BELLE2-NOTE-PH-2021-055

Measurement of the Λ_c^+ lifetime at Belle II

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Contamination from $\Xi_c \to \Lambda_c$

- John Yelton noted that $\Xi_c^0 \to \Lambda_c^+\pi^-$ has been roughly measured and $\Xi_c^+ \to \Lambda_c^+\pi^0$ is expected to be of the same order
  - LHCb measurement (PhysRevD.102.071101): $BR(\Xi_c^0 \to \Lambda_c^+\pi^-) = 0.55 \pm 0.20\,\%$
  - Prediction (https://arxiv.org/pdf/2111.14111.pdf): $BR(\Xi_c^+ \to \Lambda_c^+\pi^0) = 1.11\,\%$
  - https://belle.kek.jp/secured/belle_note/gn1621/BN_1621_openbox_v1.pdf
    - $N(\Xi_c^0)/fb = N(\Xi_c^0 \to \Lambda_c^+\pi^-)/(\epsilon * BF_{\Xi_c^0} * BF_{\Lambda_c^+} * \mathscr{L}) = 1293/(0.1422 * 0.0061 * 0.0628 * 983) = 2.4 \times 10^4$ events
  - At Belle II (208/fb)
    - $N(\Lambda_c^+) = N(\Lambda_c^+ \to pK^-\pi^+)/(\epsilon * BF) = 1.64 \times 10^5/(0.122 * 0.0628) = 2.14 \times 10^7$ events
    - $N(\Xi_c^0 \to \Lambda_c^+\pi^-) = N(\Xi_c^0) * BF_{\Xi_c^0} * \mathscr{L} = 2.4 \times 10^4 * 0.0061 * 208 = 3.0 \times 10^4$ events ~ 0.14%

  - In 140/fb of Belle data (https://arxiv.org/pdf/hep-ex/0409065.pdf): approx. 3.0×10^6 Ξ_c^0 events, 2.75×10^6 Ξ_c^+ events
    - Extrapolating to 208/fb: 2.5×10^4 $\Xi_c^0 \to \Lambda_c^+\pi^-$ events, 4.5×10^4 $\Xi_c^+ \to \Lambda_c^+\pi^0$ events

Contamination from $\Xi_c \to \Lambda_c$

- Signal efficiency (signal MC) = 12.2%
- Number of Λ_c^+ in 1/ab generic MC = 5.26×10^5 (truth-matched)/0.122 = 4.31×10^6 events
- Assume 0.1% of Λ_c^+ comes from Ξ_c, $N(\Xi_c)$ = $4.31 \times 10^6 * 0.001 = 4.31 \times 10^3$ events
- Produced signal MC in batches of 10,000 events → overestimated by factor of 2

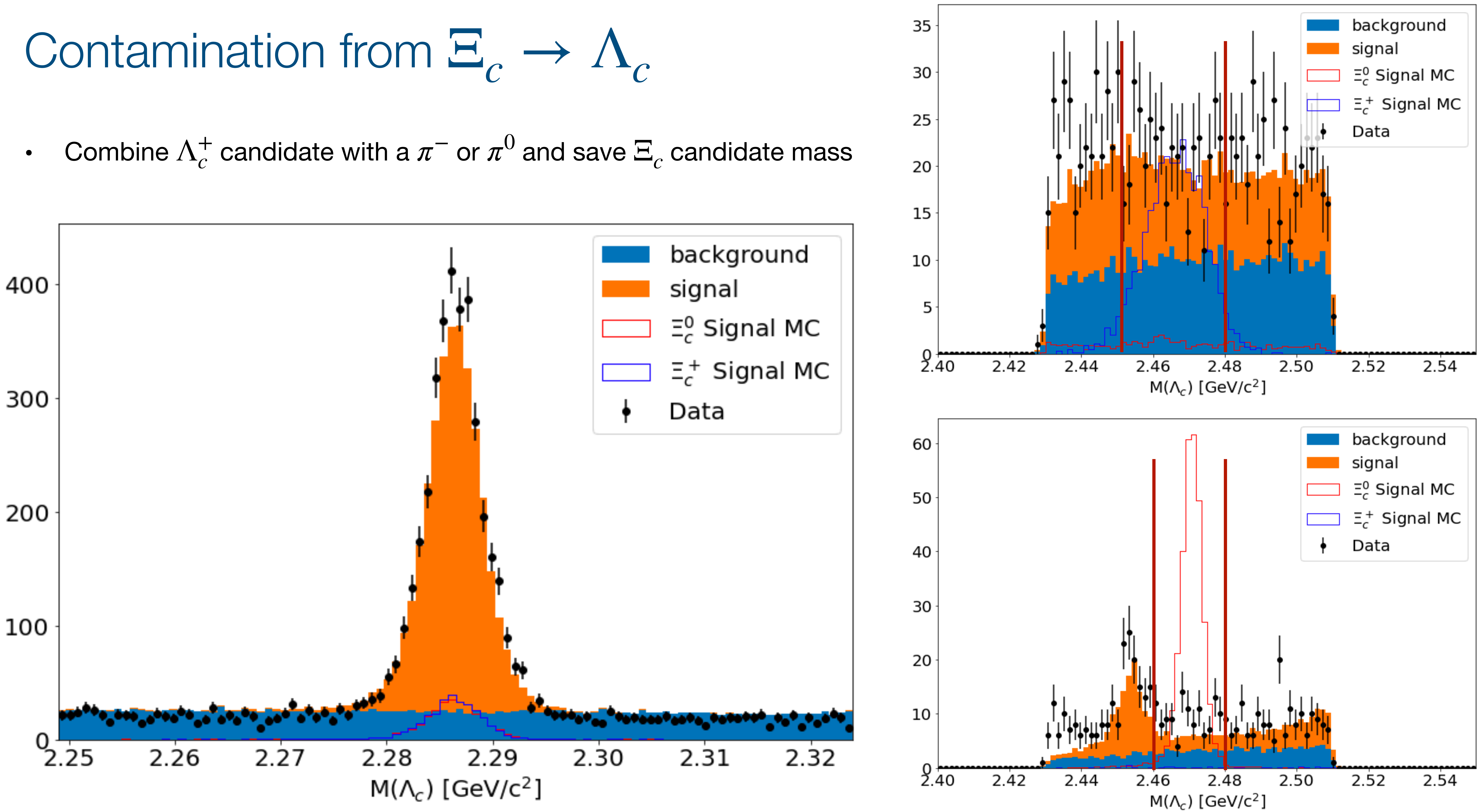
- Fits to 1/ab MC sample (true lifetime = 201.836 fs)
  - Signal only without Ξ_c: 202.353 ± 0.385 fs
  - Signal only with Ξ_c^0: 202.489 ± 0.384, difference = 0.136 fs
  - Signal only with Ξ_c^+: 202.686 ± 0.385, difference = 0.333 fs

- Fits to 100/fb MC sample
  - Without Ξ_c mass cut: 201.127 ± 1.247 fs
  - With Ξ_c mass cut: 200.847 ± 2.976 fs

Source	uncertainty (fs)
Resolution model	0.46
Background contamination	0.20
Imperfect alignment	0.46
Momentum scale correction	0.09
Input charm masses	0.01
Total systematic uncertainty	0.69
Statistical uncertainty	0.88

Contamination from $\Xi_c \rightarrow \Lambda_c$

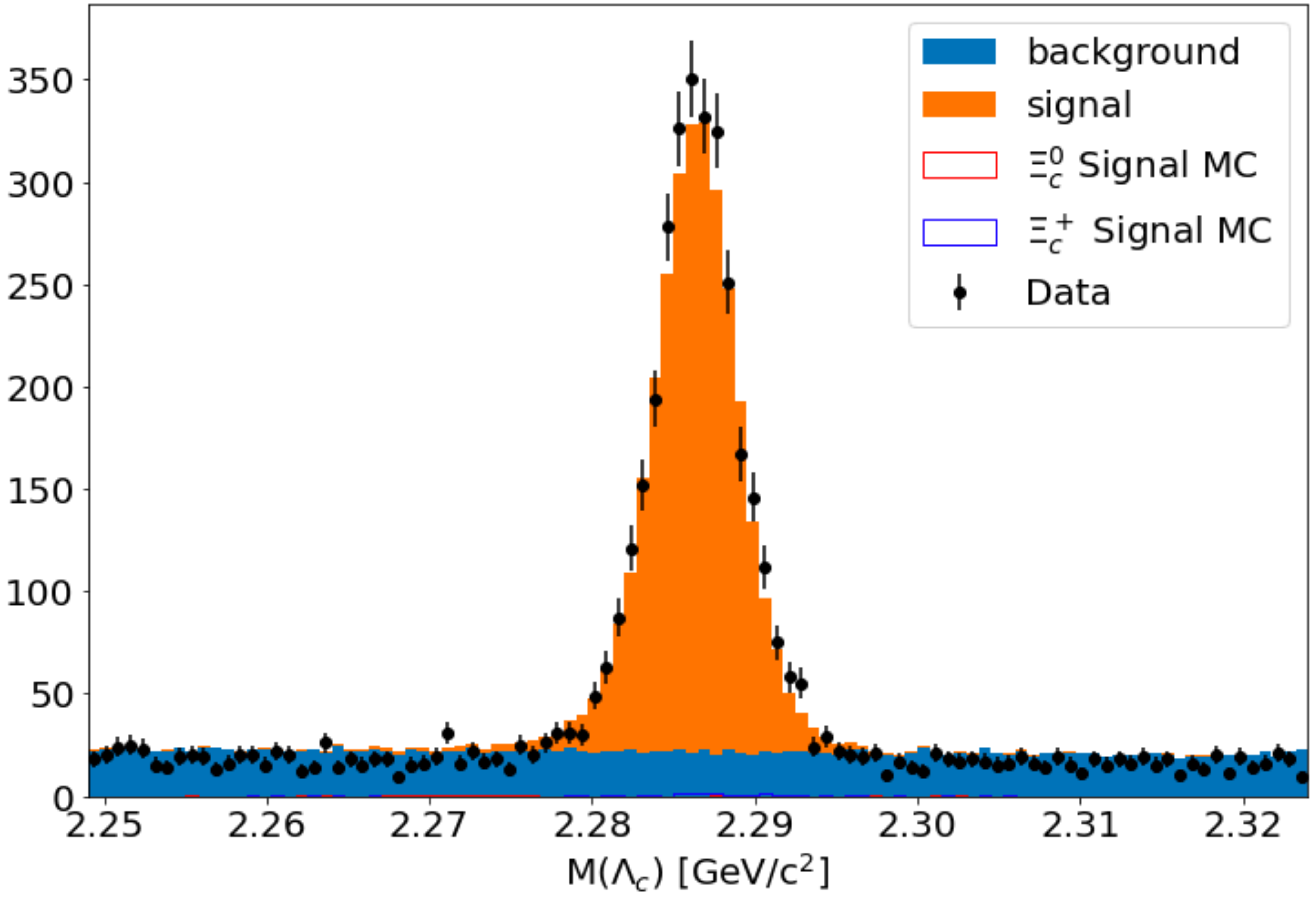
- Combine Λ_c^+ candidate with a π^- or π^0 and save Ξ_c candidate mass



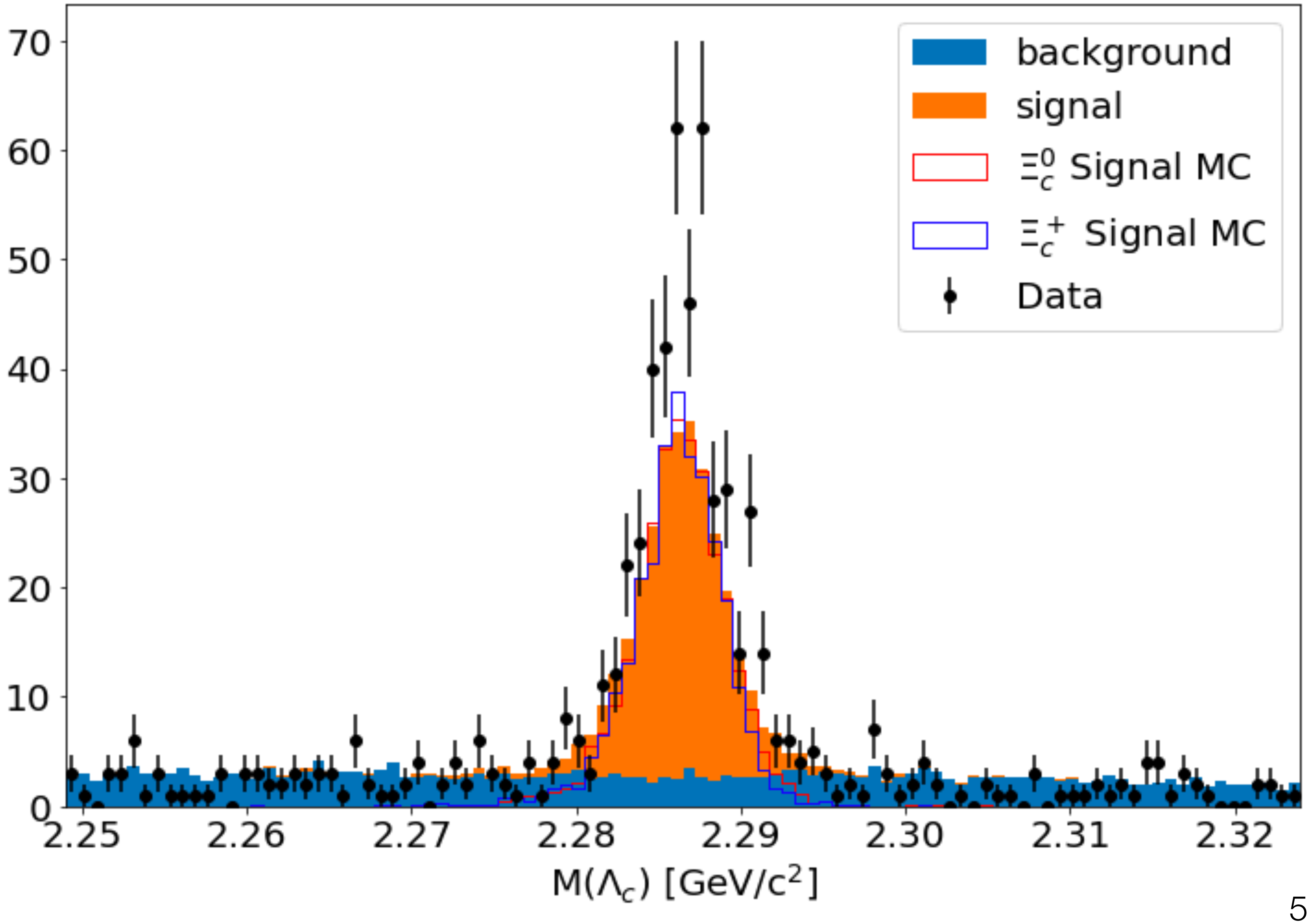
Contamination from $\Xi_c \rightarrow \Lambda_c$

- Combine Λ_c^+ candidate with a π^- or π^0 and save Ξ_c candidate mass
  - Signal efficiency ~90%
  - Approximate uncertainty: 0.88 fs -> 0.93 fs (statistical) versus 0.69 fs -> 0.76 fs (systematic)

With Ξ_c mass cuts



With opposite Ξ_c mass cuts



All the details…

Introduction

- BSM searches rely on accurate theory descriptions with predictive tools like Heavy Quark Expansion (HQE)
  - e.g. to determine decay widths of heavy hadrons
  - Charm lifetimes sensitive to higher order contributions, provide stringent tests of theory

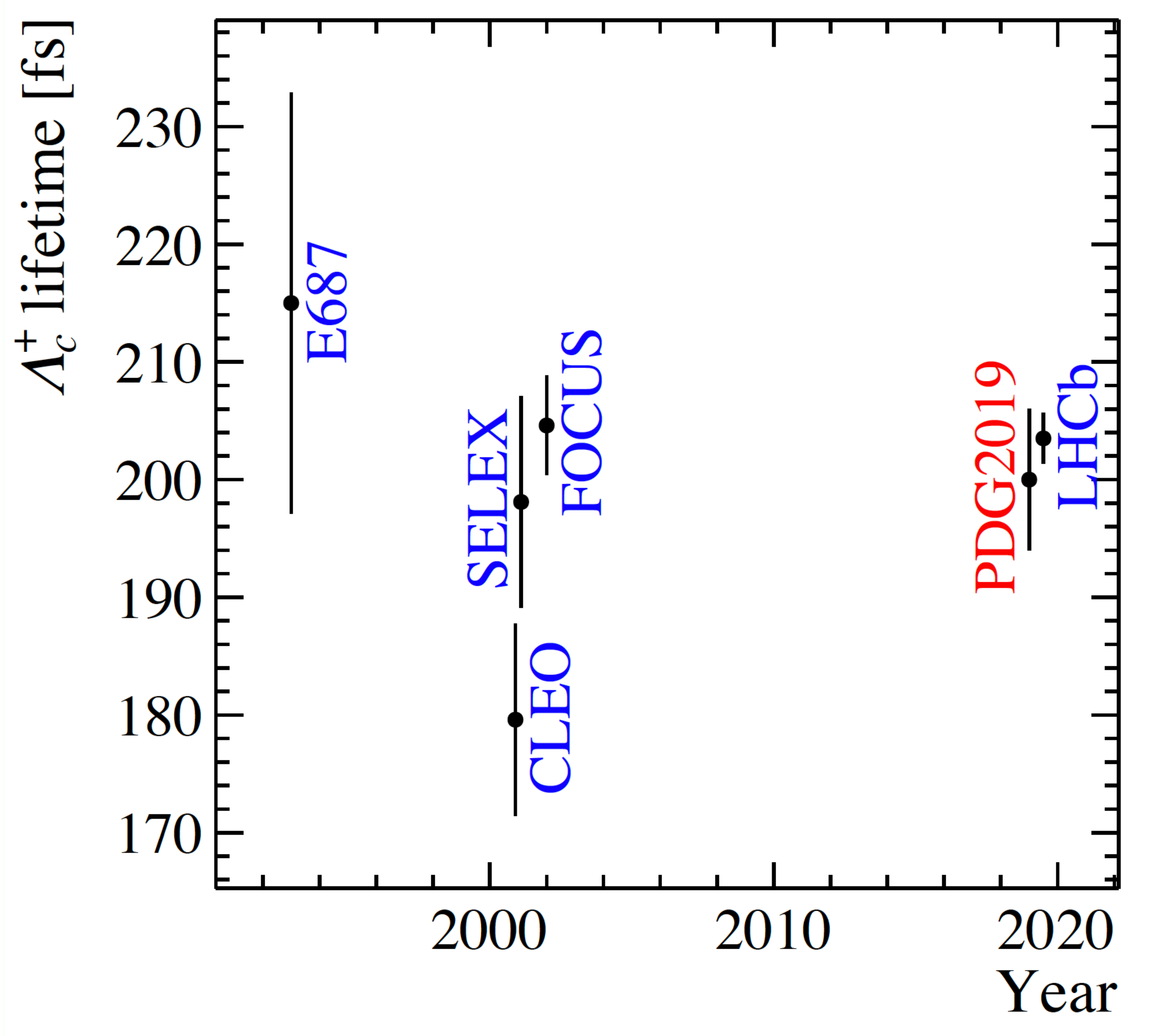
- This study: measure the Λ_c^+ lifetime using the decay $\Lambda_c^+ \to pK^-\pi^+$
  - Also provides an opportunity to test capability of Belle II for precision measurements
  - Competitive measurement with existing data
  - Uses tools from D^0/D^+ lifetime measurement (PRL 127 211801 2021)

- Samples
  - Data: “Moriond 2022" ~208/fb (blinded) from HLT hadron skim
  - MC: MC14ri_a,d (1/ab) (run-dependent samples not available)
  - Signal MC for systematics

$LHCB,\ \tau = 203.5 \pm 1.0 \pm 1.3 \pm 1.4\ fs$

$FOCUS,\ \tau = 204.6 \pm 3.4 \pm 2.5\ fs$

$CLEO,\ \tau = 179.6 \pm 6.9 \pm 4.4\ fs$



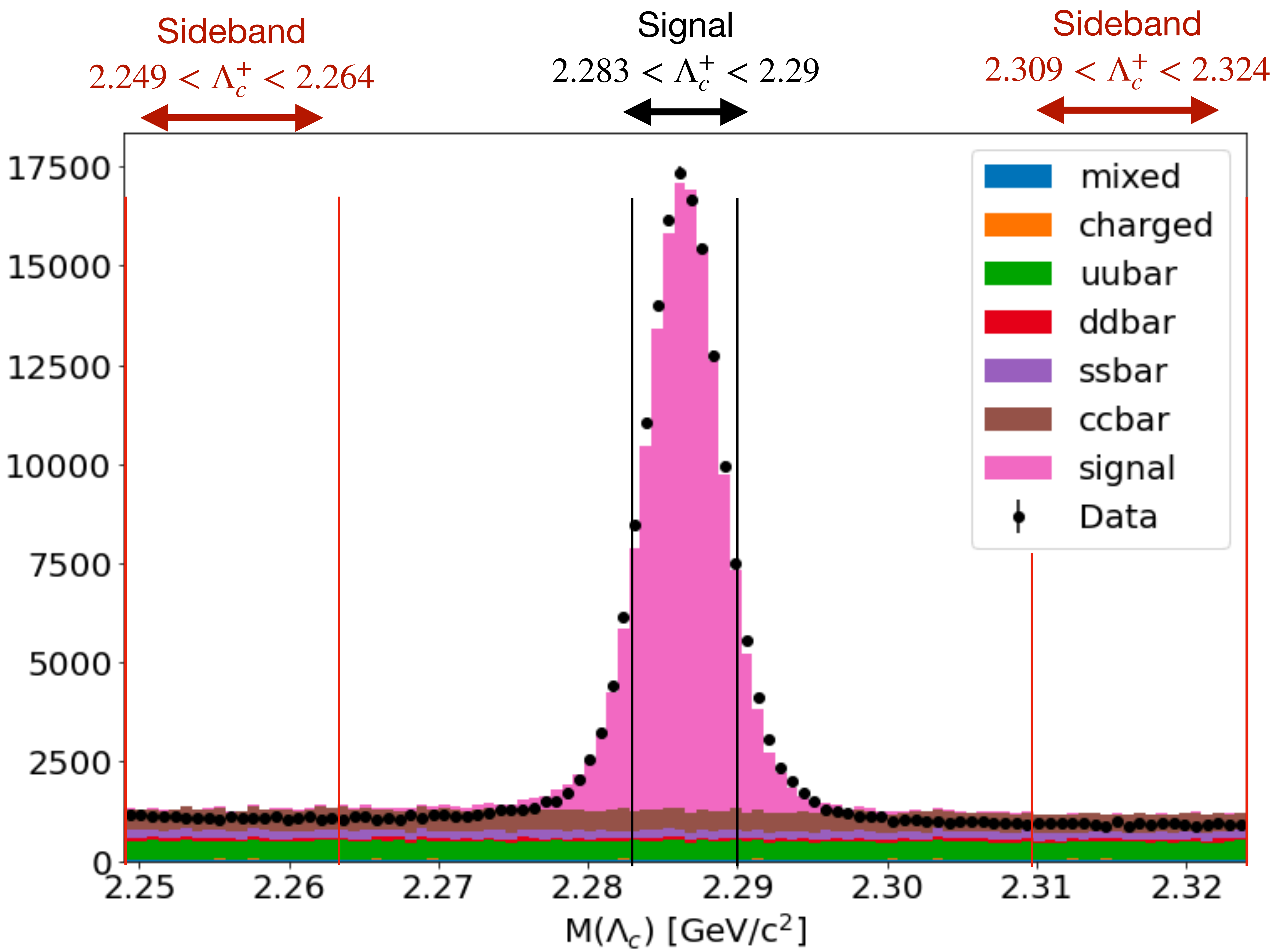
Event selection criteria

Software version: light-2104-poseidon

Lifetime fitting code: https://stash.desy.de/projects/B2CHARM/repos/charm_lifetimes/browse (lambdac_lifetime branch)

Selection criteria:

- Tracks must be in the CDC acceptance and have at least 20 CDC hits, at least one PXD hit, and a hit in the first layer of the SVD
- dr < 0.5 cm, |dz| < 2 cm (standard track cuts)
- Vertex fit (TreeFitter with IP constraint) conf_level > 0.01
- Λ_c CM momentum > 2.5 GeV/c
- Remove charm backgrounds by cutting on M(pKπ) with pion hypothesis for proton track
- Proton PID (trinary) > 0.9
- Kaon PID (global) > 0.6
- $p_t(\pi)$ > 0.35 GeV/c, $p_t(p)$ > 0.7 GeV/c
- Events with multiple candidates are discarded



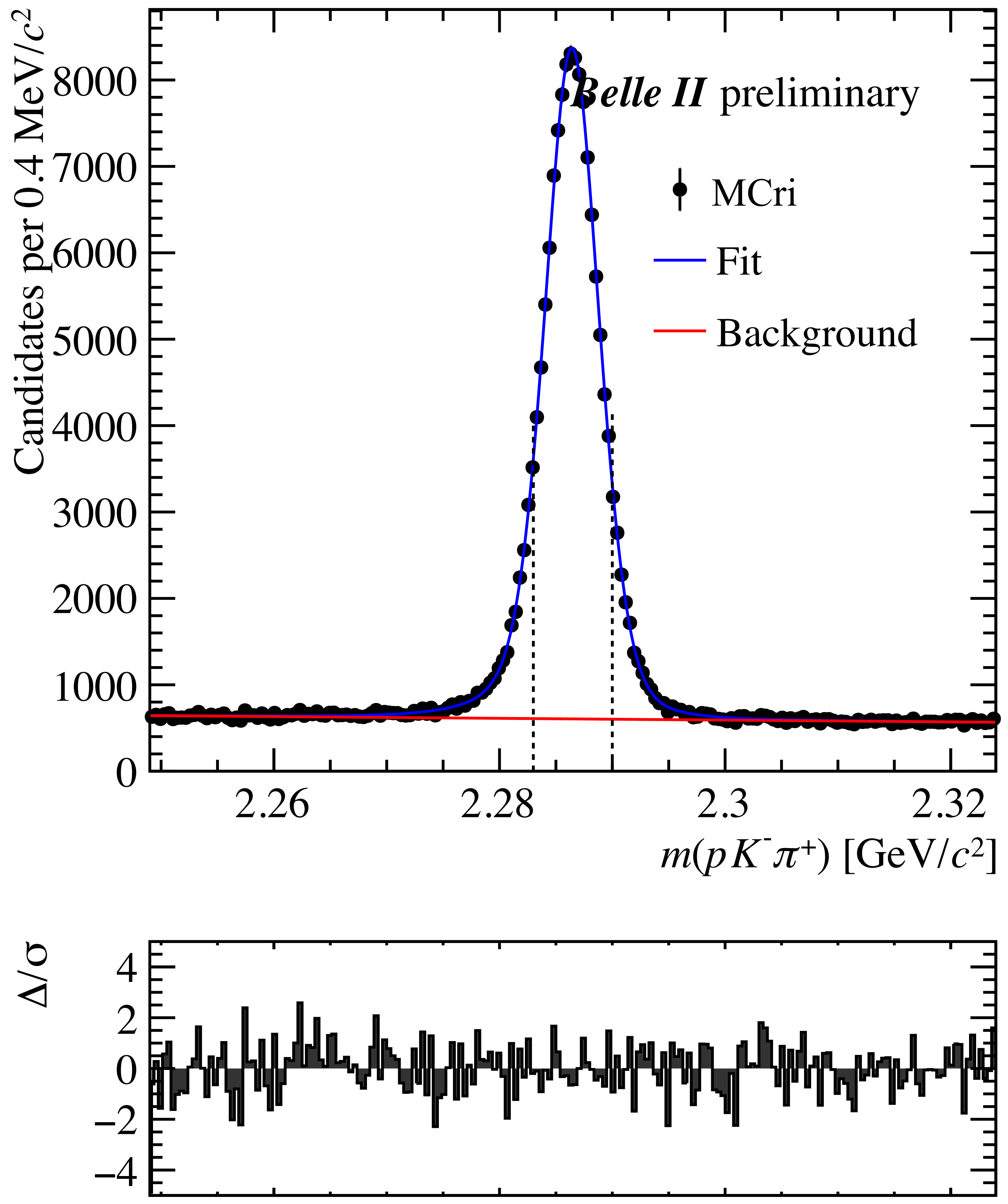
MC scaled to luminosity in data (207.233/200)

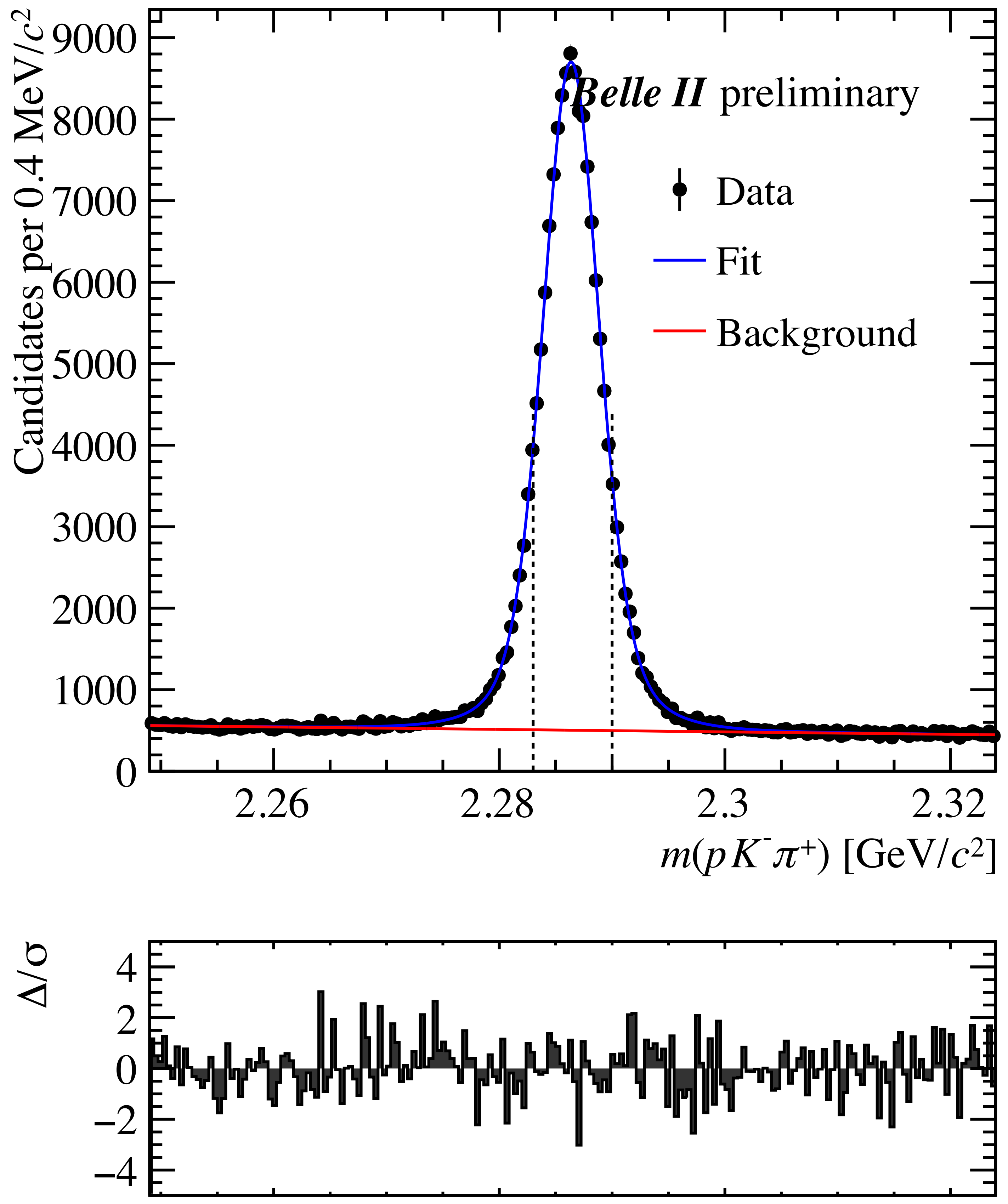
Invariant mass fit

$$J_{SU}(x,\mu,\sigma,\delta,\gamma) = \frac{\delta}{\sqrt{2\pi\sigma^2}\sqrt{1+(\frac{x-\mu}{\sigma})^2}} e^{-\frac{1}{2}[\gamma+\delta sinh^{-1}(\frac{x-\mu}{\sigma})]^2}$$

- Invariant mass fit to events passing all selection criteria
  - Signal: Gaussian + Johnson S_U function
  - Background: first-order polynomial

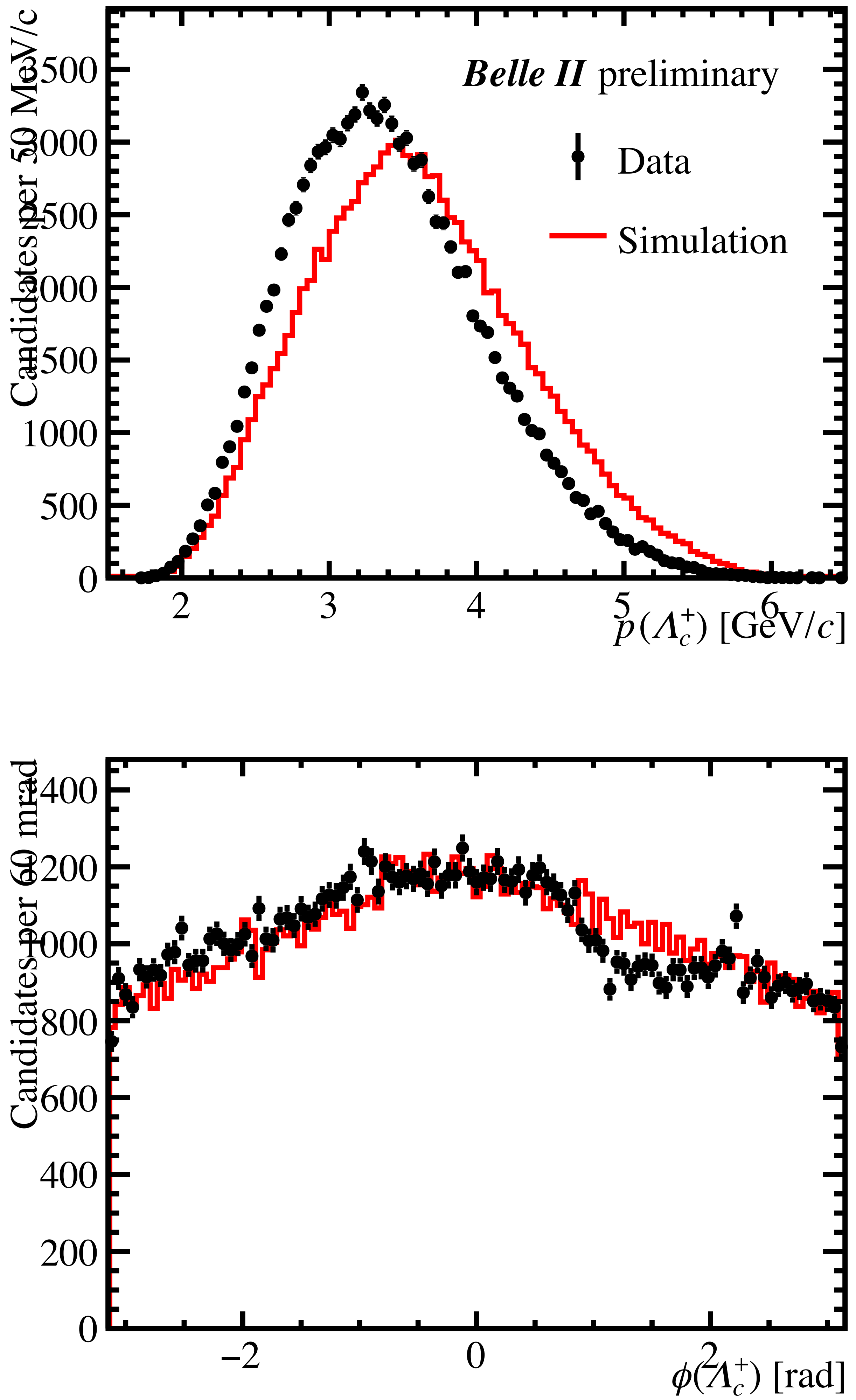
Parameter	200 fb^{-1} MC	Data
N_{sig}	135756 ± 680	151516 ± 616
f_G	0.599 ± 0.034	0.487 ± 0.035
μ_G	0.0006 ± 0.0002	-0.0001 ± 0.0002
σ_G	0.0025 ± 0.00004	0.0025 ± 0.00006
l_J	0.0029 ± 0.0003	0.0037 ± 0.0003
g_J	0.163 ± 0.023	-0.028 ± 0.014
d_J	1.010 ± 0.092	1.180 ± 0.089
N_{bkg}	121059 ± 669	100578 ± 573
c	-0.348 ± 0.006	-0.382 ± 0.002



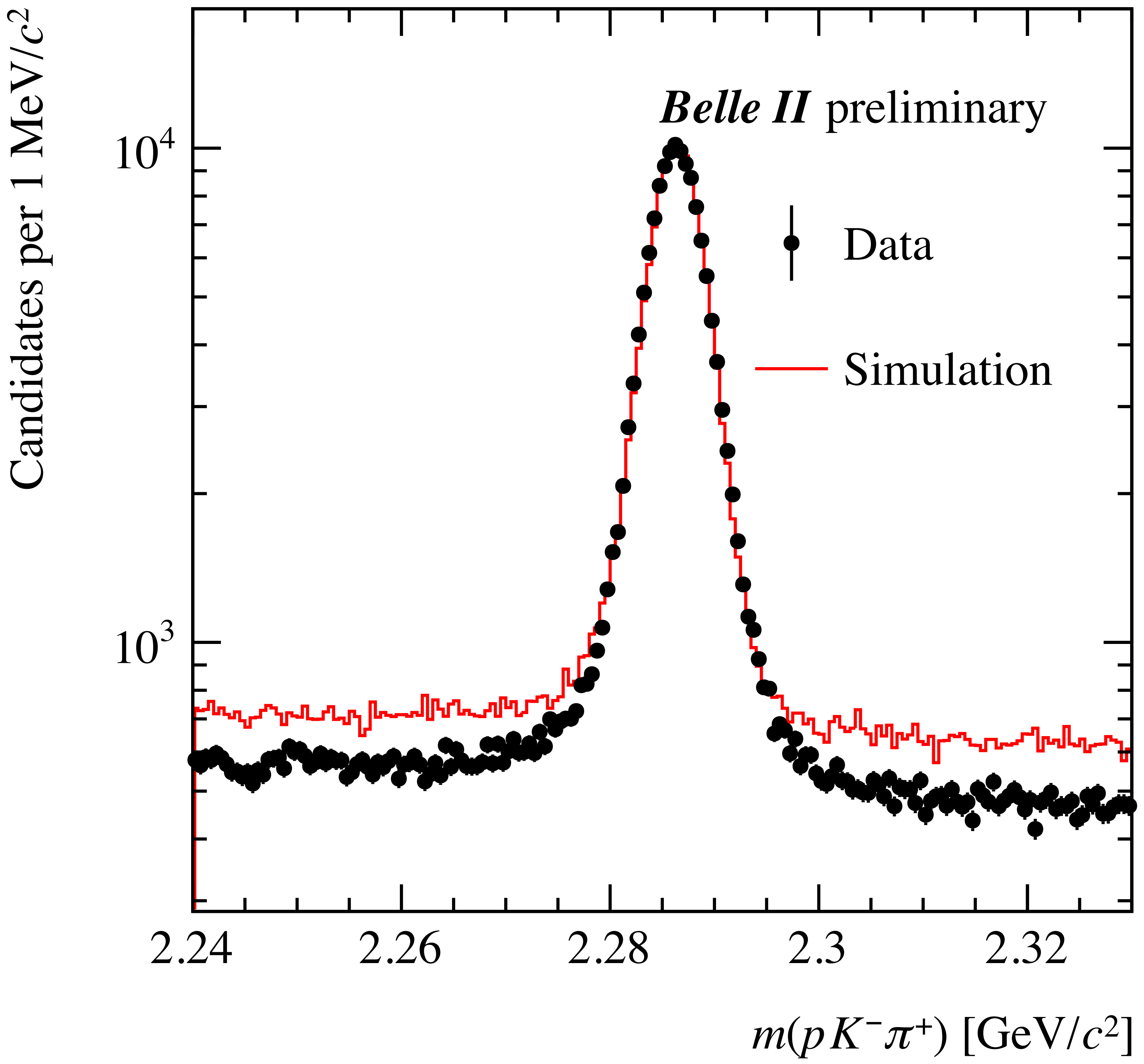


- Background fractions:
  - MC - 9.59 ± 0.02%
  - Data - 7.53 ± 0.02%
- Applied as constraint in lifetime fit

Data/MC comparison



- Some differences in momentum distributions, likely due to mismodeling in the simulation
- Discrepancy in background contamination between data and MC
  - Note: MC only for validation, not used in measurement with data



Lifetime fit

- Unbinned maximum-likelihood fit to the 2D distribution of decay time (t) and decay-time uncertainty (σ_t):

Binned template from data

$$pdf(t, \sigma_t \,|\, \tau, f, b, s_1, s_2) = pdf(t \,|\, \sigma_t, \tau, f, b, s_1, s_2)\, pdf(\sigma_t)$$

$$\propto \int_0^\infty e^{-t_{true}/\tau} R(t - t_{true} \,|\, \sigma_t, f, b, s_1, s_2) dt_{true}\;\; pdf(\sigma_t)$$

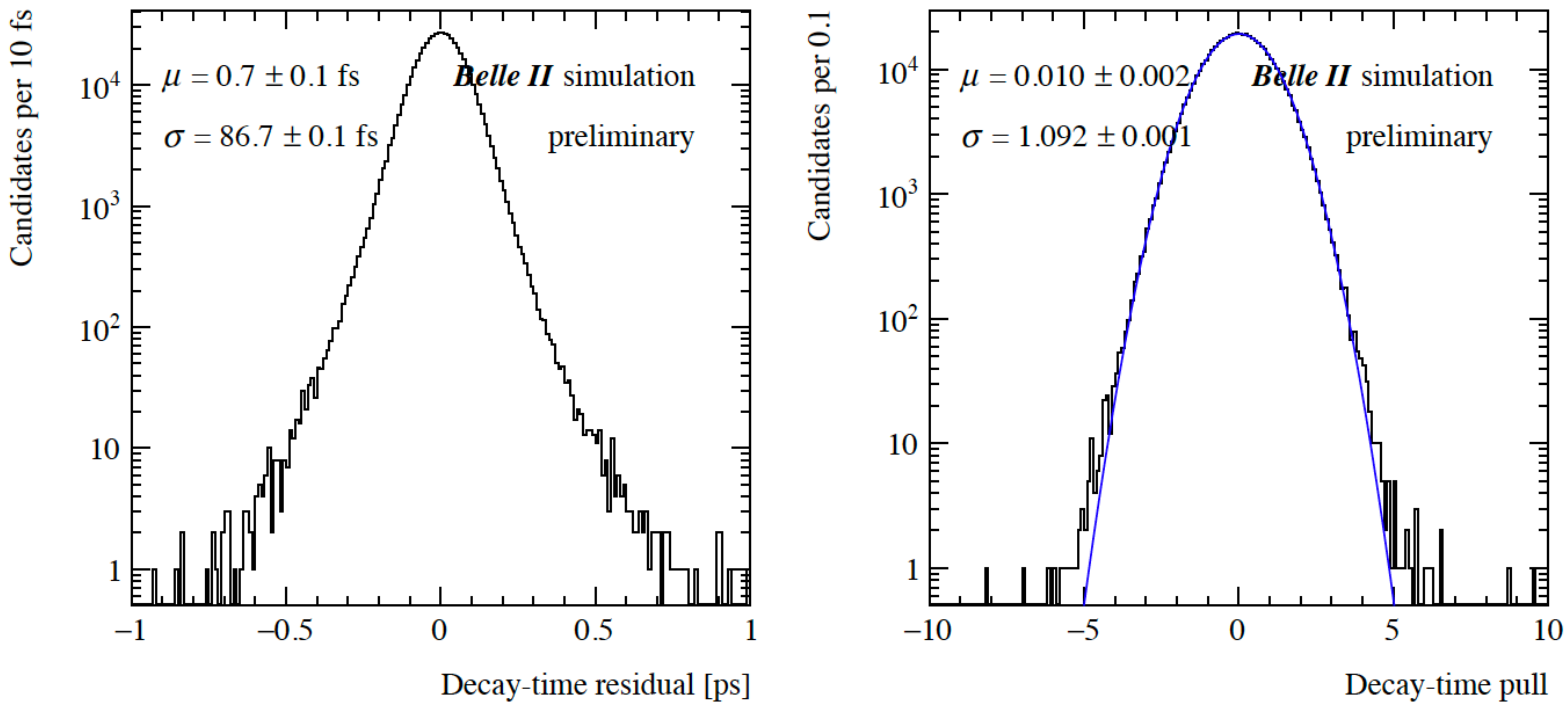
Lifetime fit

- Resolution model: single- or double-Gaussian function (common mean)

Proper time scaling error

$$R(t - t_{true} \,|\, \sigma_t, f, b, s_1, s_2) = f\, G(t - t_{true} \,|\, b, s_1\sigma_t) + (1 - f) G(t - t_{true} \,|\, b, s_2\sigma_t)$$

Common bias



Lifetime fit

- Full lifetime function

$$L(\tau, f_{bg}, f_\tau, f_{\tau_1}, \tau_{bg1}, \tau_{bg2}, s_1, s_2, f, s_{bkg}) = \prod_i \{ (1 - f_{bg}) \times pdf(t_i, \sigma_{t,i} | \tau, f, b, s_1, s_2)$$

$$+ f_{bg} \, (f_\tau \, [f_{\tau_1} \, pdf(t_i, \sigma_{t,i} | \tau_{bg1}, f, b, s_1, s_2, s_{bkg}) + (1 - f_{\tau_1}) \, pdf(t_i, \sigma_{t,i} | \tau_{bg2}, f, b, s_1, s_2, s_{bkg})] + (1 - f_\tau) \, R(t_i | \sigma_{t,i}, f, b, s_1, s_2, s_{bkg}) \, pdf(\sigma_t))\}$$

- Model background with two lifetime-background terms:

$$f_{\tau 1} \, pdf(t, \sigma_t | \tau_{bkg1}, f, b, s_1, s_2, s_{bkg}) - (1 - f_{\tau 1}) \, pdf(t, \sigma_t | \tau_{bkg2}, f, b, s_1, s_2, s_{bkg})$$

and a zero-lifetime background term:

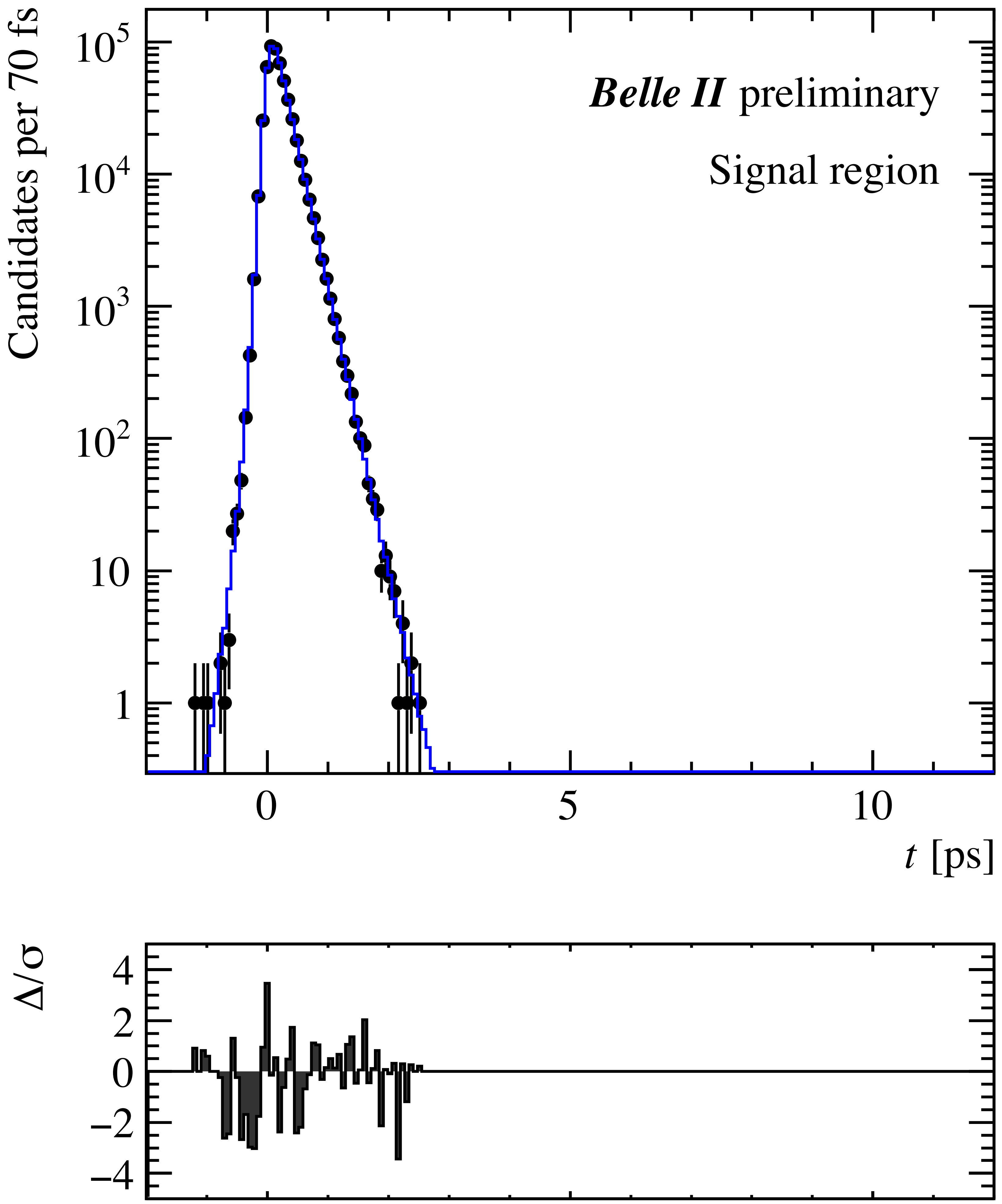
$$R(t - t_{true} | \sigma_t, f, b, s_1, s_2, s_{bkg}) \, pdf(\sigma_t)$$

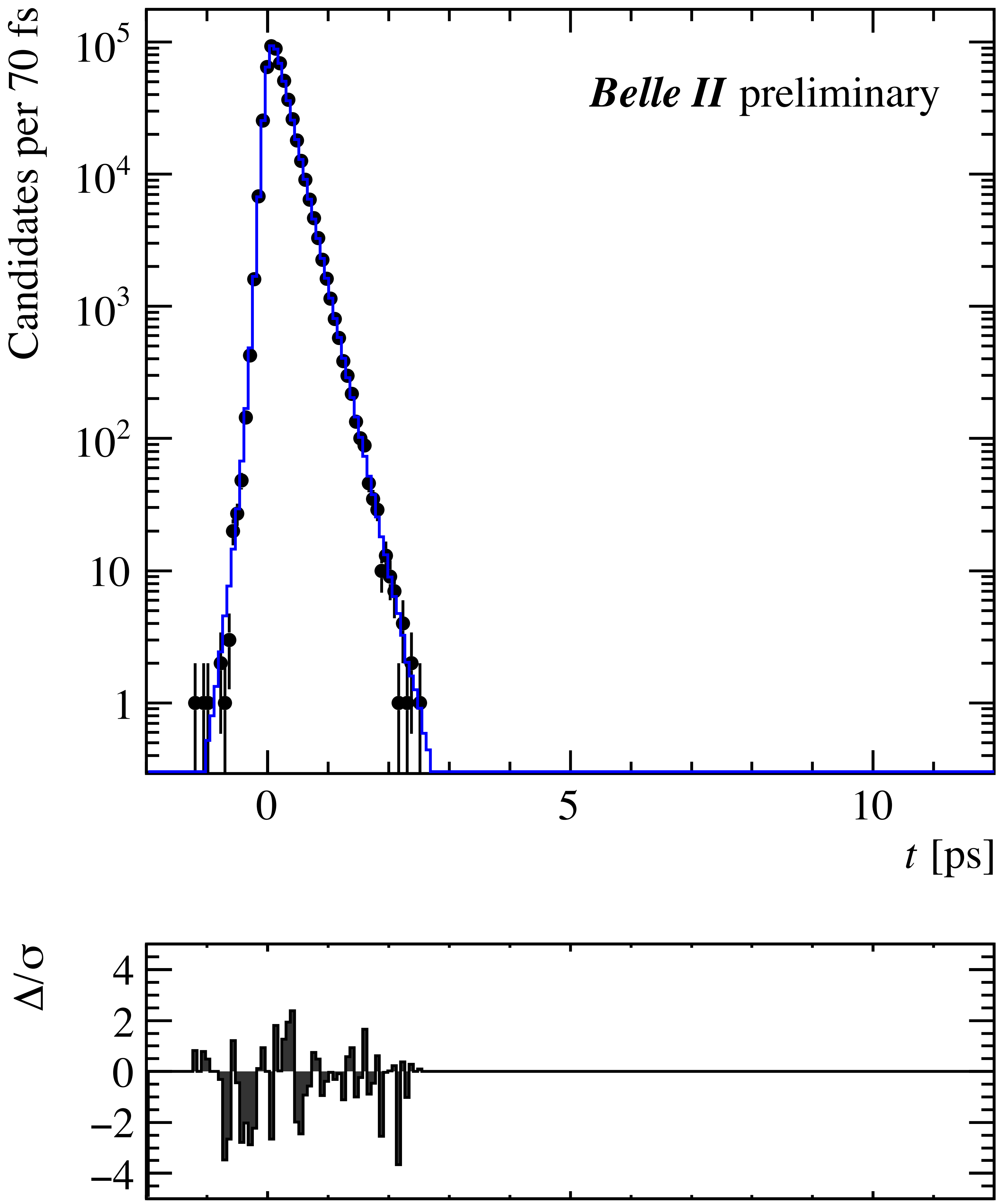
- Additional penalty factor added to $-2ln(L)$ to constrain background level from invariant mass fit

$$\frac{(f_{bkg,fit} - f_{bkg,expected})^2}{\sigma^2_{bkg,expected}}$$

Signal-only fit

Parameter	Fit result w/single Gaussian	Fit result w/double Gaussian
τ (fs)	202.35 ± 0.38	202.53 ± 0.39
b (fs)	0.13 ± 0.28	-0.04 ± 0.28
s_1	1.080 ± 0.003	1.0601 ± 0.0075
s_2		1.7013 ± 0.1556
f		0.9783 ± 0.0138



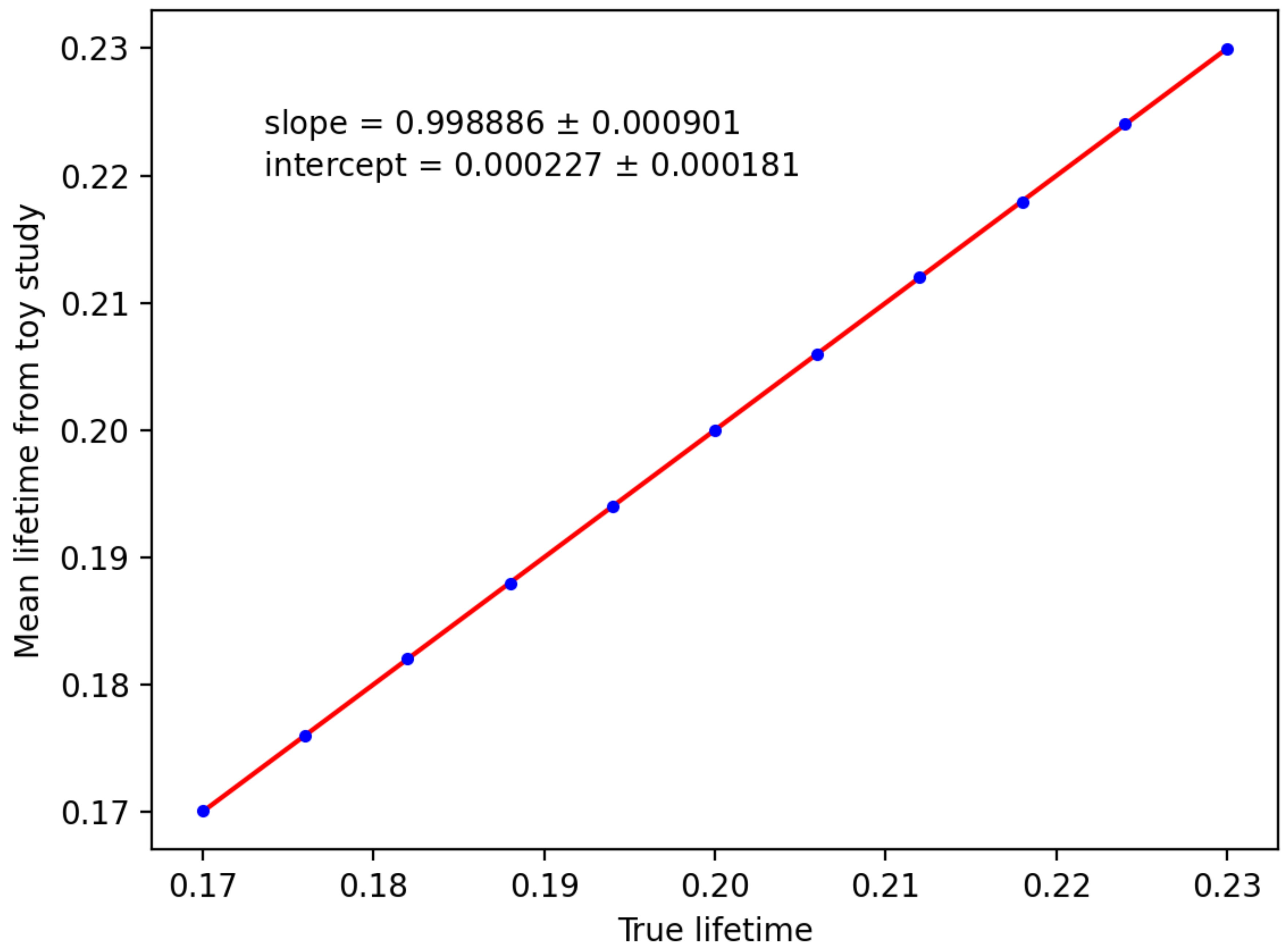


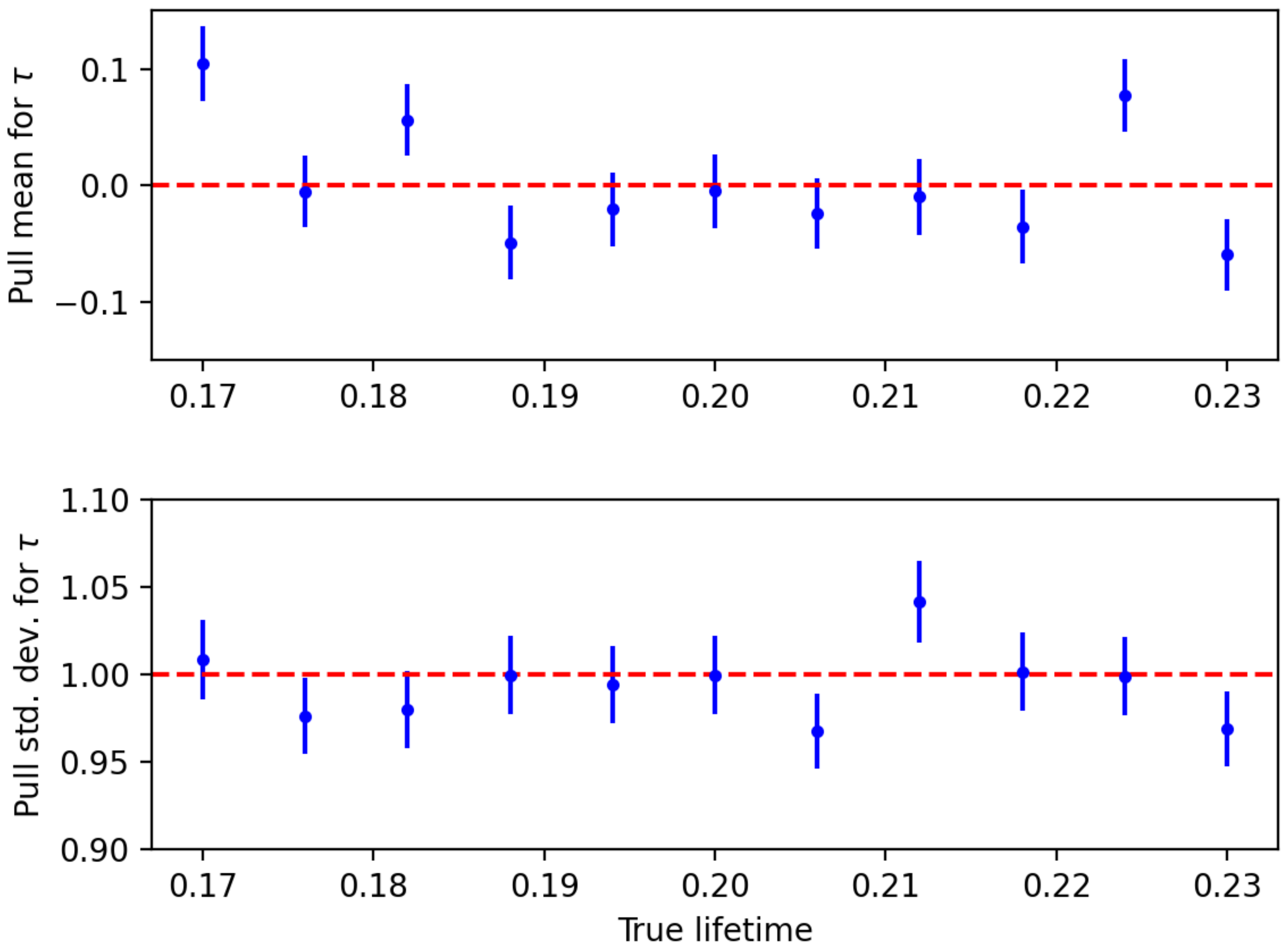
- Single- (left) and double-(right) Gaussian resolution function
- Truth-matched signal from 1/ab equivalent MC14ri_a

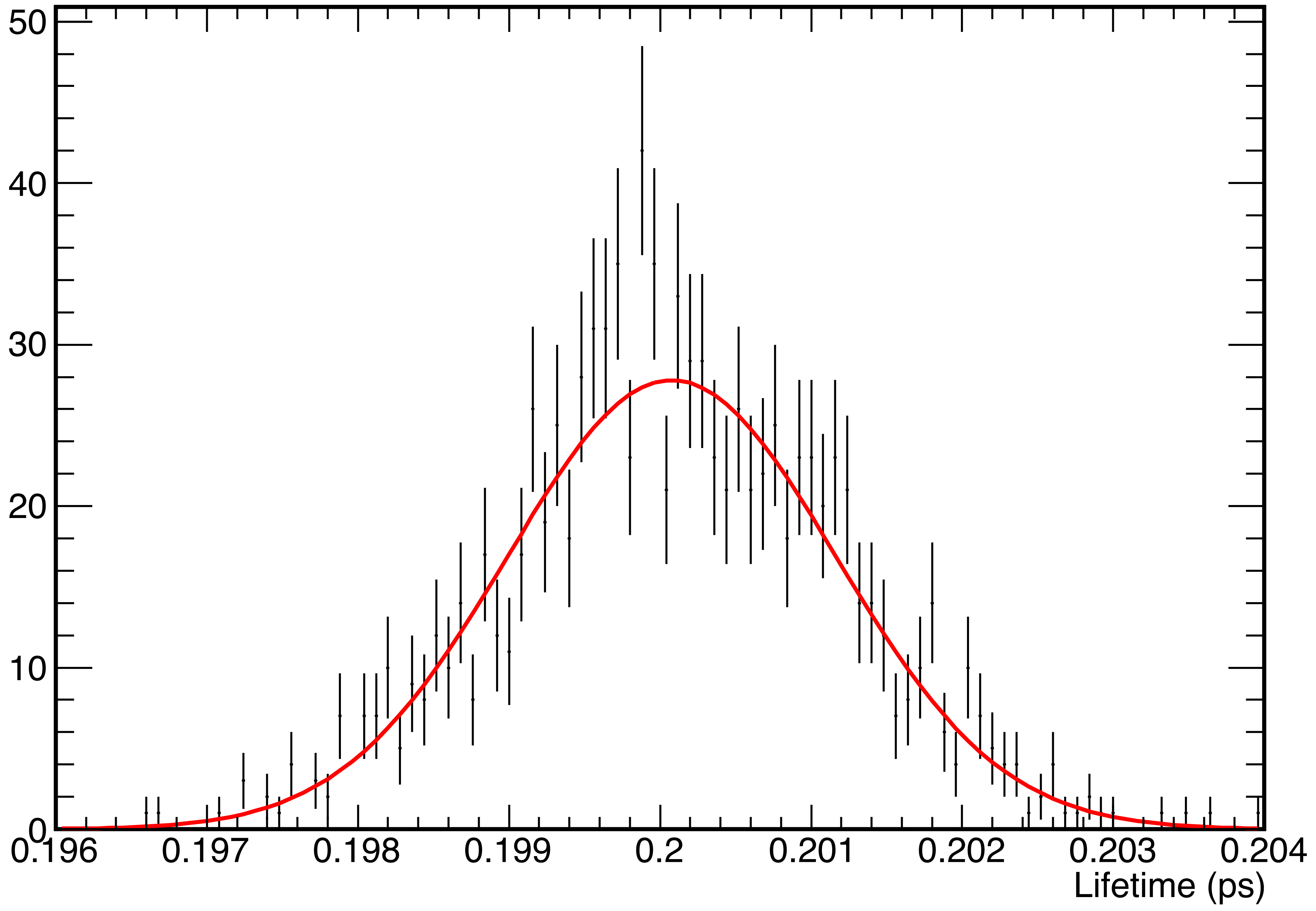
True value (average from truth matched events in the signal region): **201.84 ± 0.28 fs**

Validation with pseudoexperiments

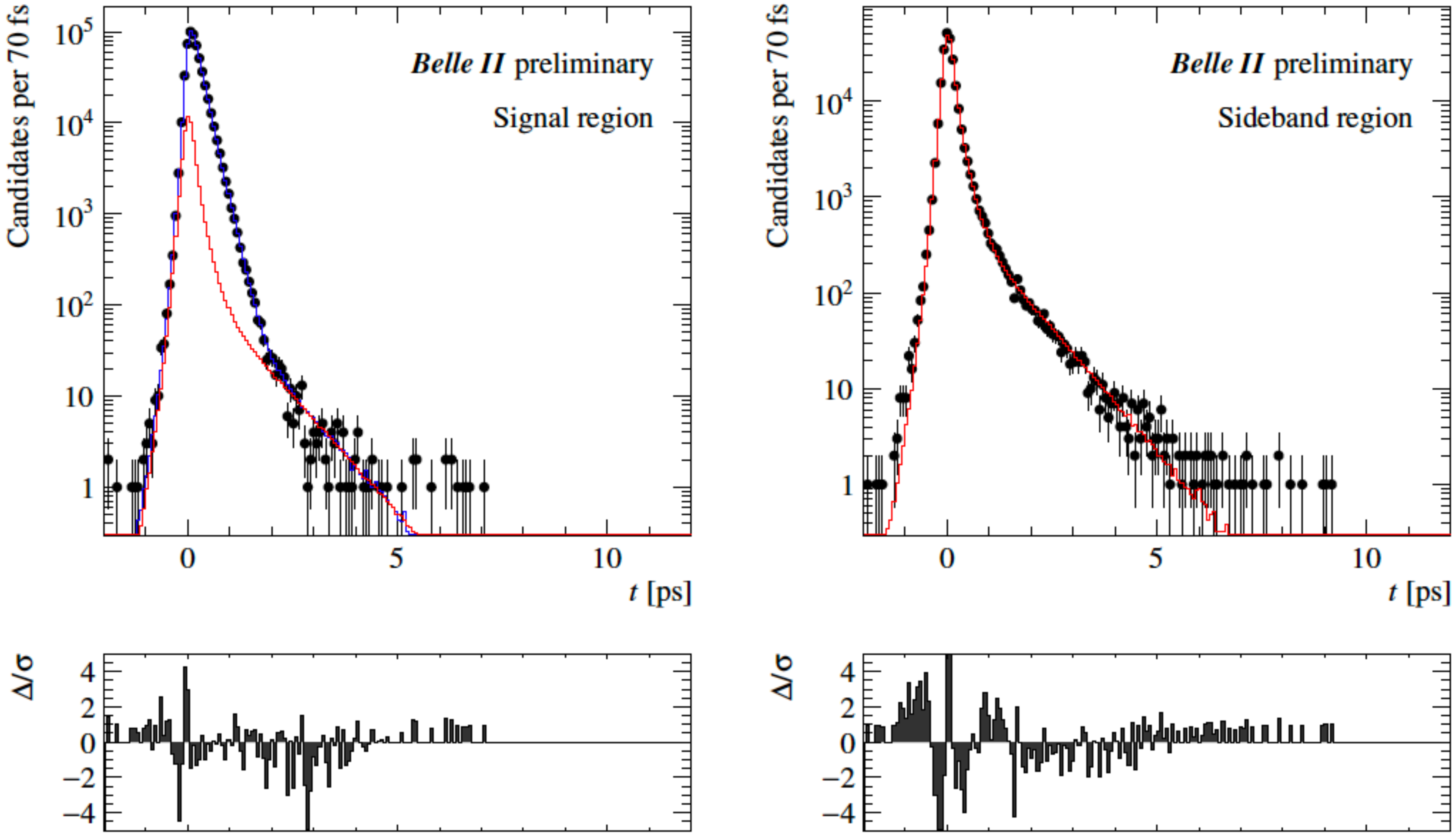
- Use 1/ab equivalent MC14ria to bootstrap toy samples according to the pdf from a blinded fit to the data
  - Vary input lifetime for each set of 1000 fits
  - Extract mean and width of the lifetimes for each toy sample
  - Check linearity between input and measured lifetimes
  - No obvious bias







Lifetime fit results on MC with single-Gaussian resolution - 1/ab



$LHCB$, $\tau = 203.5 \pm 1.0 \pm 1.3 \pm 1.4\ fs$

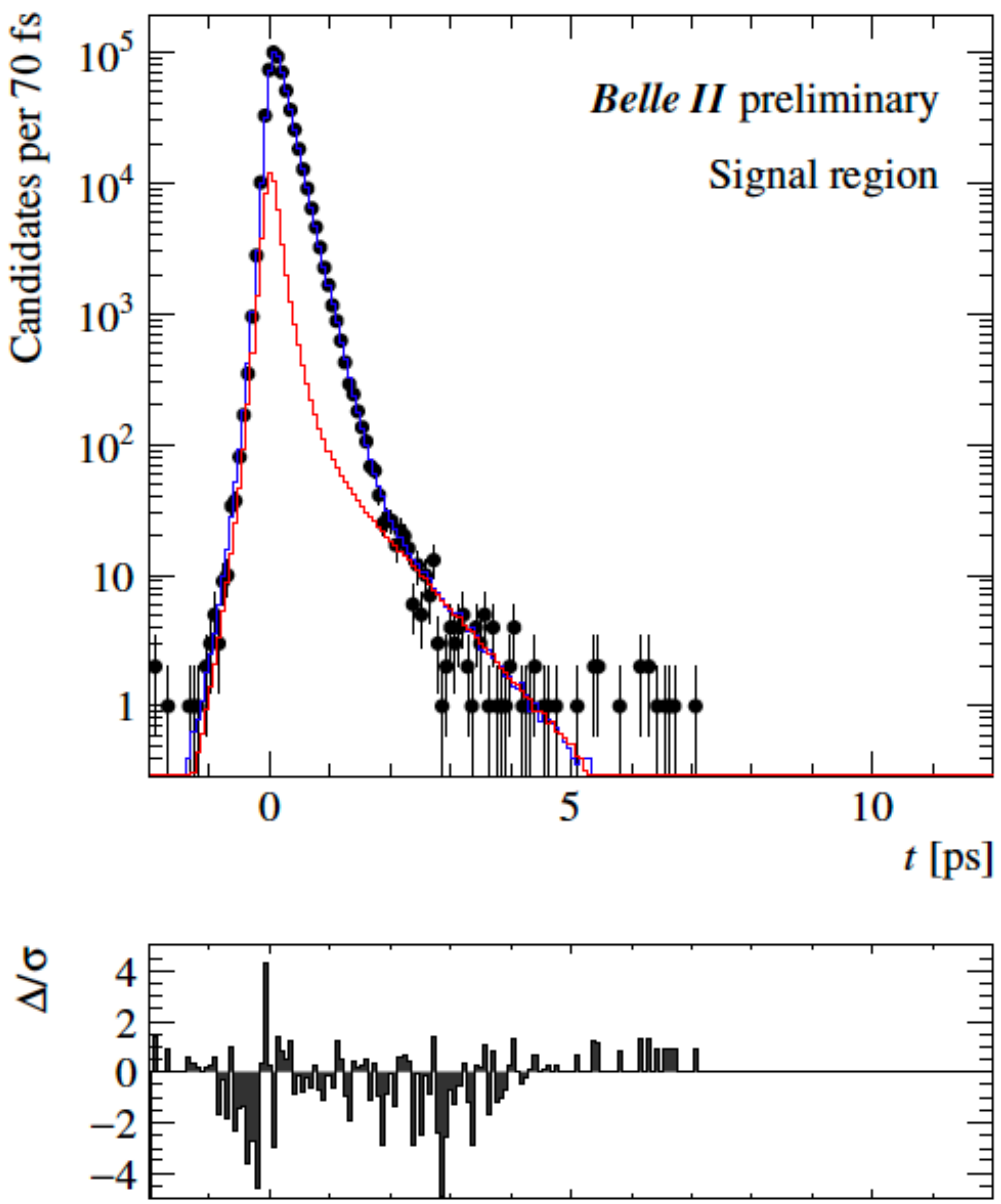
$FOCUS$, $\tau = 204.6 \pm 3.4 \pm 2.5\ fs$

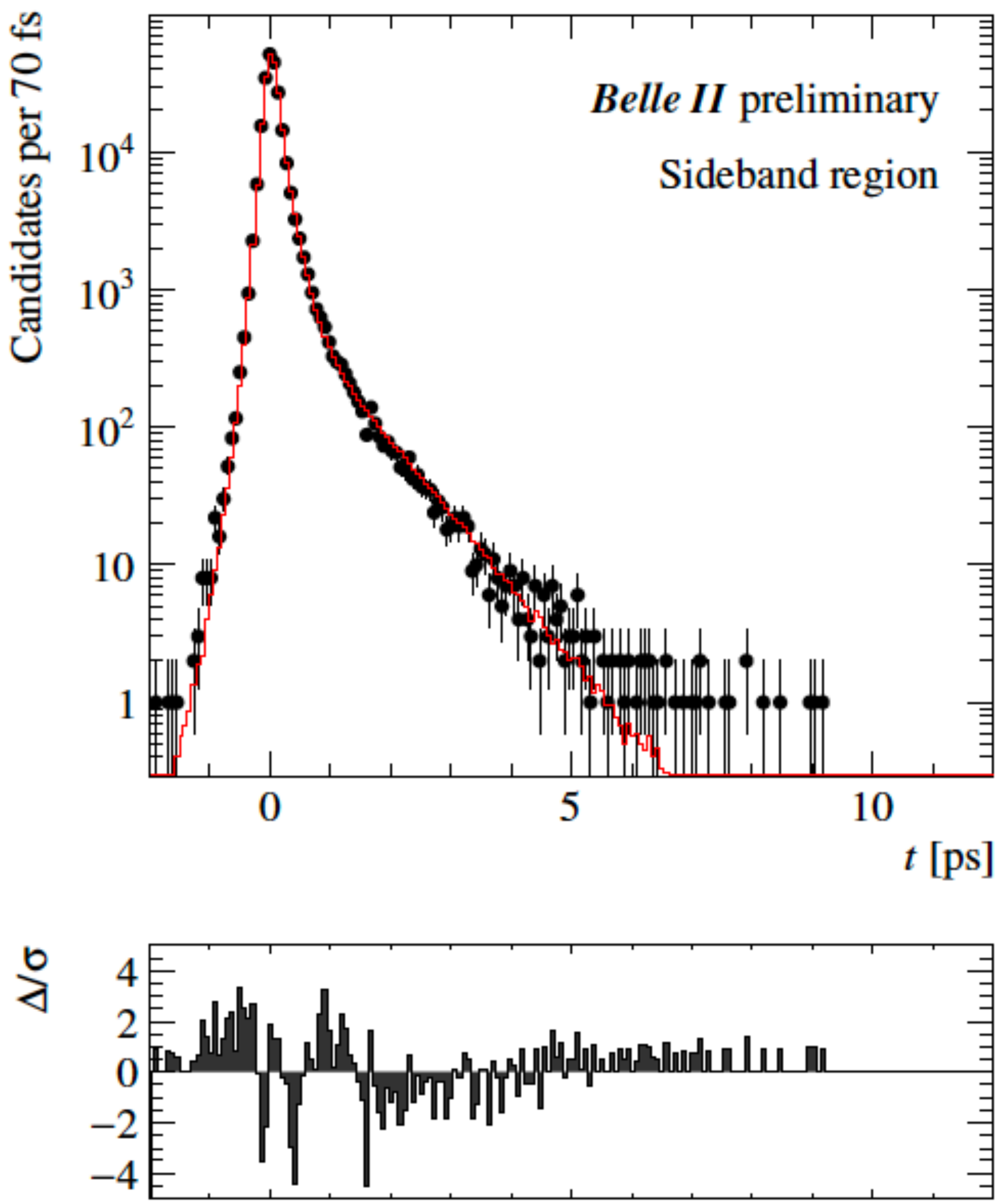
$CLEO$, $\tau = 179.6 \pm 6.9 \pm 4.4\ fs$

Parameter	Fit result w/single Gaussian
τ (fs)	201.77 ± 0.40
b (fs)	1.53 ± 0.27
s_1	1.0721 ± 0.0045
s_2	
f	
f_{bg}	0.09762 ± 0.00014
f_{τ}	0.2840 ± 0.0036
$f_{\tau 1}$	0.8477 ± 0.0047
τ_{bg1} (fs)	181.3 ± 3.0
τ_{bg2} (fs)	869.2 ± 16.5
s_{bg}	1.1758 ± 0.0058

True value (average from truth matched events in the signal region): **201.84 ± 0.28 fs**

Lifetime fit results on MC with double-Gaussian resolution - 1/ab





LHCB, $\tau = 203.5 \pm 1.0 \pm 1.3 \pm 1.4\ fs$

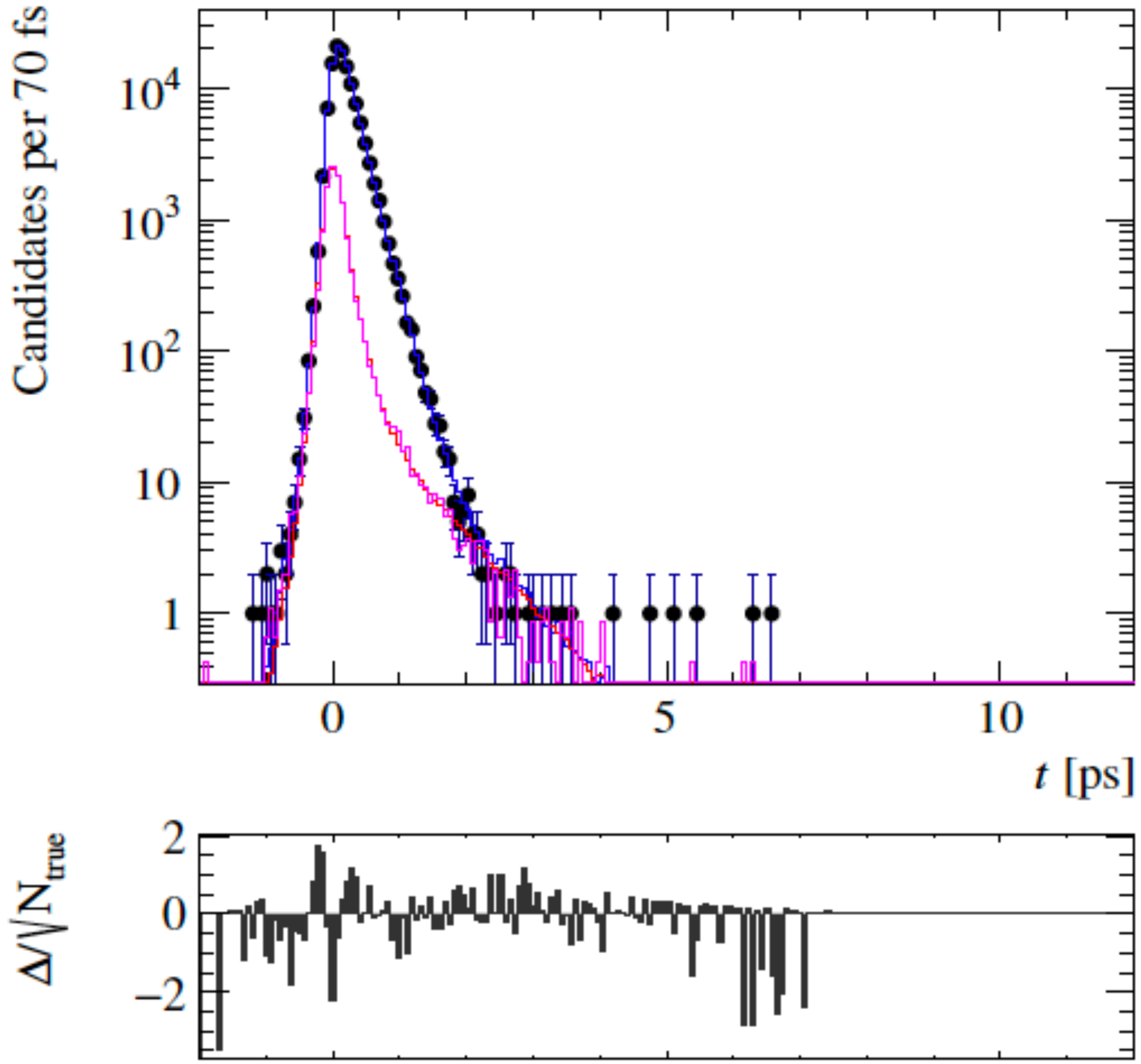
FOCUS, $\tau = 204.6 \pm 3.4 \pm 2.5\ fs$

CLEO, $\tau = 179.6 \pm 6.9 \pm 4.4\ fs$

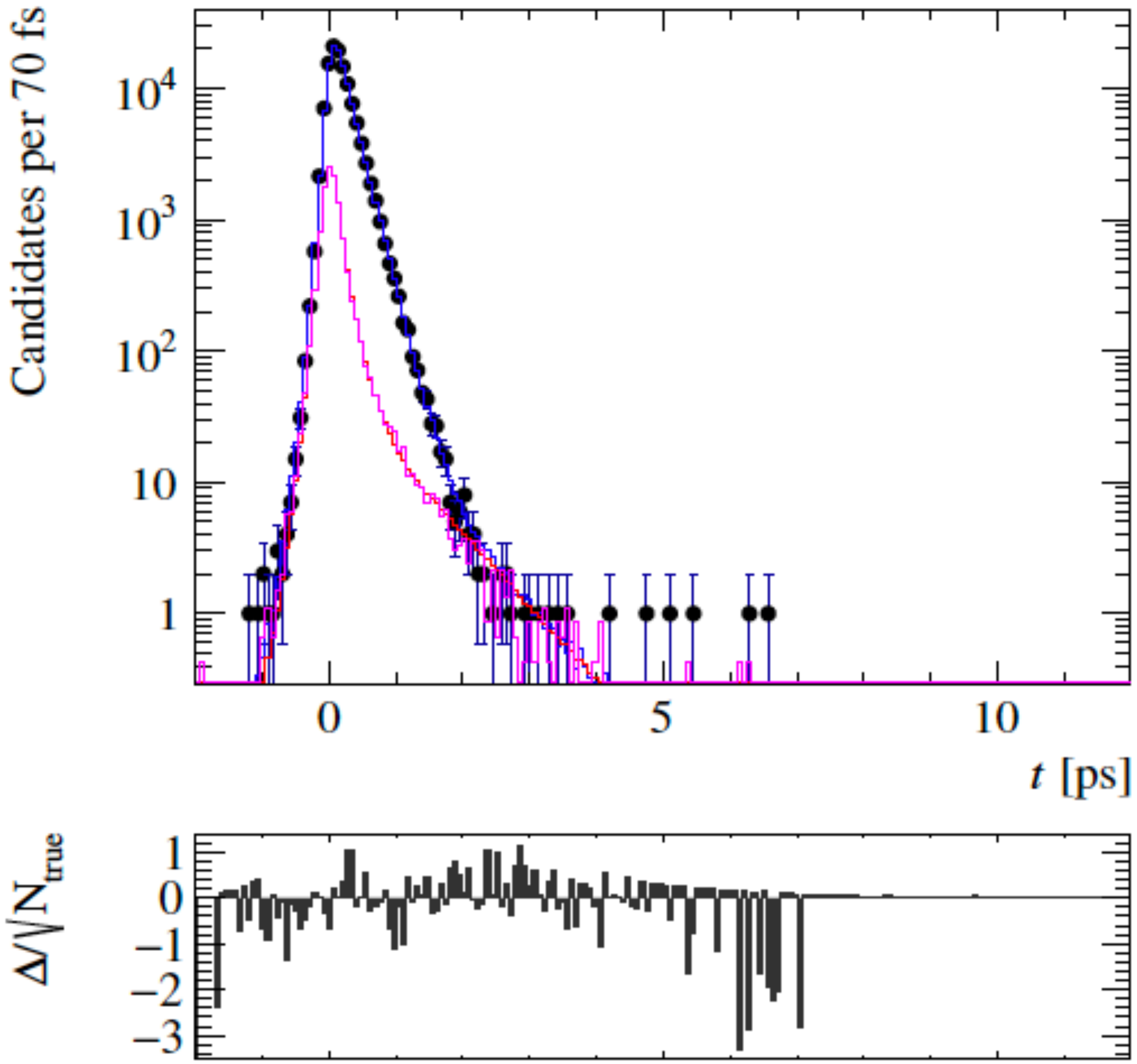
Parameter	Fit result w/double Gaussian
τ (fs)	202.16 ± 0.39
b (fs)	0.66 ± 0.26
s_1	1.0409 ± 0.0040
s_2	2.2978 ± 0.0484
f	0.9716 ± 0.0024
f_{bg}	0.09758 ± 0.00014
f_τ	0.3081 ± 0.0037
$f_{\tau 1}$	0.8503 ± 0.0043
τ_{bg1} (fs)	168.8 ± 2.6
τ_{bg2} (fs)	846.1 ± 15.0
s_{bg}	1.1319 ± 0.0044

True value (average from truth matched events in the signal region): **201.84 ± 0.28 fs**

Lifetime fit results - comparison with truth-matched backgrounds

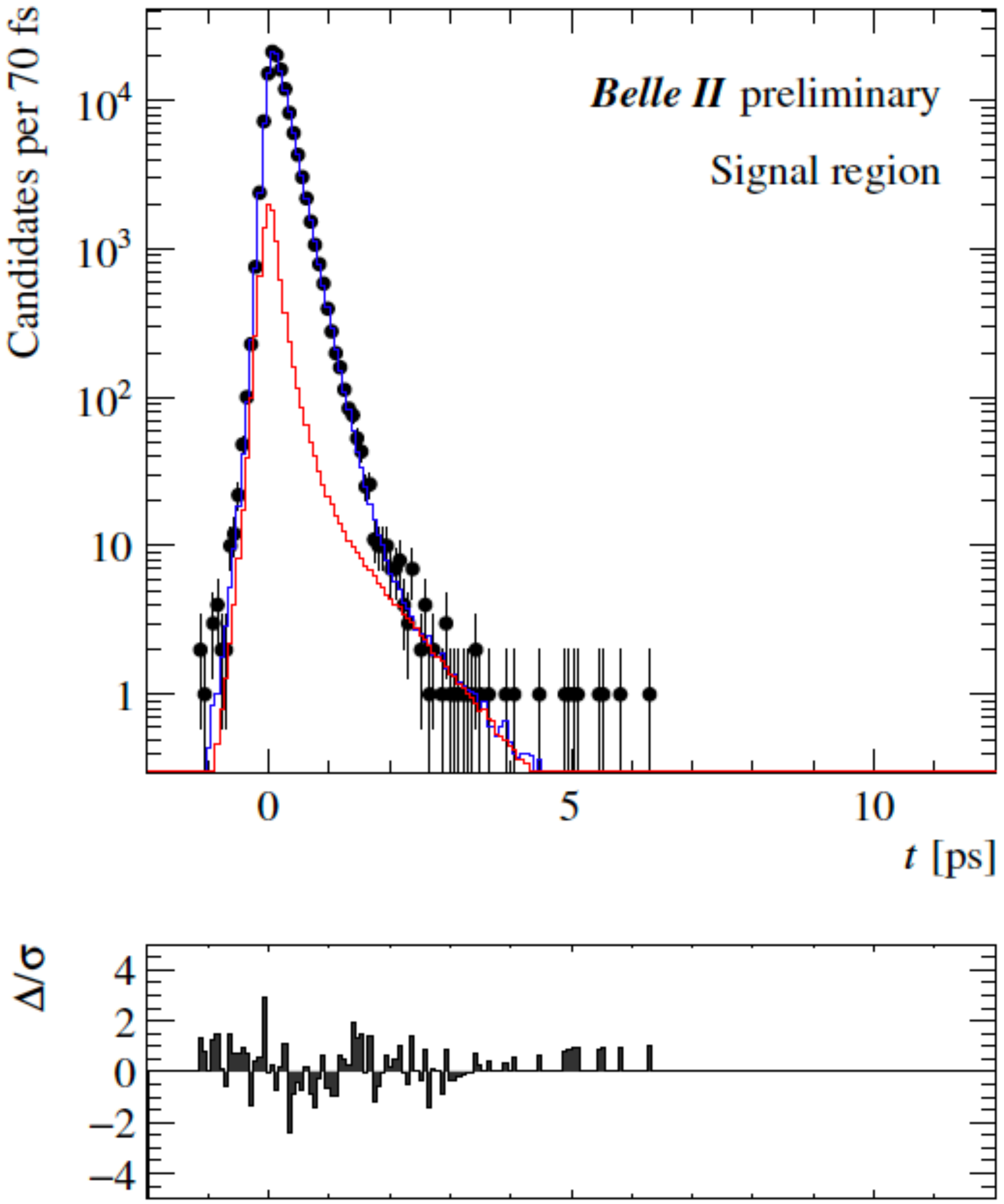


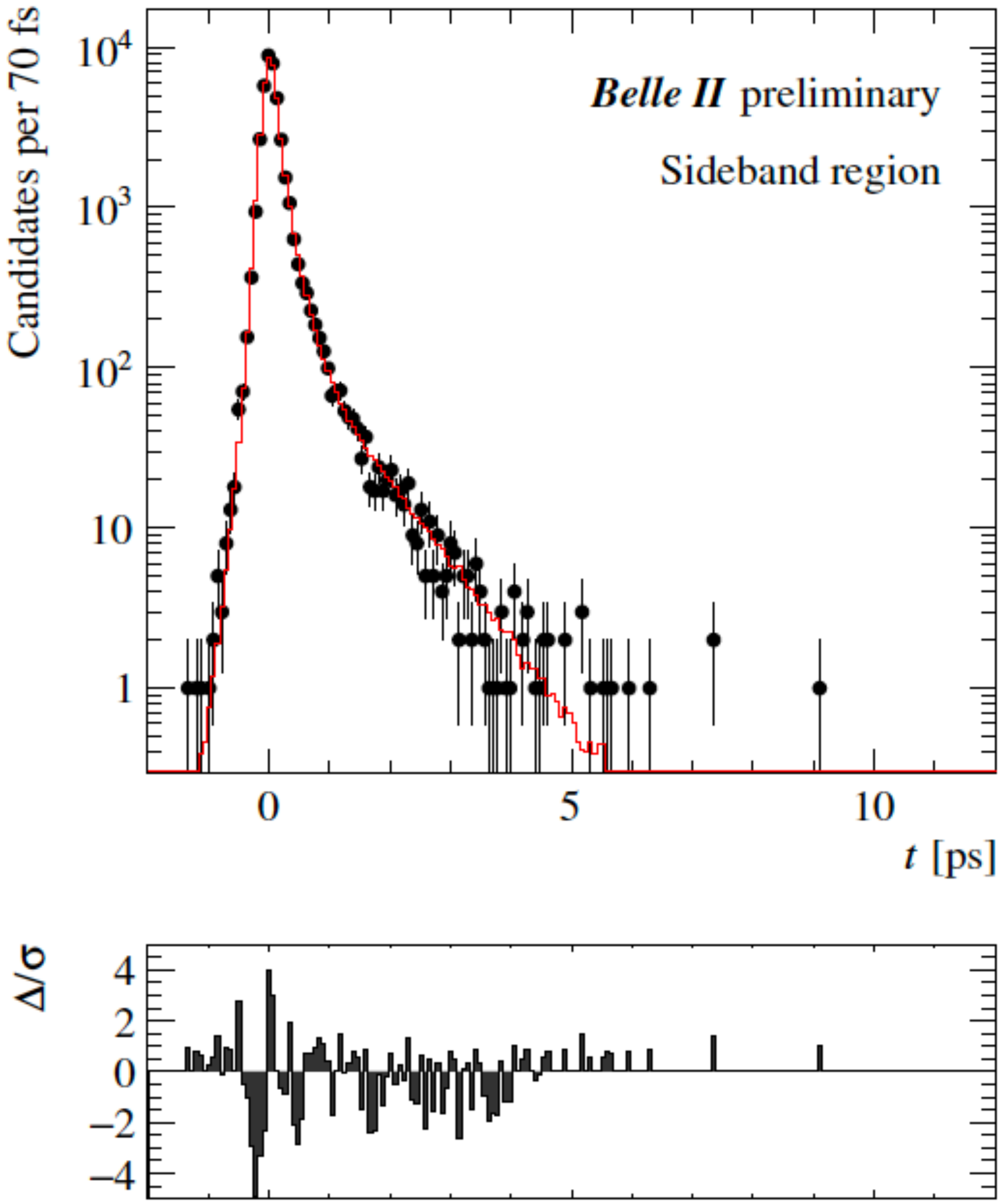
Single-Gaussian resolution function



Double-Gaussian resolution function

Blinded fit to the data (~208/fb) - single Gaussian resolution





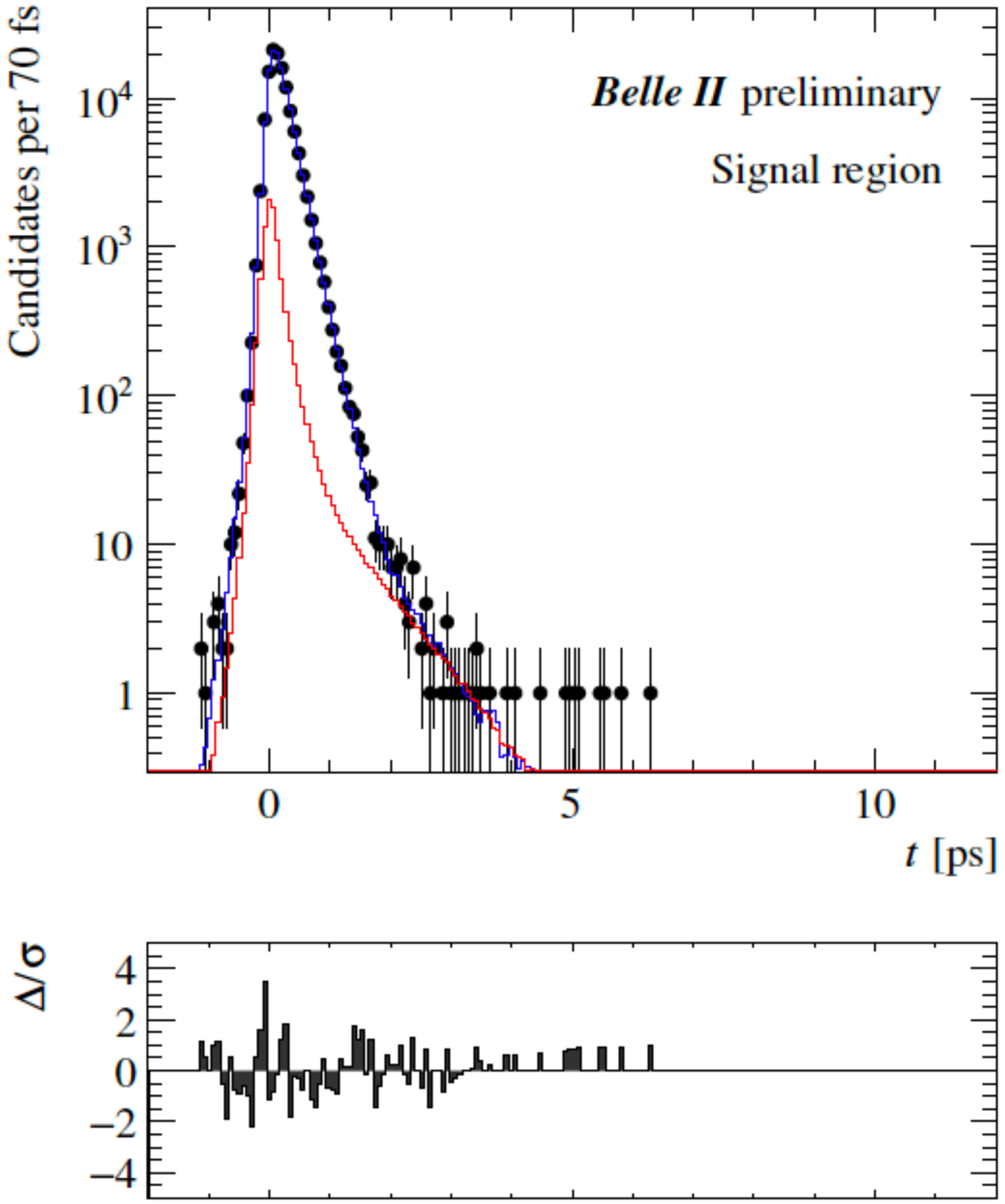
$LHCB,\ \tau = 203.5 \pm 1.0 \pm 1.3 \pm 1.4\ fs$

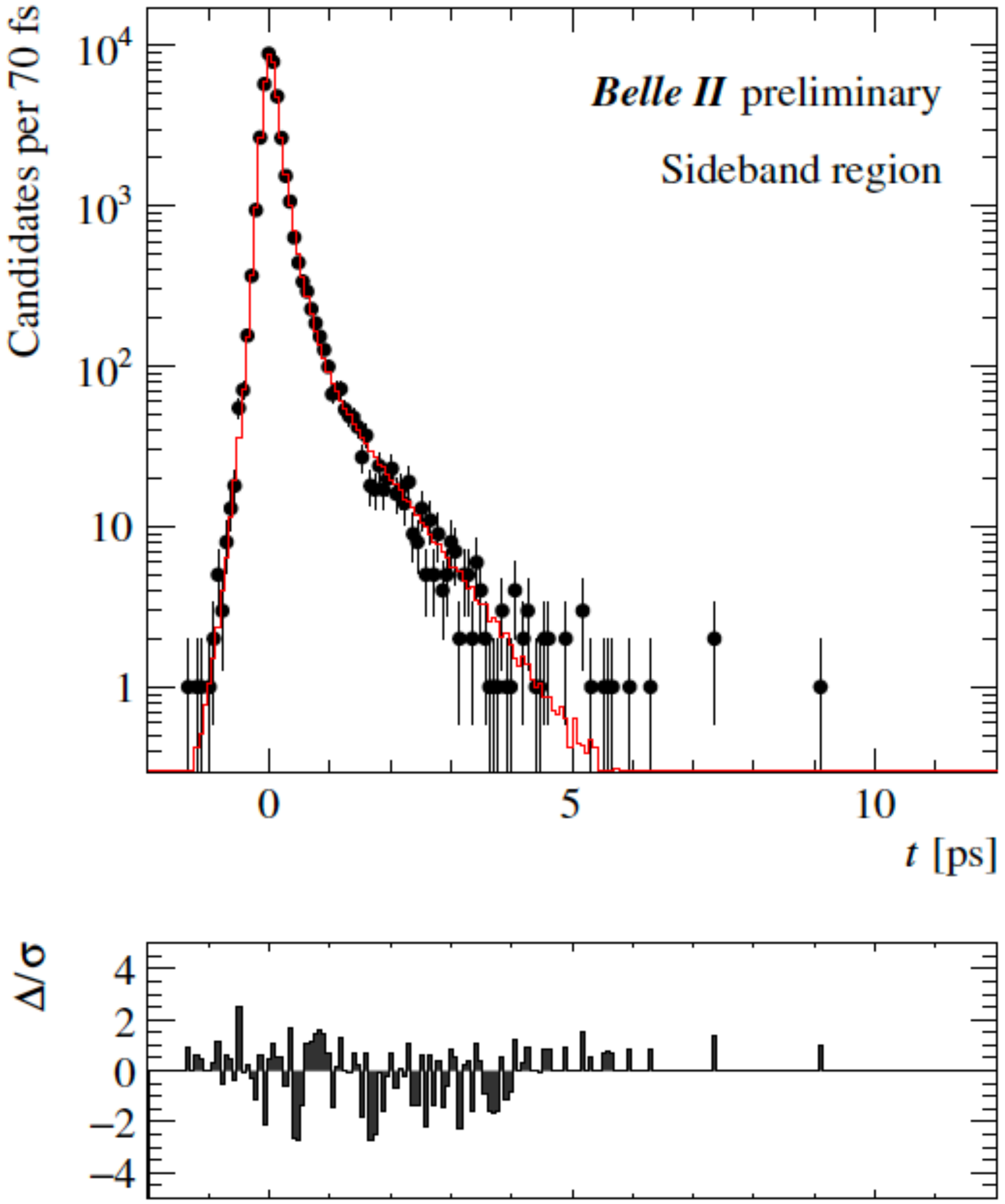
$FOCUS,\ \tau = 204.6 \pm 3.4 \pm 2.5\ fs$

$CLEO,\ \tau = 179.6 \pm 6.9 \pm 4.4\ fs$

Parameter	Fit result w/single Gaussian
τ (fs) with arb. shift	209.72 ± 0.88
b (fs)	4.58 ± 0.63
s_1	1.1050 ± 0.0071
s_2	
f	
f_{bg}	0.07539 ± 0.00022
f_{τ}	0.2918 ± 0.0081
$f_{\tau 1}$	0.7967 ± 0.0115
τ_{bg1} (fs)	196.1 ± 6.8
τ_{bg2} (fs)	865.1 ± 28.4
s_{bg}	1.1434 ± 0.0088

Blinded fit to the data (~208/fb) - double Gaussian resolution





$LHCB, \tau = 203.5 \pm 1.0 \pm 1.3 \pm 1.4\ fs$

$FOCUS, \tau = 204.6 \pm 3.4 \pm 2.5\ fs$

$CLEO, \tau = 179.6 \pm 6.9 \pm 4.4\ fs$

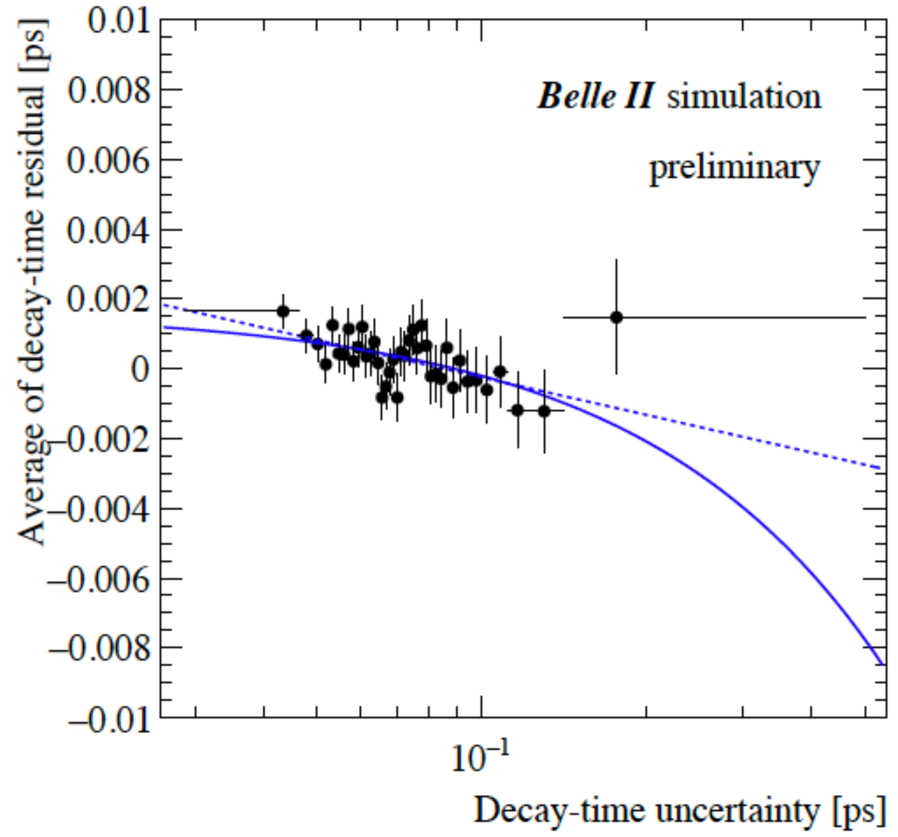
Parameter	Fit result w/double Gaussian
τ (fs) with arb. shift	210.08 ± 0.85
b (fs)	3.72 ± 0.58
s_1	1.0713 ± 0.0146
s_2	2.4043 ± 0.3134
f	0.9727 ± 0.0145
f_{bg}	0.07536 ± 0.00022
f_τ	0.3172 ± 0.0085
$f_{\tau 1}$	0.8000 ± 0.0126
τ_{bg1} (fs)	180.7 ± 7.3
τ_{bg2} (fs)	841.8 ± 32.0
s_{bg}	1.0947 ± 0.0092

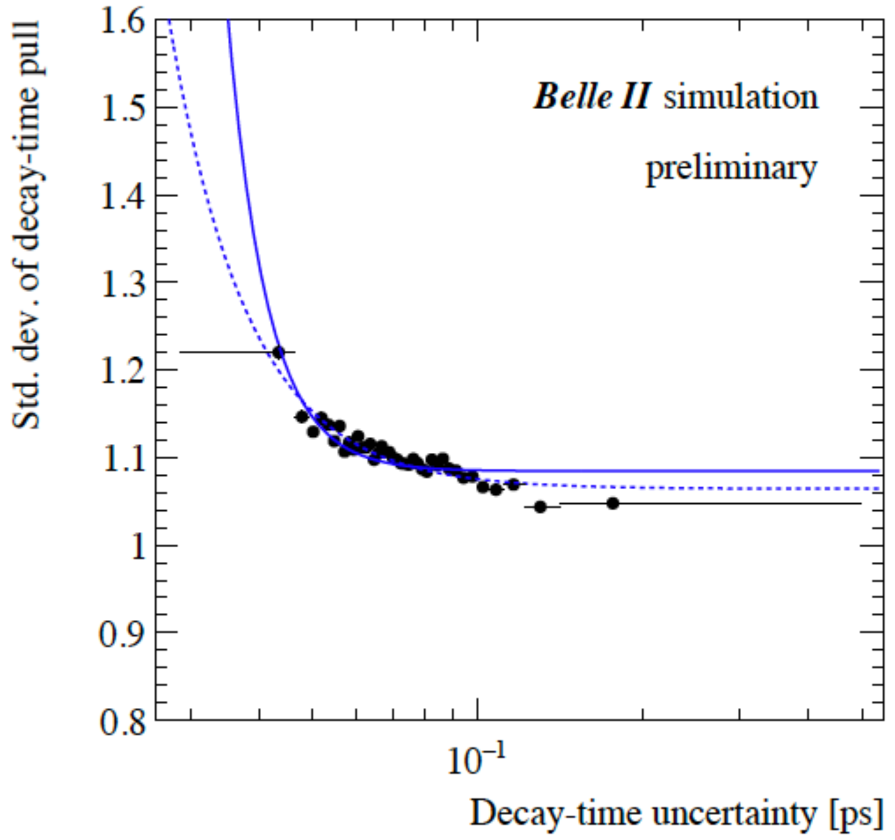
Resolution model

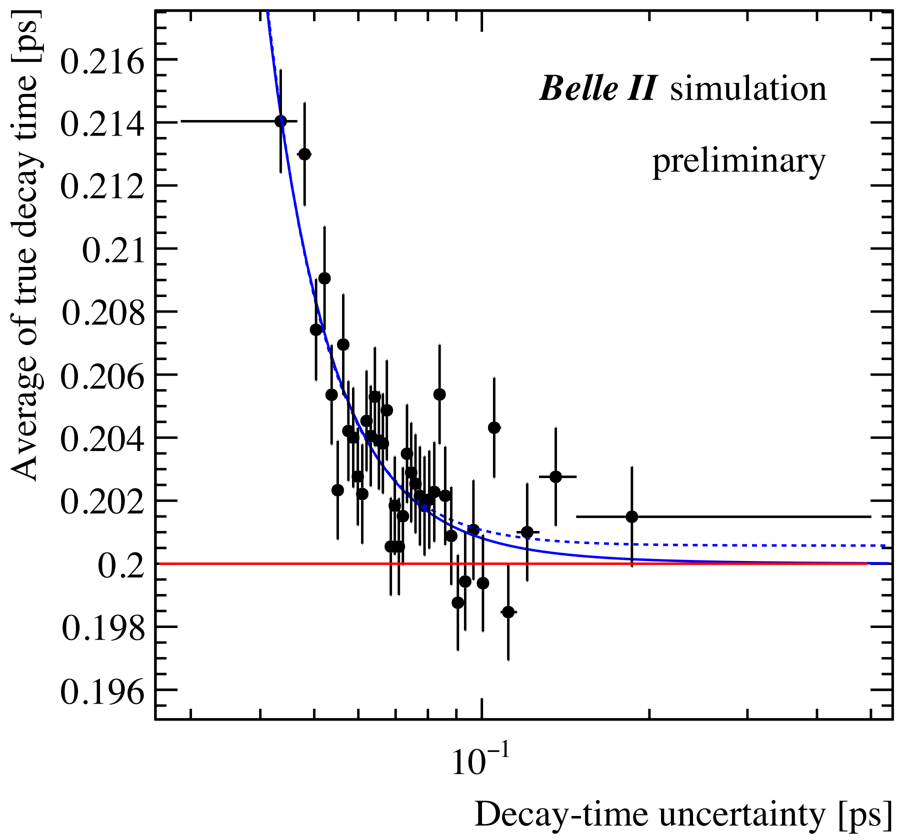
- Correlations between t and σ_t are neglected in the resolution model, which may result in discrepancies between the fit model and the data in the 2D distribution
- Assess with pseudoexperiments bootstrapped from truth-matched signal events in 1/ab equivalent from MC14ri_a
    - True lifetime: $201.84 \pm 0.28\ fs$
    - Fit results: $202.30 \pm 0.02\ fs$
    - Difference: $0.46\ fs$

- Cross check: compare single and double Gaussian resolution
    - Single Gaussian: $\tau = 209.720 \pm 0.882\ fs$
    - Double Gaussian: $\tau = 210.077 \pm 0.852\ fs$
    - Difference: $0.357 \pm 0.228\ fs$

- Vary bin size for decay-time uncertainty PDF to avoid bins with zero content
    - No significant change (less than 0.02 fs)







Backgrounds

- Simulation is expected to reproduce background decay-time distributions
- Assess with pseudoexperiments bootstrapped from events in the 1/ab equivalent from MC14ri for the signal region and the data sideband events for the sideband region.
  - True lifetime: $201.84 \pm 0.28\ fs$
  - Fit results: $202.04 \pm 0.03\ fs$
  - Difference: $0.20\ fs$

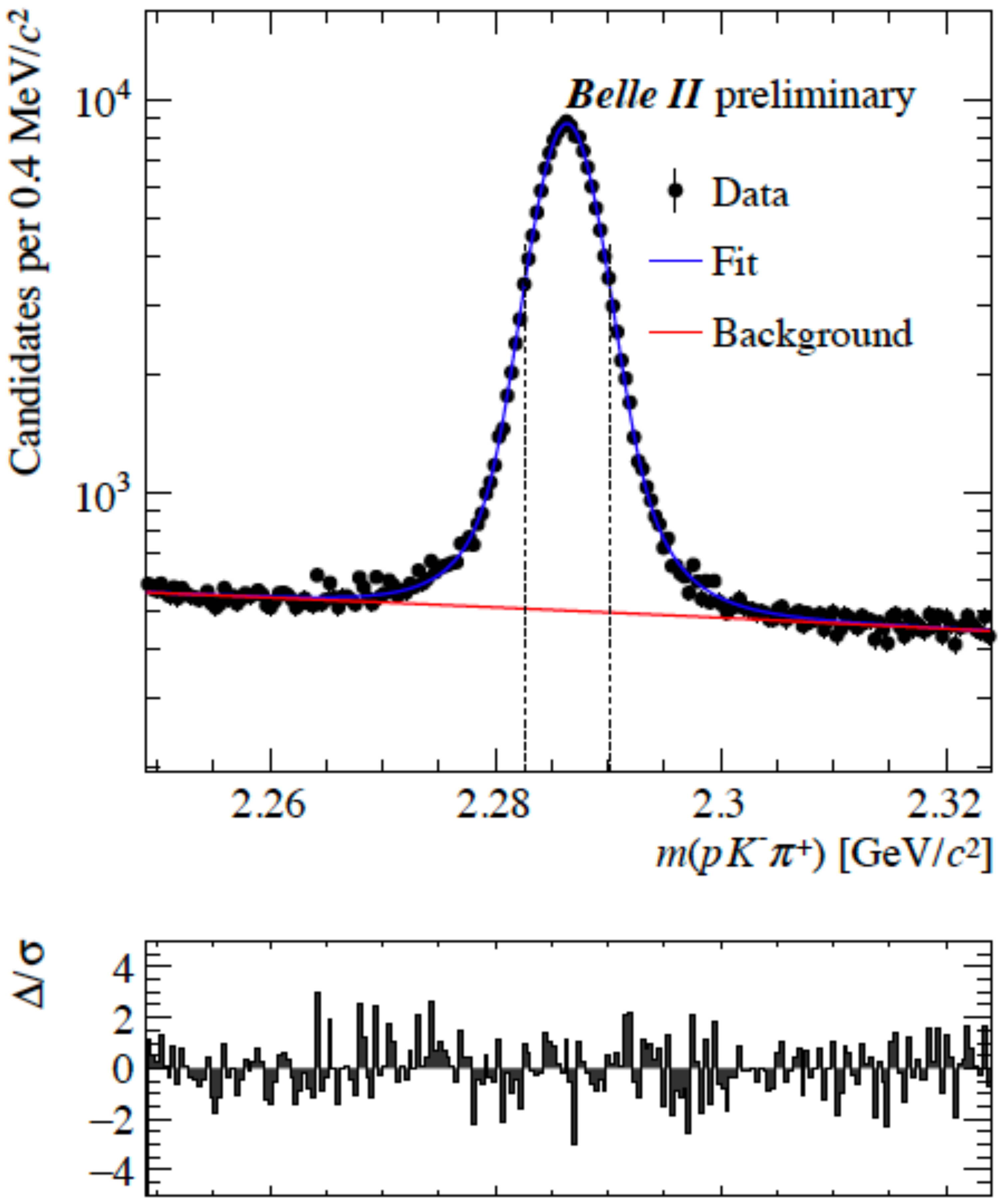
- Cross check:
  vary invariant mass signal window by ±0.2 MeV/c²
  - Nominal: $\tau = 209.72 \pm 0.88\ fs$
  - Lifetime difference:
    -0.16 ± 0.23 fs (+0.2), 0.26 ± 0.30 fs (-0.2)
  - Bias difference:
    -0.38 ± 0.22 fs (+0.2), 0.75 ± 0.25 fs (-0.2)

Table 13: Results of lifetime fits to events in data with an invariant mass signal region shifted by ±0.2 MeV/c^2. The measured lifetime is shifted by an arbitrary amount within a range of ±5 σ, according to the world-average value.

Parameter	[2.2828,2.2898] GeV/c^2	[2.2832,2.2902] GeV/c^2
τ (fs)	209.56 ± 0.85	209.98 ± 0.83
b (fs)	4.20 ± 0.59	5.33 ± 0.58
s_1	1.1044 ± 0.0058	1.0901 ± 0.0055
f_{bg}	0.07493 ± 0.00037	0.07508 ± 0.00037
f_τ	0.2947 ± 0.0082	0.2858 ± 0.0069
$f_{\tau 1}$	0.7963 ± 0.0109	0.7977 ± 0.0135
τ_{bg1} (fs)	194.0 ± 6.9	200.6 ± 7.1
τ_{bg2} (fs)	861.5 ± 26.5	874.0 ± 33.9
s_{bg}	1.1428 ± 0.0081	1.1526 ± 0.0081

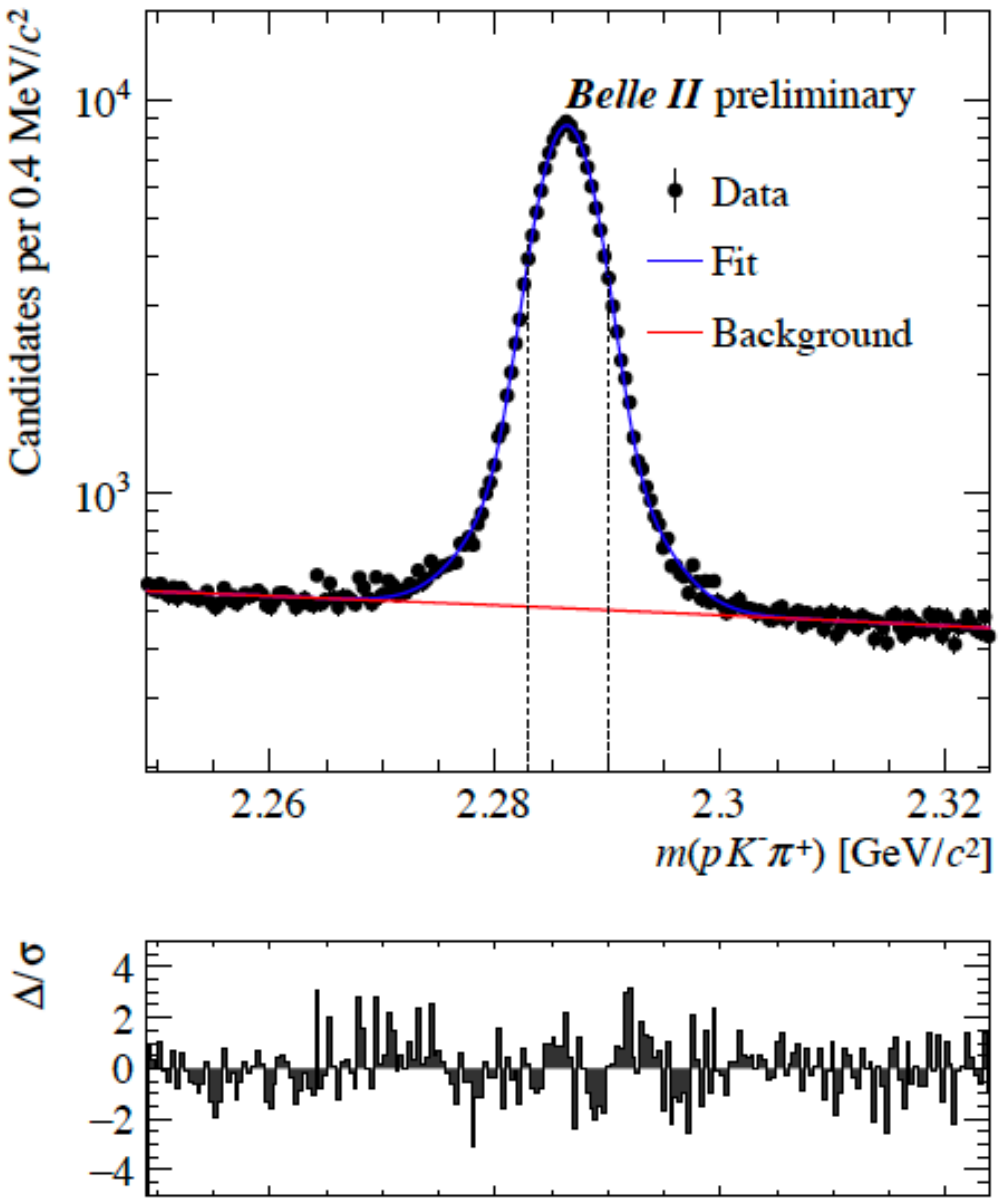
Backgrounds: change signal pdf in mass fit

Signal: Gaussian + Johnson function
(transformation of normal distribution)



Background:
0.0753 +- 0.0002

Signal: Double Gaussian



Background:
0.0762 +- 0.0001

- Determine background fraction in the signal region with alternative mass models and repeat lifetime fit to data

- Gaussian + Johnson: $\tau = 209.720 \pm 0.882\ fs$
- Double Gaussian: $\tau = 209.751 \pm 0.851\ fs$
- Difference: $0.03 \pm 0.23\ fs$

Detector alignment

- Misalignment of the tracking detectors may affect the decay-length and therefore the lifetime
- Generate signal samples with different alignment global tags: https://confluence.desy.de/display/BI/Misalignments

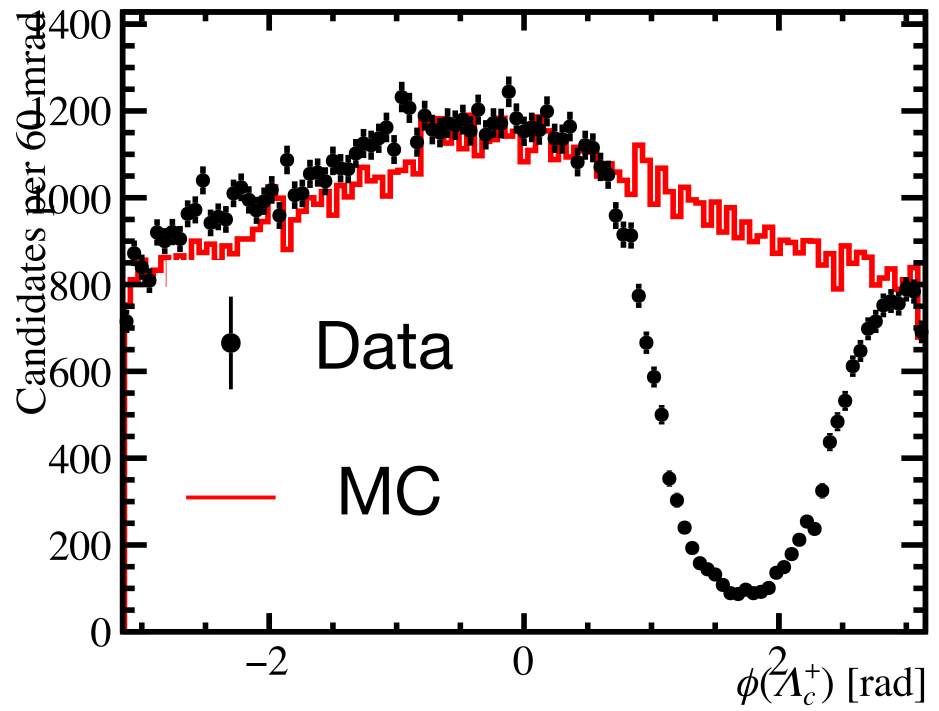
GT name
alignment_misalignment_prompt_to_proc12stage1_v4 (a) nominal prompt alignment systematic uncertainty
alignment_misalignment_VXDCDCwires_v1 (b) residual misalignment for telescope weak mode
charm_misalignment_v0 (c) day-to-day misalignment
charm_misalignment_v0_1
charm_misalignment_v1 (d) residual misalignment from MC studies
charm_misalignment_v1_1

$$\delta t = Fit - True \qquad \Delta t = \delta t_{misaligned} - \delta t_{aligned}$$

Configuration	Fit result (fs)	True lifetime (fs)	$\delta\tau$ (fs)	$\Delta\tau$ (fs)
Nominal	203.105 ± 0.736	202.514	0.591	
a	203.580 ± 0.750	202.837	0.743	0.152
b	203.130 ± 0.746	203.240	-0.110	-0.701
c	202.819 ± 0.744	202.498	0.321	-0.270
d	203.275 ± 0.556	202.696	0.579	-0.012
RMS				0.383

Size comparable to data

- RMS for samples without PXD inefficiency (MC14ri default): 0.383 fs



Detector alignment

- Misalignment of the tracking detectors may affect the decay-length and therefore the lifetime
- Generate signal samples with different alignment global tags: https://confluence.desy.de/display/BI/Misalignments

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alignment_misalignment_prompt_to_proc12stage1_v4	(a) nominal prompt alignment systematic uncertainty
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charm_misalignment_v0	(c) day-to-day misalignment
charm_misalignment_v0_1	
charm_misalignment_v1	(d) residual misalignment from MC studies
charm_misalignment_v1_1	

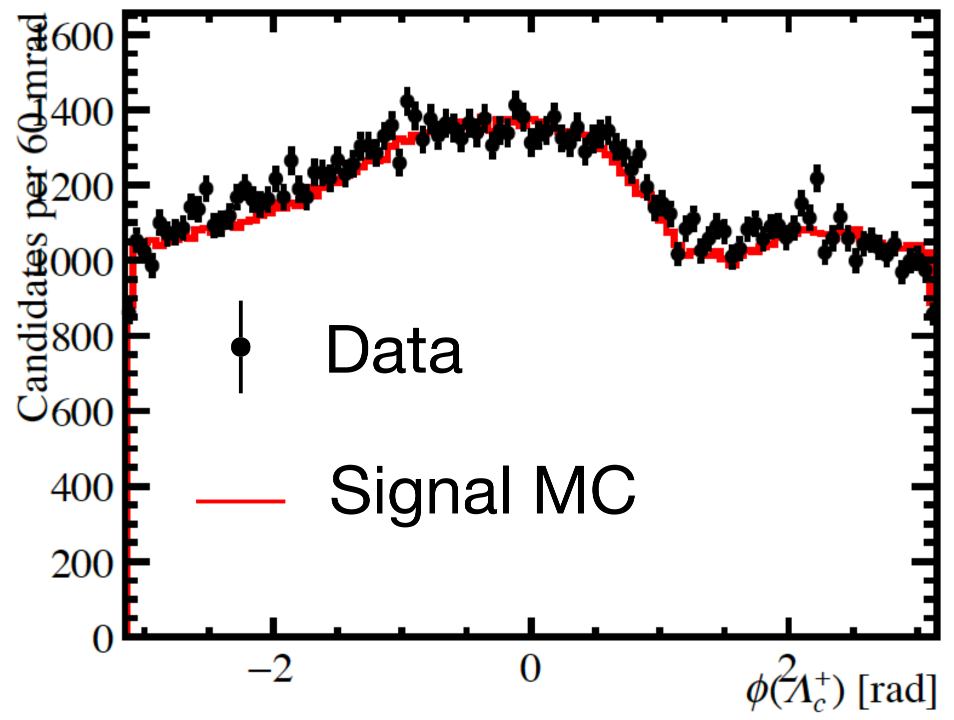
$$\delta t = Fit - True \qquad \Delta t = \delta t_{misaligned} - \delta t_{aligned}$$

Configuration	Fit result (fs)	True lifetime (fs)	$\delta\tau$ (fs)	$\Delta\tau$ (fs)
Nominal	201.827 ± 0.810	201.801	0.026	
a	202.738 ± 0.805	202.406	0.332	0.306
b	202.418 ± 0.769	201.735	0.683	0.657
c	203.266 ± 0.805	202.701	0.565	0.539
d	202.216 ± 0.701	201.983	0.233	0.207
RMS				0.463
Nominal	202.792 ± 0.254	202.267	0.525	
c	202.760 ± 0.253	202.535	0.225	-0.300

Size comparable to data

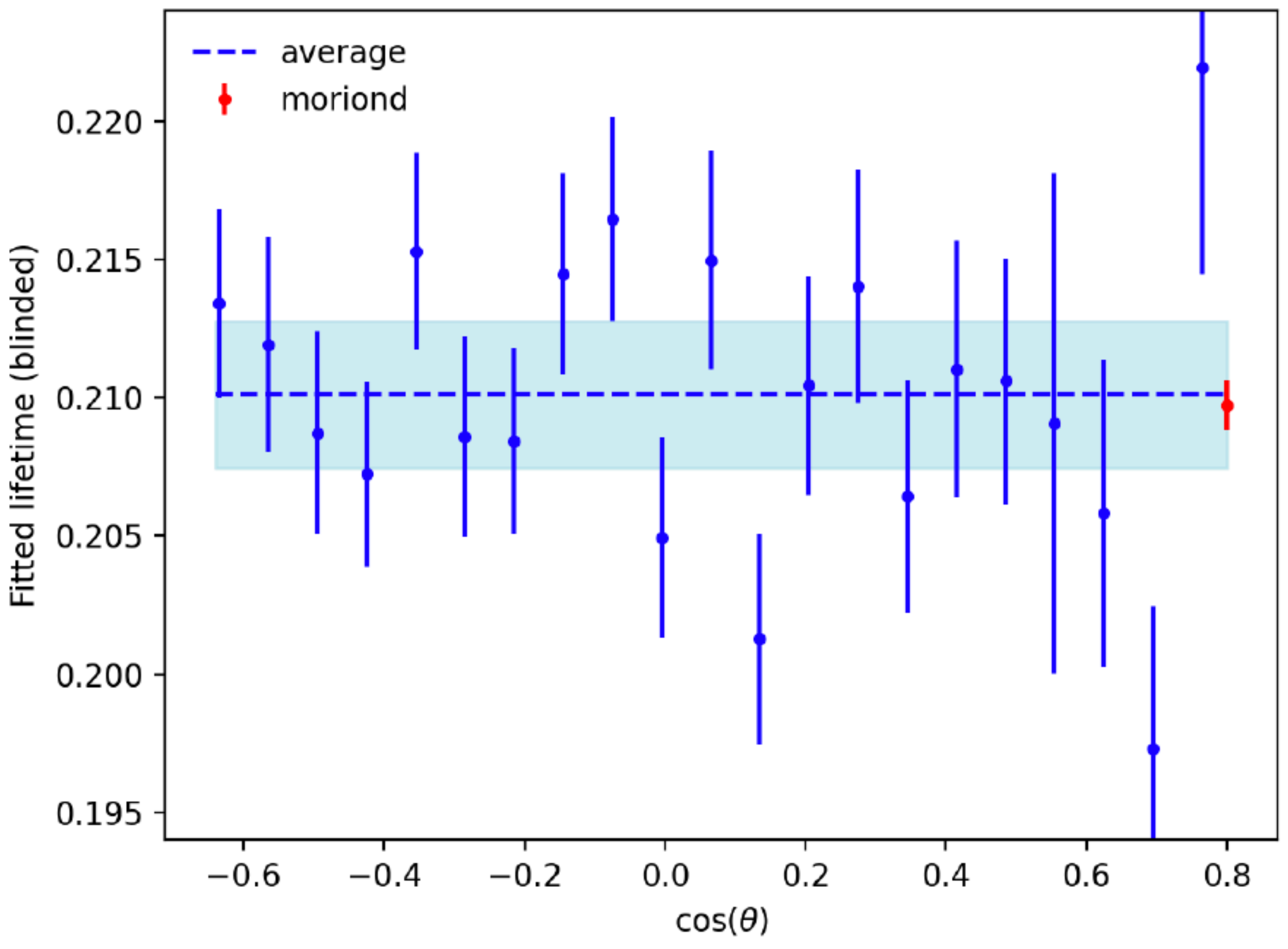
10x stats

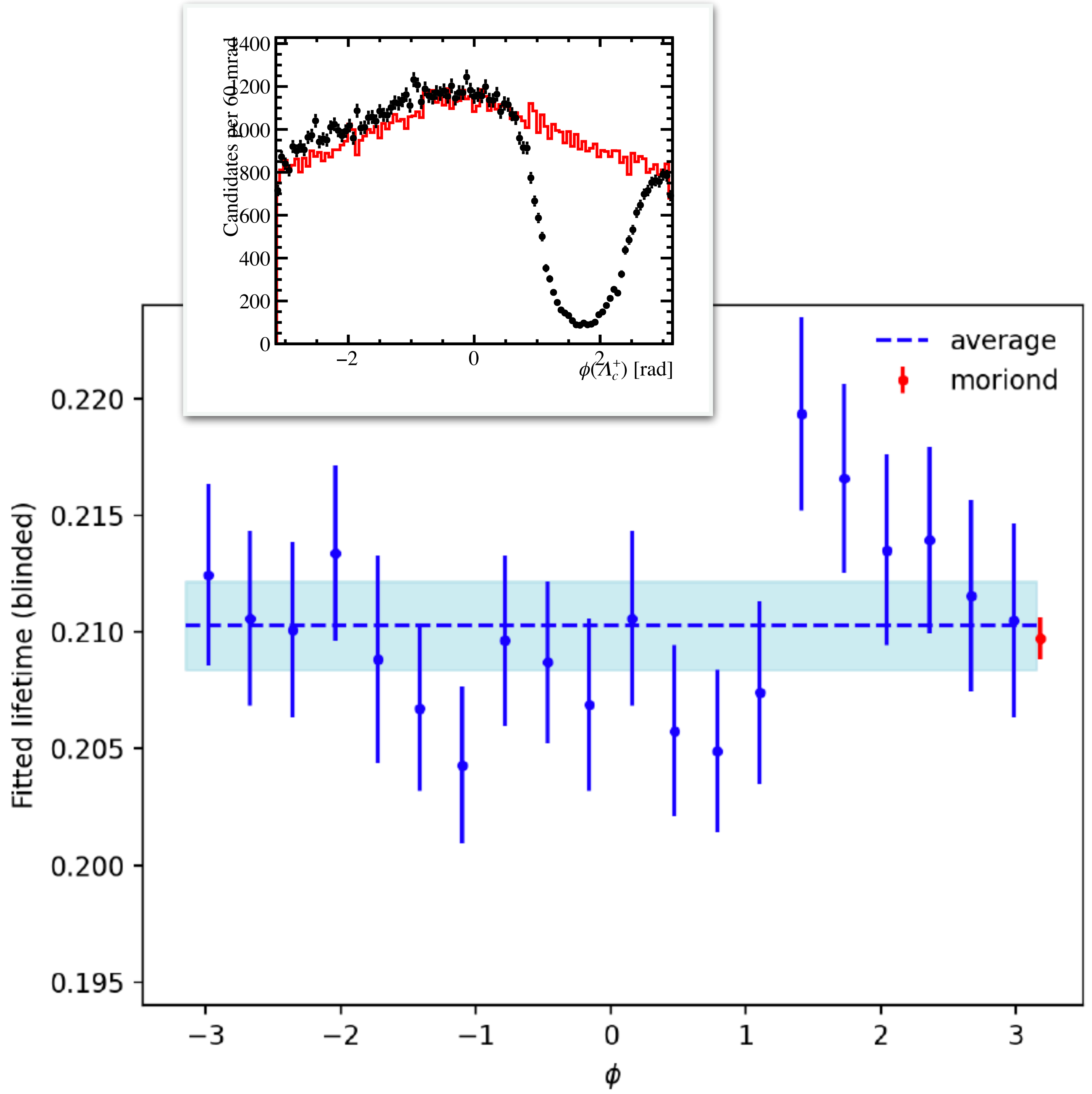
- RMS for samples without PXD inefficiency (MC14ri default): 0.38 fs
- RMS for samples with PXD inefficiency: 0.46 fs
  - Take as systematic uncertainty due to alignment

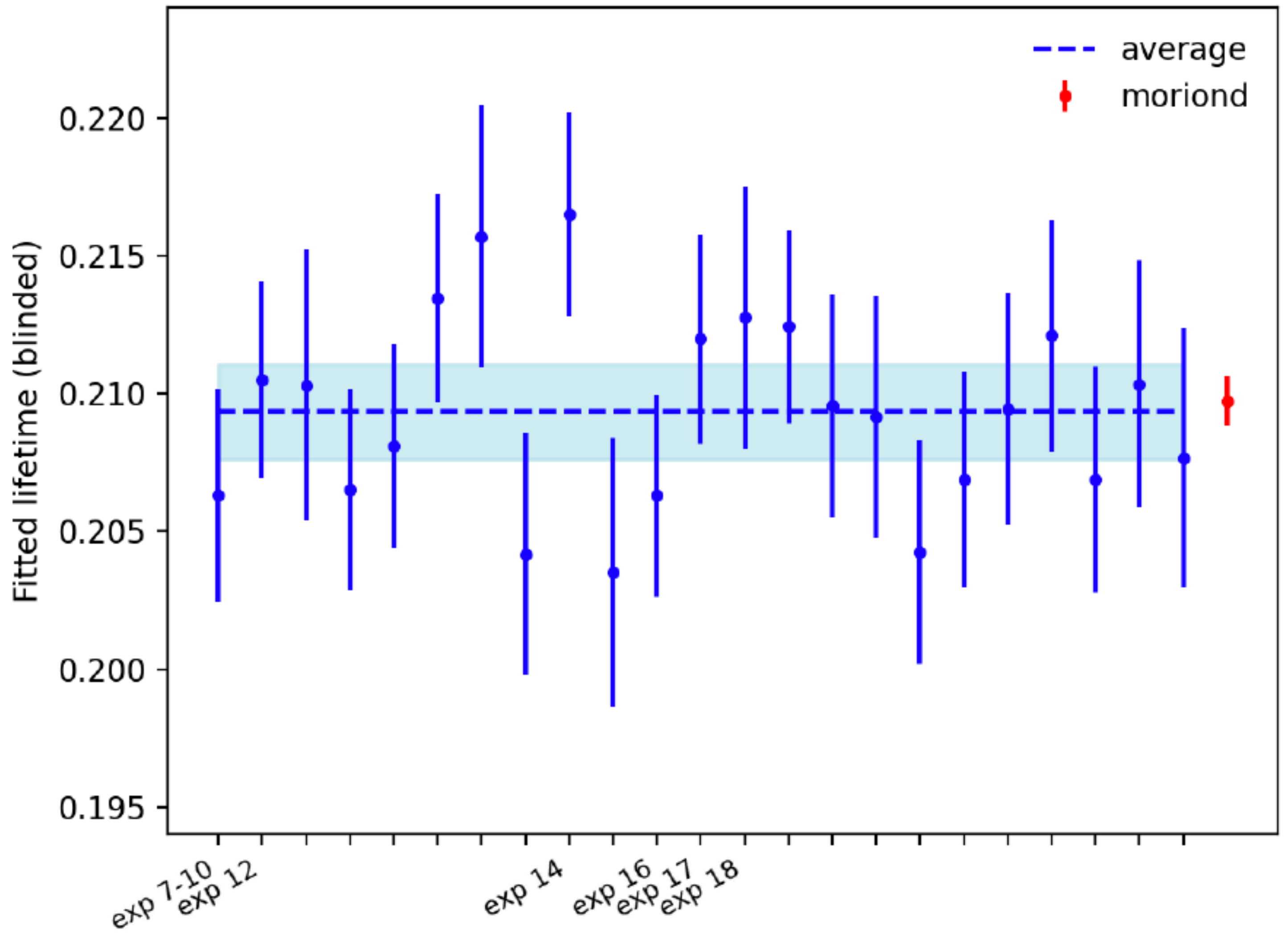


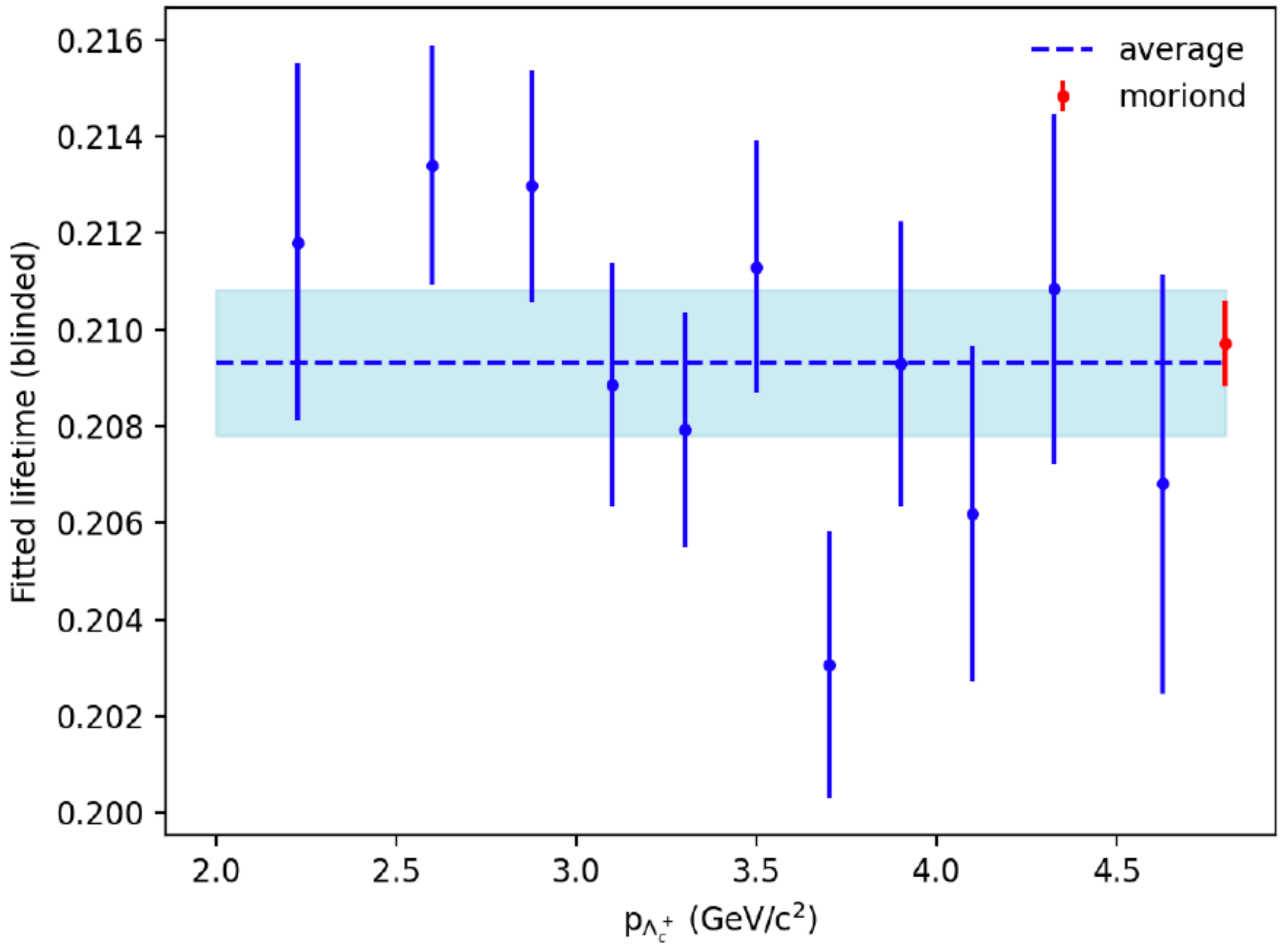
Consistency checks

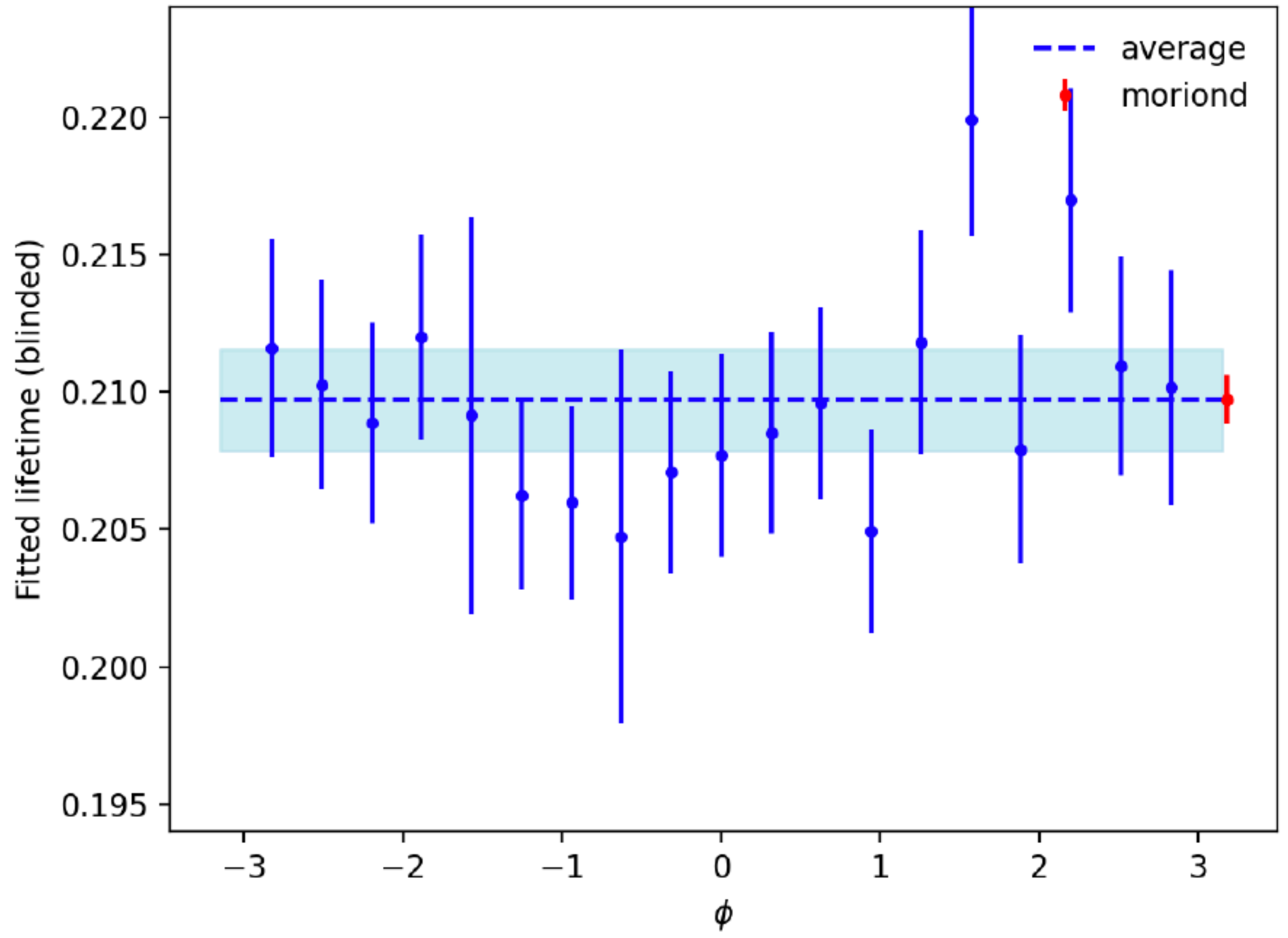
- Blinded lifetime fits as a function of experiment number, angle, momentum, charmness, with and without multiple candidate events
- No obvious bias, nothing unexpected











Summary

- Lifetime fit to simulation gives result consistent with true lifetime
- Significant improvement in precision compared to LHCb
- Working group approval granted, review committee in place

Source	uncertainty (fs)
Resolution model	0.46
Background contamination	0.20
Imperfect alignment	0.46
Momentum scale correction	0.09
Input charm masses	0.01
Total systematic uncertainty	0.69
Statistical uncertainty	0.88

$$LHCB,\ \tau = 203.5 \pm 1.0 \pm 1.3 \pm 1.4\ fs$$

$$FOCUS,\ \tau = 204.6 \pm 3.4 \pm 2.5\ fs$$

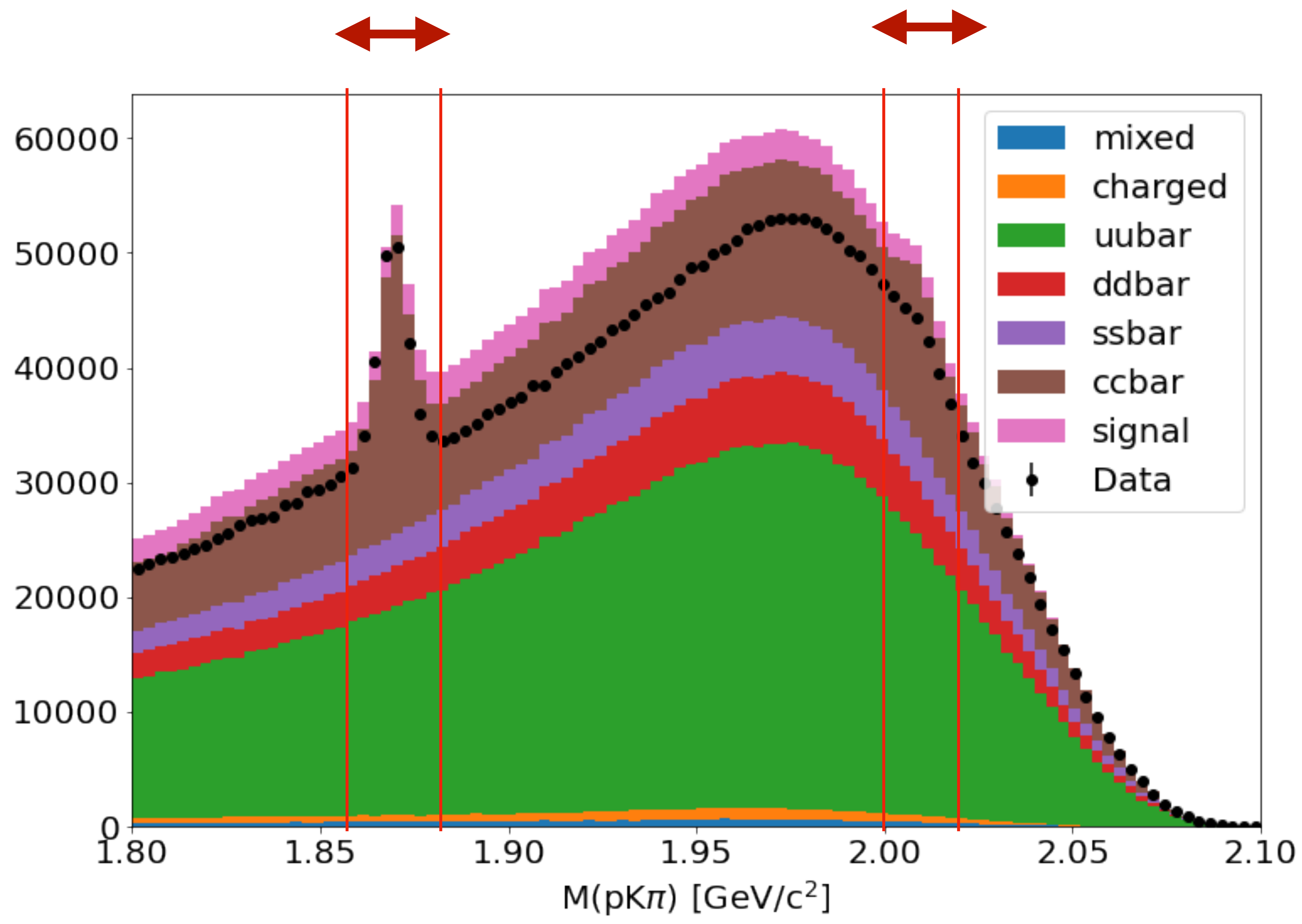
$$CLEO,\ \tau = 179.6 \pm 6.9 \pm 4.4\ fs$$

Extra slides

Charm backgrounds

- Most problematic backgrounds from long lived charm backgrounds
  - Remove charm backgrounds by cutting on M(pKπ) with pion hypothesis for proton track
  - Reduce backgrounds from $D^+ \to K^-\pi^+\pi^+$ $(1.858 < M(pK\pi) < 1.881)$ and $D^{*+} \to K^-\pi^+\pi^+$ $(2.000 < M(pK\pi) < 2.020)$

- Any remaining long-lived backgrounds are accounted in a lifetime background term in the likelihood fit
  - ccbar MC used to characterize remaining backgrounds of this type
  - Tighten additional selection criteria to reduce charm backgrounds as much as possible

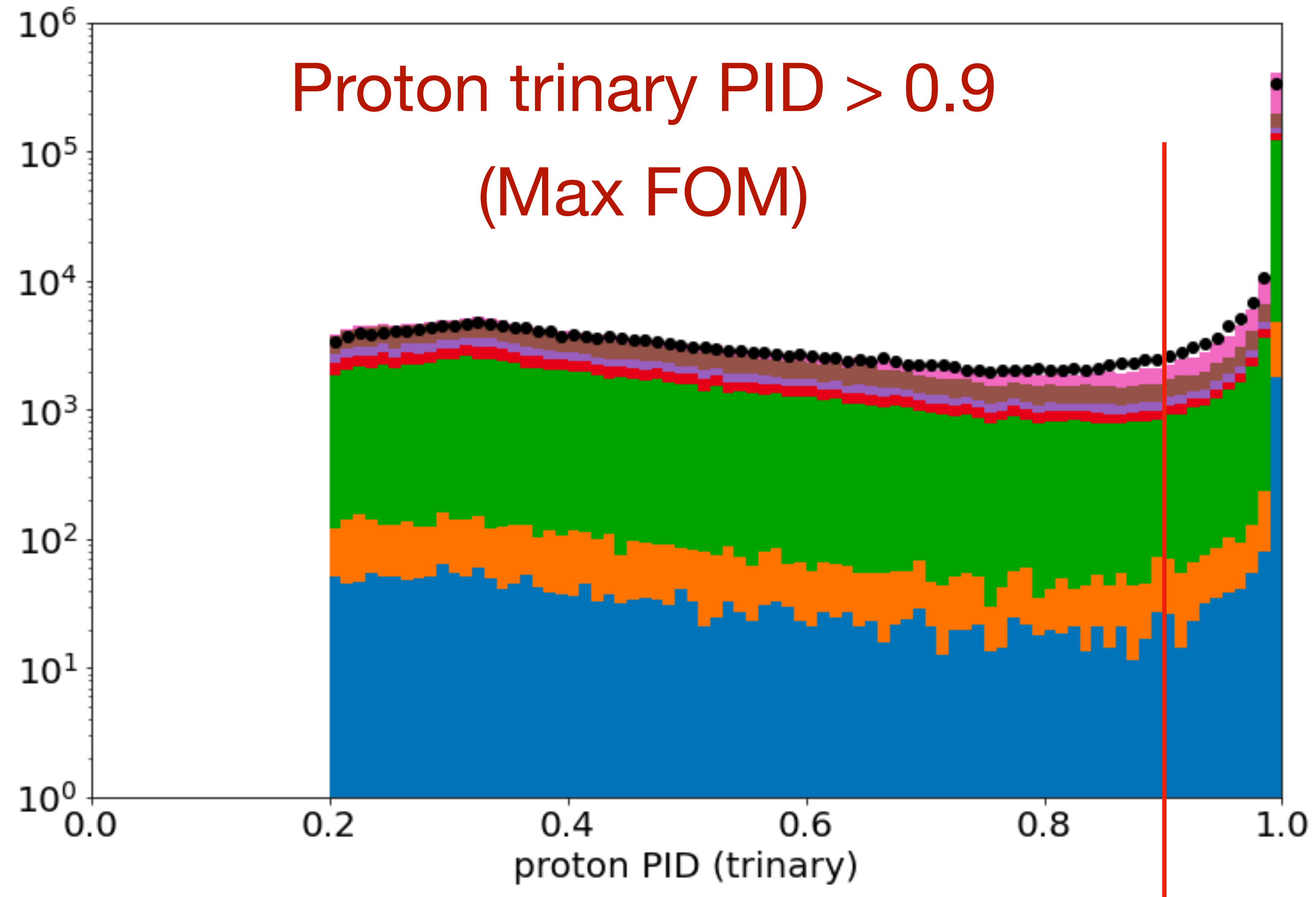


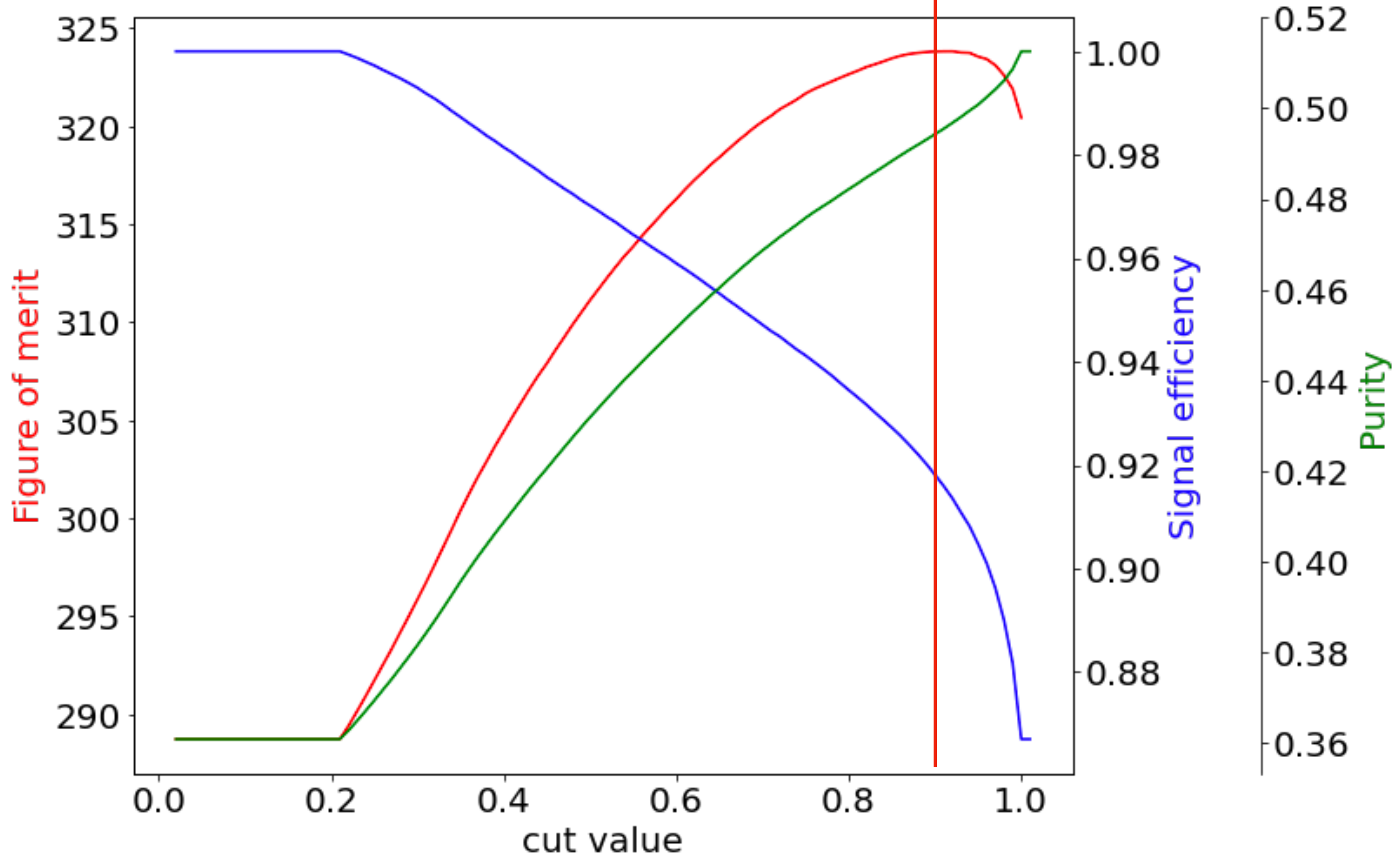
PID selection criteria

$$FOM = \frac{S}{\sqrt{S+B}}$$

- Reduce backgrounds from misidentified tracks with PID selection criteria
  - All available detector information is used (VXD dE/dx was not available in the data and MC samples used)

Proton trinary PID: $\dfrac{L(p)}{L(p)+L(K)+L(\pi)} > 0.9$





PID selection criteria

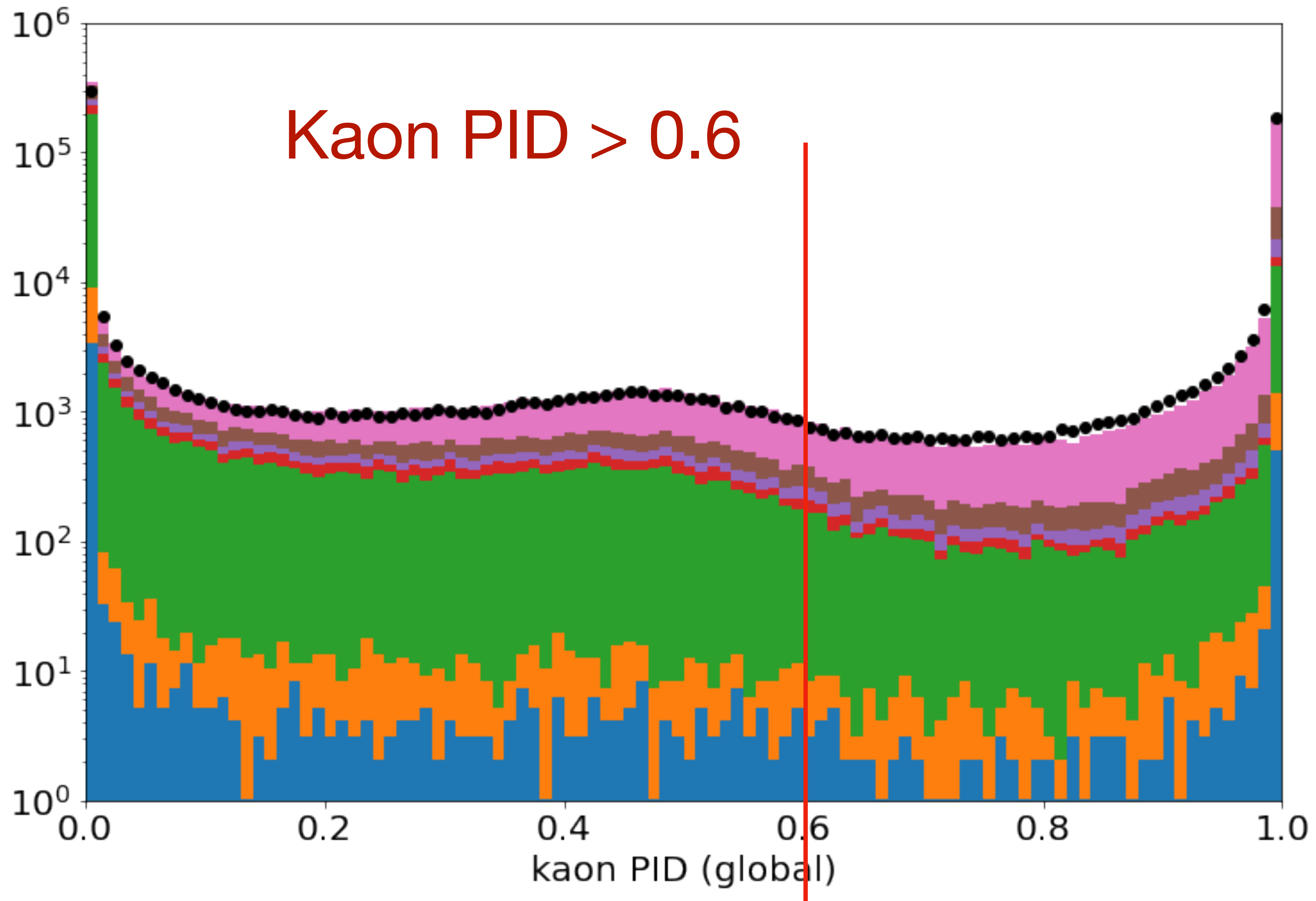
- Reduce backgrounds from misidentified tracks with PID selection criteria
  - All available detector information is used (VXD dE/dx was not available in the data and MC samples used)

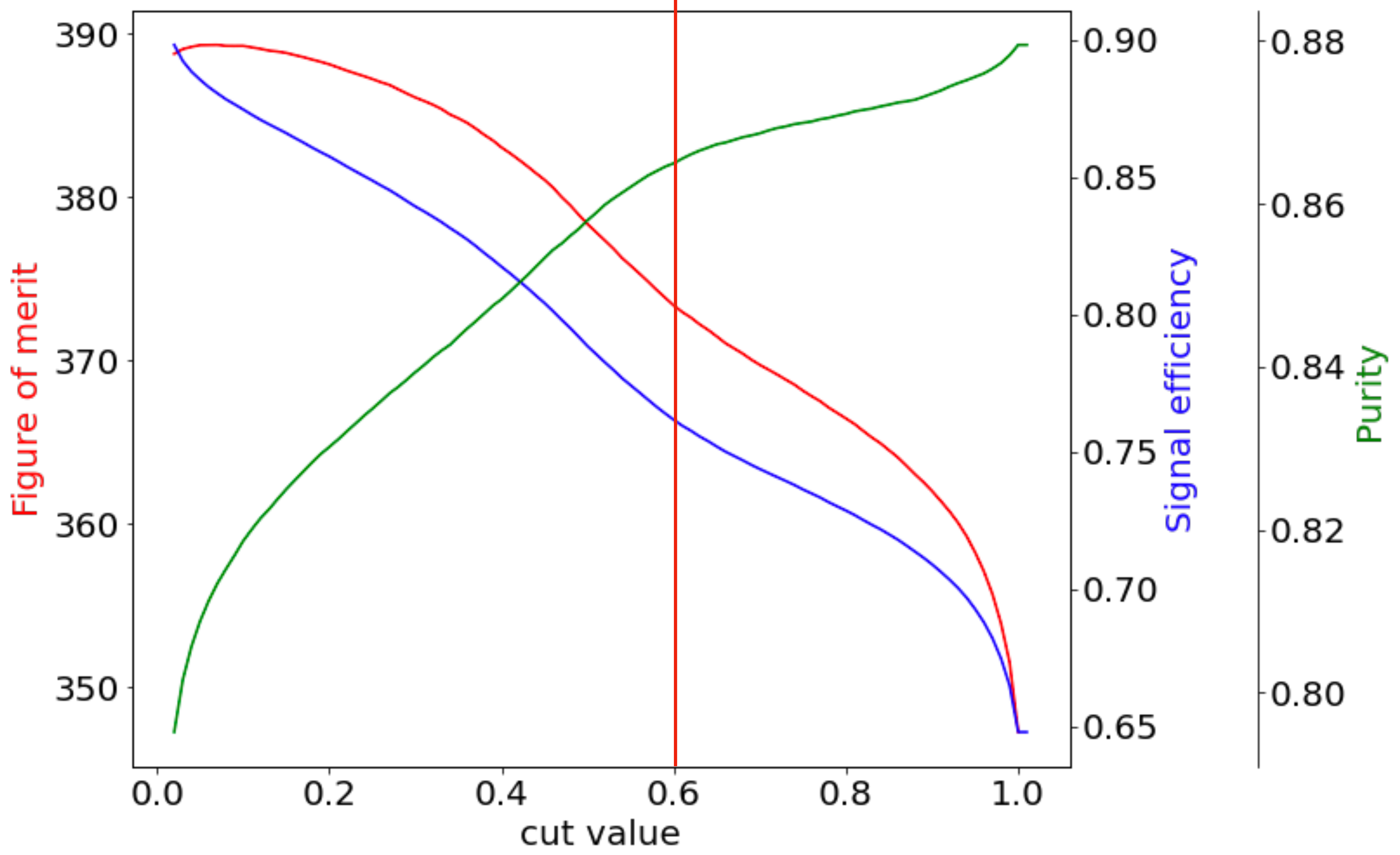
Proton trinary PID: $\frac{L(p)}{L(p)+L(K)+L(\pi)} > 0.9$

Kaon global PID: $\frac{L(K)}{L(p)+L(K)+L(\pi)+L(d)+L(e)+L(\mu)} > 0.6$

- KaonID cut placed near shoulder in signal purity, $\frac{S}{S+B}$

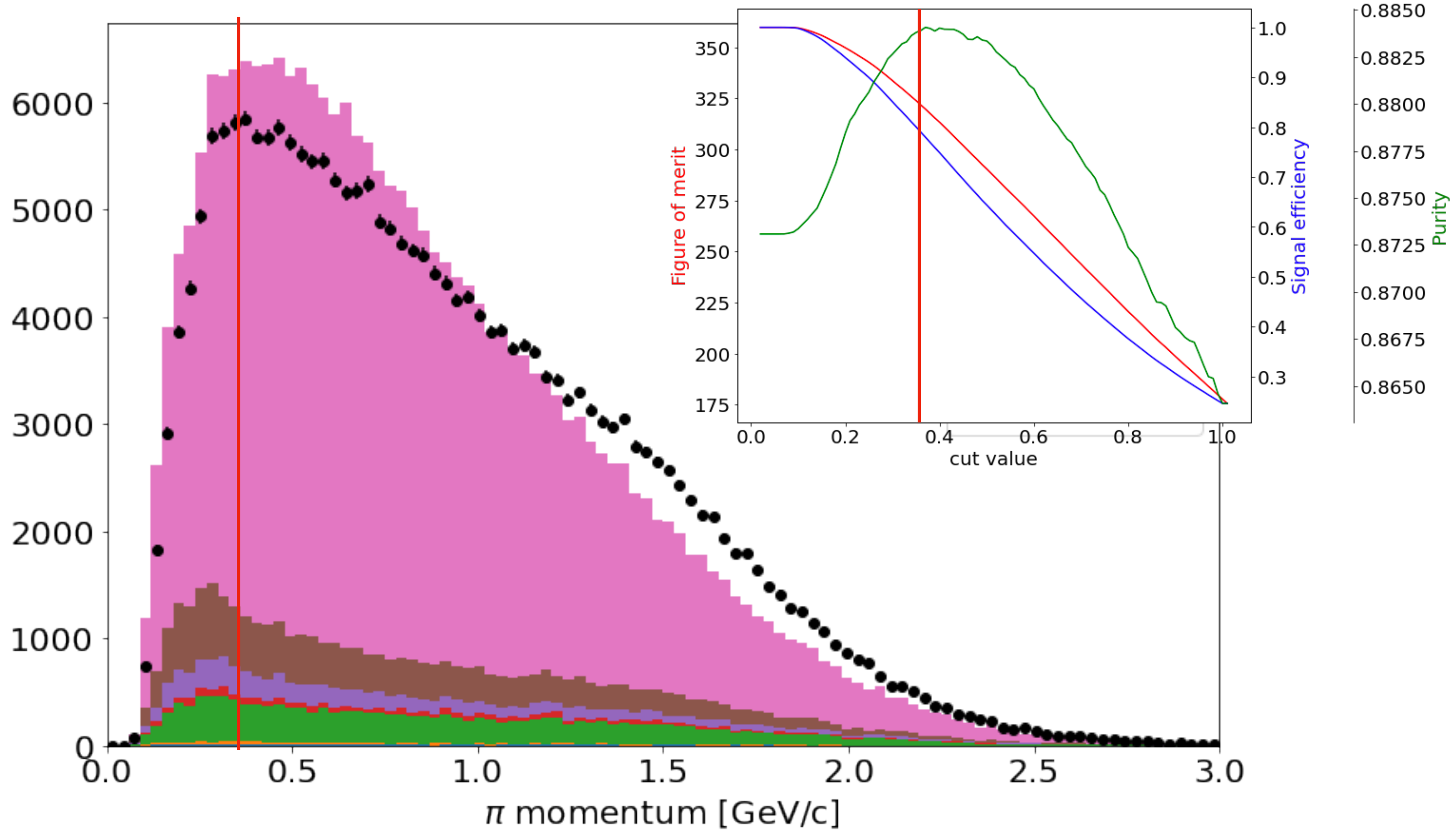
$$FOM = \frac{S}{\sqrt{S+B}}$$

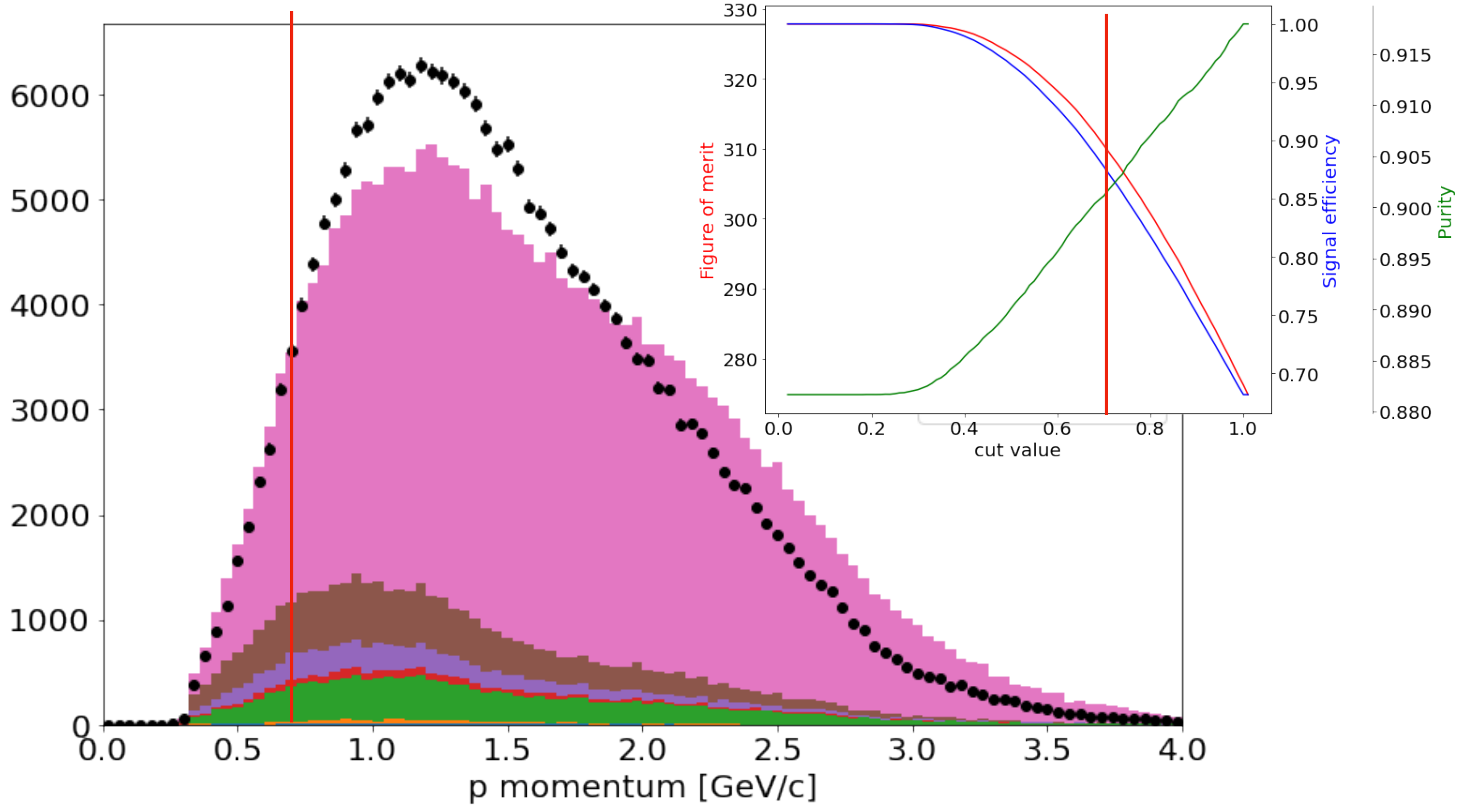




Daughter momenta

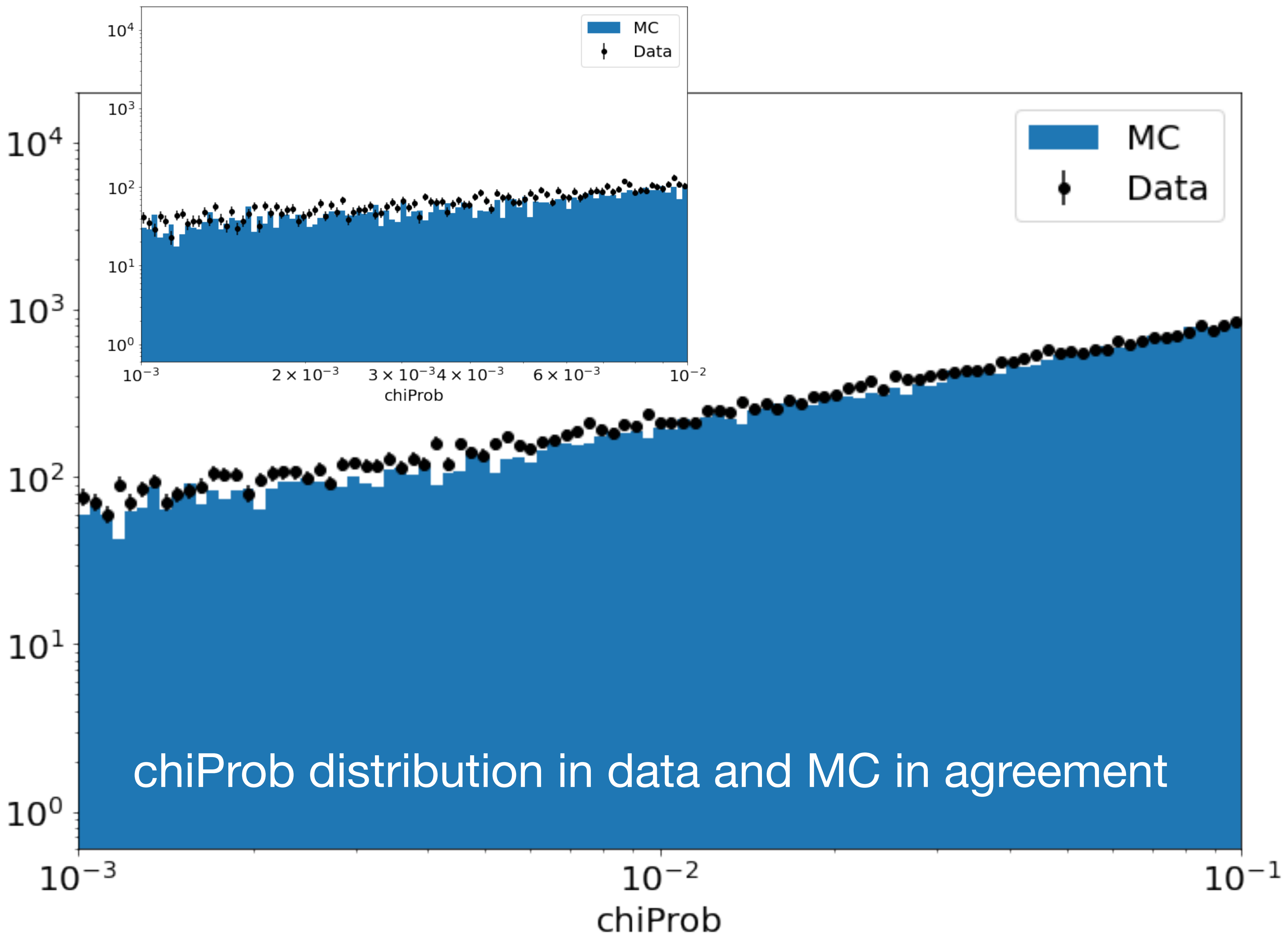
- Further suppress charm backgrounds by cutting on transverse momentum of Λ_c^+ daughters
  - $p_t(\pi) > 0.35$ (maximize signal purity)
  - $p_t(p) > 0.7$ (reduce backgrounds below 10% in MC)

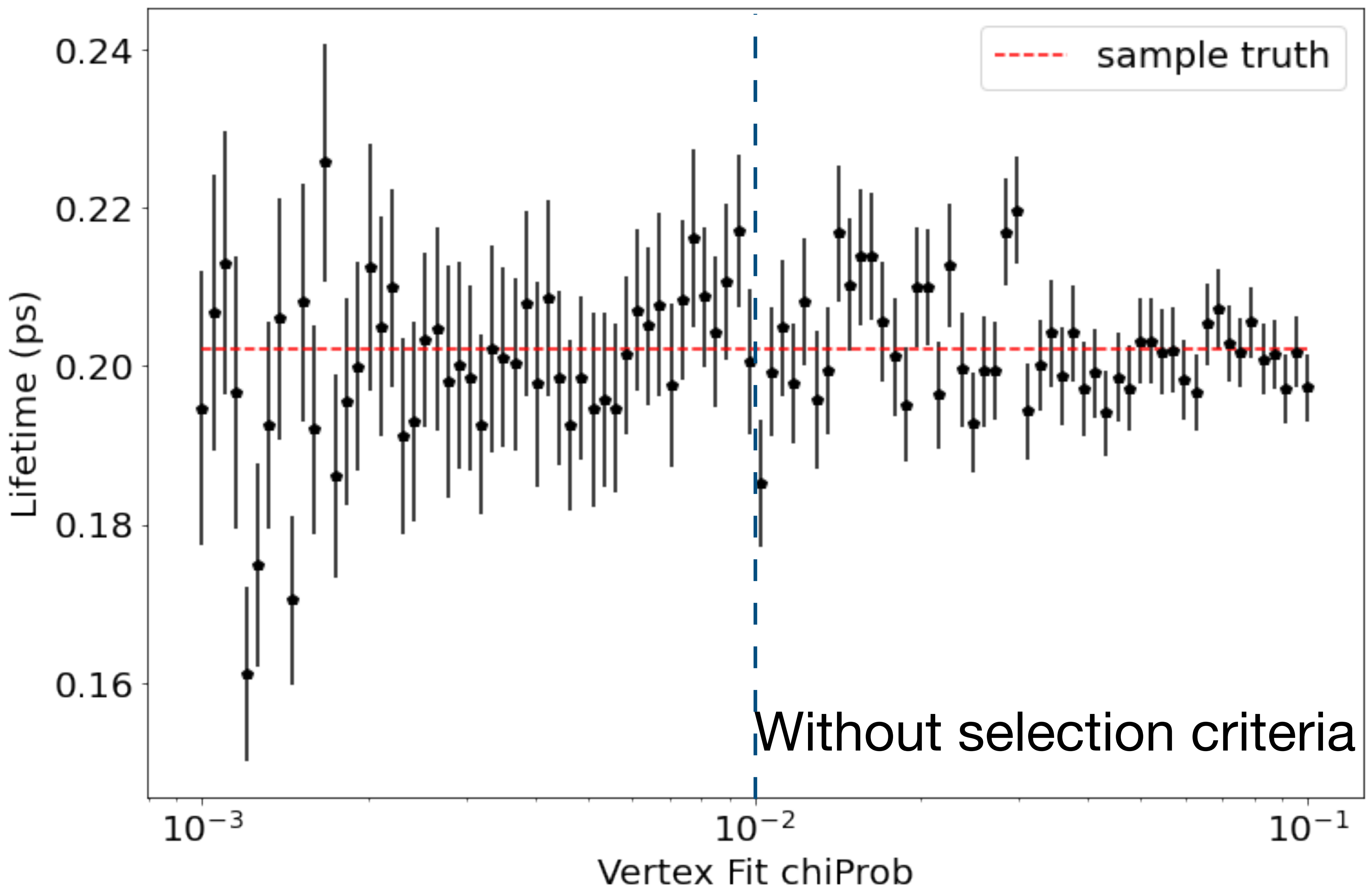


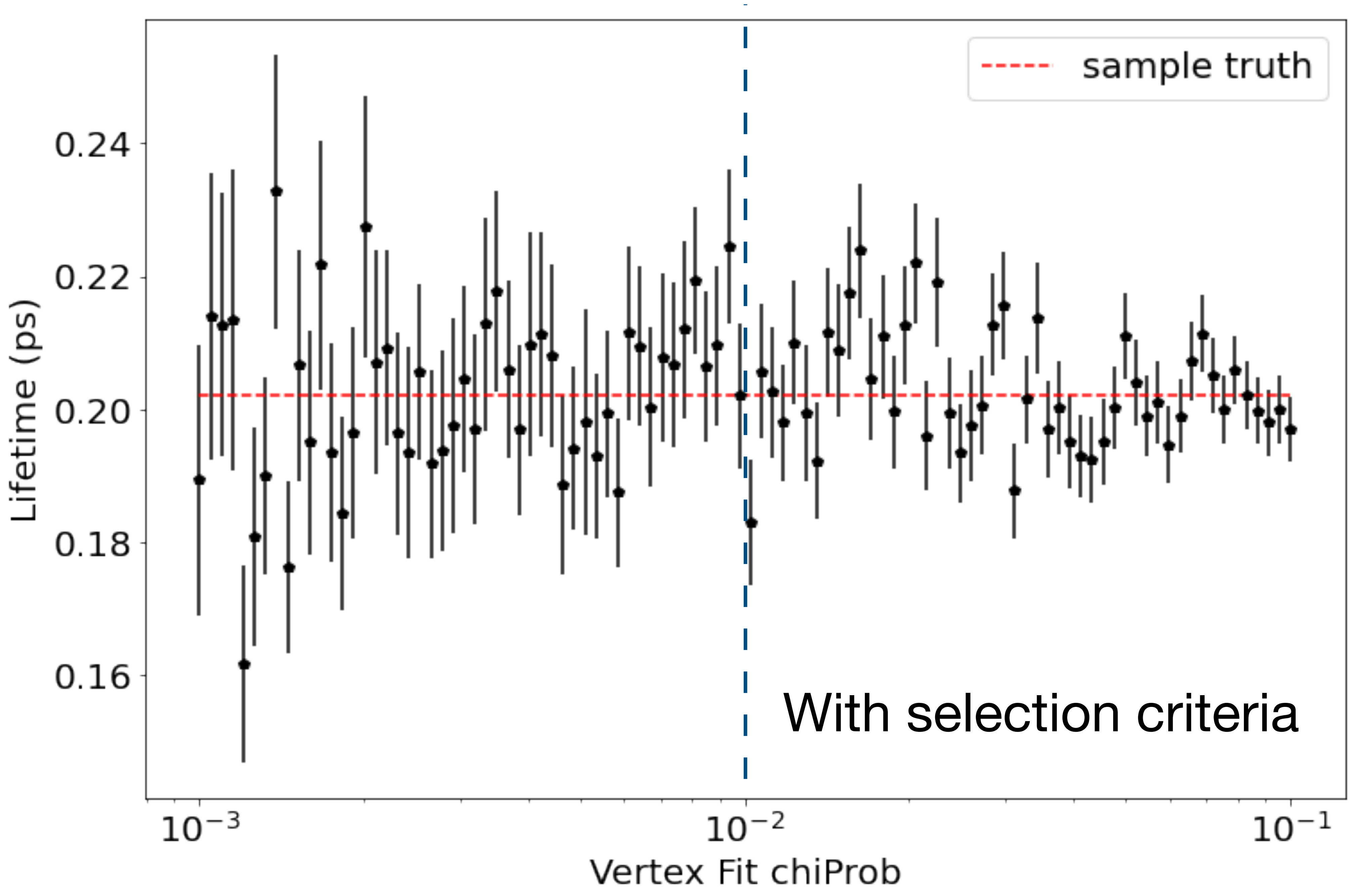


Check for selection bias

- A restriction is placed on the vertex fit quality (chiProb > 0.01)
  - To check for bias, the true lifetimes are binned vs chiProb and the true lifetime is calculated for each bin
  - Repeat with and without the selection criteria applied (except for track quality and IP cuts)
  - No obvious bias is observed







Check for bias on true lifetime

- Check the true lifetime for truth-matched signal events in the signal region
- Each cut is applied in succession (includes cuts to the left) and includes Lambdac_p_CMS > 2.5 and chiProb > 0.001
- Possible cumulative(?) effect, but difficult to diagnose without much larger sample

- 200/fb equivalent MC sample:

Cut	None	chiProb>0.01	Charm mass cuts	kaonID	protonID	pi_pt	p_pt
True lifetime	202.13 +- 0.4	202.07 +- 0.41	201.90 +- 0.42	201.84 +- 0.49	201.80 +- 0.51	202.14 +- 0.57	202.17 +- 0.62
Sigma from generated	0.65	0.79	1.14	1.13	1.15	0.43	0.37

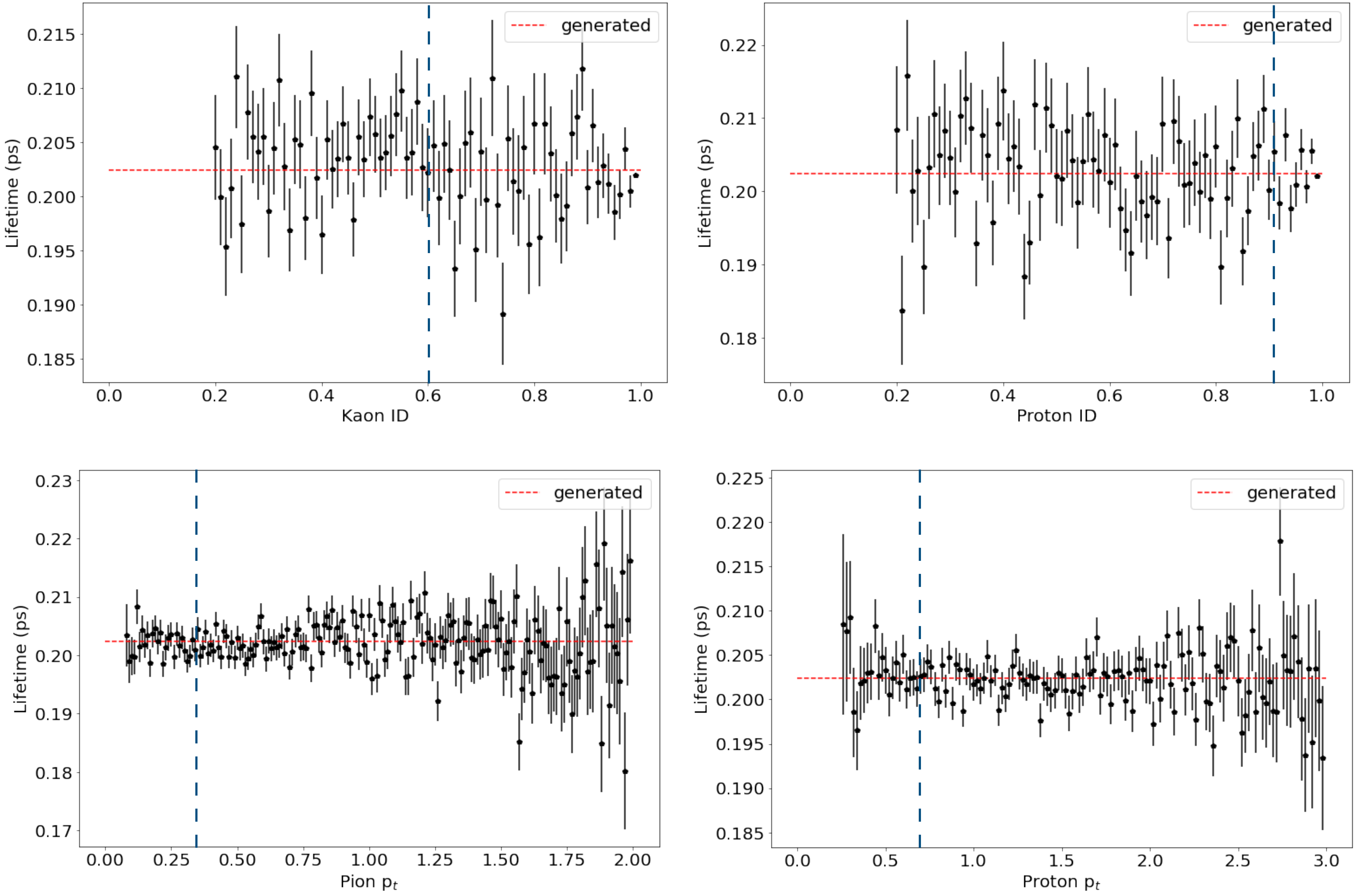
- 1/ab equivalent MC sample:

Cut	None	chiProb>0.01	Charm mass cuts	kaonID	protonID	pi_pt	p_pt
True lifetime	202.31 +- 0.19	202.30 +- 0.19	202.21 +- 0.20	201.99 +- 0.22	202.01 +- 0.23	201.94 +- 0.25	201.84 +- 0.27
Sigma from generated	0.41	0.46	0.89	1.82	1.66	1.75	2.07

Check for selection bias

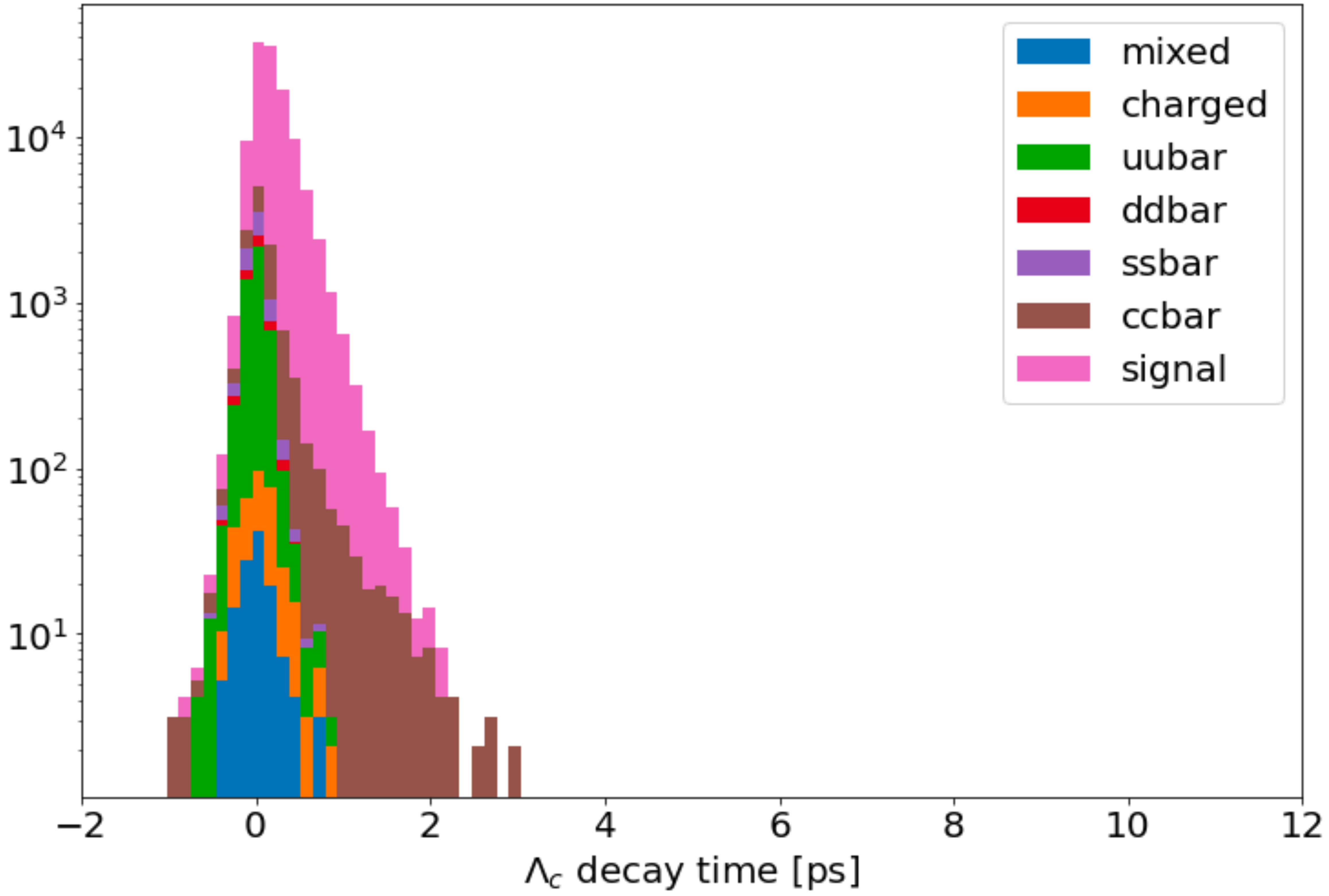
- Each sample includes the Λ_c CM momentum cut, charm mass cut, and only selects events in the signal region

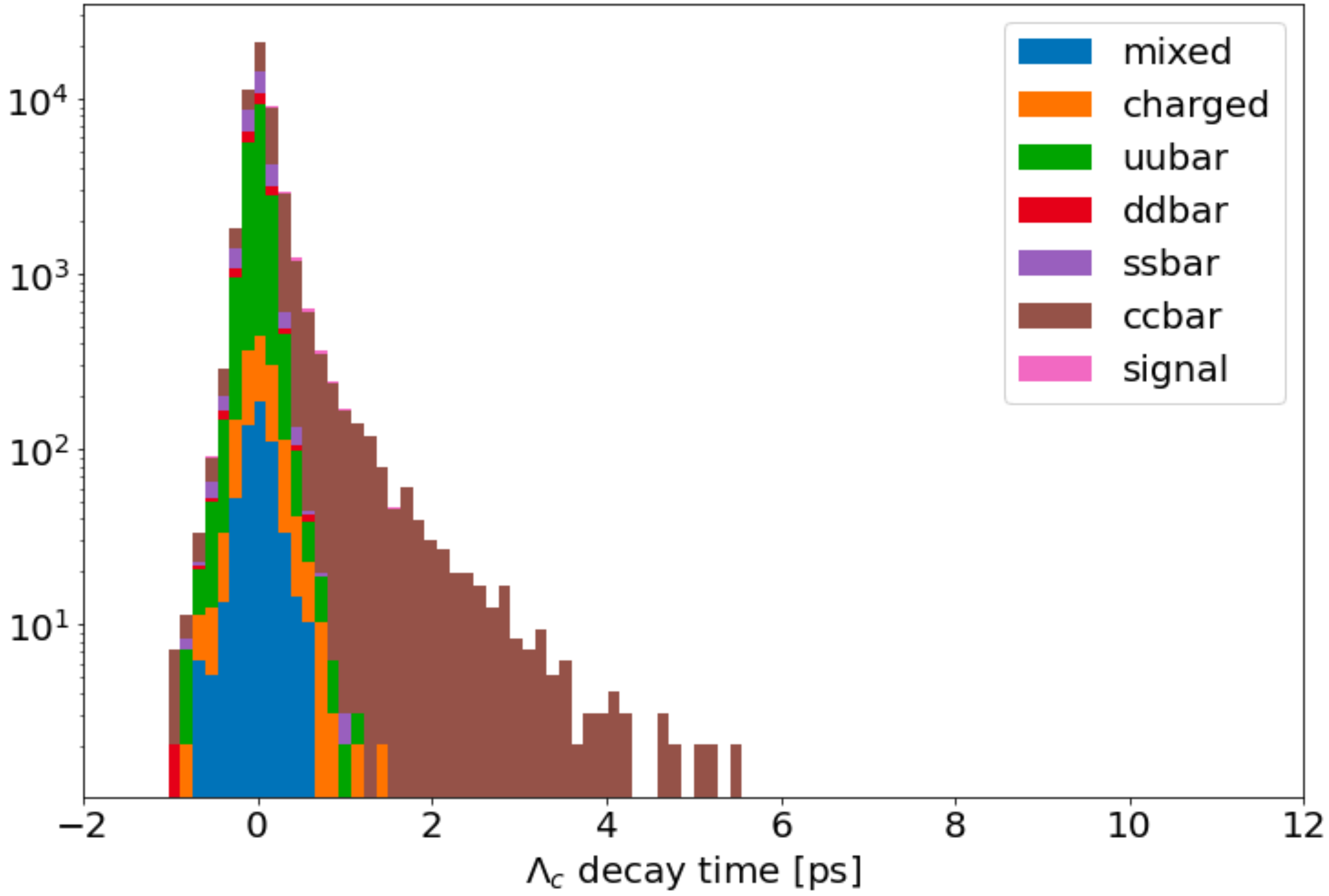
- Check for selection bias
  - True lifetimes are binned vs selection criteria, true lifetime is calculated for each bin
  - No obvious bias is observed



Data/MC lifetime comparison

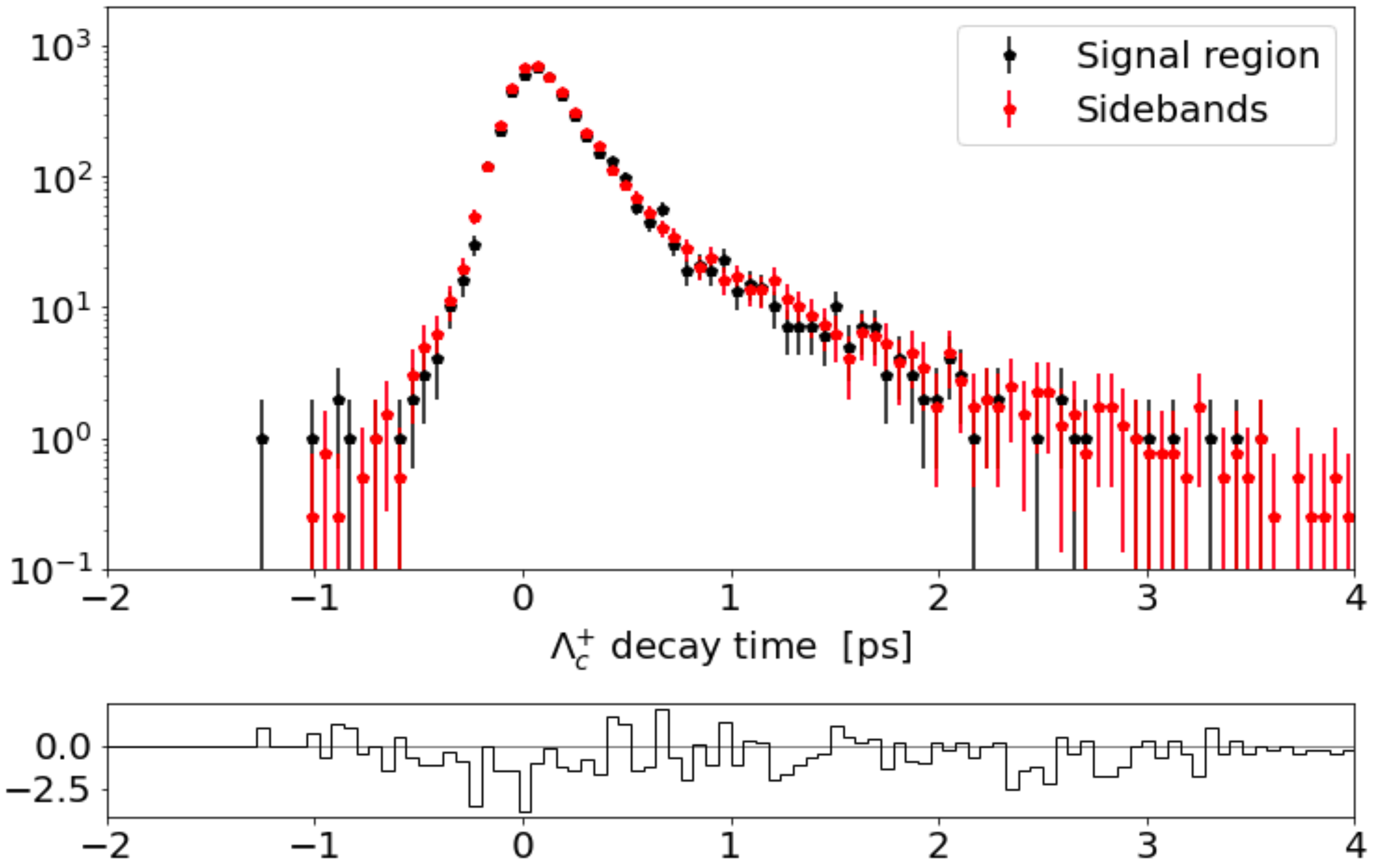
- Remaining background still includes small fraction of long lived charm decays
  - Accounted in a lifetime background term (no dedicated PDF)
  - With current statistics, no bias from discrepancies between signal and sideband regions above 4 ps (see later slides)

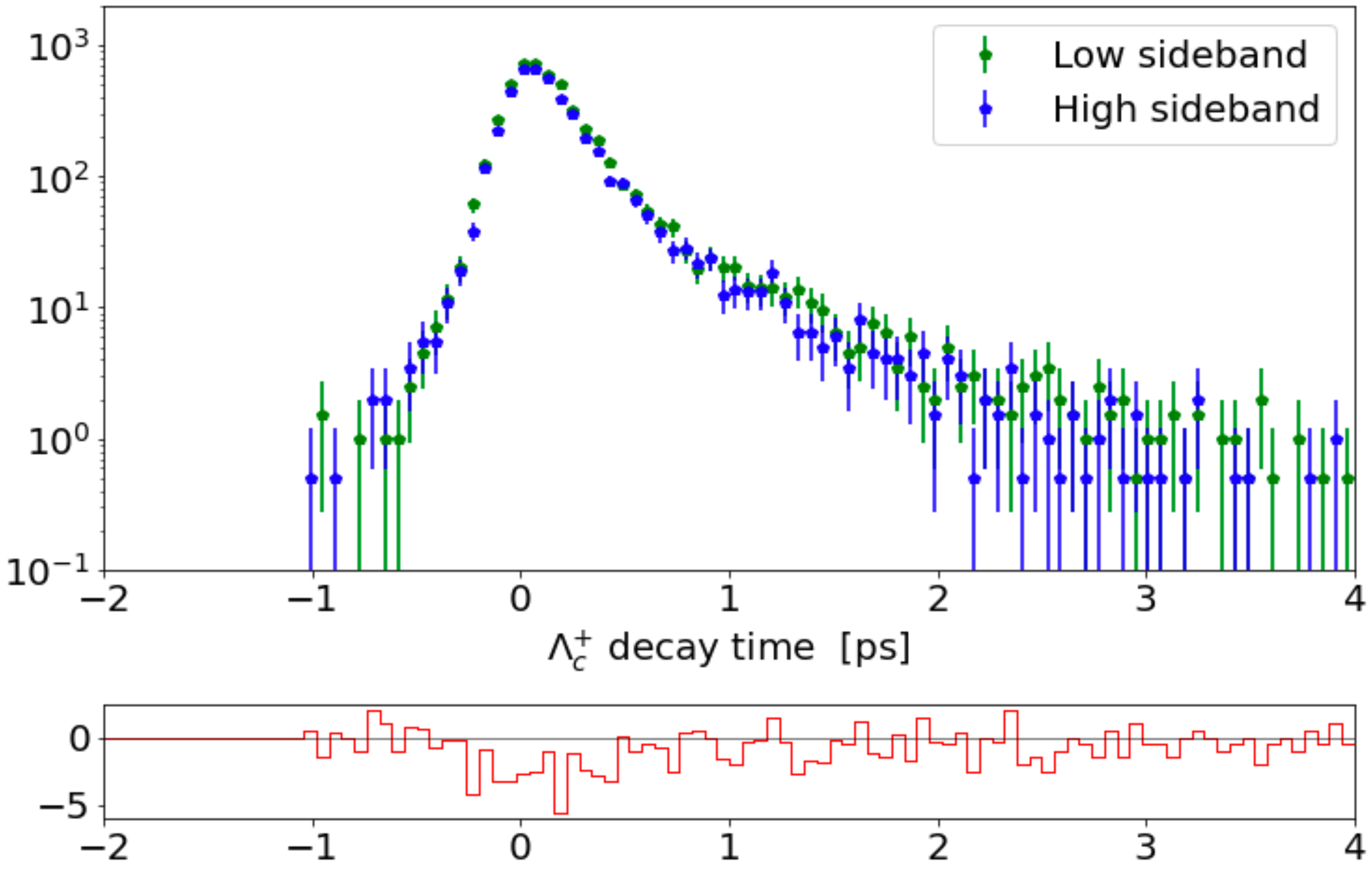




Background comparison - charm backgrounds

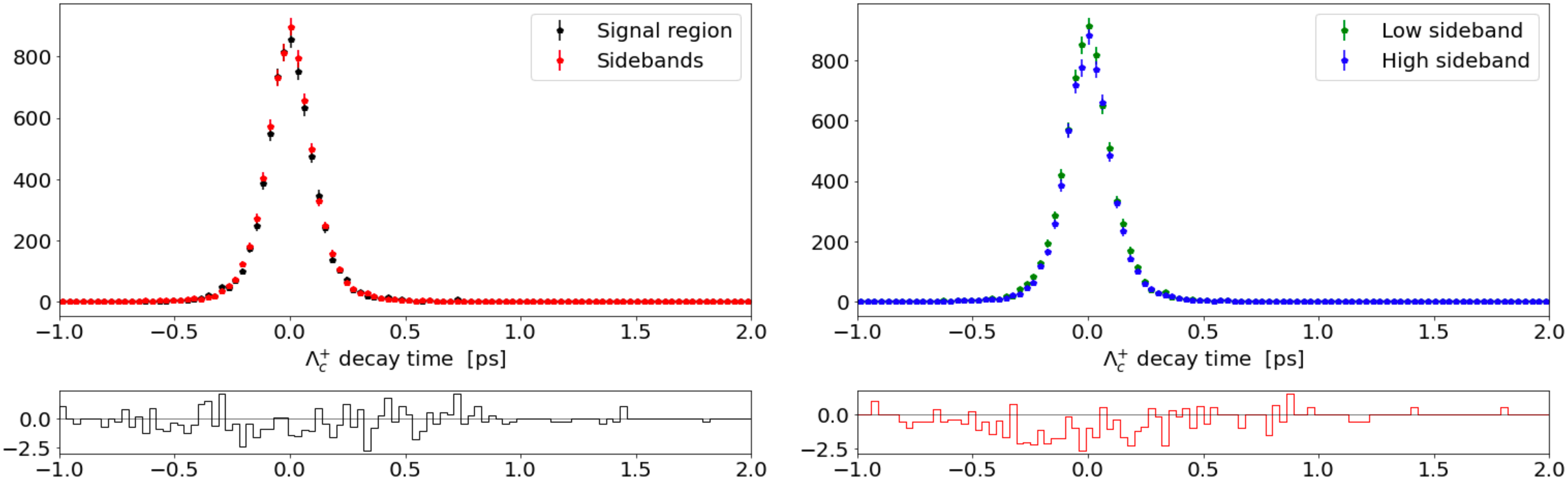
- Comparison of truth-matched backgrounds in signal region with events in the sidebands for events in ccbar MC
  - No significant discrepancies
  - Reasonable agreement between low and high sidebands





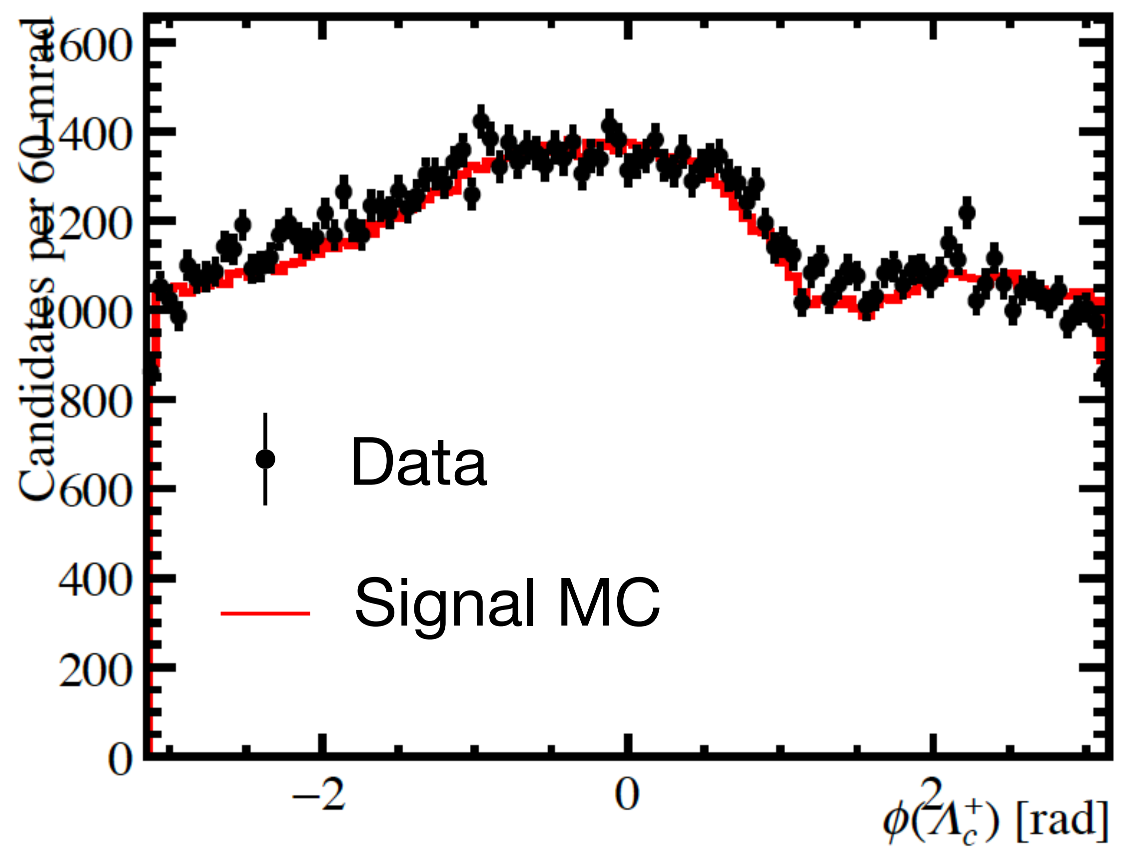
Background comparison - combinatorial backgrounds

- Comparison of truth-matched backgrounds in signal region with events in the sidebands for events in buds MC
  - No significant discrepancies
  - Reasonable agreement between low and high sidebands

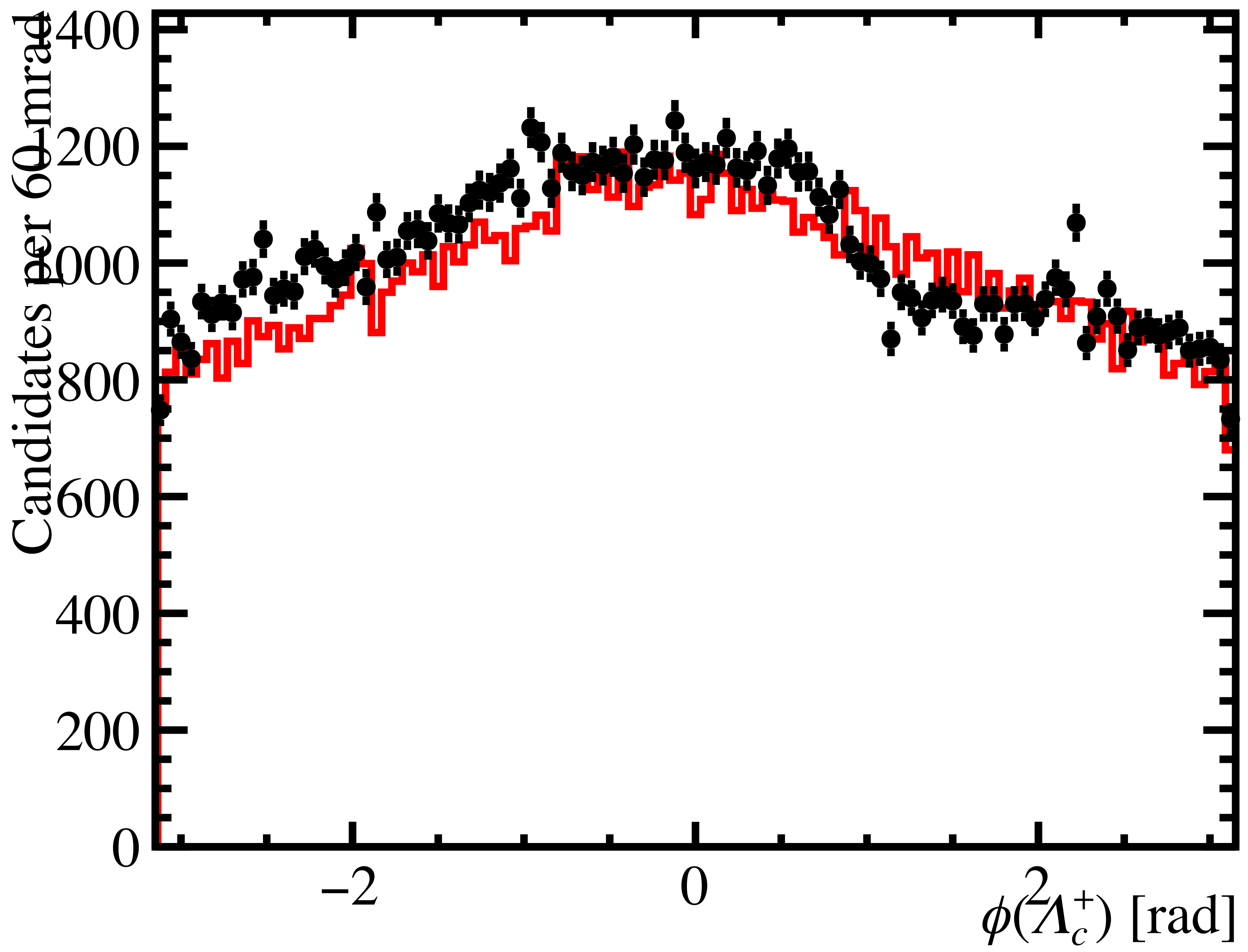


PXD performance in simulation and data samples

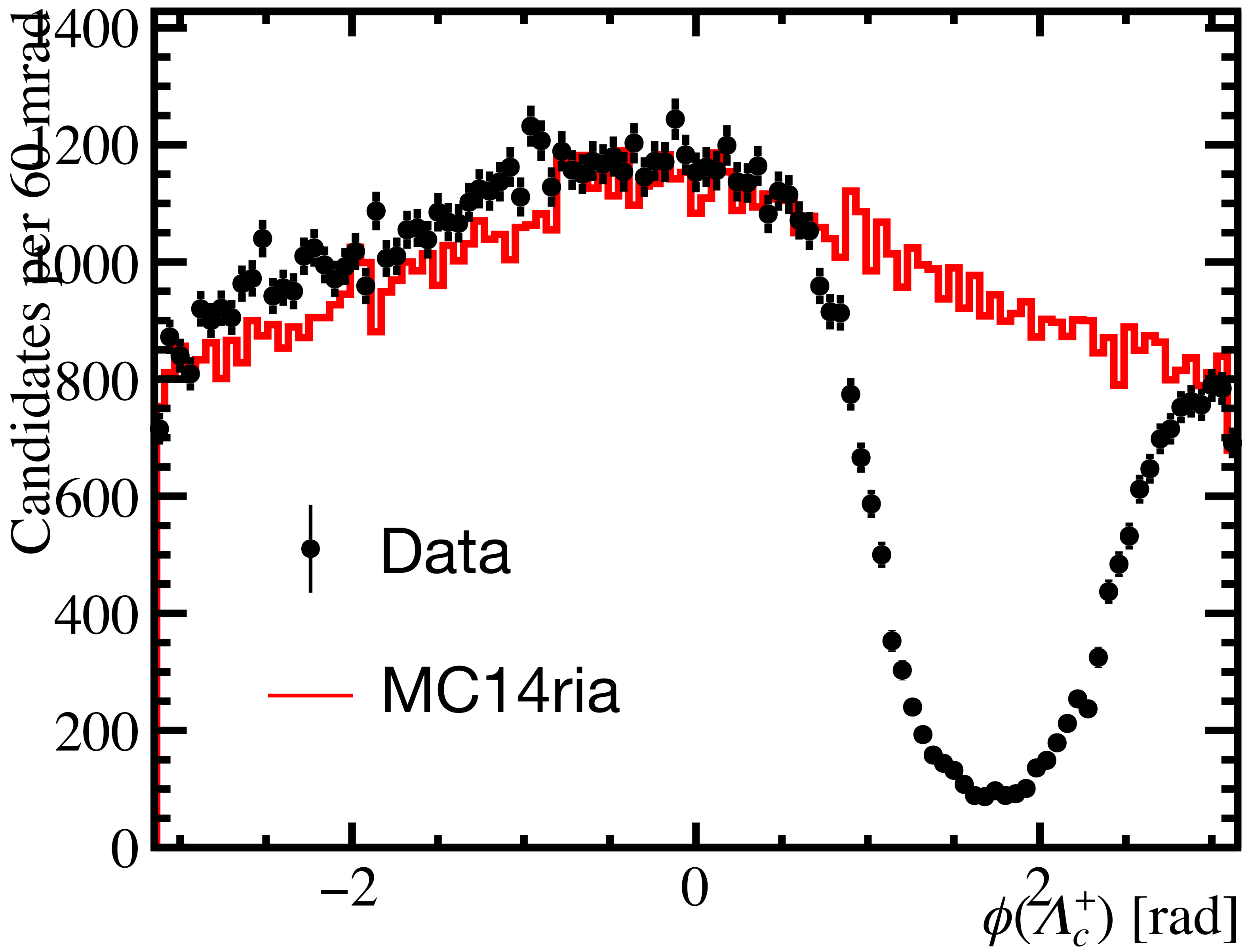
- Part of PXD layer 1 experienced an inefficiency in data (region in ϕ)
  - Partial layer 2 covers the same region, so no requirement is applied to require a hit in the first PXD layer (as for D^0 measurement)
  - MC14ri does not include this inefficiency (note: MC not used as input for measurement in data)
  - Signal MC samples produced with PXD inefficiency as cross-check



No requirement on VXD layer 1

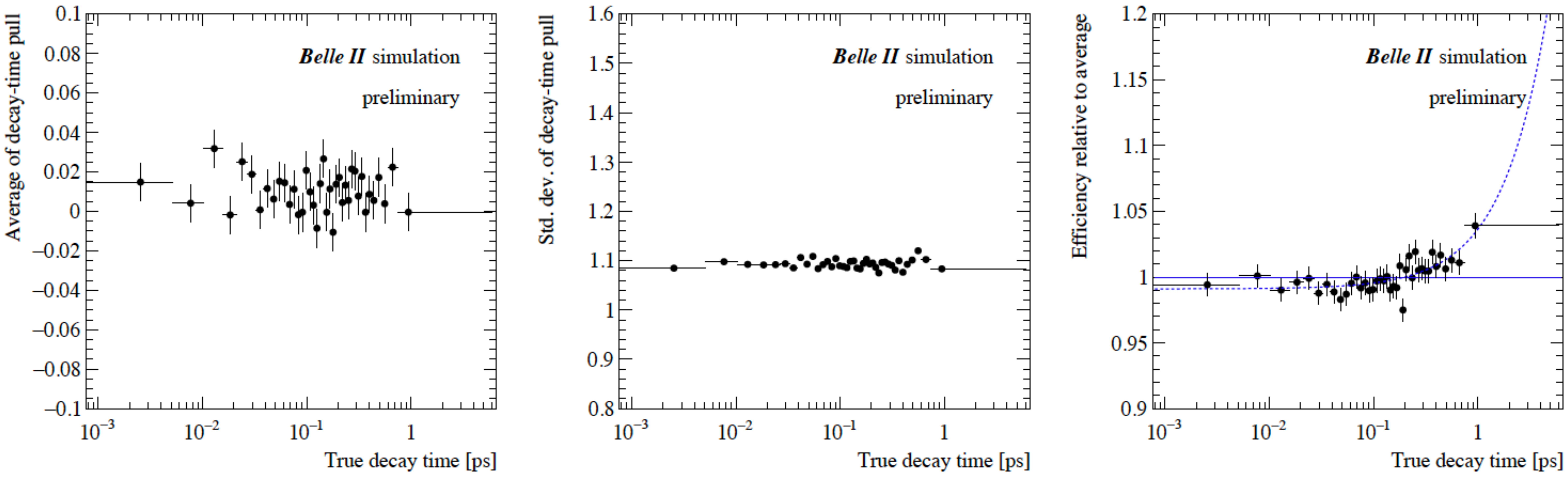


Require first hit on VXD layer 1



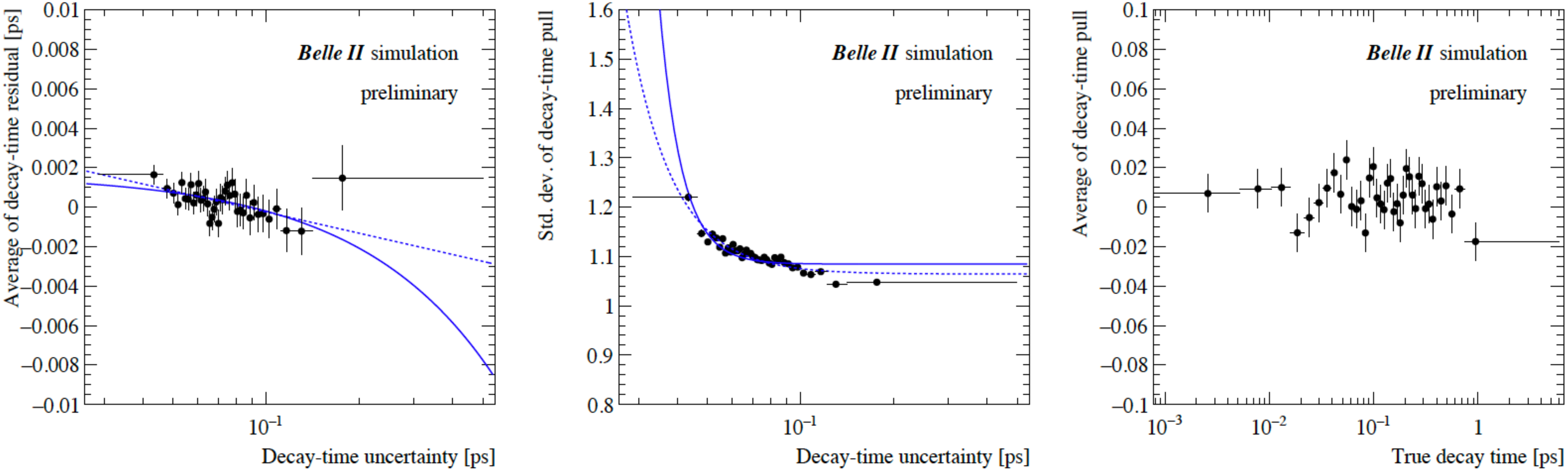
Decay time dependencies

- No significant dependence on the true decay-time
  - Some suggestion in signal efficiency (no obvious bias in lifetime result - see later slides)



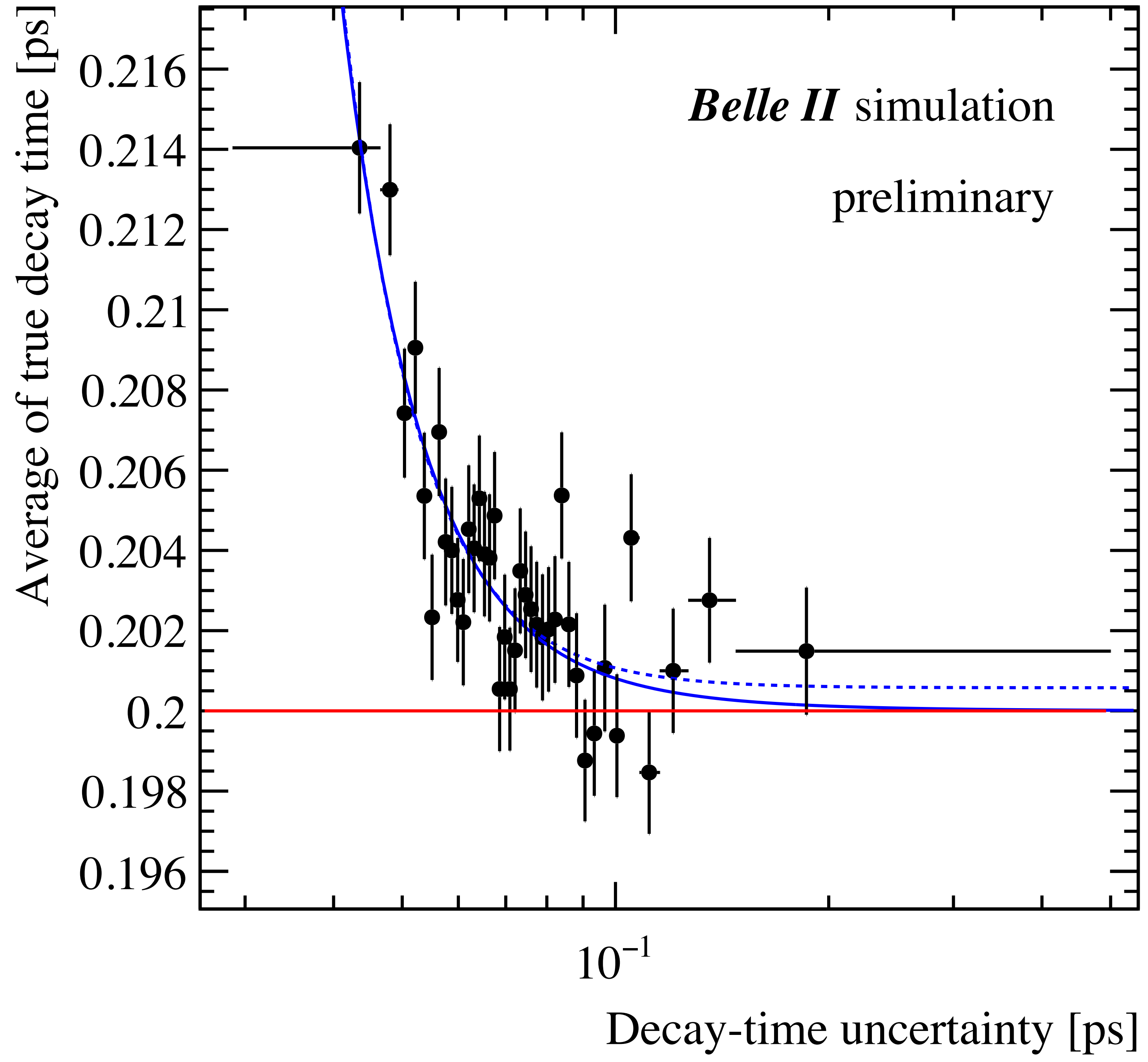
Decay time dependencies

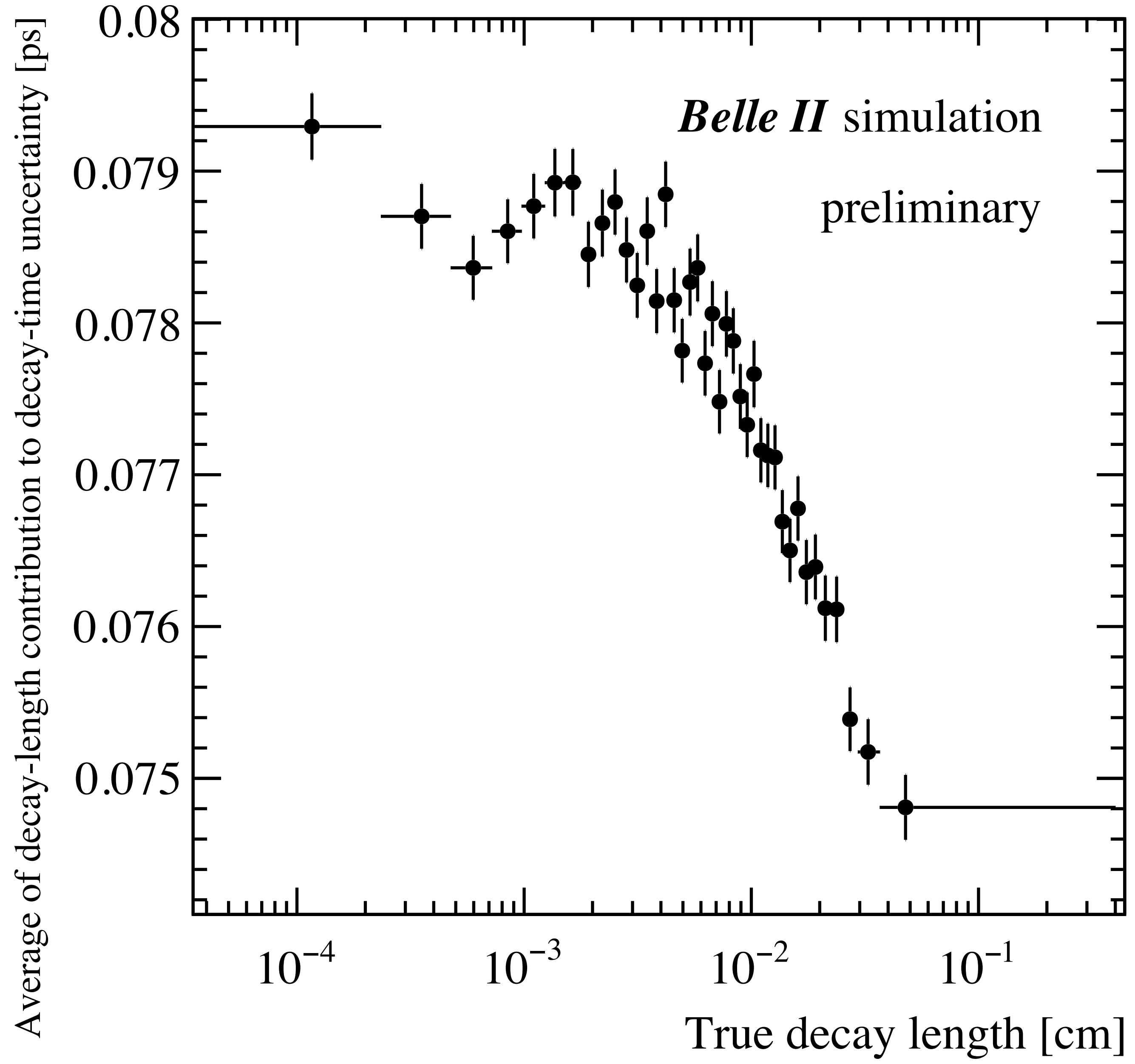
- Average of decay-time residual and std dev of decay-time pull vary as a function of decay-time uncertainty
  - Relative underestimation of decay-time uncertainty depends on measured decay-time uncertainty



Decay time dependencies

Mild variation of average true decay time versus measured decay time uncertainty



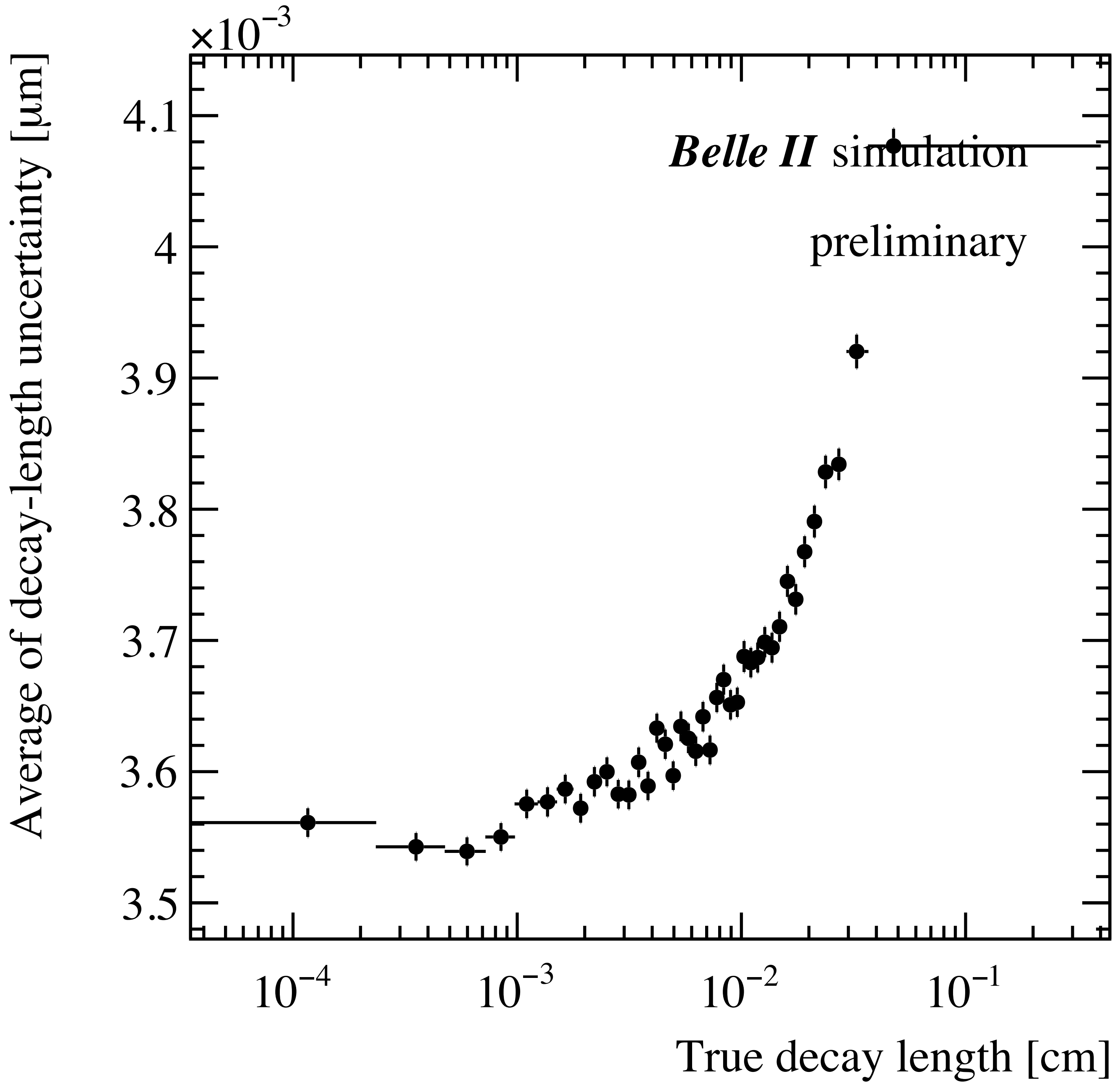


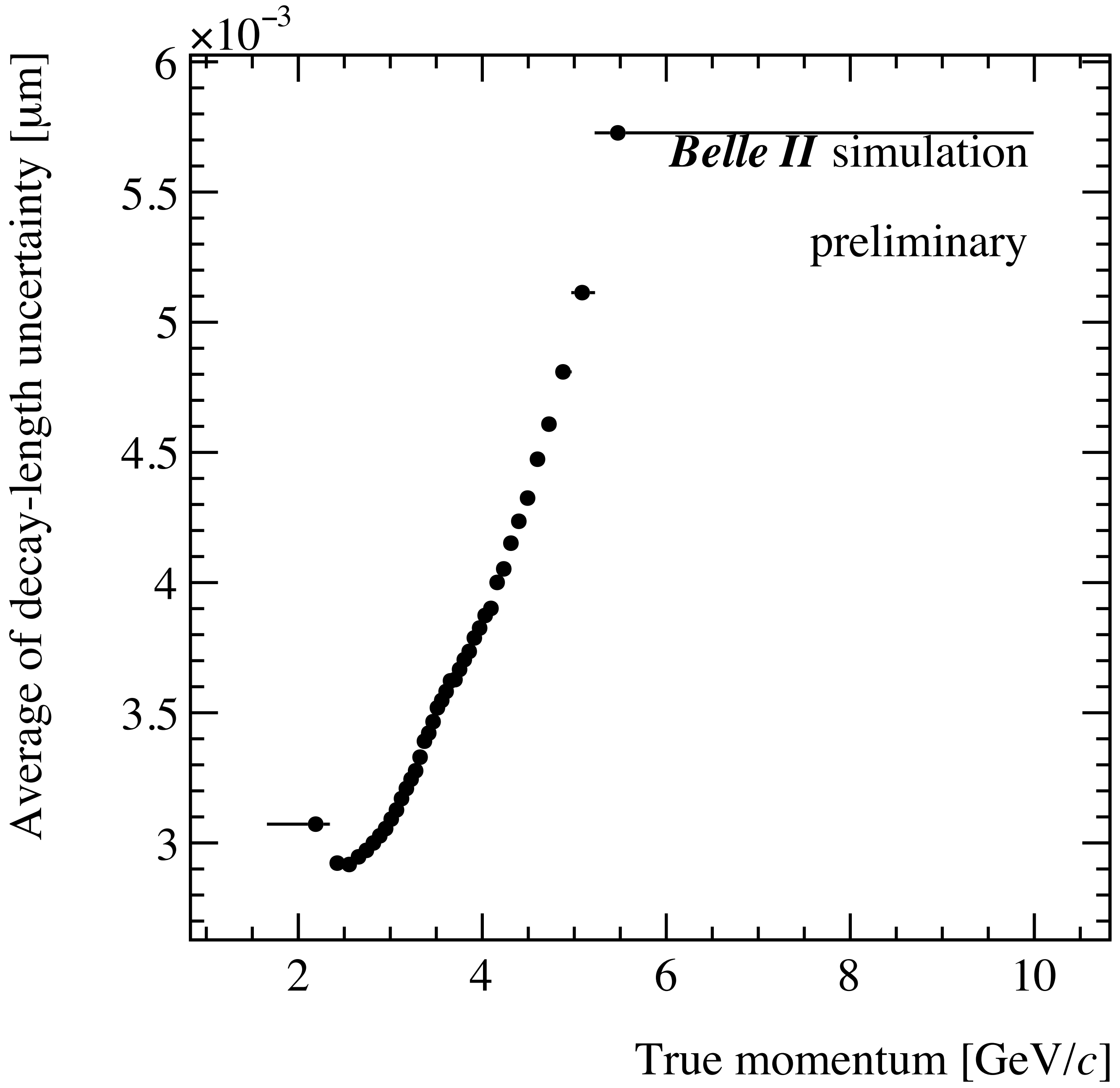
$$t = \frac{m\,L}{p\,c}$$

$$\sigma_t^2 = \left(\frac{m}{pc}\sigma_L\right)^2 + \left(\frac{t}{p}\sigma_p\right)^2 - 2\left(\frac{mt}{p^2c}\right)\rho_{Lp}\sigma_L\sigma_p$$

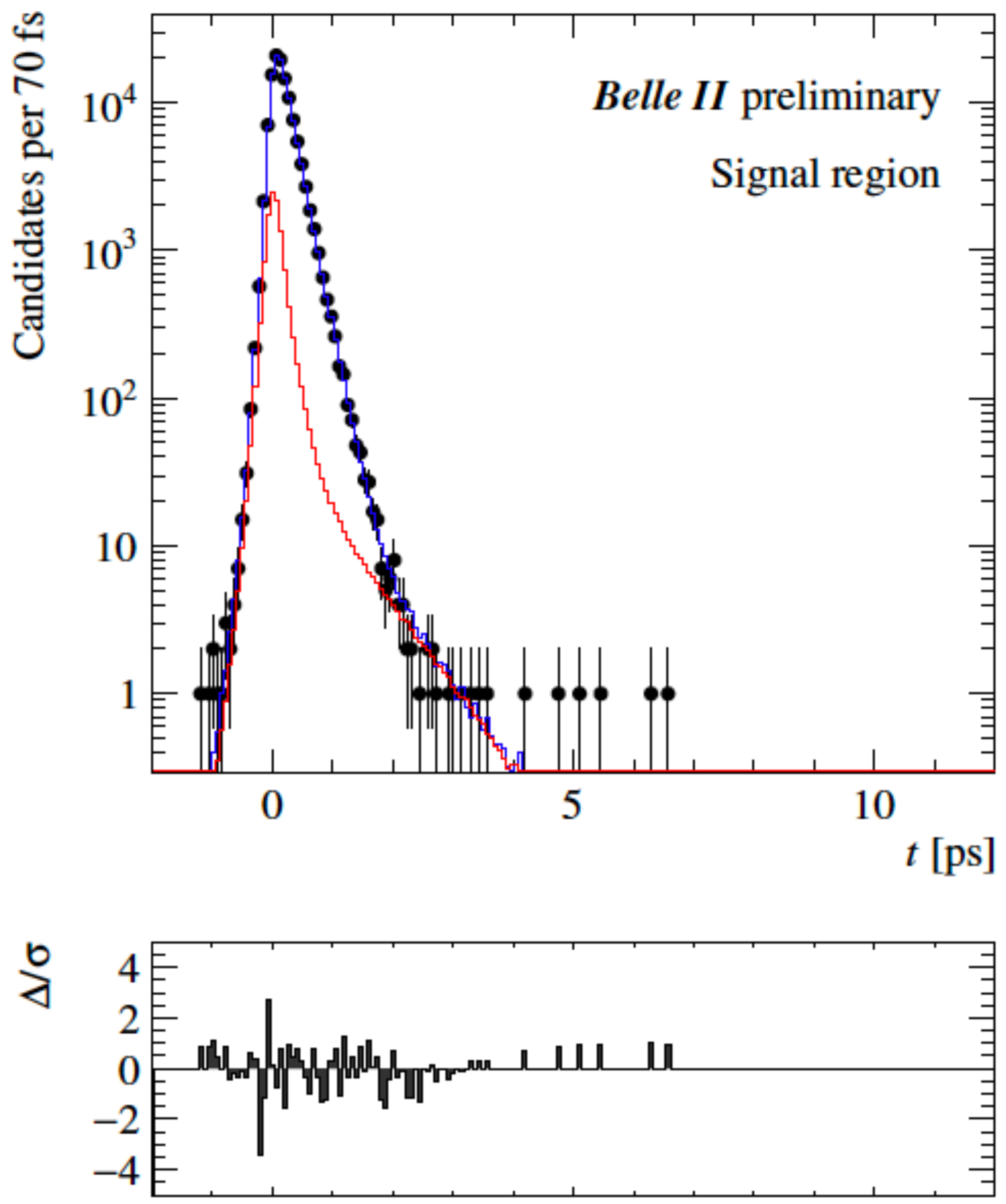
Decay time uncertainty dependence on true decay time due to decay length uncertainty dependence on true decay time and true momentum

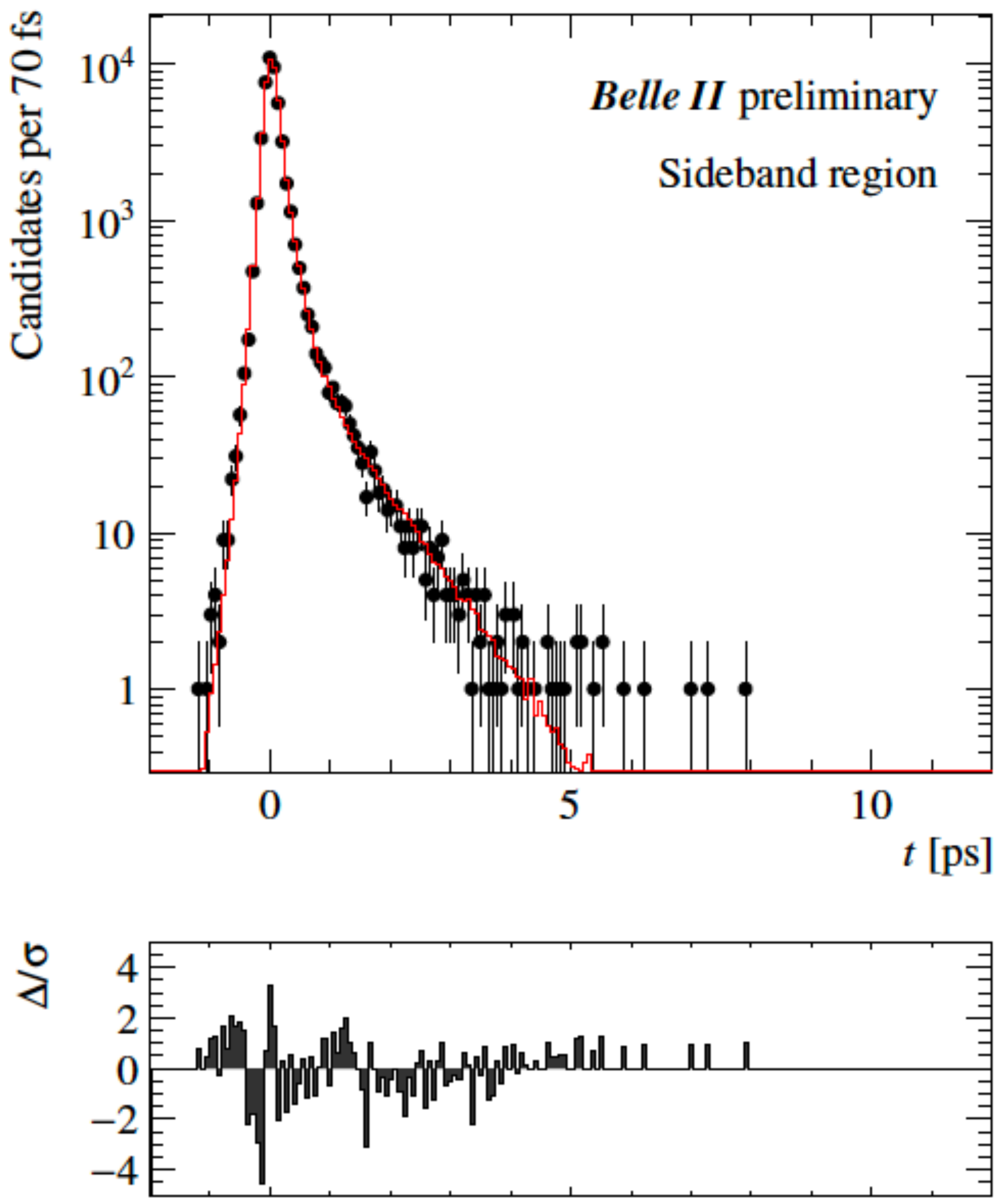
Assumed to be well simulated and ignored in the lifetime fit





Lifetime fit results on MC with single-Gaussian resolution - 200/fb





$LHCB, \tau = 203.5 \pm 1.0 \pm 1.3 \pm 1.4\ fs$

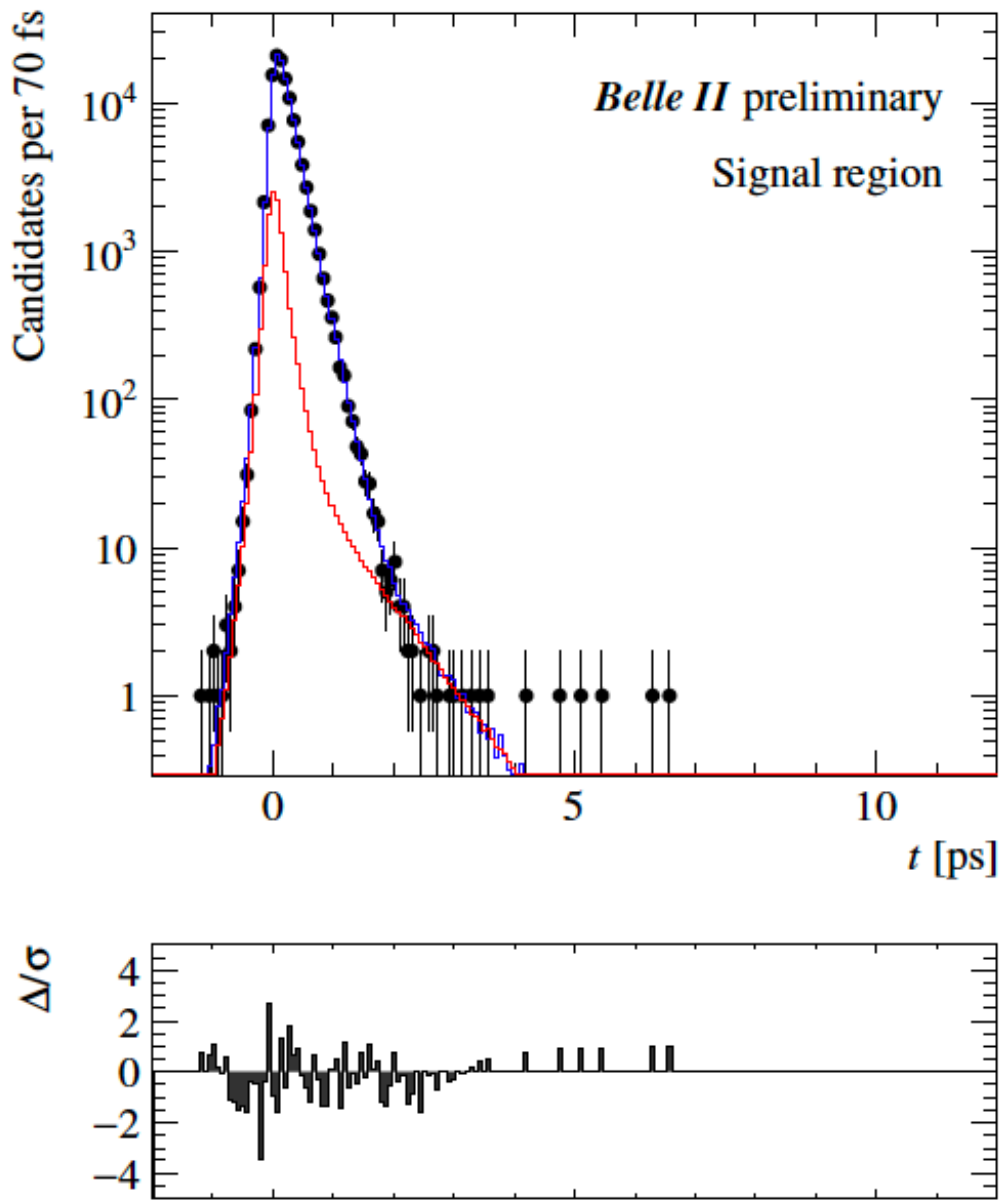
$FOCUS, \tau = 204.6 \pm 3.4 \pm 2.5\ fs$

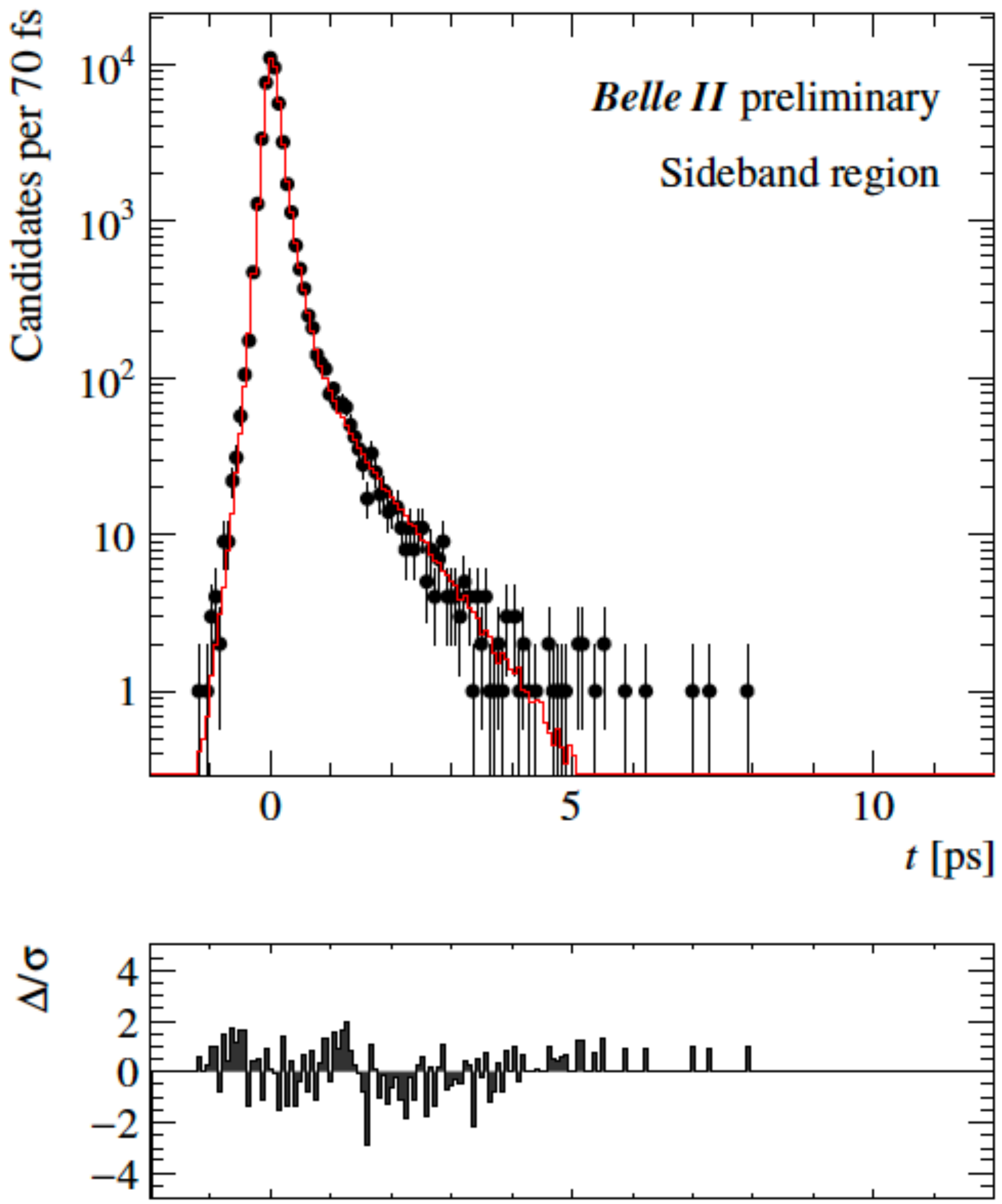
$CLEO, \tau = 179.6 \pm 6.9 \pm 4.4\ fs$

Parameter	Fit result w/single Gaussian
τ (fs)	202.43 ± 0.85
b (fs)	0.90 ± 0.58
s_1	1.0771 ± 0.0062
s_2	
f	
f_{bg}	0.09594 ± 0.00026
f_τ	0.2879 ± 0.0086
$f_{\tau 1}$	0.8269 ± 0.0095
τ_{bg1} (fs)	168.3 ± 5.6
τ_{bg2} (fs)	792.4 ± 25.8
s_{bg}	1.1638 ± 0.0079

True value (average from truth matched events in the signal region): **202.17 ± 0.62 fs**

Lifetime fit results on MC with double-Gaussian resolution - 200/fb





$LHCB,\ \tau = 203.5 \pm 1.0 \pm 1.3 \pm 1.4\ fs$

$FOCUS,\ \tau = 204.6 \pm 3.4 \pm 2.5\ fs$

$CLEO,\ \tau = 179.6 \pm 6.9 \pm 4.4\ fs$

Parameter	Fit result w/double Gaussian
τ (fs)	202.87 ± 0.88
b (fs)	0.04 ± 0.60
s_1	1.0472 ± 0.0100
s_2	2.2938 ± 0.1082
f	0.9730 ± 0.0051
f_{bg}	0.09591 ± 0.00026
f_τ	0.3103 ± 0.0091
$f_{\tau 1}$	0.8328 ± 0.0101
τ_{bg1} (fs)	158.4 ± 6.2
τ_{bg2} (fs)	779.8 ± 29.5
s_{bg}	1.1262 ± 0.0104

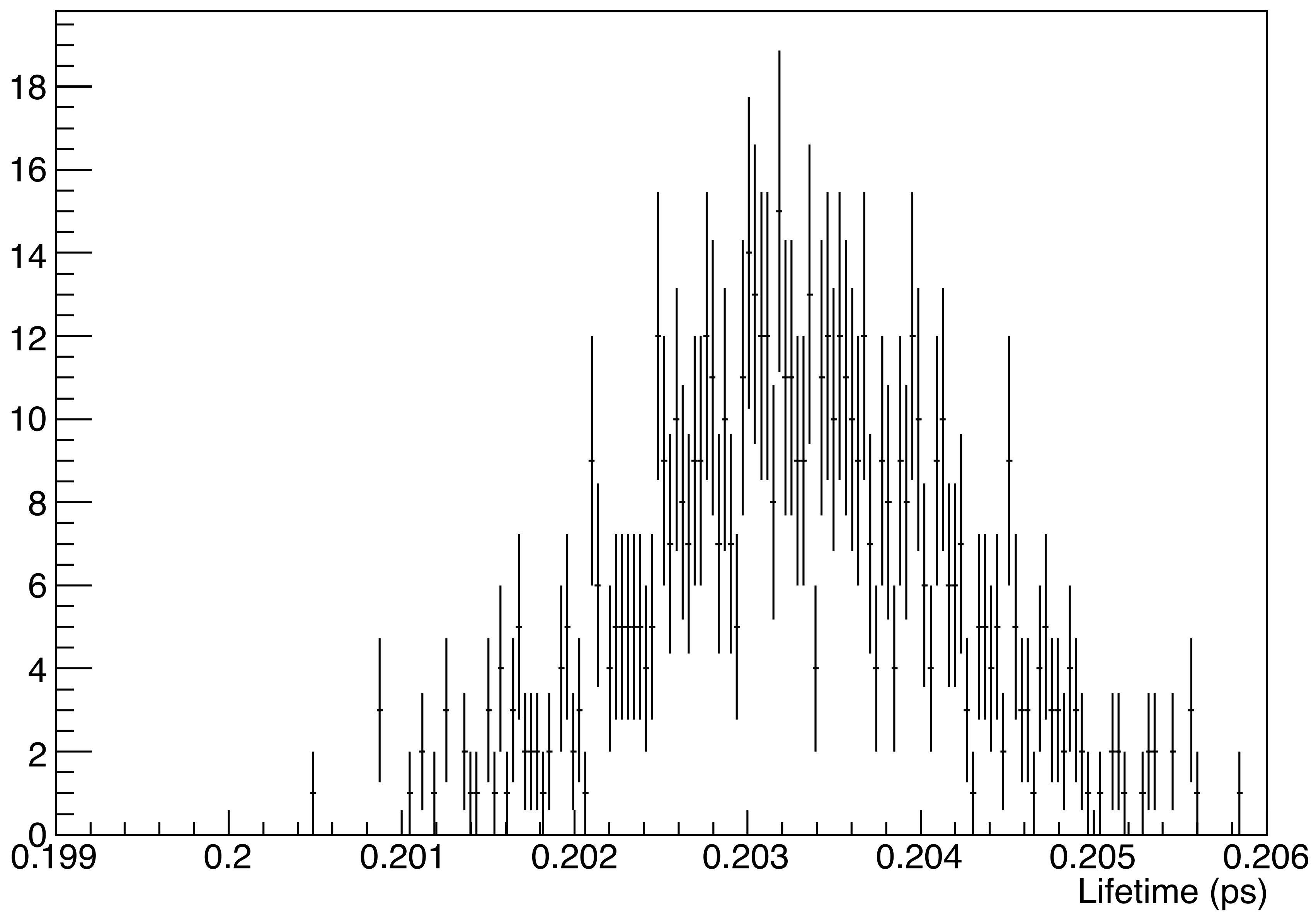
True value (average from truth matched events in the signal region): **202.17 ± 0.62 fs**

Background bias parameter

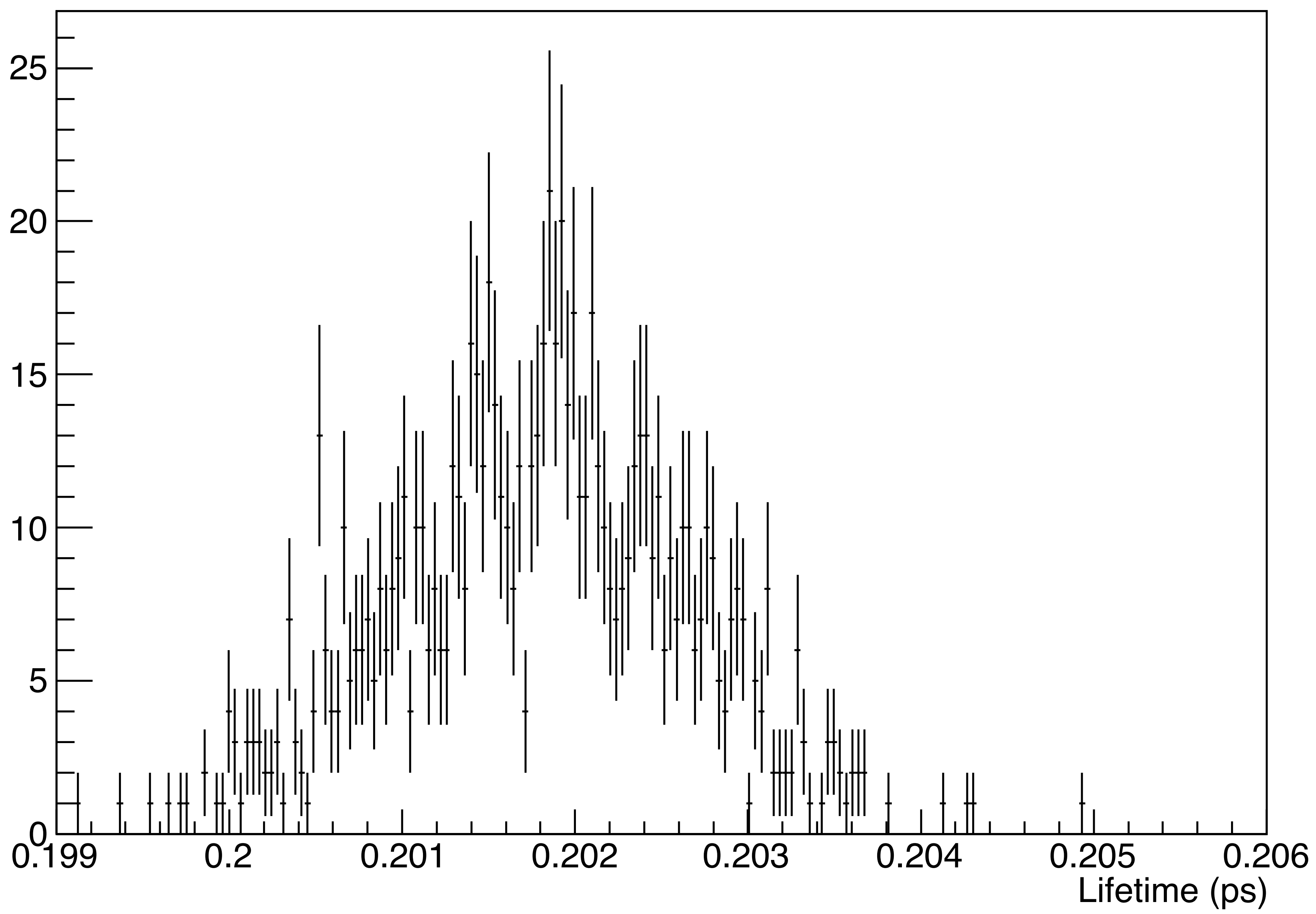
- The lifetime fit includes a multiplicative scale factor for the width scale parameter of the background pdf
- May also introduce a(n additive) background bias parameter

- Generate pseudoexperiments bootstrapped from 1/ab MC and fit with and without background bias parameter
  - Mean fitted lifetime with background bias parameter: 203.28 ± 0.03 fs, difference with true = 1.44 fs
  - Mean fitted lifetime without background bias parameter: 201.78 ± 0.03 fs, difference with true = 0.06 fs

With background bias parameter



Without background bias parameter

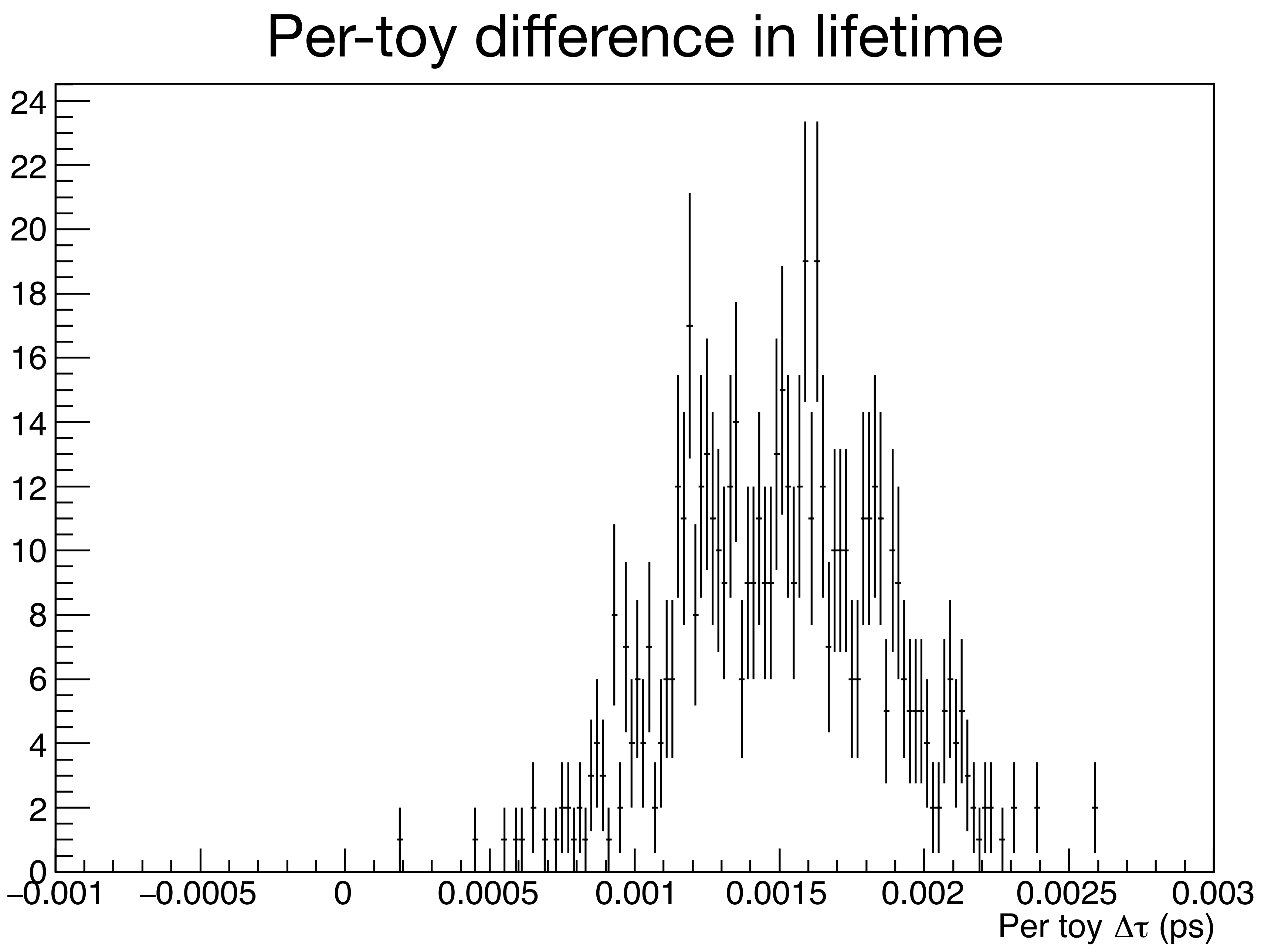


Background bias parameter

- The lifetime fit includes a multiplicative scale factor for the width scale parameter of the background pdf
- May also introduce a(n additive) background bias parameter

- Generate pseudoexperiments bootstrapped from 1/ab MC and fit with and without background bias parameter
  - Mean fitted lifetime with background bias parameter: 203.28 ± 0.03 fs, difference with true = 1.44 fs
  - Mean fitted lifetime without background bias parameter: 201.78 ± 0.03 fs, difference with true = 0.06 fs
  - Mean per-toy lifetime difference: 1.50 ± 0.02 fs

- Bias parameter appears to shift the lifetime measurement away from the true value
  - Consistent result between data and MC (see next slides)
  - Additional background bias parameter may cause overfitting
  - Background bias parameter neglected in lifetime fit



Background bias parameter

- The lifetime fit includes a multiplicative scale factor for the width scale parameter of the background pdf
- May also introduce a(n additive) background bias parameter

- Generate pseudoexperiments bootstrapped from 1/ab MC in the signal region and from data for the sidebands and fit with and without background bias parameter
  - Mean fitted lifetime with background bias parameter: 202.57± 0.03 fs, difference with true = 0.73 fs
  - Mean fitted lifetime without background bias parameter: 202.04 ± 0.03 fs, difference with true = 0.20 fs
  - Mean per-toy lifetime difference: 0.51 ± 0.04 fs

Background bias parameter

- The lifetime fit includes a multiplicative scale factor for the width scale parameter of the background pdf
- May also introduce a(n additive) background bias parameter
  - -2 ln(L) improves with the addition
  - Shift in the lifetime for the case of a single Gaussian resolution function (not much effect with double Gaussian)
    - In Data: lifetime difference = 1.33 fs, bias shift = -1.6 fs, background bias = 3.79 fs

Table 7: Results of the lifetime fit to events in data. The measured lifetime is shifted by an arbitrary amount within a range of $\pm 5\ \sigma$, according to the world-average value.

Parameter	Fit result w/single Gaussian	Fit result w/double Gaussian
τ (fs) with arb. shift	209.72 ± 0.88	210.08 ± 0.85
b (fs)	4.58 ± 0.63	3.72 ± 0.58
s_1	1.1050 ± 0.0071	1.0713 ± 0.0146
s_2		2.4043 ± 0.3134
f		0.9727 ± 0.0145
f_{bg}	0.07539 ± 0.00022	0.07536 ± 0.00022
f_τ	0.2918 ± 0.0081	0.3172 ± 0.0085
$f_{\tau 1}$	0.7967 ± 0.0115	0.8000 ± 0.0126
τ_{bg1} (fs)	196.1 ± 6.8	180.7 ± 7.3
τ_{bg2} (fs)	865.1 ± 28.4	841.8 ± 32.0
s_{bg}	1.1434 ± 0.0089	1.0947 ± 0.0092

Table 10: Results of the lifetime fit to events in data with an additive background bias parameter. The measured lifetime is shifted by an arbitrary amount within a range of $\pm 5\ \sigma$, according to the world-average value.

Parameter	Fit result w/single Gaussian	Fit result w/double Gaussian
τ (fs) with arb. shift	211.05 ± 0.90	210.51 ± 0.90
b (fs)	2.98 ± 0.69	3.21 ± 0.68
s_1	1.0978 ± 0.0066	1.0691 ± 0.0173
s_2		2.3889 ± 0.3999
f		0.9725 ± 0.0188
f_{bg}	0.07537 ± 0.00022	0.07535 ± 0.00022
f_τ	0.2651 ± 0.0087	0.3043 ± 0.0116
$f_{\tau 1}$	0.7997 ± 0.0125	0.8002 ± 0.0133
τ_{bg1} (fs)	216.4 ± 8.0	188.2 ± 9.4
τ_{bg2} (fs)	902.9 ± 31.6	856.2 ± 35.5
s_{bg}	1.1651 ± 0.0095	1.1032 ± 0.0115
b_{bg} (fs)	5.39 ± 1.27	2.04 ± 1.37

Background bias parameter

- The lifetime fit includes a multiplicative scale factor for the width scale parameter of the background pdf
- May also introduce a(n additive) background bias parameter
  - -2 ln(L) improves with the addition
  - Shift in the lifetime for the case of a single Gaussian resolution function (not much effect with double Gaussian)
    - In Data: lifetime difference = 1.33 fs, bias shift = -1.6 fs, background bias = 3.79 fs
    - In MC: lifetime difference = 1.51 fs, bias shift = -1.86 fs, background bias = 4.03 fs

Table 6: Results of lifetime fits to simulated events in the 1 ab^{-1} equivalent MC sample.

Parameter	Fit result w/single Gaussian	Fit result w/double Gaussian
τ (fs)	201.77 $\pm$ 0.40	202.16 $\pm$ 0.39
b (fs)	1.53 $\pm$ 0.27	0.66 $\pm$ 0.26
s_1	1.0721 $\pm$ 0.0045	1.0409 $\pm$ 0.0040
s_2		2.2978 $\pm$ 0.0484
f		0.9716 $\pm$ 0.0024
f_{bg}	0.09762 $\pm$ 0.00014	0.09758 $\pm$ 0.00014
f_τ	0.2840 $\pm$ 0.0036	0.3081 $\pm$ 0.0037
$f_{\tau 1}$	0.8477 $\pm$ 0.0047	0.8503 $\pm$ 0.0043
τ_{bg1} (fs)	181.3 $\pm$ 3.0	168.8 $\pm$ 2.6
τ_{bg2} (fs)	869.2 $\pm$ 16.5	846.1 $\pm$ 15.0
s_{bg}	1.1758 $\pm$ 0.0058	1.1319 $\pm$ 0.0044

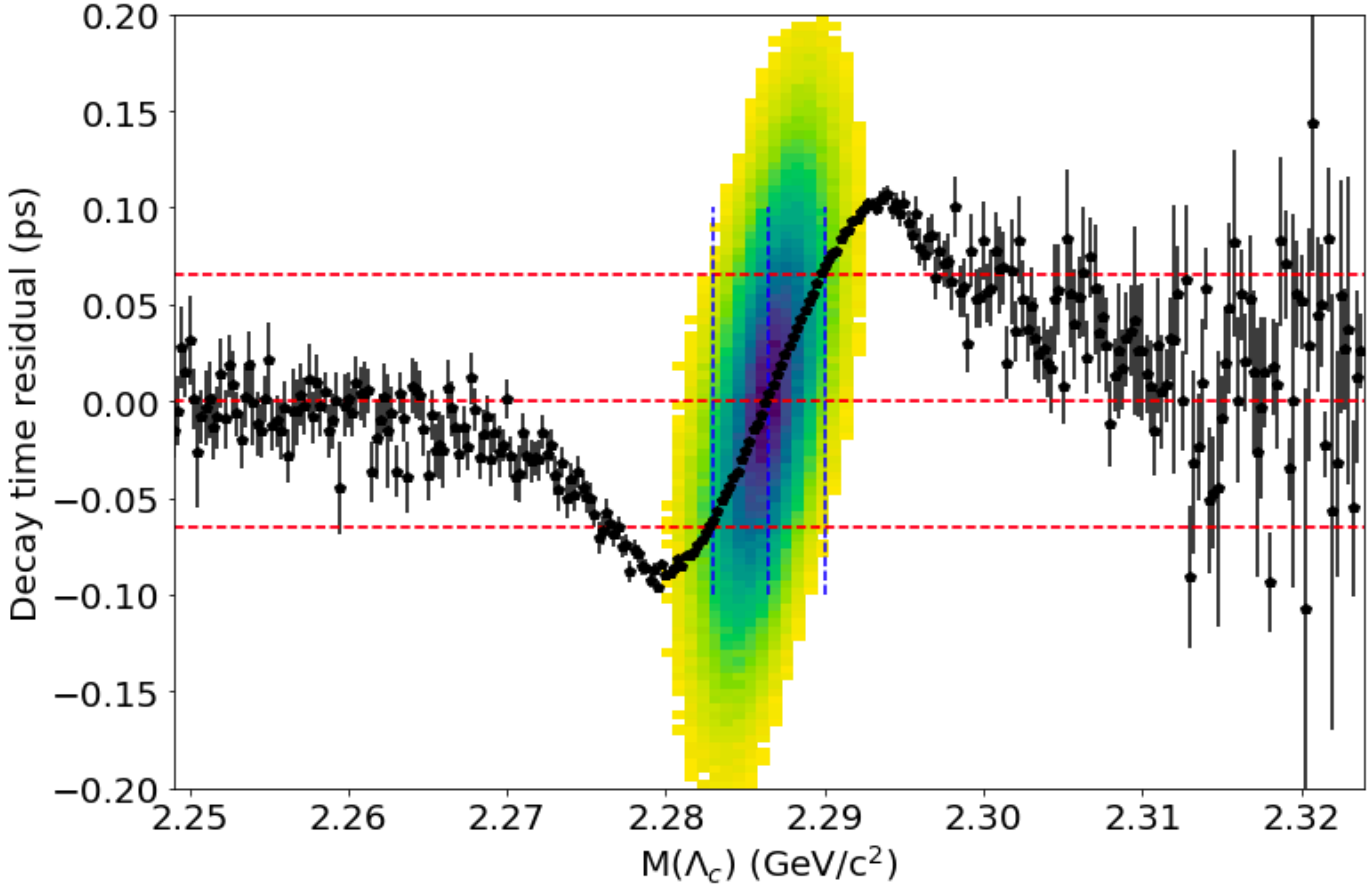
Table 9: Results of lifetime fits to events in simulation (1 ab^{-1}) with a background bias parameter. The results of the nominal fit are included for reference.

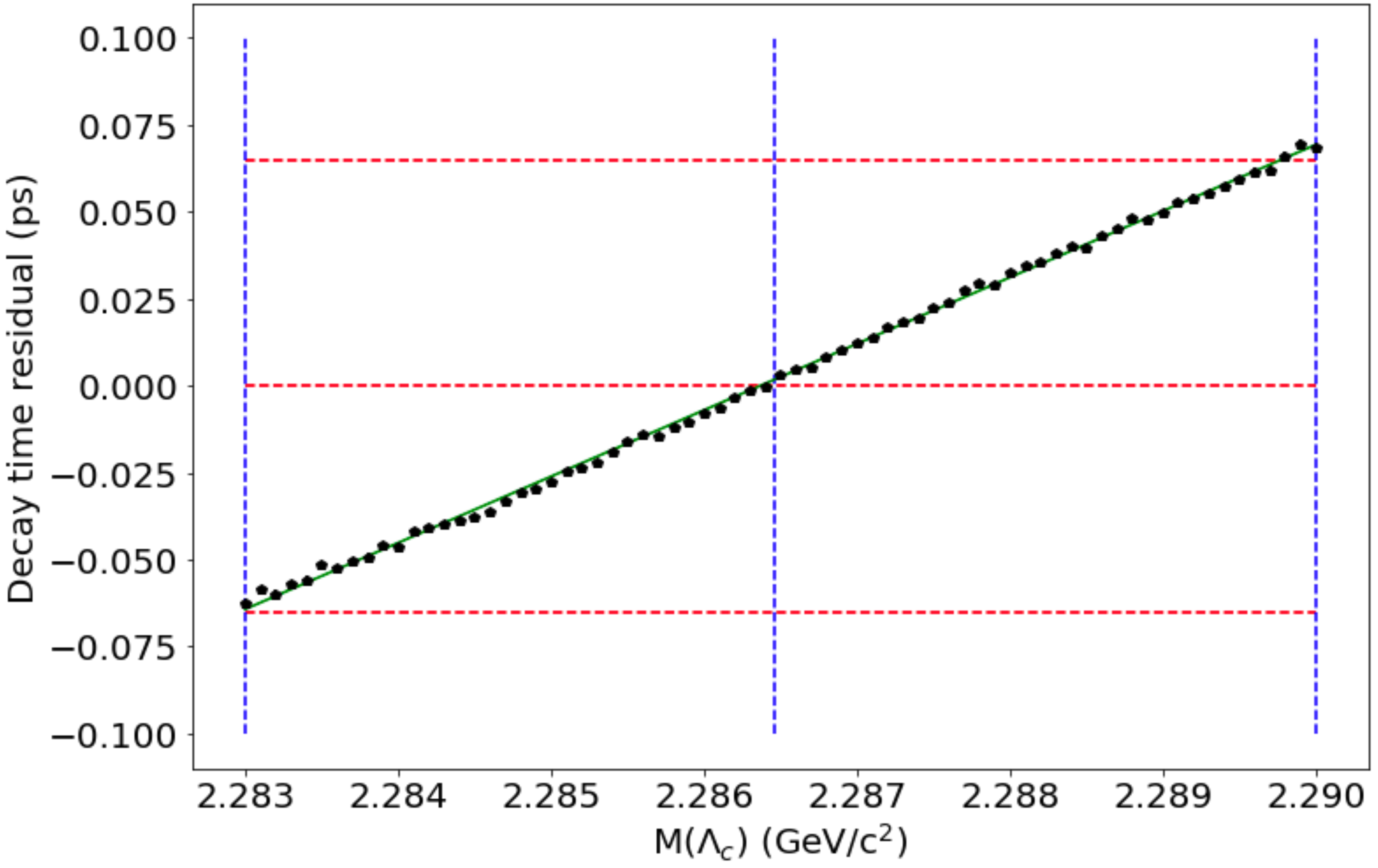
Parameter	Fit result w/single Gaussian	Fit result w/double Gaussian
τ (fs)	203.28 $\pm$ 0.39	202.72 $\pm$ 0.41
b (fs)	-0.33 $\pm$ 0.28	-0.01 $\pm$ 0.32
s_1	1.0637 $\pm$ 0.0029	1.0380 $\pm$ 0.0039
s_2		2.2793 $\pm$ 0.0314
f		0.9715 $\pm$ 0.0016
f_{bg}	0.09758 $\pm$ 0.00014	0.09756 $\pm$ 0.00014
f_τ	0.2537 $\pm$ 0.0056	0.2923 $\pm$ 0.0061
$f_{\tau 1}$	0.8493 $\pm$ 0.0053	0.8500 $\pm$ 0.0040
τ_{bg1} (fs)	199.9 $\pm$ 5.1	176.2 $\pm$ 3.4
τ_{bg2} (fs)	913.4 $\pm$ 21.5	863.8 $\pm$ 13.7
s_{bg}	1.2008 $\pm$ 0.0042	1.1428 $\pm$ 0.0057
b_{bg} (fs)	5.89 $\pm$ 0.63	2.48 $\pm$ 0.71

Decay-time, mass correlation

Parameter	200 fb^{-1} MC	Data
N_{sig}	135756 ± 680	151516 ± 616
f_{Gaus}	0.599 ± 0.034	0.487 ± 0.035
μ (GeV/c^2)	0.00006 ± 0.00002	-0.0001 ± 0.0002
σ_G (GeV/c^2)	0.0025 ± 0.00004	0.0025 ± 0.00006
σ_J (GeV/c^2)	0.0029 ± 0.0003	0.0037 ± 0.0003
γ_J	0.163 ± 0.023	-0.028 ± 0.014
δ_J	1.010 ± 0.092	1.180 ± 0.089
N_{bkg}	121059 ± 669	100578 ± 573
c	-0.348 ± 0.006	-0.382 ± 0.002

- Bin truth-matched signal events from 1/ab MC sample and extract mean true lifetime versus invariant mass
  - Signal window: 2.283 < M < 2.29
    (7 MeV window, rounded from 2.28296 < M < 2.28996)
  - Data-MC mass difference from invariant mass fit is less than 2 MeV/c^2





Lifetime fits

- Data-MC mass difference from invariant mass fit is less than 2 MeV/c^2
- Shift mass window by ±0.2 MeV/c^2
  - Lifetime difference:
    0.16 ± 0.23 fs (+), 0.26 ± 0.30 fs (-)
  - Bias difference:
    0.38 ± 0.22 fs (+), 0.75 ± 0.25 fs (-)
- Shift mass window by ±0.5 MeV/c^2
  - Lifetime difference:
    0.28 ± 0.14 fs (+), 0.83 ± 0.19 fs (-)
  - Bias difference:
    1.04 ± 0.16 fs (+), 1.94 ± 0.25 fs (-)

Table 13: Results of lifetime fits to events in data with an invariant mass signal region shifted by ±0.2 MeV/c^2. The measured lifetime is shifted by an arbitrary amount within a range of $\pm5\ \sigma$, according to the world-average value.

Parameter	[2.2828,2.2898] GeV/c^2	[2.2832,2.2902] GeV/c^2
τ (fs)	209.56 ± 0.85	209.98 ± 0.83
b (fs)	4.20 ± 0.59	5.33 ± 0.58
s_1	1.1044 ± 0.0058	1.0901 ± 0.0055
f_{bg}	0.07493 ± 0.00037	0.07508 ± 0.00037
f_{τ}	0.2947 ± 0.0082	0.2858 ± 0.0069
$f_{\tau 1}$	0.7963 ± 0.0109	0.7977 ± 0.0135
τ_{bg1} (fs)	194.0 ± 6.9	200.6 ± 7.1
τ_{bg2} (fs)	861.5 ± 26.5	874.0 ± 33.9
s_{bg}	1.1428 ± 0.0081	1.1526 ± 0.0081

Table 15: Results of lifetime fits to events in data with an invariant mass signal region shifted by ±0.5 MeV/c^2. The measured lifetime is shifted by an arbitrary amount within a range of $\pm5\ \sigma$, according to the world-average value.

Parameter	[2.2825,2.2895] GeV/c^2	[2.2835,2.2905] GeV/c^2
τ (fs)	209.44 ± 0.87	210.55 ± 0.86
b (fs)	3.54 ± 0.61	6.52 ± 0.58
s_1	1.1016 ± 0.0063	1.0901 ± 0.0062
f_{bg}	0.07533 ± 0.00037	0.07571 ± 0.00038
f_{τ}	0.2998 ± 0.0084	0.2776 ± 0.0073
$f_{\tau 1}$	0.7969 ± 0.0084	0.7998 ± 0.0119
τ_{bg1} (fs)	190.9 ± 6.7	207.2 ± 6.9
τ_{bg2} (fs)	857.4 ± 27.9	888.4 ± 30.4
s_{bg}	1.1427 ± 0.0081	1.1653 ± 0.0082

Detector alignment

- Generate signal samples with different alignment global tags: https://confluence.desy.de/display/BI/Misalignments

GT name	Payloads	Scale/Type	Status	Comments	Validation/analysis feedback
alignment_misalignment_prompt_to_proc12stage1_v4 (a) nominal prompt alignment systematic uncertainty	VXDAlignment CDCAlignment (incl. wire misalignment)	Scale of prompt alignment systematics - small to medium	OK - recommended (analyst first choice)	This is a difference between reprocessing alignment and prompt alignment. The biases removed from prompt are reproduced by this misalignment to a large degree. This is a realistic misalignment estimation for prompt and safe upper limit for reprocessing. prepend BS payload in **alignment_misalignment_prompt_to_proc12stage1_v4_BeamSpot** to get the re-calibration of the BeamSpot	Cosmic validation does reproduce prompt biases. Dimuon validation does reproduce prompt biases.
alignment_misalignment_VXDCDCwires_v1 (b) residual misalignment for telescope weak mode	VXDAlignment CDCAlignment (incl. wire misalignment)	Very small (realistic long-term) (residual misalignment)	OK - recommended	iteration 2 of full global alignment (from zeros) including CDC wires prepend BS payload in **alignment_misalignment_VXDCDCwires_v1_BeamSpot**to get the re-calibration of the BeamSpot	Medians of VXD sensors residuals for MC dimuons even better than for ideal MC 😃
charm_misalignment_v0 (c) day-to-day misalignment	VXDAlignment CDCAlignment BeamSpot	Small (realistic prompt 2020) (single day-to-day difference from data)	OK - recommended	prepend BS payload in **charm_misalignment_v0_BeamSpot** to get the re-calibration of the BeamSpot	Medians of VXD sensor residuals for MC dimuons ~1um in U and ~2um in V - very similar to real data validation of bucket14
charm_misalignment_v0_1	VXDAlignment		OK	prepend *also* charm_beamSpot_misalignment_v0_1 to get the re-calibration of the BeamSpot	OK: TODO
charm_misalignment_v1 (d) residual misalignment from MC studies	VXDAlignment CDCAlignment	Very small (realistic long-term) (residual misalignment)	OK - recommended	After telescope weak mode alignment challenge. prepend BS payload in **charm_misalignment_v1_BeamSpot** to get the re-calibration of the BeamSpot	OK: TODO
charm_misalignment_v1_1	VXDAlignment		OK		OK: TODO

Other sources of systematic uncertainty

- **Momentum scale correction**: Vary the momentum scale correction between suggested values
  - Recommended scale factor: 0.99976
  - Recommended for systematic uncertainties: 0.99918 - 1.00006
  - Take semi-difference as relative uncertainty: (1.00006-0.99918)/2 = 4.4 x 10^{-4}
  - Absolute uncertainty for Λ_c^+ lifetime (202.4 fs): 0.09 fs

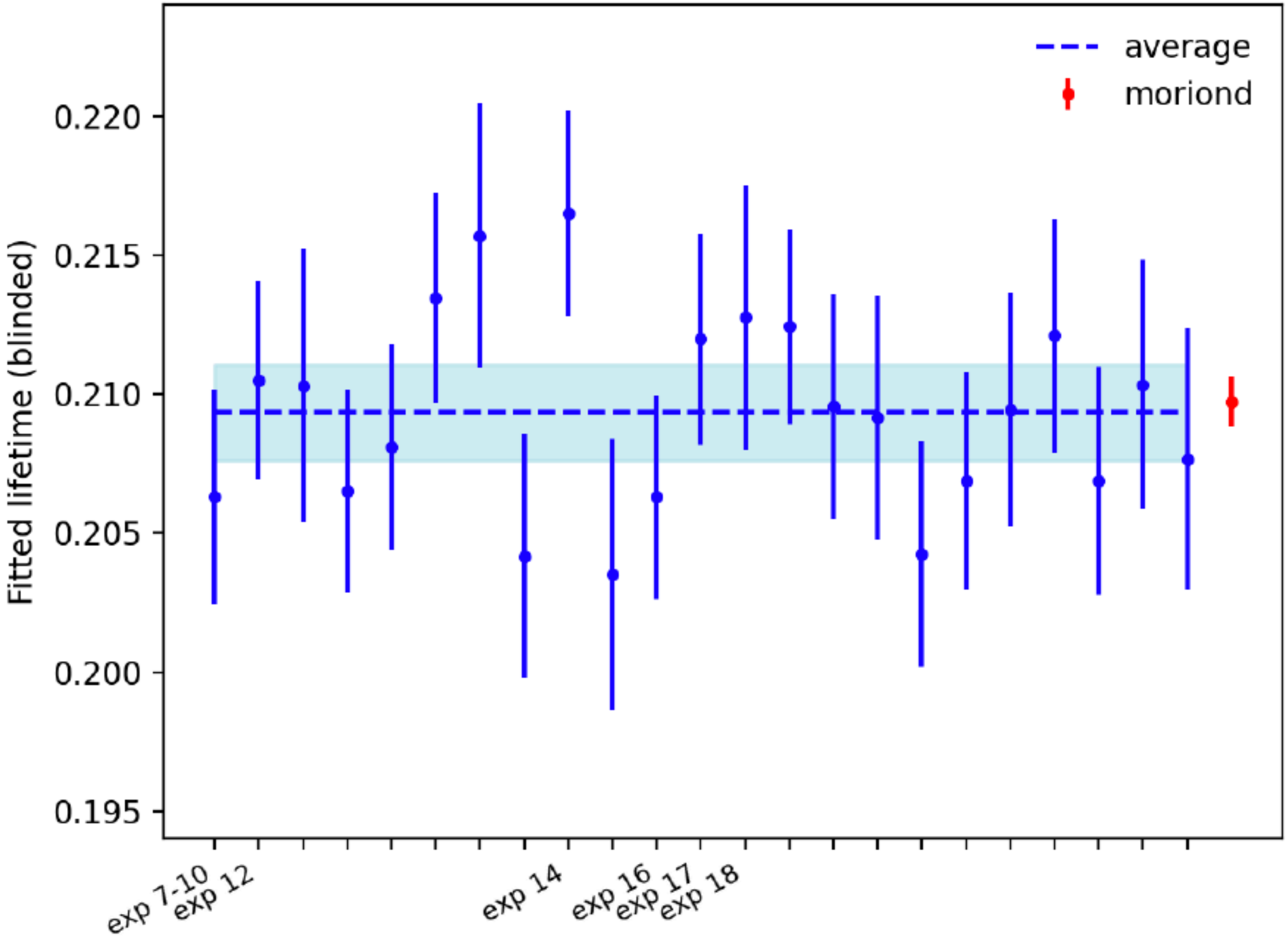
- **Input charm masses**: Check the relative uncertainty of the world-averaged values of the Λ_c^+ invariant mass
  - Relative uncertainty: 6.1 x 10^{-5}
  - Absolute uncertainty for Λ_c^+ lifetime (202.4 fs): 0.01 fs

VALUE (MeV)	
2286.46 ± 0.14	**OUR FIT**

Consistency checks

- Perform blinded lifetime fit to data subsets
  - Moriond 2022 (~208/fb)
  - Repeat fits in bins of ~10/fb

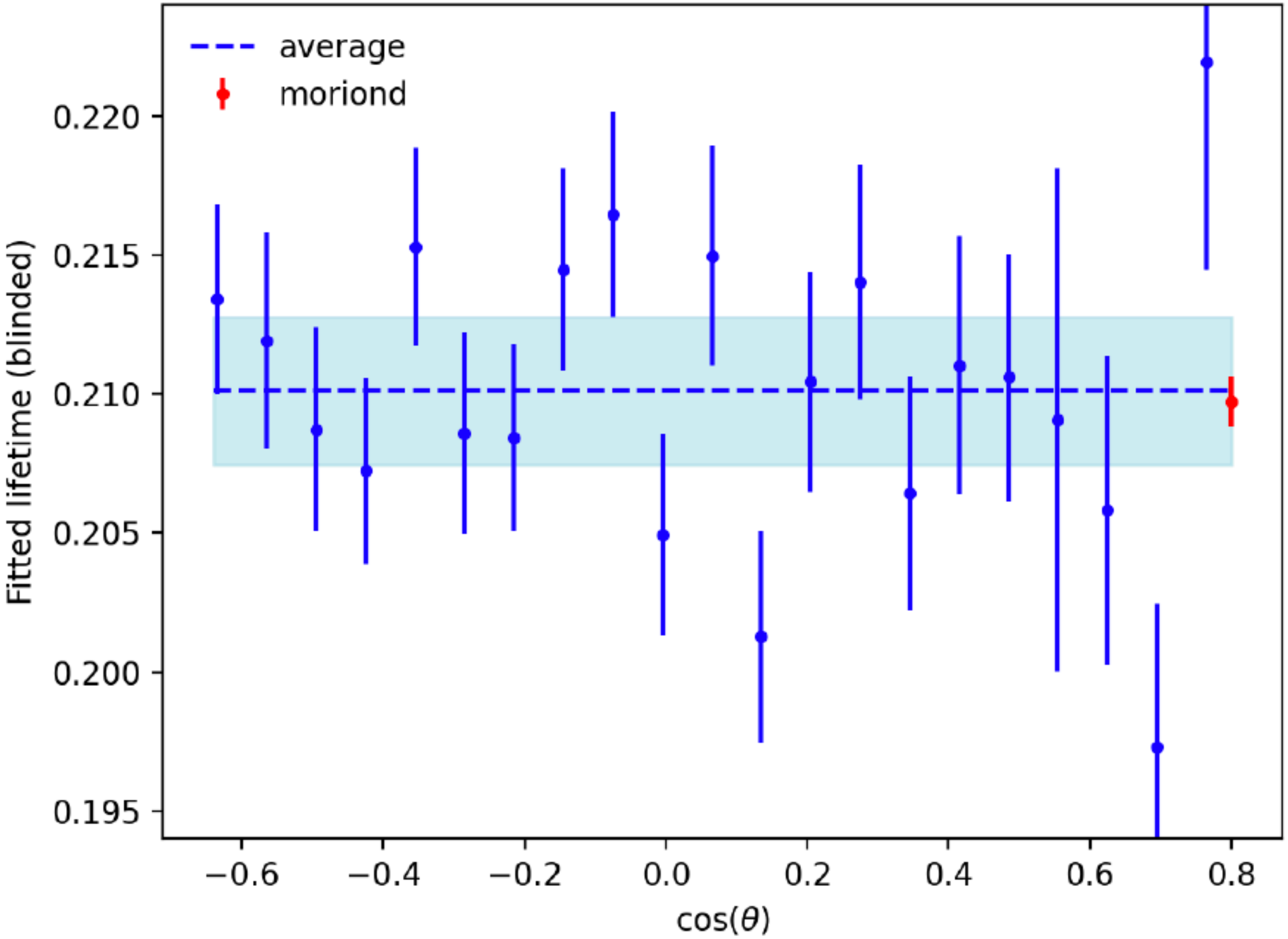
- Results consistent within uncertainties
  - Moriond 2022: $209.7 \pm 0.9\ fs$
  - Avg of exp bins: $209.3 \pm 0.9\ fs$



Consistency checks

- Perform blinded lifetime fit to data subsets
  - Bins of cos(θ)

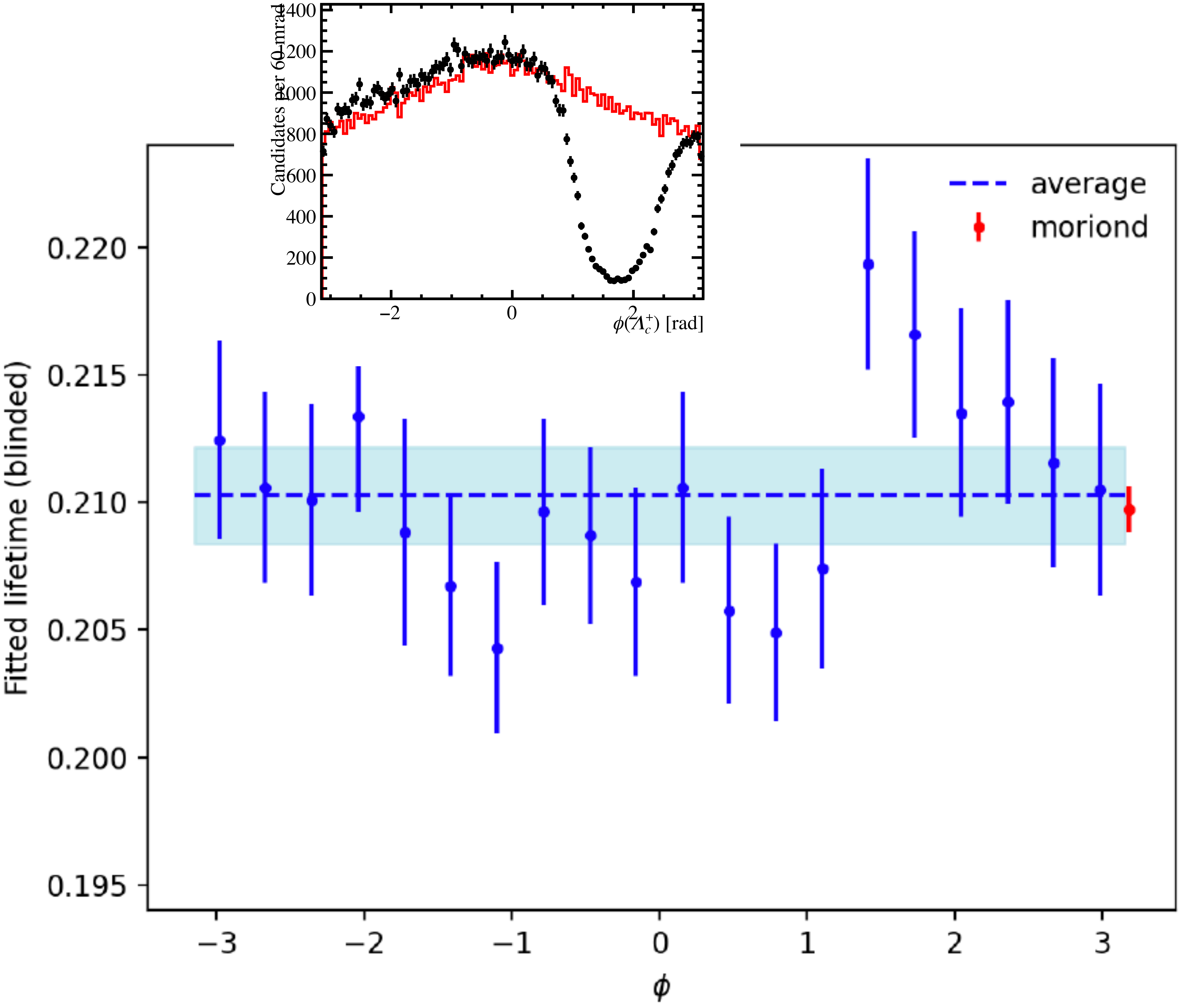
- Results consistent within uncertainties
  - Moriond 2022: $209.7 \pm 0.9\ fs$
  - Avg of exp bins: $209.3 \pm 0.9\ fs$
  - Avg of cos(θ) bins: $210.1 \pm 1.0\ fs$



Consistency checks

- Perform blinded lifetime fit to data subsets
  - Bins of ϕ

- Results consistent within uncertainties
  - Moriond 2022: $209.7 \pm 0.9\ fs$
  - Avg of exp bins: $209.3 \pm 0.9\ fs$
  - Avg of cos(θ) bins: $210.1 \pm 1.0\ fs$
  - Avg of ϕ bins 1: $210.3 \pm 0.9\ fs$

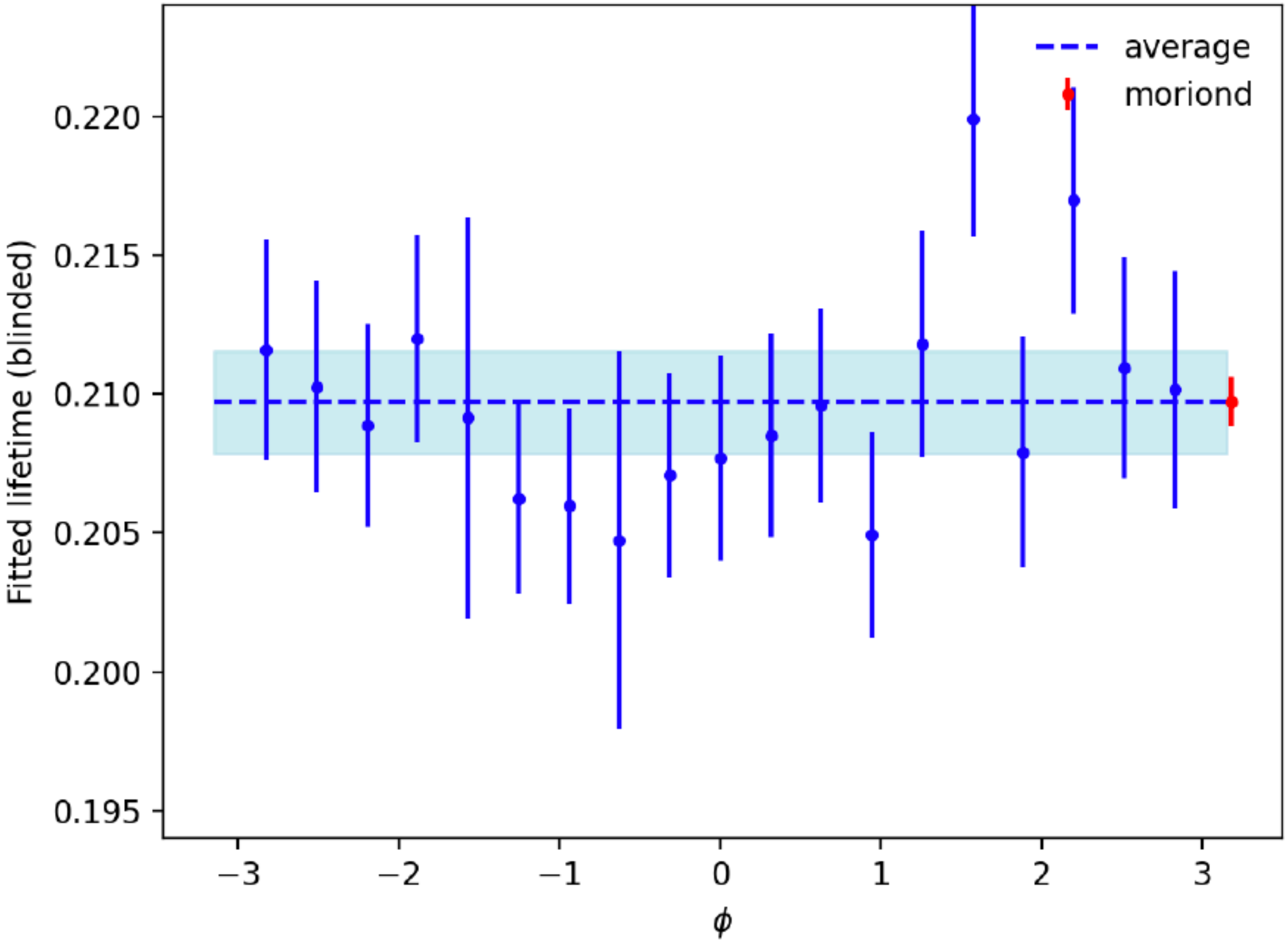


Consistency checks

- Perform blinded lifetime fit to data subsets
  - Bins of ϕ

- Results consistent within uncertainties
  - Moriond 2022: $209.7 \pm 0.9\ fs$
  - Avg of exp bins: $209.3 \pm 0.9\ fs$
  - Avg of cos(θ) bins: $210.1 \pm 1.0\ fs$
  - Avg of ϕ bins 1: $210.3 \pm 0.9\ fs$
  - Avg of ϕ bins 2: $209.7 \pm 1.0\ fs$

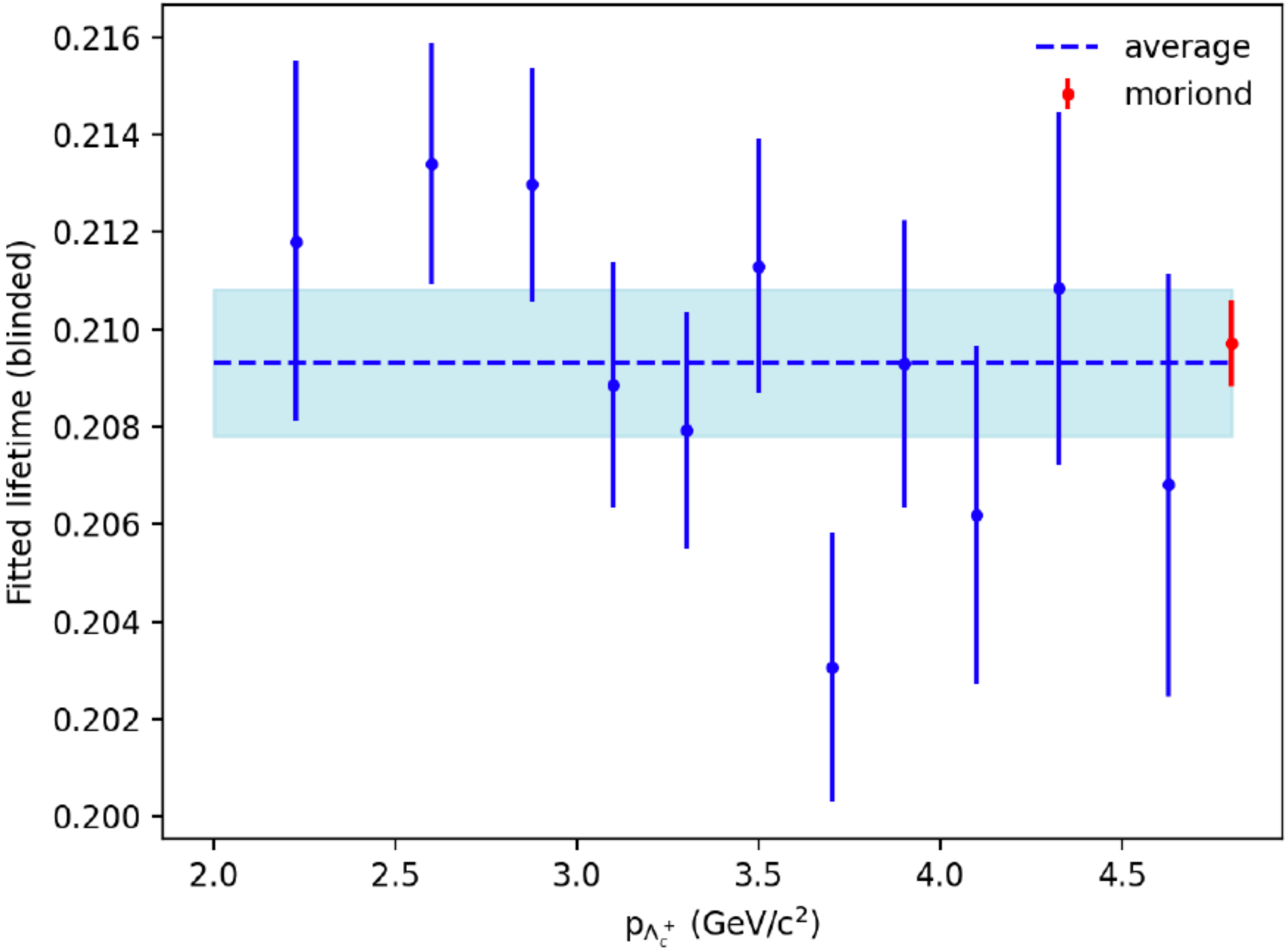
Repeat fits after shifting bins by one-half bin size
No obvious systematic shift



Consistency checks

- Perform blinded lifetime fit to data subsets
  - Bins of momentum

- Results consistent within uncertainties
  - Moriond 2022: $209.7 \pm 0.9\ fs$
  - Avg of exp bins: $209.3 \pm 0.9\ fs$
  - Avg of cos(θ) bins: $210.1 \pm 1.0\ fs$
  - Avg of ϕ bins 1: $210.3 \pm 0.9\ fs$
  - Avg of ϕ bins 2: $209.7 \pm 1.0\ fs$
  - Avg of momentum bins: $209.7 \pm 1.0\ fs$



Consistency checks

- Split data samples by charmness
  - Lifetime difference between the charm and anti-charm fits is $0.35 \pm 1.72\ fs$ ($209.936 \pm 1.195\ fs$ and $209.586 \pm 1.235\ fs$, respectively)
  - Consistent with statistical fluctuations

- In the nominal result, events with multiple candidates are rejected (273 out of 164,689 events)
- Repeat lifetime fit after accepting candidates with the best probability from the vertex fit or randomly keeping one candidate for events with multiple candidates
  - Lifetime difference with the nominal result is $0.07 \pm 0.23\ fs$ and $0.05 \pm 0.28\ fs$, respectively
  - Consistent with statistical fluctuations

Systematics and cross-checks

- **Resolution model**
  - Generate pseudoexperiments by bootstrapping from truth-matched signal events from 1/ab equivalent from MC14ri_a
  - Cross check with double-Gaussian resolution model
  - Vary σ_t bin sizes to avoid zero bins and check the difference in the fitted lifetime
- **Background contamination**
  - Generate pseudoexperiments by bootstrapping events from 1/ab equivalent from MC14ri_a for the signal region and the data sideband events for the sideband region
  - Change the signal model in the invariant mass fit and adjust the Gaussian constraint on the background in the lifetime fit
  - Repeat mass fit with different signal and sideband ranges, adjust the Gaussian constraint on the background in the lifetime fit
  - Check the effect of fixing or floating background mean and width scale factors
- **Imperfect detector alignment**: Generate dedicated MC with residual misalignment, imperfections in beam-spot parameters
- **Momentum scale correction**: Vary the momentum scale correction between suggested values
- **Input charm masses**: Check the relative uncertainty of the world-averaged values of the Λ_c invariant mass
- **Consistency checks**
  - Repeat the analysis for: (1) equipopulated, disjoint data sets, and (2) the full data sample split into bins of polar angle, azimuthal angle, and momentum, (3) on vs. off-resonance data, (4) charm vs. anti-charm events, (5) treatment of multiple-candidate events