RESURRECTING y_b FROM $b\bar{b}h$ STUDY WITH KINEMATIC SHAPES

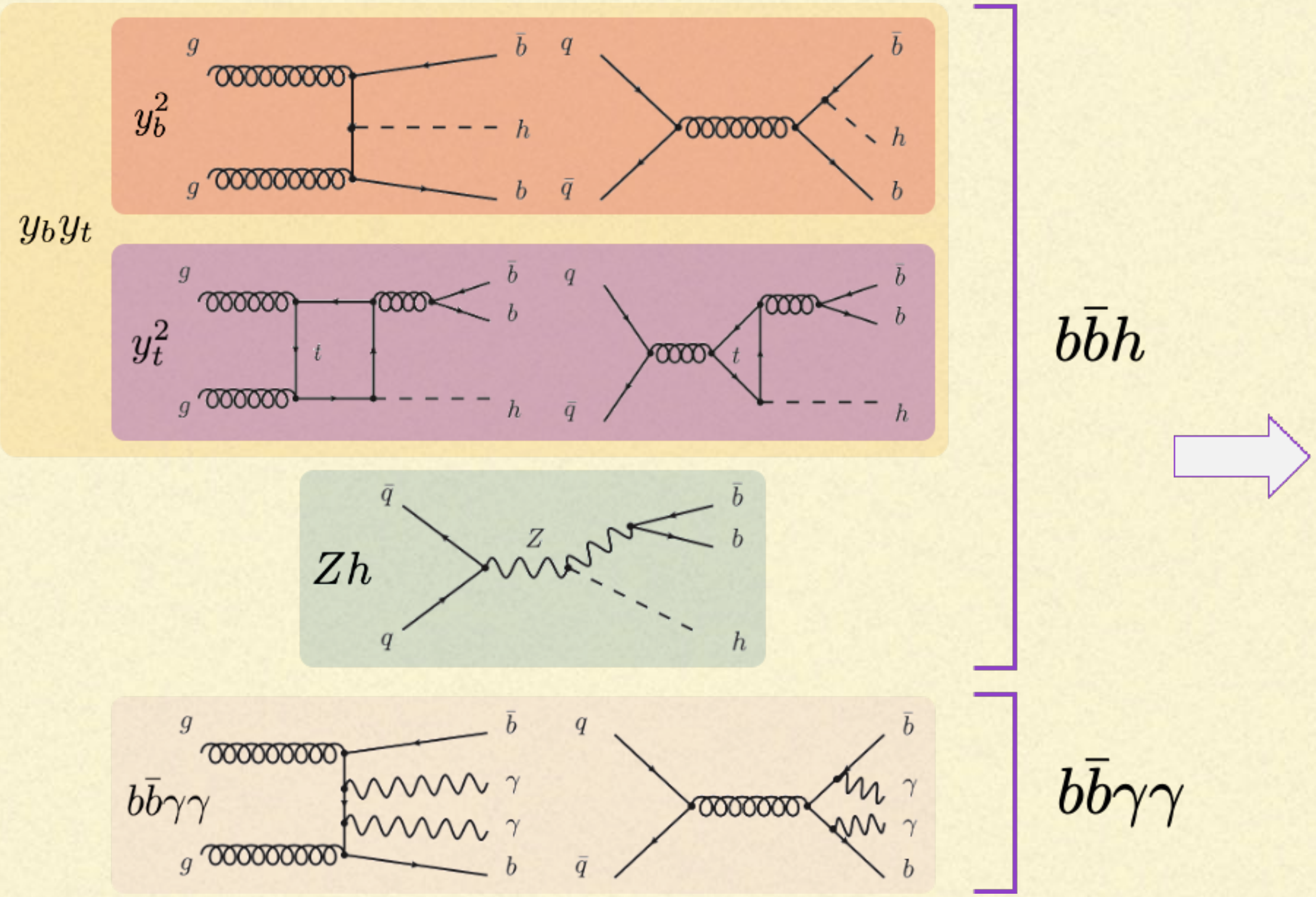
Zhuoni Qian @ Pheno, May 2021
On behalf of C. Grojean, A. Paul
arXiv: 2011.13945

$b\bar{b}h$ signal at the (HL-)LHC, y_b sensitivity

Motivation: Bottom Yukawa measure is a recent achievement:

o Phase of the Yukawa not well measured

o Interplay between Yukawa phases in EDM and collider



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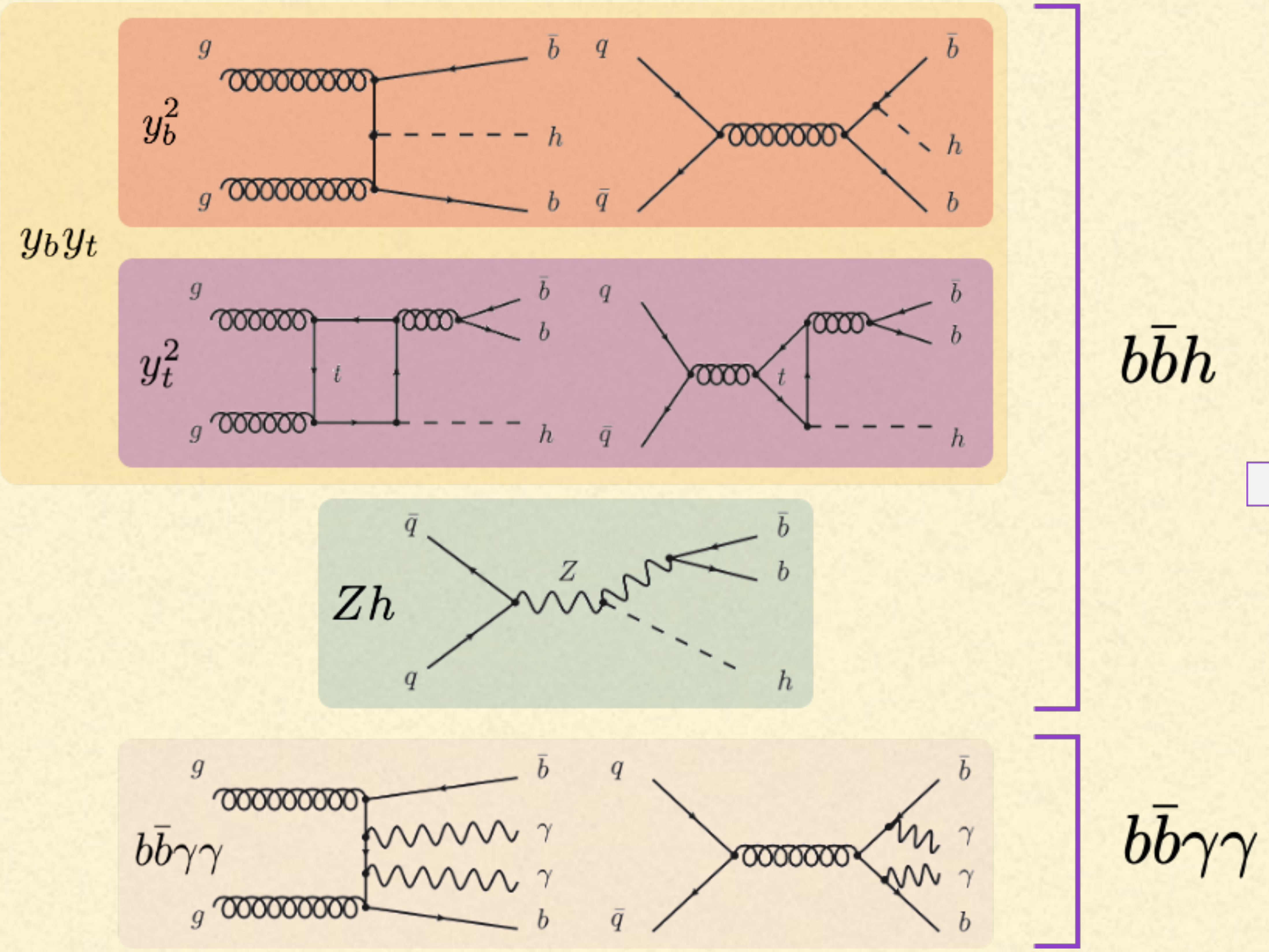

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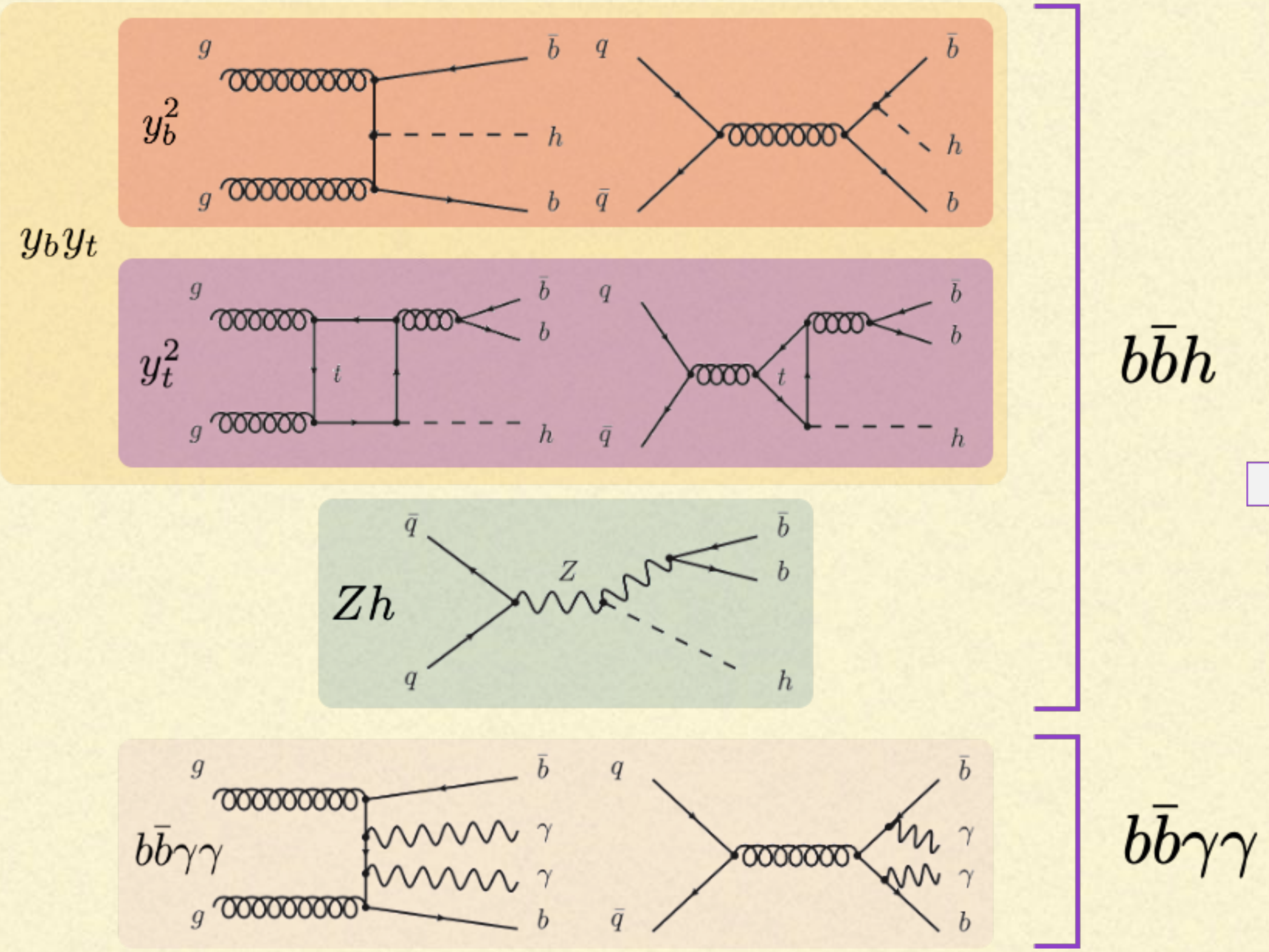
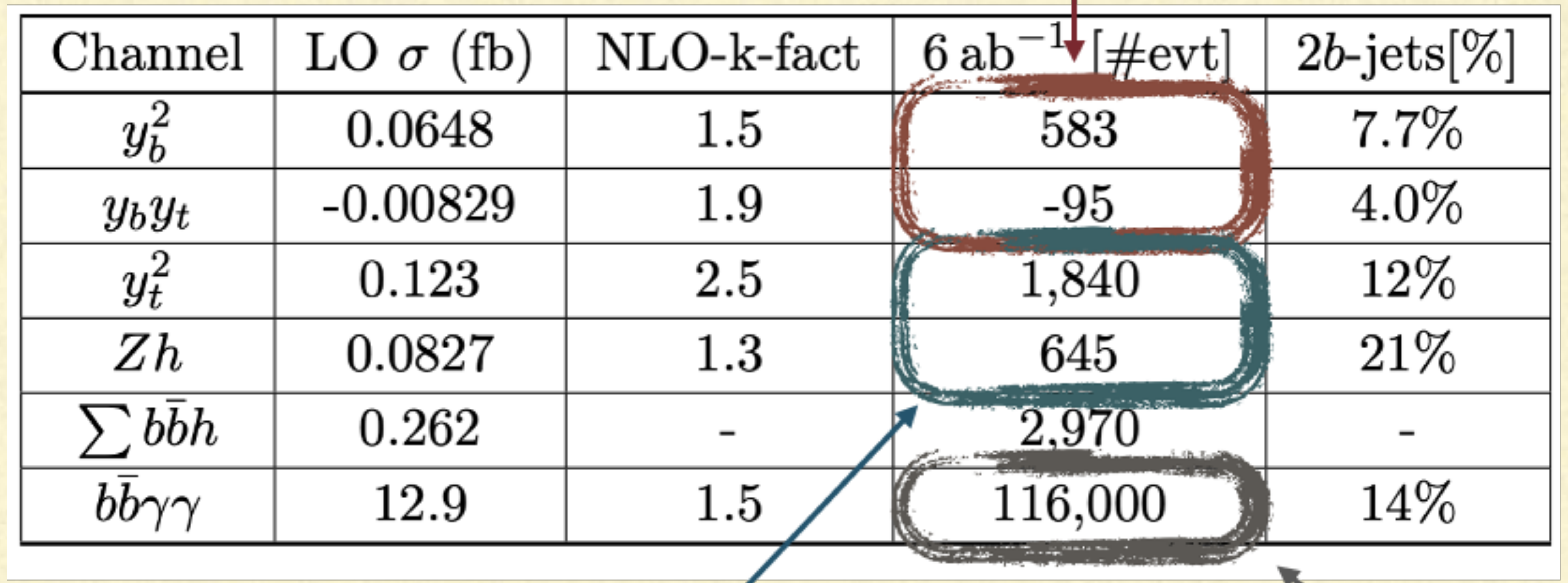


signals



Channel	LO σ (fb)	NLO-k-fact	6 ab^{-1}[#evt]	$2b$-jets[%]
y_b^2	0.0648	1.5	583	7.7%
$y_b y_t$	-0.00829	1.9	-95	4.0%
y_t^2	0.123	2.5	1,840	12%
Zh	0.0827	1.3	645	21%
$\sum b\bar{b}h$	0.262	-	2,970	-
$b\bar{b}\gamma\gamma$	12.9	1.5	116,000	14%

$b\bar{b}h$ background

$b\bar{b}\gamma\gamma$ **background**

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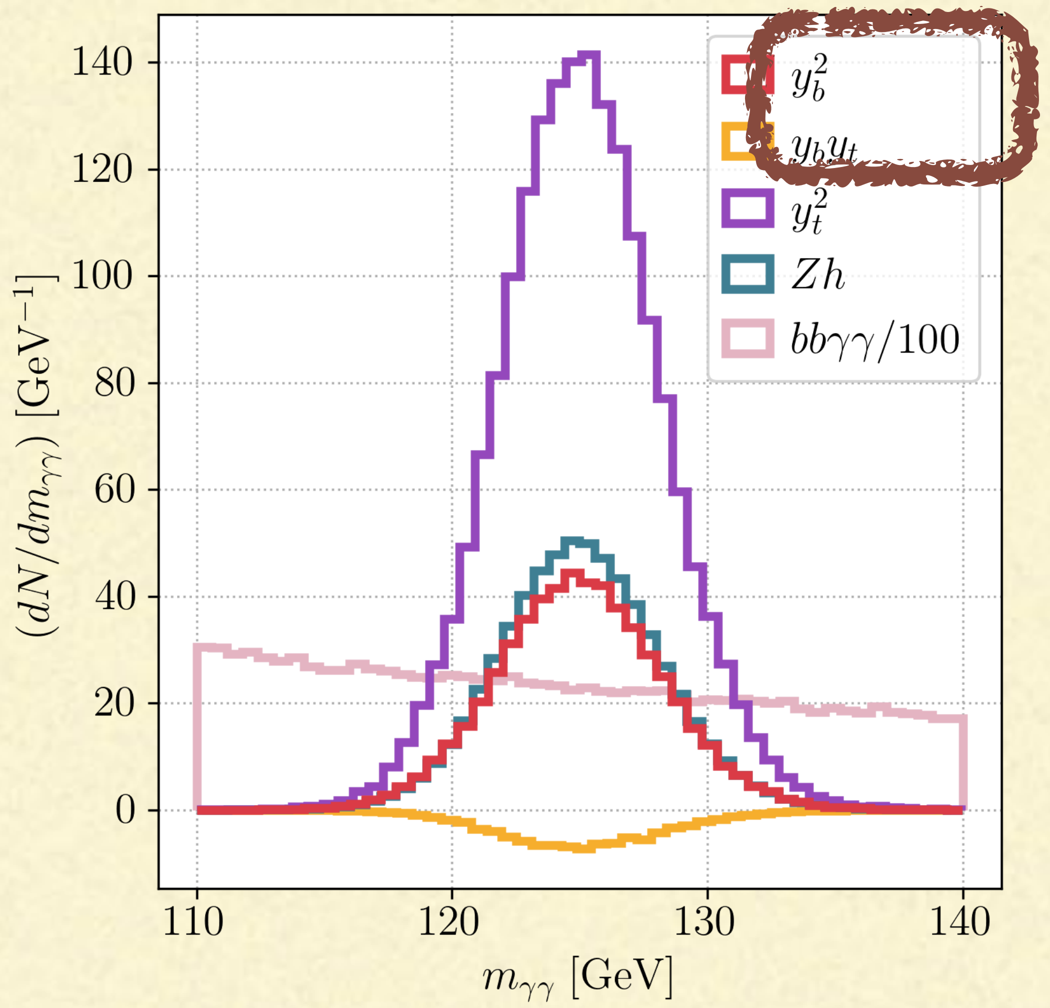
1D Differential Distribution

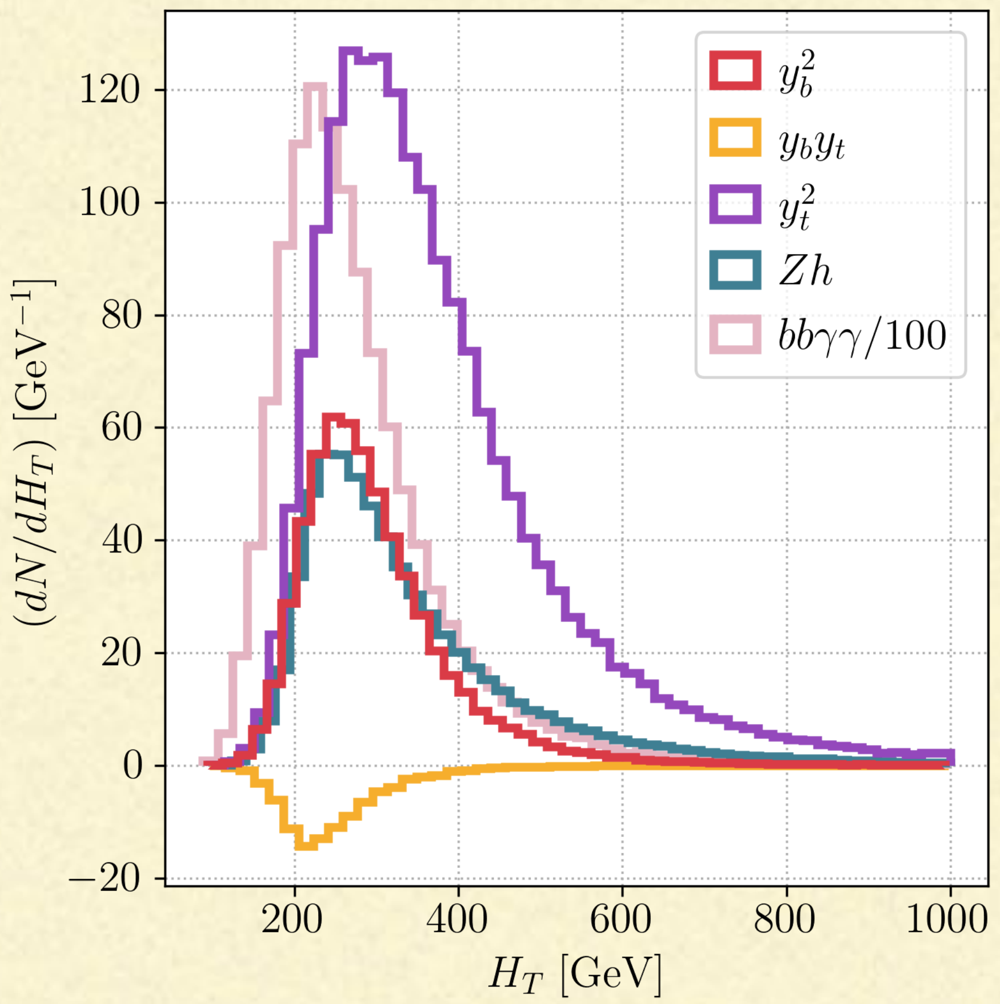
Observable and distributions:

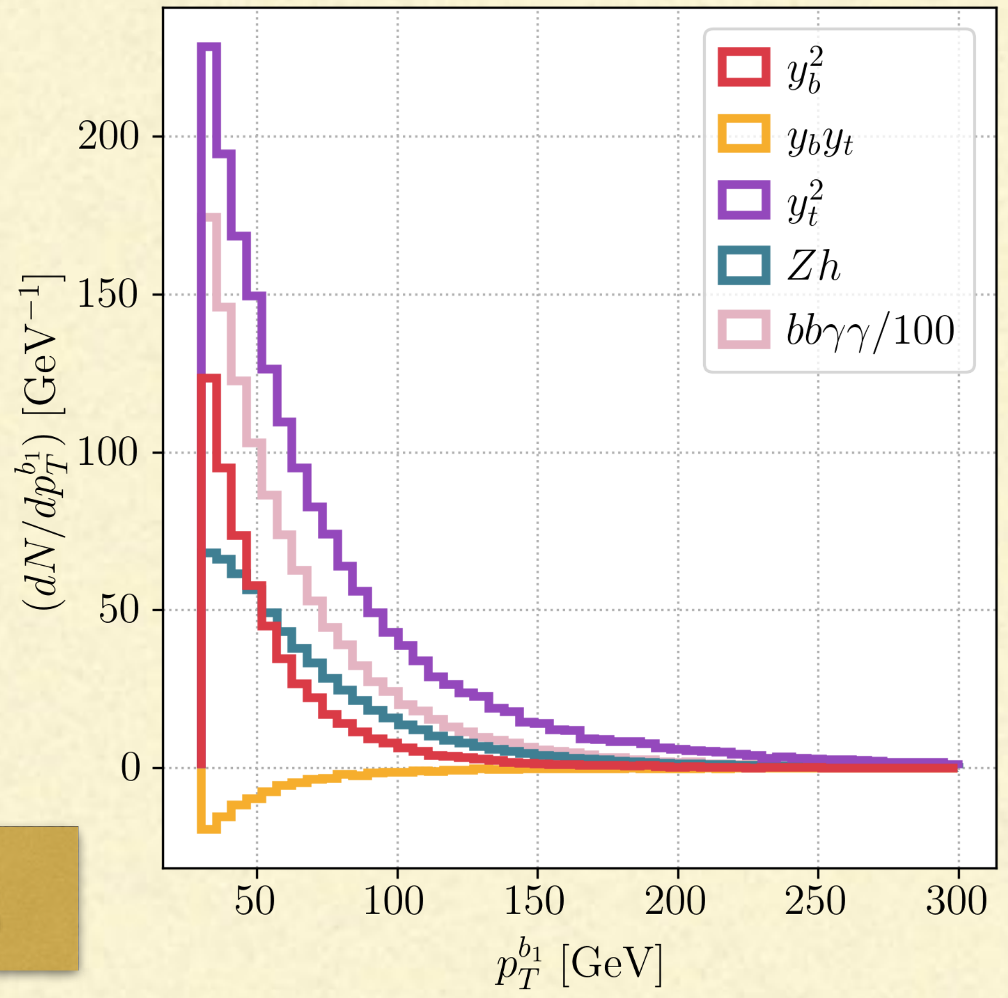
- $p_T^{b_1}, p_T^{b_2}, p_T^{\gamma_1}, p_T^{\gamma\gamma},$
- $\eta_{b_{j1}}, \eta_{b_{j2}}, \eta_{\gamma_1}, \eta_{\gamma\gamma},$
- $n_{bjet}, n_{jet}, \Delta R_{\text{min}}^{b\gamma}, \Delta\phi_{\text{min}}^{bb},$
- $m_{\gamma\gamma}, m_{bb}, m_{b_1 h}, m_{b\bar{b}h}, H_T.$

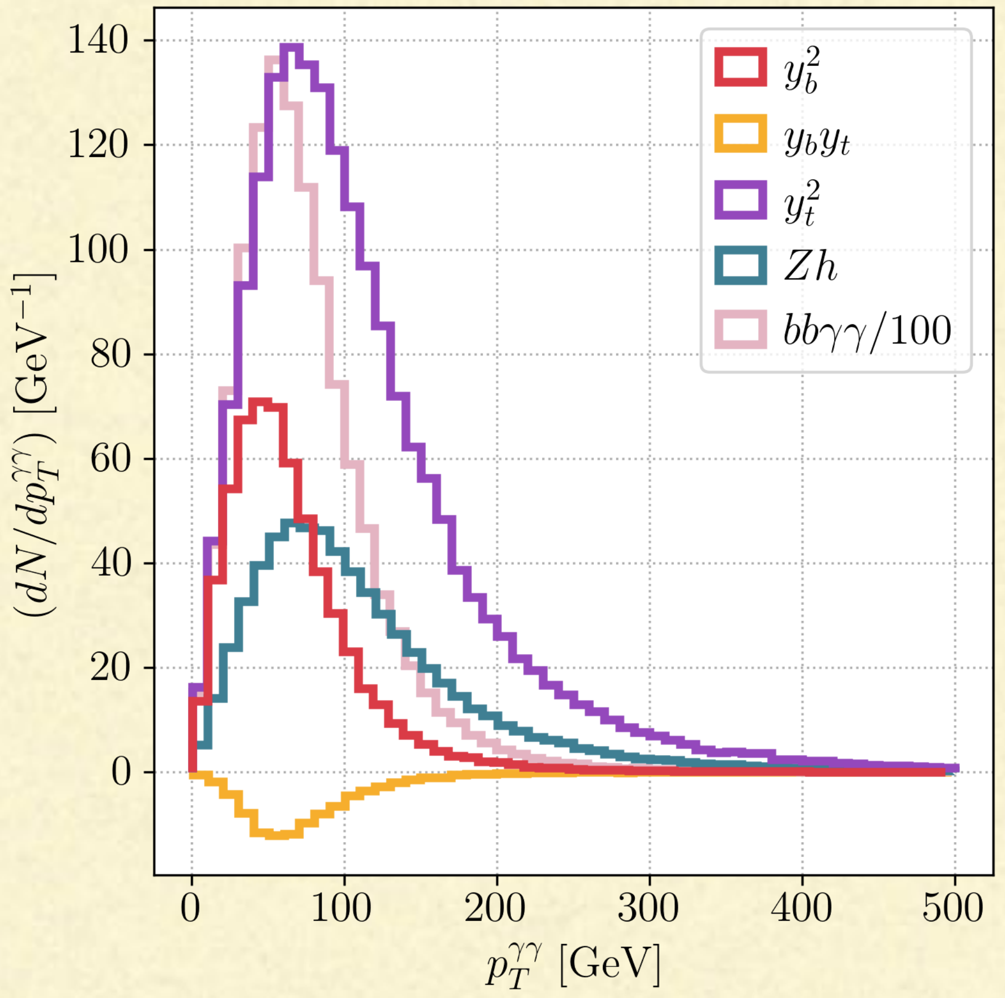
Begin with an over-complete set of median/high level observables

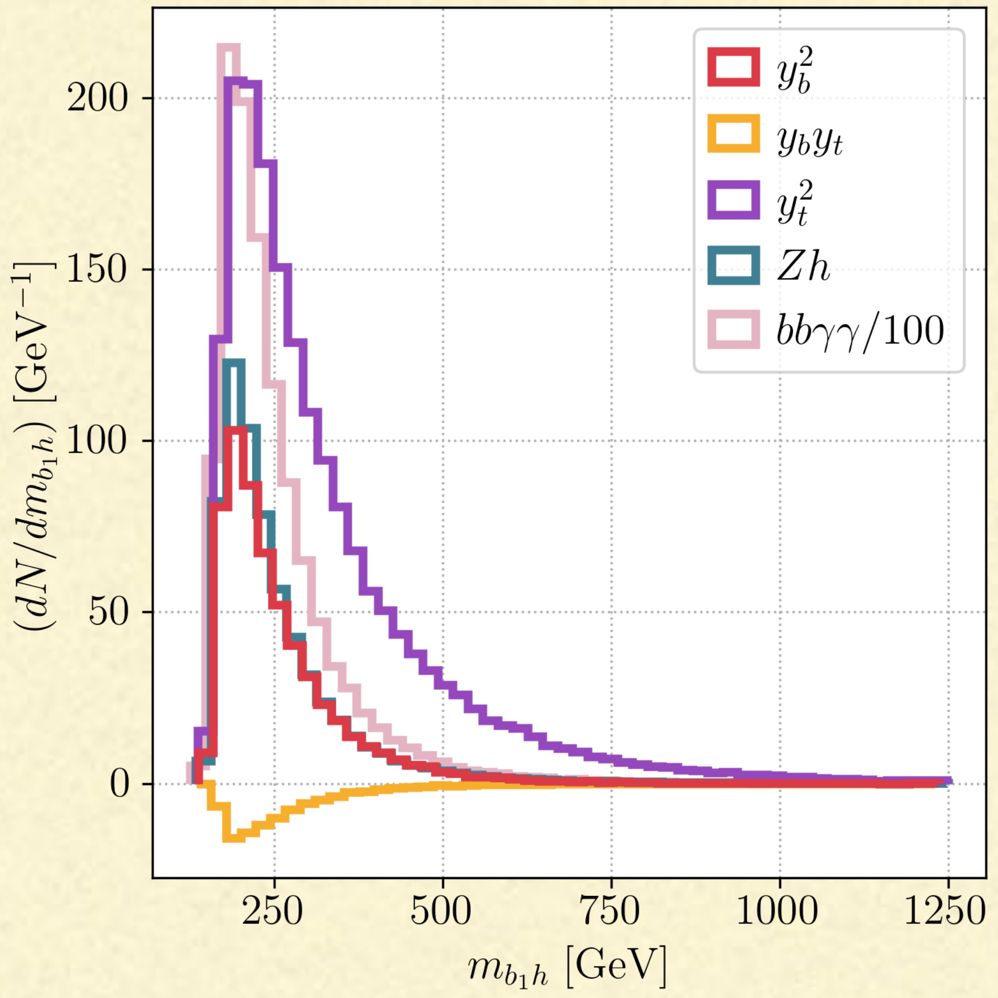
Challenging to distinguish channels











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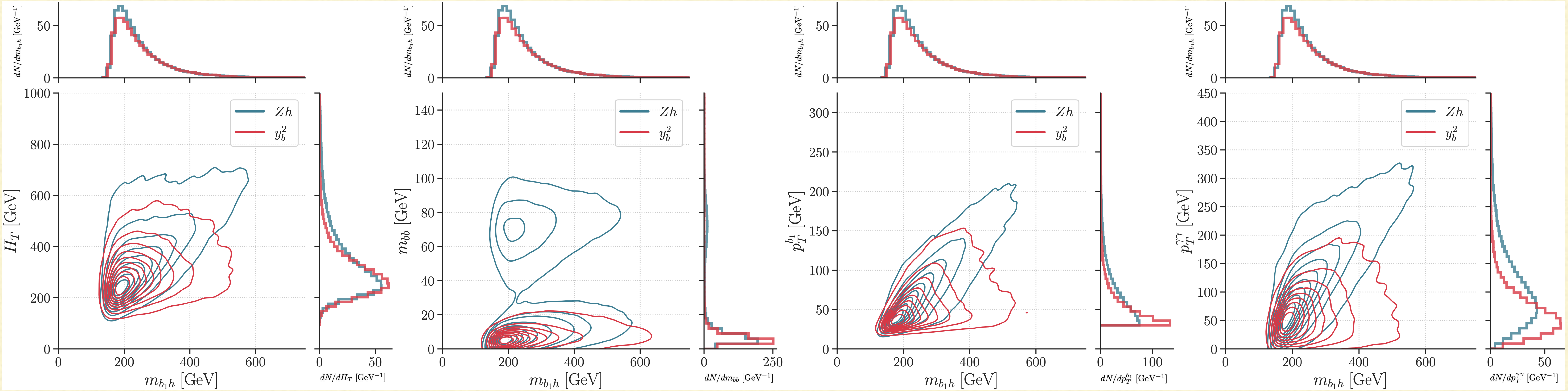
2D Differential Distribution (y_b^2 and Zh)



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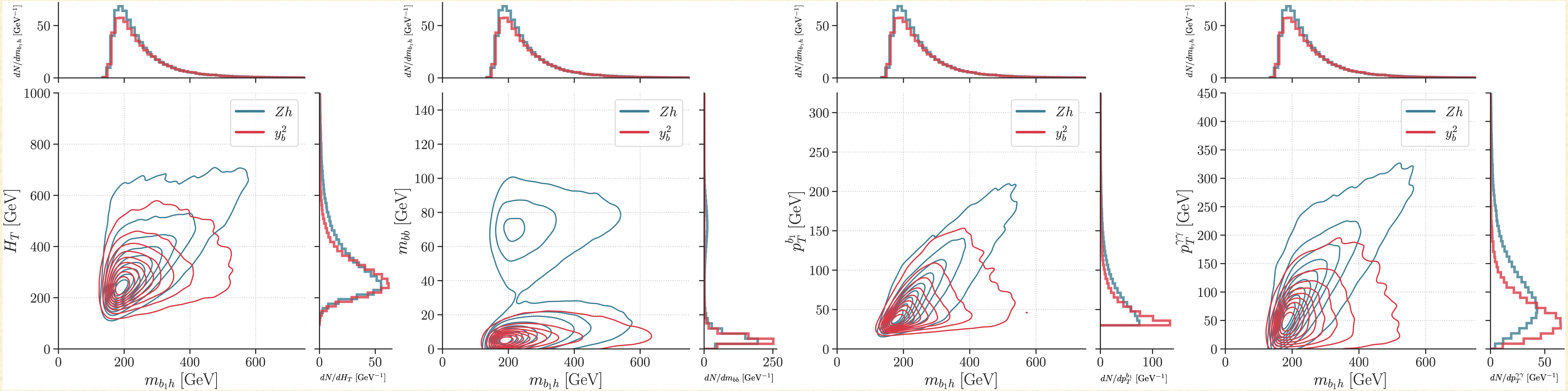

- High dimensional features reveal further difference
- Designed cut, smarter/optimal observable, matrix element method

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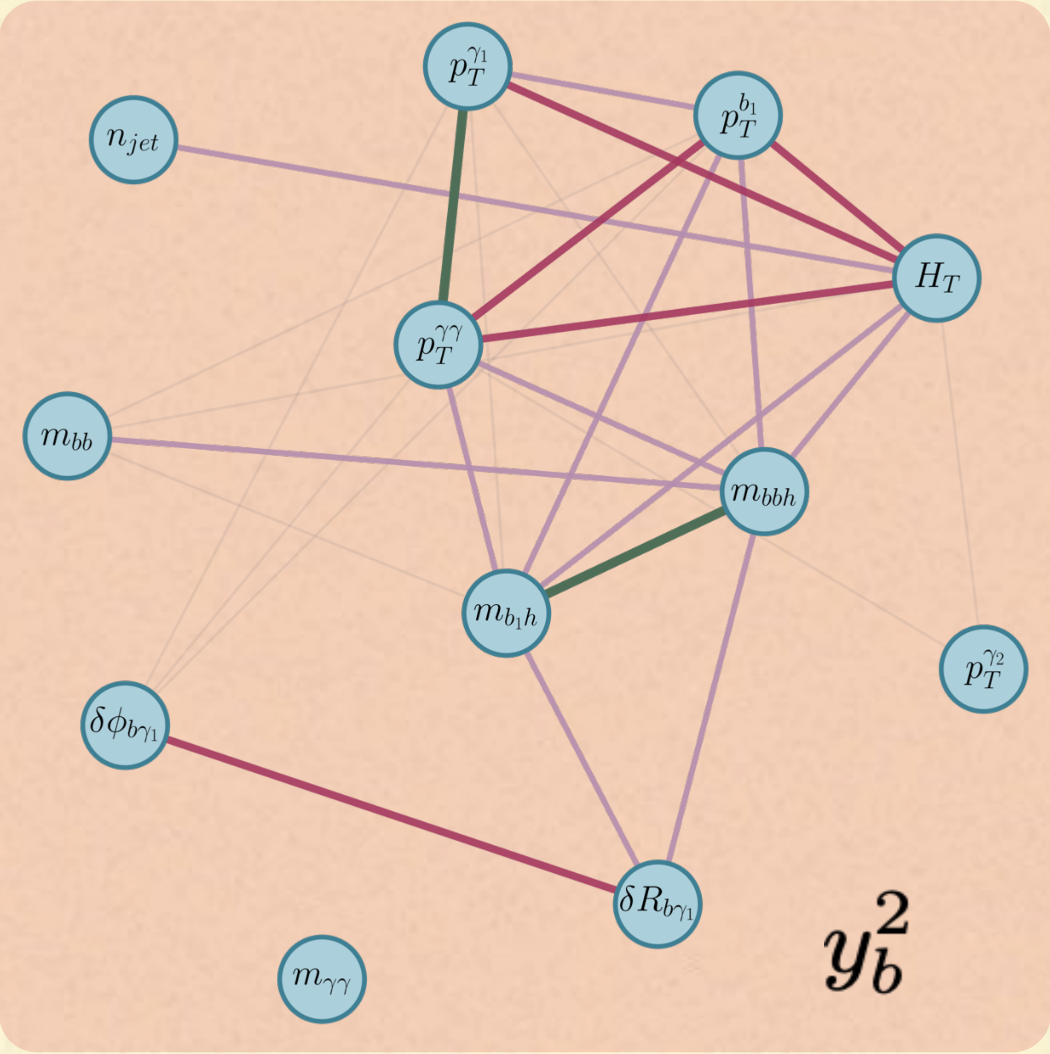
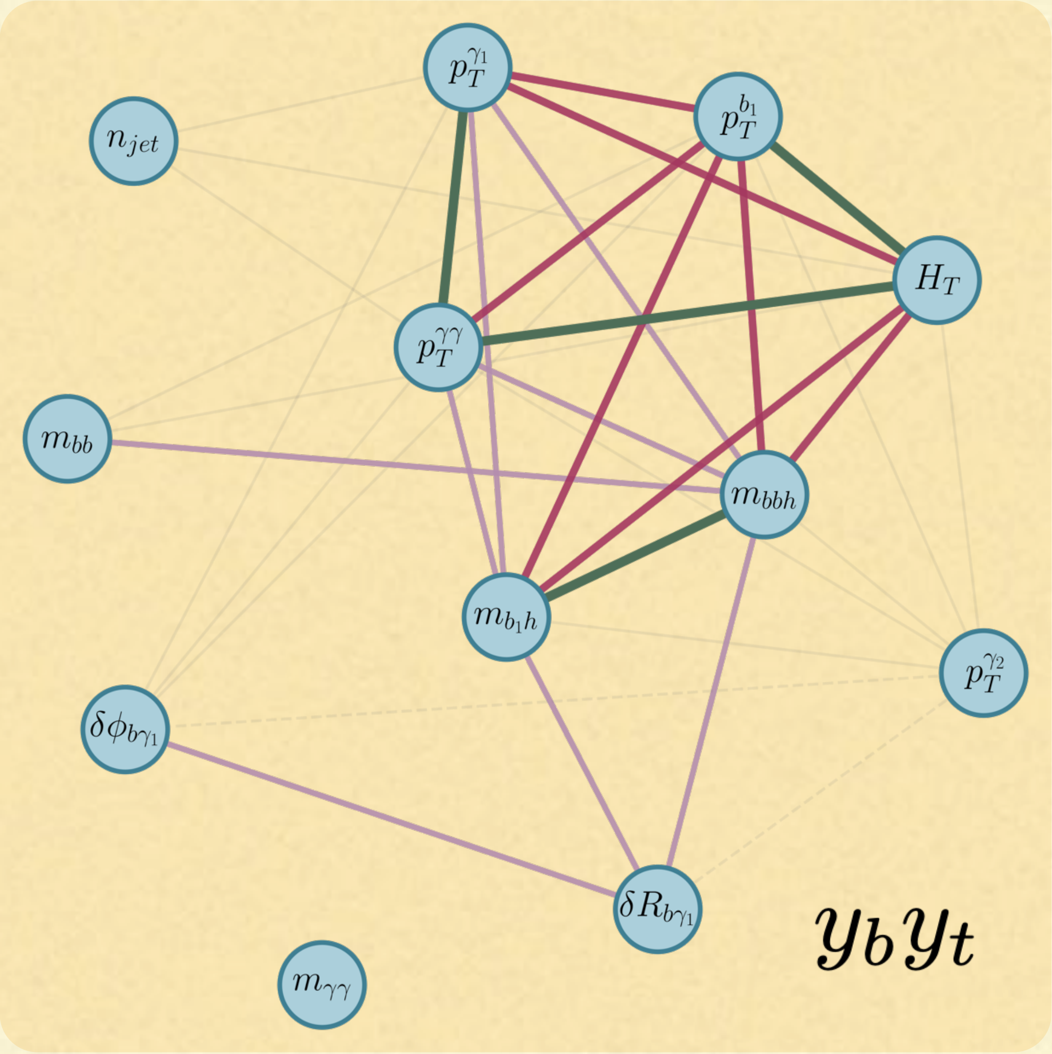
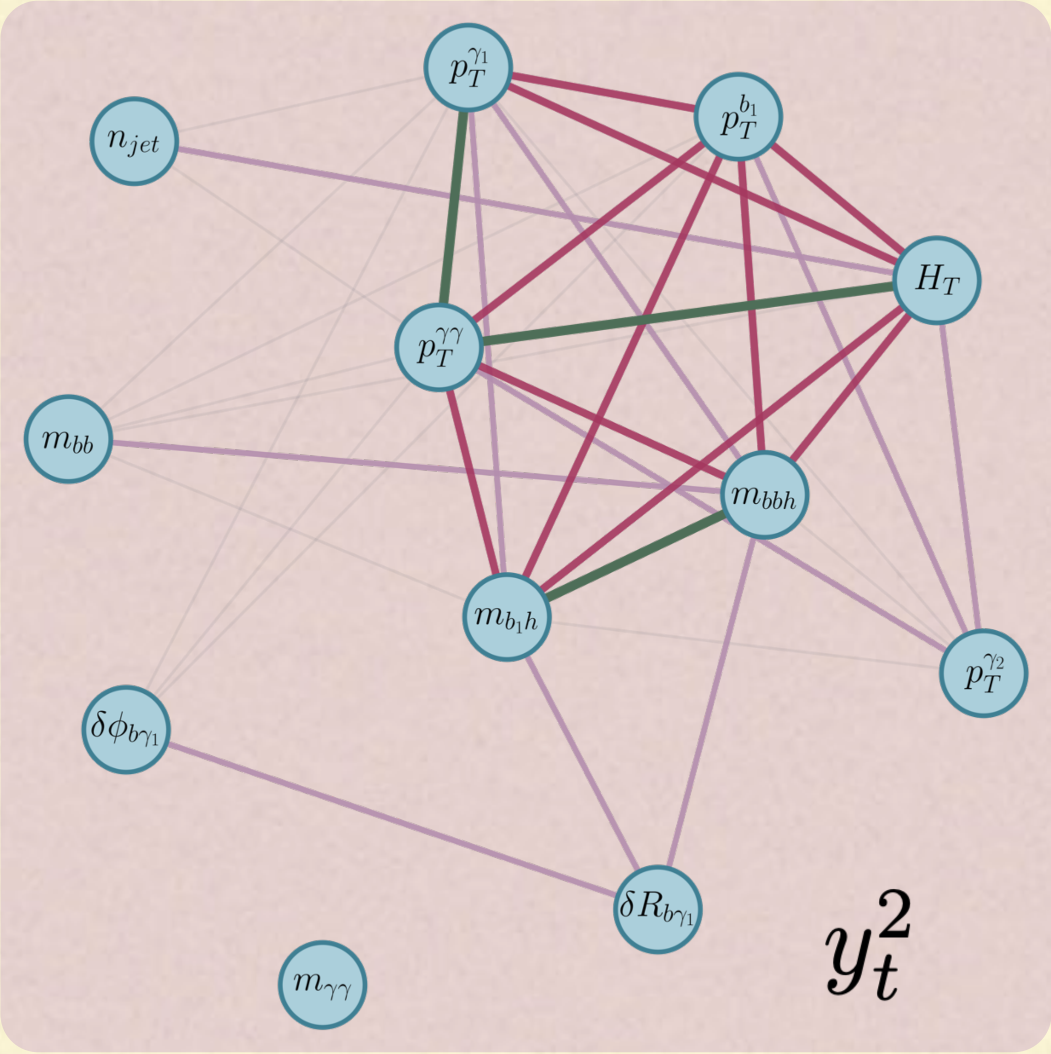
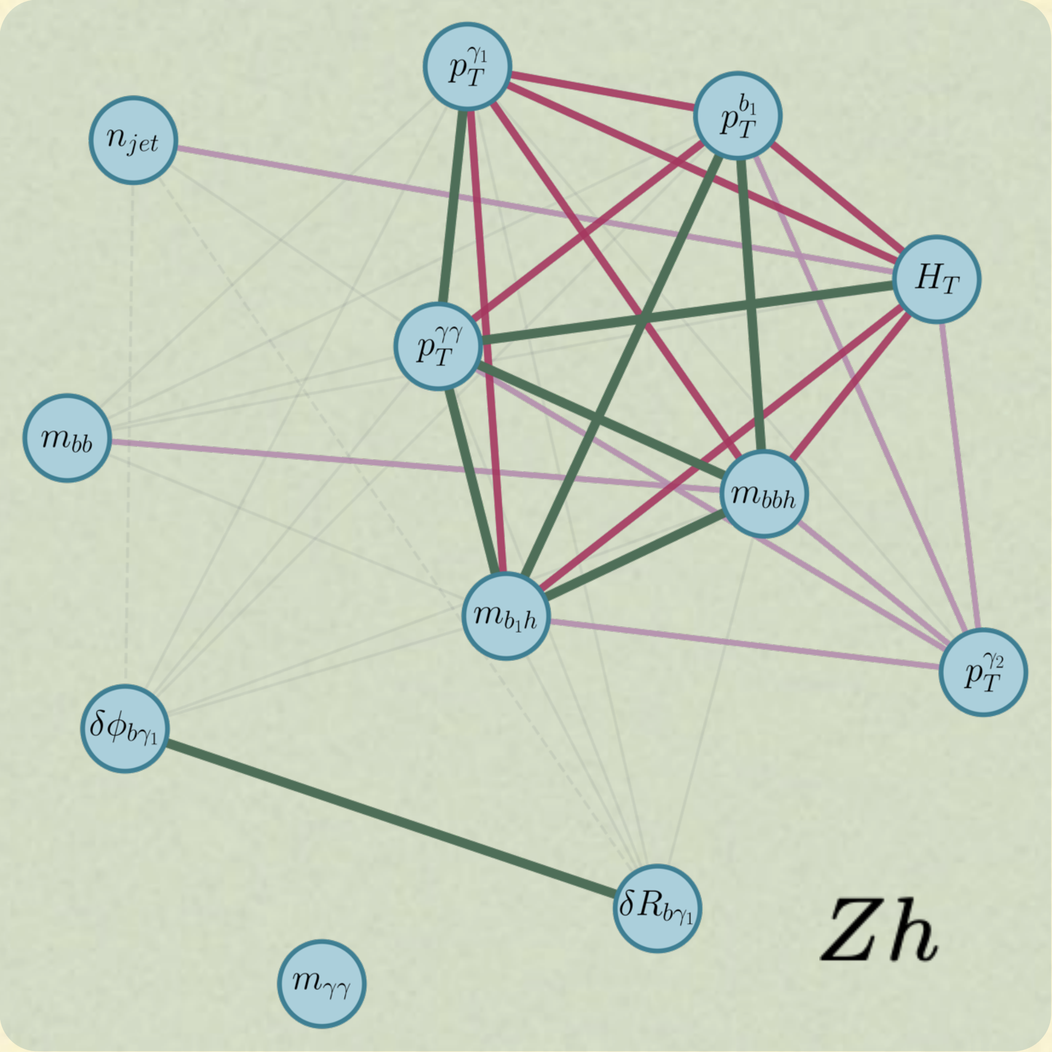
Diving into higher dimension



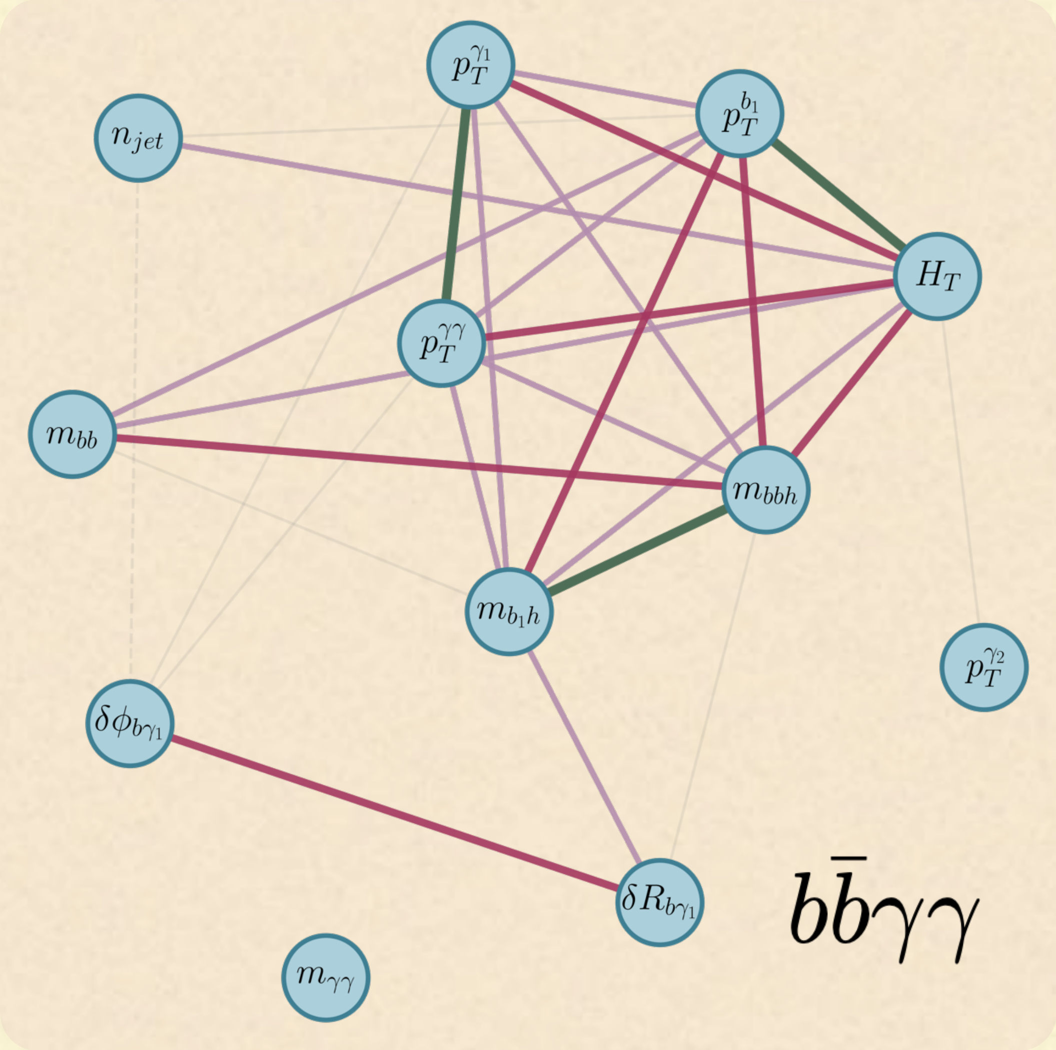






⬜ $0.2 \le |\rho| < 0.4$ 🟪 $0.4 \le |\rho| < 0.6$ 🟥 $0.6 \le |\rho| < 0.8$ 🟩 $0.8 \le |\rho| < 1.0$

--- $-\rho$ — $+\rho$



Into higher dimensions:

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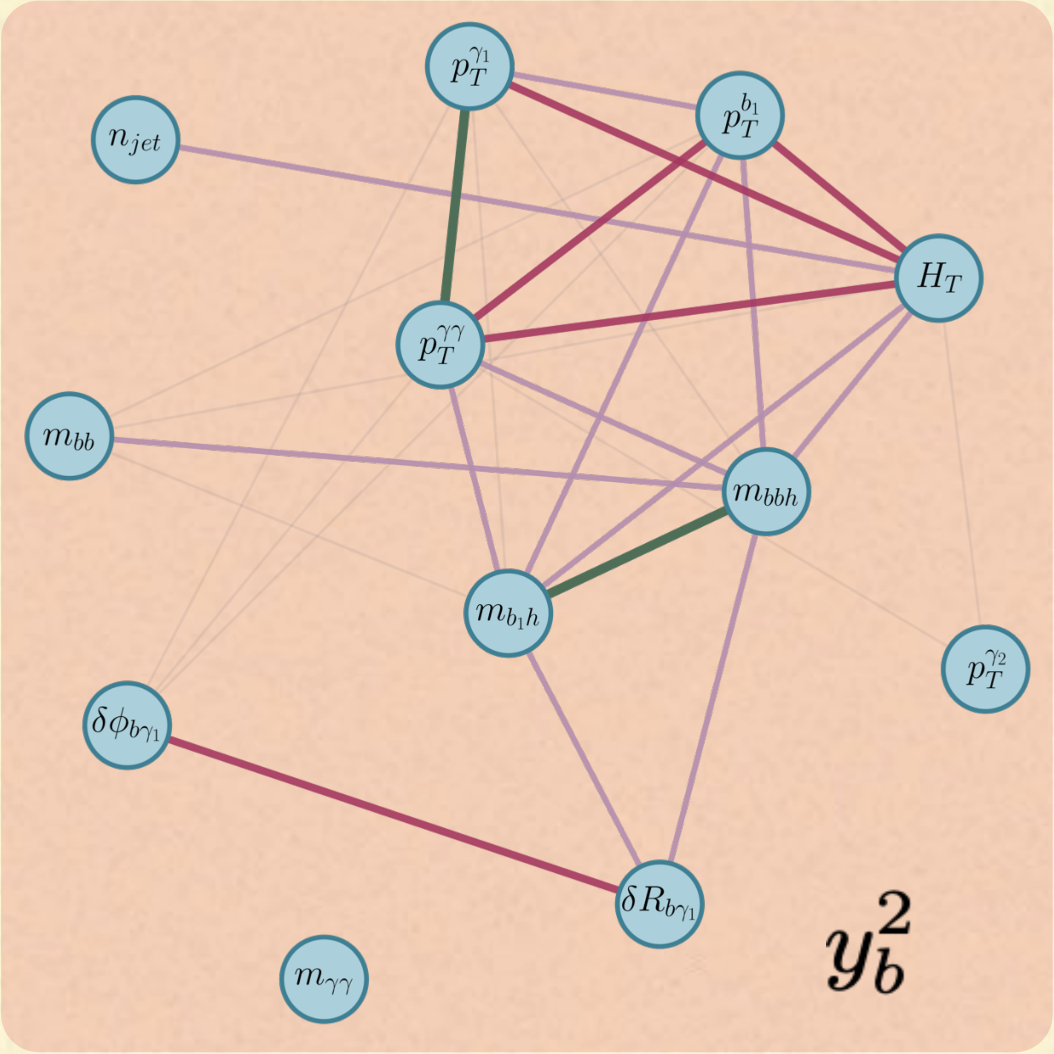
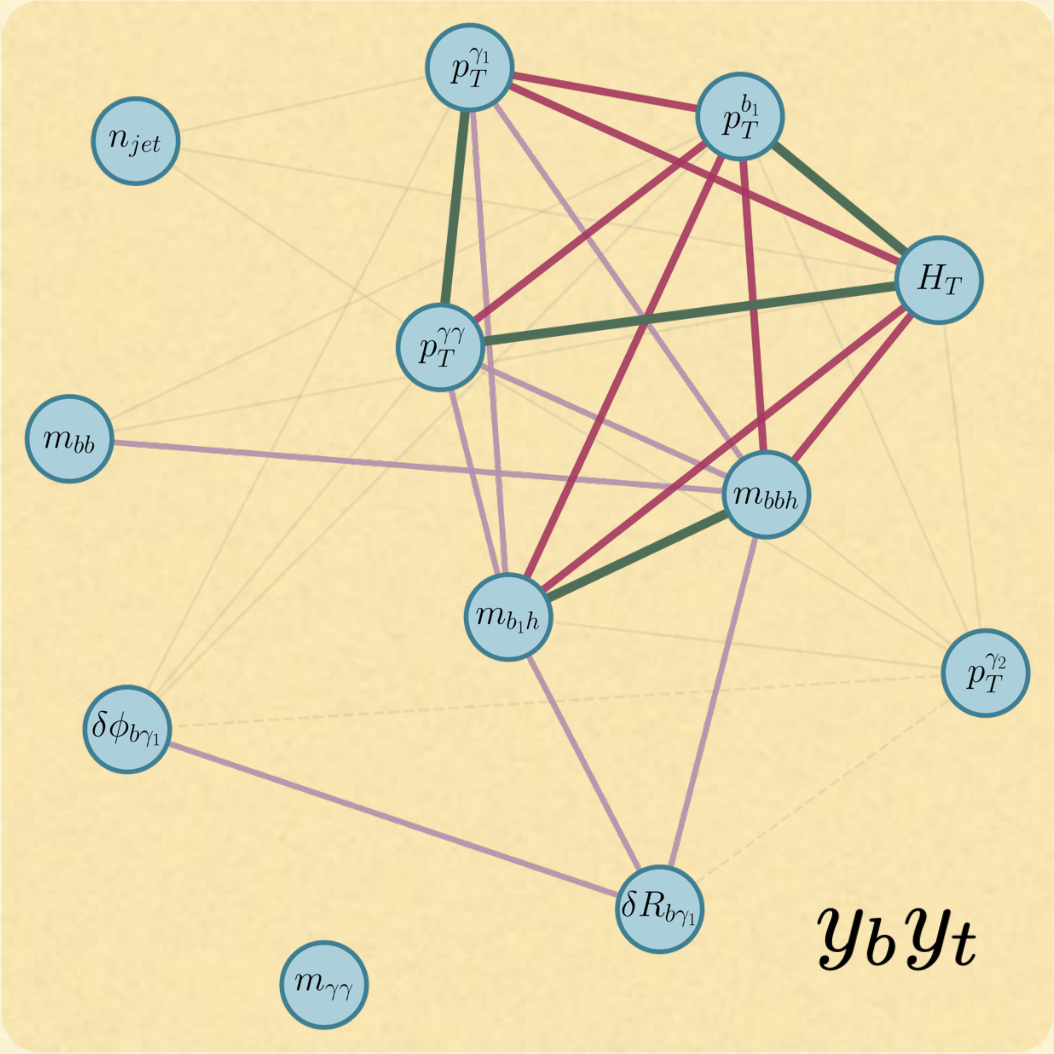
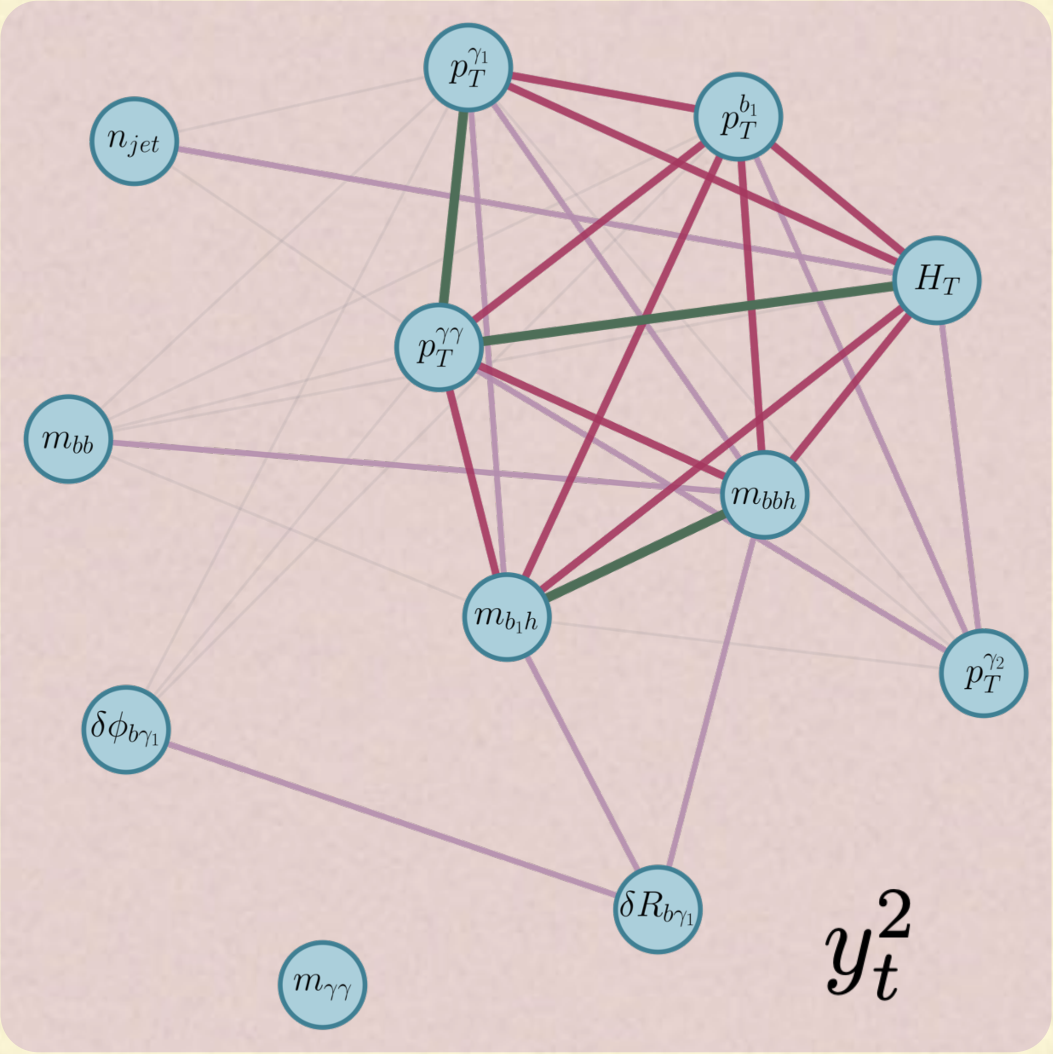
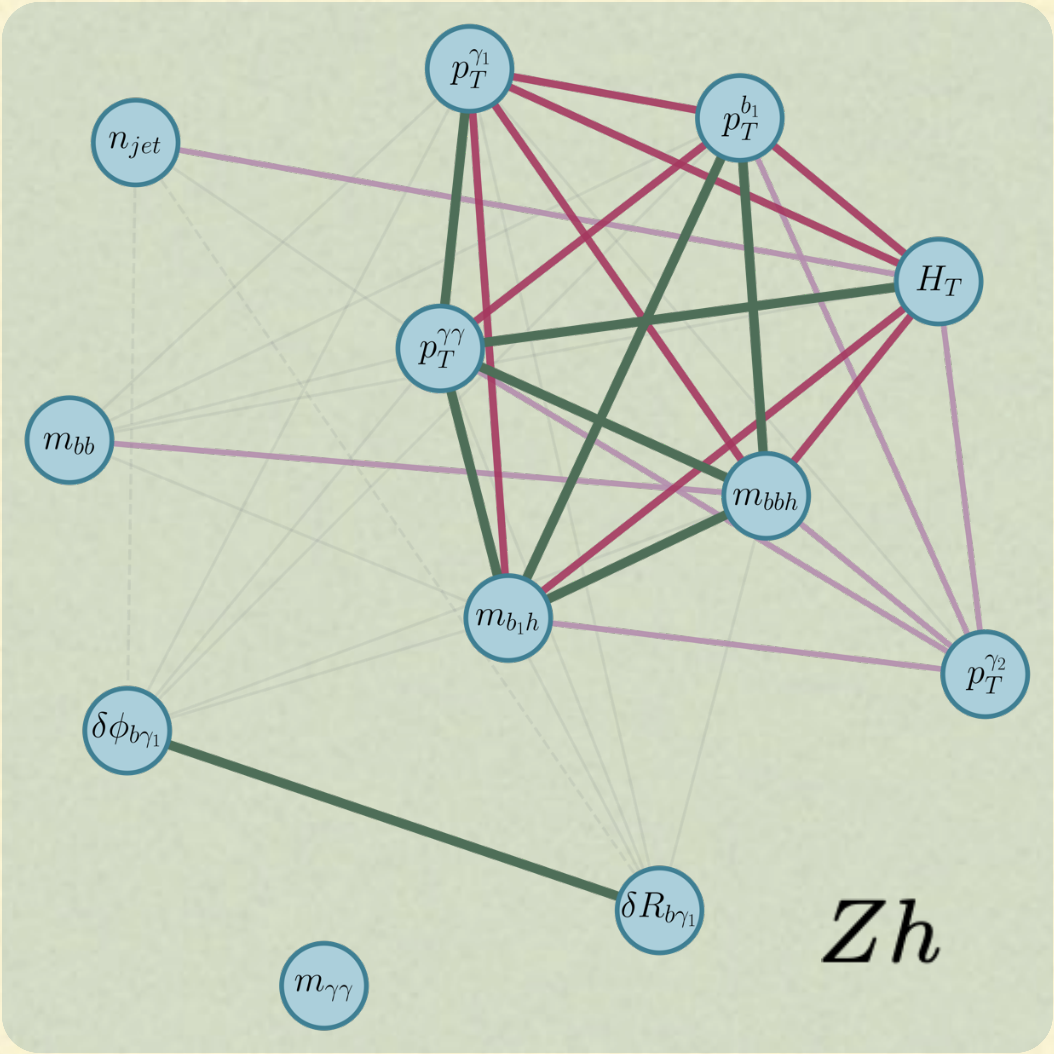
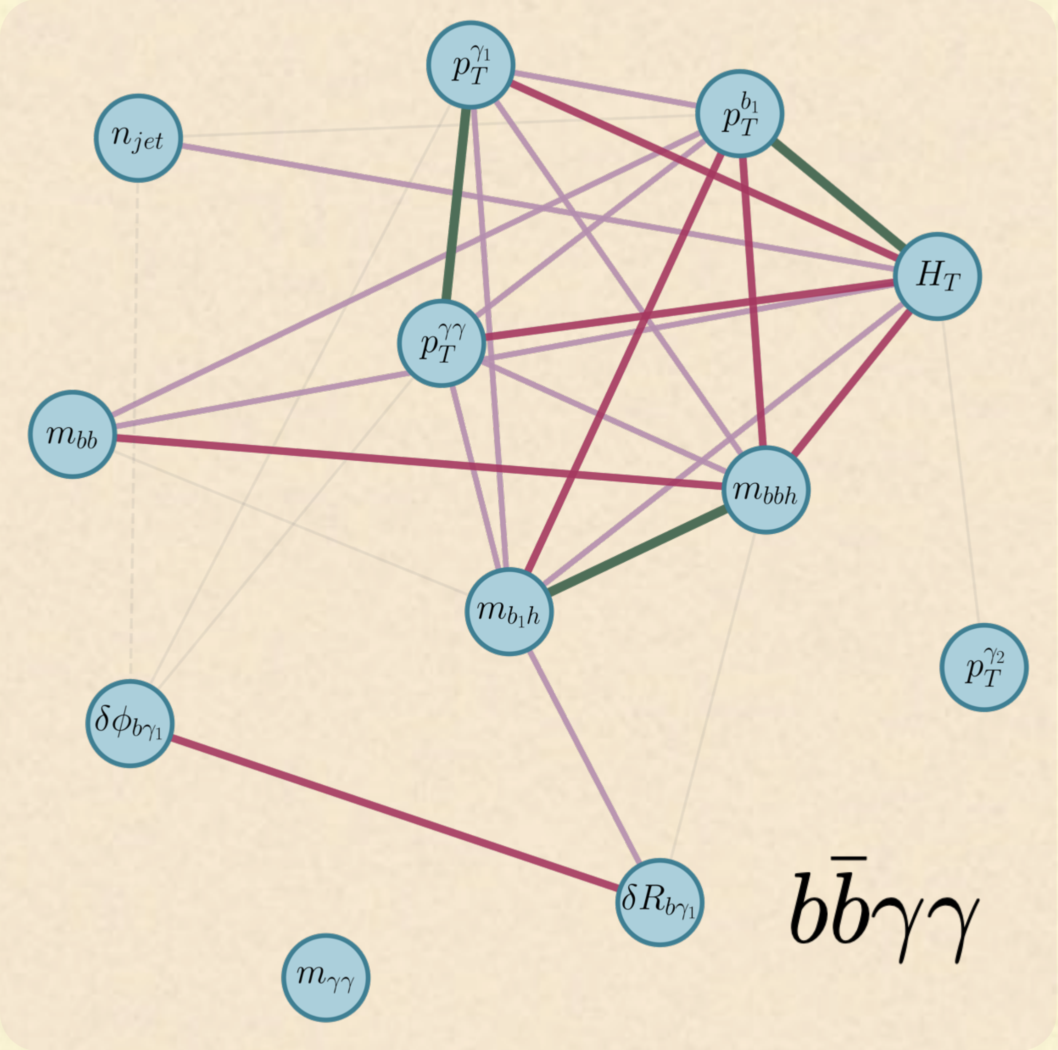
Diving into higher dimension











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--- $-\rho$ — $+\rho$

Into higher dimensions:

- The channel-specific multivariable correlation pattern (detector level)
- NLO (colour) effects, Parton shower, detector effects, etc.
- By Multivariable Analysis (MVA, e.g. BDT, NN) on simulated events

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An Importance Measure/Distribution:

Machine Interpretation: Shapley value (2012):

- Shapley value: an importance "measure" of "group member", through marginalising contribution over the set:

$$\phi_j(val) = \sum_{S\subseteq\{x_1,\ldots,x_p\}\setminus\{x_j\}} \frac{|S|!(p-|S|-1)!}{p!}\left(val\left(S\cup\{x_j\}\right)-val(S)\right)$$

- Shapley value approach log-likelihood ratio in binary-class:

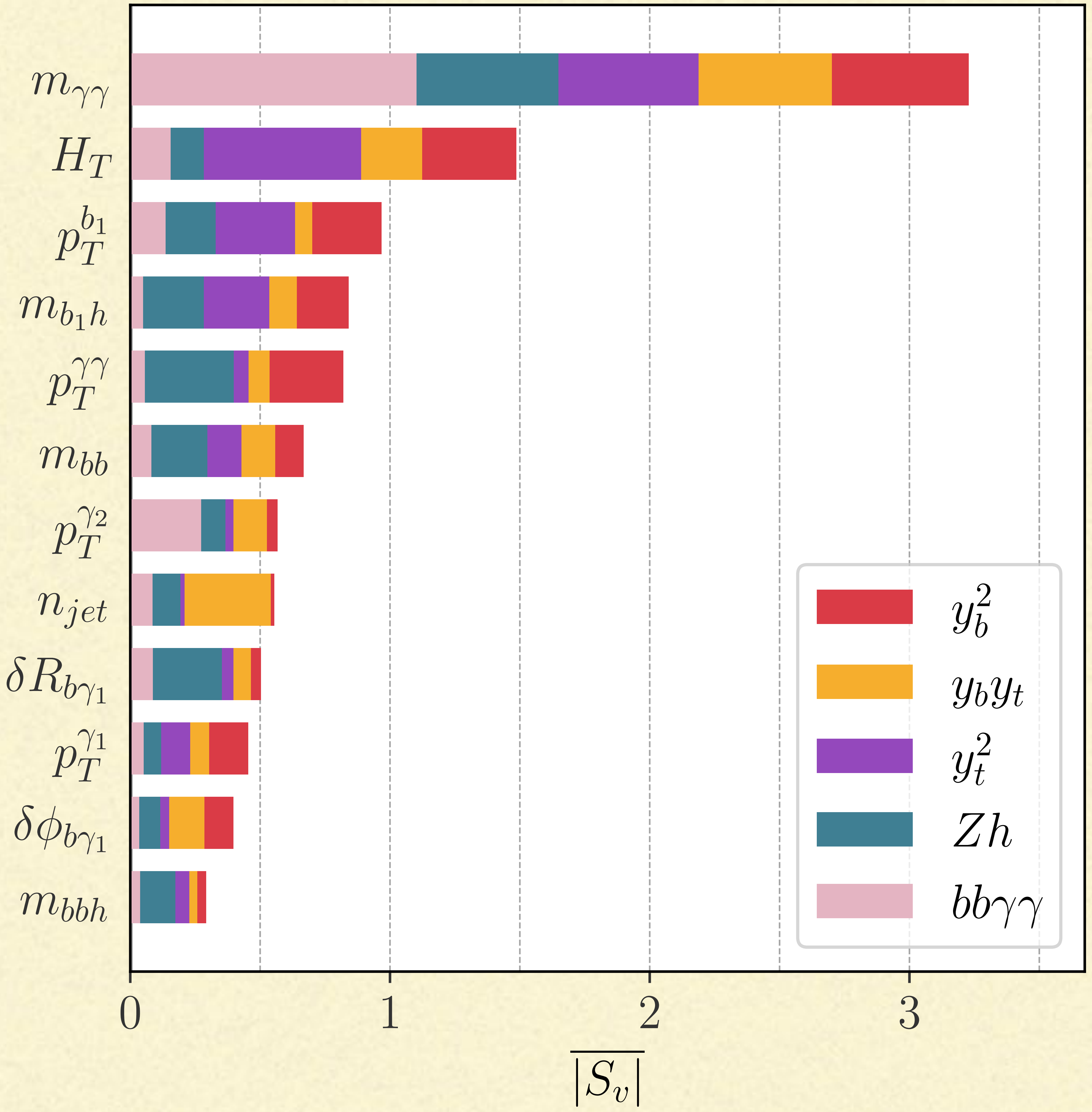
$$LL = \log(\frac{\sum_{i,j}\int f_i f_j|\mathcal{M}_1^{ij\to\vec{f}}|^2}{\sum_{I,J}\int f_I f_J|\mathcal{M}_2^{IJ\to\vec{f}}|^2}) \approx -S^{(n)}(v_1,..v_k)$$

- Feature importance: the averaged abs value of local Shapley:

$$I_j = \sum_{i=1}^{n} |\phi_j^{(i)}|$$

- Reduction of d.o.f. , Additivity over phase space, Distribution Correlation and more.. (Ongoing)

Shapley Feature Importance:



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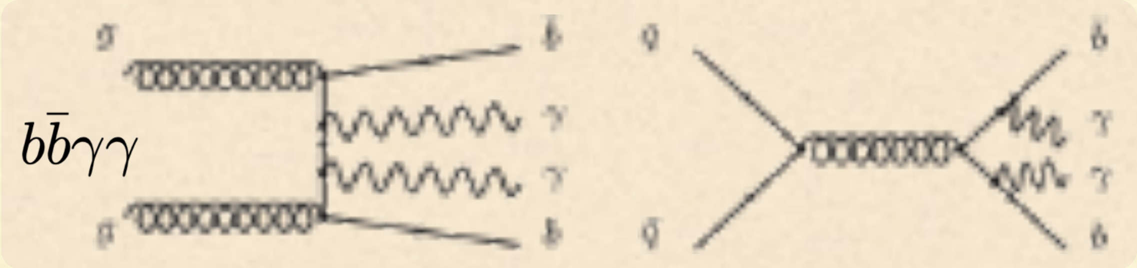
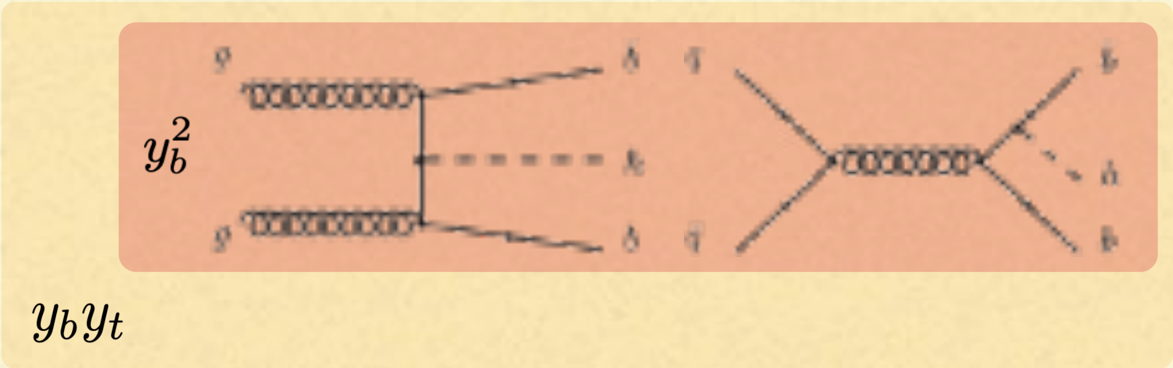
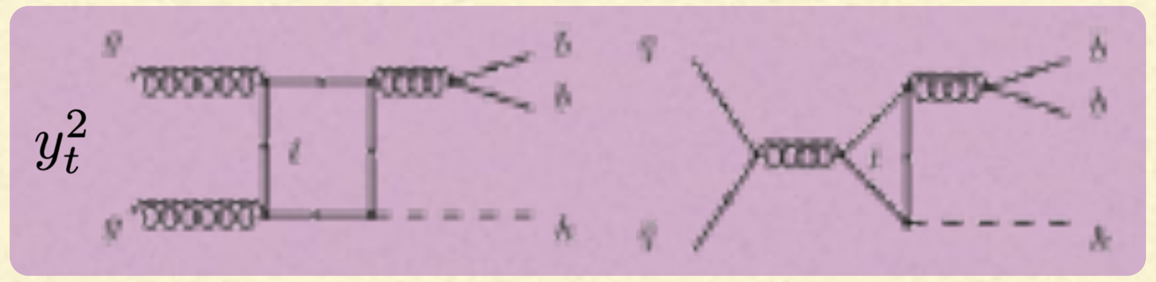
An Interpretable Framework:

Interpretable variables







QCD-QED Backgrounds

Signal

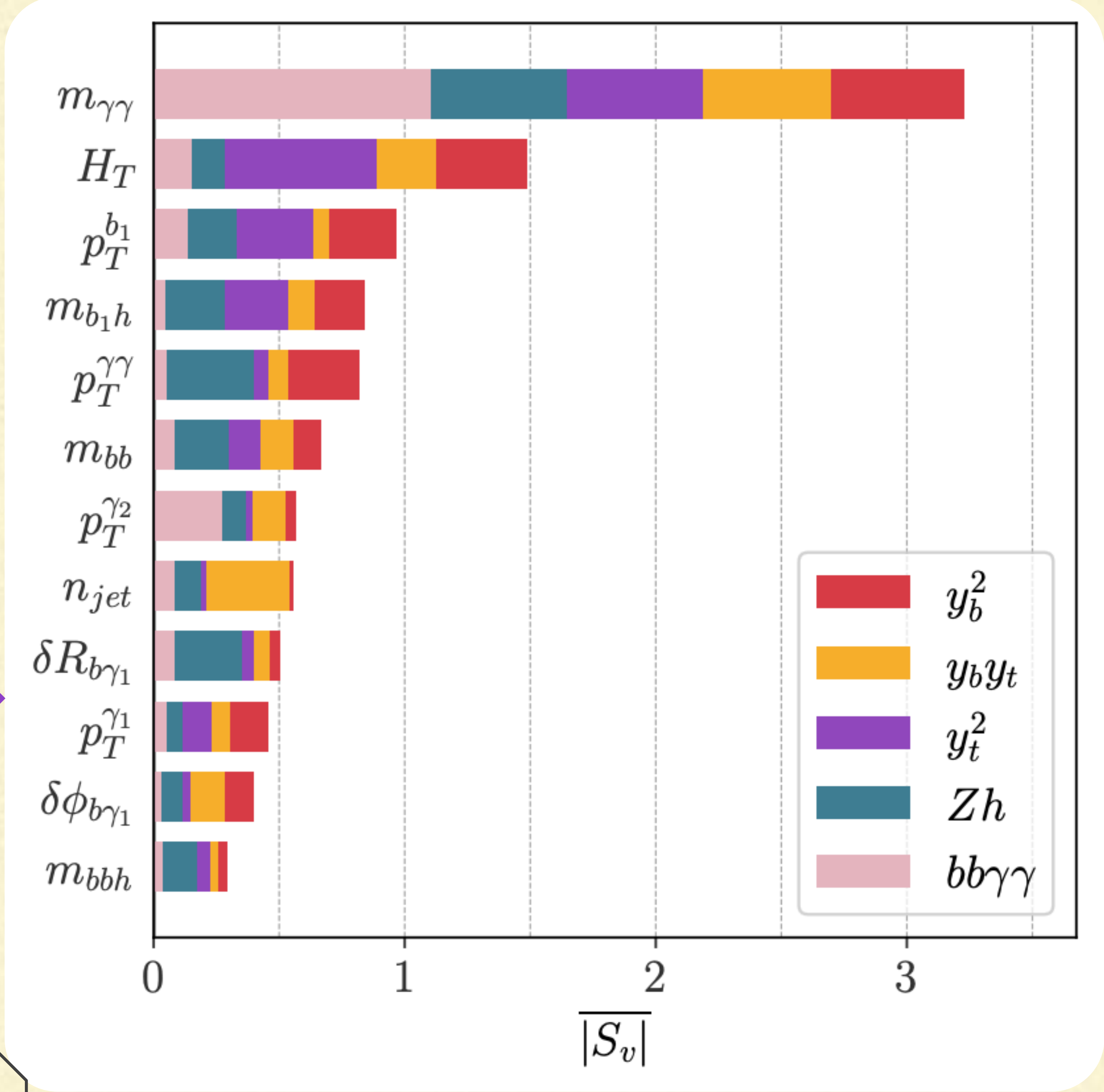
$b\bar{b}h$ backgrounds

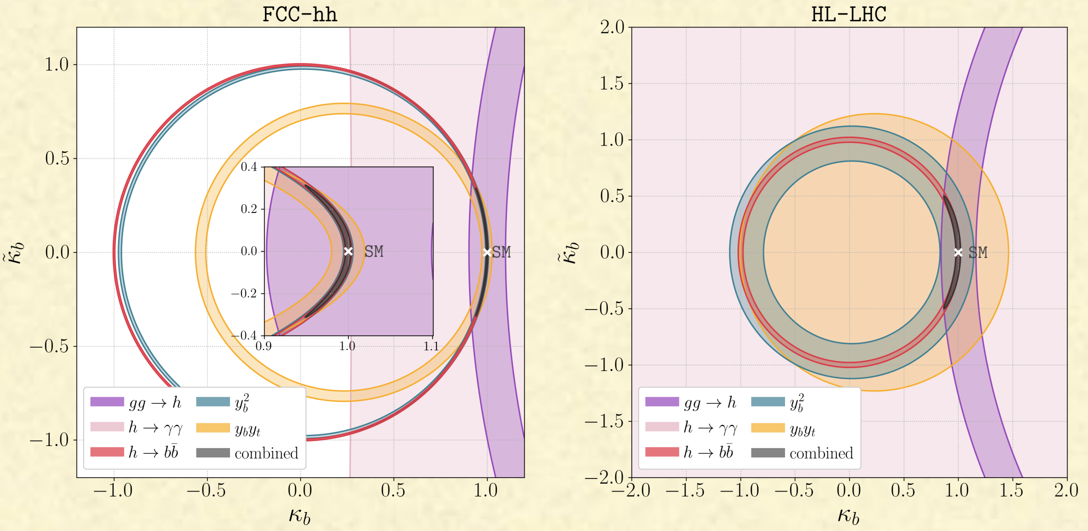
Shapley values + Physics Insights

Boosted Decision Trees + Signal Classification

Interpretable model

Interpretable results





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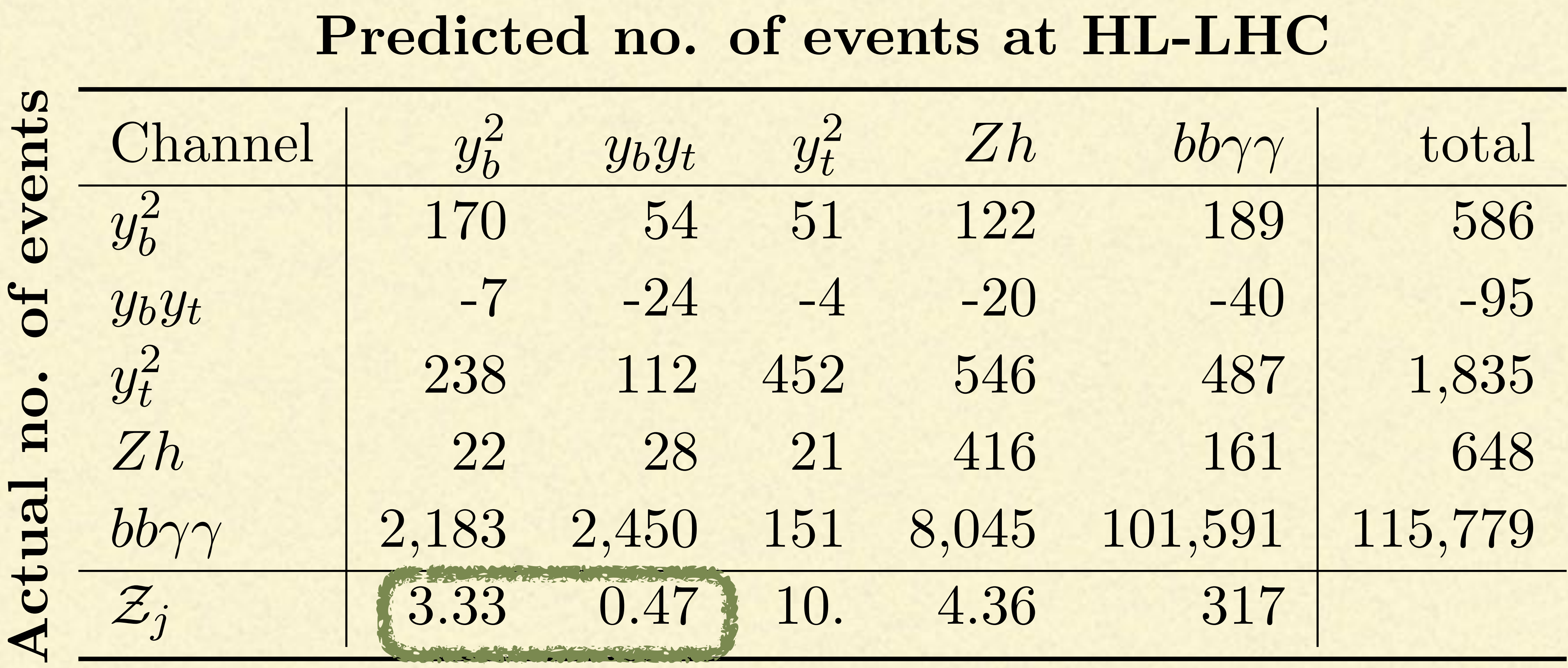
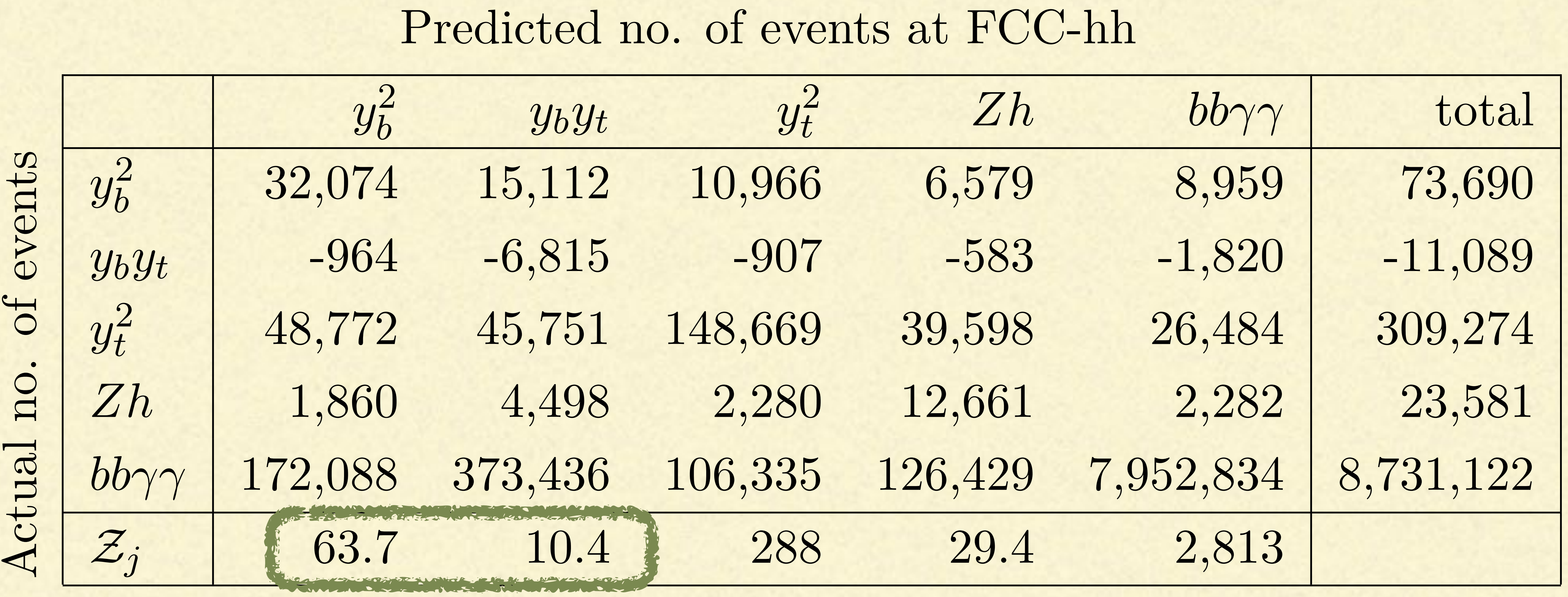
Improved Channel Sensitivity:



Predicted no. of events at HL-LHC

Actual no. of events

Channel	y_b^2	y_by_t	y_t^2	Zh	$bb\gamma\gamma$	total
y_b^2	170	54	51	122	189	586
y_by_t	-7	-24	-4	-20	-40	-95
y_t^2	238	112	452	546	487	1,835
Zh	22	28	21	416	161	648
$bb\gamma\gamma$	2,183	2,450	151	8,045	101,591	115,779
$\mathcal{Z}_j$	3.33	0.47	10.	4.36	317	



Predicted no. of events at FCC-hh

Actual no. of events

	y_b^2	y_by_t	y_t^2	Zh	$bb\gamma\gamma$	total
y_b^2	32,074	15,112	10,966	6,579	8,959	73,690
y_by_t	-964	-6,815	-907	-583	-1,820	-11,089
y_t^2	48,772	45,751	148,669	39,598	26,484	309,274
Zh	1,860	4,498	2,280	12,661	2,282	23,581
$bb\gamma\gamma$	172,088	373,436	106,335	126,429	7,952,834	8,731,122
$\mathcal{Z}_j$	63.7	10.4	288	29.4	2,813	

Optimised BDT/NN classification

$$Z_j = \frac{|N_{jj}|}{\sqrt{\sum_i N_{ij}}}$$

About $\sim 60\,\%$ gain in **significance** over traditional cut analysis.

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Physics Interpretation:

A Real Bottom Yukawa: κ-scheme

$$\mathcal{L} \supset -\kappa_b \frac{m_b}{v} \bar{b} b h$$

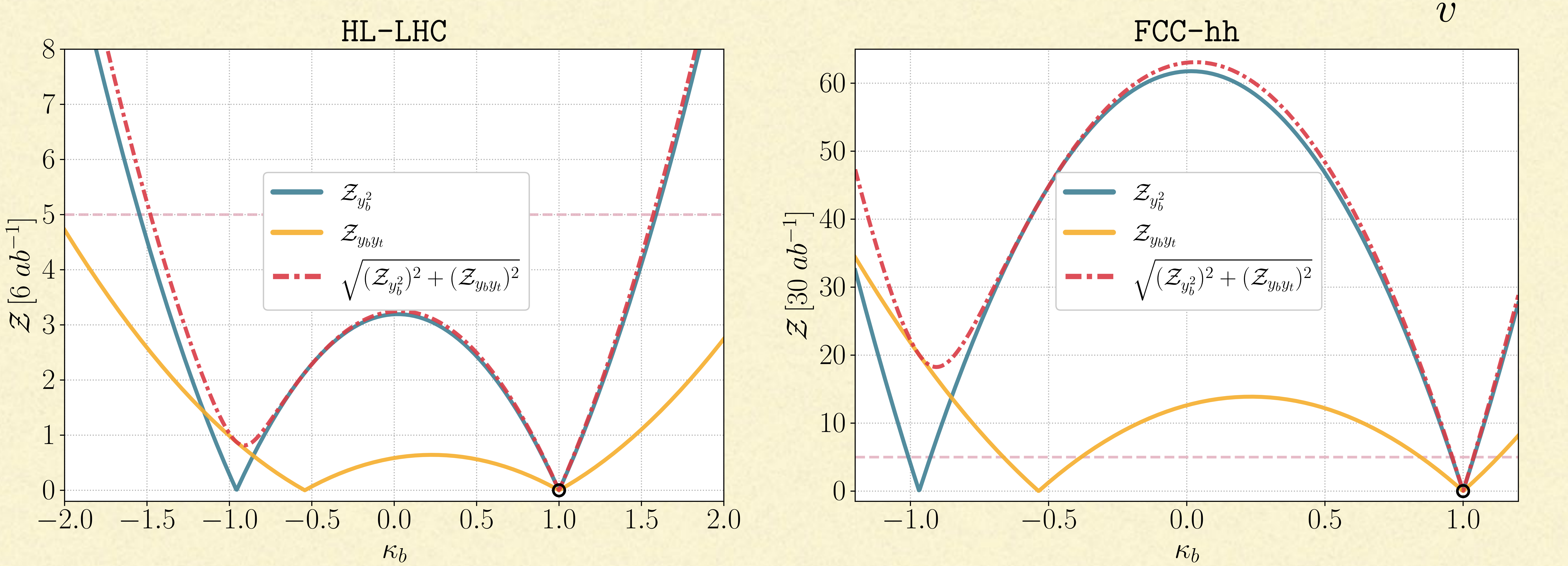

Figure 7. *Significance, $\mathcal{Z}$, as a function of κ_b at HL-LHC (ATLAS+CMS combined, 6 ab^{-1}) and FCC-hh (30 ab^{-1}). A SM signal is injected.*

=> Unambiguous sign determination at FCC-hh.

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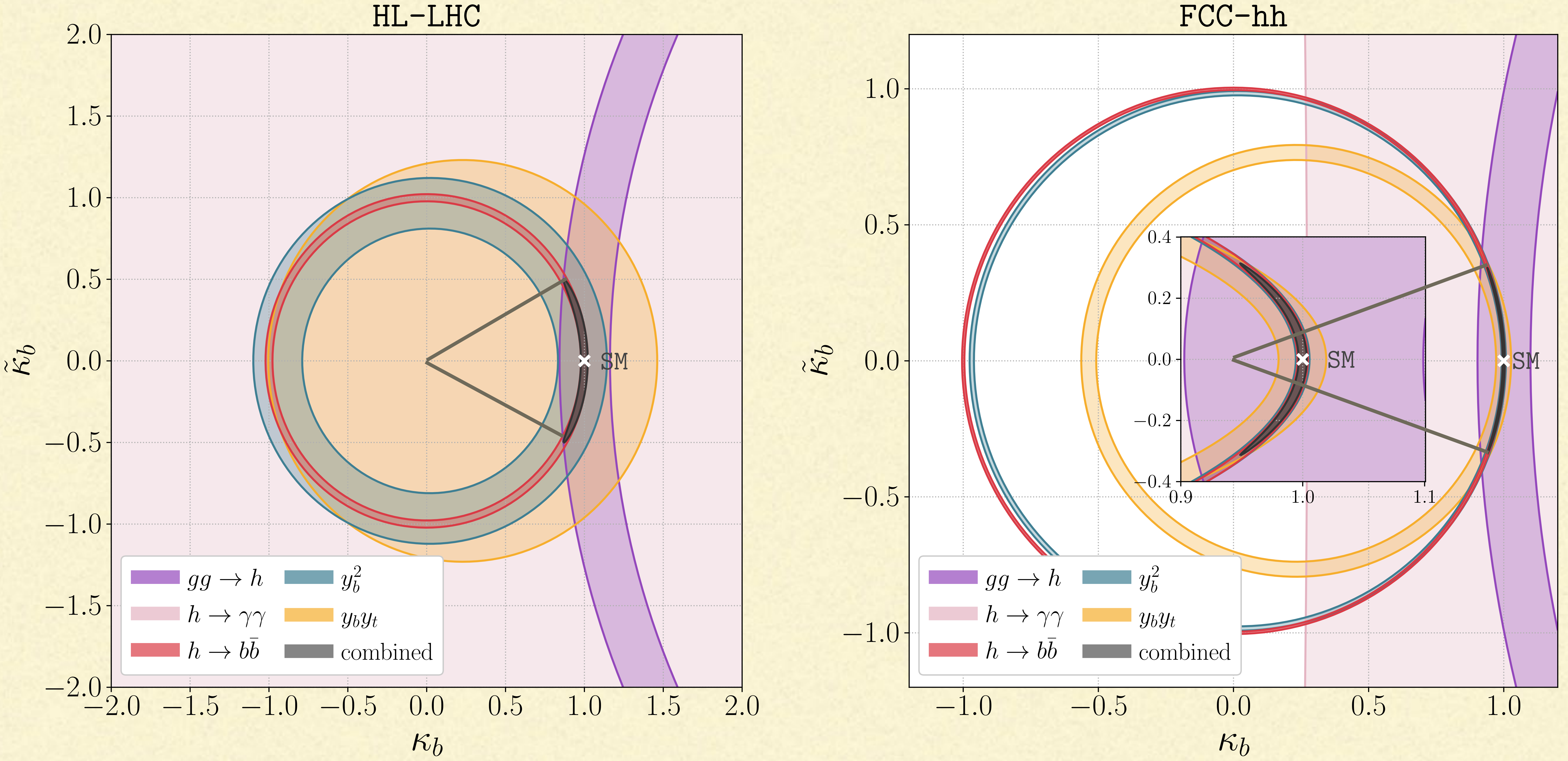
Physics Interpretation:

A complex Bottom Yukawa (CP-phase)

$$\mathscr{L} \sim -\frac{m_b}{v}(\kappa_b \bar{b} b + i\tilde{\kappa}_b \bar{b}\gamma_5 b)h$$



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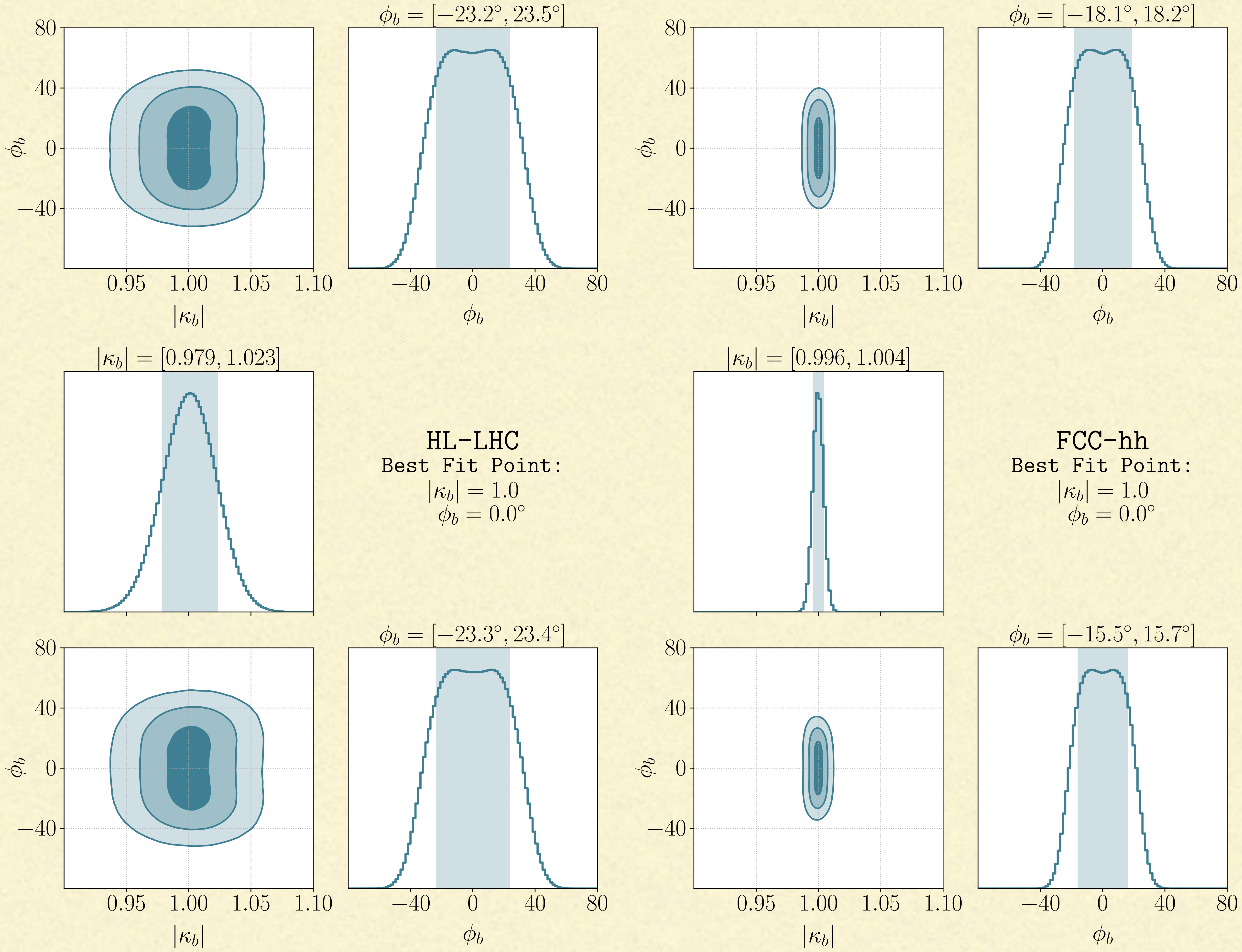

Comparison to LHC:

HL-LHC: $\phi_b = [-23.2°, 23.5°]$ => $\tilde{\kappa}_b \lesssim$ 0.4

FCC-hh: $\phi_b = [-15.5°, 15.7°]$ => $\tilde{\kappa}_b \lesssim$ 0.3

+ 15% to indirect bounds

Comparison to EDM:

Hadronic EDM (free of y_e assumption):

nEDM: $\sum A\kappa_q\tilde{\kappa}_{\mathbf{q}} + B\tilde{\kappa}_{\mathbf{q}}\kappa_{\mathbf{q}}$ => $\tilde{\kappa}_b \lesssim 5.$

Electron EDM:

eEDM: $\sum A\kappa_e\tilde{\kappa}_{\mathbf{q}} + B\tilde{\kappa}_e\kappa_{\mathbf{q}}$ => $\tilde{\kappa}_b \lesssim 0.5$

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Conclusions:

- Associated production of $b\bar{b}h$ stands to gain at HL-LHC, FCC
- Direct sensitivity on a complex phase of y_b from interference term, compared to $gg \to h, h \to \gamma\gamma$, or e-EDM, n-EDM
- Multi-channel multi-dimensional final states benefit from or rely on MVA
- MVA (BDT, NN ML etc) can be better understood with importance measure such as Shapley values, retaining interpretability.

Backup

References

Measurement of $H \to b\bar{b}$

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Recent theory papers on $b\bar{b}h$

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- D. Pagani, H.-S. Shao and M. Zaro, *RIP $Hb\bar{b}$: How other Higgs production modes conspire to kill a rare signal at the LHC*, arXiv:2005.10277.

Papers on Higgs couplings fits

- M. Cepeda et al., *Report from Working Group 2: Higgs Physics at the HL-LHC and HE-LHC*, vol. 7, pp. 221–584. 12, 2019. arXiv:1902.00134.
- J. de Blas et al., *Higgs Boson Studies at Future Particle Colliders*, JHEP 01 (2020) 139, [arXiv:1905.03764].

Shapley values and interpretable machine learning

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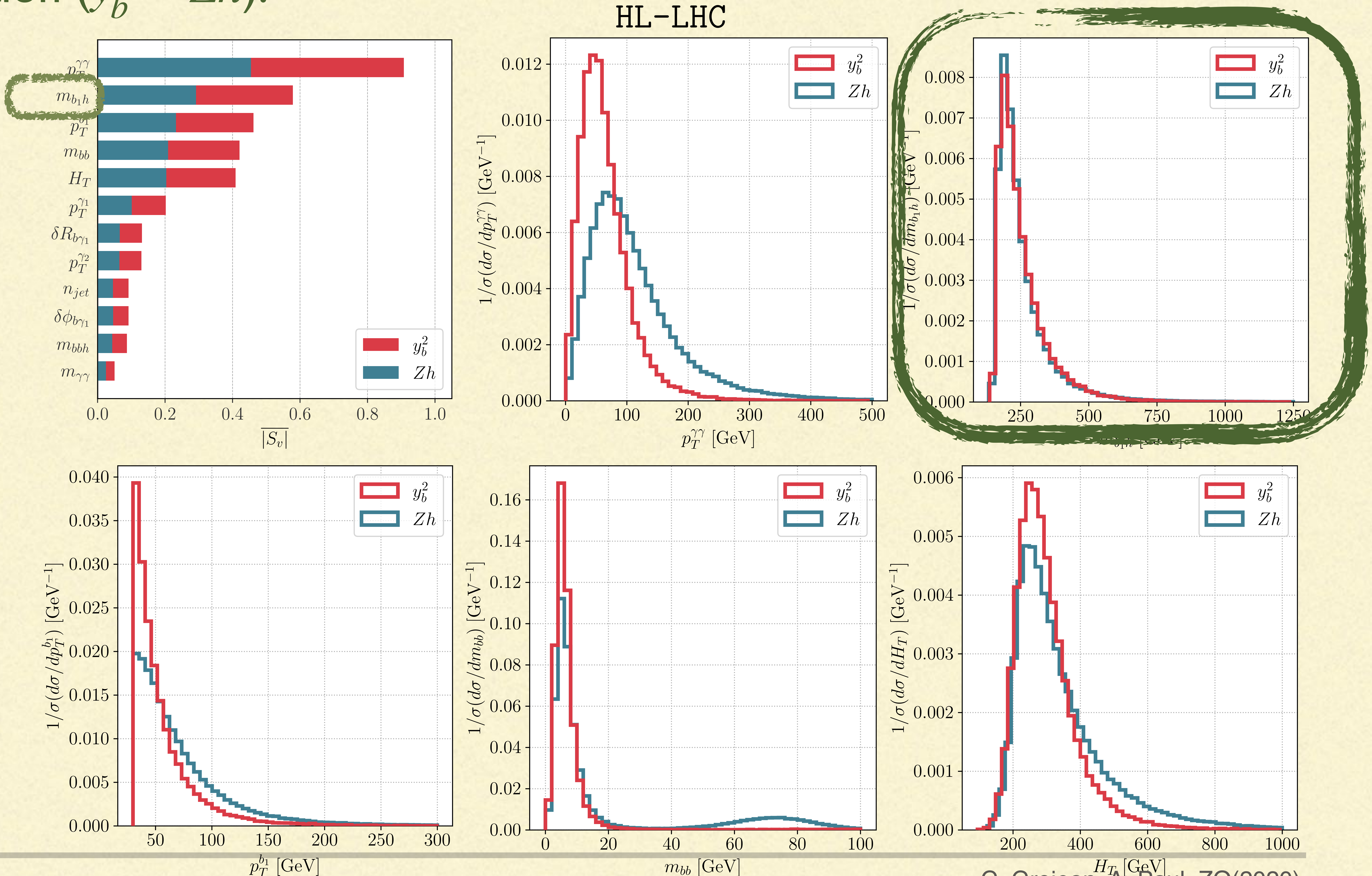
- S. M. Lundberg, G. G. Erion and S.-I. Lee, Consistent Individualized Feature Attribution for Tree Ensembles, arXiv e-prints (Feb. 2018) , [arXiv:1802.03888].
- S. M. Lundberg, G. Erion, H. Chen, A. DeGrave, J. M. Prutkin, B. Nair et al., *From local explanations to global understanding with explainable AI for trees*, Nature Machine Intelligence 2 (2020) 56–67.

Machine Interpretation ($y_b^2 - Zh$):



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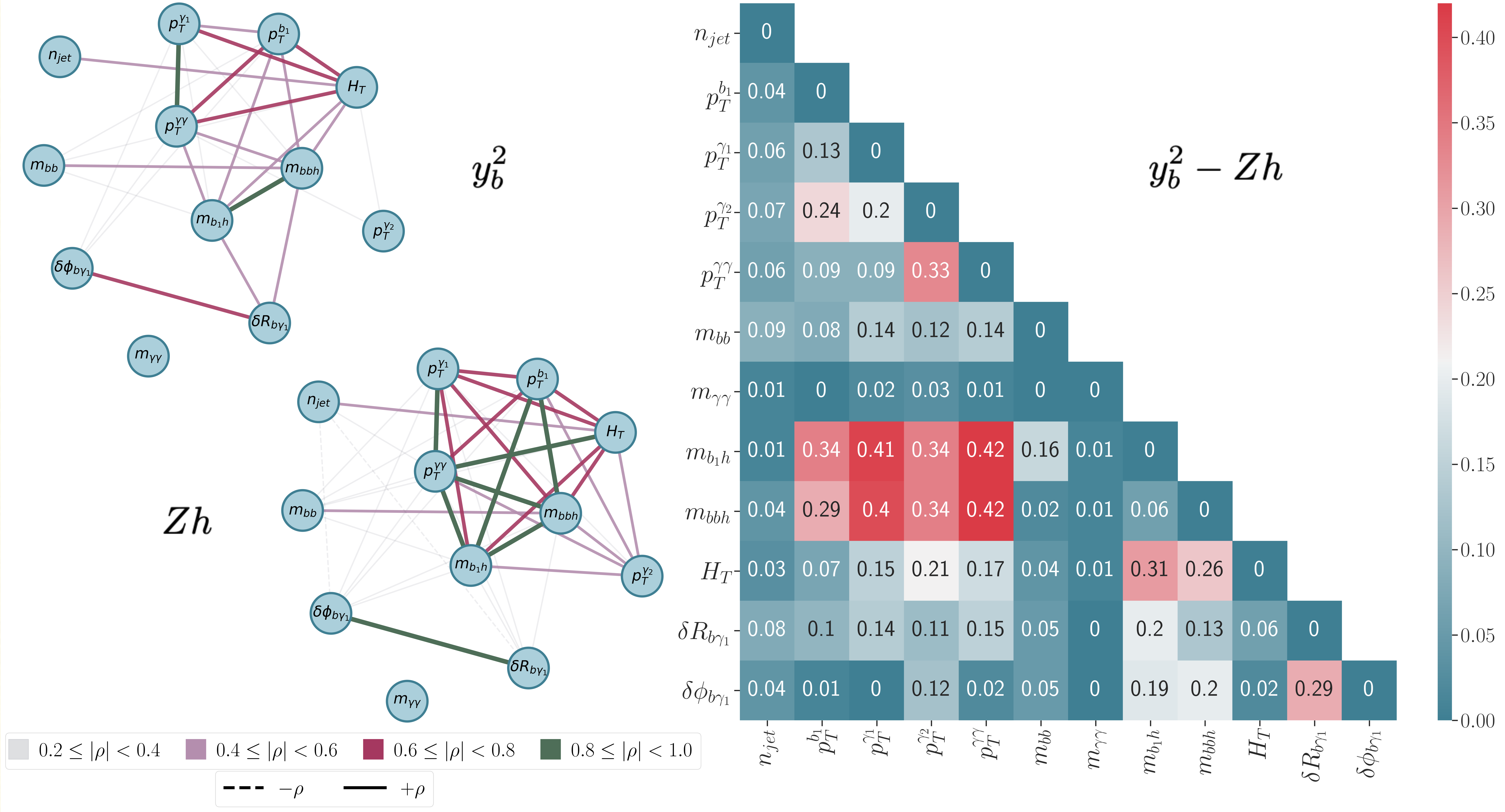
Machine Interpretation ($y_b^2 - Zh$):

“importance of m_{b1h} variable visualised through correlation”

HL-LHC



	n_{jet}	$p_T^{b_1}$	$p_T^{\gamma_1}$	$p_T^{\gamma_2}$	$p_T^{\gamma\gamma}$	m_{bb}	$m_{\gamma\gamma}$	m_{b_1h}	m_{bbh}	H_T	$\delta R_{b\gamma_1}$	$\delta\phi_{b\gamma_1}$
n_{jet}	0											
$p_T^{b_1}$	0.04	0										
$p_T^{\gamma_1}$	0.06	0.13	0									
$p_T^{\gamma_2}$	0.07	0.24	0.2	0								
$p_T^{\gamma\gamma}$	0.06	0.09	0.09	0.33	0							
m_{bb}	0.09	0.08	0.14	0.12	0.14	0						
$m_{\gamma\gamma}$	0.01	0	0.02	0.03	0.01	0	0					
m_{b_1h}	0.01	0.34	0.41	0.34	0.42	0.16	0.01	0				
m_{bbh}	0.04	0.29	0.4	0.34	0.42	0.02	0.01	0.06	0			
H_T	0.03	0.07	0.15	0.21	0.17	0.04	0.01	0.31	0.26	0		
$\delta R_{b\gamma_1}$	0.08	0.1	0.14	0.11	0.15	0.05	0	0.2	0.13	0.06	0	
$\delta\phi_{b\gamma_1}$	0.04	0.01	0	0.12	0.02	0.05	0	0.19	0.2	0.02	0.29	0

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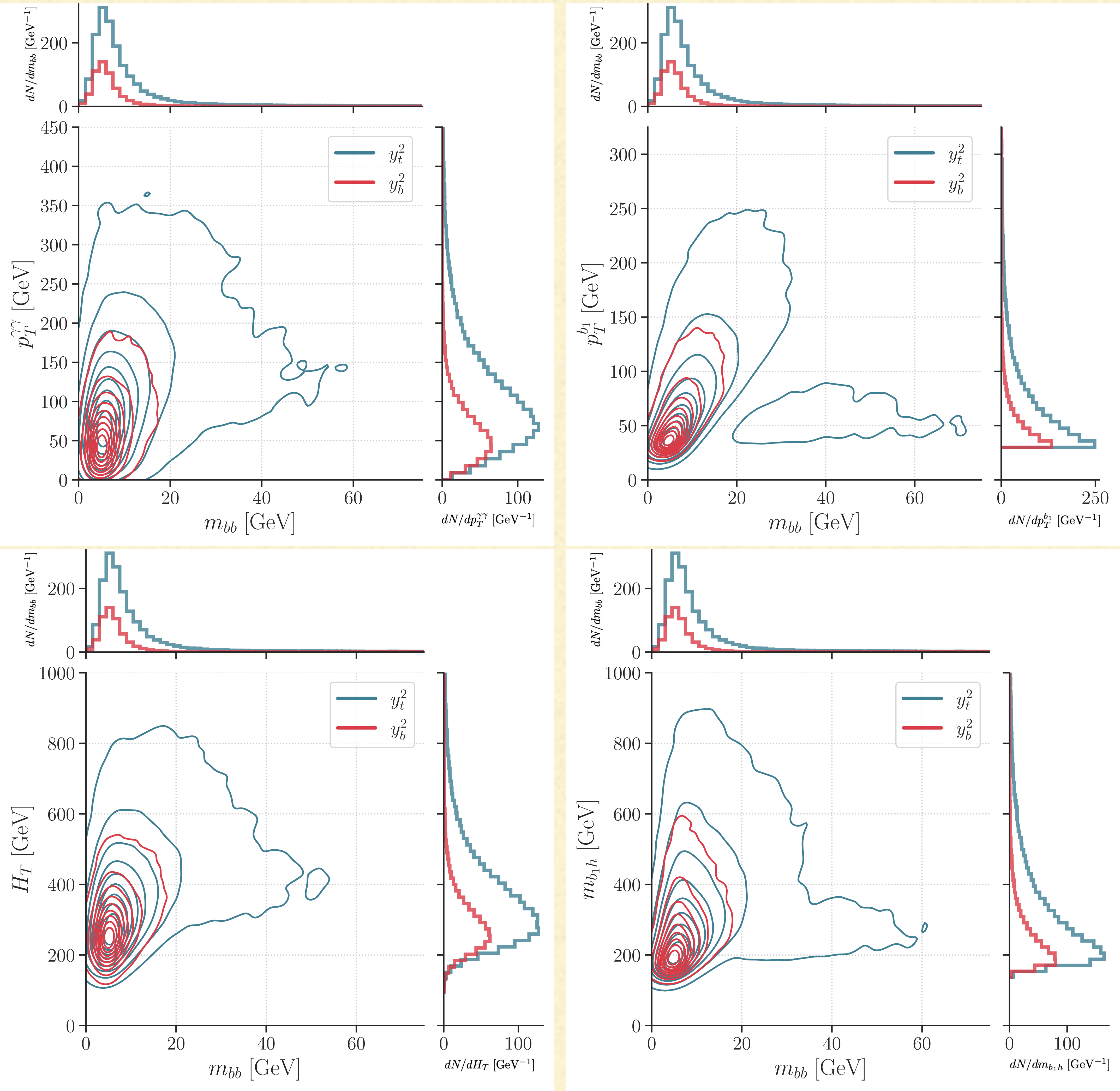
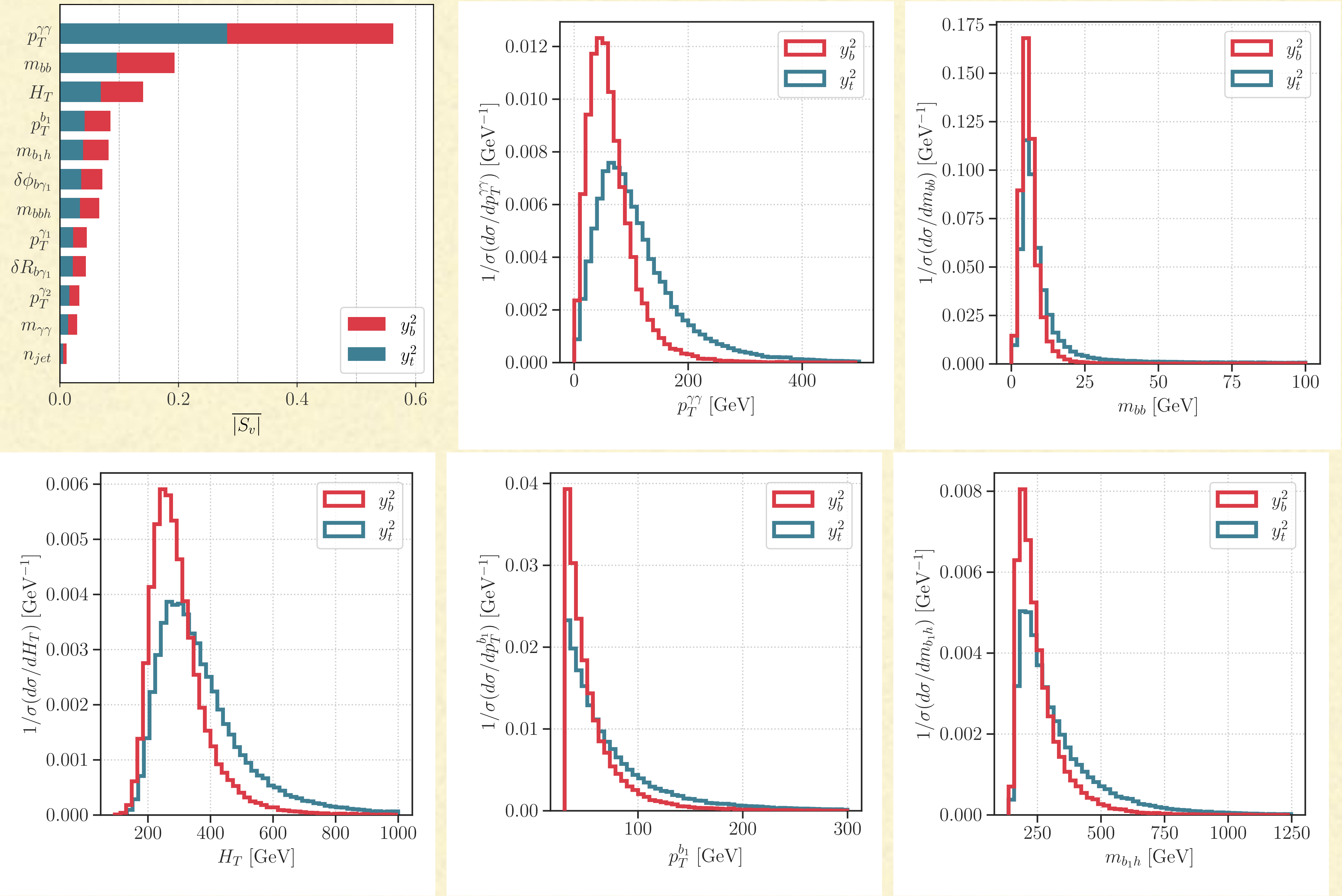
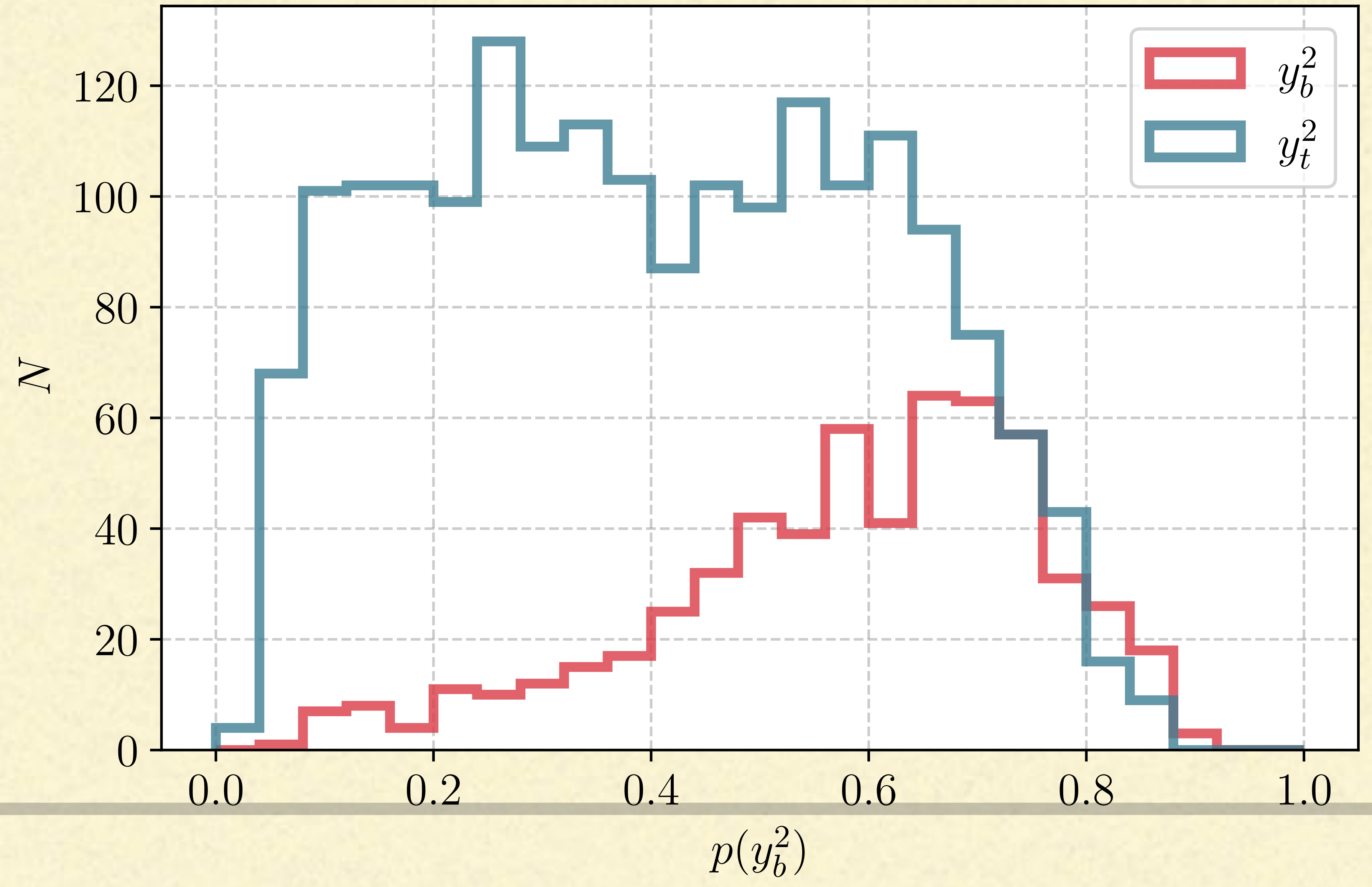
Machine Interpretation ($y_b^2 - y_t^2$):

HL-LHC



HL-LHC

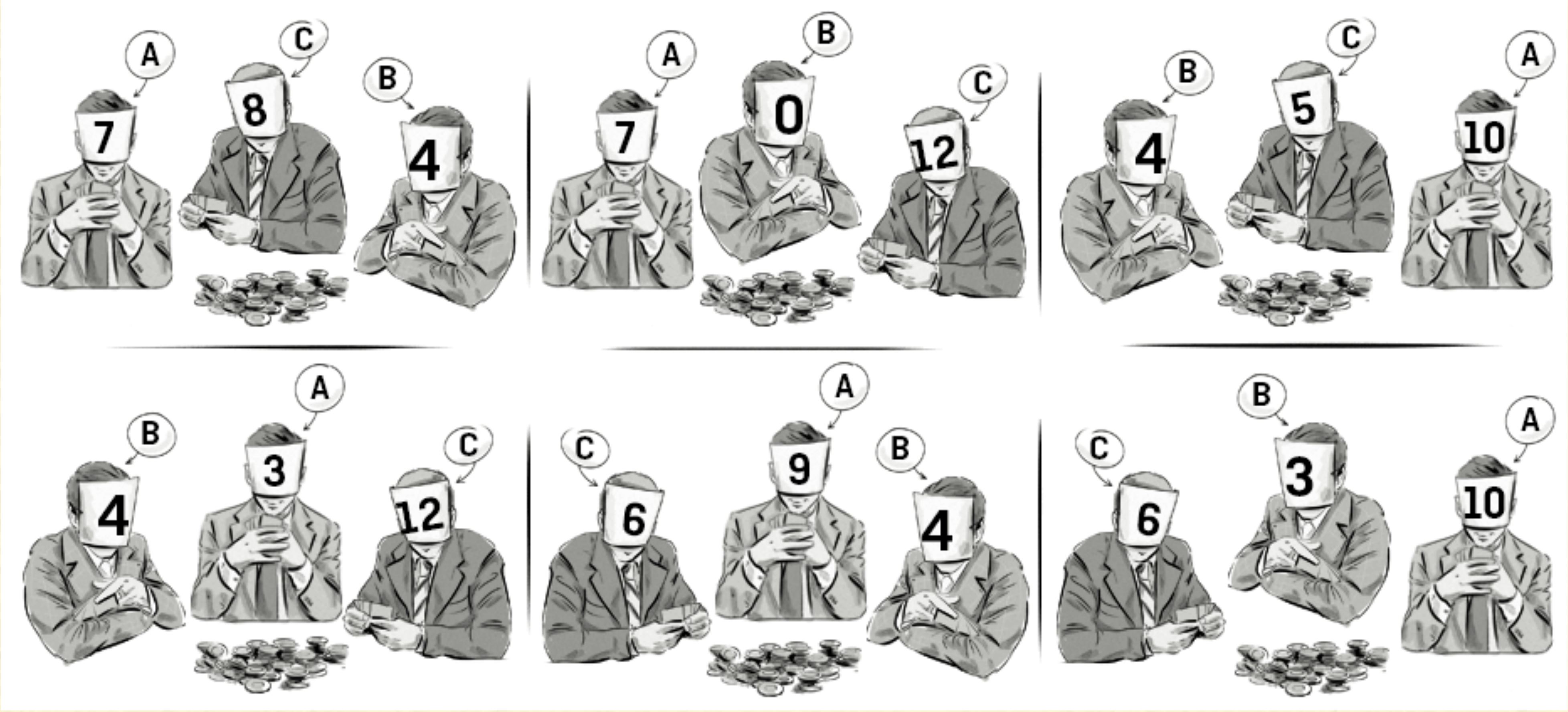




Shapley value from Cooperative game theory :

The value of each player and each combination of players

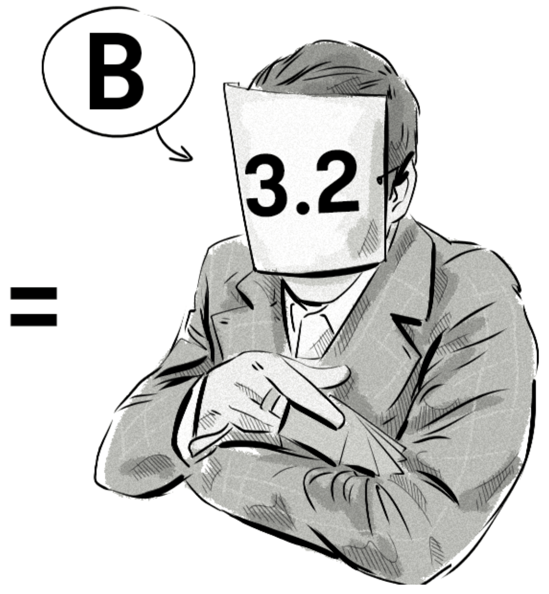
The value of the player in each game



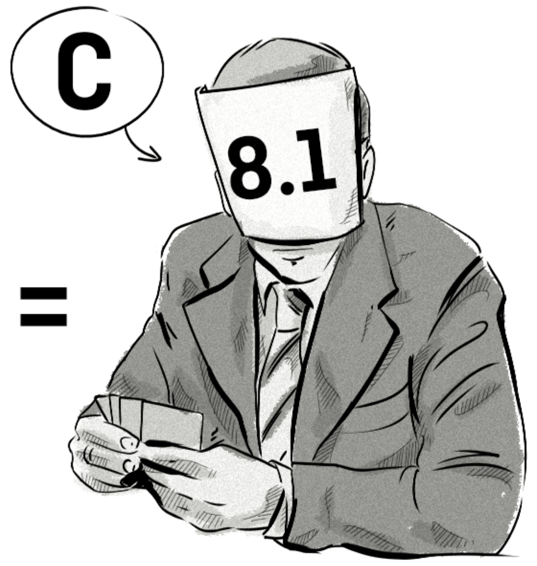
Marginalized values

(7+7+10+3+9+10) / 6 =

(4+0+4+4+4+3) / 6 =



(8+12+5+12+6+6) / 6 =



The most important player

L. S. Shapley, Notes on the n-Person Game-II: The Value of an n-Person Game (1951).

$b\bar{b}h$: Additional background discussion

- VBF: light-jet veto kills the VBF while careful simulation is further needed.
- di-Higgs: both mbb and mγγ clustered around the Higgs-mass peak, distinct final state shape to be separate
- $gg \to Zh$: small at HL-LHC, but grows rapidly with s, and comparable but subdominant to the yb-sensitive channels at FCC-hh. Can be further distinguished as the case of $q\bar{q} \to Zh$.
- Fakes: ccxaa, jjxaa, caa, jjja, etc.: subdominant yet comparable to bbxaa. Needs attention and study in future for better control

$b\bar{b}h$: Additional background discussion

systematics	HL-LHC (6 ab^{-1})		FCC-hh (30 ab^{-1})	
	y_b^2	$y_b y_t$	y_b^2	$y_b y_t$
0%	3.33	0.47	63.7	10.4
0.5%	3.26	0.46	32.2	3.44
1%	3.06	0.42	17.9	1.80
5%	1.41	0.18	3.72	0.36