Rare leptonic and semileptonic charm decays at LHCb

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FSP LHCb
Erforschung von
Universum und Materie

UNIVERSITÄT
HEIDELBERG
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SEIT 1386

Rare (semi)leptonic charm decays

- Rare decays: Branching ratios $\leq \mathcal{O}(10^{-6})$ and decays able to test Flavour Changing Neutral Currents (FCNC)

<u>Semileptonic transitions (FCNC)</u>

down-type	up-type
$b \to s l^+ l^-$	$t \to c l^+ l^-$
$b \to d l^+ l^-$	$t \to u l^+ l^-$
$s \to d l^+ l^-$	$c \to u l^+ l^-$

Rare (semi)leptonic charm decays

- Rare decays: Branching ratios $\leq \mathcal{O}(10^{-6})$ and decays able to test Flavour Changing Neutral Currents (FCNC)
- Charm decays provide a unique probe, only bound system to study up-typ FCNC
- Some New Physics (NP) models predict enhancements in decay rates, CP asymmetries or angular observables

Semileptonic transitions (FCNC)

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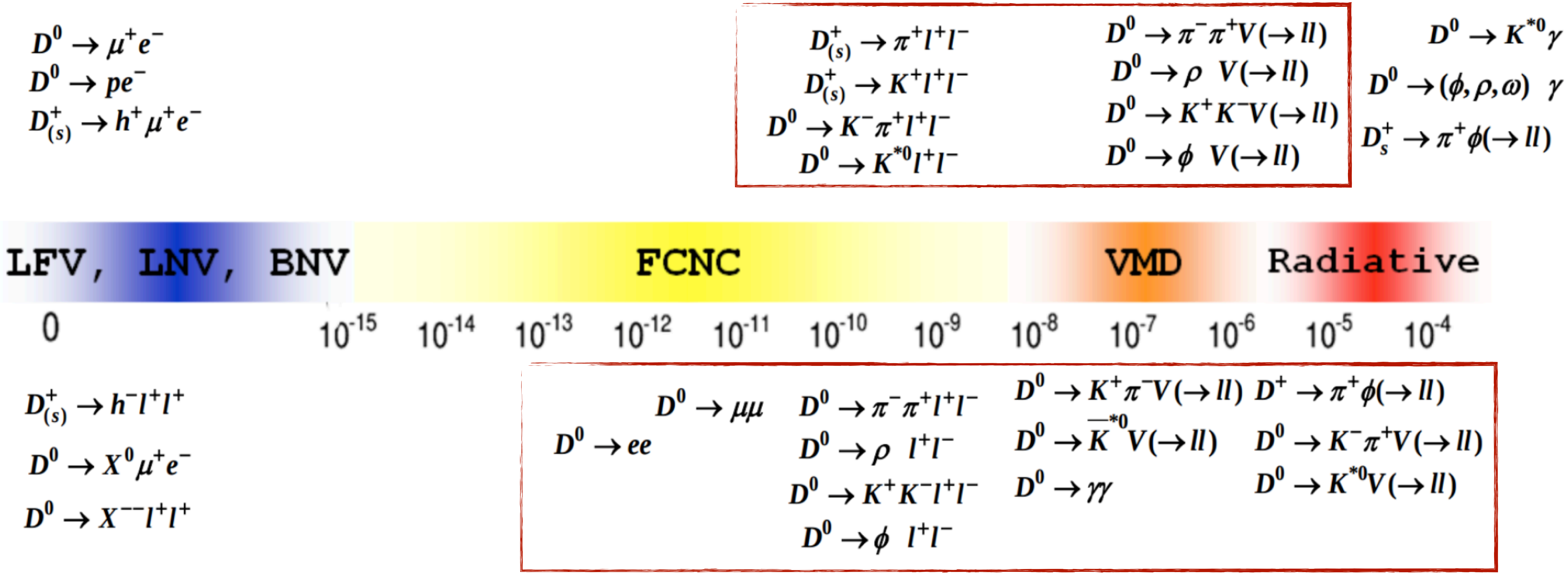
$b \to s l^+ l^-$	$t \to c l^+ l^-$
$b \to d l^+ l^-$	$t \to u l^+ l^-$
$s \to d l^+ l^-$	$c \to u l^+ l^-$

Landscape of rare and forbidden charm decays



Search for new physics

- Test new amplitudes

- Test new phases

- Test Lorentz structure

Search for new physics

- Test new amplitudes

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

- Test new phases

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

- Test Lorentz structure

$$\sim \bar{\Psi} \Gamma_{NP} \Psi$$

Search for new physics

- Test new amplitudes

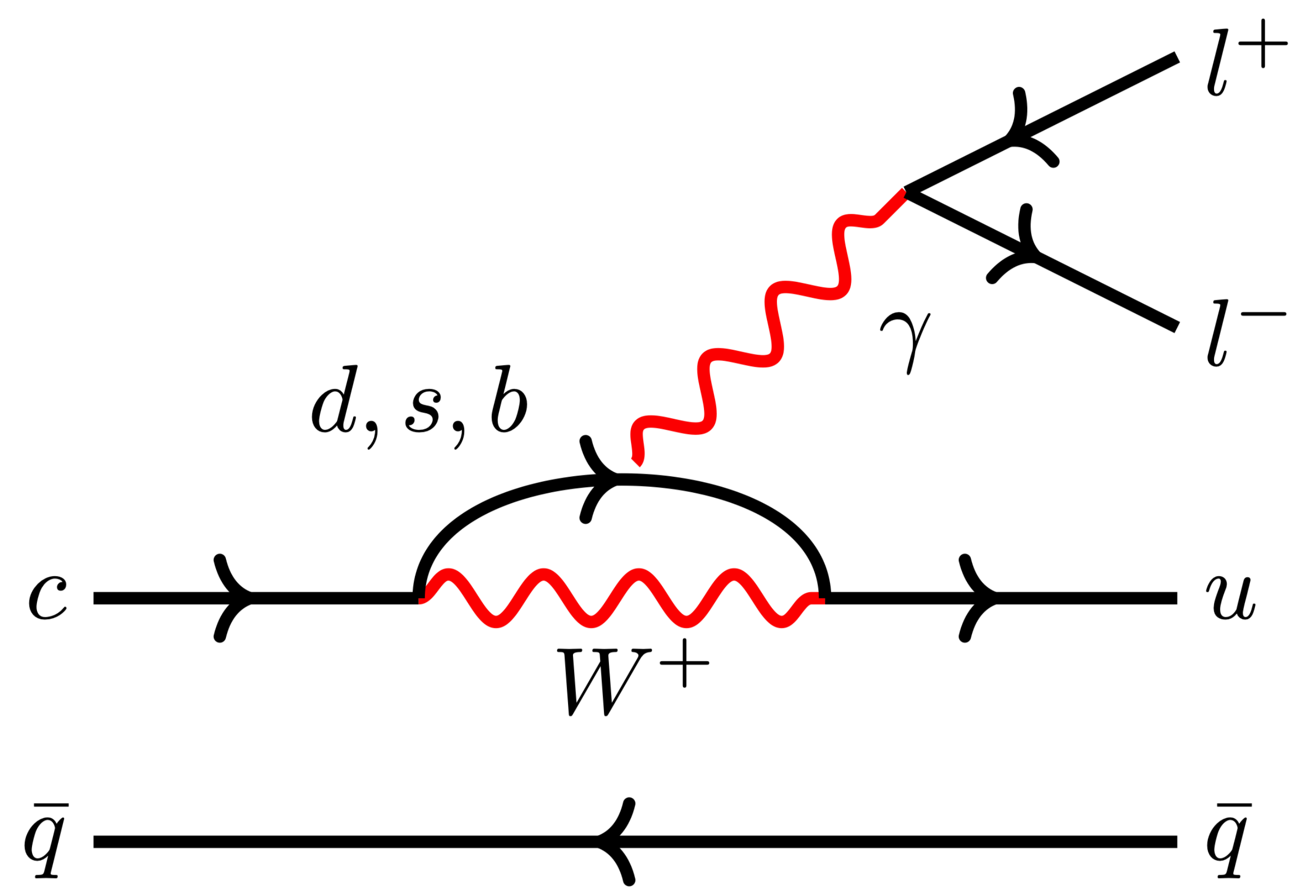
extremely suppressed due to GIM $\Rightarrow$ below experimental sensitivity $\mathscr{B} < \mathscr{O}(10^{-10})$

- Test new phases

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

- Test Lorentz structure

no lepton axial vector coupling due to GIM suppression
parity conservation



Search for new physics

- Test new amplitudes

$$\mathcal{A} = \mathcal{A}_0 \left(\frac{c_{SM}}{m_W^2} + \frac{c_{NP}}{\Lambda_{NP}^2} \right) \Rightarrow$$ Enhancements possible up to $\mathcal{O}(10^{-7})$

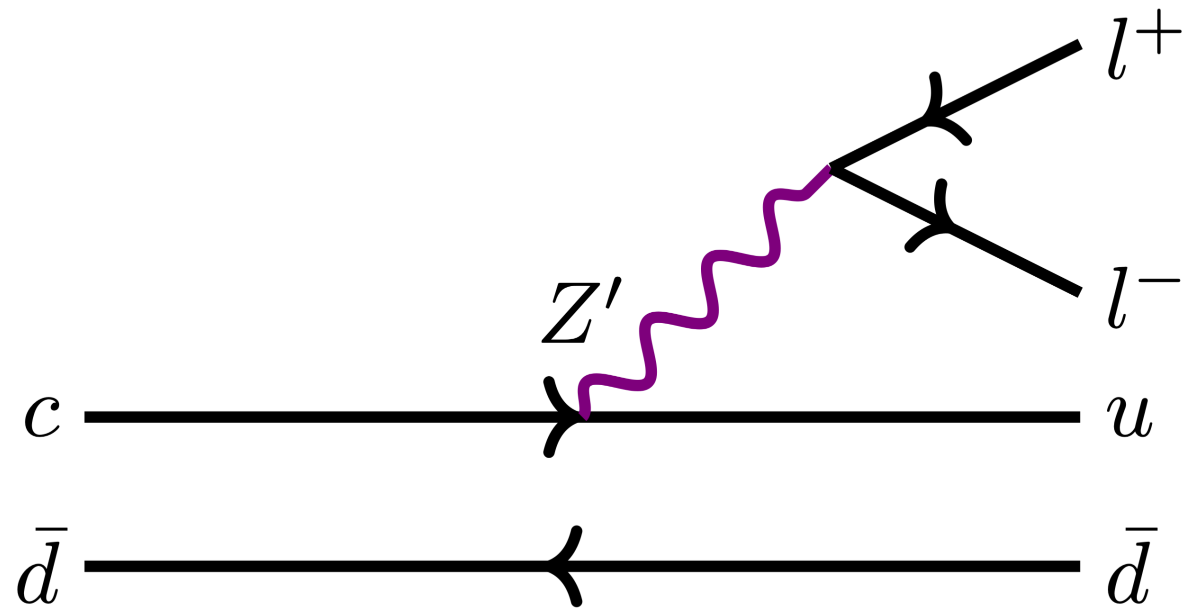
- Test new phases

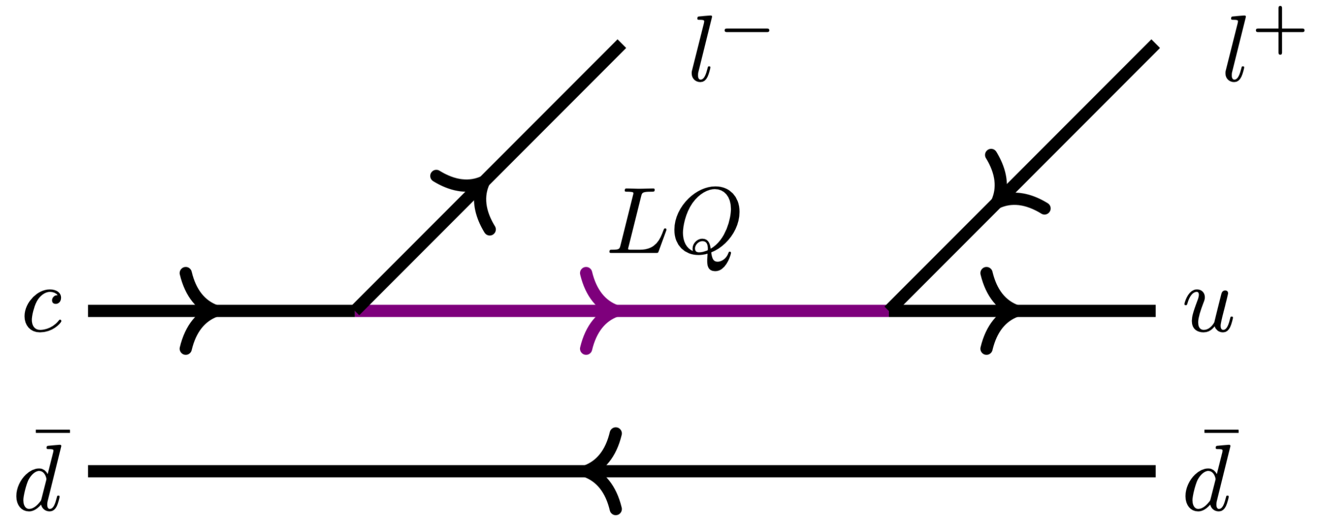
$$\sim |\mathcal{A}_{SM}||\mathcal{A}_{NP}| \sin \Delta\phi_{NP} \Rightarrow$$ CPV effects up to a few %

- Test Lorentz structure

$$\sim \bar{\Psi}\Gamma_{NP}\Psi \Rightarrow$$ modified or enhanced

New Physics contributions examples:

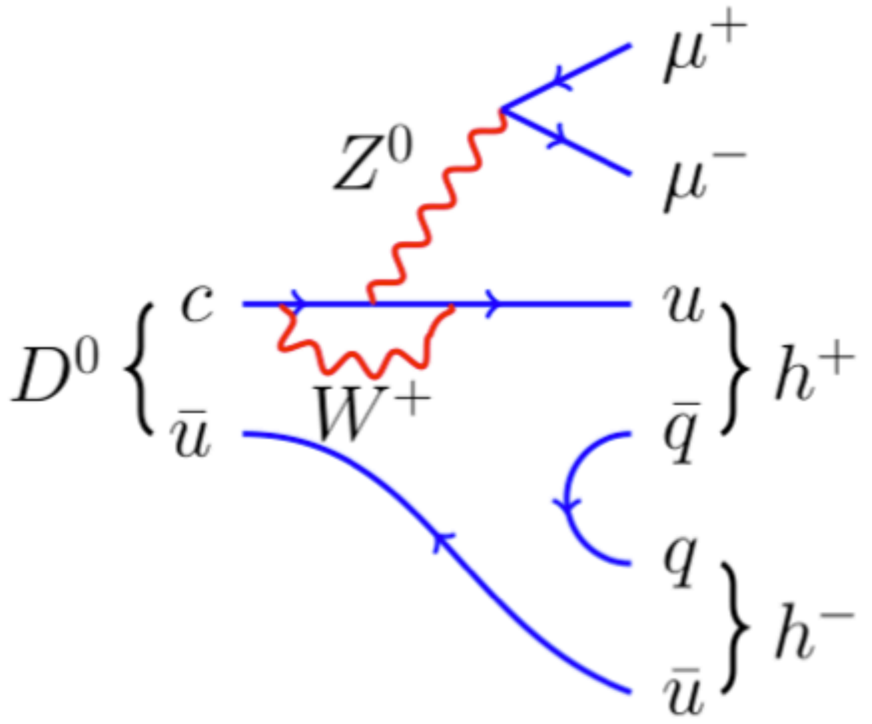




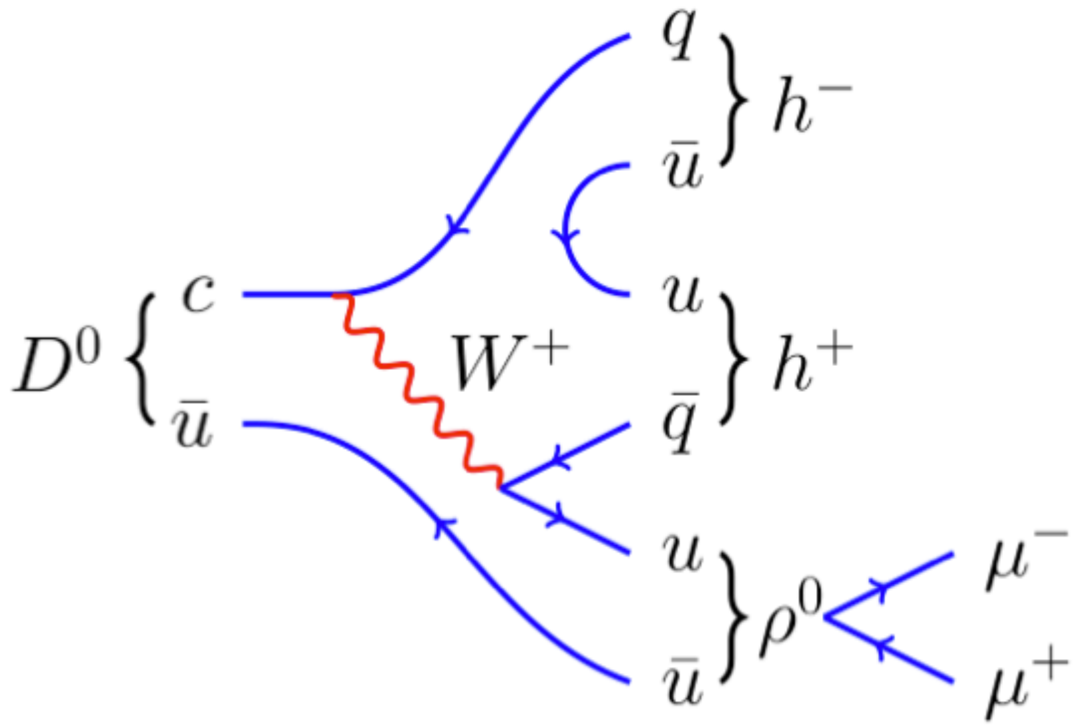
QCD effects

- Rare Charm decays are often dominated by Long Distance interactions (mesonic vector resonances) with tree-level dynamics competing with loop-diagrams.

Example Short Distance (SD) contribution:
Phys. Rev. Lett. **119**, 181805 (2017)



Example Long Distance (LD) contribution:
Phys. Rev. Lett. **119**, 181805 (2017)



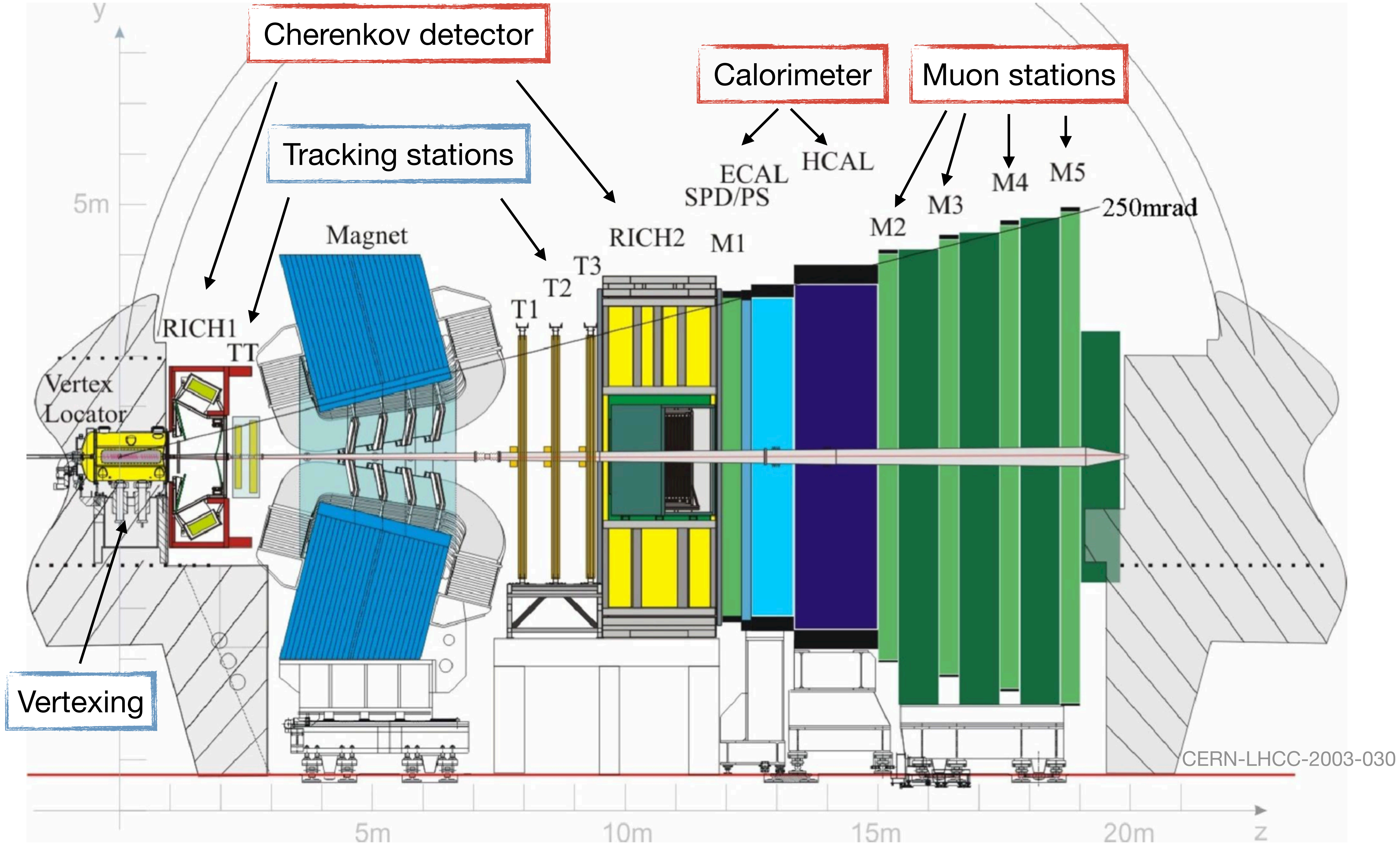
- Precise theoretical predictions are difficult for the branching fractions ($m_c \sim \Lambda_{QCD}$) resulting in predictions with high uncertainty.

- Task is to find ways to look for NP despite LD dominance:
  - Searches in certain regions of the phase space
  - Null tests based on (approximate) symmetries

The LHCb detector run 1&2 (2009-2018)

Int.J.Mod.Phys. A 30, 1530022 (2015)

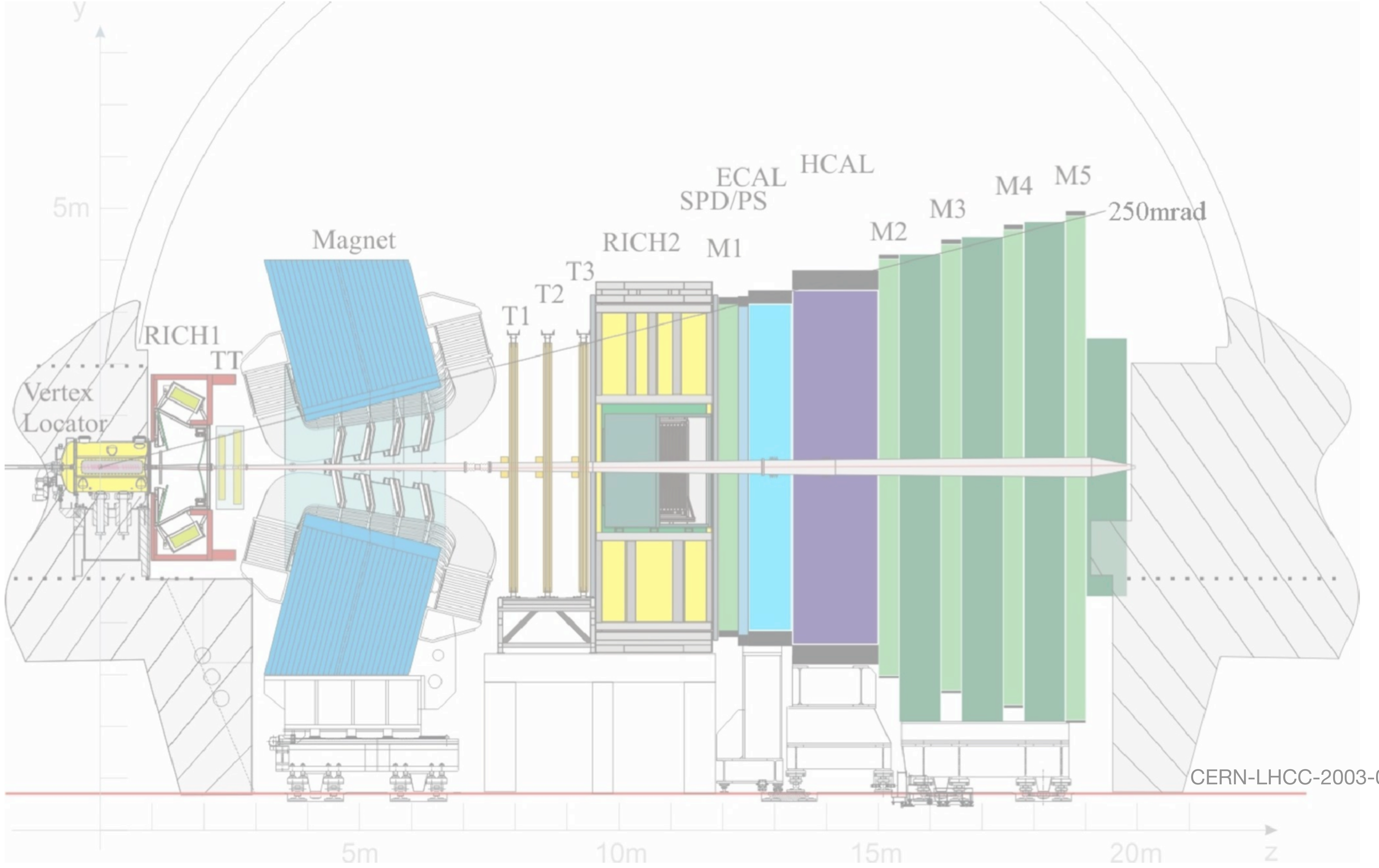
- LHCb is a forward spectrometer at the LHC, optimised to study b- and c-hadrons
- Excellent vertex resolution, momentum resolution $\sigma_p/p \sim 0.5\,\%$
- Particle identification with calorimeter, muon stations and Cherenkov detectors (RICH), particle misidentification rate $\sim 1\,\%$
- Worlds largest sample of charm decays: More than 10×10^{12} $c\bar{c}$ pairs produced within the LHCb acceptance between 2015 and 2018
  - The charm cross section is ~20 times larger than the b cross section [JHEP03(2016)159]



Detection of Leptons at LHCb

In general:

- Small transverse momentum → hard to trigger on (difficult but LHCb is build for this)



CERN-LHCC-2003-030

Detection of Leptons at LHCb

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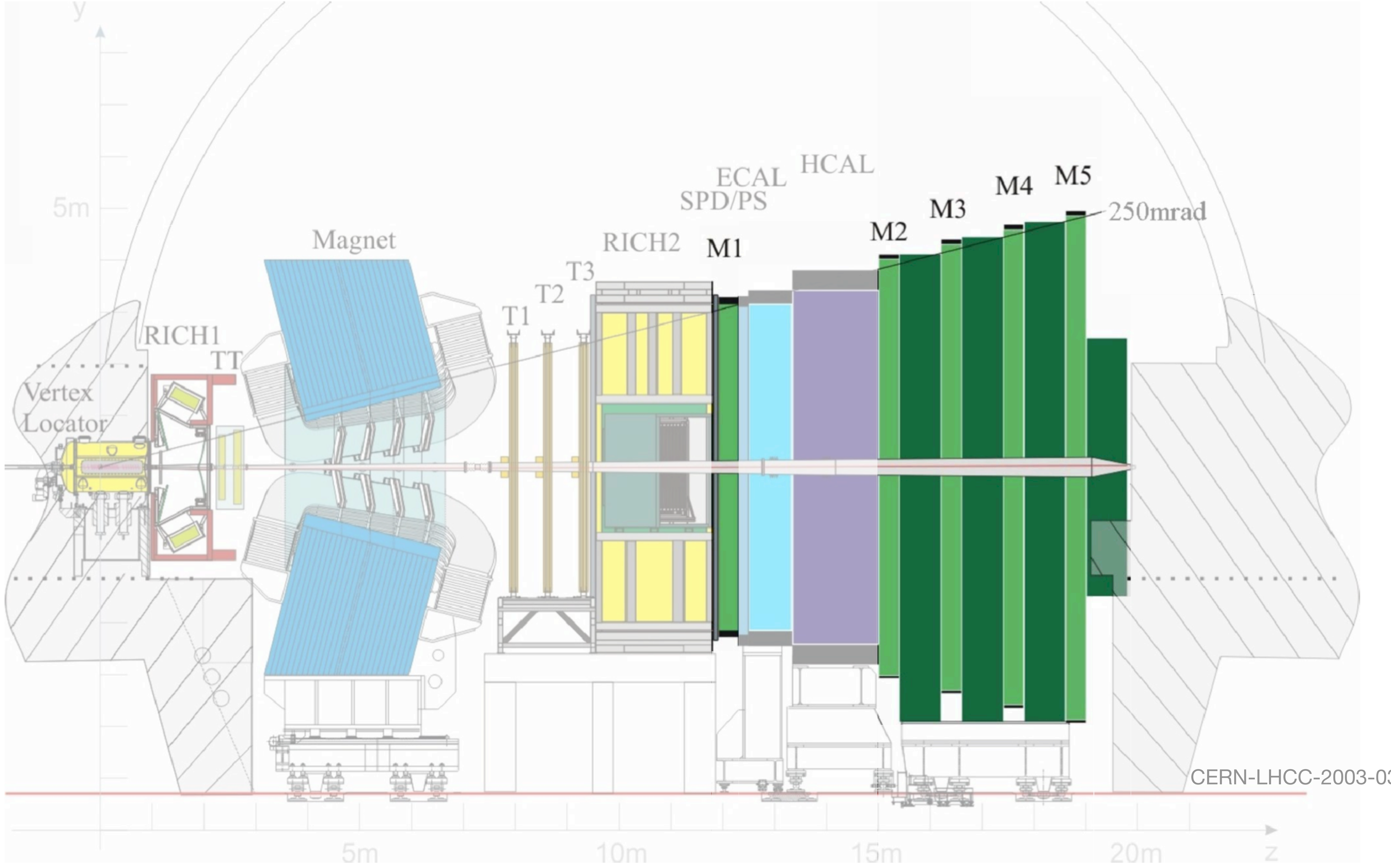
Muons:

- Dedicated muon chambers allow for excellent muon identification and reconstruction in addition to the tracking stations



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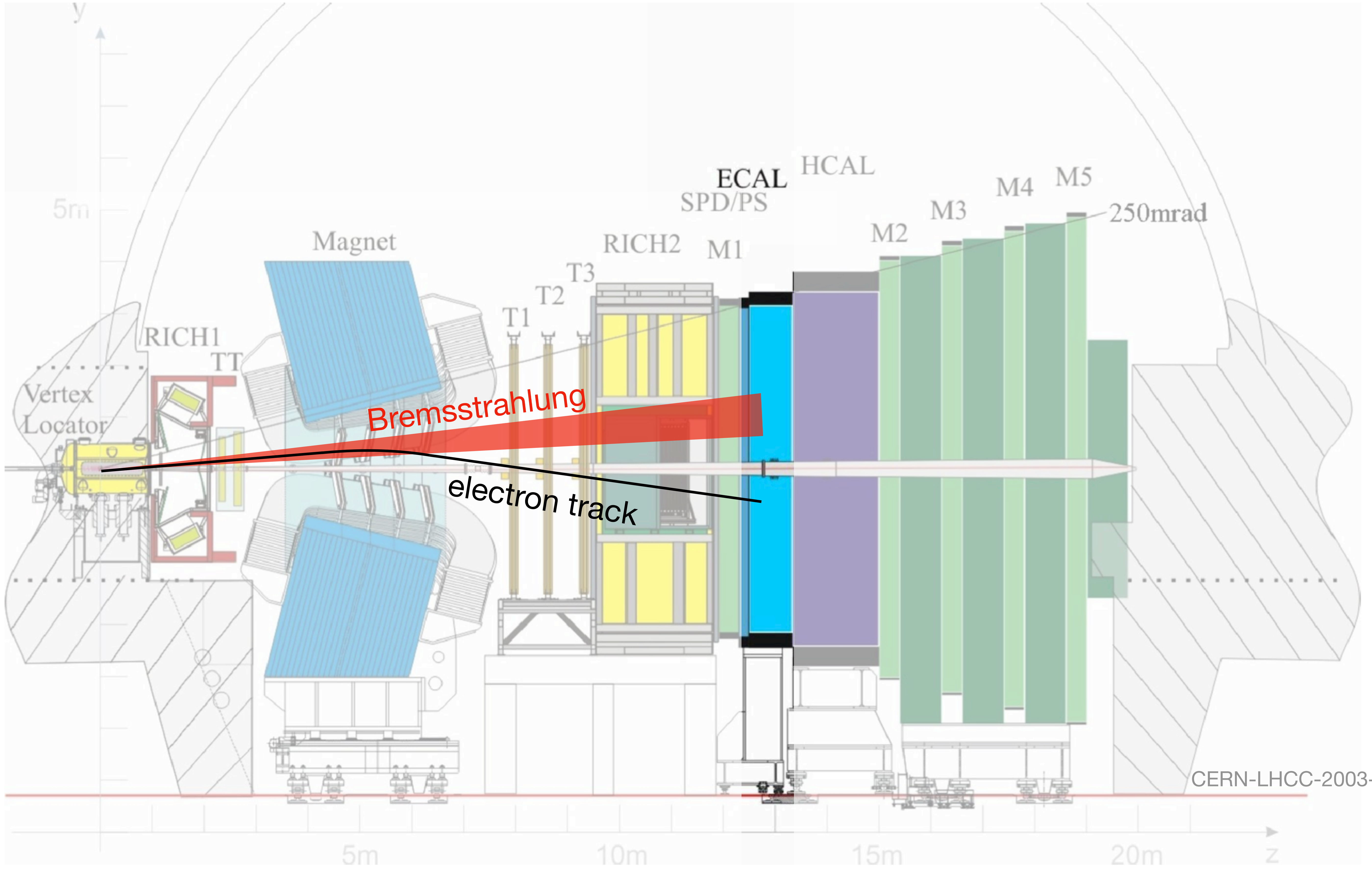
Electrons:

- The electron emits bremsstrahlung before magnet → limited efficiency on bremsstrahlung recovery



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Detection of Leptons at LHCb

JHEP 06 (2021) 044

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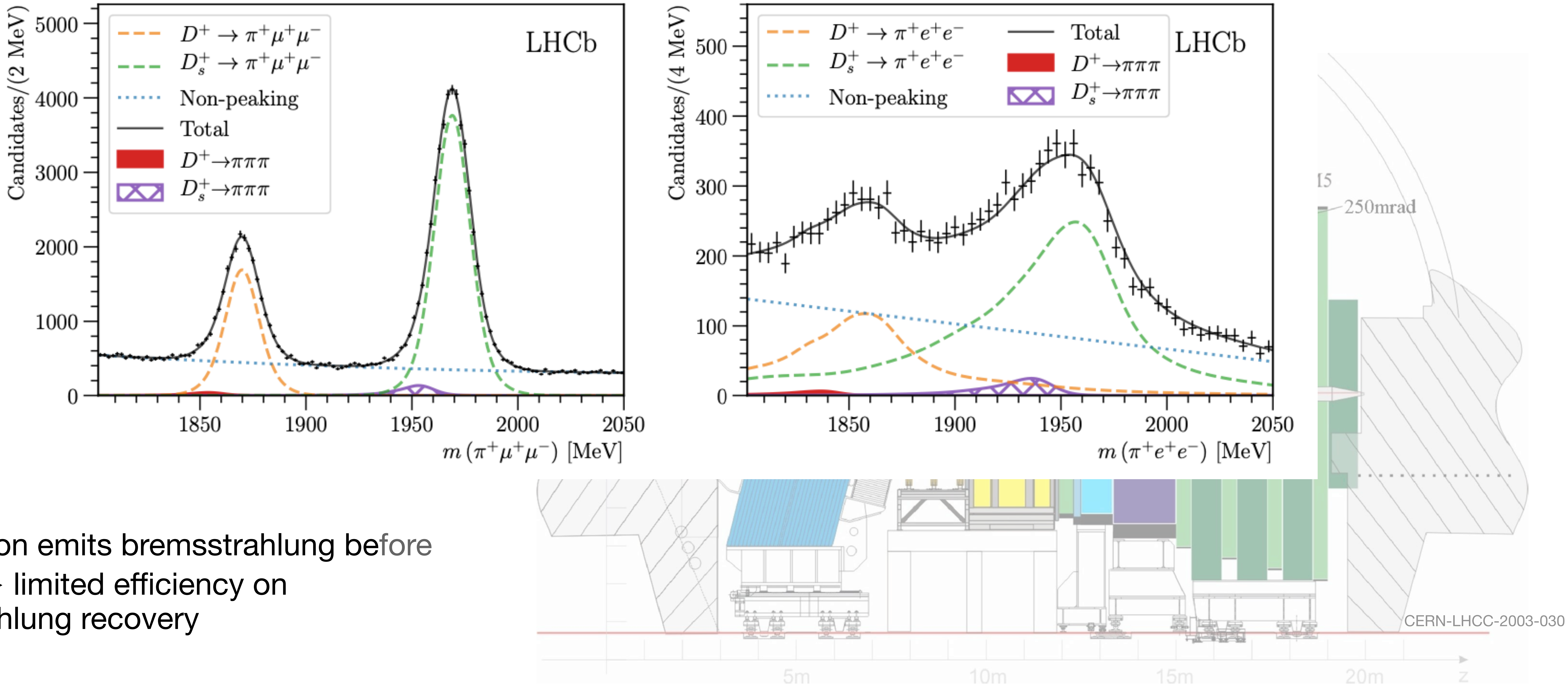

CERN-LHCC-2003-030

Story of rare (semi)leptonic charm decays at LHCb*

*omitting superseded measurements

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  Phys. Lett. B 757 (2016) 558
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Latest Measurements

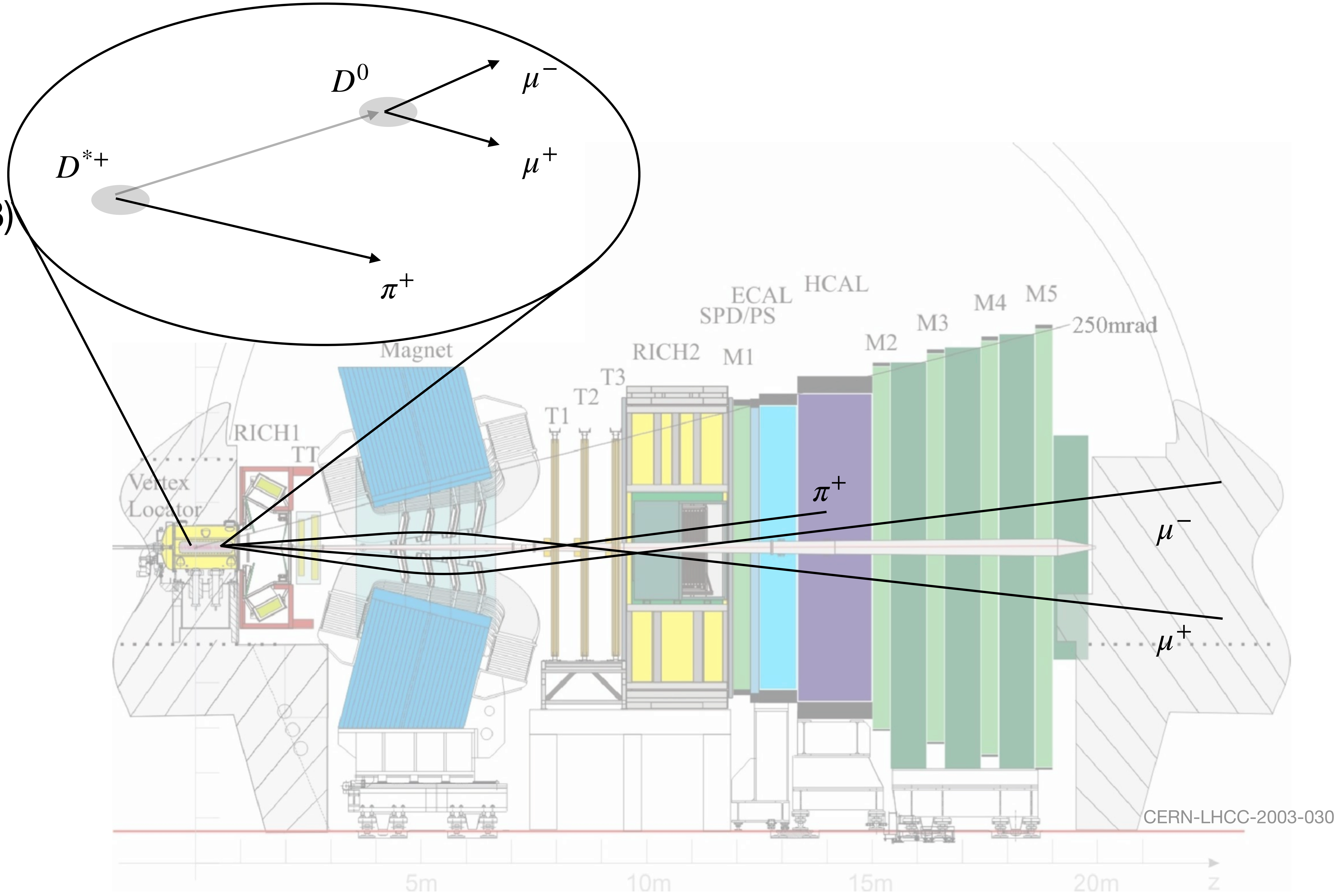
Search for the decay $D^0 \to \mu^+\mu^-$

arXiv:2212.11203v1 [hep-ex] 21 Dec 2022

Used dataset:

- Run 1 (2011-2012) and Run 2 (2015-2018)
- Center of mass energy: 7, 8 and 13 TeV
- Luminosity: $9.0\ \mathrm{fb}^{-1}$

High momentum muons (at least for charm decays) and final state contains no quarks!

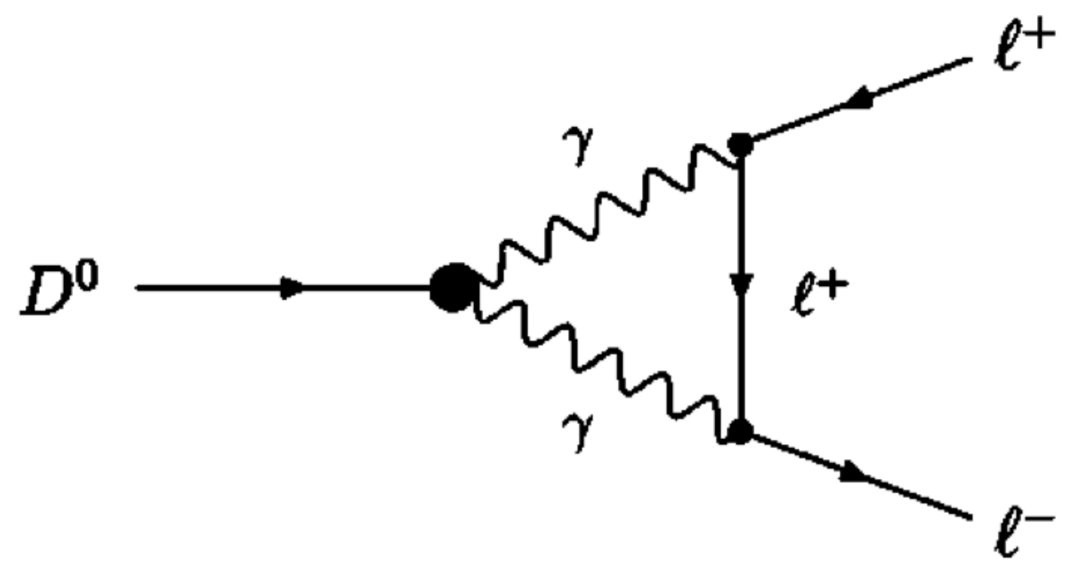


Search for the decay $D^0 \to \mu^+\mu^-$

arXiv:2212.11203v1 [hep-ex] 21 Dec 2022

Long distance contribution:

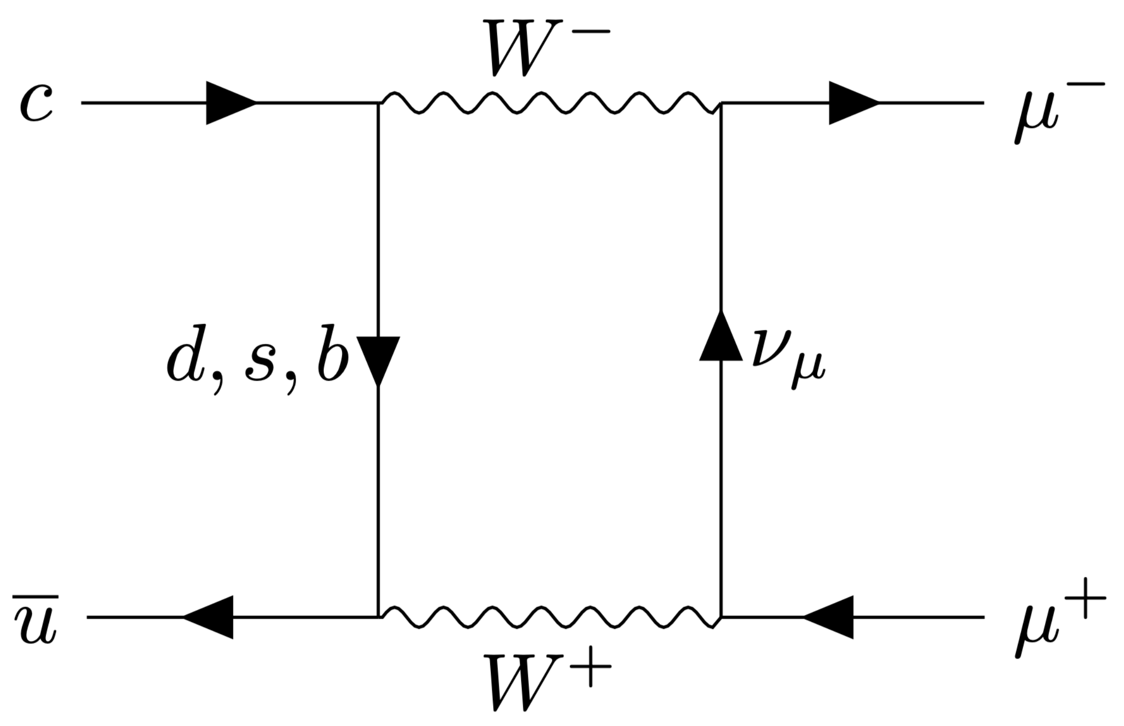
- Expected to be dominated by intermediate two γ state
  Phys. Rev. D 66, 014009 (2002)
- Expected branching ratio $\mathcal{O}(10^{-13})$
  Phys. Rev. D 66, 014009 (2002)
- Branching ratio contribution of intermediate two γ state below $\mathcal{O}(10^{-11})$ due to experimental limit on $D^0 \to \gamma\gamma$ by Belle
  Phys. Rev. D93 (2016) 051102



Phys. Rev. D 66, 014009 (2002)

Short distance contribution:

- Expected branching ratio $\mathcal{O}(10^{-18})$
  Phys. Rev. D 66, 014009 (2002)
- Strong chirality suppression
- Rate could be enhanced by NP!



$\rightarrow$ null test!

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

arXiv:2212.11203v1 [hep-ex] 21 Dec 2022

- Goal is to set a limit on or measure the branching ratio:

$$\mathcal{B}(D^0 \to \mu^+\mu^-) = \frac{N(D^0 \to \mu^+\mu^-)}{\sigma(pp \to D^0)\ \mathcal{L}^{int}} \times \frac{1}{\epsilon(D^0 \to \mu^+\mu^-)}$$

- Difficult to measure absolute rates at LHCb due to large uncertainties on cross section and luminosity

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

arXiv:2212.11203v1 [hep-ex] 21 Dec 2022

Determined by fit to the invariant D^0 mass and $\Delta m(\mu\mu)$

External input:
$\mathcal{B}(D^0 \to K^-\pi^+) \sim (10^{-2})$
$\mathcal{B}(D^0 \to \pi^-\pi^+) \sim (10^{-3})$

$$\mathcal{B}(D^0 \to \mu^+\mu^-) = \frac{N(D^0 \to \mu^+\mu^-)}{N(D^0 \to h^{(\prime)-}h^+)} \times \frac{\epsilon(D^0 \to h^{(\prime)-}h^+)}{\epsilon(D^0 \to \mu^+\mu^-)} \times \mathcal{B}(D^0 \to h^{(\prime)-}h^+)$$

From simulations, corrected and cross checked by data driven methods

- The relative branching fraction is normalised to $D^0 \to K^-\pi^+$ and $D^0 \to \pi^-\pi^+$ donated as $D^0 \to h^{(\prime)-}h^+$

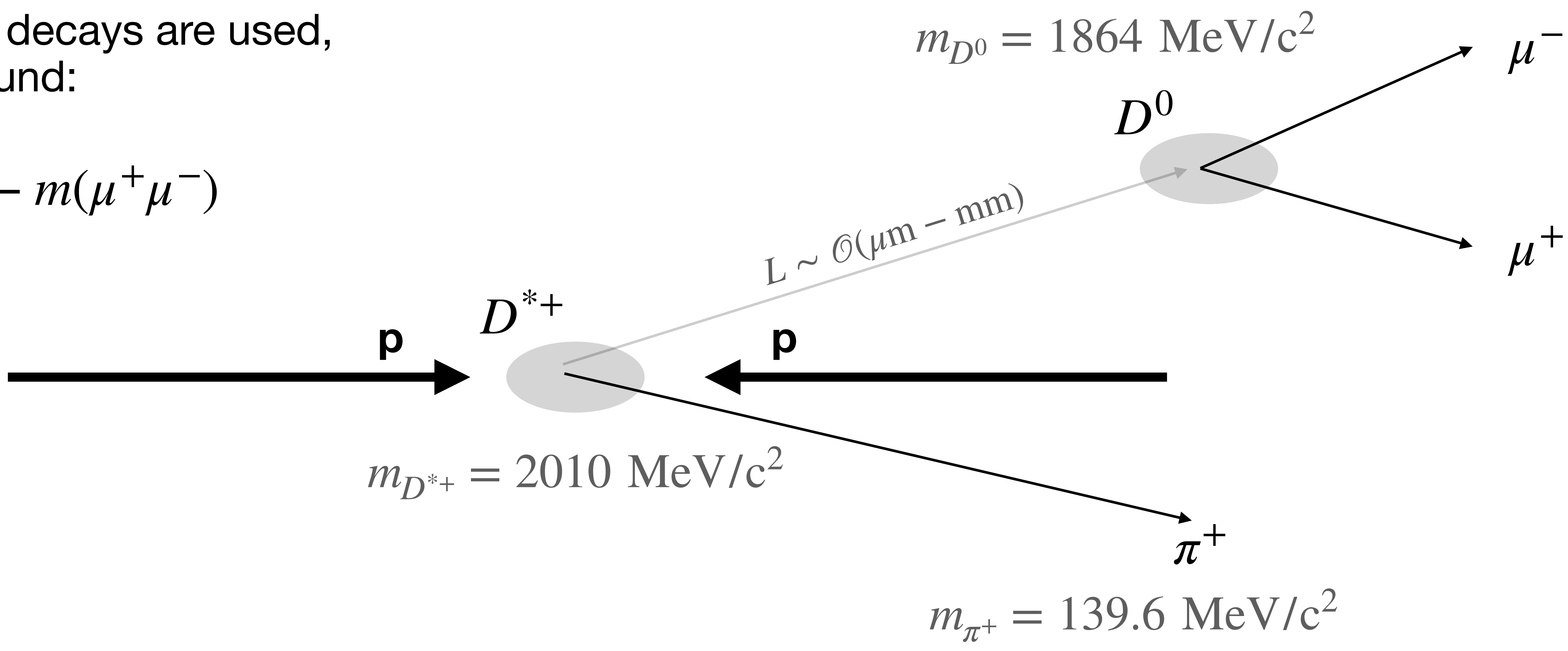
Search for the decay $D^0 \to \mu^+\mu^-$

arXiv:2212.11203v1 [hep-ex] 21 Dec 2022

- Topological and kinematic properties are used to reconstruct possible candidates

- D^0 produced in D^{*+} decays are used, to suppress background:

  $\Delta m = m(\mu^+\mu^-\pi^+) - m(\mu^+\mu^-)$



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

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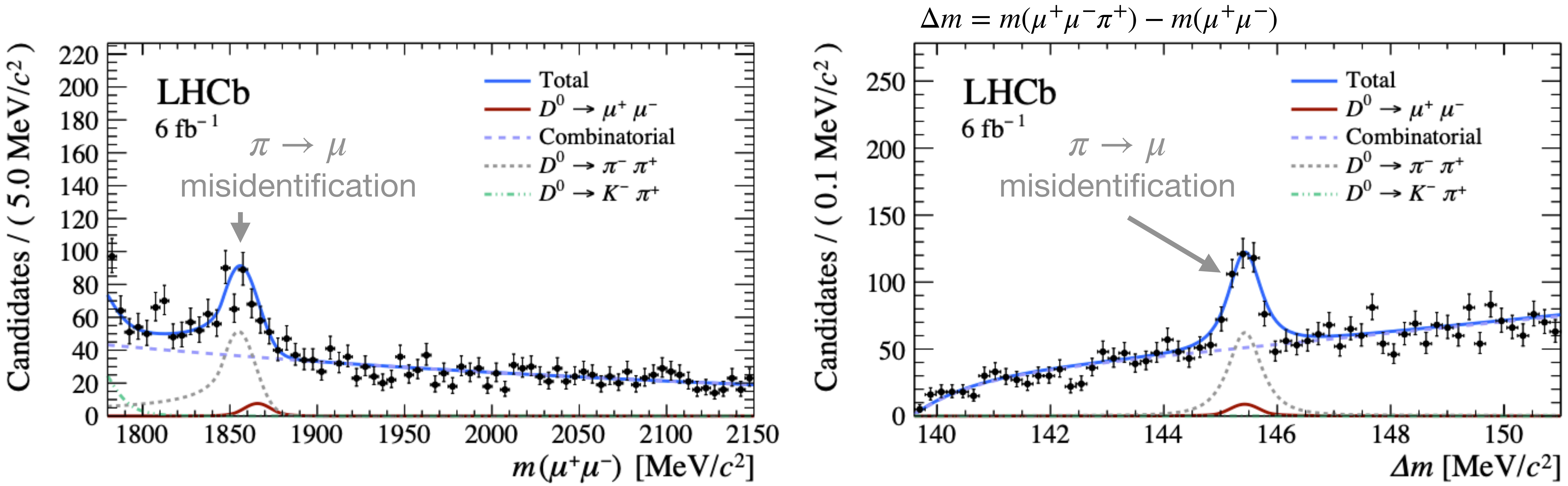

- Fit to $m(\mu\mu)$ and Δm

  $\Delta m = m(\mu^+\mu^-\pi^+) - m(\mu^+\mu^-)$

- Number of misidentified, $\pi \to \mu$, $D^0 \to \pi^+\pi^-$ decays constraint by MC studies

- Validated and crosschecked with data driven methods

- No significant signal is observed

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

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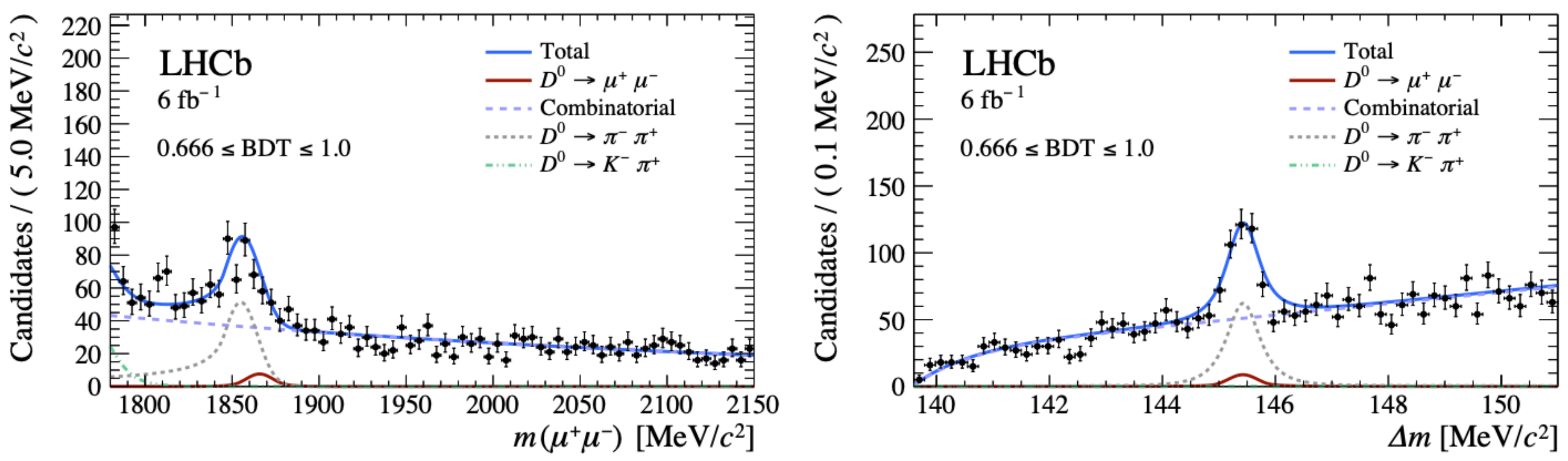
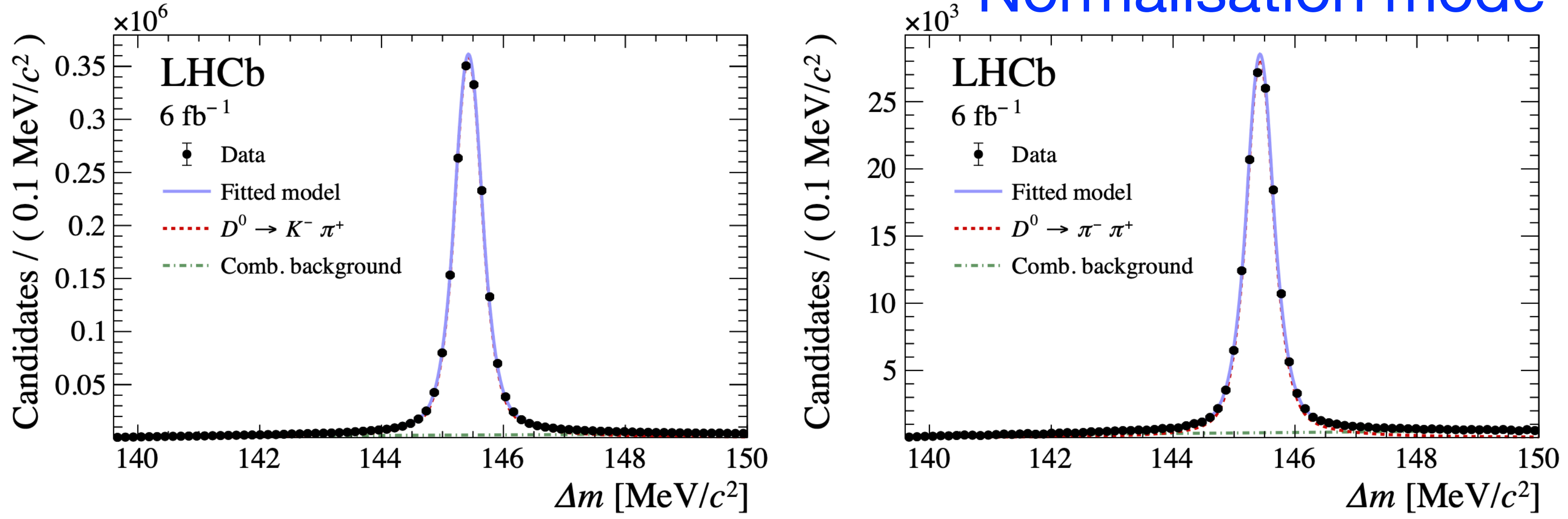
Signal mode



Normalisation mode



$$\mathscr{B}(D^0 \to \mu^+\mu^-) = \frac{N(D^0 \to \mu^+\mu^-)}{N(D^0 \to K^-\pi^+)} \times \frac{\epsilon(D^0 \to K^-\pi^+)}{\epsilon(D^0 \to \mu^+\mu^-)} \times \mathscr{B}(D^0 \to K^-\pi^+)$$

Most stringent limit on leptonic charm decays

$$\mathscr{B}(D^0 \to \mu^+\mu^-) \leq 3.1 \times 10^{-9} \ (90\,\%\ CL)$$

arXiv:2212.11203v1 [hep-ex] 21 Dec 2022

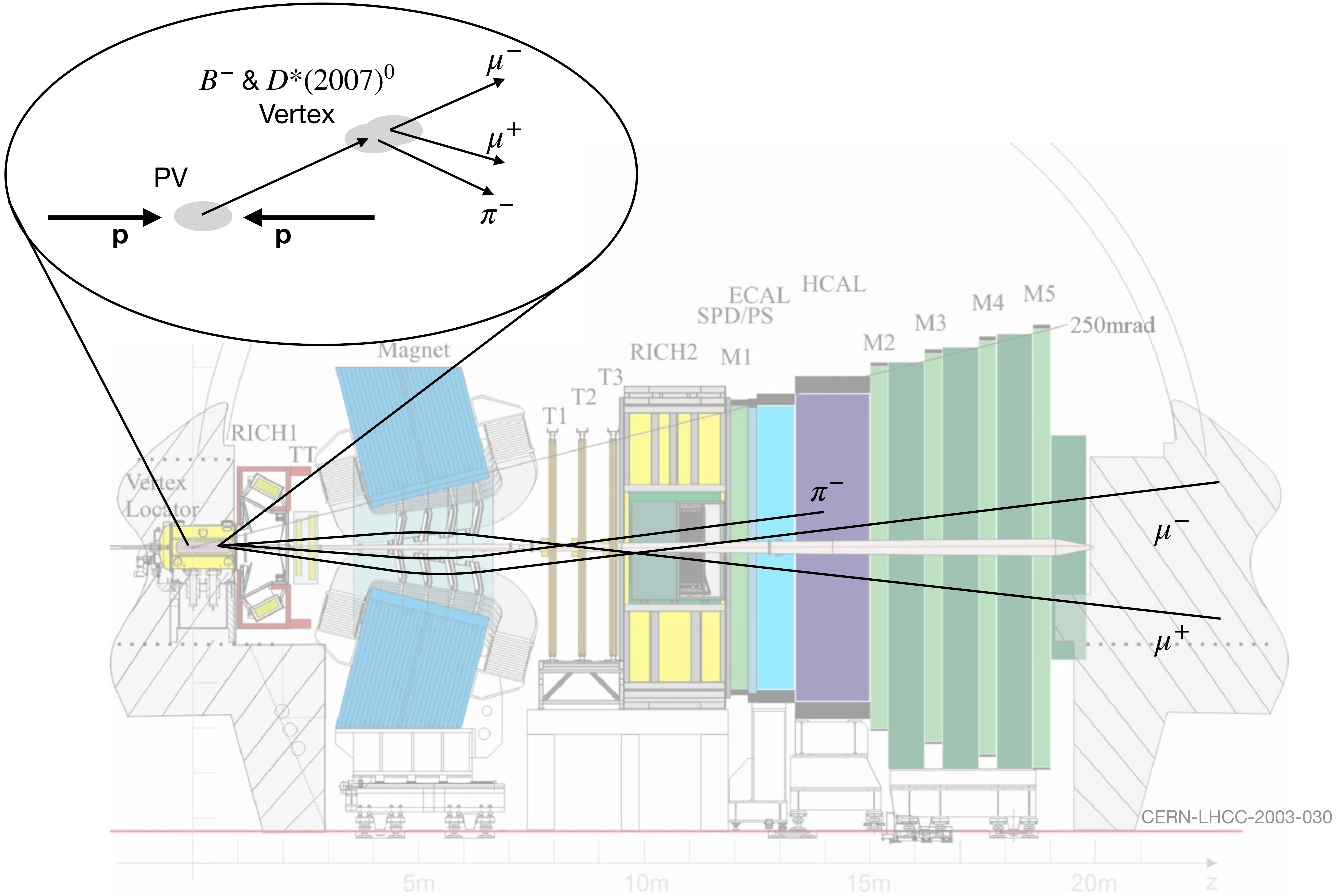
Search for the decay $D^*(2007)^0 \to \mu^+\mu^-$ in $B^- \to \pi^-\mu^+\mu^-$ decays

arXiv:2304.01981v2 [hep-ex] 5 Apr 2023

Used dataset:

- Run 1 (2011-2012) and Run 2 (2015-2018)
- Center of mass energy: 7, 8 and 13 TeV
- Luminosity: $9.0\ \mathrm{fb}^{-1}$

Using $D^*(2007)^0$ arising from B^- for better background separation



CERN-LHCC-2003-030

Search for the decay $D^*(2007)^0 \to \mu^+\mu^-$ in $B^- \to \pi^-\mu^+\mu^-$ decays

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- Never been measured before
- Contrary to $D^0 \to \mu^+\mu^-$ (pseudo-scalar) the excited vector state $D^*(2007)^0$ decaying to two muons has no chirality suppression
- Assuming Lepton Universality, decays with muon and electrons should have same branching ratio*
  *apart from phase space arguments
- SM prediction for the branching ratio $\mathscr{B}(D^*(2007)^0 \to e^+e^-) \sim \mathcal{O}(10^{-18})$
  JHEP 11 (2015) 142
- CMD-3:

$$\mathscr{B}(D^*(2007)^0 \to e^+e^-) \leq 1.7 \times 10^{-6} \ (90\,\%\ CL)$$

Phys. Atom. Nucl. 83 (2020) 954

Search for the decay $D^*(2007)^0 \to \mu^+\mu^-$ in $B^- \to \pi^-\mu^+\mu^-$ decays

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- Normalised to $B^- \to J/\psi(\to \mu^+\mu^-)\pi^-$
- Additional branching fraction information needed to calculate $\mathcal{B}(D^{*0} \to \mu^+\mu^-)$

$$\mathcal{B}(D^{*0} \to \mu^+\mu^-) = \frac{N(B^- \to D^{*0}(\to \mu^+\mu^-)\pi^-)}{N(B^- \to J/\psi(\to \mu^+\mu^-)K^-)} \times \frac{\epsilon(B^- \to J/\psi(\to \mu^+\mu^-)K^-)}{\epsilon(B^- \to D^{*0}(\to \mu^+\mu^-)\pi^-)} \times \frac{\mathcal{B}(B^- \to J/\psi K^-)}{\mathcal{B}(B^- \to D^{*0}\pi^-)} \times \mathcal{B}(J/\psi \to \mu^-\mu^+)$$

Determined by fit to the invariant D^{*0} and B^- mass

From simulations, corrected and cross checked by data driven methods

External input:
$\mathcal{B}(J/\psi \to \mu^-\mu^+) \sim (10^{-2})$
$\mathcal{B}(B^- \to J/\psi K^-) \sim (10^{-3})$
$\mathcal{B}(B^- \to D^{*0}\pi^-) \sim (10^{-3})$
Exp. Phys. 2022 (2022) 083C01

Search for the decay $D^*(2007)^0 \to \mu^+\mu^-$ in $B^- \to \pi^-\mu^+\mu^-$ decays

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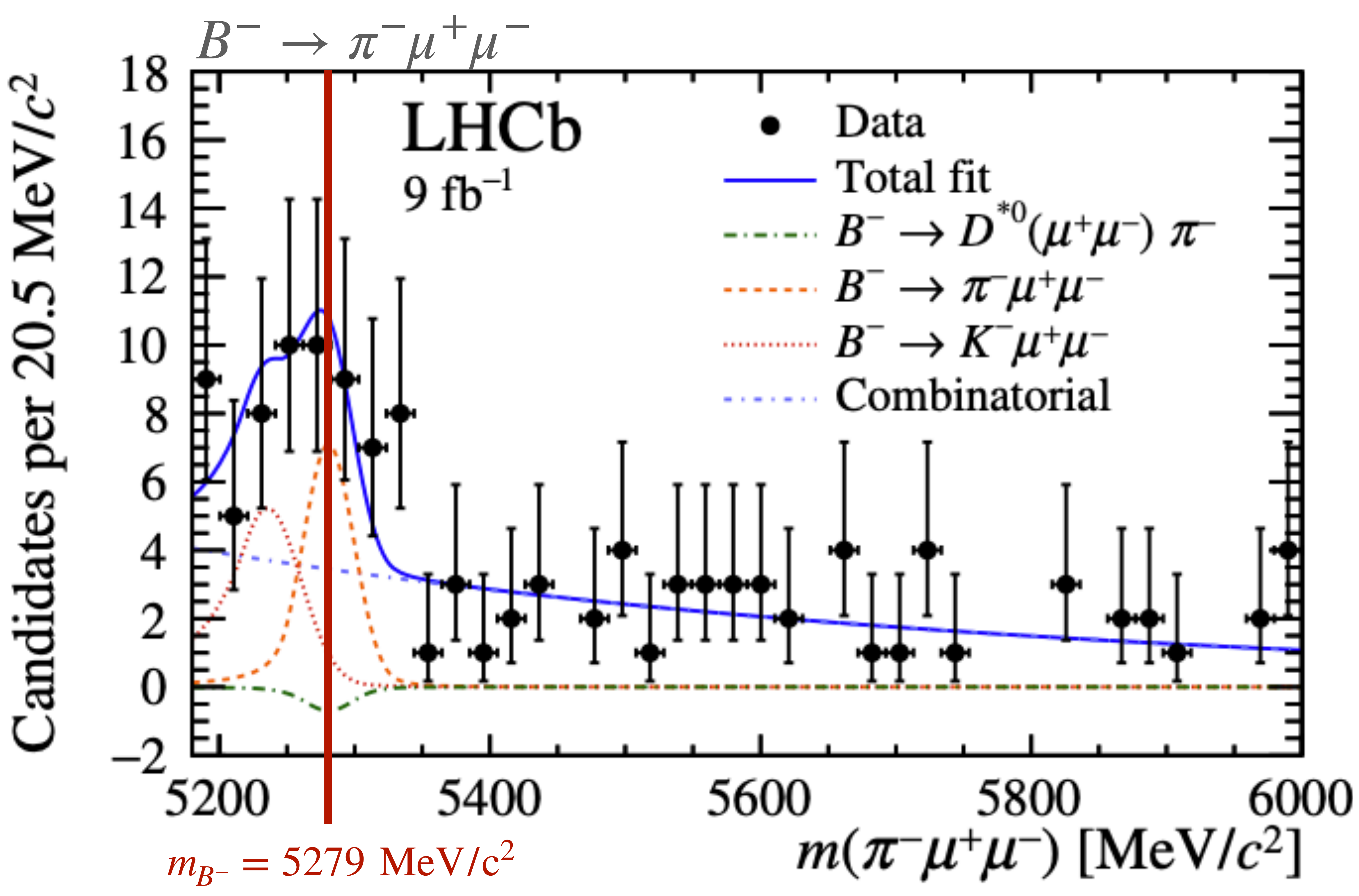
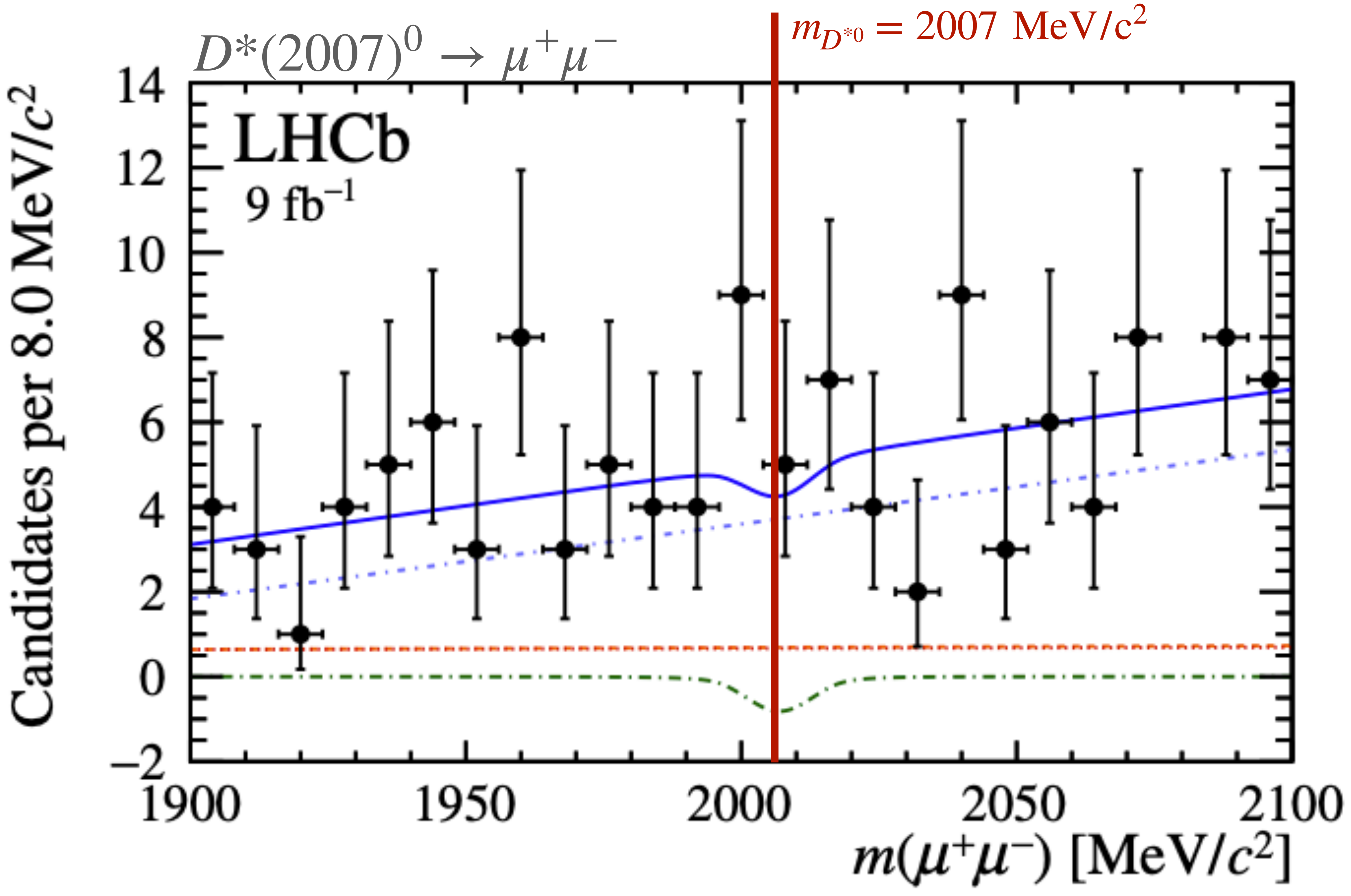
- Two dimensional fit to $m(\mu\mu)$ and $m(\pi\mu\mu)$
- Background due to a wrongly identified kaon and non resonant $B^- \to \pi^-\mu^+\mu^-$ is flat within the fit range in the dimuon spectrum





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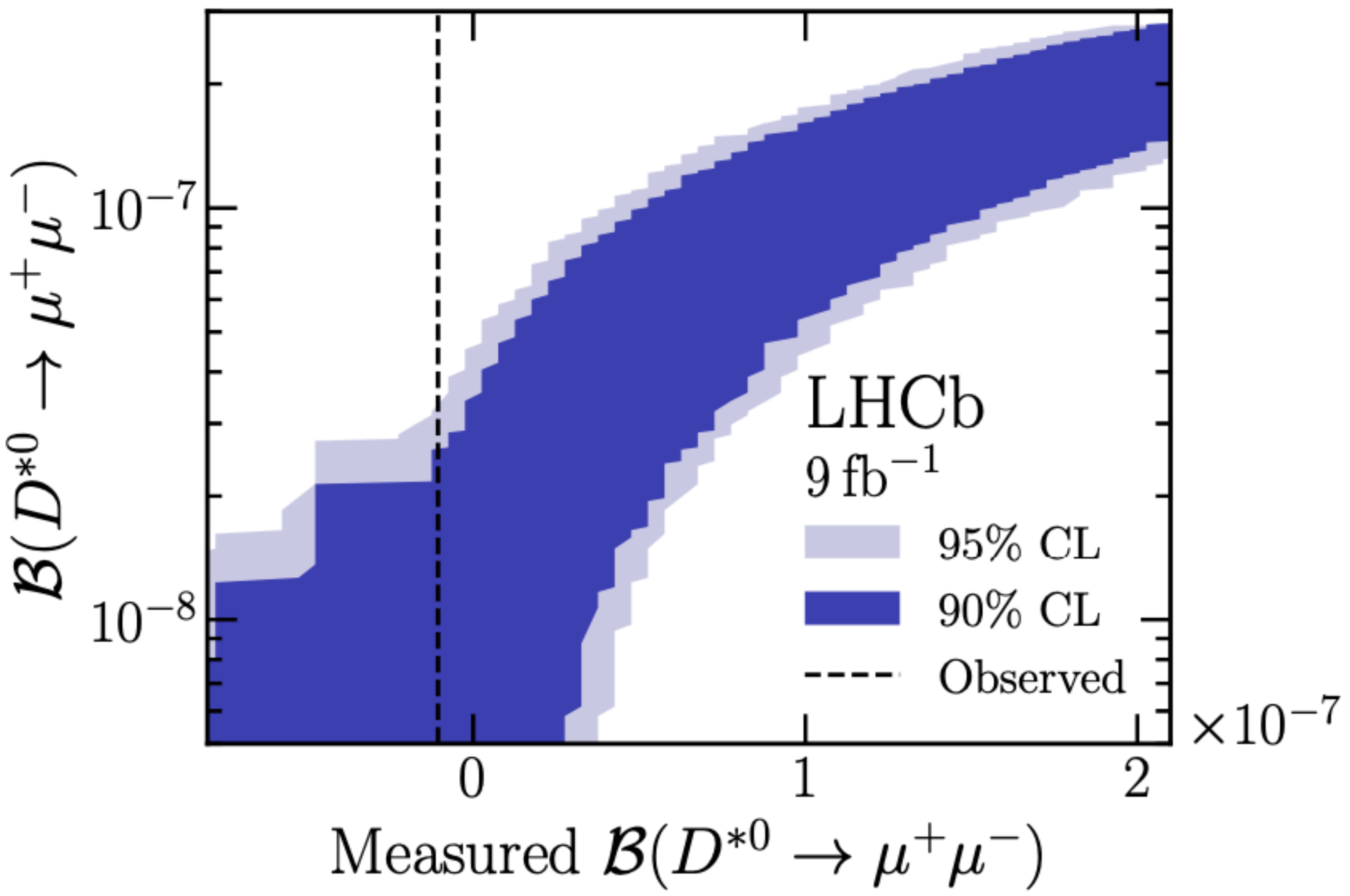
- First limit for $D^*(2007)^0 \to \mu^+\mu^-$:

$$\mathscr{B}(D^*(2007)^0 \to \mu^+\mu^-) \leq 2.6 \times 10^{-8}\ (90\,\%\ CL)$$

- Assuming LFU, increases constraints on $D^*(2007)^0 \to e^+e^-$ set by CMD-3 by two orders of magnitude



Searches for rare decays of charged D^+ and D_s^+ mesons

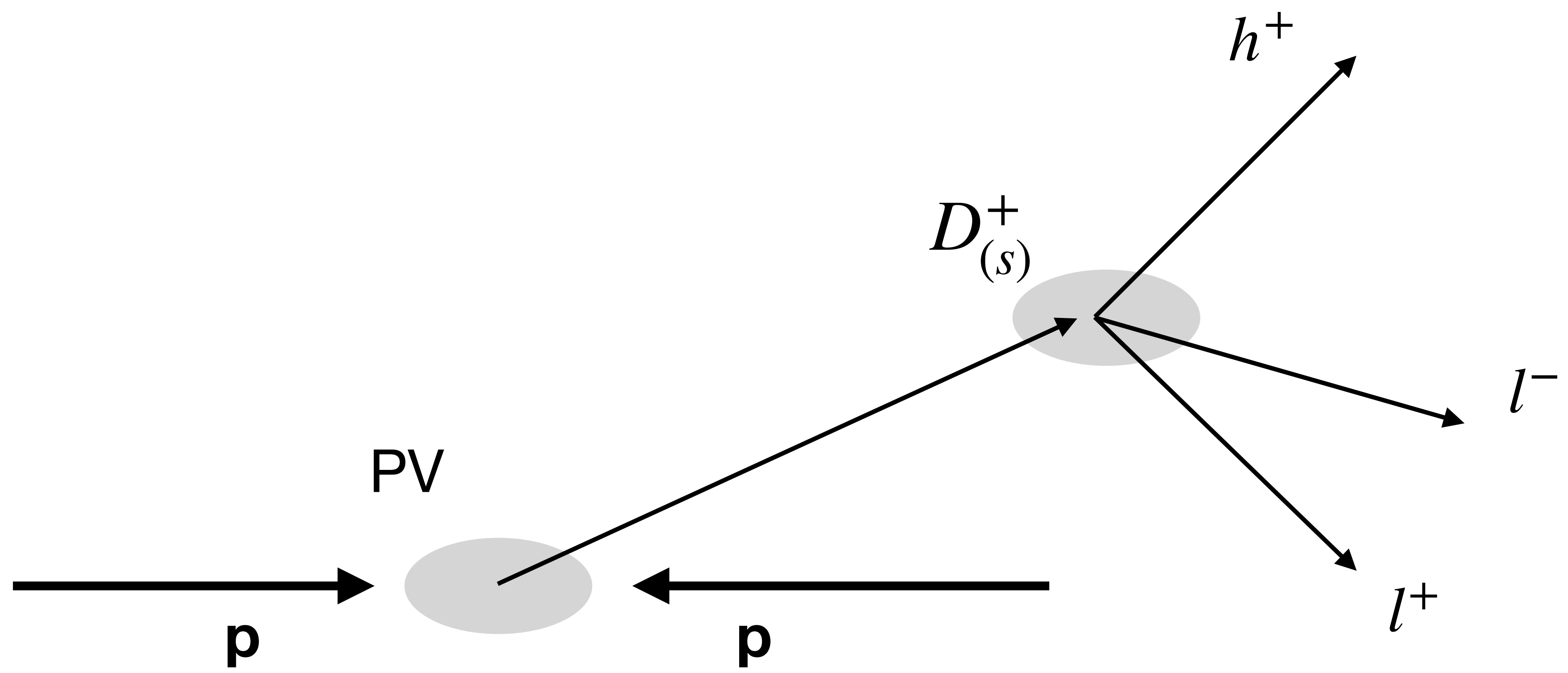
JHEP 06 (2021) 044

Used dataset:

- Run 2 (only 2016)
- Center of mass energy: 13 TeV
- Luminosity: $1.6\ \mathrm{fb}^{-1}$

Study of 25 rare and forbidden decays

→ forbidden decays provide perfect null test



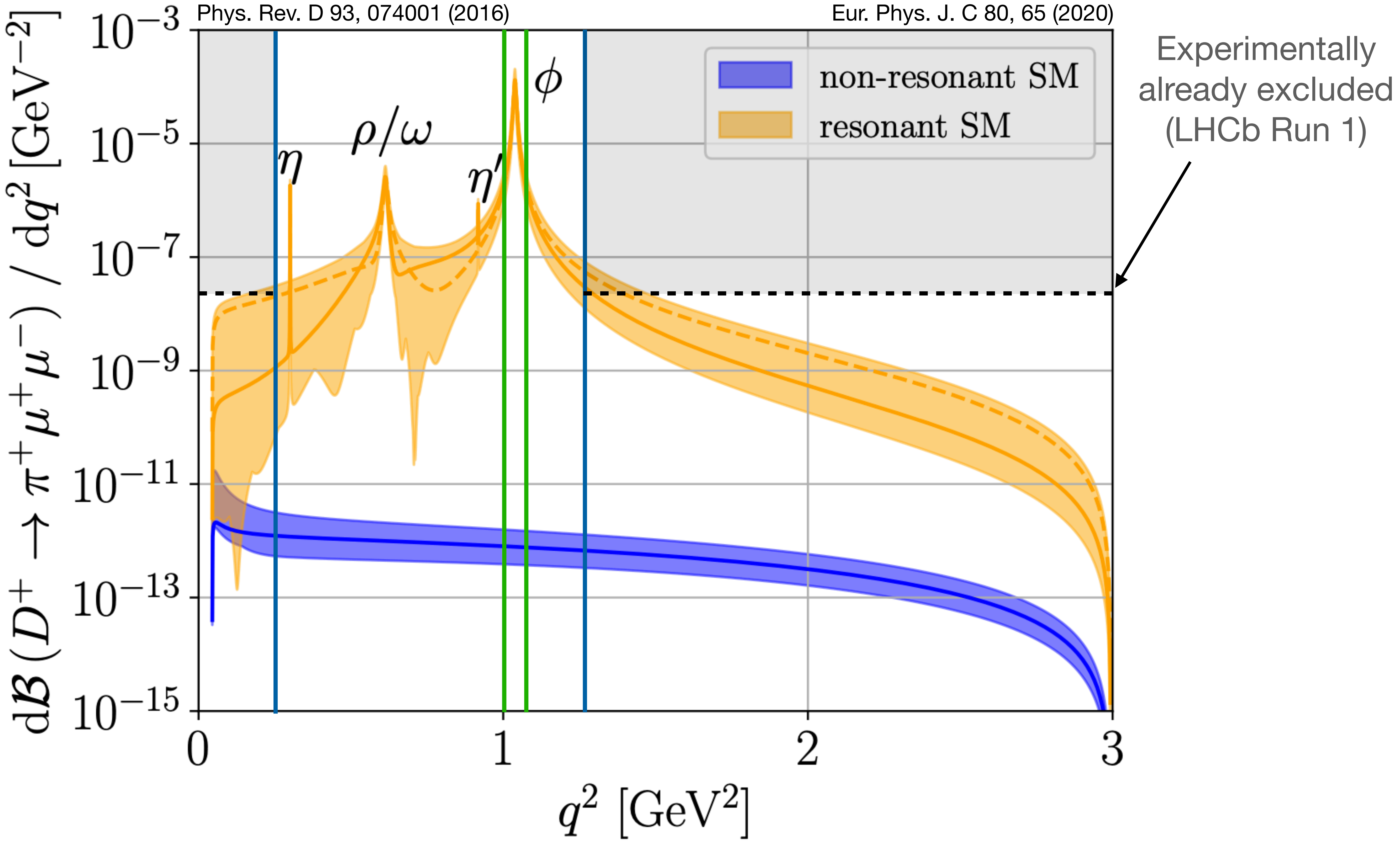
$D^+ \to \pi^+\mu^+\mu^-$	$D^+ \to \pi^+e^+e^-$	$D^+ \to K^+e^+e^-$	$D_s^+ \to \pi^+e^+\mu^-$	$D_s^+ \to K^+\mu^+e^-$
$D^+ \to \pi^-\mu^+\mu^+$	$D^+ \to \pi^-e^+e^+$	$D_s^+ \to \pi^+\mu^+\mu^-$	$D_s^+ \to \pi^+e^+e^-$	$D_s^+ \to K^-\mu^+e^+$
$D^+ \to \pi^+\mu^+e^-$	$D^+ \to K^+\mu^+\mu^-$	$D_s^+ \to \pi^-\mu^+\mu^+$	$D_s^+ \to \pi^-e^+e^+$	$D_s^+ \to K^+e^+\mu^-$
$D^+ \to \pi^-\mu^+e^+$	$D^+ \to K^+\mu^+e^-$	$D_s^+ \to \pi^+\mu^+e^-$	$D_s^+ \to K^+\mu^+\mu^-$	$D_s^+ \to K^+e^+e^-$
$D^+ \to \pi^+e^+\mu^-$	$D^+ \to K^+e^+\mu^-$	$D_s^+ \to \pi^-\mu^+e^+$	$D_s^+ \to K^-\mu^+\mu^+$	$D_s^+ \to K^-e^+e^+$

Searches for rare decays of charged D^+ and D_s^+ mesons

JHEP 06 (2021) 044

- For SM allowed decays, resonant area, $q = m(ll) \in [525\,\text{MeV}, 1250\,\text{MeV}]$, containing $D^+_{(s)} \to V(\to l^+l^-)\pi^+$ with $V = \eta, \rho^0/\omega, \phi$ and $l = \mu, e$, vetoed

- Normalised to ϕ resonance $D^+_{(s)} \to \phi(\to \mu^+\mu^-)\pi^+$ and $D^+_{(s)} \to \phi(\to e^+e^-)\pi^+$ for decays with muons and electrons, respectively



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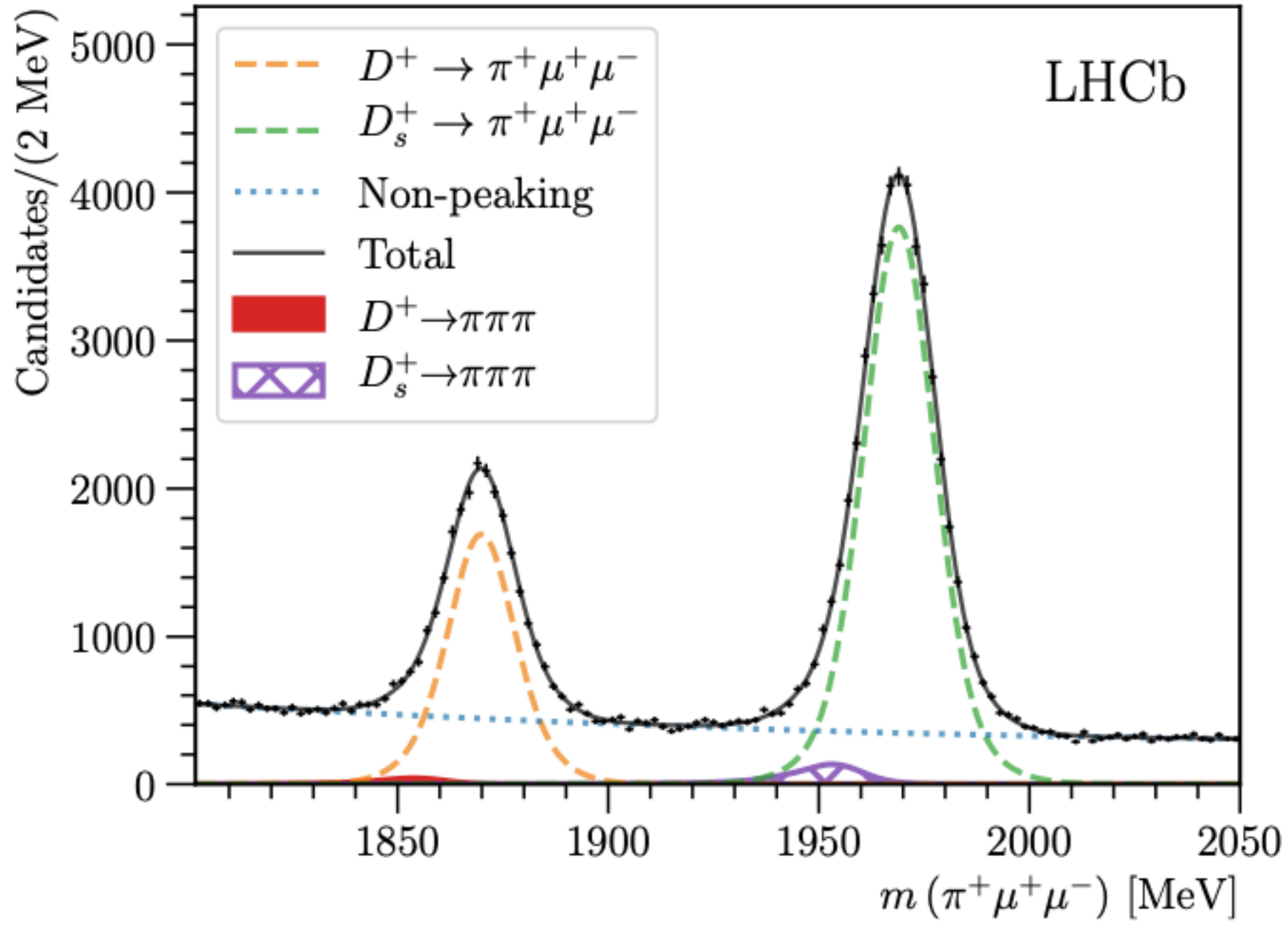
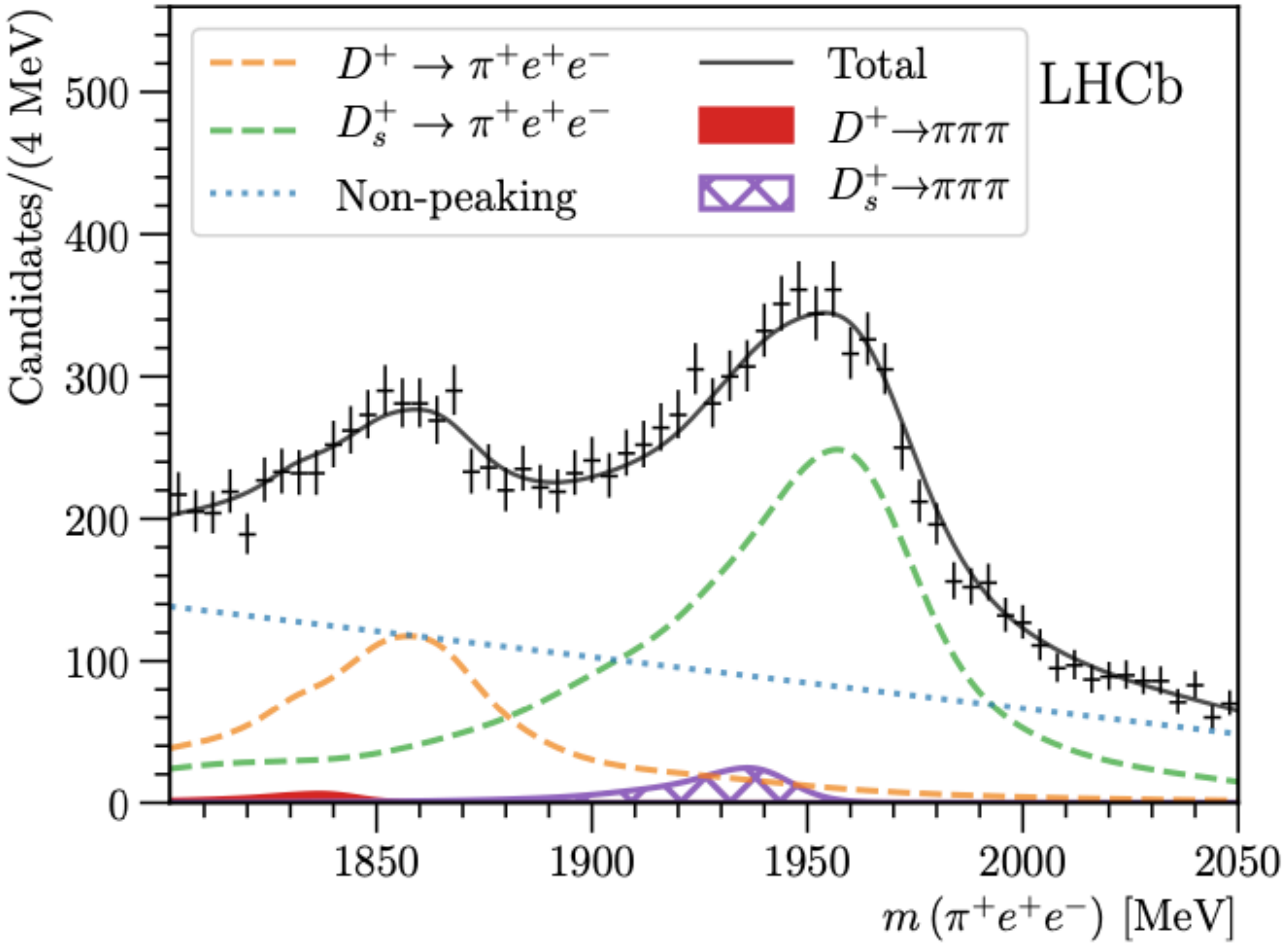
JHEP 06 (2021) 044

- Normalisation yield estimated by fit to $m(\pi^+\mu^-\mu^+)$ and $m(\pi^+e^-e^+)$
- A bremsstrahlung reconstruction procedure is used to correct the momentum for the electron candidates



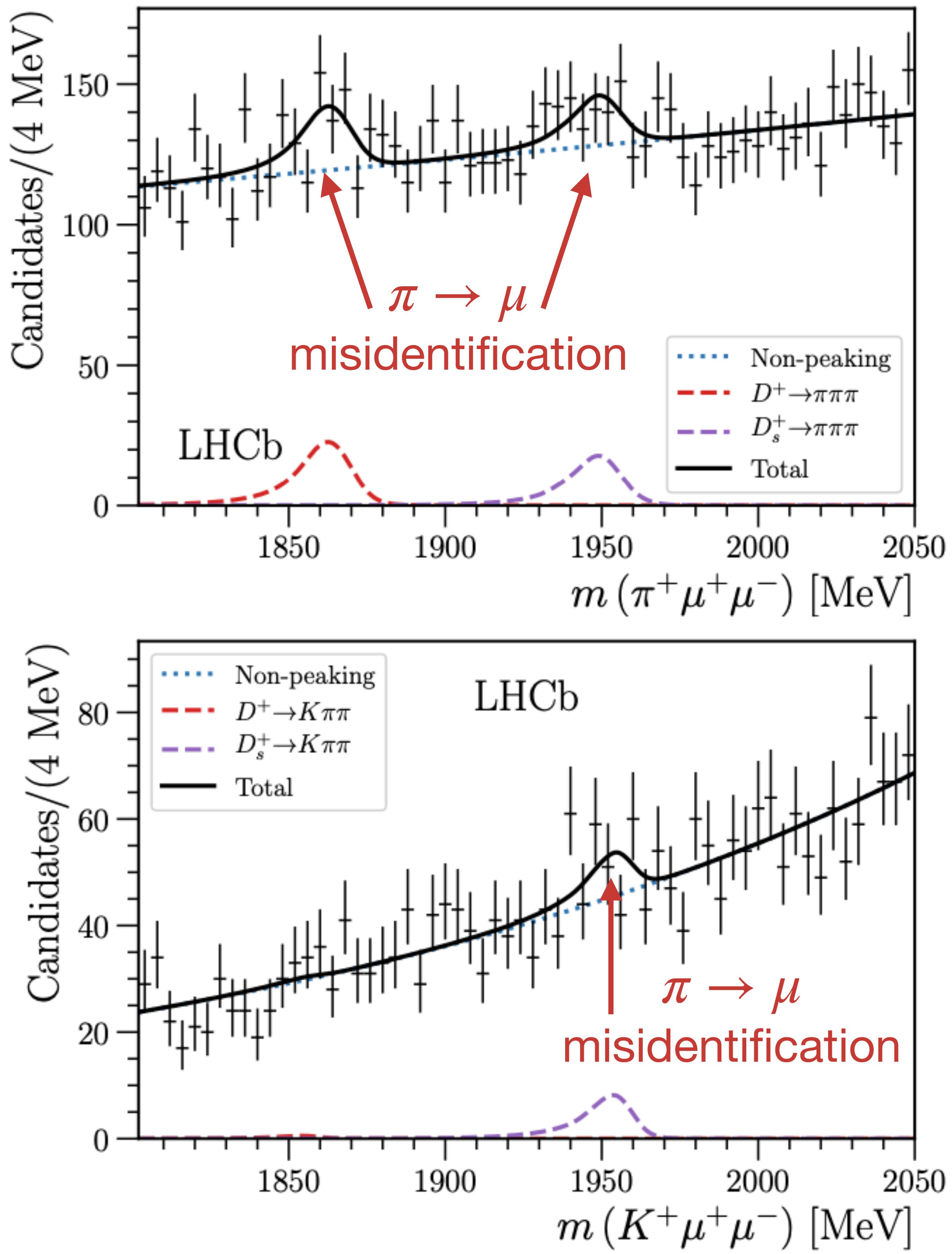


Searches for rare decays of charged D^+ and D_s^+ mesons

JHEP 06 (2021) 044

- Fit to three body invariant mass
- PID selection to suppress mis-identified background due to hadronic decays
- BDT selection to suppress combinatorial background
- Branching fractions are normalised to $D_{(s)}^+ \to \phi(\to \mu^+\mu^-)\pi^+$

Background only hypothesis



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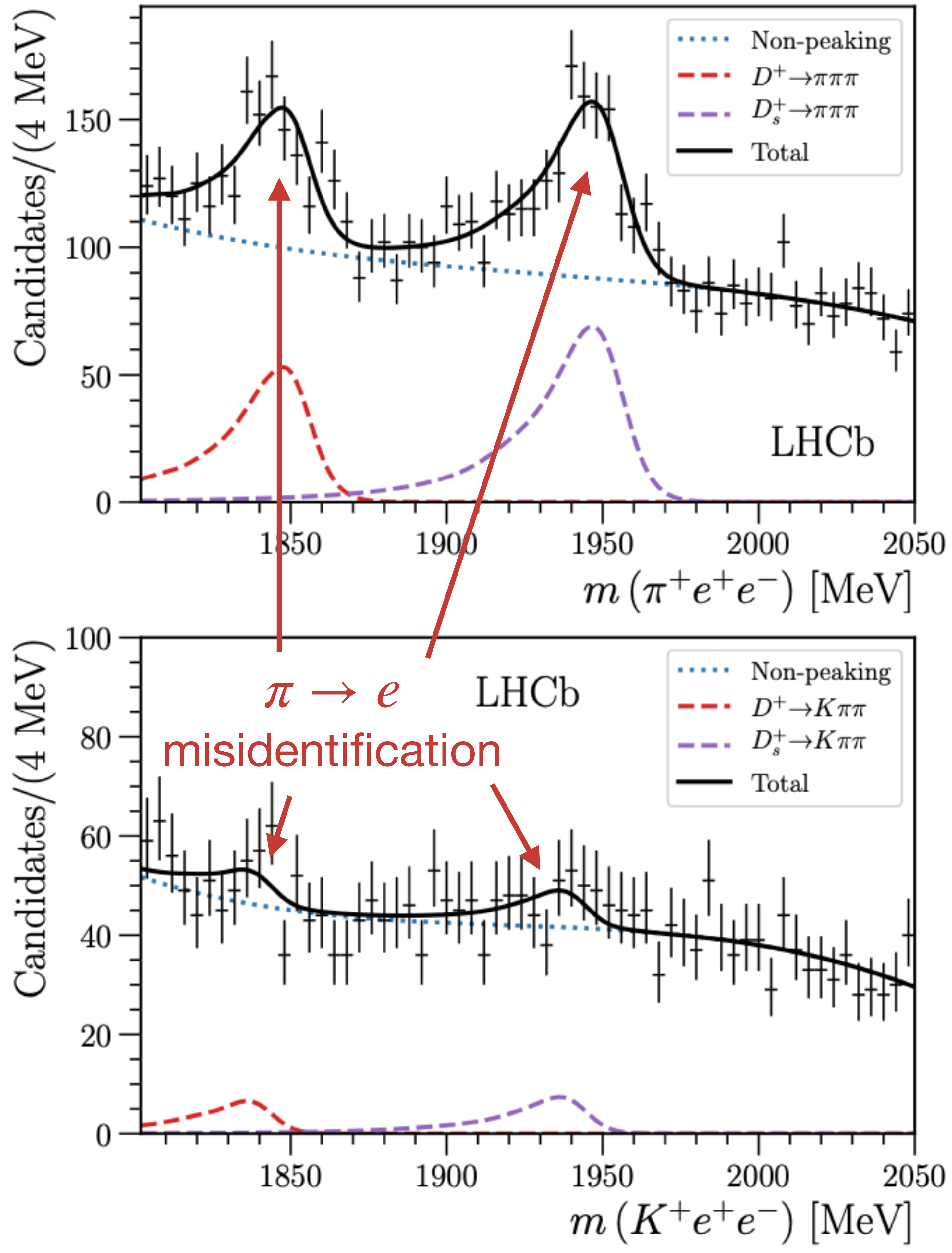
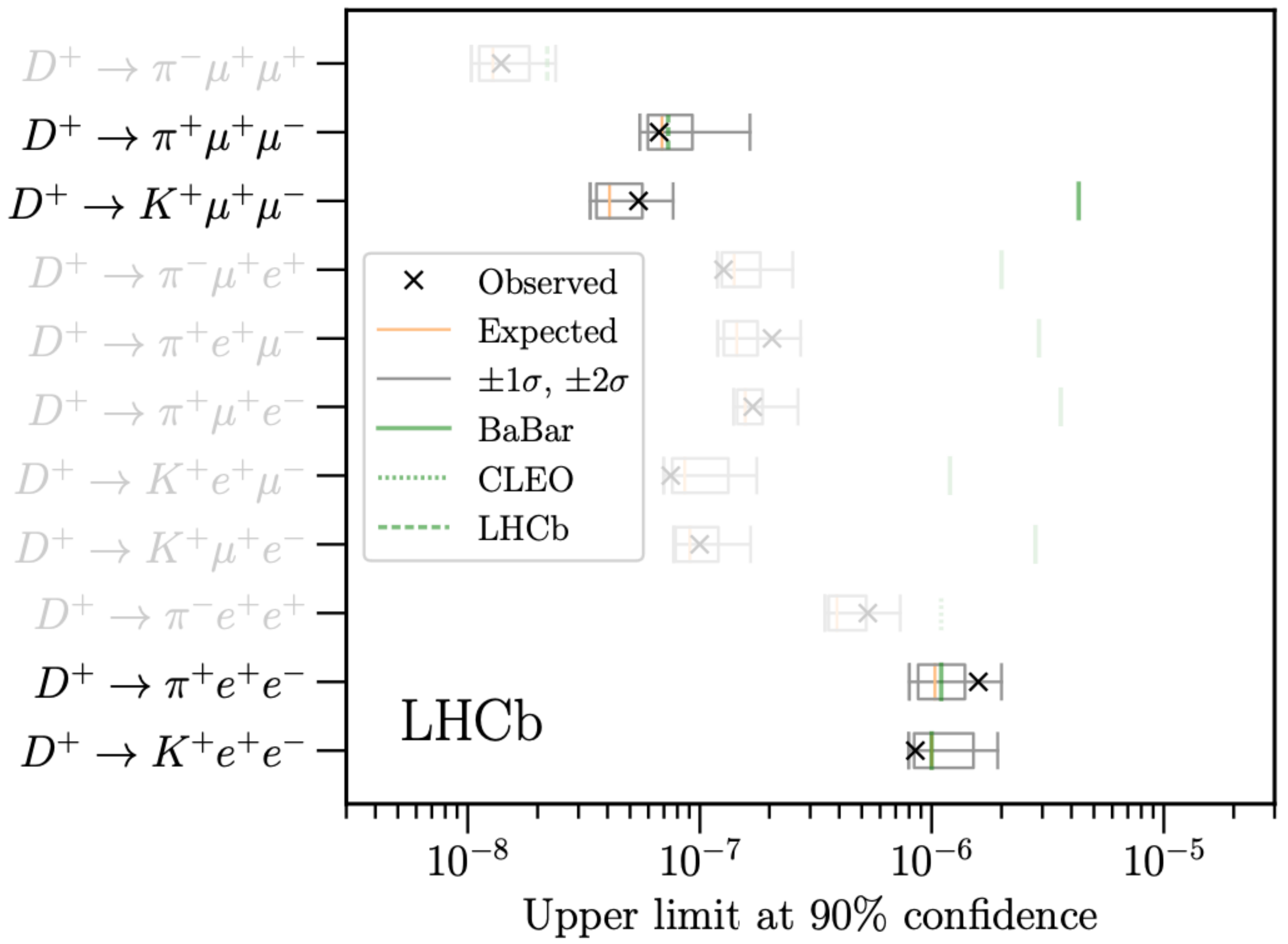
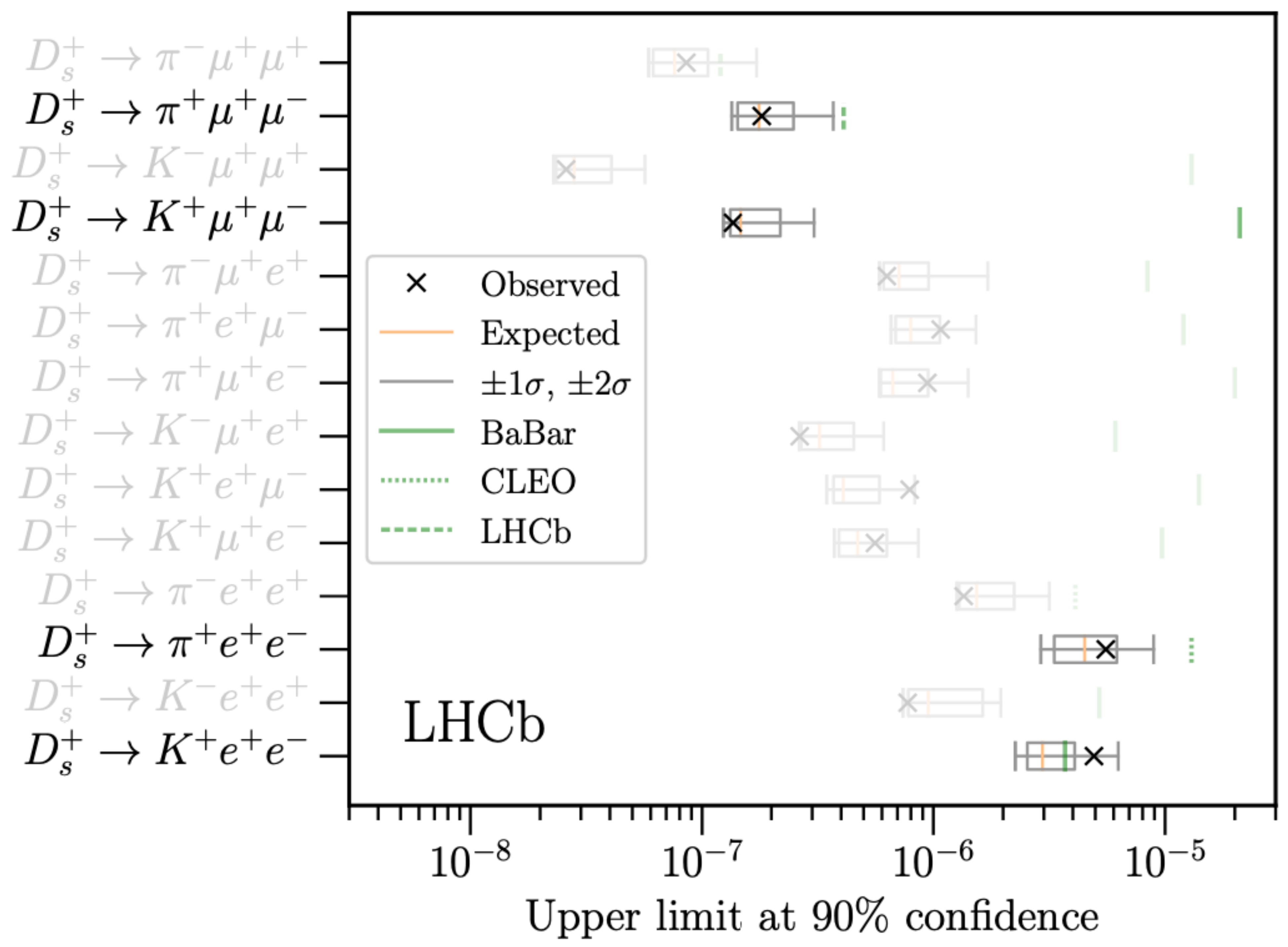


Searches for rare decays of charged D^+ and D_s^+ mesons

JHEP 06 (2021) 044

- Provides competitive results, improves old limits up to two orders of magnitude
- Background only hypothesis is consistent with the results





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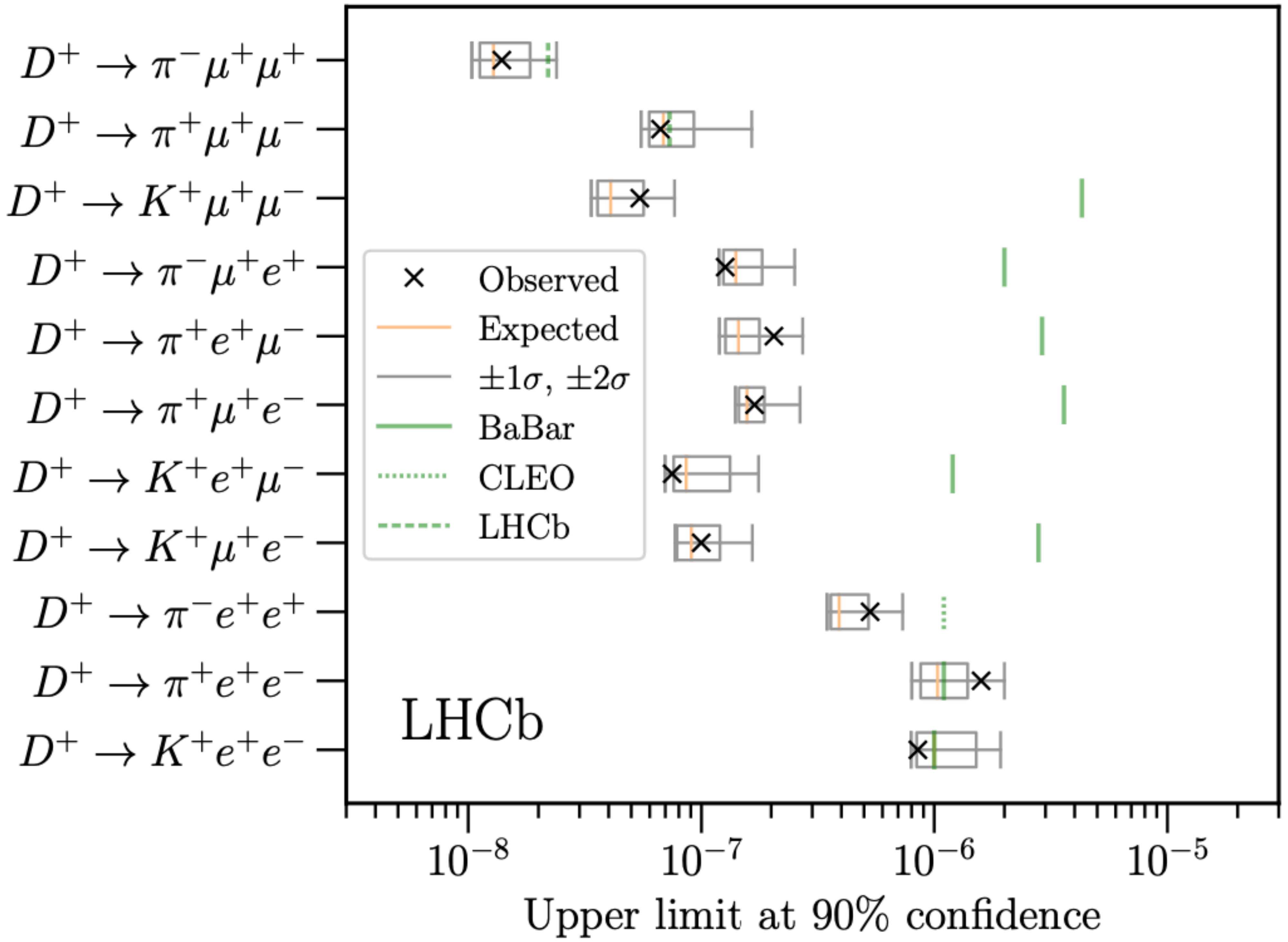

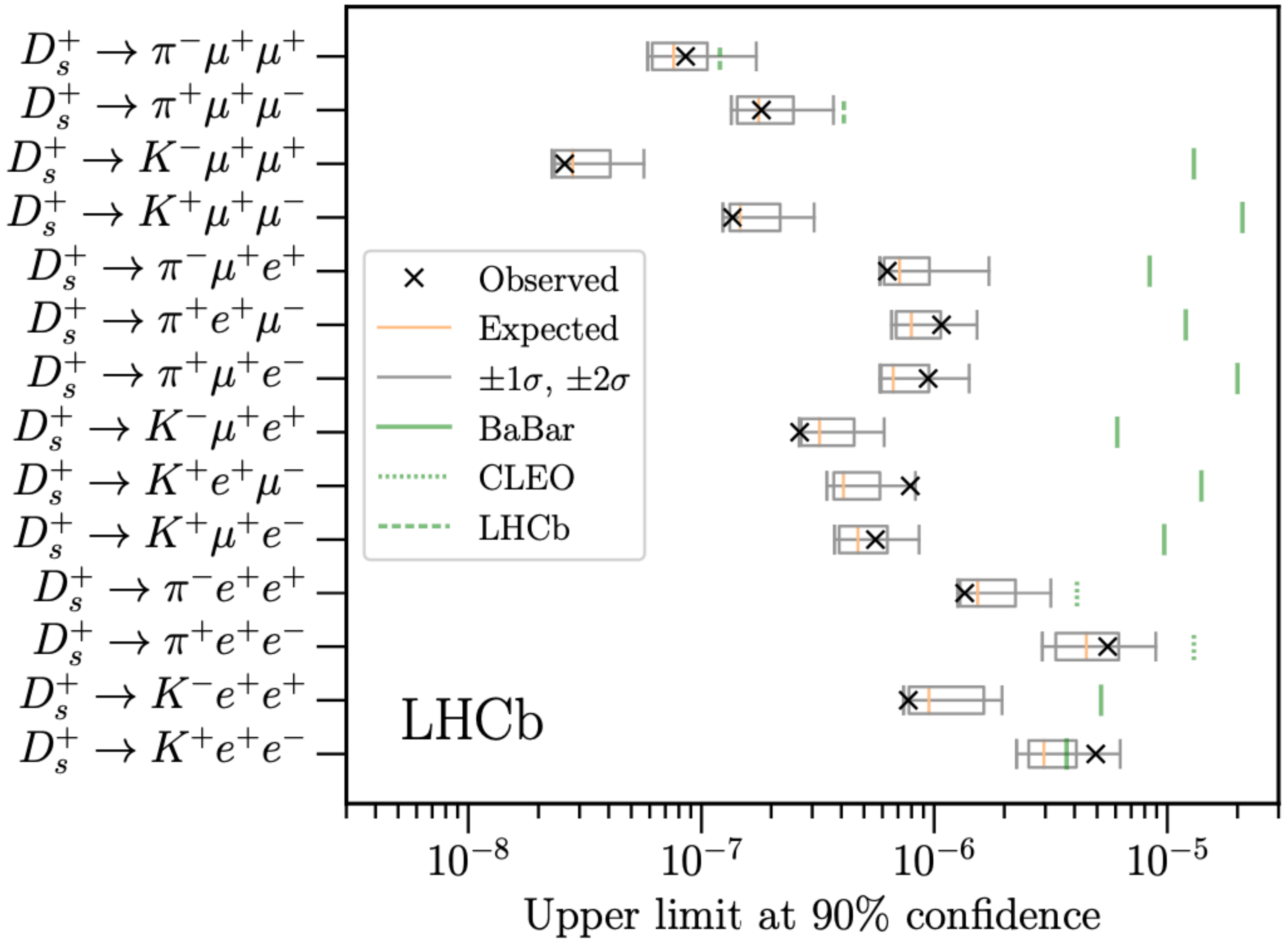

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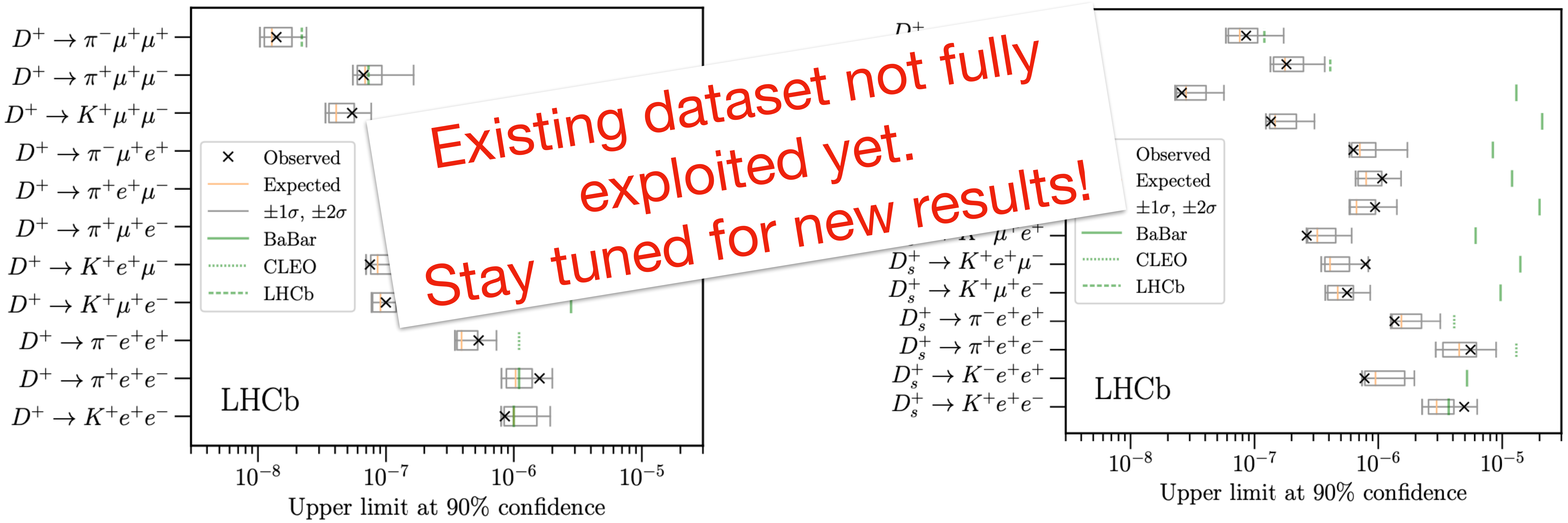


Existing dataset not fully exploited yet.

Stay tuned for new results!

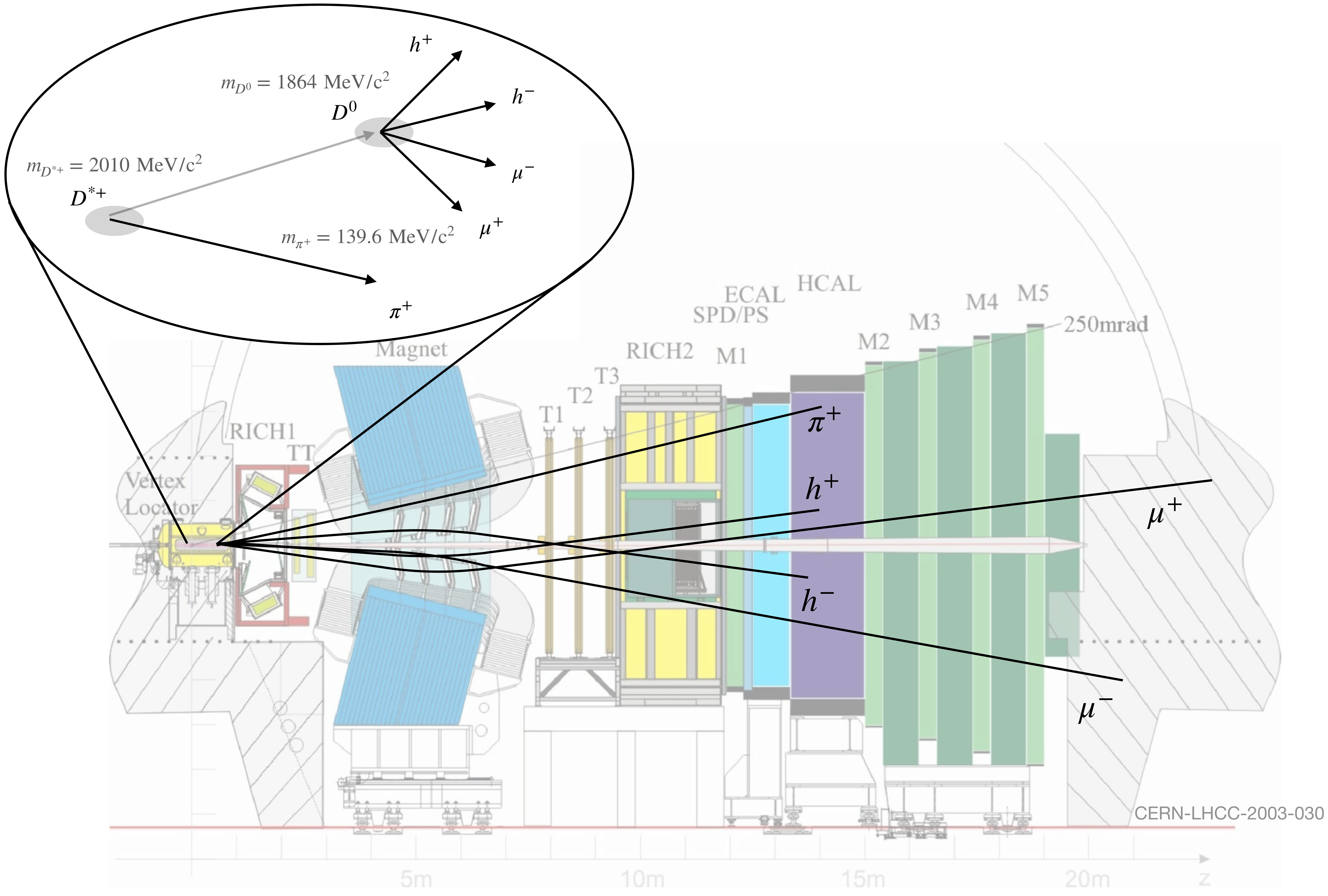
Study of $D^0 \to KK\mu\mu$ and $D^0 \to \pi\pi\mu\mu$

First observation:
Phys. Rev. Lett. **119**, 181805 (2017)

- Run 1 (only 2012)
- Center of mass energy: 8 TeV
- Luminosity: $2.0\ \mathrm{fb}^{-1}$

Angular analysis:
Phys. Rev. Lett. **128**, 221801 (2022)

- Run 1 (2011-2012) and Run 2 (2015-2018)
- Center of mass energy: 7, 8 and 13 TeV
- Luminosity: $9.0\ \mathrm{fb}^{-1}$

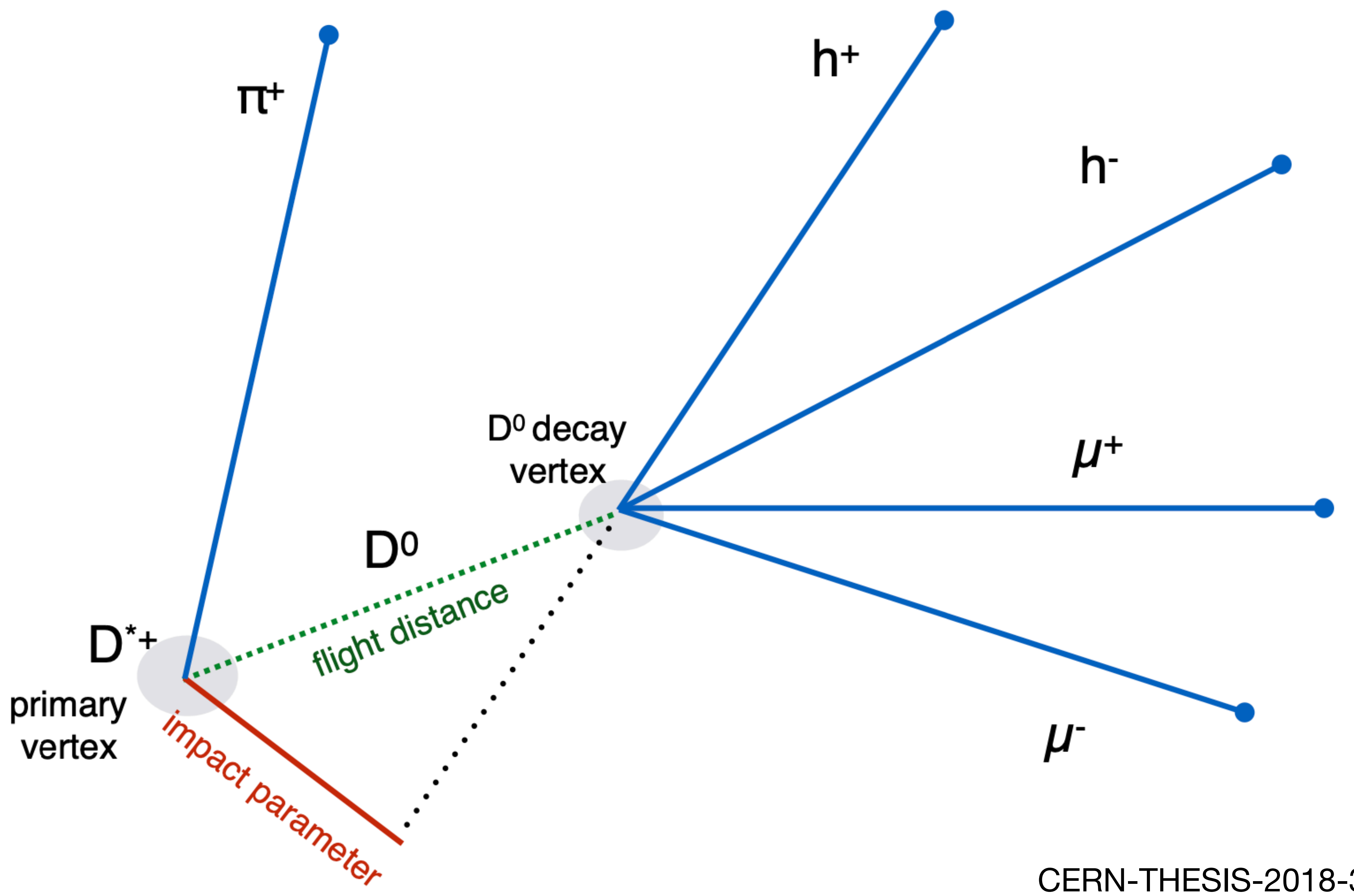


First observation of $D^0 \to KK\mu\mu$ and $D^0 \to \pi\pi\mu\mu$

Phys. Rev. Lett. **119**, 181805 (2017)

Analysis strategy:

- D^0 produced in D^{*+} decays are used, to suppress background
- PID selection to suppress mis-identified background due to hadronic decays
- BDT selection to suppress combinatorial background



CERN-THESIS-2018-376

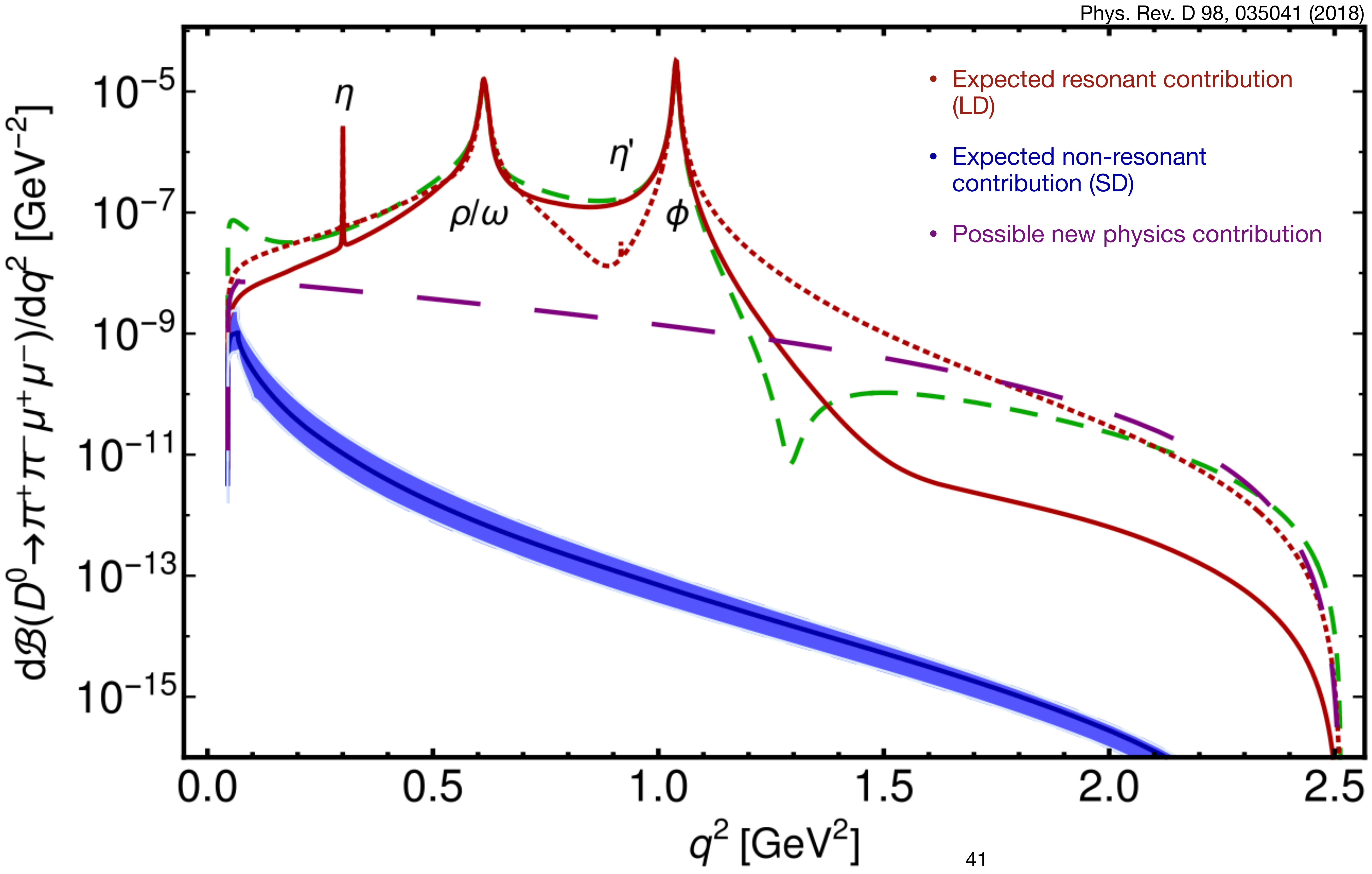
Measured dimuon-mass integrated branching ratio:

$$\mathscr{B}(D^0 \to K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.18) \times 10^{-7}$$

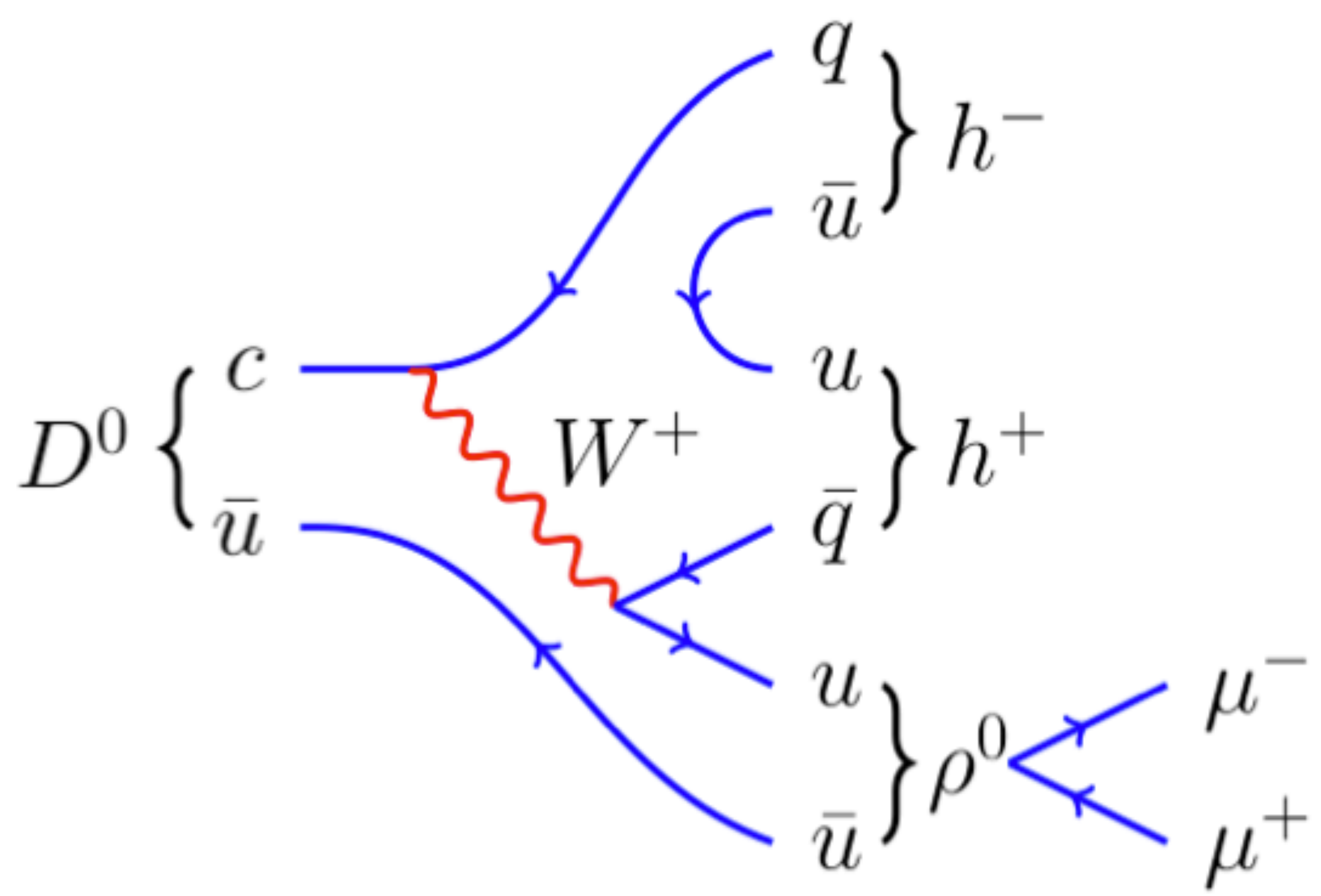
$$\mathscr{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 1.10) \times 10^{-7}$$

First observation of $D^0 \to KK\mu\mu$ and $D^0 \to \pi\pi\mu\mu$

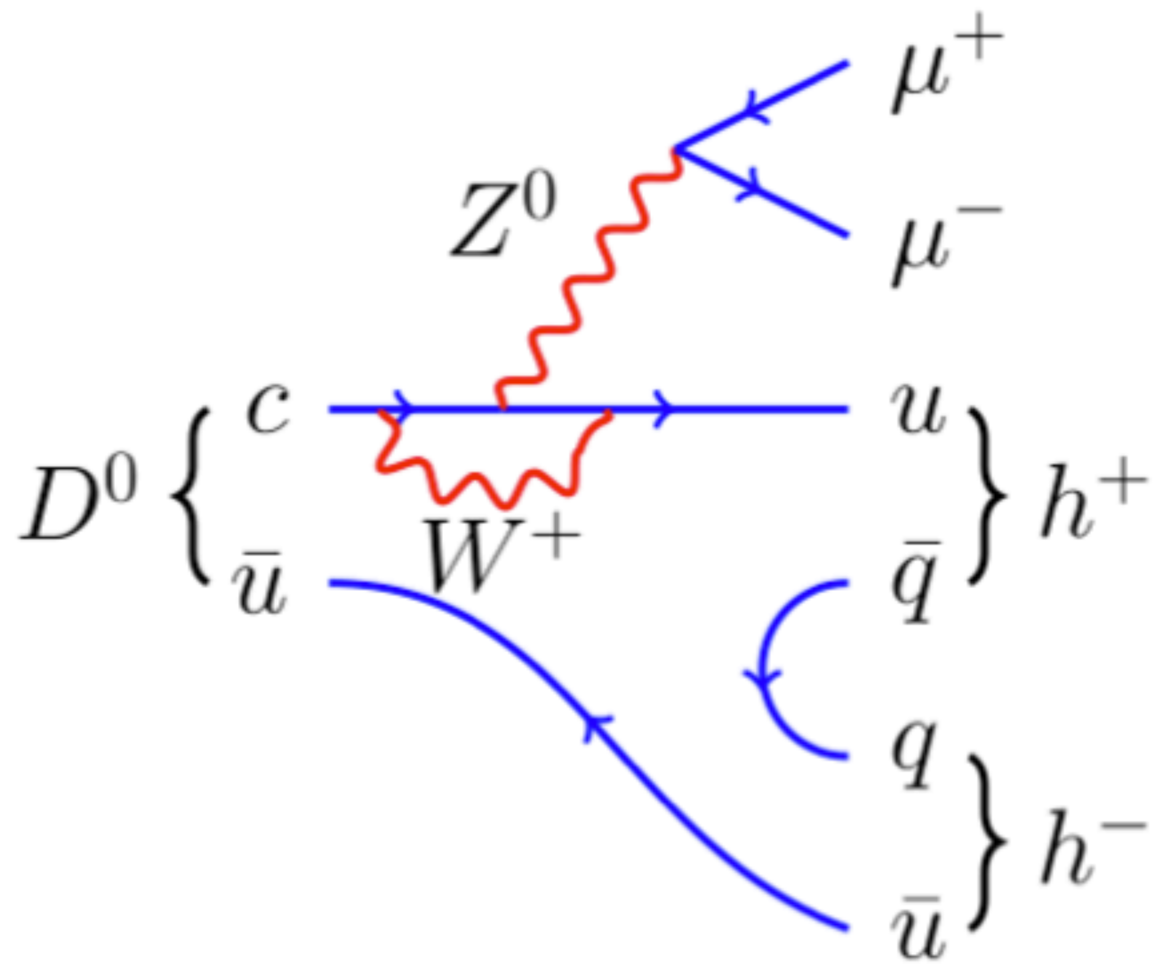
Phys. Rev. Lett. **119**, 181805 (2017)



LD contribution example:



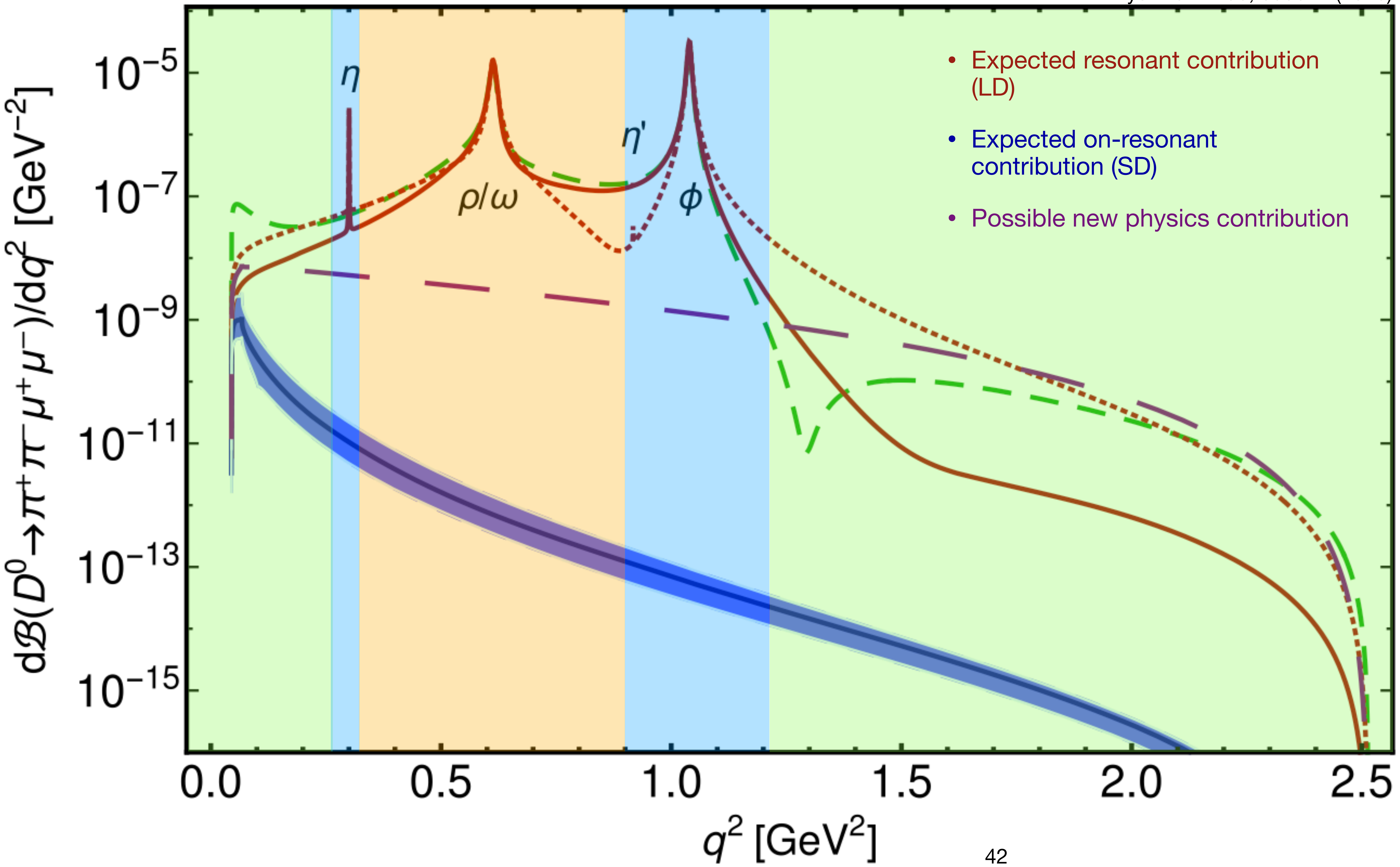
SD contribution example:



First observation of $D^0 \to KK\mu\mu$ and $D^0 \to \pi\pi\mu\mu$

Phys. Rev. Lett. **119**, 181805 (2017)

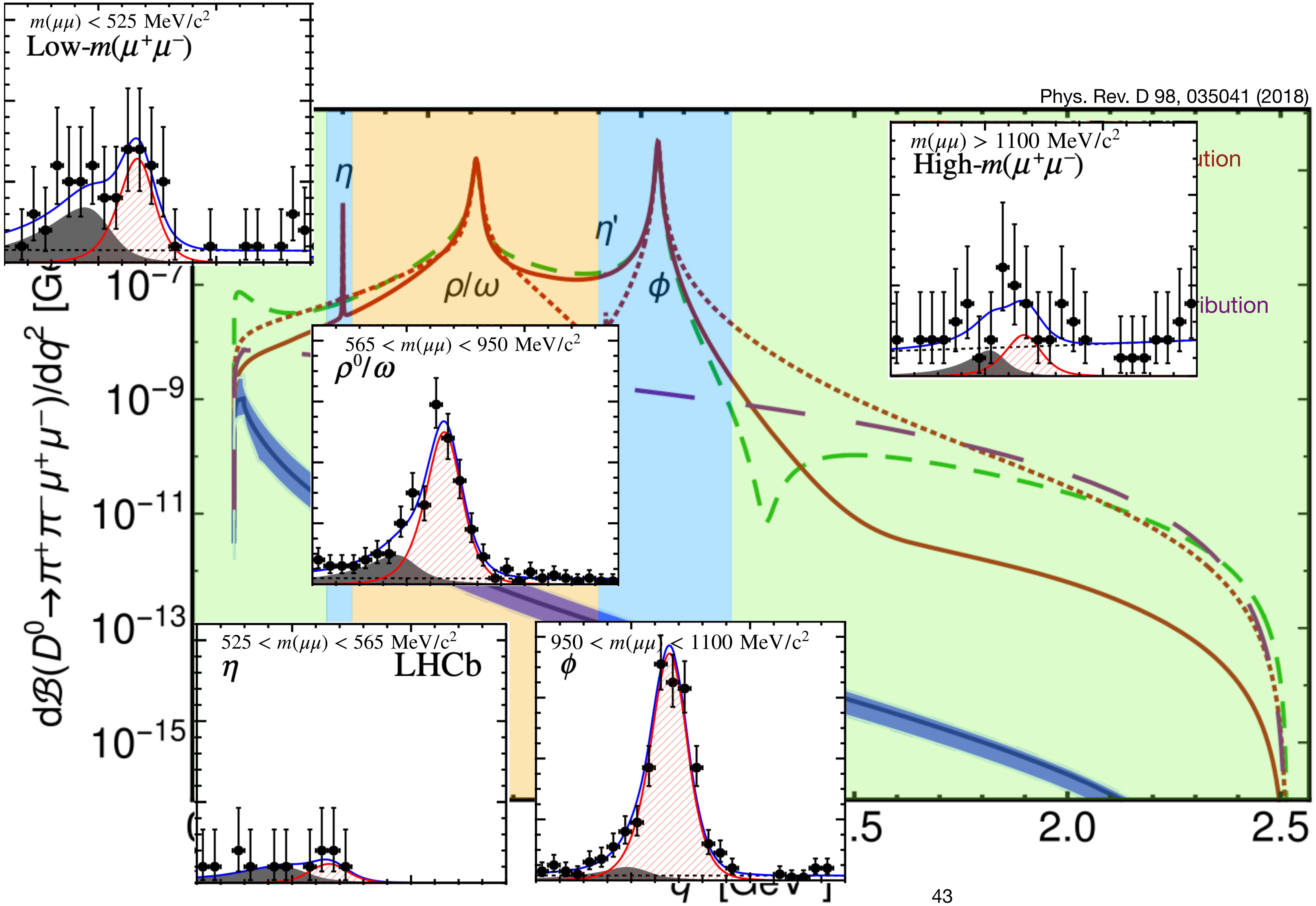
Phys. Rev. D 98, 035041 (2018)



- Split into kinematic bins to search for NP away from decays with intermediate resonances

First observation of $D^0 \rightarrow KK\mu\mu$ and $D^0 \rightarrow \pi\pi\mu\mu$

Phys. Rev. Lett. **119**, 181805 (2017)



- Split into kinematic bins to search for NP away from decays with intermediate resonances

Search for CP Violation and Angular Analysis of $D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$

Phys. Rev. Lett. **128**, 221801 (2022)

First observation:

Phys. Rev. Lett. **119**, 181805 (2017)

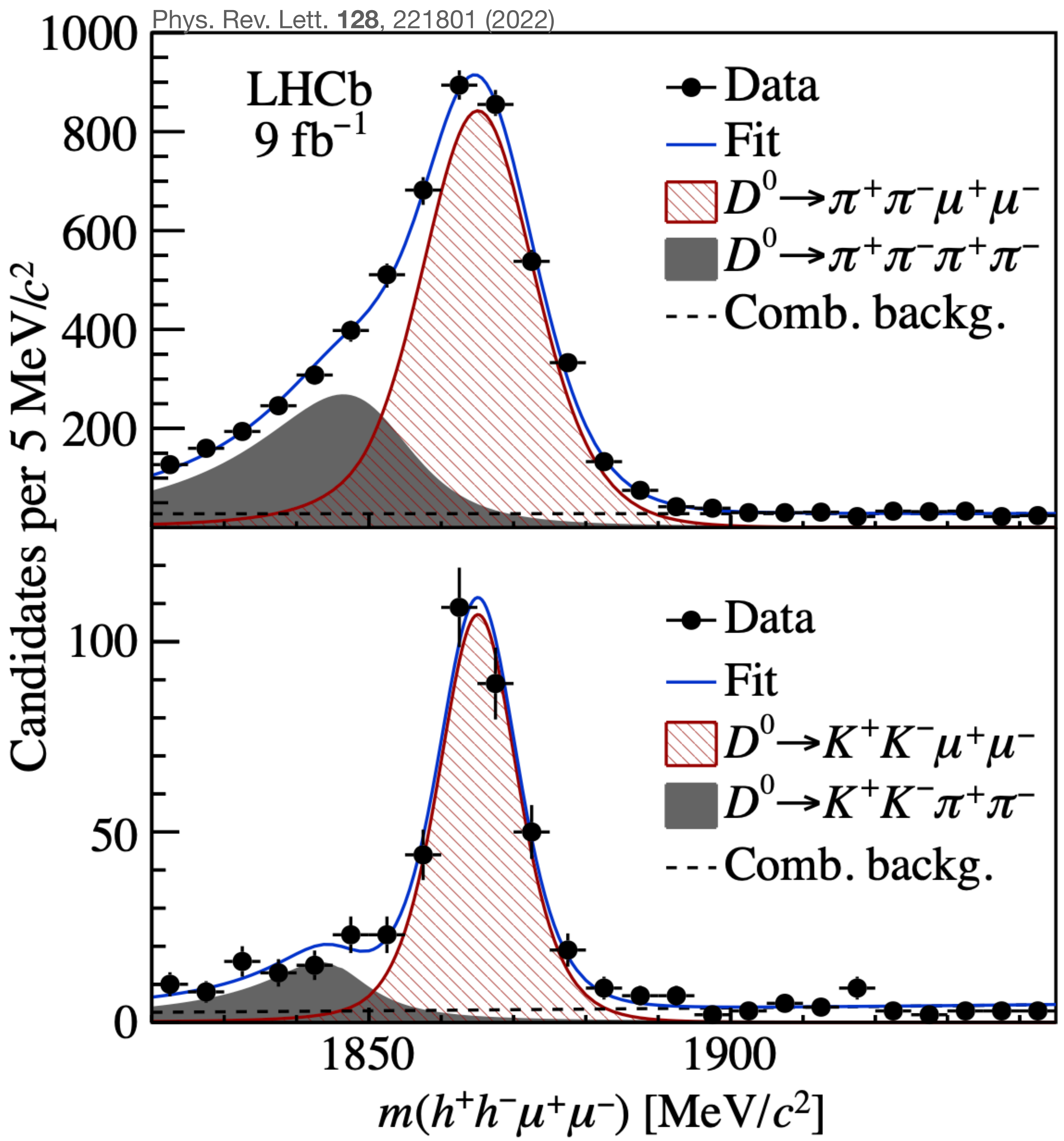
- $N(D^0 \to K^+K^-\mu^+\mu^-) \sim 35$
- $N(D^0 \to \pi^+\pi^-\mu^+\mu^-) \sim 550$

Angular analysis (full dataset):

Phys. Rev. Lett. **128**, 221801 (2022)

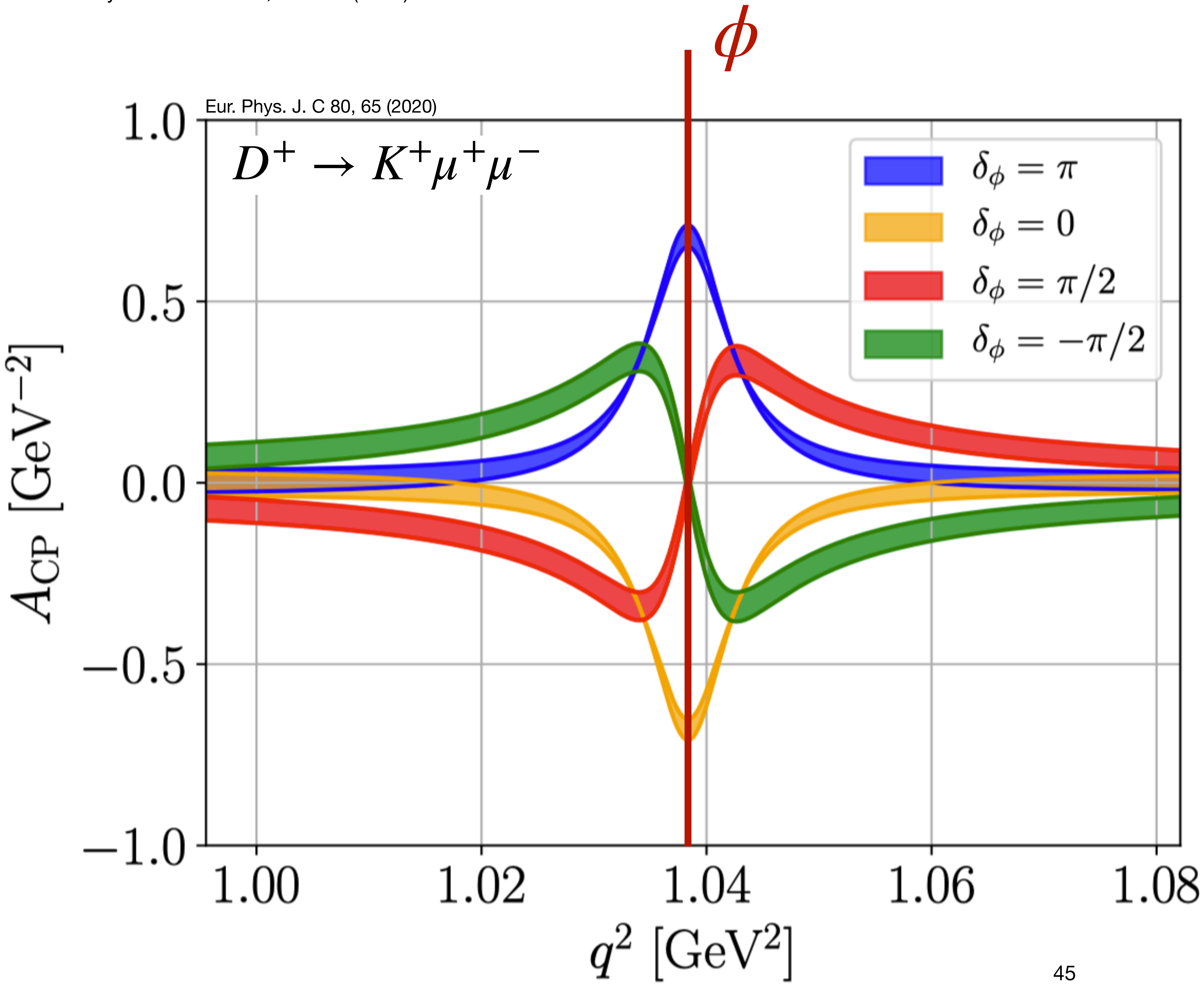
- $N(D^0 \to K^+K^-\mu^+\mu^-) \sim 300$
- $N(D^0 \to \pi^+\pi^-\mu^+\mu^-) \sim 3500$

Enough statistics to perform full angular analysis and search for CPV!



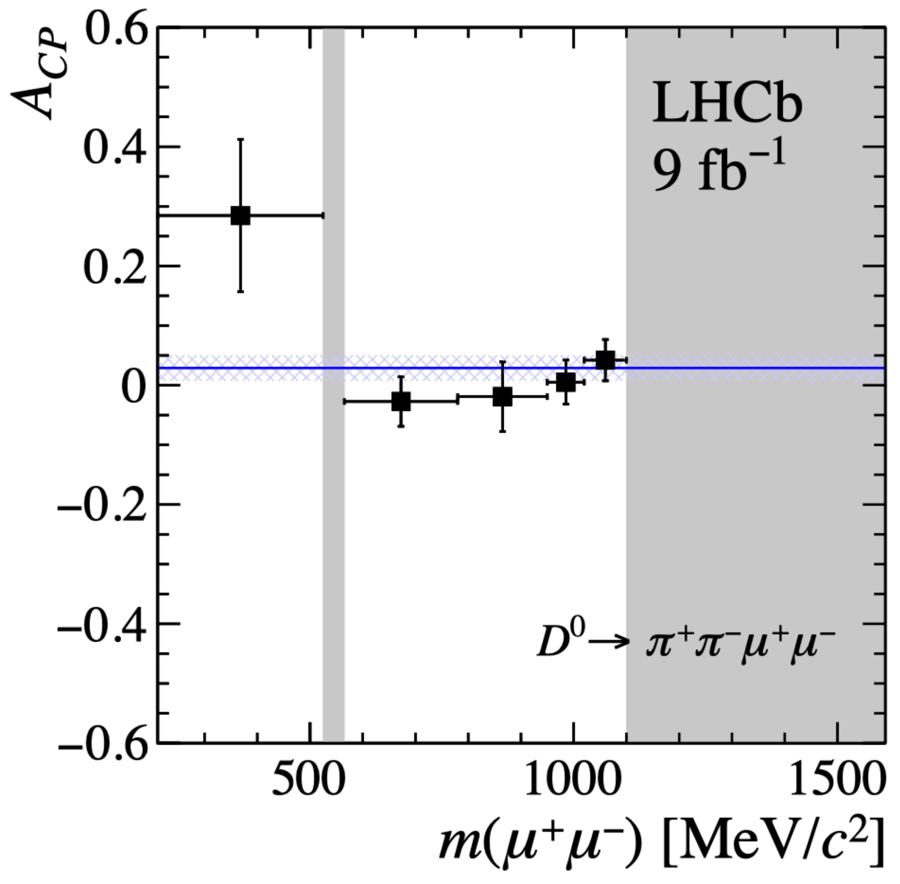
Search for CP Violation and Angular Analysis of $D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$

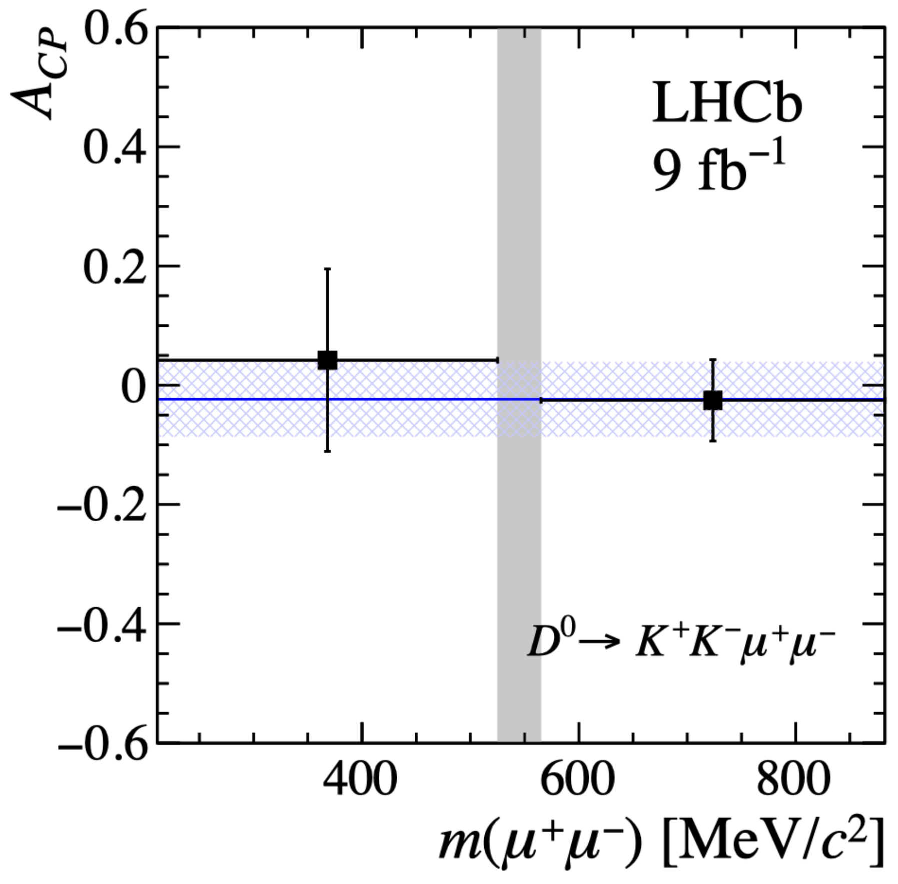
Phys. Rev. Lett. **128**, 221801 (2022)



- Observed decays allow to study asymmetries:

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

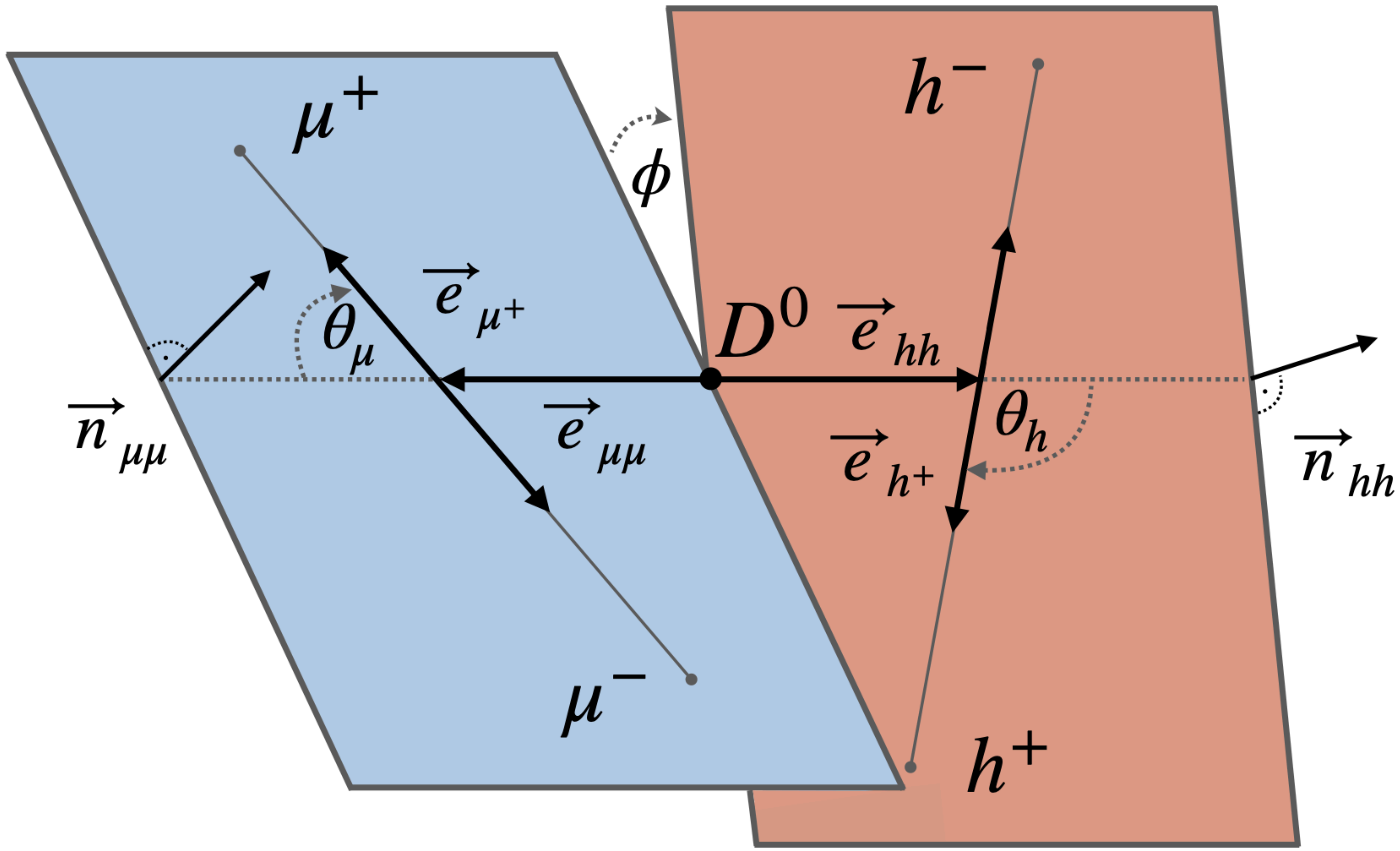




Search for CP Violation and Angular Analysis of $D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$

Phys. Rev. Lett. **128**, 221801 (2022)

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



Search for CP Violation and Angular Analysis of $D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$

Phys. Rev. Lett. **128**, 221801 (2022)

$$\frac{d\Gamma}{d\cos(\theta_\mu)\ d\cos(\theta_h)\ d\phi} = I_1 +$$
$$I_2 \cdot \cos(2\theta_\mu) +$$
$$I_3 \cdot \sin^2(2\theta_\mu)\ \cos(2\phi) +$$
$$I_4 \cdot \sin(2\theta_\mu)\ \cos(\phi) +$$
$$I_5 \cdot \sin(\theta_\mu)\ \cos(\phi) +$$
$$I_6 \cdot \cos(\theta_\mu) +$$
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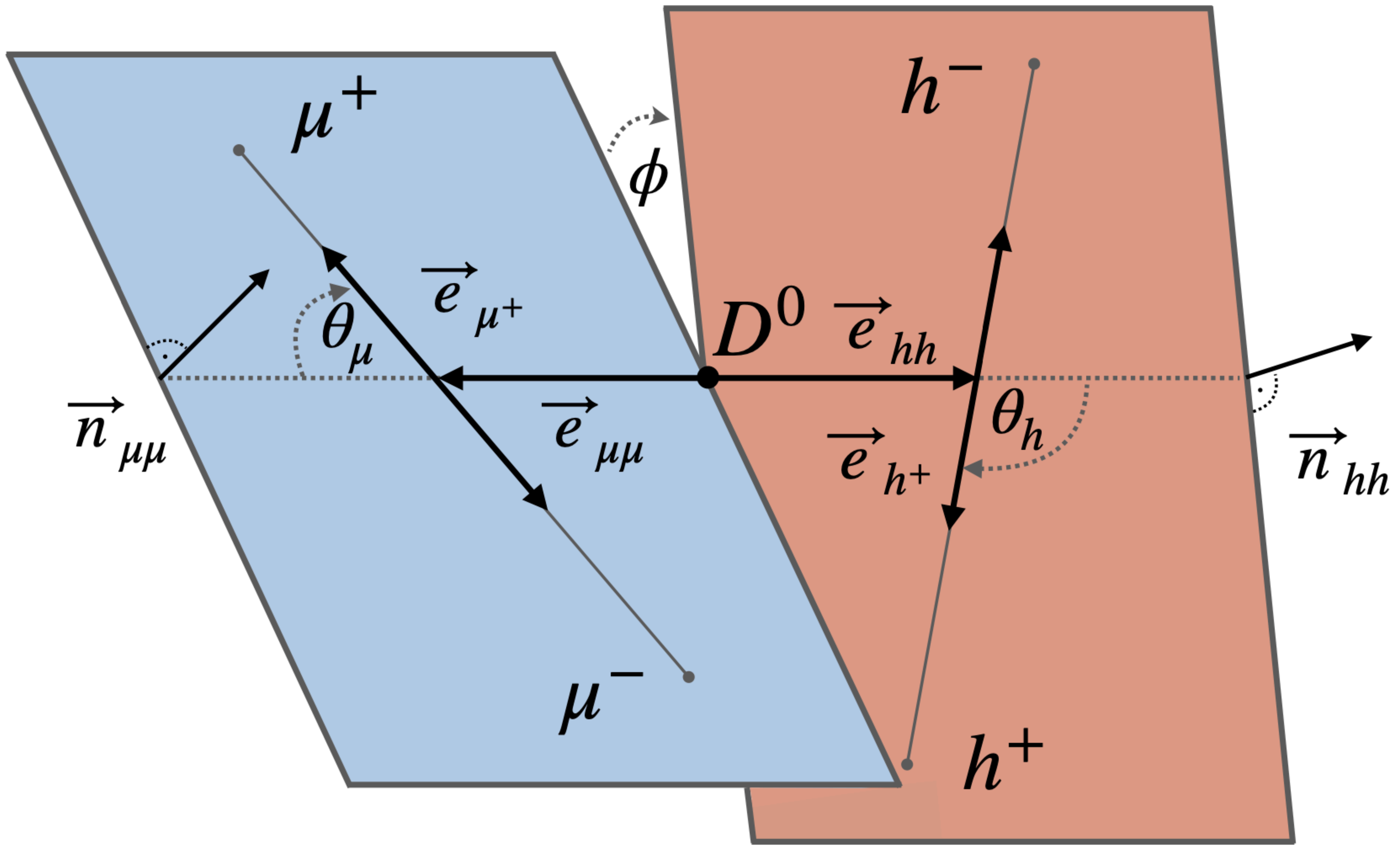

- No axial-vector couplings in rare charm decays, due to GIM suppression
- Clean null-test in $I_{5,6,7}$

Search for CP Violation and Angular Analysis of $D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$

Phys. Rev. Lett. **128**, 221801 (2022)

$$\frac{d\Gamma}{d\cos(\theta_\mu)\, d\cos(\theta_h)\, d\phi} = I_1 +$$
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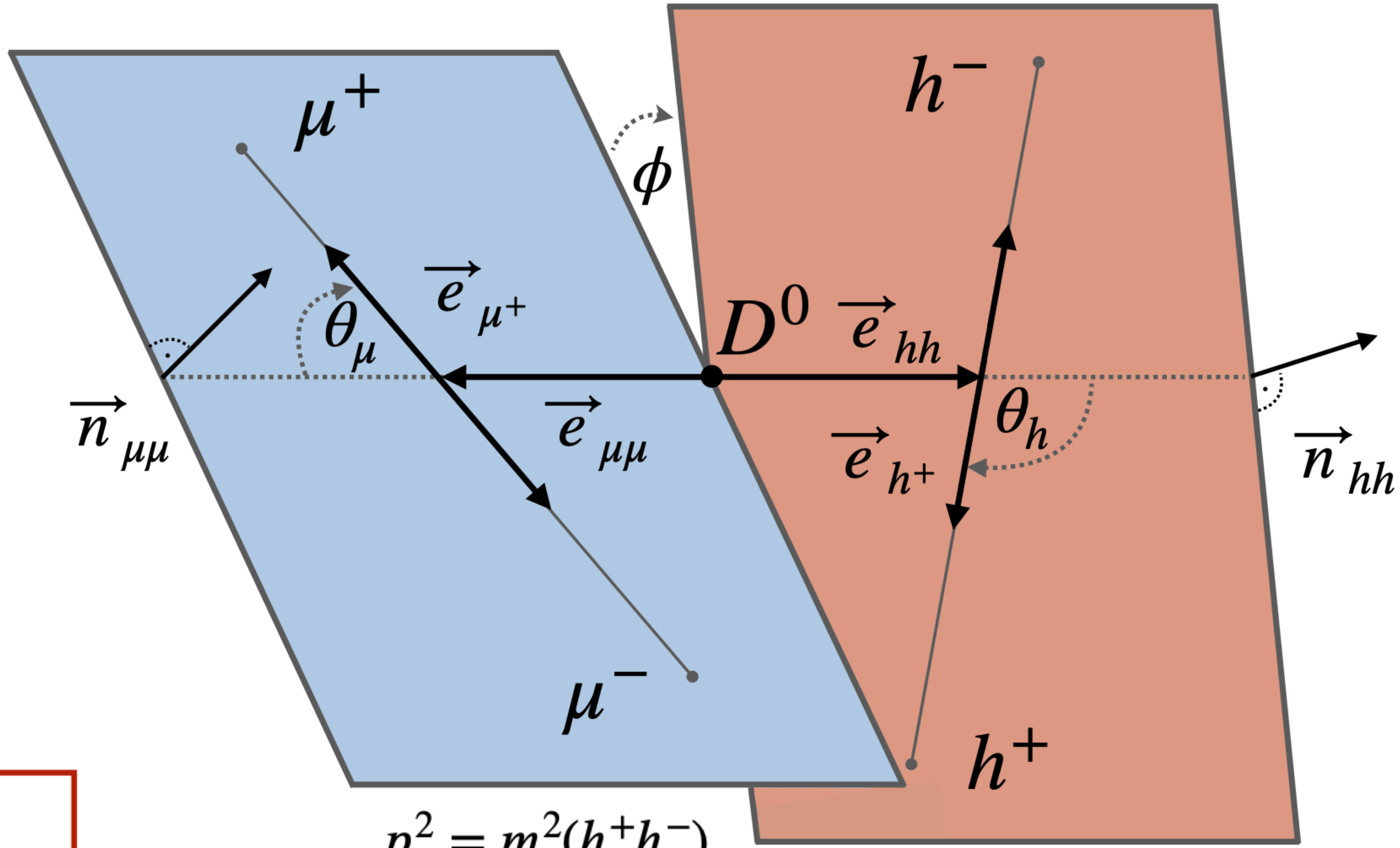
$$I_8 \cdot \sin(2\theta_\mu)\, \sin(\phi) +$$
$$I_9 \cdot \sin^2(2\theta_\mu)\, \sin(2\phi) +$$

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

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



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

Search for CP Violation and Angular Analysis of $D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$

Phys. Rev. Lett. **128**, 221801 (2022)

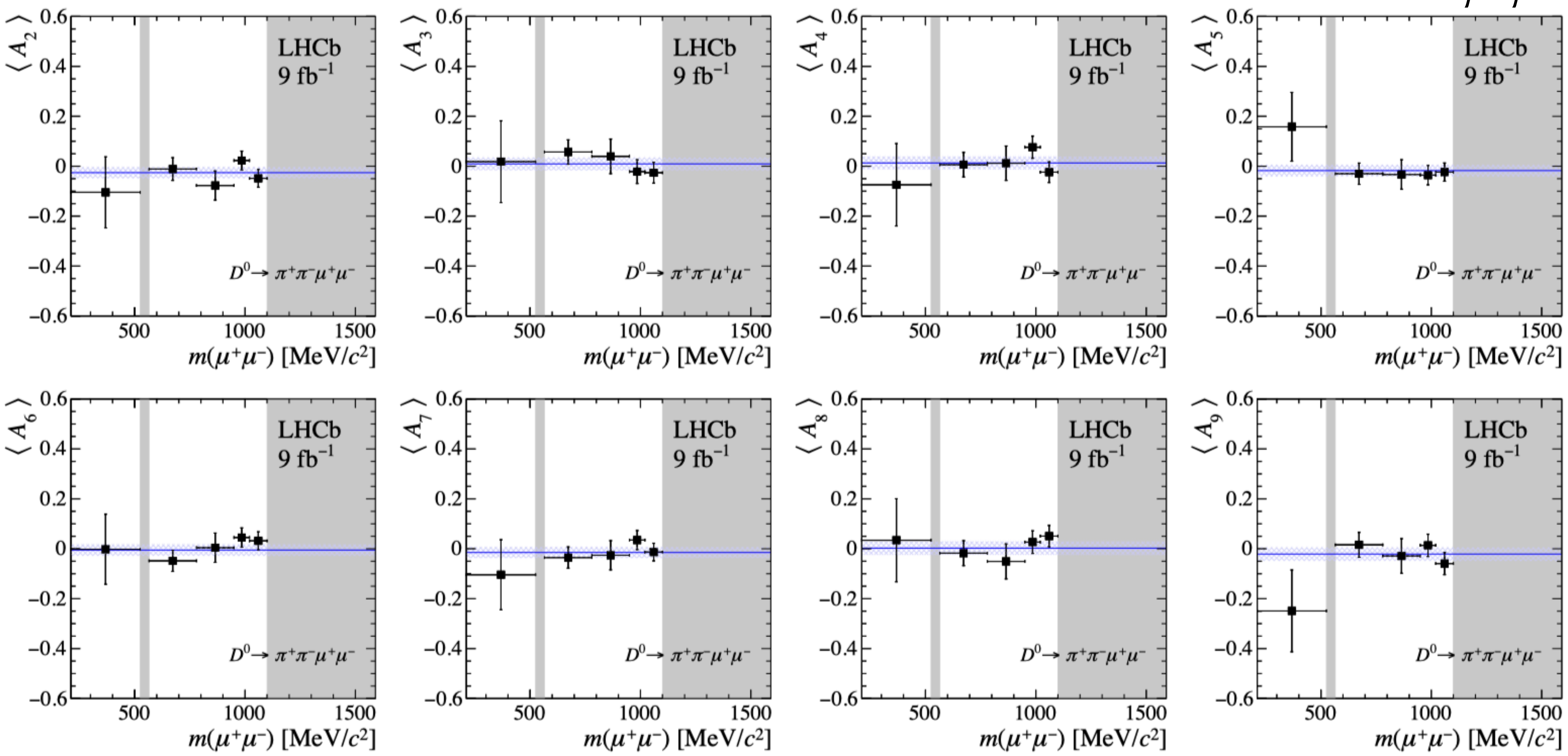
- Parity is conserved due to absence of axial-vector currents
- *CP* asymmetries:

$$\langle A_{\mathrm{i}}\rangle = \frac{1}{2}\left[\langle I_{\mathrm{i}}\rangle - (+)\langle \overline{I}_{\mathrm{i}}\rangle\right]$$

  for *CP*-even (*CP*-odd) coefficients are expected to be 0

- All asymmetries consistent with zero
- No dependency on dimuon mass

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



CP-even: $I_{2,3,4,7}$
CP-odd: $I_{5,6,8,9}$

Search for CP Violation and Angular Analysis of $D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$

Phys. Rev. Lett. **128**, 221801 (2022)

- *CP* averages:

  $$\langle S_i \rangle = \frac{1}{2}\left[\langle I_i \rangle + (-)\langle \overline{I}_i \rangle\right]$$

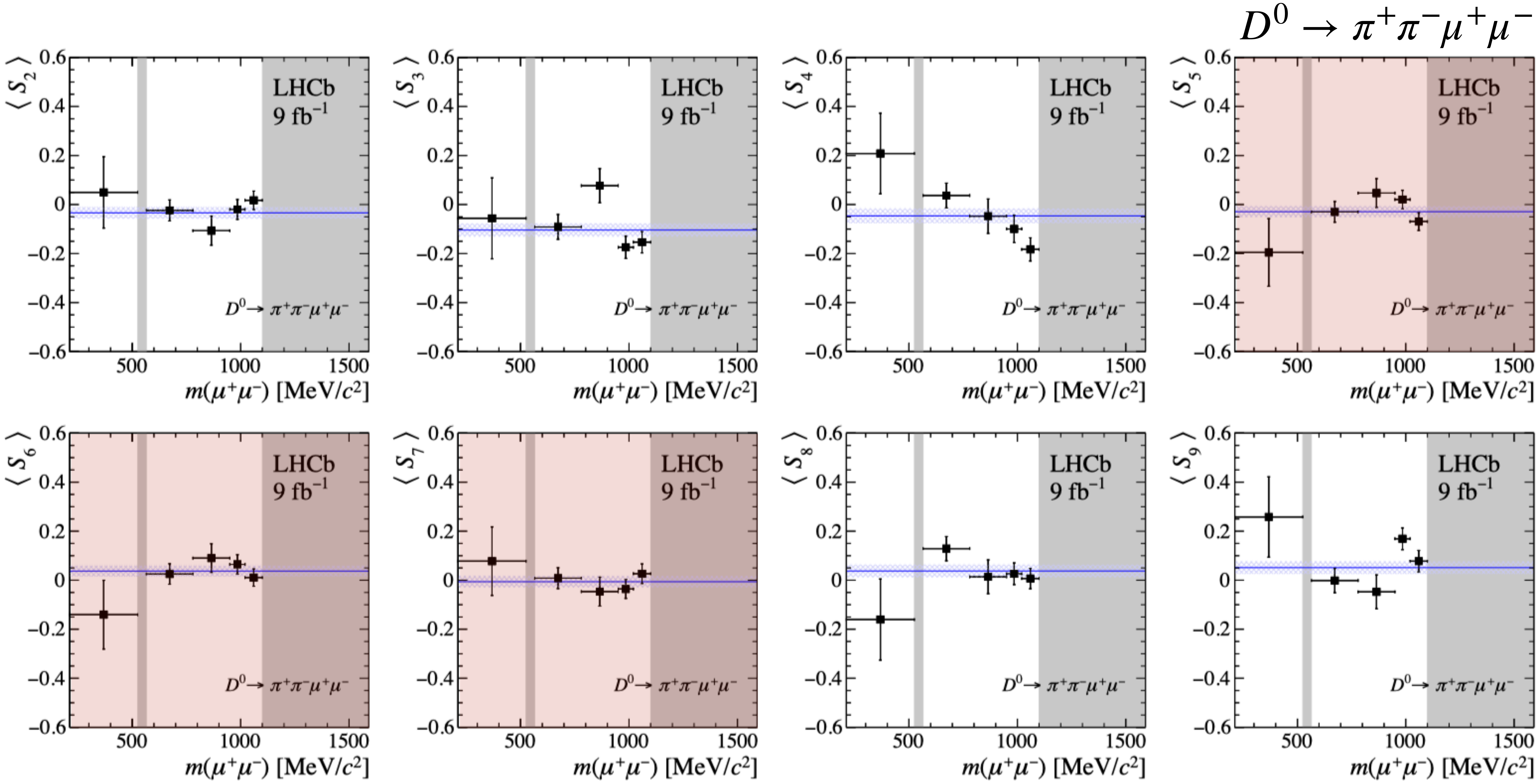
  for *CP*-even (*CP*-odd) coefficients

- $< S_{5,6,7} >$ compatible with zero

- No dimuon mass dependence observed

- Measured null-test observables in agreement with the SM null hypothesis

- p values of 79% (0.8%) for $D^0 \to \pi^+\pi^-\mu^+\mu^-$ ($D^0 \to K^+K^-\mu^+\mu^-$)



CP-even: $I_{2,3,4,7}$
CP-odd: $I_{5,6,8,9}$

Summary

(Particle Data Group), Prog. Theor. Exp. Phys. 2022

- Statistical precision of angular analysis ~2%
- Branching ratios precision up to $\mathcal{O}(10^{-9})$
  - Full Run 2 dataset:

$\mathscr{B}(D^0 \to \mu^+\mu^-) \leq 3.1 \times 10^{-9}$ (90 % CL)

$\mathscr{B}(D^*(2007)^0 \to \mu^+\mu^-) \leq 2.6 \times 10^{-8}$ (90 % CL)

$\mathscr{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 1.10) \times 10^{-7}$

$\mathscr{B}(D^0 \to K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.18) \times 10^{-7}$

  - Partial Run 2 dataset:

$\mathscr{B}(D^+ \to \pi^+\mu^+\mu^-) \leq 6.7 \times 10^{-8}$ (90 % CL)

$\mathscr{B}(D^+ \to K^+\mu^+\mu^-) \leq 5.4 \times 10^{-8}$ (90 % CL)

$\mathscr{B}(D_s^+ \to \pi^+\mu^+\mu^-) \leq 18 \times 10^{-8}$ (90 % CL)

$\mathscr{B}(D_s^+ \to K^+\mu^+\mu^-) \leq 14 \times 10^{-8}$ (90 % CL)

$\mathscr{B}(D^+ \to \pi^+e^+e^-) \leq 160 \times 10^{-8}$ (90 % CL)

$\mathscr{B}(D^+ \to K^+e^+e^-) \leq 85 \times 10^{-8}$ (90 % CL)

$\mathscr{B}(D_s^+ \to \pi^+e^+e^-) \leq 550 \times 10^{-8}$ (90 % CL)

$\mathscr{B}(D_s^+ \to K^+e^+e^-) \leq 490 \times 10^{-8}$ (90 % CL)

+17 more

The not so far future

Things to do

- $D^+ \to h^+ l^- l^+$ fully exploit the Run 2 dataset with updates of existing measurement and new analyses

- $D^0 \to h^+ h^- l^+ l^-$ possibility to intensify efforts with dielectron final state

$$\mathscr{B}(D^0 \to K^-\pi^+\mu^-\mu^+) = (4.17 \pm 0.12 \pm 0.40) \times 10^{-6}$$

Phys. Lett. B757 (2016) 558

$$\mathscr{B}(D^0 \to K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.18) \times 10^{-7}$$

$$\mathscr{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 1.10) \times 10^{-7}$$

Phys. Rev. Lett. **119**, 181805 (2017)

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

Phys.Rev.Lett. 122 (2019) 8, 081802 (BaBar)

$$\mathscr{B}(D^0 \to K^+K^-e^+e^-) = ?$$

$$\mathscr{B}(D^0 \to \pi^+\pi^-e^+e^-) = ?$$

Lepton Flavour Universality

- Charm can provide a complementary test of LFU:

$$R^c_{hh} = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(D^0 \to h^+h^-\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(D^0 \to h^+h^-e^+e^-)}{dq^2} dq^2}$$

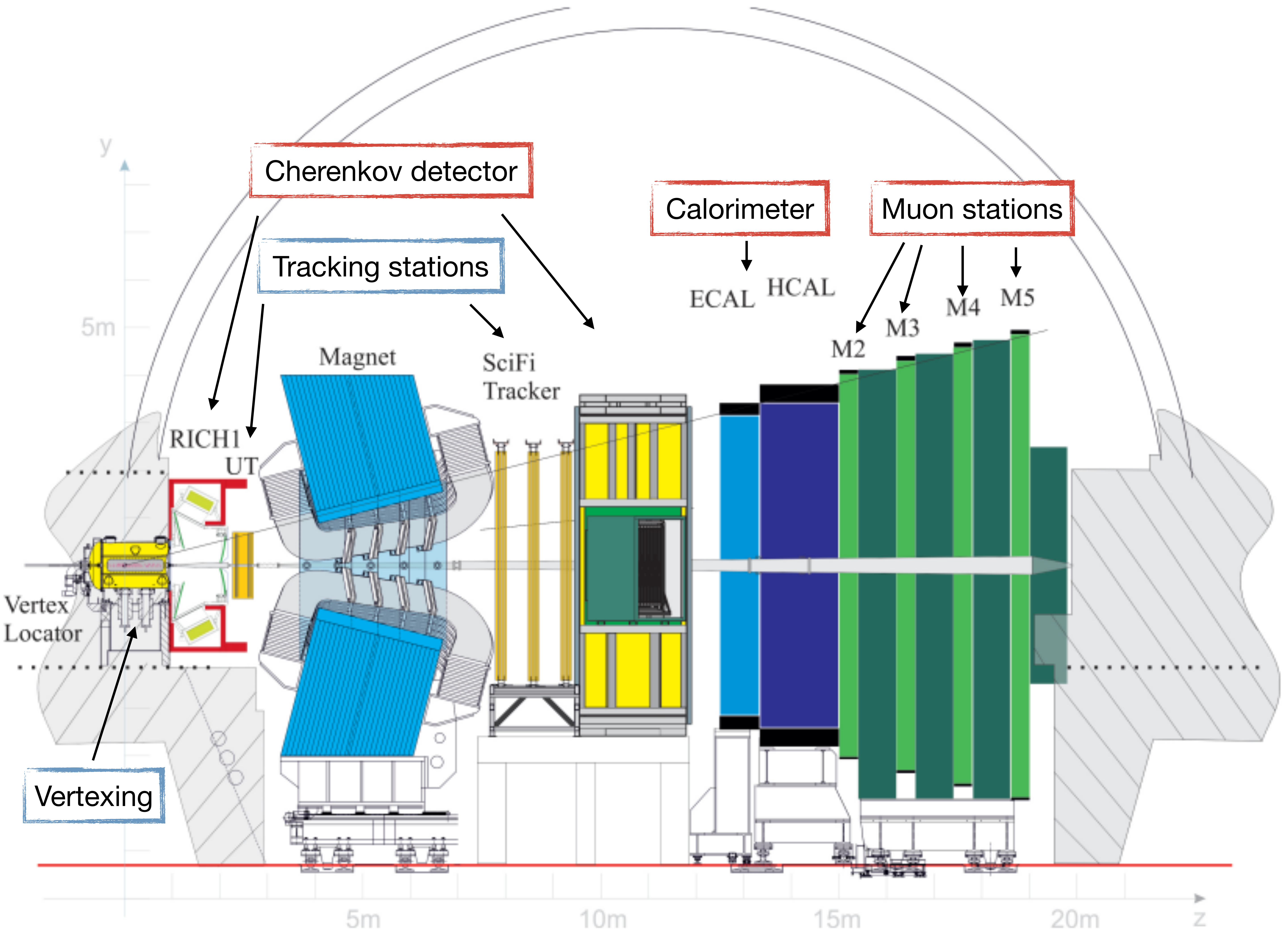
- Any observation of LFU violation, apart from phase space effects, would immediately hint to new physics

The Future

Upgrade I (2022+)

LHCb-TDR-12

- LHCb is an all-purpose spectrometer placed at the LHC optimised to study b- and c-hadrons
- Completely new Tracker and Vertex Locator for a better vertex resolution, tracking resolution
- Particle identification with calorimeter, muon stations and Cherenkov detectors (RICH)
- Capable of a higher read out rate, up to 40 MHz!



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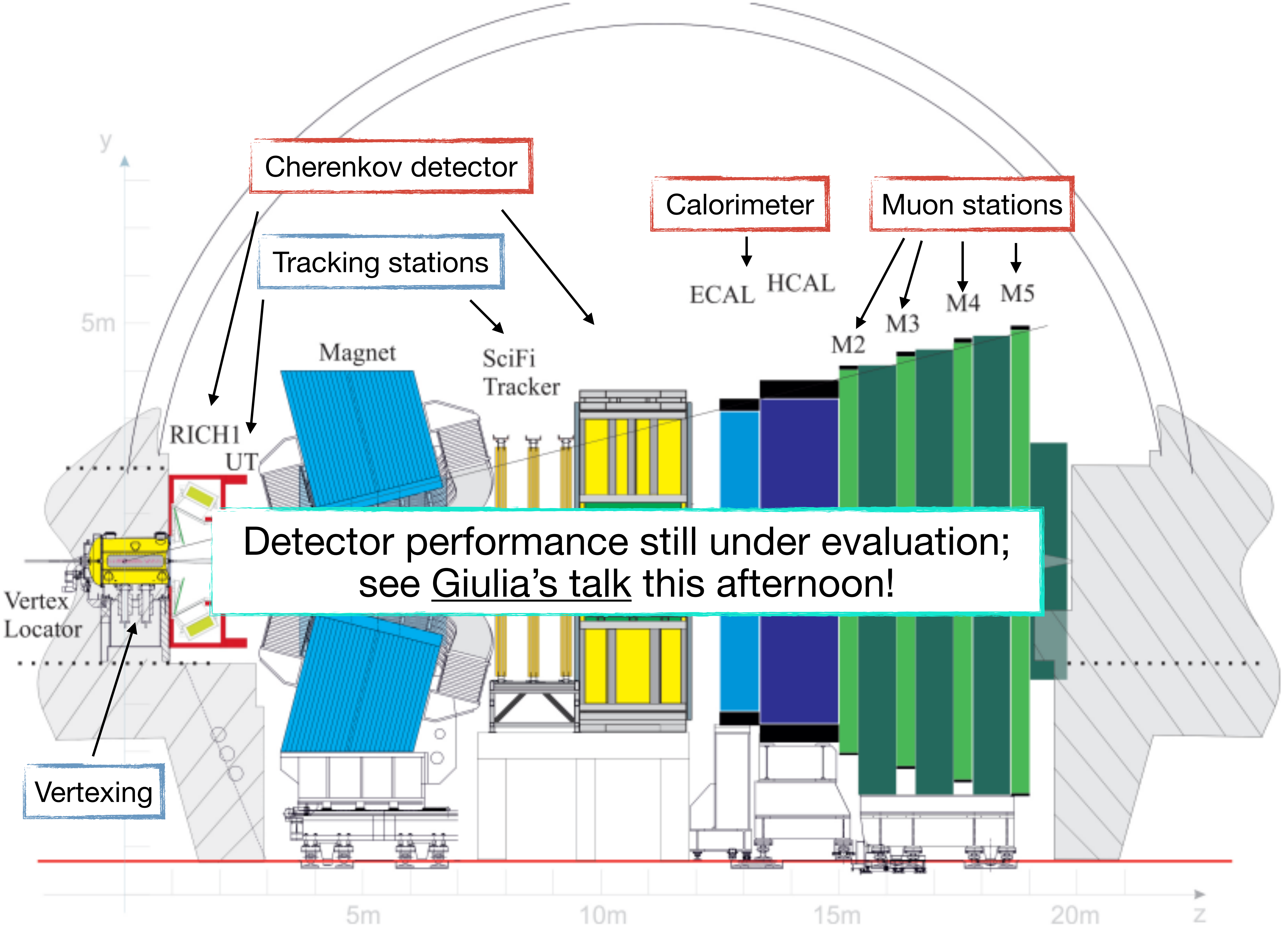
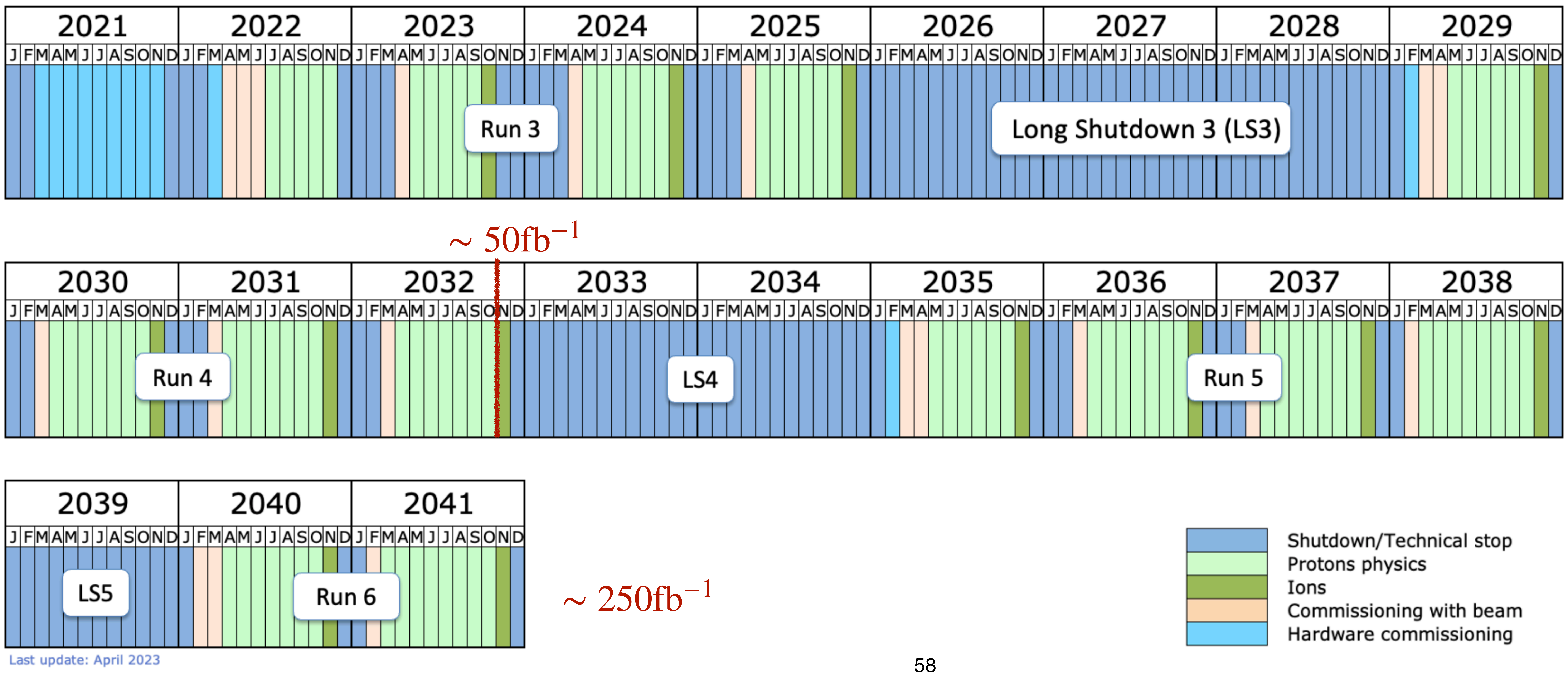


Detector performance still under evaluation; see Giulia's talk this afternoon!

Expected LHCb schedule

LHCb-TDR-23

- Goal is to collect about 50fb^{-1} of data until LS4, with an increased trigger efficiency for charm
- Potentially increasing this number by a factor of ~5 after LS4



Future Sensitivity

LHCB-TDR-023

- Potential new limits on branching ratios* Upgrade 1, 2022-2030, and Upgrade 2, 2030+:

Mode	Run1-2 (1-9 fb^{-1})	Upgrade1 (50 fb^{-1})	Upgrade2 (300 fb^{-1})
$D^0 \to \mu^+\mu^-$	~~6.2×10^{-9}~~ 3.1×10^{-9}	4.2×10^{-10}	1.3×10^{-10}
$D^+ \to \pi^+\mu^+\mu^-$	6.7×10^{-8}	10^{-8}	3×10^{-9}
$D_s^+ \to K^+\mu^+\mu^-$	2.6×10^{-8}	10^{-8}	3×10^{-9}
$\Lambda_c^+ \to p\mu^+\mu^-$	9.6×10^{-8}	1.1×10^{-8}	4.4×10^{-9}
$D^0 \to e^\pm\mu^\mp$	1.3×10^{-8}	10^{-9}	4.1×10^{-9}

A.Contu - Towards ultimate precision in Flavour Physics, Durham (2-4 April 2019)

- Statistical precision* on asymmetries:

Mode	Run1-2 (1-9 fb^{-1})	Upgrade1 (50 fb^{-1})	Upgrade2 (300 fb^{-1})
$D^+ \to \pi^+\mu^+\mu^-$		0.2 %	0.08 %
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	~~3.8 %~~ 2%	1 %	0.4 %
$D^0 \to K^-\pi^+\mu^+\mu^-$		0.3 %	0.13 %
$D^0 \to K^+\pi^-\mu^+\mu^-$		12 %	5 %
$D^0 \to K^+K^-\mu^+\mu^-$	~~11 %~~ 6%	4 %	1.7 %

A.Contu - Towards ultimate precision in Flavour Physics, Durham (2-4 April 2019)

*scaled by luminosity

Conclusion and prospects

- This presentation summarised the most recent results of rare (semi)leptonic charm decays at LHCb
- Reaching a precision on the branching ratios of $\mathcal{O}(10^{-9})$ and a statistical precision on angular observables of $\mathcal{O}(\%)$
- All measurements are **statistical limited**. New measurements, using complete Run 2 dataset, are on the way!
- Increased read out rate and improved trigger selection in Run 3

Conclusion and prospects

- This presentation summarised the most recent results of rare (semi)leptonic charm decays at LHCb
- Reaching a precision on the branching ratios of $\mathcal{O}(10^{-9})$ and a statistical precision on angular observables of $\mathcal{O}(\%)$
- All measurements are **statistical** … complete Run 2 dataset, are on the way!
- Increased read out rate and improved trigger selection in Run 3

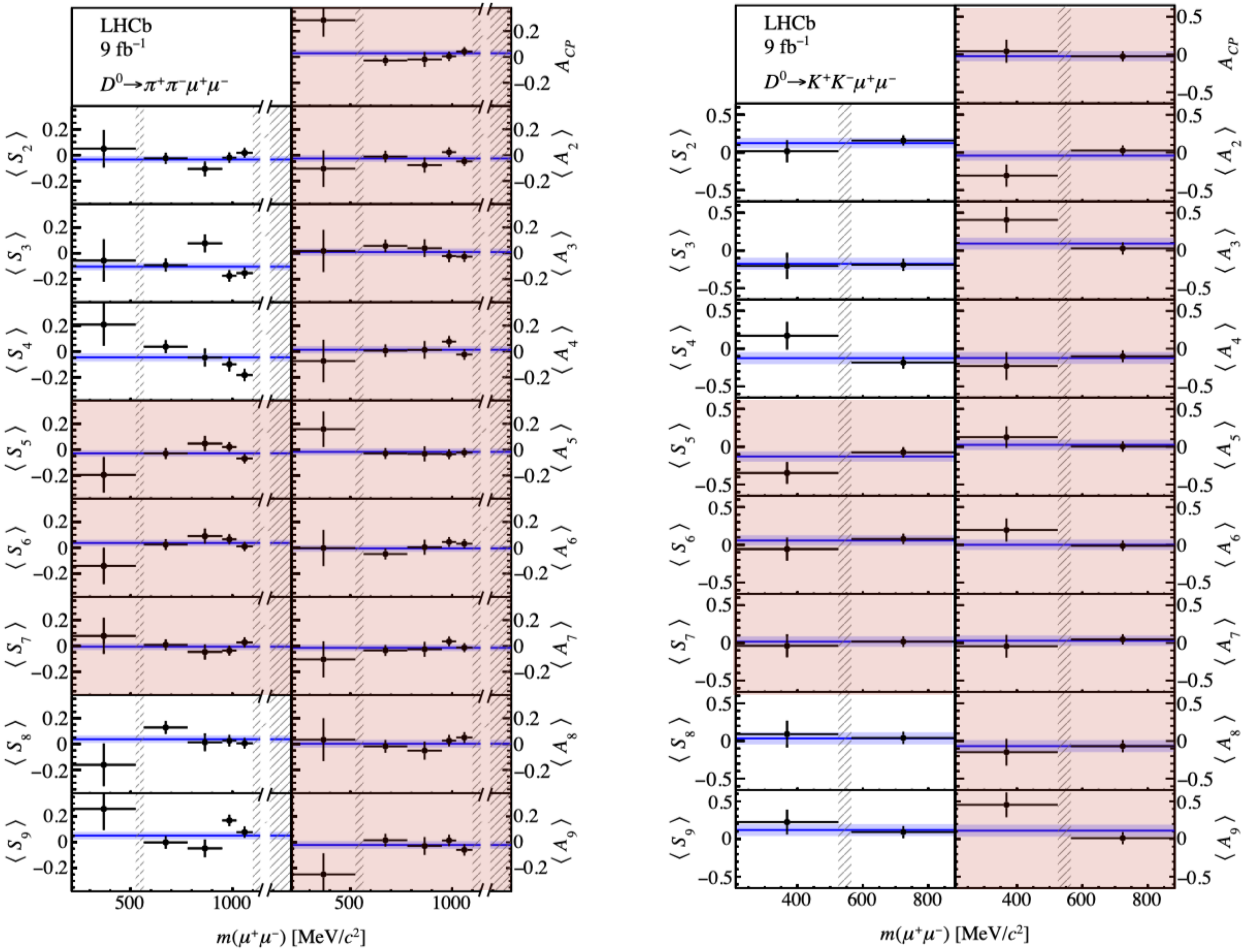
Stay tuned for new results!

Backup

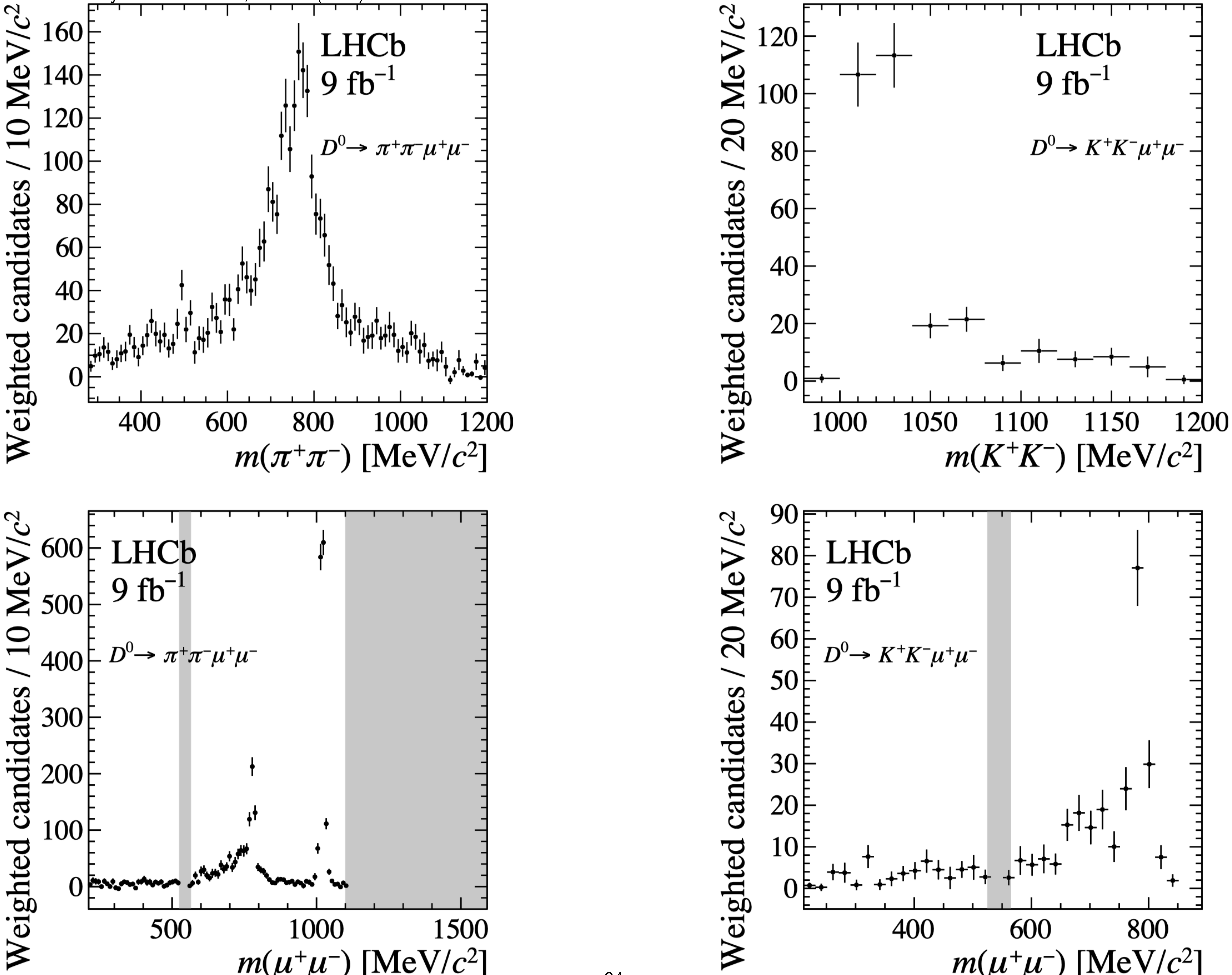
Angular Analysis of $D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$

Phys. Rev. Lett. **128**, 221801 (2022)

- Red marked observables are clean null tests



Phys. Rev. Lett. **128**, 221801 (2022)



First observation of $D^0 \to KK\mu\mu$ and $D^0 \to \pi\pi\mu\mu$

Phys. Rev. Lett. **119**, 181805 (2017)

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