Early Charmless B Decay Results from Belle II

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on behalf of the Belle II Collaboration

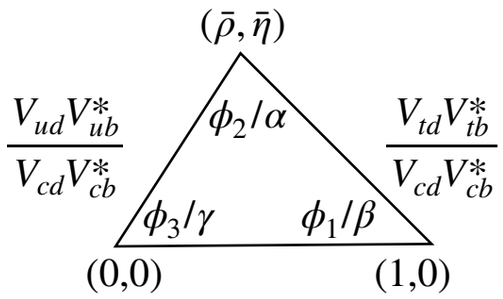
Epiphany 2021

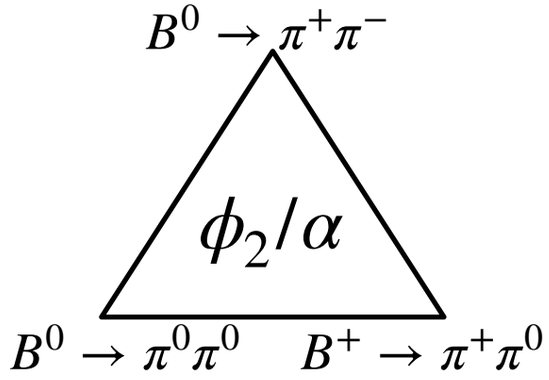
國立臺灣大學
National Taiwan University

Hadronic Charmless B decays

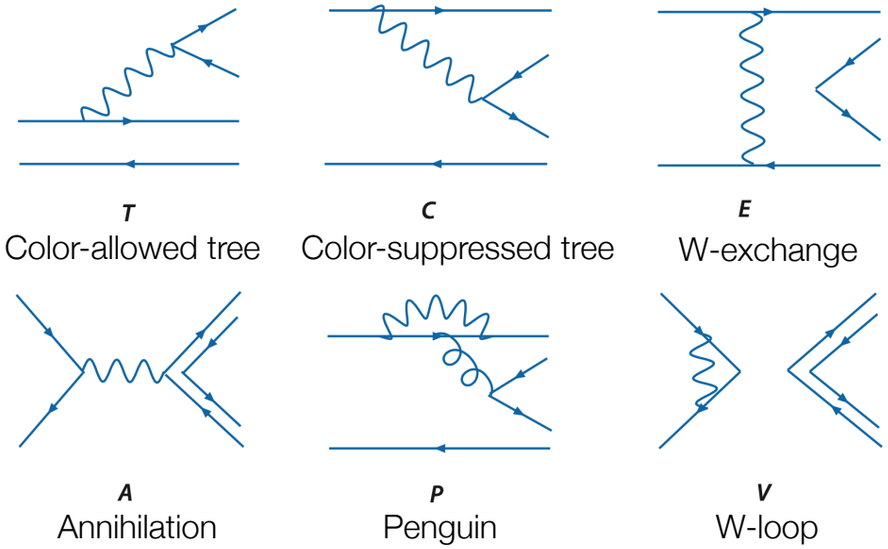
SM

- **Precise measurement of flavor physics (CKM angle)**

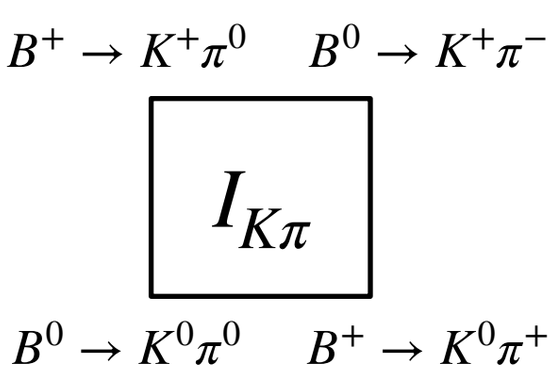




Dominant amplitudes of charmless B decays



- **Sum rule test**



NP? (New Physics)

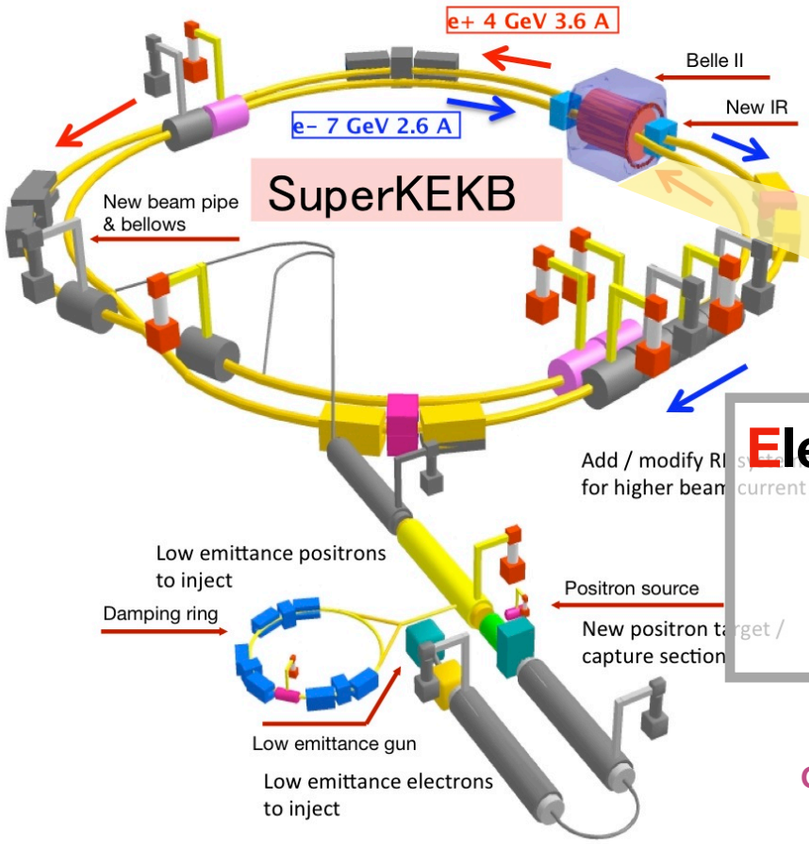
- $b \to s$ **loop diagram + time dependent CP violation analysis:** $B^0 \to \phi K_S^0$

- **Three-body Dalitz analysis: local CP asymmetries**

- **Belle II strength: high luminosity + neutral final states**
  (c.f. LHCb)

Introduction

SuperKEKB & Belle II detector



Belle II detector

Electromagnetic CaLorimeter

$$(\frac{\sigma_E}{E} = \frac{0.2\,\%}{E} \oplus \frac{1.6\,\%}{\sqrt[4]{E}} \oplus 1.2\%)$$

γ, π^0 reconstruction

$e^{\pm}$ identification

K_L and Muon detector

$(\sigma_p/p \approx 18\%)$

K_L / μ identification

Time-of-Propagation counter

($\epsilon > 99\,\%$ at $< 0.5\,\%$ π fake prob.)

Particle identification

on $\Upsilon(4S)$ resonance

7 GeV e^-

on $\Upsilon(4S)$ resonance

4 GeV e^+

Vertex Detector

$(\sigma_{z_0} = 20\ \mu\mathrm{m})$

2 layers DEPFET + 4 layers DSSD

B vertex determination

~7 m

Aerogel RICH

($\epsilon \sim 96\,\%$ at $< 1\,\%$ π fake prob.)

Particle identification

Central Drift Chamber

$$(\sigma_{p_t}/p_t = \sqrt{(0.2\,\%\, p_t)^2 + (0.3\,\%/\beta)^2}$$

$\sigma_{dE/dx} = 5\%)$

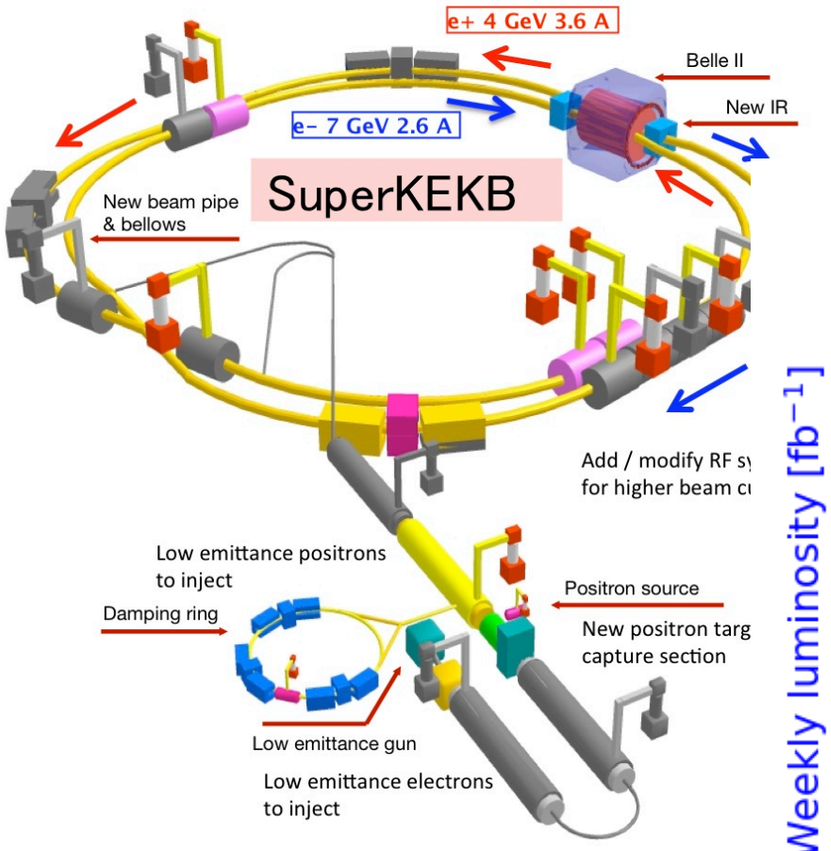
Charged track momentum

Particle identification

(for details see backup)

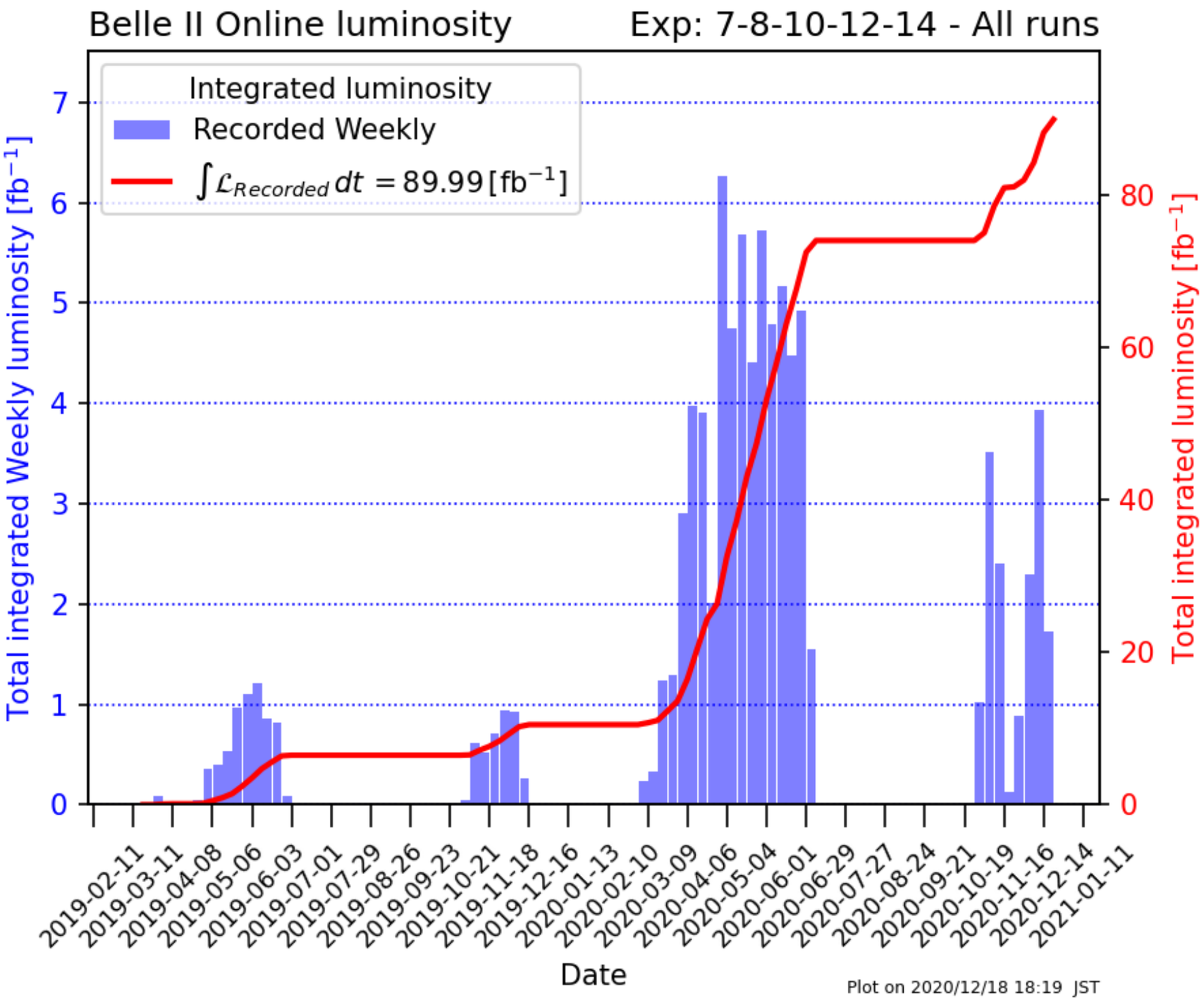
Introduction

Current integrated luminosity



World record

$L_{\text{peak}} \approx 2.4 \times 10^{-34}\ \text{cm}^{-2}\text{s}^{-1}$



Charmless B decays at Belle II

$\int Ldt = 34.6\ \mathrm{fb}^{-1}$ good-quality skimmed data collected in 2019 - 2020 summer

arXiv: 2009.09452

- **Two-body**
  - Two tracks:
    $B^0 \to K^+\pi^-, B^0 \to \pi^+\pi^-$
  - Decays with π^0:
    $B^+ \to K^+\pi^0, B^+ \to \pi^+\pi^0$
  - K^0_S benchmarking:
    $B^+ \to K^0\pi^+, B^0 \to K^0\pi^0$
- **Three-body:**
  $B^+ \to K^+K^-K^+$,
  $B^+ \to K^+\pi^-\pi^+$

arXiv: 2008.03873

- ***B → VP*:**
  $B^+ \to \phi K^+, B^0 \to \phi K^0$
- ***B → VV*:**
  $B^+ \to \phi K^{*+}, B^0 \to \phi K^{*0}$

Analysis strategy

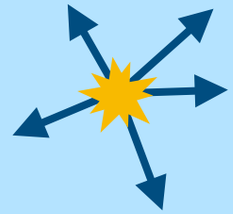
Selections

- Charged tracks: impact parameter + PID
- π^0 (2 γ with $E_\gamma > 20$ MeV): $M(\gamma\gamma)$ + helicity angle
- K^0_S ($\pi^+\pi^-$ from the same vertex): $|\vec{p}(K^0_S)|$ + flight distance
- Peaking-background veto for three-body final states

Challenge

Continuum suppression

$|\vec{p}(B)| \approx 0.3$ GeV/c



Spherical

$e^+e^- \to \Upsilon(4S) \to B\bar{B}$

$|\vec{p}(q)| \approx 5$ GeV/c

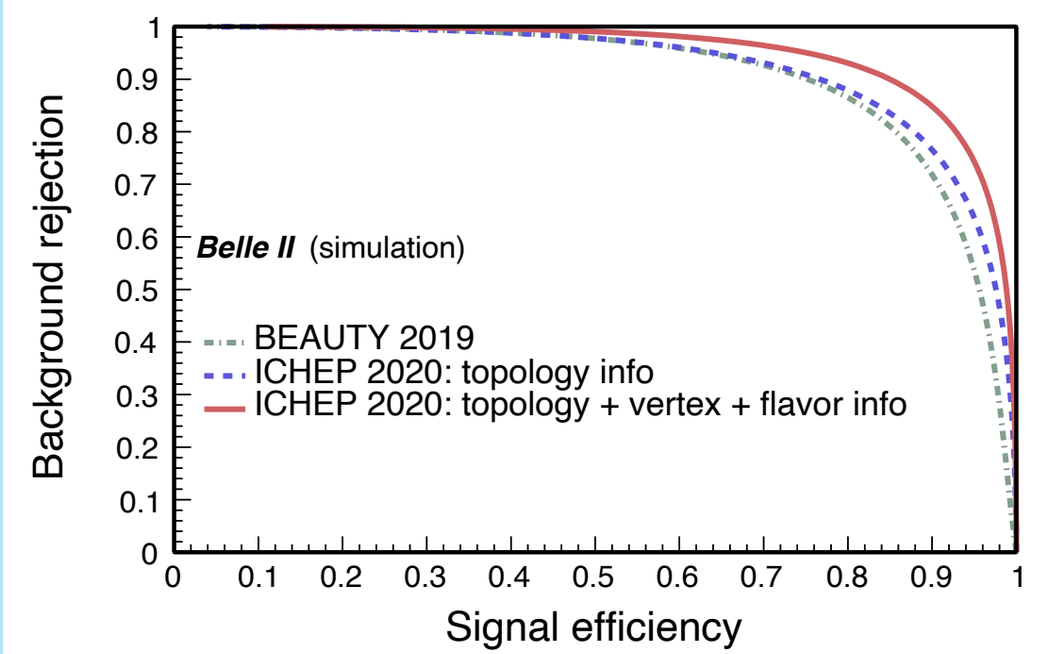
Jet-like

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

Multivariate algo. w/ training inputs:

event topology — flavor tagging

vertex information — kinematic fit



Signal extraction (Unbinned maximum likelihood fit)

Analysis strategy

Selections

Continuum suppression

Signal extraction (Unbinned maximum likelihood fit)

Energy difference: $\Delta E \equiv E_B^* - \sqrt{s}/2$

Beam-energy-constrained mass:

$$M_{bc} \equiv \sqrt{s/(4c^4) - (p_B^*/c)^2}$$

- **For 2- & 3-body K/π modes:**

  ΔE fits with signal region: $M_{bc} > 5.27\ \mathrm{GeV}/c^2$

- **For $B \to VP, B \to VV$:**

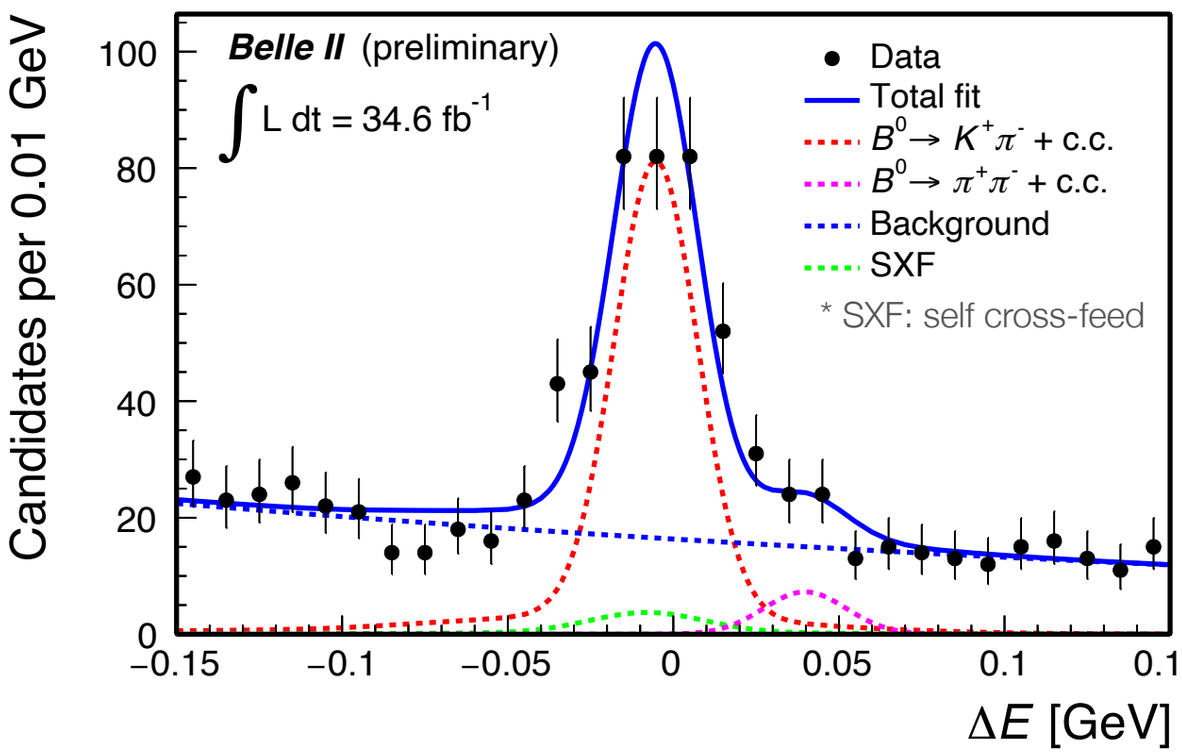
  Multidimensional fits on $M_{bc}, \Delta E$

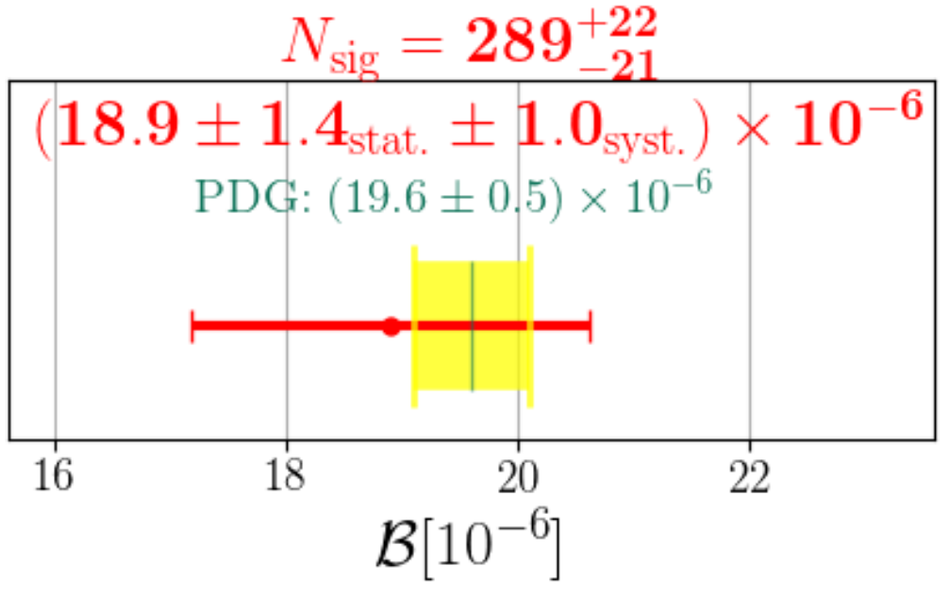
  C'_{out} (transformed continuum-suppression output)

  $m(K^+K^-), m(K\pi)$ (invariant masses)

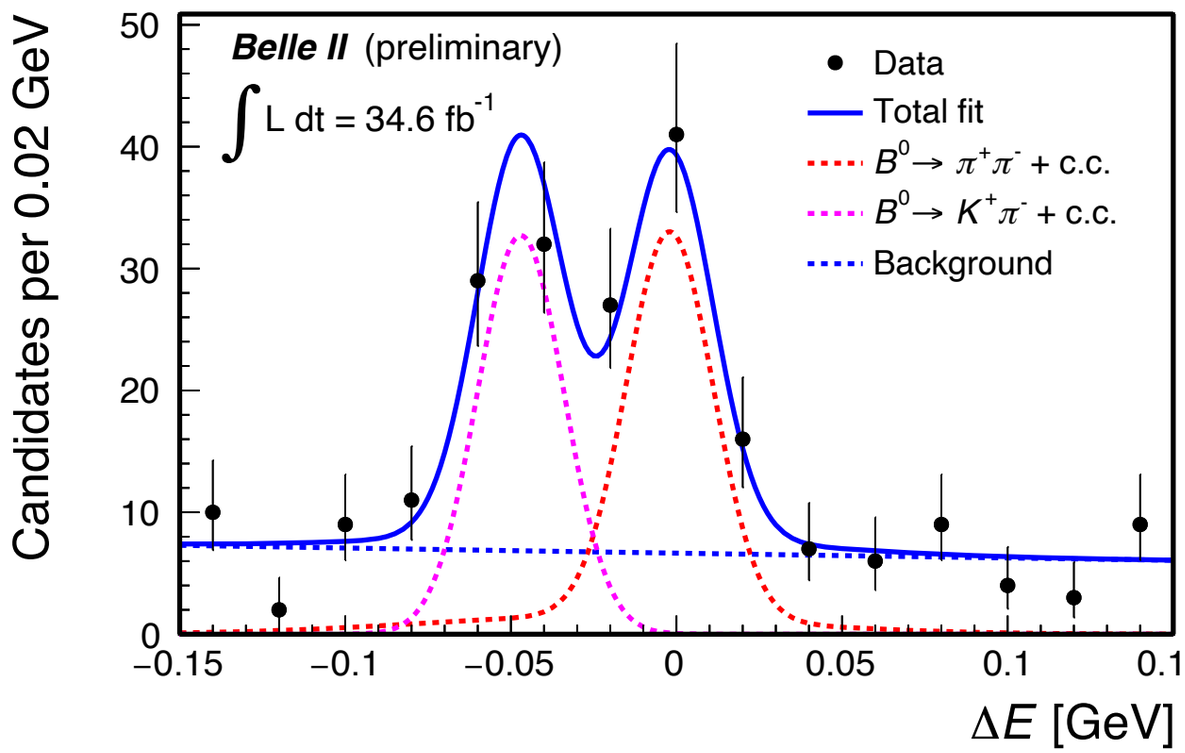
  $\cos\theta_{H,\phi}, \cos\theta_{H,K^*}$ (cosines of helicity angle)

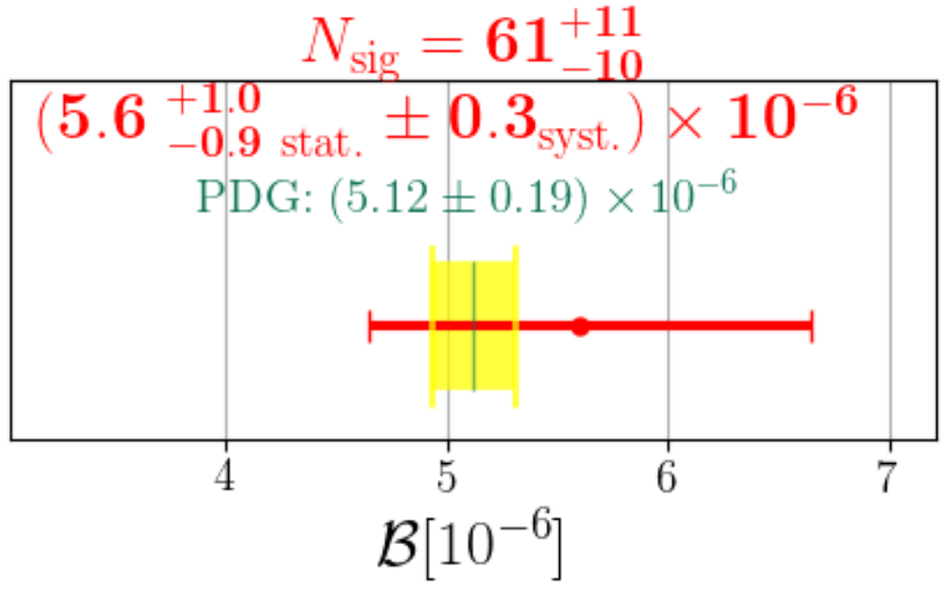
$B^0 \to K^+\pi^-$





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



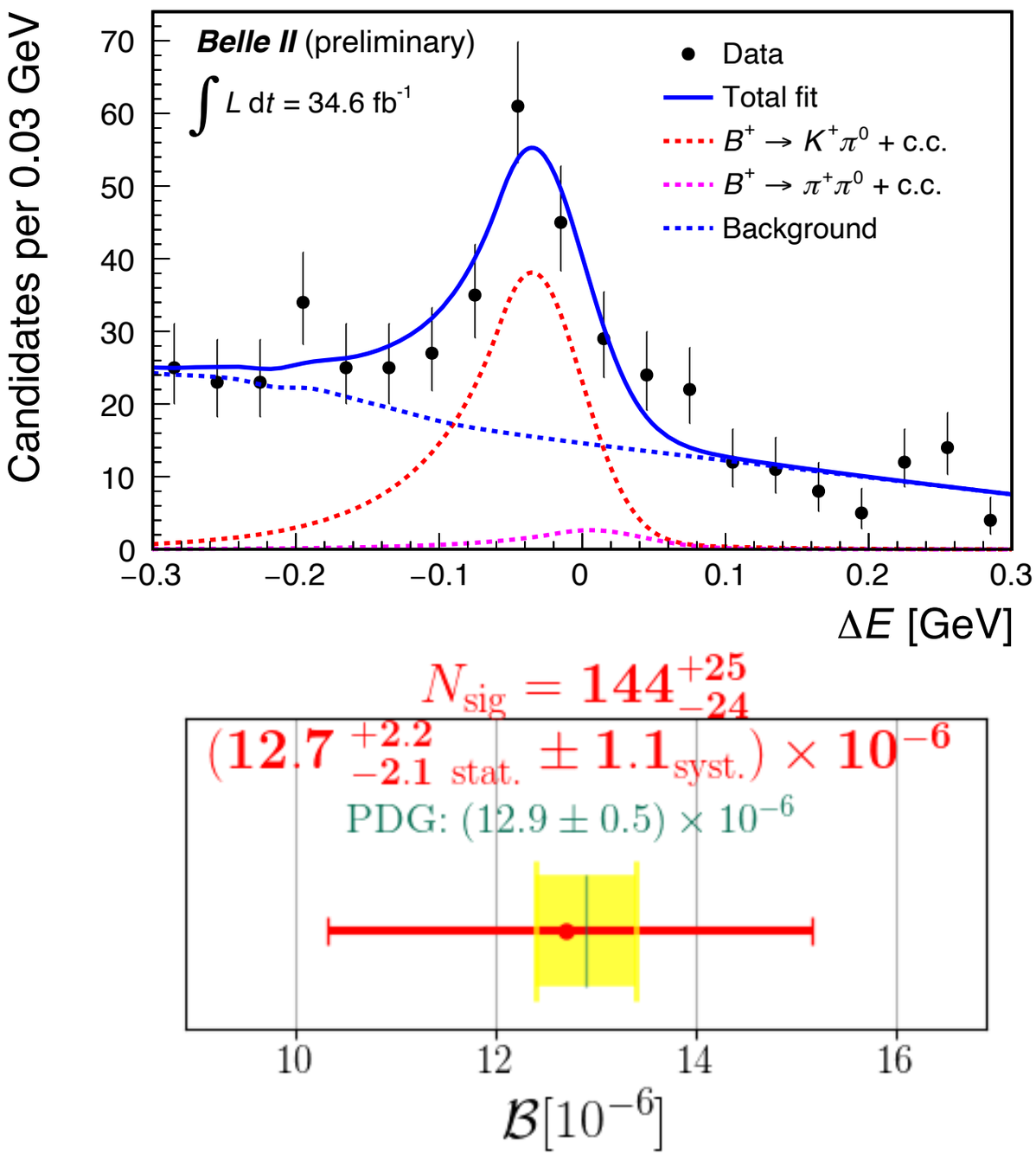


Effective hadron identification

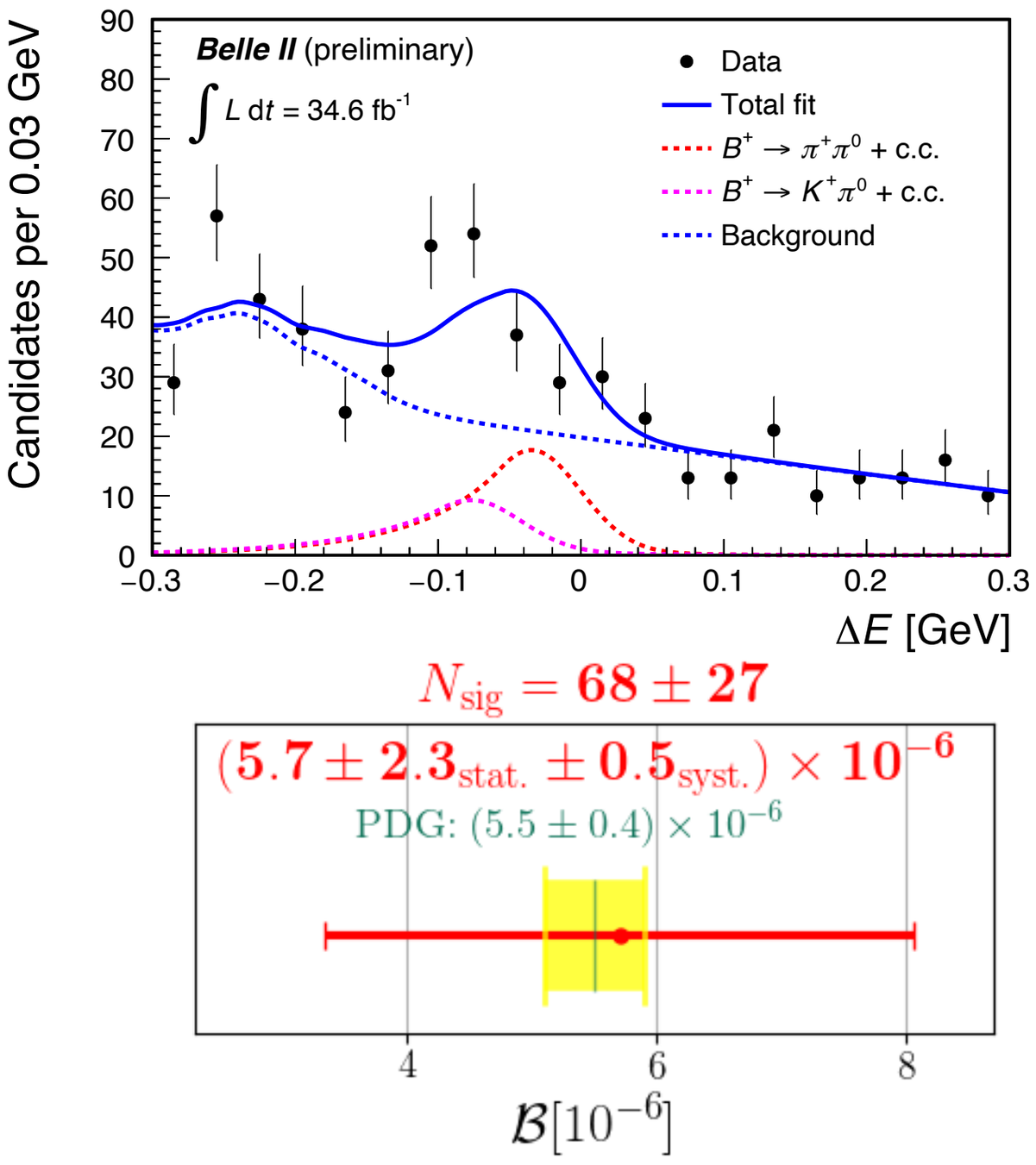
Branching fractions

First reconstruction in Belle II

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



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



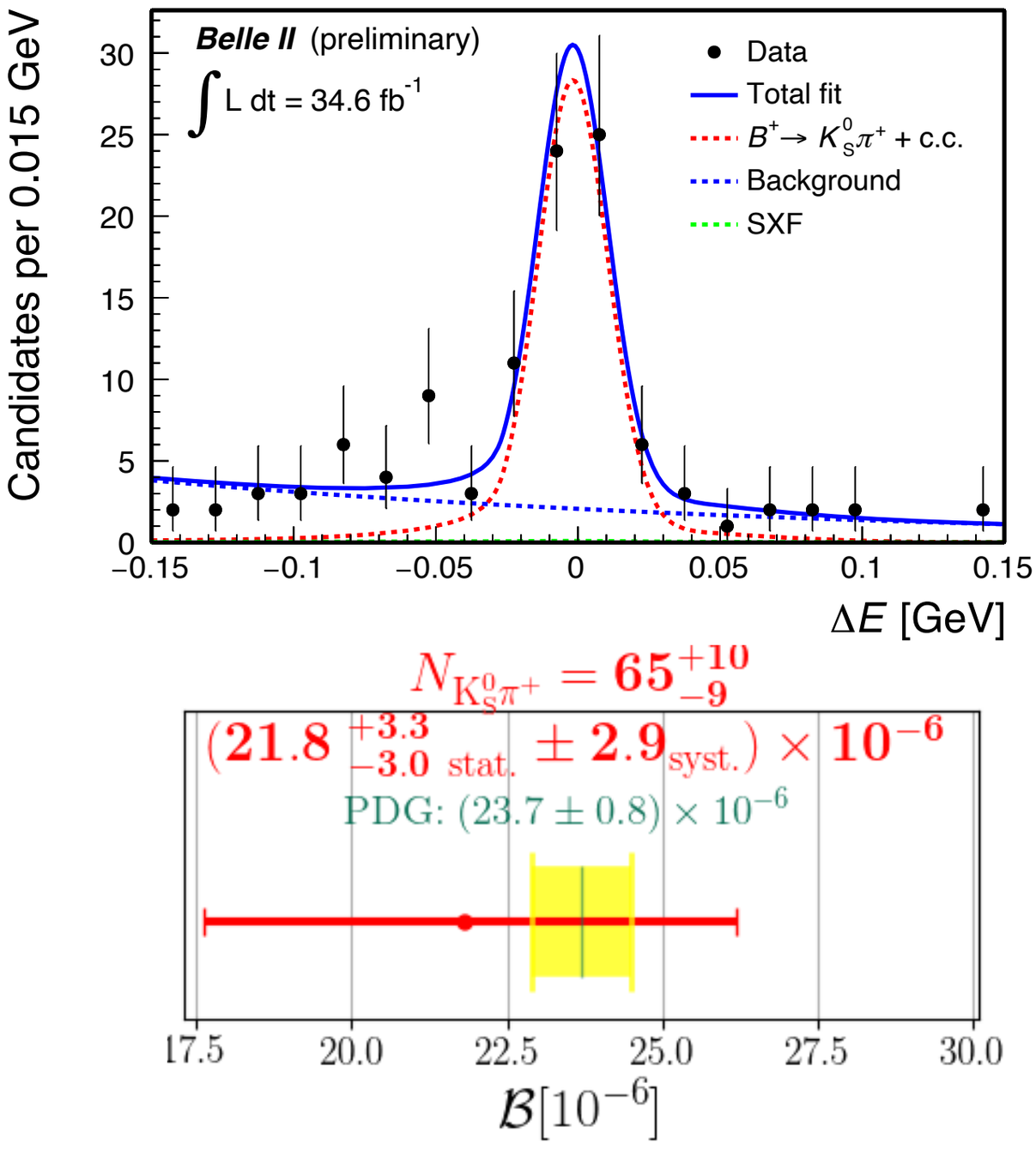
π^0 reconstruction

π^0 mass plot can be checked in backup

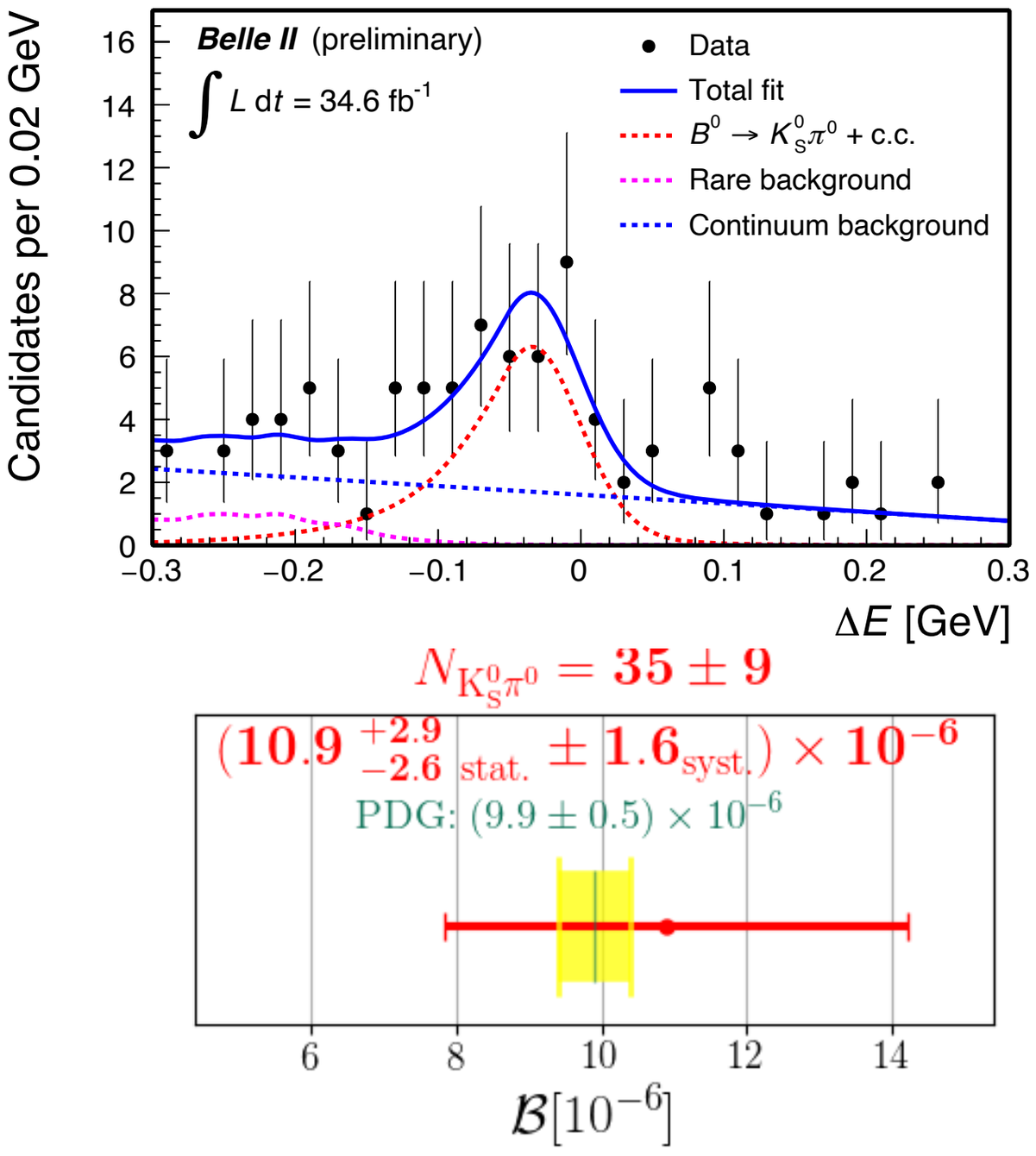
Branching fractions

First reconstruction in Belle II

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



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

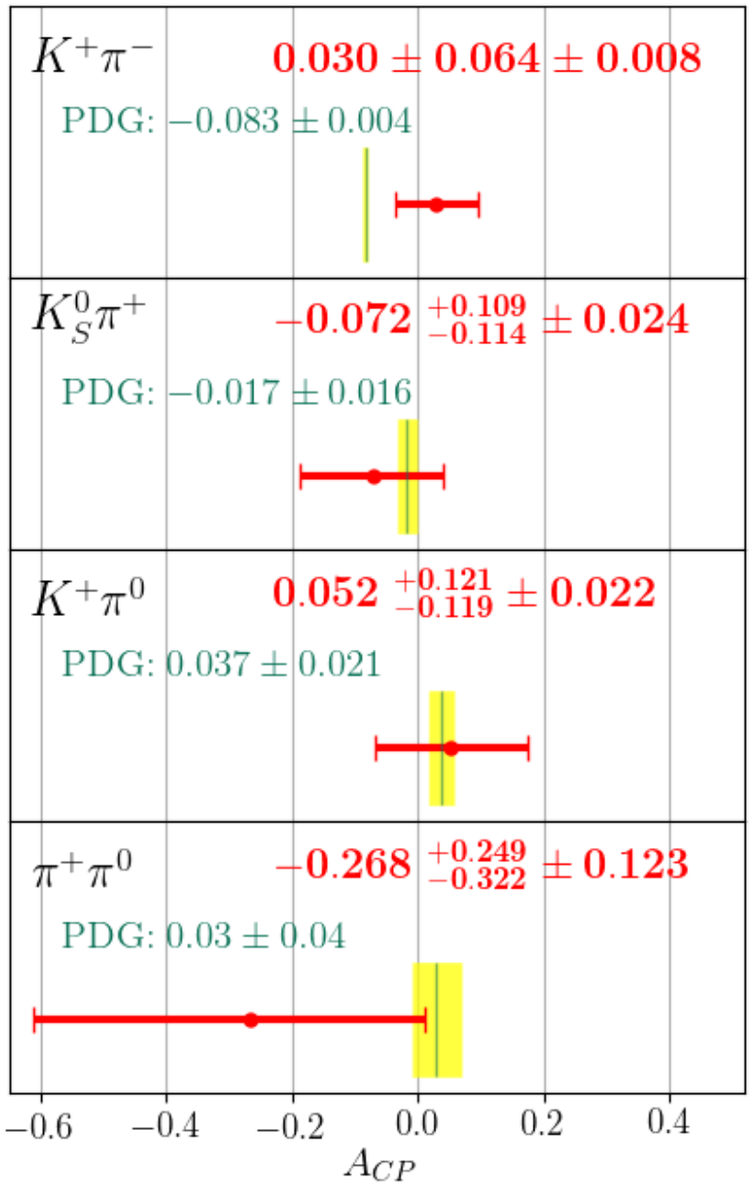


K^0_S reconstruction

K^0_S mass plot can be checked in backup

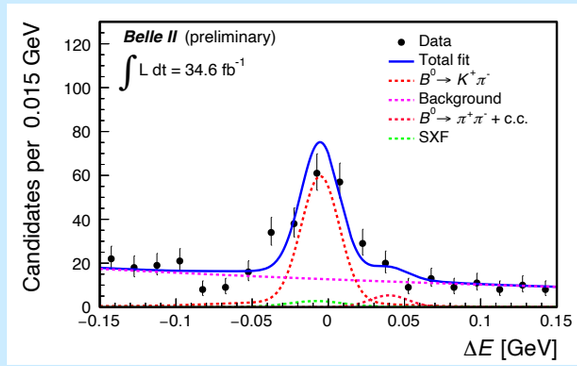
Two-body CP asymmetries

$$A_{\text{raw}} = \frac{N(b) - N(\bar{b})}{N(b) + N(\bar{b})} = A_{CP} + A_{\text{det}}$$

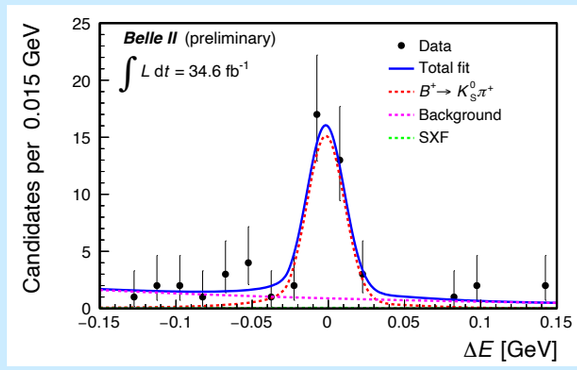


Instrumental asymmetries constrained from data

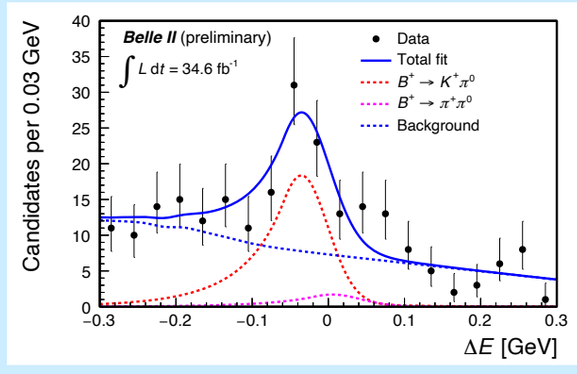
$B^+(B^0)$ decays



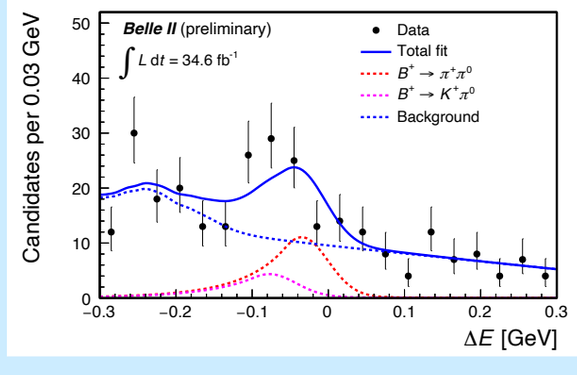
$B^0 \to K^+\pi^-$



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

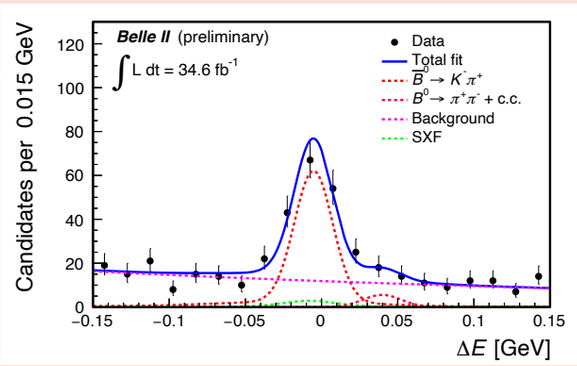


$B^+ \to K^+\pi^0$

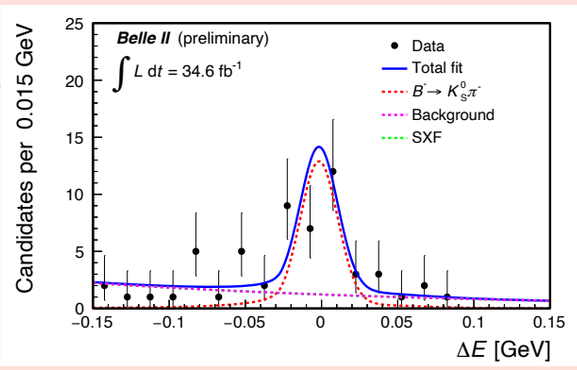


$B^+ \to \pi^+\pi^0$

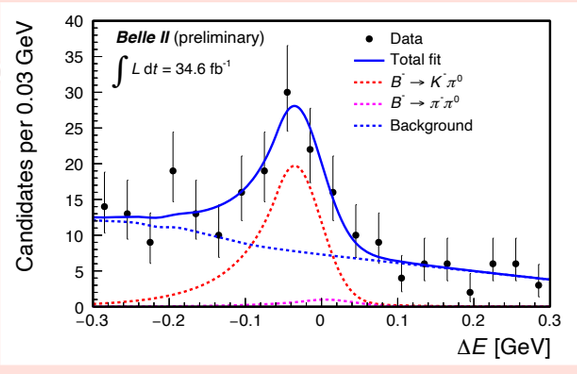
$B^-(\bar{B}^0)$ decays



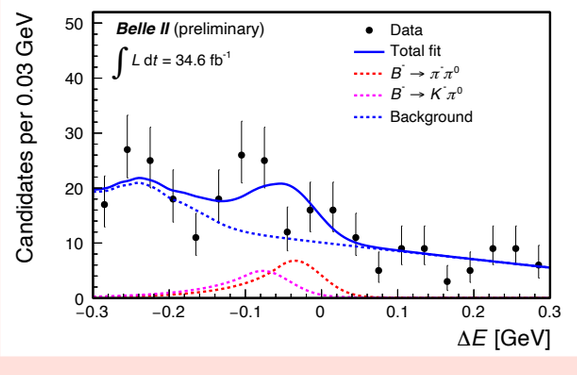
$B^0 \to K^+\pi^-$



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



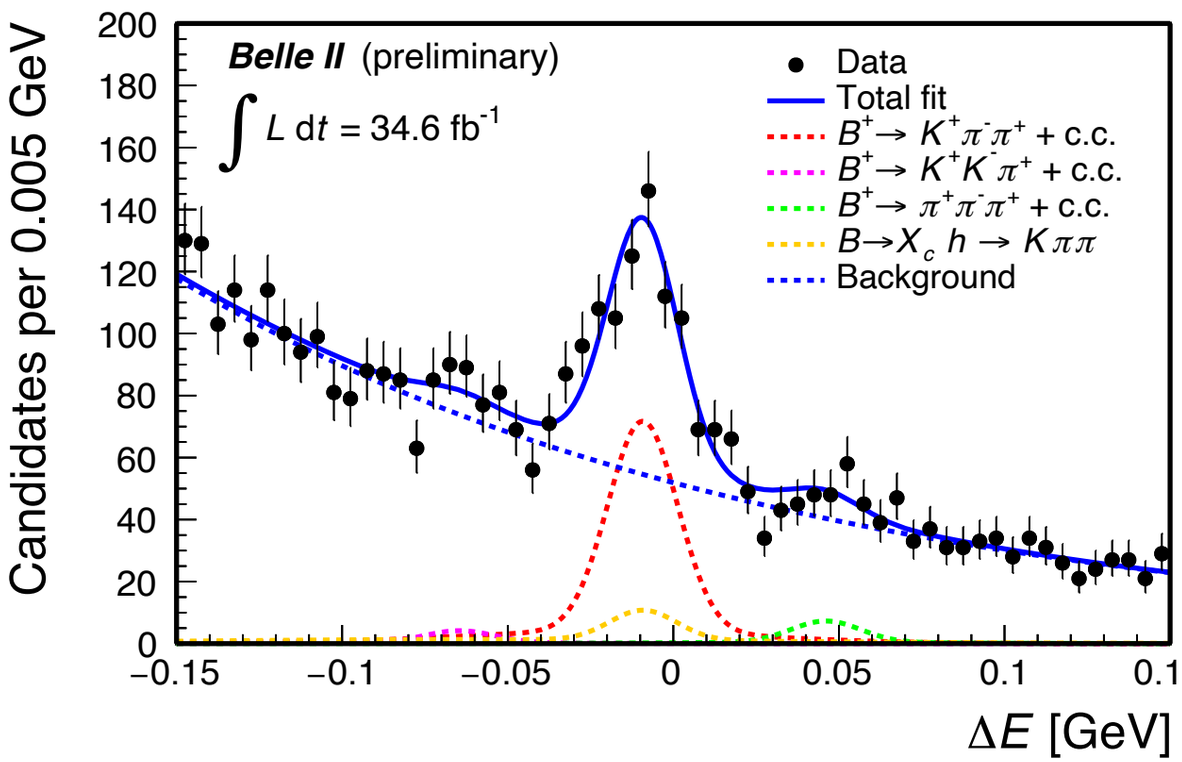
$B^+ \to K^+\pi^0$

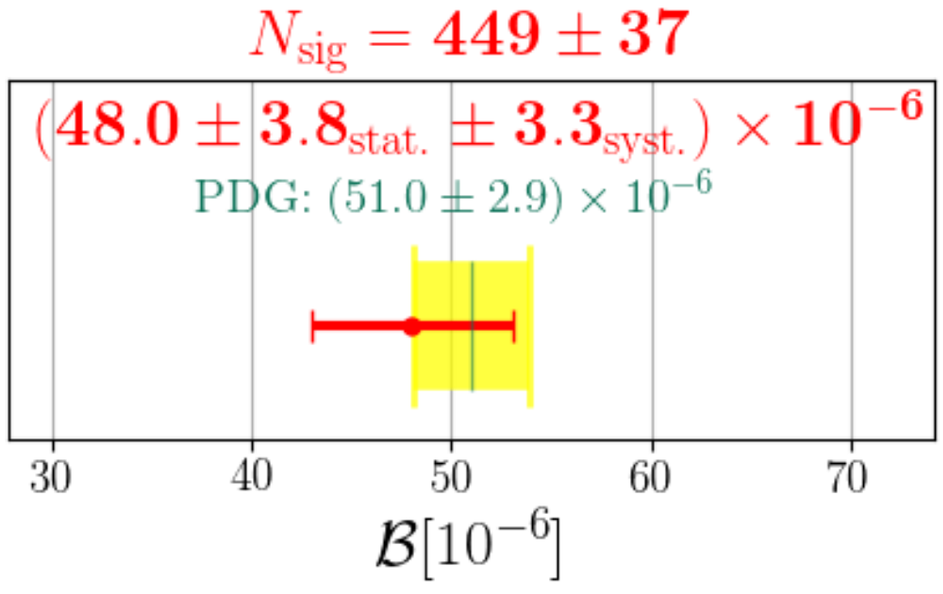


$B^+ \to \pi^+\pi^0$

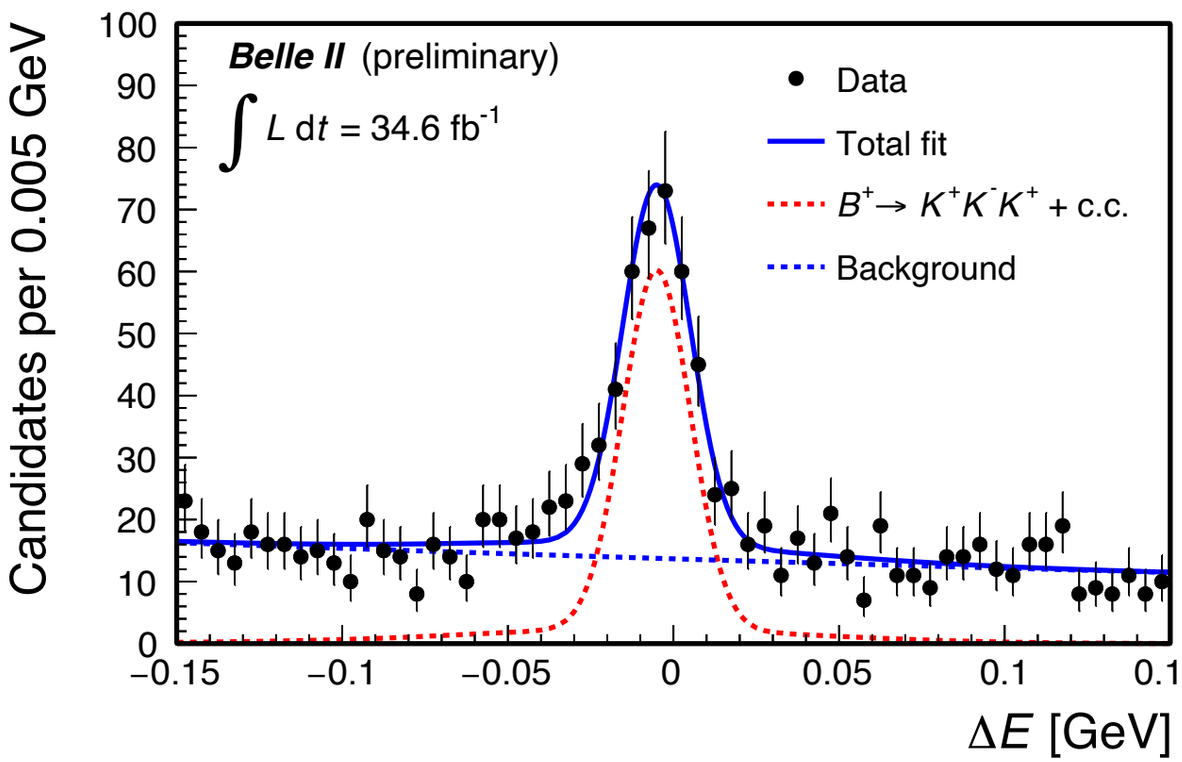
Branching fractions

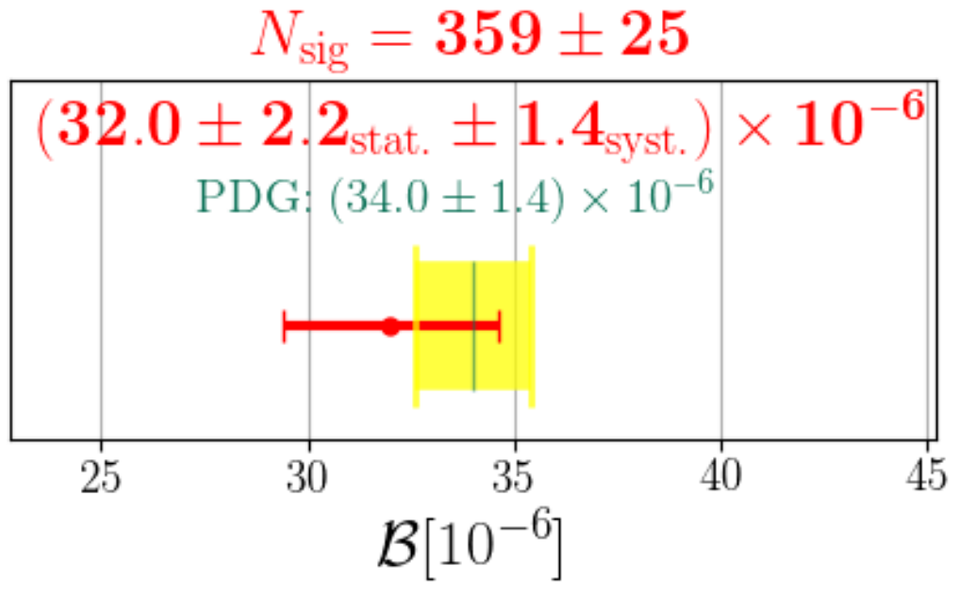
$B^+ \to K^+\pi^-\pi^+$





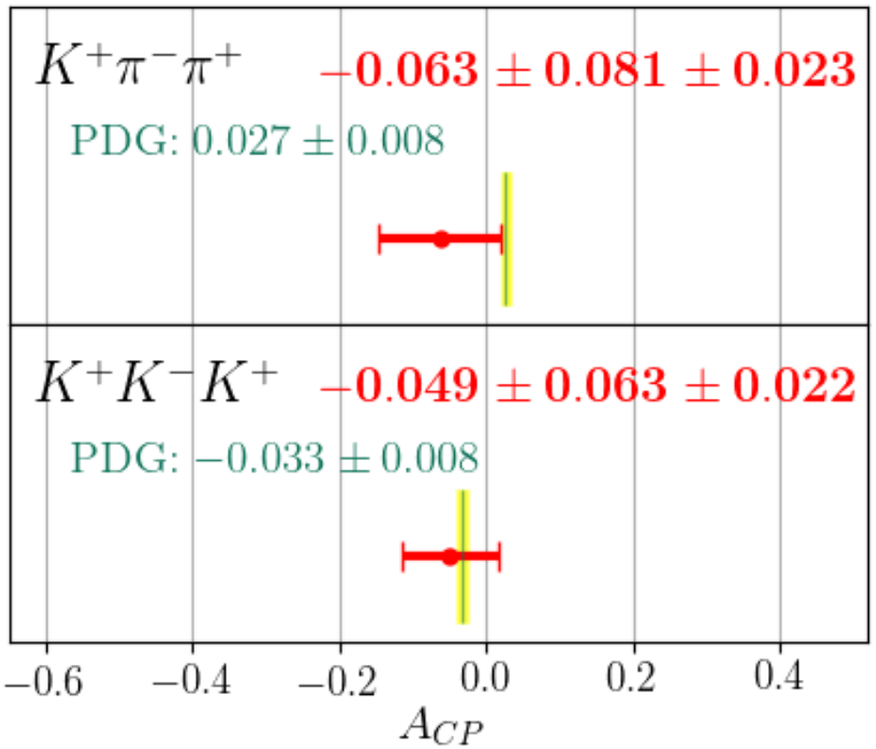
$B^+ \to K^+K^-K^+$





Control of peaking backgrounds

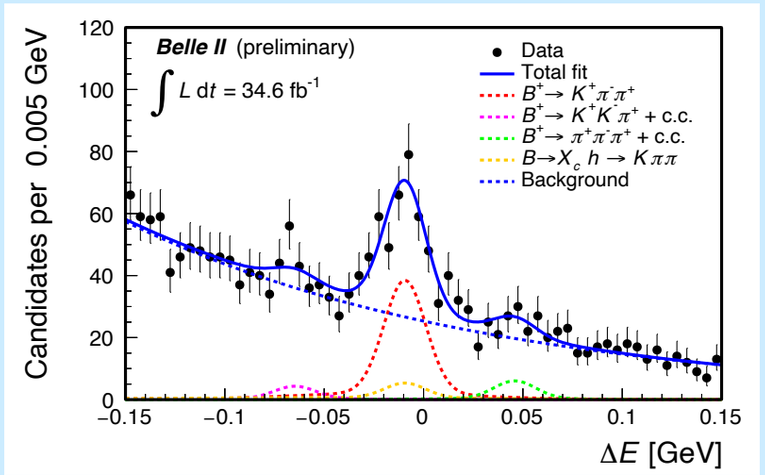
Three-body CP asymmetries



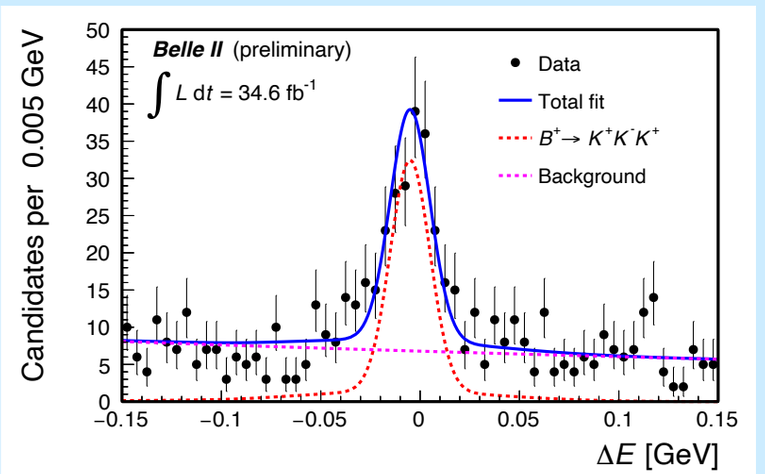
Control of peaking backgrounds

B^+ decays

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

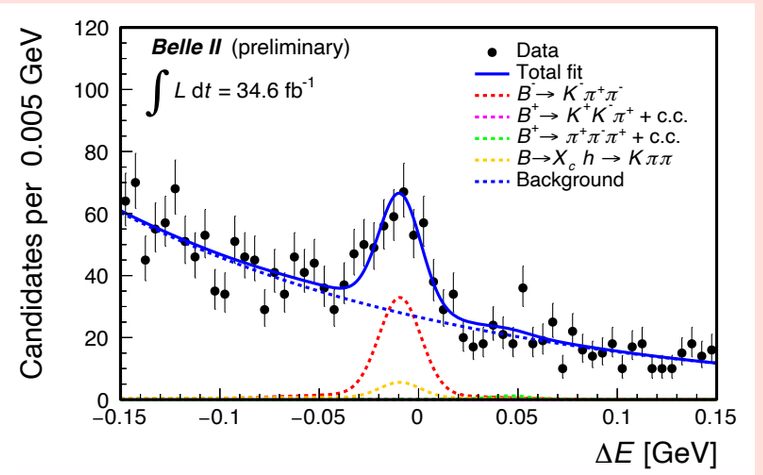


$B^+ \to K^+K^-K^+$

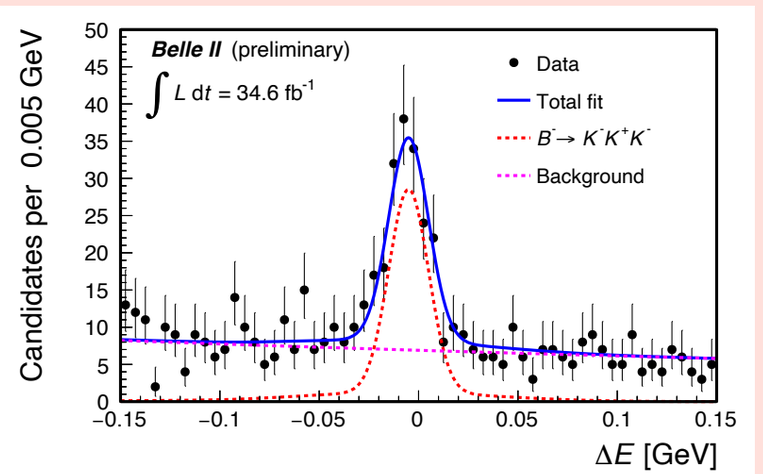


B^- decays

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



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

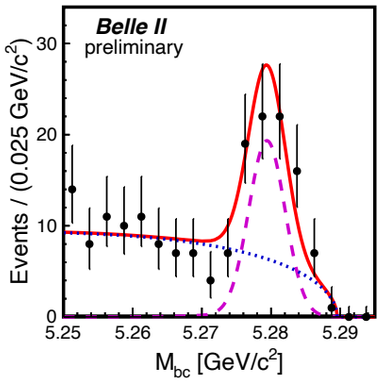


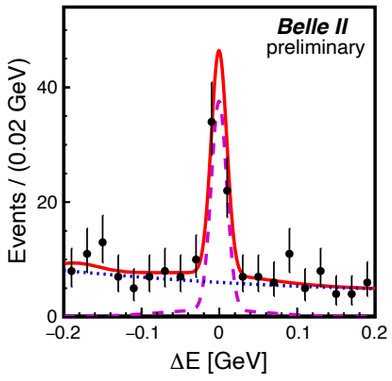
Branching fractions

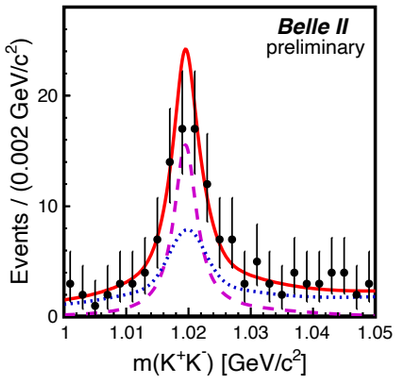
C'_{out}: transformed continuum-supp. output
$m(K^+K^-)$: invariant mass
$\cos\theta_{H,\phi}$: cosine of helicity angle

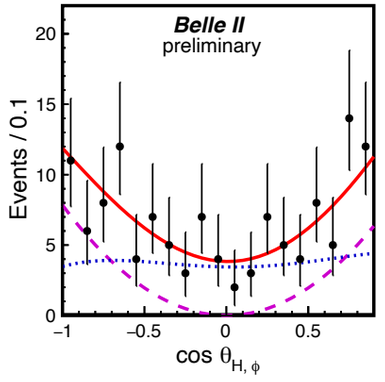
$B^+ \to \phi K^+$

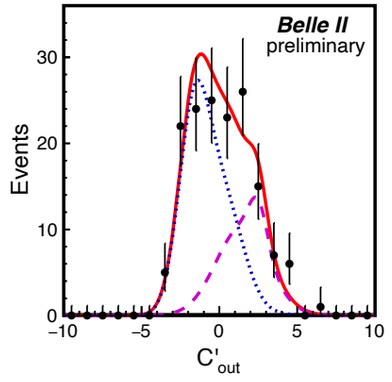
First reconstruction in Belle II

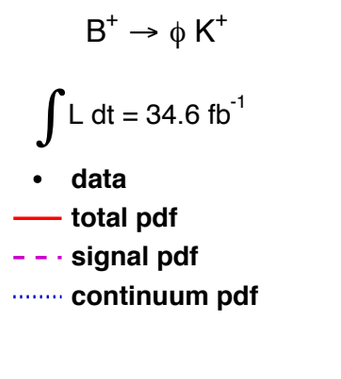






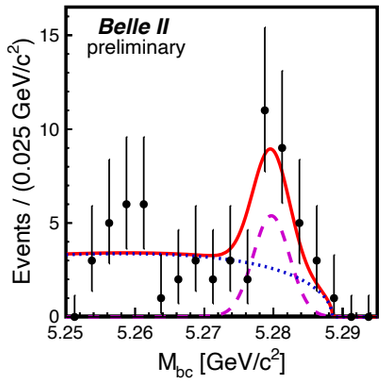


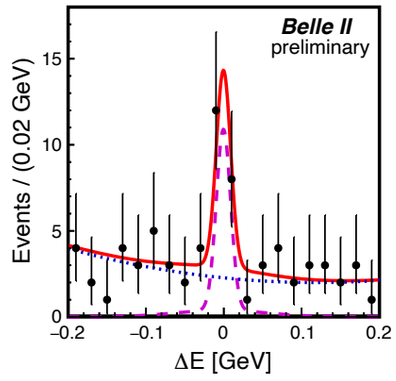


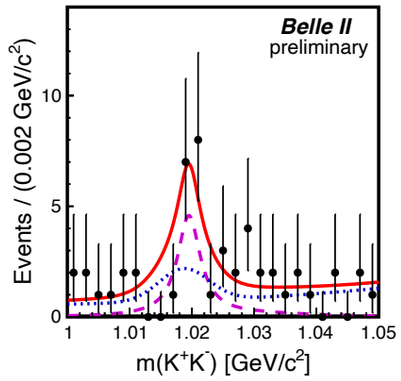


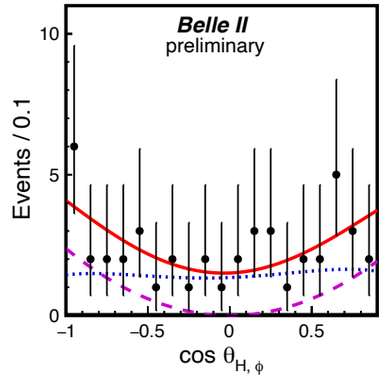
N_{sig}	55 ± 9
$\mathcal{B}[10^{-6}]$	$6.7 \pm 1.1_{\text{stat.}} \pm 0.5_{\text{syst.}}$
$\mathcal{B}_{\text{PDG}}[10^{-6}]$	8.8 ± 0.7

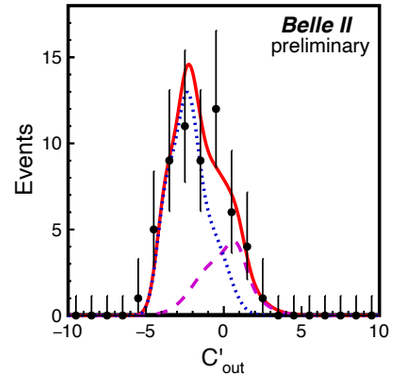
$B^0 \to \phi K^0$

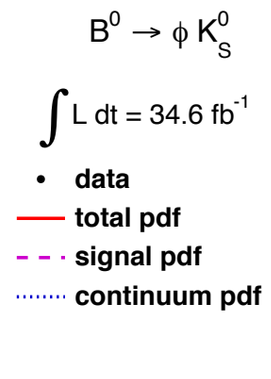










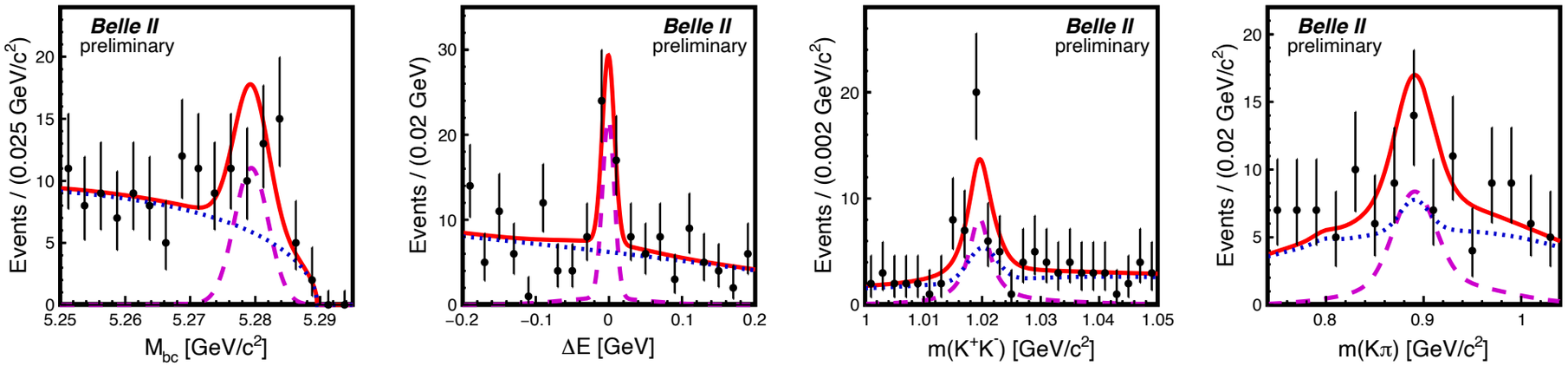


N_{sig}	16 ± 5
$\mathcal{B}[10^{-6}]$	$5.9 \pm 1.8_{\text{stat.}} \pm 0.7_{\text{syst.}}$
$\mathcal{B}_{\text{PDG}}[10^{-6}]$	7.3 ± 0.7

Branching fractions, longitudinal polarizations

$$B^+ \to \phi K^{*+}$$

First reconstruction in Belle II



N_{sig}	33 ± 8
$\mathcal{B}[10^{-6}]$	$21.7 \pm 4.6_{stat.} \pm 1.9_{syst.}$
$\mathcal{B}_{PDG}[10^{-6}]$	10.0 ± 2.0
f_L	$0.58 \pm 0.23_{stat.} \pm 0.02_{syst.}$
$f_{L,PDG}$	0.50 ± 0.05

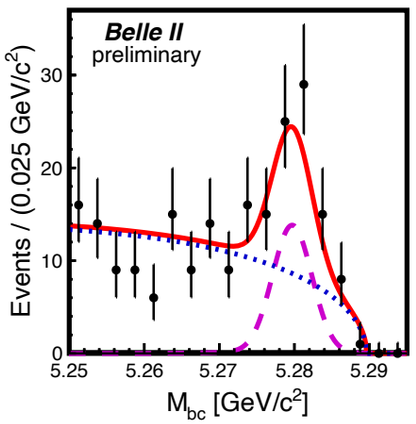
C'_{out}: transformed continuum-supp. output
$m(K^+K^-), m(K\pi)$: invariant masses
$\cos\theta_{H,\phi}, \cos\theta_{H,K^*}$: cosines of helicity angle

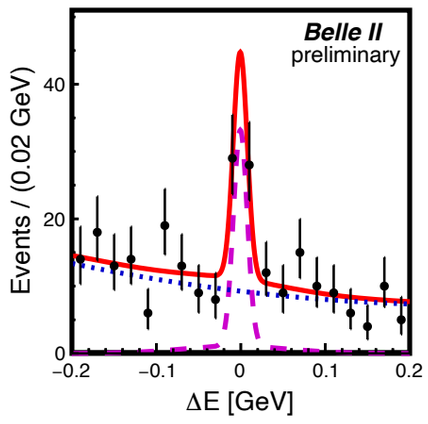
Control of angular acceptances

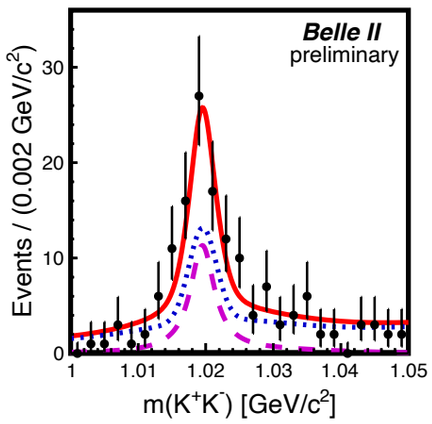
Branching fractions, longitudinal polarizations

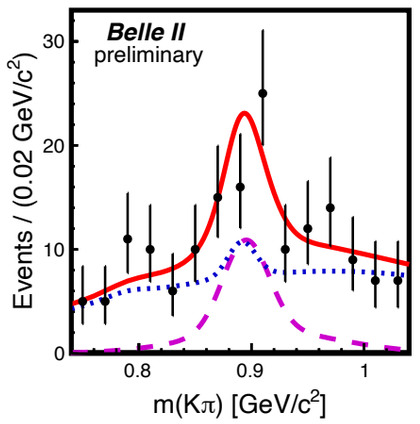
$$B^0 \to \phi K^{*0}$$

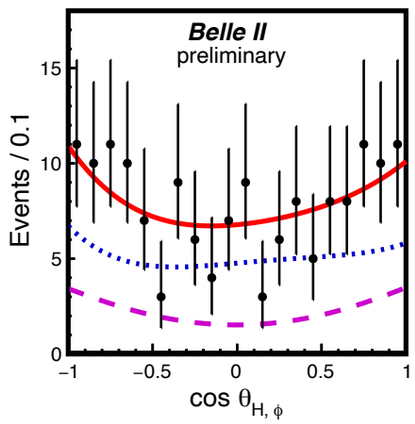
First reconstruction in Belle II

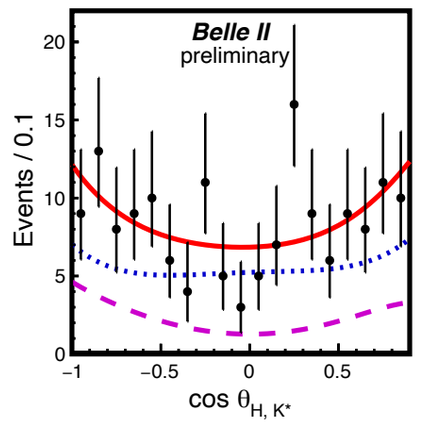


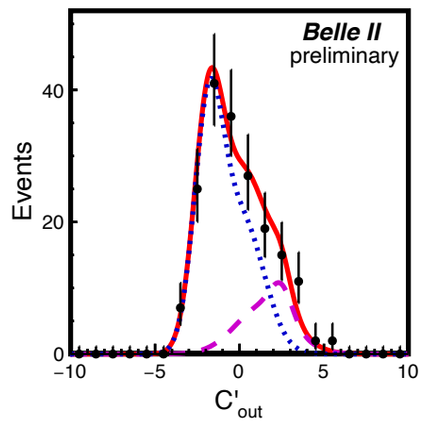


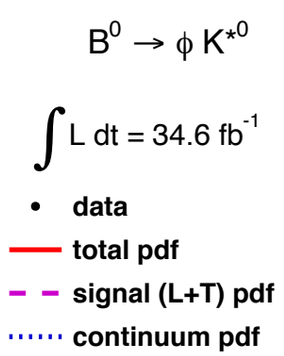












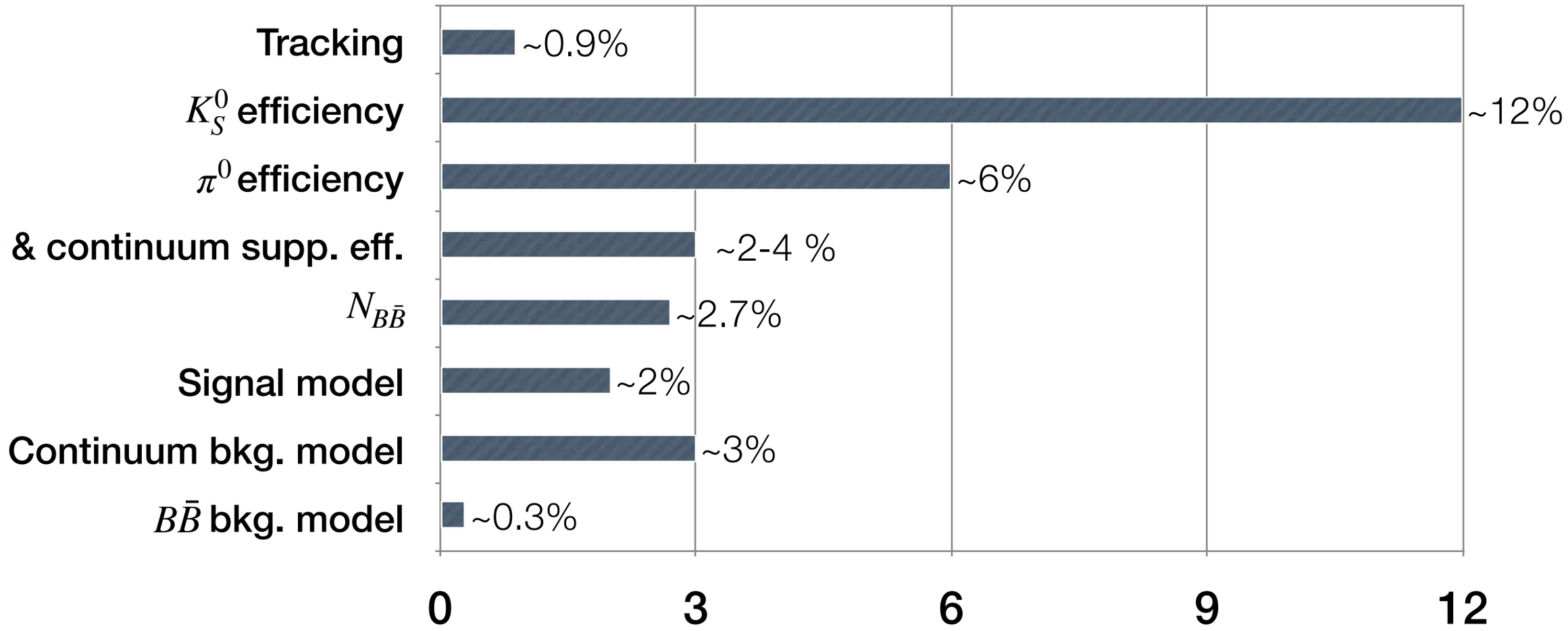
C'_{out}: transformed continuum-supp. output
$m(K^+K^-), m(K\pi)$: invariant masses
$\cos\theta_{H,\phi}, \cos\theta_{H,K^*}$: cosines of helicity angle

N_{sig}	48 ± 10
$\mathcal{B}[10^{-6}]$	$11.0 \pm 2.1_{\text{stat.}} \pm 1.1_{\text{syst.}}$
$\mathcal{B}_{\text{PDG}}[10^{-6}]$	10.0 ± 0.5
f_L	$0.57 \pm 0.20_{\text{stat.}} \pm 0.04_{\text{syst.}}$
$f_{L,\text{PDG}}$	0.497 ± 0.017

Control of angular acceptances

Systematics

- **Branching fractions**



(relative uncertainties in %)

- **Instrumental asymmetries**

Instrumental asymmetry	Value
$\mathcal{A}_{\rm det}(K^+\pi^-)$	-0.010 ± 0.003
$\mathcal{A}_{\rm det}(K^0_{\rm S}\pi^+)$	-0.007 ± 0.022
$\mathcal{A}_{\rm det}(K^+)$	-0.015 ± 0.022
$\mathcal{A}_{\rm det}(\pi^+)$	-0.007 ± 0.022

- **Longitudinal polarizations**
  - Modeling of transformed continuum-supression output ($C'_{\rm out}$)
  - Acceptance function for helicity angles

Summary

- First measurements in charmless B decays with:

  12 branching fractions ($\mathscr{B}$)

  6 CP asymmetries (A_{CP})

  2 longitudinal polarizations (f_L)

  are reported using 2019-2020 summer Belle II data

- Yields and purities are comparable with Belle's best

- Establishes solid understanding of detector and analysis workflow

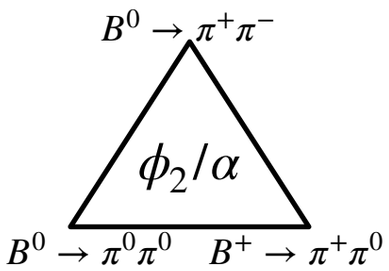
- Near future:
  $B^0 \to \pi^0\pi^0$ to complete ϕ_2/α determination
  $A_{CP}(K^0\pi^0)$ to complete sum rule test

- Long run: data accumulating & analysis ongoing!

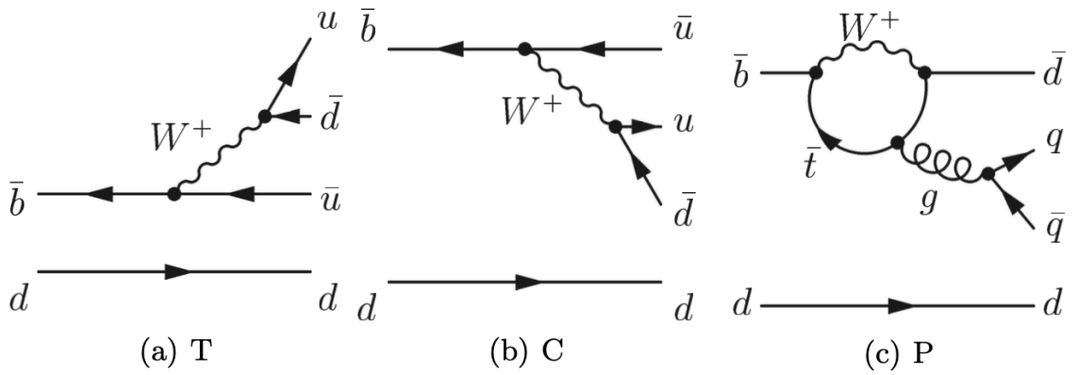
Backup

Hadronic Charmless B decays — ϕ_2/α Measurements

- **Isospin relation**



Feynman diagrams for $B \to \pi\pi, B \to \rho\rho$ systems



arXiv: 1002.5012

$$A(B^0 \to \pi^+\pi^-) + \sqrt{2}A(B^0 \to \pi^0\pi^-) = \sqrt{2}A(B^+ \to \pi^+\pi^0)$$

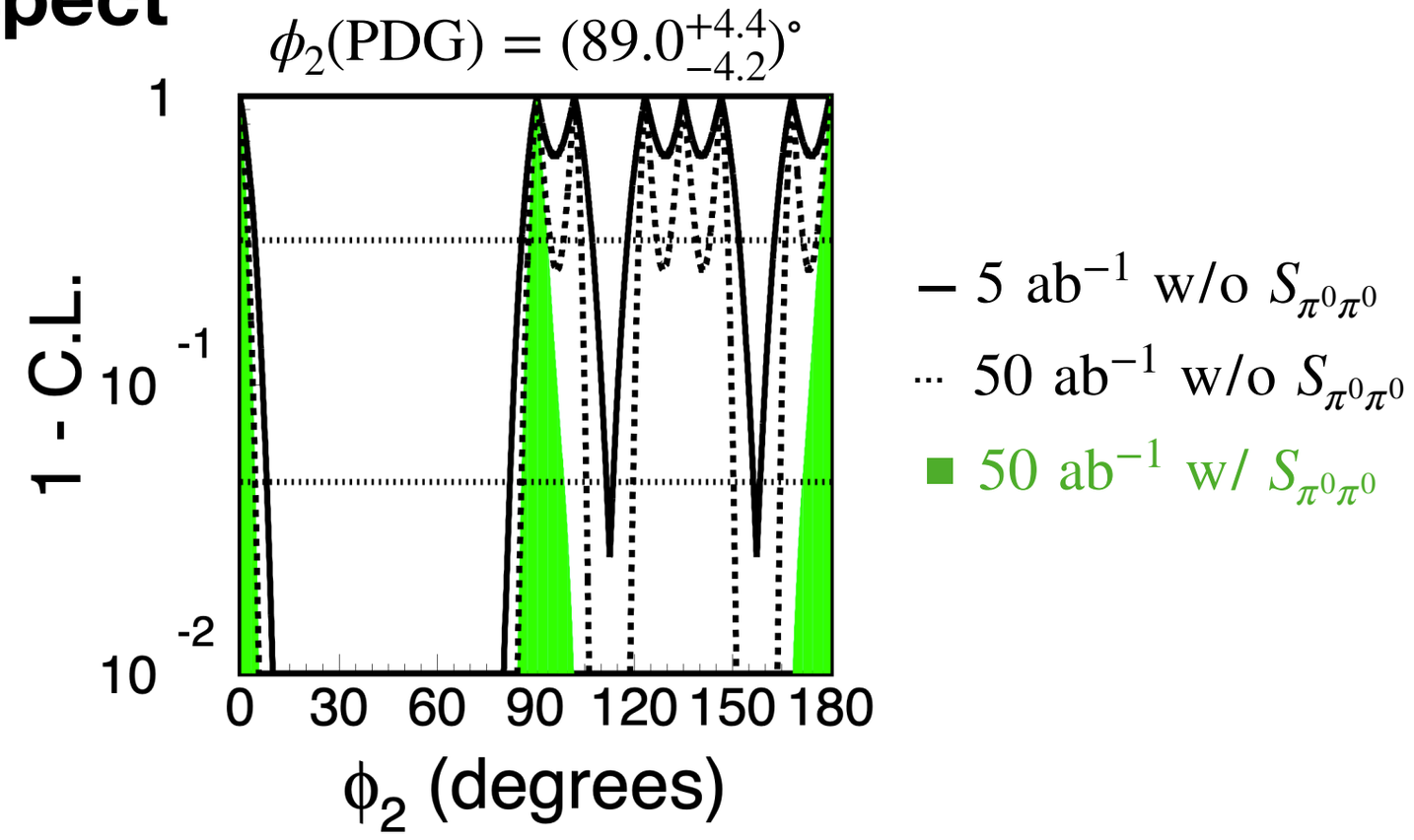
$$A(B^0 \to \pi^+\pi^-) = \sqrt{2}(A_2 - A_0)$$

$$A(B^0 \to \pi^0\pi^0) = 2A_2 + A_0$$

$$A(B^+ \to \pi^+\pi^0) = 3A_2$$

(A_0, A_2: amplitudes of the isospin 0, 2 final state)

- **SuperKEKB prospect**



Hadronic Charmless B decays — K-π puzzle

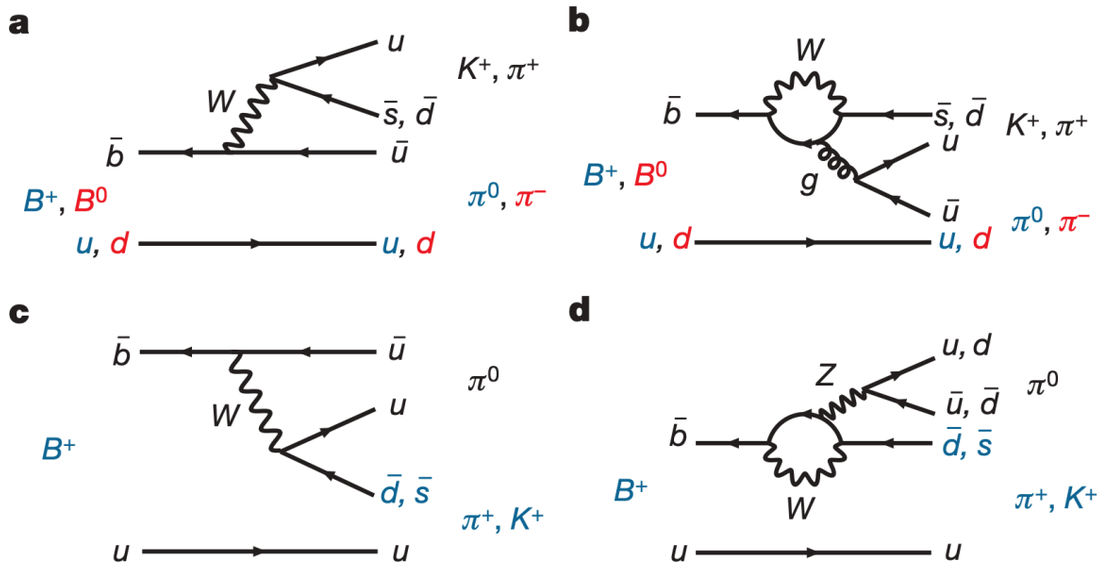
- **SU(3) symmetry**

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

$I_{K\pi}$

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

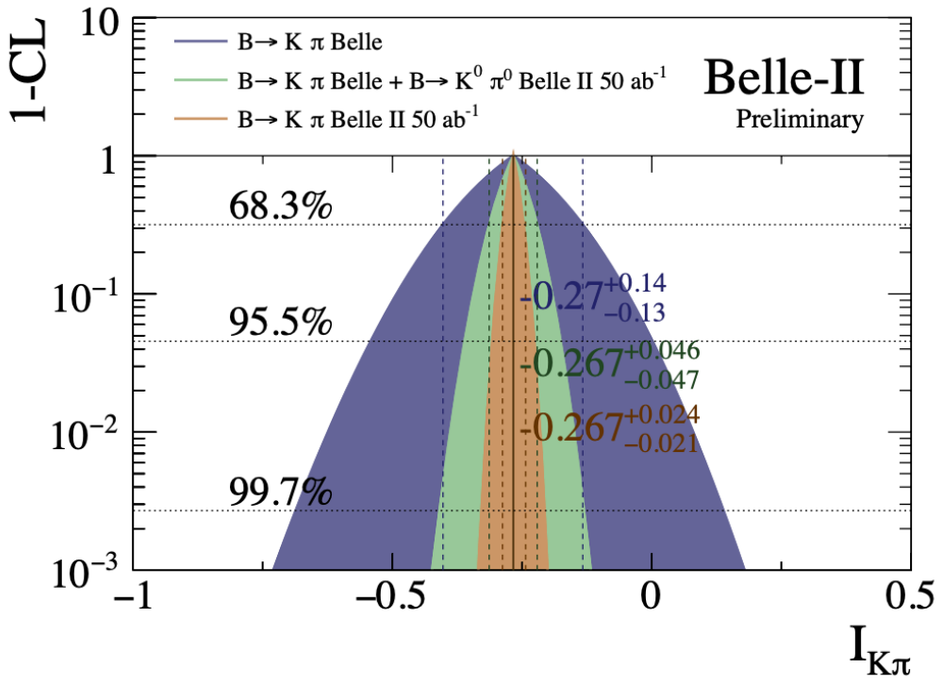
Feynman diagrams for $B \to K\pi, B \to \pi\pi$ systems

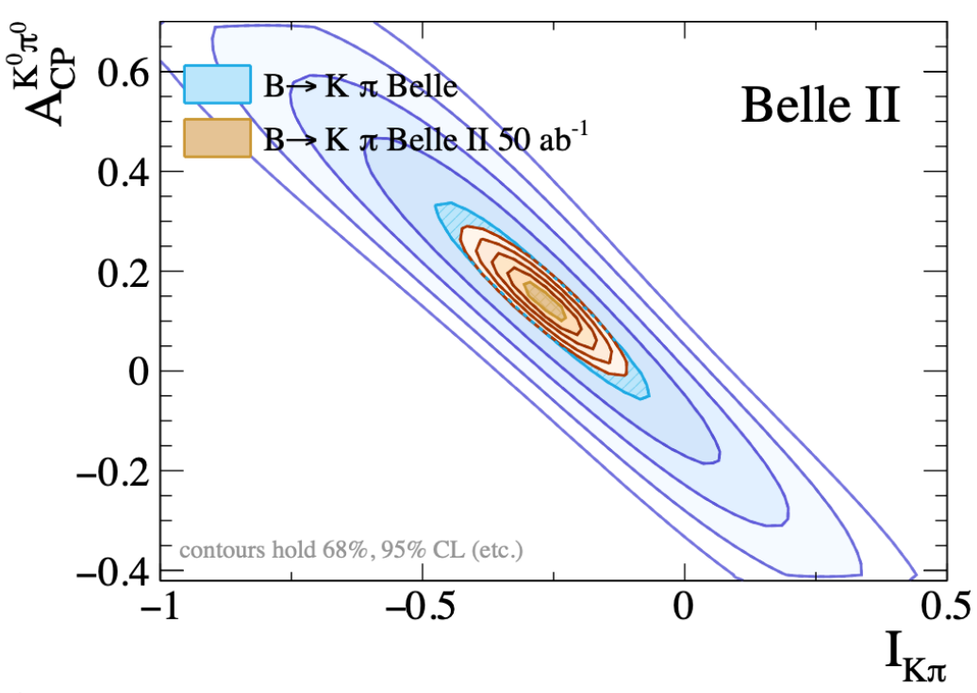


$$I_{K\pi} = A_{CP}^{K^+\pi^-} + A_{CP}^{K^0\pi^+}\frac{B(K^0\pi^+)}{B(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2A_{CP}^{K^+\pi^0}\frac{2B(K^+\pi^0)}{B(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2A_{CP}^{K^0\pi^0}\frac{2B(K^0\pi^0)}{B(K^+\pi^-)}$$

- **SuperKEKB prospect**

arXiv:1808.10567





Prospects of Belle II experiment

arXiv: 1002.5012

Summary of sensitivity

Observable	Belle 2006 ($\sim$0.5 ab^{-1})	SuperKEKB (5 ab^{-1})	SuperKEKB (50 ab^{-1})	†LHCb (2 fb^{-1})	†LHCb (10 fb^{-1})
Unitarity triangle parameters					
$\sin 2\phi_1$	0.026	0.016	0.012	$\sim$0.02	$\sim$0.01
ϕ_2 $(\pi\pi)$	11°	10°	3°	-	-
ϕ_2 $(\rho\pi)$	$68° < \phi_2 < 95°$	3°	1.5°	10°	4.5°
ϕ_2 $(\rho\rho)$	$62° < \phi_2 < 107°$	3°	1.5°	-	-
ϕ_2 (combined)		2°	$\lesssim 1°$	10°	4.5°

Observable	Belle 2006 ($\sim$0.5 ab^{-1})	SuperKEKB (5 ab^{-1})	SuperKEKB (50 ab^{-1})	†LHCb (2 fb^{-1})	†LHCb (10 fb^{-1})
Hadronic $b \to s$ transitions					
$\Delta\mathcal{S}_{\phi K^0}$	0.22	0.073	0.029		0.14
$\Delta\mathcal{S}_{\eta' K^0}$	0.11	0.038	0.020		
$\Delta\mathcal{S}_{K^0_S K^0_S K^0_S}$	0.33	0.105	0.037	-	-
$\Delta\mathcal{A}_{\pi^0 K^0_S}$	0.15	0.072	0.042	-	-
$\mathcal{A}_{\phi\phi K^+}$	0.17	0.05	0.014		
$\phi_1^{eff}(\phi K_S)$ Dalitz		3.3°	1.5°		

arXiv: 1011.0352

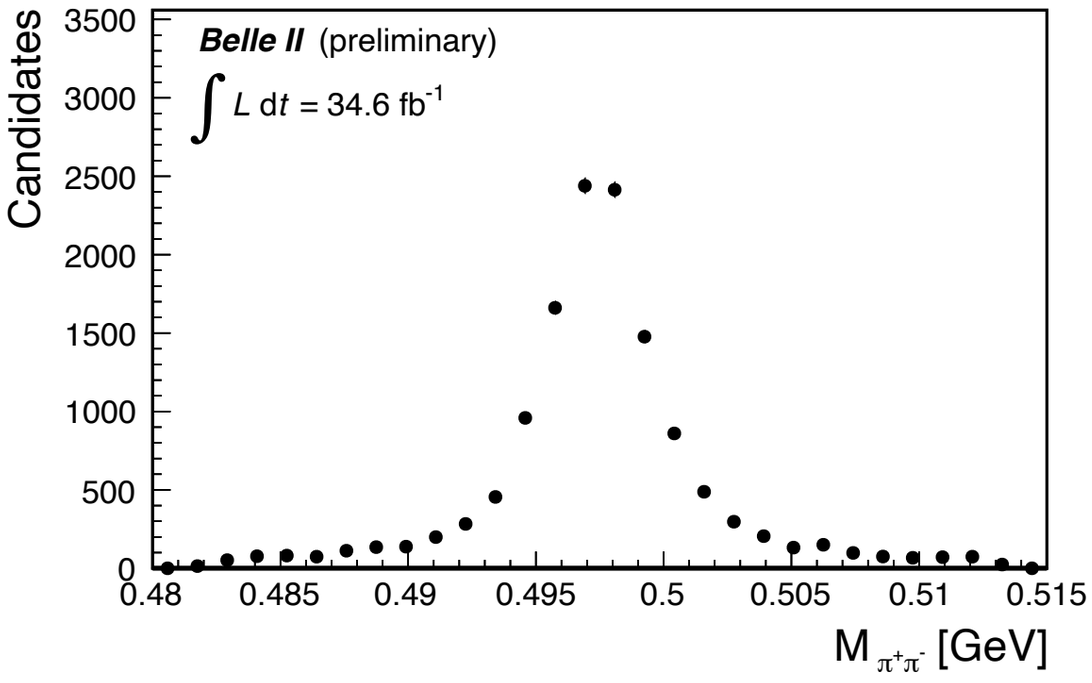
Table 1.3: Expected performance of components of the Belle II spectrometer.

Component	Type	Configuration	Readout	Performance
Beam pipe	Beryllium double-wall	Cylindrical, inner radius 10 mm, 10 μm Au, 0.6 mm Be, 1 mm coolant (paraffin), 0.4 mm Be		
PXD	Silicon pixel (DEPFET)	Sensor size: 15×100 (120) mm^2 pixel size: 50×50 (75) μm^2 2 layers: 8 (12) sensors	10 M	impact parameter resolution $\sigma_{z_0} \sim 20$ μm (PXD and SVD)
SVD	Double sided Silicon strip	Sensors: rectangular and trapezoidal Strip pitch: 50(p)/160(n) - 75(p)/240(n) μm 4 layers: 16/30/56/85 sensors	245 k	
CDC	Small cell drift chamber	56 layers, 32 axial, 24 stereo r = 16 - 112 cm - 83 $\leq z \leq$ 159 cm	14 k	$\sigma_{r\phi} = 100$ μm, $\sigma_z = 2$ mm $\sigma_{p_t}/p_t = \sqrt{(0.2\%p_t)^2 + (0.3\%/\beta)^2}$ $\sigma_{p_t}/p_t = \sqrt{(0.1\%p_t)^2 + (0.3\%/\beta)^2}$ (with SVD) $\sigma_{dE/dx} = 5\%$
TOP	RICH with quartz radiator	16 segments in ϕ at $r \sim 120$ cm 275 cm long, 2 cm thick quartz bars with 4x4 channel MCP PMTs	8 k	$N_{p.e.} \sim 20$, $\sigma_t = 40$ ps K/π separation : efficiency > 99% at < 0.5% pion fake prob. for $B \to \rho\gamma$ decays
ARICH	RICH with aerogel radiator	4 cm thick focusing radiator and HAPD photodetectors for the forward end-cap	78 k	$N_{p.e.} \sim 13$ K/π separation at 4 GeV/c: efficiency 96% at 1% pion fake prob.
ECL	CsI(Tl) (Towered structure)	Barrel: r = 125 - 162 cm End-cap: z = -102 cm and +196 cm	6624 1152 (F) 960 (B)	$\frac{\sigma E}{E} = \frac{0.2\%}{E} \oplus \frac{1.6\%}{\sqrt[4]{E}} \oplus 1.2\%$ $\sigma_{pos} = 0.5$ cm$/\sqrt{E}$ (E in GeV)
KLM	barrel: RPCs end-caps: scintillator strips	14 layers (5 cm Fe + 4 cm gap) 2 RPCs in each gap 14 layers of $(7-10) \times 40$ mm^2 strips read out with WLS and G-APDs	θ: 16 k, ϕ: 16 k 17 k	$\Delta\phi = \Delta\theta = 20$ mradian for K_L ~ 1 % hadron fake for muons $\Delta\phi = \Delta\theta = 10$ mradian for K_L $\sigma_p/p = 18\%$ for 1 GeV/c K_L

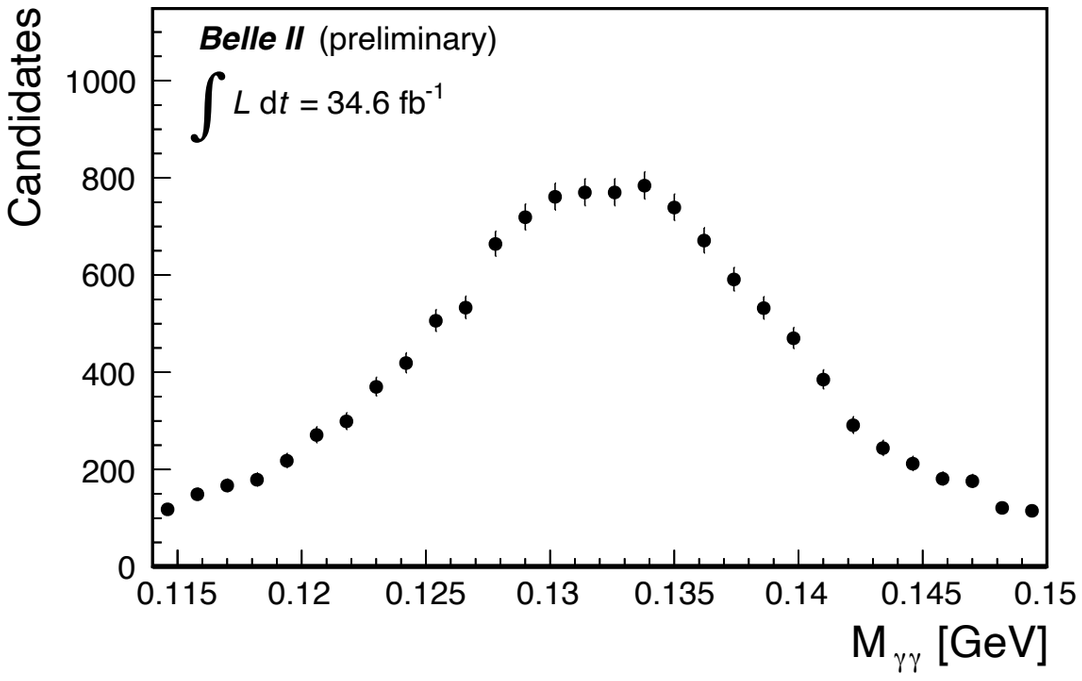
Reconstruction

K_S^0, π^0 reconstructed mass

$K_S^0(\rightarrow \pi^+\pi^-)$

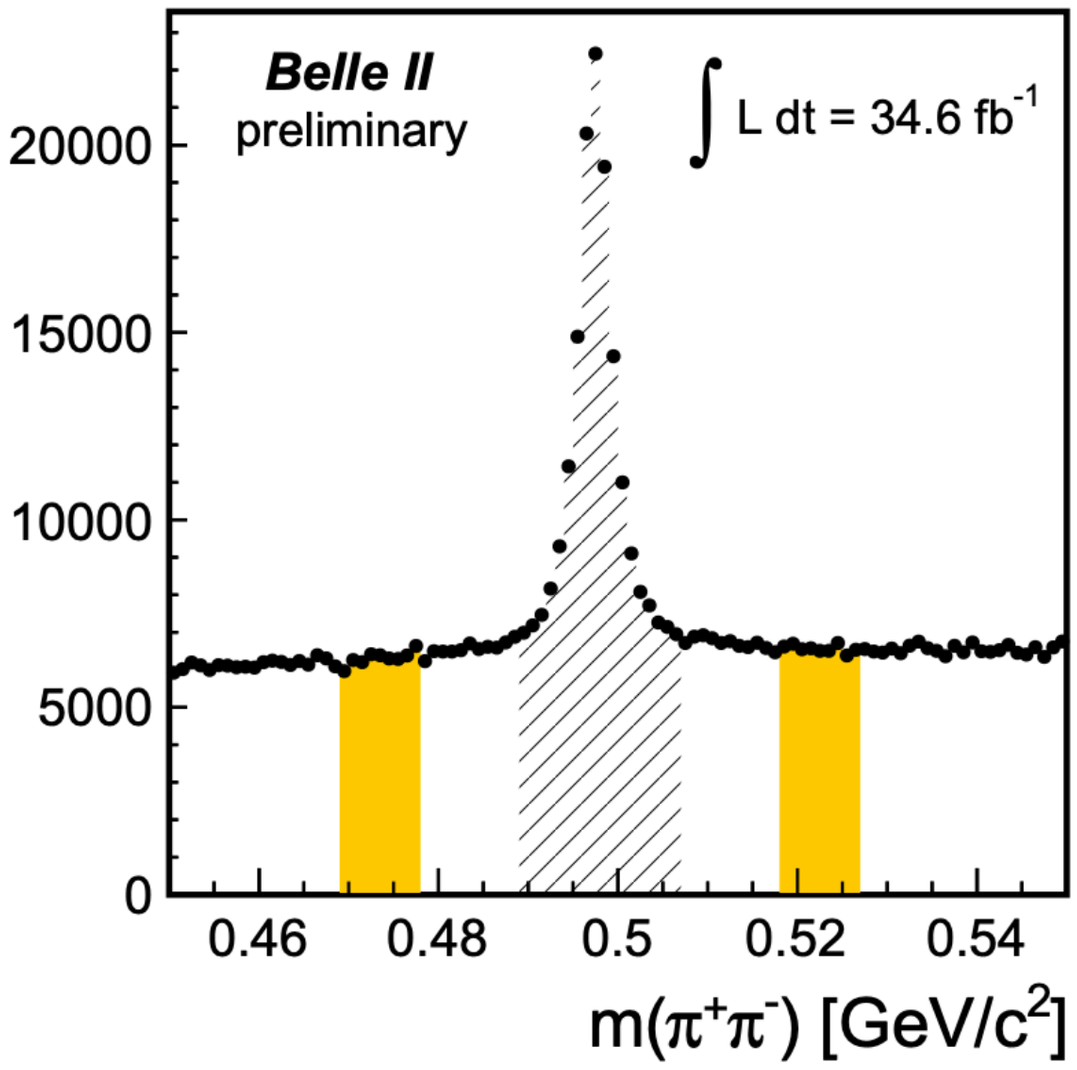


$\pi^0(\rightarrow \gamma\gamma)$



from $B^0 \rightarrow K_S^0\pi^0$ candidates in data

$K_S^0(\rightarrow \pi^+\pi^-)$



from $B^0 \rightarrow \phi K_S^0$ candidates in data

Systematics

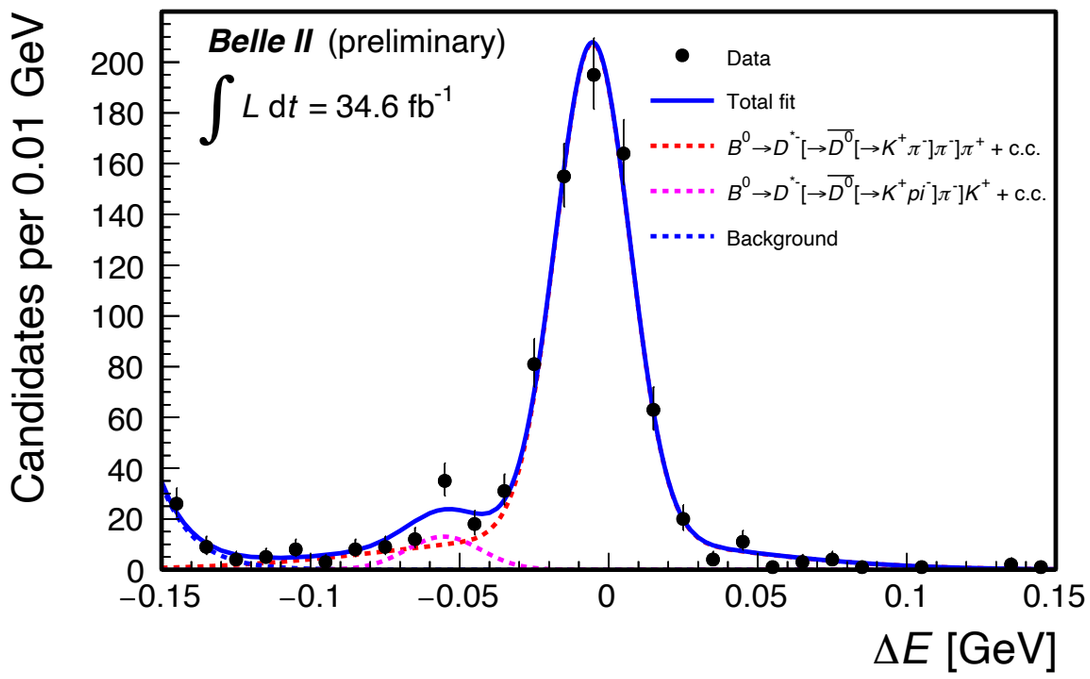
K_S^0, π^0 reconstruction efficiencies

arXiv:2008.03873

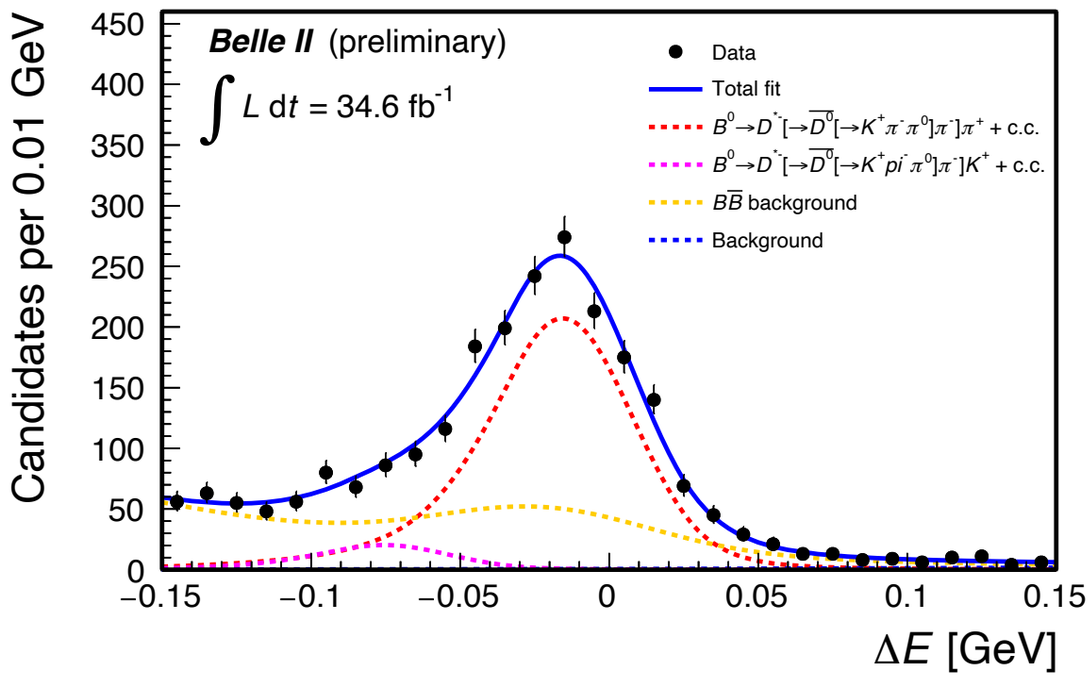
- K_S^0 reconstruction
  Average flight distance in signal MC (truth-matched) * 1%

- π^0 reconstruction
  The uncertainty is evaluated as the difference of efficiency ratio of $\frac{B^0 \to D^{*-}(\to \bar{D}^0(\to K^+\pi^-\pi^0)\pi^-)\pi^+}{B^0 \to D^{*-}(\to D^0(\to K^+\pi^-)\pi^-)\pi^+}$ in MC & data

$B^0 \to D^{*-}(\to D^0(\to K^+\pi^-)\pi^-)\pi^+$



$B^0 \to D^{*-}(\to \bar{D}^0(\to K^+\pi^-\pi^0)\pi^-)\pi^+$



Instrumental asymmetries A_{det}

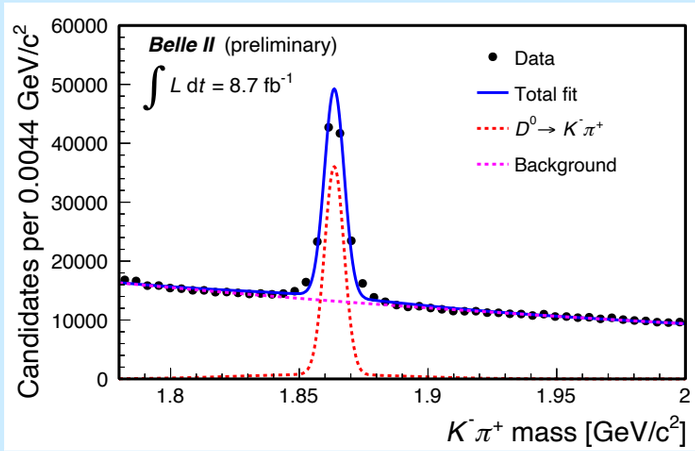
- CP asymmetry correction with instrumental effects:

$$A_{\text{raw}} = \frac{N(b) - N(\bar{b})}{N(b) + N(\bar{b})} = A_{CP} + A_{\text{det}}$$

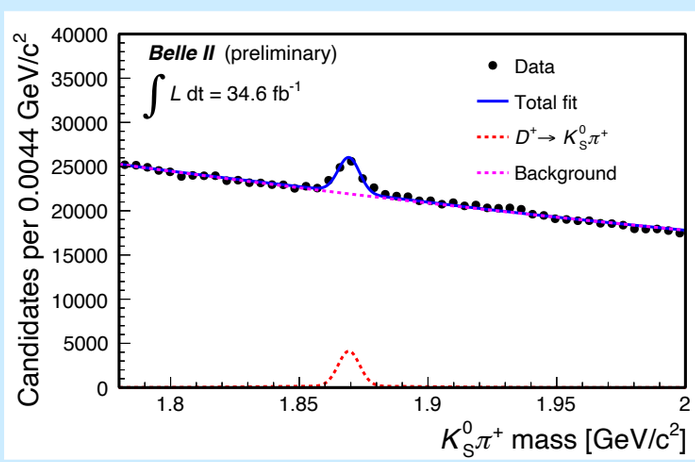
- A_{det} assessment:

$D^+(D^0)$ decays

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

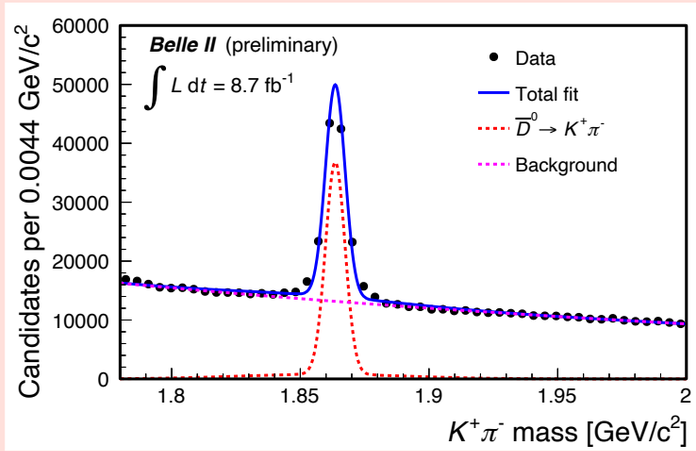


$D^+ \to K^0_S\pi^+$

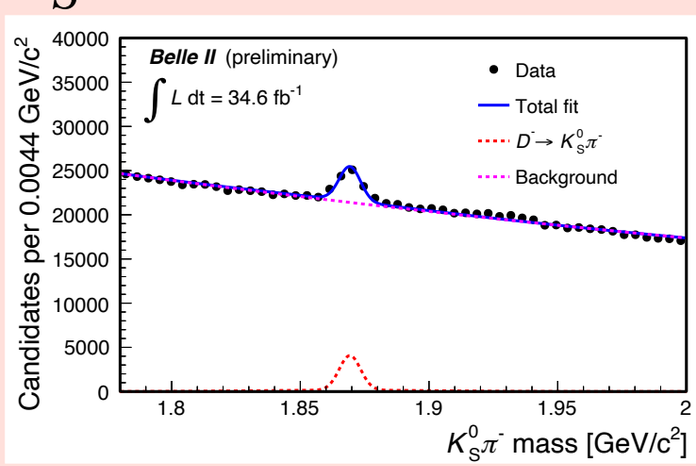


$D^-(\bar{D}^0)$ decays

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



$D^+ \to K^0_S\pi^+$



Instrumental asymmetry	Value
$\mathcal{A}_{\text{det}}(K^+\pi^-)$	-0.010 ± 0.003
$\mathcal{A}_{\text{det}}(K^0_S\pi^+)$	-0.007 ± 0.022
$\mathcal{A}_{\text{det}}(K^+)$	-0.015 ± 0.022
$\mathcal{A}_{\text{det}}(\pi^+)$	-0.007 ± 0.022

$$A_{\text{det}}(K) = A_{\text{det}}(K\pi) - A_{\text{det}}(K^0_S\pi) + A(K^0_S)$$
$$A_{\text{det}}(\pi) = A_{\text{det}}(K^0_S\pi) - A(K^0_S)$$

($A(K^0_S)$ is quoted from LHCb results)