Dalitz Plot Analysis of charmless B Meson Decays at the Belle II Experiment

Markus Reif

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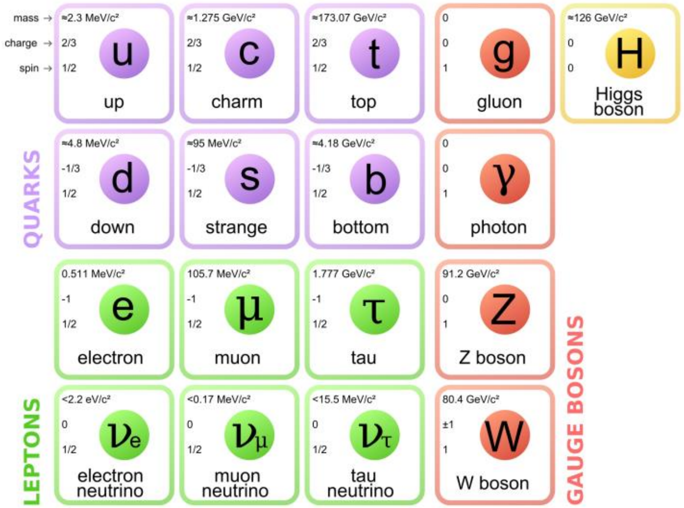
MAX-PLANCK-INSTITUT FÜR PHYSIK

UPPSALA UNIVERSITET

What do we have and what do we want?

What we have

Standard Model to describe microscopic world

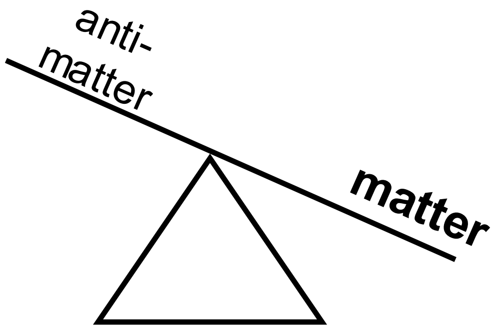


graphic from Wikimedia Commons

make predictions
→ so far confirmed in experiments

Problems

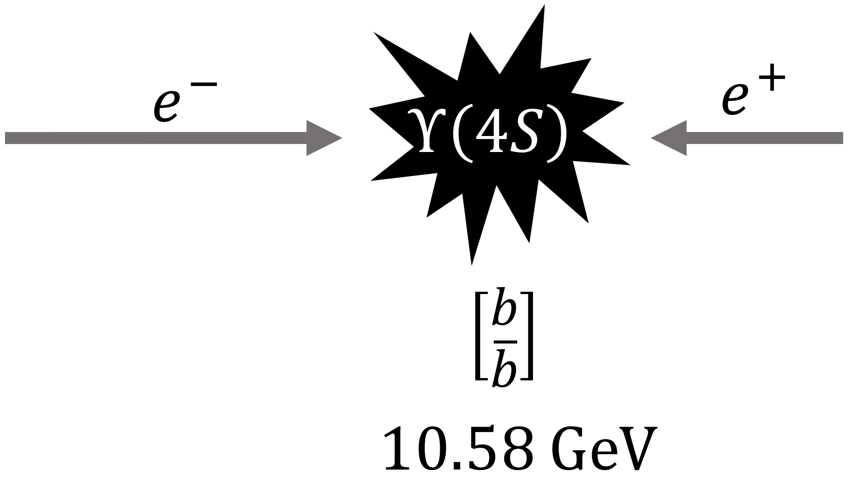
- gravity not included
- dark matter?
- matter – anti-matter asymmetry



What we want

New Physics beyond Standard Model

SuperKEKB and the Belle II Experiment



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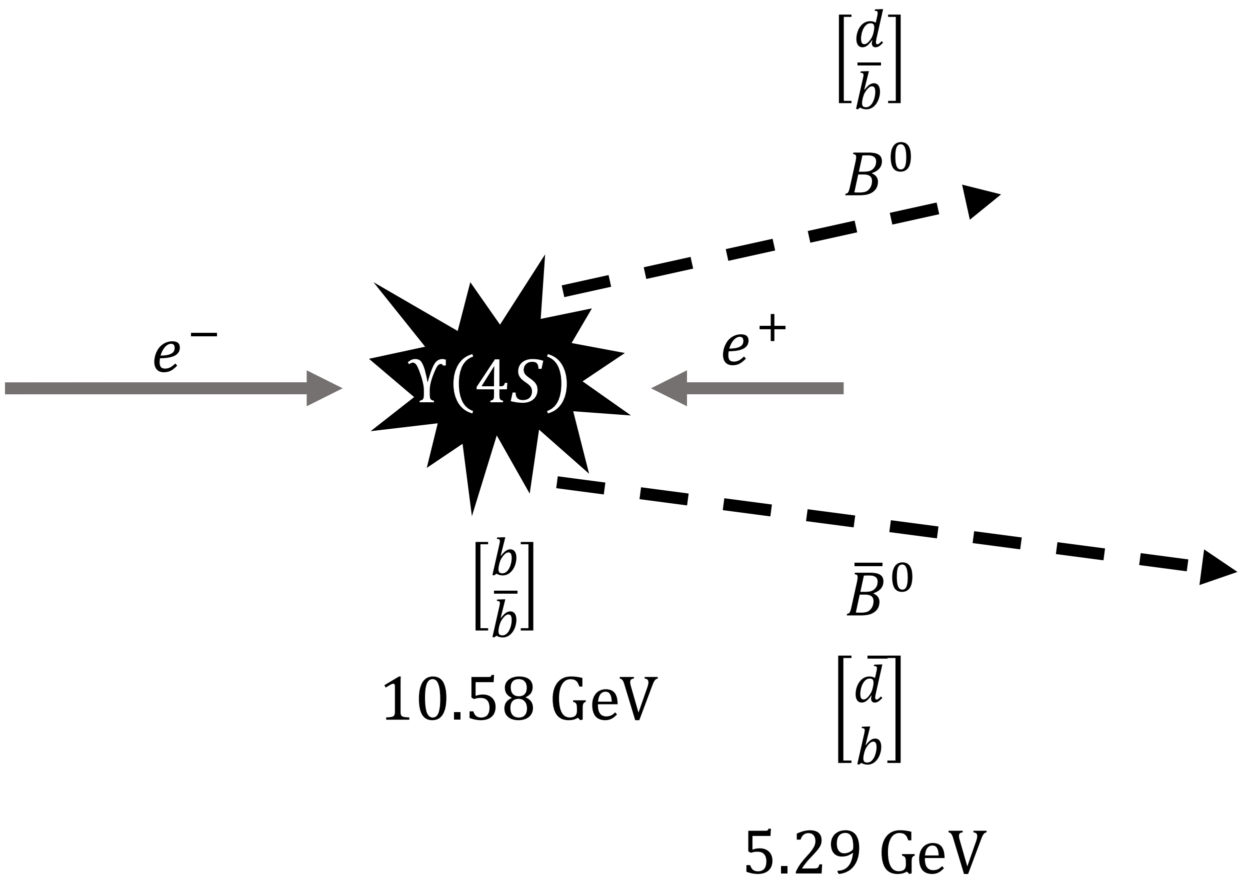

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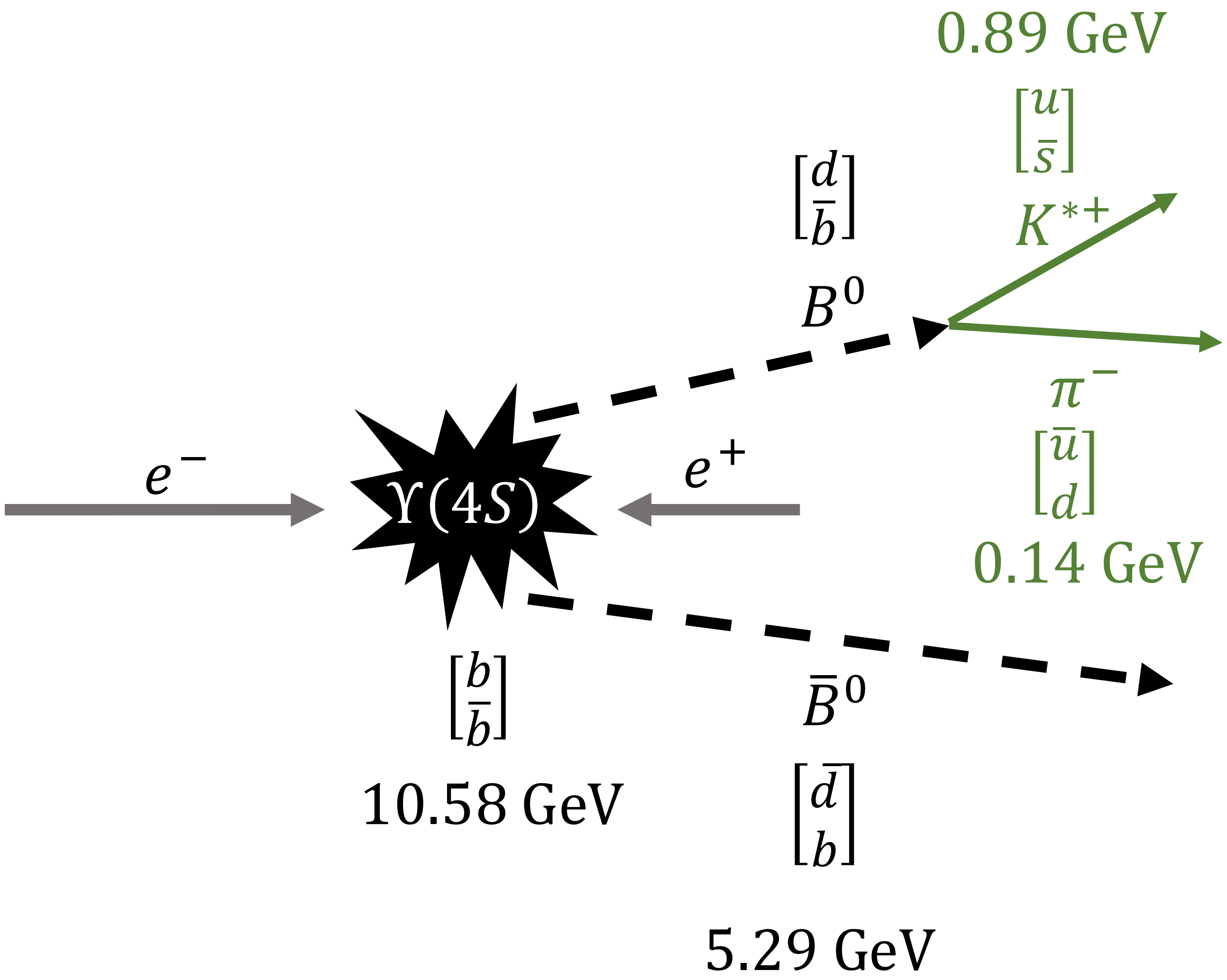

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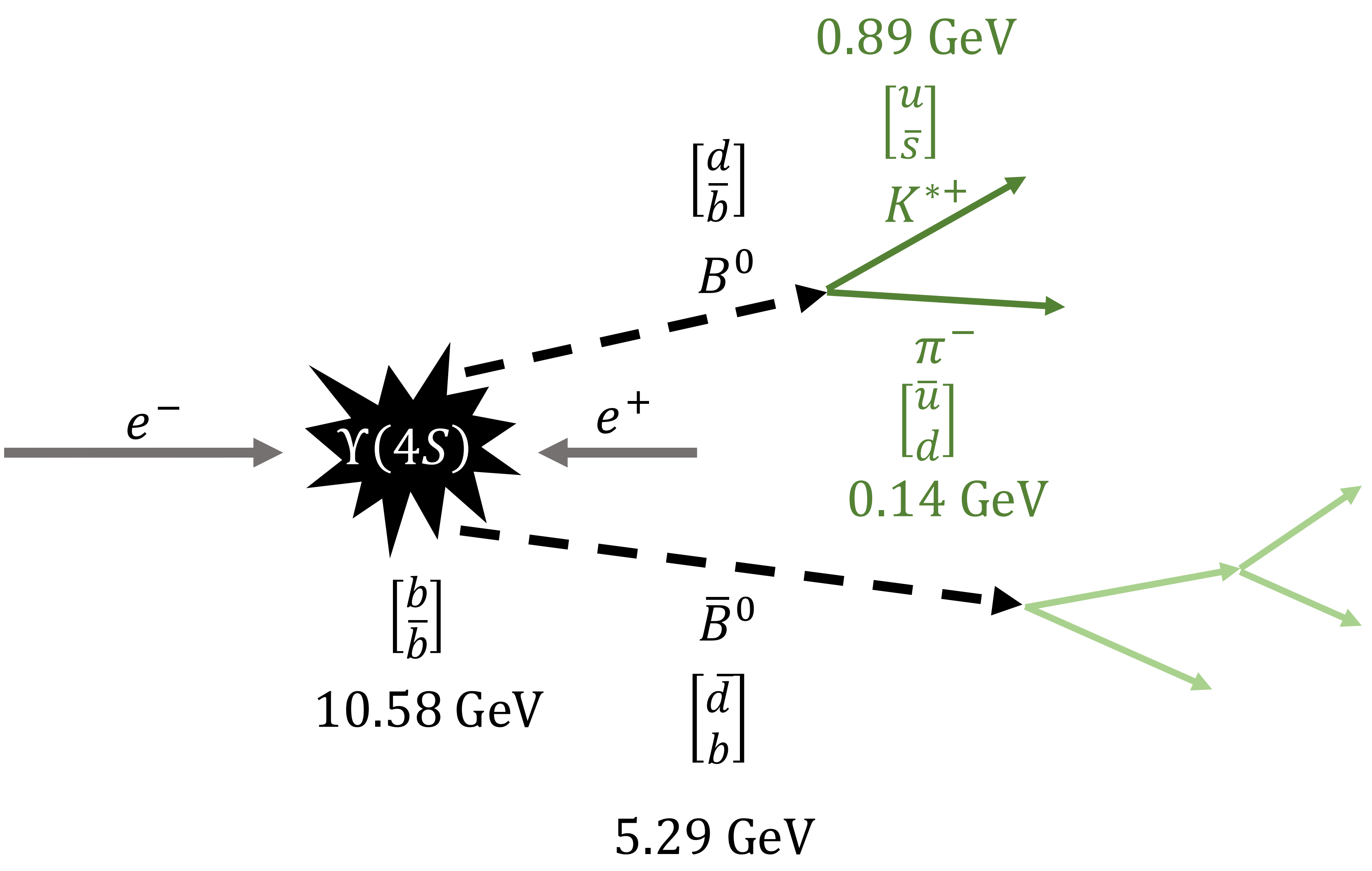

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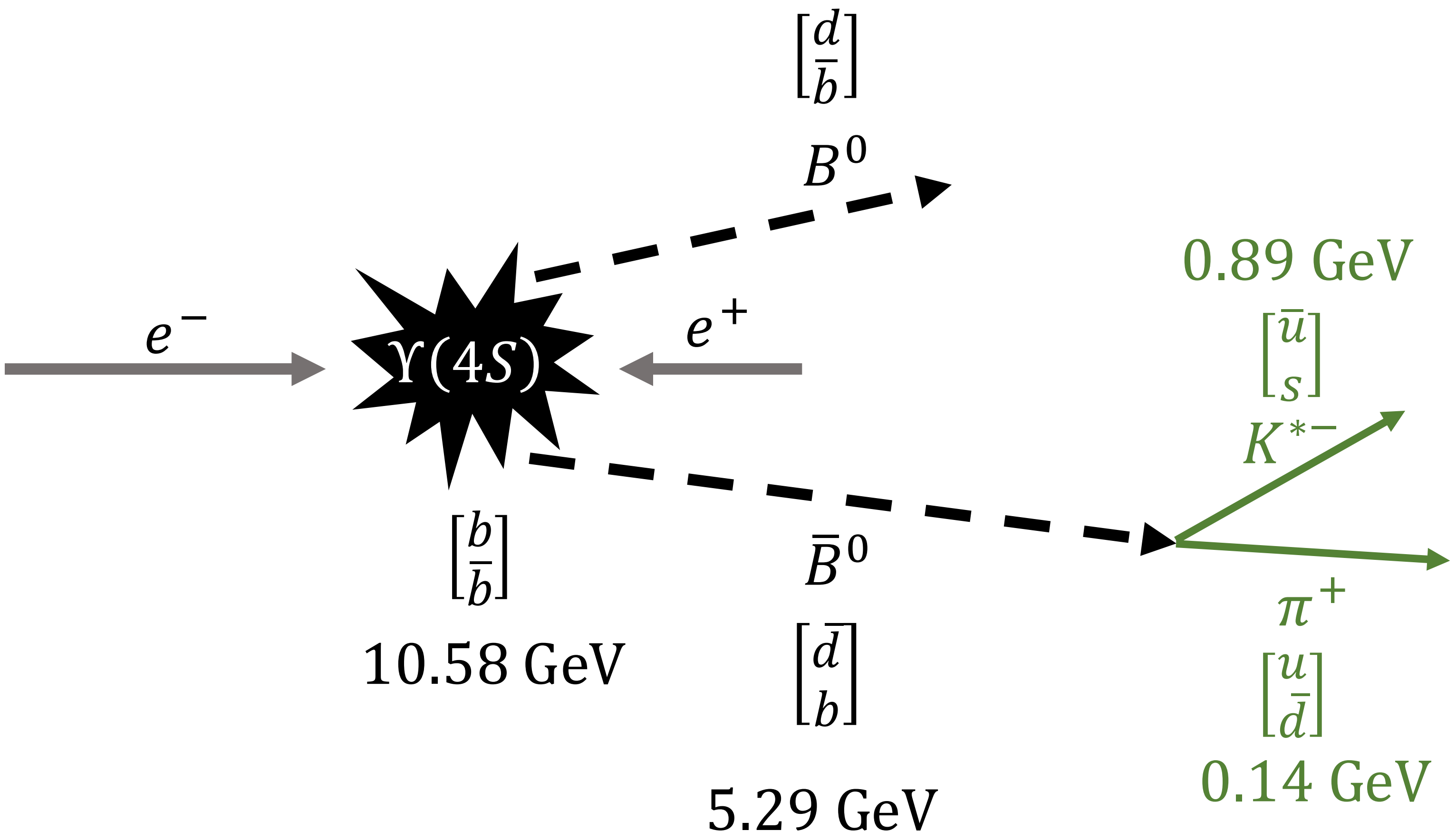

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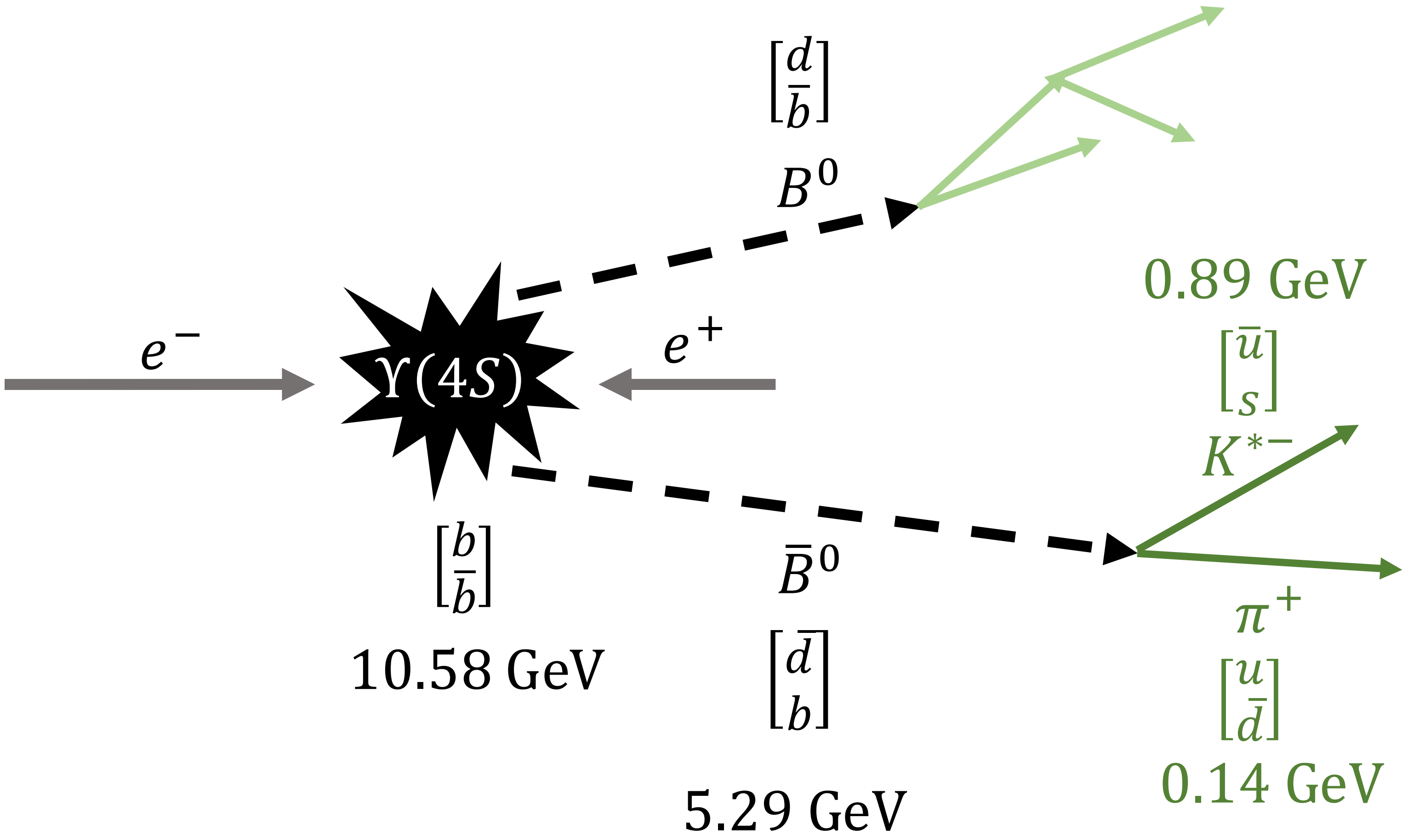

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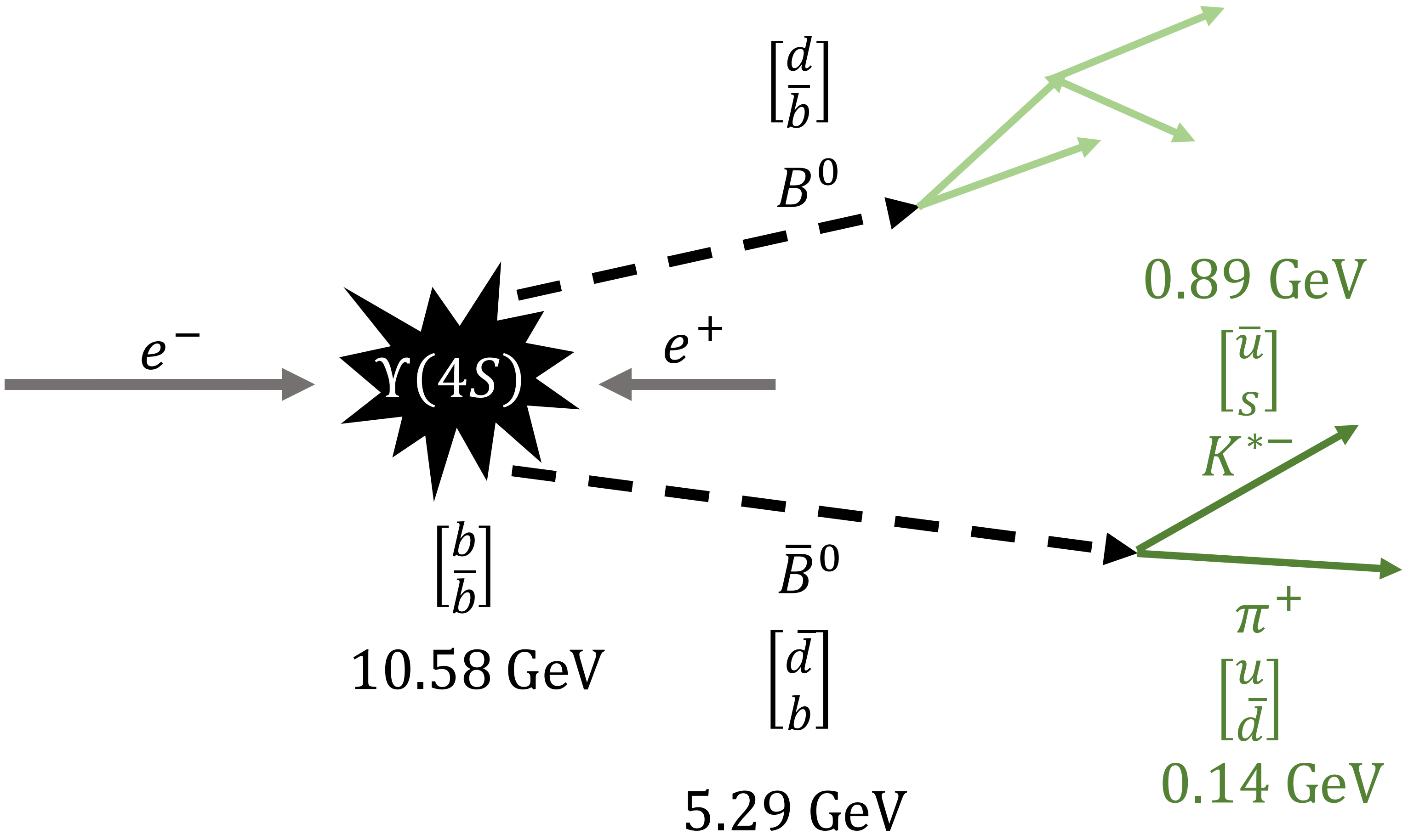

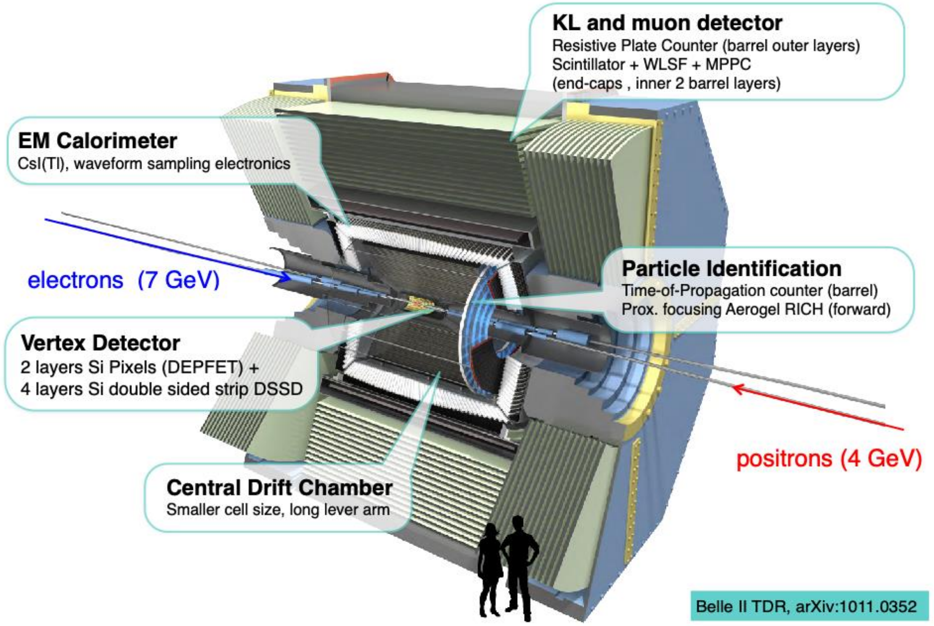

Belle II detector measures properties of final state particles

Experiment vs Standard Model

- want to compare experimentally measured parameter with theory prediction

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Experiment:

branching fraction: $\mathcal{B} = \frac{N(\bar{B}^0 \to K^{*-}\pi^+) + N(B^0 \to K^{*+}\pi^-)}{N(\text{total } \bar{B}^0) + N(\text{total } B^0)}$

direct CP-violation: $\mathcal{A}^{CP} = \frac{N(\bar{B}^0 \to K^{*-}\pi^+) - N(B^0 \to K^{*+}\pi^-)}{N(\bar{B}^0 \to K^{*-}\pi^+) + N(B^0 \to K^{*+}\pi^-)}$

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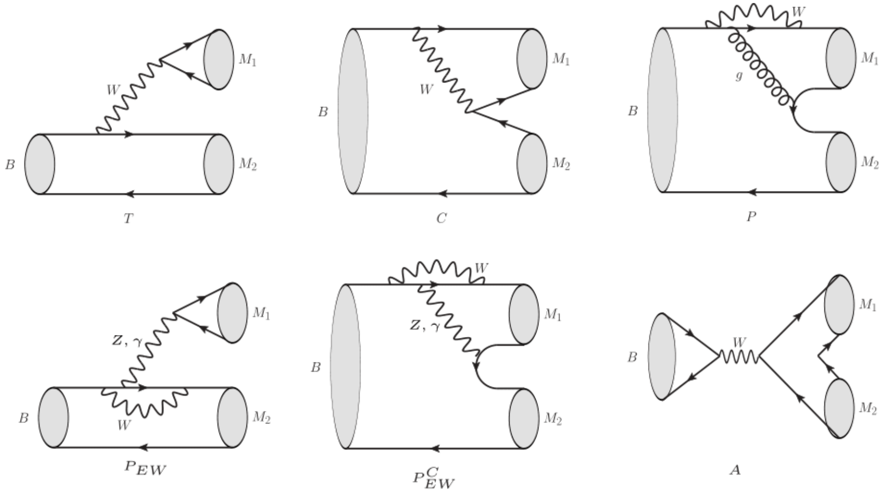

adapted from Belle II Physics Book: https://arxiv.org/pdf/1808.10567

Theory:

limited precision on prediction of $\mathcal{B}$ and $\mathcal{A}^{CP}$ for single decay modes, as many Feynman diagrams contribute

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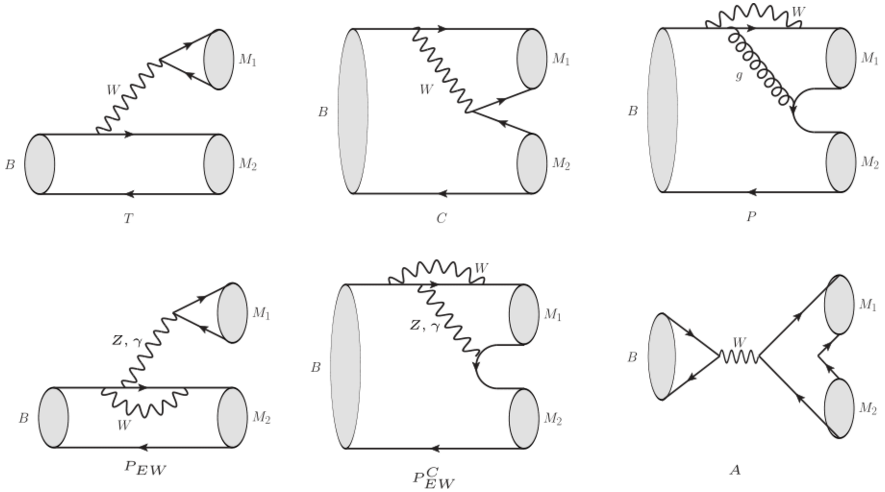

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- ➢ combine multiple decay modes related by symmetry (isospin) to "cancel" Feynman diagrams,

e.g.: $B^0 \to K^{*+}\pi^-$, $B^0 \to K^{*0}\pi^0$, $B^+ \to K^{*+}\pi^0$, $B^+ \to K^{*0}\pi^+$

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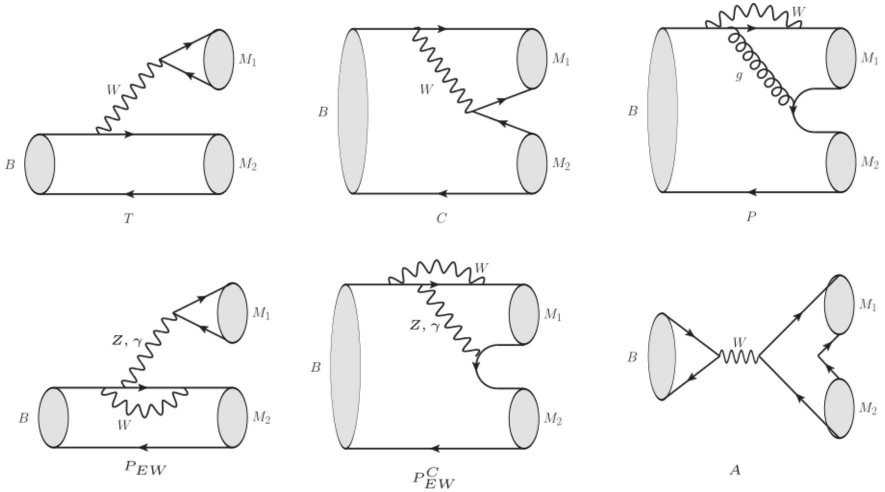

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$$\boxed{I_{K^*\pi} = \mathcal{A}^{CP}_{K^{*+}\pi^-} + \mathcal{A}^{CP}_{K^{*0}\pi^+} \frac{\mathcal{B}(K^{*0}\pi^+)}{\mathcal{B}(K^{*+}\pi^-)} \frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{B}^{CP}_{K^{*+}\pi^0} \frac{\mathcal{B}(K^{*+}\pi^0)}{\mathcal{B}(K^{*+}\pi^-)} \frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}^{CP}_{K^{*0}\pi^0} \frac{\mathcal{B}(K^{*0}\pi^0)}{\mathcal{B}(K^{*+}\pi^-)} \approx 0 \pm O(\text{few } \%)}$$

$B^0 \to K^+\pi^-\pi^0$

- K^* resonances are no stable particles, but they decay further to kaons and pions

$$B^0 \to \begin{cases} K^{*+}\pi^- \\ K^{*0}\pi^0 \end{cases}$$

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$$\begin{tikzcd}
 & K^{*+}\pi^- \arrow[dr] & \\
B^0 \arrow[ur] \arrow[r] & K^{*0}\pi^0 \arrow[r] & K^+\pi^-\pi^0
\end{tikzcd}$$

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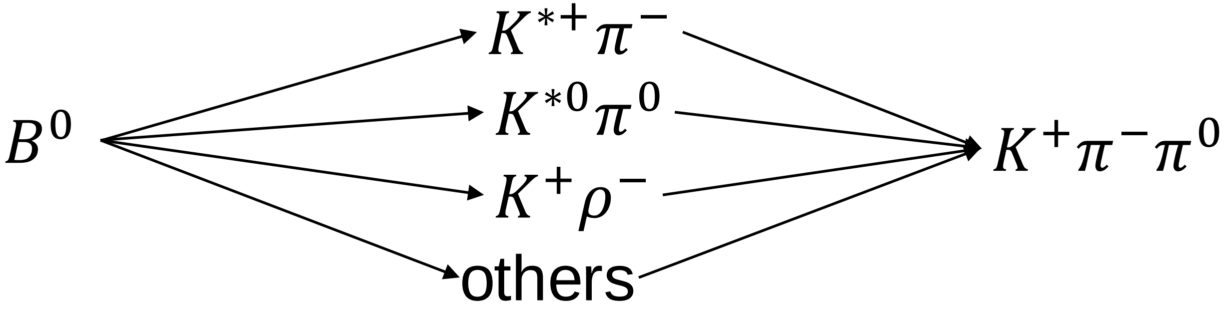

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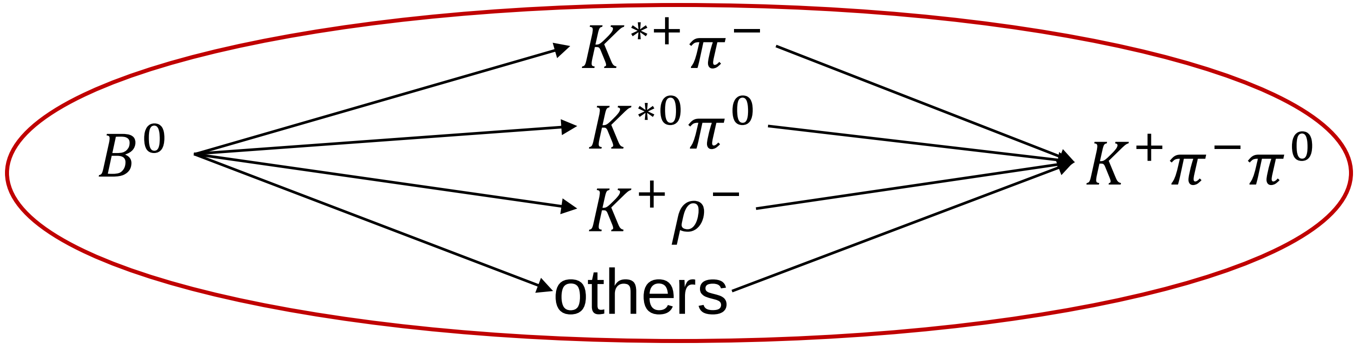

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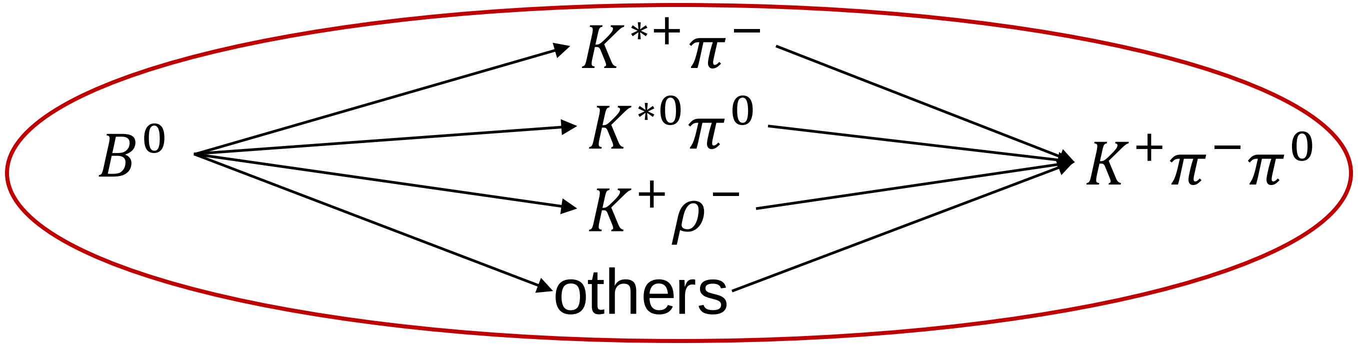

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magnitude and phase

!This is what we want to measure!

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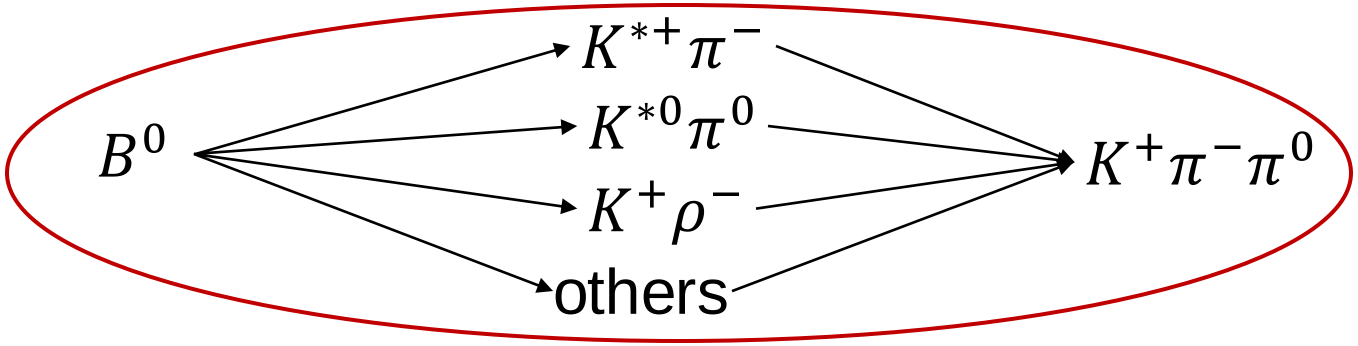

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$$\mathcal{A}_a^{CP}(r_a, \varphi_a)$$

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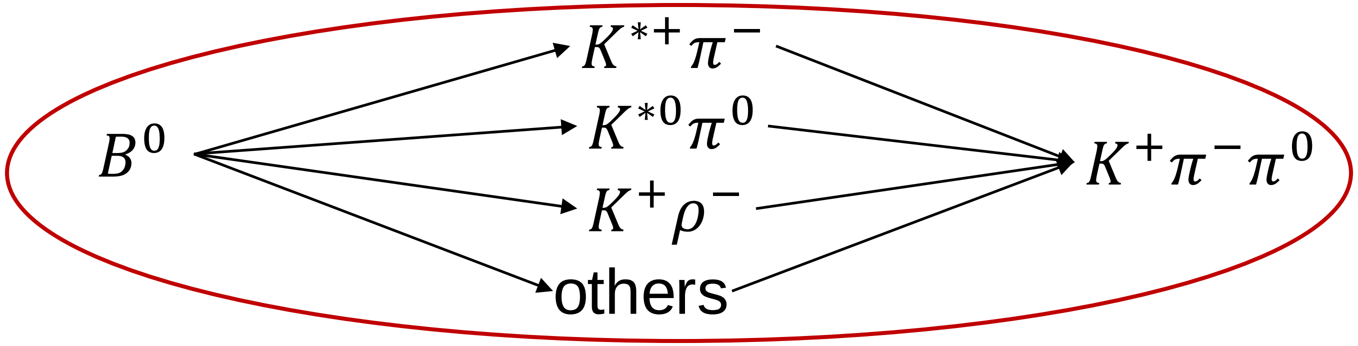

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$$I_{K^*\pi}$$

magnitude and phase

!This is what we want to measure!

Intensity (of $B^0 \to K^+\pi^-\pi^0$)

What we "see" is the intensity

$$\mathcal{I} = |A|^2 = \left|\sum_a A_a\right|^2 = \left|\sum_a r_a \cdot e^{i\cdot\varphi_a} \cdot \psi_a\right|^2$$

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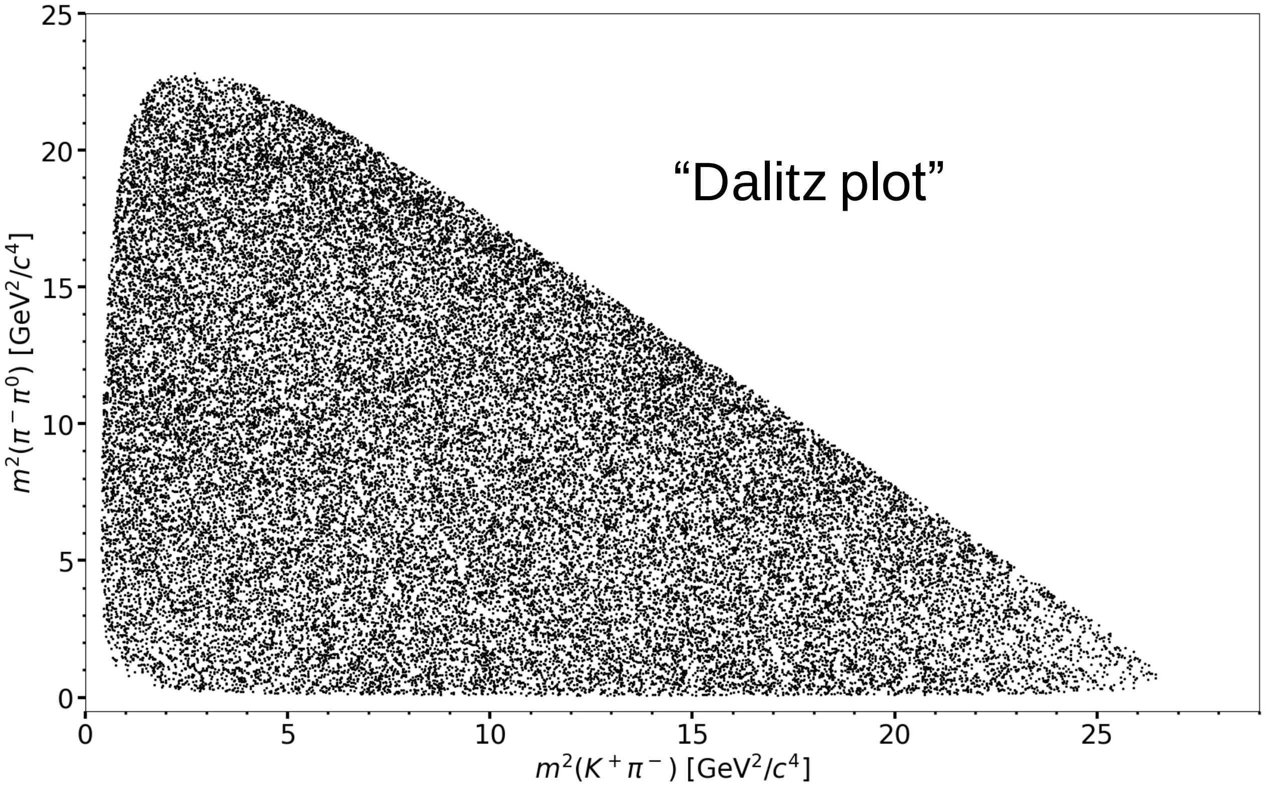

- $\mathcal{I}$ / A / ψ_a is only a function of two variables
- $m^2(K^+\pi^-)$ vs. $m^2(\pi^-\pi^0)$: Dalitz plot

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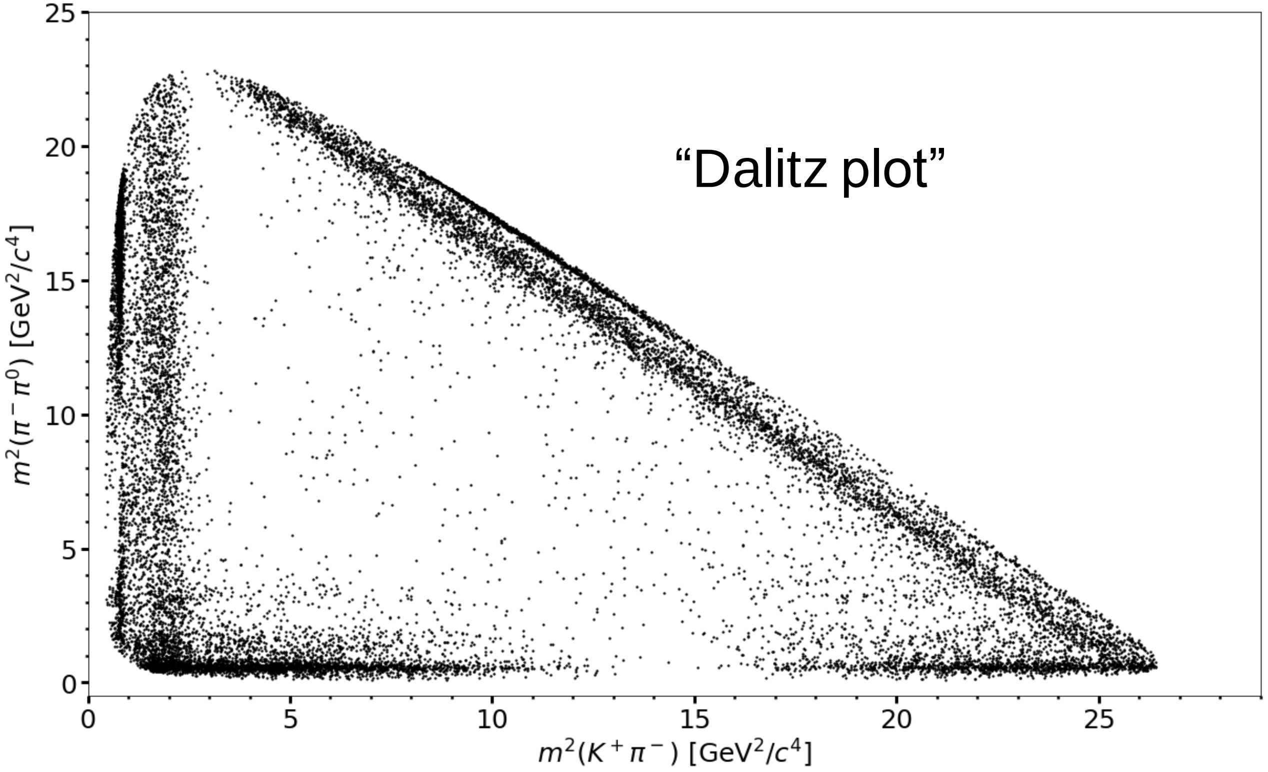
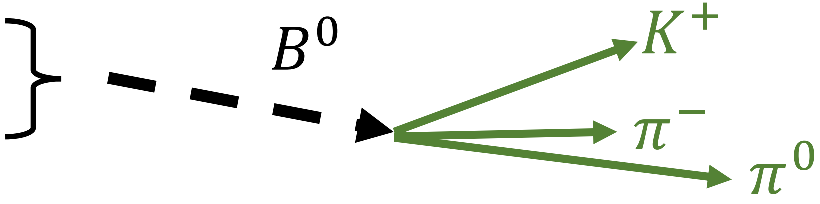


- $\mathcal{I}$ / A / ψ_a is only a function of two variables
- $m^2(K^+\pi^-)$ vs. $m^2(\pi^-\pi^0)$: Dalitz plot
- "real" Dalitz plot mostly empty
- resonances appear as "bands"

What we actually observe

- pure physics: $|A|^2$



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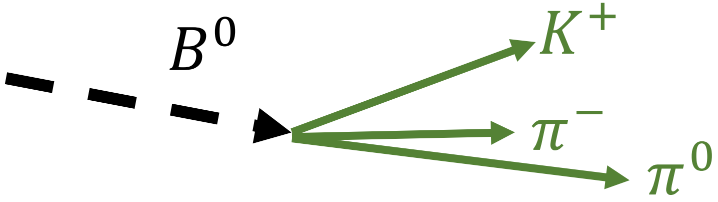
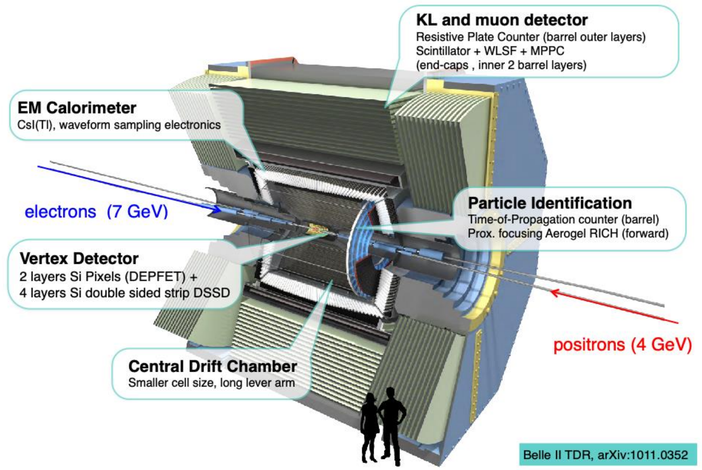
+

-

+

-





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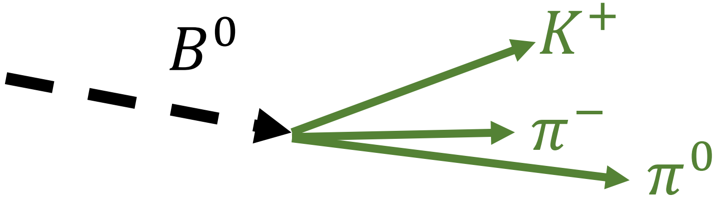
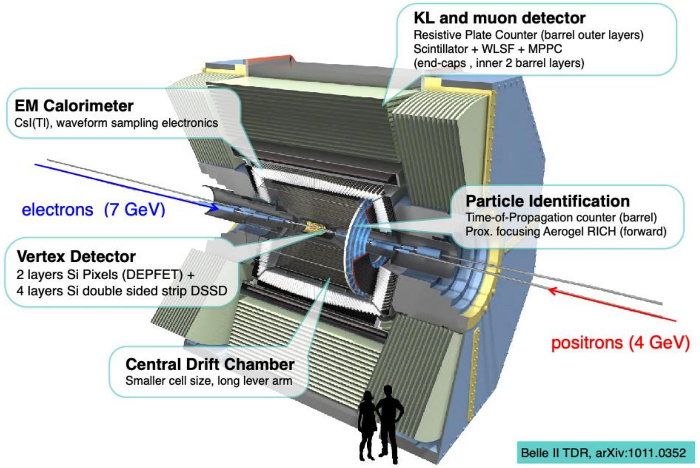


+

- acceptance/efficiency



+

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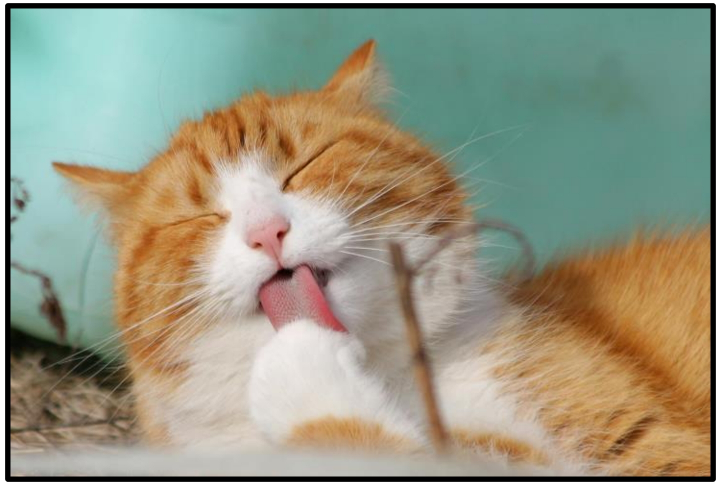
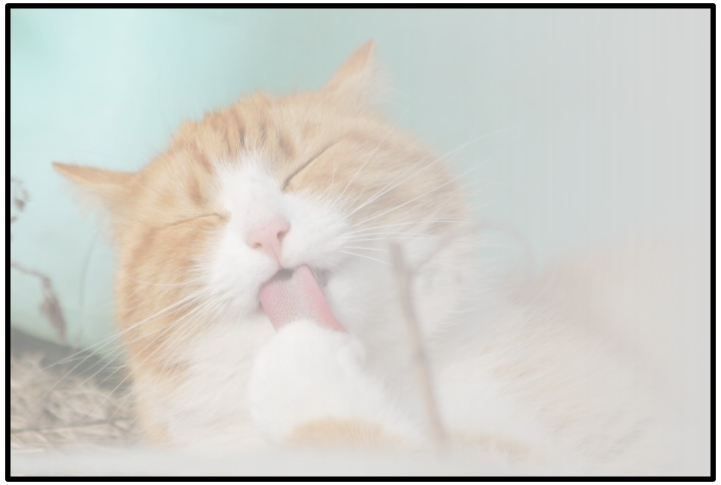


acceptance



What we actually observe

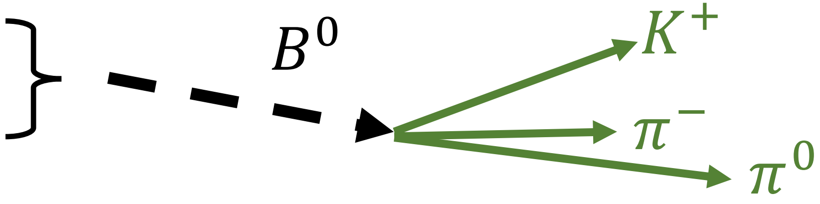
- pure physics: $|A|^2$

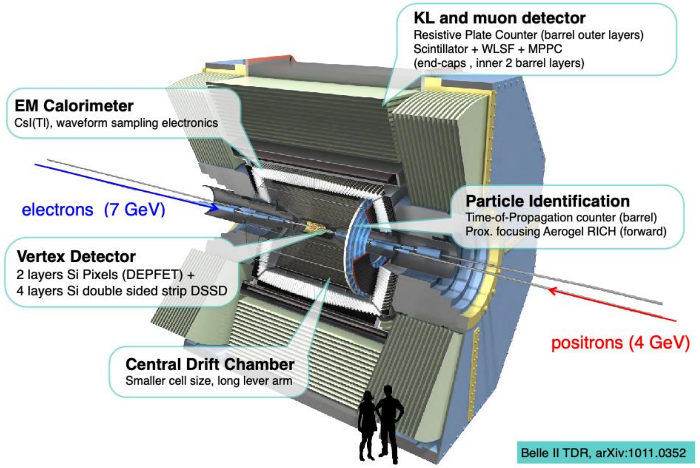
+

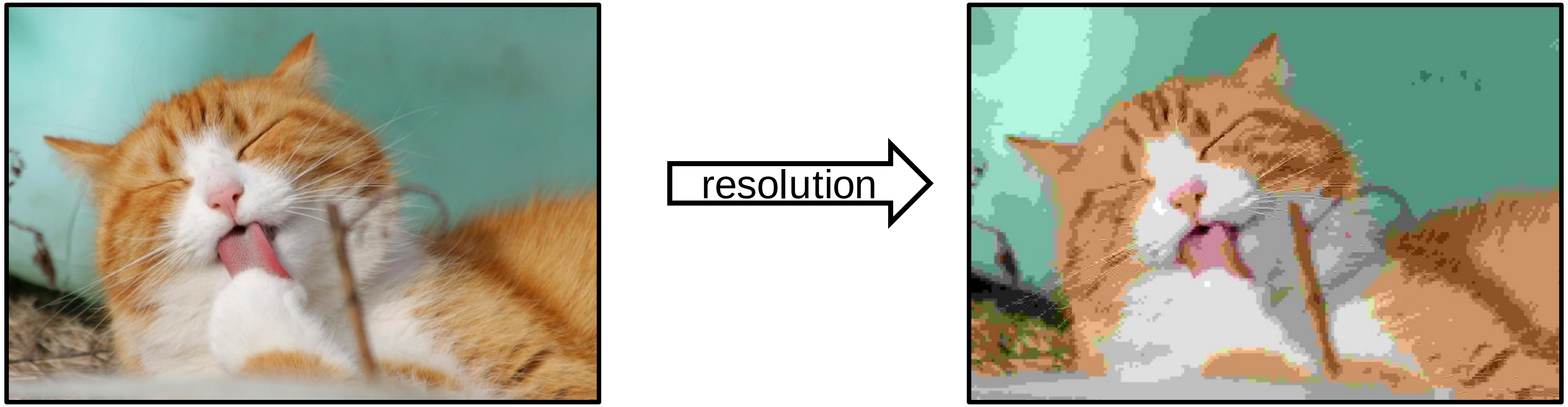
- acceptance/efficiency

+

- resolution

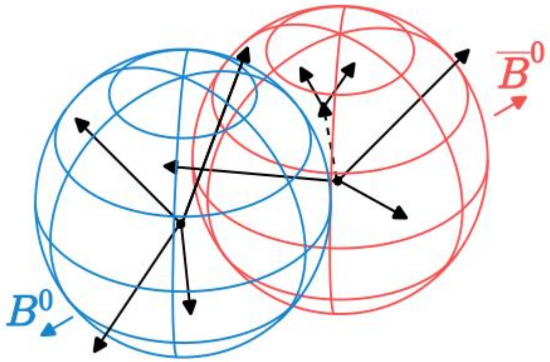






Backgrounds of $B^0 \rightarrow K^+\pi^-\pi^0$

- $B\bar{B}$: random combinations of $B\bar{B}$ decays, e.g. $B^+ \rightarrow \bar{D}^0[K^+\pi^-]\rho^+[\pi^0\pi^+]$



$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\overline{B}^0$

$$E_{e^+e^-} = \begin{bmatrix} b \\ \bar{b} \end{bmatrix}$$

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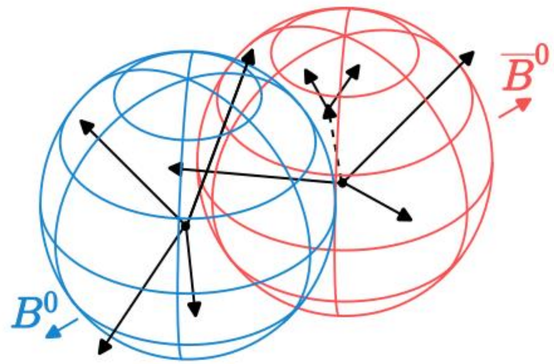
- $q\bar{q}$: continuum $e^+e^- \to u\bar{u},\ d\bar{d},\ s\bar{s},\ c\bar{c}$ about three times larger than $e^+e^- \to \Upsilon(4S) \to B\bar{B}$



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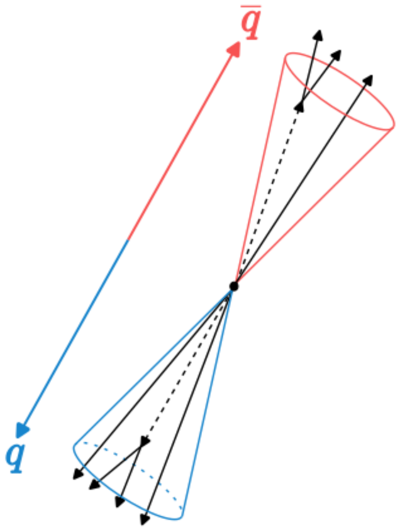

$e^+e^- \to q\bar{q}$

$$E_{e^+e^-} > \begin{bmatrix} u \\ \bar{u} \end{bmatrix}, \begin{bmatrix} d \\ \bar{d} \end{bmatrix}, \begin{bmatrix} s \\ \bar{s} \end{bmatrix}, \begin{bmatrix} c \\ \bar{c} \end{bmatrix}$$

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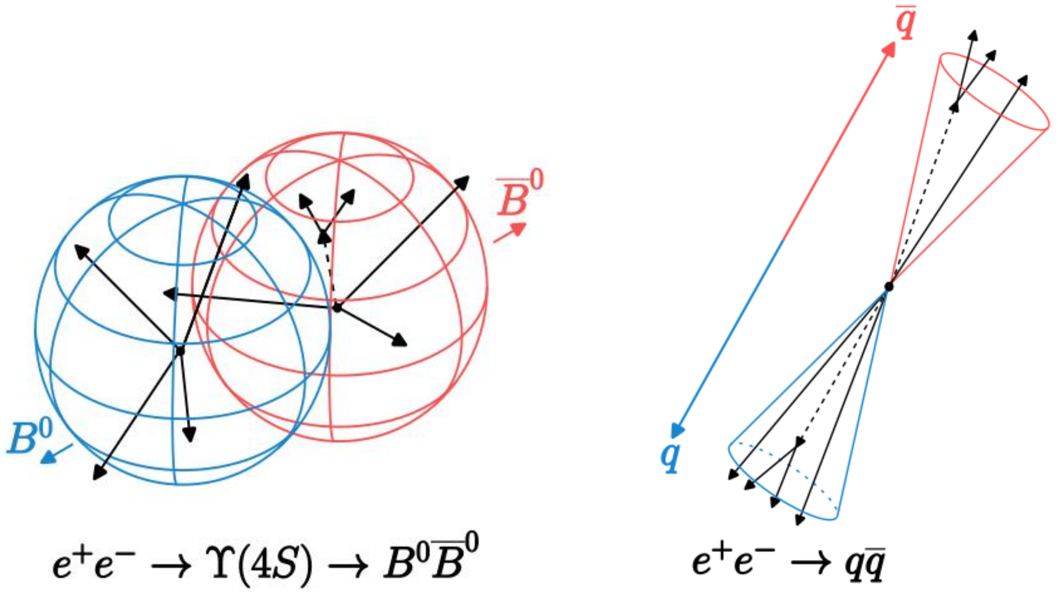

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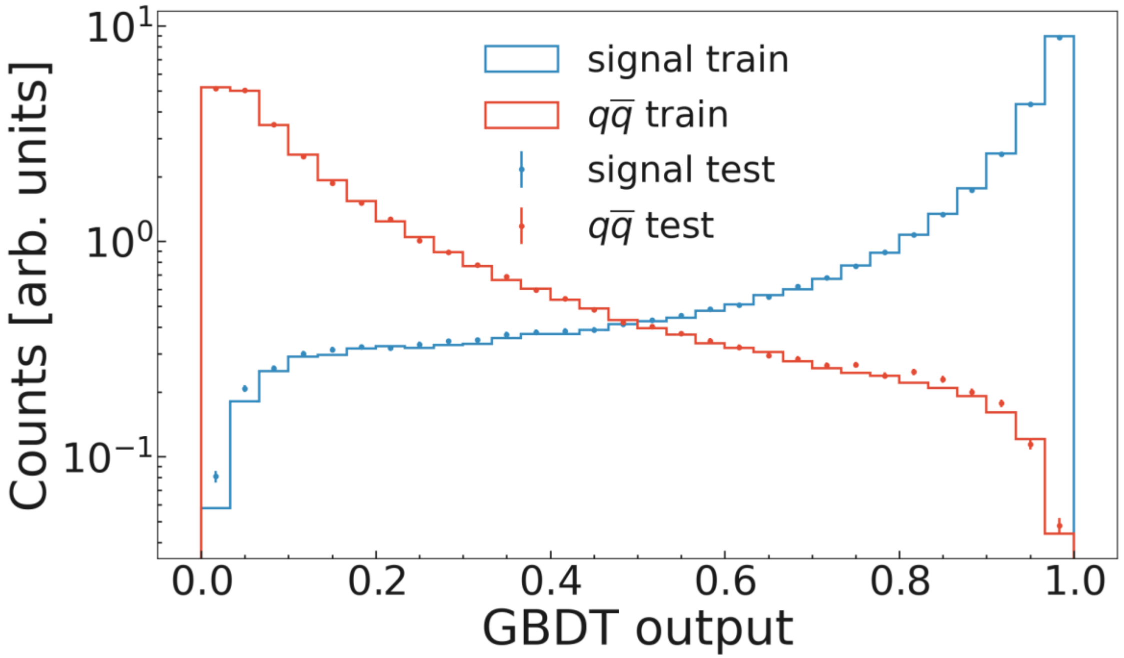
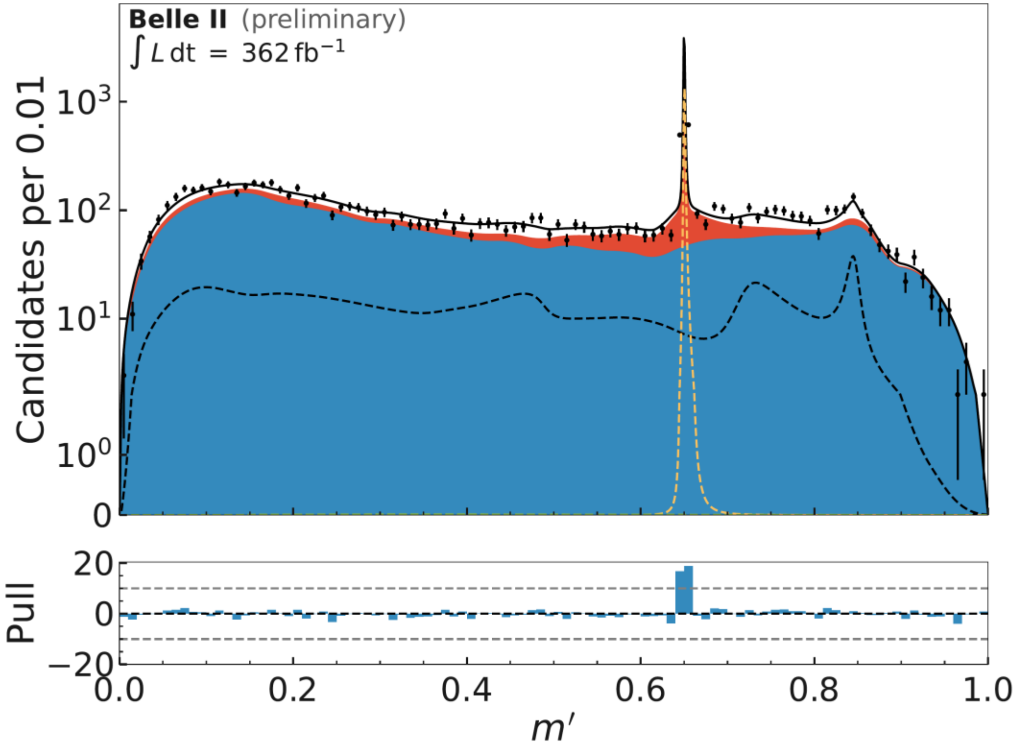
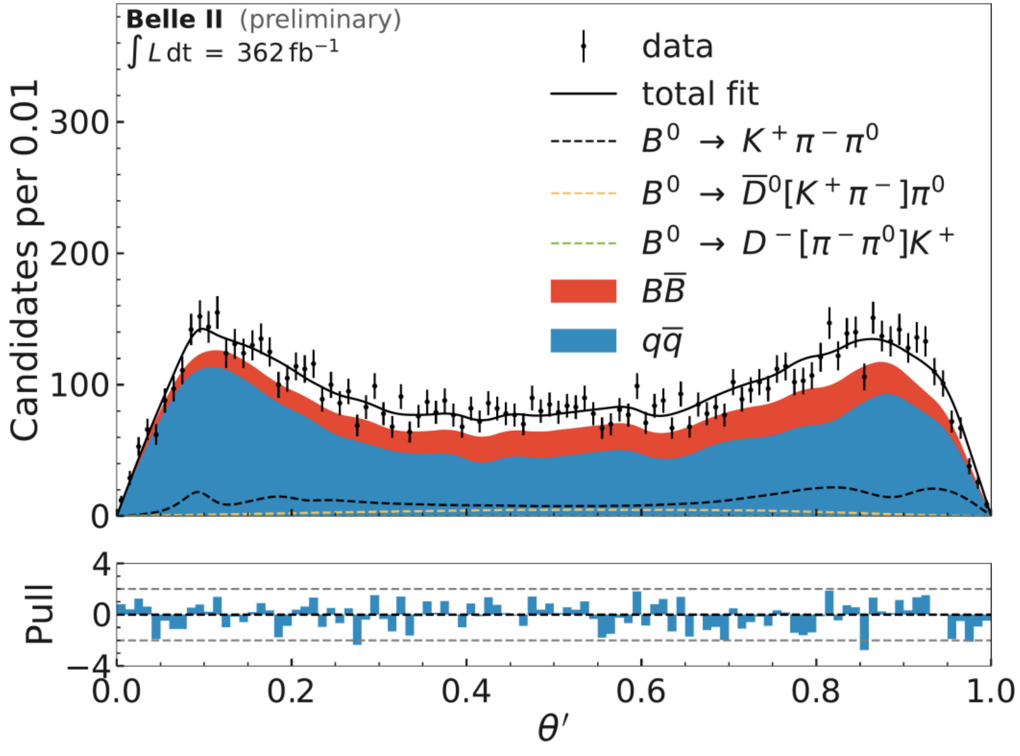


- exploit topological differences to train machine learning algorithm (GBDT)

Fit on Belle II Data



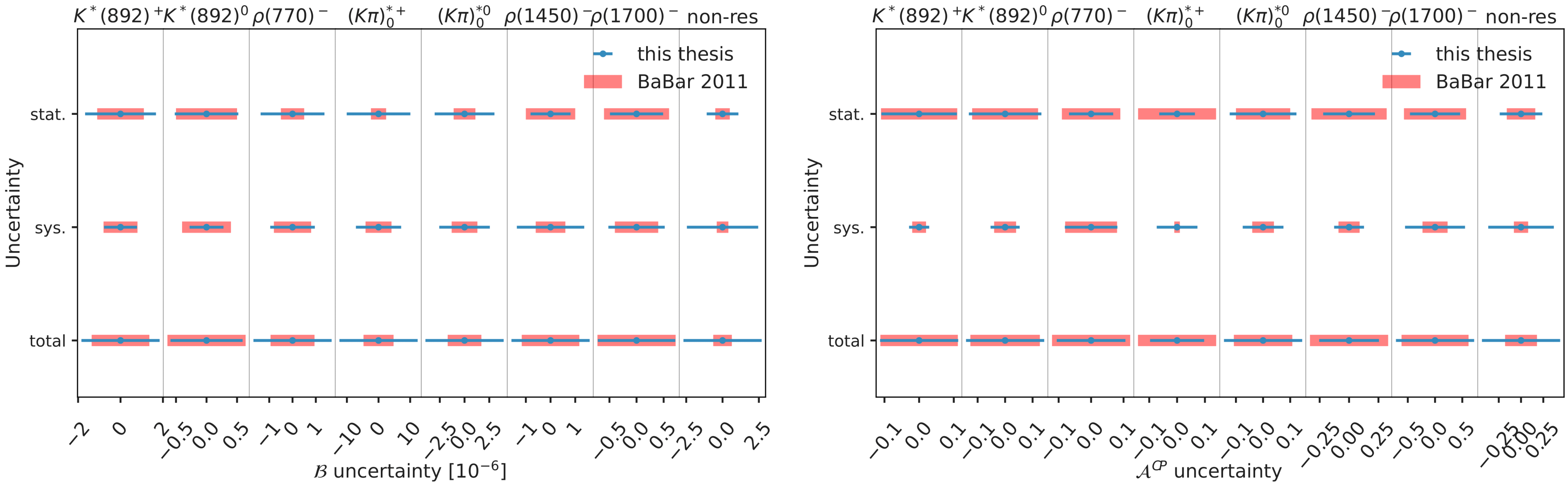
$(m^2(K^+\pi^-))$



$(m^2(\pi^-\pi^0))$

- fit projections in data look good
- central values of analysis were not unblinded, as I haven‘t gone through review

“Results”



- achieve precision on par with BaBar analysis despite using ~14% smaller dataset
- developed first Dalitz plot analysis within Belle II

Summary & Outlook

$$I_{K^*\pi} = A^{CP}_{K^{*+}\pi^-} + A^{CP}_{K^{*0}\pi^+} \frac{B(K^{*0}\pi^+)}{B(K^{*+}\pi^-)} \frac{\tau_{B^0}}{\tau_{B^+}} - 2A^{CP}_{K^{*+}\pi^0} \frac{B(K^{*+}\pi^0)}{B(K^{*+}\pi^-)} \frac{\tau_{B^0}}{\tau_{B^+}} - 2A^{CP}_{K^{*0}\pi^0} \frac{B(K^{*0}\pi^0)}{B(K^{*+}\pi^-)} \approx 0 \pm O(\text{few }\%)$$

- developed $B^0 \to K^+\pi^-\pi^0$ Dalitz plot analysis to provide two inputs for isospin sum rule
- other two channels in $B^+ \to K^0\pi^+\pi^0$ (fellow PhD student)
- we target the first measurement of the $K^*\pi$ isospin sum

Backup

Systematic Uncertainties 1

Source	$\mathcal{B}_{\text{inclusive}}$	$\mathcal{A}^{CP}_{\text{inclusive}}$
Fit bias	1.3%	< 0.001
Tracking efficiency	0.5%	-
$B\overline{B}$ pair counting	1.5%	-
f^{00}	2.5%	-
Continuum suppression efficiency	0.5%	-
PID efficiency	1.7%	0.001
π^0 efficiency	4.6%	0.001
Resonances lineshape parameters	1.0%	0.002
Amplitude model	4.2%	0.018
Continuum model	0.5%	0.001
$B\overline{B}$ model	0.4%	0.002
Total	7.3%	0.018

Resonance	Source	$\mathcal{B}$	$\mathcal{A}^{CP}$
	Fit bias	$< 0.1\%$	0.009
	Tracking	0.5%	-
	$B\overline{B}$ pair counting	1.5%	-
	f^{00}	2.5%	-
	Continuum suppression efficiency	0.5%	-
	PID efficiency	1.5%	0.002
$K^*(892)^+$	π^0 efficiency	1.5%	0.003
	Resonances lineshape parameters	3.6%	0.007
	Amplitude model	8.0%	0.026
	Continuum model	1.5%	0.004
	$B\overline{B}$ model	1.5%	0.003
	Total	9.7%	0.029
	Fit bias	1.2%	0.021
	Tracking	0.5%	-
	$B\overline{B}$ pair counting	1.5%	-
	f^{00}	2.5%	-
	Continuum suppression efficiency	0.5%	-
	PID efficiency	1.7%	0.004
$K^*(892)^0$	π^0 efficiency	1.2%	0.002
	Resonances lineshape parameters	2.7%	0.007
	Amplitude model	6.6%	0.048
	Continuum model	1.6%	0.004
	$B\overline{B}$ model	1.6%	0.003
	Total	8.4%	0.053

Systematic Uncertainties 2

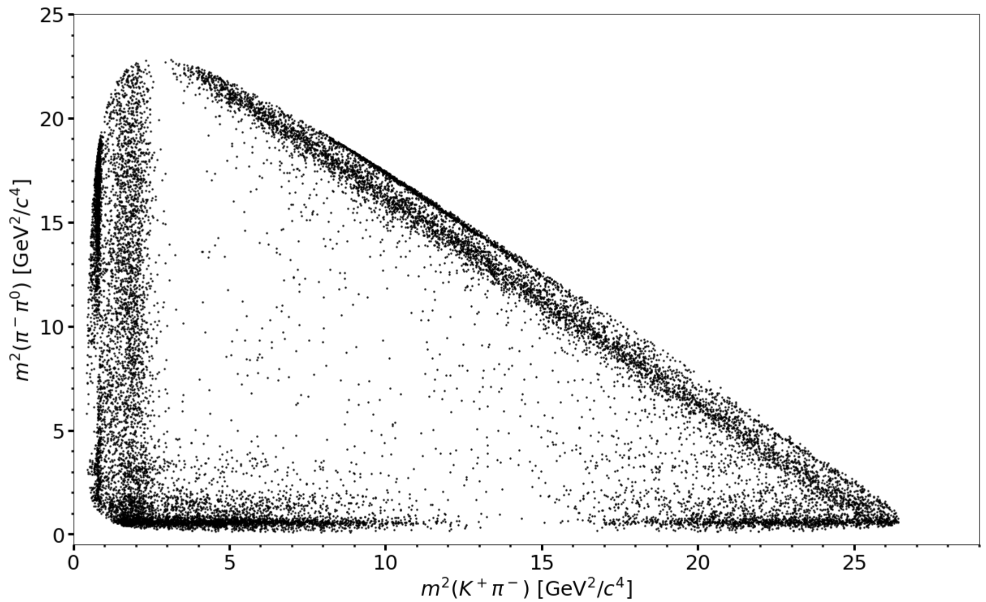
Resonance	Source	$\mathcal{B}$	$\mathcal{A}^{CP}$
	Fit bias	1.1%	0.016
	Tracking	0.5%	-
	$B\overline{B}$ pair counting	1.5%	-
	f^{00}	2.5%	-
	Continuum suppression efficiency	0.5%	-
	PID efficiency	1.0%	0.003
$\rho(770)^-$	π^0 efficiency	0.6%	0.005
	Resonances lineshape parameters	2.8%	0.012
	Amplitude model	13.8%	0.078
	Continuum model	0.7%	0.003
	$B\overline{B}$ model	0.6%	0.003
	Total	14.5%	0.081
	Fit bias	0.8%	< 0.001
	Tracking	0.5%	-
	$B\overline{B}$ pair counting	1.5%	-
	f^{00}	2.5%	-
	Continuum suppression efficiency	0.5%	-
	PID efficiency	1.1%	0.004
$(K\pi)_0^{*+}$	π^0 efficiency	0.8%	0.006
	Resonances lineshape parameters	20.3%	0.018
	Amplitude model	3.2%	0.070
	Continuum model	0.9%	0.006
	$B\overline{B}$ model	1.1%	0.007
	Total	20.9%	0.073

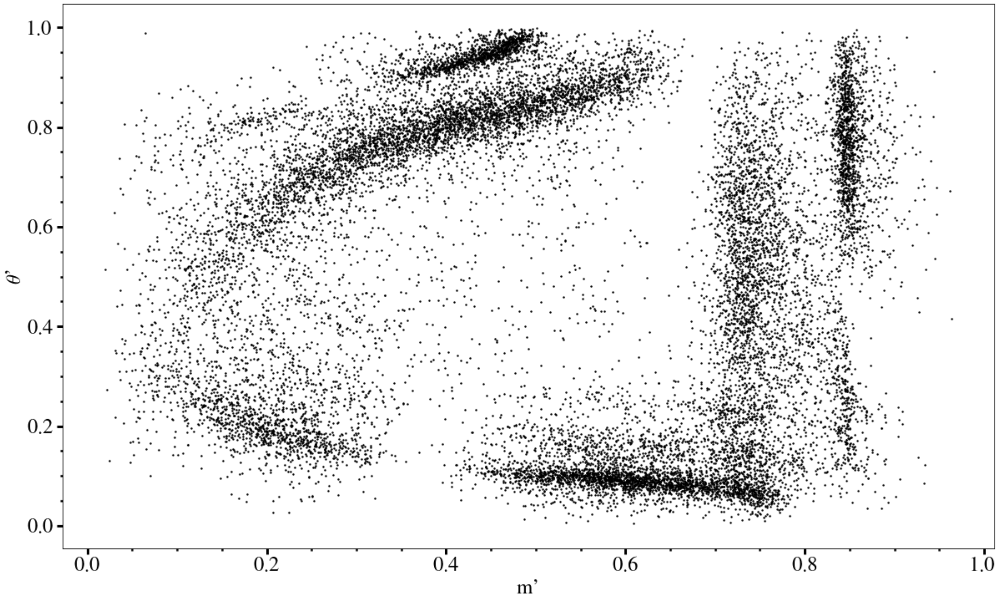
Resonance	Source	$\mathcal{B}$	$\mathcal{A}^{CP}$
	Fit bias	$< 0.1\%$	0.009
	Tracking	0.5%	-
	$B\overline{B}$ pair counting	1.5%	-
	f^{00}	2.5%	-
	Continuum suppression efficiency	0.5%	-
	PID efficiency	2.1%	
$(K\pi)_0^{*0}$	π^0 efficiency	1.0%	0.011
	Resonances lineshape parameters	22.4%	0.020
	Amplitude model	19.0%	0.070
	Continuum model	1.0%	0.009
	$B\overline{B}$ model	1.0%	0.009
	Total	29.7%	0.075
	Fit bias	6.0%	0.036
	Tracking	0.5%	-
	$B\overline{B}$ pair counting	1.5%	-
	f^{00}	2.5%	-
	Continuum suppression efficiency	0.5%	-
	PID efficiency	1.8%	0.007
$\rho(1450)^-$	π^0 efficiency	2.3%	0.015
	Resonances lineshape parameters	19.0%	0.101
	Amplitude model	52.7%	0.063
	Continuum model	4.3%	0.015
	$B\overline{B}$ model	3.7%	0.014
	Total	56.8%	0.127

Systematic Uncertainties 3

Resonance	Source	$\mathcal{B}$	$\mathcal{A}^{CP}$
$\rho(1700)^-$	Fit bias	13.2%	0.062
	Tracking	0.5%	-
	$B\overline{B}$ pair counting	1.5%	-
	f^{00}	2.5%	-
	Continuum suppression efficiency	0.5%	-
	PID efficiency	4.1%	0.021
	π^0 efficiency	4.1%	0.037
	Resonances lineshape parameters	84.5%	0.154
	Amplitude model	10.5%	0.521
	Continuum model	3.8%	0.033
	$B\overline{B}$ model	3.5%	0.017
	Total	86.6%	0.550
non-resonant	Fit bias	8.5%	0.026
	Tracking	0.5%	-
	$B\overline{B}$ pair counting	1.5%	-
	f^{00}	2.5%	-
	Continuum suppression efficiency	0.5%	-
	PID efficiency	2.8%	0.037
	π^0 efficiency	2.4%	0.046
	Resonances lineshape parameters	22.3%	0.129
	Amplitude model	83.9%	0.334
	Continuum model	5.2%	0.040
	$B\overline{B}$ model	4.3%	0.037
	Total	87.6%	0.368

The Square Dalitz Plot





Square Dalitz plot

- events are clustered at edges
- Dalitz plot has ‘triangularish’ shape

➢ events are spread out

➢ phase space occupies a square