$B_s^0 \to D_s K$ benchmark with IDEA

Tools and first results

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Italy-France FCC workshop - 22/11/2022 - Lyon

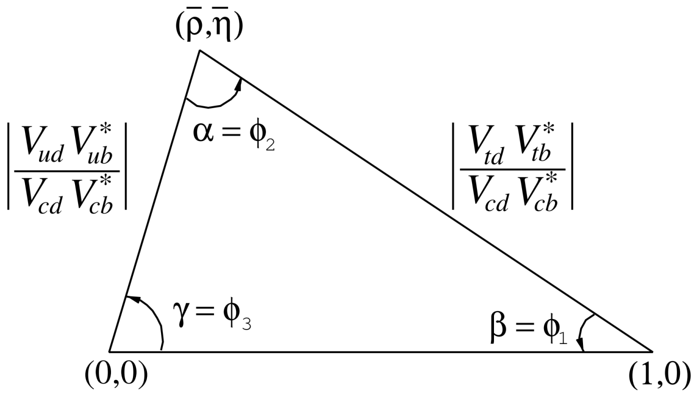
Flavor Physics at FCC-ee

CKM unitarity triangle is a stepping stone for flavor physics

- Any deviation from unitarity would lead to physics beyond standard model
- At the end of HL-LHC and Belle2 programs, γ angle will be known with ~1° error

FCC-ee will be a **Tera-Z factory**

- CKM analyses can be performed by studying $\mathbf{Z \rightarrow b\bar{b}}$
- This will result in:
  - 75 Billions B_s^0,
  - 310 Billions B^0



This work aims to understand the feasibilty of

1. $\mathbf{B_s^0 \rightarrow D_s K}$
2. $B_s^0 \rightarrow J/\psi\Phi$ (*later*)

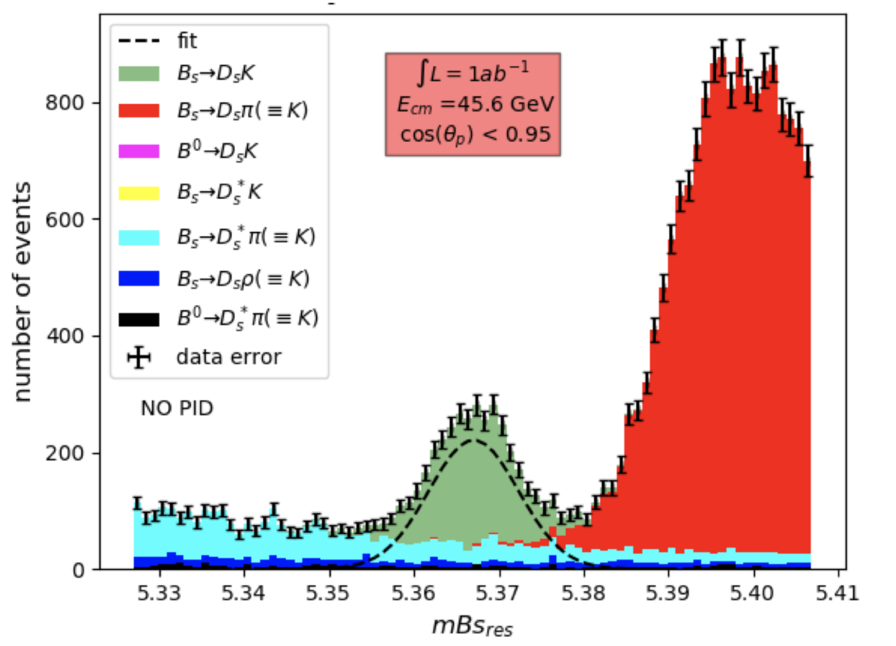
With the B_s^0 sample, **FCC can measure:**

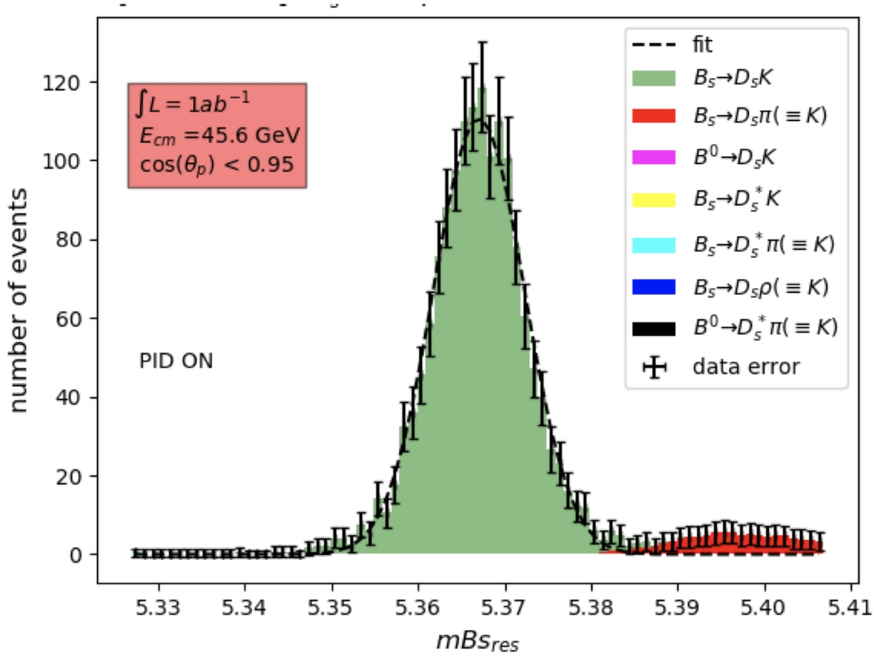
- **γ with a precision of 0.4°**
- β_s with a precision of $(3.4\text{x}10^{-2})°$

Our guiding light

arXiv: 2107.02002

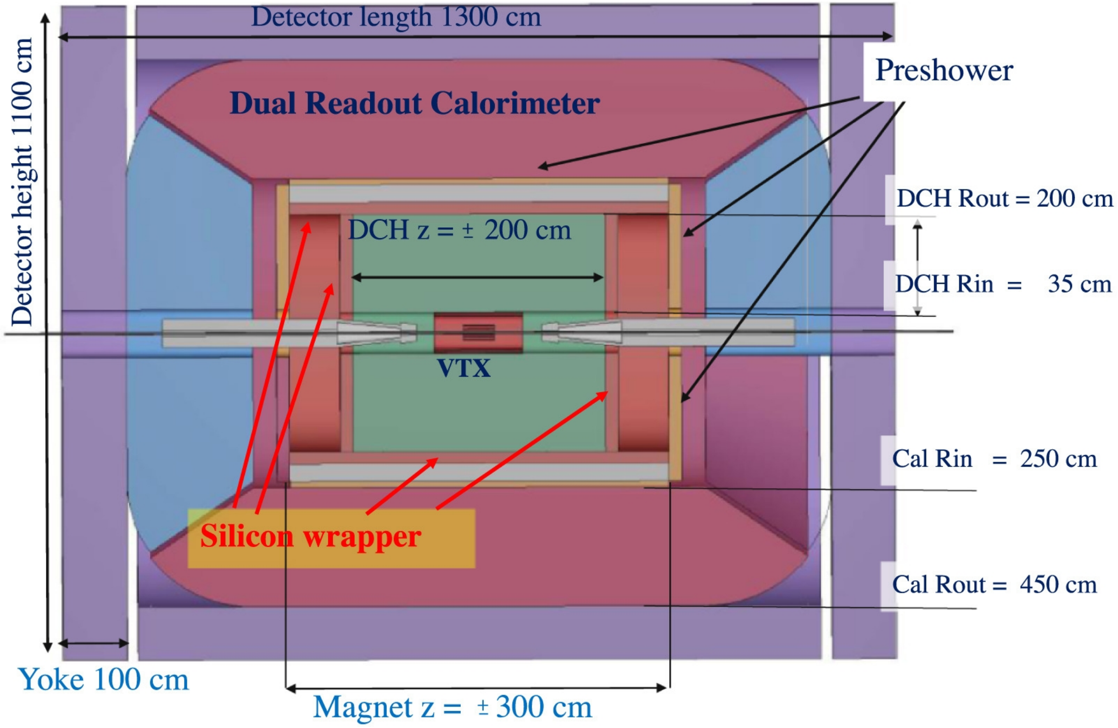
There is a study by R. Aleksan, L. Oliver, and E. Perez showing the possibility of doing B_s physics and measure unitary triangles at FCC-ee





In the paper, they implement a generic FCC-ee detector (see backup).

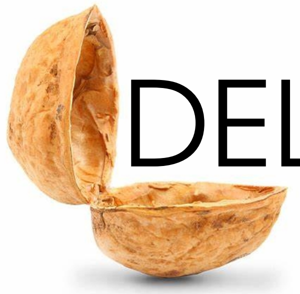
Flavor Physics with IDEA



This work makes use of fast and full simulations of **IDEA detector**:

- to establish impact of **tracking** and **PID** and guide further development
- To **test** the **tools** for doing physics analyses
- to estimate the **sensitivity** of
  - $\boldsymbol{\varphi = \gamma_{CKM} + \gamma_{ds} - 2\beta_s}$ **with** $\boldsymbol{B_s \to DK}$
  - $2\beta_s$ *with* $B_s \to J/\psi\, \Phi$

The work is performed in FCC analyses framework: **key4HEP/EDM4HEP**



DELPHES

Delphes is a **modular framework** that simulates the **response** of a multipurpose **detector** in parametrized fashion

It includes main feaures:
- Charged particles propagation
- EM/Had calorimeters
- Particle flow

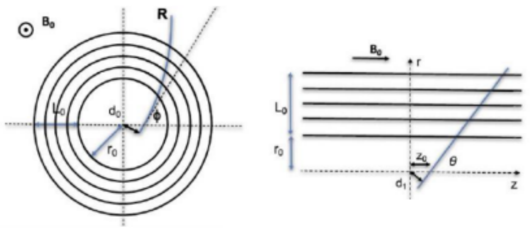
→

It provides:
- Lepton, photons, neutral hadrons
- Jets missing energy

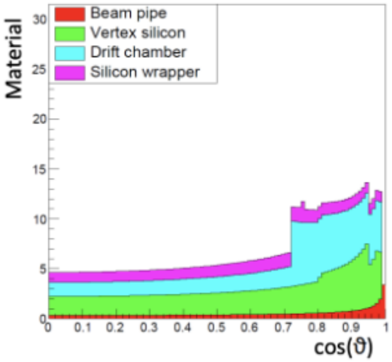
It has been originally designed for hadronic environment but it is well suited also for e^+e^- studies, including **IDEA detector cards**

Fast Tracking

From M. Selvaggi: https://indico.desy.de/event/33640/contributions/128007/attachments/77587/100359/delphes_ecfa2022.pdf

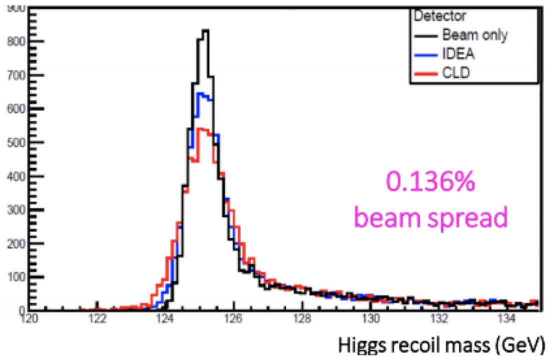


$$\vec{\alpha} = (D,\ \varphi_0,\ C,\ z_0,\ \lambda)$$



Track Smearing

- Simple tracker geometry implementation, **including material**
- Computes **full covariance matrix** (in present Delphes we have "diagonal" smearing in the 5 tracking parameters)
- Can be used for studying impact of material and realistic **HF tagging** simulation

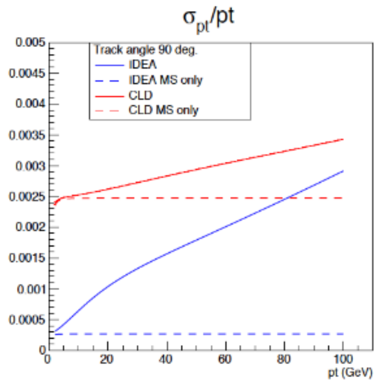


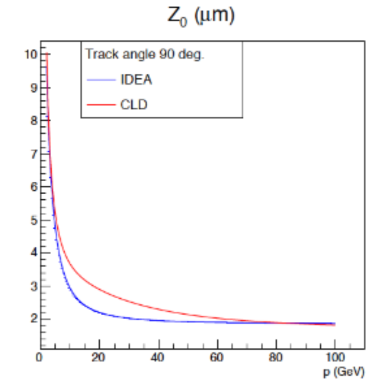
Bedeschi, Gouskos, MS, [2202.03285]

FCCee TrackCovariance

```
########################################
# Smearing for charged tracks
########################################

module TrackCovariance TrackSmearing {

    set InputArray TrackMergerPre/tracks
    set OutputArray tracks

    ## minimum number of hits to accept a track
    set NMinHits 6

    ## magnetic field
    set Bz $B

    ## uses https://raw.githubusercontent.com/selvaggi/FastTrackCovariance/master/GeoIDEA_BASE.txt
    set DetectorGeometry {
```

```
# barrel  name      zmin   zmax   r       w (m)     X0      n_meas  th_up (rad) th_down (rad)  reso_up (m)  reso_down (m)  flag

1         PIPE      -100   100    0.015   0.001655  0.2805  0       0           0              0            0              0
1         VTXLOW    -0.12  0.12   0.017   0.00028   0.0937  2       0           1.5708         3e-006       3e-006         1
1         VTXLOW    -0.16  0.16   0.023   0.00028   0.0937  2       0           1.5708         3e-006       3e-006         1
1         VTXLOW    -0.16  0.16   0.031   0.00028   0.0937  2       0           1.5708         3e-006       3e-006         1
1         VTXHIGH   -1     1      0.32    0.00047   0.0937  2       0           1.5708         7e-006       7e-006         1
1         VTXHIGH   -1.05  1.05   0.34    0.00047   0.0937  2       0           1.5708         7e-006       7e-006         1
```





TrackCovariance module

- **Requires:**
  - Geometry input
    - cylinder coaxial
    - planar disks
  - Magnetic field

From M. Selvaggi: https://indico.desy.de/event/33640/contributions/128007/attachments/77587/100359/delphes_ecfa2022.pdf

$B_s \to D_s K$

- **Final state of interest is $D_s \to \Phi\pi$ + bachelor K, with $\Phi \to KK$.**

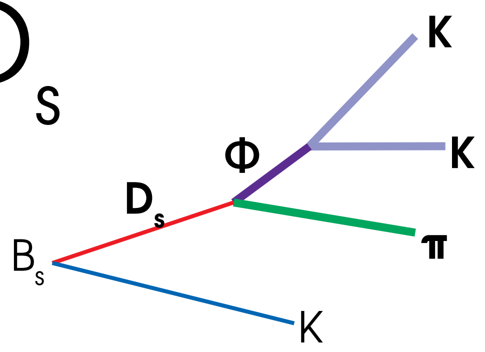
- Generated 10k events at Z peak, exclusive $Z \to b\bar{b}$.
  - One b hadronizes in B_s, the other goes inclusively
  - Winter `21 DELPHES simulation.

- In order to study the impact, two approaches:
  1) Truth-matching (TM)
  2) Reconstruction

- Generated also main backgrounds and tested with the reconstruction routines

```
#
Decay B_s0
  1.000 MyD_s- K+ PHSP;
Enddecay
CDecay anti-B_s0
#
Decay MyD_s-
  1.000 Myphi pi- PHSP;
Enddecay
CDecay MyD_s+
#
Decay Myphi
      1.000  K+ K-  VSS;
Enddecay
#
End
```

Results with TM - D_s



Apply few general selections

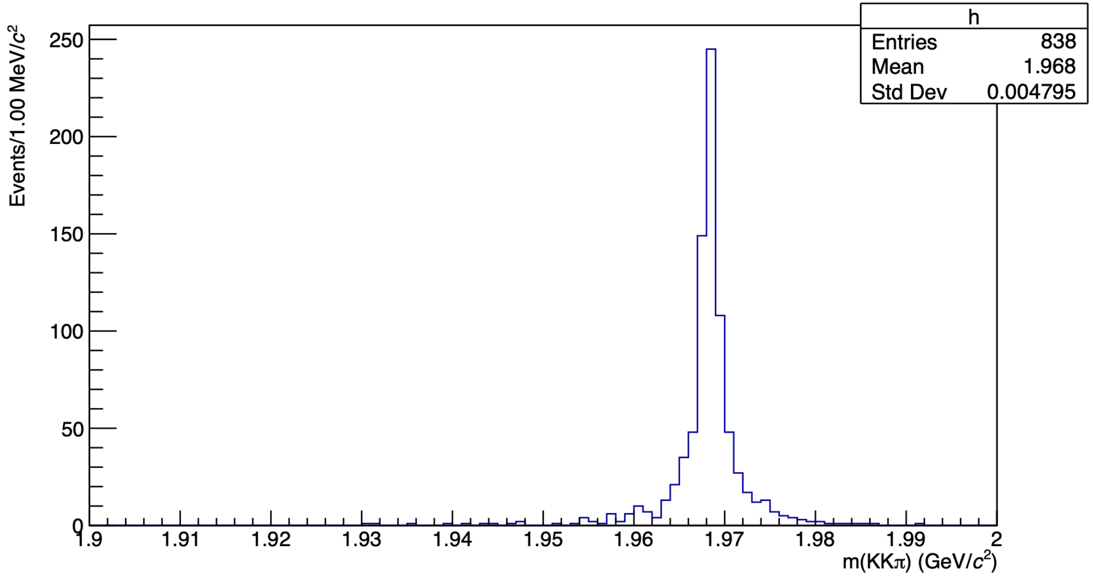
- $Q_{tot} = 0$
- $N_K \geqslant 3$
- $N_\pi \geqslant 1$
- $Q_{KK} = 0$

Φ and **prompt Kaons** are already **separated**

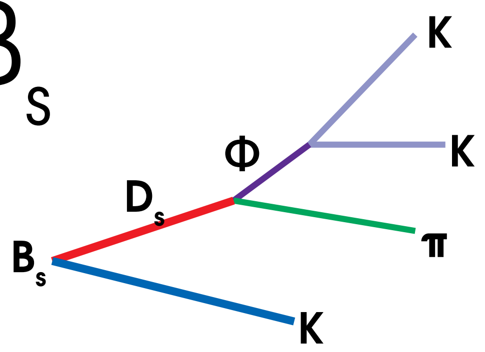
To reconstruct D_s, apply **vertex fit** to **KKπ** tracks

PID is 100% via PDG-ID

Reconstructed $D^{\pm}_s$ mass



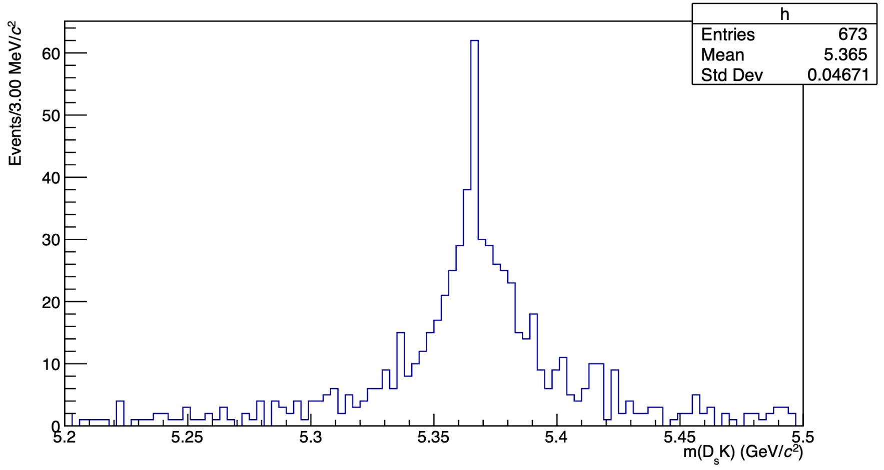
Results with TM - B_s



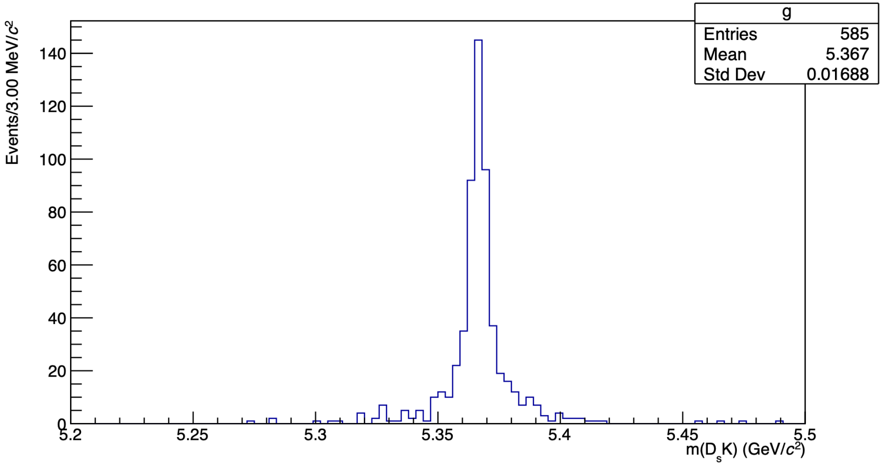
To reconstruct B_s, **vertex fit** of D_s and bachelor K

- will study the B_s impact parameter with covariance matrix already in DELPHES

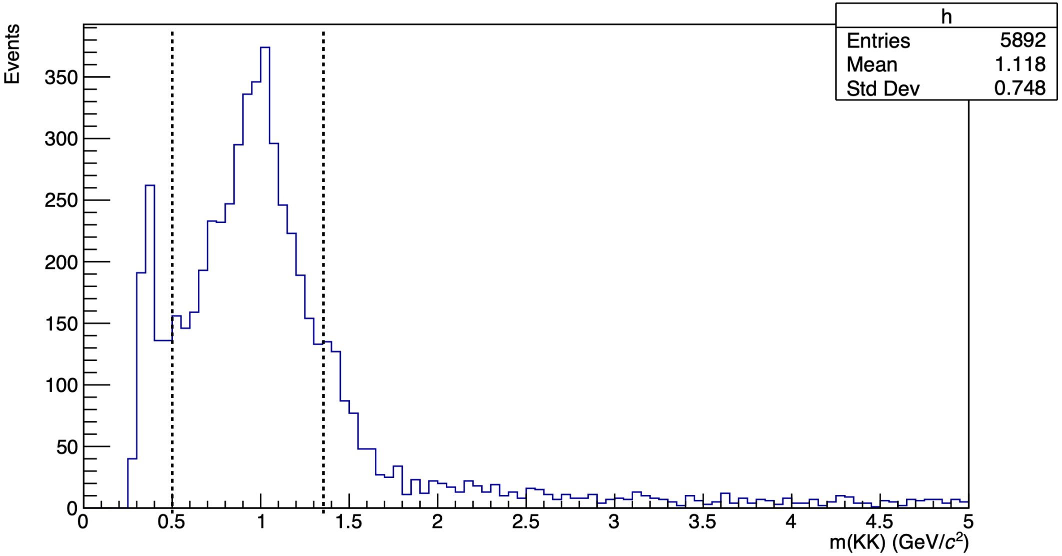
B_s^0 mass without vertexing



B_s^0 mass with vertexing



Result with Reconstruction



Apply few general selections

- $Q_{tot} = 0$
- $N_K \geqslant 3$
- $N_\pi \geqslant 1$
- $Q_{KK} = 0$

Vertexing allows to separate Φ and prompt kaons

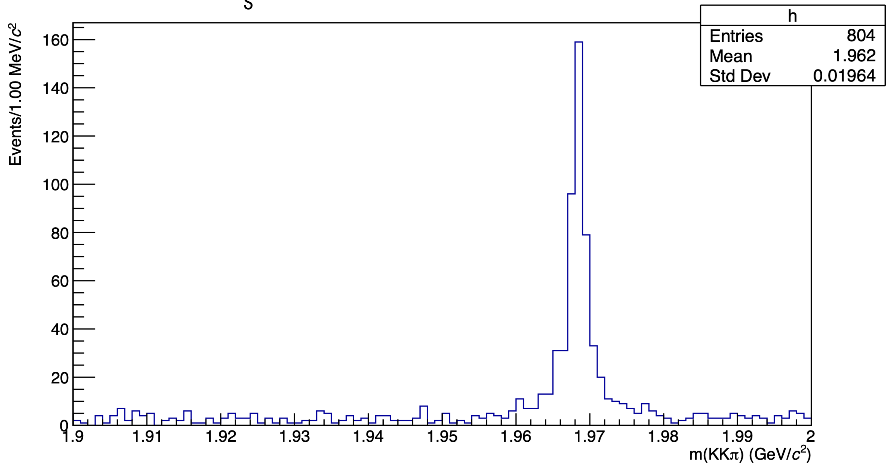
PID is 100% via PDG-ID

Result with Reconstruction – D_s and B_s

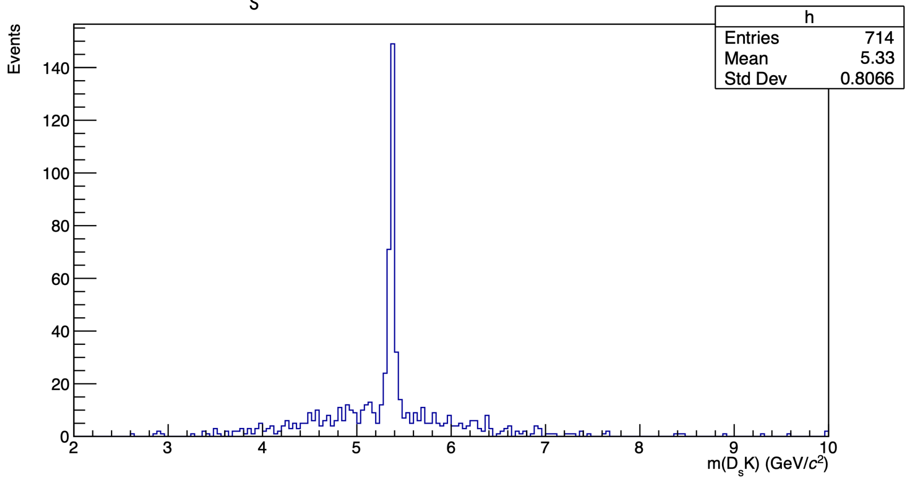
By applying a similar procedure as in the TM case, we identify **D_s** and **B_s candidates**.

We add a loose selection on **D_s candidates** mass **$1.9\ GeV/c^2 < mass(\Phi\pi) < 2\ GeV/c^2$**

D_s mass reconstruction

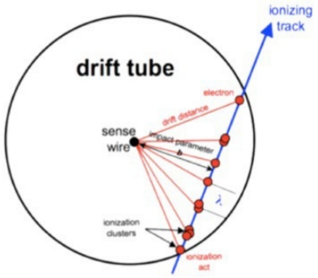


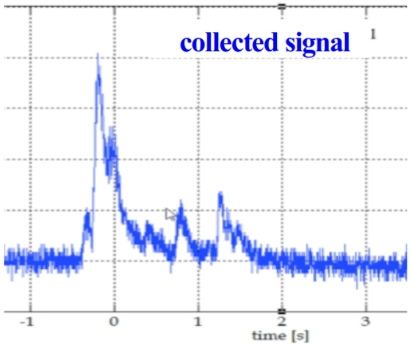
B_s mass reconstruction

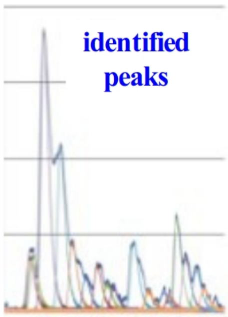


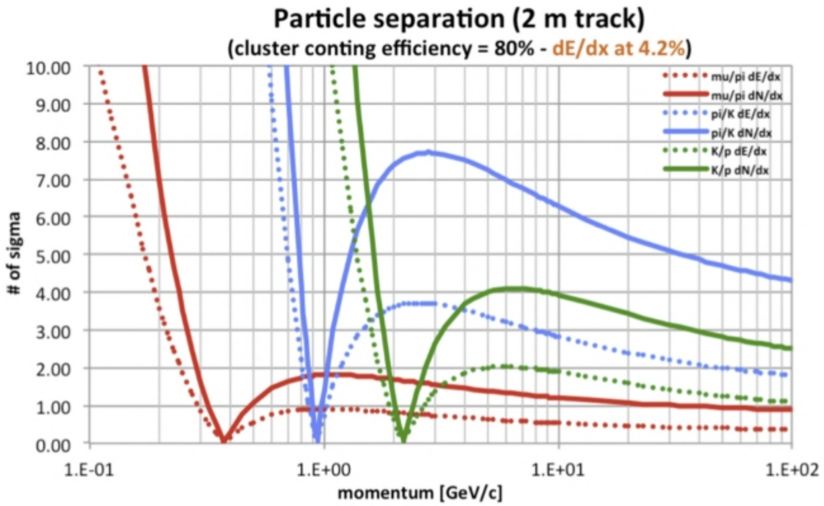
About PID

IDEA will use innovative dN/dx cluster counting technique for PID in the Drift chamber









This grants an improved PID with respect to conventional dE/dx

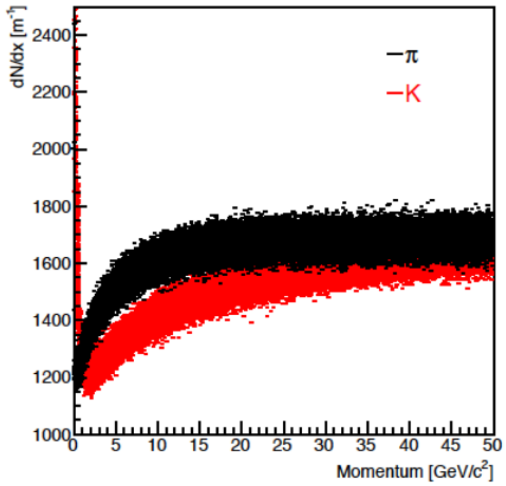
Possibility to add timing layer to improve in (0.85, 1.05) GeV/c region

More details in https://indico.desy.de/event/33640/contributions/128012/attachments/77613/100467/DeFilippis_IDEA_PID_DCH.pdf

Implementation in simulation

```
###################
# Cluster Counting
###################

module ClusterCounting ClusterCounting {

  add InputArray TrackSmearing/tracks
  set OutputArray tracks

  set Bz $B

  ## check that these are consistent with DCHCANI/DCHNANO parameters in TrackCovariance module
  set Rmin $DCHRMIN
  set Rmax $DCHRMAX
  set Zmin $DCHZMIN
  set Zmax $DCHZMAX

  # gas mix option:
  # 0:  Helium 90% - Isobutane 10%
  # 1:  Helium 100%
  # 2:  Argon 50% - Ethane 50%
  # 3:  Argon 100%

  set GasOption 0

}
```

Cluster counting is implemeted in DELPHES with GARFIELD parametrization for βγ dependence



To be tested in the future on this benchmark

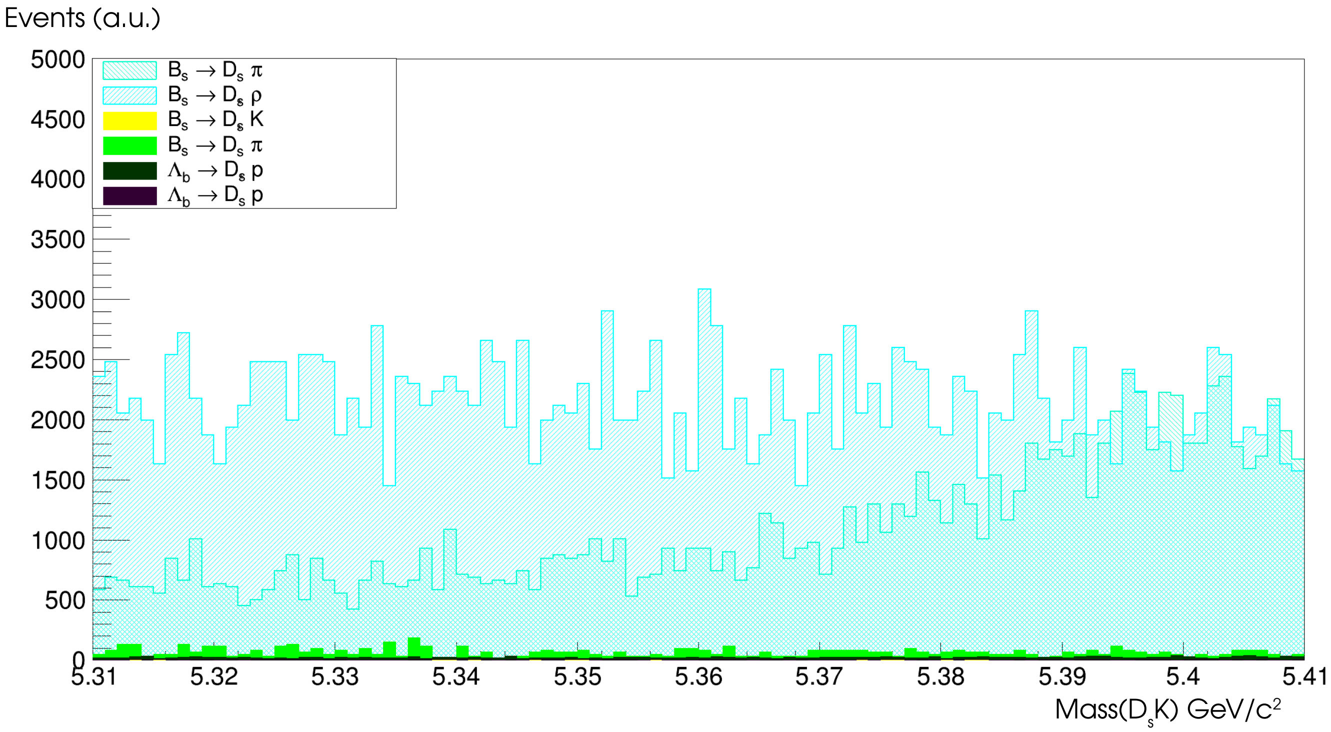
Main backgrounds

500k events generated and analysed with the same routines

Main mode	Decay chain	Background mode	Decay chain
$\boldsymbol{B_s \to D_s^{\pm} K^{\mp}}$	$D_s^{\pm} \to \phi\pi^{\pm}, \phi \to K^+K^-$	$\boldsymbol{B_s \to D_s^{*\pm} K^{\mp}}$	$D_s^{*\pm} \to \gamma\phi\pi^{\pm}, \phi \to K^+K^-$
"	$D_s^{\pm} \to \phi\rho^{\pm}, \phi \to K^+K^-$	"	$D_s^{*\pm} \to \gamma\phi\rho^{\pm}, \phi \to K^+K^-, \rho^{\pm} \to \pi^{\pm}\pi^0$
		$\boldsymbol{B_s \to D_s^{\pm} K^{*\mp}}$	$D_s^{\pm} \to \phi\pi^{\pm}, \phi \to K^+K^-, K^{*\mp} \to K^{\mp}\pi^0$
		"	$D_s^{\pm} \to \phi\rho^{\pm}, \phi \to K^+K^-, \rho^{\pm} \to \pi^{\pm}\pi^0, K^{*\mp} \to K^{\mp}\pi^0$
		$\boldsymbol{B_s \to D_s^{\pm} \pi^{\mp}}$	$D_s^{\pm} \to \phi\pi^{\pm}, \phi \to K^+K^-$
		"	$D_s^{\pm} \to \phi\rho^{\pm}, \phi \to K^+K^-, \rho^{\pm} \to \pi^{\pm}\pi^0$
		$\boldsymbol{B_s \to D_s^{\pm} \rho^{\mp}}$	$D_s^{\pm} \to \phi\pi^{\pm}, \phi \to K^+K^-, \rho^{\mp} \to \pi^{\mp}\pi^0$
		$\boldsymbol{B^0 \to D_s^{\pm} K^{\mp}}$	$D_s^{\pm} \to \phi\pi^{\pm}, \phi \to K^+K^-$
		"	$D_s^{\pm} \to \phi\rho^{\pm}, \phi \to K^+K^-, \rho^{\pm} \to \pi^{\pm}\pi^0$
		$\boldsymbol{\Lambda_b^0 \to D_s^{-} p^{+}}$	$D_s^{\pm} \to \phi\pi^{\pm}, \phi \to K^+K^-$
		"	$D_s^{\pm} \to \phi\rho^{\pm}, \phi \to K^+K^-, \rho^{\pm} \to \pi^{\pm}\pi^0$
		$\boldsymbol{\Lambda_b^0 \to D_s^{*-} p^{+}}$	$D_s^{\pm} \to \gamma\phi\pi^{\pm}, \phi \to K^+K^-$
		"	$D_s^{\pm} \to \gamma\phi\rho^{\pm}, \phi \to K^+K^-, \rho^{\pm} \to \pi^{\pm}\pi^0$

Delphes FCCee Physic events dev production (IDEA with Track Covariance full matrix lower triangle)
http://fcc-physics-events.web.cern.ch/fcc-physics-events/Delphesevents_dev_IDEA.php

Background results



Largest contribution from:

- $B_s \to D_s\pi$
- $B_s \to D_s\rho$

Mainly from **combinatorial**

Negligible for other cases

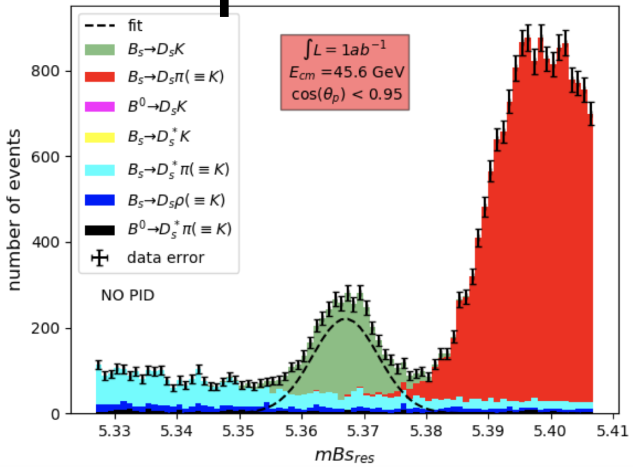
Summary and next steps - I

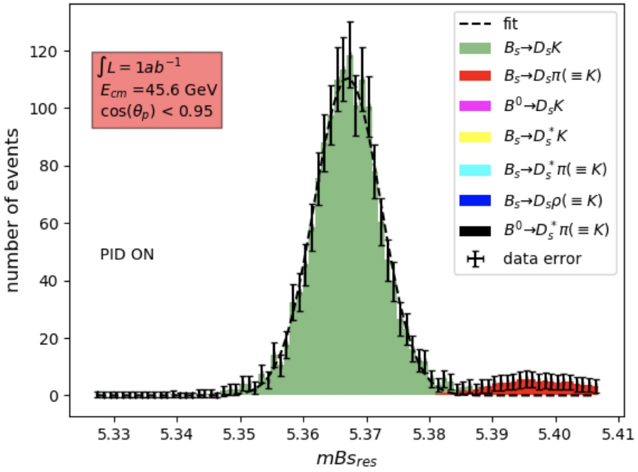
- First fast simulation of $B_s \rightarrow D_s$ K benchmark for flavor physics prepared
  - Tools tested and ready for more complex analyses
  - A new version of vertexing is now available to ease the analysis job

- With a preliminary analysis on $B_s \rightarrow D_s$ K:
  - Good reconstruction of B_s candidate mass with vertexing with covariance matrix
  - Combinatorial background from 2 B_s decays with larger branching ratio
    - Further development are undergoing to further suppress those contributions (hemisphere selection, impact parameters)

Summary and next steps - II

- Add a more realistic PID
  - Cluster counting implemented in DELPHES
- Reproduce results of arXiv: 2107.02002 with EDM4HEP
  - First with DELPHES, later with full simulation, thanks to EDM4HEP
  - Study also final states with neutrals → impact of calorimeters (see backup)



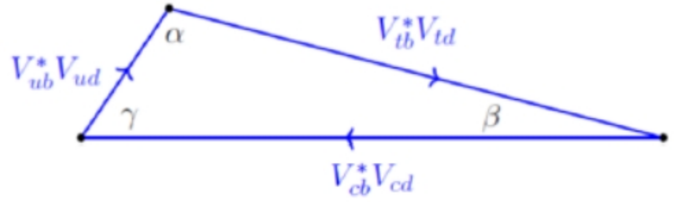


THANKS

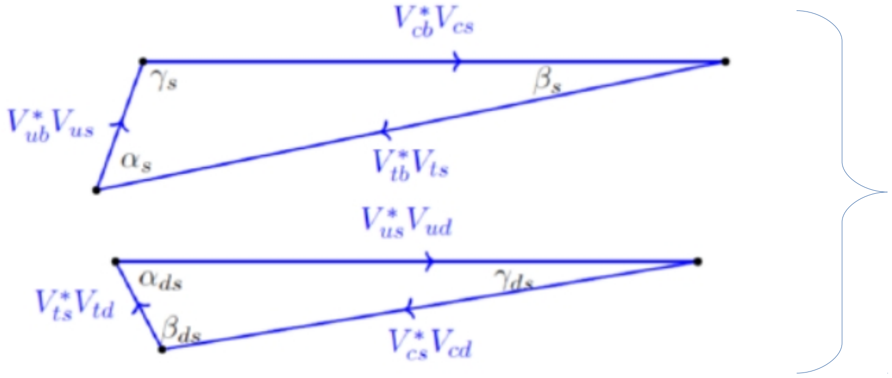
ADDITIONAL MATERIAL

Unitary triangles

$$
\begin{aligned}
UT_{db} &\equiv V_{ub}^*V_{ud} + V_{cb}^*V_{cd} + V_{tb}^*V_{td} &= 0 \\
UT_{sb} &\equiv V_{ub}^*V_{us} + V_{cb}^*V_{cs} + V_{tb}^*V_{ts} &= 0 \\
UT_{ds} &\equiv V_{us}^*V_{ud} + V_{cs}^*V_{cd} + V_{ts}^*V_{td} &= 0
\end{aligned}
$$



"Conventional" Unitarity triangle



"Flat" Unitarity triangles

Generic Detector

From arXiv: 2107.02002

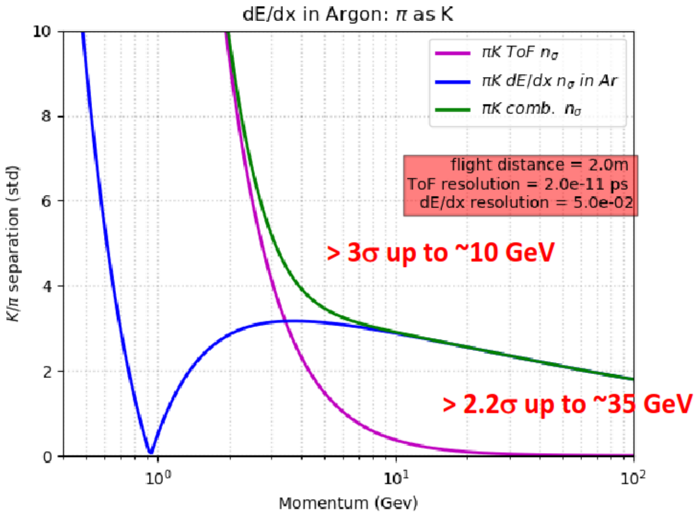
Acceptance :	$\lvert\cos\theta\rvert$	$<$	0.95
Charged particles :			
$\mathrm{p_T}$ resolution :	$\frac{\sigma(p_T)}{p_T^2}$	$=$	$2. \times 10^{-5} \oplus \frac{1.2\times10^{-3}}{p_T \sin\theta}$
ϕ,θ resolution :	$\sigma(\phi,\theta)\ \mu\mathrm{rad}$	$=$	$18 \oplus \frac{1.5\times10^{3}}{p_T \sqrt[3]{\sin\theta}}$
Vertex resolution :	$\sigma(\mathrm{d_{Im}})\ \mu\mathrm{m}$	$=$	$1.8 \oplus \frac{5.4\times10^{1}}{p_T \sqrt{\sin\theta}}$
e, γ particles :			
Energy resolution :	$\frac{\sigma(E)}{E}$	$=$	$\frac{5\times10^{-2}}{\sqrt{E}} \oplus 5 \times 10^{-3}$
EM ϕ,θ resolution :	$\sigma(\phi,\theta)$ mrad	$=$	$\frac{7}{\sqrt{E}}$

PID in generic detector

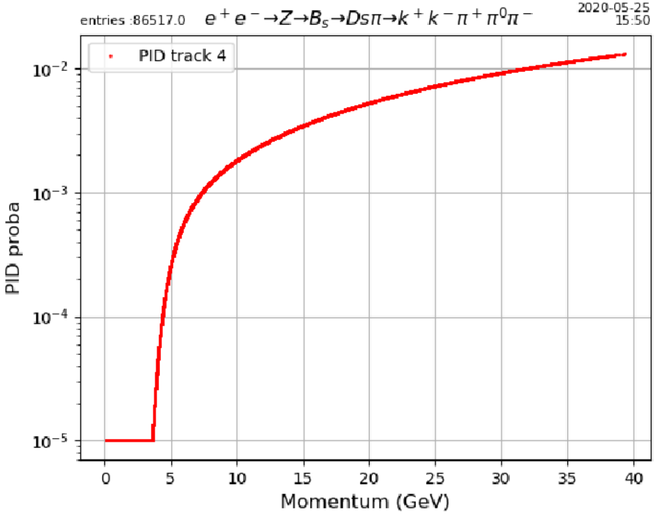
Inclusion of « standard and modest » PID (dE/dx and ToF)

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%



https://indico.cern.ch/event/932973/contributions/4059396/attachments/2141084/3607689/FCCee-week-2020_Bs-DsK.pdf

Present IDEA guide lines for performance

Physics Process	Measured Quantity	Critical Detector	Required Performance
$ZH \to \ell^+\ell^- X$	Higgs mass, cross section	Tracker	$\Delta(1/p_\mathrm{T}) \sim 2 \times 10^{-5}$
$H \to \mu^+\mu^-$	$\mathrm{BR}(H \to \mu^+\mu^-)$		$\oplus 1 \times 10^{-3}/(p_\mathrm{T} \sin\theta)$
$H \to b\bar{b},\ c\bar{c},\ gg$	$\mathrm{BR}(H \to b\bar{b},\ c\bar{c},\ gg)$	Vertex	$\sigma_{r\phi} \sim 5 \oplus 10/(p \sin^{3/2}\theta)\ \mu\mathrm{m}$
$H \to q\bar{q},\ VV$	$\mathrm{BR}(H \to q\bar{q},\ VV)$	ECAL, HCAL	$\sigma_E^{\mathrm{jet}}/E \sim 3-4\%$
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\sigma_E \sim 16\%/\sqrt{E} \oplus 1\%$ (GeV)

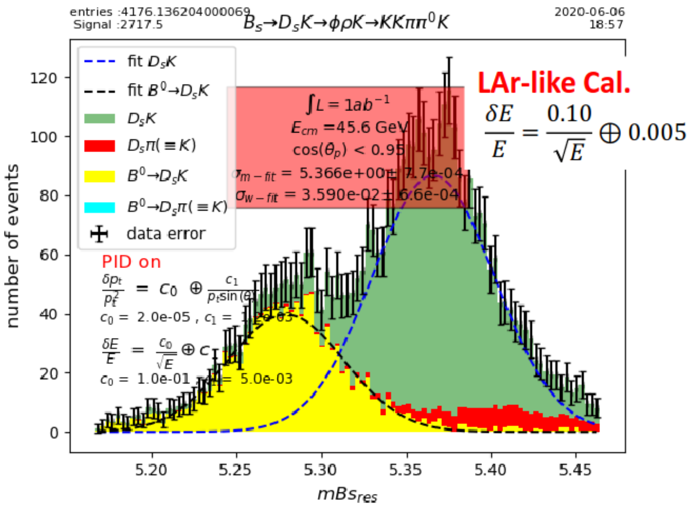
For details about the developments, please refer to the talks in the dedicated parallel sessions and to the presentation of tomorrow by Grancagnolo and Boudry

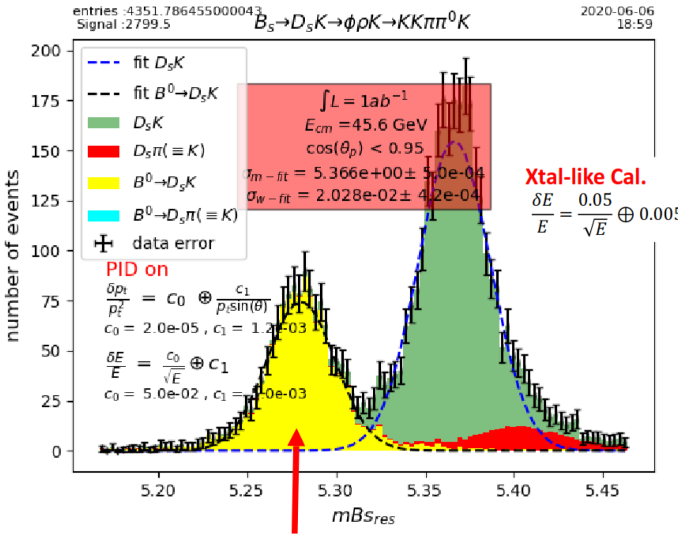
Why neutrals?

https://indico.cern.ch/event/932973/contributions/4059396/attachments/2141084/3607689/FCCee-week-2020_Bs-DsK.pdf

D_s final state with neutrals can potentially lead to a **x3 increase** in statistics, i.e. $D_s \rightarrow \Phi\rho^{\pm}$.

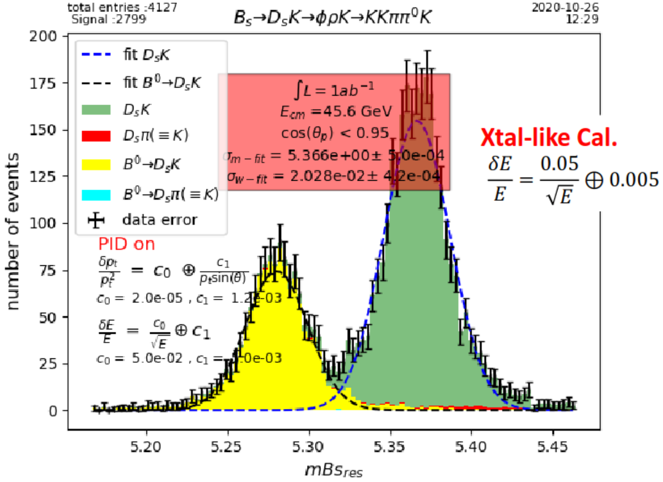
This puts **more stringent requirements** on **PID** and **Calorimetry**





« Irreducible bkg », only mass resolution can beat it

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



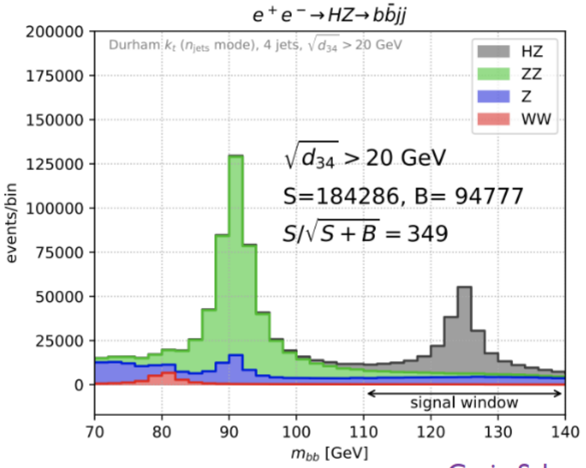
With 10 ps timing layer

Jet Clustering in DELPHES

Jet Clustering

- Implemented Durham **inclusive/exclusive** clustering in both "dcut" and "njet" mode
- "Valencia" algorithm

```
#################################
# Jet finder Durham exclusive
#################################

module FastJetFinder FastJetFinderDurhamN2 {
#  set InputArray Calorimeter/towers
  set InputArray EFlowMerger/eflow

  set OutputArray jets

  # algorithm: 11 ee-durham kT algorithm
  # ref: https://indico.cern.ch/event/1173562/contributions/4929025/a
  # to run exclusive njet mode set NJets to int
  # to run exclusive dcut mode set DCut to float
  # if DCut > 0 will run in dcut mode

  set JetAlgorithm 11
  set ExclusiveClustering true
  set NJets 2
  # set DCut 10.0

}
```



Gavin Salam

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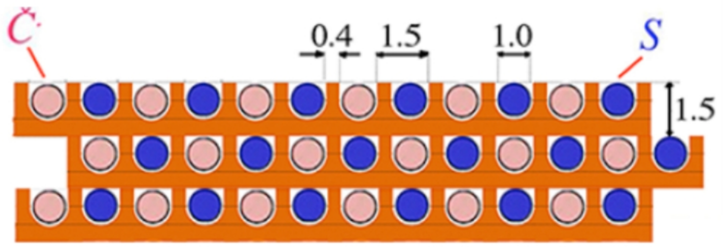
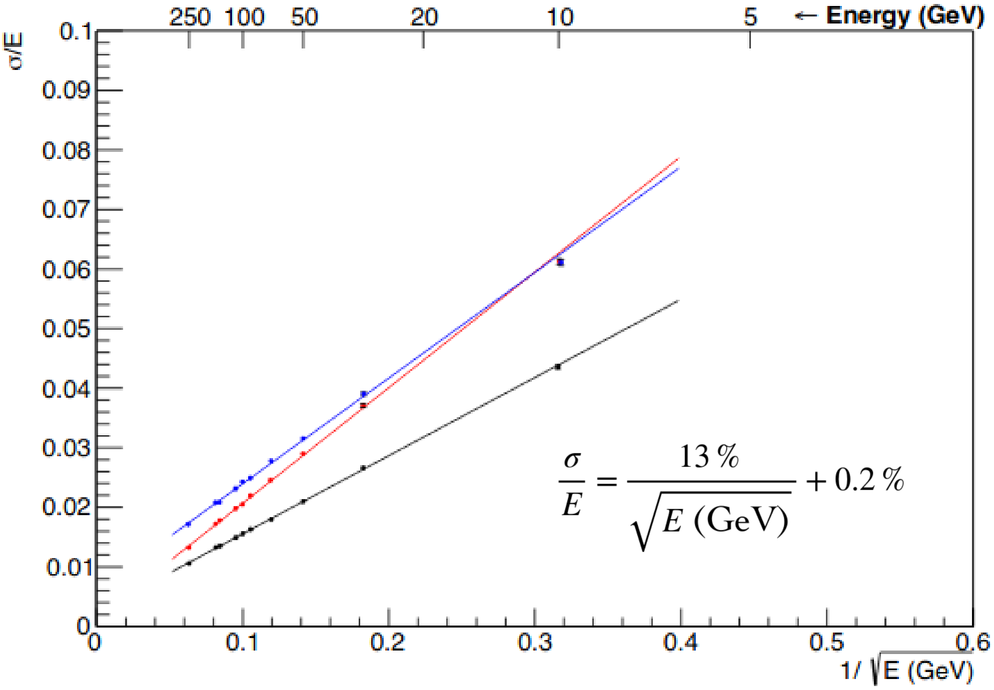
IDEA Calorimetry

Dual readout calorimeter – EM & Hadronic in one single sampling detector

- 1.5 mm fiber pitch
- Cherenkov/Scintillation

Working principle demonstrated by DREAM/RD-52





More details in the presentation in the parallel session on detector