Study of the time-dependent CP violation at the Belle II experiment

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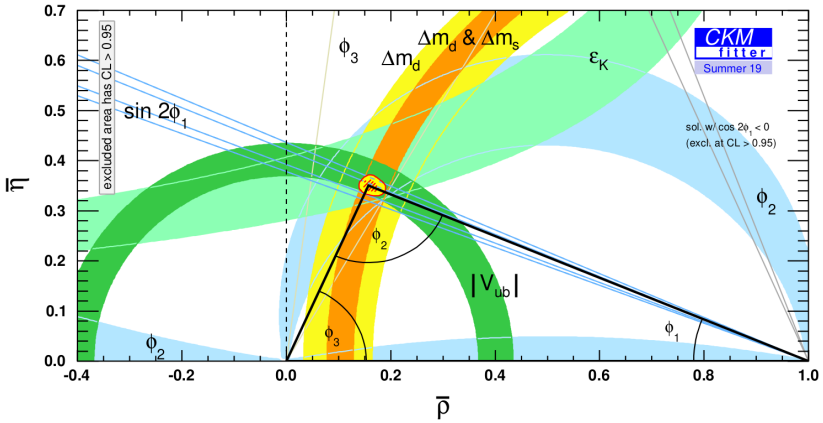
May 26, 2021

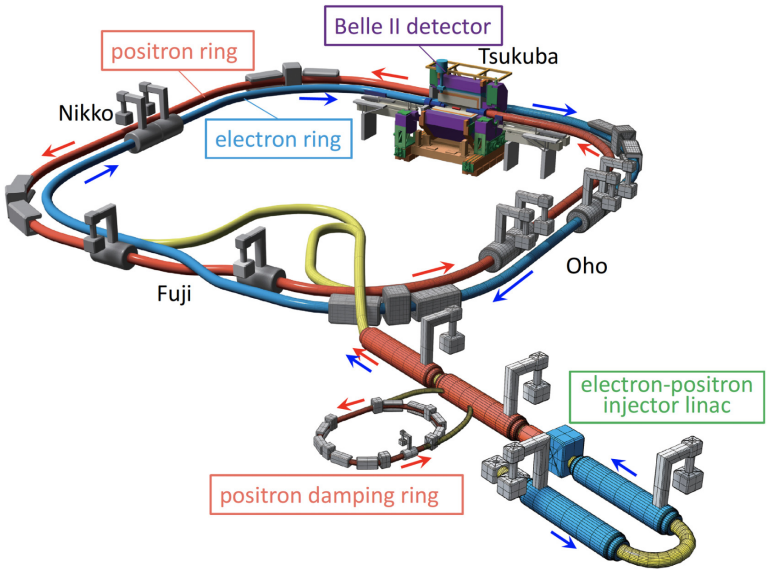
Outline

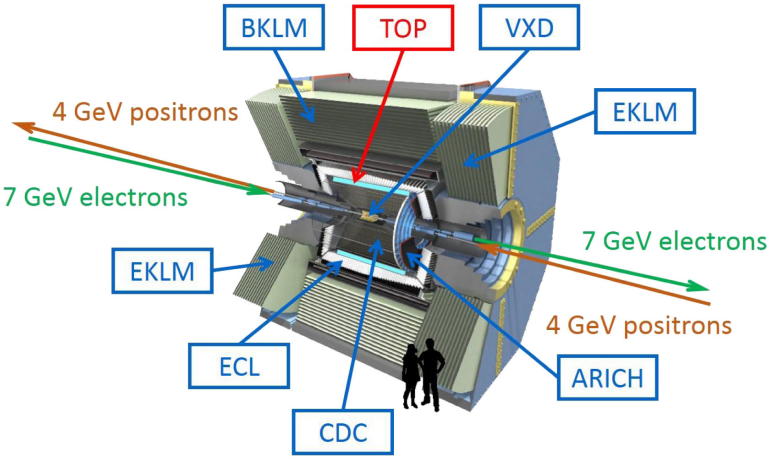
1. Belle II Experiment
2. Data/MC Comparison
3. Δt resolution & Lifetime Fit

Belle II and SuperKEKB

- Belle II experiment - SuperKEKB, Tsukuba, Japan
- B - Factory studying CP violation
- Asymmetric e^+e^- collider - provides B-meson pair with boost (making time-dependent studies possible)





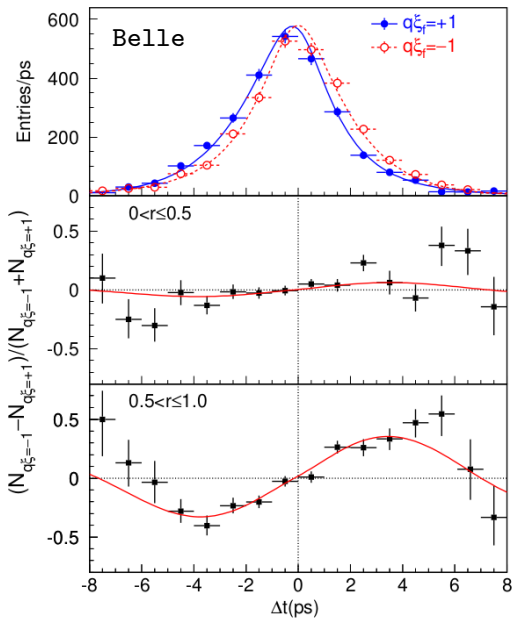


CP-violation studies in neutral B-meson systems

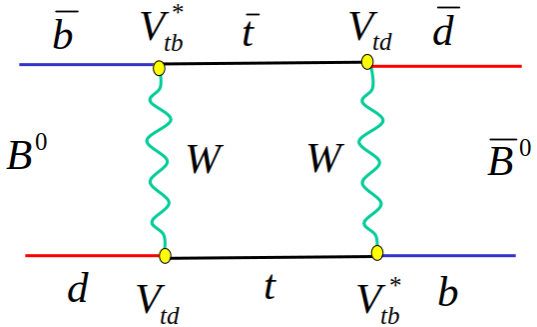
$$f_{\pm}(\Delta t) = \frac{\exp - \frac{|\Delta t|}{\tau_B}}{4\tau_B} \left\{ 1 \pm \mathscr{D} \left[S \sin \Delta m \Delta t + A \cos \Delta m \Delta t \right] \right\}$$

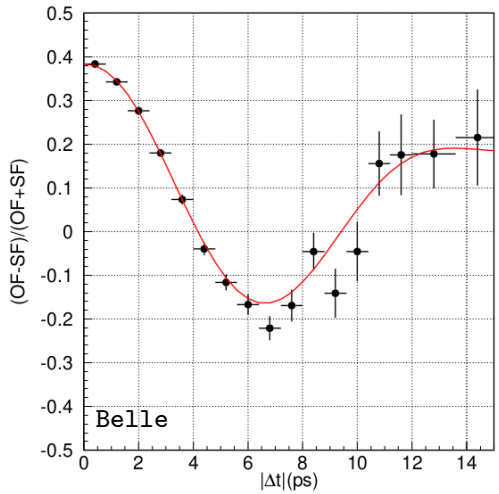
where $\Delta t = t(\mathrm{B_{sig}}$ - fully reconstructed) - $t(\mathrm{B_{tag}}$ - partially reconstructed)

- **CP asymmetry** measurement = $B\overline{B} \to f_{fl}(B_{tag}) f_{CP}(B_{sig})$
- **Mixing frequency** measurement = $B\overline{B} \to f_{fl}(B_{tag}) f_{fl}(B_{sig})$



10.1103/PhysRevD.71.072003





10.1103/PhysRevD.71.072003

MC/Data Comparison

Vertexing procedure - important for precise determination of B- and $\overline{B}$-meson decay vertex spatial separation (later used for Δt estimation)

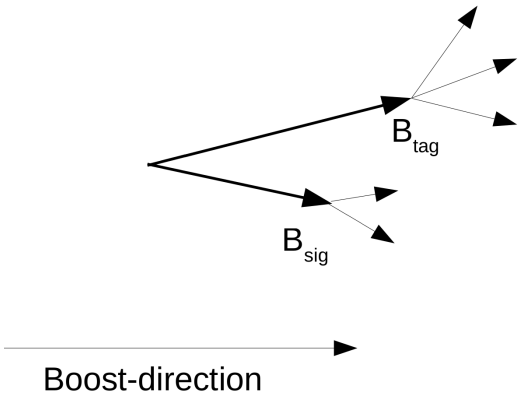
- **Three tag-side constraint** options
  - noConstraint
  - IP
  - Tube
- **Two signal-side constraints**
  - noConstraint
  - IP-pointing

BeamSpot

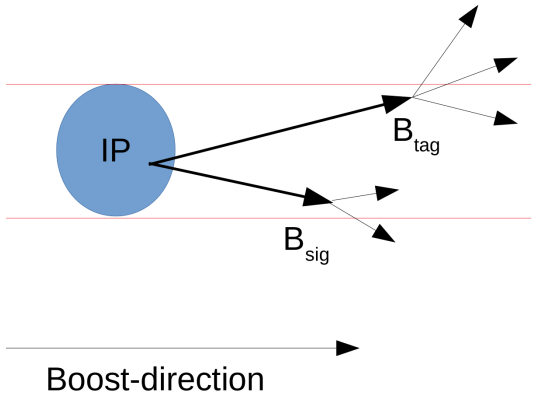
- BeamSpot - Luminous region of the collisions,primary interaction vertices
- New calibration - smaller BeamSpot size, re-calculated every couple minutes

Purpose of the study :

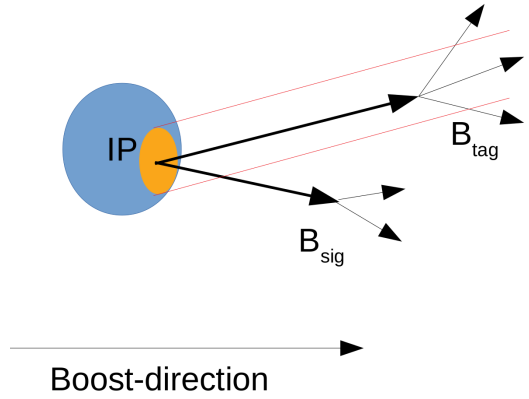
- Find combination of vertexing constraints giving most precise results
- Validate new time-dependent BeamSpot calibration



"noConstraint" option



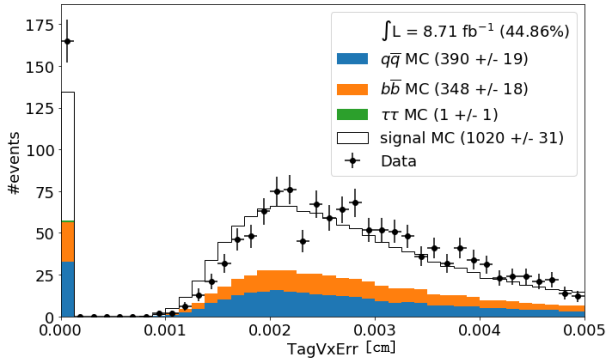
"IP"constraint

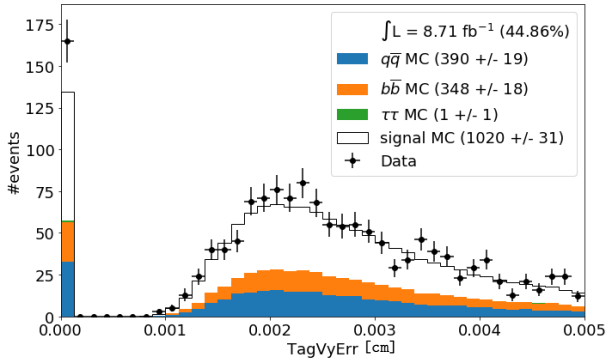


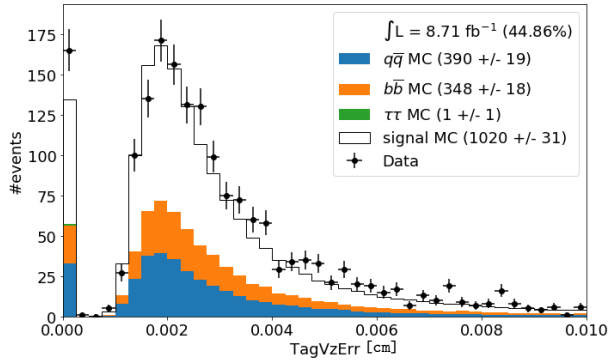
"Tube" constraint

Summer Results ($B^0 \to \pi^+ + D^-(\to K^+ + \pi^- + \pi^-)$): Tag - Side

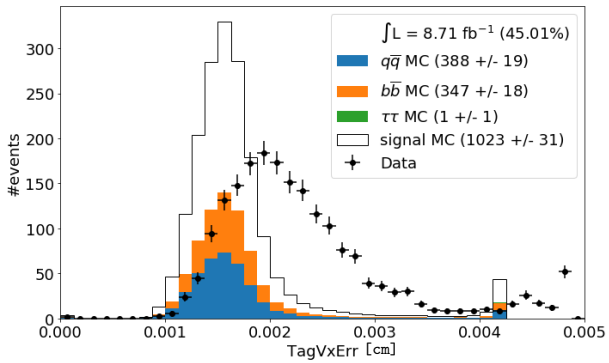
Vertexing of tagging side with "noConstraint" option

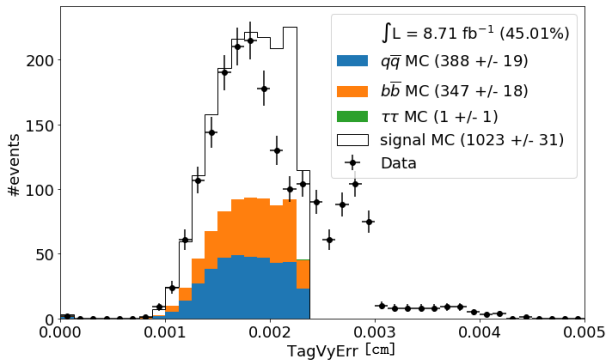


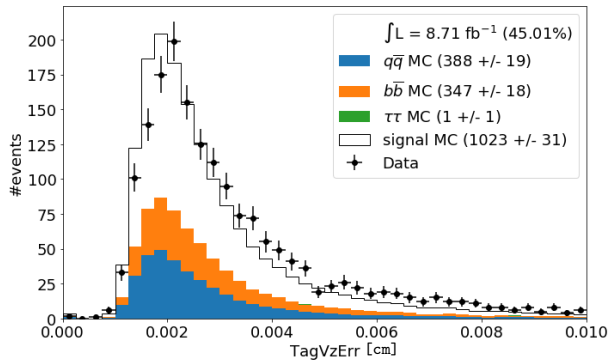




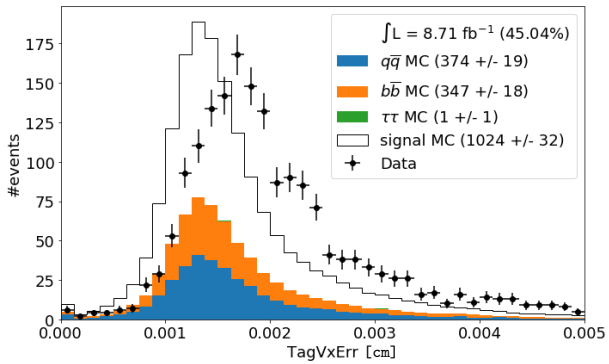
Vertexing of tagging side with "IP" option

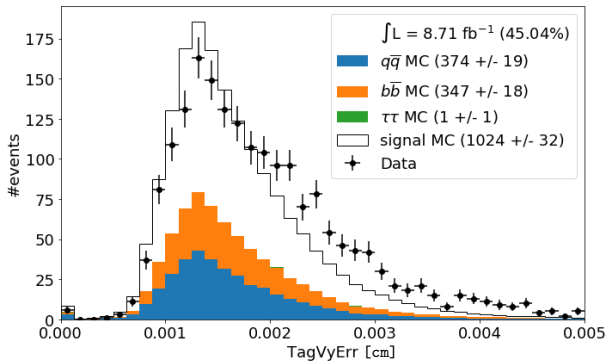


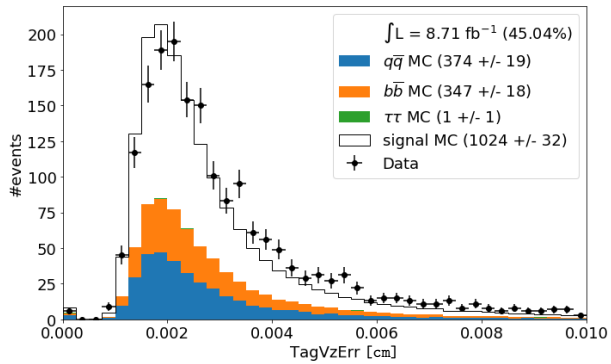




Vertexing of tagging side with "Tube" option

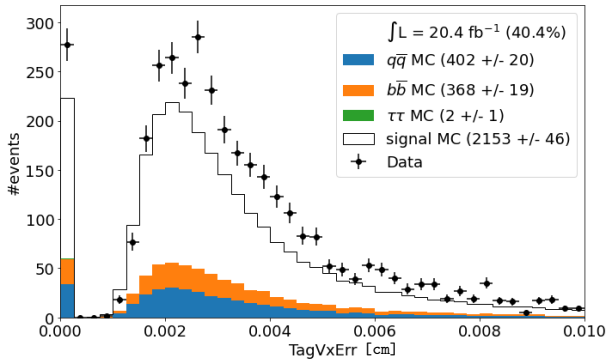


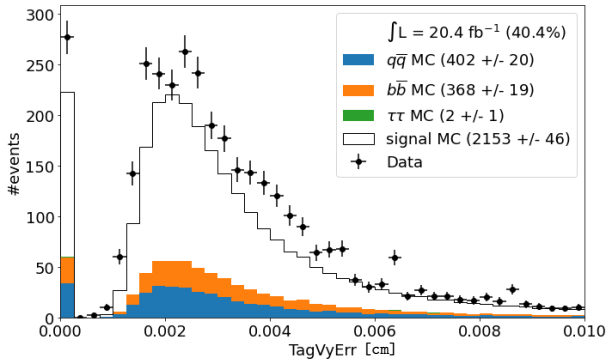


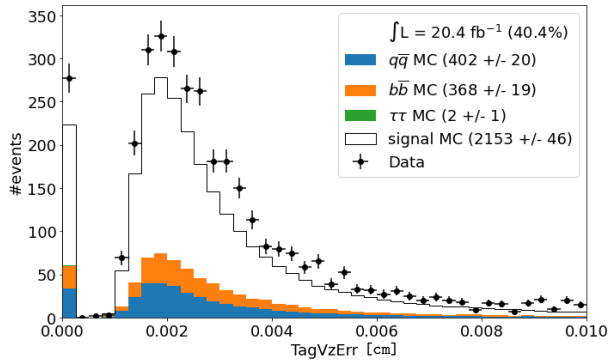


New Results ($B^0 \to \pi^+ + D^-(\to K^+ + \pi^- + \pi^-)$): Tag - Side

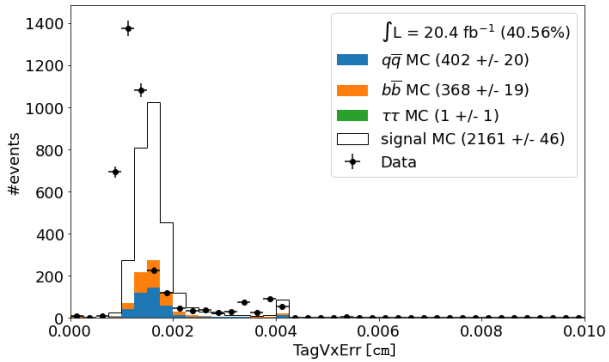
Vertexing of the tagging side with "noConstraint" option:

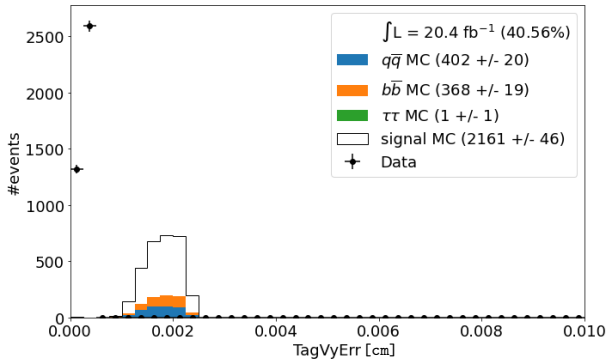


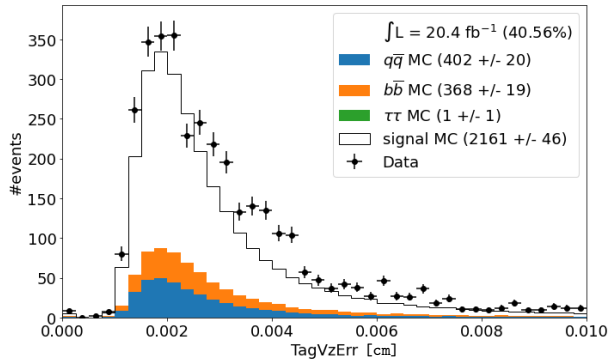




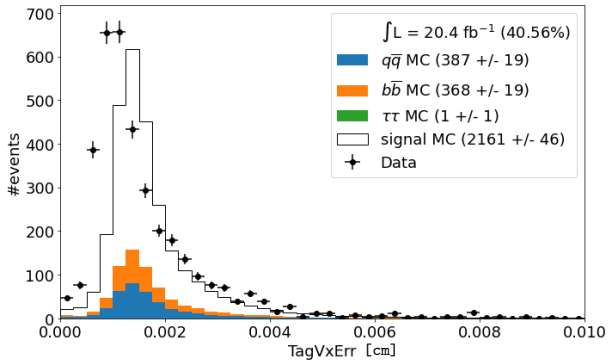
Vertexing of the tagging side with "IP" option:

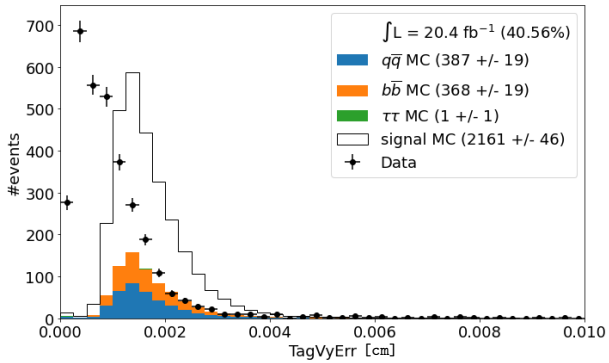


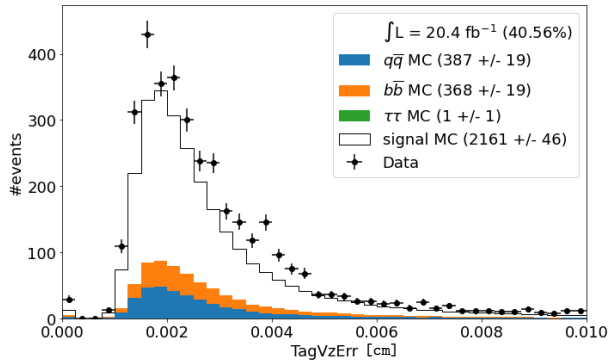




Vertexing of the tagging side with "Tube" option:

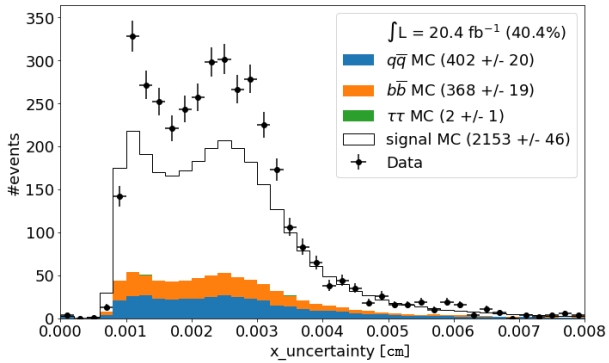


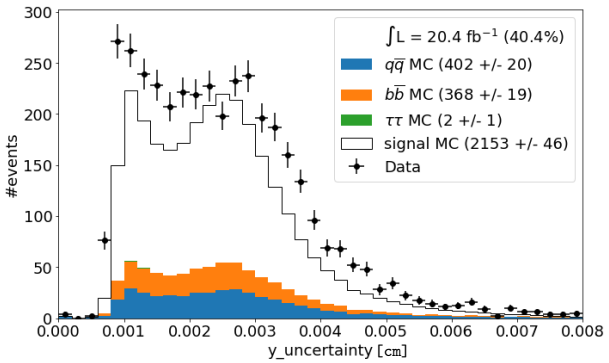


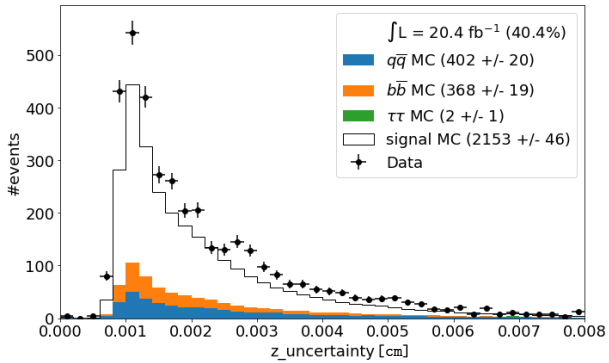


New Results ($B^0 \to \pi^+ + D^-(\to K^+ + \pi^- + \pi^-)$): Signal-side

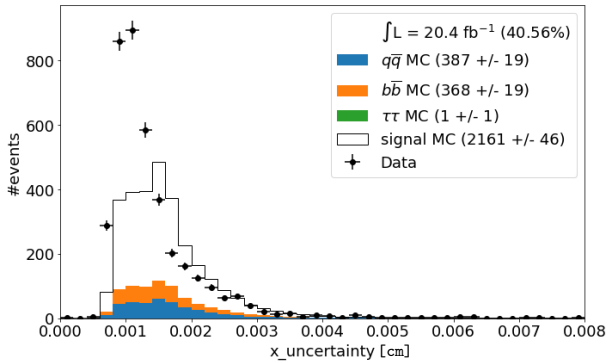
Vertexing of the signal side with "`noConstraint`" option

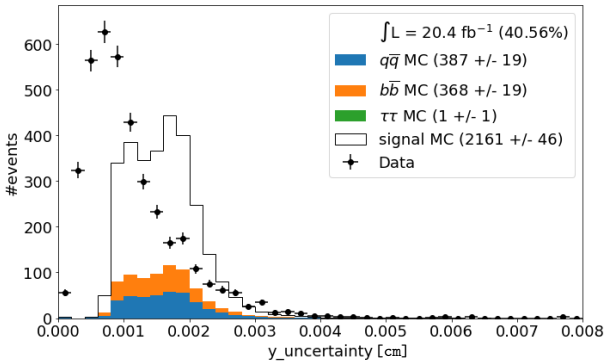


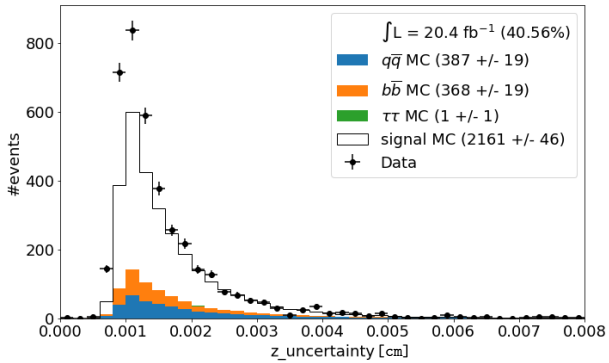




Vertexing of the signal side with "`IP-pointing`" constraint







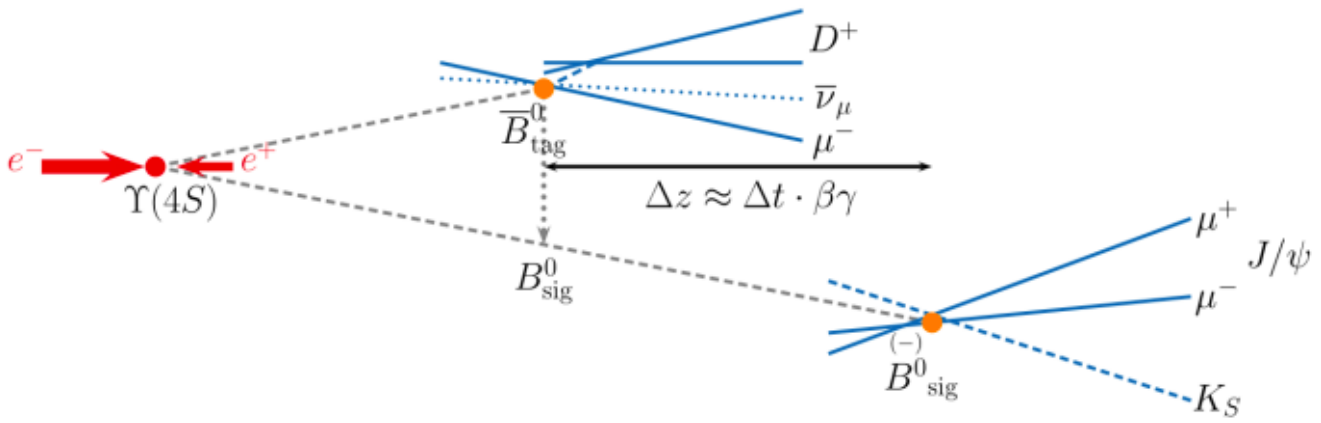
Summary - MC/Data Comparison

MC/Data Comparison

- Data processed with the new BeamSpot (BS) calibration algorithm exhibit better behaviour in terms of position uncertainties
- MC datasets used for the analysis were processed without the BS calibration - discrepancies in shape of spectra is observed
- Newly processed data
- Newly developed time-dependent BS calibration which provides more realistic size of the luminous region improves the reconstruction precision (shifts toward the origin reflect this improvement)
- It is necessary to wait for MC dataset processed using new version of the software

- Best results obtained using:
  - "`Tube`" option for the tag side vertexing
  - "`IP-pointing`" option for the signal side
  - + New BeamSpot calibration

- Main interest : accurate determination of the B meson lifetime
- Important variable - difference of proper decay times (in the rest frame of each B meson)
  - $\Delta t = \tau(B_{sig})$ - $\tau(B_{tag}) \overset{in\ \Delta z\ approx}{=} \frac{\Delta z}{\gamma^* \gamma \beta c}$
- Decays of both B mesons fitted so as to obtain the Δz



- 9 channels analyzed - 5 neutral decay modes, 4 charged modes

Time resolution function

First step

- Fit of the residual Δt_{res} = Δt - Δt_{MC} using the f_{res}:

$$f_{res}(\Delta t_{res}) = (1 - f_{big}) \cdot G(\Delta t_{res}; \mu, \sigma)$$
$$\otimes$$
$$[(1 - f_M) \cdot \delta_D + f_M \cdot ((1 - f_{TR}) \cdot \exp_R(c_{RMs} \Delta t_{res}) + f_{TR} \cdot \exp_L(-c_{LMs} \Delta t_{res}))]$$
$$+$$
$$f_{big} \cdot G(\Delta t_{res}; \mu, b \cdot \sigma)$$
$$\otimes$$
$$[(1 - f_B) \cdot \delta_D + f_B \cdot ((1 - f_{TR}) \cdot \exp_R(c_{RBs} \Delta t_{res}) + f_{TR} \cdot \exp_L(-c_{LBs} \Delta t_{res}))]$$

- Free parameters of the fit : f_M, f_{big}, μ, σ, f_{TR}, c_{RMs}, c_{LMs}, f_B, b, c_{RBs}, c_{LBs}

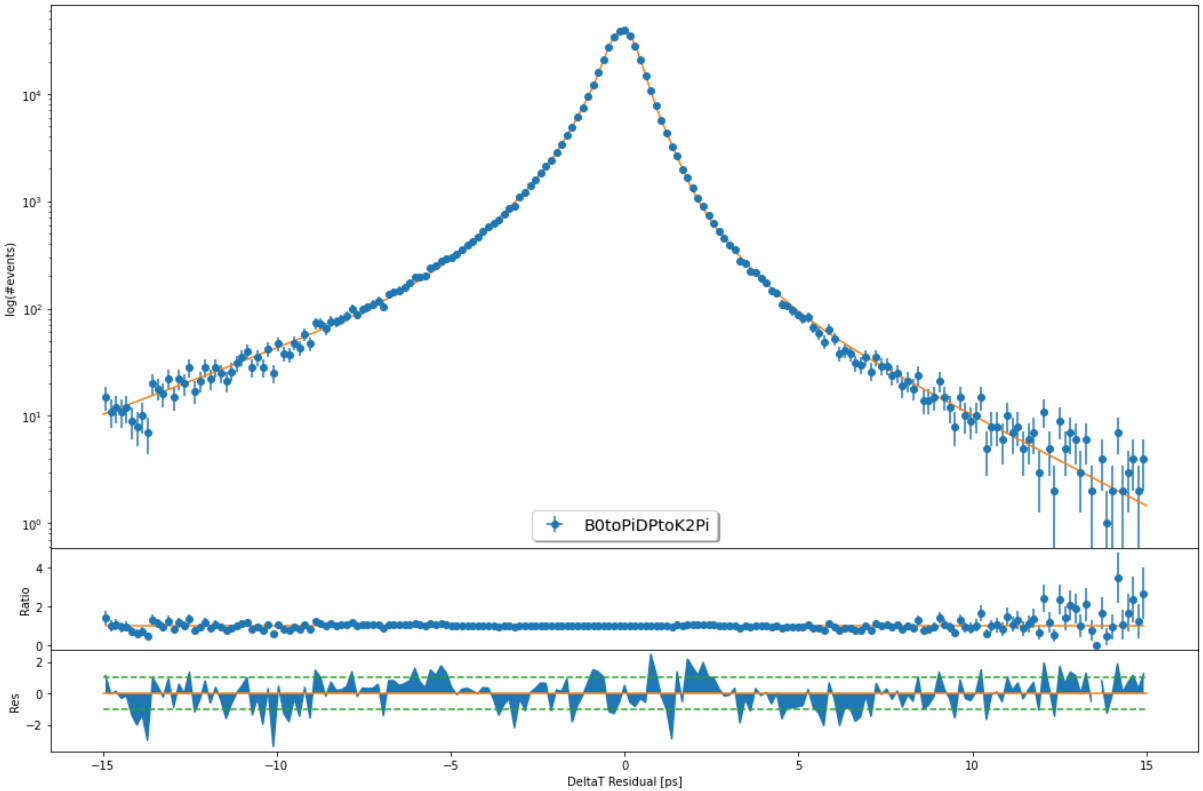
Next step:

- Fix the parameter values from Δt_{res} fit (describing detector effects)
- Leave only τ parameter left free-floating in the fitting function:

  $f_{res} \otimes \exp(-\frac{|\Delta t|}{\tau})$ + kinematic smearing (not included in the resolution function, nor the physical distribution)

Resolution function - Δt_{res} fit $(B^0 \to \pi^+ + D^-(\to K^+ + \pi^- + \pi^-))$

- Fit Δt_{res} using the detector resolution function f_{res}
- Fit results are demonstrated using $B^0 \to \pi^+ + D^-(\to K^+ + \pi^- + \pi^-)$ decay mode

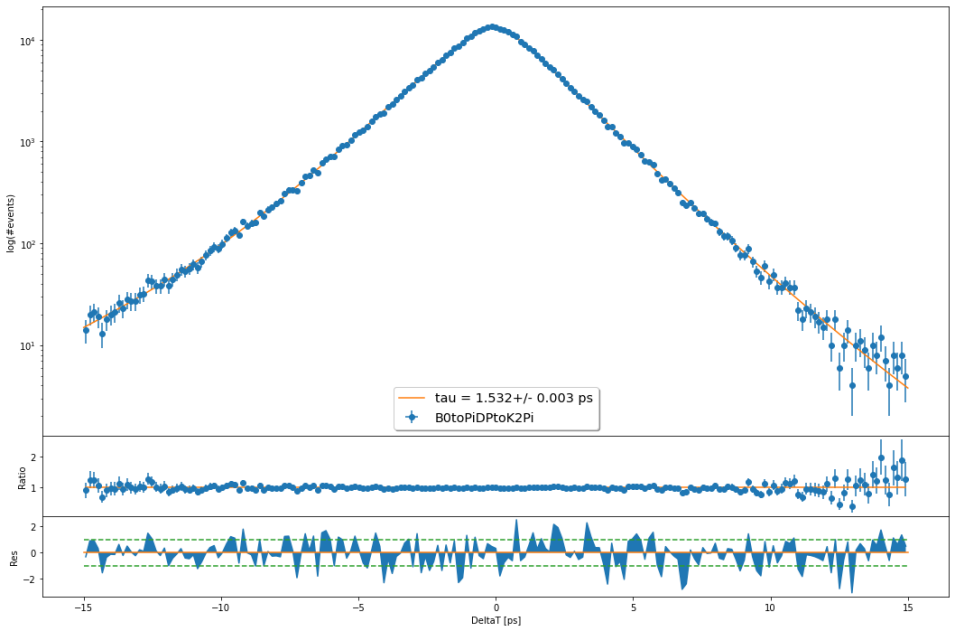


Param	Value
μ	-0.0356 $\pm$ 0.0028
σ	0.3592 $\pm$ 0.0048
f_M	0.4923 $\pm$ 0.0164
f_{TR}	0.3397 $\pm$ 0.0091
f_{big}	0.1878 $\pm$ 0.0130
c_{LMs}	0.9596 $\pm$ 0.0226
c_{RMs}	1.1502 $\pm$ 0.0381
c_{LBs}	0.2810 $\pm$ 0.0090
c_{RBs}	0.3867 $\pm$ 0.0120
b	2.0548 $\pm$ 0.0273
f_B	0.3230 $\pm$ 0.0100

Lifetime fit ($B^0 \to \pi^+ + D^-(\to K^+ + \pi^- + \pi^-)$)

- Parameter values from Δt_{res} fit fixed
- Only τ parameter left free-floating in the fitting function:

  $f_{res} \otimes \exp(-\frac{|\Delta t|}{\tau})$ + kinematic smearing (not included in the resolution function, nor the physical distribution)
- Reference values (used for MC generation):
  - $\tau_{MC}(B^0) = 1.525$ ps
  - $\tau_{MC}(B^+) = 1.638$ ps



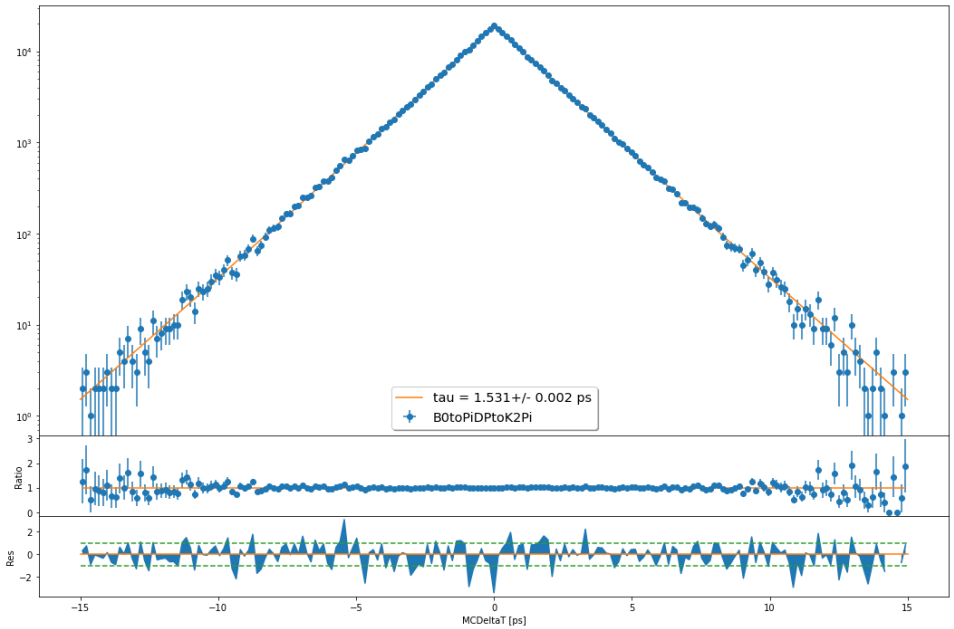
Channel	τ	σ	$\frac{\tau-\tau_{MC}}{\sigma}$
B0toJPsiKStoEE	1.524	0.004	-0.3
B0toJPsiKStoMuMu	1.530	0.003	1.7
B0toPiDPtoK2Pi	1.532	0.003	2.3
B0toPiDStoK2Pi	1.528	0.005	0.6
B0toPiDStoK4Pi	1.524	0.006	-0.2
BPtoJPsiKtoEE	1.639	0.004	-0.8
BPtoJPsiKtoMuMu	1.644	0.003	2.0
BPtoPiD0toK3Pi	1.644	0.003	0.3
BPtoPiD0toKPi	1.641	0.002	1.5

τ values from DeltaT fit

Consistency check ($B^0 \to \pi^+ + D^-(\to K^+ + \pi^- + \pi^-)$)

- Consistency check - Lifetime value fit repeated on `MCDeltaT` variable

  `MCDeltaT` - gen-level equivalent of `DeltaT`



Channel	τ	σ	$\frac{\tau-\tau_{MC}}{\sigma}$
B0toJPsiKStoEE	**1.523**	**0.003**	**-0.7**
B0toJPsiKStoMuMu	**1.528**	**0.002**	**1.5**
B0toPiDPtoK2Pi	**1.531**	**0.002**	**3.0**
B0toPiDStoK2Pi	**1.531**	**0.004**	**1.5**
B0toPiDStoK4Pi	**1.523**	**0.005**	**-0.4**
BPtoJPsiKtoEE	**1.639**	**0.003**	**0.3**
BPtoJPsiKtoMuMu	**1.641**	**0.002**	**1.5**
BPtoPiD0toK3Pi	**1.644**	**0.003**	**-0.3**
BPtoPiD0toKPi	**1.639**	**0.002**	**2.0**

τ values from MCDeltaT fit

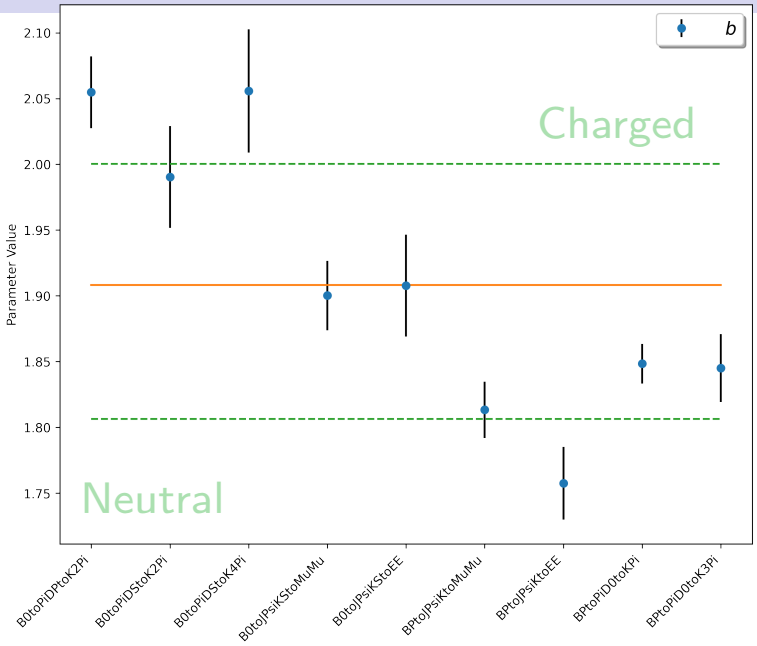
Values of B-meson lifetimes obtained from `DeltaT` and `MCDeltaT` fits agree within 2-σ uncertainty interval

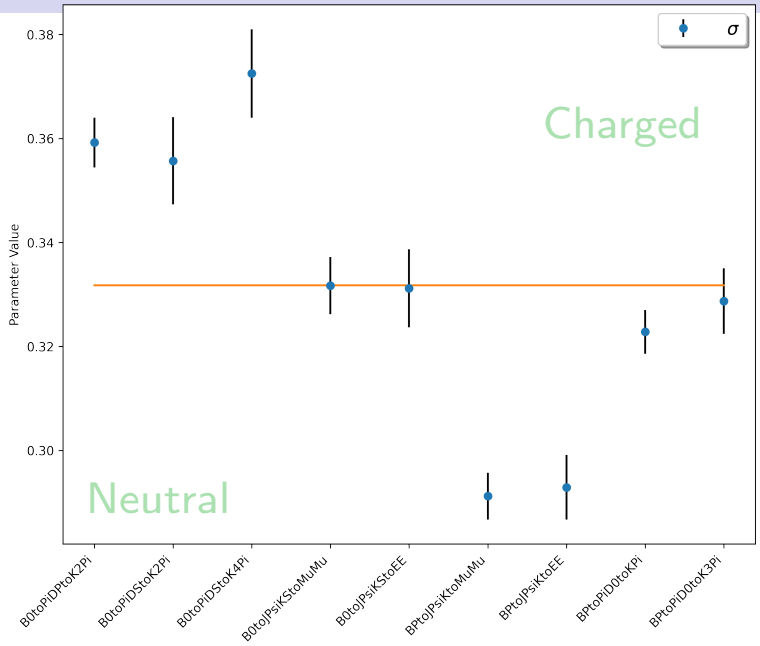
Time resolution function - B-Charge-independent parameters

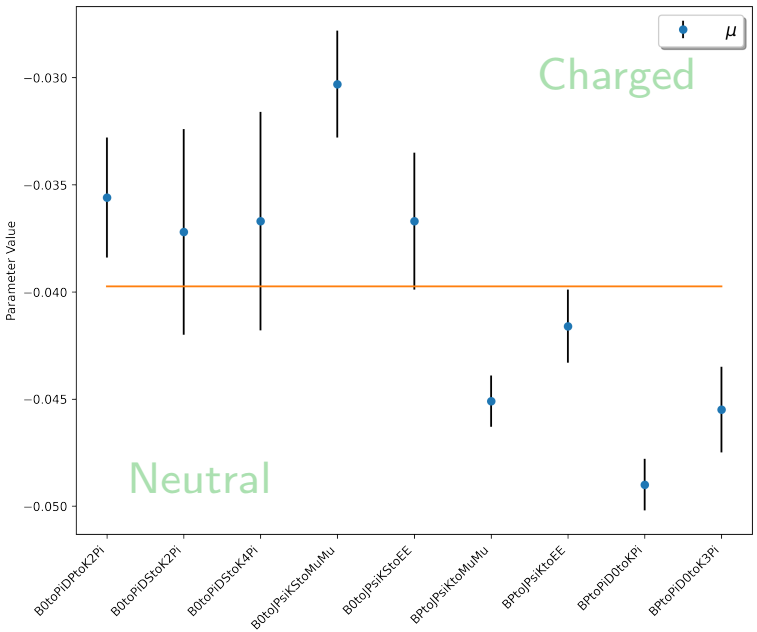
- b, σ, μ, f_{TR} parameters turn out to be independent on the charge of the decaying B meson

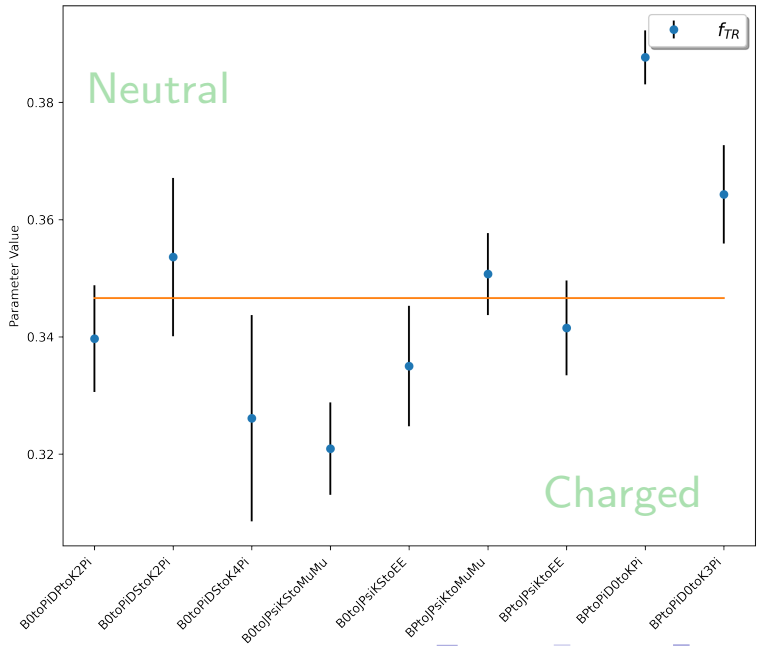
$$
\begin{aligned}
f_{res}(\Delta t_{res}) = (1-f_{big})\cdot G(\Delta t_{res};\mu,\sigma) \\
\otimes \\
[(1-f_M)\cdot\delta_D + f_M\cdot((1-f_{TR})\cdot \exp_R(c_{RMs}\Delta t_{res}) + f_{TR}\cdot\exp_L(-c_{LMs}\Delta t_{res}))] \\
+ \\
f_{big}\cdot G(\Delta t_{res};\mu, b\cdot\sigma) \\
\otimes \\
[(1-f_B)\cdot\delta_D + f_B\cdot((1-f_{TR})\cdot \exp_R(c_{RBs}\Delta t_{res}) + f_{TR}\cdot\exp_L(-c_{LBs}\Delta t_{res}))]
\end{aligned}
$$

Summary of fit results - B-charge-independent parameters







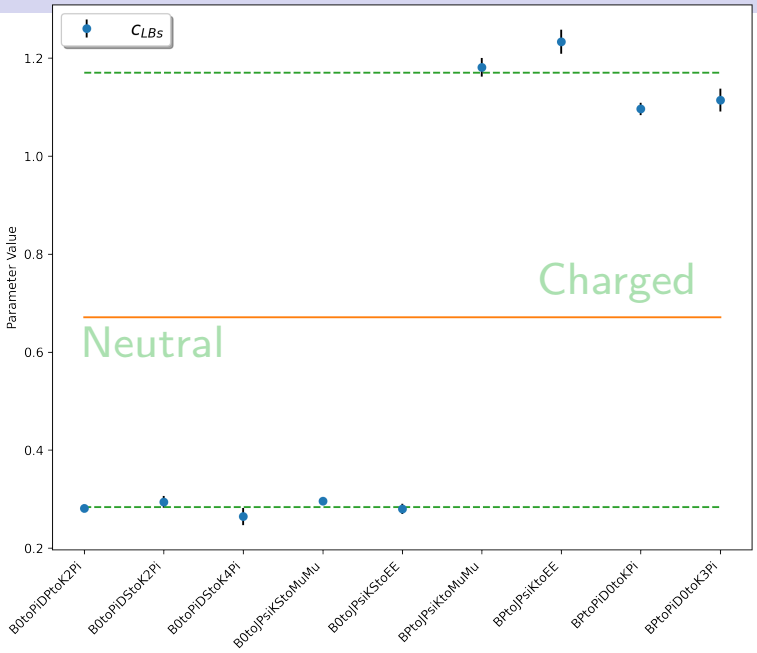


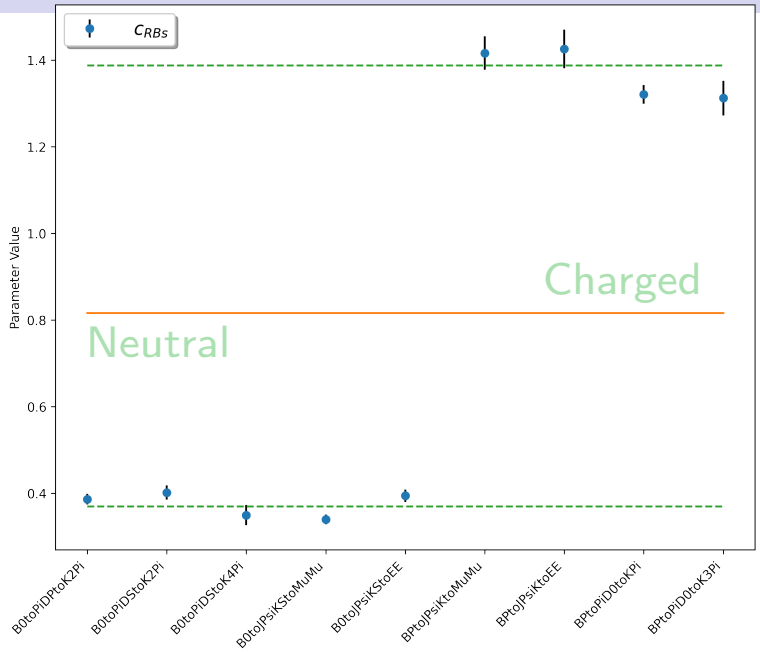
Time resolution function - B-charge-dependent parameters

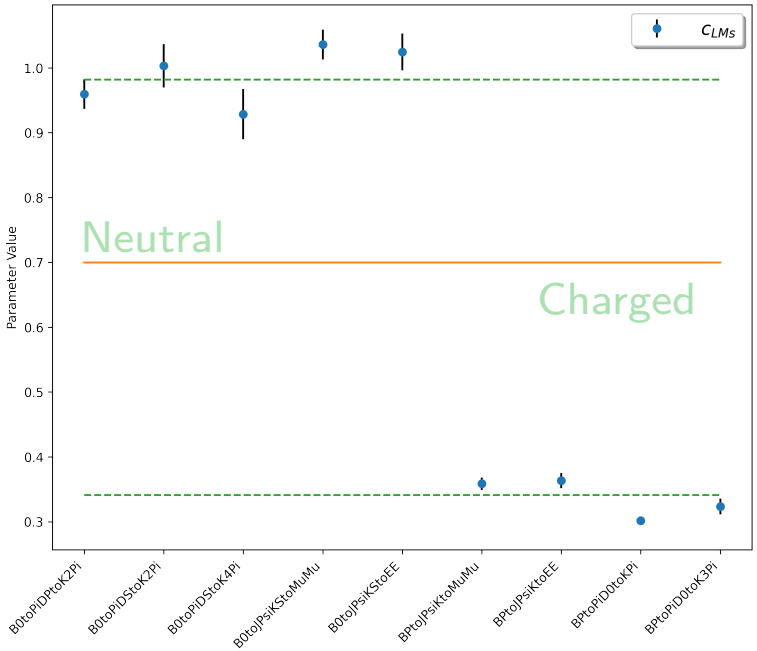
- f_M,f_{big}, c_{RMs}, c_{LMs}, f_B, c_{RBs}, c_{LBs} parameters turn out to be dependent on the charge of the decaying B meson

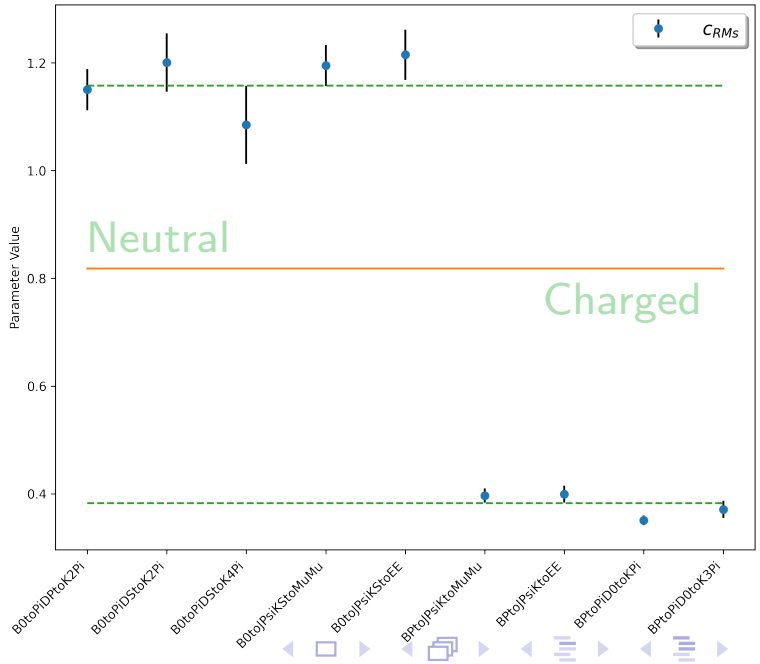
$$
\begin{aligned}
f_{res}(\Delta t_{res}) = (1-f_{big})\cdot G(\Delta t_{res};\mu,\sigma) \\
\otimes \\
[(1-f_M)\cdot\delta_D + f_M\cdot((1-f_{TR})\cdot \exp_R(c_{RMs}\Delta t_{res}) + f_{TR}\cdot\exp_L(-c_{LMs}\Delta t_{res}))] \\
+ \\
f_{big}\cdot G(\Delta t_{res};\mu,b\cdot\sigma) \\
\otimes \\
[(1-f_B)\cdot\delta_D + f_B\cdot((1-f_{TR})\cdot \exp_R(c_{RBs}\Delta t_{res}) + f_{TR}\cdot\exp_L(-c_{LBs}\Delta t_{res}))]
\end{aligned}
$$

B-charge-dependent parameters

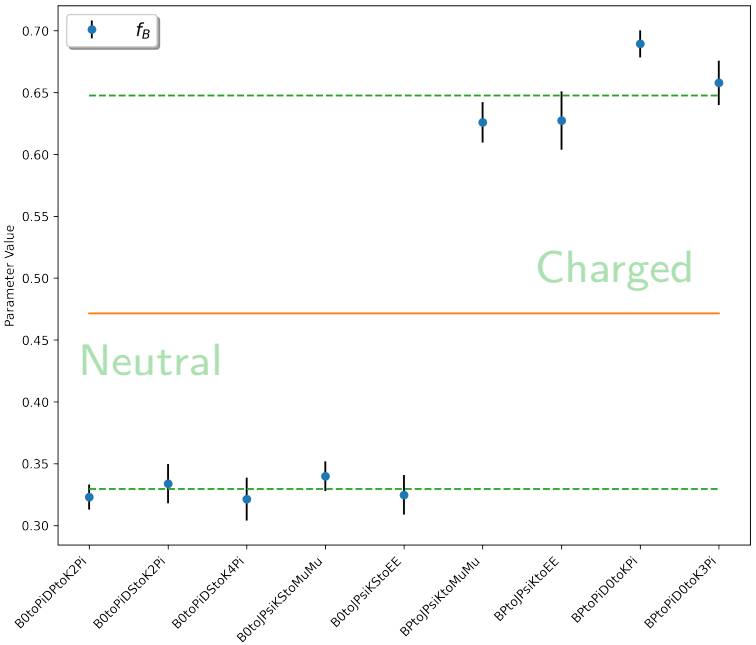


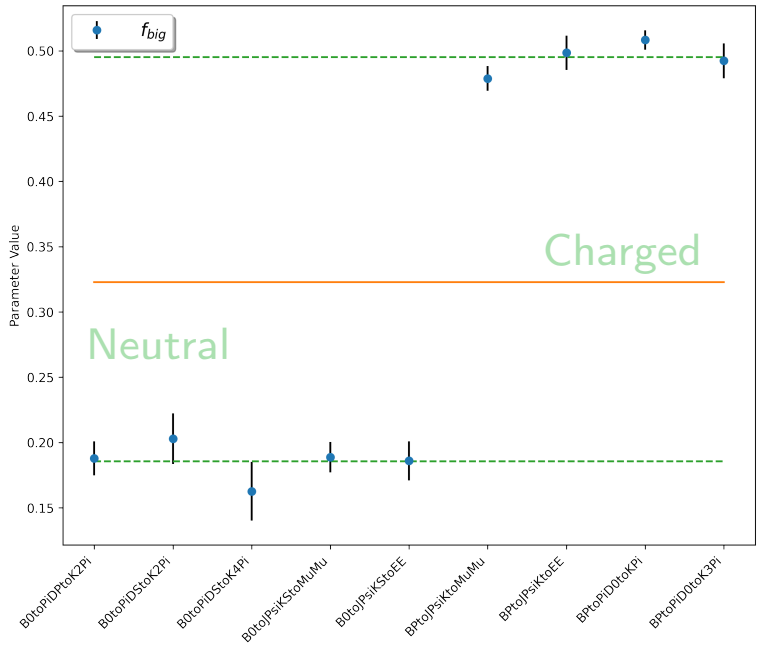


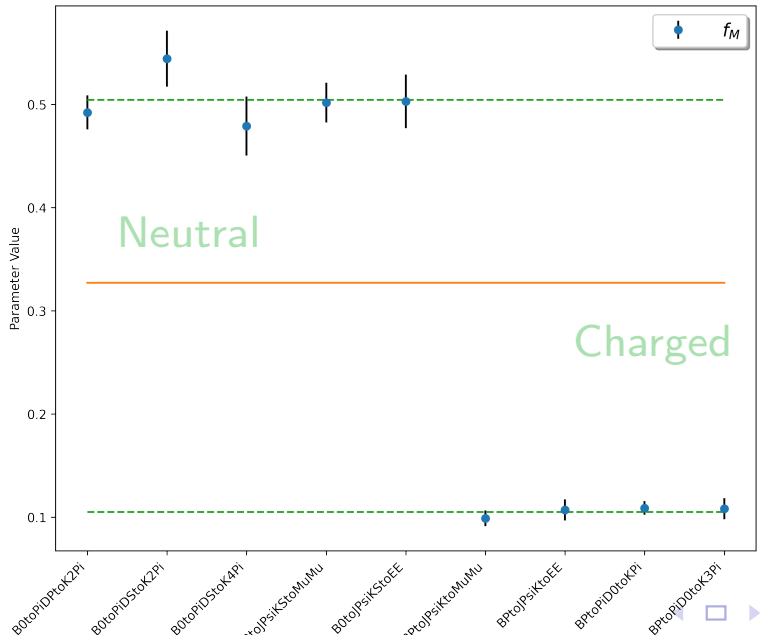




B-charge-dependent parameters

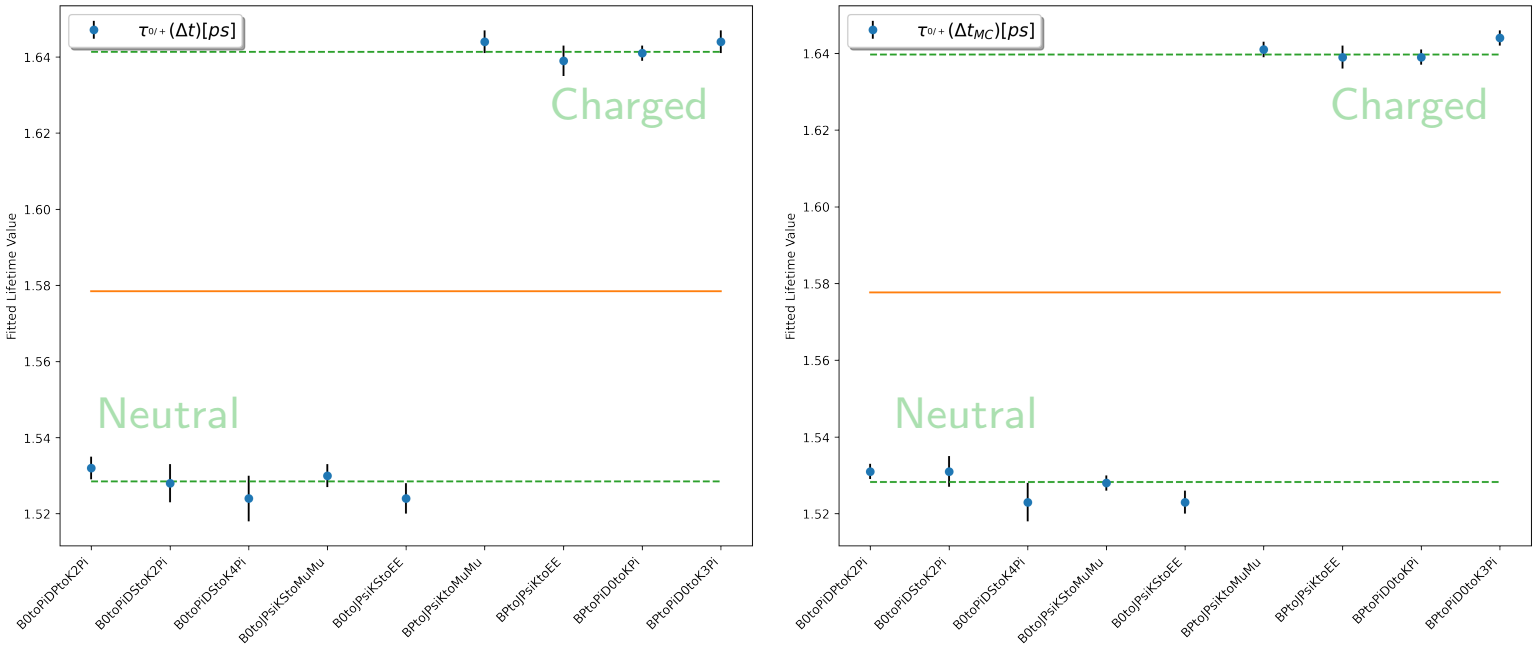






Lifetime fit agreement

Summary of the consistency check between lifetime values obtained by fitting the `DeltaT` and `MCDeltaT` variable



Lifetime values are in mutual agreement and do not significantly deviate from the expected values (used for MC generation.

Summary - Δt resolution and lifetime fit

Resolution function and lifetime fit

- The studied time-resolution function proved to be universal - applicable to all studied channels
- Lifetime values obtained across fits of 9 decay modes are consistent with value used for MC generated
- Several fitted parameters exhibit charge dependence
  - Can be explored further by fixing their values for neutral / charged channels and repeating the fit
- The studied form of the resolution function appears to be a good candidate for real data analysis

Thank you for your attention!

@lisbouche

Decay channel	Channel Label
$B^0 \to D^-[\to K^+\pi^-\pi^-]\pi^+$	B0toPiDPtoK2Pi
$B^0 \to D^{*-}[\to [\overline{D}^0 \to K^-\pi^+]\pi^-]\pi^+$	B0toPiDStoK2Pi
$B^0 \to D^{*-}[\to [\overline{D}^0 \to K^-\pi^+\pi^-\pi^+]\pi^-]\pi^+$	B0toPiDStoK4Pi
$B^0 \to [J/\Psi \to \mu^+\mu^-][K^0_S \to \pi^+\pi^-]$	B0toJPsiKStoMuMu
$B^0 \to [J/\Psi \to e^+e^-][K^0_S \to \pi^+\pi^-]$	B0toJPsiKStoEE
$B^+ \to [J/\Psi \to \mu^+\mu^-]K^+$	BPtoJPsiKtoMuMu
$B^+ \to [J/\Psi \to e^+e^-]K^+$	BPtoJPsiKtoEE
$B^+ \to [\overline{D}^0 \to K^-\pi^+]\pi^+$	BPtoPiD0toKPi
$B^+ \to [\overline{D}^0 \to K^-\pi^+\pi^-\pi^+]\pi^+$	BPtoPiD0toK3Pi

Table: B decay modes used for the analysis