Measurement of D_s^+ lifetime at Belle II

US Belle II Summer Workshop 2022

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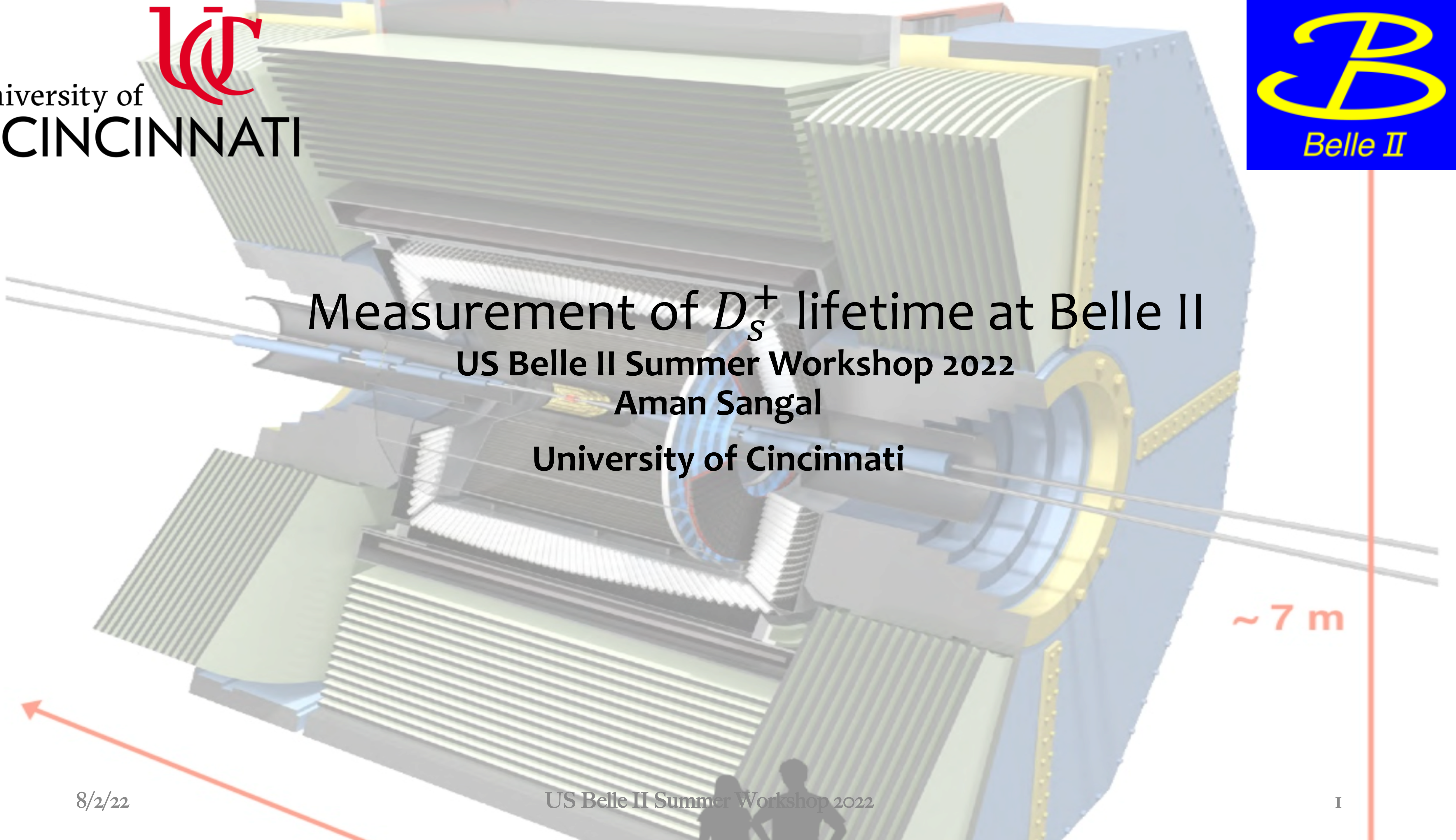


Why measure D_s^+ lifetime ?

- **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 the underlying interaction.
  - D_s^+ lifetime world average value is $(5.04\pm0.04)\times10^{-13}$ s *[PDG 2022]*

- **Why measure D_s^+ lifetime ?**
  - Using fraction of current Belle II data, we can achieve world's best precision.
  - Will add one more measurement to the list of charm lifetime measurements from Belle II.
  - A precision measurement of D_s^+ lifetime adds to the demonstration of:
    - Good Belle II detector performance
    - Excellent vertexing capabilities.

Proper decay time t:

- **Proper decay time:** $t = \frac{(\Delta\vec{r}\cdot\hat{p})}{(|\vec{p}|/m)c}$ → distance, velocity
  - $\Delta\vec{r}$ 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* $e^+e^- \rightarrow c\bar{c}$)

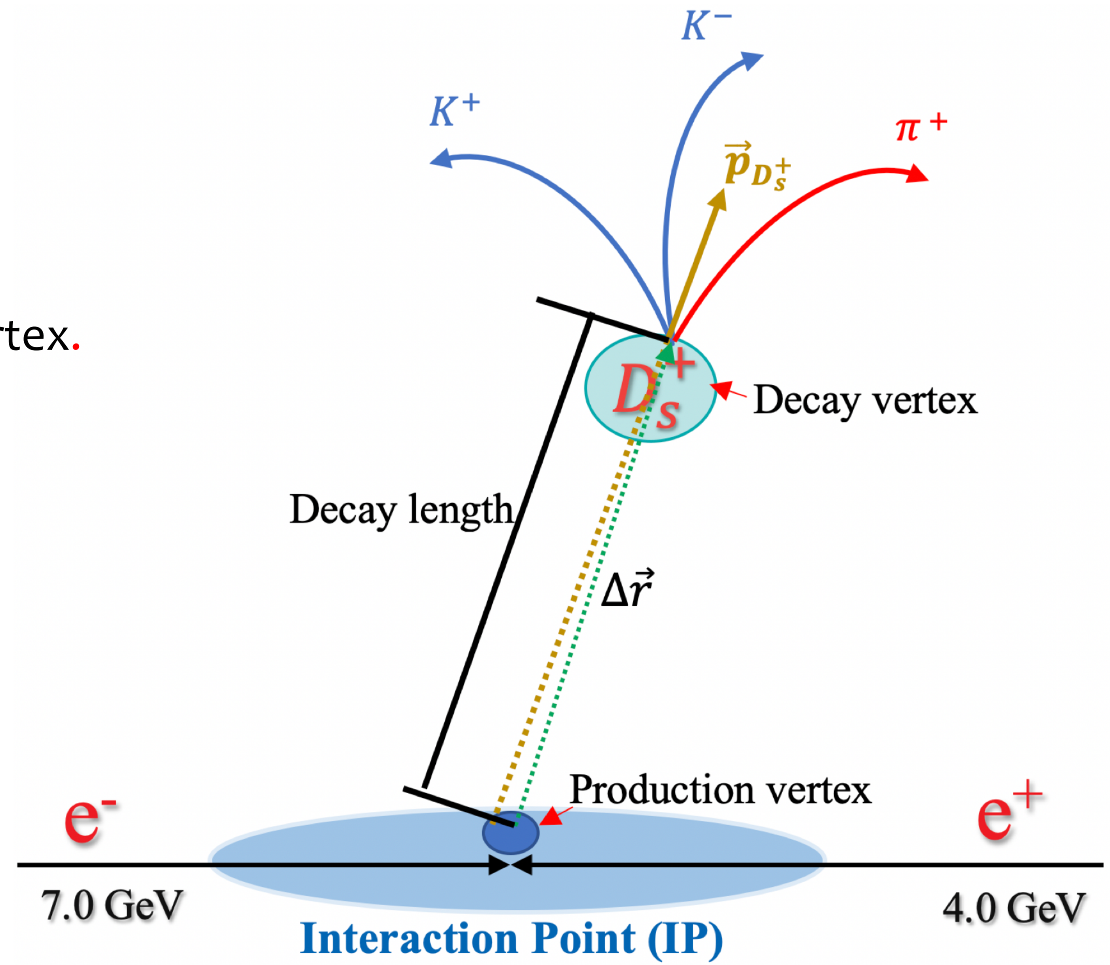
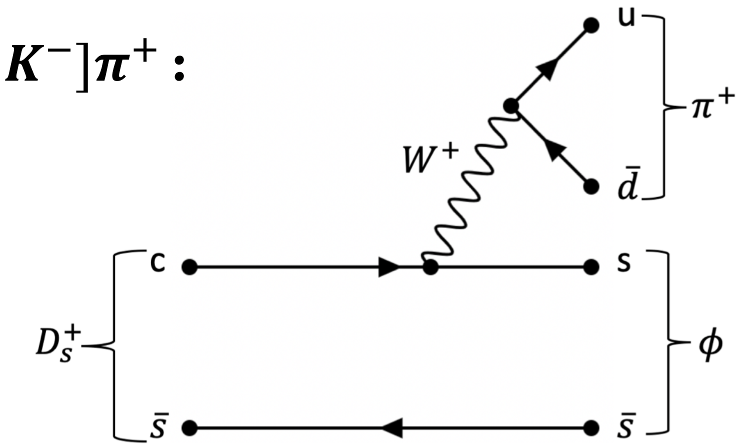


Fig. not to scale

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: $\boldsymbol{D_s^+ \to \phi[K^+K^-]\pi^+}$ **:**
  - Large branching fraction : 2.24 ± 0.08 % *[PDG 2021]*
  - Three charged tracks, K^+K^- and π^+ in the final state.
  - High sample purity of ~94 % in the signal region.



Data and MC sample used for measurement:

- **MC sample:**
  - Run independent MC sample
  - MC 14ri_d (200 fb^{-1})
  - Processed 3 independent 200 fb^{-1} samples for MC studies (*always a good idea to have different independent MC samples to separate statistical and systematic effects*)

- **Data:**
  - All data until Exp. 18 bucket 25
  - Total: ~ 207 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	$\lvert dr \rvert < 0.5$ cm
dz	$\lvert dz \rvert < 2.0$ 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	$\lvert cos(\theta_{hel}) \rvert > 0.45$
$P^*_{D_s^+}$	> 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

Selecting tracks originating near IP

Selecting tracks with momentum measured with better precision.

Identification of charged tracks as pion or kaon.

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

To suppress the background

B mesons have a finite lifetime

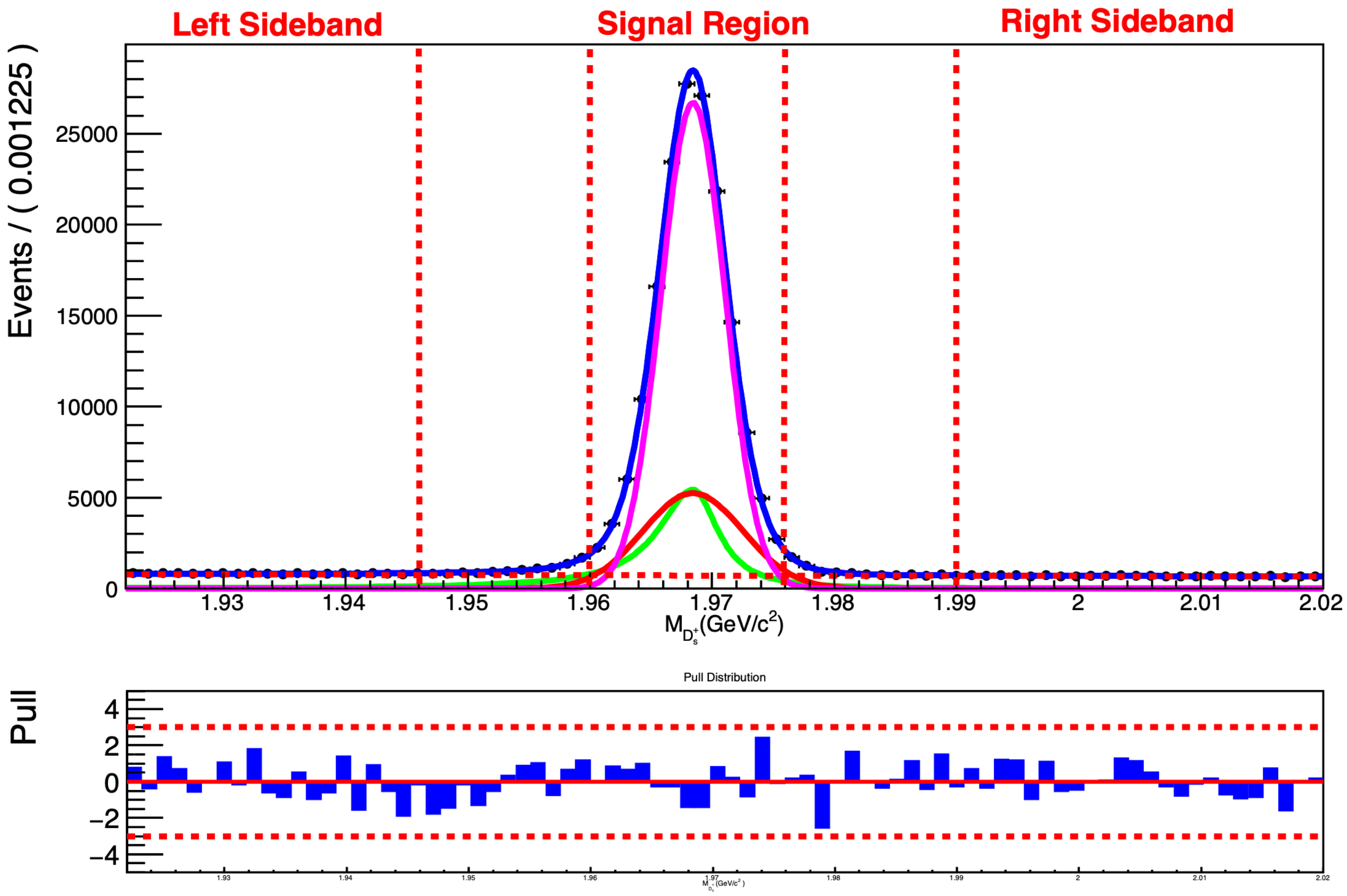
Results from MC studies

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

D_s^+ mass distributions after reconstruction:

- We fit for lifetime in a Signal region (SR) of (1.96, 1.976) GeV/c^2
- To study the background we use left and right sidebands
- For 200 fb^{-1} MC sample we have **~160k D_s^+ decays in the SR**

- **Sample purity $[S/(S+B)]$ = ~ 94.3** % in the SR where S and B are the number of signal and background events in the signal region



Lifetime PDF:

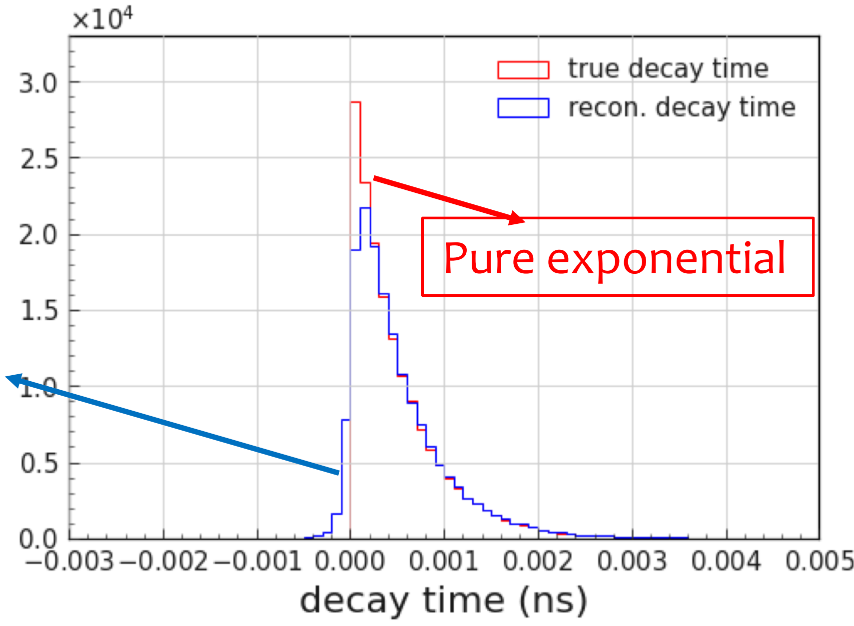
- **Signal Events:** Real D_s^+ decays to $K^+K^-\pi^+$ final state:
  - Probability of an event to decay at time t :

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

Convolution of natural decay law and experimental resolution function

Natural decay law
No experimental effects

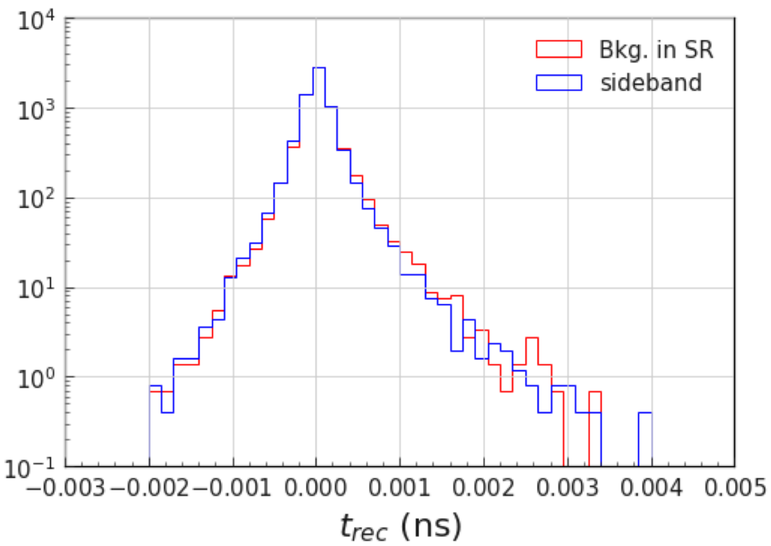
Detector resolution effect

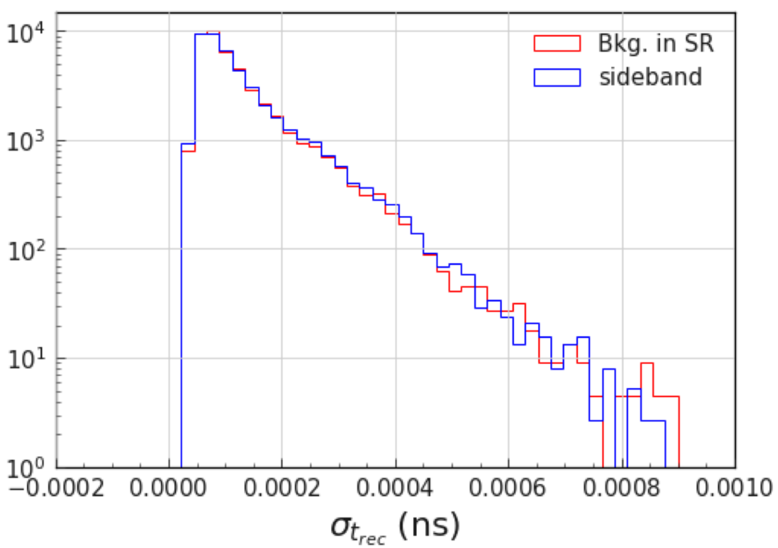


- **Event level resolution function:** $R(t - t' : mean, s, \sigma_t^i)$
  - A single gaussian is used as resolution function.
  - Resolution function has different width for each event.
  - We use the σ_t^i , error in decay time t for event i as the width of resolution function for that event.
  - σ_t^i 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)*





Lifetime pdf:

- Total decay time t pdf:
  - We use a 2d pdf, f(t, σ_t) in fit variables: decay time (t), error in decay time (σ_t) *

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

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

$F_{sig}(\sigma_t)$, $F_{sig}(t)$:
- Model decay time t for signal events
- $F_{sig}(\sigma_t)$: background subtracted histogram PDF

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

$F_{bkg}(\sigma_t)$, $F_{bkg}(t)$:
- Model decay time t for background events.
- $F_{bkg}(\sigma_t)$: histogram PDF
- ***Fixed*** to shapes obtained using sideband events.

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

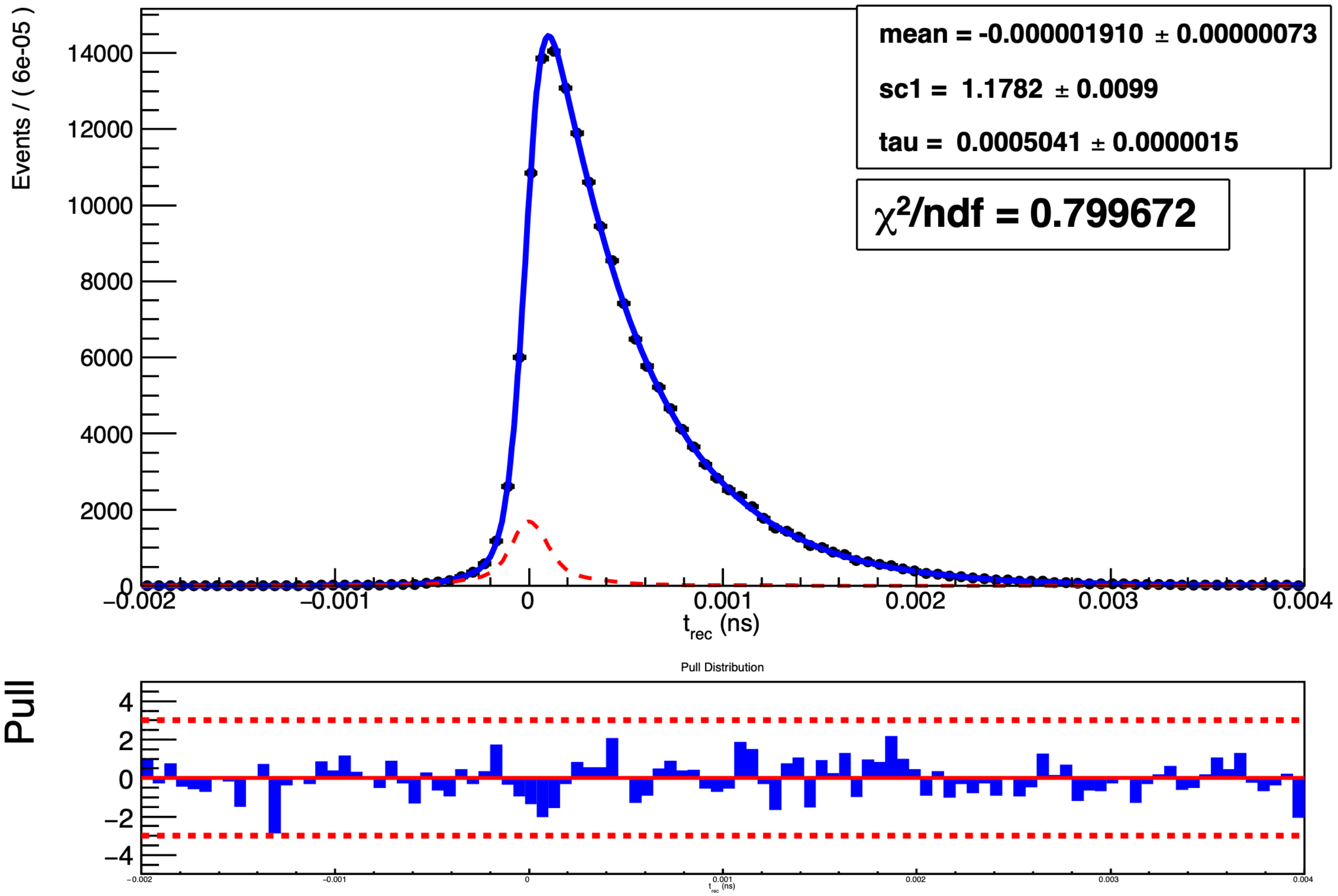
** Previously used 3d fit in t, σ_t, . Found bias in lifetime due to mass PDF*

Final fit results (MC):

Results from 200 fb^{-1} MC sample:

- **Lifetime value from fit is:**
  - $\tau = (504.10 \pm 1.47)\ fs$
- Result consistent with lifetime value used in Belle II simulation $\tau = 504.00\ fs$
- Lifetime measured on other independent MC stream **505.22 +- 1.47 fs**

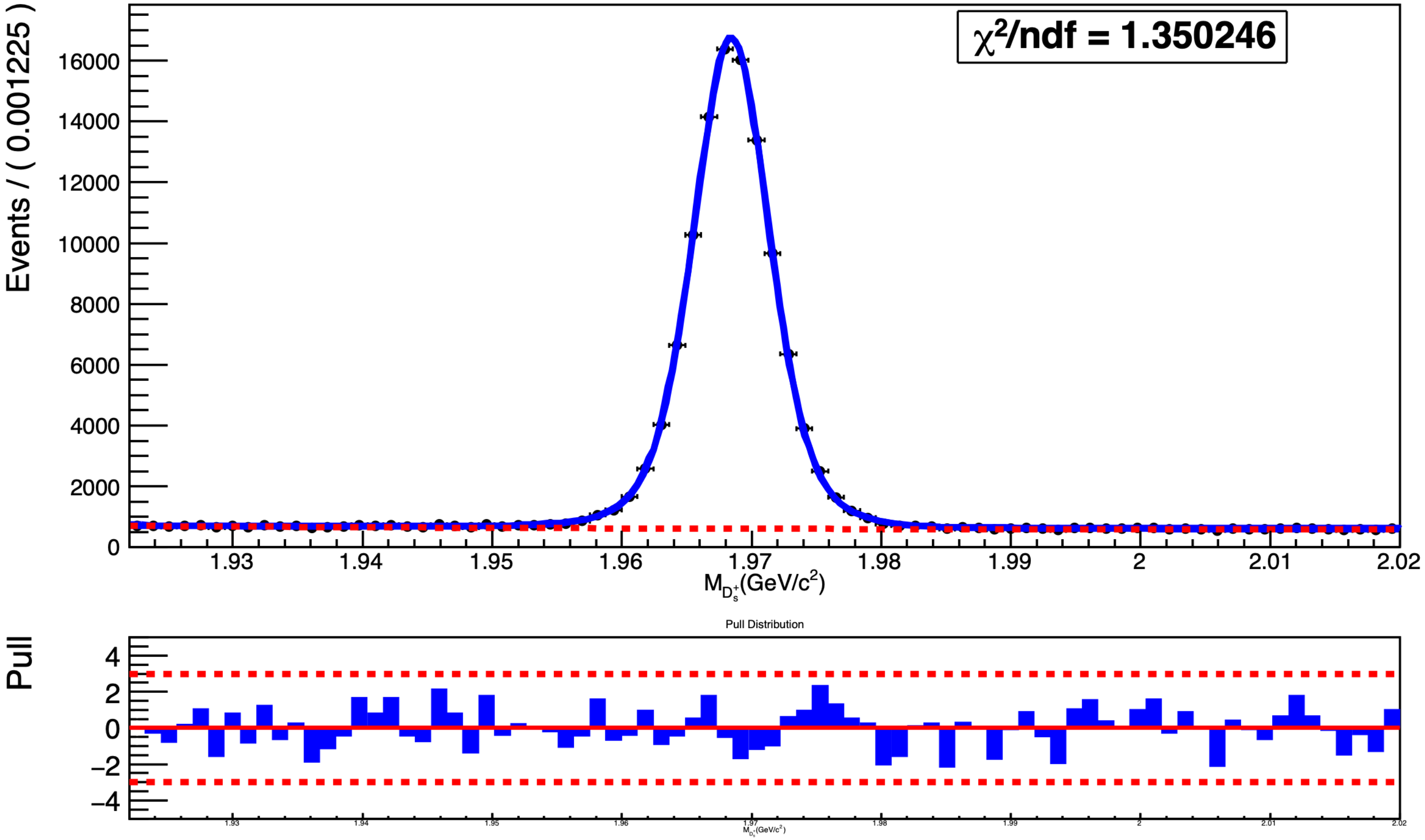
(also consistent within 1 sigma)



D_s^+ mass fit in data:

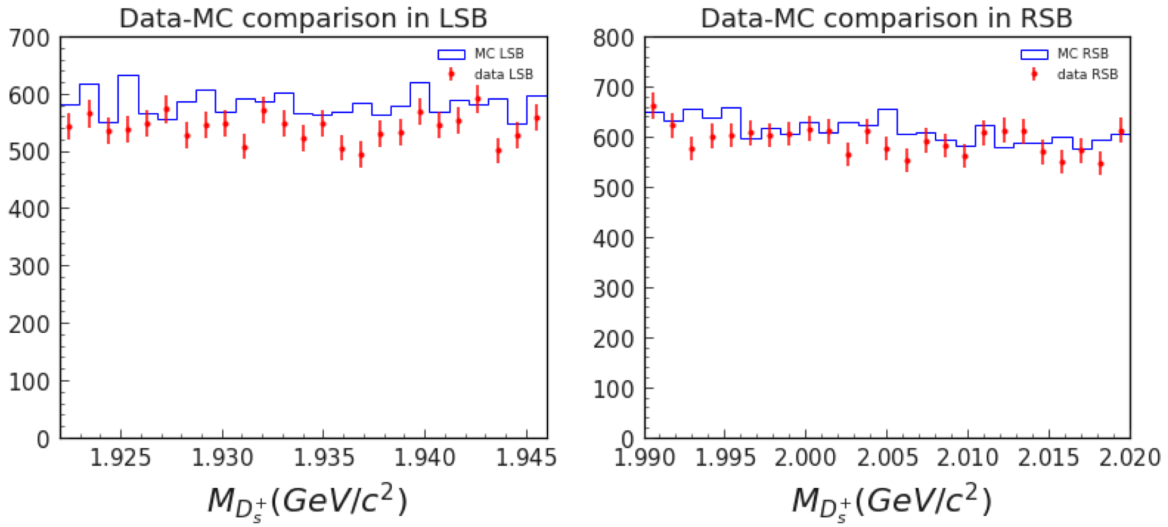
- The plot on right shows D_s^+ mass fit on data sample using same functional form as used for MC

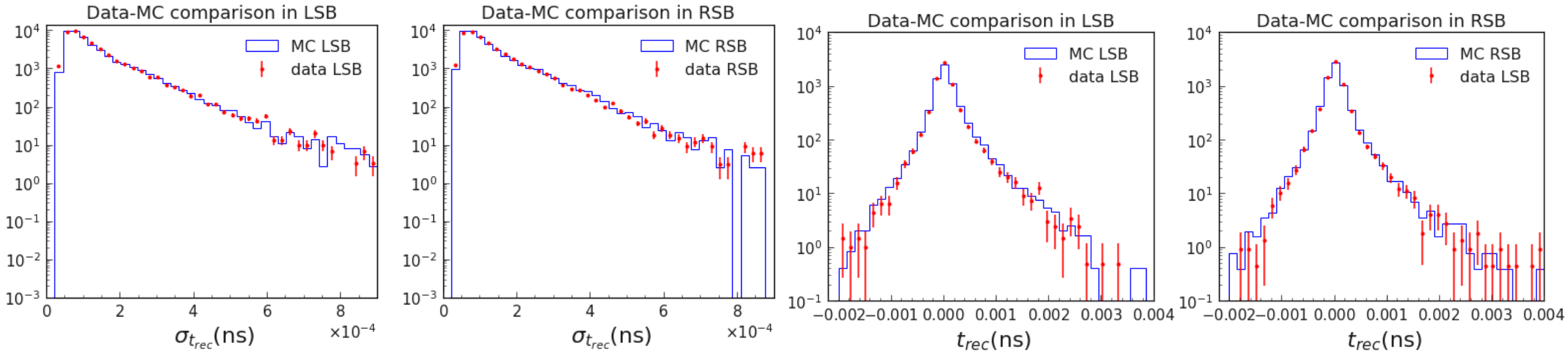
- **Purity of data = 92.61 %**
    - Lower compared to MC (94.3%)
    - Nsig(data)/Nsig(MC) ~ 70%
    - Nbkg(data)/Nbkg(MC) ~ 95%



Comparing data-MC sidebands (t, σ_t)

- MC is scaled to match data luminosity.
- In the sideband, the data-MC shapes are consistent for (MD_s^+, t, σ_t)





Summary:

- Presented a basic overview of D_s^+ lifetime measurement using ~ 207 fb^{-1} Belle II data.
- Discussion is applicable in general to other lifetime measurements as well
- If interested in lifetime measurements, check Belle II notes for recent charm lifetime results (Λ_c, Ω_c, D^0, D^+)

- Lifetime measurement results obtained using MC sample:
  - Results from MC sample I : **τ = (504.10 ± 1.47) fs**
  - Results from MC sample II: **τ = (505.22 ± 1.47) fs**
  - Both are consistent with generated MC value of 504.00 fs.

- Looked at data (lifetime blinded)
  - Fit the D_s^+ mass distribution in data
  - The t, σ_t shapes in sideband are consistent between data and MC

- Analysis got delayed due to commitments to Belle analysis
- Plan to release first draft of Belle II note soon.

Backup

Selection variables:

Cut on helicity angle:

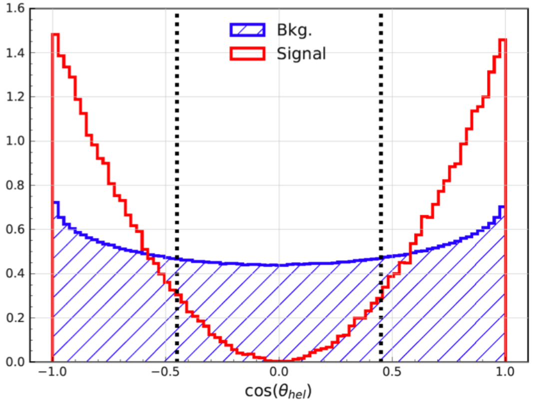
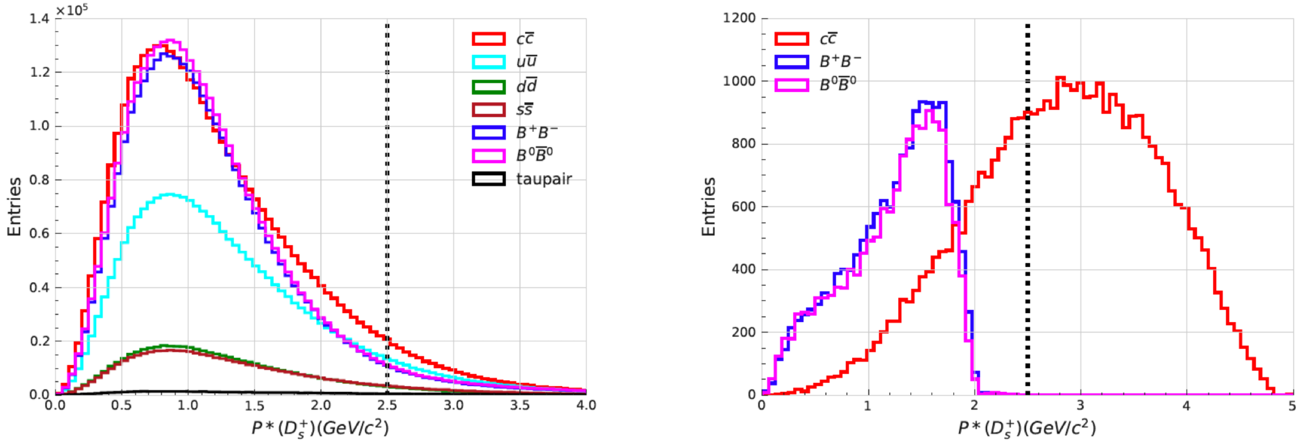


FIG. 6: Distribution of $\cos(\theta_{\text{hel}})$ for truth matched signal (red) and background (blue) events. To suppress the maximum amount of background and retain maximum amount of signal we require $|cos(\theta_{hel})|$ >0.45

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.