Measurement of the Λ_c^+ lifetime at Belle II

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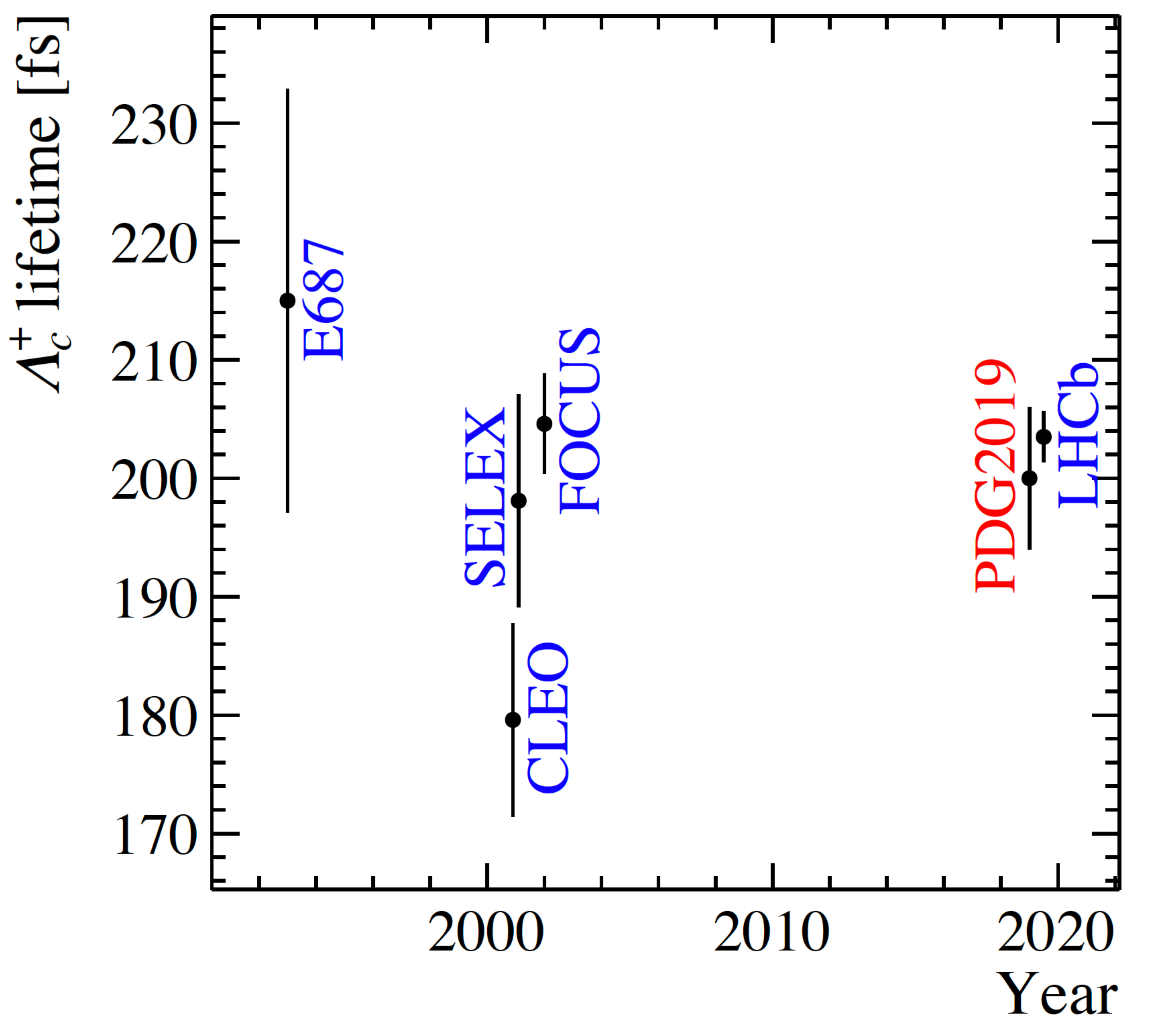
Introduction

- Goal: Measure the Λ_c^+ lifetime using the decay mode $\Lambda_c^+ \to pK^-\pi^+$
  - Opportunity to test impact of calibration (vertexing, alignment, etc)
  - Competitive measurement with existing data
- Samples
  - Data: “Moriond 2022" ~208/fb (blinded)
  - MC: MC14ri_a (200/fb)

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

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



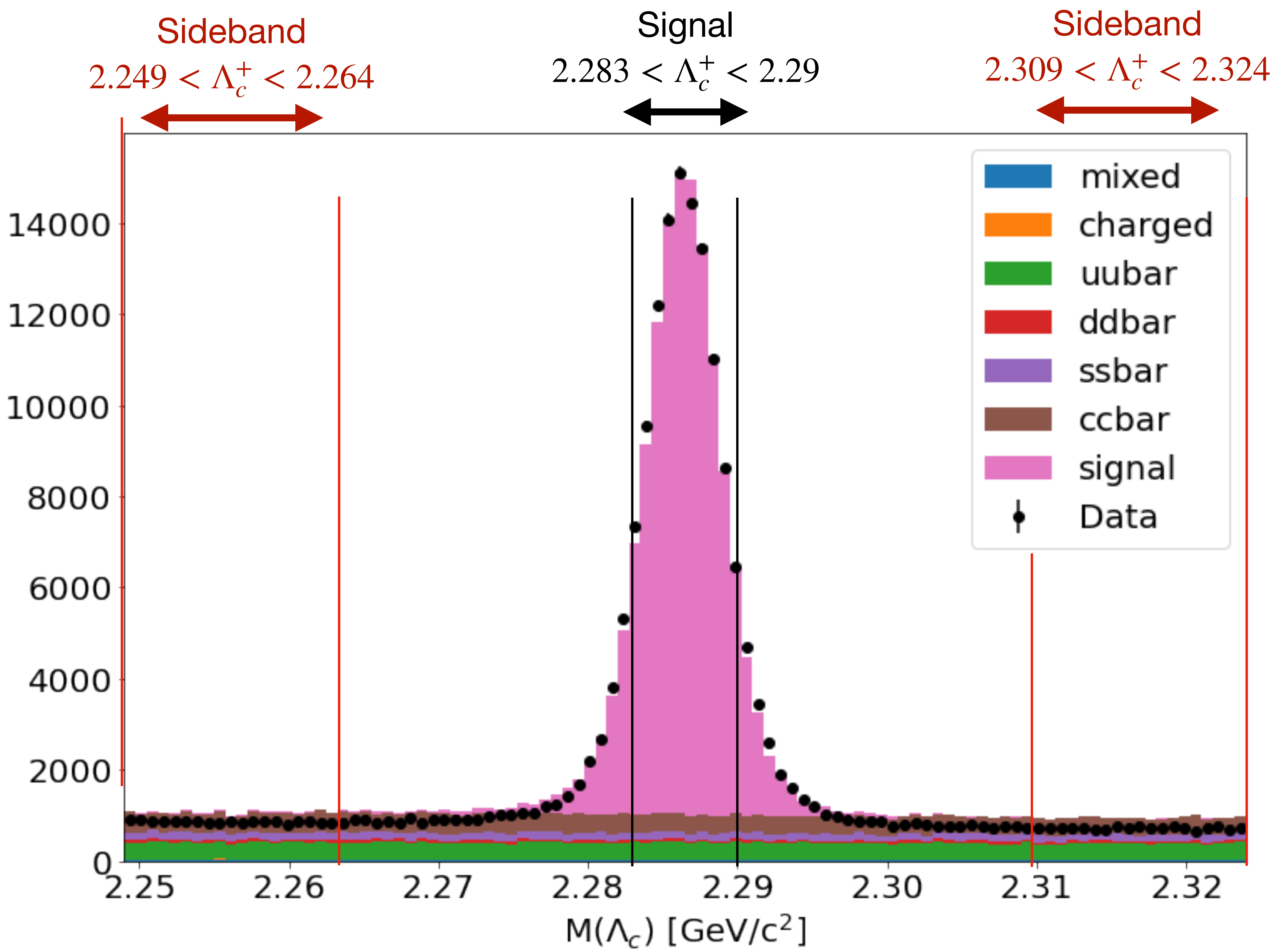
Event selection criteria

Updated: new bucket19 processing, adjusted scale factor to account for missing data (https://agira.desy.de/browse/BIIDP-4995)

- (207.833-0.6)/200 = 1.036165

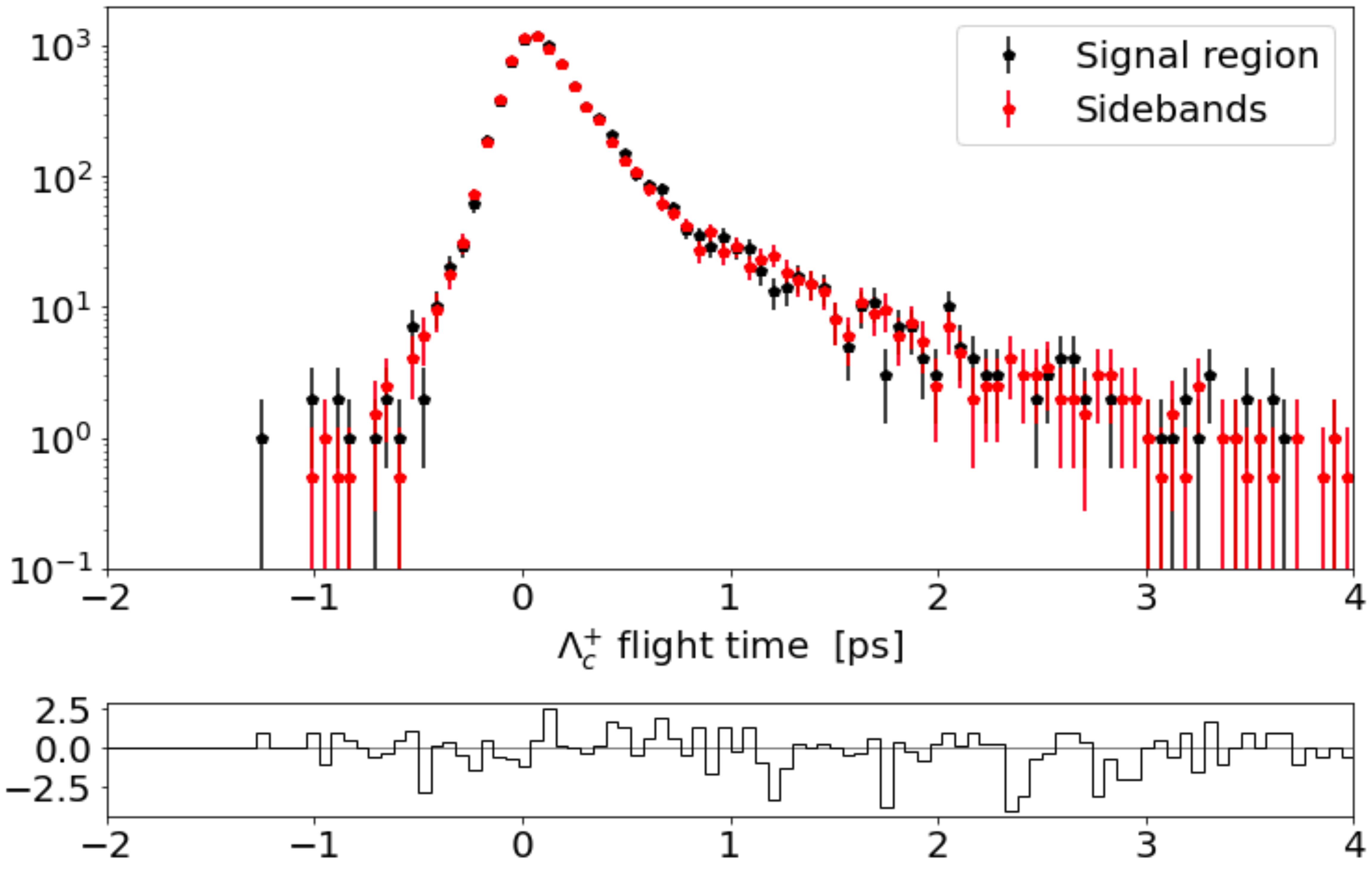
Selection criteria:

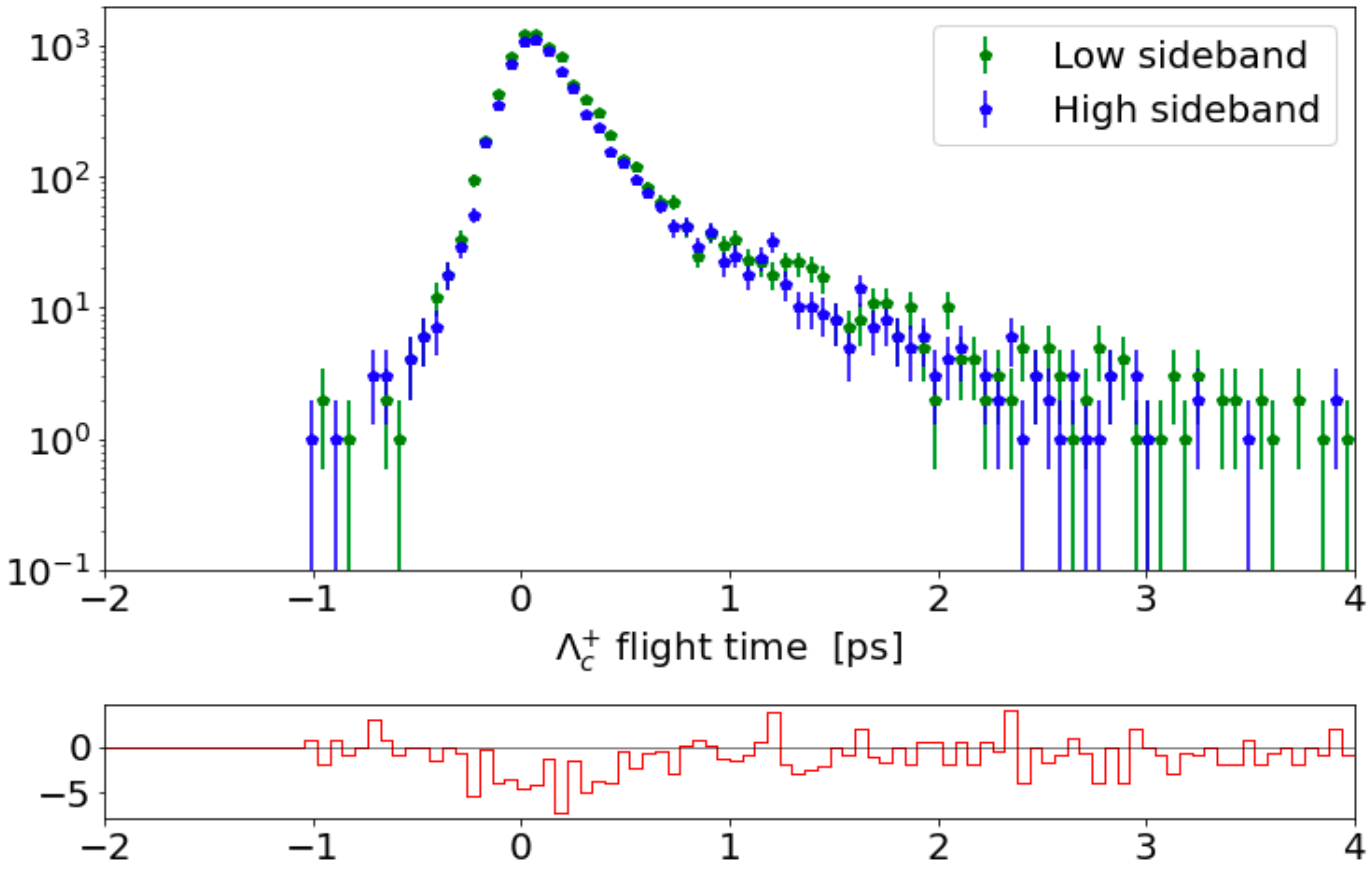
- Tracks must be in the CDC acceptance and have at least 20 CDC hits, at least one PXD hit, and the first SVD hit layer > 2
- d_0 < 0.5 cm, $|z_0|$ < 2 cm (standard track cuts)
- Vertex fit (TreeFitter with IP constraint) conf_level > 0.01
- Λ_c CM momentum > 2.5 GeV
- Proton PID (global) > 0.9
- Kaon PID (global) > 0.6
- Remove charm backgrounds by cutting on M(pKπ) with pion hypothesis for proton track
- $p_t(\pi)$ > 0.35, $p_t(p)$ > 0.8
- Events with multiple candidates are discarded



Background comparison

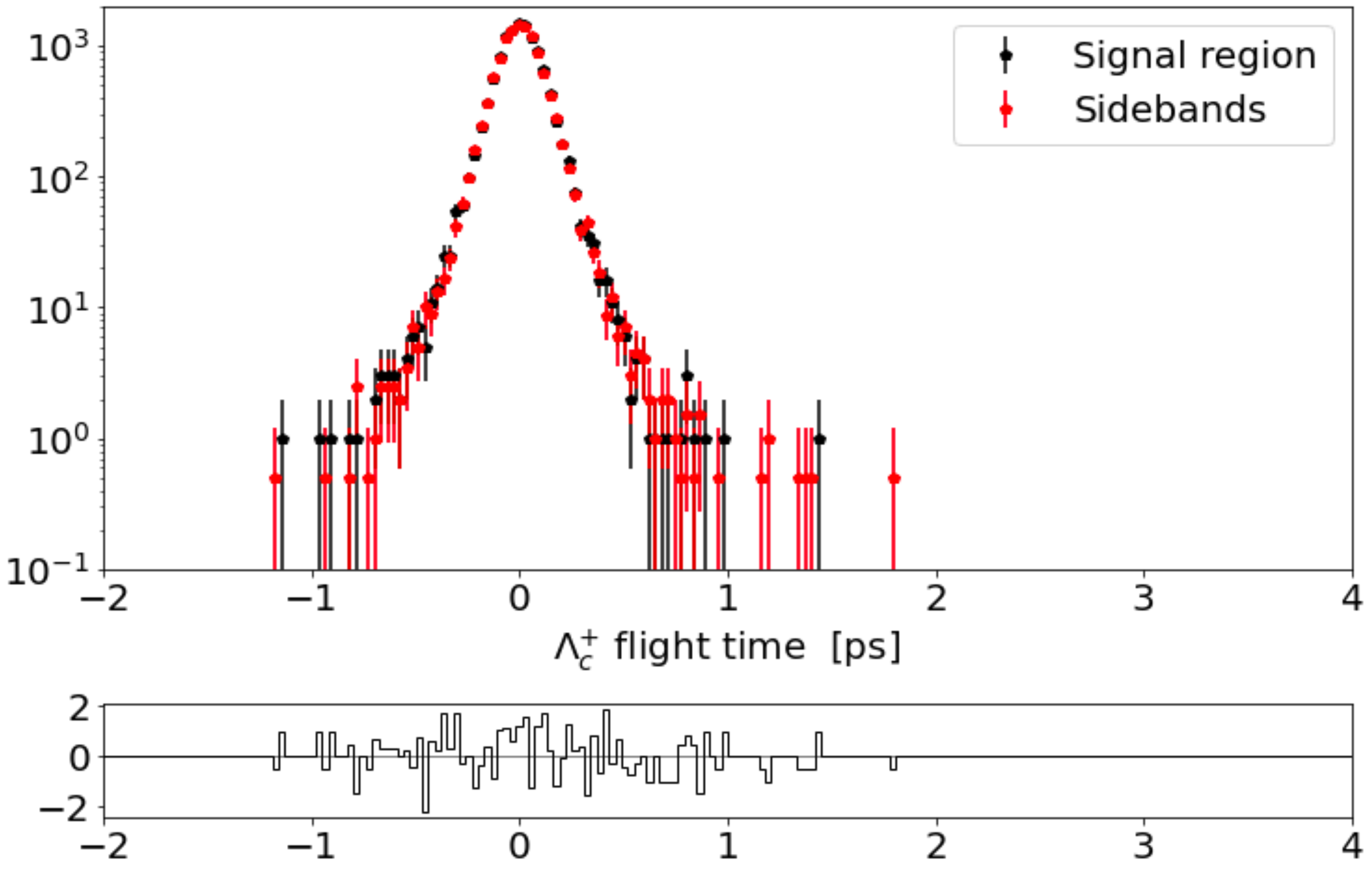
- Comparison of truth-matched charm backgrounds in signal and sideband regions: no obvious discrepancies
  - Some deviations between low and high sidebands

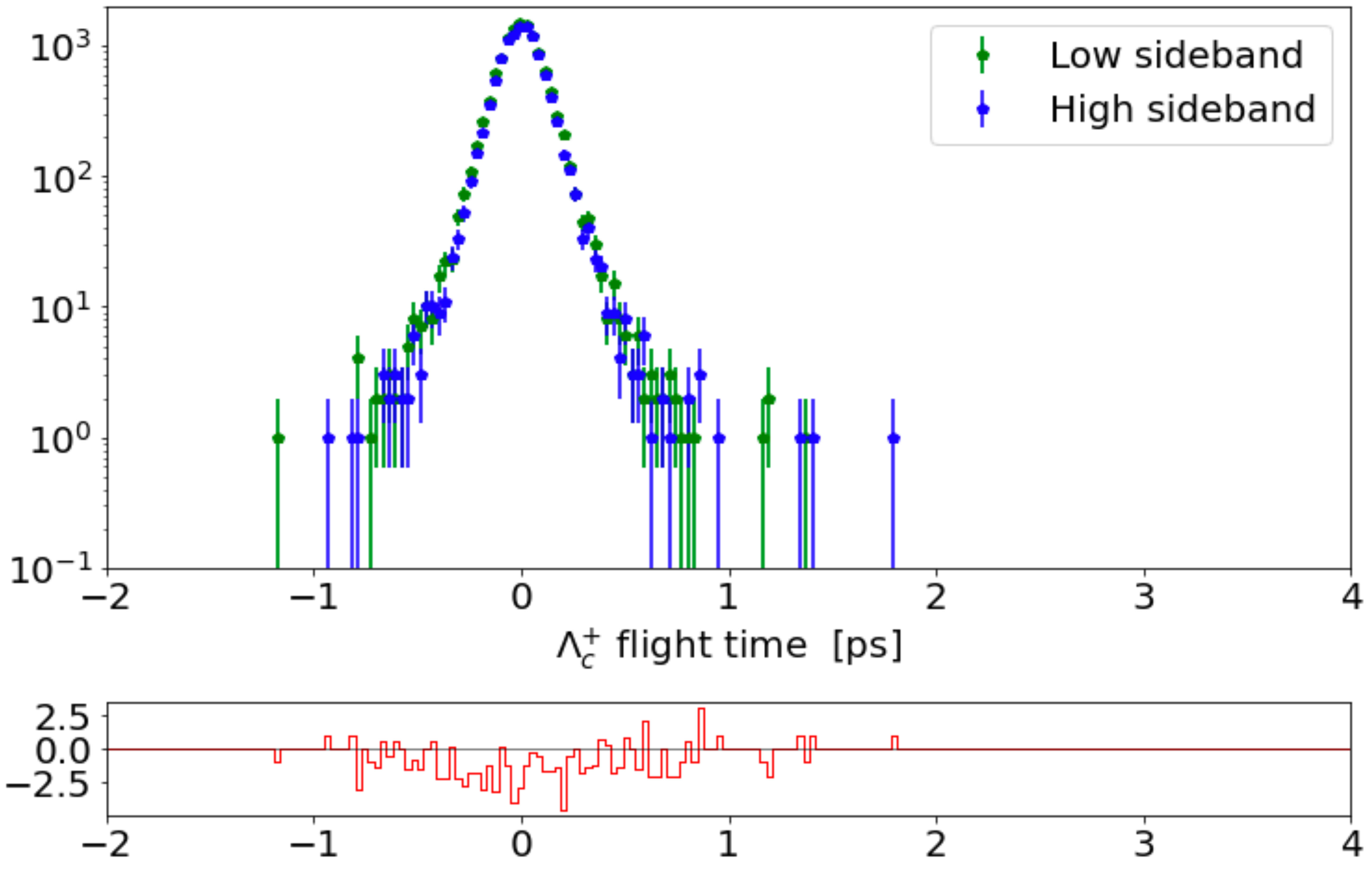




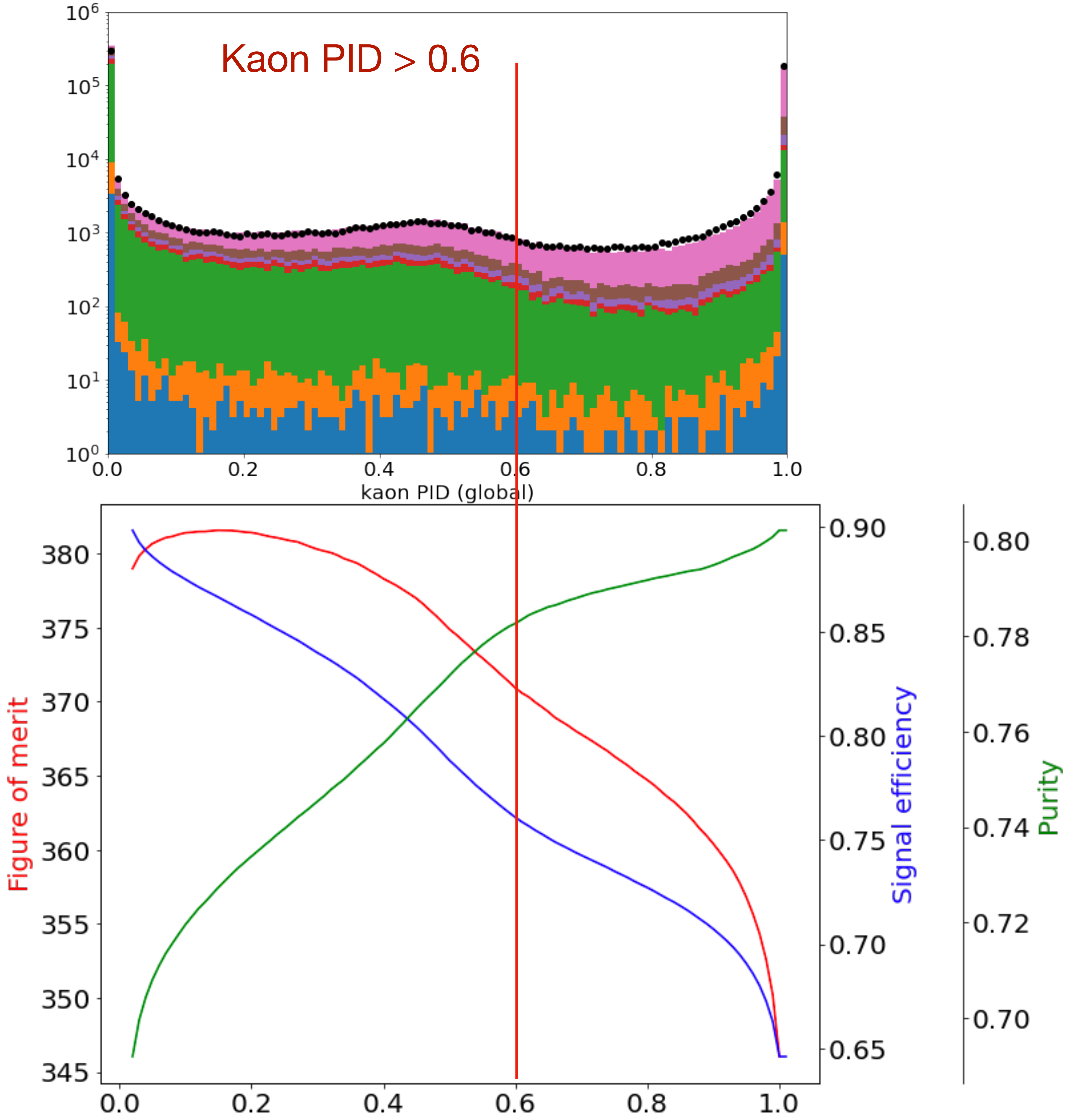
Background comparison

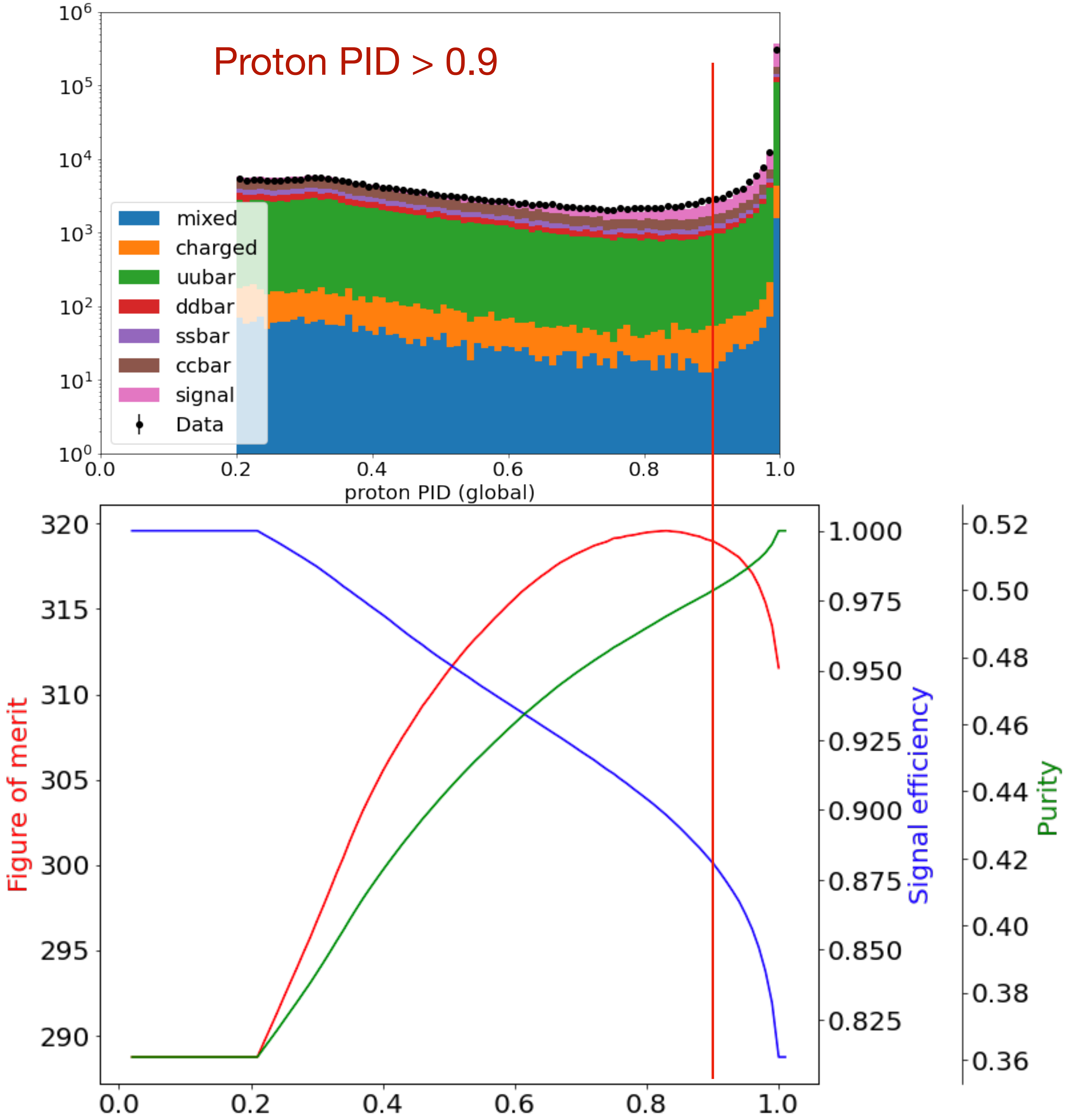
- Comparison of truth-matched continuum backgrounds in signal and sideband regions: no obvious discrepancies
  - Some deviations between low and high sidebands





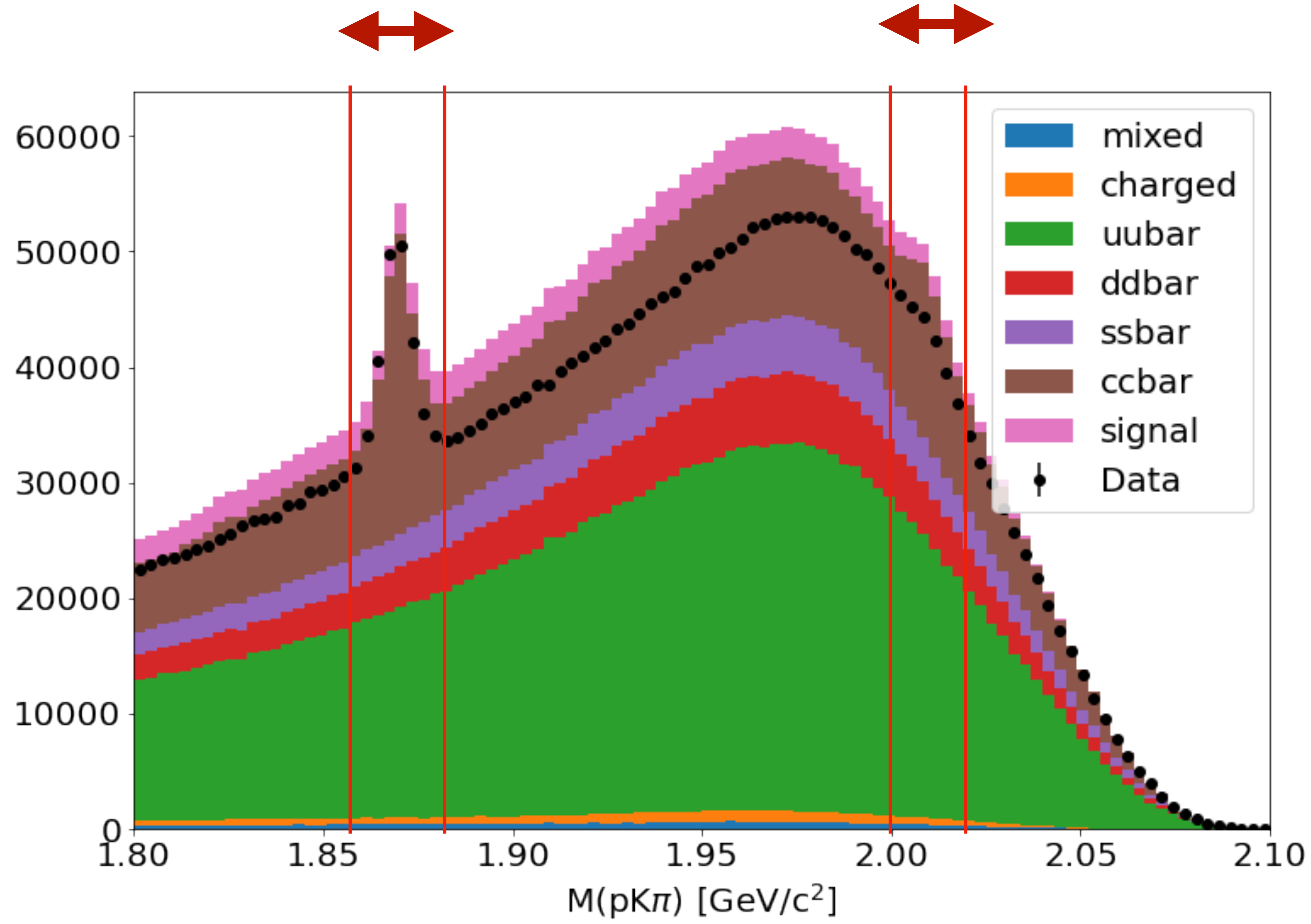
PID selection criteria

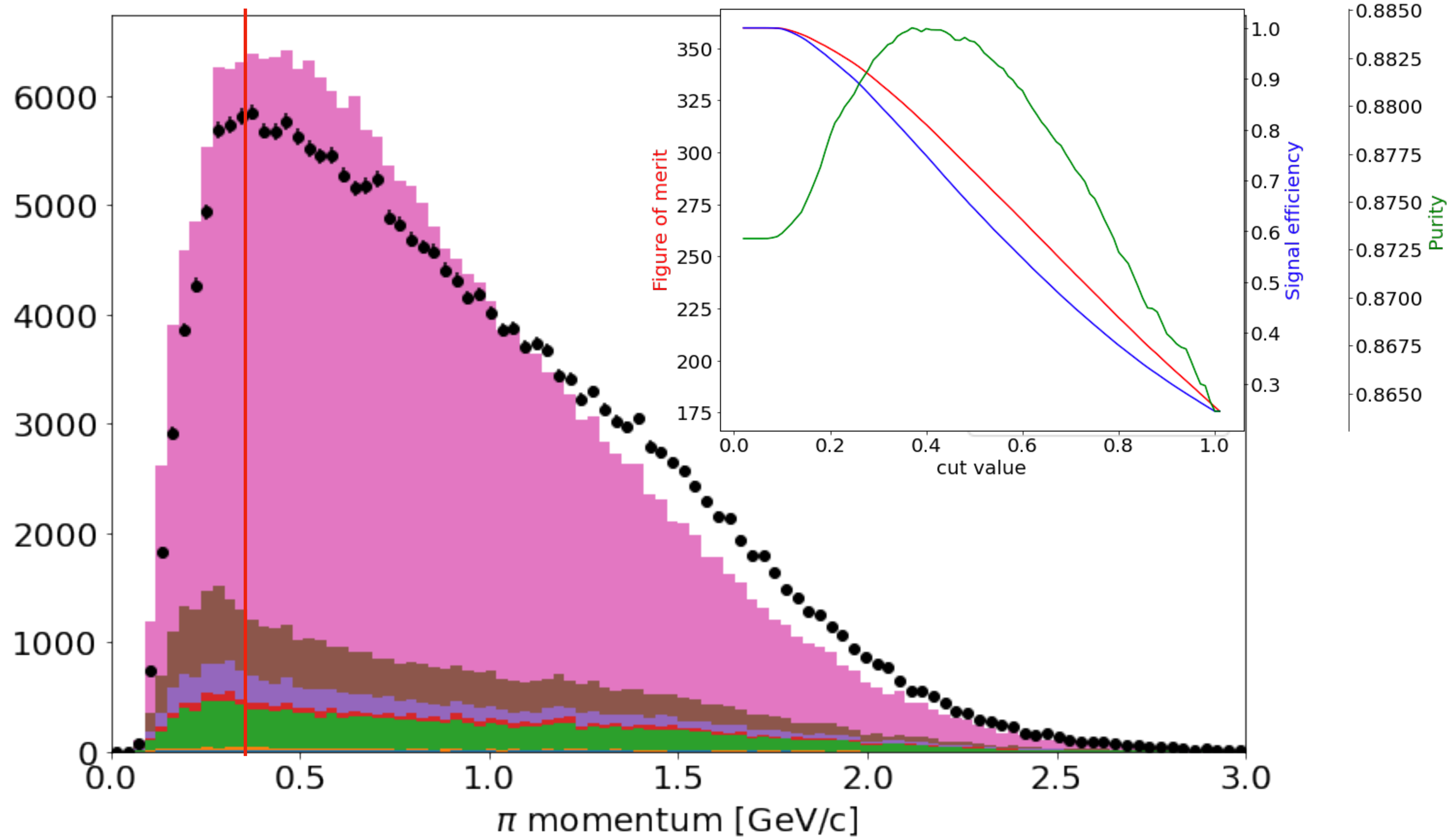


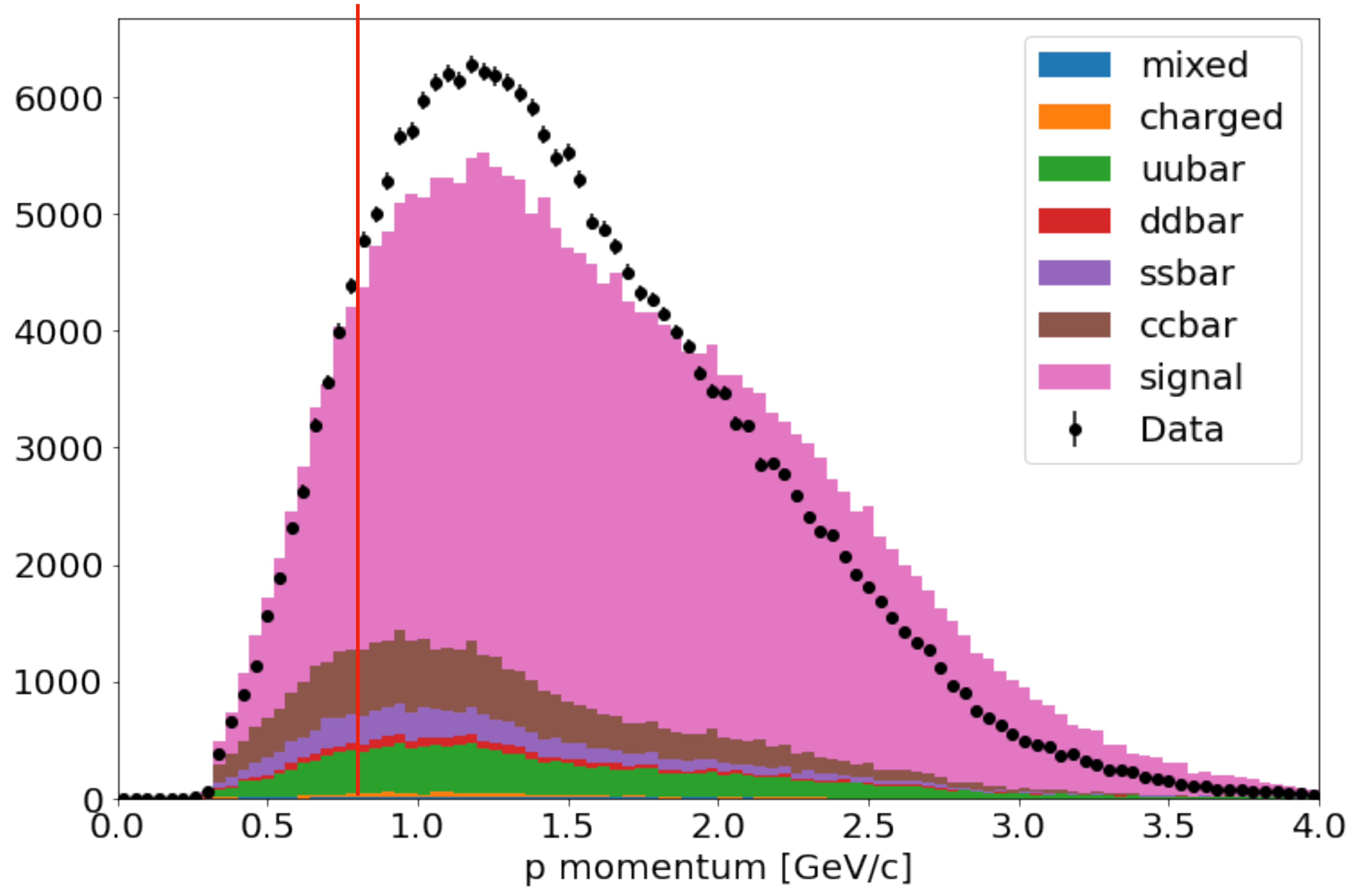


Selection criteria

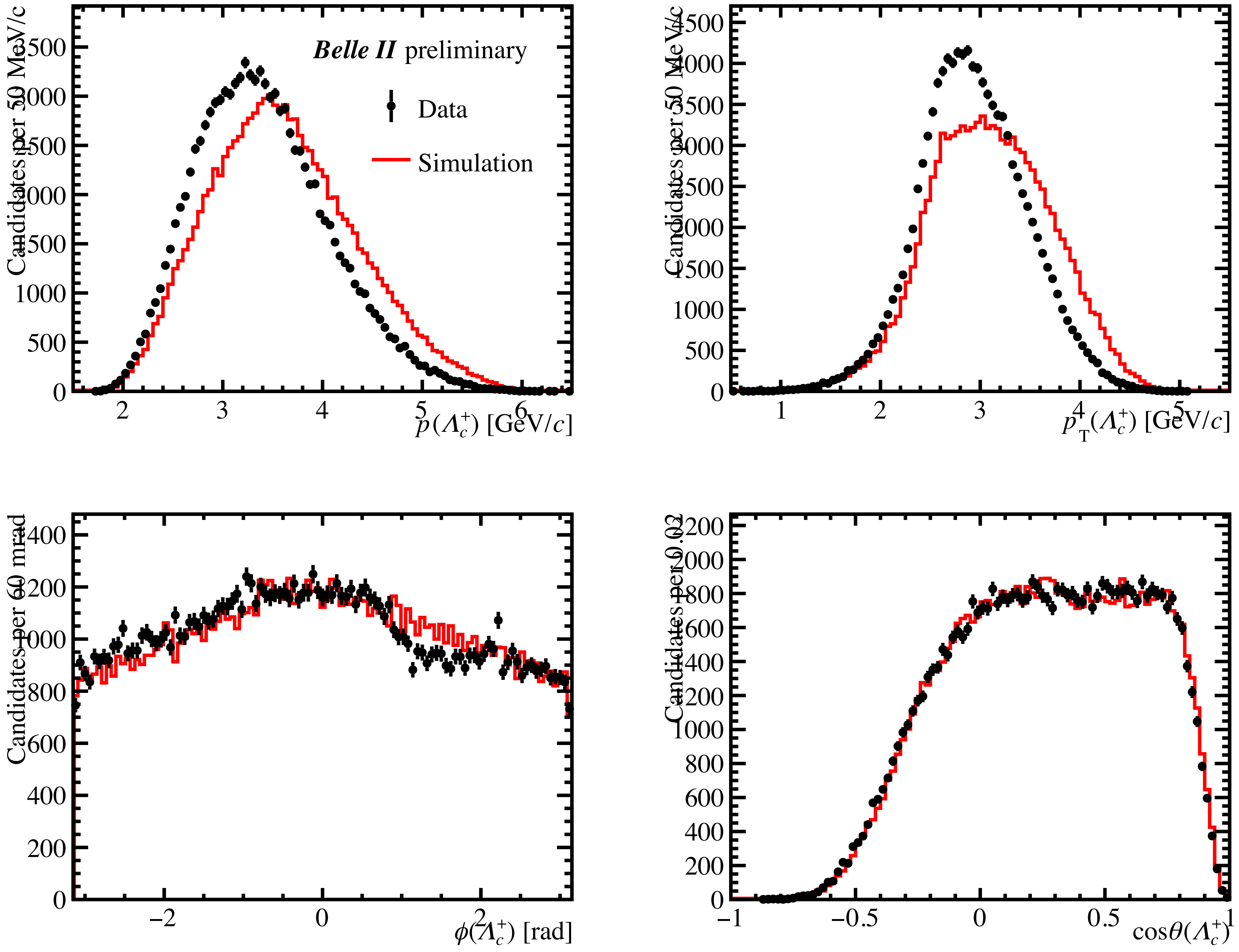
- Remove charm backgrounds by cutting on M(pKπ) with pion hypothesis for proton track
  - !((1.858 < M(pKπ) < 1.881) or (2.0 < M(pKπ) < 2.02))
- $p_t(\pi) > 0.35$ (maximize signal purity and remove charm bkgs)
- $p_t(p) > 0.8$ (reduce backgrounds below 9% and remove charm)



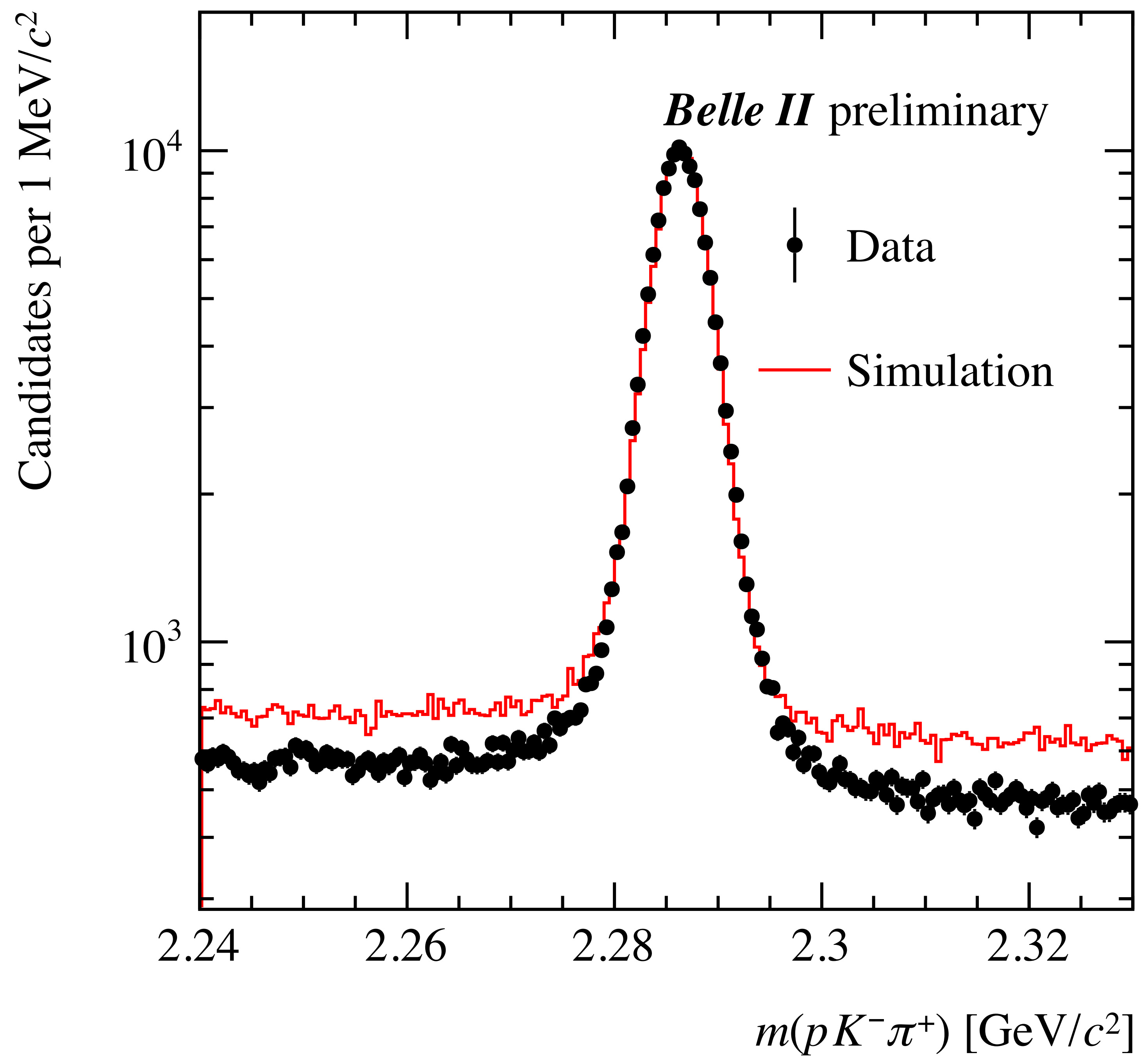




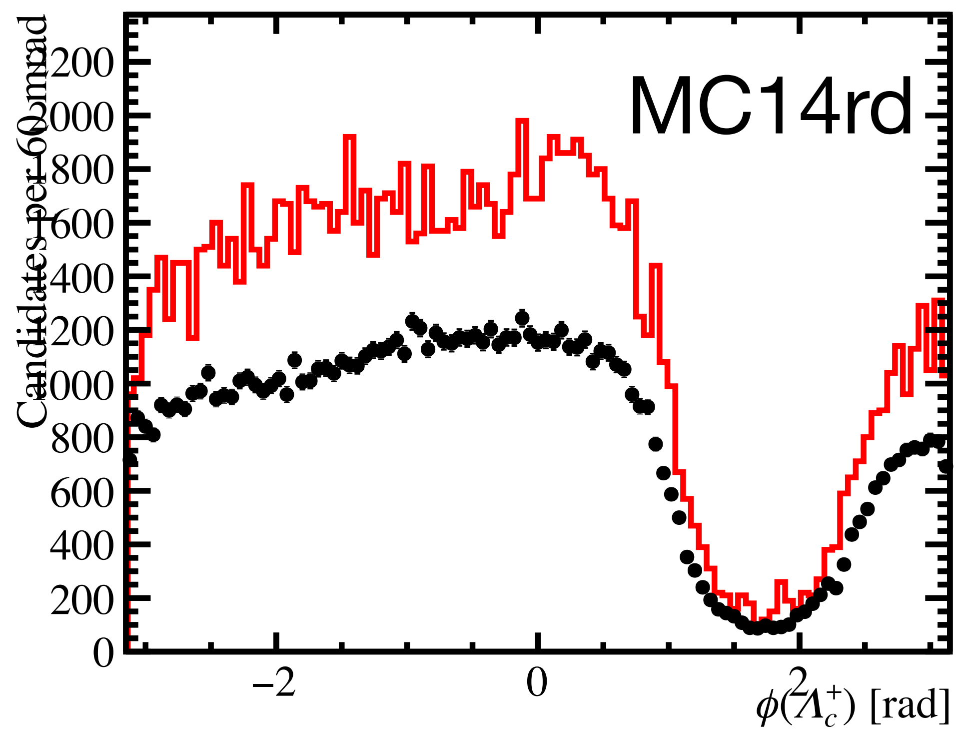
Data/MC comparison



- Some differences in momentum distributions, likely due to mismodeling in the simulation
- Discrepancy in background contamination between data and MC

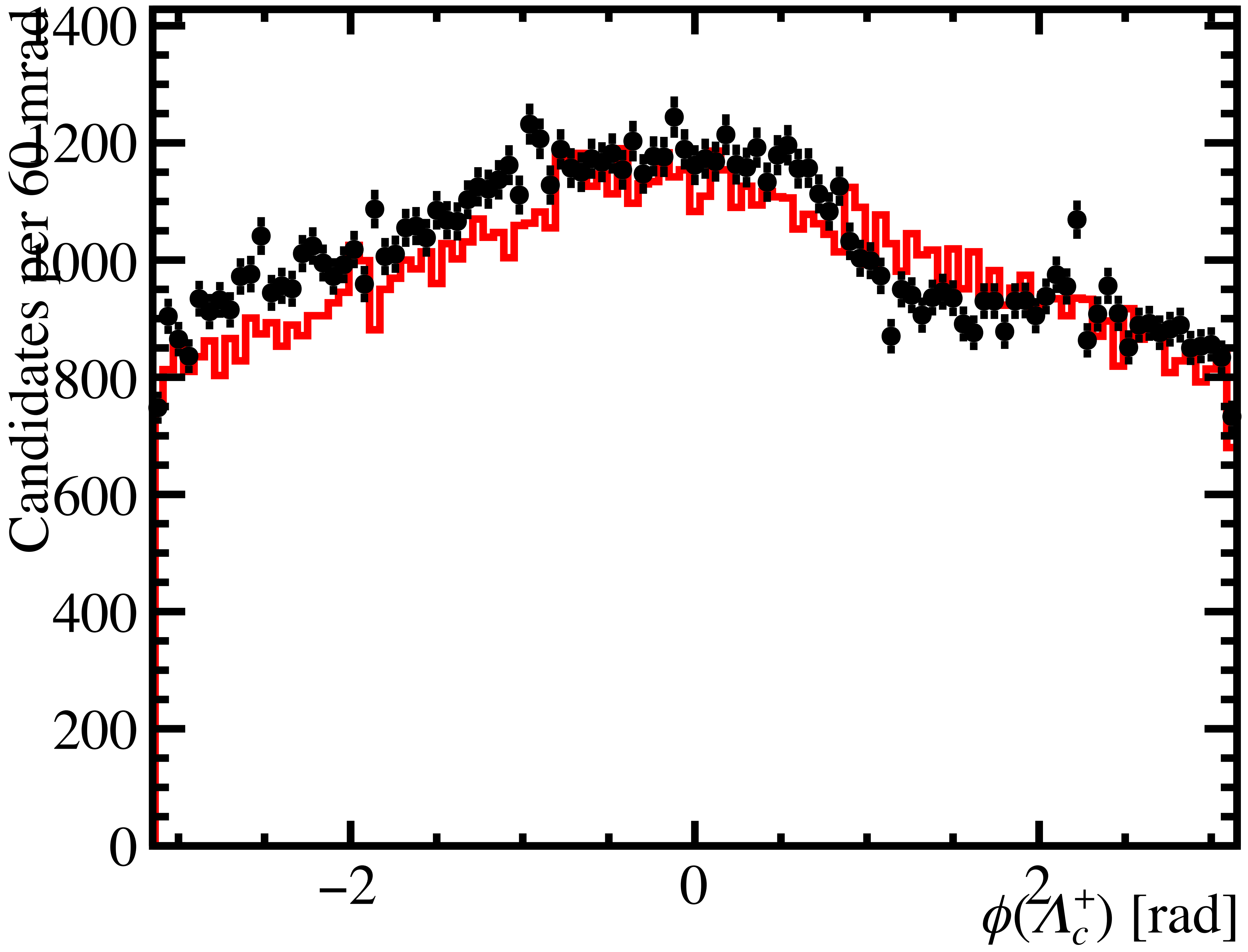


PXD performance in MC14ri_a

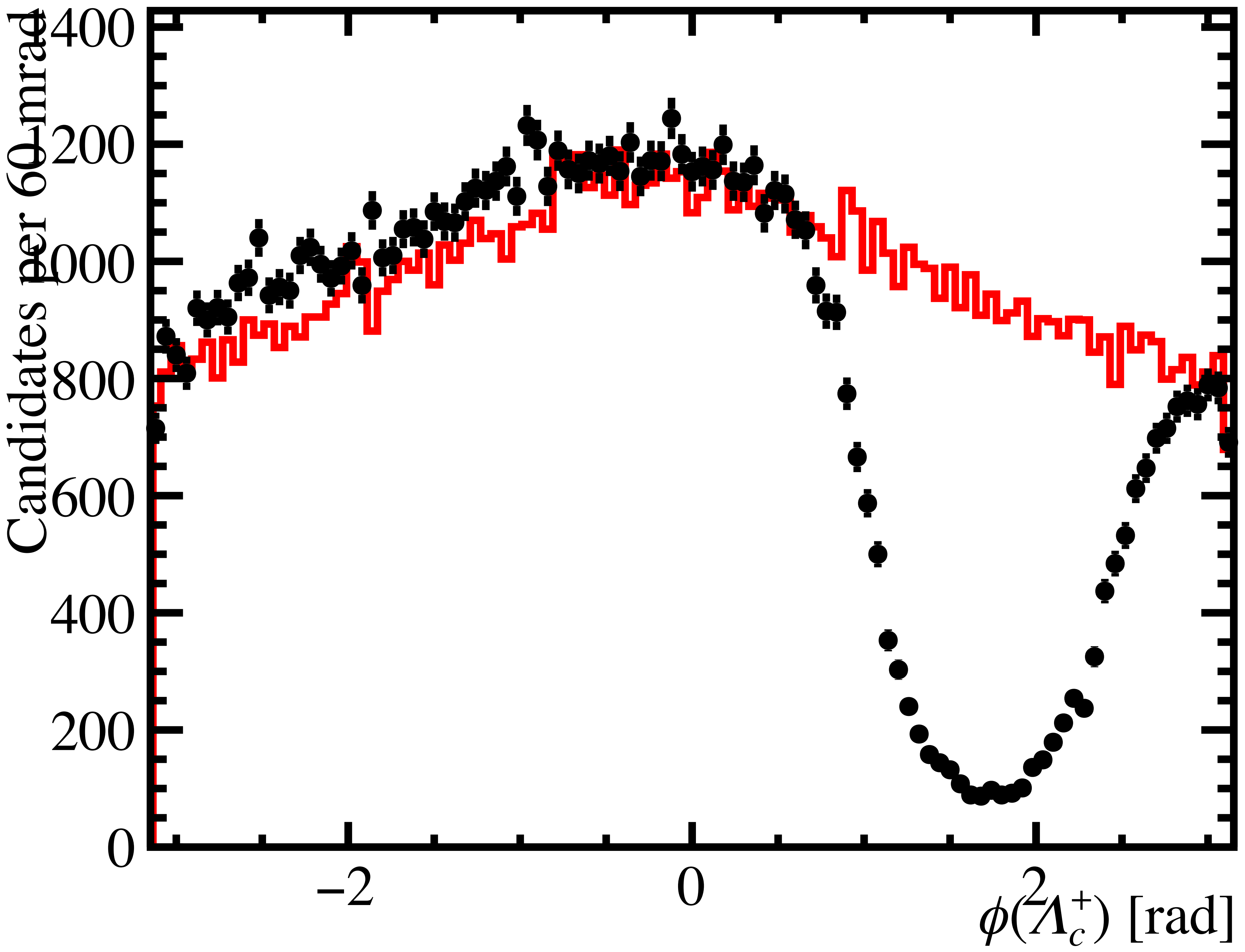


- Not requiring a hit in PXD layer 1, where there are known differences
  - will investigate effects on resolution

No requirement on VXD layer 1

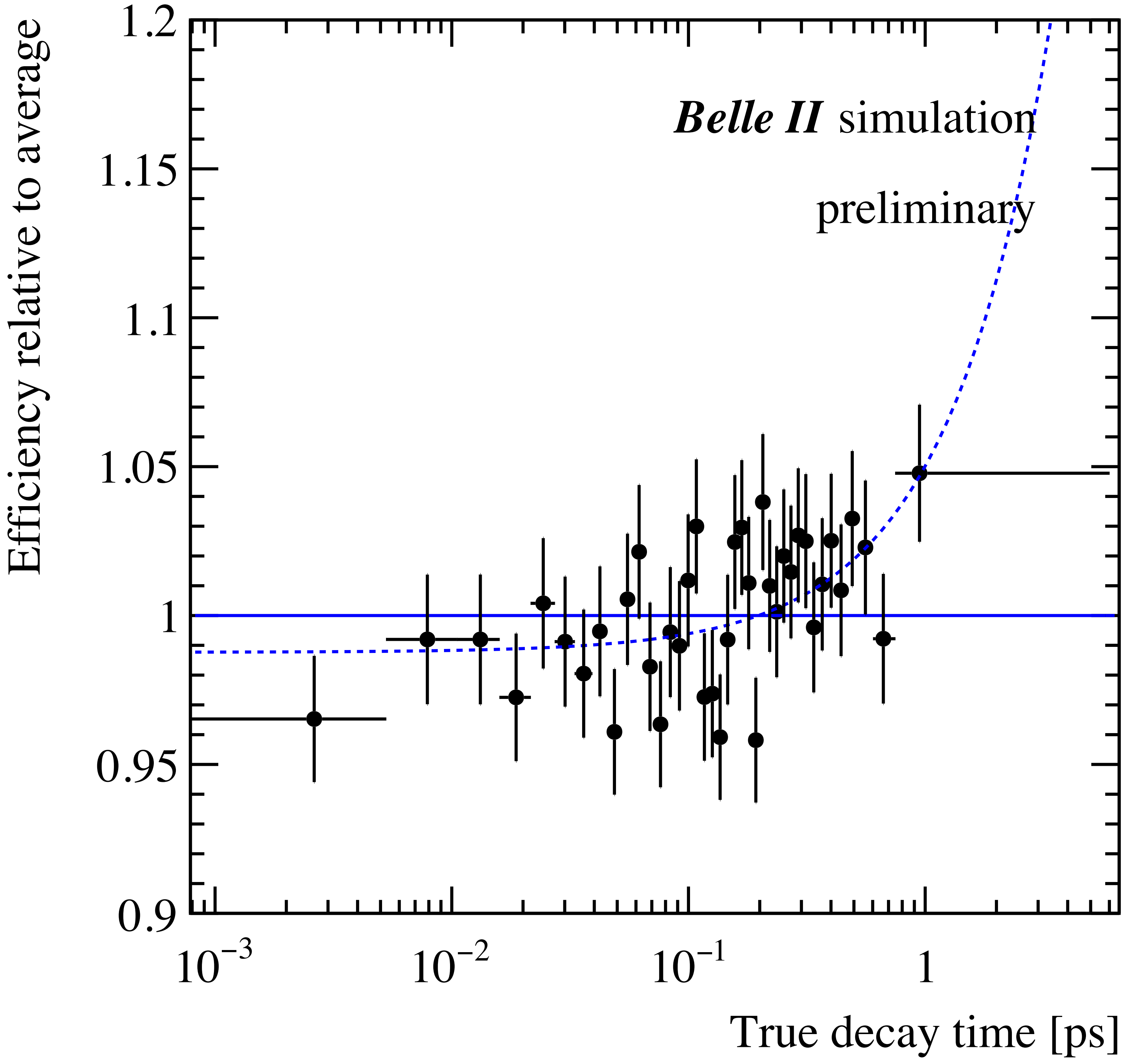


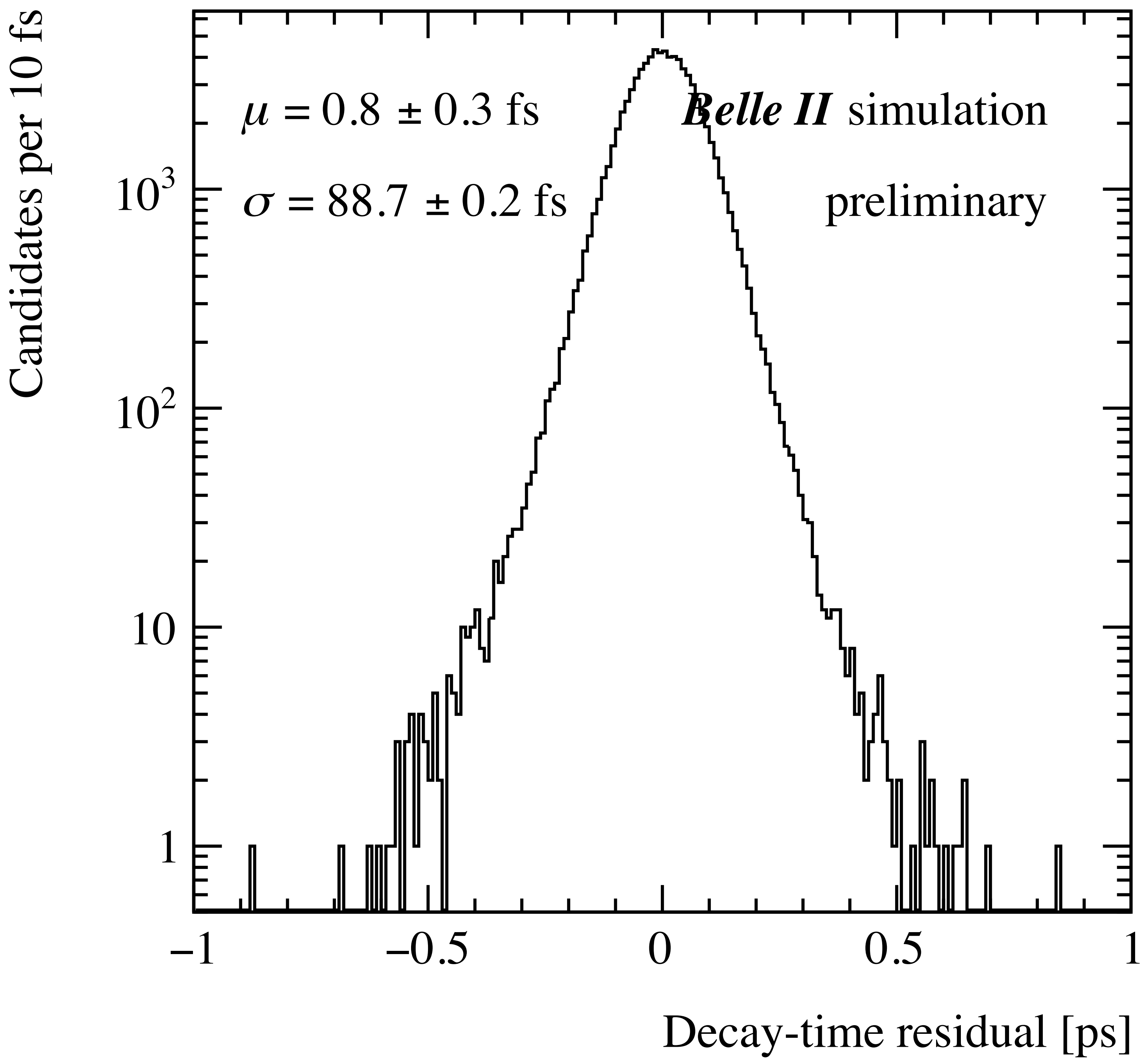
Require first hit on VXD layer 1

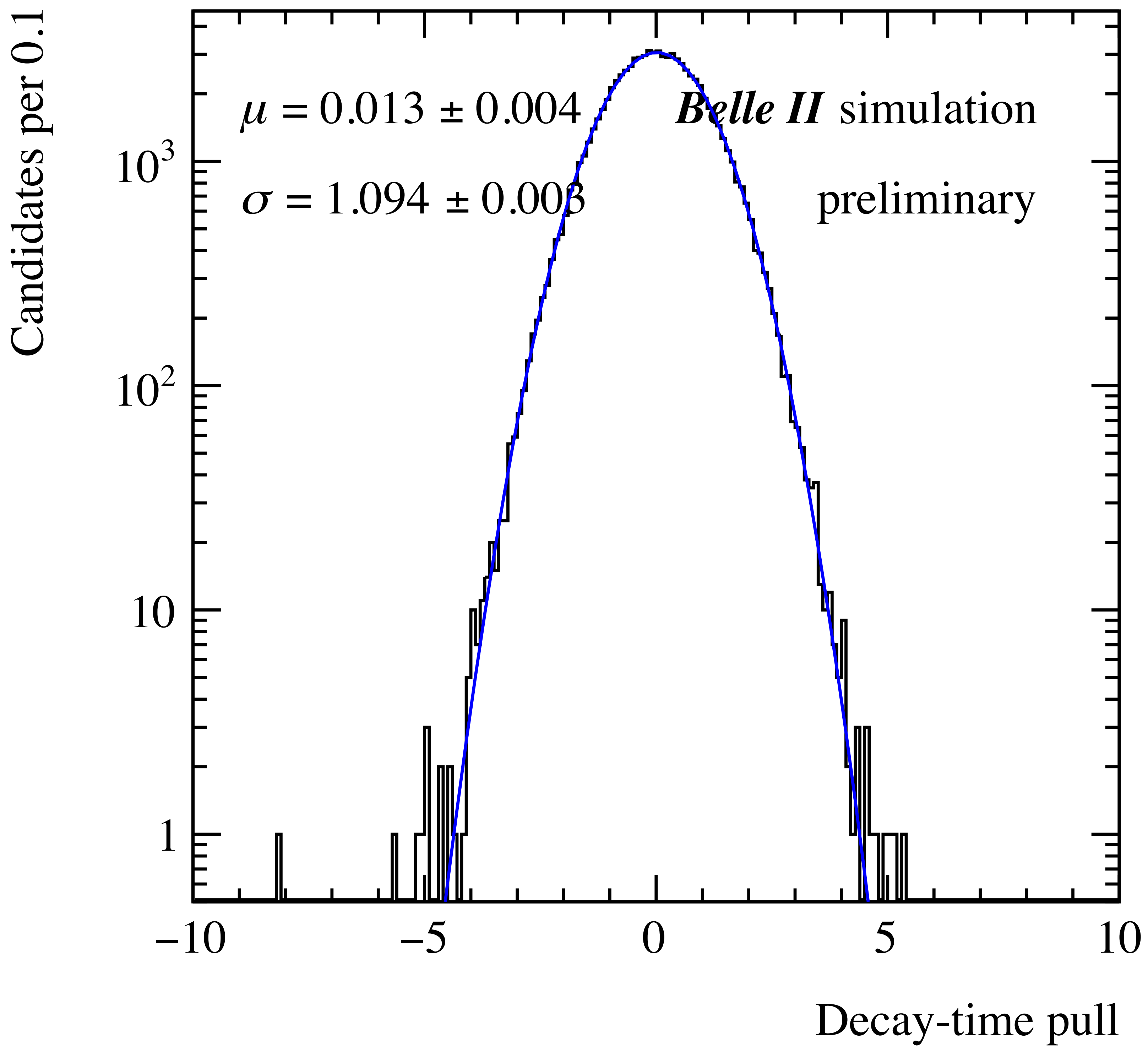


Reconstruction effects - tight cuts

Minimal variation of efficiency versus decay time

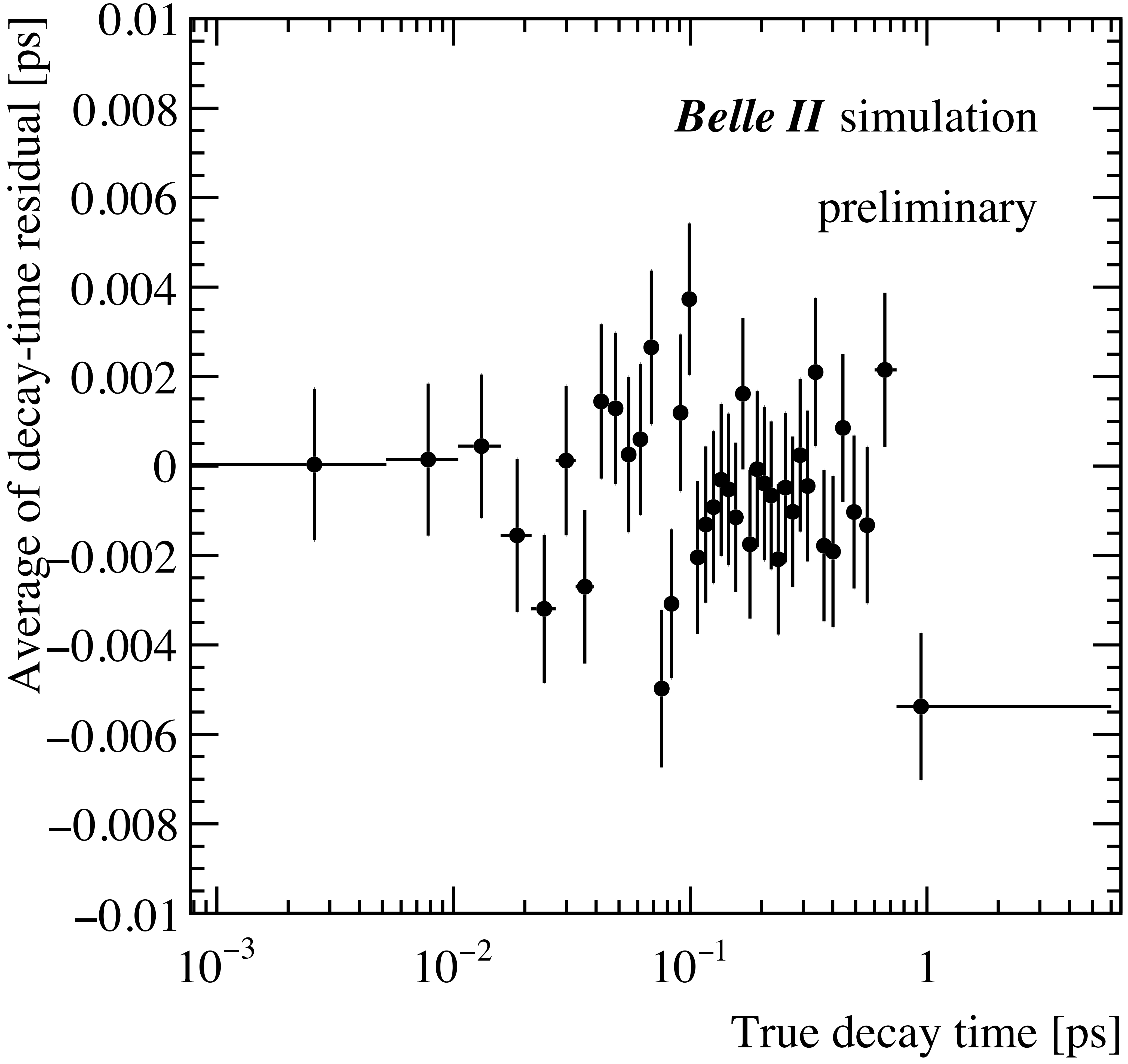


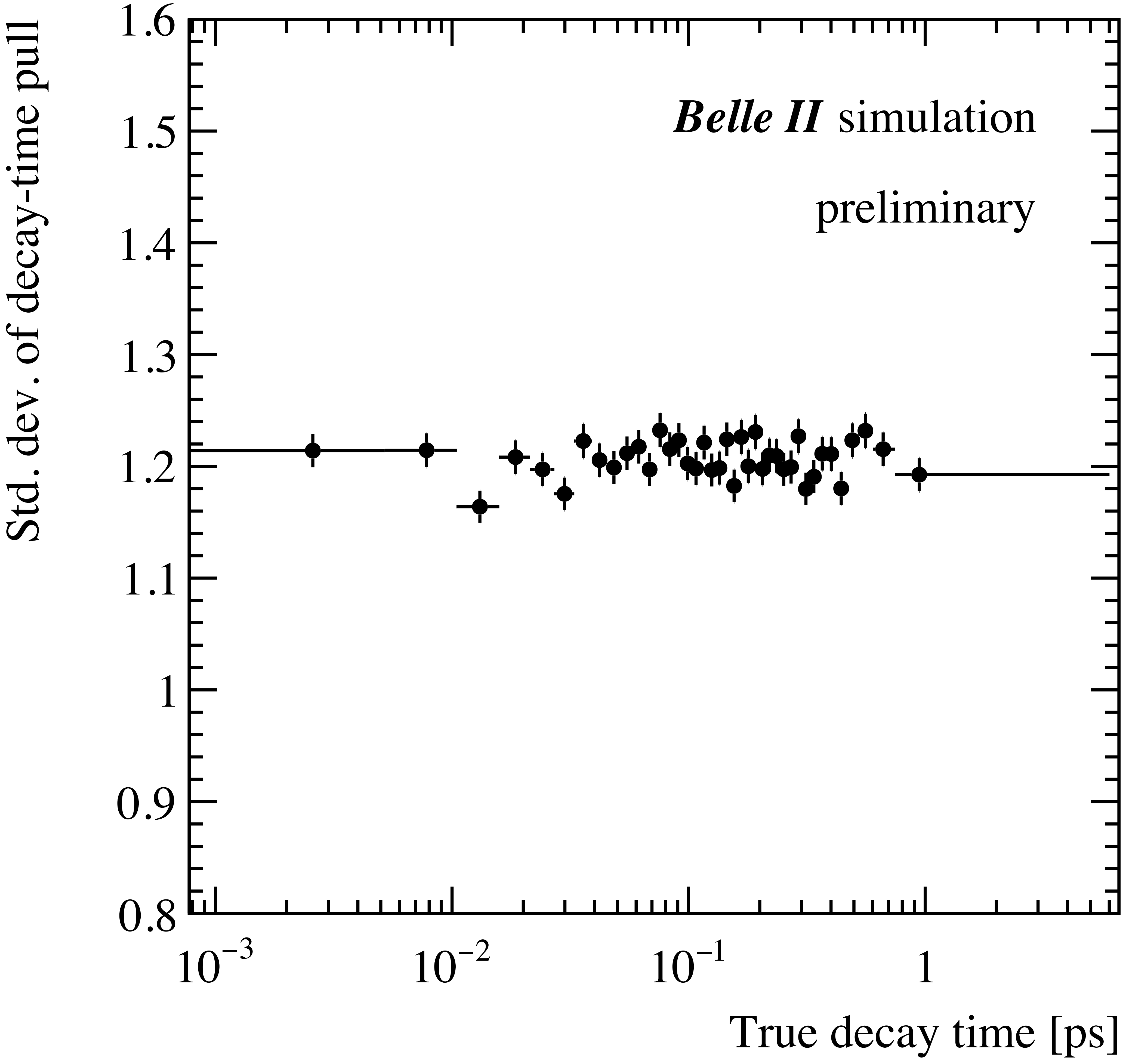




Decay time dependencies - tight cuts

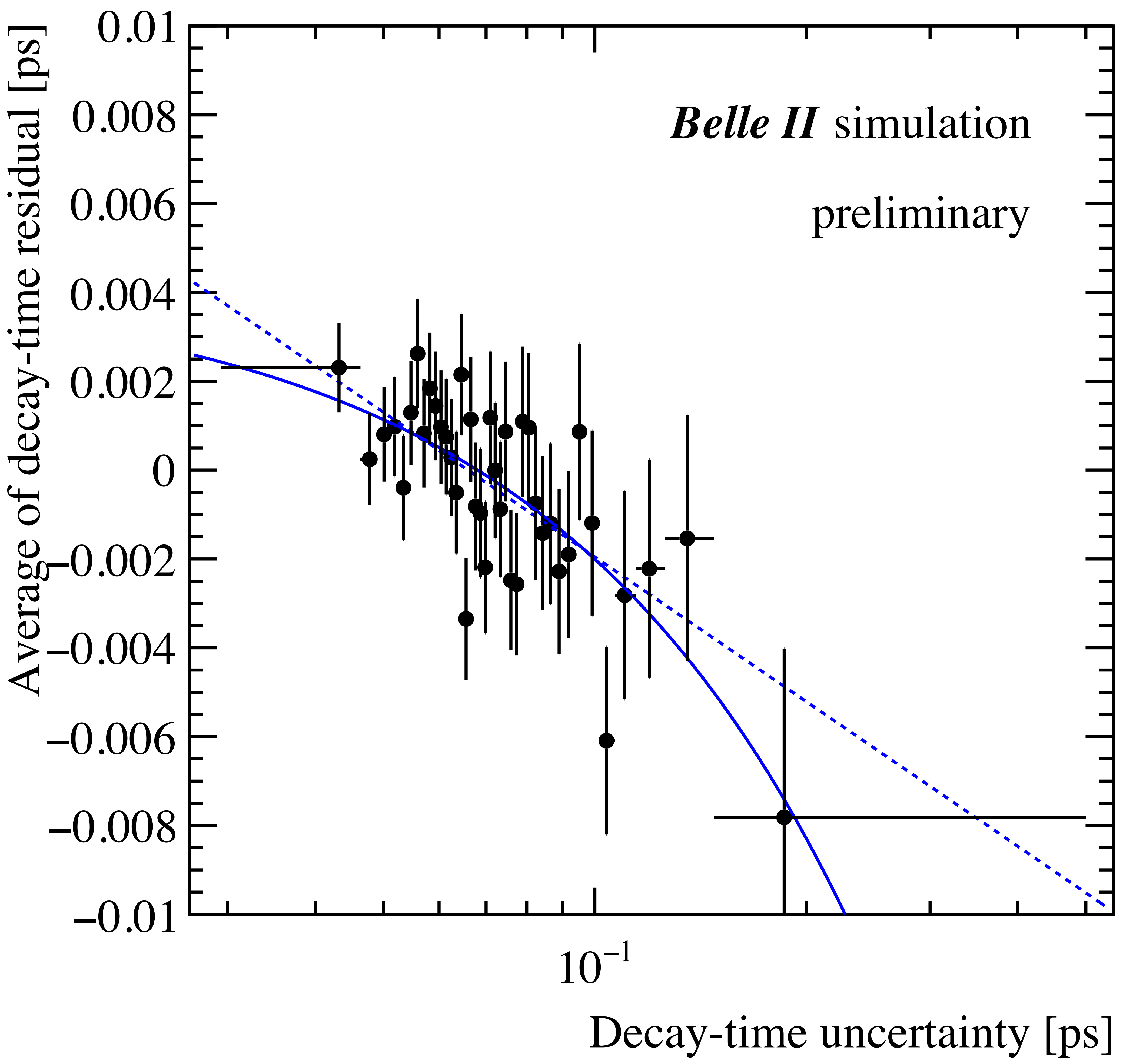
No dependence of decay time residual/pull on true decay time

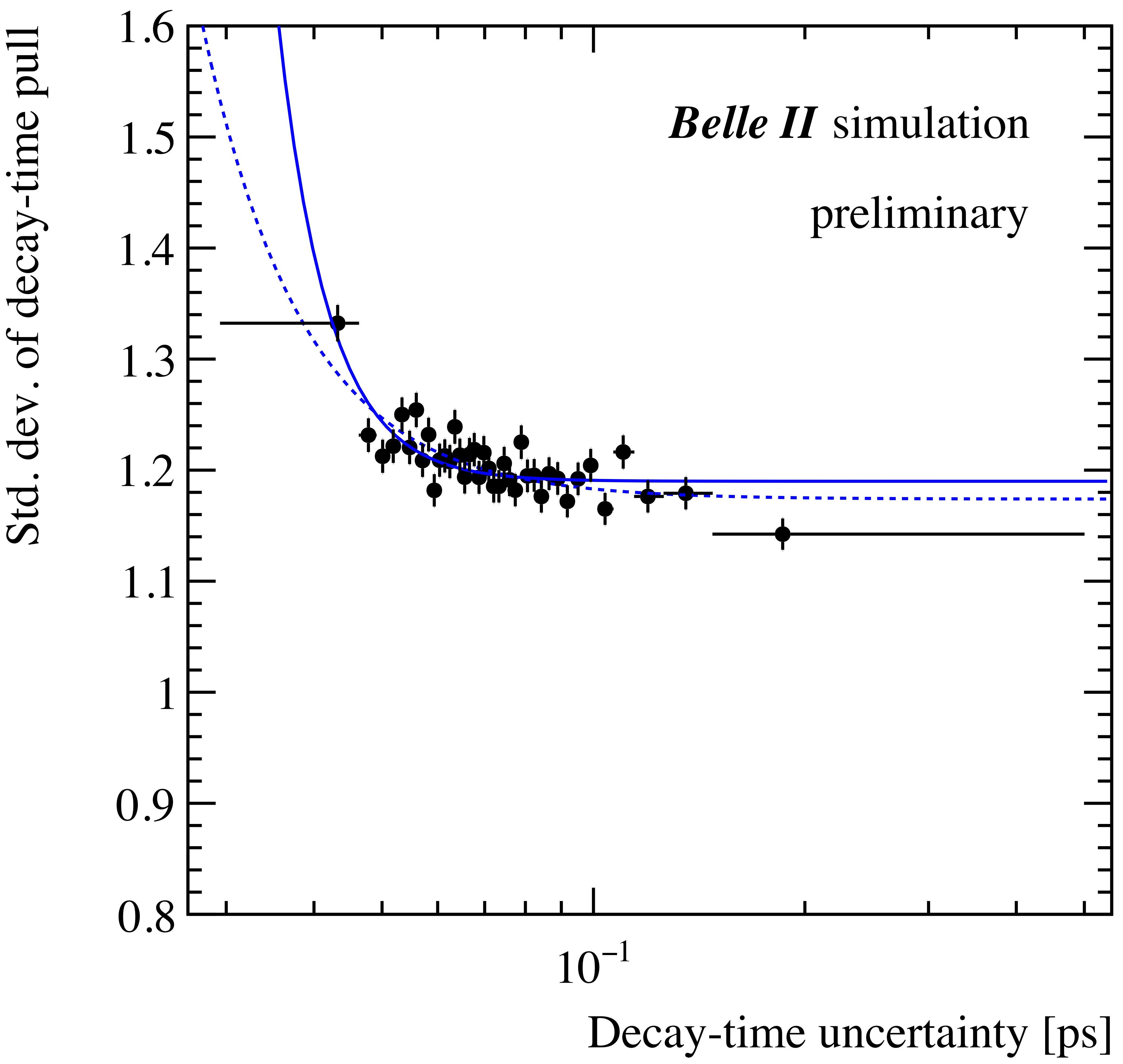




Decay time dependencies - tight cuts

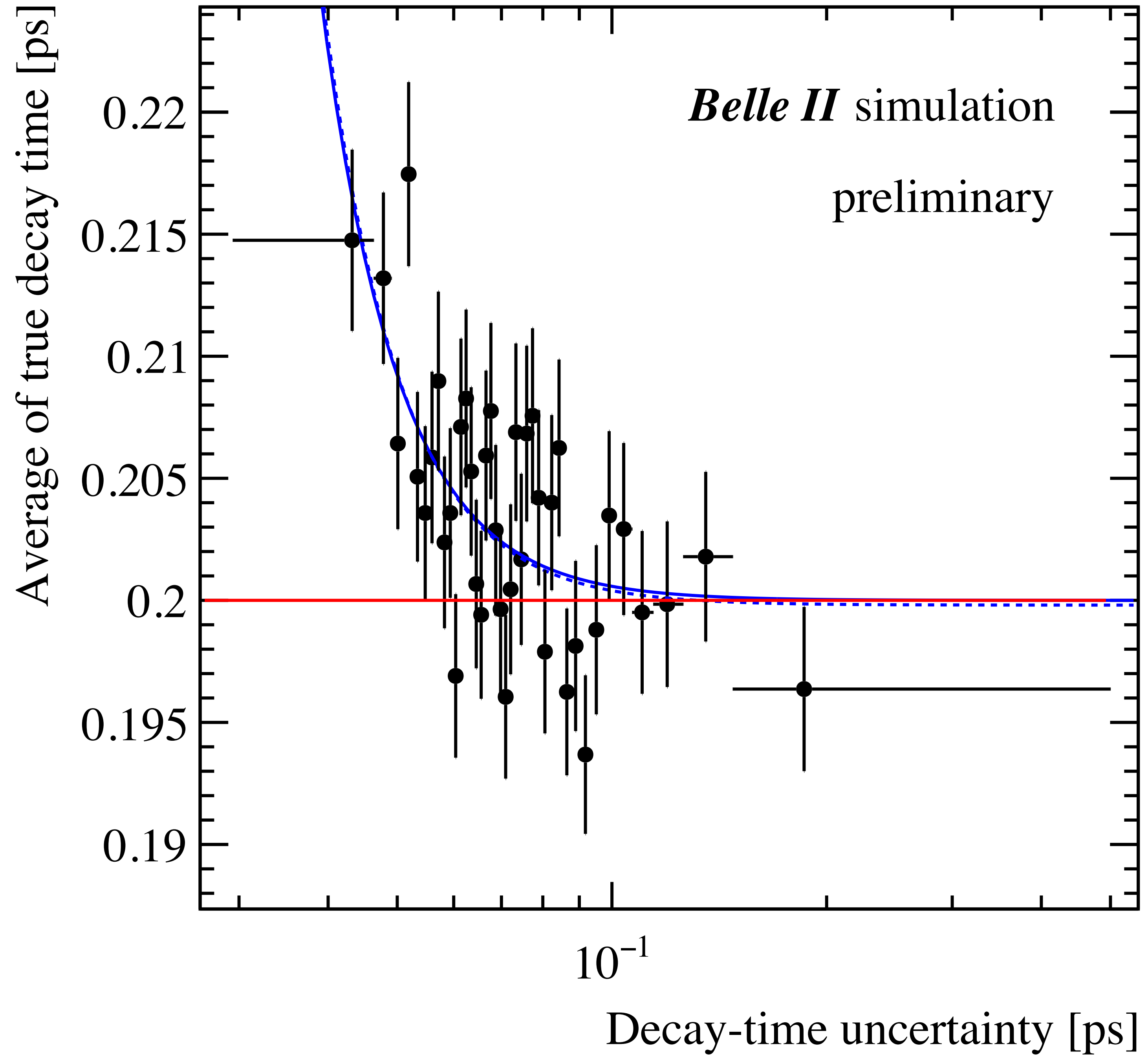
Average decay time residual and pull width vary mildly as a function of decay time uncertainty

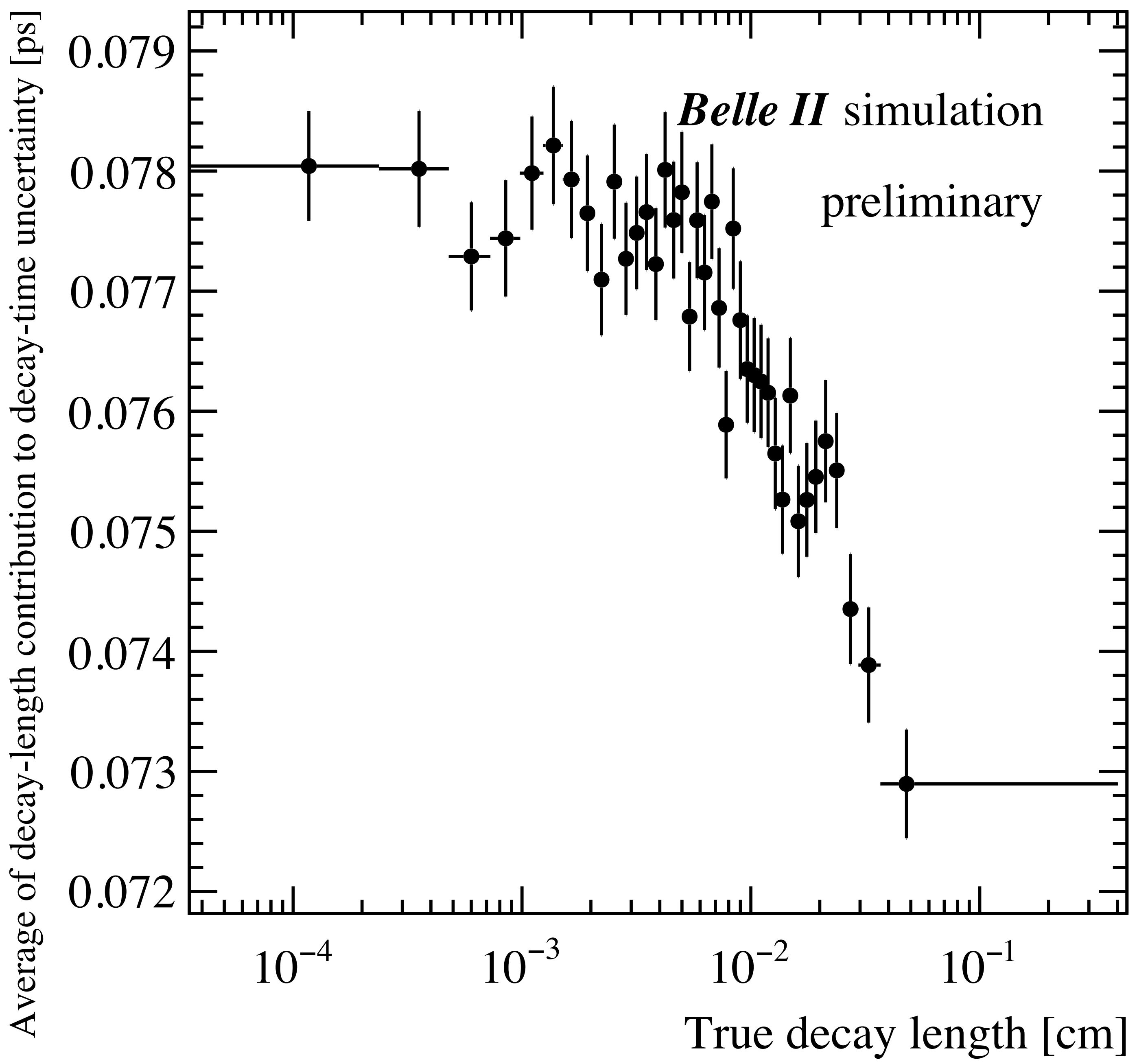




Decay time dependencies - tight cuts

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



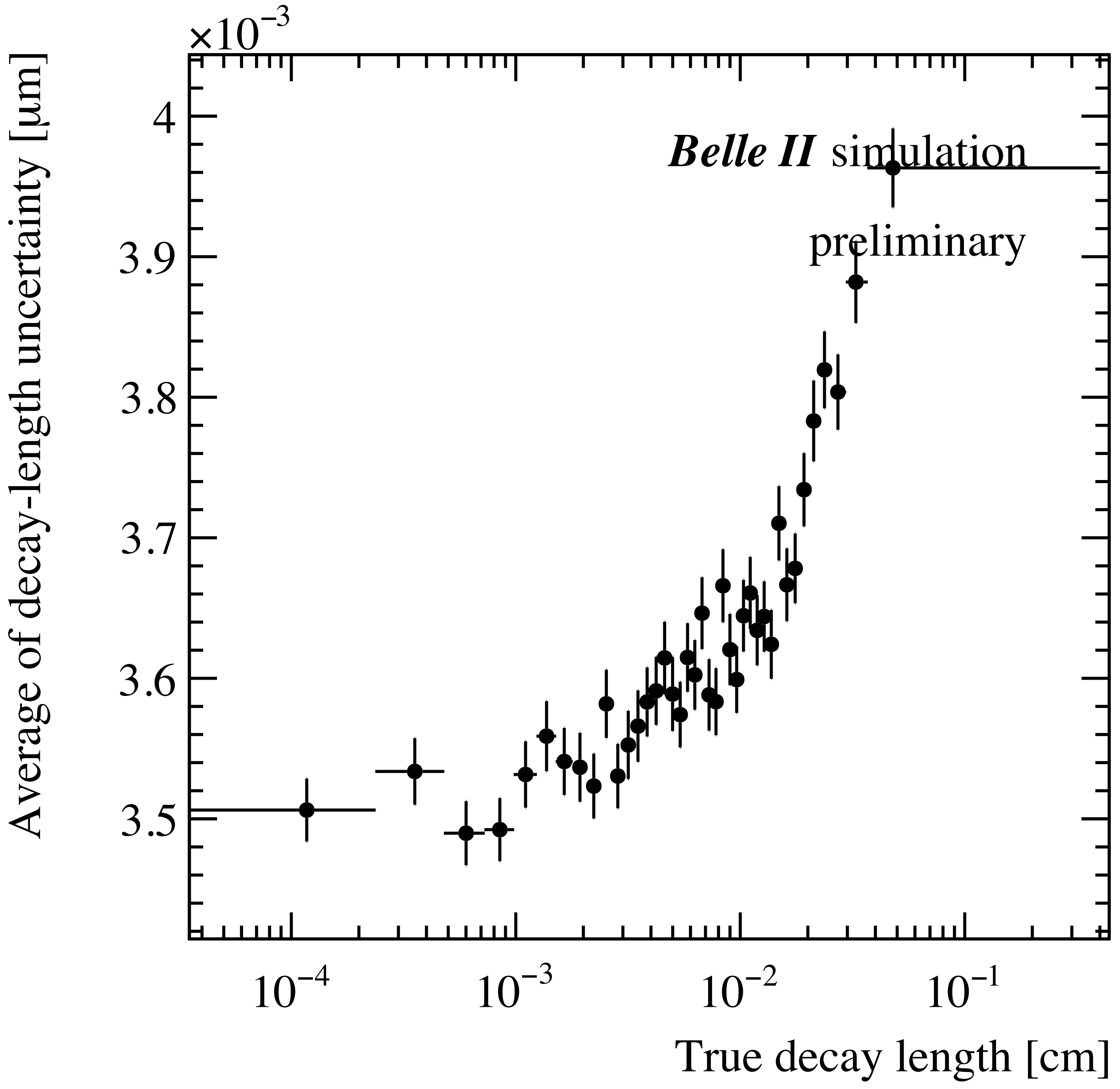


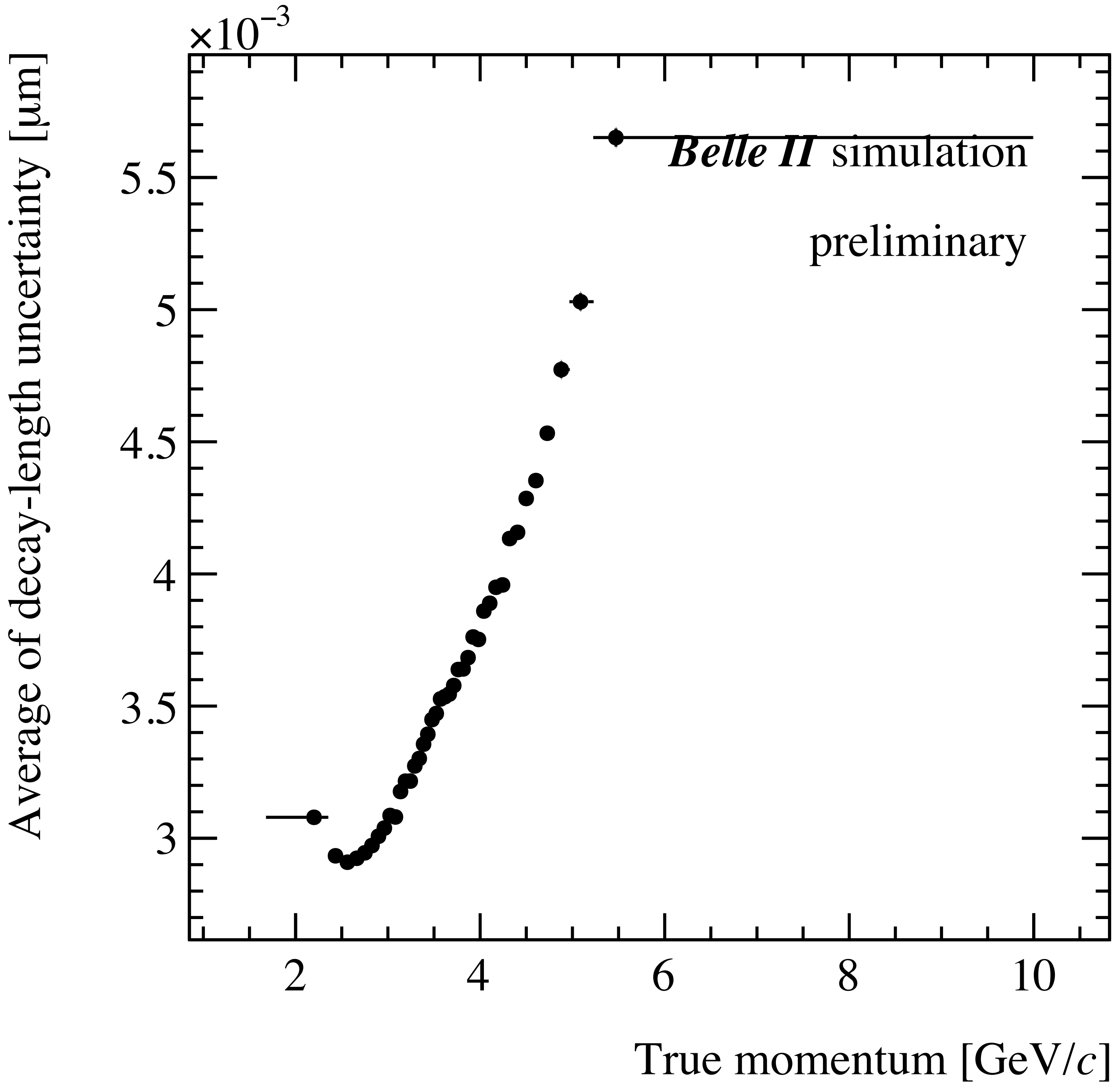
$$t = \frac{m\,L}{p\,c}$$

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

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

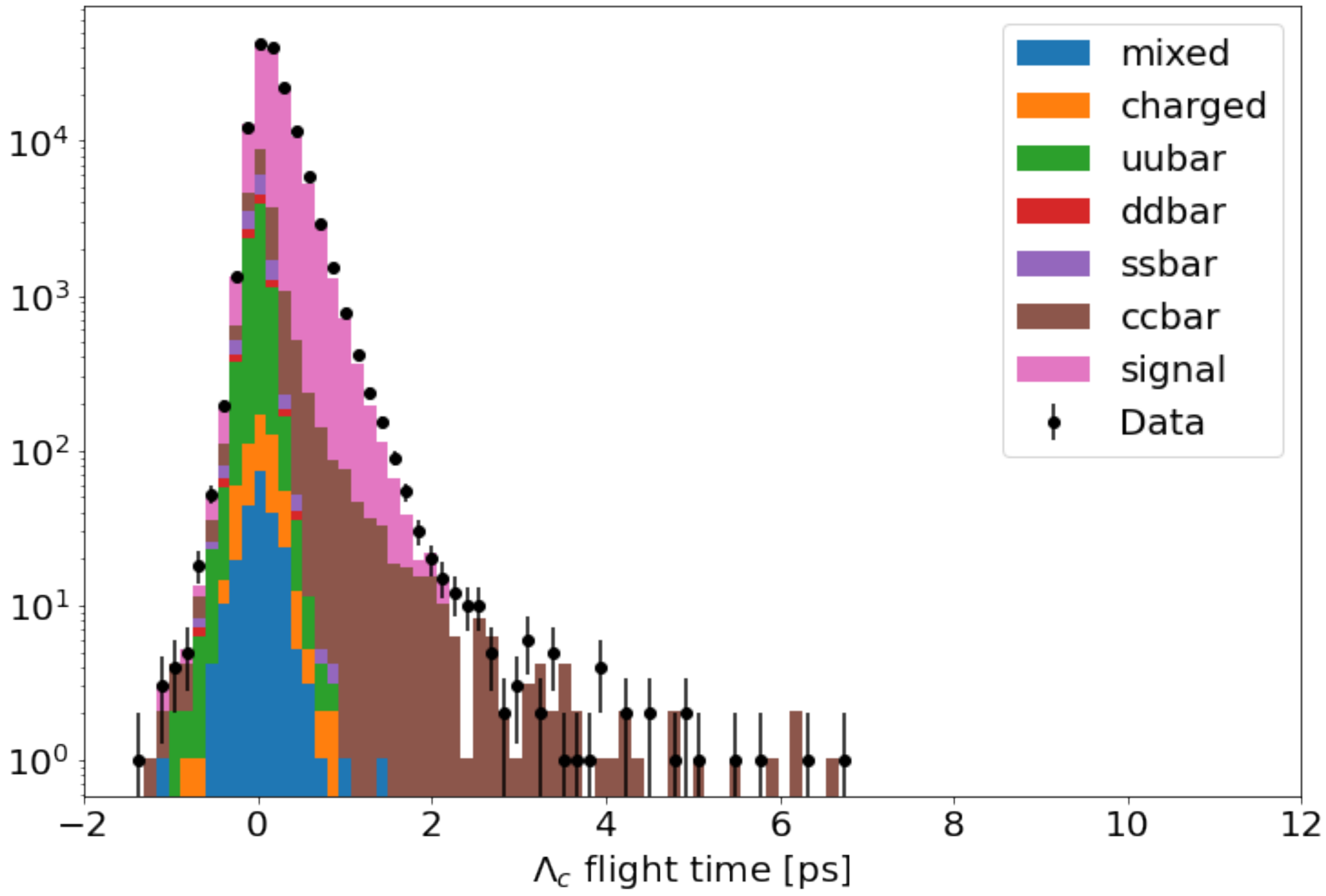
Assumed to be well simulated and ignored in the lifetime fit

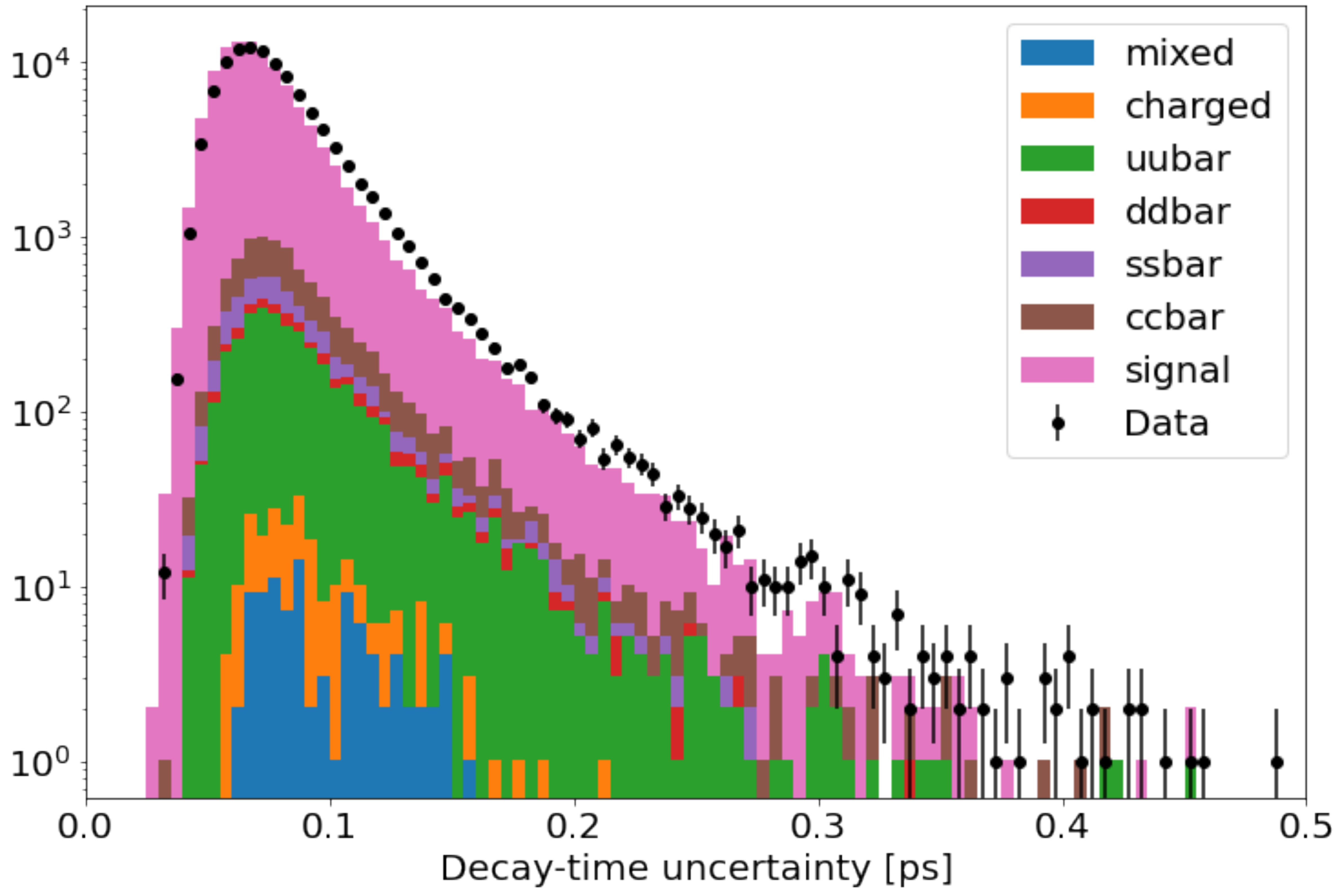




Data/MC lifetime comparison

- Remaining background still includes long lived charm decays





Lifetime fit

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

$$pdf(t, \sigma_t | \tau, \mu, f, s, s_{wide}) \propto \int_0^{\inf} e^{-t_{true}/\tau} R(t - t_{true} | \sigma_t, \mu, f, s, s_{wide}) dt_{true} pdf(\sigma_t)$$

Proper time scaling error

$$R(t - t_{true} | \sigma_t, \mu, f, s, s_{wide}) = f\, G(t - t_{true} | \mu, s, \sigma_t) + (1 - f) G(t - t_{true} | \mu, s_{wide}, \sigma_t)$$

Common bias

- Model background with two lifetime shapes (double Gaussian resolution case shown):

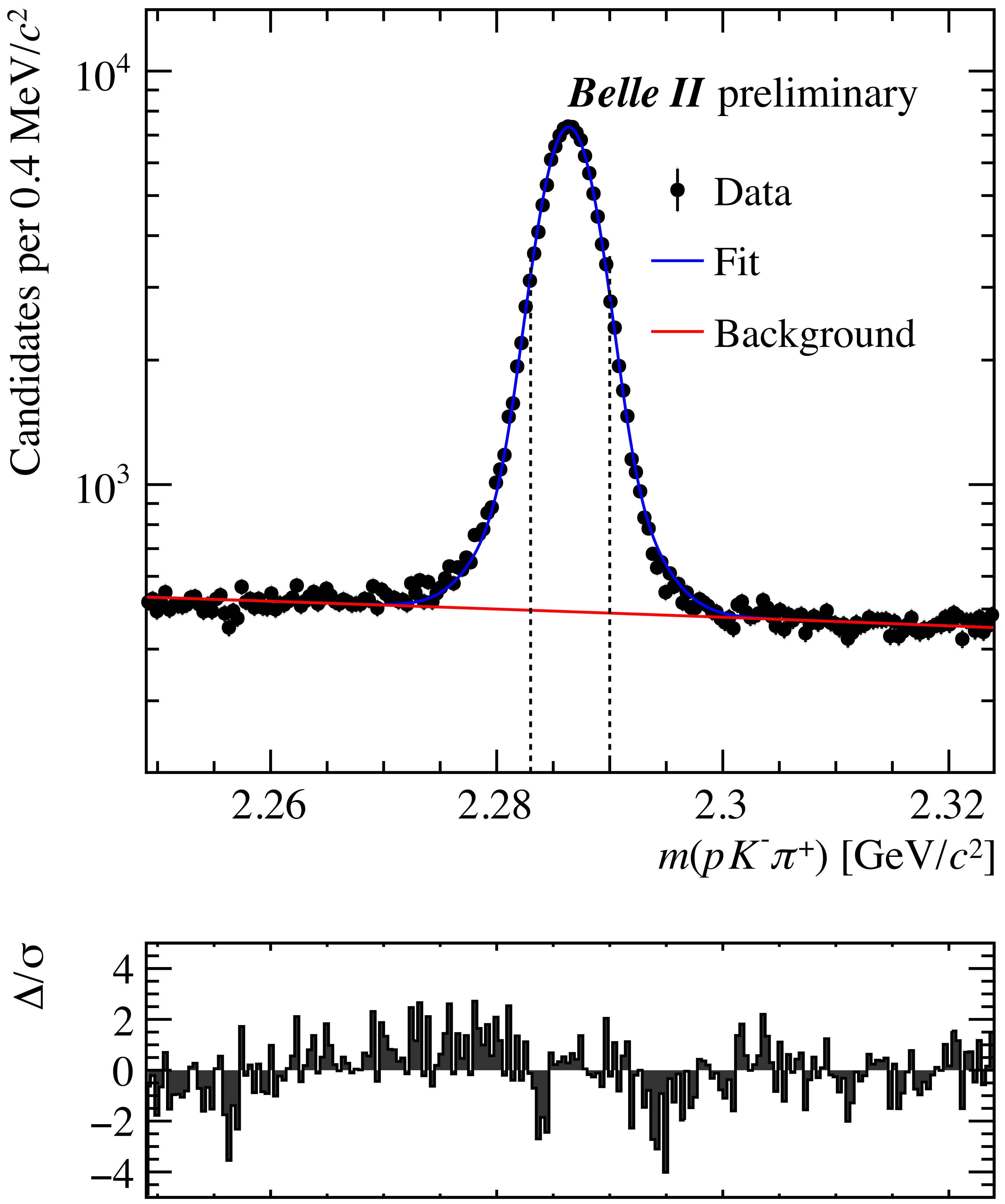
$$pdf(bkg) = f_{bl}[f_{\tau 1} pdf(t, \sigma_t | \tau_{bkg1}, \mu, f, s, s_{wide}) - (1 - f_{\tau 1}) pdf(t, \sigma_t | \tau_{bkg2}, \mu, f, s, s_{wide})] + (1 - f_{bl}) R(\sigma_t, \mu, f, s, s_{wide}) pdf(\sigma_t)$$

- Additional penalty factor added to likelihood to constrain background level from invariant mass fit

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

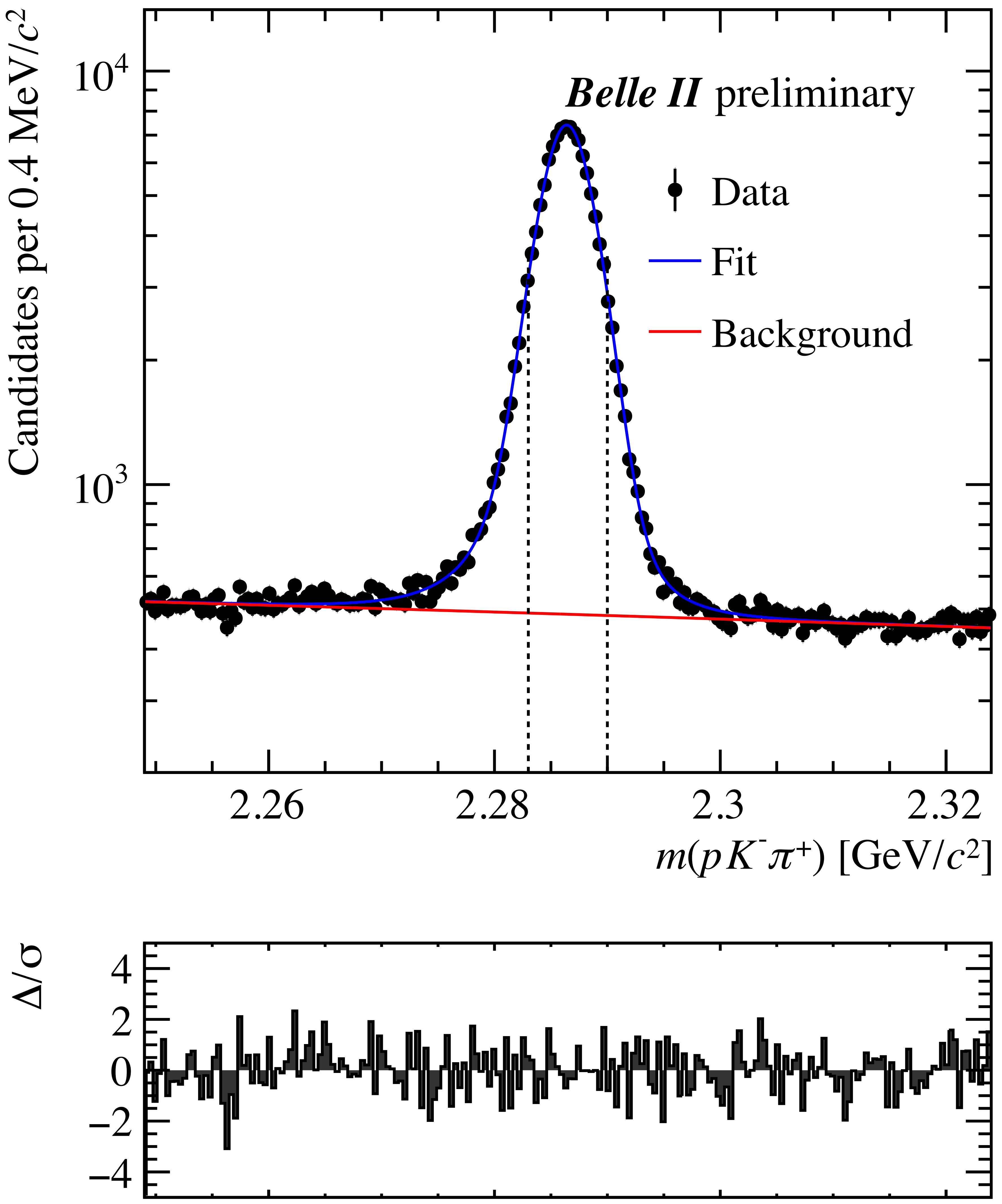
Invariant mass fit: MC

Updated: switch to Gaussian + Johnson function for signal



Signal: Double Gaussian

Background:
0.088433 +- 0.000101

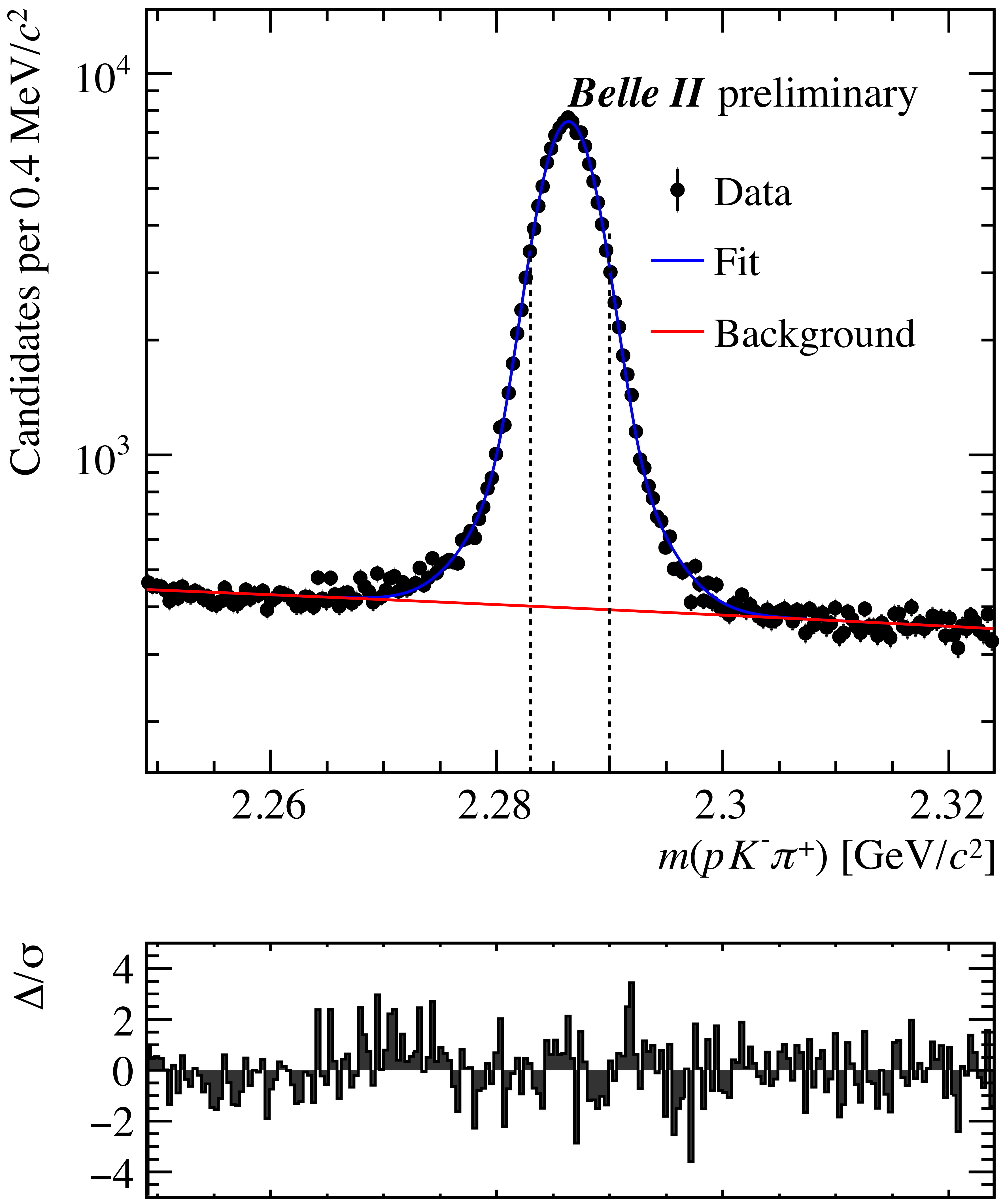


Signal: Gaussian + Johnson function
(transformation of normal distribution)

Background:
0.087289 +- 0.000164

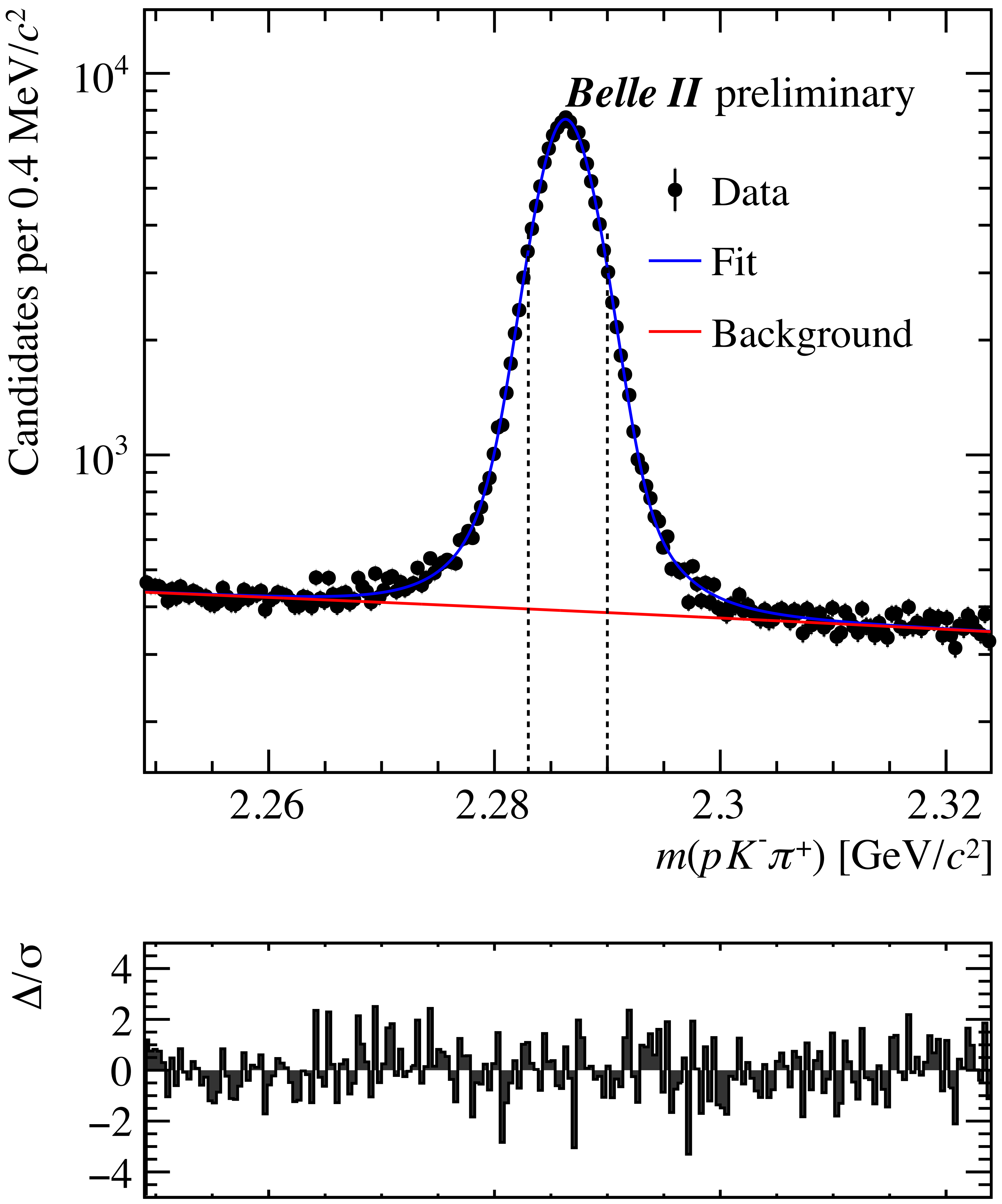
Invariant mass fit: Data

Updated: switch to Gaussian + Johnson function for signal



Signal: Double Gaussian

Background:
0.068586 +- 0.000132

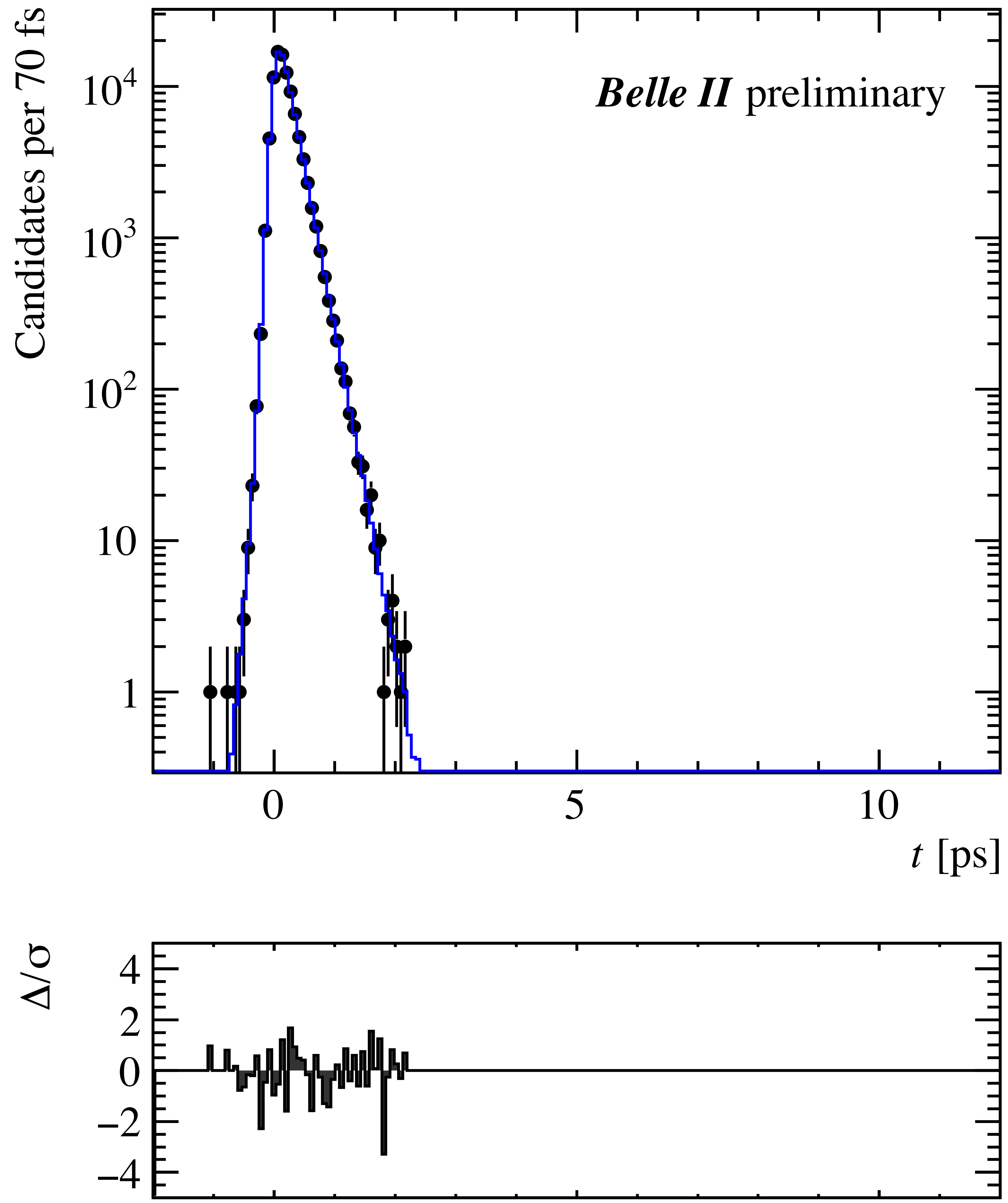


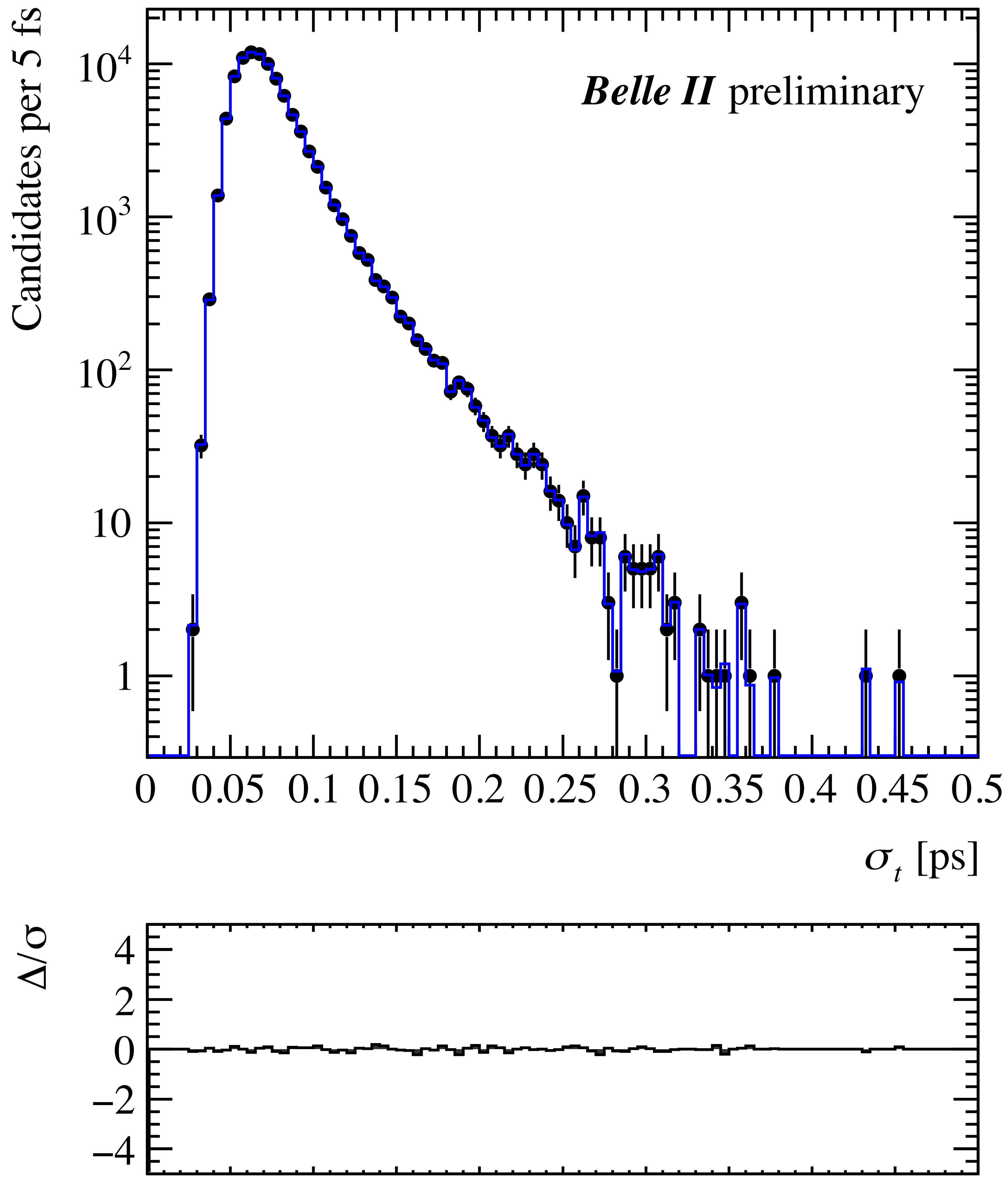
Signal: Gaussian + Johnson function (transformation of normal distribution)

Background:
0.067525 +- 0.000241

Signal-only fit

$$pdf(t, \sigma_t \,|\, \tau, \mu, f, s) \qquad R(t - t_{true} \,|\, \sigma_t, \mu, f, s) = G(t - t_{true} \,|\, \mu, s, \sigma_t)$$





- Truth-matched signal from 200/fb equivalent MC14ri_a

$$\tau = 0.20229 \pm 0.00090$$

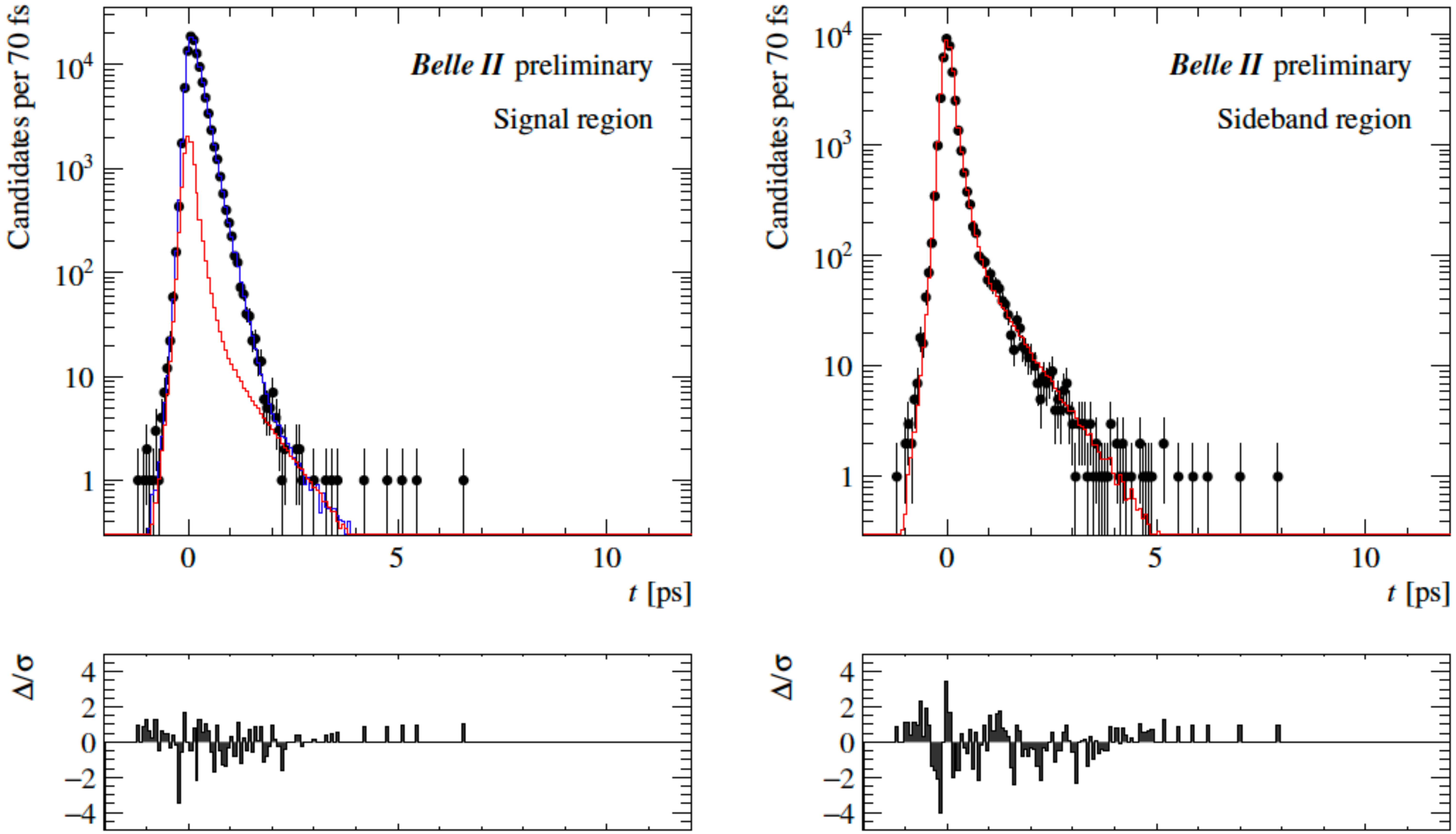
$$\mu = 0.0006 \pm 0.0007$$

$$s = 1.079 \pm 0.007$$

Generated value (taken from truth matched events in the signal region): **201.71 fs**

Lifetime fit results on MC with single-Gaussian resolution

$$(1 - f_{bkg}) \times pdf(t, \sigma_t \,|\, \tau, \mu, s) + f_{bkg} \times pdf(bkg)$$



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

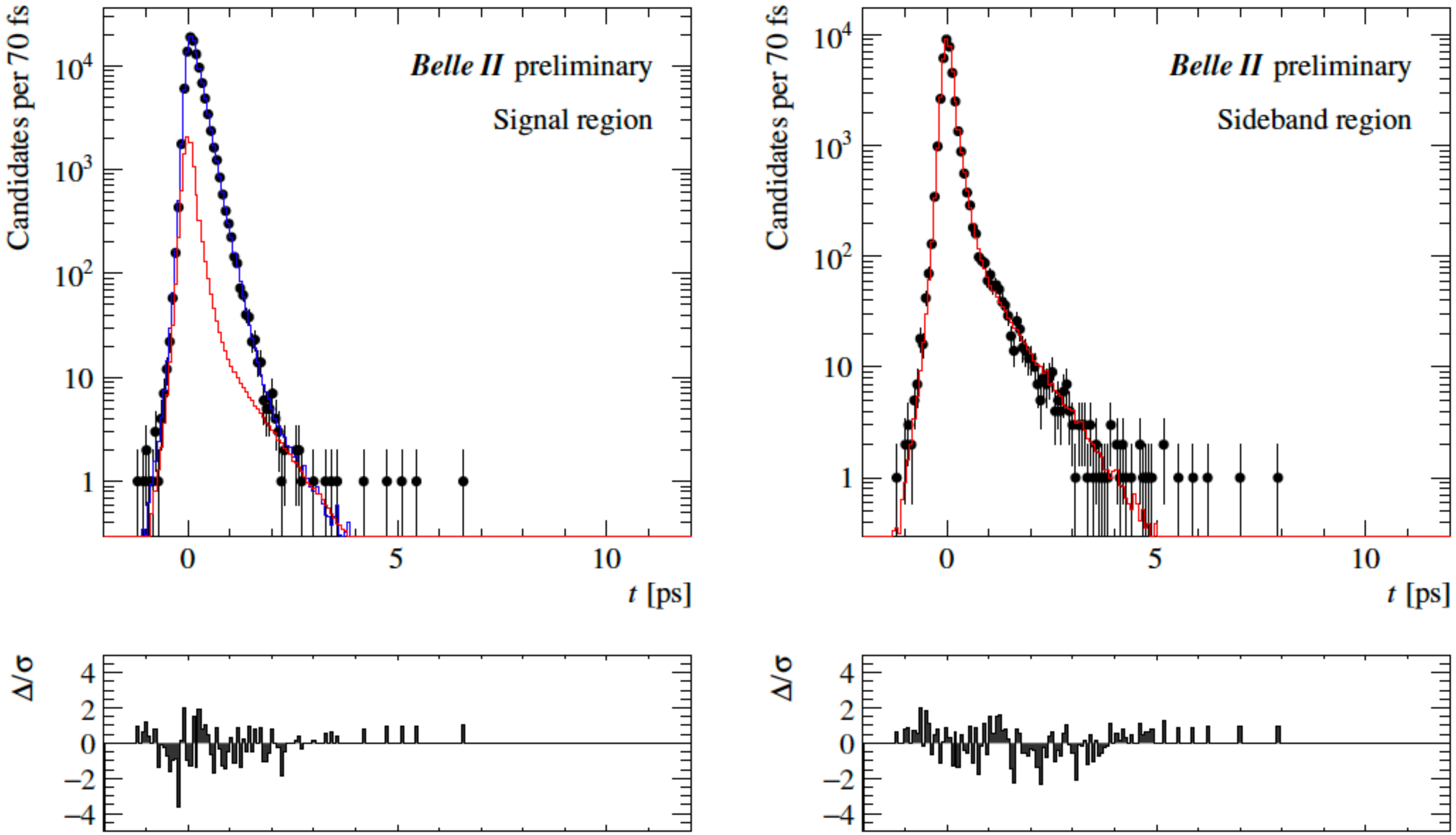
$CLEO,\ \tau = 179.6 \pm 6.9 \pm 4.4\ fs$

Parameter	Fit result w/single Gaussian
τ (fs)	202.0 ± 0.9
b (fs)	0.9 ± 0.6
s_1	1.075 ± 0.007
s_2	
f	
f_{bg}	0.0873 ± 0.0002
f_τ	0.291 ± 0.010
$f_{\tau 1}$	0.828 ± 0.010
τ_{bg1} (fs)	161 ± 6
τ_{bg2} (fs)	778 ± 26
s_{bg}	1.166 ± 0.009

Generated value (taken from truth matched events in the signal region): **201.71 fs**

Lifetime fit results on MC with double-Gaussian resolution

$$(1 - f_{bkg}) \times pdf(t, \sigma_t \,|\, \tau, \mu, f, s, s_{wide}) + f_{bkg} \times pdf(bkg)$$



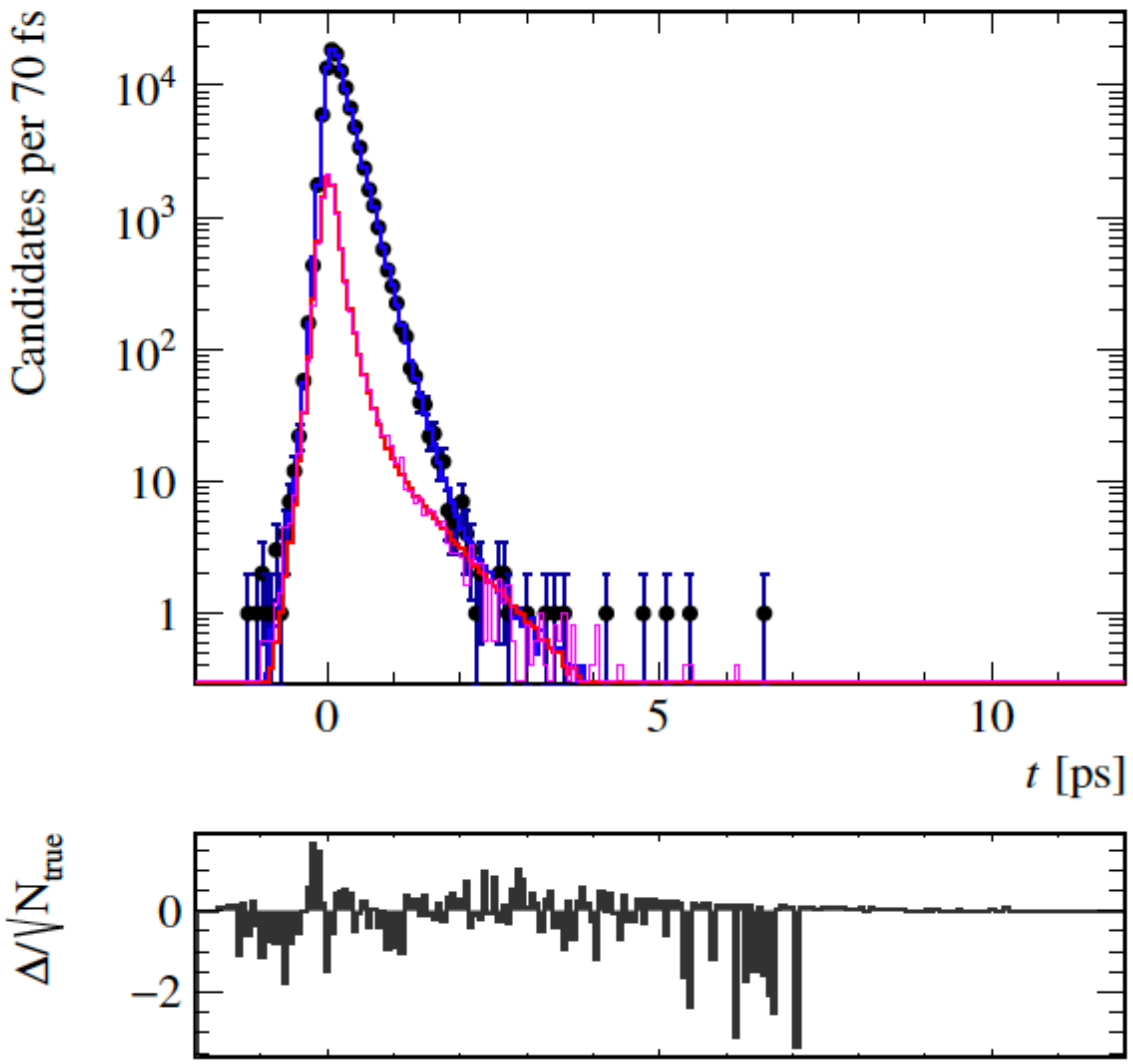
$LHCB,\ \tau = 203.5 \pm 1.0 \pm 1.3 \pm 1.4\ fs$

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

Parameter	Fit result w/double Gaussian
τ (fs)	202.4 ± 0.9
b (fs)	0.1 ± 0.6
s_1	1.051 ± 0.009
s_2	2.412 ± 0.123
f	0.980 ± 0.004
f_{bg}	0.0873 ± 0.0002
f_τ	0.311 ± 0.009
$f_{\tau 1}$	0.835 ± 0.010
τ_{bg1} (fs)	154 ± 5
τ_{bg2} (fs)	770 ± 30
s_{bg}	1.130 ± 0.011

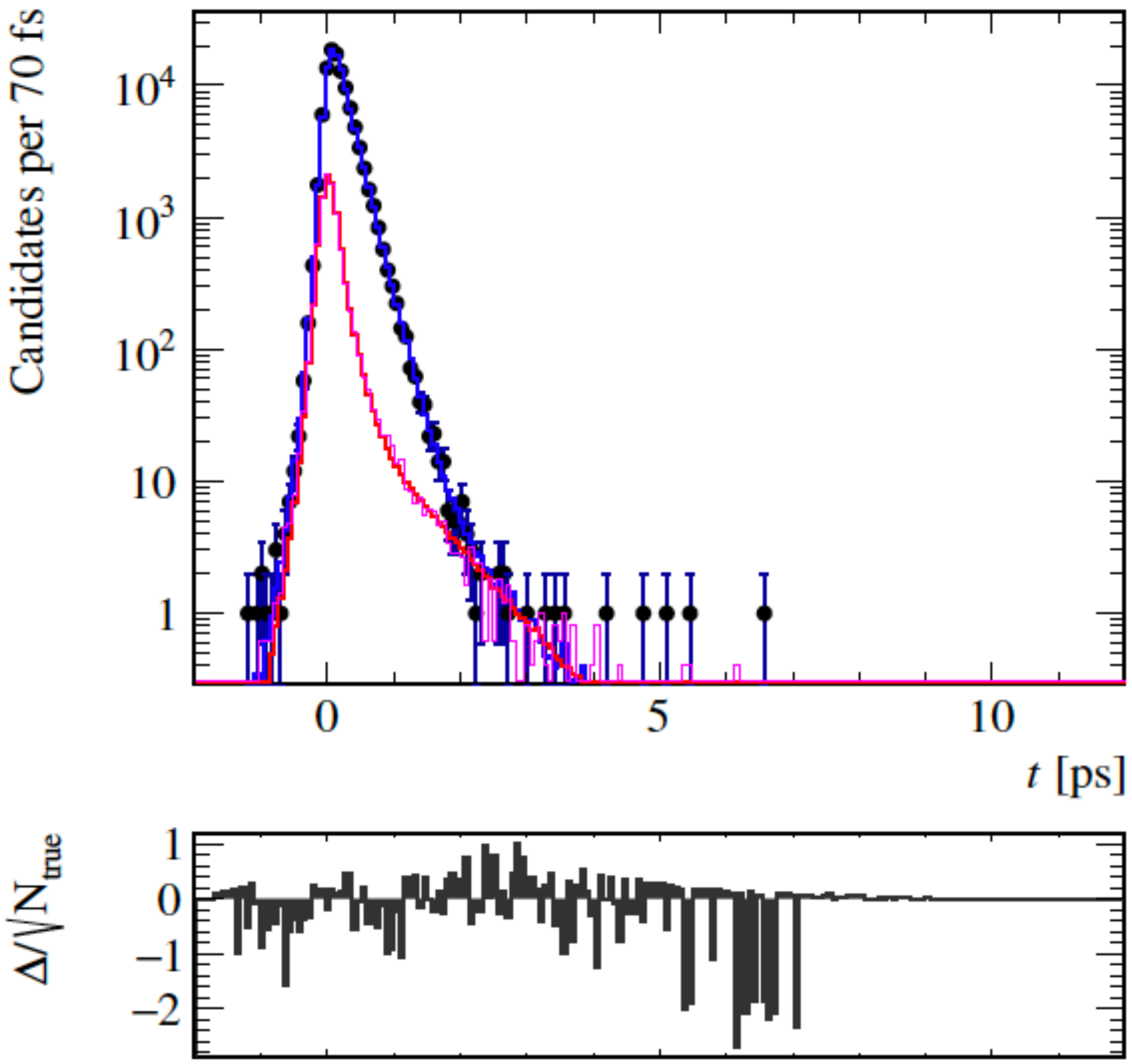
Generated value (taken from truth matched events in the signal region): **201.71 fs**

Lifetime fit results - comparison with truth-matched backgrounds



Single-Gaussian resolution function

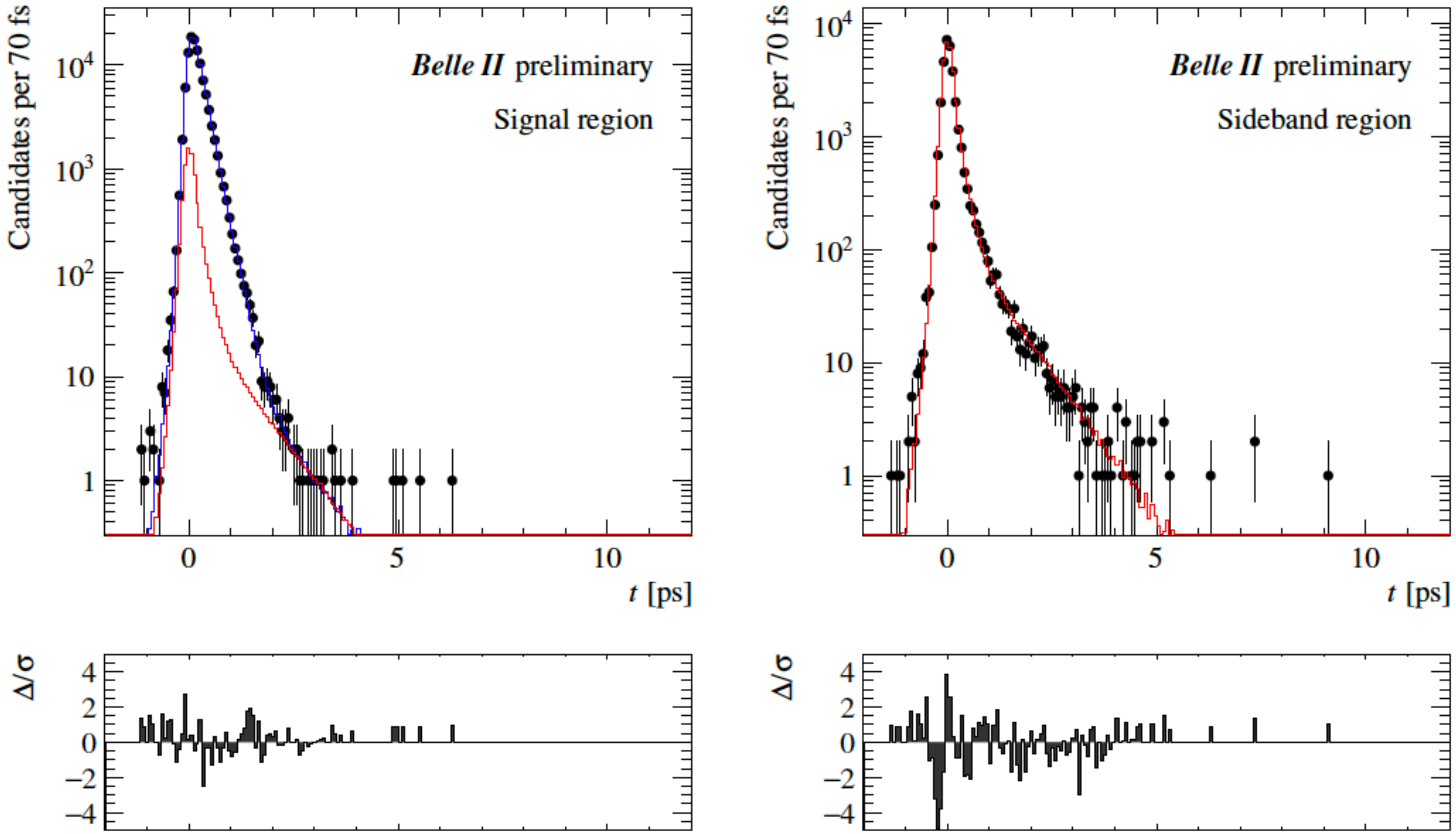
$\tau = 0.2020 \pm 0.0009$



Double-Gaussian resolution function

$\tau = 0.2024 \pm 0.0009$

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

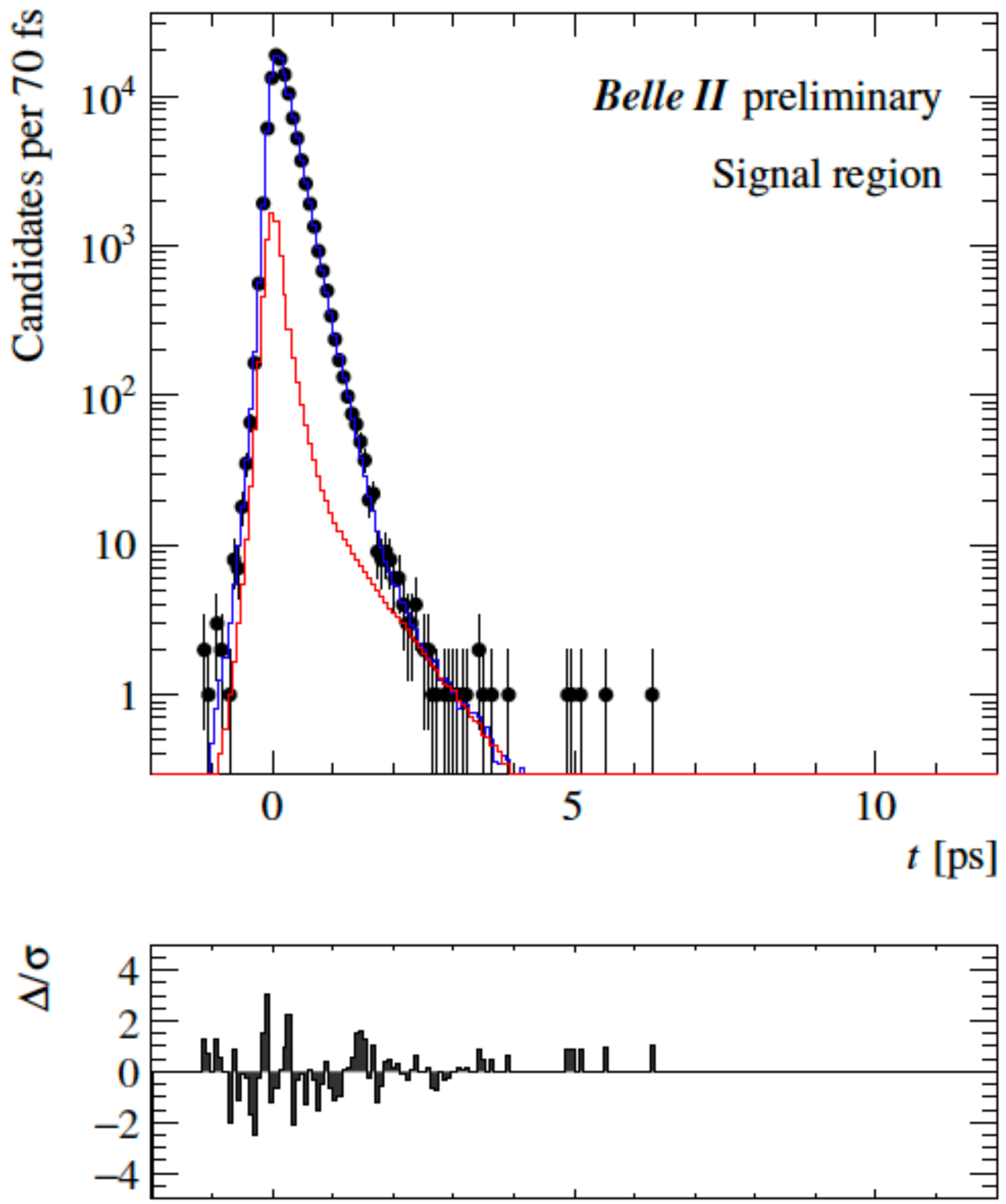


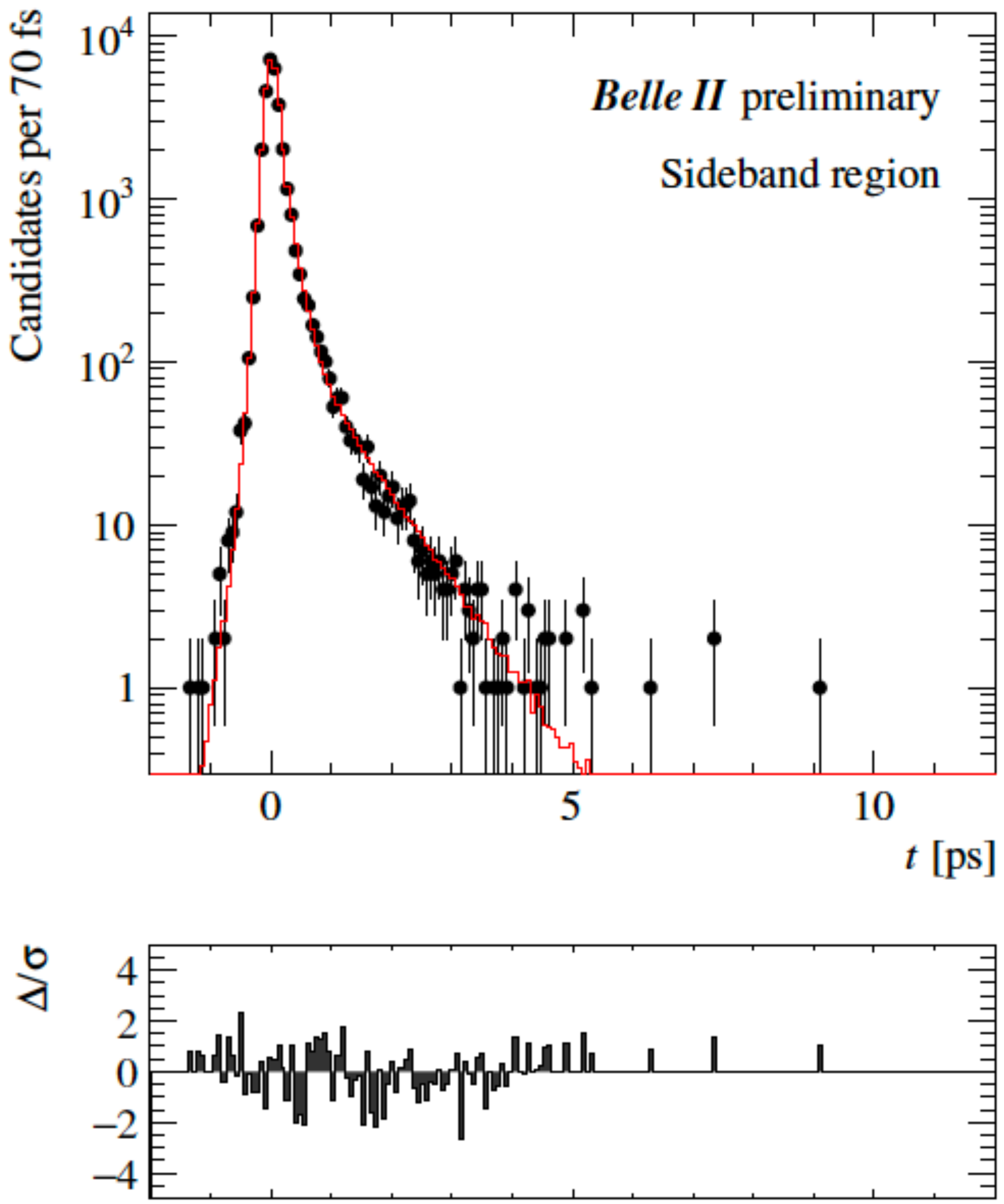
LHCB, $\tau = 203.5 \pm 1.0 \pm 1.3 \pm 1.4\ fs$

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

Parameter	Fit result w/single Gaussian
τ (fs) with arb. shift	209.8 ± 0.9
b (fs)	4.3 ± 0.6
s_1	1.102 ± 0.007
s_2	
f	
f_{bg}	0.0676 ± 0.0002
f_τ	0.292 ± 0.009
$f_{\tau 1}$	0.789 ± 0.014
τ_{bg1} (fs)	191 ± 9
τ_{bg2} (fs)	835 ± 32
s_{bg}	1.154 ± 0.009

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





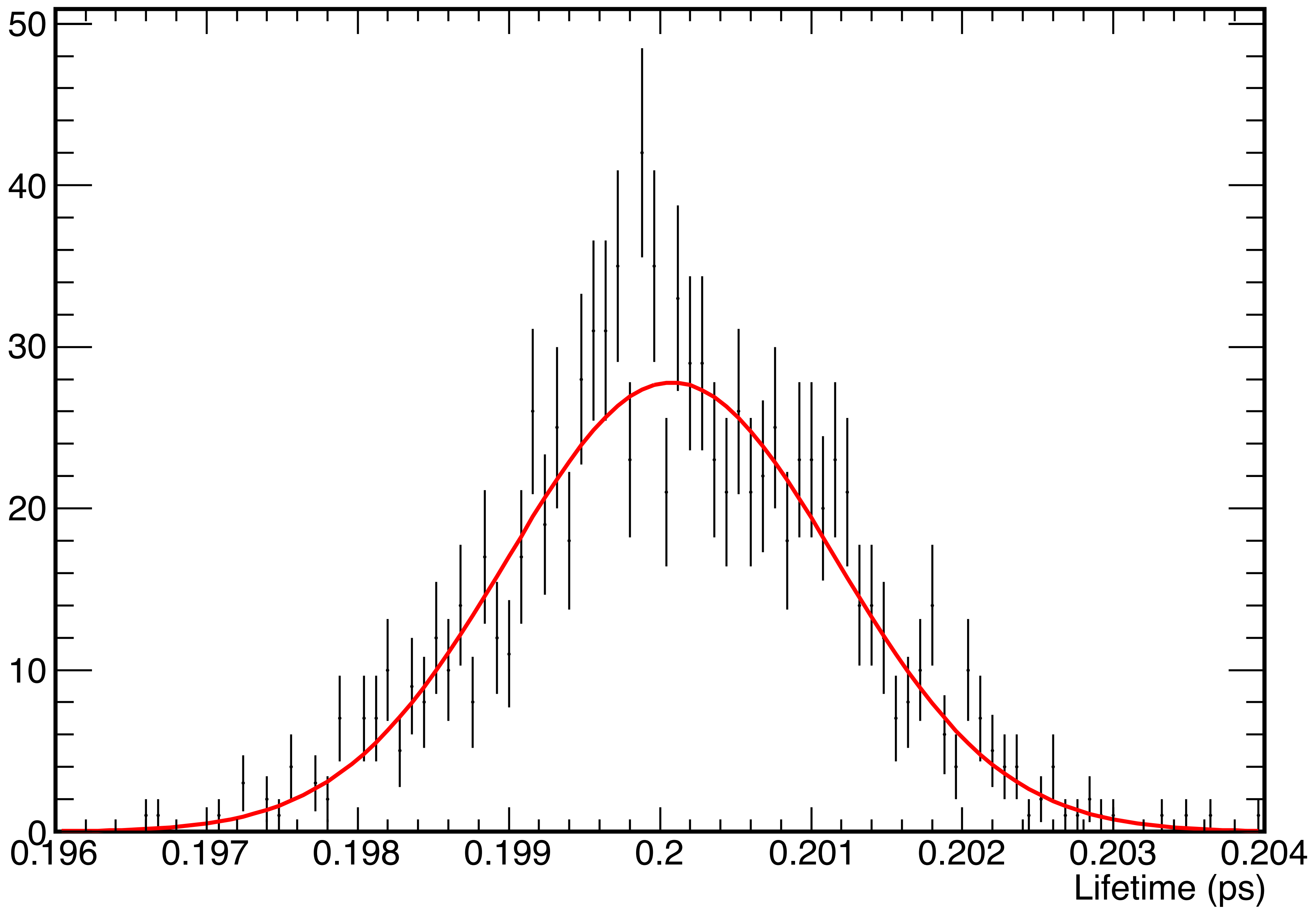
$LHCB$, $\tau = 203.5 \pm 1.0 \pm 1.3 \pm 1.4\ fs$

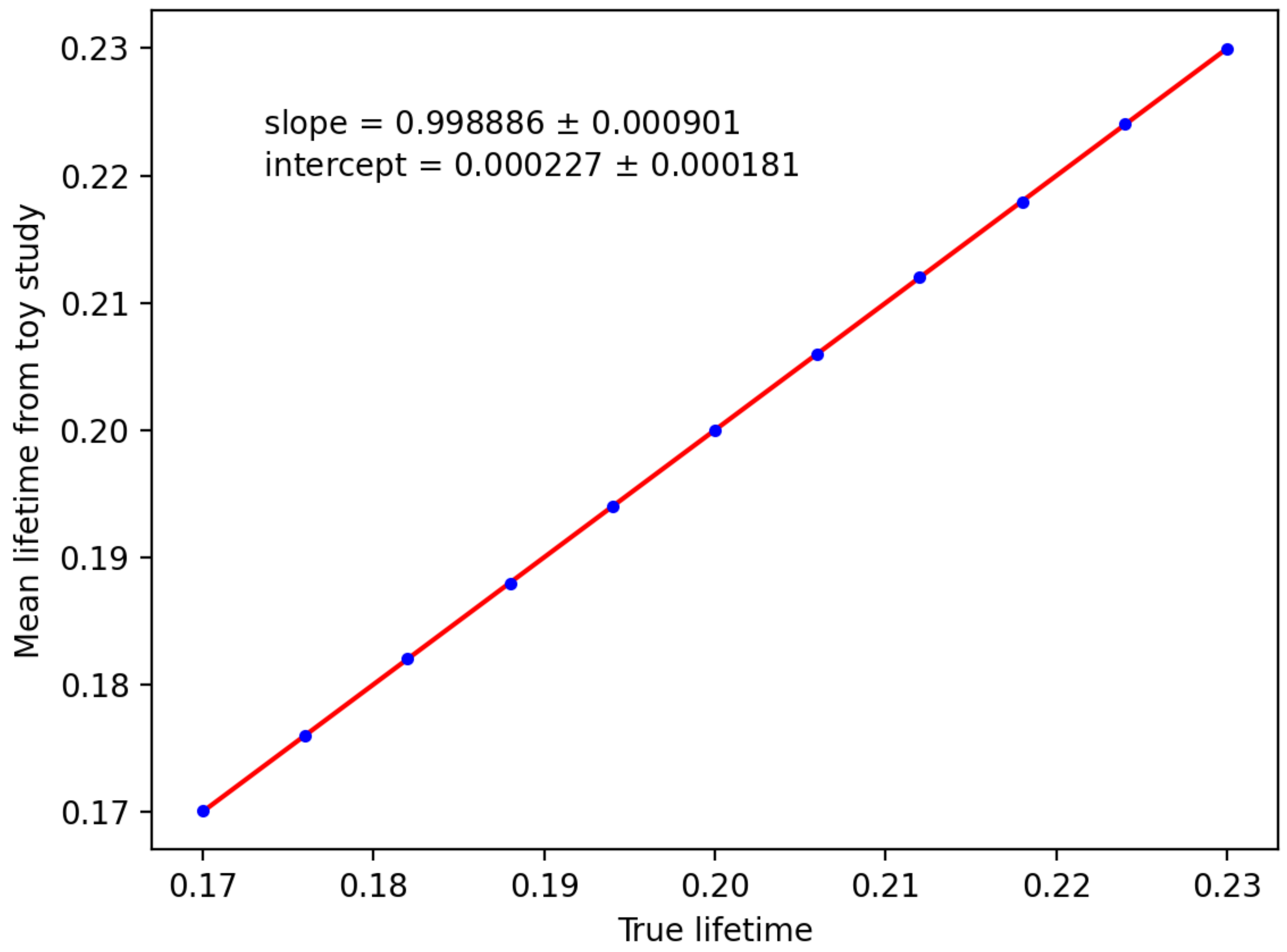
$CLEO$, $\tau = 179.6 \pm 6.9 \pm 4.4\ fs$

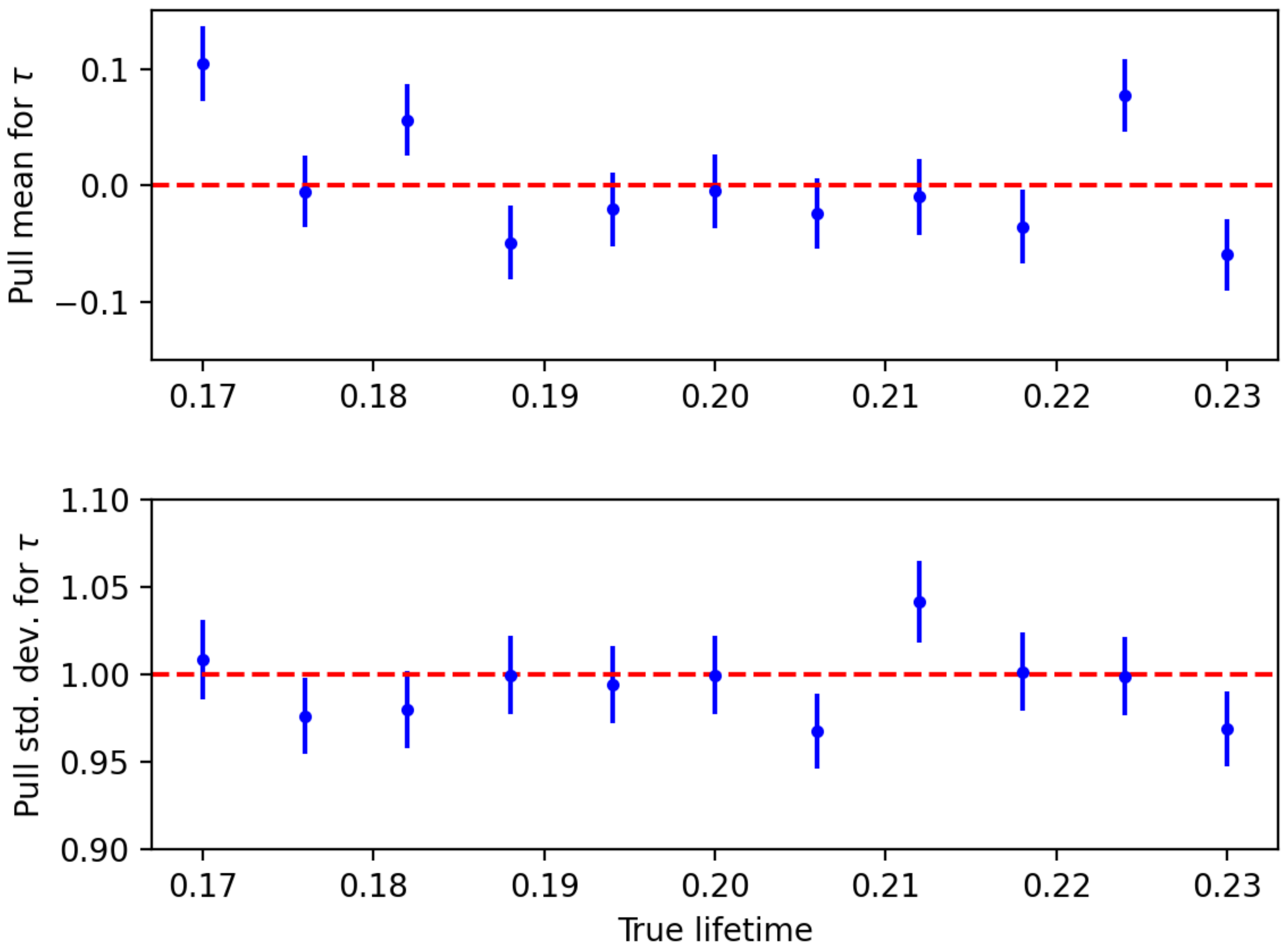
Parameter	Fit result w/double Gaussian
τ (fs) with arb. shift	210.3 ± 1.0
b (fs)	3.4 ± 0.7
s_1	1.066 ± 0.021
s_2	2.397 ± 0.441
f	0.972 ± 0.021
f_{bg}	0.0675 ± 0.0002
f_τ	0.321 ± 0.011
$f_{\tau 1}$	0.792 ± 0.012
τ_{bg1} (fs)	173 ± 7
τ_{bg2} (fs)	807 ± 28
s_{bg}	1.102 ± 0.010

Consistency checks

- Use 1/ab equivalent MC14ri 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







*To be finished

Systematics and cross-checks

- **Resolution model**
  - Generate pseudoexperiments by bootstrapping from truth-matched signal events from 1/ab equivalent from MC14ri_a. Take the sum of the absolute difference and uncertainty with the true lifetime of the parent sample as the systematic uncertainty due to the resolution model.
  - 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) off-set mass window (6) treatment of multiple-candidate events

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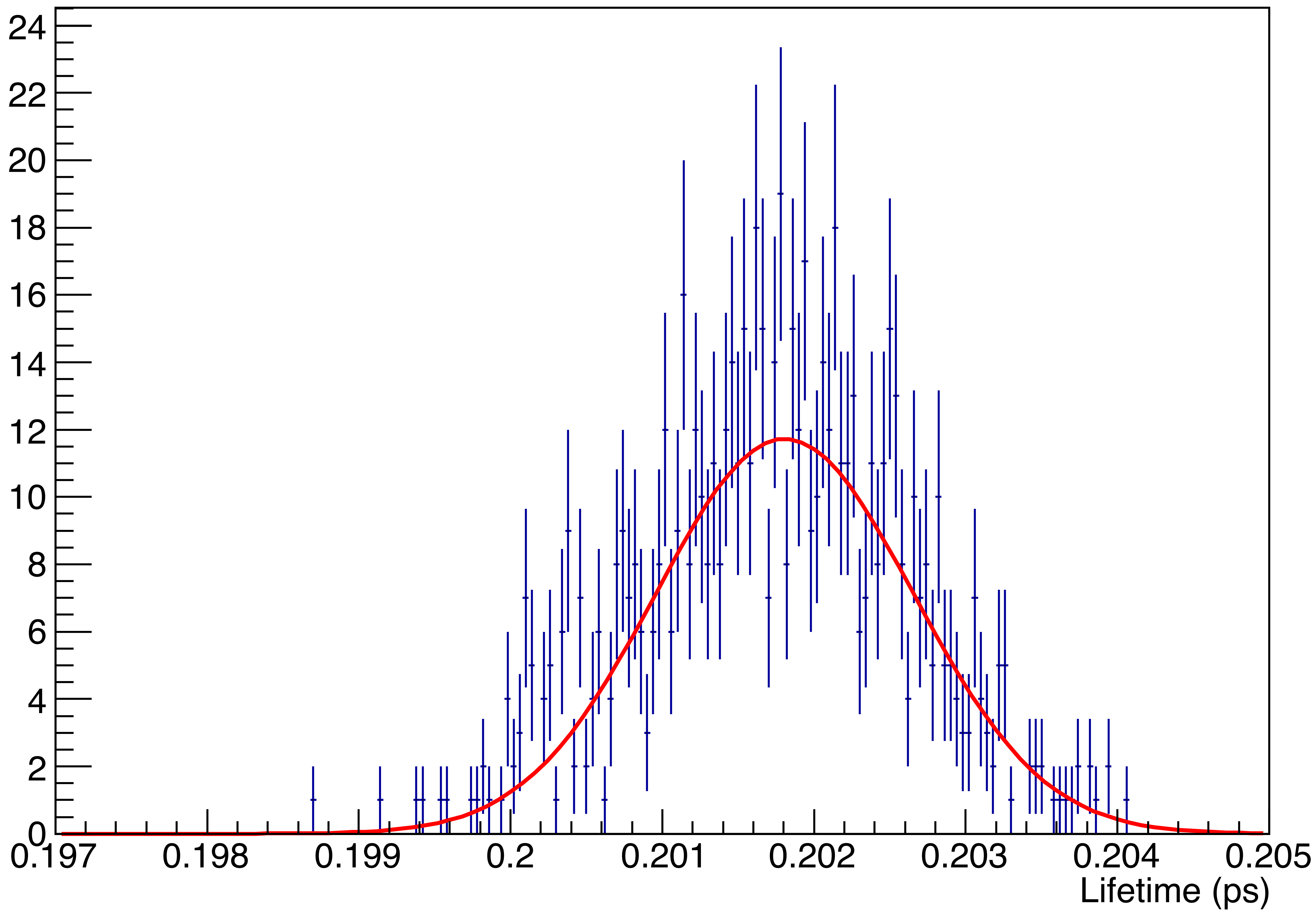
- **Imperfect detector alignment**: Generate dedicated MC with residual misalignment, imperfections in beam-spot parameters
- **Momentum scale correction**: Vary the momentum scale correction between suggested values
- **Input charm masses**: Check the relative uncertainty of the world-averaged values 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) off-set mass window (6) treatment of multiple-candidate events

Resolution model

- Generate pseudoexperiments by bootstrapping from truth-matched signal events in 1/ab equivalent from MC14ri_a
  - Generated lifetime: $201.78\ fs$
  - Fit results: $201.81 \pm 0.04\ fs$
  - **Difference:** $0.03 \pm 0.04\ fs$
    - Take this as systematic uncertainty



- Cross check with double Gaussian resolution
  - Single Gaussian: $\tau = 209.846 \pm 0.892\ fs$
  - Double Gaussian: $\tau = 210.303 \pm 0.954\ fs$
  - Difference: $0.454 \pm 1.306\ fs$

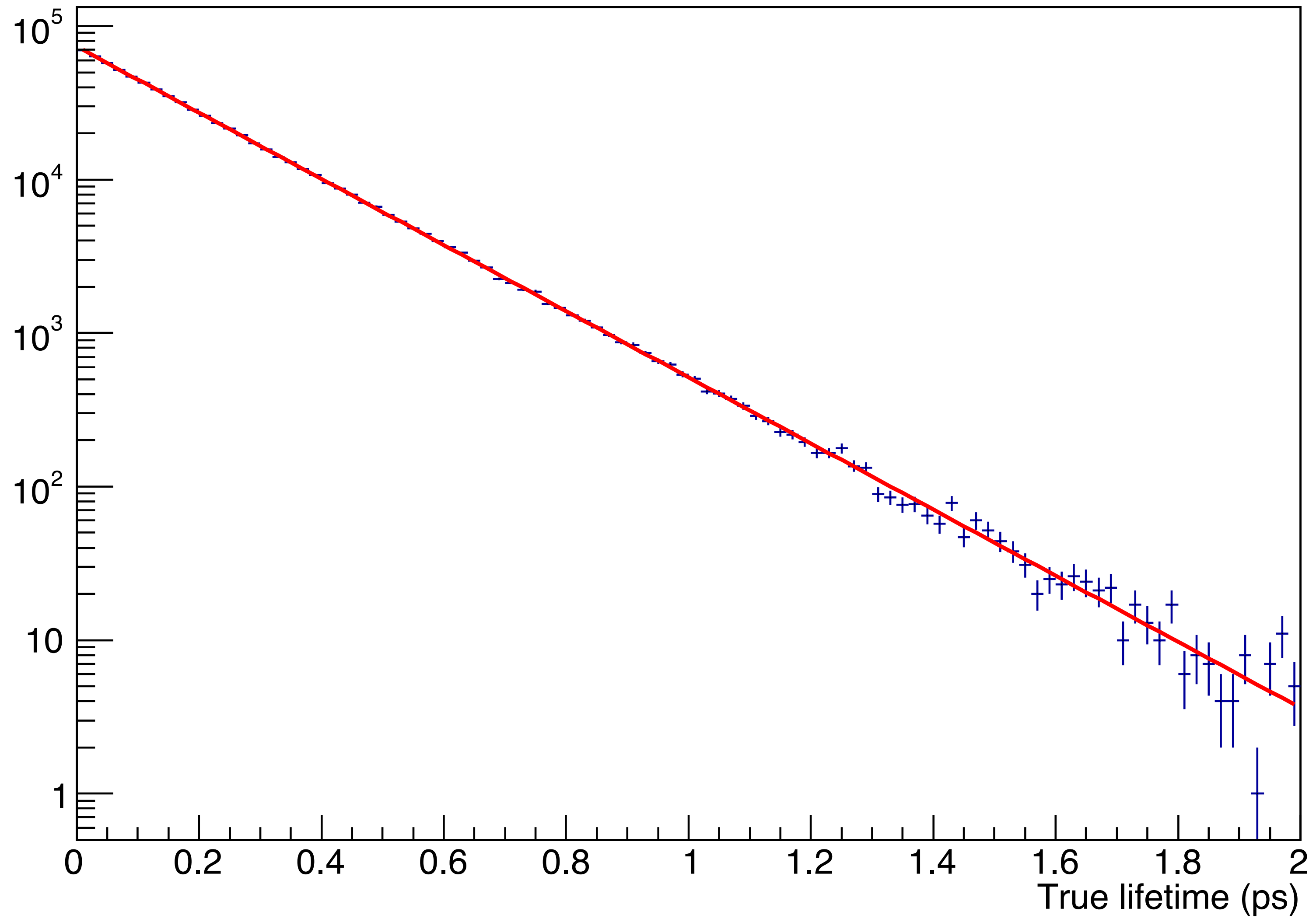
- To do: Vary σ_t bin sizes to avoid zero bins and check the difference in the fitted lifetime

Systematics and cross-checks

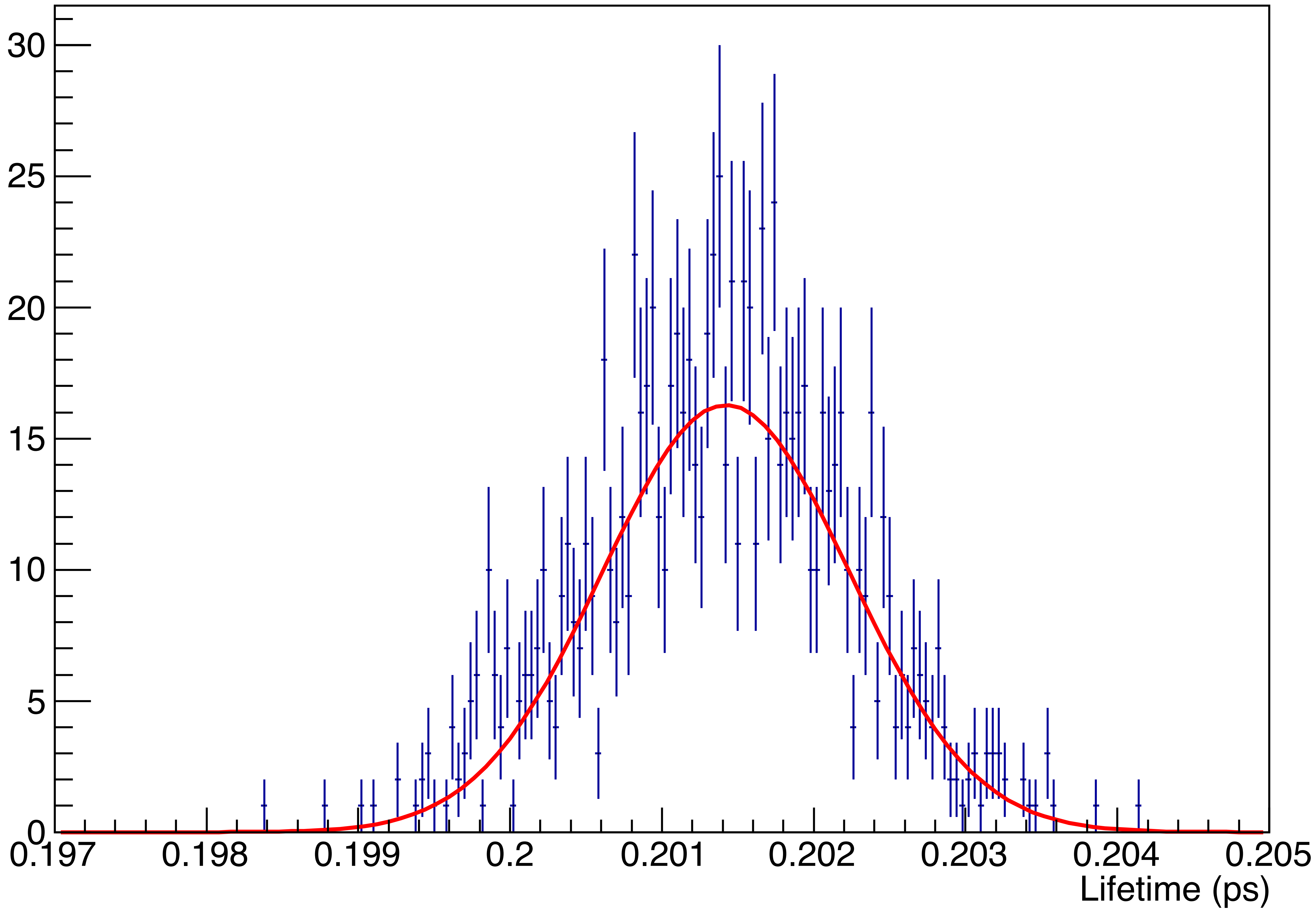
- **Resolution model**
  - Generate pseudoexperiments by bootstrapping from truth-matched signal events from 1/ab equivalent from MC14ri_a. Take the sum of the absolute difference and uncertainty with the true lifetime of the parent sample as the systematic uncertainty due to the resolution model.
  - 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) off-set mass window (6) treatment of multiple-candidate events

Backgrounds

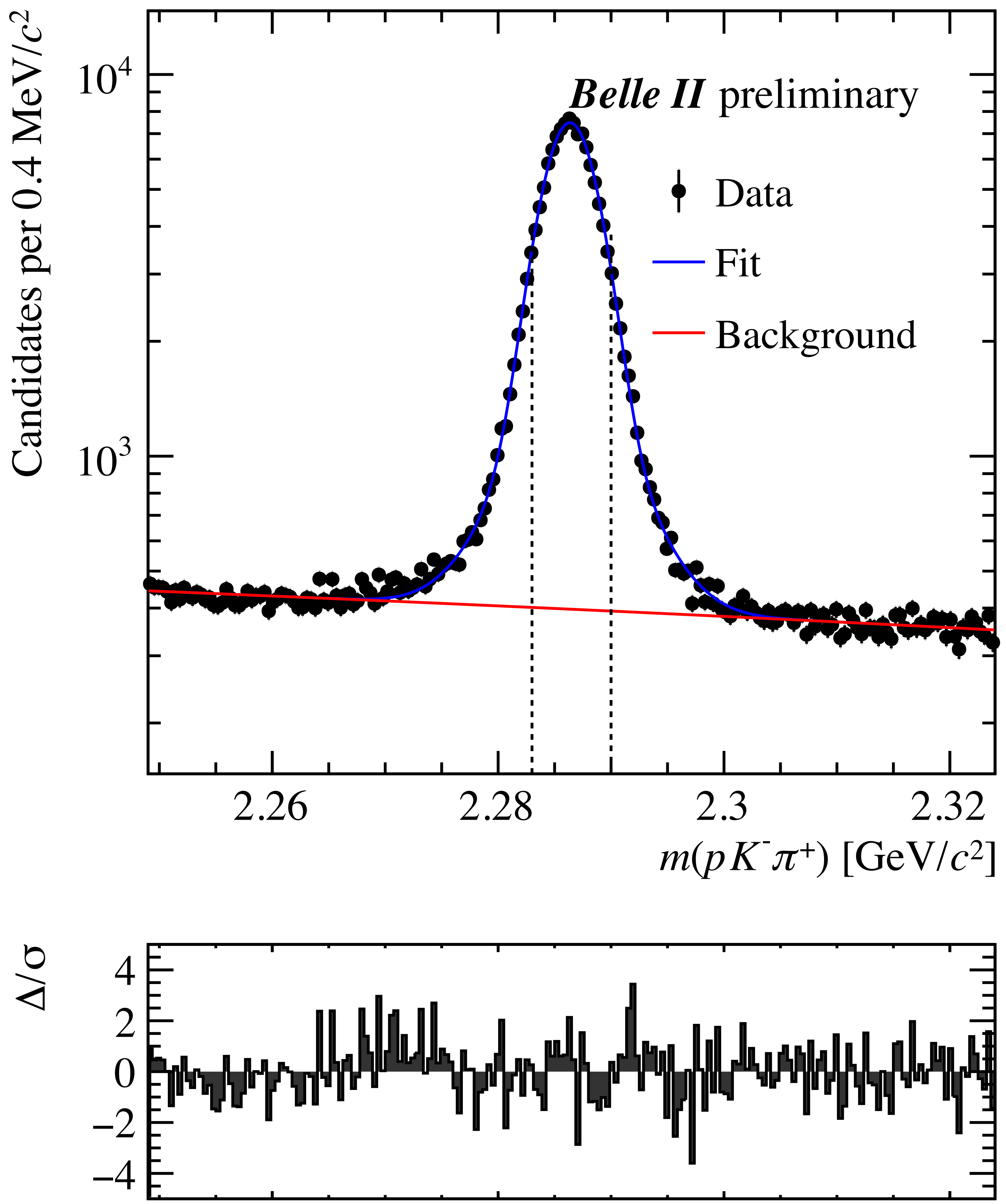
- Generate pseudoexperiments by bootstrapping events from 1/ab equivalent from MC14ri_a for the signal region and the data sideband events for the sideband region.



- Generated lifetime: $201.71\ fs$
- Fit results: $201.42 \pm 0.03\ fs$
- **Difference:** $0.29 \pm 0.03\ fs$
  - Take this as systematic uncertainty

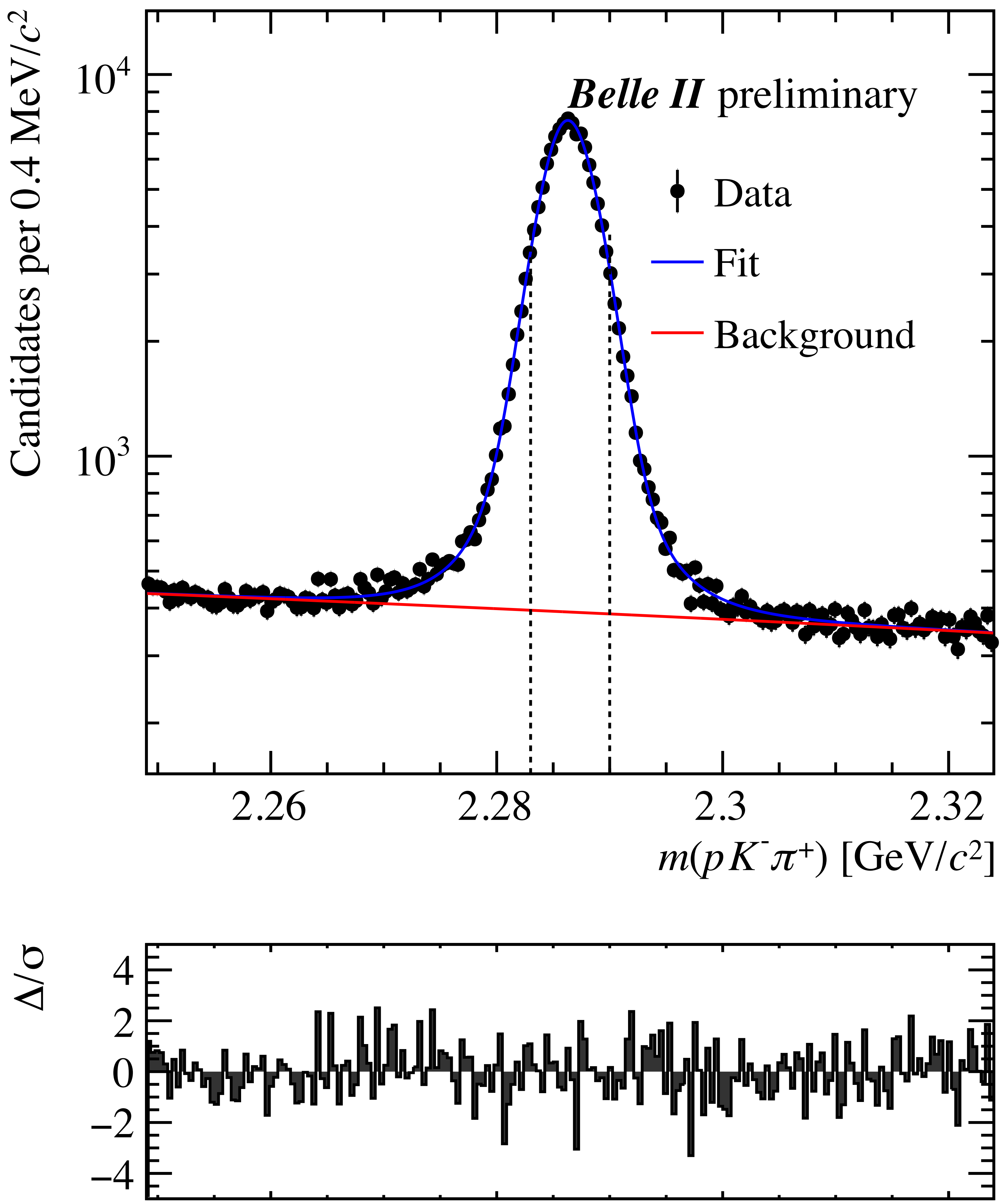


Backgrounds: change signal pdf in mass fit



Signal: Double Gaussian

Background:
0.068586 +- 0.000132

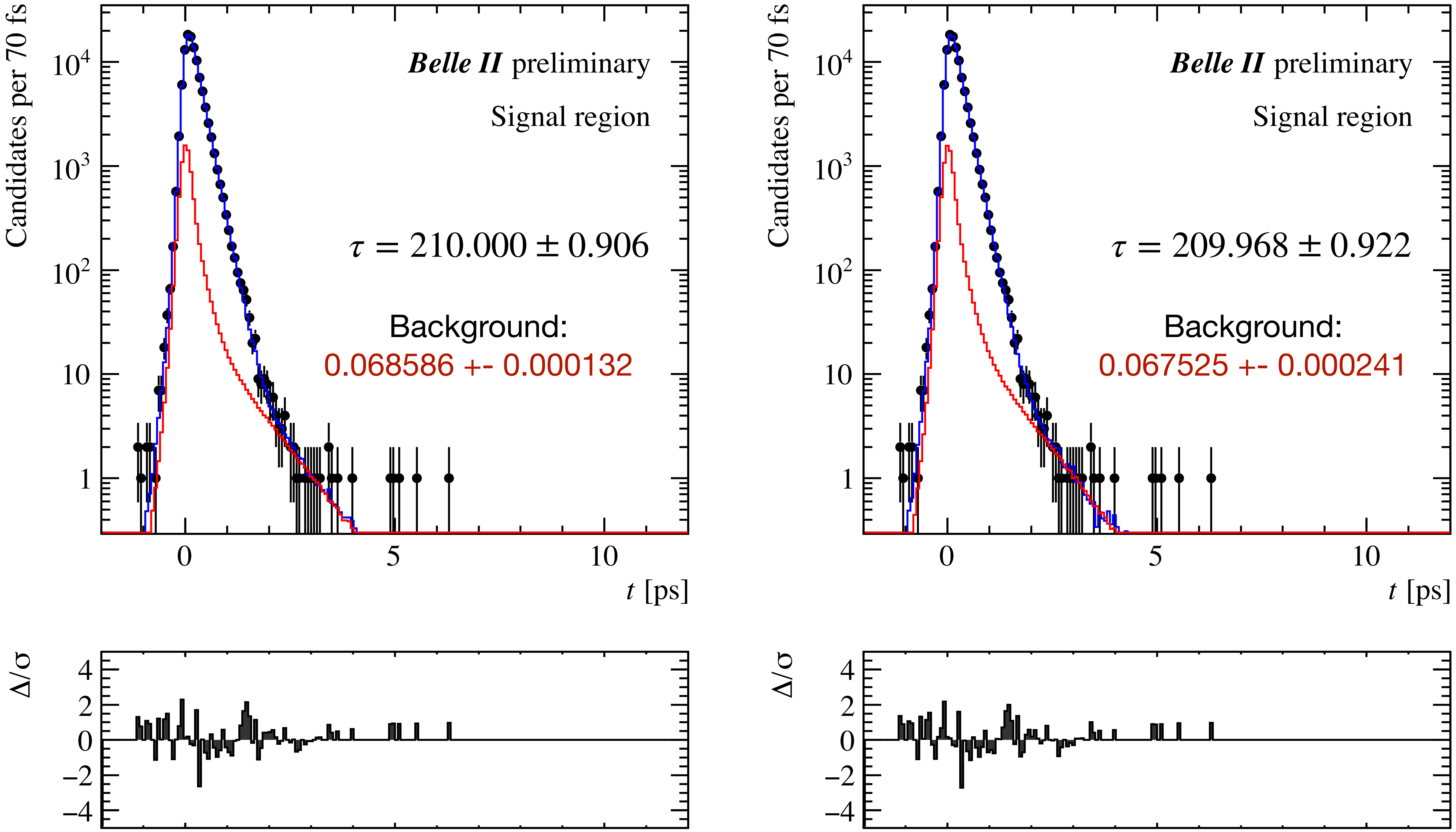


Signal: Gaussian + Johnson function
(transformation of normal distribution)

Background:
0.067525 +- 0.000241

Backgrounds

- Change the signal model in the invariant mass fit and adjust the Gaussian constraint on the background in the lifetime fit
  - Signal model in invariant mass fit: double Gaussian (left) vs. Johnson+Gaussian (right)



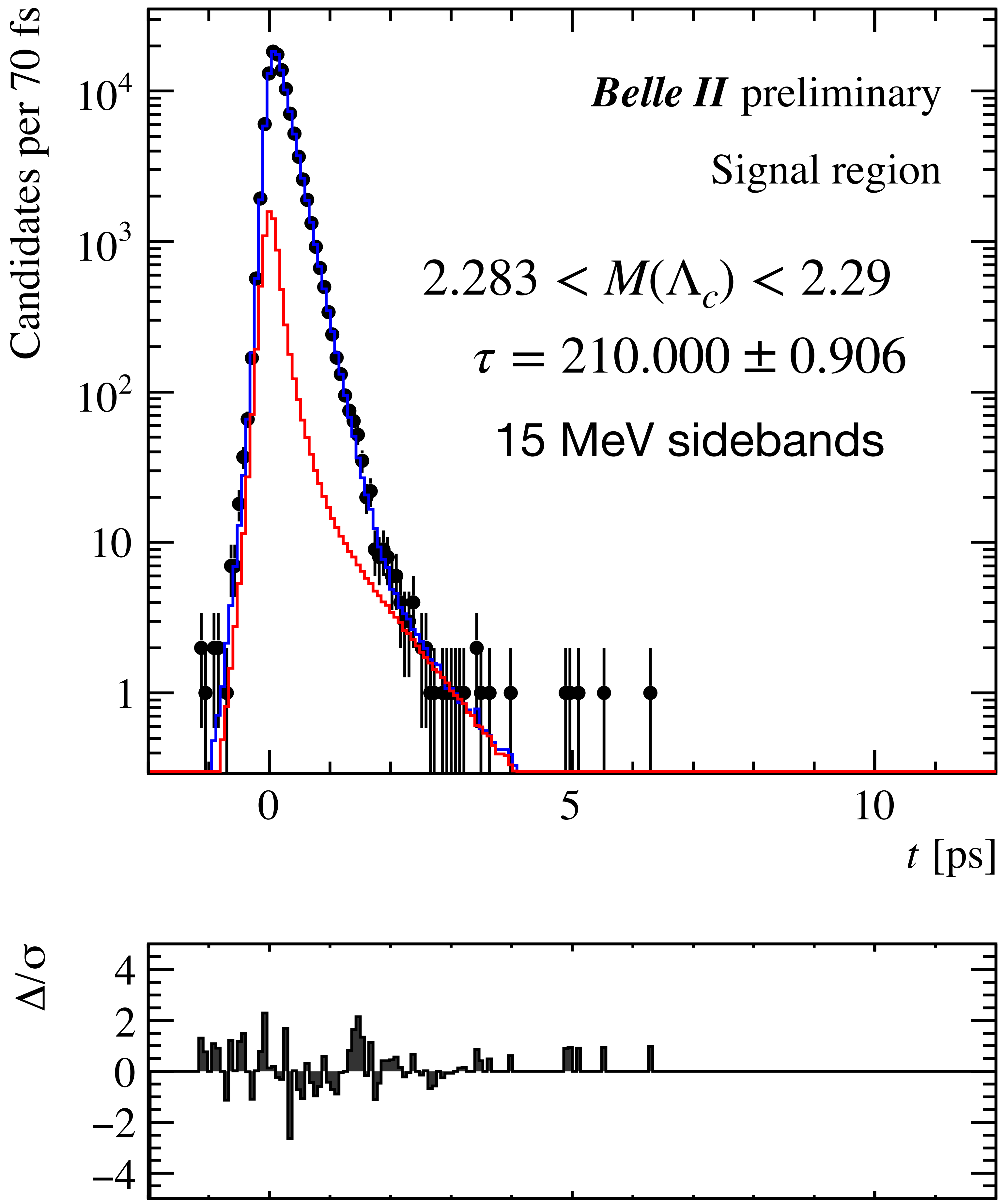
- Difference in lifetime: 0.032 fs
- Difference in quadrature of uncertainties: 0.171 fs

- Within the assigned systematic uncertainty due to backgrounds

Backgrounds - cross check

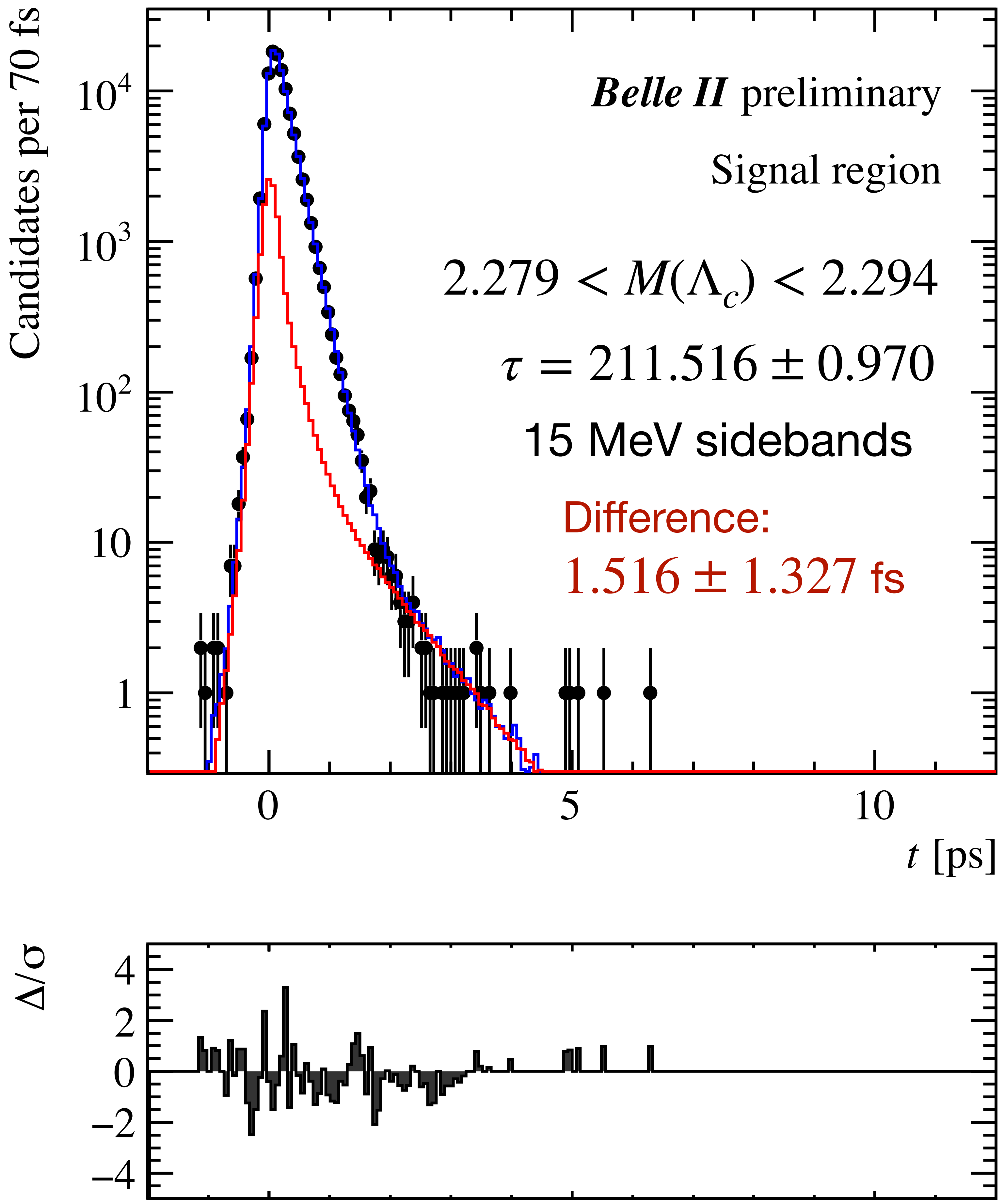
- Repeat mass fit with different signal and sideband ranges, adjust Gaussian constraint on the background in the lifetime fit

Nominal fit



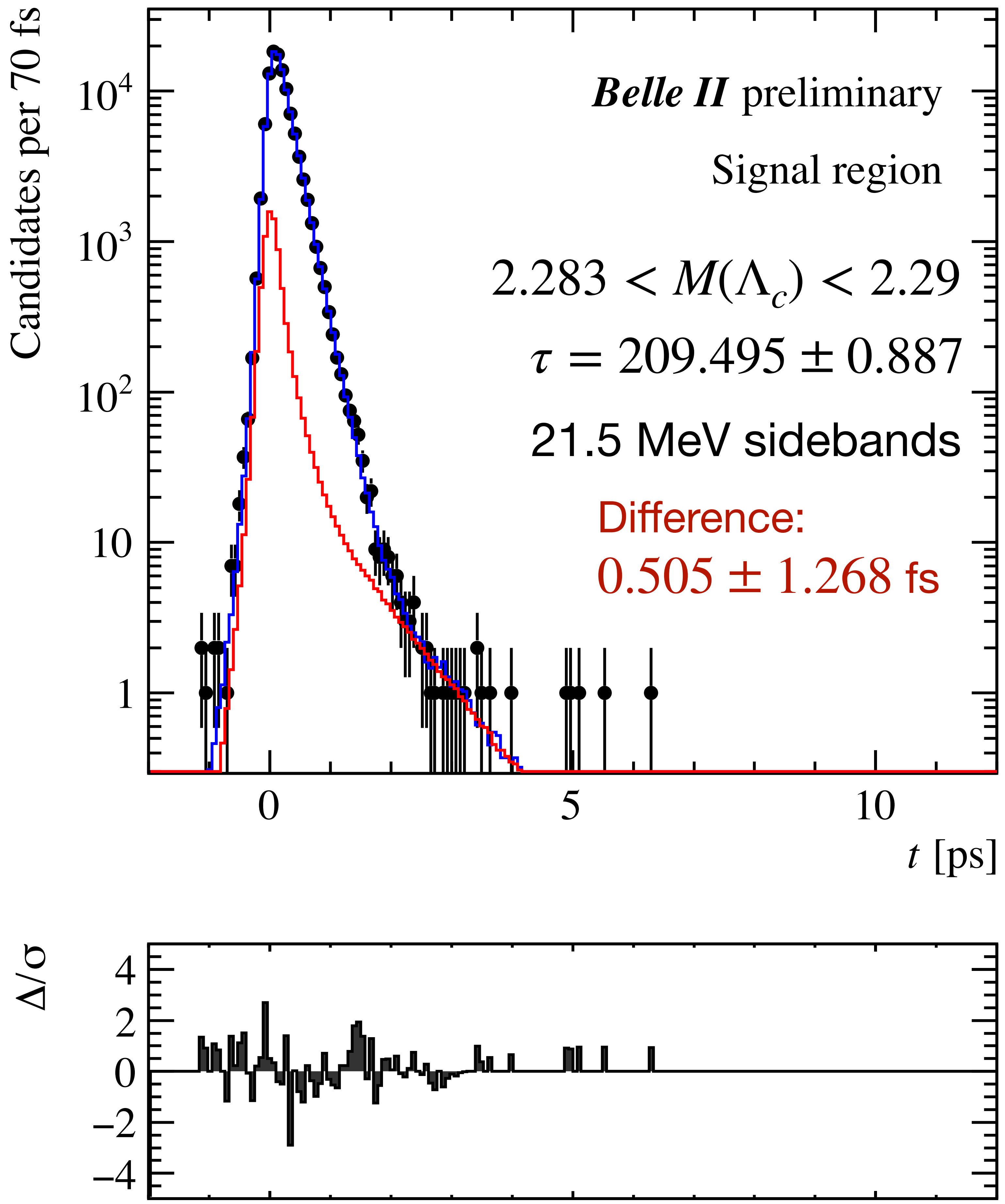
Background fraction in signal region: 6.86%

Wide signal region



Background fraction in signal region: 11.2%

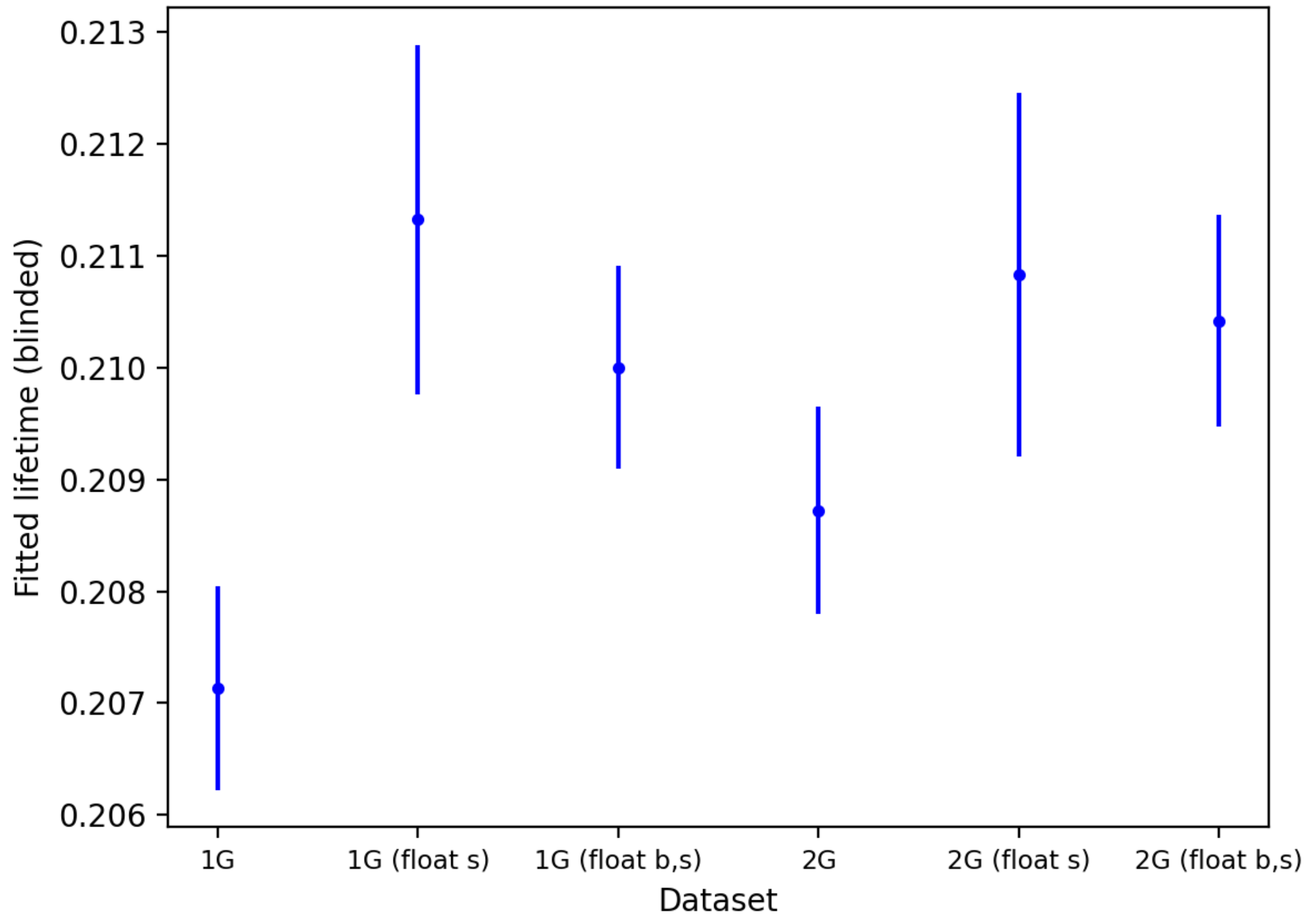
Wider sidebands

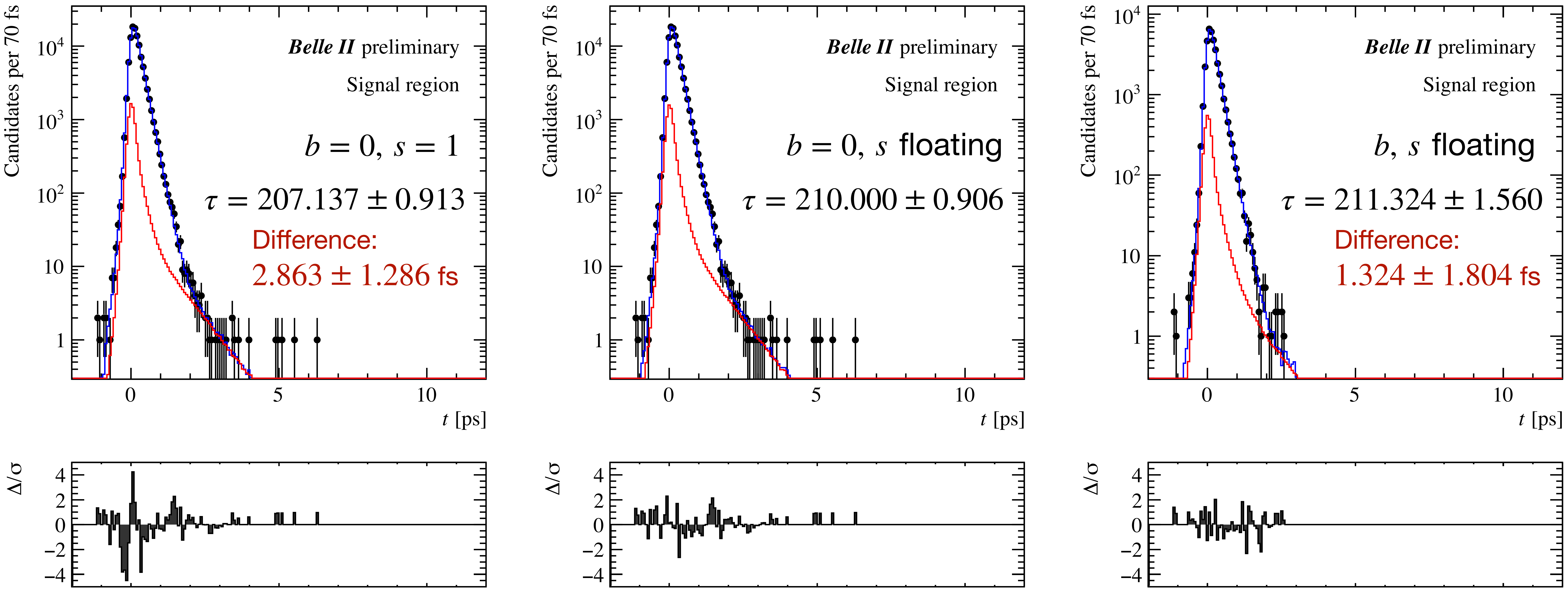


Background fraction in signal region: 6.86%

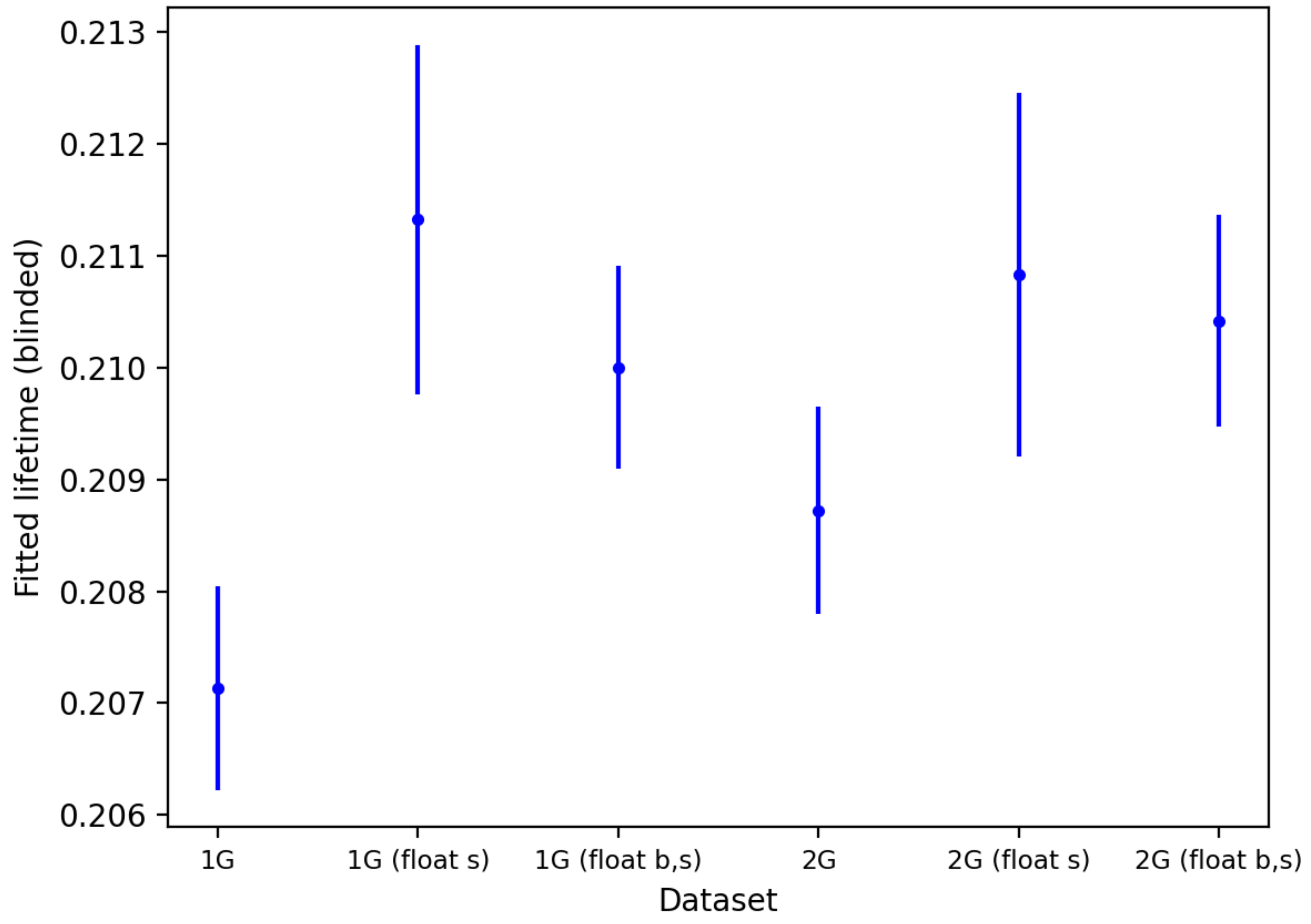
Backgrounds

- Check the effect of fixing or floating background mean and width scale factors
  - Poor fit without floating width scale factor
  - Difference ~1.3, 0.9 fs for fixed/floating mean scale factor

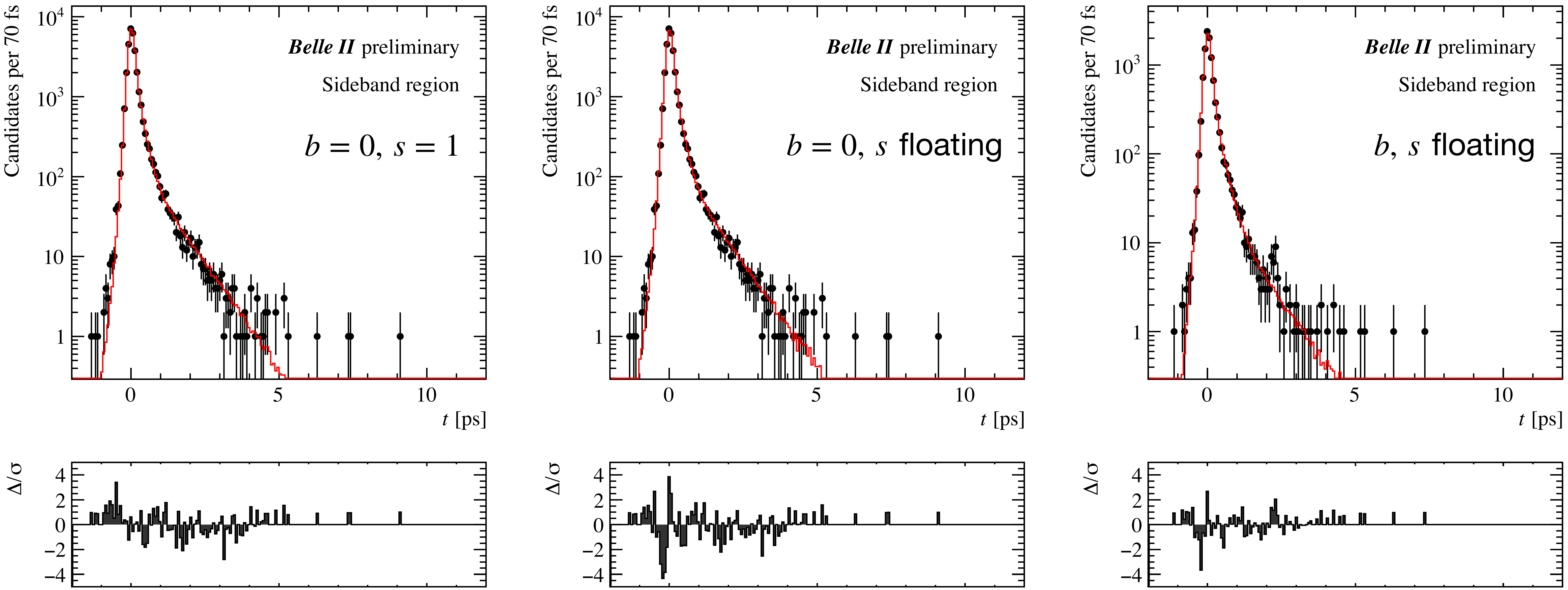




Backgrounds

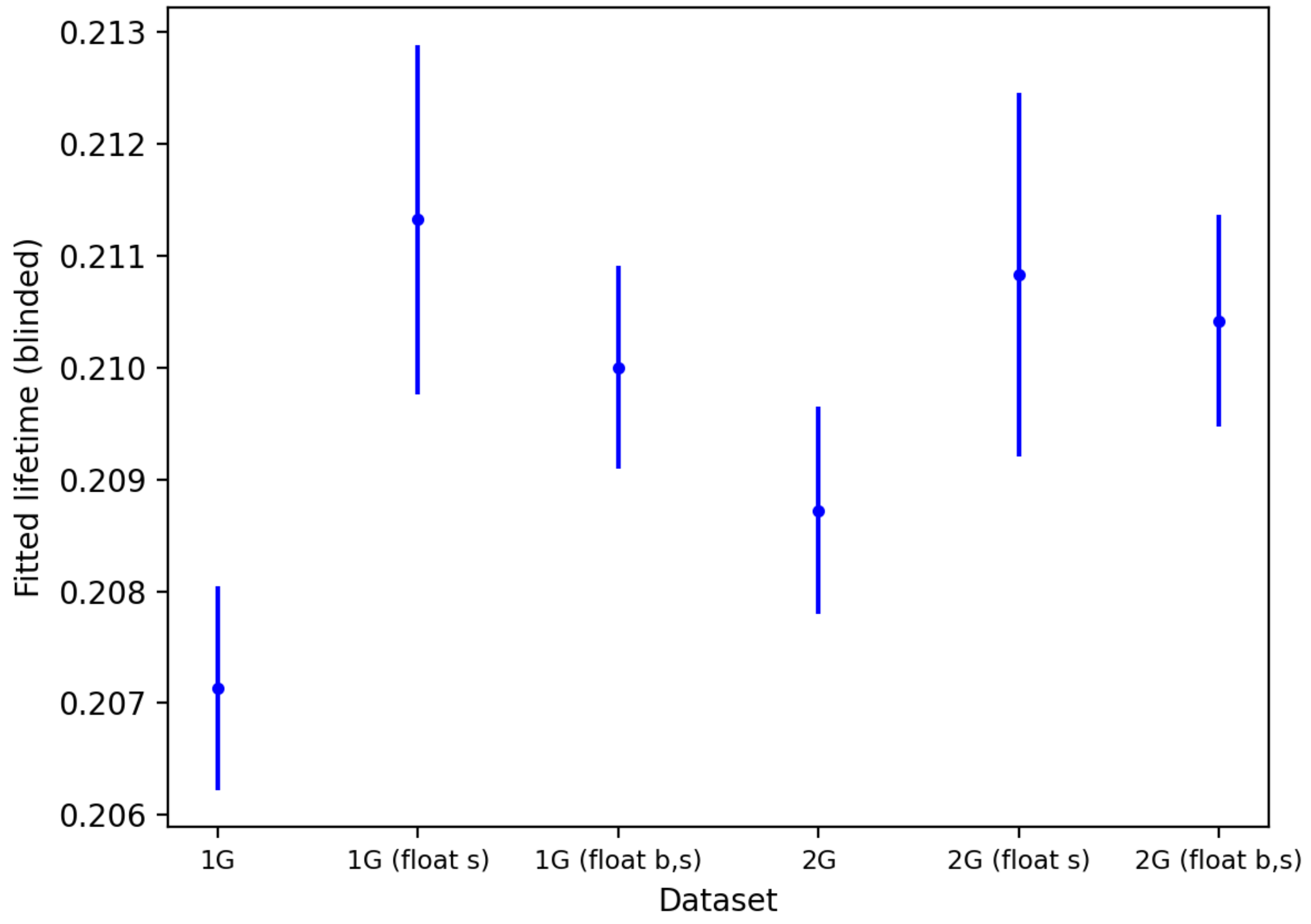


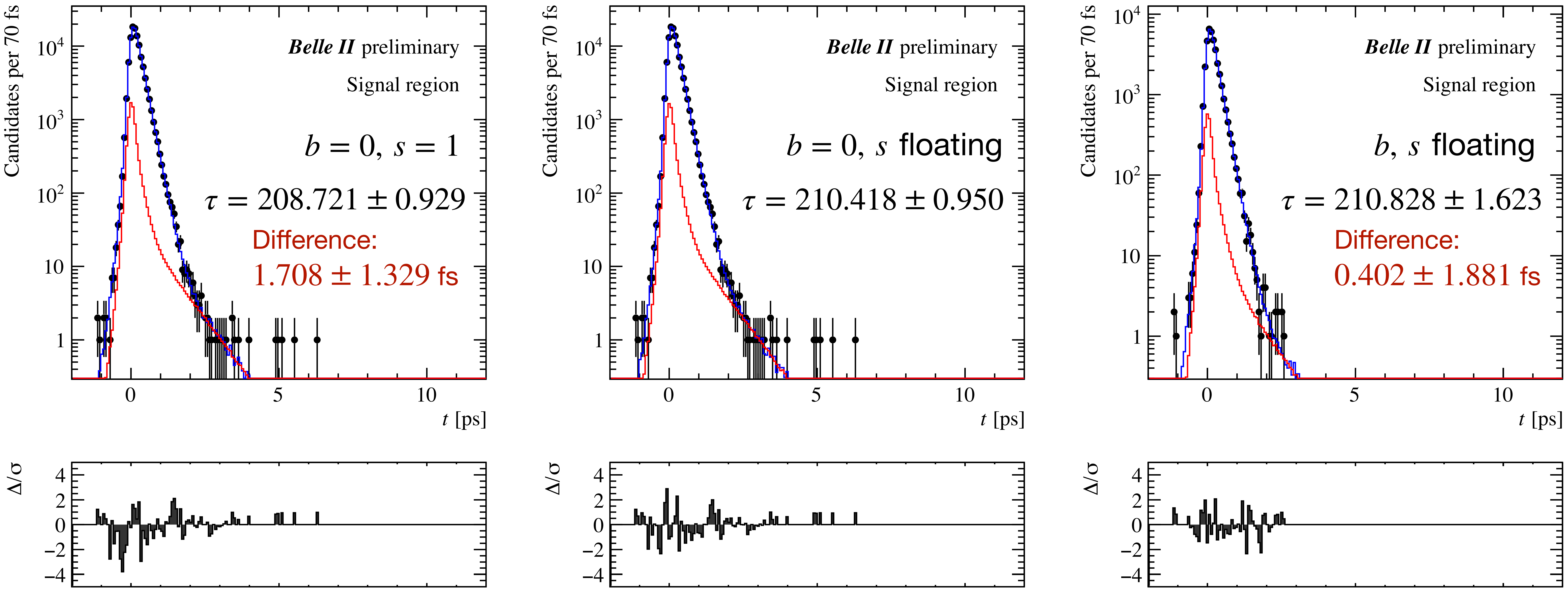
- Check the effect of fixing or floating background mean and width scale factors
  - Poor fit without floating width scale factor
  - Difference ~1.3, 0.9 fs for fixed/floating mean scale factor



Backgrounds

- Check the effect of fixing or floating background mean and width scale factors
  - Poor fit without floating width scale factor
  - Difference ~1.3, 0.9 fs for fixed/floating mean scale factor





Backgrounds

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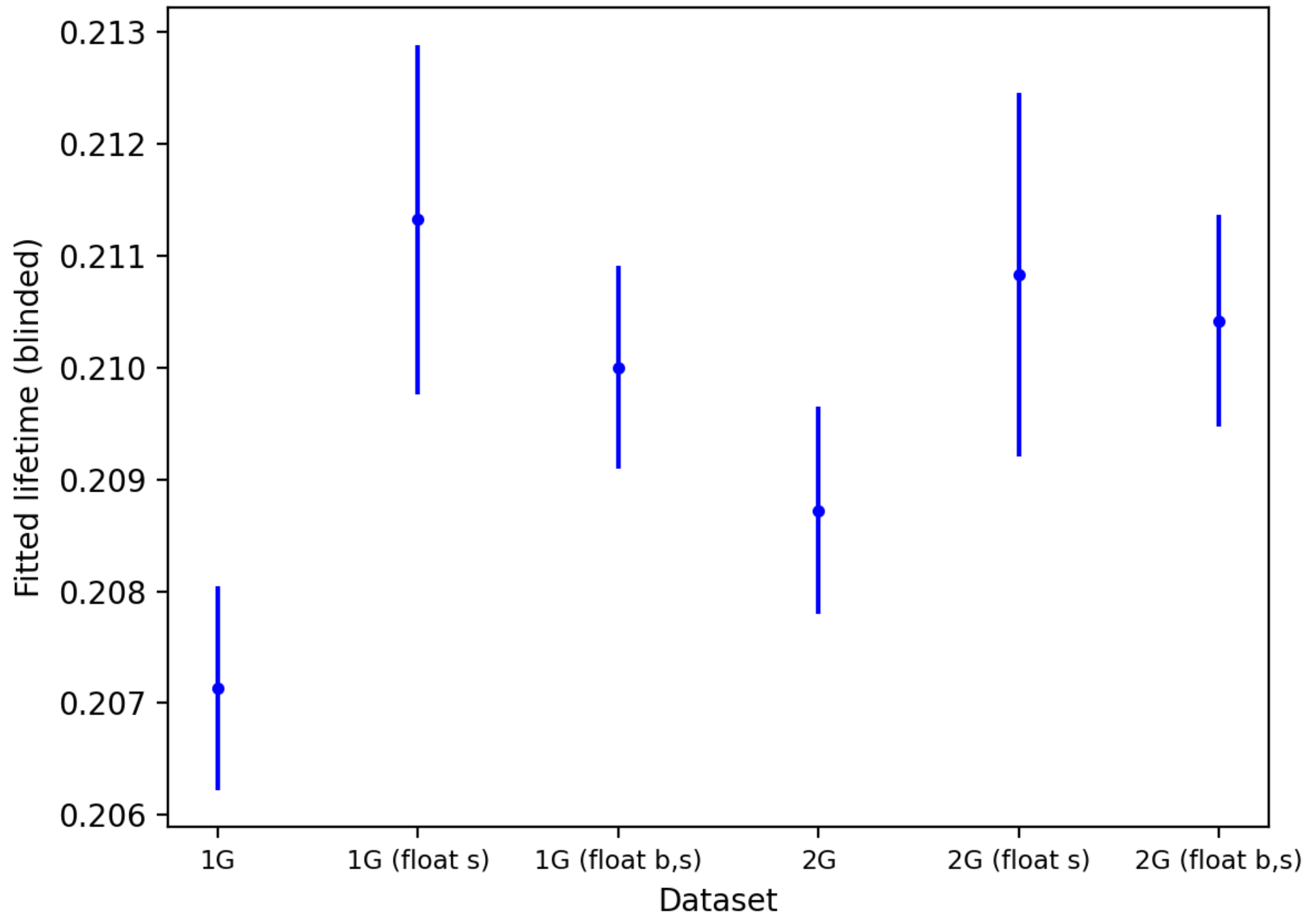
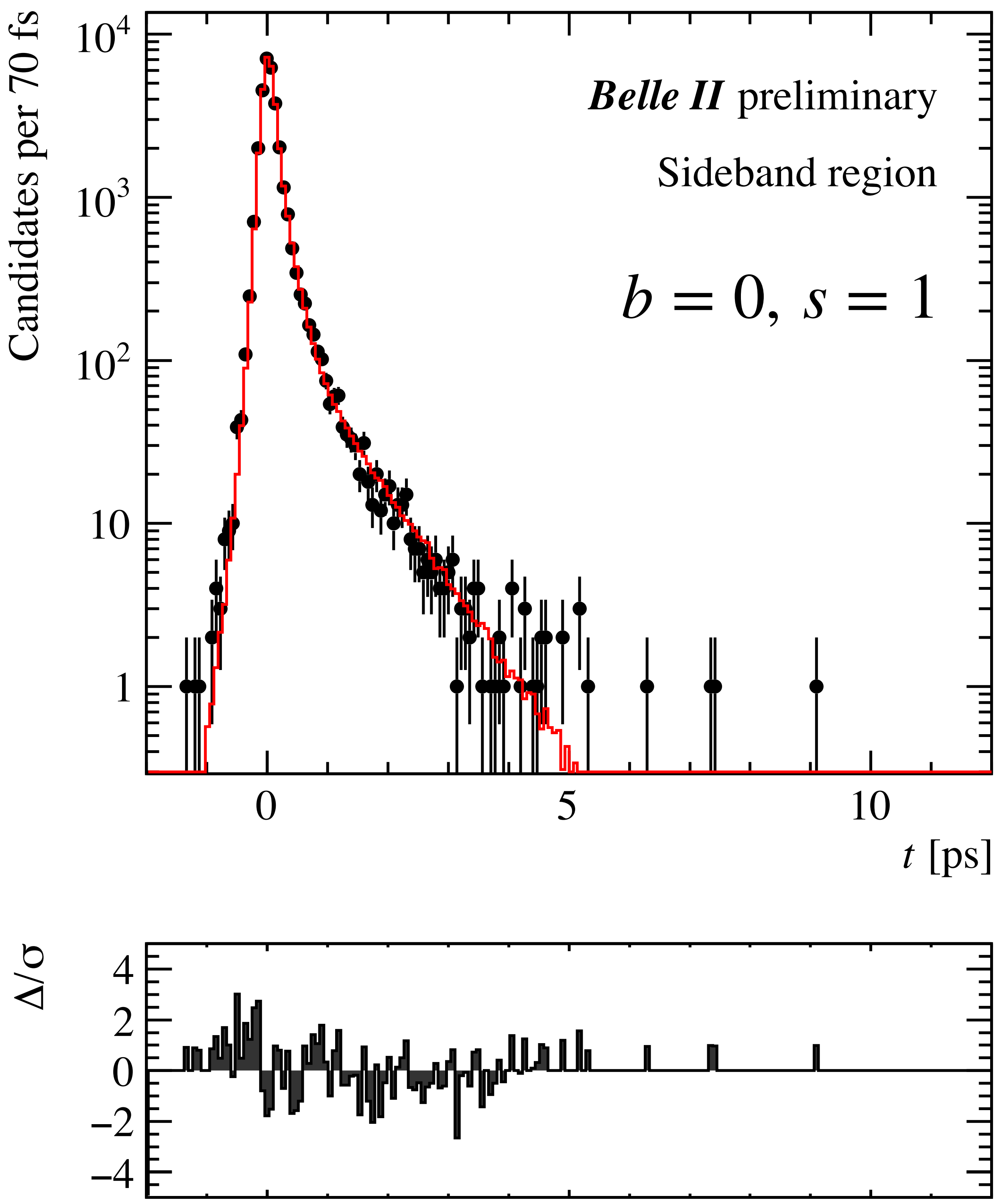
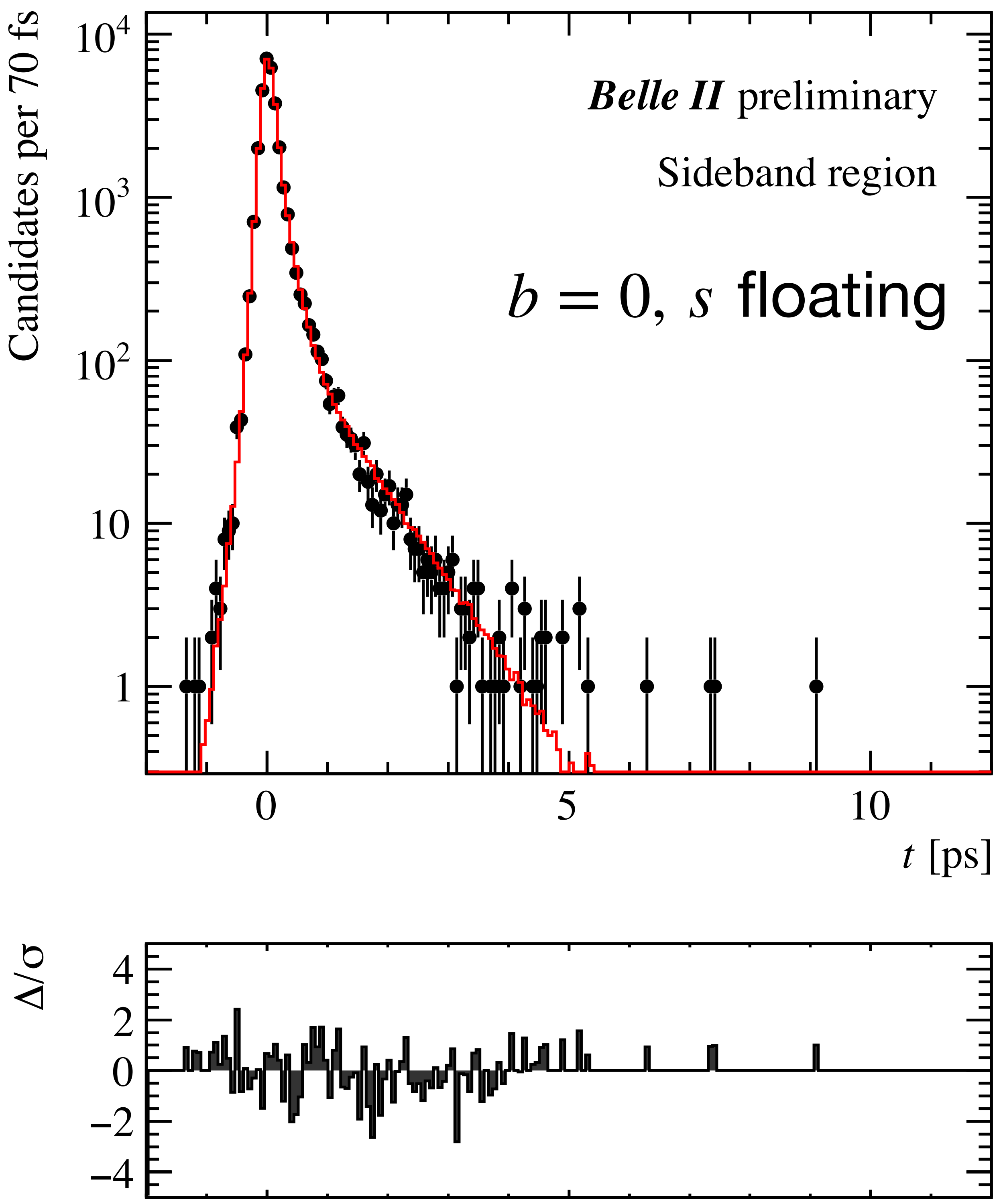
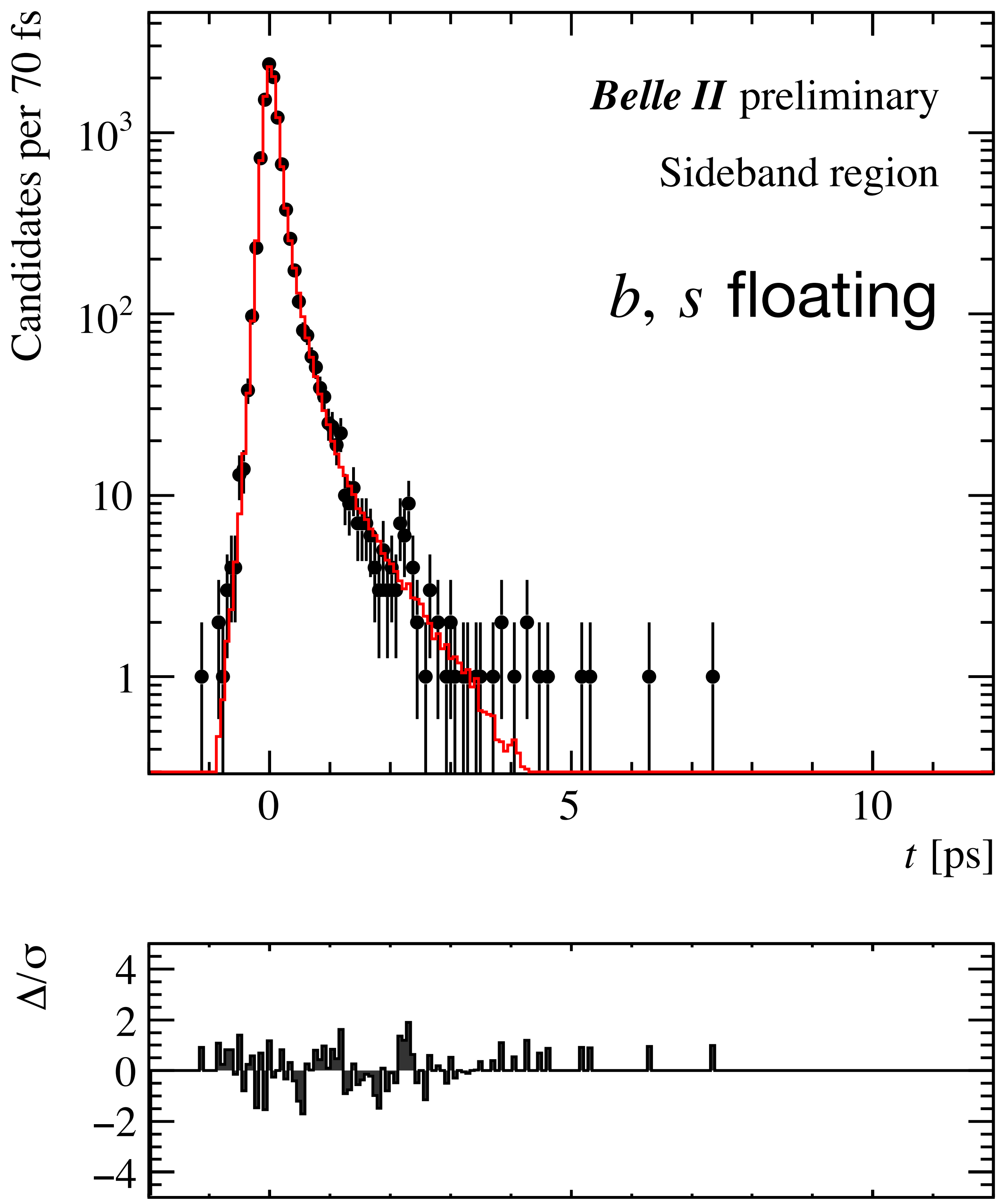
  - Poor fit without floating width scale factor
  - Difference ~1.3, 0.9 fs for fixed/floating mean scale factor









Systematics and cross-checks

- **Resolution model**
  - Generate pseudoexperiments by bootstrapping from truth-matched signal events from 1/ab equivalent from MC14ri_a. Take the sum of the absolute difference and uncertainty with the true lifetime of the parent sample as the systematic uncertainty due to the resolution model.
  - Cross check with double-Gaussian resolution model.
  - Vary σ_t bin sizes to avoid zero bins and check the difference in the fitted lifetime.
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  - 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) off-set mass window (6) treatment of multiple-candidate events

Detector alignment

- 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

Detector alignment

- 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

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

Table 5: Results of lifetime fits to signal MC samples produced with different alignment configurations.

Configuration	Fit result	True lifetime	$\delta\tau$	$\Delta\tau$
Nominal	203.075 ± 0.773	202.147	0.928	
a	203.435 ± 0.769	202.726	0.709	-0.219
b	203.400 ± 0.768	203.006	0.394	-0.534
c	202.865 ± 0.515	203.059	-0.194	-1.122
d	203.815 ± 0.760	202.438	1.377	0.449

- Systematic uncertainty, sum in quadrature of weak mode (b) and day-to-day misalignment: 1.25 fs
- Note: comparable to results for 3-body D^+ decay (1.70 fs)

Systematics and cross-checks

- **Resolution model**
  - Generate pseudoexperiments by bootstrapping from truth-matched signal events from 1/ab equivalent from MC14ri_a. Take the sum of the absolute difference and uncertainty with the true lifetime of the parent sample as the systematic uncertainty due to the resolution model.
  - 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) off-set mass window (6) treatment of multiple-candidate events

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**

Systematics and cross-checks

- **Resolution model**
  - Generate pseudoexperiments by bootstrapping from truth-matched signal events from 1/ab equivalent from MC14ri_a. Take the sum of the absolute difference and uncertainty with the true lifetime of the parent sample as the systematic uncertainty due to the resolution model.
  - 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**
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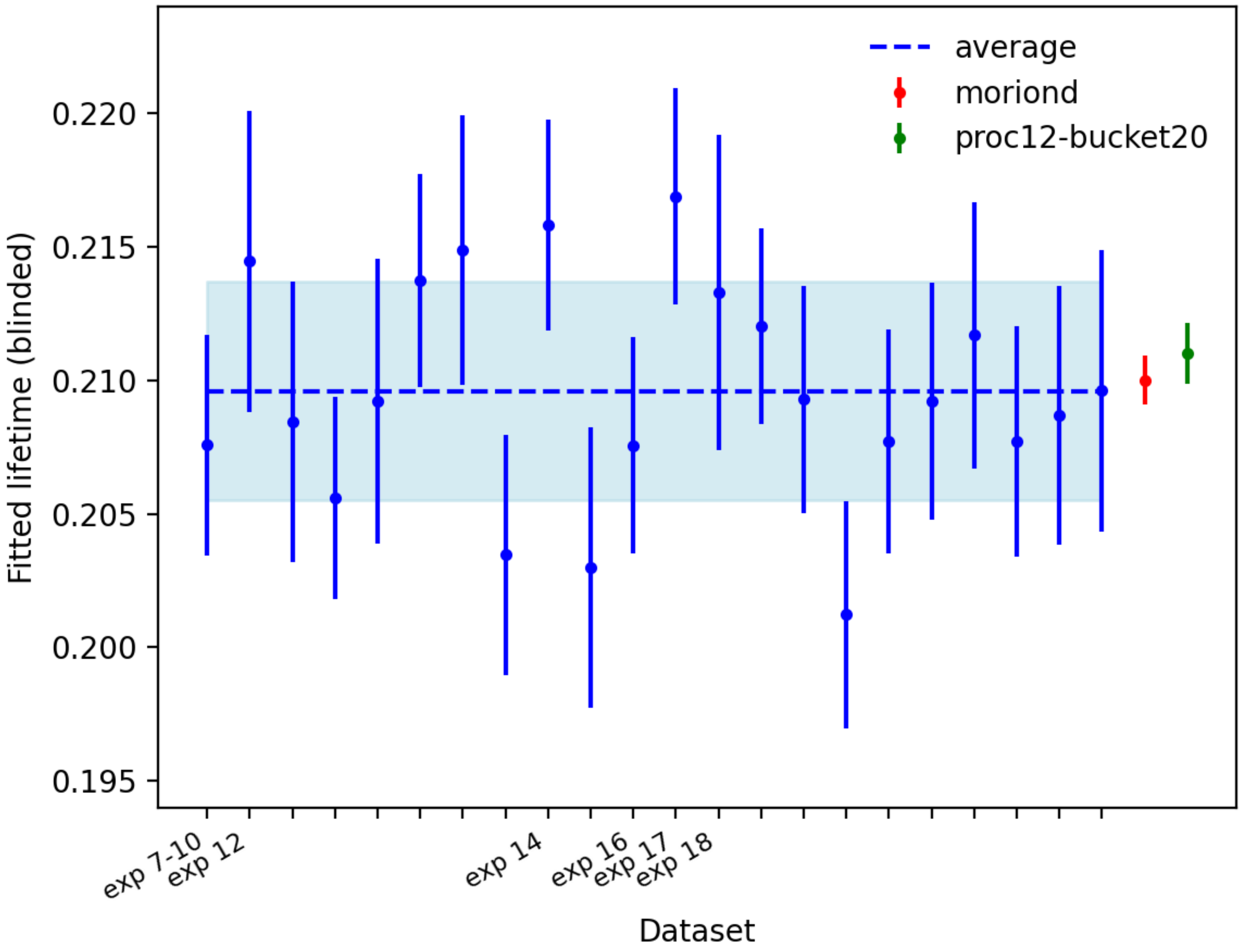
  - Change the signal model in the invariant mass fit and adjust the Gaussian constraint on the background in the lifetime fit
  - Repeat mass fit with different signal and sideband ranges, adjust the Gaussian constraint on the background in the lifetime fit
  - Check the effect of fixing or floating background 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) off-set mass window (6) treatment of multiple-candidate events

Consistency checks

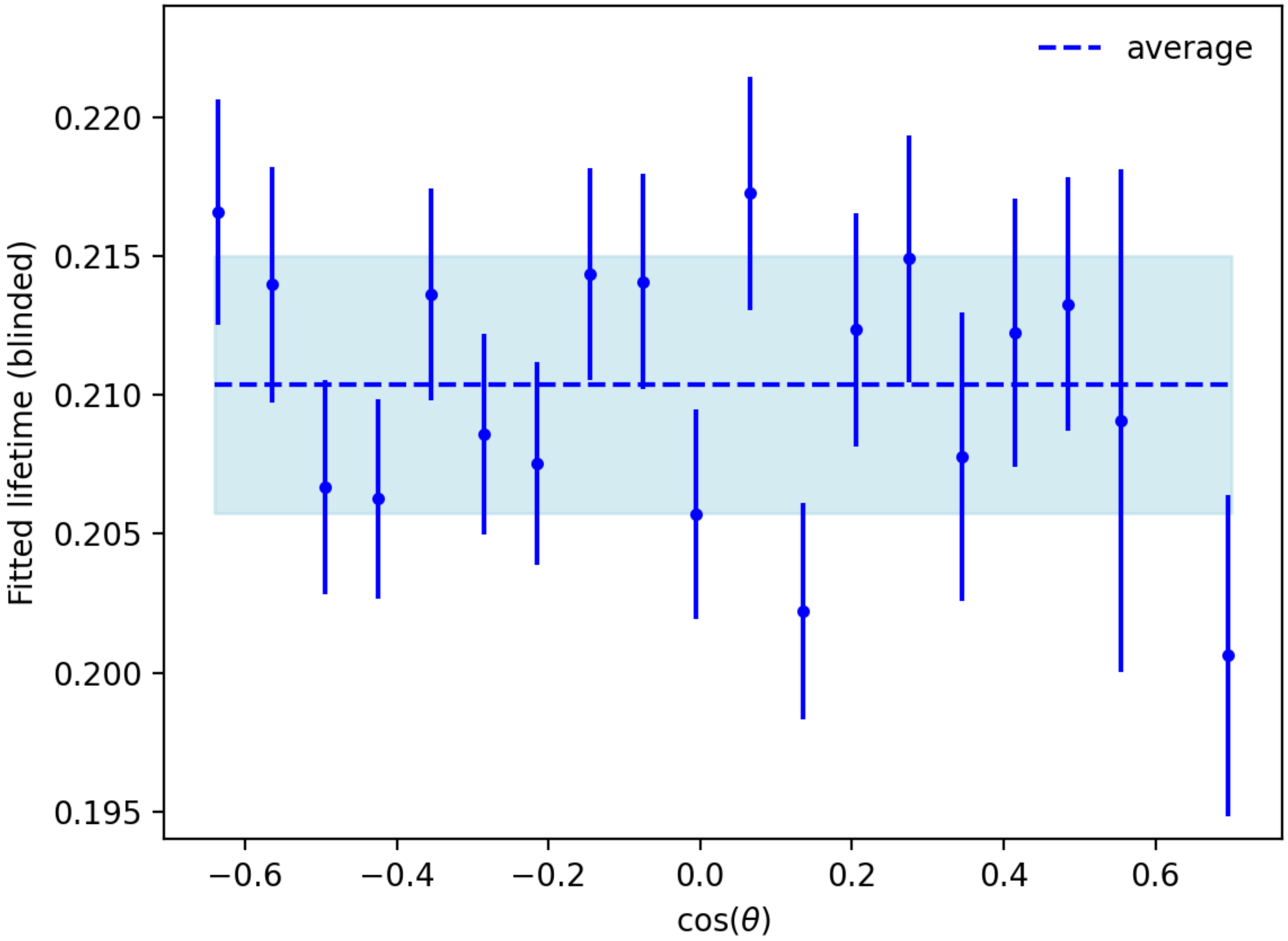
- Perform blinded lifetime fit to data subsets
  - Moriond 2022 (~208/fb)
  - Repeat up to bucket 20 (~130/fb)
    - Potential problems with alignment in buckets 21-25
  - Repeat fits in bins of ~10/fb

- Results consistent within uncertainties
  - Moriond 2022: 210.0 ± 0.9 fs
  - proc12-bucket20: 211.0 ± 1.1 fs
  - Avg of exp bins: 209.6 ± 1.0



Consistency checks

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

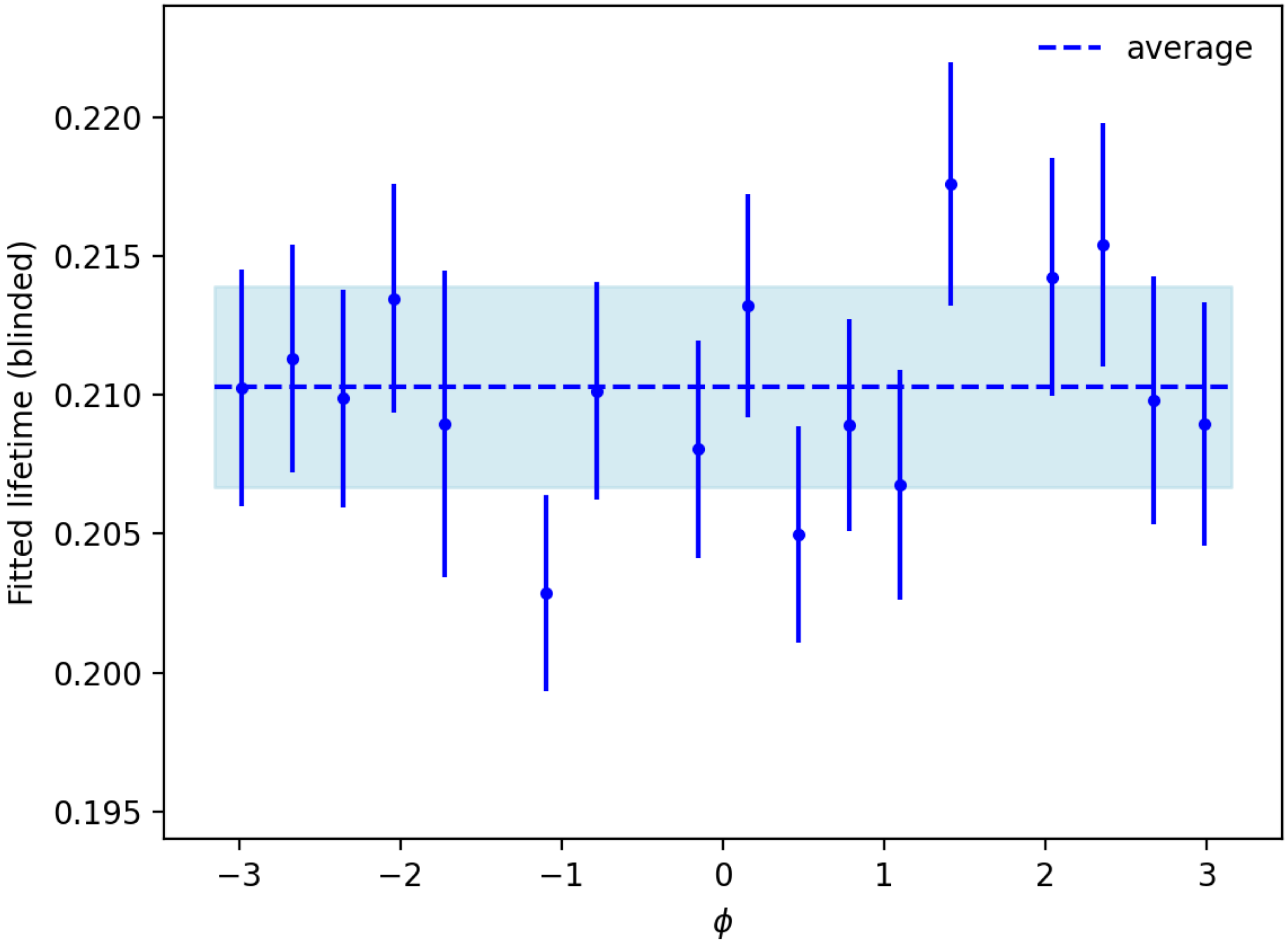


- Results consistent within uncertainties
  - Moriond 2022: 210.0 ± 0.9 fs
  - proc12-bucket20: 211.0 ± 1.1 fs
  - Avg of exp bins: 209.6 ± 1.0
  - Avg of cos(θ) bins: 210.4 ± 1.1

Consistency checks

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

- Results consistent within uncertainties
  - Moriond 2022: 210.0 ± 0.9 fs
  - proc12-bucket20: 211.0 ± 1.1 fs
  - Avg of exp bins: 209.6 ± 1.0
  - Avg of cos(θ) bins: 210.4 ± 1.1
  - Avg of ϕ bins: 210.3 ± 1.0



Summary

- Lifetime fit to simulation gives result consistent with generated value
- Limiting systematic uncertainty: imperfect alignment
- Small improvement in precision compared to LHCb

- Still to do:
  - Vary σ_t bin sizes to avoid zero bins and check the difference in the fitted lifetime
  - Few remaining cross checks
  - Potential resolution effects due to missing PXD inefficiency in simulation

Source	uncertainty (fs)
Resolution model	0.03
Background contamination	0.29
Imperfect alignment	1.25
Momentum scale correction	0.09
Input charm masses	0.01
Total systematic uncertainty	1.29
Statistical uncertainty	0.9

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

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