New Physics Searches in Charm Hadron Decays

Liang Sun

Wuhan University

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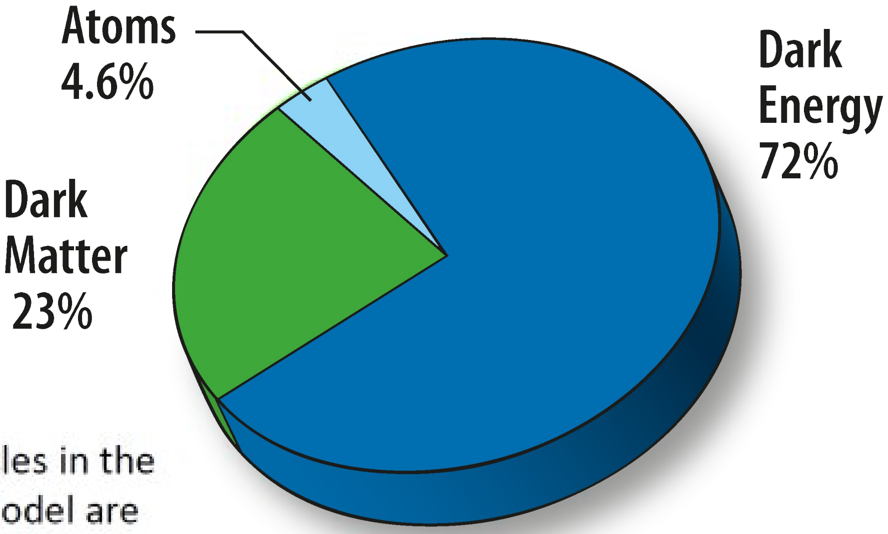
Outline

- Motivation
- Experiments on charm physics
- Searches for (vary) rare charm decays
  - FCNC/LFV/LNV/BNV/Invisible
- Semileptonic charm decays for NP searches
- Summary

Why New Physics?

- Standard Model extremely successful during past decades
- Some outstanding issues still unaccounted for, such as dark matter & energy

Presence of dark matter in the universe?

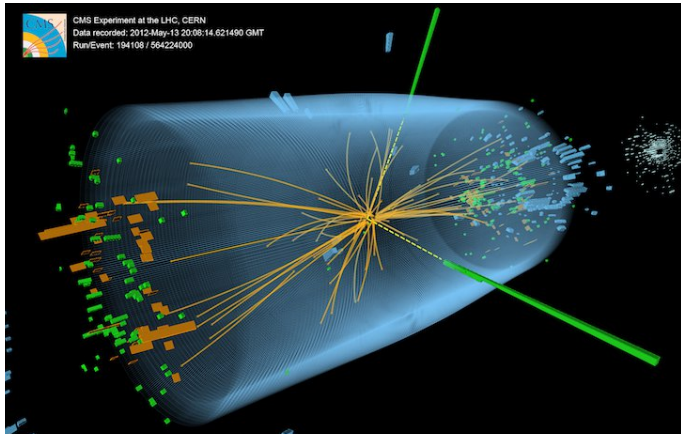


None particles in the Standard Model are satisfactory candidates for it

What is the dark matter made of?

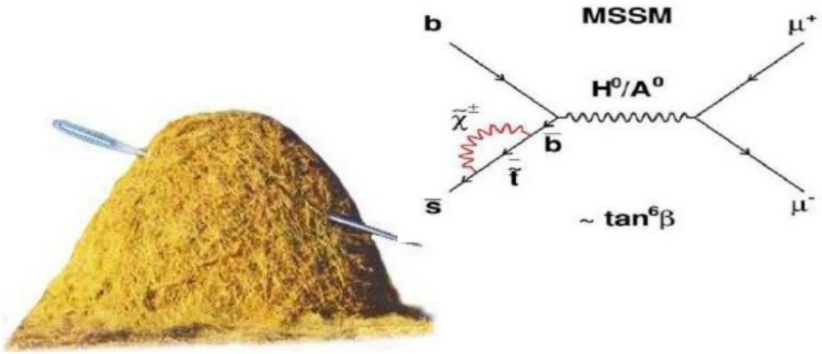
Searches for NP

An example: Higgs discovery

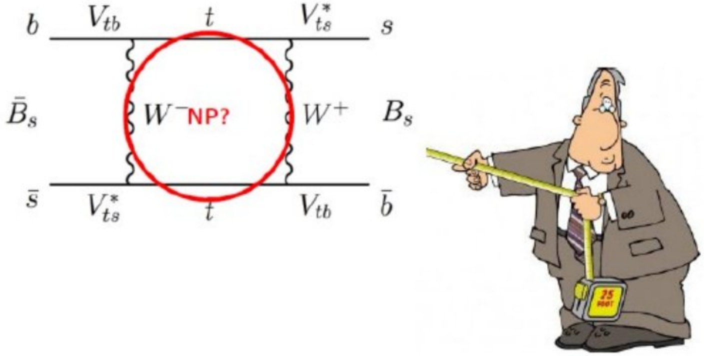


- Direct search (ATLAS / CMS): Look for production of new particles

- Indirect search (LHCb / BESIII / BelleII): Look for “hints” of new particles in loops



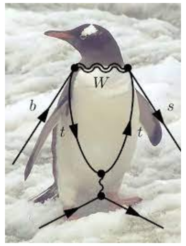
Enhancement of the branching fraction of very rare decays

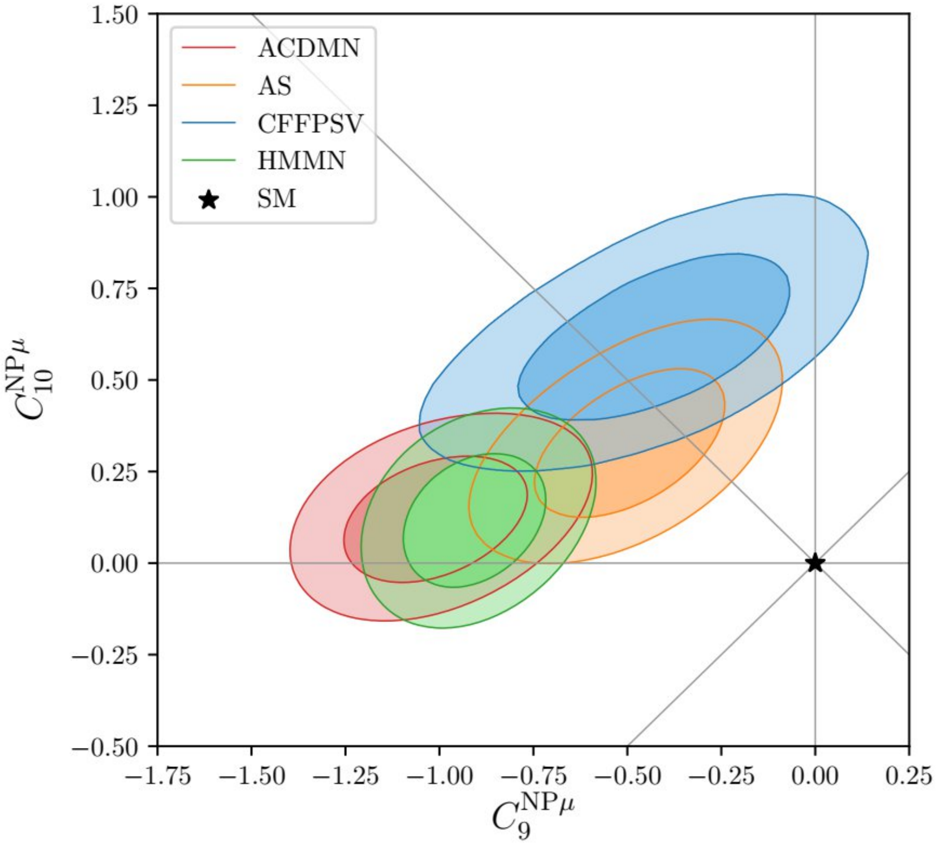


Effects on the value of Standard Model parameters (precise measurements to look for discrepancy)

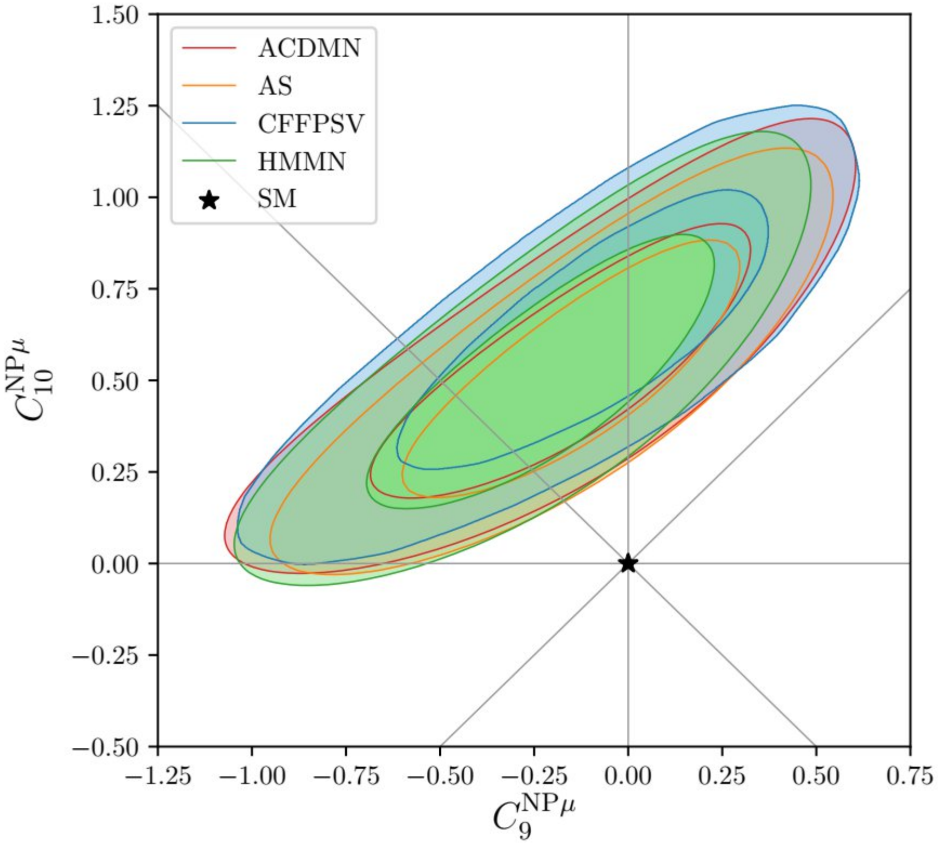
A bit of history (1970): charm suggested to explain suppression of $K_S^0 \to \mu^+\mu^-$ before J/ψ discovery

NP searches in b-sector: a coherent pattern?





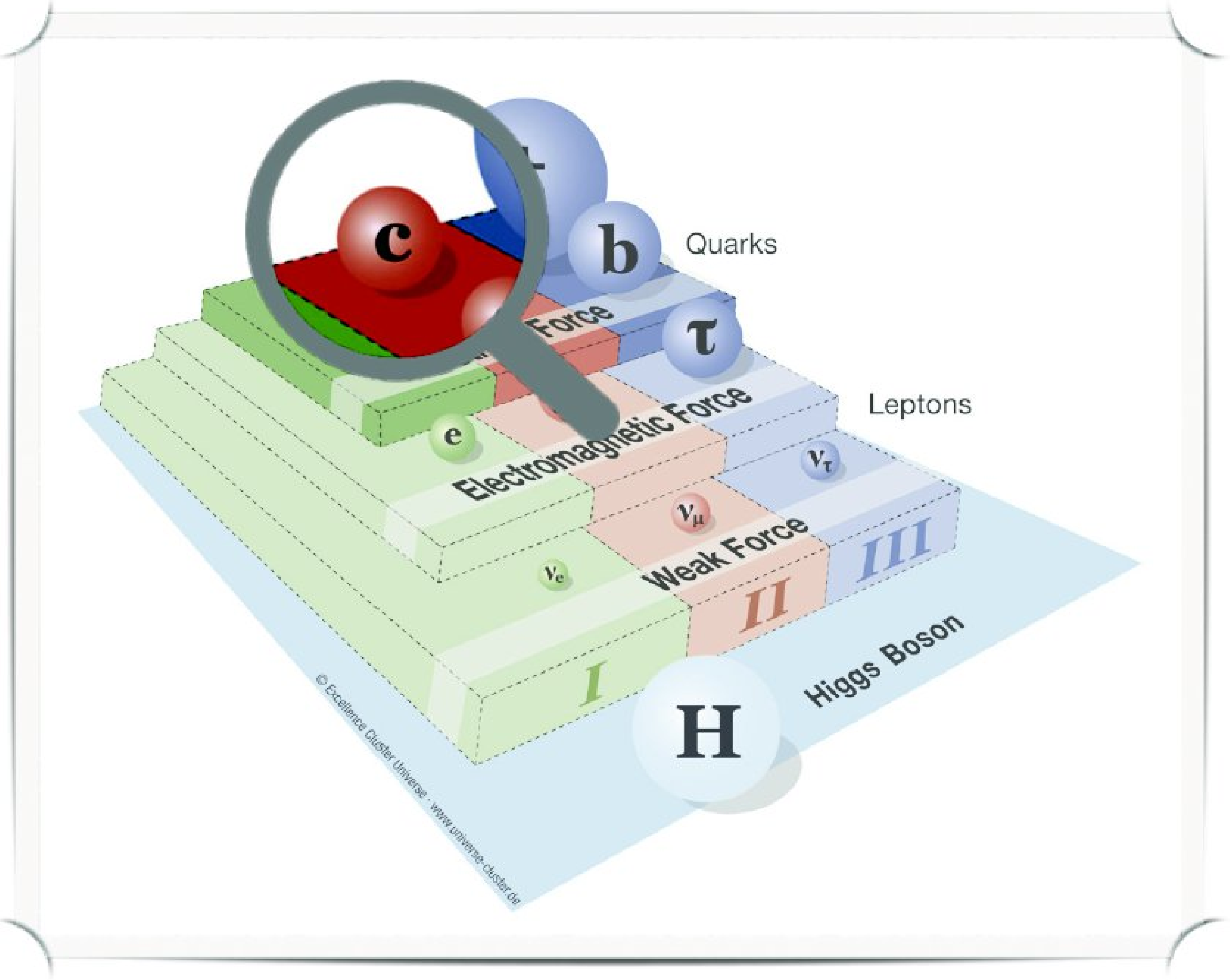
Global fit based on experimental inputs from $b \to s\ell\ell$ and $b \to s\gamma$



fit to LFU observables + $B_s \to \mu\mu$

From B. Capdevila *et al.*'s talk @ Flavour Anomaly Workshop 2021

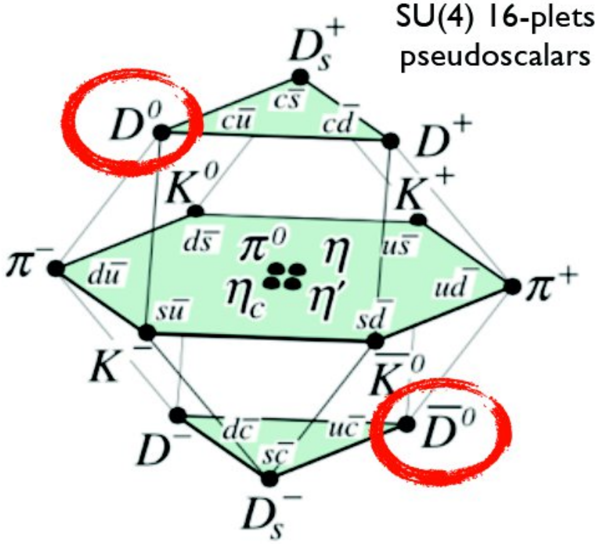
See also, e.g., LHCb实验上的味物理反常 by 何吉波

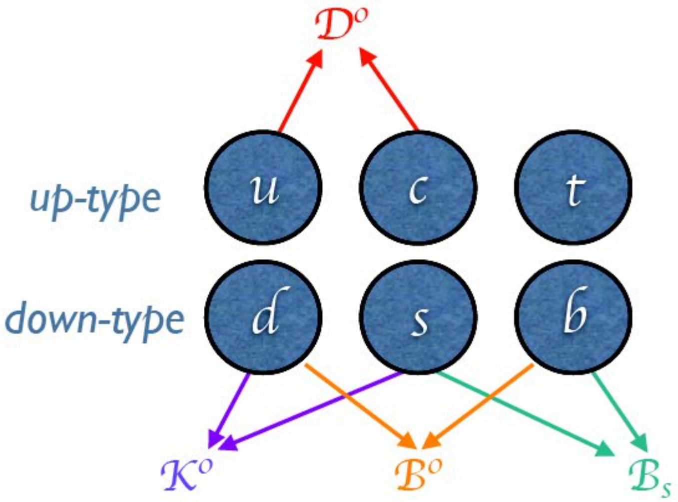


Zooming on Charm

Why is Charm so charming?

- *charm* is an up-type quark, of mass ~ 1.25 GeV/c^2
  - not heavy (m(b) ~ 4.2 GeV/c^2) nor light (m(s) ~ 100MeV/c^2)
- it forms charged and neutral mesons and baryons
- In particular the neutral meson D^0 *is the only mixing meson made of up-type quarks:*
  - the top quark decays before forming bound states
  - π^0 coincides with its own antiparticle





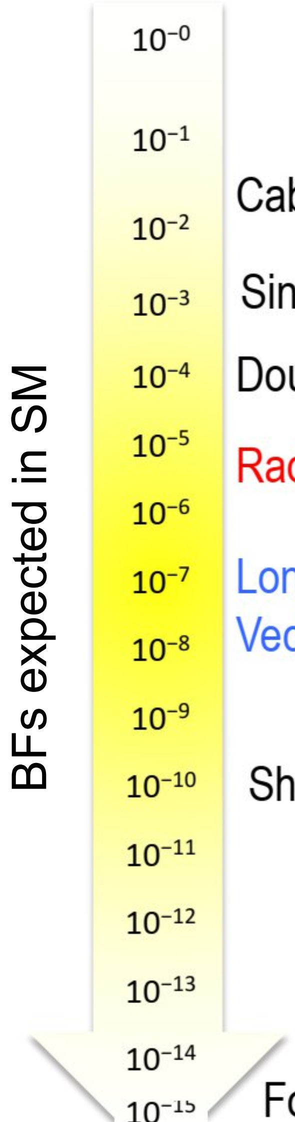
charm flavour physics

- complementary informations provided w.r.t. K and B mixing (and CPV)
- eventual NP contributions must couple to the up-type sector
- constraints NP models probing a different parameters space

Summary of charm decays

Charm provide a unique environment for testing the SM rare/forbidden decays and searching for NP

Complementary information to B and K sectors with down-type quarks



Cabibbo favor

Single Cabibbo suppressed

Doubly Cabibbo suppressed

Radiative decays

$D^0 \rightarrow K^{*0}\gamma/\phi\gamma/\omega\gamma/\rho\gamma$

$D^+_{(S)} \rightarrow K^{*+}\gamma/\rho^+\gamma$

Long distance:
Vector meson Dominance (SM)

$D^{0+} \rightarrow \gamma\gamma/VV'(l^+l^-)/ hV(l^+l^-)/ hh'V(l^+l^-)$

Rare decays

Short distance FCNC (SM+NP)

$D^{0/+} \rightarrow \gamma\gamma/Vl^+l^-/hl^+l^-/hh'l^+l^-$

$D^0 \rightarrow \mu^+\mu^- /e^+ e^-$

$D \rightarrow (hh)\mu^+\mu^+/(hh)e^+e^+$

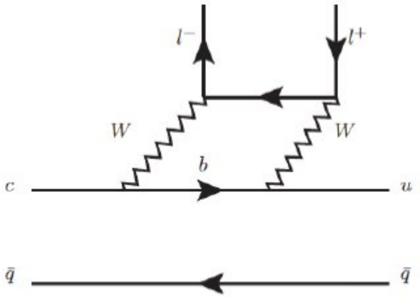
$D \rightarrow (h)\mu^+e^-$

(NP)
Forbidden decays: LNV, LFV, BNV

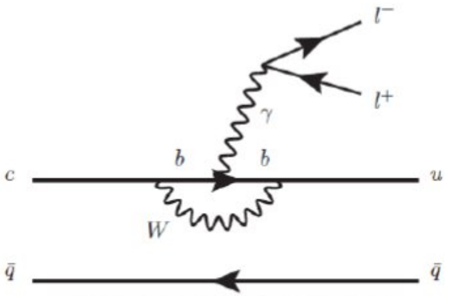
$D \rightarrow (h)pe^-$

Flavor **C**hanging **N**eutral **C**urrents

- Forbidden at tree level in SM, only allowed in loop and box diagrams
    - Strongly suppressed due to GIM cancellation:
    - BF ~O(10^{-9})
- $D \to X\ell^+\ell^-$ dominated by Long-Distance contributions
    - Vector Meson dominance (VMD)
    - BF ~O(10^{-6})
- No VMD in $D \to X\nu\bar{\nu}$

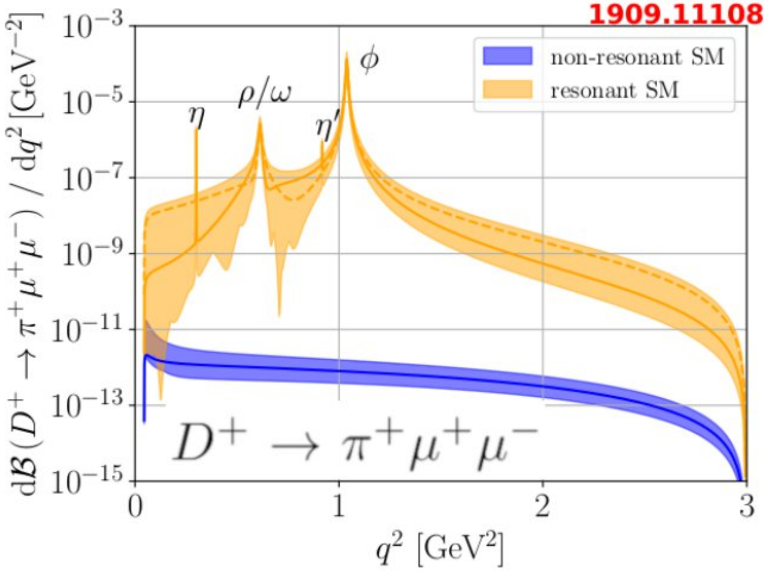


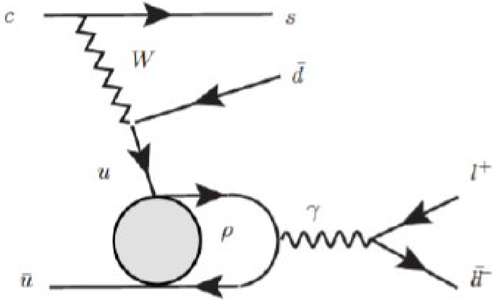
box diagram



penguin diagram

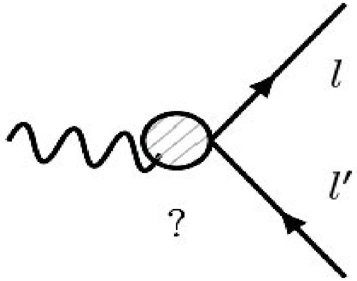
1909.11108





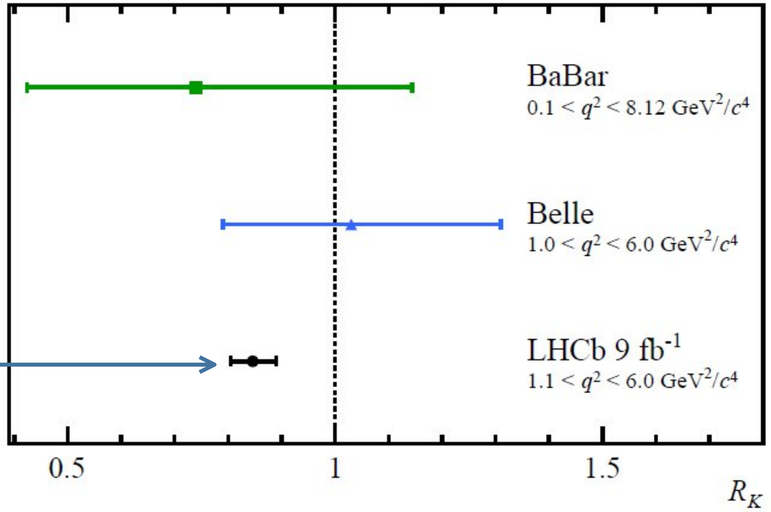
VMD

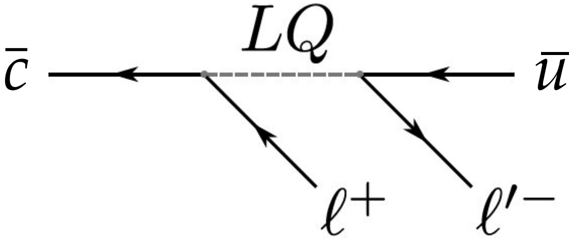
Lepton **F**lavor **V**iolation



- LFV exists in neutrino oscillation
- Observation of charged LFV (cLFV) decays will be a clear sign for NP
- Lepton flavor non-universality closely related to cLFV
  - LHCb recently reported 3.1σ tension with SM in $b \to s\ell^+\ell^-$

    [Nature Phys. 18 (2022) 3, 277]
- BSM models (lepto-quark, Z’, etc.) may induce cLFV and enhance BF up to O(10^{-5})



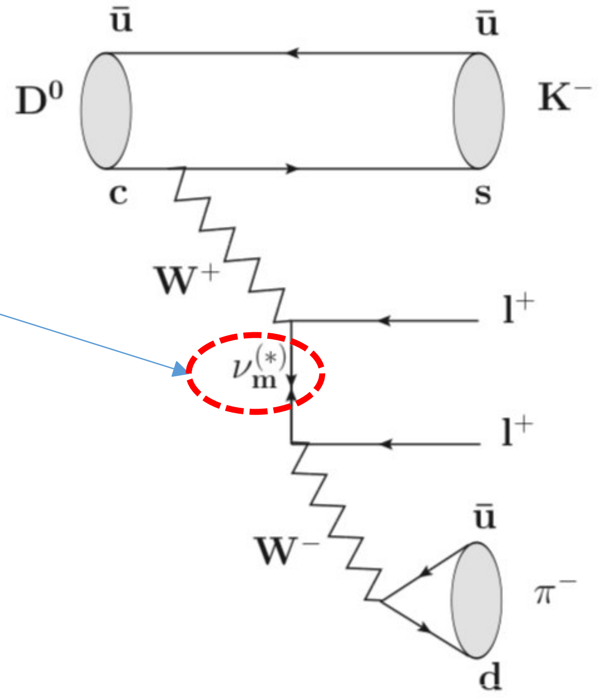


Lepton **N**umber **V**iolation

- Lepton **N**umber **V**iolation ($\Delta L \neq 0$) is forbidden in SM
- Neutrino oscillation → $m_{\nu} \neq 0$ → New Physics needed to explain mass origin
- Nature of neutrino: Dirac or Majorana (ν_{m})?
- Majorana neutrino can lead to $\Delta L = 2$ LNV processes
- LNV is introduced in many NP models:
  - 4th quark generation, SO(10) SUSY GUT, exotic Higgs, etc.
- LNV processes have been widely searched for in τ, K, D, and B decays

$$\begin{pmatrix}\nu_{\uparrow}\\ \nu_{\downarrow}\\ \bar{\nu}_{\uparrow}\\ \bar{\nu}_{\downarrow}\end{pmatrix} \quad \text{or} \quad \begin{pmatrix}\nu_{\uparrow}\\ \nu_{\downarrow}\end{pmatrix}$$

Dirac Majorana

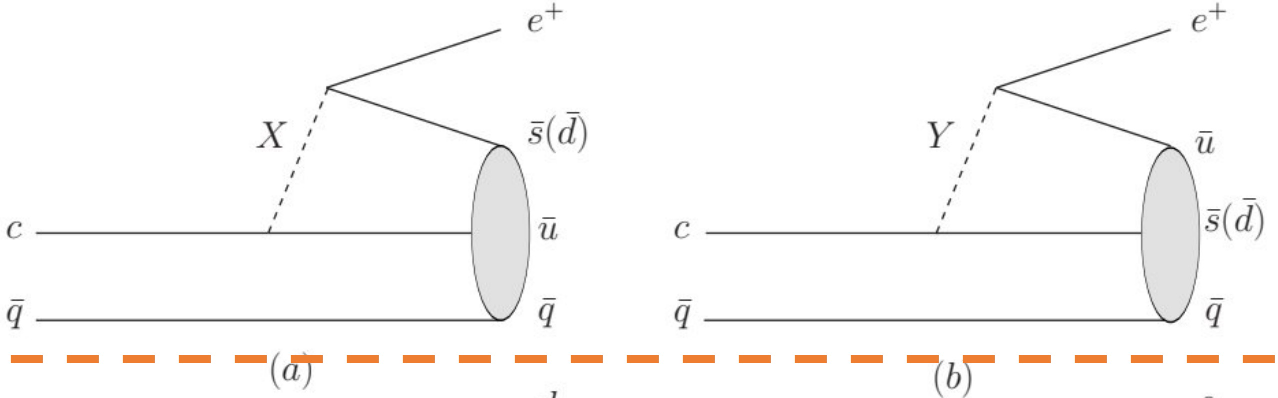


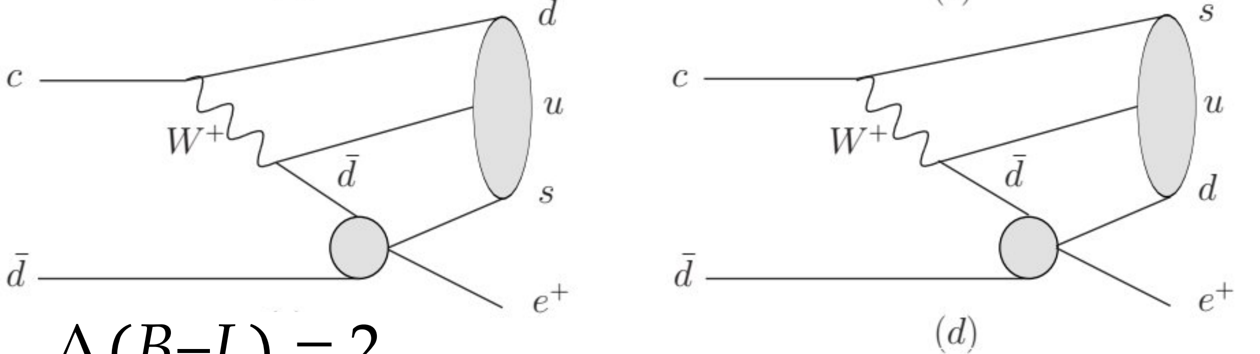
Baryon **N**umber **V**iolation

- Excess of baryons over antibaryons in the Universe → BNV processes exist
- BNV is allowed in GUTs and some SM extensions
    - Accompanied by LNV
- BFs of $D \rightarrow B\ell$, $B = \Lambda,\Sigma,\mathrm{p},\mathrm{n}$ expected to be no more than $\mathscr{O}(10^{-29})$ [PRD 72, 095001 (2005)]

$\Delta\,(B{-}L) = 0$

Feynman diagrams under operators with dimension six

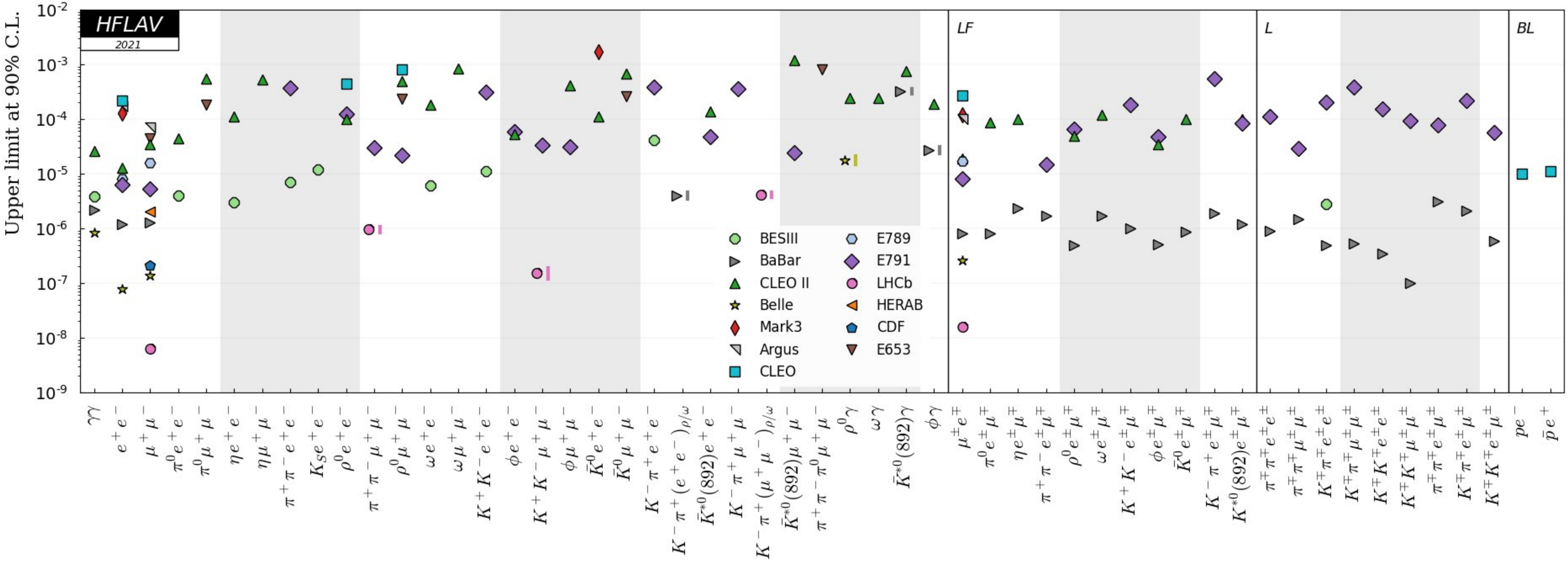




$\Delta\,(B{-}L) = 2$

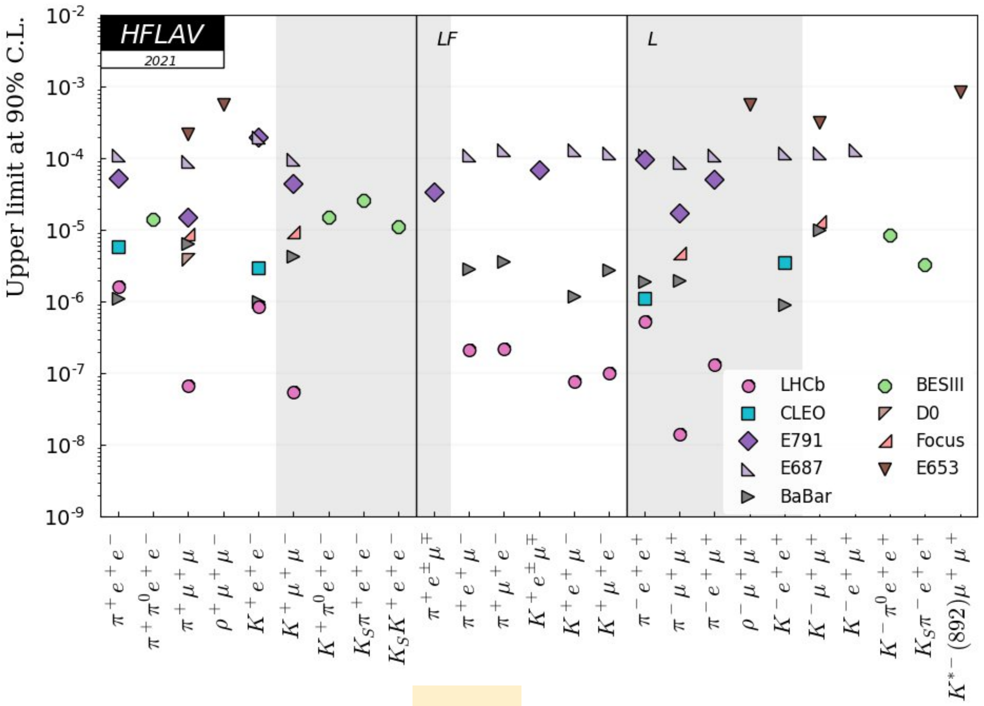
Feynman diagrams under operators with dimension seven

Results on rare charm decays (D^0)

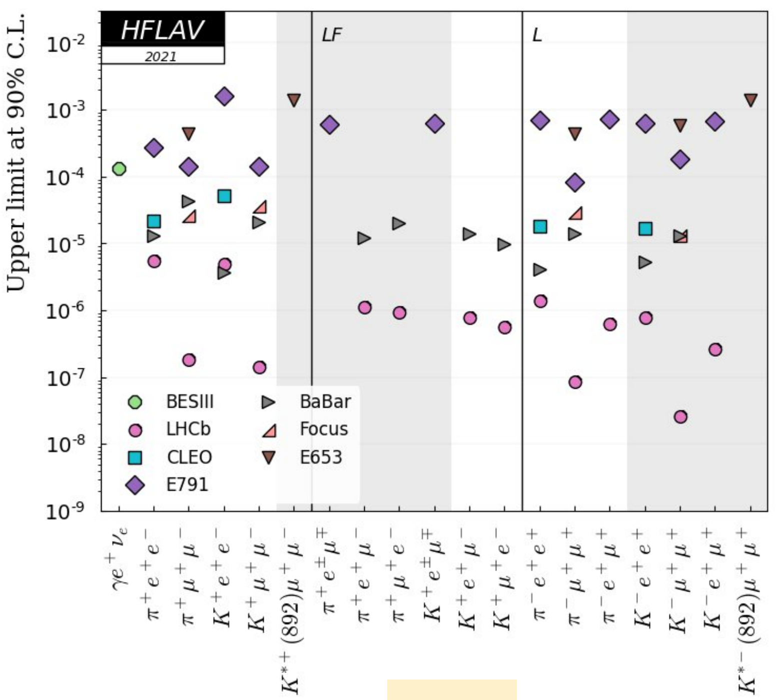


https://hflav-eos.web.cern.ch/hflav-eos/charm/rare/Spring2021/rare_charm.html

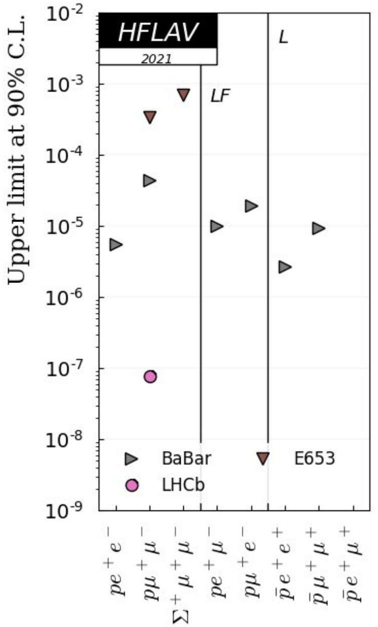
Results on rare charm decays



D^+



D_s^+



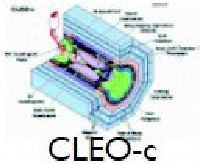
Λ_c^+

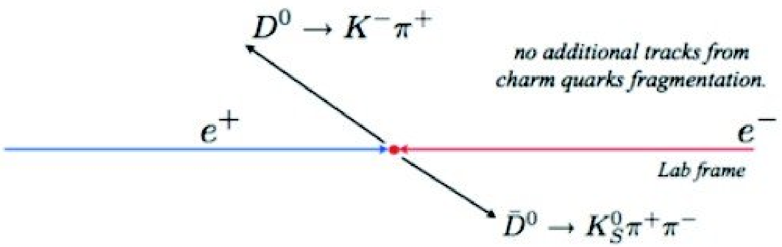
https://hflav-eos.web.cern.ch/hflav-eos/charm/rare/Spring2021/rare_charm.html

Major experiments on charm physics

threshold production

BESIII

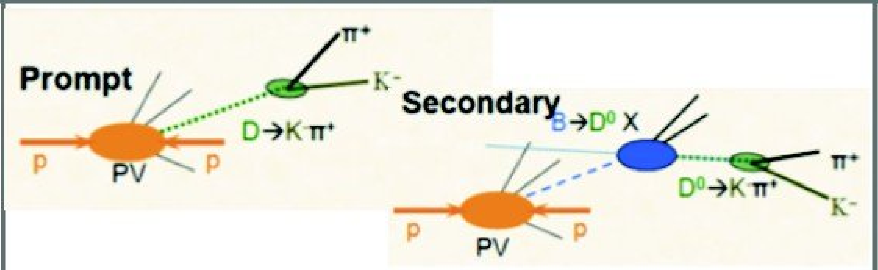




- ✓ double-tag method for bkg. suppr. & neutrino reco.
- ✓ extremely clean environment
- ✓ high efficiency detection on electrons/neutrals
- ✓ quantum coherence
- ● no CM boost, no T-dep analyses

hadron colliders

CDF LHCb DØ



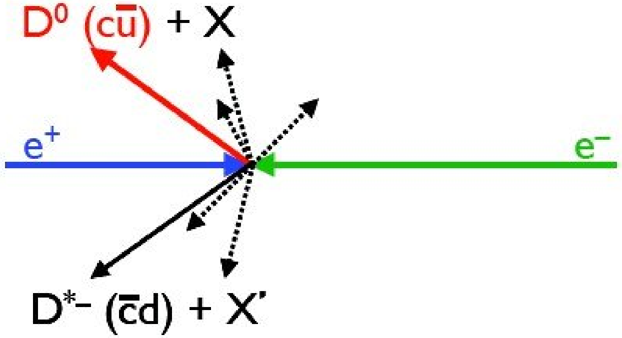
- ✓ large production cross-section
- ✓ large boost: excellent time res
- ● dedicated trigger required
- ● hard to do neutrals and neutrinos

B-Factories

BELLE

high-luminosity B-Factory

Belle II

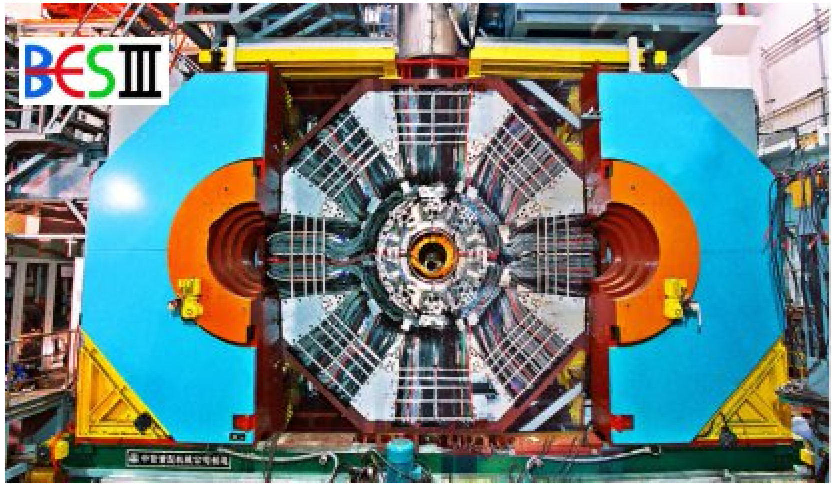


- ✓ clean event environment
- ✓ high trigger efficiency
- ✓ high-efficiency detection of neutrals
- ✓ many high-statistics control samples
- ✓ time-dependent analysis
- ● smaller cross-section than hadron colliders

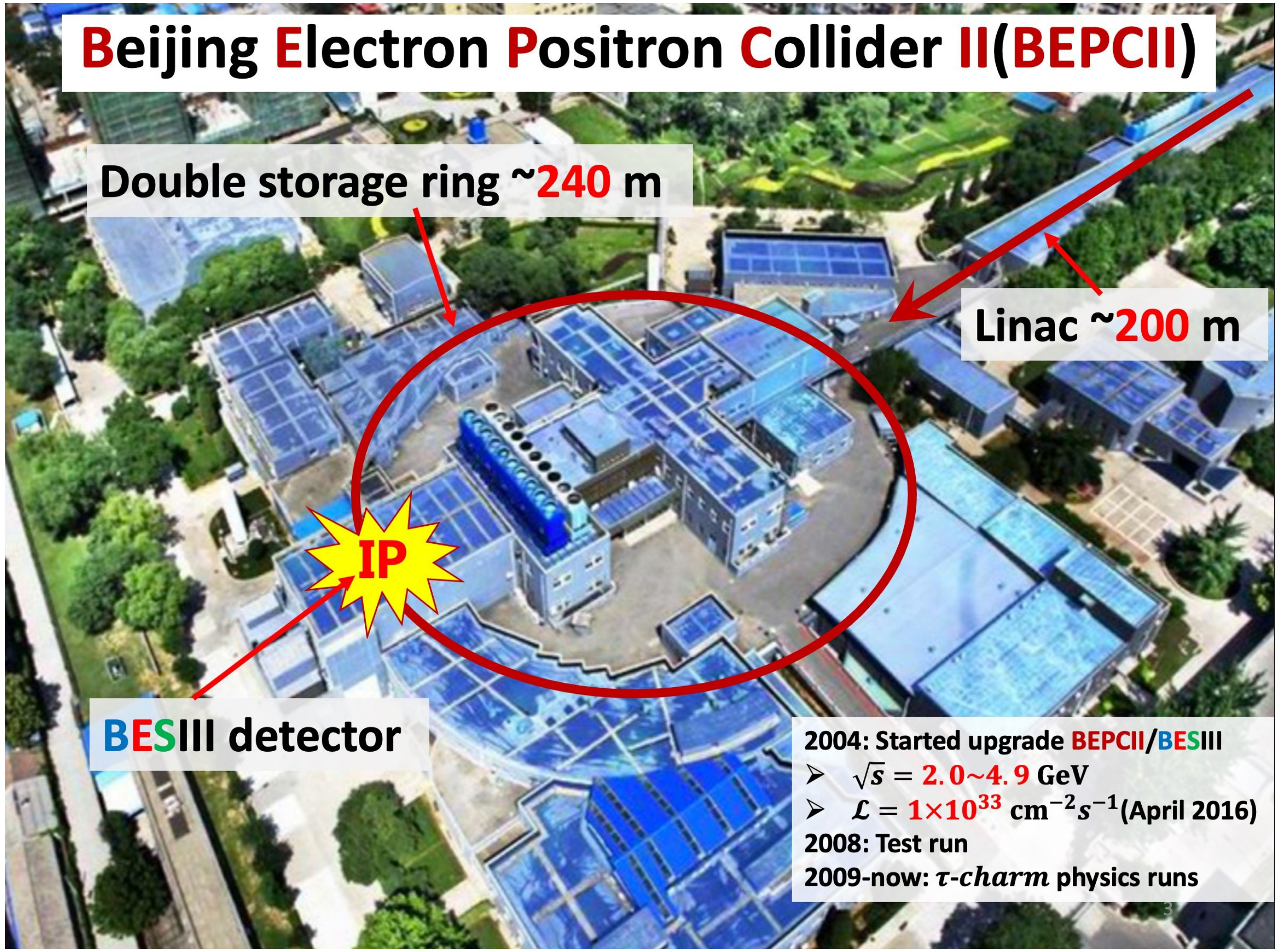
A tale of two experiments: selected topics

- $D^0 \to \pi^0 \nu \bar{\nu}$
- $D^0 \to pe$
- $D^+ \to n(\bar{n})e^+$

- $D^+_{(s)} \to h\ell\ell^{(\prime)}$
- $D^0 \to (\pi^+\pi^-/K^+K^-)\mu^+\mu^-$



BEPCII & BESIII



2004: Started upgrade BEPCII/BESIII
- $\sqrt{s} = 2.0\sim4.9$ GeV
- $\mathcal{L} = 1\times10^{33}\ \mathrm{cm}^{-2}s^{-1}$(April 2016)

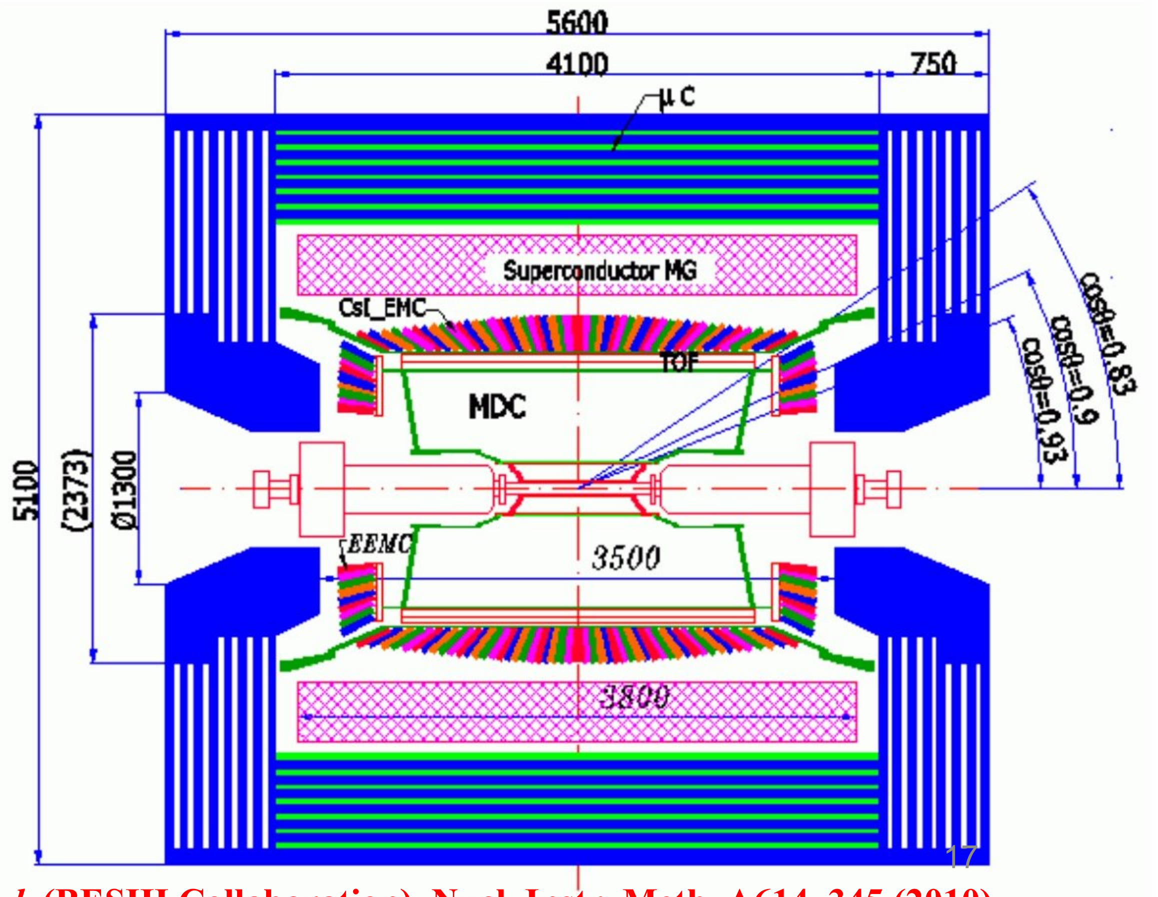
2008: Test run
2009-now: τ-$charm$ physics runs

Electromagnetic CsI(Tl) Calorimeter (EMC)
$\sigma_E/E < 2.5\%$ @ 1 GeV (barrel)
$\sigma_E/E < 5\%$ @ 1 GeV (end-caps)

Time-of-Flight (TOF)
$\sigma_t = 90$ ps (barrel)
$\sigma_t = 120$ ps (end-caps)

Main Drift Chamber (MDC)
$\sigma_{r\phi} = 130\ \mu\mathrm{m}$ (single wire)
$\sigma_{p_t}/p_t = 0.5\%$ @ 1 GeV

Superconducting solenoid (1 Tesla)

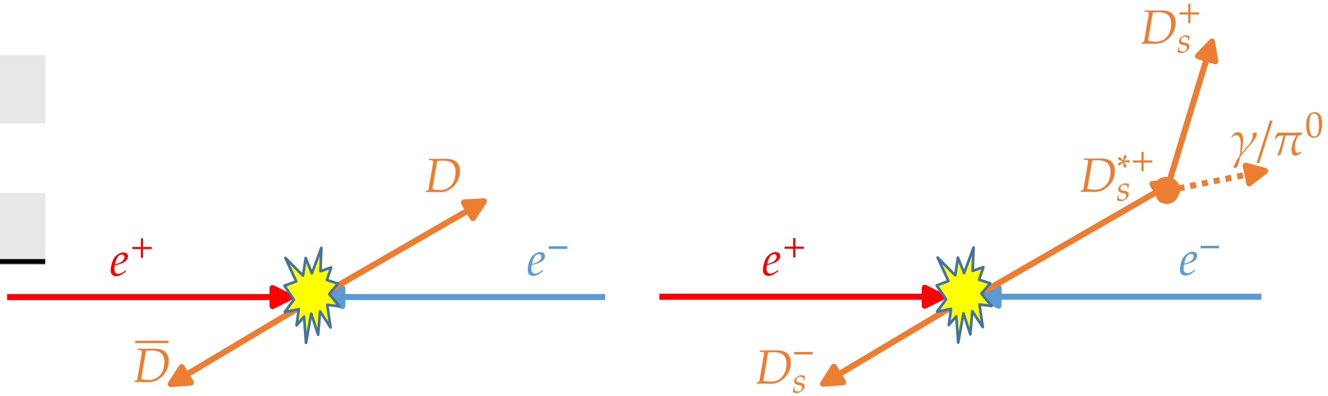


M. Ablikim *et al.* (BESIII Collaboration), Nucl. Instr. Meth. A614, 345 (2010)

Charm datasets @ BESIII

- Pairs of $D_{(s)}$ produced near threshold w/o additional hadrons

Data samples	$\sqrt{s}$ (GeV)	Int. $\mathcal{L}$ (fb^{-1})
$D\bar{D}$	3.773	2.93
$D_s\bar{D}_s^*$	4.178	3.19
$D_s\bar{D}_s^*$	4.189 – 4.226	3.18
$\Lambda_c^+\bar{\Lambda}_c^-$	4.599	0.567
$\Lambda_c^+\bar{\Lambda}_c^-$	4.612 – 4.698	3.8



- Advantages:
  - Low background level
  - Full event info, neutrino kinematics can be inferred
  - Absolute branching fraction measurement possible with one $D_{(s)}$ tagged
  - Superb EMC performance on e / γ / π^0

Double-Tag method

- Fully reconstructed $\bar{D}$ at tag side (**ST**)
- Requiring signal decay at the other side (**DT**)

ST yields:

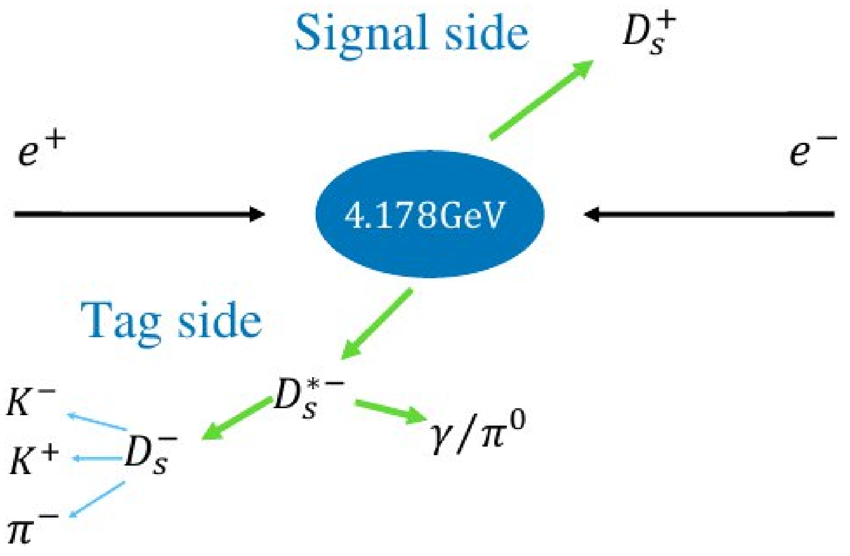
$$N_{D_{(s)}}^{\mathrm{ST}} = 2 \times N_{D\bar{D}} \times B_{ST} \times \varepsilon_{ST}$$

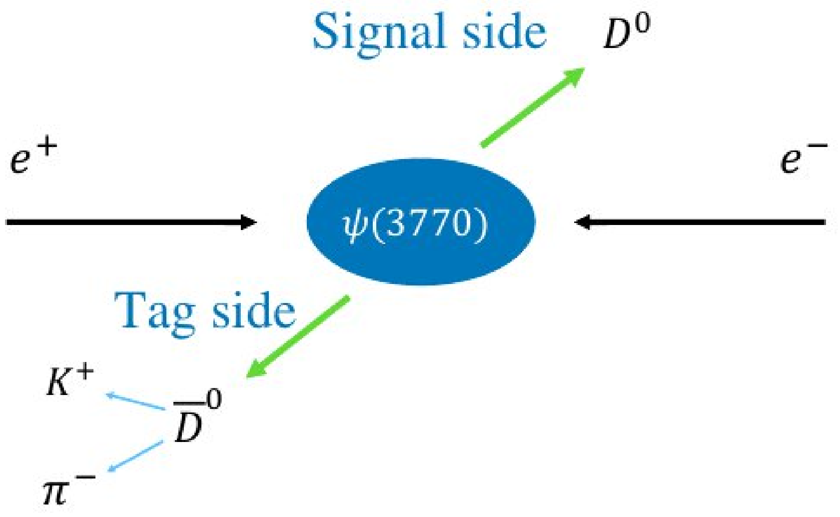
DT yield:

$$N_{\mathrm{DT}}^{\mathrm{signal}} = 2 \times N_{D\bar{D}} \times B_{ST} \times B_{sig} \times \varepsilon_{ST,sig}$$

The signal branching fraction:

$$B_{\mathrm{sig}} = \frac{N_{\mathrm{DT}}^{\mathrm{signal}}}{N_{D_{(s)}}^{\mathrm{ST}} \times \varepsilon}$$

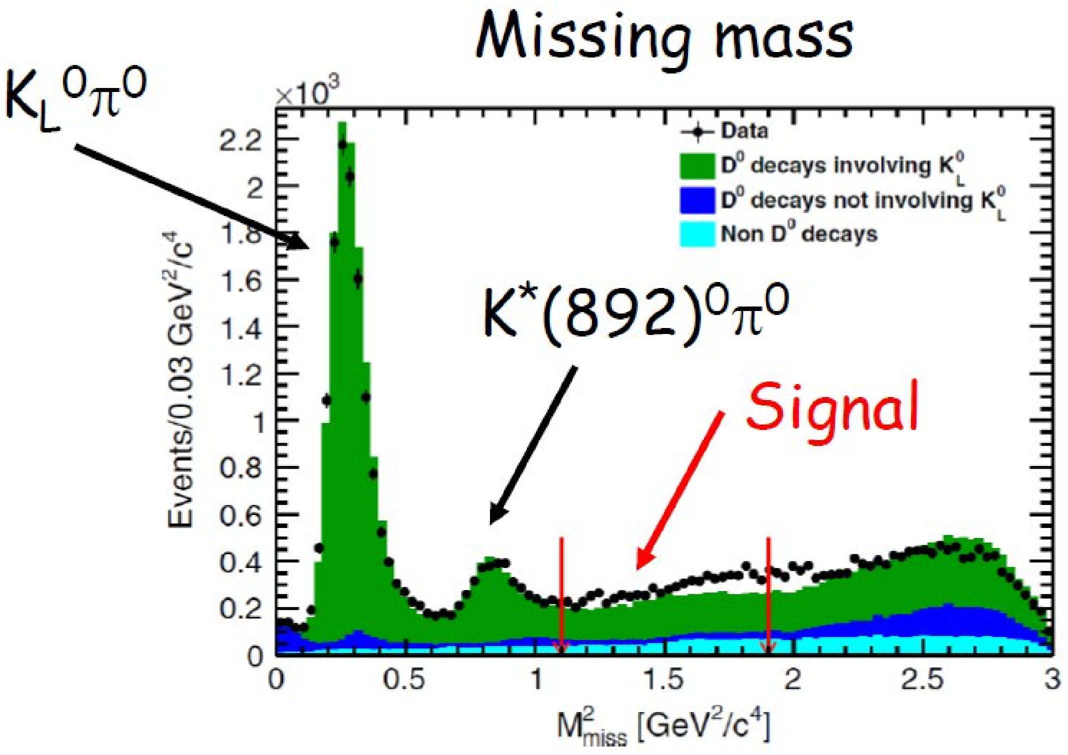




PRD 105 (2022) L071102

$D^0 \rightarrow \pi^0 \nu\bar{\nu}$

- First search on charm hadron decays into $\nu\bar{\nu}$ final states
- Reliable modeling of K_L^0 backgrounds crucial for this analysis
- Data-driven method to model energy deposits from $D^0 \rightarrow \pi^0 K_L^0 X$ decays as dominating residual background

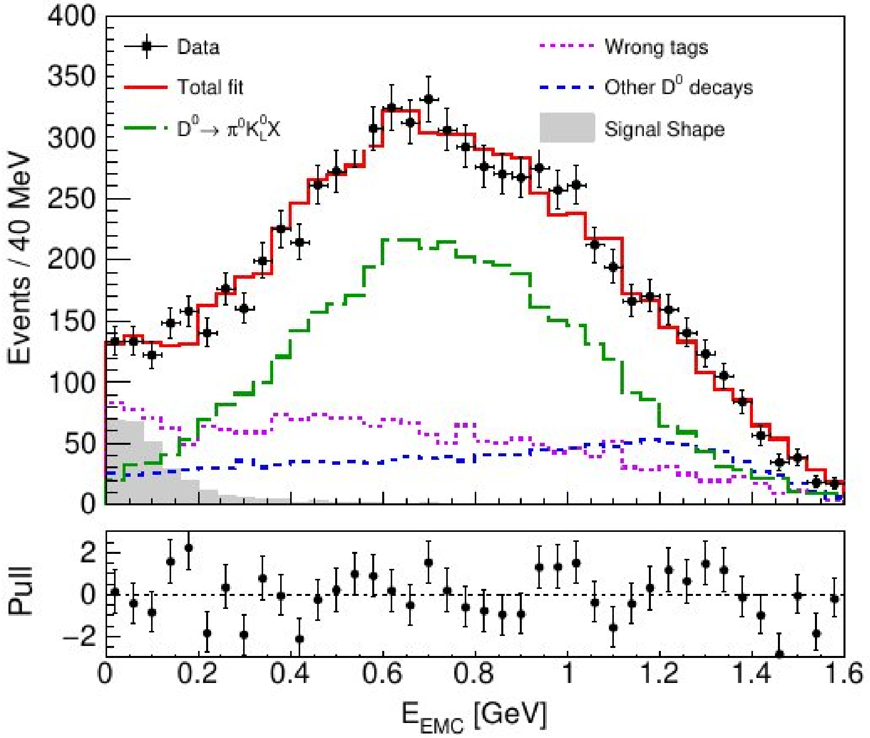


PRD 105 (2022) L071102

$D^0 \to \pi^0 \nu\bar{\nu}$

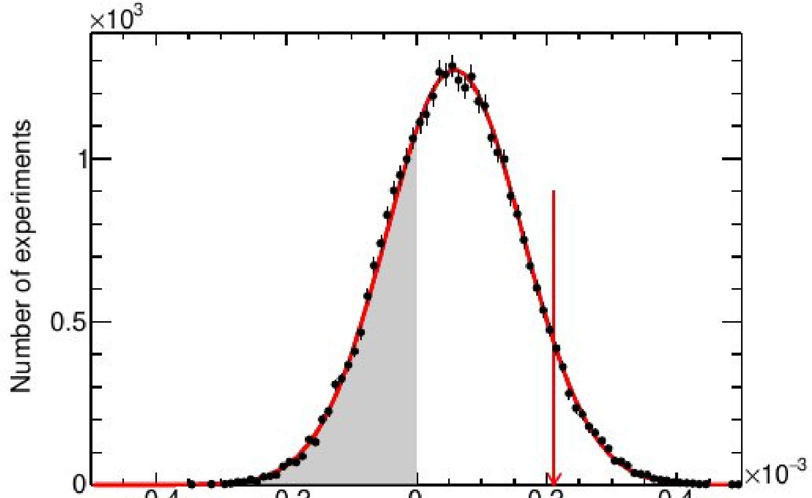
Fit with MC shape

$N_{sig} = 14 \pm 30$



- First search on charm hadron decays into $\nu\bar{\nu}$ final states
- Reliable modeling of K_L^0 backgrounds crucial for this analysis
- Data-driven method to model energy deposits from $D^0 \to \pi^0 K_L^0 X$ decays as dominating residual background

$$B\left(D^0 \to \pi^0 \nu\bar{\nu}\right) < 2.1 \times 10^{-4} \text{ @ } 90\% \, CL$$



$D^0 \to pe$

- Flavor of D determined from tag side
- Background suppression with:

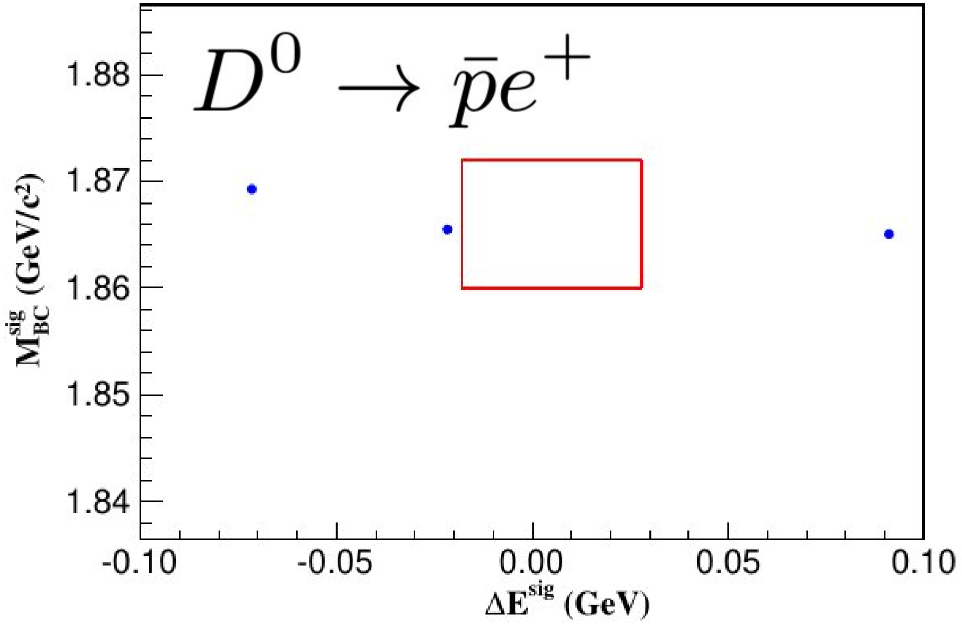
Energy difference: $\Delta E = E_{D0bar} - E_{beam}$

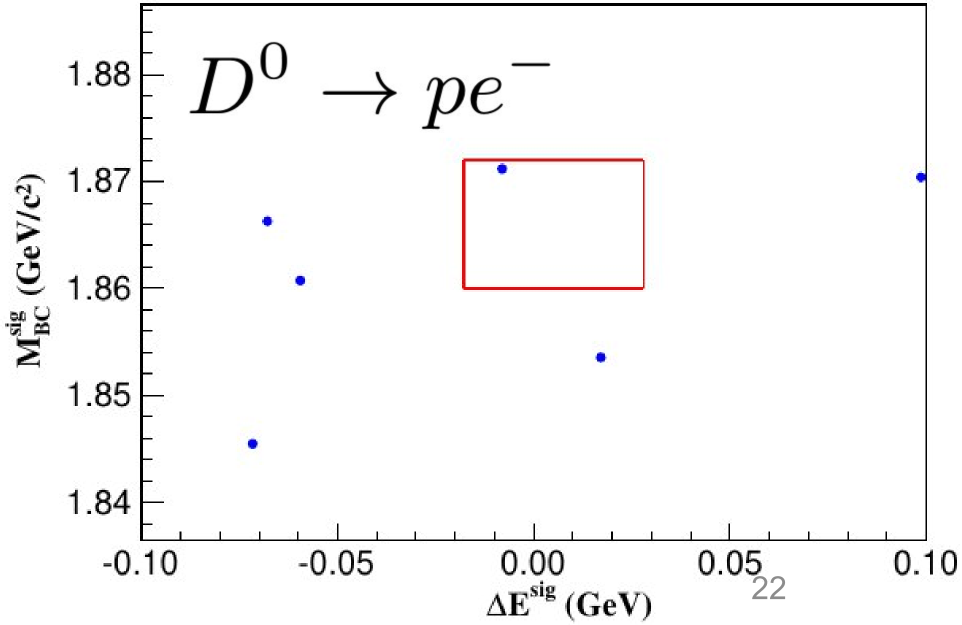
Beam constrained mass: $M_{BC} = \sqrt{E_{beam}^2/c^4 - |\vec{p}_{\bar{D}^0}|^2/c^2}$

- Almost background free
- No signal found, upper limits @ 90% CL are set:

$$\mathcal{B}_{D^0 \to \bar{p}e^+} < 1.2 \times 10^{-6}$$

$$\mathcal{B}_{D^0 \to pe^-} < 2.2 \times 10^{-6}$$





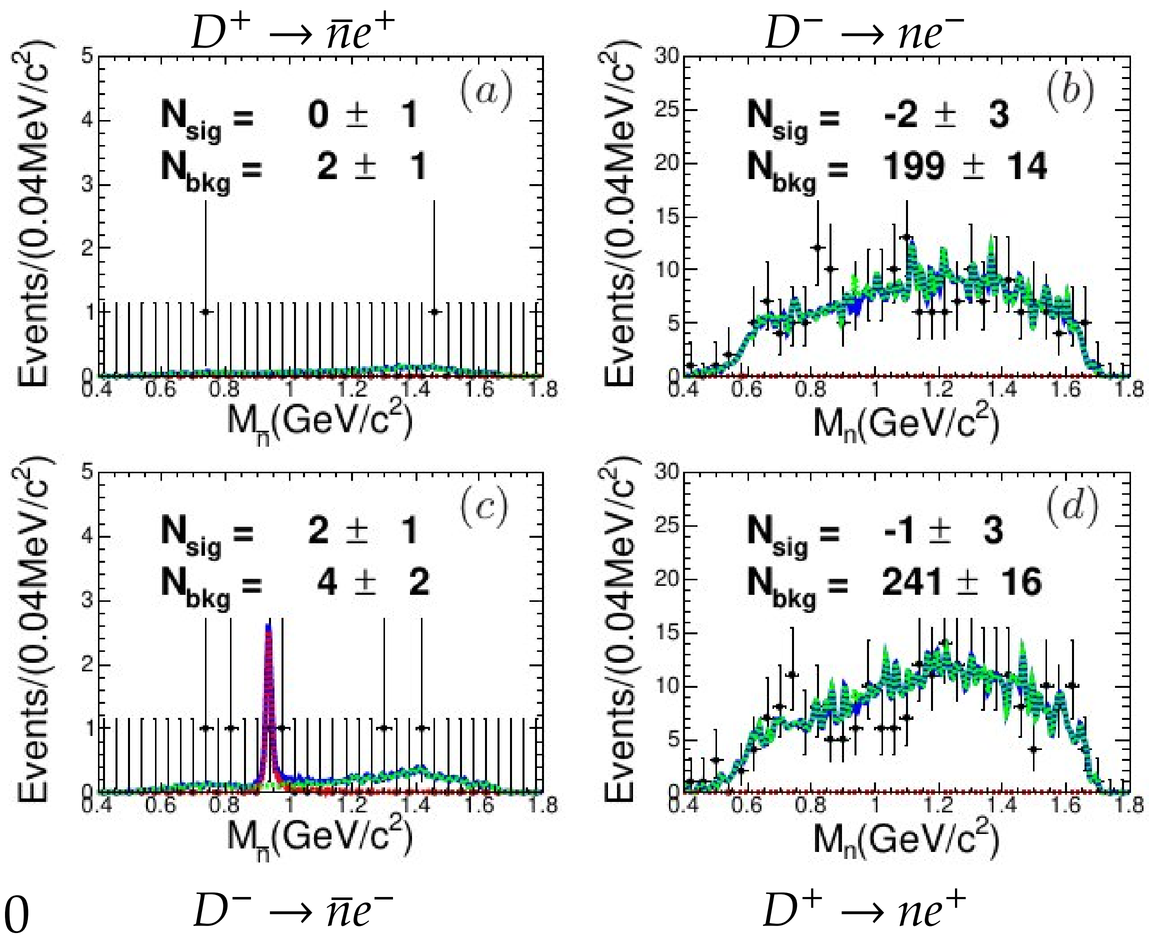
arXiv:2209.05787

$D^+ \to n(\bar{n})e^+$

- D^- tagged to suppress non-$D\bar{D}$ backgrounds
- $n(\bar{n})$ regarded as missing particle
- GBDT based on EMC shower shape trained to suppress background
- Fit to $n(\bar{n})$ mass to extract signals
- Upper limits @ 90% CL are set:

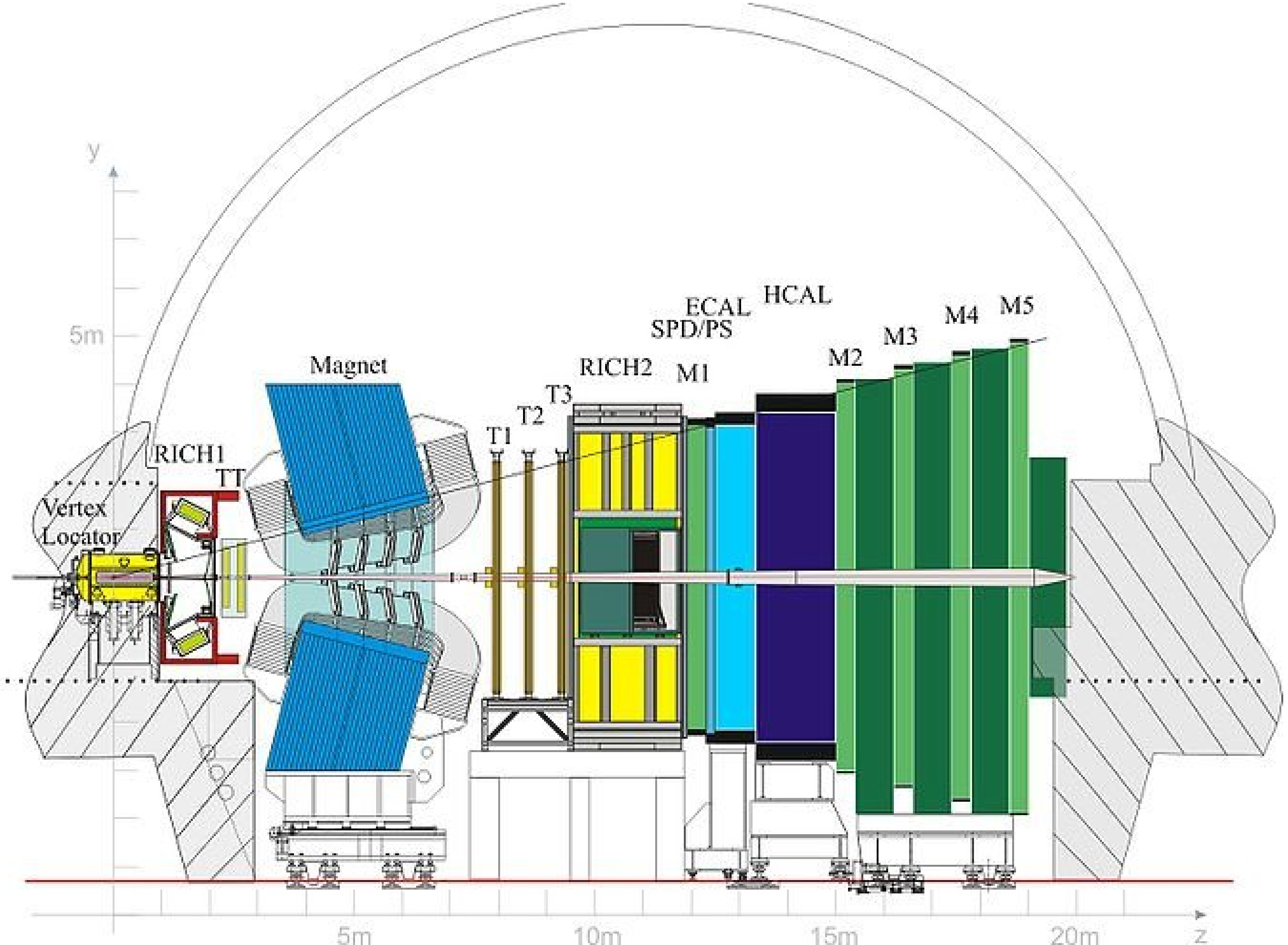
$$B\left(D^{+(-)} \to \bar{n}\,(n)\,e^{+(-)}\right) < 1.43 \times 10^{-5} \quad \text{w/ } \Delta|B-L| = 0$$

$$B\left(D^{+(-)} \to n\,(\bar{n})\,e^{+(-)}\right) < 2.91 \times 10^{-5} \quad \text{w/ } \Delta|B-L| = 2$$



LHCb detector in a nutshell

By design: study *CP*-violating processes and rare *b*-hadron decays



- can profit from the large $b\bar{b}$ and $c\bar{c}$ cross-sections and from the larger production at high pseudorapidity
- $\sigma(pp \to b\bar{b}X) = 144 \pm 1 \pm 21\,\mu\text{b}$ at 13 TeV in the LHCb acceptance $\Rightarrow\sim$ 25% of the total inside LHCb **[Phys.Rev.Lett. 118, 052002]**
- $\sigma(pp \to c\bar{c}X) \sim 2.5$ mb $\Rightarrow$ 1 MHz $c\bar{c}$ pairs in the LHCb acceptance **[JHEP 05 (2017) 074]**

LHCb detector in a nutshell

By design: study CP-violating processes and rare *b*-hadron decays

- Particle detection in the forward region (down to the beam-pipe)
- Excellent resolution for localization of decay vertices (Vertex Locator)
  → Excellent time resolution, enough to resolve B_s – B_s oscillation
- Excellent momentum resolution ($\sigma(m_B)$~25 MeV for 2-body decays)
- Excellent particle identification to distinguish p, $K^{\pm}$, $\pi^{\pm}$, $\mu^{\pm}$
- Excellent leptonic and hadronic triggers

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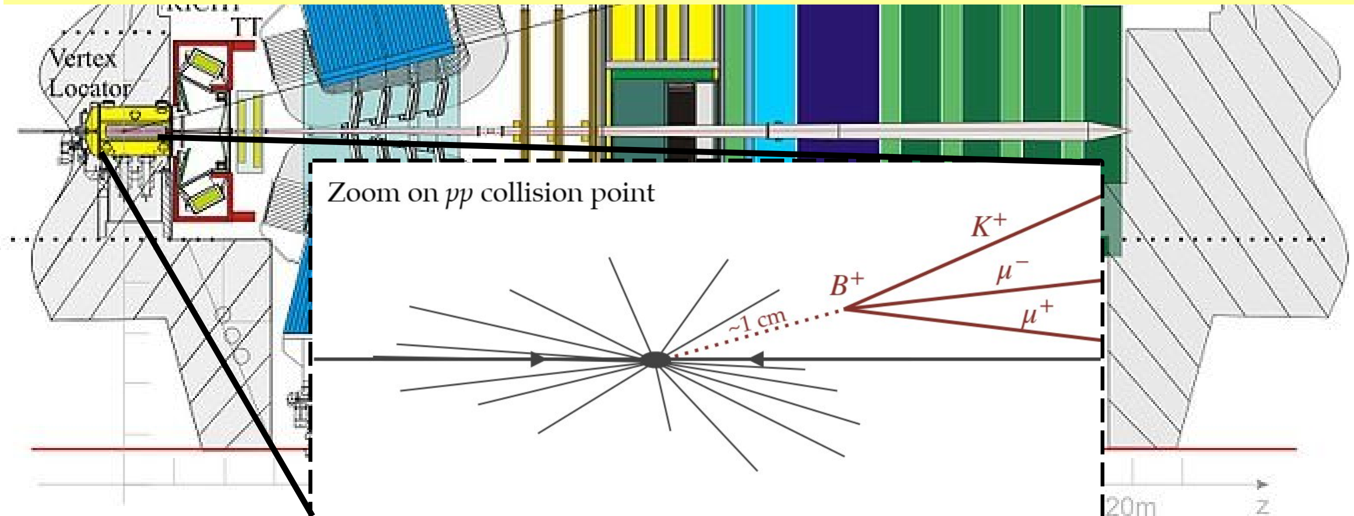
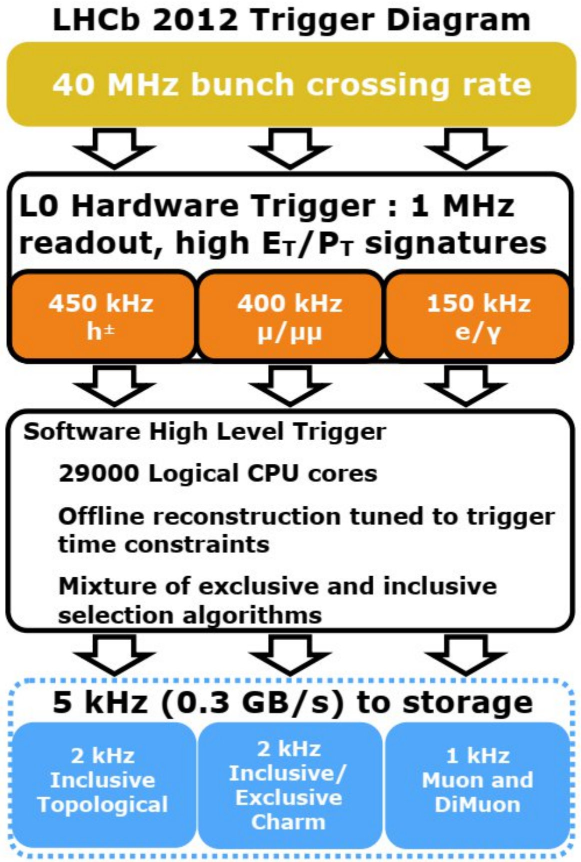
$\Rightarrow\sim$ 25% of the total inside LHCb
[Phys.Rev.Lett. 118, 052002]

- $\sigma(pp \to c\bar{c}X) \sim 2.5$ mb $\Rightarrow$ 1 MHz $c\bar{c}$ pairs in the LHCb acceptance **[JHEP 05 (2017) 074]**



LHCb trigger scheme



LHCb 2012 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

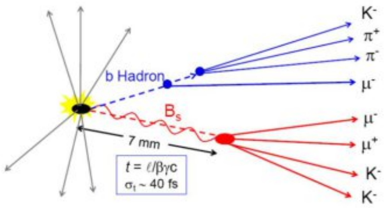
450 kHz $h^{\pm}$	400 kHz $\mu/\mu\mu$	150 kHz e/γ

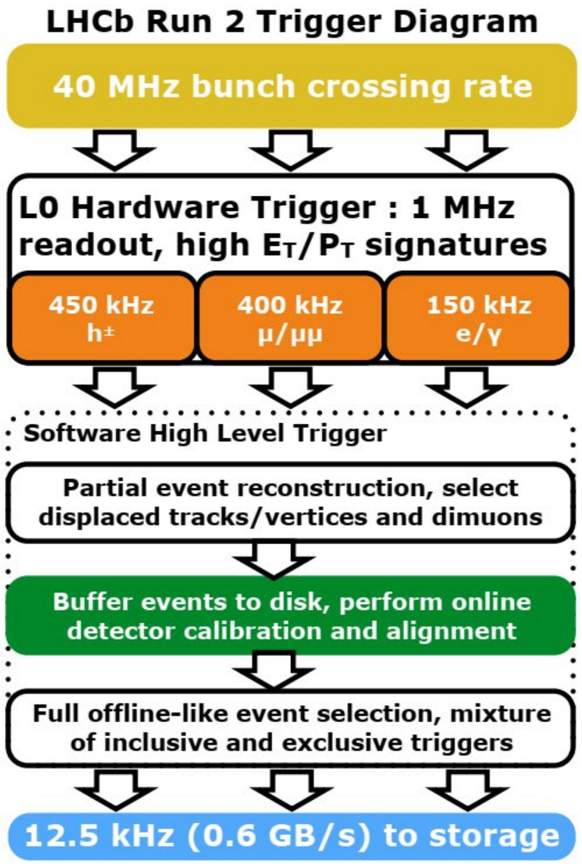
Software High Level Trigger

- 29000 Logical CPU cores
- Offline reconstruction tuned to trigger time constraints
- Mixture of exclusive and inclusive selection algorithms

5 kHz (0.3 GB/s) to storage

2 kHz Inclusive Topological	2 kHz Inclusive/ Exclusive Charm	1 kHz Muon and DiMuon





LHCb Run 2 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz $h^{\pm}$	400 kHz $\mu/\mu\mu$	150 kHz e/γ

Software High Level Trigger

Partial event reconstruction, select displaced tracks/vertices and dimuons

Buffer events to disk, perform online detector calibration and alignment

Full offline-like event selection, mixture of inclusive and exclusive triggers

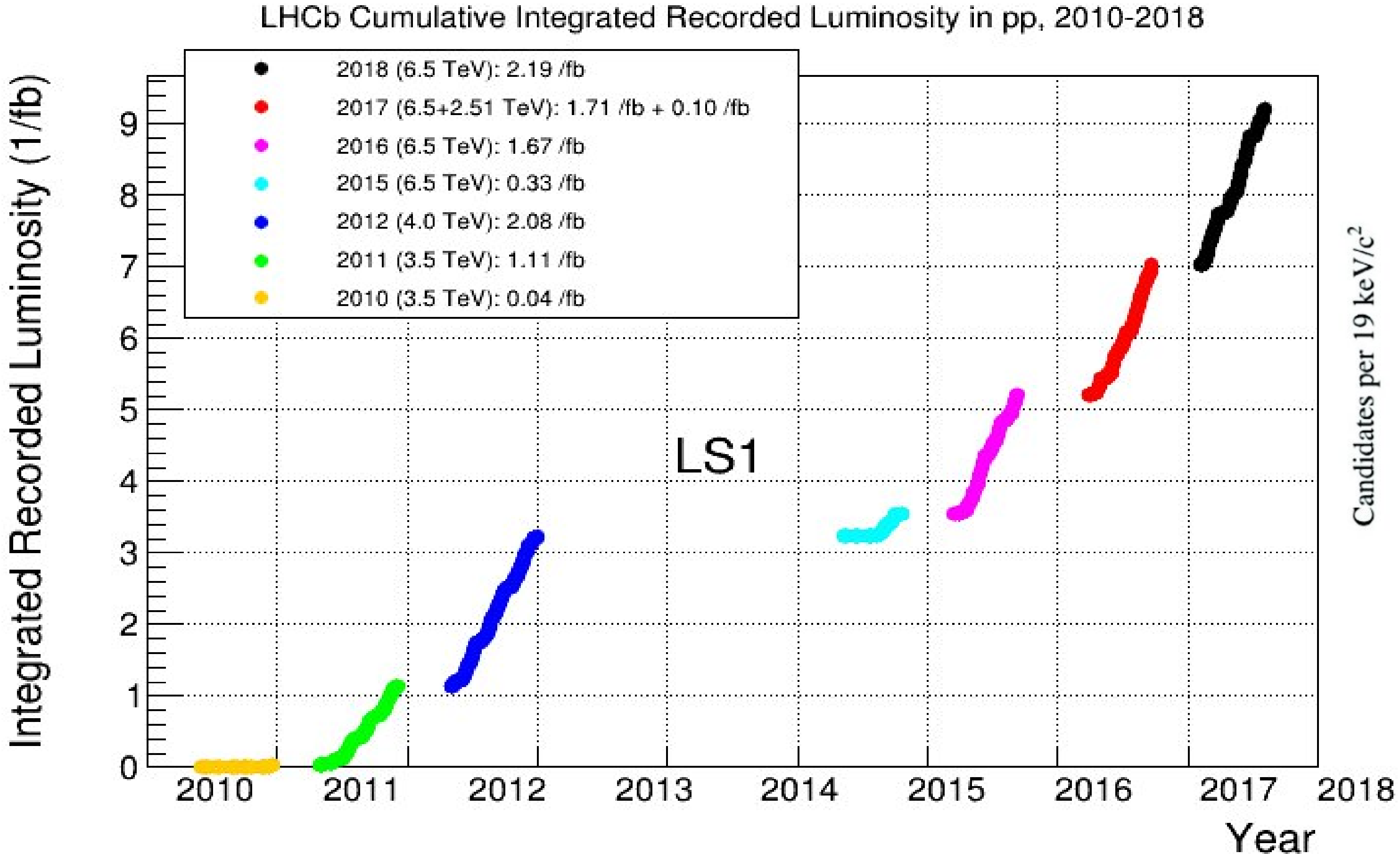
12.5 kHz (0.6 GB/s) to storage

trigger efficiency: $\sim 90\%$ on muons, $\sim 30\%$ for multi-body hadronic final states

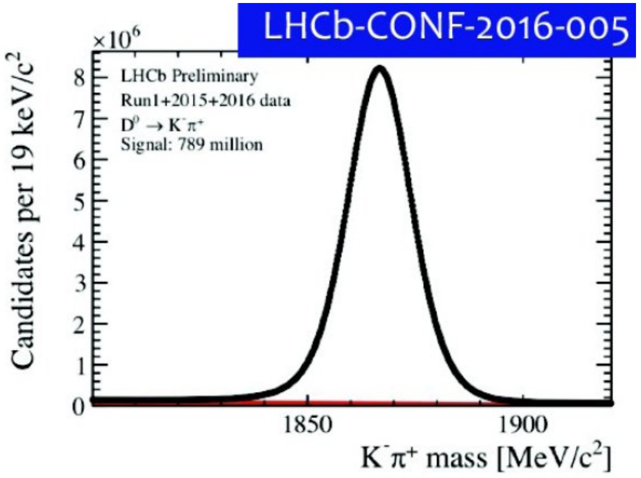
LHCb data samples

- **levelled** instantaneous luminosity of $\mathcal{L} = 4 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Run 1: $\sim 3\,\mathrm{fb}^{-1}$ of pp collisions at $\sqrt{s} = 7\text{-}8\,\mathrm{TeV}$
- Run 2: $\sim 6\,\mathrm{fb}^{-1}$ of pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$
- $\sigma(pp \to Q\bar{Q}X) \propto \sqrt{s} \Rightarrow$ 4x b- and c-hadrons in Run 2

More than 1B of $D^0 \to K^-\pi^+$ events reconstructed with full LHCb data sample



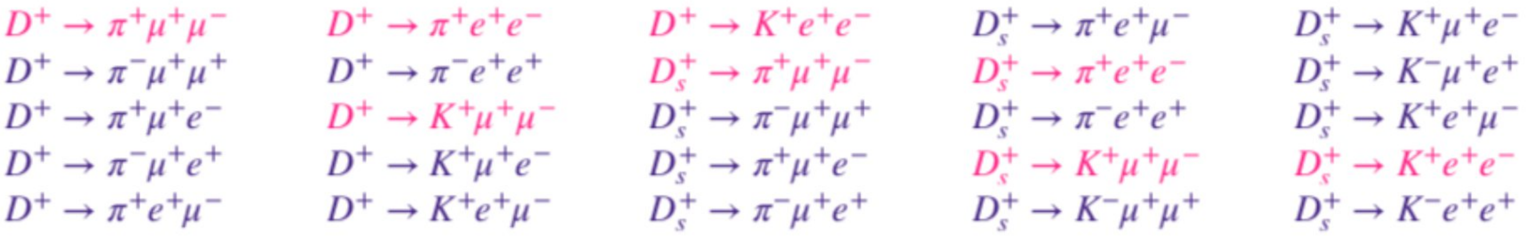
LHCb-CONF-2016-005



Search for $D^+_{(s)} \to h^\pm \ell^+ \ell^{(\prime)\mp}$ decays

- 25 decays

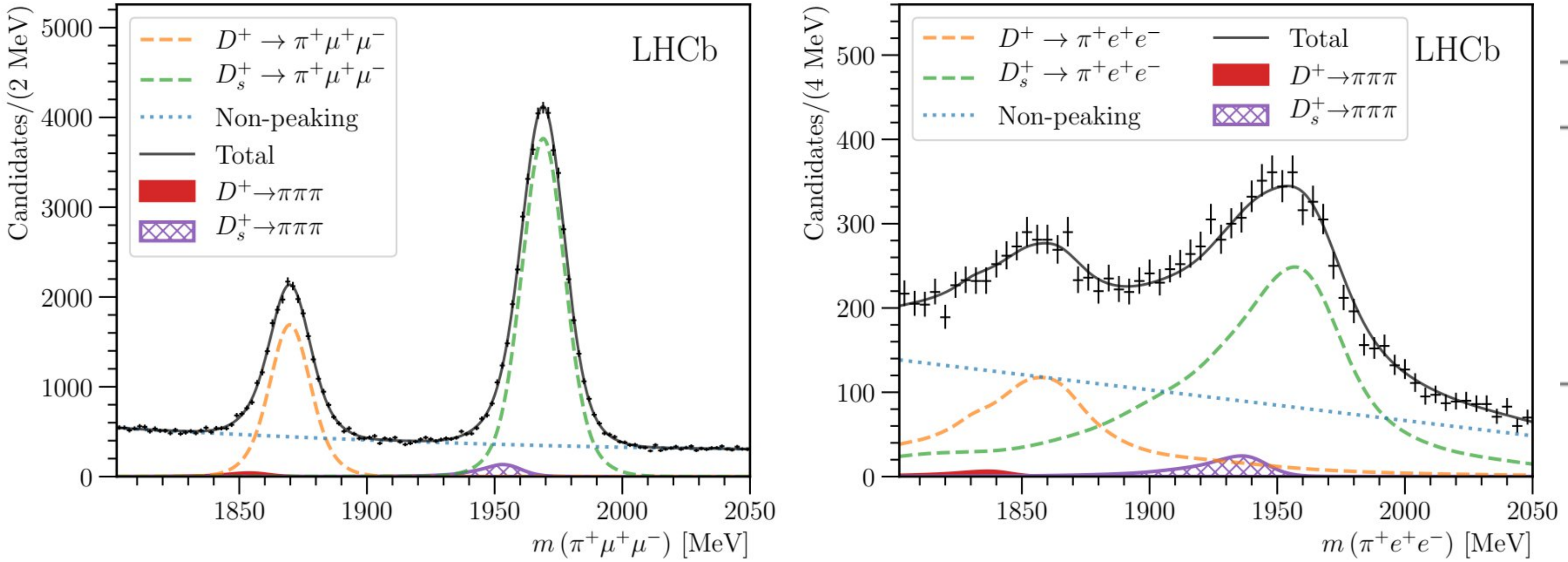
  LFV & LNV included

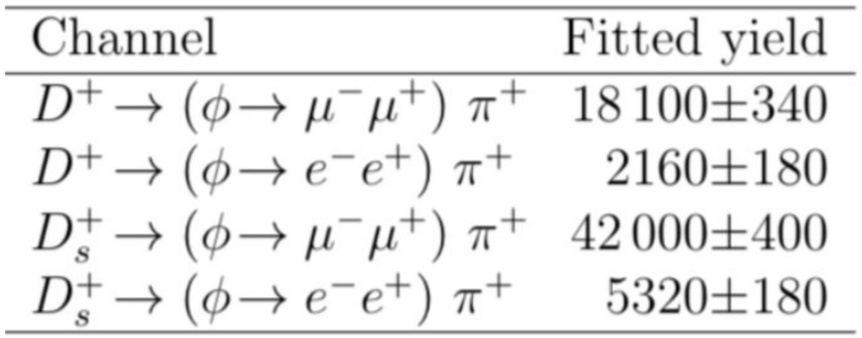


$D^+ \to \pi^+\mu^+\mu^-$
$D^+ \to \pi^-\mu^+\mu^+$
$D^+ \to \pi^+\mu^+e^-$
$D^+ \to \pi^-\mu^+e^+$
$D^+ \to \pi^+e^+\mu^-$
$D^+ \to \pi^+e^+e^-$
$D^+ \to \pi^-e^+e^+$
$D^+ \to K^+\mu^+\mu^-$
$D^+ \to K^+\mu^+e^-$
$D^+ \to K^+e^+\mu^-$
$D^+ \to K^+e^+e^-$
$D_s^+ \to \pi^+\mu^+\mu^-$
$D_s^+ \to \pi^-\mu^+\mu^+$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

Allowed in the SM, Forbidden in the SM

- Normalized with $D^+_{(s)} \to \phi\,(\ell\ell)\,\pi^+$
- Analysis based on 2016 dataset (1.7 fb^{-1})





Channel	Fitted yield
$D^+ \to (\phi \to \mu^-\mu^+)\,\pi^+$	18 100±340
$D^+ \to (\phi \to e^-e^+)\,\pi^+$	2160±180
$D_s^+ \to (\phi \to \mu^-\mu^+)\,\pi^+$	42 000±400
$D_s^+ \to (\phi \to e^-e^+)\,\pi^+$	5320±180

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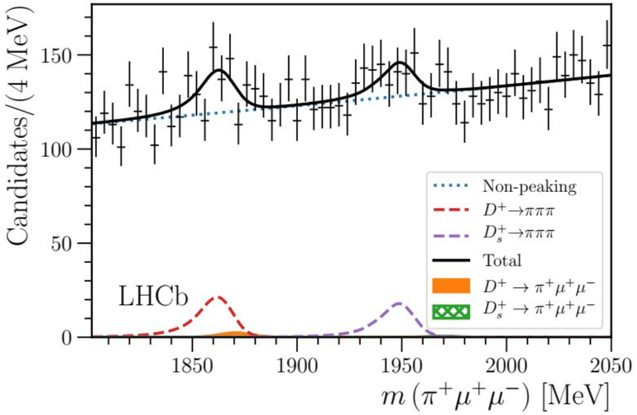
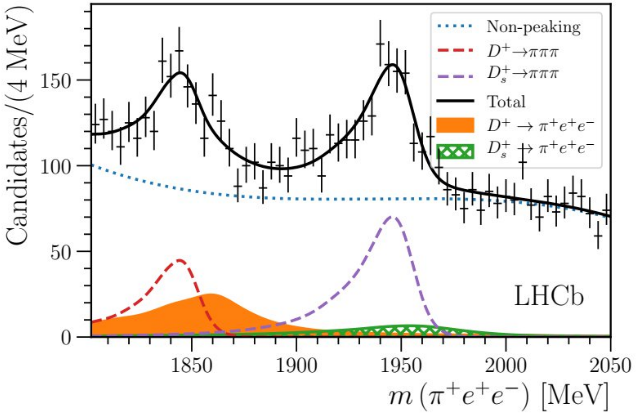
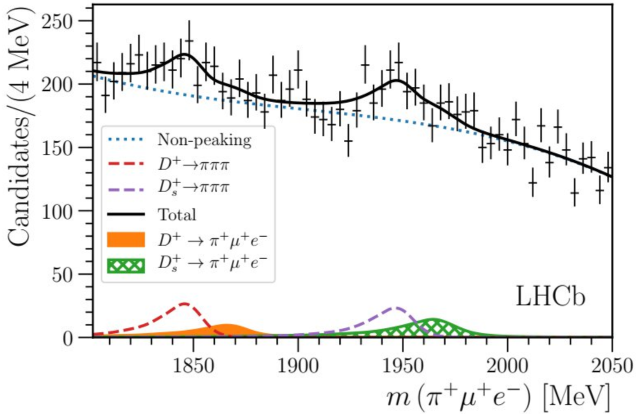
Search for $D^+_{(s)} \to h^\pm \ell^+ \ell^{(\prime)\mp}$ decays

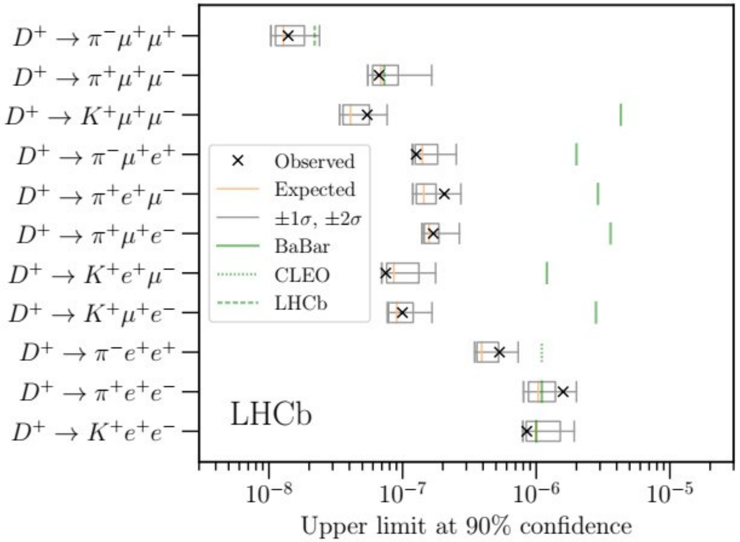
- No signal observed, BF limits are set down to $\mathscr{O}(10^{-8})$
- Results improve the prior world's best by up to a factor of 500

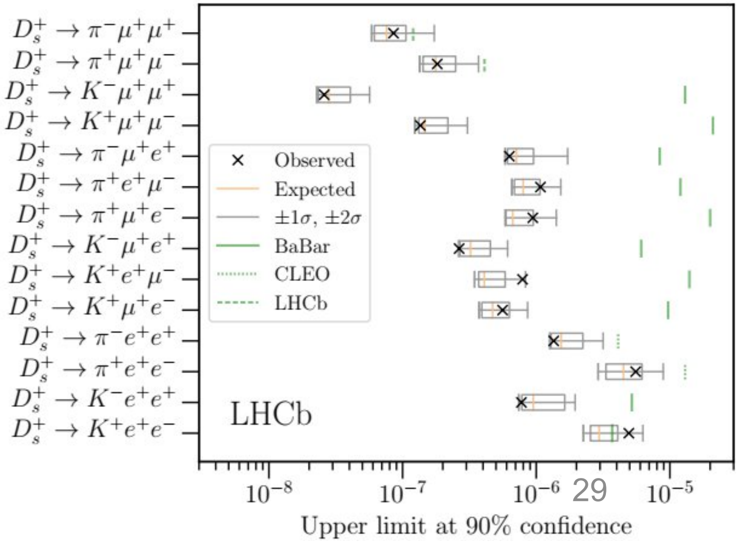




Regions dominated by resonances in dilepton mass spectrum are vetoed







PRL 128 (2022) 221801

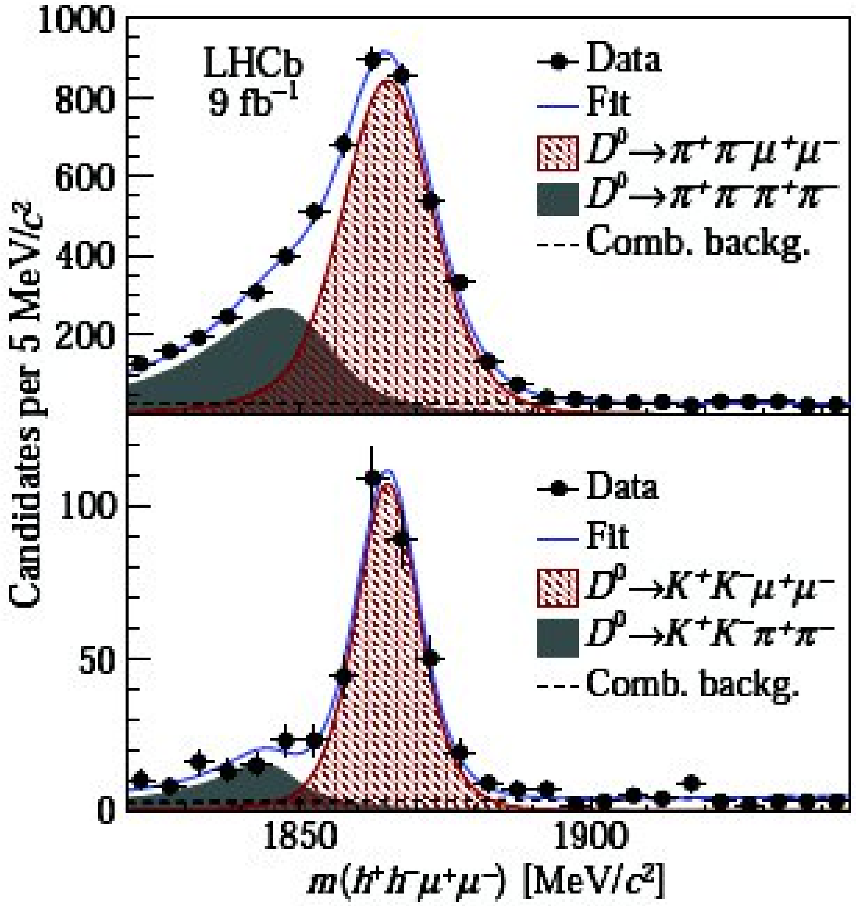
CPV and angular analysis in $D^0 \to hh\mu^+\mu^-$

- Rarest charm meson decays observed, dominated by resonant contributions

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

- First full angular analysis with 9 fb^{-1} data
- D^0 selected from flavor specific $D^{*+} \to D^0\pi^+$

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

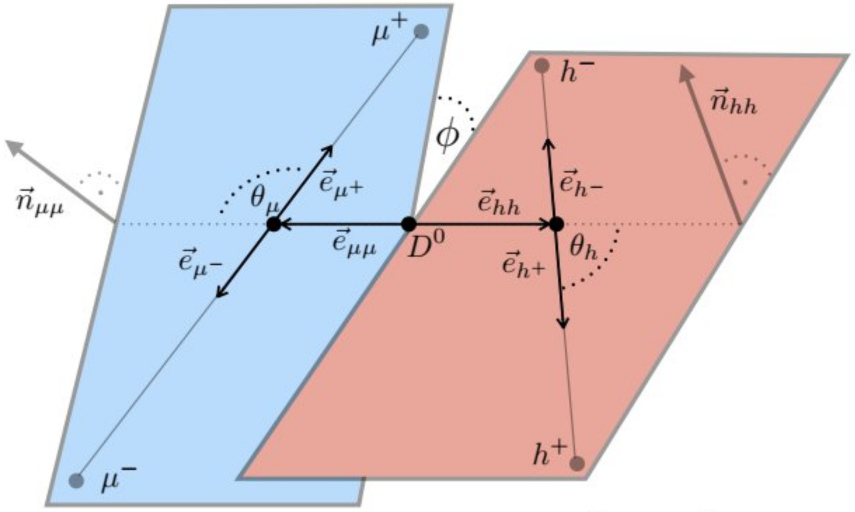


PRL 128 (2022) 221801

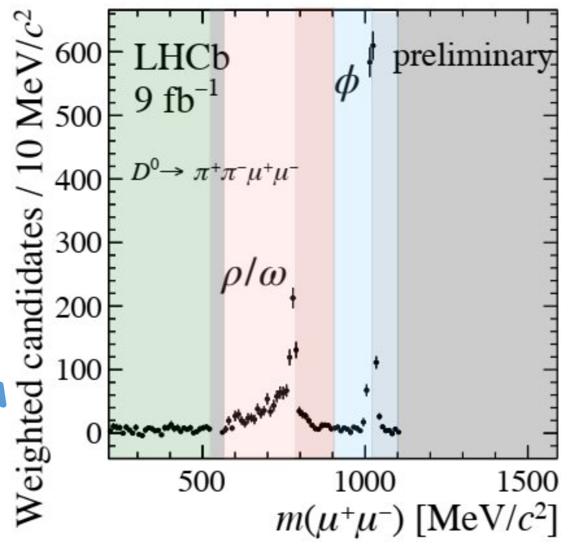
Differential decay rate in $D^0 \to hh\mu^+\mu^-$

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

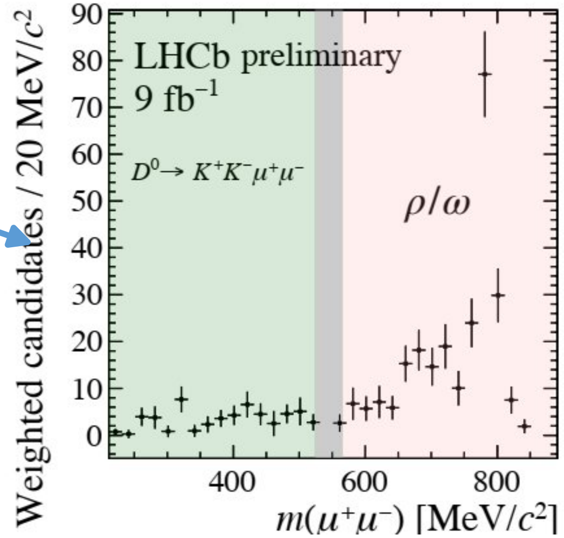
I_5, I_6, I_7 clean null tests!



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



- Measure p^2, $\cos\theta_h$ integrated $\langle I_i \rangle$ separately for $D^0/\overline{D}^0$ in **q^2 bins**



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

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

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

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

i=2,..,9

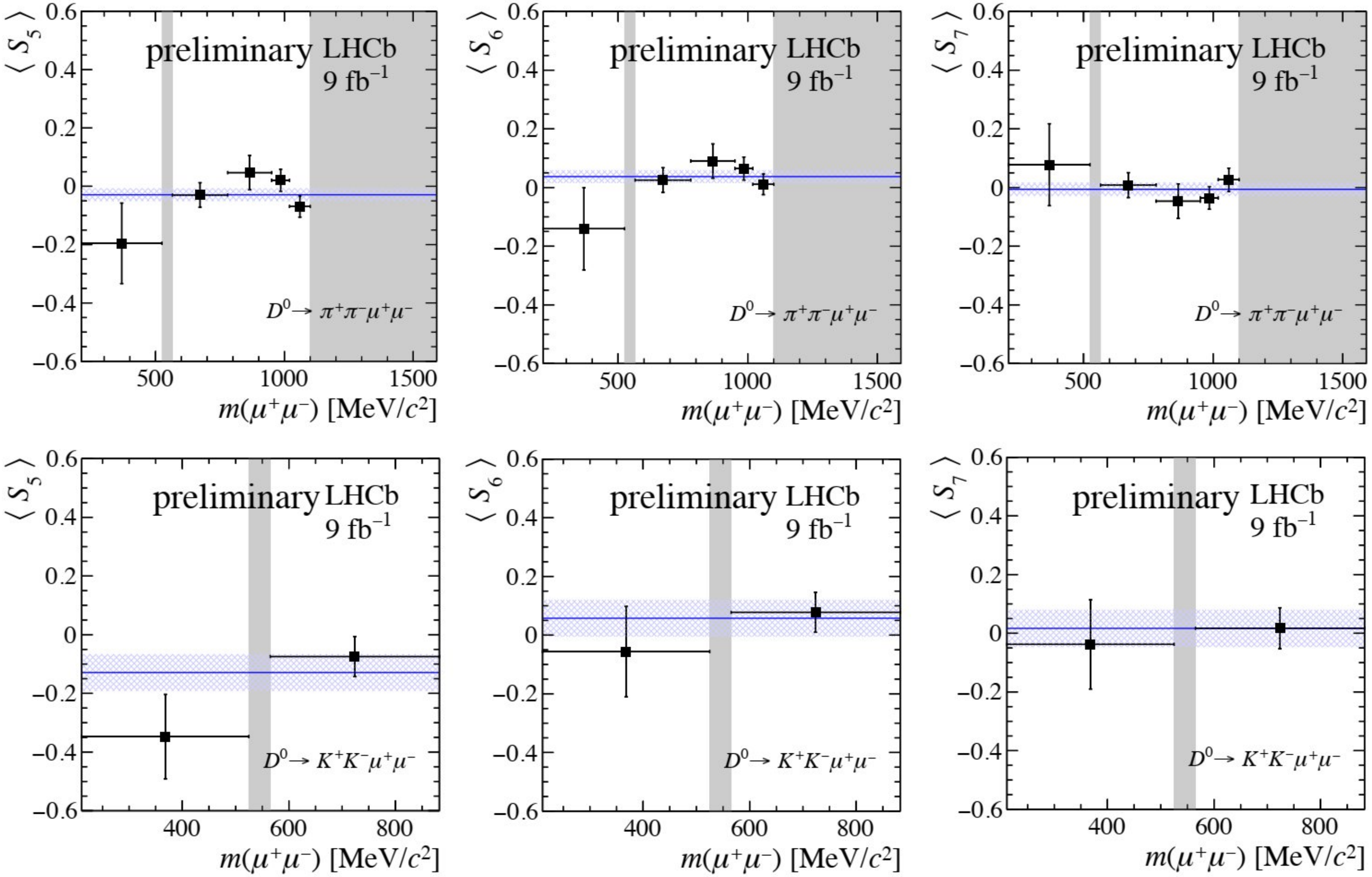
for CP even (CP odd) coefficients

PRL 128 (2022) 221801

Flavor-averaged observables $\langle S_i \rangle$

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

From D. Mitzel's talk @ 11th workshop on "Implications of LHCb measurements and future prospects"



agreement with SM predictions

[JHEP 04 135 (2013), PRD 98, 035041(2018)]

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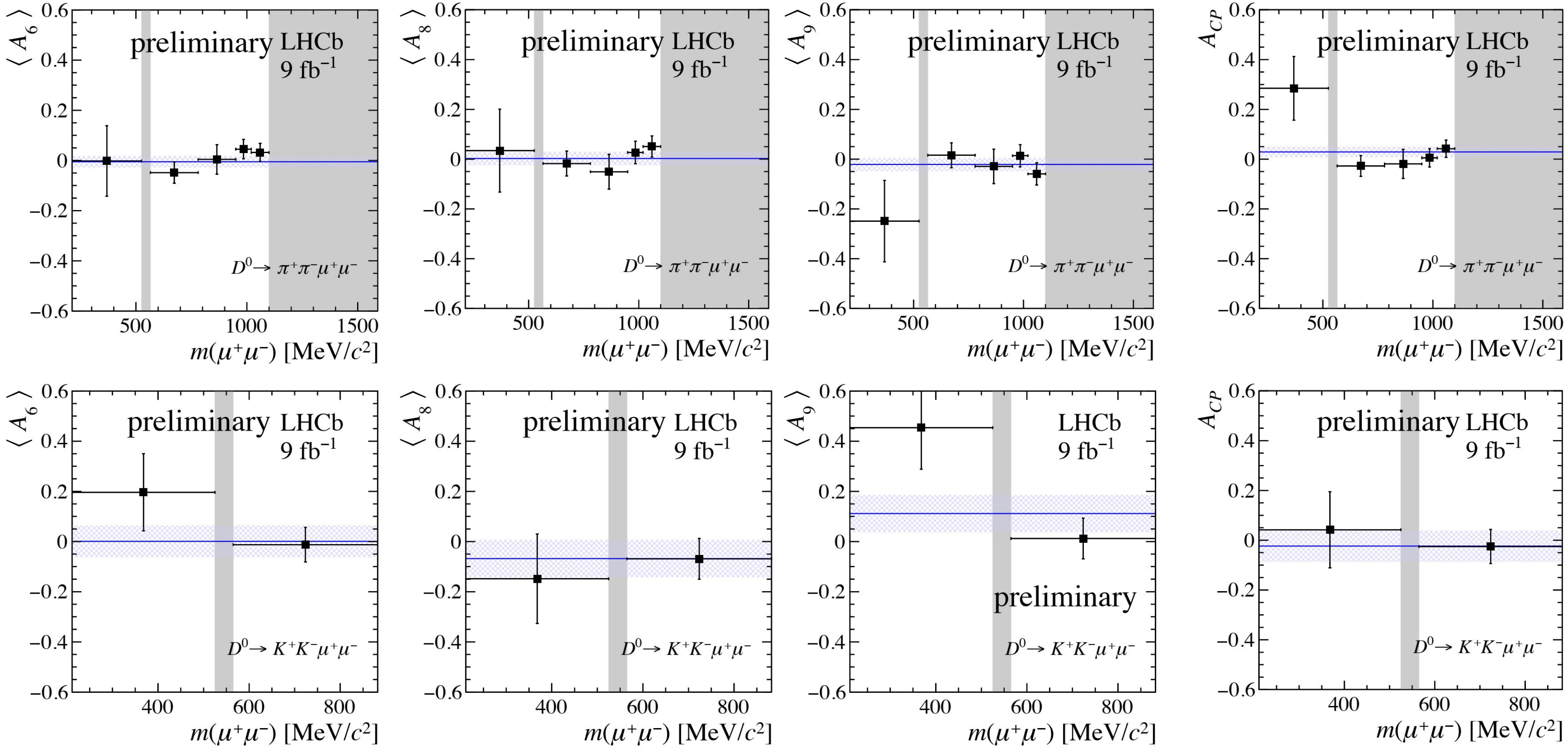
CP asymmetries $\langle A_i \rangle$

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

From D. Mitzel's talk @ 11th workshop on "Implications of LHCb measurements and future prospects"

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



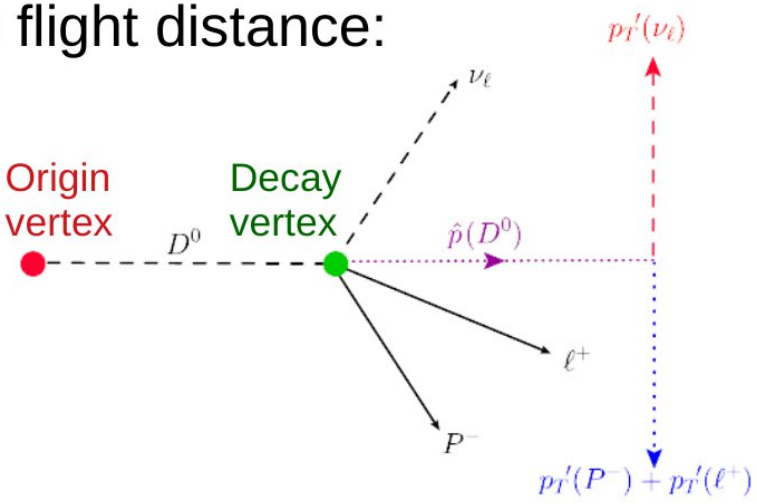
- overall agreement wrt. to SM hypothesis considering A_{CP}, $\langle A_{2-9} \rangle$ & $\langle S_{5,6,7} \rangle$:

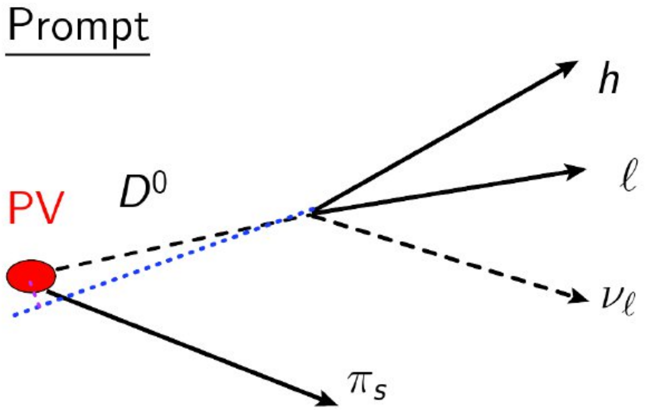
$D^0 \to \pi^+\pi^-\mu^+\mu^-$ p = 79% (0.3σ)
$D^0 \to K^+K^-\mu^+\mu^-$ p = 0.8% (2.7σ)
preliminary

consistent with SM

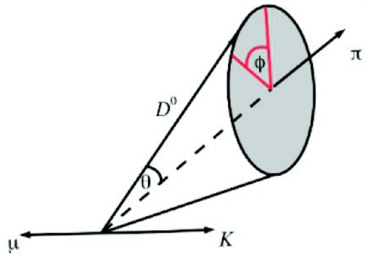
Semileptonic charm decays

- Challenge: only partially reconstructed final state
- For e^+e^- machines such as BESIII, use the other side of the event and beam energy to constrain neutrino momentum
- For a hadron collider like LHCb, neutrino momentum can be constrained by the D flight distance:





- A two-fold ambiguity for total neutrino momentum can be solved by using D^{*+} mass constraint with D^0 from $D^{*+} \rightarrow D^0\pi_s^+$
  - The cone-closure method [FERMILAB-THESIS-1995-05]



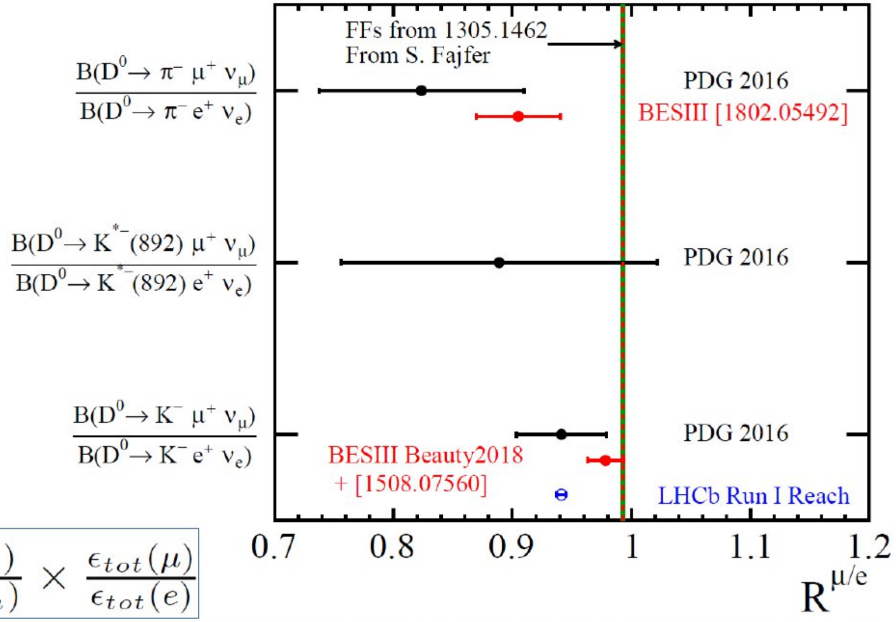
Test of LFU in D decays

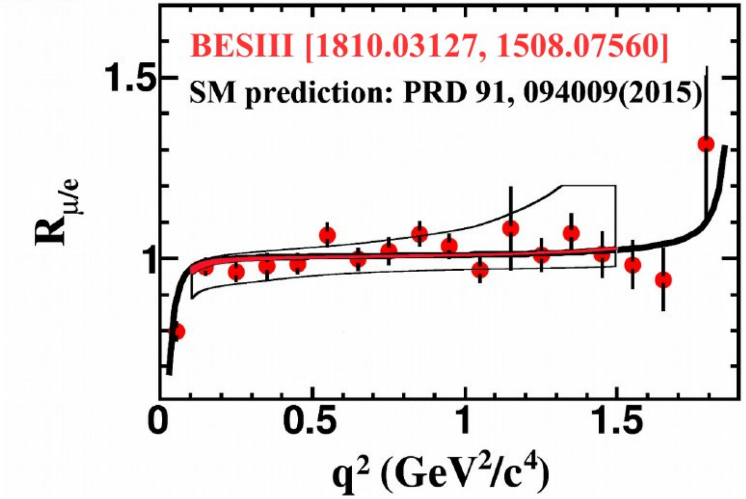
- LFU in the charm sector is a relatively unexplored area
- LHCb is expected to collect millions of $D^{*+} \rightarrow D^0\pi^+$, $D^0 \rightarrow h^-\ell^+\nu$ events with Runs 1-2 datasets, about three orders of magnitude higher than BESIII statistics [arXiv:1703.10695]
- Measurement on the ratio of

$$R^{e/\mu} = \frac{\mathcal{B}(D^0 \to K^- e^+ \nu_e)}{\mathcal{B}(D^0 \to K^- \mu^+ \nu_\mu)} = \frac{N(D^0 \to K^- e^+ \nu_e)}{N(D^0 \to K^- \mu^+ \nu_\mu)} \times \frac{\epsilon_{tot}(\mu)}{\epsilon_{tot}(e)}$$

in bins of q^2, which can be reconstructed with the cone-closure method

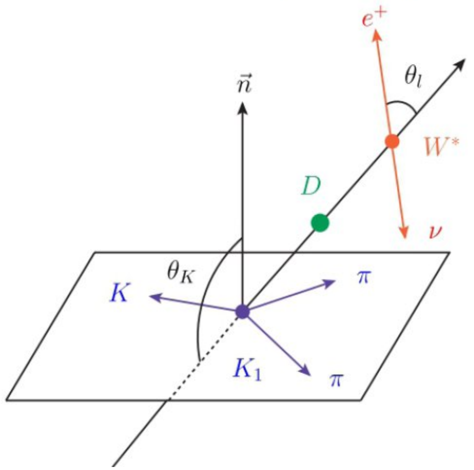
- Uncertainties will be dominated by systematics

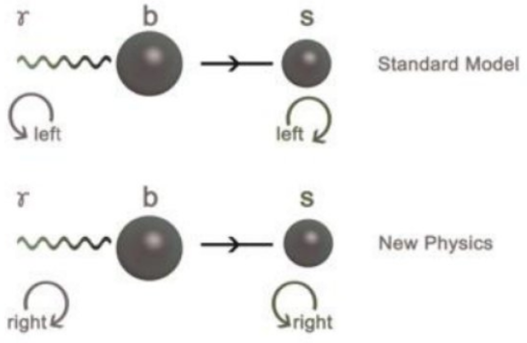




$b \to s\gamma$ photon polarization with $D \to K_1 \ell \nu$

- Photon Polarization in $b \to s\gamma$ is sensitive to BSM
- A noval method is provided to combine the $B \to K_1 \gamma$ and $D \to K_1 e^+ \nu_e$ to determine the photon helicity [PRL 125, 051802 (2020)]





● Picture taken from report of Fu-Sheng Yu

$$\mathcal{A}'_{\rm UD} \equiv \frac{\left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_K \frac{d\Gamma_{K_1 e\nu_e}}{d\cos\theta_K}}{\left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_l \frac{d\Gamma_{K_1 e\nu_e}}{d\cos\theta_l}}$$

$D \to K_1(\to K\pi\pi)e^+\nu$

$$\mathcal{A}'_{\rm UD} = \frac{{\rm Im}[\vec{n}\cdot(\vec{J}\times\vec{J}^*)]}{|\vec{J}|^2}.$$

$$\mathcal{A}_{UD} \equiv \frac{\left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_K \frac{d\hat{\Gamma}_{K_1\gamma}}{d\cos\theta_K}}{\left[\int_0^1 + \int_{-1}^0\right] d\cos\theta_K \frac{d\hat{\Gamma}_{K_1\gamma}}{d\cos\theta_K}} = \lambda_\gamma \frac{3}{4} \frac{{\rm Im}[\vec{n}\cdot(\vec{J}\times\vec{J}^*)]}{|\vec{J}|^2}$$

$B \to K_1(\to K\pi\pi)\gamma$

$$\lambda_\gamma = \frac{4}{3}\frac{\mathcal{A}_{UD}}{\mathcal{A}'_{\rm UD}}$$ In SM, $\lambda_\gamma \simeq 1$

[1.1-1.3]GeV:

LHCb:
PRL112.161801(2014)

$\mathcal{A}_{UD} = (6.9 \pm 1.7) \times 10^{-2}$

If SM

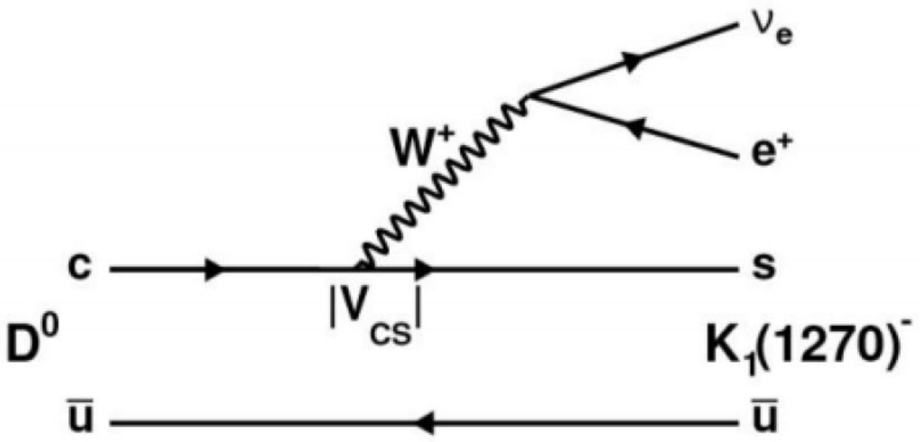
$\mathcal{A}'_{UD} = (9.2 \pm 2.3) \times 10^{-2}$

Taken from Up-down asymmetries and angular distributions in D->K_1(->Kpipi)l+v_l, by 边苓竹

$D \to K_1(\to K\pi\pi)e^+\nu_e$ at BESIII

- Using 2.93 fb^{-1} of e^+e^- collision data at BESIII , first observation of $D^0 \to K_1(1270)^- e^+\nu_e$ and $D^+ \to K_1(1270)^0 e^+\nu_e$ have been both published with ~100 signals [PRL 127, 131801 (2021)] , [PRL 123, 231801 (2019)].
  - $B(D^0 \to K_1(1270)^- e^+\nu_e) = (1.09 \pm 0.13^{+0.09}_{-0.16} \pm 0.12) \times 10^{-3}$
  - $B(D^+ \to K_1(1270)^0 e^+\nu_e) = (2.30 \pm 0.26^{+0.18}_{-0.21} \pm 0.25) \times 10^{-3}$

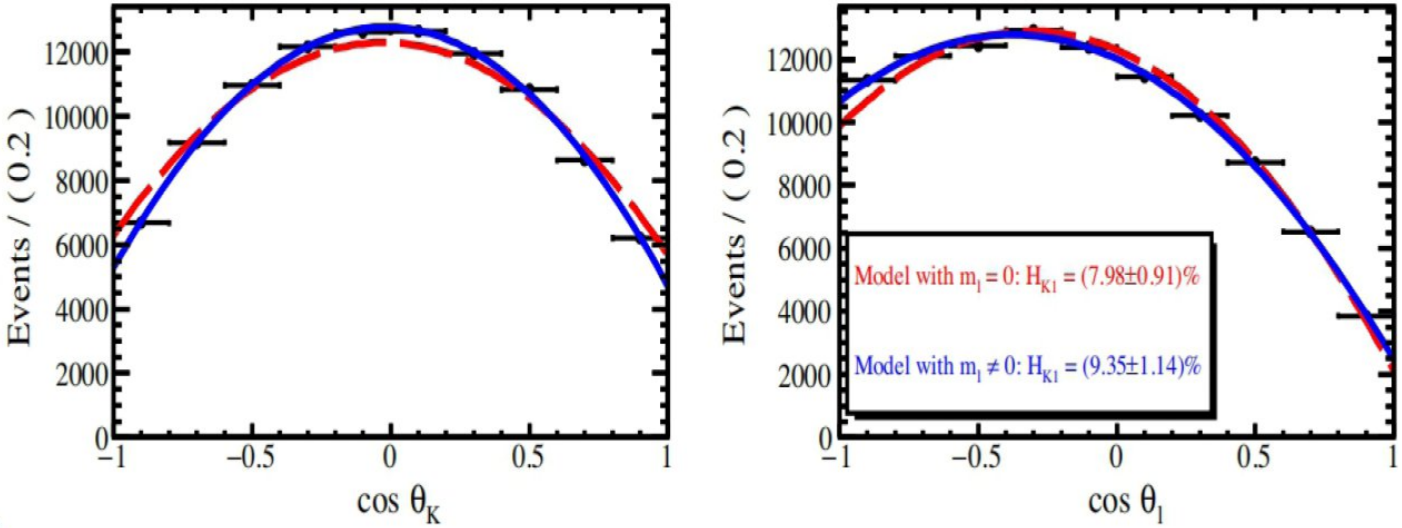
The yield is too small for angular analysis and A_{UD}' measurement



Taken from Up-down asymmetries and angular distributions in D->K_1(->Kpipi)l+v_l, by 边苓竹

Prospect of $D^0 \to K_1(\to K\pi\pi)^-\mu^+\nu_\mu$ at LHCb

- About 2000 $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+\mu^+\mu^-$ candidates at LHCb, 2 fb^{-1}at 8 TeV [PRL 119,181805 (2017)]
- $B(D^0 \to K_1(\to K\pi\pi)^-\mu^+\nu_\mu)$ two orders of magnitude higher than $\mathrm{B}(D^0 \to K^-\pi^+\mu^+\mu^-)$
- Conservatively estimation: 10^5 $D^0 \to K_1(\to K\pi\pi)^-\mu^+\nu_\mu$ candidates based on 9 fb^{-1} at LHCb



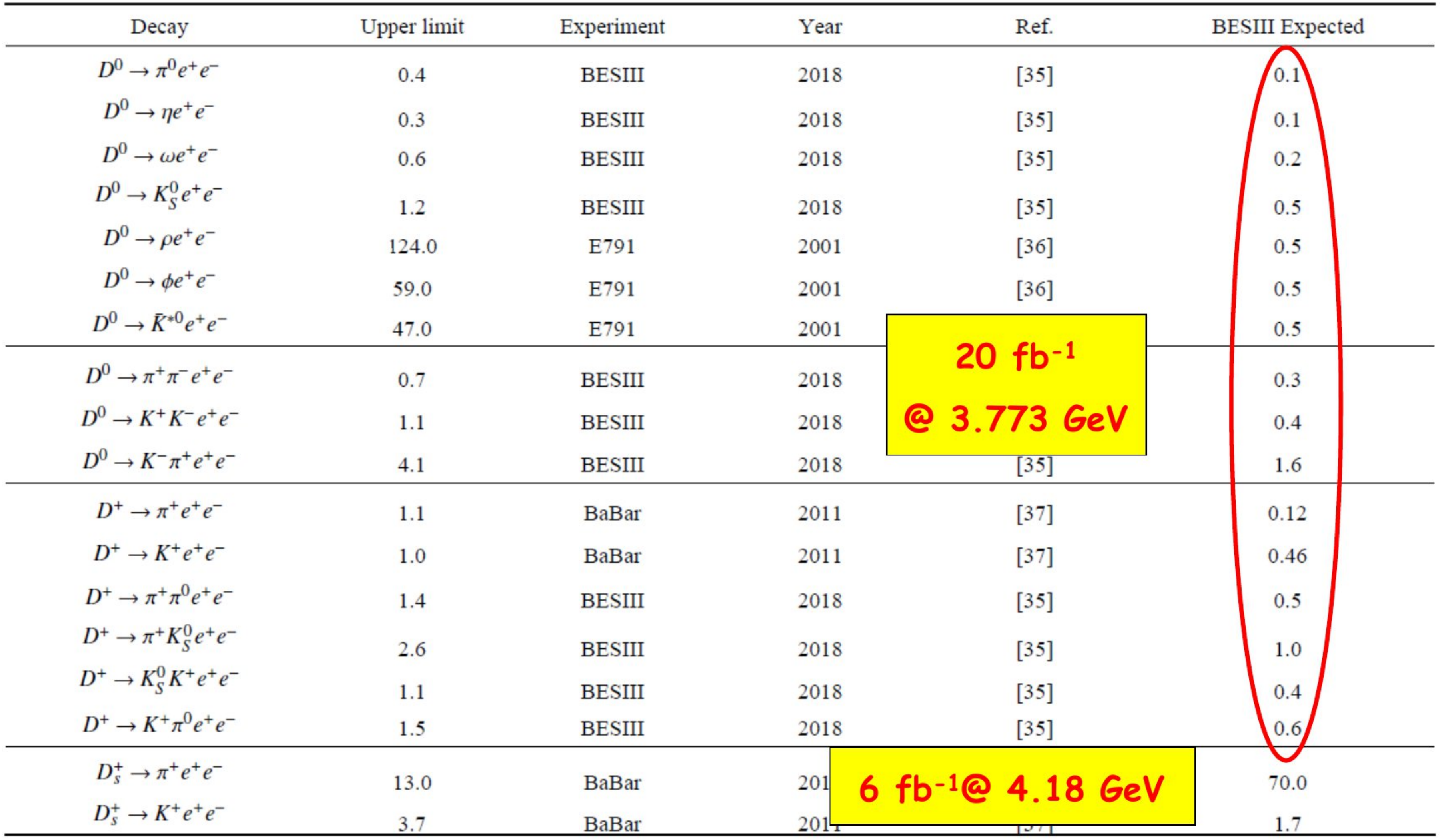
- $\sim 10^5$ $D^0 \to K_1(\to K\pi\pi)^-\mu^+\nu_\mu$ signals generated by RapidSim [Comput.Phys. Commun. 214, 239 (2017).]
- Muon mass can not be neglected
- Statistical sensitivity of H_{K_1}:1.1% [PRD 104, 053003 (2021)]

Taken from Up-down asymmetries and angular distributions in D->K_l(->Kpipi)l+v_l, by 边苓竹

White Paper
CPC 44 (2020) 040001

BESIII prospects

10^{-6} 10^{-6}

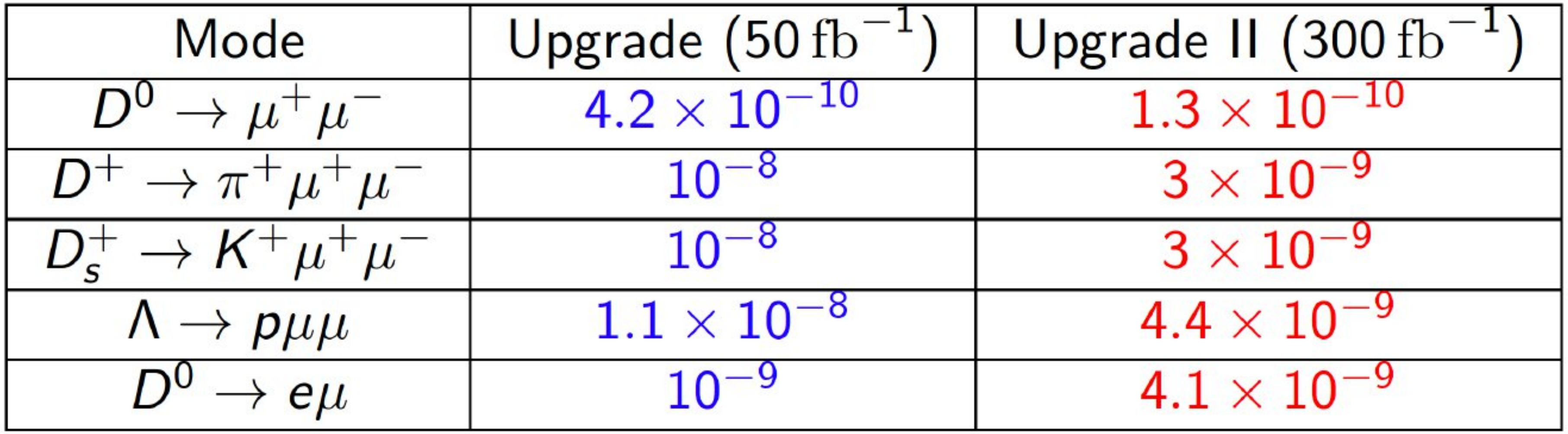


Decay	Upper limit	Experiment	Year	Ref.	BESIII Expected
$D^0 \to \pi^0 e^+ e^-$	0.4	BESIII	2018	[35]	0.1
$D^0 \to \eta e^+ e^-$	0.3	BESIII	2018	[35]	0.1
$D^0 \to \omega e^+ e^-$	0.6	BESIII	2018	[35]	0.2
$D^0 \to K_S^0 e^+ e^-$	1.2	BESIII	2018	[35]	0.5
$D^0 \to \rho e^+ e^-$	124.0	E791	2001	[36]	0.5
$D^0 \to \phi e^+ e^-$	59.0	E791	2001	[36]	0.5
$D^0 \to \bar{K}^{*0} e^+ e^-$	47.0	E791	2001		0.5
$D^0 \to \pi^+ \pi^- e^+ e^-$	0.7	BESIII	2018		0.3
$D^0 \to K^+ K^- e^+ e^-$	1.1	BESIII	2018		0.4
$D^0 \to K^- \pi^+ e^+ e^-$	4.1	BESIII	2018	[35]	1.6
$D^+ \to \pi^+ e^+ e^-$	1.1	BaBar	2011	[37]	0.12
$D^+ \to K^+ e^+ e^-$	1.0	BaBar	2011	[37]	0.46
$D^+ \to \pi^+ \pi^0 e^+ e^-$	1.4	BESIII	2018	[35]	0.5
$D^+ \to \pi^+ K_S^0 e^+ e^-$	2.6	BESIII	2018	[35]	1.0
$D^+ \to K_S^0 K^+ e^+ e^-$	1.1	BESIII	2018	[35]	0.4
$D^+ \to K^+ \pi^0 e^+ e^-$	1.5	BESIII	2018	[35]	0.6
$D_s^+ \to \pi^+ e^+ e^-$	13.0	BaBar	201		70.0
$D_s^+ \to K^+ e^+ e^-$	3.7	BaBar	201		1.7

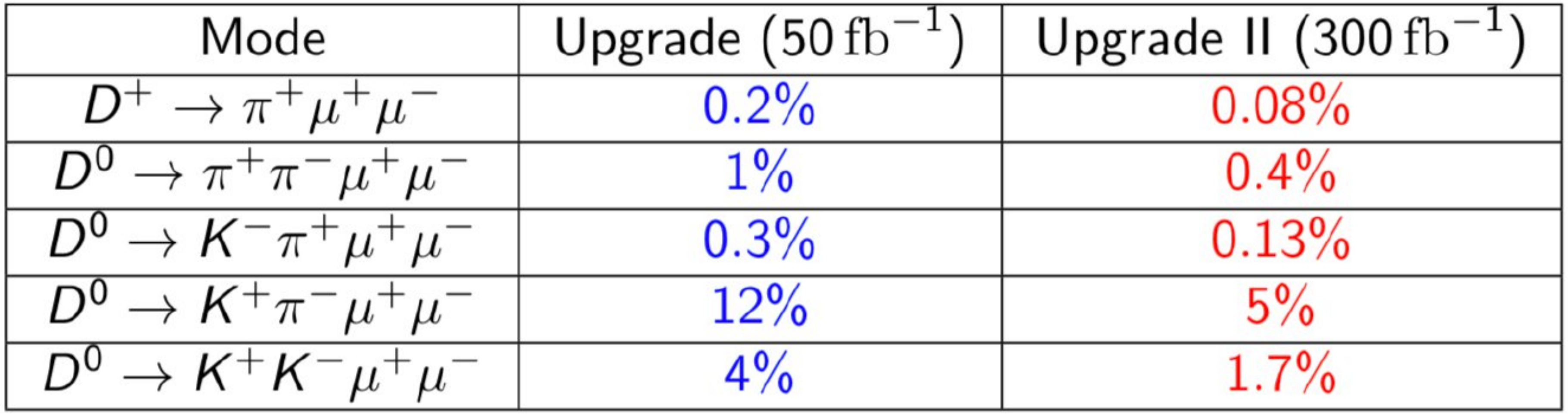
20 fb^{-1}
@ 3.773 GeV

6 fb^{-1}@ 4.18 GeV

LHCb prospects



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



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

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

Summary

- Charm hadron decays offer unique opportunities for Indirect NP searches
- LHCb & BESIII are two major players in the field:
  - LHCb: Dominant role for charm decays to all-track final states due to overwhelming statistics
  - BESIII: Advantages in reconstruction of neutrals ($\pi^0/\eta/K_S^0/\Lambda$/...) and invisible particles ($\nu/K_L^0/n$/DM/...)
- More results on the way: more decay modes currently under study & more data in a few years
- Uncovered topics today:
  - Charm mixing & CPV: See **LHCb上粲强子混合与CP破坏研究** by Shanzhen Chen
  - Radiative charm decays
  - Charm decays into invisible final states