Search for QCD Axion at Belle II

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FY2021 学術変革領域「ダークマター」シンポジウム 2022/03/30

Physics Motivation

- There is a CP violation factor in Lagrangian in QCD in the SM.

$$\mathscr{L} = \theta \frac{g^2}{32\pi^2} G_{a\mu\nu} \tilde{G}^{a\mu\nu}$$

($G_{a\mu\nu}$: tensor of gluon field)

- This would introduce neutron electric dipole moment (nEDM, $|d_n|$).

➡ $|d_n| < 1.8 \times 10^{-26}\ e \cdot \mathrm{cm}$ (PRL 124, 081803 (2020))

➡ Stringent limit on $\theta \lesssim 10^{-10}$ ⇒ **Strong CP problem.**

- To solve strong CP problem, PQ symmetry was introduced by Peccei & Quinn (PRL 38 (1977) 1440).

➡ **Axion (or QCD axion)**: pNG boson in PQ violation.

(Weinberg, PRL 40 (1978) 223 & Wilczek, PRL 40 (1978) 271)

Physics Motivation

- QCD axion mass m_a and decay constant f_a: $m_a f_a \simeq m_\pi f_\pi$
  - ➡ If axion is dark matter, the mass range is $10^{-6} \lesssim m_a \lesssim 10^{-3}$ eV。
  - ➡ Axion quality problem due to large f_a.

- Heavy QCD axion (PRL 123 031803 (2019), PRD 104 055036 (2021))
  - $m_a \gg m_\pi f_\pi / f_a$ ($m_a > 400$ MeV$/c^2$), interaction: $aG\tilde{G}$
  - Solve strong CP problem.
  - Axion quality problem can be avoided.
  - This may provide some hints of dark matter search (although this might not be DM)
  - $B^+ \to K^+ a,\ a \to \text{hadrons}$ $\Rightarrow$ **This can be searched for in Belle II**

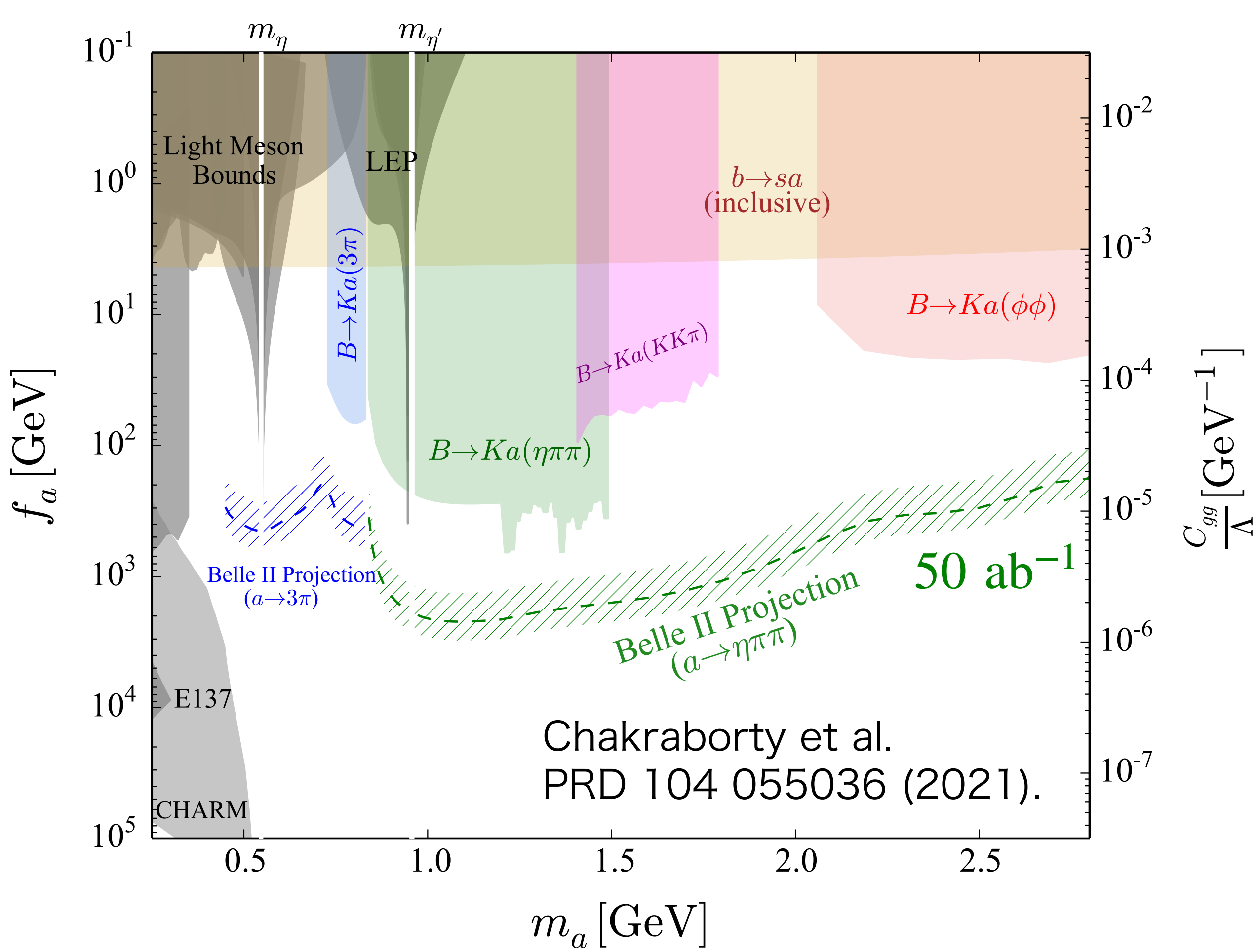
$B^+ \to K^+ a,\ a \to \text{hadrons}$

- Chakraborty et al. (PRD 104 055036 (2021)) estimated sensitivity of heavy QCD axion using some (not DM search) experimental data.
  - $a \to \eta\pi^+\pi^-$: 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),

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



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

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

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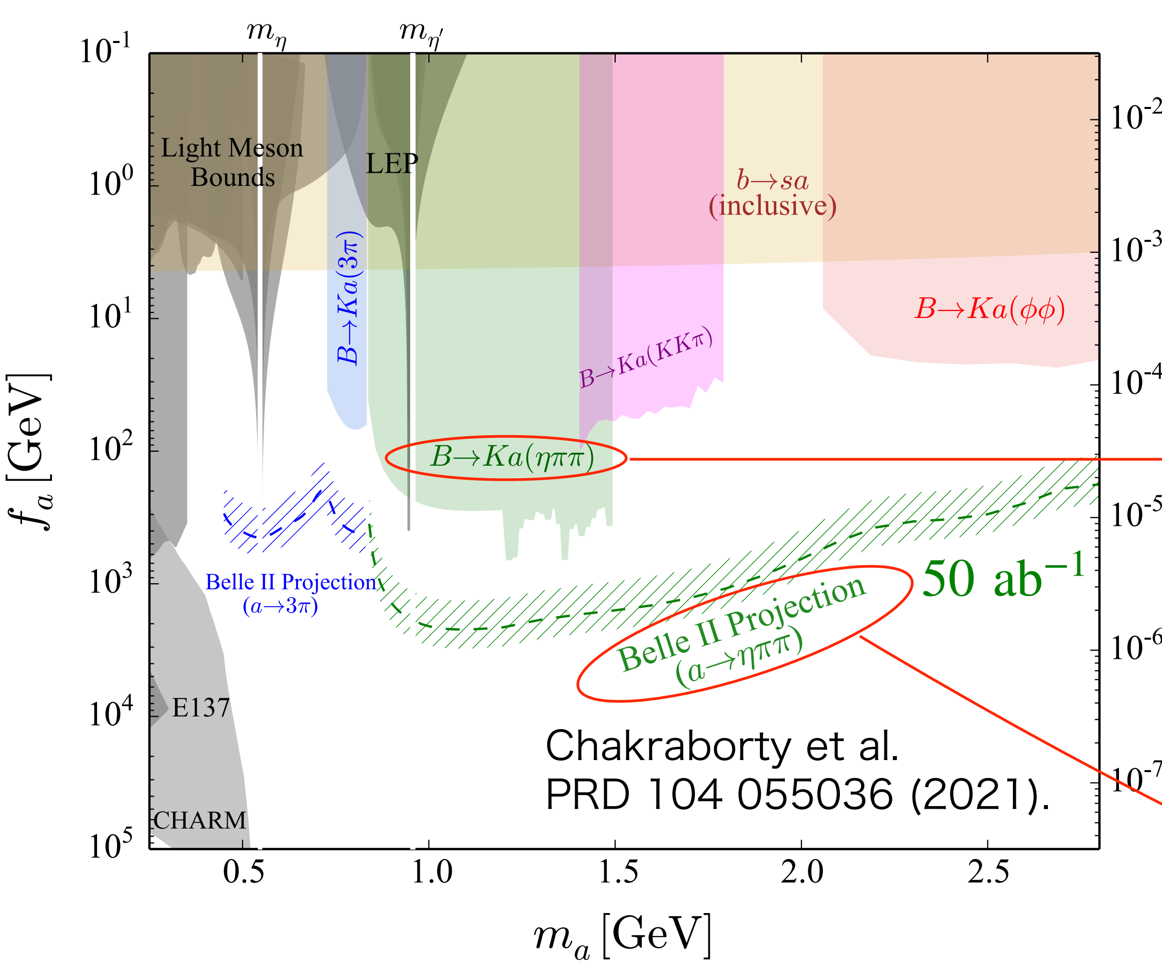

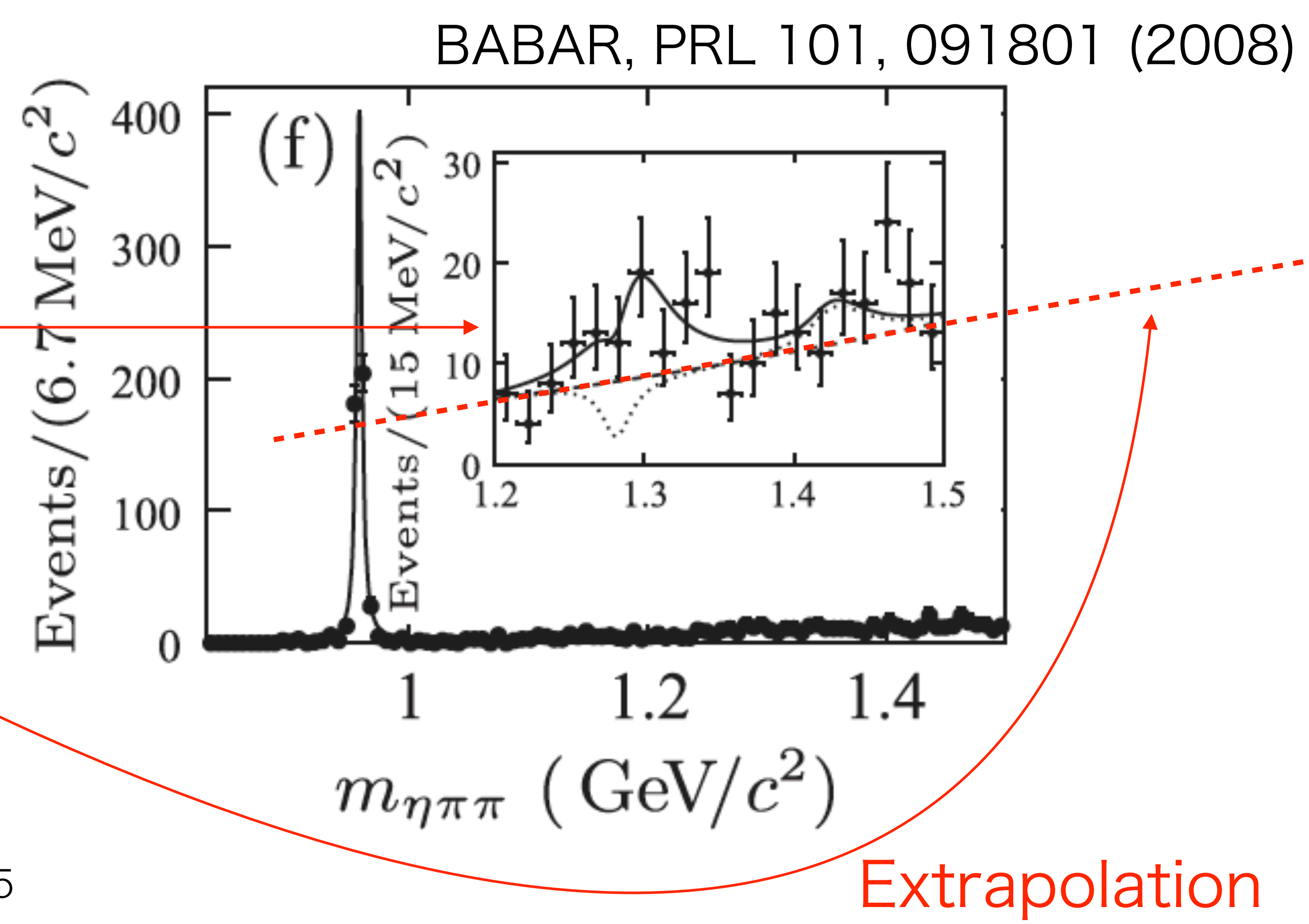

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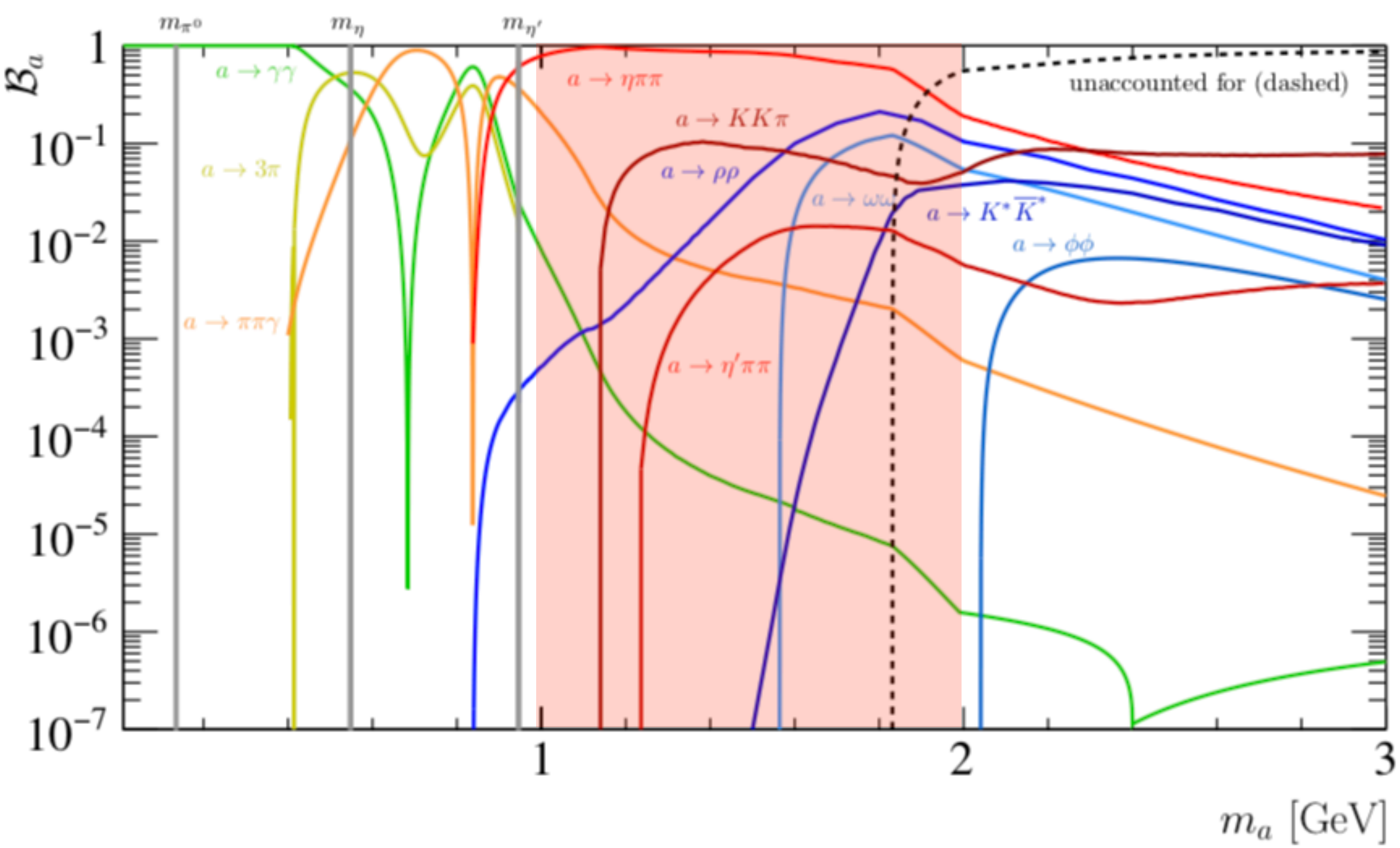
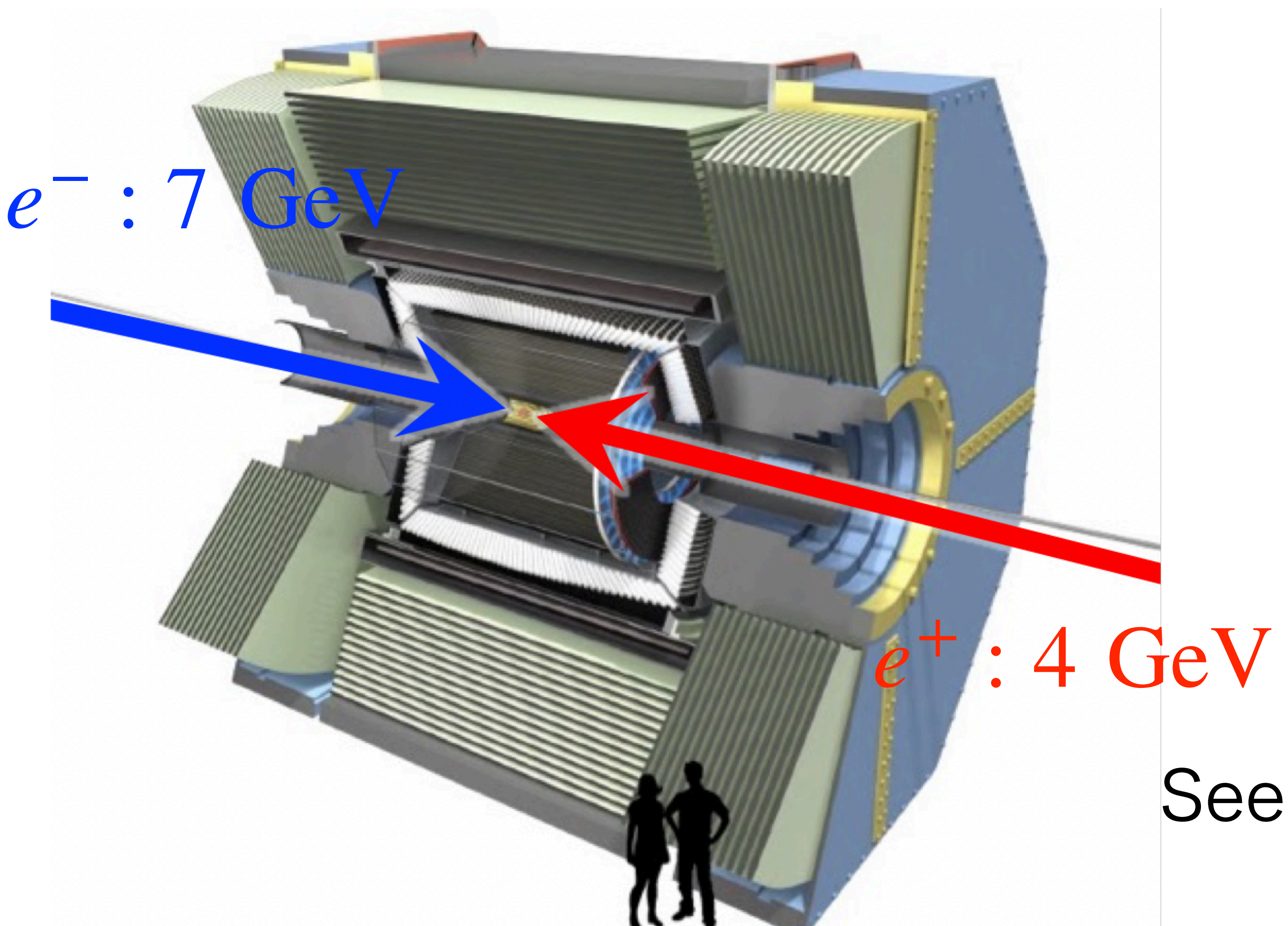
Branching Fraction of Axion

- Branching fraction of heavy QCD axion: PRL 123 031803 (2019)
  - $a \rightarrow \eta\pi\pi$ is dominant in $1.0\ \mathrm{GeV}/c^2 < m_a < 2.0\ \mathrm{GeV}/c^2$.
  - Very short lifetime for this decay mode: $c\tau < 10^{-5}$ mm
- **This is the first heavy QCD axion search!!**
- I'll discuss the progress of analysis and expected sensitivity.



The Belle II Experiment

- e^+e^- collider experiment using Super-KEKB.
  - ➡ $\sqrt{s} = 10.58$ GeV, $e^+e^- \to \Upsilon(4S) \to B\bar{B}$.
  - ➡ Flavor physics, dark matter search, and so on.
- As of December 2021, $\mathscr{L}_{\mathrm{peak}} = 3.8 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ (world record)、$\mathscr{L}_{\mathrm{int}} = 268\ \mathrm{fb}^{-1}$ (target is $50\ \mathrm{ab}^{-1}$, which corresponds to x50 larger statistics than the Belle experiment).



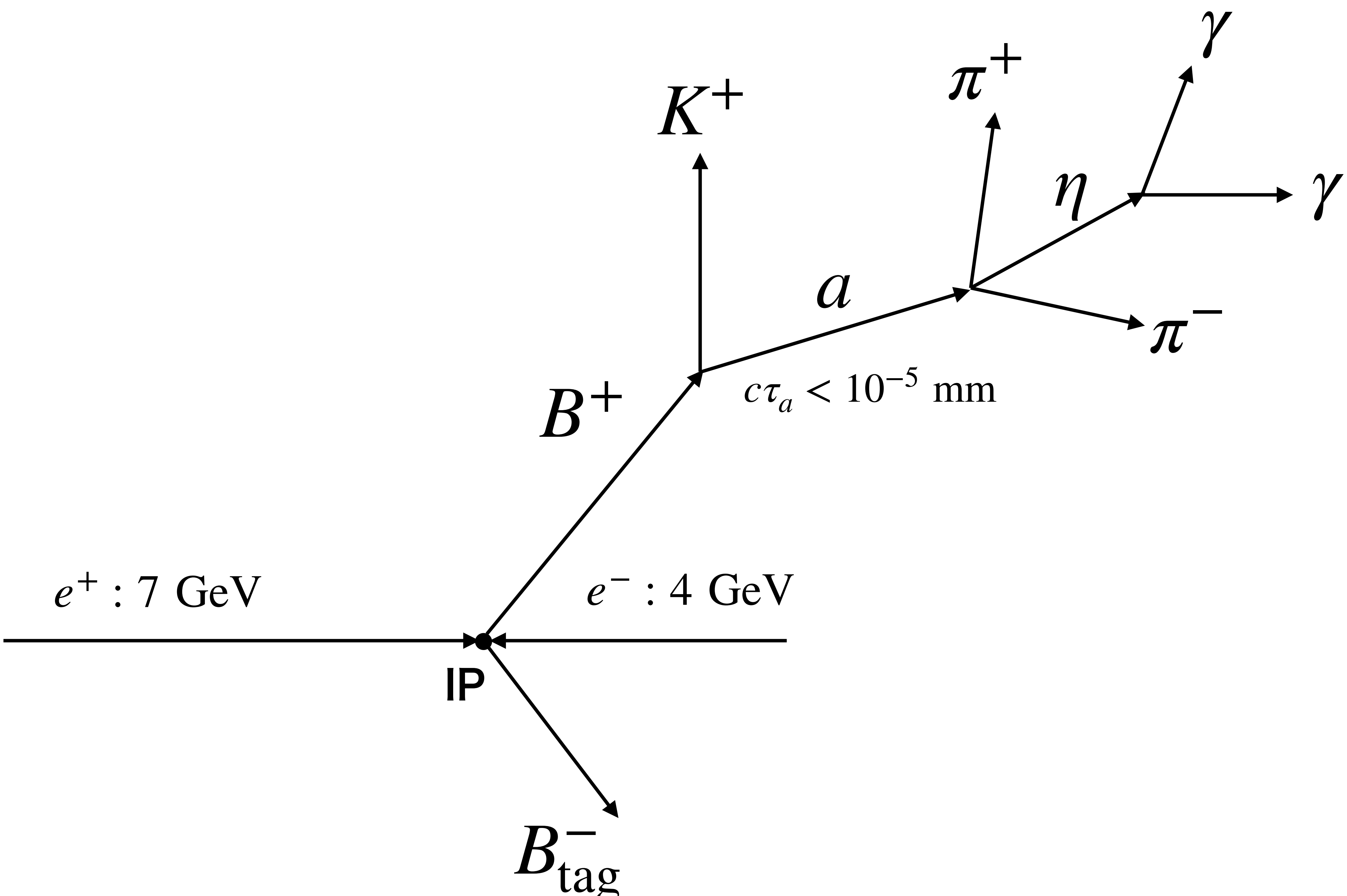
From inside

PXD	IP
SVD	IP, track
CDC	Track, momentum
TOP, ARICH	K/π ID
ECL	Energy
KLM	K_L、μ ID

See Nishida-san's talk in more detail.

Event Reconstruction and Selection

- Establish analysis method suing MC simulation (200/fb).
- Event reconstruction: $B^+ \to K^+ a, a \to \eta \pi^+ \pi^-, \eta \to \gamma\gamma$



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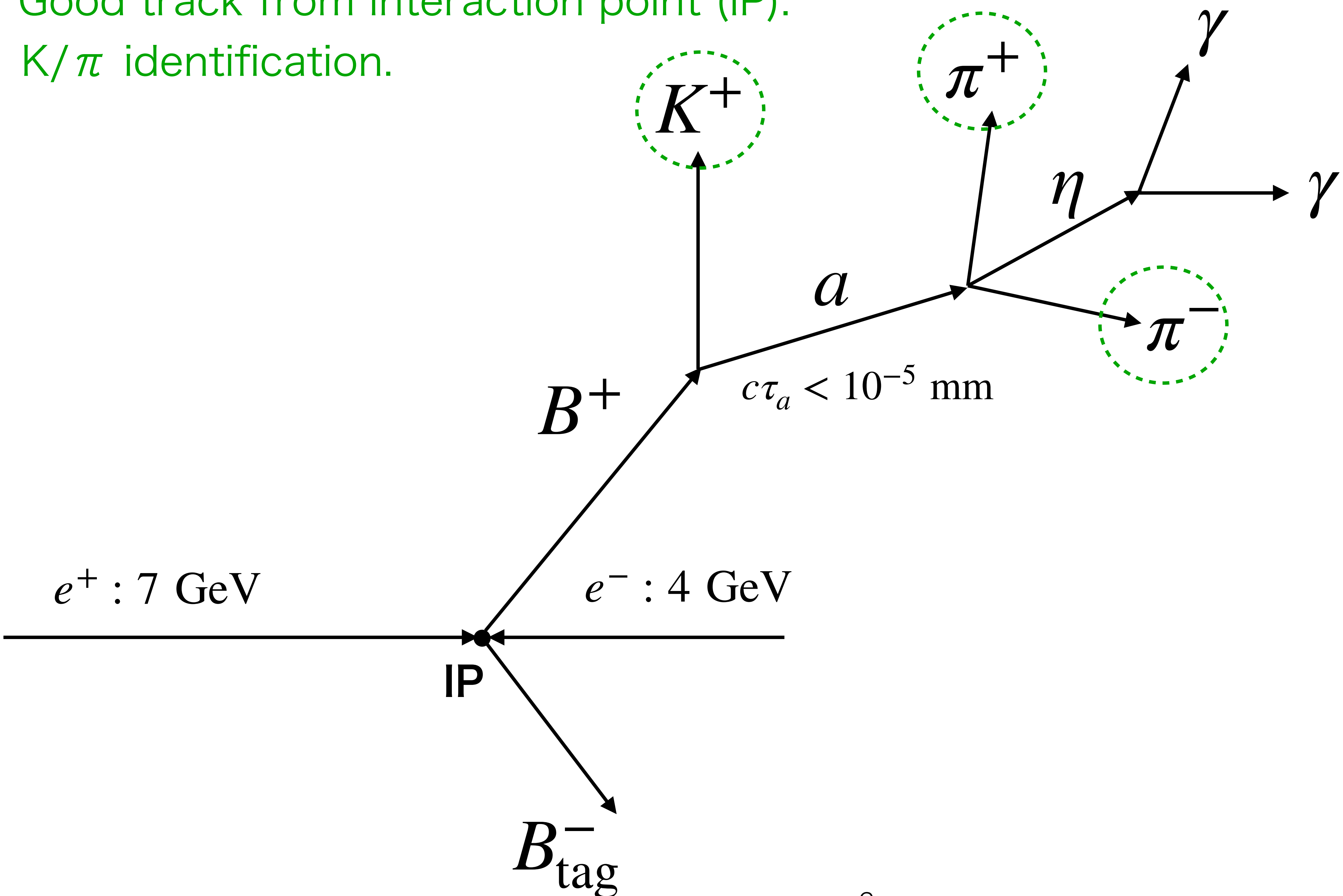
Good track from interaction point (IP).
K/π identification.



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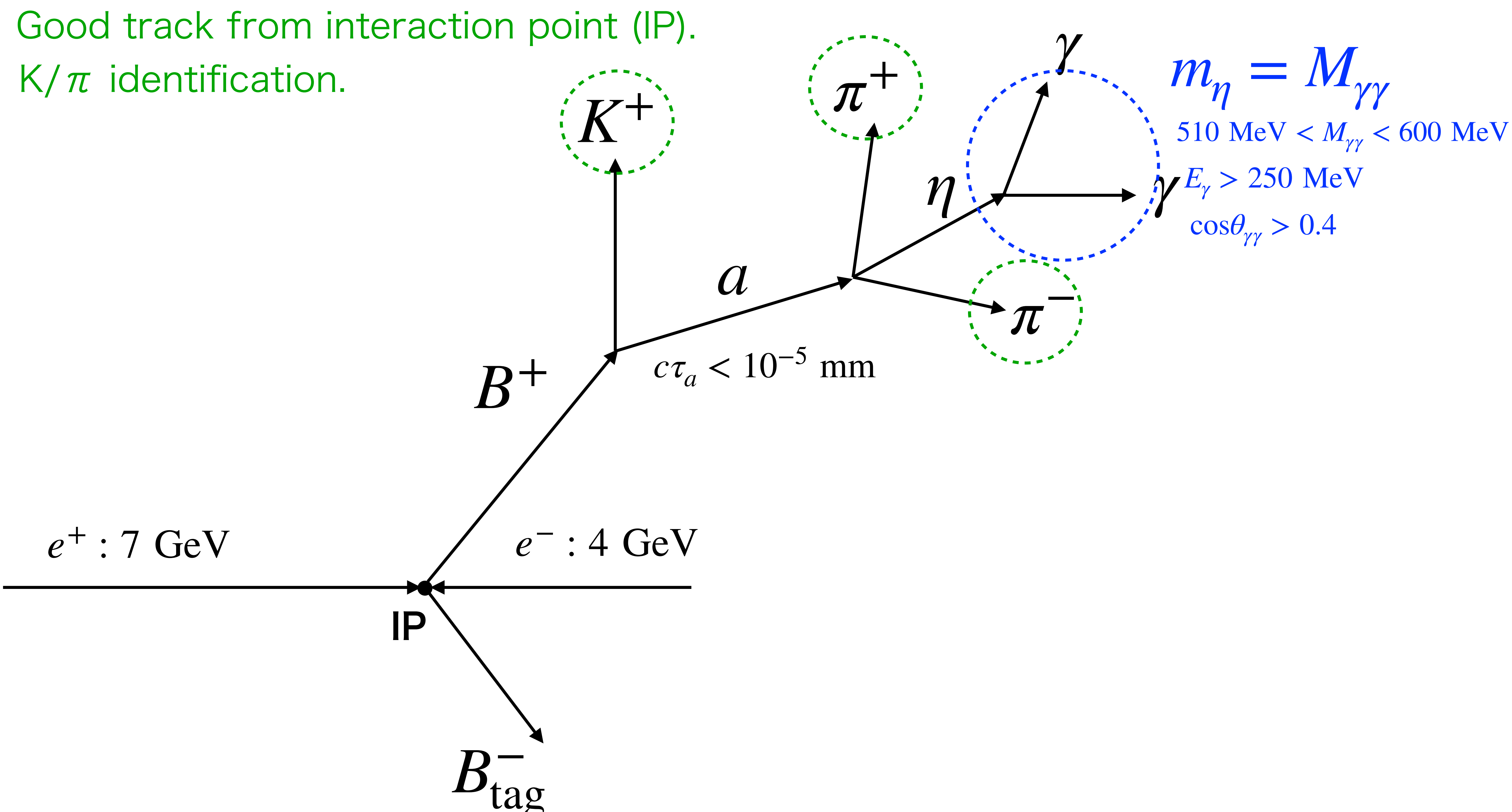

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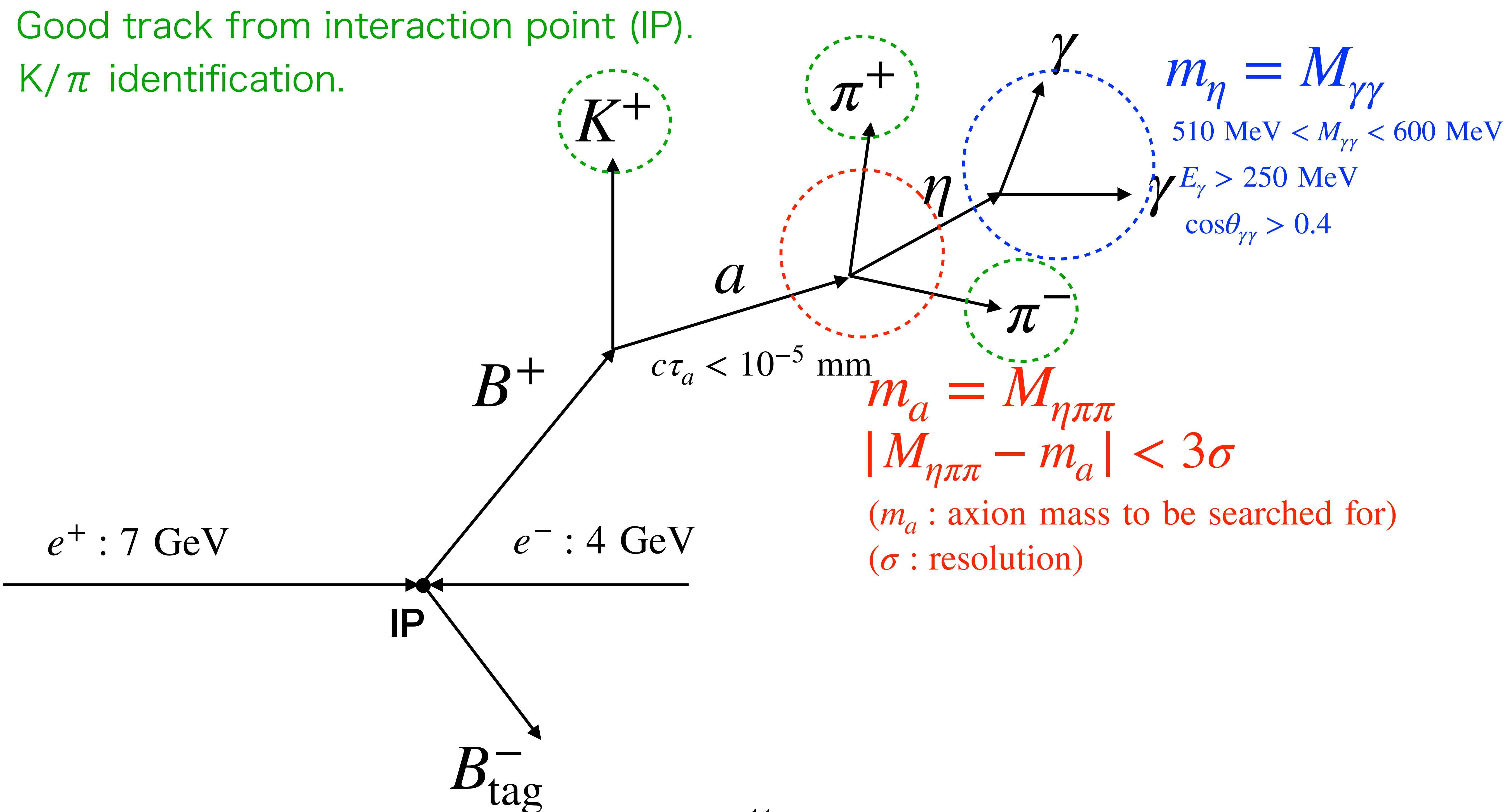

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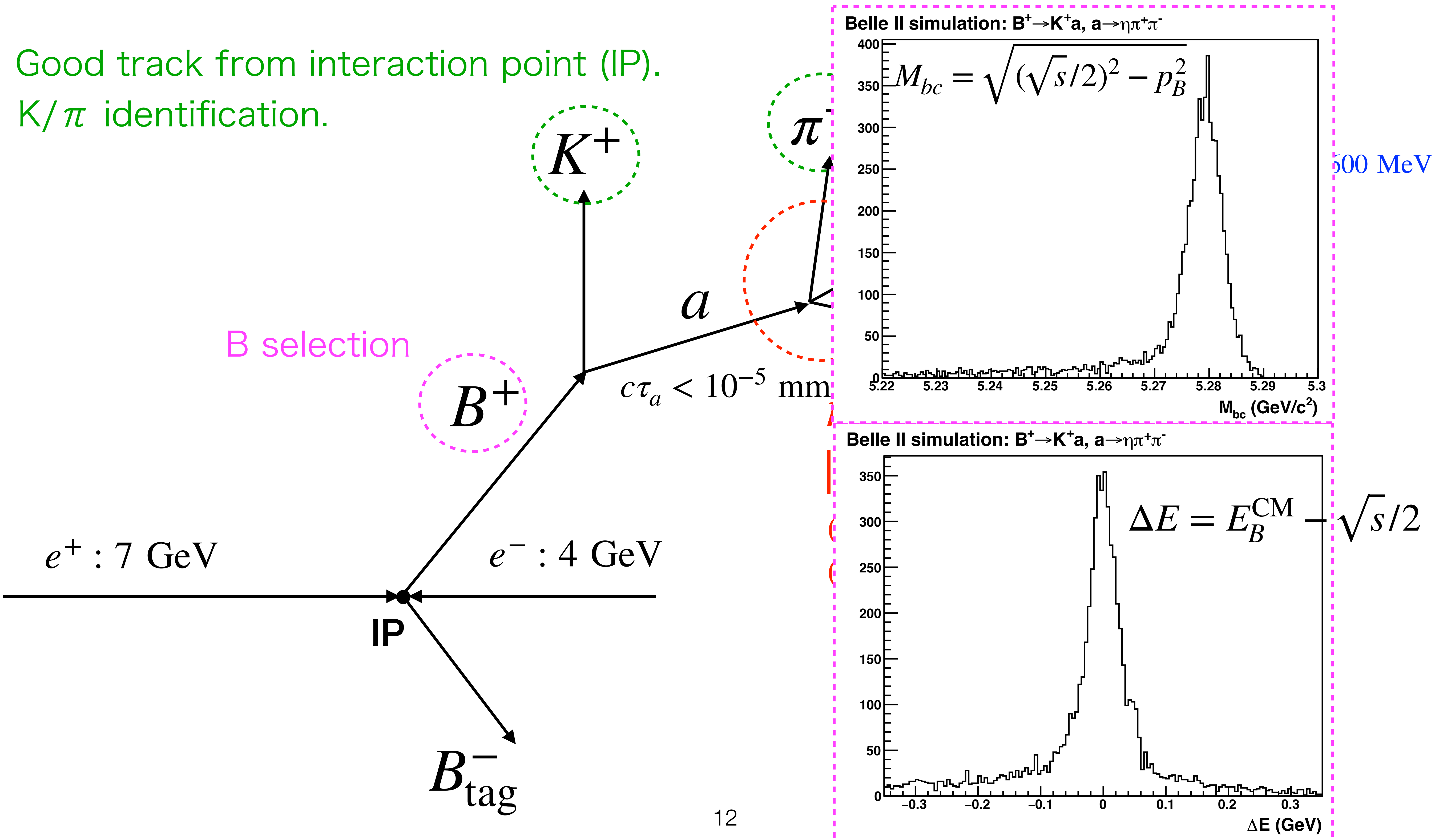
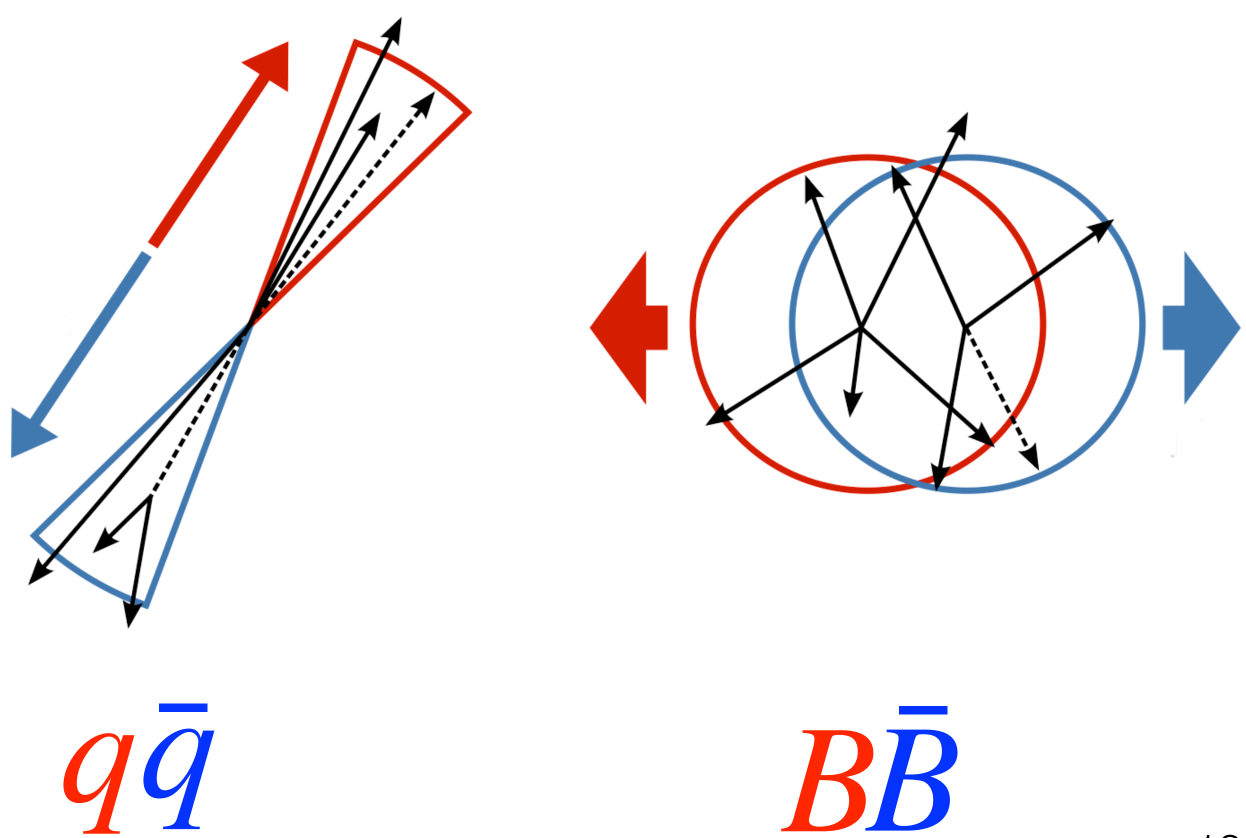


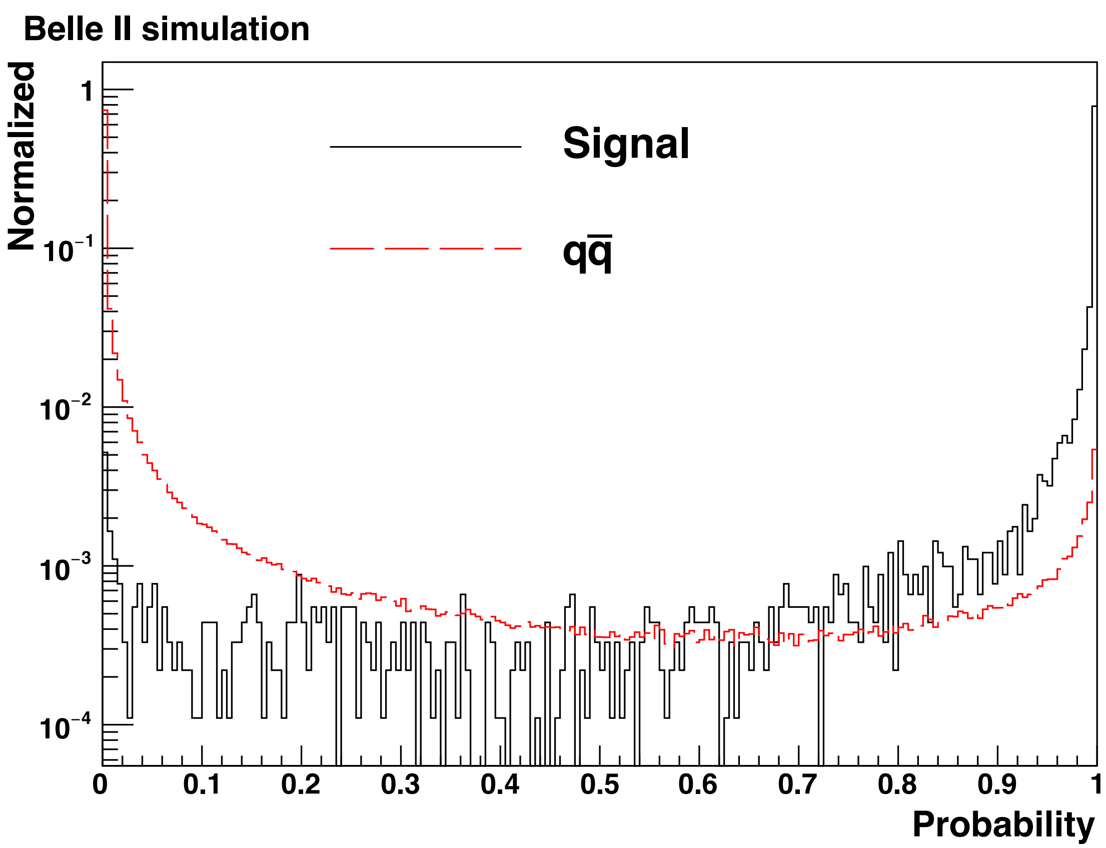
$q\bar{q}$ Background Rejection

- The most dominant background is $q\bar{q}$ (u, d, c, s) event.
- The background can be rejected using the different distribution.
  - $B\bar{B}$:uniformly distribute.
  - $q\bar{q}$:strongly collimated due to the decay to light hadrons.
- Signal MC and $q\bar{q}$ MC samples were used for machine learning.

➡ ~10% signal efficiency, $\sim 1/10^5$ background rejection.

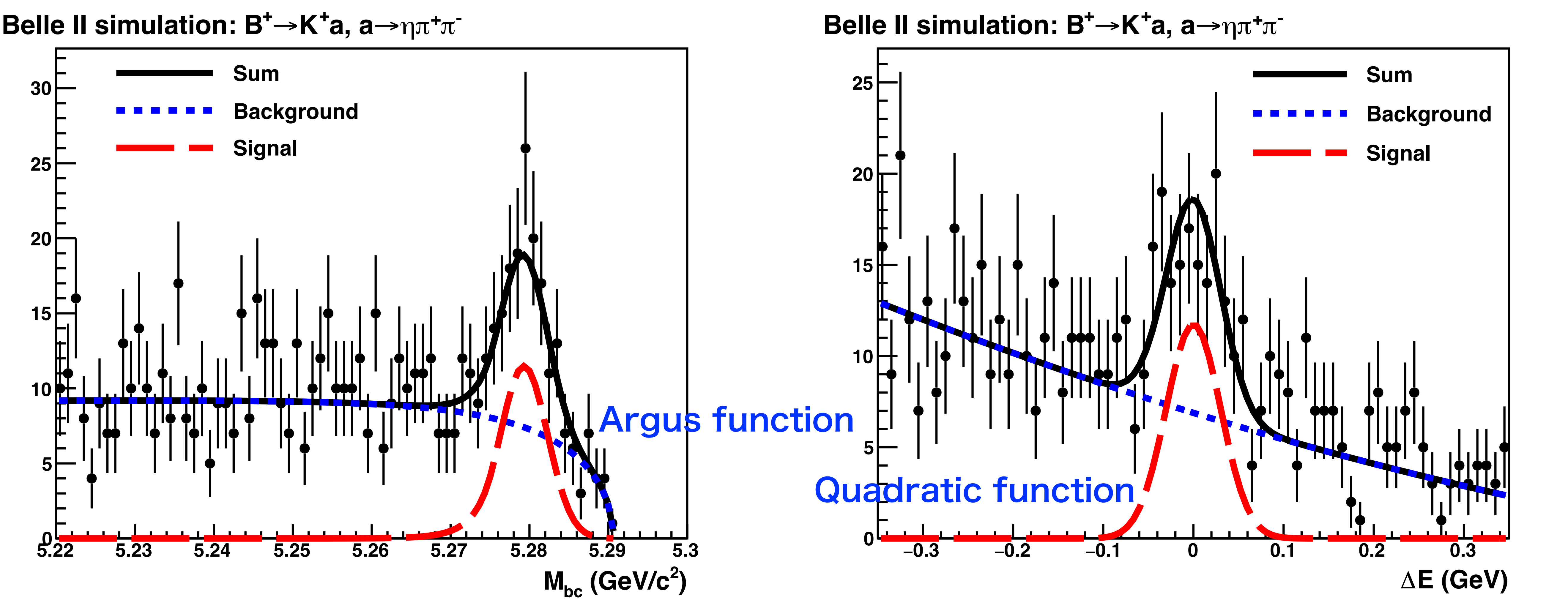
- Optimization is ongoing.





M_{bc}, ΔE Spectra Fitting

- After event selection, M_{bc} and ΔE spectra were simultaneously fitted including background to obtain the branching fraction.
- To estimate sensitivity, M_{bc} and ΔE spectra were generated using MC.

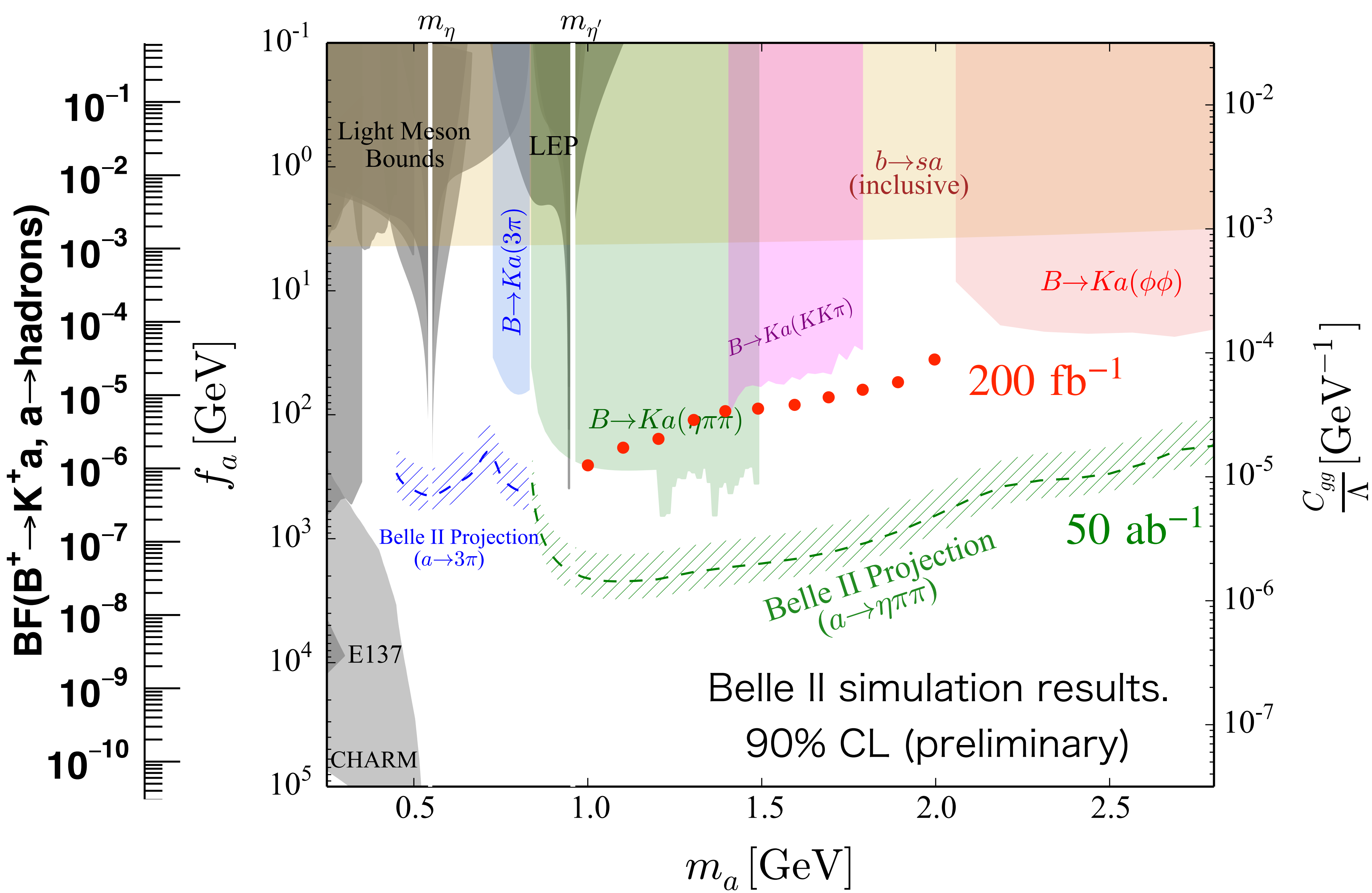


$$m_a = 1.5\ \mathrm{GeV}/c^2,\ BF(B^+ \to K^+a) = 5 \times 10^{-5},\ 200\ \mathrm{fb}^{-1}$$

Expected Sensitivity in Belle II

- Background spectra were generated using MC, spectra were fitted, and BF was estimated including the correction of signal efficiency.

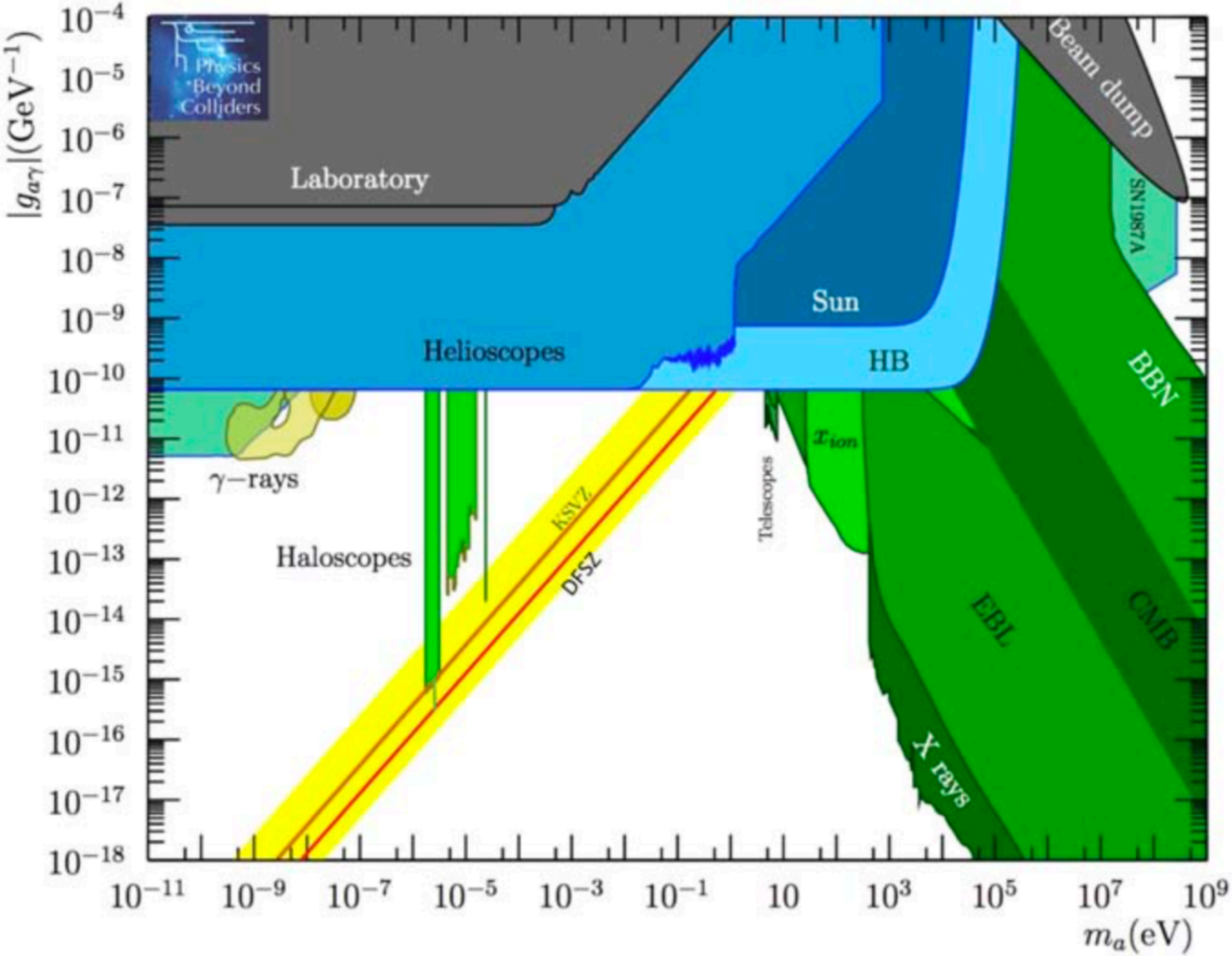
➡ Repeated with the mass range $1.0\ \mathrm{GeV}/c^2 < m_a < 2.0\ \mathrm{GeV}/c^2$.



Summary

- Heavy QCD axion to solve strong CP problem.
  - ➡ This can be searched for in Belle II.
- Study of $B^+ \to K^+ a, a \to \eta\pi^+\pi^-$ using MC.
  - Optimization of event selection cuts and background rejection is ongoing.
  - Expected sensitivity was estimated.
    - ➡ This is the first search of heavy QCD axion.
- Establish more accurate and effective cuts using MC, and analyze real data.

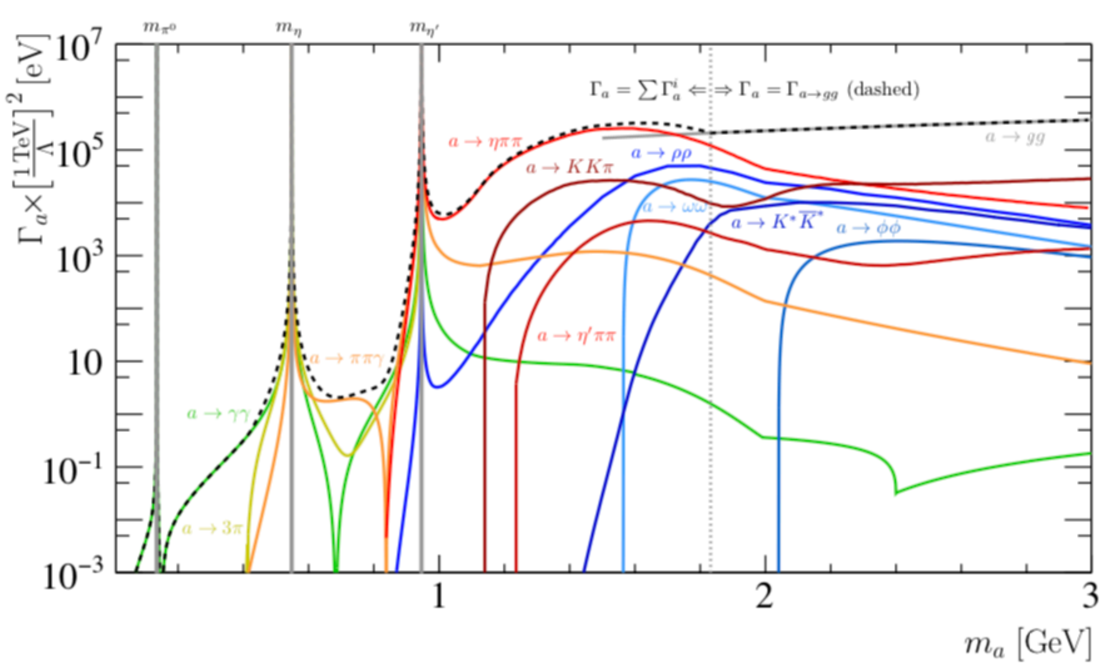
Back Up

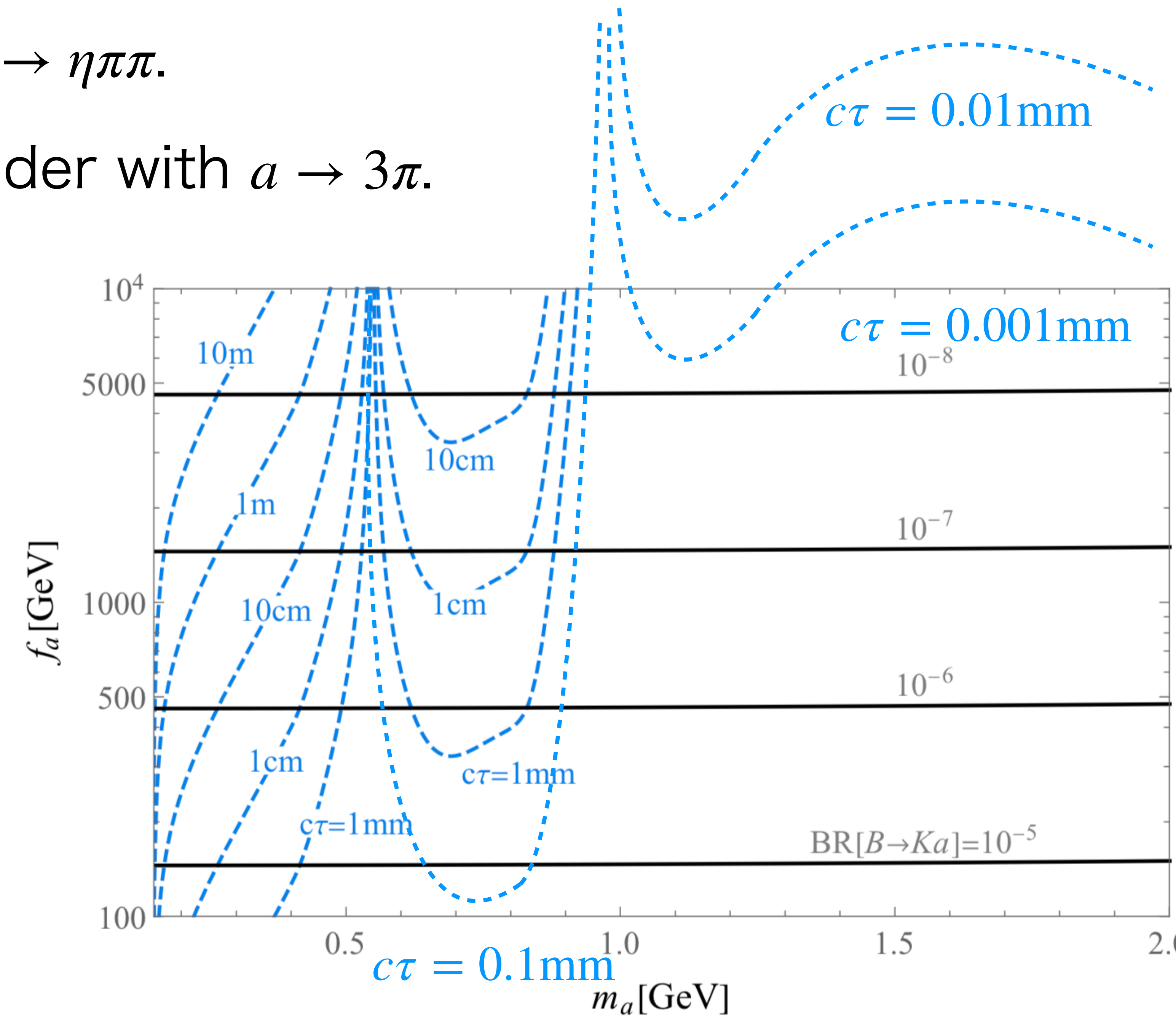


Physics Beyond Colliders
Laboratory
Helioscopes
Sun
HB
Beam dump
SN1987A
BBN
γ−rays
Haloscopes
KSVZ
DFSZ
Telescopes
x_{ion}
EBL
CMB
X rays
$|g_{a\gamma}|(\mathrm{GeV}^{-1})$
$m_a(\mathrm{eV})$

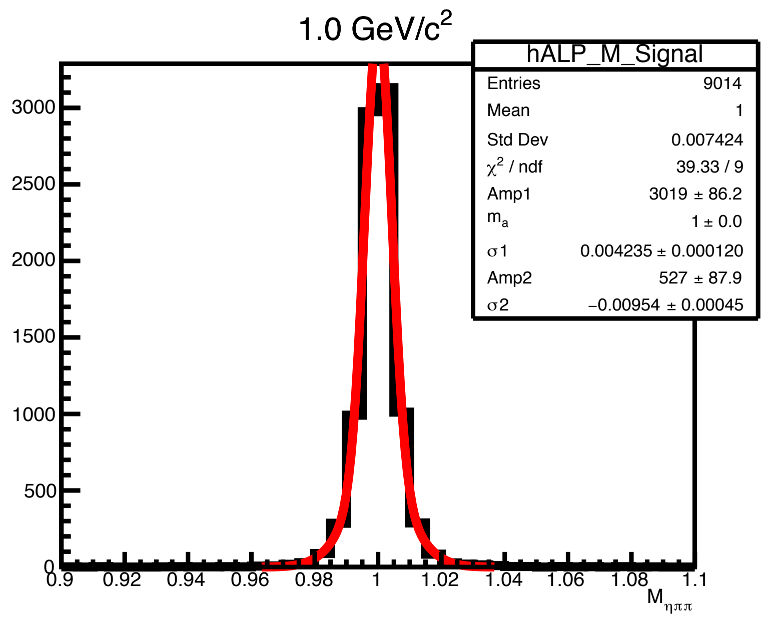
Lifetime of Axion

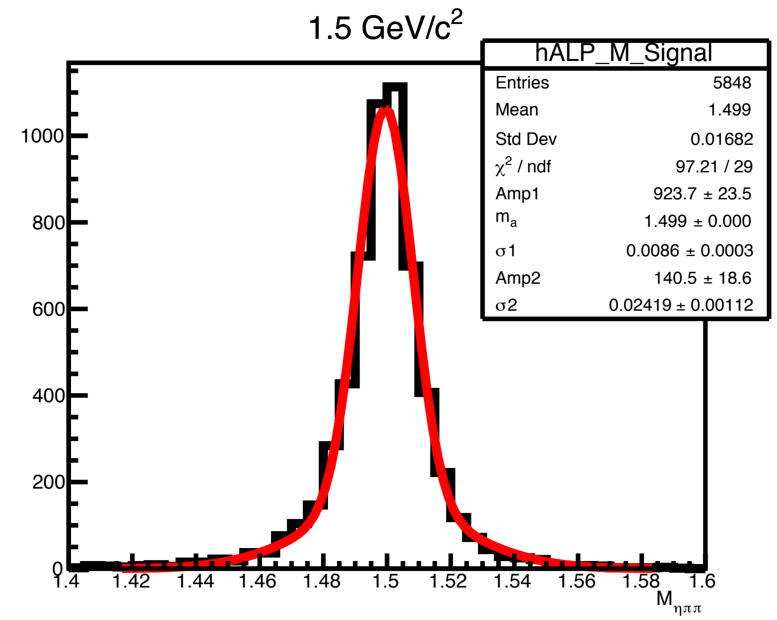
- Lifetime can be determined using the decay width.
- The decay constant, mass, and lifetime are seen.
  - Very short lifetime for $a \to \eta\pi\pi$.
  - Lifetime should be consider with $a \to 3\pi$.

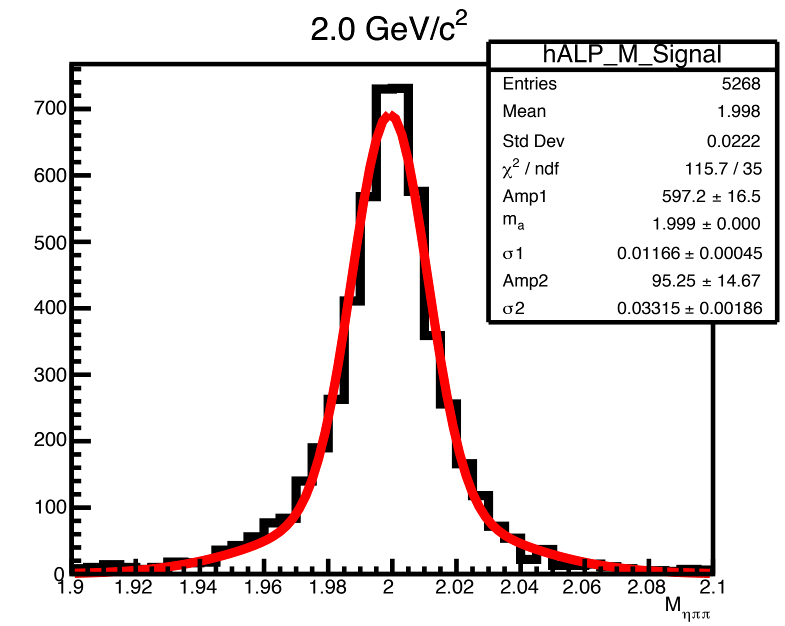




Invariant Mass $m_{\eta\pi\pi}$ for Axion (Signal MC, isSignal==1)





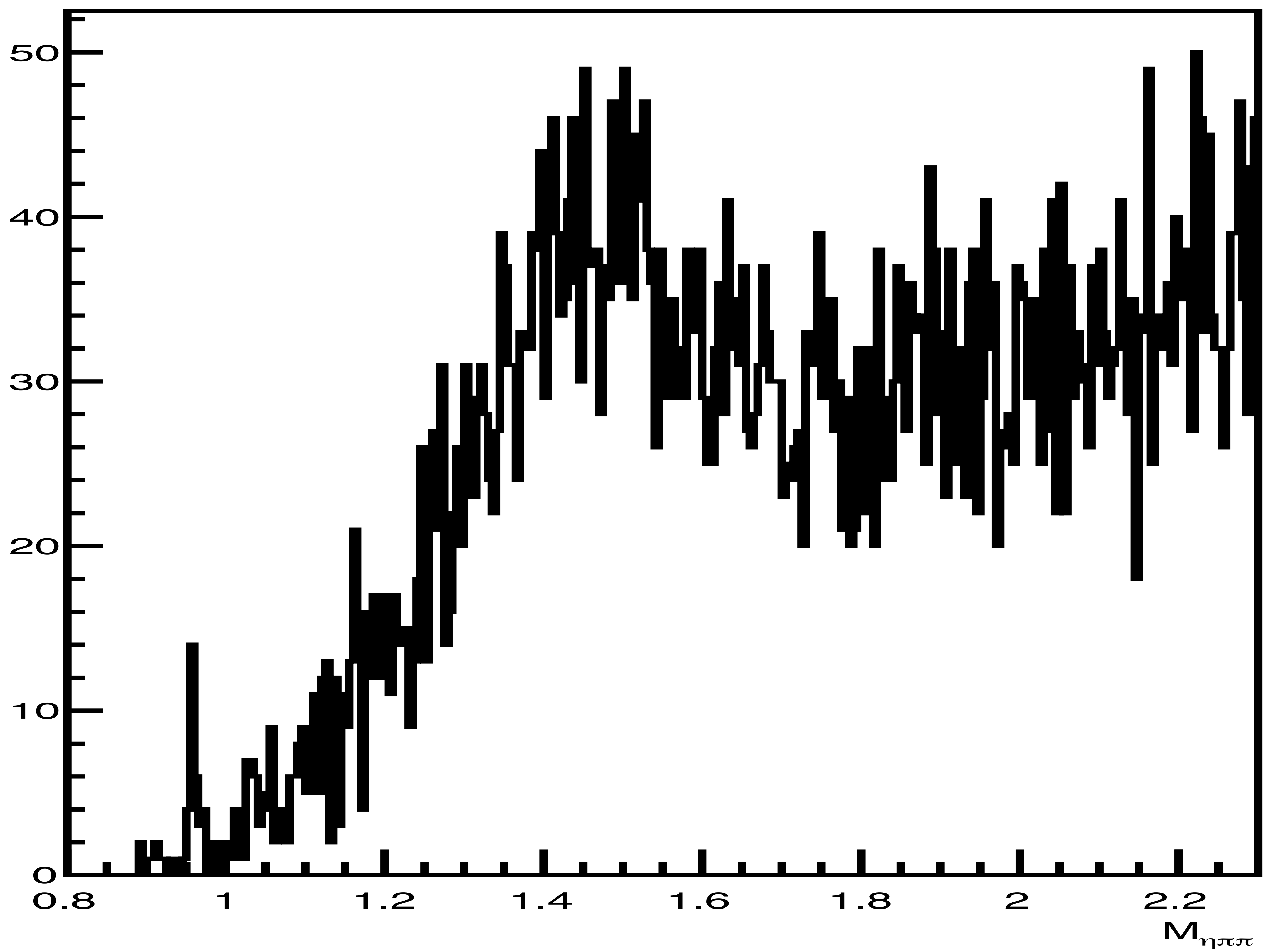


- Axion mass $m_a = 1.0 \sim 2.0\ \mathrm{GeV}/c^2$, after the black square cuts and isSignal==1.
- The number of simulated events is 60,000.
- Spectra were fitted to double gaussian.
- Std Dev value was used as σ

  for the cut $|M_{\eta\pi\pi} - m_a| < 3\sigma\ \mathrm{GeV}/c^2$.

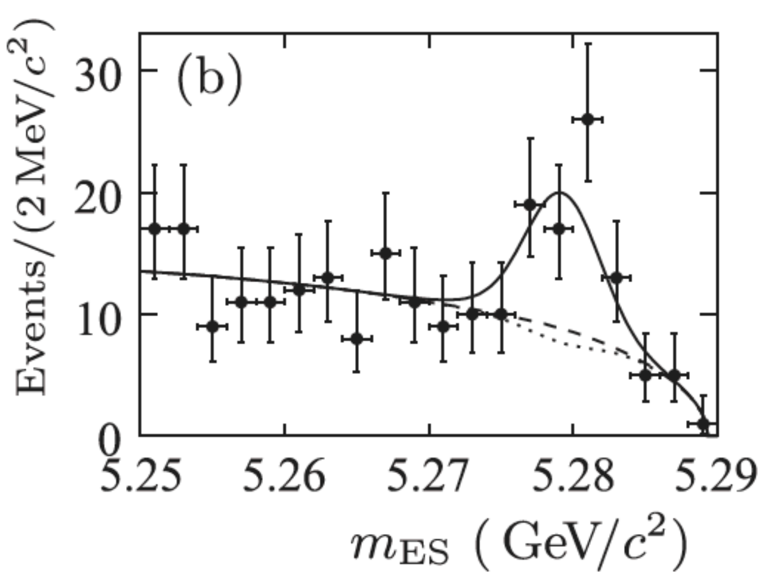
Axion mass [GeV/c2]	Std Dev [GeV/c2]	Signal efficiency
1	0.0074	14.5%
1.1	0.0097	12.7%
1.2	0.0116	10.7%
1.3	0.0136	9.6%
1.4	0.0156	9.1%
1.5	0.0168	9.0%
1.6	0.0177	8.6%
1.7	0.0203	8.1%
1.8	0.0203	8.0%
1.9	0.0209	8.1%
2	0.0222	7.8%

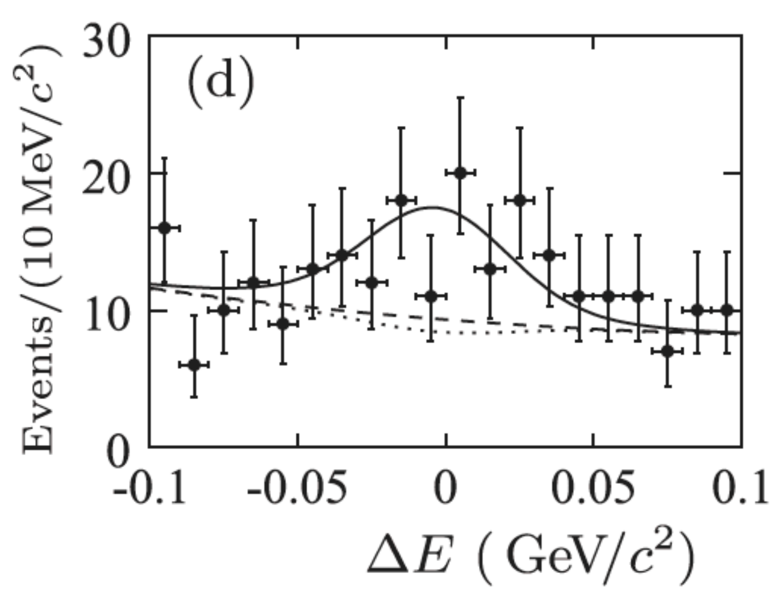
$M_{\eta\pi\pi}$

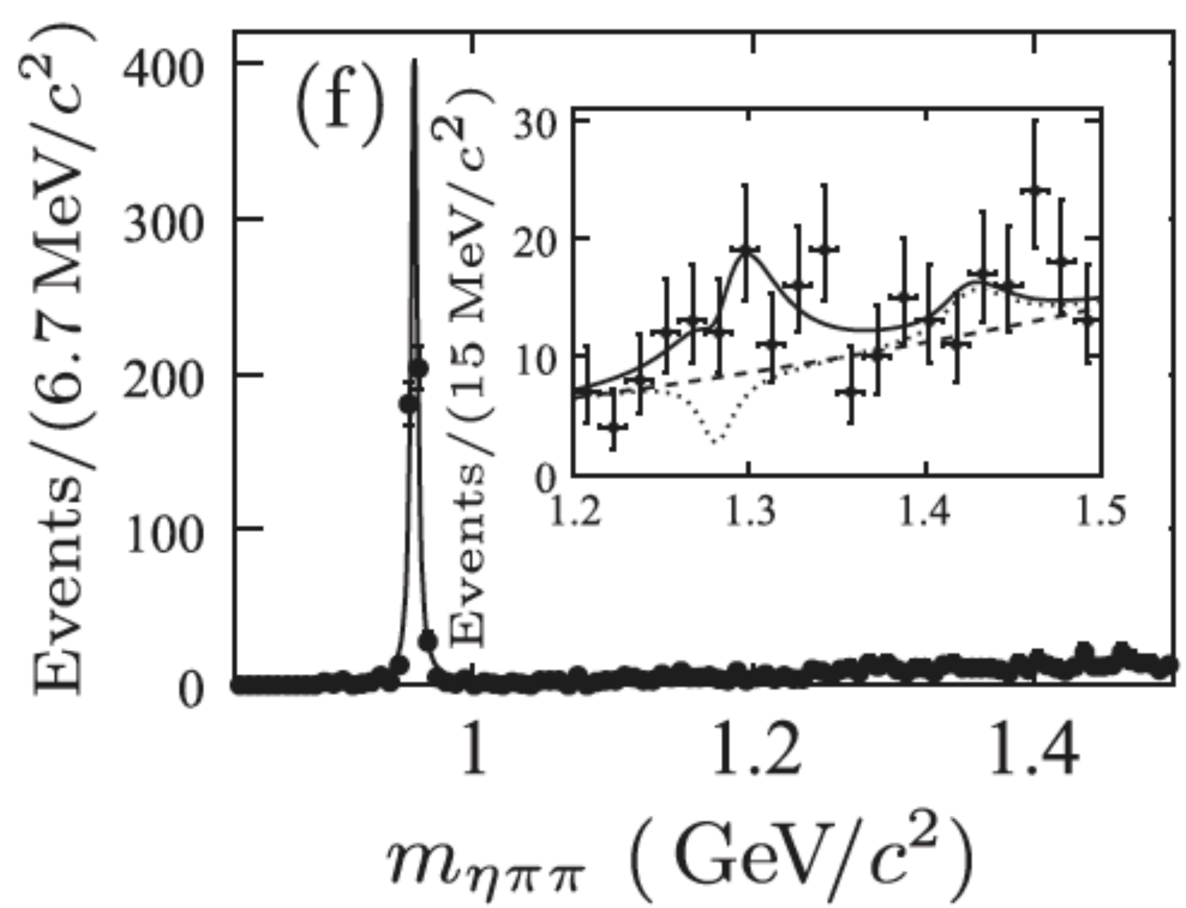


Peaking Background Study

$\eta_X \to \eta\pi\pi$	$\eta(1295)$	$f_1(1285)$	$\eta(1405)$	$f_1(1420)$
m_0/Γ [4], MeV	1294(4)/55(5)	1281.8(0.6)/24.2(1.1)		
n_{sig}	$131^{+35}_{-33} \pm 10(3.5\sigma)$	$-30^{+21}_{-19} \pm 14$	$-14^{+36}_{-33} \pm 6$	$49^{+35}_{-34} \pm 11$
90% C.L.	<179	<30	<54	<99
$\mathcal{B}(B^+ \to \eta_X K^+)\mathcal{B}(\eta_X \to \eta\pi\pi)$	$(2.9^{+0.8}_{-0.7} \pm 0.2)10^{-6}$	$(-0.8^{+0.6}_{-0.5} \pm 0.4)10^{-6}$	$(-0.3^{+0.9}_{-0.8} \pm 0.1)10^{-6}$	$(1.4 \pm 1.0 \pm 0.3)10^{-6}$
90% C.L.	$<4.0 \times 10^{-6}$	$<0.8 \times 10^{-6}$	$<1.3 \times 10^{-6}$	$<2.9 \times 10^{-6}$
$\mathcal{B}(B \to f_1(1285)K^+)$	...	$(-1.5^{+1.1}_{-1.0} \pm 1.2)10^{-6}$	...	...
90% C.L.	...	$<2.0 \times 10^{-6}$	...	...
ϵ (%)	17.6 ± 0.3	14.1 ± 0.9	16.5 ± 1.2	13.5 ± 0.6







Belle Analysis ($B \to \omega K$, $\omega \to 3\pi$)