Status and plan of $B^0 \to K^0\pi^0$ Time-dependent study

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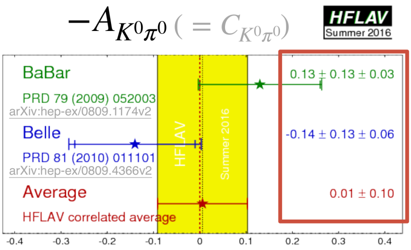
Motivation

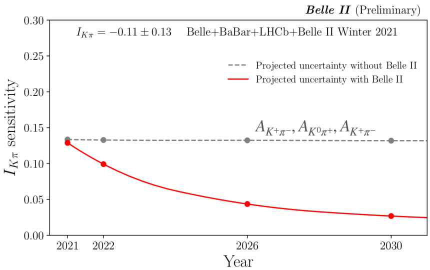
- In the SM, the decay $B^0 \to K^0\pi^0$ proceeds via $b \to s$ loop diagrams.
- Such FCNC transitions are highly suppressed in the SM and sensitive to non-SM particles appearing in the loops.
- Sum rule relation for $B \to K\pi$ decays

$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)} = 0$$

Predicting $A_{K^0\pi^0} = -0.17 \pm 0.06$ (Phys.Lett. B627 (2005) 82-8)



BELLE2-NOTE-PH-2020-046

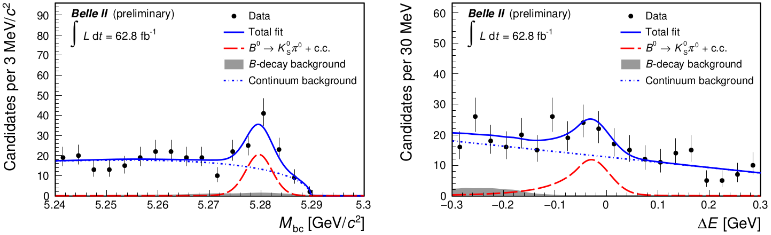


Recap till Moriond

2D ($M_{bc}, \Delta E$) Extended Fit

BELLE2-NOTE-PH-2020-046

- Fit to determine yield info of signal, rare B & continuum background
- Fixed params: shape parameters of PDFs
- Gaussian constraints:
  $\rightarrow N_{rare}$: from know rare decays (see backup p. 5)
  $\rightarrow \Delta E$ shift: μ and σ from $B^+ \rightarrow K^+\pi^0$ (ONLY ON DATA)
- Floated params: qq ΔE slope, $\mathscr{B}$



$N(B^0 \rightarrow K^0\pi^0) = 45^{+9}_{-8}$ $\mathscr{B}(B^0 \rightarrow K^0\pi^0) = [8.5^{+1.7}_{-1.6}(stat) \pm 1.2(syst)] \times 10^{-6}$

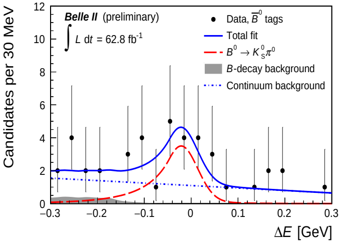
Time-integrated $A_{K^0\pi^0}$ extraction

$(M_{bc}, \Delta E) \times$ q Fraction Fit

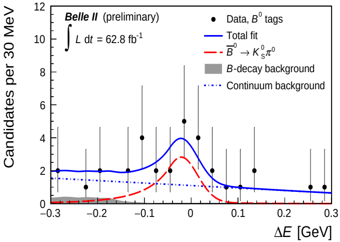
BELLE2-NOTE-PH-2020-046

- $P_{sig}(q) = \frac{1}{2}.(1 - q.\Delta w_r + q.(1-2w_r).(1-2.\chi_d).A_{K^0\pi^0})$
- 7 r-bin simultaneous CP-fit
- χ_d :time-integrated B^0 mixing probability (external input)
- Flavor parameters$(w_r, \Delta w_r, \epsilon_r)$ from [BELLE2-NOTE-PH-2021-001].
- Assume null A_{CP}^{rare} + continuum flavor symmetric

$B^0 \to K_S^0\pi^0$



$\bar{B}^0 \to K_S^0\pi^0$

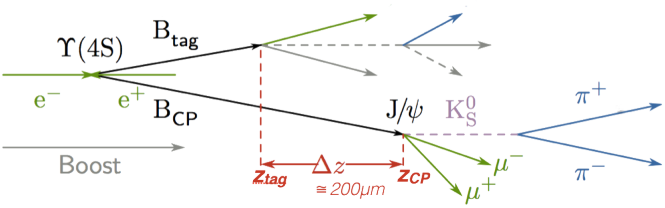


$$A_{K^0\pi^0} = -0.40^{+0.46}_{-0.44}(stat) \pm 0.04(syst)$$

Ongoing work

Time-dependent analysis

- $\mathcal{P}(q,\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}[1 + q\{\mathcal{A}\cos(\Delta m_d \Delta t) + \mathcal{S}\sin(\Delta m_d \Delta t)\}]$
  $$\Delta t \approx (z_{\rm rec} - z_{\rm tag})/\beta\gamma c$$
- The key challenge arises due to the absence of primary charged final-state particles at the B decay vertex
- Δt resolution study
- $B^0 \to J/\psi K^0_S$ as control chanel to check the vertex resolution



Δt uncentainty(Δt_{err}) study

Selection criteria

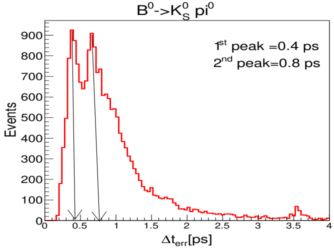
$B^0 \to K_s^0 \pi^0$

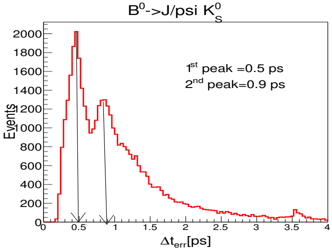
- Criteria are taken from BELLE2-NOTE-PH-2020-046
- For CP-side RaveFit: IP constraint and only K_S^0 vertexing
- For tag-side : IP constraint

$B^0 \to J/\psi K_S^0$

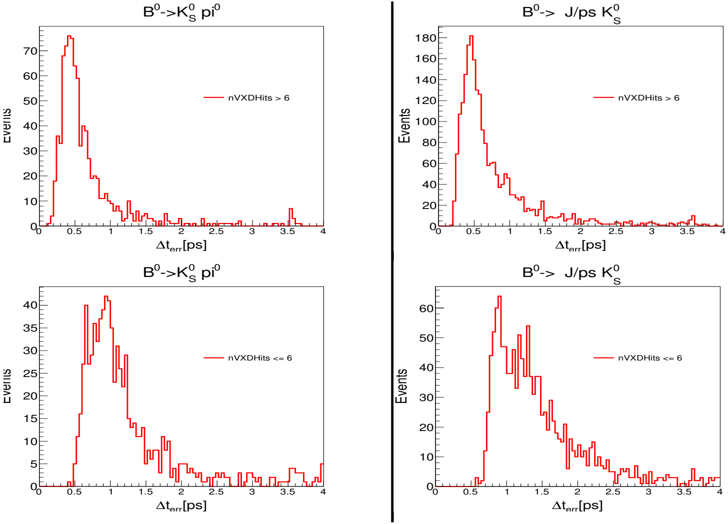
- Criteria are taken from BELLE2-NOTE-PH-2020-038

double-peak structure !





Δt_{err} double peak



- The second peak due to K_S^0 decays outside VXD giving fewer hits.

Validation

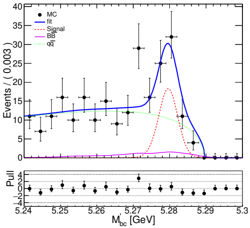
Plans

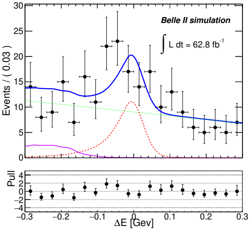
- To validate time-dependent framework, first reproduce the BELLE2-NOTE-PH-2020-046 results
- Unblind time-independent analysis on Moriond sample and compare BF and A_{CP} results

Current status & strategy

- All selections are same except raveFitter for B^0 vertex reconstruction to take only K_S^0
- raveFitter is only option to vertex using only K_S^0
- Follow the same fitting strategy both for branching fraction and A_{CP} measurements.

Results





Parameter	62.8 fb^{-1} MC cocktail
B.F.($\times 10^{-6}$)	$8.27^{+1.53}_{-1.44}$
N_{qq}	$182.1^{+14.4}_{-14.0}$ (exp.=180)
N_{bb}	$12.6^{+1.1}_{-1.1}$ (exp.=12)
$q\bar{q}\Delta E$ slope	$-0.8240^{+0.4697}_{-0.4617}$

BELLE2-NOTE-PH-2020-046

Parameter	62.8 fb^{-1} MC cocktail
$\mathcal{B}$ [$\times 10^{-6}$]	$9.13^{+1.73}_{-1.59}$
N_{qq}	$241.3^{+17.1}_{-16.4}$
N_{rare}	$12.7^{+1.1}_{-1.1}$
$q\bar{q}$ ΔE slope	$-1.1181^{+0.3888}_{-0.3721}$
ΔE mean-shift [MeV]	-

- $A_{K^0\pi^0} = 0.342^{+0.460}_{-0.472}$

$A_{K^0\pi^0} = +0.215^{+0.431}_{-0.443}$

- We believe small diffrence due to (raveFiter + our CS weight file), investigation is going on.

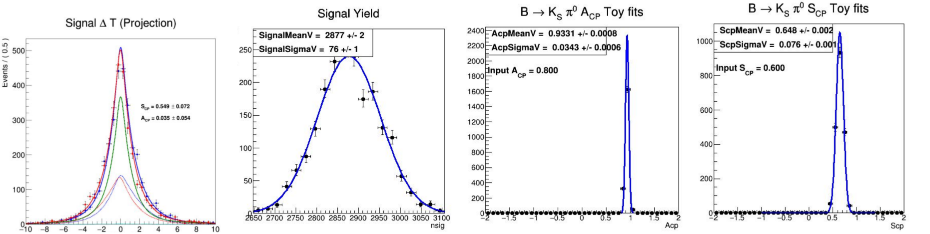
Developing Time-dependent fitter

- Apply cut $\Delta t_{err} < 2.5$ ps
- Fitting to Δt $\rightarrow$ B-Physics PDF convolved with a double gaussian:

$$P_{sig}(\Delta t, q) = \frac{\exp^{-|\Delta t|/\tau_{B0}}}{4\tau_{B0}}([1 - q\Delta w + q\mu_i(1-2w)] + [q(1-2w) + \mu_i(1 - q\Delta w)](A_{CP}\cos(\Delta m_d \Delta t) - S_{CP}\cos(\Delta m_d \Delta t)))$$

$\rightarrow$ Core gaussian & Tail gaussian

- 4 dimensional fit to 8 bins of $q.r$ ($M_{bc}, \Delta E, \Delta t$, cont. suppression)



- Development of time-dependent fit ongoing in parallel

Summary & plans

Summary

- Shown the recap of Moriond resuls.
- Time-dependent analysis recent development and strategy.

Plans

- Develop the time-dependent part on $B^0 \to J/\psi K_S^0$ decays using only K_S^0 vertex.
- Repeat the time-independent analysis on Moriond data sample with $\Delta t_{err} < 2.5$ ps
- A_{CP} & S_{CP} measurement
- Two groups are working on $B^0 \to K_s^0 \pi^0$ time-dependent analysis
- Expect to have preliminary result in next winter conference.

Thank You

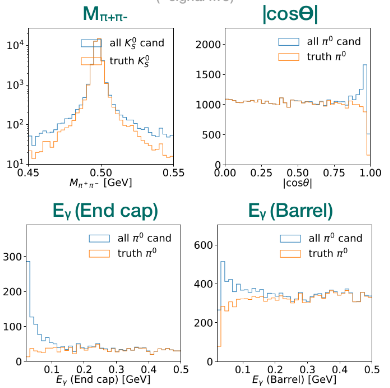
Backup

Candidates selections

- K_S^0 selection
  - pairs of oppositely charged particles that originate from a common space-point
  - `goodBelleKshort`

    requirements dependent on K_S^0 momentum,
    the K_S^0 flight distance,
    the distance between trajectories of the two charged-pion candidates,
    the angle between the pion-pair momentum and the direction of the K_S^0 flight
  - $0.482 \leq M_{\pi^+\pi^-} \leq 0.513$ [GeV/c²]
- π^0 selection
  - $0.119 \leq M_{\gamma\gamma} \leq 0.150$ [GeV/c²]
  - $|\cos\theta_{hel}| \leq 0.953$
- γ selection
  - E_γ (Endcap) ≥ 0.223 GeV
  - E_γ (Barrel) ≥ 0.080 GeV

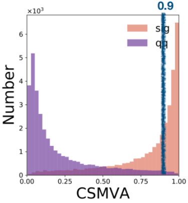
(* signal MC)

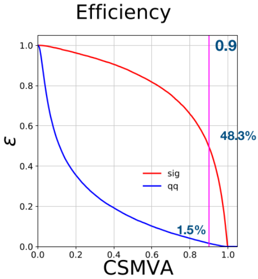


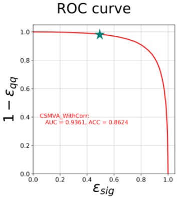
Continuum suppression

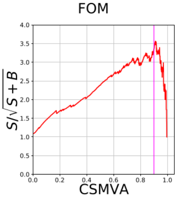
Belle II @ ICHEP2020
arXiv:hep-ex/2009.09452

- Select at CSMVA > 0.9
- Optimize by FOM ($S/\sqrt{S+B}$) in the signal enhanced region: $M_{bc} > 5.27$ GeV/c^2









6

Efficiency

- The analysis region is defined as
  $M_{bc} > 5.24$ GeV/c^2, $-0.3 < \Delta E < 0.3$ GeV
  The signal enhanced region is: (used for fit projection)
  $M_{bc} > 5.27$ GeV/c^2, $-0.16 < \Delta E < 0.08$ GeV

- Efficiency evaluation by Monte Carlo counting:

Operation	$\epsilon_{\rm sig}$	$\epsilon_{\rm B\bar{B}+rare}$	$\epsilon_{\rm q\bar{q}}$
Reconstruction	0.388	7.619×10^{-6}	0.001
Pre-selection	0.317	4.476×10^{-7}	1.278×10^{-4}
Continuum Suppression	0.156	1.810×10^{-7}	1.032×10^{-6}

Rare components investigation

2D (M_{bc}, ΔE) Extended Fit (Cont'd)

- Rare background contributing to the analysis region:

expected @ 62.8 fb⁻¹

$N = \int \mathscr{L}dt \cdot \sigma \cdot f^{+-} \cdot 2 \cdot \mathscr{B} \cdot \epsilon$

$N = \int \mathscr{L}dt \cdot \sigma \cdot f^{00} \cdot 2 \cdot \mathscr{B} \cdot \epsilon$

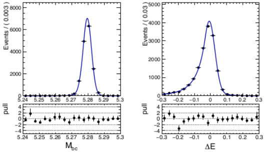
	Mode	$\mathcal{B}[10^{-6}]$ (PDG2020 Avg. [3])	ϵ[%]	Yield
B^+	$\rho^+ K^0$	$7.3^{+1.0}_{-1.2}$	1.05	5.5 ± 0.8
	$K^*(892)^+\pi^0$	6.8 ± 0.9	0.85	4.1 ± 0.5
	$X_{s,u}\gamma$	349 ± 19	<0.01	0.7 ± 0.0
	$a_1(1260)^+K^0$	35 ± 7	<0.01	0.1 ± 0.0
B^0	$f_2(1270)K^0$	$2.7^{+1.3}_{-1.2}$	0.52	1.0 ± 0.4
	$f_0(980)K^0$	4.1 ± 0.4	0.19	0.5 ± 0.1
	$X_{s,d}\gamma$	349 ± 19	<0.01	0.5 ± 0.0
	$K^0_S K^0_S$	0.61 ± 0.08	0.50	0.2 ± 0.0
	$K^0\eta'$	66 ± 4	<0.01	0.1 ± 0.0
Sum				12.7 ± 1.1

dominant processes
$B \to K^0\pi^+\pi^0$
(PDG; PRD)

- Finally assign a Gauss(μ=12.7, σ=1.1) constraint on the normalization of rare background

PDF Modelling

2D (M_{bc}, ΔE) Extended Fit (Cont'd)

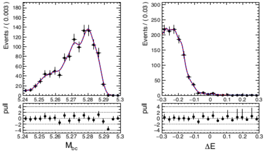


Signal

$$\mathcal{P}_{sig} \equiv \mathcal{P}_{sig}(M_{\rm bc}) \times \mathcal{P}_{sig}(\Delta E),$$

$$\begin{cases} \mathcal{P}_{sig}(M_{\rm bc}) & : 1 \text{ Gaussian} + 1 \text{ Crystal ball} \\ \mathcal{P}_{sig}(\Delta E) & : 1 \text{ Crystal ball} + 2 \text{ Gaussians} \end{cases}$$

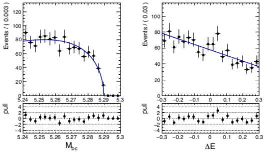
common means & relative widths



B decays background

$$\mathcal{P}_{rare} \equiv H_{rare}(M_{\rm bc}, \Delta E),$$

$$H_{rare}(M_{\rm bc}, \Delta E) : \text{2D kernel estimation PDF}$$



Continuum background

$$\mathcal{P}_{q\bar{q}} \equiv \mathcal{P}_{q\bar{q}}(M_{\rm bc}) \times \mathcal{P}_{q\bar{q}}(\Delta E),$$

$$\begin{cases} \mathcal{P}_{q\bar{q}}(M_{\rm bc}) & : 1 \text{ Argus} \\ \mathcal{P}_{q\bar{q}}(\Delta E) & : \text{Linear function} \end{cases}$$

9

Systematic — Branching fraction

$$\mathcal{B} = \frac{N_{sig}}{\epsilon \cdot \mathcal{B}_s \cdot 2 \cdot N_{B\bar{B}}}$$

$$\mathcal{B}_s = f(K^0 \to K_S^0) = 50\,\%$$

$$N_{B\bar{B}} = \int L dt \cdot \sigma_{e^+e^- \to \Upsilon(4S)} \cdot f^{00}$$

1. $N(B\bar{B})$
2. Tracking efficiency ($K_S^0 \to \pi^+\pi^-$): 2*0.91%
3. K_S^0 reconstruction
   - Average 3D flight distance * 0.31%
   - For 2nd & 3rd layer of vertex detector: additional uncertainty of 15%
4. π^0 reconstruction

   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
5. Continuum suppression efficiency

   Efficiency ratio of $B^+ \to \bar{D}^0(\to K^+\pi^-\pi^0)\pi^+$ in MC & data at CSMVA > 0.9 cut point
6. Signal modeling
   1. $M_{\rm bc}$: 1CB + 1Gaus → 1CB + 2Gaus (~0.01%)
   2. ΔE: 1CB + 2Gaus → 1CB + 1Gaus (~0.01%)
7. Continuum background modeling
   1. $M_{\rm bc}$: Argus → Argus + Gaus (~0.01%)
   2. ΔE: Linear → 2nd order Chebyshev polynomial (1.4%)

* Uncertainty on rare modeling is addressed in the Gaussian constrained N_{rare} normalization

1. Flavor tagging modeling:
   An alternative fit with the flavor parameters obtained by the signal MC (accounting for decay mode dependence)
2. B^0 mixing parameter χ_d

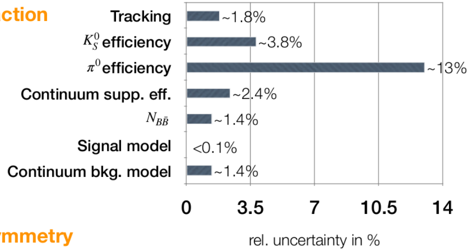
   An alternative fit with χ_d varied by its uncertainty

   ($\chi_{d,\,WA} = 0.1858 \pm 0.0011$)
3. *B*-decay background asymmetry
   An alternative fit with *B*-decay background asymmetry varied to ± 1 (conservative)
4. Continuum background asymmetry
   Allow non-zero asymmetry for continuum background ($A_{CP,\,qq}$), yielding a $A_{CP,\,qq}$ consistent with zero with a 7% uncertainty

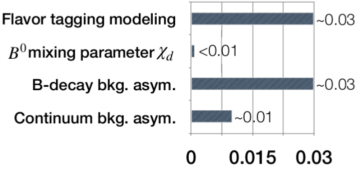
* Uncertainty in determining of flavor parameters ($\Delta w, w, \epsilon$) are addressed with Gaussian constraints in the nominal fit
⇒ propagated as the statistical uncertainty of $A_{K^0\pi^0}$

$\mathscr{B}, A_{K^0\pi^0}$ for 62.8 fb^{-1} Moriond data

Branching fraction



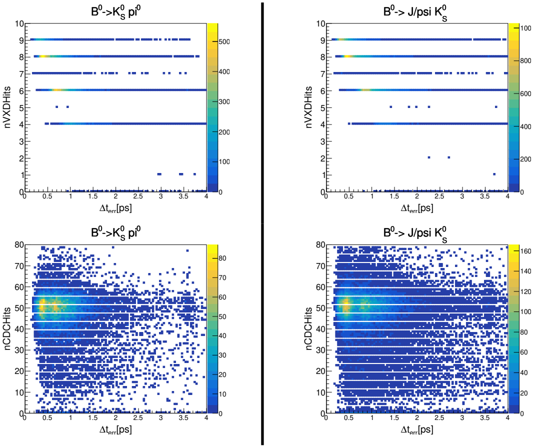
Direct *CP* asymmetry



$$\mathscr{B} = (8.5^{+1.7}_{-1.6} \pm 1.2) \times 10^{-6}$$

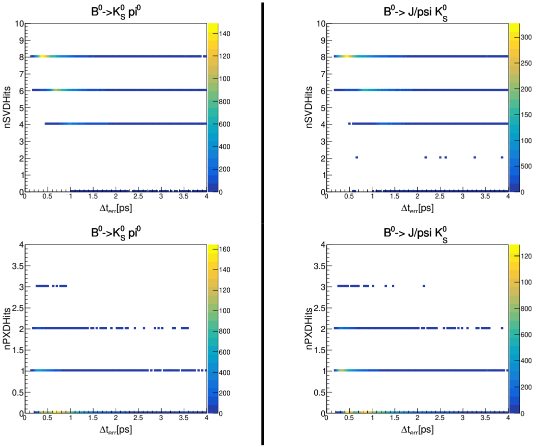
$$A_{K^0\pi^0} = -0.40^{+0.46}_{-0.44} \pm 0.04$$

Δt_{err} vs. Hits(VXD + CDC)



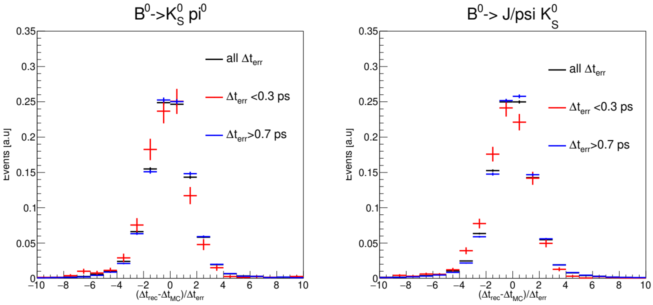
- We plots number of hits in VXD and CDC to find out the double peak structure in the Δt_{err} distribution.

Δt_{err} vs. Hits (SVD +PXD)



- We plots number of hits in SVD and PXD to find out the double peak structure in the Δt_{err} distribution.

Pull distribution

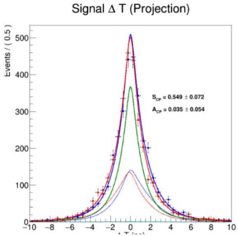


- Pull distribution shows similar behaviourn for both signal and control chanels.

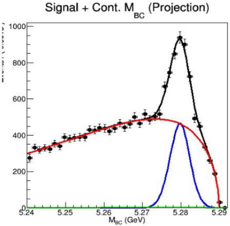
Single Fits

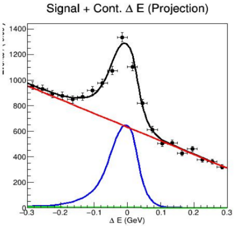
Scp = 0.549 ± 0.072 (Expected: 0.6)
Acp = 0.035 ± 0.054 (Expected: 0.0)
Yield: 2852 ± 71 (Expected: 3051)

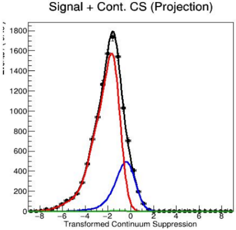
Simulated Luminosity: $5 ab^{-1}$



Currently using 8 bins of q.r - Working on changing to 7







1

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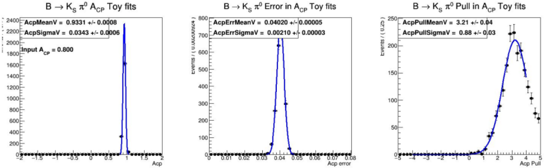
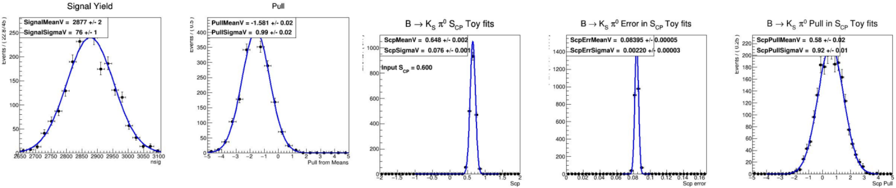
MC Toy Results

Scp = 0.648 ± 0.084 (Expected: 0.6)
Acp = 0.933 ± 0.040 (Expected: 0.8)
Yield: 2877 ± 75 (Expected: 3051)





2

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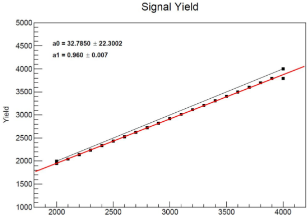
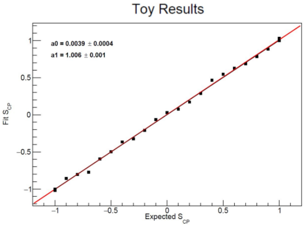
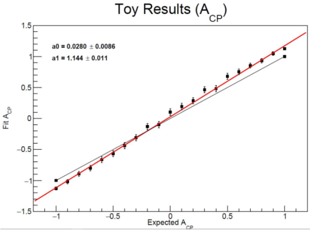
Linearity Tests

~4% Bias in Yield	~0.6% Bias in Scp	~14% Bias in Acp
a0 = 32.78	a0 = 0.0039	a0 = 0.028
a1 = 0.96	a1 = 1.006	a1 = 1.14







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