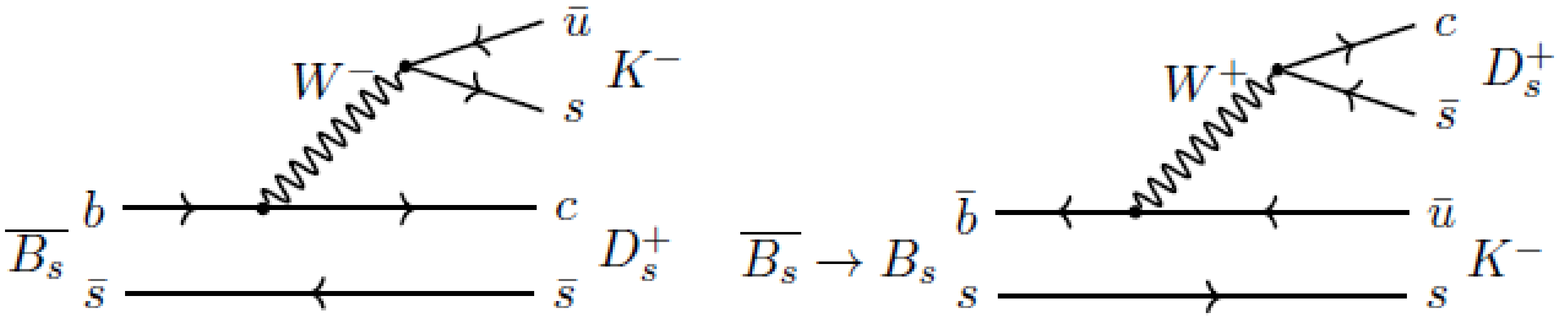
Study of B_s -> D_s K at FCC-ee

R. Aleksan
21/5/2020



Motivations

- Study of CP violation :
  - Sensitivity on UT_{CKM} angle γ (… and mixing parameter $\frac{\Delta m}{\Gamma}$)
- Study of CP detector resolutions :
  - Tracking
  - Calorimetry
  - PId

Time dependent B_s decay

R.A. , I. Dunietz, B. Kayser Z. Phys. C54, 653 (1992)
https://doi.org/10.1007/BF01559494

$$\Gamma(B_s \to f) = |<f|B_s>|^2 \times e^{\Gamma t}\{[1-\omega(1-\rho^2)]\cos^2\frac{\Delta m t}{2} + [\rho^2+\omega(1-\rho^2)]\sin^2\frac{\Delta m t}{2} - (1-2\omega)\rho\sin\phi^+_{CP}\sin\Delta m t\}$$

$$\Gamma(\overline{B_s} \to f) = |<f|B_s>|^2 \times e^{\Gamma t}\{[\rho^2+\omega(1-\rho^2)]\cos^2\frac{\Delta m t}{2} + [1-\omega(1-\rho^2)]\sin^2\frac{\Delta m t}{2} + (1-2\omega)\rho\sin\phi^+_{CP}\sin\Delta m t\}$$

$$\Gamma(B_s \to \overline{f}) = |<f|B_s>|^2 \times e^{\Gamma t}\{[\rho^2+\omega(1-\rho^2)]\cos^2\frac{\Delta m t}{2} + [1-\omega(1-\rho^2)]\sin^2\frac{\Delta m t}{2} - (1-2\omega)\rho\sin\phi^-_{CP}\sin\Delta m t\}$$

$$\Gamma(\overline{B_s} \to \overline{f}) = |<f|B_s>|^2 \times e^{\Gamma t}\{[1-\omega(1-\rho^2)]\cos^2\frac{\Delta m t}{2} + [\rho^2+\omega(1-\rho^2)]\sin^2\frac{\Delta m t}{2} + (1-2\omega)\rho\sin\phi^-_{CP}\sin\Delta m t\}$$

$\Delta\Gamma_s$ neglected

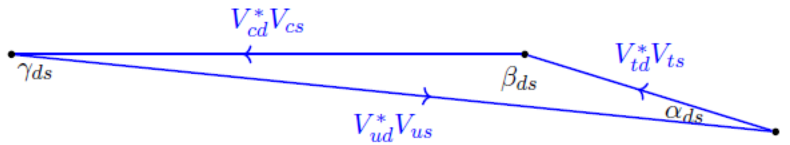
$$\rho = \frac{A(B_s \to D_s^+ K^-)}{A(\overline{B_s} \to D_s^+ K^-)} \approx 0.7$$

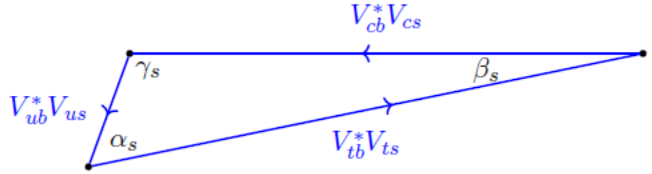
$$\rho(D_s^+\pi^-) = 0$$

$$\omega = wrong\ tagging$$

	LEP	BaBar	LHCb
$\epsilon(1-2\omega)^2$	25-30%	30%	6%

$$\phi^{\pm}_{CP} = \phi_{CKM} \pm \delta_s$$
$$\phi_{CKM} = \gamma + \gamma_{ds} - 2\beta_s$$





$$\gamma_{ds} \approx 0.04°$$
$$\beta_s \approx 1° \ (B_s \to J/\psi\,\phi)$$

$$\sin^2\phi_{CKM} = \frac{1}{2} \times \{1 + \sin\phi^+_{CP}\sin\phi^-_{CP} \pm \sqrt{(1-\sin{\phi^+_{CP}}^2)(1-\sin{\phi^-_{CP}}^2)}\}$$

2-fold ambiguity

Expected number of events

(To be x 2 for B_s)

$\sigma(e^+e^- \to Z)$ nb	number of Z	$E_{cm} = 91.2$ GeV and $\int L = 150ab^{-1}$ $f(Z \to \overline{B}_s)$	Number of produced $\overline{B}_s$
~ 42.9	$\sim 6.4\ 10^{12}$	0.0159	$\sim 1\ 10^{11}$

$\overline{B}_s$ decay Mode	Decay Mode	Final State	Number of $\overline{B}_s$ decays
		nonCP eigenstates	
$D_s^+\pi^-$	$D_s^+ \to \phi\pi$	$K^+K^-\pi^+\pi^-$	$\sim 6.9\ 10^6$
$D_s^+\pi^-$	$D_s^+ \to \phi\rho$	$K^+K^-\pi^+\pi^-\pi^0$	$\sim 12.9\ 10^6$
$D_s^+K^-$	$D_s^+ \to \phi\pi$	$K^+K^-\pi^+K^-$	$\sim 5.2\ 10^5$
$D_s^+K^-$	$D_s^+ \to \phi\rho$	$K^+K^-\pi^+K^-\pi^0$	$\sim 9.8\ 10^5$
$D^0\phi$	$D^0 \to K\pi$	$K^-\pi^+K^+K^-$	$\sim 6.1\ 10^4$
$D^0\phi$	$D^0 \to K\rho$	$K^-\pi^+K^+K^-\pi^0$	$\sim 1.7\ 10^5$
		CP eigenstates	
$J/\psi\phi$	$J/\psi \to \mu^+\mu^-$	$\mu^+\mu^-K^+K^-$	$\sim 3.2\ 10^6$
$\phi\phi$	$\phi \to K^+K^-$	$K^+K^-K^+K^-$	$\sim 4.8\ 10^5$

Detector response is parametrized

$$\text{Acceptance :} \quad |\cos\theta| < 0.95$$

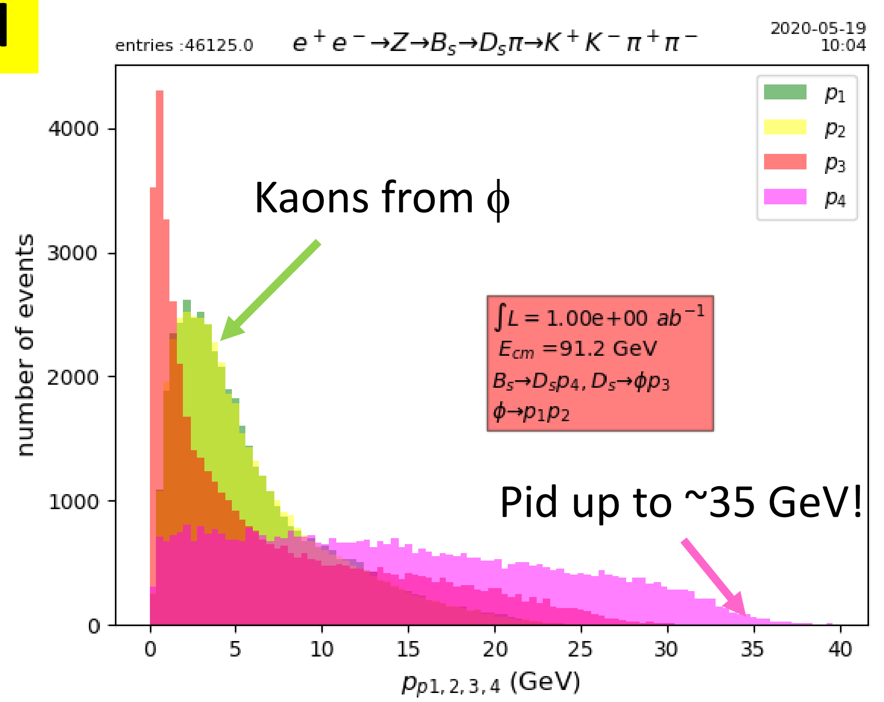
$$\text{Track } p_T \text{ resolution :} \quad \frac{\sigma(p_T)}{p_T^2} = 2. \times 10^{-5} \oplus \frac{1.2\times10^{-3}}{p_T \sin\theta}$$

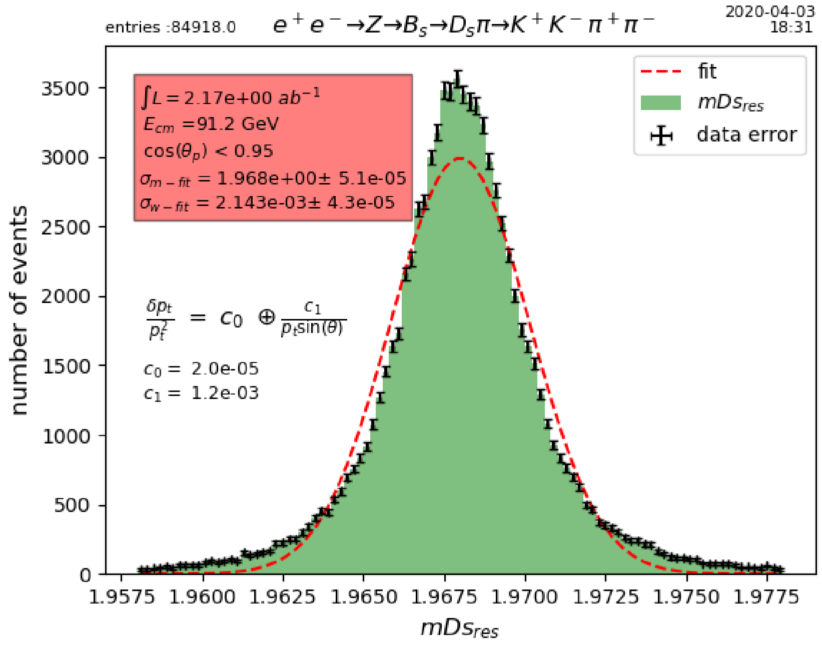
$$\text{Track } \phi,\theta \text{ resolution :} \quad \sigma(\phi,\theta)\ \mu\text{rad} = 18 \oplus \frac{1.5\times10^{3}}{p_T \sqrt[3]{\sin\theta}}$$

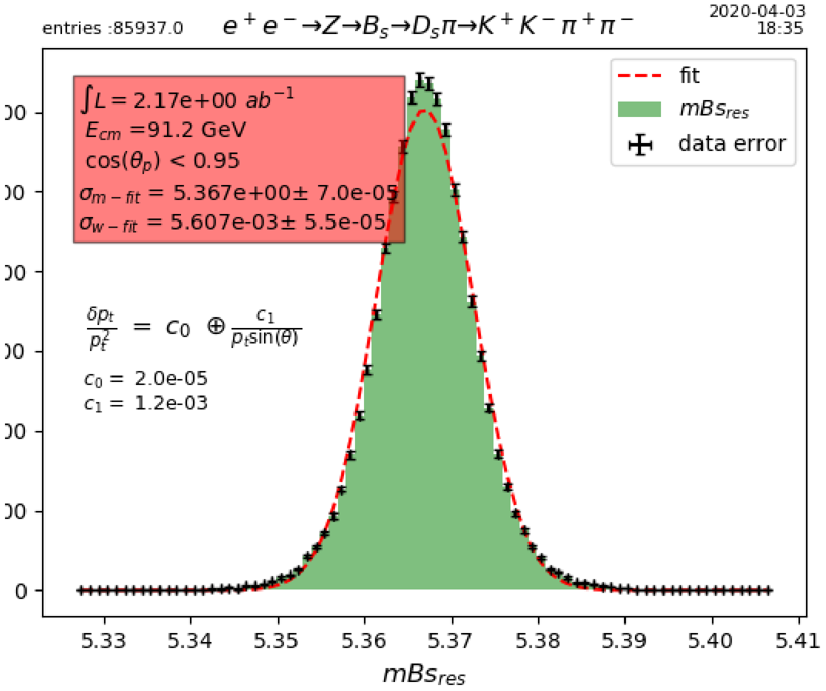
$$\text{Vertex resolution :} \quad \sigma(\mathrm{d_{Im}})\ \mu\text{m} = 1.8 \oplus \frac{5.4\times10^{1}}{p_T \sqrt{\sin\theta}}$$

$$\text{Vertex resolution :} \quad \langle \sigma(\mathrm{d_{Im}}) \rangle \simeq 10\ \mu m$$ (Bachelor π/K)

$$\text{Calorimeter resolution :} \quad \frac{\sigma(E)}{E} = \frac{5\times10^{-2}}{\sqrt{E}} \oplus 5\times10^{-3}$$







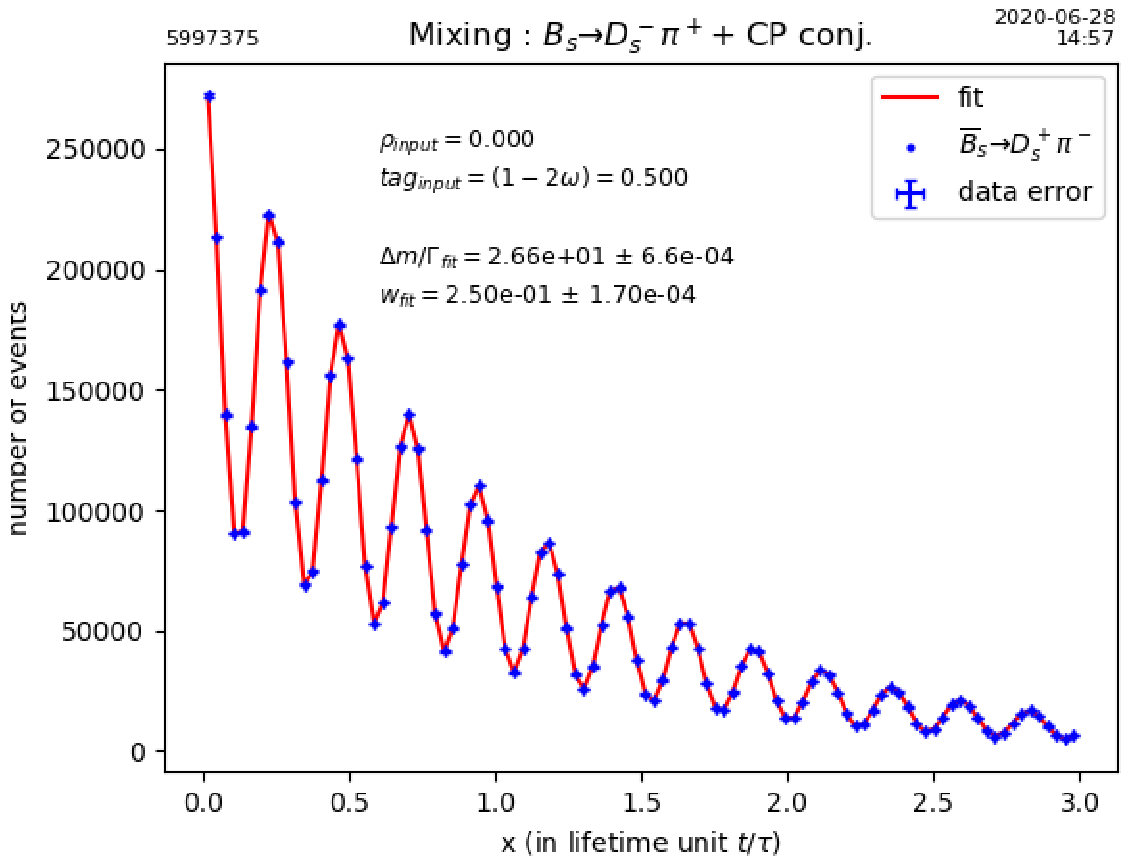
	unit	value
acceptance	%	86
$\sigma(m_{D_s})$	MeV	~ 2.1
$\sigma(m_{B_s})$	MeV	~ 5.6

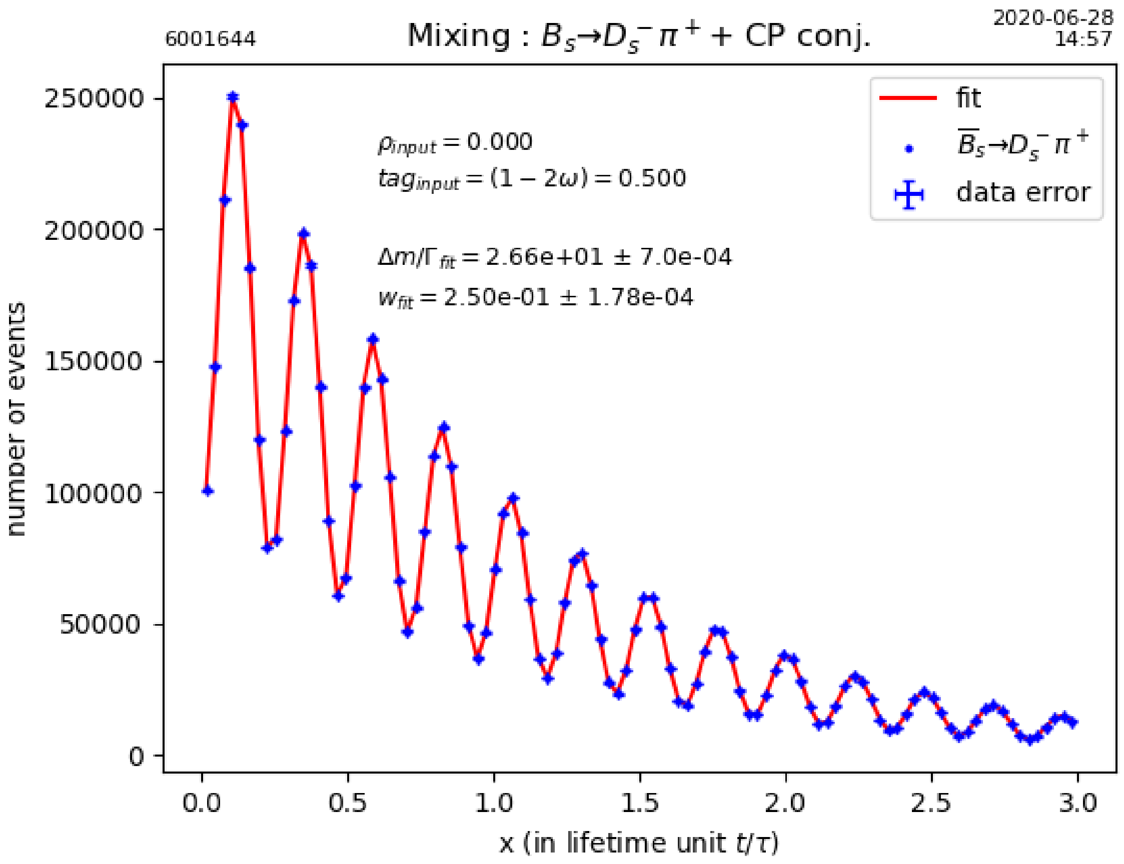
To be compared to

$$\boldsymbol{\sigma(mB_s)_{LHCb} \approx 17\ MeV}$$

B_s Mixing Measurement with $B_s \to D_s\pi$

Mean B flight distance ≈ 3000 μm
Flight distance resolution < 20 μm (negligible) ➪ full simulation and vertex fit would be useful
Background mainly combinatorics (very small)

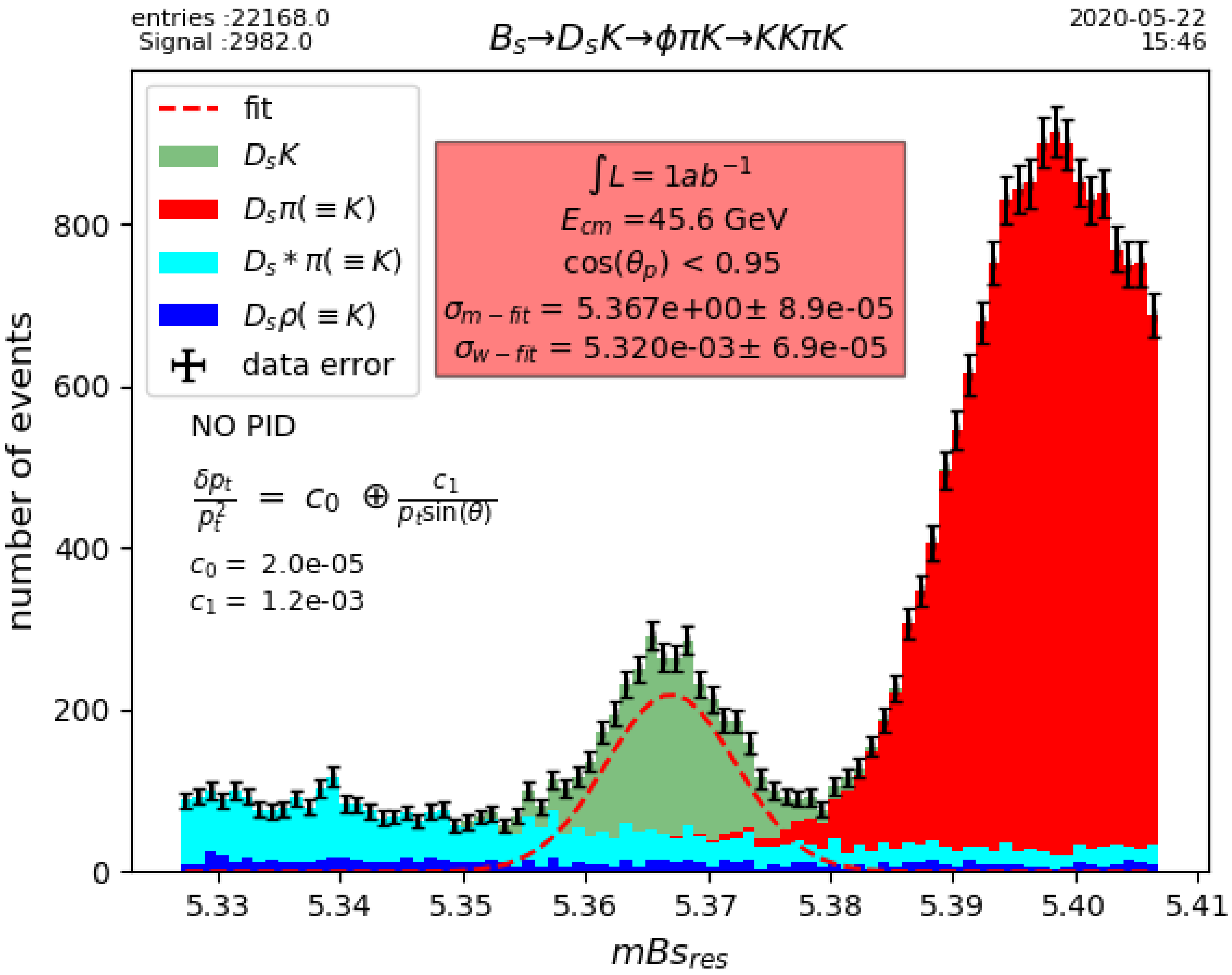




$$\delta(\Delta m_{Bs})_{stat} \approx \left(5 \times 10^{-4}\right) 10^{12}\hbar s^{-1} \ \left[PDG: \left(2.1 \times 10^{-2}\right) 10^{12}\hbar s^{-1}\right]$$

$$\delta(\omega)_{stat} = 1.4 \times 10^{-4}$$

Measurement of CP violation with $B_s \to D_s K$

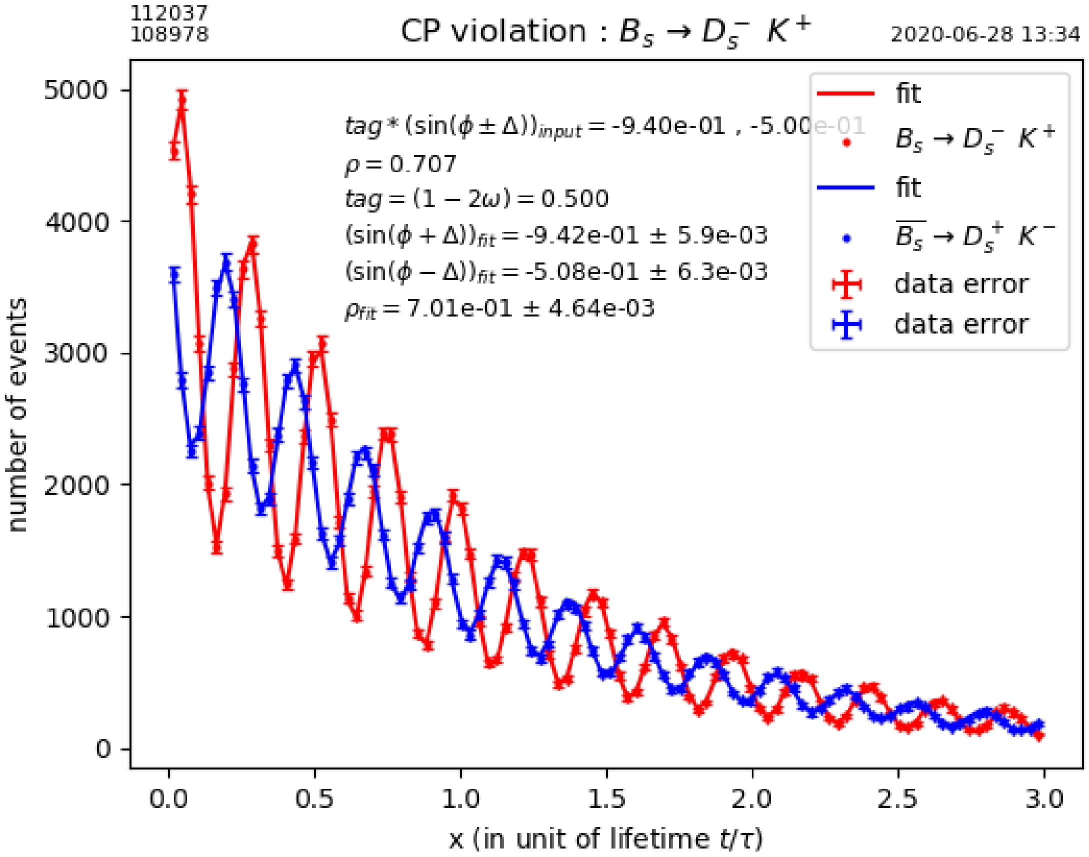


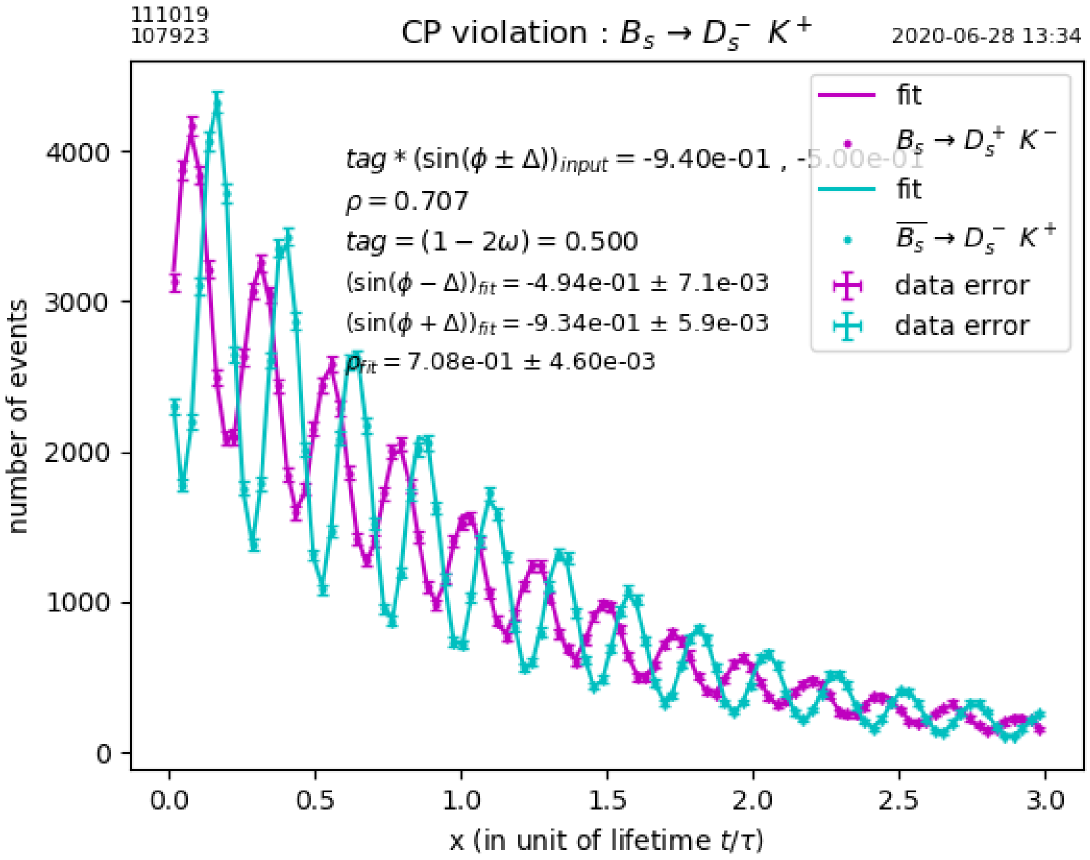
- Tracking resolution crucial to reduce background
- Combinatoric background to be added (expected to be relatively small)
- A modest PId (ToF + dE/dx) enough (see later)

Measurement of CP violation with $B_s \to D_s K$

$$\int Ldt = 150\ ab^{-1}$$

PDG: $\gamma = (71.1^{+4.6}_{-5.3})°$





$\delta(\rho) \approx 3.2 \times 10^{-3} (stat.)$

$\delta(sin^2\phi_{CKM}) \approx \delta(sin^2\gamma) \approx 5 \times 10^{-3} (stat.) \cong \delta(\gamma) \approx 0.4° (stat.)$

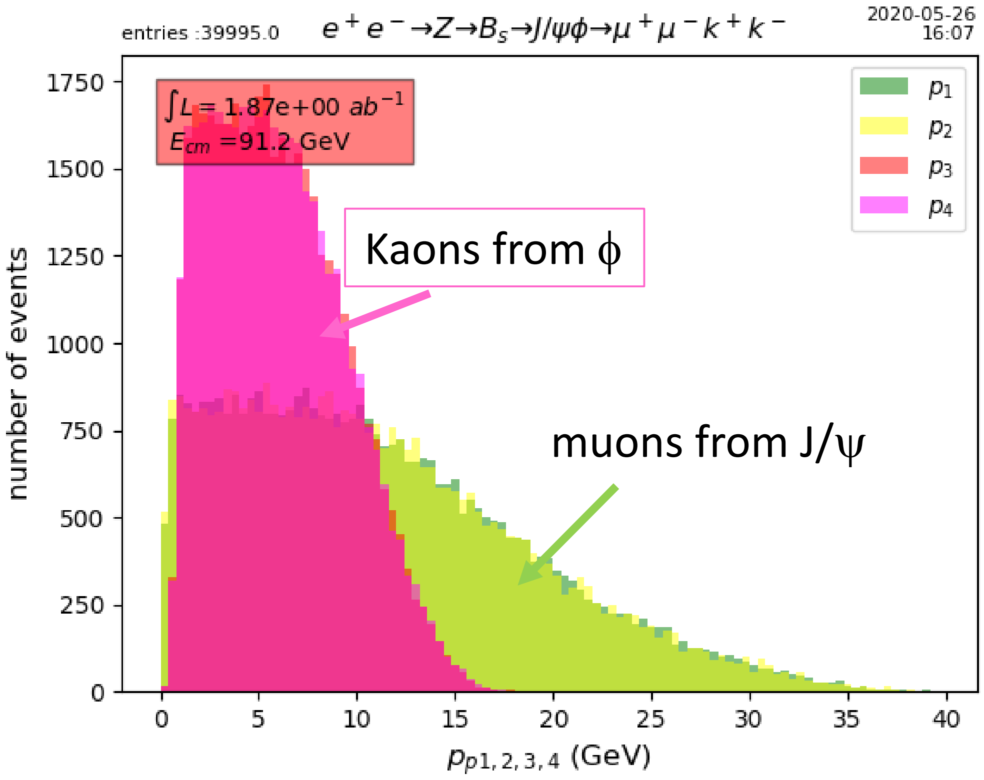
Potential to increase statistics by factor 4-5 with $D_s^\pm \to K^{*0}K^\pm, \phi\rho^\pm$, ... but background needs to be studied

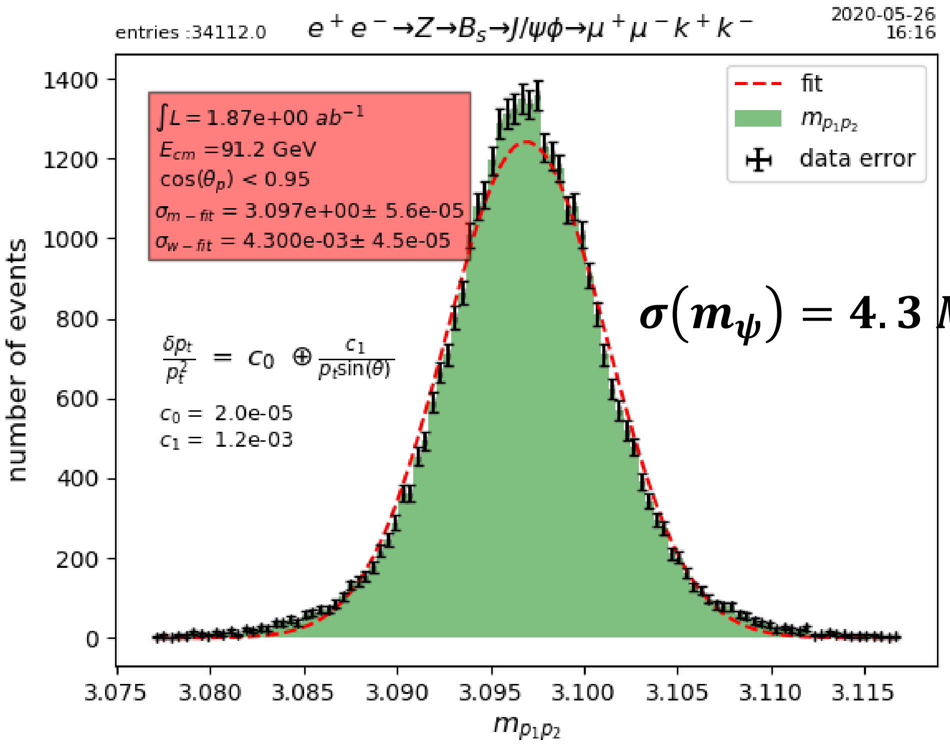
Measurement of CP violation with $B_s \to J/\psi\phi \to \mu^+\mu^-K^+K^-$

With $\boldsymbol{B_s \to D_sK}$: $\delta(\phi_{CKM}) = \delta(\gamma + \gamma_{ds} - 2\beta_s) \lesssim 0.4° \ (stat.)$

To take advantage of the full sensitivity , β_s needed

With $\boldsymbol{B_s \to J/\psi\phi}$ $\quad \phi_{CKM} = 2\beta_s \approx 2°$





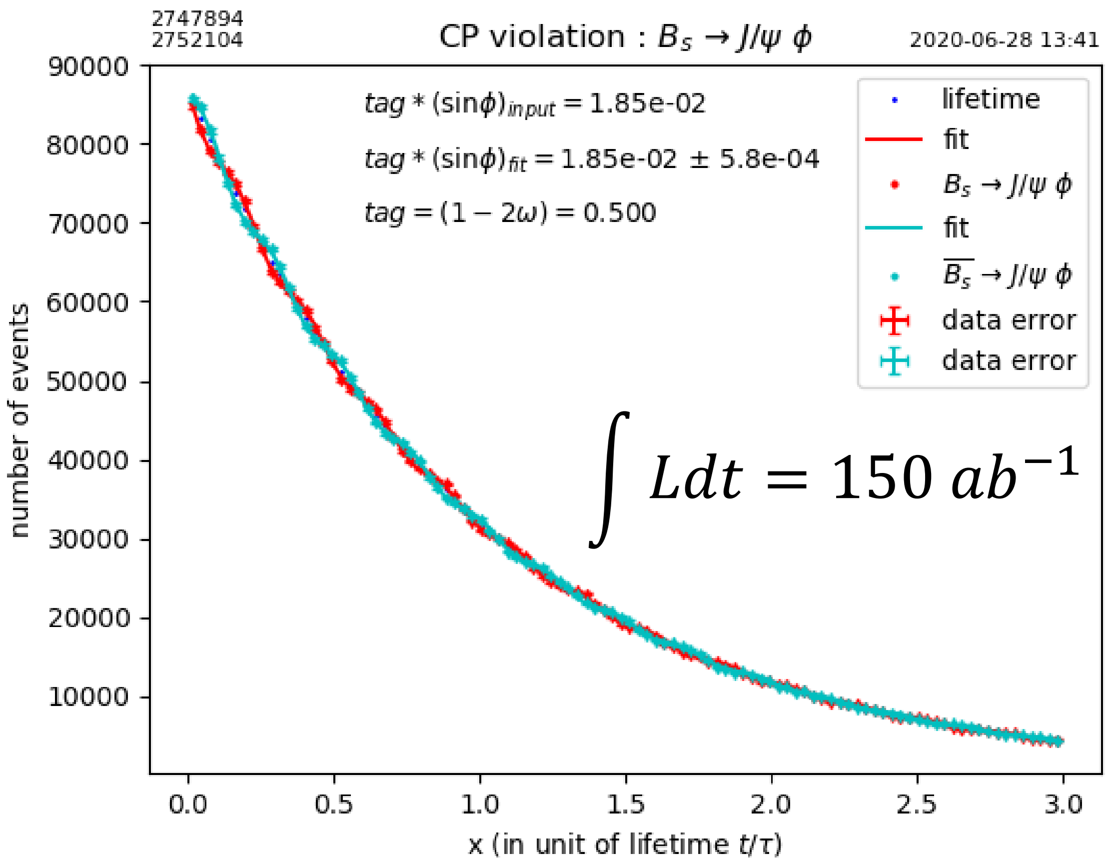
$\boldsymbol{\sigma(m_\psi) = 4.3\ MeV}$

Measurement of CP violation with $B_s \to J/\psi\phi \to \mu^+\mu^-K^+K^-$

CKM: $\beta_s \approx 1°$

PDG: $\beta_s = (0.60 \pm 0.89)°$

Should $\Gamma_L/\Gamma = 1$



However for $B_s \to J/\psi\phi$

PDG		
Γ_L/Γ	$\mathbf{0.527 \pm 0.008}$	CP = +
$\Gamma_\parallel/\Gamma$	0.228 ± 0.007	CP = +
$\Gamma_\perp/\Gamma$	0.245 ± 0.004	CP = -

In HQS , $\Gamma_\parallel = \Gamma_\parallel \Rightarrow \mathcal{A}^{mix} = \mathcal{A}_L^{mix}$

Angular analysis required (tbd)
Otherwise additional dilution factor ~0.5
Slightly reduced sensitivity

$$\delta(sin\phi_{CKM}) = \delta(sin2\beta_s) \approx 1.2\ \times 10^{-3}\ \cong \delta(\beta_s) \approx 3.4° \times 10^{-2}(stat.)$$

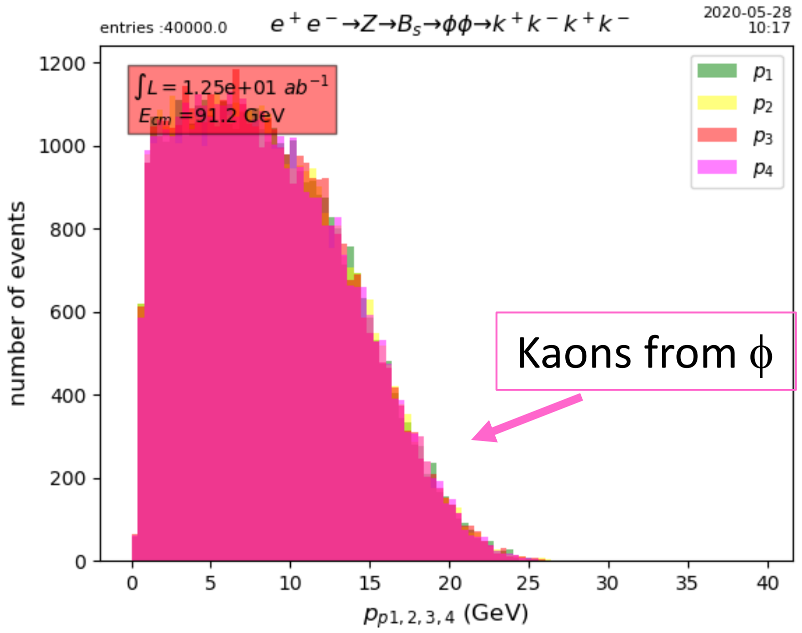
Study of CP violation with $B_s \to \phi\phi \to K^+K^-K^+K^-$

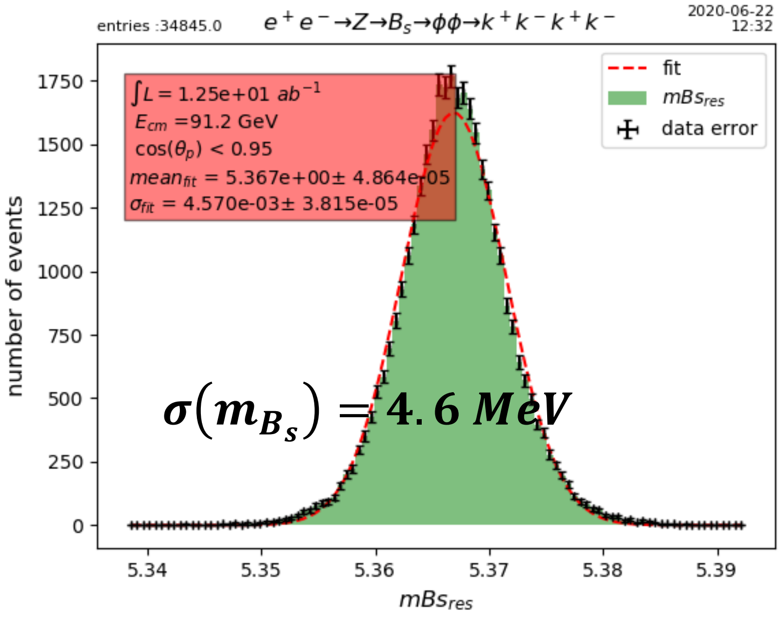
With $B_s \to \phi\phi$

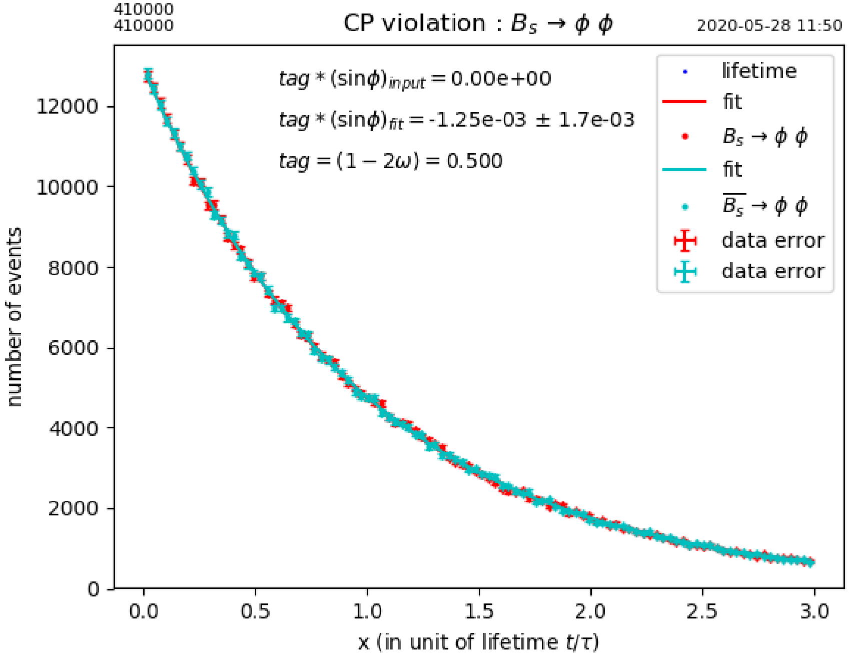
$\phi_{CKM} \approx 0°$

$\phi_{CKM} = 0°\ (t\ quark\ only)$

⇨ Very good for probing BSM







PDG		
Γ_L/Γ	$\mathbf{0.378 \pm 0.013}$	CP=+
$\Gamma_\parallel/\Gamma$	0.330 ± 0.016	CP=+
$\Gamma_\perp/\Gamma$	0.292 ± 0.009	CP=-

Angular analysis required (tbd)
Otherwise additional dilution factor ~0.4

$\delta(sin\phi_{CKM}) \approx 3.4 \times 10^{-3}$
$\cong \delta(\phi_{CKM}) \approx 0.2°\ (stat.)$

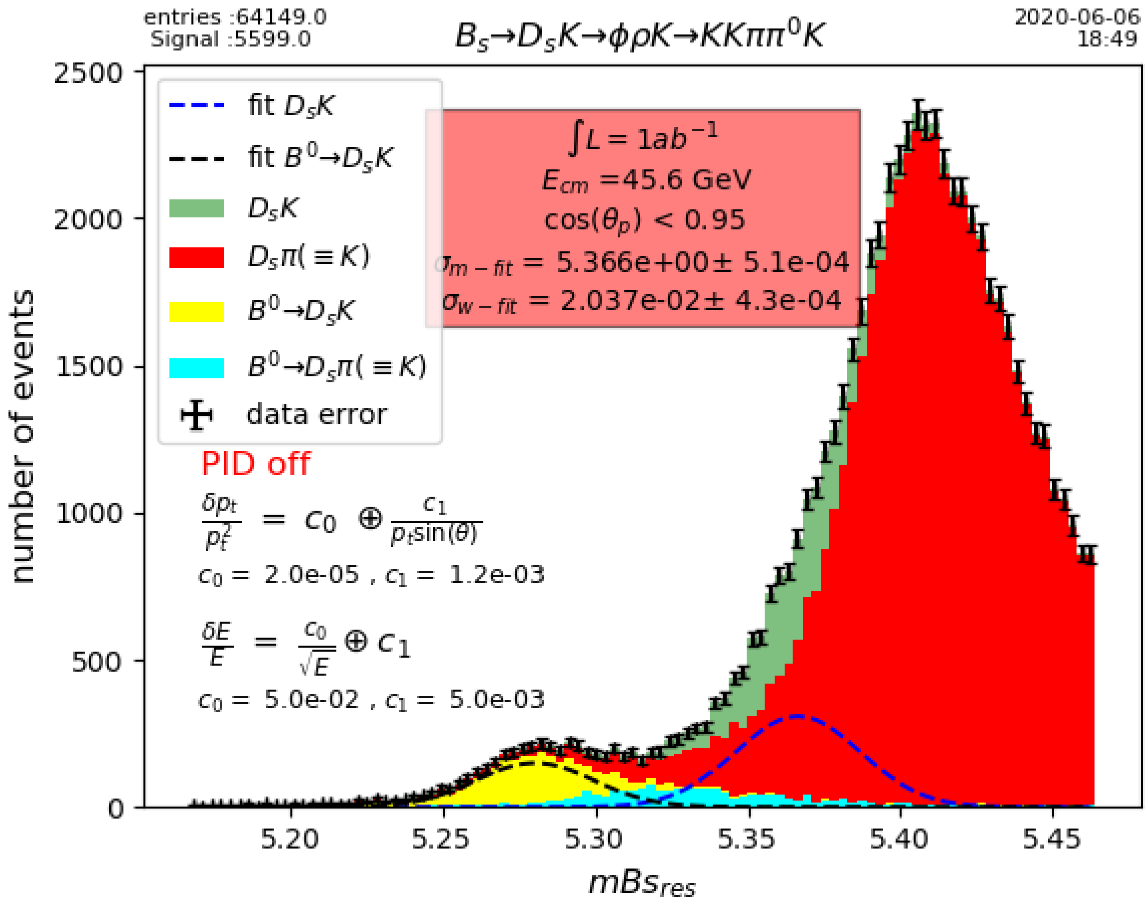
NO PId

Inclusion of neutrals for $B_s \to D_s K$ reconstruction

e.g. could potentially increase statistics (x 3) by adding $D_s^\pm \to \phi\rho^\pm$ $\quad \dfrac{D_s^\pm \to \phi\rho^\pm}{D_s^\pm \to \phi\pi^\pm} \approx 1.9$

More generally many physics topics (such as flavor physics) would benefit by using neutrals

➪ Big advantage compared to LHCb ➪ constraint on calorimeter and PId



With very good calorimeter resolution (Xtal type)

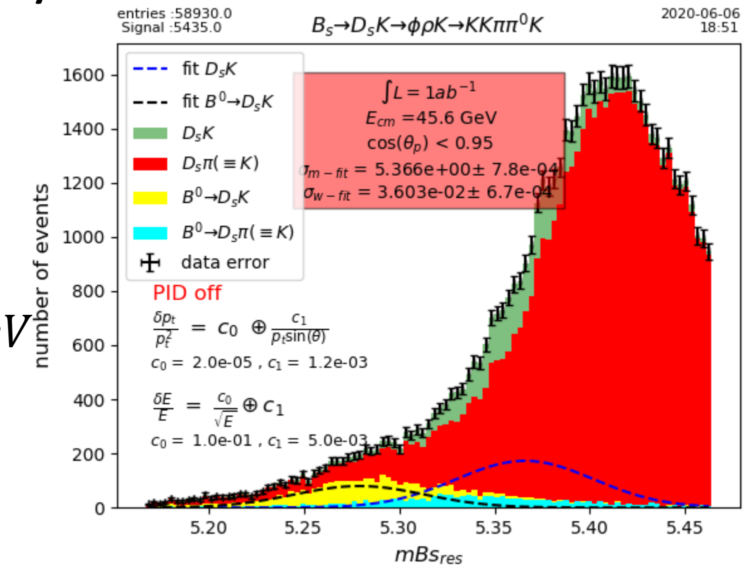
$\sigma\left(D_s^\pm(\phi\pi^\pm)K^\mp\right) \approx 5.6MeV \to \sigma\left(D_s^\pm(\phi\rho^\pm)K^\mp\right) \approx 20MeV$

➪ Background $D_s^\pm(\phi\rho^\pm)\pi^\mp$ huge

➪ **PId mandatory**

Much worse with LAr type Cal.

$\sigma\left(D_s^\pm(\phi\rho^\pm)K^\mp\right) \approx 36.MeV$



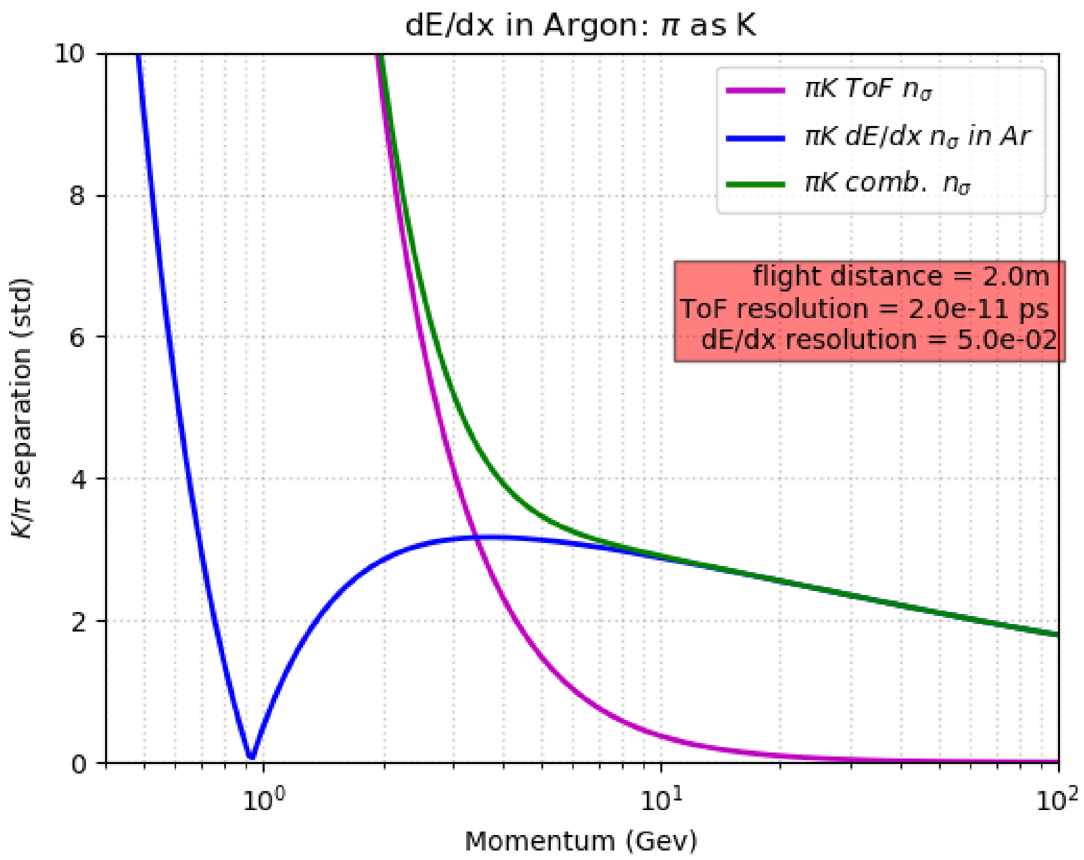
Inclusion of dE/dx and ToF

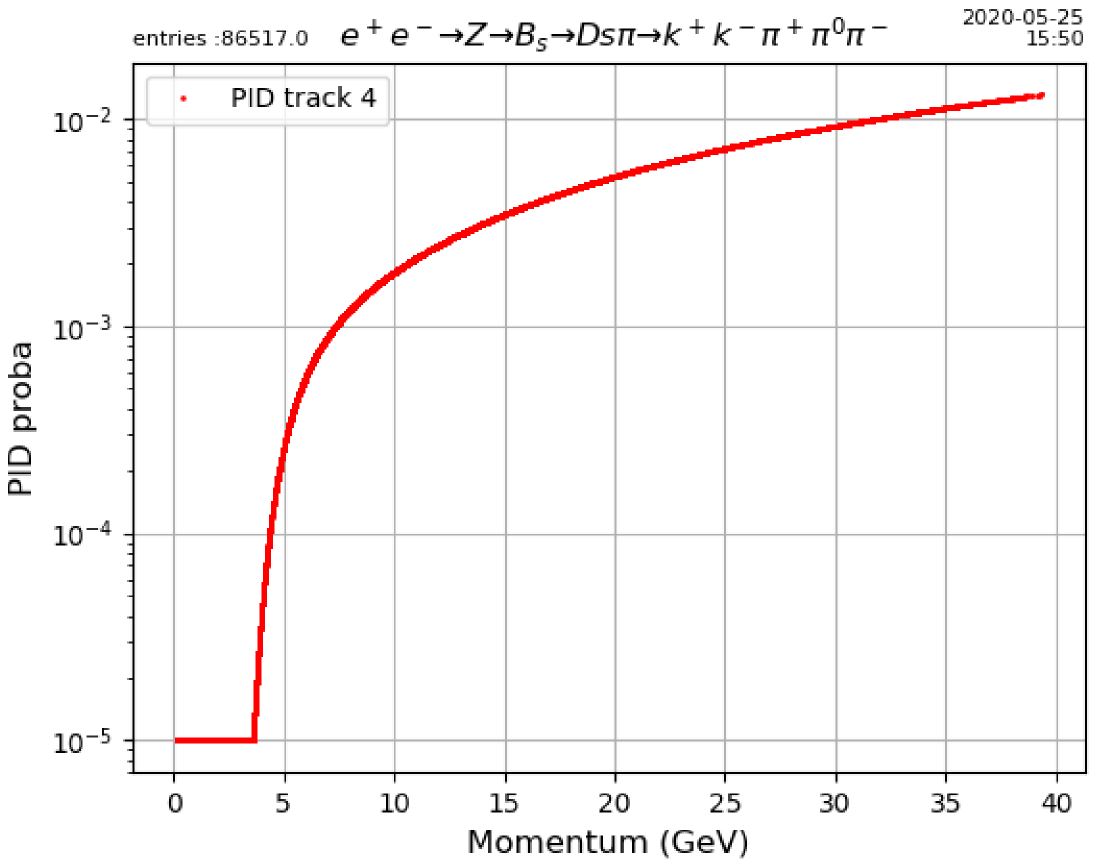
Resolution $\sigma\left(\frac{dE}{dx}\right) = 5\%$

Resolution $\sigma(ToF) = 20ps$

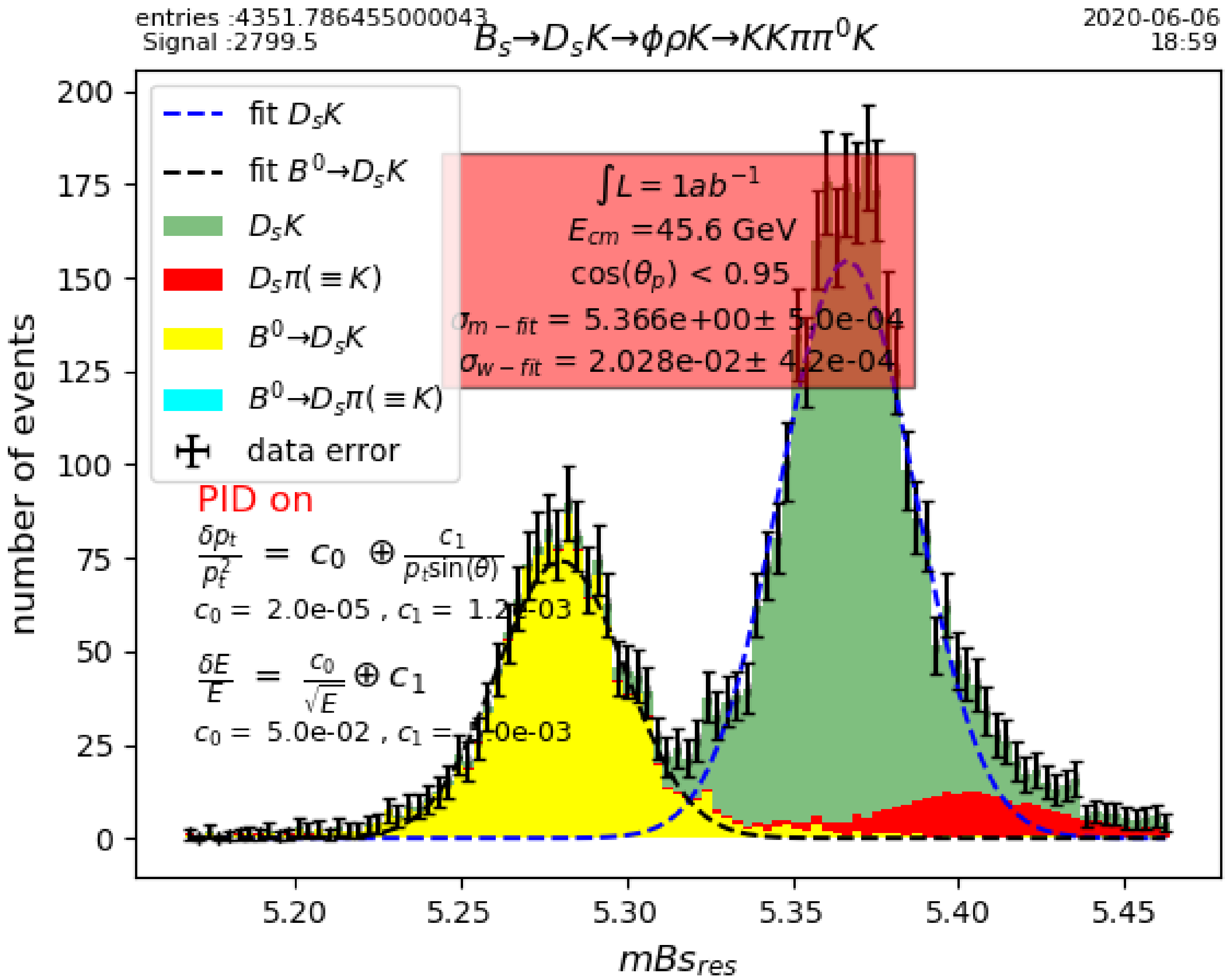
Detector location : 2m from IP

π Rejection factor with $\varepsilon(K)$=50%



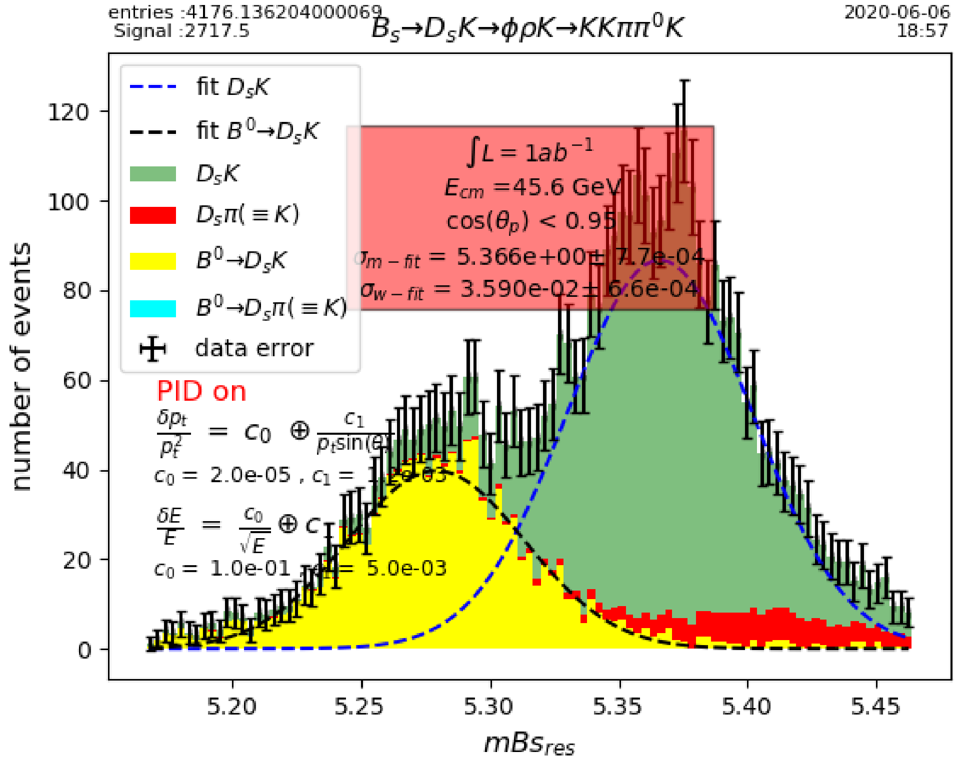


Effect of dE/dx and ToF



Other backgrounds have to be added
dE/dx + simple ToF probably not enough unless

- beyond state-of-the-art is achieved for dE/dx and ToF
- or addition of a dedicated PId system



Conclusions

$\boldsymbol{B_s \to D_s K}$ (as well as $\boldsymbol{B_s \to J/\psi\phi}$, $\boldsymbol{B_s \to \phi\phi}$) are excellent showcases for

- Studying sensitivity on CP violation (measurement of CKM angle γ, β_s)
- Search of BSM physics , in particular with $B_s \to \phi\phi$
- Determining constraints on detector

$\delta(\gamma) \lesssim 0.4° \; (stat.) \;\; \delta(\beta_s) \lesssim 3.4° \times 10^{-2} (stat.)$ achievable

More that 1 order of magnitude improvement compared to present PDG errors

However this requires

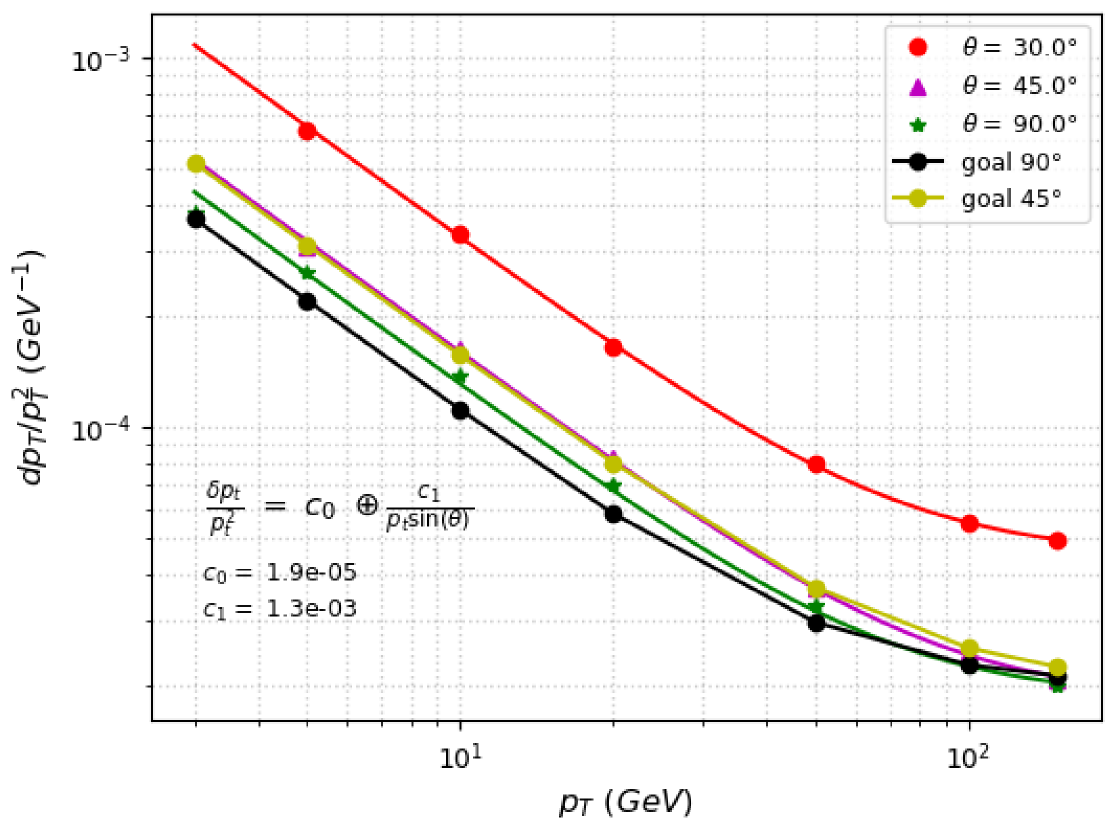
- Excellent tracking and vertexing resolution , $\frac{\sigma(p_T)}{p_T^2} \leq 2.\times 10^{-5} \oplus \frac{1.2 \times 10^{-3}}{p_T sin\Theta}$
- Excellent calorimetry resolution, ideally $\frac{\sigma(E)}{E} \lesssim \frac{5 \times 10^{-2}}{\sqrt{E}} \oplus 5 \times 10^{-3}$
- AND Excellent PId resolution $\gtrsim 3\,\sigma\; K/\pi$ separation up to 25 GeV , Ideally up to 35 GeV

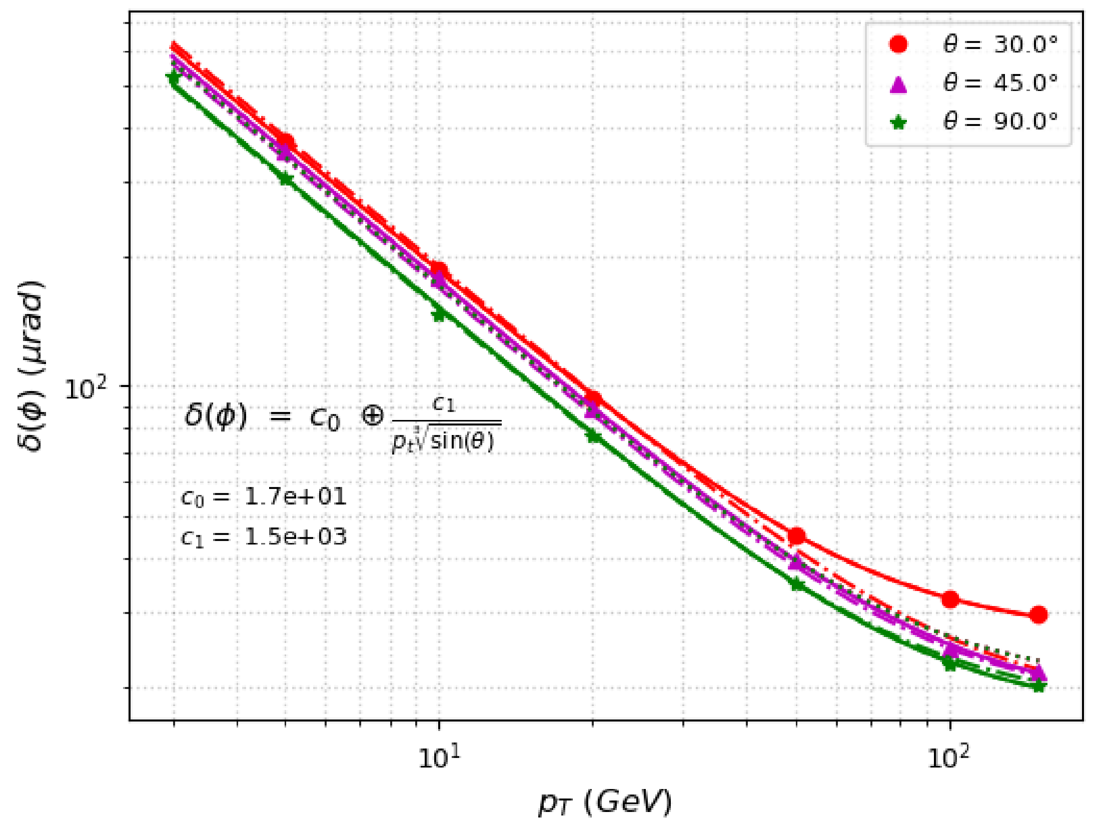
A full simulation would be useful to refine further analysis, in particular for vertexing

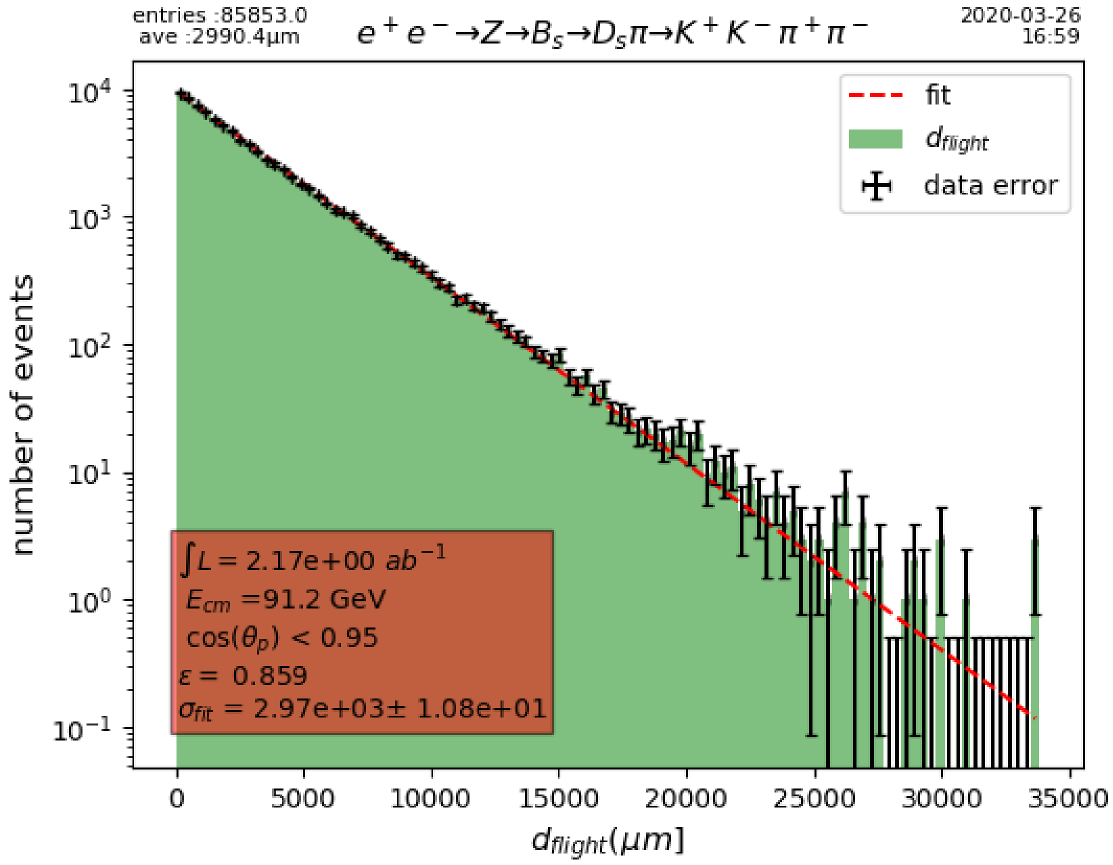
Backup Slides

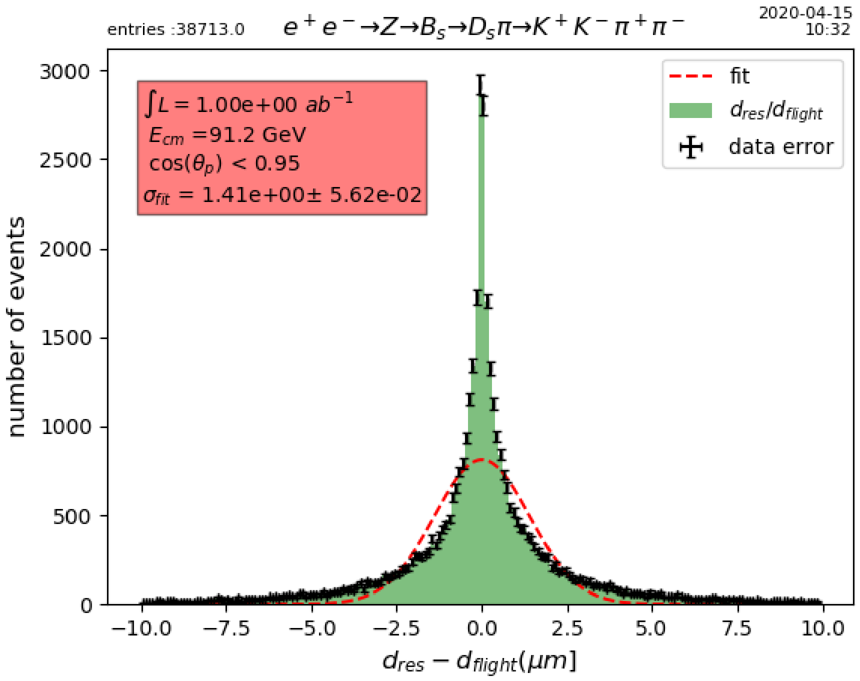
Detector resolutions

ILD type detector (6 vertex Si layers + 2 Inner Si layers + TPC + 1 outer Si layer)

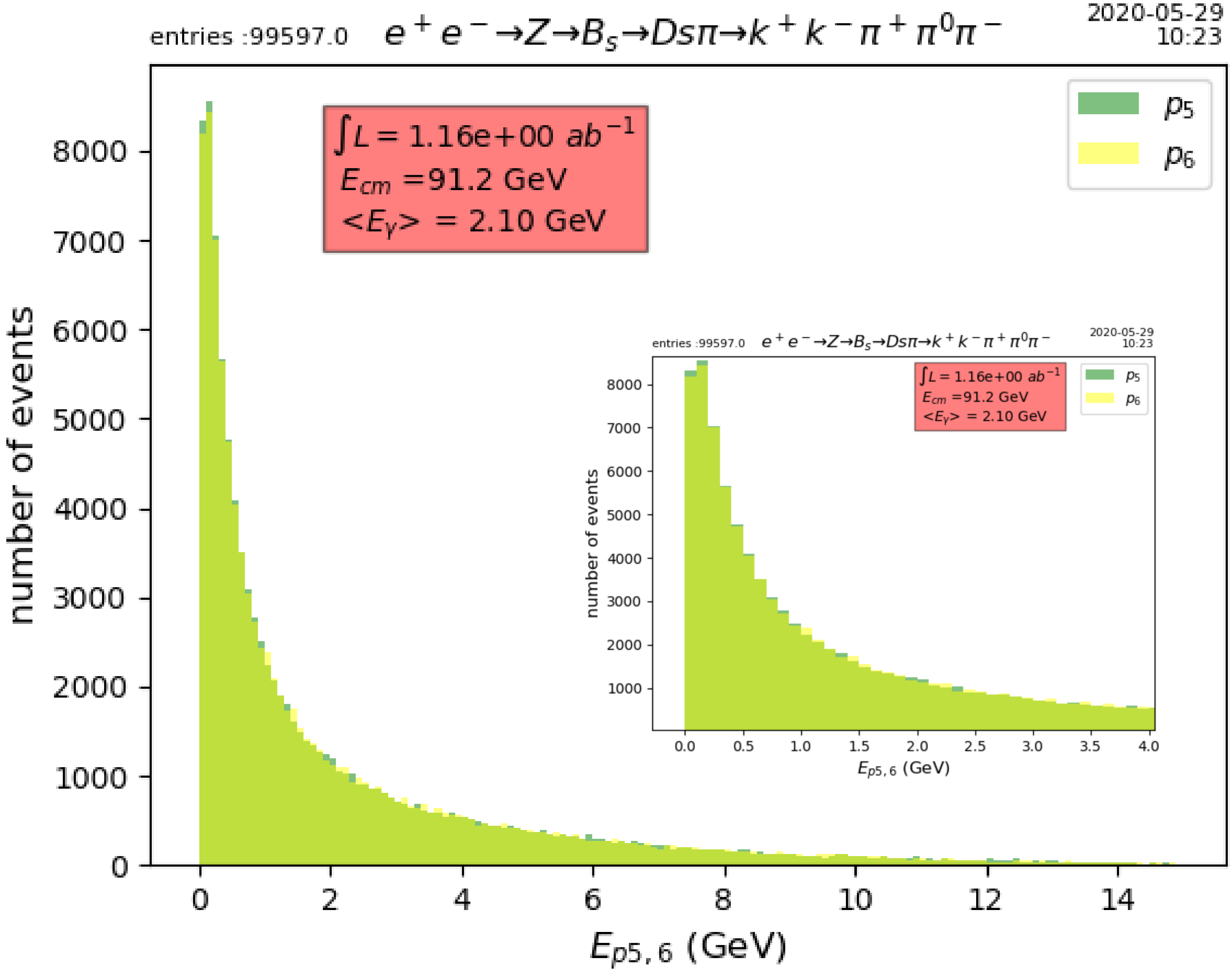


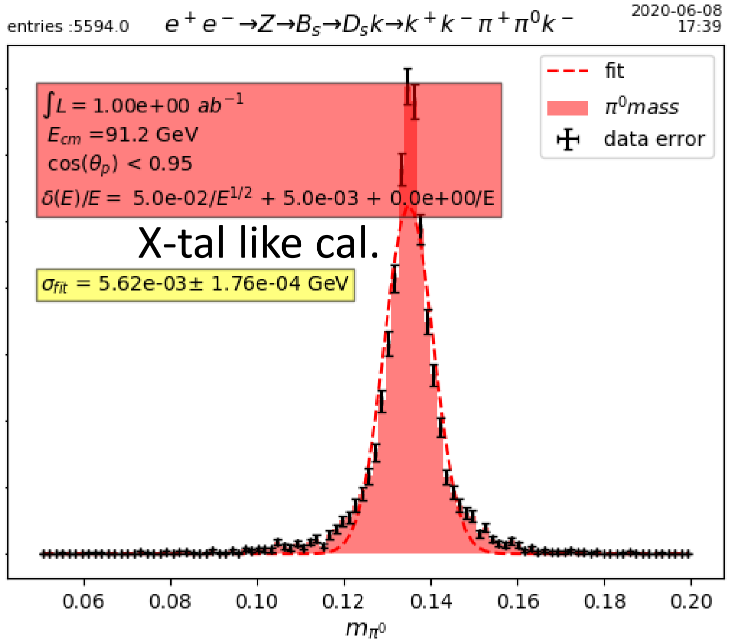


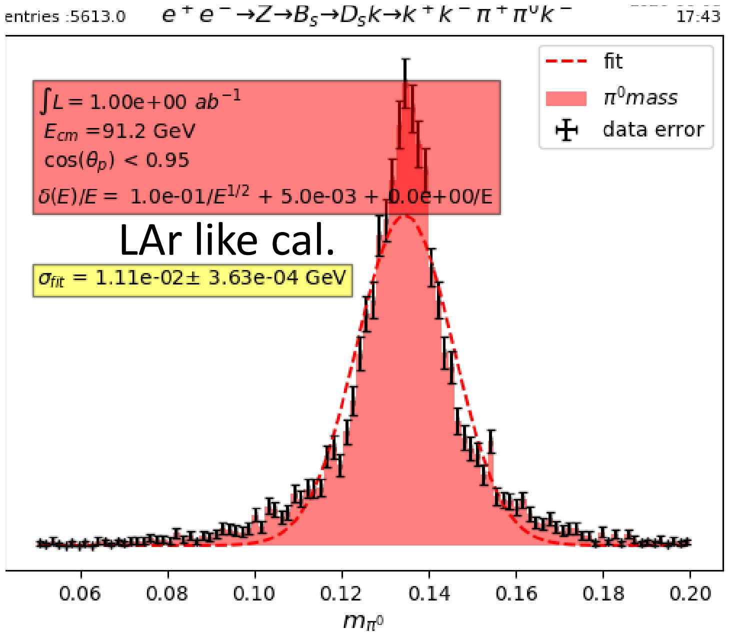

entries :85853.0
ave :2990.4µm
$e^+e^-\to Z\to B_s\to D_s\pi\to K^+K^-\pi^+\pi^-$
2020-03-26
16:59
fit
d_{flight}
data error
$\int L = 2.17e+00\ ab^{-1}$
E_{cm} =91.2 GeV
$\cos(\theta_p)$ < 0.95
ϵ = 0.859
σ_{fit} = 2.97e+03± 1.08e+01
number of events
$d_{flight}(\mu m)$


entries :38713.0
$e^+e^-\to Z\to B_s\to D_s\pi\to K^+K^-\pi^+\pi^-$
2020-04-15
10:32
$\int L = 1.00e+00\ ab^{-1}$
E_{cm} =91.2 GeV
$\cos(\theta_p)$ < 0.95
σ_{fit} = 1.41e+00± 5.62e-02
fit
d_{res}/d_{flight}
data error
number of events
$d_{res} - d_{flight}(\mu m)$

Energy spectrum of γ from $D_s^- \to \phi\rho^- \to (K^+K^-)_\phi(\pi^-\pi^0)_\rho$







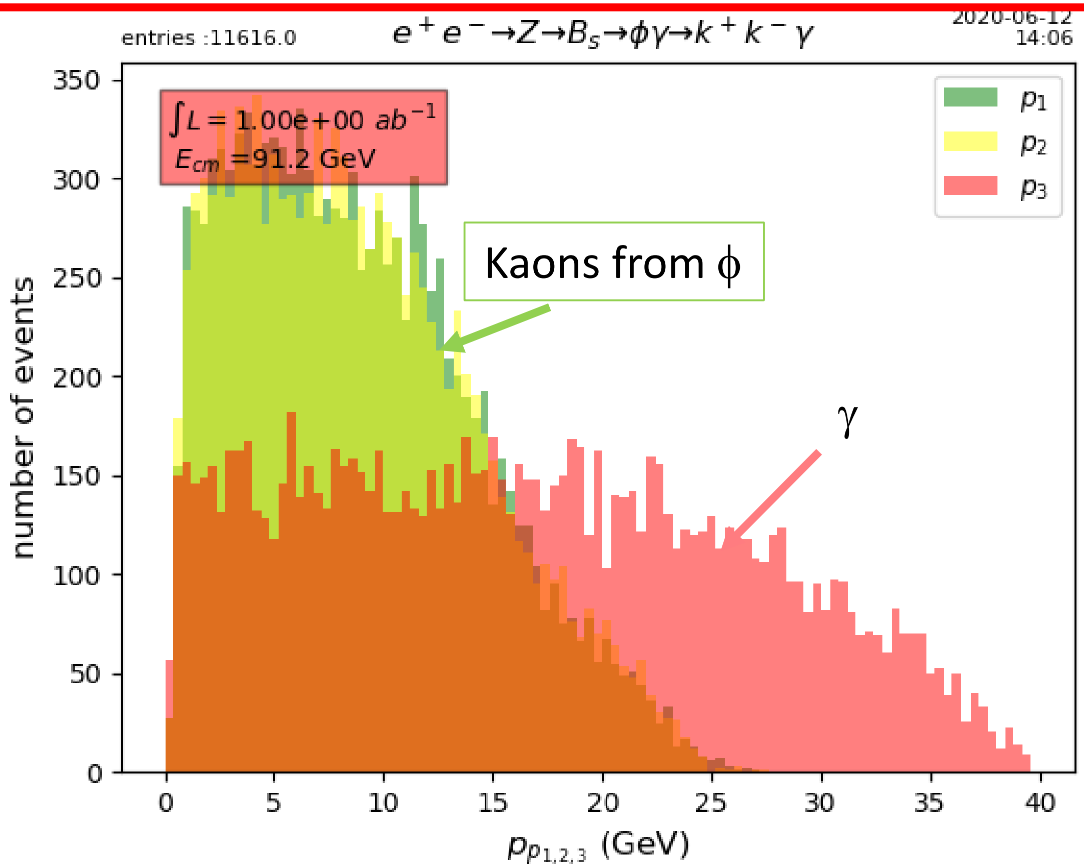
Study of CP violation with $B_s \to \phi\gamma$

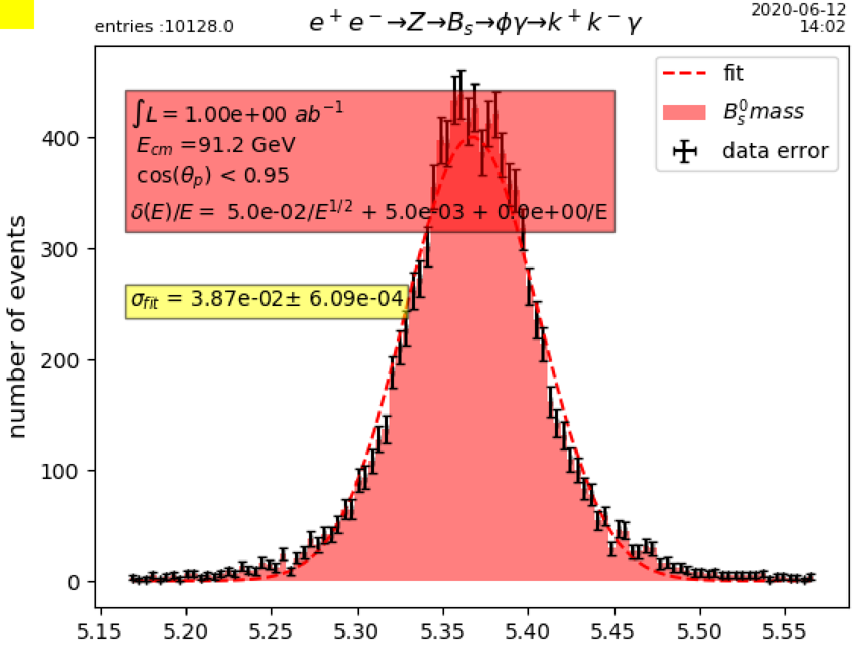
Same as $\boldsymbol{B_s \to \phi\phi}$ $\phi_{CKM} \approx 0°$ $Br(B_s \to \phi\gamma) = 3.4 \times 10^{-5}$

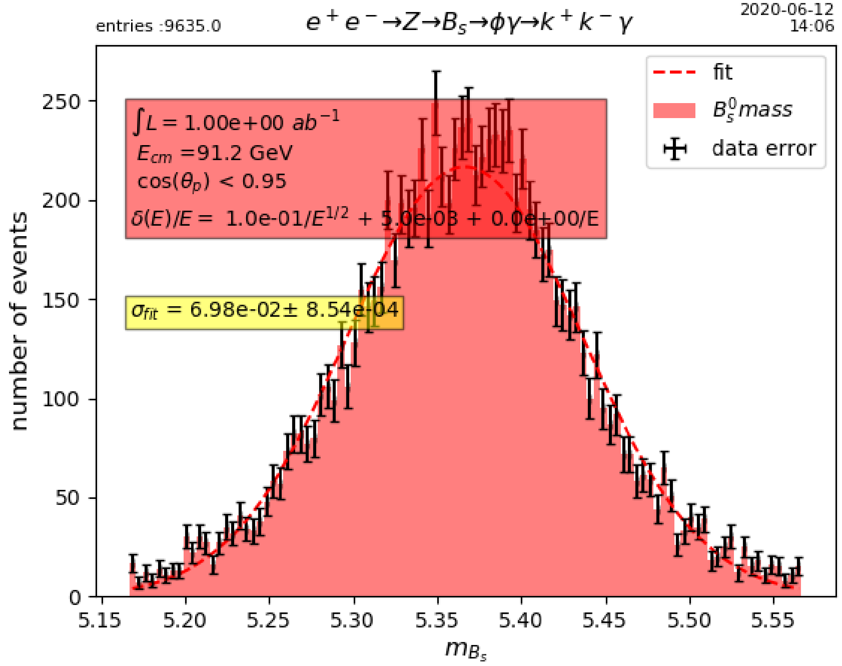
⇨ Very good for probing BSM $\cong 1.7 \times 10^6$ *events with* $150\ ab^{-1}$

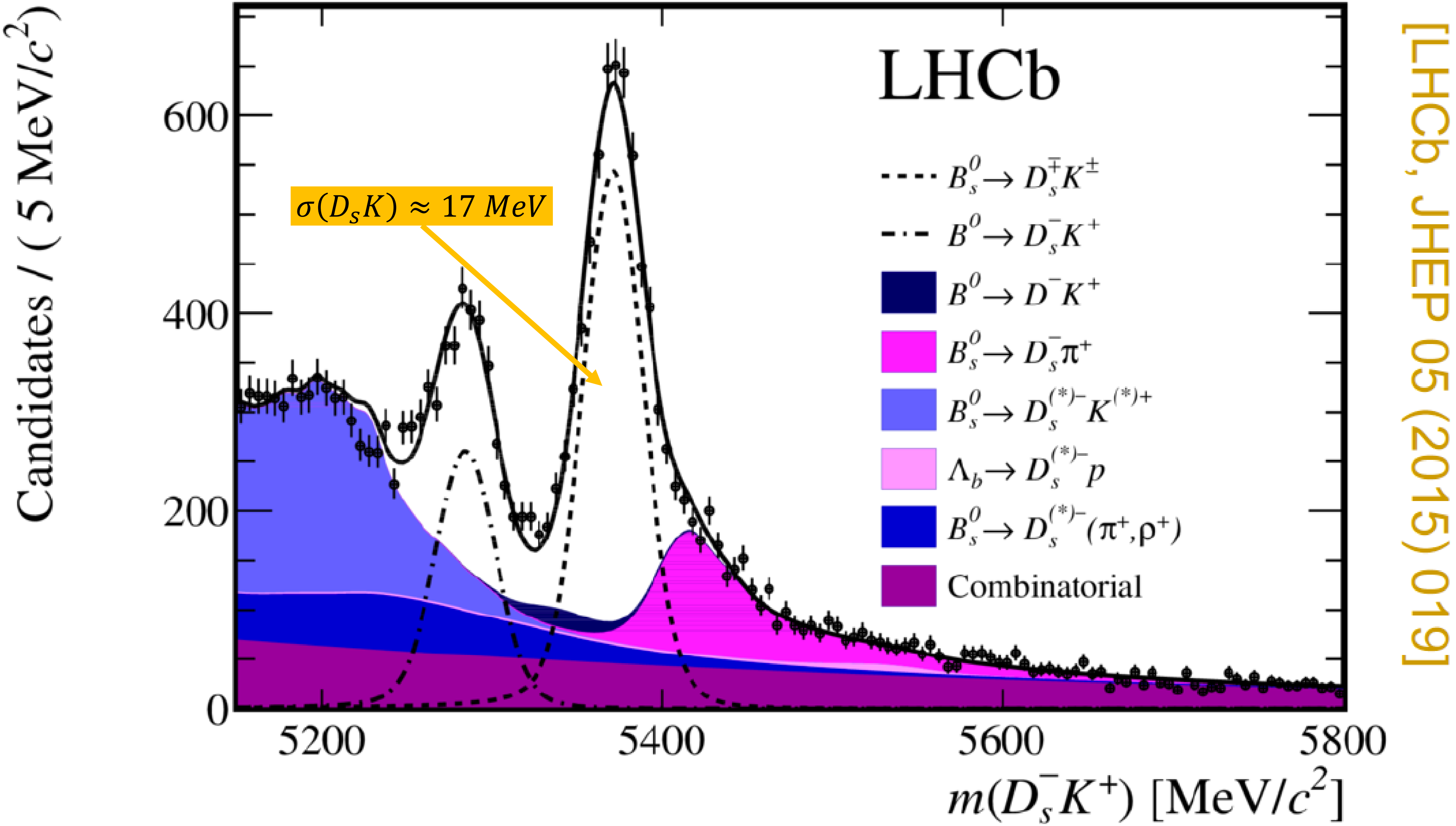
2 main issues requiring dedicated study

- Study of background as mass resolution is poor
  - $\sigma(m_{Bs}) \approx 39\ MeV$ with Xtal like calo.
  - $\sigma(m_{Bs}) \approx 70\ MeV$ with Lar like calo.
- Study of vertex resolution as ϕ is strongly boosted ($\sigma > 400\mu m$!)









LHCb
$\sigma(D_s K) \approx 17\ MeV$
$B_s^0 \to D_s^{\mp} K^{\pm}$
$B^0 \to D_s^- K^+$
$B^0 \to D^- K^+$
$B_s^0 \to D_s^- \pi^+$
$B_s^0 \to D_s^{(*)-} K^{(*)+}$
$\Lambda_b \to D_s^{(*)-} p$
$B_s^0 \to D_s^{(*)-} (\pi^+, \rho^+)$
Combinatorial
Candidates / (5 MeV/c^2)
$m(D_s^- K^+)$ [MeV/c^2]
0
200
400
600
5200
5400
5600
5800
[LHCb, JHEP 05 (2015) 019]