Measurement of the Λ_c^+ lifetime at Belle II

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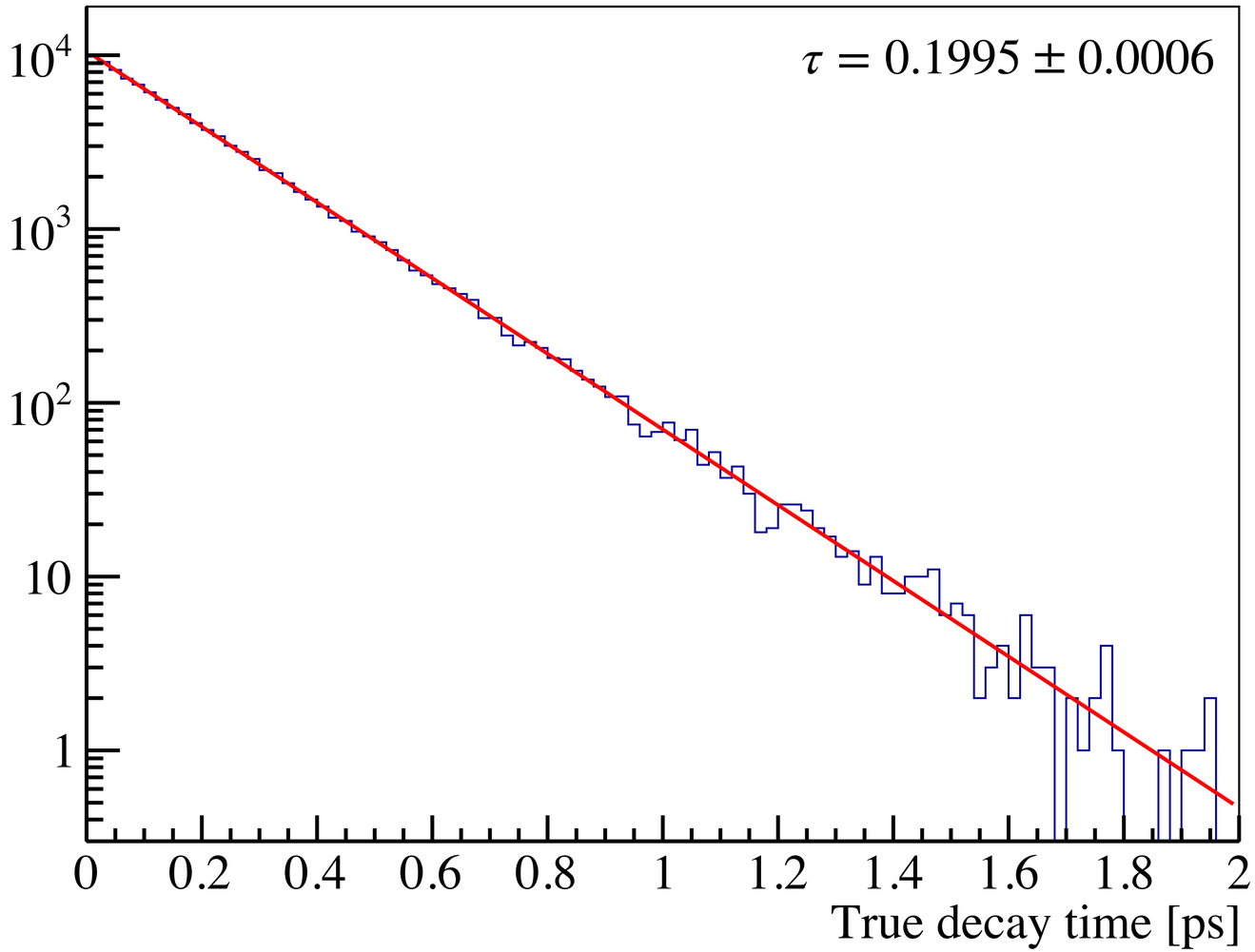
Fit to true flight time

- Simple fit to an exponential function
  - Consistent with expected 200 fs



Lifetime fit

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

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

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

Proper time scaling error

Common bias

- CLEO method:

$$L(\tau_{\Lambda_c^+}, f_{\rm bg}, \tau_{\rm bg}, S, f_{\rm mis}, \sigma_{\rm mis}, f_{\rm wide}) = \prod_i \int_0^{\infty} dt' \left[\underbrace{p_{{\rm sig},i} E(t' \,|\, \tau_{\Lambda_c^+})}_{\text{signal fraction}} + \underbrace{(1 - p_{{\rm sig},i})[f_{\rm bg} E(t' \,|\, \tau_{\rm bg}) + (1 - f_{\rm bg})\delta(t')]}_{\text{background fraction}} \right]$$

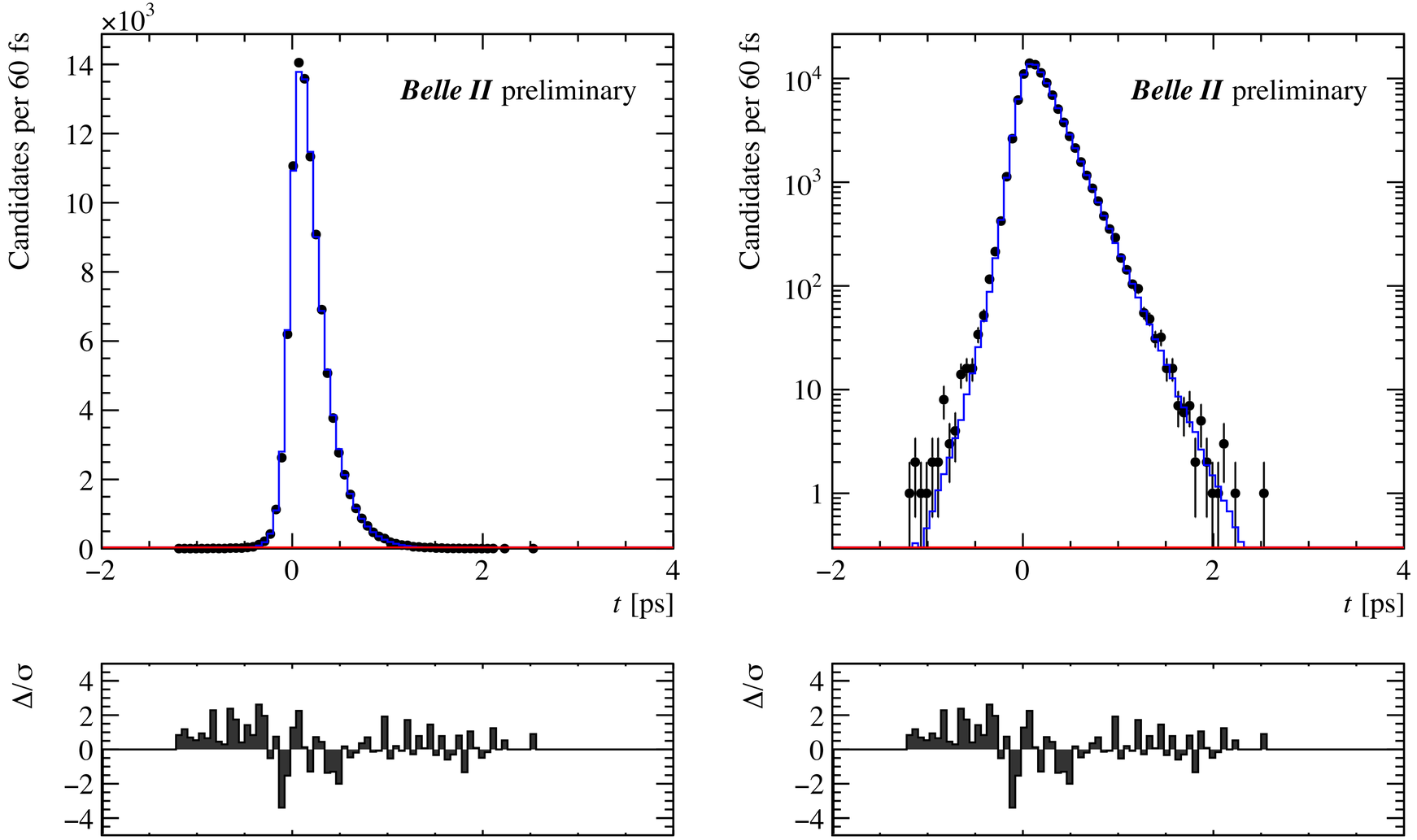
$$\times \left[\underbrace{(1 - f_{\rm mis} - f_{\rm wide}) G(t_i - t' \,|\, S\sigma_{t,i})}_{\text{proper time resolution}} \right.$$

$$\left. + \underbrace{f_{\rm mis} G(t_i - t' \,|\, \sigma_{\rm mis}) + f_{\rm wide} G(t_i - t' \,|\, \sigma_{\rm wide})}_{\text{mismeasured fraction}} \right],$$

Signal only fit

$$pdf(t, \sigma_t \,|\, \tau, \mu, f, s, s_{wide})$$

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



$\tau = 0.1975 \pm 0.0010$

$\mu = 0.0012 \pm 0.0007$

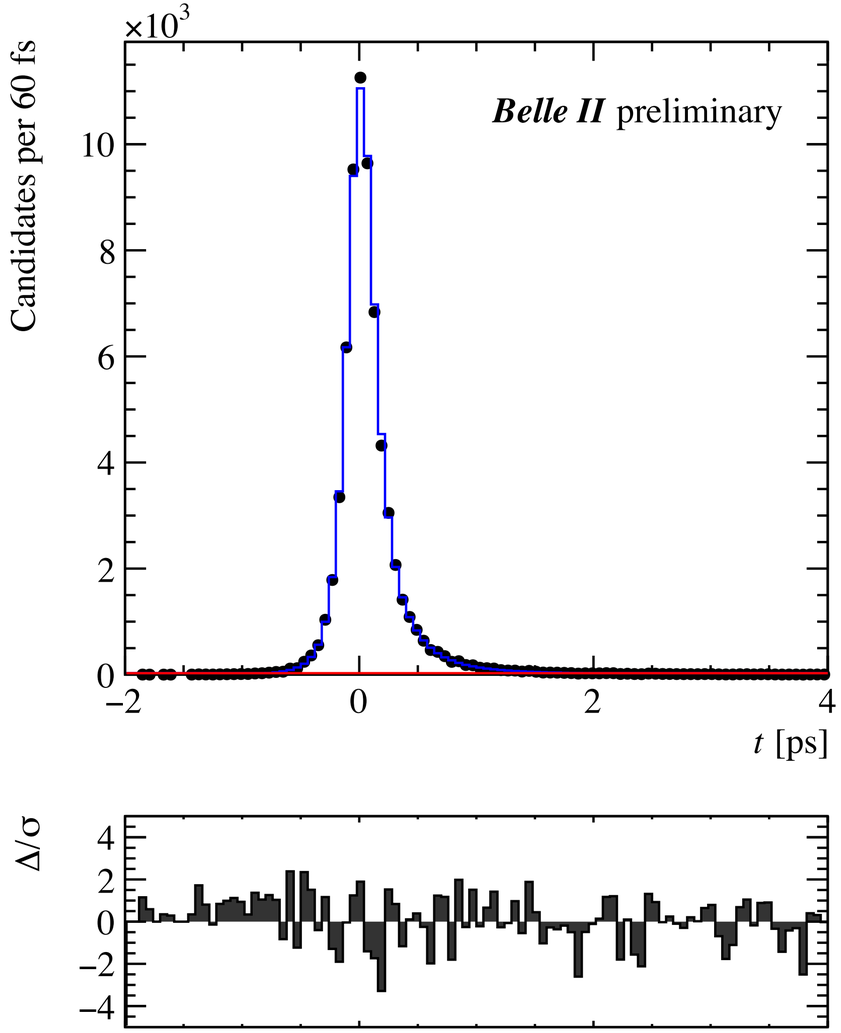
$s = 0.976 \pm 0.031$

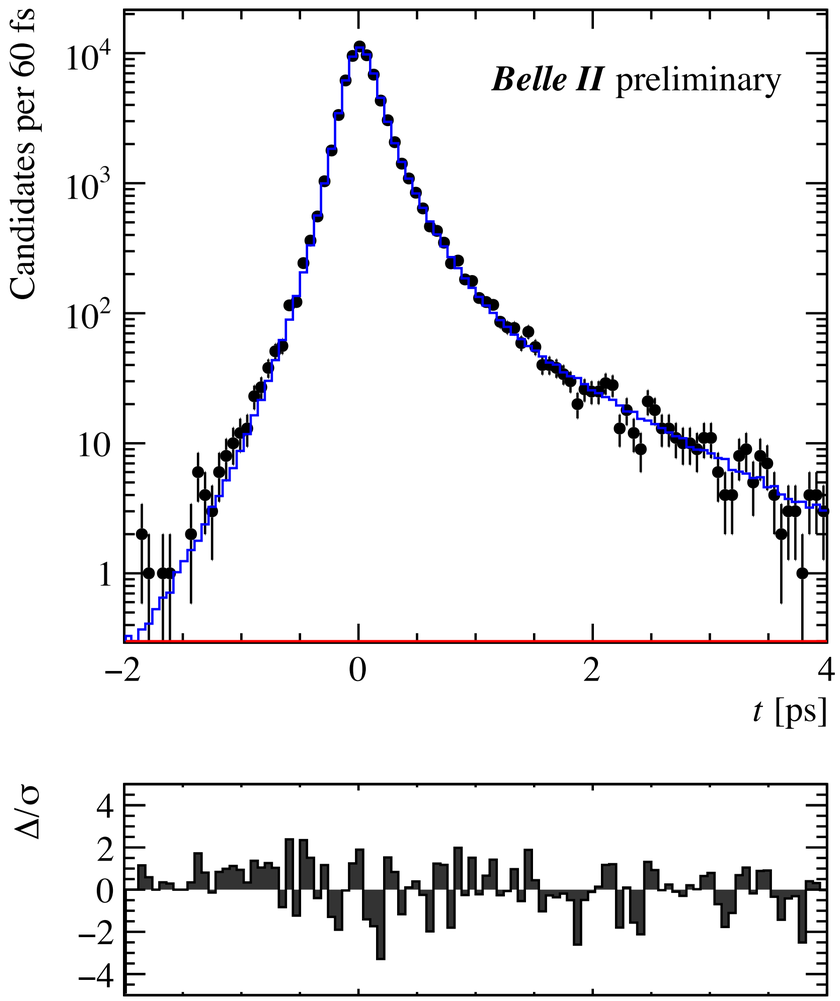
$s_{wide} = 2.634 \pm 1.859$

$f = 0.993 \pm 0.020$

Lifetime fit to sidebands (background component to fit)

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





$\tau_{bkg1} = 0.887 \pm 0.051$

$\tau_{bkg2} = 0.221 \pm 0.010$

$\mu = 0.0053 \pm 0.0010$

$s = 1.024 \pm 0.007$

$s_{wide} = 2.246 \pm 0.078$

$f_\tau = 0.258 \pm 0.008$

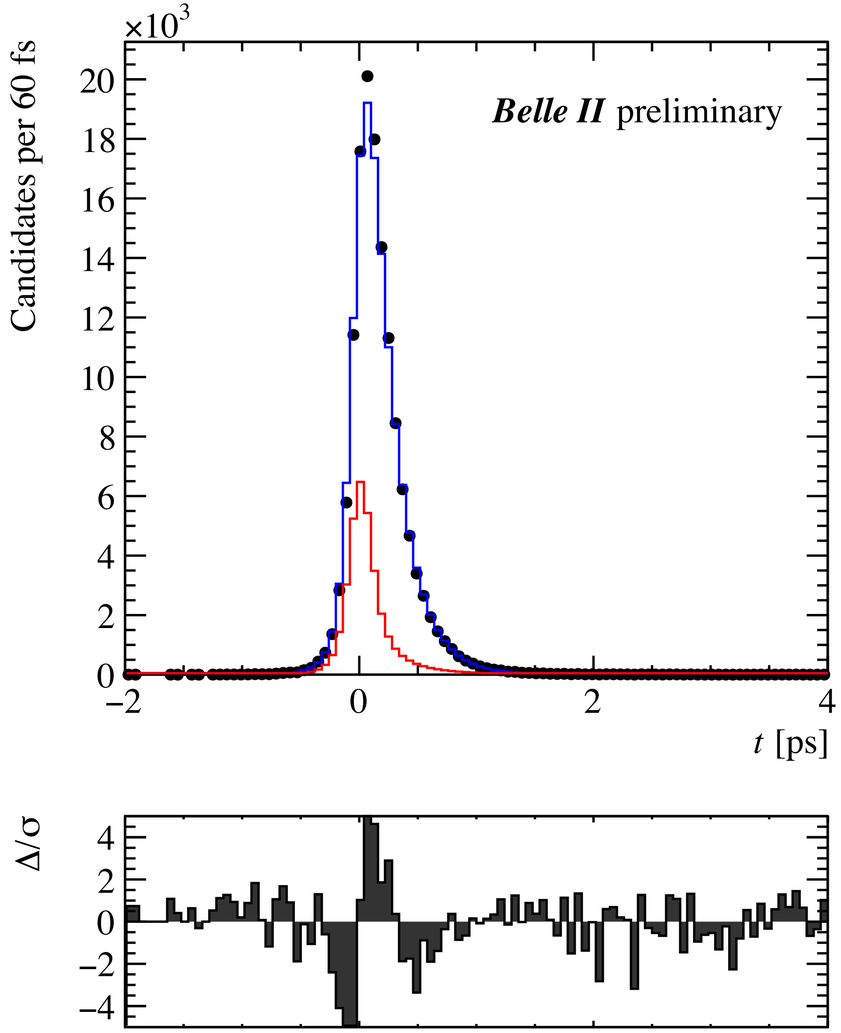
$f_{\tau_1} = 0.196 \pm 0.017$

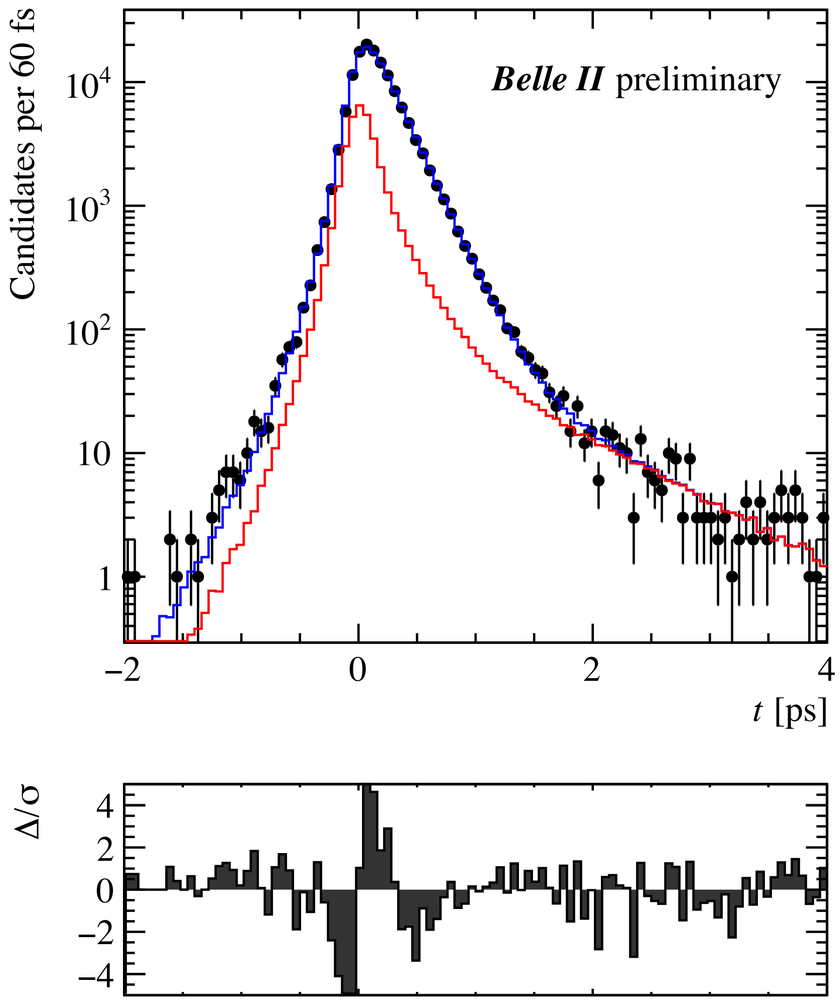
$f = 0.934 \pm 0.007$

Lifetime fit

Fixed from fit to sidebands

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





$f_{bkg} = 0.2482$ $(fixed)$

$\tau = 0.1948 \pm 0.0007$

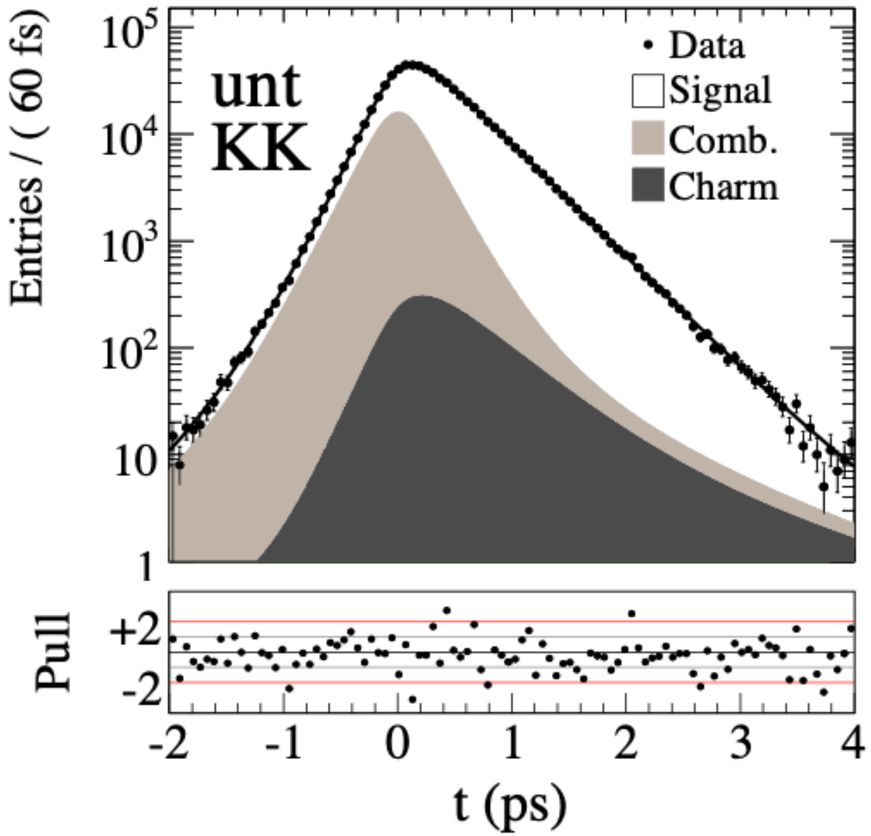
$\tau_{true} = 0.200$

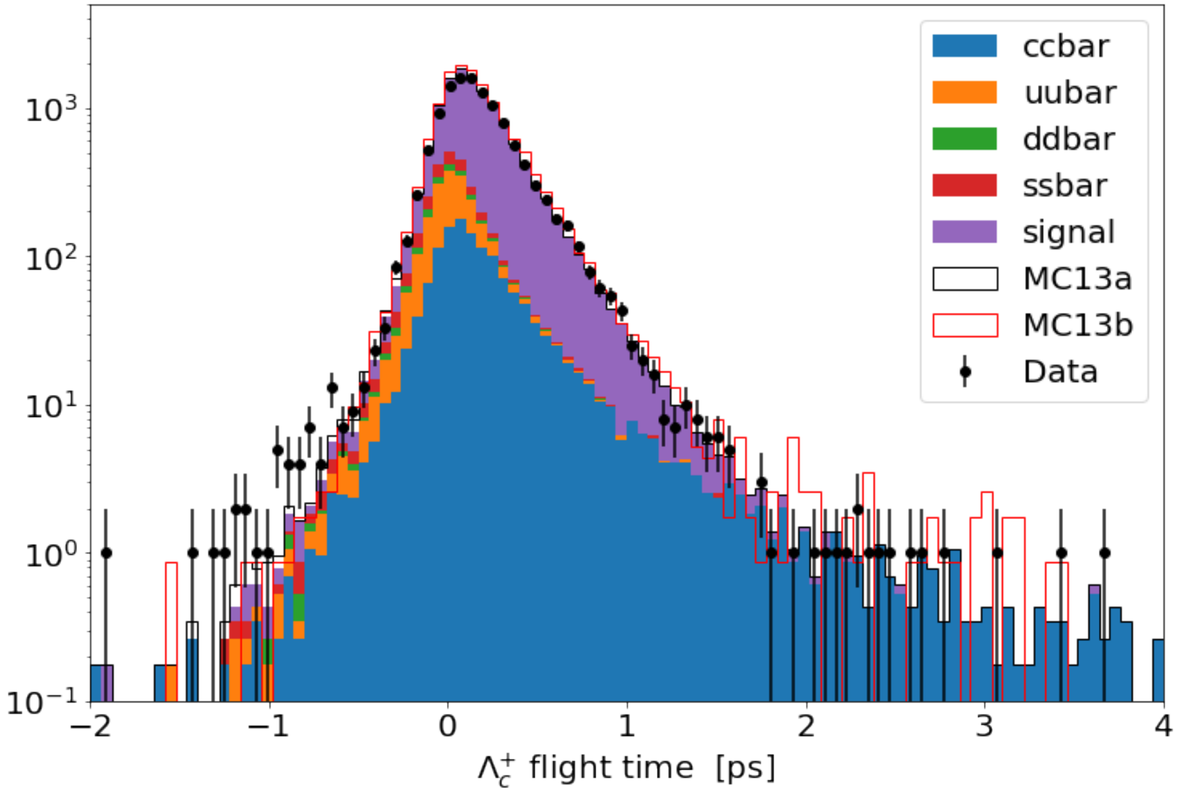
LHCB, $\tau = 203.5 \pm 1.0 \pm 1.3 \pm 1.4$ *fs*

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

Next attempt

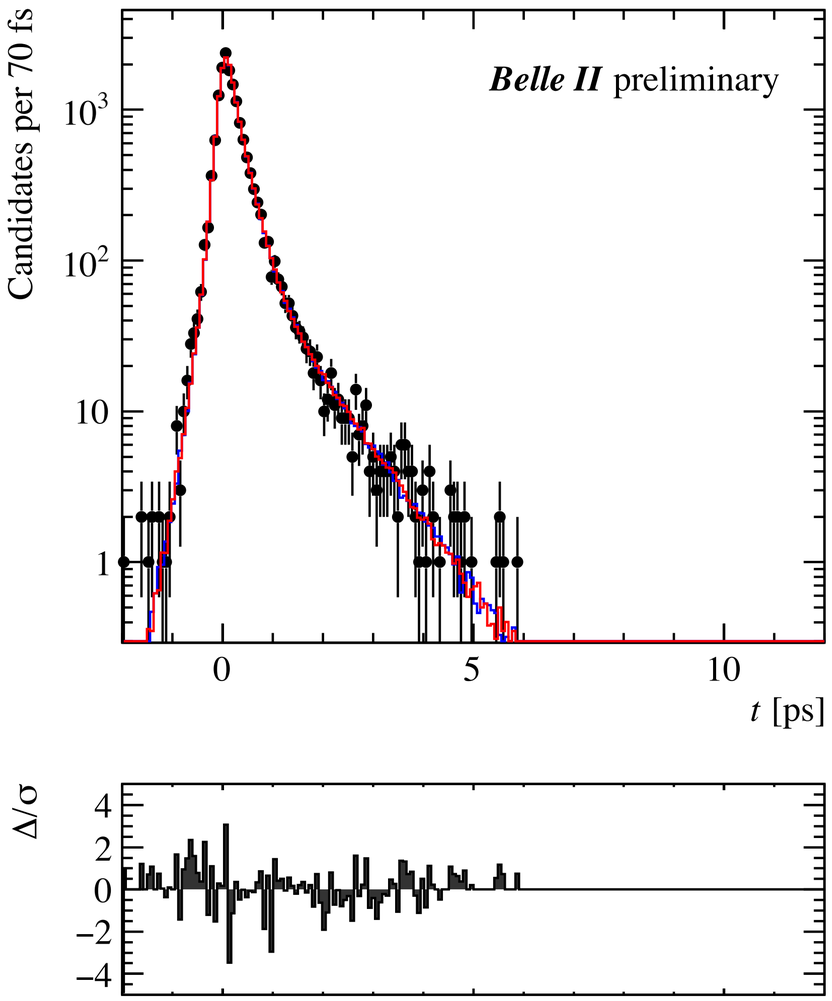
- Use a similar technique to yCP measurement at BaBar:
  - Fit MC-tagged charm backgrounds
  - Fix charm-related pdf and extract combinatorial backgrounds with weighted average from sideband fits



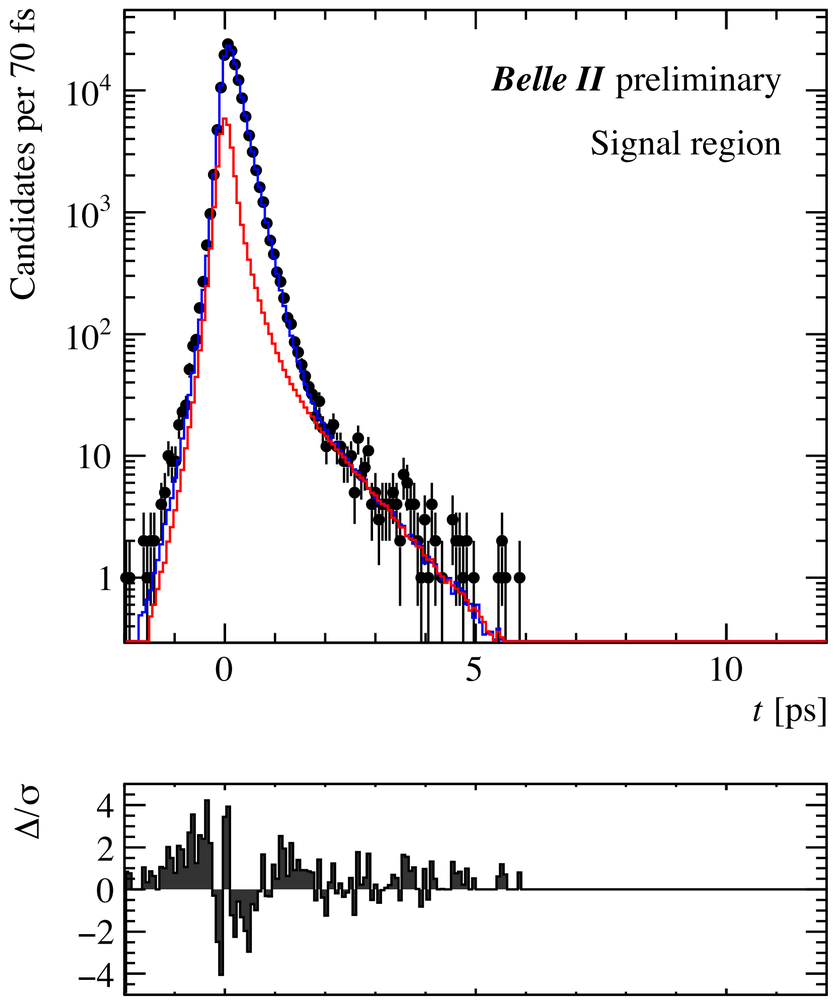


First attempt

Fit ccbar MC with “background” pdf



Fix lifetime background in fit to full sample



$$\tau = 0.1896 \pm 0.0002$$

$$f_{bkg} = 0.2671 \pm 0.005$$

$$\tau_{bkg1} = 0.235 \text{ (fixed)}$$

$$\tau_{bkg2} = 0.935 \text{ (fixed)}$$

$$\mu = 0.01747 \pm 0.0004$$

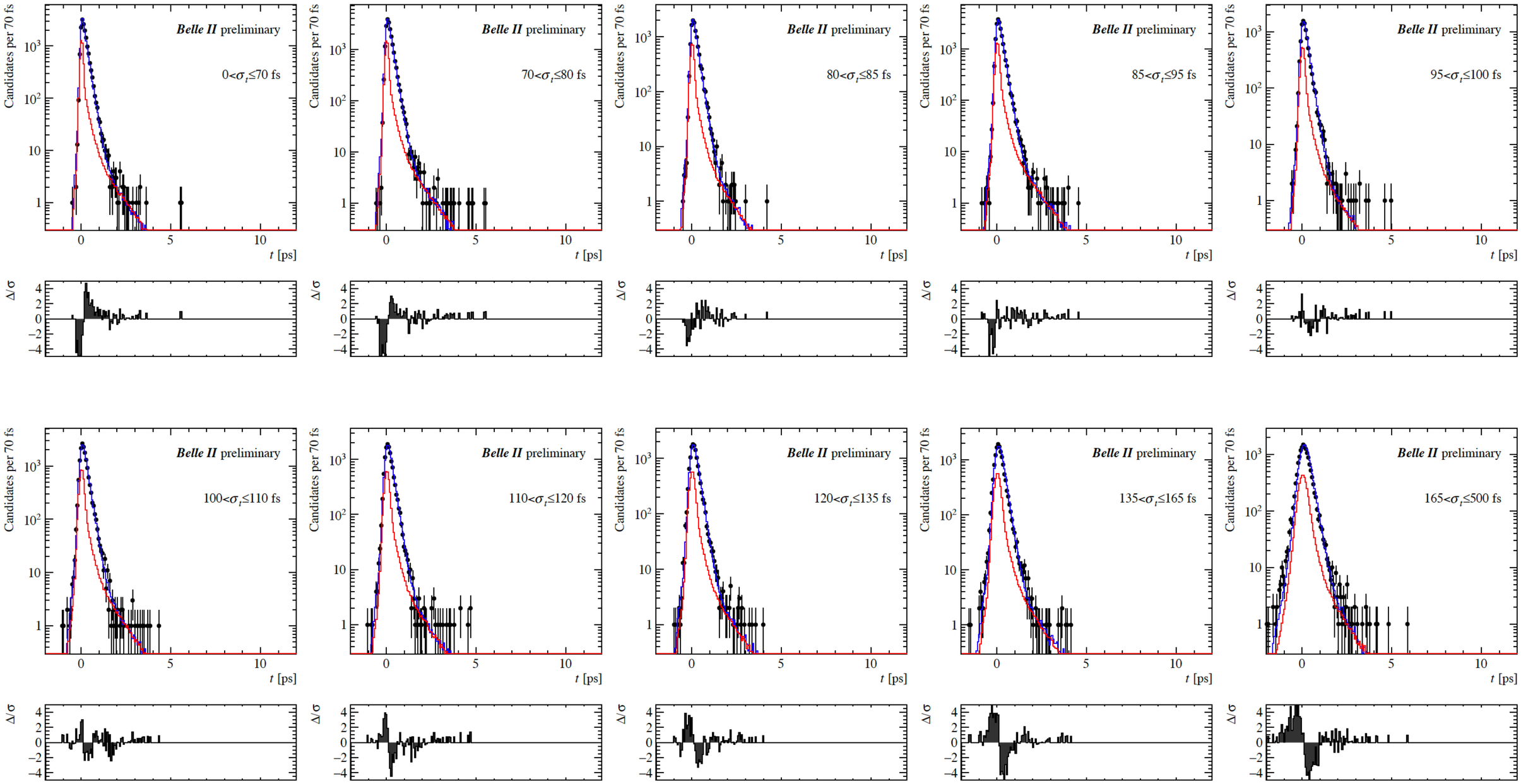
$$s = 1.043 \pm 0.005$$

$$s_{wide} = 2.6891 \pm 0.0001$$

$$f_{\tau} = 0.221 \pm 0.008$$

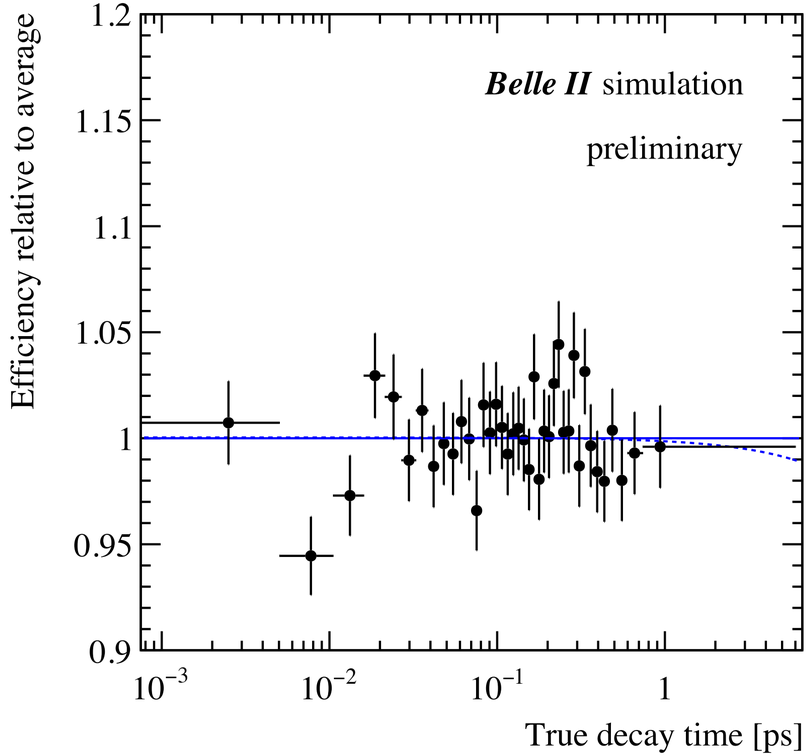
$$f_{\tau_1} = 0.791 \text{ (fixed)}$$

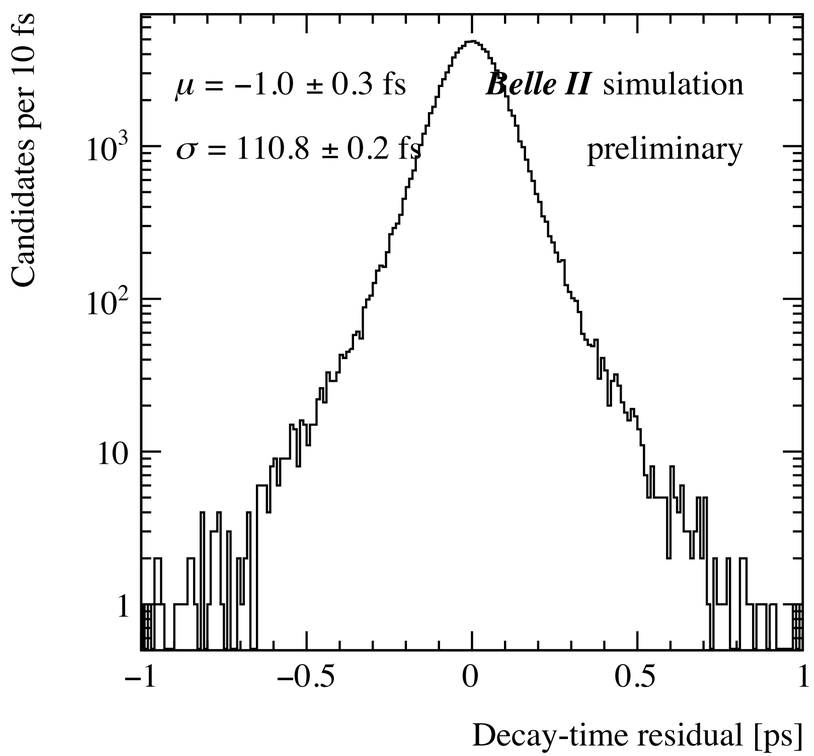
$$f = 0.966 \pm 0.002$$


Belle II preliminary
0<σt≤70 fs
70<σt≤80 fs
80<σt≤85 fs
85<σt≤95 fs
95<σt≤100 fs
100<σt≤110 fs
110<σt≤120 fs
120<σt≤135 fs
135<σt≤165 fs
165<σt≤500 fs
Candidates per 70 fs
t [ps]
Δ/σ

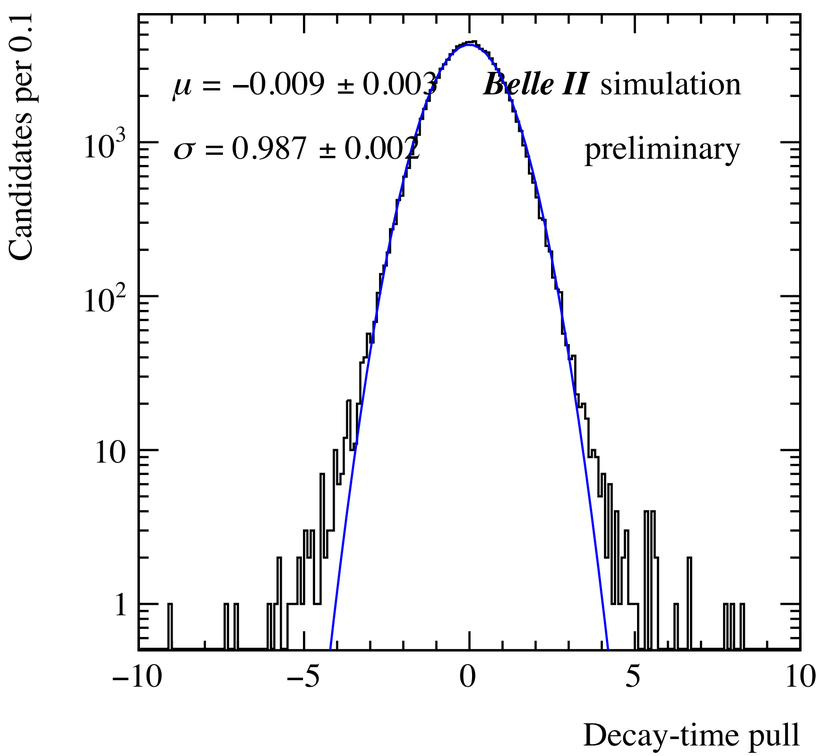
Reconstruction effects

- No evidence of reconstruction effects that would bias the decay time

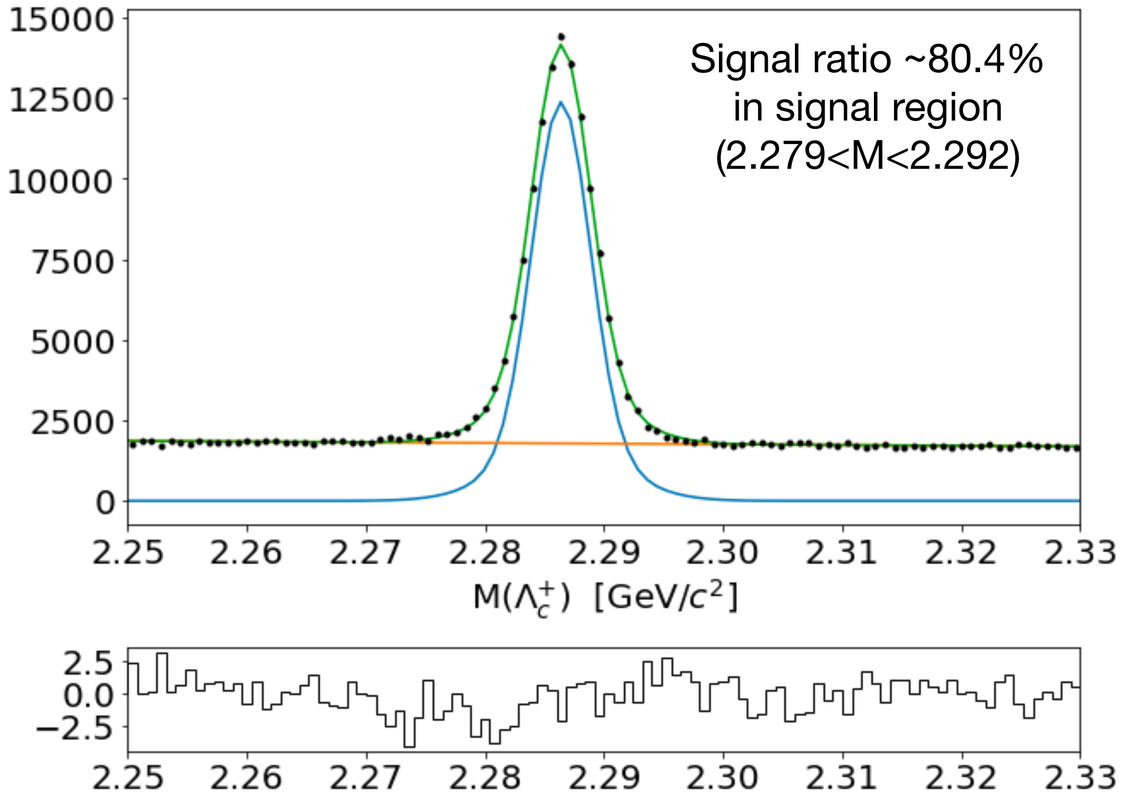




- Approximately Gaussian decay-time pull from truth-matched events

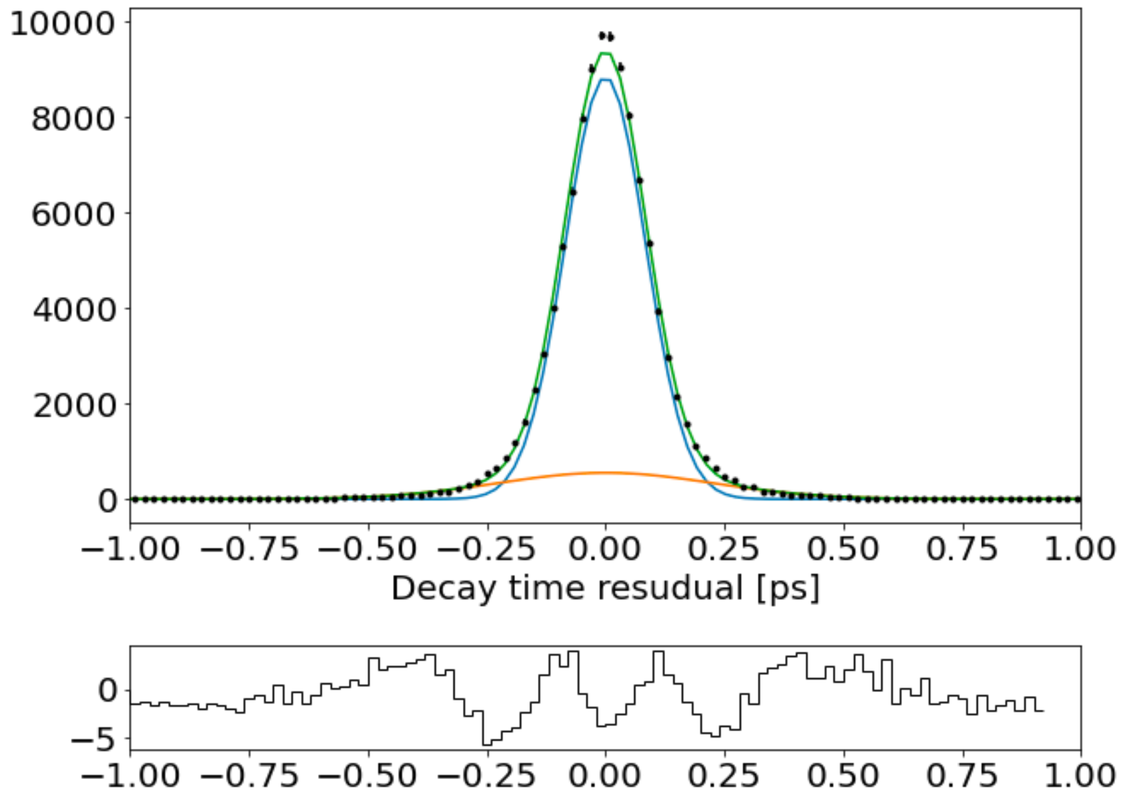


- Fit to Λ_c^+ invariant mass
  - Double Gaussian signal
  - 2D polynomial background



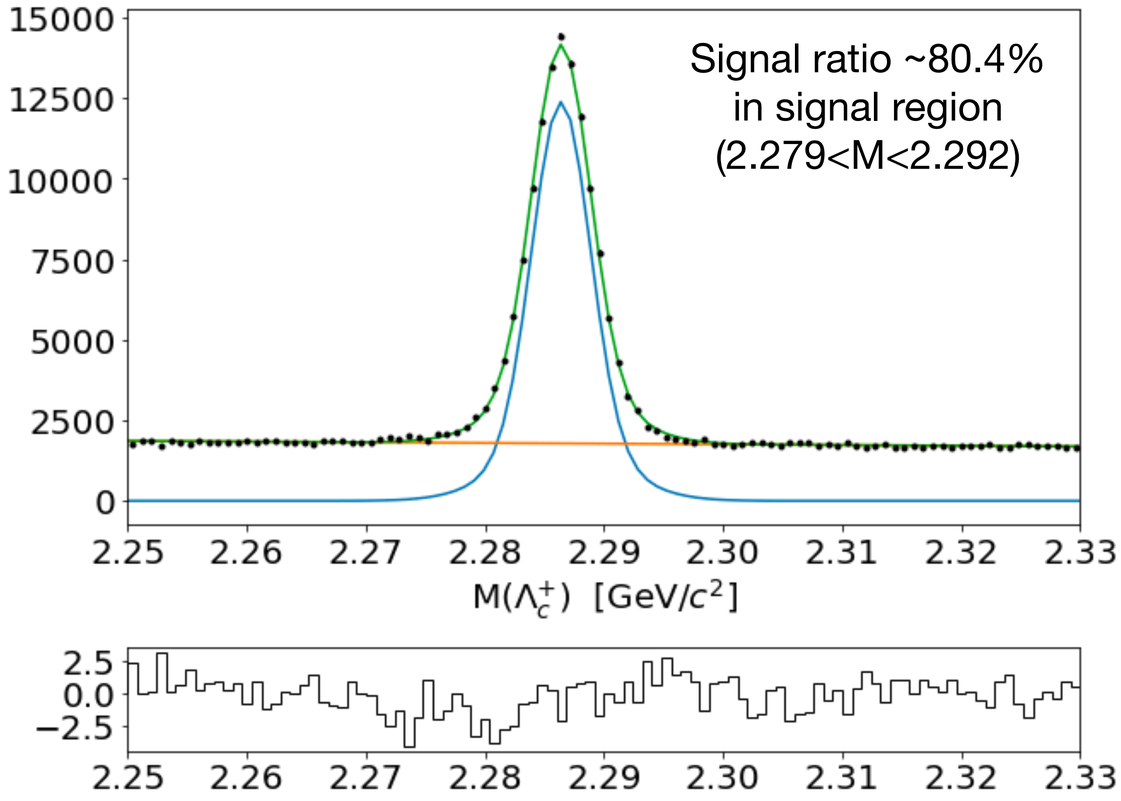
name	value	minuit_hesse	minuit_minos		at limit
sig_yield	106100	+/- 4.9e+02	-5.1e+02	+4.9e+02	False
bkg_yield	177600	+/- 5.6e+02	-5.5e+02	+5.7e+02	False
fg1	0.2302	+/- 0.028	- 0.028	+ 0.038	False
mu1	2.286	+/- 1.1e-05	-1.1e-05	+1.1e-05	False
s1	0.004853	+/- 0.00029	-0.00032	+0.00033	False
s2	0.002419	+/- 3.4e-05	-4.6e-05	+3.4e-05	False
a	-0.04864	+/- 0.0042	- 0.0042	+ 0.0041	False

- Double Gaussian fit to decay time residual for true events in Λ_c^+ signal region



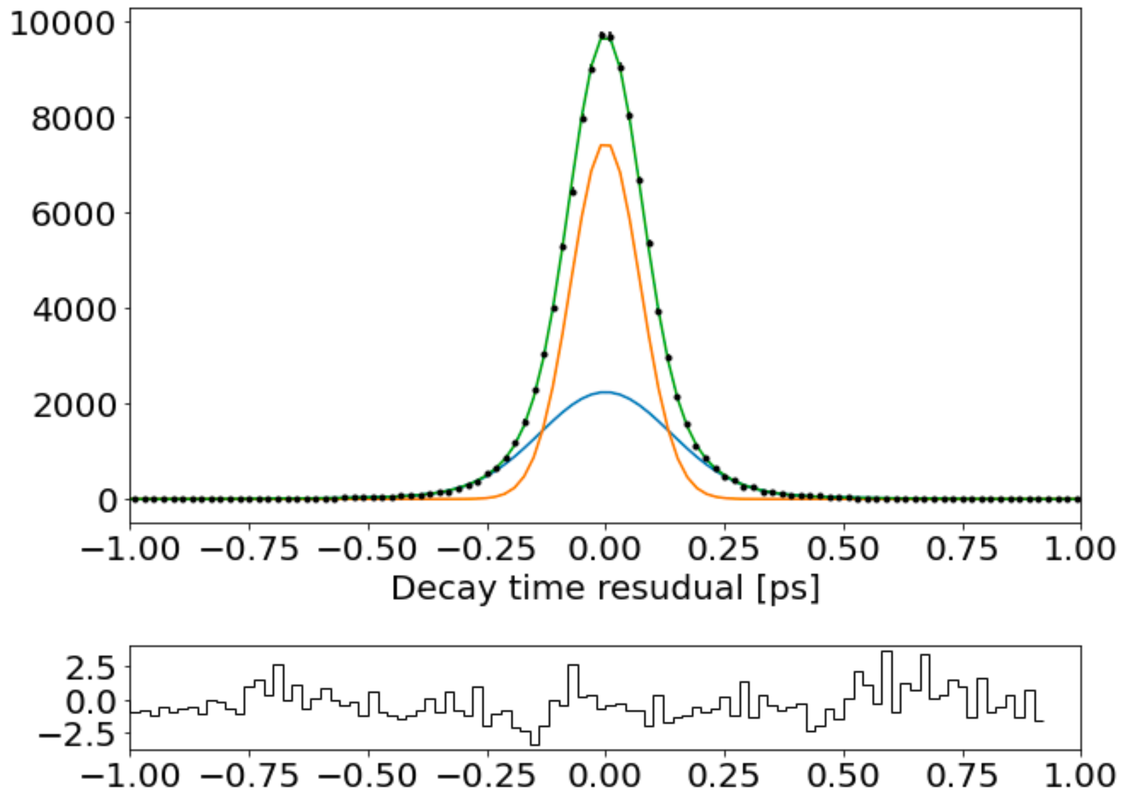
name	value	minuit_hesse	minuit_minos		at limit
sig_yield_mc	109000	+/- 3.3e+02	-3.3e+02	+3.3e+02	False
fg1_mc	0.8569	+/- 0.0039	- 0.004	+ 0.0039	False
mu1_mc	-0.0004268	+/- 0.0003	- 0.0003	+ 0.0003	False
s1_mc	0.08435	+/- 0.00039	-0.00039	+0.00039	False
s2_mc	0.2263	+/- 0.0023	- 0.0023	+ 0.0023	False

- Fit to Λ_c^+ invariant mass
  - Double Gaussian signal
  - 2D polynomial background



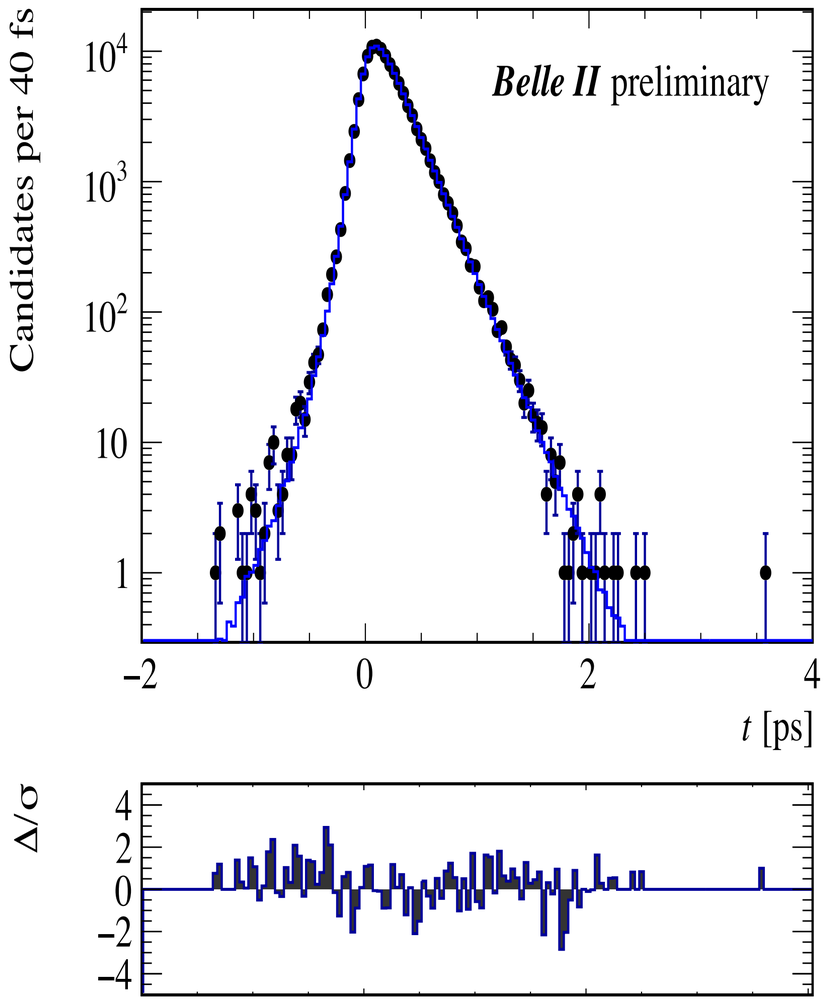
name	value	minuit_hesse	minuit_minos		at limit
sig_yield	106100	+/- 4.9e+02	-5.1e+02	+4.9e+02	False
bkg_yield	177600	+/- 5.6e+02	-5.5e+02	+5.7e+02	False
fg1	0.2302	+/- 0.028	- 0.028	+ 0.038	False
mu1	2.286	+/- 1.1e-05	-1.1e-05	+1.1e-05	False
s1	0.004853	+/- 0.00029	-0.00032	+0.00033	False
s2	0.002419	+/- 3.4e-05	-4.6e-05	+3.4e-05	False
a	-0.04864	+/- 0.0042	- 0.0042	+ 0.0041	False

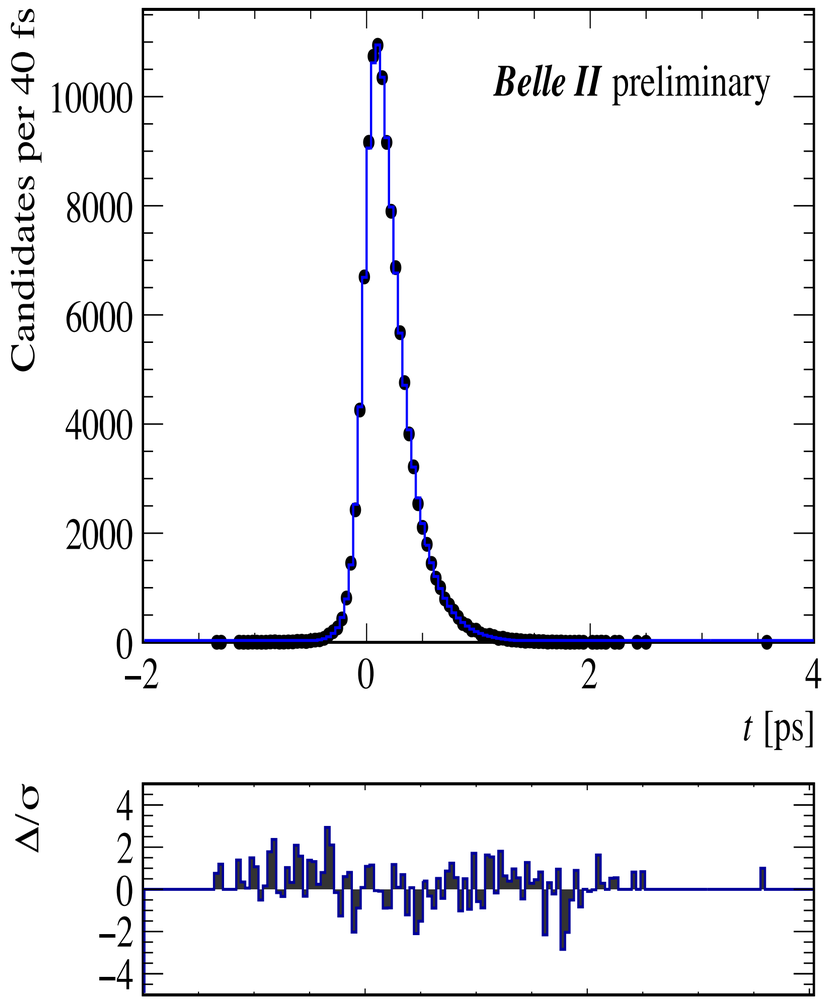
- Double Gaussian fit to decay time residual for true events in Λ_c^+ signal region



name	value	minuit_hesse	minuit_minos		at limit
sig_yield_mc	109000	+/- 3.3e+02	-3.2e+02	+3.4e+02	False
fg12_mc	0.374	+/- 0.023	- 0.023	+ 0.026	False
fg1_mc	0.1087	+/- 0.0083	- 0.0084	+ 0.0088	False
mu1_mc	-0.0003633	+/- 0.0003	-0.00027	+0.00033	False
s1_mc	0.3121	+/- 0.0092	- 0.0095	+ 0.01	False
s2_mc	0.1364	+/- 0.0036	- 0.004	+ 0.0039	False
s3_mc	0.07285	+/- 0.001	- 0.0011	+ 0.001	False

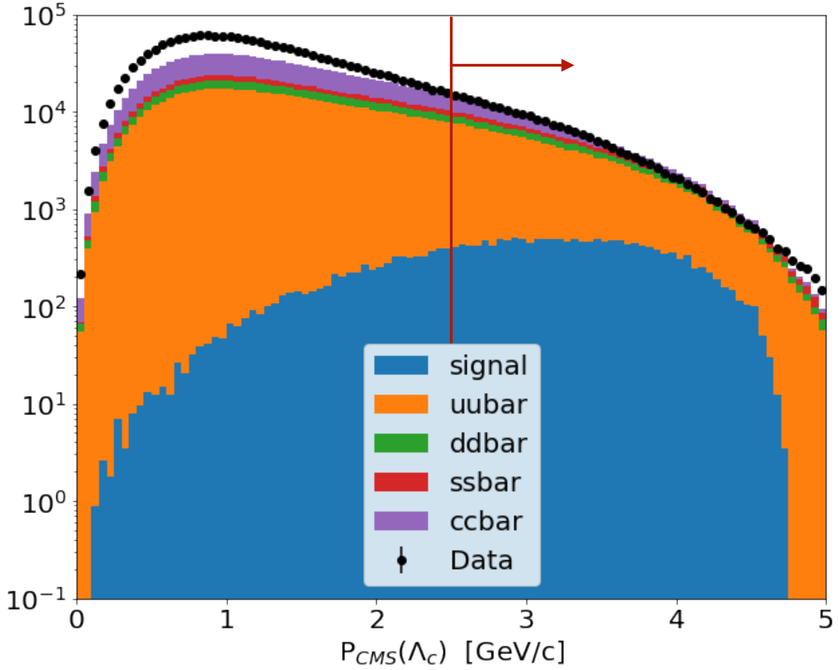
Lifetime with with triple Gaussian

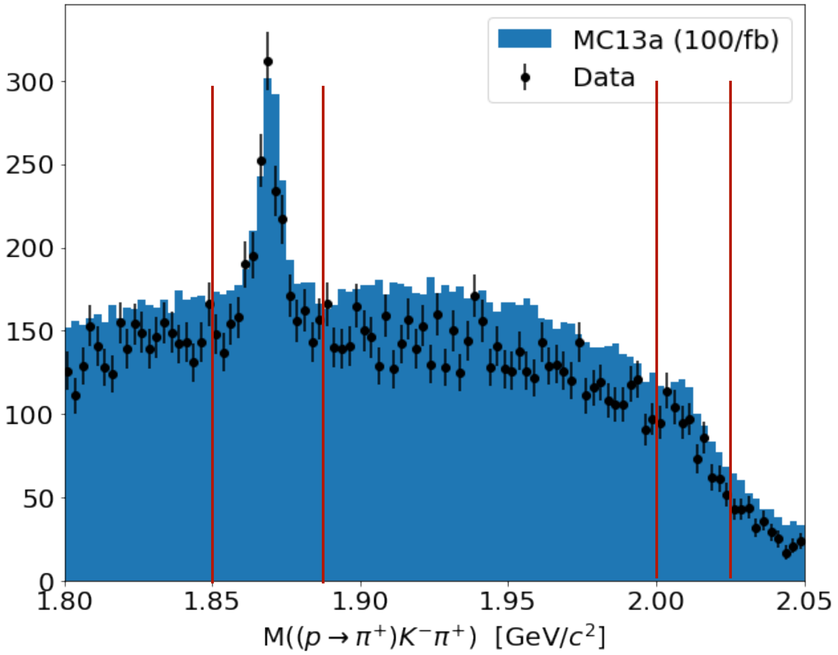




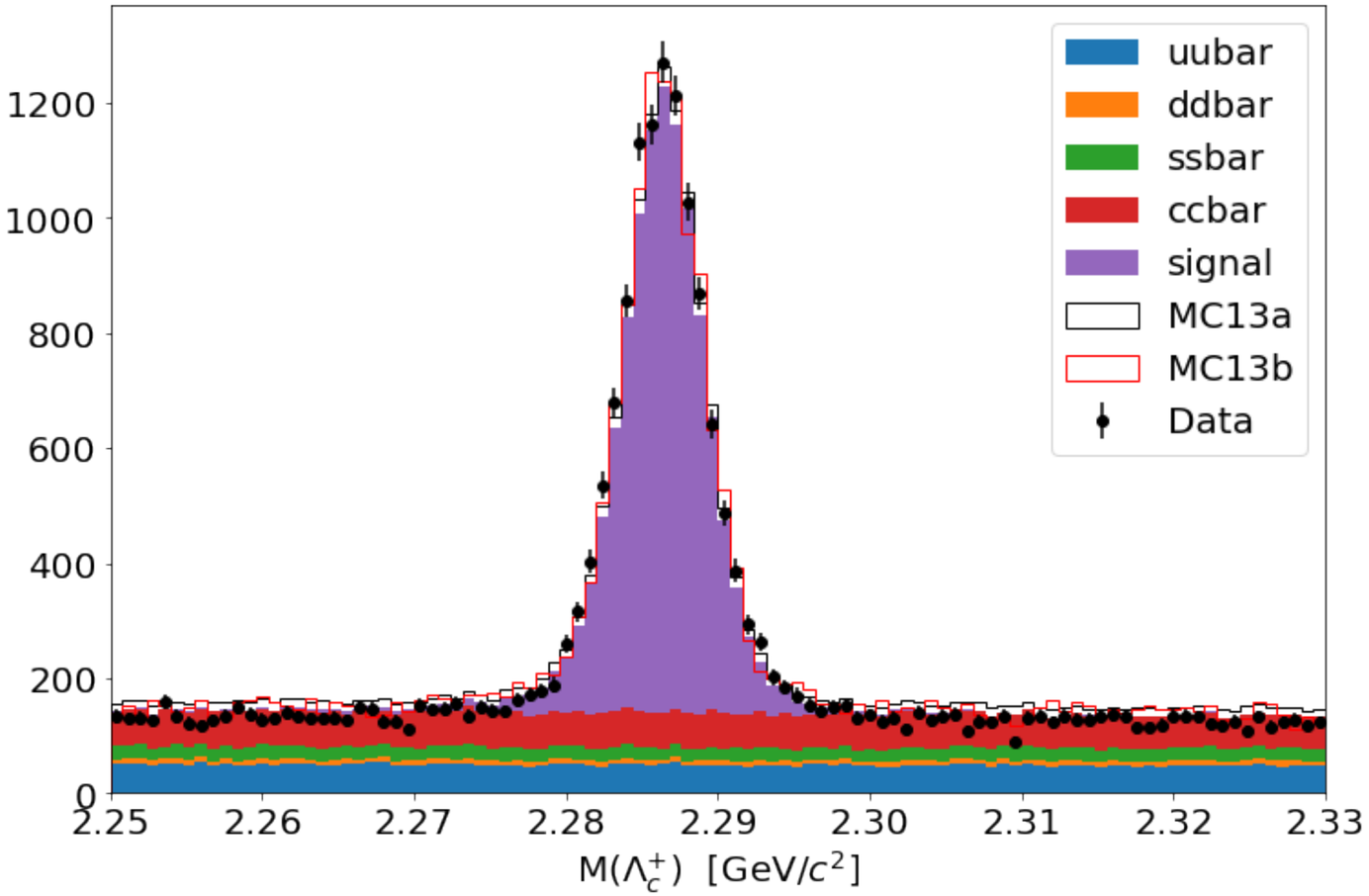
Event selection

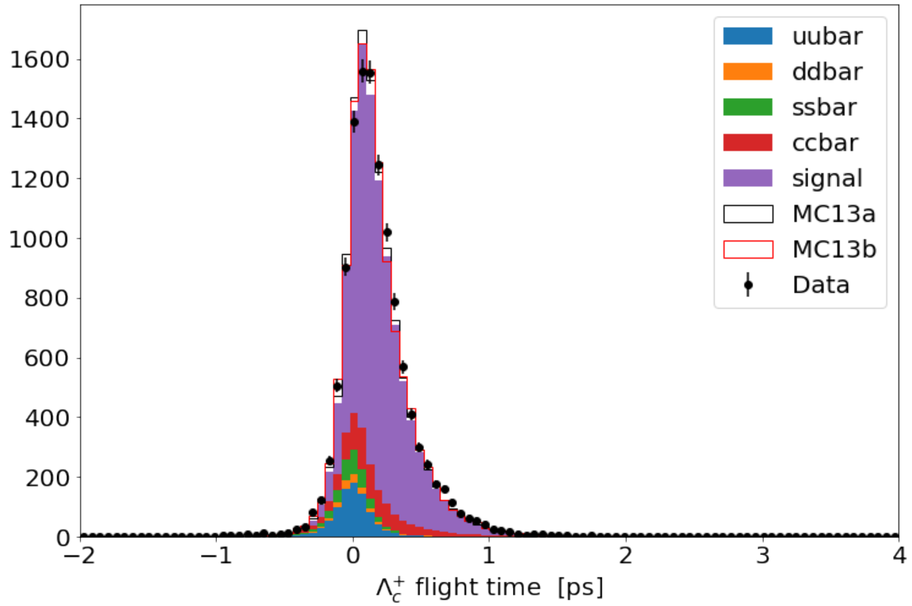
- Selection criteria:
  - Tracks must be in the CDC acceptance and have at least 20 CDC hits, at least one PXD hit, and the first SVD hit layer > 2
  - $d_0 < 0.5$ cm, $|z_0| < 2$ cm (standard track cuts)
  - Vertex fit (TreeFitter with IP constraint) conf_level > 0.001
  - Λ_c CM momentum > 2.5 GeV
  - Proton PID (trinary) > 0.8
  - Kaon PID (global) > 0.5
  - Remove charm backgrounds by cutting on M(pKπ) with pion hypothesis for proton track
- Samples
  - Data: proc11 (8.764/fb), ~blinded
  - MC: MC13a (100/fb), MC13b_proc11 (10/fb)

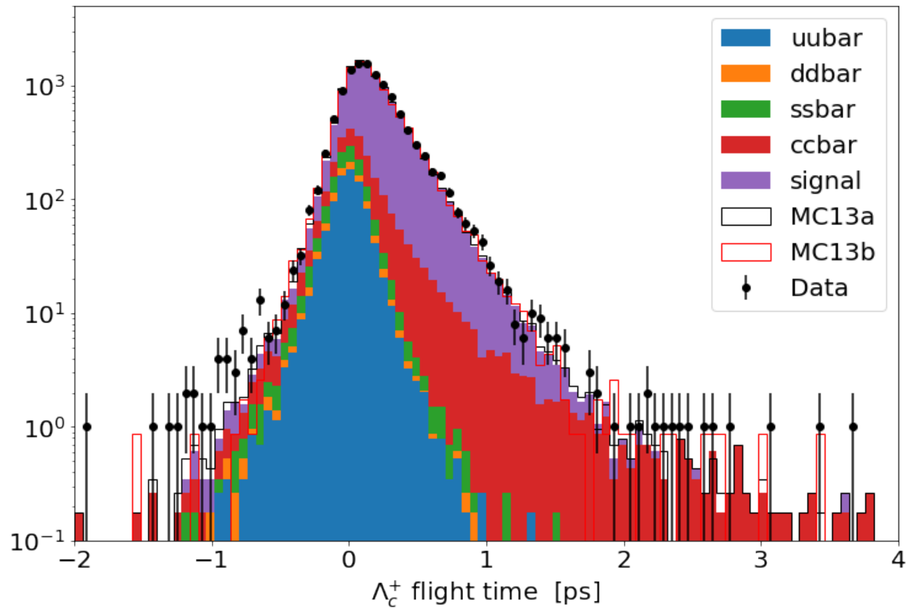




Invariant mass after all cuts



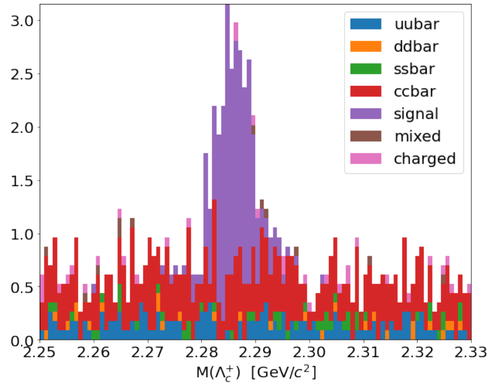




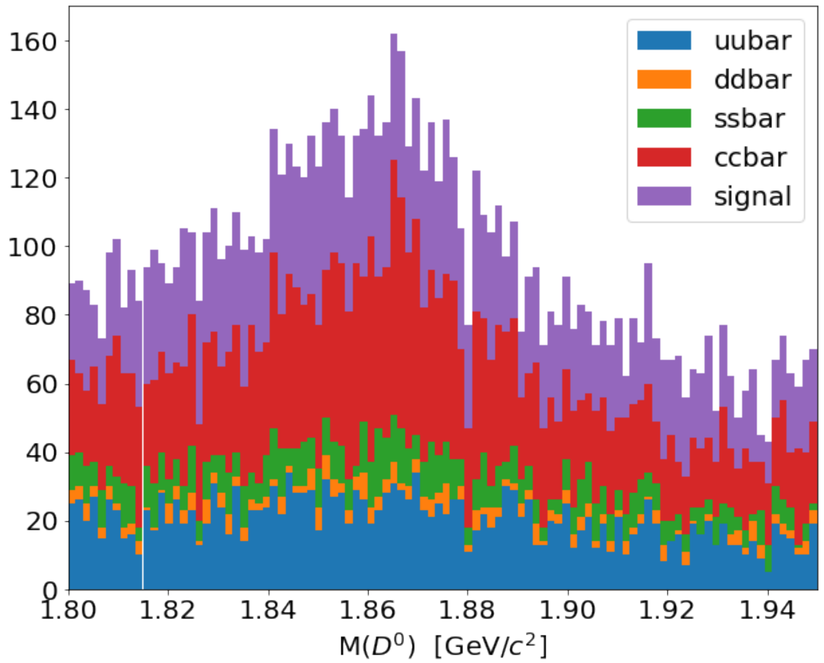
- Sizable remaining backgrounds from long-lived charm decays (complicated the lifetime fit)

Remaining backgrounds

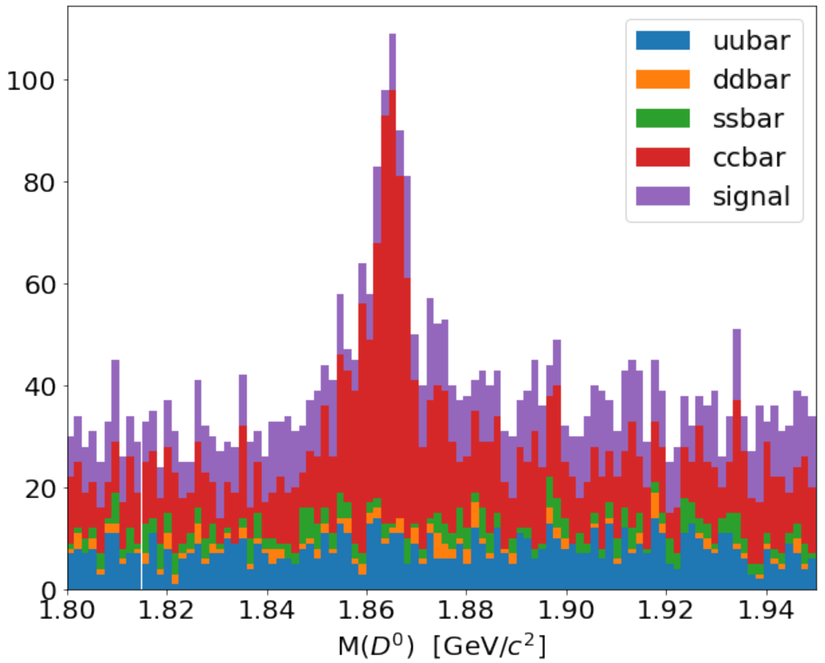
- Kaons from D^0 decays (47.4%)
  - Of those events, 36% also have a pion from a D^0 decay
- Kaons from D^+ decays (8%)
  - Of those events, 77% also have a pion from a D^+ decay
- Smaller backgrounds from K*, ϕ, ρ, virtual Z^0



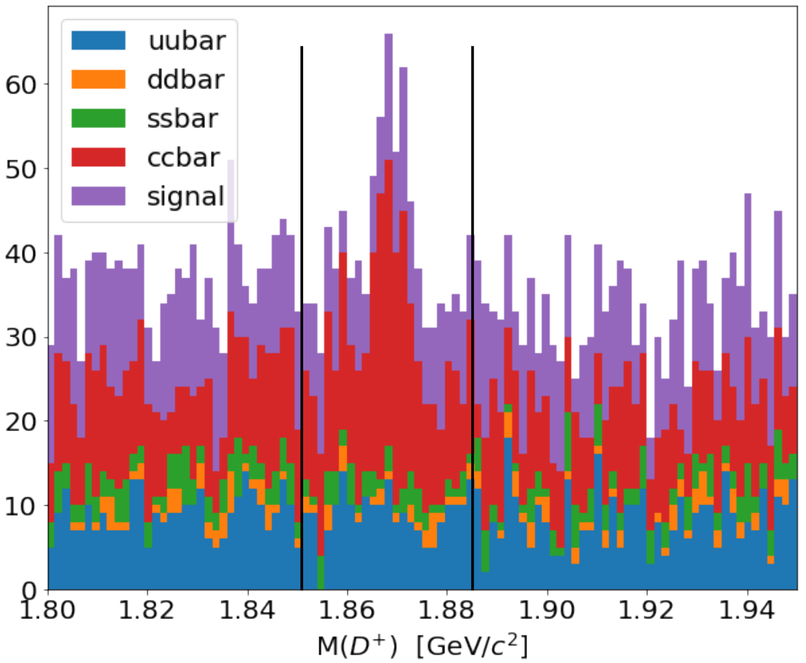
Combine signal $K^-\pi^+$ with a π^0 from the ROE



Combine signal $K^-\pi^+$ with a $\pi^-\pi^+$ from the ROE

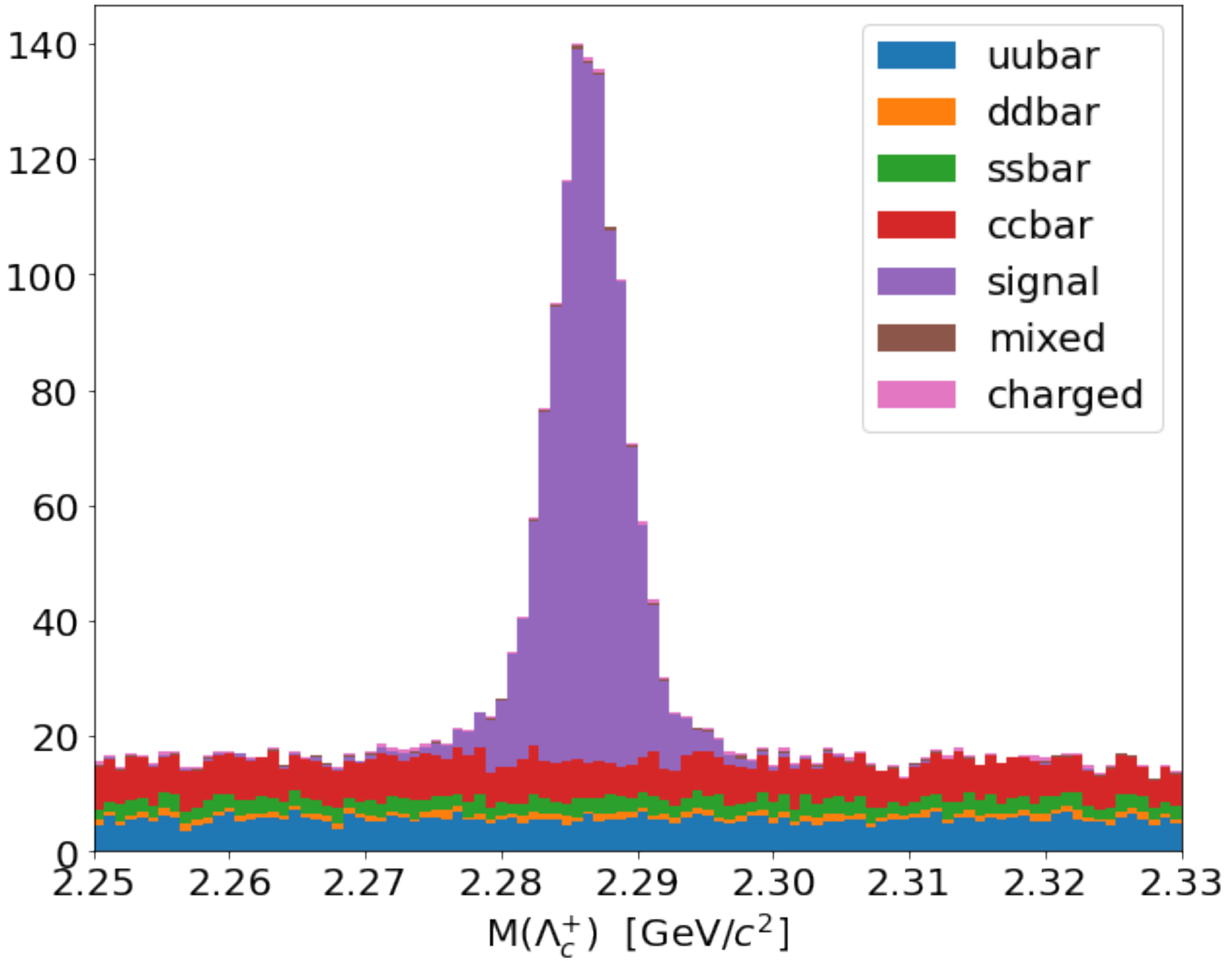


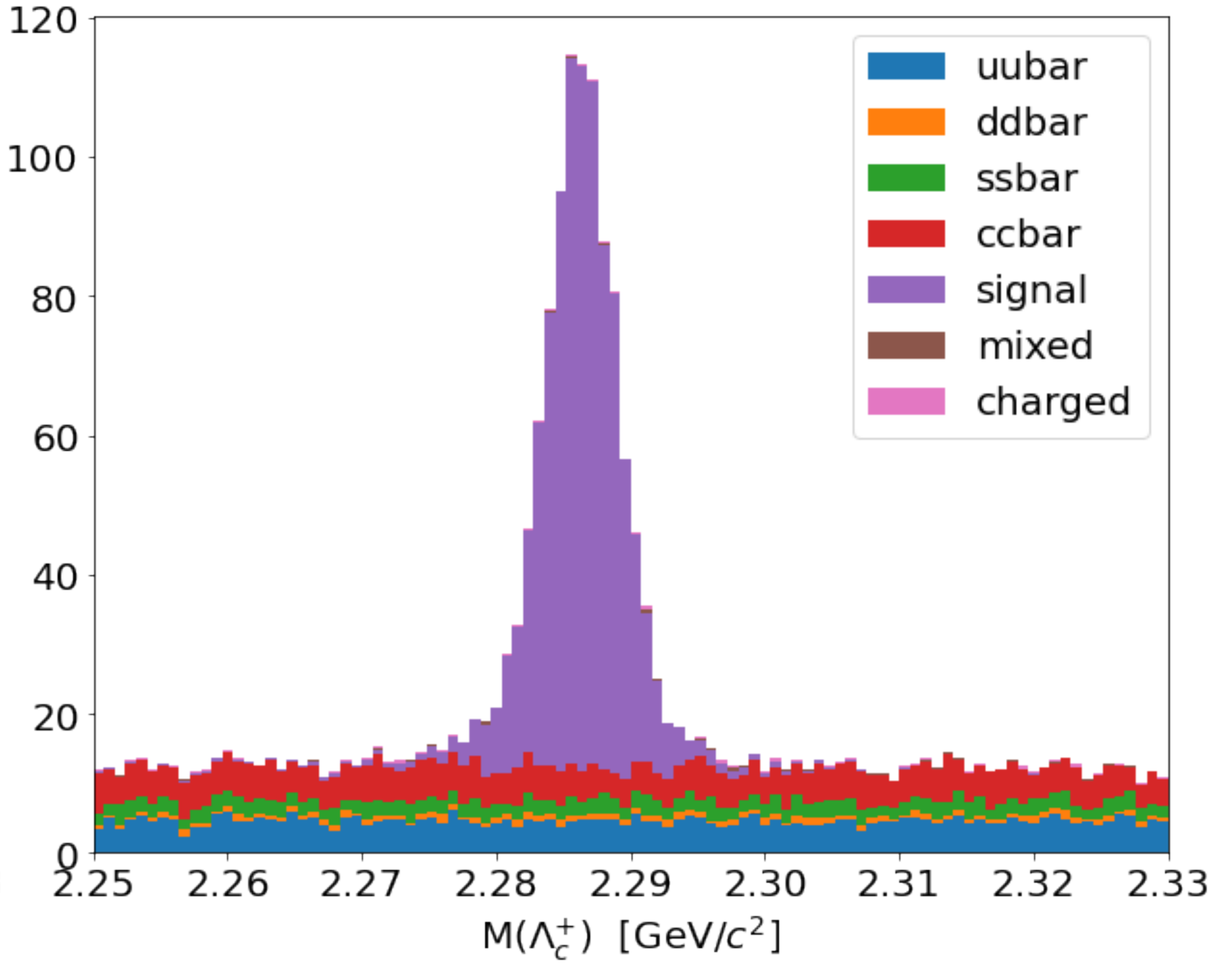
Combine signal $K^-\pi^+$ with a π^+ from the ROE



Applying D^0 and D^+ vetos (all combinations)

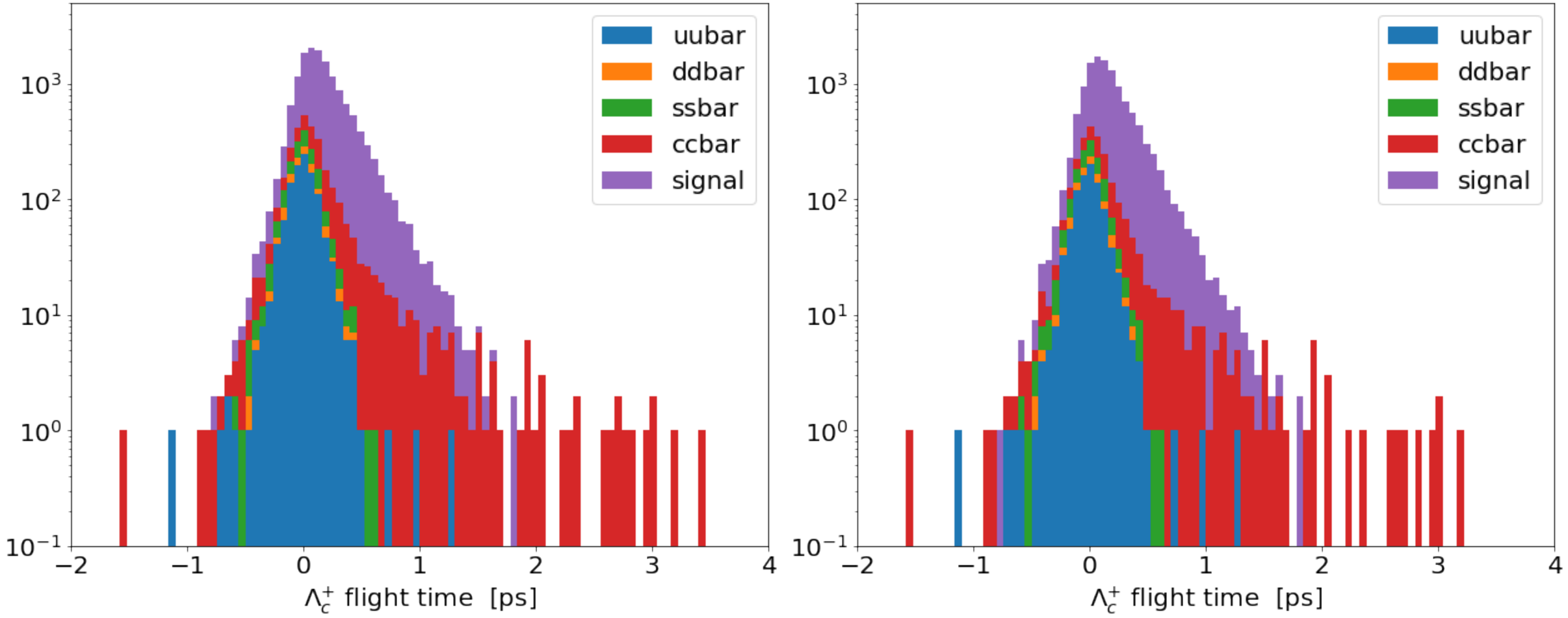
- Relatively small reduction in ccbar background - no significant improvement for signal/background



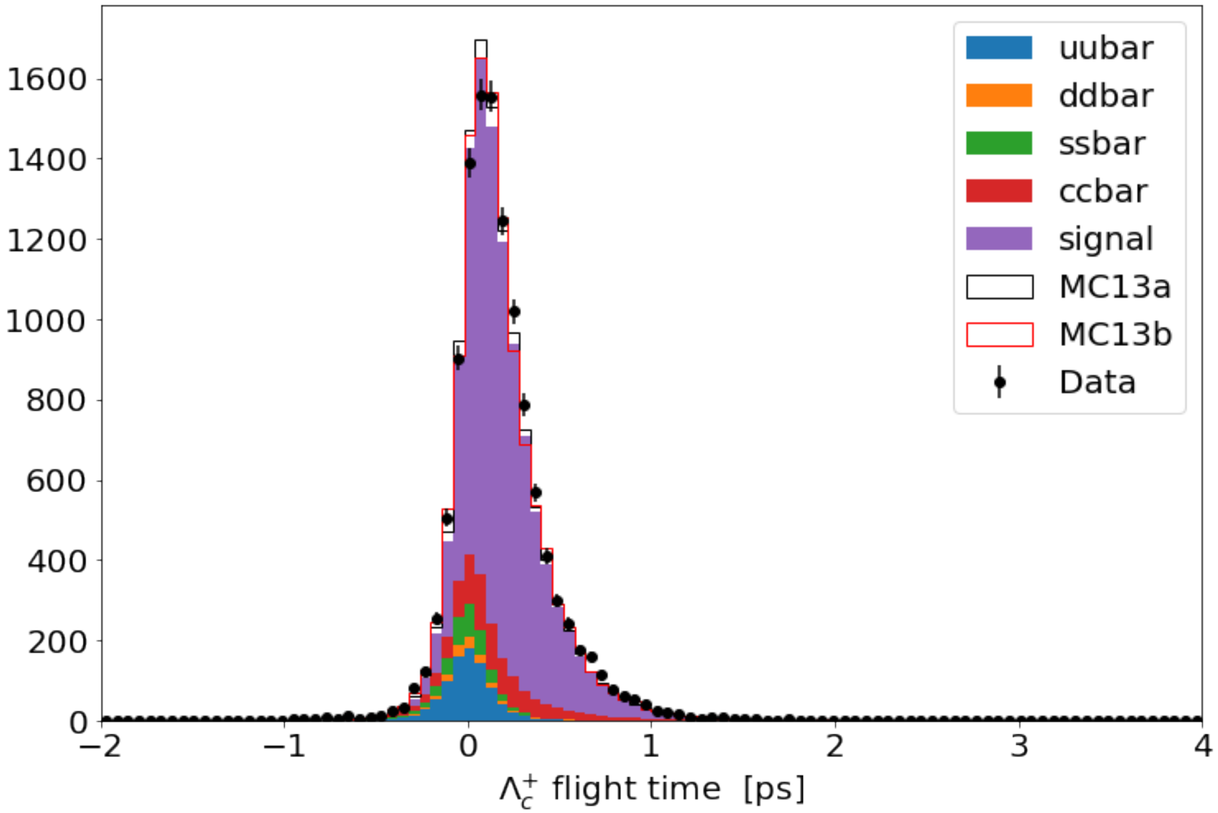


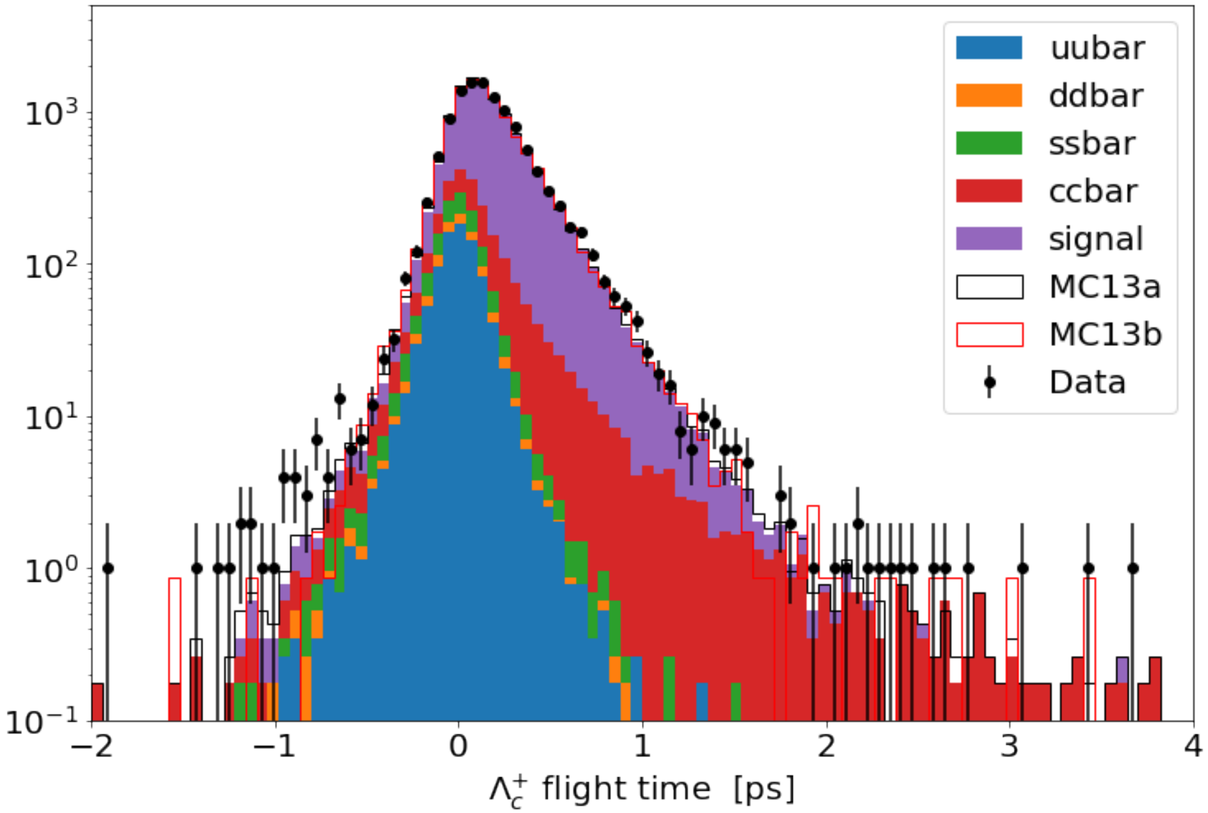
Applying D^0 and D^+ vetos (all combinations)

- Relatively small reduction in ccbar background (~30%) - similar reduction in signal (~20%)



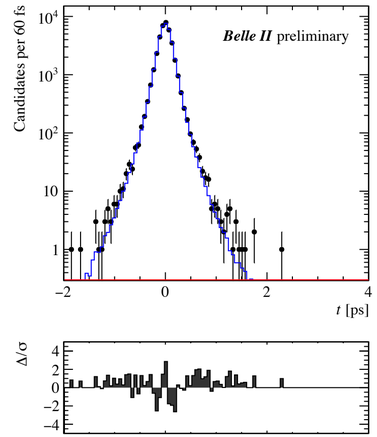
Decay time after all cuts



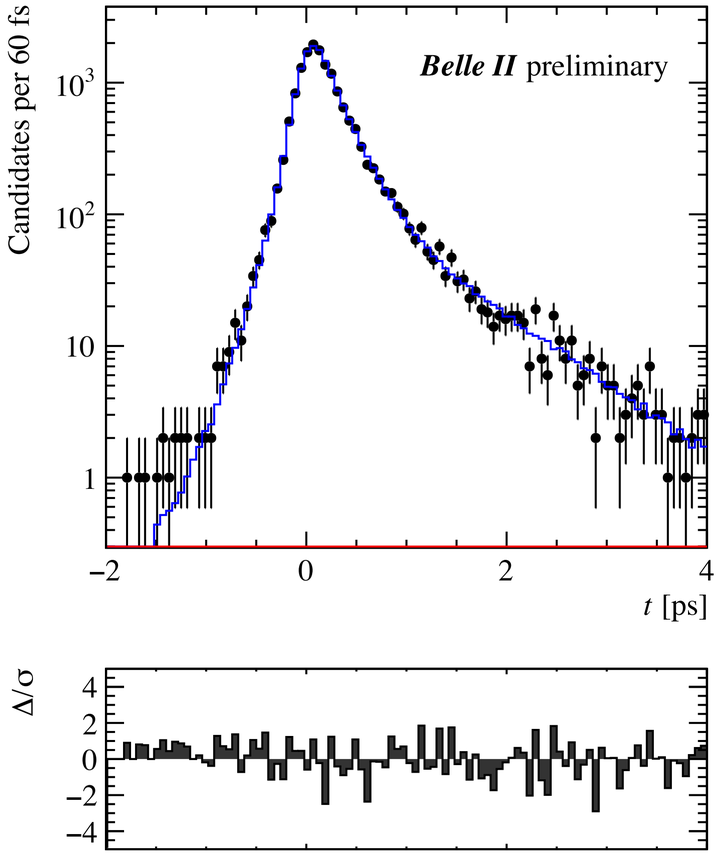


- Good data/MC agreement for both MC13a (run-independent) and MC13b (run-dependent)
- Still a significant background from long-lived particles

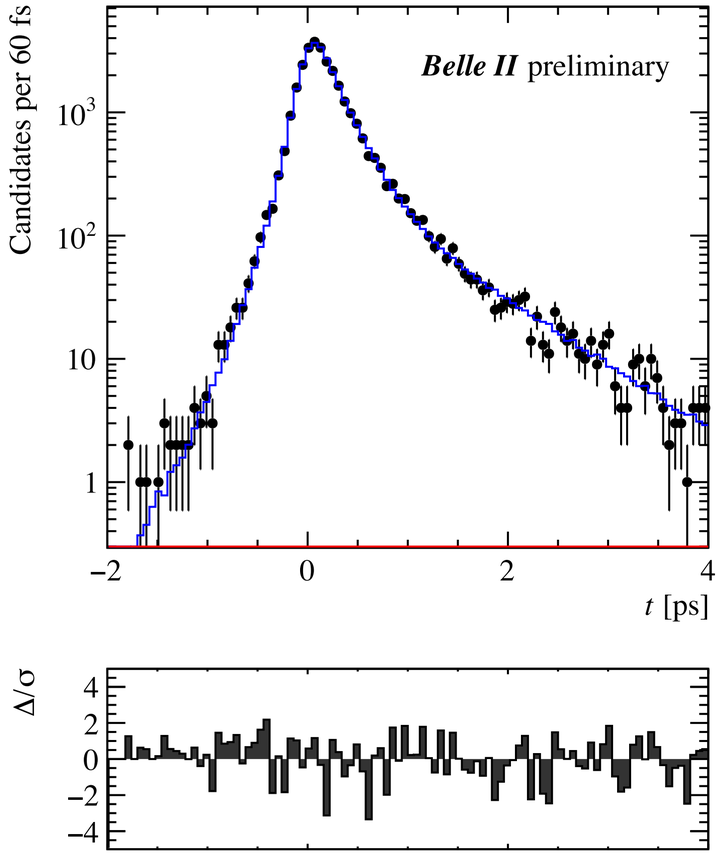
Fit to ccbar sidebands



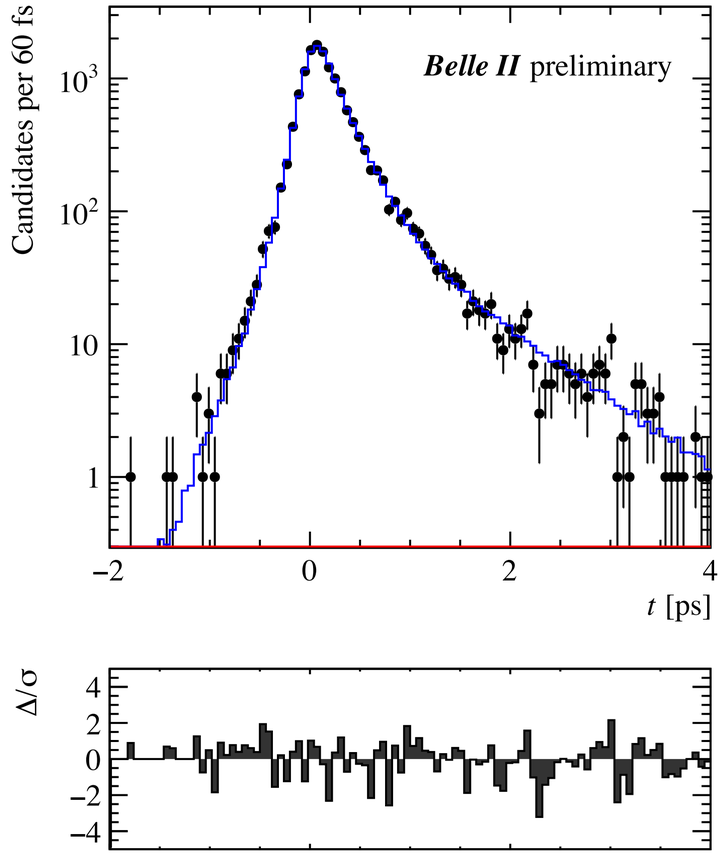
Low side



Combined

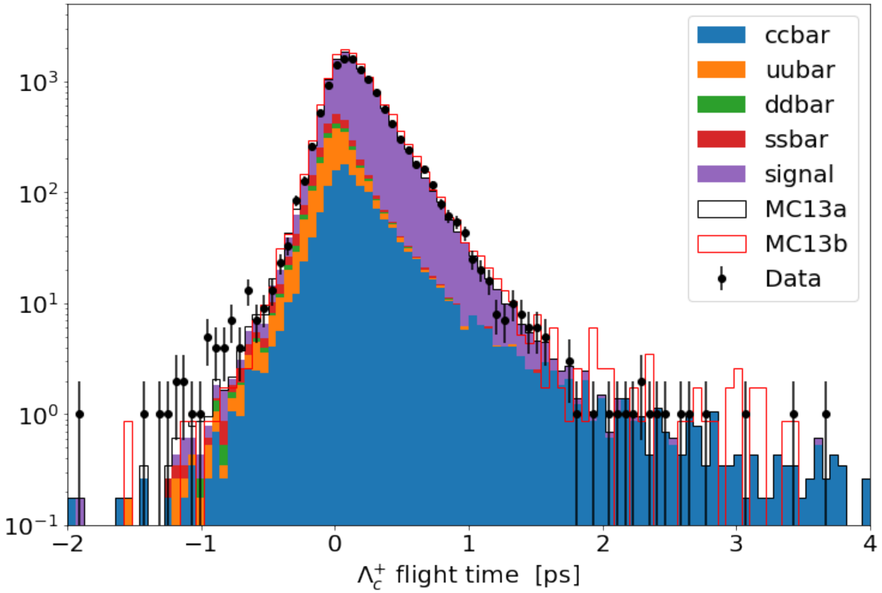


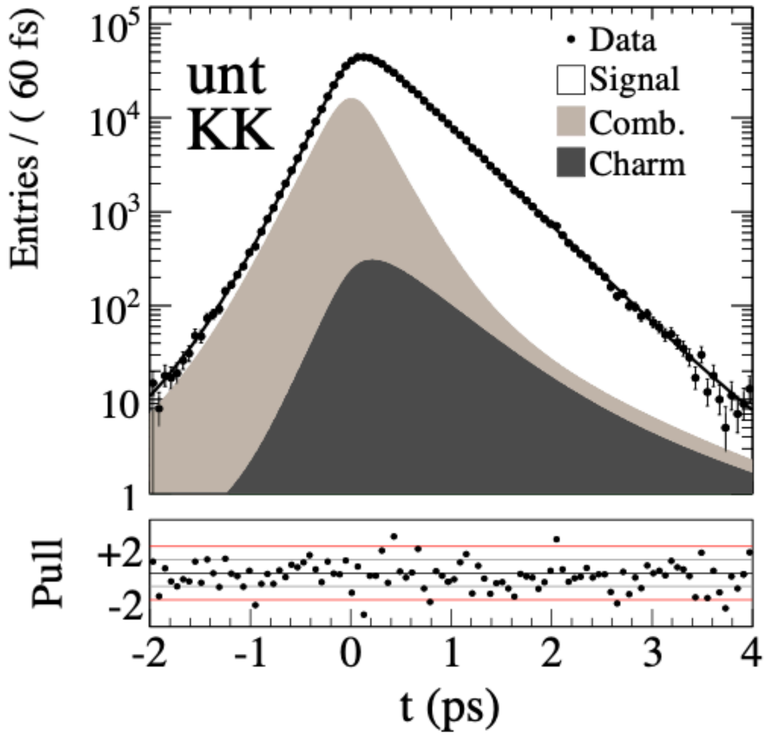
High side



Next steps

- Continue exploring reduction for charm backgrounds
- Use a similar technique to yCP measurement at BaBar:
  - Fit MC-tagged charm backgrounds with signal pdf
  - Fix charm-related pdf and extract combinatorial backgrounds with weighted average from sideband fits
- Implement 3D fit including invariant mass
- Try a simultaneous fit to signal and background regions

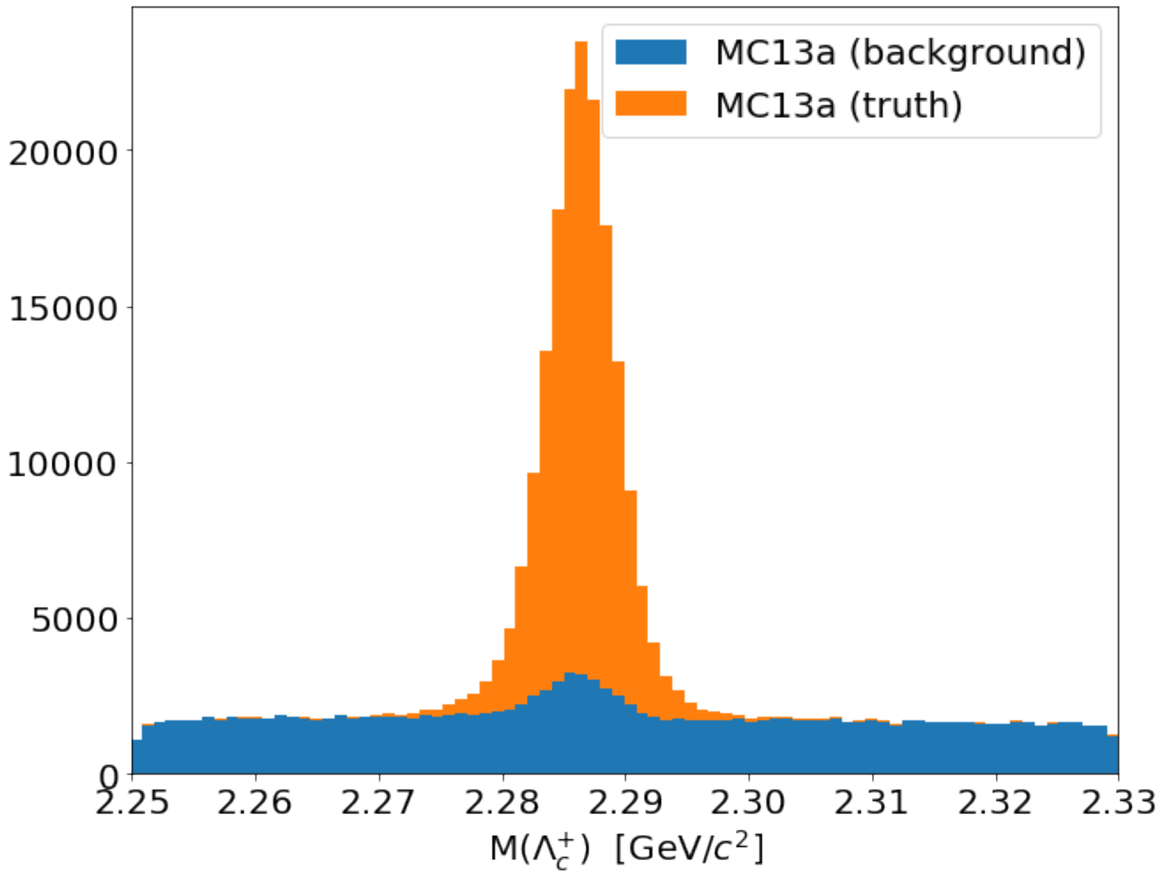




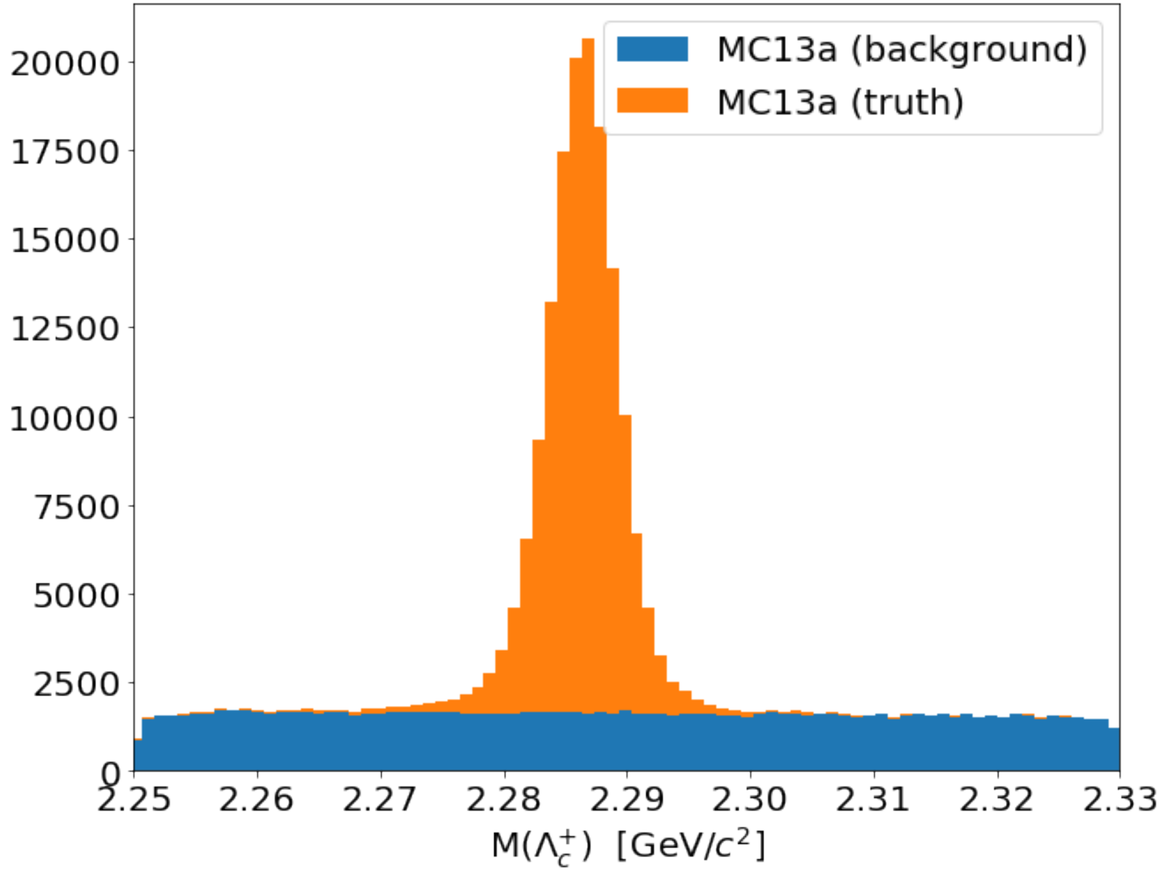
MC truth matching

- Use mcErrors to allow: missing FSR, missing intermediate resonance, decay in flight, missing neutrino, missing photon, missing final state particle, missing KLID
- Background includes (among others) misidentification, invalid matches, etc.

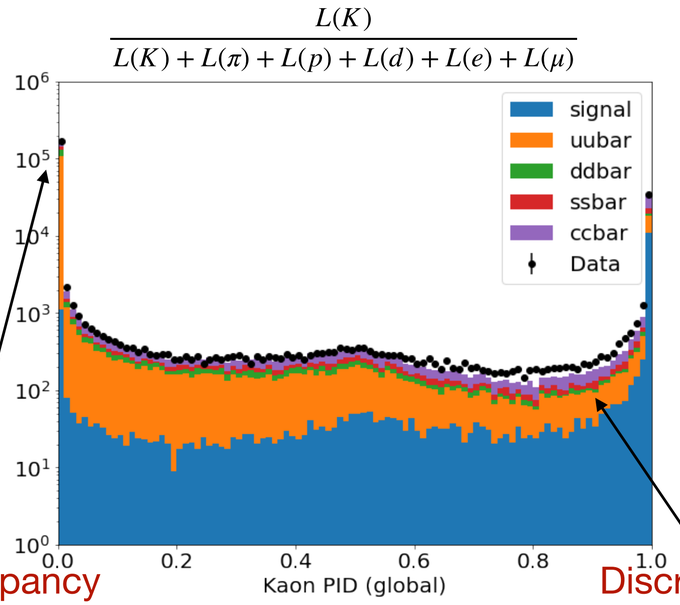
isSignal==1

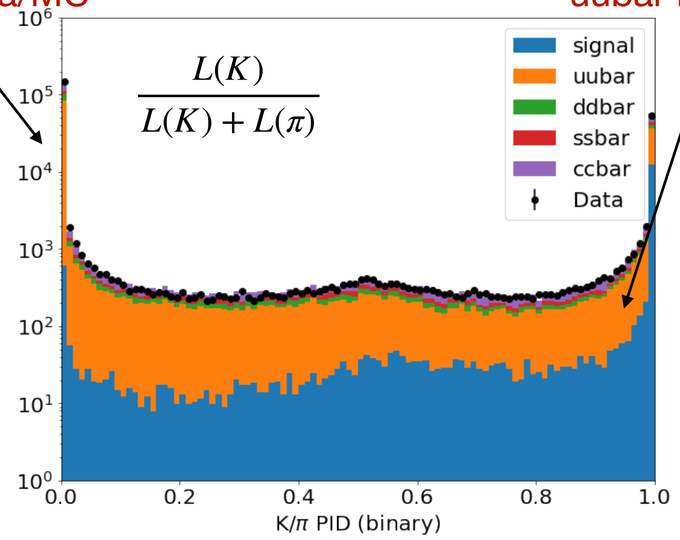


isSignal==1 or mcErrors < 128



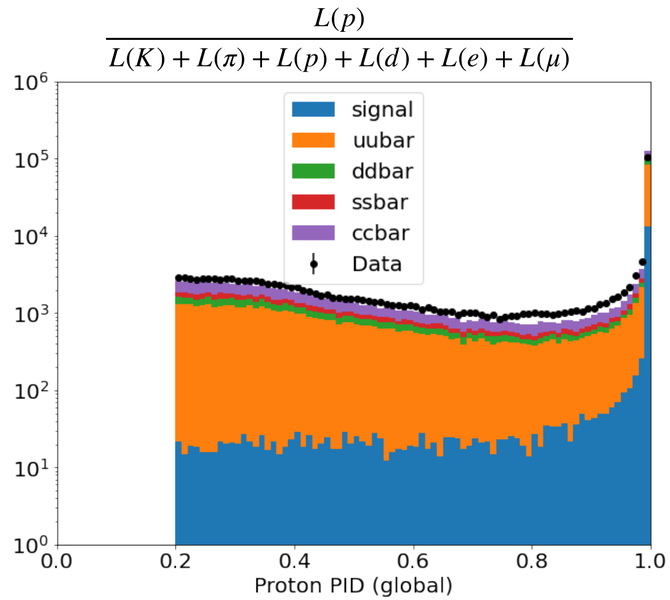
PID (global versus trinary/binary)

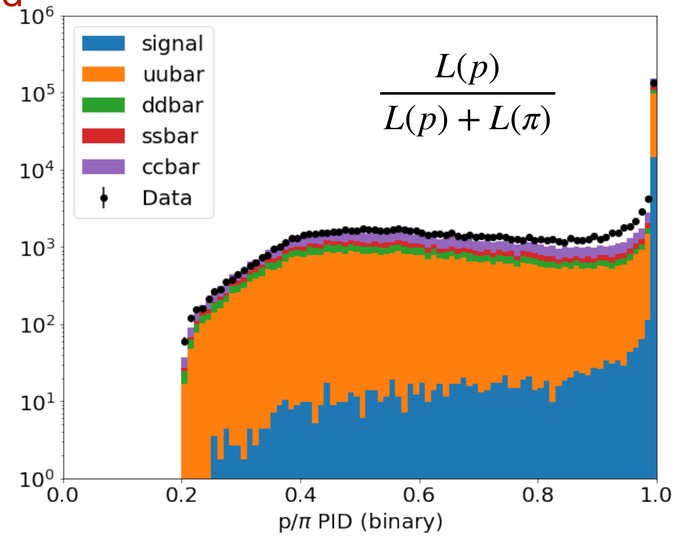


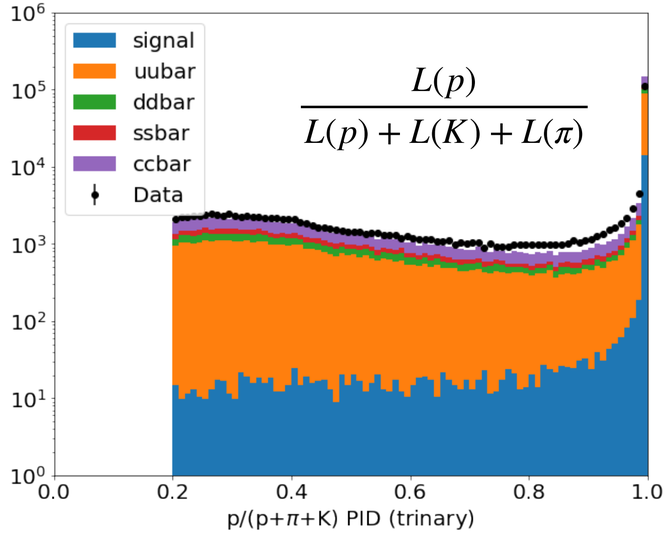


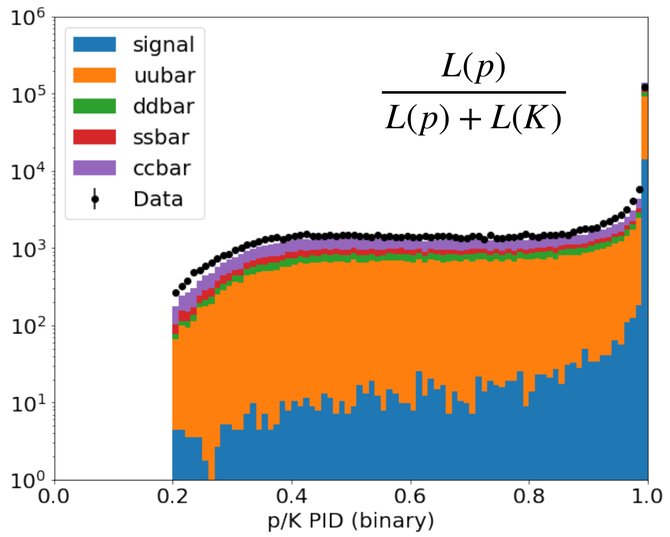
Discrepancy in data/MC

Discrepancy in uubar background





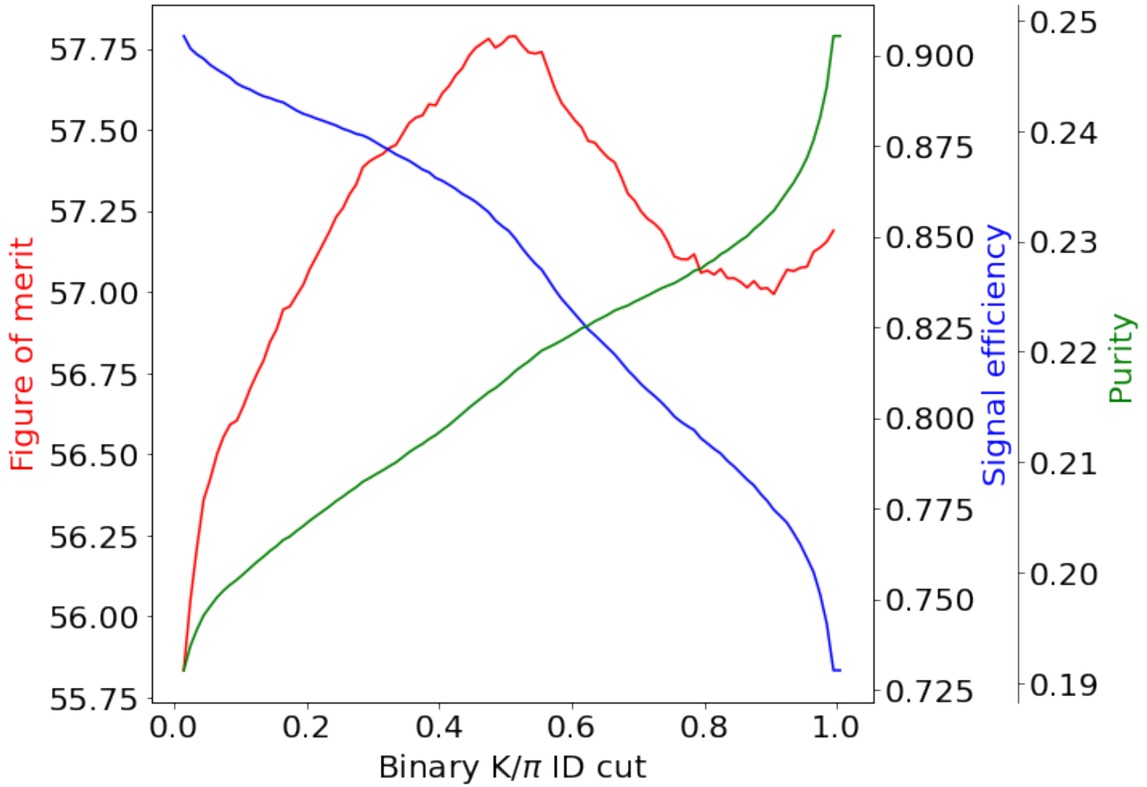




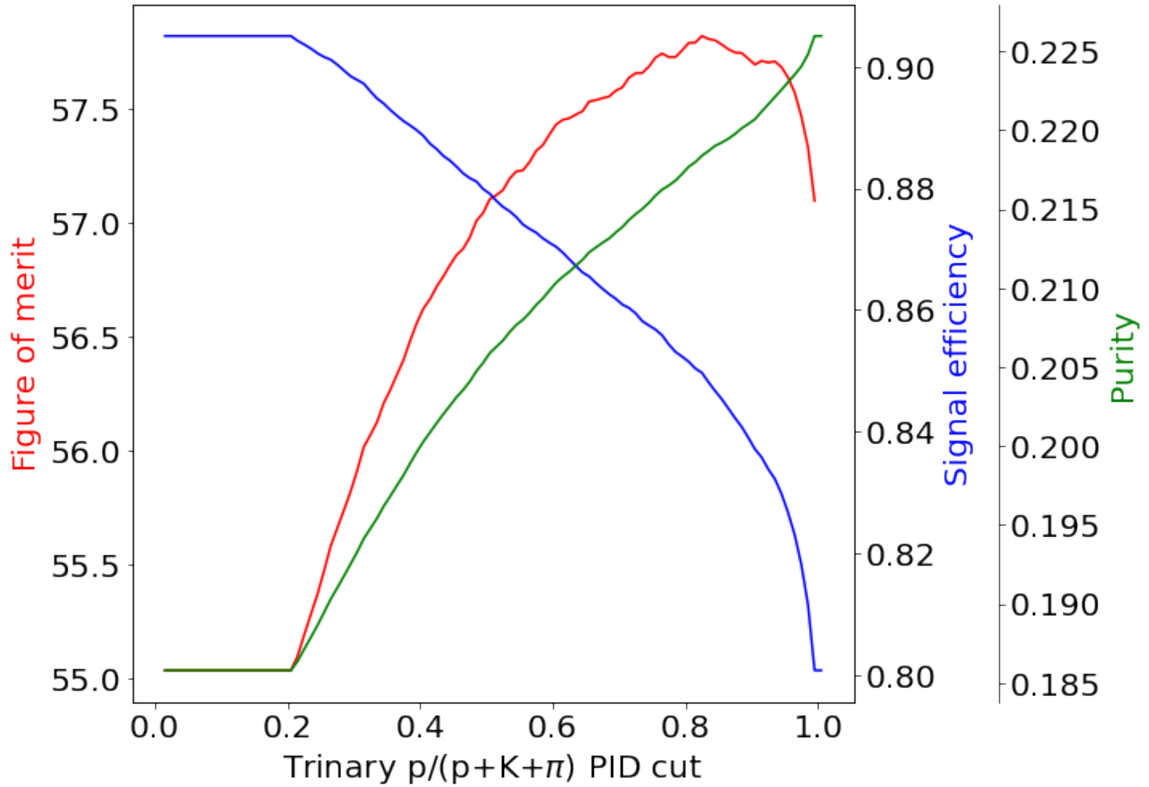
PID optimization

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

K/π ID with proton trinary PID > 0.8



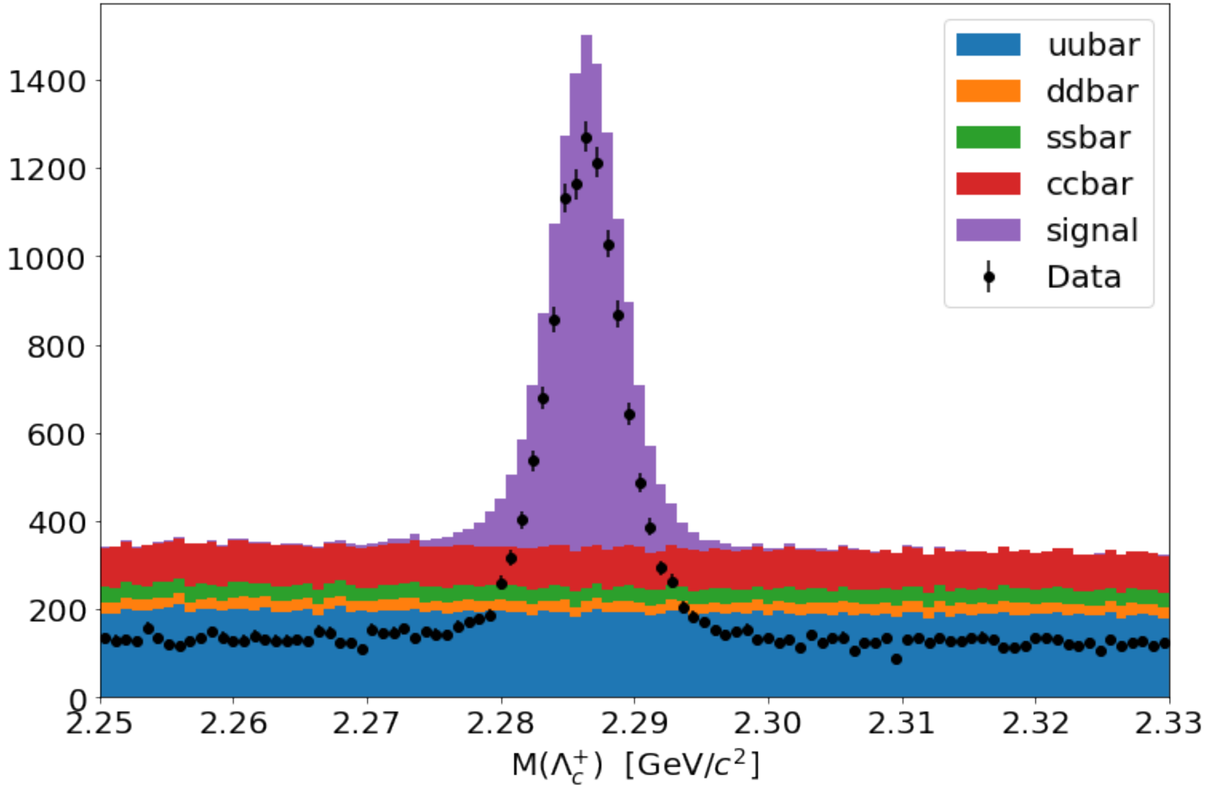
Proton ID with K/π binary PID > 0.5



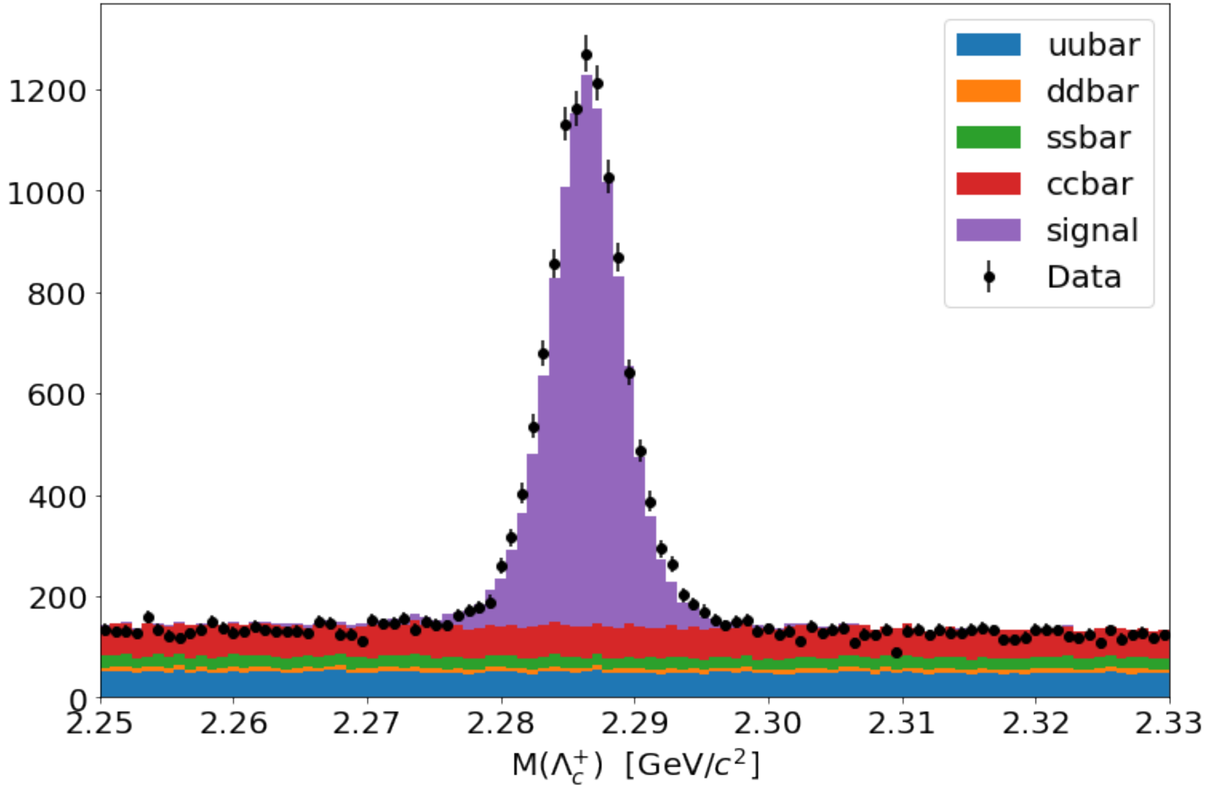
*Similar distributions/maxima for global PID variables

Binary/trinary versus global PID

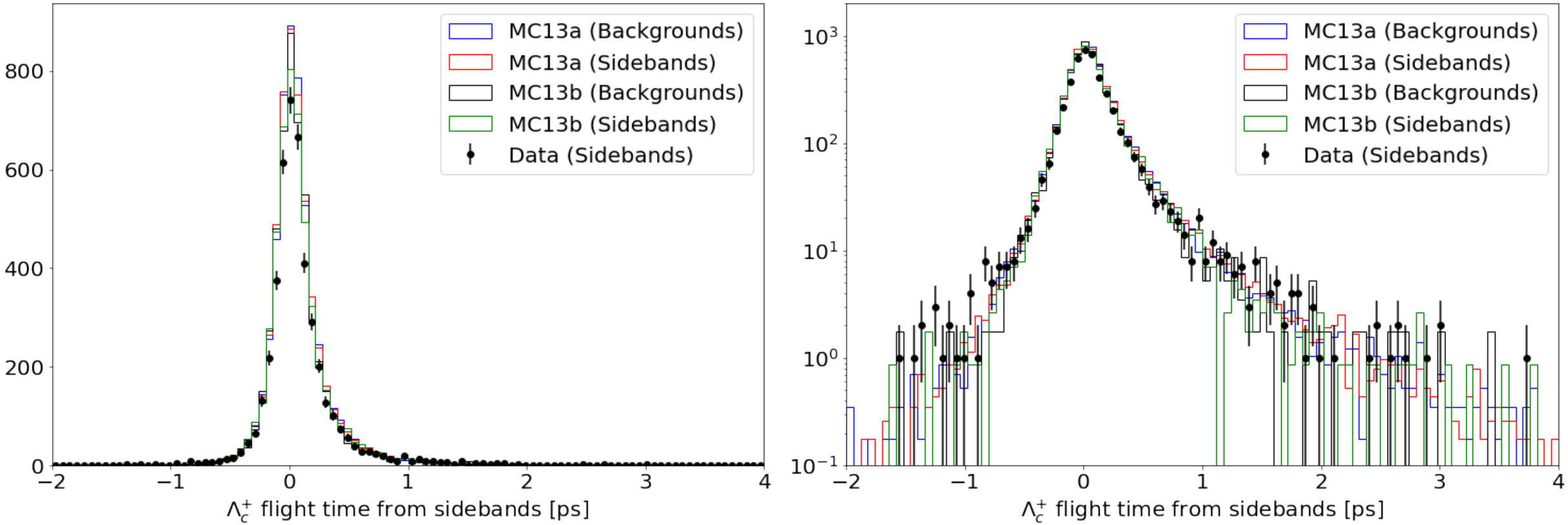
Proton trinary PID > 0.8
K/π binary PID > 0.5



Proton trinary PID > 0.8
Kaon global PID > 0.5

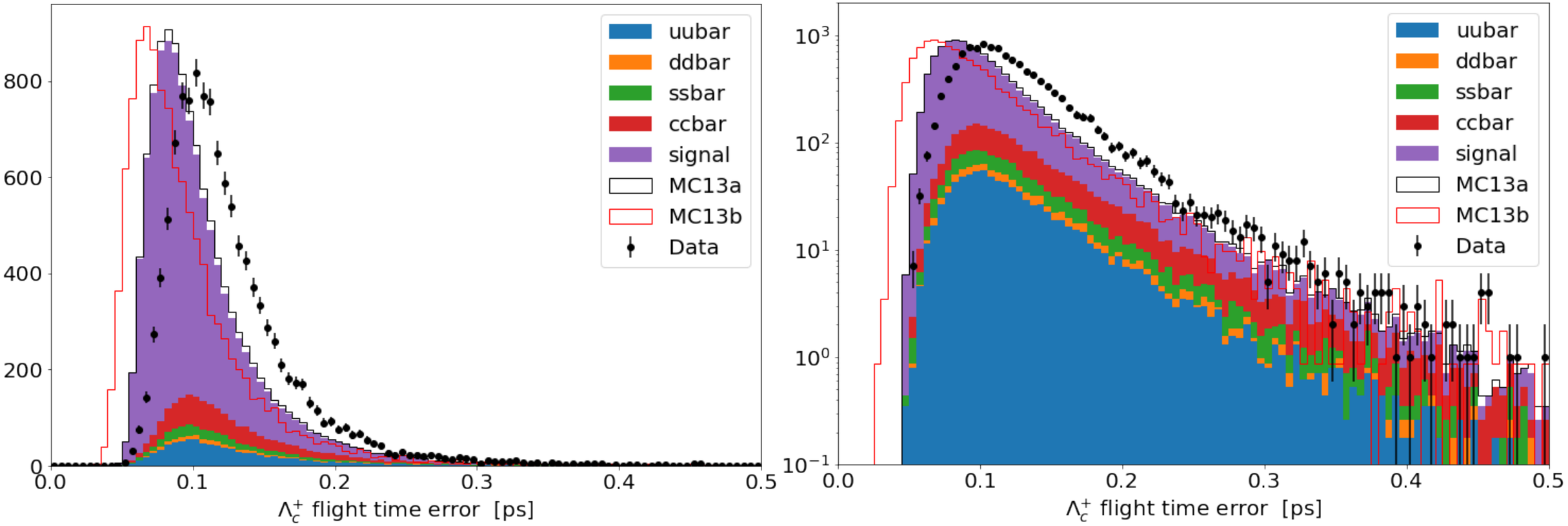


Compare truth-matching to sidebands



- Good data/MC agreement for both MC13a (run-independent) and MC13b (run-dependent)
- Still a significant background from long-lived particles

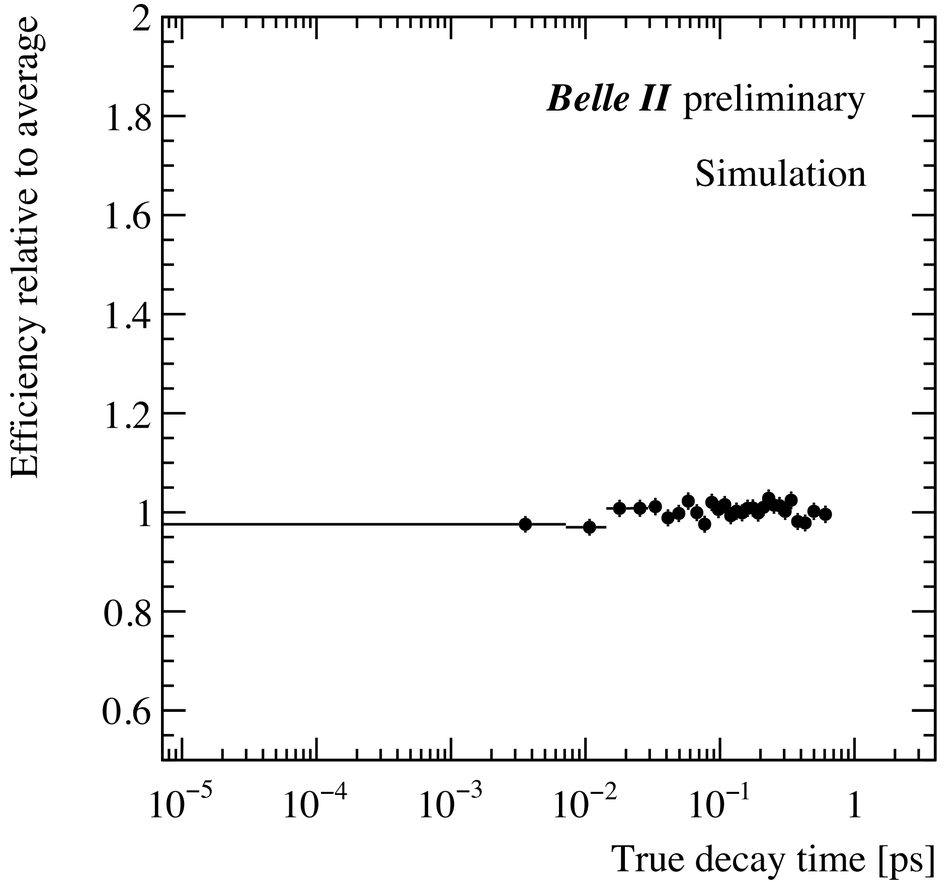
Decay time uncertainty

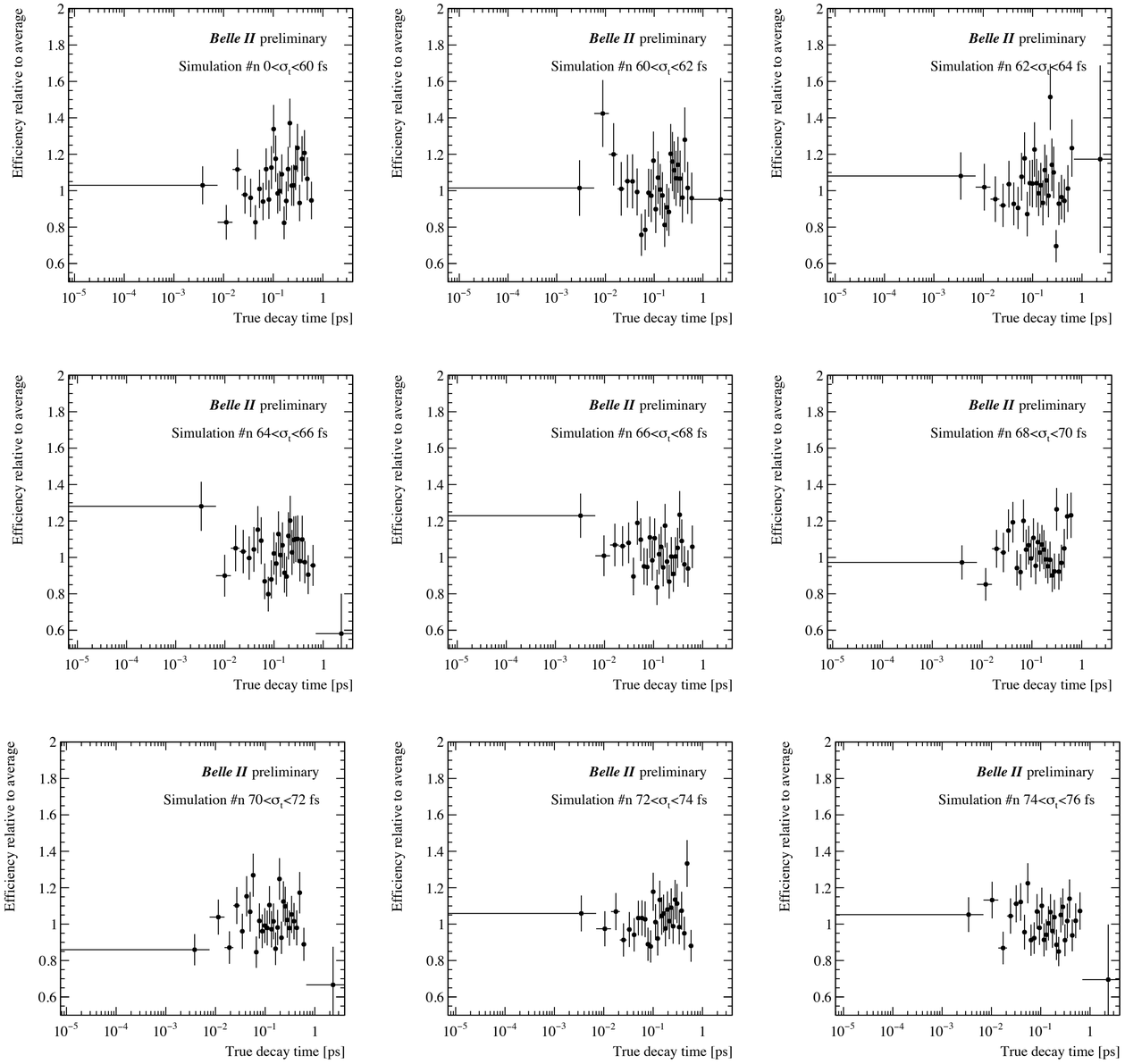


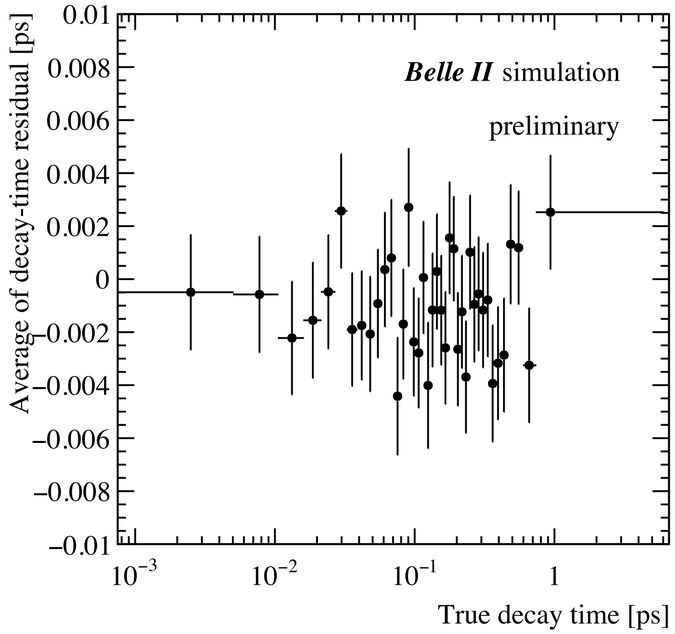
- Discrepancies between data and MC for flight time uncertainty (even between MC13a and MC13b)

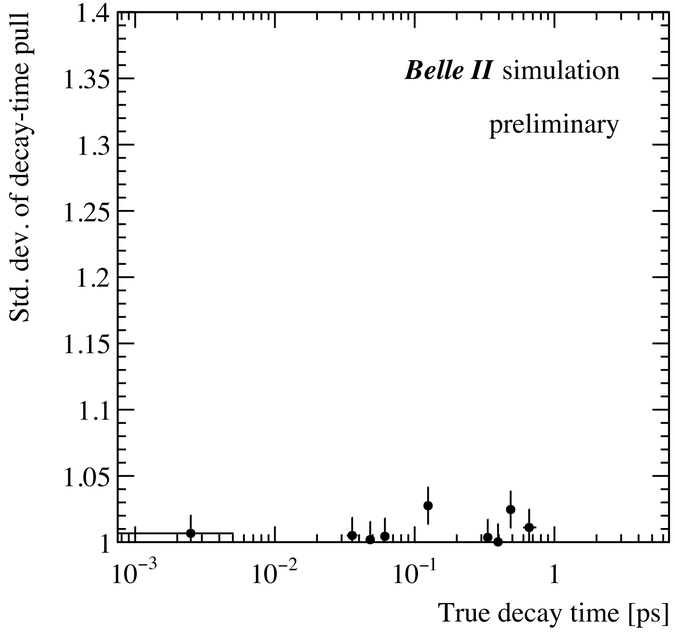
Efficiency dependence on flight time uncertainty

- No apparent efficiency dependence on t, σ_t
  - Outside region of apparent shift in D analyses

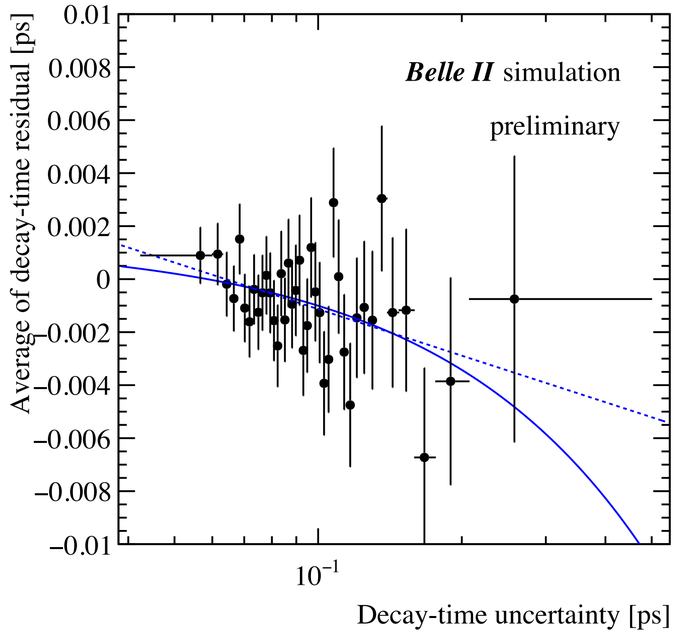


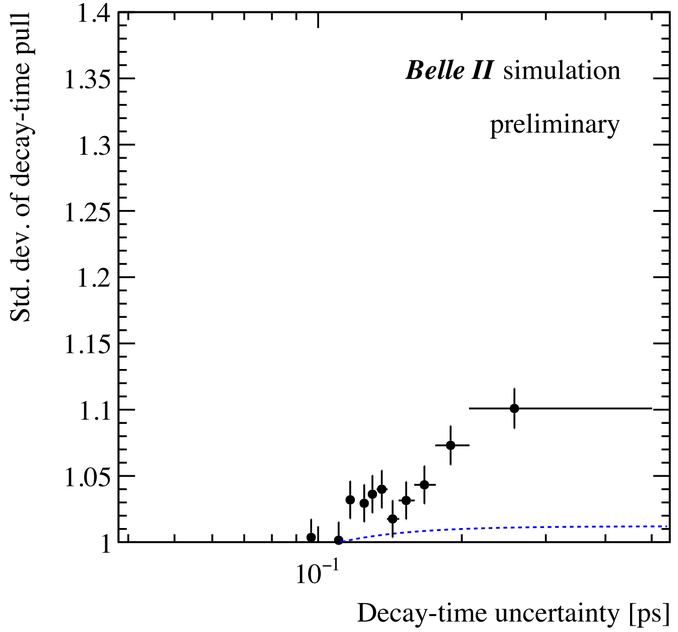




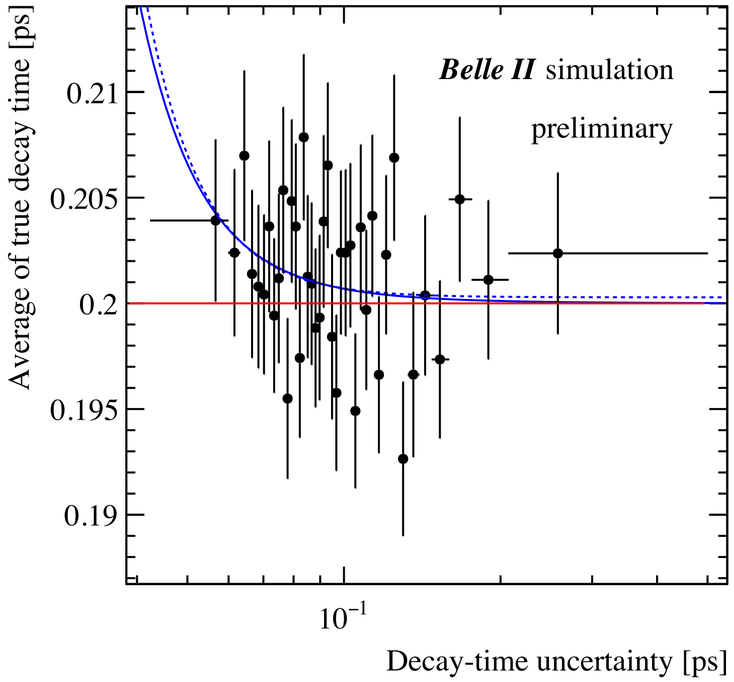


- No dependence of the decay-time residual/pull on true decay time

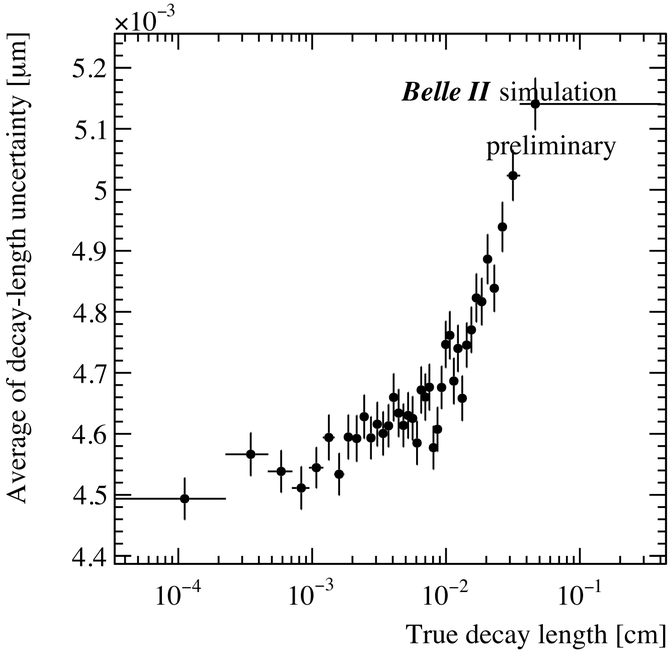


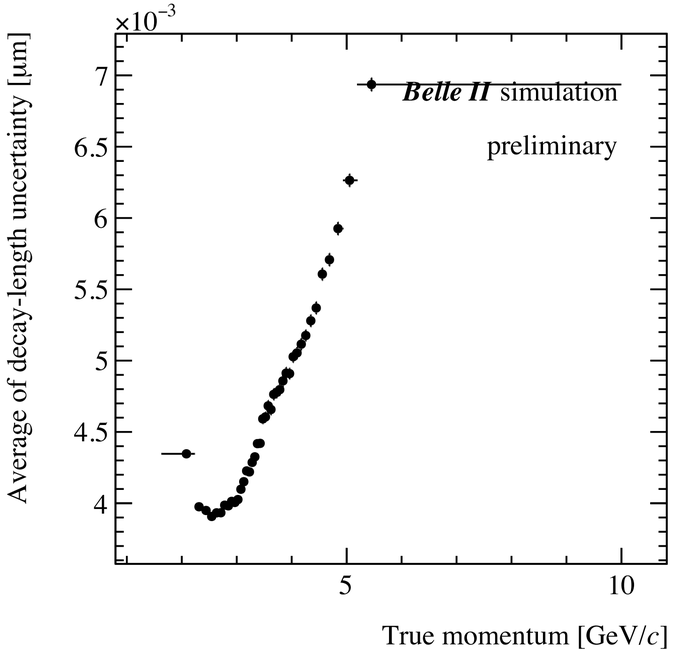


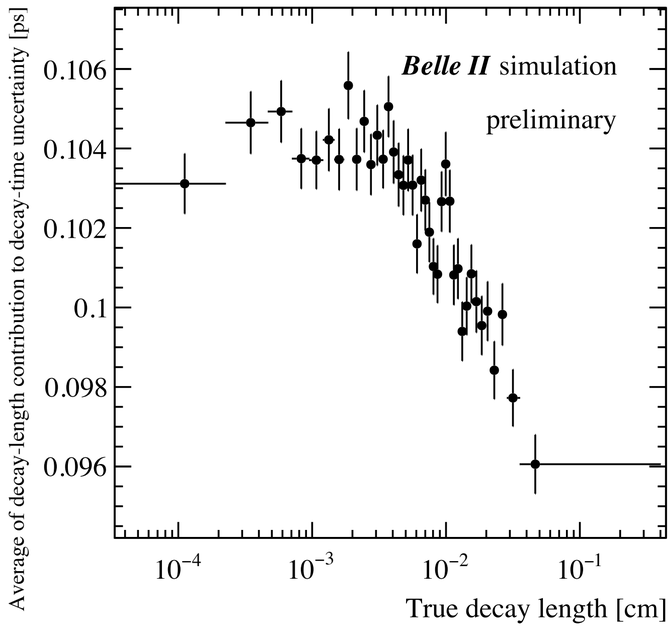
- Some dependence on decay-time resolution

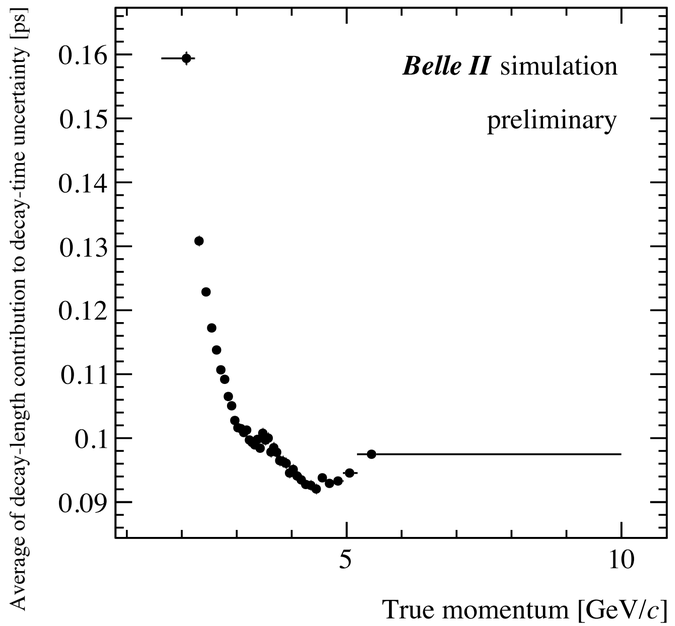


- No significant variation of true decay-time vs uncertainty









- Expected dependencies on decay-length uncertainty on the true decay time and momentum
  - Neglected in the lifetime fit