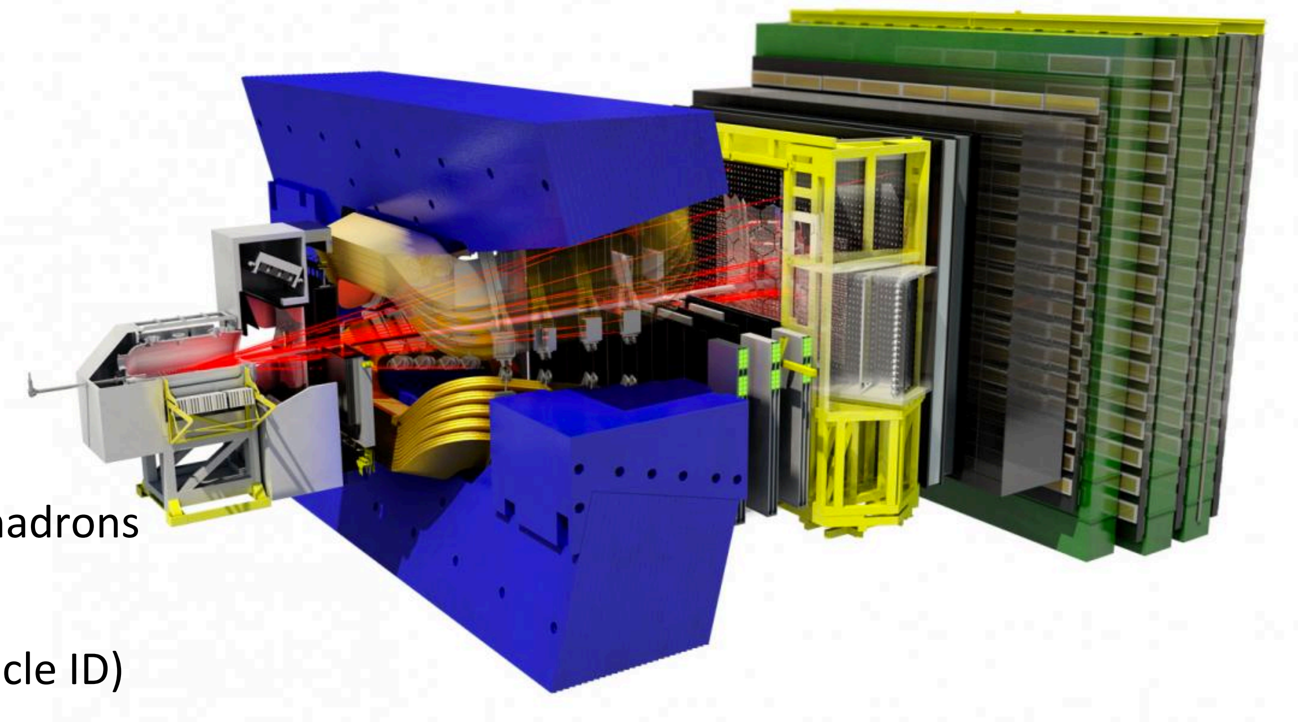
Charm Physics at LHCb

MANCHESTER 1824
The University of Manchester

Mark Williams, on behalf of the LHCb collaboration
UK Flavour Meeting, IPPP, Durham
4 September 2017

Charm at LHCb: Why?



A charm factory:

- Huge samples of charm hadrons
- Precision capabilities (vertexing, tracking, particle ID)

A fruitful field:

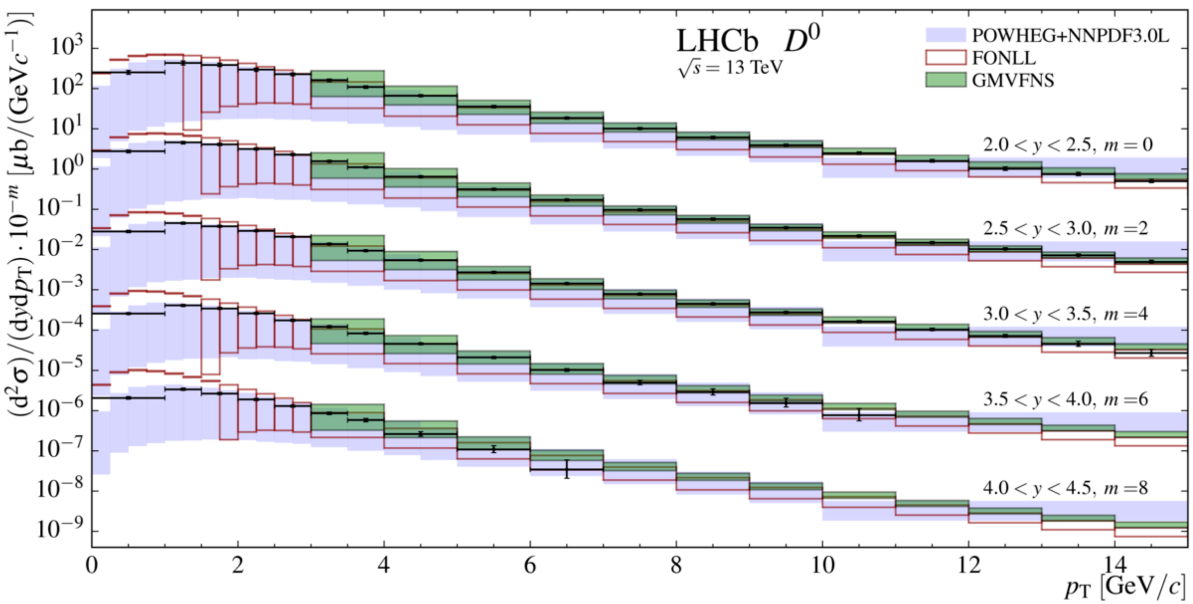
- Charm mixing: is mass difference (x) non-zero? Do parameters agree with SM?
- Any CP violation? (direct or indirect) − none yet observed.
- Rare charm decays: many limits are very old − low-hanging fruit for NP searches

Charm at LHCb: How?

Charmed particles produced copiously at LHCb

$$\sigma(pp \to D^0 X) = 2072 \pm 2 \pm 124\,\mu\text{b}$$
$$\sigma(pp \to D^+ X) = 834 \pm 2 \pm 78\,\mu\text{b}$$
$$\sigma(pp \to D_s^+ X) = 353 \pm 9 \pm 76\,\mu\text{b}$$
$$\sigma(pp \to D^{*+} X) = 784 \pm 4 \pm 87\,\mu\text{b}$$

JHEP 05 (2017) 074
ARXIV:1510.01707
(13 TeV,
2 < η < 4.5,
0 < pT < 8 GeV/c)



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⇒ In 2017:
>5% of all bunch crossings produce a charm meson within LHCb acceptance

~2 MHz → **~1 MHz** → **~15 kHz**

Charm mesons in acceptance → Hardware trigger limit → Event rate written to tape

How do we deal with this abundance of riches?!

Charm at LHCb: How?

A: Novel trigger strategy – the ‘Turbo’ approach

- Full event reconstruction used in trigger decision (with real-time detector calibration and alignment)

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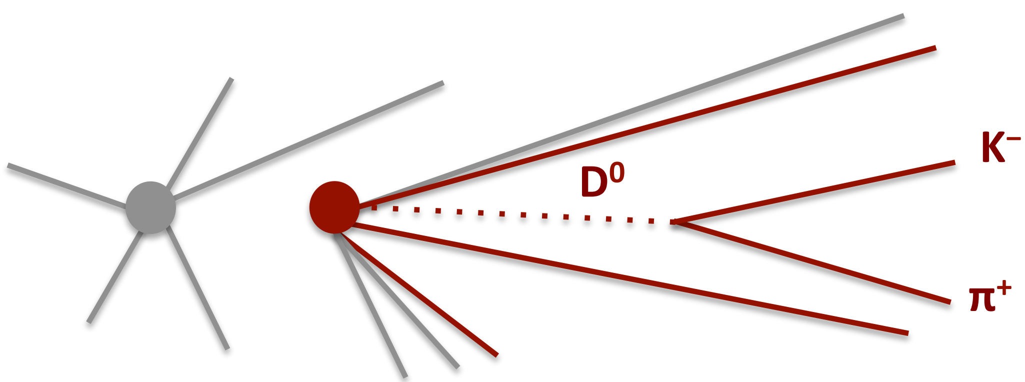
- Flexible approach – custom trigger line for each channel ⇒ **different information can be stored for different analysis needs**



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'Traditional' triggers:
~10 kHz total
~600 MB/s

Turbo triggers:
~3 kHz total
~60 MB/s

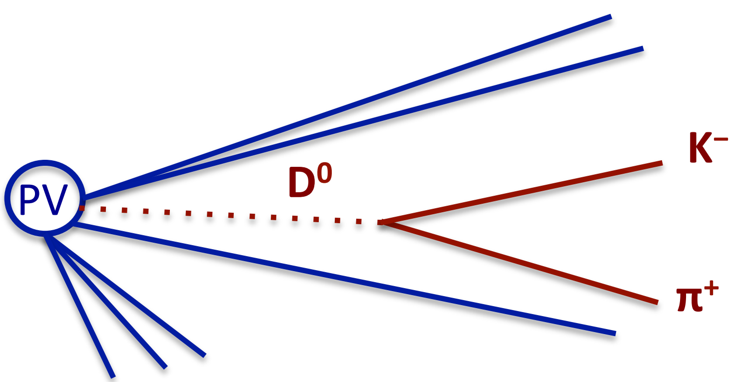
Charm at LHCb: How?

A: Novel simulation and analysis tools

Monte Carlo sample sizes starting to limit precision on high-statistics analyses

CPU-expensive

⇒ New ReDecay method implemented: Reuse underlying event multiple times – **10-50x faster** than ‘Full’ MC.



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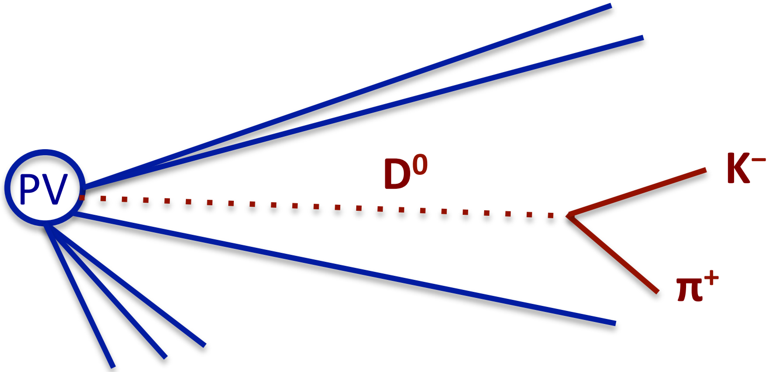

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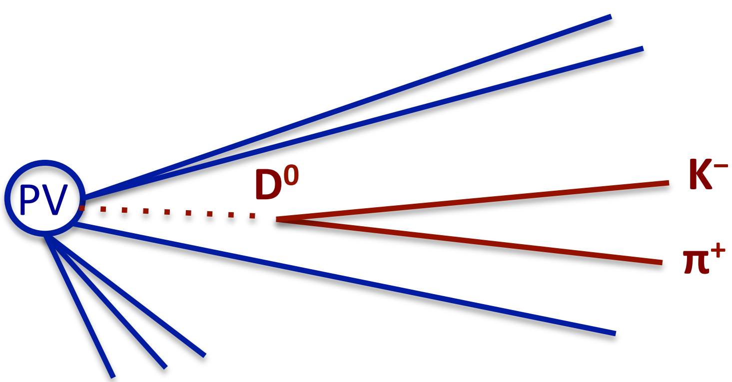

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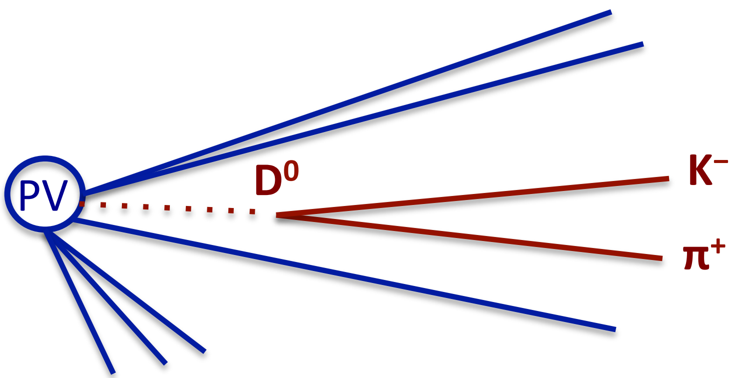
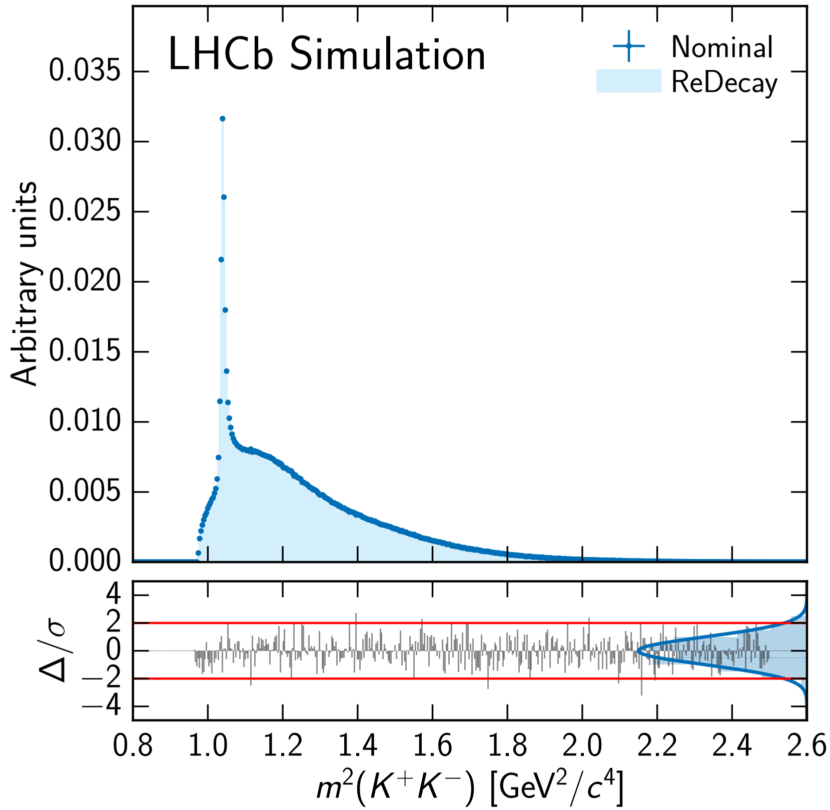
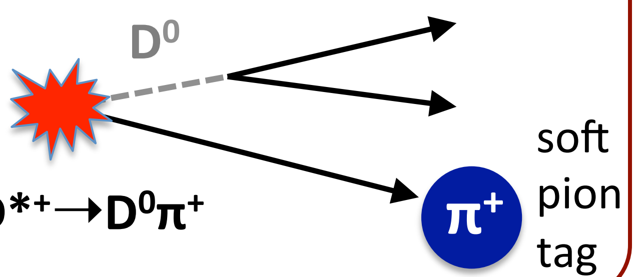




Charm at LHCb: How?

A: Complementary samples

π-tagged ("prompt charm")



$pp \to D^{*+} \to D^0\pi^+$

Lifetime-biasing trigger
⇒ must apply correction in analysis.

Narrow reconstructed D* peak
⇒ **High signal purity**

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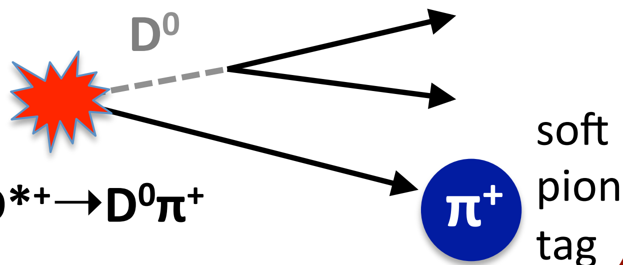

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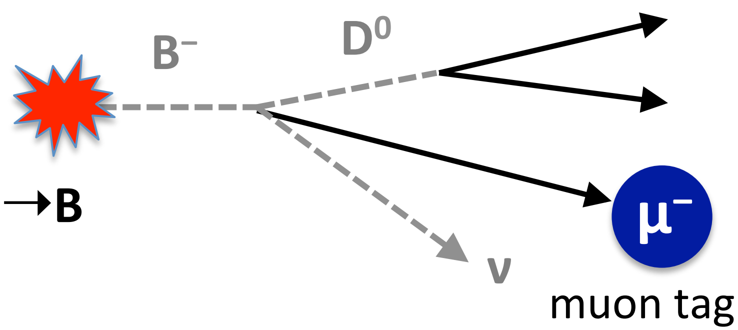
μ-tagged ("charm from B")



$pp \rightarrow B$

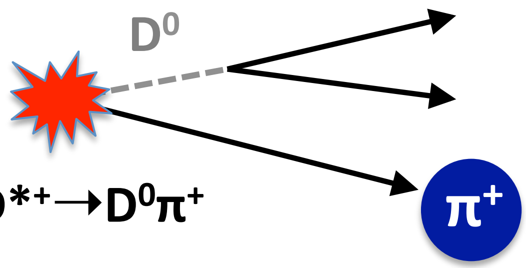
Lifetime unbiased trigger selection

No $D^{*\pm}$ mass peak to cut on
⇒ **higher backgrounds**

Charm at LHCb: How?

A: Complementary samples

π-tagged ("prompt charm")



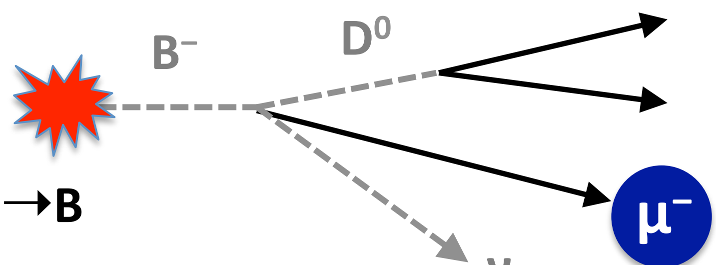
$pp \rightarrow D^{*+} \rightarrow D^0\pi^+$

soft pion tag

Lifetime-biasing trigger
⇒ must apply correction in analysis.

Narrow reconstructed D* peak
⇒ **High signal purity**

μ-tagged ("charm from B")



$pp \rightarrow B$

muon tag

Lifetime unbiased trigger selection

No $D^{*\pm}$ mass peak to cut on
⇒ **higher backgrounds**

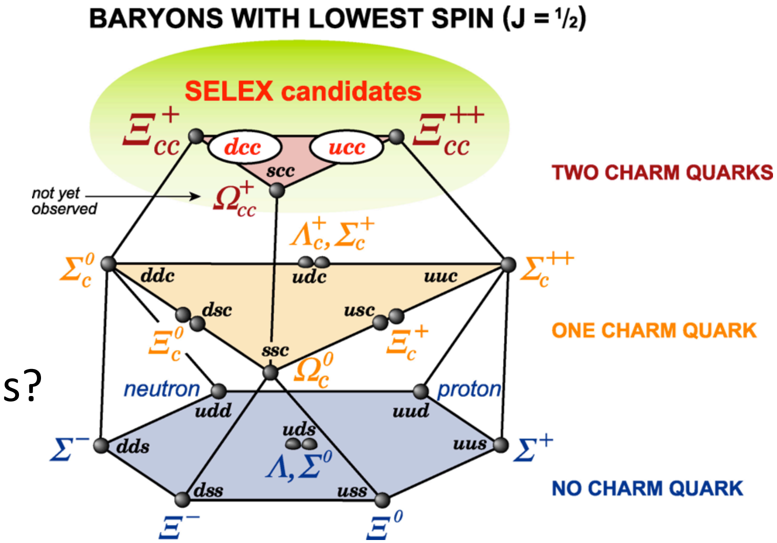
+ Double-tagged:
$(B^0 \rightarrow \mu^-\nu X)D^{*+} \rightarrow \pi^+D^0$
Best of both worlds (but lower yields)

Charm at LHCb: What?

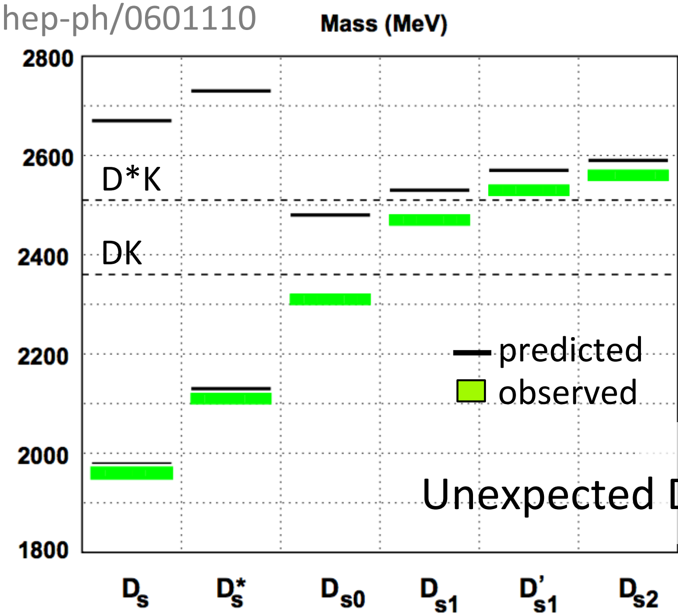
Three main analysis strands:

1. **Production and decay properties**

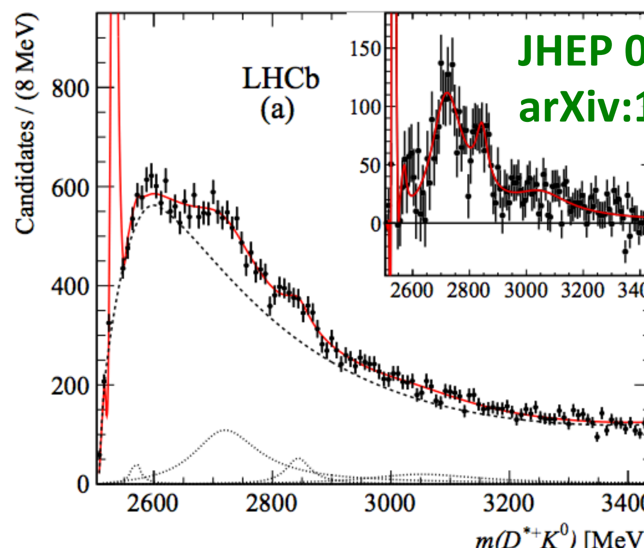
Double-heavy baryons?



Swanson, arXiv:hep-ph/0601110



Unexpected D_{sJ} states?



JHEP 02 (2016) 133
arXiv:1601.01495

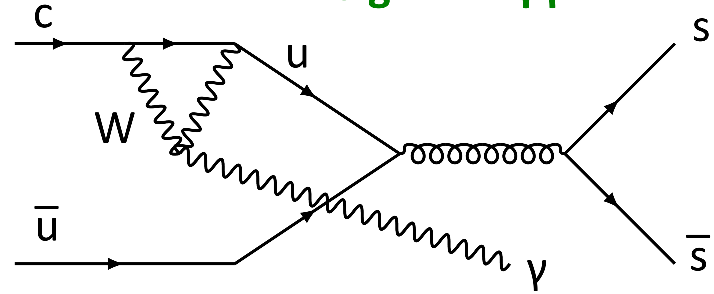
$D^*_{s2}(2573)^+$
$D^*_{s1}(2700)^+$
$D^*_{sJ}(2860)^+$
$D_{sJ}(3040)^+$

Charm at LHCb: What?

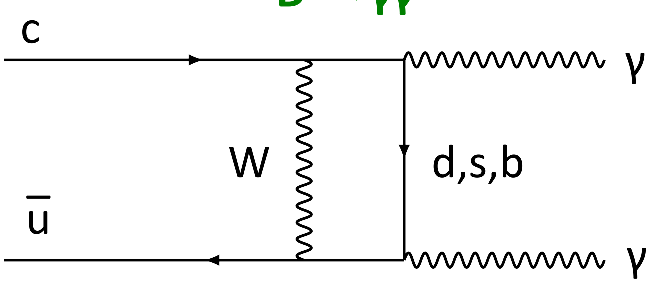
Three main analysis strands:

1. Production and decay properties
2. **Rare Charm Decays**

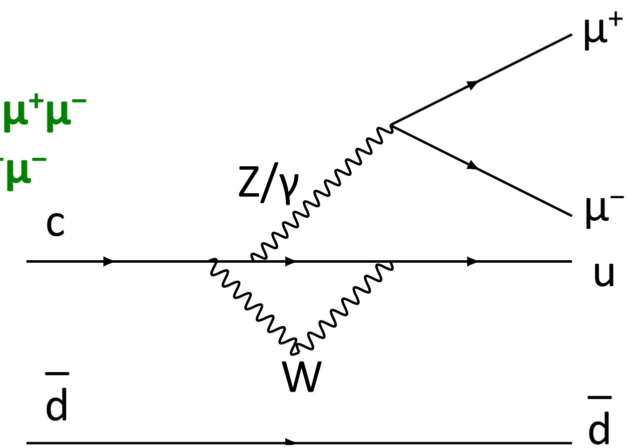
Radiative
e.g. $D^0 \to \phi\gamma$

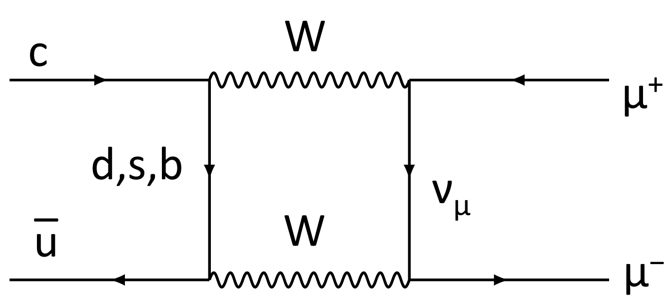


$D^0 \to \gamma\gamma$



FCNC
e.g. $D^0 \to \mu^+\mu^-$
$D^+ \to \pi^+\mu^+\mu^-$



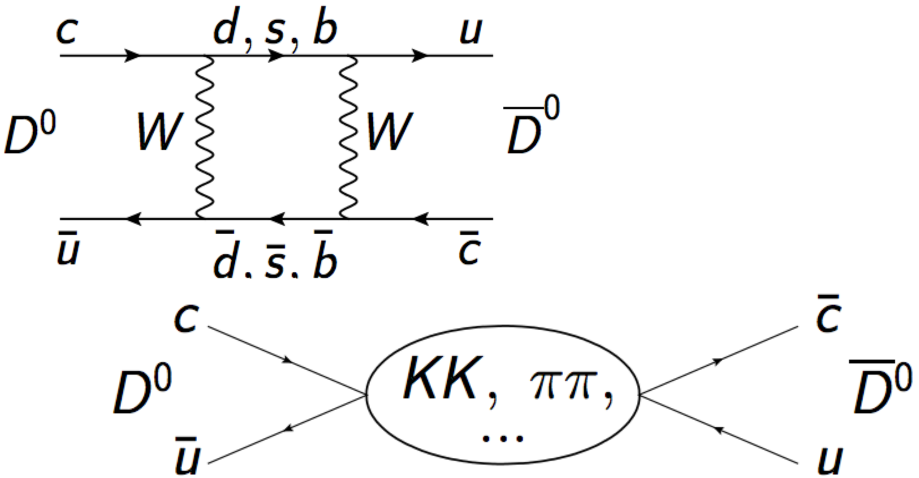


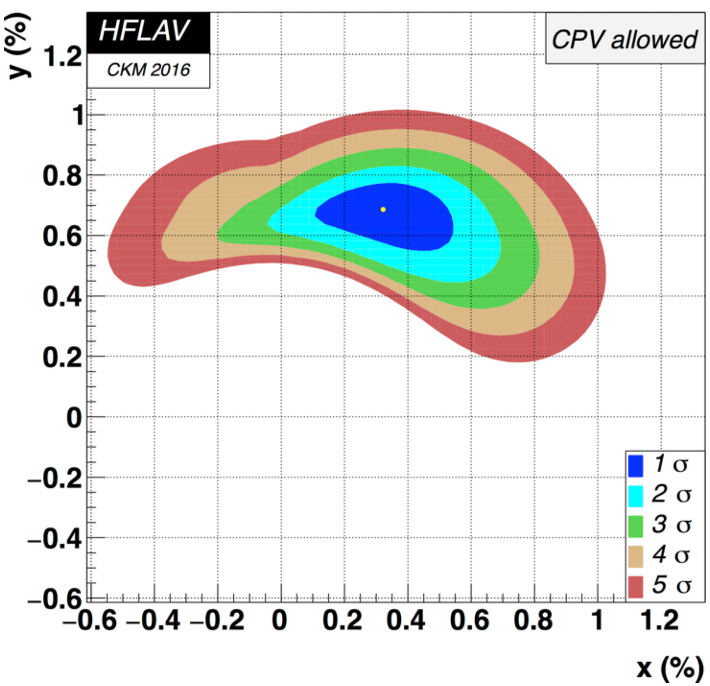
+ LFV
+ LNV
+ ...

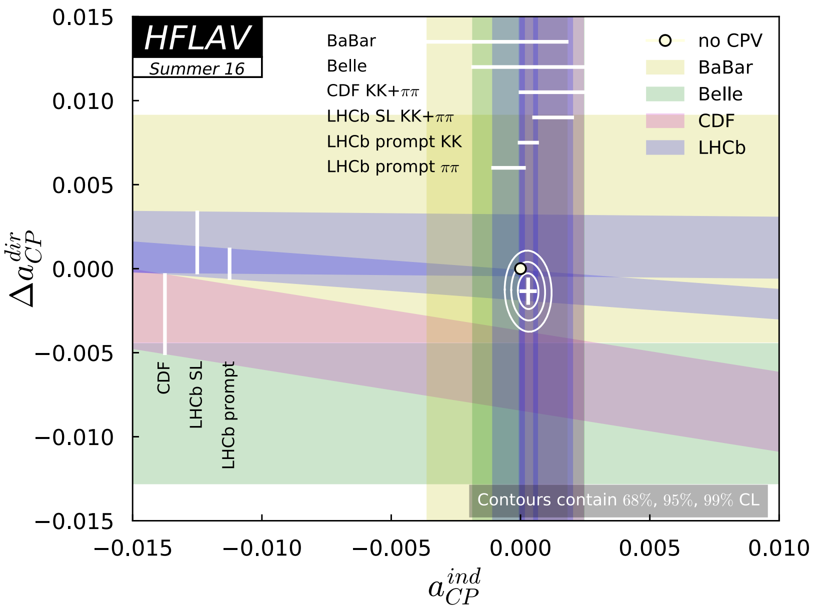
Charm at LHCb: What?

Three main analysis strands:

1. Production and decay properties
2. Rare Charm Decays
3. **Mixing and CP violation**

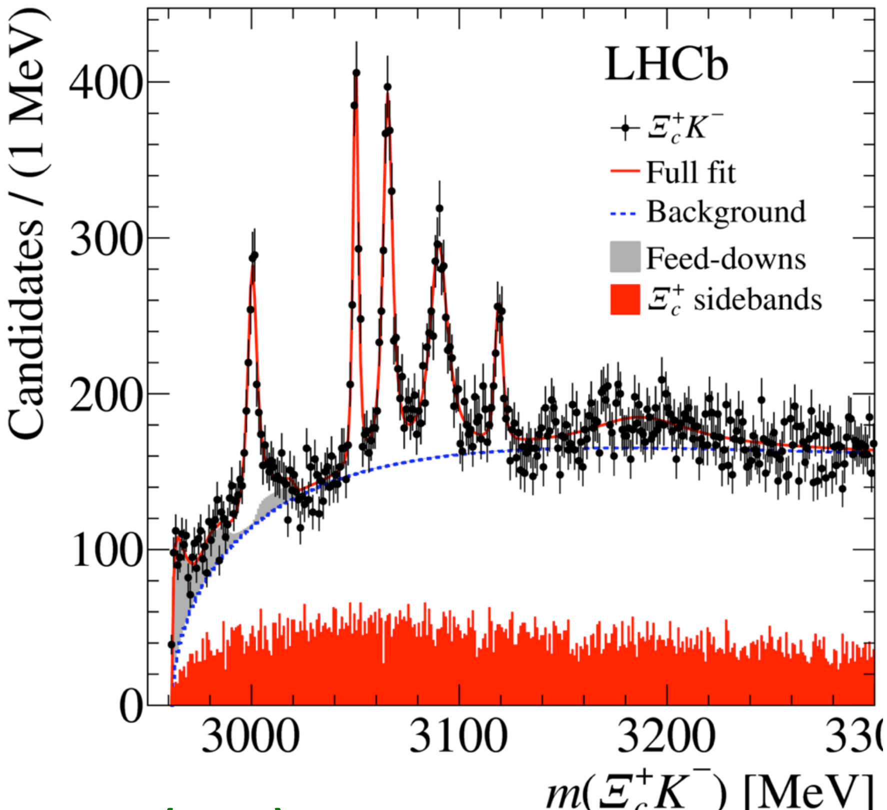






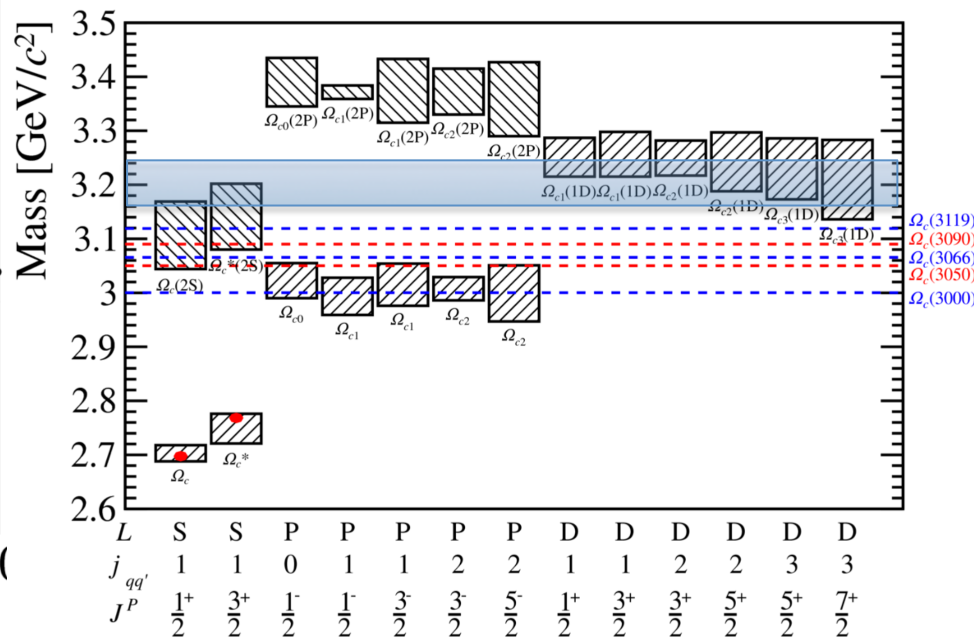
Production and decay properties

Spectroscopy – See talk by P. Spradlin



PRL 118 (2017) 182001
arXiv:1703.04639

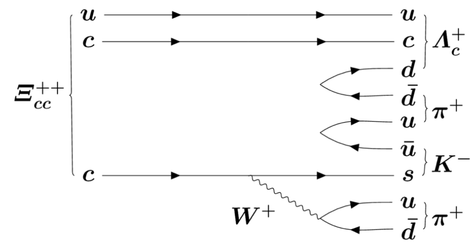
- 5 **new** Ω_c^{0**} peaks observed (>10 sigma)
- + broad excess at 3200 MeV



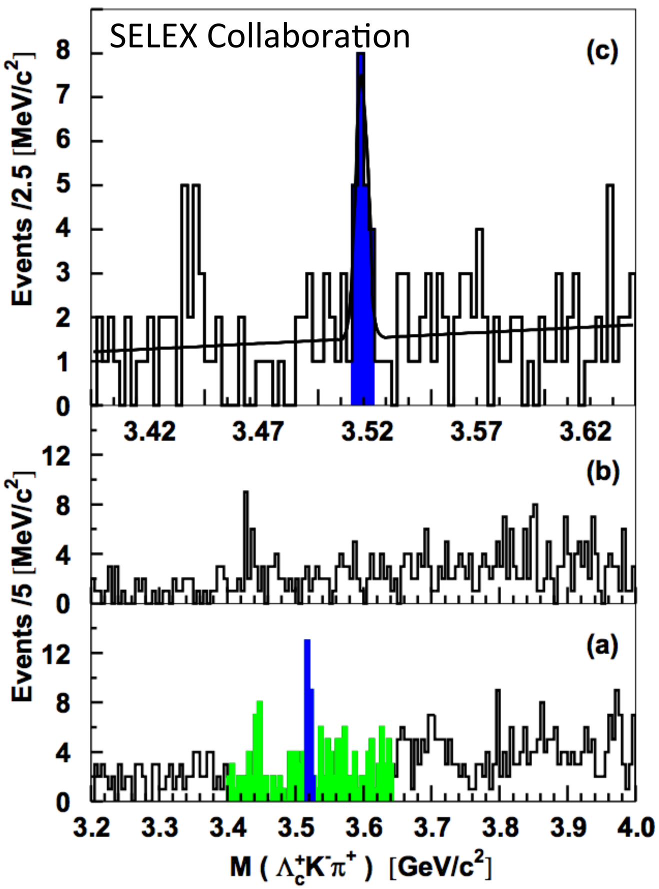
- Work ongoing in other channels to identify quantum numbers

Production and decay properties

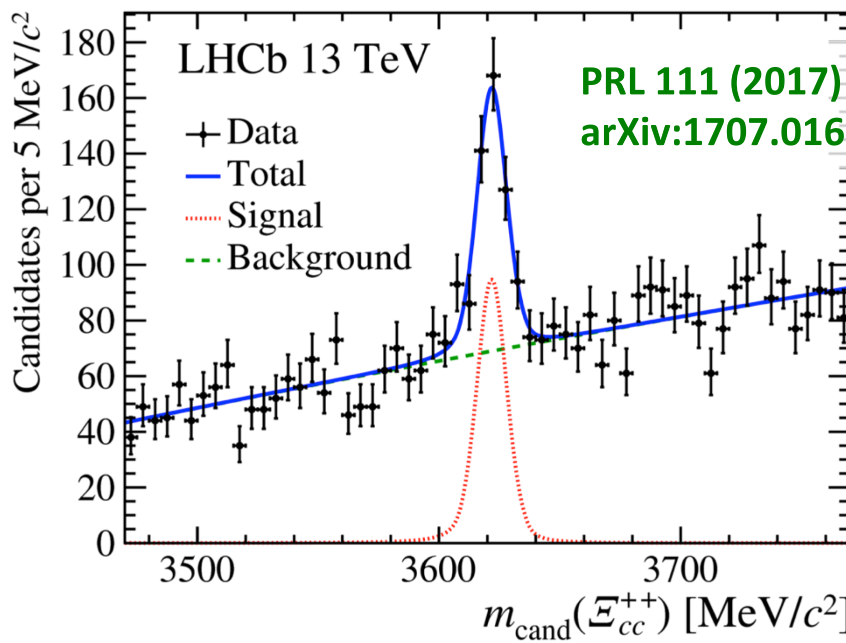
Spectroscopy – See talk by P. Spradlin



- First observation of double-charmed baryon Ξ_{cc}^{++}
- Mass inconsistent with SELEX Ξ_{cc}^{+} state
- Long-lived (full lifetime analysis ongoing)



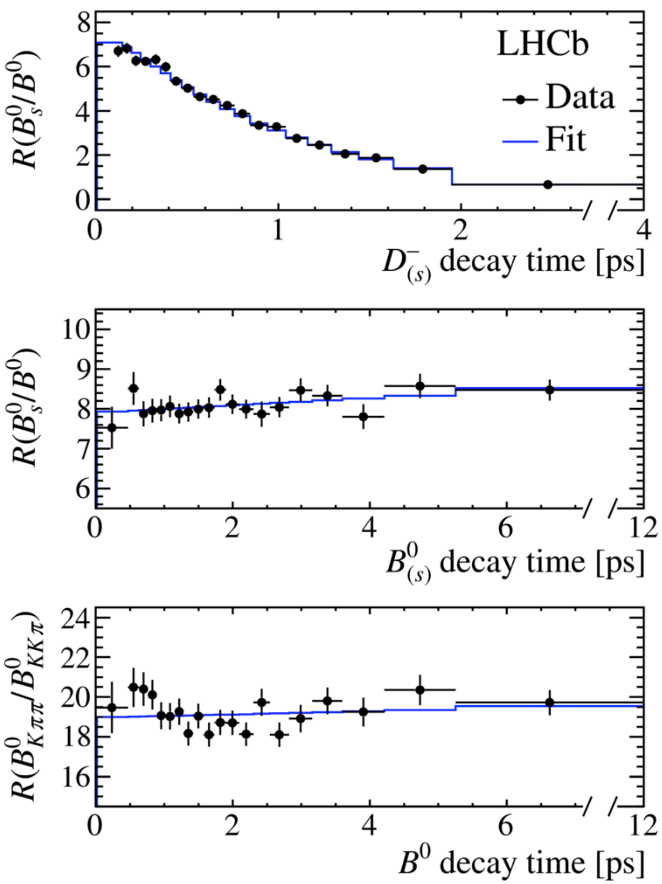
arXiv:hep-ex/0208014 (2002)



PRL 111 (2017) 180001
arXiv:1707.01621

Production and decay properties

Charm lifetimes



arXiv:1705.03475
Submitted to PRL

Reconstruct $B_s^0 \to D_s^{(*)-} \mu^+ \nu_\mu$ $B^0 \to D^{(*)-} \mu^+ \nu_\mu$
in same final state $K^+K^-\pi^-\mu^+$

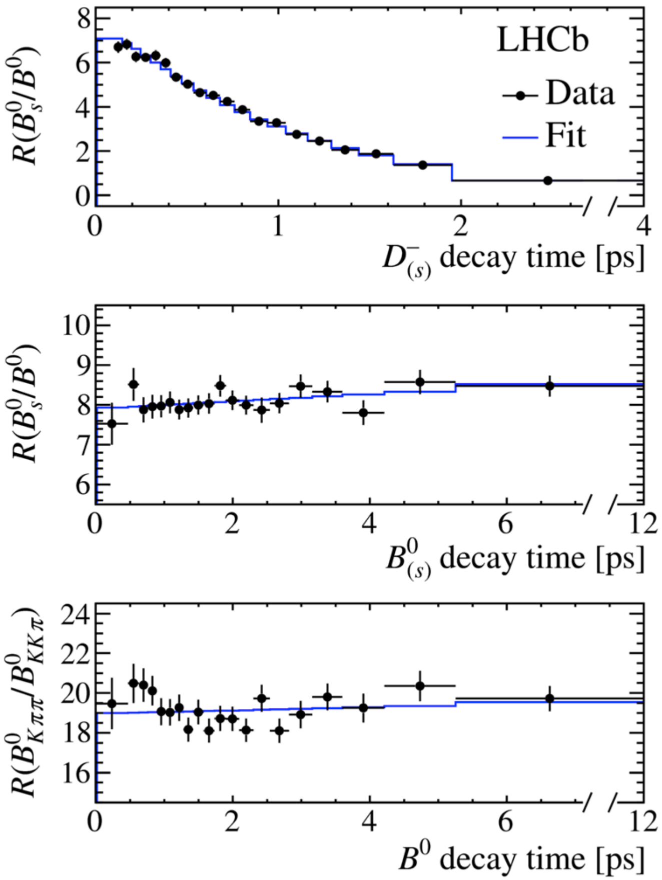
Use known B^0 and D^- lifetimes as references, to determine B_s^0 and D_s^- lifetimes:

$\tau(D_s^-) = 0.5064 \pm 0.0030 \pm 0.0017 \pm 0.0017$ ps
(stat) (syst) [$\tau(D^-)$]

WA: 0.5000 ± 0.0070 ps

Production and decay properties

Charm lifetimes



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(stat) (syst) [$\tau(D^-)$]

WA: 0.5000 ± 0.0070 ps

- Now developing this method for other time-dependent analyses (**y_{CP}**)
- New **decay-time unbiased triggers** added for Run 2 – using these in parallel to measure charm lifetimes

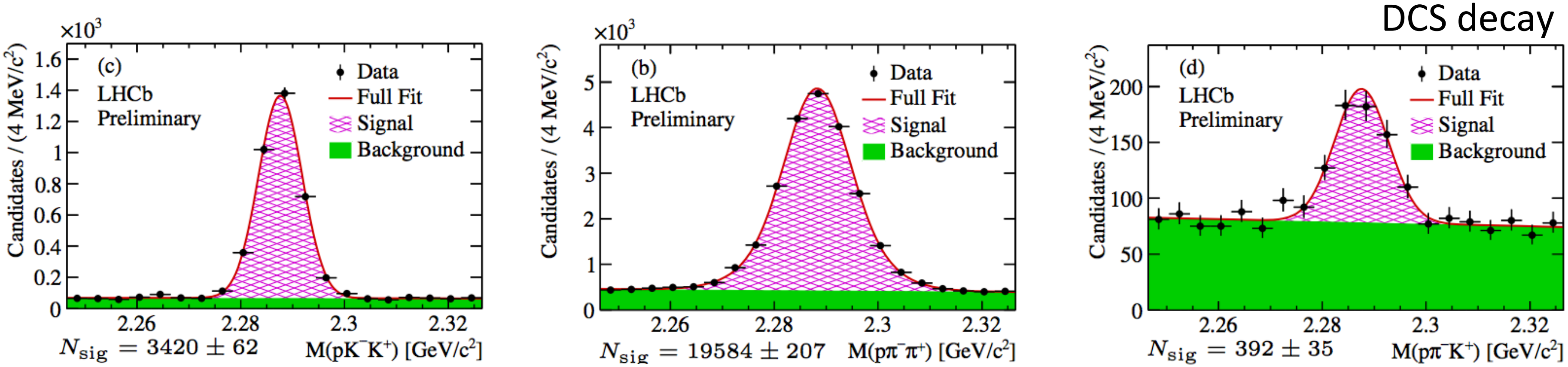
Λ_c^+ Branching Ratios

Until recently, Λ_c^+ branching fractions poorly known

Hot-off-the-press LHCb analysis measures ratios of decay rates for CF, SCS, and DCS modes:

$$\frac{\mathcal{B}(\Lambda_c^+ \to pK^-K^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} \qquad \frac{\mathcal{B}(\Lambda_c^+ \to p\pi^-\pi^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} \qquad \frac{\mathcal{B}(\Lambda_c^+ \to p\pi^-K^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)}.$$

DCS decay



Use both μ-tagged sample (shown) and π-tagged sample

In preparation
LHCb-PAPER-2017-026

Production and decay properties

Λ_c^+ Branching Ratios

Results consistent between samples

μ-tagged

$$\frac{\mathcal{B}(\Lambda_c^+ \to pK^-K^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (1.70 \pm 0.03(\text{stat}) \pm 0.03(\text{syst}))\ \%,$$
$$\frac{\mathcal{B}(\Lambda_c^+ \to p\pi^-\pi^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (7.44 \pm 0.08(\text{stat}) \pm 0.18(\text{syst}))\ \%,$$
$$\frac{\mathcal{B}(\Lambda_c^+ \to p\pi^-K^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (0.165 \pm 0.015(\text{stat}) \pm 0.005(\text{syst}))\ \%,$$

Significantly lower than the naive expectation

[Lipkin,
Nucl. Phys. Proc. Suppl.
115 (2003) 117

π-tagged

$$\frac{\mathcal{B}(\Lambda_c^+ \to pK^-K^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (1.68 \pm 0.14(\text{stat}) \pm 0.11(\text{syst}))\ \%,$$
$$\frac{\mathcal{B}(\Lambda_c^+ \to p\pi^-\pi^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (7.86 \pm 0.40(\text{stat}) \pm 0.36(\text{syst}))\ \%,$$

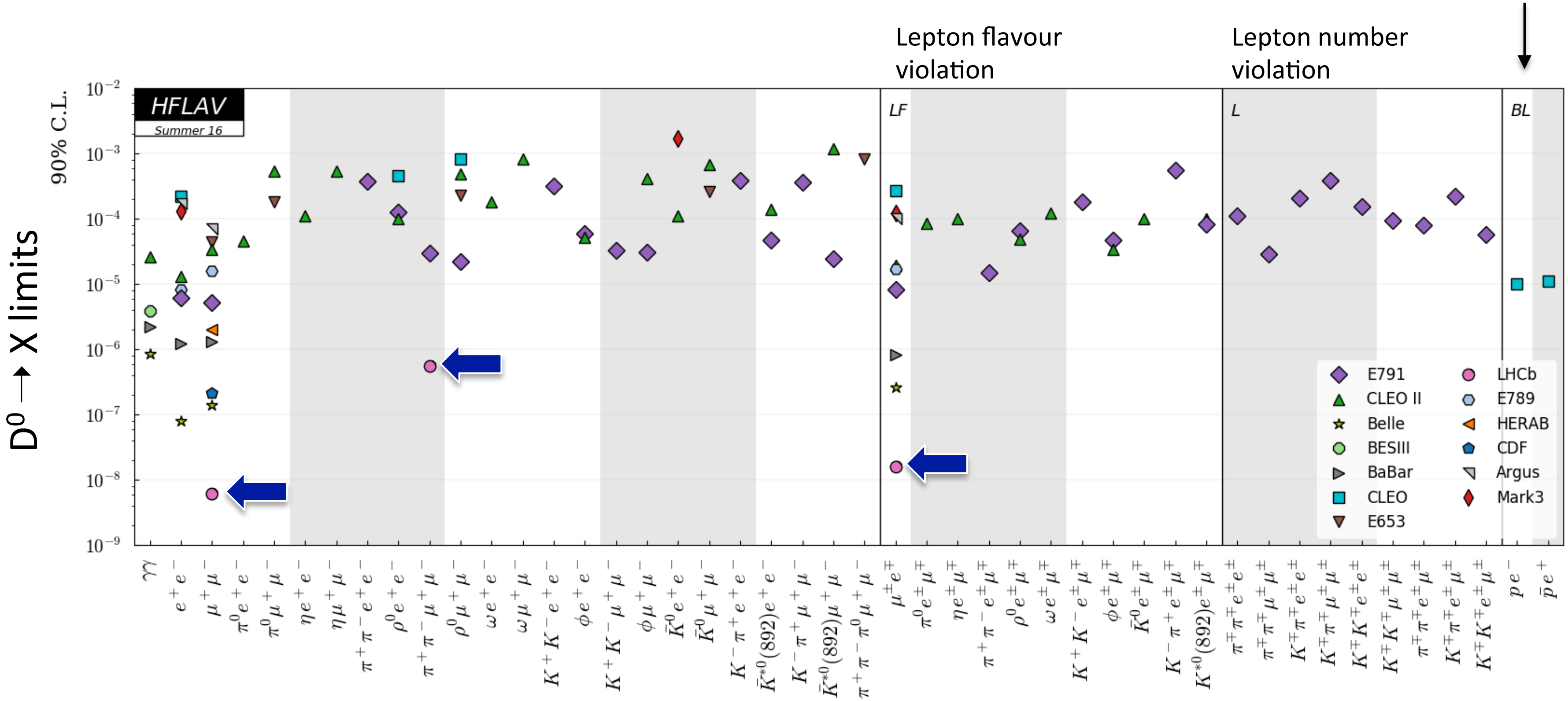
In preparation
LHCb-PAPER-2017-026

Rare Decays

Huge charm samples, but large backgrounds in hadron collisions

- LHCb strong in muon final-states
- Next step: extend to more challenging modes with electrons / photons

Baryon + Lepton number violation

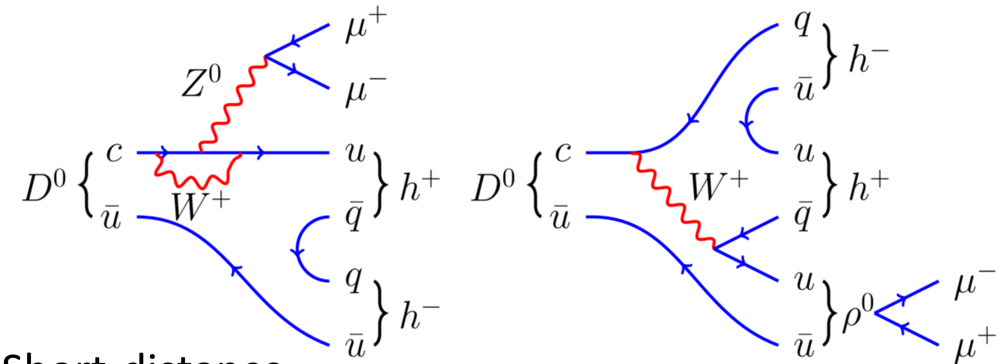


Rare Decays

Observation of $D^0 \to h^+h^-\mu^+\mu^-$

FCNC : short-distance effects sensitive to NP

But hard to disentangle from long-distance tree-level processes



Short-distance
BR $O(10^{-9})$

Long-distance
BR $O(10^{-6})$

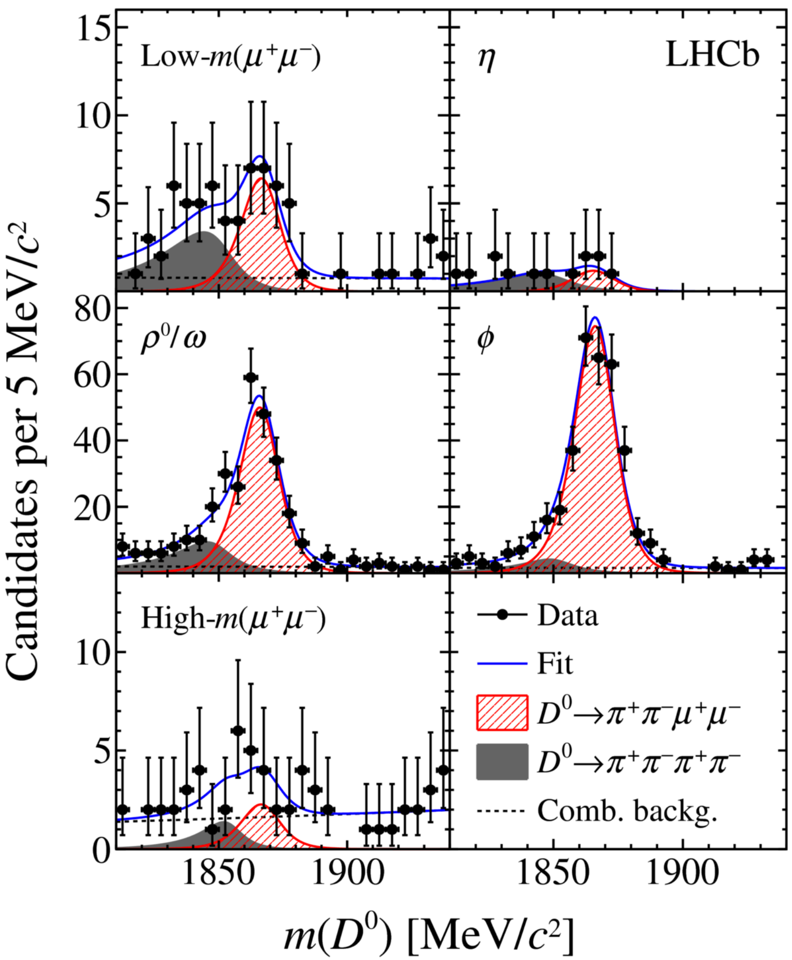
Some discrimination by splitting into m(μμ) regions:

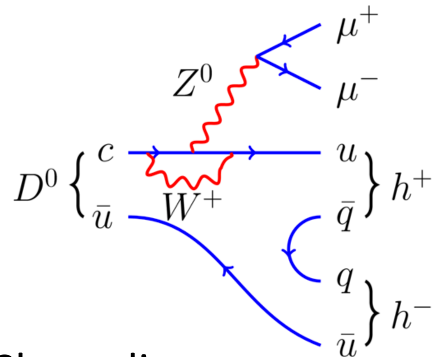
- Low-mass: m(μμ) < 525 MeV
- η-region: 525-565
- ρ/ω-region: 565-950 (or until kinematic limit for KKμμ case)
- ϕ-region: 950-1100
- High-mass: >1100

(ϕ-region and High-mass:) only for ππμμ

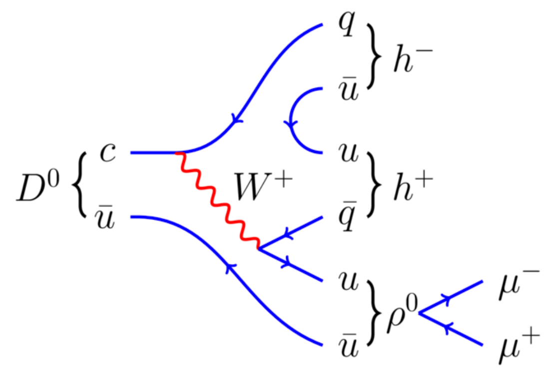
Rare Decays

Observation of $D^0 \to h^+h^-\mu^+\mu^-$





Short-distance
BR $O(10^{-9})$



Long-distance
BR $O(10^{-6})$

Run 1 data (2012), use π-tag to improve purity

Observe significant peaks:

- $\pi^+\pi^-\mu^+\mu^-$: low-mass, ρ/ω, ϕ
- $K^+K^-\mu^+\mu^-$: low-mass, ρ/ω

arXiv:1707.08377
Submitted to PRL

Rare Decays

Observation of $D^0 \to h^+h^-\mu^+\mu^-$

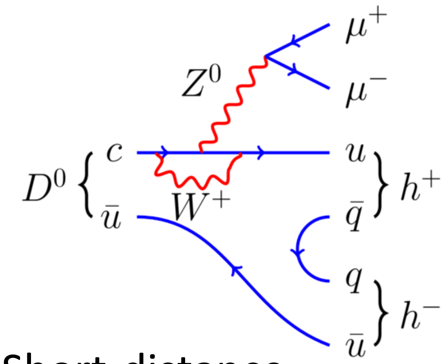
Branching ratios calculated using $D^0 \to K^-\pi^+[\mu^+\mu^-]_{\rho/\omega}$ as reference channel

$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \times 10^{-7}$$

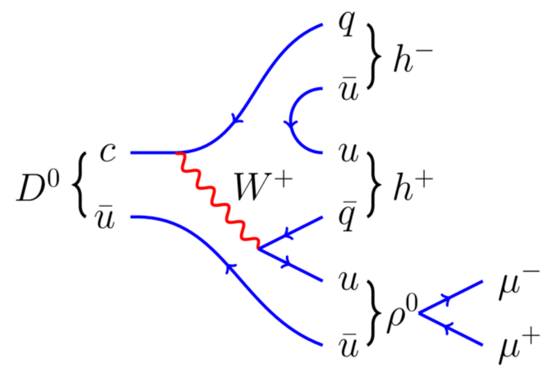
$$\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \times 10^{-7}$$

Rarest charm-hadron decays ever observed.

Four-body decay : can later use angular analysis to disentangle short/long-distance components



Short-distance
BR O(10^{-9})



Long-distance
BR O(10^{-6})

$m(\mu^+\mu^-)$ region	[MeV/c^2]	$\mathcal{B}$ [10^{-8}]
$D^0 \to \pi^+\pi^-\mu^+\mu^-$		
Low mass	< 525	$7.8 \pm 1.9 \pm 0.5 \pm 0.8$
η	525–565	$< 2.4\,(2.8)$
ρ^0/ω	565–950	$40.6 \pm 3.3 \pm 2.1 \pm 4.1$
ϕ	950–1100	$45.4 \pm 2.9 \pm 2.5 \pm 4.5$
High mass	> 1100	$< 2.8\,(3.3)$
$D^0 \to K^+K^-\mu^+\mu^-$		
$m(\mu^+\mu^-)$ region	[MeV/c^2]	$\mathcal{B}$ [10^{-8}]
Low mass	< 525	$2.6 \pm 1.2 \pm 0.2 \pm 0.3$
η	525–565	$< 0.7\,(0.8)$
ρ^0/ω	> 565	$12.0 \pm 2.3 \pm 0.7 \pm 1.2$

arXiv:1707.08377
Submitted to PRL

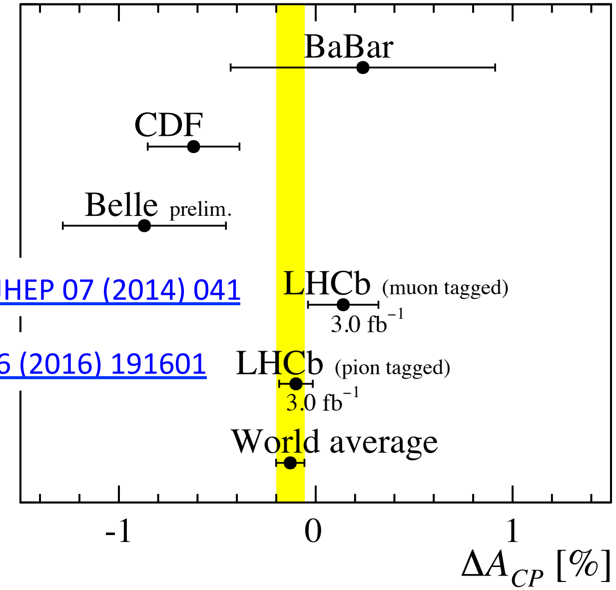
Mixing and CP Violation

Direct CP violation

Early interest in $\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$
but recent results consistent with SM (zero)

JHEP 07 (2014) 041

PRL 116 (2016) 191601



$$A_{CP}(D^0 \to K^-K^+) \equiv \frac{\Gamma(D^0 \to K^-K^+) - \Gamma(\bar{D}^0 \to K^-K^+)}{\Gamma(D^0 \to K^-K^+) + \Gamma(\bar{D}^0 \to K^-K^+)}$$

Experimentally easier – detector asymmetries cancel

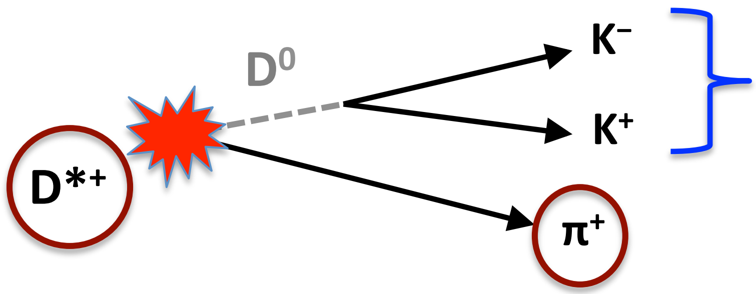
Measuring individual CP asymmetries more challenging…

Direct CP Violation

Main challenge:
Disentangle CP asymmetry from detector and production asymmetries

⇒

Solution:
Over-constrain the system using multiple control channels



$A_{CP}(K^+K^-) = \quad A_{raw}(K^+K^-) + \ldots$

$D^{*\pm}$ production asymmetry

Pion detection asymmetry

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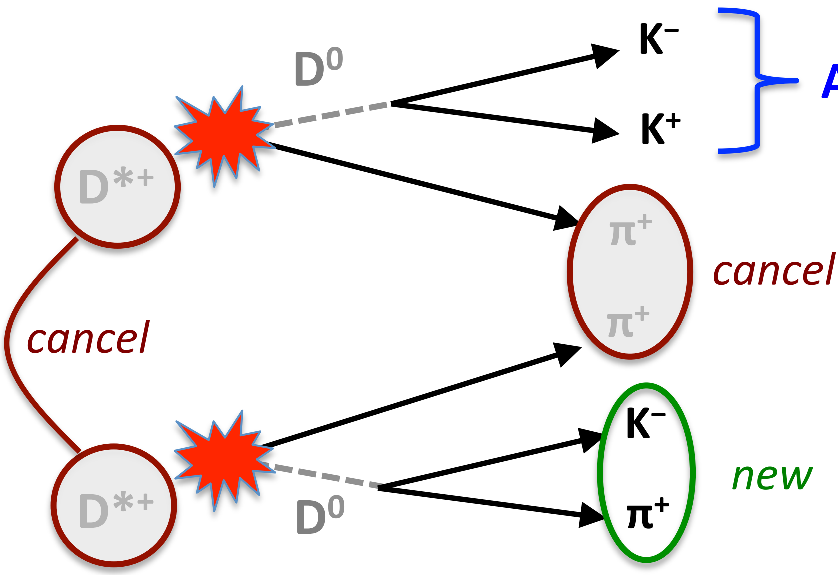

$$A_{CP}(K^+K^-) = A_{raw}(K^+K^-) - A_{raw}(K^-\pi^+) + \ldots$$

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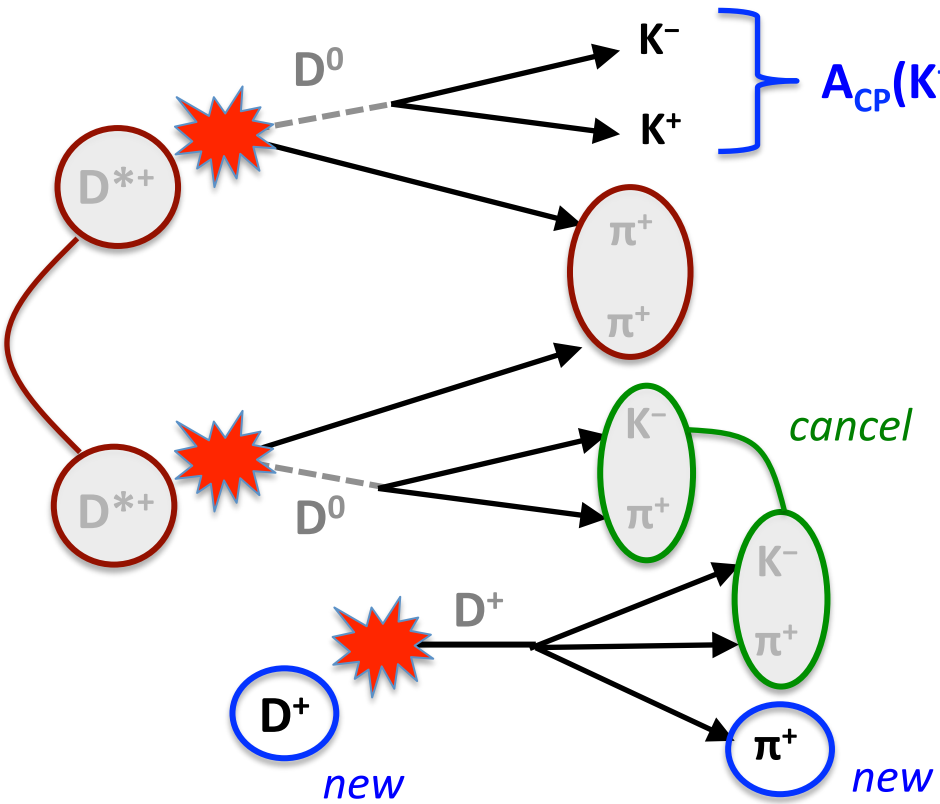

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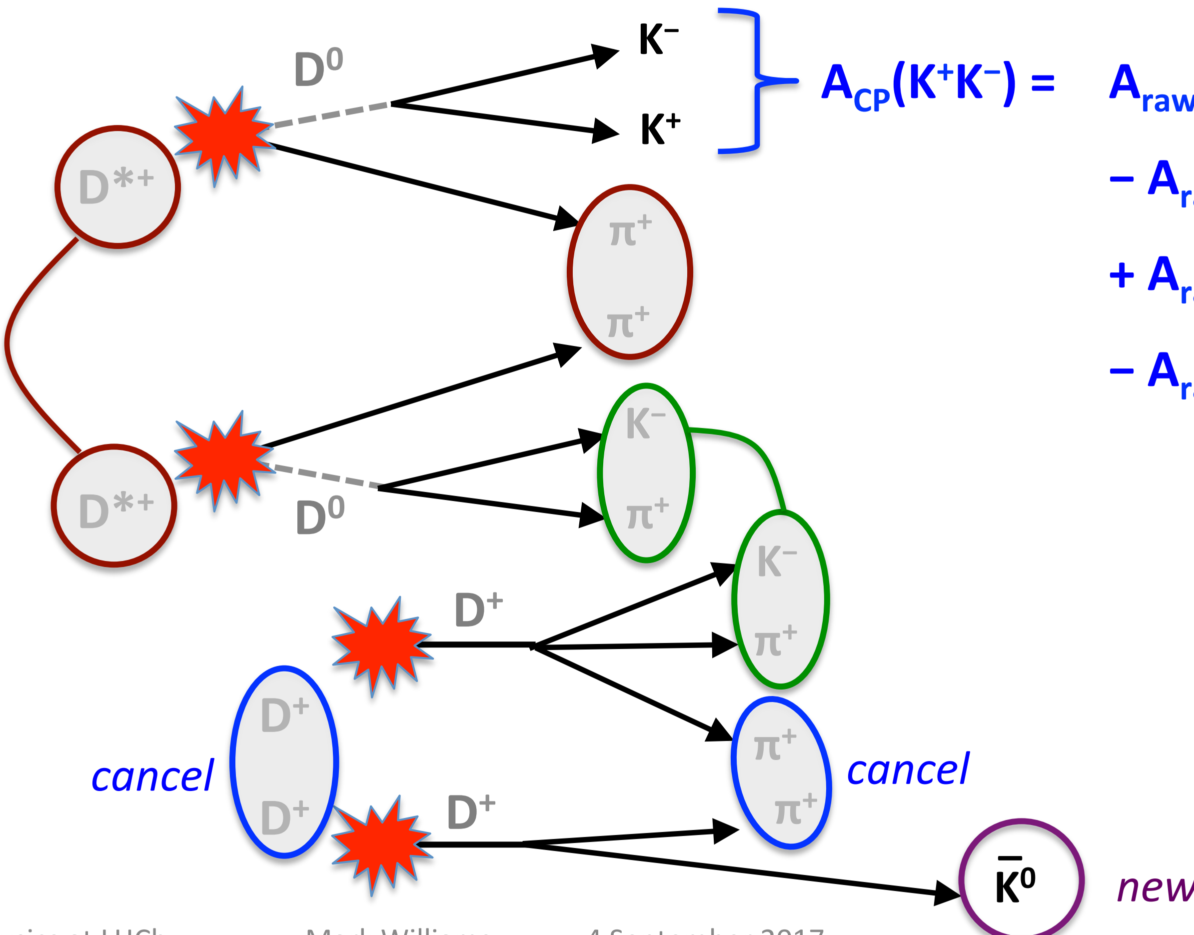

$$A_{CP}(K^+K^-) = A_{raw}(K^+K^-) - A_{raw}(K^-\pi^+) + A_{raw}(K^-\pi^+\pi^+) - A_{raw}(\bar{K}^0\pi^+) + \ldots$$

Direct CP Violation

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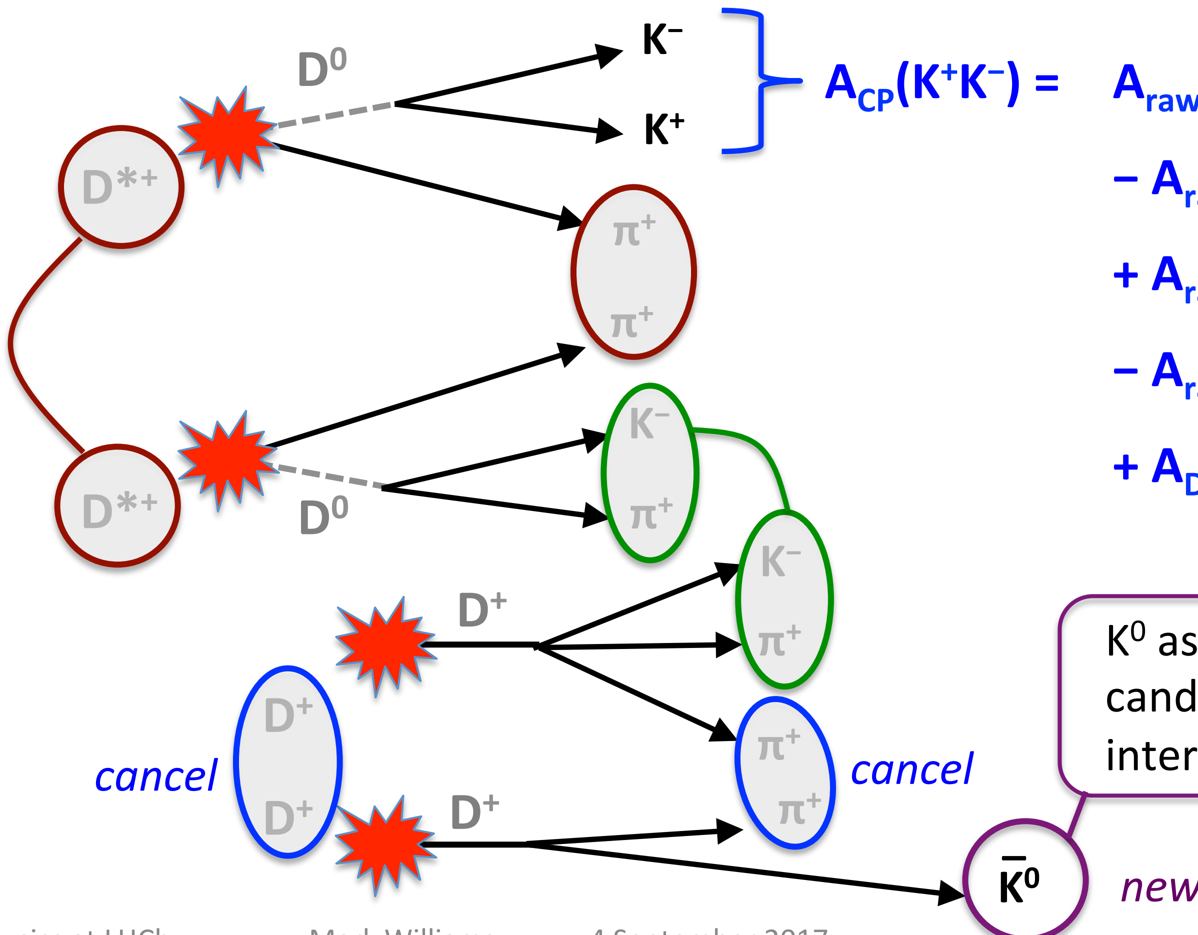


$$A_{CP}(K^+K^-) = A_{raw}(K^+K^-) - A_{raw}(K^-\pi^+) + A_{raw}(K^-\pi^+\pi^+) - A_{raw}(\overline{K}^0\pi^+) + A_D(\overline{K}^0)$$

K^0 asymmetry determined per candidate using known material interaction asymmetry

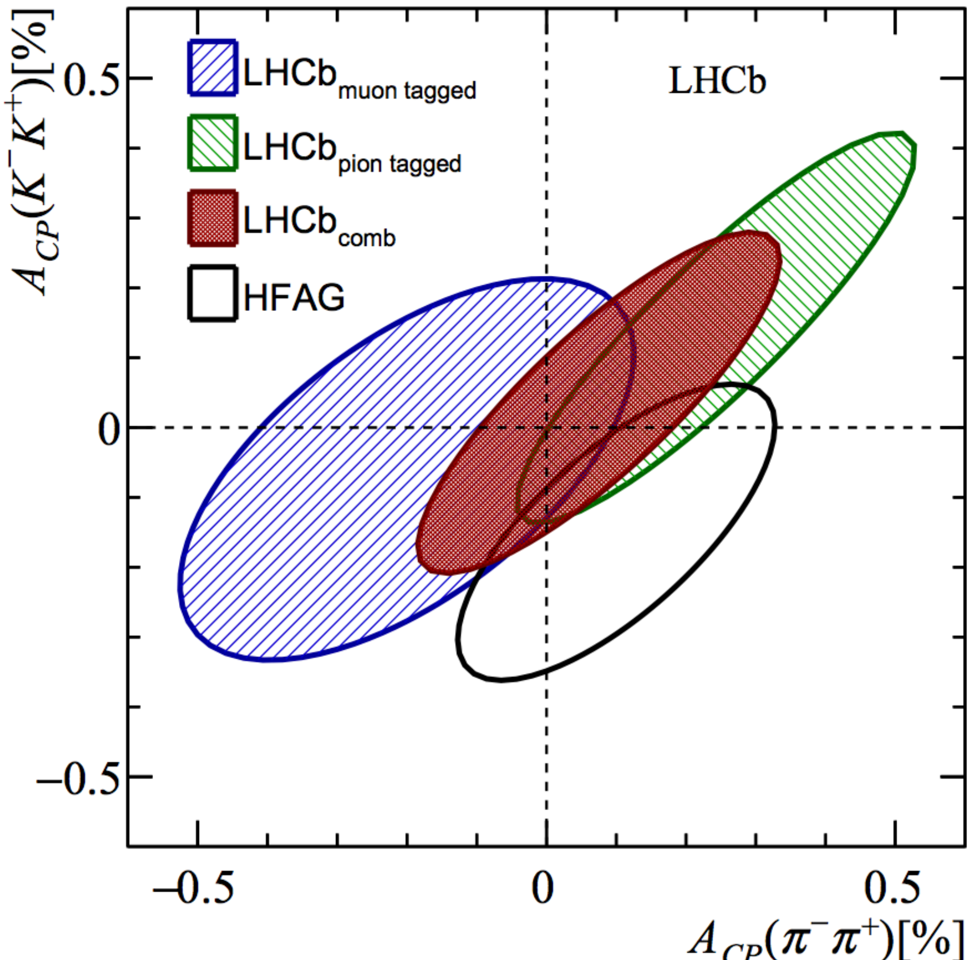
Direct CP Violation

Result: $A_{CP}^{\pi\text{-tag}}(K^+K^-) = [0.14 \pm 0.15\ (\text{stat.}) \pm 0.10\ (\text{syst.})]\%$

PLB 767 (2017) 177
arXiv:1610.09476

Complete set of Run 1 measurements in K^+K^- and $\pi^+\pi^-$

No indication of any CP violation



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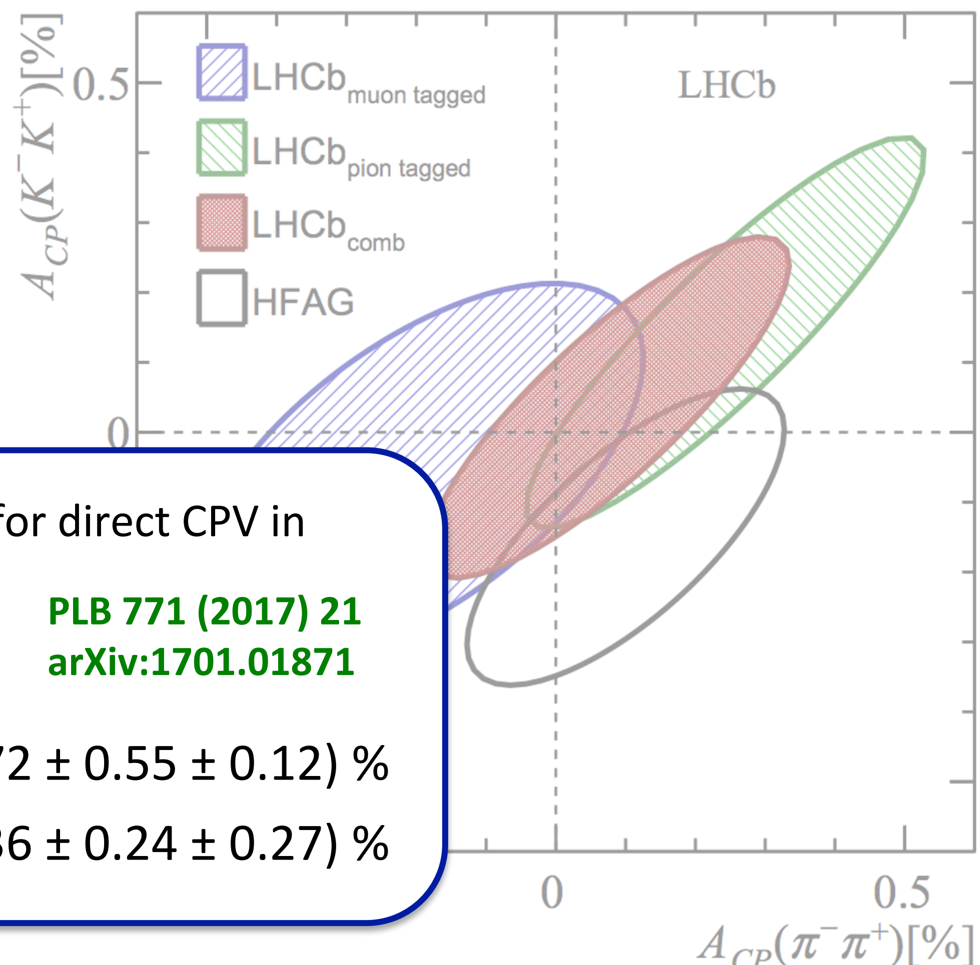


Now for first time at LHCb searching for direct CPV in final states with photons.
New result:

PLB 771 (2017) 21
arXiv:1701.01871

$$\mathcal{A}_{CP}(D^\pm \to \eta'\pi^\pm) = (-0.61 \pm 0.72 \pm 0.55 \pm 0.12)\ \%$$
$$\mathcal{A}_{CP}(D_s^\pm \to \eta'\pi^\pm) = (-0.82 \pm 0.36 \pm 0.24 \pm 0.27)\ \%$$

Direct CP Violation

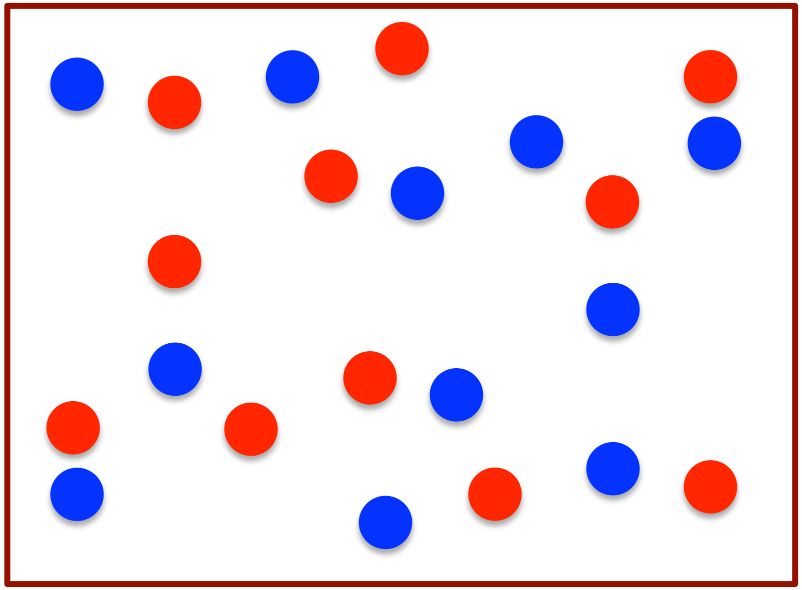
Local CP violation in $D^0 \to \pi^+\pi^-\pi^+\pi^-$

Energy test method : Compute test statistic based on separation of same- and opposite-flavour D^0 mesons across **5D** phase space

Compare to distribution from tag-randomised ensemble of pseudo-experiments

Previously used in LHCb $D^0 \to \pi^+\pi^-\pi^0$ analysis

PLB 740 (2015) 158
arXiv:1410.4170



Electric charge analogy:

+q and –q **evenly distributed**
⇒ potential energy **E = 0**

Direct CP Violation

Local CP violation in $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$

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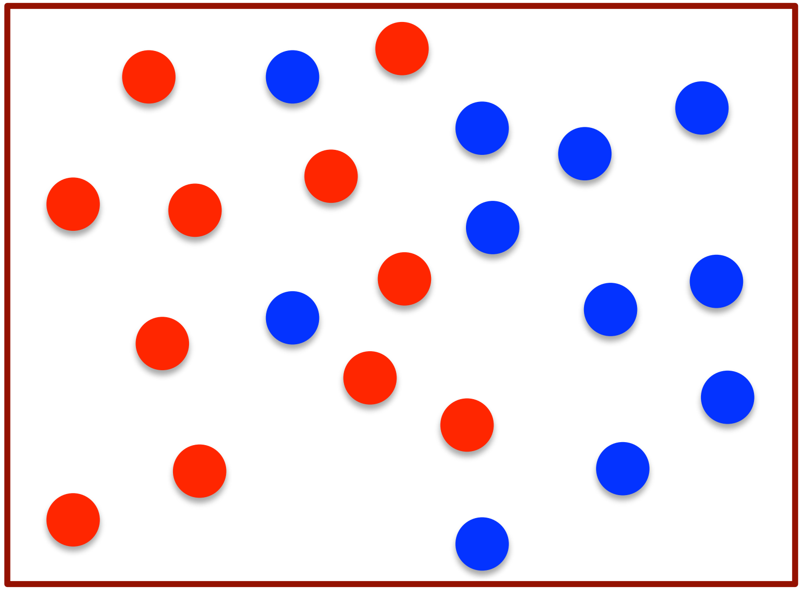


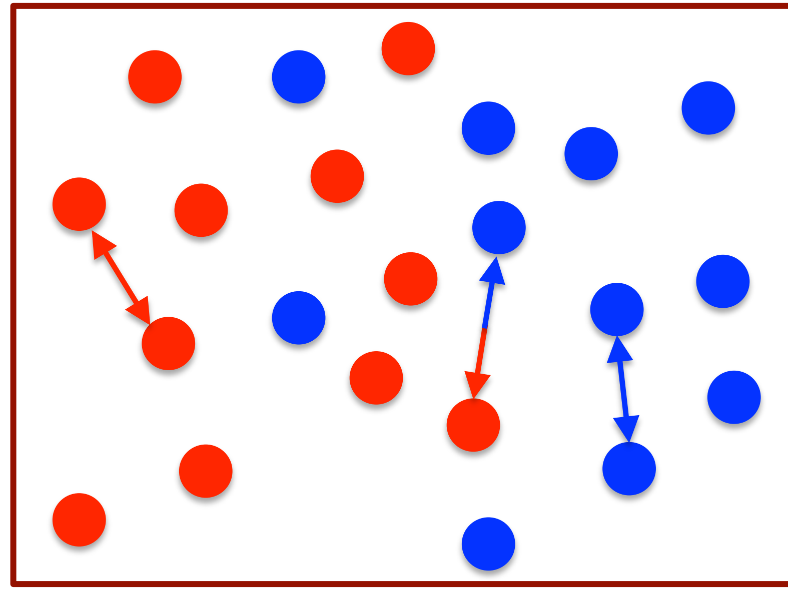
Electric charge analogy:

+q and –q distributions **different**
⇒ potential energy **E > 0**

Direct CP Violation

Local CP violation in $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$

Energy test method : Compute test statistic based on separation of same- and opposite-flavour D^0 mesons across **5D** phase space



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PLB 740 (2015) 158
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$$T = \sum_{i,j>i}^{n} \frac{\psi_{ij}}{n(n-1)} + \sum_{i,j>i}^{\overline{n}} \frac{\psi_{ij}}{\overline{n}(\overline{n}-1)} - \sum_{i,j}^{n,\overline{n}} \frac{\psi_{ij}}{n\overline{n}}$$

D^0-D^0 $\quad$ $\overline{D}^0$-$\overline{D}^0$ $\quad$ D^0-$\overline{D}^0$

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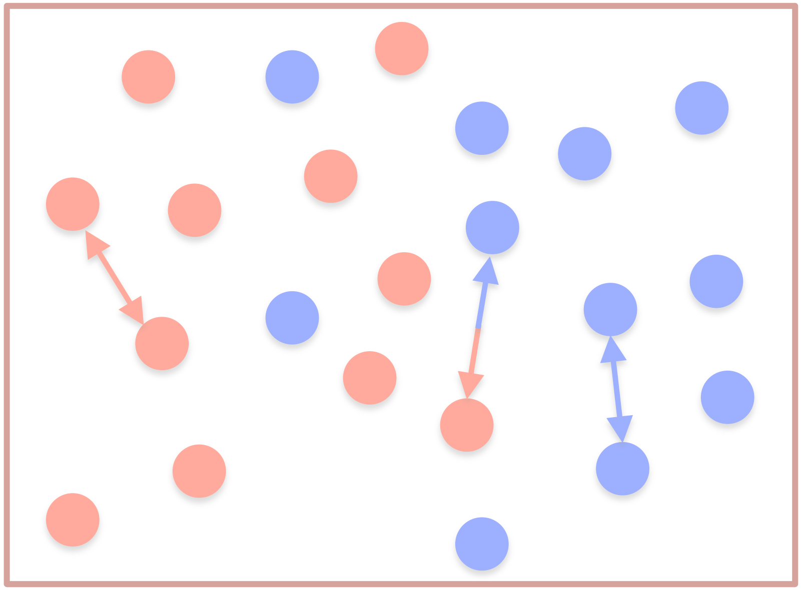

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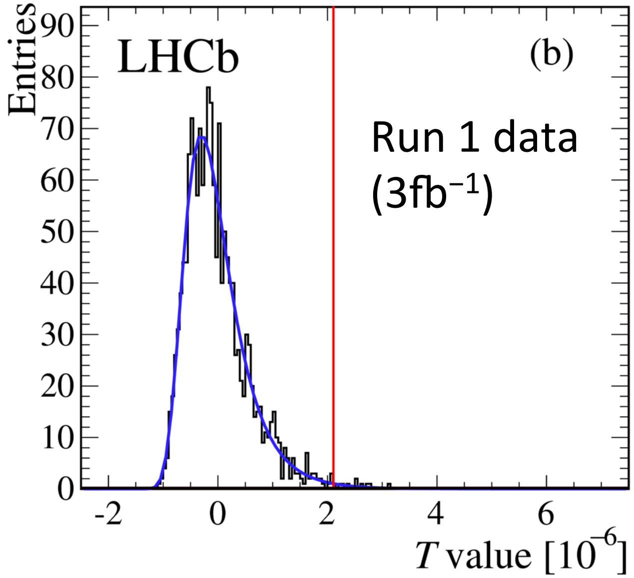

Perform both P-odd and P-even tests (by splitting samples according to triple product C_T)

P-even CPV: **p-value = (4.3 ± 0.6) %**
P-odd CPV: **p-value = (0.6 ± 0.2) %**

PLB 769 (2017) 345
arXiv:1612.03207

Direct CP Violation

Local CP violation in $D^0 \to \pi^+\pi^-\pi^+\pi^-$

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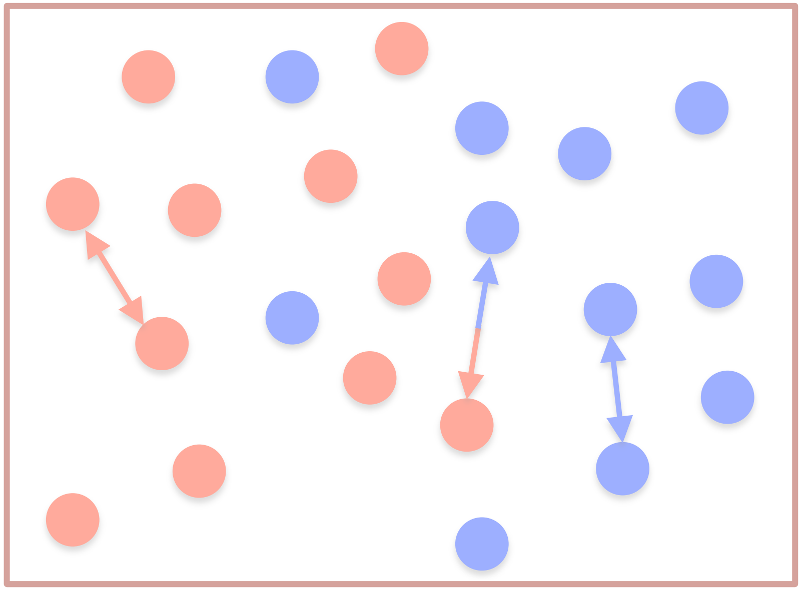

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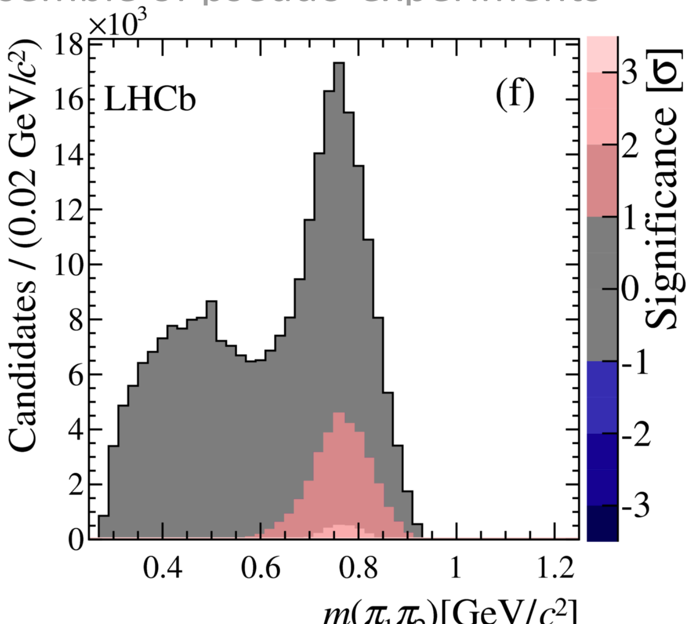

Can find regions with largest contributions

⇒ need amplitude analysis for complete interpretation

PLB 769 (2017) 345
arXiv:1612.03207

Direct CP Violation

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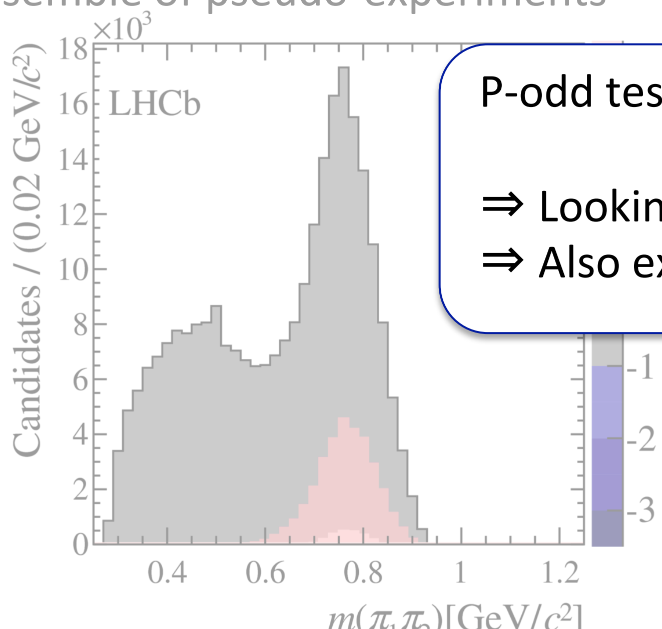
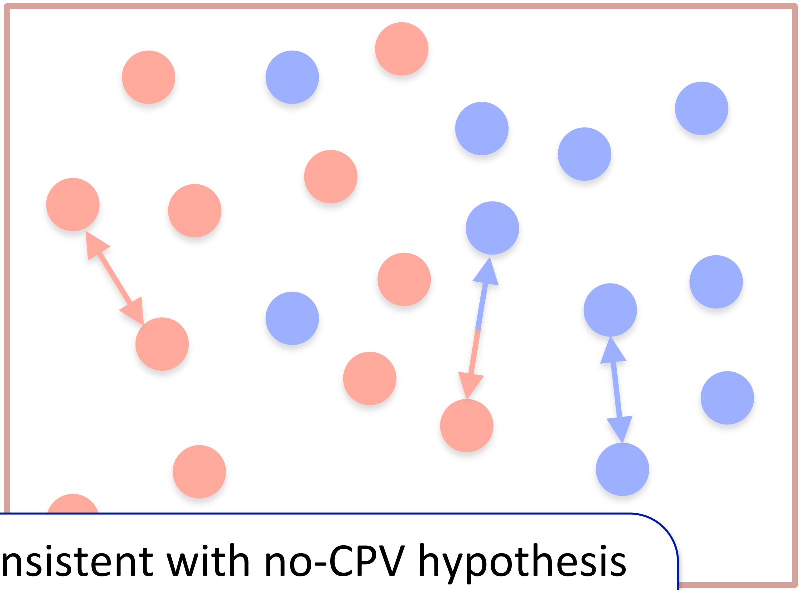




P-odd test *marginally* consistent with no-CPV hypothesis

⇒ Looking forward to results with Run 2 data
⇒ Also extending to other channels (e.g. KKππ)

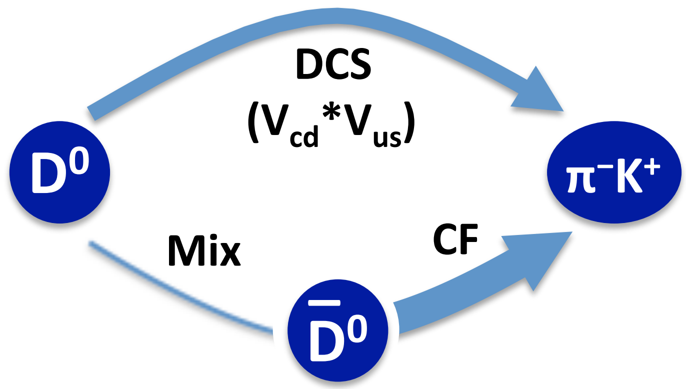
⇒ need amplitude analysis for complete interpretation

PLB 769 (2017) 345
arXiv:1612.03207

Charm Mixing

Charm mixing now established :

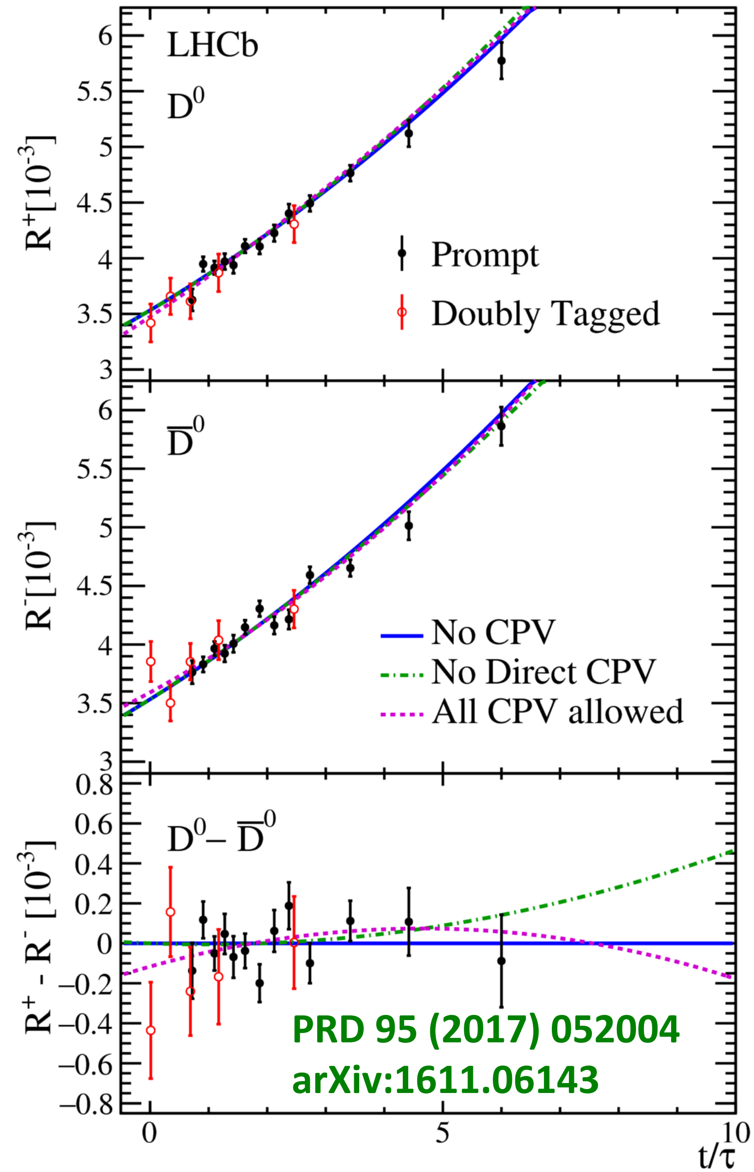
Wrong-sign (WS) $D^0 \to \pi^- K^+$



Latest LHCb Run 1 result adds double-tagged candidates to boost precision by 20%.

Parameter	Value
	No CPV
$R_D[10^{-3}]$	$3.48 \pm 0.10 \pm 0.01$
$x'^2[10^{-4}]$	$0.28 \pm 3.10 \pm 0.11$
$y'[10^{-3}]$	$4.60 \pm 3.70 \pm 0.18$
χ^2/NDF	$6.293/7$

No evidence for CP violation (direct or indirect)



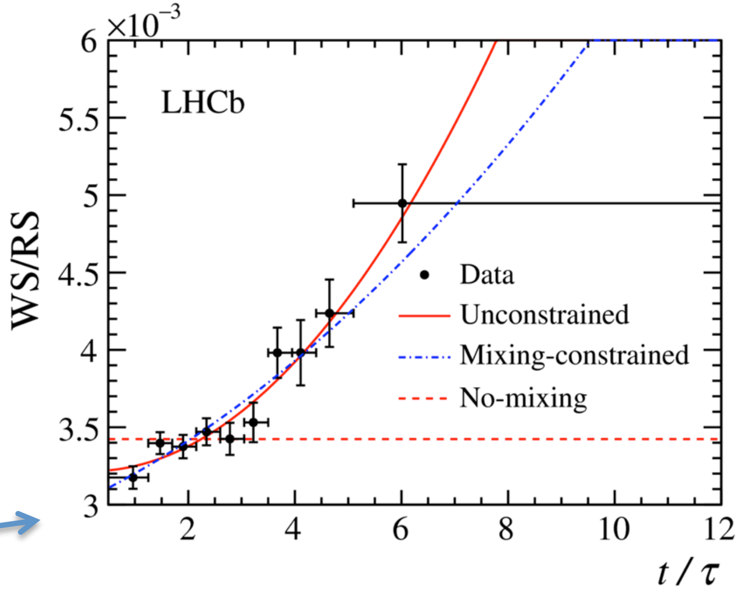
Charm Mixing

Wrong-sign K3π:

\+ Potentially a very sensitive channel to determine mixing and CPV parameters

– But experimentally challenging – 5D phase space

First measurement: simplify by integrating over phase space (lose sensitivity)



Assume no CPV in mixing or decay.

8.2σ evidence for mixing (first time in this channel)

PRL 116 (2016) 241801
arXiv:1602.07224

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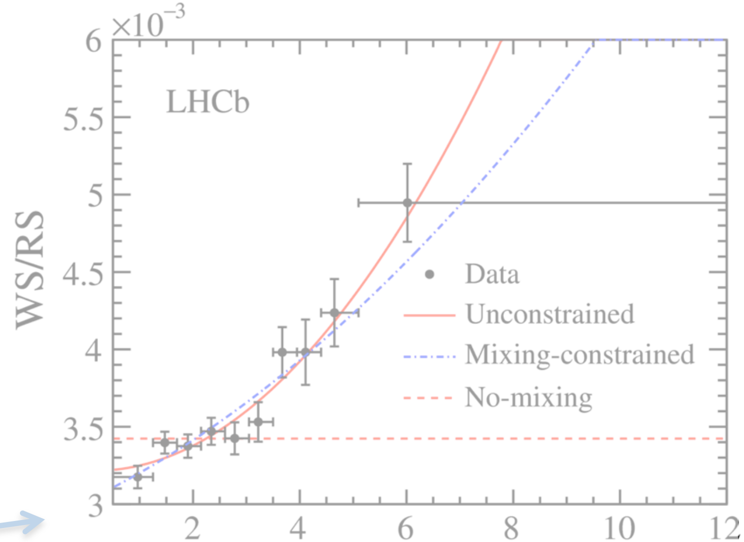

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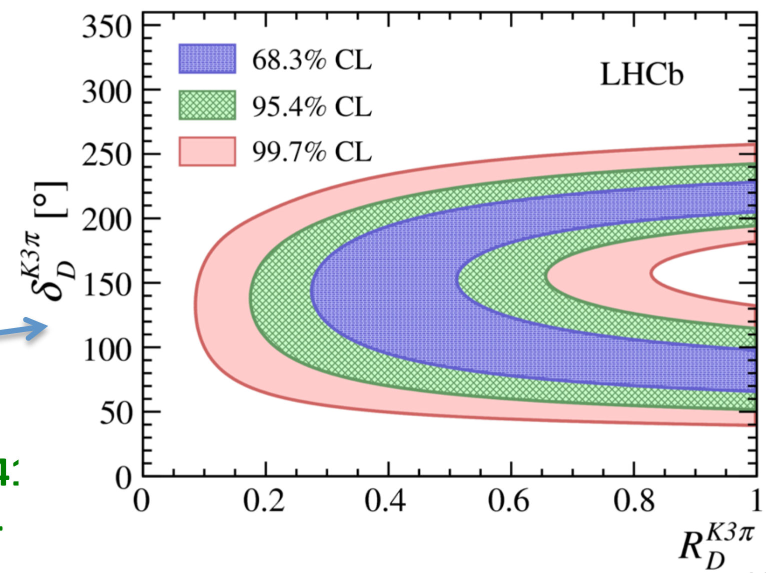
8.2σ evidence for mixing (first time in this channel)

Also constrain (x,y) to WA to measure γ inputs

($R_D^{K3\pi}$, $\delta_D^{K3\pi}$) constraints from mixing-constrained fit – reduces overall WA uncertainties by ~50%.



PRL 116 (2016) 24:
arXiv:1602.07224

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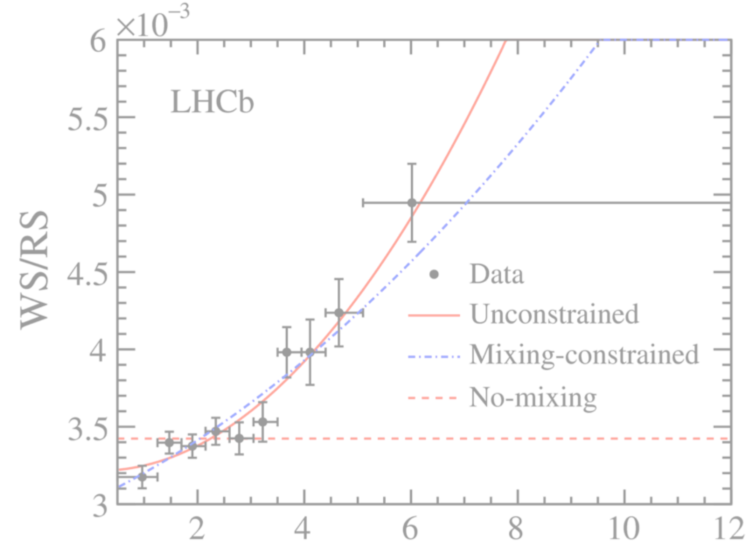

Assume no CPV in mixing

8.2σ evidence for mixing

Now working on full time and phase-space-dependent analysis using Run 2 data

⇒ ~4x more signal yield / fb^{-1}

Also constrain (x,y) to W

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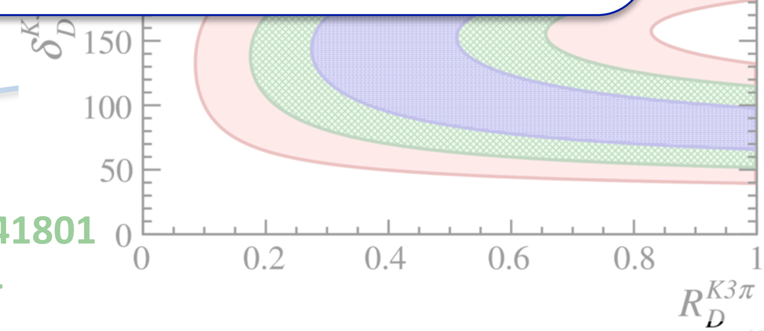


PRL 116 (2016) 241801
arXiv:1602.07224

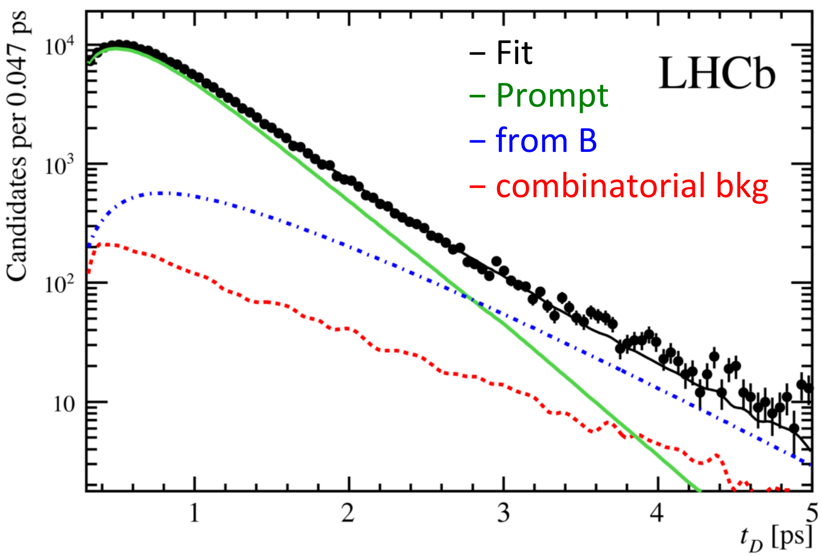
Charm Mixing

Golden Mode: $D^0 \to K_S{}^0 \pi^+\pi^-$

Measure (x, y, q/p, ϕ) simultaneously

Mass splitting parameter ***x*** still not well constrained experimentally − consistent with zero (i.e. no oscillations)

$D^0 \to K_S{}^0 \pi^+\pi^-$ is our best bet to constrain it



Single measurement from LHCb using $1fb^{-1}$ of Run 1 data

- π-tagged
- model independent

$$x = (-0.86 \pm 0.53 \pm 0.17) \times 10^{-2}$$
$$y = (+0.03 \pm 0.46 \pm 0.13) \times 10^{-2}$$

JHEP 04 (2016) 033
arXiv:1510.01664

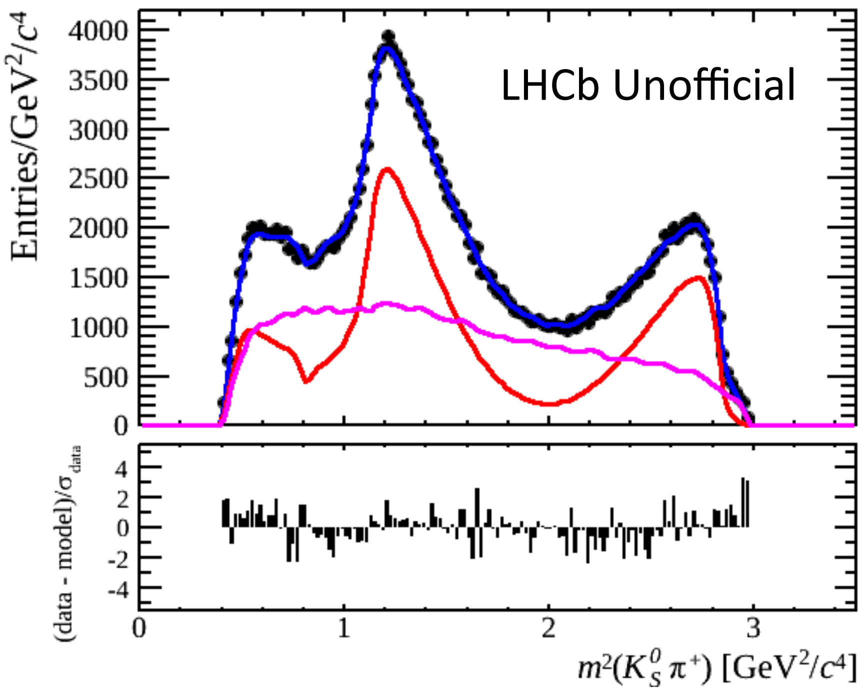
Charm Mixing

Golden Mode: $D^0 \to K_S^0\, \pi^+\pi^-$

Measure (x, y, q/p, ϕ) simultaneously

Complex analysis – attack from as many angles as possible – **updates in progress!**

Model dependent, μ-tagged and double-tagged samples



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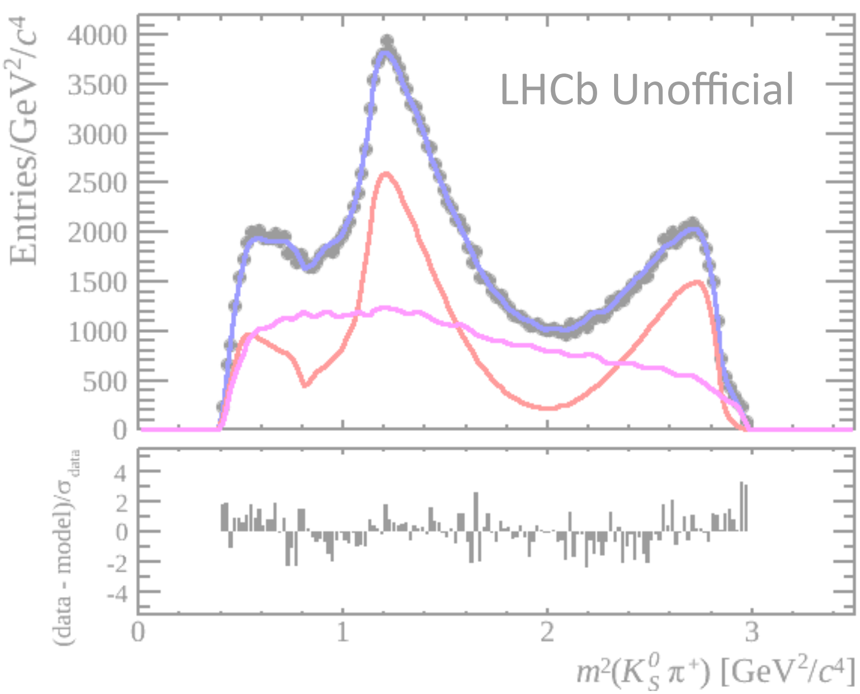
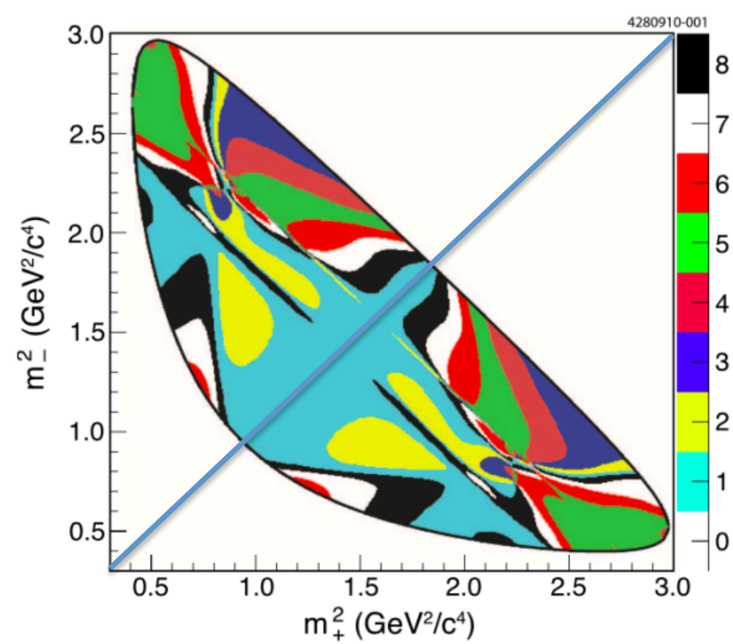


Model independent approach – compare yields in each bin with those in the mirror image (bin-flip method)

– Lose some sensitivity to (x,y)

+ Cancel decay-time acceptance effects



CPV in mixing: $A_\Gamma(KK)$, $A_\Gamma(\pi\pi)$

For small x,y, CP asymmetry of D^0 decay rates are 1st order in time:

$$A_{CP}(t) = \frac{\Gamma(D^0(t)\to f) - \Gamma(\overline{D}^0(t)\to f)}{\Gamma(D^0(t)\to f) + \Gamma(\overline{D}^0(t)\to f)} \simeq a_d - A_\Gamma \frac{t}{\tau_D}$$

CPV in decay

CPV in mixing/interference
$A_\Gamma = f(x, y, q, p)$

⇒ Extract A_Γ by fitting $A_{CP}(t)$ to straight line

- Two complementary methods ("binned" vs "unbinned")
- Run 1, π-tagged sample
- $D^0 \to K^-\pi^+$ used to validate methods

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CPV in decay (a_d)

CPV in mixing/interference (A_Γ)
$A_\Gamma = f(x, y, q, p)$

⇒ Extract A_Γ by fitting $A_{CP}(t)$ to straight line

- Two complementary methods ("binned" vs "unbinned")
- Run 1, π-tagged sample
- $D^0 \to K^- \pi^+$ used to validate methods

Main challenge:

Detector **asymmetries** ⟷ **non-uniform decay time** acceptance ⟷ Candidate **kinematics** ⟷ Detector **asymmetries**

⇒ biased A_Γ measurement

CPV in mixing: $A_\Gamma(KK)$, $A_\Gamma(\pi\pi)$

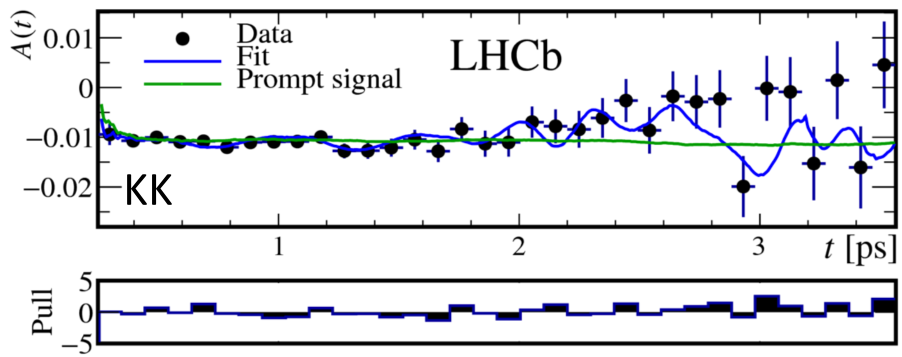
Unbinned Results (8 TeV only):

$A_\Gamma(K^+K^-) = (-0.03 \pm 0.46 \pm 0.10) \times 10^{-3}$

$A_\Gamma(\pi^+\pi^-) = (+0.03 \pm 0.79 \pm 0.16) \times 10^{-3}$

Combine with published 7 TeV result to determine Run 1 average (KK + ππ):

$A_\Gamma = (-0.07 \pm 0.34) \times 10^{-3}$



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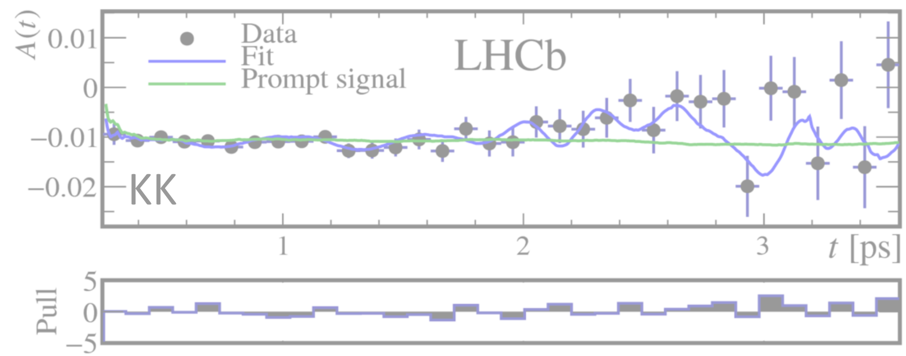


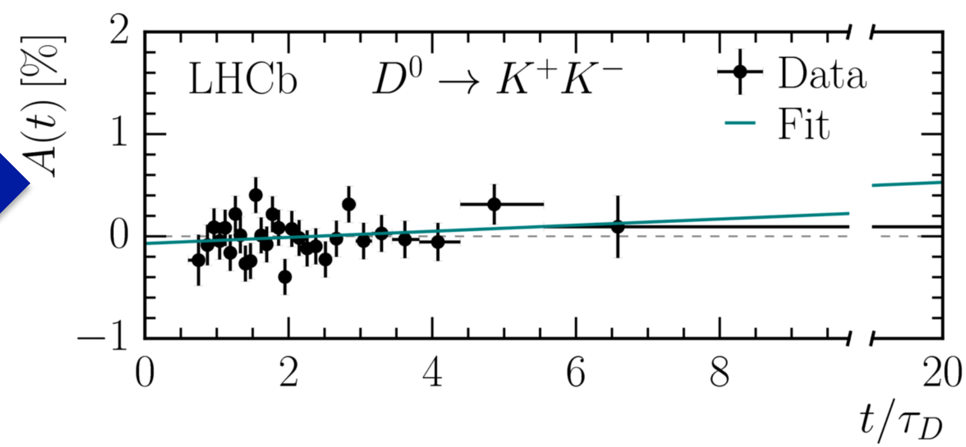
Binned Results (7+8 TeV):

$A_\Gamma(K^+K^-) = (-0.30 \pm 0.32 \pm 0.14) \times 10^{-3}$

$A_\Gamma(\pi^+\pi^-) = (+0.46 \pm 0.58 \pm 0.16) \times 10^{-3}$

Run 1 KK+ππ average:

$A_\Gamma = (-0.13 \pm 0.30) \times 10^{-3}$



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Run 1 KK+ππ average:

$A_\Gamma = (-0.13 \pm 0.30) \times 10^{-3}$

Run 1 μ-tagged results:

$A_\Gamma(K^+K^-) = (-1.34 \pm 0.77 ^{+0.26}_{-0.34}) \times 10^{-3}$

$A_\Gamma(\pi^+\pi^-) = (-0.92 \pm 1.45 ^{+0.25}_{-0.33}) \times 10^{-3}$

JHEP 04 (2015) 043
arXiv:1501.06777

Full Run 1 average: $\mathbf{A_\Gamma = -0.29 \pm 0.28 \times 10^{-3}}$

- Two methods consistent
- No evidence for CPV
- Most precise measurements of CPV in charm system ever made
- **Still statistically limited**

PRL 118 (2017) 261803
arXiv:1702.06490

Summary…

Rich and diverse programme of charm physics at LHCb

New Ω_c^{0**} states:	PRL 118 (**2017**)182001	arXiv:1703.04639
Ξ_{cc}^{++} discovery:	PRL 111 **(2017)** 180001	arXiv:1707.01621
D_s^- lifetime:	Submitted to PRL	arXiv:1705.03475
Λ_c^+ branching ratios:	In preparation	LHCb-PAPER-2017-026
$D^0 \rightarrow h^+h^-\mu^+\mu^-$ observation:	Submitted to PRL	arXiv:1707.08377
$A_{CP}(D^0 \rightarrow K^+K^-)$:	PLB 767 **(2017)** 177	arXiv:1610.09476
$A_{CP}(D_{(s)}^\pm \rightarrow \eta'\pi^\pm)$:	PLB 771 **(2017)** 21	arXiv:1701.01871
$D^0 \rightarrow 4\pi$ energy test:	PLB 769 **(2017)** 345	arXiv:1612.03207
Wrong-sign $D^0 \rightarrow K\pi$:	PRD 95 **(2017)** 052004	arXiv:1611.06143
Wrong-sign $D^0 \rightarrow K3\pi$:	PRL 116 **(2016)** 241801	arXiv:1602.07224
$D^0 \rightarrow K_S^0\pi^+\pi^-$:	JHEP 04 **(2016)** 033	arXiv:1510.01664
Indirect CPV (A_Γ):	PRL 118 **(2017)** 261803	arXiv:1702.06490

Summary…

Rich and diverse programme of charm physics at LHCb

- Era of precision measurements…   …but still new states to discover!
- No evidence for any CP violation so far
- Measurements still statistically limited
- Many systematics also scale inversely with sample size (control sample reweighting, background modelling, …)

Summary and Outlook

Rich and diverse programme of charm physics at LHCb

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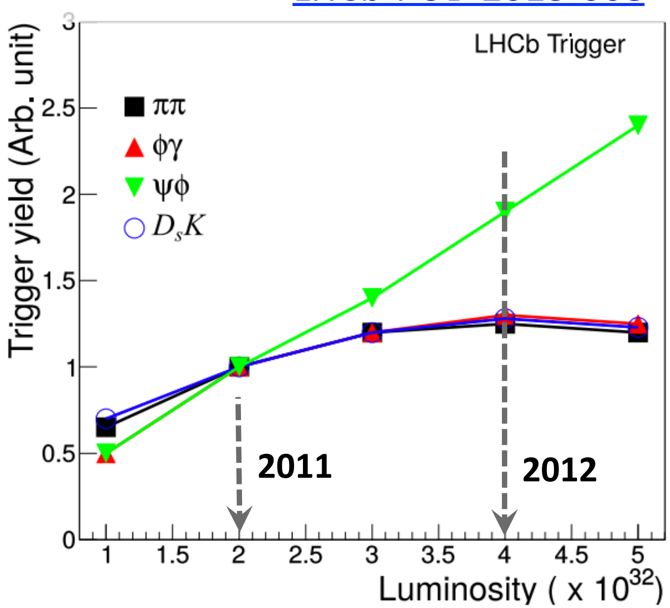
- Many systematics also scale inversely with sample size (control sample reweighting, background modelling, …)

LHCb-PUB-2013-008



Run 2 and beyond offers significant opportunity for charm physics

- Run 2: ×2 yield from energy, + trigger gains, + new lifetime unbiased hadronic triggers
- ≥Run 3: Upgraded detector – full event reconstruction at all trigger levels, & better vertex resolution
- Much more to come! Stay tuned.

Extra Slides

Common themes: detector asymmetries

Measure **raw asymmetries** in yields of process X:

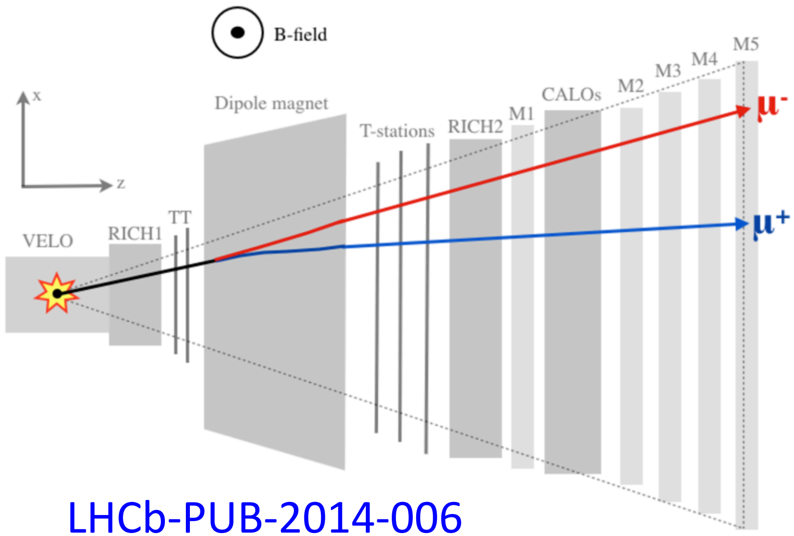
$$A_{raw}(X) = \frac{N(X) - N(\bar{X})}{N(X) + N(\bar{X})}$$

= sum of CP asymmetry and detector asymmetries

Detector asymmetries:

Magnet sweeps opposite-charged particles in different directions (detector not perfectly symmetric)

⇒



LHCb-PUB-2014-006

Common themes: detector asymmetries

Measure **raw asymmetries** in yields of process X:

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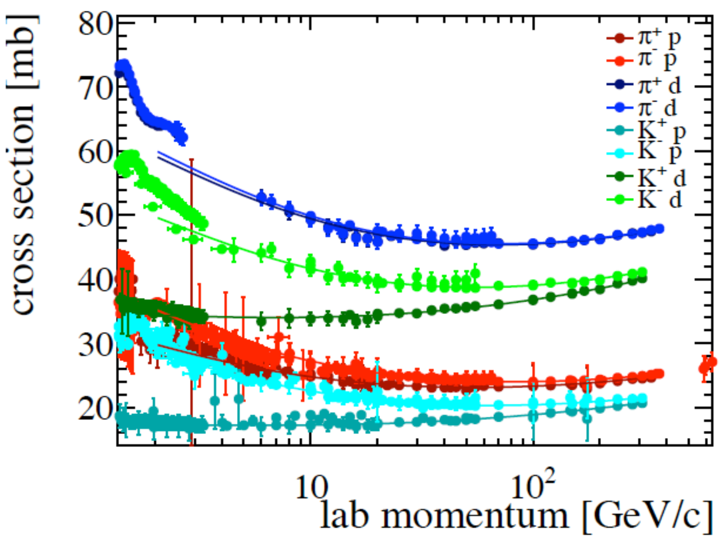
Material interactions: different for particles/antiparticles

⇒

Chin. Phys. C 38 (2014) 090001



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$\Rightarrow$

Regularly reverse polarity

Fiducial cuts to remove most asymmetric regions

Material interactions: different for particles/antiparticles

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⇒

Regularly reverse polarity

Fiducial cuts to remove most asymmetric regions

Material interactions: different for particles/antiparticles

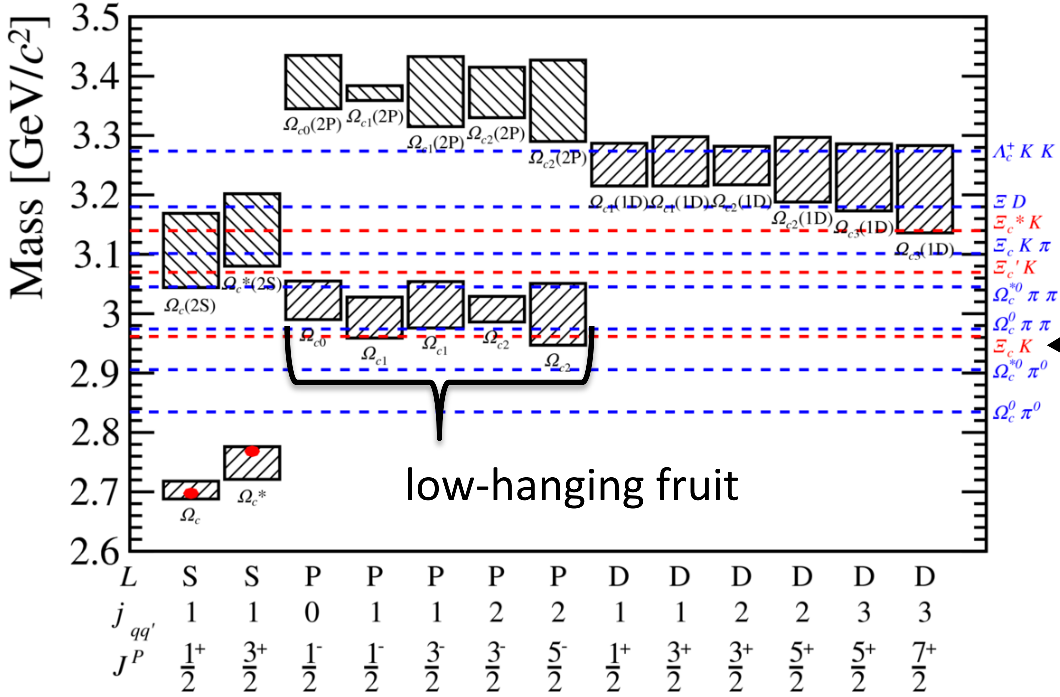
⇒

Irreducible: measure in control channels

Depend on kinematics – ensure matching with signal sample (reweighting, or binned correction)

Production and decay properties

Excited charm baryons

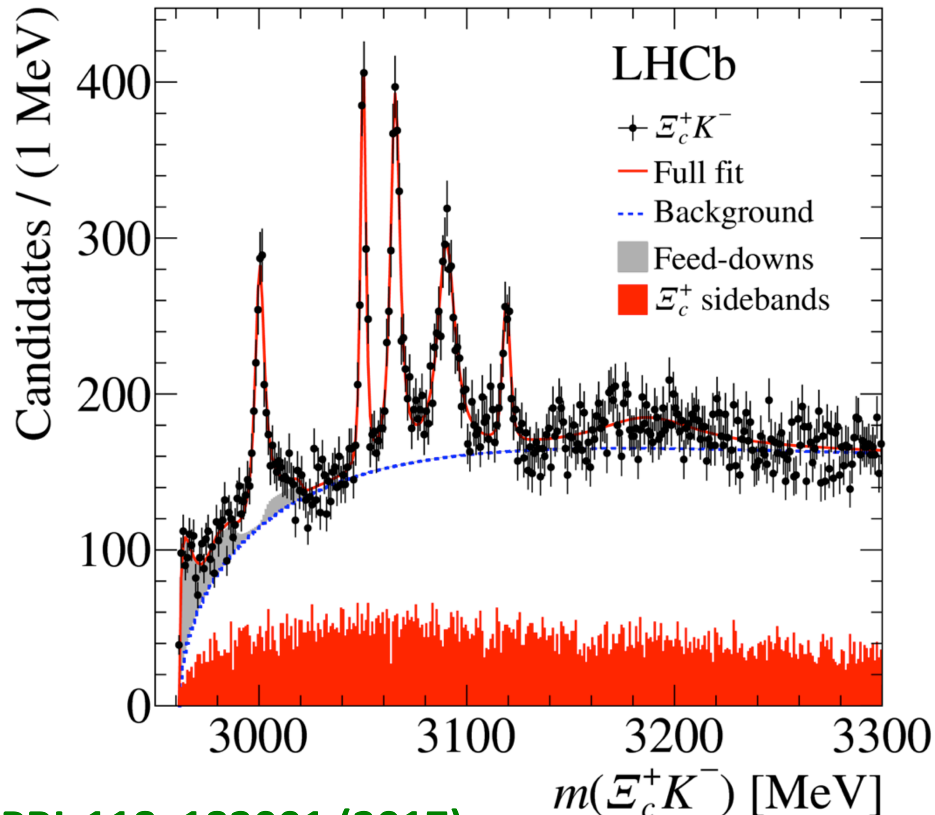


For Ω_c^0 system:

- Only ground-states $J^P = ½^+$ and $3/2^+$ are established
- Five P-wave states predicted
- Search in $\Xi_c^+ K^-$ final state [$\Omega_c^{(*)0}\pi^0$ isospin suppressed]

Production and decay properties

Excited charm baryons



PRL 118, 182001 (2017)
arXiv:1703.04639

- 5 clear peaks observed (>10 sigma)
- Broad excess at ~3200 MeV : could be superposition of several states
- Peaking feed-down backgrounds from $\Omega_c(X)^0 \to \Xi'^+_c(\to \Xi_c^+ \gamma)K^-$ with missing γ

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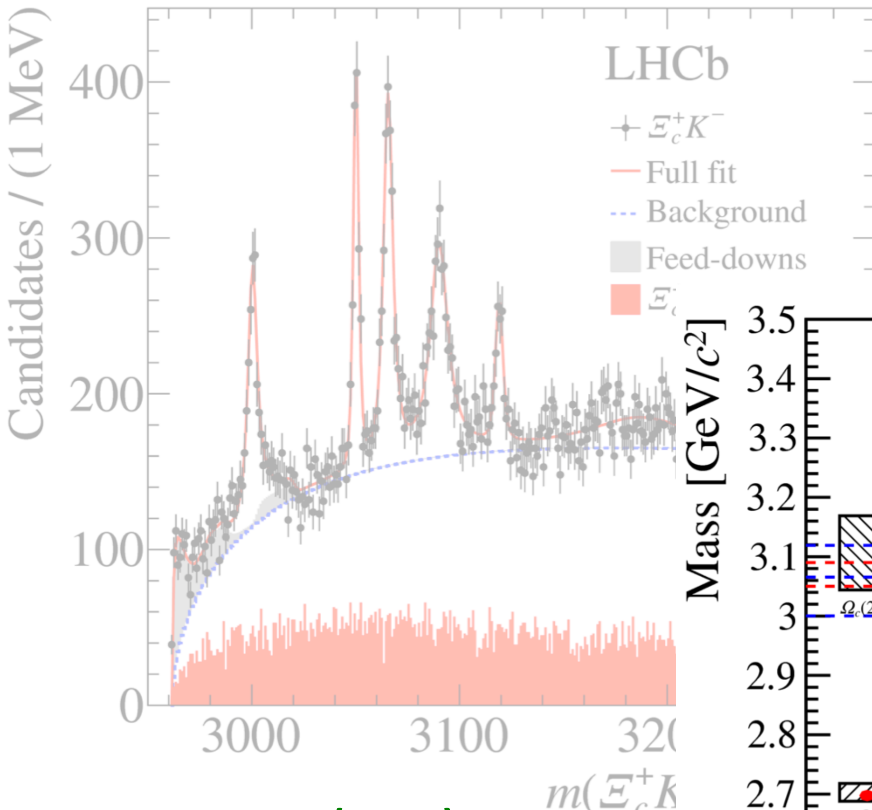

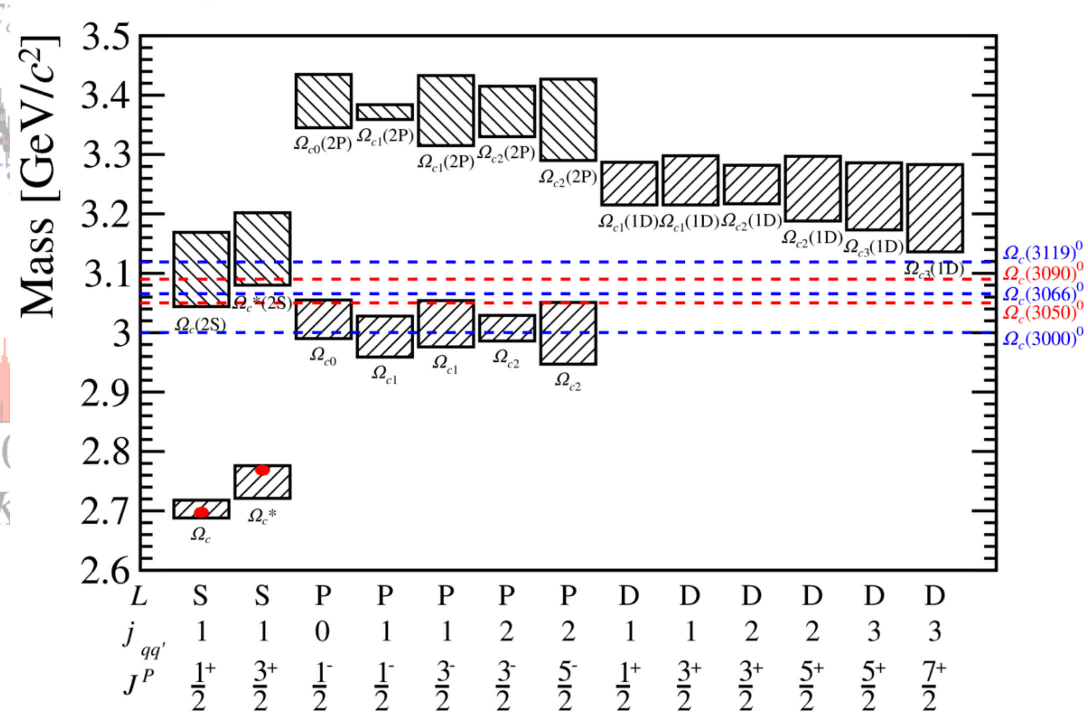

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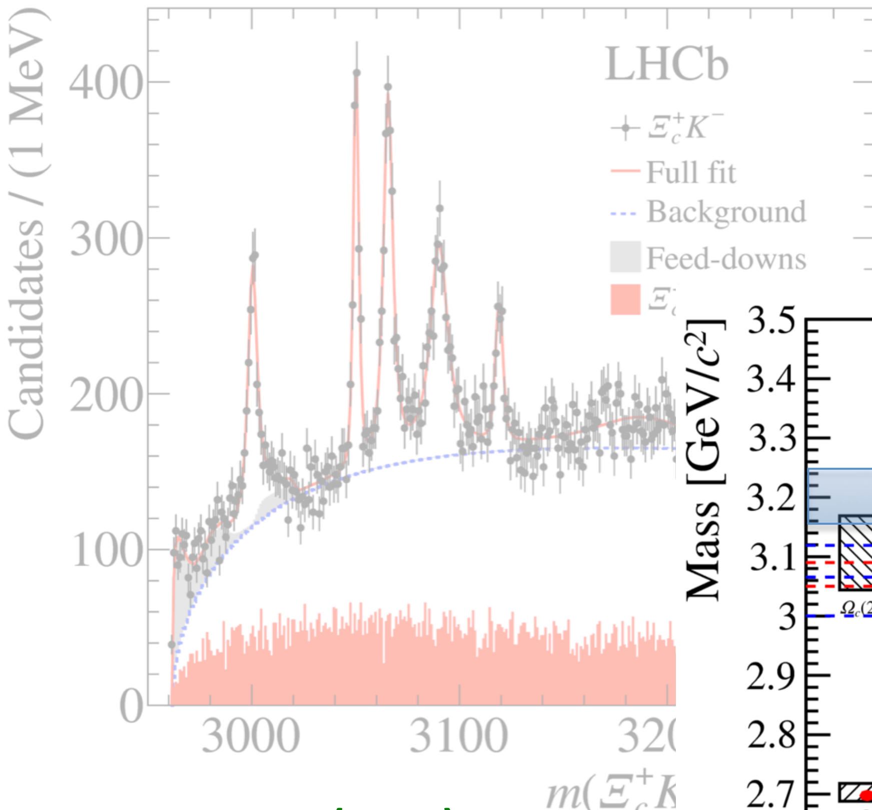

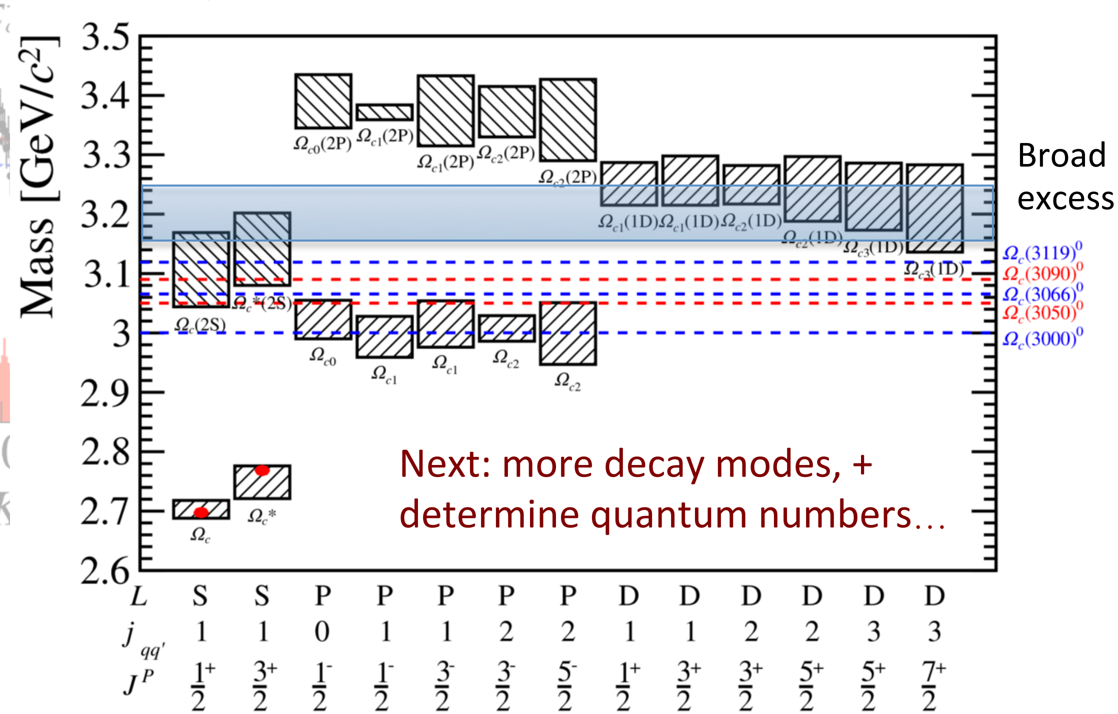

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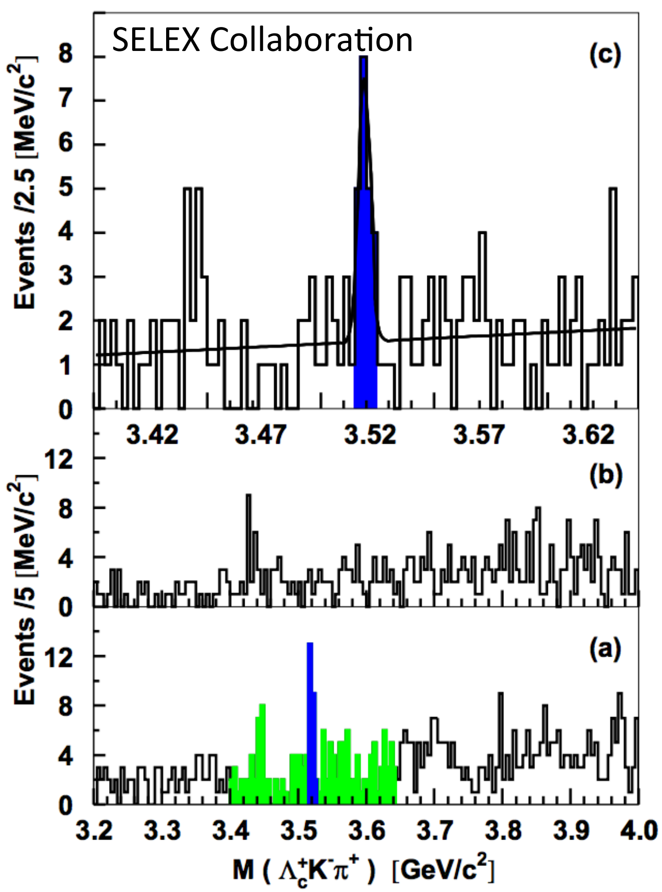
Production and decay properties

Double charmed baryons



arXiv:hep-ex/0208014 (2002)

Long-standing puzzle…

Previous SELEX observations of Ξ_{cc}^+ (*ccd*) with:

- $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ (6.3σ)
- $\Xi_{cc}^+ \to p D^+ K^-$ (4.8σ)

Unexpected findings:

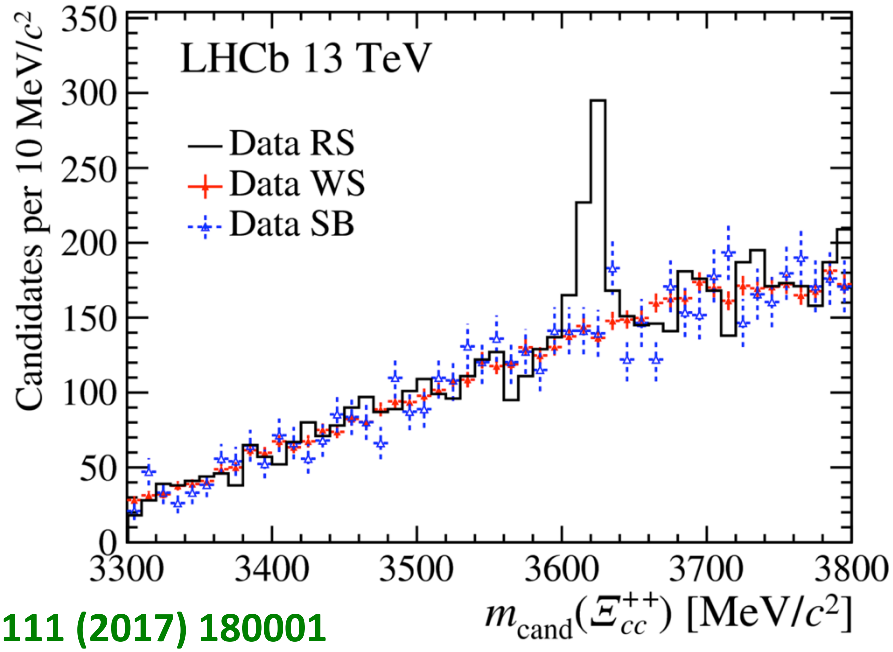
- $\tau(\Xi_{cc}^+) < 33$fs @ 90% CL
- ~20% of all Λ_c^+ from this Ξ_{cc}^+ decay

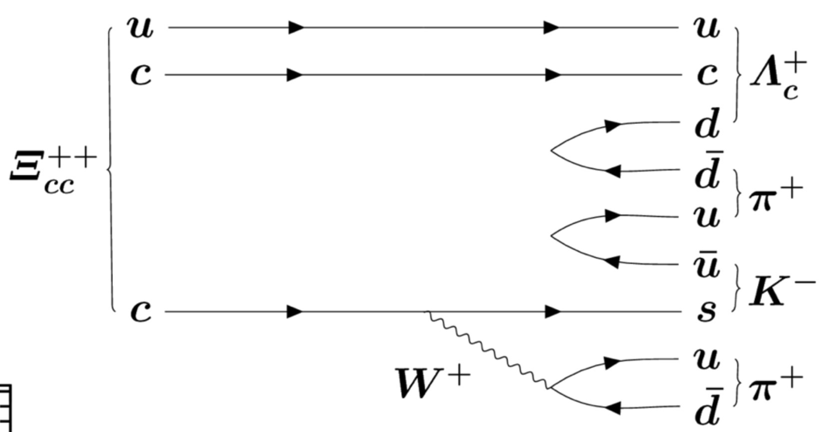
Not seen by other experiments, but unique collision environment means state cannot be ruled out.

Production and decay properties

Double charmed baryons

New LHCb results searches for doubly-charged isospin partner (ccu) of claimed SELEX state





Significant excess above smooth background

No peaking in wrong-sign or sideband samples

PRL 111 (2017) 180001
arXiv:1707.01621

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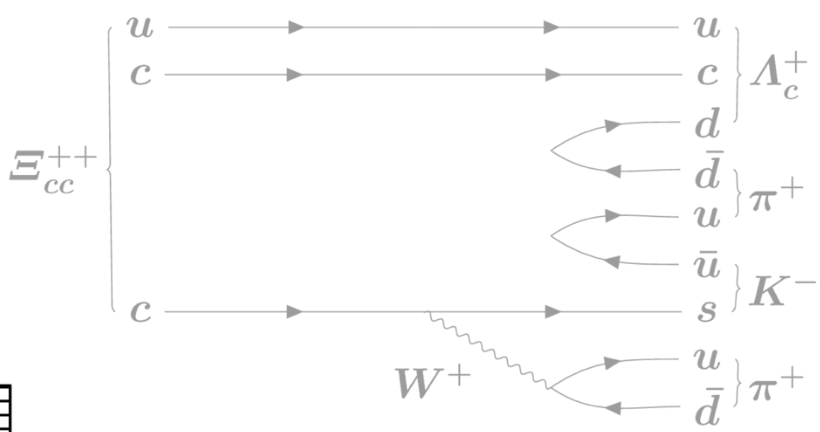

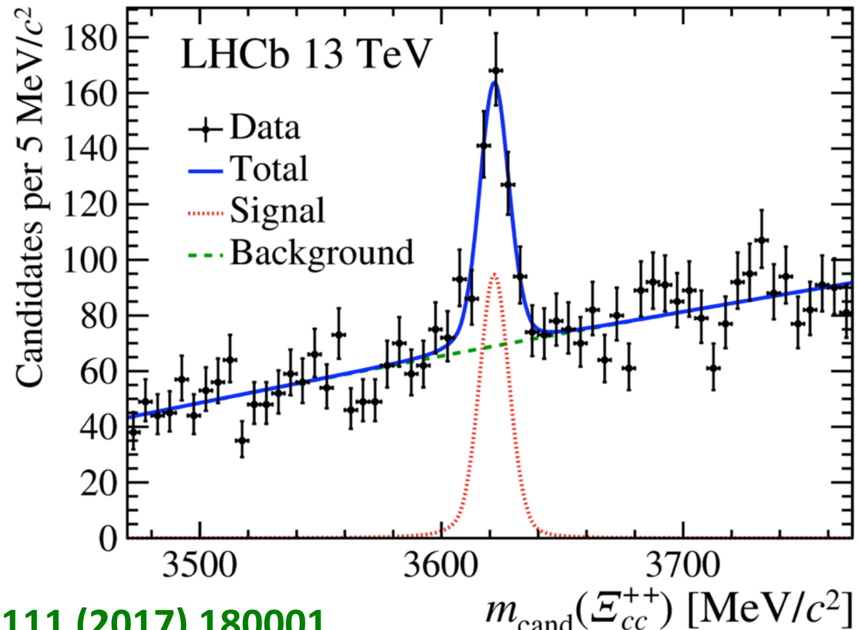

UML fit:

> **12σ** significance

M(Ξ_{cc}^{++}) = 3621.40 ± 0.72 ± 0.27 ± 0.14 MeV/c^2
(stat) (syst) (Λ_c^+)

>100 MeV from SELEX peak (3519 ± 2 MeV) – disfavours prior Ξ_{cc}^+ hypothesis

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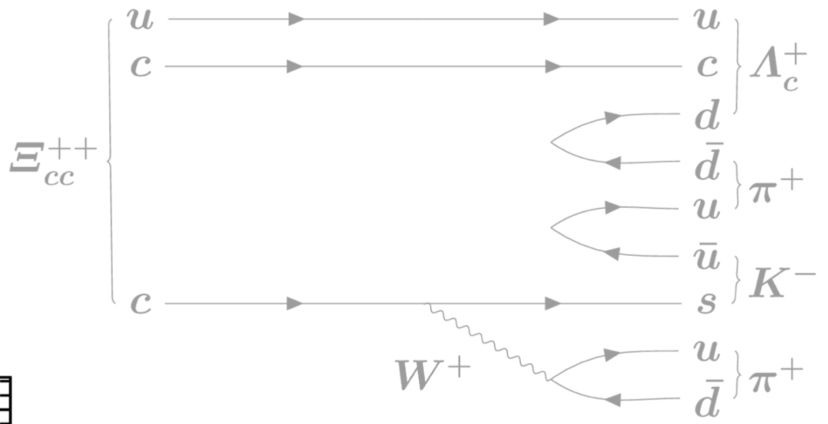

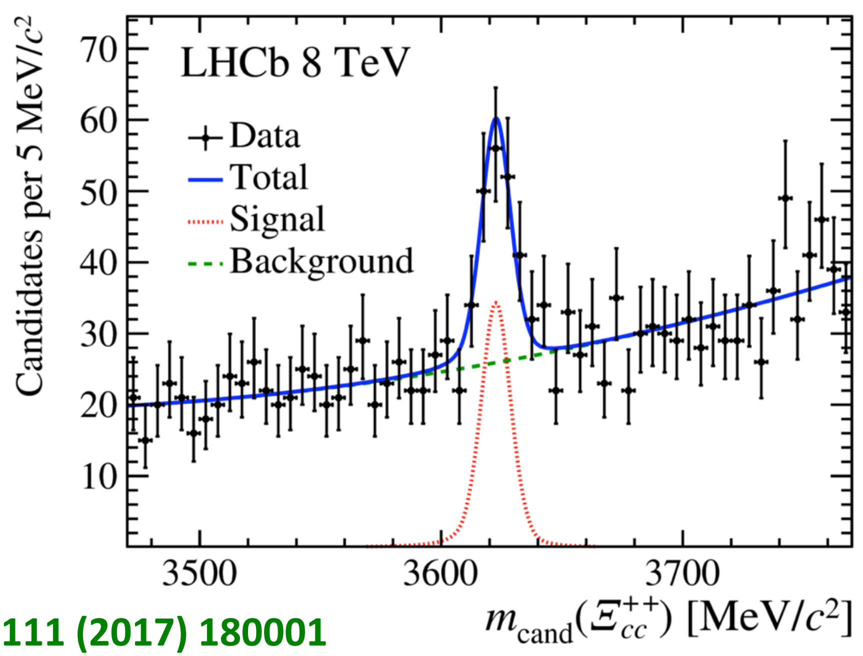

Significant peak in LHCb Run 1 (8 TeV) sample.

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Production and decay properties

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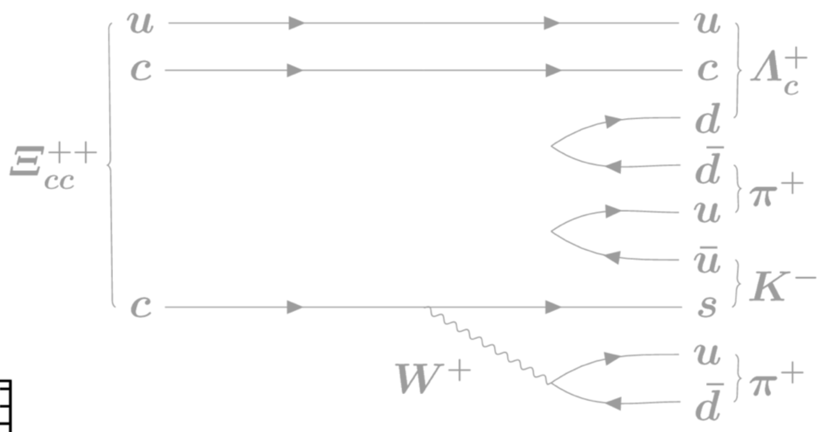

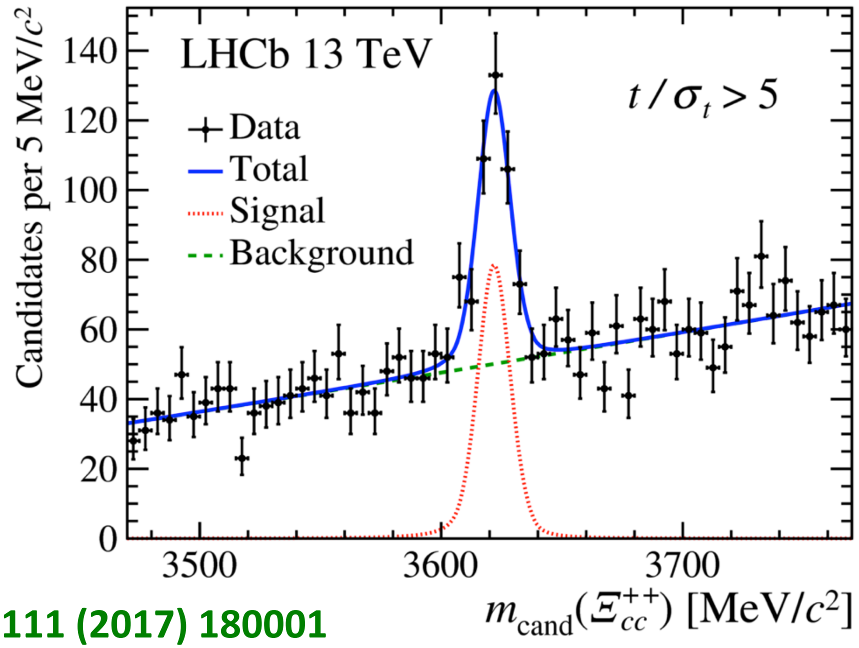

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Significant peak in LHCb Run 1 (8 TeV) sample.

Peak still present for **highly-significant decay-time region**.

Production and decay properties

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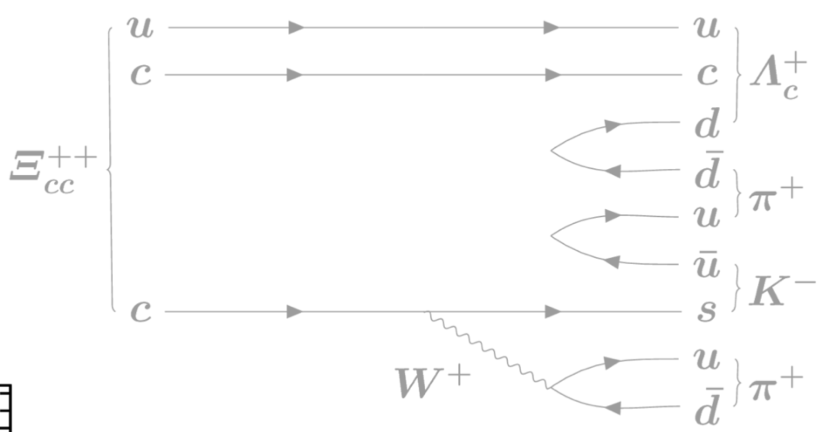

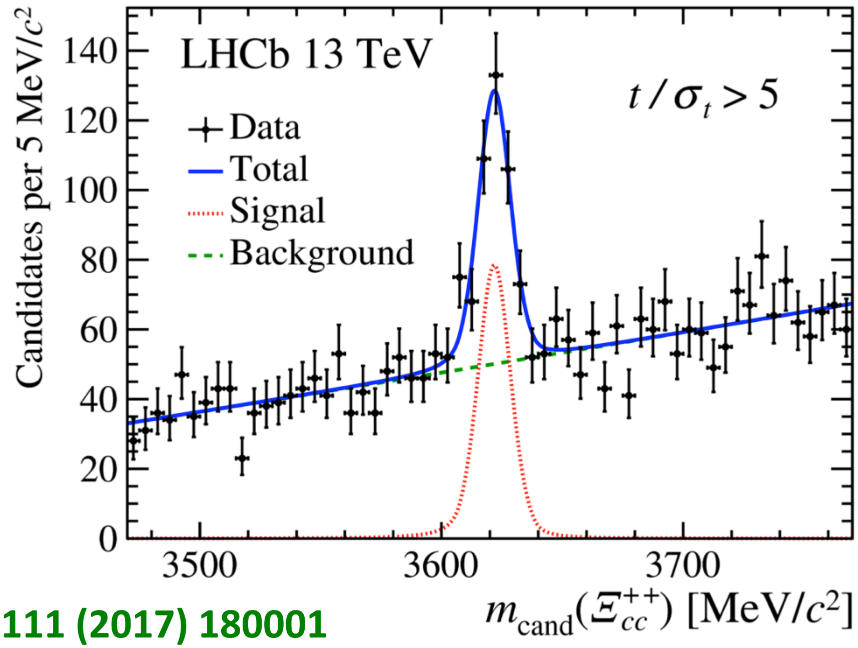

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Next steps:

- Full lifetime measurement
- Ξ_{cc}^+ (ccd)
- Ω_{cc}^+ states (ccs)
- More decay channels (~30 new trigger conditions for 2017 running)