Novel approaches to search for New Physics in rare charm decays

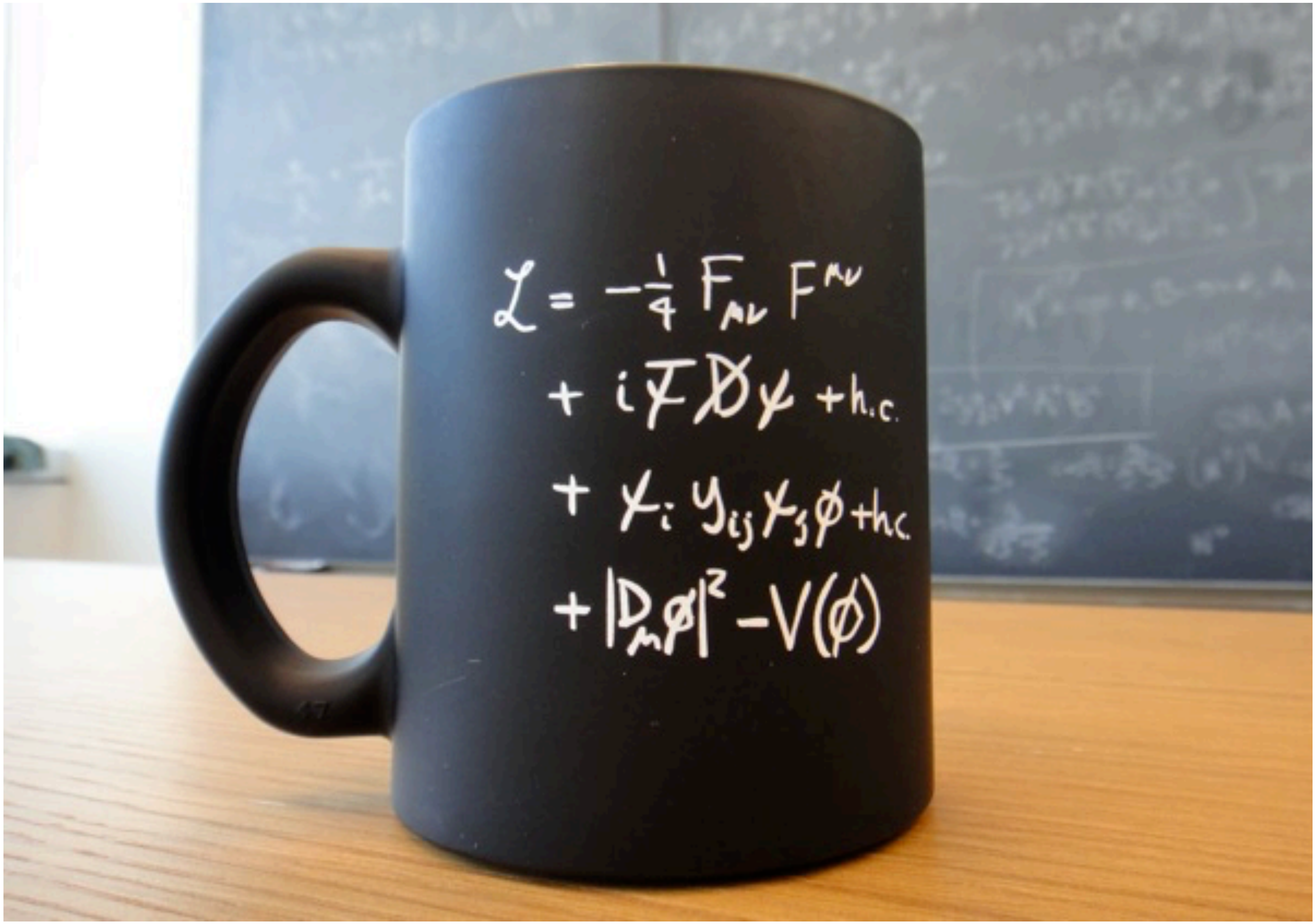
Dominik Mitzel

TU Dortmund

Particle Physics Seminar at BNL

18 November 2021

The Standard Model of Particle Physics



https://www.quantumdiaries.org/wp-content/uploads/2011/06/cernmug.jpg

Limits of the Standard Model

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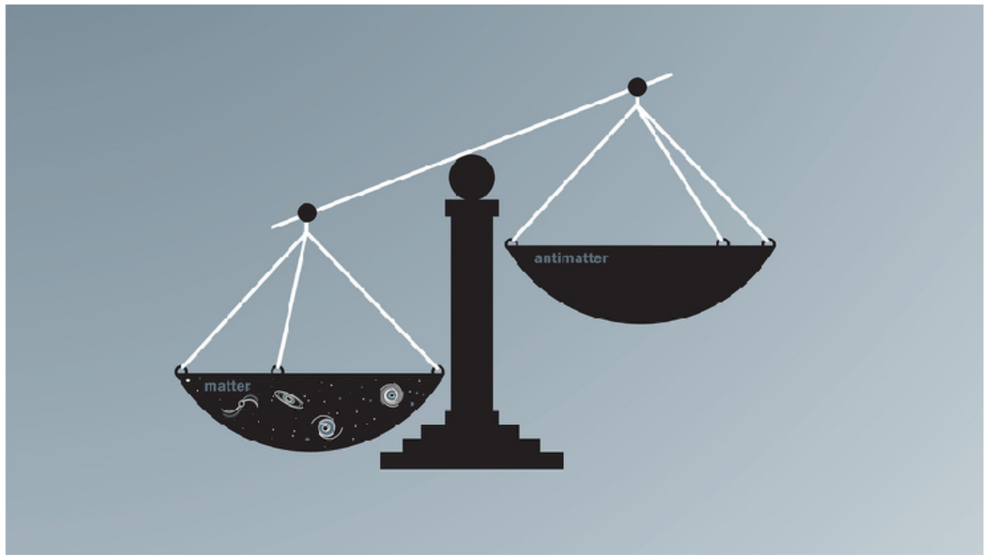
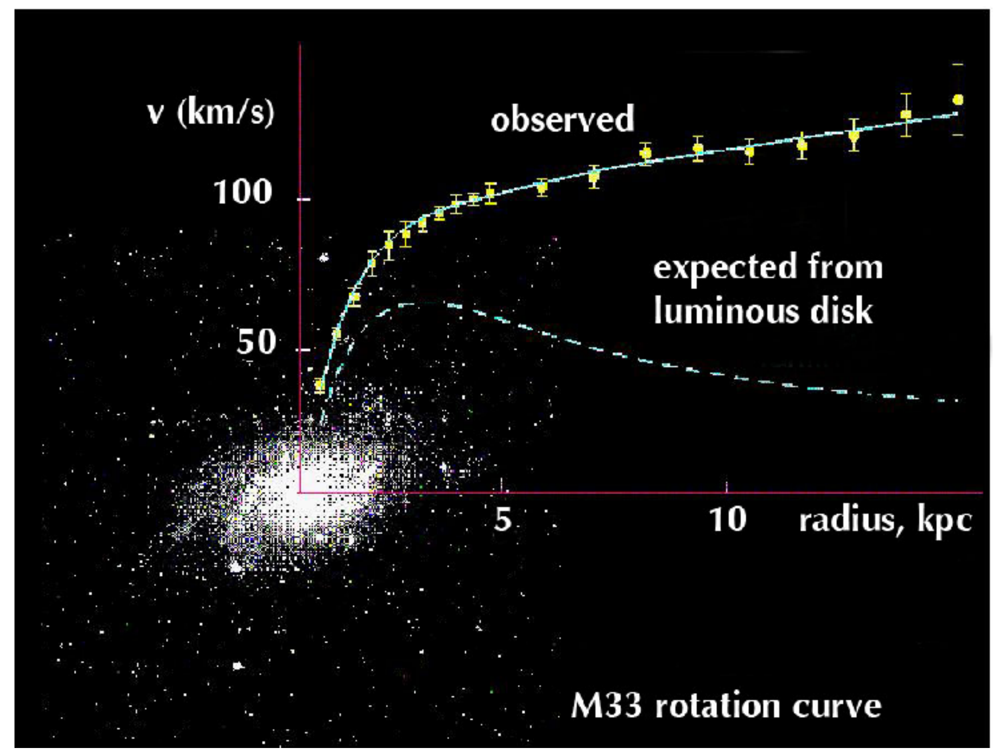


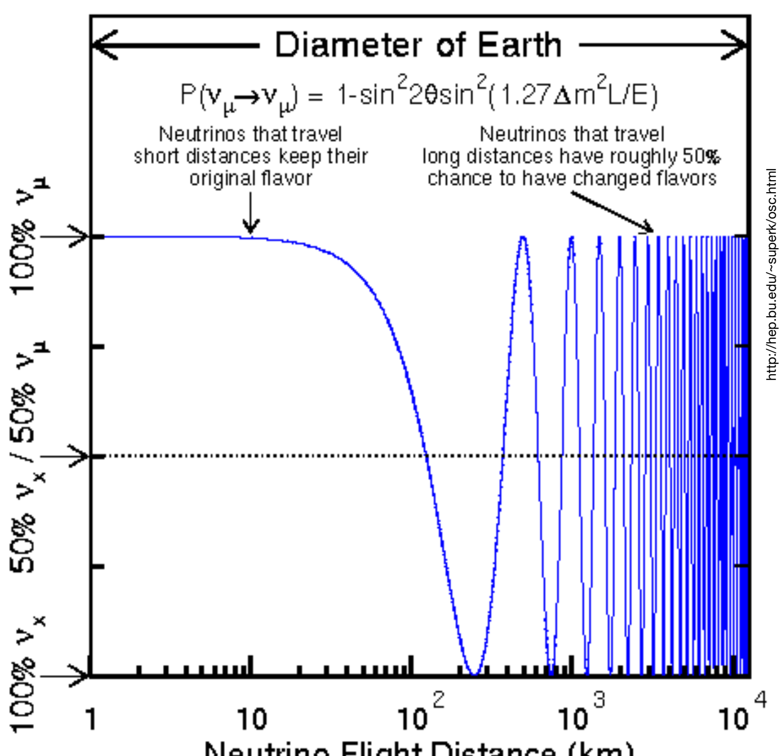
https://www.symmetrymagazine.org/article/october-2005/explain-it-in-60-seconds

Where does the matter-antimatter asymmetry come from?

What is dark matter?



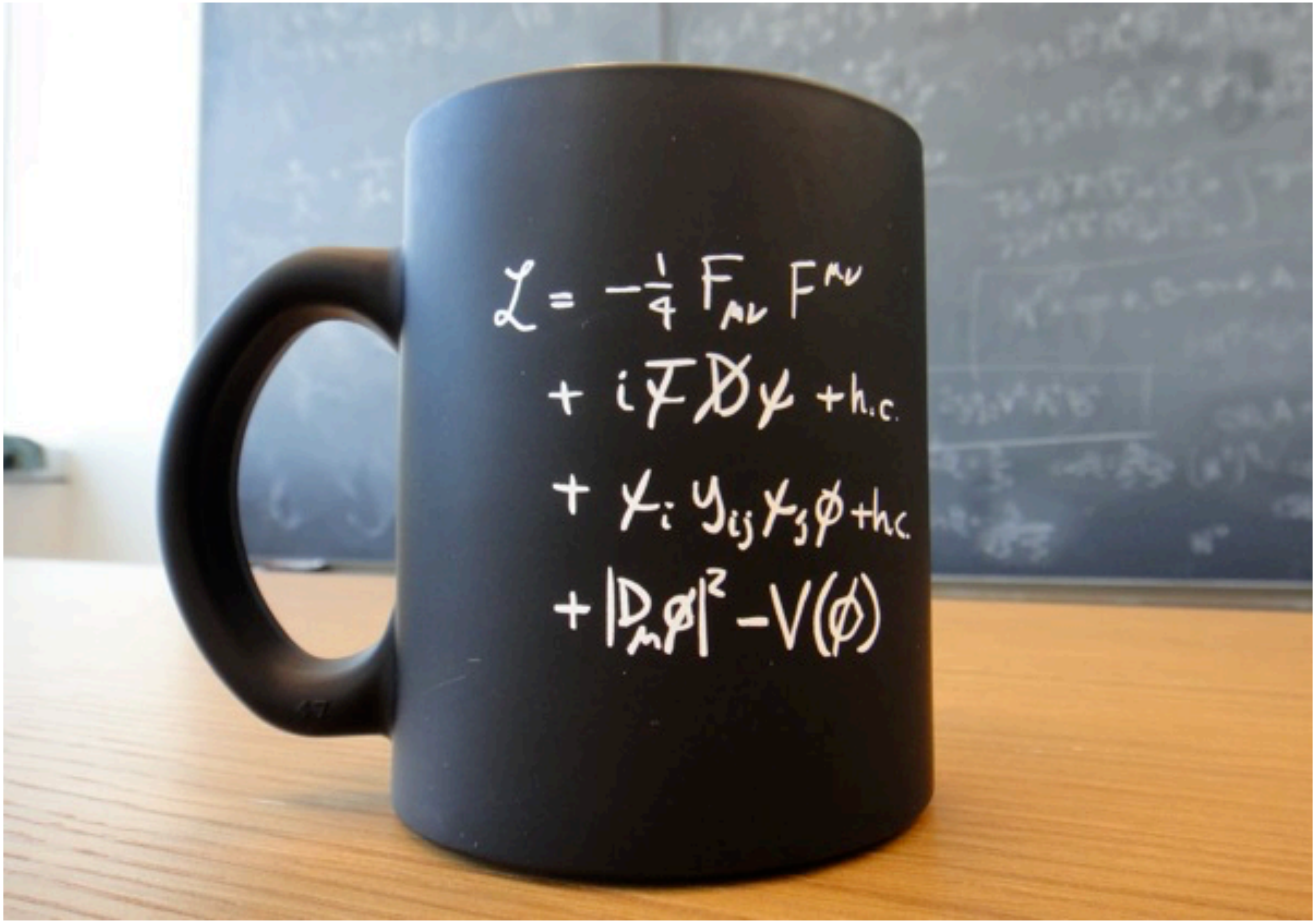
https://commons.wikimedia.org/wiki/File:M33_rotation_curve.jpg



http://hep.bu.edu/~superk/osc.html

Why do neutrinos have mass?

Limits of the Standard Model



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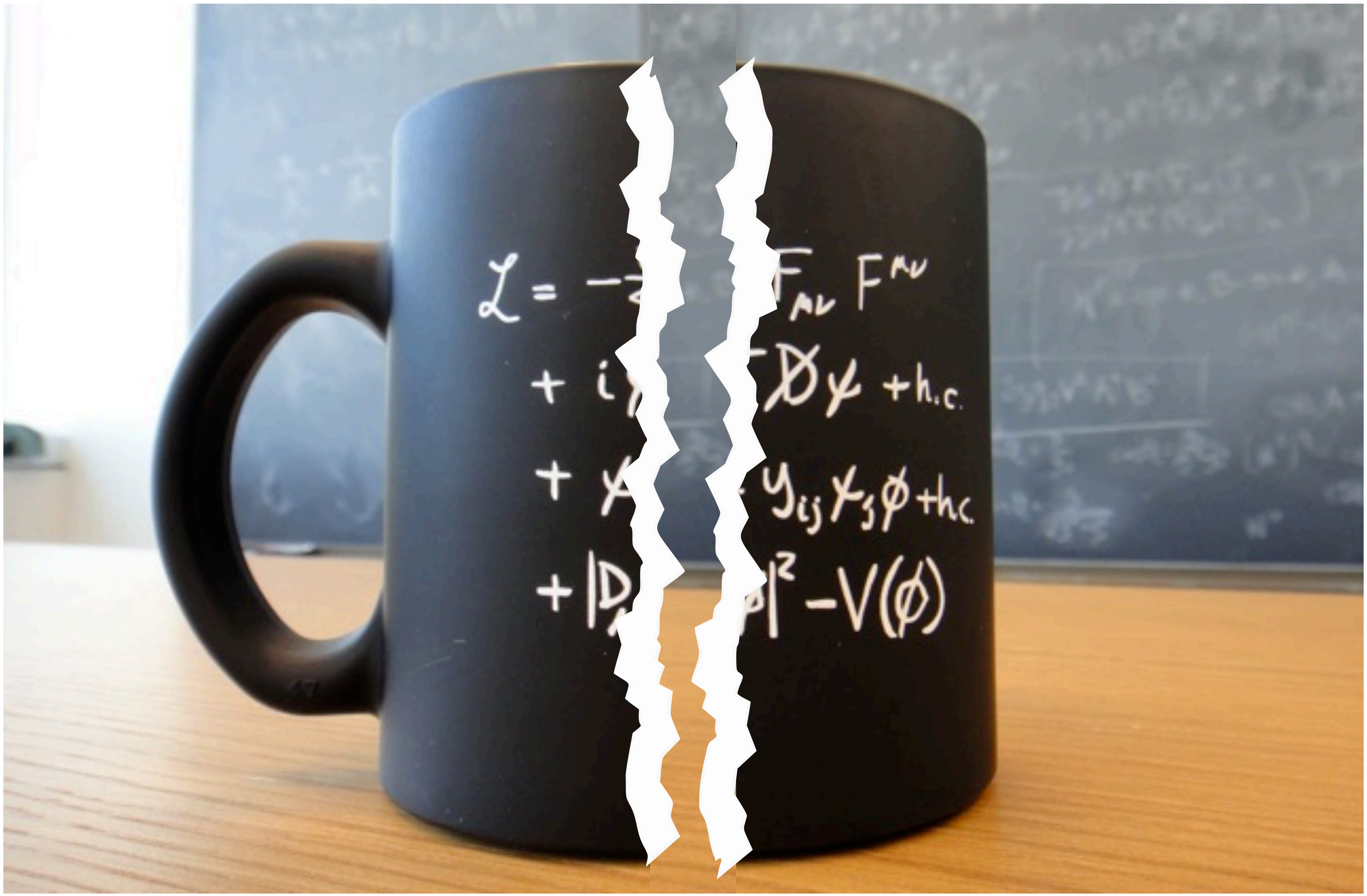
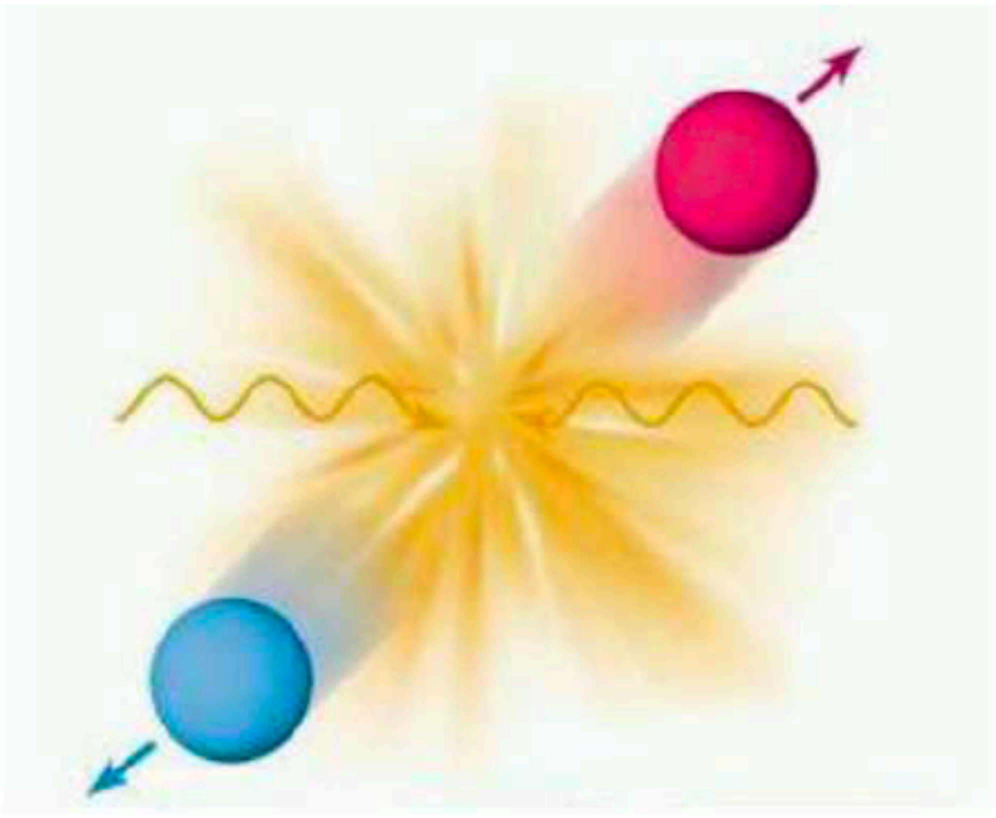


https://www.quantumdiaries.org/wp-content/uploads/2011/06/cernmug.jpg (heavily modified)

Search for new Physics…

Energy frontier



$$E = mc^2$$

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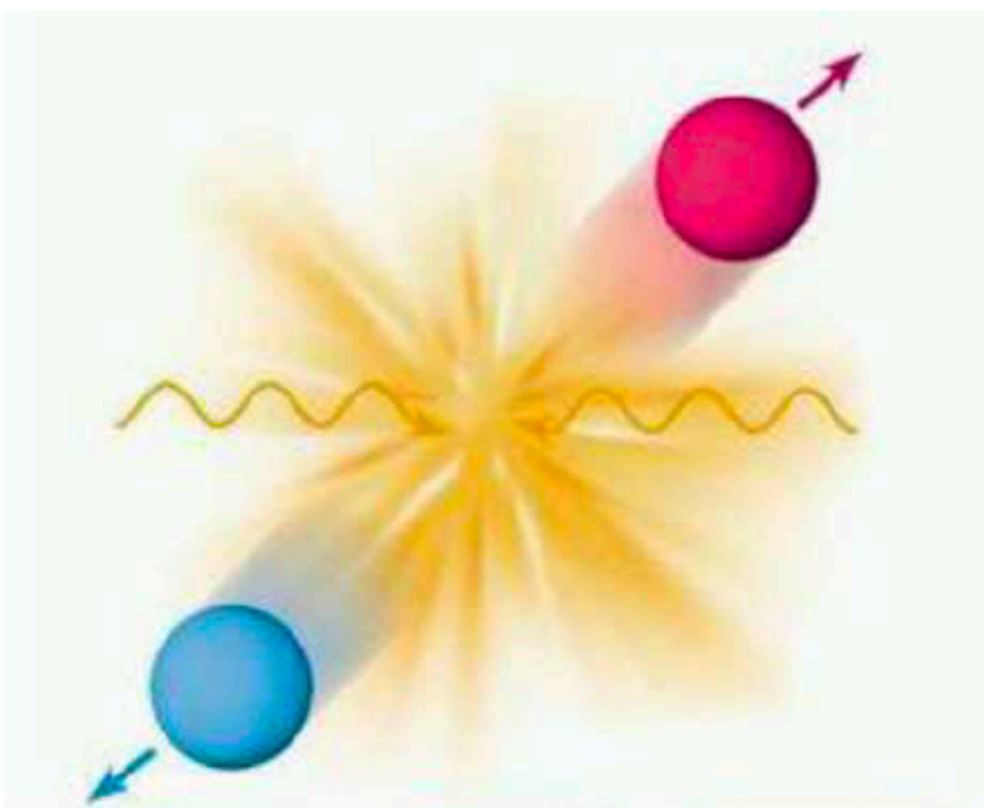

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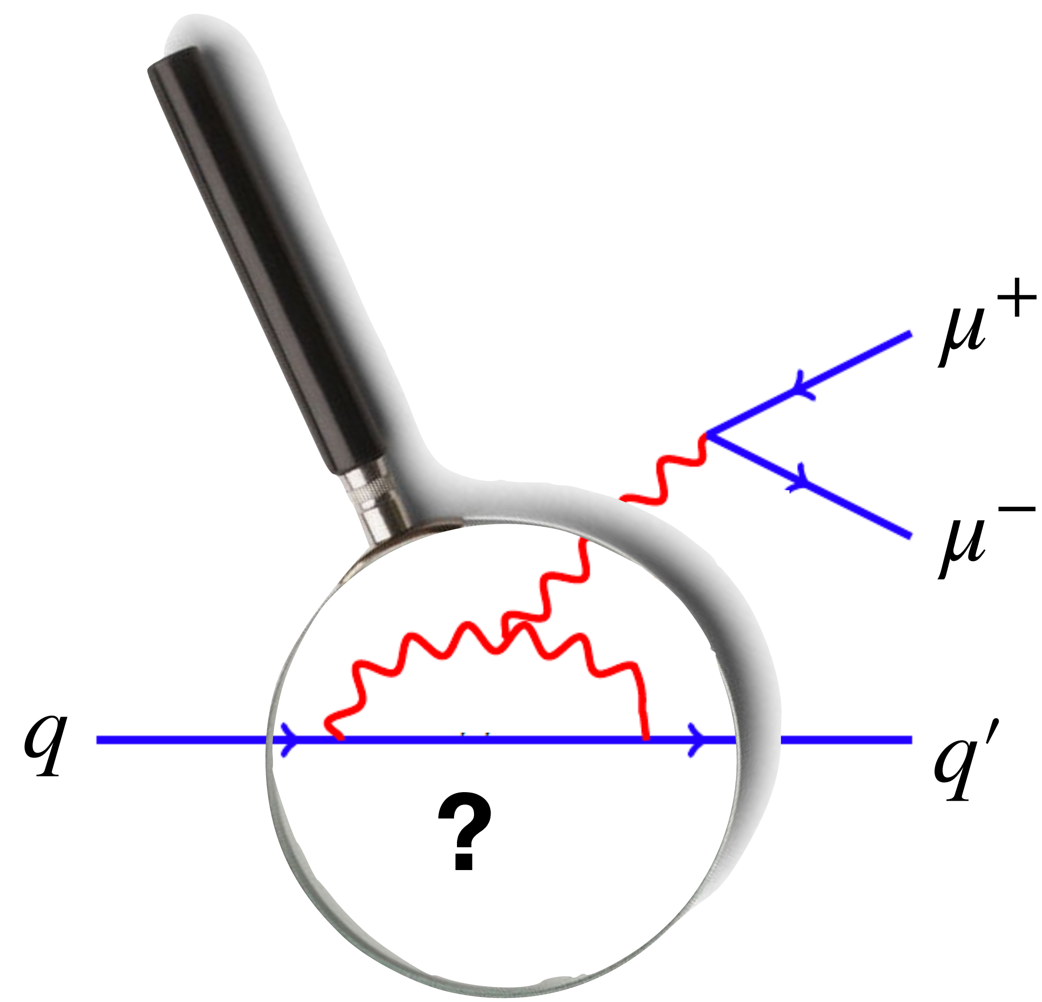
Precision frontier



$$\hbar/2 \leq \Delta t\ \Delta E$$

Search for new Physics…

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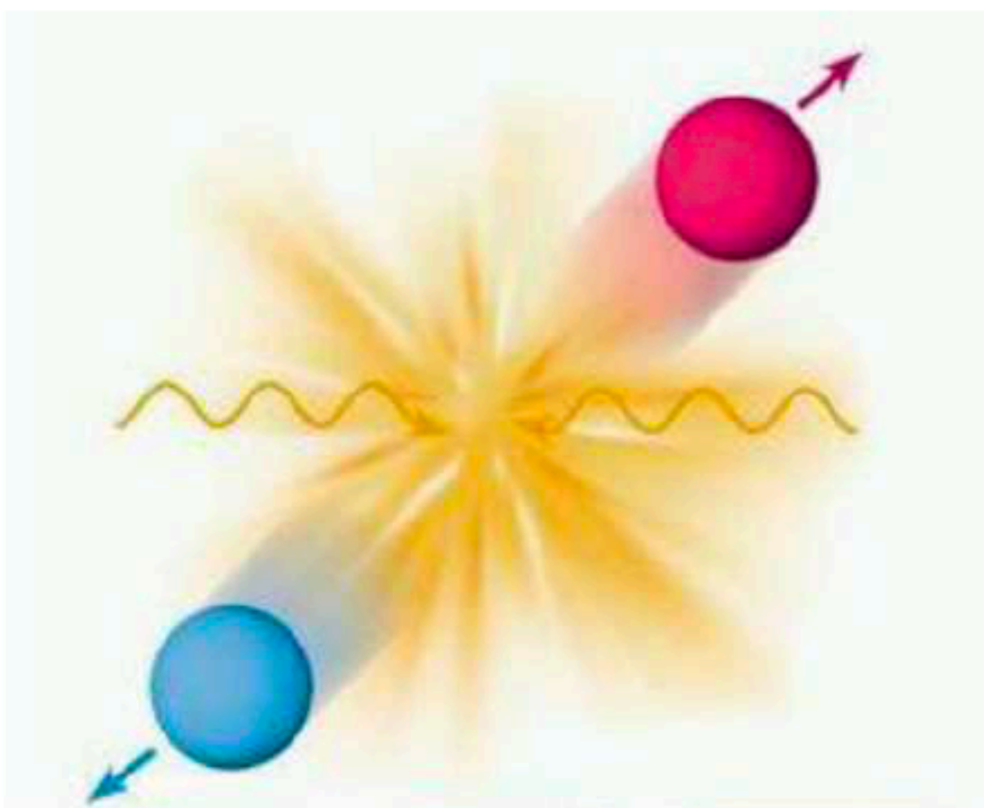

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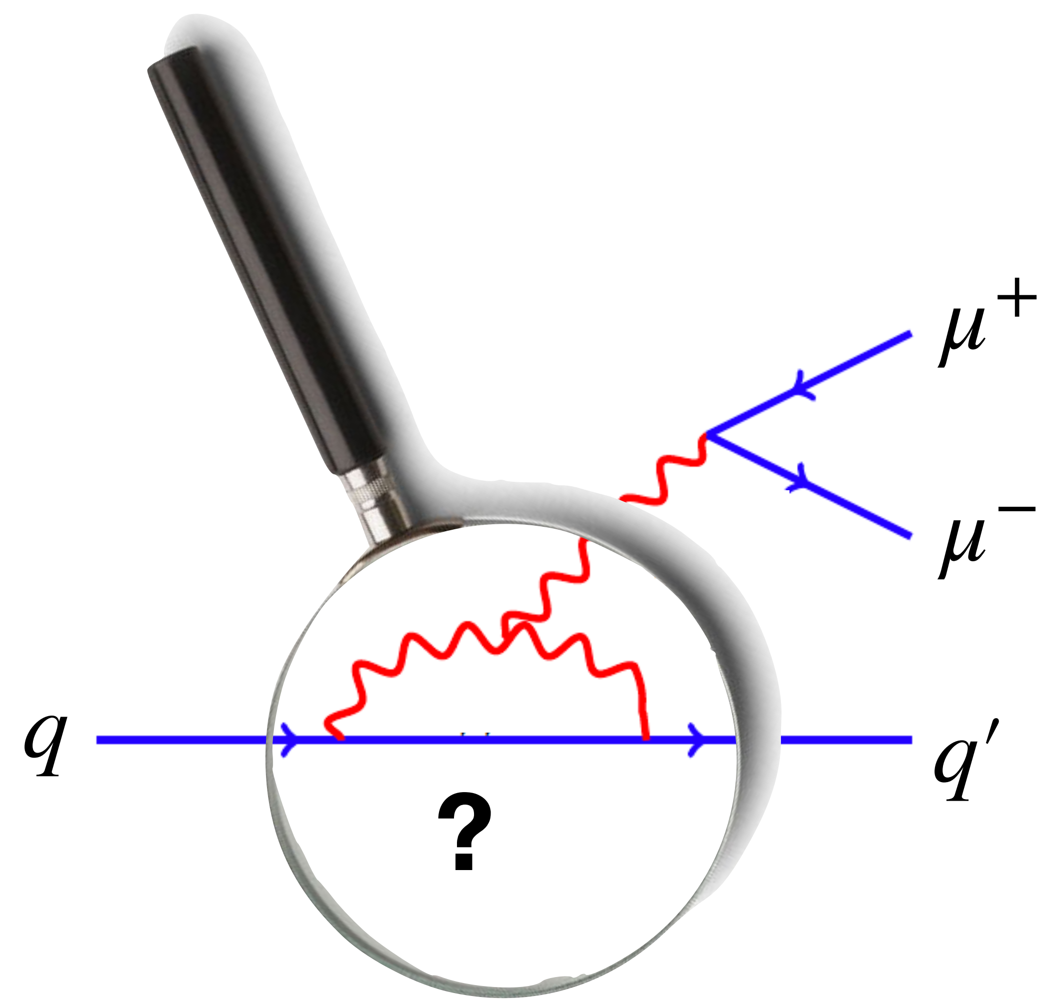

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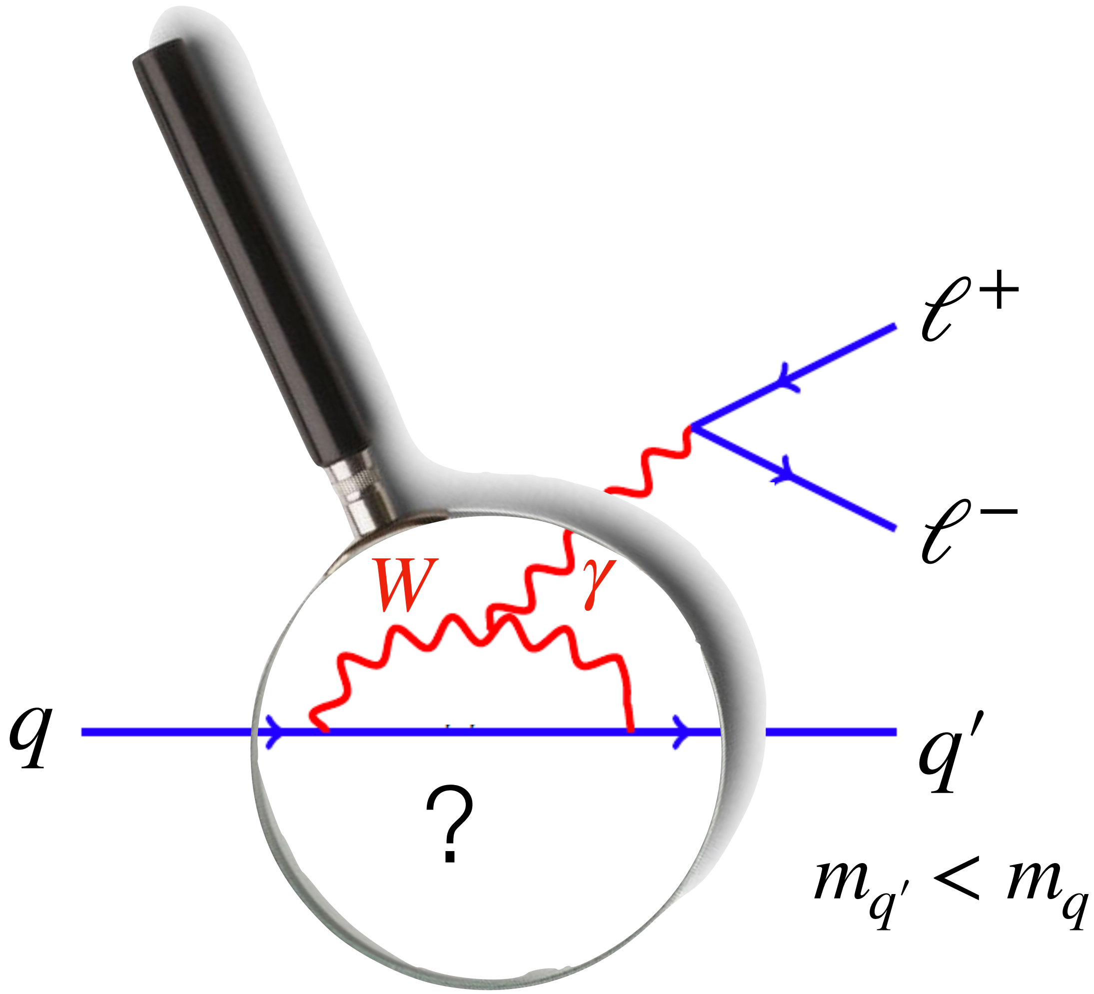
Search for New Physics in rare decays…



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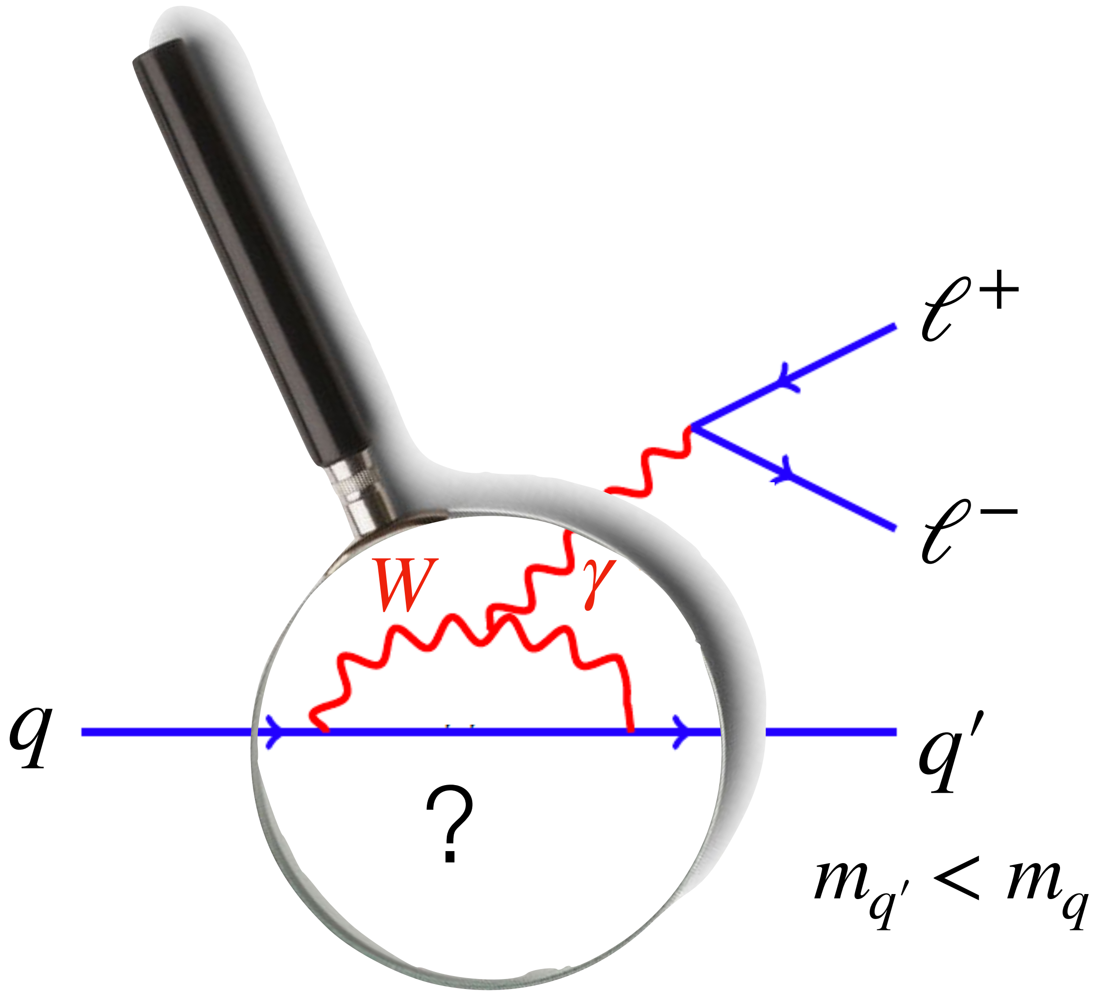

- Rates (branching fractions)

$$\sim \mathscr{A} = \mathscr{A}_0 \left(\frac{c_{SM}}{m_W^2} + \frac{c_{NP}}{\Lambda_{NP}^2} \right)$$

- CP Asymmetries

$$\sim |\mathscr{A}_{SM}||\mathscr{A}_{NP}| \sin \mathbf{\Delta\phi_{NP}}$$

- Angular distributions

$$\sim \text{Lorentz-Structure } \overline{\psi}\Gamma_{NP}\psi$$

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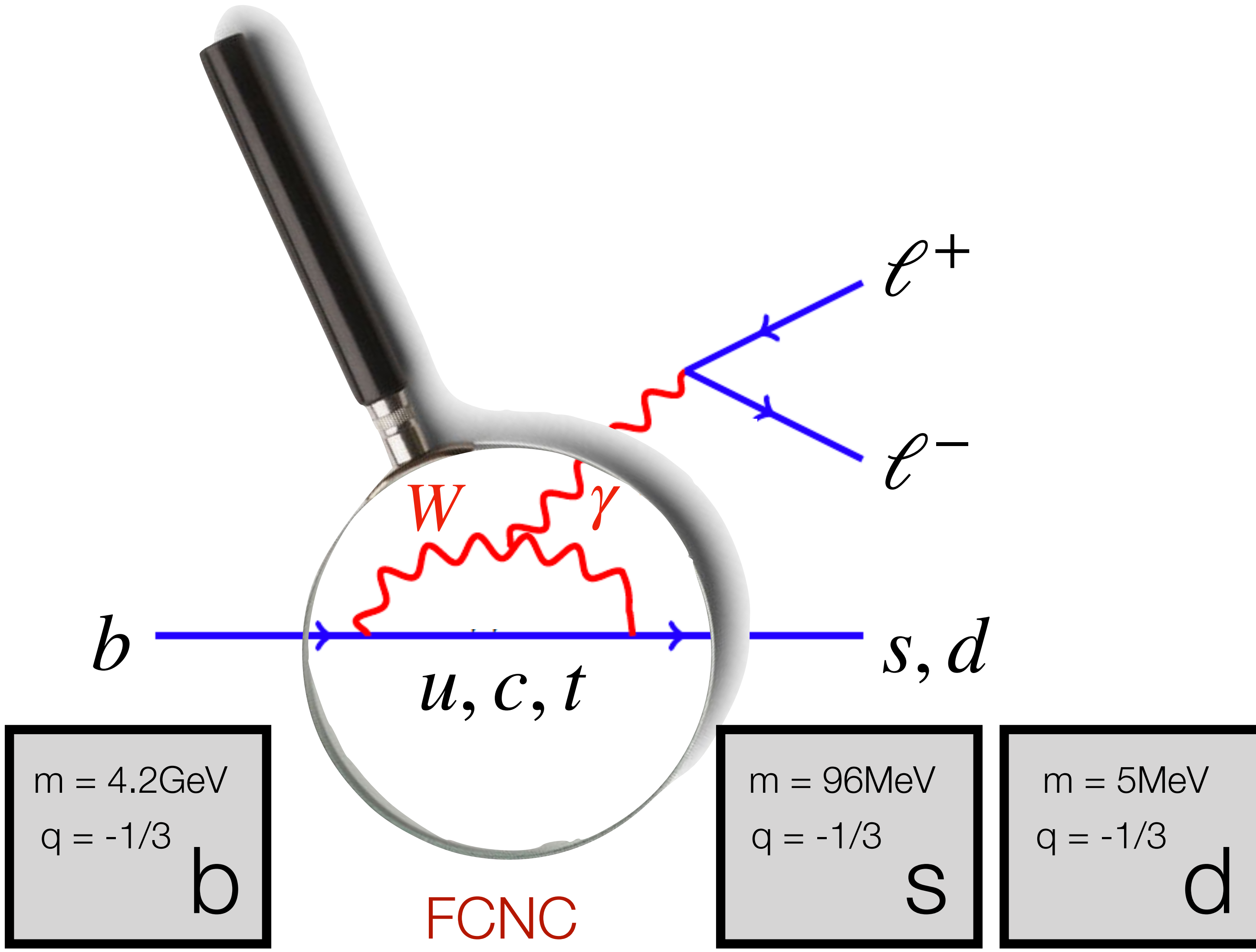

B-physics: $b \to s\ell^+\ell^-, b \to d\ell^+\ell^-$

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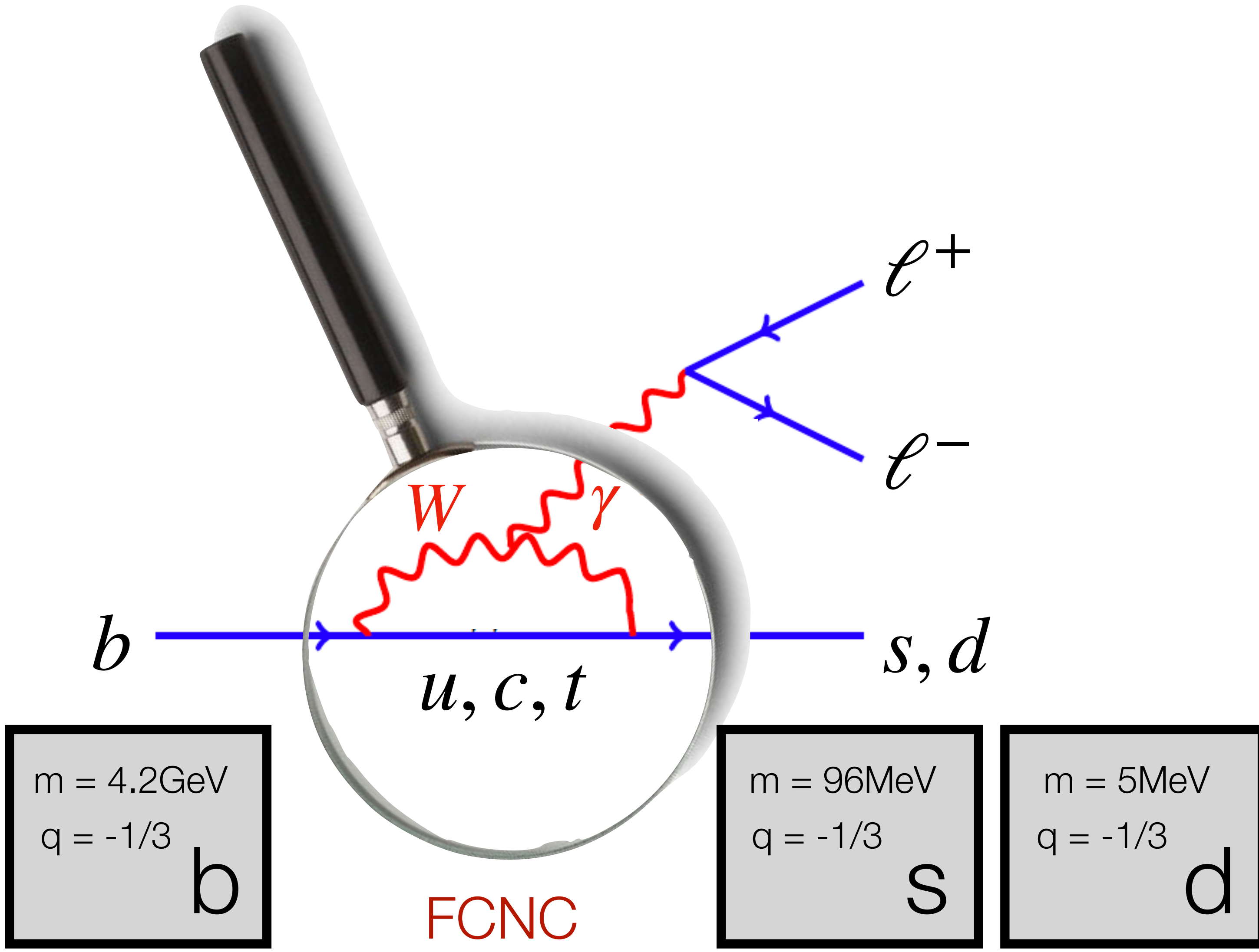

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Flavour anomalies in $b \to s\ell^+\ell^-$ transitions!

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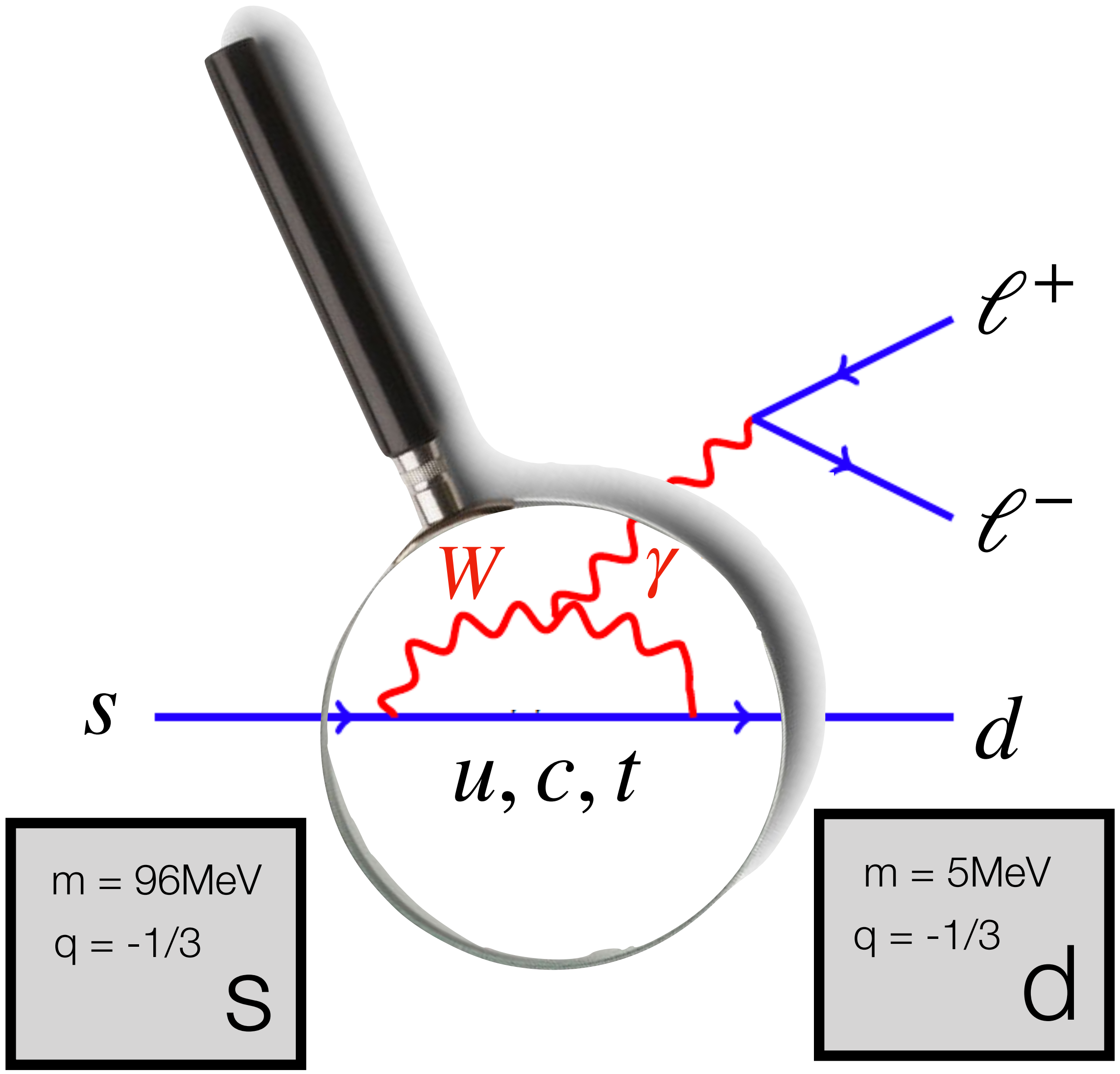

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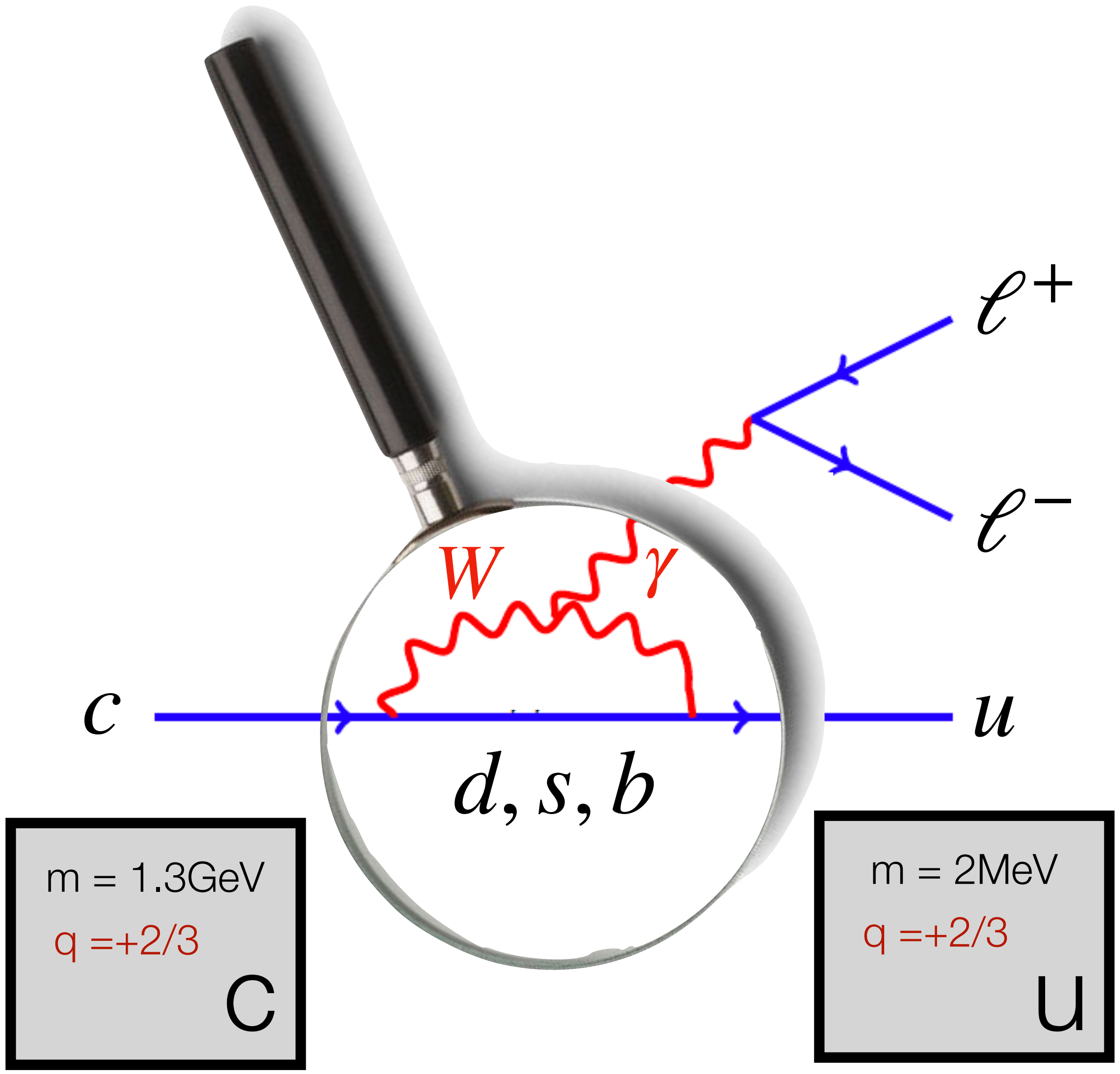

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Charm-physics: $c \to u\ell^+\ell^-$

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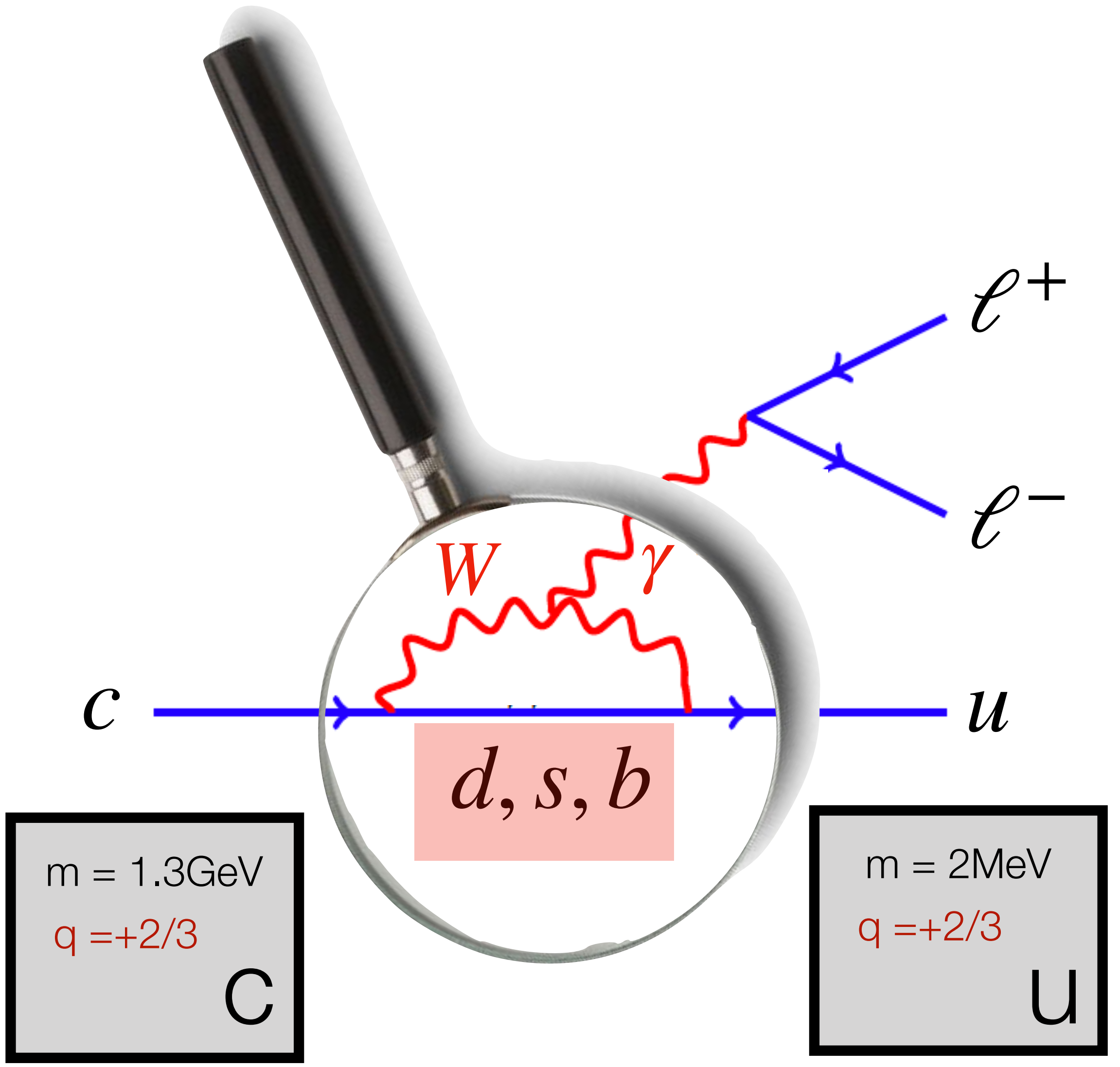


u-type quarks! → orthogonal couplings

Charm-physics: $c \to u\ell^+\ell^-$

- Rates (branching fractions)

  typically $D \to X\mu^+\mu^-$ ~$O(10^{-12})$
  (**extremely suppressed**)

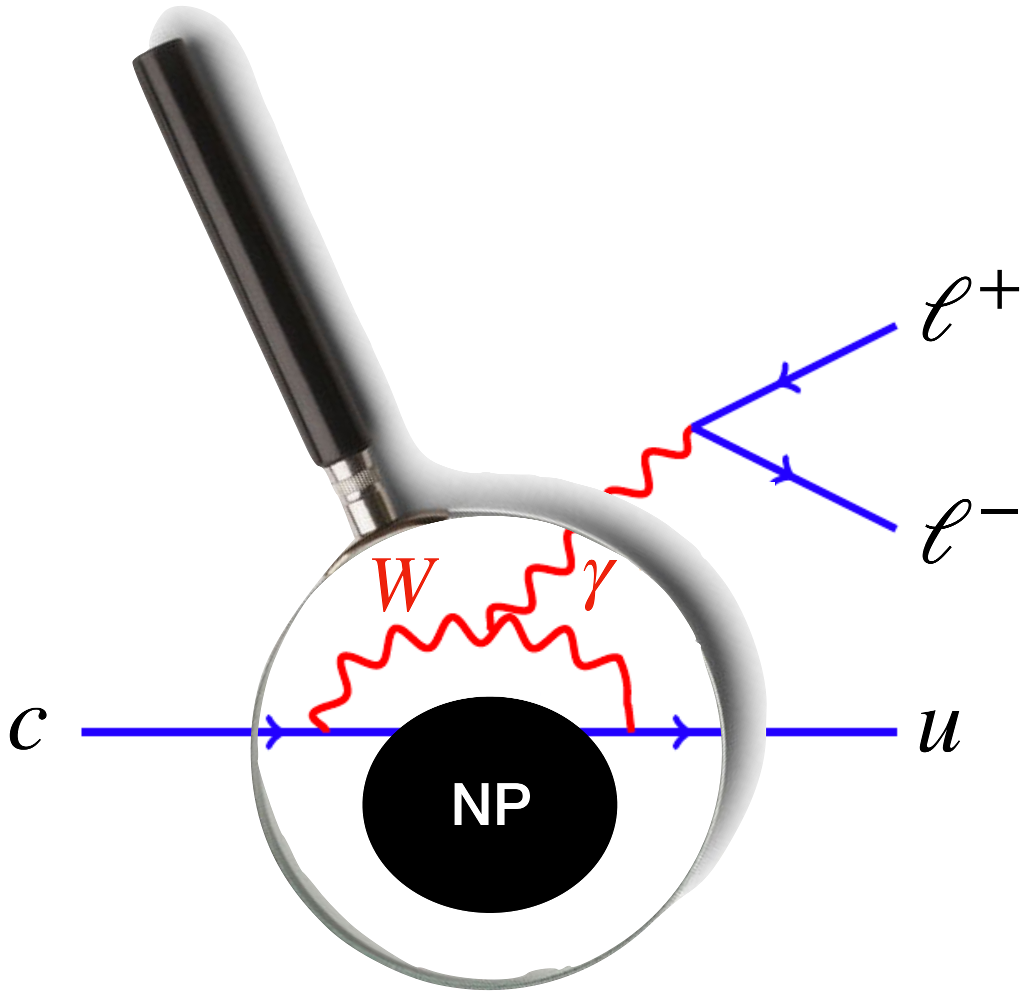
- CP Asymmetries

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

- Angular distributions

  no lepton axial vector coupling
  Parity conservation

Search for New Physics in rare decays…



u-type quarks! ⟶ orthogonal couplings

Charm-physics: $c \to u\ell^+\ell^-$

- Rates (branching fractions)

  D→Xl+l- up to O(10-7)*

- CP Asymmetries

  CPV effects up to few %*

- Angular distributions

  Modified*

*very much depending on the model

see eg. MPLA 36 (2021) 2130002

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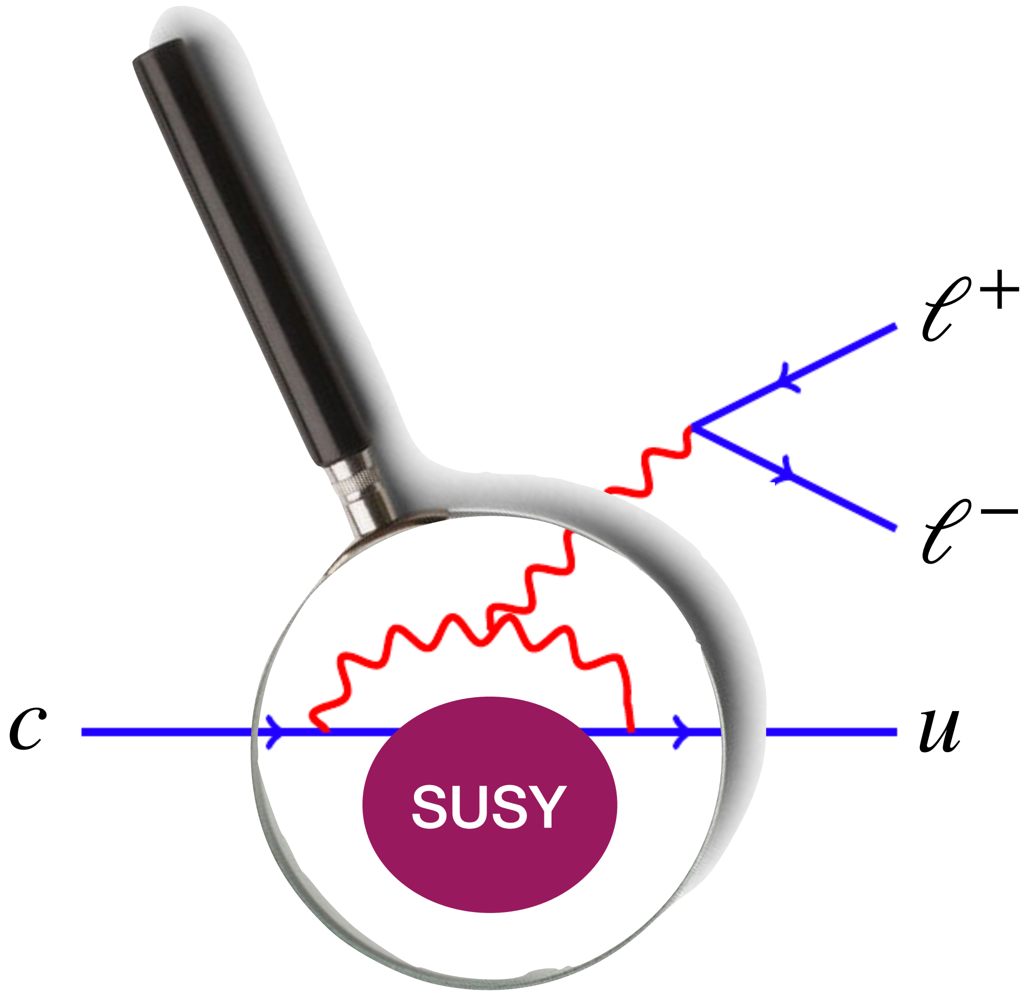

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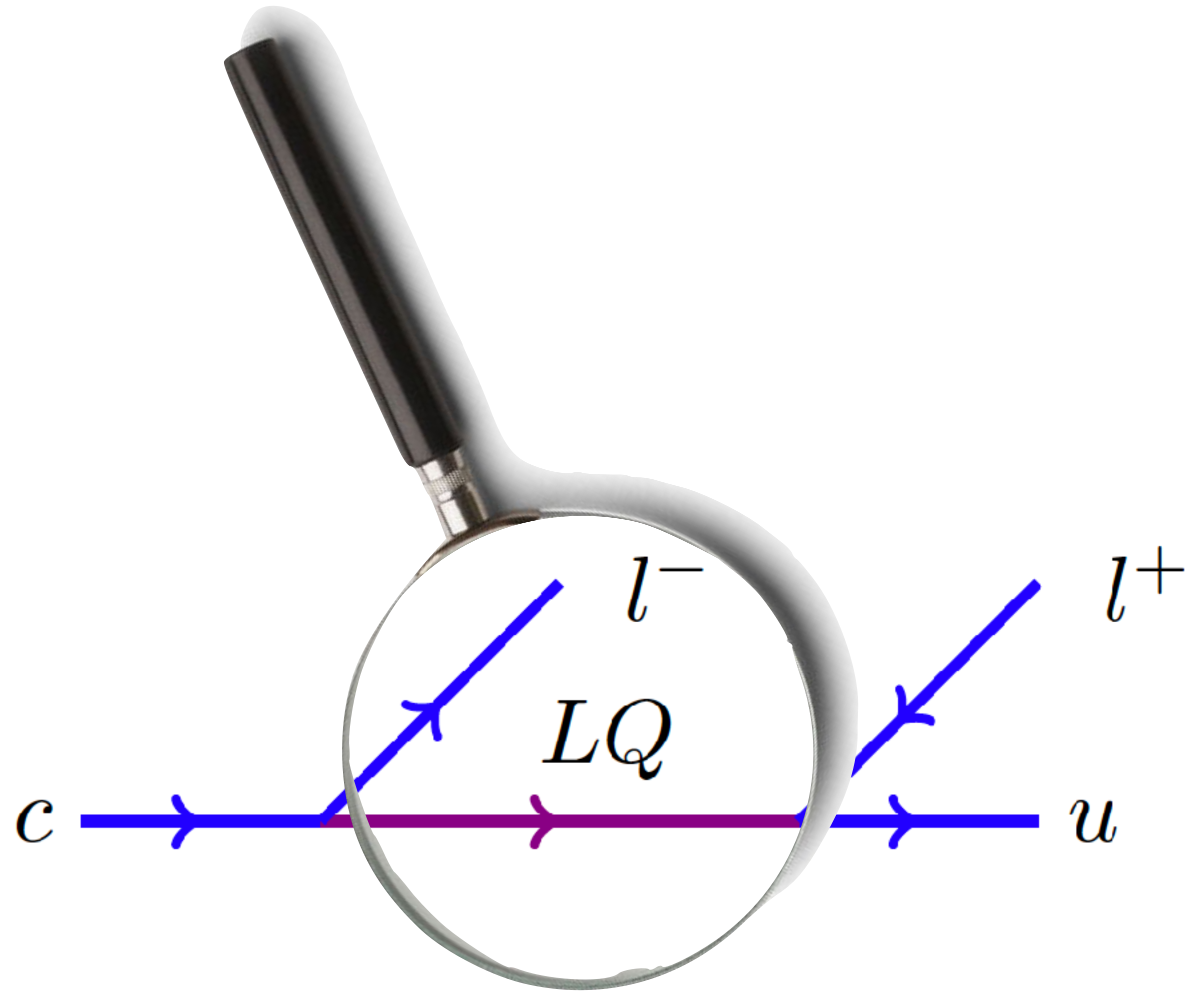

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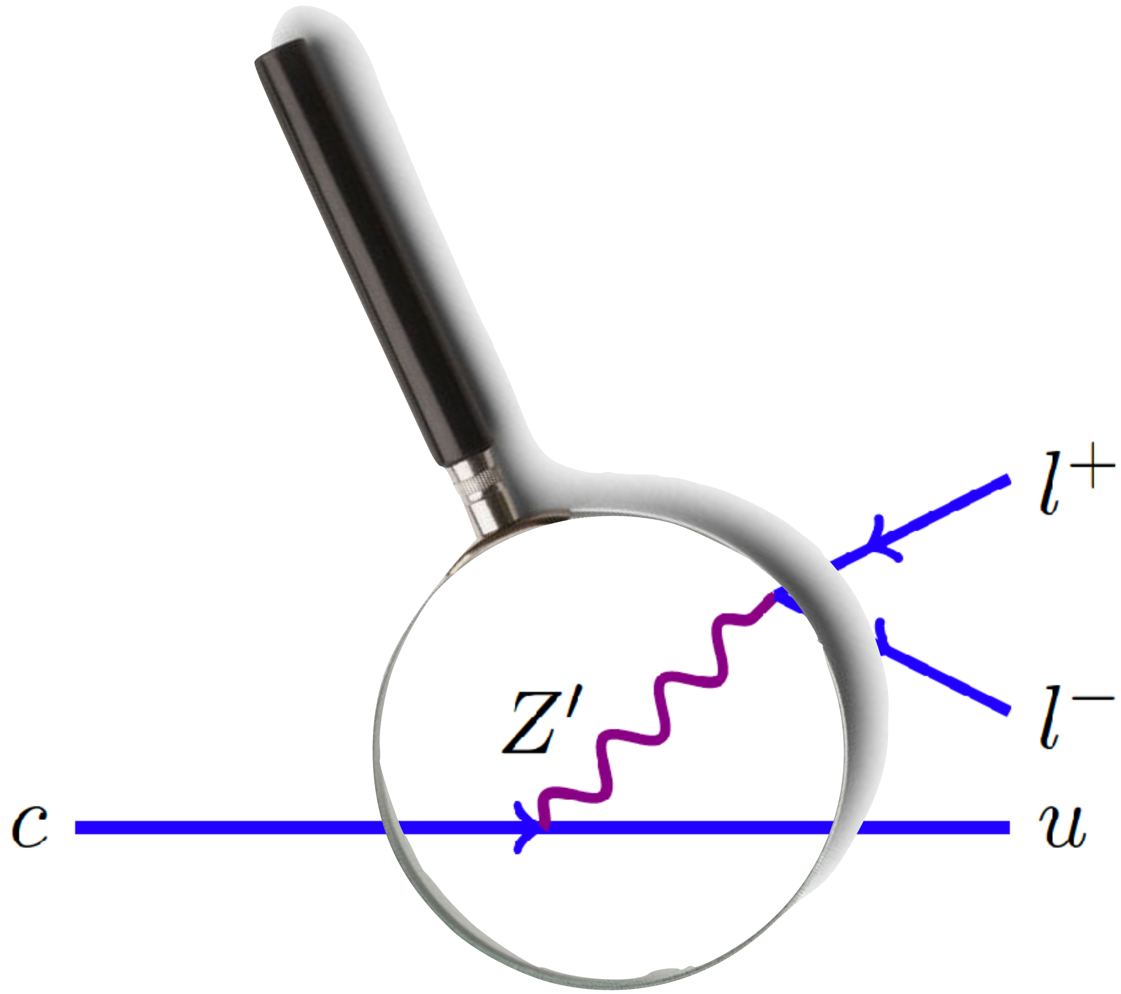

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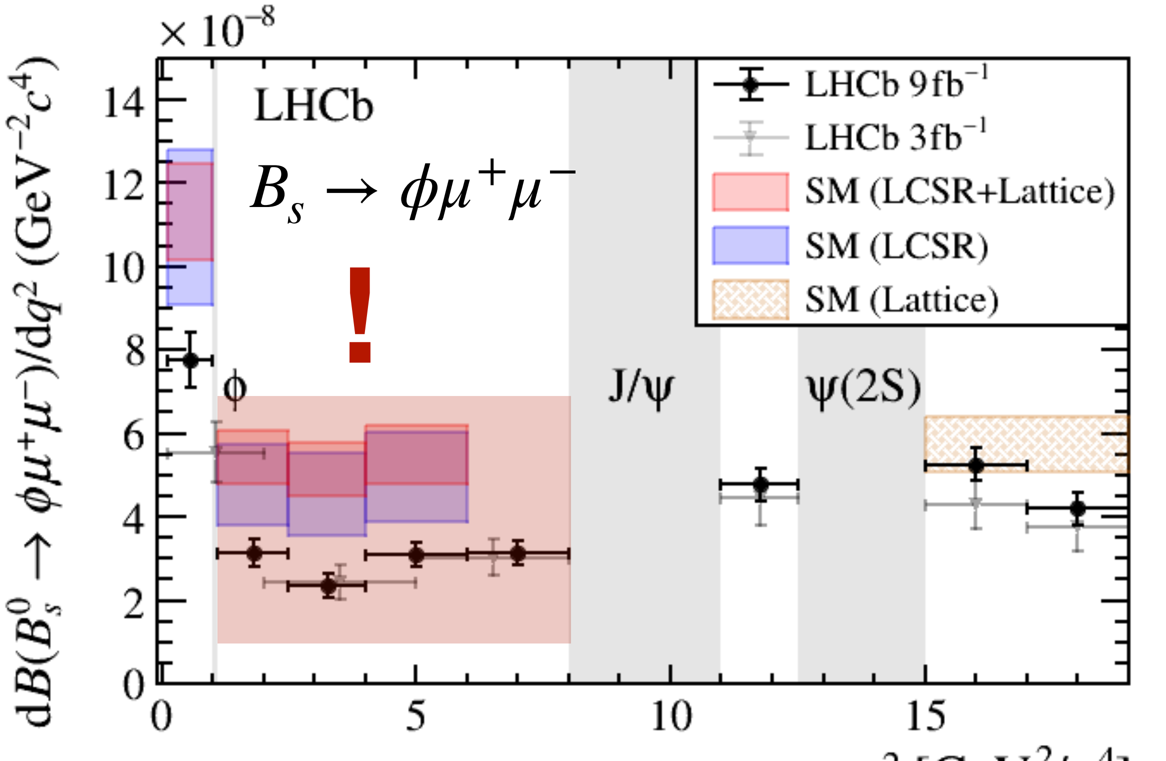
see eg. MPLA 36 (2021) 2130002

Glimpsing at the **b**(ig) brother

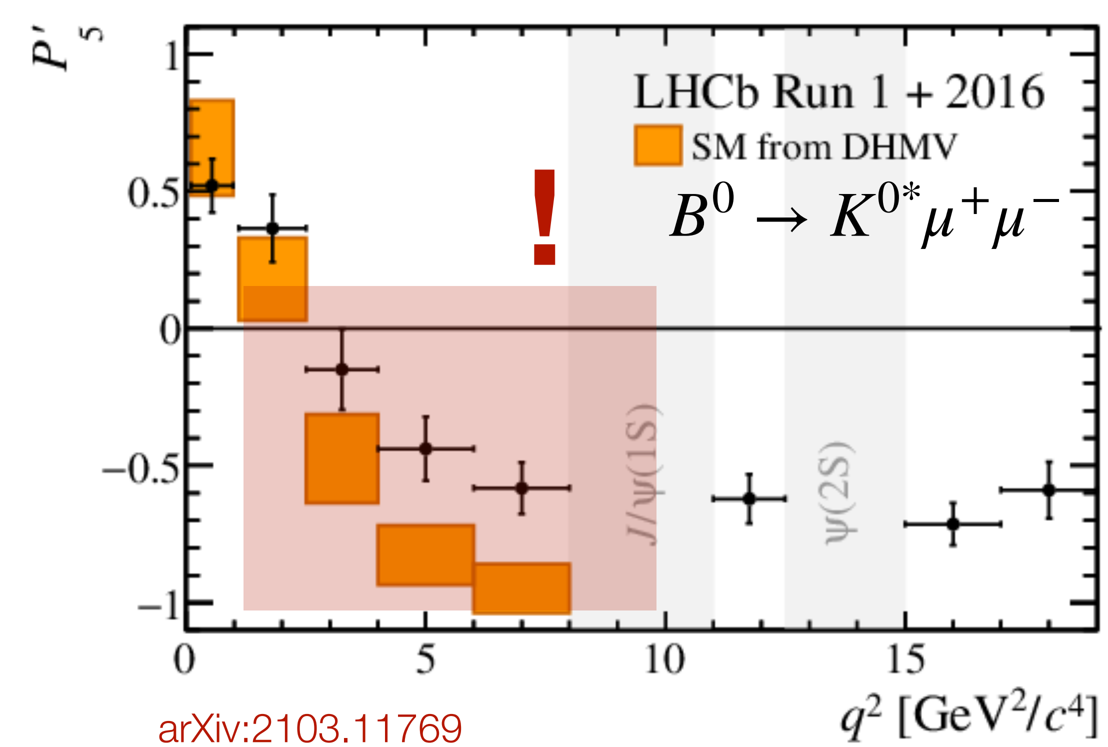
- intriguing pattern in $b \to s\ell^+\ell^-$ transitions ….

PRL 125 (2020) 011802

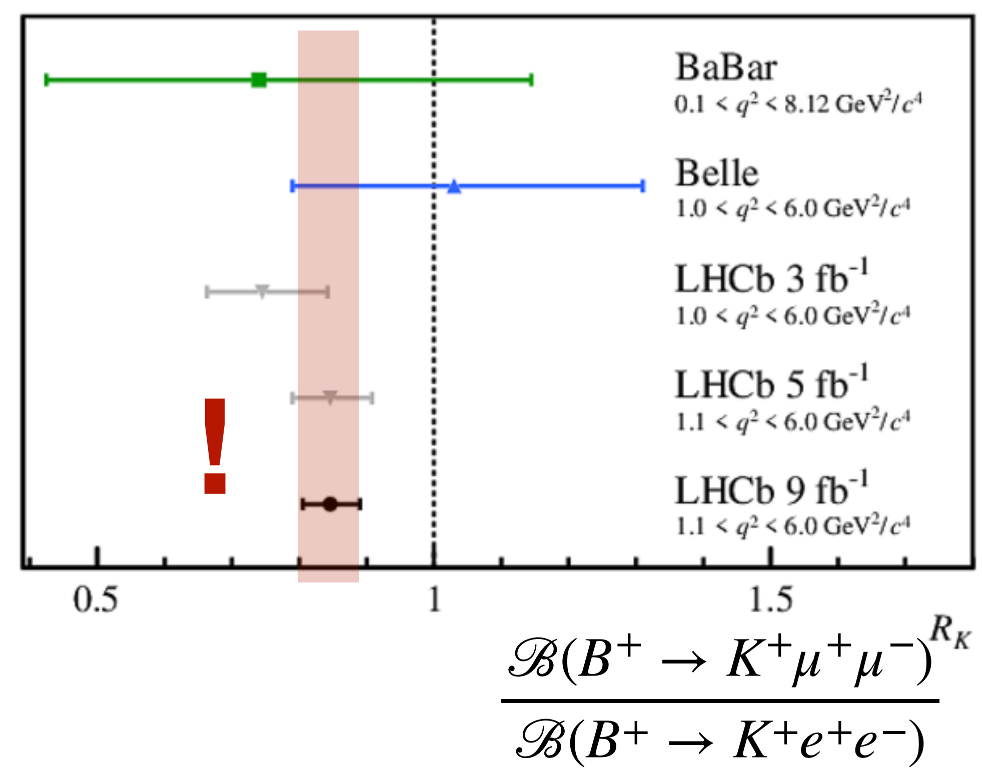


JHEP 11 (2021) 043

= m²($\mu^+\mu^-$) [GeV²/c⁴]



arXiv:2103.11769



- … in branching fractions
- … in angular distributions
- … in lepton flavour universality tests

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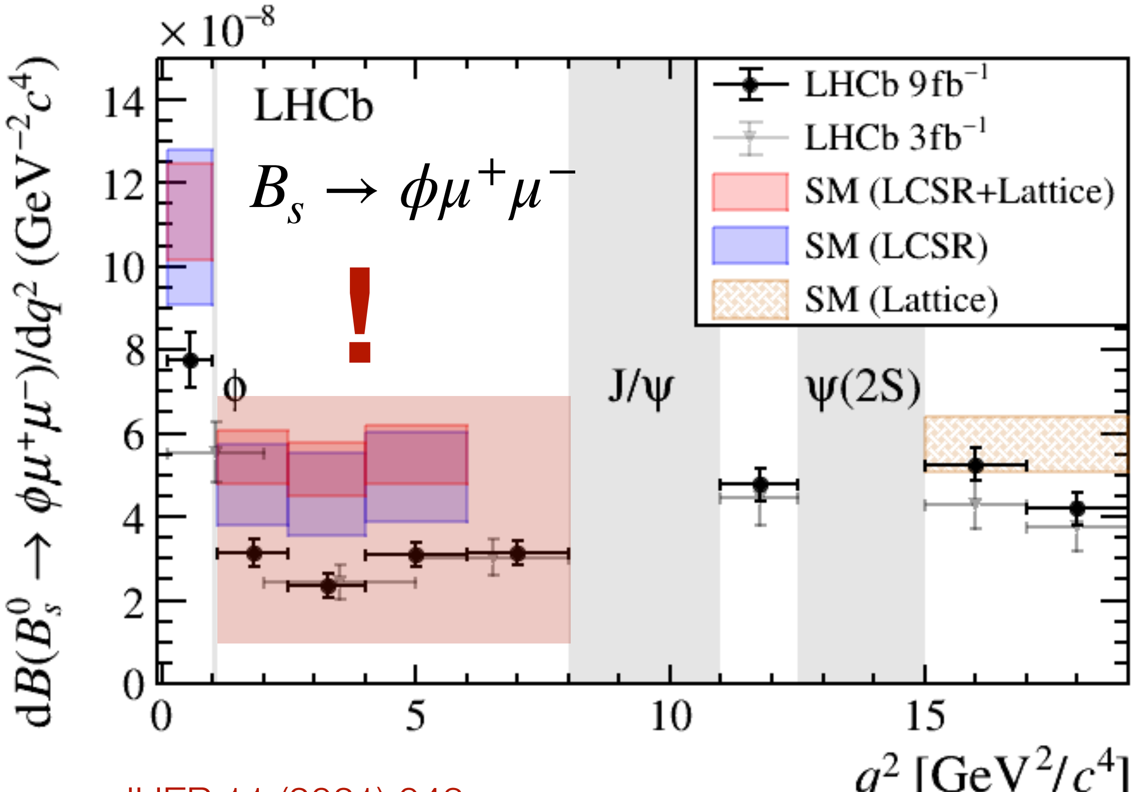

JHEP 11 (2021) 043

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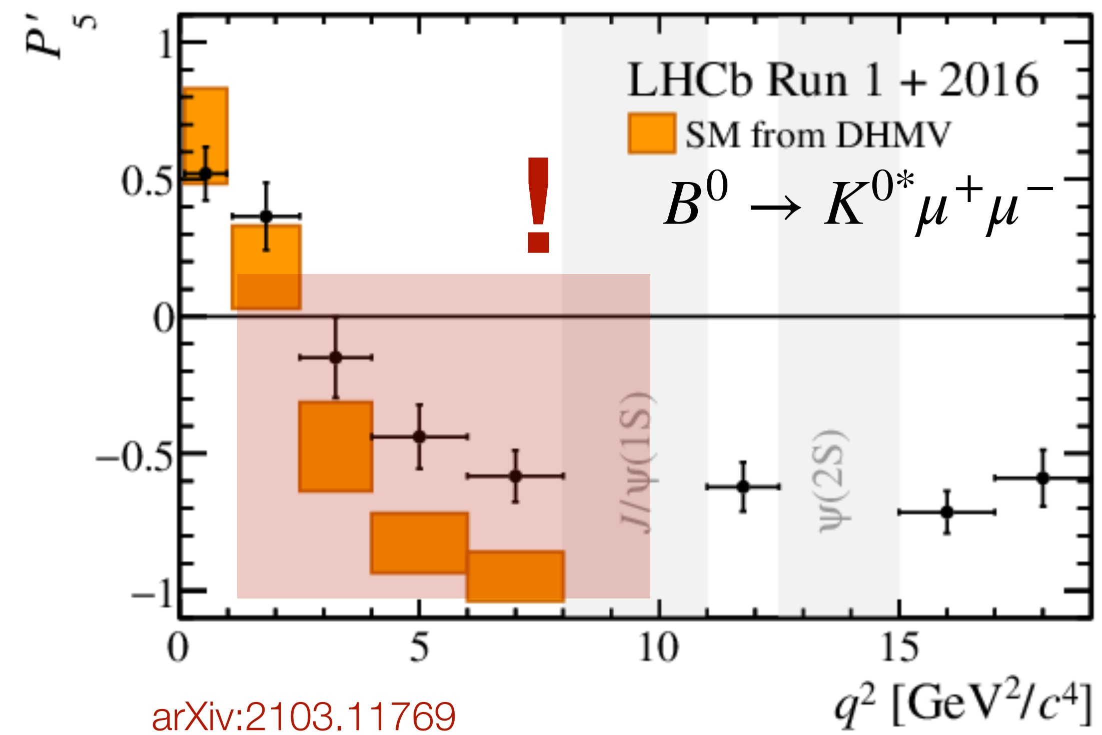

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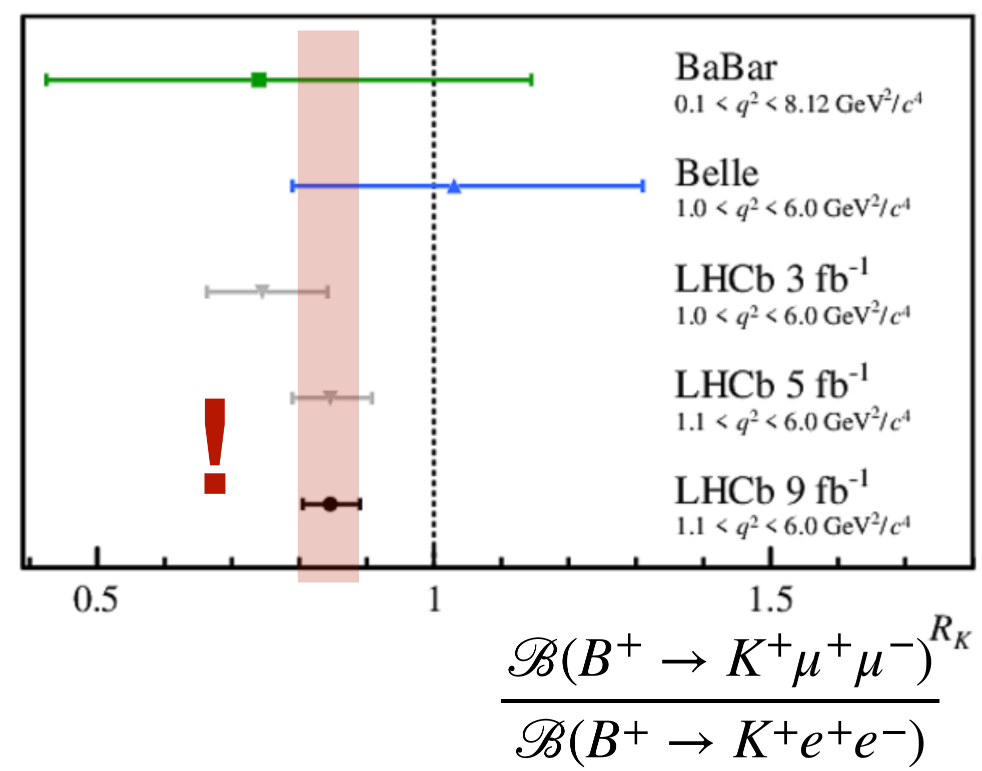
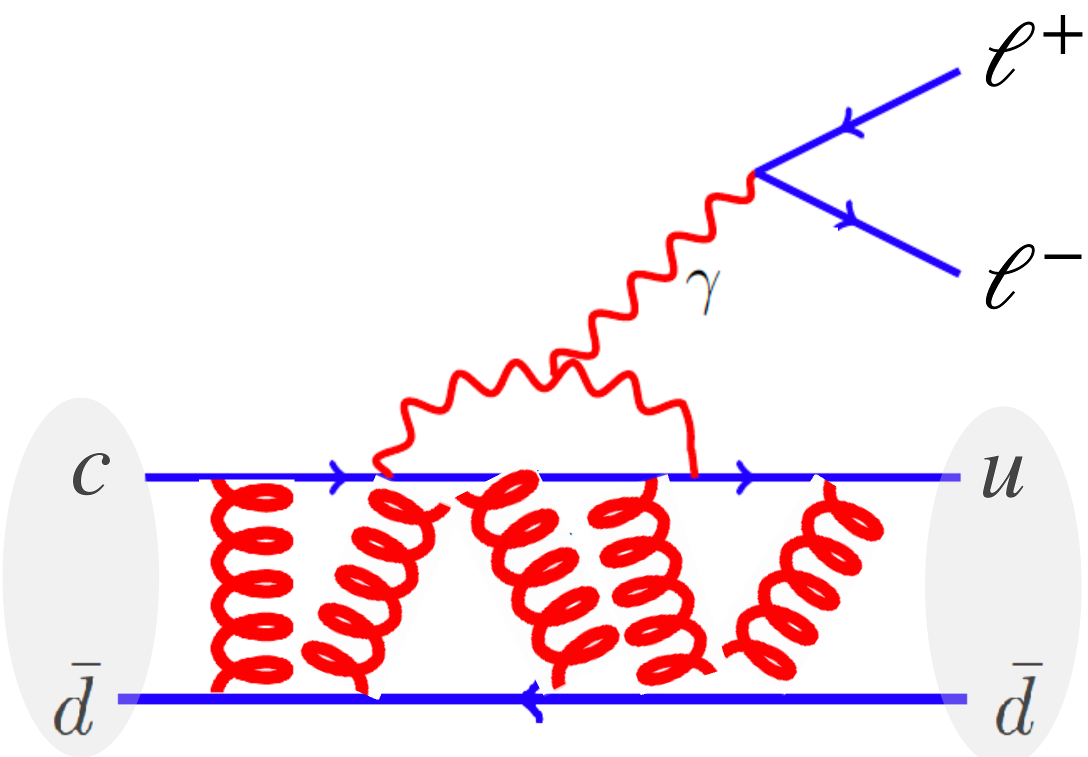


- … in branching fractions
- … in angular distributions
- … in lepton flavour universality tests

And in charm? Most promising NP explanations (LQ, Z') also generate $c \to u\ell^+\ell^-$

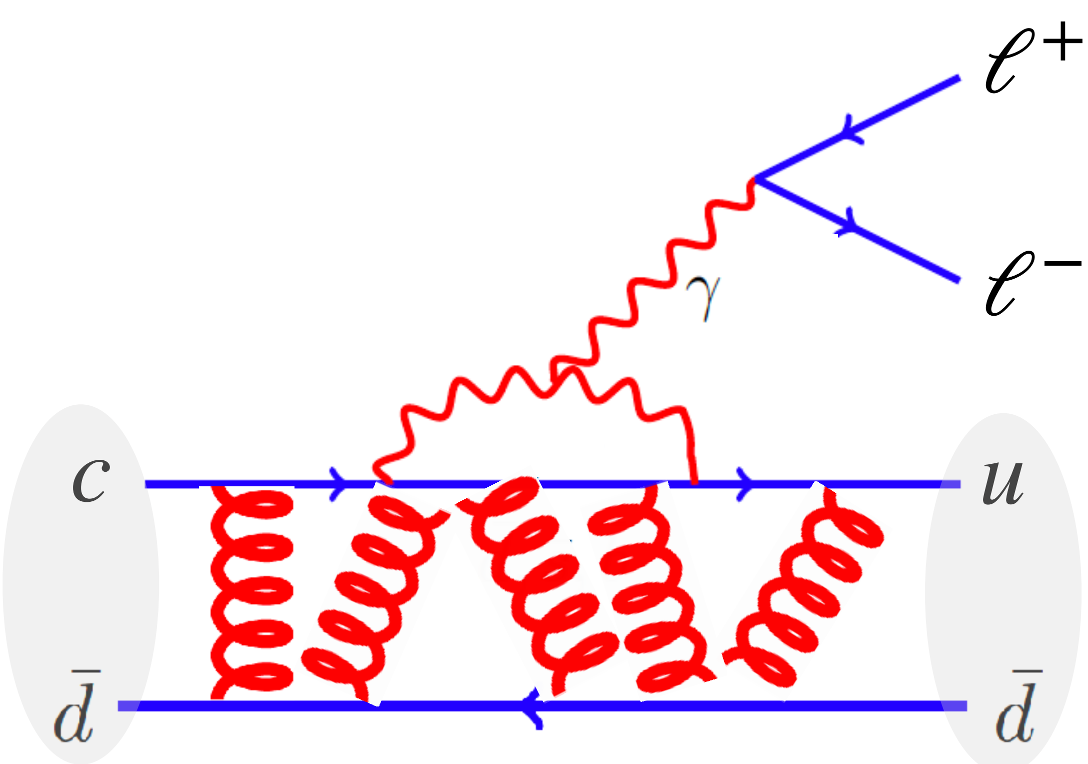
The curse of QCD



$D \to \pi \ell^+ \ell^-$

- $m_c \sim \Lambda_{QCD}$ leads to large uncertainties coming from QCD effects

The curse of QCD



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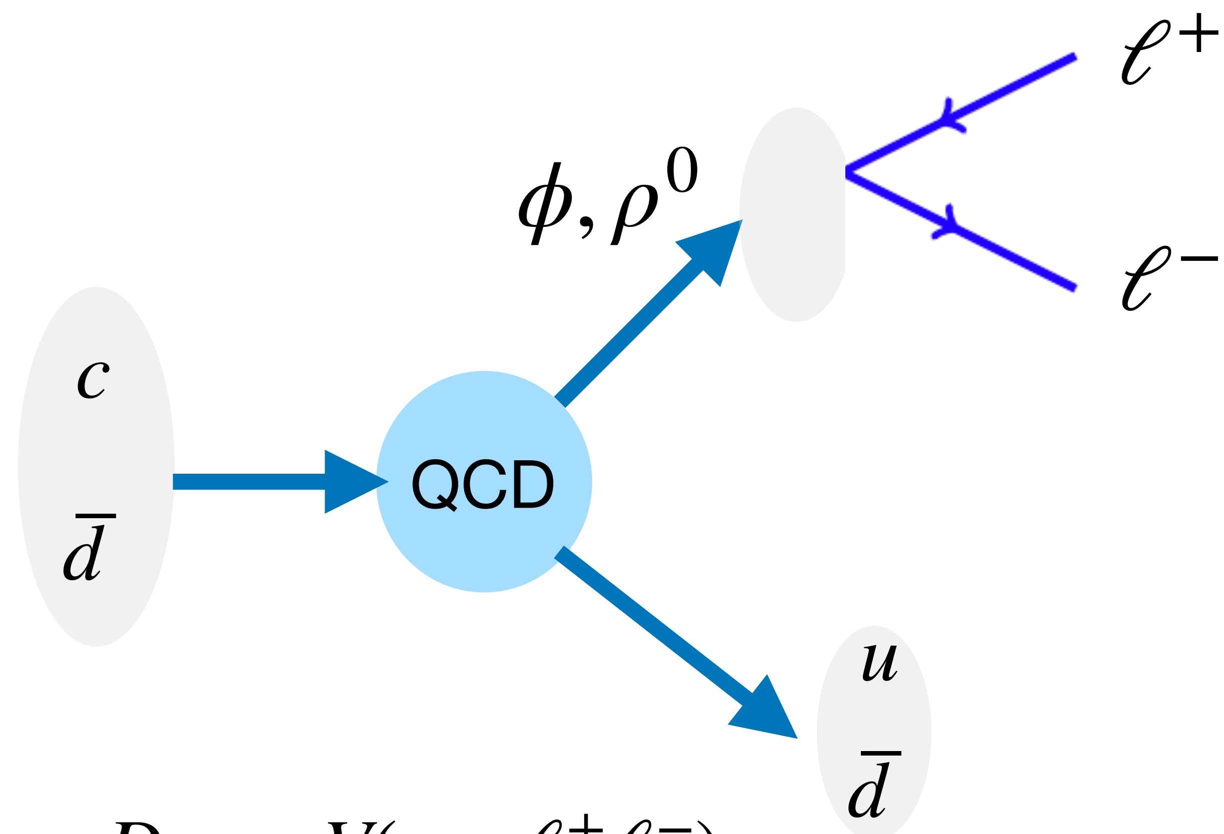
$\mathscr{B} \sim \mathcal{O}(10^{-12})$



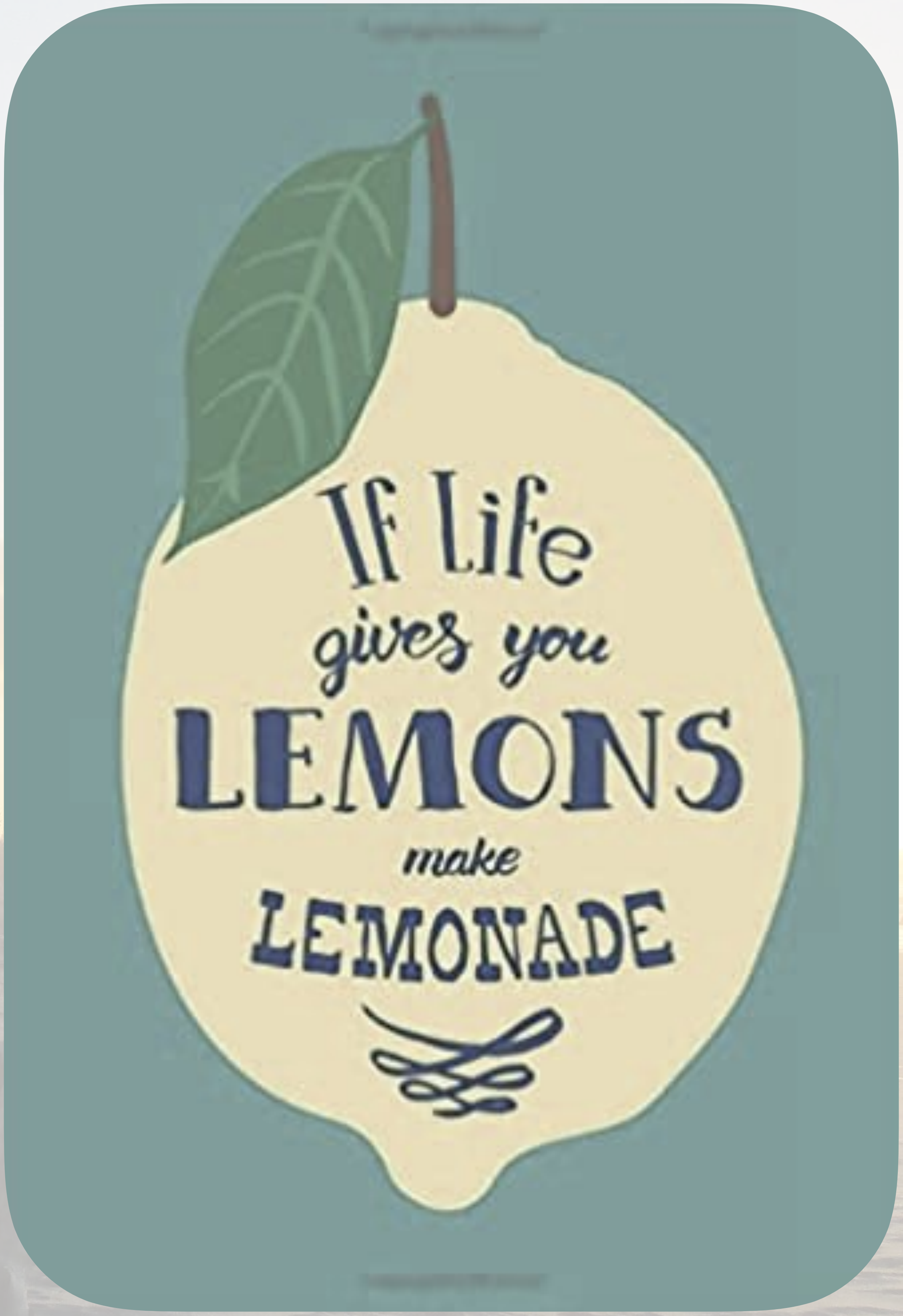
$D \to \pi V(\to \ell^+ \ell^-)$

$\mathscr{B} \sim \mathcal{O}(10^{-8} - 10^{-6})$

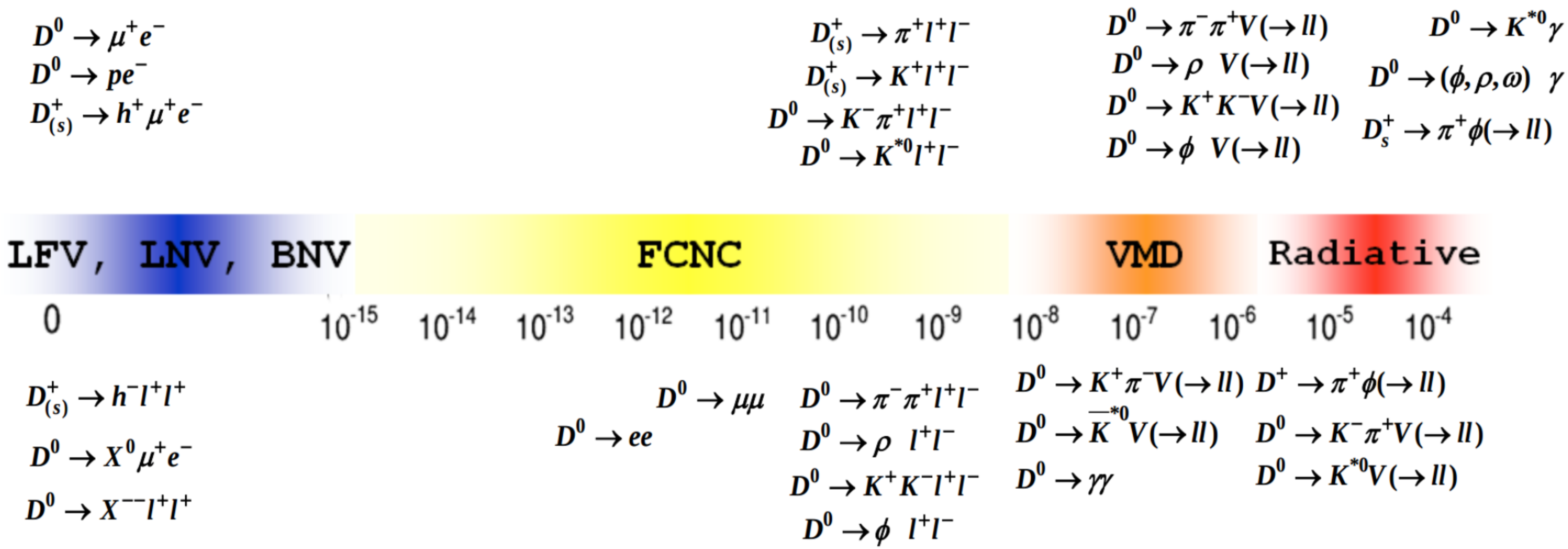
- $m_c \sim \Lambda_{QCD}$ leads to large uncertainties coming from QCD effects
- often, non-perturbative long distance (resonance) dynamics dominate!

For long, rare charm has been considered as less promising! (Disclaimer: It's not)

We need to find ways to overcome (even profit from) LD contributions



The landscape of decays



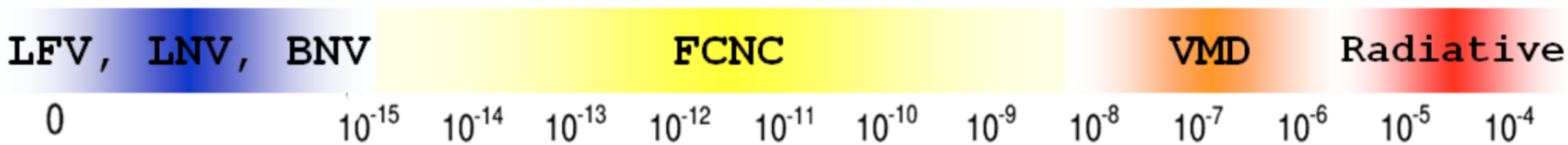
The landscape of decays

$D^0 \to \mu^+ e^-$
$D^0 \to p e^-$
$D^+_{(s)} \to h^+ \mu^+ e^-$

$D^+_{(s)} \to \pi^+ l^+ l^-$
$D^+_{(s)} \to K^+ l^+ l^-$
$D^0 \to K^- \pi^+ l^+ l^-$
$D^0 \to K^{*0} l^+ l^-$

$D^0 \to \pi^- \pi^+ V(\to ll)$
$D^0 \to \rho \; V(\to ll)$
$D^0 \to K^+ K^- V(\to ll)$
$D^0 \to \phi \; V(\to ll)$

$D^0 \to K^{*0} \gamma$
$D^0 \to (\phi, \rho, \omega) \; \gamma$
$D^+_s \to \pi^+ \phi(\to ll)$



$D^+_{(s)} \to h^- l^+ l^+$
$D^0 \to X^0 \mu^+ e^-$
$D^0 \to X^{--} l^+ l^+$

$D^0 \to \mu\mu$
$D^0 \to ee$

$D^0 \to \pi^- \pi^+ l^+ l^-$
$D^0 \to \rho \; l^+ l^-$
$D^0 \to K^+ K^- l^+ l^-$
$D^0 \to \phi \; l^+ l^-$

$D^0 \to K^+ \pi^- V(\to ll)$
$D^0 \to \overline{K}^{*0} V(\to ll)$
$D^0 \to \gamma\gamma$

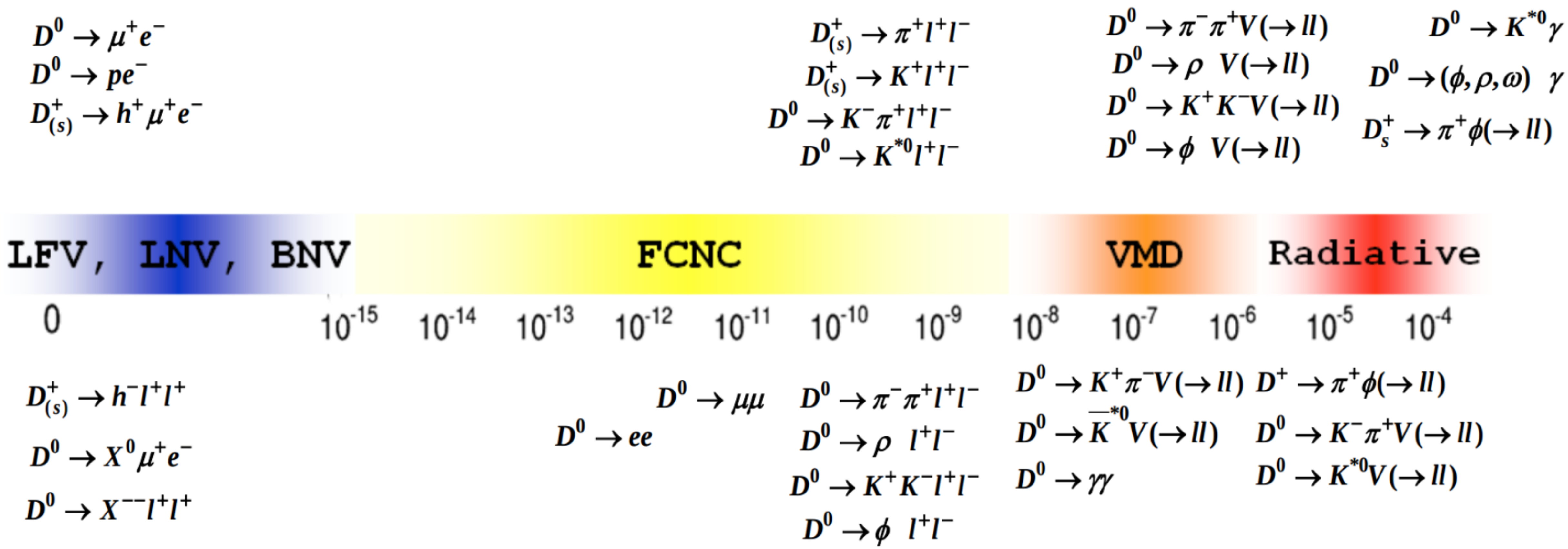
$D^+ \to \pi^+ \phi(\to ll)$
$D^0 \to K^- \pi^+ V(\to ll)$
$D^0 \to K^{*0} V(\to ll)$

‘SM-Forbidden’ decays

- lepton-flavour violation
- lepton-number violation
- baryon-number violation

no SM background

The landscape of decays



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Very rare decays

- purely leptonic
- local regions in decay phase space of multi-body decays

reduced hadronic uncertainties

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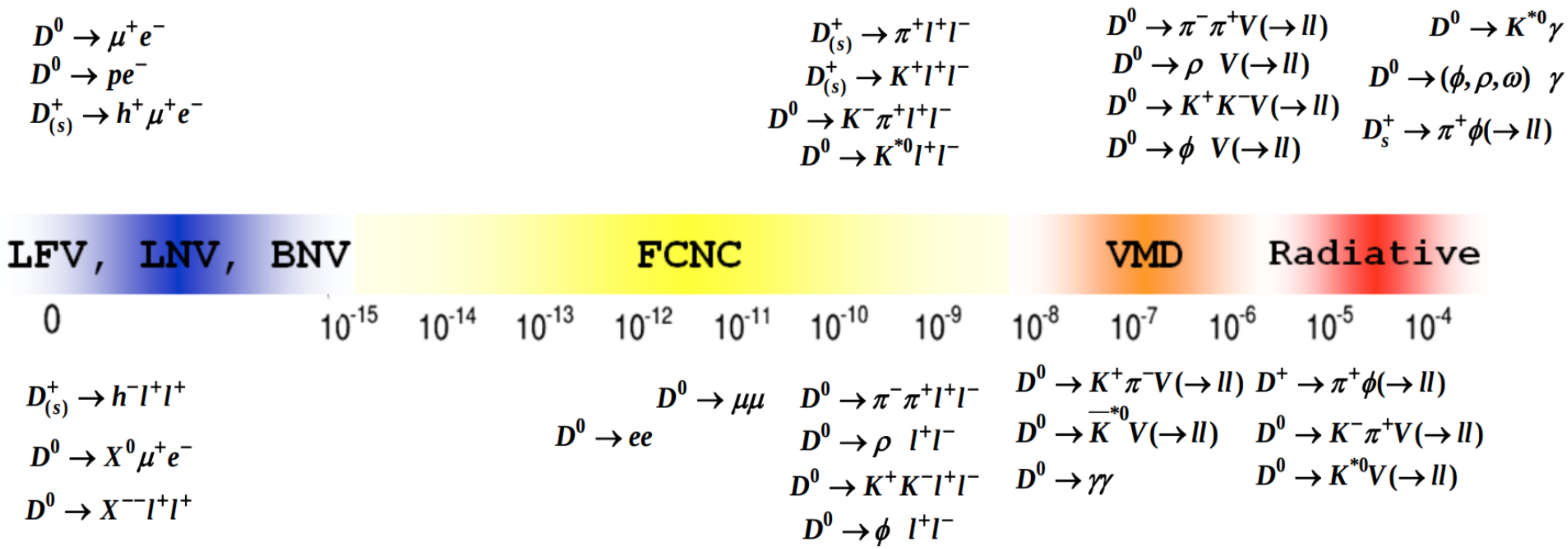

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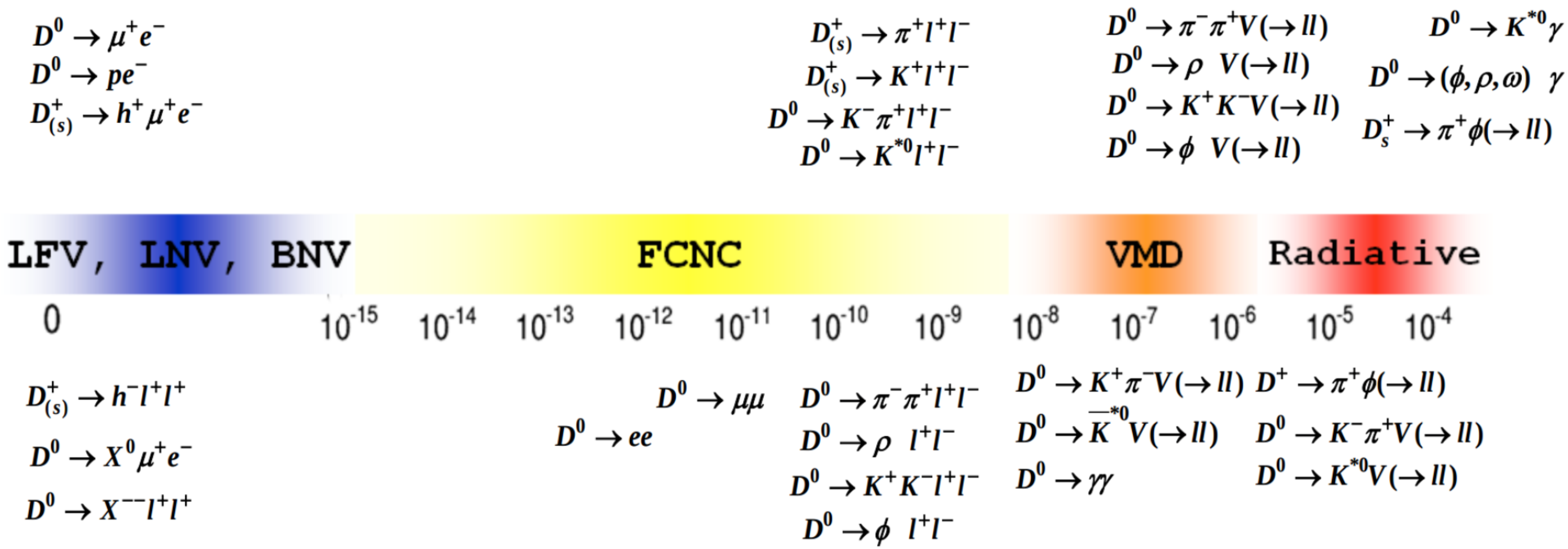
Rare resonance dominated & radiative decays

- test of lepton-universality
- CP asymmetries
- angular distributions

'clean' SM null-tests

The landscape of decays



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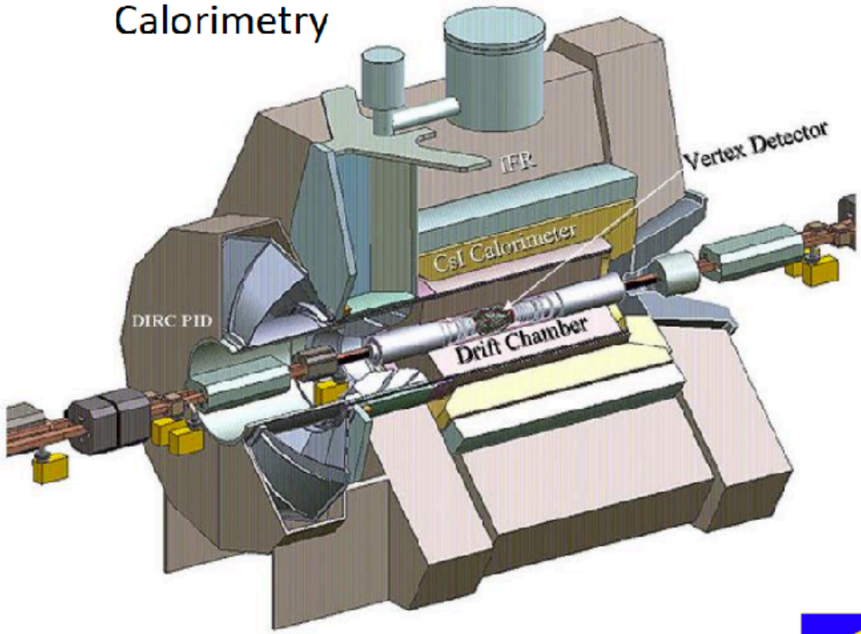
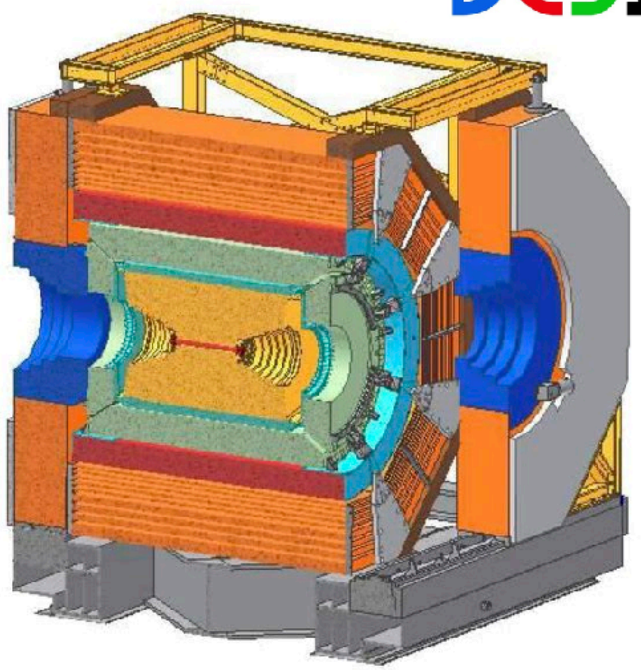
The most recent experimental players

BABAR

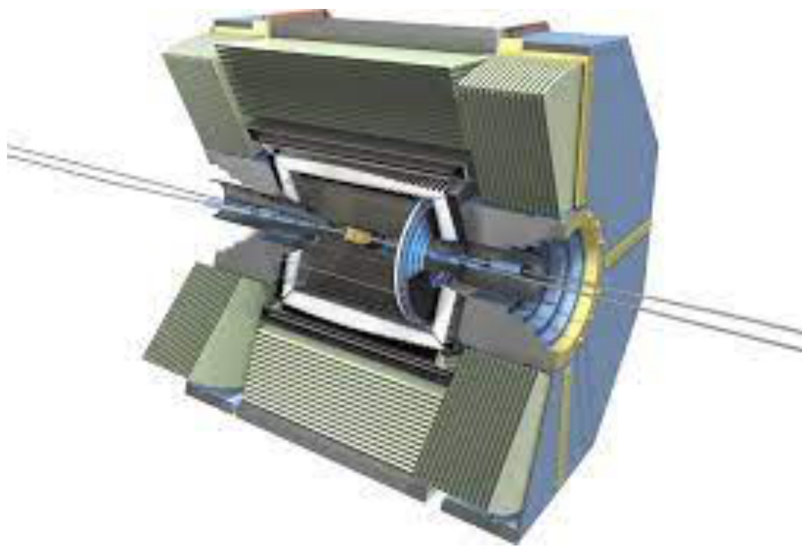
Vertex + tracking detectors
Particle ID
Calorimetry



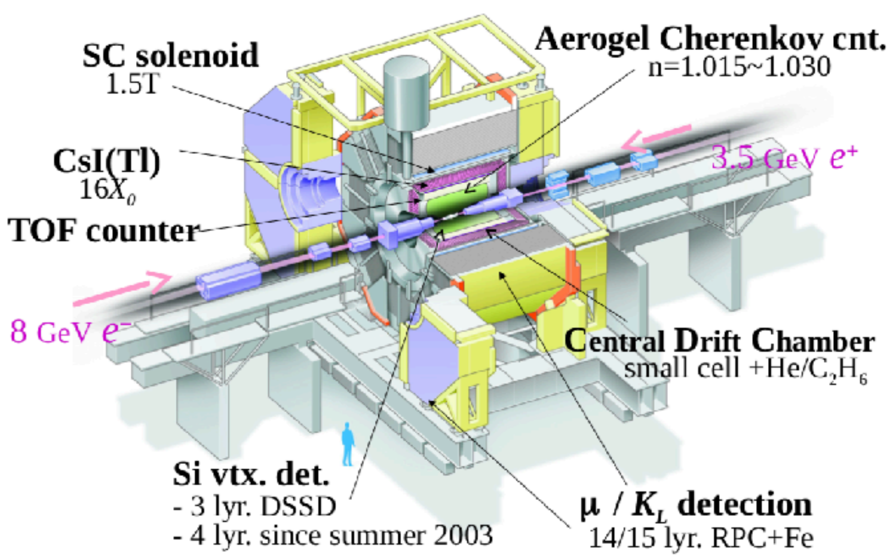
BESIII



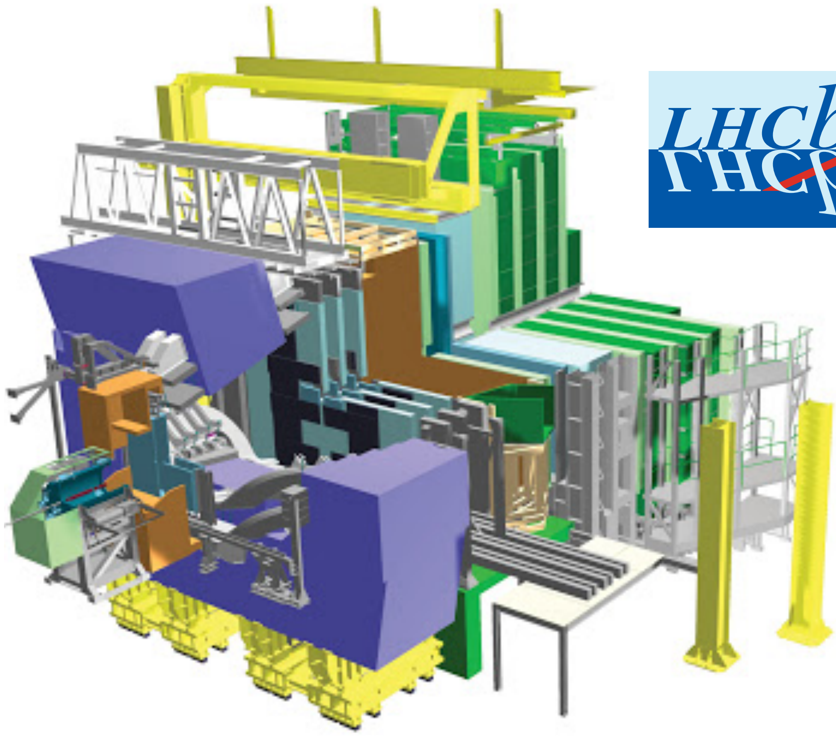
Belle II



BELLE



LHCb



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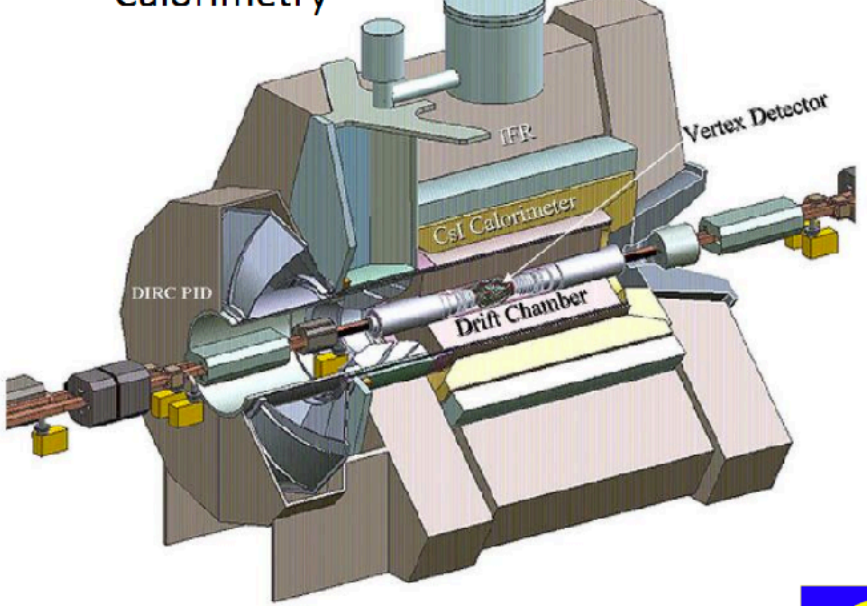
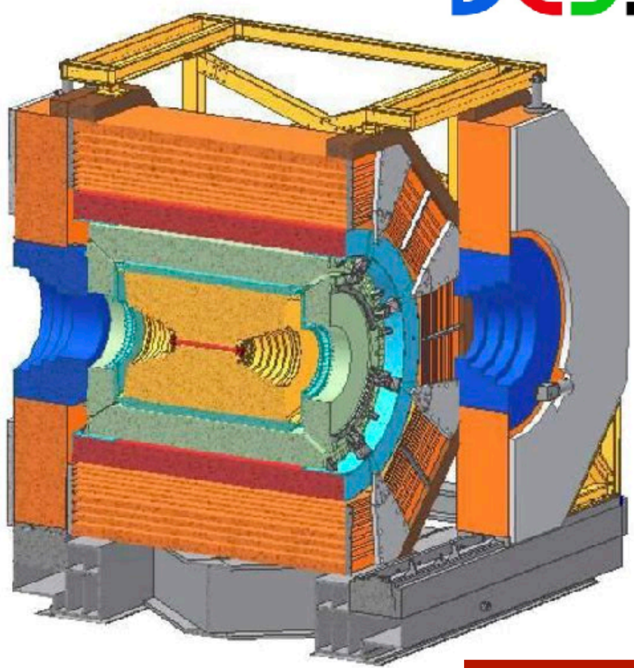
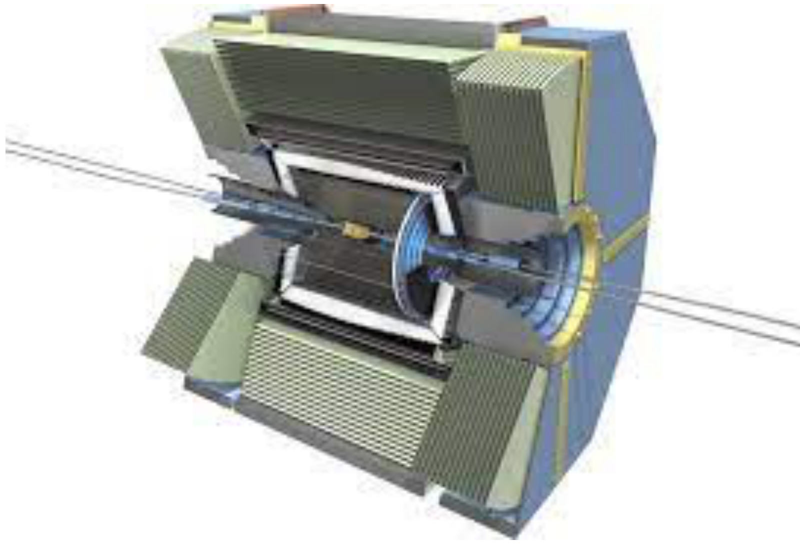
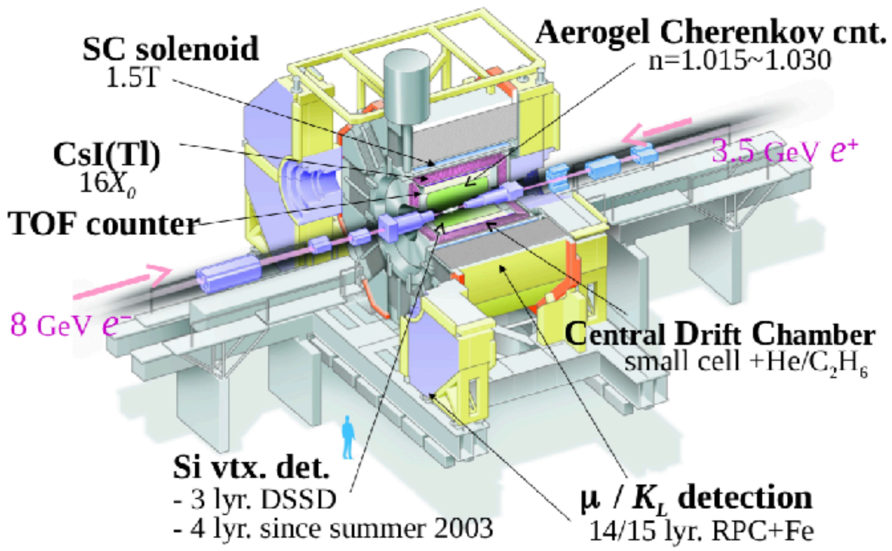
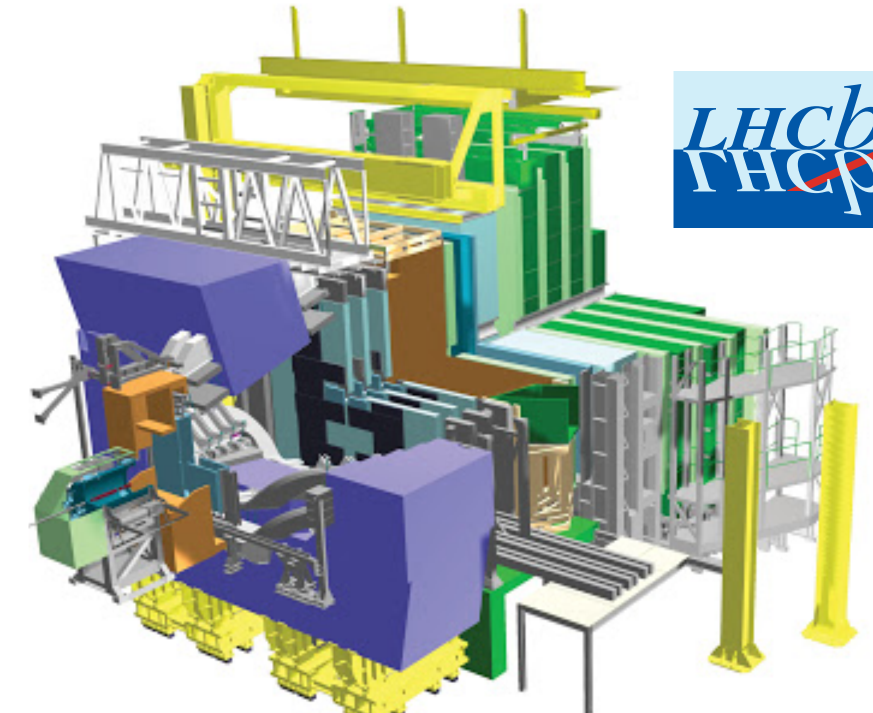








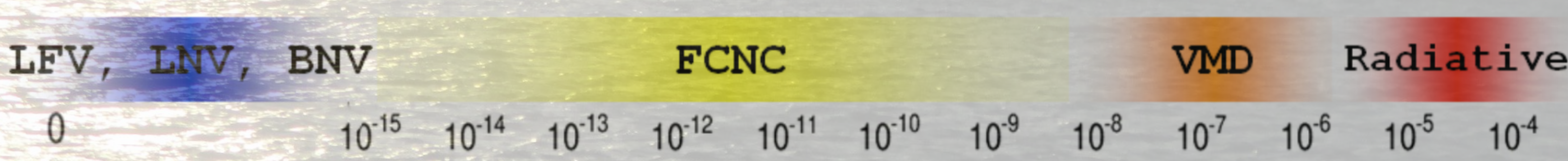


Searches in decay rates

Search for rare and forbidden semi-leptonic decays

Searches for 25 rare and forbidden decays of D^+ and D_s^+ mesons

JHEP 06 (2021) 44



Search for rare and forbidden semi-leptonic decays

Searches for 25 rare and forbidden decays of D^+ and D_s^+ mesons

JHEP 06 (2021) 44

LFV, LNV, LNV & LFV

$D^+_{(s)} \to \pi^+\mu^\pm e^\mp$

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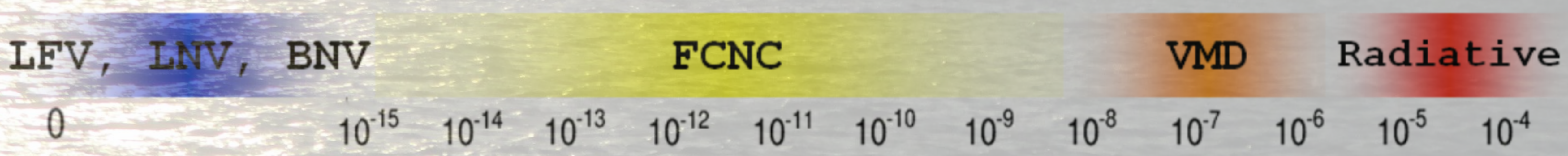
clean null tests!



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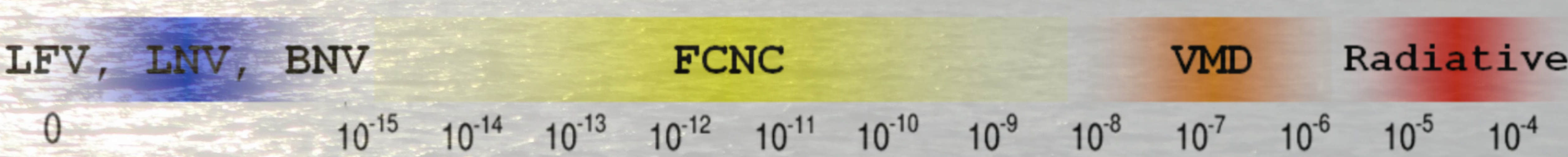

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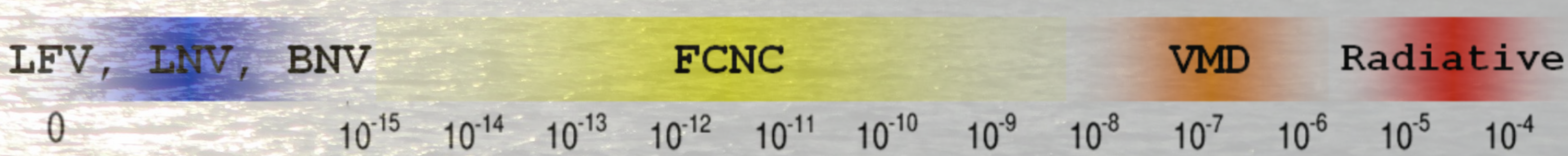
rare resonance dominated (as reference)

$D^+_{(s)} \to \pi^+\phi[\mu^+\mu^-]$

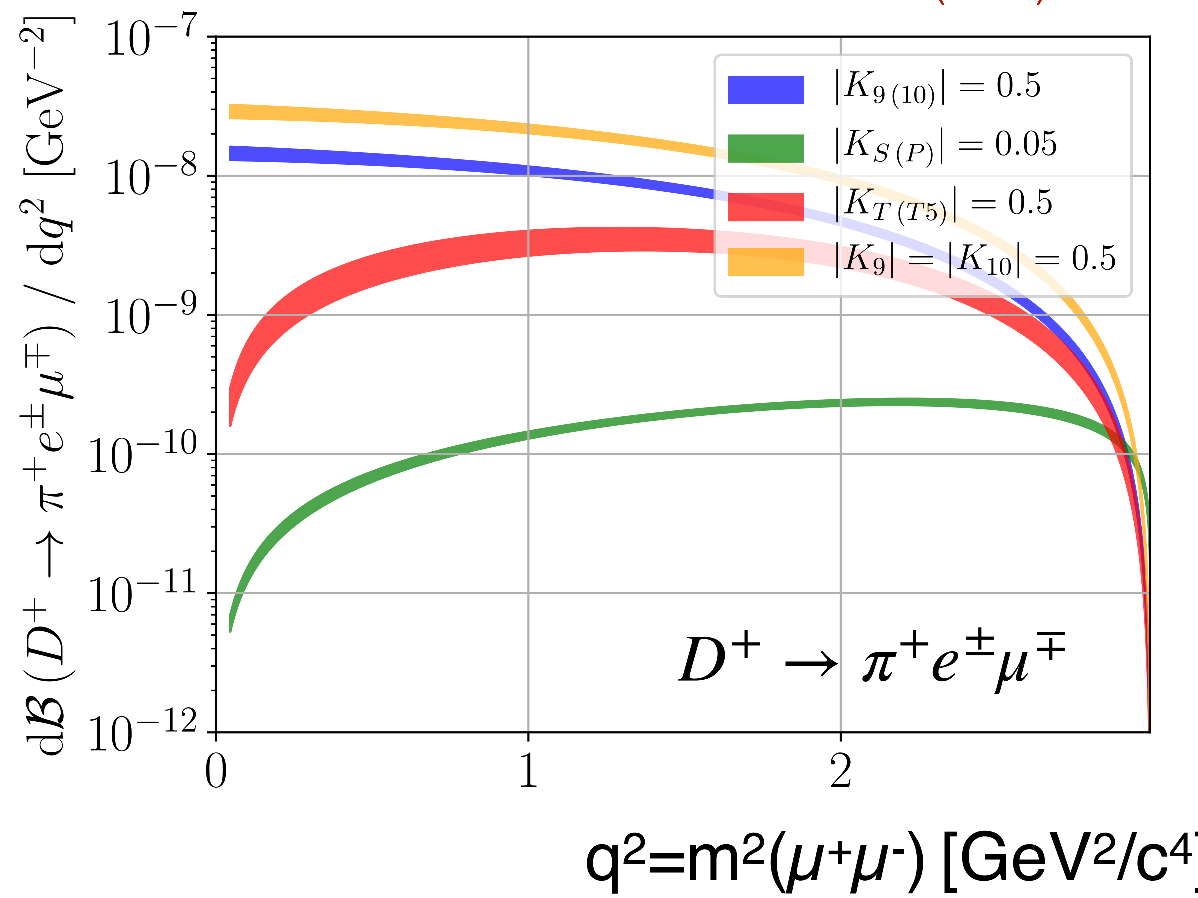
$D^+_{(s)} \to K^+\phi[e^+e^-]$



Search for the rare decays $D \rightarrow hl^{\pm}l^{(')\mp}$

- For forbidden modes any signal = NP

EPJC 80 (2020) 65



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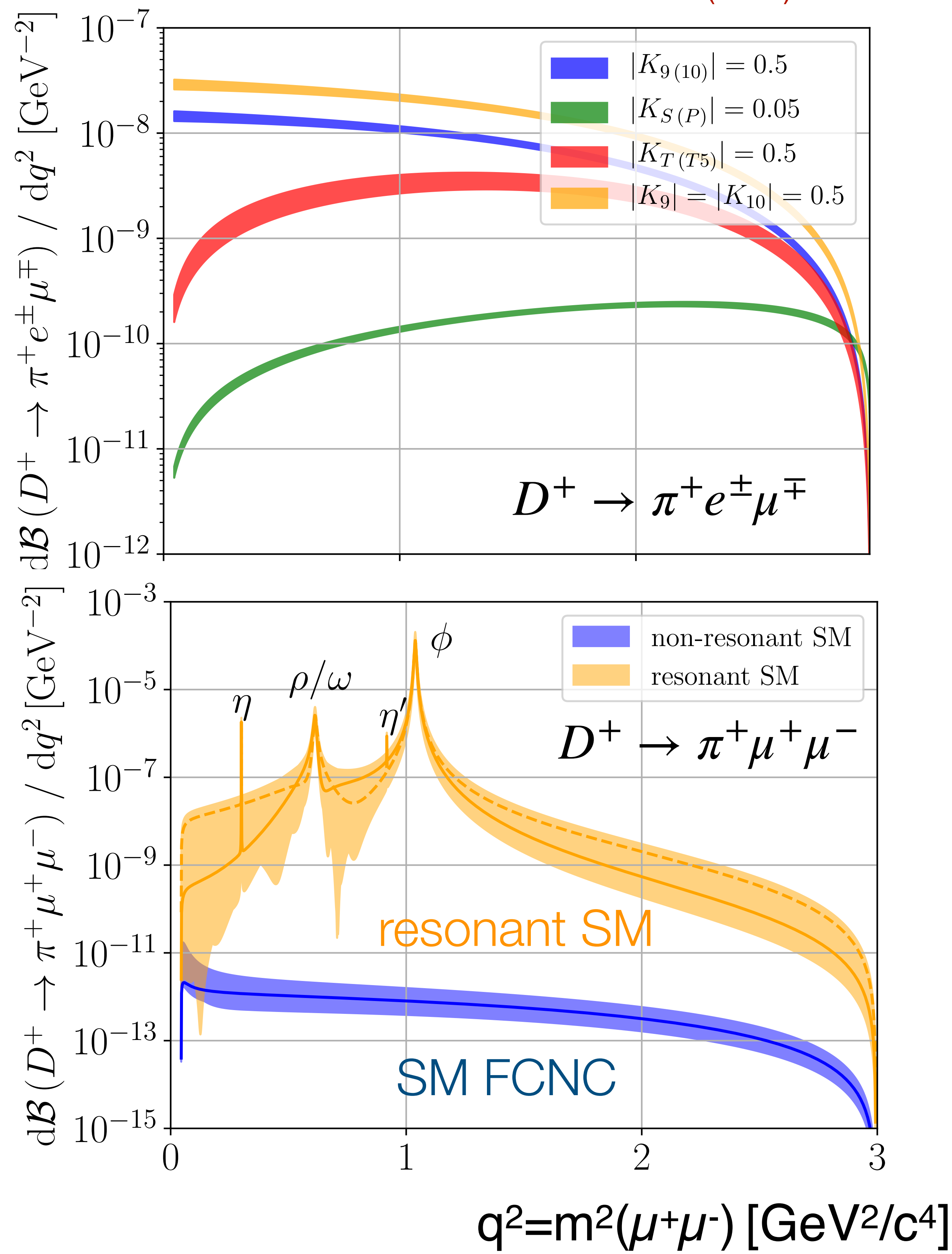

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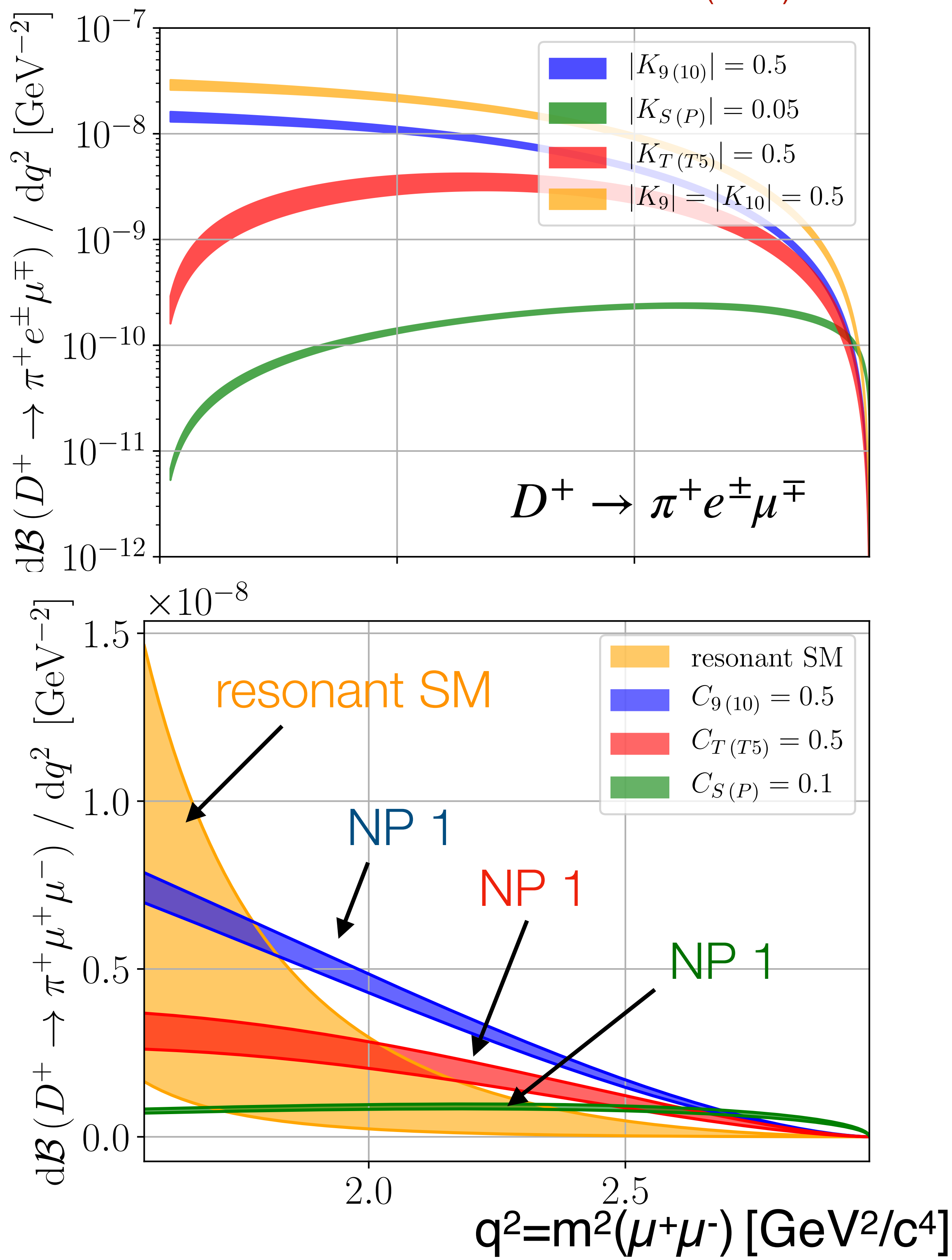

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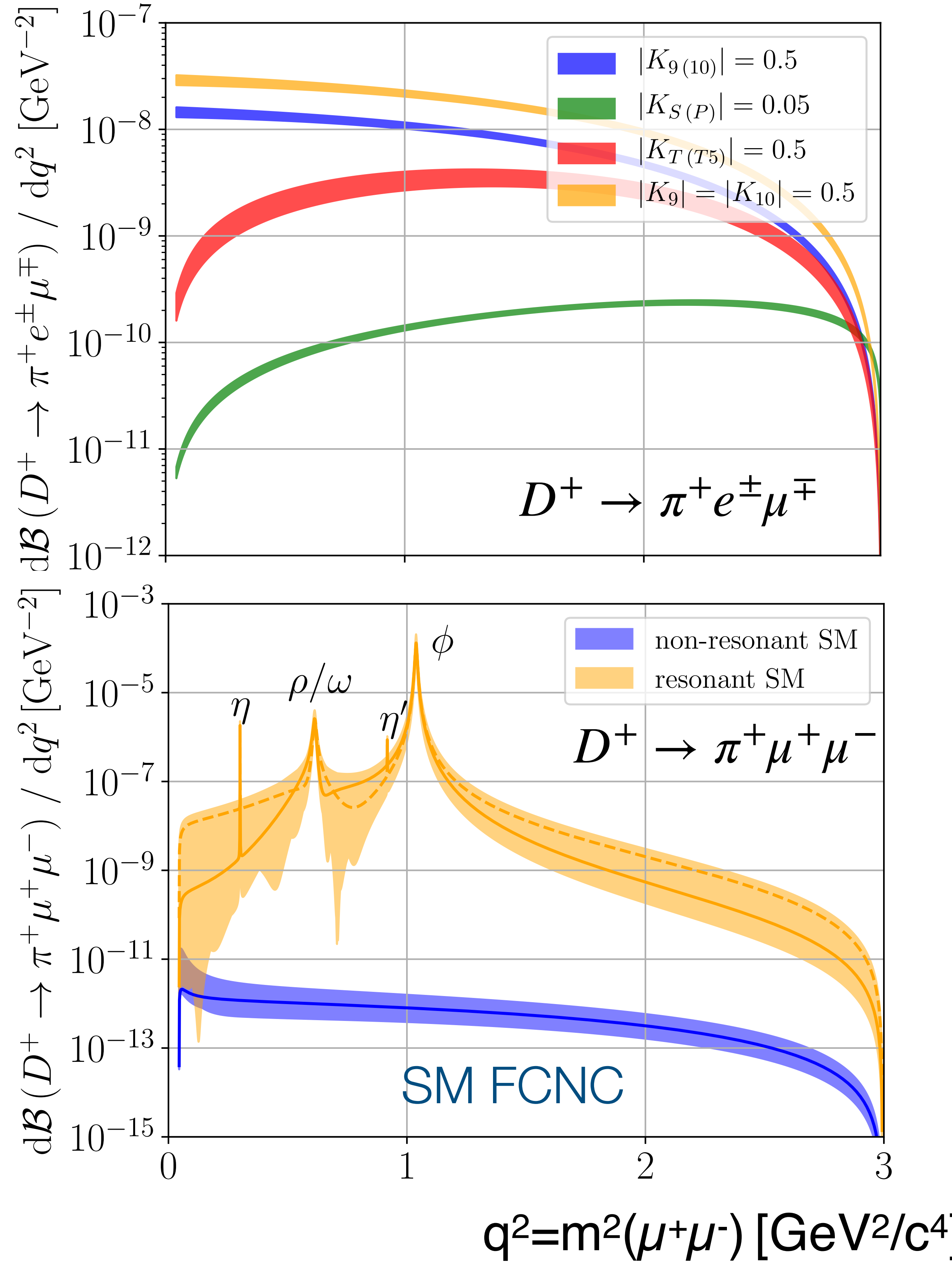
EPJC 80 (2020) 65



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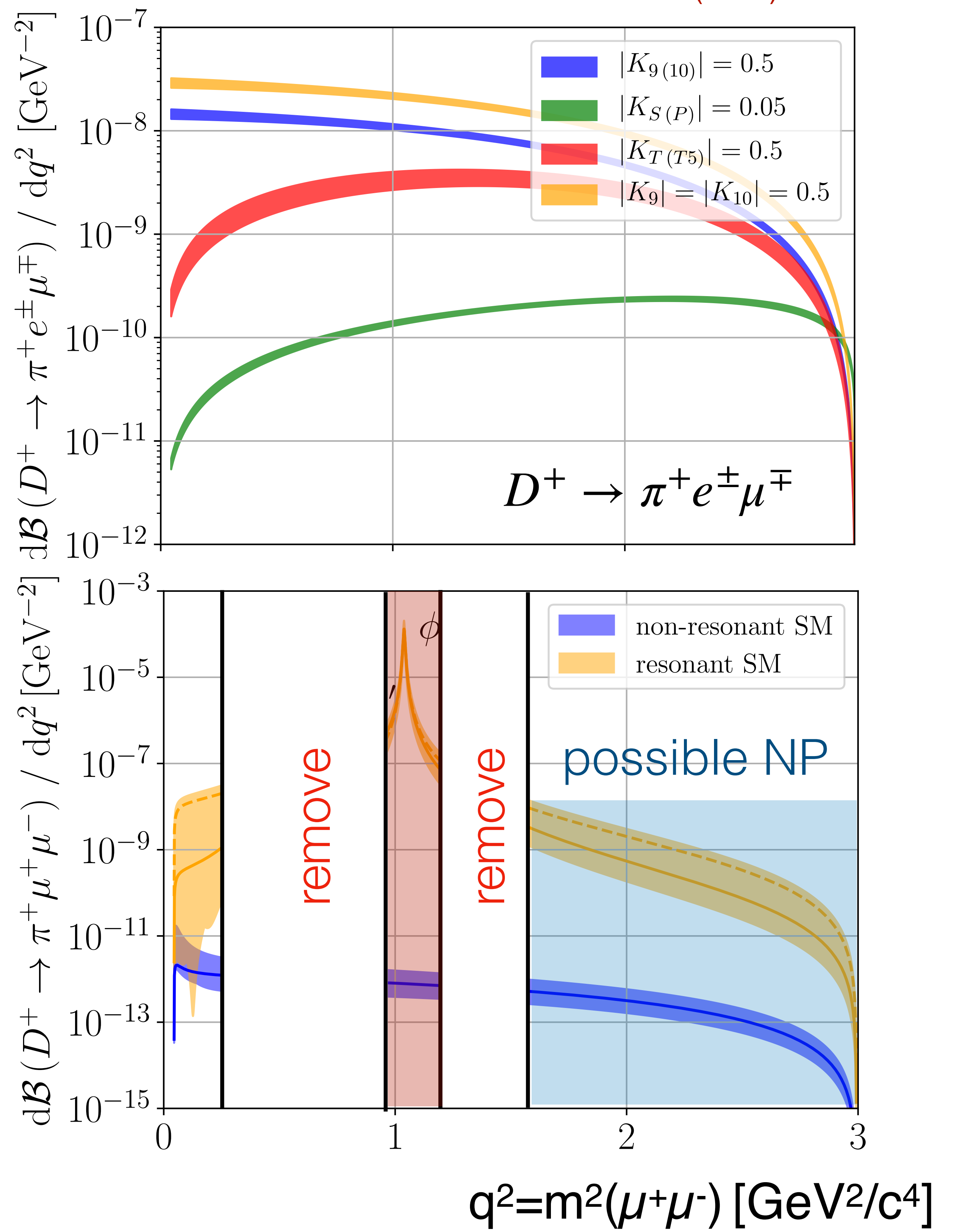

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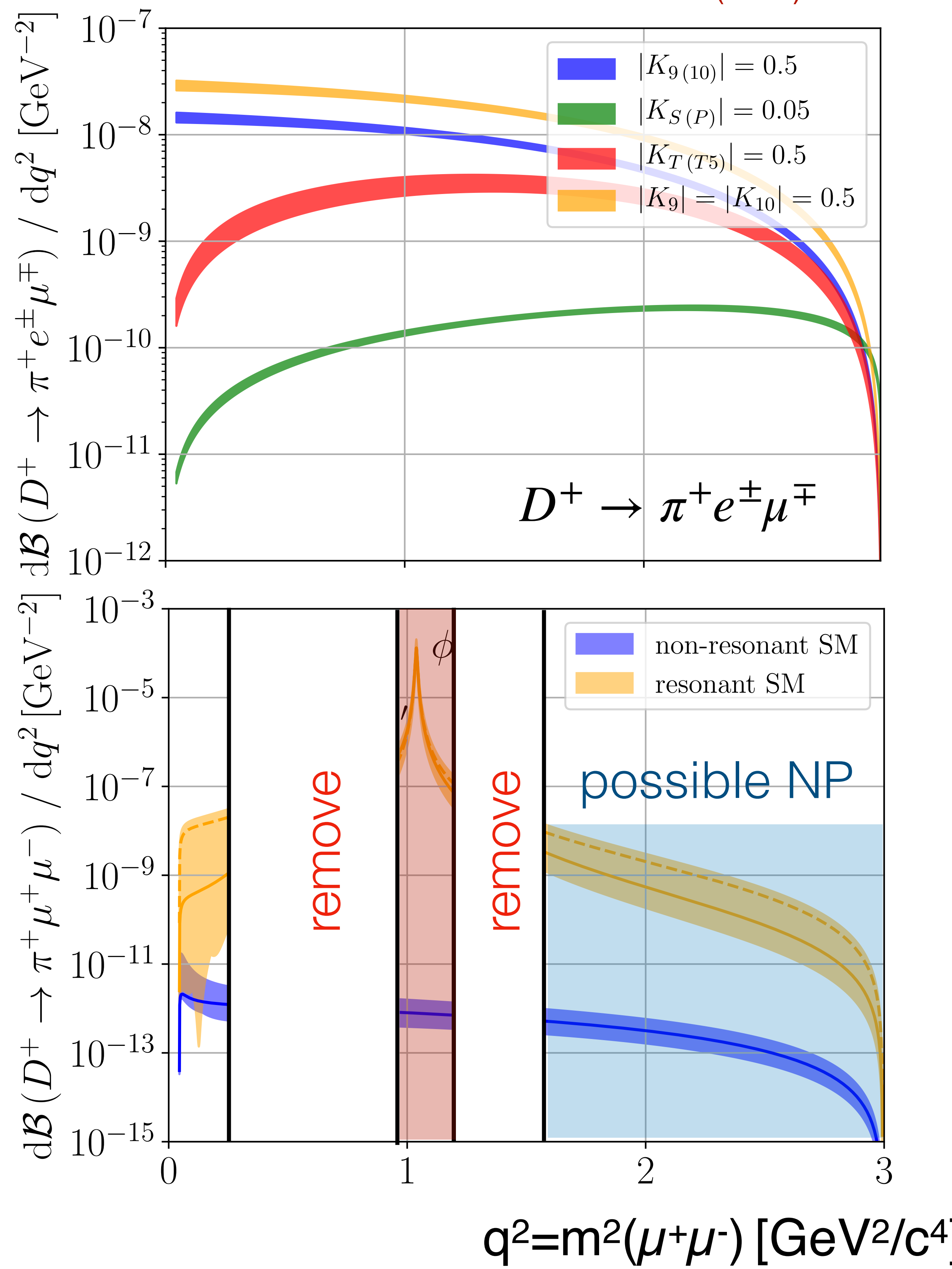
- Remove η, ρ/ω regions, use $D^+_{(s)} \to \pi\phi[\mu^+\mu^-]$ as normalisation
- Analysis presented uses 1.6/fb data collected in 2016 JHEP 06 (2021) 44

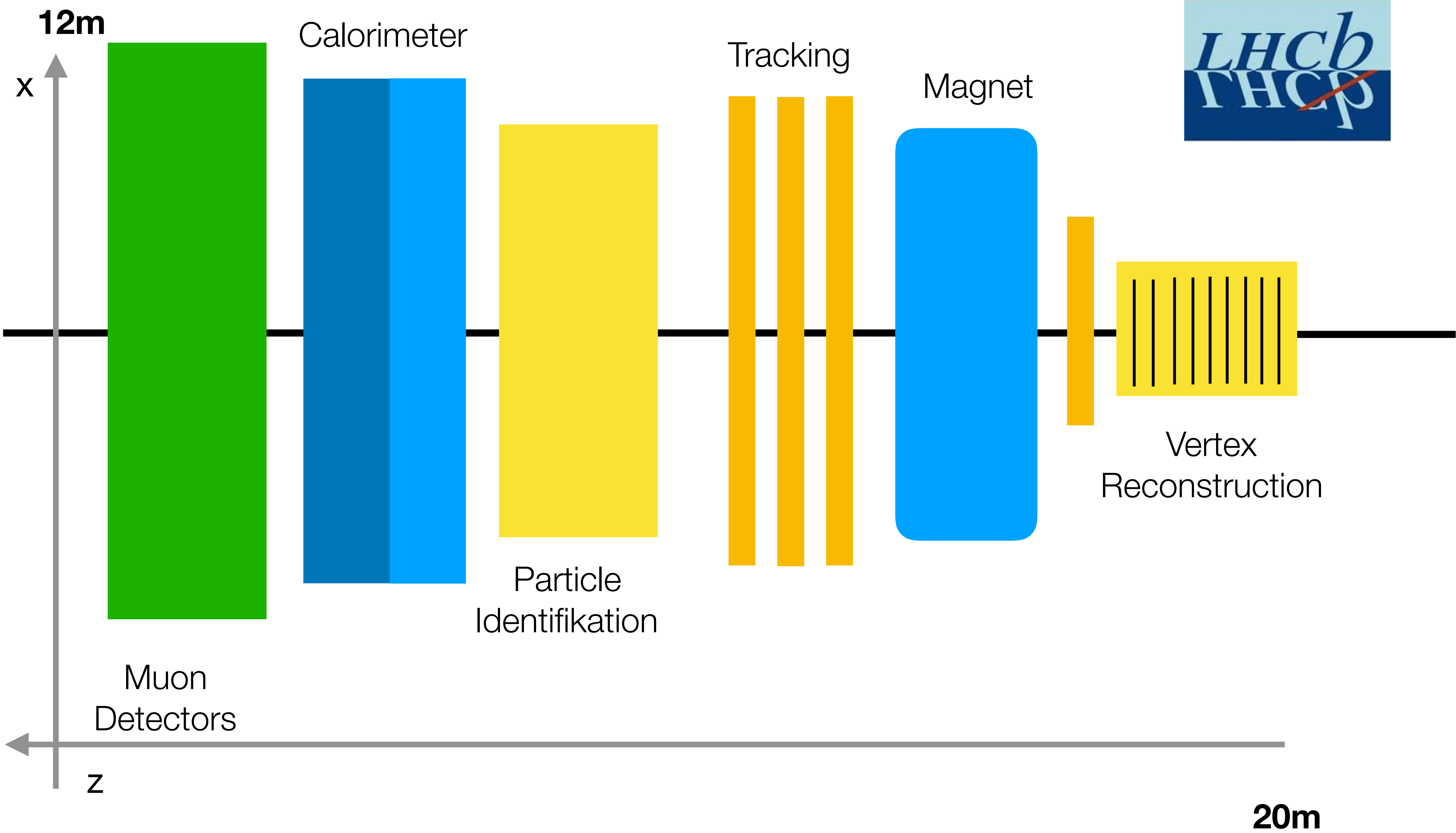
EPJC 80 (2020) 65



LHCb detector

https://lhcb.web.cern.ch/lhcb/speakersbureau/html/Material_for_Presentations.html

LHCb detector



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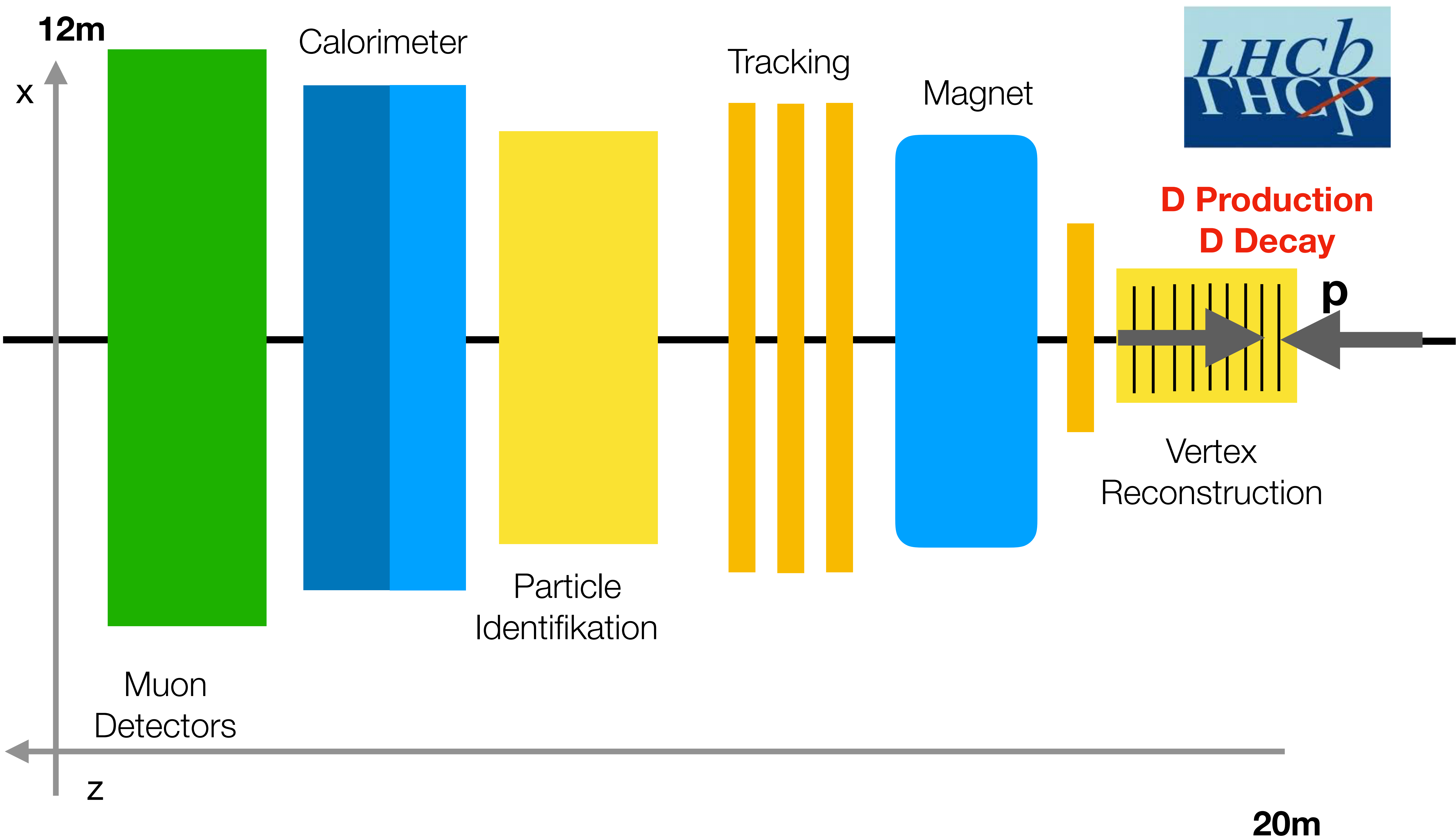

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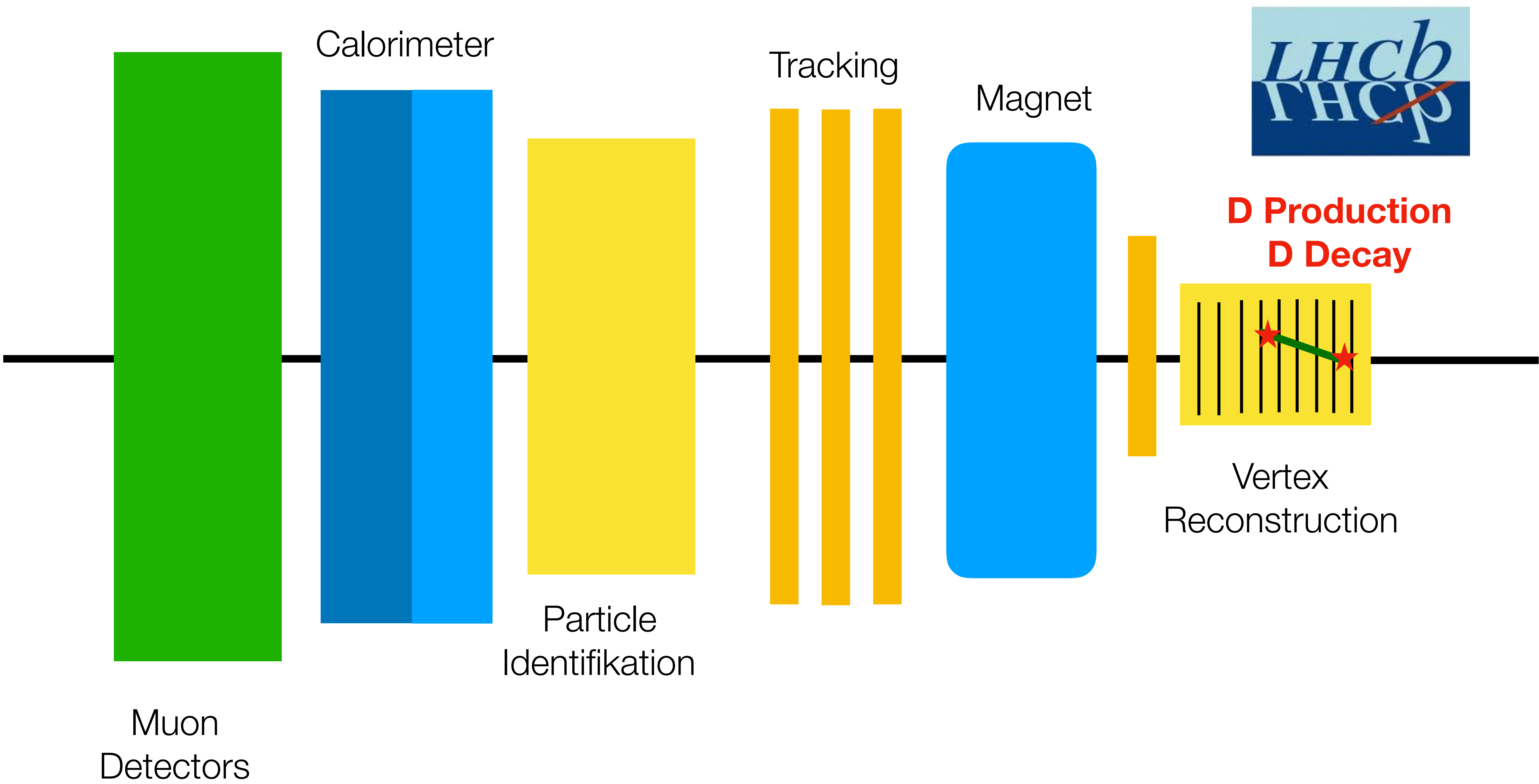

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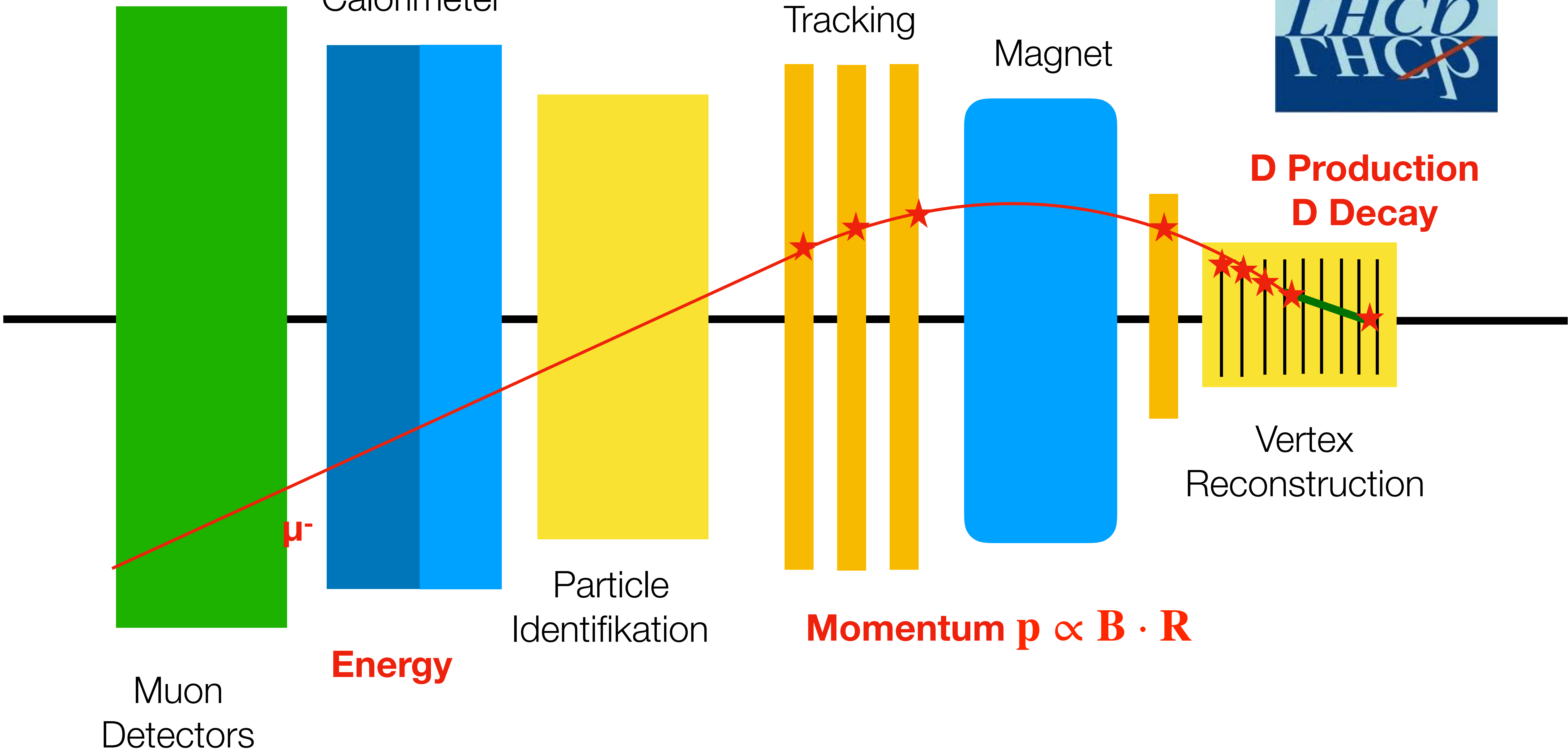

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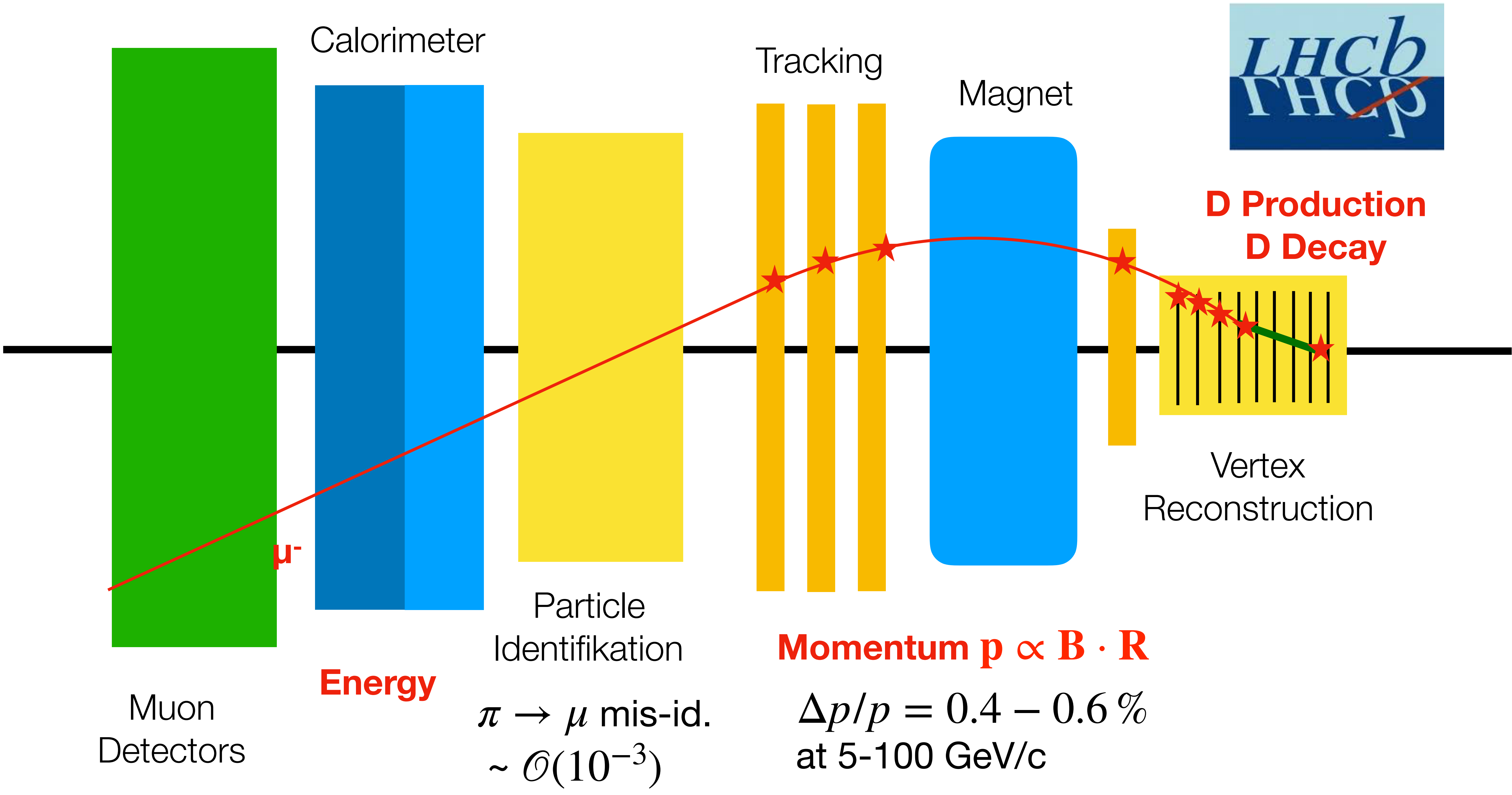

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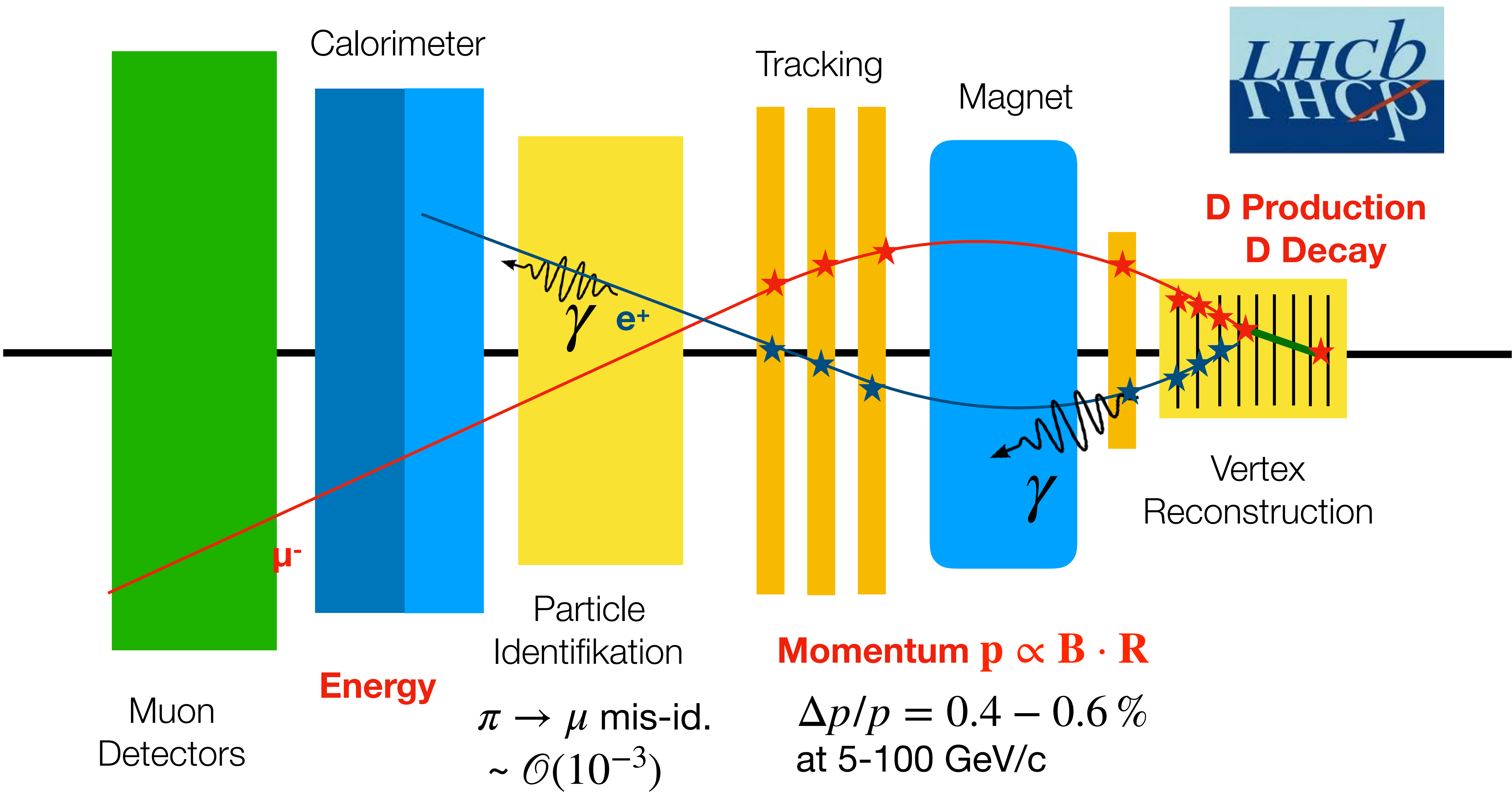

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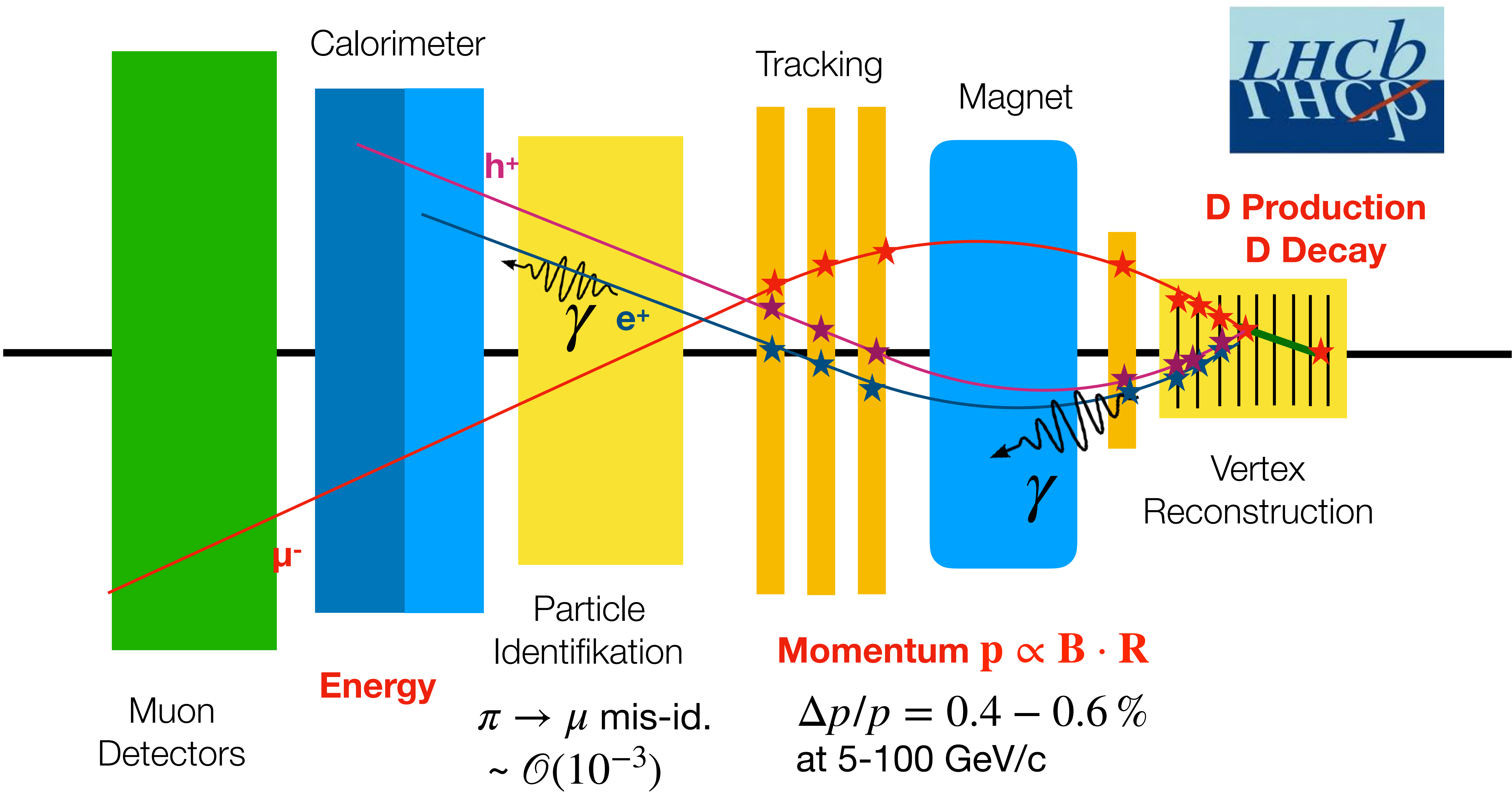

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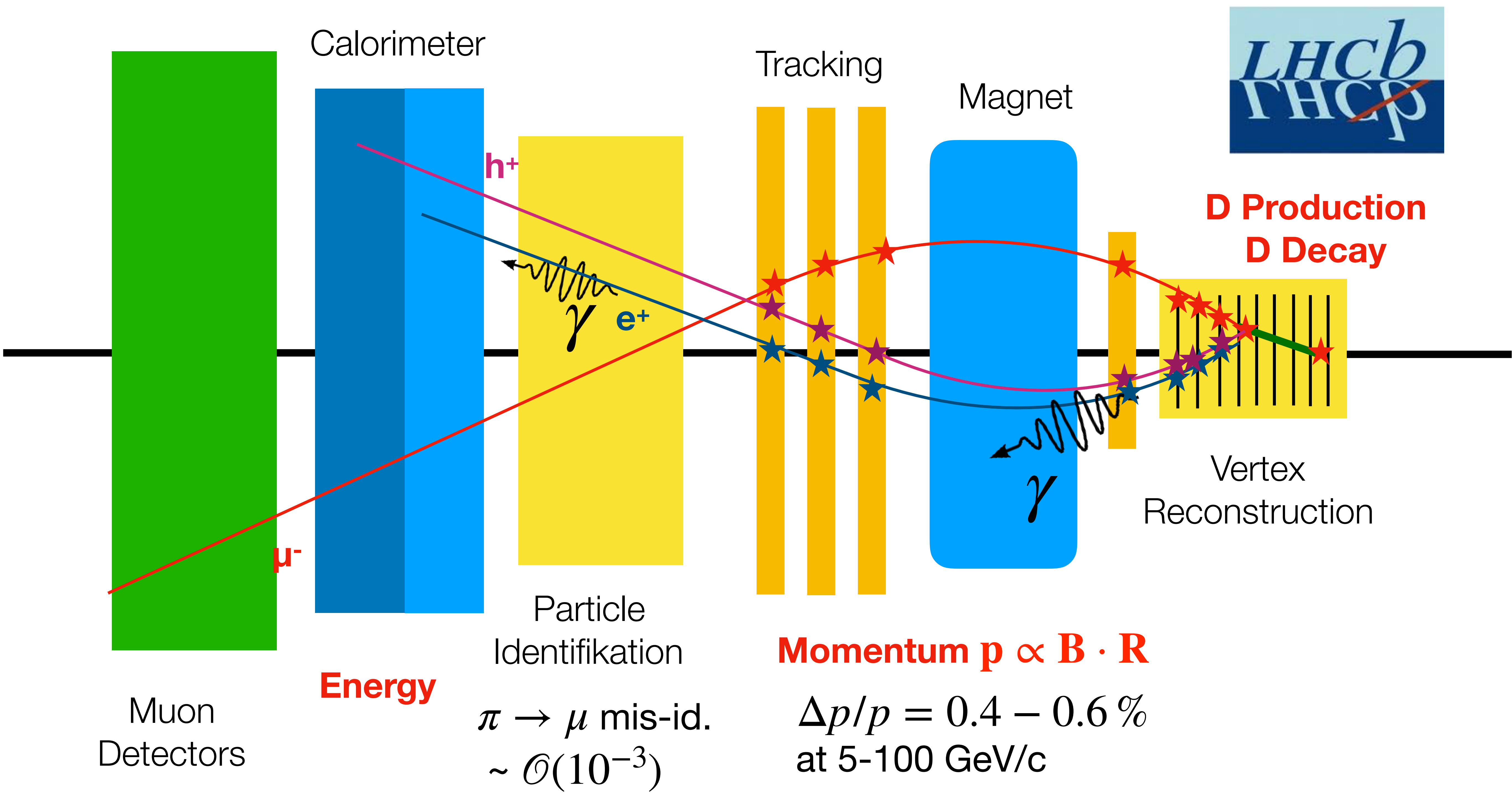
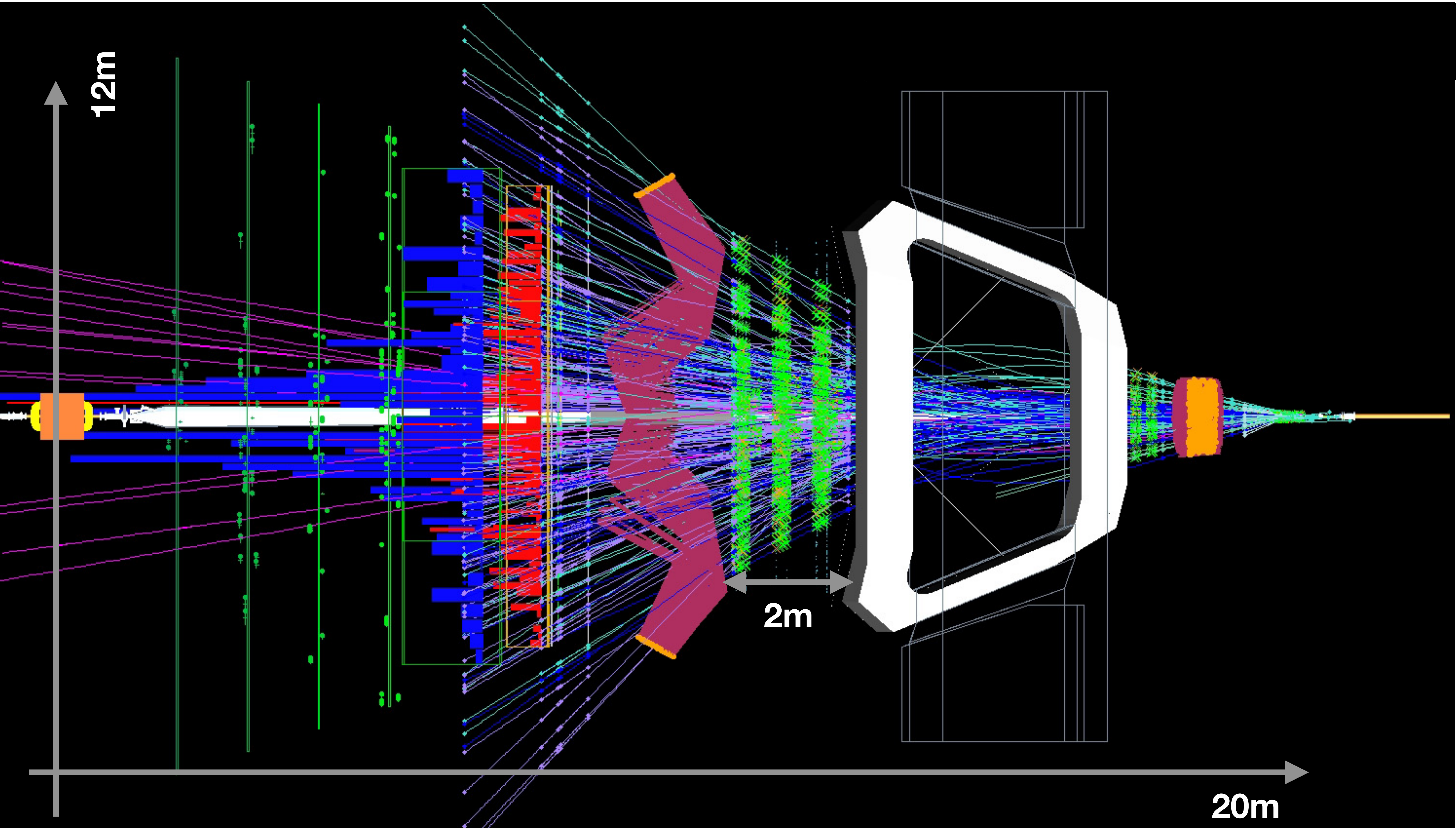


40 millions (!) collisions per second

LHCb detector



Selecting candidates

Search for

$$D^+ \to h^+\ell^+\ell^-$$

$$\tau_{D^+} = 1 \times 10^{-12} s$$

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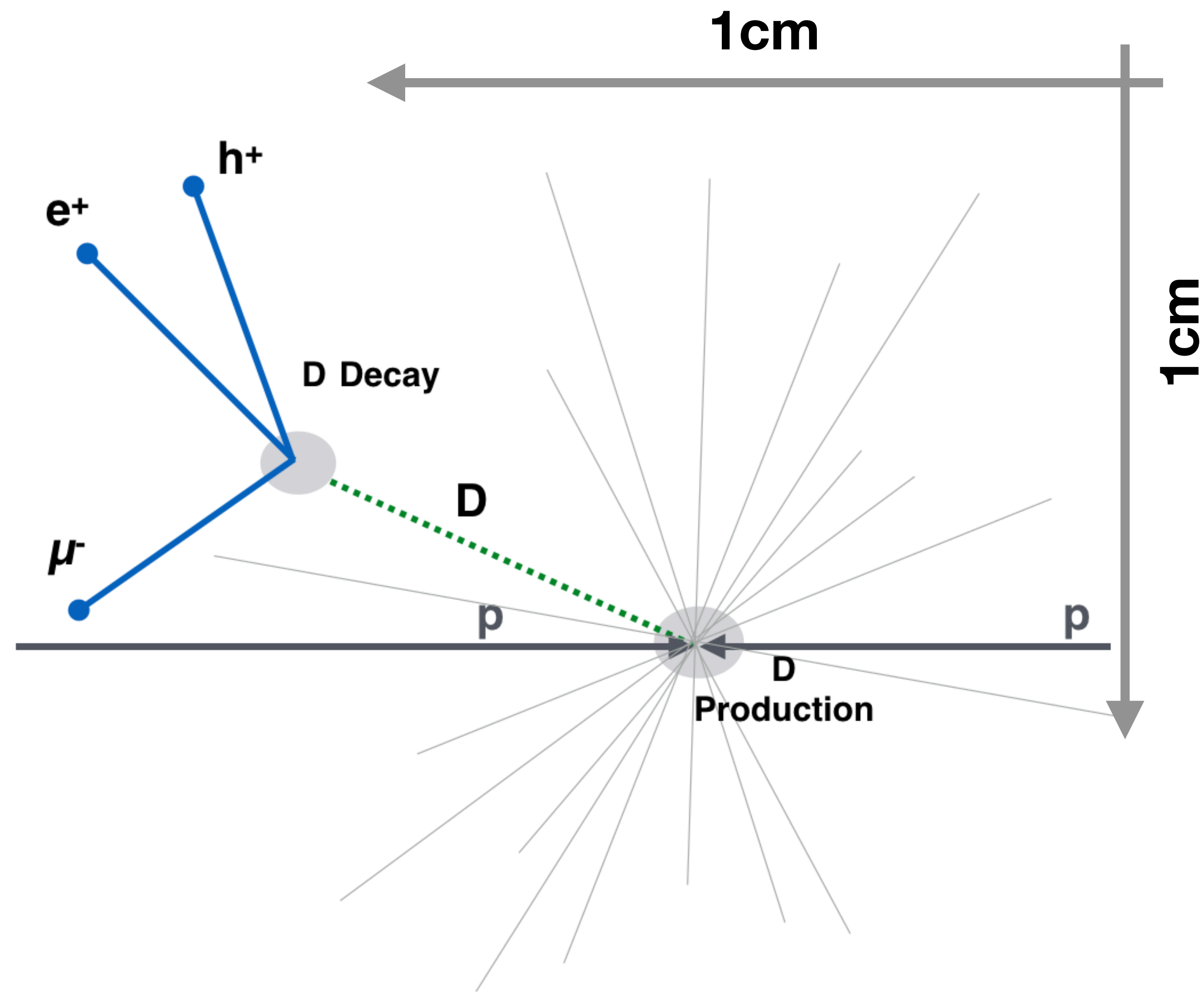

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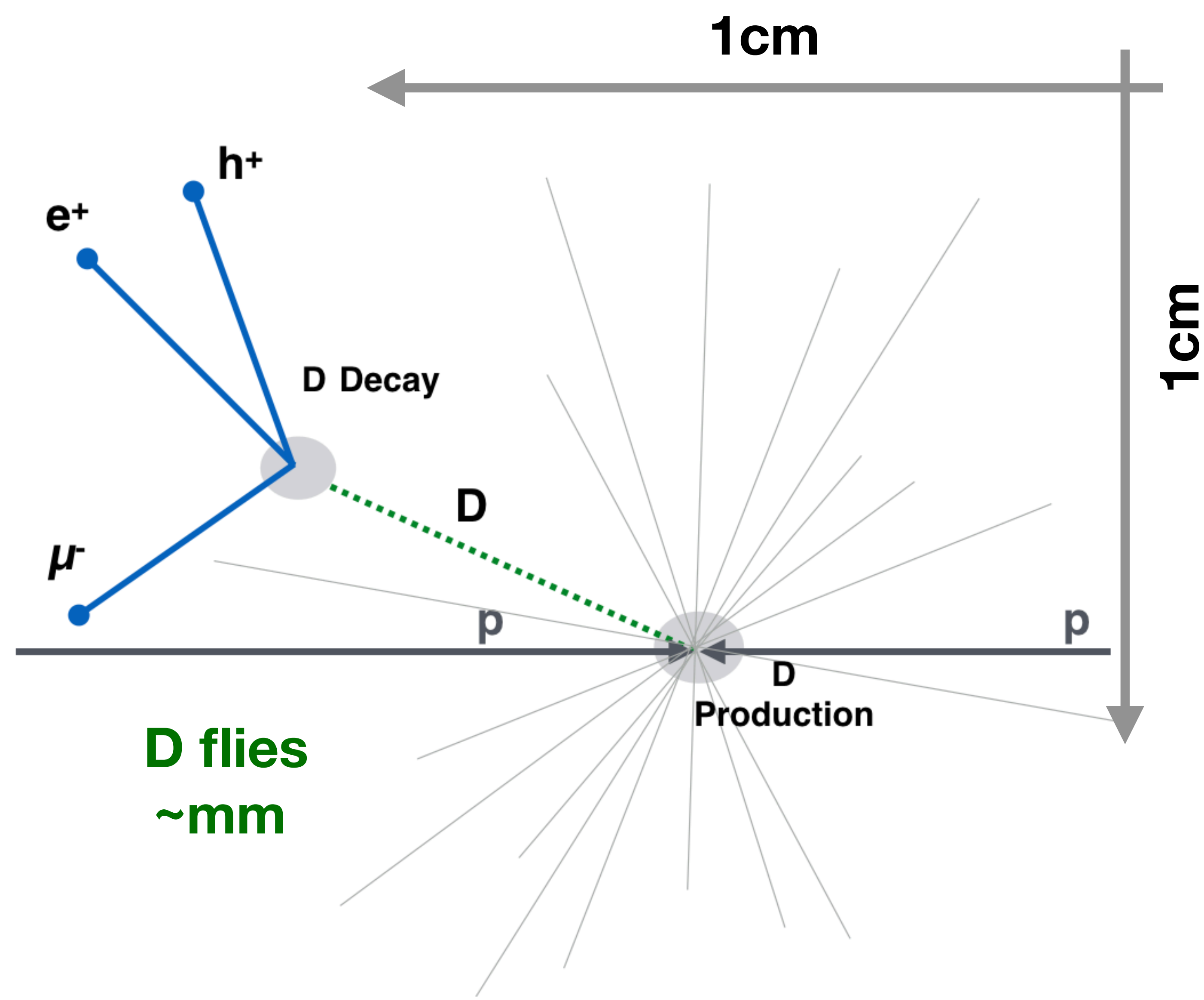

Topologic criteria

Selecting candidates

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$$D^+ \to h^+\ell^+\ell^-$$

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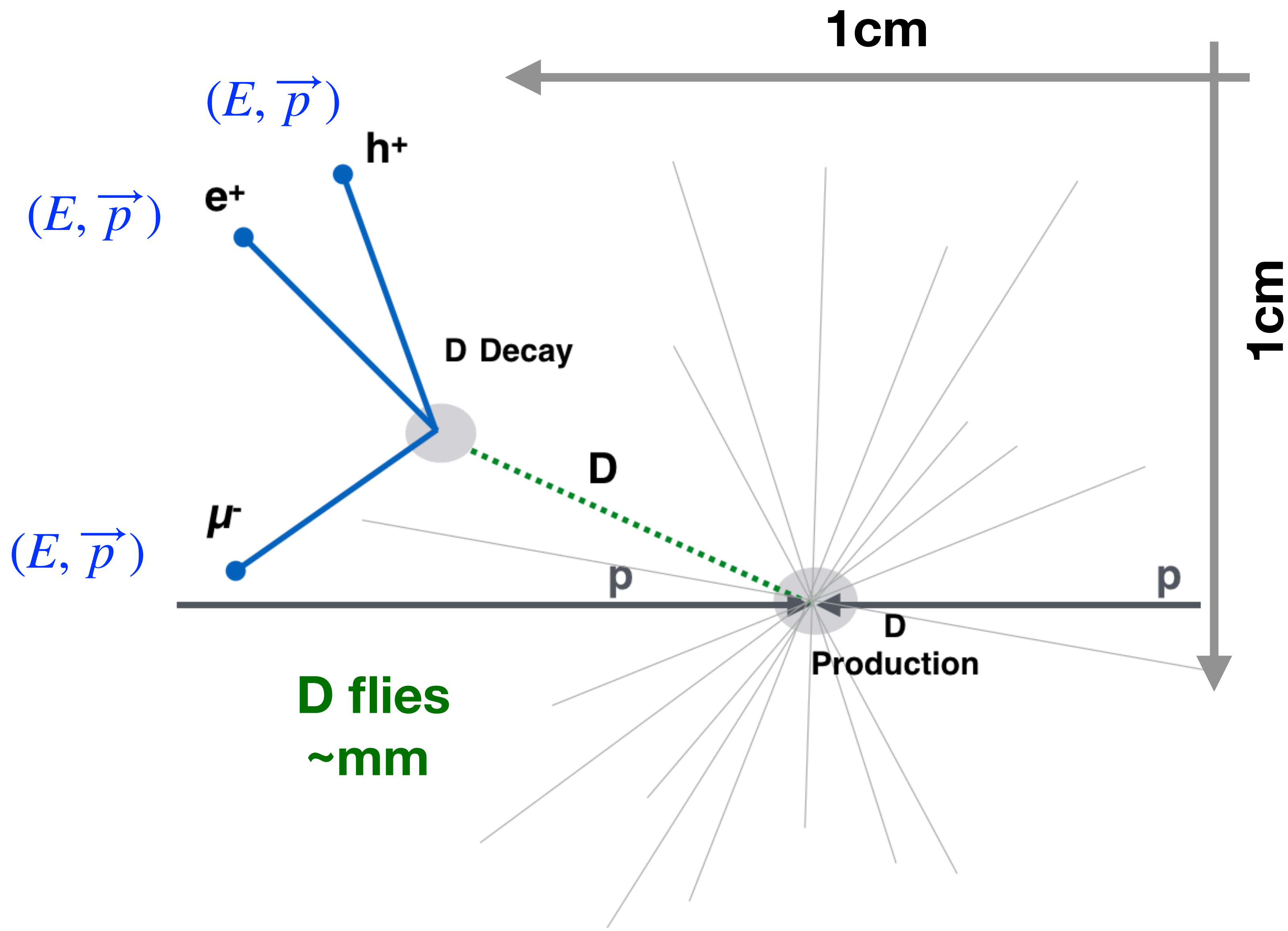

Topologic criteria

Kinematic criteria

Selecting candidates

Search for

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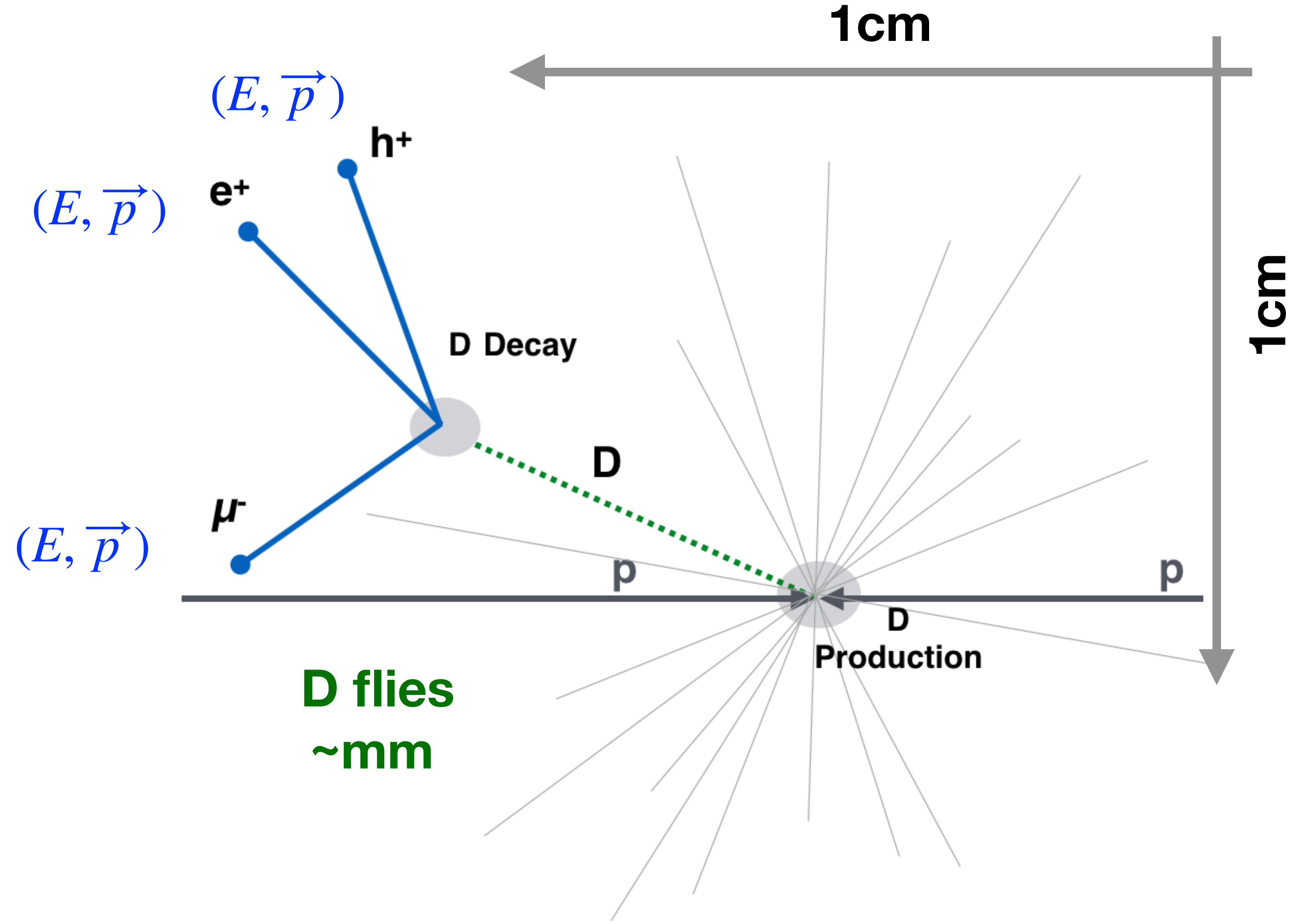


Topologic criteria

Kinematic criteria

Multivariate Analysis

Search for the rare decays $D \to h l^{\pm} l^{(\prime)\mp}$

JHEP 06 (2021) 044

$$\mathcal{B}(D^+_{(s)} \to h^+\ell^+\ell^-) = \frac{N(D^+_{(s)} \to h^+\ell^+\ell^-)}{N(D^+_{(s)})} \cdot \frac{1}{\epsilon(D^+_{(s)} \to h^+\ell^+\ell^-)}$$

Search for the rare decays $D \to h l^{\pm} l^{(\prime)\mp}$

JHEP 06 (2021) 044

$$\mathcal{B}(D^+_{(s)} \to h^+\ell^+\ell^-) = \frac{N(D^+_{(s)} \to h^+\ell^+\ell^-)}{N(D^+_{(s)} \to \pi^+\phi[\ell^+\ell^-])} \cdot \frac{\epsilon(D^+_{(s)} \to \pi^+\phi[\ell^+\ell^-])}{\epsilon(D^+_{(s)} \to h^+\ell^+\ell^-)} \cdot \mathcal{B}(D^+_{(s)} \to \pi^+\phi[\ell^+\ell^-])$$

determination through maximum likelihood fits

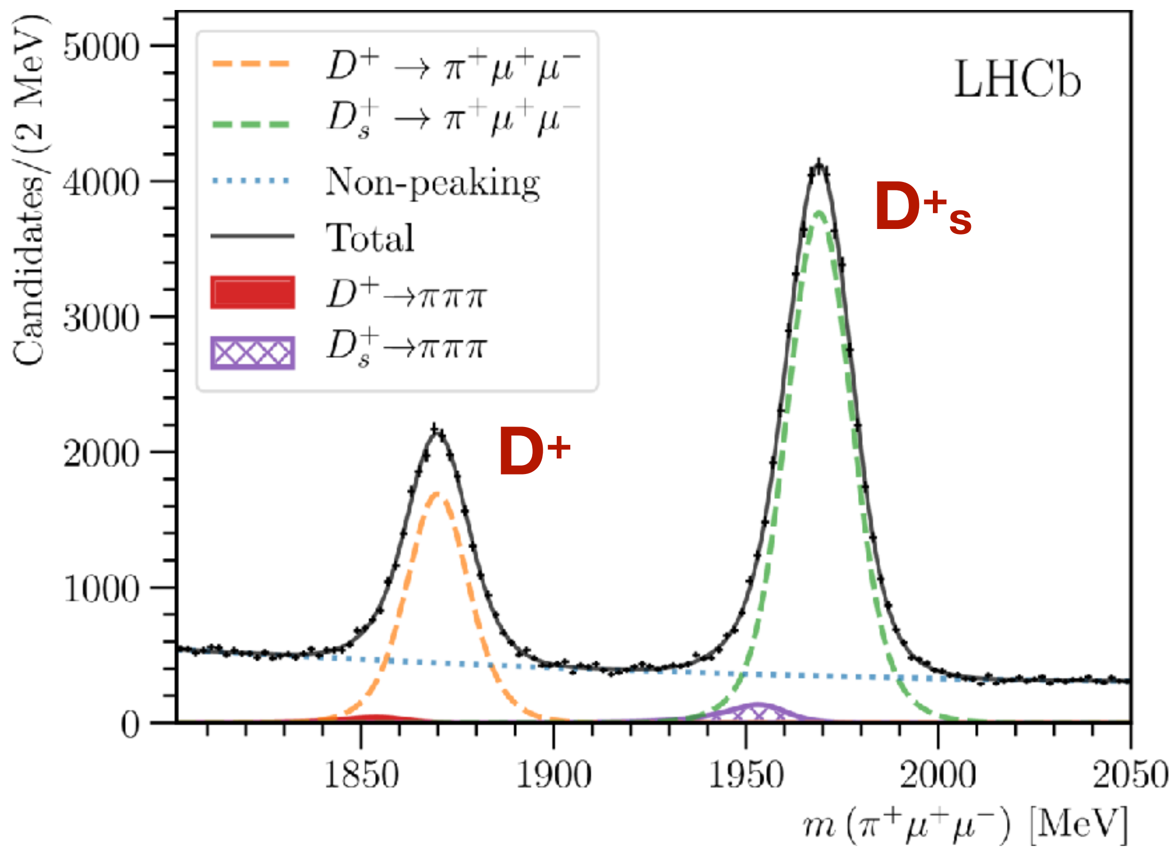
mainly from simulations, data driven methods when possible

external input

Search for the rare decays $D \rightarrow h l^{\pm} l^{(\prime)\mp}$

JHEP 06 (2021) 044

$D^+_{(s)} \rightarrow \pi\phi[\mu^+\mu^-]$



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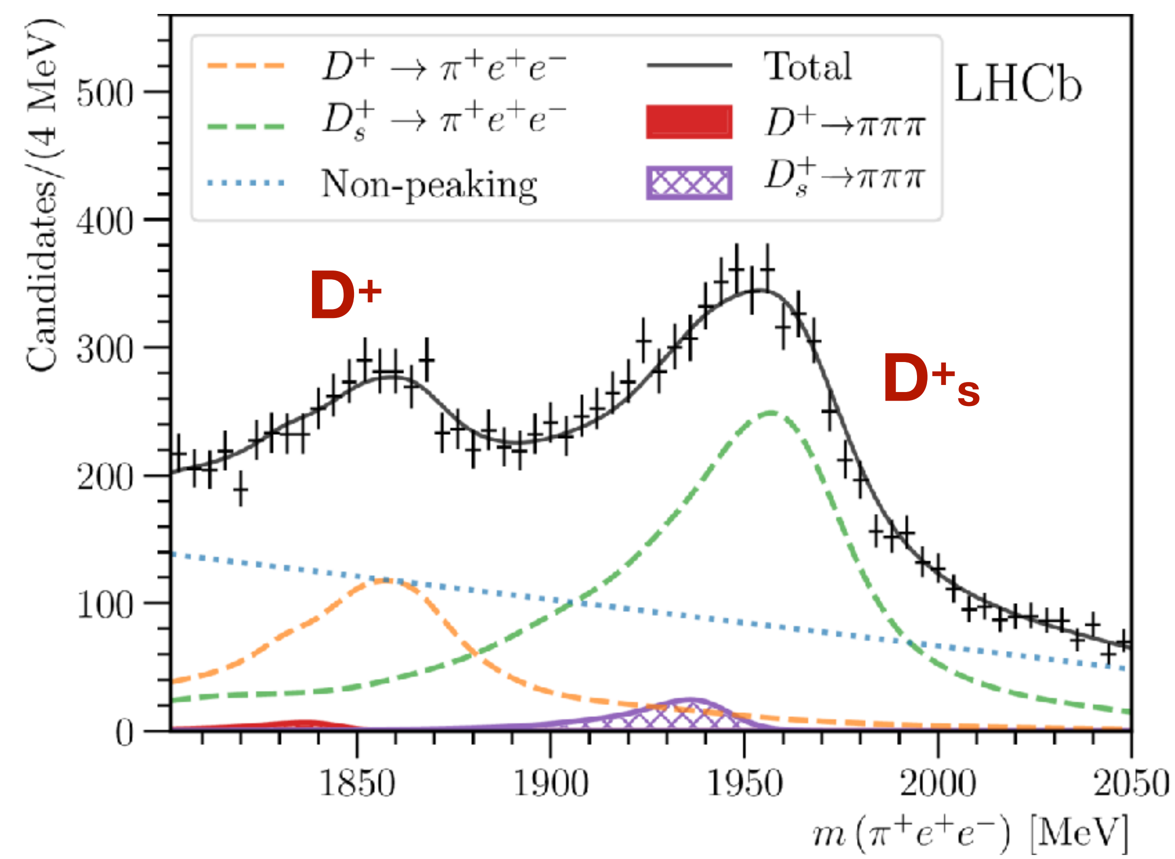

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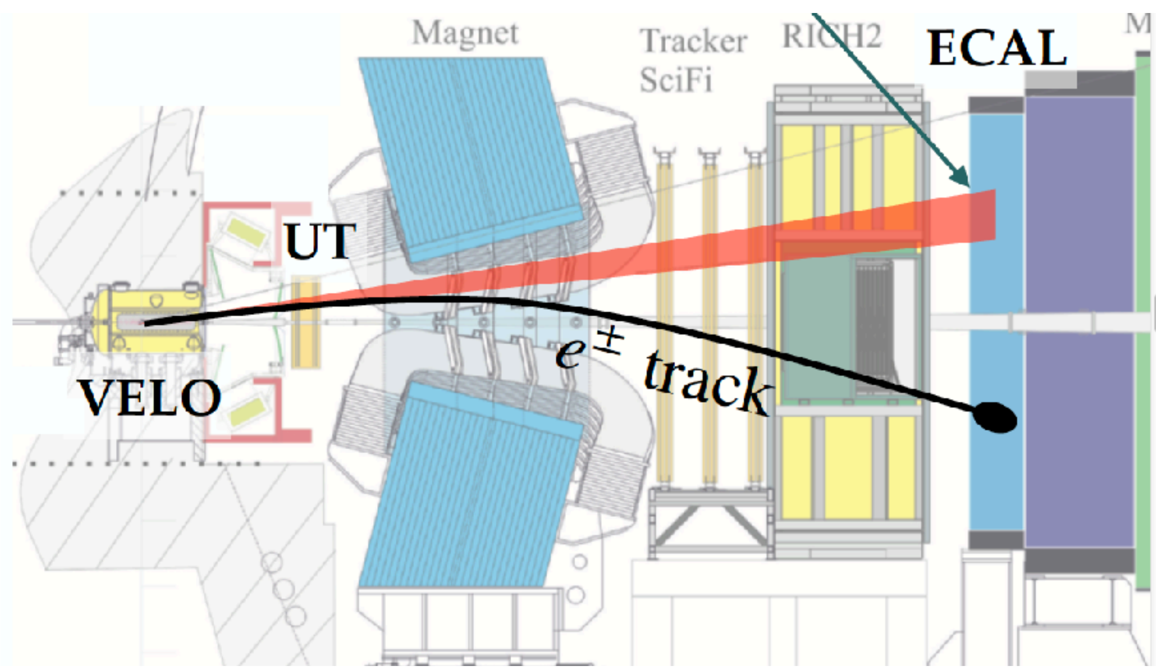
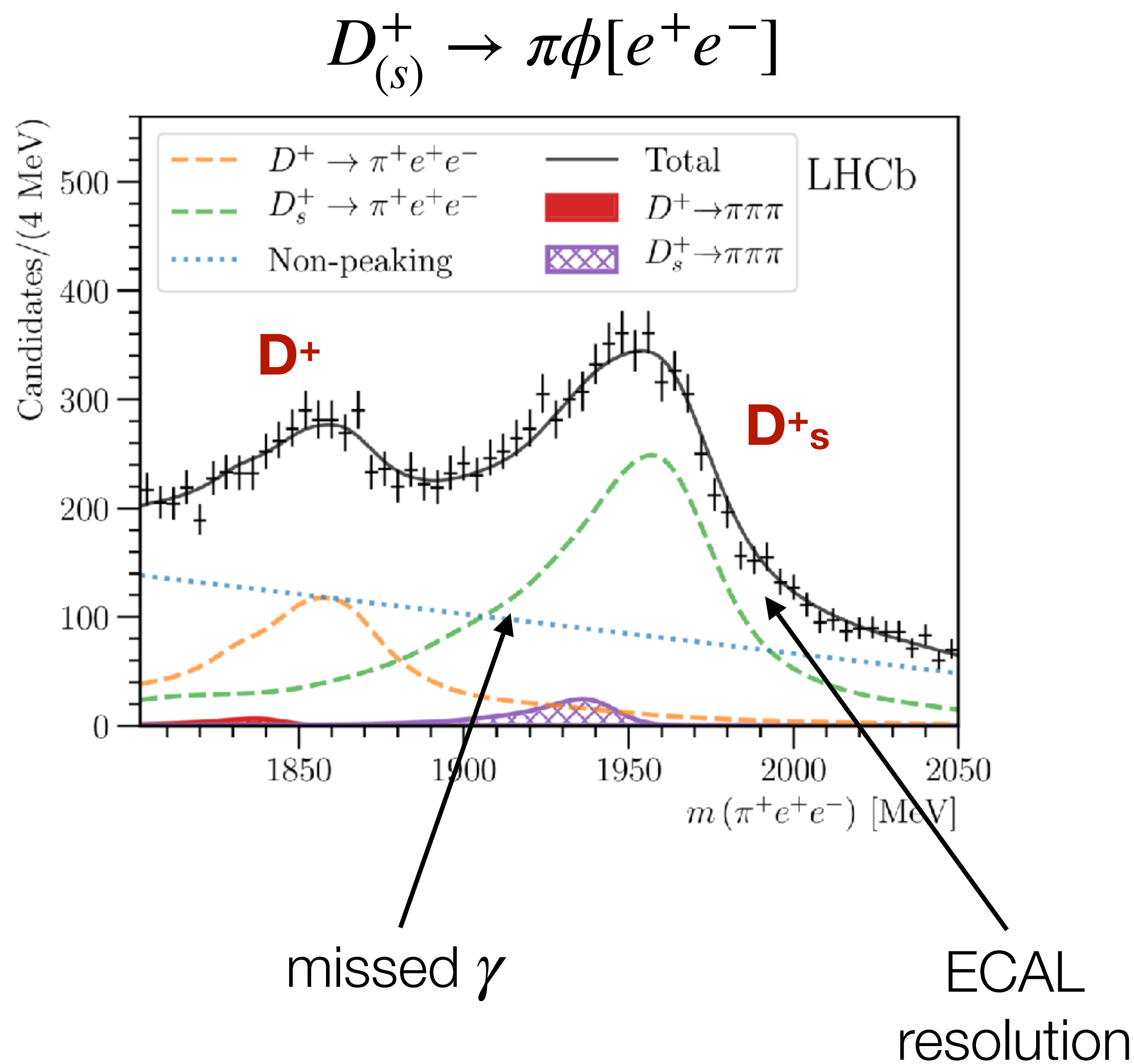
JHEP 06 (2021) 044



presented by Martino Borsato, Electron reconstruction at LHCb and Belle II, GDR-InF workshop - LPNHE 8-9 July 2019



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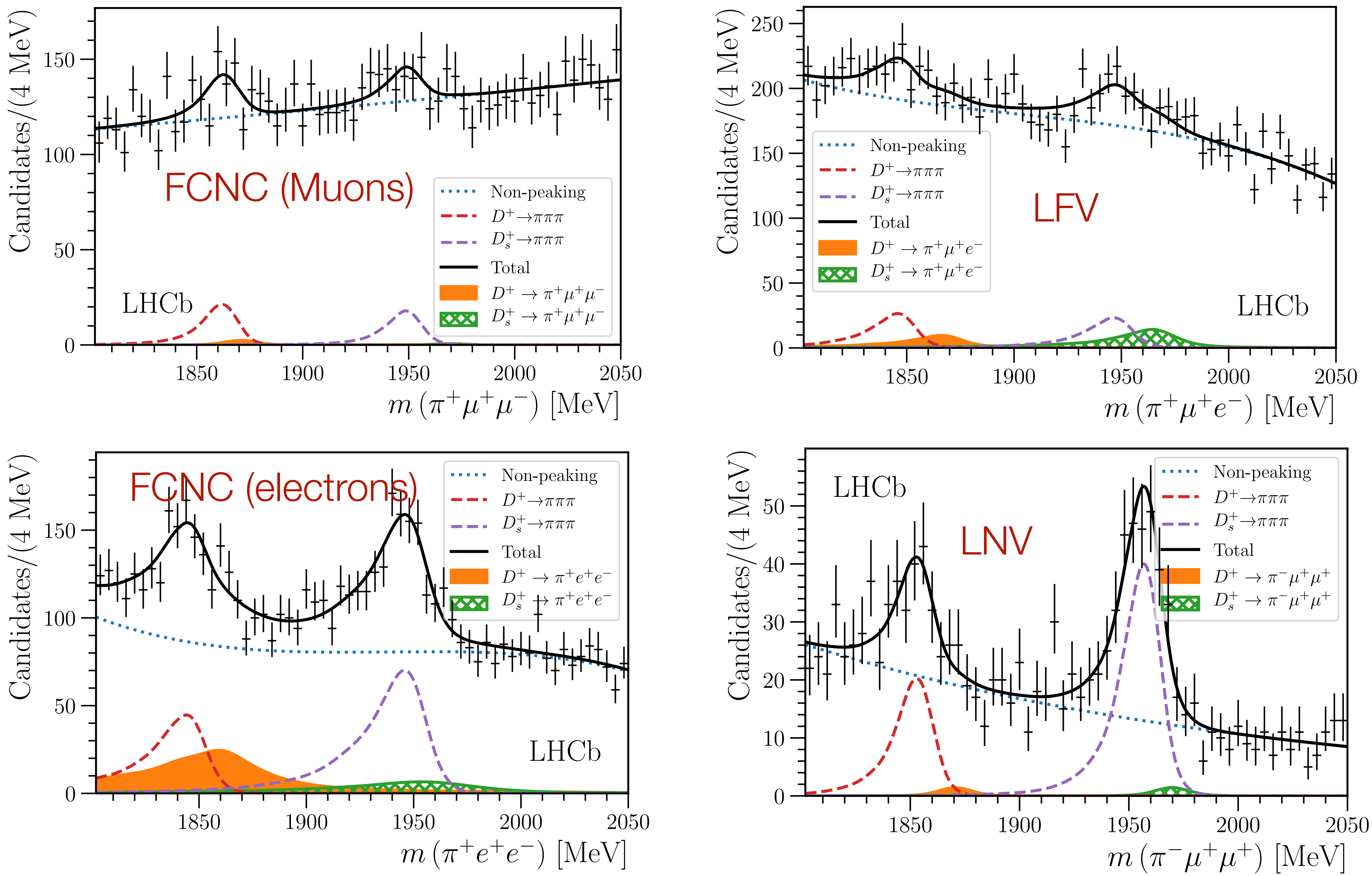
JHEP 06 (2021) 044



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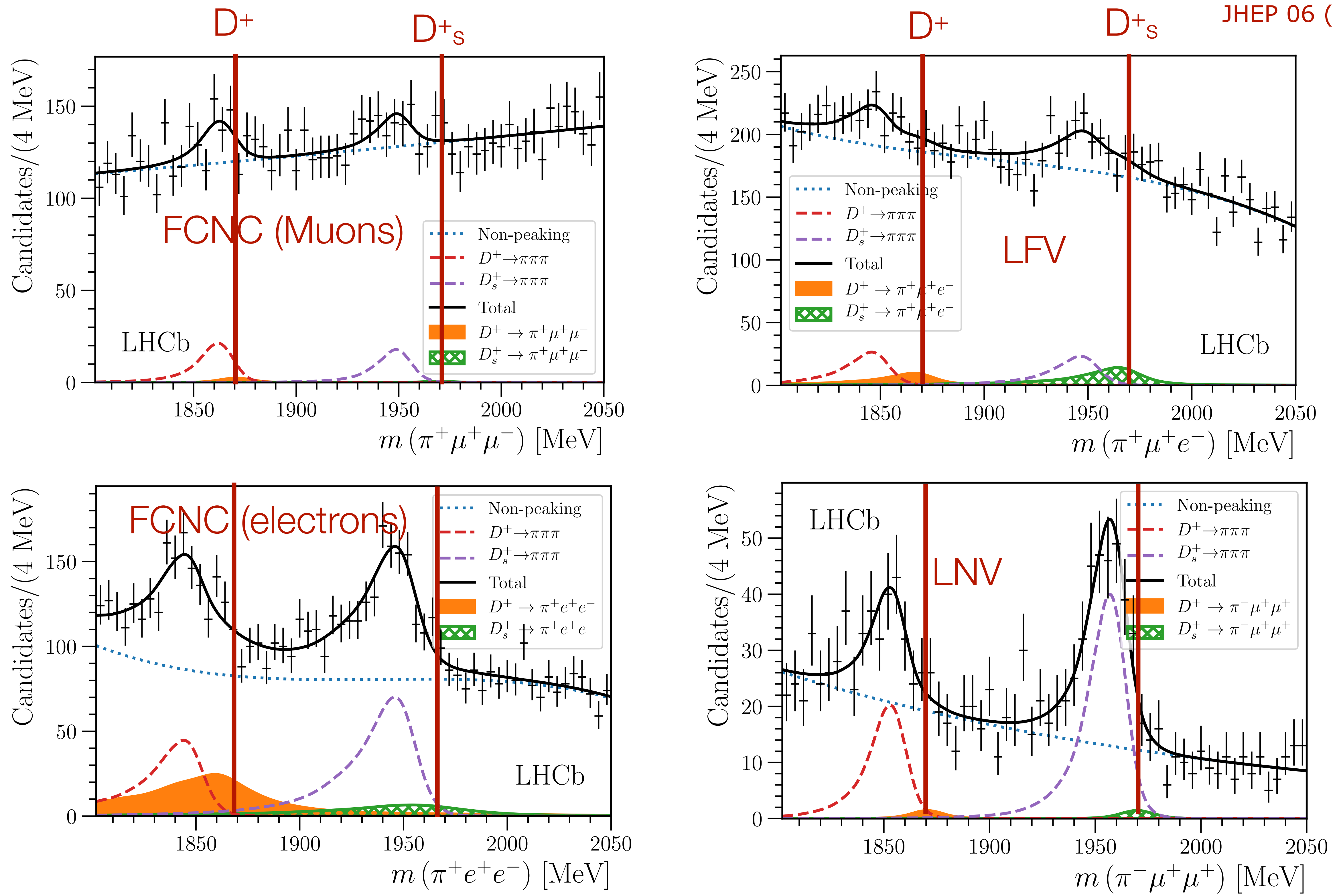

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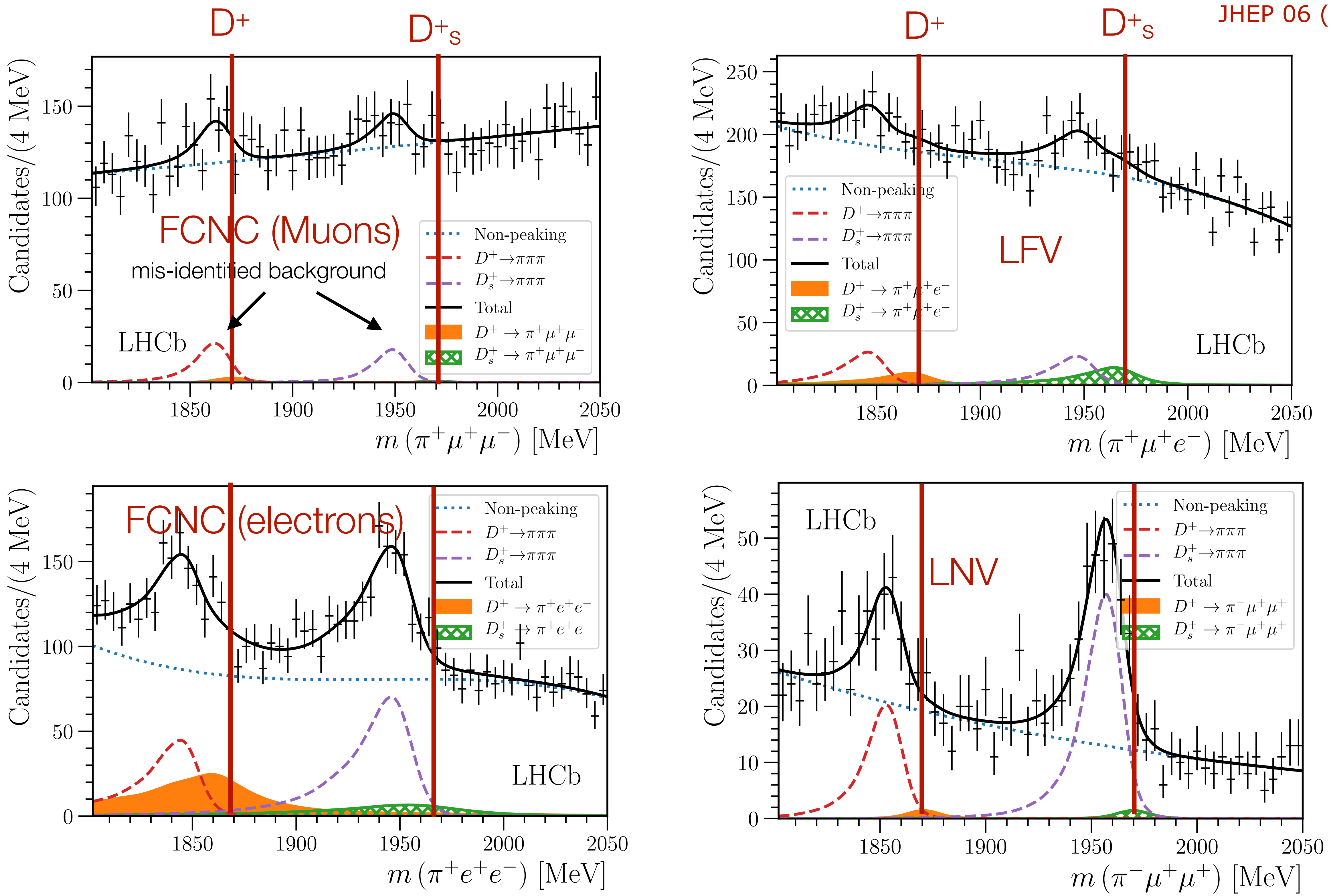
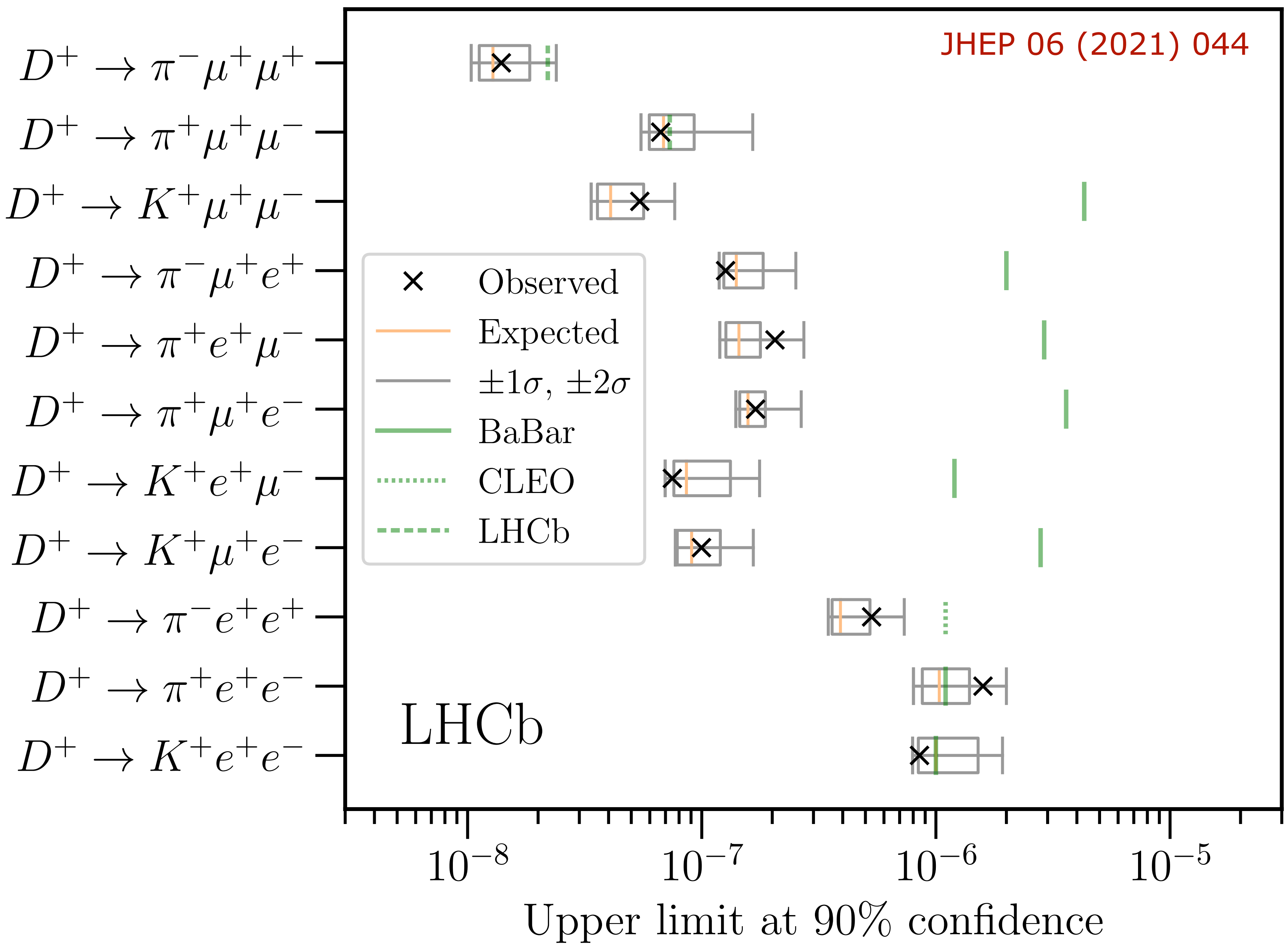


- All mass spectra well described by background only hypothesis

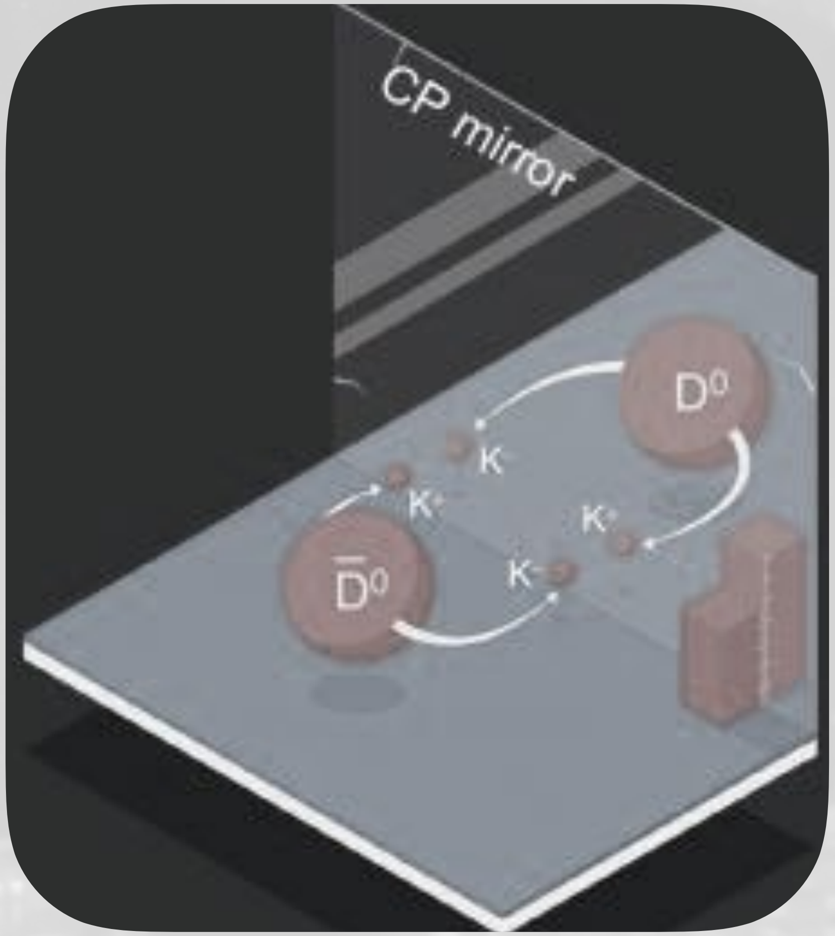
Search for the rare decays $D \rightarrow h l^{\pm} l^{(')\mp}$

- No significant signal found [1.6/fb (2016)]
- Improved limits by several orders of magnitude
- See JHEP 06 (2021) 044 for limit on D_s^+ modes

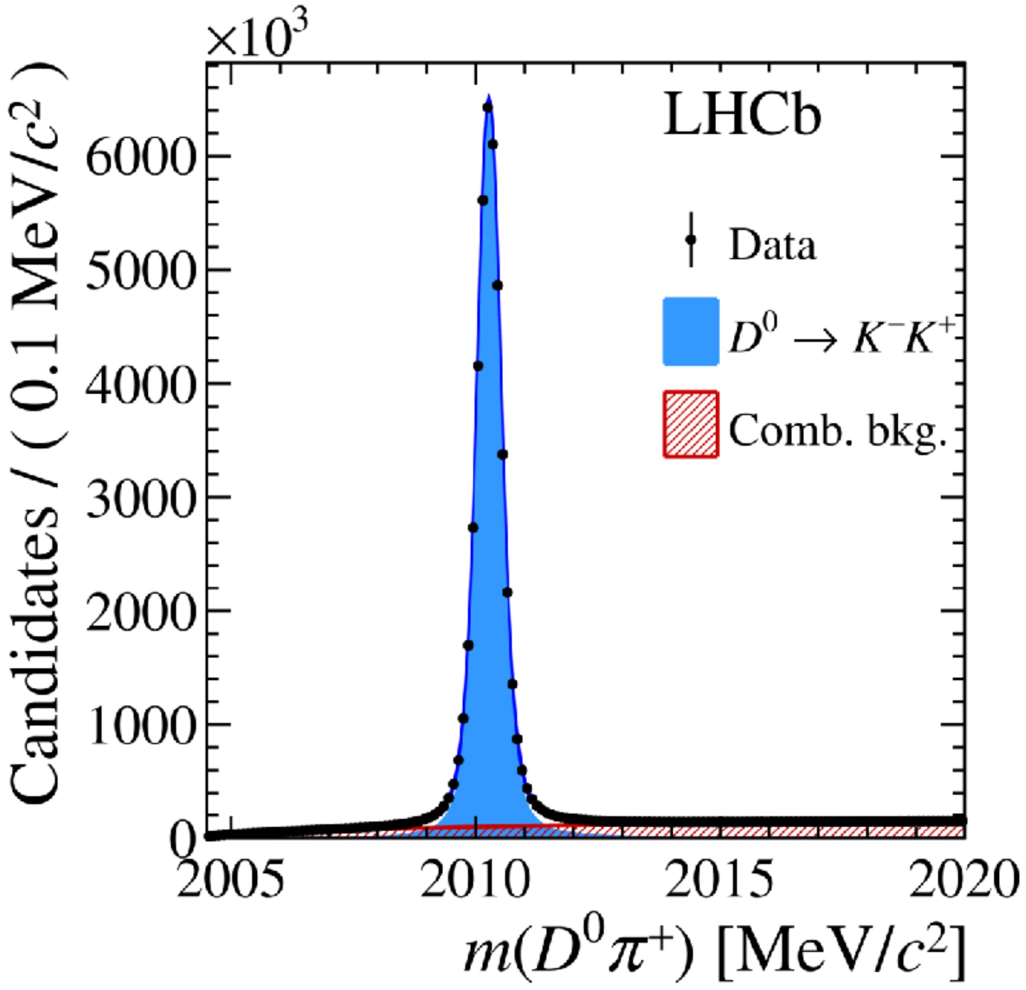
update with full Run2 data set in preparation



New Physics in CP asymmetries & angular distributions



NP searches in CP asymmetries



- Observation of CPV $[\Delta A_{CP} = (15.4 \pm 2.9) \times 10^{-4}]$ in charm leaves room for NP

PRL 122 (2019) 211803

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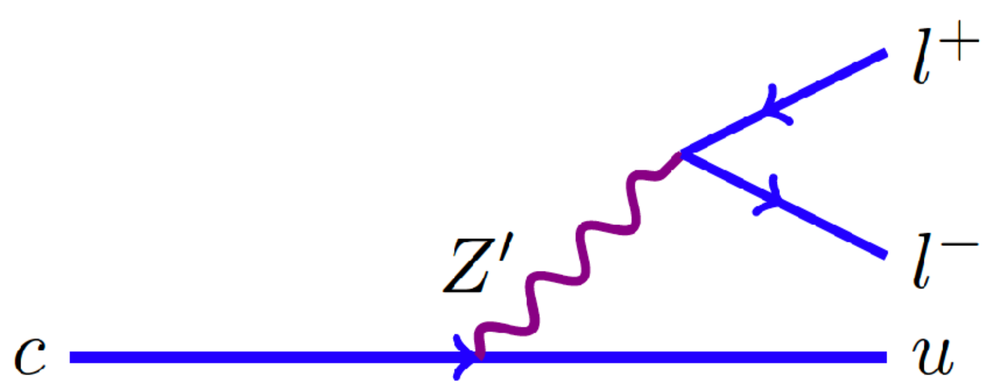

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PRD 101 (2020) 115006

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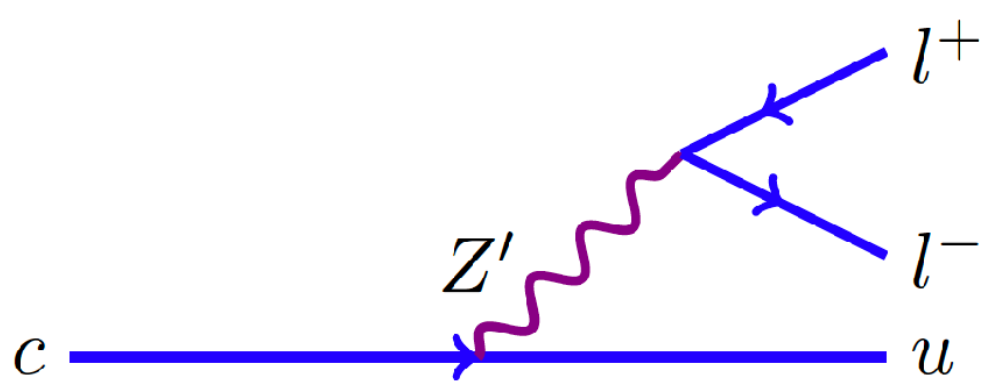

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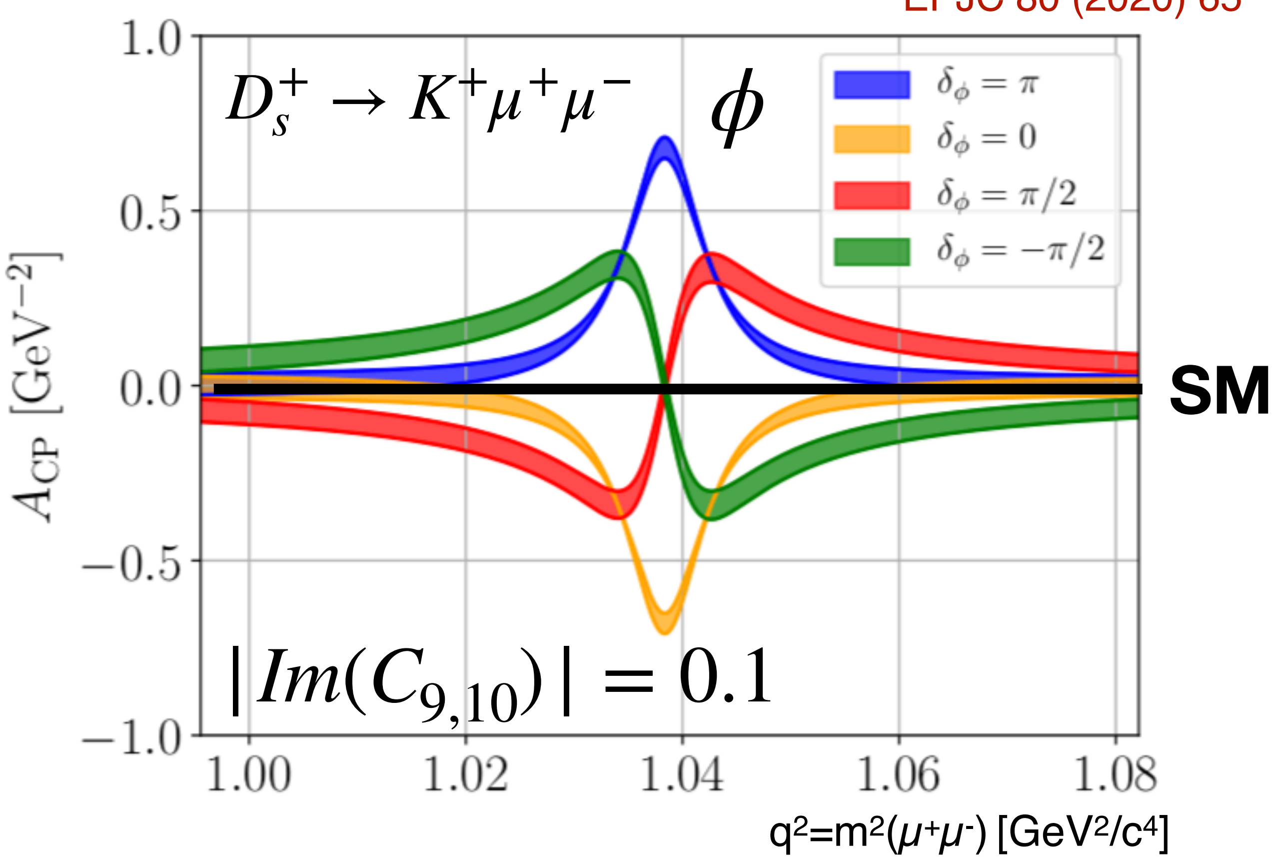
EPJC 80 (2020) 65



- Enhancement in vicinity of resonances, we profit from them

"resonance enhanced"

$$\cong A_{CP}^{NP} \approx \mathcal{O}(\%)$$

remember: $A_{CP}^{SM} \approx 0$

NP searches in angular distributions

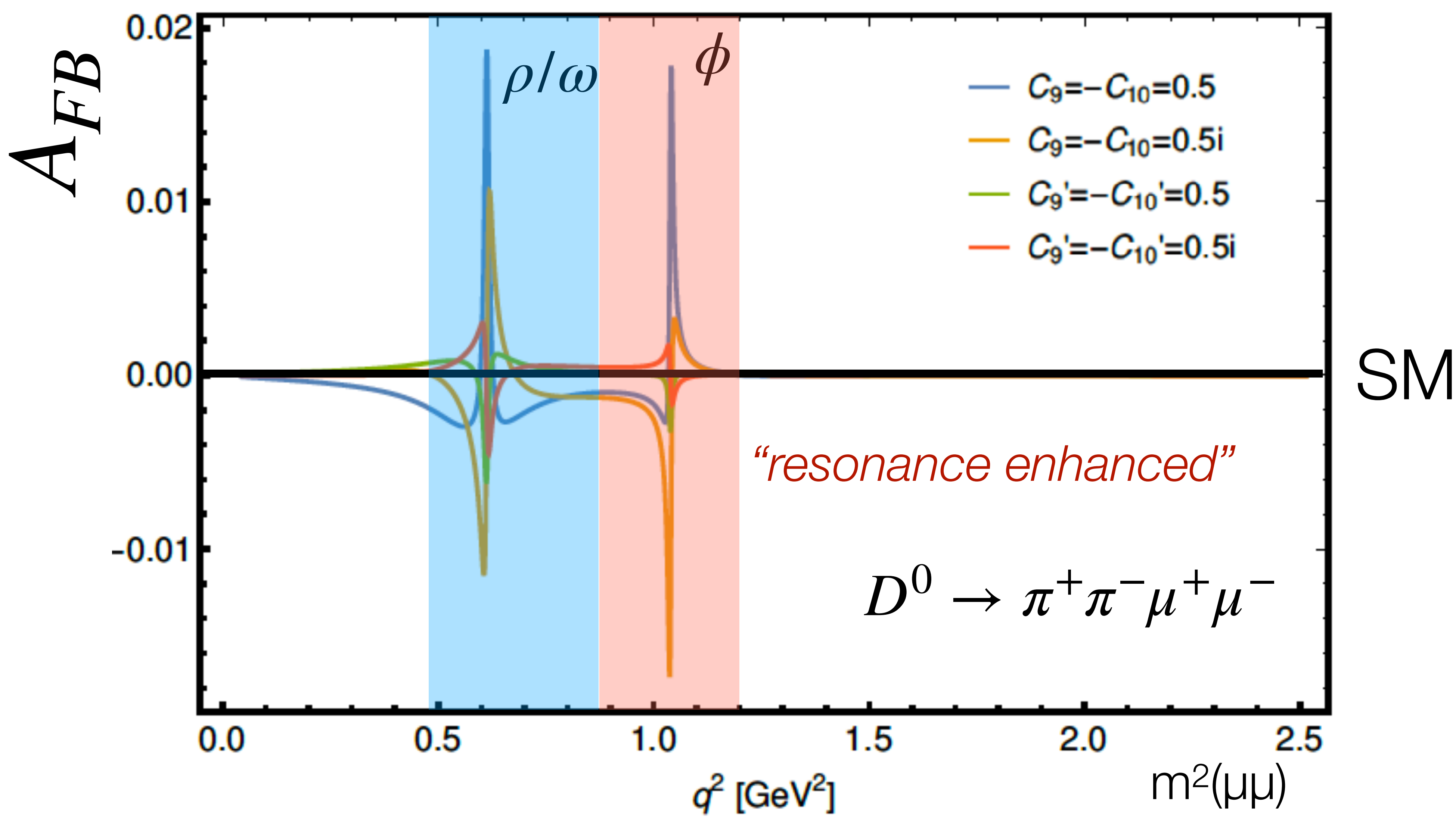
- Absence of axial vector couplings (pure vector current!) in lepton system is distinctive feature

NP searches in angular distributions

- Absence of axial vector couplings (pure vector current!) in lepton system is distinctive feature
  - New particles with (pseudo)scalar, tensorial or axial vector couplings lead to modifications, independent of hadronic uncertainties which allow for clear null tests

!

PRD 98 (2018) 035041



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

NEW

LHCb-PAPER-2021-035
arXiv:2111.03327

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

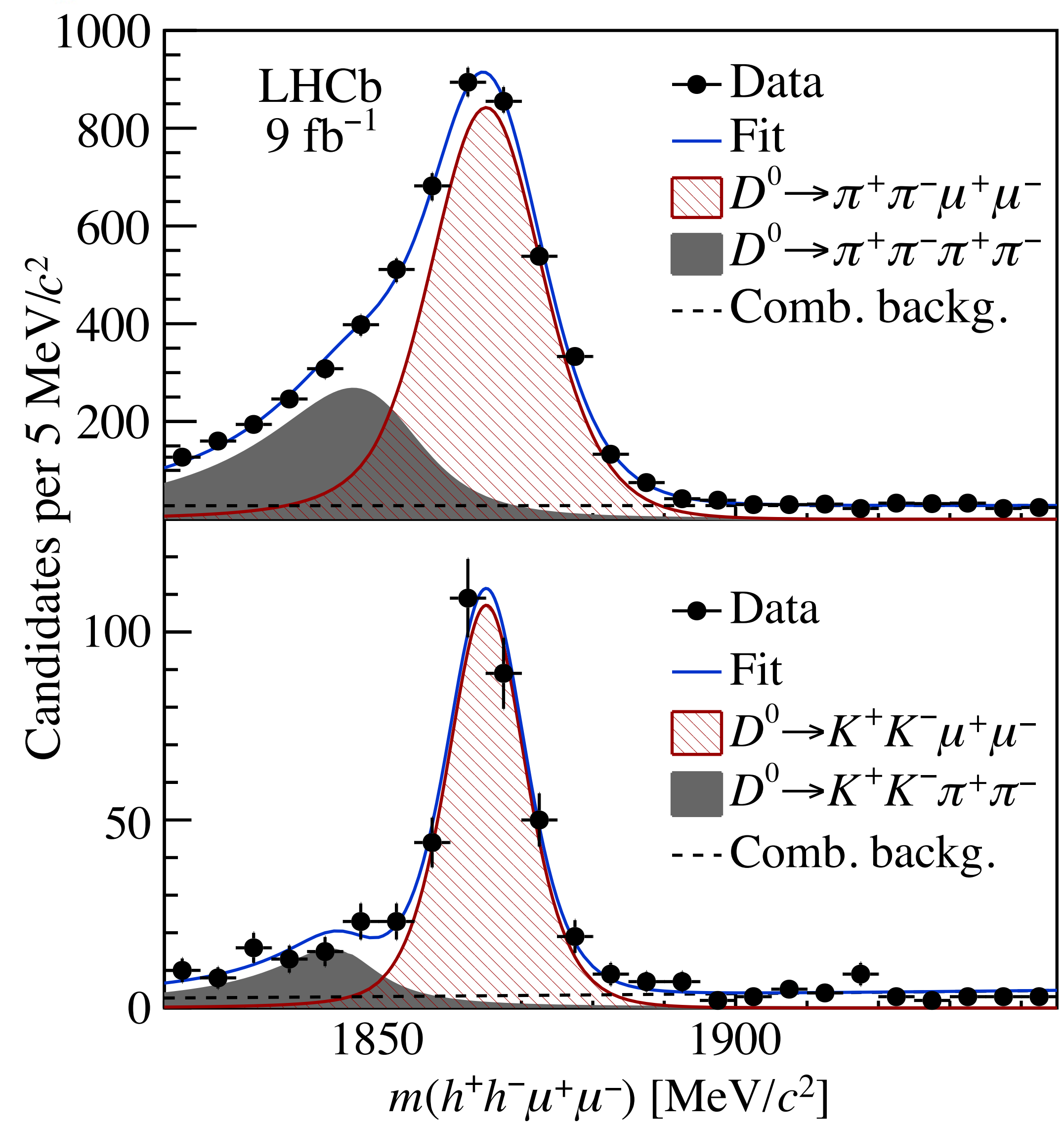
- measurement selected angular and CP asymmetries with 5/fb consistent with SM

PRL 121 (2018) 091801

- TODAY: First full angular analysis with 9/fb from 2011-2018 arXiv:2111.03327
  - select D^0 from flavour sepecific $D^{*+} \to D^0\pi^+$ decays

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

arXiv:2111.03327



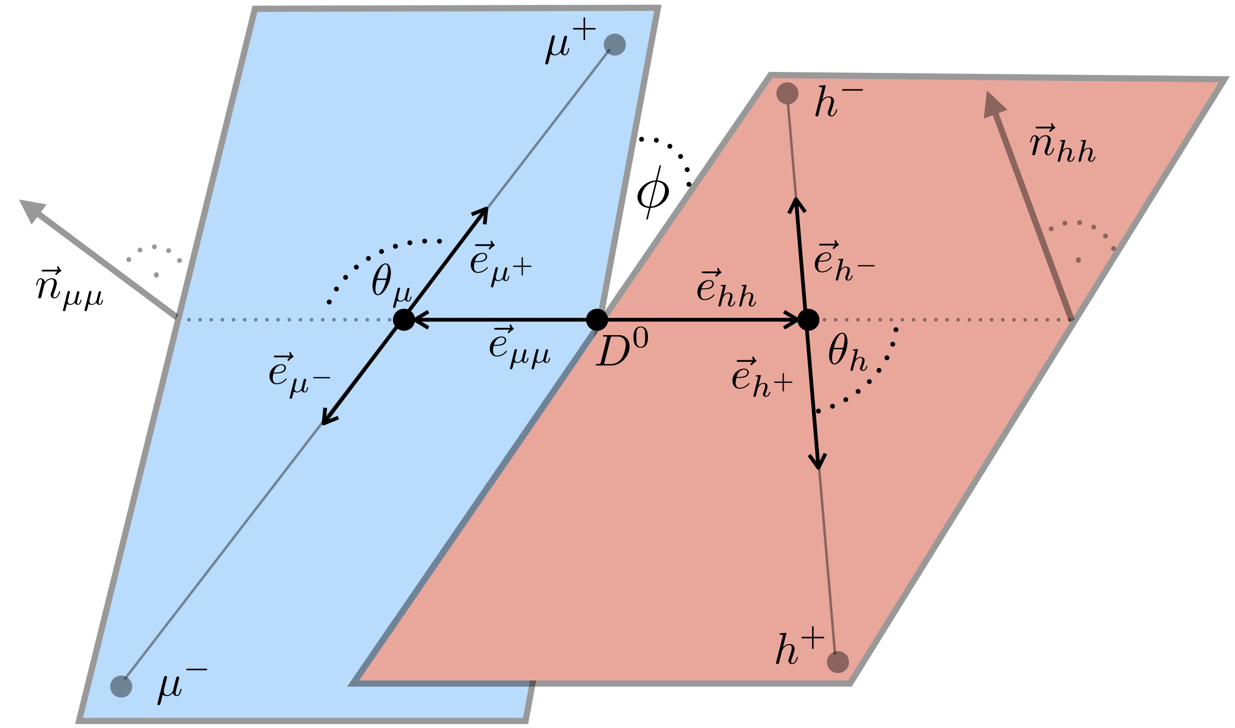
Differential decay rate

arXiv:2111.03327

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

I_5, I_6, I_7 clean null tests!

$[I_6 = A_{FB}]$



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

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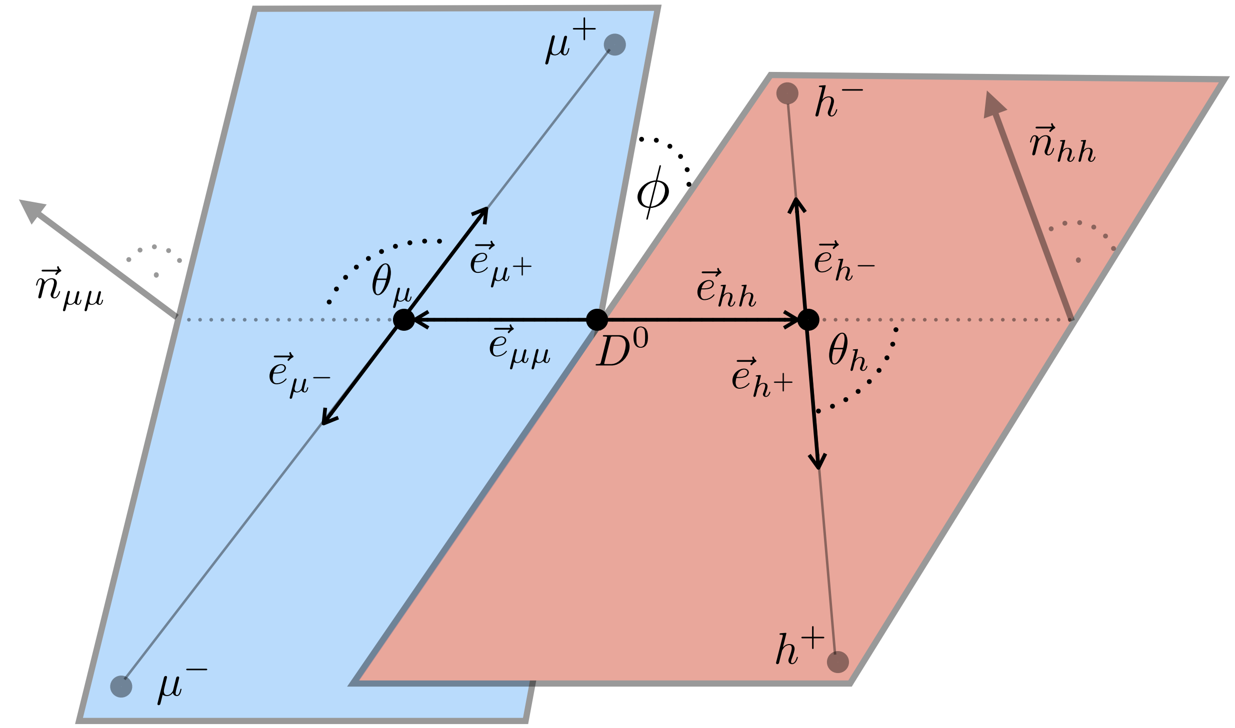

$p^2 = m^2(h^+h^-)$
$q^2 = m^2(\mu^+\mu^-)$

- 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

arXiv:2111.03327

- 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}

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

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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

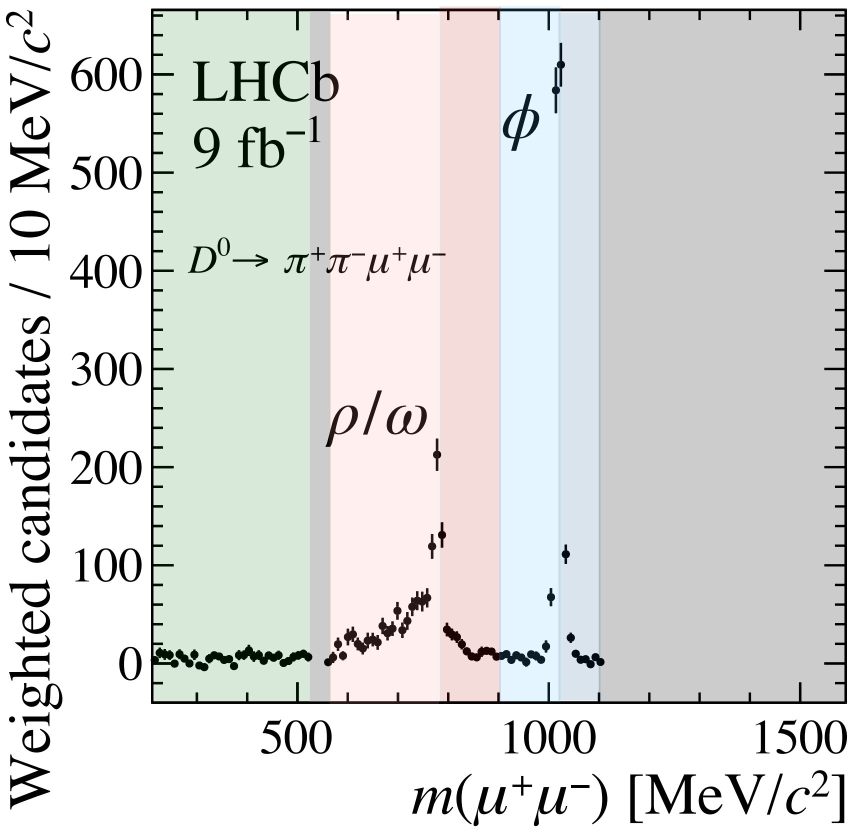
- updated measurement of A_{CP}

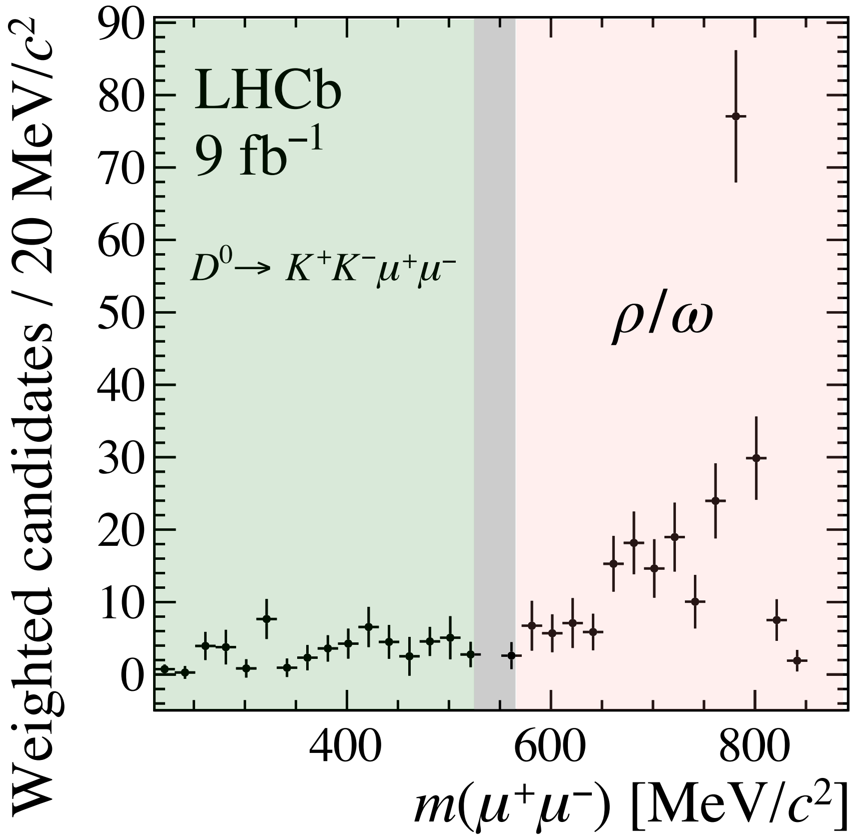
$$A_{CP} = \frac{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) - \Gamma(\overline{D}^0 \to h^+h^-\mu^+\mu^-)}{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) + \Gamma(\overline{D}^0 \to h^+h^-\mu^+\mu^-)}$$

- 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

arXiv:2111.03327

- measure angular observables via yield asymmetries, eg:

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

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

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

Experimental strategy

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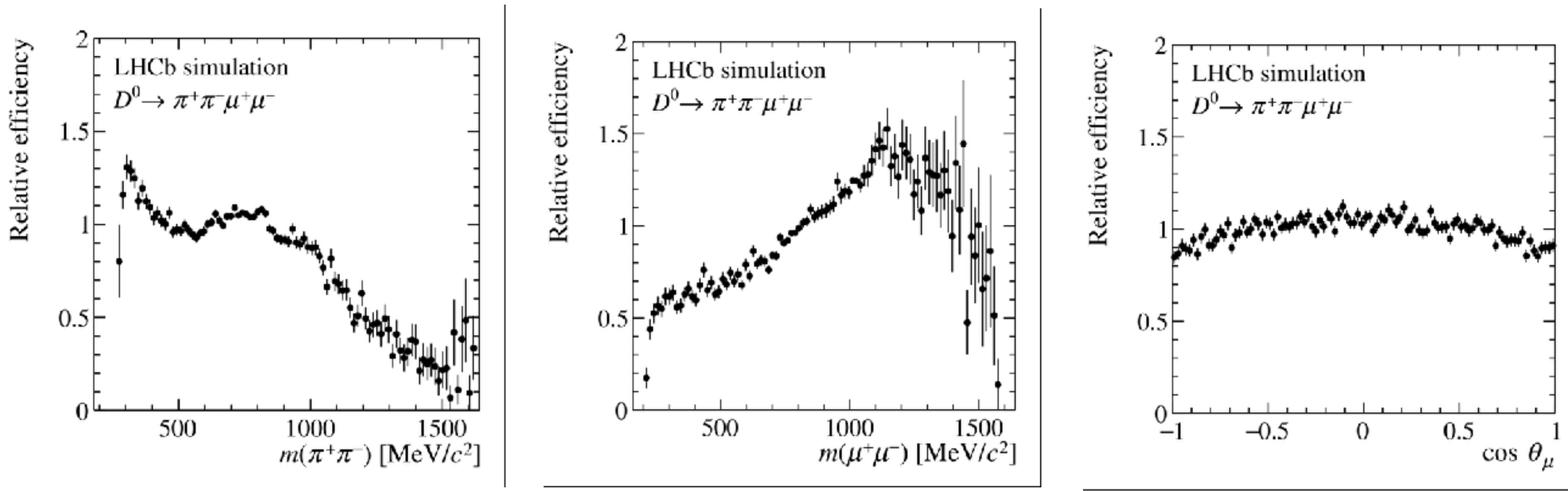
- correct for acceptance effects across the 5D phase space



PRL 121 (2018) 091801

…

Multivariate Analysis

Experimental strategy

arXiv:2111.03327

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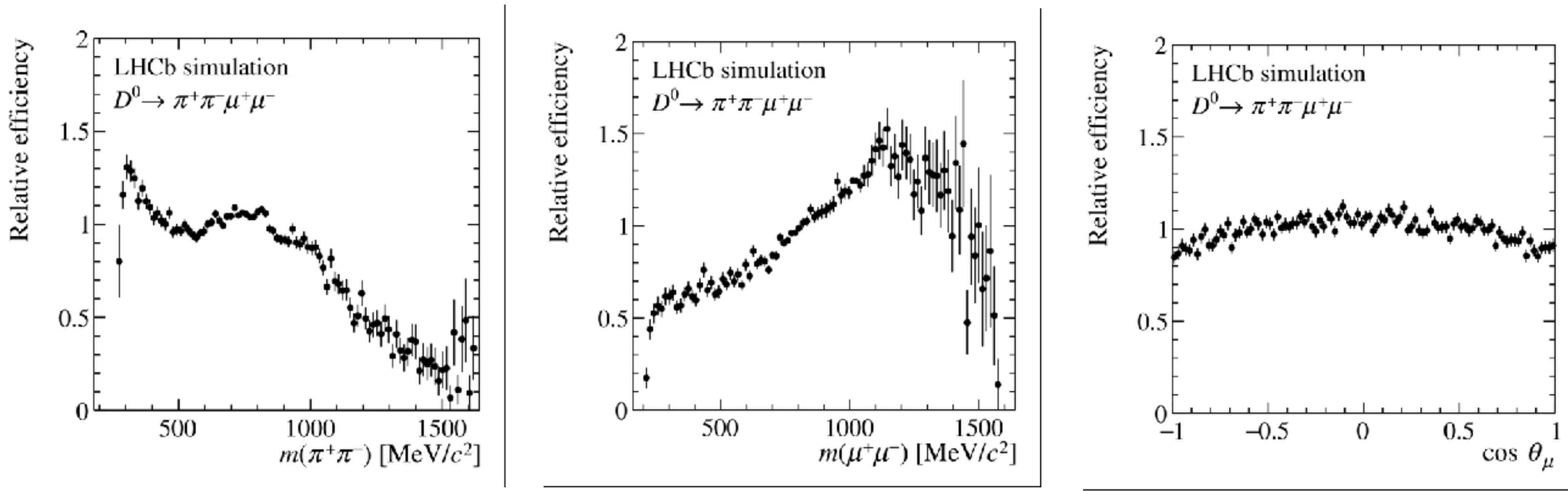

PRL 121 (2018) 091801

... → Multivariate Analysis

- 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]

Experimental strategy

arXiv:2111.03327

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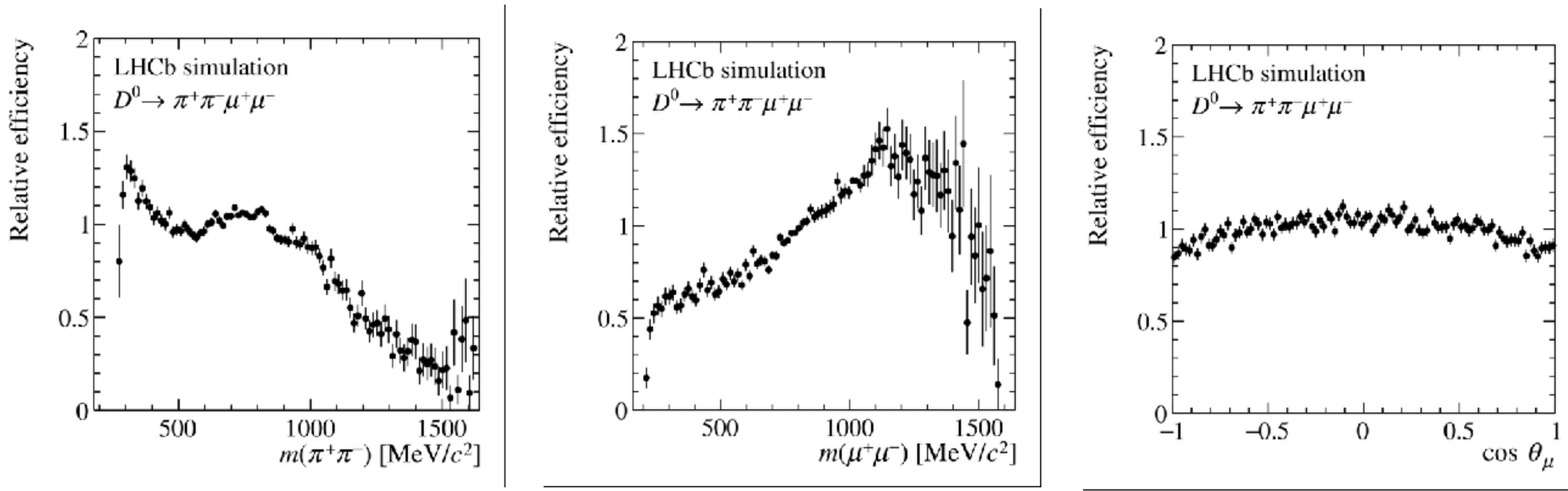

PRL 121 (2018) 091801

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

- evaluate systematic uncertainties

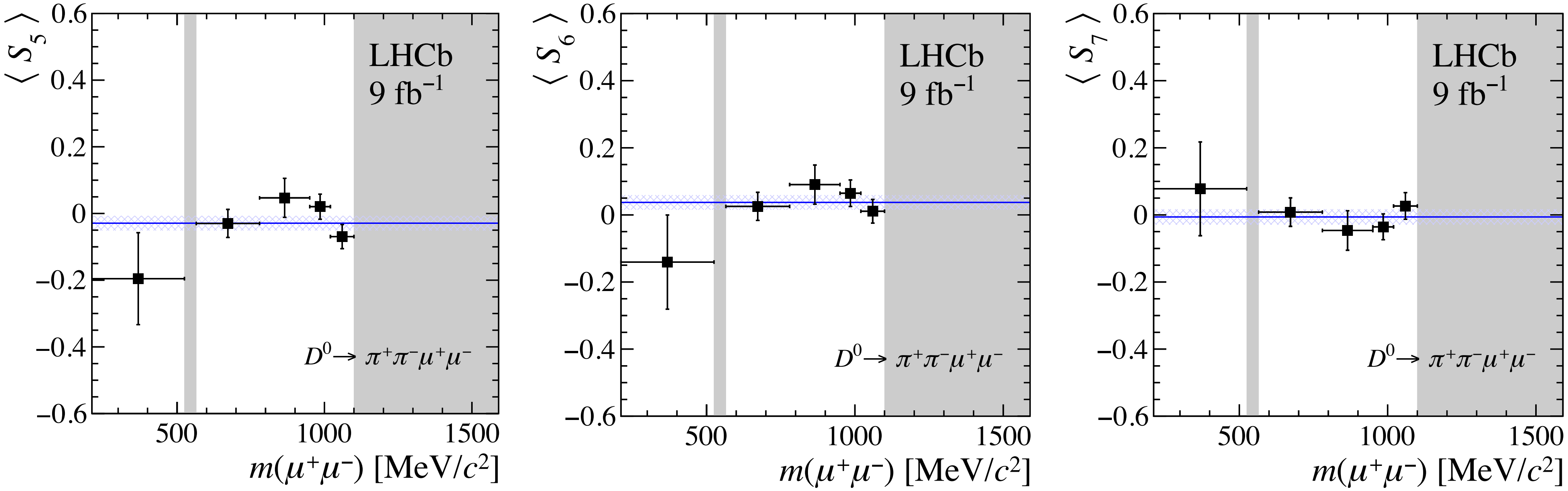
typically $\frac{\sigma_{sys}}{\sigma_{stat}} \sim (10 - 50)\,\%$

limited by statistics!

Flavour-averaged observables $\langle S_i \rangle$

arXiv:2111.03327

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



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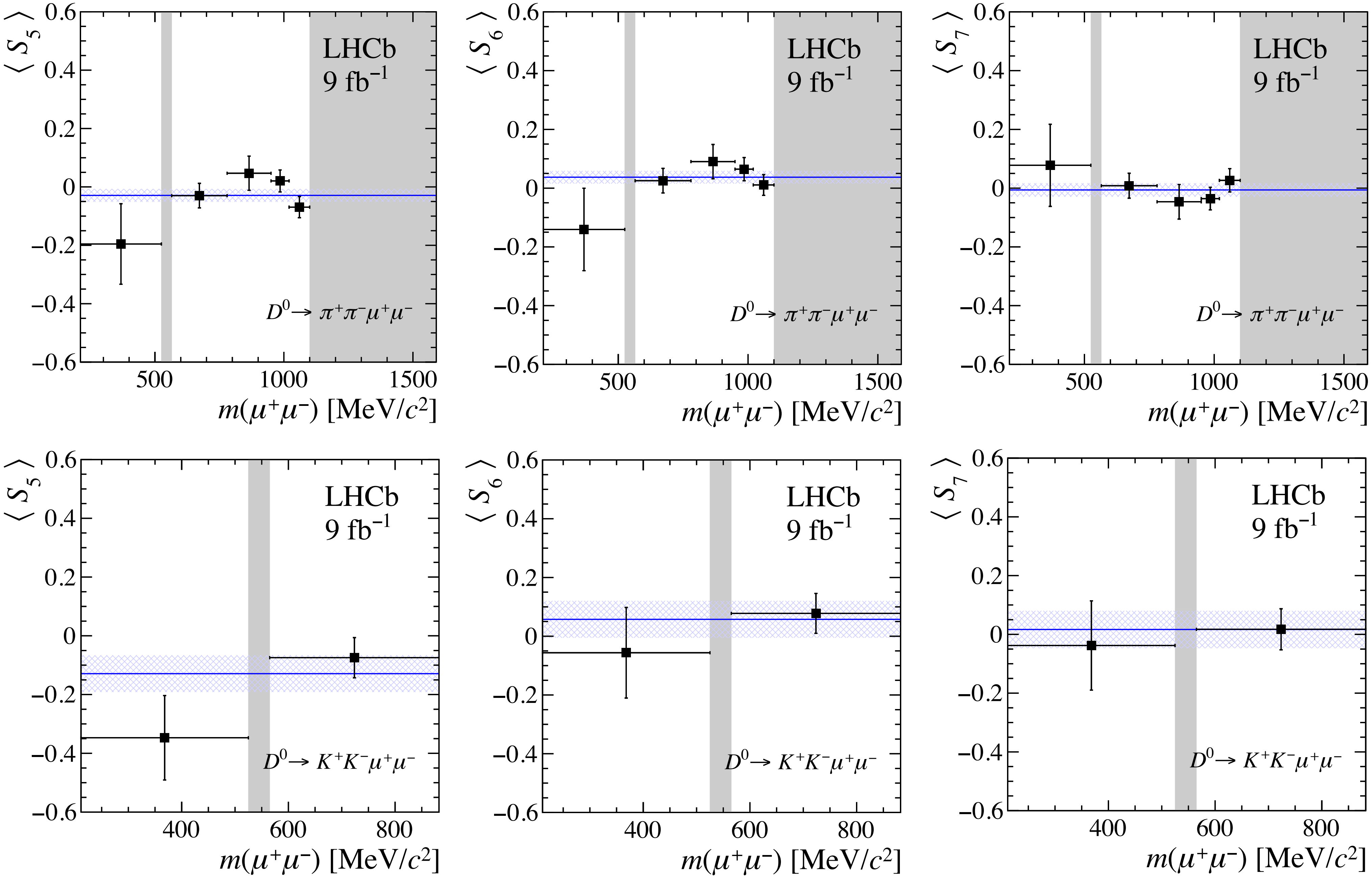

- all observables in appendix, tabulated version & correlation matrices in LHCb-PAPER-2021-035

CP asymmetries $\langle A_i \rangle$

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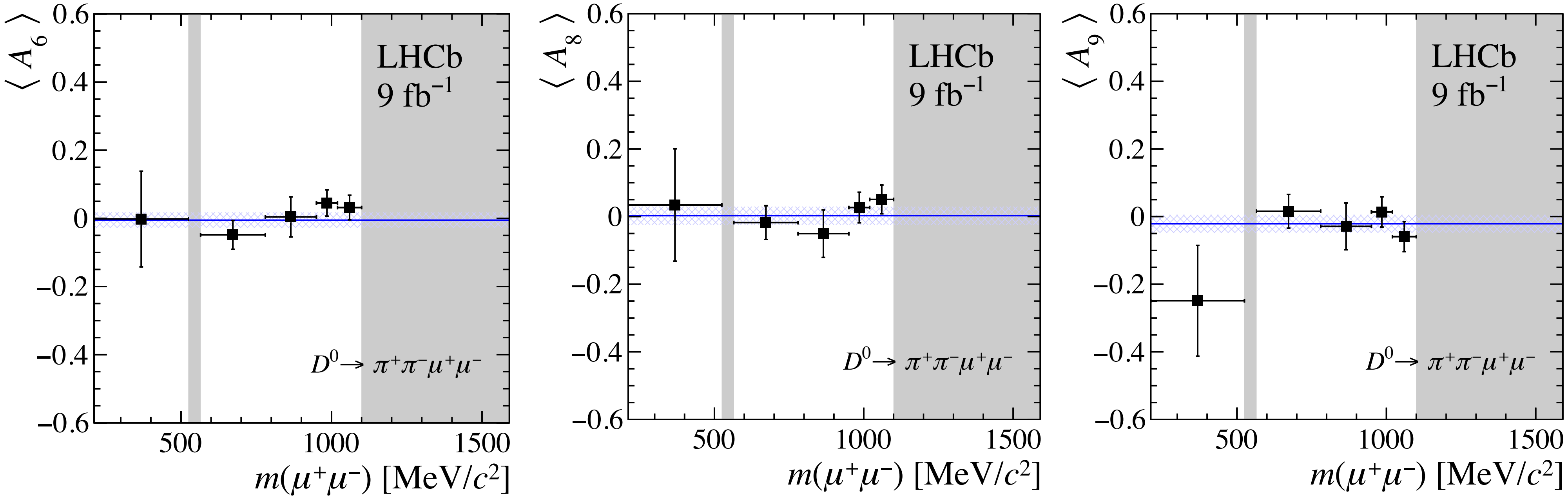
- Shown: $\langle A_6 \rangle$ [$\langle A_6 \rangle \sim A_{FB}^{CP}$], $\langle A_{8,9} \rangle$ [triple-product-asym.]



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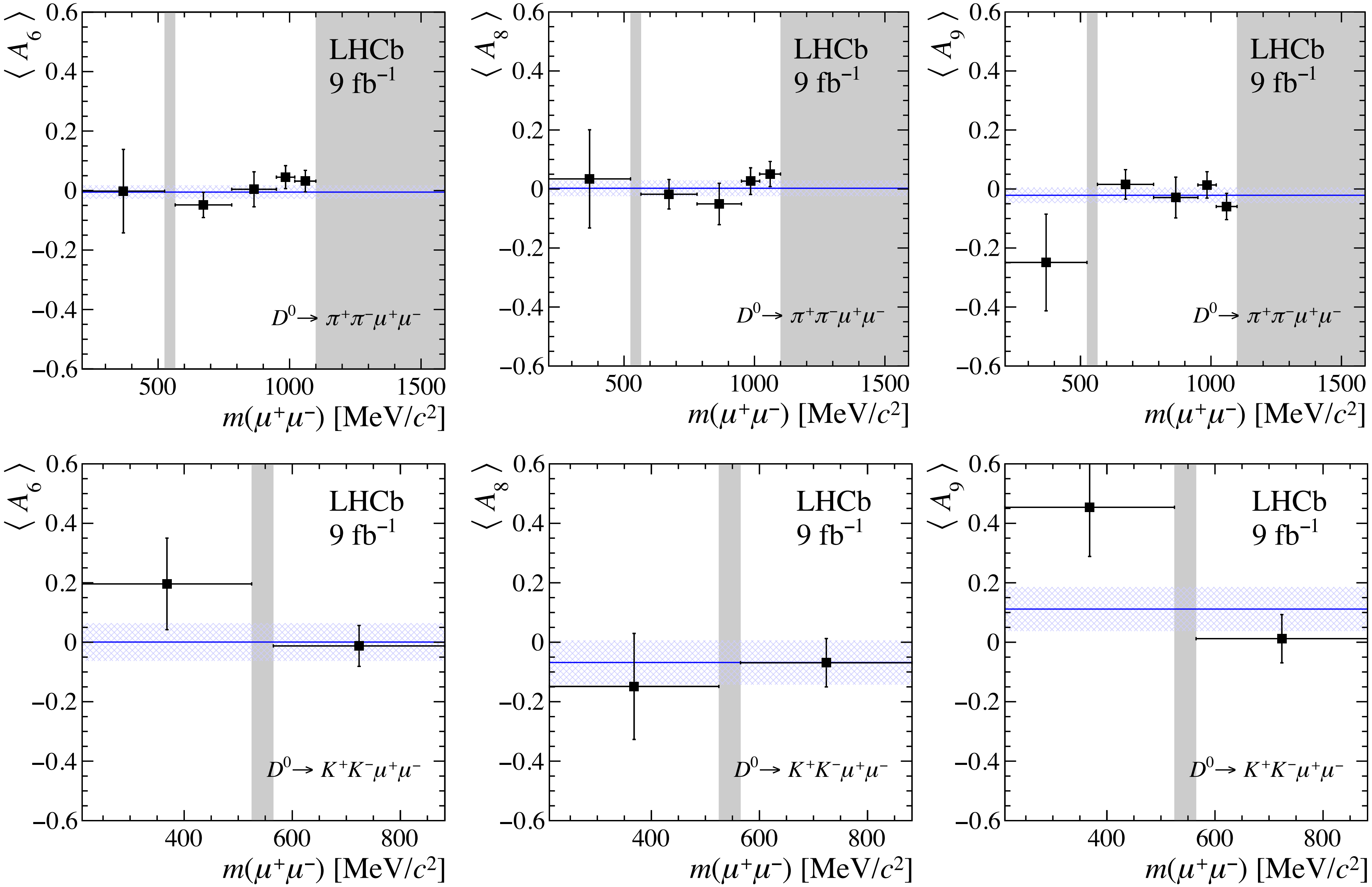

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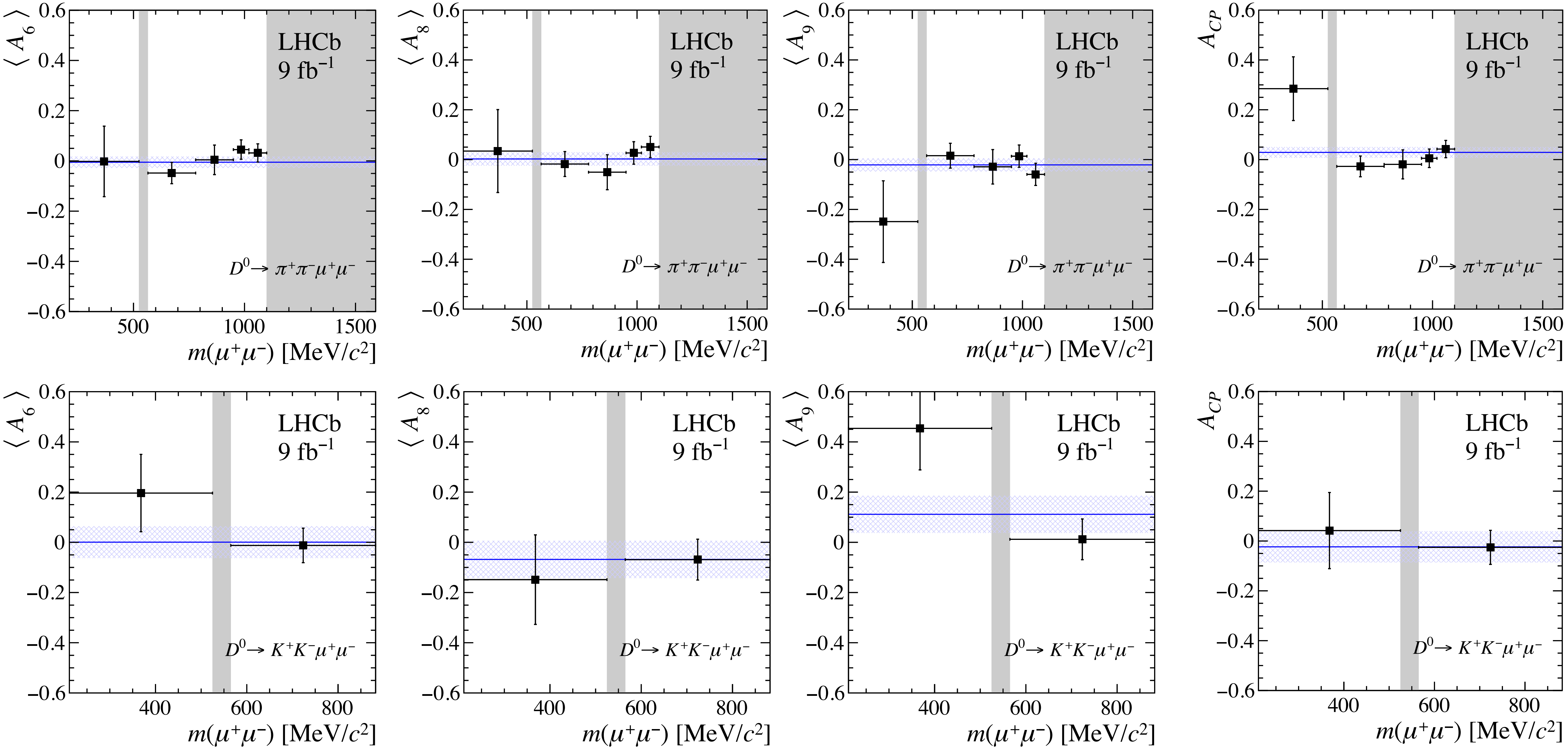

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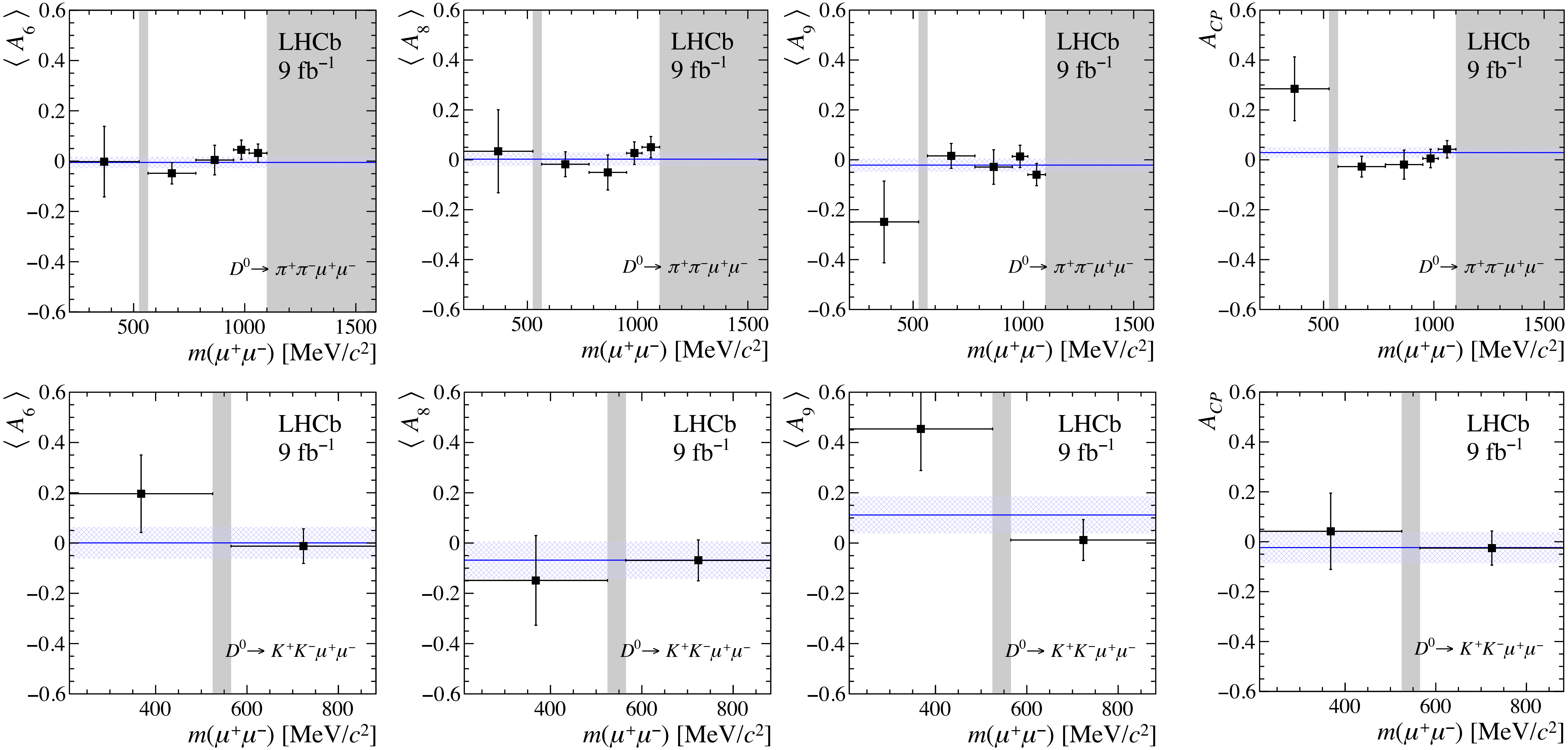

- overall agreement wrt. to SM hypothesis considering A_{CP}, $\langle A_{2-9} \rangle$ & $\langle S_{5,6,7} \rangle$:

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

consistent with SM

Further opportunities & Future prospect

Lepton Universality

- Ratio of BF muon vs electron decay modes [smoking gun in B-physics!]

$$R^D_{P_1 P_2} = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} d\mathcal{B}/dq^2(D \to P_1 P_2 \mu^+ \mu^-)}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} d\mathcal{B}/dq^2(D \to P_1 P_2 e^+ e^-)}$$

* in equal q^2 range

hadronic uncertainties cancel,
clean null test!

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- Also in charm significant deviation from unity possible
  - mainly in non-resonant regions (far future LHCb upgrade II)
  - ~O(15%) q^2 integrated (near future!)

full q^2	SM	BSM	LQ	hi q^2 SM	LQs	lo q^2 SM	BSM
$R^D_{\pi\pi}$	$1.00 \pm \mathcal{O}(\%)$	0.85 ...0.99	SM-like	$1.00 \pm \mathcal{O}(\%)$	0.7 ...4.4		
R^D_{KK}	$1.00 \pm \mathcal{O}(\%)$	SM-like	SM-like	NA	NA	$0.83 \pm \mathcal{O}(\%)$	0.60..0.87

G. Hiller , Angular distributions of rare D decays, Implications LHCb, CERN, October 17, 2018

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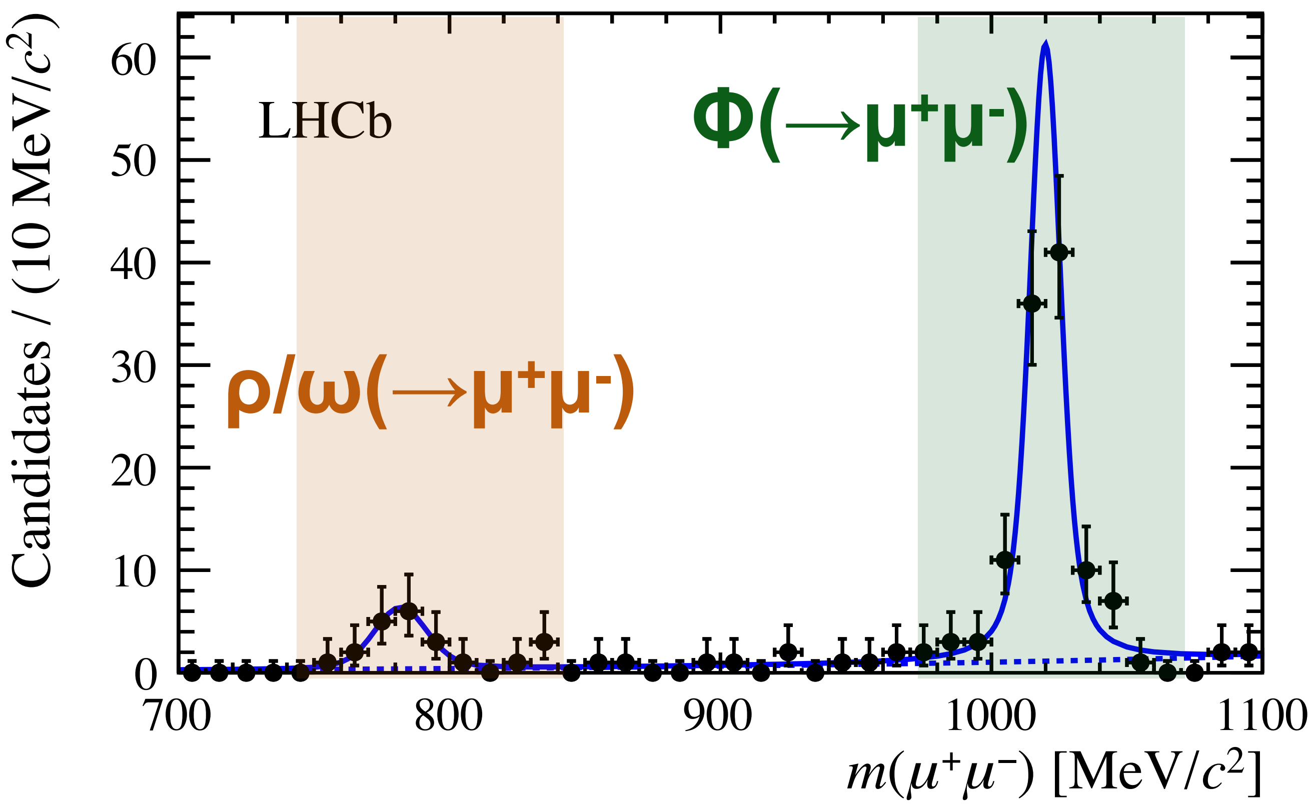
branching ratio	$D^0 \to \pi^+\pi^-\mu^+\mu^-$	$D^0 \to K^+K^-\mu^+\mu^-$	$D^0 \to \pi^+\pi^-e^+e^-$	$D^0 \to K^+K^-e^+e^-$
LHCb 17	$(9.64 \pm 1.20) \times 10^{-7}$	$(1.54 \pm 0.33) \times 10^{-7}$	–	–
BESIII 18	–	–	$< 0.7 \times 10^{-5}$	$< 1.1 \times 10^{-5}$

LHCb and Belle II should be able to do much better!
[And observe some of the channels very soon]

Charm baryon decays



- first measurement of rare decays of charmed baryons at LHCb (3/fb)

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

PRD 97 (2018) 091101

- total BF dominated by resonant LD contributions:
  - $\Lambda_c \rightarrow p\Phi(\rightarrow \mu^+\mu^-)$
  - $\Lambda_c \rightarrow p\rho/\omega(\rightarrow \mu^+\mu^-)$

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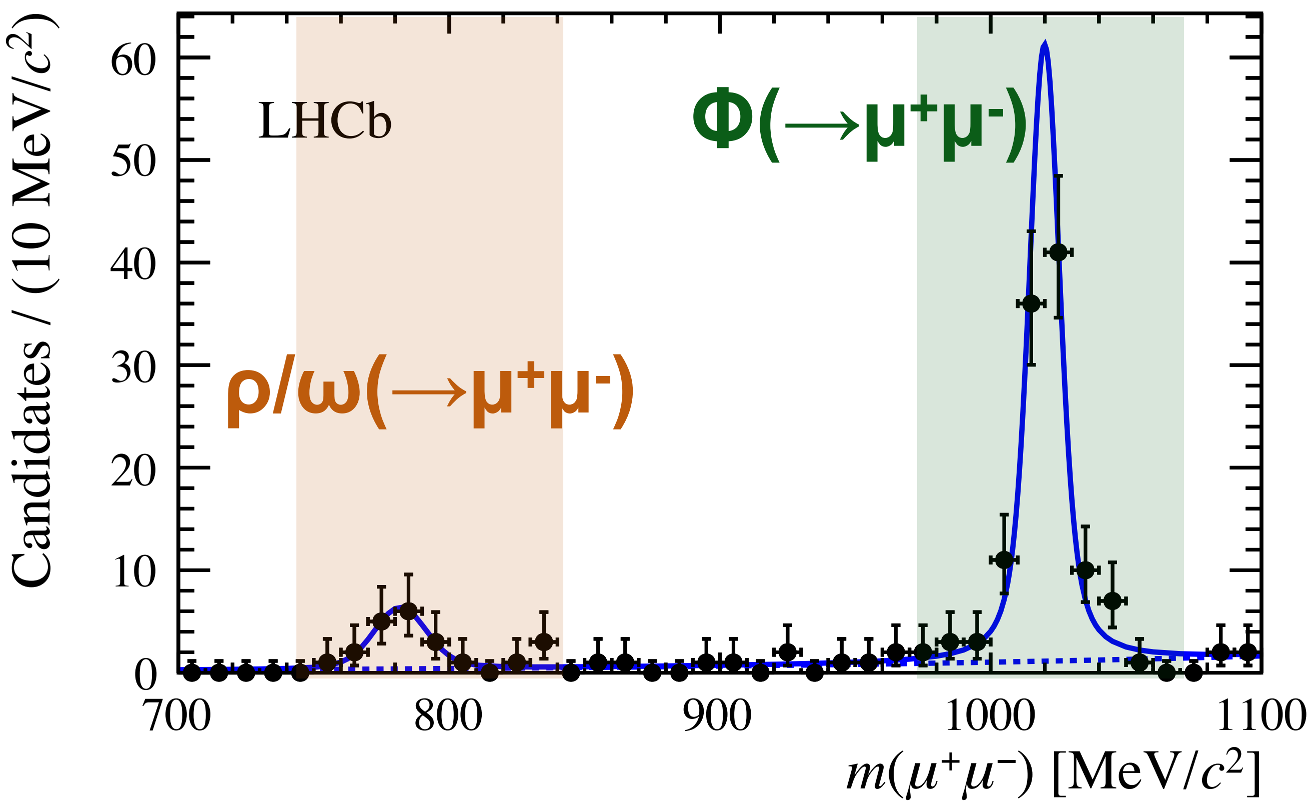

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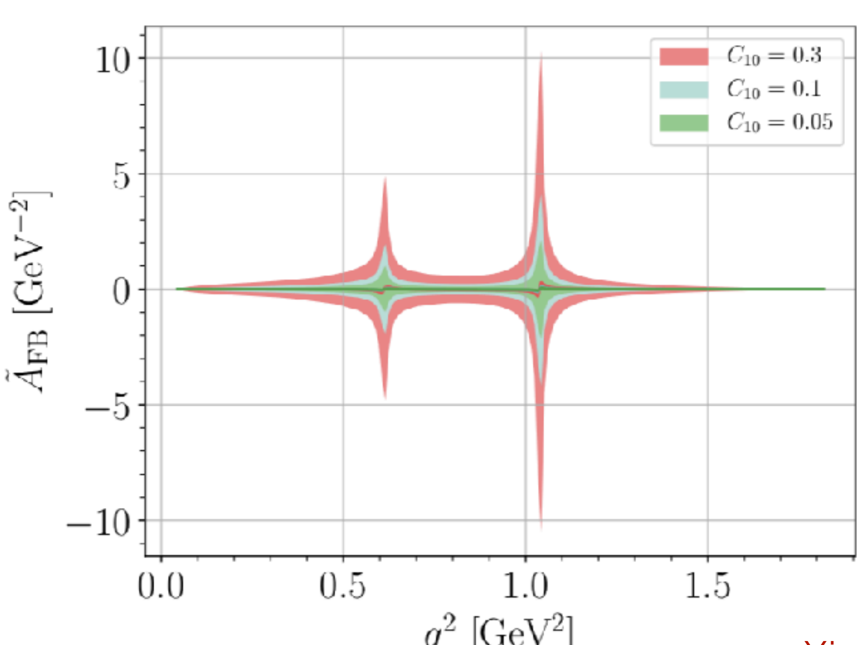

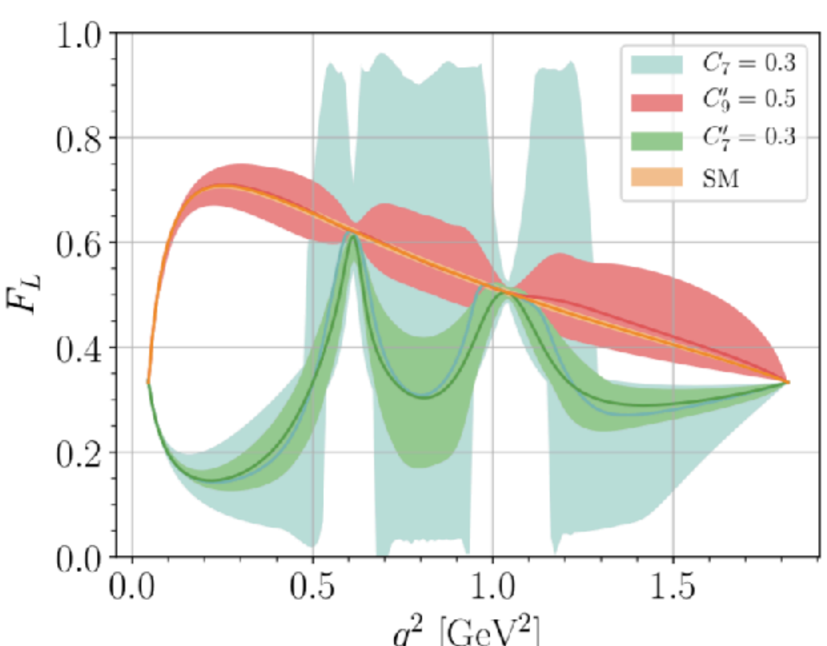

arXiv:2107.13010

Great opportunities to test SM!

Soon possible at LHCb
Precision tests in future!

Radiative charm decays

- Complementary information wrt. to SL decays
  - CP asymmetries in $D^0 \to V\gamma$ ($V = K^*, \phi, \rho$) in SM < 10^{-3} , ~$\mathcal{O}(10\%)$ in BSM
  - Belle: A_{CP} in $D^0 \to V\gamma$ compatible with zero at 2%-15% PRL 118 (2017) 051801

expect competition from LHCb, impressive prospects at Belle II

LHCB-PUB-2018-009 arXiv:1808.10567

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- often: SM dominated (U-spin related) partner exist such that theory computation of SM-prediction is not needed (but measured!)
  - Up-down asymmetry in $D_s^+ \to K_1(\to K\pi\pi)\gamma$, $D^+ \to K_1(\to K\pi\pi)\gamma$

PRD 99 (2019) 075023

BSM sensitive

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PRD 99 (2019) 075023

BSM sensitive (D_s^+ mode) — SM dominated (D^+ mode)

$\mathcal{B}(D^+ \to K_1\gamma) \sim \mathcal{O}(10^{-5})$

$\mathcal{B}(D_s^+ \to K_1\gamma) \sim \mathcal{O}(10^{-4})$

experimentally unexplored and $\mathcal{O}(1)$ effects possible!

PRD 99 (2019) 075023

Di-neutrino decay modes

- FCNC $c \to u\nu\bar{\nu}$ transitions are very clean probes of the SM (no resonances!)
  - large enhancement of BF possible, any signal → NP!

arXiv:2007.05001
PRD 103 (2021) 015033

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PRD 103 (2021) 015033

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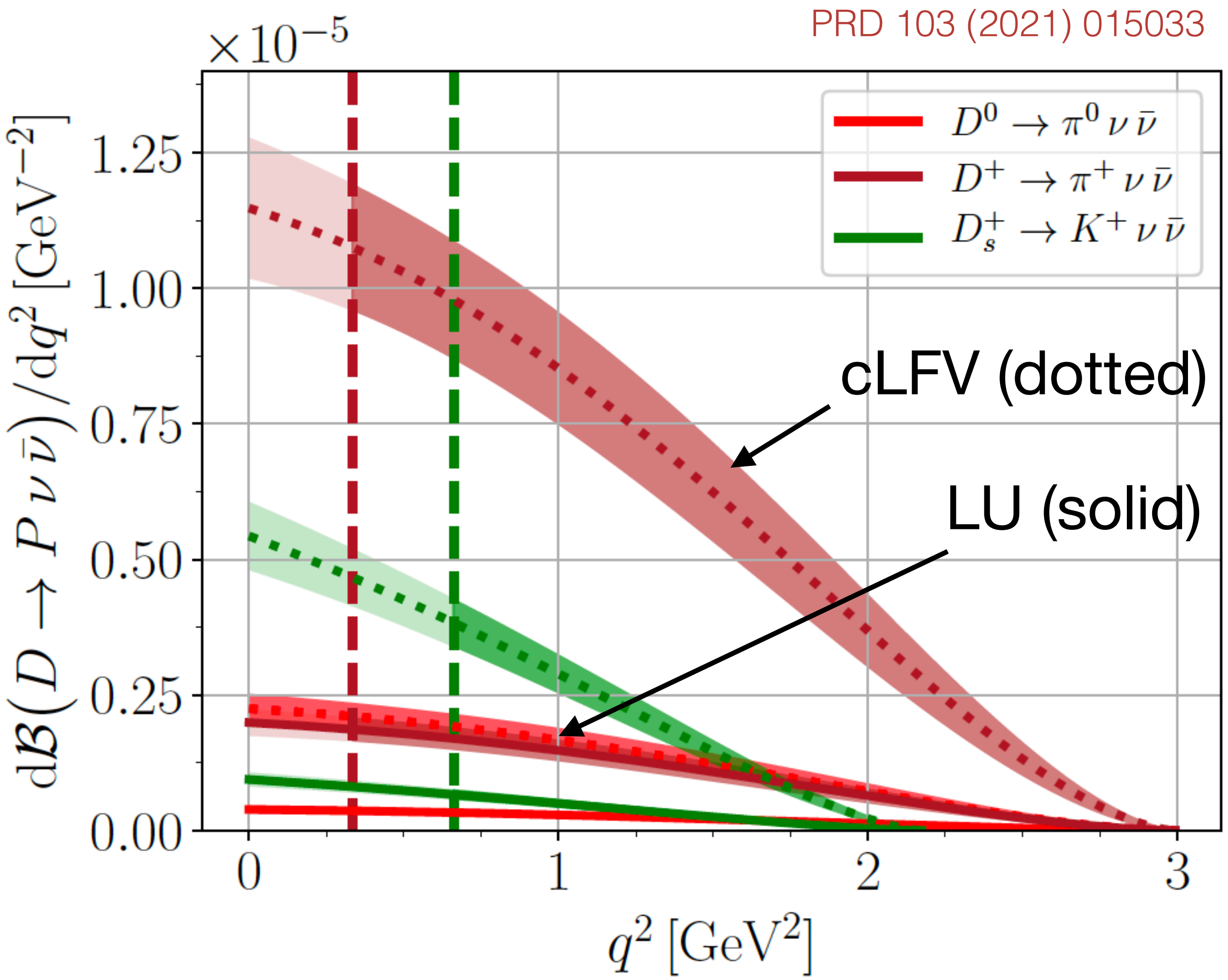

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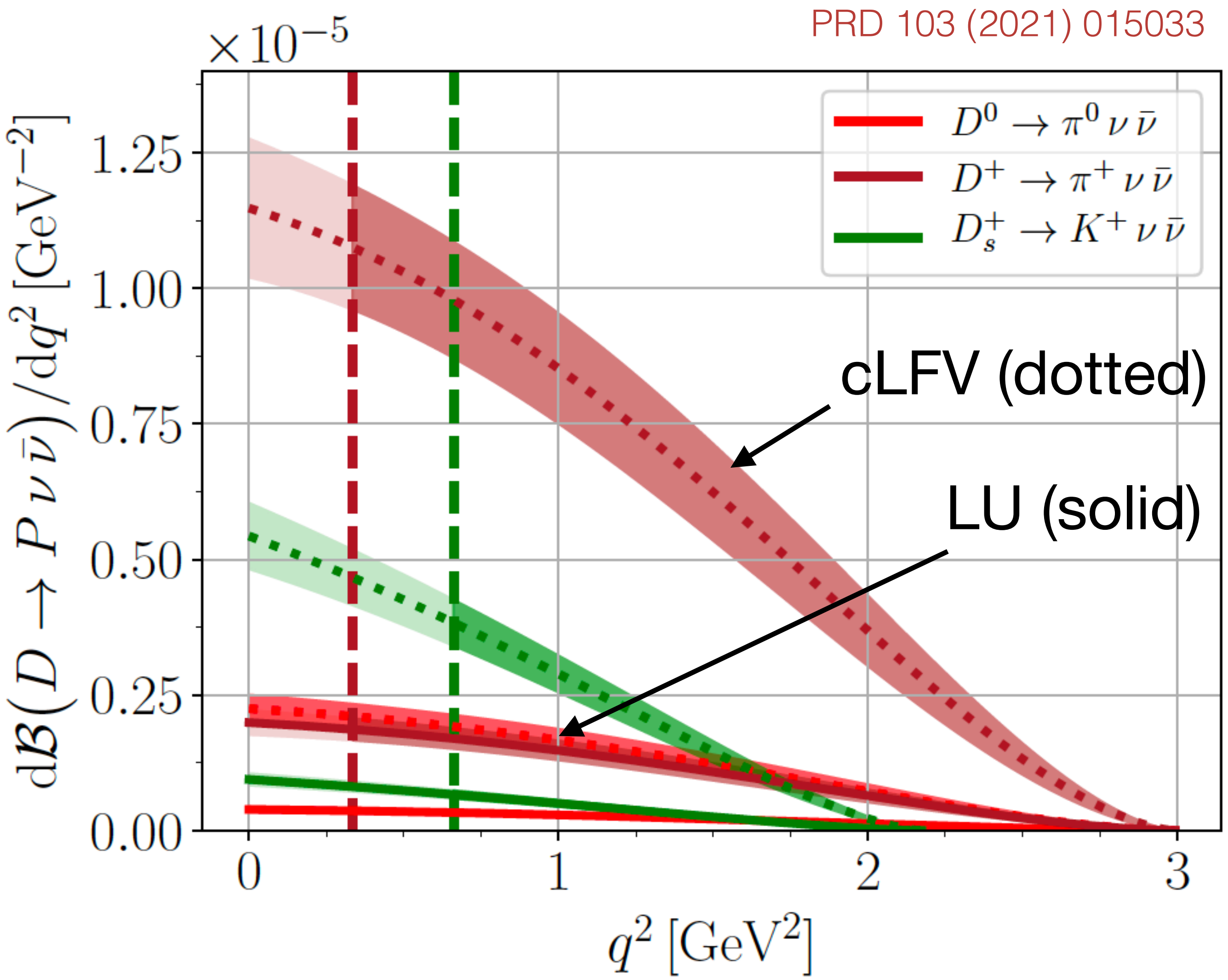


PRD 103 (2021) 015033

h_c	$f(c \to h_c)$	$N(h_c)$ (a)	$N(h_c)$ (b)
D^0	0.59	$6 \cdot 10^{11}$	$8 \cdot 10^{10}$
D^+	0.24	$3 \cdot 10^{11}$	$3 \cdot 10^{10}$
D_s^+	0.10	$1 \cdot 10^{11}$	$1 \cdot 10^{10}$
Λ_c^+	0.06	$7 \cdot 10^{10}$	$8 \cdot 10^9$

FCC-ee Belle II (50/ab)

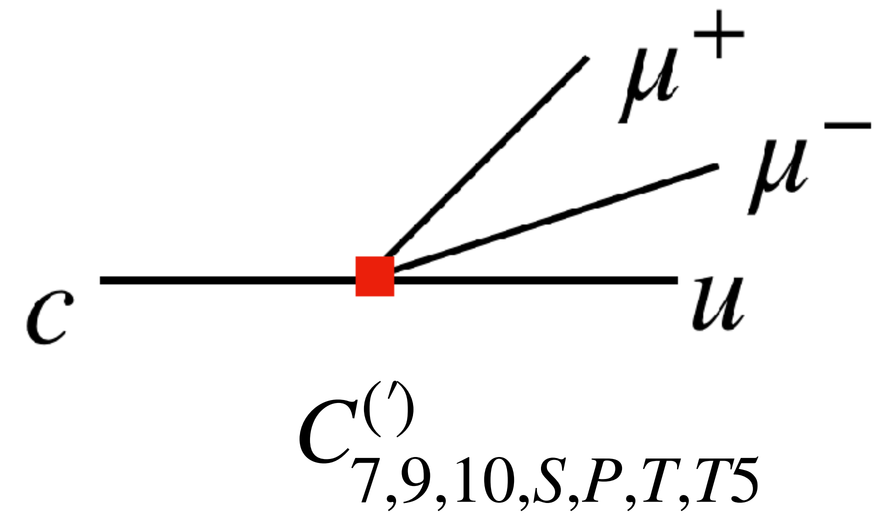
Very rough estimation: limits $\mathcal{O}(10^{-7} - 10^{-6})$?

Fully unexplored!
Belle II ?

Model-independent interpretation

- Use measurement to set limits on effective NP couplings

$$H_{eff} \sim \sum C_i \cdot \mathcal{O}_i \qquad C_{10,S,P,T,T5} \overset{\text{SM}}{=} 0$$



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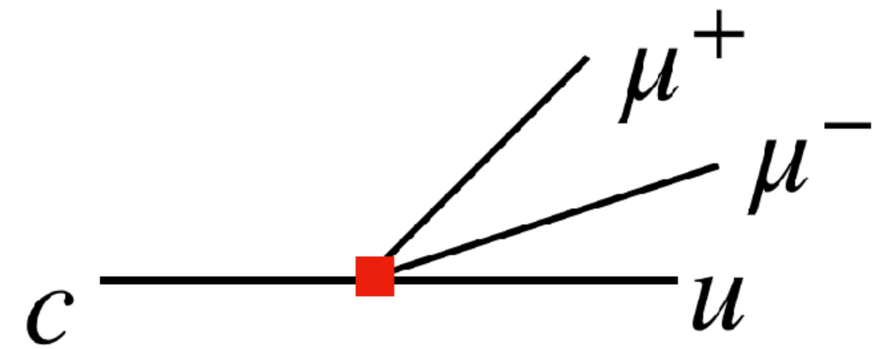

$$C^{(\prime)}_{7,9,10,S,P,T,T5}$$

- We need many decays to constrain all couplings!

$$\mathcal{B}(D \to \ell\ell) \sim C_P, C_S$$

$$\mathcal{B}(D \to h\ell\ell) \sim C_i + C_i'$$

RH quark currents

$$\mathcal{B}(D \to hhe\mu') \sim K_i^{e\mu} - K_i^{\prime e\mu}$$

LFV

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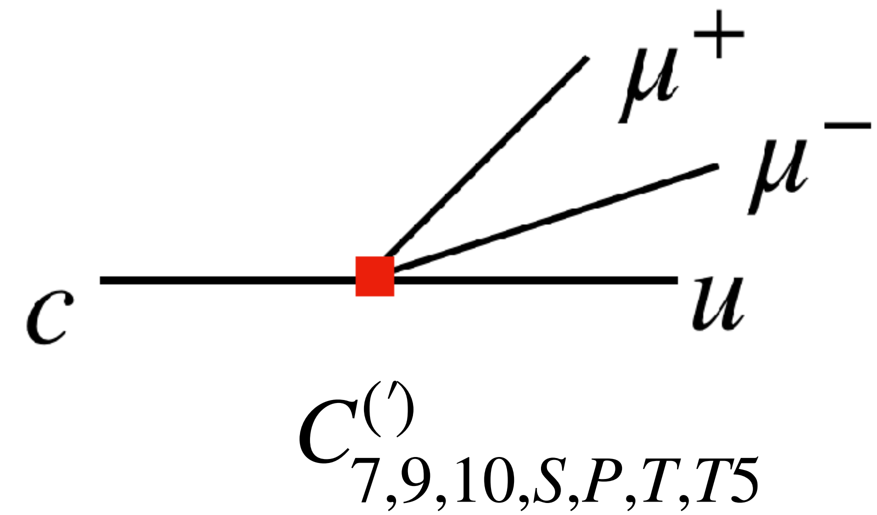

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$$\mathcal{B}(D \to h\ell\ell) \sim C_i + C_i'$$ ← RH quark currents

$$\mathcal{B}(D \to hhe\mu') \sim K_i^{e\mu} - K_i^{\prime e\mu}$$ ← LFV

arXiv:2107.13010

$$|C_7^{(\prime)}| \lesssim 0.3\,, \quad |C_9^{(\mu)(\prime)}| \lesssim 0.9\,,$$

$$|C_{10}^{(\mu)(\prime)}| \lesssim 0.8\,, \quad |C_{9,10}^{(e)(\prime)}| \lesssim 4\,,$$

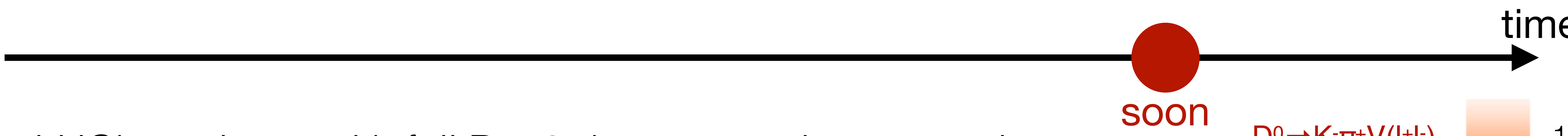
$$|K_{9,10}^{(\mu e)(\prime)}| \lesssim 1.6$$

comparable to B physics at least 10 years ago!

We need more measurements!

What about the future ?

What will come in the near future?

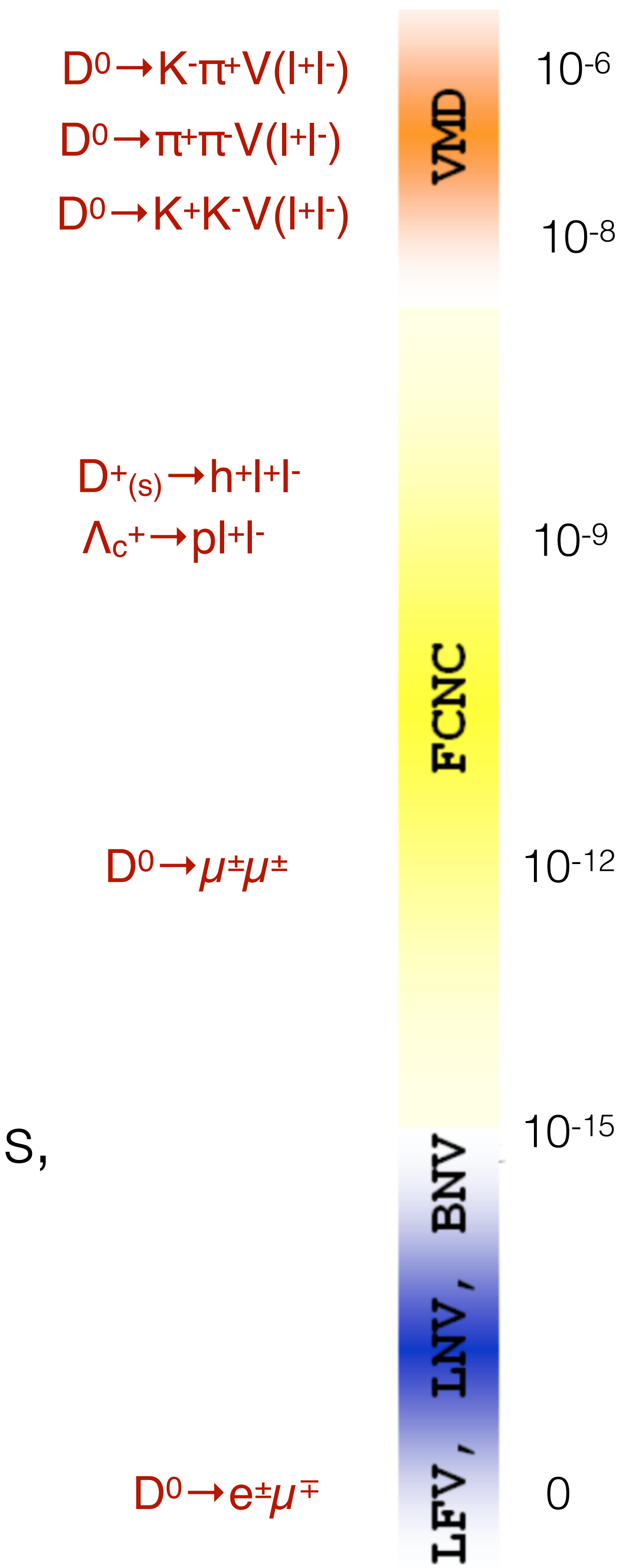


- LHCb analyses with full Run2 data set are in preparation
  - Searches for rare and forbidden decays
    - $D^0 \to \mu^+\mu^-, D^0 \to \mu e$
    - $D^+_{(s)} \to h\ell\ell^{(\prime)}$
    - $\Lambda_c \to p\ell\ell^{(\prime)}$
    - $D^0 \to h^+h^-e^+e^-$
- We hope for Belle II to join the game soon!

	Int. luminosity	$A_{CP}(D^0 \to \rho^0\gamma)$		
Belle result	1 ab^{-1}	+0.056	±0.152	±0.006
	5 ab^{-1}		±0.07	
Belle II statistical error	15 ab^{-1}		±0.04	
	50 ab^{-1}		±0.02	
		$A_{CP}(D^0 \to \phi\gamma)$		
Belle result	1 ab^{-1}	−0.094	±0.066	±0.001
	5 ab^{-1}		±0.03	
Belle II statistical error	15 ab^{-1}		±0.02	
	50 ab^{-1}		±0.01	
		$A_{CP}(D^0 \to \overline{K}^{*0}\gamma)$		
Belle result	1 ab^{-1}	−0.003	±0.020	±0.000
	5 ab^{-1}		±0.01	
Belle II statistical error	15 ab^{-1}		±0.005	
	50 ab^{-1}		±0.003	

Prog Theor Exp Phys (2019)

+ decays with electrons, neutrals, invisibles?

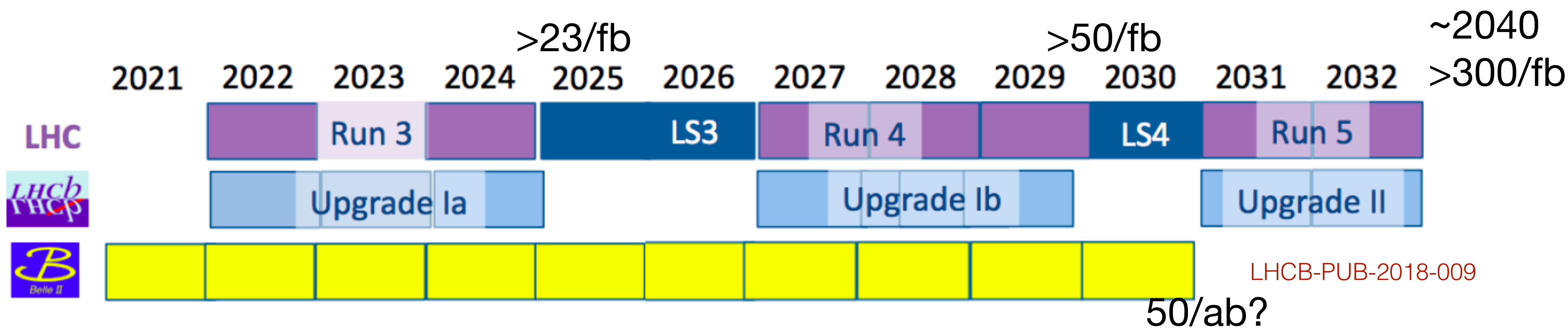


… in the (not so) near future?

less soon

time

- LHCb upgrade ahead with at least 5x statistics (50/fb) until 2030



LHCB-PUB-2018-009

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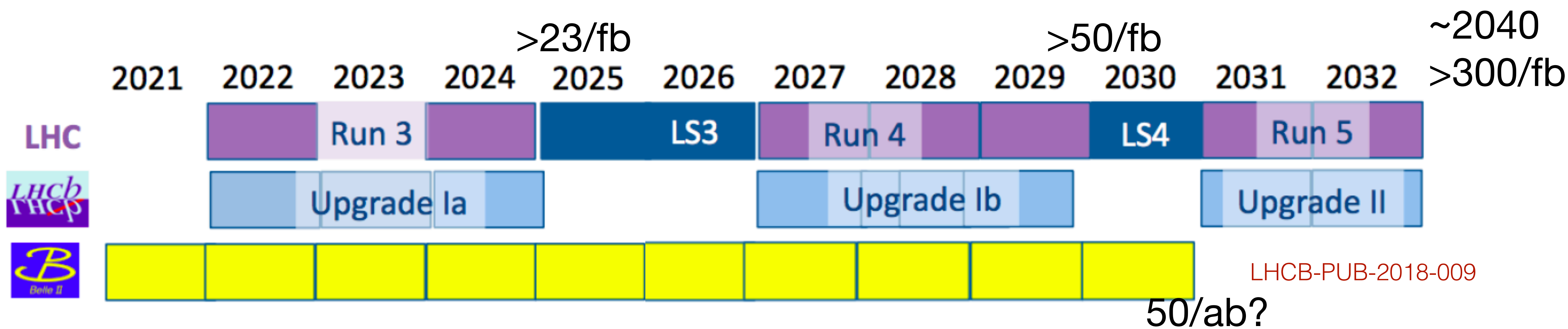


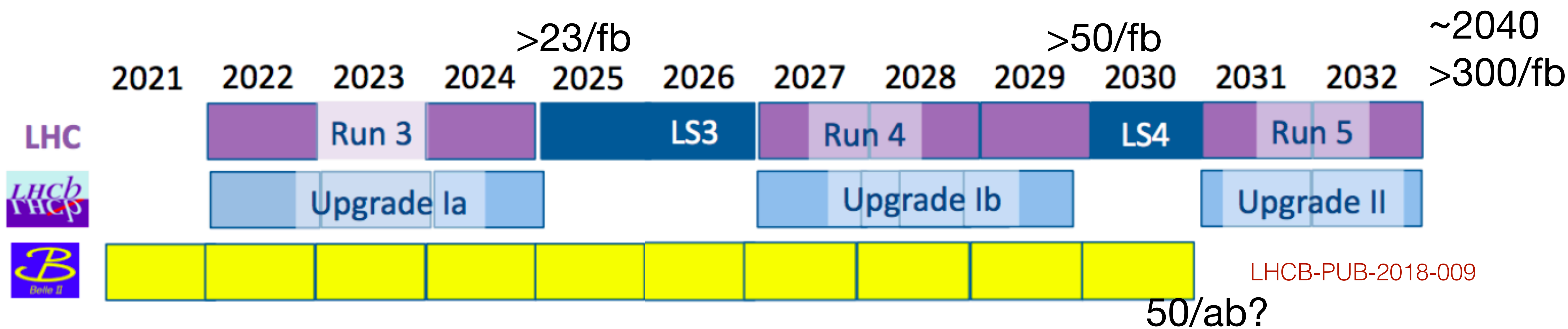
Mode	Upgrade ($50\,\mathrm{fb}^{-1}$) (~2030)	Upgrade II ($300\,\mathrm{fb}^{-1}$) (~2040)
$D^+ \to \pi^+\mu^+\mu^-$	0.2%	0.08%
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	1%	0.4%
$D^0 \to K^-\pi^+\mu^+\mu^-$	0.3%	0.13%
$D^0 \to K^+\pi^-\mu^+\mu^-$	12%	5%
$D^0 \to K^+K^-\mu^+\mu^-$	4%	1.7%

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}

A. Contu, Towards the Ultimate Precision in Flavour Physics, Durham, United Kingdom, 2 - 4 Apr 2019

… in the (not so) near future?

- LHCb upgrade ahead with at least 5x statistics (50/fb) until 2030



Mode	Upgrade (50 fb^{-1}) (~2030)	Upgrade II (300 fb^{-1}) (~2040)
$D^+ \to \pi^+\mu^+\mu^-$	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%

Mode	Upgrade (50 fb^{-1})	Upgrade II (300 fb^{-1})
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A. Contu, Towards the Ultimate Precision in Flavour Physics, Durham, United Kingdom, 2 - 4 Apr 2019

- BESIII has proven to make significant contributions to the field
- future projects such as FCCee and future charm tau factories already considered in some theory studies of di-neutrino decays arXiv:2010.02225

Summary

dmitzel@cern.ch

- The low SM rates and unique phenomenology make the field a perfect place to look for physics beyond the SM
  - Don't be afraid of LD effects! Clear SM null test allow for stringent NP searches
  - complementary sensitivity with respect to K and B physics, often (re)use of B physics methodology
- Great theoretical and experimental improvements over the last years
  - still rather unexplored and promising
  - bright prospects at (upgrade) LHCb, Belle II, BES III and long-term flavour experiments
- "Charm is the new beauty… but beauty never goes out of style"

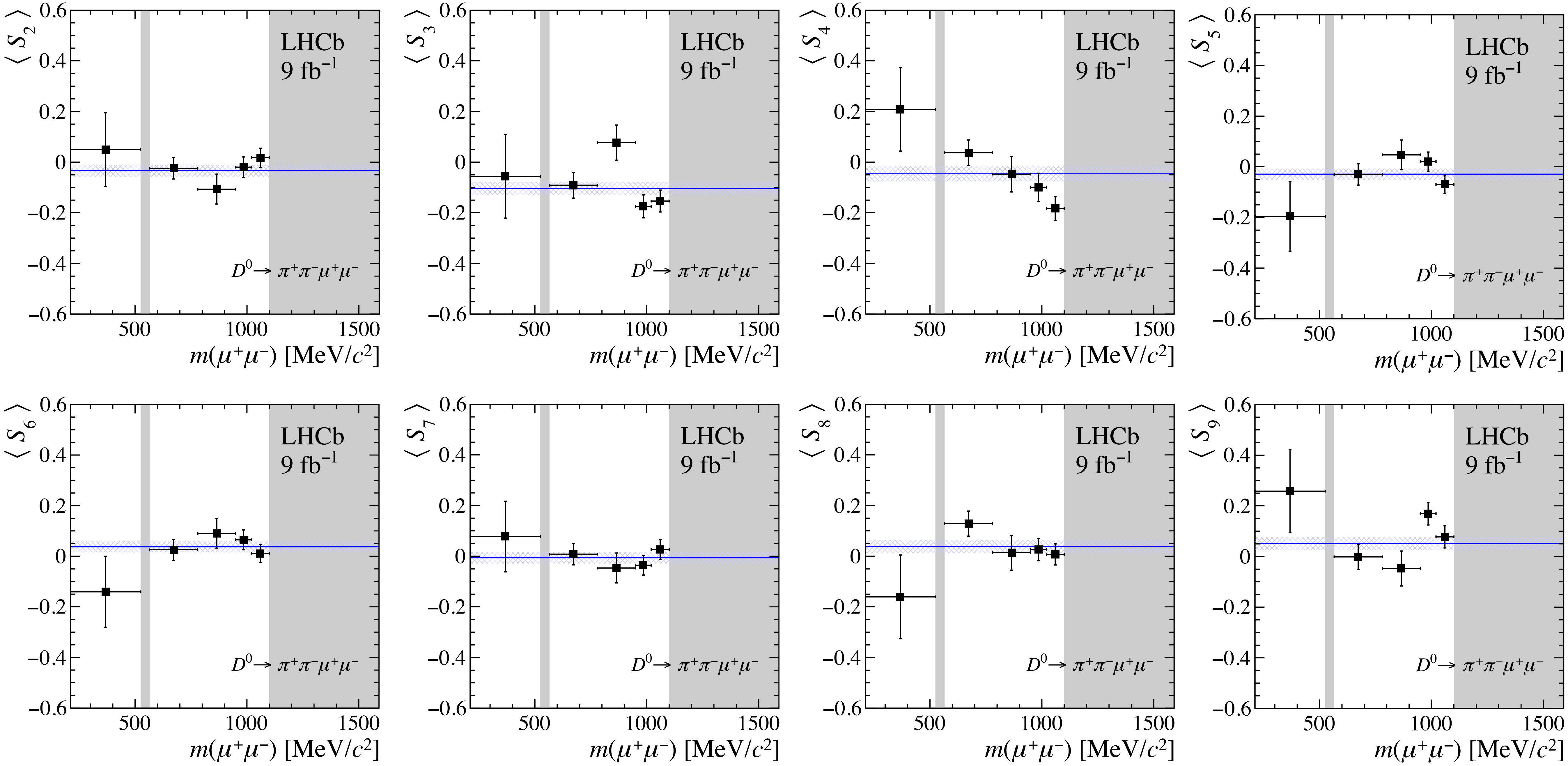
[G. Hiller@ LHCb implication workshop 2020]

More? MPLA 36 (2021) 2130002


Thank you!

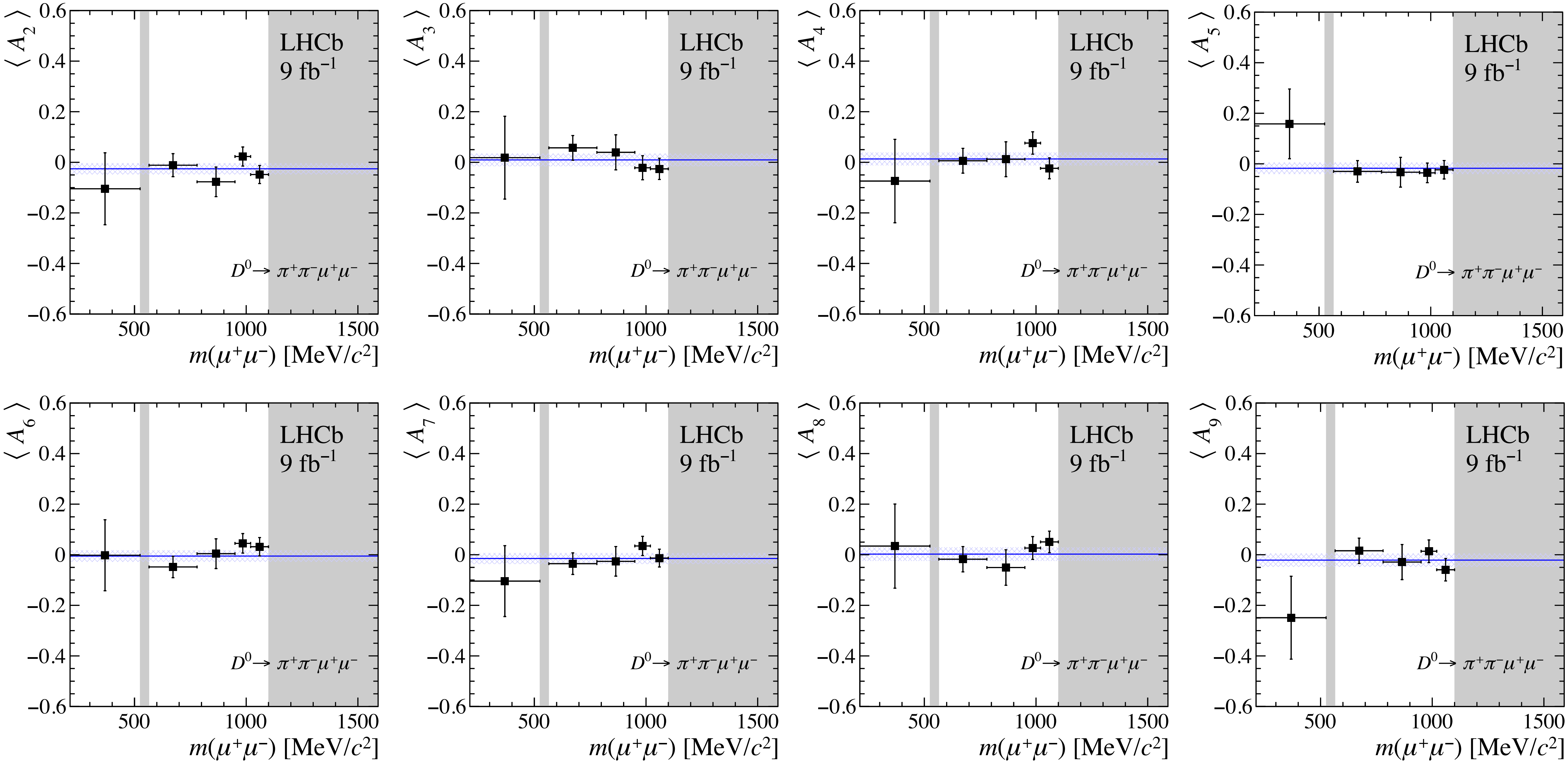
Flavour-averaged observables

LHCb-PAPER-2021-035
in preparation



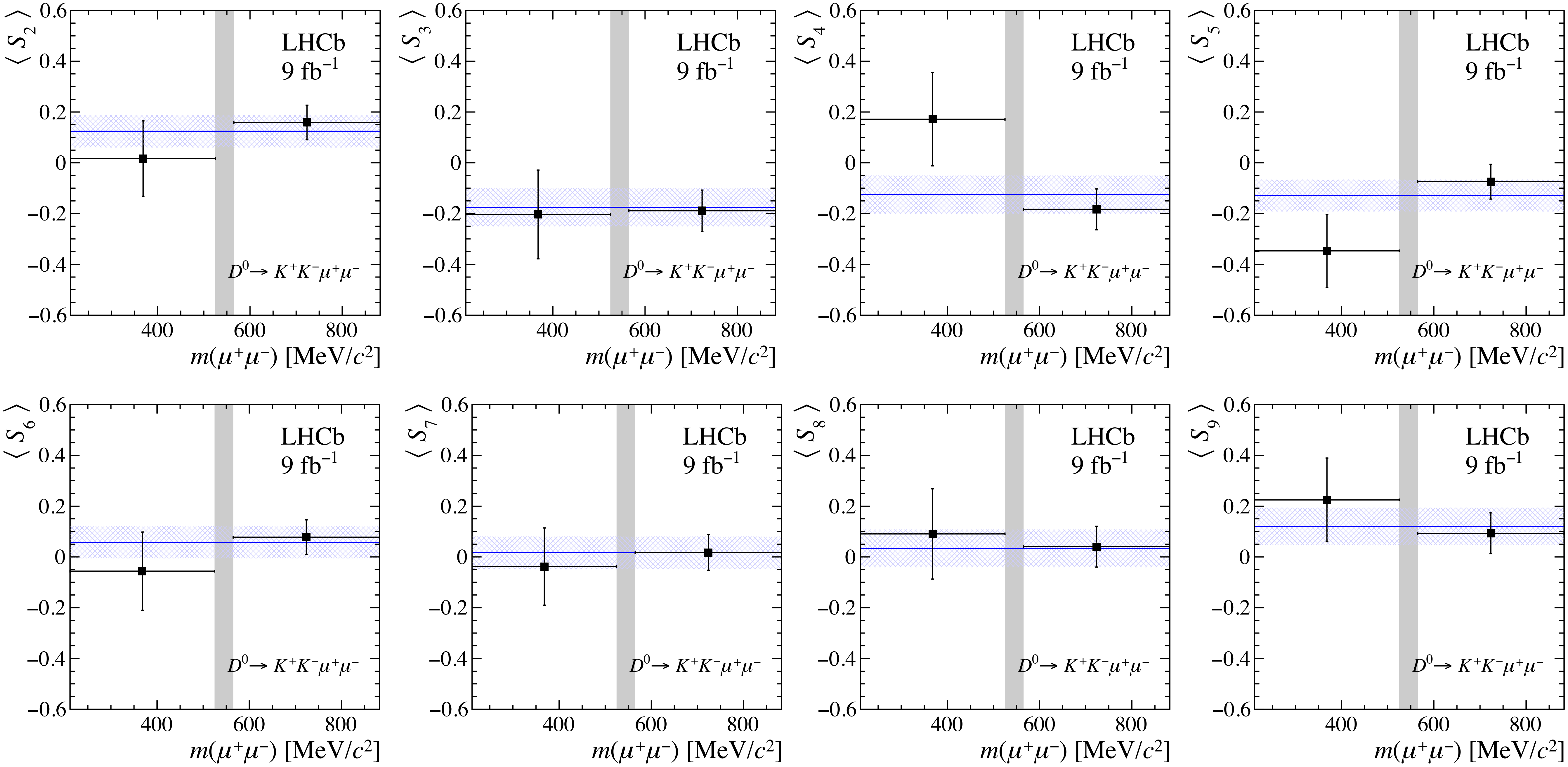
Flavour-averaged observables

LHCb-PAPER-2021-035
in preparation



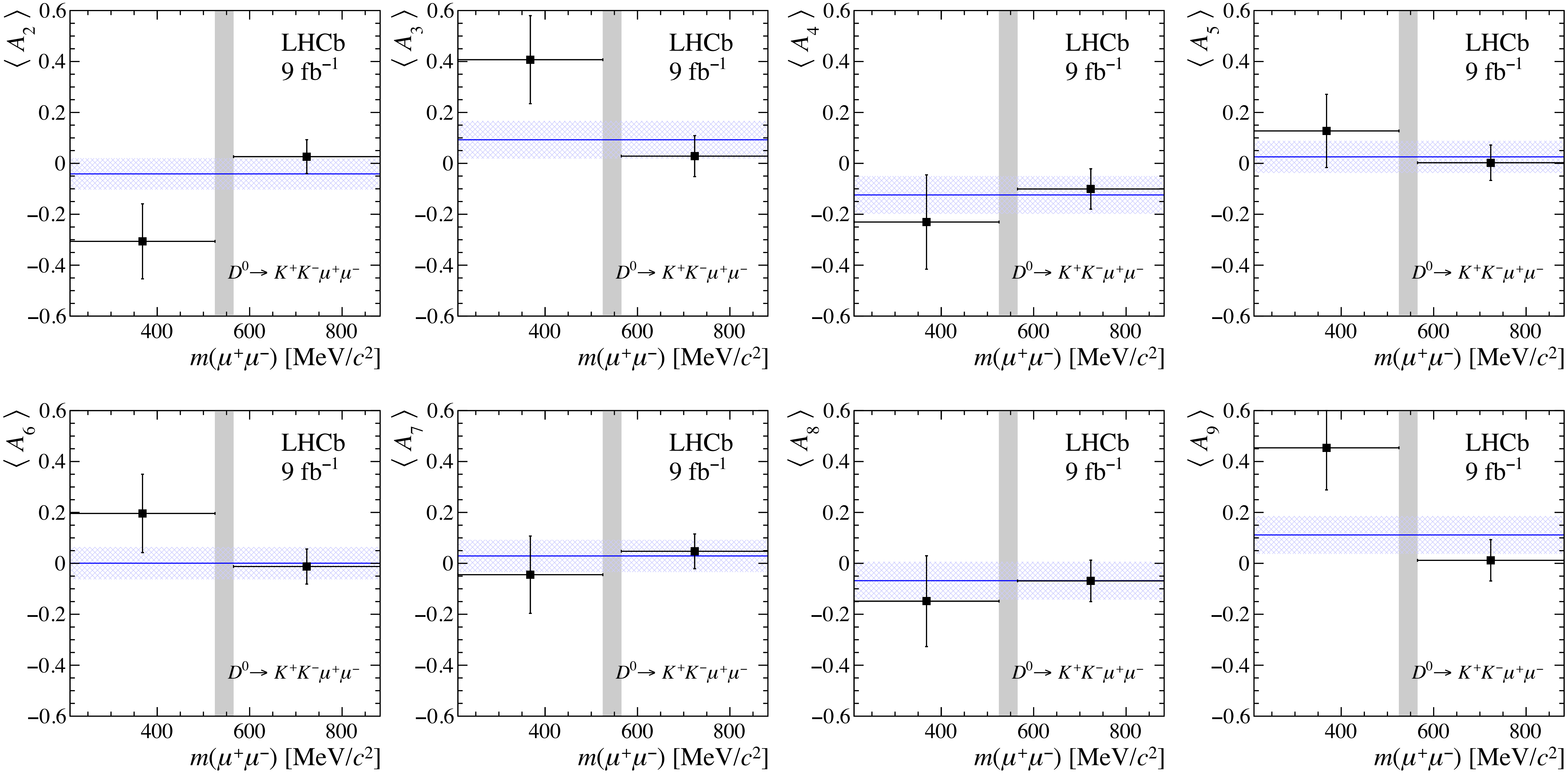
CP asymmetries $\langle A_i \rangle$

LHCb-PAPER-2021-035
in preparation



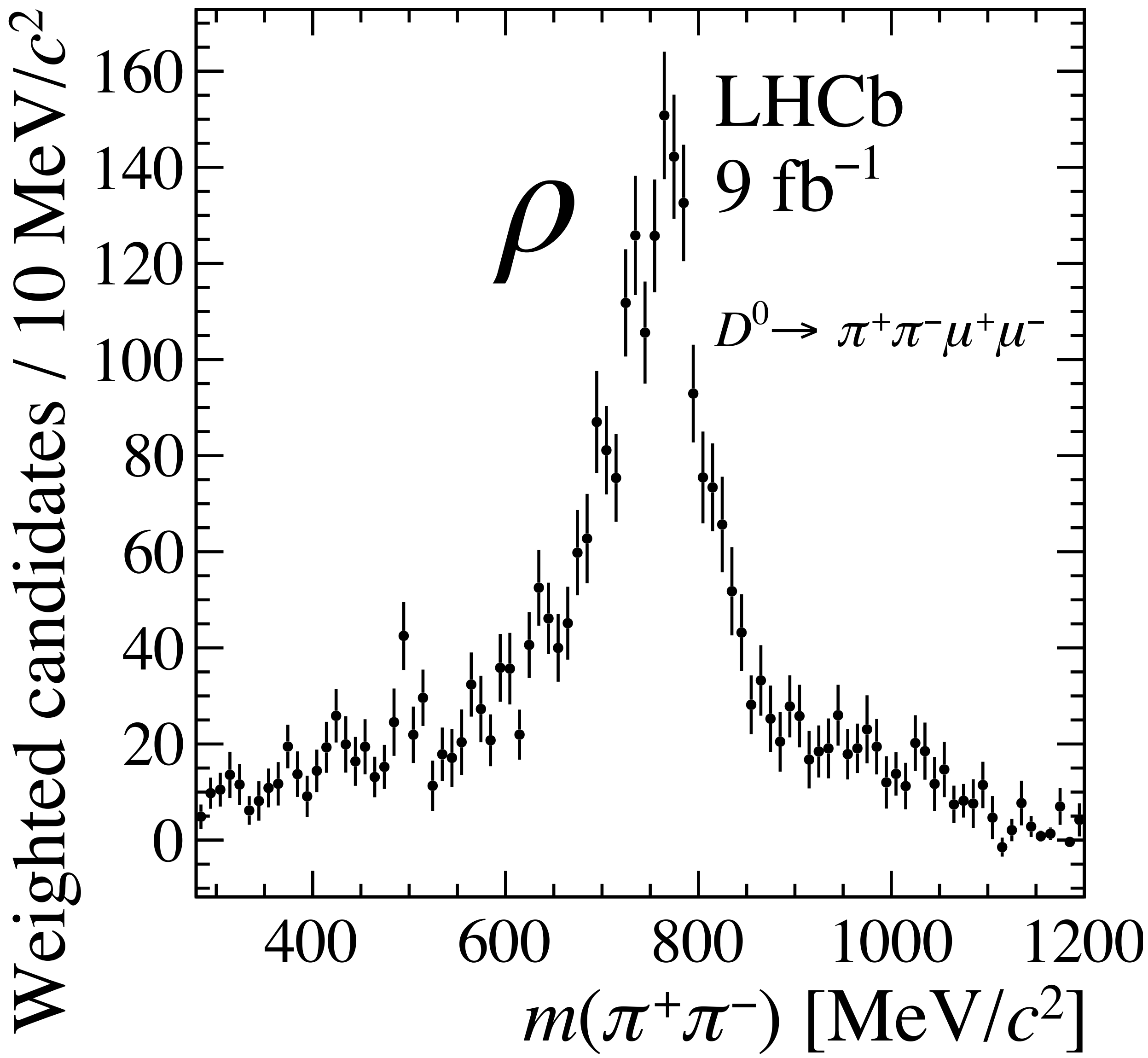
CP asymmetries $\langle A_i \rangle$

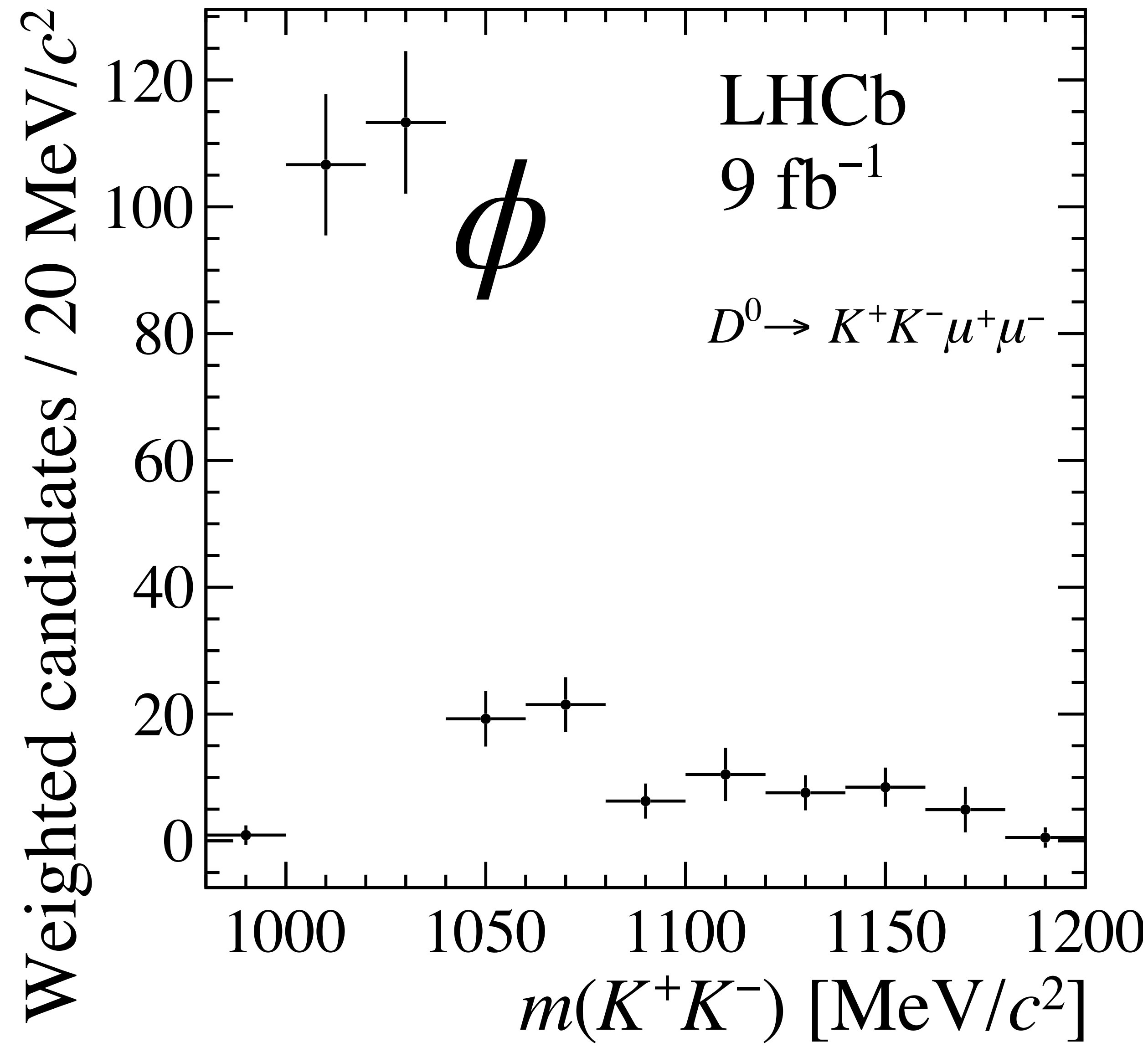
LHCb-PAPER-2021-035
in preparation



Hadron spectra

LHCb-PAPER-2021-035
in preparation





Hand-waving prospects

Disclaimer: no official numbers!

- Prospects @LHCb

Asymmetries (CP & angular, phase-space integrated)

Mode	Upgrade (50 fb^{-1})	Upgrade II (300 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%

A. Contu, Towards the Ultimate Precision in Flavour Physics, Durham, United Kingdom, 2 - 4 Apr 2019

$N(D^+ \to \pi^+\mu^+\mu^-) \approx \mathcal{O}(250k - 500k)$

$N(D^0 \to \pi^+\pi^-\mu^+\mu^-) \approx \mathcal{O}(10k - 20k)$ @LHCb 50/fb

$N(D^0 \to K^-\pi^+\mu^+\mu^-) \approx \mathcal{O}(100k)$

↓ conservative! $\epsilon(D \to Xe^+e^-) = 1/10 \times \epsilon(D \to X\mu^+\mu^-)$

$R^D_{\pi\pi} \approx \mathcal{O}(2 - 3\%)$

$A(D^+ \to \pi^+e^+e^-) \approx \mathcal{O}(0.5\%)$

- LHCb has proven to control the relevant systematics (acc., eff.,inst. asym.) at this level
- expect competition in $D^0 \to V\gamma$ from LHCb [LHCB-PUB-2018-009]

- Prospects @Belle2

	Int. luminosity	$A_{CP}(D^0 \to \rho^0\gamma)$		
Belle result	1 ab^{-1}	+0.056	±0.152	±0.006
	5 ab^{-1}		±0.07	
Belle II statistical error	15 ab^{-1}		±0.04	
	50 ab^{-1}		±0.02	
		$A_{CP}(D^0 \to \phi\gamma)$		
Belle result	1 ab^{-1}	−0.094	±0.066	±0.001
	5 ab^{-1}		±0.03	
Belle II statistical error	15 ab^{-1}		±0.02	
	50 ab^{-1}		±0.01	
		$A_{CP}(D^0 \to \overline{K}^{*0}\gamma)$		
Belle result	1 ab^{-1}	−0.003	±0.020	±0.000
	5 ab^{-1}		±0.01	
Belle II statistical error	15 ab^{-1}		±0.005	
	50 ab^{-1}		±0.003	

Prog Theor Exp Phys (2019)

start from $N(D^0 \to K^-\pi^+e^+e^-) \approx 70$ (@BaBar, 0.5/ab) [PRL 122 (2019) 081802]

↓ $\epsilon_{BaBar} = \epsilon_{Belle2}$

$N(D^0 \to K\pi ee) \approx \mathcal{O}(7k)$ yields (50/ab) for di-electron modes might be comparable with LHCb (50/fb)

- expect contributions to di-neutrino ($c \to u\nu\bar{\nu}$) decays and decays with neutral hadrons in final state (also from BESIII, FCC-ee)

[See Hector Gisbert's talk on last Tuesday]

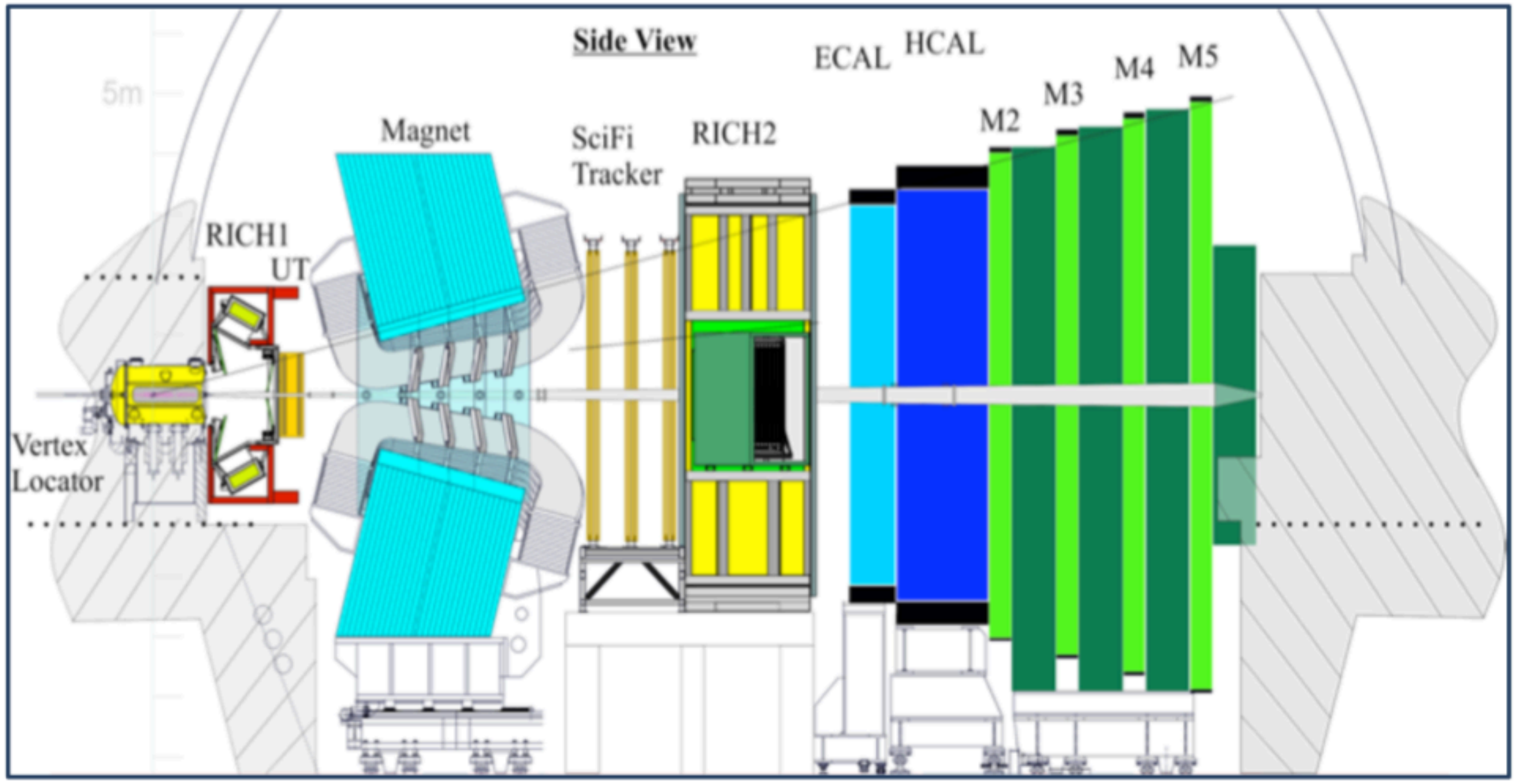
Taken from Chris Parkes, LHCb: Highlights & Perspectives, LHCP, 7 June 2021

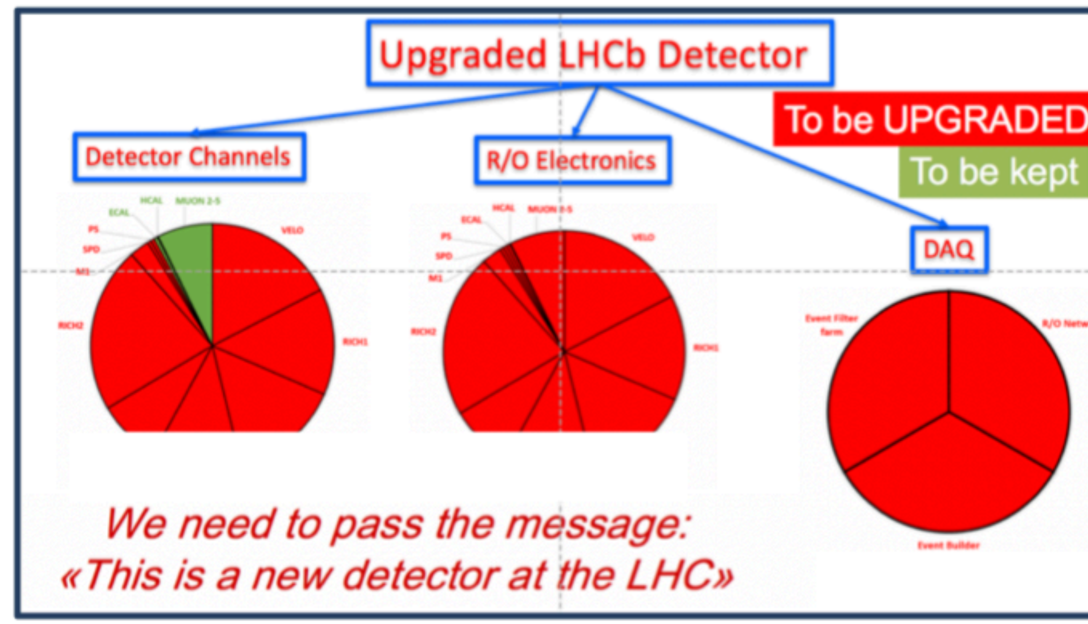
Upgrade I: Reminder

LHCb

Tomasz Szumlak, Wednesday 17:42

- All sub-detectors read out at 40 MHz for a **fully software trigger** with new data centre





- Pixel detector VELO with silicon microchannel cooling 5mm from LHC beam
- New RICH mechanics, optics and photodetectors
- New silicon strip upstream tracker UT detector
- New SciFi tracker with 11,000 km of scintillating fibres
- New electronics for muon and calorimeter systems

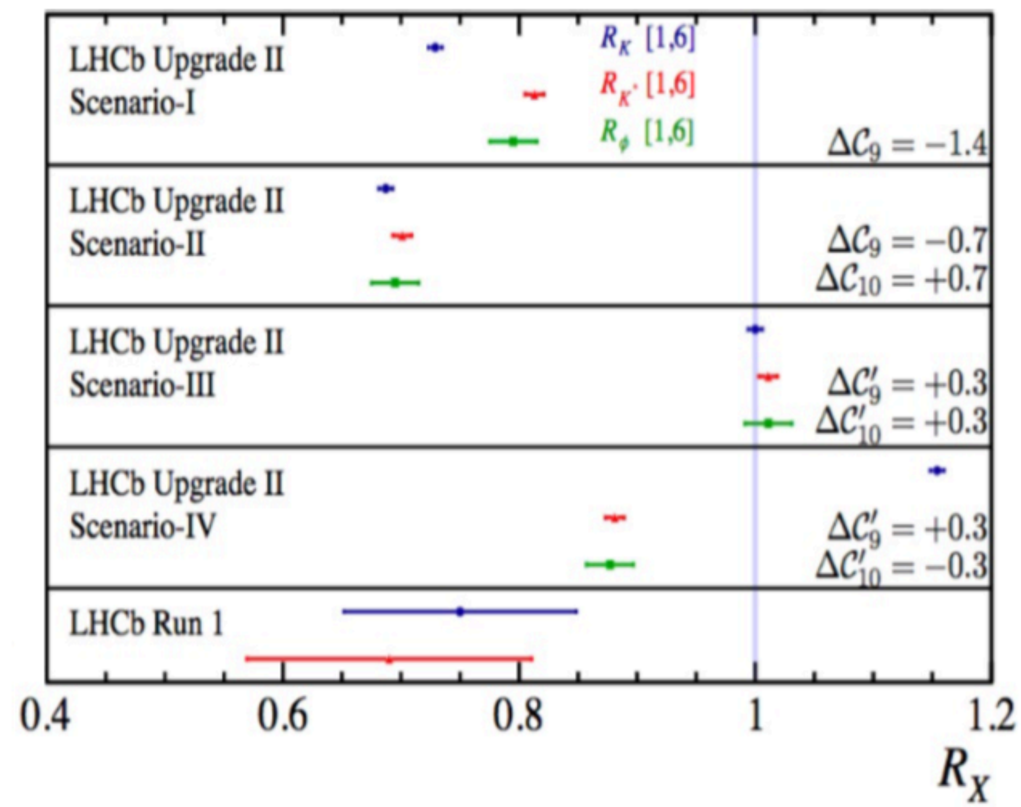
Major project being installed currently for operation in Run 3

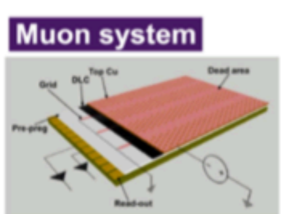
Taken from Chris Parkes, LHCb: Highlights & Perspectives, LHCP, 7 June 2021

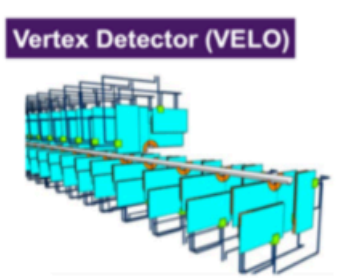
LHCb Upgrade II : Framework TDR

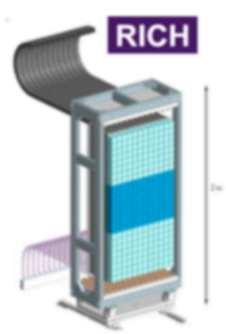
Francesca Dordei, Monday 17:54   Silvia Gambetta, Wednesday 14:39

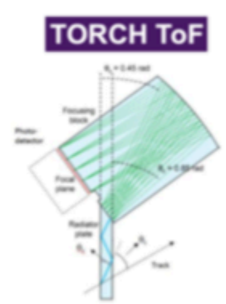
- **Fully exploit LHC facility for flavour physics & beyond, for LS4**
  - Expression of interest (2017), Physics Case (2018)
  - Strong support in European Strategy (2020)
- Framework Technical Design Report
  - Options to achieve physics programme
  - Drafting in progress, for delivery later this year

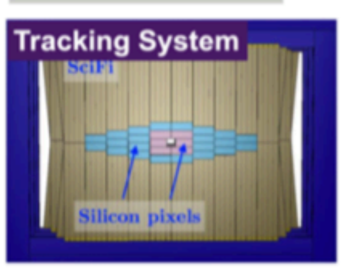


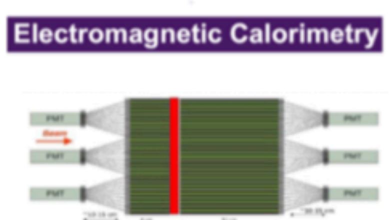


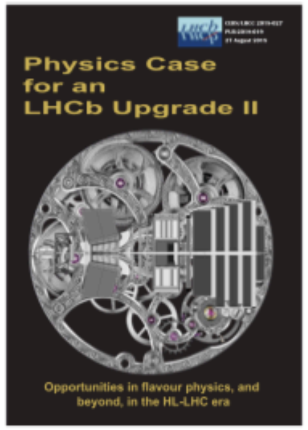












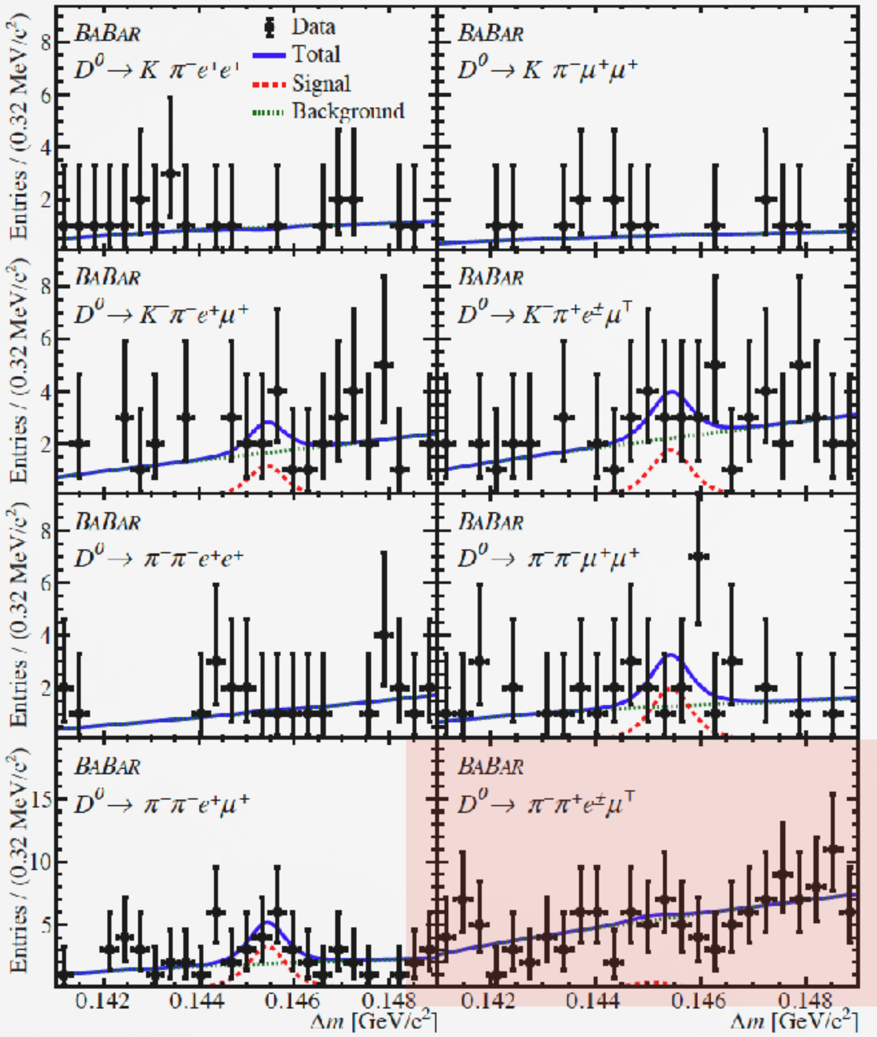
Technology synergy with future projects

Lepton Flavour Violation

NP models: PRD 98 (2018) 035041

$\mathcal{B}(D^0 \to \pi^+\pi^- e^\pm\mu^\mp) \lesssim 10^{-7}$

$\mathcal{B}(D^0 \to K^+K^- e^\pm\mu^\mp) \lesssim 10^{-9}$



PRL 124 (2020) , 071802

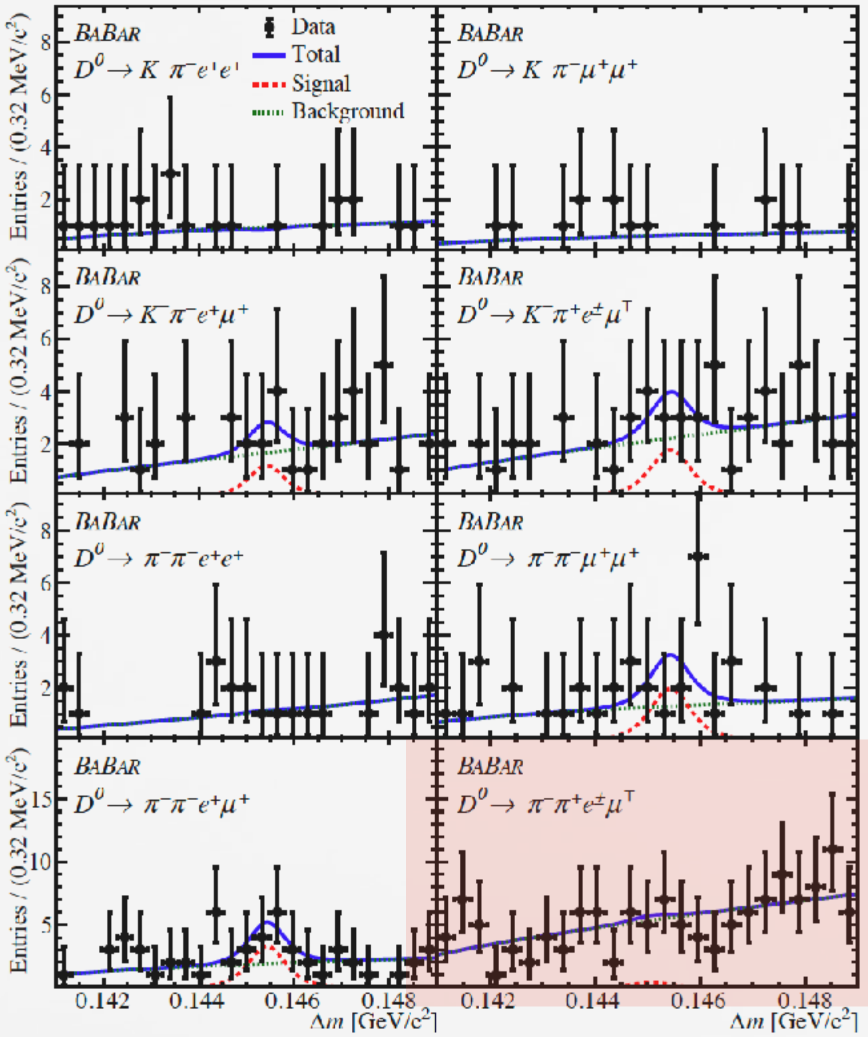
- limits $\mathcal{O}(10^{-7})$ on $D^0 \to h^+h^-\mu e$ by BarBar

Decay mode $D^0 \to$	N_{sig} (candidates)	ϵ_{sig} (%)	$\mathcal{B}$ ($\times 10^{-7}$)	$\mathcal{B}$ 90% U.L. ($\times 10^{-7}$)
$\pi^-\pi^-e^+e^+$	$0.22 \pm 3.15 \pm 0.54$	4.38	$0.27 \pm 3.90 \pm 0.67$	9.1
$\pi^-\pi^-\mu^+\mu^+$	$6.69 \pm 4.88 \pm 0.80$	4.91	$7.40 \pm 5.40 \pm 0.91$	15.2
$\pi^-\pi^-e^+\mu^+$	$12.42 \pm 5.30 \pm 1.45$	4.38	$15.4 \pm 6.59 \pm 1.85$	30.6
$\pi^-\pi^+e^\pm\mu^\mp$	$1.37 \pm 6.15 \pm 1.28$	4.79	$1.55 \pm 6.97 \pm 1.45$	17.1
$K^-\pi^-e^+e^+$	$-0.23 \pm 0.97 \pm 1.28$	3.19	$-0.38 \pm 1.60 \pm 2.11$	5.0
$K^-\pi^-\mu^+\mu^+$	$-0.03 \pm 2.10 \pm 0.40$	3.30	$-0.05 \pm 3.34 \pm 0.64$	5.3
$K^-\pi^-e^+\mu^+$	$3.87 \pm 3.96 \pm 2.36$	3.48	$5.84 \pm 5.97 \pm 3.56$	21.0
$K^-\pi^+e^\pm\mu^\mp$	$2.52 \pm 4.60 \pm 1.35$	3.65	$3.62 \pm 6.61 \pm 1.95$	19.0
$K^-K^-e^+e^+$	$0.30 \pm 1.08 \pm 0.41$	3.25	$0.43 \pm 1.54 \pm 0.58$	3.4
$K^-K^-\mu^+\mu^+$	$-1.09 \pm 1.29 \pm 0.42$	6.21	$-0.81 \pm 0.96 \pm 0.32$	1.0
$K^-K^-e^+\mu^+$	$1.93 \pm 1.92 \pm 0.83$	4.63	$1.93 \pm 1.93 \pm 0.84$	5.8
$K^-K^+e^\pm\mu^\mp$	$4.09 \pm 3.00 \pm 1.59$	4.83	$3.93 \pm 2.89 \pm 1.45$	10.0

Lepton Flavour Violation

NP models: PRD 98 (2018) 035041

$$\mathcal{B}(D^0 \to \pi^+\pi^- e^\pm\mu^\mp) \lesssim 10^{-7}$$
$$\mathcal{B}(D^0 \to K^+K^- e^\pm\mu^\mp) \lesssim 10^{-9}$$



PRL 124 (2020) , 071802

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$K^-K^+e^\pm\mu^\mp$	$4.09 \pm 3.00 \pm 1.59$	4.83	$3.93 \pm 2.89 \pm 1.45$	10.0

- updated limits on $D^0 \to h^0\mu e$ very recently

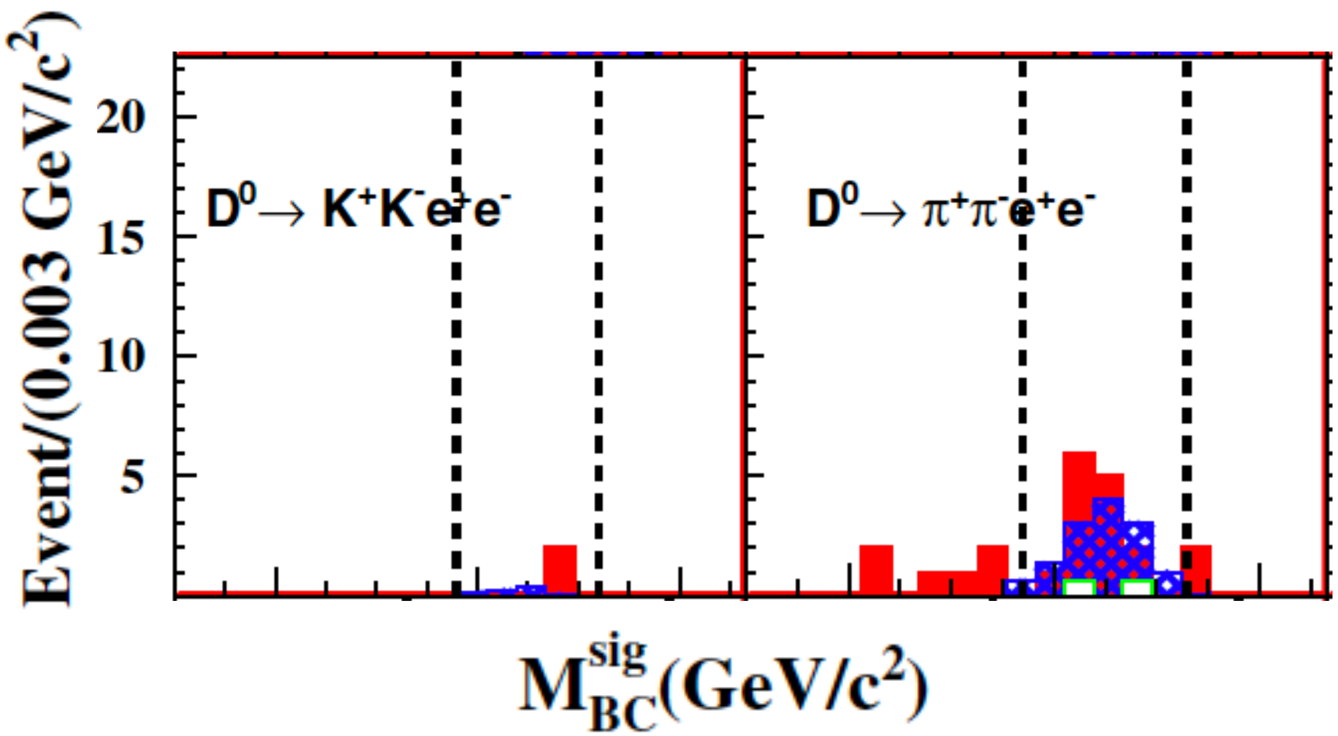
Decay mode	N_{sig} (candidates)	ϵ_{sig} (%)	$\mathcal{B}$ ($\times 10^{-7}$)	$\mathcal{B}$ 90% U.L. ($\times 10^{-7}$) BABAR	Previous
$D^0 \to \pi^0 e^\pm\mu^\mp$	$-0.3 \pm 2.0 \pm 0.9$	2.15 ± 0.03	$-0.6 \pm 4.8 \pm 2.3$	8.0	860
$D^0 \to K^0_S e^\pm\mu^\mp$	$0.7 \pm 1.7 \pm 0.7$	3.01 ± 0.04	$1.9 \pm 4.6 \pm 1.9$	8.6	500
$D^0 \to \overline{K}^{*0} e^\pm\mu^\mp$	$0.8 \pm 1.8 \pm 0.8$	2.31 ± 0.03	$2.8 \pm 6.1 \pm 2.6$	12.4	830
$D^0 \to \rho^0 e^\pm\mu^\mp$	$-0.7 \pm 1.7 \pm 0.4$	2.10 ± 0.03	$-1.8 \pm 4.4 \pm 1.0$	5.0	490
$D^0 \to \phi e^\pm\mu^\mp$	$0.0 \pm 1.4 \pm 0.3$	3.43 ± 0.04	$0.1 \pm 3.8 \pm 0.9$	5.1	340
$D^0 \to \omega e^\pm\mu^\mp$	$0.4 \pm 2.3 \pm 0.5$	1.46 ± 0.03	$1.8 \pm 9.5 \pm 1.9$	17.1	1200
$D^0 \to \eta e^\pm\mu^\mp$			$6.1 \pm 9.7 \pm 2.3$	22.5	1000
with $\eta \to \gamma\gamma$	$1.6 \pm 2.3 \pm 0.5$	2.96 ± 0.04	$7.0 \pm 10.5 \pm 2.4$	24.0	
with $\eta \to \pi^+\pi^-\pi^0$	$0.0 \pm 2.8 \pm 0.7$	2.46 ± 0.04	$0.4 \pm 25.8 \pm 6.0$	42.8	

PRD 101 (2020), 112003

LHCb and Belle2 should hopefully be able to do better!

What about Electron Modes

PRD 97 (2018) 072015

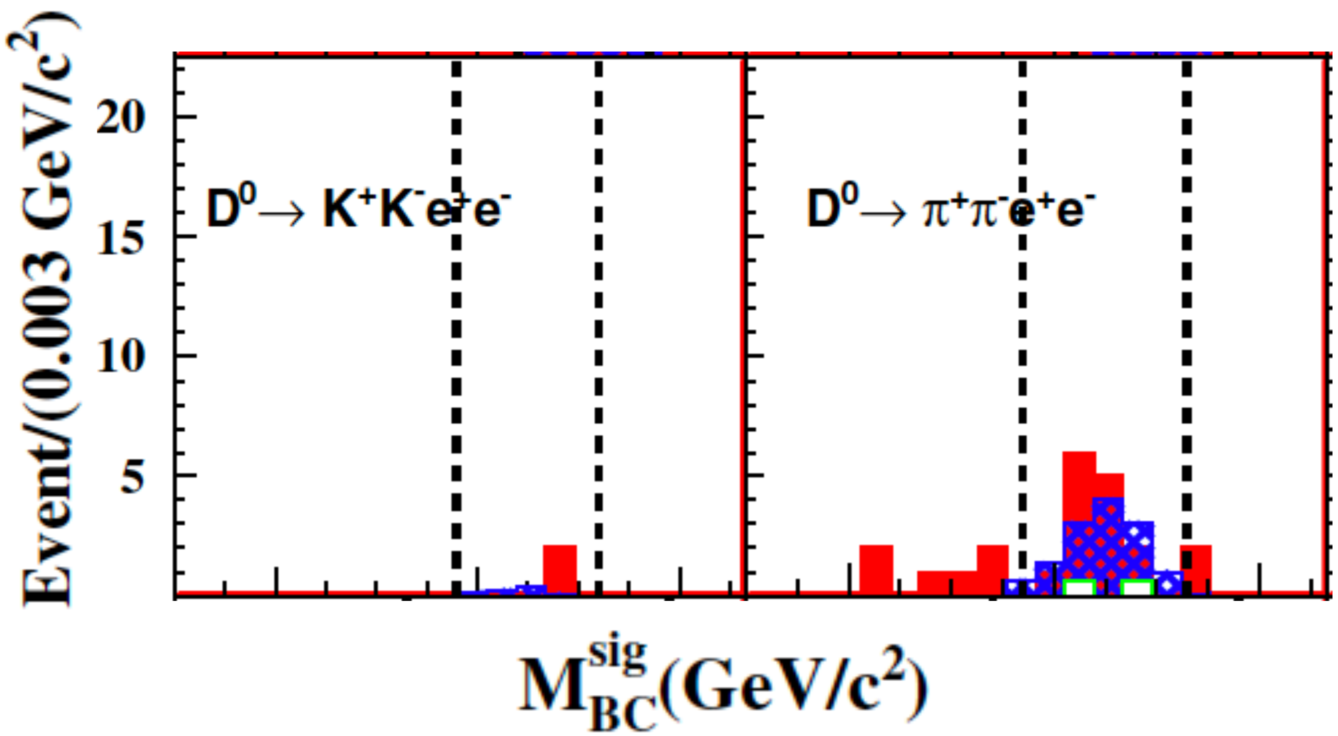


- limits $\mathcal{O}(10^{-5})$ on $D \to Xe^+e^-$ by BESIII

Signal decays	$\mathcal{B}$ ($\times 10^{-5}$)	PDG [9] ($\times 10^{-5}$)
$D^+ \to \pi^+\pi^0 e^+e^-$	<1.4	⋯
$D^+ \to K^+\pi^0 e^+e^-$	<1.5	⋯
$D^+ \to K^0_S\pi^+ e^+e^-$	<2.6	⋯
$D^+ \to K^0_S K^+ e^+e^-$	<1.1	⋯
$D^0 \to K^-K^+ e^+e^-$	<1.1	<31.5
$D^0 \to \pi^+\pi^- e^+e^-$	<0.7	<37.3
$D^0 \to K^-\pi^+ e^+e^{-\dagger}$	<4.1	<38.5
$D^0 \to \pi^0 e^+e^-$	<0.4	<4.5
$D^0 \to \eta e^+e^-$	<0.3	<11
$D^0 \to \omega e^+e^-$	<0.6	<18
$D^0 \to K^0_S e^+e^-$	<1.2	<11

What about Electron Modes

PRD 97 (2018) 072015



- limits $\mathcal{O}(10^{-5})$ on $D \to Xe^+e^-$ by BESIII

Signal decays	$\mathcal{B}$ ($\times 10^{-5}$)	PDG [9] ($\times 10^{-5}$)
$D^+ \to \pi^+\pi^0e^+e^-$	<1.4	···
$D^+ \to K^+\pi^0e^+e^-$	<1.5	···
$D^+ \to K_S^0\pi^+e^+e^-$	<2.6	···
$D^+ \to K_S^0K^+e^+e^-$	<1.1	···
$D^0 \to K^-K^+e^+e^-$	<1.1	<31.5
$D^0 \to \pi^+\pi^-e^+e^-$	<0.7	<37.3
$D^0 \to K^-\pi^+e^+e^{-\dagger}$	<4.1	<38.5
$D^0 \to \pi^0e^+e^-$	<0.4	<4.5
$D^0 \to \eta e^+e^-$	<0.3	<11
$D^0 \to \omega e^+e^-$	<0.6	<18
$D^0 \to K_S^0e^+e^-$	<1.2	<11

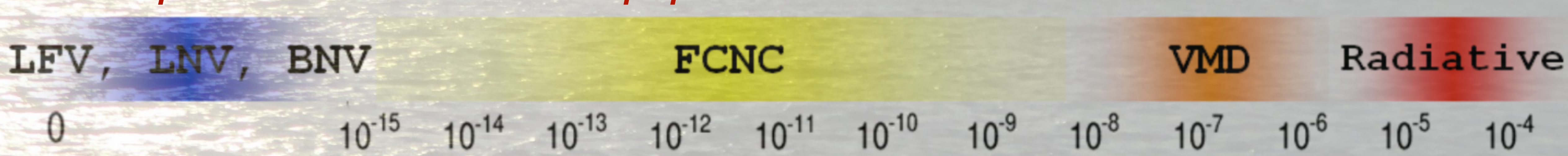
Search for forbidden and rare leptonic decays

"Search for the lepton-flavour violating decay $D^0 \to e\mu$"

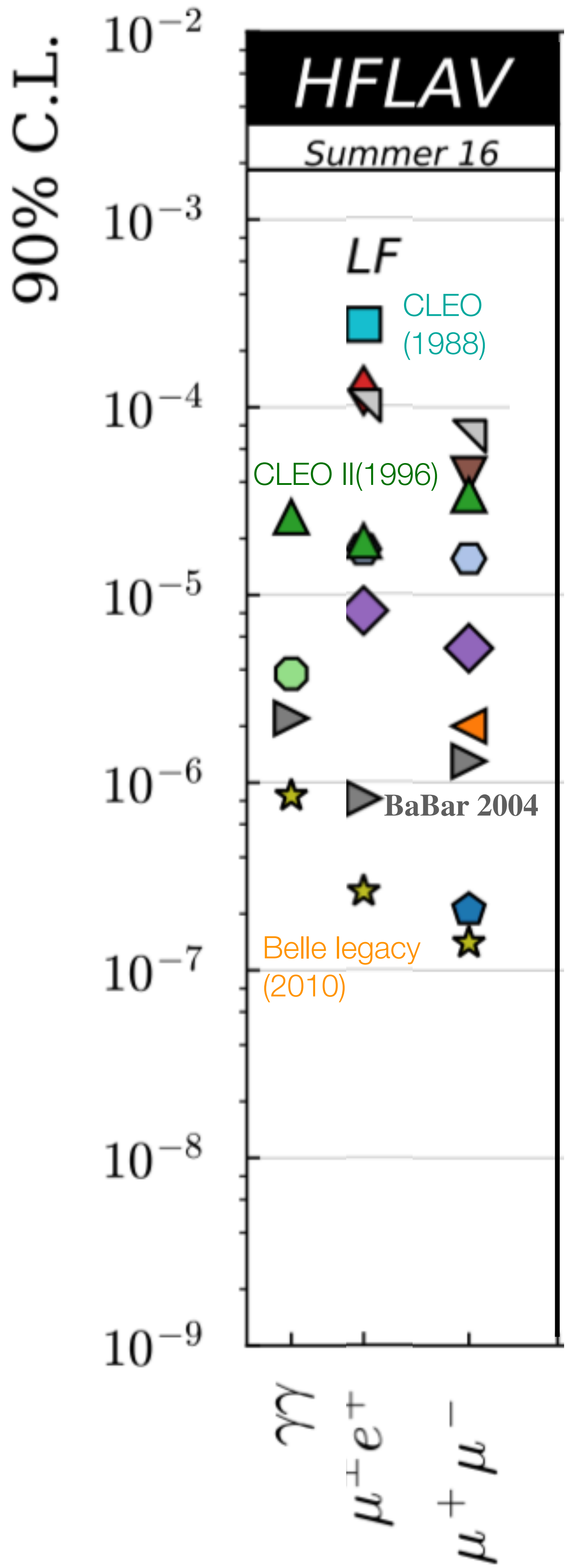
PLB 754 (2016) 167

"Search for the rare decay $D^0 \to \mu^+\mu^-$" PLB 725 (2013) 15-24

$D^0 \to e^\pm\mu^\mp$ $D^0 \to \mu^\pm\mu^\mp$



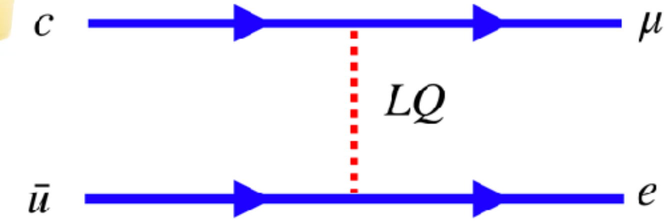
Forbidden and rare leptonic decays



$D^0 \rightarrow e^{\pm}\mu^{\mp}$

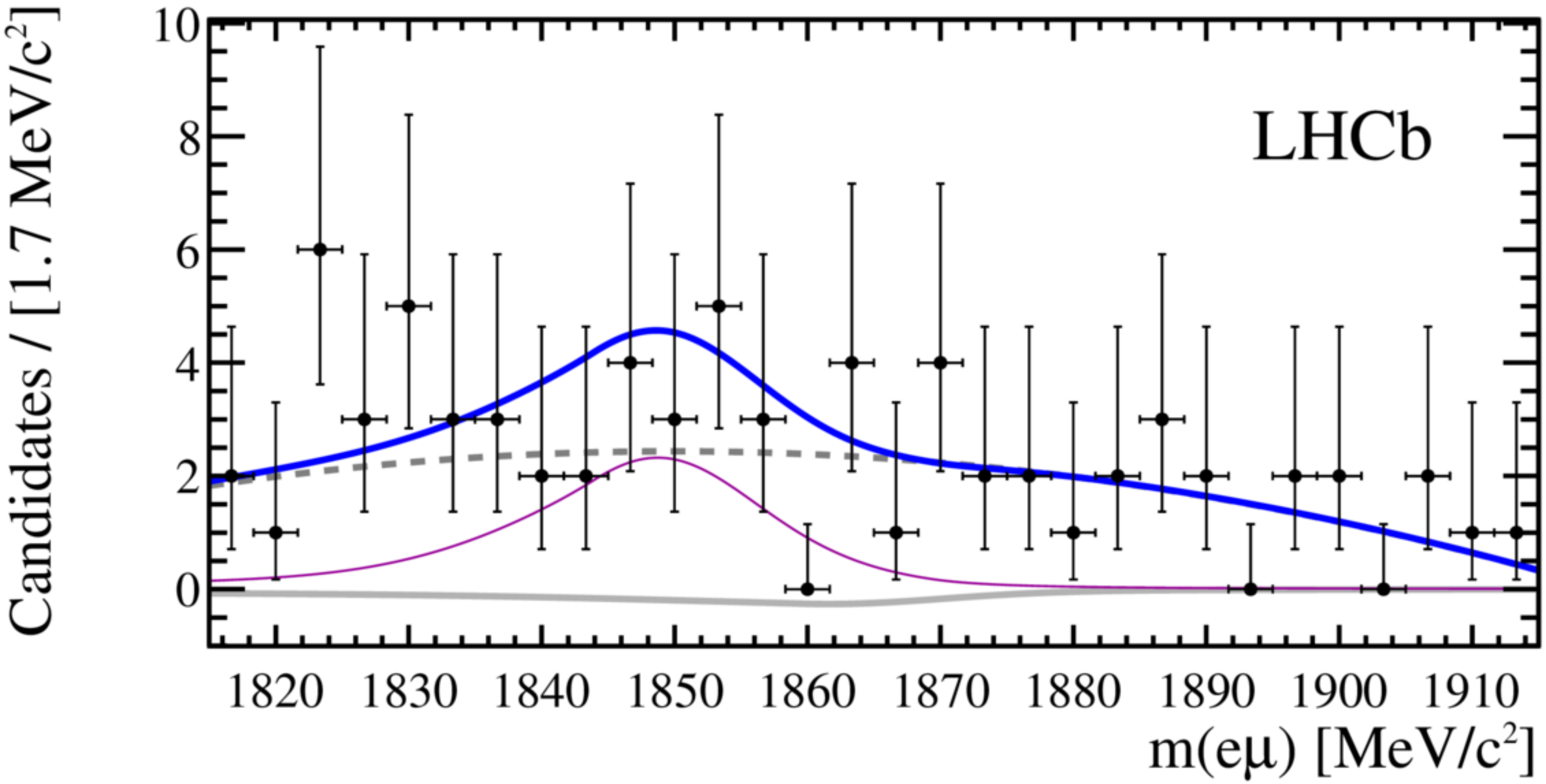
- strictly forbidden in the SM
  - any signal clear indication of NP
  - SM extensions: BF in [10^{-14}-10^{-6}]

clean null test!



Search for decay $D^0 \rightarrow \mu^+\mu^-$

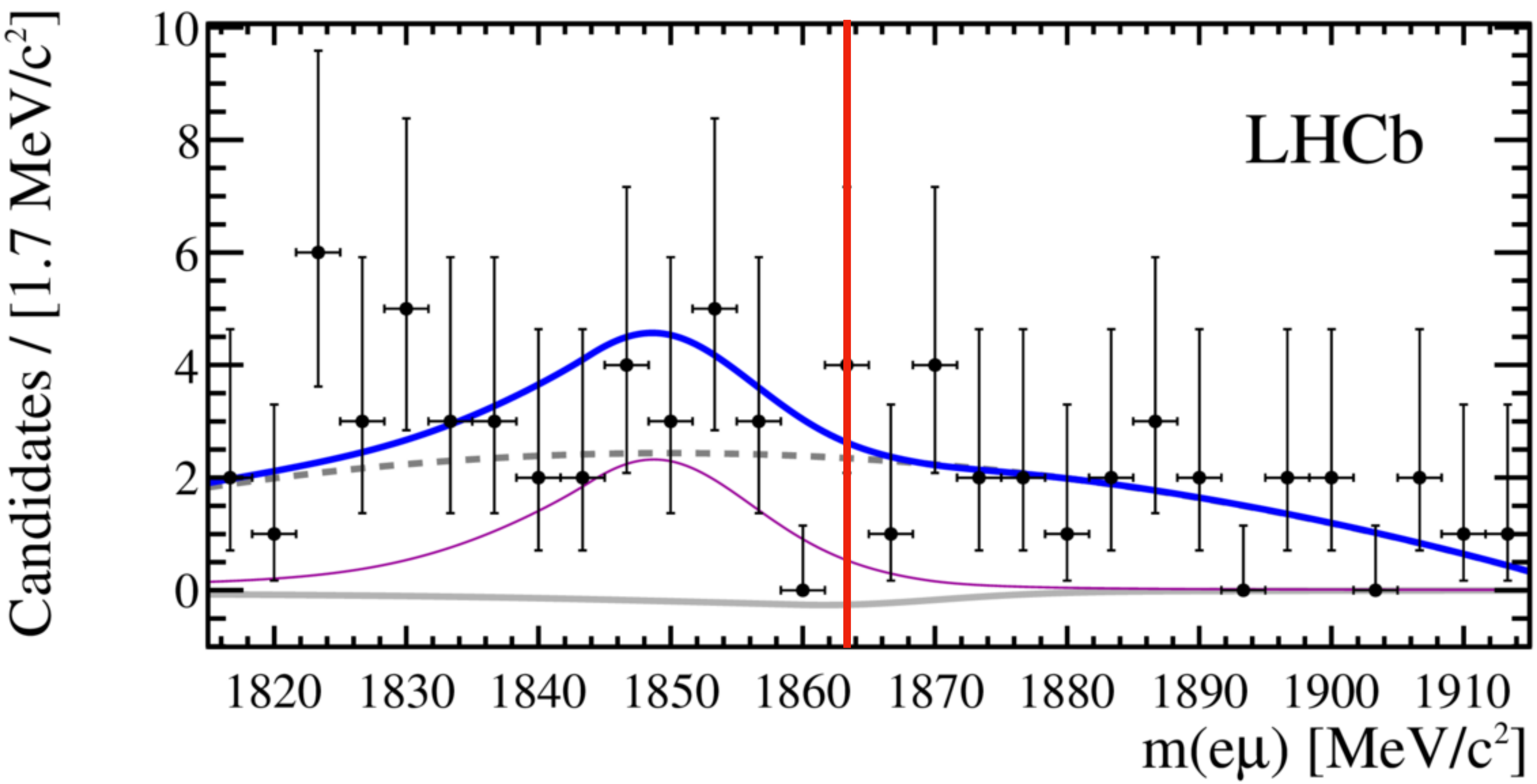
PLB 725 (2013) 15-24



Search for decay $D^0 \rightarrow \mu^+\mu^-$

PLB 725 (2013) 15-24

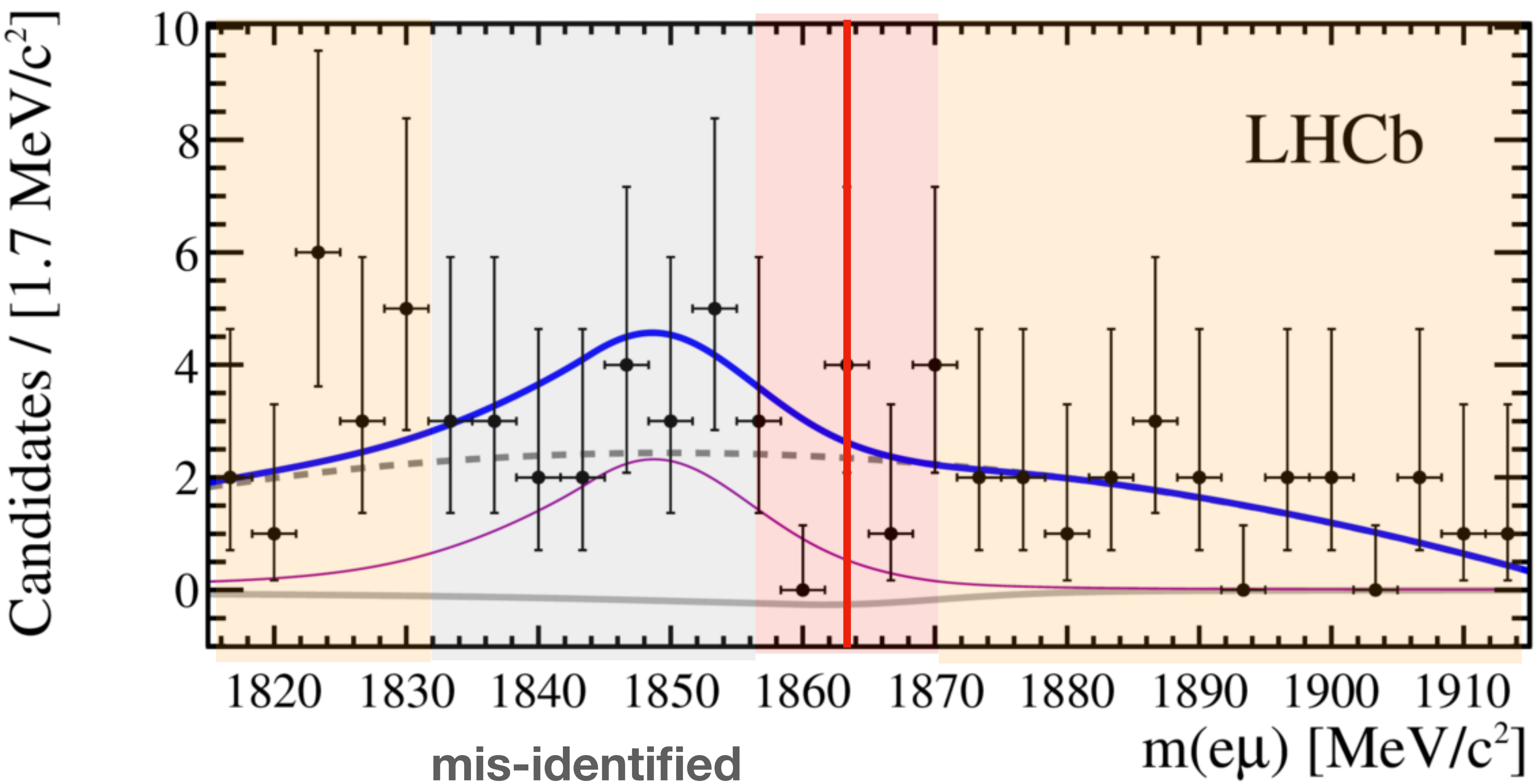
$D^0 \rightarrow \mu^+\mu^-$ Signals



Search for decay $D^0 \to \mu^+\mu^-$

PLB 725 (2013) 15-24

$D^0 \to \mu^+\mu^-$ Signals



mis-identified $D^0 \to \pi^+\pi^-$ decays

Combinatorial Background

Search for decay $D^0 \to \mu^+\mu^-$

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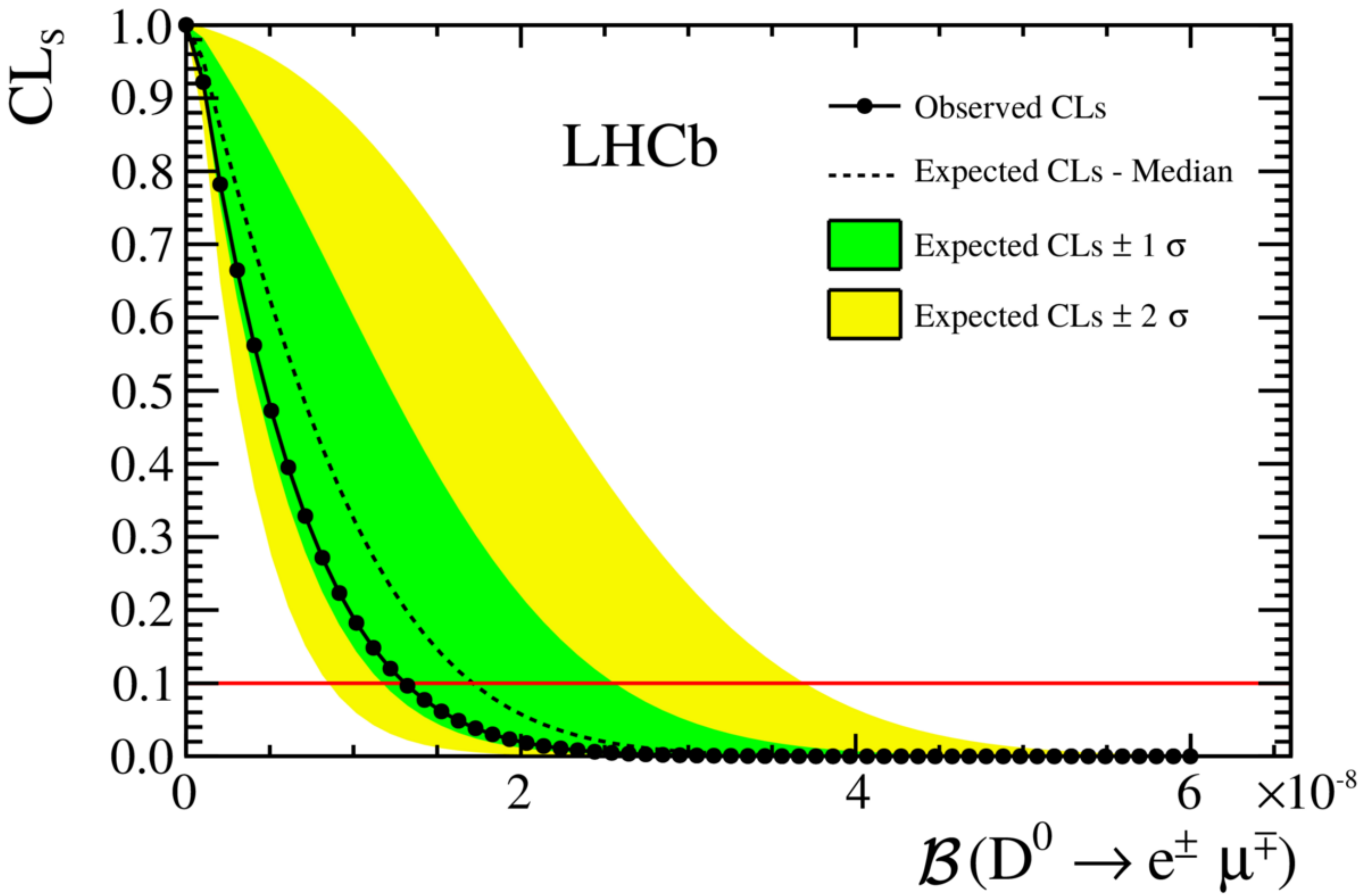
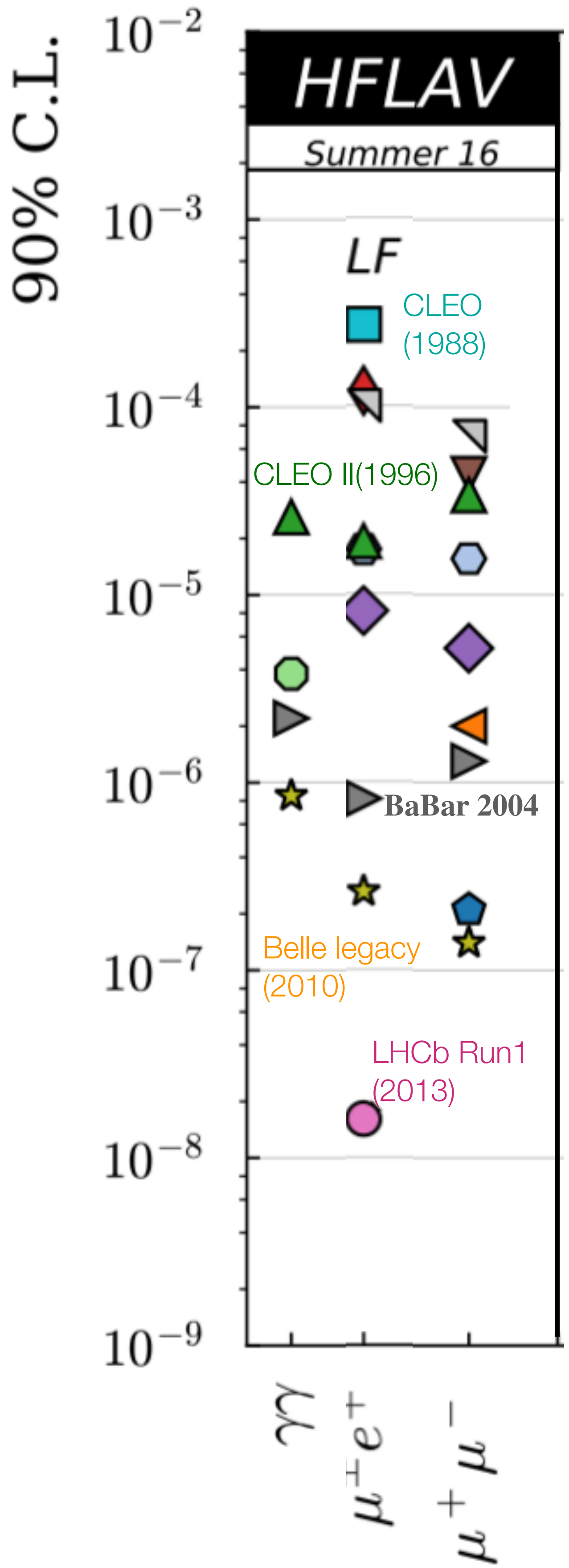
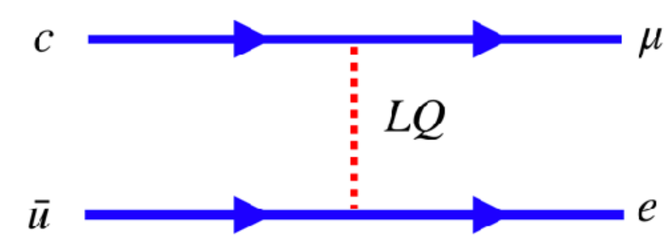


Forbidden and rare leptonic decays



$D^0 \rightarrow e^{\pm}\mu^{\mp}$

- strictly forbidden in the SM — clean null test!
  - any signal clear indication of NP
  - SM extensions: BF in [10^{-14}-10^{-6}]

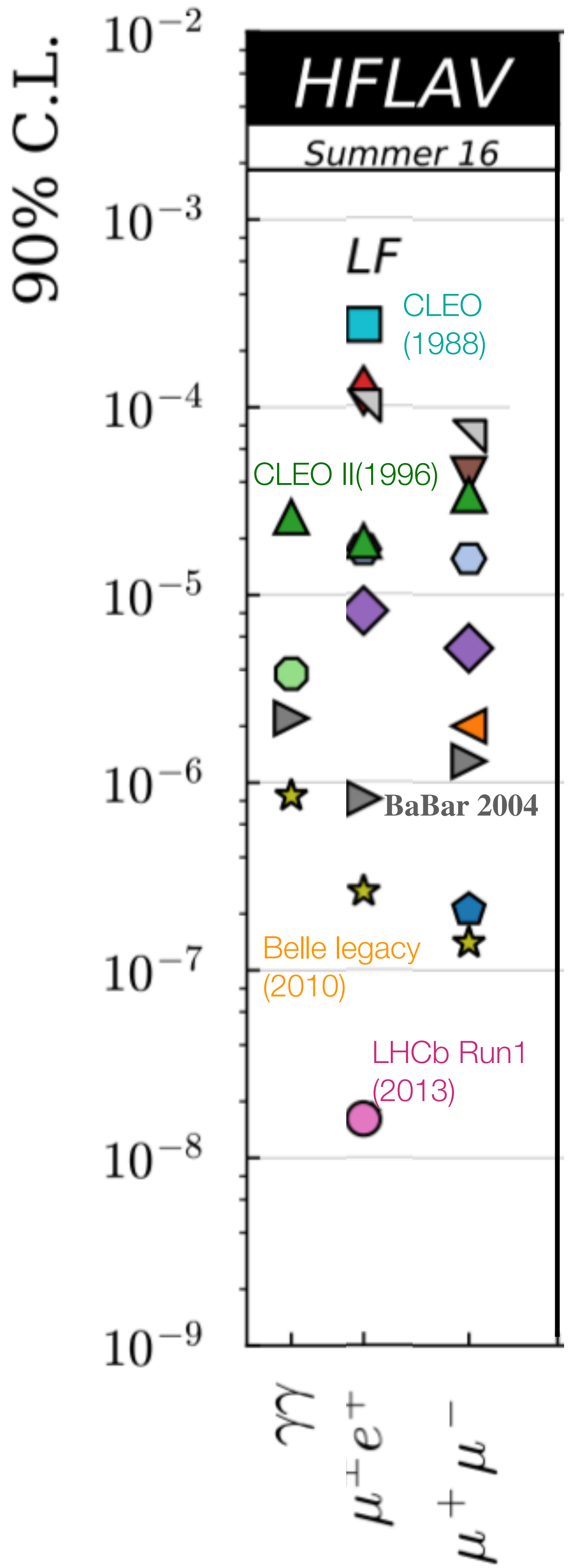


$$\mathcal{B}(D^0 \rightarrow e^{\pm}\mu^{\mp}) < 1.3 \times 10^{-8} \text{ at } 90\% \text{ CL}$$

(LHCb 3/fb Run1)

PLB 754 (2016) 167

Forbidden and rare leptonic decays



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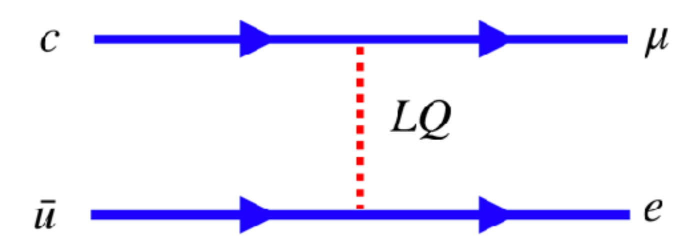

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(LHCb 3/fb Run1)

PLB 754 (2016) 167

$D^0 \rightarrow \mu^\pm\mu^\mp$

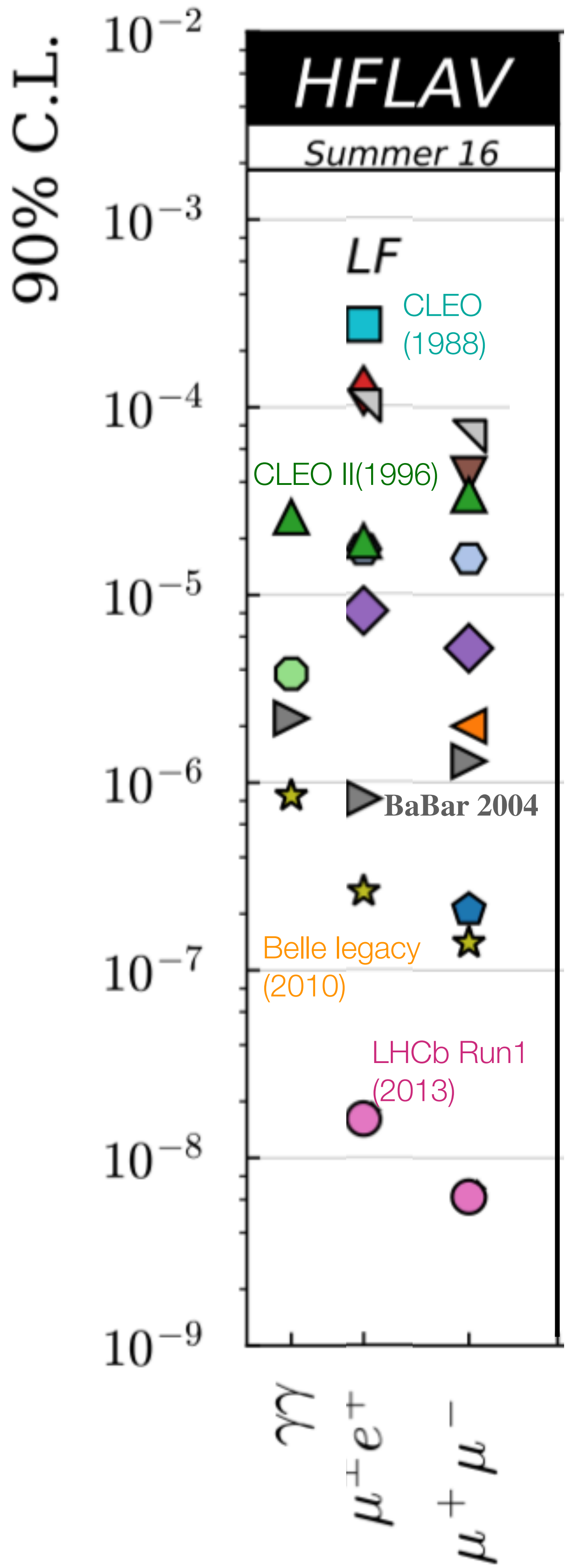
- SM BF extremely low, dominated by two-photon intermediate state ~$O(10^{-13})$

PRD 66 (2002) 014009
PRD 79 (2009) 114030
PRD 82 (2010) 094006
PRD 93 (2016) 074001

- in NP scenarios $BF_{NP} \lesssim BF_{EXP}$

PLB 725 (2013) 15-24

Forbidden and rare leptonic decays



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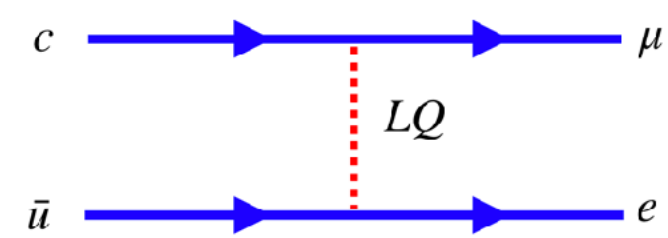

  - any signal clear indication of NP
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(LHCb 3/fb Run1)

PLB 754 (2016) 167

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- in NP scenarios $BF_{NP} \lesssim BF_{EXP}$

PLB 725 (2013) 15-24

$$\mathcal{B}(D^0 \to \mu^{+}\mu^{-}) < 6.2 \times 10^{-9} \text{ at } 90\% \text{ CL}$$

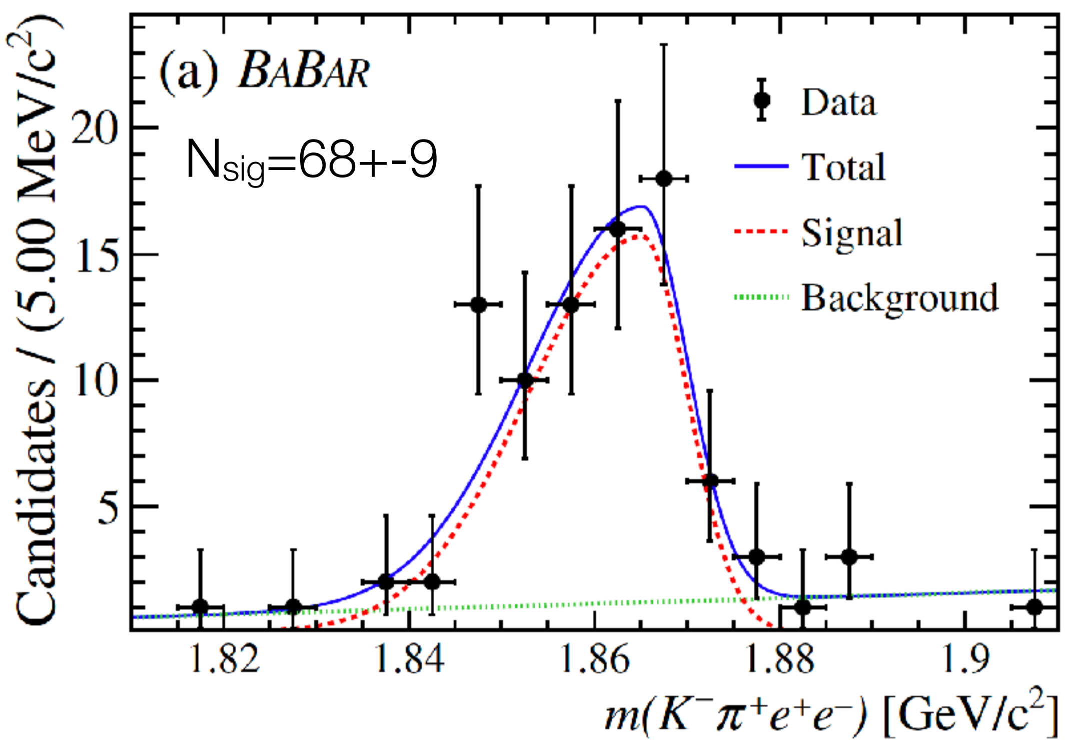
(LHCb 1/fb Run1)

update in the pipeline with full LHCb data set

Electron Modes

- Only one observed electron mode $D^0 \to K^-\pi^+e^-e^+$ (BaBar)
  - Measurement restricted to m(e+e-) in [675-875] MeV

PRL 122 (2019) 081802



$$\mathscr{B}(D^0 \to K^-\pi^+e^-e^+) = (4.0 \pm 0.5 \pm 0.2 \pm 0.1) \times 10^{-6}$$

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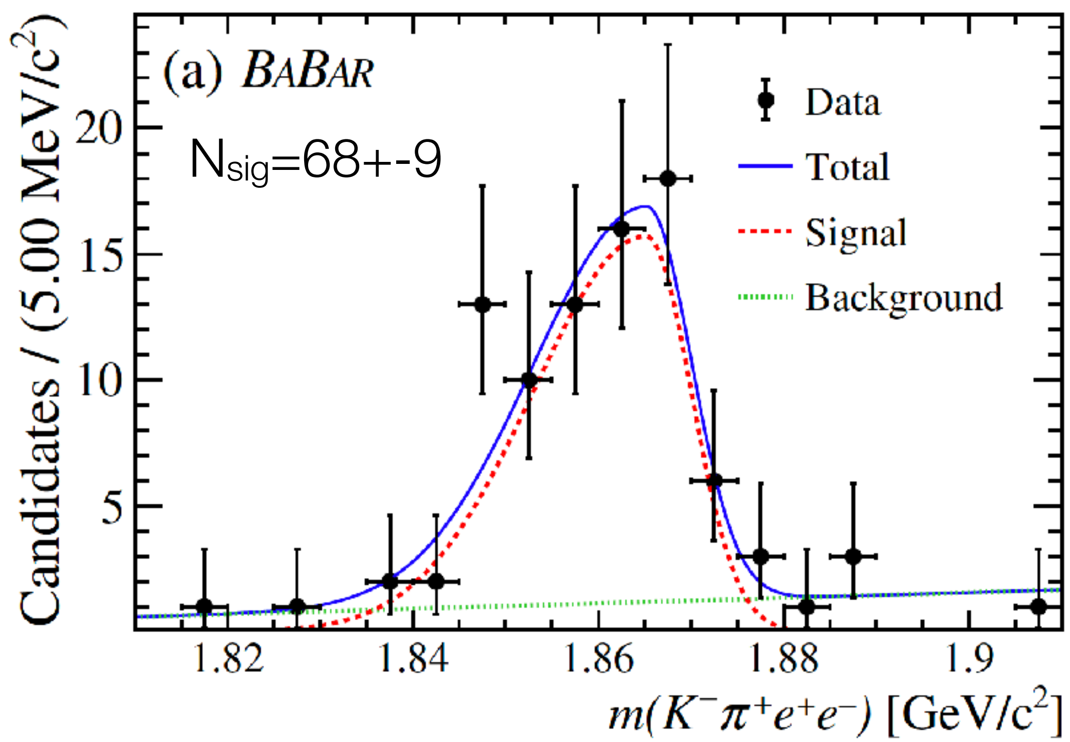
PRL 122 (2019) 081802



$$R^D_{K\pi} = 1.03 \pm 0.17$$

*private average

"Proof of principles" decay not sensitive to FCNC processes!

$$\mathcal{B}(D^0 \to K^-\pi^+e^-e^+) = (4.0 \pm 0.5 \pm 0.2 \pm 0.1) \times 10^{-6}$$

$$\mathcal{B}(D^0 \to K^-\pi^+\ell^-\ell^+)$$
$$\sim 4 \times \mathcal{B}(D^0 \to \pi^-\pi^+\ell^-\ell^+)$$
$$\sim 25 \times \mathcal{B}(D^0 \to K^-K^+\ell^-\ell^+)$$

- Muonic mode has been measured by LHCb (2/fb)

PLB 757 (2016) 558

$$\mathcal{B}(D^0 \to K^-\pi^+\mu^-\mu^+) = (4.12 \pm 0.12 \pm 0.38) \times 10^{-6}$$

uncertainties are statistical, systematic