ALP search at Belle II

Sourav Dey for B05 group, April 24, 2025

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 θ-term

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

the gluon field strength tensor

quark fields for each flavor f

Quark mass

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Quark mass

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

Physics Motivation

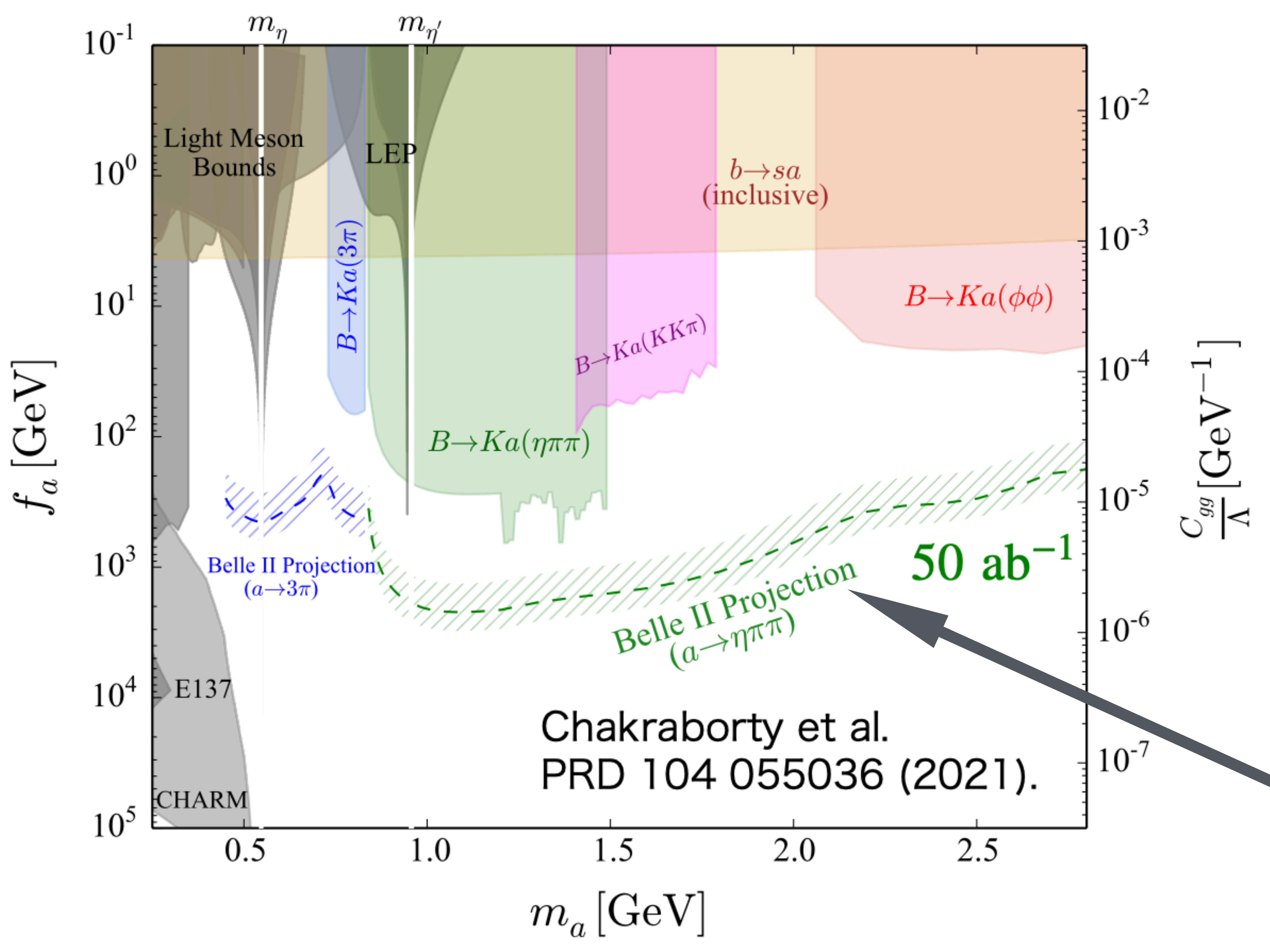
- Proposed solution of strong CP problem, PQ symmetry was introduced by Peccei & Quinn (PRL 38 (1977) 1440)
  - Promote to a *field* θ dynamically settles the CP phase to the minimum
  - PQ Symmetry: Global U(1) that generates the **axion** *as* a Nambu-Goldstone boson.
  - An attractive **dark matter**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

From QCD Axion to Heavy QCD Axion

- Standard QCD axion has mass prediction ~ 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).

$B^+ \to K^+ a, a \to$ Hadrons

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



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

Extrapolation bases on BaBar

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

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

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

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

$B^+ \to K^+ a, a \to$ Hadrons

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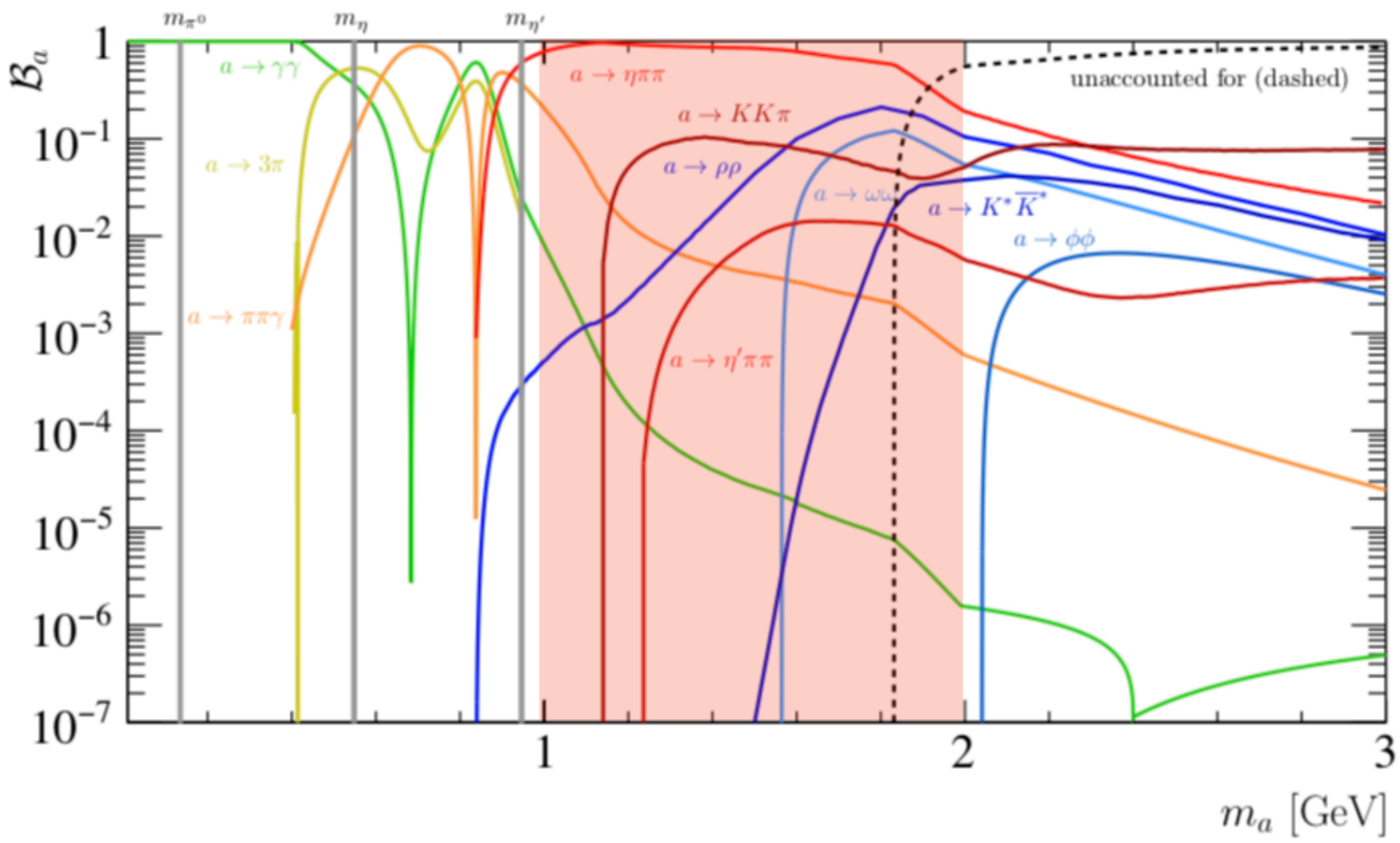
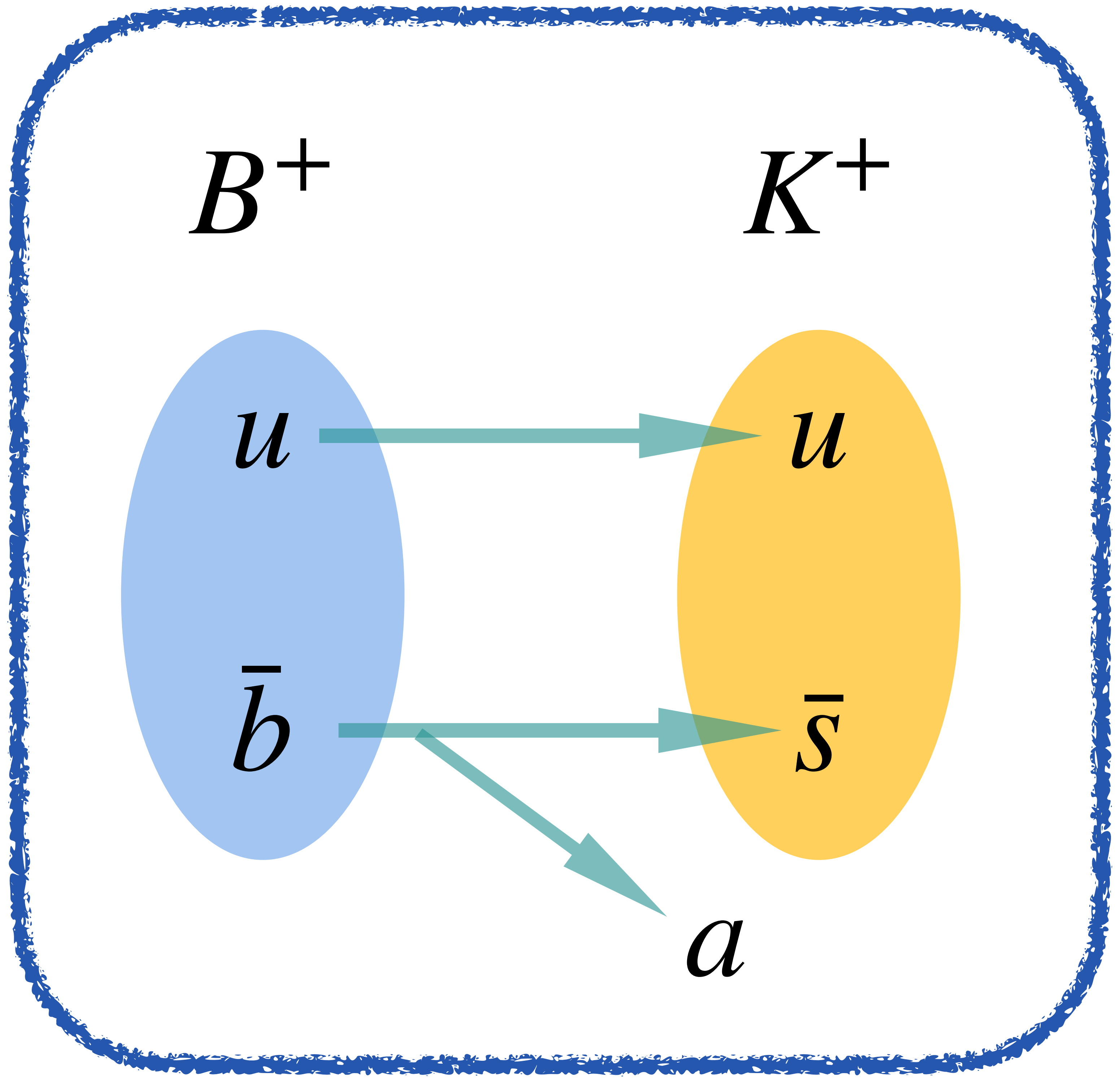


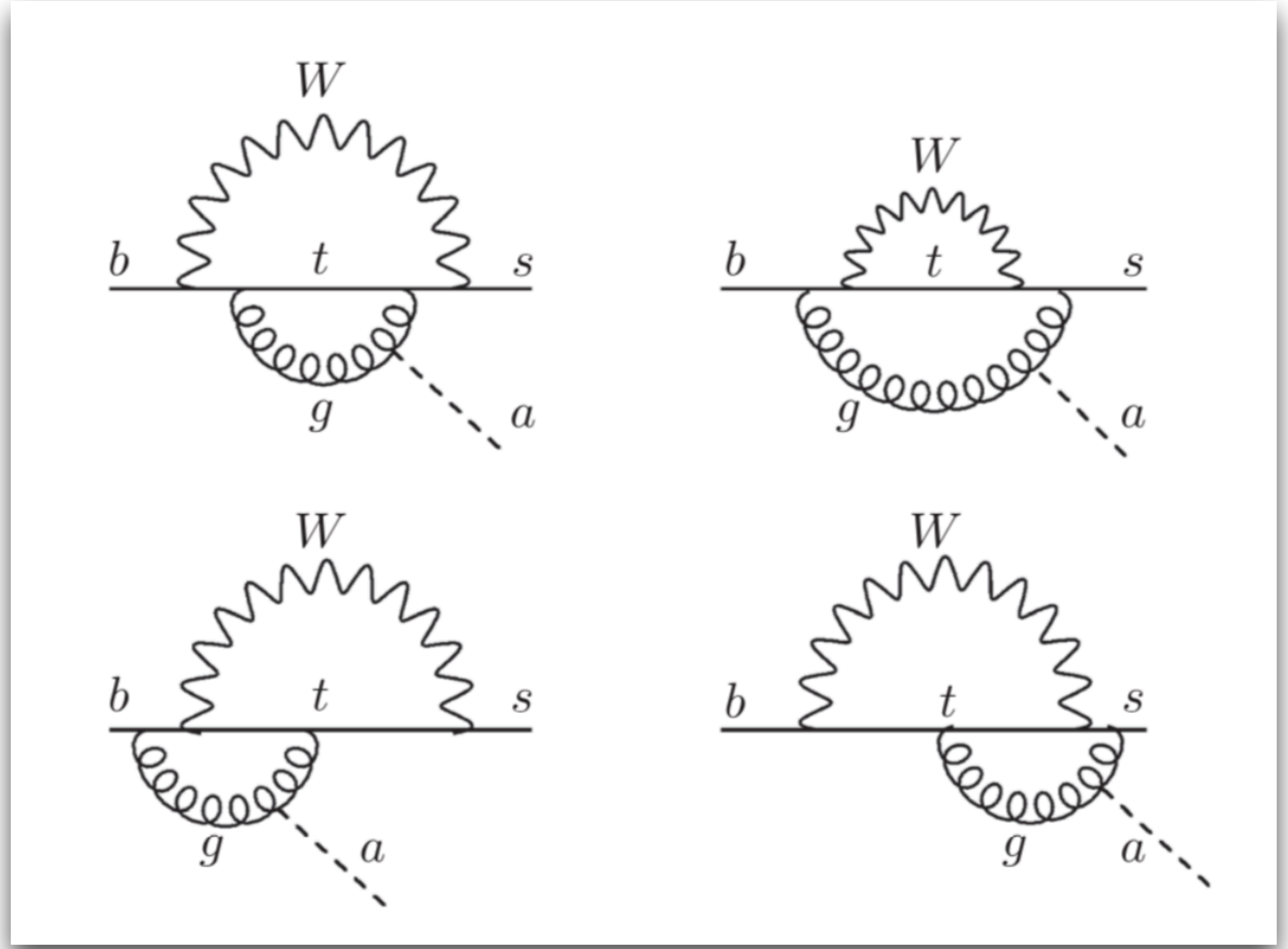
What are we trying to do at Belle II?

- The main channels we are exploring are:

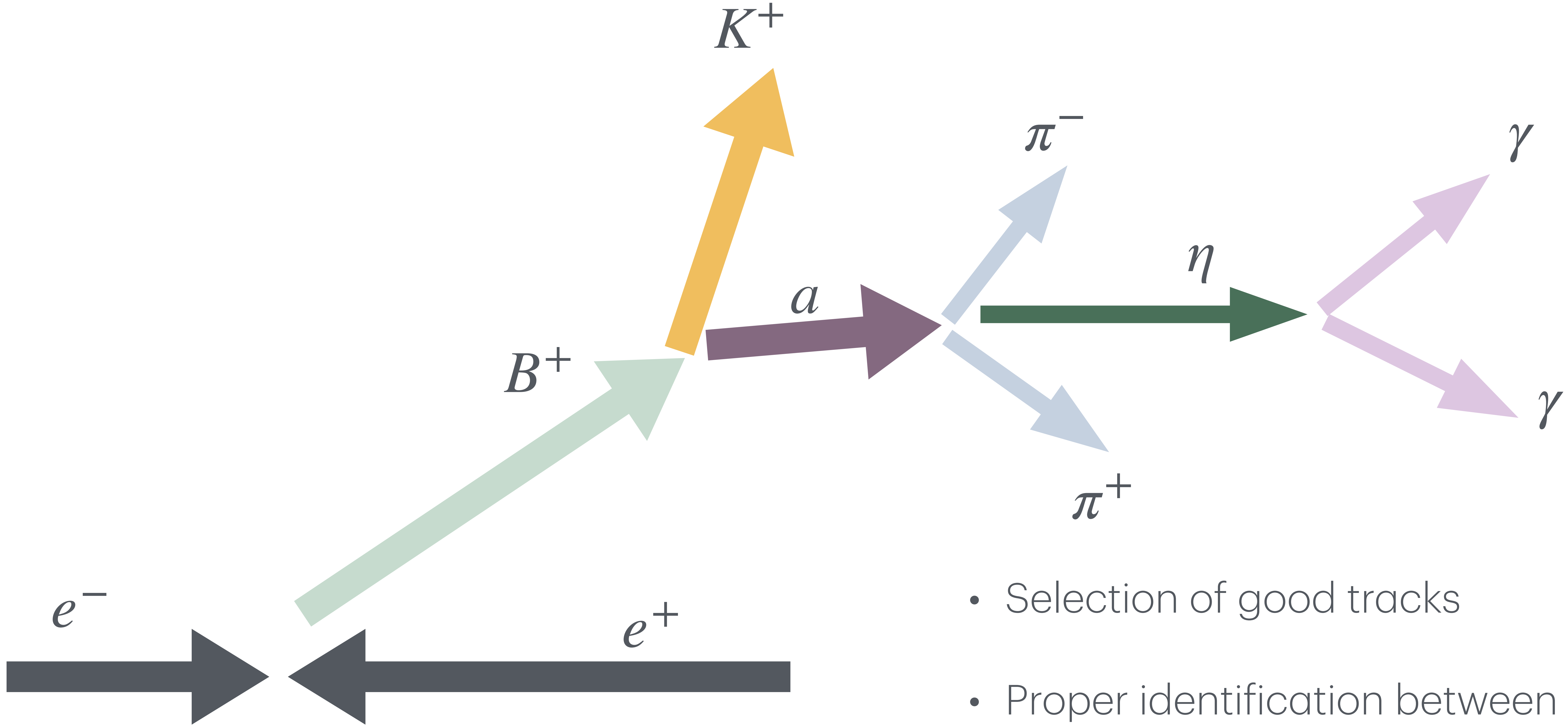
$B^+ \to K^+ a, a \to \eta\pi^+\pi^-, \eta \to \gamma\gamma$ Sourav Dey

$B^+ \to K^+ a, a \to K_s^0 K^+ \pi^-$ 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

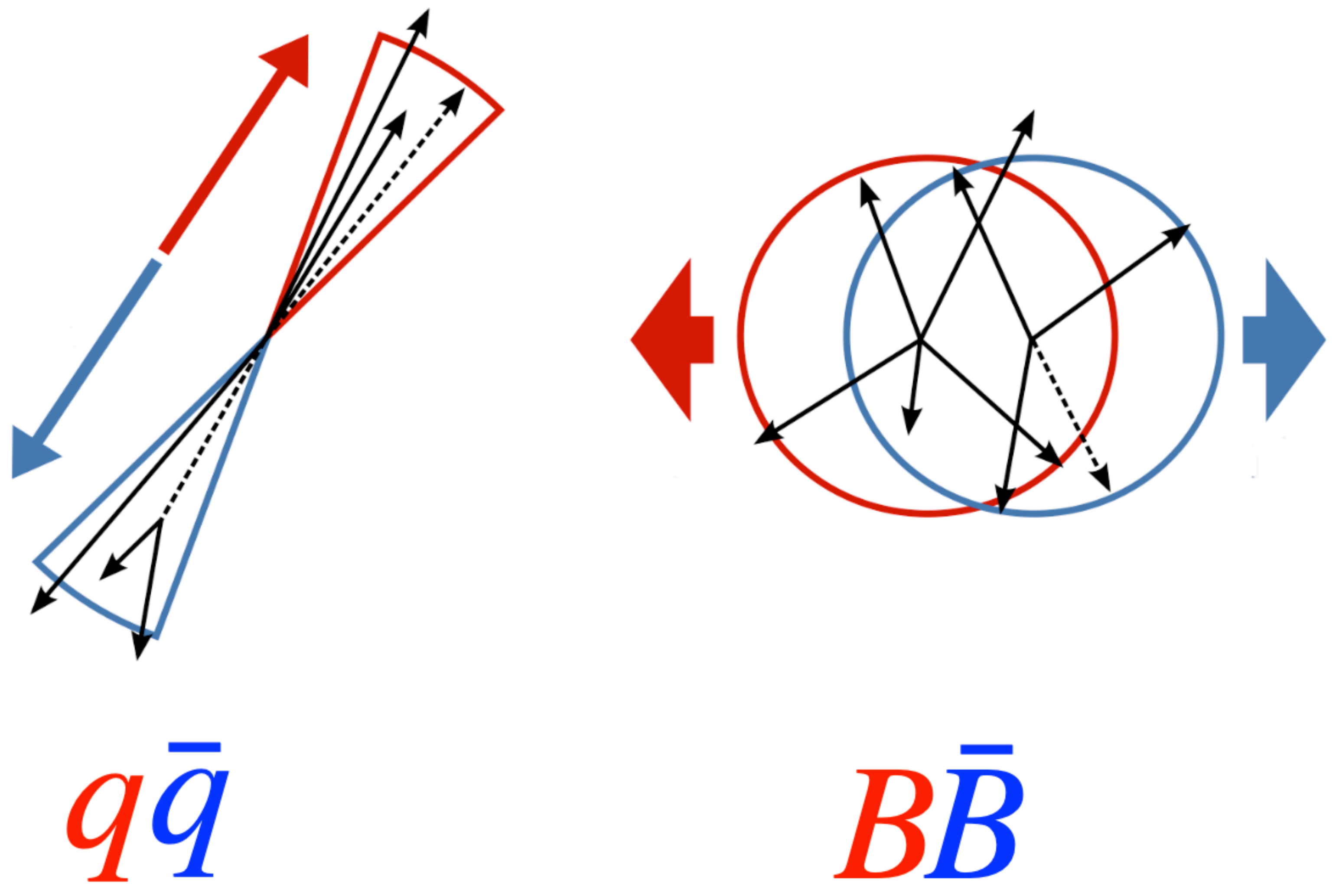
Generated mass in Gev	1	1.5	2	2.5
Mass cut during reconstruction	$m < 1.25$	$1.25 \leq m < 1.75$	$1.75 \leq m < 2.25$	$2.25 \leq m$

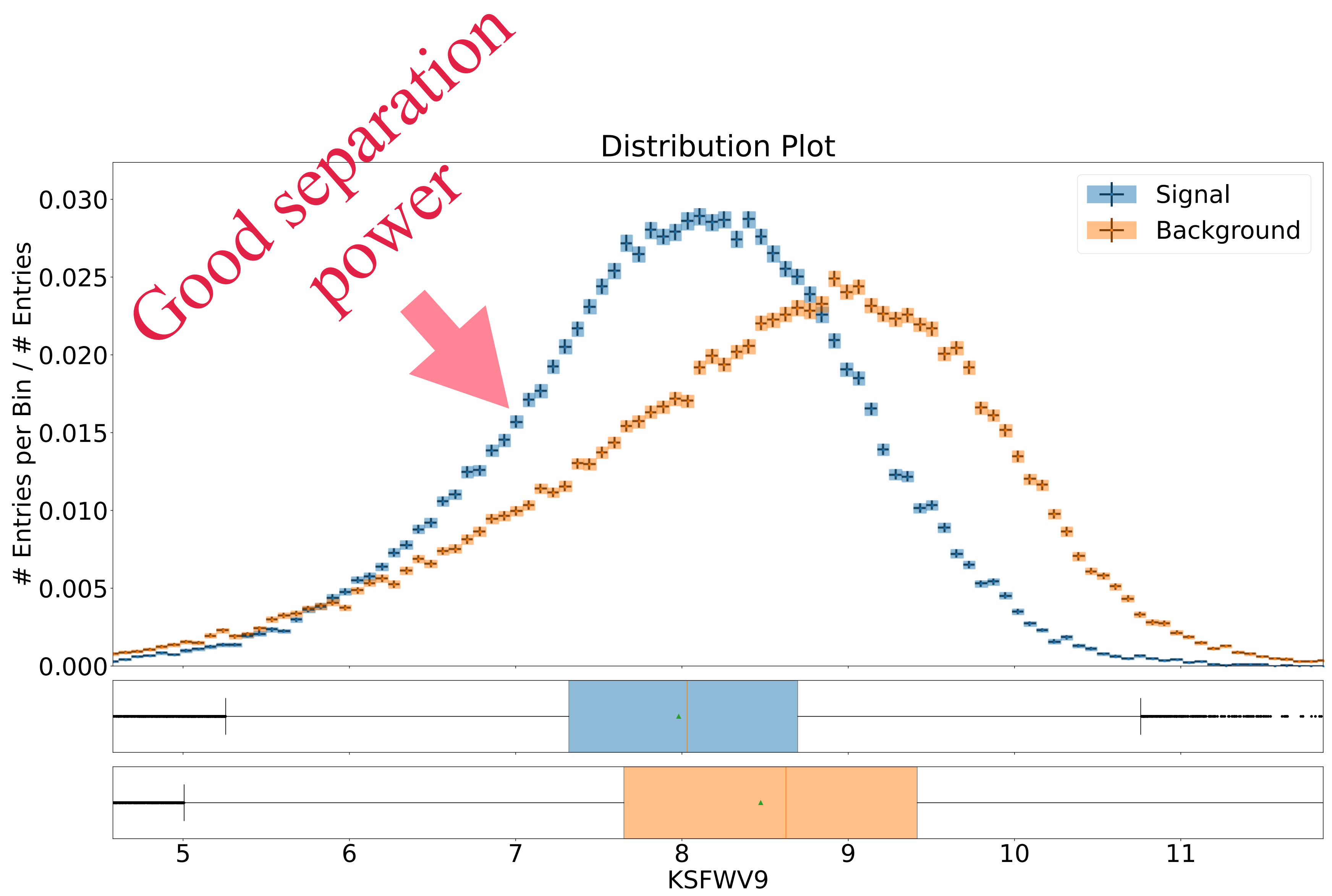
- $M_{bc} > 5.27$ and $|\Delta E| < 0.1$(for continuum suppression)
- Good pion and kaon tracks from the interaction point: |dz| < 4 cm and dr < 2 cm
- Selection of η mass: 470 MeV < $M_{\gamma\gamma}$ < 600 MeV
- Gamma cuts: "thetaInCDCAcceptance" and "goodGamma"
- Global pion ID: pionID > 0.1
- Global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

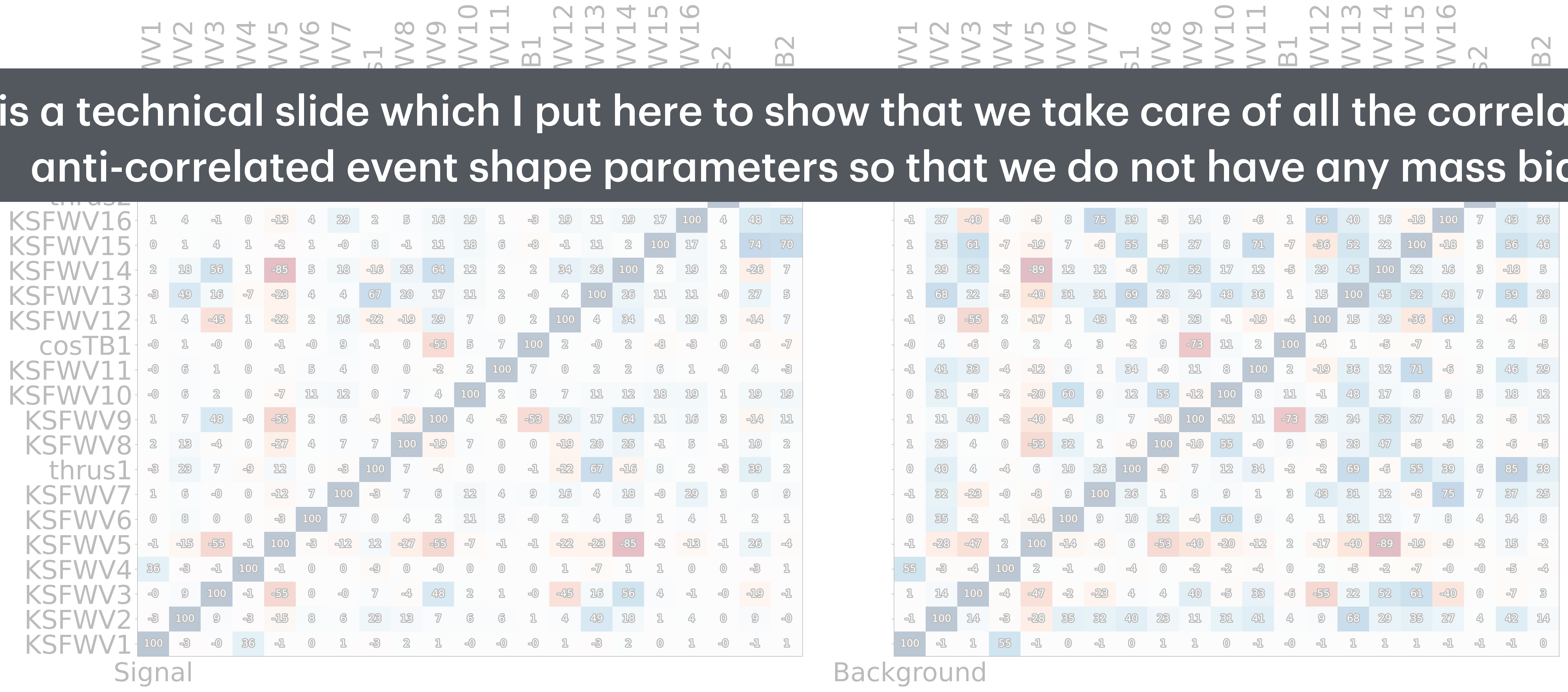




Rethinking about which variable are to keep for continuum suppression

$m=1.5\ GeV$

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



'KSFWVariables(et)', 'KSFWVariables(mm2)', 'KSFWVariables(hso00)', 'KSFWVariables(hso02)', 'KSFWVariables(hso04)', 'KSFWVariables(hso10)', 'KSFWVariables(hso12)', 'KSFWVariables(hso14)', 'KSFWVariables(hso20)', 'KSFWVariables(hso22)', 'KSFWVariables(hso24)', 'KSFWVariables(hoo0)', 'KSFWVariables(hoo1)', 'KSFWVariables(hoo2)','KSFWVariables(hoo3)', 'KSFWVariables(hoo4)',

Removed all the variables correlated with R2 or ThrustBm

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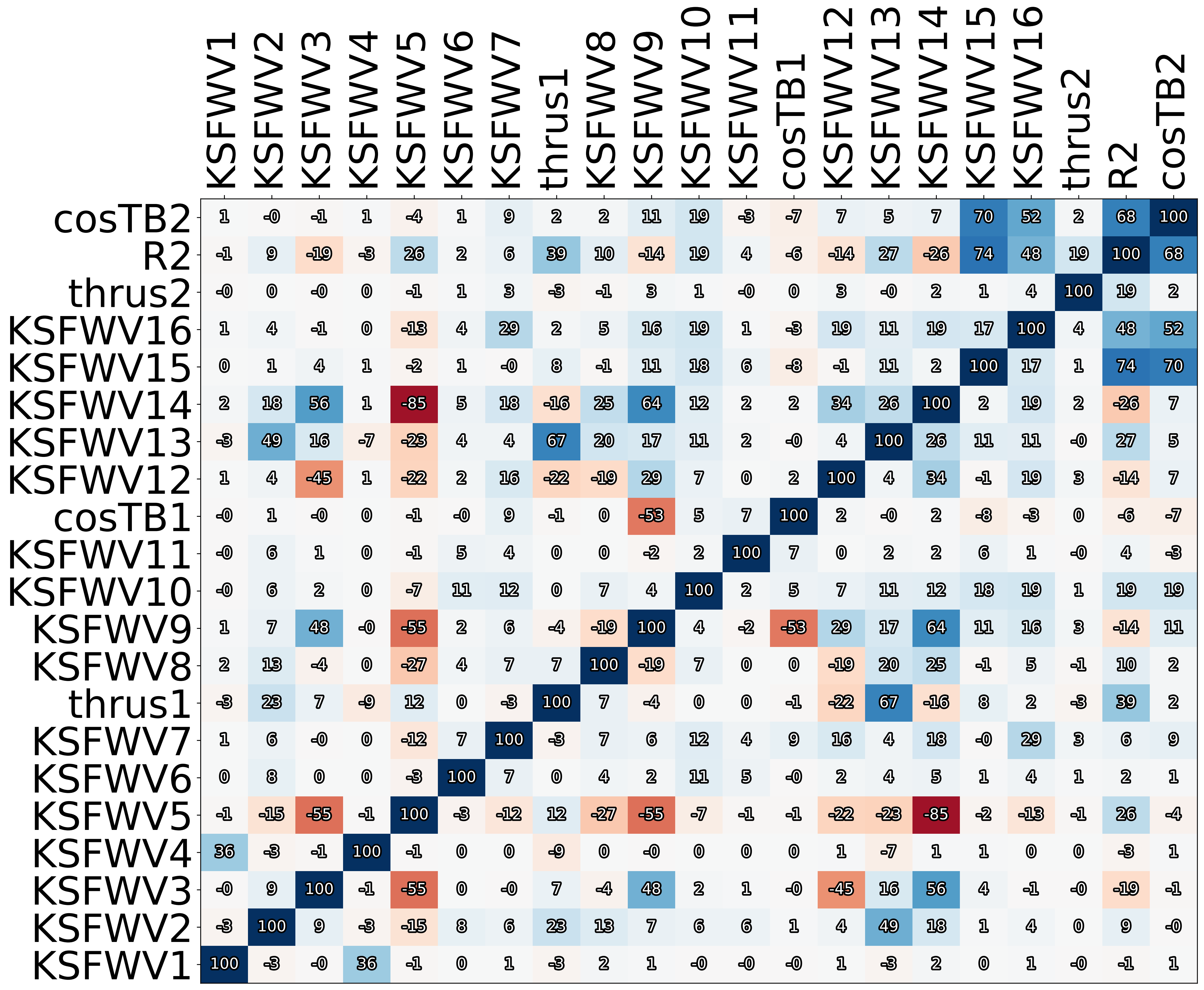
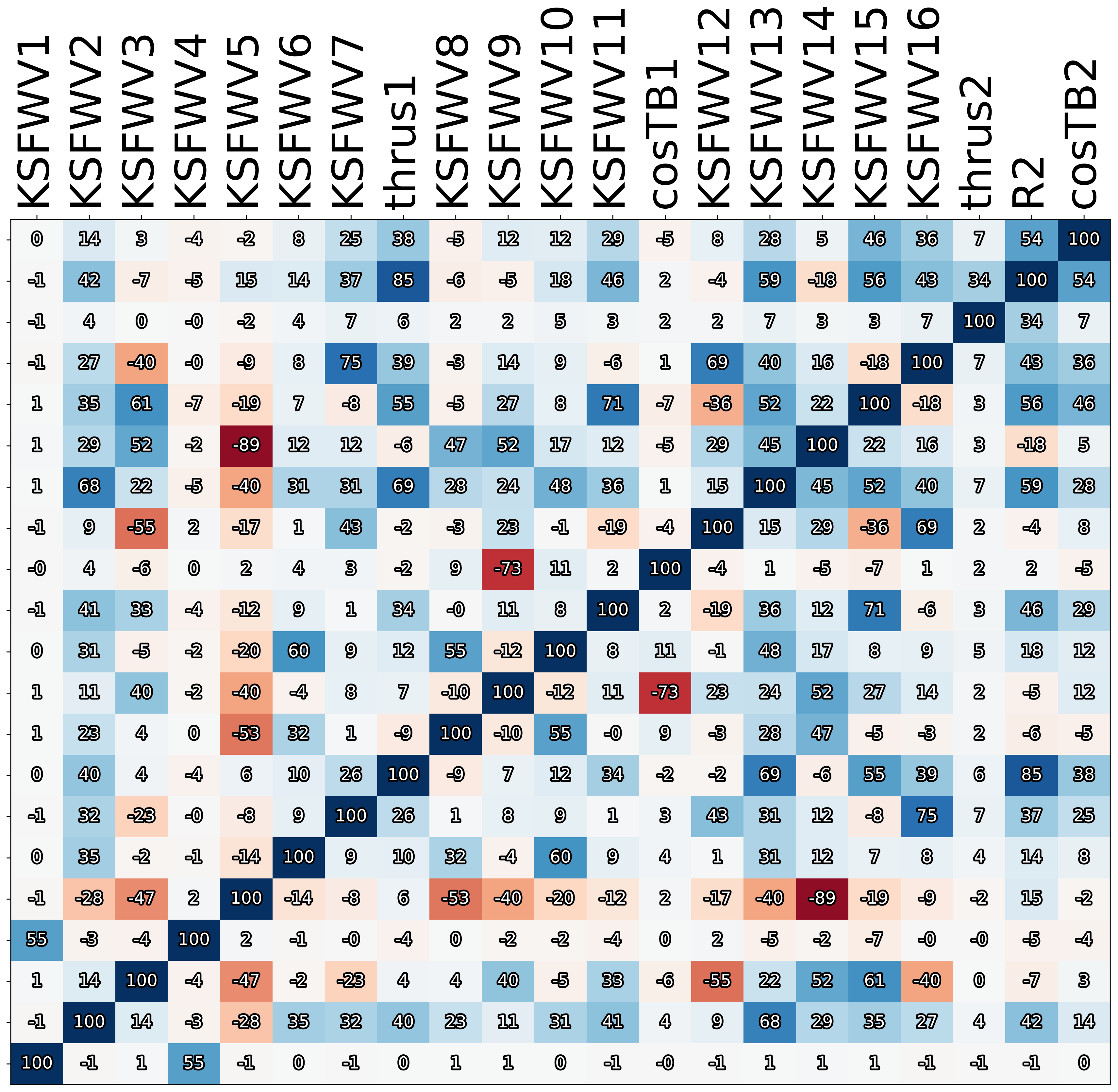


Signal



Background

'KSFWVariables(et)', 'KSFWVariables(mm2)', 'KSFWVariables(hso00)', 'KSFWVariables(hso02)', 'KSFWVariables(hso04)', 'KSFWVariables(hso10)', 'KSFWVariables(hso12)', 'KSFWVariables(hso14)', 'KSFWVariables(hso20)', 'KSFWVariables(hso22)', 'KSFWVariables(hso24)', 'KSFWVariables(hoo0)', 'KSFWVariables(hoo1)', 'KSFWVariables(hoo2)','KSFWVariables(hoo3)', 'KSFWVariables(hoo4)',

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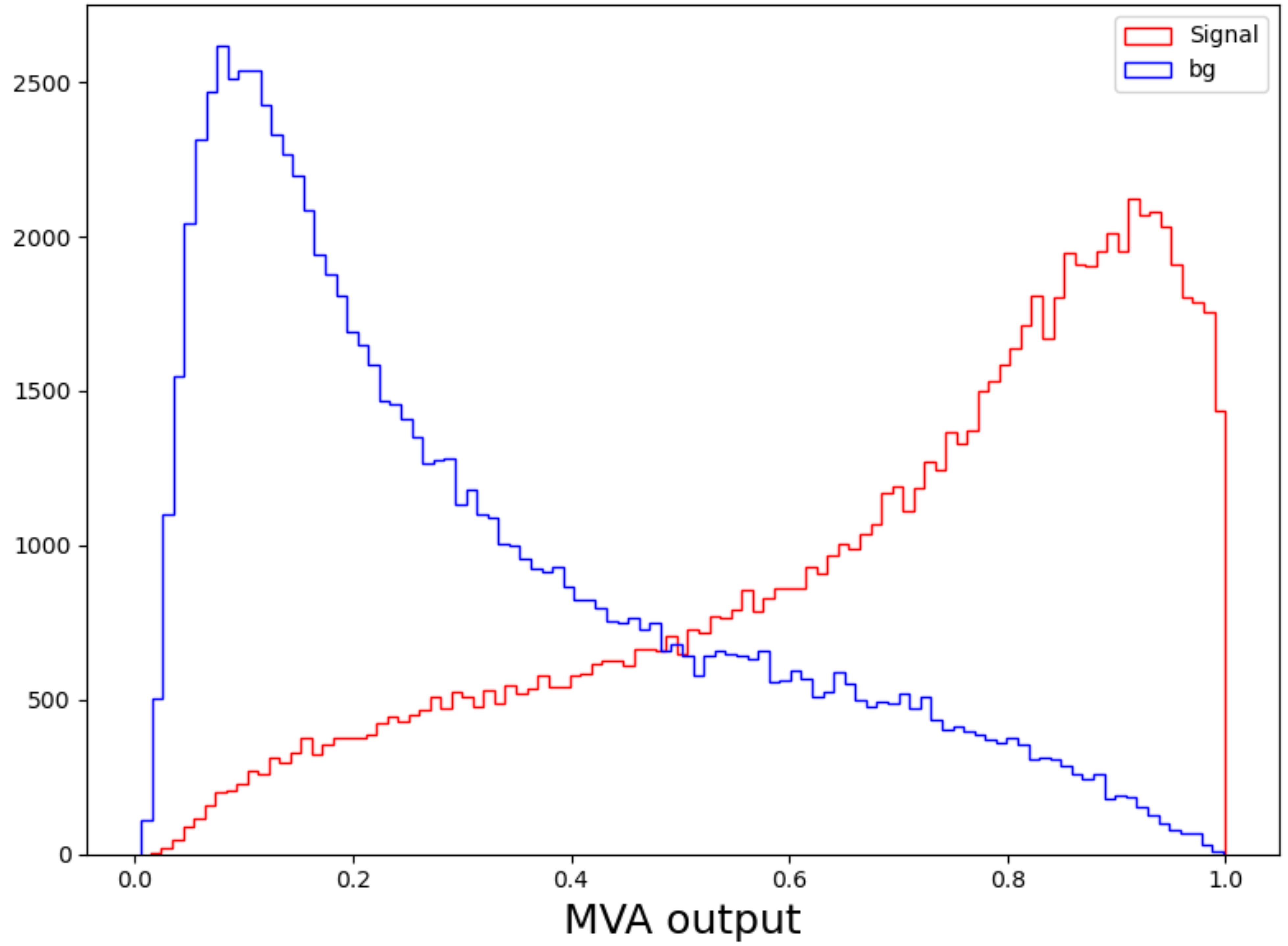
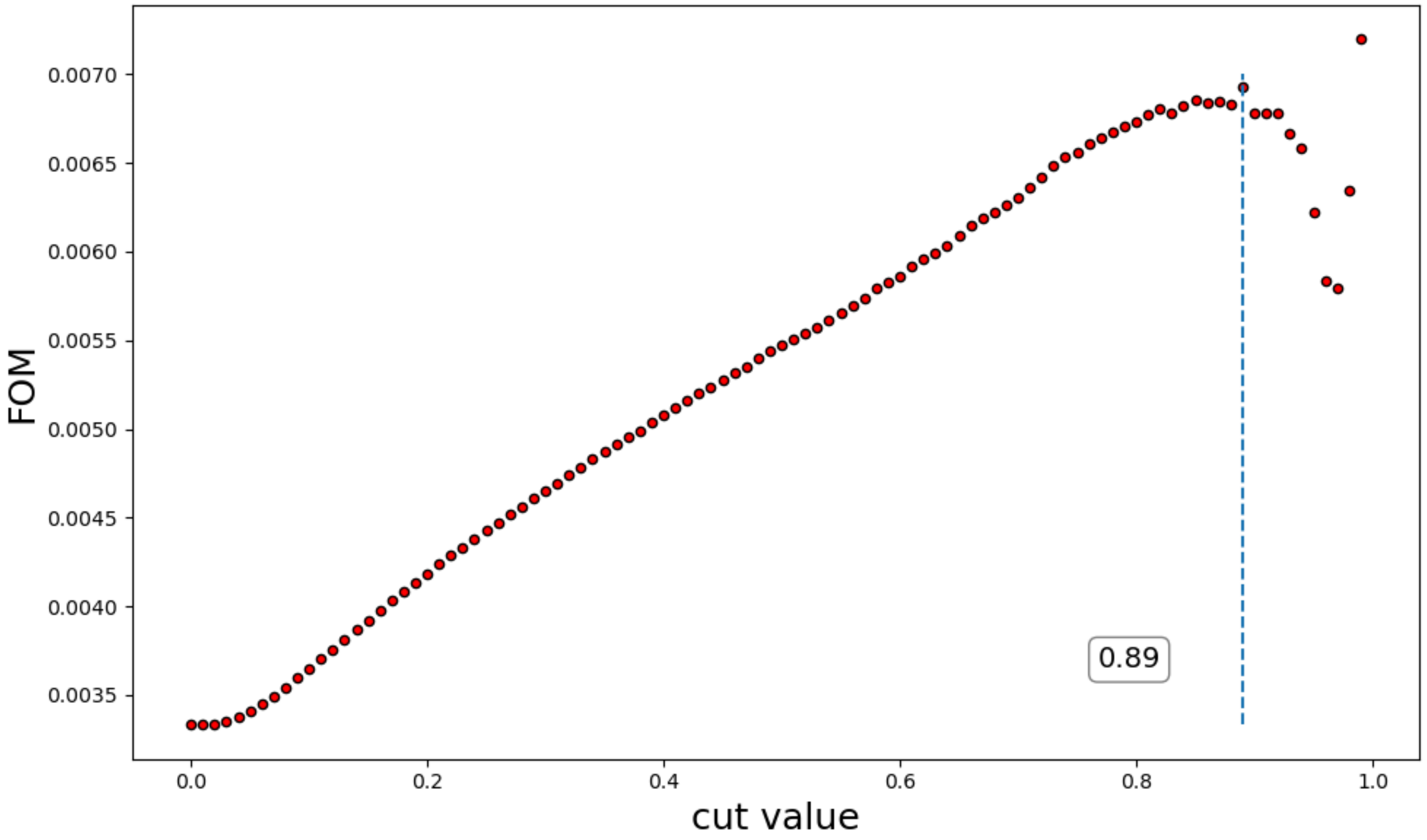
An Example result of Continuum Suppression

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

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

a = significance =3(here)



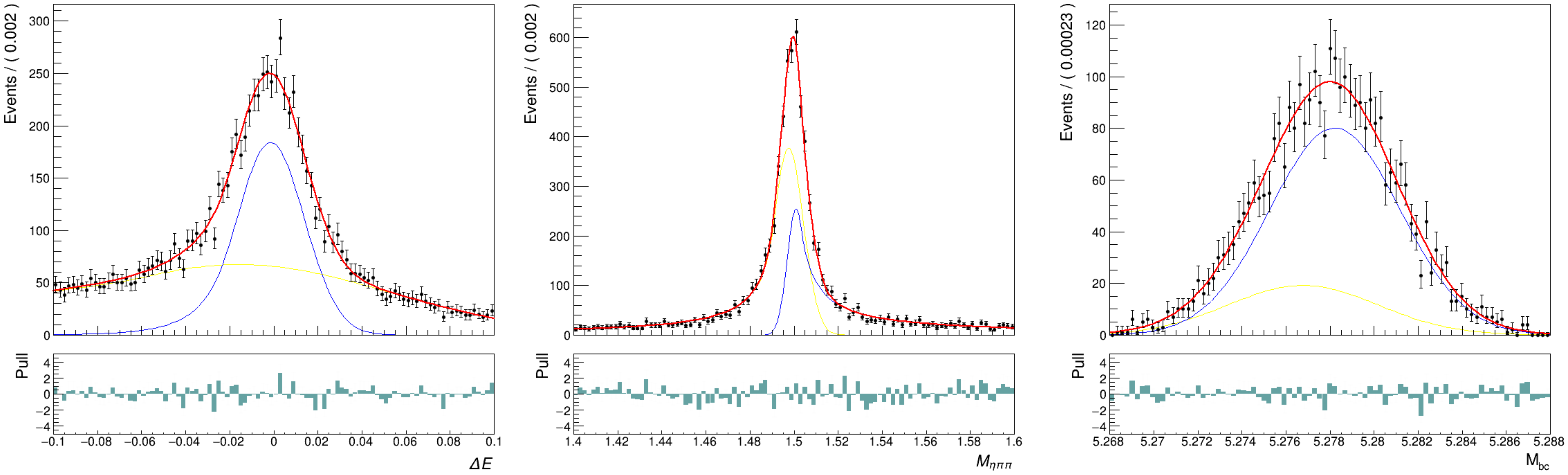


Signal and Background MC samples are used to train with Multivariate Analysis

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

1.5 GeV

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



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 fb^{-1}.
- We have more data and MC now, we also included the $K\pi\pi$ channel. So we expect better sensitivity.