Looking for new physics in rare semileptonic charm baryon decays

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Charm InDor workshop 2024

What are we discussing today?

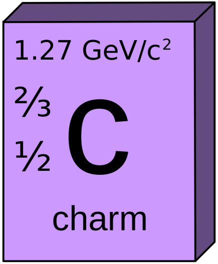
- Introduction to charm physics at LHCb:
  - can we do charm physics at LHCb?
- Introduction to baryonic charm decay physics:
  - why are we interested in baryonic charm decays?
  - which observables can we look at?
- Branching fraction measurements of $\Lambda_c^+ \to p\mu^+\mu^-$:
  - motivation, strategy and results.
- *CP* and Parity violation measurements in $\Lambda_c^+ \to p\ \phi\ (\to\mu^+\mu^-)$:
  - motivation and strategy.
  - few (really a few) technical things.
  - blinded results and outlook.
- Conclusions.

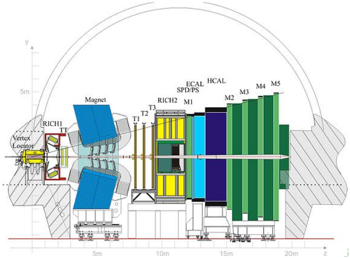
Charm at LHCb

- The study of charm decays is a **unique probe for physics Beyond the Standard Model (BSM)**.
- Charm studies are complementary to the b and s sectors:
  - c is the **only up-like heavy quark that hadronizes**;
  - theoretical predictions have **large uncertainties** (non-perturbative QCD regime);
- At LHCb is possible to study it:

$$\sigma(pp \to c\bar{c}X, \sqrt{s} = 13\,\text{TeV}) \sim 2.4\ mb$$
$$\sigma(pp \to b\bar{b}X, \sqrt{s} = 13\,\text{TeV}) \sim 0.1\ mb$$

- LHCb collected the **largest charm hadron dataset** to perform studies.



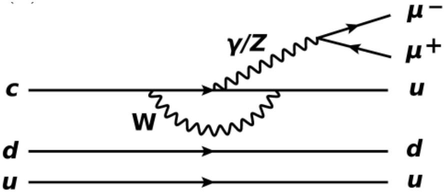


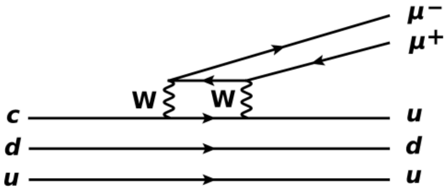
Why are we into charm baryonic decays?

- Flavor changing neutral current processes in the SM are highly suppressed.
- Amplitude $A(c \to u)$ depends on CKM elements ($\lambda_i = V^*_{ci} V_{ui}$) and loop functions ($f_i$):

$$A(c \to u) = \sum_{i=d,s,b} \lambda_i f_i = \lambda_s \left((f_s - f_d) + \frac{\lambda_b}{\lambda_s}(f_b - f_d) \right)$$

- **CKM suppression** and **Glashow-Iliopoulos-Maiani (GIM)** mechanism lead to extreme suppression of branching fractions and CP asymmetries.
- Penguin contributions are very small ($< 10^{-8}$).





Two complementary approaches

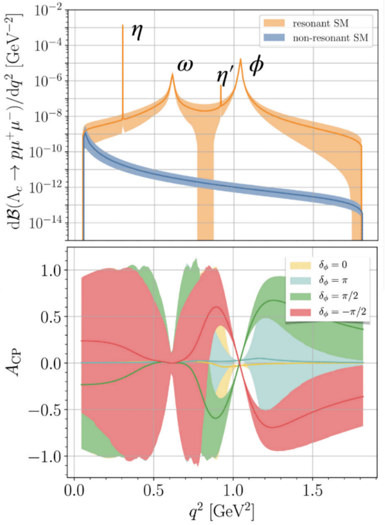
In SM $c \to u l^+ l^-$ transitions are heavily suppressed: may lead to the observation of NP.

Looking to $\Lambda_c^+ \to p\mu^+\mu^-$ decay one can:

- measure the branching fraction of the decays;
- make a null test on A_{FB} in the lepton system;
- measure A_{CP} of the decay;

Today we can discuss:

- **branching ratio analysis** from the past (RUN1): *"Search for the rare decay $\Lambda_c^+ \to p\mu^+\mu^-$"*
- **null test measurements** currently ongoing:
  - we are working on an analysis on the 2016-2018 data to measure A_{FB} and A_{CP} in 2 bins of $m_{\mu\mu}$ around the ϕ−resonant spectrum.



Branching ratio measurement: motivation and strategy

The branching ratio of the short distance $\Lambda_c^+ \to p\mu^+\mu^-$ is extremely suppressed in SM:

- Beyond the Standard Model phyiscs effects may enhance it.

We select events containing **pairs of muons** at LHCb.

Long distance contributions can increase the branching fraction up to $\sim O(10^{-6})$:

- **the phase space is split in 3 regions:**
  - ϕ resonant region $m_{\mu\mu} \in [985, 1055]$ MeV (control);
  - ω resonant region $m_{\mu\mu} \in [759, 805]$ MeV;
  - a non resonant regions excluding $|m_{\mu\mu} - m_{reso}| < 40$ MeV

We define the branching ratio with respect to the control as:

In the non resonance mode: $$\frac{B(\Lambda_c^+ \to p\mu^+\mu^-)}{B(\Lambda_c^+ \to p\phi)B(\phi \to \mu^+\mu^-)} = \frac{\epsilon_{norm}}{\epsilon_{sig}} \times \frac{N_{sig}}{N_{norm}}$$

In the resonance mode: $$\frac{B(\Lambda_c^+ \to p\omega)B(\omega \to \mu^+\mu^-)}{B(\Lambda_c^+ \to p\phi)B(\phi \to \mu^+\mu^-)} = \frac{\epsilon_{norm}}{\epsilon_{sig}} \times \frac{N_{sig}}{N_{norm}}$$

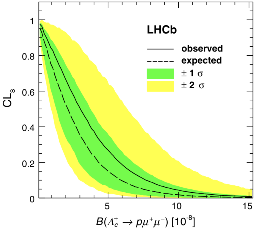
Branching ratio measurement: results from LHCb RUN1

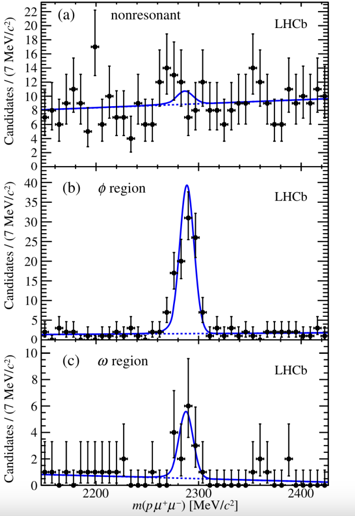
In the ω resonant region a signal has been observed with 5.0σ of significance:

$$B\left(\Lambda_c^+ \rightarrow p\omega\right) = (9.4 \pm 3.2 \pm 1.0 \pm 2.0) \times 10^{-4}$$

It is possible to infer an upper limit on the Branching ratio in the non resonant region as:

$$B(\Lambda_c^+ \rightarrow p\mu^+\mu^-) < 7.7 \times 10^{-8} \text{ at 90\% CL}$$





General overview on charm baryonic BR measurements

- BaBar limit on $\Lambda_c^+ \to pe^+e^-$ mode [1]:
$$B(\Lambda_c^+ \to pe^+e^-) < 2.7 \times 10^{-6}$$
- LHCb limit on the $\Lambda_c^+ \to p\mu^+\mu^-$ mode [2]:
$$B(\Lambda_c^+ \to p\mu^+\mu^-) < 7.7 \times 10^{-8}$$
- LHCb measurement on $\Lambda_c^+ \to p\mu^+\mu^-$ in the ω resonance region [2]:
$$B(\Lambda_c^+ \to p\omega(\to \mu^+\mu^-)) = (9.4 \pm 3.2 \pm 1.0 \pm 2.0) \times 10^{-4}$$
- A measurement on the Σ_c baryon has been done by E653 [3]:
$$B(\Sigma_c \to \Sigma^-\mu^+\mu^-) < 7 \times 10^{-4}$$
- Belle measurements on $\Xi_c^0 \to \Xi^0\ell^+\ell^-$ modes [4]:
$$B(\Xi_c^0 \to \Xi^0\mu^+\mu^-) < 6.5 \times 10^{-5}$$
$$B(\Xi_c^0 \to \Xi^0e^+e^-) < 9.9 \times 10^{-5}$$

A nice coincidence...

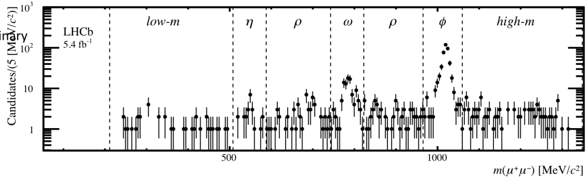
RUN2 update of the $\Lambda_c^+ \to p\mu^+\mu^-$ branching ratio measurement **is being presented at CERN today**:

Summary

- Rare mode, extrapolating to full mass region from low- and high masses:
  - signal region (extrapolated): $\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 7.3\ (8.2) \times 10^{-8}$ at 90% (95%) CL.
  - **low-mass:** $\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 6.5\ (7.8) \times 10^{-8}$ at 90% (95%) CL
  - **high-mass:** $\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 11.8\ (13.1) \times 10^{-8}$ at 90% (95%) CL
- Resonant mode mass regions (assuming no interference):

$$\mathcal{B}(\Lambda_c^+ \to p\omega) = (9.82 \pm 1.23\ (\text{stat.}) \pm 0.72\ (\text{syst.}) \pm 2.79\ (\text{ext.})) \times 10^{-4}$$
$$\mathcal{B}(\Lambda_c^+ \to p\rho) = (1.52 \pm 0.34\ (\text{stat.}) \pm 0.14\ (\text{syst.}) \pm 0.24\ (\text{ext.})) \times 10^{-3}$$
$$\mathcal{B}(\Lambda_c^+ \to p\eta) = (1.67 \pm 0.69\ (\text{stat.}) \pm 0.23\ (\text{syst.}) \pm 0.34\ (\text{ext.})) \times 10^{-3}$$

preliminary



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We can measure the branching fraction...

Or at least put upper limits...

Can we perform the **null tests** I primised you?

We can!

How the *CP* asymmetry looks like?

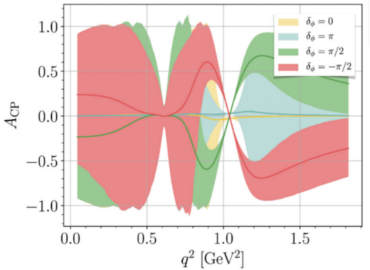
We can define the *CP* asymmetry over the spectrum of the dilepton mass as:

$$A_{CP}\left(q^2\right) = \frac{1}{\Gamma + \overline{\Gamma}}\left(\frac{d\Gamma}{dq^2} - \frac{d\overline{\Gamma}}{dq^2}\right)$$

where $\Gamma(\overline{\Gamma})$ is the integrated branching fraction of $\Lambda_c^+ \to p\mu^+\mu^-$ $(\overline{\Lambda}_c^- \to \overline{p}\mu^+\mu^-)$.

- **We are sensitive to interference of NP with the resonant mode.**

- $A_{CP}^{SM} < 5 \times 10^{-3}$ in the ϕ resonance region.
- The *CP* asymmetry can take different shapes the dilepton mass spectrum;
  - dependency on the strong phase;
  - we can measure it in different dilepton mass bins.



How to access the CP asymmetry

We cannot access A_{CP} directly, we only can measure the so called raw-asymmetry (A_{CP}^{raw}):

- A_{CP}^{raw} contains nuisance asymmetries (production and detection related):

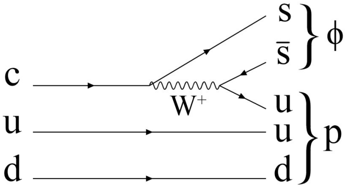
$$A_{CP}^{raw}\left(\Lambda_c^+ \to p\mu^+\mu^-\right) = A_{CP} + A_P\left(\Lambda_c^+\right) + A_D\left(p\right) + \left(A_D\left(\mu^+\mu^-\right) = 0\right)$$

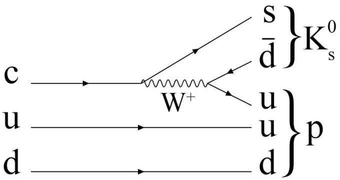
- a control sample of $\Lambda_c^+ \to pK_s^0$ can be used to estimate the nuisance asymmetries:

$$A_{CP}^{raw}\left(\Lambda_c^+ \to pK_s^0\right) = A_P\left(\Lambda_c^+\right) + A_D\left(p\right) + \left(A_D\left(K_s^0\right) = 0\right)$$

These asymmetries depend on the kinematic of the particle.
Reweight the control sample on data :

- transverse momentum (PT), pseudorapidity (η), azimutal angle (ϕ) of Λ_c^+ and p

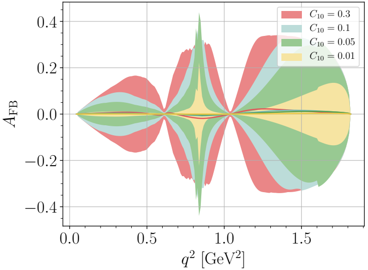




How the FB asymmetry looks like?

The SM angular distribution is defined by the **absence of an axial vector current**.
The angular distribution is defined like:

$$\frac{d\Gamma}{dq^2 d\cos\theta} = a\left(q^2\right) + b\left(q^2\right)\cos\theta + c\left(q^2\right)\cos^2\theta$$



- Two observables are provided:

$$A_{FB}\left(q^2\right) = \frac{b\left(q^2\right)}{\Gamma}$$
$$F_H\left(q^2\right) = \frac{2}{\Gamma}\left(a\left(q^2\right) + c\left(q^2\right)\right)$$

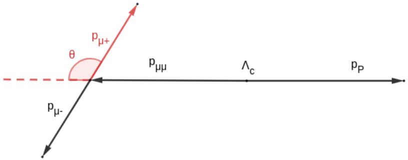
- In SM A_{FB} naturally vanishes ($\mathcal{C}_{10}^{SM} = 0$).
- A small presence of NP may interfere with the resonant mode ($A_{FB} \sim \mathcal{C}_9^R \mathcal{C}_{10}$).

$$O_{10} = (\overline{u}_L \gamma_\mu c_L)(\overline{\ell}\gamma^\mu \gamma_5 \ell)$$
$$O_9^R = (\overline{u}_L \gamma_\mu c_L)(\overline{\ell}\gamma^\mu \ell)$$

How to access the FB asymmetry

The A_{FB} is defined with respect to $\theta-$angle between:

- **direction of the lepton in the dilepton frame**;
- **direction of the dilepton in the Λ_c frame**.



$$A_{FB} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}$$

The measurement of A_{FB} will be done:

- in two bins of the $m_{\mu\mu}$ spectrum around m_ϕ;
- distinguishing between the two flavours Λ_c^+ and $\overline{\Lambda}_c^-$.

It is also possible to evaluate the relevant combinations:

$$\Sigma A_{FB} = \frac{1}{2}\left(A_{FB}^{\Lambda_c^+} + A_{FB}^{\Lambda_c^-}\right) \qquad \Delta A_{FB} = \frac{1}{2}\left(A_{FB}^{\Lambda_c^+} - A_{FB}^{\Lambda_c^-}\right)$$

How to model and fit

A total model to fit the offline selected mass distribution has been studied:

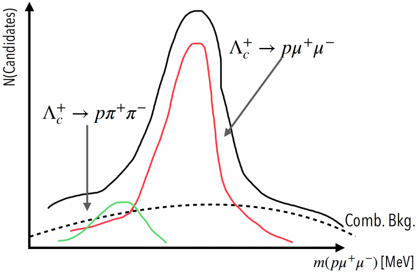
$$f_{tot}(m; N_1, ..., N_n) = \sum_{i=1}^{n} N_i f_i(m; \vec{x_i})$$

The shapes of the different components ($\vec{x_i}$) have been fixed by previous fits:

- $\Lambda_c^+ \to p\mu^+\mu^-$ signal is fixed from a **fit on the simulation**;
- combinatorial background is fixed by a **fit on a control data sample**;
- $\Lambda_c^+ \to p\pi^+\pi^-$ MIS-ID is fixed by a **fit on the simulation**.

Multiple integrated fits has been applied to optimize the data selection.

- In the integrated fit only the yields (N_i) are free for each component.



Efficiency correction over the phasespace

The detector and the offline selection may have different efficiencies in different regions of the $(m_{\mu\mu}, \cos\theta)$-phase space.

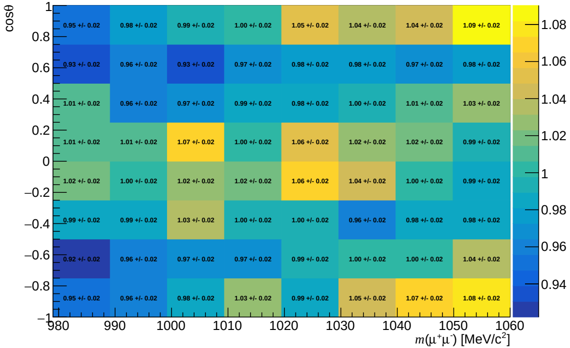
The distributions **at the production level** and **after the offline selection** are compared in the simulations.

The **relative efficiencies** are:

$$\epsilon\left(m_{\mu\mu}, \cos\theta\right) = \frac{f_{selected}\left(m_{\mu\mu}, \cos\theta\right)}{f_{production}\left(m_{\mu\mu}, \cos\theta\right)}$$

and the **acceptance weights**:

$$\lambda_{corr} = \frac{1}{\epsilon}$$



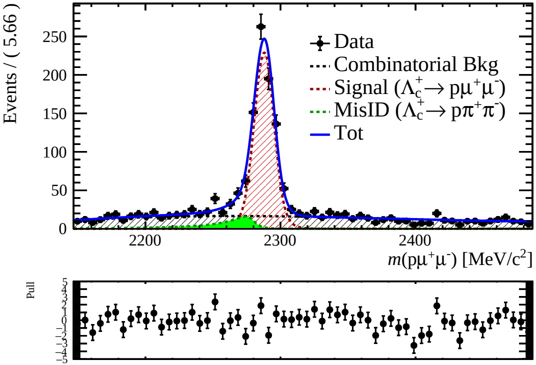
A **total fit** has been done on efficiency corrected data:

The free parameters are **the yields** of the components and the **position of the signal peak**:

- a shift of the signal peak between the two $m_{\mu\mu}$−bins has been observed.

The results (asymmetries blinded) are:

Asym.	$m(\mu^+\mu^-)$	N_{sig}	N_{misID}	N_{comb}	A_{sig}
A_{CP}^{raw}	ϕ_{low}	341 ± 21	65 ± 21	435 ± 26	$xxx \pm \sim 6\%$
	ϕ_{high}	432 ± 22	38 ± 16	390 ± 24	$xxx \pm \sim 5\%$
$A_{FB}^{\Lambda_c^+}$	ϕ_{low}	–	–	–	$xxx \pm \sim 9\%$
	ϕ_{high}	–	–	–	$xxx \pm \sim 7\%$
$A_{FB}^{\Lambda_c^-}$	ϕ_{low}	–	–	–	$xxx \pm \sim 9\%$
	ϕ_{high}	–	–	–	$xxx \pm \sim 7\%$



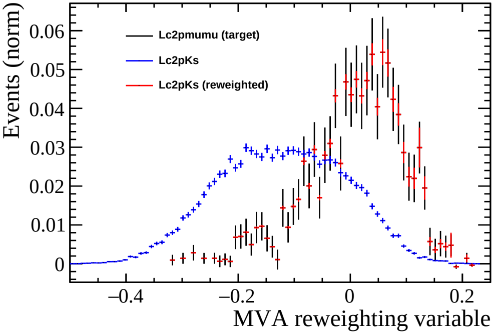
Instrumental asymmetry evaluation: reweighting

The nuisance asymmetries are: $A_{CP}^{raw}\left(\Lambda_c^+ \to pK_s^0\right) = A_P\left(\Lambda_c^+\right) + A_D(p) + \left(A_D\left(K_s^0\right) = 0\right)$

- we want the control sample $(\Lambda_c^+ \to pK_S^0)$ to be kinematically similar to $\Lambda_c^+ \to p\mu^+\mu^-$;
- the control sample has been reweighted on the data sample.

To overcome the low statistics a **MVA-based 1-dimensional reweighing** has been applied:

- a 6 variables BDT is trained on:
  - PT, ETA and PHI of the Λ_c^+;
  - PT, ETA and PHI of the p;
- the multivariate variable has been used to compute kinematic weights;
- a **loss in statistics** in the control sample is expected.



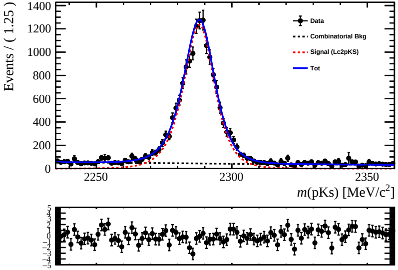
Instrumental asymmetry evaluation: fit

$A_{CP}^{raw}(\Lambda_c^+ \to pK_s^0) = A_P(\Lambda_c^+) + A_D(p)$ is evaluated on the re-weighted $\Lambda_c^+ \to pK_s^0$ dataset:

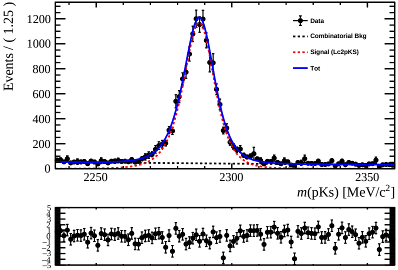
- $A_{CP}^{raw}(\Lambda_c^+ \to pK_s^0) = (3.0 \pm 1.2) \times 10^{-2}$ for the re-weighted sample.
- $A_{CP}^{raw}(\Lambda_c^+ \to pK_s^0) = (2.4 \pm 0.6) \times 10^{-2}$ for the NON re-weighted sample;

The uncetrainty on $A_{CP}(\Lambda_c^+ \to p\mu^+\mu^-)$ is dominated by the one on $A_{CP}^{raw}(\Lambda_c^+ \to p\mu^+\mu^-)$ ($\sim 5-6\%$).

Λ_c^+ events in the control sample



$\overline{\Lambda_c^+}$ events in the control sample



Systematics on our measurement

Systematic studies

Multiple systematic effects have been taken into account:

- **imperfect mass shape** in the model;
- **limited Montecarlo** in the efficiency correction;
- imperfect **modeling of the efficiency correction**;
- **imperfect reweighting** of the control sample;
- **secondary decay contamination** in the data and control samples;
- **angular resolution** effects.
  - All the systematic effects, individually, are $\sim 10^{-3}$.

Correlation

The effect of the **limited Montecarlo in the efficiency correction** and the **angular resolution effects** have high correlation between $A_{FB}^{\Lambda_c^+}$ and $A_{FB}^{\Lambda_c^-}$.

Final results

Finally the blinded measured values of A_{CP} and A_{FB} are:

	ϕ_{low}	ϕ_{high}
A_{CP}	$(xxx \pm \sim 6(\text{stat}) \pm \sim 0.5(\text{syst})) \times 10^{-2}$	$(xxx \pm \sim 5(\text{stat}) \pm \sim 0.5(\text{syst})) \times 10^{-2}$
$A_{FB}^{\Lambda_c^+}$	$(xxx \pm \sim 9(\text{stat}) \pm \sim 1(\text{syst})) \times 10^{-2}$	$(xxx \pm \sim 7(\text{stat}) \pm \sim 1(\text{syst})) \times 10^{-2}$
$A_{FB}^{\Lambda_c^-}$	$(xxx \pm \sim 9(\text{stat}) \pm \sim 1(\text{syst})) \times 10^{-2}$	$(xxx \pm \sim 7(\text{stat}) \pm \sim 1(\text{syst})) \times 10^{-2}$

combined in ΣA_{FB} and ΔA_{FB}:

	ϕ_{low}	ϕ_{high}
ΣA_{FB}	$(xxx \pm \sim 6(\text{stat}) \pm \sim 1(\text{syst})) \times 10^{-2}$	$(xxx \pm \sim 5(\text{stat}) \pm \sim 1(\text{syst})) \times 10^{-2}$
ΔA_{FB}	$(xxx \pm \sim 6(\text{stat}) \pm \sim 1(\text{syst})) \times 10^{-2}$	$(xxx \pm \sim 5(\text{stat}) \pm \sim 1(\text{syst})) \times 10^{-2}$

- The measurements are **statistically limited**.

Conclusions and outlook

Conclusions

- Charm baryonic decays give access to interesting **observalbes to scrutinize SM predictions**:
  - multiple analysis in the past and in the present are measuring them.
- The analysis to measure the **branching ratio** of $\Lambda_c^+ \to p\mu^+\mu^-$ are currently **setting upper limits to it.**
- The analysis performing **null tests** in the ϕ region of $\Lambda_c^+ \to p\mu^+\mu^-$ is **possible but statistically limited.**

Outlook

- A new analysis updating $B(\Lambda_c^+ \to p\mu^+\mu^-)$ with RUN2 data is close to the pubblication.
- Null test analysis on $\Lambda_c^+ \to p\,\phi\,(\to\mu^+\mu^-)$ is close to the unblinding.
- A preceeding result on $\Lambda_c^+ \to p\,\omega\,(\to\mu^+\mu^-)$ opens the possibility to perform null tests.

Thank you for the attention.

Enjoy the Charm In Dor.