



# ALP search at Belle II



# Physics Motivation

- The Strong CP problem : is the puzzling question of why QCD does not appear to violate CP symmetry, despite allowing for such a violation through the  $\theta$ -term

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4}G_{\mu\nu}^a G^{a\mu\nu} + \sum_f \bar{\psi}_f (i\gamma^\mu D_\mu - m_f) \psi_f + \theta \frac{g_s^2}{32\pi^2} G_{\mu\nu}^a \tilde{G}^{a\mu\nu}$$

the gluon field strength tensor

quark fields for each flavor  $f$

Quark mass

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the gluon field strength tensor

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Quark mass

- Neutron EDM sets a very stringent upper bound:  $\theta \leq 10^{-10}$

# Physics Motivation

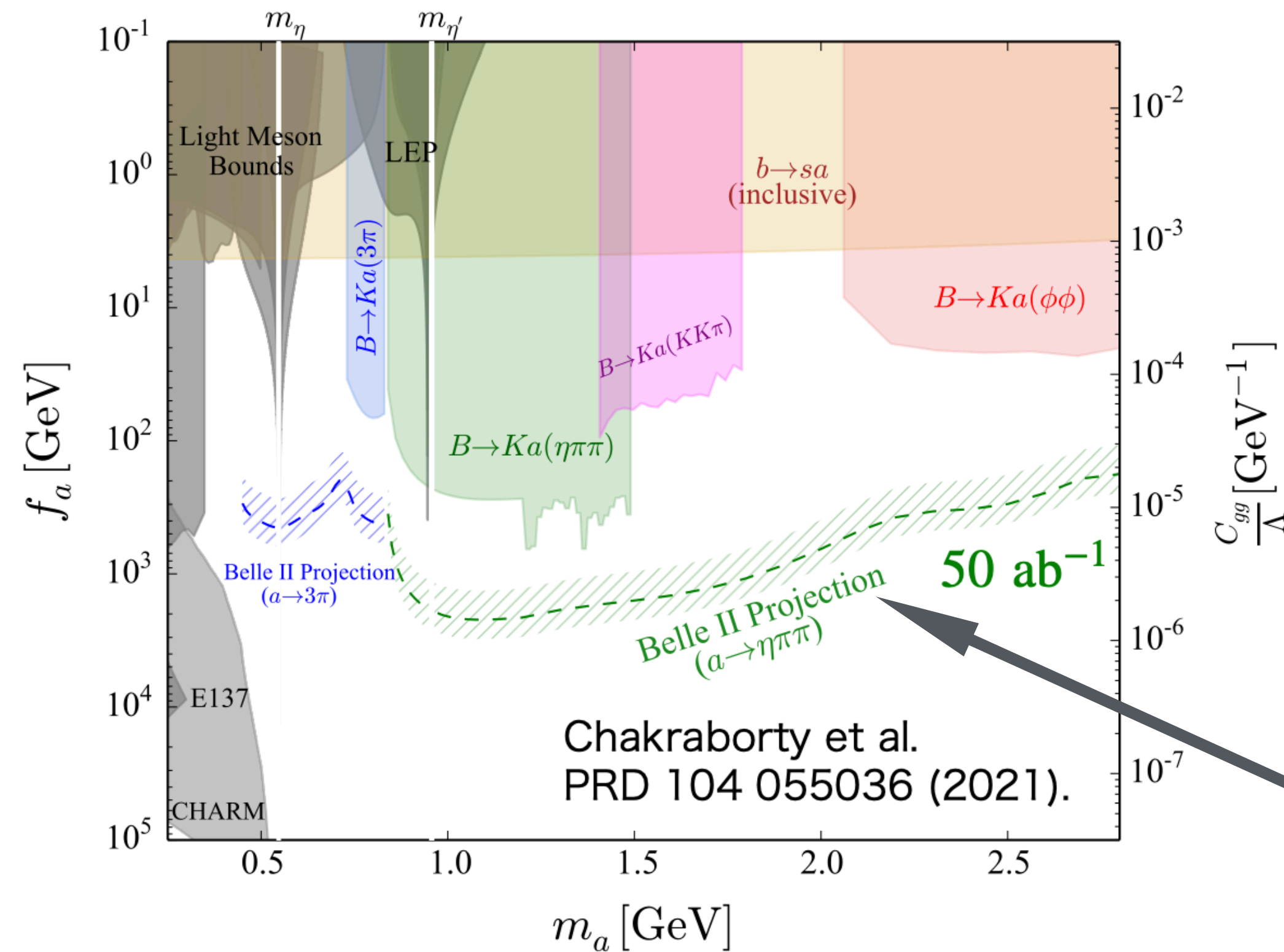
- Proposed solution of strong CP problem, PQ symmetry was introduced by Peccei & Quinn (PRL 38 (1977) 1440)
  - Promote to a *field*  $\theta$  dynamically settles the CP phase to the minimum
  - PQ Symmetry: Global U(1) that generates the **axion** as a Nambu-Goldstone boson.
  - An attractive **dark matter** candidate, typically below meV

# From QCD Axion to Heavy QCD Axion

- Standard QCD axion has mass prediction  $\sim 0.1$  MeV
- Heavy QCD axion, axion heavier than “standard mass”
  - Viable with lower breaking scale. It should cover mass  $> 100$  MeV
  - PQ symmetry quality will be better
  - Most likely not a dark matter : decays in cosmological time scale. It's not cold enough. If produced in the early universe, heavy axions often disrupt Big Bang Nucleosynthesis (BBN) or Cosmic Microwave Background (CMB) predictions unless they decay very early.
- Why Interesting:
  - They can show up in colliders, beam dump experiments, or rare meson decays.
  - They solve the strong CP problem in a non-standard way.
  - They might be part of a larger dark sector (e.g., decaying into other dark particles).

# $B^+ \rightarrow K^+ a, a \rightarrow \text{Hadrons}$

- Chakraborty et al. (PRD 104 055036 (2021)) estimated sensitivity of heavy QCD axion using some (not DM search) experimental data.



$a \rightarrow \eta \pi^+ \pi^-$ : BABAR, PRL 101, 091801 (2008),

$B^+ \rightarrow \eta_X K^+, \eta_X \rightarrow \eta \pi^+ \pi^-, \sim 400 \text{ fb}^{-1}$ .

$a \rightarrow \pi^0 \pi^+ \pi^-$ : Belle, PRD 90, 012002 (2014),

$B^+ \rightarrow \omega K^+, \omega \rightarrow \pi^0 \pi^+ \pi^-, \sim 700 \text{ fb}^{-1}$ .

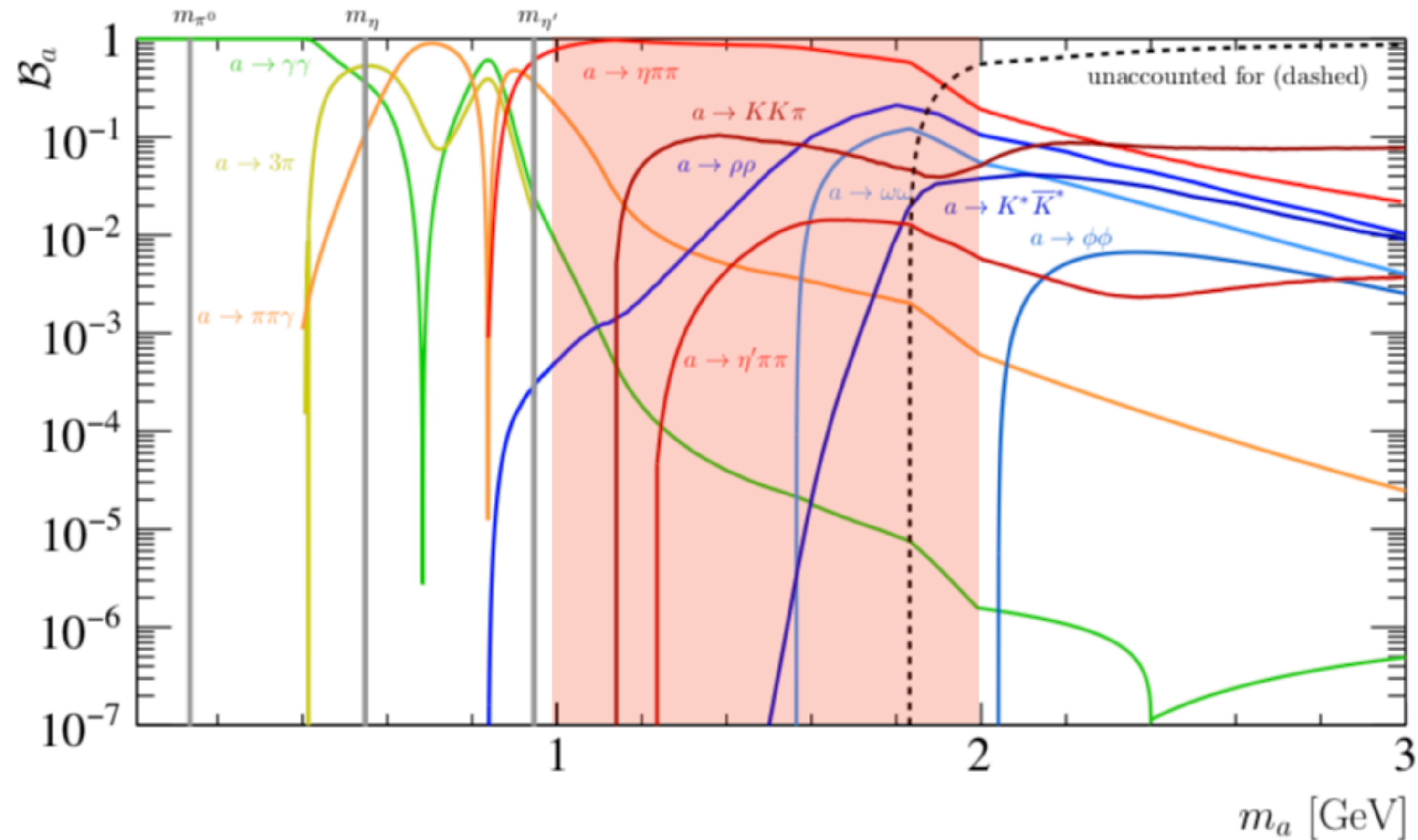
Extrapolation  
bases on BaBar

$$BF(B^+ \rightarrow K^+ a) \sim 10^{-5} (100 \text{ GeV} / f_a)^2$$



# $B^+ \rightarrow K^+ a, a \rightarrow \text{Hadrons}$

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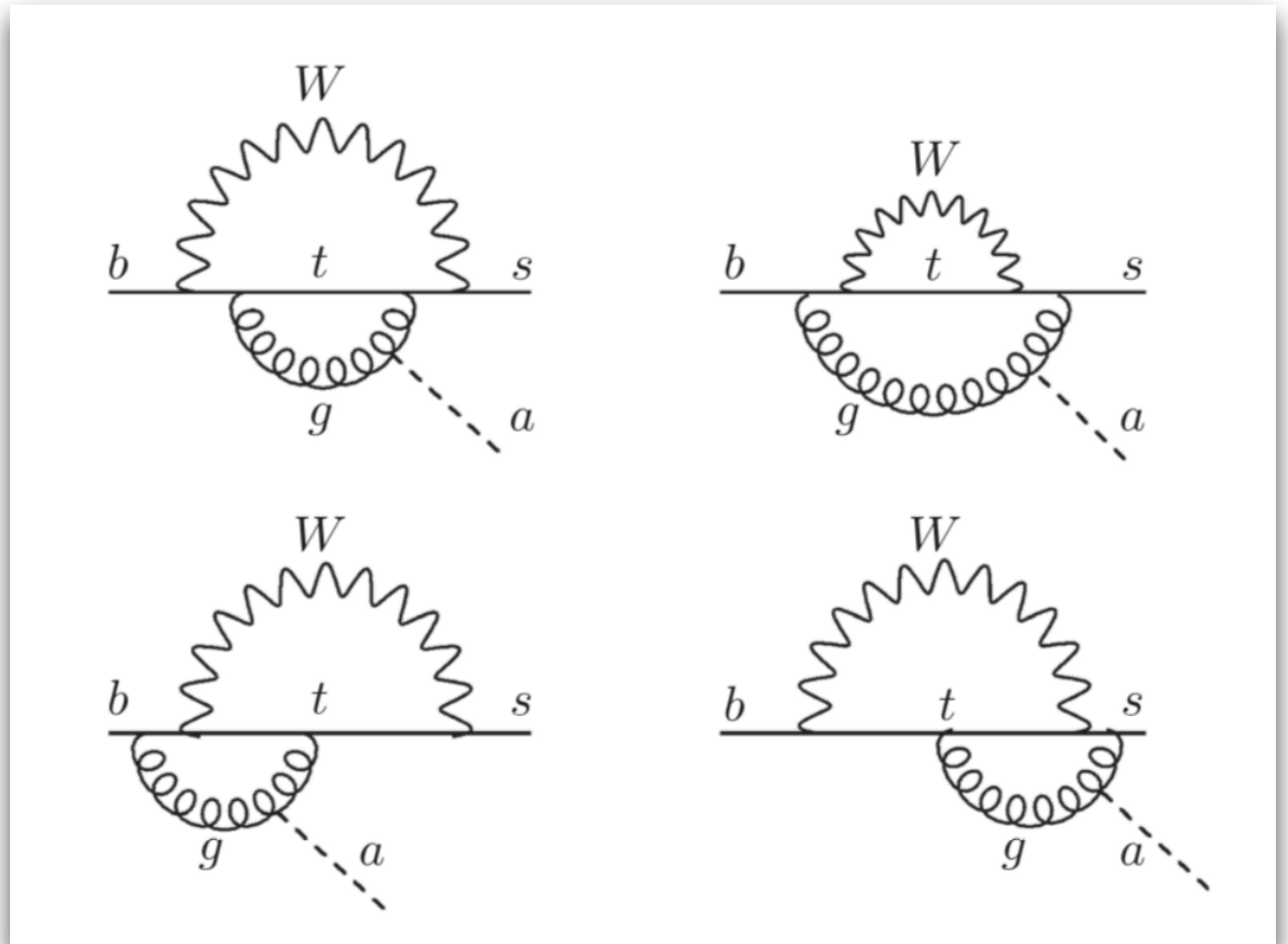
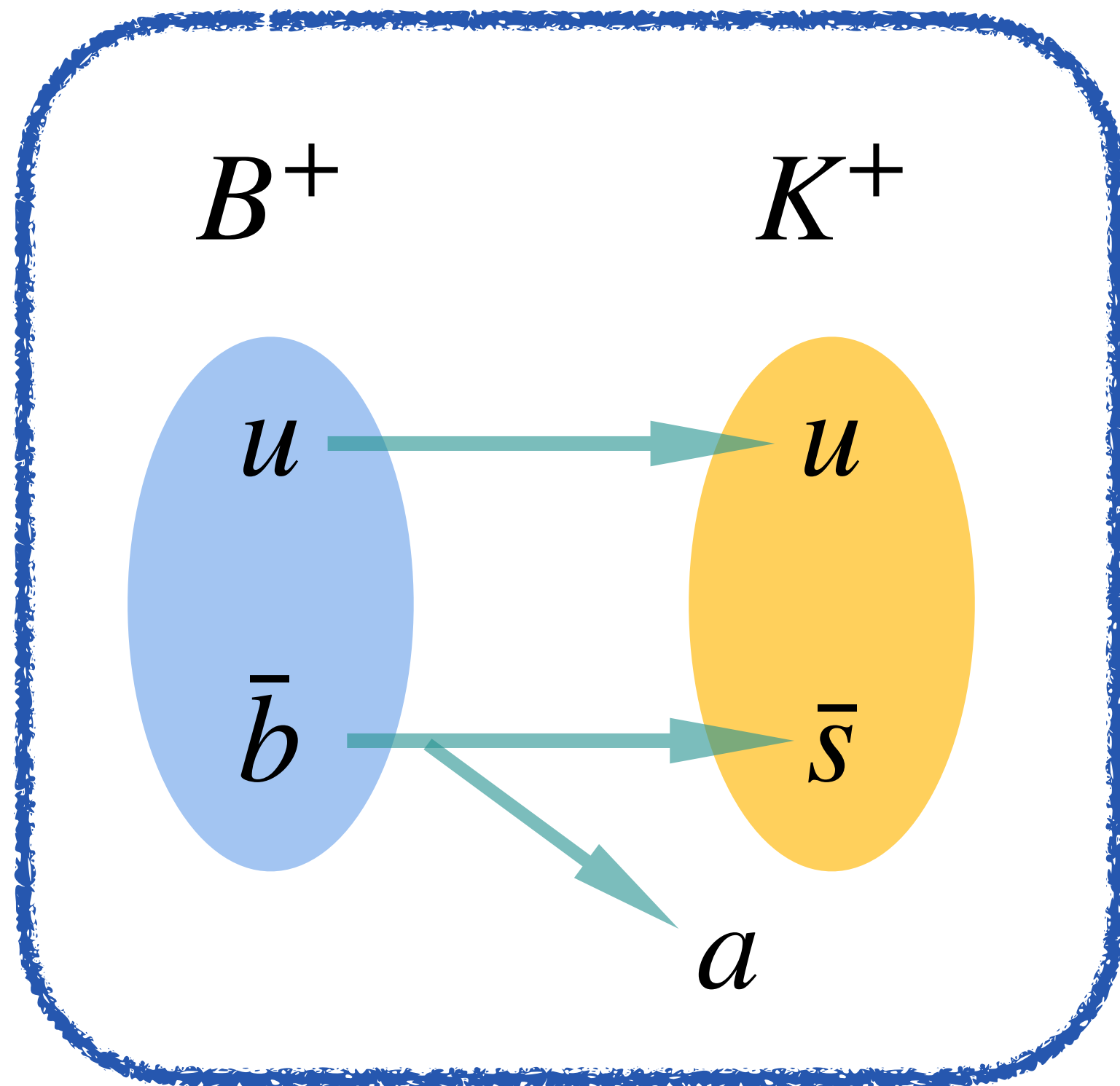


# What are we trying to do at Belle II?

- The main channels we are exploring are:

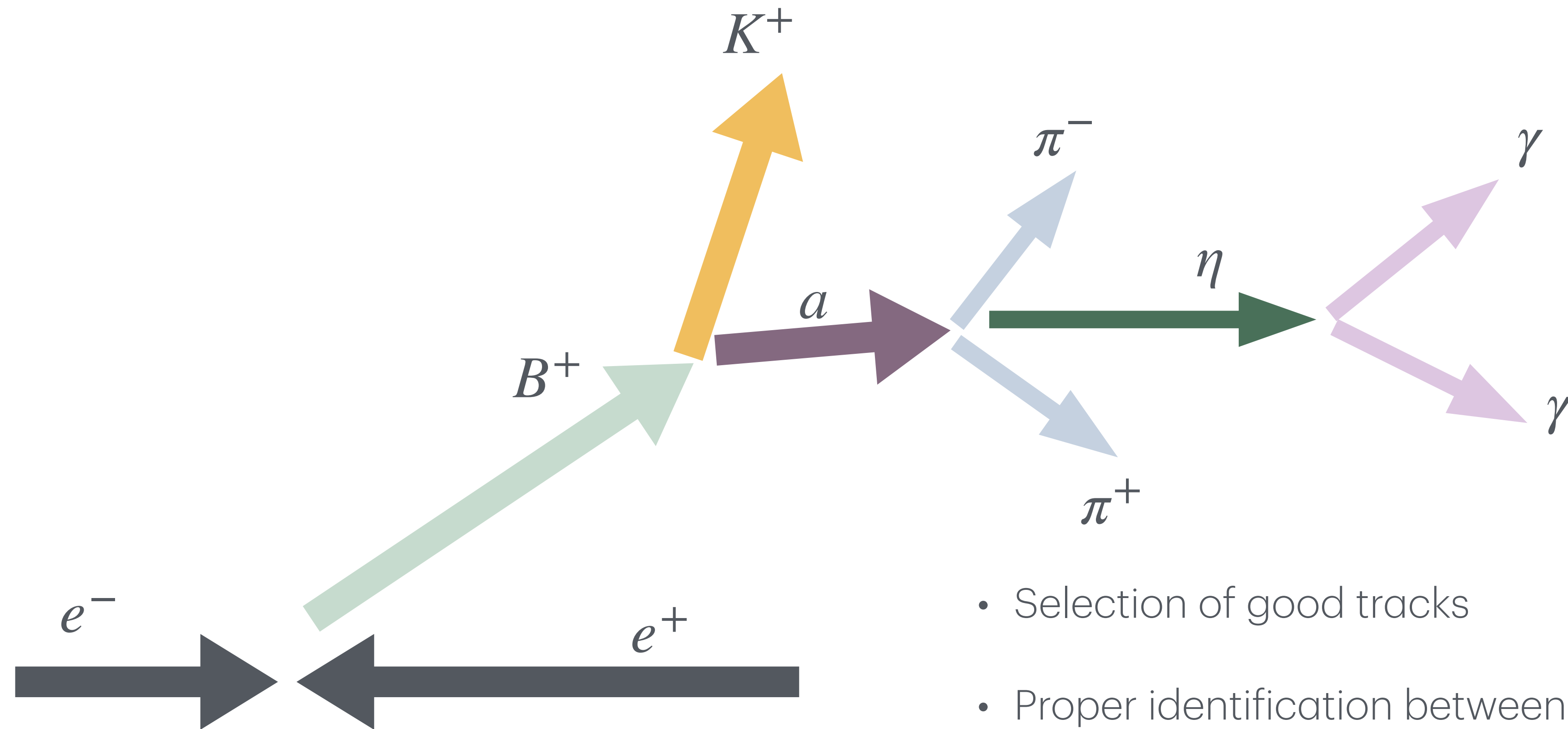
$$B^+ \rightarrow K^+ a, a \rightarrow \eta \pi^+ \pi^-, \eta \rightarrow \gamma \gamma \quad \text{Sourav Dey}$$

$$B^+ \rightarrow K^+ a, a \rightarrow K_s^0 K^+ \pi^- \quad \text{Eiasha Waheed}$$





# Event reconstruction and selection



- Selection of good tracks
- Proper identification between Kaon and Pion
- Lifetime assumption of the axion : displaced vertex vs prompt. This selection changes the analysis strategy completely. We are here looking at the prompt only

# ALP reconstruction

Generated mass in Gev	1	1.5	2	2.5
Mass cut during reconstruction	$m < 1.25$	$1.25 \leq m < 1.75$	$1.75 \leq m < 2.25$	$2.25 \leq m$

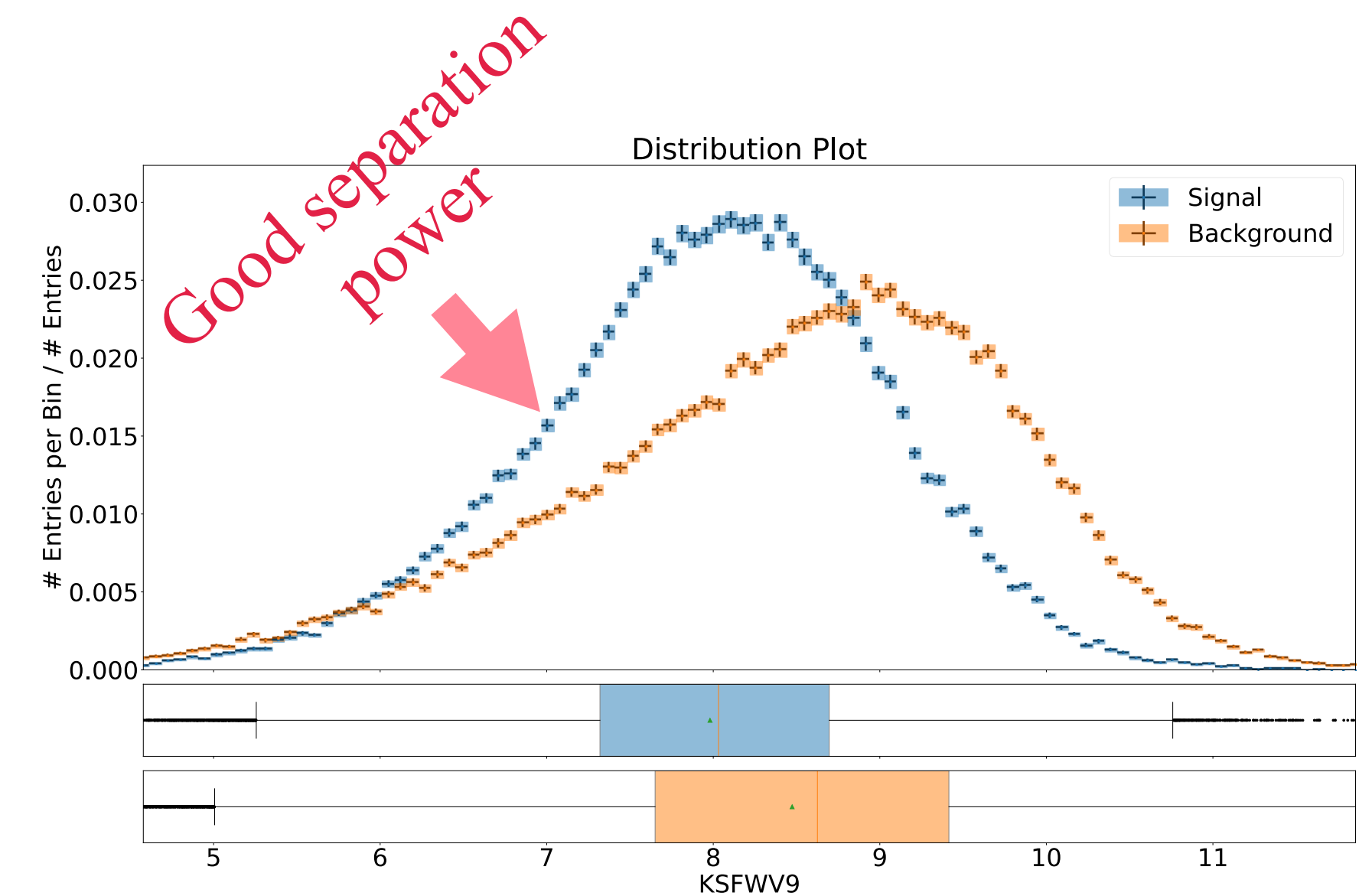
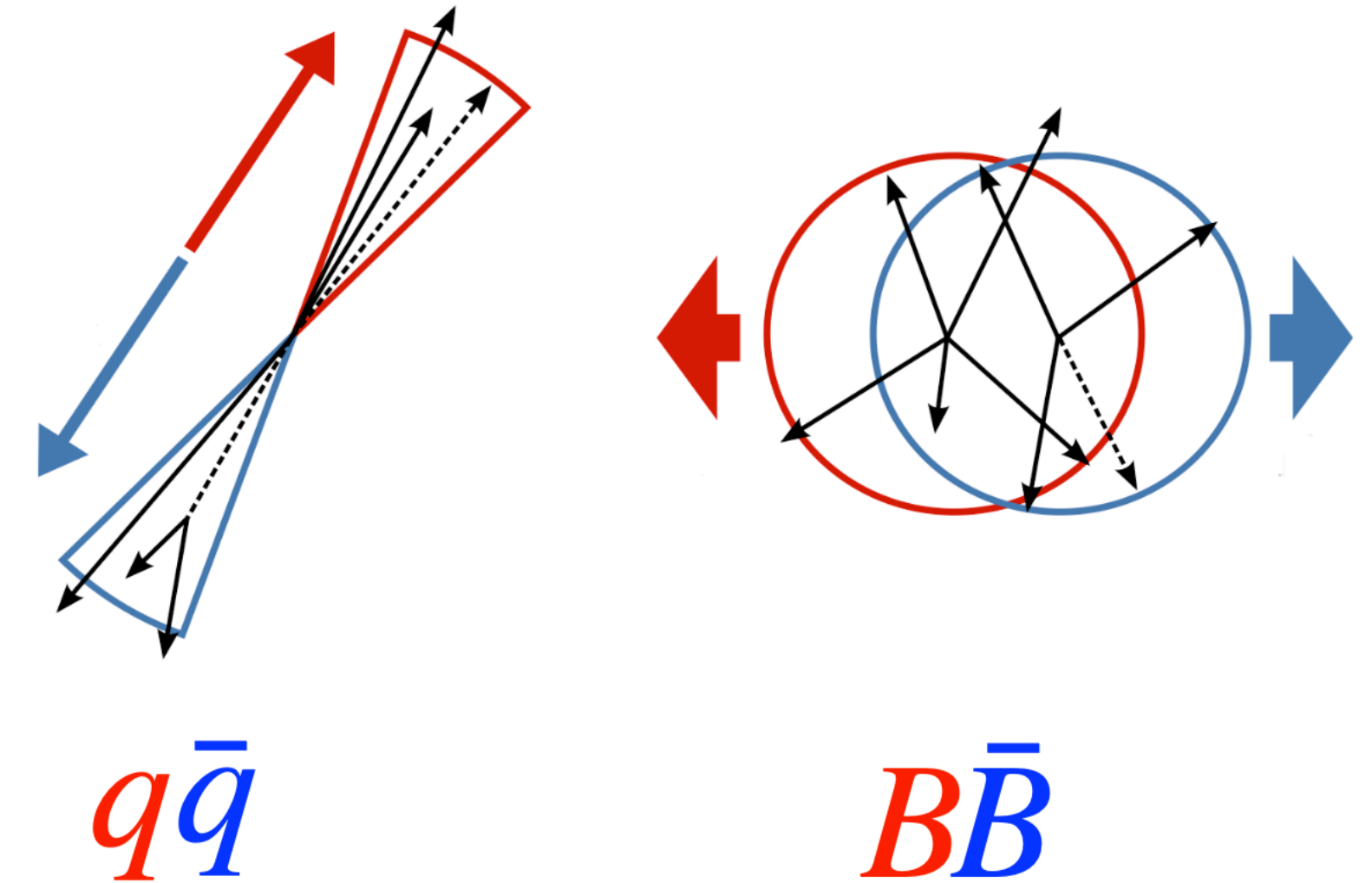
- $M_{bc} > 5.27$  and  $|\Delta E| < 0.1$  (for continuum suppression)
- Good pion and kaon tracks from the interaction point:  $|dz| < 4$  cm and  $dr < 2$  cm
- Selection of  $\eta$  mass:  $470 \text{ MeV} < M_{\eta} < 600 \text{ MeV}$
- Gamma cuts: "thetaInCDCAcceptance" and "goodGamma"
- Global pion ID:  $\text{pionID} > 0.1$
- Global kaon id:  $\text{kaonID} > 0.6$

500000 events are generated in each bin for continuum suppression. At reconstruction level, we get different number of events due to efficiency



# Continuum Suppression

- The most dominant background :  $q\bar{q}$
- The distribution of  $q\bar{q}$  and  $B\bar{B}$  events are different
- We exploit the event shape difference to distinguish the background
- Some of the event shape parameters are correlated with mass. These we cannot use as we do not know the mass of axion



Rethinking about which variable are to keep for continuum suppression

$$m=1.5 \text{ GeV}$$

This is a technical slide which I put here to show that we take care of all the correlated and anti-correlated event shape parameters so that we do not have any mass bias

	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	B1	V12	V13	V14	V15	V16
KSFV16	1	4	-1	0	-13	4	29	2	5	16	19	1	-3	19	11	19	17
KSFV15	0	1	4	1	-2	1	-0	8	-1	11	18	6	-8	-1	11	2	100
KSFV14	2	18	56	1	-85	5	18	-16	25	64	12	2	2	34	26	100	2
KSFV13	-3	49	16	-7	-23	4	4	67	20	17	11	2	-0	4	100	26	11
KSFV12	1	4	-45	1	-22	2	16	-22	-19	29	7	0	2	100	4	34	-1
cosTB1	-0	1	-0	0	-1	-0	9	-1	0	-53	5	7	100	2	-0	2	-8
KSFV11	-0	6	1	0	-1	5	4	0	0	-2	2	100	7	0	2	2	6
KSFV10	-0	6	2	0	-7	11	12	0	7	4	100	2	5	7	11	12	18
KSFV9	1	7	48	-0	-55	2	6	-4	-19	100	4	-2	-53	29	17	64	11
KSFV8	2	13	-4	0	-27	4	7	7	100	-19	7	0	0	-19	20	25	-1
thrus1	-3	23	7	-9	12	0	-3	100	7	-4	0	0	-1	-22	67	-16	8
KSFV7	1	6	-0	0	-12	7	100	-3	7	6	12	4	9	16	4	18	-0
KSFV6	0	8	0	0	-3	100	7	0	4	2	11	5	-0	2	4	5	1
KSFV5	-1	-15	-55	-1	100	-3	-12	12	-27	-55	-7	-1	-1	-22	-23	-85	-2
KSFV4	36	-3	-1	100	-1	0	0	-9	0	-0	0	0	0	1	-7	1	0
KSFV3	-0	9	100	-1	-55	0	-0	7	-4	48	2	1	-0	-45	16	56	4
KSFV2	-3	100	9	-3	-15	8	6	23	13	7	6	6	1	4	49	18	1
KSFV1	100	-3	-0	36	-1	0	1	-3	2	1	-0	-0	1	-3	2	0	1

Signal

	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	B1	V12	V13	V14	V15	V16
-1	27	-40	-0	-9	8	75	39	-3	14	9	-6	1	69	40	16	-18	100
1	35	61	-7	-19	7	-8	55	-5	27	8	71	-7	-36	52	22	100	-18
1	29	52	-2	-89	12	12	-6	47	52	17	12	-5	29	45	100	22	16
1	68	22	-5	-40	31	31	69	28	24	48	36	1	15	100	45	52	40
-1	9	-55	2	-17	1	43	-2	-3	23	-1	-19	-4	100	15	29	-36	69
-0	4	-6	0	2	4	3	-2	9	-73	11	2	100	-4	1	-5	-7	1
-1	41	33	-4	-12	9	1	34	-0	11	8	100	2	-19	36	12	71	-6
0	31	-5	-2	-20	60	9	12	55	-12	100	8	11	-1	48	17	8	9
1	11	40	-2	-40	-4	8	7	-10	100	-12	11	-73	23	24	52	27	14
1	23	4	0	-53	32	1	-9	100	-10	55	-0	9	-3	23	47	-5	-3
0	40	4	-4	6	10	26	100	-9	7	12	34	-2	-2	69	-6	55	39
-1	32	-23	-0	-8	9	100	26	1	8	9	1	3	43	31	12	-8	75
0	35	-2	-1	-14	100	9	10	32	-4	60	9	4	1	31	12	7	8
-1	-23	-47	2	100	-14	-8	6	-53	-40	-20	-12	2	-17	-40	-89	-19	-9
55	-3	-4	100	2	-1	-0	-4	0	-2	-2	-4	0	2	-5	-2	-7	-0
1	14	100	-4	-47	-2	-23	4	4	40	-5	33	-6	-55	22	52	61	-40
-1	100	14	-3	-23	35	32	40	23	11	31	41	4	9	68	29	35	27
100	-1	1	55	-1	0	-1	0	1	1	0	-1	-0	-1	1	1	1	-1

Background

'KSFVVariables(et)', 'KSFVVariables(mm2)', 'KSFVVariables(hso00)', 'KSFVVariables(hso02)',  
'KSFVVariables(hso04)', 'KSFVVariables(hso10)', 'KSFVVariables(hso12)', 'KSFVVariables(hso14)',  
'KSFVVariables(hso20)', 'KSFVVariables(hso22)', 'KSFVVariables(hso24)', 'KSFVVariables(hso00)',  
'KSFVVariables(hso01)', 'KSFVVariables(hso02)', 'KSFVVariables(hso03)', 'KSFVVariables(hso04)',

Removed all the variables correlated with R2 or ThrustBm



# Rethinking about which variable are to keep for continuum suppression

$m=1.5 \text{ GeV}$

	KSFWV1	KSFWV2	KSFWV3	KSFWV4	KSFWV5	KSFWV6	KSFWV7	thrus1	KSFWV8	KSFWV9	KSFWV10	KSFWV11	cosTB1	KSFWV12	KSFWV13	KSFWV14	KSFWV15	KSFWV16	thrus2	R2	cosTB2
cosTB2	1	-0	-1	1	-4	1	9	2	2	11	19	-3	-7	7	5	7	70	52	2	68	100
R2	-1	9	-19	-3	26	2	6	39	10	-14	19	4	-6	-14	27	-26	74	48	19	100	68
thrus2	-0	0	-0	0	-1	1	3	-3	-1	3	1	-0	0	3	-0	2	1	4	100	19	2
KSFWV16	1	4	-1	0	-13	4	29	2	5	16	19	1	-3	19	11	19	17	100	4	48	52
KSFWV15	0	1	4	1	-2	1	-0	8	-1	11	18	6	-3	-1	11	2	100	17	1	74	70
KSFWV14	2	18	56	1	-85	5	18	-16	25	64	12	2	2	34	26	100	2	19	2	-26	7
KSFWV13	-3	49	16	-7	-23	4	4	67	20	17	11	2	-0	4	100	26	11	11	-0	27	5
KSFWV12	1	4	-45	1	-22	2	16	-22	-19	29	7	0	2	100	4	34	-1	19	3	-14	7
cosTB1	-0	1	-0	0	-1	-0	9	-1	0	-53	5	7	100	2	-0	2	-3	-3	0	-6	-7
KSFWV11	-0	6	1	0	-1	5	4	0	0	-2	2	100	7	0	2	2	6	1	-0	4	-3
KSFWV10	-0	6	2	0	-7	11	12	0	7	4	100	2	5	7	11	12	18	19	1	19	19
KSFWV9	1	7	48	-0	-55	2	6	-4	-19	100	4	-2	-53	29	17	64	11	16	3	-14	11
KSFWV8	2	13	-4	0	-27	4	7	7	100	-19	7	0	0	-19	20	25	-1	5	-1	10	2
thrus1	-3	23	7	-9	12	0	-3	100	7	-4	0	0	-1	-22	67	-16	8	2	-3	39	2
KSFWV7	1	6	-0	0	-12	7	100	-3	7	6	12	4	9	16	4	18	-0	29	3	6	9
KSFWV6	0	8	0	0	-3	100	7	0	4	2	11	5	-0	2	4	5	1	4	1	2	1
KSFWV5	-1	-15	-55	-1	100	-3	-12	12	-27	-55	-7	-1	-1	-22	-23	-85	-2	-13	-1	26	-4
KSFWV4	36	-3	-1	100	-1	0	0	-9	0	-0	0	0	0	1	-7	1	1	0	0	-3	1
KSFWV3	-0	9	100	-1	-55	0	-0	7	-4	48	2	1	-0	-45	16	56	4	-1	-0	-19	-1
KSFWV2	-3	100	9	-3	-15	8	6	23	13	7	6	6	1	4	49	18	1	4	0	9	-0
KSFWV1	100	-3	-0	36	-1	0	1	-3	2	1	-0	-0	-0	1	-3	2	0	1	-0	-1	1

Signal

	KSFVW1	KSFVW2	KSFVW3	KSFVW4	KSFVW5	KSFVW6	KSFVW7	thrus1	KSFVW8	KSFVW9	KSFVW10	KSFVW11	cosTB1	KSFVW12	KSFVW13	KSFVW14	KSFVW15	KSFVW16	thrus2	R2	cosTB2
0	14	3	-4	-2	8	25	38	-5	12	12	29	-5	8	28	5	46	36	7	54	100	
-1	42	-7	-5	15	14	37	85	-6	-5	18	46	2	-4	59	-18	56	43	34	100	54	
-1	4	0	-0	-2	4	7	6	2	2	5	3	2	2	7	3	3	7	100	34	7	
-1	27	-40	-0	-9	8	75	39	-3	14	9	-6	1	69	40	16	-18	100	7	43	36	
1	35	61	-7	-19	7	-3	55	-5	27	8	71	-7	-36	52	22	100	-18	3	56	46	
1	29	52	-2	-89	12	12	-6	47	52	17	12	-5	29	45	100	22	16	3	-18	5	
1	68	22	-5	-40	31	31	69	23	24	48	36	1	15	100	45	52	40	7	59	23	
-1	9	-55	2	-17	1	43	-2	-3	23	-1	-19	-4	100	15	29	-36	69	2	-4	8	
-0	4	-6	0	2	4	3	-2	9	-73	11	2	100	-4	1	-5	-7	1	2	2	-5	
-1	41	33	-4	-12	9	1	34	-0	11	8	100	2	-19	36	12	71	-6	3	46	29	
0	31	-5	-2	-20	60	9	12	55	-12	100	8	11	-1	48	17	8	9	5	18	12	
1	11	40	-2	-40	-4	8	7	-10	100	-12	11	-73	23	24	52	27	14	2	-5	12	
1	23	4	0	-53	32	1	-9	100	-10	55	-0	9	-3	28	47	-5	-3	2	-6	-5	
0	40	4	-4	6	10	26	100	-9	7	12	34	-2	-2	69	-6	55	39	6	85	33	
-1	32	-23	-0	-3	9	100	26	1	8	9	1	3	43	31	12	-8	75	7	37	25	
0	35	-2	-1	-14	100	9	10	32	-4	60	9	4	1	31	12	7	8	4	14	8	
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55	-3	-4	100	2	-1	-0	-4	0	-2	-2	-4	0	2	-5	-2	-7	-0	-0	-5	-4	
1	14	100	-4	-47	-2	-23	4	4	40	-5	33	-6	-55	22	52	61	-40	0	-7	3	
-1	100	14	-3	-23	35	32	40	23	11	31	41	4	9	68	29	35	27	4	42	14	
100	-1	1	55	-1	0	-1	0	1	1	0	-1	-0	-1	1	1	1	-1	-1	-1	0	

Background

'KSFWVariables(et)', 'KSFWVariables(mm2)', 'KSFWVariables(hso00)', **'KSFWVariables(hso02)'**,  
**'KSFWVariables(hso04)'**, 'KSFWVariables(hso10)', **'KSFWVariables(hso12)'**, 'KSFWVariables(hso14)',  
 'KSFWVariables(hso20)', 'KSFWVariables(hso22)', 'KSFWVariables(hso24)', **'KSFWVariables(hso00)'**,  
 'KSFWVariables(hso01)', **'KSFWVariables(hso02)'**, 'KSFWVariables(hso03)', **'KSFWVariables(hso04)'**,

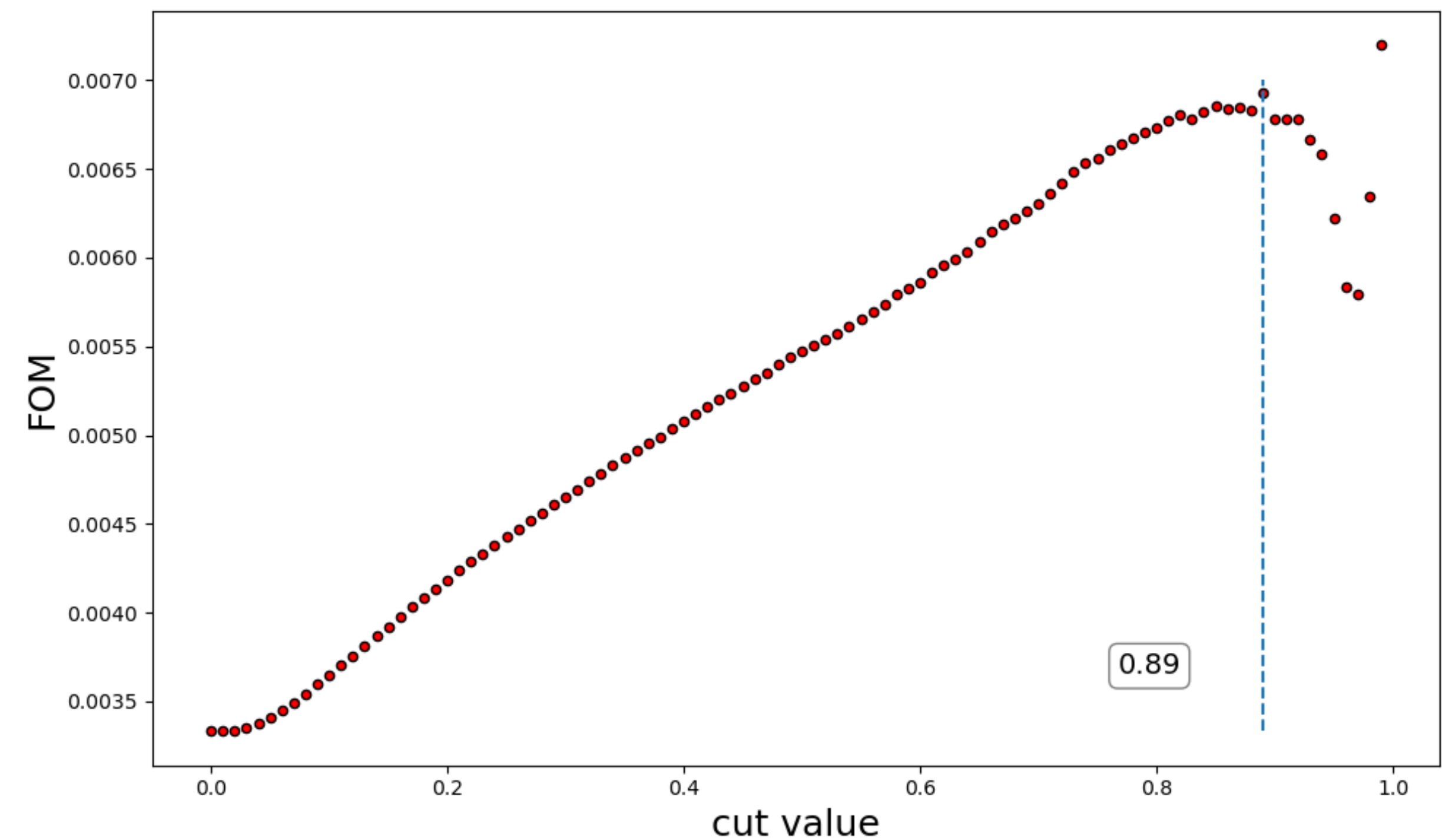
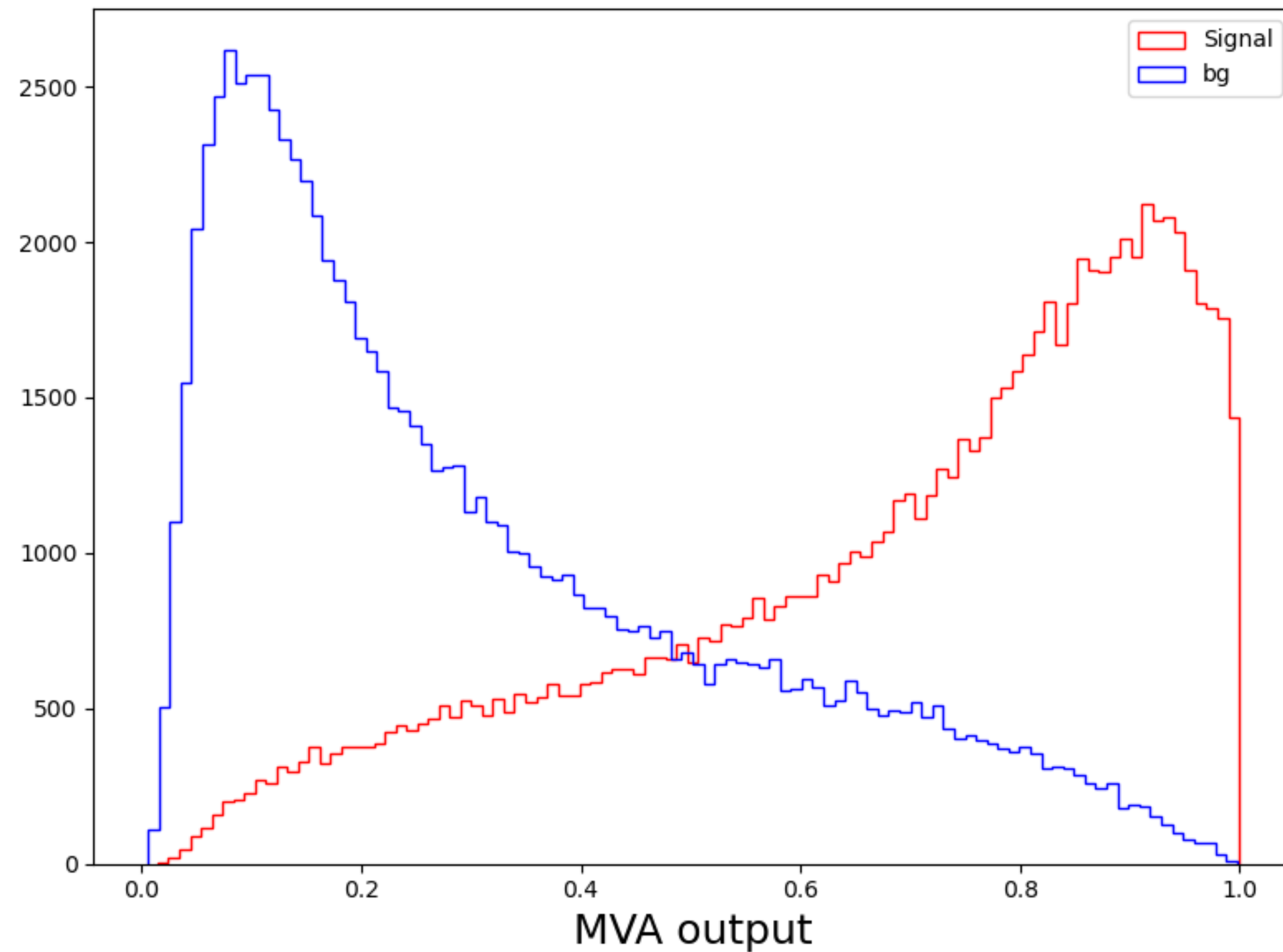
Removed all the variables correlated with R2 or ThrustBm

# An Example result of Continuum Suppression

- Mass point: 1.00 GeV
- No of reconstructed signals: 90000
- No of reconstructed background( $q\bar{q}$  only): 90000

$$\text{FOM} = \text{Punzi figure of merit} = \frac{\epsilon}{\sqrt{\frac{a}{2} + N_{BG}}}$$

$a = \text{significance} = 3(\text{here})$



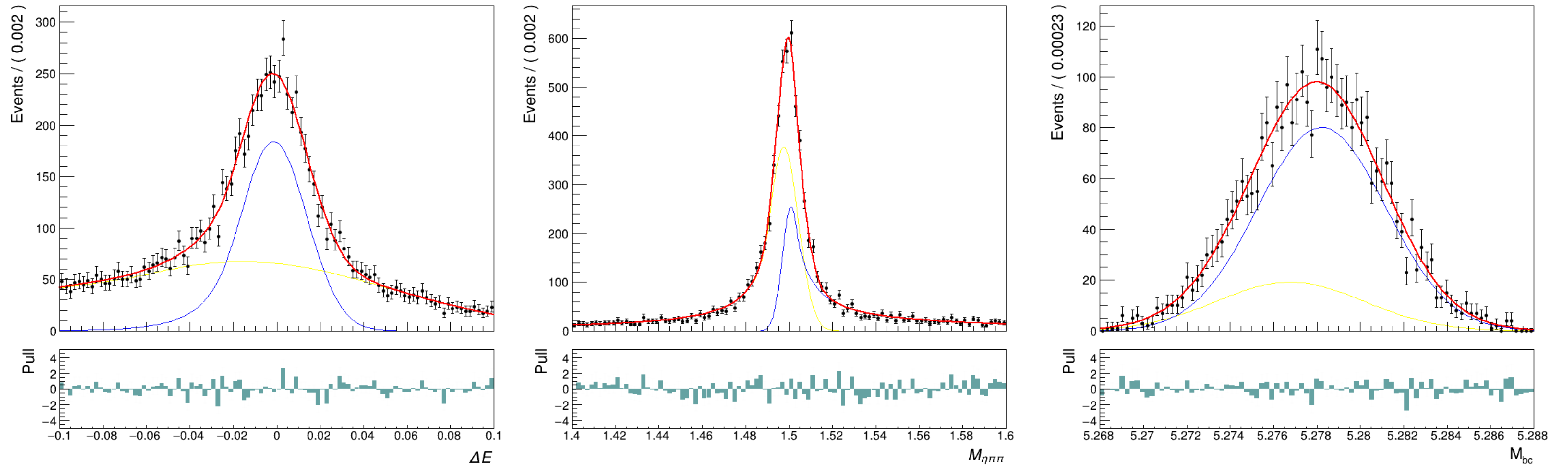
Signal and Background MC samples are used to train with Multivariate Analysis



This is a glimpse of the ongoing work where we try to model the signal. These are not finalized PDFs

1.5 GeV

$$f * F_{\text{CB1}}(\Delta E; \alpha 1, n, \overline{\Delta E}, \sigma) + (1 - f) * F_{\text{CB2}}(\Delta E; \alpha 2, n, \overline{\Delta E}, \sigma)$$



Signal shape extraction

# We expect improved sensitivity

- We have estimated the signal efficiency.
- Right now we are trying to understand all the backgrounds.
- This plot is from the analysis of Ito san, who started this analysis
- This is based on  $200\text{ fb}^{-1}$ .
- We have more data and MC now, we also included the  $K\pi\pi$  channel. So we expect better sensitivity.

