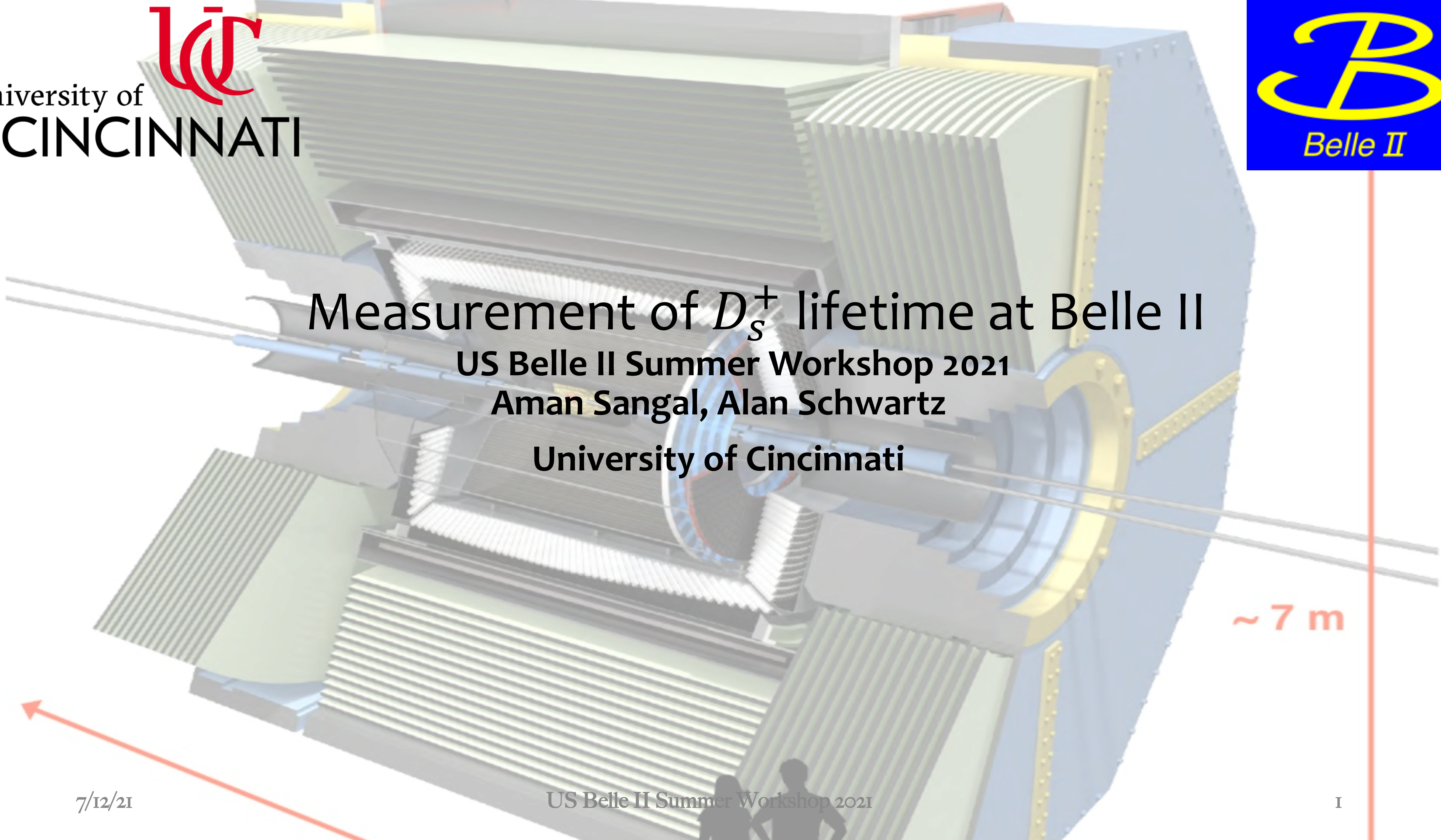


Measurement of D_s^+ lifetime at Belle II

US Belle II Summer Workshop 2021

Aman Sangal, Alan Schwartz

University of Cincinnati

Why measure D_s^+ lifetime ?

- **Why measure D_s^+ lifetime ?**
  - Using current Belle II data, we can achieve a precision competitive to existing world average.
  - We are still in the early stages of a broad Belle II physics program
  - A precision measurement of D_s^+ lifetime will be demonstration of:
    - Good Belle II detector performance .
    - Excellent vertexing capabilities.

- **What is D_s^+ lifetime ?**
  - Massive unstable particles decays to more stable particles (respecting different conservation laws), has a lifetime.
  - Lifetime depends on dominant decay modes and underlying physical interaction.
  - D_s^+ lifetime value is $(5.04\pm0.04)\times10^{-13}$ s *[PDG 2021]*

Proper decay time t:

- **Proper decay time:** $t = \frac{m(\Delta\vec{r}\cdot\hat{p})}{|\vec{p}|c}$,

  - $\Delta\vec{r}$ is vector from D_s^+ production point (IP) to the decay vertex.
  - $\vec{p}$ is the reconstructed D_s^+ momentum vector.
  - m is the D_s^+ invariant mass.
  - D_s^+ production vertex is constrained at IP (*only considering* D_s^+ *from* $e^+e^- \rightarrow c\bar{c}$)

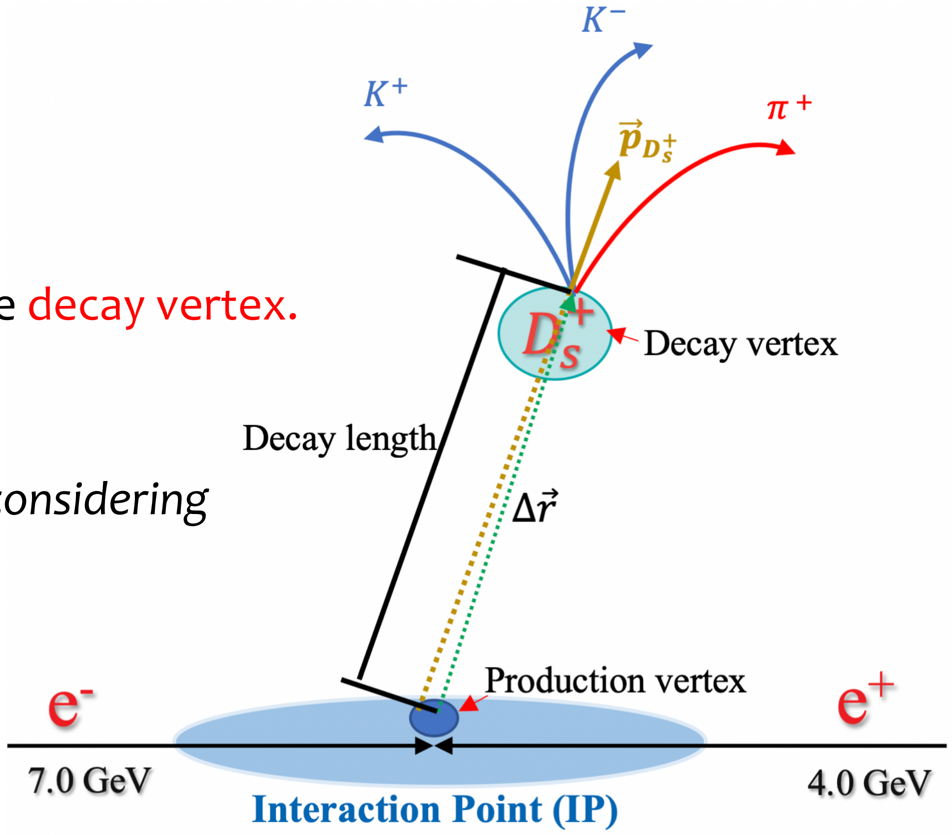
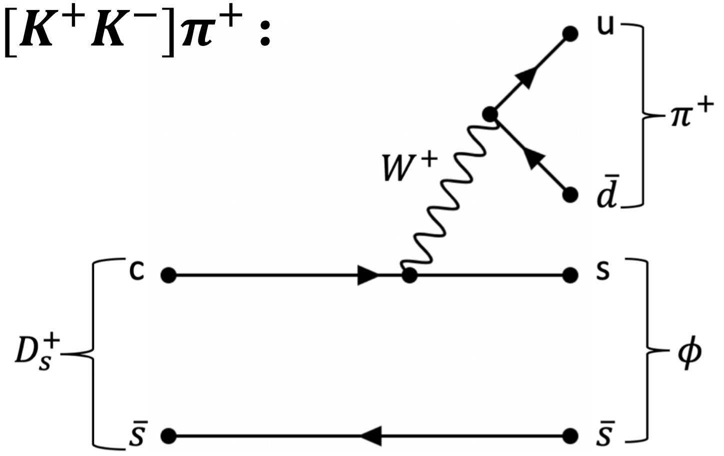


Fig. not to scale

Choice of decay mode for the D_s^+ lifetime measurement?

- We have to pick a D_s^+ decay mode with:
  - Large branching fraction. (*higher statistics for precision measurement*)
  - All charged tracks in the final state. (*very good momentum resolution and decay vertex reconstruction is crucial for lifetime precision*)
  - High sample purity i.e. ratio of signal with signal plus background.

- For lifetime measurement we chose decay mode: $\boldsymbol{D_s^+ \rightarrow \phi[K^+K^-]\pi^+}$ **:**
  - Large branching fraction : 2.24 ± 0.08 % *[PDG 2021]*
  - Three charged tracks, K^+K^- and π^+ in the final state.
  - High sample purity of 93 % in the signal region.



Data and MC sample used for measurement:

- **MC sample:**
  - Run dependent MC sample
  - MC 13b_proc11 (40 fb^{-1})
  - MC13b_prompt (40 fb^{-1})
  - Total: 80 fb^{-1}

- **Data:**
  - 2019 data: Exp. 7,8,10. 9.7 fb^{-1} (off + on resonance)
  - 2020 data: Exp. 12. 62.6 fb^{-1} (off + on resonance)
  - Total: 72.3 fb^{-1}

Check out for latest data production updates:

https://confluence.desy.de/display/BI/Data+Production+Status

Reconstruction of $D_s^+ \to \phi[K^+K^-]\pi^+$

Variable	Selection criterion
Charged tracks	
dr	$\|dr\| < 0.5$ cm
dz	$\|dz\| < 2.0$ cm
#PXD hits	≥ 1
# SVD hits	≥ 4
# CDC hits	≥ 30
PID (binary, $\frac{L_K}{L_K+L_\pi}$)	> 0.6 for K and < 0.55 for π
Vertex chi prob	> 0.001 (Tree fitter, beam spot constraint)
Helicity	$\|cos(\theta_{hel})\| > 0.45$
$P^*_{D_s^+}$	> 2.5 GeV/c (remove D_s^+ from B decays)
M_ϕ	$(1.01 < M_\phi < 1.03)$ GeV/c^2
$M_{D_s^+}$	$(1.922 < M_{D_s^+} < 2.02)$ GeV/c^2

dr, dz: Selecting tracks originating near IP

#PXD hits, # SVD hits, # CDC hits: Selecting tracks with momentum measured with better precision.

PID: Identification of charged tracks as pion or kaon.

Vertex chi prob:

- Beam spot constraint requires D_s^+ to originate from IP.
- This improves the *decay time resolution* by a factor of 3

Helicity: To suppress the background

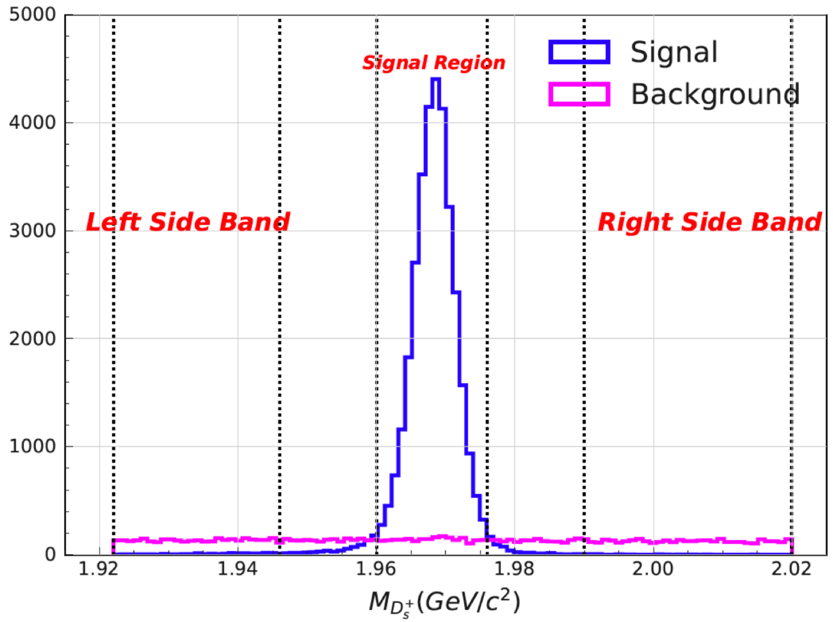
$P^*_{D_s^+}$: *B mesons have a finite lifetime*

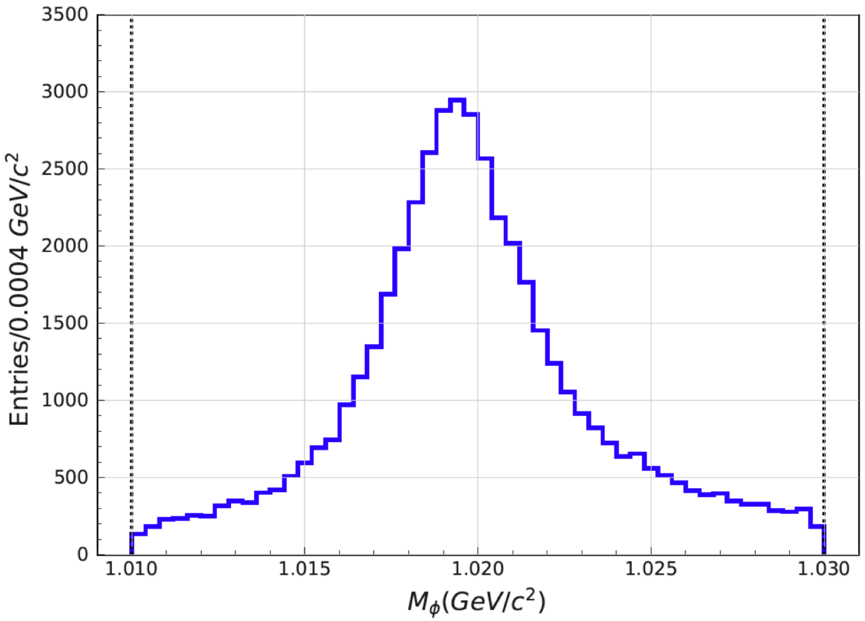
See backup slide #13 for details

Results from MC studies

- 40 fb^{-1} run dependent MC sample is used for results in following slides.

D_s^+ mass and ϕ mass distributions after reconstruction:





- Reconstructed $\mathrm{M}_{\mathrm{D_s^+}}[K^+K^-\pi^+]$ and $\mathrm{M}_{\phi}[K^+K^-]$ distributions are shown above
- We fit for lifetime only using the events in the $\mathrm{M}_{\mathrm{D_s^+}}$ signal region defined as :
  - $\mathrm{M}_{\mathrm{D_s^+}} \in (1.96, 1.976)$ GeV/c²
- Purity of sample i.e. S/(S+B) in the signal region is 93%.

Lifetime pdf:

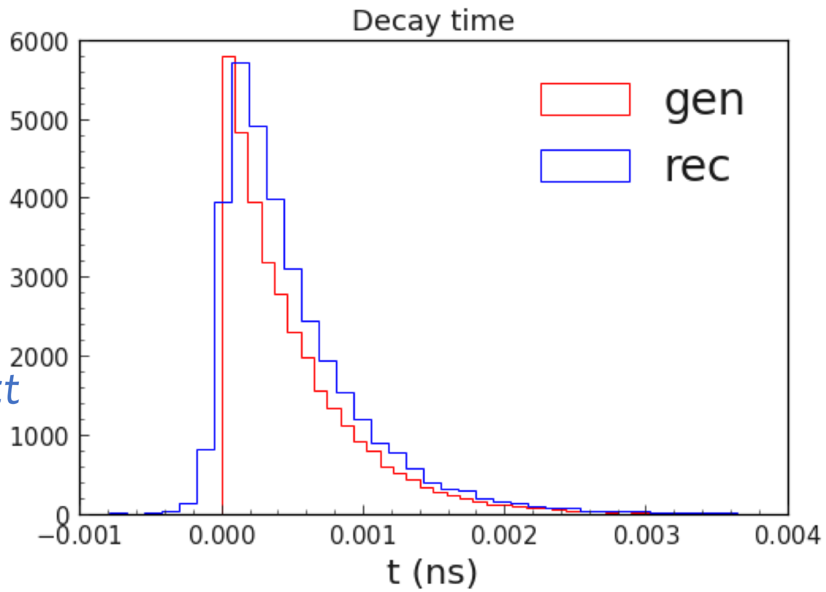
- **Signal Events:** Real D_s^+ decays to $K^+K^-\pi^+$ final state:
  - Probability of an event to decay at time t :

$$F_{sig}(t) = \int \frac{1}{\tau} \exp^{\frac{-t'}{\tau}} R(t - t' : mean, s, \sigma_t^i) dt'$$

Convolution of natural decay law and experimental resolution function

Natural decay law
No experimental effects

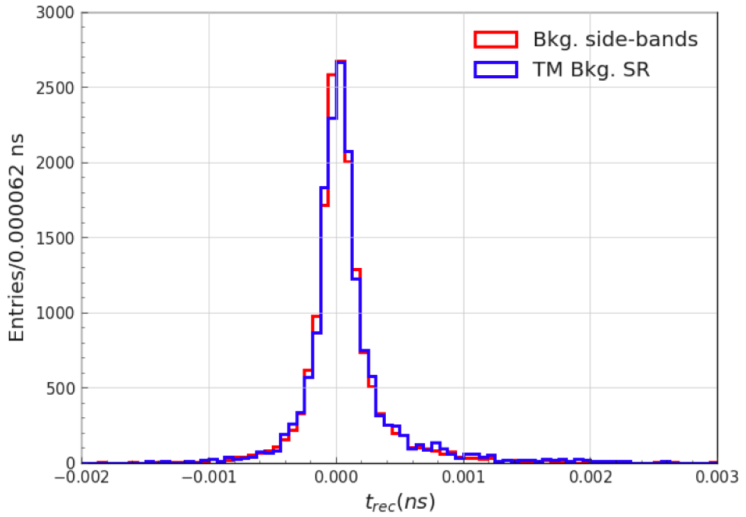
Detector resolution effect



- **Event level resolution function:** $R(t - t' : mean, s, \sigma_t^i)$
  - A single gaussian is used as resolution function.
  - Resolution function has different width for each event.
  - We use the σ_t^i , error in decay time t for event i as the width of resolution function for that event.
  - σ_t^i could be "over" or "under" estimated.
  - To correct for that, we use a scaling factor s common for all events.

Lifetime pdf:

- **Background Events:** non Ds decays, majority random combination of final state particles:
  - Distribution of decay time t for background events, $\mathrm{F_{bkg}(t)}$ is modelled using sum of 3 Asymmetric gaussian with common mean.
  - $\mathrm{F_{bkg}(t)}$ is obtained using events in $M_{D_s^+}$ sidebands.
  - We fit for background events in signal region using pdf shape obtained from sideband events assuming the distribution are same. *(assumption verified in MC using truth matching, see backup slides for details)*



Lifetime pdf:

- Total decay time t pdf:
  - We use a 3d pdf, f(t, σ_t, $M_{D_s^+}$) in fit variables: decay time (t), error in decay time (σ_t) and $M_{D_s^+}$

- $f(t, \sigma_t, M_{D_s^+}) = f_{sig} \times F_{sig}(M_{D_s^+}) \times F_{sig}(\sigma_t) \times F_{sig}(t) + (1 - f_{sig}) \times F_{bkg}(M_{D_s^+}) \times F_{bkg}(\sigma_t) \times F_{bkg}(t)$

f_{sig}:
- Ratio of # signal with # signal plus background.
- Obtained using 1d $M_{D_s^+}$ fit ***(fixed)***

$F_{sig}(M_{D_s^+})$:
- To better distinguish signal from background
- ***Fixed*** from results of 1d $M_{D_s^+}$ fit.

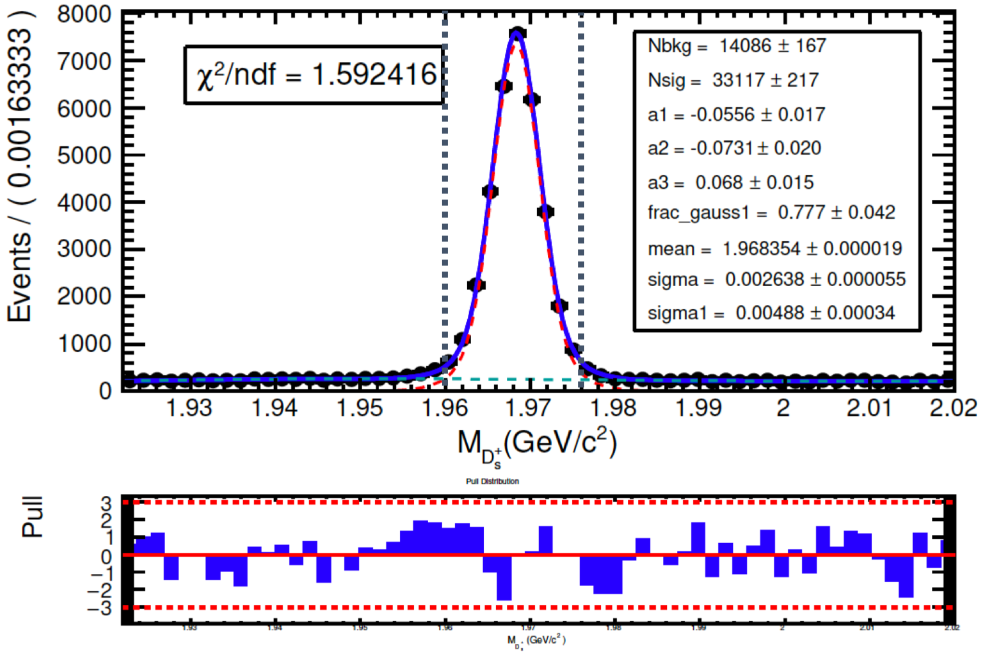
$F_{sig}(\sigma_t) \times F_{sig}(t)$:
- Model decay time t for signal events
- $F_{sig}(\sigma_t)$: sum of gaussian and Johnson SU function

$F_{bkg}(M_{D_s^+})$:
- ***Fixed*** from results of 1d $M_{D_s^+}$ fit.

$F_{bkg}(\sigma_t) \times F_{bkg}(t)$:
- Model decay time t for background events.
- $F_{bkg}(\sigma_t)$: Johnson SU function
- ***Fixed*** to shapes obtained using sideband events.

- ***For fit to data, no input (pdf shape parameters) are used from simulation.***

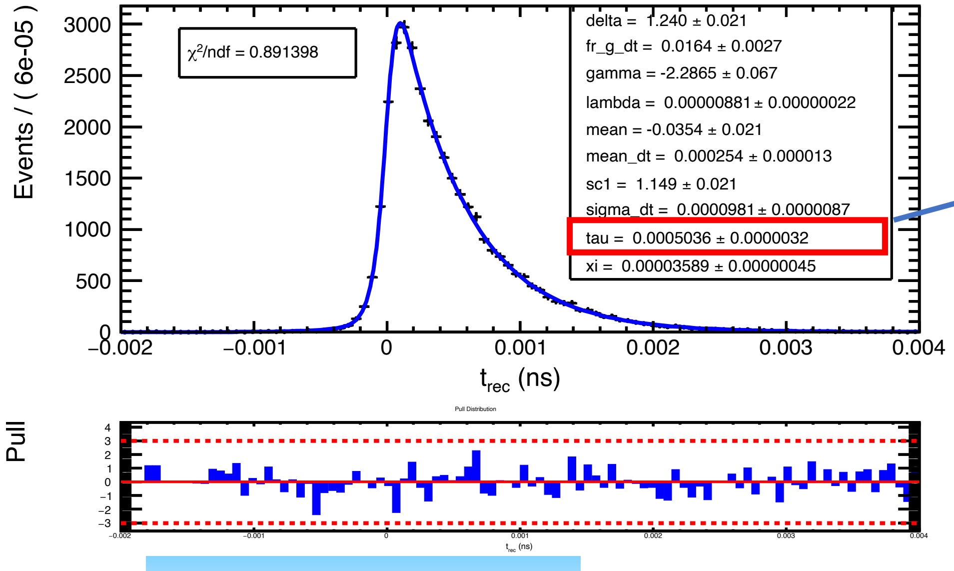
1d $M_{D_s^+}$ fit:



- Signal pdf $F_{sig}(M_{D_s^+})$: Sum of two gaussian with common mean
- Background pdf $F_{bkg}(M_{D_s^+})$: 3rd order chebychev polynomial
- In the signal region: $N_{sig} = 32293$ and $N_{bkg} = 2440$
- Sample purity = 93% .

Final fit results (MC):

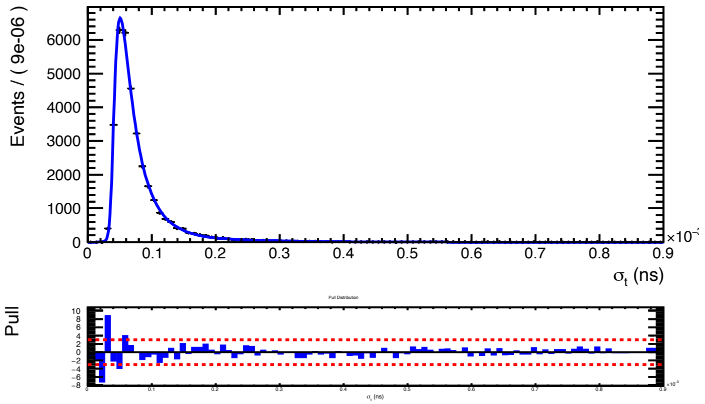
Fit Projection on t



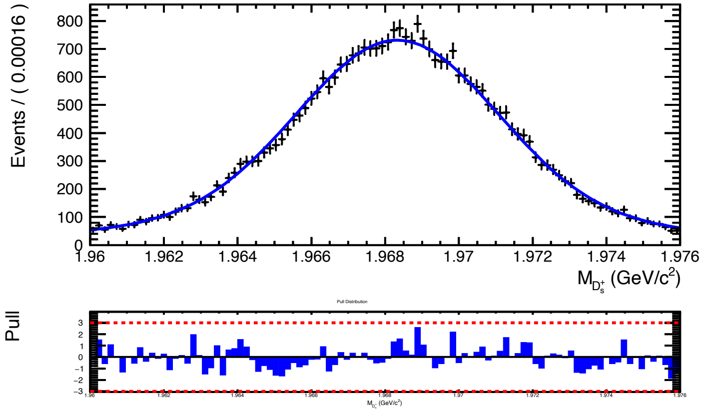
Results from 40 fb^{-1} MC sample:

- **Lifetime value from fit is:**
  - $\tau = (5.036 \pm 0.032) \times 10^{-13}$ s
- Lifetime value used in Belle II simulation is $\tau = 5.000 \times 10^{-13}$ s

Fit Projection on σ_t



Fit Projection on $M_{D_s^+}$



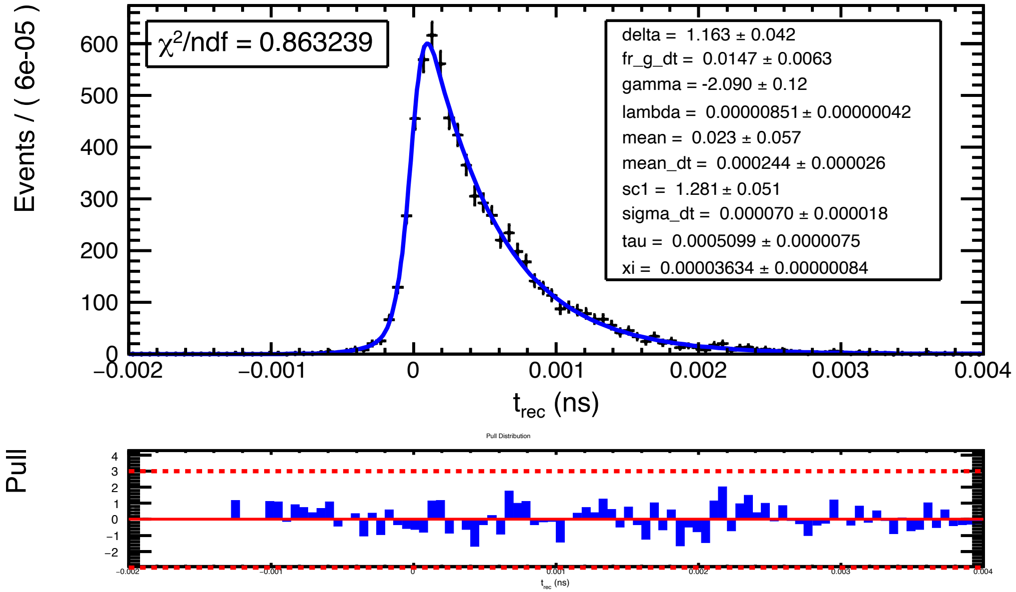
Fit for 10 fb^{-1} data:

Results from 10 fb^{-1} Belle II data:

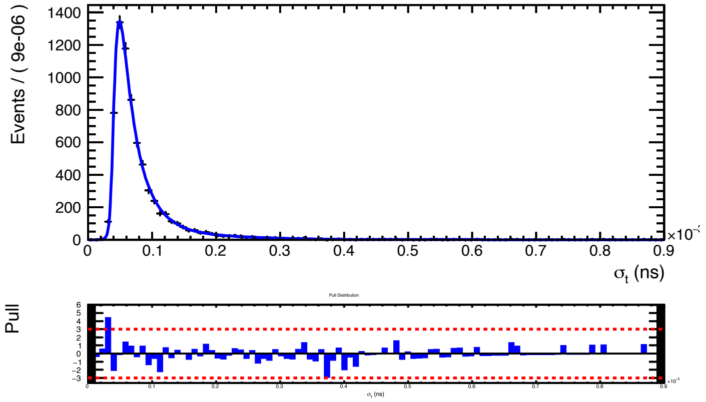
- **Lifetime value from fit is:**
  - $\tau = (5.099 \pm 0.075) \times 10^{-13}$ s
- ***Lifetime result from 10 fb^{-1} MC:***
  - $\tau = (4.988 \pm 0.065) \times 10^{-13}$ s
- Lifetime result latest PDG value is:

$\tau = (5.04 \pm 0.04) \times 10^{-13}$ s

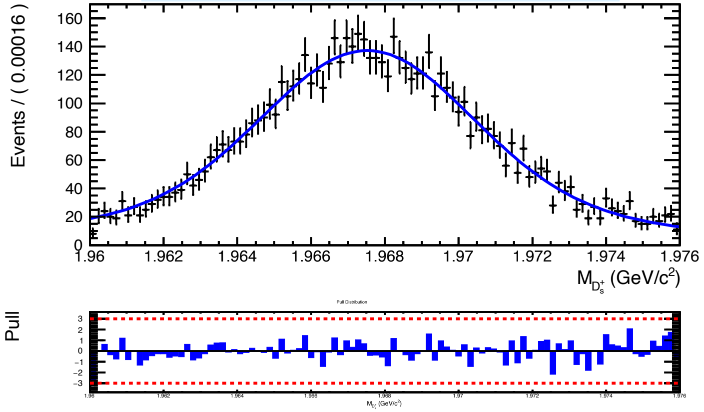
Fit Projection on t



Fit Projection on σ_t



Fit Projection on $M_{D_s^+}$



Summary:

- D_s^+ lifetime measurement at Belle II is in progress.

- Final version of lifetime fit pdf is ready.

- Lifetime measurement results obtained using MC sample:
  - Results from MC sample I : $\tau = (5.036 \pm 0.032) \times 10^{-13}$ s
  - Results from MC sample II: $\tau = (5.063 \pm 0.033) \times 10^{-13}$ s
  - Both are consistent with generated MC value of 5.000 X 10^{-13} s.

- Fitted for lifetime using above pdf for 10 fb-1 of data
  - Results from 10 fb^{-1} of data: $\tau = (5.099 \pm 0.075) \times 10^{-13}$ s.
  - Results from corresponding 10 fb^{-1} run-dependent MC: $\tau = (4.988 \pm 0.065) \times 10^{-13}$ s

- Work on cross-checks for bias and systematic uncertainty measurement ongoing.
- We plan to release first Belle II note soon.
- If interested in lifetime measurements, check other charm lifetime analysis in progress at Belle II:
  - D^0, D^+ lifetime and Λ_c^+ lifetime
  - See June B2GM slides for latest updates

Backup

Selection variables:

Cut on helicity angle:

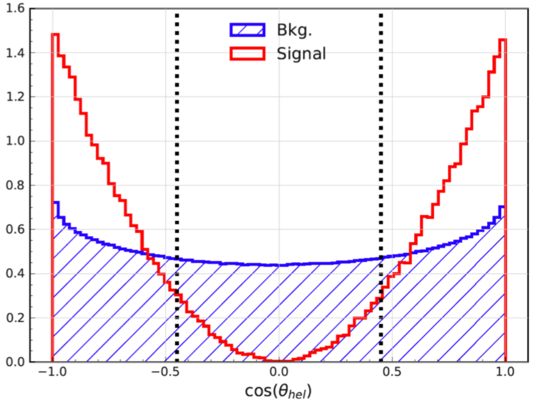
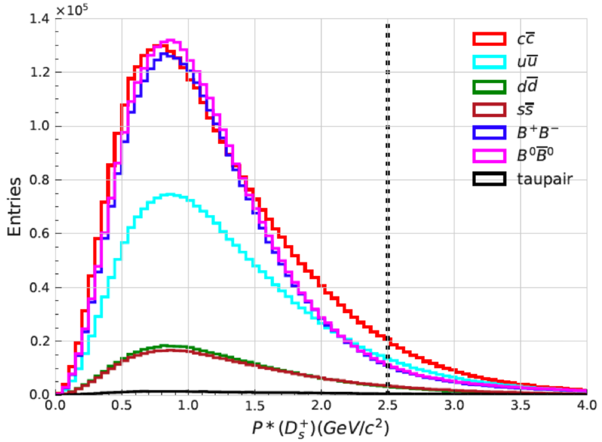
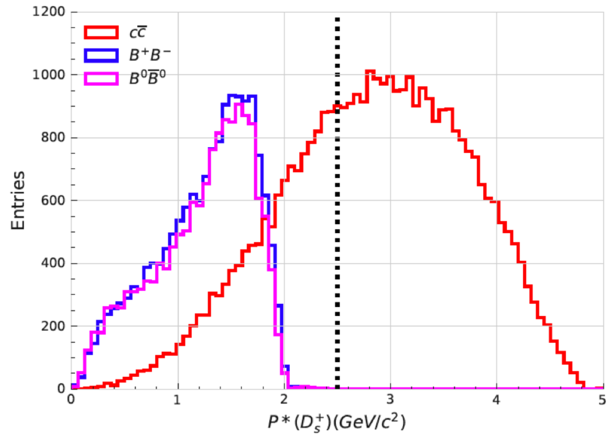


FIG. 6: Distribution of $\cos(\theta_{\mathrm{hel}})$ for truth matched signal (red) and background (blue) events. To suppress the maximum amount of background and retain maximum amount of signal we require $|cos(\theta_{hel})|$ >0.45

Cut on D_s^+ momentum in e^+e^- COM frame:



(a) $P^*_{D_s^+}$ distribution for truth matched background events

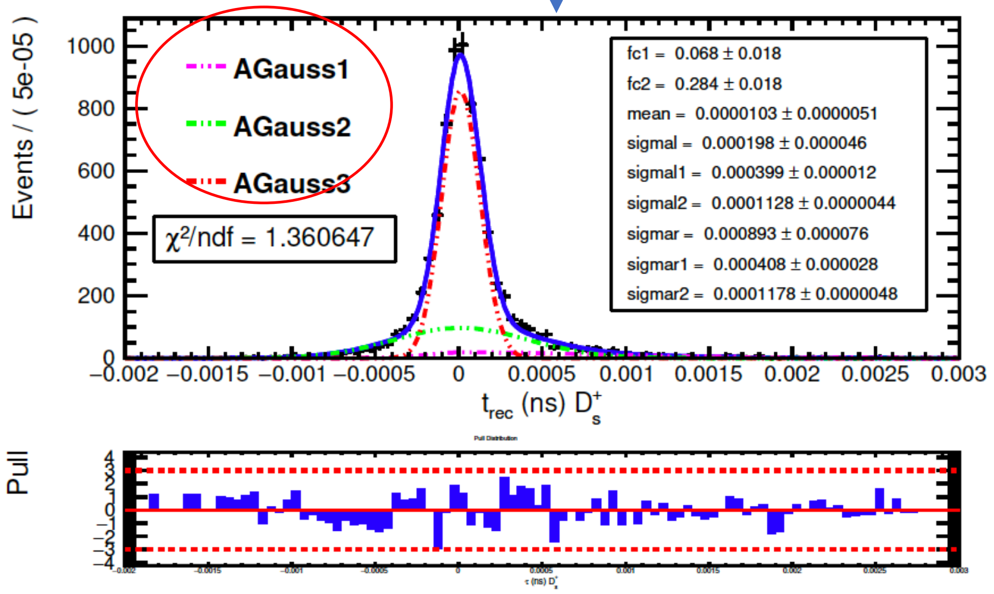


(b) $P^*_{D_s^+}$ distribution for truth matched signal events

FIG. 5: $\mathrm{P}^*_{\mathrm{D_s^+}}$ distribution for truth matched signal (5a) and background events (5b) from different production type. We require $\mathrm{P}^*_{\mathrm{D_s^+}}$ >2.5 to get rid of D_s^+ coming from B meson decays.

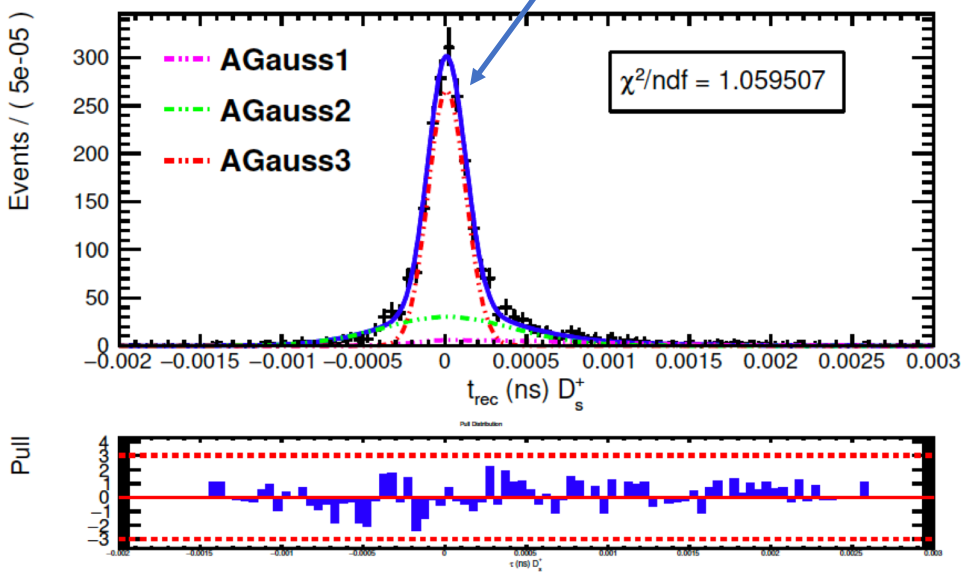
Fitting for $F_{bkg}(t)$:

Decay time t fit for events in $M_{D_s^+}$ sideband:



(a) side-band background events fit

Projecting the pdf obtained from sidebands on background events decay time distribution in signal region:



(b) signal region truth matched background events

Johnson SU Pdf and σ_t fit:

Johnson's S_U distribution.

This PDF results from transforming a normally distributed variable x to this form:

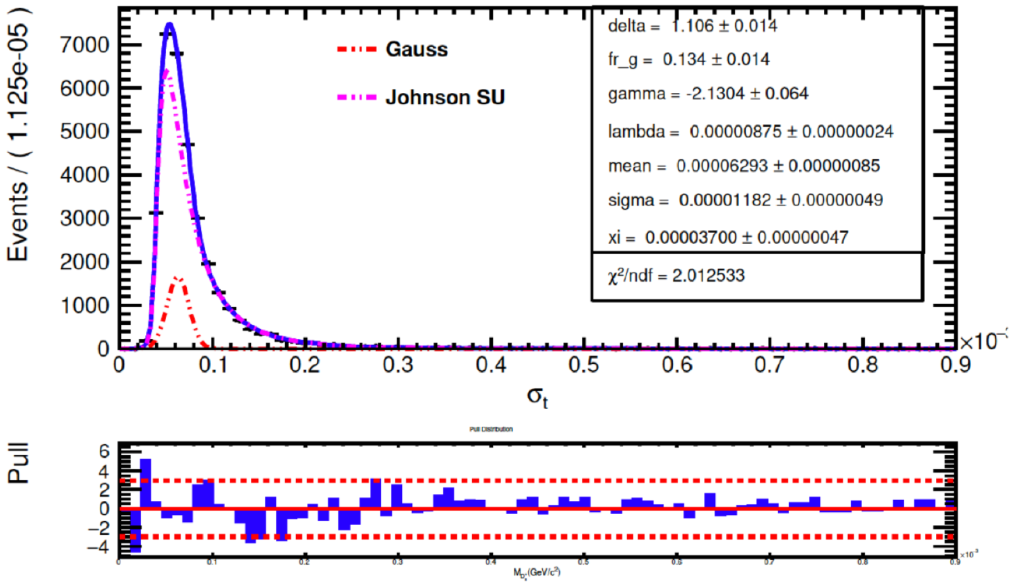
$$z = \gamma + \delta \sinh^{-1}\left(\frac{x-\mu}{\lambda}\right)$$

The resulting PDF is

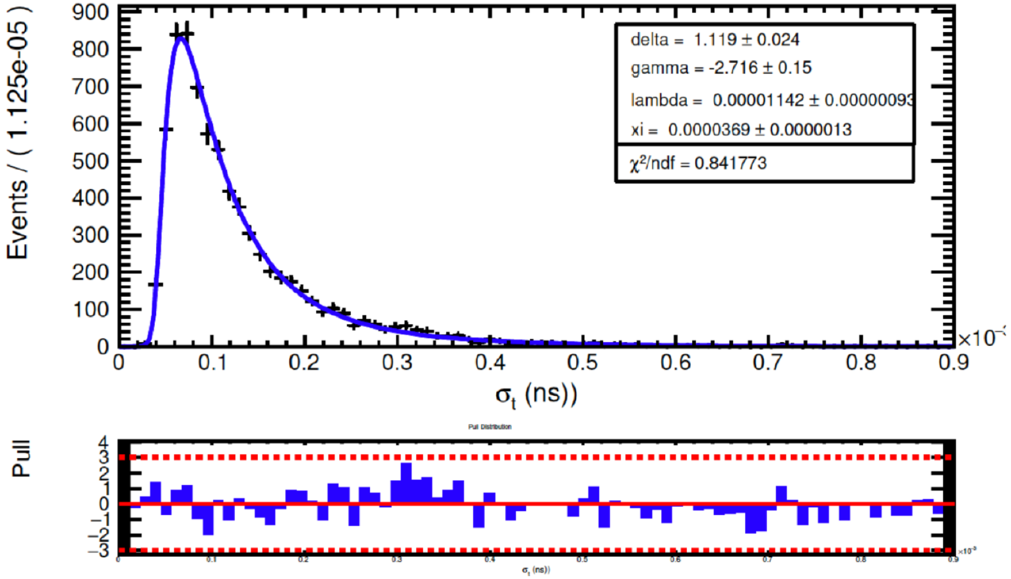
$$\text{PDF[Johnson } S_U] = \frac{\delta}{\lambda\sqrt{2\pi}} \frac{1}{\sqrt{1+\left(\frac{x-\mu}{\lambda}\right)^2}} \exp\left[-\frac{1}{2}\left(\gamma + \delta \sinh^{-1}\left(\frac{x-\mu}{\lambda}\right)\right)^2\right].$$

It is often used to fit a mass difference for charm decays, and therefore the variable x is called "mass" in the implementation. A mass threshold allows to set the PDF to zero to the left of the threshold.

Truth matched signal events , σ_t fit:



Background sideband events, σ_t fit:

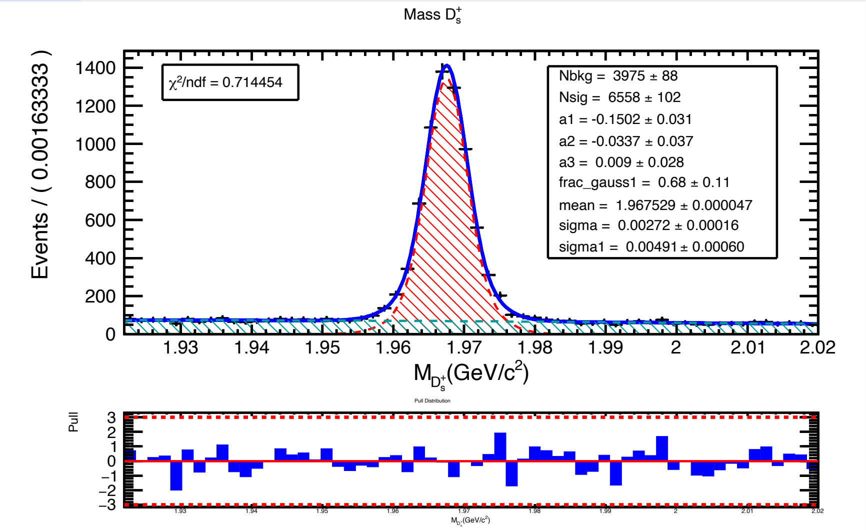


Data-MC comparison

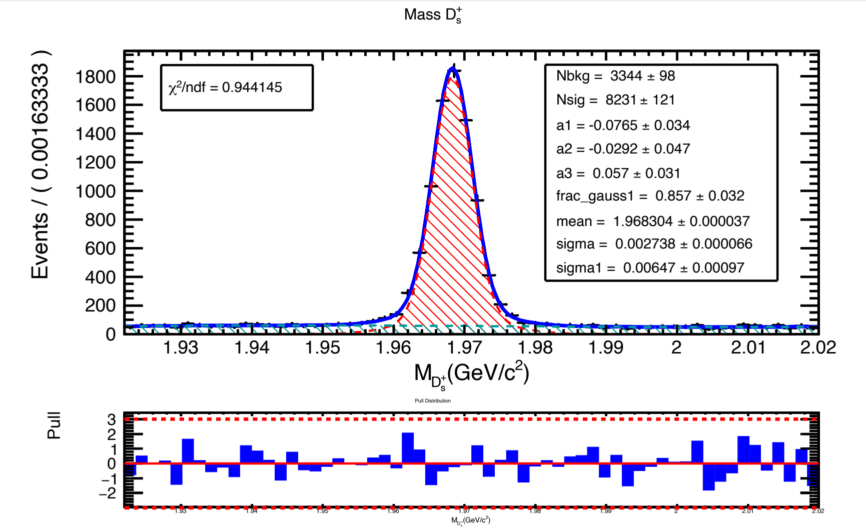
- Both data (bucket-10) and MC (run-dependent MC bucket 10) samples used correspond to an integrated luminosity of 10.4 fb^{-1}
- Will compare the $\mathbf{M_{D_s^+}}$, t and σ_t fit between data and MC.

$\mathbf{M_{D_s^+}}$ fit:

Data



MC

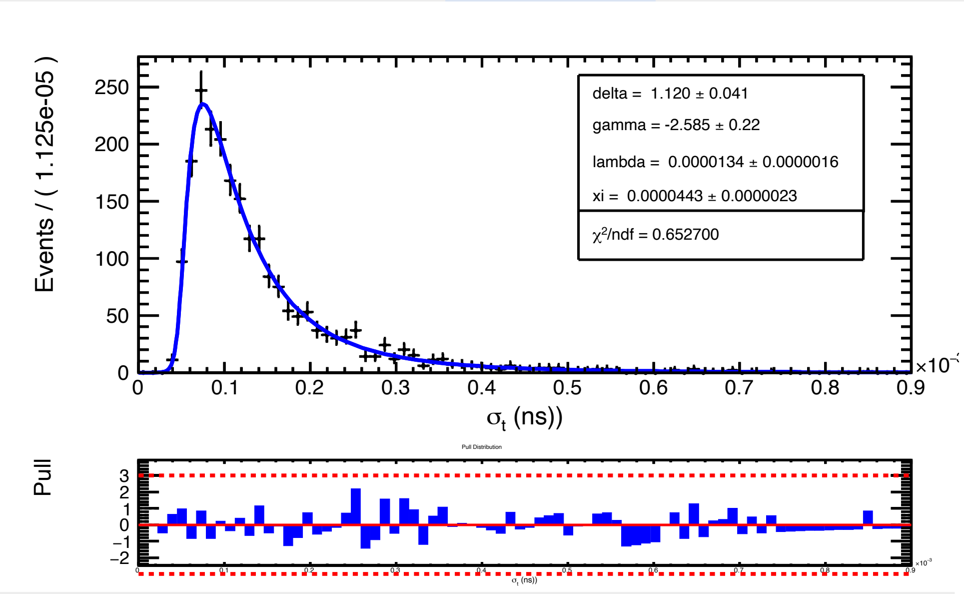


- Nsig is 6558±102 for data and 8231±121 for MC,
  - Nsig (data/MC) = 79.67 ± 1.71 % (20% lower signal in data)
- Nbkg (data) = 3975±88, MC = 3344±98, 0.00357,
  - ratio data/MC = 1.19±0.04 (20% higher bkg. in data)
- Purity in signal region: Data = 90.42 % , MC = 93.38 %

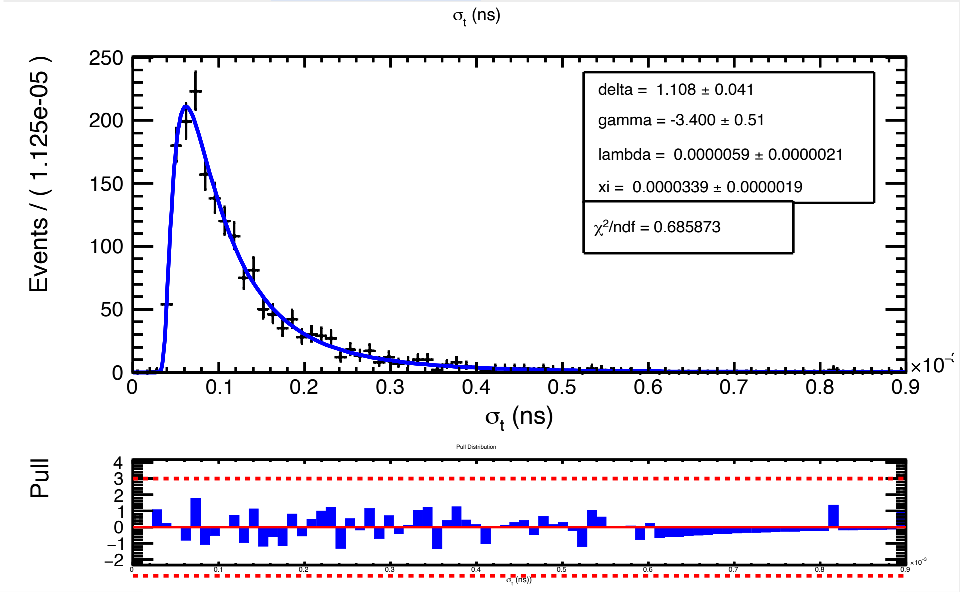
Data-MC comparison

σ_t fit for events in $M_{D_s^+}$ sidebands:

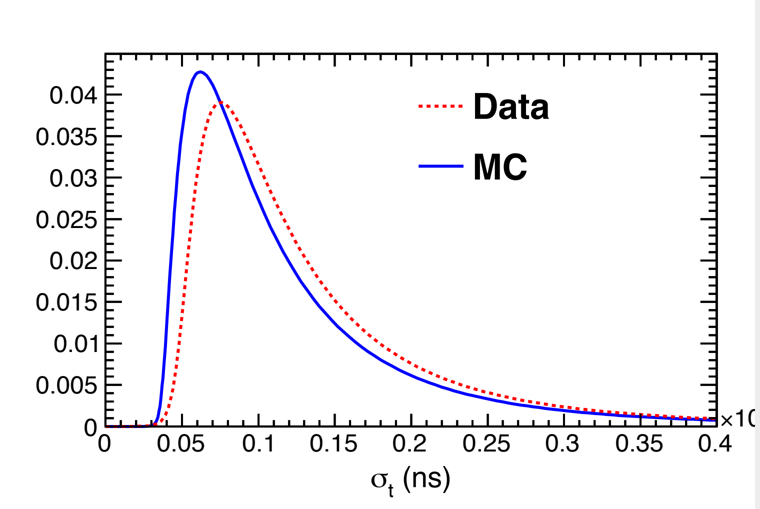
Data



MC



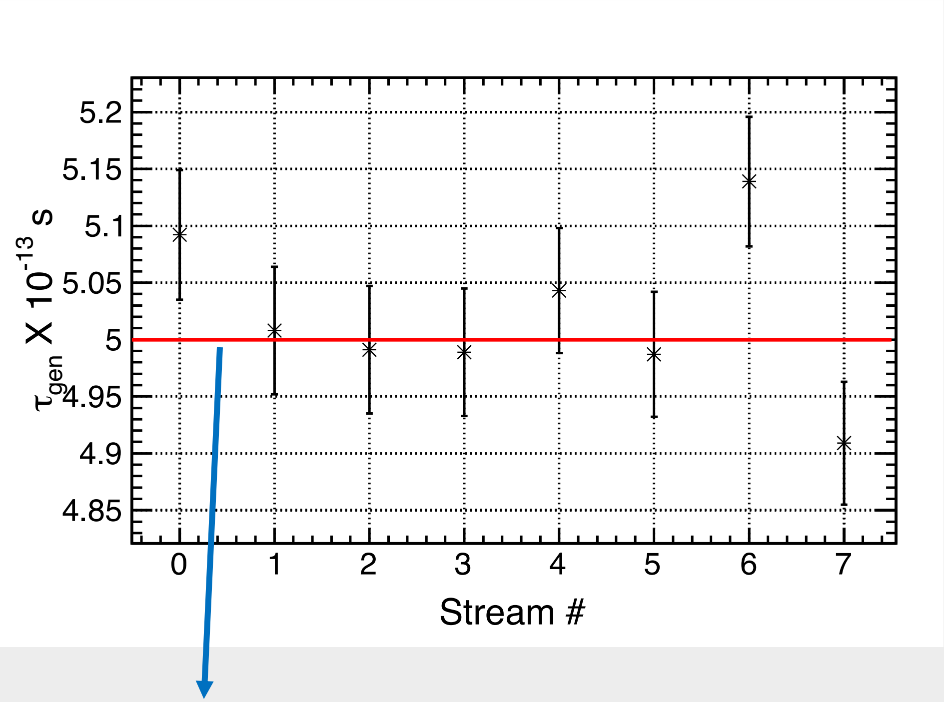
- Johnson SU pdf was used to model the σ_t for both data and MC.
- Xi parameter decides the peak of distribution, peak for MC (33.9±1.9 fs) is shifted to left compared to data (44.3±2.3 fs)
- Lambda parameters is width of distribution, MC = 5.9±2.1 fs , data = 13.4±1.6 fs.



MC study to check for bias in lifetime measurement

Bias from selection criterion:

- To check for any bias in lifetime measurement coming from reconstruction, we fit for generated decay time using the truth matched signal events.
- We fit the generated decay time t_{gen} for 8 independent MC samples with luminosity 10 fb^{-1} each.
- τ_{gen} from all 8 MC samples are consistent with no bias from the selection criterion.



Lifetime value used for MC generation.