BELLE2-PUB-DRAFT-2021-002

BELLE2-NOTE-PH-2021-017

Measurement of the D^0 and D^+ lifetimes

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Belle II Summer Workshop
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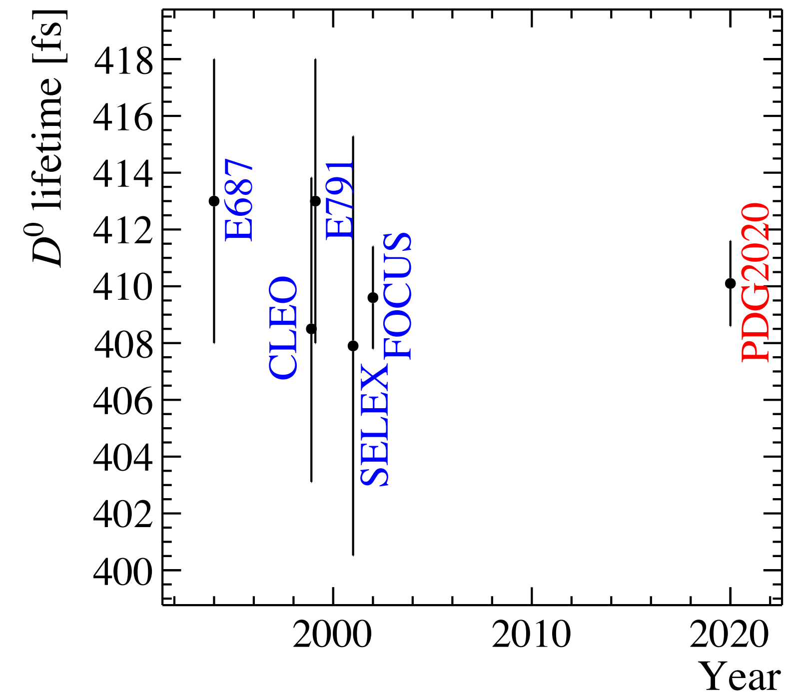
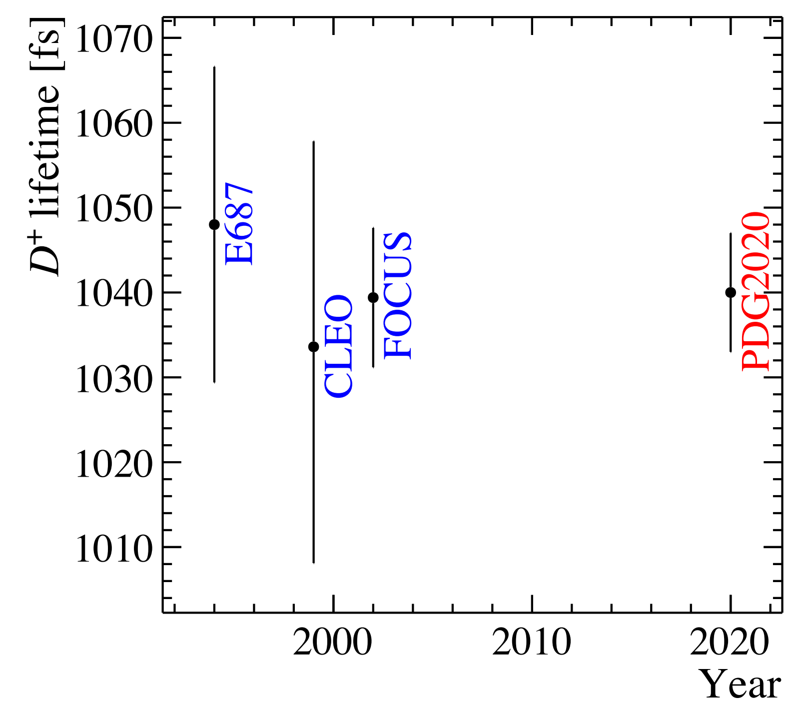
Intro/recap

- The goal is a competitive measurement of the D^0 and D^+ lifetimes with early Belle II data.
- Precise D_s^+ and charm-baryon lifetimes (relative to D^+ lifetimes) have been recently reported by LHCb.
- The D^0 and D^+ lifetimes rely on a single measurement made by the FOCUS collaboration approximately 20 years ago.
- Will prove excellent vertexing performance (e.g. decay-time resolution 2x better than Belle) and in-depth understanding of systematic effects for future TDCPV/mixing analyses.
- The analysis uses data from experiments 7, 8, 10 and 12 (72/fb). The D^0 and D^+ lifetime are measured using $D^{*+}\to D^0(\to K^-\pi^+, K^-\pi^+\pi^-\pi^+)\pi^+$ and $D^{*+}\to D^+(\to K^-\pi^+\pi^+)\pi^0$ decays.





Reconstruction/selection details

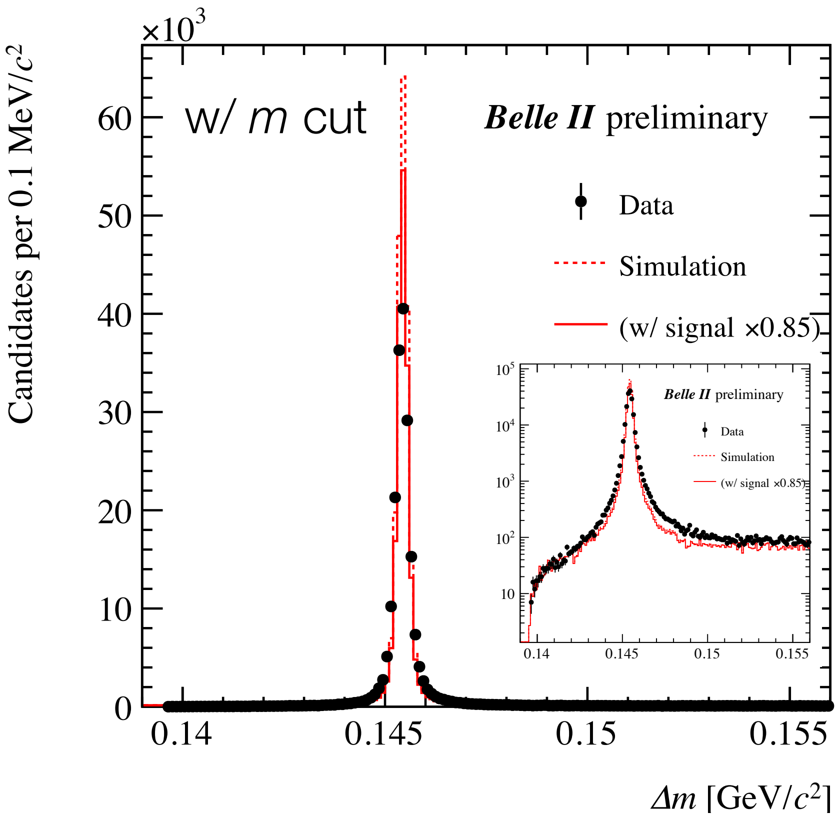
Variable	Criteria		
	$D^0 \to K^-\pi^+$	$D^0 \to K^-\pi^+\pi^+\pi^-$	$D^+ \to K^-\pi^+\pi^+$
Charged particles:			
$\|d_r\|(K, \pi, \pi_s)$	$< 0.5\,\mathrm{cm}$	$< 0.5\,\mathrm{cm}$	$< 0.5\,\mathrm{cm}$
$\|d_z\|(K, \pi, \pi_s)$	$< 2\,\mathrm{cm}$	$< 2\,\mathrm{cm}$	$< 2\,\mathrm{cm}$
# hits in first PXD layer (K, π)	> 0	> 0	> 0
# SVD hits (K, π)	> 0	> 0	> 0
# CDC hits (K, π)	> 20	> 20	> 30
# SVD hits (π_s)	> 0	> 0	–
# CDC hits (π_s)	> 0	> 0	–
$\frac{\mathcal{L}_K}{\mathcal{L}_K+\mathcal{L}_\pi}(K)$	> 0.3	> 0.3	> 0.4
$\frac{\mathcal{L}_\pi}{\mathcal{L}_K+\mathcal{L}_\pi}(\pi)$	> 0.3	> 0.1	> 0.1
p(lowest-p π)	–	–	$> 350\,\mathrm{MeV}/c$
$\frac{\mathcal{L}_\pi}{\mathcal{L}_e+\mathcal{L}_\mu+\mathcal{L}_\pi}$(highest-$p$ π)	–	–	> 0.05
Neutral pion:			
# ECL (weighted) hits	–	–	> 1.5
$E(\gamma)$ (region 1, 2, 3)	–	–	$> 80,\ 30,\ 60\,\mathrm{MeV}$
$\theta_{\mathrm{cluster}}(\gamma)$	–	–	$[0.2967, 2.6180]\,\mathrm{rad}$
$m(\gamma\gamma)$	–	–	$[120, 145]\,\mathrm{MeV}/c^2$
$p(\pi^0)$	–	–	$> 150\,\mathrm{MeV}/c$
Charm mesons:			
$m(K^-\pi^+(\pi^+)(\pi^-))$	$[1.75, 2.00]\,\mathrm{GeV}/c^2$	$[1.75, 2.00]\,\mathrm{GeV}/c^2$	$[1.75, 2.00]\,\mathrm{GeV}/c^2$
Δm	$[144.94, 145.90]\,\mathrm{MeV}/c^2$	$[144.96, 145.89]\,\mathrm{MeV}/c^2$	$[138, 143]\,\mathrm{MeV}/c^2$
$p_{\mathrm{cms}}(D^{*+})$	$> 2.5\,\mathrm{GeV}/c$	$> 2.5\,\mathrm{GeV}/c$	$> 2.6\,\mathrm{GeV}/c$
`TreeFitter` probability	> 0.01	> 0.01	> 0.01
Signal region:			
$m(K^-\pi^+(\pi^+)(\pi^-))$	$[1.851, 1.878]\,\mathrm{GeV}/c^2$	$[1.854, 1.875]\,\mathrm{MeV}/c^2$	$[1.855, 1.883]\,\mathrm{MeV}/c^2$

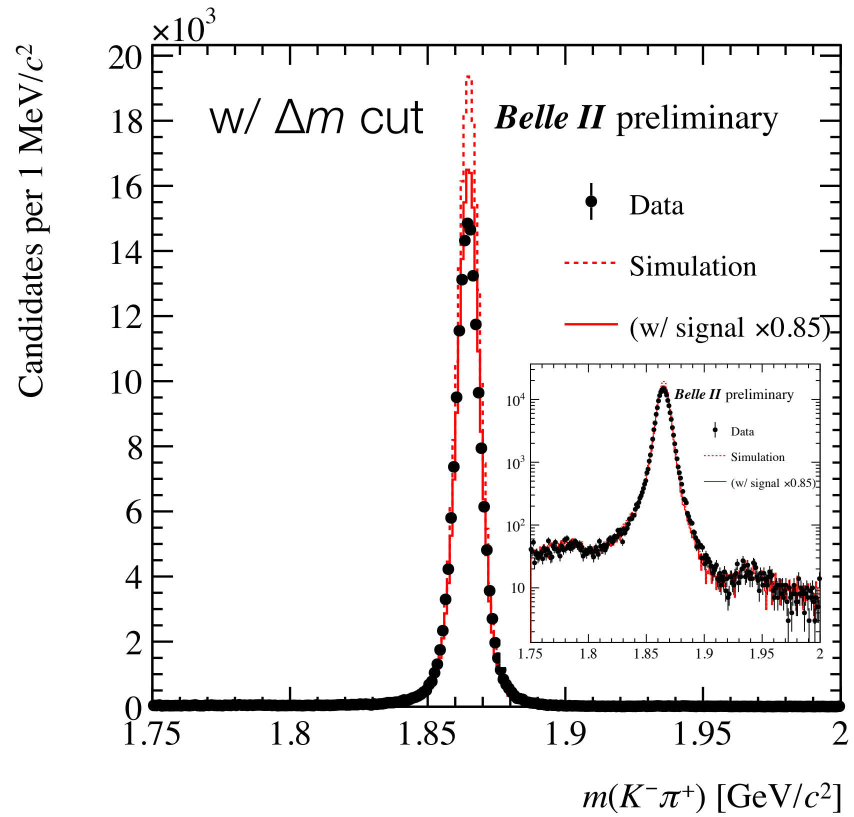
Table 1: Selection criteria. `TreeFitter` is used with an IP constraint and, for the $D^+ \to K^-\pi^+\pi^+$ case also with a π^0-mass constraint. If multiple candidates are reconstructed in the event, only one is randomly selected.

- Momentum-scale correction applied to charged tracks
- IP based on most recent beam-spot calibration

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

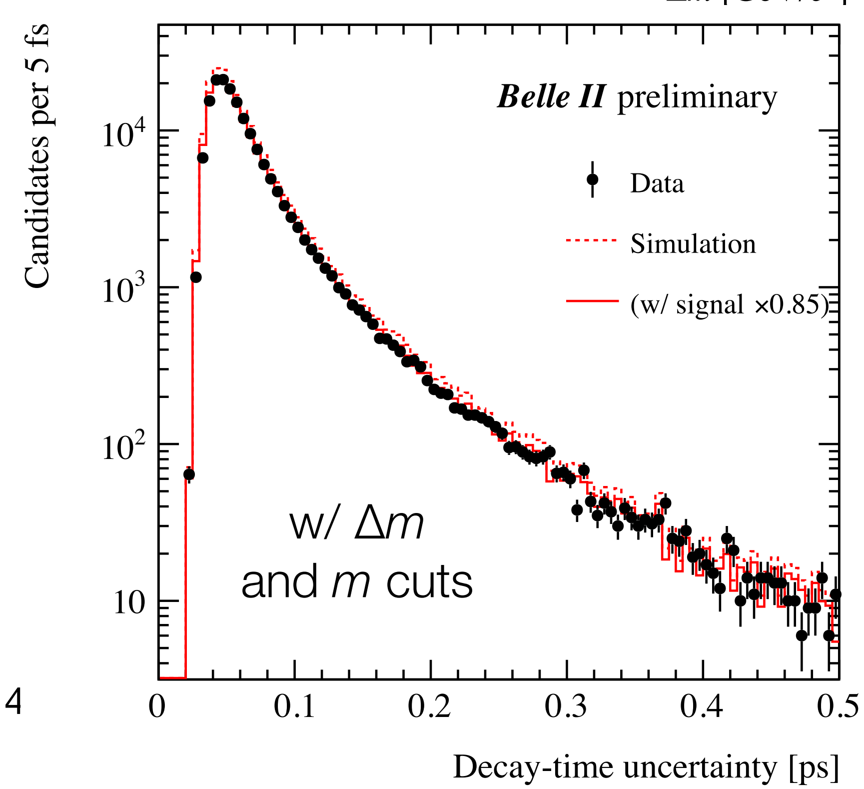
Unless specified otherwise, simulation refers to `MC13b_proc11/prompt` samples

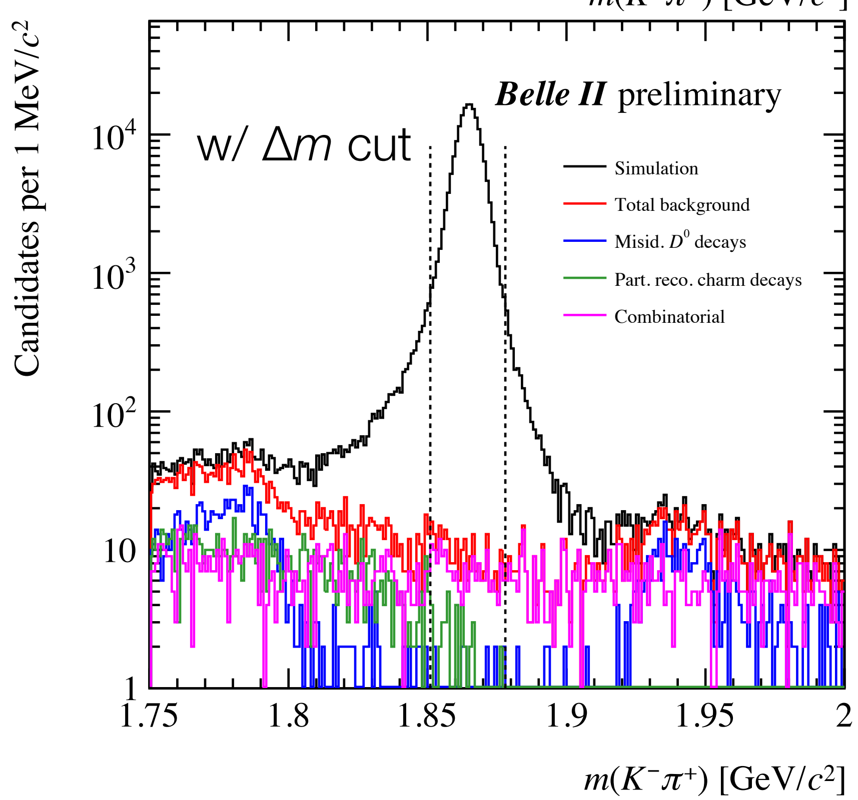


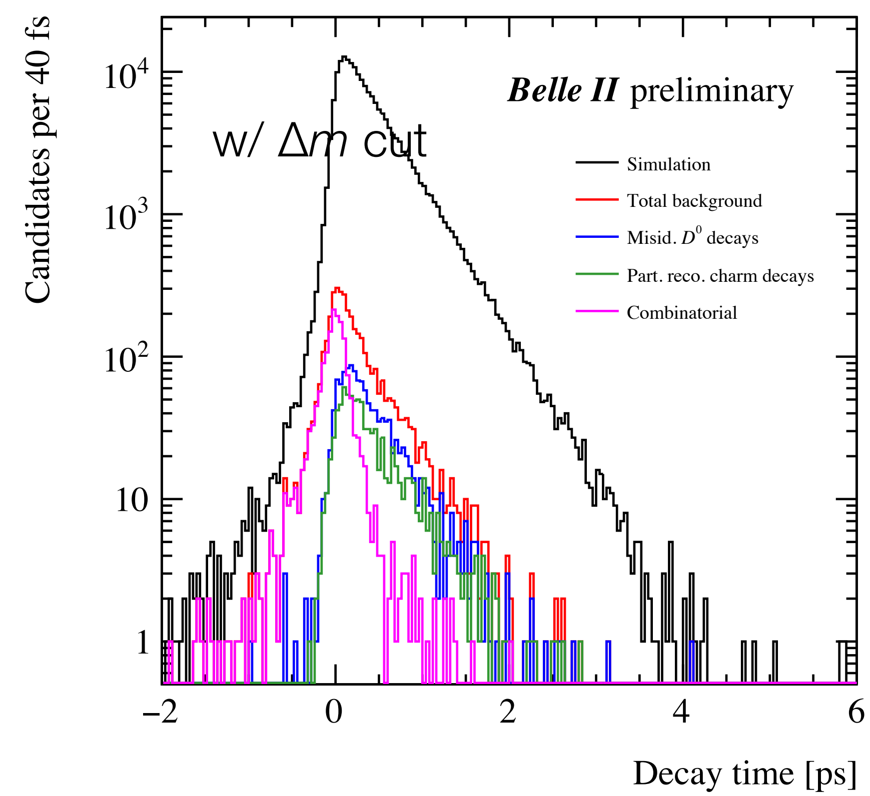


~171k signal decays in signal region

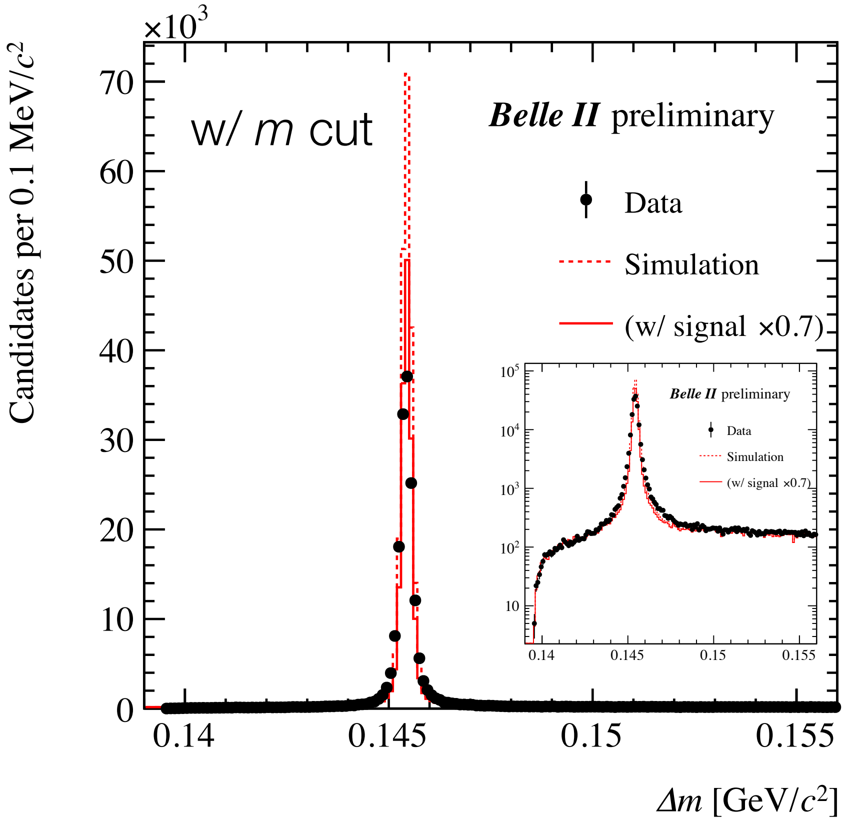
w/ background contamination of ~0.2%

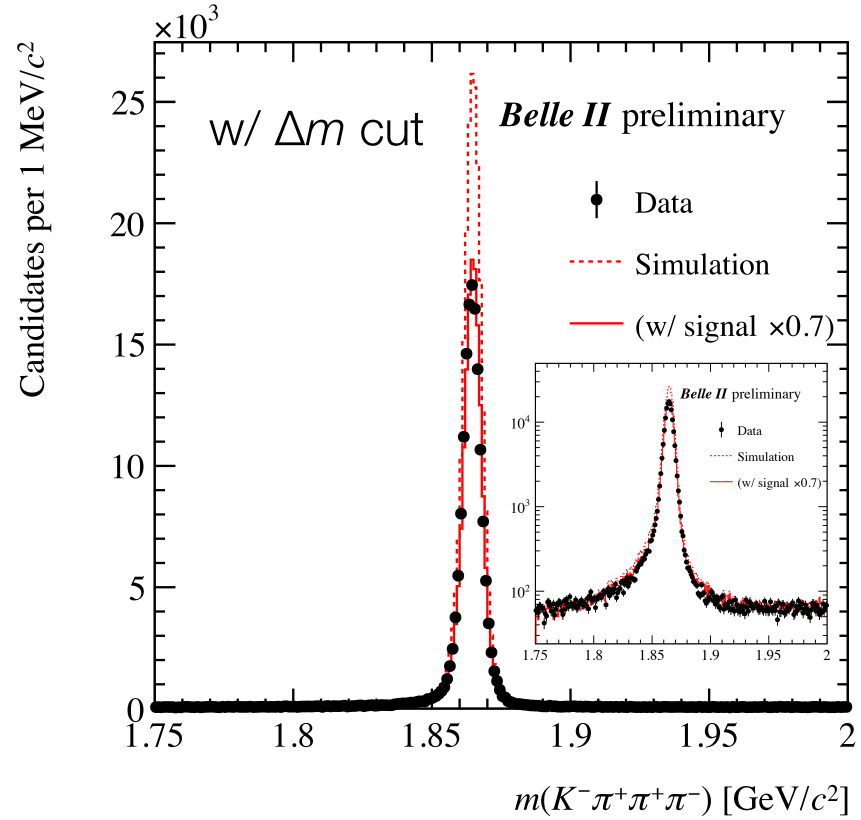






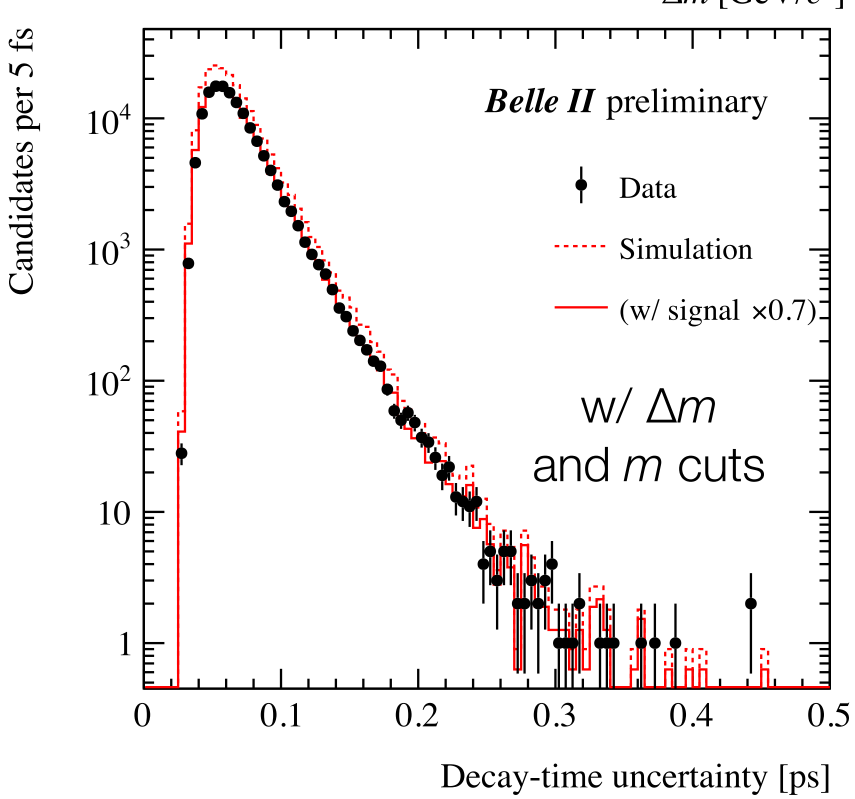
$D^{*+} \to D^0(\to K^-\pi^+\pi^-\pi^+)\pi^+$ sample

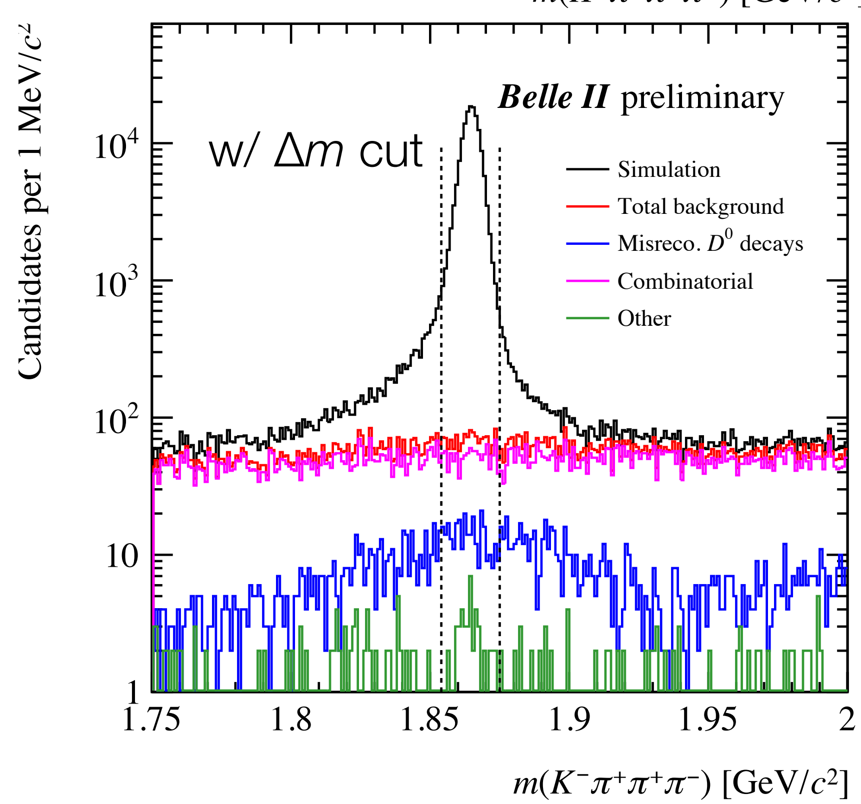


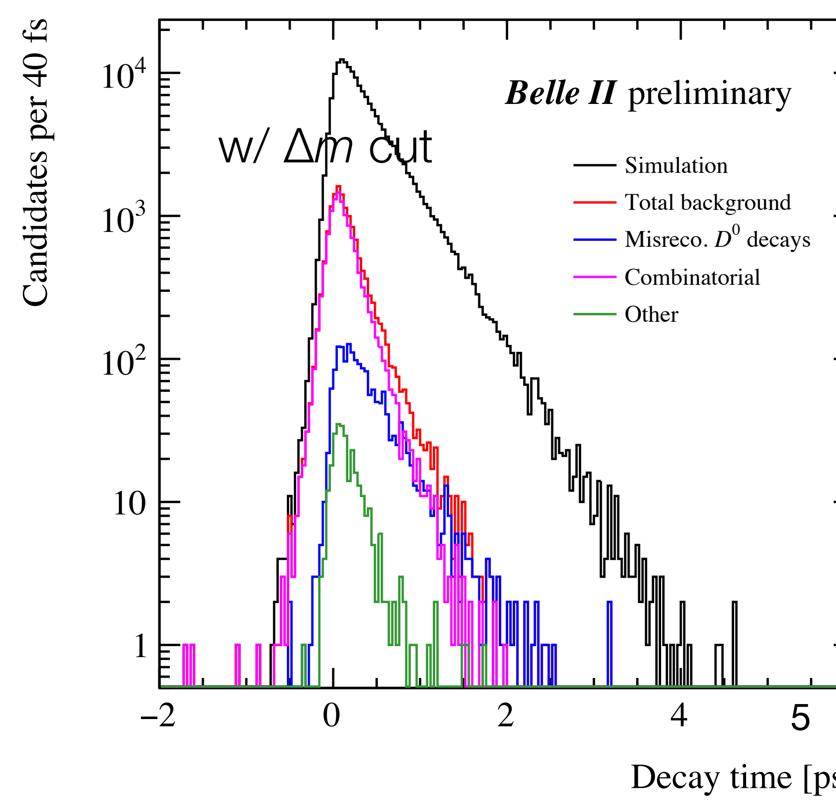


~146k signal decays in signal region

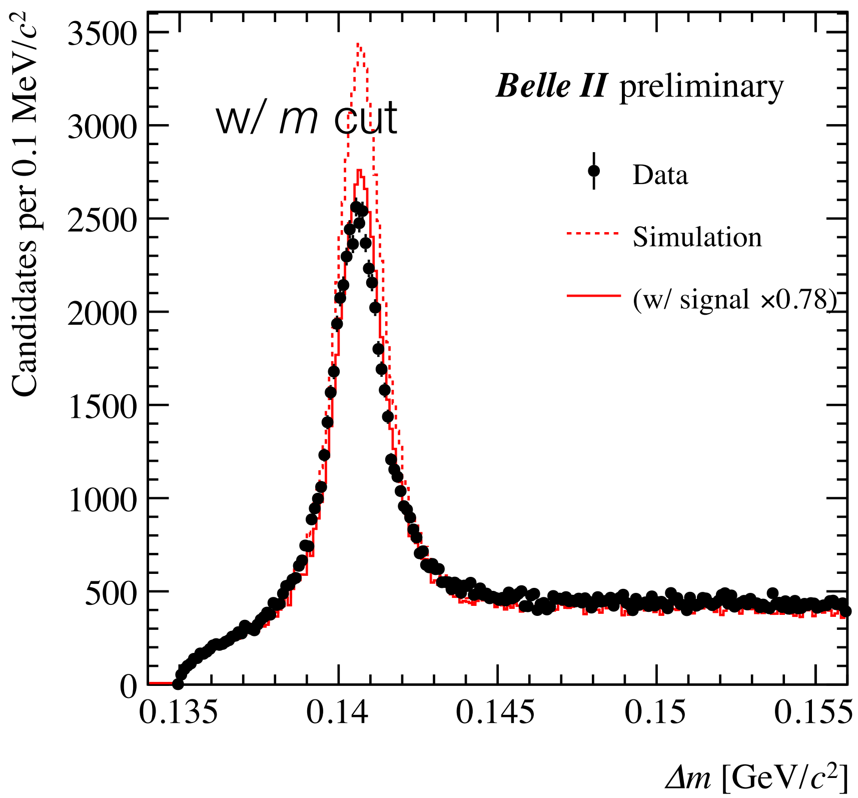
w/ background contamination of ~0.8%

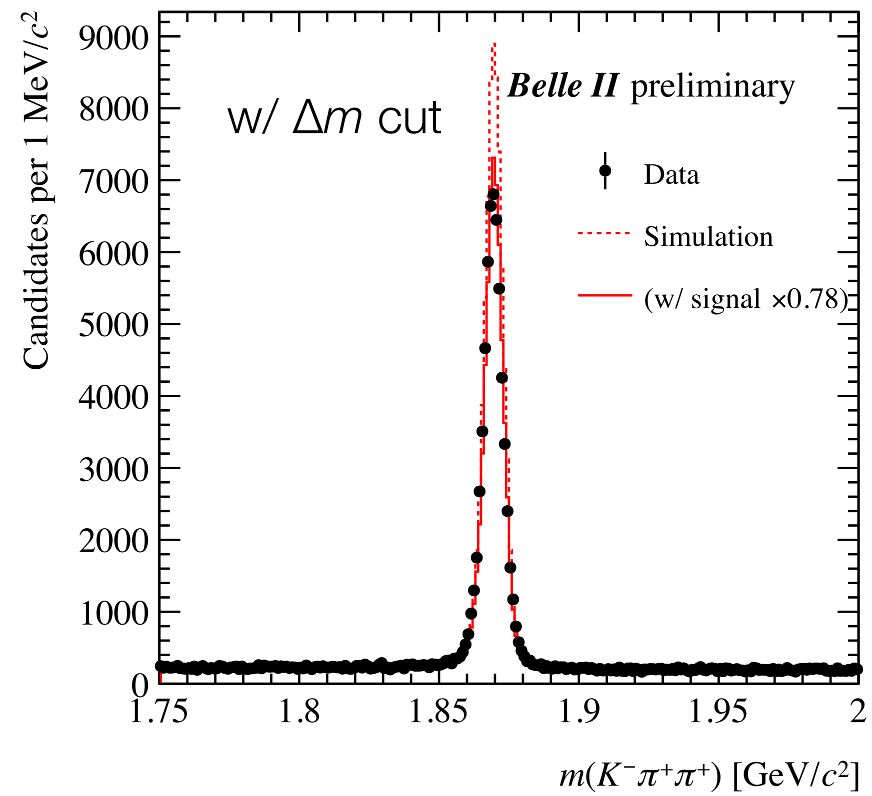






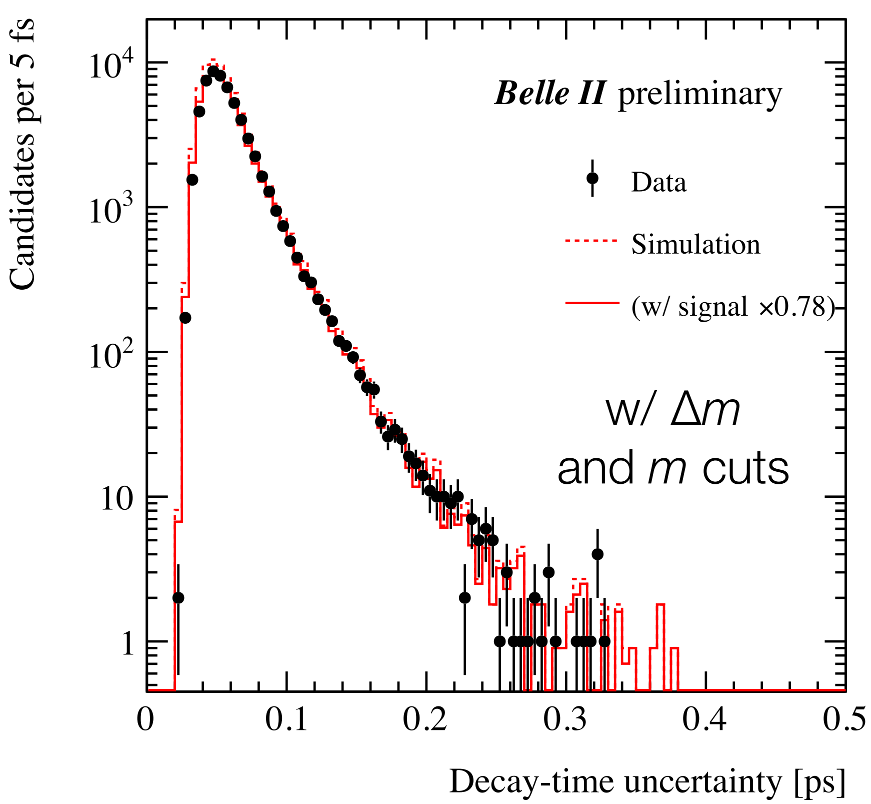
$D^{*+} \to D^+(\to K^-\pi^+\pi^+)\pi^0$ sample

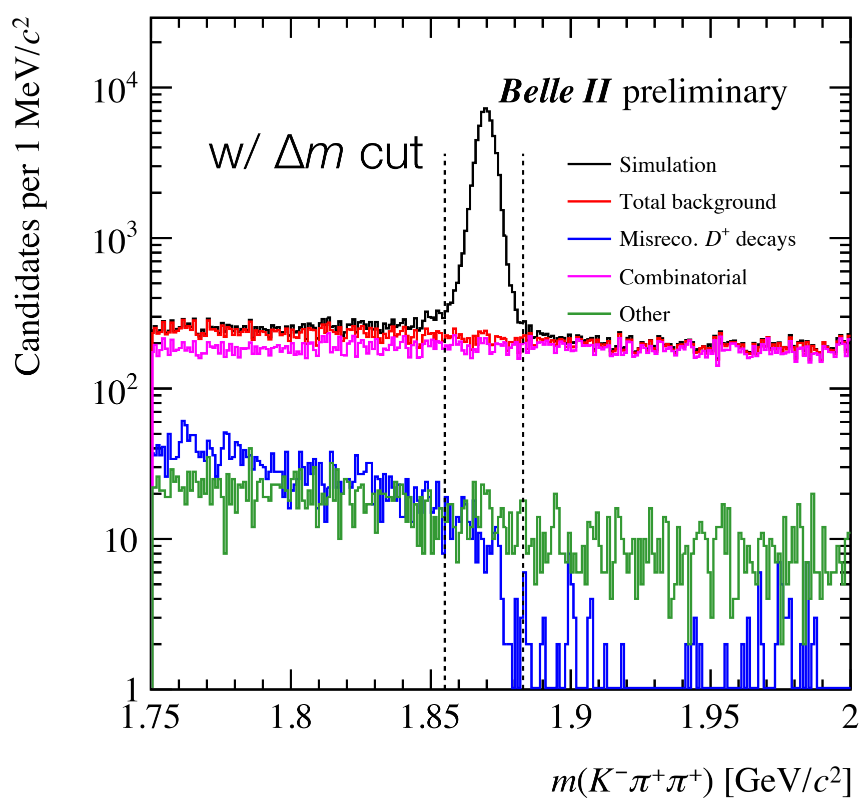


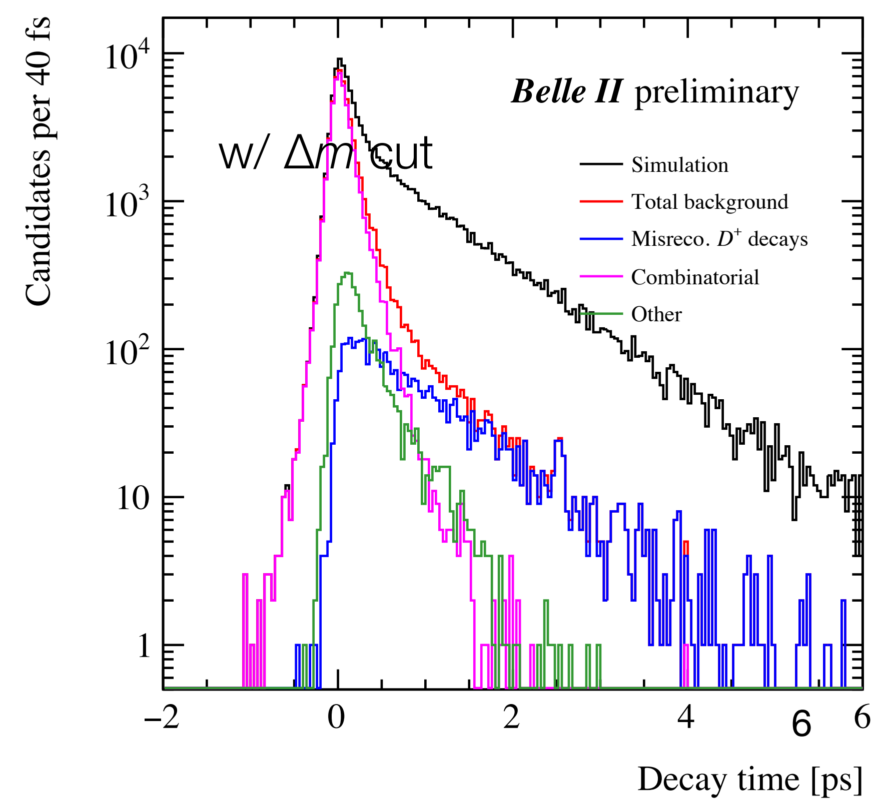


~55k signal decays in signal region

w/ background contamination of ~8.8%







Lifetime fit

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

- Signal distribution is convolution of exponential with resolution function

Fixed from data (binned template)

$$\begin{aligned}\mathrm{pdf}_{\mathrm{sgn}}(t, \sigma_t | \tau, b, s) &= \mathrm{pdf}_{\mathrm{sgn}}(t | \sigma_t, \tau, b, s) \boxed{\mathrm{pdf}_{\mathrm{sgn}}(\sigma_t)} \\ &\propto \int_0^\infty e^{-t_{\mathrm{true}}/\tau} R(t - t_{\mathrm{true}} | b, s\sigma_t) dt_{\mathrm{true}} \, \mathrm{pdf}_{\mathrm{sgn}}(\sigma_t)\end{aligned}$$

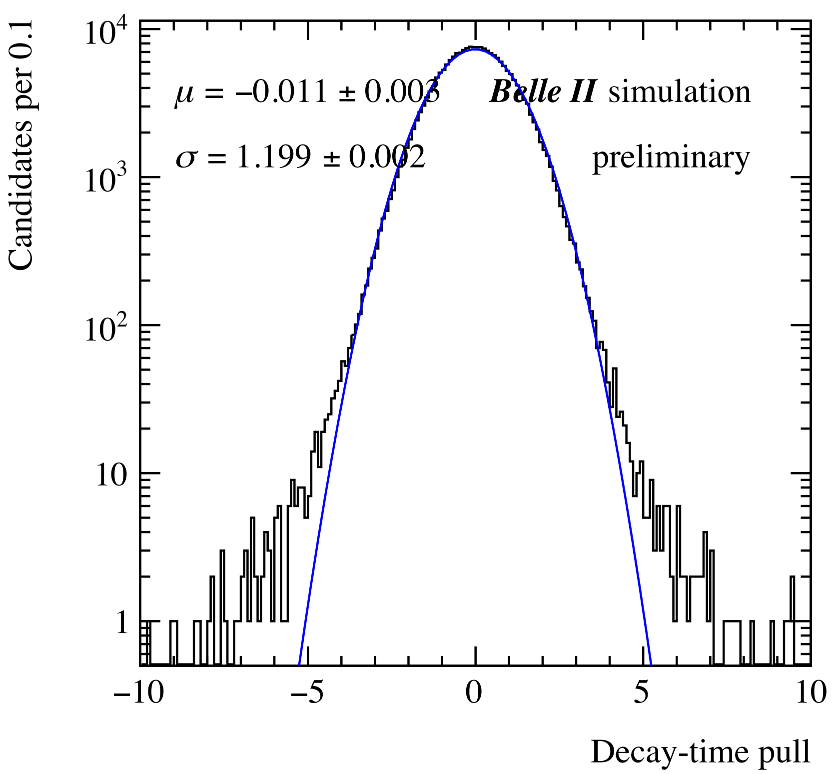
- This is the total PDF for the D^0 modes, where sub-1% background contamination is ignored

Resolution model

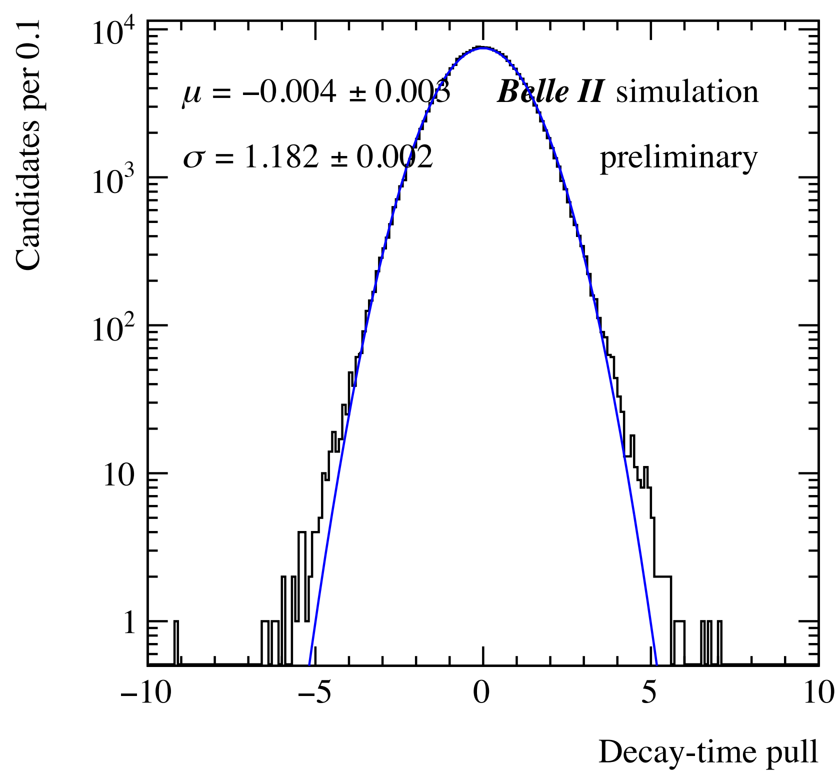
- Inspired from decay-time pull distribution in simulation: double-Gaussian function with common mean (to avoid asymmetric resolution tails) for *Kπ*; single Gaussian for *K2π* and *K3π*

- All parameters are free to float in the fit

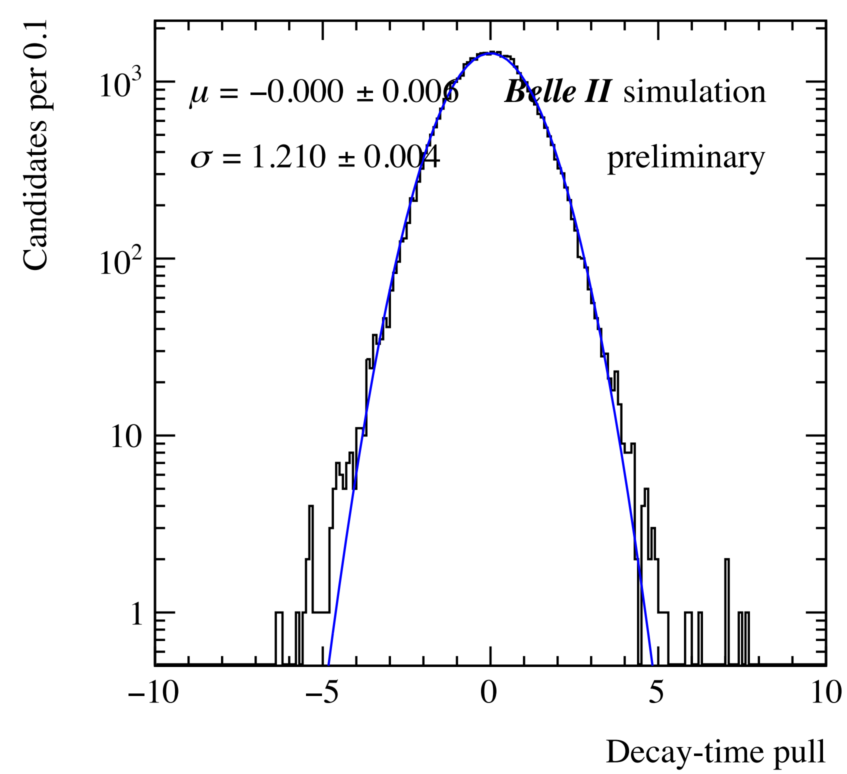
$$R(t - t_{\mathrm{true}}|f_1, b, s_1\sigma_t, s_2\sigma_t) = f_1 G(t - t_{\mathrm{true}}|b, s_1\sigma_t) + (1 - f_1) G(t - t_{\mathrm{true}}|b, s_2\sigma_t)$$



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



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



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

Background component

- In the D^+ case the ~9% background contamination cannot be ignored

$$\mathrm{pdf}(t,\sigma_t) = (1-f_b)\mathrm{pdf}_{\mathrm{sgn}}(t,\sigma_t) + f_b \mathrm{pdf}_{\mathrm{bkg}}(t,\sigma_t)$$

Fixed template from sideband data

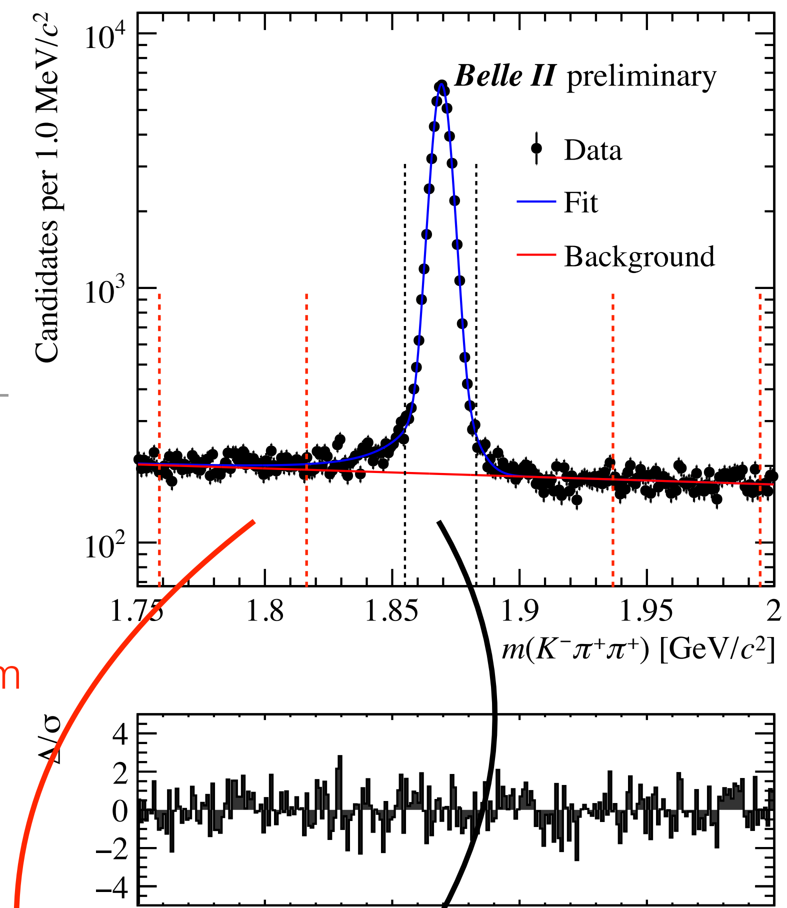
$$\mathrm{pdf}_{\mathrm{bkg}}(t,\sigma_t|\tau_{b1},\tau_{b2},f_{bl},f_{bl1},b,s) = \mathrm{pdf}_{\mathrm{bkg}}(t|\sigma_t,\tau_{b1},\tau_{b2},f_{bl},f_{bl1},b,s)\boxed{\mathrm{pdf}_{\mathrm{bkg}}(\sigma_t)}$$

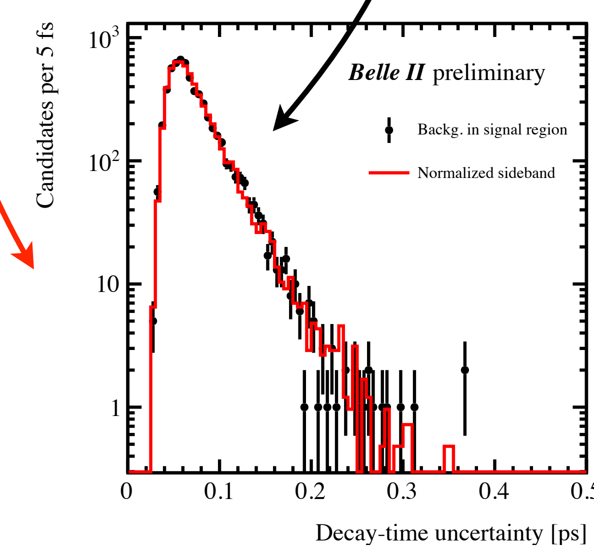
- We include it in the fit with an empiric model derived from sideband data

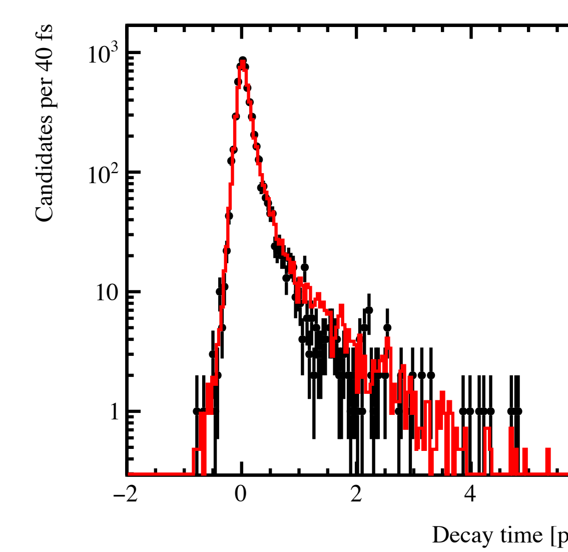
$$\begin{aligned}\mathrm{pdf}_{\mathrm{bkg}}(t|\sigma_t,\tau_{b1},\tau_{b2},f_{bl},f_{bl1},b,s) = &(1-f_{bl})R(t|b,s\sigma_t)\\ &+ f_{bl}\left[f_{bl1}\mathrm{pdf}_{\mathrm{bl1}}(t|\sigma_t,\tau_{b1},b,s) + (1-f_{bl1})\mathrm{pdf}_{\mathrm{bl2}}(t|\sigma_t,\tau_{b2},b,s)\right]\end{aligned}$$

- Simulation shows that the chosen sidebands represent a good proxy of the background in the signal region

- Signal and sideband regions are fit simultaneously with all shape parameters free; the background fraction is constrained to the result of the mass fit





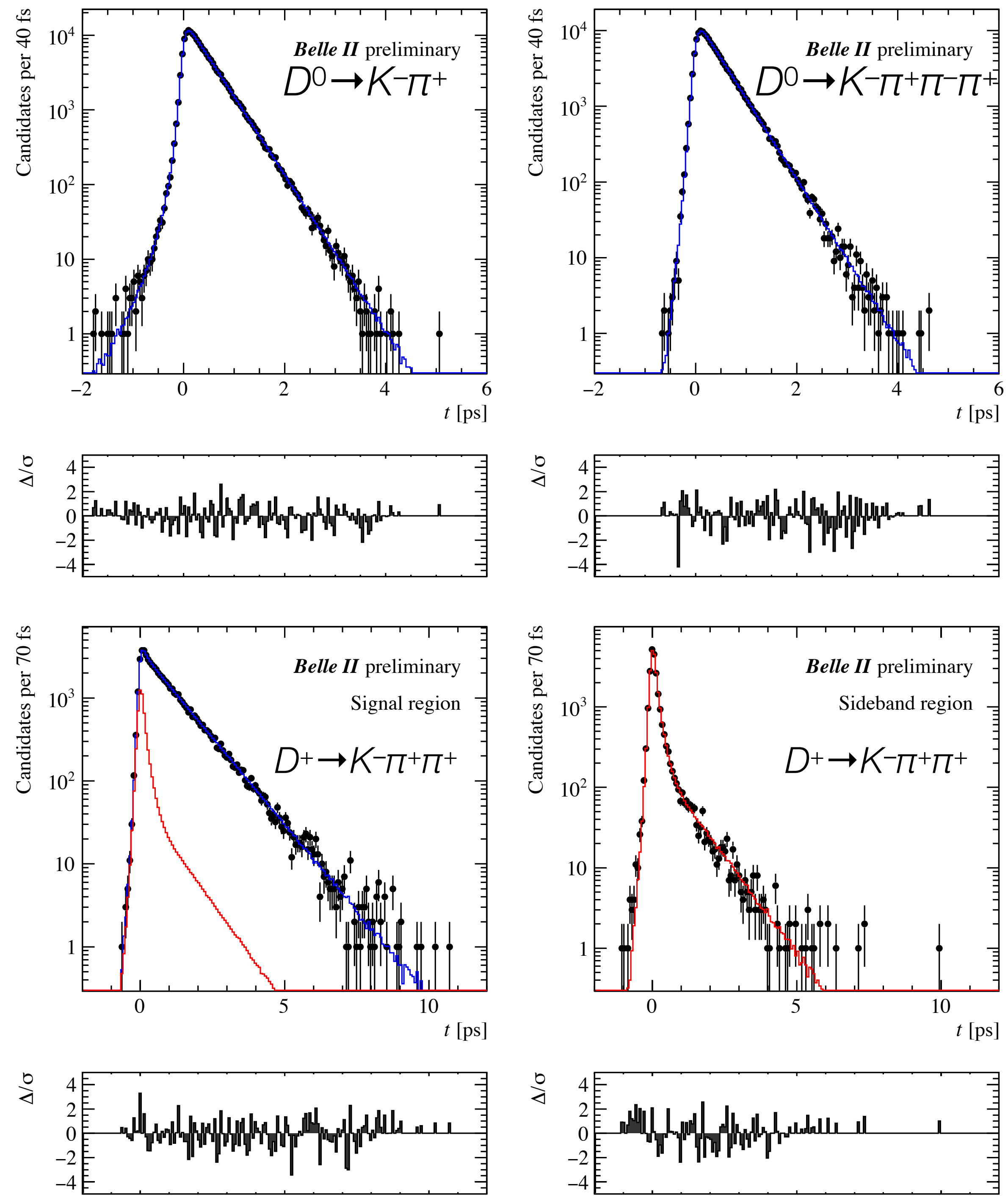


Simulation

Results to simulated decays

- Simulation weighted to match data luminosity and S/B ratio
- Results consistent with generated lifetimes of (D^0) 410.1 fs and (D^+) 1040 fs

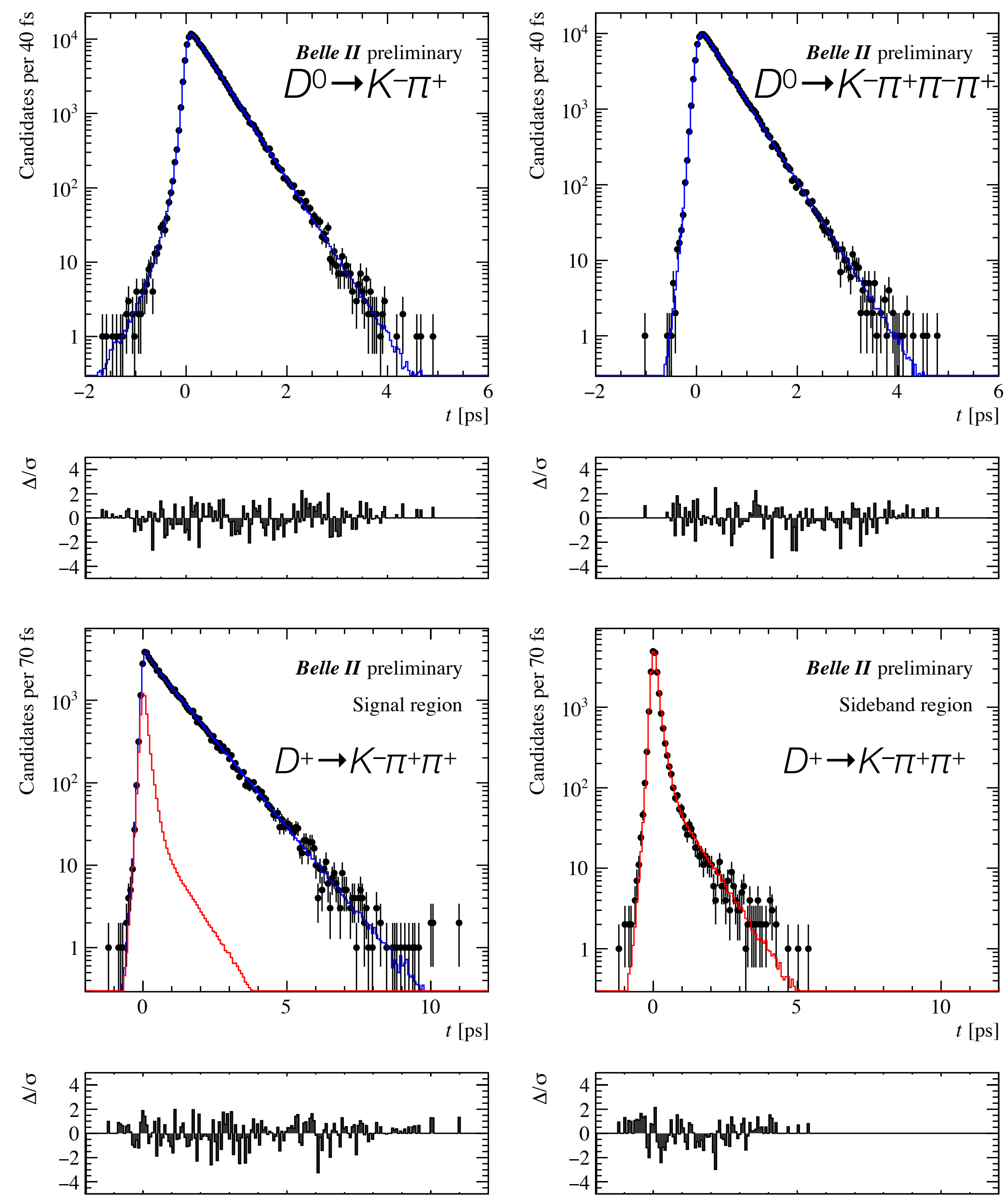
Parameter	Fit result		
	$D^0 \to K^-\pi^+$	$D^0 \to K^-\pi^+\pi^+\pi^-$	$D^+ \to K^-\pi^+\pi^+$
τ (fs)	411.9 ± 1.1	408.4 ± 1.2	1040.7 ± 4.8
b (fs)	-0.80 ± 0.56	-0.68 ± 0.64	-0.2 ± 1.7
b_{bkg} (fs)	–	–	6.9 ± 2.2
f_1	0.9777 ± 0.0068	–	–
$s_{(1)}$	1.139 ± 0.012	1.1845 ± 0.0085	1.303 ± 0.011
s_2	2.73 ± 0.21	–	–
f_b	–	–	0.08818 ± 0.00050
f_{bl}	–	–	0.441 ± 0.015
f_{bl1}	–	–	0.717 ± 0.013
τ_{b1} (fs)	–	–	163.5 ± 7.8
τ_{b2} (fs)	–	–	903 ± 30



Results to the full data sample

$$\tau(D^0) = \ \ 410.5 \pm 1.1 \pm 0.8\,\mathrm{fs}$$
$$\tau(D^+) = 1030.4 \pm 4.7 \pm 3.1\,\mathrm{fs}$$

- More precise than, and consistent with, the respective world-average values of 410.1±1.5 fs and 1040±7 fs.



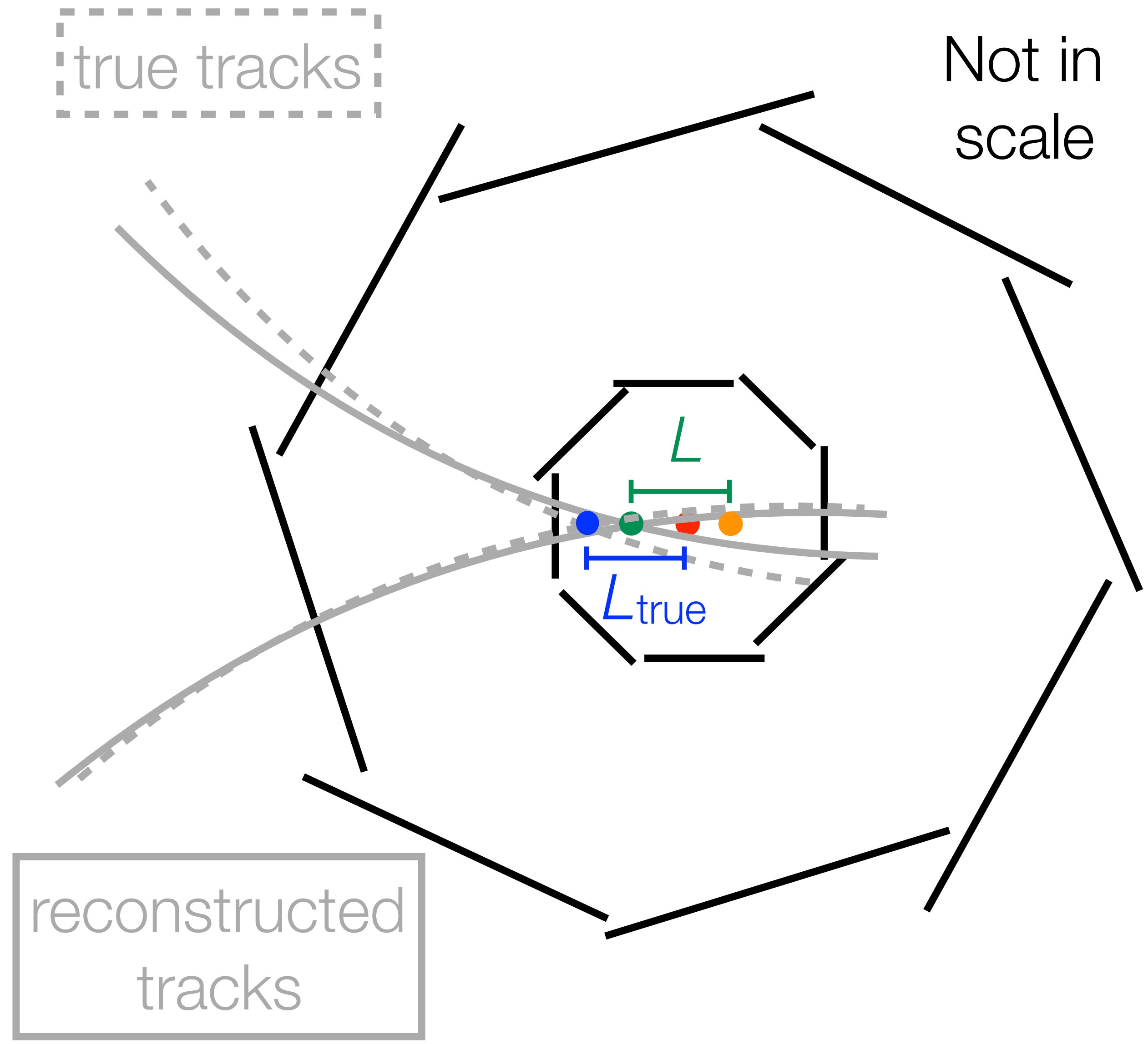
Systematic uncertainties

Source	Uncertainty (fs)		
	$D^0 \to K^-\pi^+$	$D^0 \to K^-\pi^+\pi^+\pi^-$	$D^+ \to K^-\pi^+\pi^+$
Resolution model	0.16	0.46	0.39
Backgrounds	0.24	1.23	2.52
Detector alignment	0.72	0.43	1.70
Momentum scale	0.19	0.19	0.48
Input charm masses	0.01	0.01	0.03
Total systematic	0.8	1.4	3.1
Statistical	1.1	1.2	4.7

- Uncertainties due to momentum scale and input charm masses assume world-average lifetimes

Imperfect alignment (*i.e.*, decay-length scale)

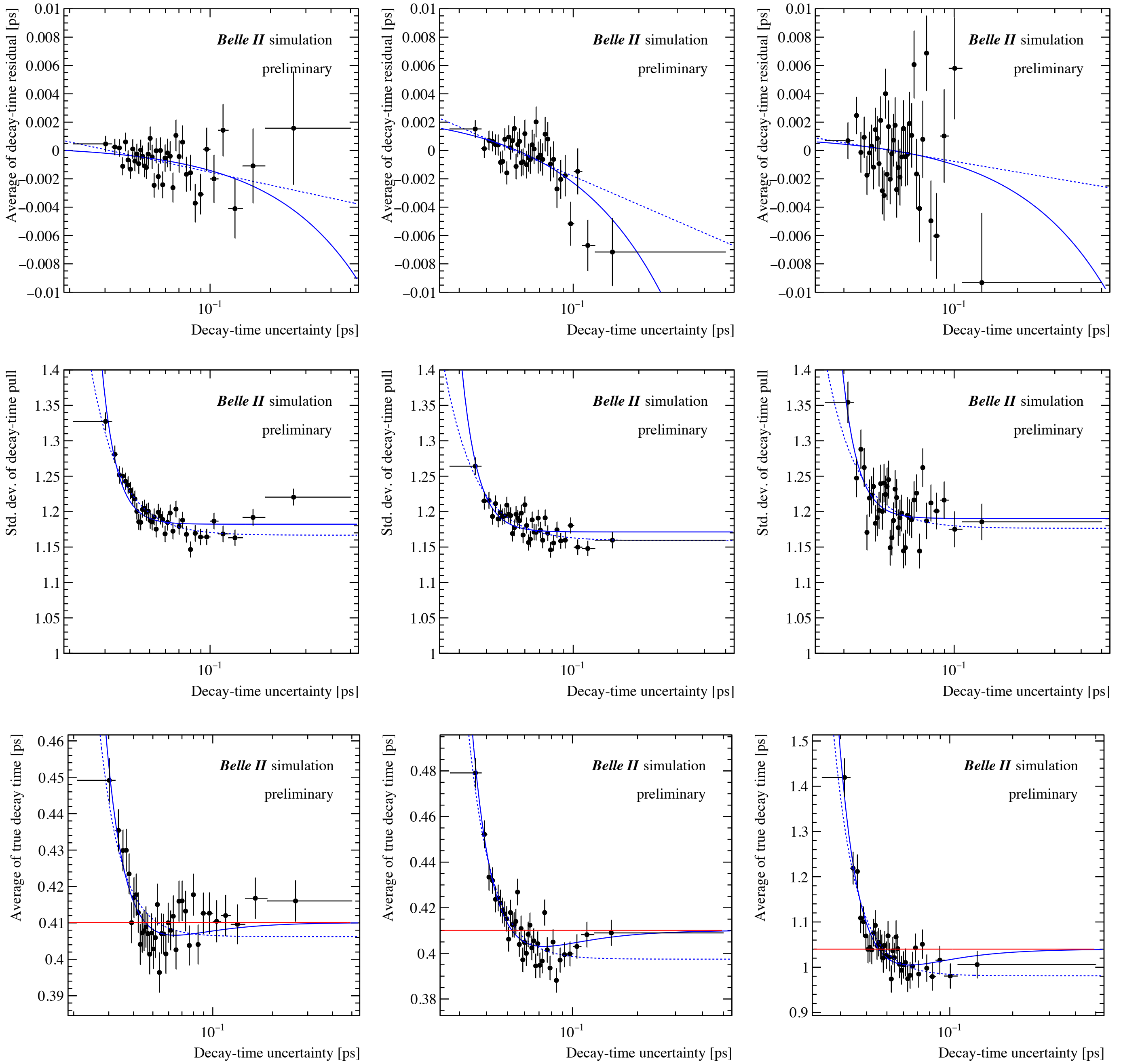
- A misalignment of the tracking detectors may affect the determination of the decay-length and hence the lifetime
  - Systematic deformations that change the decay-length scale are the most worrisome
- Privately-produced signal samples, of the same statistics as the data, are simulated introducing realistic misalignment effects
  - The same generated events are simulated with perfect alignment and with different misalignment configurations, then fit to determine the lifetime
  - For each configuration, a calibration of the beam spot is also performed using simulated dimuon events



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

Decay-time resolution model

- The resolution model ignores correlations between t and σ_t, which are clearly visible in simulation
  - The b and s parameters of the resolution function have both a dependence on σ_t
  - σ_t is correlated with the true decay time
- This results in discrepancies between the fit model and the data in the 2D (t,σ_t) distribution
- To assess the impact on the measured lifetimes, the fit is performed on 1k subsamples bootstrapped from a large sample of (run-independent) simulated signal decays
  - The average absolute differences between the measured and true lifetimes are
    ($K\pi$) 0.107 ± 0.055 fs
    ($K3\pi$) 0.417 ± 0.044 fs
    ($K2\pi$) 0.25 ± 0.14 fs
  - Apart from the $K3\pi$ case, the differences are consistent with zero. The sum of the average difference and its uncertainty is then assigned as systematic uncertainty due to imperfect resolution model



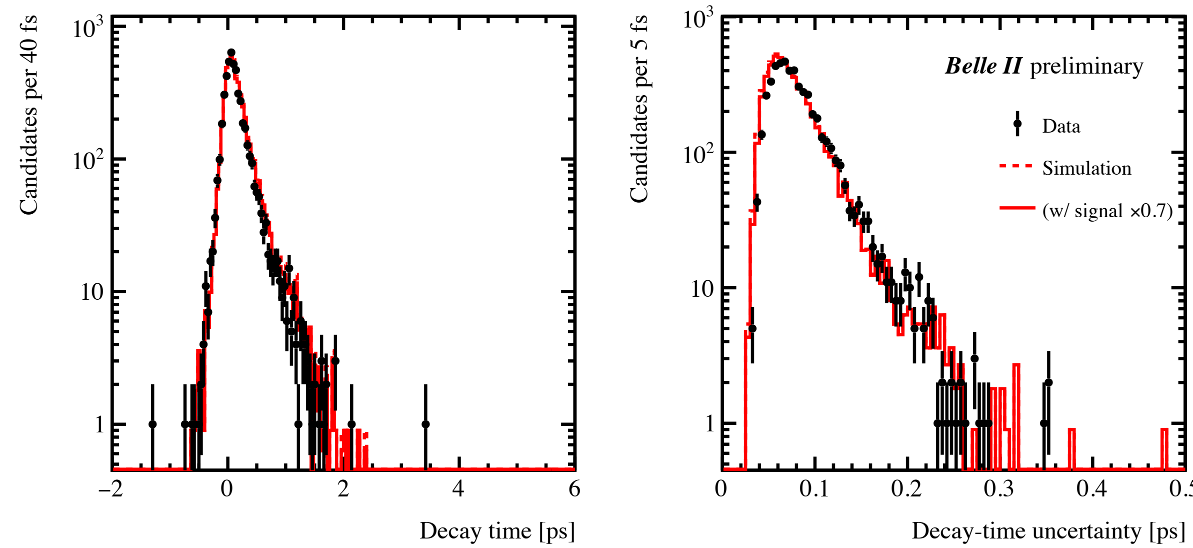
$D^0 \to K^-\pi^+$ $D^0 \to K^-\pi^+\pi^-\pi^+$ $D^+ \to K^-\pi^+\pi^+$

Backgrounds: D^0 case

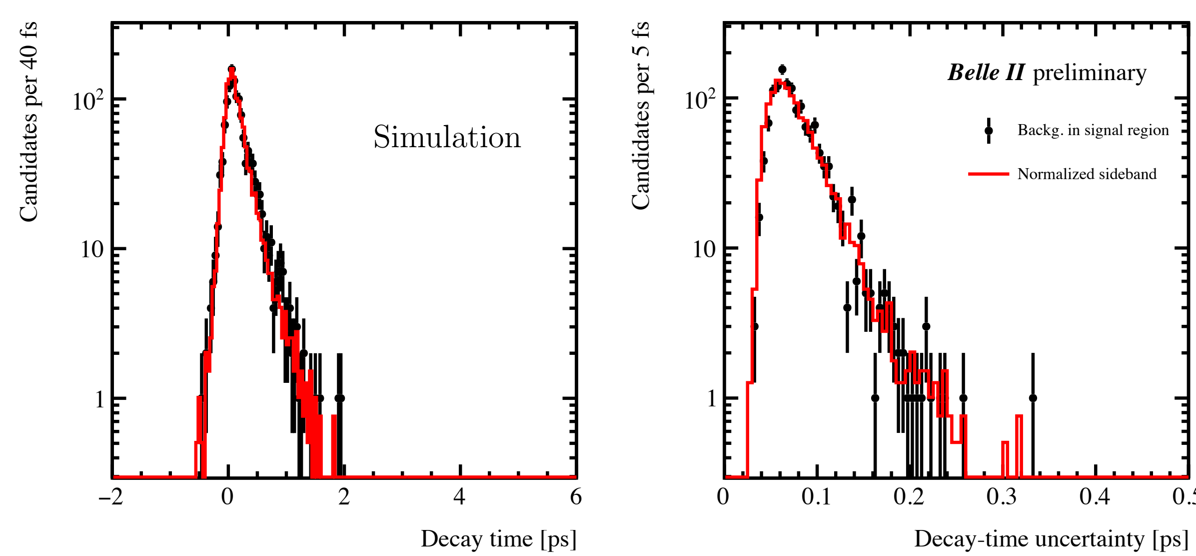
- The signal region contains <1% background, which is neglected in the fit: expect a bias on the measured lifetime ~$f_b(\tau_{\mathrm{bkg}} - \tau_{\mathrm{sig}})$
- The simulation is expected to reproduce the background decay-time distributions reasonably well
- Fits to 500 (run-independent) simulated samples of generic e^+e^- collisions, consisting of the same statistics and S/B ratio as the data, return biases of ($K\pi$) 0.24 ± 0.06 fs and ($K3\pi$) 1.23 ± 0.06 fs due to neglected backgrounds
- These are assigned as systematic uncertainties

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

Sideband data vs simulation



Sideband vs signal region simulation



Backgrounds: D^+ case

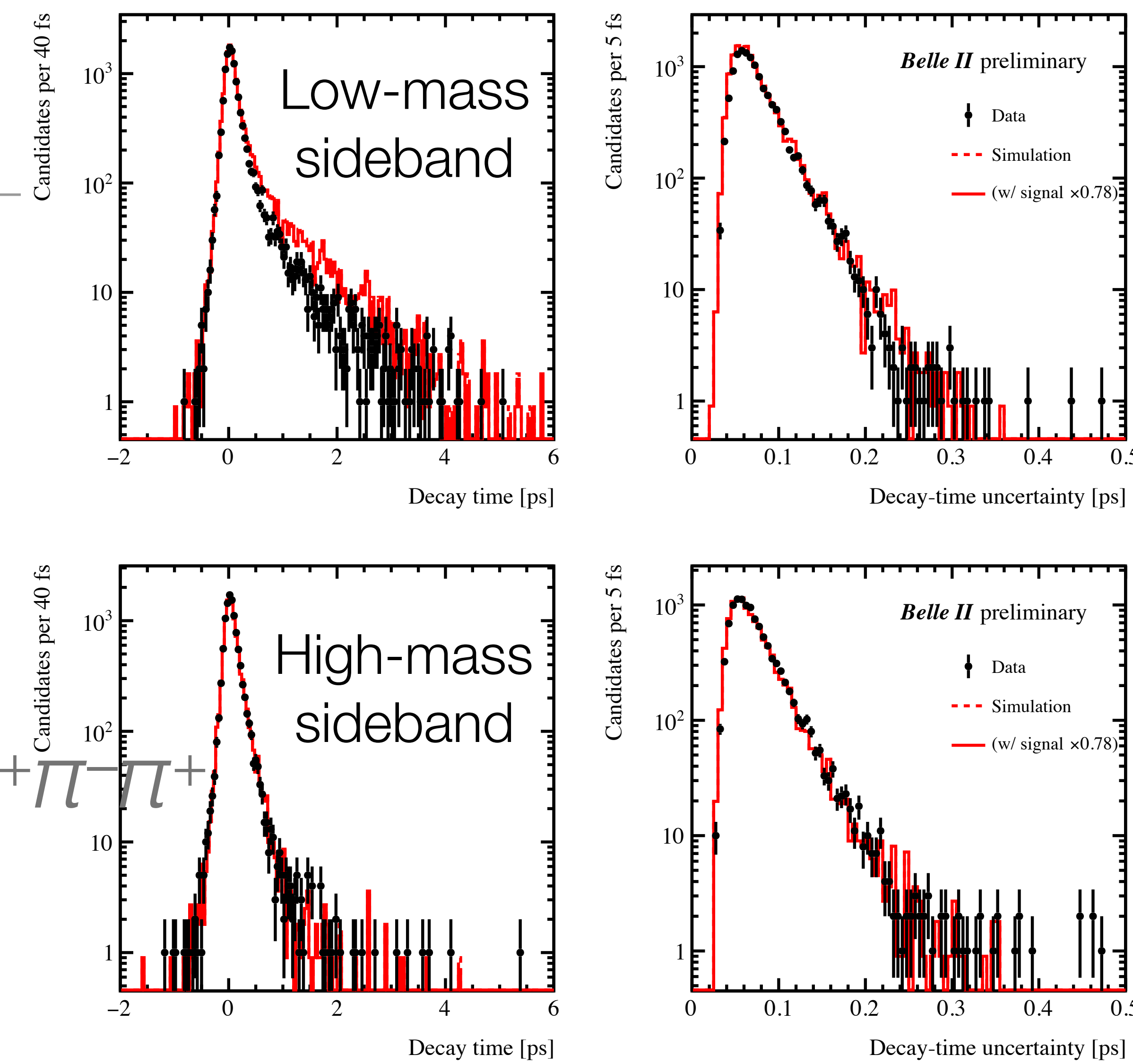
$D^+ \to K^-\pi^+\pi^+$

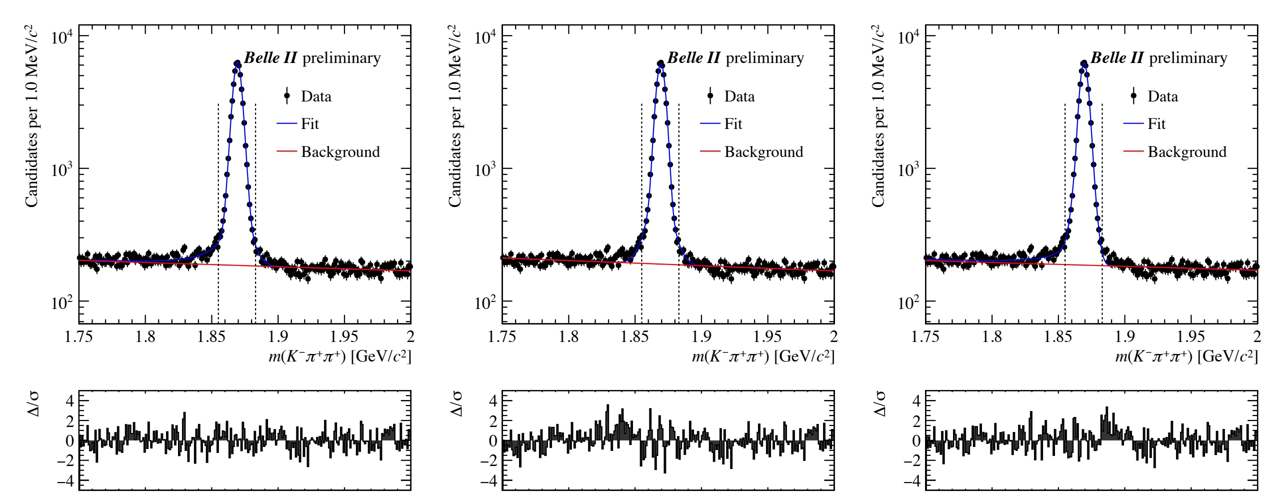
- The background is accounted for by the fit using sideband data. Two sources of uncertainties:

1. Background modeling
   - Simulation shows that sideband data describes the background in the signal region correctly, however, simulation and data sidebands show some disagreement
   - Fits to 1k pseudo experiments that micic a similar level of disagreement between signal and sidebands return an average bias of 2.52 ± 0.16 fs, which is assigned as systematic uncertainty

• , $K^-\pi^+\pi^-\pi^+$

2. Background fraction
   - Determine background fraction in signal region with alternative mass models and repeat fit to the data
   - Average variation wrt to nominal result of 0.14 ± 0.32 fs is consistent with zero (no additional systematic uncertainty assigned)





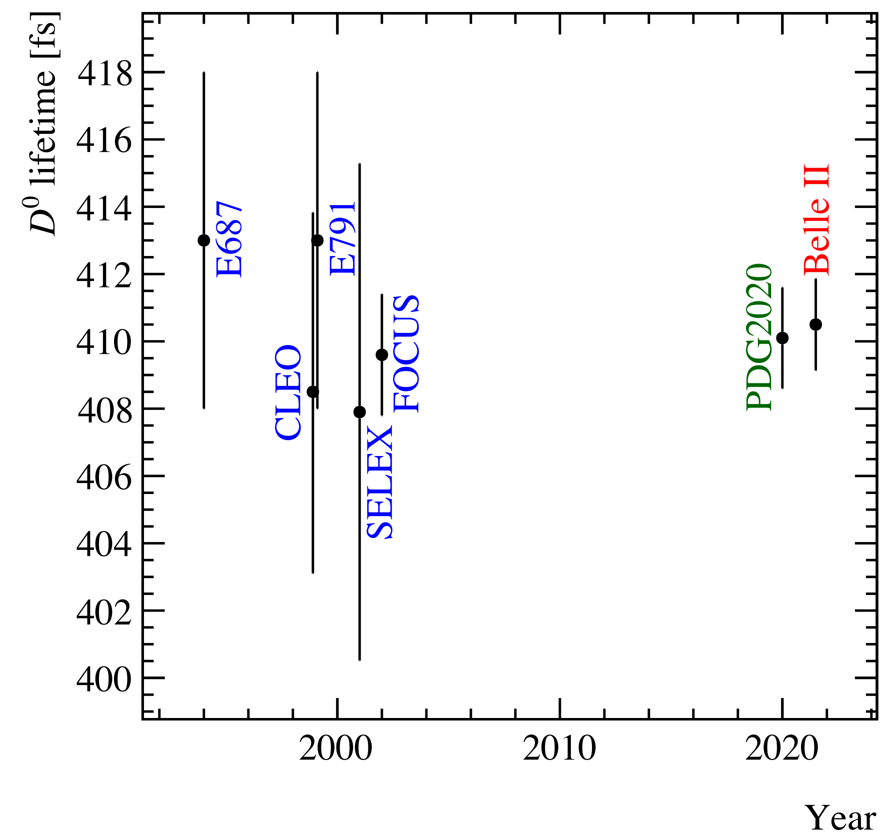
nominal

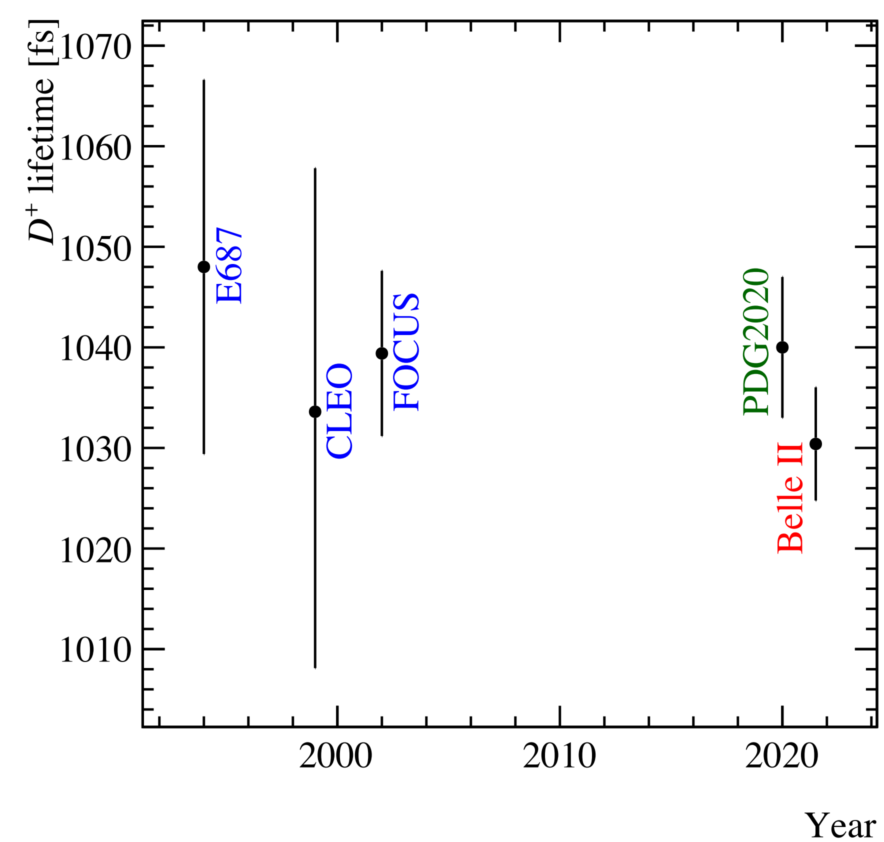
alternative

Conclusion

$$\tau(D^0) = \quad 410.5 \pm 1.1 \pm 0.8\,\mathrm{fs}$$
$$\tau(D^+) = 1030.4 \pm 4.7 \pm 3.1\,\mathrm{fs}$$

- World's best results of D^0 and D^+ lifetime, consistent with current world averages.
- Sub-1% accuracy establishes excellent performance of our detector!

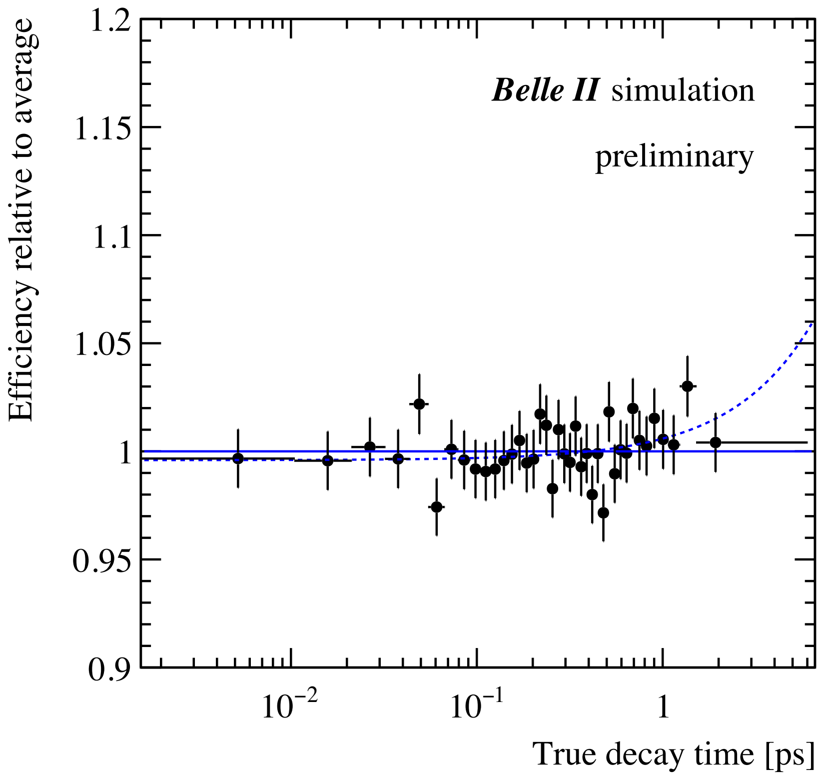




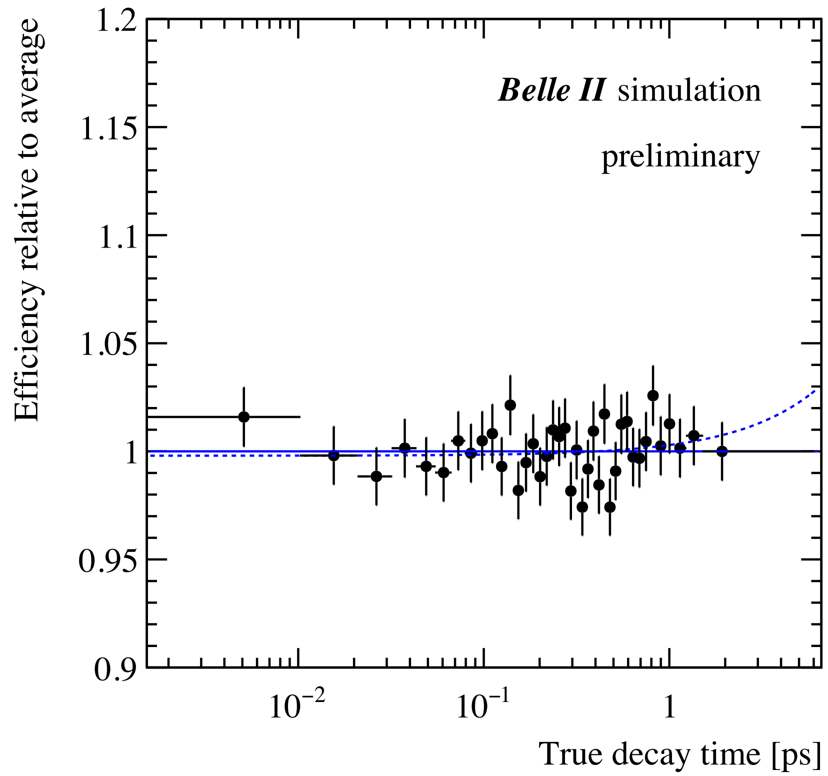
Backup

Efficiency vs decay time

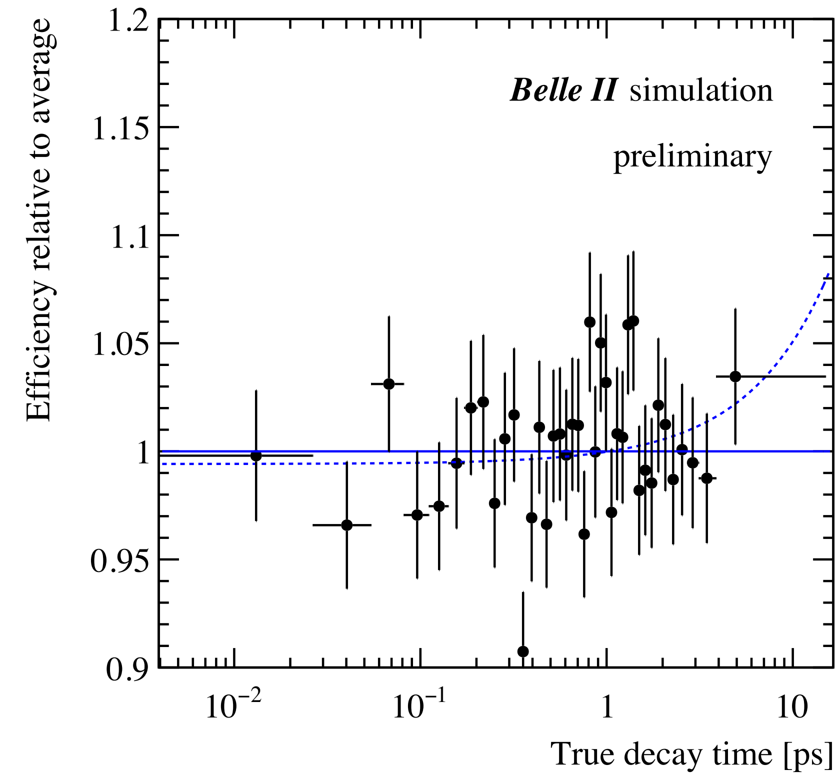
$D^0 \to K^-\pi^+$



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



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



- Efficiency consistent with being independent of decay time
- Average true decay times consistent with generated lifetimes of 410.1. fs and 1040 fs (values in parenthesis are from larger sample of run-independent simulation)

411.73 ± 0.88 fs	410.86 ± 0.87 fs	1047.6 ± 5.0 fs
(410.72 ± 0.37 fs)	(409.98 ± 0.40 fs)	(1042.8 ± 1.8 fs)

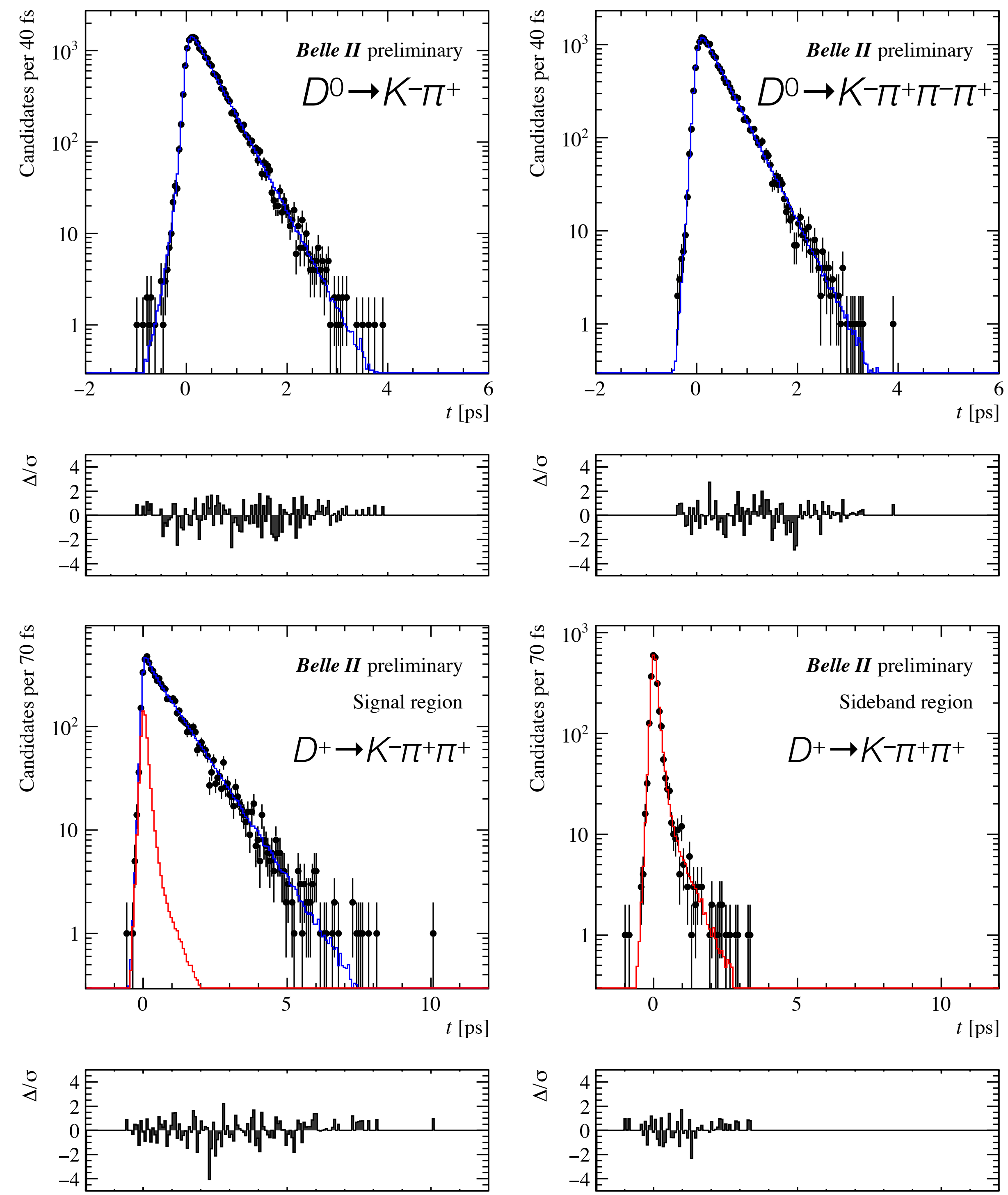
Results from 2019 data (unblinded)

- All lifetimes well consistent with world-average values

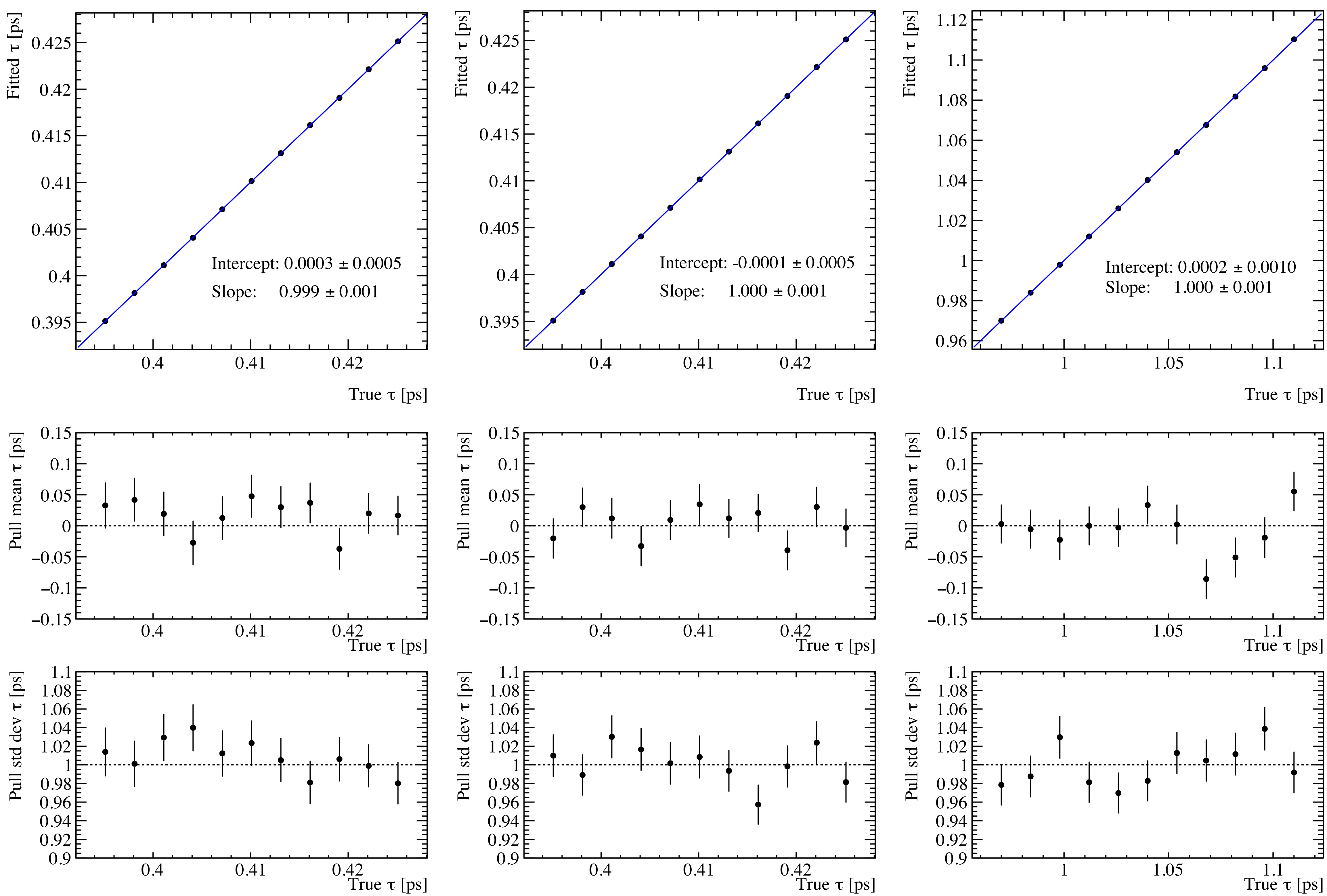
$$\tau(D^0) = 410.1 \pm 1.5\,\mathrm{fs}$$
$$\tau(D^+) = 1040 \pm 7\,\mathrm{fs}$$

- Reasonable modeling of the decay-time distributions

Parameter	Fit result		
	$D^0 \to K^-\pi^+$	$D^0 \to K^-\pi^+\pi^+\pi^-$	$D^+ \to K^-\pi^+\pi^+$
τ (fs)	414.8 ± 3.2	406.1 ± 3.5	1022 ± 13
b (fs)	3.0 ± 1.6	1.8 ± 1.8	3.4 ± 4.2
s	1.225 ± 0.022	1.147 ± 0.024	1.260 ± 0.030
f_b	–	–	0.0830 ± 0.0015
f_{bl}	–	–	0.468 ± 0.063
f_{bl1}	–	–	0.798 ± 0.037
τ_{b1} (fs)	–	–	121 ± 19
τ_{b2} (fs)	–	–	642 ± 83



Validation with pseudo experiments

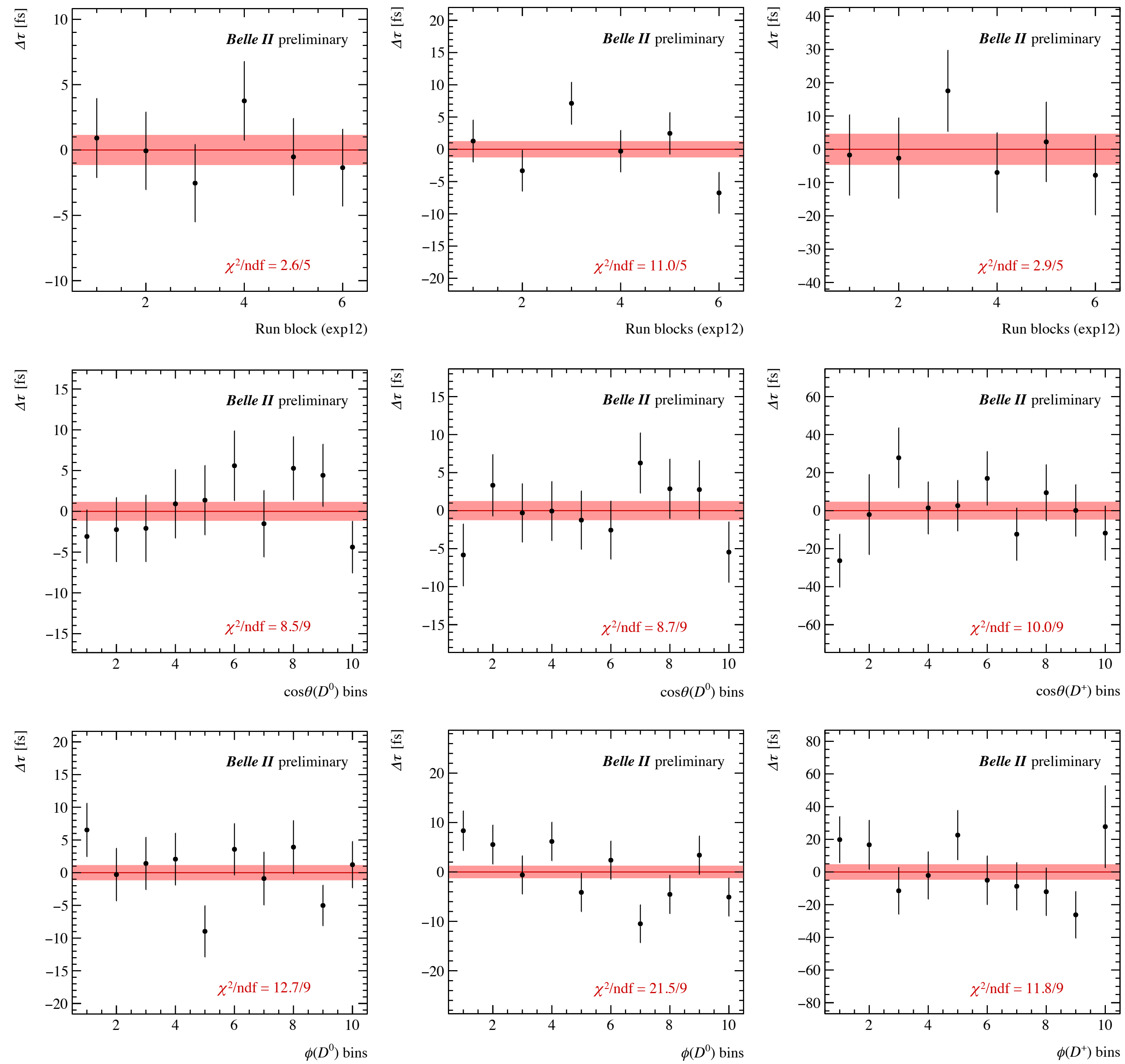


Consistency checks

- Several additional checks are performed targeting the particular systematic uncertainties that have been already discussed and/or possible other unexpected effects

- Nothing unexpected observed

- As an example: the lifetimes measured in bins of run number, polar angle and azimuthal angle show variations that are consistent with statistical fluctuations



(Blind) Results to the full data sample

- Blinding offsets sampled random between (D^0) [–7.5,7.5] fs and (D^+) [–35,+35] fs
    - Same blinding for $K\pi$ and $K3\pi$ final states
- D^0 lifetime consistent between the two modes
- Statistical precision competitive with world average: (D^0) 1.5 fs, (D^+) 7 fs

Parameter	Fit result		
	$D^0 \to K^-\pi^+$	$D^0 \to K^-\pi^+\pi^+\pi^-$	$D^+ \to K^-\pi^+\pi^+$
τ (fs)	416.1 ± 1.1	414.4 ± 1.2	1036.0 ± 4.7
b (fs)	3.30 ± 0.55	5.27 ± 0.64	7.5 ± 1.7
b_{bkg} (fs)	–	–	4.4 ± 2.3
f_1	0.969 ± 0.010	–	–
$s_{(1)}$	1.118 ± 0.013	1.1648 ± 0.0084	1.2887 ± 0.0099
s_2	2.47 ± 0.18	–	–
f_b	–	–	0.08803 ± 0.00050
f_{bl}	–	–	0.401 ± 0.017
f_{bl1}	–	–	0.825 ± 0.011
τ_{b1} (fs)	–	–	153.1 ± 6.5
τ_{b2} (fs)	–	–	818 ± 34