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and the 11th KIAS Workshop on Particle Physics and Cosmology
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Potential of the HL-LHC to probe light fermiophobic Higgs boson signals via diphoton jets

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3rd International Joint Workshop on the Standard Model and Beyond

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Search for new physics in the τ lepton plus missing transverse momentum final state in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$

The CMS Collaboration

Abstract

A search for physics beyond the standard model (SM) in the final state with a hadronically decaying tau lepton and a neutrino is presented. This analysis is based on data recorded by the CMS experiment from proton-proton collisions at a center-of-mass energy of 13 TeV at the LHC, corresponding to a total integrated luminosity of 138 fb^{-1}. The transverse mass spectrum is analyzed for the presence of new physics. No significant deviation from the SM prediction is observed. Limits are set on the production cross section of a W' boson decaying into a tau lepton and a neutrino.

Too early to give up!

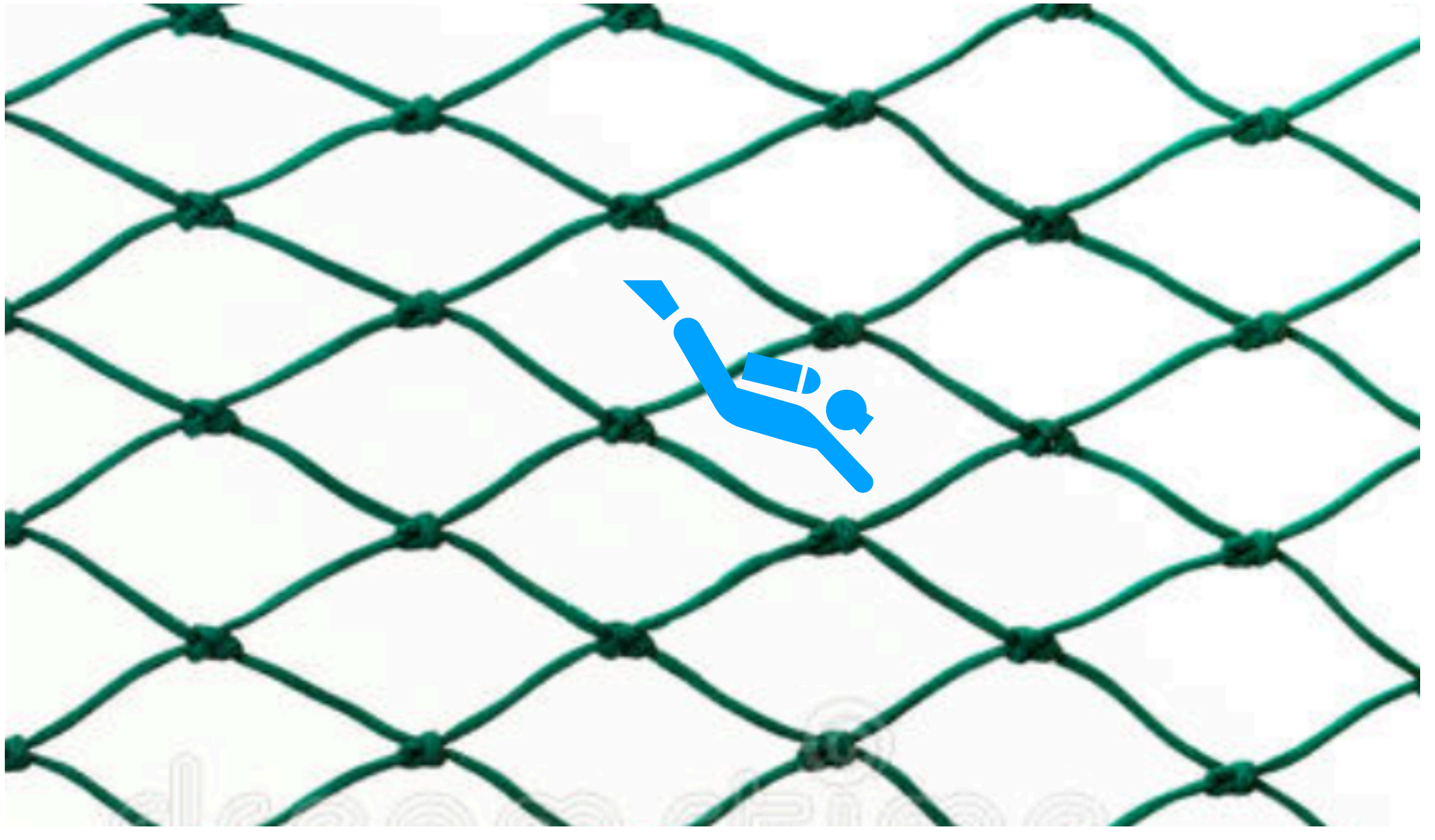
Let’s check every loophole.

What if the NP signal is hidden in the shadow under the lamp?

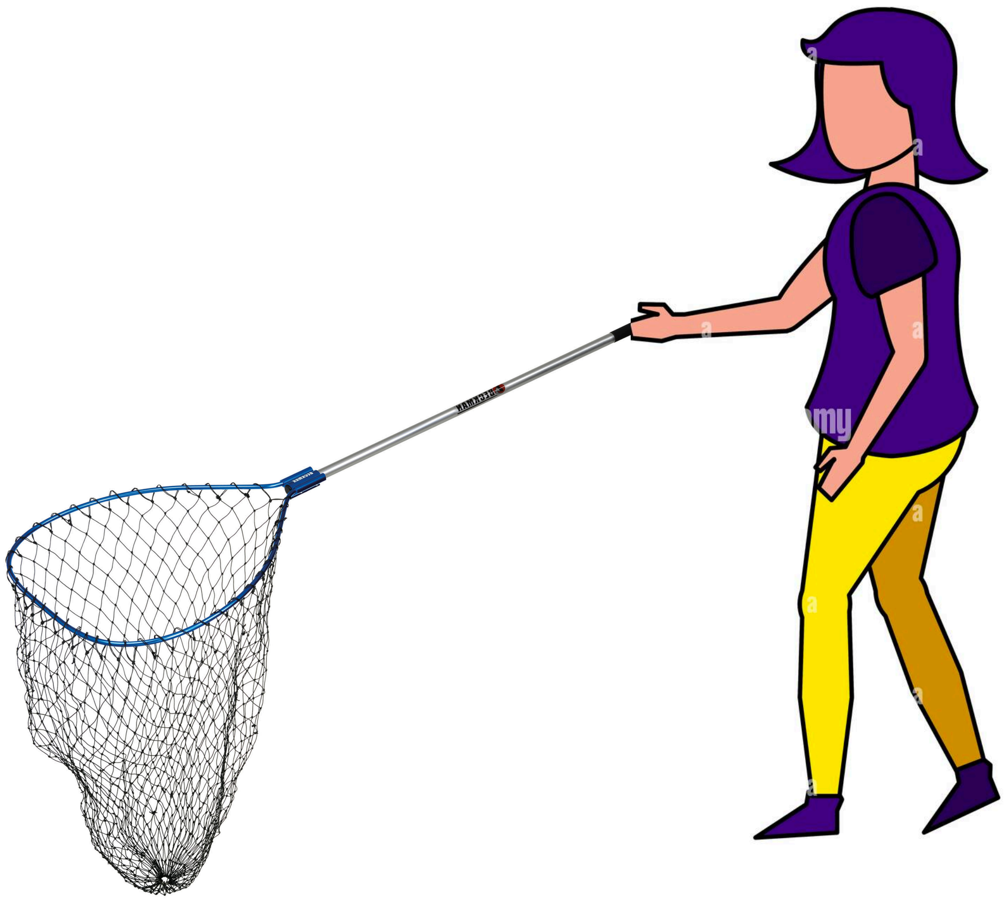
We have been missing the signal.

Two explanations

1. The new particle is generically elusive at the LHC.



2. We did not search the right place.



A new particle
which satisfies two conditions:

Very light fermiophobic Higgs boson
in type-I 2HDM

1. Very light fermiophobic Higgs boson in Type-I 2HDM

2. Jet subparticles and pileups

3. Cut-based analysis

4. Mass reconstructions

5. Machine Learning Techniques

6. Conclusions

1. Very light fermiophobic Higgs boson in Type-I 2HDM

- Two Higgs doublet fields

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

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

- Discrete Z_2 symmetry to avoid tree-level FCNC

$$\boxed{\Phi_1 \to \Phi_1, \quad \Phi_2 \to -\Phi_1}$$

- SM Higgs boson: a linear combination of 2 CP-even Higgs bosons

$$\boxed{h_{\rm SM} = s_{\beta-\alpha} h + c_{\beta-\alpha} H.}$$

Two setups in Type-I

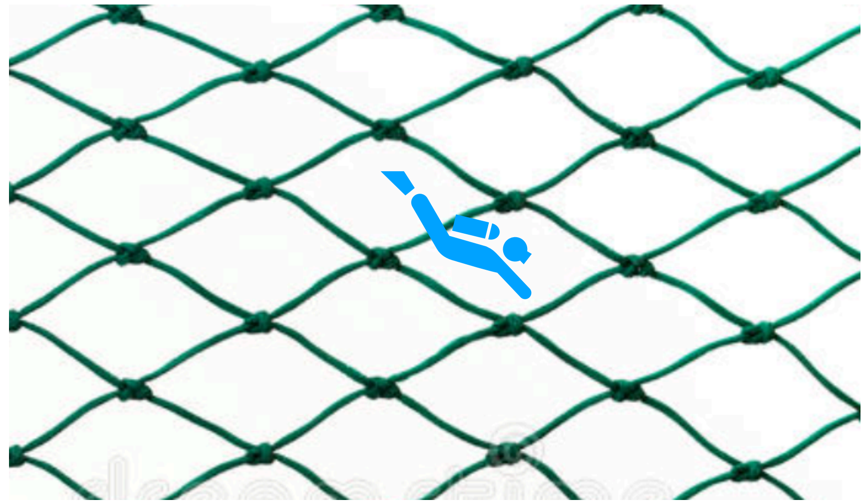
1. Inverted Higgs scenario

2. Fermiophobic light CP-even Higgs boson

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

$$\xi_f^h = \cancelto{\mathbf{0}}{\frac{c_\alpha}{s_\beta}}, \quad \kappa_f^H = \frac{s_\alpha}{s_\beta}, \quad \xi_t^A = -\xi_b^A = -\xi_\tau^A = \frac{1}{t_\beta}.$$

h_f **: fermiophobic Higgs boson**



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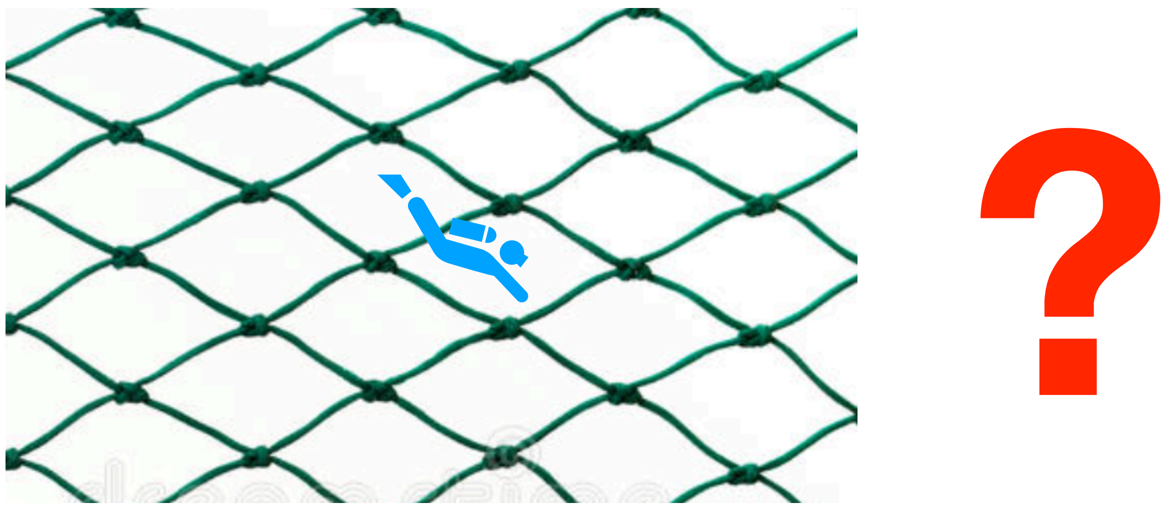
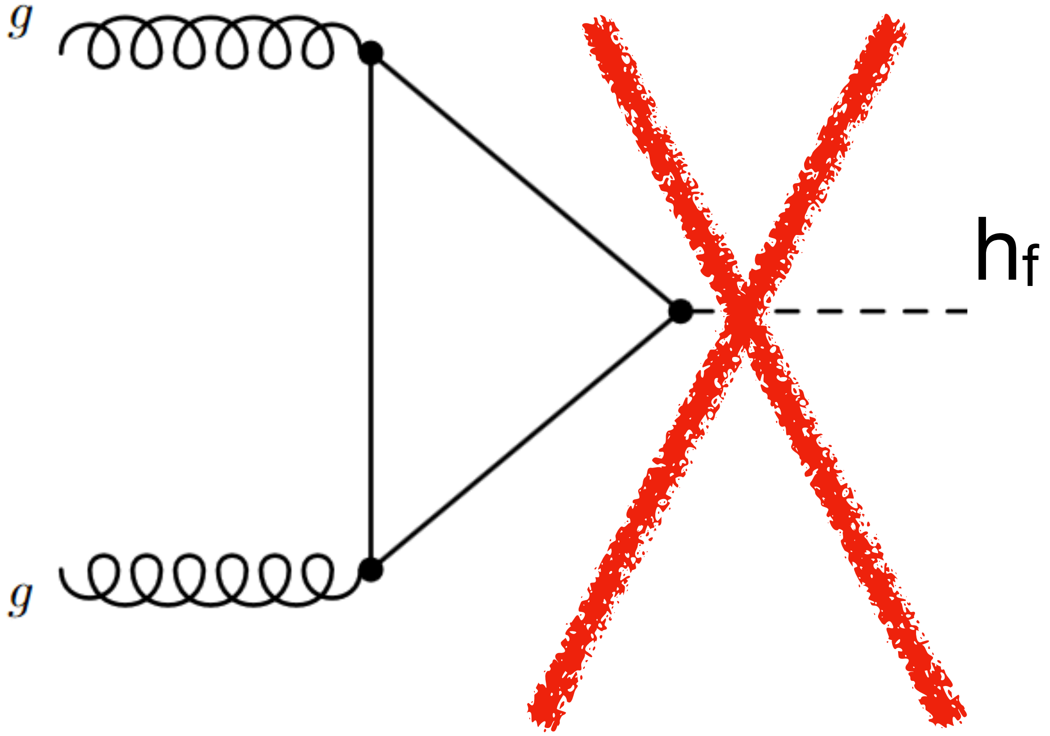
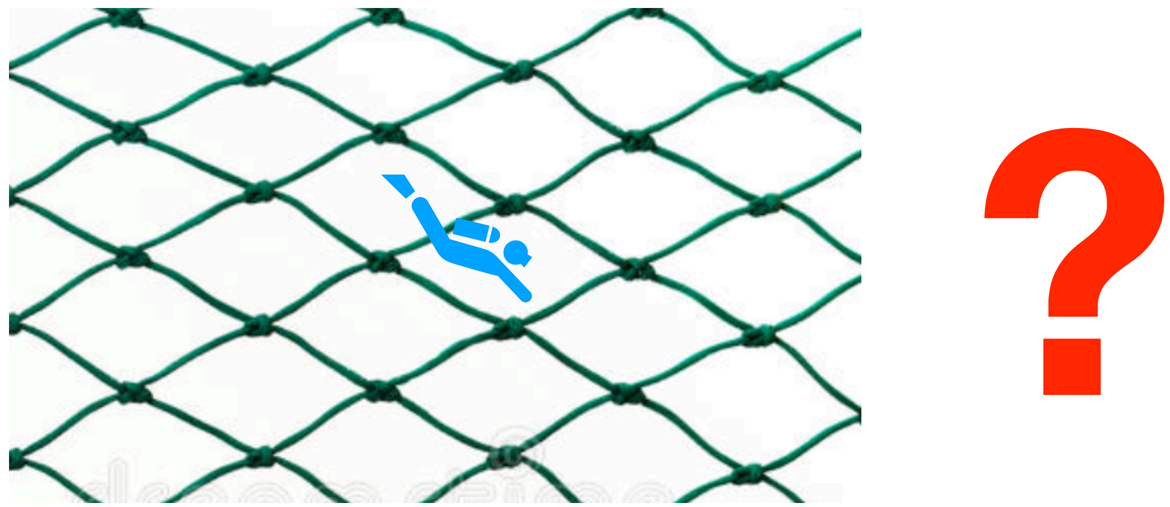
Why is h_f elusive?
Production is suppressed.





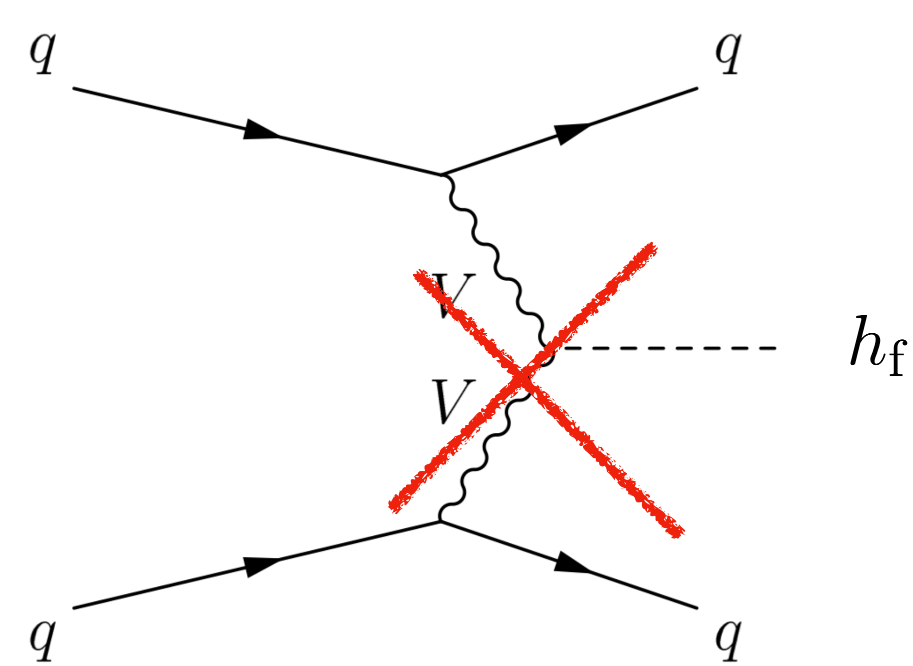
Gluon fusion productions are prohibited!



VBF is also prohibited!

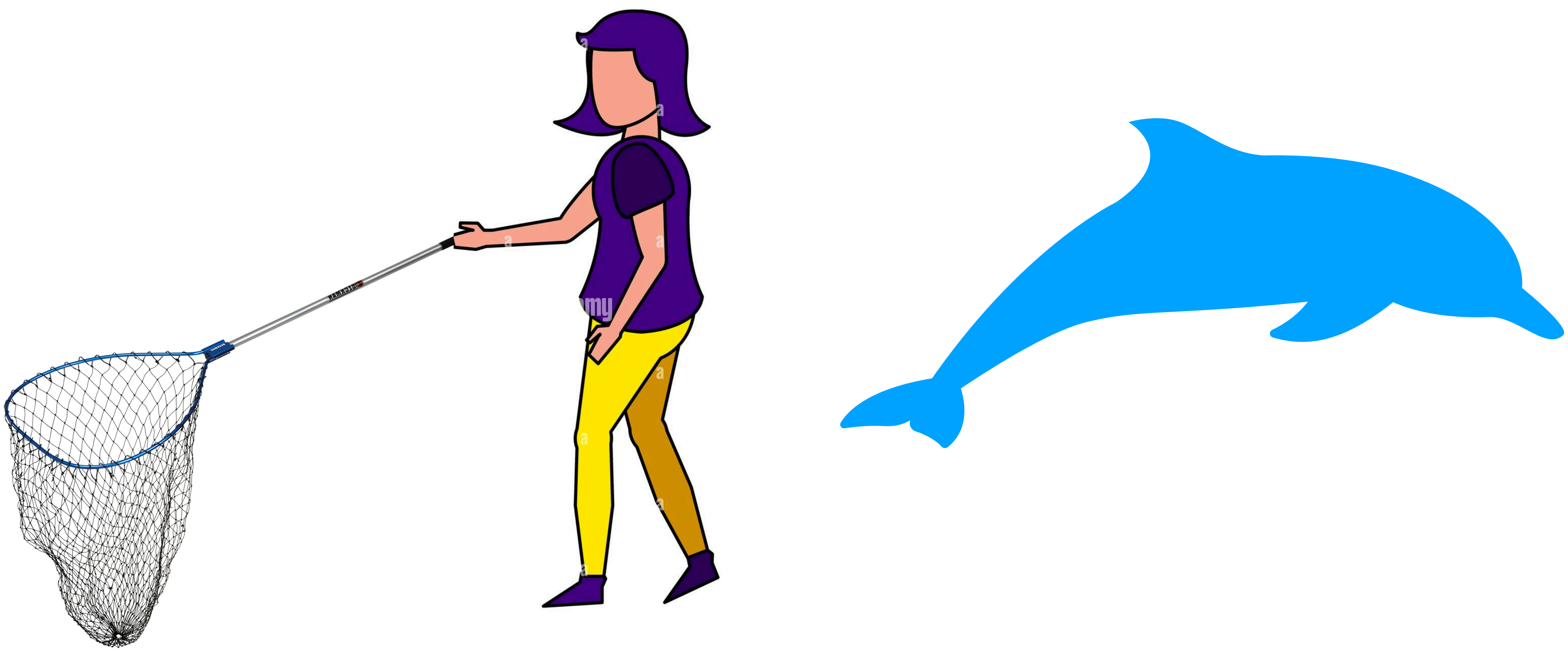
- Near the Higgs alignment limit:

$$\boxed{c_{\beta-\alpha} \simeq 1 \Longrightarrow g_{h_{\rm f}-V-V} \simeq 0}$$



What about the decay modes?
Are we really searching the wrong place?

We need to obtain the viable parameter space.



(1) Theoretical stabilities

— Scalar potential bounded from below

— Perturbative unitarity of scalar-scalar scattering at tree level

— Vacuum stability

— cutoff scale > 10 TeV

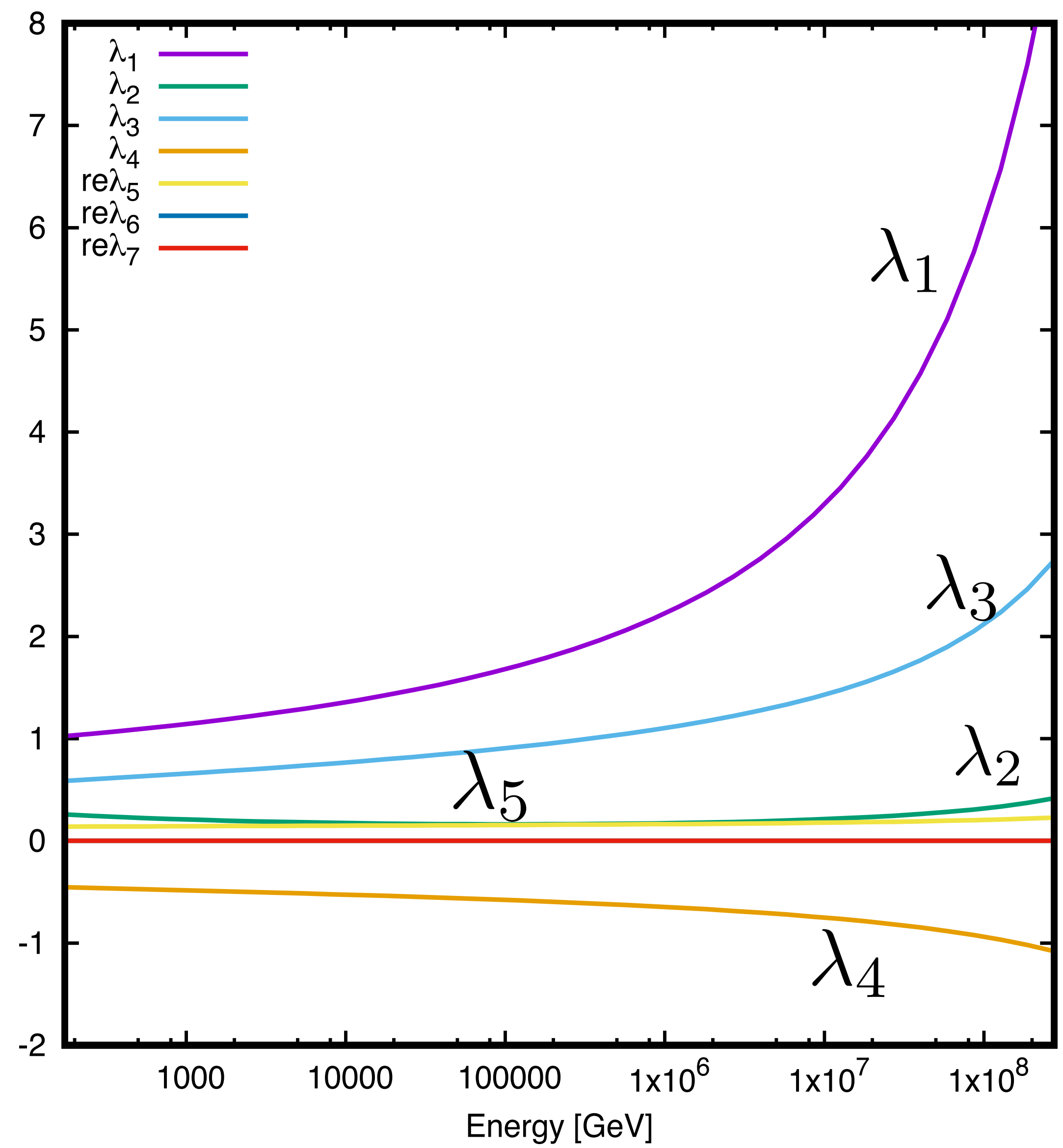
(2) Experimental constraints

— B physics

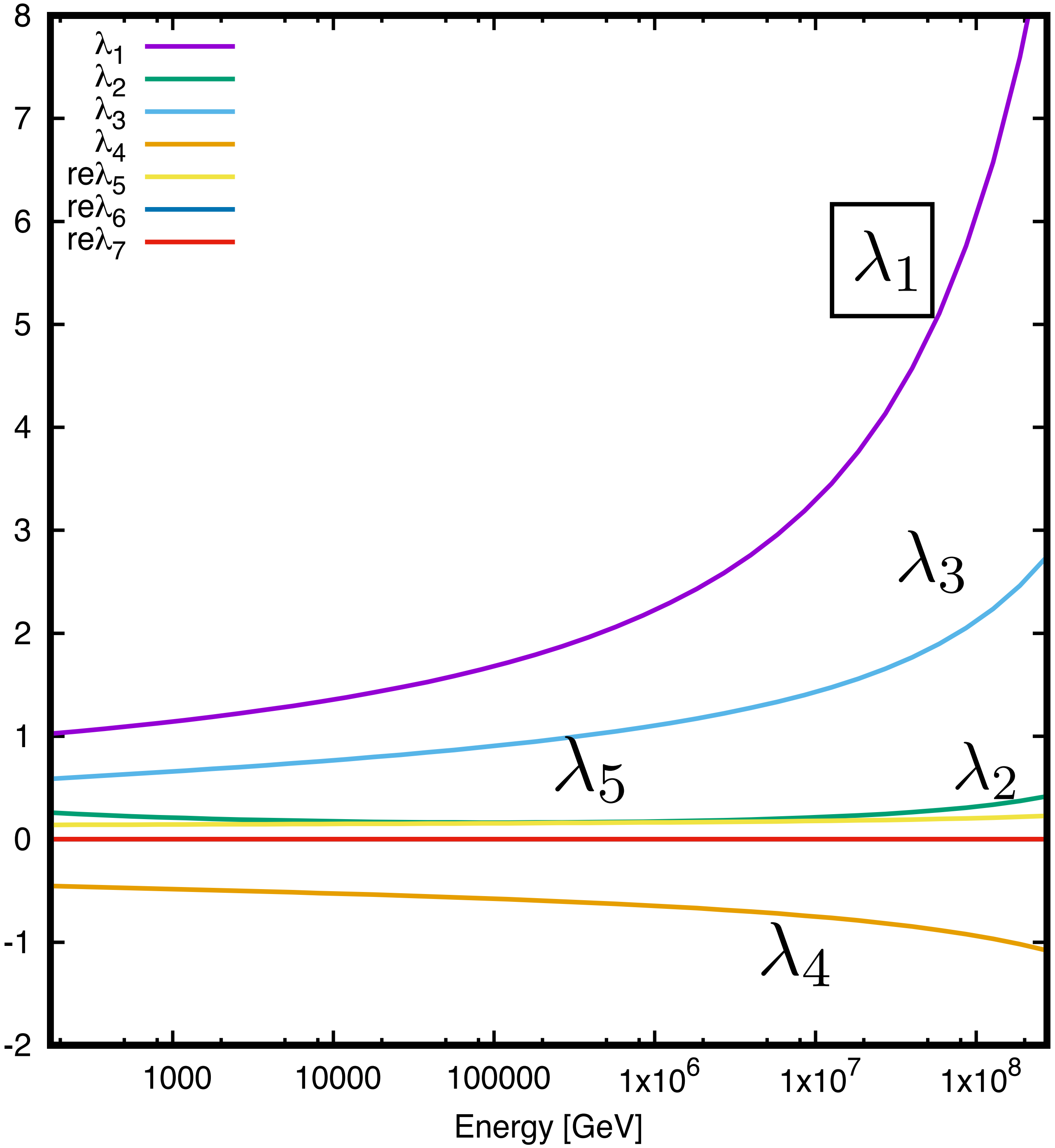
— Higgs precision data via HiggsSignals

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

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



- Quartic couplings can be very large at high energy scale.



Theoretical stability is broken at Λ.

⬇

NP is not valid at Λ.

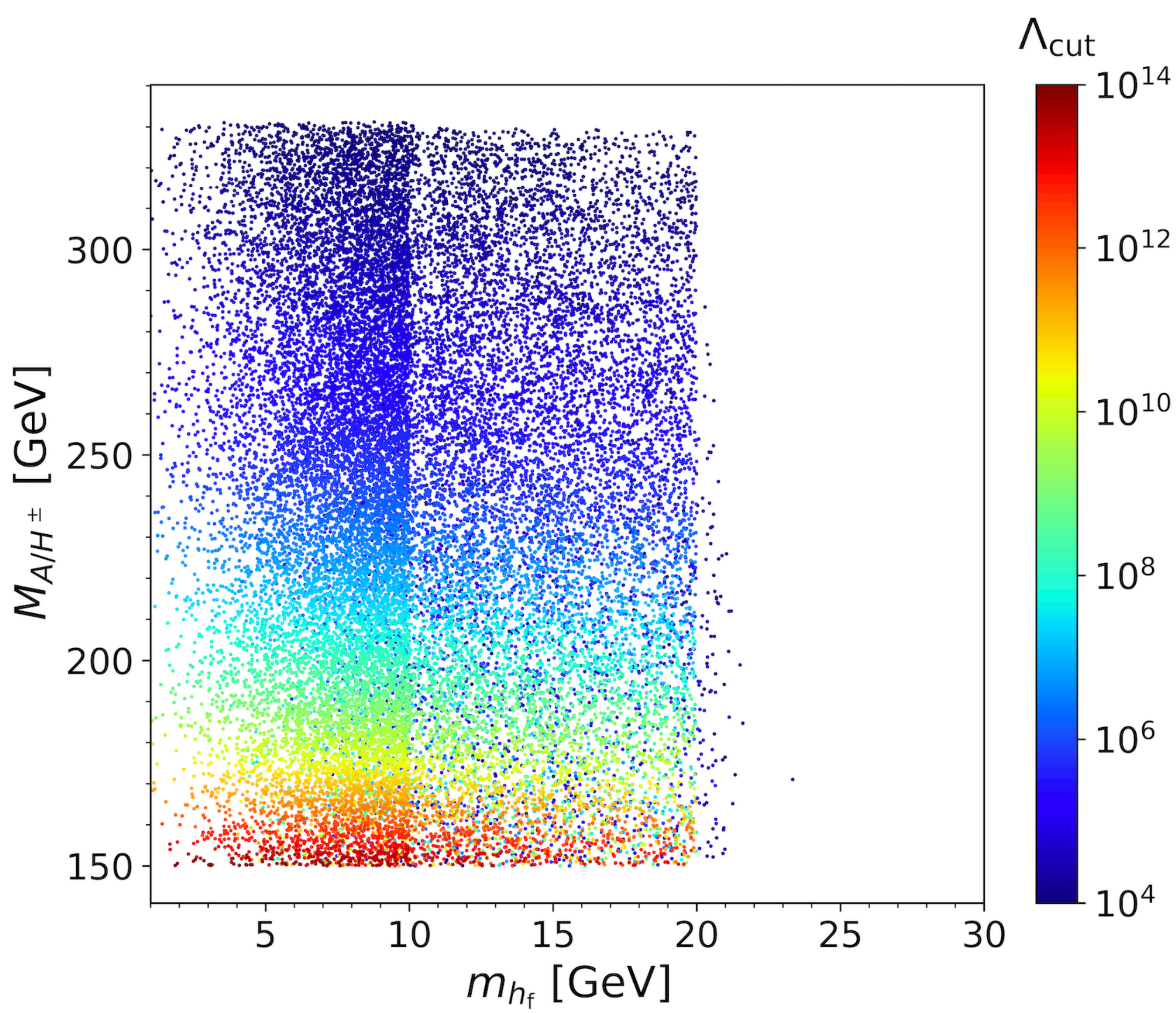
⬇

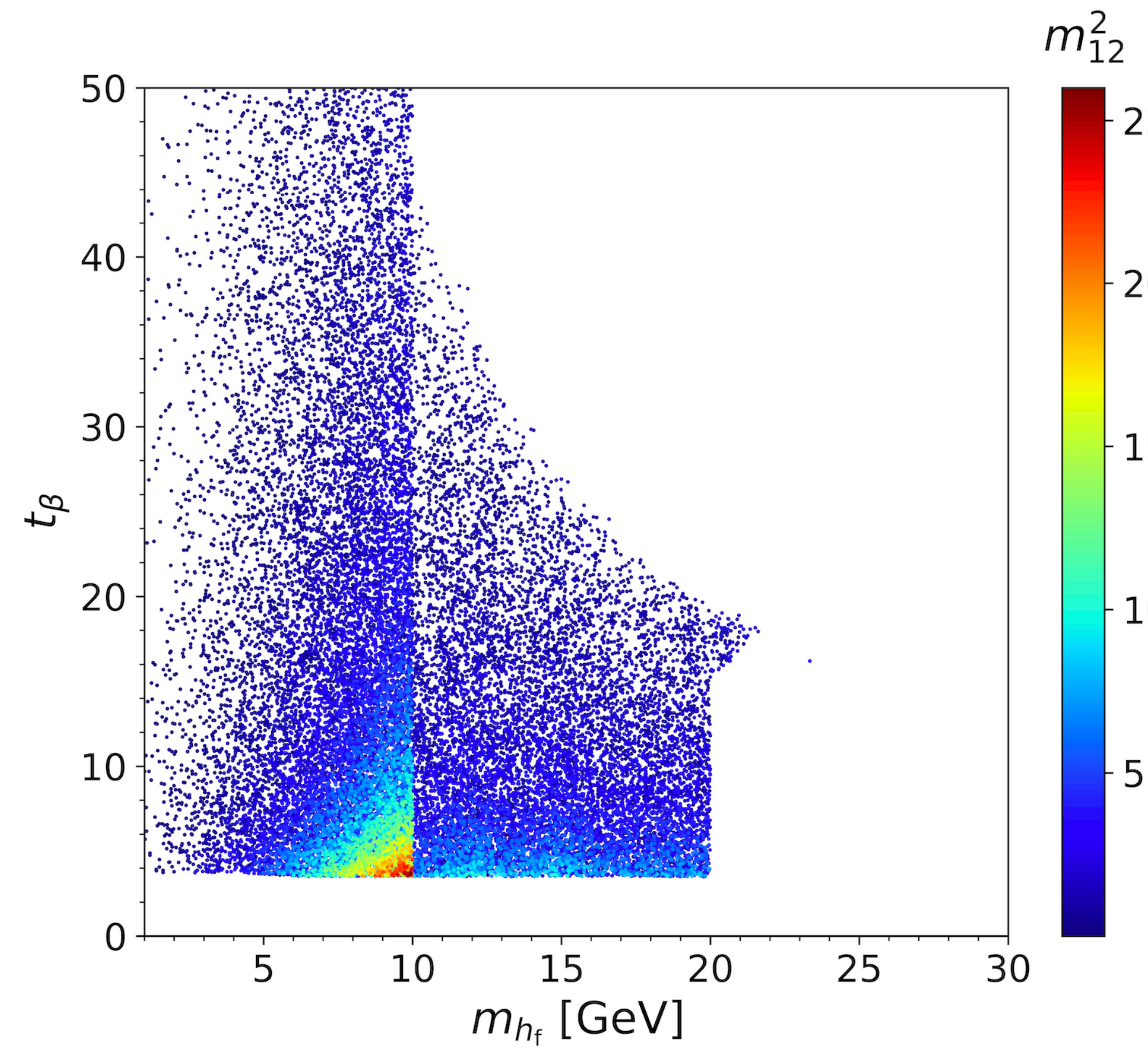
Λ is the cutoff scale of NP.

Focusing on the light fermion phobic Higgs boson, Let's scan the parameter space.

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

Viable parameter space





- Charge Higgs boson and A masses below about 330 GeV.
- Survival rate is high for m_{h_f} in [1,10] GeV.

Very light fermion phobic Higgs boson.

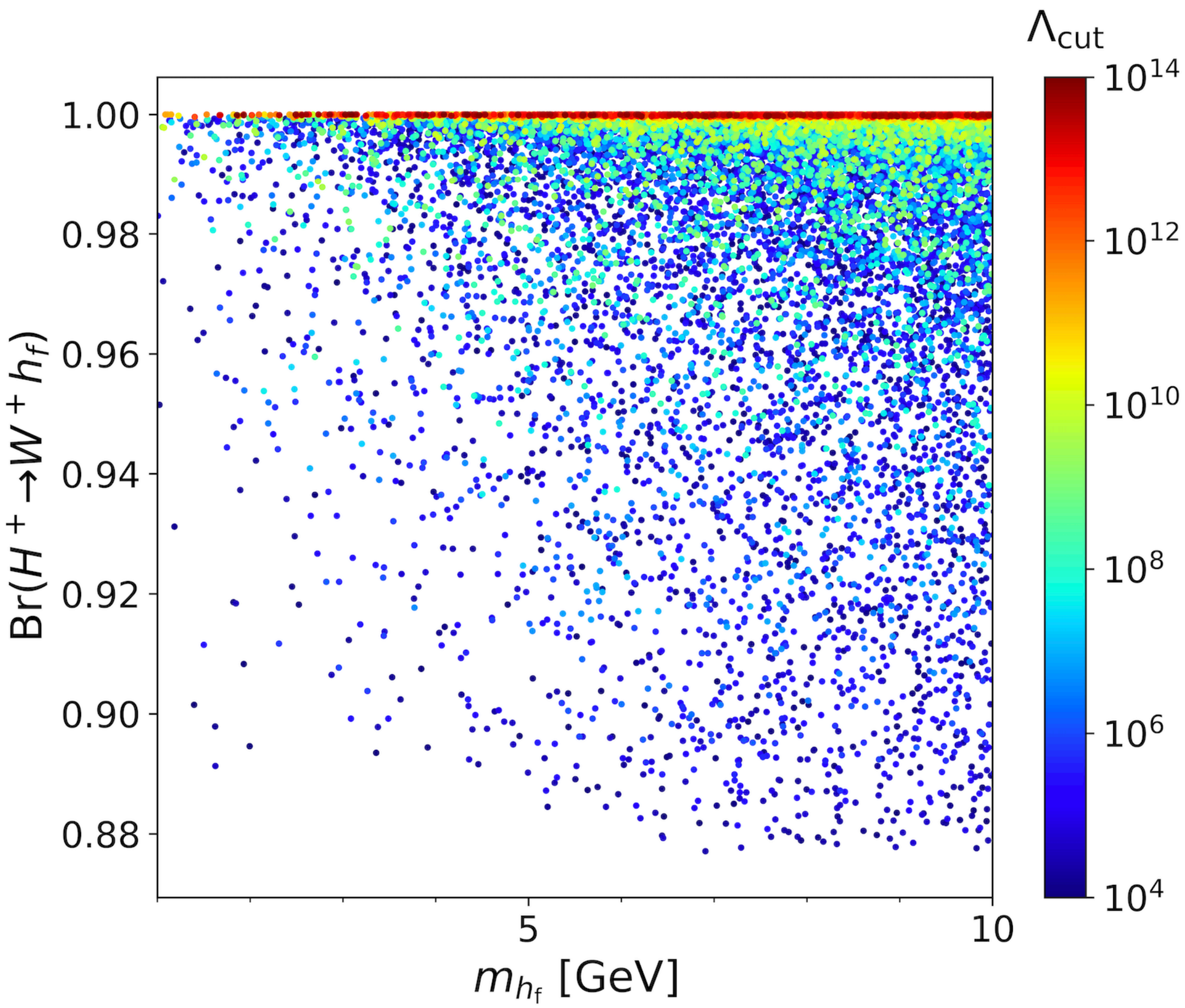
$$m_{h_{\rm f}} \in [1, 10]\ \mathrm{GeV}.$$

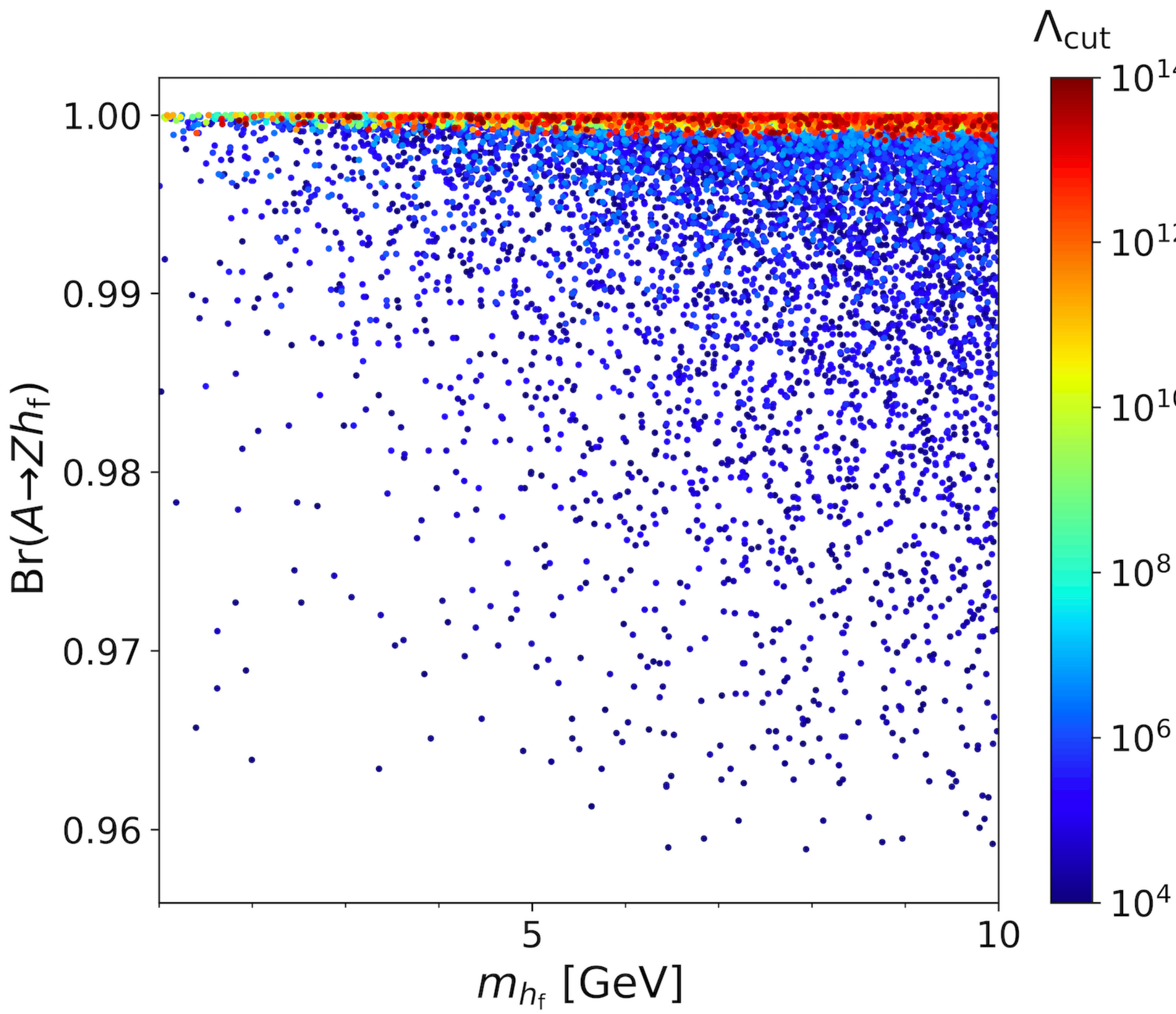
Unexplored!!

Almost fixed decay modes

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

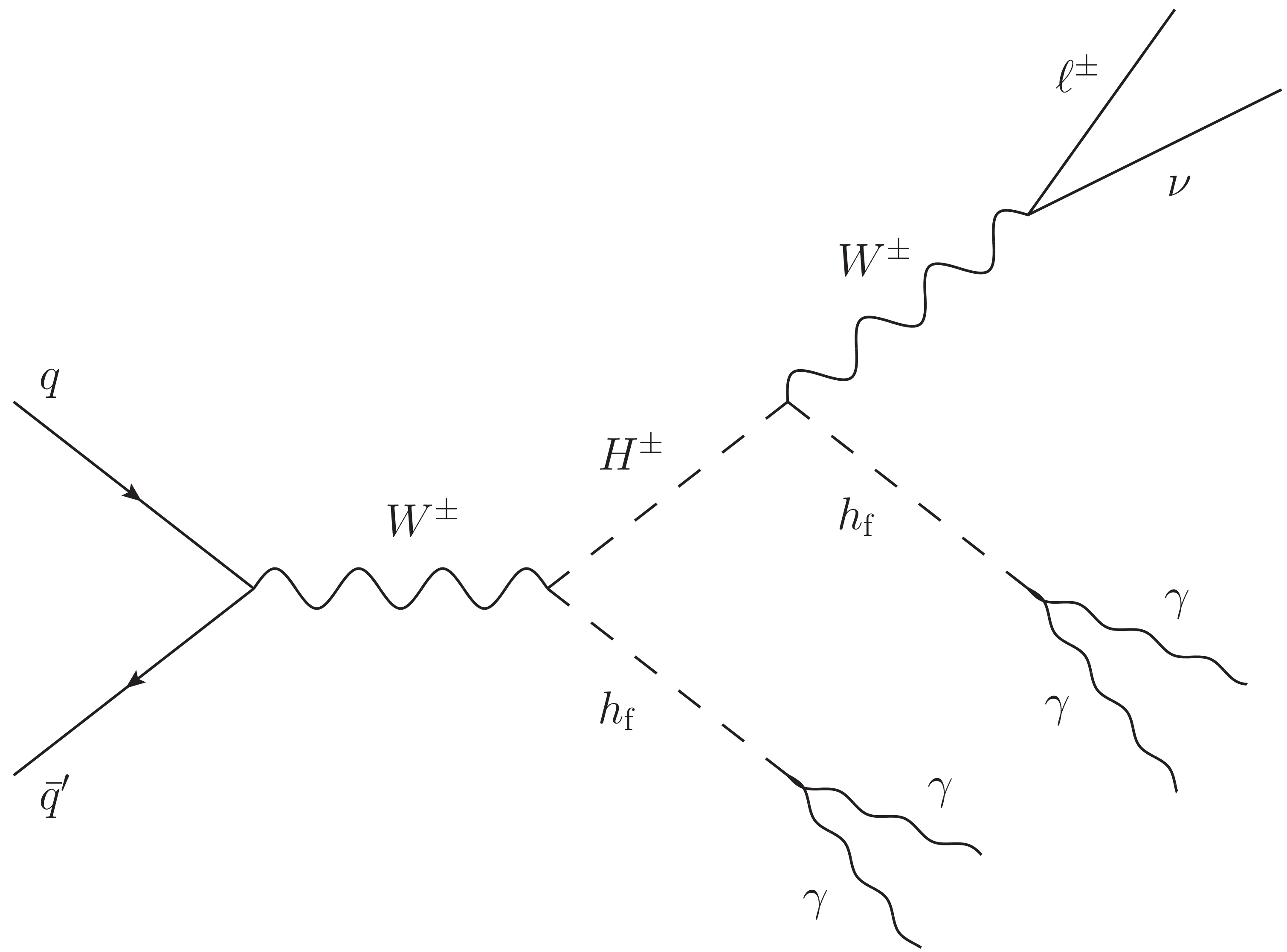
Almost fixed decay modes for $H^{\pm}, A$



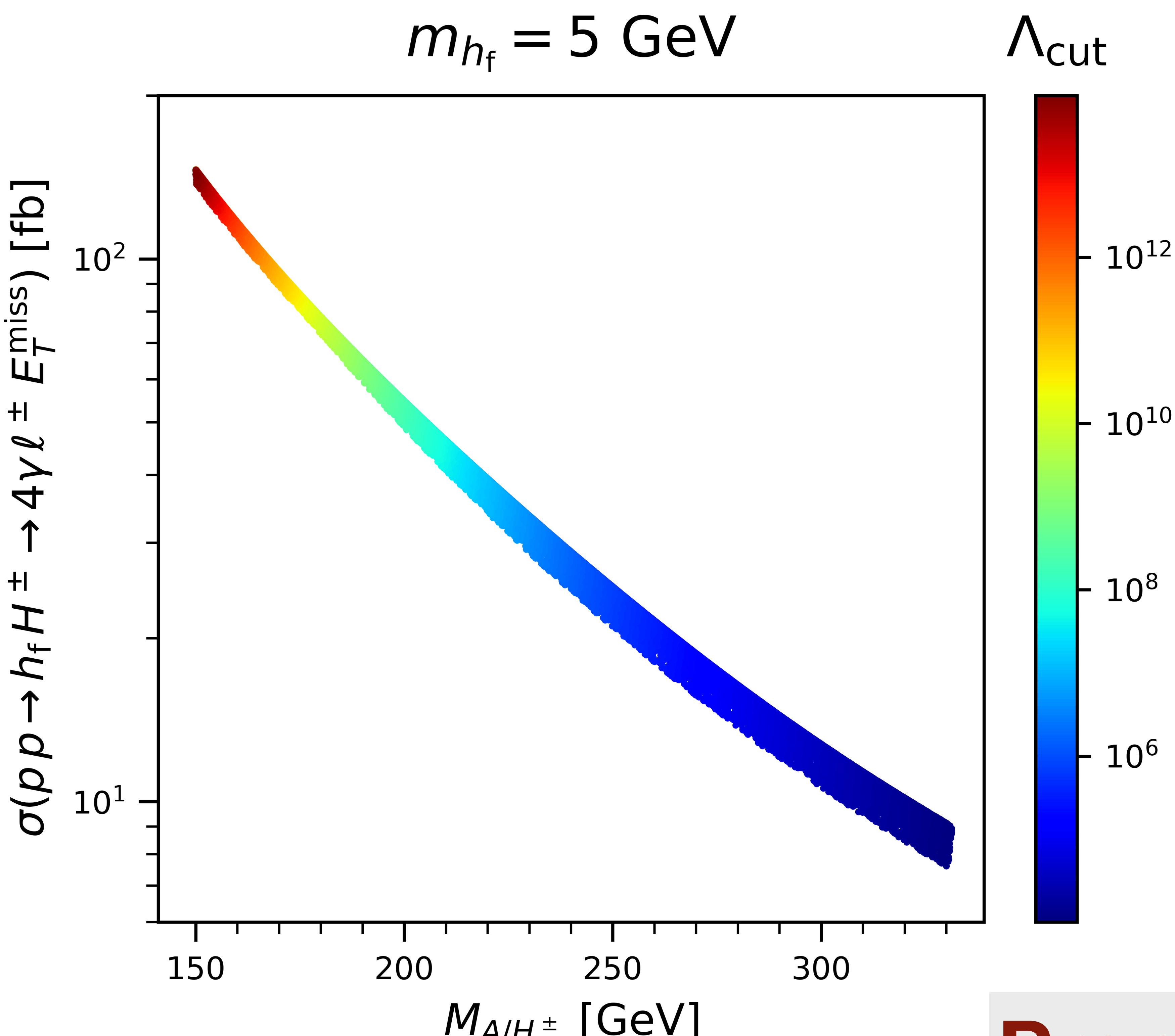


Golden discovery mode at the HL-LHC

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

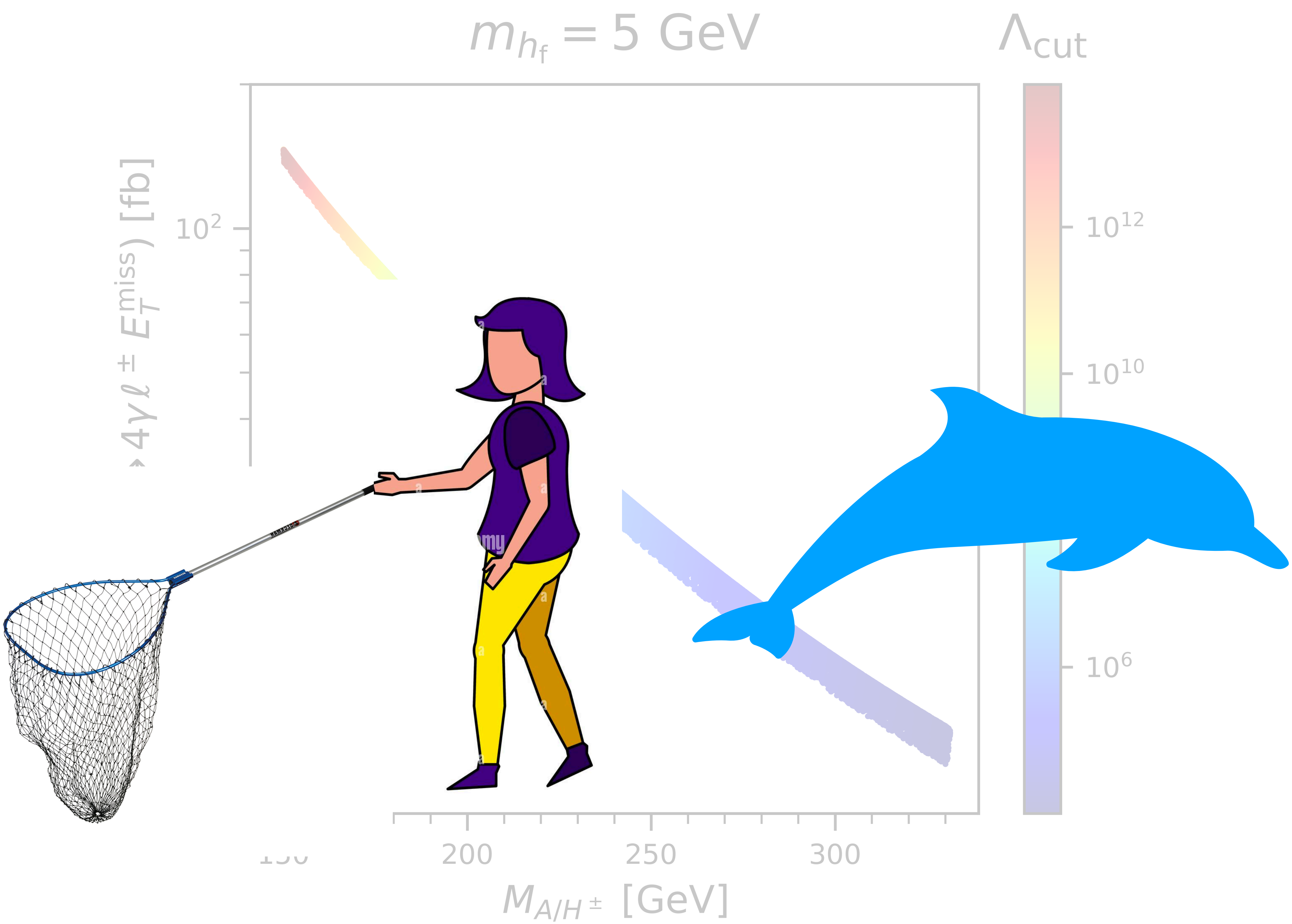


Sizable cross sections



Promising?

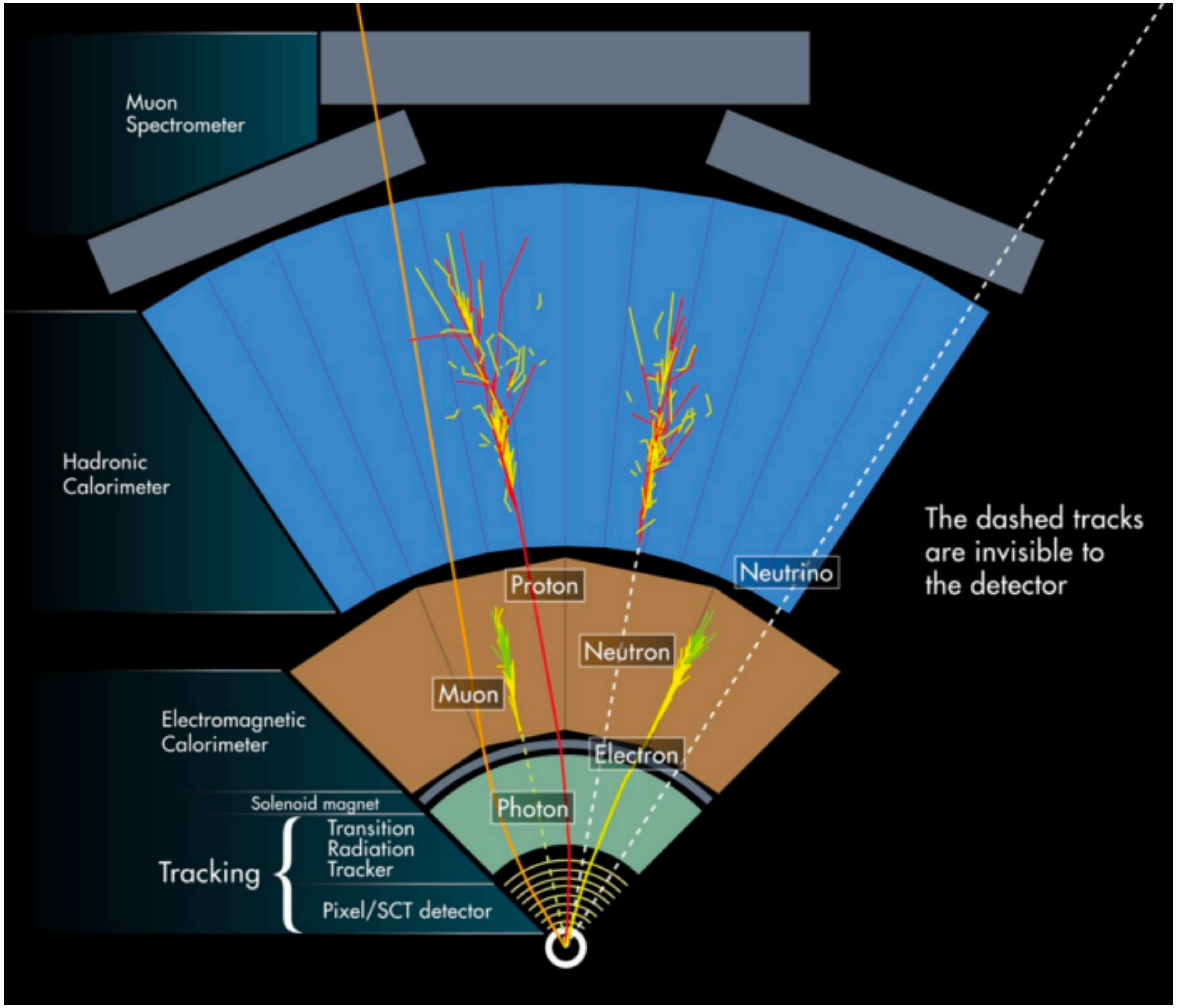
Why we are missing?



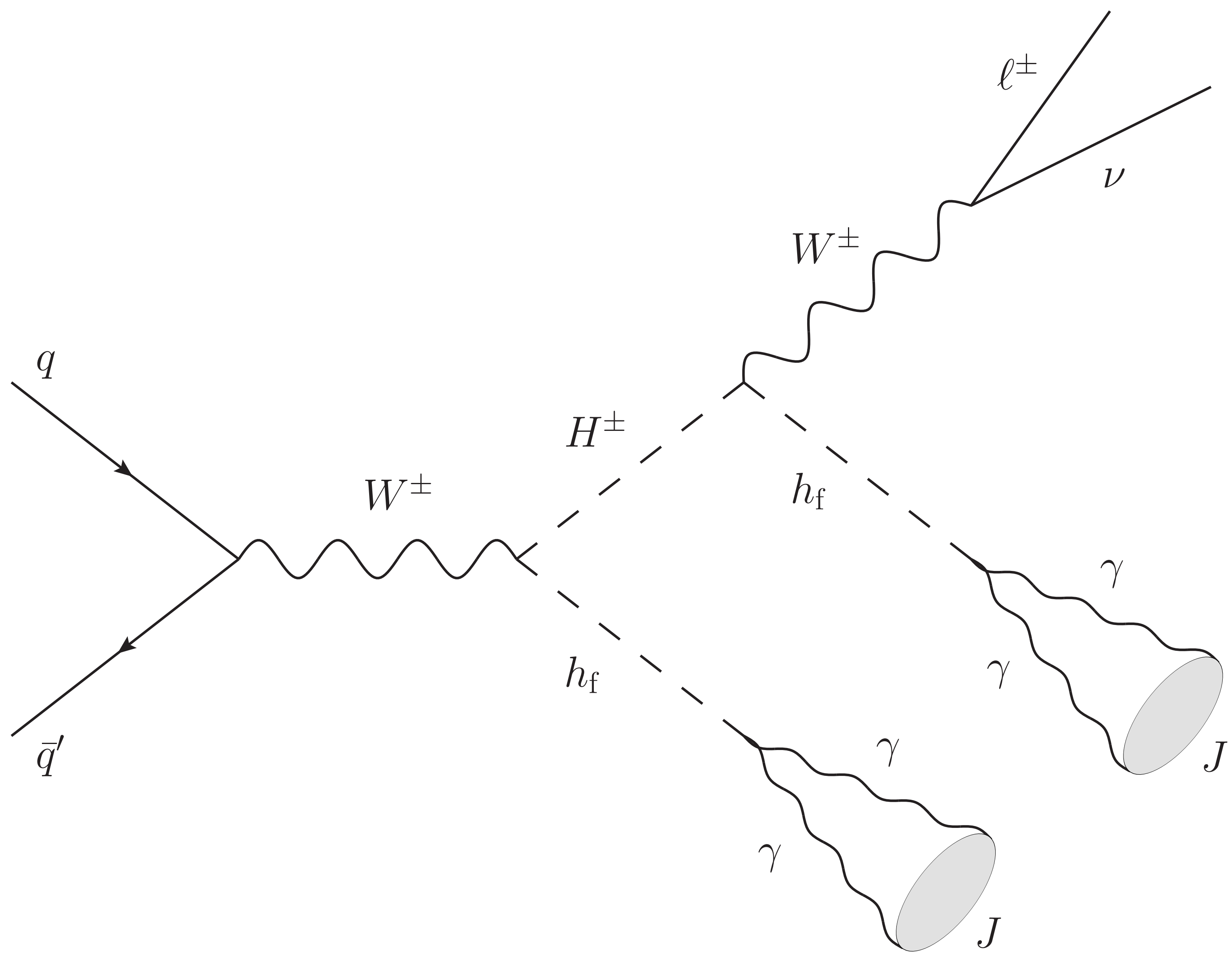
Light mass in [1,10] GeV

➡ Highly collimated two photons

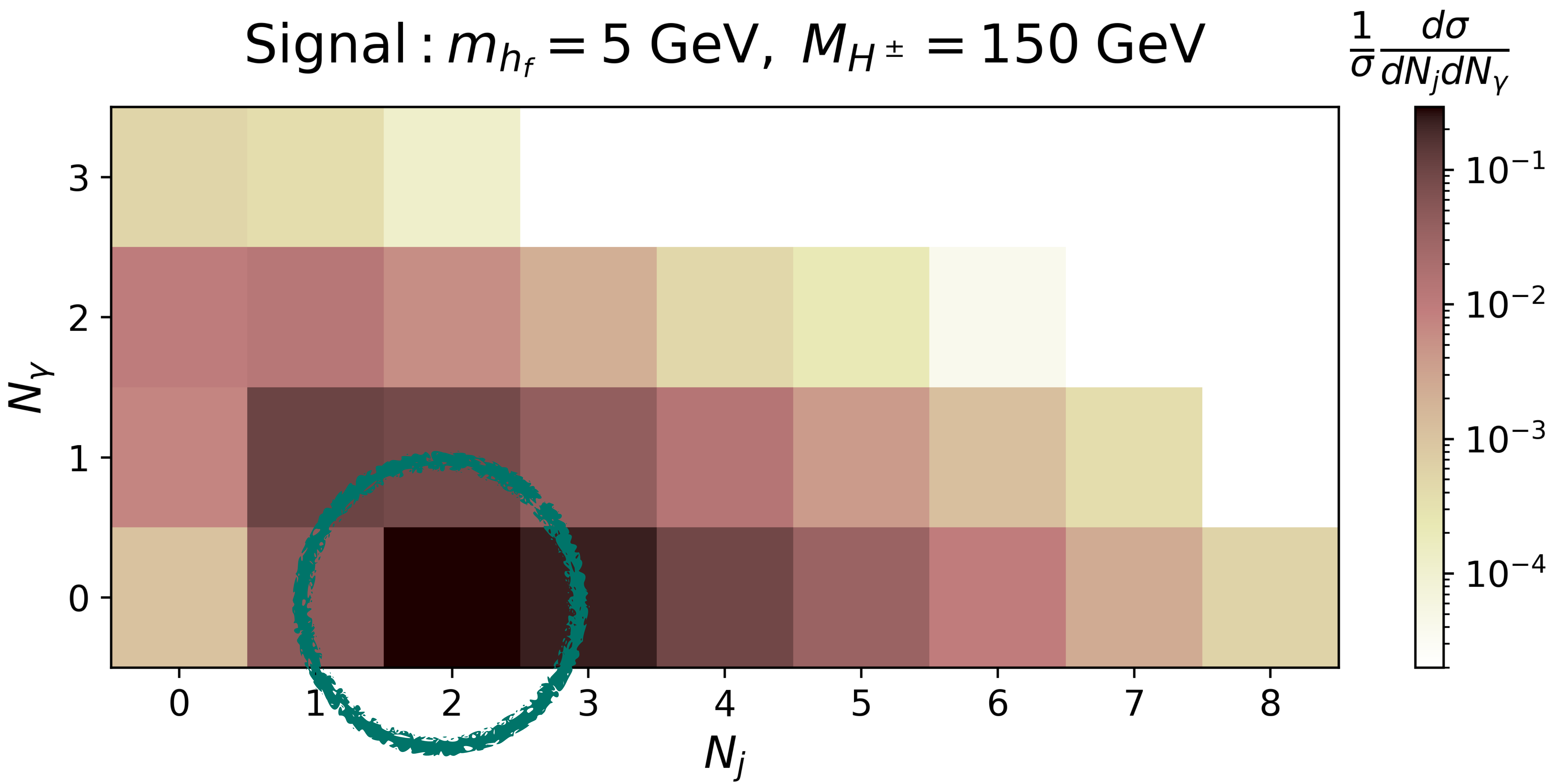
➡ Failing photon isolation!



Two collimated photons are tagged as a jet



The signal appears as two jets!

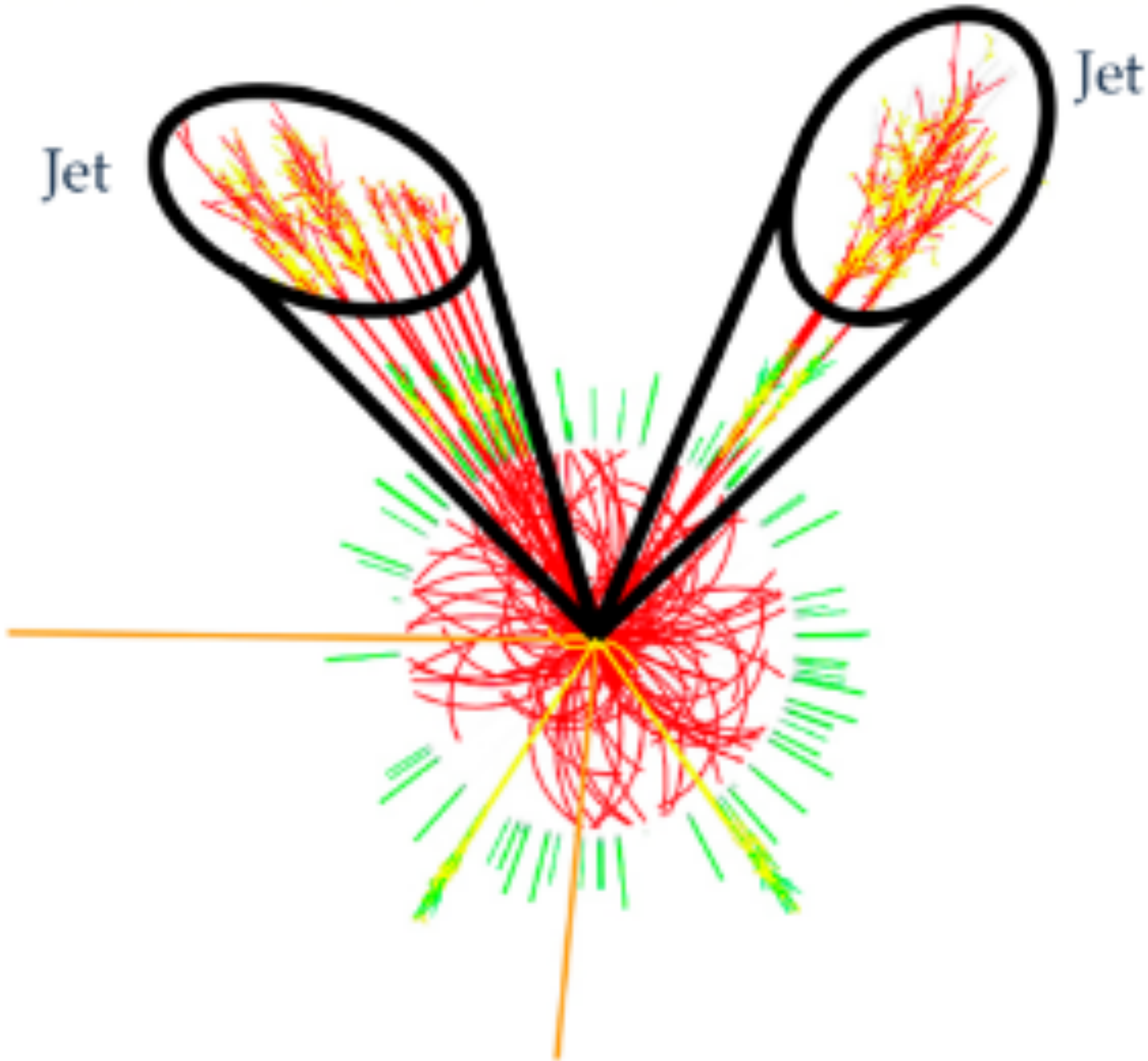


Huge QCD backgrounds!!

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

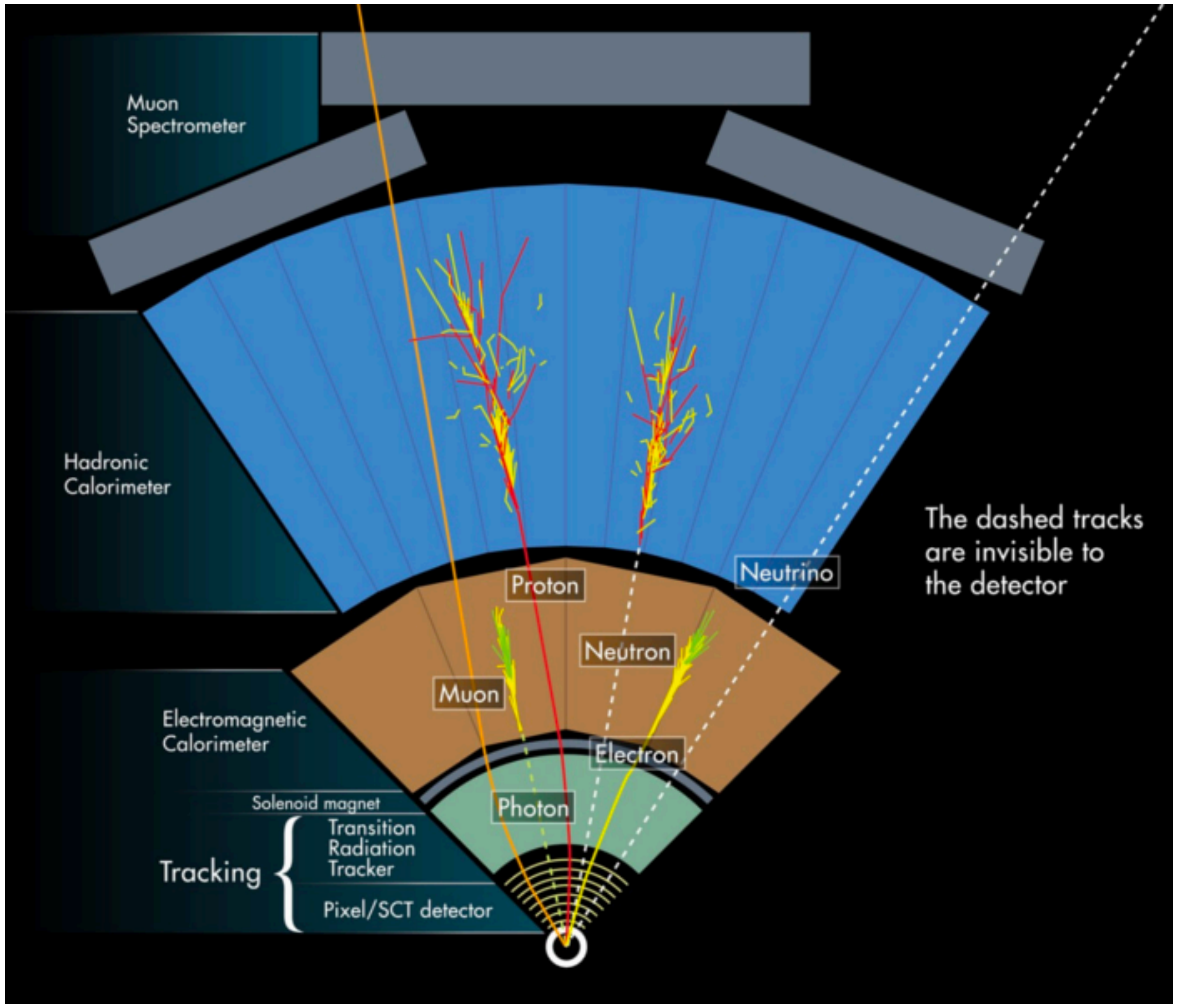
We need to look inside the jets!

2. Jet subparticles and pileups



A jet consists of many subparticles

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



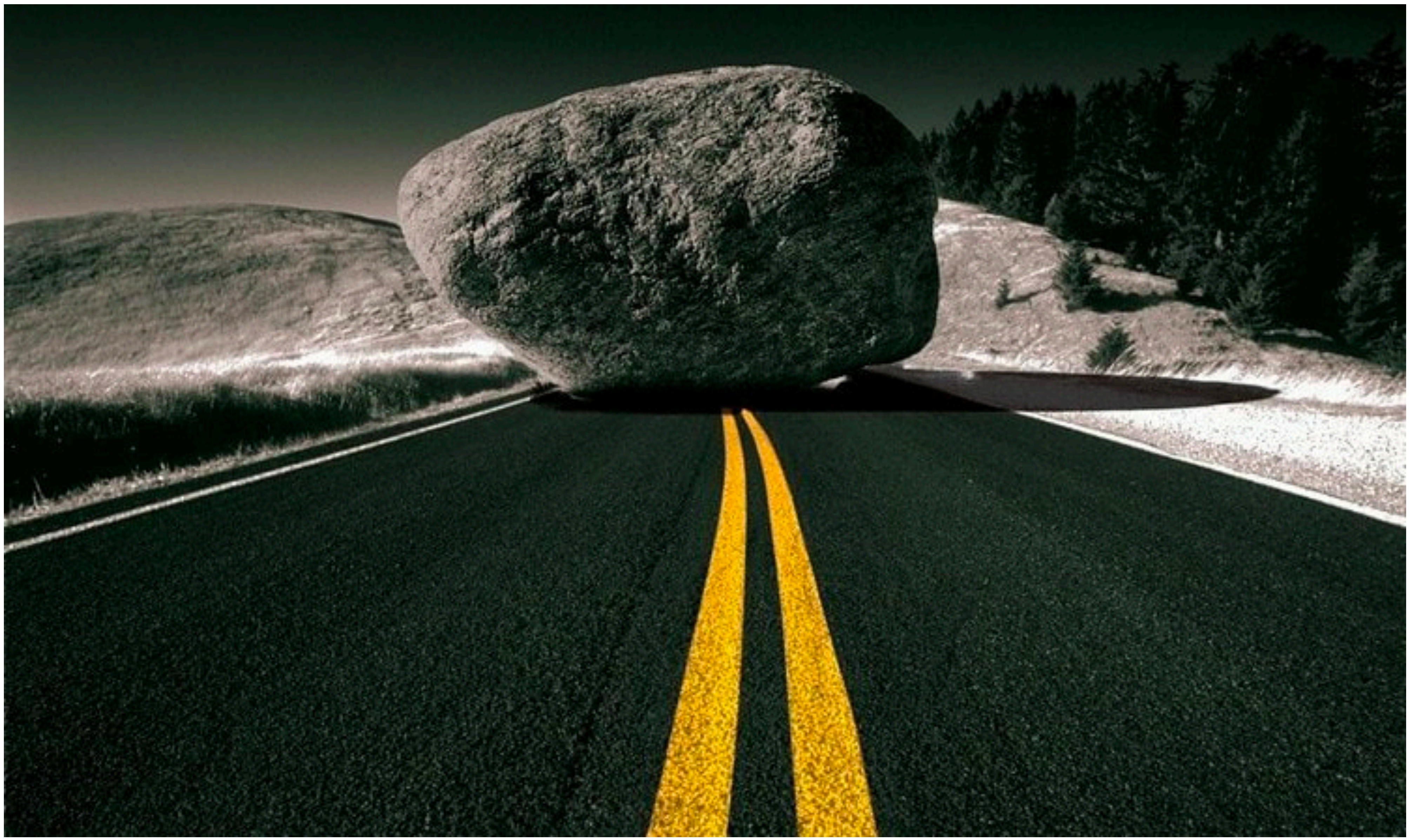
	With track	Without track
ECAL	Electron	EFlowPhoton
HCAL	EFlowChargedHadron	EFlowNeutralHadron

The signal jet should consist of two photons!

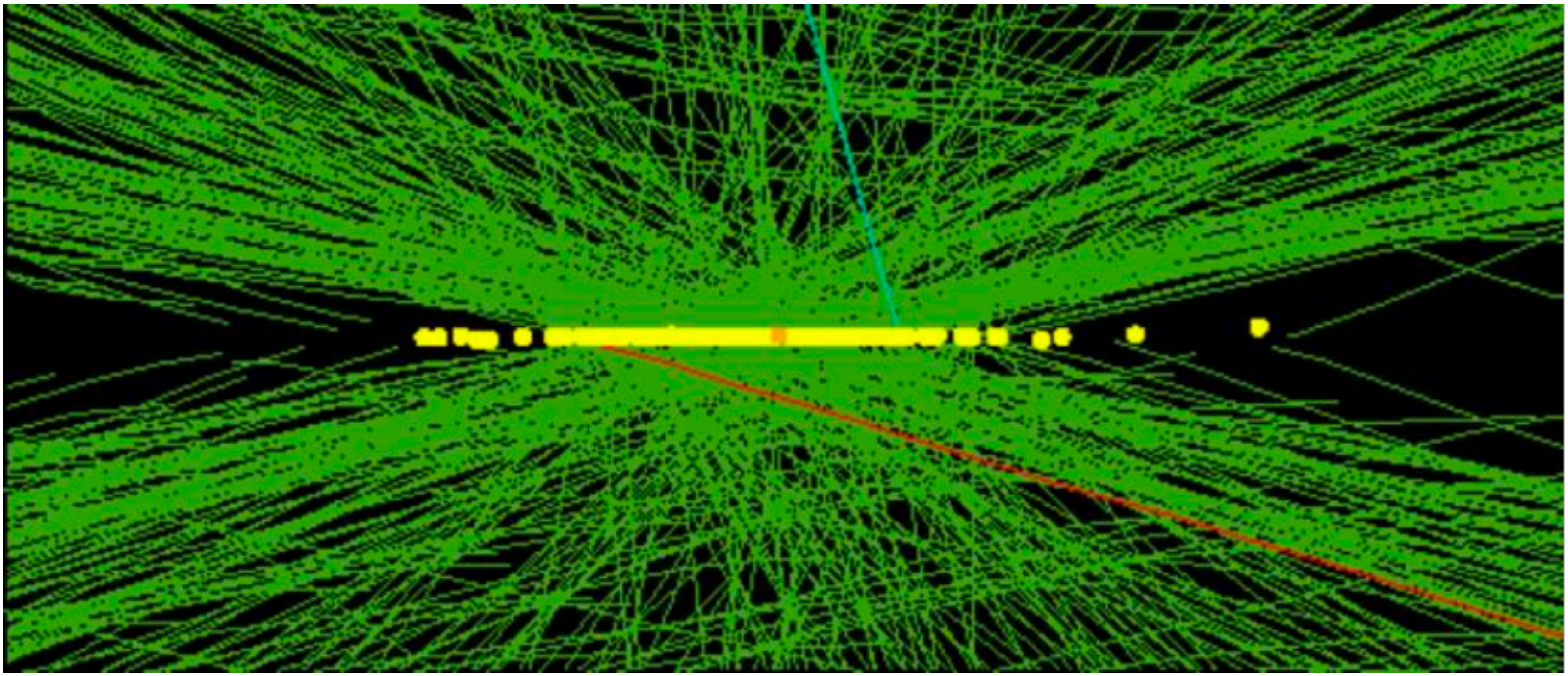
Diphoton jet

BUT

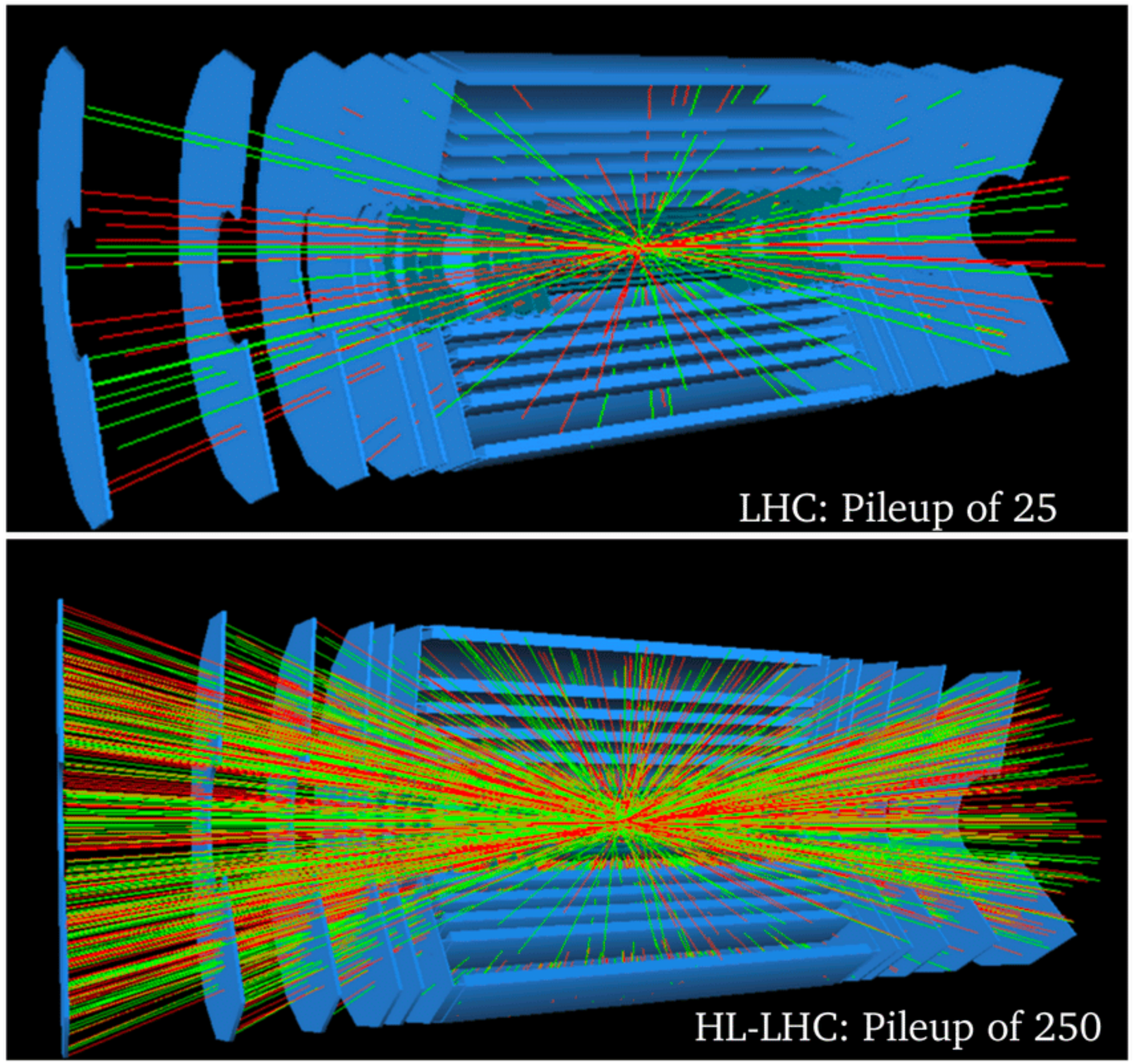
Big obstacle!



200 Pileups at the HL-LHC



200 Pileups at the HL-LHC could blur the diphoton jet.

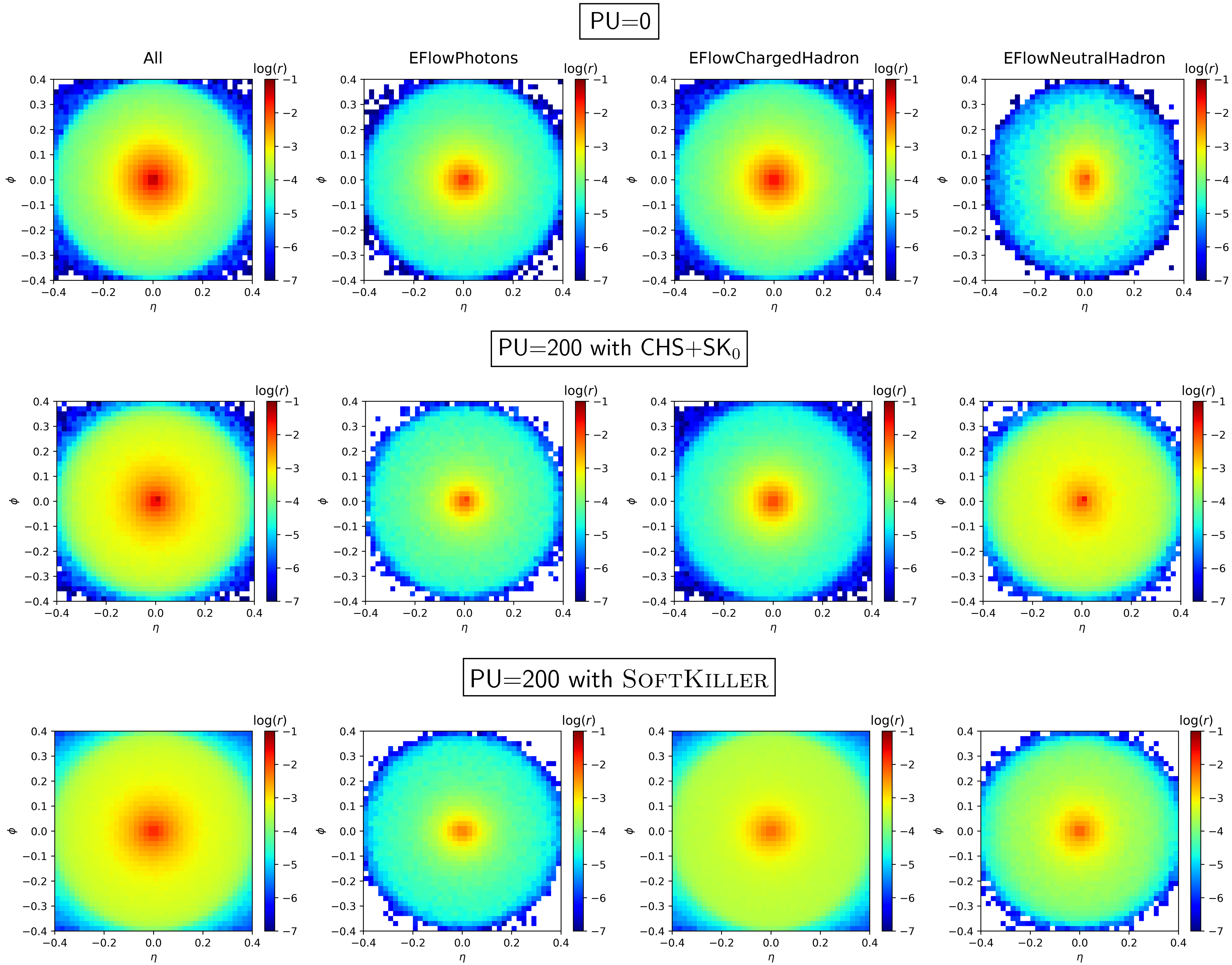


Pileup subtraction is crucial.

Pileup subtraction is important. Hybrid method: CHS + SoftKiller$_0$

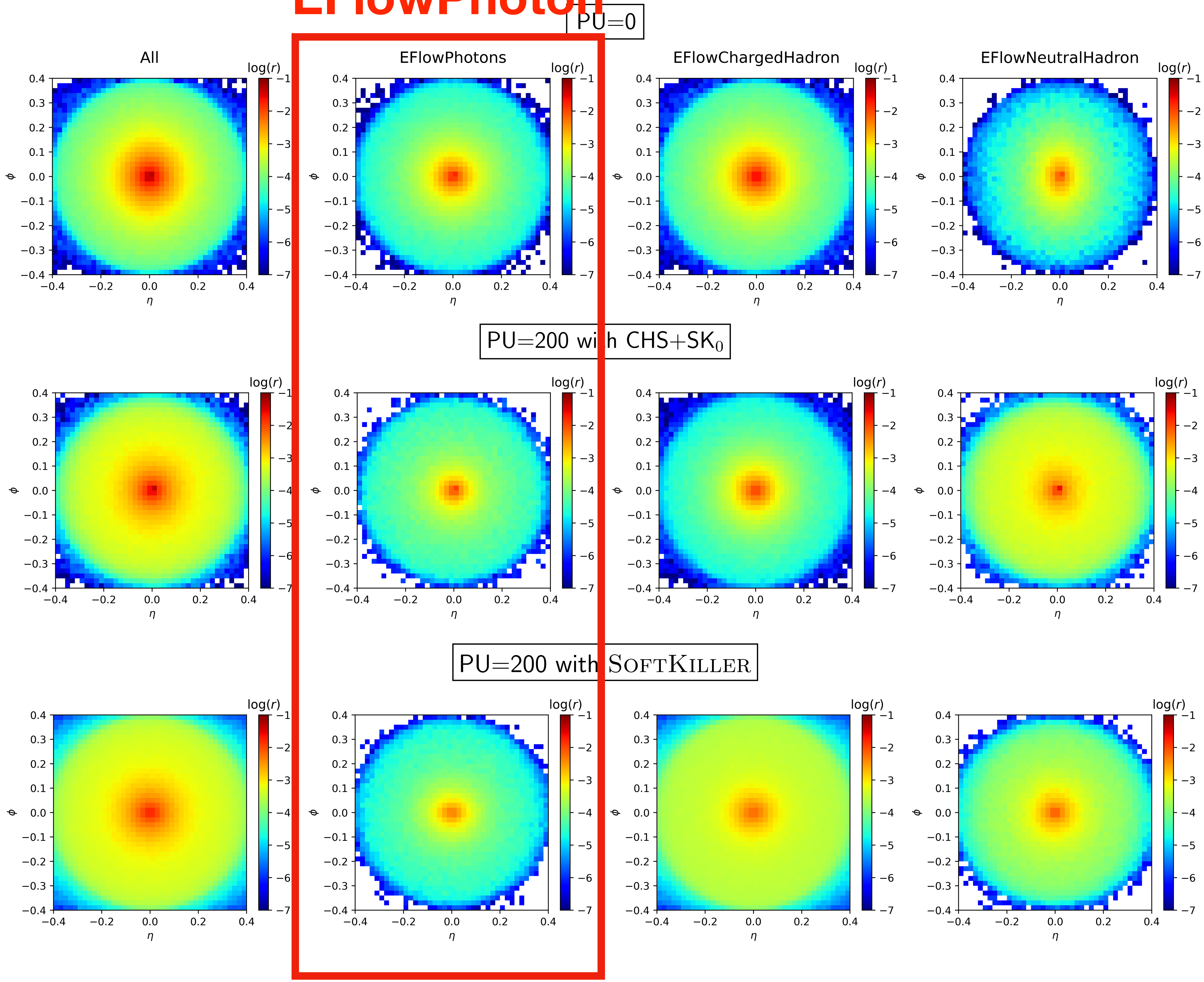
- Charged Hadron Subtraction (CHS) removes charged pileup particles
- SoftKiller removes neutral pileup particles

Jet images to demonstrate the superiority of CHS+SK0

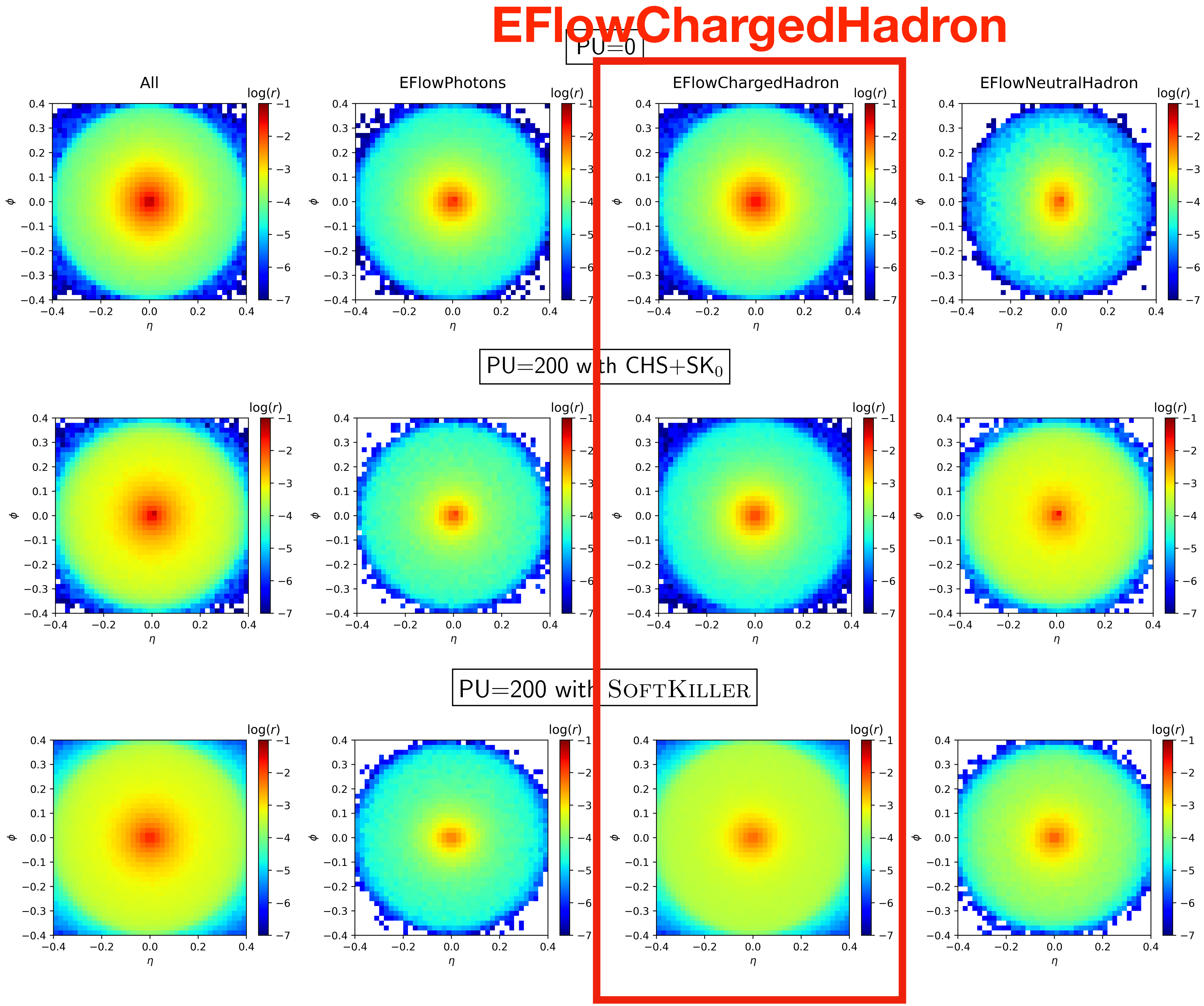


Jet images to demonstrate the superior of CHS+SK0

EFlowPhoton

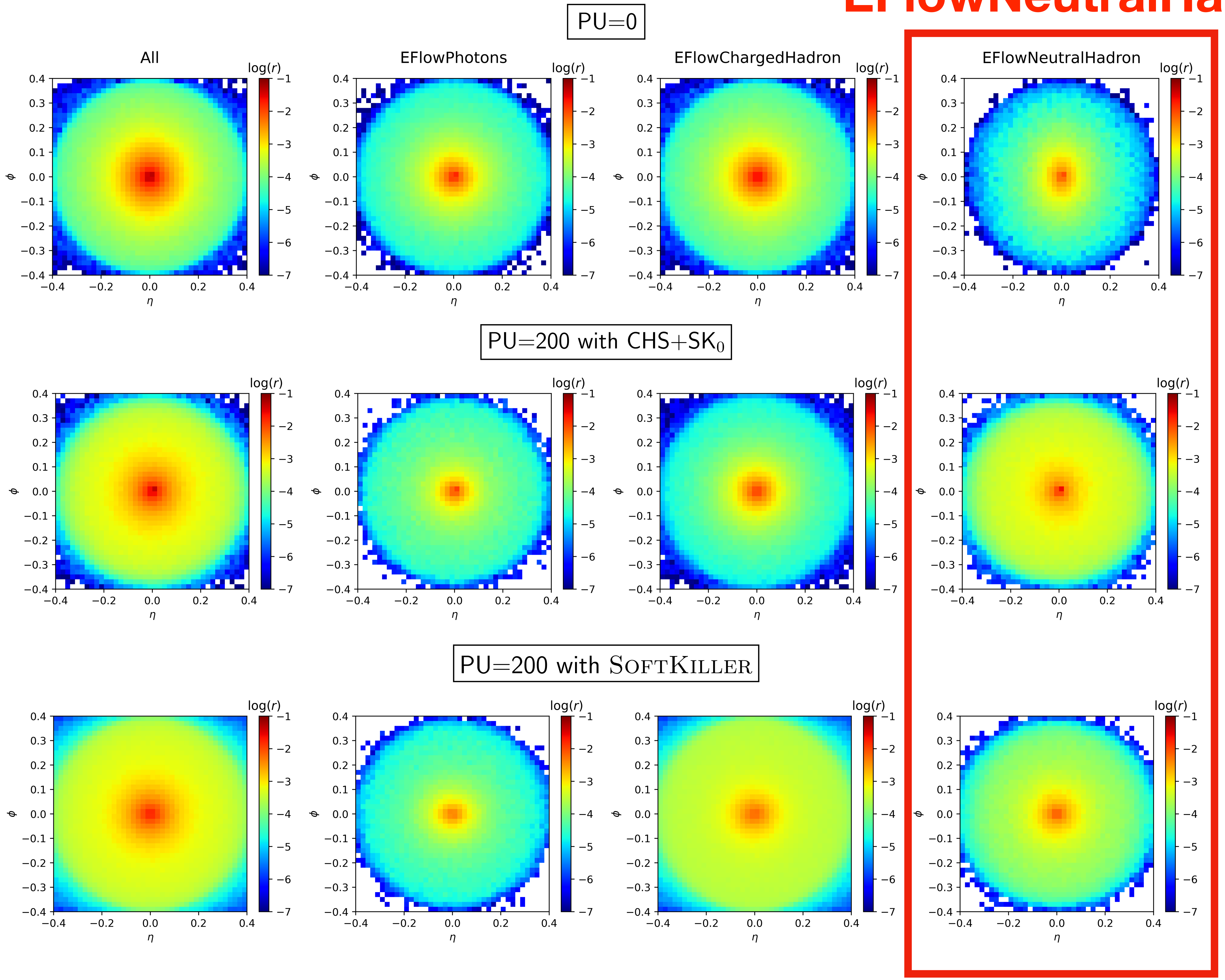


Jet images to demonstrate the superior of CHS+SK0



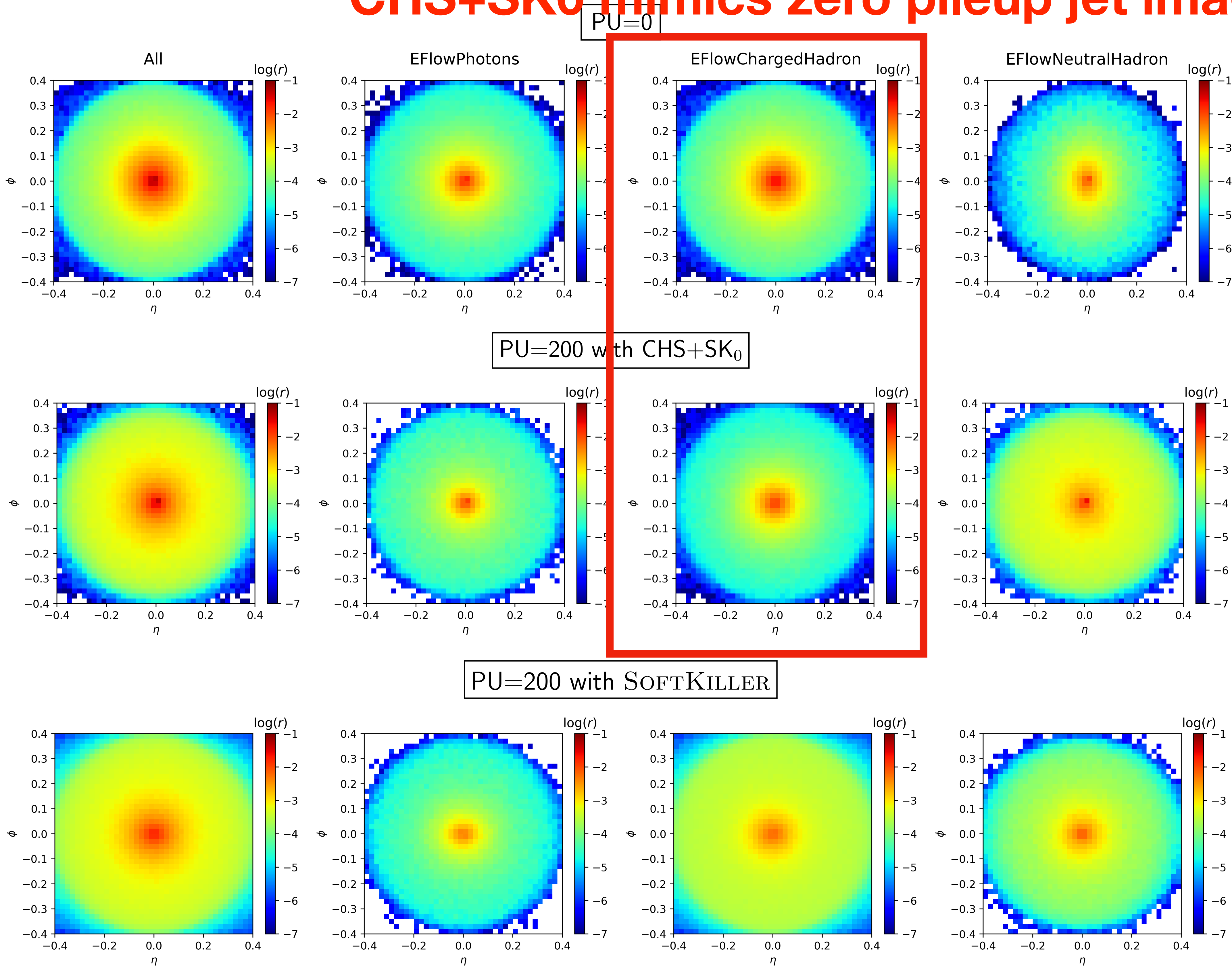
Jet images to demonstrate the superior of CHS+SK0

EFlowNeutralHadron



Jet images to demonstrate the superior of CHS+SK0

CHS+SK0 mimics zero pileup jet images

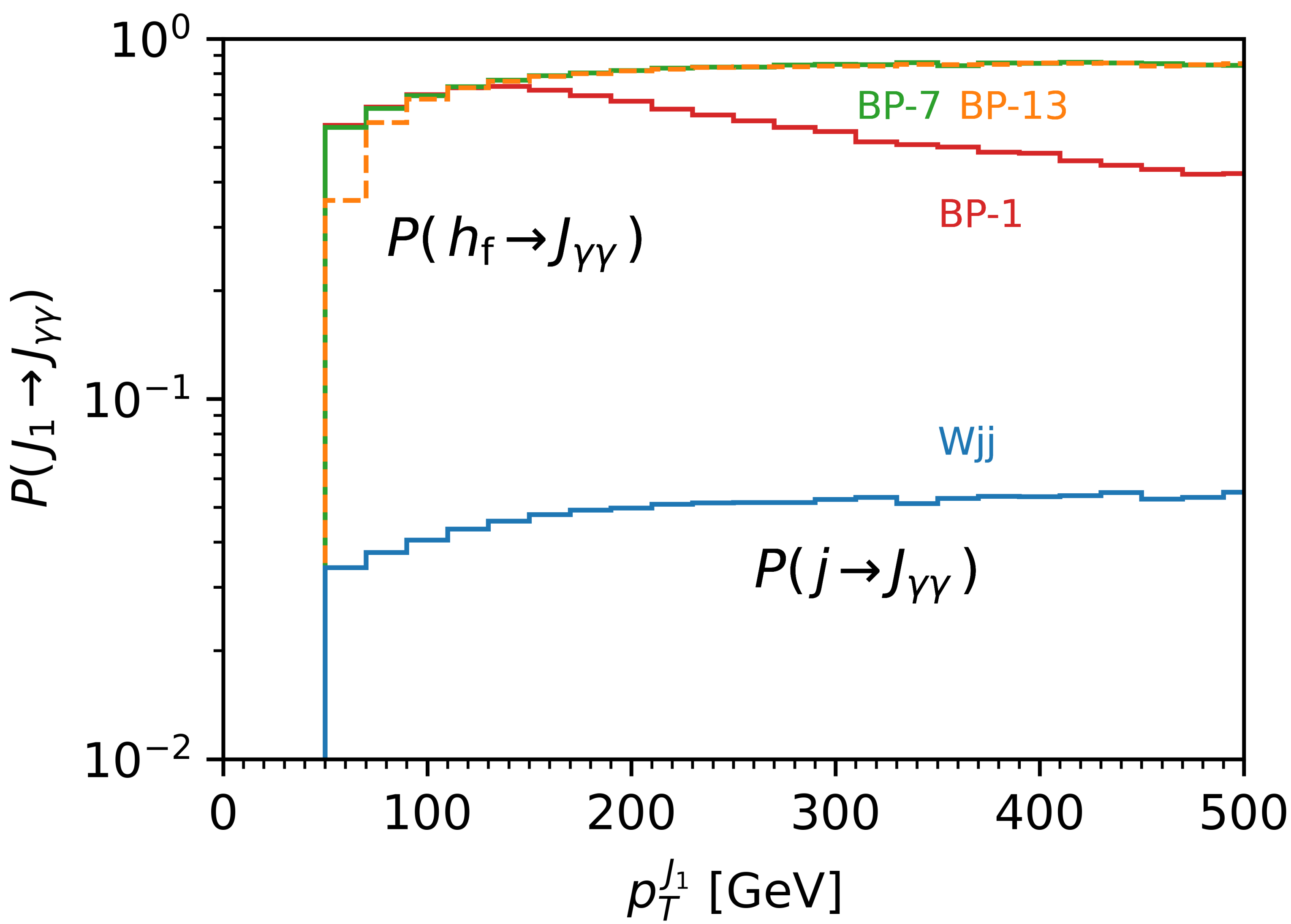


3. Cut-based analysis

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-article are EFlowPhotons.

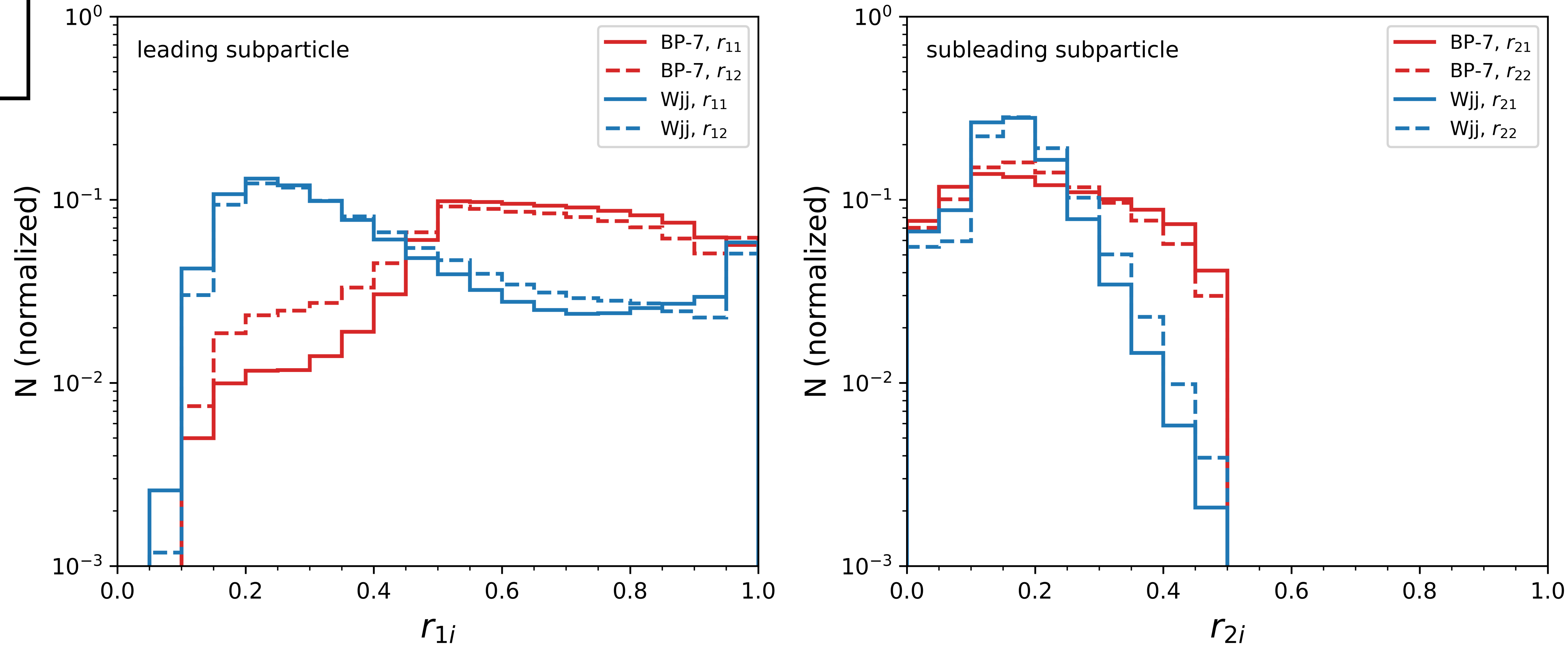


Mistagging rate is only a few percent.

Second characteristics of the signal

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

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



Significance w/ 10% uncertainty

Cross sections in units of fb at the 14 TeV LHC with $\mathcal{L}_{\mathrm{tot}} = 3\ \mathrm{ab}^{-1}$

Cut	BP-7	$W^{\pm}jj$	Zjj	$t\bar{t}$	$W^{\pm}j\gamma$	$\mathcal{S}^{10\%}_{\mathrm{BP-7}}$
Basic	34.8	372 622	27 727	32 052	3 047	1.09×10^{-3}
$E_T^{\mathrm{miss}} > 50$ 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

Significances for all 18 benchmark points

Results in the cut-based analysis at the 14 TeV LHC with $\mathcal{L}_{\rm tot} = 3\ \mathrm{ab}^{-1}$								
	$\sigma_{\rm final}$ [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

Most have more than 5σ

Significances for all 18 benchmark points

Results in the cut-based analysis at the 14 TeV LHC with $\mathcal{L}_{\mathrm{tot}} = 3\ \mathrm{ab}^{-1}$

	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
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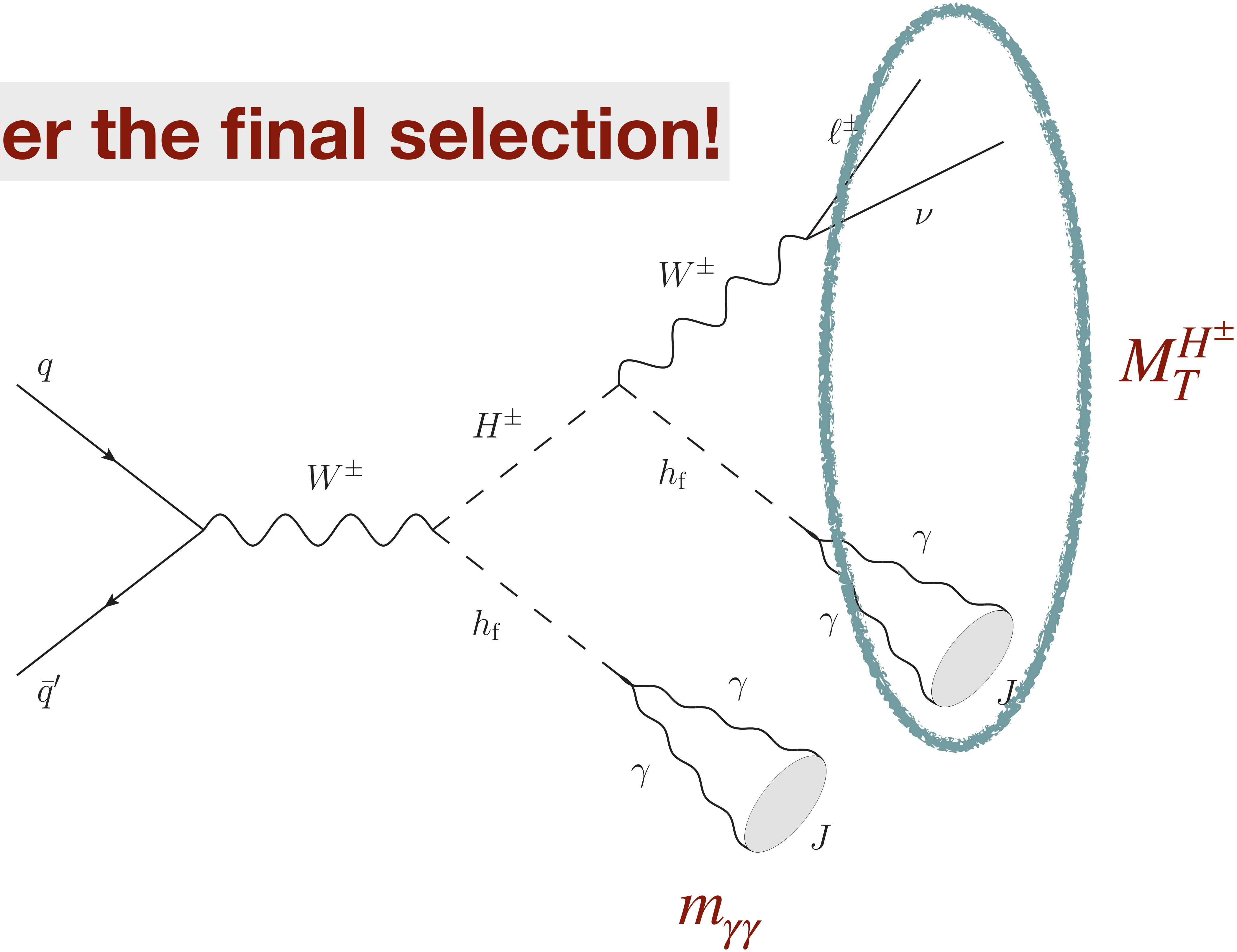
BP-5	0.303	5.49	BP-11	0.582	9.40	BP-17	0.566	9.19
BP-6	0.216	4.09	BP-12	0.457	7.74	BP-18	0.456	7.72

Still challenging!

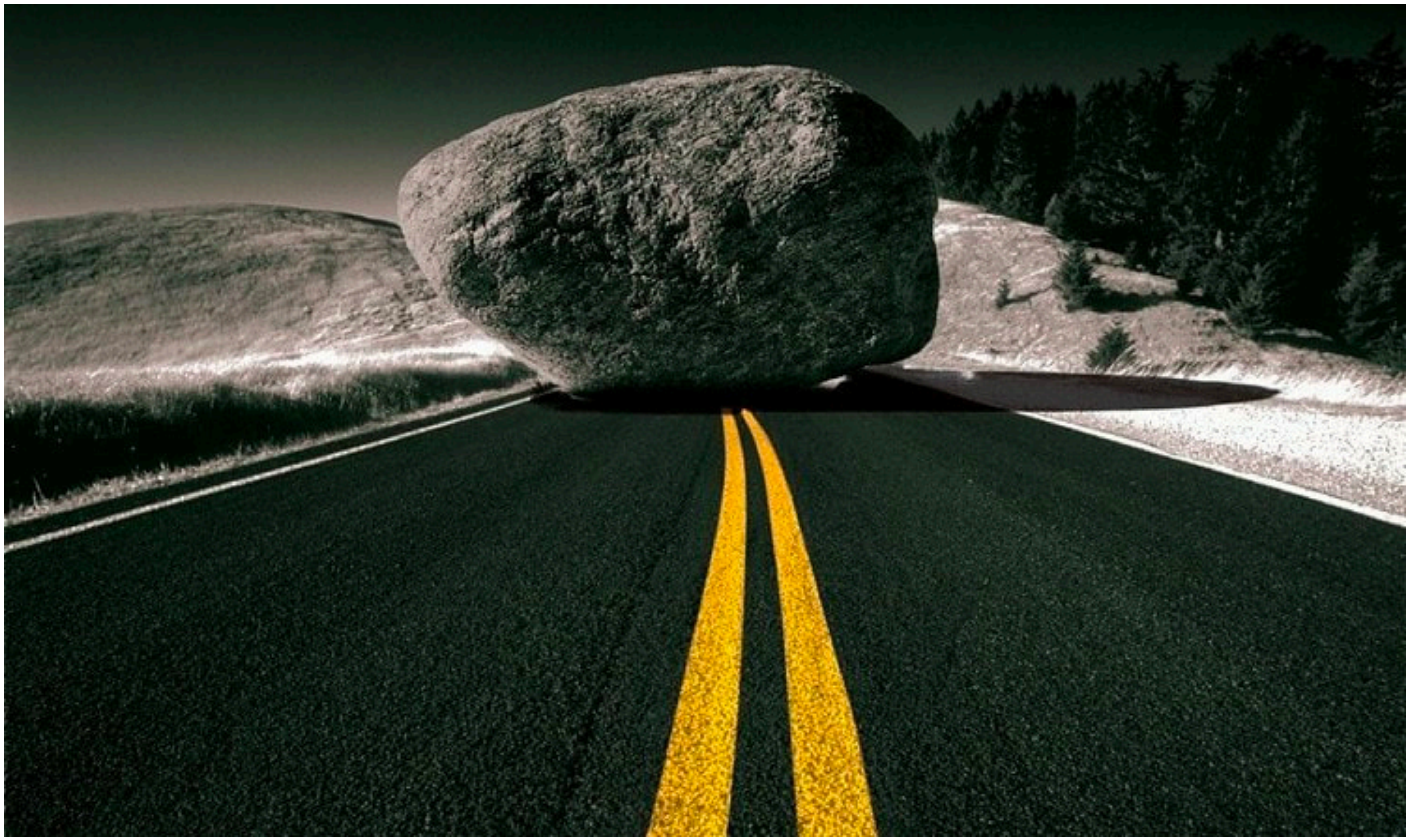
4. Mass reconstruction

Although we could observe two diphoton signals with 5σ, can we tell its origin?

After the final selection!



Another big obstacle!



Too small background events after the final selection

Only 51 events

Background	Cross section [pb]	n_{gen}	Background	Cross section [pb]	n_{gen}
$W^{\pm}(\to L^{\pm}\nu)jj$	3.54×10^3	$\boxed{5 \times 10^8}$	$W^{\pm}Z$	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

Too small background events after the final selection

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
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$t\bar{t}(\to b\bar{b}W_{L\nu}W_{jj})$	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

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

No reliable distribution for the 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

Infeasible to enhance the event generation!

Weighting Factor Method

Some terminologies

N : the expected number of events

n : the number of generated events

E_{cut} : the set of events satisfying "cut"

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

Cut-based analysis

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

Either 0 or 1

Cut-based analysis

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

Weighting Factor Method

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

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

Cut-based analysis

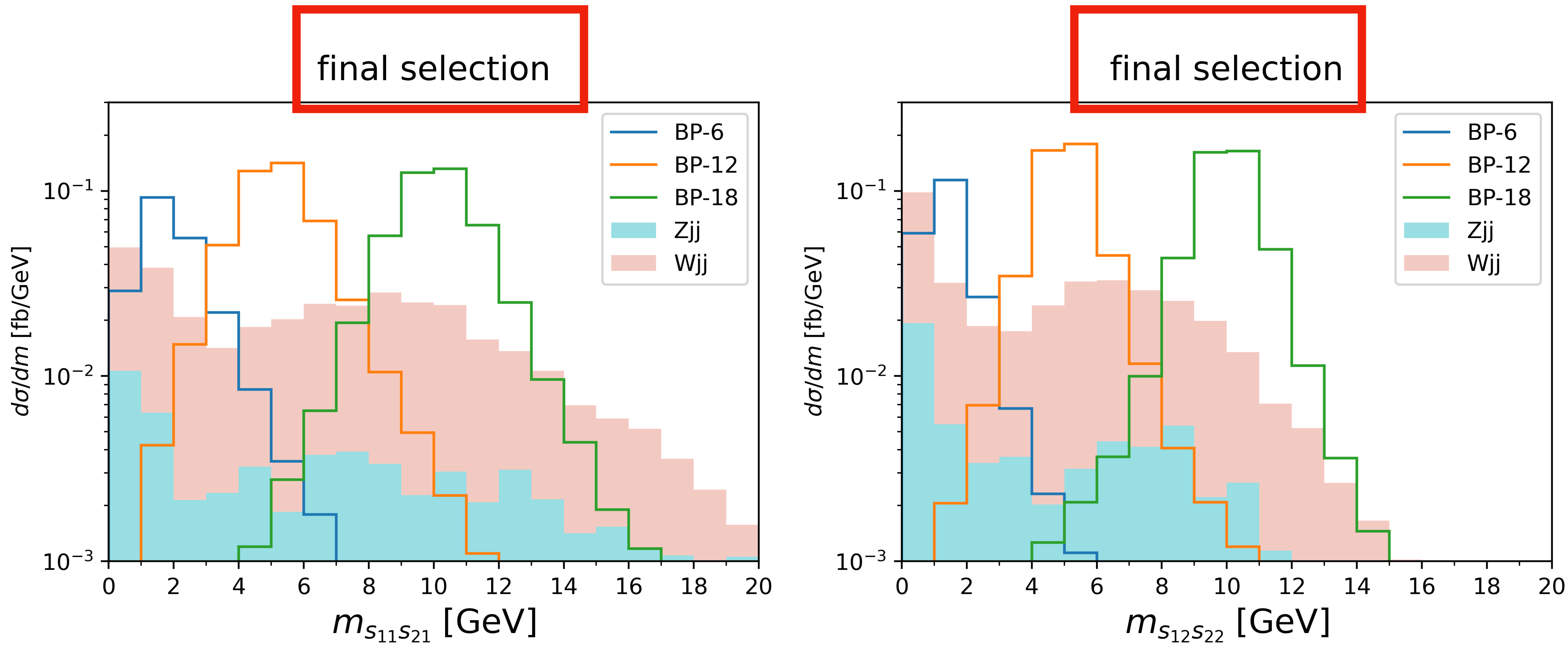
$$\sigma_{\text{final}}^{\text{cut-based}} = \sum_{e \in E_{\text{final}}} 1 \times \frac{\sigma_{\text{tot}}}{n_{\text{gen}}} = \frac{n_{\text{final}}}{n_{\text{gen}}}\,\sigma_{\text{tot}}\,,$$

Weighting Factor Method

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

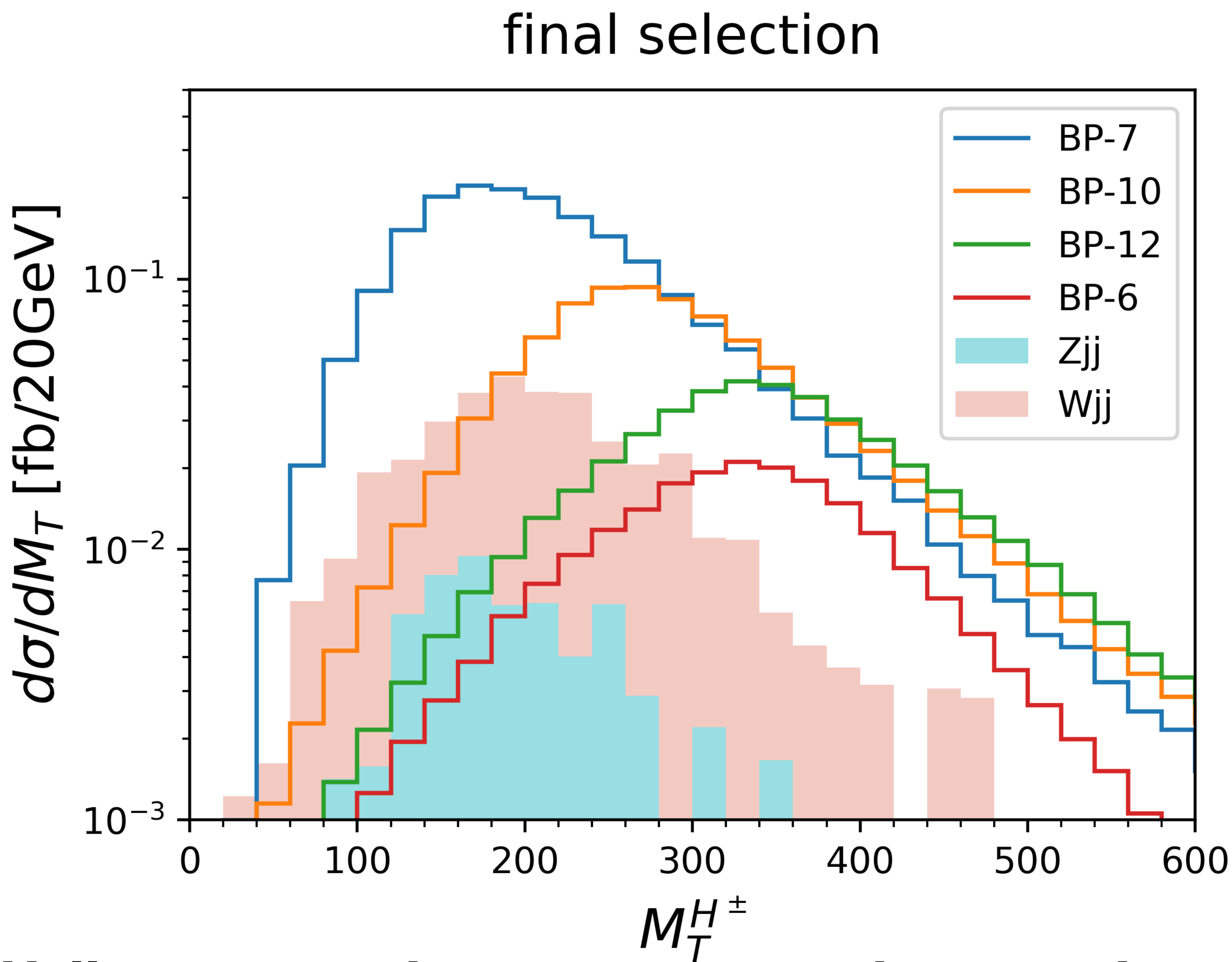
Continuous nature of weighting factor

Invariant mass of two leading subparticles



Well-separated resonance peak around m_{h_f}

Transverse mass for $H^{\pm}$

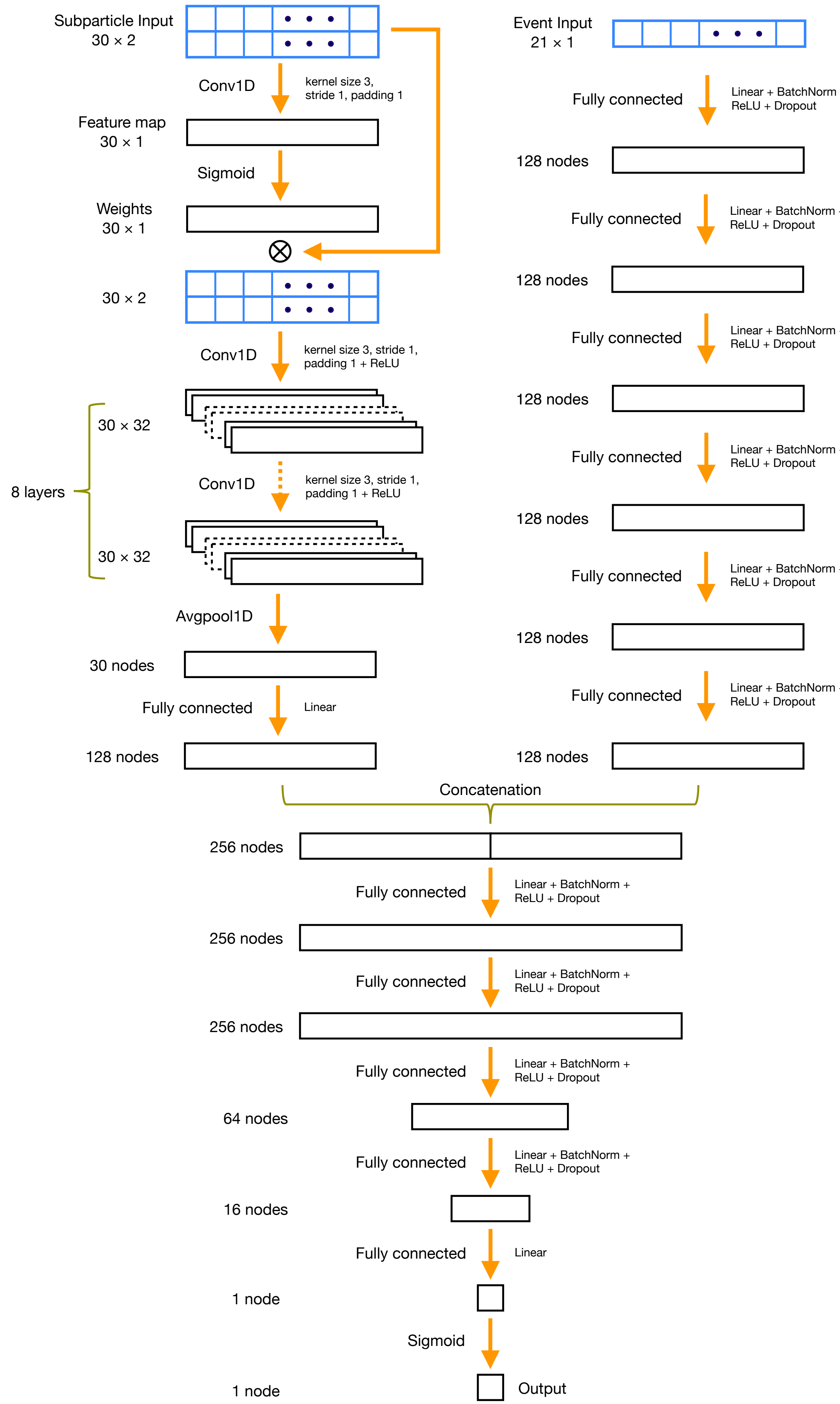


Well-separated resonance peak around m_{h_f}

5. Machine Learning Techniques to enhance the significances

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

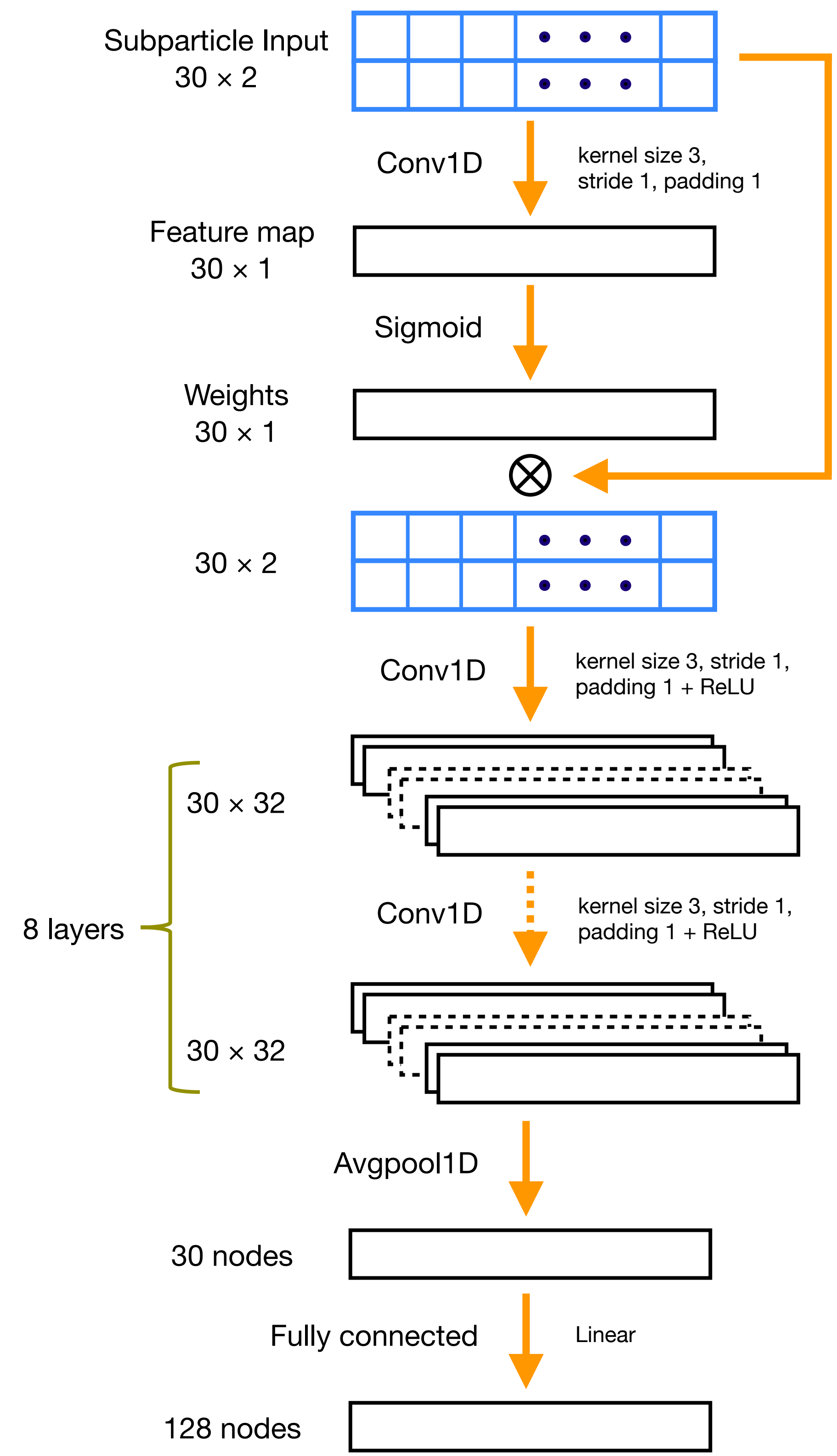

Subparticle Input
30 × 2
Conv1D
kernel size 3, stride 1, padding 1
Feature map
30 × 1
Sigmoid
Weights
30 × 1
30 × 2
Conv1D
kernel size 3, stride 1, padding 1 + ReLU
30 × 32
8 layers
Conv1D
kernel size 3, stride 1, padding 1 + ReLU
30 × 32
Avgpool1D
30 nodes
Fully connected
Linear
128 nodes
Event Input
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
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

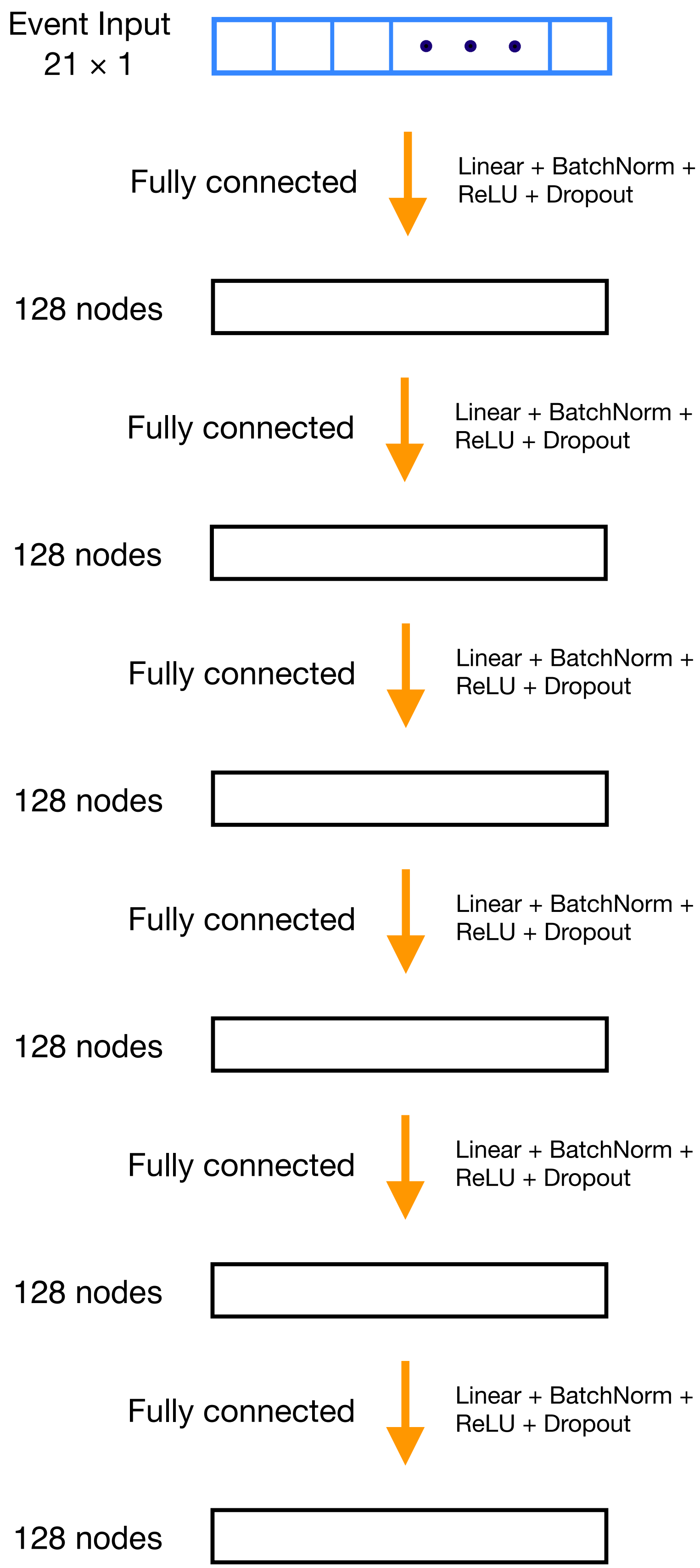
Subparticle features:
For 2 jets, 10 leading subparticles

$$p_T, \eta, \phi$$

$$30 \times 2$$



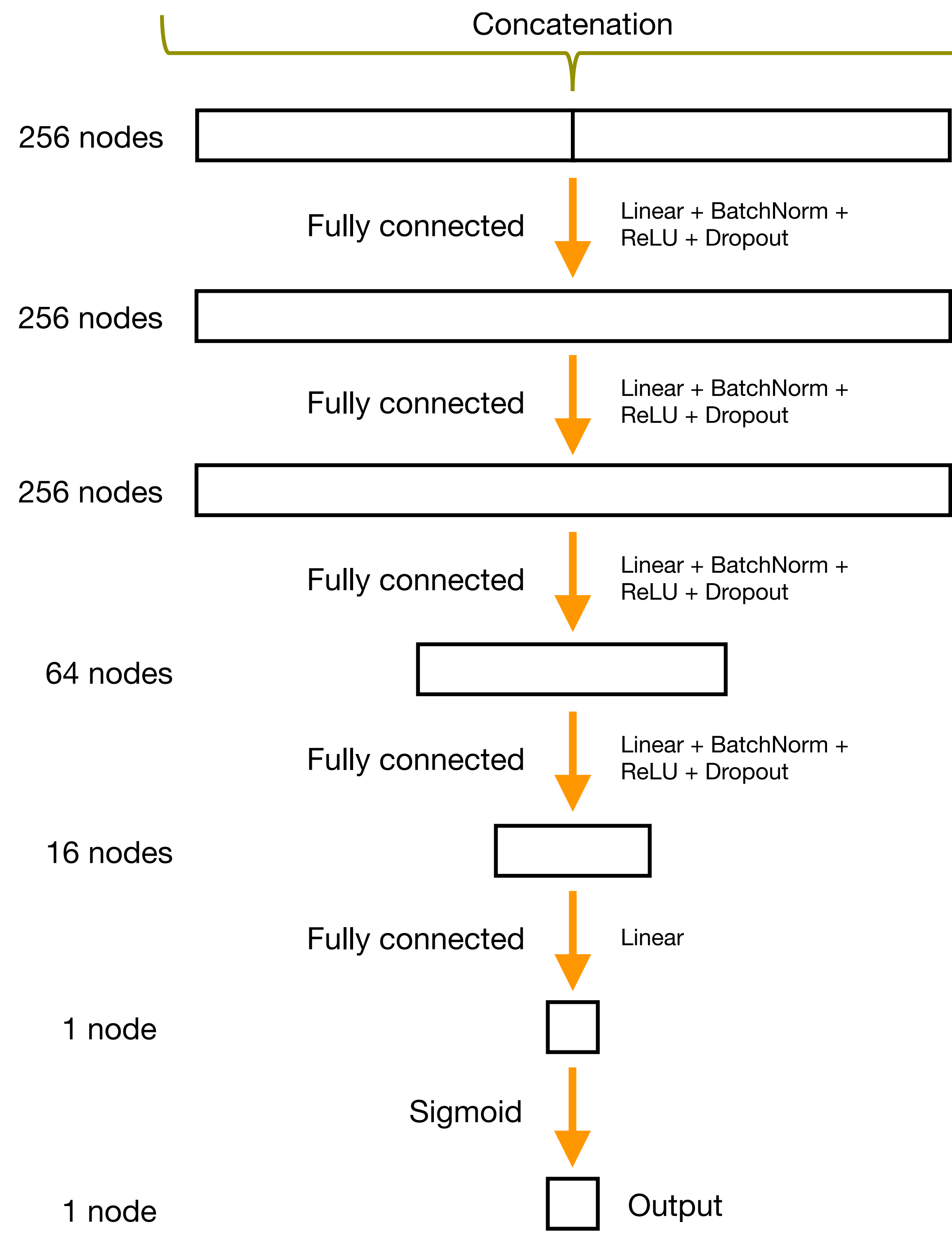
MLP1



Events features:

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

MLP1



Final number for signal

Impressive enhancement

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

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

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.