Measurement of CP asymmetries in $D^0 \to K^0_S K^0_S$ decays using Run II data.

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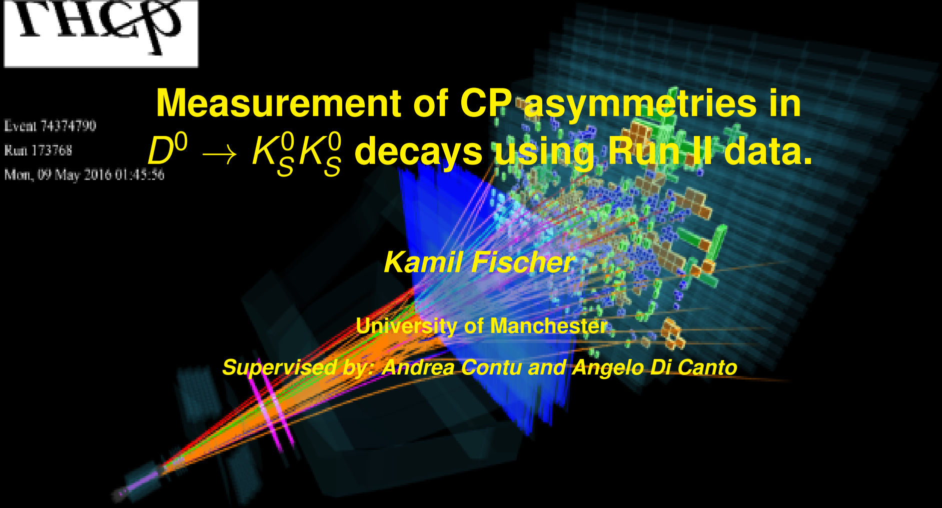


About me

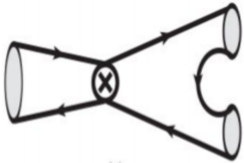
- I am a third year masters student. (MPhys)
- I study at the University of Manchester in the UK.
- I was born in Poland.

Motivation

- CP violation has not been observed in charm.
- $D^0 \to K_S^0 K_S^0$ is a promising channel for discovery.
  - (I) The decay amplitudes are suppressed. Main contribution is due to SU(3) symmetry breaking.
  - (II) Standard Model expectation: $|A_{CP}^{dir}(D^0 \to K_S^0 K_S^0)| < 1.1\%$
  - (III) May be enhanced by new physics.

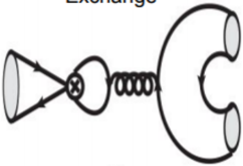
$A_{CP}[\%]$	Yield	Year	Collaboration
-23±19	65±14	2008	CLEO
-2.9±5.2 ± 2.2	635±74	2015	LHCb Run 1
-0.02±1.53 ± 0.17	5399±87	2016	Belle

Current experimental results



(a)

Exchange



(b)

Penguin annihilation

Experimental Approach

- A sample of flavour tagged $D^{*\pm} \to D^0(\to K^0_S K^0_S)\pi^\pm_S$ candidates is used.
- The measured asymmetry is given by:

$$A_{raw} = \frac{N_{D^0} - N_{\bar{D}^0}}{N_{D^0} + N_{\bar{D}^0}} \quad (1)$$

- For small values of the asymmetries:

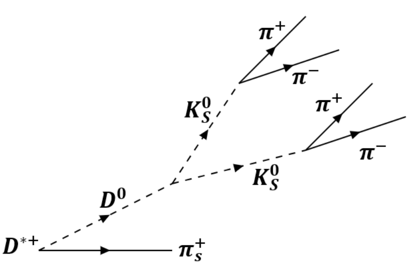
$$A_{raw} \approx A_{CP} + A_{prod} + A_{det} \quad (2)$$

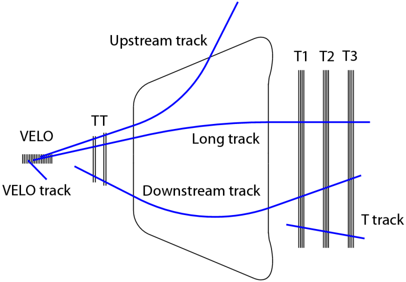
- D^* production asymmetry → A_{prod}
- $\pi^\pm_S$ detection asymmetry → A_{det}

- A_{prod} and A_{det} are subtracted via ΔA_{CP} using $D^0 \to K^+K^-$ as the control channel.
  (I) $A_{CP}(D^0 \to K^+K^-) = (0.04 \pm 0.12 \pm 0.10)\%$ [LHCb Run 1]

Decay reconstruction

- K_S^0 Long(L): Both pion daughters have a LONG track type.
- K_S^0 Down(D): Both pion daughters have a DOWNSTREAM track type.





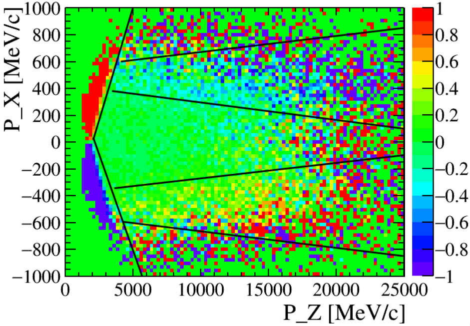
Fiducial cuts and trigger selection

- Trigger selection is applied to the D^0 and D^* candidates by requiring:

  (I) L0: D0_L0HadronDecision_TOS or DS_L0Global_TIS

  (II) Hlt1: D0_Hlt1TrackMVADecision_TOS

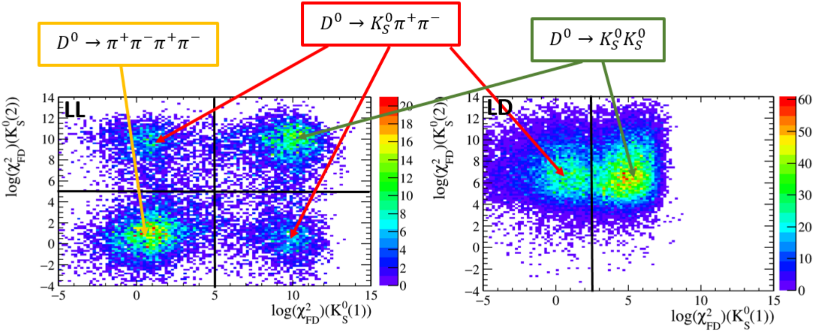
- Cuts on the momentum of the slow pion are introduced to reduce large sources of detection asymmetry.



Sources of background

- Combinatorial background
  - (I) Main source of background
  - (II) Reduced by applying cuts on P_T of D^*, D^0 and π_S^+. Selection of D^* vertex χ^2, D^0 flight distance and DIRA of D^0 can be useful.
- Prompt peaking background
  - (I) An important source of background originates from $D^0 \to K_S^0\pi^+\pi^-$ and $D^0 \to \pi^+\pi^-\pi^+\pi^-$ channels in which the dipion mass falls close to the K_S^0 mass.
- Prompt non-peaking background
- Secondaries

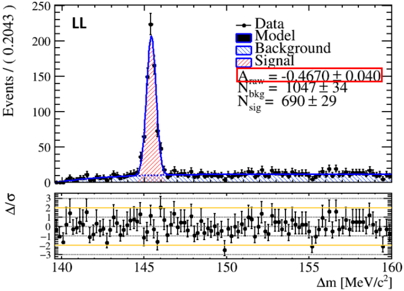
Prompt peaking background

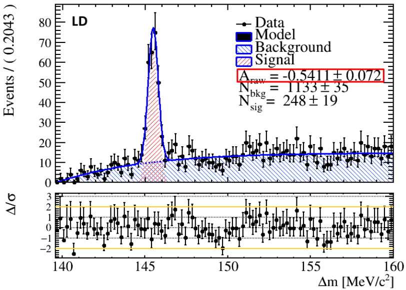


Prompt non-peaking background and Secondaries

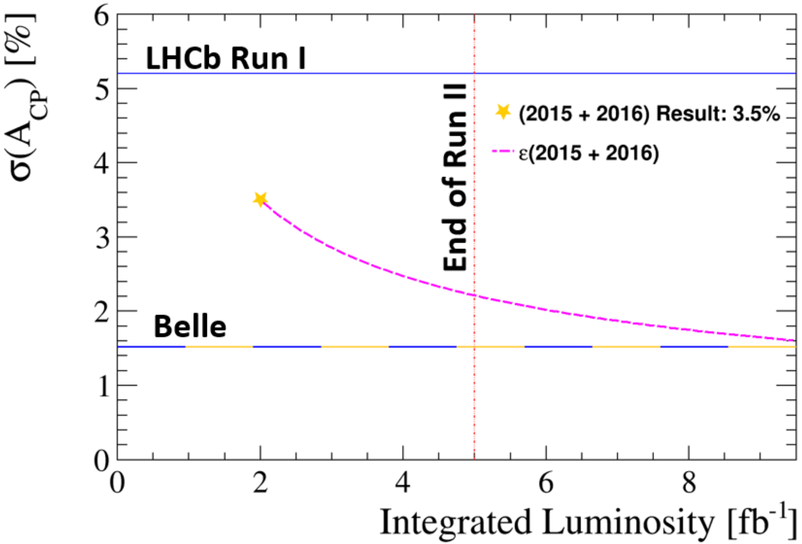
- Prompt non-peaking background originates from charm meson decays ($D_S^{\pm} \rightarrow K_S^0 K_S^0 \pi_S^{\pm}$).
  - (I) Doesn't peak in D^0 or D^* mass distributions.
  - (II) Can be suppressed with: $|m(K_S^0 K_S^0) - 1865| < 20.$
- Secondary decays occur when the D^* candidate originates from the decay of a b-hadron.
  - (I) This results in a shift of A_{raw} due to a different A_{prod}.
  - (II) Can be suppressed with cuts on $\chi^2_{IP}(D^0)$, $\chi^2_{IP}(\pi_S^{\pm})$ and $\chi^2_{SV-PV}(D^*)$.

Candidates from 2015 + 2016





- Combined statistical precision: 3.5%.
- No DD candidates due to a bug in the trigger $\rightarrow$ Hlt1: required at least one of the D^0 final states to be long. (Fixed for 2017)

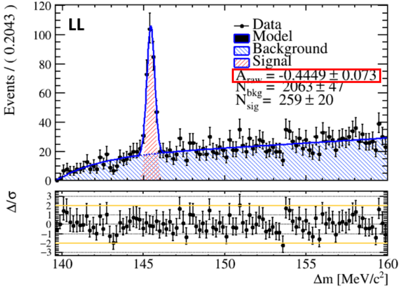


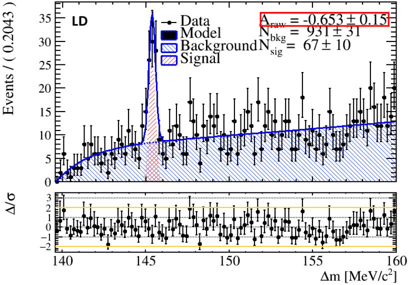
σ(A_CP) [%]
6
5
4
3
2
1
0
LHCb Run I
End of Run II
(2015 + 2016) Result: 3.5%
ε(2015 + 2016)
Belle
0
2
4
6
8
Integrated Luminosity [fb^-1]

Improved Hlt2 selection for 2017

- Selection criteria of Hlt2 has been updated:
  (I) LL sample: relaxed D^0 lifetime requirements, lower $K_S^0(\chi^2_{IP})$ thresholds and removed HLT1 requirement.
  (II) LD/DD sample: lower $\sum_{PT} K_S^0$, looser D^0 lifetime requirement, lower $K_S^0(P_T)$ and no HLT1 requirement.
- Trigger efficiencies are calculated by applying L0,Hlt1 and Hlt2 conditions to an MC sample of 4061 candidates.
  (I) LL/LD: Expect an improvement in the efficiency of Hlt2 by a factor of 3.5-5.
  (II) DD: Hlt2 efficiency relative to L0 events (1.4$\pm$0.1)%.

Candidates from 2017

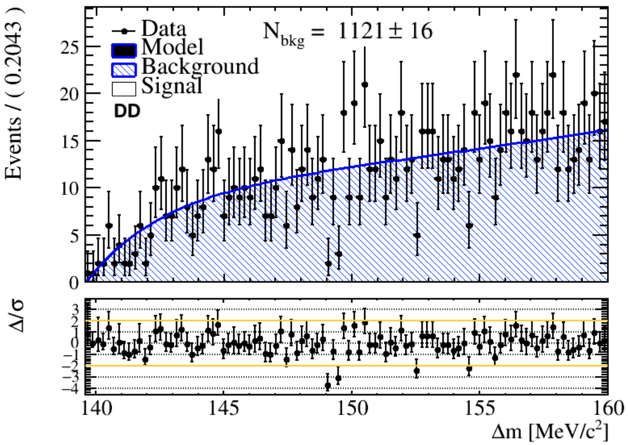




Improvement in $\frac{N_{sig}}{fb^{-1}}$ = 2.15 ± 0.23

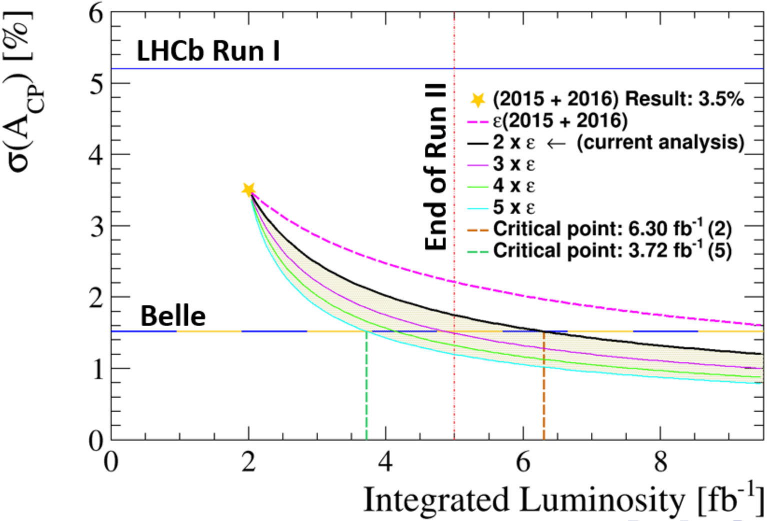
Improvement in $\frac{N_{sig}}{fb^{-1}}$ = 1.53 ± 0.27

- Combined improvement (early 2017 data): 1.9 ± 0.2.
- Yields are extracted using offline selection optimised for the 2015 + 2016 sample.



- A basic offline selection has been developed.
- The baseline selection must be reoptimised.
- A signal peak is still not observed.

Projected statistical uncertainty of $A_{CP}(D^0 \to K_S^0 K_S^0)$



Conclusion

- Performed a measurement of $A_{CP}(D^0 \to K_S^0 K_S^0)$ using 2015+2016 data.
- Selection criteria inherited from LHCb-ANA-2017-XXX. (Pisa Group)
- Developed and fitted a model to data.
- Fitting and blinding method validated with pseudo-experiments.
- Looked at the 2017 data for the first time and found a factor ≈ 2 improvement in yields/integrated luminosity for LL and LD candidates (where a factor 3.5-5 was expected).
- Confirmed that the bug affecting the DD selection is resolved, but no signal yet observed.
- Still to do:

  I Reoptimize the selection for LL/LD candidates for the 2017 data sample.

  II Improve the efficiency of Hlt2 and develop a new selection criteria for DD candidates.

BACKUP

Data set and selection

- Decay Tree Fitter (DTF)
  (I) Primary vertex (PV) constraint on the D^* candidate.
  (II) Constraint on the mass of the kaon daughters $m(K_S^0)$.

Baseline selection LL:

Selection
Preliminary selection
L0: `D0_L0Hadron_TOS or DS_L0Global_TIS`
HLT1: `KS_Hlt1TrackMVA_TOS`
Fiducial cuts
Prompt-peaking background
$[\log(\chi^2_{FD}(K^0_{S1})) - 10]^2 + [\log(\chi^2_{FD}(K^0_{S2})) - 10]^2 < 16$
$\lvert m(K^0_{S1-2}) - 497.6\rvert < 10.5$ MeV/c^2
Secondaries
$\log(\chi^2_{IP}(D^0)) < 3$
$\log(\chi^2_{SV-PV}(D^{*\pm})) < 2.5$
$\log(\chi^2_{IP}(\pi_{tag})) < 2$
Combinatorial background
$p_T(\pi_{tag}) > 200$ MeV/c^2
$p_T(D^0) > 2000$ MeV/c^2
$\log_{10}(\mathcal{P}(\chi^2_{vtx}(D^{*\pm}))) > -4$
$\chi^2_{SV-PV}(D^0) > 3$

Baseline selection LD:

Selection
Preliminary selection
L0: `D0_L0Hadron_TOS or DS_L0Global_TIS`
Fiducial cuts
Prompt-peaking background
$\log(\chi^2_{FD}(K^0_{S\,L})) > 2.5$
$\lvert m(K^0_{S\,L}) - 497.6\rvert < 10.5$ MeV/c^2
$\lvert m(K^0_{S\,D}) - 497.6\rvert < 15$ MeV/c^2
Secondaries
$\log(\chi^2_{IP}(D^0)) < 4$
$\log(\chi^2_{SV-PV}(D^{*\pm})) < 2$
$\log(\chi^2_{IP}(\pi_{tag})) < 3.5$
Combinatorial background
$p_T(\pi_{tag}) > 250$ MeV/c^2
$p_T(D^0) > 3500$ MeV/c^2
$\mathrm{Log}_{10}(\mathrm{Prob}(\chi^2_{vtx}(D^{*\pm}), \mathrm{ndof})) > -2$
$p_T(K^0_{S\,D}) > 950$ MeV/c^2
$p_T(K^0_{S\,L}) > 750$ MeV/c^2
$\cos(\theta_{DIRA}(K^0_{S\,D})) > 0.999992$

Fit methodology

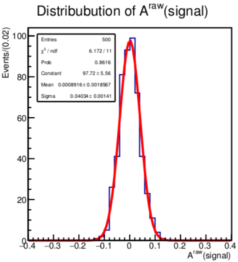
- The signal candidates are extracted by fitting a normalized gaussian to the Δm distribution.
- The background is extracted by fitting an empirical function:

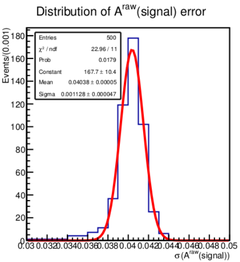
$$(1 - e^{\frac{\Delta m - m_{th}}{c}})(\frac{\Delta m}{m_{th}})^{a} + b(\frac{\Delta m}{m_{th}} - 1) \quad (3)$$

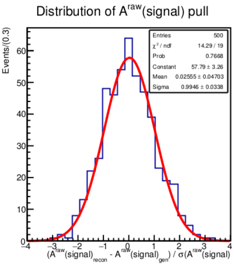
- The D^0 and $\bar{D}^0$ candidates are fit with an identical shape.
- A single background distribution is simultaneously fit for D^0 and $\bar{D}^0$ candidates with common parameters a (set to 0), b and c.

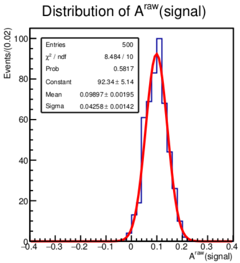
Fit validation

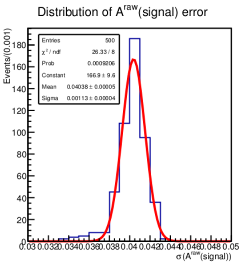
- $D^0 \to K_S^0 K_S^0$ and $\bar{D}^0 \to K_S^0 K_S^0$ samples are generated. The number of generated events in each sample is chosen such that a particular value of A_{raw} is obtained.
- The asymmetry values are selected in the range [-0.1,0.1] and a poissonian fluctuation is added to the number of generated events.
- The individual signal and background regions are generated separately, the total pdf is then simultaneously fit to the two samples.
- A total of 500 samples is generated for each value of the asymmetry. (MC seed is set to 50)

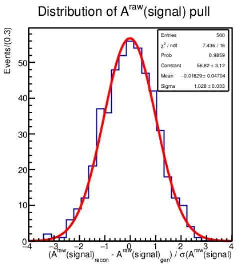

Distribubution of A^raw(signal)
Entries 500
χ² / ndf 6.172 / 11
Prob 0.8616
Constant 97.72 ± 5.56
Mean 0.0008916 ± 0.0018567
Sigma 0.04034 ± 0.00141
Events/(0.02)
A^raw(signal)


Distribution of A^raw(signal) error
Entries 500
χ² / ndf 22.96 / 11
Prob 0.0179
Constant 167.7 ± 10.4
Mean 0.04038 ± 0.00005
Sigma 0.001128 ± 0.000047
Events/(0.001)
σ(A^raw(signal))

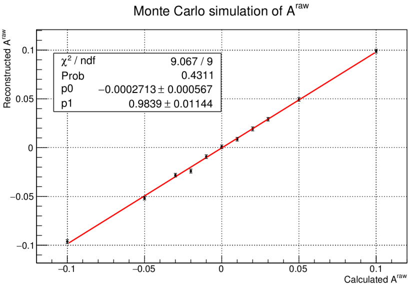

Distribution of A^raw(signal) pull
Entries 500
χ² / ndf 14.29 / 19
Prob 0.7668
Constant 57.79 ± 3.26
Mean 0.02555 ± 0.04703
Sigma 0.9946 ± 0.0338
Events/(0.3)
(A^raw(signal)_recon - A^raw(signal)_gen) / σ(A^raw(signal))


Distribution of A^raw(signal)
Entries 500
χ² / ndf 8.484 / 10
Prob 0.5817
Constant 92.34 ± 5.14
Mean 0.09897 ± 0.00195
Sigma 0.04258 ± 0.00142
Events/(0.02)
A^raw(signal)


Distribution of A^raw(signal) error
Entries 500
χ² / ndf 26.33 / 8
Prob 0.0009206
Constant 166.9 ± 9.6
Mean 0.04038 ± 0.00005
Sigma 0.00113 ± 0.00004
Events/(0.001)
σ(A^raw(signal))


Distribution of A^raw(signal) pull
Entries 500
χ² / ndf 7.436 / 18
Prob 0.9859
Constant 56.82 ± 3.12
Mean −0.01629 ± 0.04704
Sigma 1.028 ± 0.033
Events/(0.3)
(A^raw(signal)_recon - A^raw(signal)_gen) / σ(A^raw(signal))

Generated A^{raw}	Reconstructed value		Pull	
	μ	σ	μ	σ
0.00	0.001 ±0.002	0.040±0.001	0.026 ±0.047	0.995 ±0.034
+0.01	0.009 ±0.002	0.041 ±0.001	-0.034 ±0.046	0.997 ±0.034
+0.02	0.019 ±0.002	0.040 ±0.002	-0.081 ±0.047	1.008 ±0.037
+0.03	0.029 ±0.002	0.039 ±0.001	-0.055 ±0.044	0.959 ±0.032
+0.05	0.049 ±0.002	0.039 ±0.001	-0.045 ±0.044	0.955 ±0.030
+0.10	0.099 ±0.002	0.043 ±0.001	-0.016 ±0.047	1.028 ±0.033
-0.01	-0.01 ±0.002	0.041 ±0.001	0.022 ±0.045	0.975 ±0.037
-0.02	-0.024 ±0.002	0.039 ±0.001	-0.082 ±0.046	0.978 ±0.033
-0.03	-0.028 ±0.002	0.040 ±0.001	0.037 ±0.045	0.984 ±0.035
-0.05	-0.052 ±0.002	0.040 ±0.001	-0.070 ±0.045	0.958 ±0.031
-0.10	-0.10 ±0.002	0.042 ±0.002	0.06 ±0.048	1.006 ±0.038



Calculating raw asymmetry

- The number of signal events is parameterised in terms of total number of candidates (N) and asymmetry:

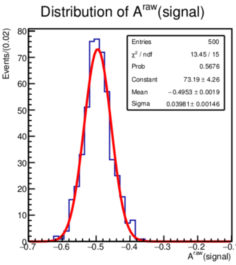
$$N_{sig}^{\pm} = \frac{N(1 \pm A_{raw})}{2} \quad (4)$$

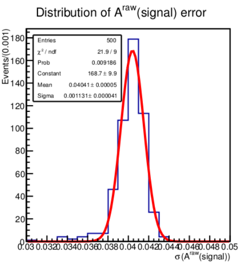
- The asymmetries are blinded using a randomly generated offset from a uniform distribution [0,1] with a preset seed.
- This is performed by shifting the parameter such that:

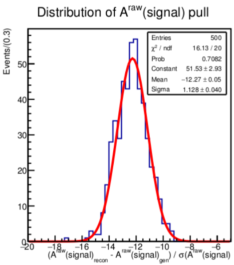
$$N_{sig}^{\pm} = \frac{N(1 \pm (A_{raw} + \delta))}{2} \quad (5)$$

Validation of blinding technique

- New samples are generated using the blinded signal distribution.
- The mean of the A_{raw} distribution corresponds to the value of the blinding offset $\rightarrow$ the blinding method is validated.







Hlt2 Selection

OLD (2015 + 2016):

Variable	$D^0 \to K^0_{SL} K^0_{SL}$	$D^0 \to K^0_{SL} K^0_{SD}$	$D^0 \to K^0_{SD} K^0_{SD}$
$\sum_{K^0_S} P_T$	$> 1500\ MeV/c$	$> 2000\ MeV/c$	
$P_T(K^0_S)$	$> 500\ MeV/c$	$> 750\ MeV/c$	
$\chi^2(K^0_S)$	> 9	> 4	
$\chi^2(D^0_{FD})$	> 20	> 10	
$m(K^0_S K^0_S)$	$\in [1789, 1949]\ MeV/c^2$		
$\chi^2_{vtx}/ndf(D^0)$	< 10		
$\theta_{DIRA}(D^0)$	$< 34.6\ mrad$		
$\tau(D^0)$	$> 0.2\ ps$		
$m(D^0\pi_{tag}) - m(K^0_S K^0_S)$	$\in [130, 160]\ MeV/c^2$		
$P_T(\pi_{tag})$	$>\ MeV/c$		
$P_{ghost})\pi_{tag})$	< 0.4		
$\chi^2/ndf(\pi_{tag})$	< 3		
$\chi^2_{vtx}/ndf(D^*)$	< 25		
$Hlt1$	D^0 is Hlt1.*Track.*Decision%TOS		

NEW (2017):

Variable	$D^0 \to K^0_{SL} K^0_{SL}$	$D^0 \to K^0_{SL} K^0_{SD}$	$D^0 \to K^0_{SD} K^0_{SD}$
$\sum_{K^0_S} P_T$	$> 1500\ MeV/c$	$> 1500\ MeV/c$	
$P_T(K^0_S)$	$> 500\ MeV/c$	$> 500\ MeV/c$	
$\chi^2(K^0_S)$	> 4	> 4	
$\chi^2(D^0_{FD})$	> 5	> 5	
$m(K^0_S K^0_S)$	$\in [1775, 1955]\ MeV/c^2$		
$\chi^2_{vtx}/ndf(D^0)$	< 10		
$\theta_{DIRA}(D^0)$	$< 34.6\ mrad$		
$\tau(D^0)$	$> -999\ ps$		
$m(D^0\pi_{tag}) - m(K^0_S K^0_S)$	$\in [-70, 170]\ MeV/c^2$		
$P_T(\pi_{tag})$	$>\ MeV/c$		
$P_{ghost})\pi_{tag})$	< 0.4		
$\chi^2/ndf(\pi_{tag})$	< 3		
$\chi^2_{vtx}/ndf(D^*)$	< 25		
$Hlt1$	No requirement		

Basic offline selection for DD candidates

Selection
Preliminary selection
L0: D0_L0Hadron_TOS or DS_L0Global_TIS
HLT1: No Requirement
Fiducial Cuts
Prompt-peaking background
$\log(\chi^2_{FD}(K^0_S(L))) > 2.5$
$\lvert m(K^0_S - 497.6) \rvert < 17\ MeV/c^2$
$\lvert m(D^0) - 1865 \rvert < 20\ MeV/c^2$
Secondaries
$\log(\chi^2_{IP}(D^0)) < 4$
$\log(\chi^2_{FD}(D^*)) < 3$
$\log(\chi^2_{IP}(\pi_{tag})) < 3.5$
Combinatorial background
$P_T(\pi_{tag}) > 250\ MeV/c$
$P_T(D^0) > 3000\ MeV/c$
$P_T(K^0_{S1}) > 950\ MeV/c$ or $P_T(K^0_{S2}) > 950\ MeV/c$