Study of B_s -> D_s K at FCC-ee and constraints on detector

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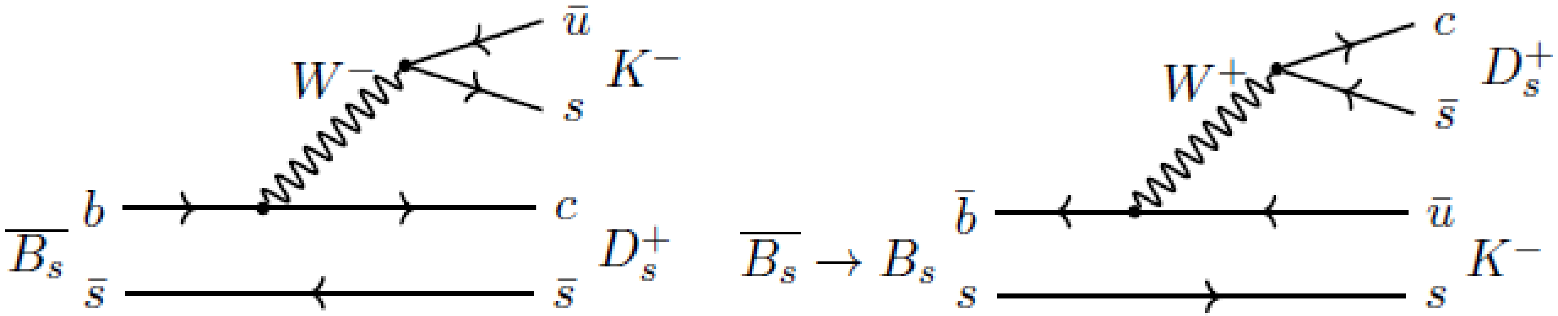
20/1/2021



$$\phi_{CKM} = \alpha_s - \beta_s = \gamma + \gamma_{ds} - 2\beta_s$$

UT

tiny

small

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

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

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

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

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

Note: $\Delta\Gamma_s$ neglected

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

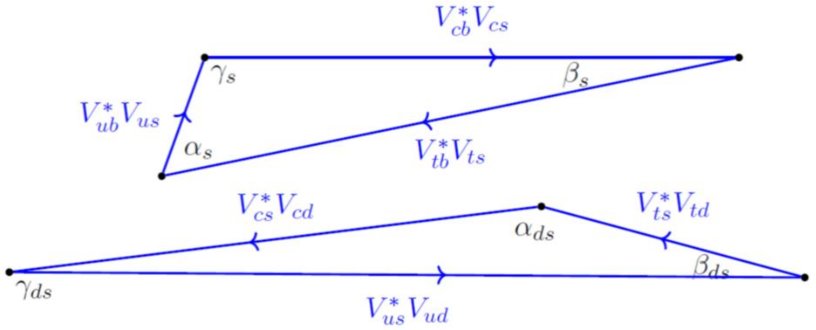
$$\rho(D_s^+\pi^-) = 0$$

ω = *wrong tagging*

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

$$\phi^{\pm}_{CP} = \phi_{CKM} \pm \delta_s$$

$$\phi_{CKM} = \gamma + \gamma_{ds} - 2\beta_s$$



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

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

2-fold ambiguity

Expected number of events

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

(To be x 2 for B_s)

$\overline{B}_s$ 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

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

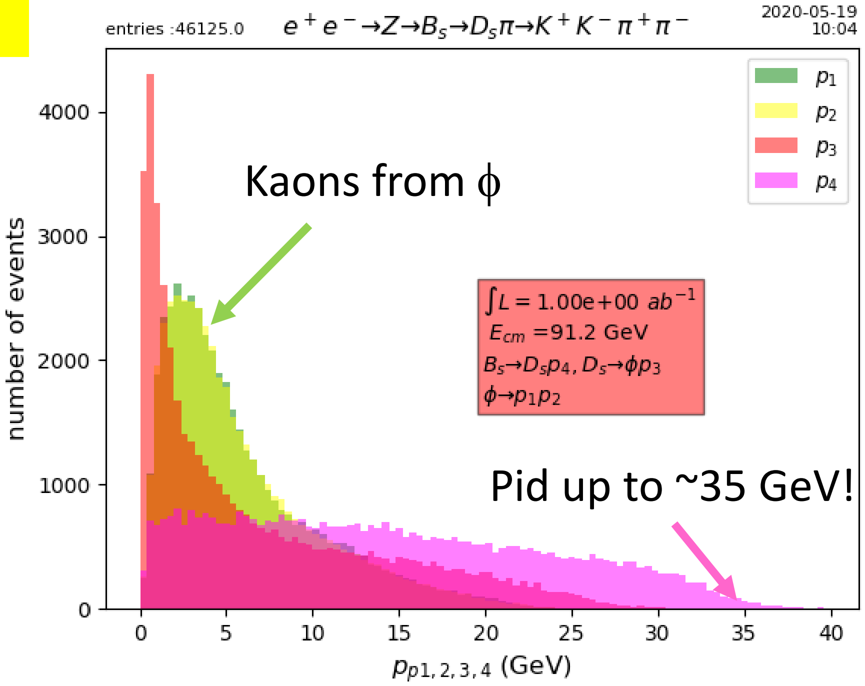
$$\text{Track } p_T \text{ resolution}: \quad \frac{\sigma(p_T)}{p_T^2} = 2.\times 10^{-5} \oplus \frac{1.2\times 10^{-3}}{p_T \sin\theta}$$

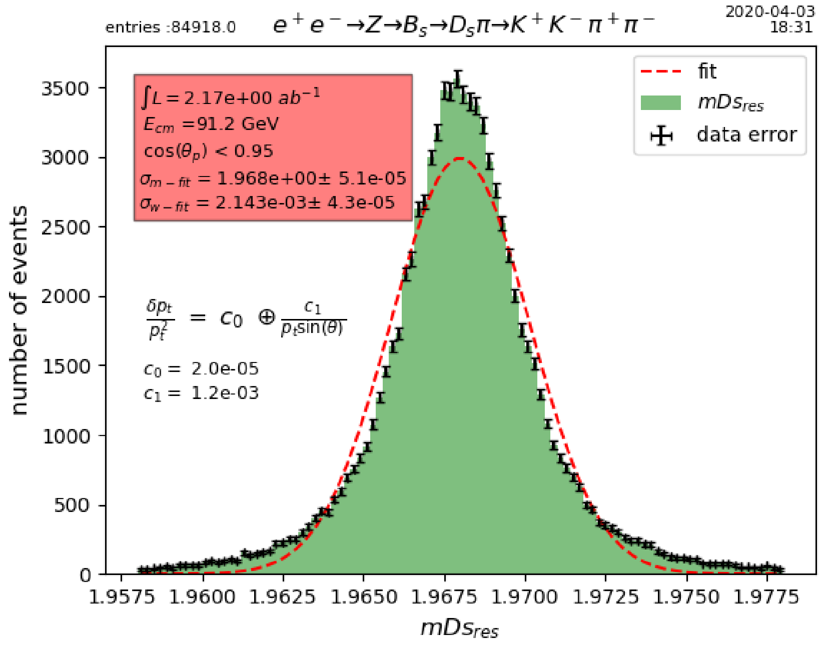
$$\text{Track } \phi,\theta \text{ resolution}: \quad \sigma(\phi,\theta)\ \mu\text{rad} = 18 \oplus \frac{1.5\times 10^{3}}{p_T \sqrt[3]{\sin\theta}}$$

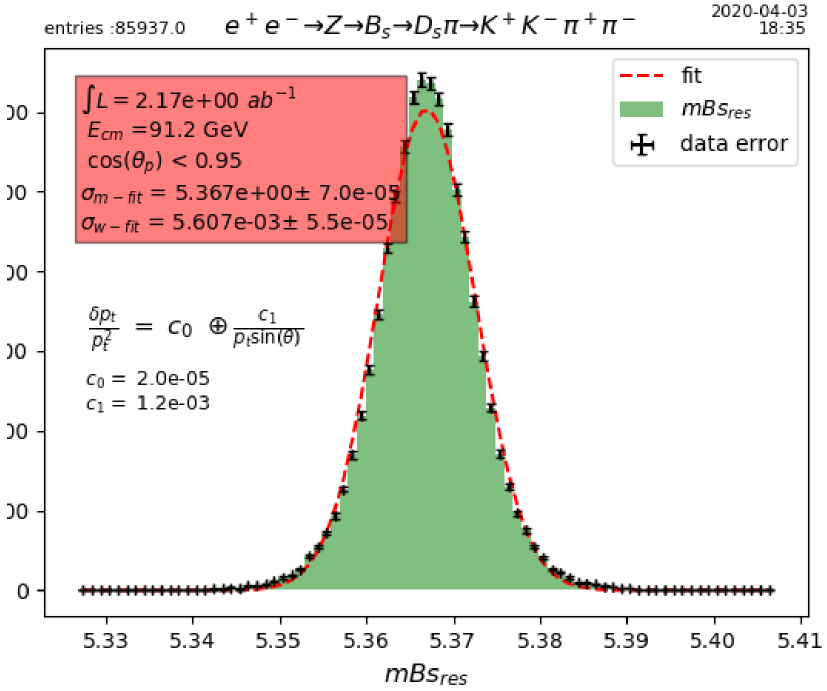
$$\text{Vertex resolution}: \quad \sigma(d_{\text{Im}})\ \mu m = 1.8 \oplus \frac{5.4\times 10^{1}}{p_T \sqrt{\sin\theta}}$$

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

$$\text{Calorimeter resolution}: \quad \frac{\sigma(E)}{E} = \frac{5\times 10^{-2}}{\sqrt{E}} \oplus 5\times 10^{-3}$$







Charged final state only

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

To be compared to

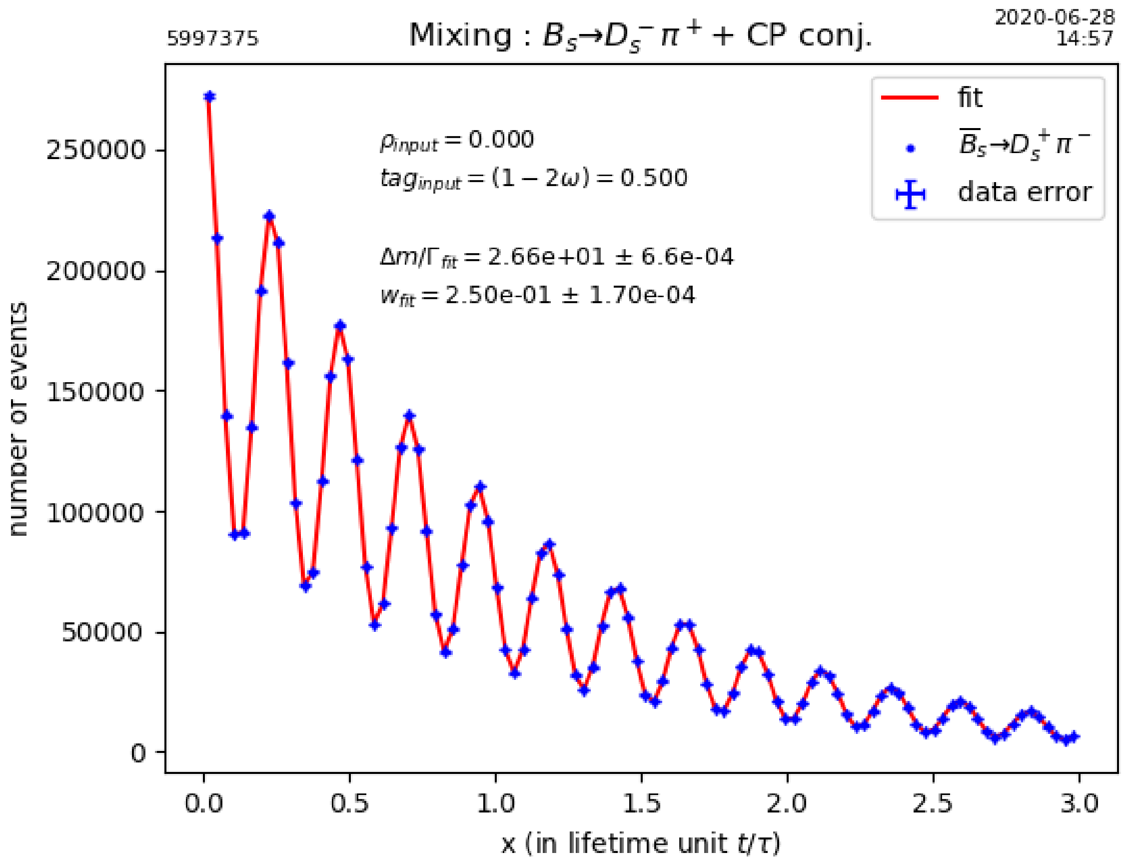
$$\boldsymbol{\sigma(mB_s)_{LHCb} \approx 17\ MeV}$$

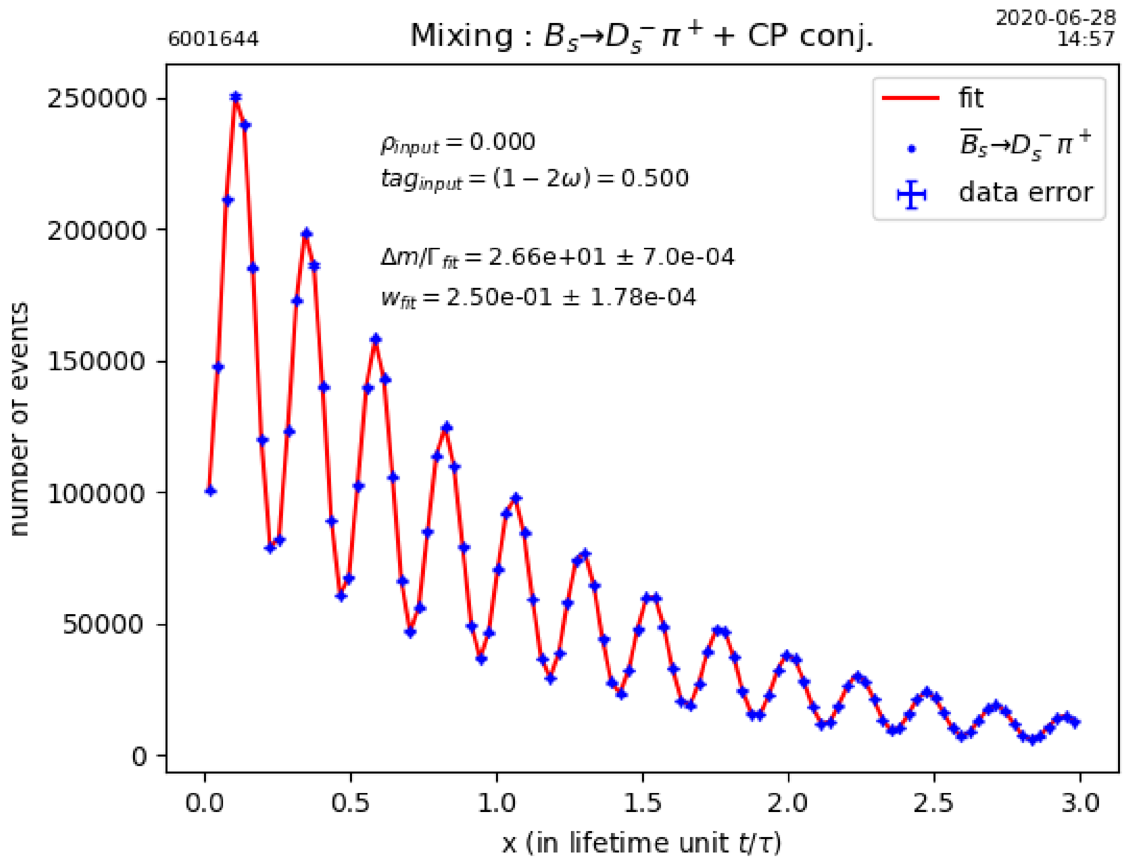
B_s Mixing Measurement with $B_s \to D_s\pi$

Mean B flight distance ≈ 3000 μm

Flight distance resolution < 20 μm (negligible) ⇨ full simulation and vertex fit would be useful (**cf E.Perez**)

Background mainly combinatorics (very small)



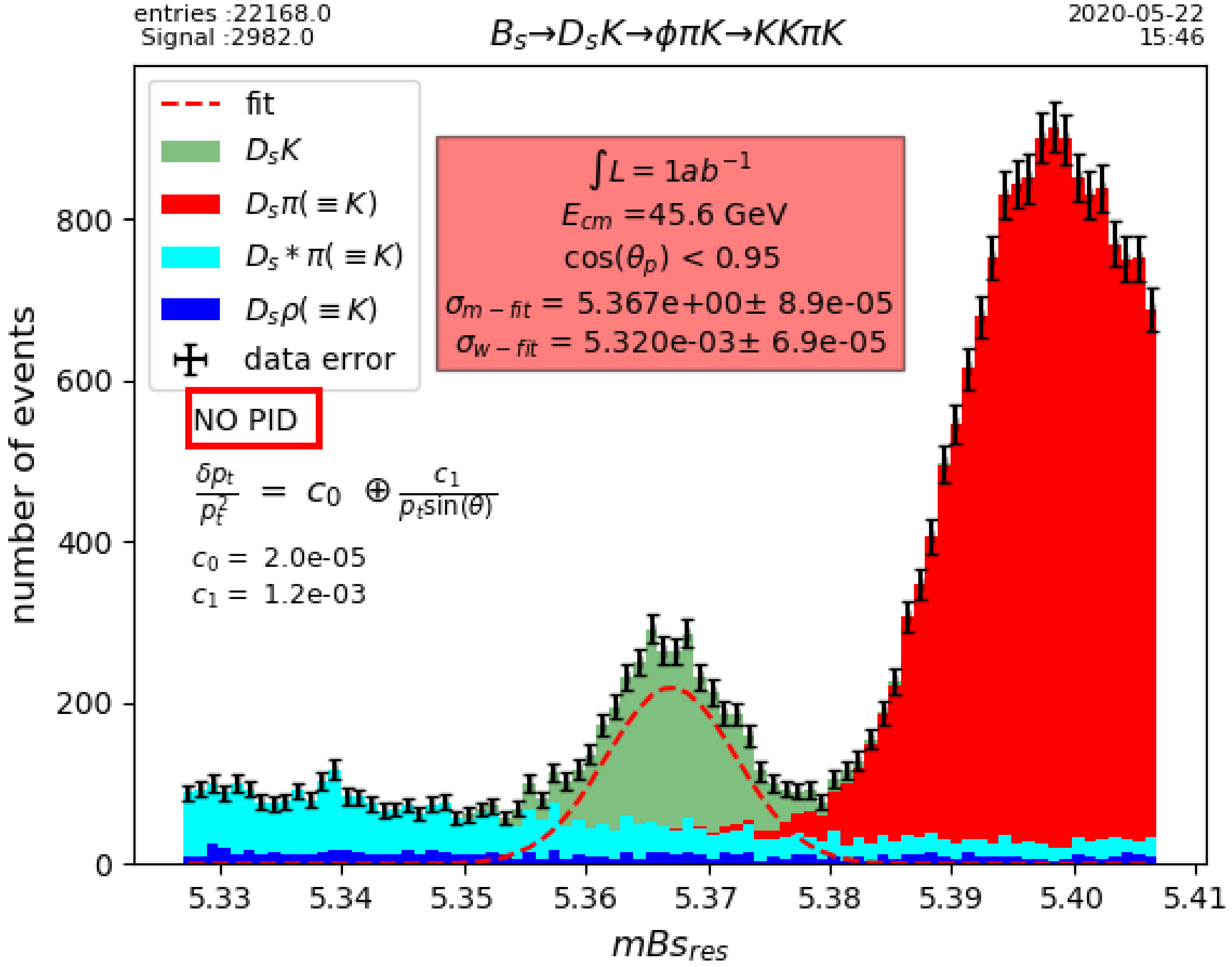


Result 1 :

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

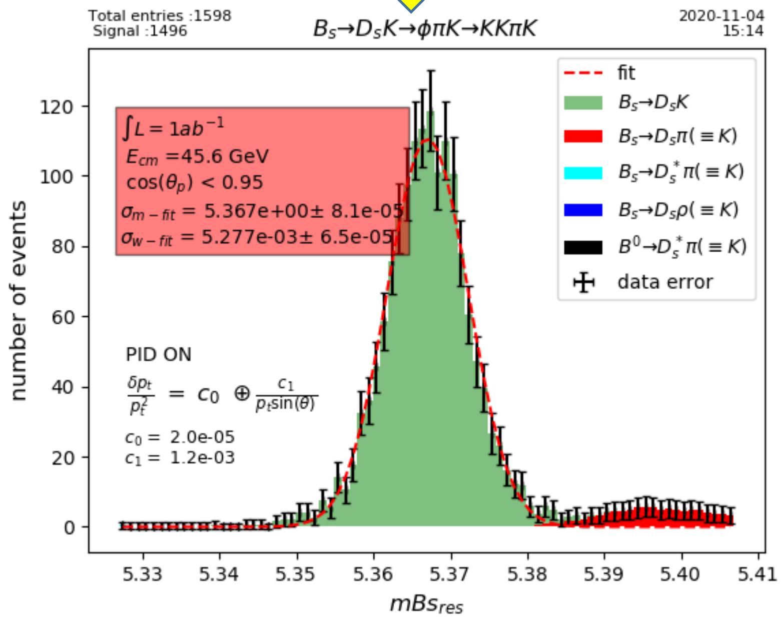
$\delta(\omega)_{stat} = 1.4 \times 10^{-4}$ ⇨ **Wrong tagging measured very precisely**

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



Result 2 :

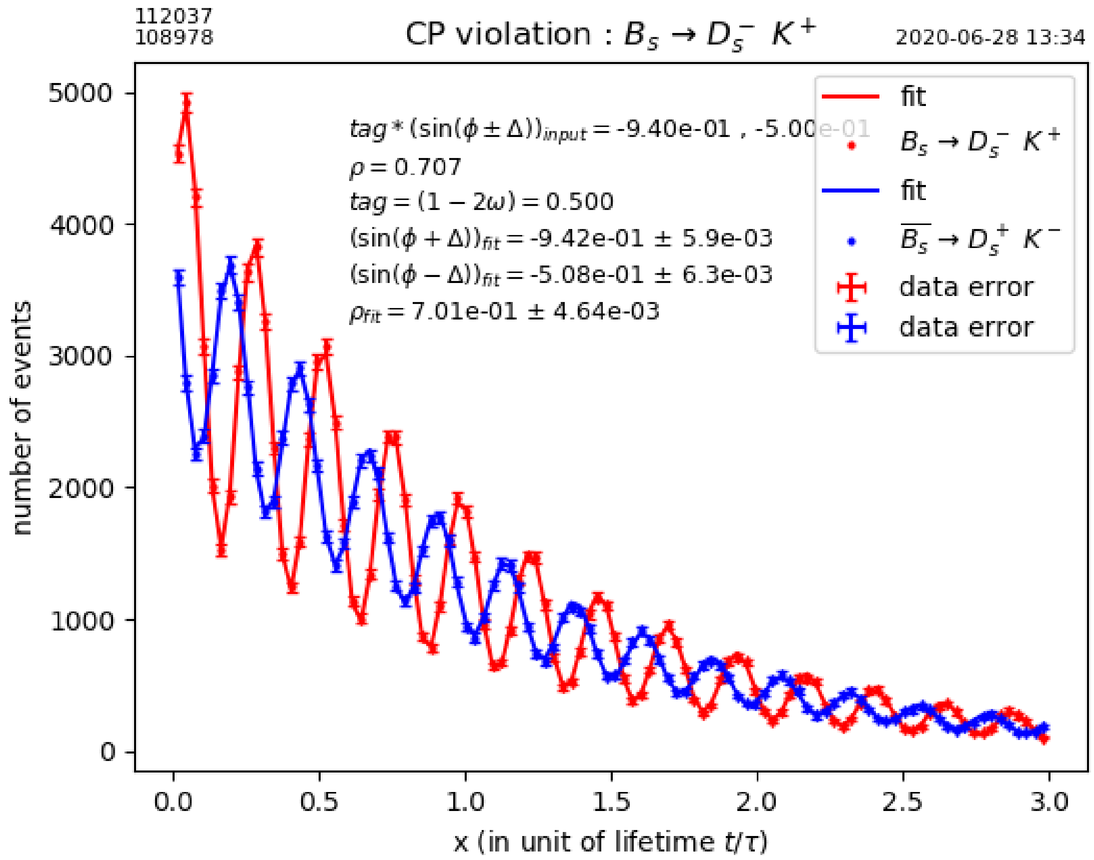
- Tracking resolution crucial to reduce background
- Combinatoric background to be added (but expected to be relatively small)
- A modest PId (ToF + dE/dx) enough (see presentation later this afternoon)

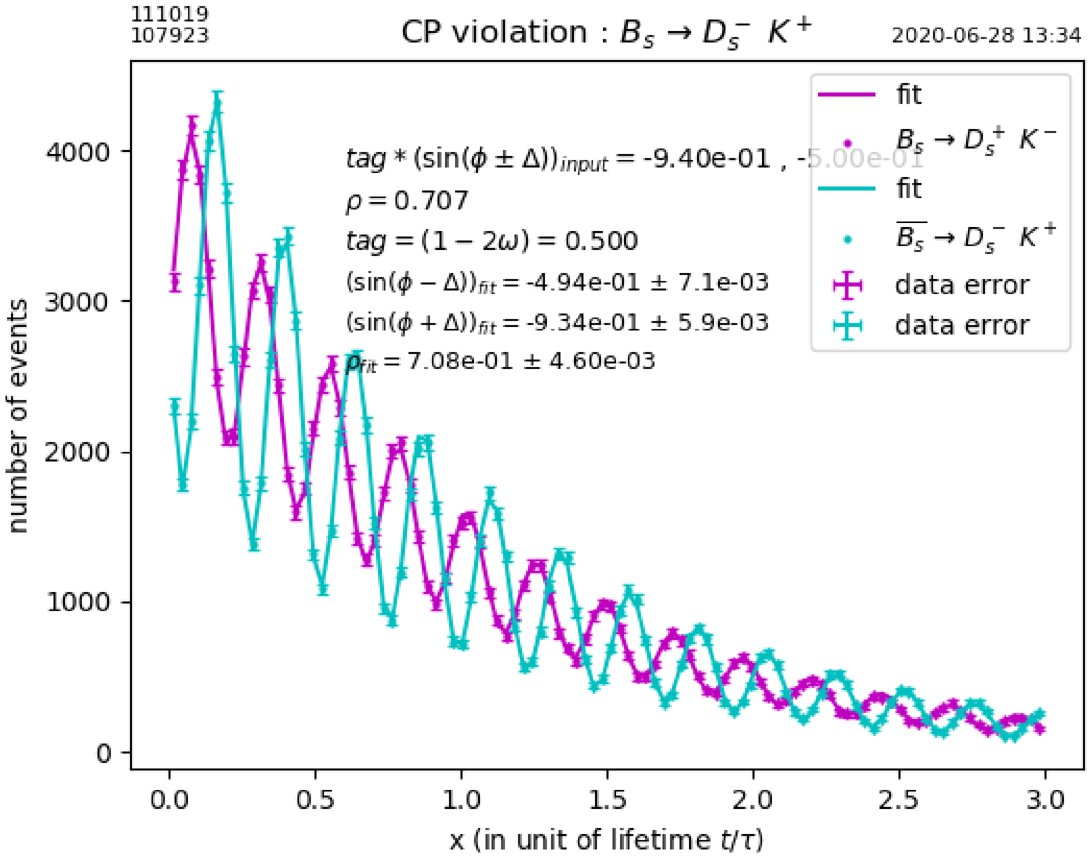


Measurement of CP violation with $B_s \rightarrow D_s K$

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

PDG: $\gamma = (71.1^{+4.6}_{-5.3})°$





Result 3 :

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

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

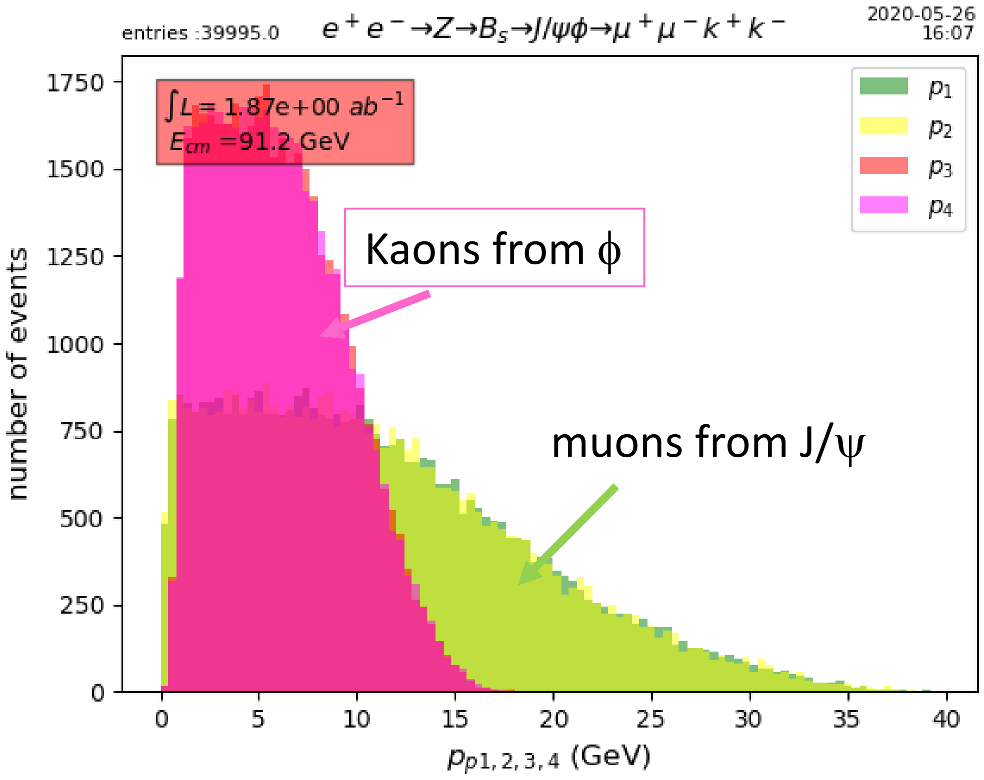
Potential statistical gain of factor 4-5 with $D_S^{\pm} \rightarrow K^{*0}K^{\pm}, \phi\rho^{\pm}$, ... but background needs to be studied (see later)+
Additionnal potential gain (another factor ~2) with $B_s \rightarrow D_S^{*\pm}K^{\mp}, D_S^{\pm}K^{*\mp}, D_S^{*\pm}K^{*\mp}$, most modes including γ(s)

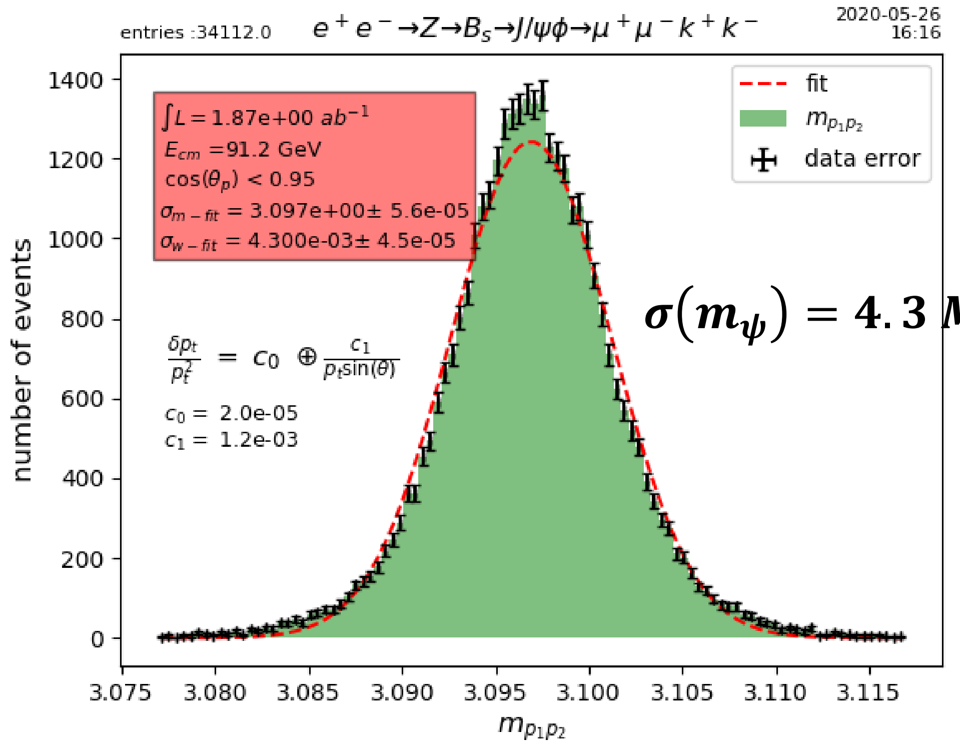
Measurement of CP violation with $B_s \to J/\psi\phi \to \mu^+\mu^- K^+K^-$

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

To take advantage of the full sensitivity , measurement of β_s needed

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





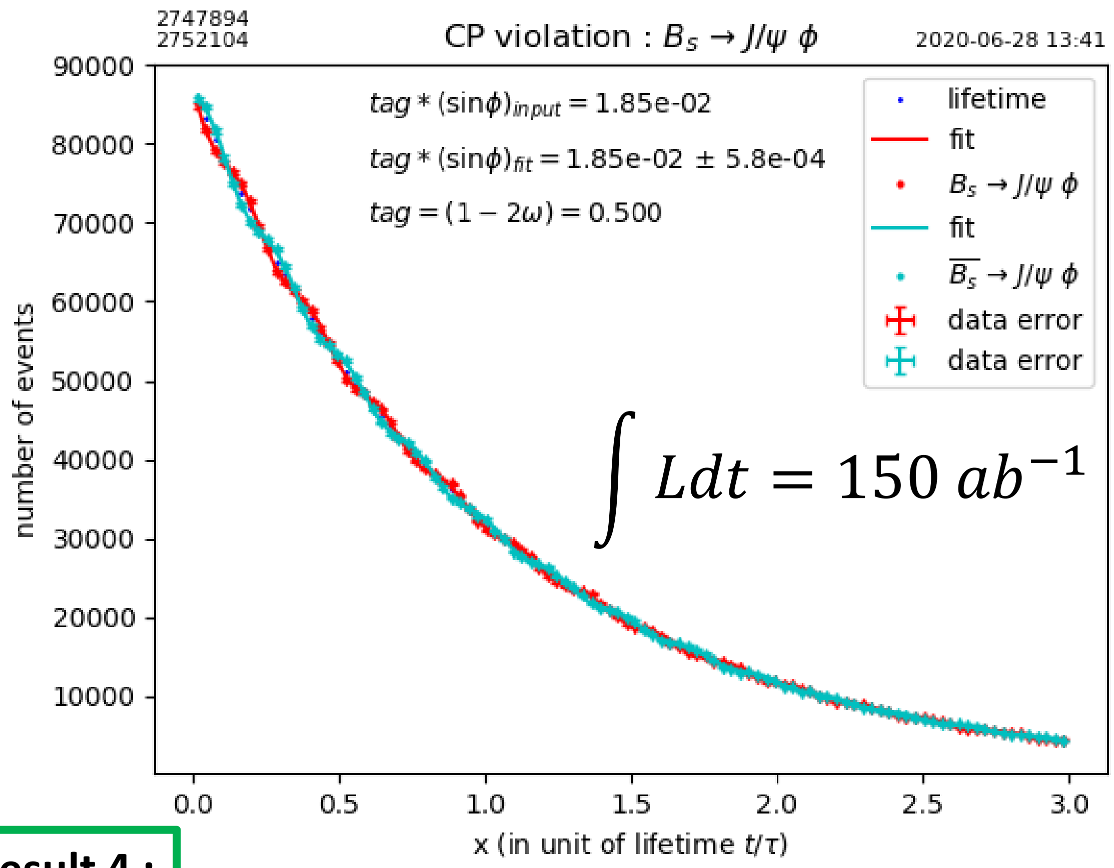
$\sigma(m_\psi) = 4.3\ MeV$

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

CKM: $\beta_s \approx 1°$

PDG: $\beta_s = (0.60 \pm 0.89)°$

With $\Gamma_L/\Gamma = 1$



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

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

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

Angular analysis required (tbd) : $\Gamma_L/\Gamma \neq 1$
Otherwise additional sinΦ term amplitude reduction by factor $\sim(1-2f_\perp)$
Reduced sensitivity by factor ~2 (can be partly compensated using $J/\psi \to e^+ e^-$)

Result 4 :

$$\delta(sin\phi_{CKM}) = \delta(sin2\beta_s) \approx 1.2 \times 10^{-3} \cong \delta(\beta_s) \approx 3.5° \times 10^{-2}(stat.)$$

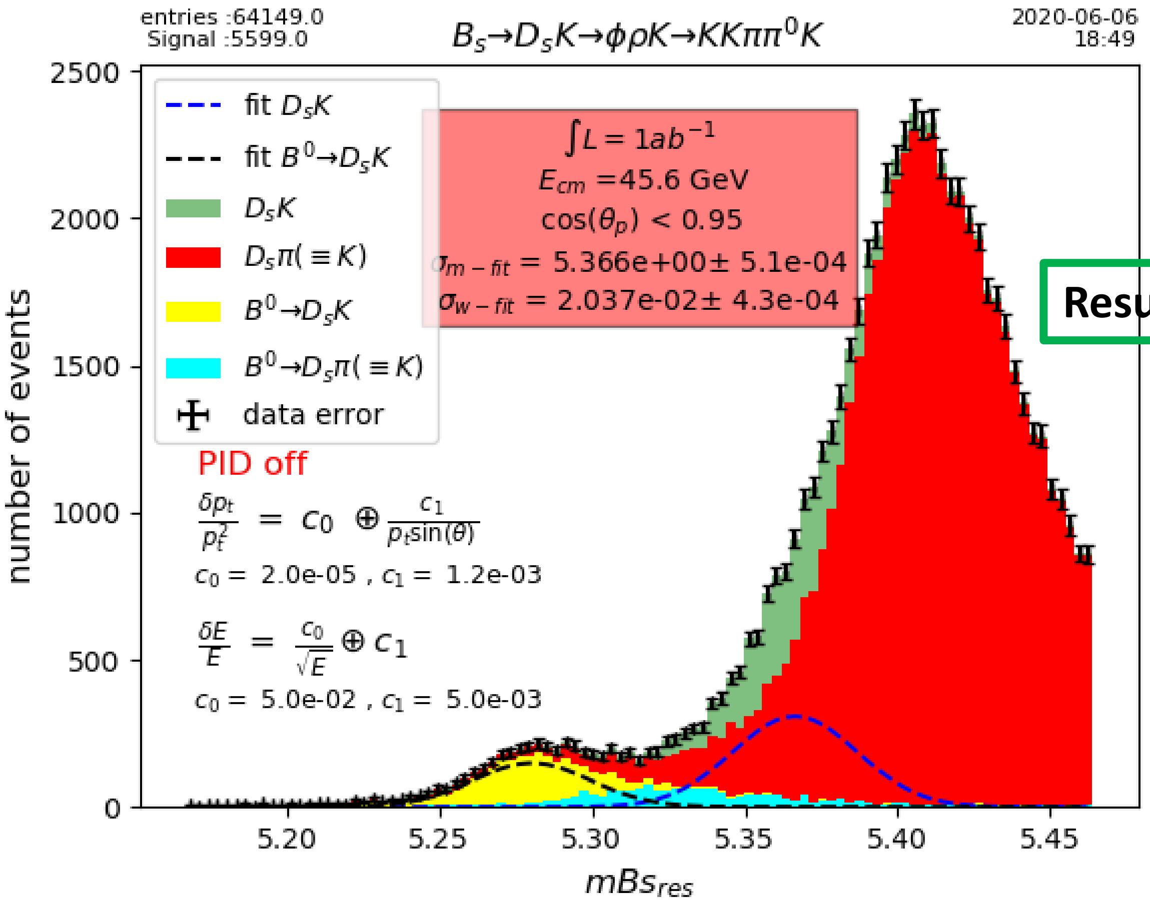
NO PId

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

⇨ Significant advantage compared to LHCb ⇨ constraint on calorimeter and PId



With very good calorimeter resolution (Xtal type)

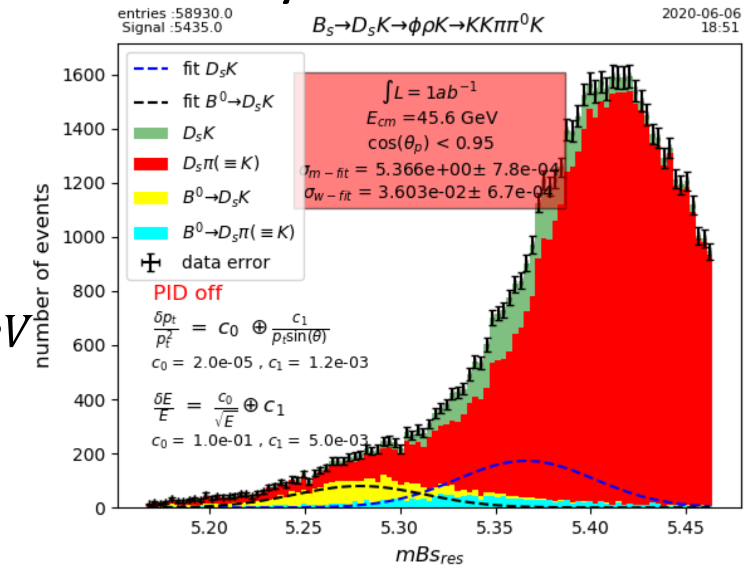
$\sigma\left(D_s^{\pm}(\phi\pi^{\pm})K^{\mp}\right) \approx 5.6MeV \;\to \sigma\left(D_s^{\pm}(\phi\rho^{\pm})K^{\mp}\right) \approx 20MeV$

⇨ Background $D_s^{\pm}(\phi\rho^{\pm})\pi^{\mp}$ huge

Result 6 : ⇨ Excellent PId mandatory

Much worse with
LAr type Cal.

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

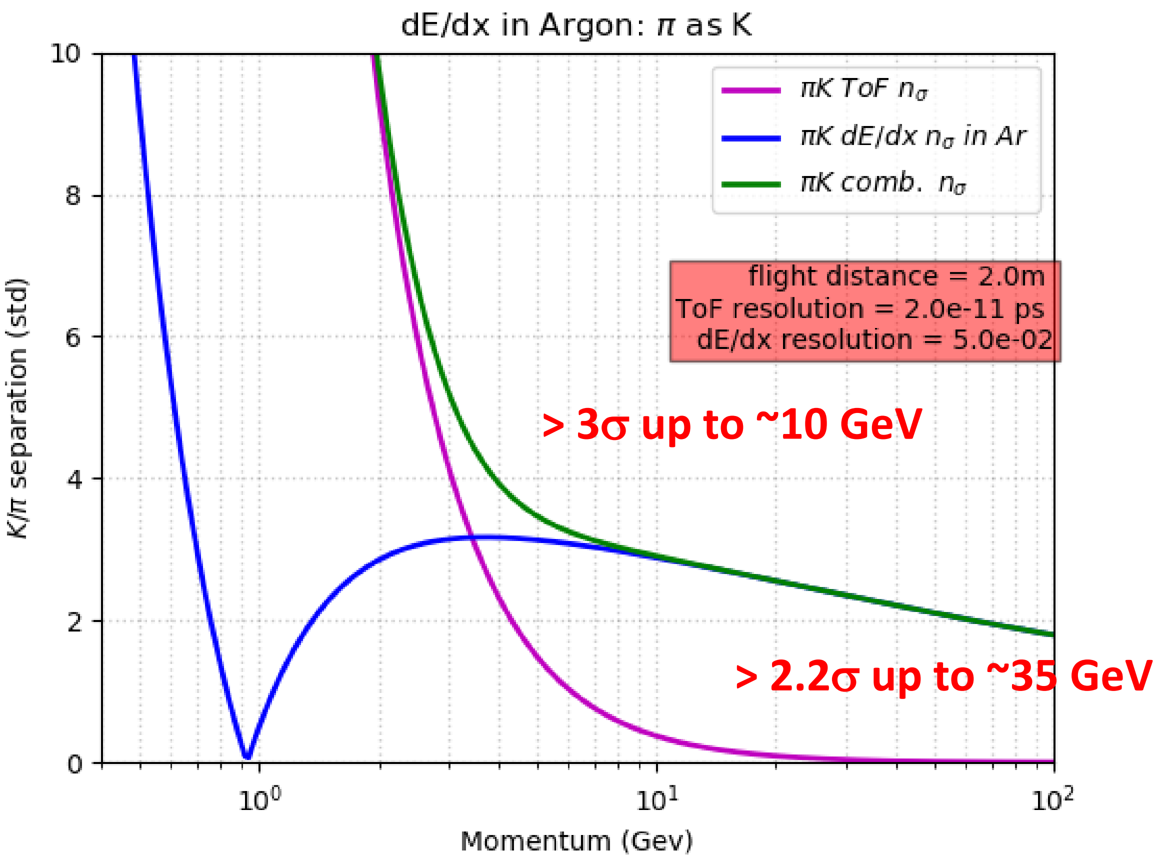


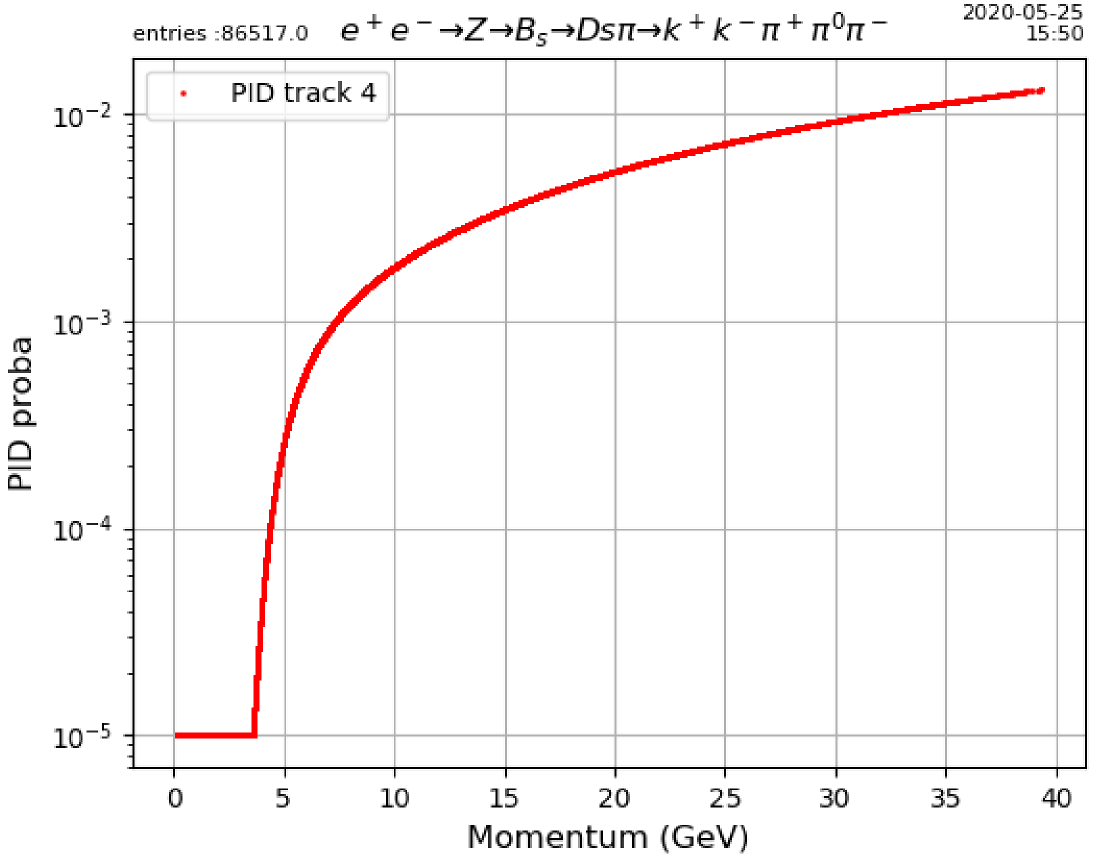
Inclusion of « standard and modest » PID (dE/dx and ToF)

Somewhat conservative PID

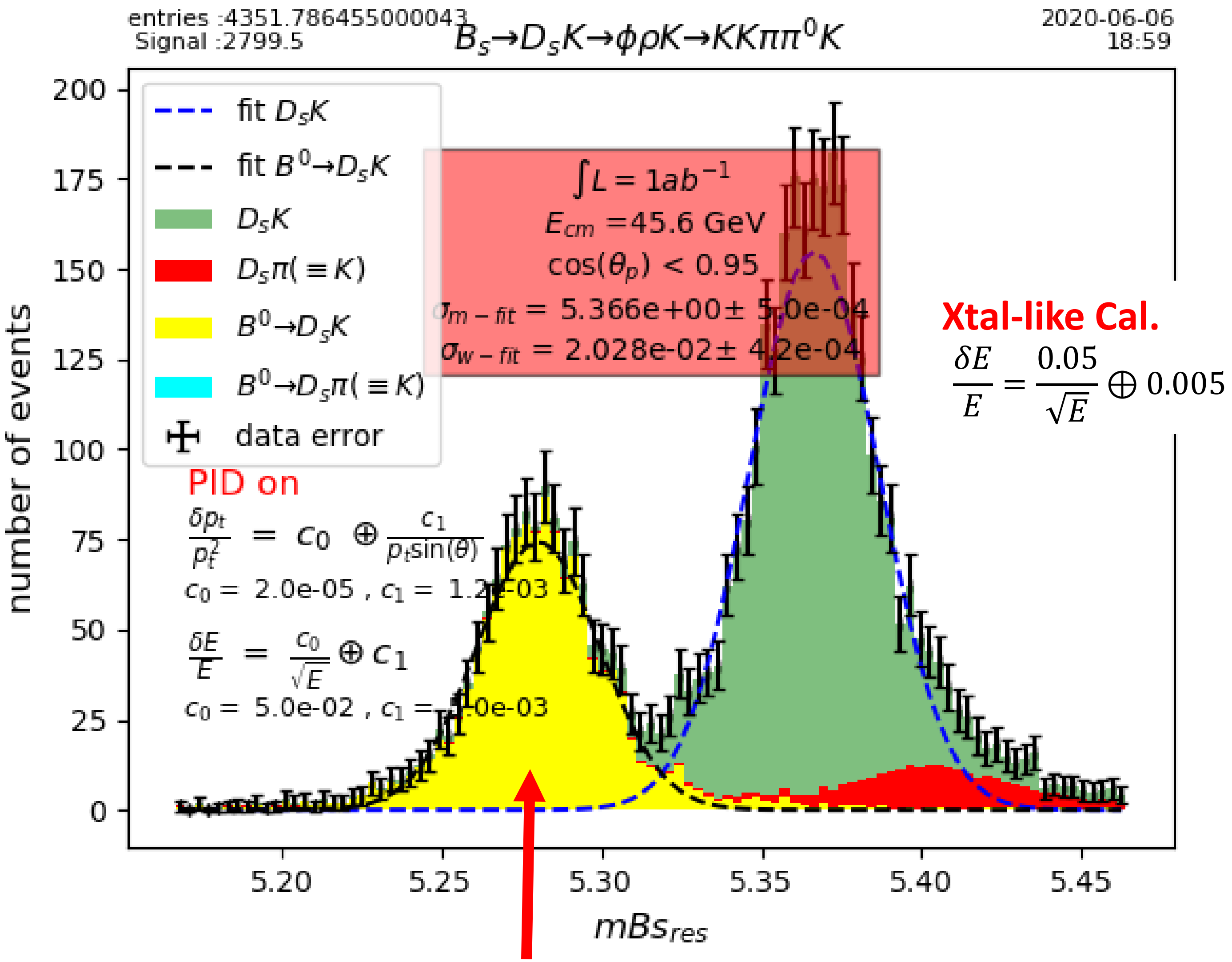
- Resolution $\sigma\left(\frac{dE}{dx}\right) = 5\%$
- Resolution $\sigma(ToF) = 20\text{ps}\ (\cong 6\text{mm})$
- ToF Detector location : 2m from IP

Probability of π misidentification as K with ε(K)=50%





Effect of dE/dx and ToF

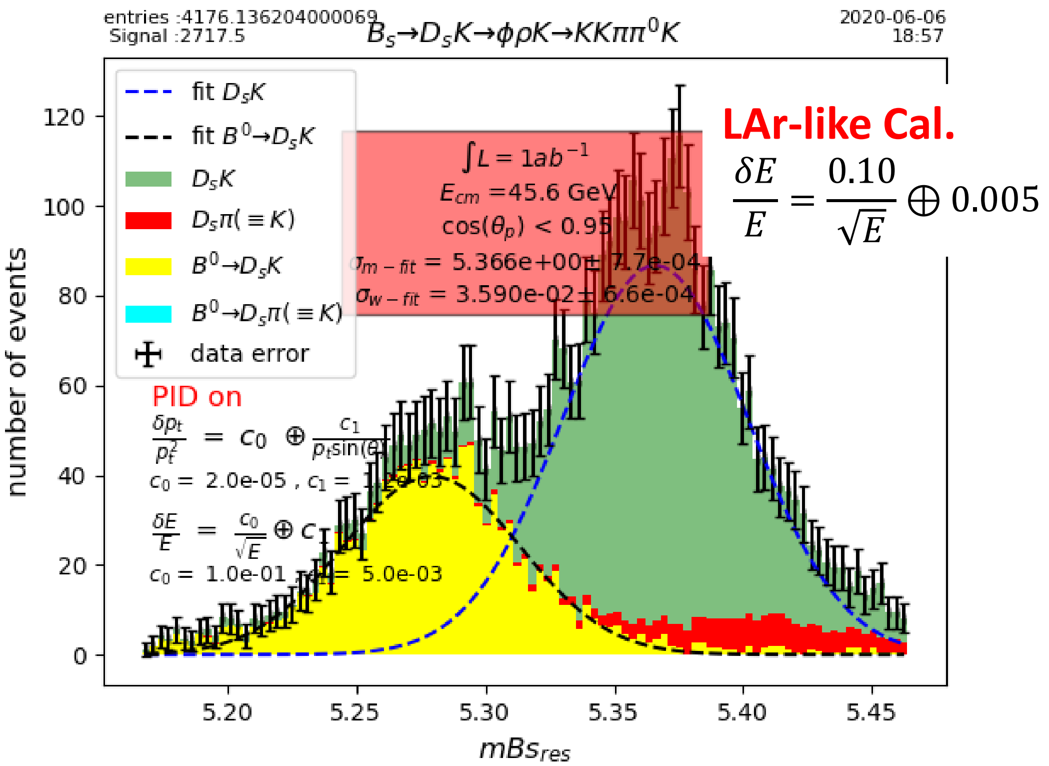


« Irreducible bkg » , only mass resolution can beat it

Result 7 : Excellent calorimetry (Xtal like) is also mandatory

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

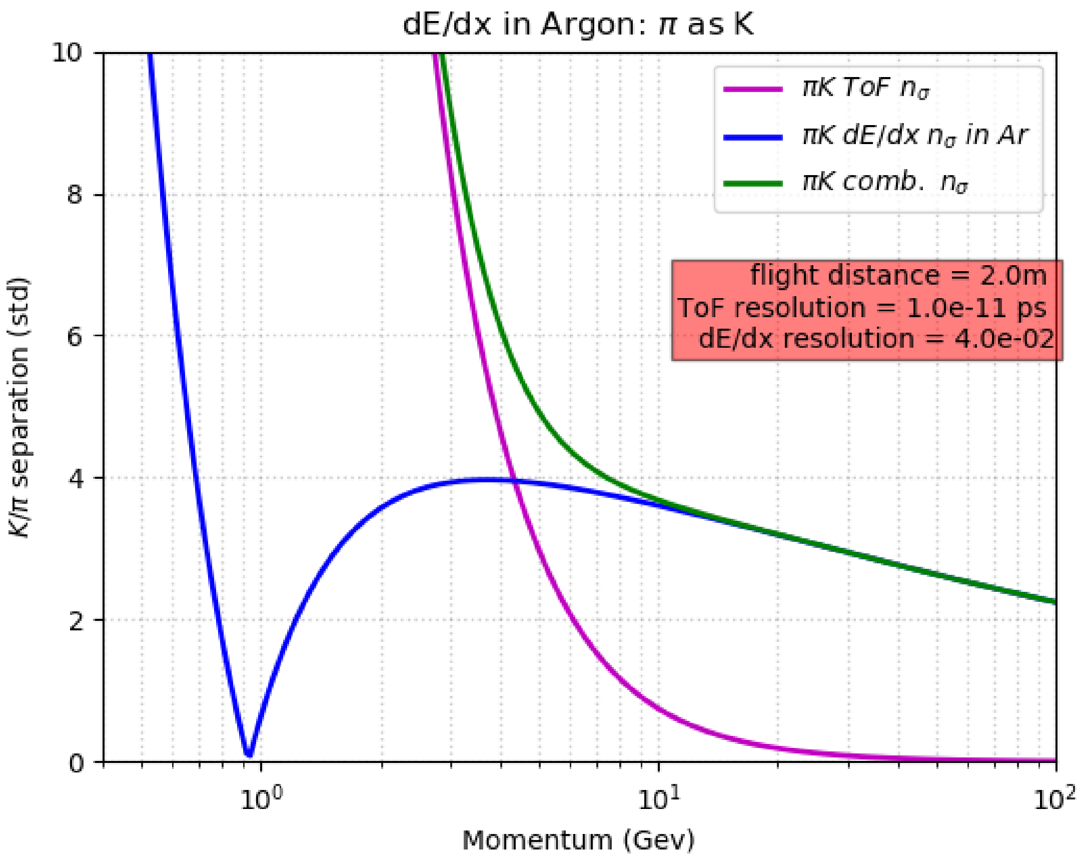


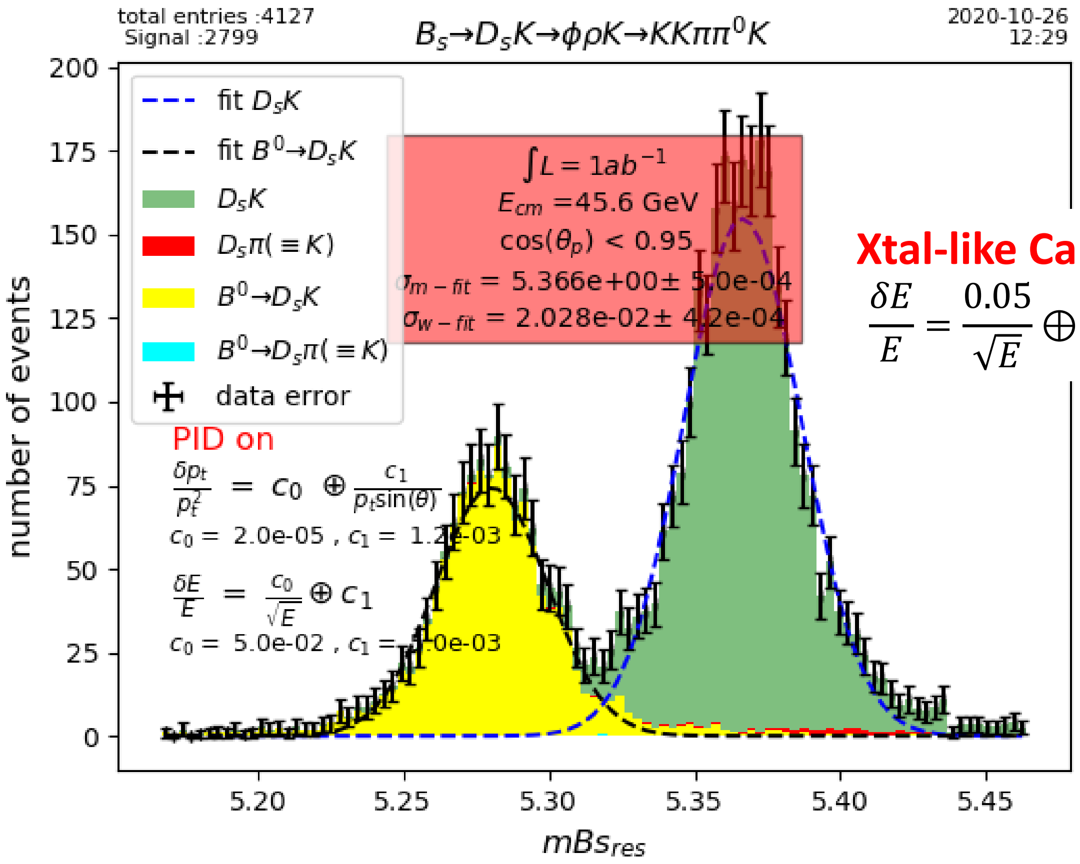
Inclusion of « improved » dE/dx and ToF

Resolution $\sigma\left(\frac{dE}{dx}\right) = 4\%$

Resolution $\sigma(ToF) = 10\text{ps}\ (\cong 3\text{mm})$

Detector location : 2m from IP





Xtal-like Cal.

$$\frac{\delta E}{E} = \frac{0.05}{\sqrt{E}} \oplus 0.005$$

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)
- Excellent for search of BSM physics , in particular with $B_s \to \phi\phi$
- Determining constraints on detector

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

with only 1 decay mode !!!

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 $\frac{\sigma(E)}{E} \lesssim \frac{5 \times 10^{-2}}{\sqrt{E}} \oplus 5 \times 10^{-3}$

Allows to use many other decay mode !!!

AND Excellent PId resolution

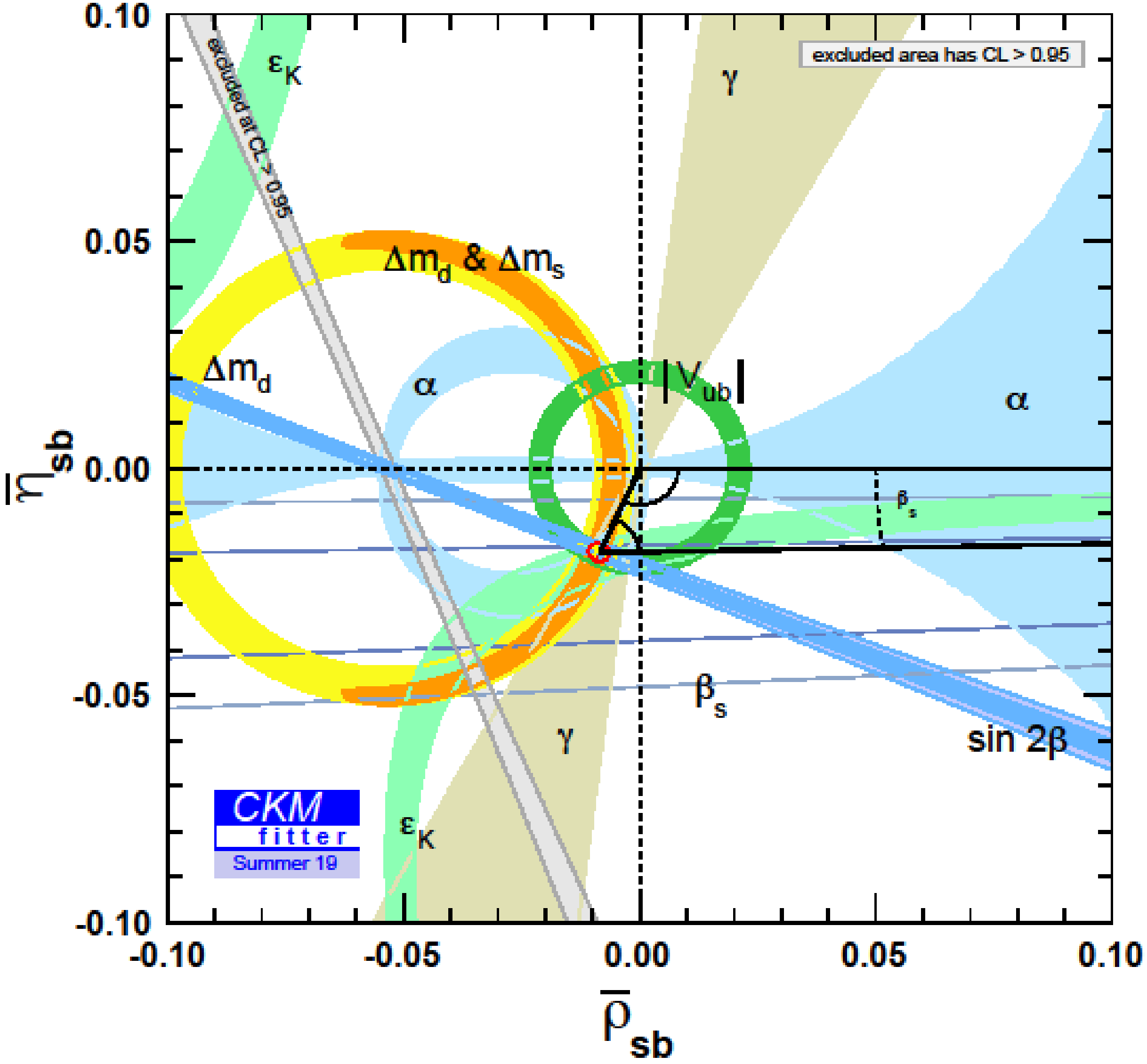
$> 3\ \sigma\ K/\pi$ separation up to 25 GeV (covers also K tagging), Ideally up to 35 GeV

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

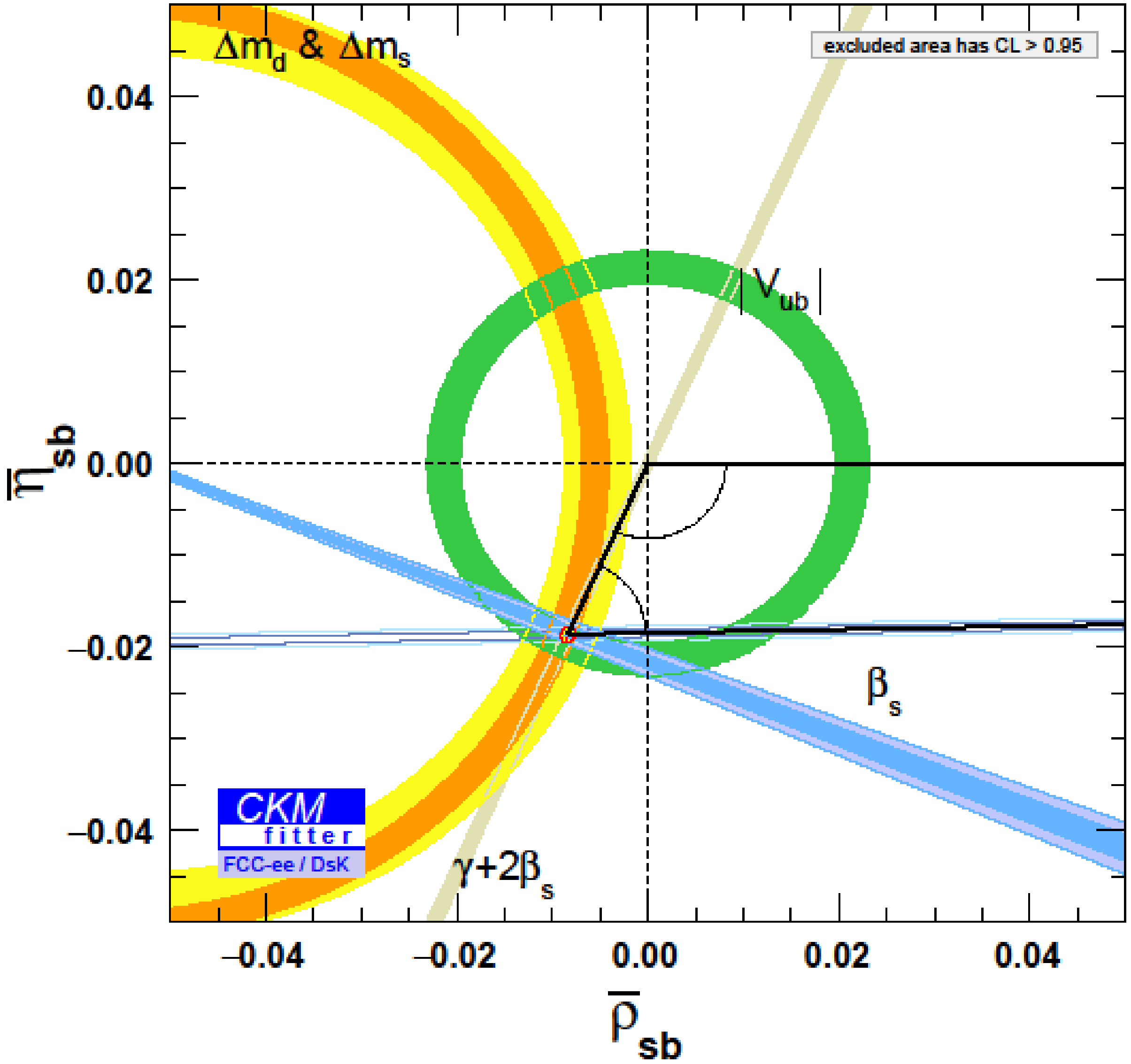
Impact on « flat » UT_{sb}

Courtesy S. Monteil

Present situation



Foreseen situation with FCCee
(Note the different scale)



Backup Slides

In SM , only few other possible diagrams with same CKM element as tree diagram

⇨ well defined CKM angle measured

⇨ no direct CP violation expected

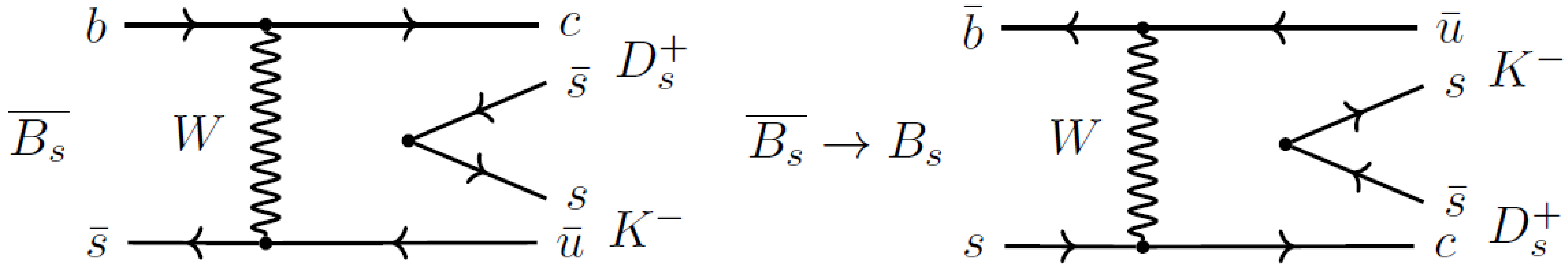


Figure 5: Exchange (sub-dominant) diagrams for $\bar{B}_s \to D_s^+ K^-$

Simulated detector configuration

B= 3.8T

Silicon vertex and tracking detector 2020-10-01 14:56

layer	r (cm)	δ (μm)	x0
1	1.60e+00	3.00e+00	1.50e-03
2	1.80e+00	6.00e+00	1.50e-03
3	3.70e+00	4.00e+00	1.50e-03
4	3.90e+00	4.00e+00	1.50e-03
5	5.80e+00	4.00e+00	1.50e-03
6	6.00e+00	4.00e+00	1.50e-03
7	1.53e+01	7.00e+00	6.50e-03
8	3.00e+01	7.00e+00	6.50e-03

Silicon outter detector

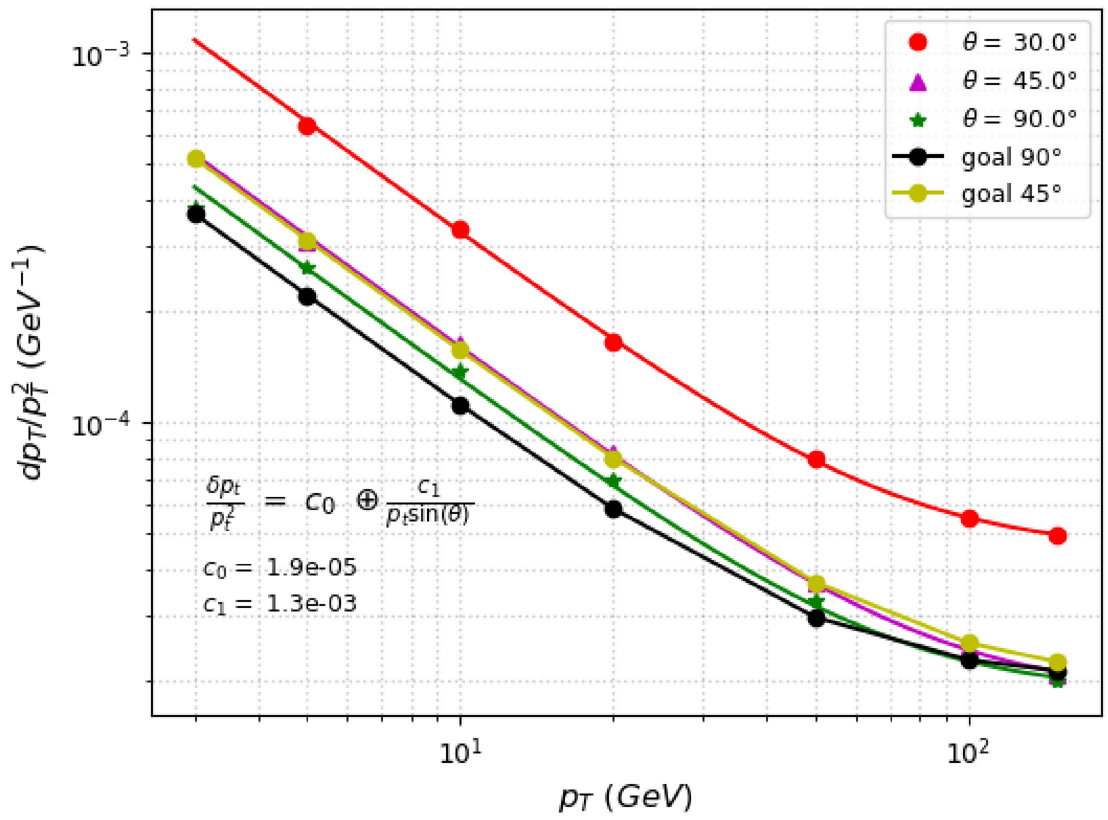
layer	r (cm)	δ (μm)	x0
1	1.81e+02	7.00e+00	1.00e-02

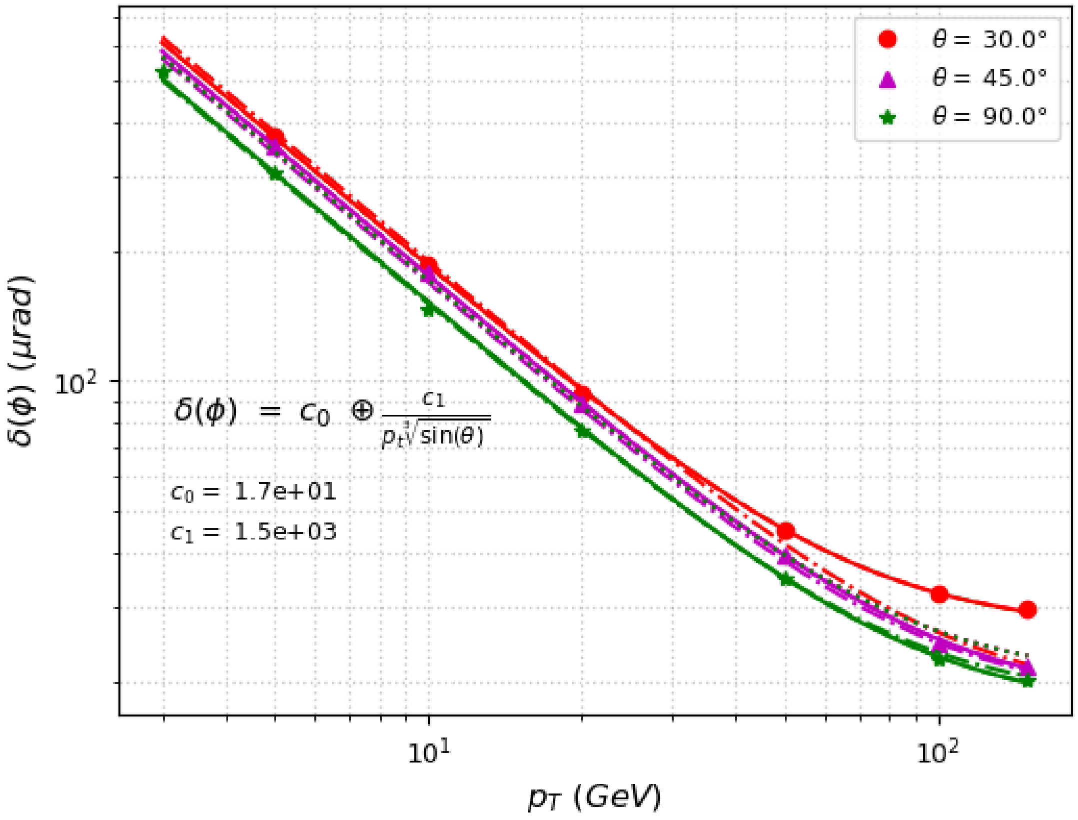
TPC detector

layer	r (cm)	δ (μm)	x0
1	4.00e+01	1.00e+02	5.95e-05
...	4.07e+01	1.00e+02	5.95e-05
200	1.80e+02	1.00e+02	5.95e-05

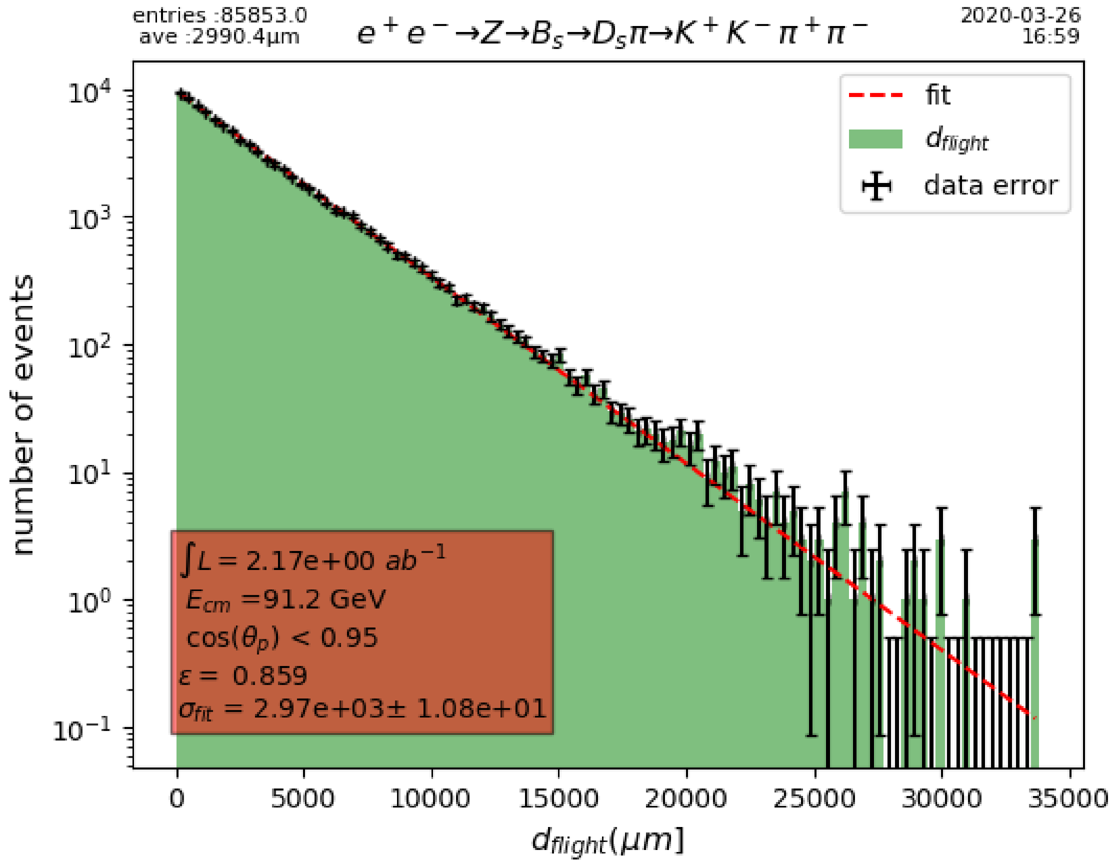
Detector resolutions

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

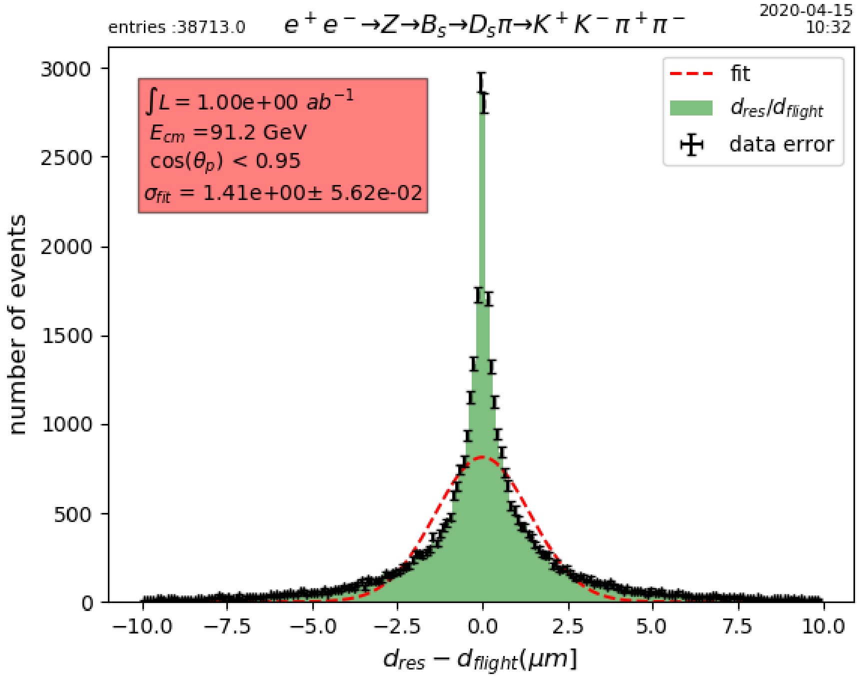




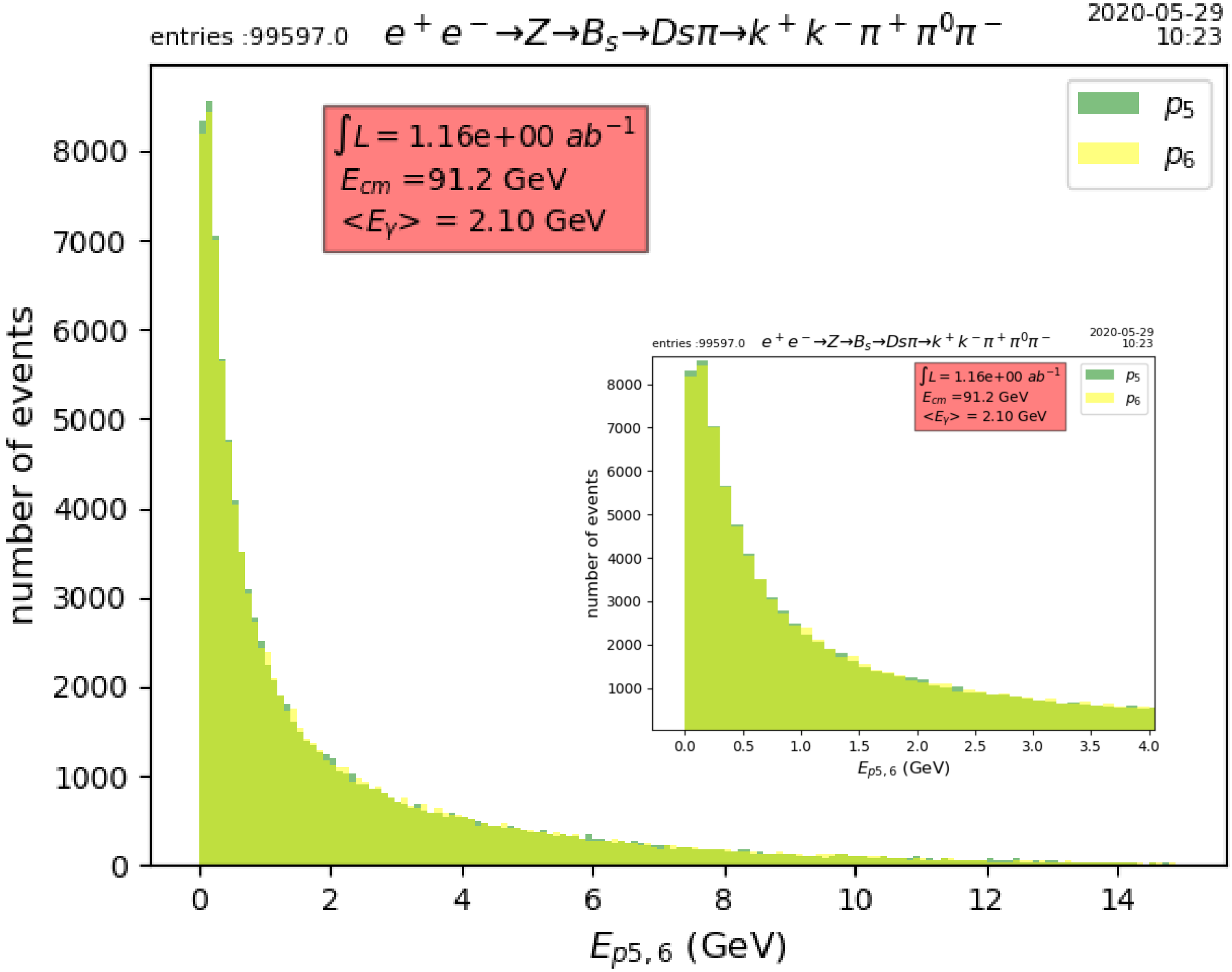
< B flight distance > ≈ 3000 μm

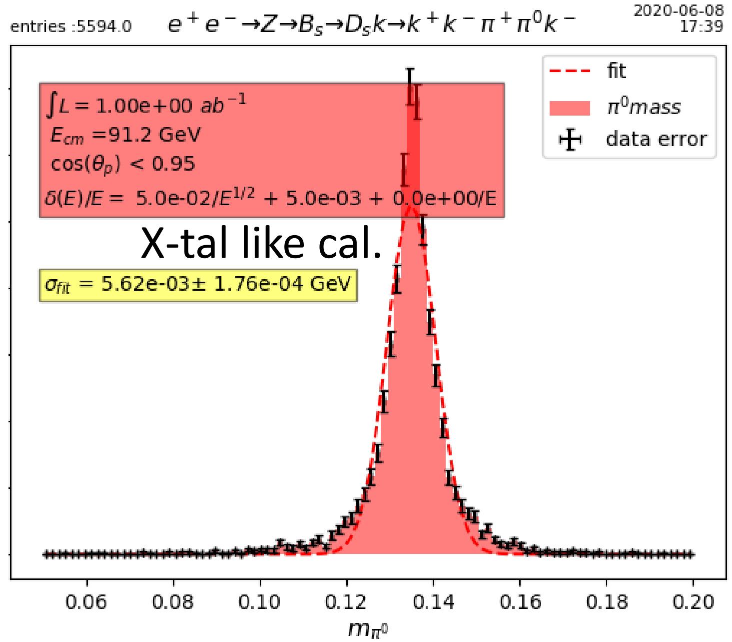


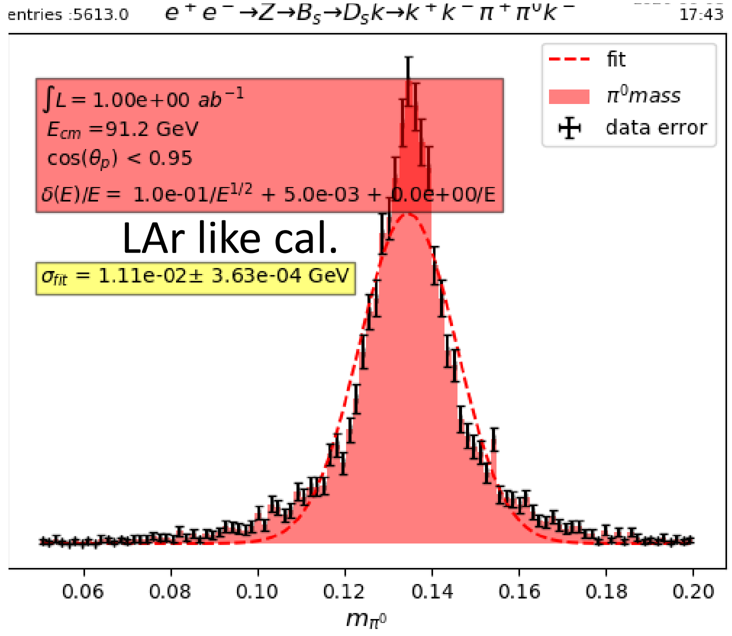
B Flight distance error due to error on B momentum measurement



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

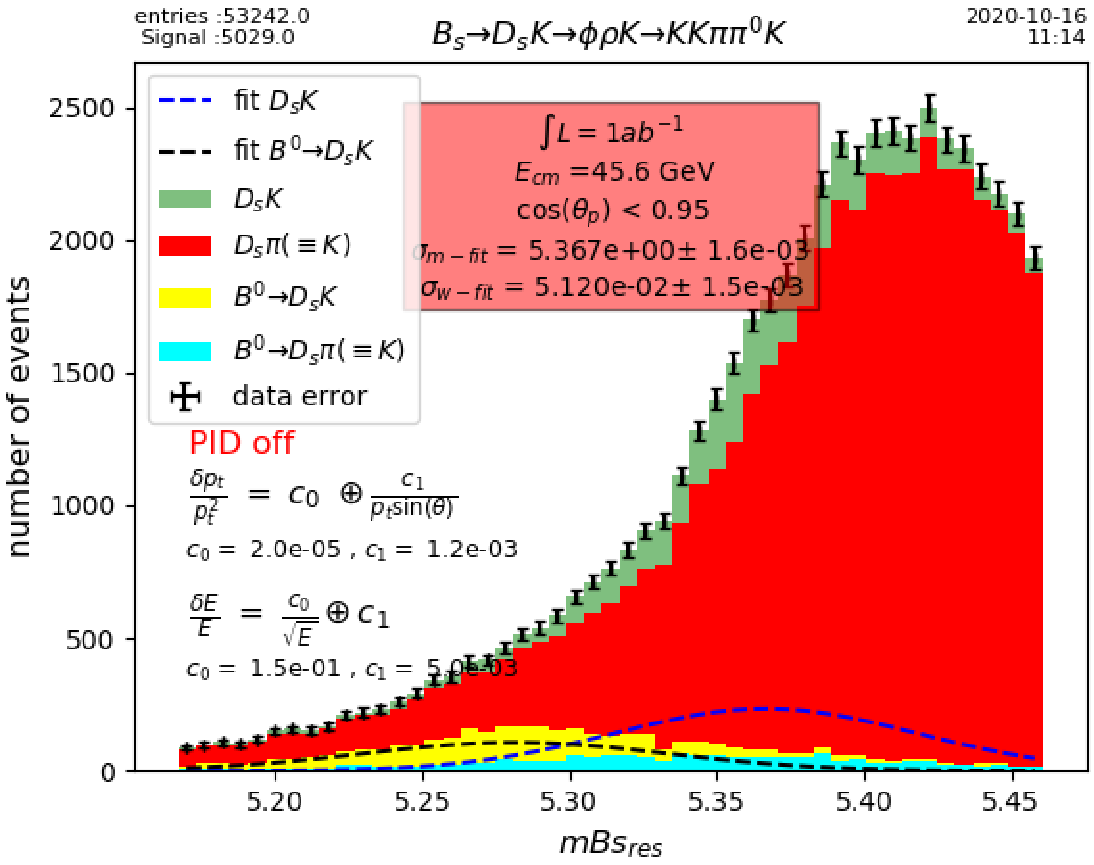


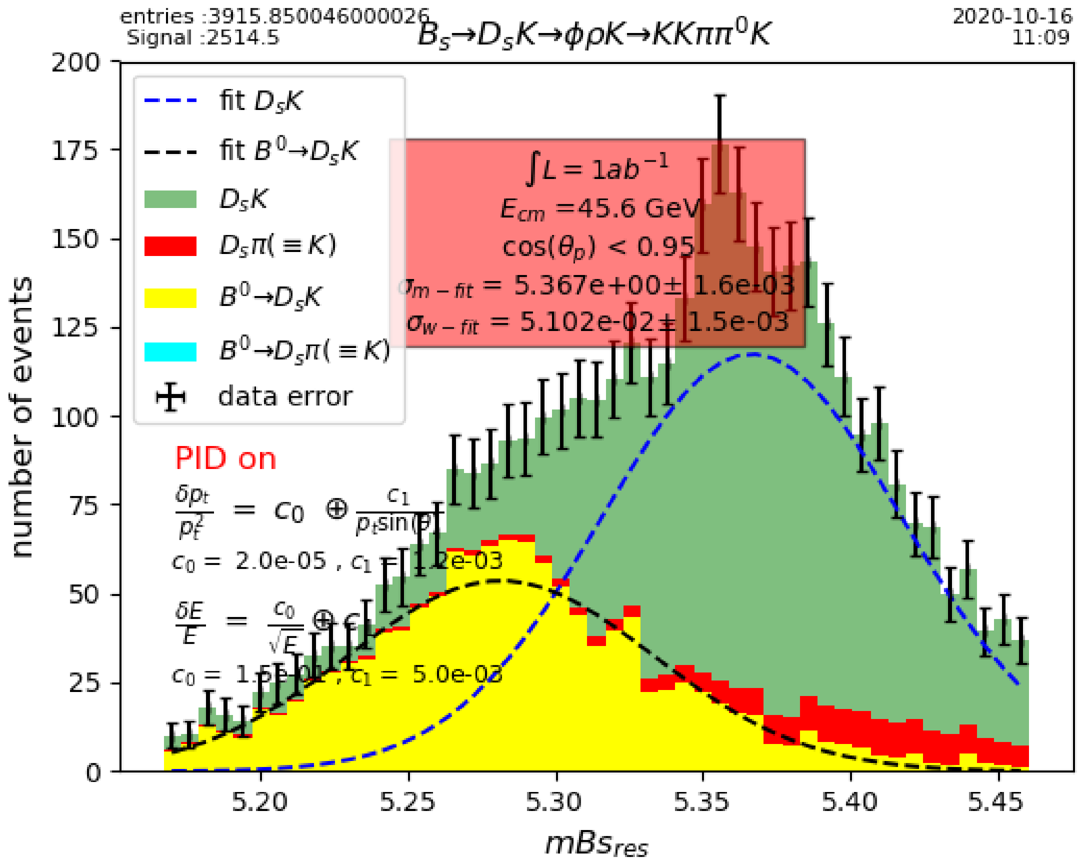




Inclusion of neutrals for $B_s \to D_s K$ reconstruction

Assuming HGCal like calorimeter with $\frac{\delta E}{E} = \frac{0.15}{\sqrt{E}} \oplus 0.005$





Xtal type to HGCal Type : $\sigma\left(D_s^{\pm}(\phi\rho^{\pm})K^{\mp}\right) \approx 20MeV \to 51MeV$

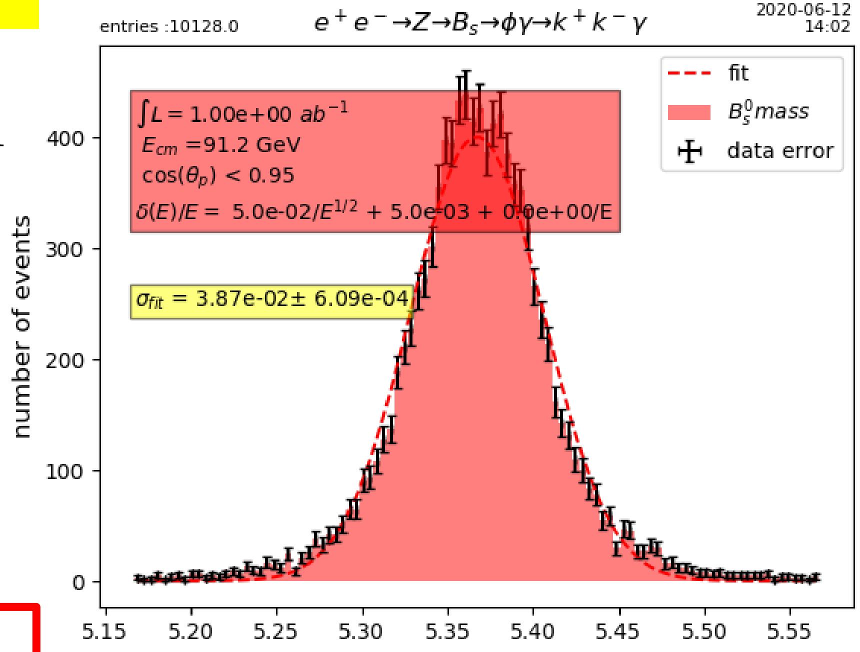
Study of CP violation with $B_s \to \phi\gamma$

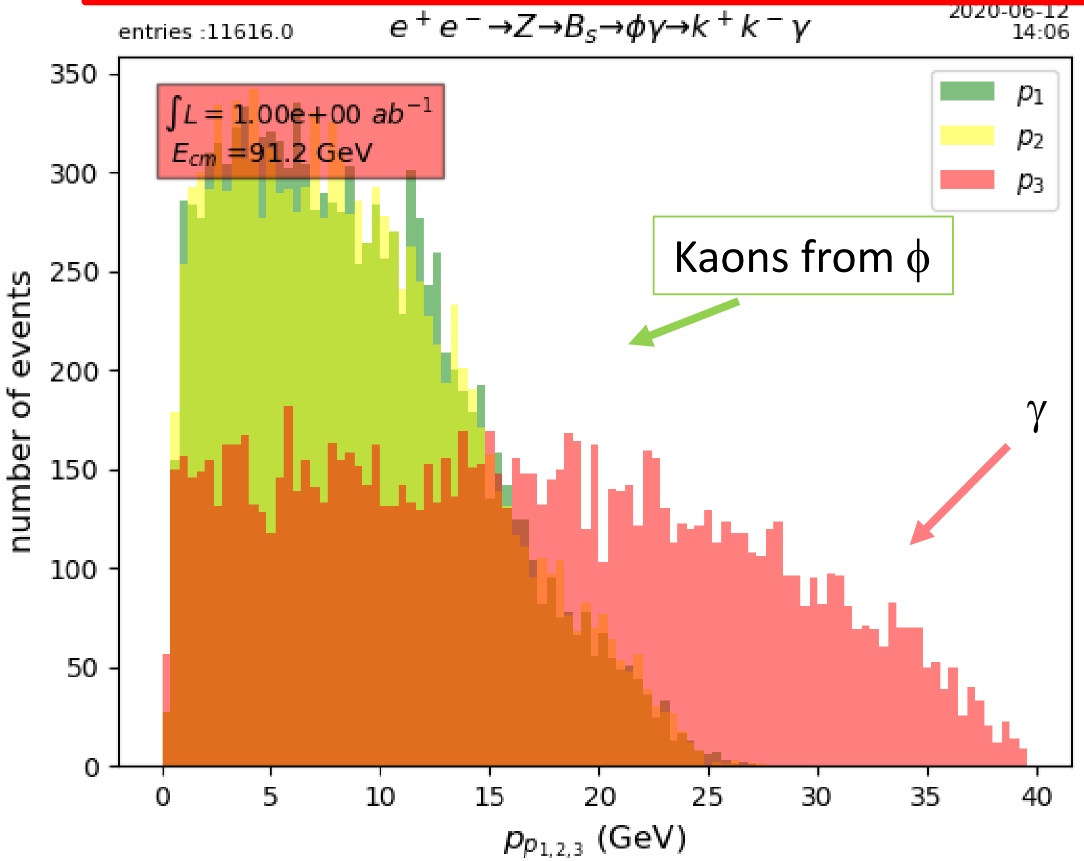
Same as $\boldsymbol{B_s \to \phi\phi}$ $\phi_{CKM} \approx 0°$ $Br(B_s \to \phi\gamma) = 3.4 \times 10^{-5}$

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

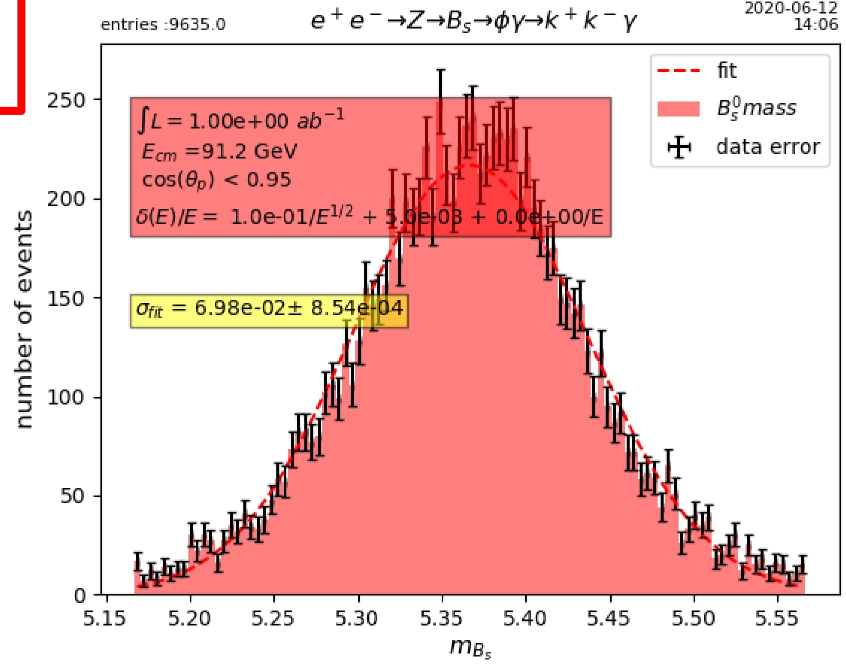
2 main issues requiring dedicated study

- 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 ($\sigma > 400\mu m$!)





PID needed to reject $\boldsymbol{B^0 \to K^{*0}\gamma}$ where π from $\boldsymbol{K^{*0}}$ is used as K

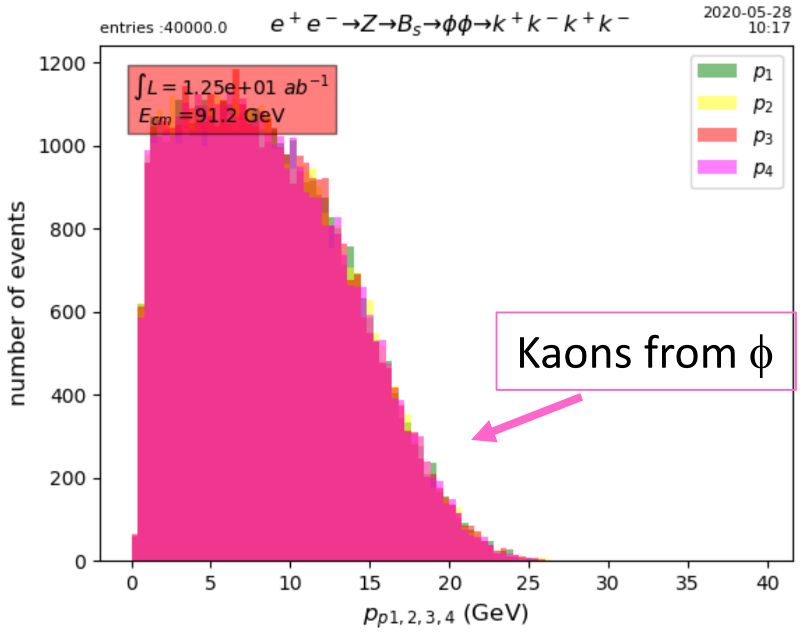


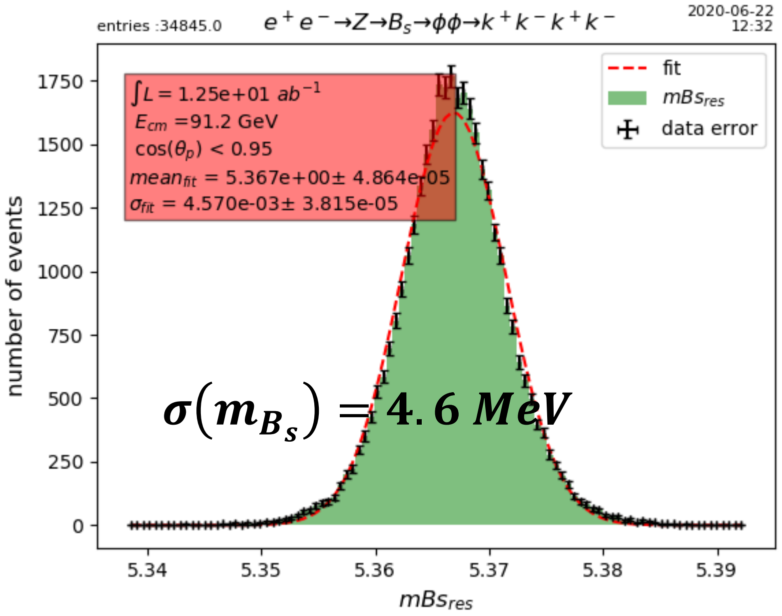
(Digression) Study of CP violation with $B_s \to \phi\phi \to K^+K^-K^+K^-$

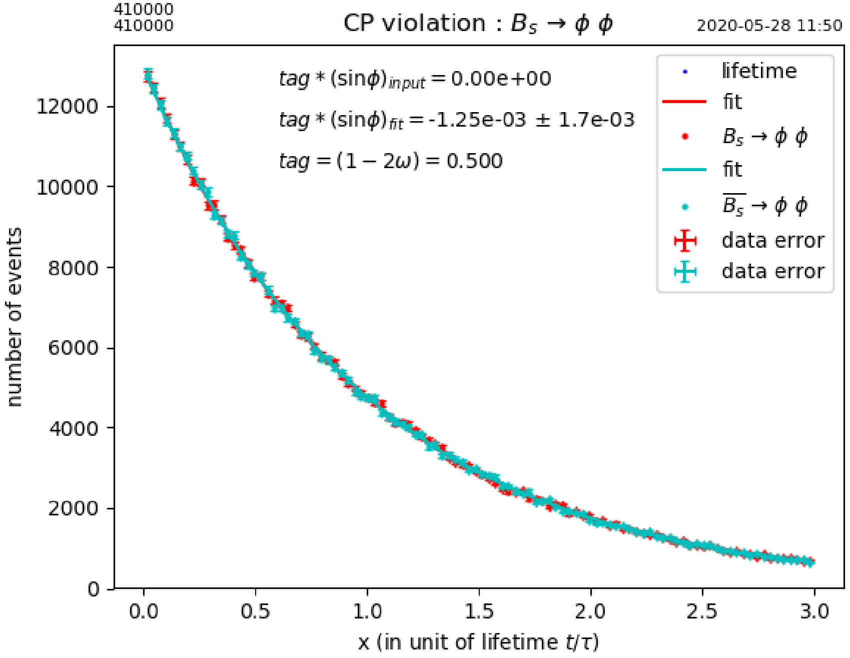
With $B_s \to \phi\phi$

$\phi_{CKM} \approx 0.5° \; (u, c, t \; quarks)$
$\phi_{CKM} = 0° \; (t \; quark \; only)$

⇨ Very good for probing BSM





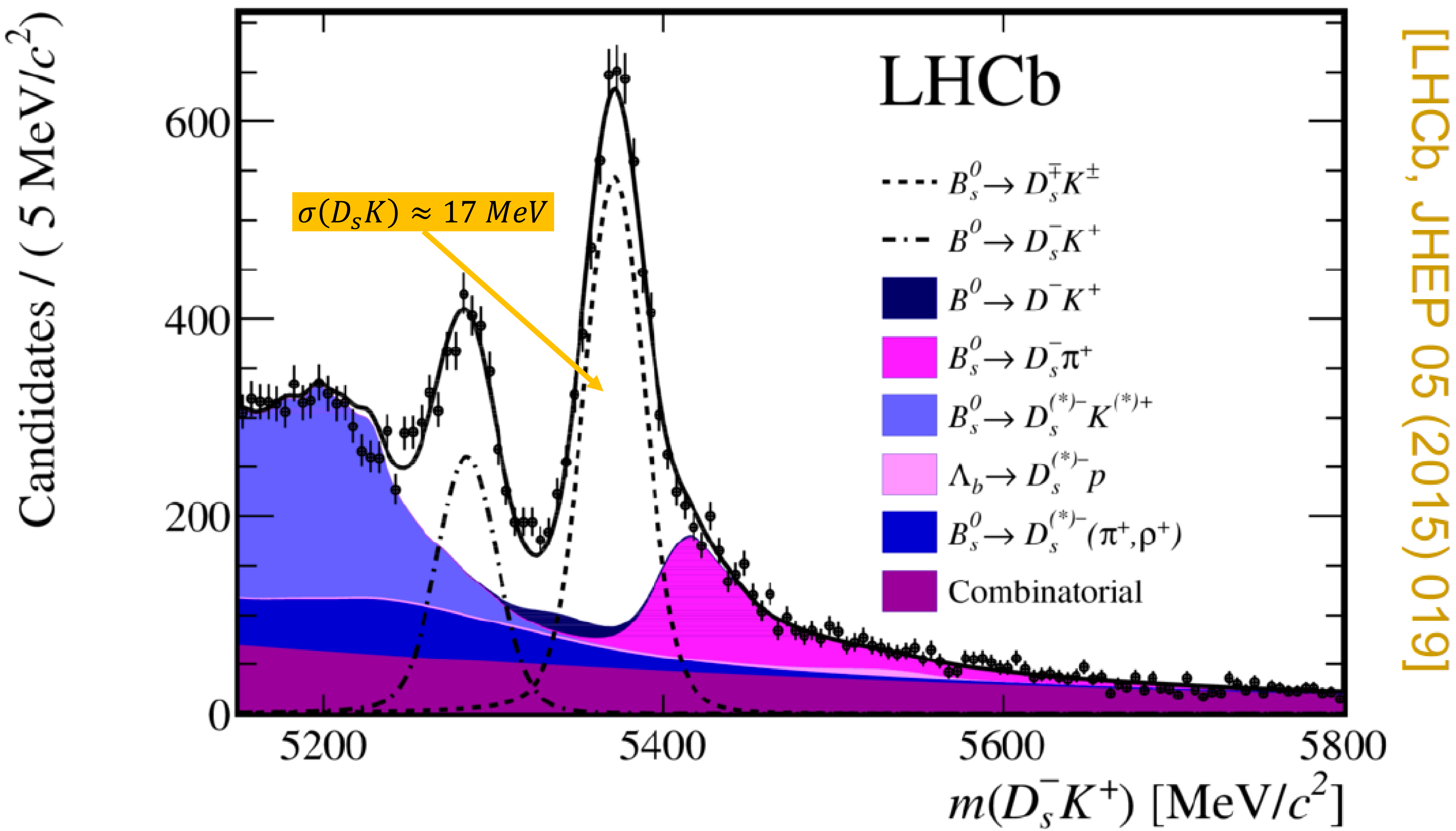


PDG		
$f_L = \Gamma_L/\Gamma$	$\mathbf{0.378 \pm 0.013}$	CP=+
$f_\parallel = \Gamma_\parallel/\Gamma$	0.330 ± 0.016	CP=+
$f_\perp = \Gamma_\perp/\Gamma$	0.292 ± 0.009	CP=-

Angular analysis required (tbd)

Otherwise reduced sensitivity by factor $\frac{1}{1-2f_\perp} \approx 2.4$

Result 5 : $\delta(\sin\phi_{CKM}) \approx 3.4 \times 10^{-3} \cong \delta(\phi_{CKM}) \approx 0.2° \; (stat.)$


LHCb
σ(D_s K) ≈ 17 MeV
B_s^0 → D_s^∓ K^±
B^0 → D_s^- K^+
B^0 → D^- K^+
B_s^0 → D_s^- π^+
B_s^0 → D_s^(*)- K^(*)+
Λ_b → D_s^(*)- p
B_s^0 → D_s^(*)- (π^+, ρ^+)
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]