CP violation and determination of the “squashed” (b,s) unitarity triangle at FCC-ee

R. Aleksan (CEA/IRFU), L. Oliver (IJCLab), E.Perez (CERN)

3rd Workshop FCC France, Nov 30 – Dec 2, 2021, Annecy

- CP violation and determination of the bs "flat" unitarity triangle at FCC-ee, https://arxiv.org/abs/2107.02002
- Study of CP violation in $B^{\pm}$ decays to D^0 ($\overline{D}^0$) $K^{\pm}$ at FCC-ee https://arxiv.org/abs/2107.05311

Unitarity triangles

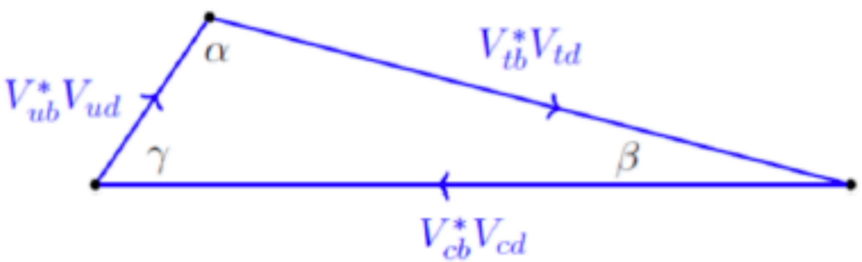
Six triangular relations from unitarity of V_{CKM} .
Among them :

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

The (usual) "(b, d) triangle" :

$$V^*_{ub} V_{ud} + V^*_{cb} V_{cd} + V^*_{tb} V_{td} = 0$$

$$(\lambda^3, \quad \lambda^3, \quad \lambda^3)$$

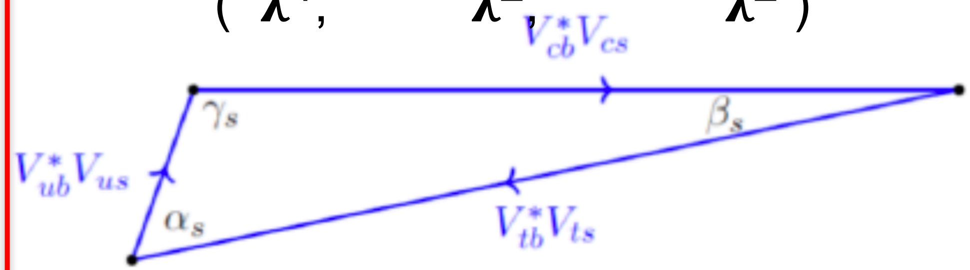


All angles are (quite) large.
Extensively studied experimentally

The "(b, s) triangle" :

$$V^*_{ub} V_{us} + V^*_{cb} V_{cs} + V^*_{tb} V_{ts} = 0$$

$$(\lambda^4, \quad \lambda^2, \quad \lambda^2)$$



$(\alpha_s, \beta_s, \gamma_s) \sim (67^o, 1^o, 111^o)$
Can be measured directly at FCC-ee

The "(d, s) triangle": even more squashed

(SM: Relations between the angles of these triangles)

- Study expected precision at FCC-ee on $(\alpha_s, \beta_s, \gamma_s)$
- Requirements on the detectors from these measurements

Experimental sensitivities and detector response

- Expected sensitivities given for 10^{11} produced $\overline{B}_s$ and 3.9 10^{11} produced B^+ , corresponding to 150 ab^{-1} at FCC-ee at the Z peak.

- Modelisation of the detector response :
  - Smearing of the momenta and angles of particles in the decays of interest
    - Parametrisation based on typical performance of a light tracker at a future ee detector
    - Excellent EM calo resolution
    - Used for most results shown here

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

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

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

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

$$\text{Vertex resolution} : < \sigma(\mathrm{d_{Im}}) > \text{bachelor K in } D_s K$$

$$< \sigma(\mathrm{d_{Im}}) > \simeq 10\ \mu\text{m}$$

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

- Common SW : Full MC events + response of the IDEA detector with DELPHES
  - Detailed description of tracks, accounting for multiple scattering
  - Genuine vertex fitting

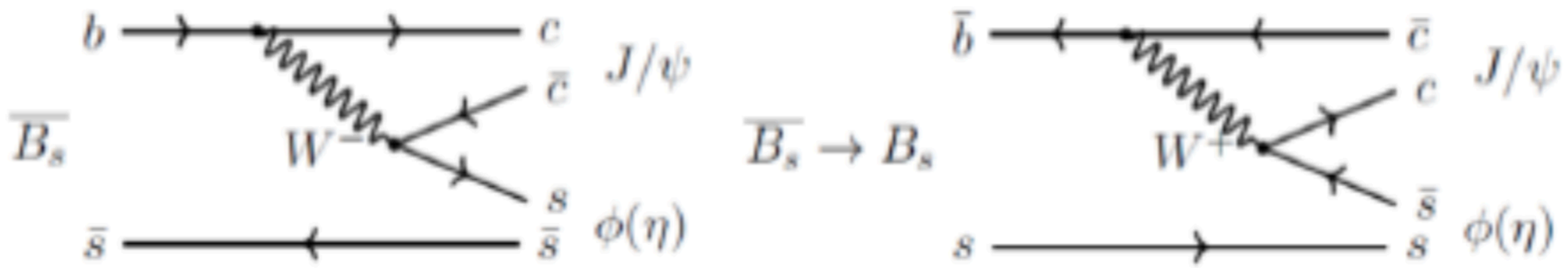
Measurement of β_s

$$\beta_s = \arg\left(-\frac{V_{tb}^* V_{ts}}{V_{cb}^* V_{cs}}\right)$$

β_s : very small in the SM (1 degree), and known precisely.
Hence can set strong constraints on New Physics.

- Golden channel: $B_s \to J/\psi\ \phi$
  - Measure CP violation in the interference between B_s mixing and $b \to ccs$ decay
- Analogous of $B_d \to J/\psi\ K_s$ from which $\sin(2\beta)$ is extracted
- Already largely used at LHC, but low precision so far:

PDG: $\beta_s = (0.60 \pm 0.89)°$



$V_{cb}\ V^*_{cs}$ $\qquad$ $\dfrac{V_{tb}\ V^*_{ts}}{V_{ts}\ V^*_{tb}}$ x $V_{cs}\ V^*_{cb}$

When final state f is a CP eigenstate:

$\Phi_{CKM}\ (\ J/\psi\ \Phi) = 2\ \beta_s\ (+\pi)$

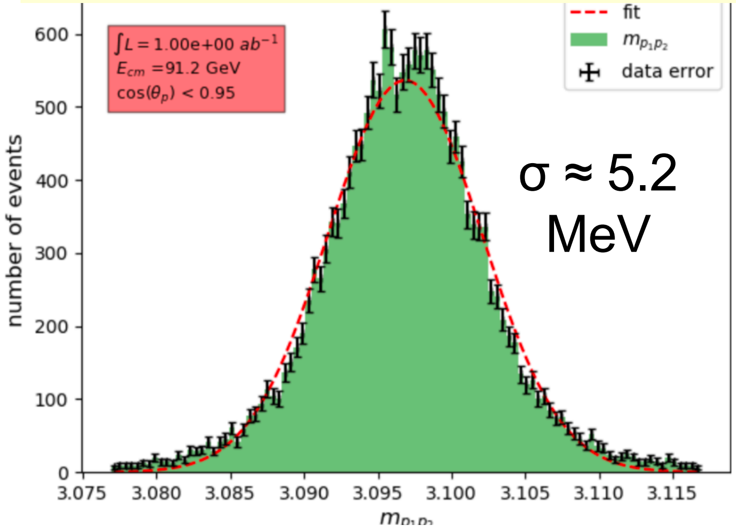
$$\Gamma\ (\overset{(-)}{B_s}(t) \to f\ ) \sim e^{-\Gamma t}\ [\ 1 \mp \eta_{f,CP}\ (1-2\omega) \sin \Phi_{CKM} \sin(\Delta m_s\ t)\ ]$$

ω = mistag rate, (well) measured independently, see later

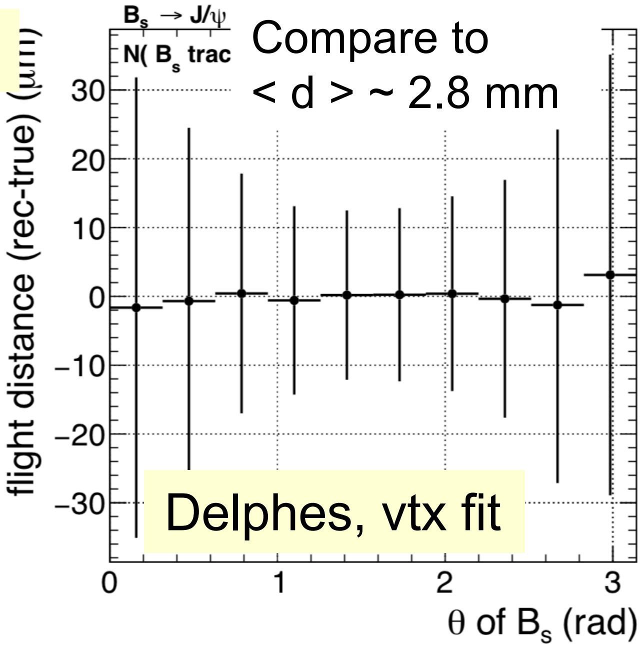
Measurement of β_s

Final state: two muons from J/ψ + two kaons from Φ

Parametrized response, m(J/ψ)



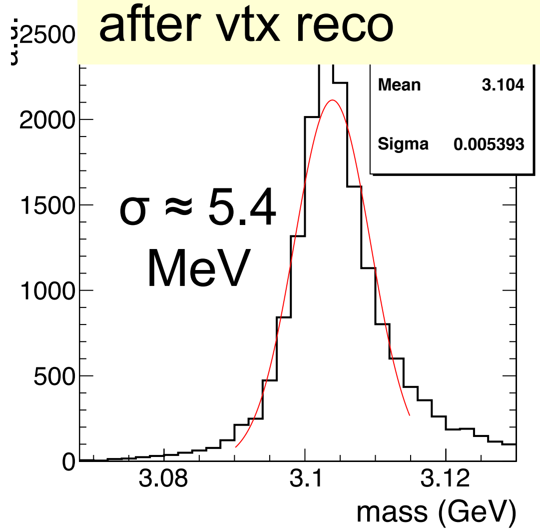
σ ≈ 5.2 MeV



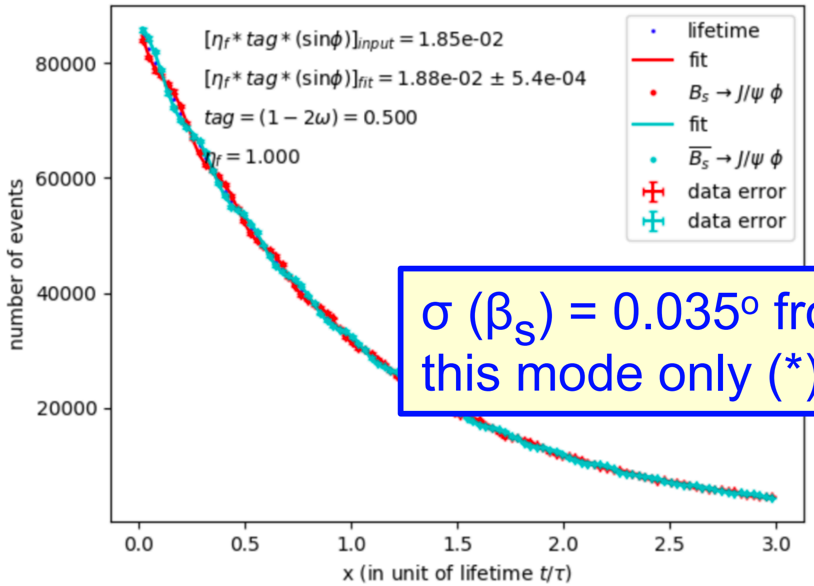
Compare to
< d > ~ 2.8 mm

Delphes, vtx fit

Delphes, m(J/ψ) after vtx reco



σ ≈ 5.4 MeV



σ (β_s) = 0.035° from this mode only (*)

Statistics: 3 M B_s decays, large enough to measure precisely the small modulation.

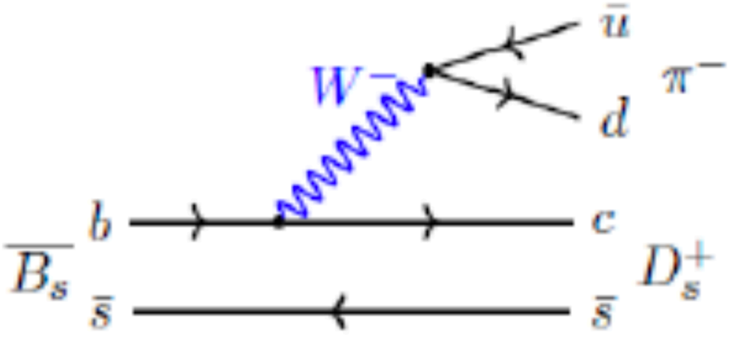
β_s will be known very precisely !

- O(25x) better than current average
- O(7 x) better than expected from upgrades of LHCb/BelleII (late 2030s)

(*) $J/\psi\ \Phi$: need an angular analysis as different polarisations of VV have a different CP

E.Perez

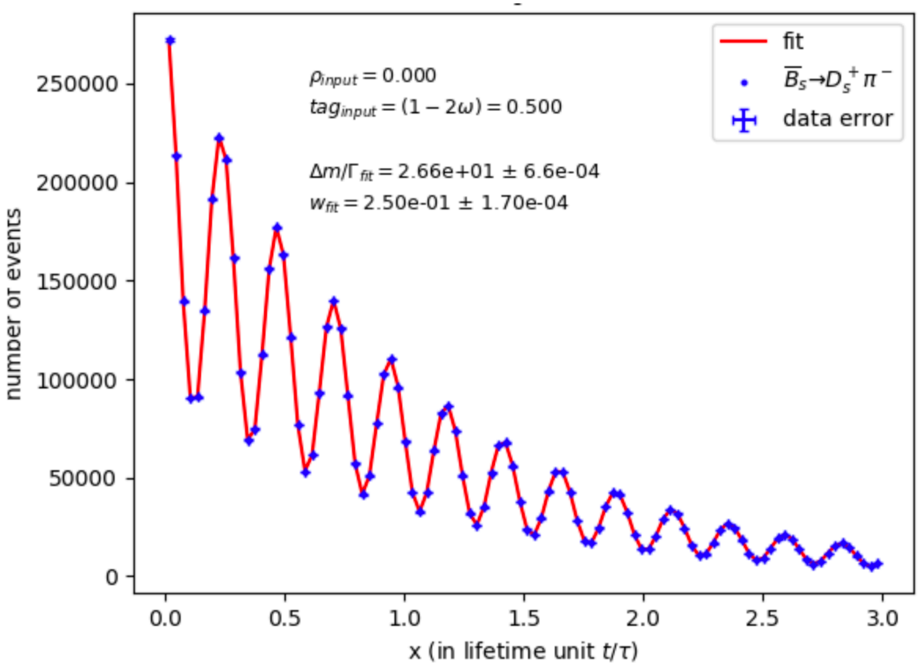
Measurement of the mistag rate: $\overline{B}_s \rightarrow D_s^+ \pi^-$



- Relatively large BR, 0.3 %
  - Expect 14 M such decays
- No diagram for $B_s \rightarrow Ds^+ \pi^-$, i.e. flavour-specific decay and no CP violation in this mode.

Very convenient for probing the B_s tagging :

$$\Gamma\,(\,\overline{B}_s\,(t) \rightarrow D_s^+\,\pi^-\,) \sim e^{-\Gamma t}\,[\;(\,1-\omega)\cos^2 \Delta mt/2 \;+\; \omega\;\sin^2 \Delta mt/2\,)\;]$$
$$\Gamma\,(\,B_s\,(t) \rightarrow D_s^+\,\pi^-\,) \sim e^{-\Gamma t}\,[\;\omega\;\cos^2 \Delta mt/2 \;+ (\,1 - \omega\,)\sin^2 \Delta mt/2\,)\;]$$

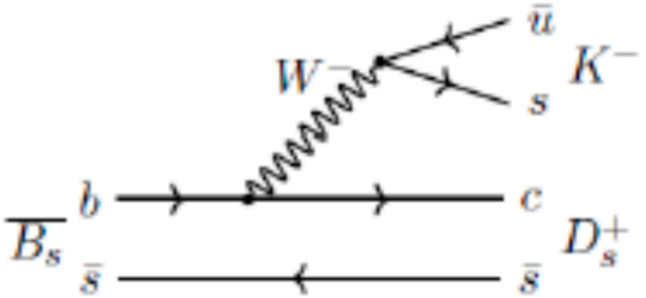


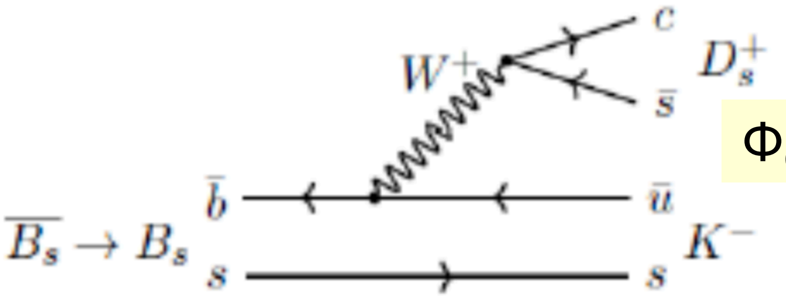
Very precise determination of the mistag rate,
$\sigma(\,\omega\,) \sim 1.3\;10^{-4}$

And an improved determination of Δm_s, Δm_s / Γ_s to 5 10^{-4}
i.e. O(100x) better than current PDG.

Measurement of α_s : B_s to D_s K

$$\alpha_s = \arg\left(-\frac{V_{ub}^* V_{us}}{V_{tb}^* V_{ts}}\right)$$





$\Phi_{CKM} = \pi - (\alpha_s - \beta_s)$

- Again CPV from the interference of mixing and decay
- But now have four time-dependent rates

$$\overline{B}_s \to D^+_s K^-,\ \overline{B}_s \to D^-_s K^+,\ B_s \to D^+_s K^-,\ B_s \to D^-_s K^+$$

$$\begin{aligned}\Gamma(B_s(t) \to f) &= |< f \mid B_s >|^2 \ e^{-\Gamma t}\{[1-\omega(1-\rho^2)]\cos^2\tfrac{\Delta mt}{2} \\ &+ [\rho^2 + \omega(1-\rho^2)]\sin^2\tfrac{\Delta mt}{2} \\ &\boxed{-(1-2\omega)\rho\sin\phi^+_{CP}\sin\Delta mt\}} \\ \Gamma(\overline{B_s}(t) \to \overline{f}) &= |< f \mid B_s >|^2 \ e^{-\Gamma t}\{[1-\omega(1-\rho^2)]\cos^2\tfrac{\Delta mt}{2} \\ &+ [\rho^2 + \omega(1-\rho^2)]\sin^2\tfrac{\Delta mt}{2} \\ &\boxed{+(1-2\omega)\rho\sin\phi^-_{CP}\sin\Delta mt\}}\end{aligned}$$

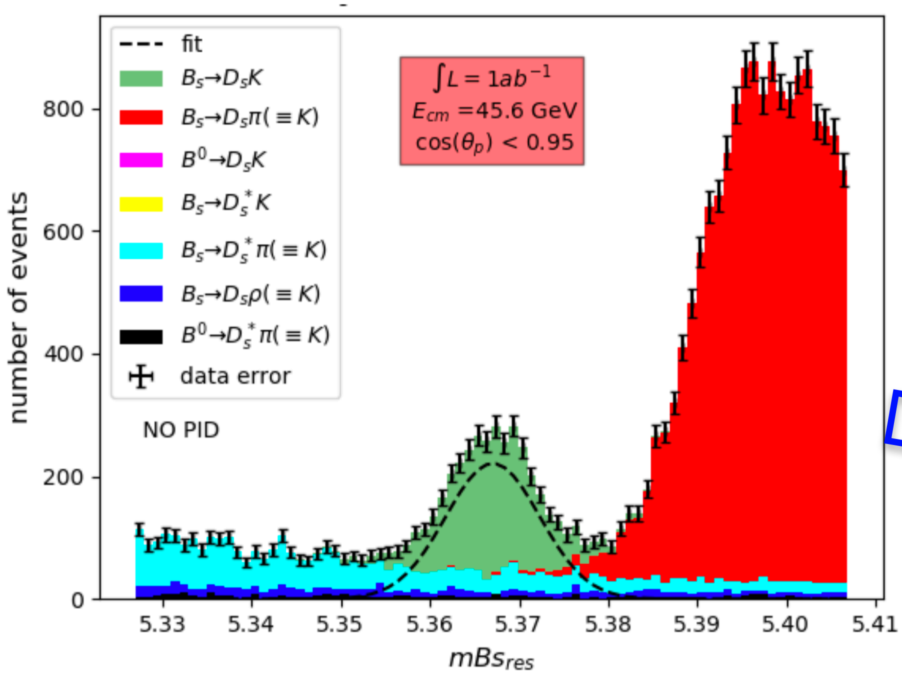
(+ two other equations not shown)

$$\boxed{\Phi^{\pm}_{CP} = \Phi_{CKM} \pm \delta}$$

δ = strong phase difference
ρ = ratio of |amplitudes|

Hadronic parameters ρ and δ can be determined from the data together with Φ_{CKM} (2-fold ambiguity) , hence negligible theoretical uncertainties

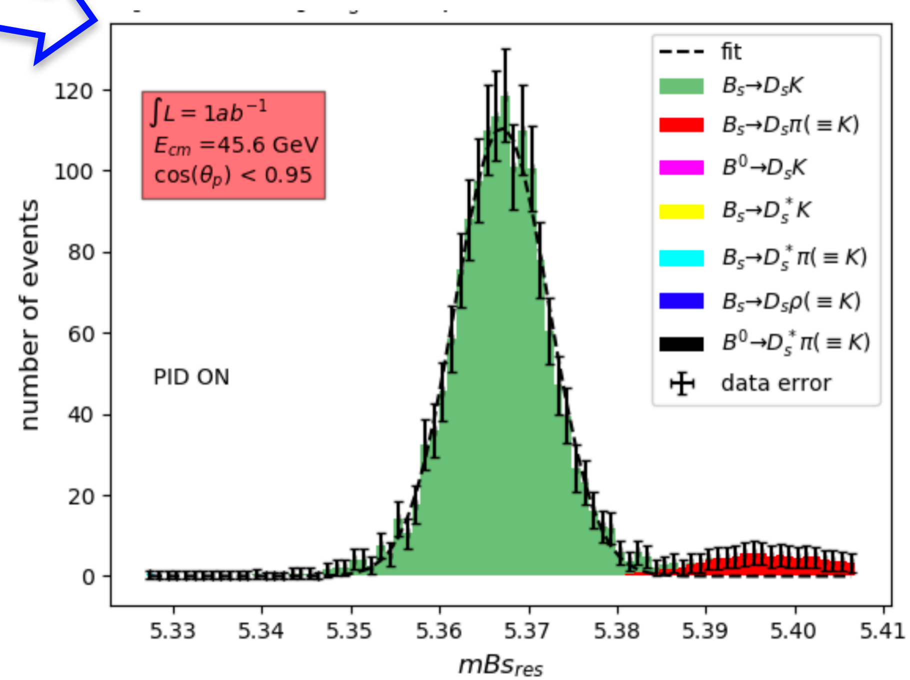
B_s to D_sK : signal reconstruction when $D_s \to \Phi(KK)\ \pi$

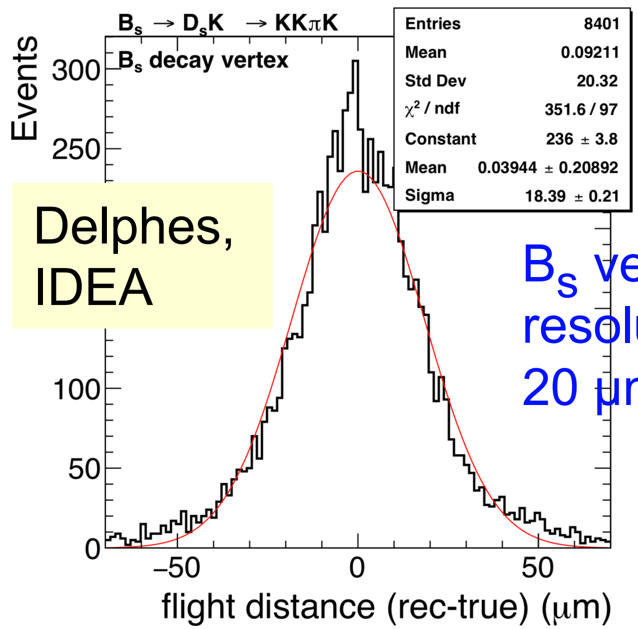


150 ab^{-1}: O(1 M) B_s + $\overline{B}_s$ such decays.

Background from D_s π already suppressed thanks to the mass resolution.

Modest PID



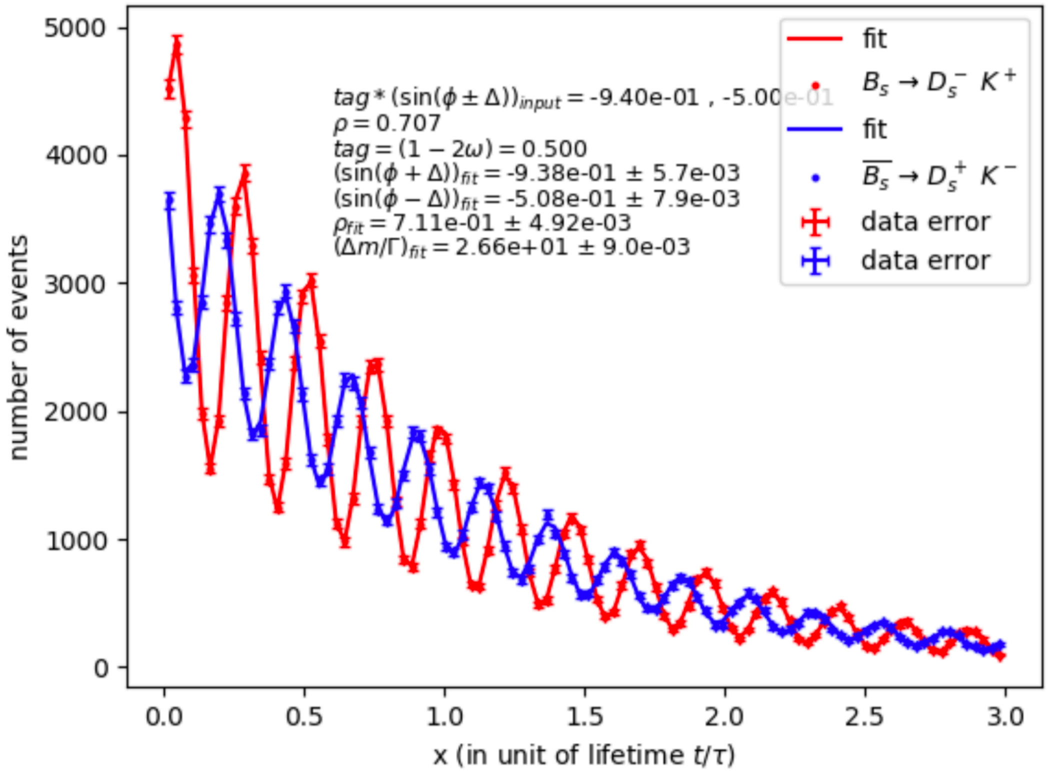


Delphes, IDEA

B_s vertex resolution about 20 μm

Full analysis with Delphes MC samples has started (Marco Scodeggio, Ferrara)

Sensitivity on α_s (or on γ)



Statistical precision on Φ_{CKM} (on α_s) with 150 ab^{-1} : 0.4 degrees

Resolution on Bs vertex = 20 μm i.e. O(40) x better than the wave-length of the oscillation. Hence vertexing performance as given with IDEA good enough for this measurement.

Algebra of the args($V_{\alpha i} V^*_{\beta j} / V_{\mu k} V^*_{\nu l}$) :

$\alpha_S = \gamma - \beta_s$ + tiny angle from the (d,s) triangle

Hence this measurements is also a measurement of γ.

Current: PDG: $\gamma = (71.1^{+4.6}_{-5.3})°$

- i.e. 10x improvement w.r.t. current
- LHCb/BelleII (late 2030s) : similar sensitivity expected - PRD 102, 056023 (2020)

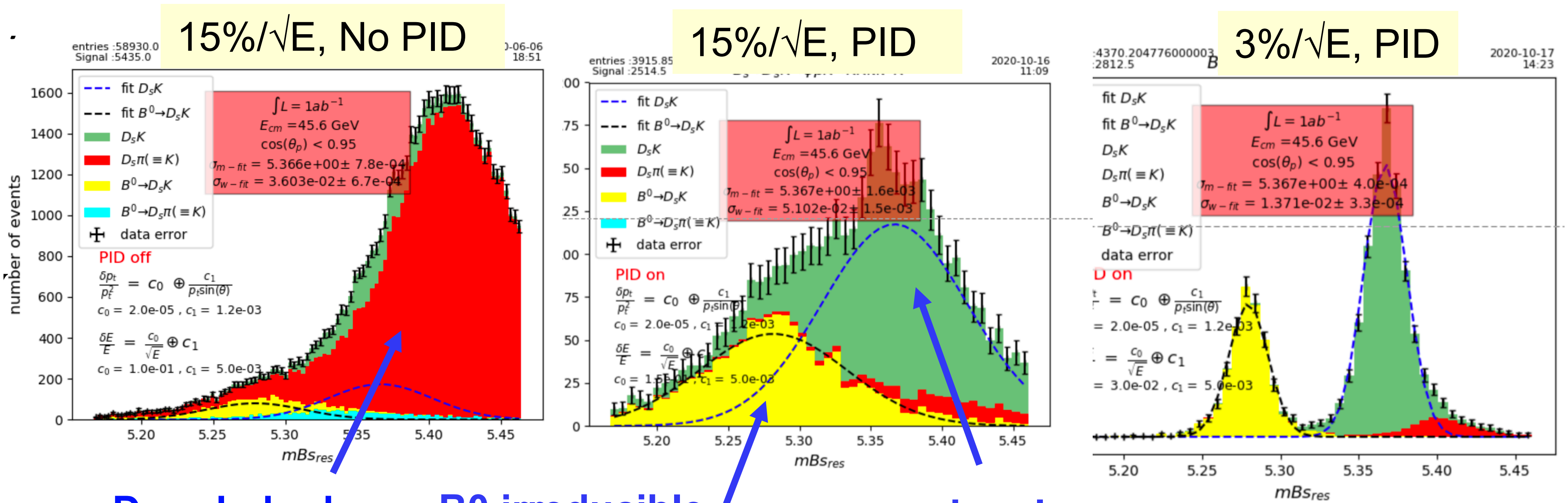
B_s to D_sK : inclusion of other modes

Resolution could be further improved by including other modes, that add a photon (e.g. Bs → Ds* K) or a π0 (e.g. Bs → Ds K*) to the final state.

Most promising boost in statistics: Bs → Ds K with Ds → Φ ρ → K^+K^- π π^0.
Could increase the statistics by a factor of 3.

Control of backgrounds: exquisite EM resolution (< 5%/√E) + PID (dEdx and ToF at 2m with 20 ns resolution used here)

Roy Aleksan, FCC workshop, Nov 2020



Ds π bckgd

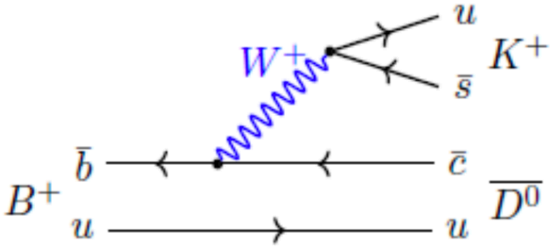
B0 irreducible bckgd

signal

Measurement of γ_s : B^+ to D^0 K+

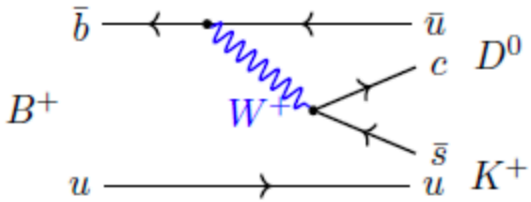
$$\gamma_s = \arg\left(-\frac{V_{cb}^* V_{cs}}{V_{ub}^* V_{us}}\right)$$

Direct CP violation in decays of B+ to D^0 ($\bar{D}^0$) K^+ : well-known method to measure the γ angle of the “usual” UT. Can be applied too to measure γ_s.



$B^+ \rightarrow \bar{D}^0 K^+$

$V_{us} V^*_{cb}$



$B^+ \rightarrow D^0 K^+$

$V_{cs} V^*_{ub}$

With a final state f that is accessible to both D^0 and $\bar{D}^0$: interference, and CPV.

D^0 ($\bar{D}^0$) $\rightarrow$ $K^+ K^-$ (η_{CP} = 1) or $K_s \pi^0$ (η_{CP} = -1) : Φ_{CKM} = $\pi + \gamma_s$

$\Gamma (B^+ \rightarrow f_{(D)} K^+) \neq \Gamma (B^- \rightarrow f_{(D)} K^-)$. Asymmetry $\mathcal{A}_{CP}$ given by :

$$\frac{\pm 2\mathcal{R} \sin\Delta \sin\gamma_s}{1+\mathcal{R}^2 \mp 2\mathcal{R}\cos\Delta\cos\gamma_s}$$

$$\mathcal{R}^2 = \frac{Br(B^+ \rightarrow D^0 K^+)}{Br(B^+ \rightarrow \overline{D^0} K^+)}$$

R already known to 5%, can be much improved with D0 semi-leptonic decays

Δ = strong phase difference. PDG: -130^o ± 5^o

Combination of $\mathcal{A}^+_{CP}$ ($K^+ K^-$) and $\mathcal{A}^-_{CP}$ ($K_s \pi^0$) gives Δ and γ_s (8-fold ambiguity)

Expected sensitivities

BR (B+ → D0 K+) ~ 3.6 10 $^{-4}$
BR (B+ → D0 K+) ~ 3.6 10 $^{-6}$
BR (D0 → K+ K-) ~ 4.1 10 $^{-3}$
BR (D0 → Ks π0) ~ 1.2 10 $^{-2}$

$\overline{D^0}K^+$	$\overline{\mathrm{D}^0} \rightarrow \mathrm{K}^+\mathrm{K}^-$	$\sim 5.8\ 10^5$
D^0K^+	$\mathrm{D}^0 \rightarrow \mathrm{K}^+\mathrm{K}^-$	$\sim 5.7\ 10^3$
$\overline{D^0}K^+$	$\overline{\mathrm{D}^0} \rightarrow \mathrm{K_s}\pi^0$	$\sim 1.2\ 10^6$
D^0K^+	$\mathrm{D}^0 \rightarrow \mathrm{K_s}\pi^0$	$\sim 1.2\ 10^4$

(indicative # of B+ decays)

Asymmetries are sizable. E.g. with Δ = -130^o and γ_s = 108^o :

$\mathcal{A}^+_{CP}$ ($K^+ K^-$) ≈ - 15% and $\mathcal{A}^-_{CP}$ ($K_s\ \pi^0$) ≈ 14 %

with expected statistical uncertainties of ~ 0.1% (absolute, accounting for approx. acceptance and efficiencies), which corresponds to σ (γ_s) of 2.8^o

(uncertainty on γ_s depends on the value of Δ – ranges between < 1^o to a few deg.)

Possible improvements with additional modes, e.g. D → K_s η, B^+ → D K^{*+}

Measurement of γ_s to 1^o – 2^o within reach.

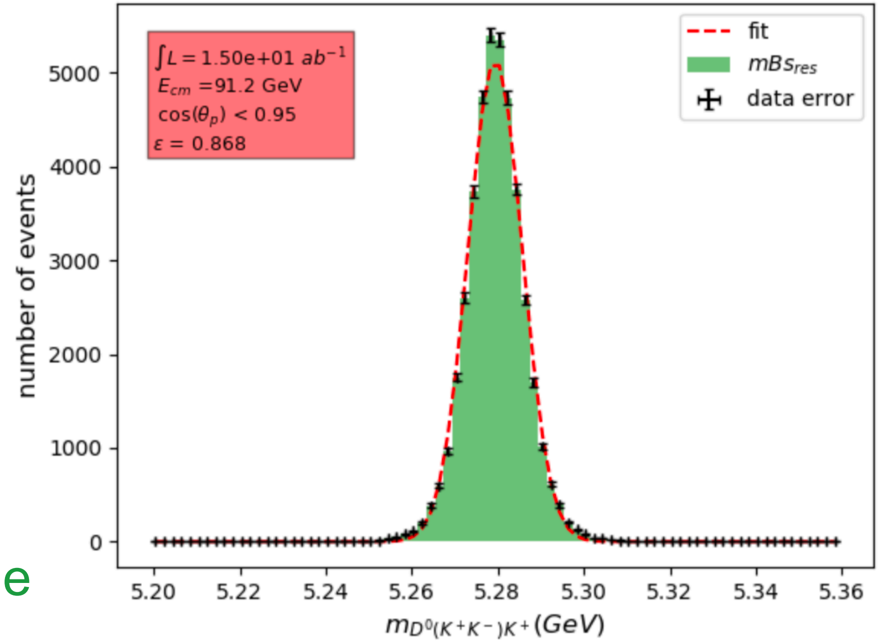
Signal reconstruction

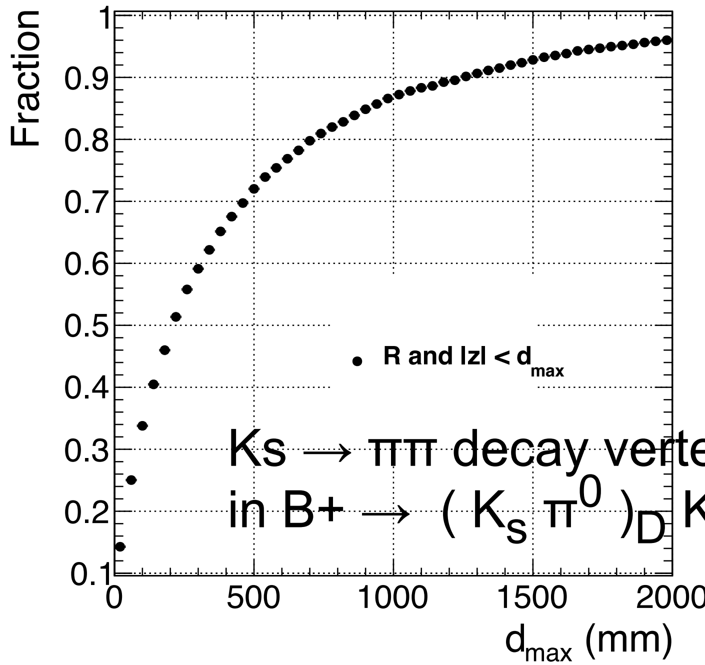
- $B^+ \to (K^+ K^-)_D K^+$: should be quite easy thanks to excellent mass resolution

  σ ~ 6 MeV on the B+ mass

- $B^+ \to (K_S \pi^0)_D K^+$: much more challenging

  - Displaced pion tracks from Ks decay : Up to O(1m) from the IP. Demands a large enough tracker
  - Worse mass resolutions :
    - π^0 : naïve σ worsens to 12 MeV even with exquisite EM resolution of 3%/√E
    - Finite resolution on Ks vertex will degrade this further: IDEA likely much better than Si tracker
  - Hence more background comes in: Requires K / π separation in a wide p range 1 – 30 GeV





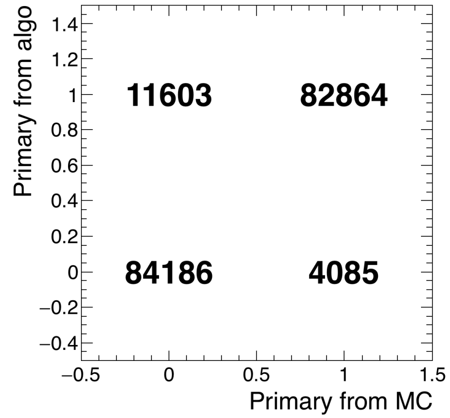
$K_S \to \pi\pi$ decay vertex in $B+ \to (K_S \pi^0)_D K^+$

Reconstruction of Ks decays (WIP)

0th version of Ks reconstruction algorithm developed in FCCAnalyses, based on DELPHES samples. Known caveat: over-optimistic resolution on parameters of displaced tracks, will be fixed in the next version (F. Bedeschi).

- Identify the non-primary tracks
  - Fit a primary vertex with all tracks
  - Remove the track with the highest chi2 if this chi2 is > some cut (25)
  - Run the fit again, iterate

Probability correct assignment: ~ 90%

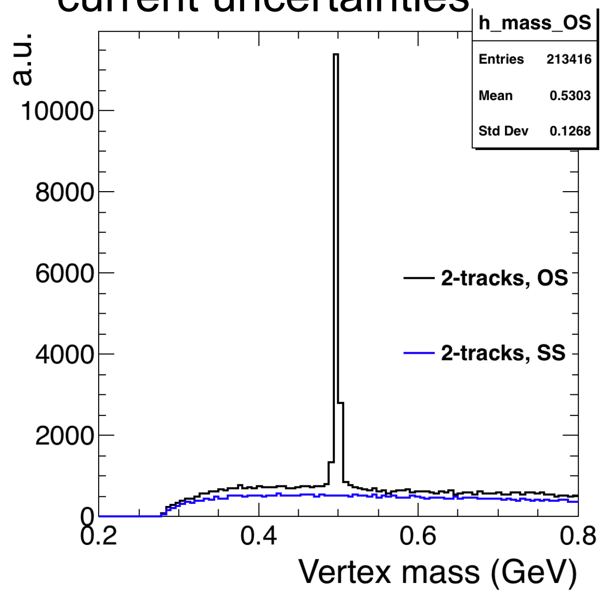


- Using the non-primary tracks: find Ks candidates from all 2-track combinations
  - Fit the 2 tracks to a common vertex
  - Propagate the tracks to this vertex
  - Build the vertex mass, using m = pion mass for each leg

Loose chi2 cut, mass window, opposite-charge pairs: good efficiency and purity..

To be quantified with:
- upgraded version of DELPHES
- the FullSim tracking of the CLD detector

Mass resolution ~ 3 MeV with current uncertainties



Summary

- Precise direct measurement of the three angles of the “squashed” (b,s) unitarity triangle possible at FCC-ee :

β_s : to 0.035^o or better (0.035%) via Bs → J/ψ Φ
- 25x better than the current precision

α_s : to 0.4^o or better (0.5%) via Bs → Ds K

γ_s : to 1^o (1%) via B+ → D0 K+

- Simple relation between the phases measured in these three processes :

$$-\Phi\,(\,\mathrm{DsK}\,) + \Phi\,(\,J/\psi\ \Phi\,) + \Phi\,(\,\mathrm{D0K}\,) = 0$$

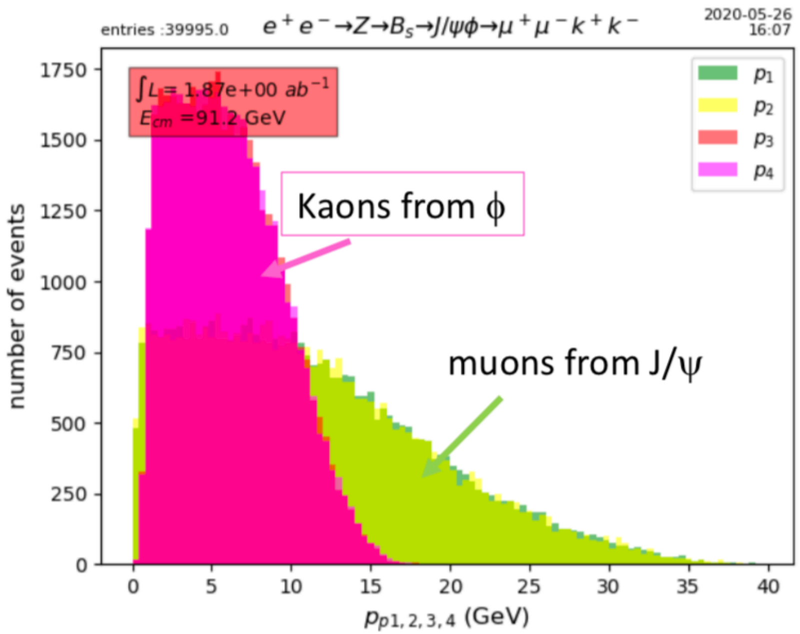
should hold in the Standard Model.

- These processes also provide good benchmarks for detector performance:
  - Excellent tracking performance (mass resolutions)
  - Excellent EM resolution (modes with neutrals)
  - K/Pi separation in a wide p range
  - Ks reconstruction (crucial for many flavour analyses)

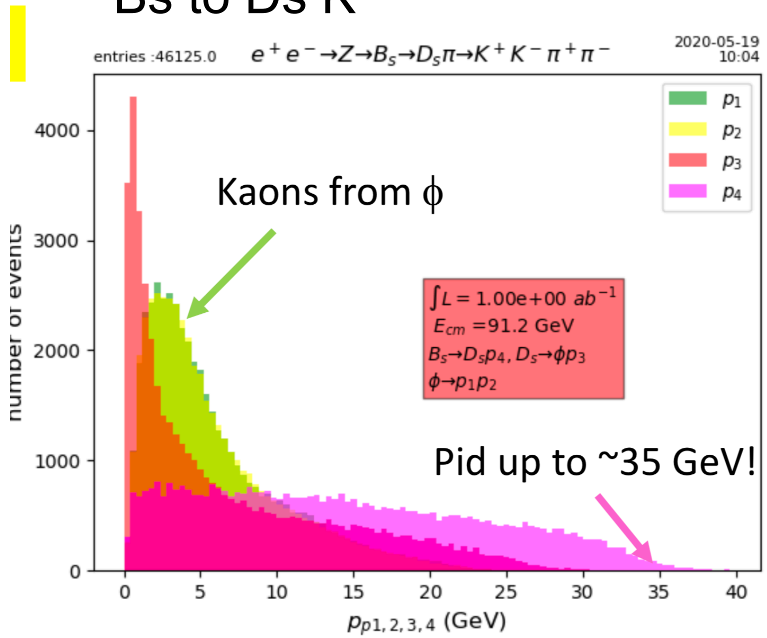
Backup

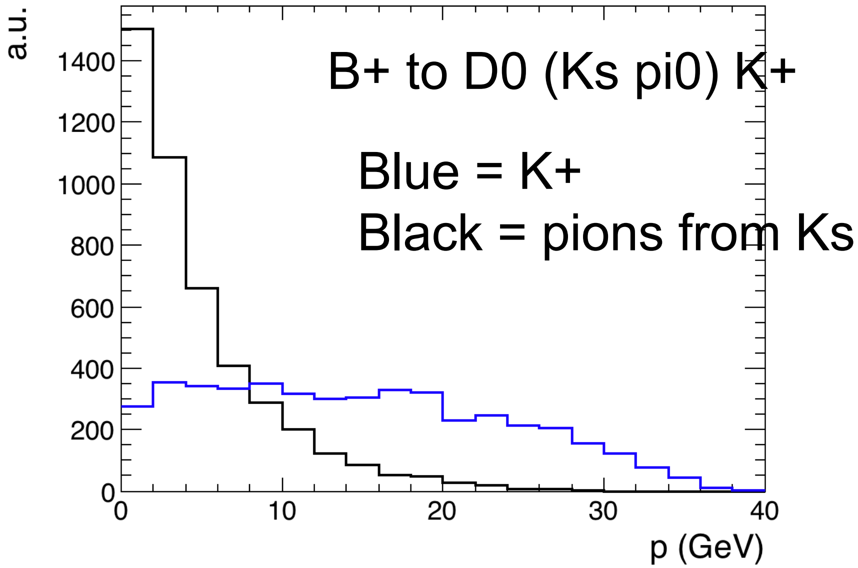
Kinematic distributions

Bs to Jpsi Phi



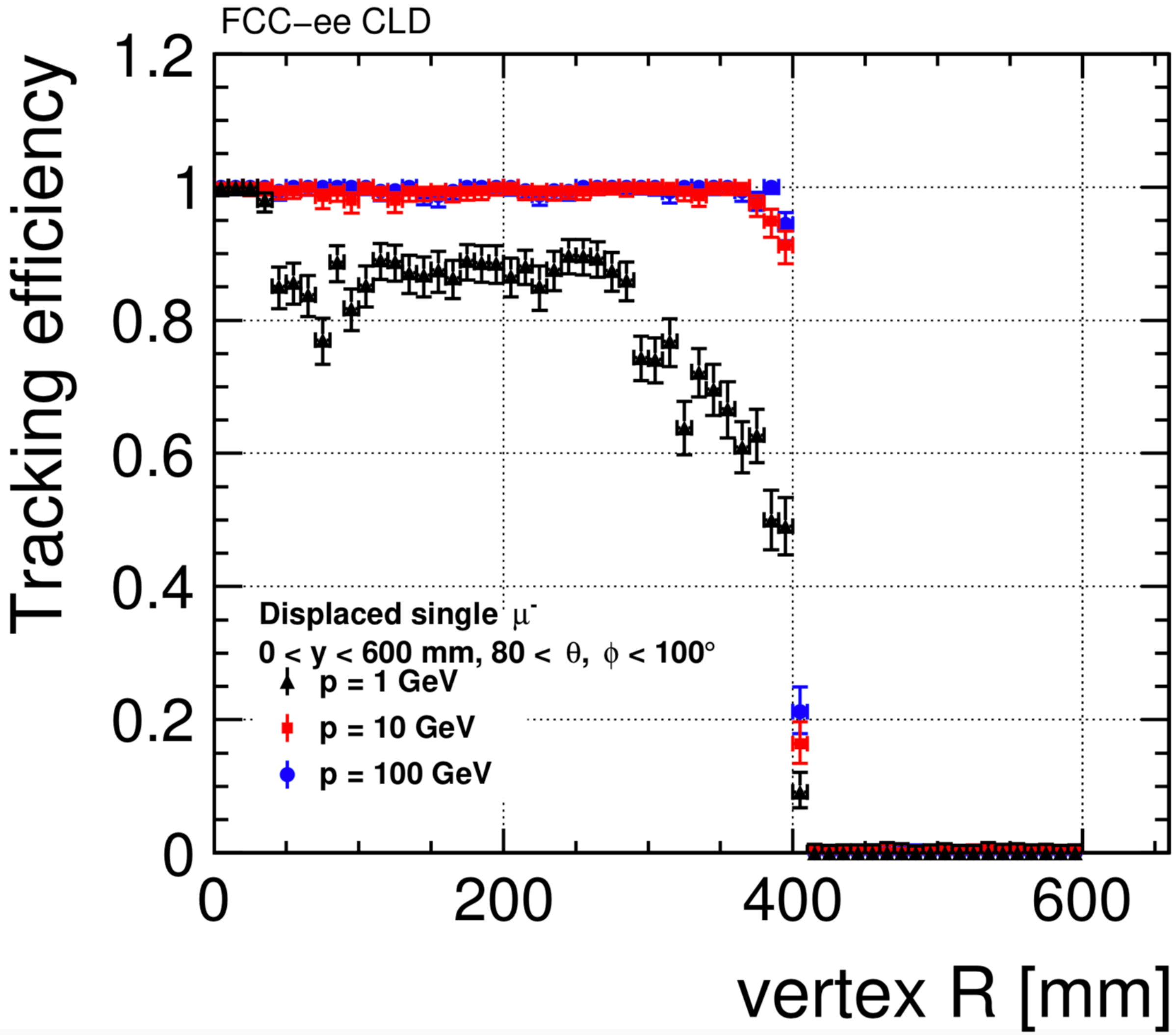
Bs to Ds K





Reconstruction of displaced tracks in CLD

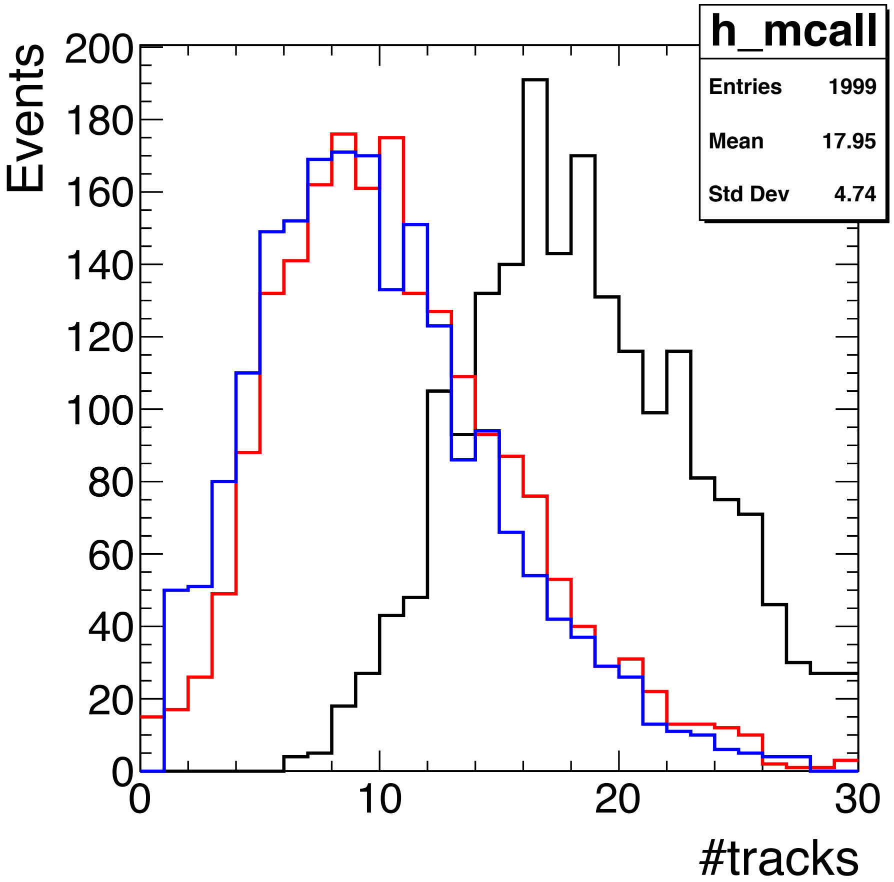
Full simulation results. Cf CLD paper, https://arxiv.org/abs/1911.12230



Selection of secondary tracks

In view of a Ks reconstruction: need to select secondary tracks

- Fit a primary vertex with all tracks
- Remove the track with the highest chi2 if this chi2 is > some cut (25)
- Run the fit again, iterate



Black = all tracks

Red = tracks that are MC-matched with primary particles

Blue = the reco'ed primary tracks with this procedure.

Conclusion: decent selection of non-primary tracks