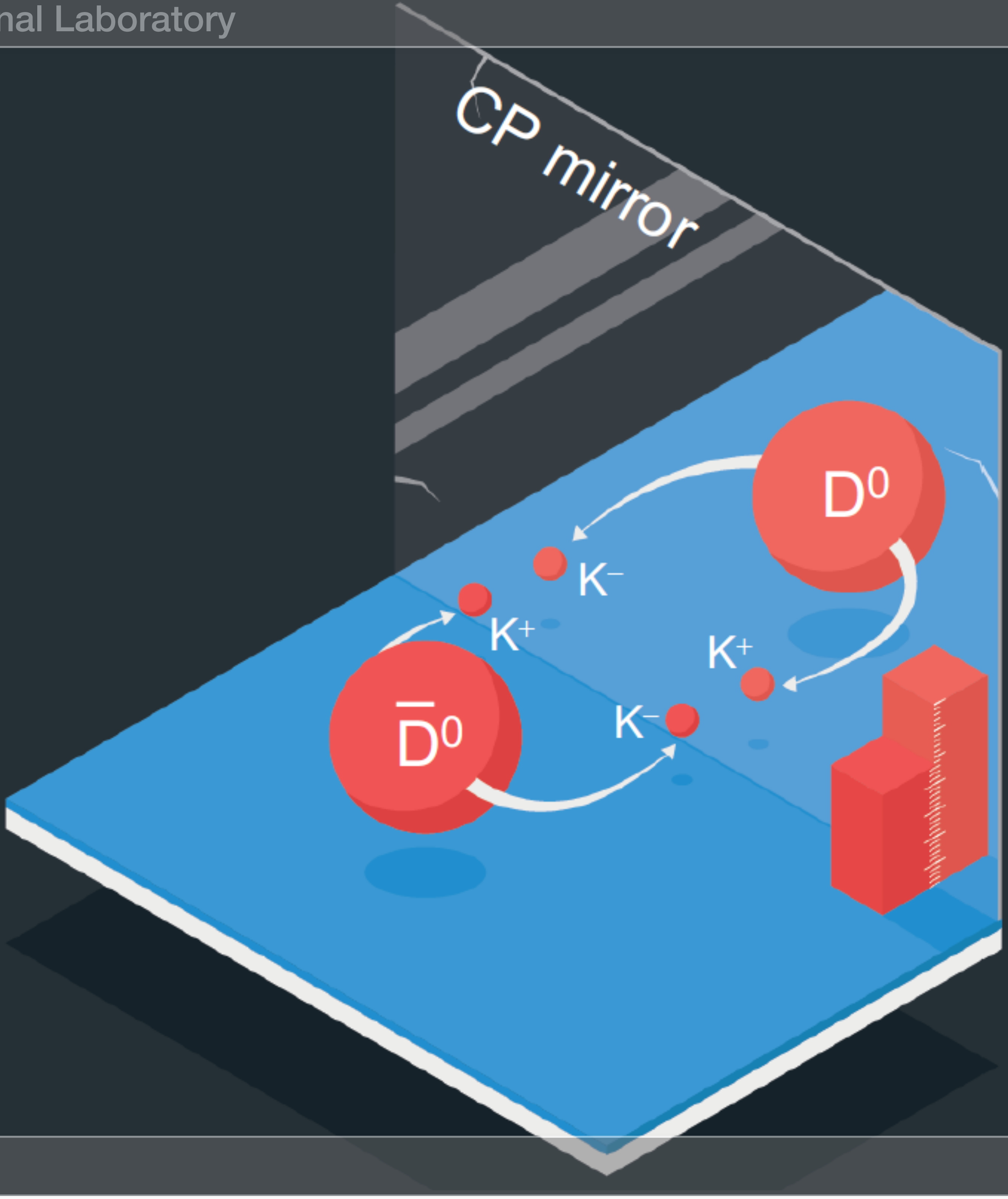
Particle Physics Seminar, Brookhaven National Laboratory



May 3rd, 2019

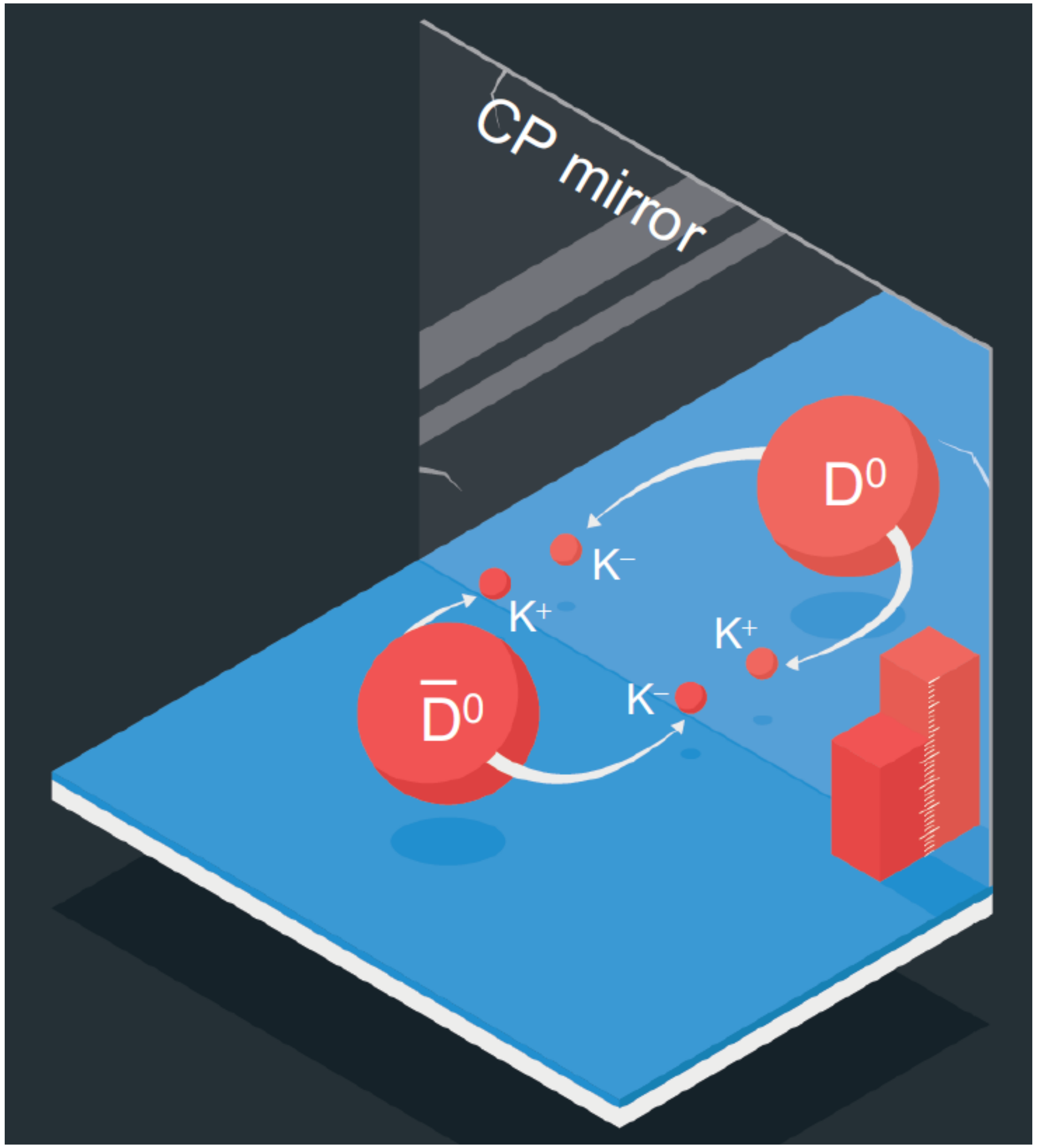
Observation of *CP* violation in charm decays

Angelo Di Canto

on behalf of the LHCb collaboration

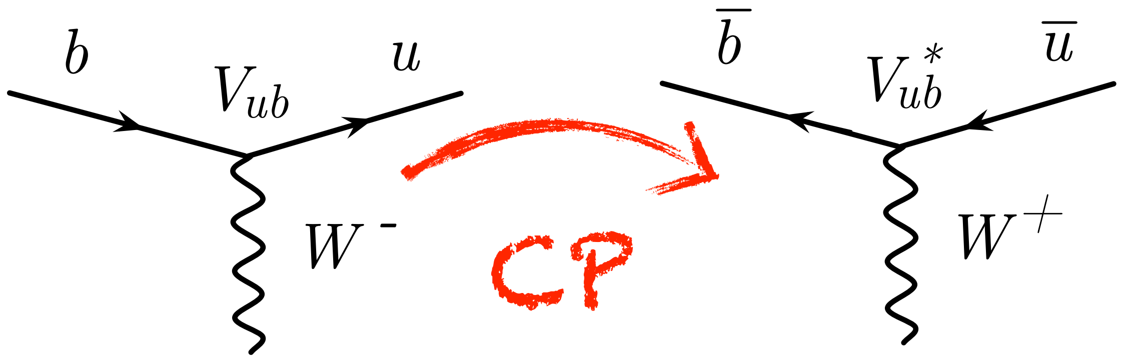
What is *CP* violation?

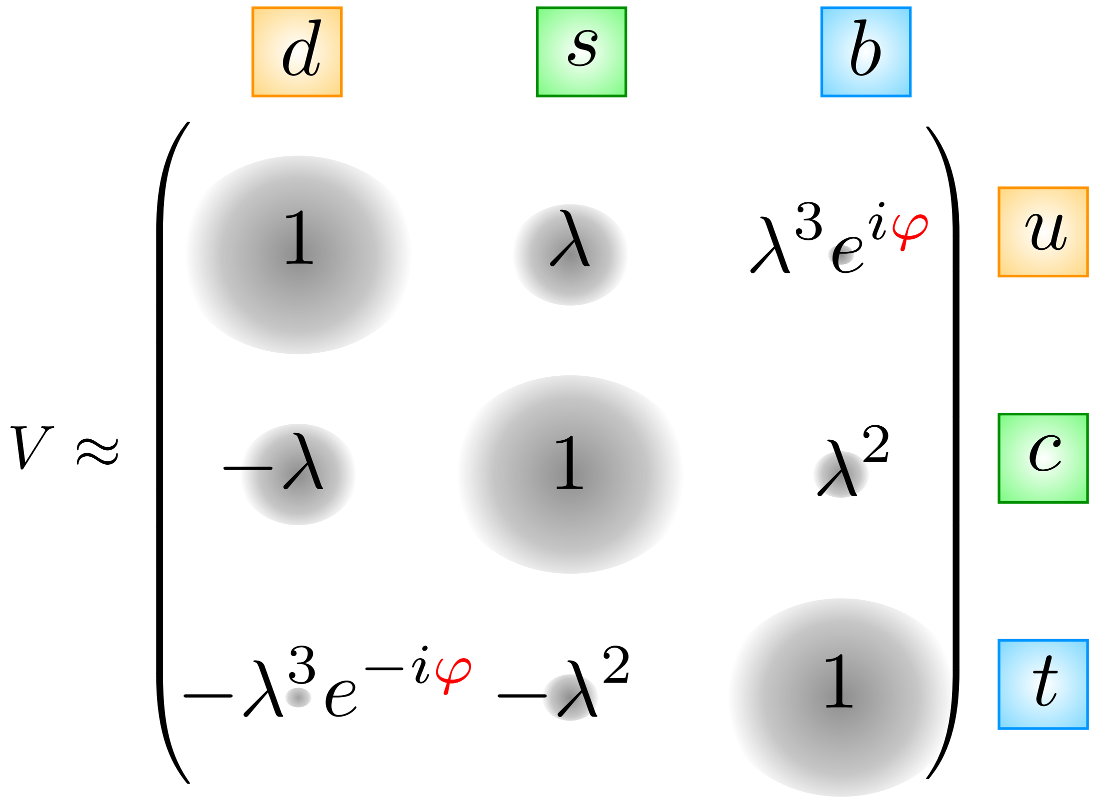
- Combination of mirror-reversal of the spatial arrangement (*P*) and replacement of particles with antiparticles (*C*)
- Dynamics of quarks (and maybe also leptons) is not invariant invariant under *CP* transformation



From where does it come?

- Irreducible phase of the Cabibbo-Kobayashi-Maskawa matrix describing the charged currents of quarks
- Potentially large effects in transitions involving the third generation
- Highly suppressed for charm, which has small couplings to the third generation

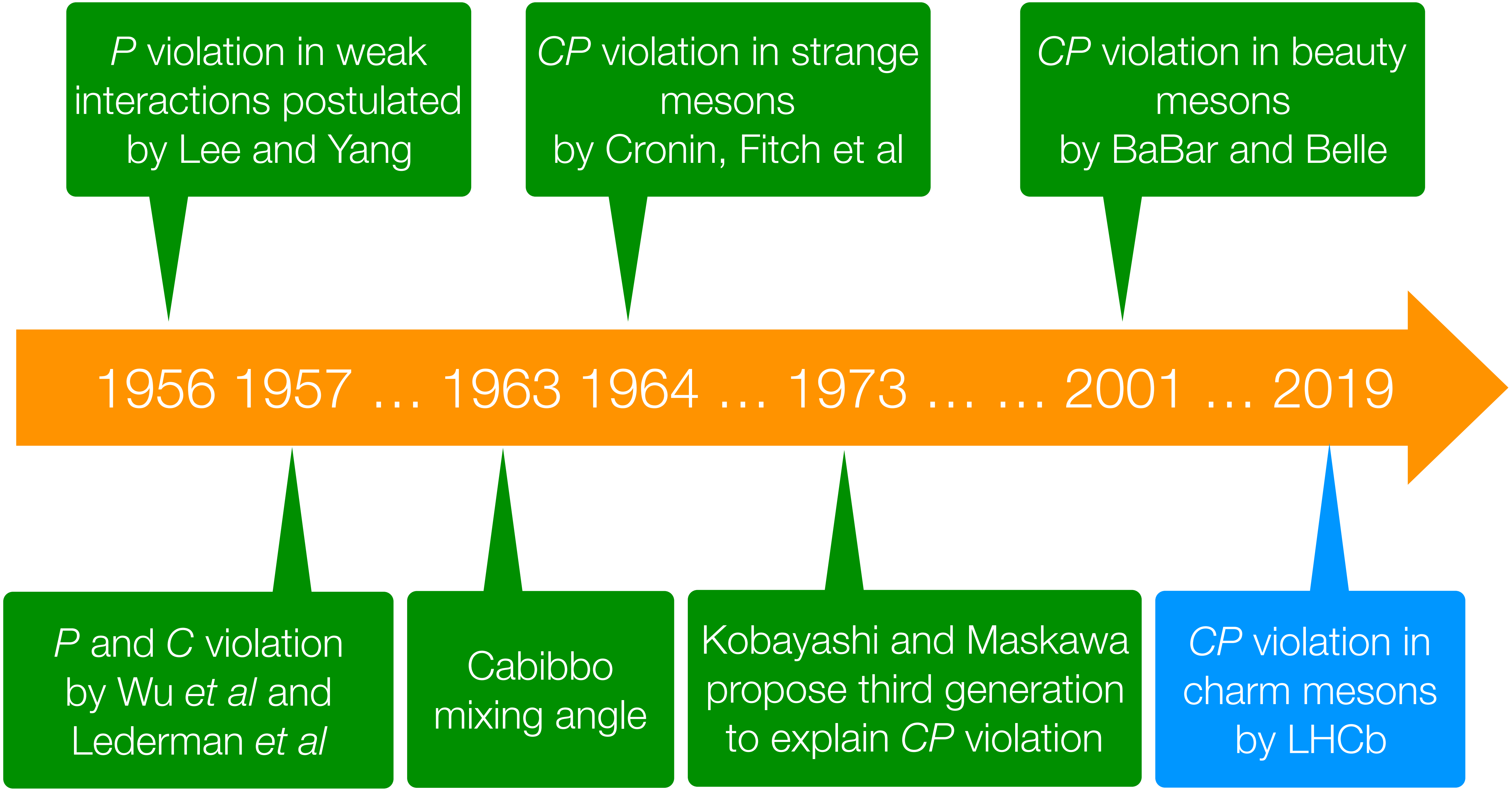




$$V \approx \begin{array}{cccc} d & s & b & \\ 1 & \lambda & \lambda^3 e^{i\varphi} & u \\ -\lambda & 1 & \lambda^2 & c \\ -\lambda^3 e^{-i\varphi} & -\lambda^2 & 1 & t \end{array}$$

$$\lambda \approx 0.22$$

Brief history of *CP* violation



P violation in weak interactions postulated by Lee and Yang

CP violation in strange mesons by Cronin, Fitch et al

CP violation in beauty mesons by BaBar and Belle

1956 1957 … 1963 1964 … 1973 … … 2001 … 2019

P and *C* violation by Wu *et al* and Lederman *et al*

Cabibbo mixing angle

Kobayashi and Maskawa propose third generation to explain *CP* violation

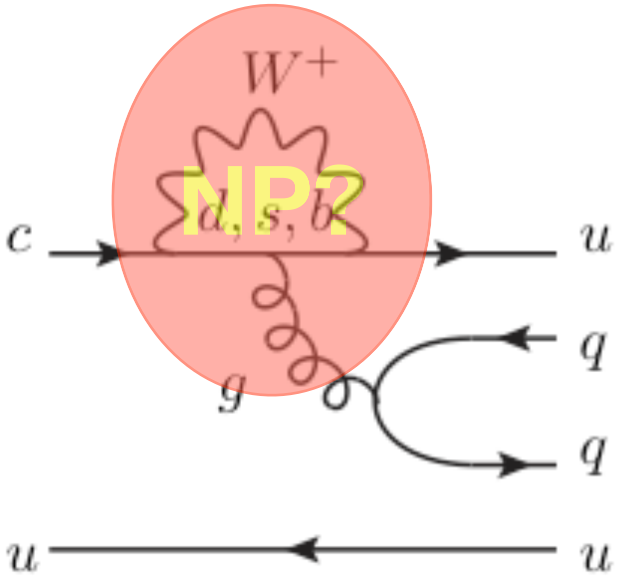
CP violation in charm mesons by LHCb

Why shall we bother about charm?

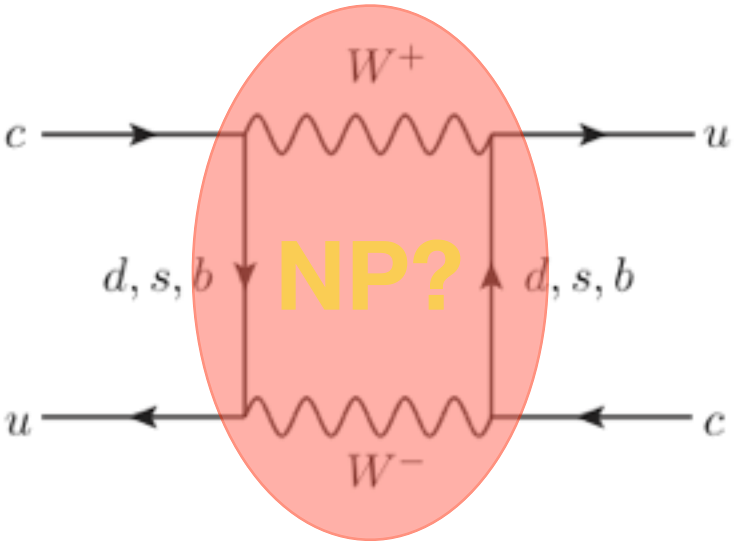
Discovery tool, standard model effects are $\sim 10^{-3}$ or smaller, potential room for new physics to show up

Unique, gives sensitivity to new physics coupling to up-type quarks (complementary to K and $B_{(s)}$ decays)

Challenging, need O(1-100M) yields and control over systematic uncertainties. Predictions are difficult, not a precision probe



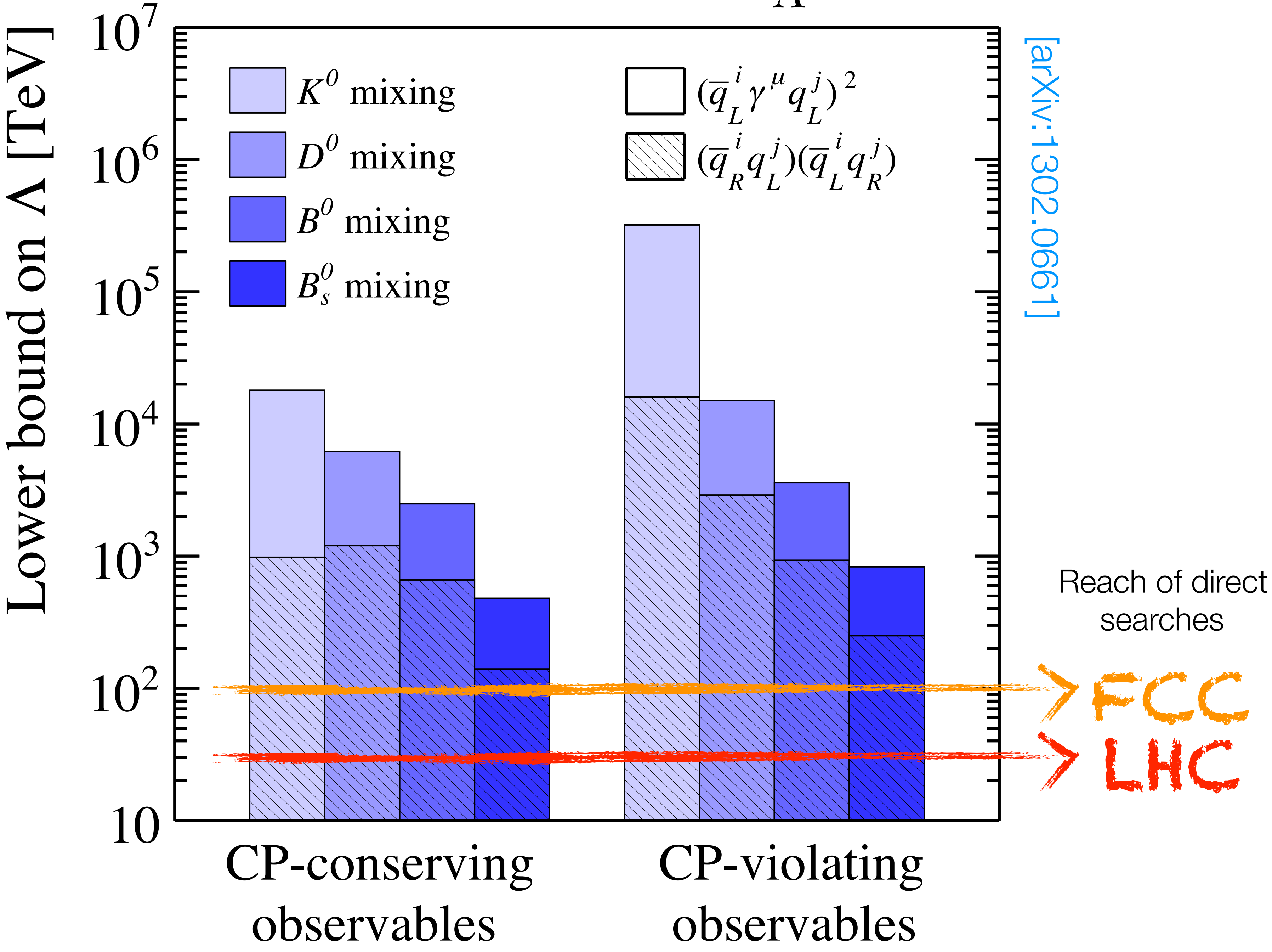
ΔC=1



ΔC=2

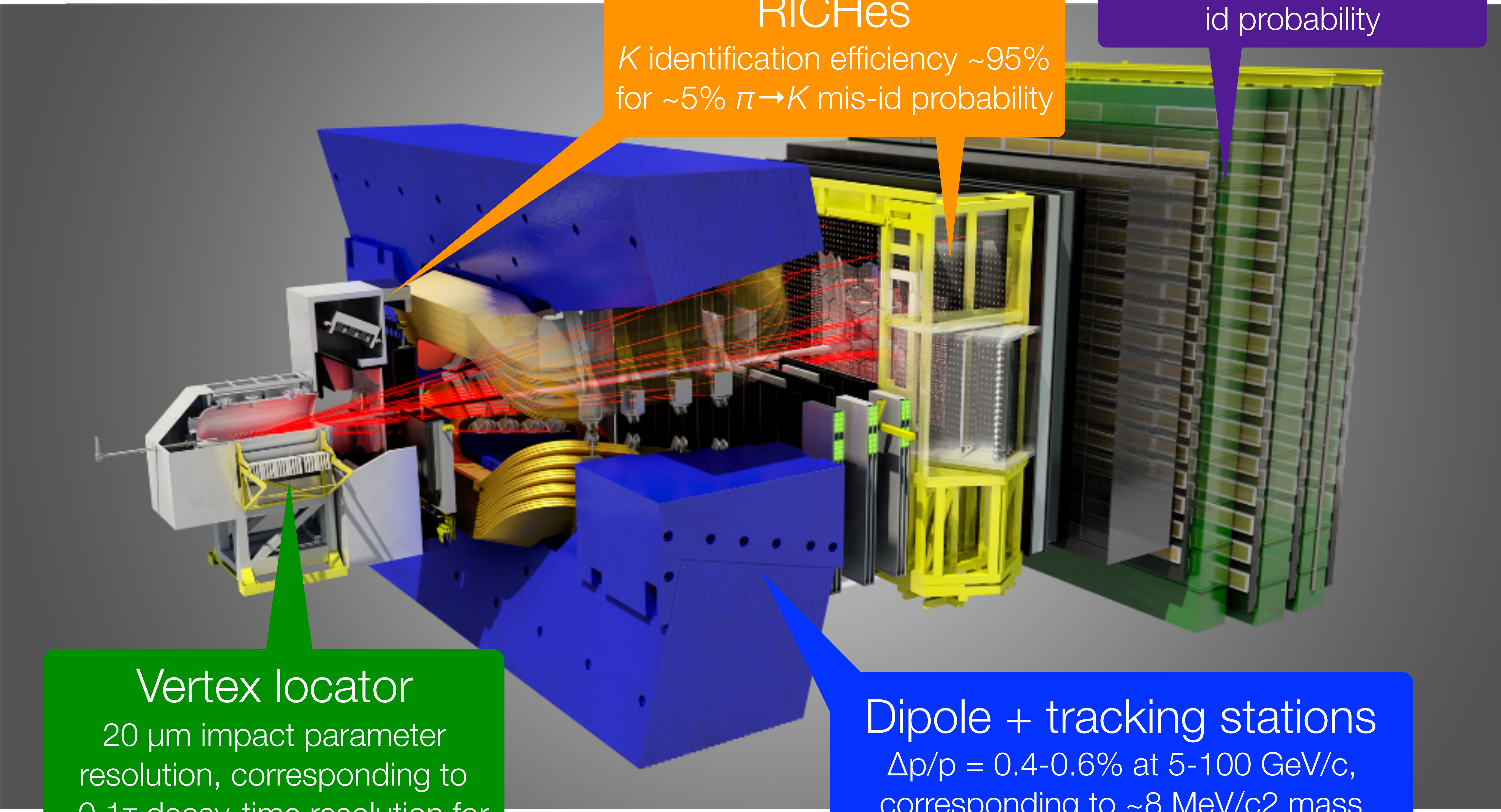
Reach/impact

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\mathcal{O}_{\Delta F=2}$$



[arXiv:1302.0661]

The beauty of the LHC



RICHes

K identification efficiency ~95% for ~5% $\pi \to K$ mis-id probability

Muon stations

μ identification efficiency ~97% for 1-3% $\pi \to \mu$ mis-id probability

Vertex locator

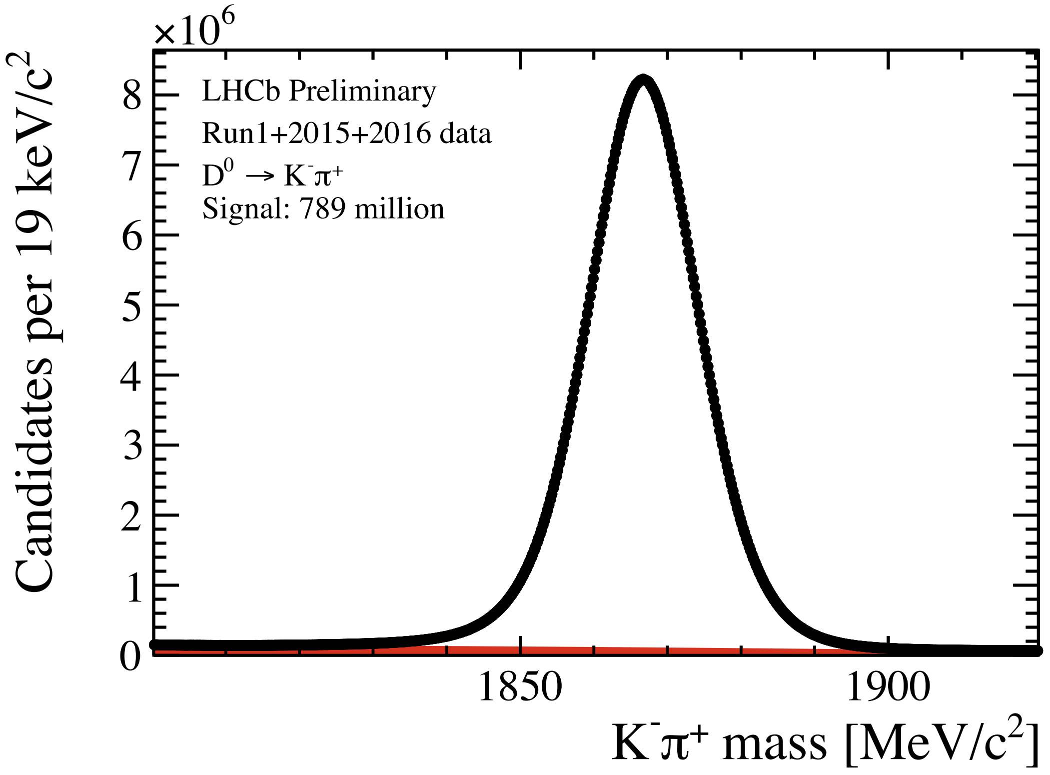
20 μm impact parameter resolution, corresponding to ~0.1τ decay-time resolution for a two-body charm decay

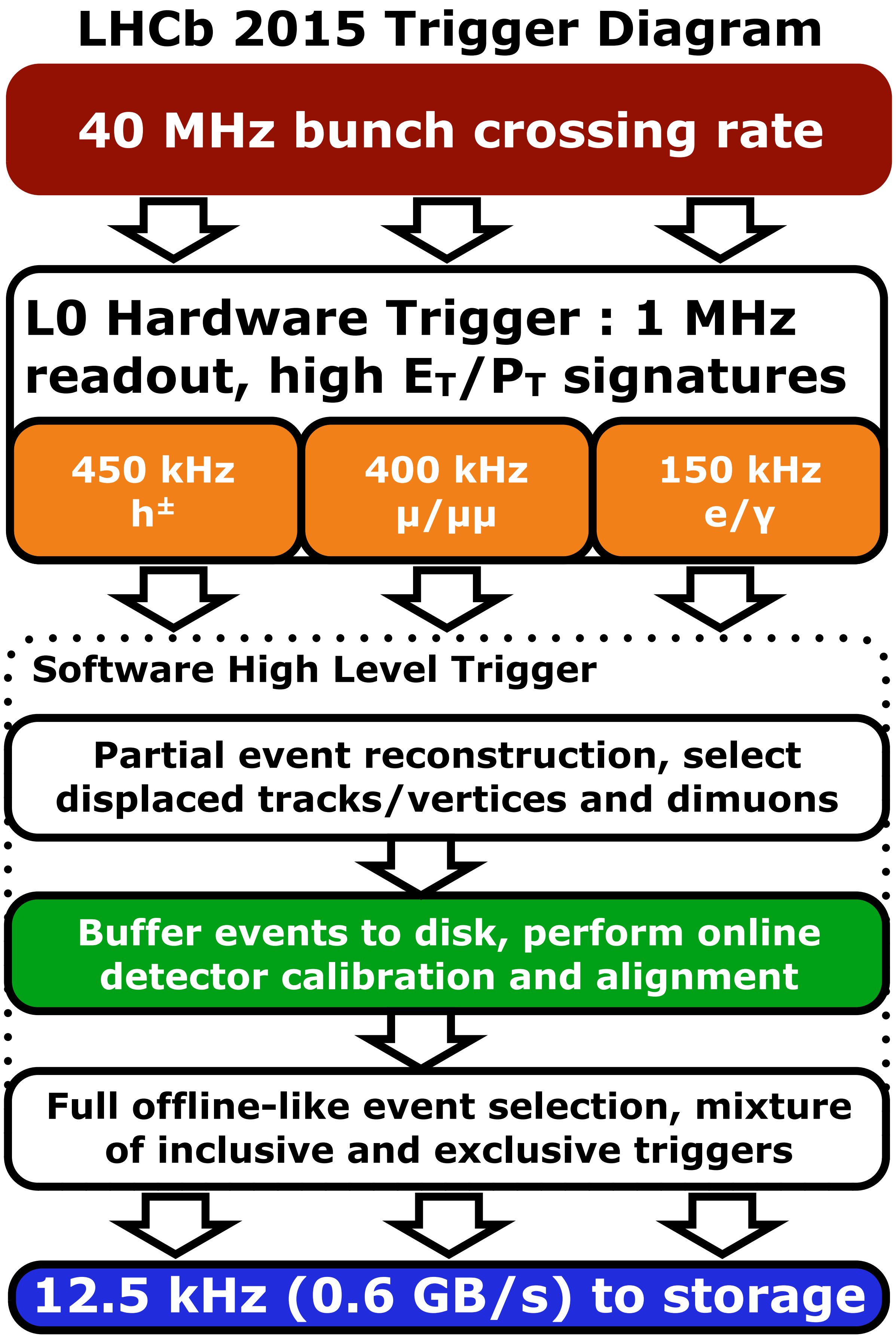
Dipole + tracking stations

$\Delta p/p$ = 0.4-0.6% at 5-100 GeV/c, corresponding to ~8 MeV/c2 mass resolution for a two-body charm decay

The trigger

- Real-time calibration of the detector allows offline-quality reconstruction
- Trigger candidates are used directly in the analysis





LHCb 2015 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

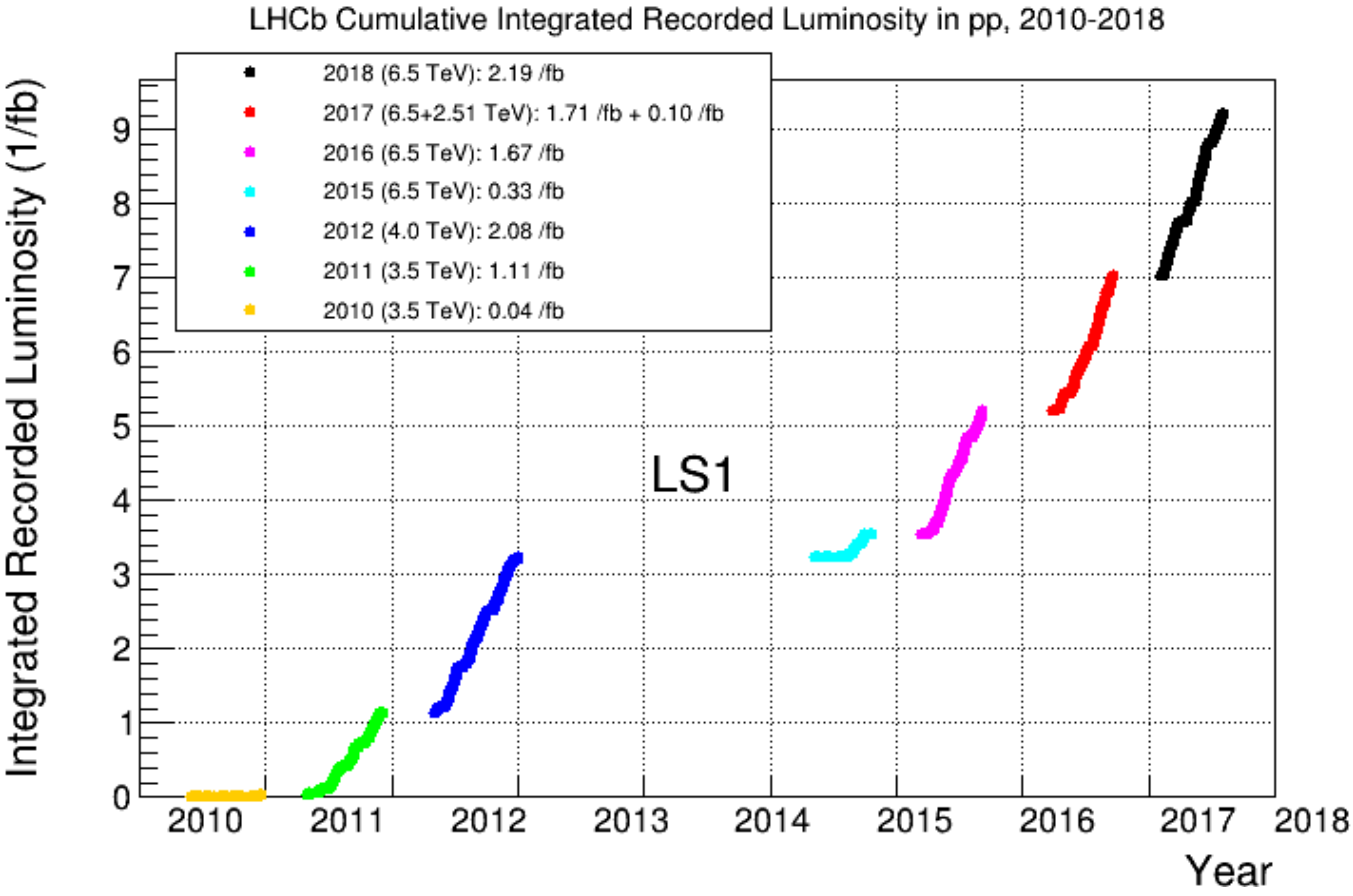
Software High Level Trigger

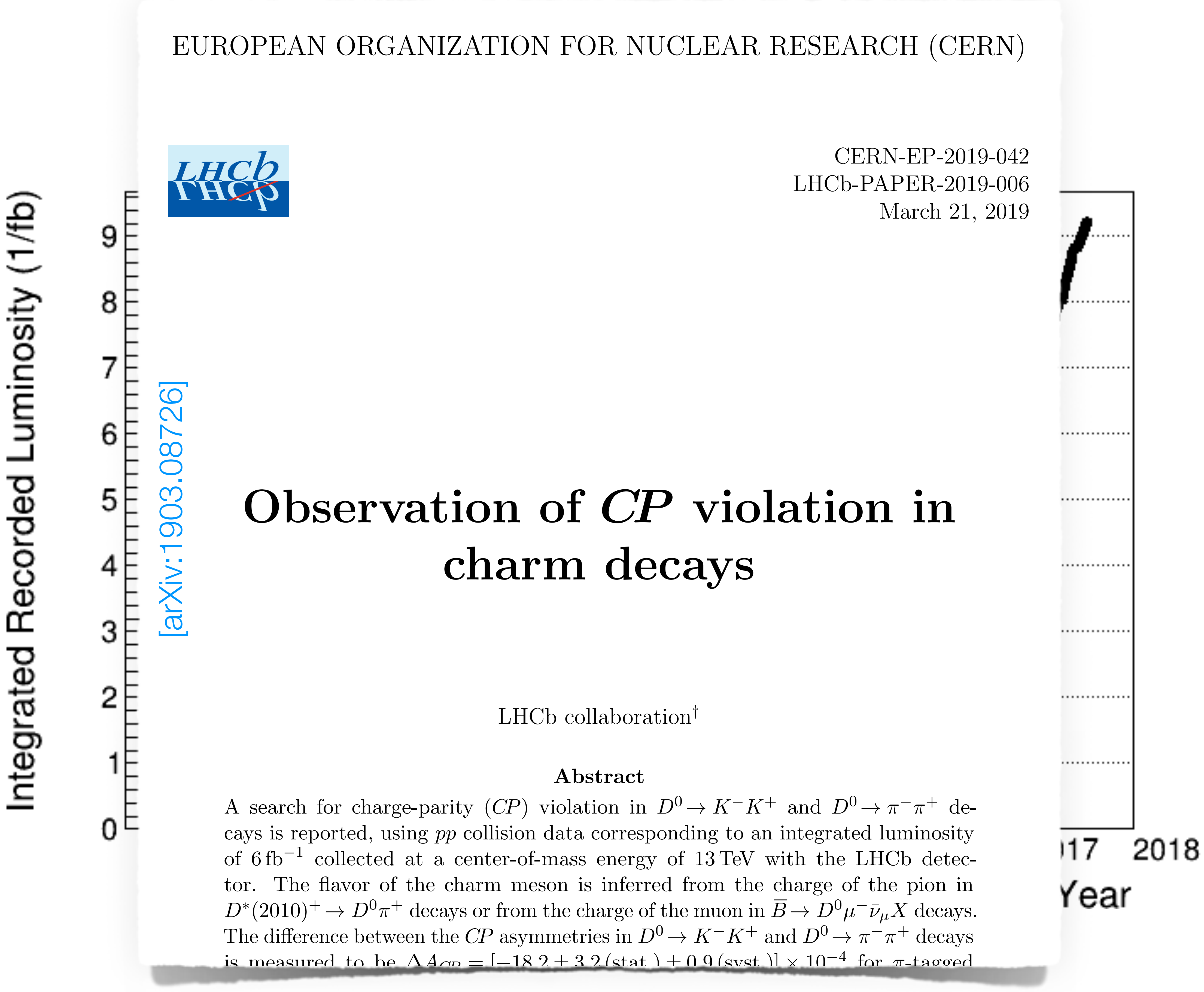
Partial event reconstruction, select displaced tracks/vertices and dimuons

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


LHCb Cumulative Integrated Recorded Luminosity in pp, 2010-2018
2018 (6.5 TeV): 2.19 /fb
2017 (6.5+2.51 TeV): 1.71 /fb + 0.10 /fb
2016 (6.5 TeV): 1.67 /fb
2015 (6.5 TeV): 0.33 /fb
2012 (4.0 TeV): 2.08 /fb
2011 (3.5 TeV): 1.11 /fb
2010 (3.5 TeV): 0.04 /fb
LS1
Integrated Recorded Luminosity (1/fb)
0
1
2
3
4
5
6
7
8
9
2010
2011
2012
2013
2014
2015
2016
2017
2018
Year



[arXiv:1903.08726]

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2019-042
LHCb-PAPER-2019-006
March 21, 2019

Observation of *CP* violation in charm decays

LHCb collaboration[†]

Abstract

A search for charge-parity (*CP*) violation in $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ decays is reported, using *pp* collision data corresponding to an integrated luminosity of 6 fb^{-1} collected at a center-of-mass energy of 13 TeV with the LHCb detector. The flavor of the charm meson is inferred from the charge of the pion in $D^*(2010)^+ \to D^0 \pi^+$ decays or from the charge of the muon in $\overline{B} \to D^0 \mu^- \bar{\nu}_\mu X$ decays. The difference between the *CP* asymmetries in $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ decays is measured to be $\Delta A_{CP} = [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4}$ for π-tagged

First results with full statistics!

What do we measure?

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

What do we measure?

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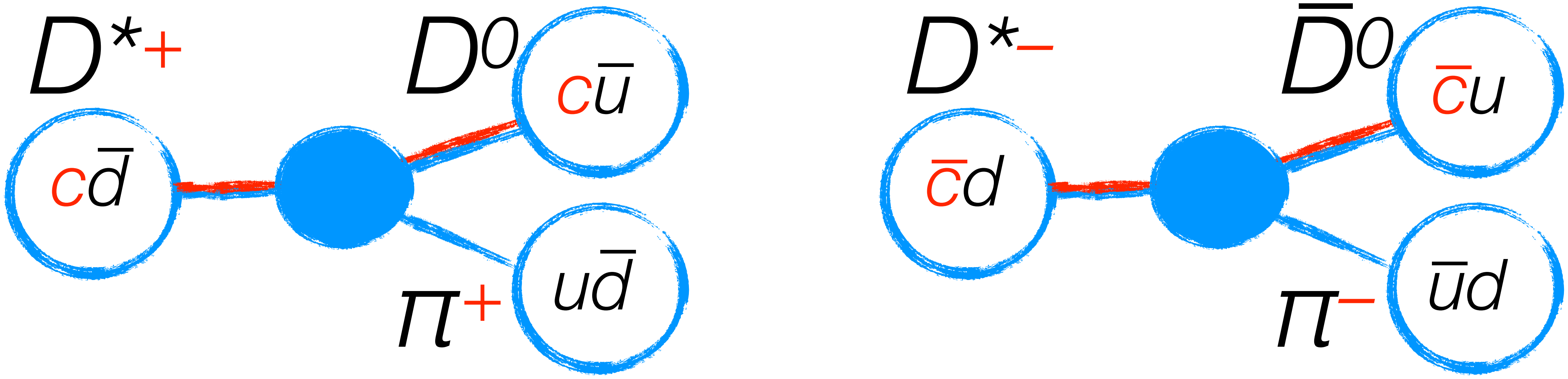
How do we tell if it’s a D^0 or a $\bar{D}^0$?



positive π ⇒ D^0

negative π ⇒ $\bar{D}^0$

What do we measure?

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

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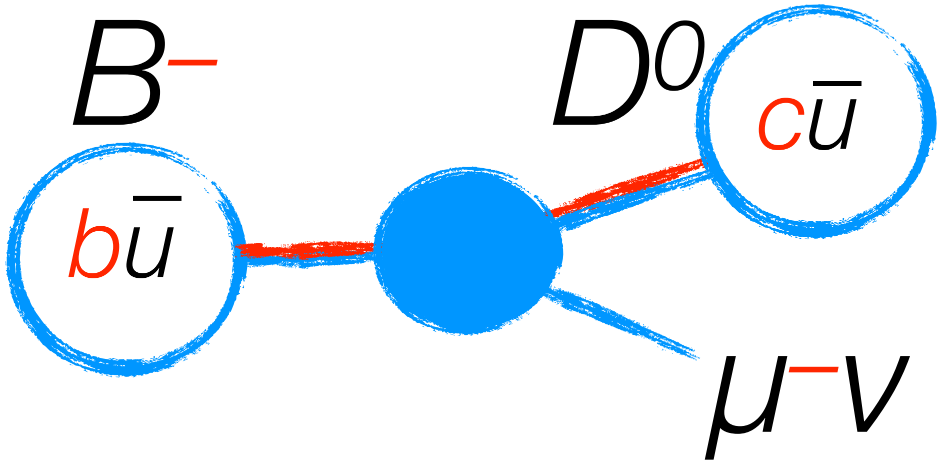
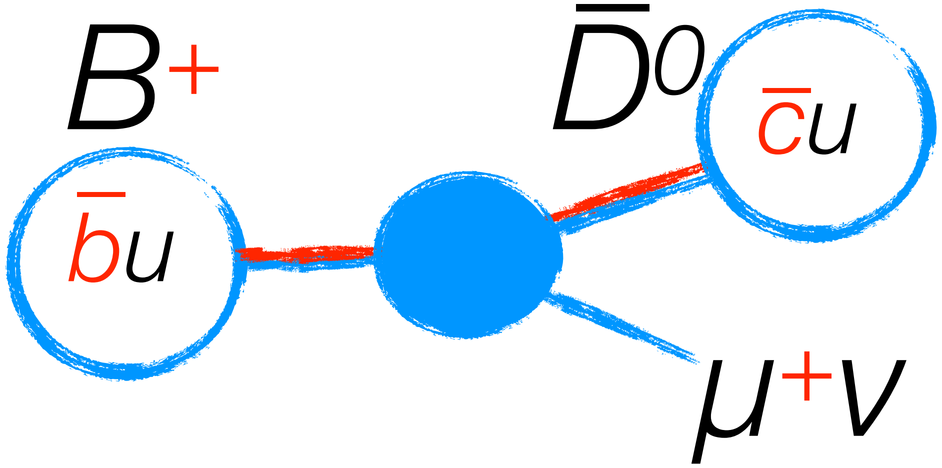




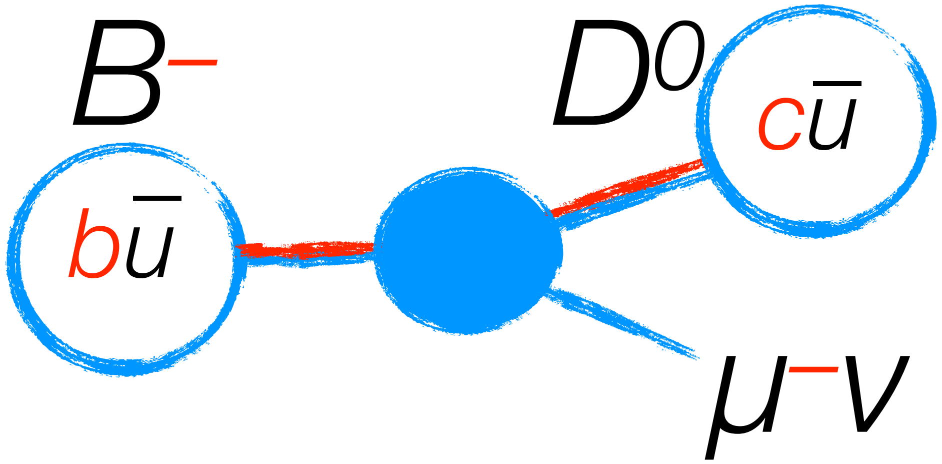
negative $\mu \Rightarrow D^0$

positive $\mu \Rightarrow \bar{D}^0$

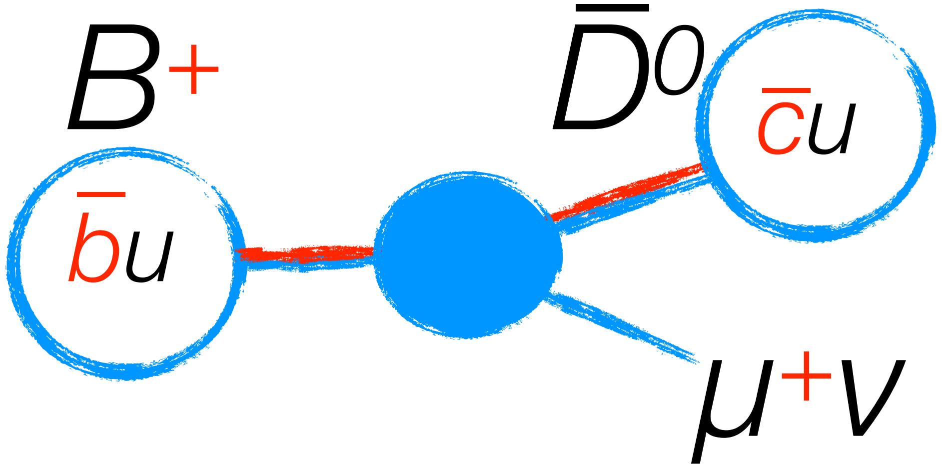
What do we measure?

$$A(D^0 \to h^+h^-) = \frac{N(D^0 \to h^+h^-) - N(\overline{D}^0 \to h^+h^-)}{N(D^0 \to h^+h^-) + N(\overline{D}^0 \to h^+h^-)}$$

How do we tell if it's a D^0 or a $\bar{D}^0$?



negative μ ⇒ D^0

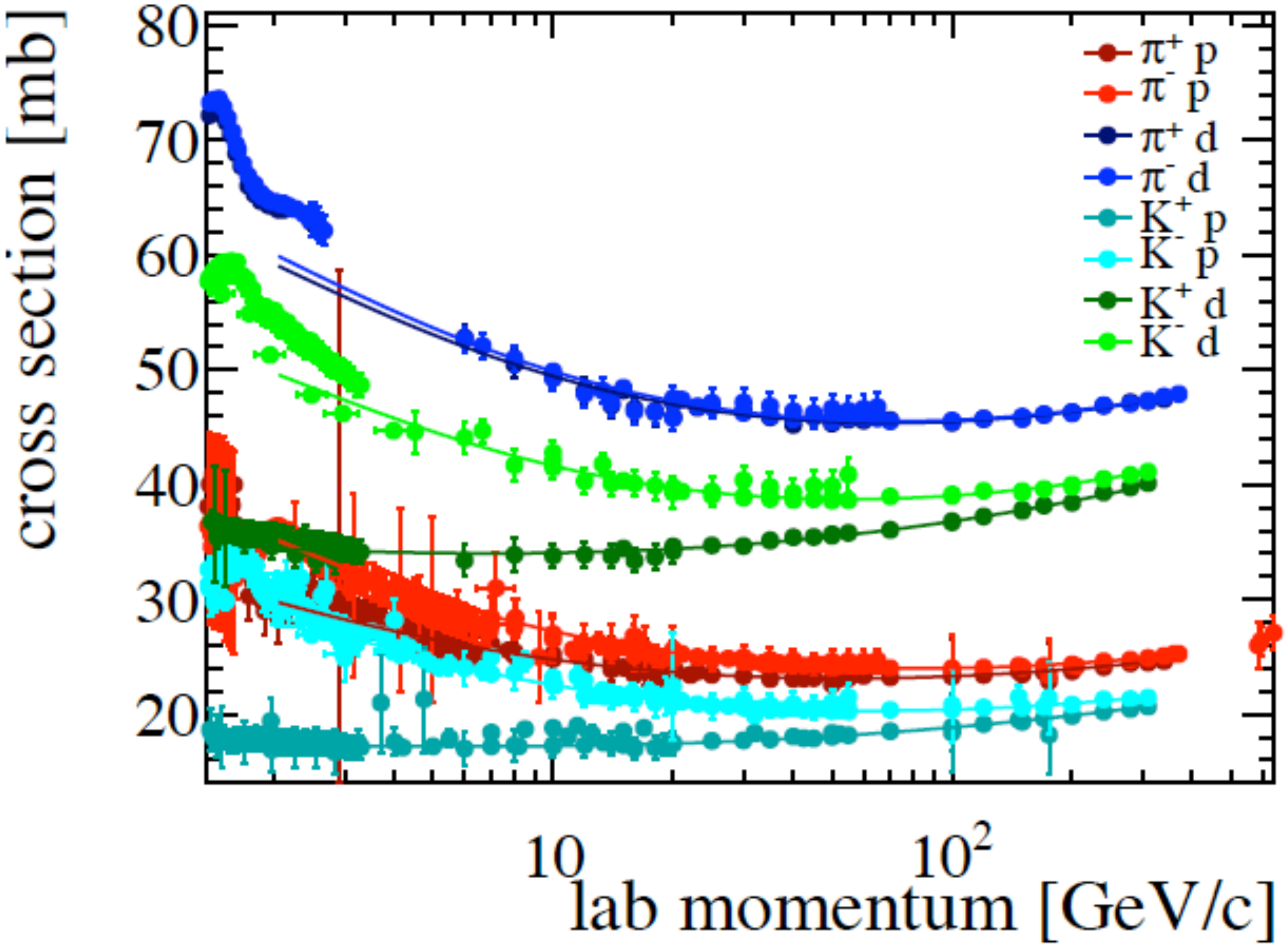


positive μ ⇒ $\bar{D}^0$

Detection asymmetries

- Detector layout and/or differences in interaction cross section result in different reconstruction efficiencies for positively and negatively charged particles

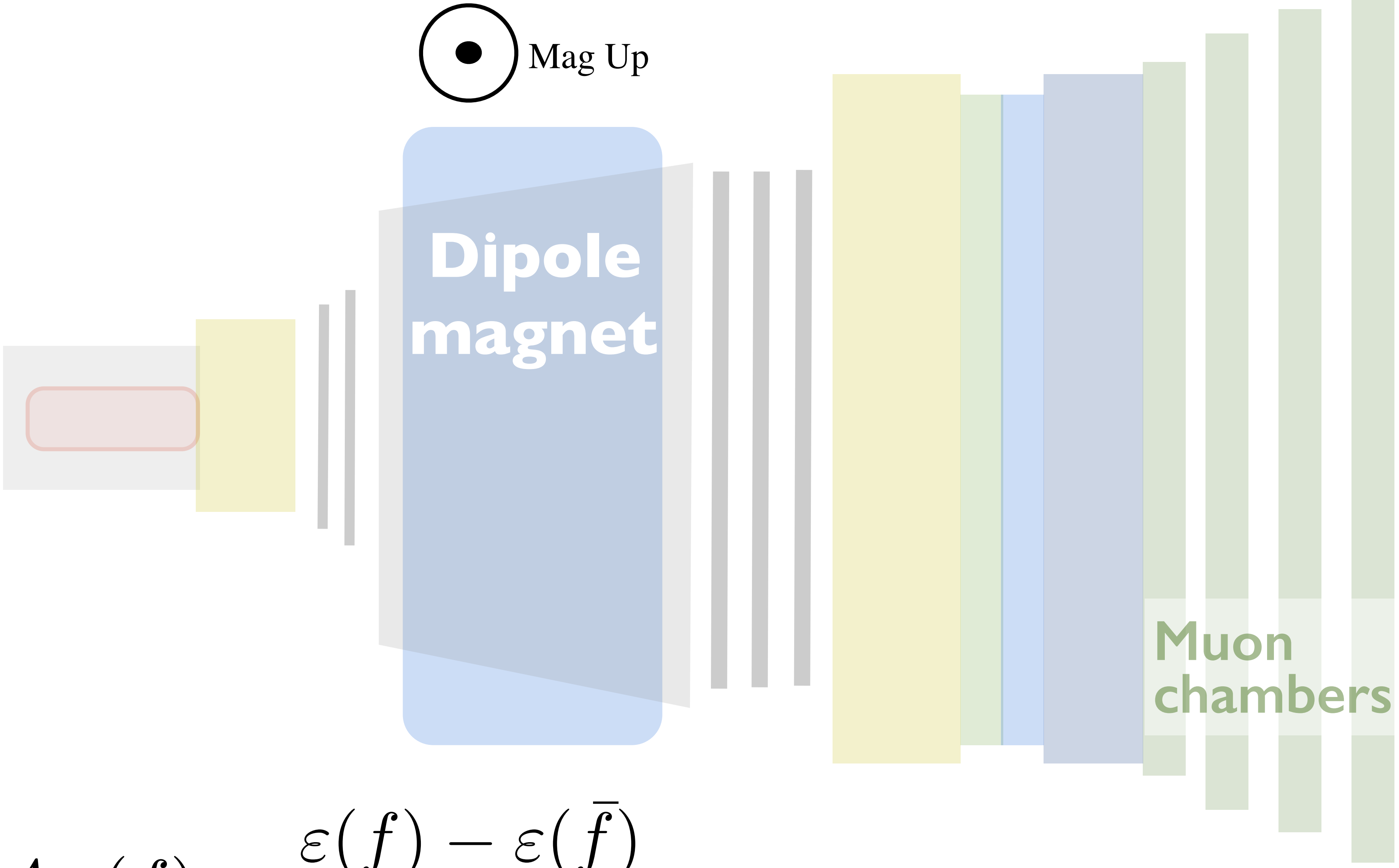
Chin. Phys. C 38 (2014) 090001



$$A_D(f) = \frac{\varepsilon(f) - \varepsilon(\bar{f})}{\varepsilon(f) + \varepsilon(\bar{f})}$$

Reversing the magnet polarity

[LHCb-PUB-2014-006]



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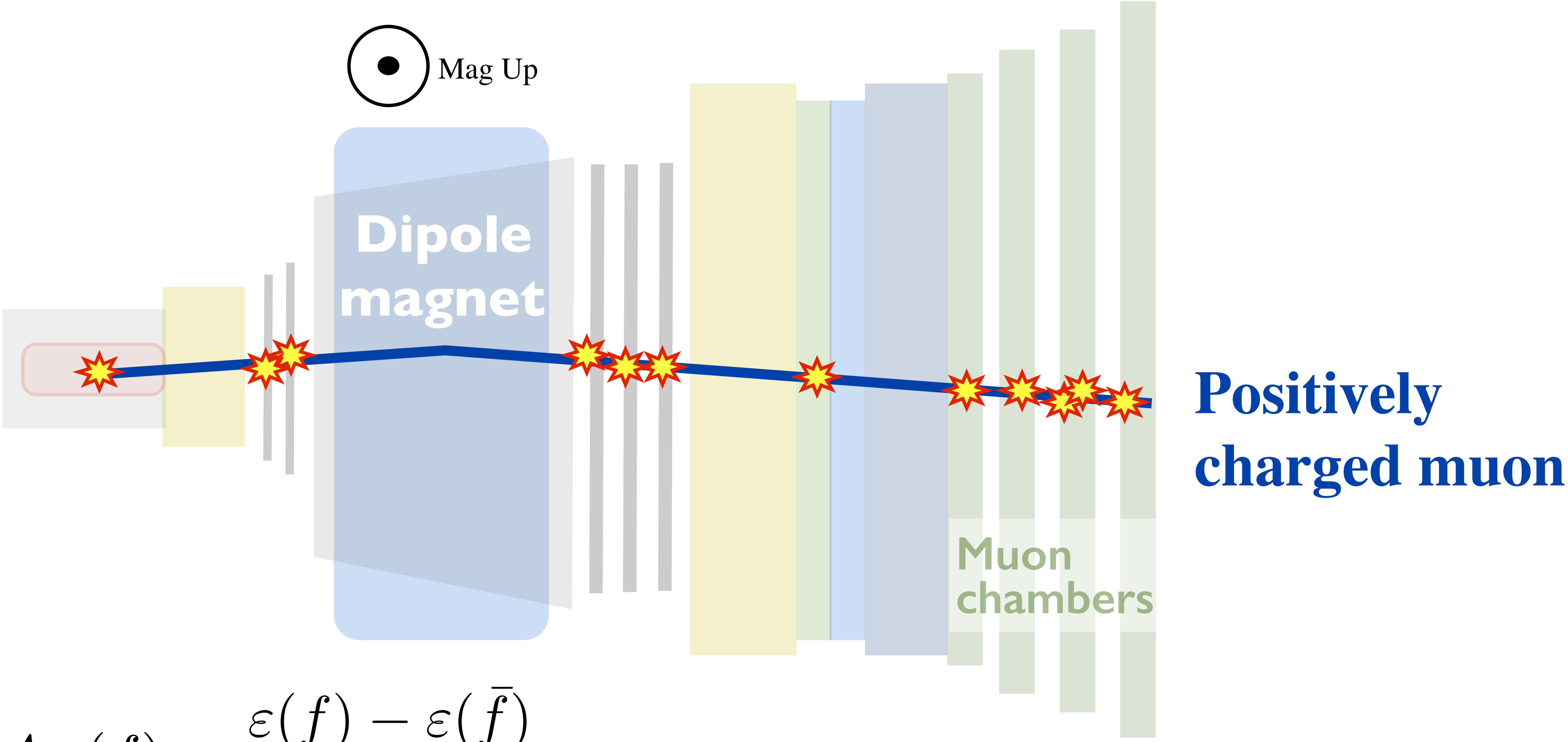

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Reversing the magnet polarity

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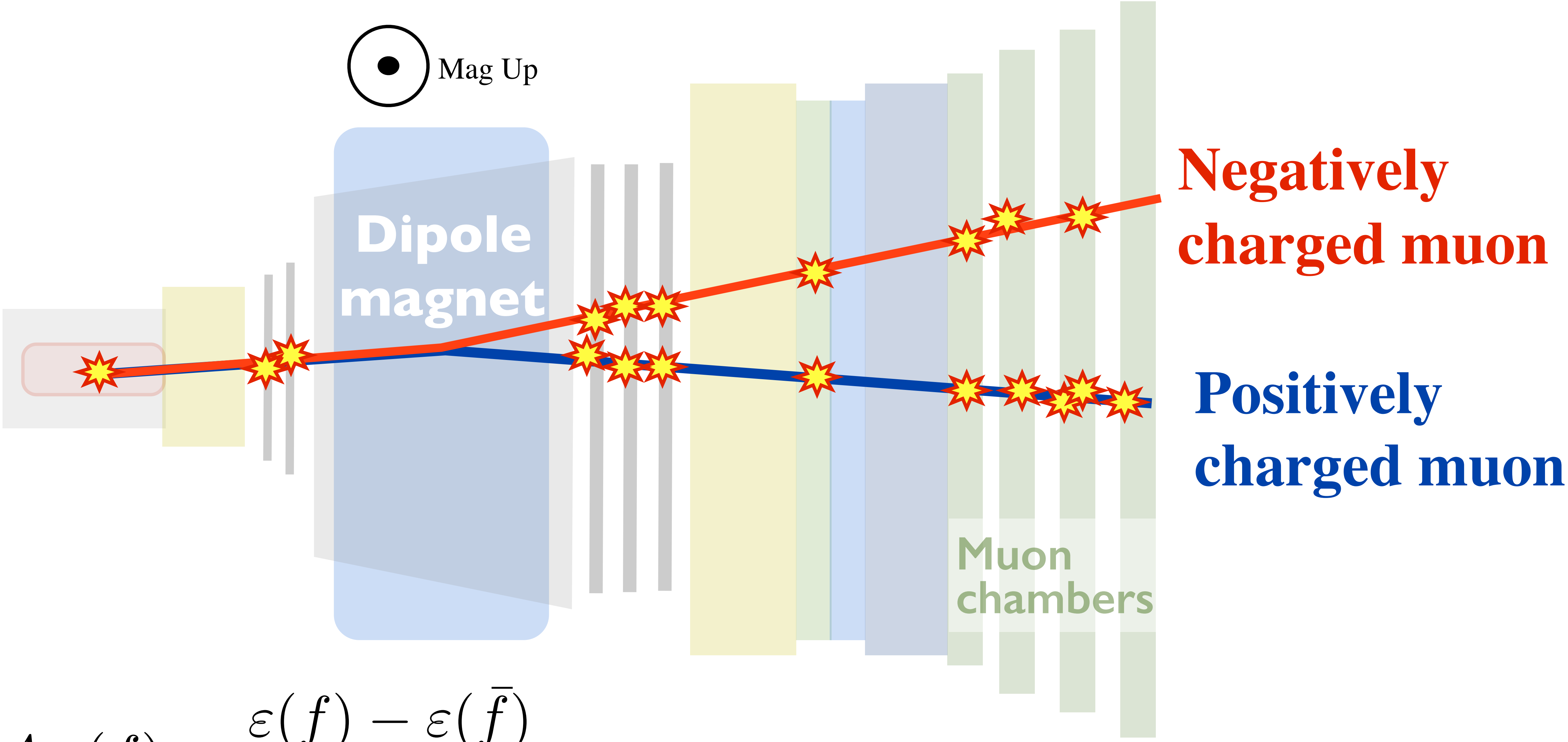

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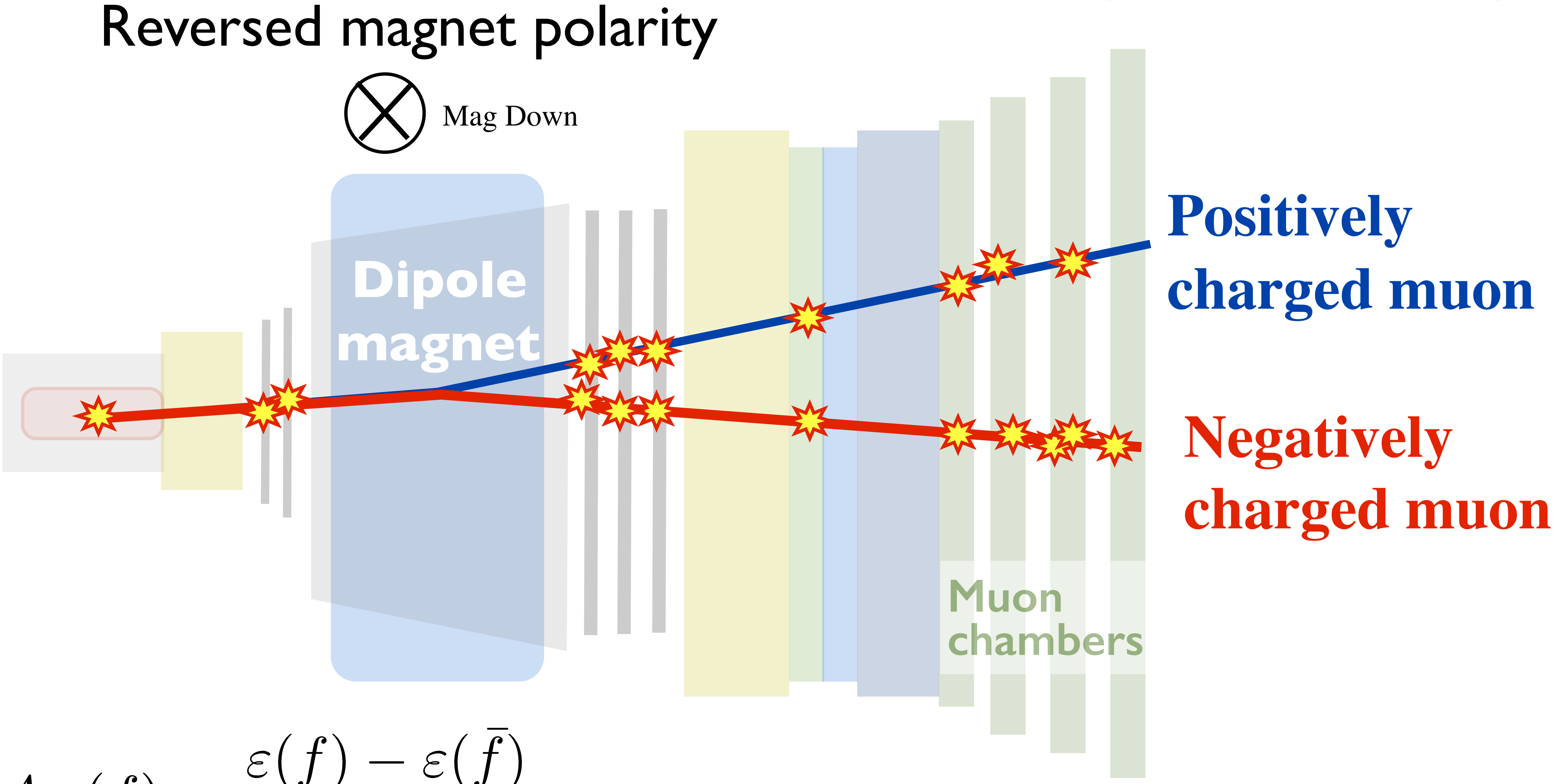

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Reversing the magnet polarity

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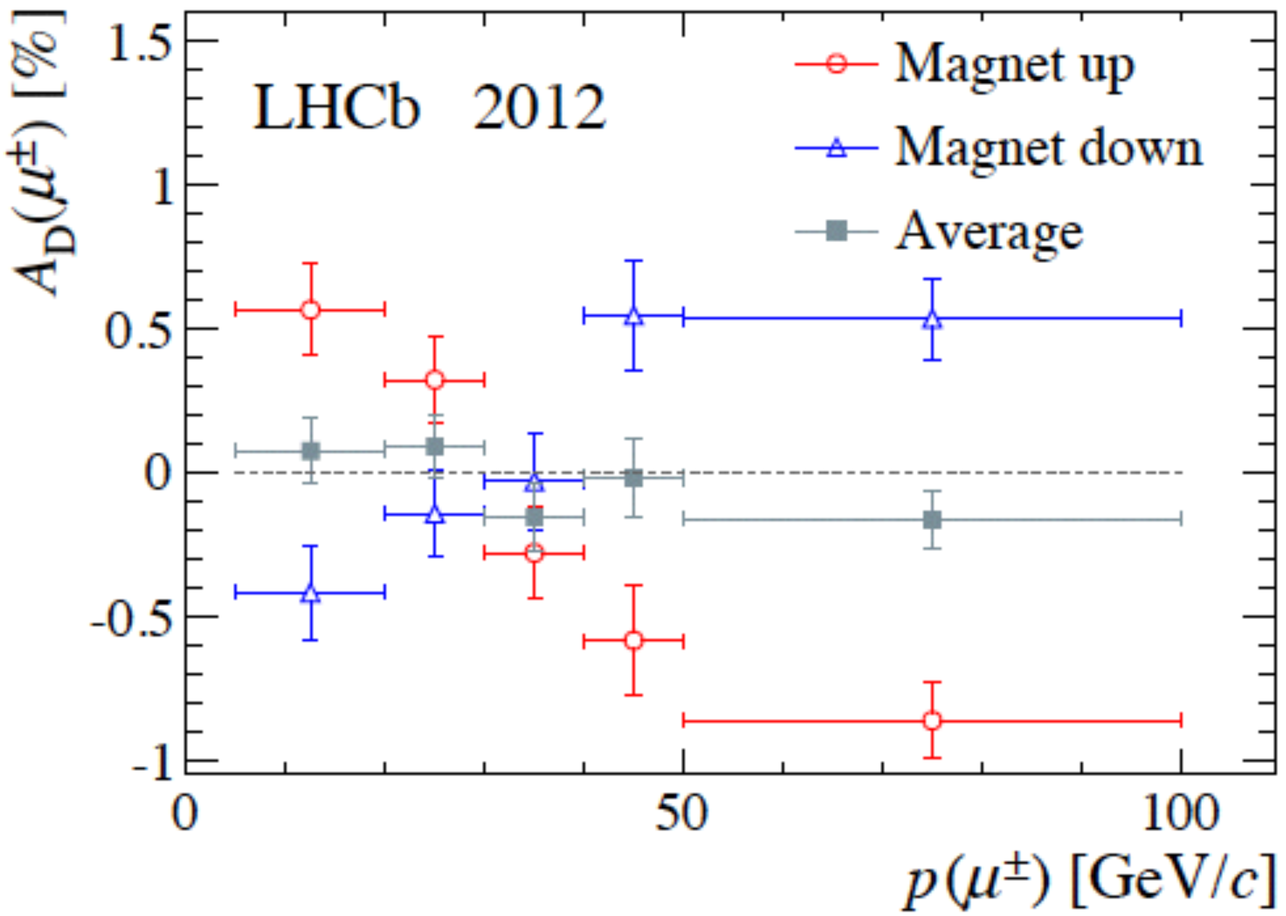


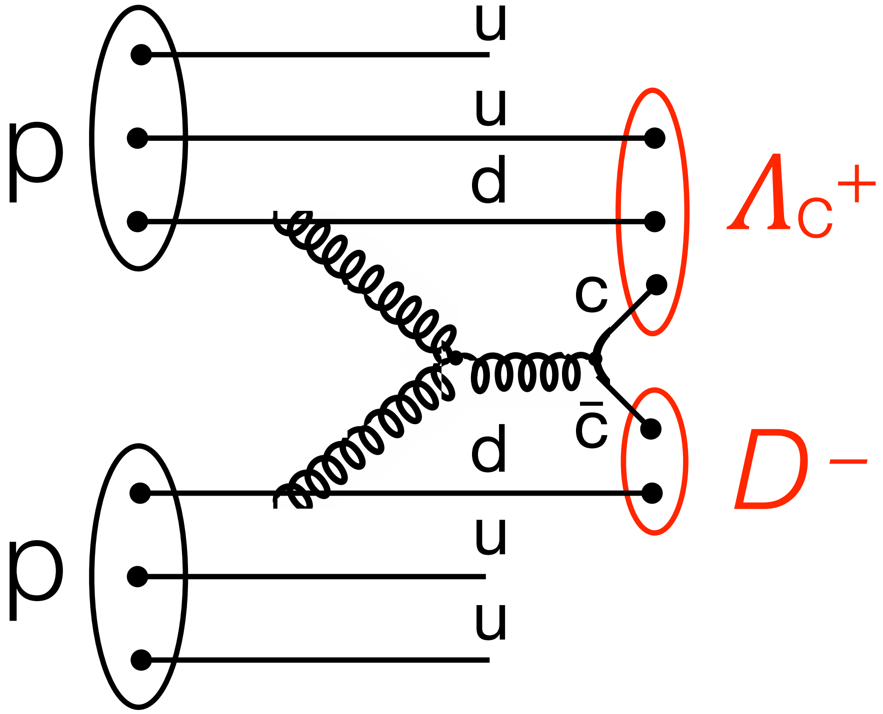
- Effectiveness depends on high frequency (2 weeks) of polarity flips
- Does not cancel asymmetries to 10^{-3} level, but crucial systematic check of results

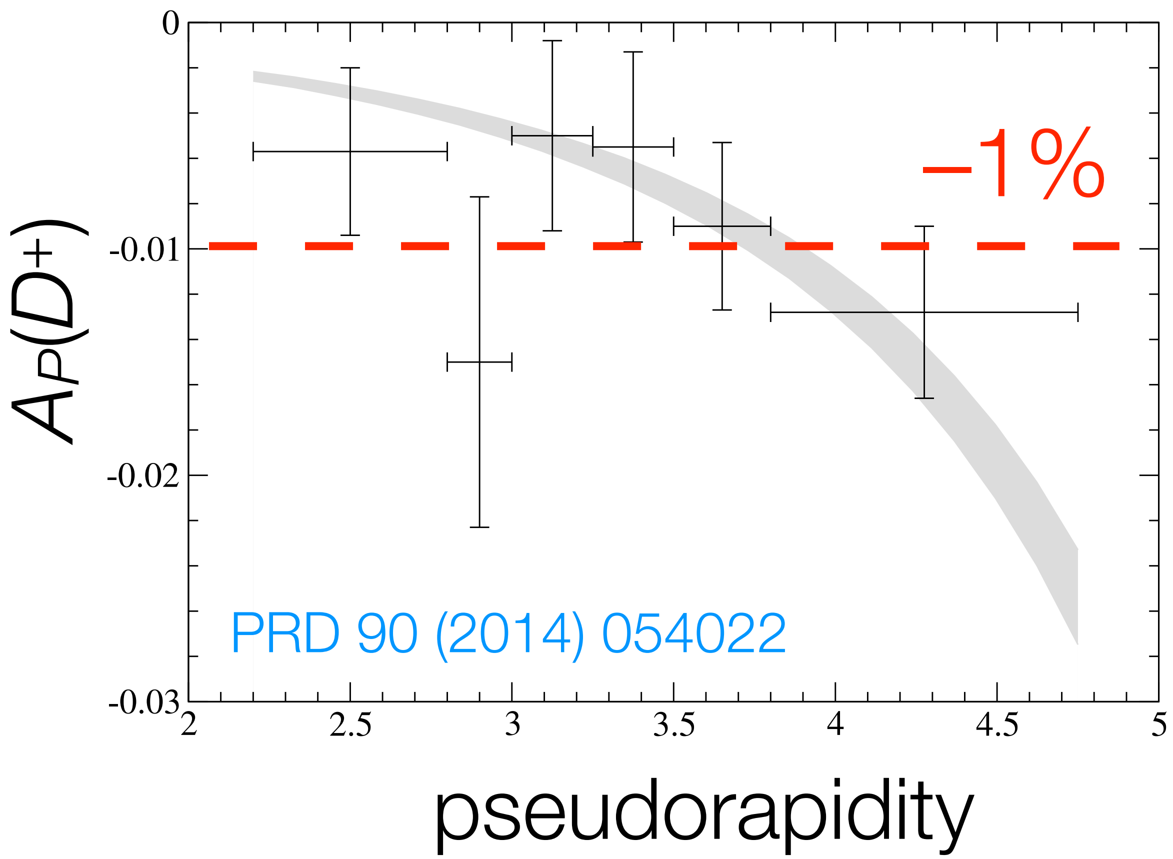
Production asymmetry

- In pp collision the charm is produced mostly through gluon fusion (which is charge symmetric)

- The quarks may “recombine” with some of the proton valence quarks (beam-drag effect) creating an asymmetric production of charm mesons or baryons

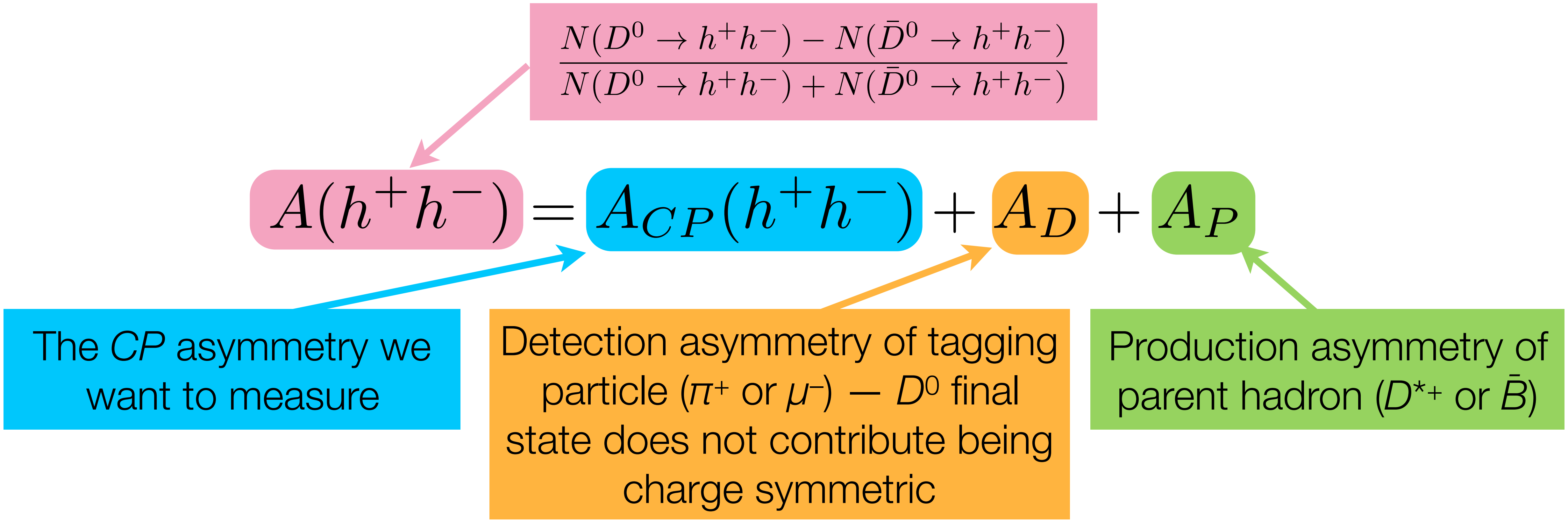
- The effect is enhanced in the forward region, where the charm pair is collinear with the protons’ direction





PRD 90 (2014) 054022

Why do we measure ΔA_{CP}?



$$\frac{N(D^0 \to h^+h^-) - N(\bar{D}^0 \to h^+h^-)}{N(D^0 \to h^+h^-) + N(\bar{D}^0 \to h^+h^-)}$$

$$A(h^+h^-) = A_{CP}(h^+h^-) + A_D + A_P$$

The *CP* asymmetry we want to measure

Detection asymmetry of tagging particle (π^+ or μ^-) — D^0 final state does not contribute being charge symmetric

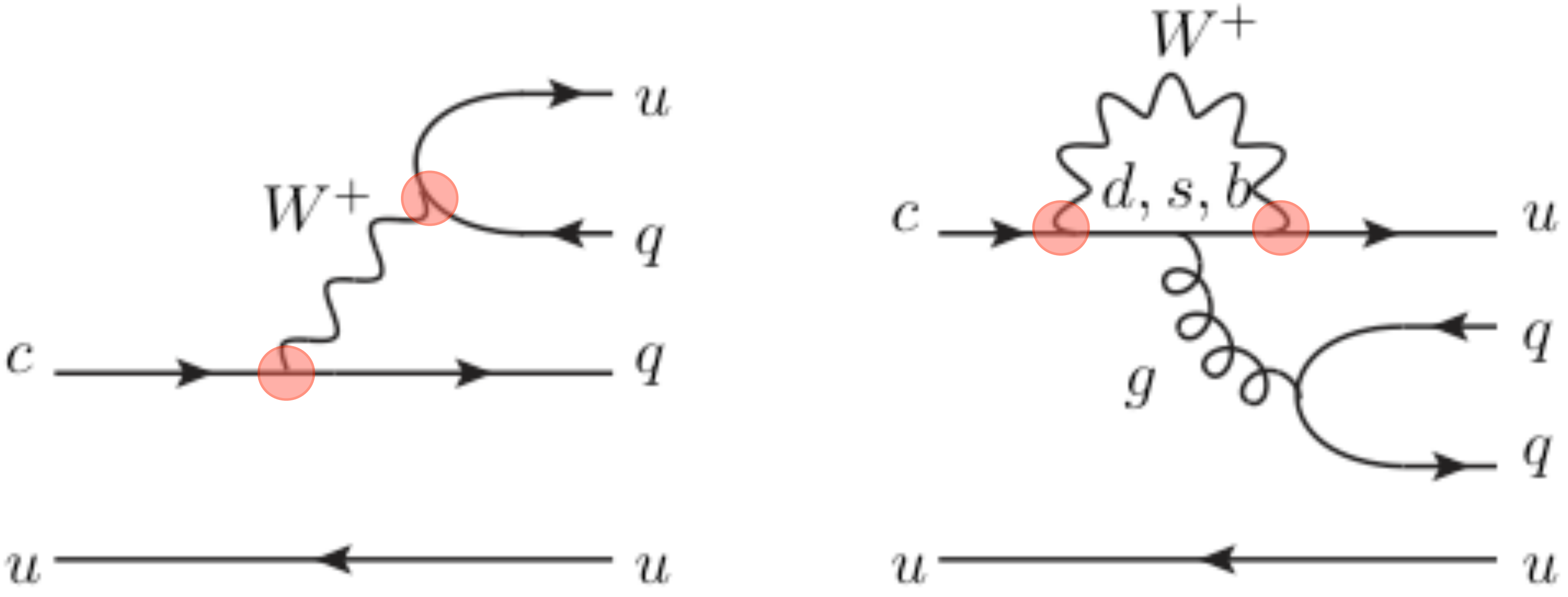
Production asymmetry of parent hadron (D^{*+} or $\bar{B}$)

- The difference between raw asymmetries of two kinematically-similar final states removes the biases due to asymmetric detection and production

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = A(K^+K^-) - A(\pi^+\pi^-)$$

Why do we measure ΔA_{CP}?

- In the standard model, *CP* violation in $D^0 \rightarrow h^+h^-$ is generated by the interference between the tree and the penguin diagrams



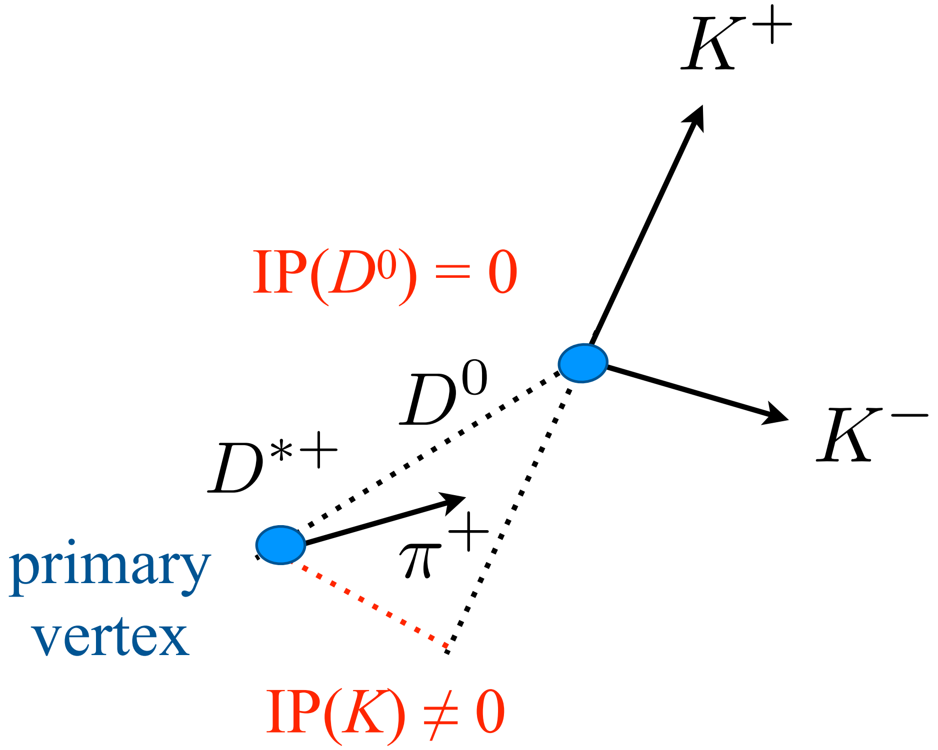
$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0$$

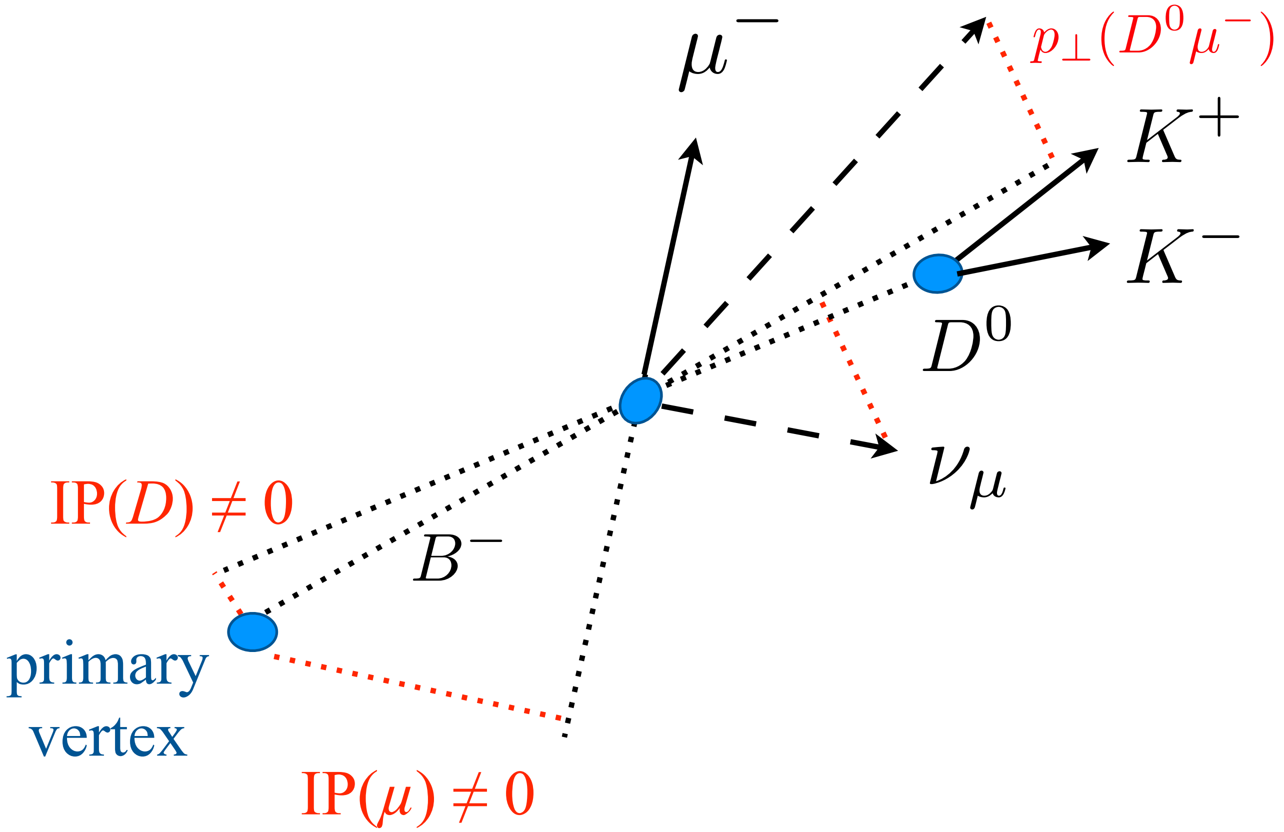
- In the limit of SU(3) symmetry (*i.e.*, ignoring QCD effects), $A_{CP}(K^+K^-)$ and $A_{CP}(\pi^+\pi^-)$ have same magnitude and opposite signs

- In addition to be robust against experimental biases, ΔA_{CP} provides enhanced sensitivity to *CP* violation

Signal (online) selection/reconstruction

$$m_{\mathrm{corr}} = \sqrt{m^2(D^0\mu^-) + p_\perp(D^0\mu^-)^2} + p_\perp(D^0\mu^-)$$

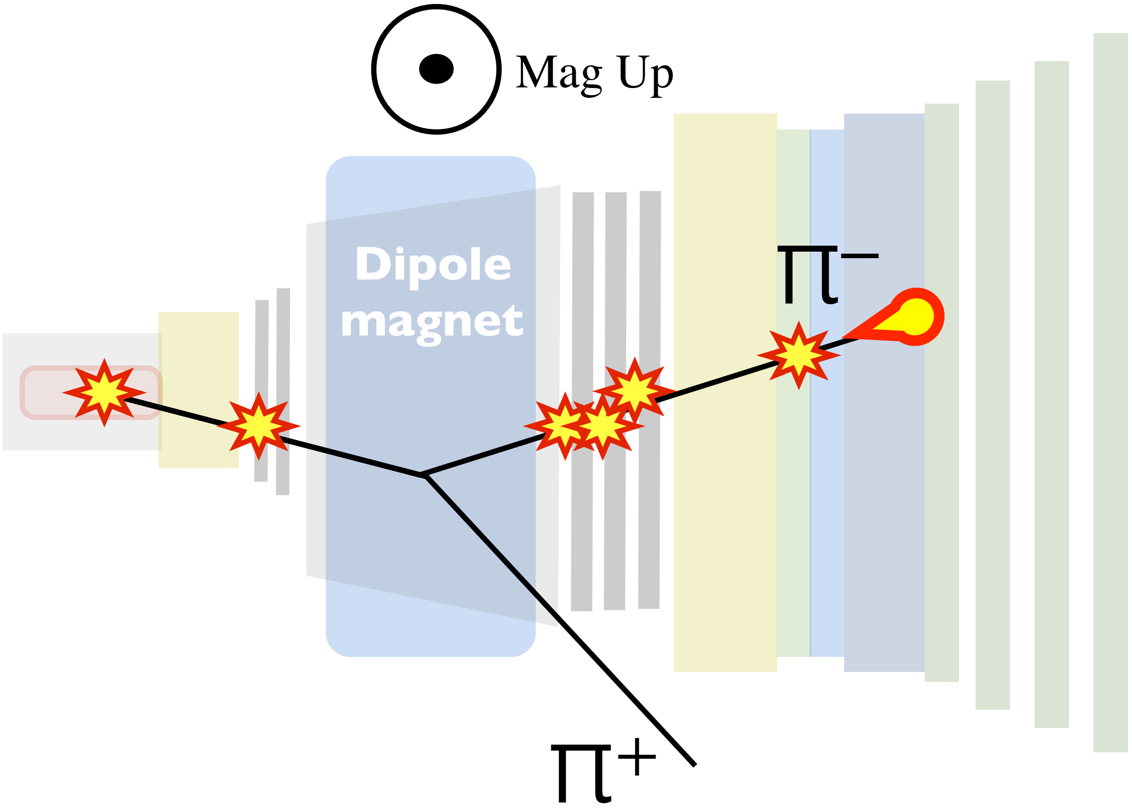




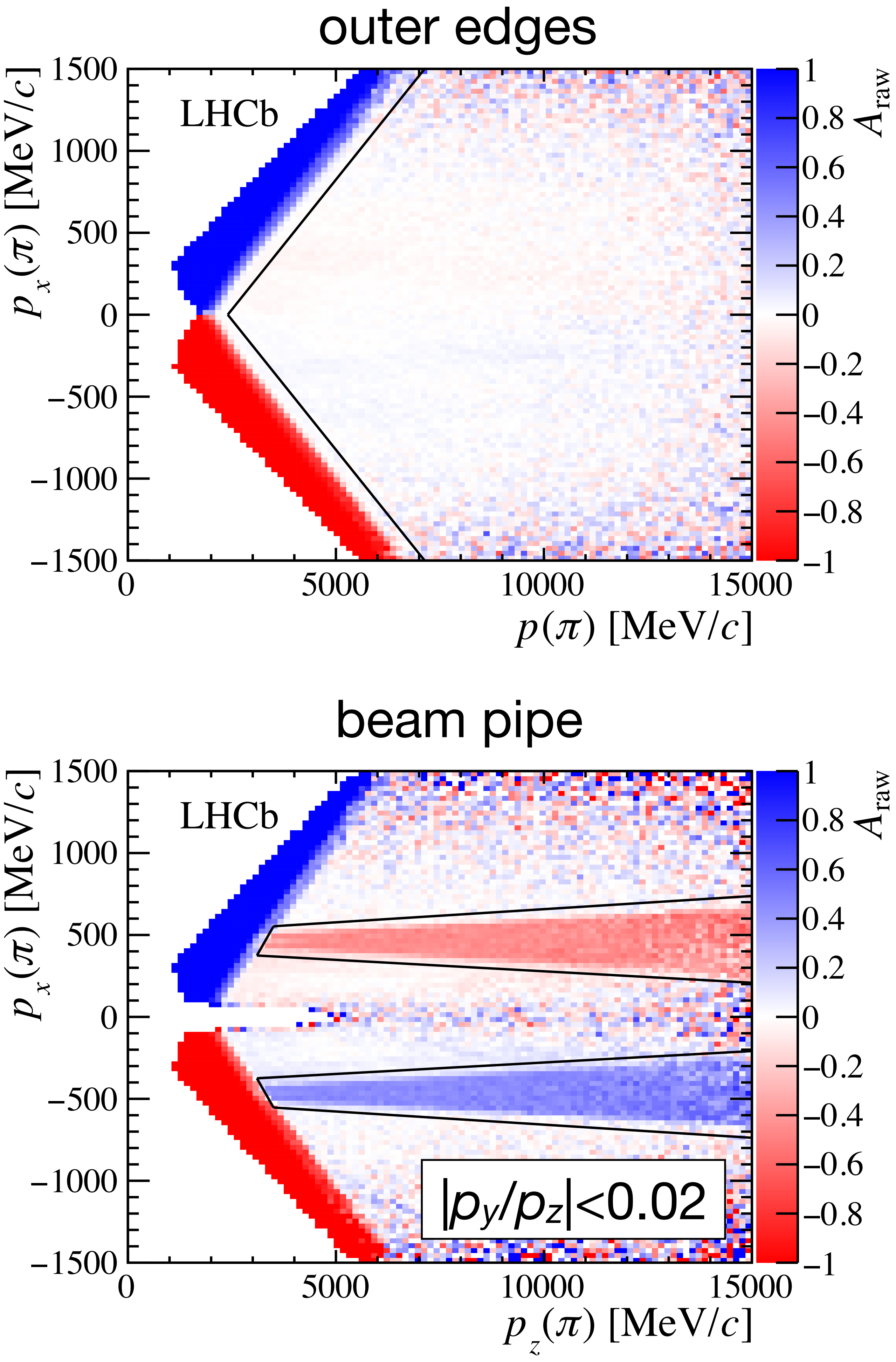
- *π* tagged: well identified kaons/pions forming a displaced secondary vertex, paired with low-momentum pion to form a D^{*+} vertex that coincides with the PV
- *μ* tagged: well identified and displaced muon paired with D^0 candidate, requirement on corrected mass to (partly) compensate for undetected neutrino

Fiducial requirements

- For specific regions of phase space, the soft pion of a given charge is kicked out of the detector acceptance by the magnetic field

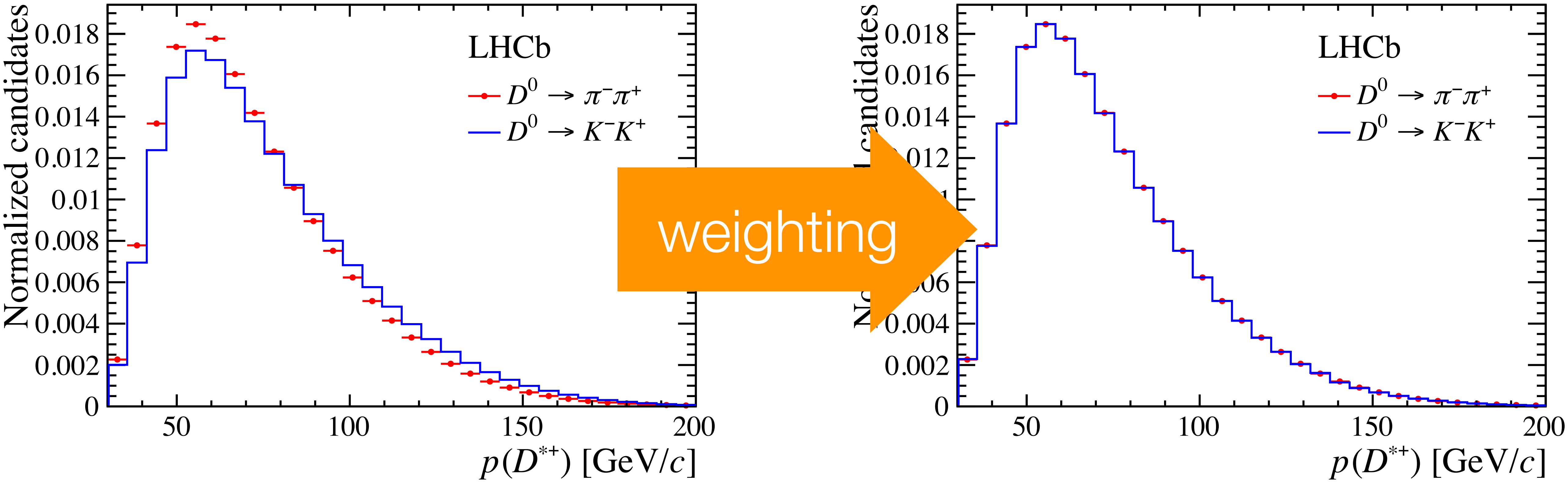


- $O(1)$ detection asymmetries break the linear decomposition of the raw asymmetry



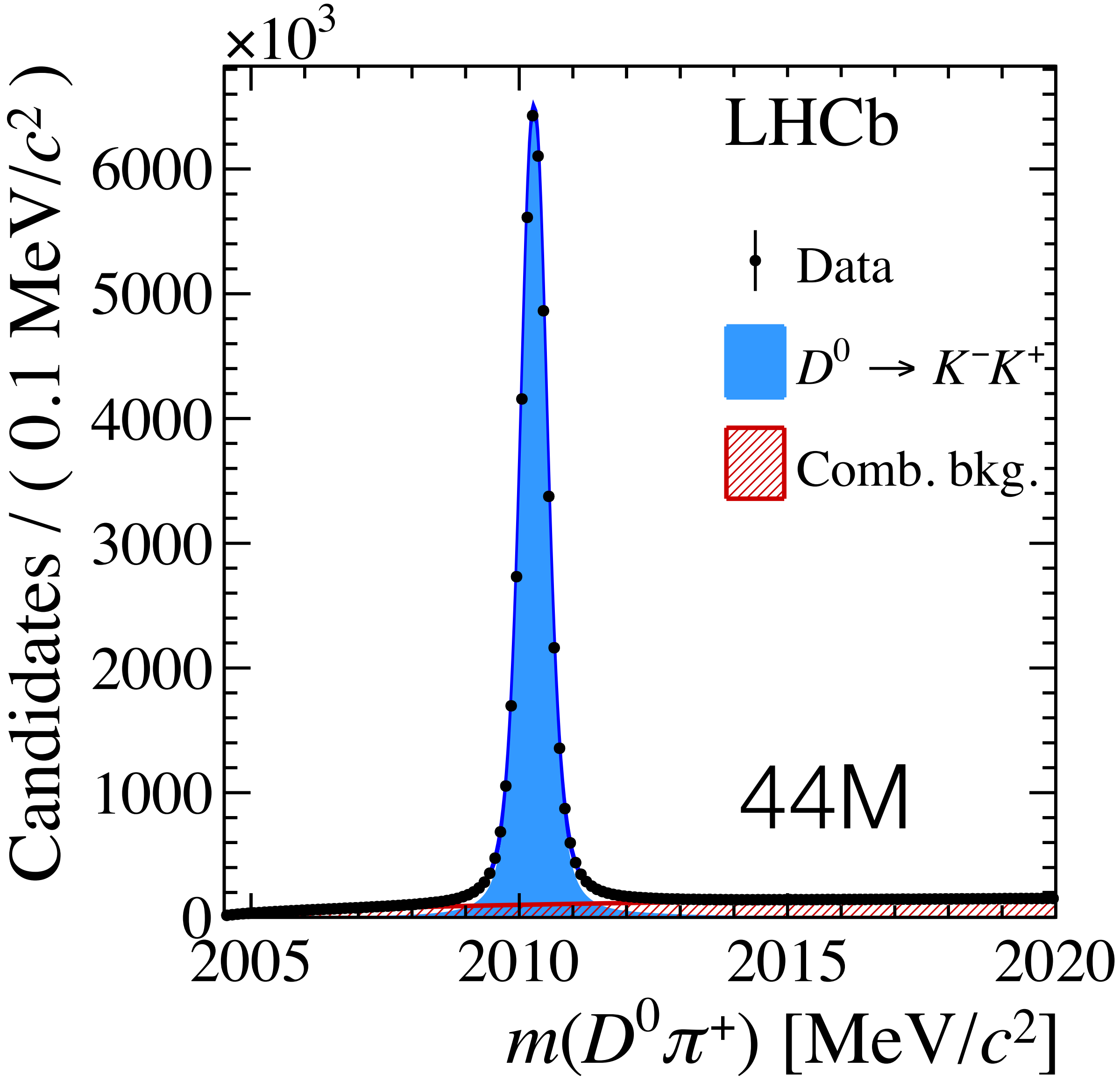
Kinematic weighting

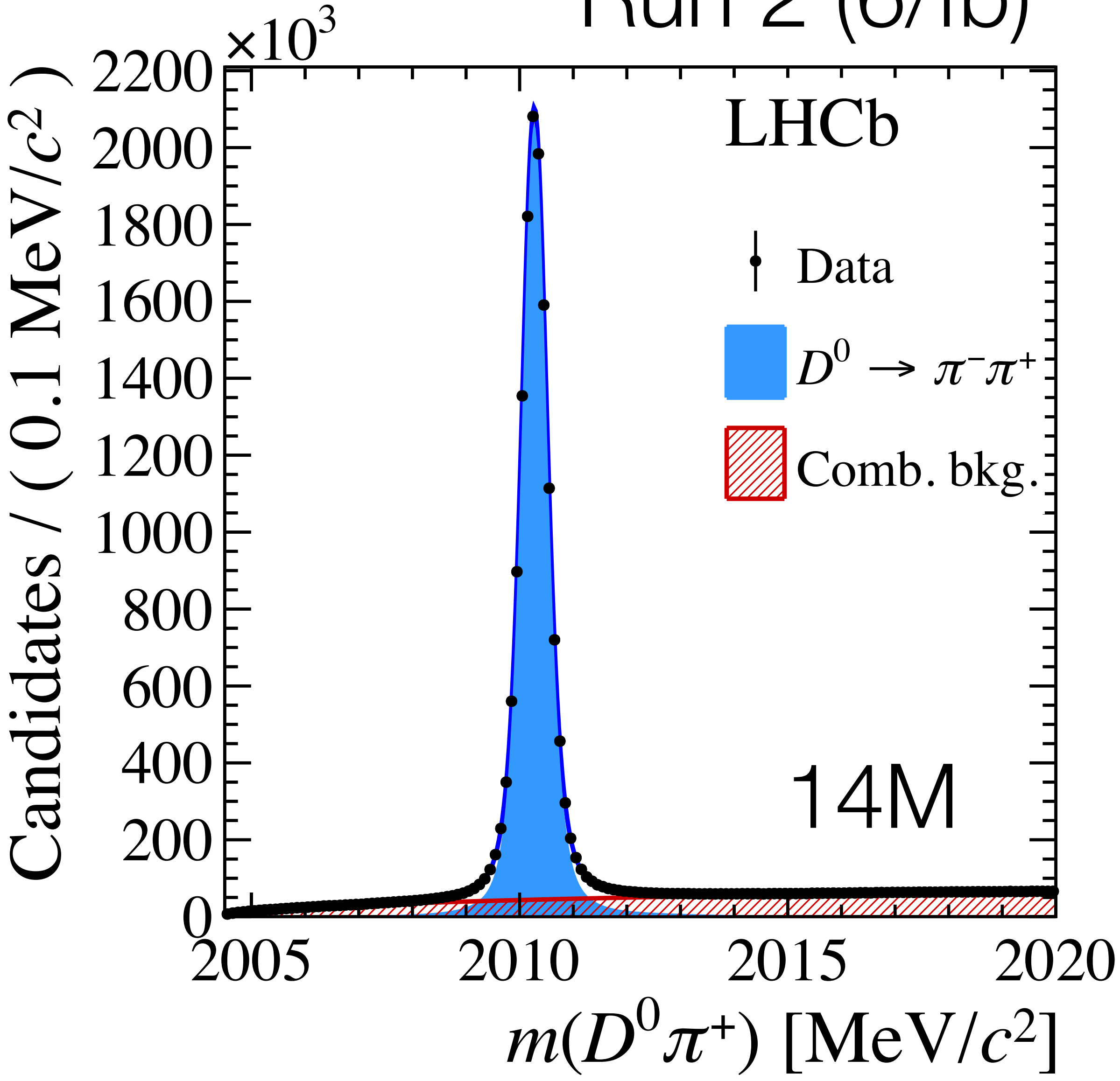
- Detection and production asymmetries are expected to depend on kinematics
- Cancellation of nuisance asymmetries may not be accurate if the kinematic distributions of the reconstructed $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ candidates differ
- The observed differences are removed through a weighting procedure — the resulting net effect on ΔA_{CP} is below 10^{-4}



π tagged samples

Run 2 (6/fb)

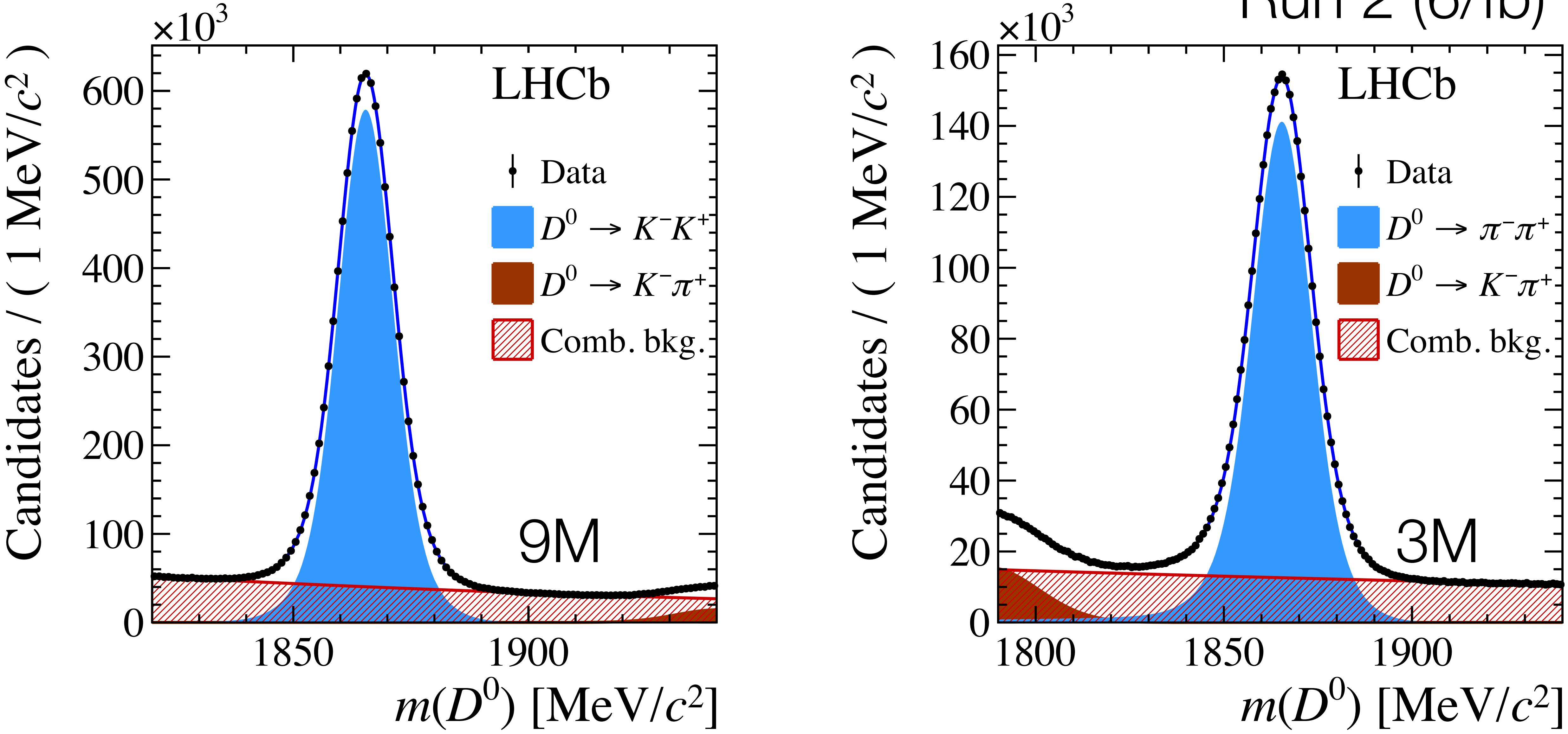




Raw asymmetries measured with sub-0.1% statistical precision from simultaneous fit to D^0 and $\bar{D}^0$ samples

μ tagged samples

Run 2 (6/fb)



Raw asymmetries measured with sub-0.1% statistical precision from simultaneous fit to D^0 and $\bar{D}^0$ samples

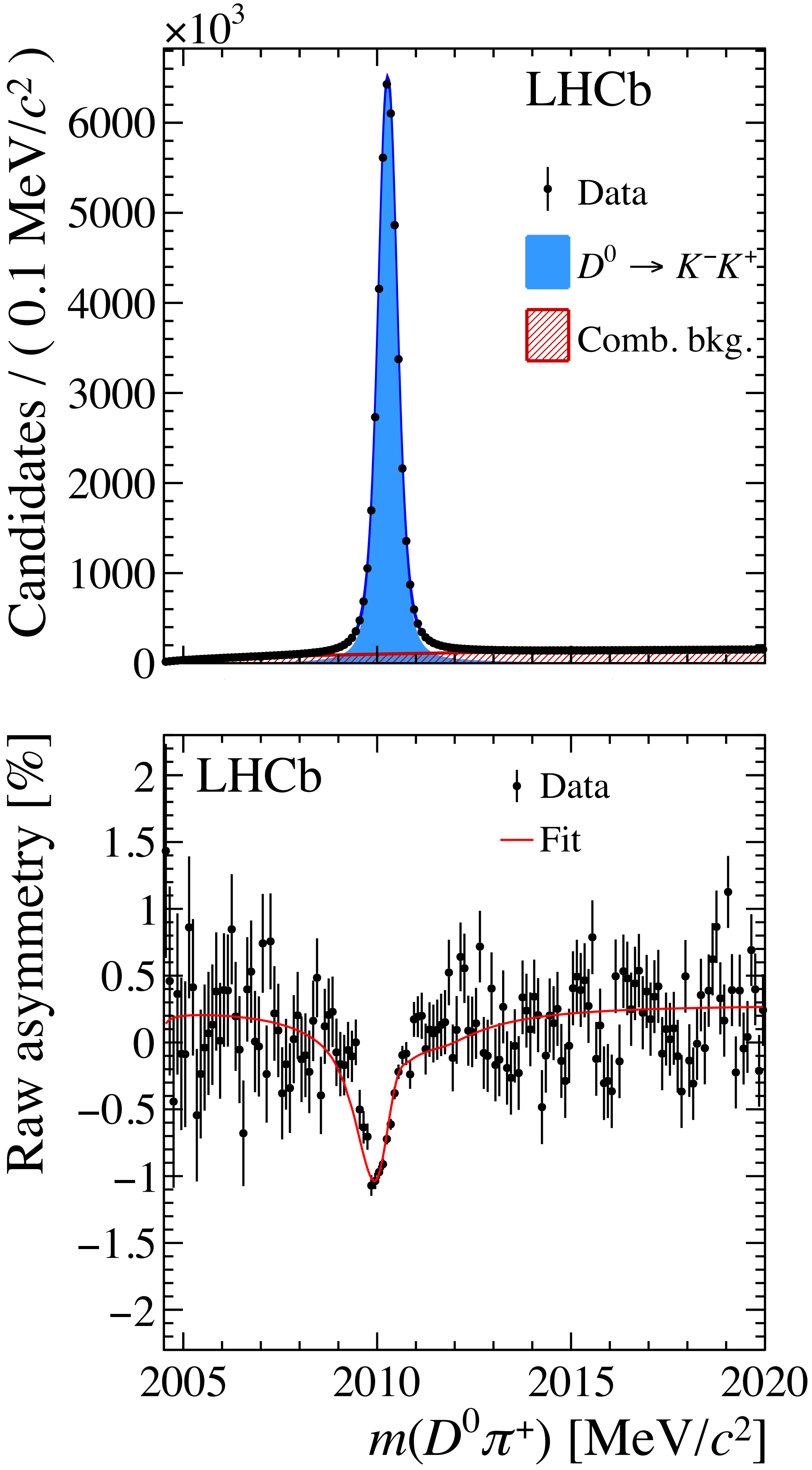
Systematic uncertainties

[10^{-4}]

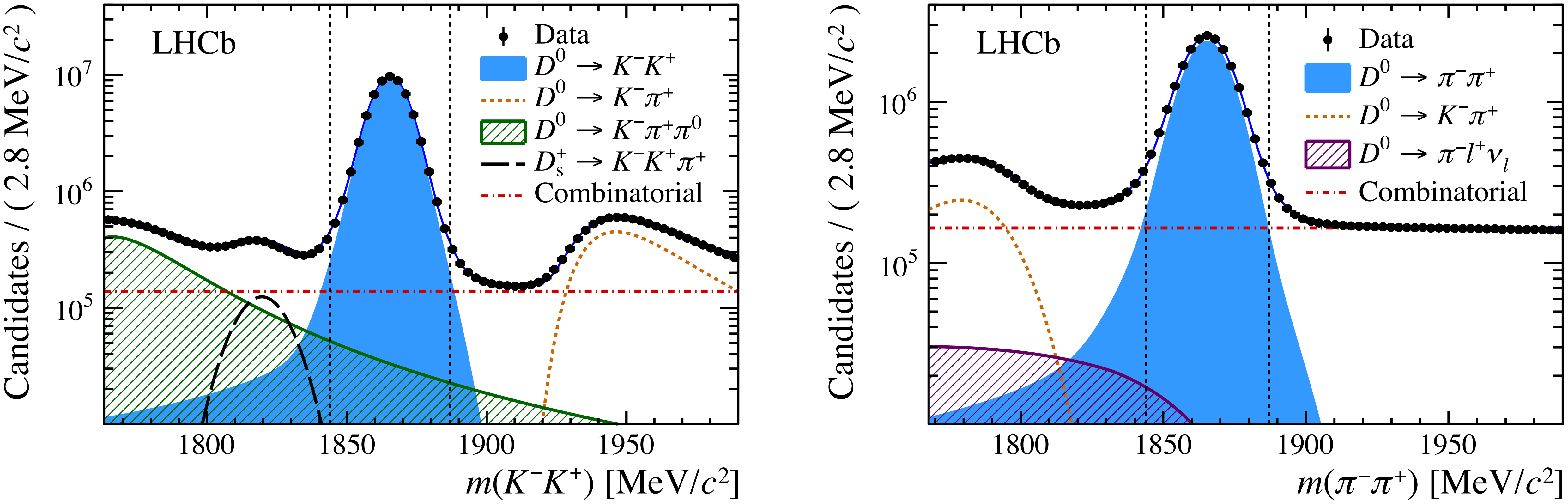
Source	π-tagged	μ-tagged
Fit model	0.6	2
Mistag	–	4
Weighting	0.2	1
Secondary decays	0.3	–
B fractions	–	1
B reco. efficiency	–	2
Peaking background	0.5	–
Total	0.9	5

Fit model

- Mass model with *O*(10M) candidates is never perfect
- Impact on asymmetries is generally marginal
- However, mass shapes may also be charge asymmetric (momentum scale/resolution is slightly asymmetric)
- Tested a variety of alternative models, bias on signal asymmetry estimated using pseudoexperments



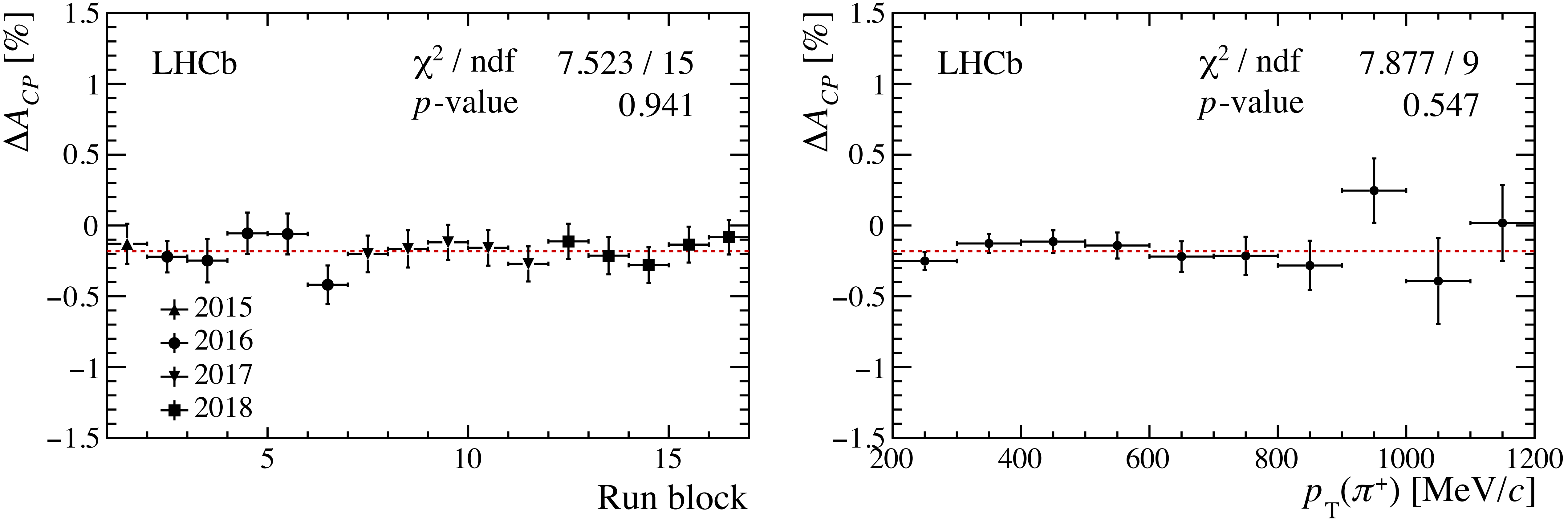
Peaking background



- Backgrounds due to $D^{*+} \to D^0\pi^+$ decays, where the D^0 is mis- or partially reconstructed would peak in $m(D^0\pi^+)$
- Bias on signal asymmetry estimated by measuring backgrounds asymmetry and contamination in the D^0-mass signal region

Consistency checks

- Measured value of ΔA_{CP} studied as a function of several variables (*e.g.*, magnet polarity, data-taking period, kinematics)



- No evidence found for unexpected dependences

Results

ΔA_{CP} [10^{-4}]	
-18.2 ± 3.2 (stat) ± 0.9 (syst)	π tagged (Run 2)
-9 ± 8 (stat) ± 5 (syst)	μ tagged (Run 2)
-10 ± 8 (stat) ± 3 (syst)	π tagged (Run 1) [PRL 116 (2016) 191601]
-14 ± 16 (stat) ± 8 (syst)	μ tagged (Run 1) [JHEP 07 (2014) 041]
-15.4 ± 2.9 (stat+syst)	combined

5.3σ deviation from zero

first observation of *CP* violation in charm

Interpretation

- The time-integrated asymmetry receives contribution from *CP* violation in the decay amplitudes (direct) and in D^0-$\bar{D}^0$ mixing (indirect)

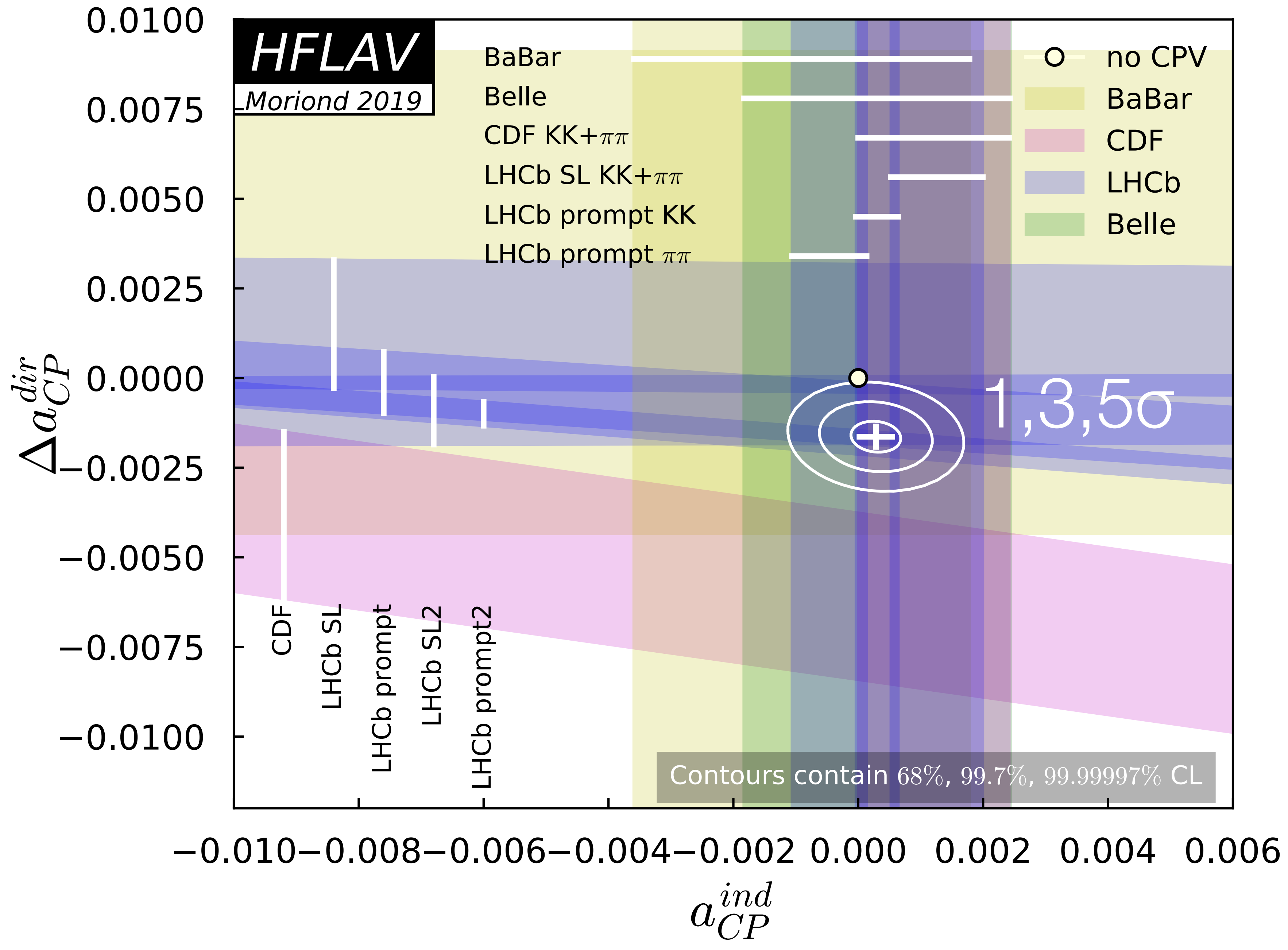
$$A_{CP}(h^+h^-) \approx a_{CP}^{\mathrm{dir}}(h^+h^-) + \frac{\langle t \rangle}{\tau} a_{CP}^{\mathrm{ind}}$$

- Indirect contribution is to a good approximation independent of the decay mode

- Since $\Delta\langle t\rangle \sim 0.1\tau$, ΔA_{CP} is mostly a measurement of direct *CP* violation

$$\Delta A_{CP} \approx \Delta a_{CP}^{\mathrm{dir}} + \frac{\Delta\langle t \rangle}{\tau} a_{CP}^{\mathrm{ind}}$$

Experimental status of *CP* violation in $D^0 \to h^+h^-$



$$\Delta a_{CP}^{\rm dir} = (-16.4 \pm 2.8) \times 10^{-4}$$

$$a_{CP}^{\rm ind} = (\quad 2.8 \pm 2.6) \times 10^{-4}$$

so what? shall I
be excited?

yes! it’s new physics!

(just two examples)

Alexander Lenz

[arXiv:1903.10490]

it’s not, but we can learn a lot about QCD

Yuval Grossman

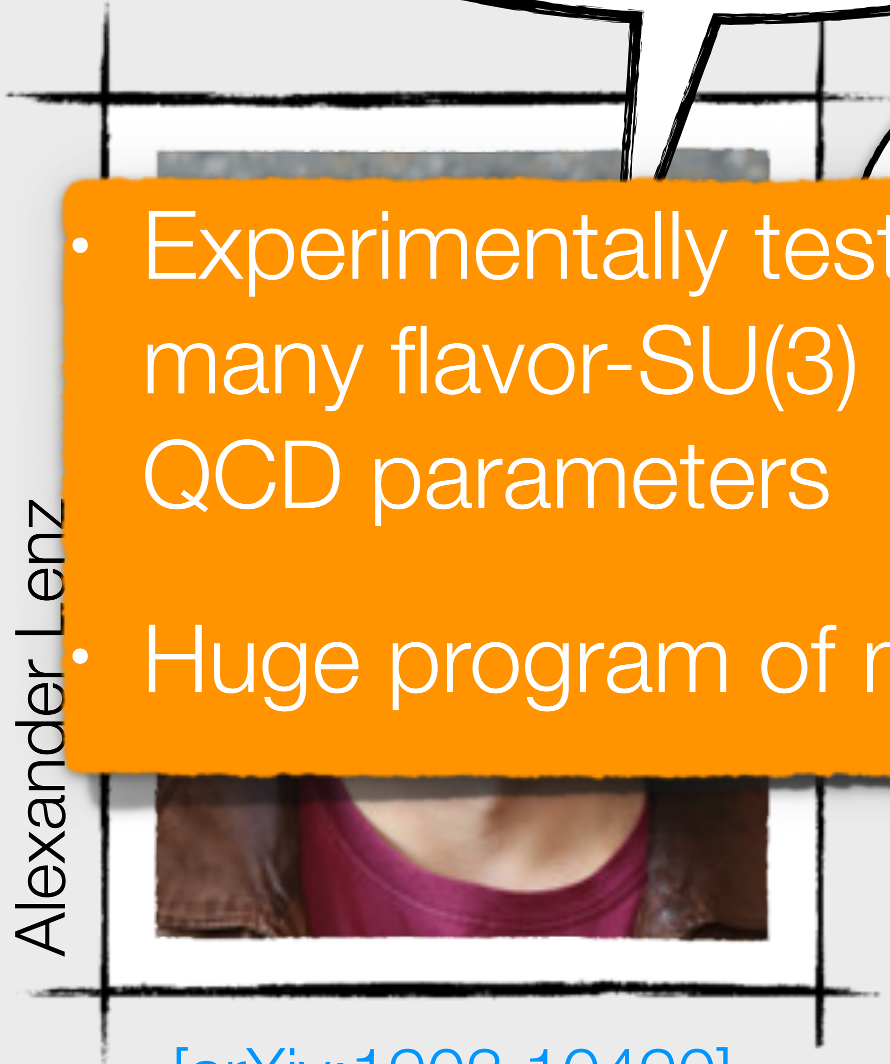
[arXiv:1903.10952]

(just two examples)

yes! it’s new physics!

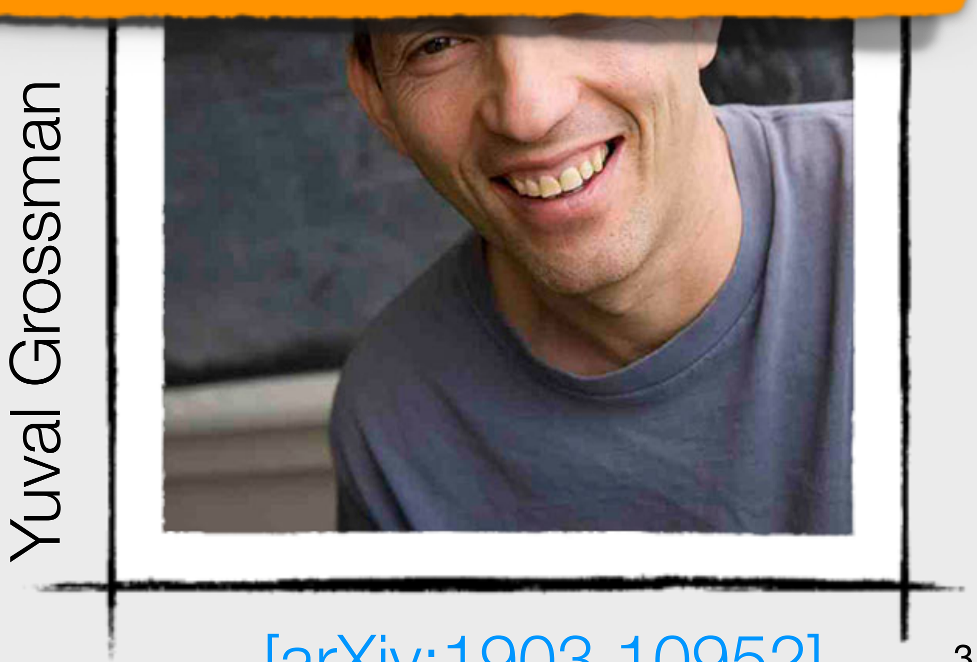
it’s not, but

- Experimentally test relations between *CP* asymmetries of many flavor-SU(3) related decays to help constraining the QCD parameters
- Huge program of measurements. Belle II role will be crucial



Alexander Lenz

[arXiv:1903.10490]



Yuval Grossman

[arXiv:1903.10952]

What about *CP* violation in mixing?

- Time-evolution described by Schrödinger's equation

$$i\frac{\partial}{\partial t}\begin{pmatrix}|P^0(t)\rangle\\|\overline{P}^0(t)\rangle\end{pmatrix}=\left[\begin{pmatrix}M_{11} & M_{12}\\M_{12}^* & M_{22}\end{pmatrix}-\frac{i}{2}\begin{pmatrix}\Gamma_{11} & \Gamma_{12}\\\Gamma_{12}^* & \Gamma_{22}\end{pmatrix}\right]\begin{pmatrix}|P^0(t)\rangle\\|\overline{P}^0(t)\rangle\end{pmatrix}$$

- Eigenstates can have different masses and decay width

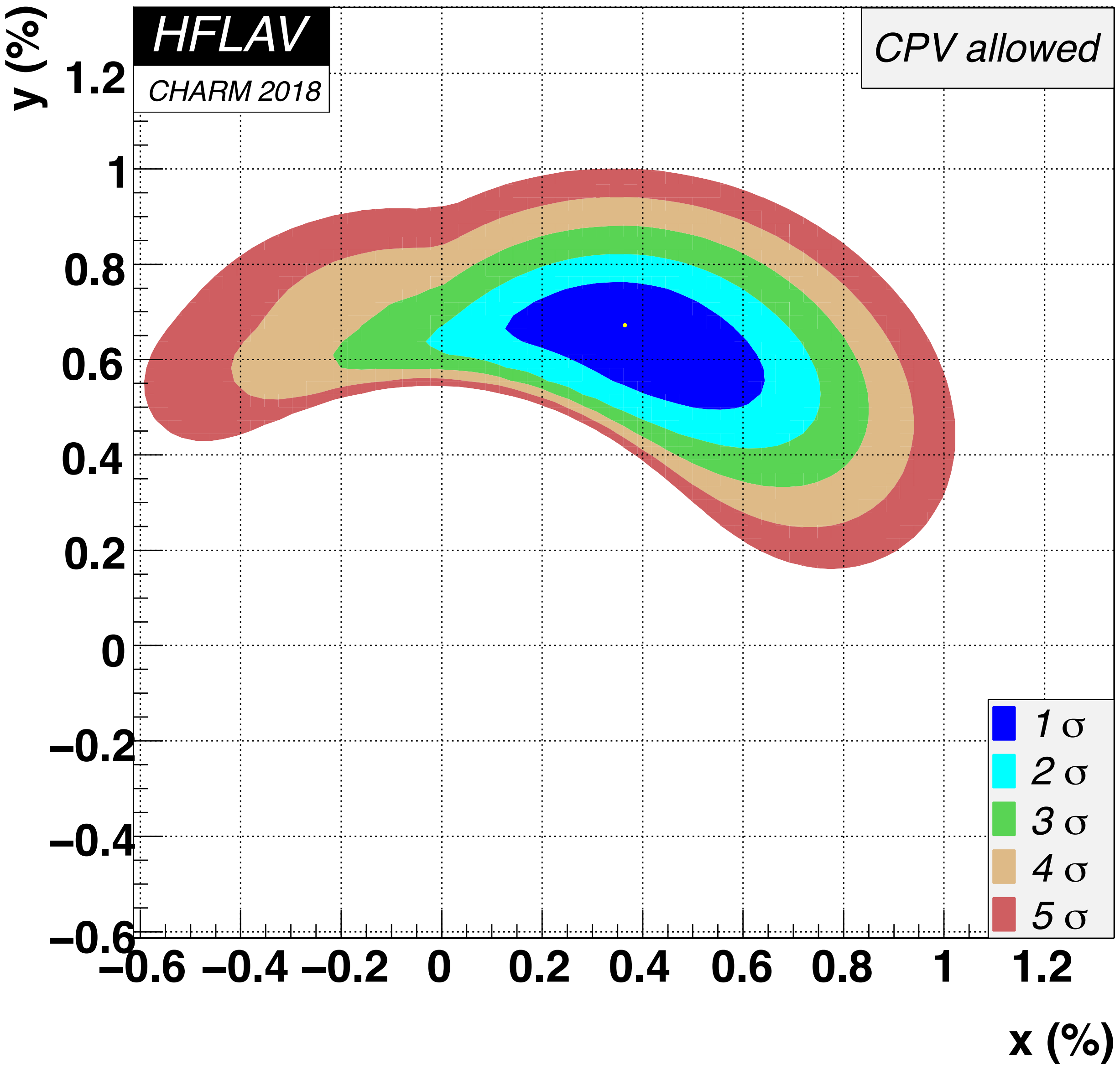
$$|P_{1,2}\rangle = p|P^0\rangle \pm q|\overline{P}^0\rangle \qquad \frac{q}{p}=\sqrt{\frac{M_{12}^*-\frac{i}{2}\Gamma_{12}^*}{M_{12}-\frac{i}{2}\Gamma_{12}}}$$

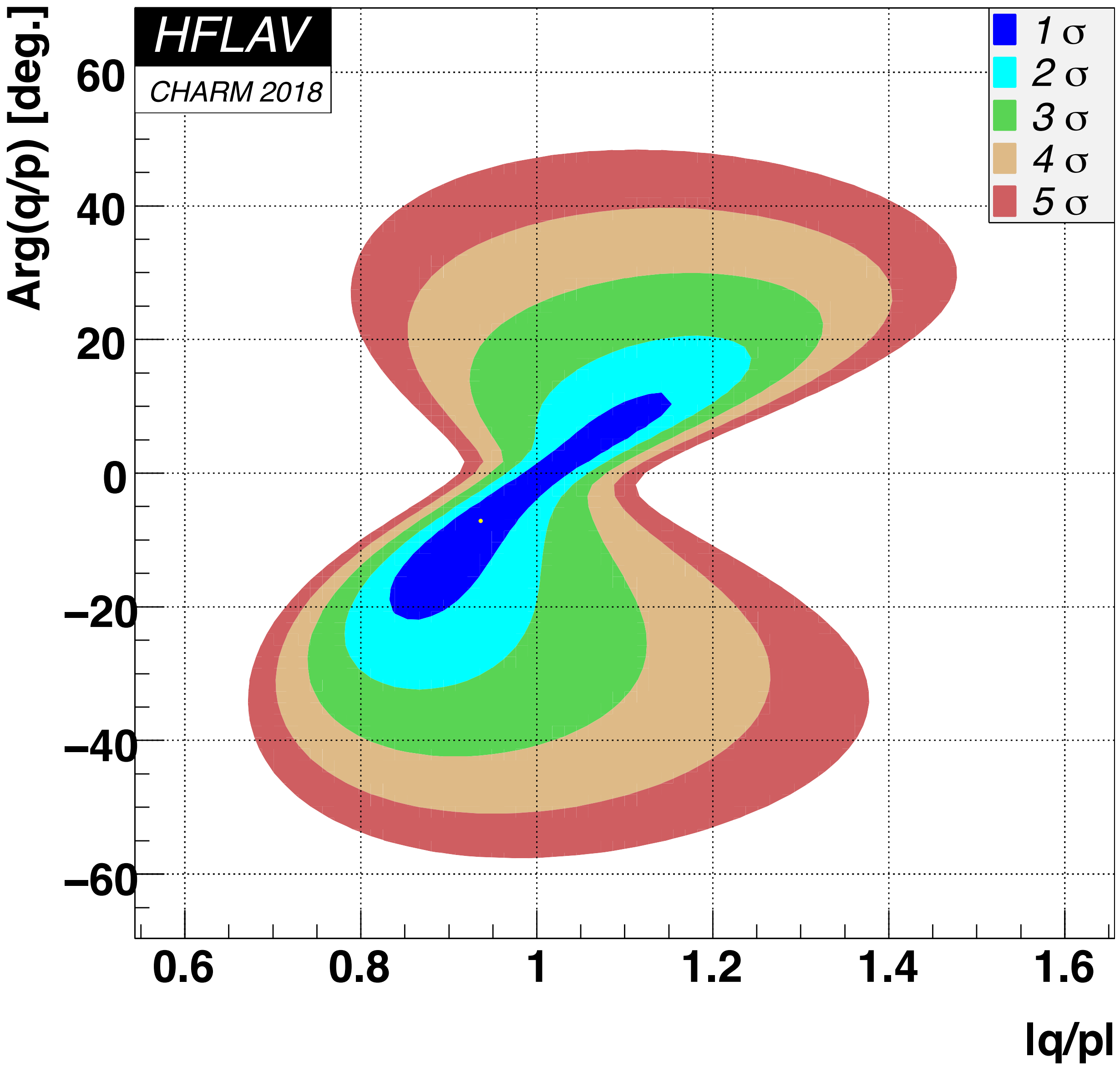
$$x=\frac{m_1-m_2}{\Gamma} \quad y=\frac{\Gamma_1-\Gamma_2}{2\Gamma} \quad \Gamma=\frac{\Gamma_1+\Gamma_2}{2}$$

- *CPT* symmetry implies $|q|^2+|p|^2=1$

- If *CP* is conserved, *q* and *p* are real, and $P_{1,2}$ are *CP* eigenstates

Pre-Moriond status





$$x = (3.6\,^{+\,2.1}_{-\,1.6}) \times 10^{-3}$$

$$y = (6.7\,^{+\,0.6}_{-\,1.3}) \times 10^{-3}$$

$$|q/p| = 0.94\,^{+\,0.17}_{-\,0.07}$$

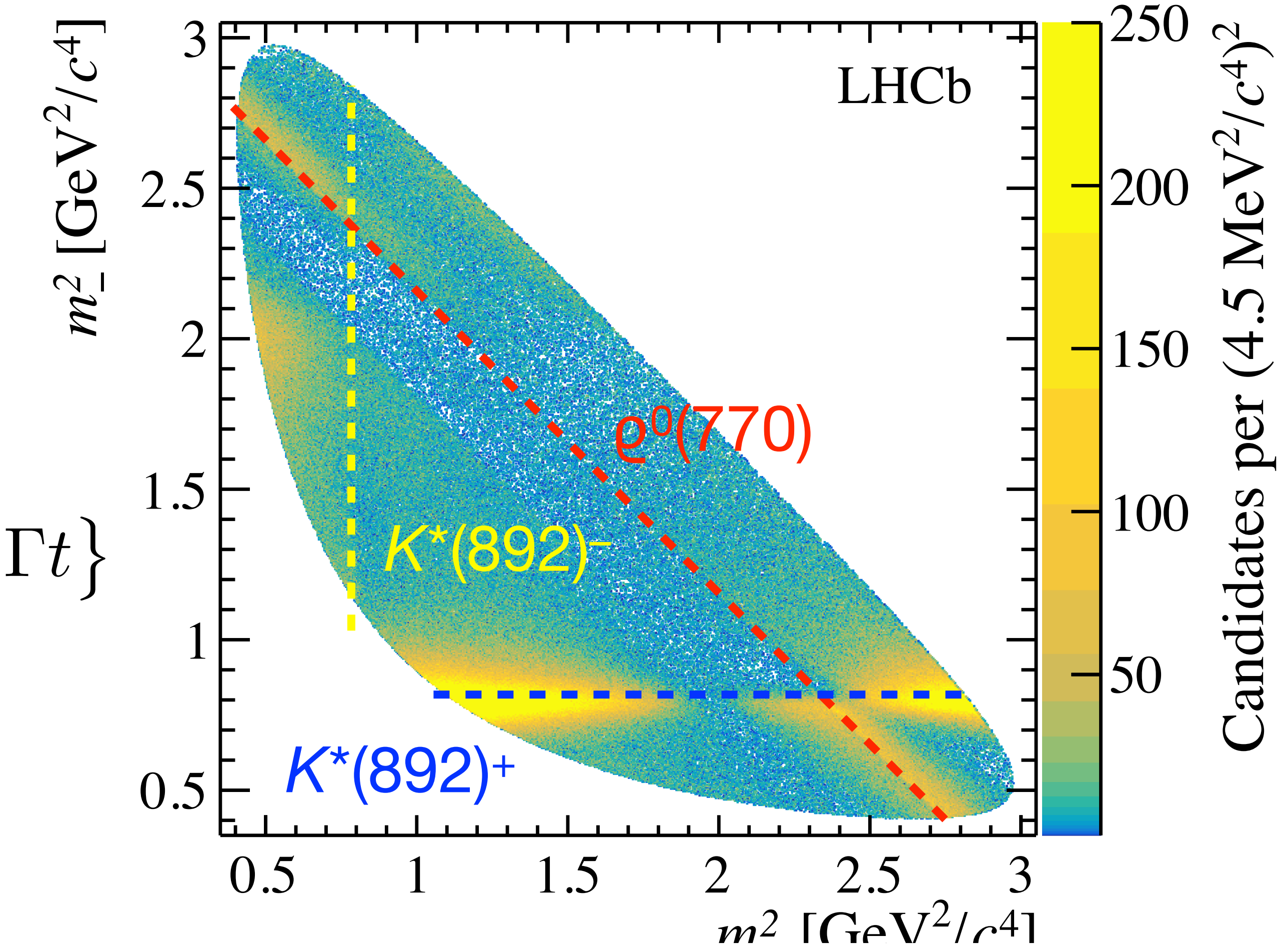
$$\phi = (-7.2\,^{+\,15}_{-\,10})^{\circ}$$

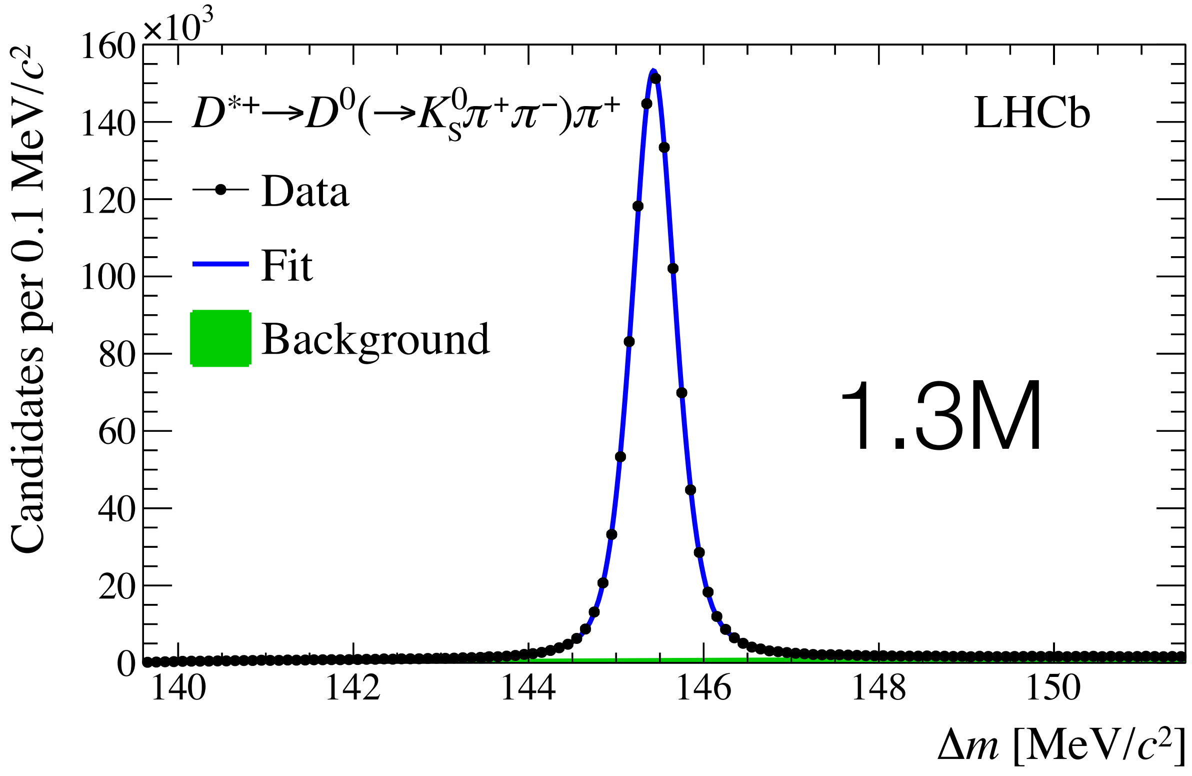
Mixing with $D^0 \to K_S\pi^+\pi^-$

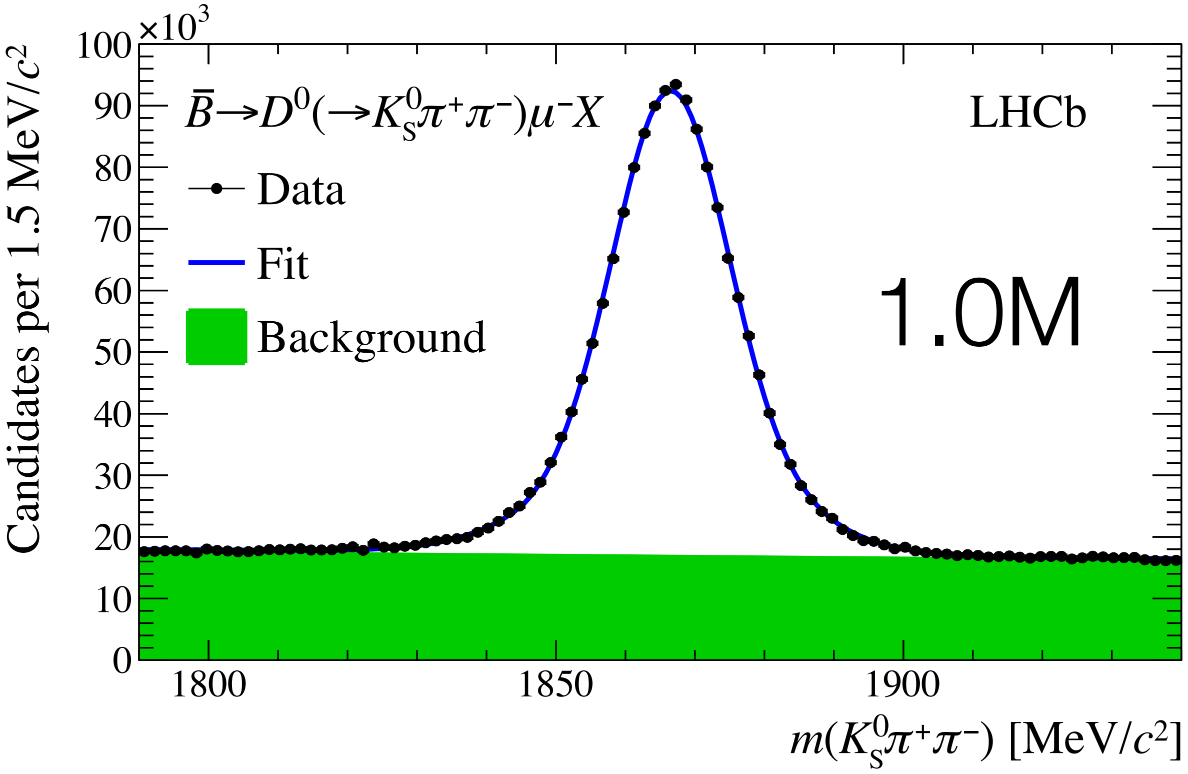
- Multiple interfering amplitudes enhance the sensitivity to mixing

$$\mathcal{P}_{D^0} \propto e^{-\Gamma t}\{|\mathcal{A}_{D^0}|^2 - \mathrm{Re}[\mathcal{A}^*_{D^0}\mathcal{A}_{\overline{D}^0}(y+ix)]\Gamma t\}$$

- New LHCb analysis with Run 1 data [arXiv:1903.03074]







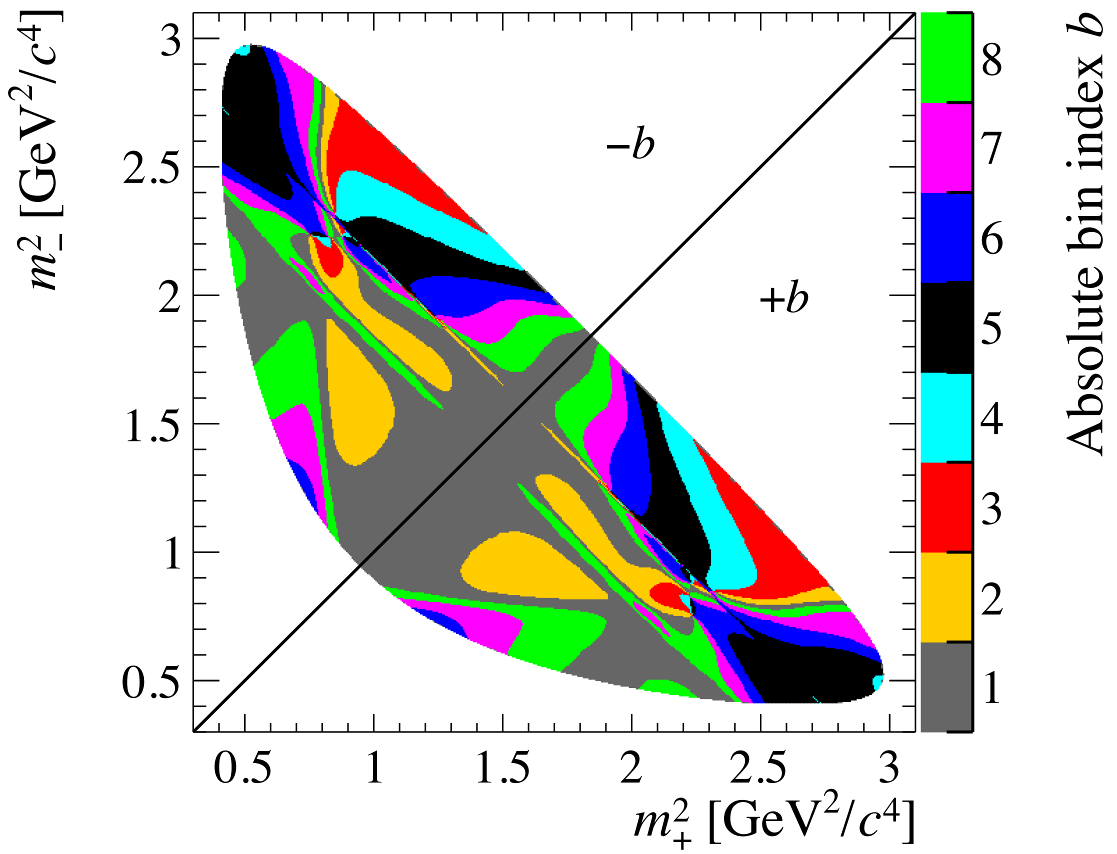
Bin-flip method

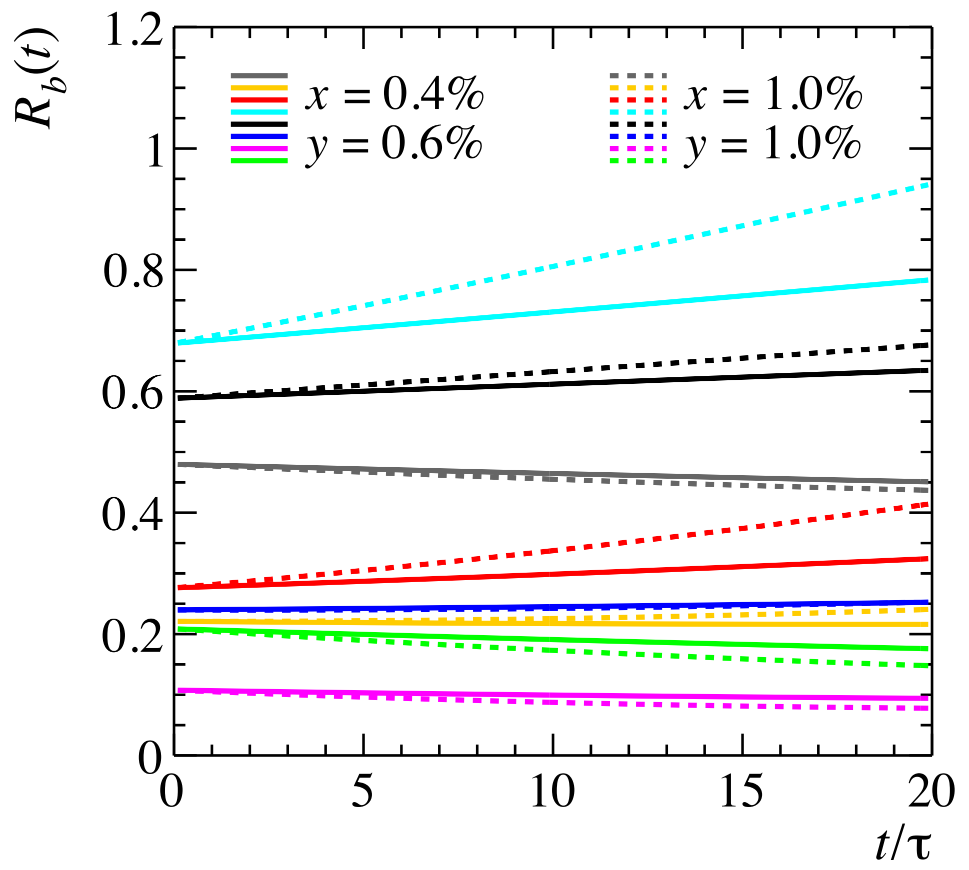
- Bin the Dalitz-plot to avoid amplitude model
- Ratio of events in bin –*b* to events in bin *b* to suppress effects due to non-uniform efficiency variations

$$R_b \approx r_b - \sqrt{r_b}\big[(1-r_b)c_b\, y - (1+r_b)s_b\, x\big]\Gamma t$$

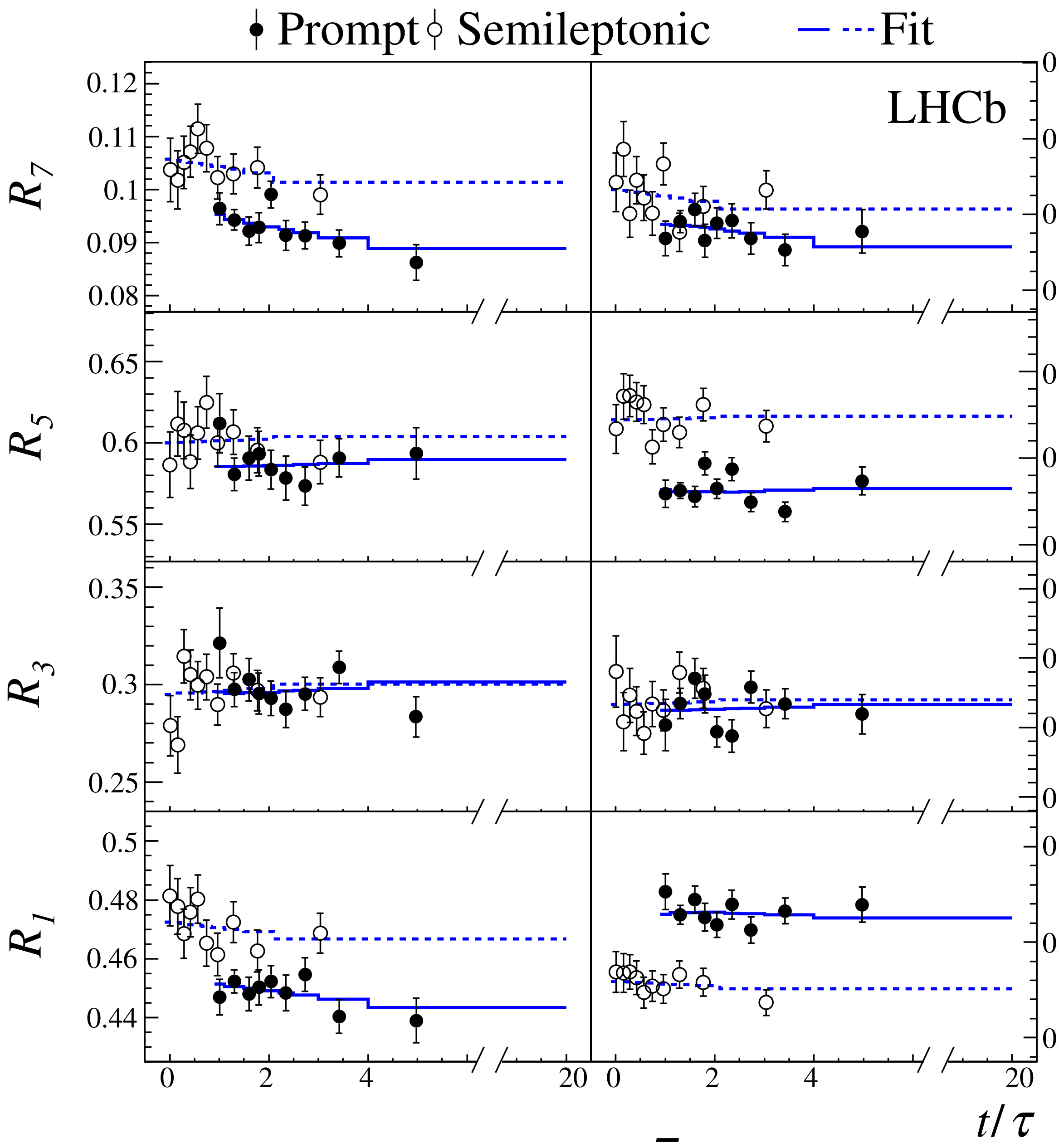
- Constrain hadronic parameters (c_b, s_b) using measurements with quantum-correlated $D^0\bar{D}^0$ pairs, *i.e.* at CLEO
- Model-independent and completely data driven
- Comes with the price of degraded sensitivity to mixing effects from *CP*-even/odd amplitudes (*i.e.*, to *y*)

[PRD 99 (2019) 012007]



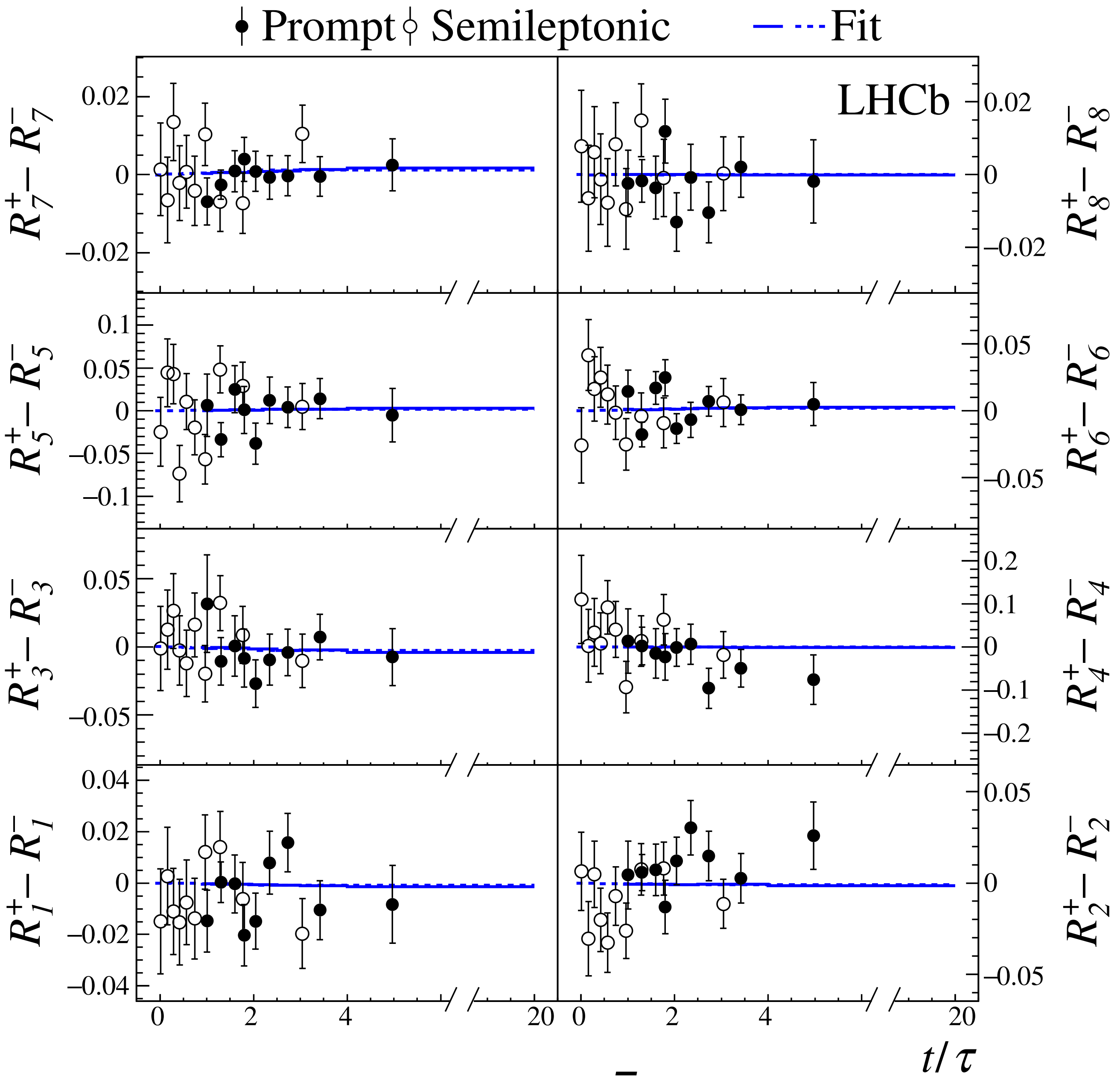


Results



$D^0 + \bar{D}^0$

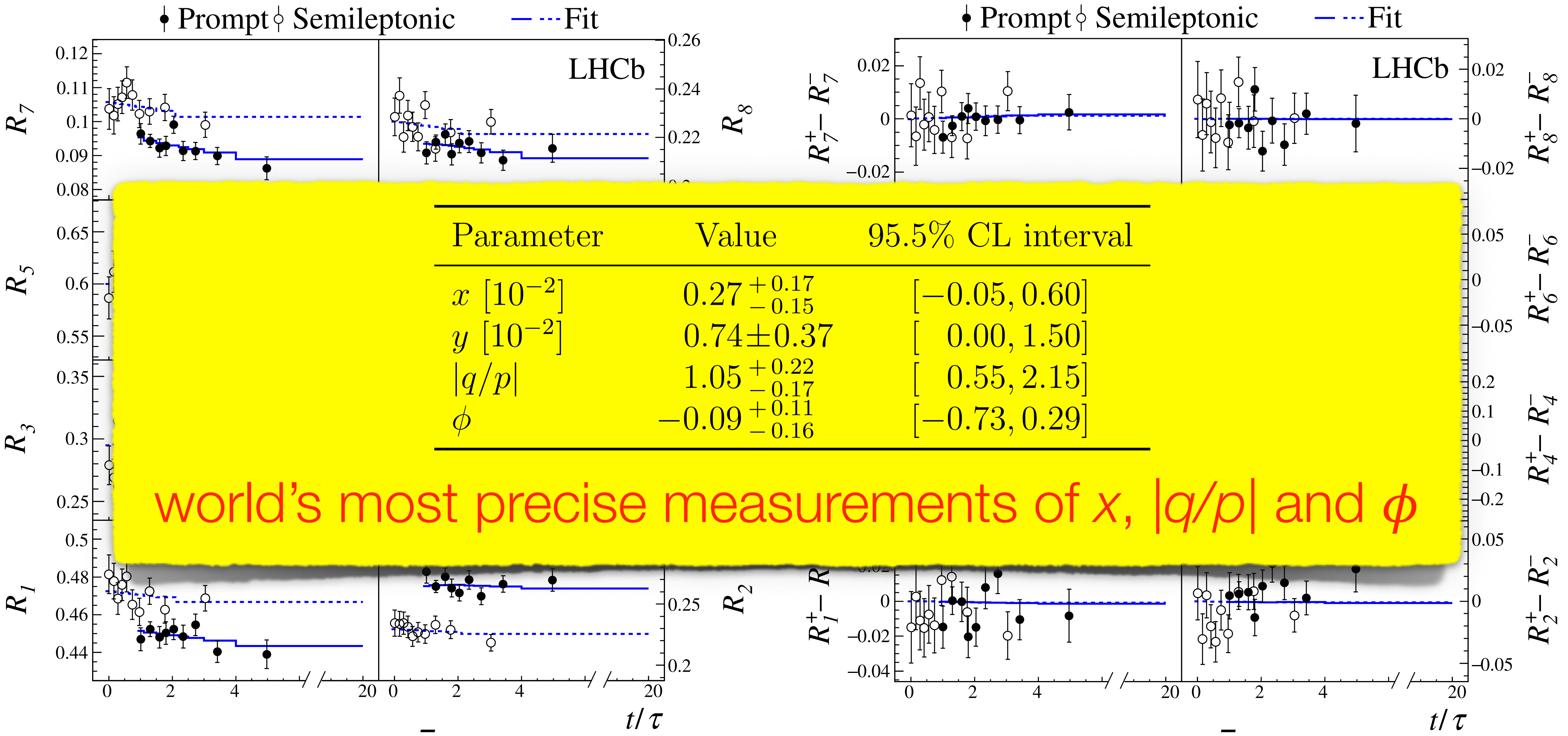
to measure mixing



$D^0 - \bar{D}^0$

to search for *CP* violation

Results



Parameter	Value	95.5% CL interval
$x\ [10^{-2}]$	$0.27\,^{+0.17}_{-0.15}$	$[-0.05, 0.60]$
$y\ [10^{-2}]$	0.74 ± 0.37	$[\ \ 0.00, 1.50]$
$\lvert q/p\rvert$	$1.05\,^{+0.22}_{-0.17}$	$[\ \ 0.55, 2.15]$
ϕ	$-0.09\,^{+0.11}_{-0.16}$	$[-0.73, 0.29]$

world’s most precise measurements of x, $|q/p|$ and ϕ

$D^0 + \bar{D}^0$

to measure mixing

$D^0 - \bar{D}^0$

to search for *CP* violation

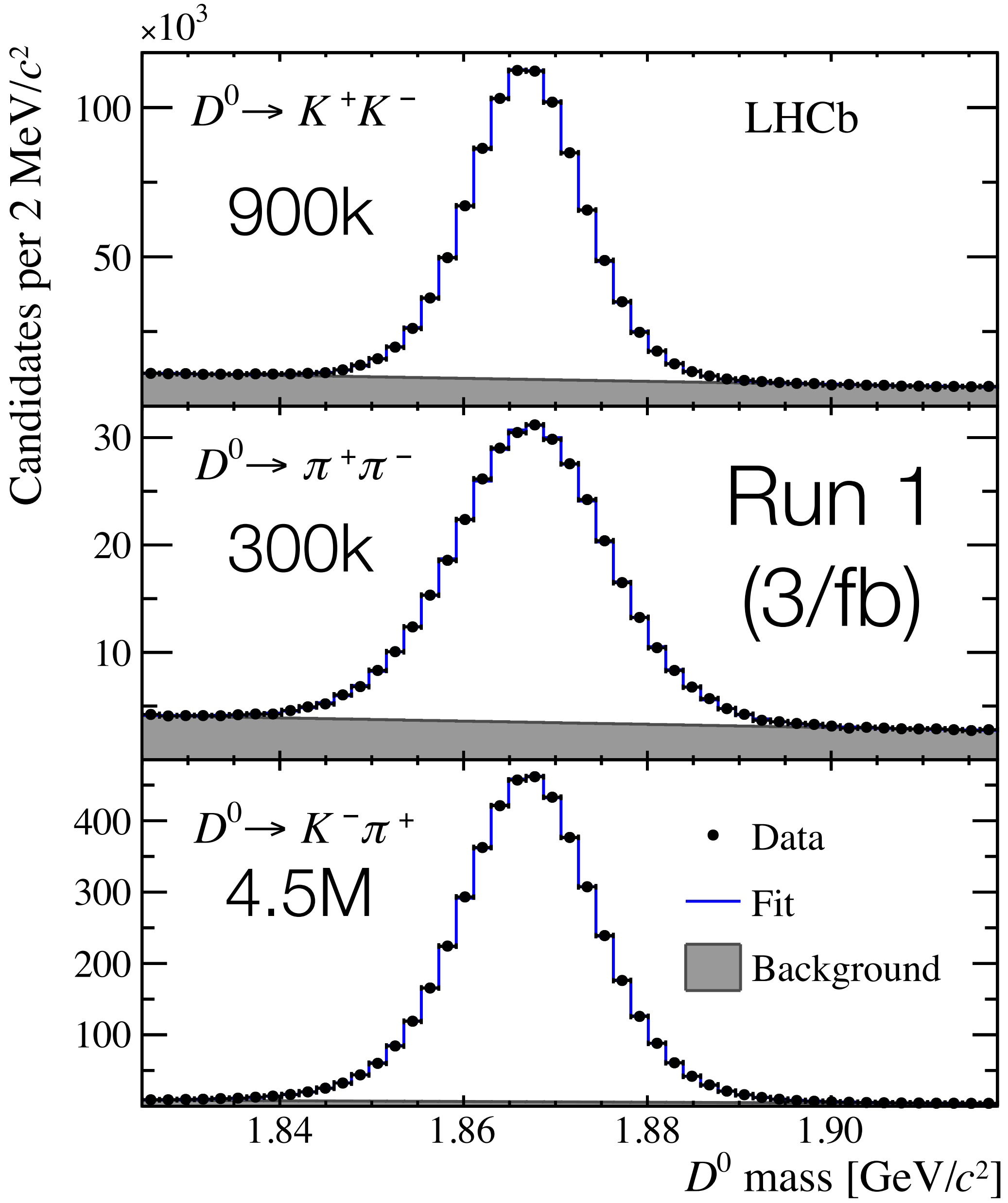
Measurement of y_{CP}

- Effective lifetime of decays to *CP*-even final state (relative to *CP*-mixed)

$$y_{CP} \equiv \frac{\tau(K^-\pi^+)}{\tau(h^+h^-)} - 1$$

- Equal to *y* in case of *CP* symmetry
- Use *μ*-tagged decays to reduce biases on D^0 decay time
- Result with Run 1 data is as precise as the world average

$$y_{CP} = (5.7 \pm 1.3 \pm 0.9) \times 10^{-3}$$



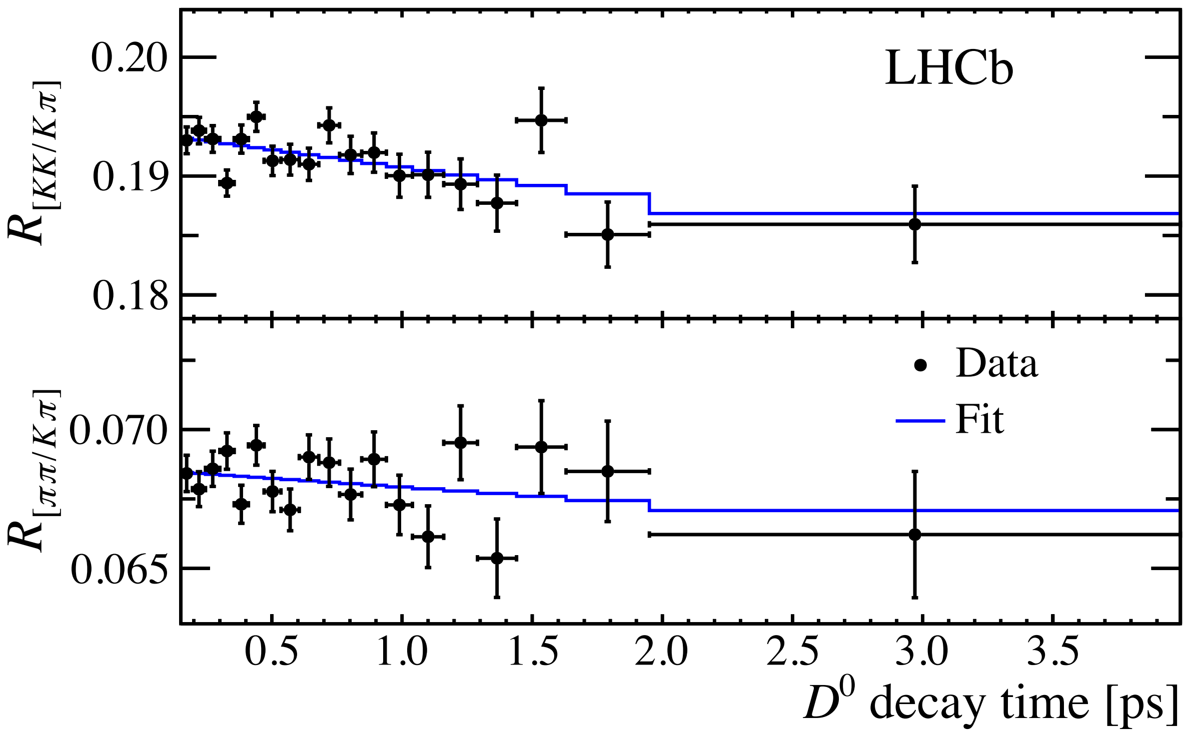
900k

300k

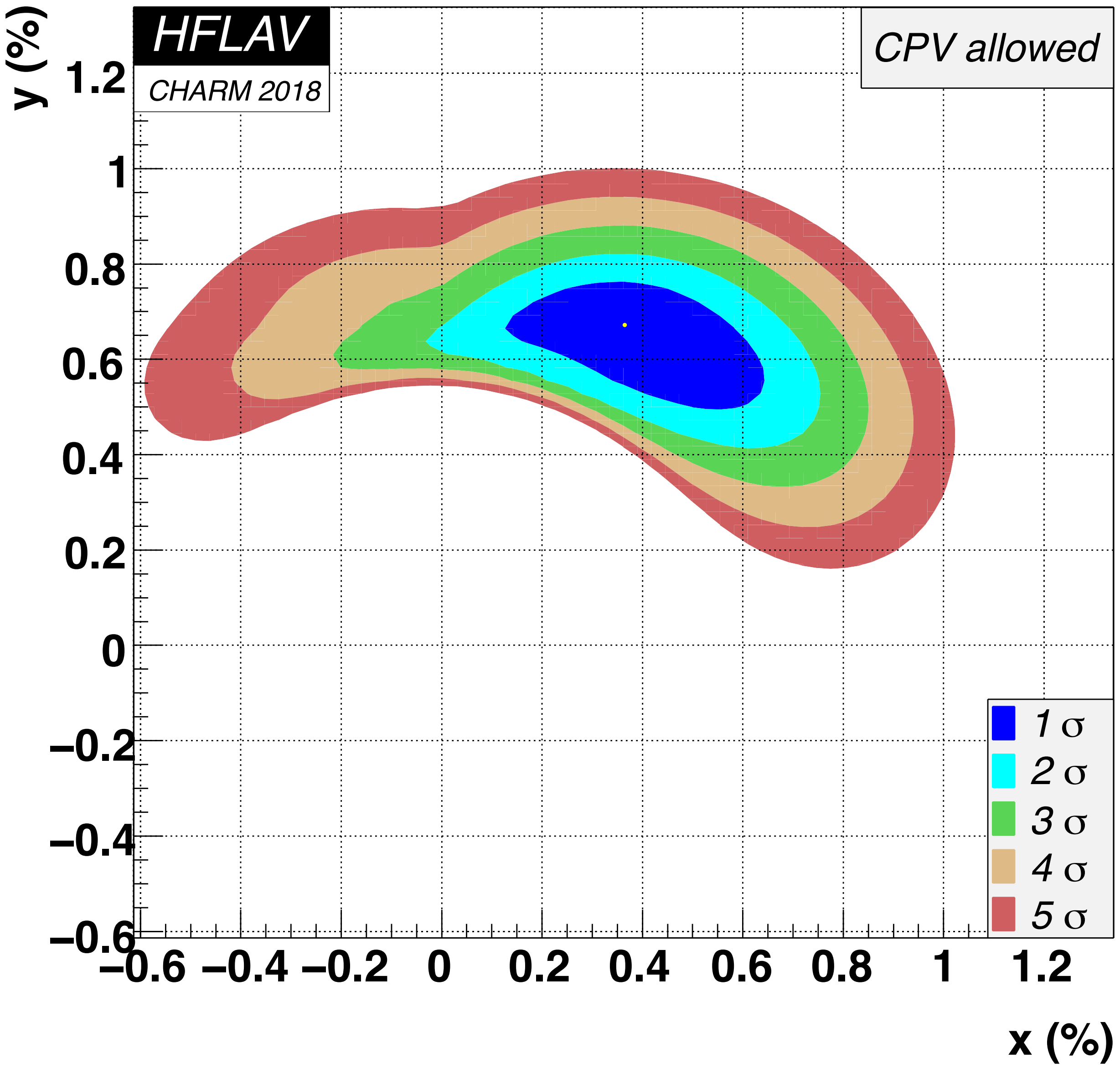
4.5M

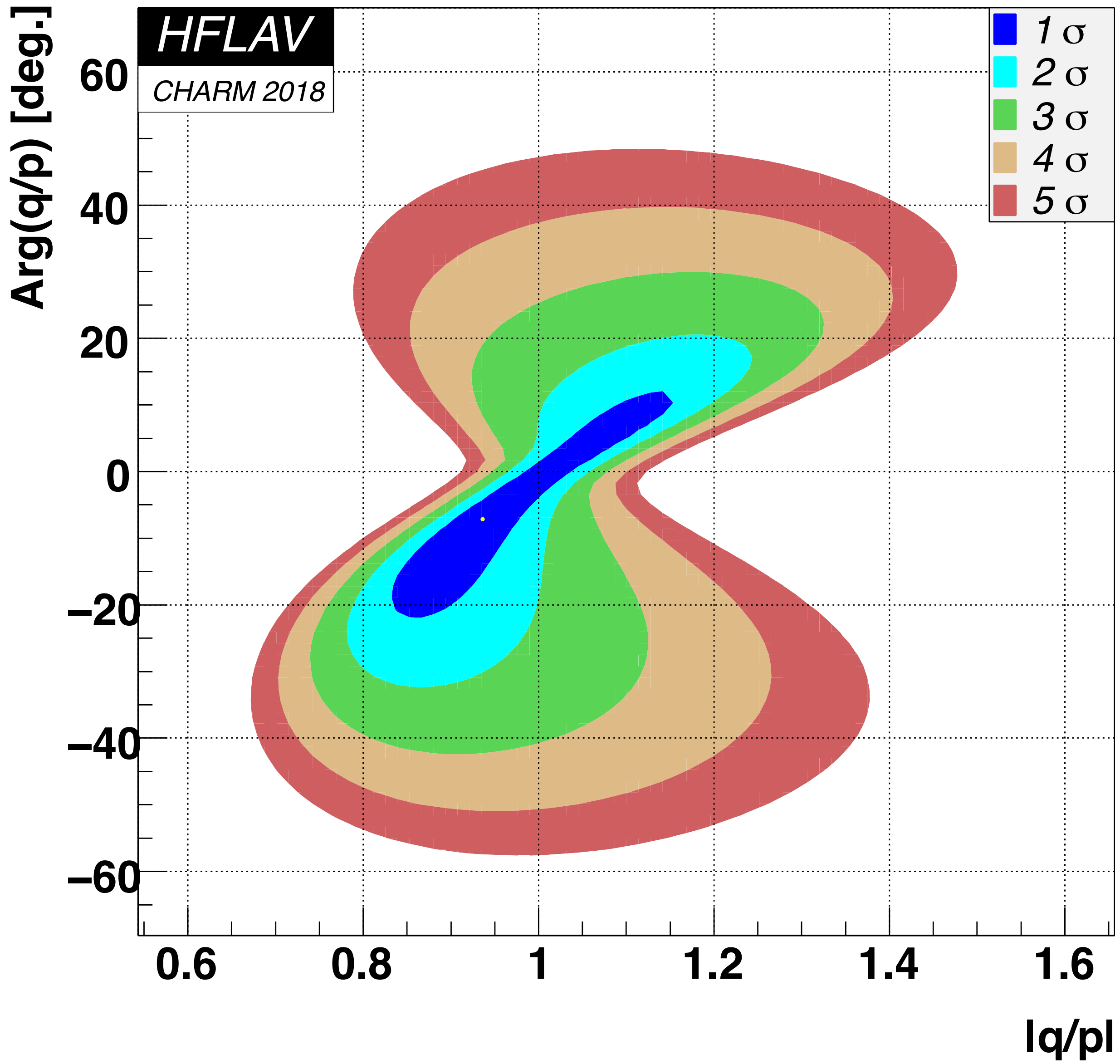
Run 1 (3/fb)

[PRL 122 (2019) 011802]

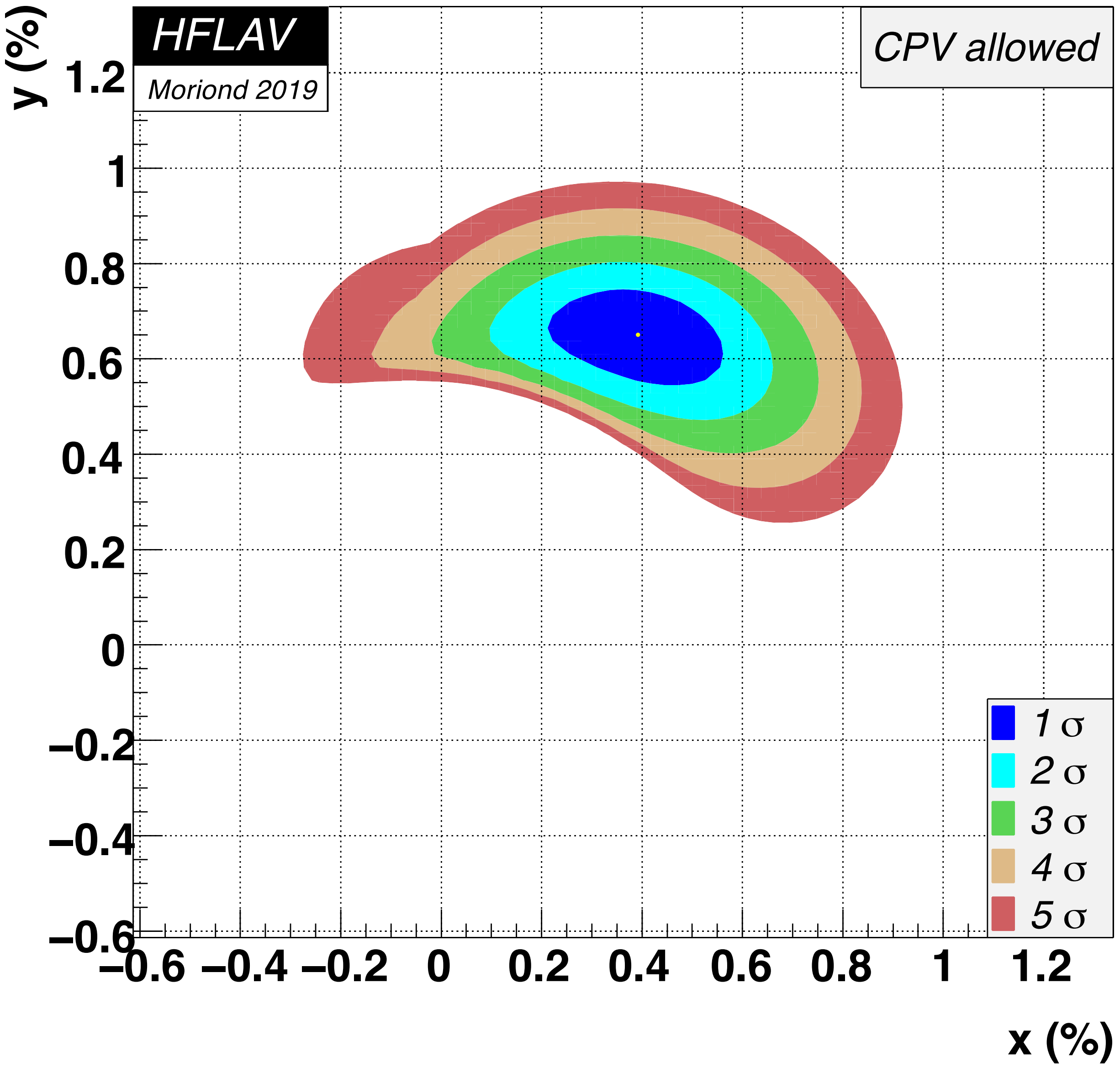


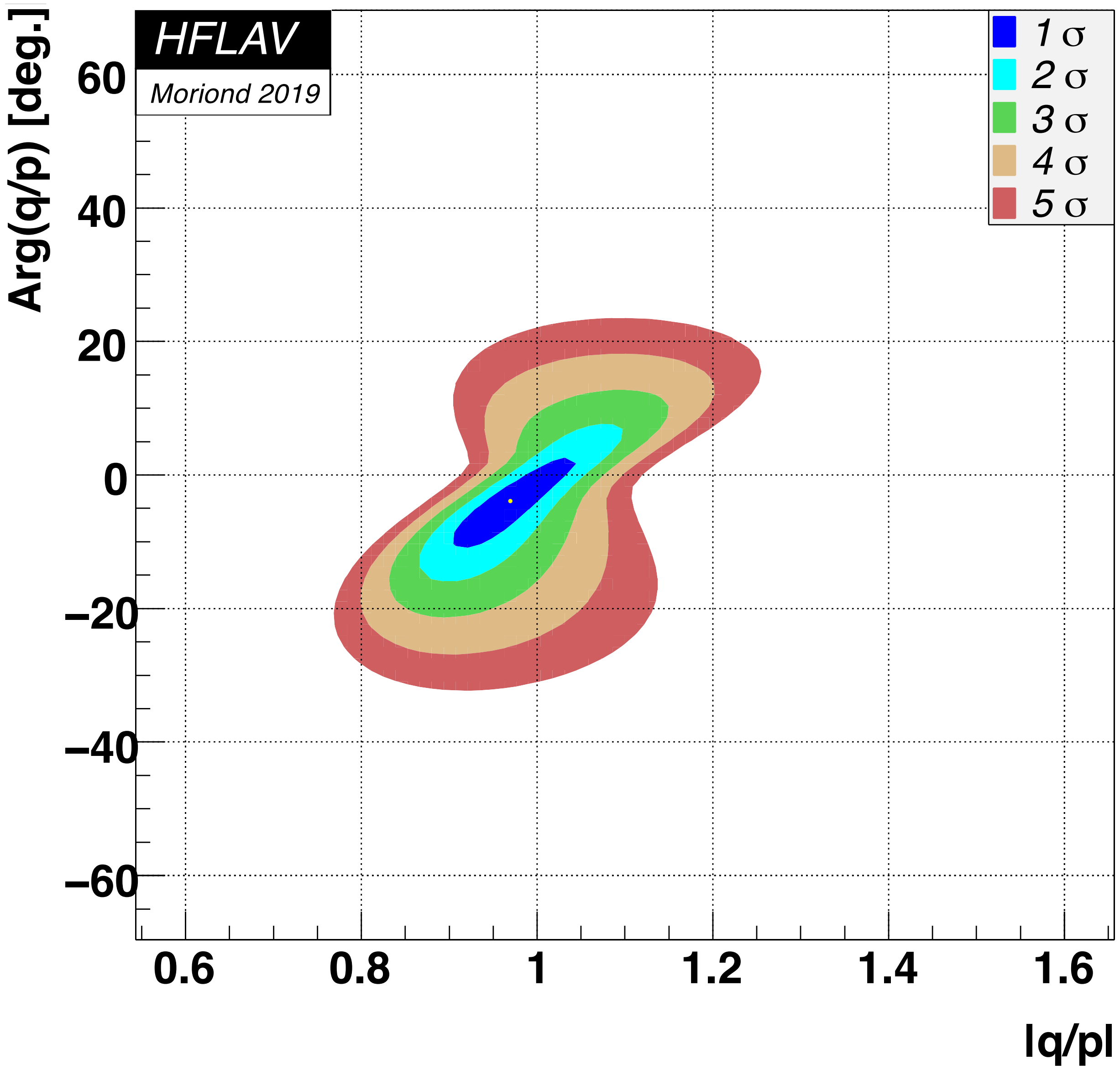
Impact on world average



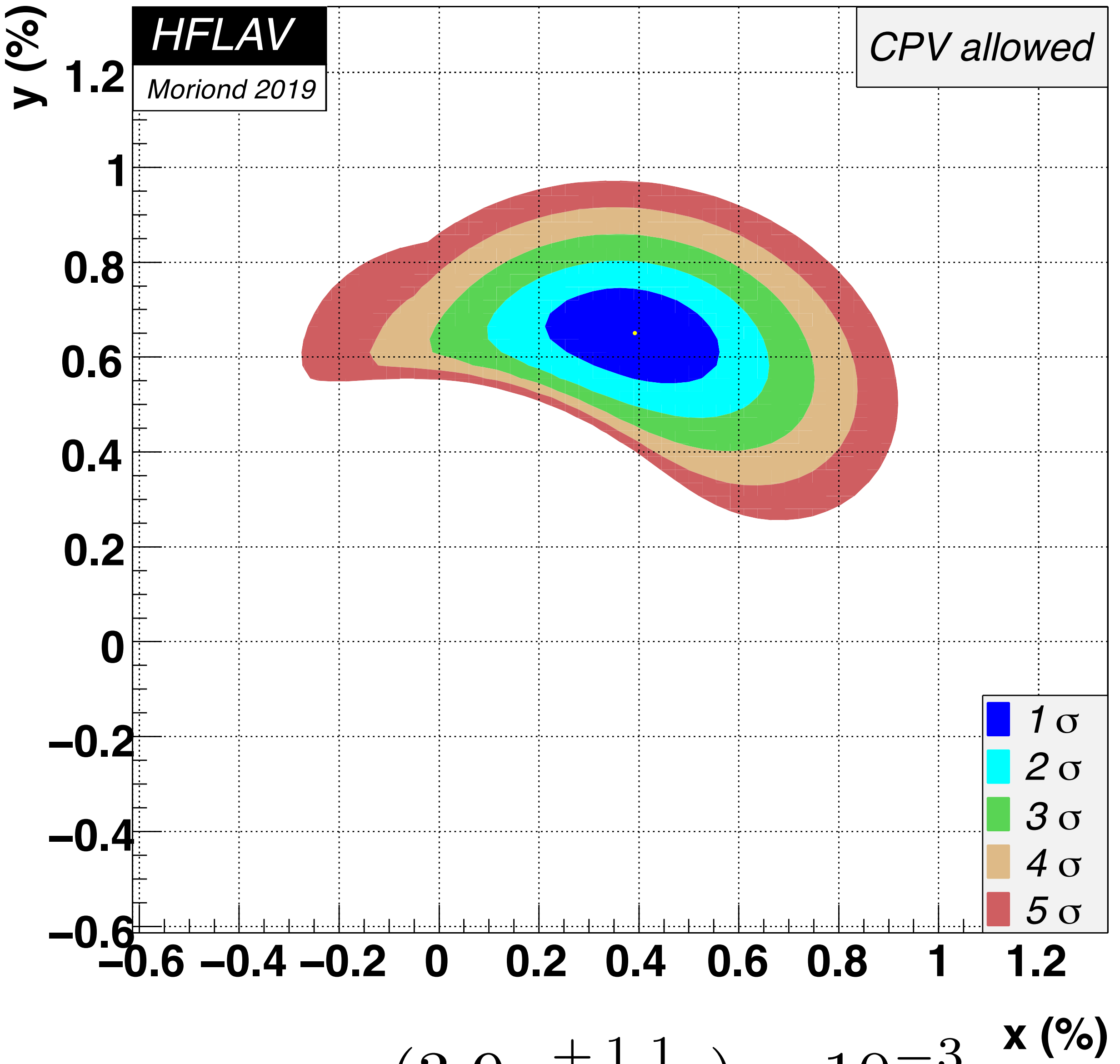


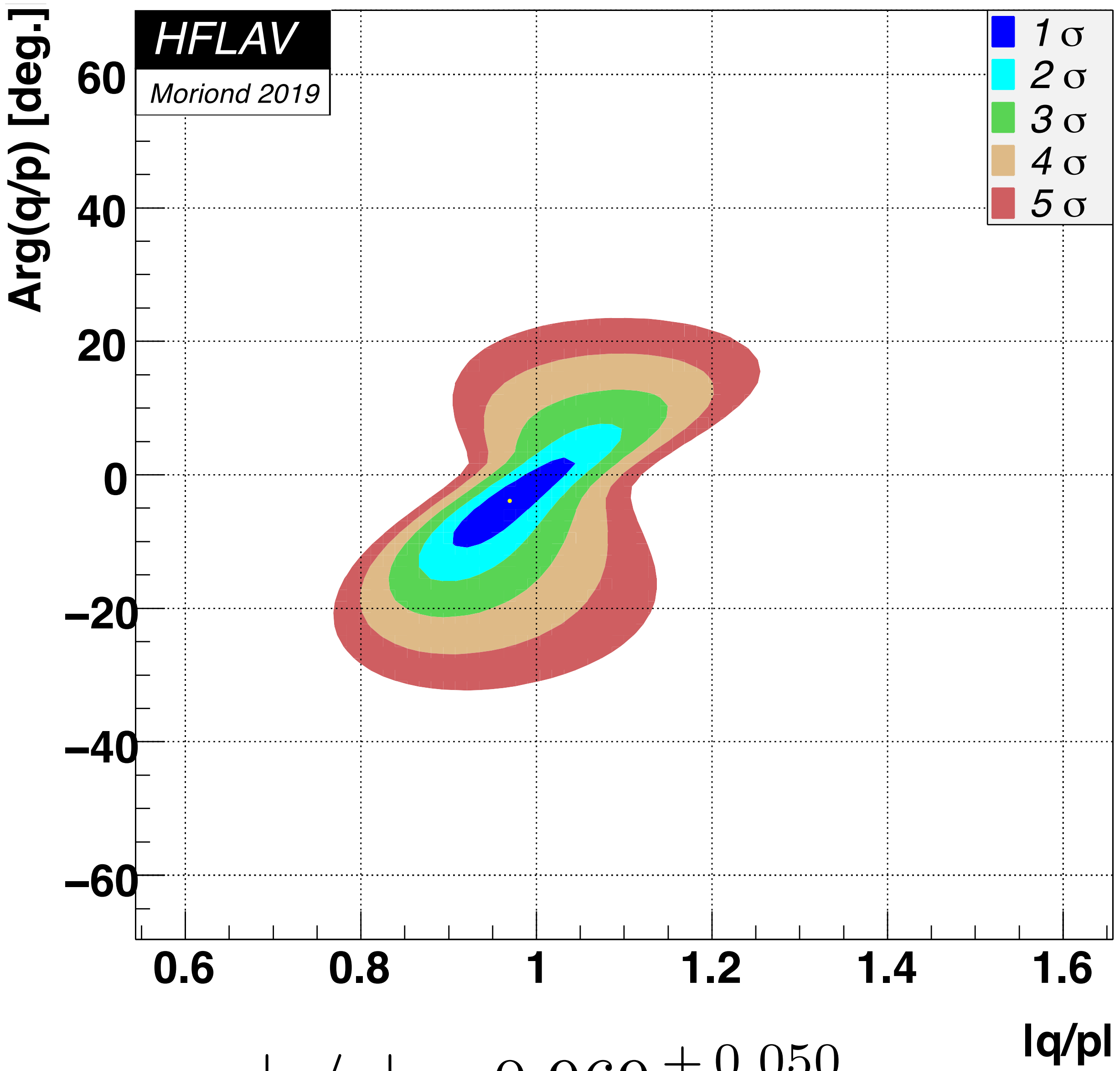
Impact on world average





Impact on world average





$$x = (3.9 \ {}^{+1.1}_{-1.2}\ ) \times 10^{-3}$$

$$y = (6.51\,{}^{+0.63}_{-0.69}) \times 10^{-3}$$

$$|q/p| = 0.969\,{}^{+0.050}_{-0.045}$$

$$\phi = (-3.9\,{}^{+4.5}_{-4.6})^{\circ}$$

first evidence for nonzero (positive) value of *x*

Summary

- Observed (direct) *CP* violation in charm decays

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

- Measured asymmetry seems consistent with standard model, although predictions suffer from large uncertainties due to strong-interaction effects

- Additional searches for *CP* violation in different decay modes can help to clarify the picture

- First evidence for nonzero difference between neutral charm-meson eigenstate. Yet no signs for mixing-induced *CP* violation


Any
Questions!