Rare Charm at LHCb

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On behalf of the LHCb Collaboration

11th workshop on
"Implications of LHCb measurements and future prospects"

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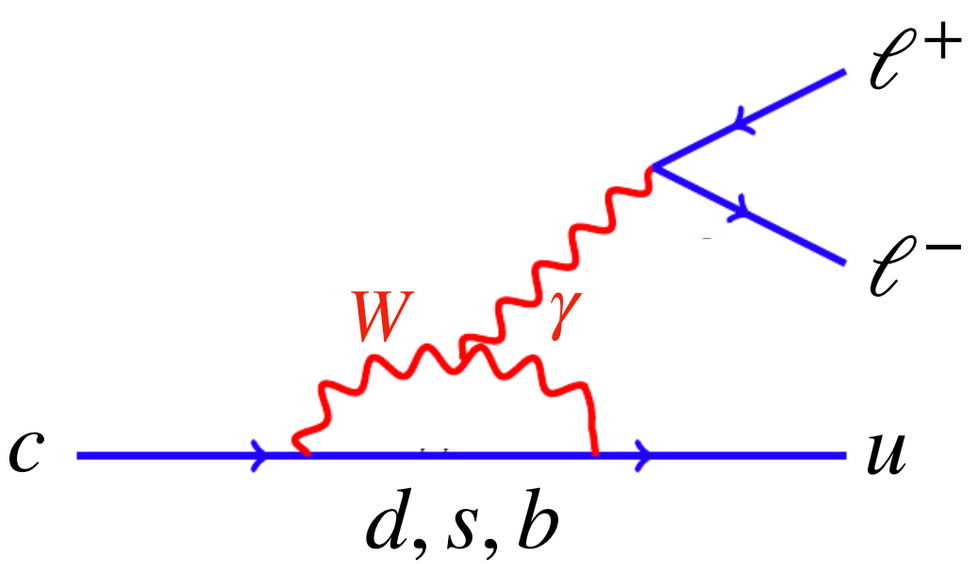
Rare charm in the SM

- unique probe of up-type quark FCNC & complementary to B and K physics!
  - almost exact GIM-cancellation in $\Delta c = \Delta u = 1$ processes



- extremely suppressed rates

  non resonant (incl. $D \to X\ell^+\ell^-$ $<\mathcal{O}(10^{-10})$
  resonant contributions $\mathcal{O}(10^{-7} - 10^{-6})$

- negligible CP asymmetries

  $\mathrm{Im}(V_{cb}^* V_{ub} / V_{cd}^* V_{ud}) \sim 10^{-3}$ $(A_{CP} \sim 0)$

- specific angular distributions

  $(C_{10}^{(\prime)} = 0)$ $\to$ parity conservation

- exploit (approximate) symmetries to test the SM with clean null-tests:
  - searches for extremely rare and forbidden decays
  - CP asymmetries and angular distributions of resonance-dominated SL decays

New physics searches at LHCb

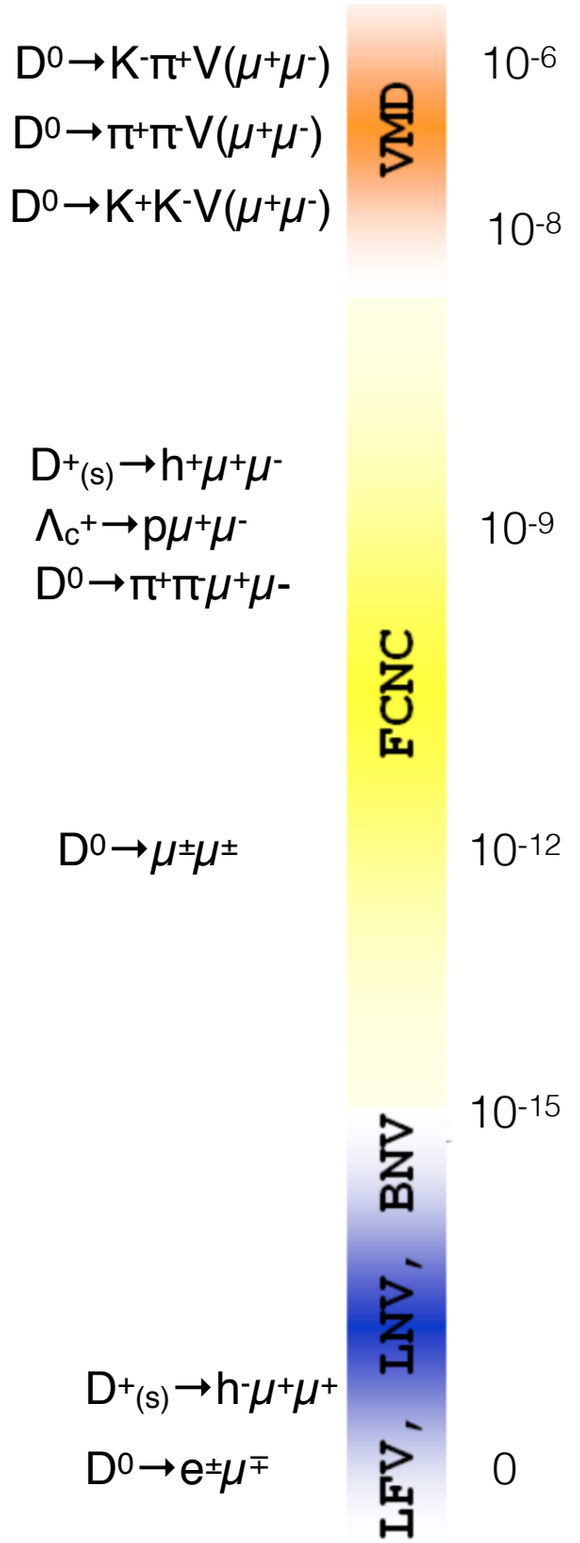
branching ratios, especially regions away from the resonances

- search for $D^0 \to \mu^+\mu^-$ [PLB 725 15-24 (2013)]
- search for $D^+_{(s)} \to h^+l^+l^-$ [PLB 724 203-212 (2013)] [JHEP 06 44 (2021)]
- search for $\Lambda_c^+ \to p\mu^+\mu^-$ [PRD 97 091101 (2018)]
- search for $D^0 \to \pi^+\pi^-\mu^+\mu^-$ [PLB 728 234-243 (2014)]
- observation of $D^0 \to h^-h^{(\prime)+} V(\mu^+\mu^-)$ [PLB 757 558-567 (2016)], [PRL 119, 181805 (2017)]

null tests based on (approximate) symmetries

- lepton-flavor/number-violation
  - search for $D^0 \to \mu^+e^-$ [PLB 754 167 (2016)]
  - search for $D^+_{(s)} \to h^-l^+l^{(\prime)+}$, $D^+_{(s)} \to h^+\mu^\pm e^\mp$ [JHEP 06 44 (2021)]
- angular observables and CP asymmetries
  - angular analysis and search for CPV in $D^0 \to h^+h^-\mu^+\mu^-$

[PRL 121 091801 (2018)], [LHCb-PAPER-2021-035]



"Angular analysis of $D^0 \to \pi^-\pi^+\mu^+\mu^-$ *and*
$D^0 \to K^-K^+\mu^+\mu^-$ *decays and search for CP violation"*

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For the first time shown today!

$D^0 \to h^+h^-\mu^+\mu^-$ decays at LHCb

- rarest charm meson decays observed, dominated by resonant contributions

$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) \sim 9.6 \times 10^{-7}$$
$$\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-) \sim 1.5 \times 10^{-7}$$

PRL 119 (2017) 181805

- measurement selected angular and CP asymmetries with 5/fb consistent with SM

PRL 121 (2018) 091801

- TODAY: First full angular analysis with 9/fb from 2011-2018 LHCb-PAPER-2021-035

  - select D^0 from flavour sepecific $D^{*+} \to D^0\pi^+$ decays

$$N(D^0 \to \pi^+\pi^-\mu^+\mu^-) \sim 3500$$
$$N(D^0 \to K^+K^-\mu^+\mu^-) \sim 300$$

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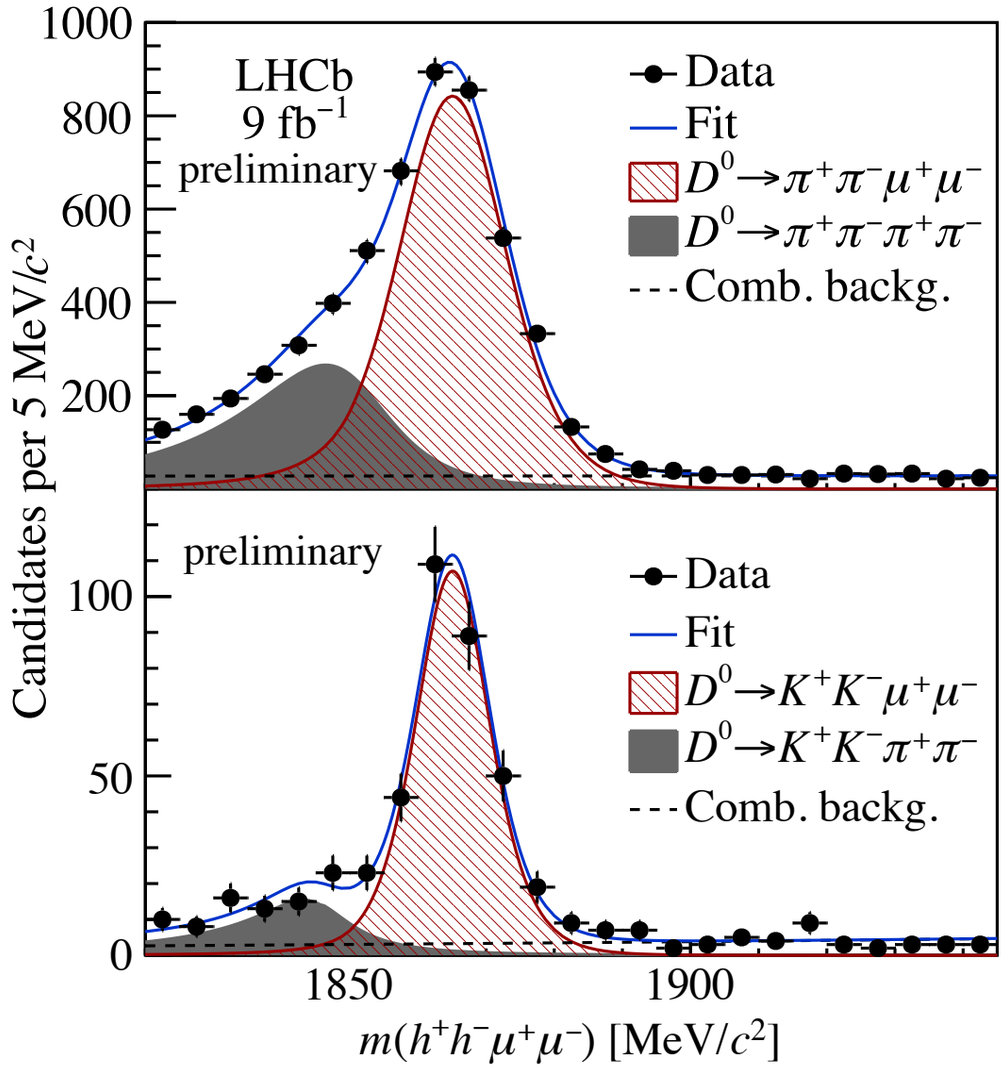

Differential decay rate

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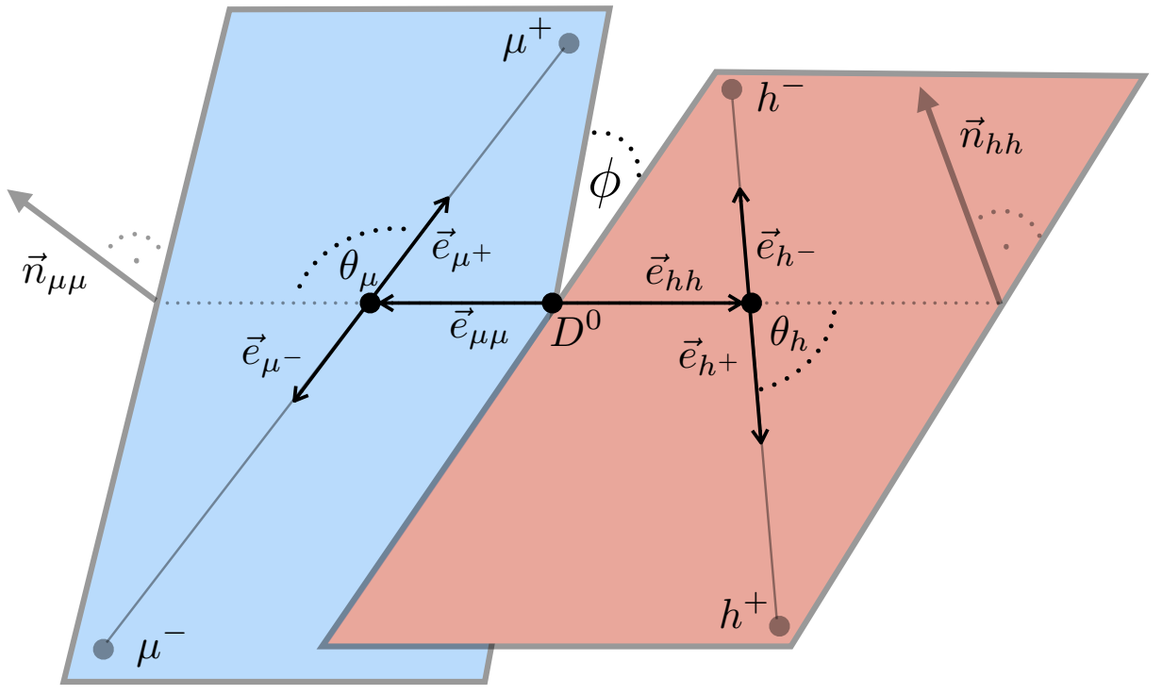
$$\frac{d\Gamma}{d\cos\theta_\mu d\cos\theta_h d\phi} = \begin{aligned} & I_1 + \\ & I_2 \cdot \cos 2\theta_\mu + \\ & I_3 \cdot \sin^2 2\theta_\mu \cos 2\phi + \\ & I_4 \cdot \sin 2\theta_\mu \cos\phi + \\ & I_5 \cdot \sin\theta_\mu \cos\phi + \\ & I_6 \cdot \cos\theta_\mu + \\ & I_7 \cdot \sin\theta_\mu \sin\phi + \\ & I_8 \cdot \sin 2\theta_\mu \sin\phi + \\ & I_9 \cdot \sin^2\theta_\mu \sin 2\phi \end{aligned}$$

I_5, I_6, I_7 clean null tests!



$$p^2 = m^2(h^+h^-)$$
$$q^2 = m^2(\mu^+\mu^-)$$

- measure $p^2, \cos\theta_h$ integrated* observables $\langle I_i \rangle$ separate for D^0 and $\overline{D^0}$

$$\langle I_{2,3,6,9} \rangle(q^2) = \frac{1}{\Gamma} \int_{4m_h}^{p^2_{max}} dp^2 \int_{-1}^{1} d\cos\theta_h \; I_{2,3,6,9}$$

$$\langle I_{4,5,7,8} \rangle(q^2) = \frac{1}{\Gamma} \int_{4m_h}^{p^2_{max}} dp^2 \left[\int_{-1}^{0} d\cos\theta_h - \int_{0}^{1} d\cos\theta_h \right] I_{4,5,7,8}$$

*optimal for p-Wave in hadron system

Measured observables and binning

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- report flavour average $\langle S_i \rangle$ and CP asymmetries $\langle A_i \rangle$

$$\langle S_i \rangle = \frac{1}{2}\left[\langle I_i \rangle + (-)\langle \overline{I}_i \rangle\right] \qquad \langle S_{5,6,7} \rangle \overset{\text{SM}}{=} 0$$

$$\langle A_i \rangle = \frac{1}{2}\left[\langle I_i \rangle - (+)\langle \overline{I}_i \rangle\right] \qquad \langle A_i \rangle \overset{\text{SM}}{=} 0$$

i=2,..,9

for CP even (CP odd) coefficients

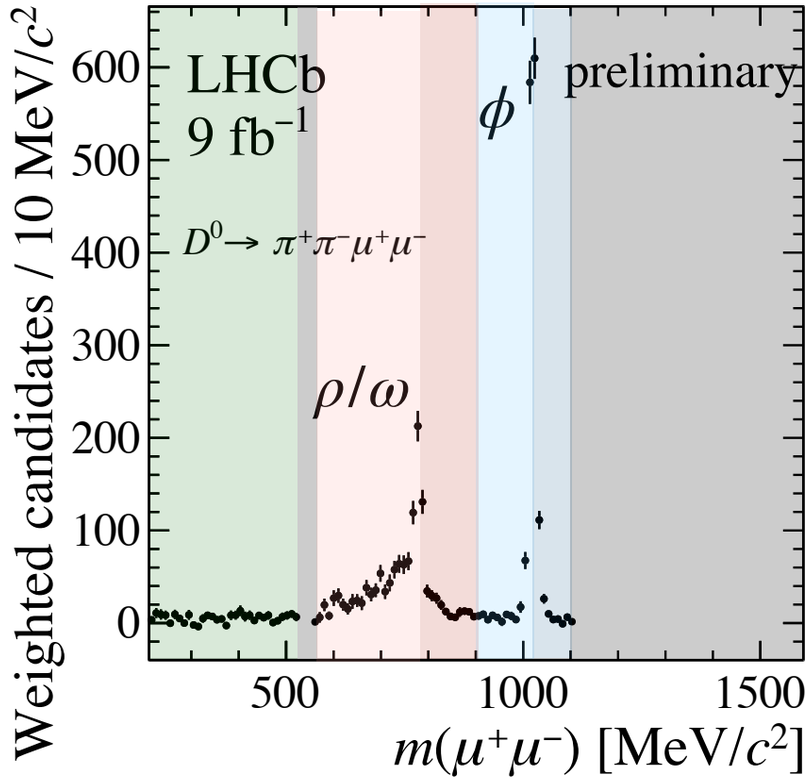
- updated measurement of A_{CP}

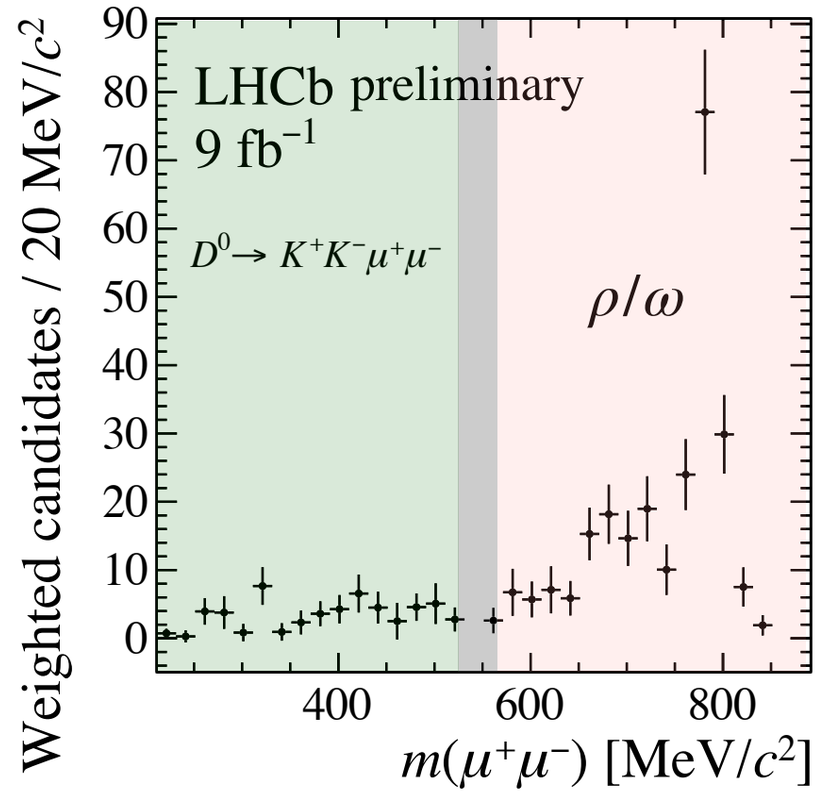
$$A_{CP} = \frac{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) - \Gamma(\overline{D}^0 \to h^+h^-\mu^+\mu^-)}{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) + \Gamma(\overline{D}^0 \to h^+h^-\mu^+\mu^-)}$$

- 17 obs./channel [12 SM null-tests] in $m(\mu^+\mu^-)$ regions ["*resonance enhanced NP effects*"]

	$m(\mu^+\mu^-)$ [MeV/c^2]						
Decay mode	low mass	η	ρ/ω		ϕ		high mass
$D^0 \to K^+K^-\mu^+\mu^-$	< 525	NS	> 565		NA		NA
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	< 525	NS	565-780	780-950	950-1020	1020-1100	NS

[NA = not available NS = no signal]





Experimental strategy

- measure angular observables via yield asymmetries, eg:

$$\langle I_6 \rangle = \frac{1}{\Gamma}\left[\int_0^1 d\cos\theta_\mu - \int_{-1}^0 d\cos\theta_\mu\right]\frac{d\Gamma}{d\cos\theta_\mu}$$

$$\langle I_6 \rangle = \frac{N(\cos\theta_\mu > 0) - N(\cos\theta_\mu < 0)}{N(\cos\theta_\mu > 0) + N(\cos\theta_\mu < 0)}$$

[see LHCb-PAPER-2021-035 for others]

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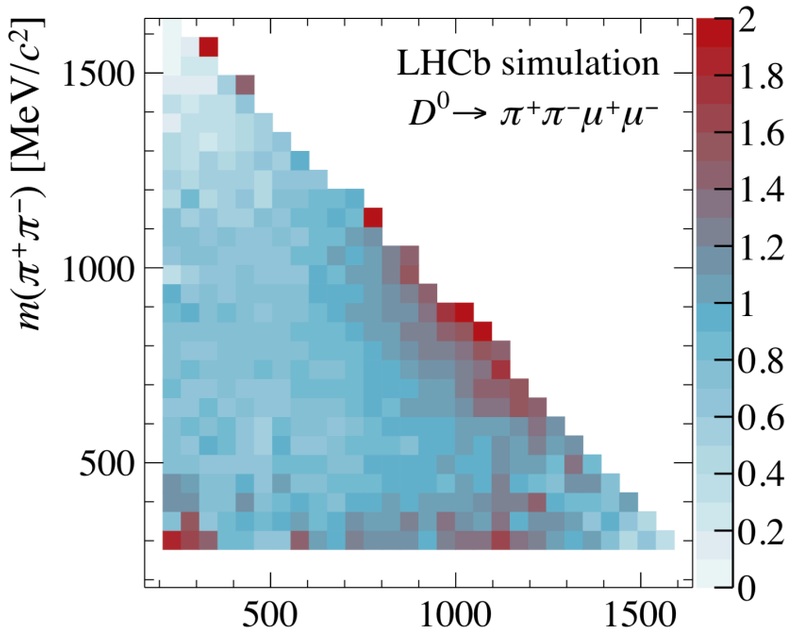

PRL 121 (2018) 091801

- correct for acceptance effects across the 5D phase space

- correct A_{CP} for nuisance asymmetries

$$A_{CP}^{raw}(f) = \frac{N(D^{*+} \to D^0(\to f)\pi^+) - N(D^{*-} \to \overline{D^0}(\to f)\pi^-)}{N(D^{*+} \to D^0(\to f)\pi^+) + N(D^{*-} \to \overline{D^0}(\to f)\pi^-)} \approx A_{CP} + A_d(\pi^\pm) + A_p(D^{*\pm})$$

[use $D^{*+} \to D^0(\to K^+K^-)\pi^+$ decays]

- evaluate systematic uncertainties

typically $\frac{\sigma_{sys}}{\sigma_{stat}} \sim (10-50)\,\%$

limited by statistics!

Flavour-averaged observables $\langle S_i \rangle$

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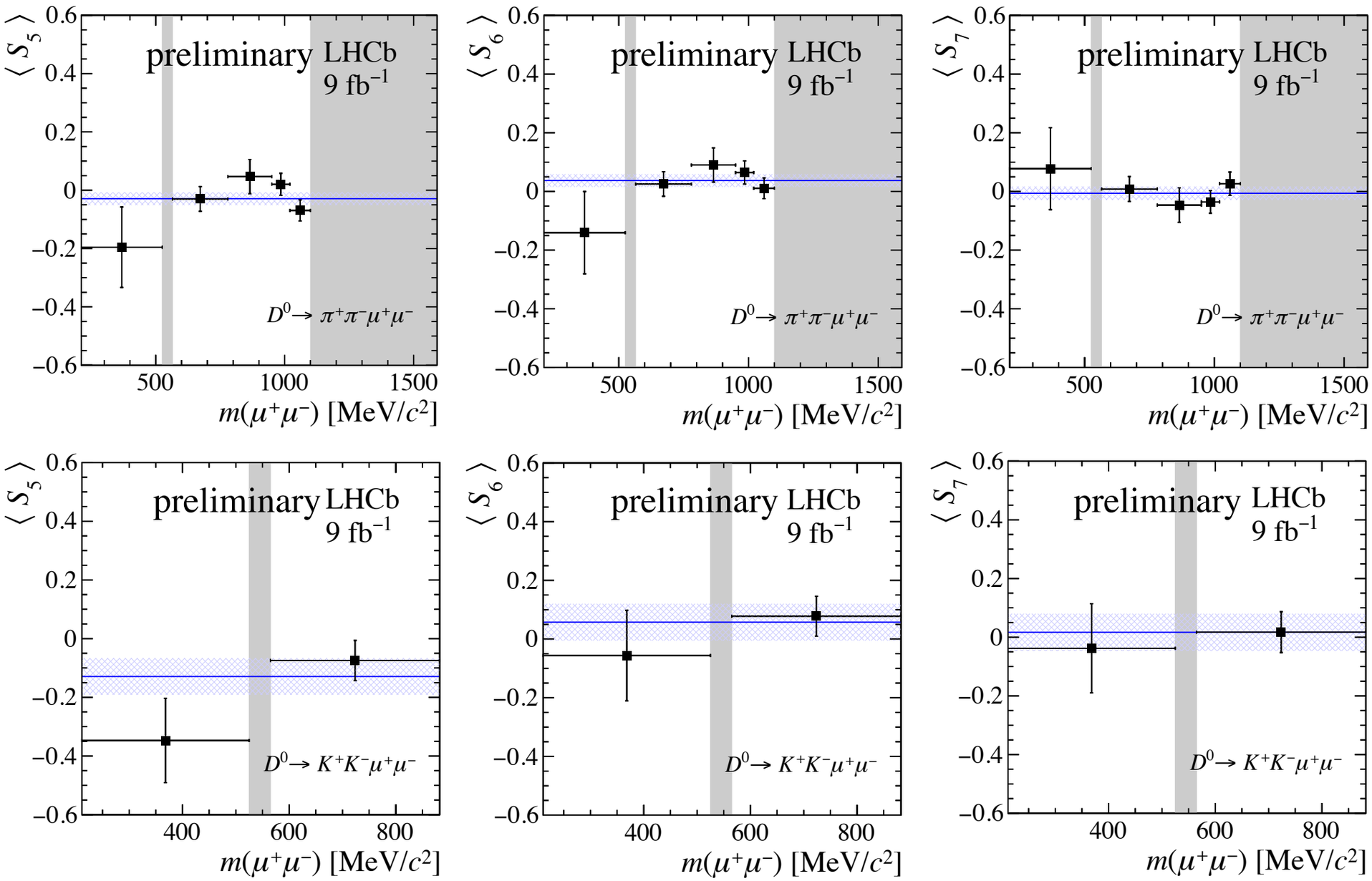
- Shown examples: SM null tests $\langle S_{5,6,7} \rangle$ [$\langle S_6 \rangle \sim A_{FB}$]



agreement with SM predictions
[JHEP 04 135 (2013), PRD 98, 035041(2018)]

- all observables in backup, tabulated version & correlation matrices in LHCb-PAPER-2021-035

CP asymmetries $\langle A_i \rangle$

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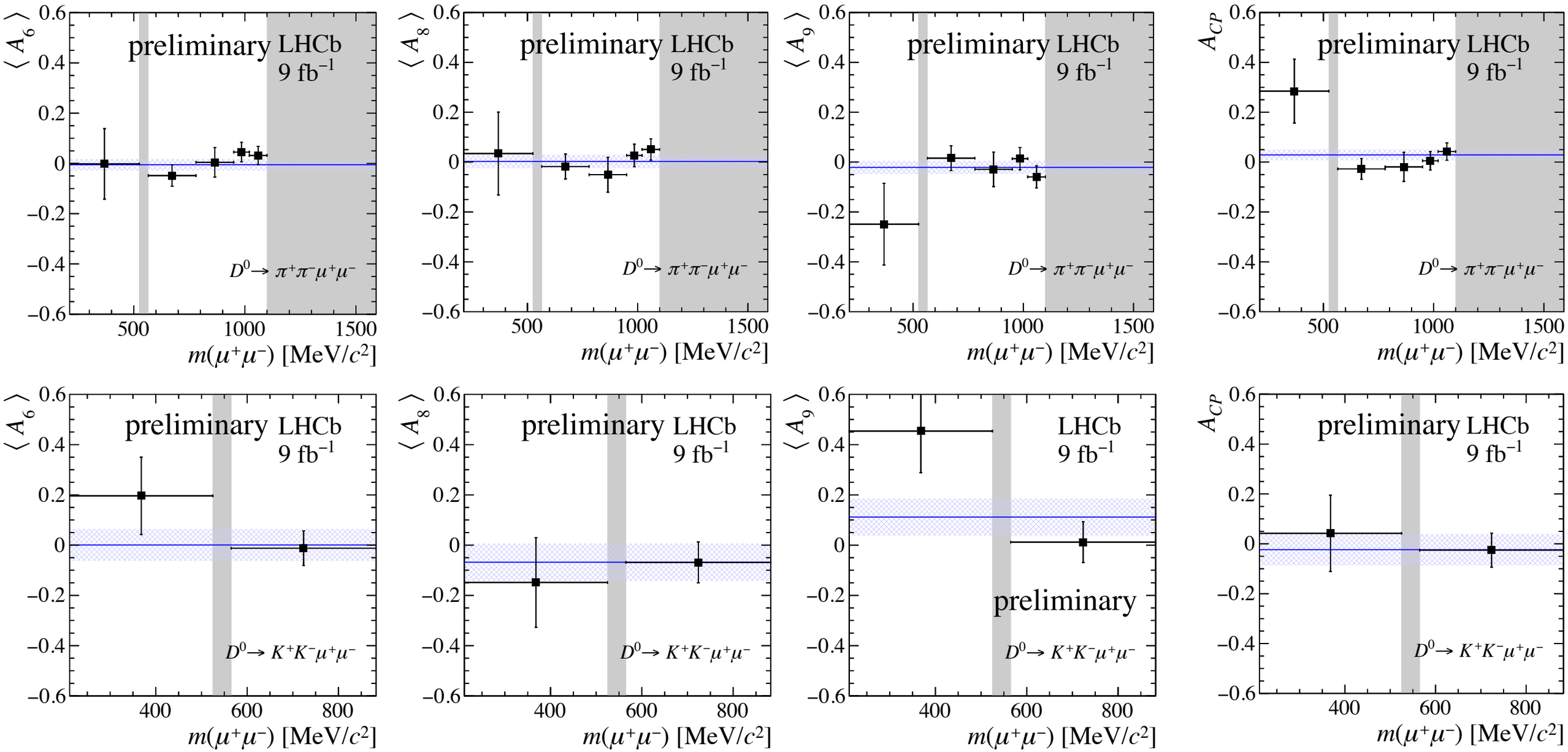
- Shown: $\langle A_6 \rangle$ [$\langle A_6 \rangle \sim A_{FB}^{CP}$], $\langle A_{8,9} \rangle$ [triple-product-asym.] & A_{CP} [others in appendix]



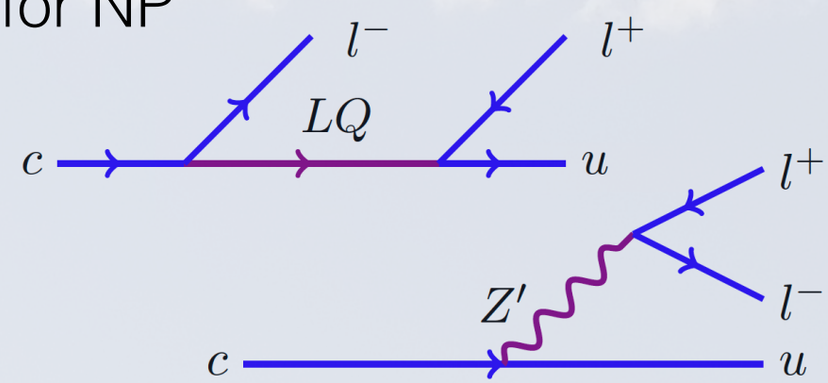
- overall agreement wrt. to SM hypothesis considering A_{CP}, $\langle A_{2-9} \rangle$ & $\langle S_{5,6,7} \rangle$:

$D^0 \to \pi^+\pi^-\mu^+\mu^-$ p = 79% (0.3σ)
$D^0 \to K^+K^-\mu^+\mu^-$ p = 0.8% (2.7σ)
preliminary

consistent with SM

Summary & outlook

- Rare charm is a unique and complementary field to look for NP
- LHCb is making major contributions
  - most measurements report world's best result
    - we hold the record for the rarest charm decays to date…
    - …and presented first angular analysis in the field today!
  - new analyses and updates will come exploring the full Run 2 data set
    - eg: updated/new searches for $D^+_{(s)} \to h^+l^+l^-$, $\Lambda_c^+ \to p\mu^+\mu^-$, $D^0 \to h^+h^{+-}e^+e^-$, $D^0 \to h^+h^+\mu^+e^-$, $D^0 \to \mu^+\mu^-$ very soon! (~limit few 10^{-9})
  - all analyses statistically limited → great prospects for the upgrade!



More? Check out Marcel's talk and MPLA 36 (2021) 2130002

Thank you

Flavour-averaged observables

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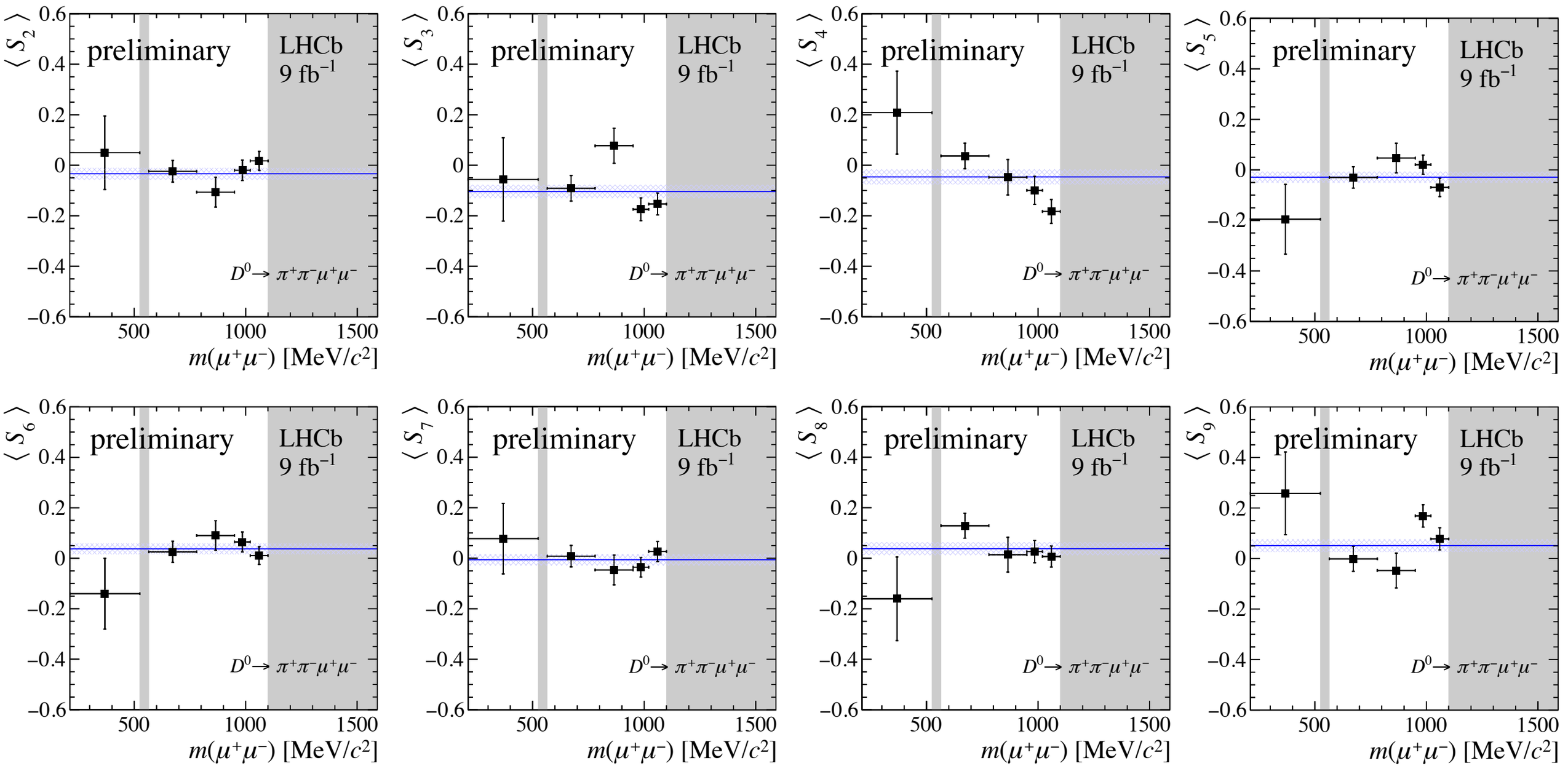

Flavour-averaged observables

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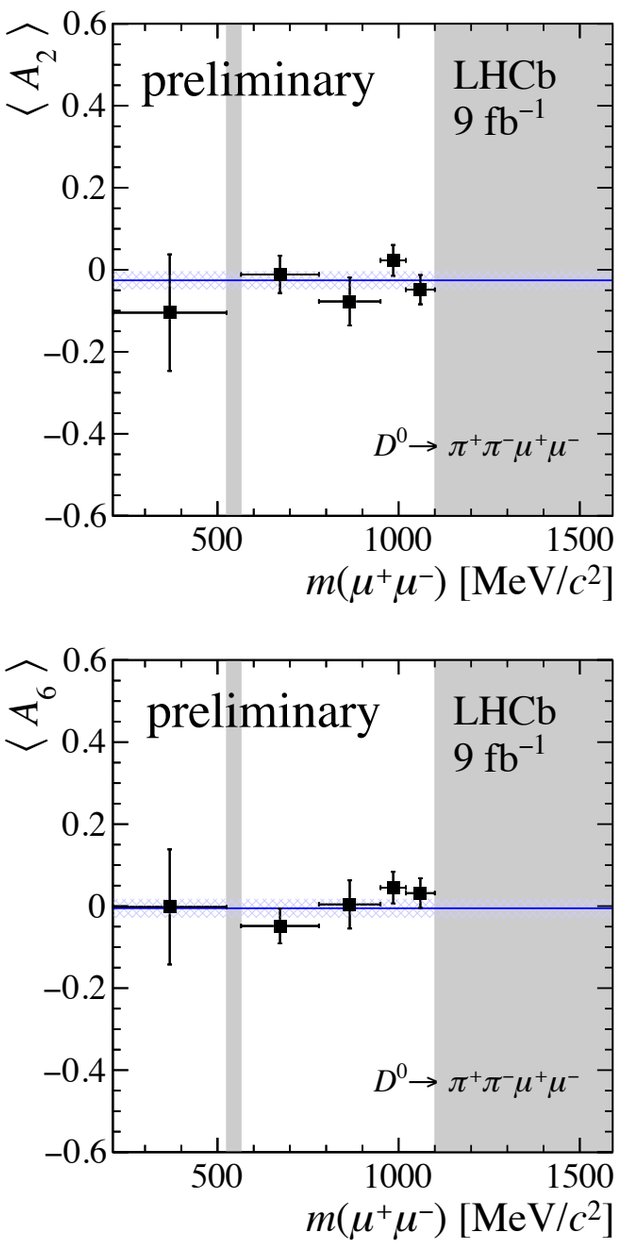

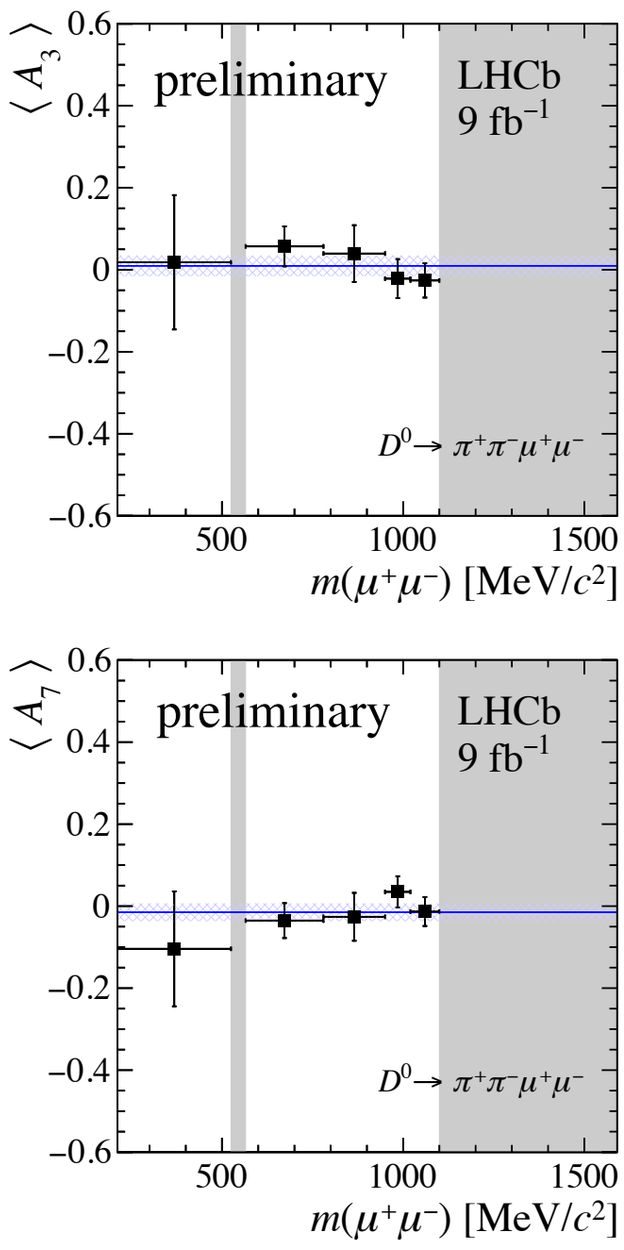

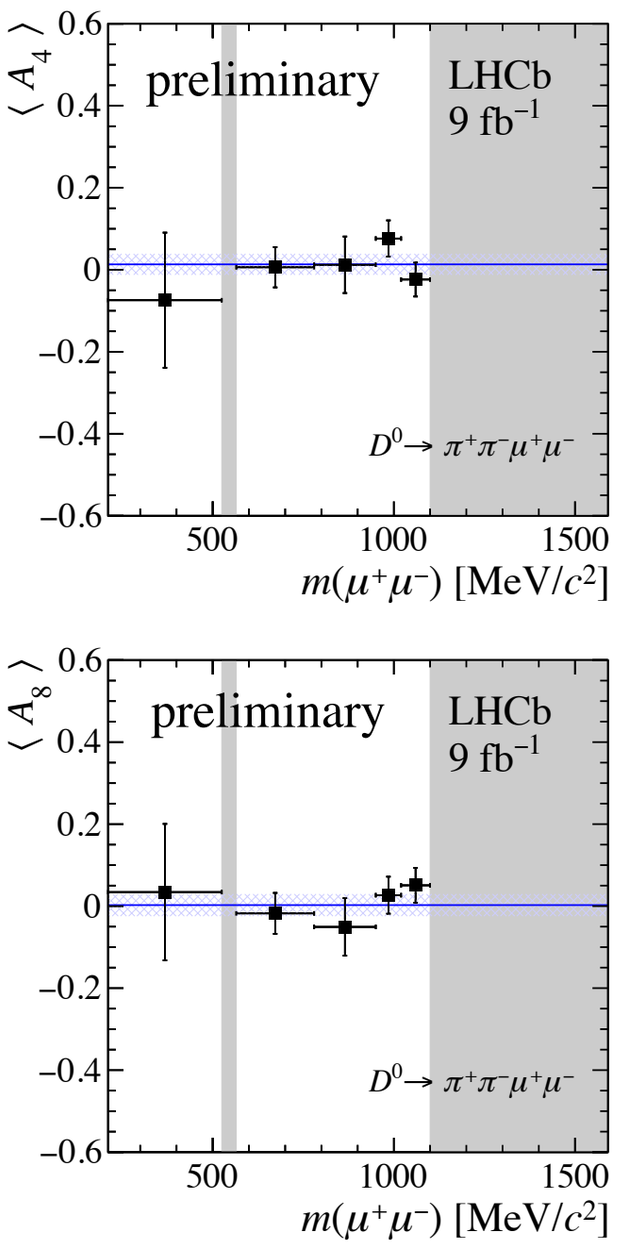

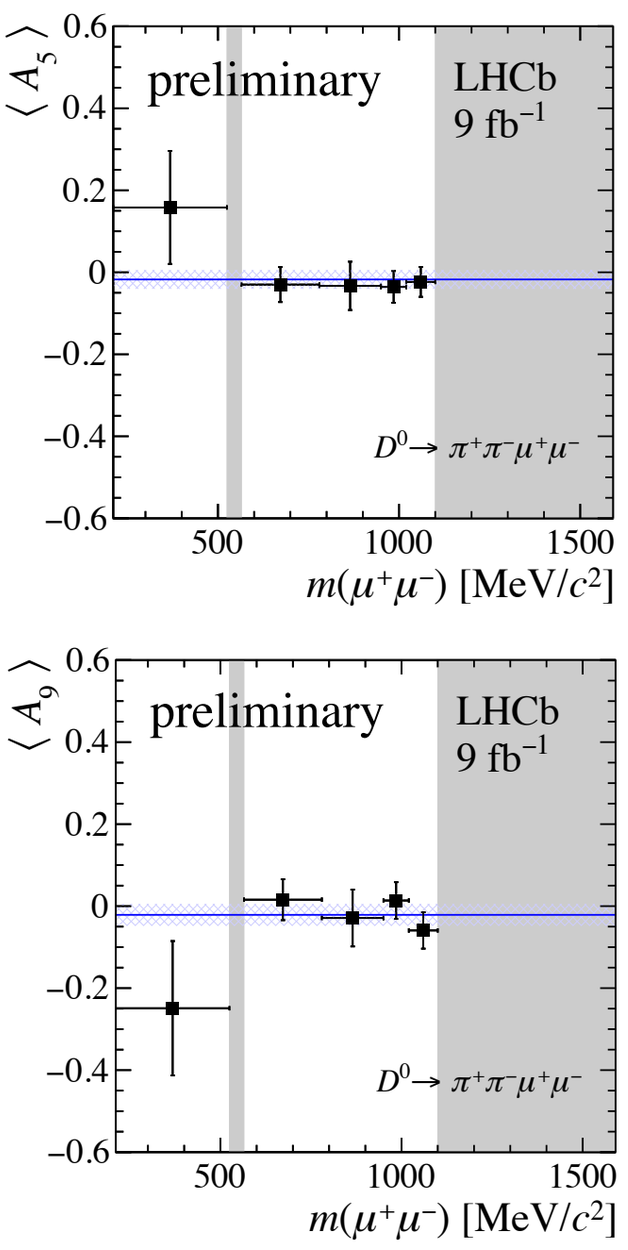

CP asymmetries $\langle A_i \rangle$

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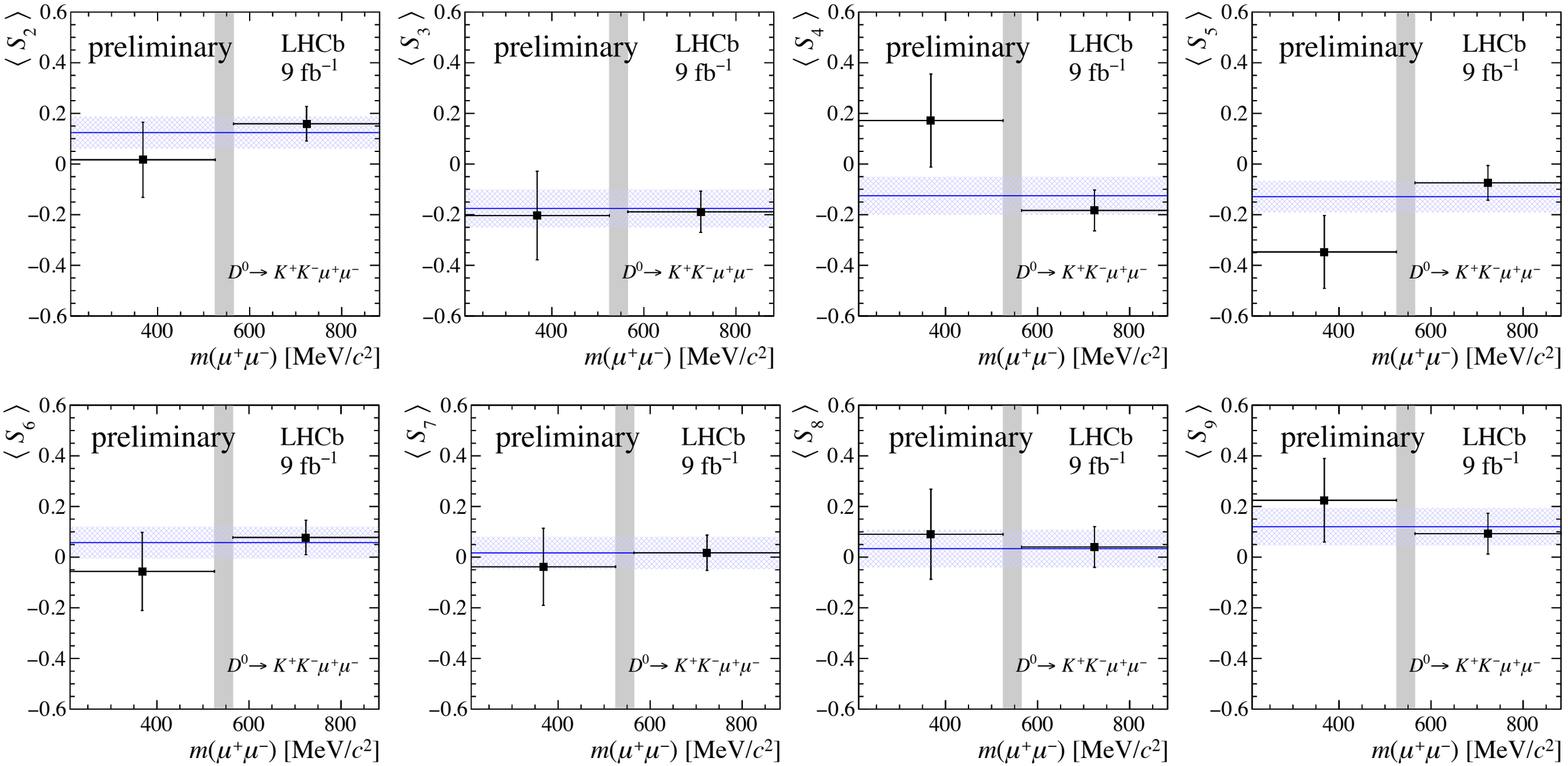

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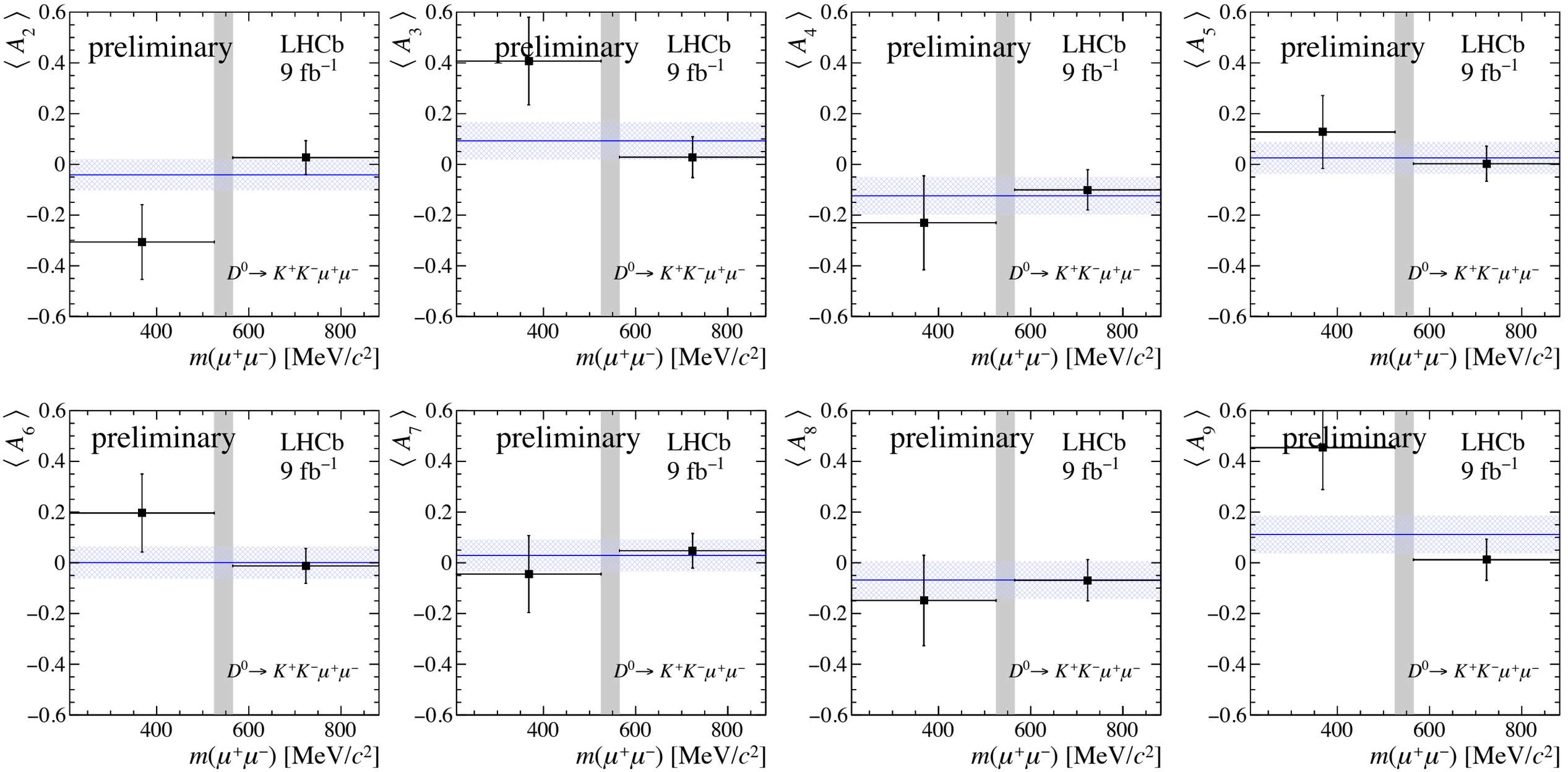

Hadron spectra

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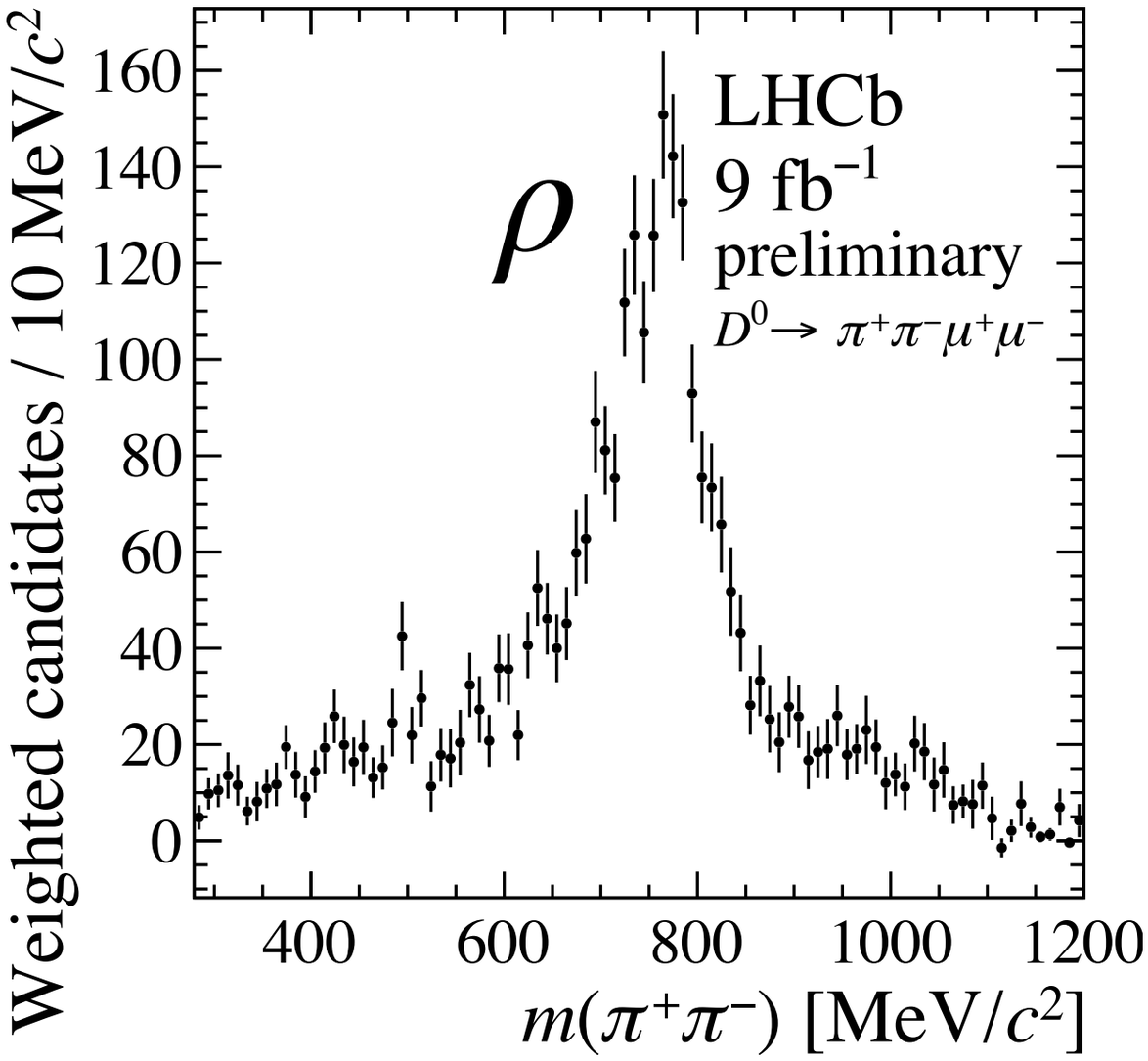
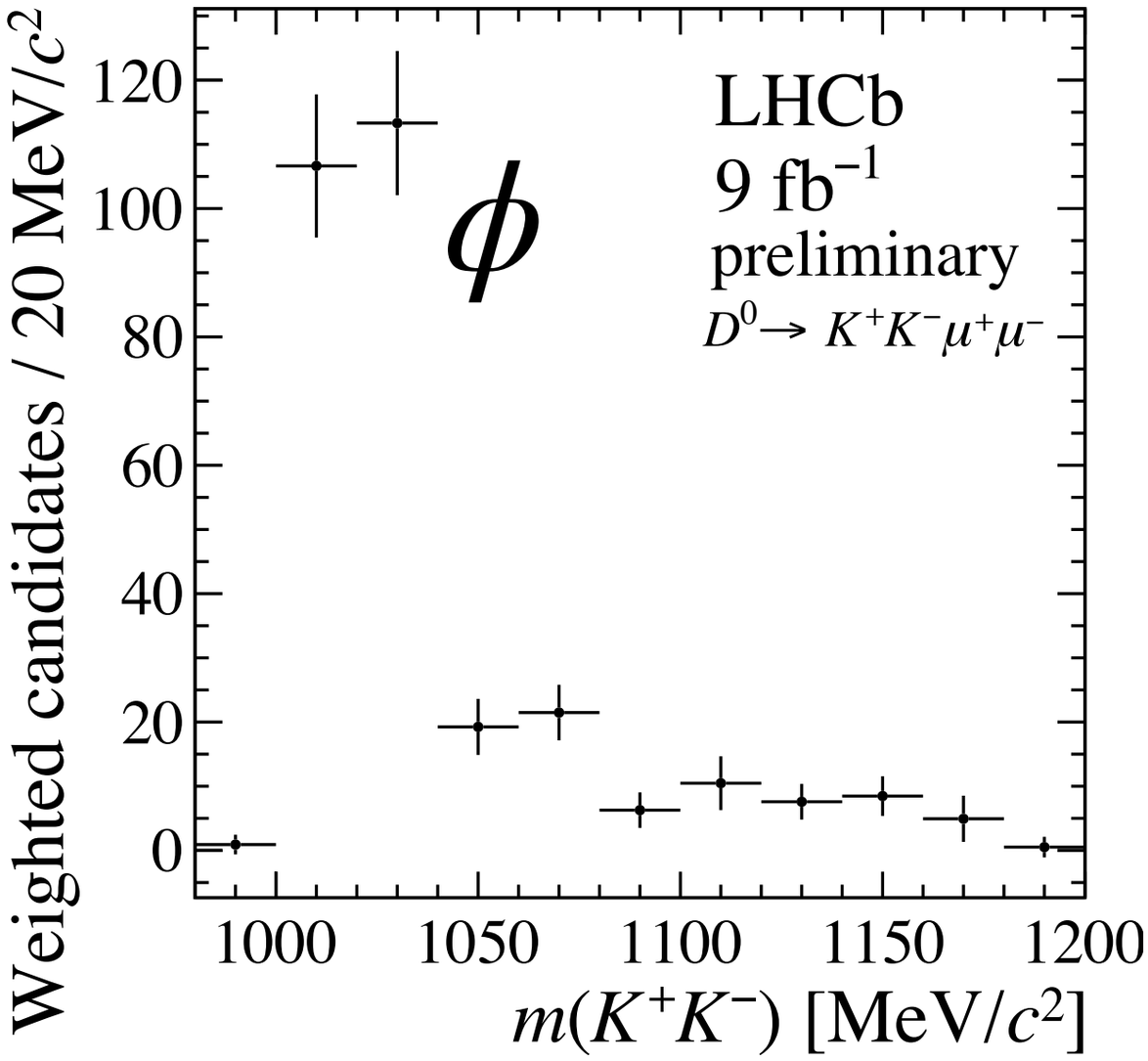
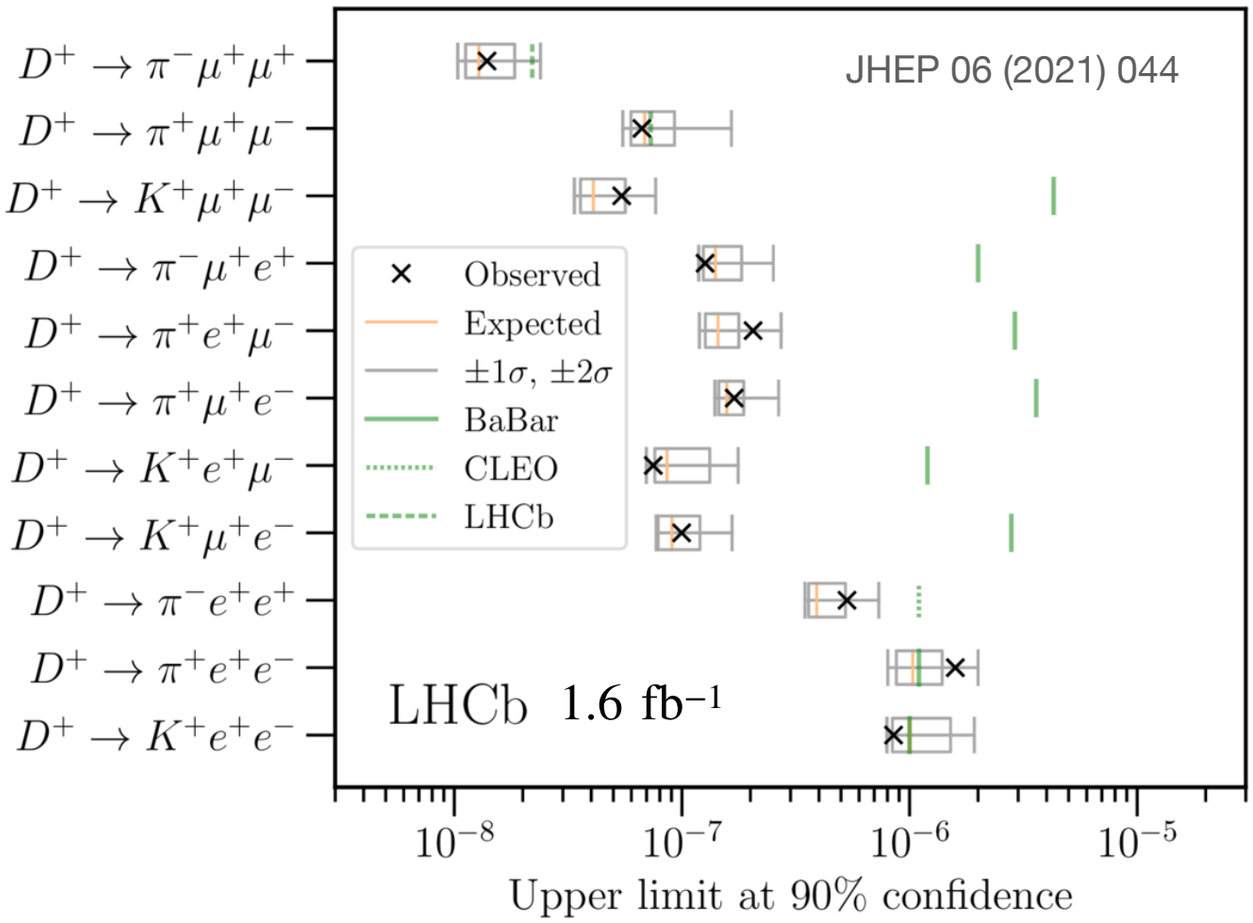
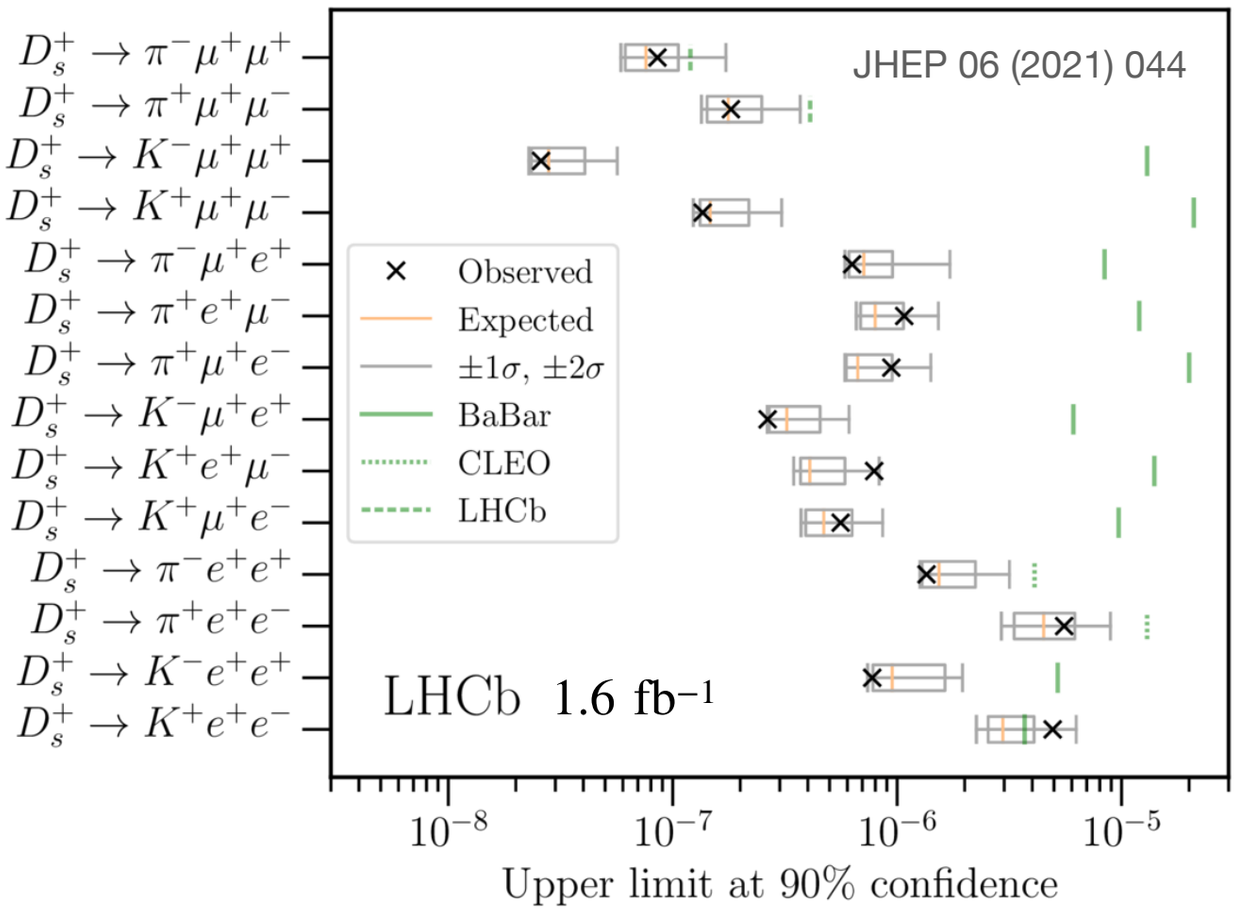




Search for 25 rare and forbidden decays





Future sensitivities

Mode	Upgrade ($50\,\mathrm{fb}^{-1}$)	Upgrade II ($300\,\mathrm{fb}^{-1}$)
$D^0 \to \mu^+\mu^-$	4.2×10^{-10}	1.3×10^{-10}
$D^+ \to \pi^+\mu^+\mu^-$	10^{-8}	3×10^{-9}
$D_s^+ \to K^+\mu^+\mu^-$	10^{-8}	3×10^{-9}
$\Lambda \to p\mu\mu$	1.1×10^{-8}	4.4×10^{-9}
$D^0 \to e\mu$	10^{-9}	4.1×10^{-9}

Mode	Upgrade ($50\,\mathrm{fb}^{-1}$)	Upgrade II ($300\,\mathrm{fb}^{-1}$)
$D^+ \to \pi^+\mu^+\mu^-$	0.2%	0.08%
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	1%	0.4%
$D^0 \to K^-\pi^+\mu^+\mu^-$	0.3%	0.13%
$D^0 \to K^+\pi^-\mu^+\mu^-$	12%	5%
$D^0 \to K^+K^-\mu^+\mu^-$	4%	1.7%