Measurement of Charm Production with Run 3 Early Data

Motivation, Status and Plan

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LHCb Starter Kit Run3 Edition

Outline

Brief introduction on the Charm early measurements, already presented by Peilian Li during the Charm meeting of the 26th of January

HLT2 selections in place, merged in charm-thor-hlt2-lines branch of Moore

Rate and efficiency studies with MooreAnalysis performed (with and without UT at the reconstruction level)

First mass distribution plots from signal MC signal and minbias samples, using DecayTreeTuple and FunTuple

HLT2 efficiency comparison between MooreAnalysis and Moore+DaVinci chain

First mass fit scripts in place and tested with Run 2 tuples

Introduction

Why early measurements?

- Run 3 data taken with fully new detector and new data acquisition system soon this year
- The first data will allow us to understand the detector and data processing pipeline
  ! Must be understood quickly and comprehensively
- Early measurement with physics channel would be efficient way to validate the performance of our detector and reconstruction
- Can provide necessary input for other analyses to begin, or more accurately characterize the running conditions

Why charm production measurements?

- Charm has interesting phenomenology as beauty: oscillations and CP violation (unique probe into up-quark sector)
- Huge production rate at LHCb with clear experimental signature
- The cross section will constrain and test the predictions of perturbative QCD, provide inputs to LHC analyses and operations: e.g. background estimation

Measuring absolute production rates

Number of charm hadrons H_c produced within the detector acceptance $(2 < y < 5)$: $N = \sigma L$

Useful to measure in kinematic bins: p_T and y

Select H_c with some inefficiencies to be accounted for, ε

Count H_c decaying to specific final states with know branching fractions, B

$$\frac{d^2\sigma_i(pp \to H_c X)}{dp_T dy} = \frac{1}{\Delta p_T \Delta y} \frac{N_i(H_c \to f + c.c.)}{\varepsilon_{\mathrm{i,tot}}(H_c \to f) B(H_c \to f) L}$$

Measuring absolute production rates

$$\frac{d^2\sigma_i(pp \rightarrow H_cX)}{dp_T dy} = \frac{1}{\Delta p_T \Delta y} \frac{N_i(H_c \rightarrow f + c.c.)}{\varepsilon_{\mathrm{i,tot}}(H_c \rightarrow f)B(H_c \rightarrow f)L}$$

$\Delta p_T \Delta y$: define a binning

- Follow Run 2 binning: 18 bins in $0 < p_T < 15$ GeV/c & 5 bins in $2.0 < y < 4.5$
- Extend to higher p_T if possible

$\varepsilon_{\mathrm{i,tot}}(H_c \rightarrow f)$: evaluate the fraction of produced hadrons passing the whole selection

Signal yields $N_i(H_c \rightarrow f + c.c.)$: extract from the selected candidates via fits

L: rely on the measurement from luminosity group

Systematic uncertainties evaluation for all related: PID, Tracking, luminosity, *etc*.

Decay modes

- Continue Run 2 measurements: important for detector validation (+cross-check modes)
  - D^0: $D^0 \to K^-\pi^+$ & $K^-\pi^+\pi^-\pi^+$
  - D^{*+}: $D^{*+} \to D^0\pi^+$ with $D^0 \to K^-\pi^+$ & $K^-\pi^+\pi^-\pi^+$
  - D^+: $D^+ \to K^-\pi^+\pi^+$ & $K^-K^+\pi^+$
  - D_s^+: $D_s^+ \to (K^+K^-)_\phi\pi^+$ & $(K^+K^-)_{\mathrm{non}-\phi}\pi^+$
- Additional meson modes: difficult for EM without UT, but HLT2 lines prepared
  - D^0: $D^0 \to K_s^0\pi^+\pi^-$ & $K_s^0K^+K^-$
  - D^{*+}: $D^{*+} \to D^0\pi^+$ with $D^0 \to K_s^0\pi^+\pi^-$ & $K_s^0K^+K^-$
- Baryon modes: challenges to evaluate the PID and tracking efficiency of proton
  - Λ_c^+: $\Lambda_c^+ \to pK^-\pi^+$
  - Ξ_c^+ (Ξ_c^0): $\Xi_c^+ \to pK^-\pi^+$ ($\Xi_c^0 \to pK^-K^-\pi^+$)

MC samples

Generated with Sim10aU1 at $\sqrt{s} = 14$ TeV (Nu7.6-25ns)

Used for the preliminary study of HLT2 lines and efficiency estimation

Need another rounds of production depends on the updates of simulation and real data conditions

More statistics needed (few millions to ensure enough statistics in each kinematic bin)

Decay modes	Event type	number of events ($\times 10^3$)	Type
$D^{*+} \to (D^0 \to K^- \pi^+)\pi^+$	27163003	200	xdigi
$D^{*+} \to (D^0 \to K^- \pi^- \pi^+\pi^+)\pi^+$	27165073	200	xdigi
$D^{*+} \to (D^0 \to K^0_S\pi^- \pi^+)\pi^+$	27265100	200	xdigi
$D^{*+} \to (D^0 \to K^0_S K^- K^+)\pi^+$	27265101	200	xdigi
$D^+ \to K^- \pi^+\pi^+$	21263010	200	xdigi
$D^+ \to K^- K^+\pi^+$	21263002	200	xdigi
$D_s^+ \to \phi\pi^+$	23263020	200	xdigi
$\Lambda_c^+ \to p^+K^- \pi^+$	25203000	200	xdigi
$\Xi_c^0 \to p^+K^- K^- \pi^+$	26104080	200	xdigi
$\Xi_c^+ \to p^+K^- \pi^+$	26103090	200	xdigi

HLT2 selections

R. Amalric, A. Gunther, P. Li, F. Oliva, R. O'Neil

Mostly follow the cuts applied in Run 2 [LHCb-ANA-2016-019]

Lines merged in Moore in the branch charm-thor-hlt2-lines

Possible optimization will be checked next

Mode	Particles	Selections
D^0 ! K π^+	π , K	$p_T > 250$ MeV, $p > 2$ GeV, $\chi^2_{tr} < 3$, $\chi^2\mathrm{IP} > 16$ $PID_K < 5$ for π , $PID_K > 5$ for K
	D^0	$1784 < m < 1944$ MeV, $DOCA < 0.1mm$, $\chi^2_{vtx} < 10$, $cos\theta_{dira} > 0.99985$, $VD\chi^2 > 49$
D $^+$! $D^0(K$ $\pi^+)\pi^+$	soft π D $^+$	$p_T(\pi) > 100$ MeV, $\chi^2_{tr} < 3$ $130 < m(D$ $^+)$ $m(D^0) < 160$ MeV, $\chi^2_{vtx} < 25$
D^+ ! K $\pi^+\pi^+$ D^+ ! K $K^+\pi^+$ $D^+(D_s^+)$! K $K^+\pi^+$	π , K	$p_T(all3, any2, any1) > 200, 400, 1000$ MeV, $p > 2$ GeV, $\chi^2_{tr} < 3$, $\chi^2_{\mathrm{IP}}(all3, any2, any1) > 4, 10, 50$, $PID_K < 5$ for π , $PID_K > 5$ for K
	D^+, D_s^+	1789 MeV $< m(D^+) <$ 1949 MeV, 1889 MeV $< m(D_s^+) <$ 2049 MeV $\chi^2_{vtx} < 25$, $cos\theta_{dira} > 0.9994$, $VD\chi^2 > 16$, $\tau > 0.150$ ps
D^0 ! K $\pi^+\pi$ π^+	π , K	$p_T > 200$ MeV, $p > 2$ GeV, $\chi^2_{tr} < 3$, $\chi^2_{\mathrm{IP}} > 4$, $PID_K < 5$ for π , $PID_K > 5$ for K
	D^0	1784 MeV $< m(D^+) <$ 1944 MeV, $m(hhh) < m(hhhh)_{\max}$ $M(\pi)$, $m(hh) < m(hhhh)_{\max}$ 2 $M(\pi)$ $\chi^2_{vtx} < 25$, $cos\theta_{dira} > 0.9998$, $VD\chi^2 > 16$, $\tau > 0.150$ ps

* $m(hhhh)_{\max}$ = 1954 MeV, $M(\pi)$ = 139.57061 MeV

HLT2 selections (baryons)

R. Amalric, A. Gunther, P. Li, F. Oliva, R. O'Neil

- Mostly follow the cuts applied in Run 2 Turbo lines
- Possible optimization will be checked after the first commissioning run
- χ^2_{trk} and $GhostProb_{Trk}$ removed, UT not in place at the beginning of the data taking
- PID variables are especially under comparison
  - ! Run 2 PID cuts on PIDp-PIDK for proton removed for ${}_c^+$, ${}_c^+$
  - ! PID cuts for ${}_c^0$ loosen with respect to Run2
  - ! Final choice to have the same PID cuts for ${}_c^+$, ${}_c^+$, ${}_c^0$

Mode	Particles	Selections
${}_c^+$ (${}_c^+$) ! pK π^+	p , π , K	$p > 1$ GeV, $\chi^2\mathrm{IP}(all3, any1, any2) > 6, 16, 9$ $\mathrm{P}_T(all3, any1, any2, sum) > 200, 1000, 400, 3000$ MeV, $\mathrm{p_p} > 10$ GeV $PID_p > 5$ for p , $PID_K < 5$ for π , $PID_K > 5$ for K
	${}_c^+$ ${}_c^+$	$2211 < m < 2362$ MeV, $\chi^2_{vtx} < 10$, $cos\theta_{dira} > 1.57$, $\tau > 0.15$ ps $2392 < m < 2543$ MeV, $\chi^2_{vtx} < 10$, $cos\theta_{dira} > 1.57$, $\tau > 0.15$ ps
${}_c^0$! pK K π^+	p , π , K	$p > 1$ GeV, $\chi^2\mathrm{IP}(all3, any1, any2) > 4, 8, 6$ $\mathrm{P}_T(all3, any1, sum) > 500, 1000, 3000$ MeV, $\mathrm{p_p} > 10$ GeV $PID_p > 5$ for p , $PID_K < 5$ for π , $PID_K > 5$ for K
	${}_c^0$	$2396 < m < 2770$ MeV, $\chi^2_{vtx} < 10$, $cos\theta_{dira} > 0.01$

HLT2 lines & Rate estimation

R. Amalric, A. Günther, P. Li, R. O'Neil

Ran over 15k old hlt1 filtered minibias sample to estimate the rate
Prescale 1 at the moment as we don't expect an high lumi at the beginning of the data taking
Currently working also on the comparison between the expected signal rate (from theoretical computation) and the rate extracted with MooreAnalysis, ongoing study using minbias sample to introduce additional cuts to help to reduce the rate

Mode	Line name	Incl. rate (kHz)	Excl. rate (kHz)
D^0 ! K $\pi^+\pi$ π^+	Hlt2CharmD0ToKmPipPipPim_XSecLine	8.81 0.76	5.61 0.60
D^0 ! K π^+	Hlt2CharmD0ToKmPip_XSecLine	11.55 0.87	8.94 0.76
D^+ ! K $K^+\pi^+$	Hlt2CharmDToKmKpPip_XSecLine	4.27 0.53	1.46 0.31
D^+ ! K $\pi^+\pi^+$	Hlt2CharmDToKmPipPip_XSecLine	11.95 0.08	10.28 0.82
D $^+$! $D^0(K$ $\pi^+\pi^+\pi$ $)\pi^+$	Hlt2CharmDstpToD0Pip_D0ToKmPipPipPim_XSecLine	2.07 0.37	0.0 0.0
D $^+$! $D^0(K$ $\pi^+)\pi^+$	Hlt2CharmDstpToD0Pip_D0ToKmPip_XSecLine	2.20 0.38	0.0 0.0
D_s^+ ! K^+K π^+	Hlt2CharmHadDsToKmKpPip_XSecLine	5.27 0.59	1.46 0.31
D^0 ! $K_S^0(K^+K$ $)_{\mathrm{DD}}$	Hlt2CharmHadD0ToKKKsDD_XSecLine	0.13 0.09	0.0 0.0
D^0 ! $K_S^0(K^+K$ $)_{\mathrm{LL}}$	Hlt2CharmHadD0ToKKKsLL_XSecLine	0.07 0.06	0.07 0.0
D^0 ! $K_S^0(\pi^+\pi$ $)_{\mathrm{DD}}$	Hlt2CharmHadD0ToPiPiKsDD_XSecLine	1.00 0.25	0.80 0.23
D^0 ! $K_S^0(\pi^+\pi$ $)_{\mathrm{LL}}$	Hlt2CharmHadD0ToPiPiKsLL_XSecLine	1.20 0.28	0.90 0.23
D $^+$! $D^0(K_S^0K^+K$ $)_{\mathrm{DD}}\pi^+$	Hlt2CharmHadDstToD0Pi_D0ToKKKsDD_XSecLine	0.07 0.06	0.0 0.0
D $^+$! $D^0(K_S^0K^+K$ $)_{\mathrm{LL}}\pi^+$	Hlt2CharmHadDstToD0Pi_D0ToKKKsLL_XSecLine	0.0 0.0	0.0 0.0
D $^+$! $D^0(K_S^0\pi^+\pi$ $)_{\mathrm{DD}}\pi^+$	Hlt2CharmHadDstToD0Pi_D0ToPiPiKsDD_XSecLine	0.13 0.09	0.0 0.0
D $^+$! $D^0(K_S^0\pi^+\pi$ $)_{\mathrm{LL}}\pi^+$	Hlt2CharmHadDstToD0Pi_D0ToPiPiKsLL_XSecLine	0.20 0.11	0.0 0.0
$_c^+$! pK π^+	Hlt2CharmHadLcpToPpKmPip_XSecLine	3.87 0.50	1.74 0.34
$_c^0$! pK K π^+	Hlt2CharmHadXic0ToPpKmKmPip_XSecLine	0.47 0.17	0.33 0.14
$_c^+$! pK π^+	Hlt2CharmHadXicpToPpKmPip_XSecLine	3.14 0.45	1.67 0.33
DD	Hlt2DoubleCharmMesonOS_XSecLine	0.27 0.13	0.0 0.0
DD	Hlt2DoubleCharmMesonSS_XSecLine	0.13 0.09	0.0 0.0
HLT2 Total:	Rate: (43.0 1.7) kHz		

Ran with Oct. FEST minibias with (Hlt1TrackMVA ¡¡ Hlt1TwoTrackMVA): (41 4.9) kHz

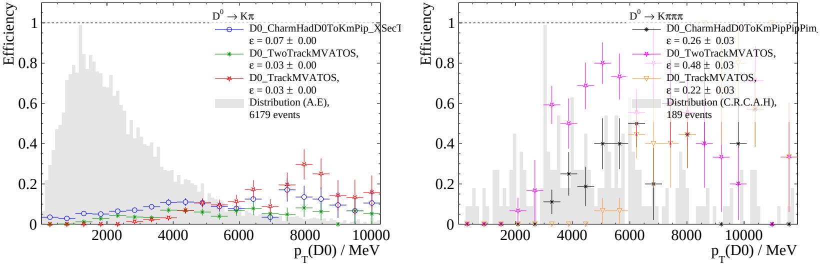
HLT1 & HLT2 efficiency

A. Günther, F. Oliva

Signal MC sample $D^0 \to K\ \pi^+$ with MooreAnalysis

$$\varepsilon_{\mathrm{triggered}|\mathrm{acc,X}} = \frac{N_{\mathrm{triggered}}}{N_{\mathrm{acc,X}}}$$

- X= daughters in acceptance (left plot) + reconstructible + HLT1 triggered (right plot)
- HLT1 triggered by HLT1TrackMVA or HLT1TwoTrackMVA
- (pseudo) TOS: MC-matched



Study on HLT1 line with low p_T carried on by A. Günther.

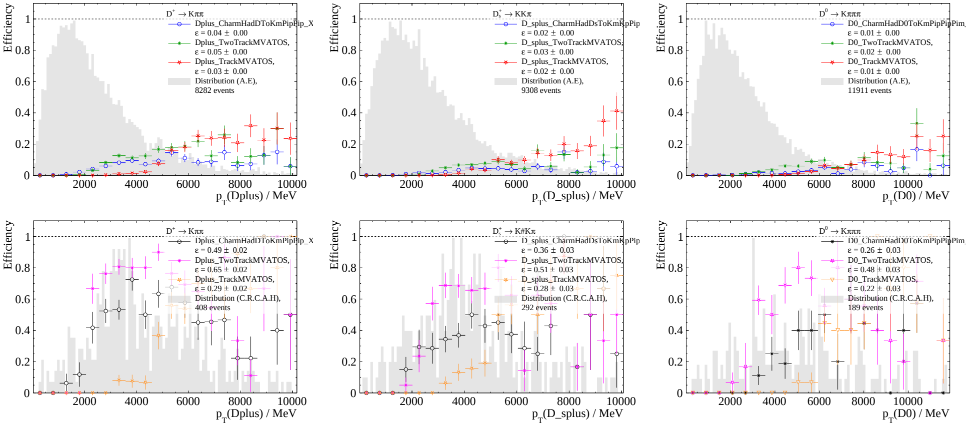
HLT1 TwoTrack line for low PT Hadrons added in A. Günther branch (Merge Request !751)

HLT1 & HLT2 efficiency sudies

A. Günther, F. Oliva

Signal MC samples $D^+ \ ! \ K \ \ \pi^+\pi^+$, $D_s^+ \ ! \ K \ \ K^+\pi^+$ and $D^0 \ ! \ K \ \ \pi \ \ \pi^+\pi^+$

- upper row: $\varepsilon_{\mathrm{HLT2}j\mathrm{acc}}$ (overall agree with Run 2)
- bottom row: $\varepsilon_{\mathrm{HLT2}j\mathrm{X}}$, X= acc+reconstructible+HLT1 triggered by HLT1TrackMVA or HLT1TwoTrackMVA

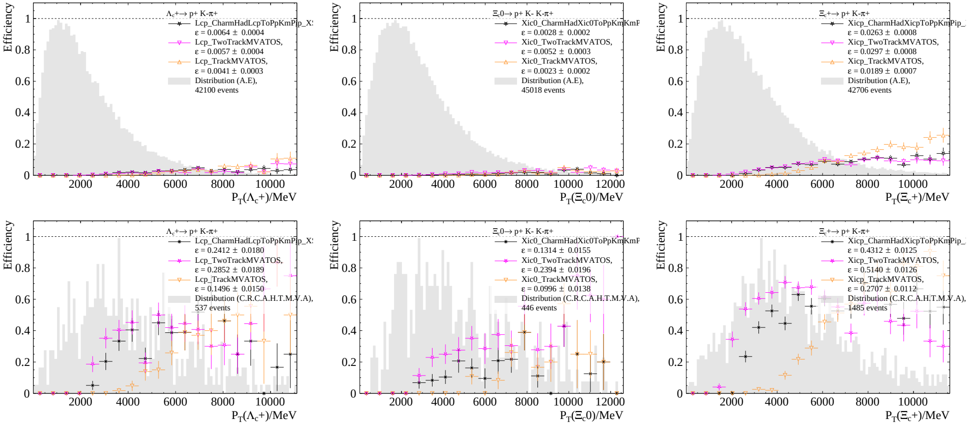


HLT1 & HLT2 efficiency studies

A. Günther, F. Oliva

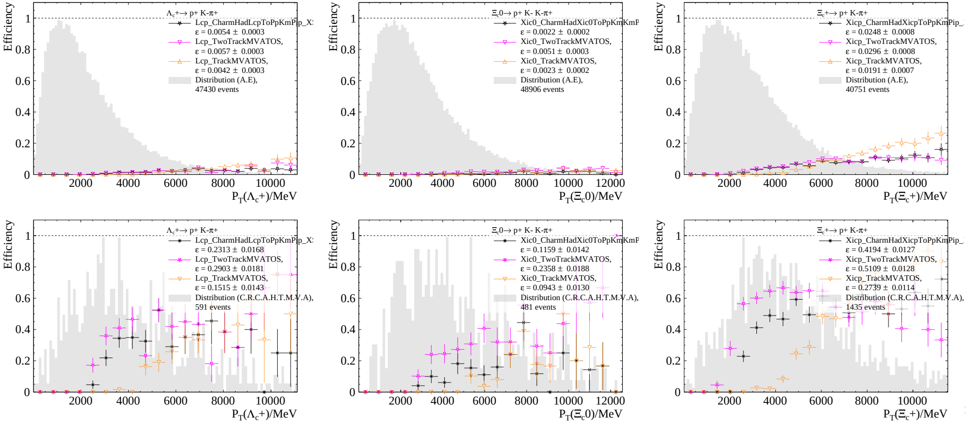
Signal MC samples $\Lambda_c^+ \to pK^-\pi^+$, $\Xi_c^0 \to pK^-K^-\pi^+$ and $\Xi_c^+ \to pK^-\pi^+$

- upper row: $\varepsilon_{\mathrm{HLT2}|\mathrm{acc}}$ (overall agree with Run 2)
- bottom row: $\varepsilon_{\mathrm{HLT2}|\mathrm{X}}$, X= acc.+reconstructible+HLT1 triggered by HLT1TrackMVA or HLT1TwoTrackMVA



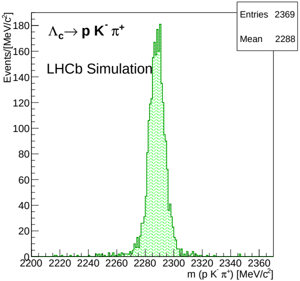
HLT1 & HLT2 efficiency studies without UT

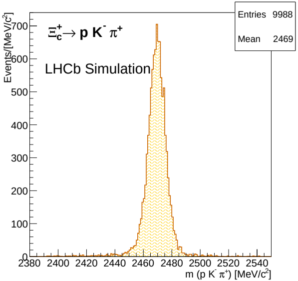
- Study performed to understand the expected efficiency during the first part of the data taking without UT (skipped in the reconstruction)
- Efficiency reduced of the 15% without UT info
- Signal MC samples below: ^+_c ! $pK\ \pi^+$, ^0_c ! $pK\ K\ \pi^+$ and ^+_c ! $pK\ \pi^+$

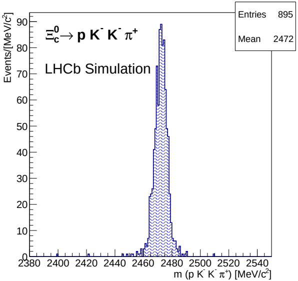


First mass distribution running available MC signal samples skipping UT at the reconstruction level

First plots produced with DaVinci v54r1 using still DecayTreeTuple







FunTuple also used, plots will be shown later for minbias

HLT2 efficiency comparison MooreAnalysis (MA) & Moore+DV (M+DV) chain

First test with Baryon lines, HLT2 efficiency considered for MooreAnalysis over the entire number of generated events.

$^{+}_{c}$! pK π^{+}

\# MC events from Dirac Portal: MD 201046, MU 204027, Tot 405073

\# tot events Truth Matching only $^{+}_{c}$ = 2369

$\epsilon_{M+DV} = 0.0058$, $\epsilon_{MA} = 0.0054$

$^{0}_{c}$! pK K π^{+}

\# MC events from Dirac Portal: MD 201707, MU 202955, Tot 404662

\# tot events Truth Matching only $^{0}_{c}$ = 895

$\epsilon_{M+DV} = 0.0022$, $\epsilon_{MA} = 0.0022$

$^{+}_{c}$! pK π^{+}

\# MC events from Dirac Portal: MD 200351, MU 200948, Tot 401299

\# tot events Truth Matching only $^{+}_{c}$ = 9988

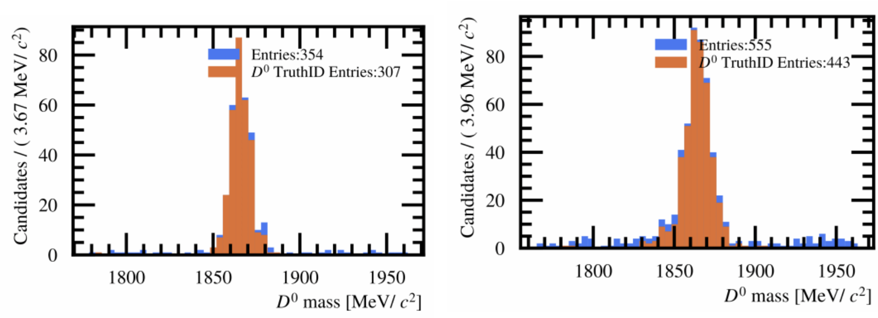
$\epsilon_{M+DV} = 0.025$, $\epsilon_{MA} = 0.0248$

First reconstruction efficiency studies from MC signal samples

Reconstruction efficiency ratio without UT extracted by R. Almalric for D^{+}: D^{+} ! D^0(! $K_S^0\pi\pi$) π^{+} extracted for K_S(LL) (left) and K_S(DD) (right) (slides)

Ratio DD/ LL different from the Run 2

Lower reconstruction efficiency of downstream tracks to be further investigate in the future

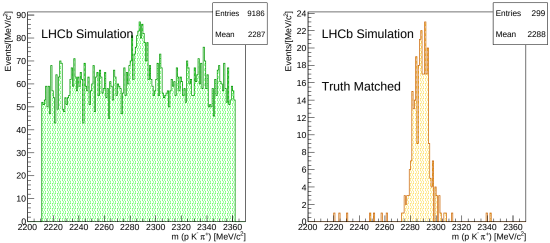


First mass distribution running minbias with high stats skipping UT at the reconstruction level

24 M events available for MagDown only (minbias with the highest statistics available)

BK path: /MC/Upgrade/30000000/Beam7000GeV-Upgrade-MagDown-Nu7.6-25ns-Pythia8/Sim10aU1/DIGI

First plots produced for baryons ($\Lambda_c^+ \to pK^- \pi^+$ below) and mesons (next slide).

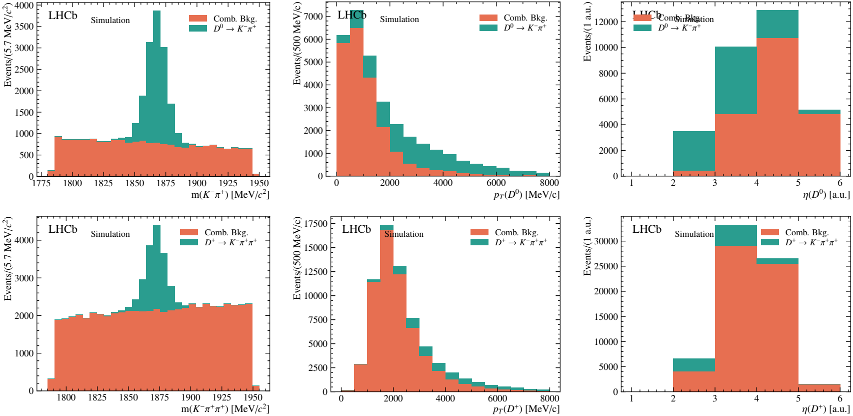


Higher background with respect Run2 expected, due to the higher luminosity

Ongoing studies to choose offline cuts to reduce background, looking at the purity of the signal

First mass distribution running minbias with high stats skipping UT at the reconstruction level

Working FunTuple code used, developed and tested by A. Günther



Signal extraction

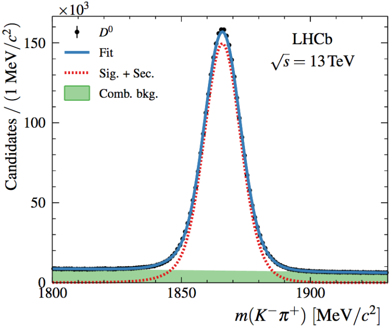
A. Burke

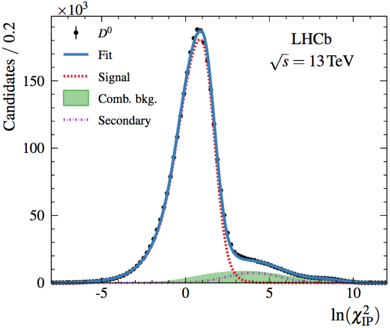
Separate signal and combination background with a mass fit

Separate prompt and secondary signal with a ln χ^2_{IP} fit

First version of mass fit scripts are ready, tested with Run 2 tuples

Background for some of the modes might be more tricky





*plots taken from Run 2 measurements as illustration

Plans

Study of additional offline cuts to reduce the background

Add HLT2 or offline monitor: *e.g.* mass distributions

Evaluation of the selection efficiencies

- HLT1 & HLT2 efficiency with and without UT in progress
- Tracking (R. Caspary): well-prepared TrackCalib, study of the hadronic interactions
- PID (E. Ejopu): just starts, check the PID calibration status for Run 3

Signal yields extraction

- Determine fit models for each decay mode
- Careful study of background for some of decay modes required

Systematic uncertainties: PID, Tracking, luminosity

Prepare analysis snakemake pipeline and documentation

Summary

- Preparation for data taking of Run 3 is in progress, regular meetings with proponents
- Repository created with snakemake skeleton implemented for analysis
- HLT2 lines merged in charm-thor-hlt2-lines branch of Moore
- Study of HLT1 and HLT2 efficiency performed with and without UT at the reconstruction level
- HLT2 efficiency with MooreAnalysis and Moore+DaVinci chain in agreement
- Working Funtuple code and first ntuples produced both for MC signal and minbias (with DecayTreeTuple and Funtuple), stored in the EM Charm WG area
- First version of mass fit scripts is ready and tested with Run 2 tuples
- Ongoing tests on additional cuts to help to reduce the overall rate
- Many pieces of work just start: PID, tracking efficiency, documentation...
- Luminosity would largely rely on the measurement of luminosity working group
- Theoretical prediction for charm meson cross sections can be provided by theorists

Thanks for your attention!

*Referred several previous talks(29-07-2019, 18-05-2020, 14-12-2020) given by Alex Pearce.

Back up: Branching fractions

Table: Branching fractions from PDG

Channels	Branching fractions
$D^0 \rightarrow K^- \pi^+$	$(3.950 \pm 0.031)\%$
$D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$	$(8.23 \pm 0.14)\%$
$D^+ \rightarrow K^- \pi^+ \pi^+$	$(9.38 \pm 0.16)\%$
$D^+ \rightarrow K^+ K^- \pi^+$	$(9.68 \pm 0.18) \times 10^{-3}$
$D^+ \rightarrow \phi(\rightarrow K^+ K^-)\pi^+$	$(5.70 \pm 0.14) \times 10^{-3}$
$D_s^+ \rightarrow K^+ K^- \pi^+$	$(5.39 \pm 0.15)\%$
$\Lambda_c^+ \rightarrow p K^- \pi^+$	$(6.28 \pm 0.32)\%$