

La Fisica del Charm a LHCb

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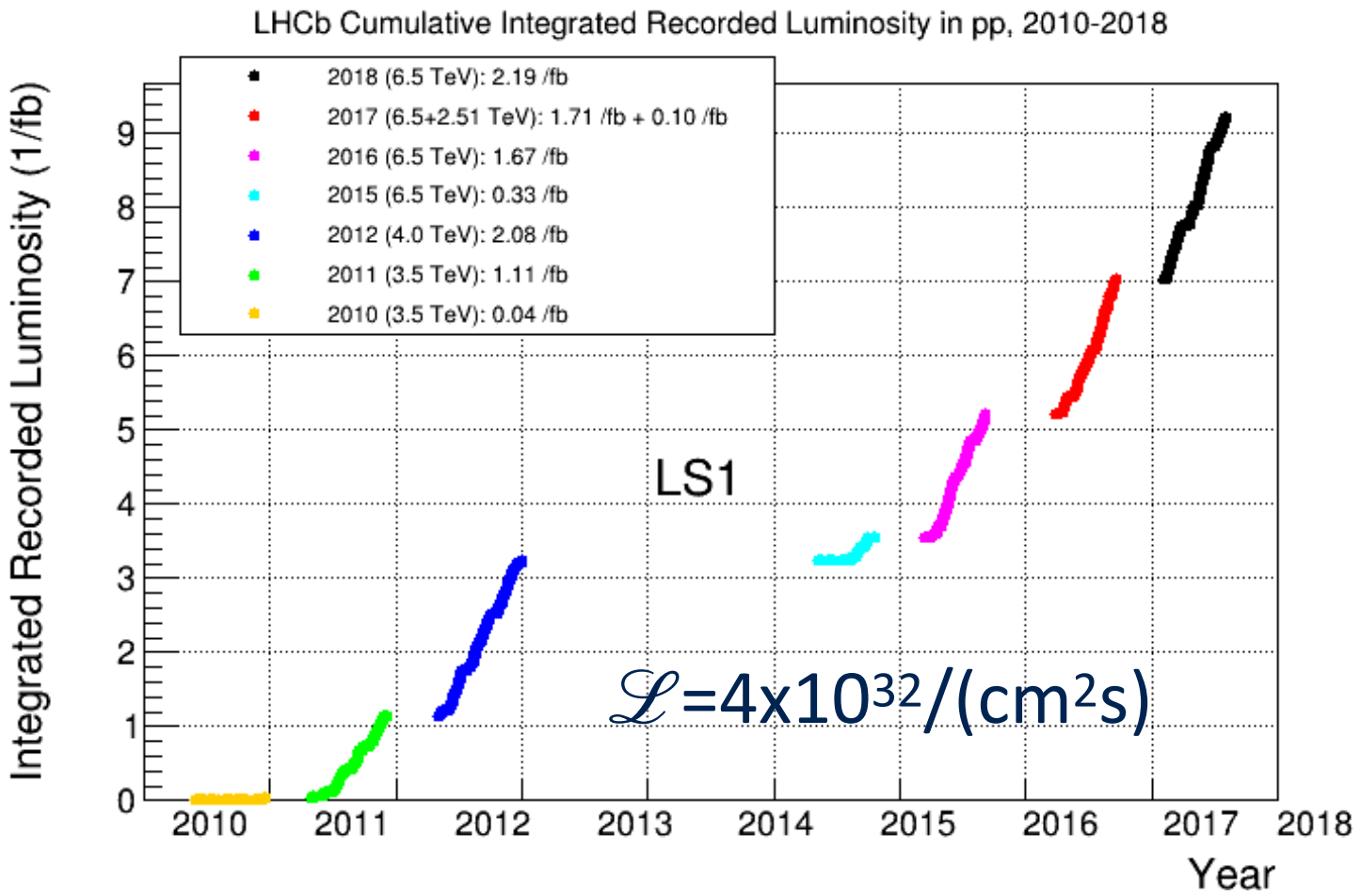
Università di Milano Bicocca
Virtual, 26.06.2020

Il Charm a LHC

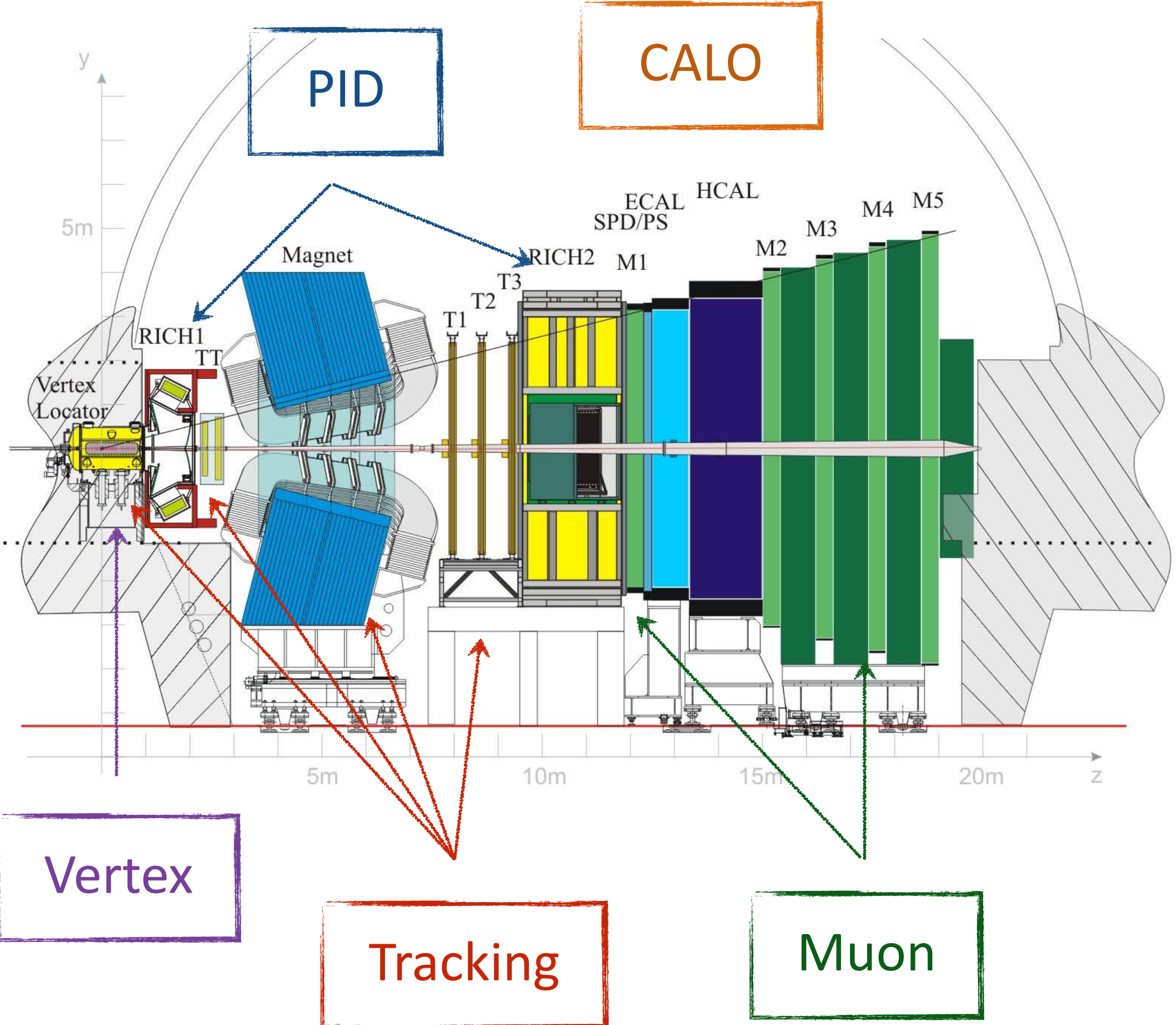
L'Esperimento LHCb

JINST 3 (2008) S08005

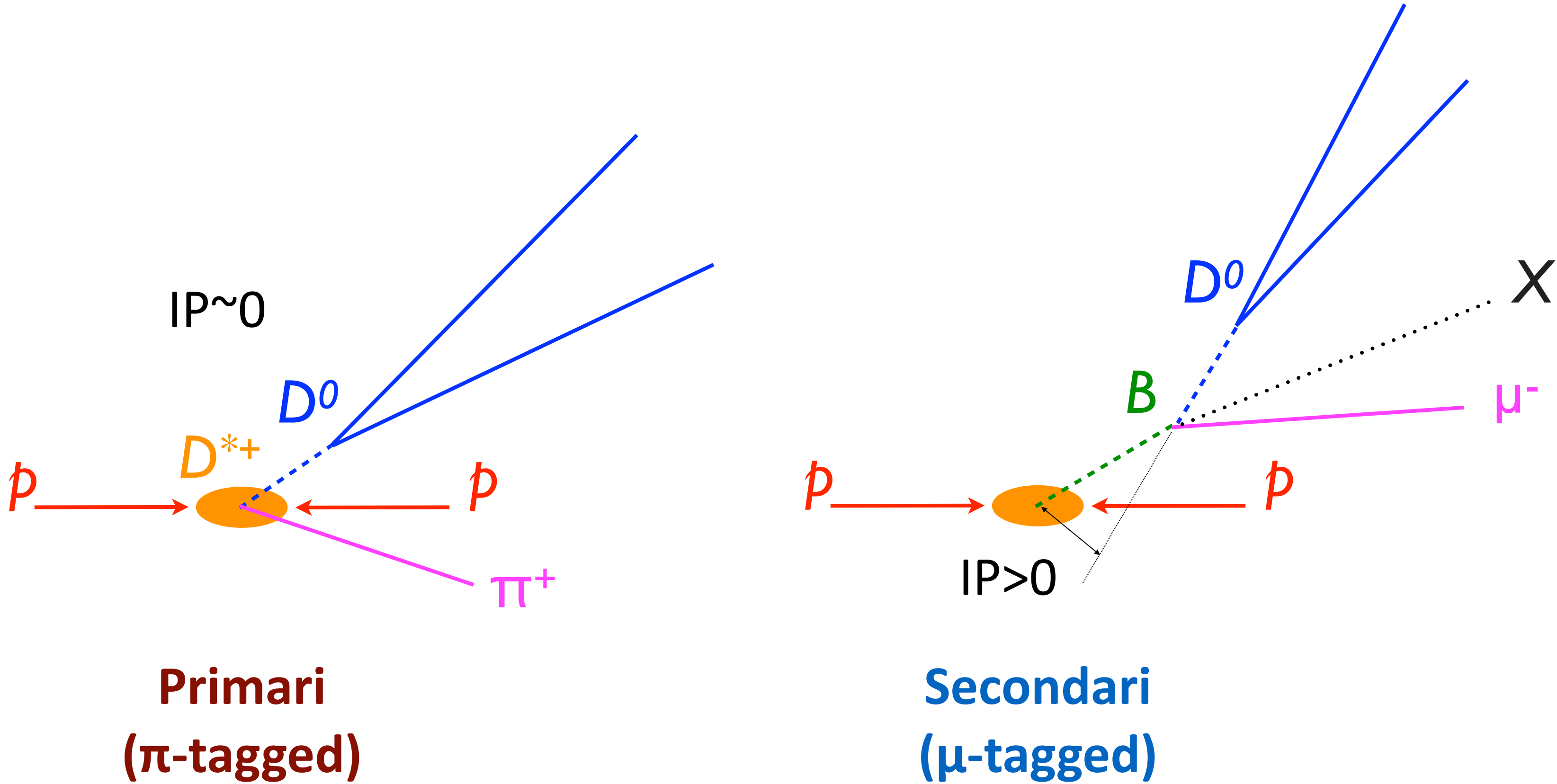
Quark Charm prodotto a alta η a LHC
 $\sigma(pp \rightarrow c\bar{c}) \sim 20\sigma(pp \rightarrow b\bar{b})$



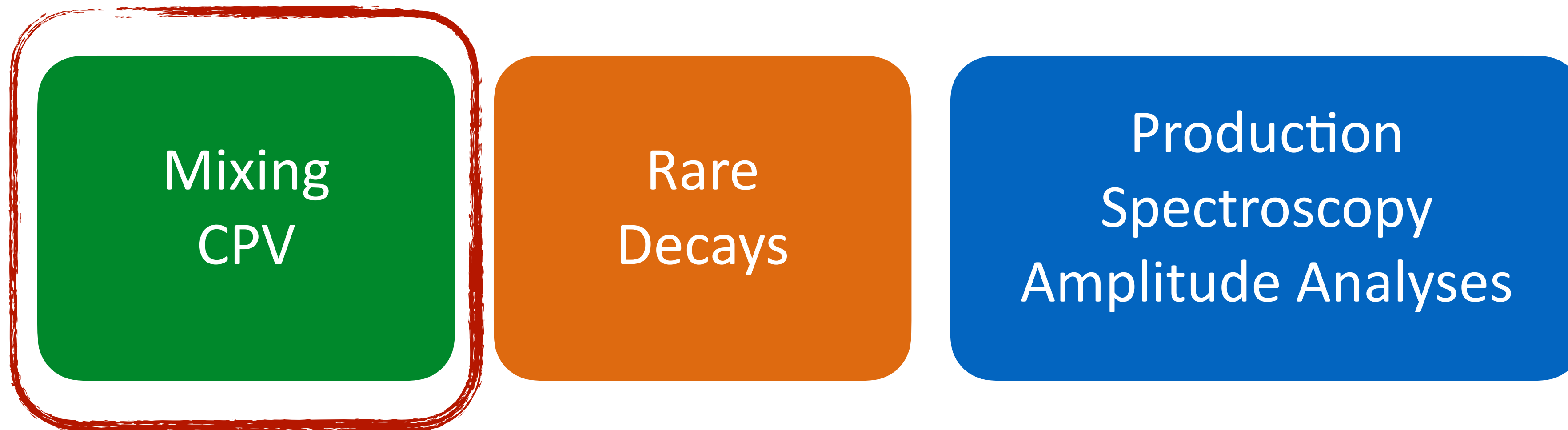
$\epsilon_{\text{VELO}} \approx 98\%$
 $\delta t/t = 45 \text{ fs}$
 $\sigma(\text{IP}) \approx 20 \mu\text{m}$
 $\delta p/p \approx 0.5\%$
 $\epsilon_{\text{Track}} \approx 95\%$
 $\epsilon_{\text{PID(K)}} \approx 95\%$
 $\epsilon_{\text{PID}(\mu)} \approx 97\%$
 $\epsilon_{\text{PID}(e)} \approx 90\%$



Meccanismi di Produzione del Charm a LHCb



Fisica del Charm a LHCb



Questo seminario

La Fisica del Charm

Il Charm e il Modello Standard

La Rivoluzione di Novembre

- La scoperta del quark Charm ha portato al Modello Standard

VOLUME 33, NUMBER 23

PHYSICAL REVIEW LETTERS

2 DECEMBER 1974

Experimental Observation of a Heavy Particle J^{\dagger}

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorrison, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

Y. Y. Lee
Brookhaven National Laboratory, Upton, New York 11973
 (Received 12 November 1974)

We report the observation of a heavy particle J , with mass $m = 3.1$ GeV and width approximately zero. The observation was made from the reaction $p + Be \rightarrow e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.

Discovery of a Narrow Resonance in e^+e^- Annihilation*

J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720
 (Received 13 November 1974)

We have observed a very sharp peak in the cross section for $e^+e^- \rightarrow \text{hadrons}$, e^+e^- , and possibly $\mu^+\mu^-$ at a center-of-mass energy of 3.105 ± 0.003 GeV. The upper limit to the full width at half-maximum is 1.3 MeV.

BNL
 PRL33,1404 (1974)

SLAC
 PRL33,1406 (1974)

SLAC

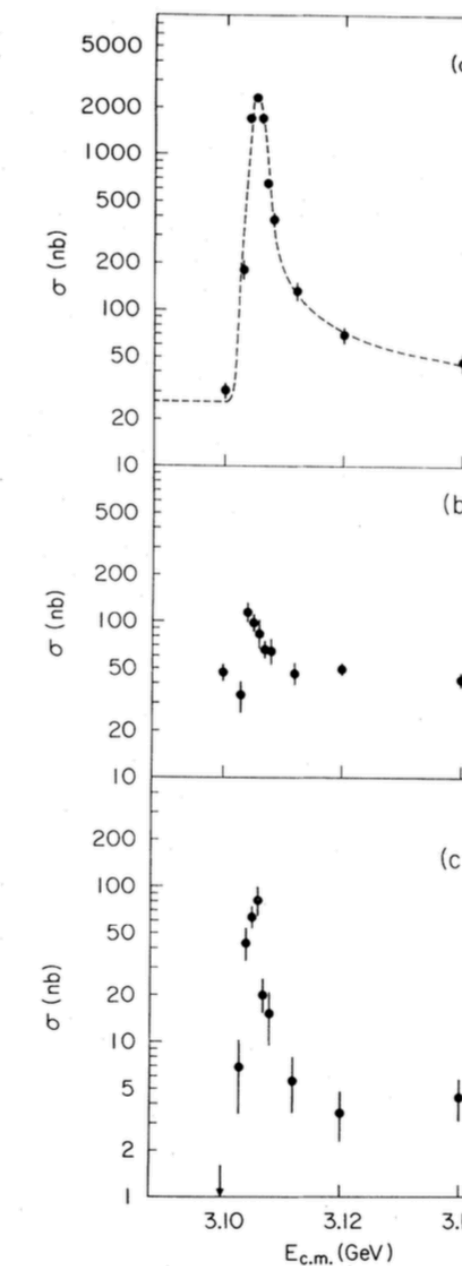


FIG. 1. Cross section versus energy for (a) multi-hadron final states, (b) e^+e^- final states, and (c) $\mu^+\mu^-$, $\pi^+\pi^-$, and K^+K^- final states. The curve in (a) is the expected shape of a δ -function resonance folded with the Gaussian energy spread of the beams and including radiative processes. The cross sections shown in (b) and (c) are integrated over the detector acceptance. The total hadron cross section, (a), has been corrected for detection efficiency.

BNL

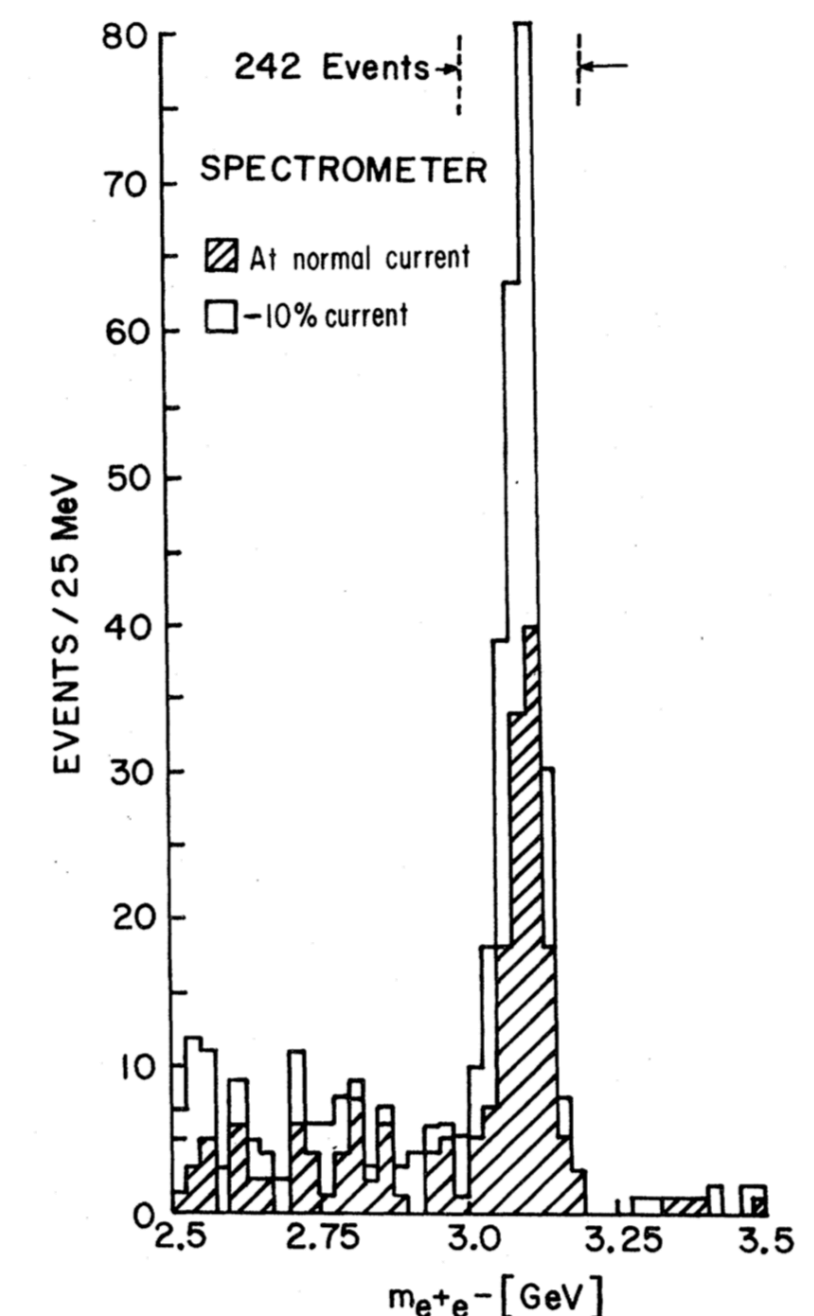


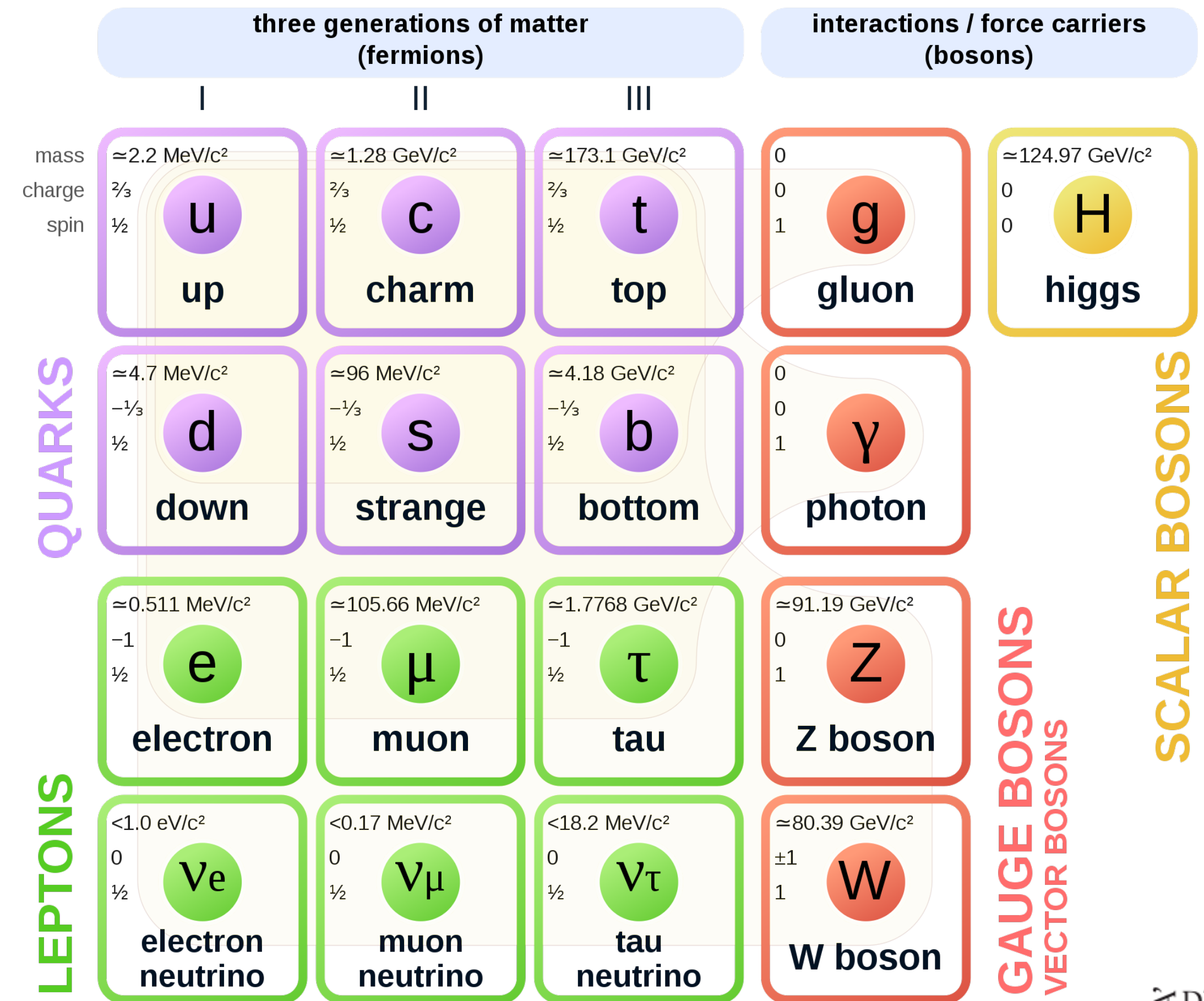
FIG. 2. Mass spectrum showing the existence of J . Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

Il Charm nel Modello Standard

Unico

- Solo quark di tipo *up* che permette di studiare il fenomeno delle oscillazioni e della violazione di CP
- Calcoli teorici difficili
La massa più alta tra i quark cui si accoppia è m_b il che rende difficile calcolare i tassi di decadimento
Troppo pesante per effettuare calcoli su lattice

Standard Model of Elementary Particles



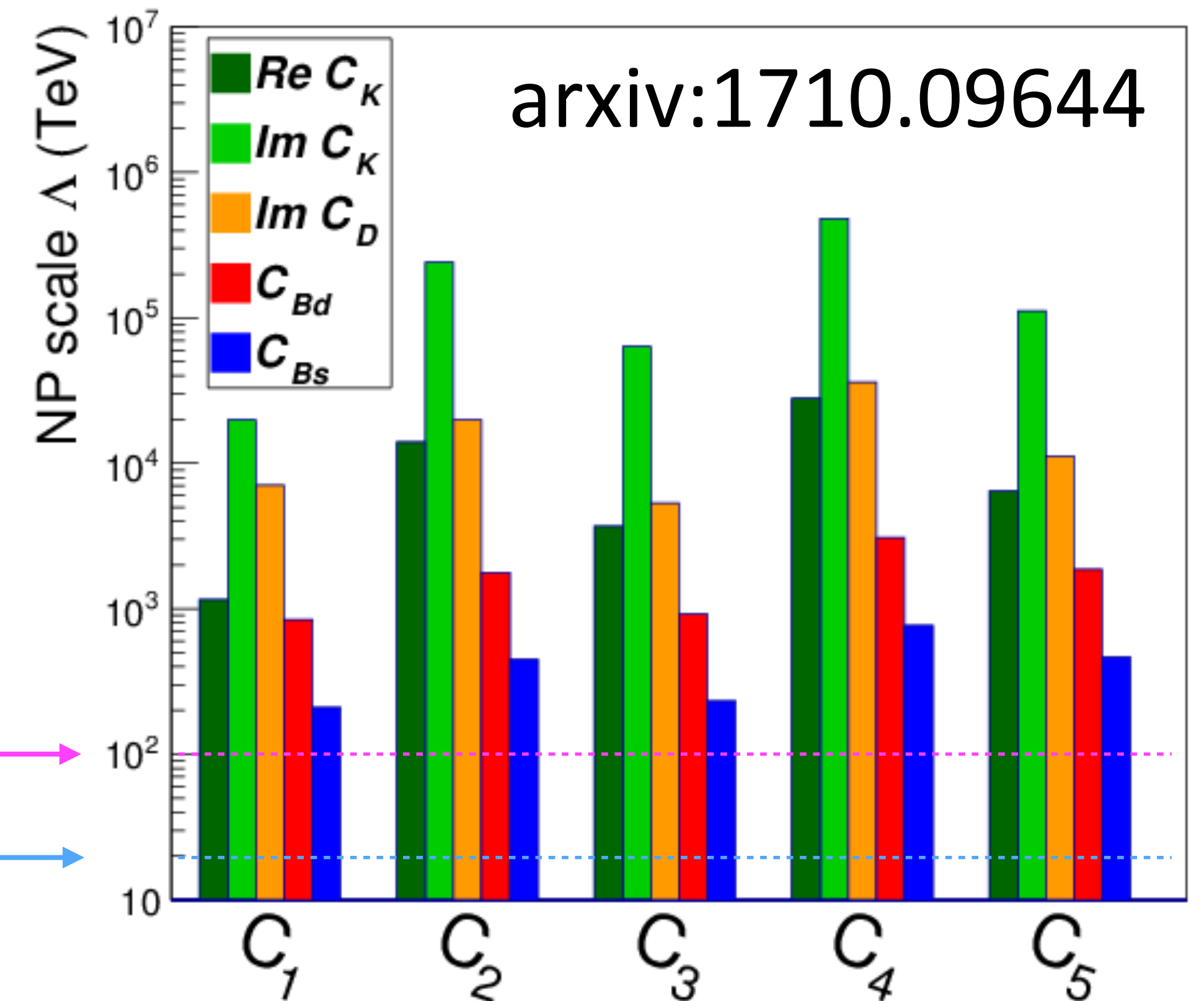
Perché Studiare il Charm

Ricerche Indirette di Nuova Fisica

- Studiare i processi con Charm può rivelare effetti oltre il Modello Standard irraggiungibili dalle ricerche dirette
- Complementari alle ricerche dirette di nuove particelle
- Ci sono miliardi di decadimenti di adroni con Charm ricostruiti a LHCb!

Future Circular Collider (2040?) →
Large Hadron Collider (2010-2035) →

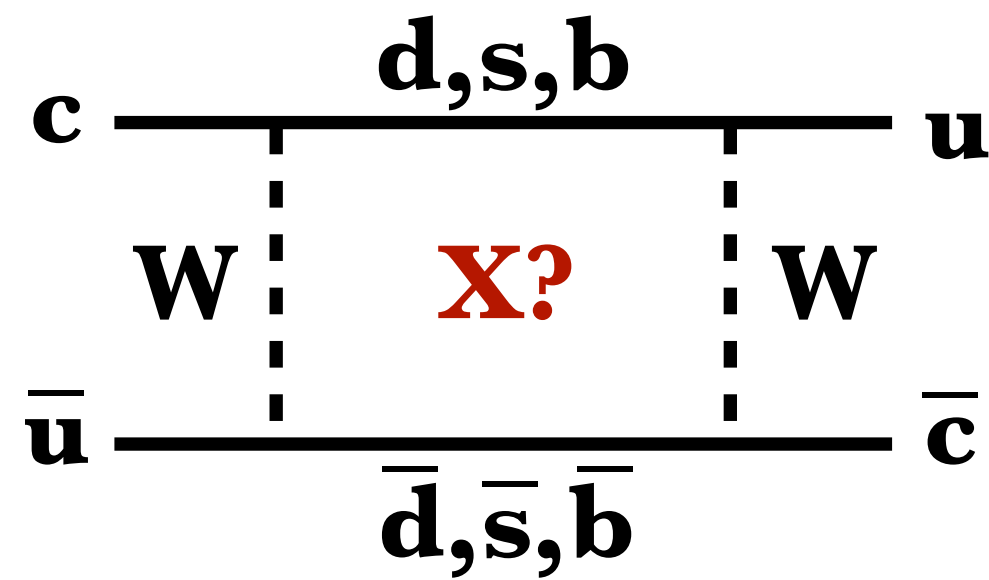
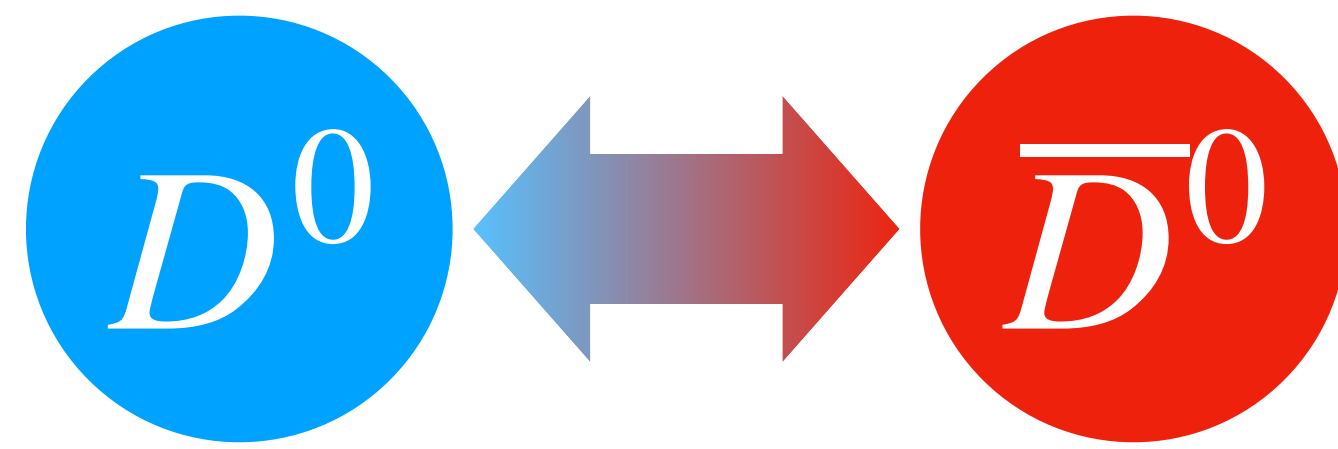
Limits



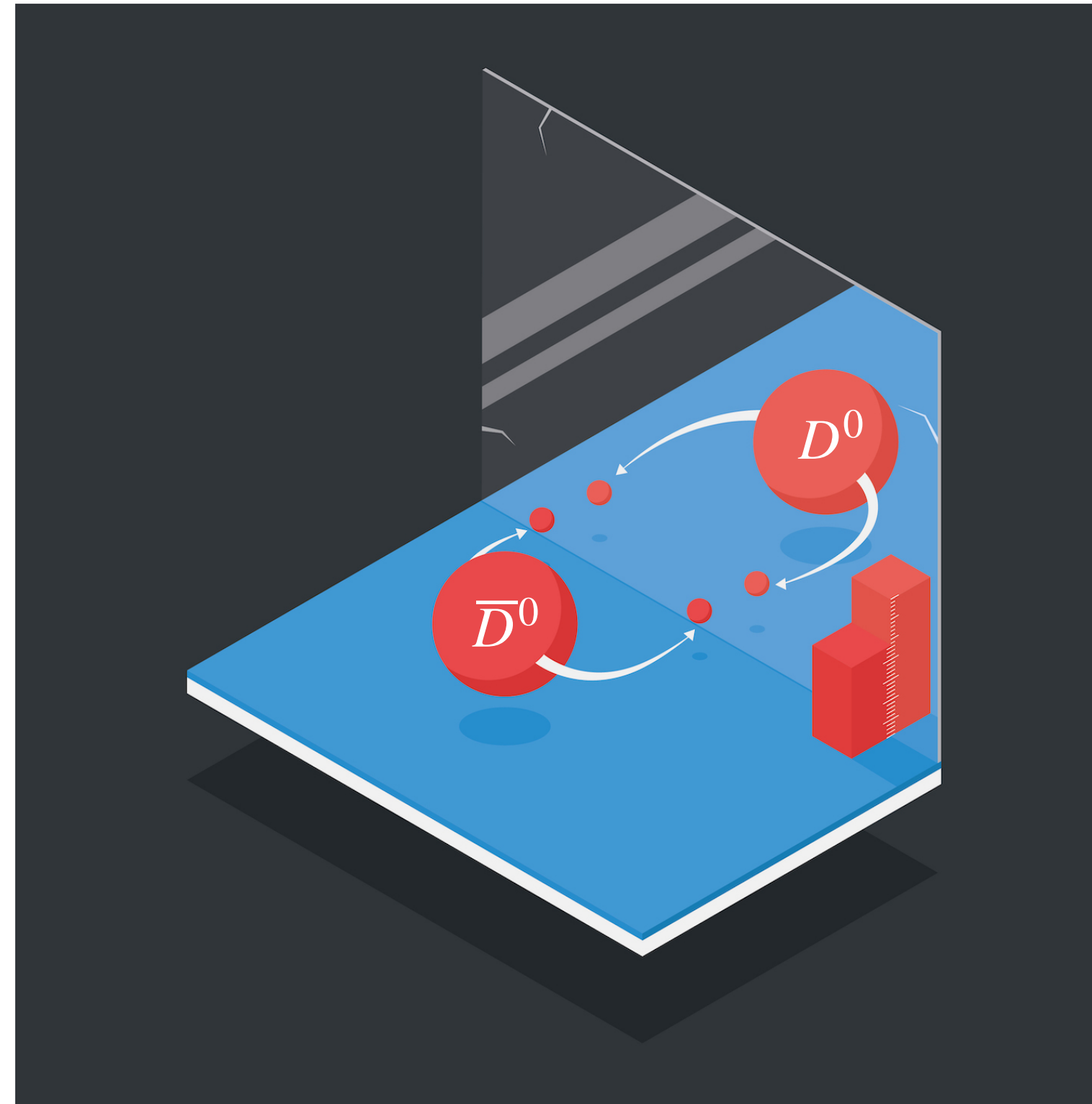
Wilson Coefficients

Oscillazioni e Asimmetrie

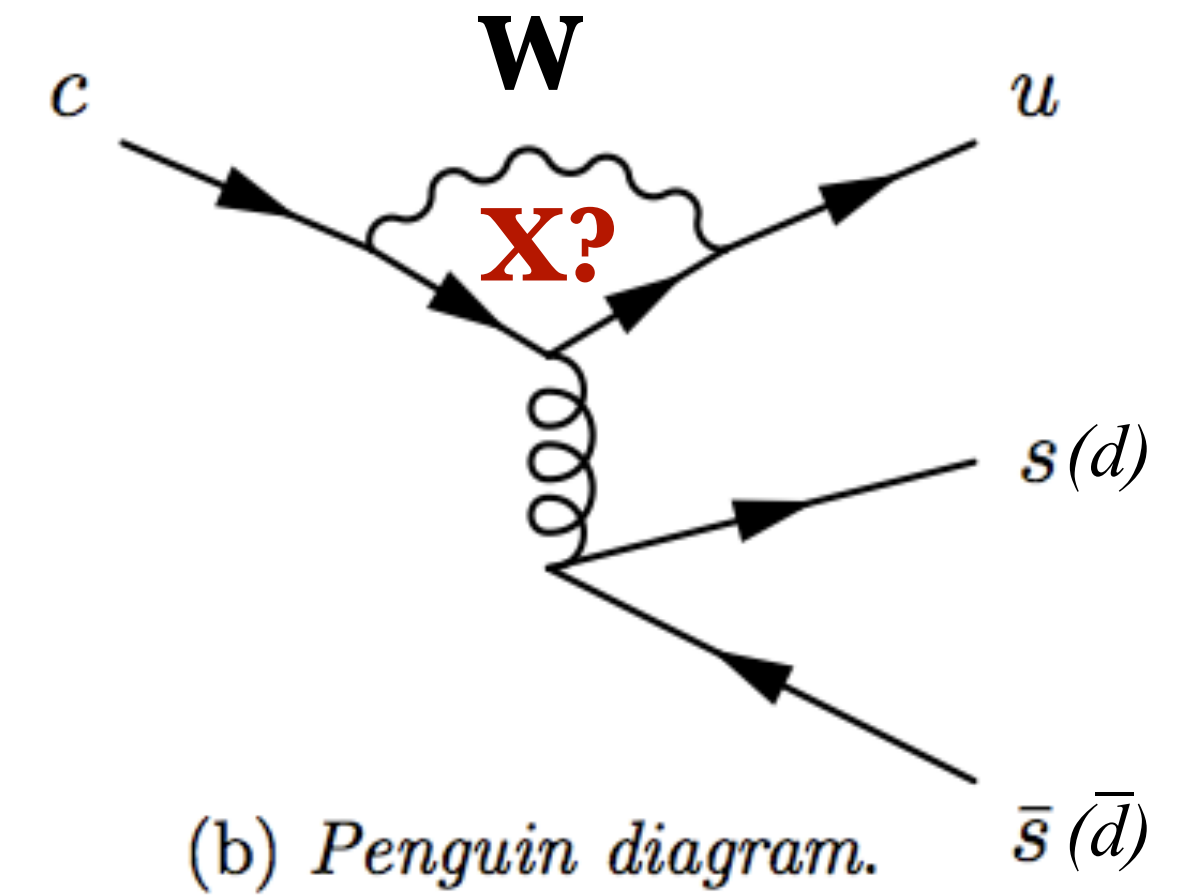
Dove Cercare Effetti di Nuova Fisica nel Charm?



OSCILLAZIONI



ASIMMETRIA MATERIA-ANTIMATERIA



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

Un Effetto Quanto-Meccanico

$$|D_1\rangle = p|D^0\rangle + q|\bar{D}^0\rangle$$

$$|D_2\rangle = p|D^0\rangle - q|\bar{D}^0\rangle$$

$$|D^0(t)\rangle = g_+(t)|D^0\rangle + \frac{q}{p}g_-(t)|\bar{D}^0\rangle$$

$$|\bar{D}^0(t)\rangle = \frac{p}{q}g_-(t)|D^0\rangle + g_+(t)|\bar{D}^0\rangle$$

Operatori di evoluzione temporale

Elementi non-diagonali dell'Hamiltoniana

$$\left(\frac{q}{p}\right)^2 = \frac{M_{12}^* - i\Gamma_{12}^*/2}{M_{12} - i\Gamma_{12}/2}$$
$$|p|^2 + |q|^2 = 1$$

Medie degli autovalori di massa e ampiezza

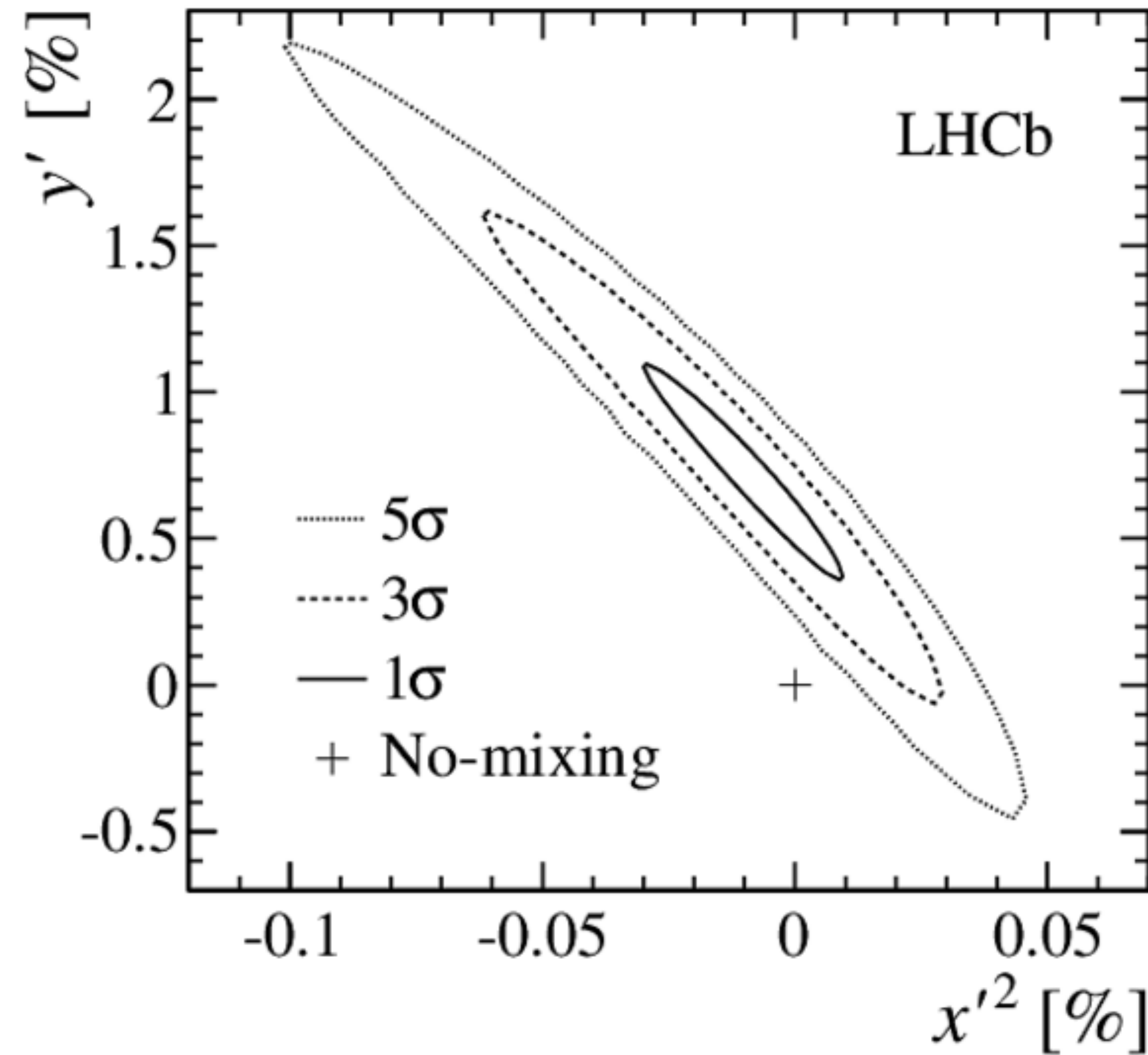
$$g_+(t) = e^{-iMt} e^{i\Gamma t/2} \cos(-i(x + iy)\Gamma t/2)$$

$$g_-(t) = e^{-iMt} e^{i\Gamma t/2} \sin(-i(x + iy)\Gamma t/2)$$

Parametri di mixing:
differenza autovalori di
massa (x) e ampiezza (y)
tra D_1 e D_2

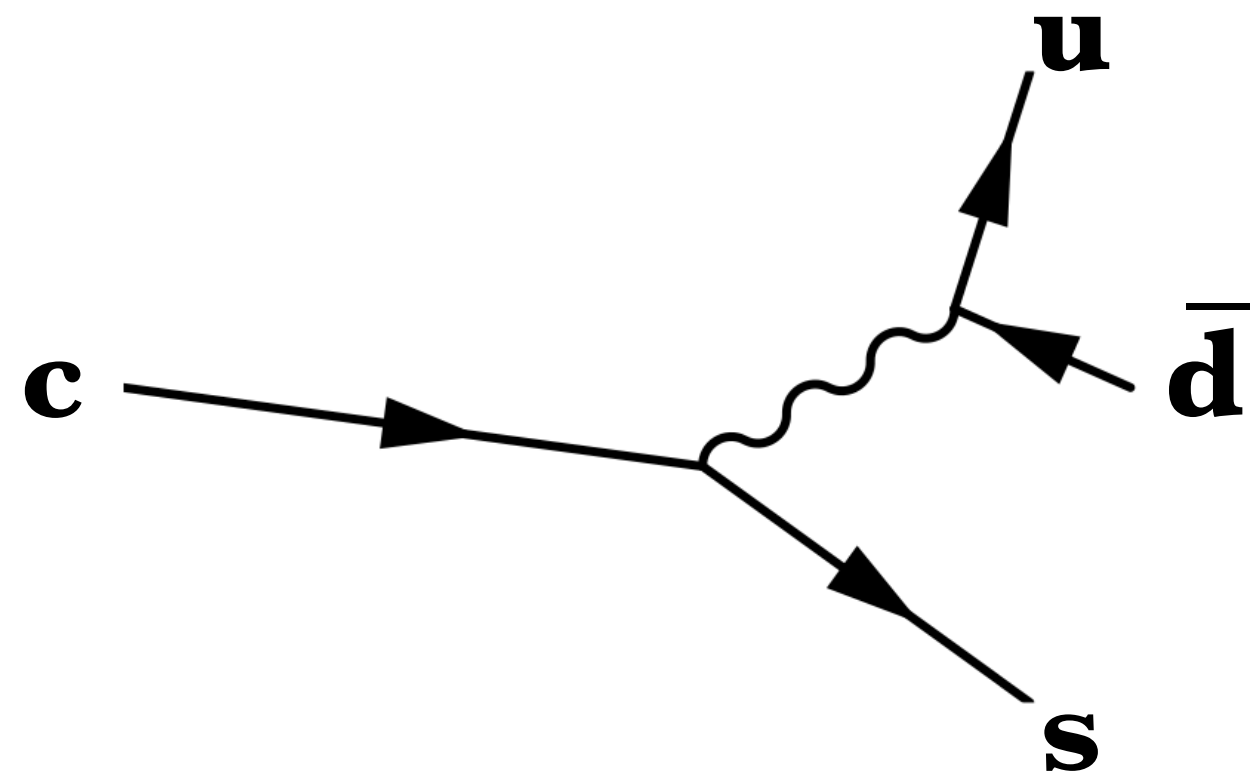
Oscillazioni D^0 - \bar{D}^0 osservate da LHCb nel 2013

PHYS. REV. LETT. 110 (2013) 101802



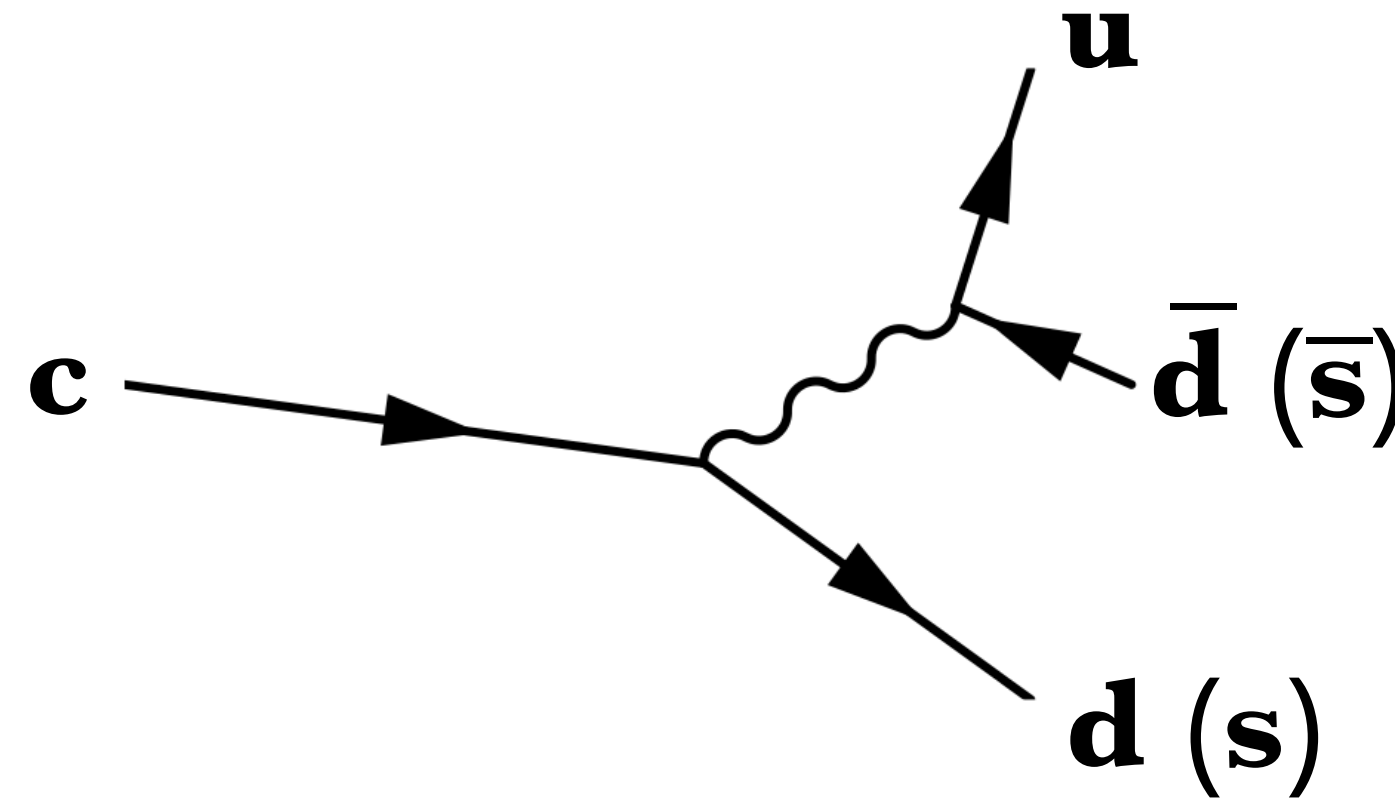
Decadimenti dei Mesoni con Charm

Cabibbo Favoriti (CF)



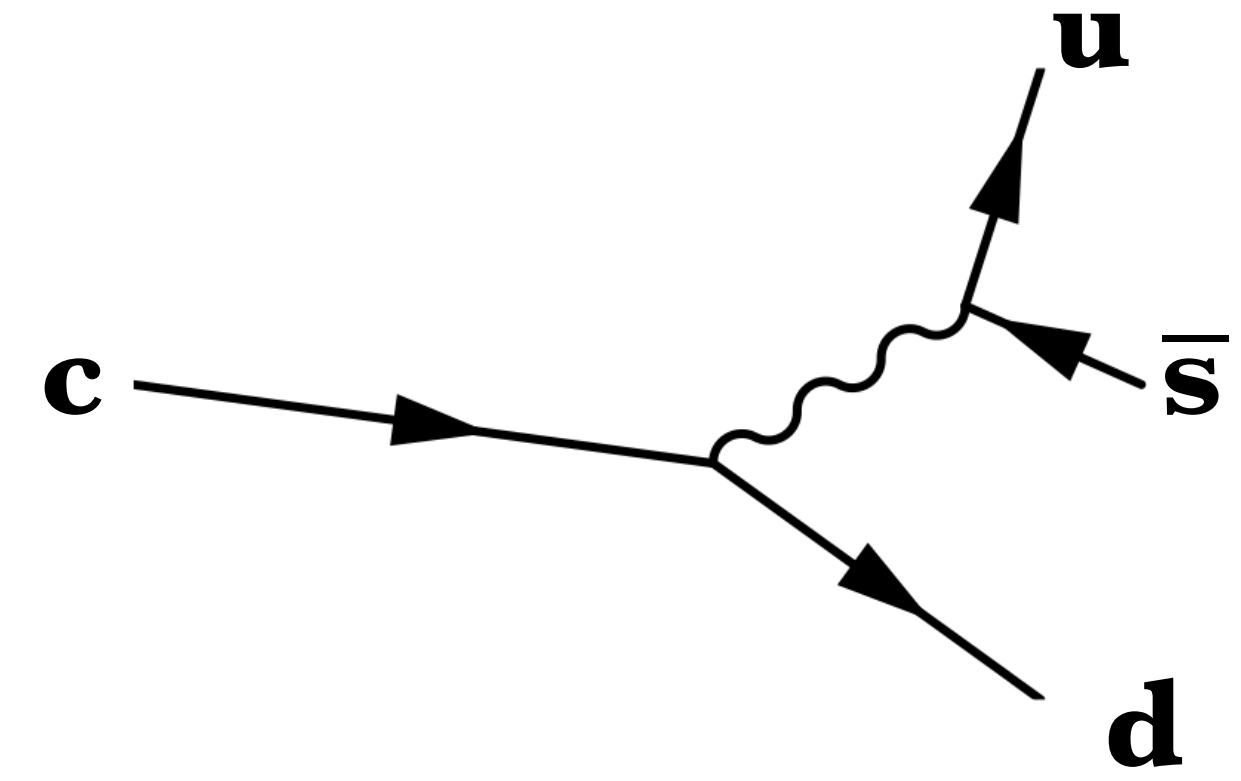
$$|V_{cs}V_{ud}^*|^2 \approx 0.9$$

Cabibbo Soppressi (CS)



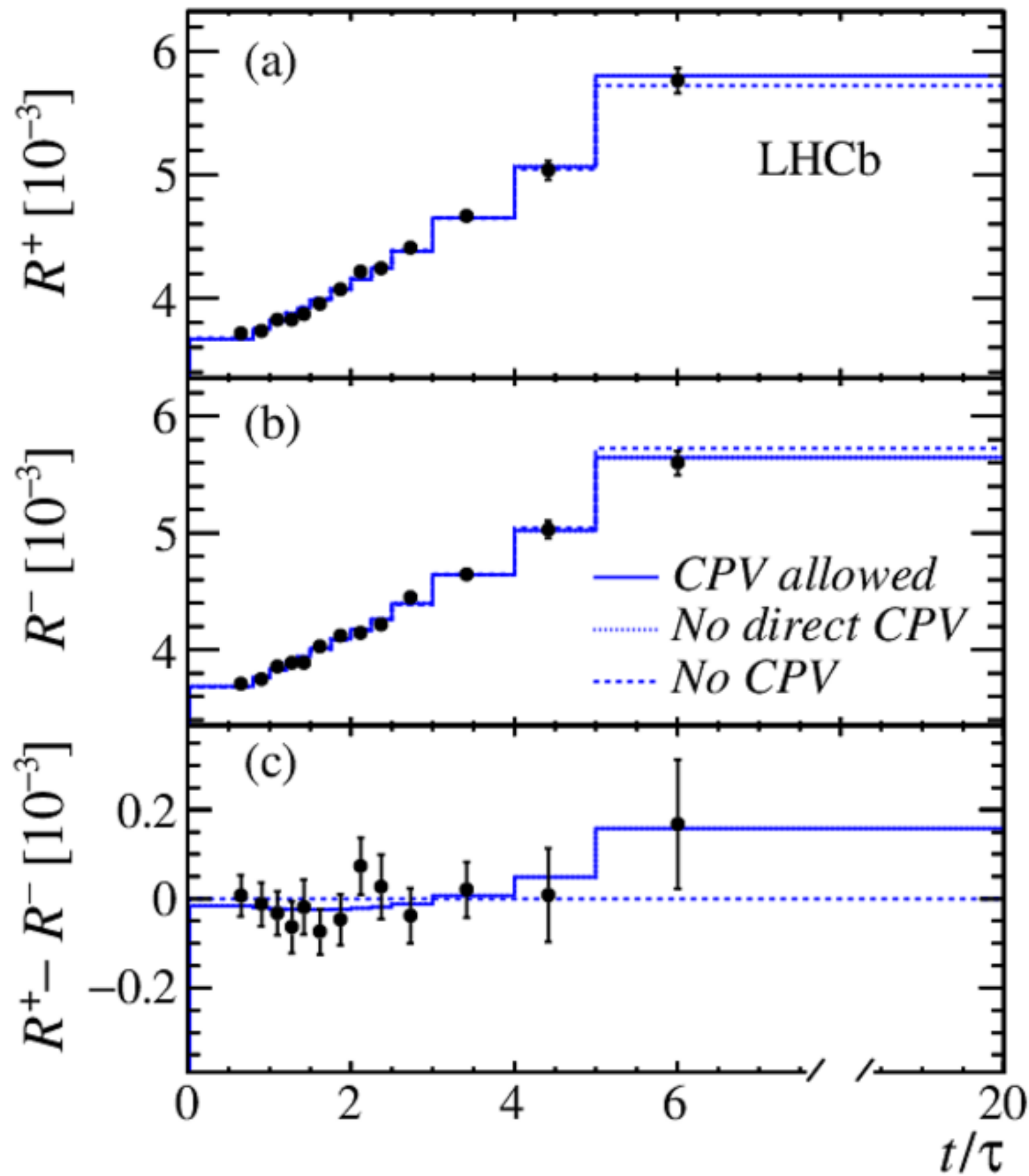
$$|V_{cd}V_{ud}^*|^2 \approx 0.04$$
$$|V_{cs}V_{us}^*|^2 \approx 0.04$$

Doppio Cabibbo Soppressi (DCS)

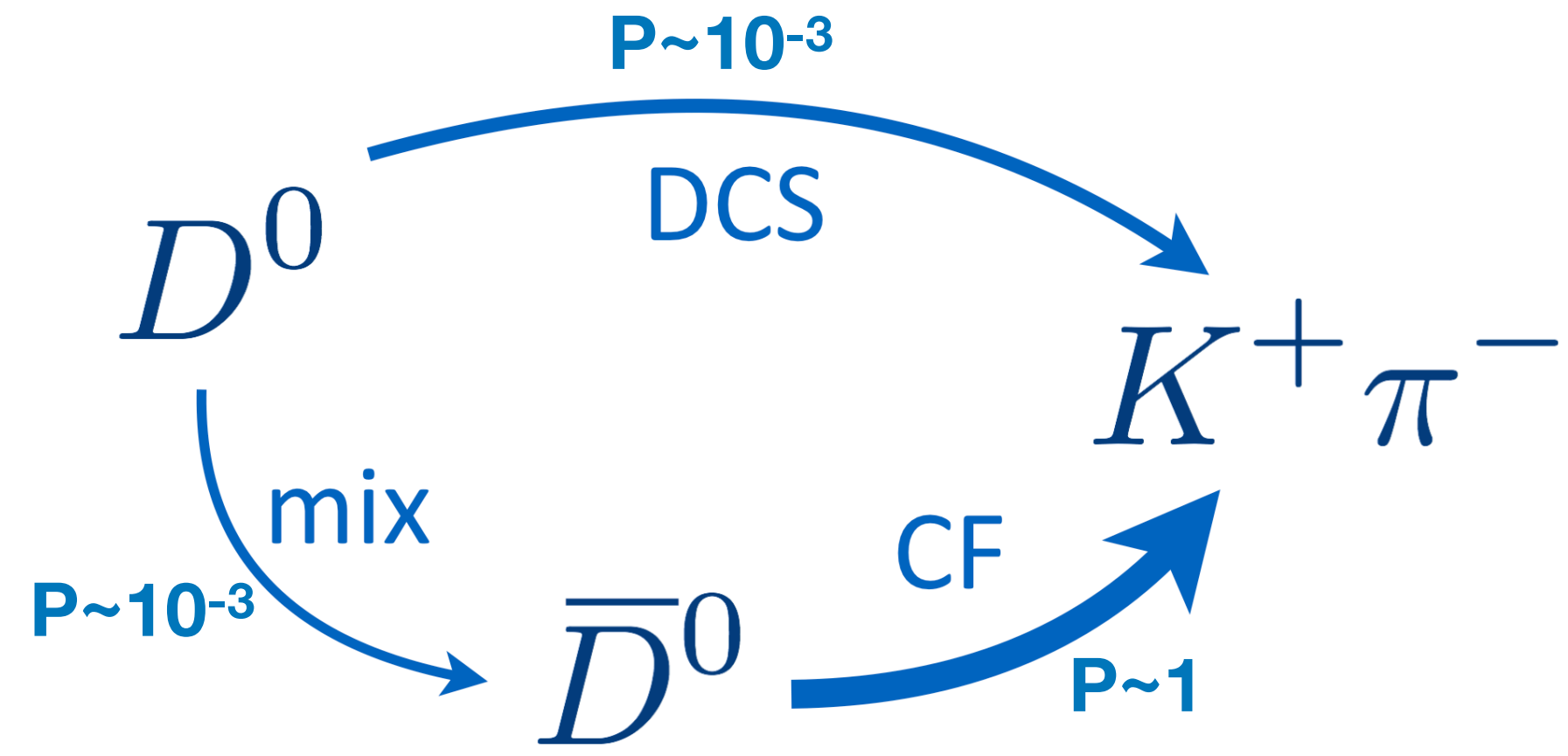


$$|V_{cd}V_{us}^*|^2 \approx 0.002$$

Rapporto "Wrong-Sign"



WS: $D^0 \rightarrow K^+ \pi^-$
RS: $D^0 \rightarrow K^- \pi^+$



$$R = \frac{N_{WS}}{N_{RS}}$$

$$R_{K\pi} \approx R_{K\pi} + \sqrt{R_{K\pi}} y' (\Gamma t) + \frac{x'^2 + y'^2}{4} (\Gamma t)^2$$

$$x'^2 = (3.9 \pm 2.7) \times 10^{-5}$$

$$y' = (5.28 \pm 0.52) \times 10^{-3}$$

$$R_D = (3.454 \pm 0.031) \times 10^{-3}$$

$$x' = x \cos \delta_{K\pi} + y \sin \delta_{K\pi}$$

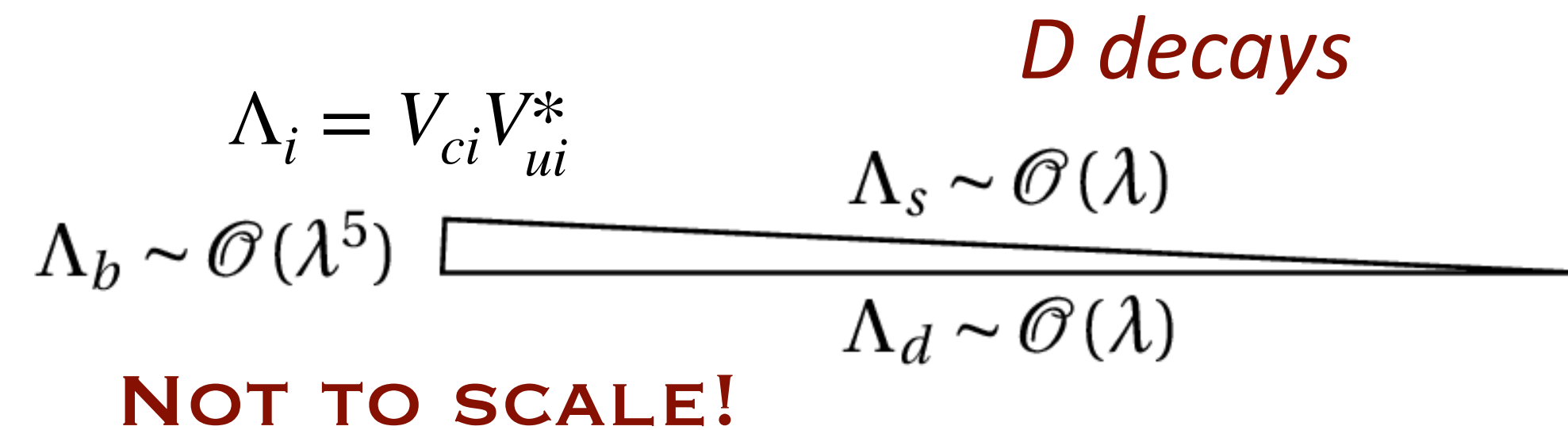
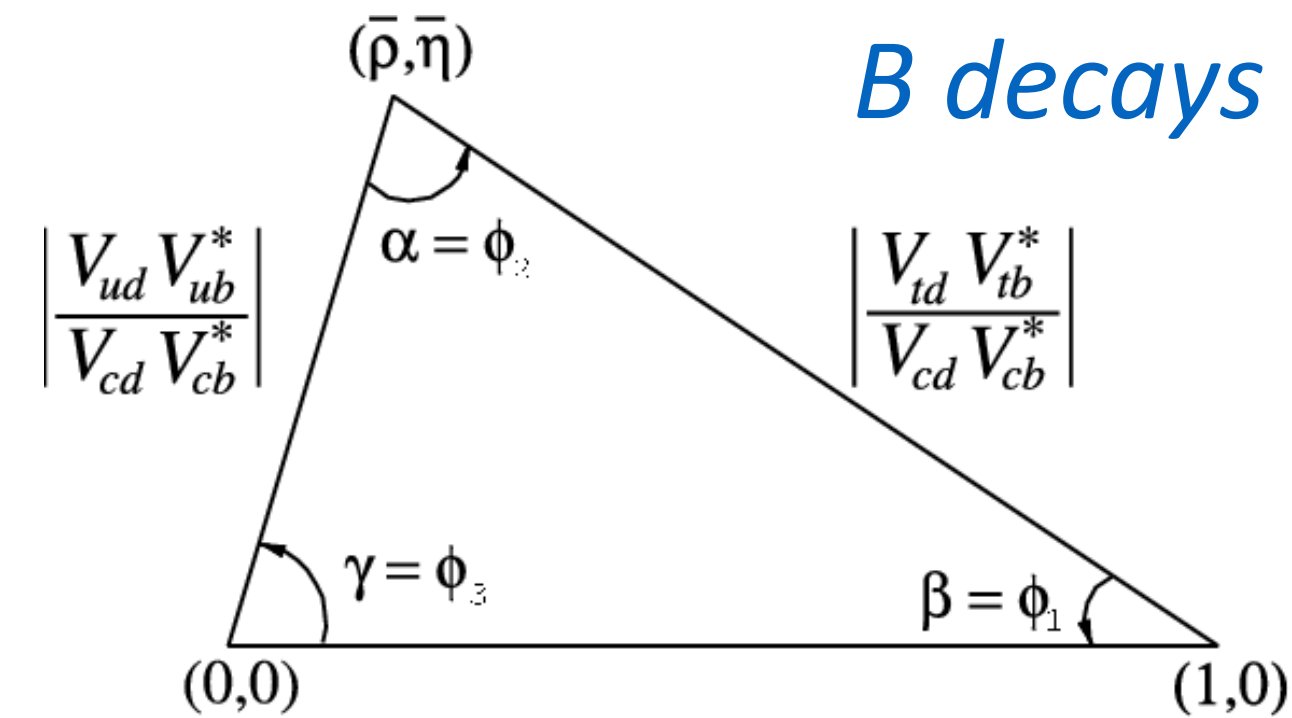
$$y' = y \cos \delta_{K\pi} - x \sin \delta_{K\pi}$$

Asimmetria Materia-Antimateria nel Charm

Violazione di CP

- Introdotta naturalmente nella matrice di Cabibbo-Kobayashi-Maskawa
- Effetti relativamente grandi nelle transizioni che coinvolgono la terza generazione di quark
- Estremamente soppressa nel Charm

	d	s	b
u	$1-\lambda^2$	λ	$A\lambda^3(\rho-i\eta)$
c	$-\lambda$ $O(\lambda^5)$	$1-\lambda^2$	$A\lambda^2$ $+O(\lambda^4)$
t	$A\lambda^3(1-\rho-i\eta)$	$-A\lambda^2$	1



Violazione di CP nel Charm Osservata da LHCb nel 2019

The screenshot shows a red header for the 'symmetry' website, with the tagline 'dimensions of particle physics'. A 'topics' dropdown menu is visible. Below the header, the article title 'LHCb discovers matter-antimatter asymmetry in charm quarks' is prominently displayed in white text. To the right, it indicates the date '03/21/19' and the author 'By Sarah Charley'. A short summary states: 'A new observation by the LHCb experiment finds that charm quarks behave differently than their antiparticle counterparts.' Below the article title, there is a decorative banner with colorful abstract shapes and a blue circle containing the symbol \bar{c} . At the bottom of the banner, the CERN logo is visible on the left and the word 'ABOUT' is on the right.

[News](#) › [Press release](#) › [Topic: Physics](#)

[Voir en français](#)

LHCb sees a new flavour of matter-antimatter asymmetry

The LHCb collaboration has observed a phenomenon known as CP violation in the decays of a particle known as a D0 meson for the first time

21 MARCH, 2019

$$A_{h^+h^-} = \frac{N(D^0 \rightarrow h^+h^-) - N(\bar{D}^0 \rightarrow h^+h^-)}{N(D^0 \rightarrow h^+h^-) + N(\bar{D}^0 \rightarrow h^+h^-)}$$

$$A_{h^+h^-} = A_{CP}(h^+h^-) + A_D + A_P \quad (\text{Valid only if } A_{hh} \text{ small})$$

L'asimmetria che vogliamo misurare

Asimmetria di rivelazione della particella di tag (μ^\pm o π^\pm)

Asimmetria di produzione (D^* o B)

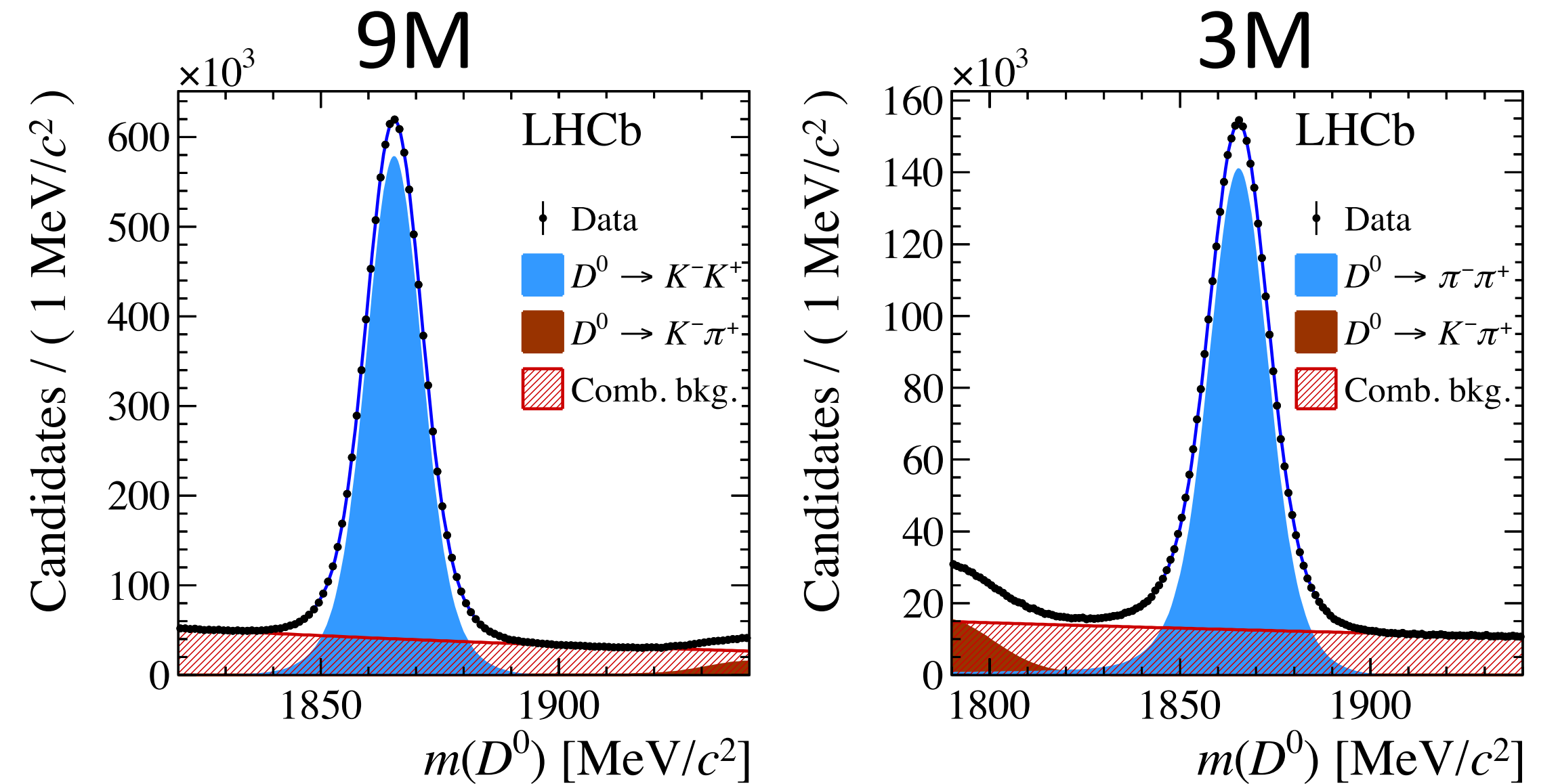
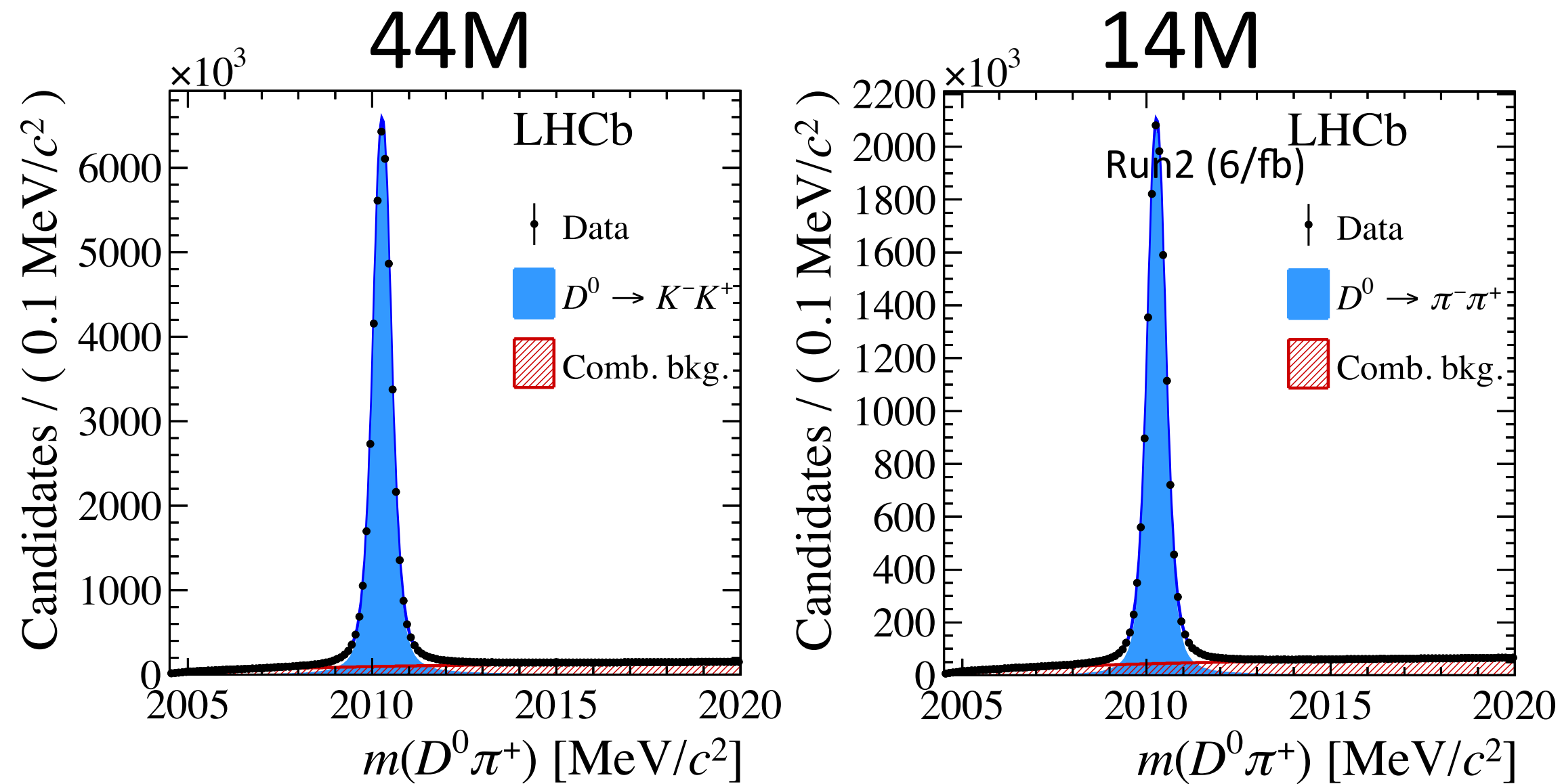
$$\Delta A_{CP} = A_{K^+K^-} - A_{\pi^+\pi^-} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

Misura di ΔA_{CP} a LHCb

PHYS. REV. LETT. 122 (2019) 211803

π -tagged

μ -tagged



$$\Delta A_{CP}^{\pi\text{-tagged}} = [-18.2 \pm 3.2(\text{stat.}) \pm 0.9(\text{syst.})] \times 10^{-4}$$

$$\Delta A_{CP}^{\mu\text{-tagged}} = [-9 \pm 8(\text{stat.}) \pm 5(\text{syst.})] \times 10^{-4}$$

Combinazione con i dati del Run1

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

5.3 σ

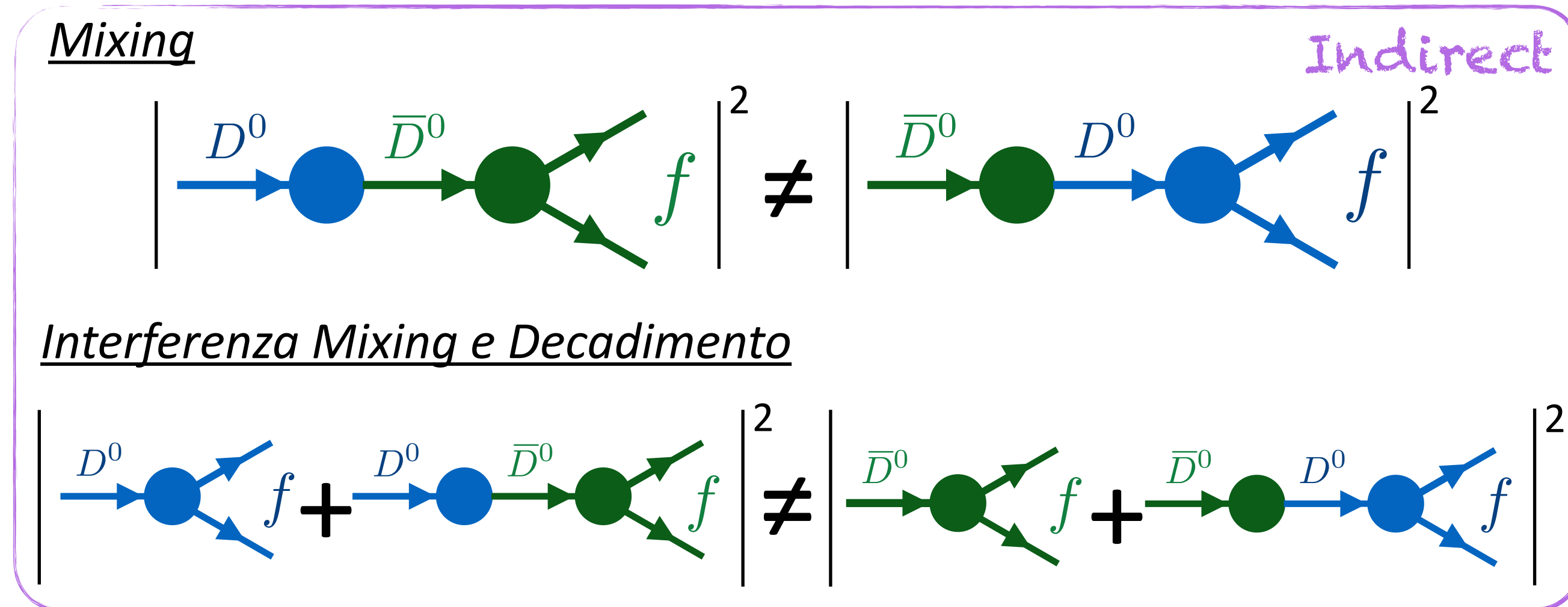
Stato dell'Arte

Cosa Sappiamo

- **Le oscillazioni e la violazione di CP sono state osservate recentemente da LHCb**
Effetti molto piccoli che richiedono una grandissima quantità di dati e misure di altissima precisione ($\sigma_{\text{syst}} < 10^{-4}$)
- **Predizioni del Modello Standard**
Difficili, data la massa del quark charm
I teorici sostengono che le misure siano compatibili con il Modello Standard ma c'è lo spazio per effetti inattesi, in particolare nell'interferenza tra violazione di CP e mixing

$$a_{CP}^{\text{ind}}(th) \approx 10^{-5}$$

$$\sigma(a_{CP}^{\text{ind}})(exp) = 10^{-4}$$



Programmi di Ricerca a Breve Termine

Programmi Futuri di LHCb nel Charm

Violazione di CP Diretta

- Misurarla in ulteriori canali di decadimento e determinare $A_{CP}(KK)$ e $A_{CP}(\pi\pi)$ separatamente

Violazione di CP Indiretta

- Ancora inosservata

Ricerca nelle asimmetrie $D^0 \rightarrow KK$ e $D^0 \rightarrow \pi\pi$ time-dependent (A_T)

Studio dei decadimenti a molti corpi $D^0 \rightarrow K^0_s hh$ ($h=\pi, K$), $D^0 \rightarrow K\pi\pi\pi$

Attività in Milano
Bicocca

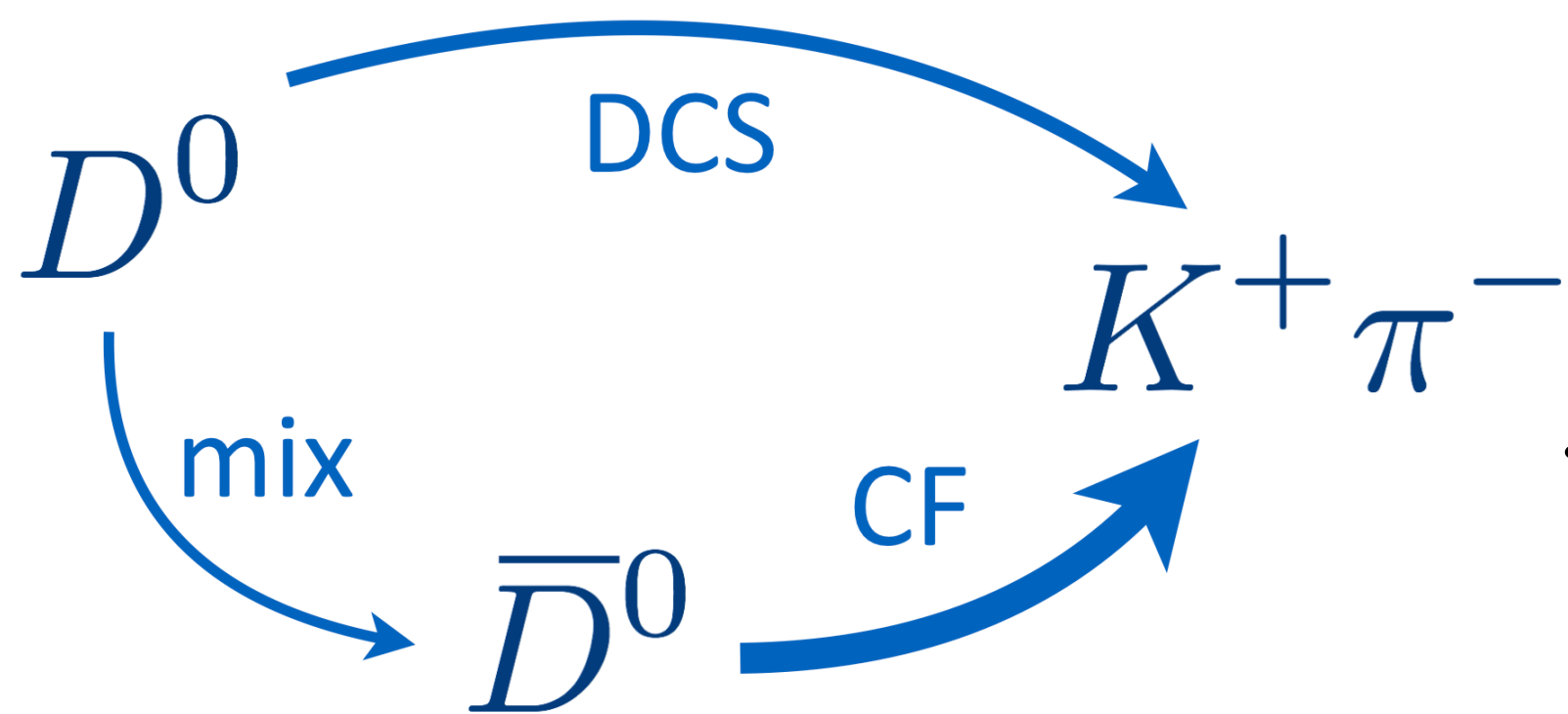
Violazione di CP e Mixing in un'unica misura: $D^0 \rightarrow K^0_s \pi^+ \pi^-$

Mixing e Violazione di CP indiretta

- Permette di misurare direttamente x e y
- Misure di violazione di CP indirect da q/p

Approccio di Analisi: Binflip PRD 99, 012007 (2019)

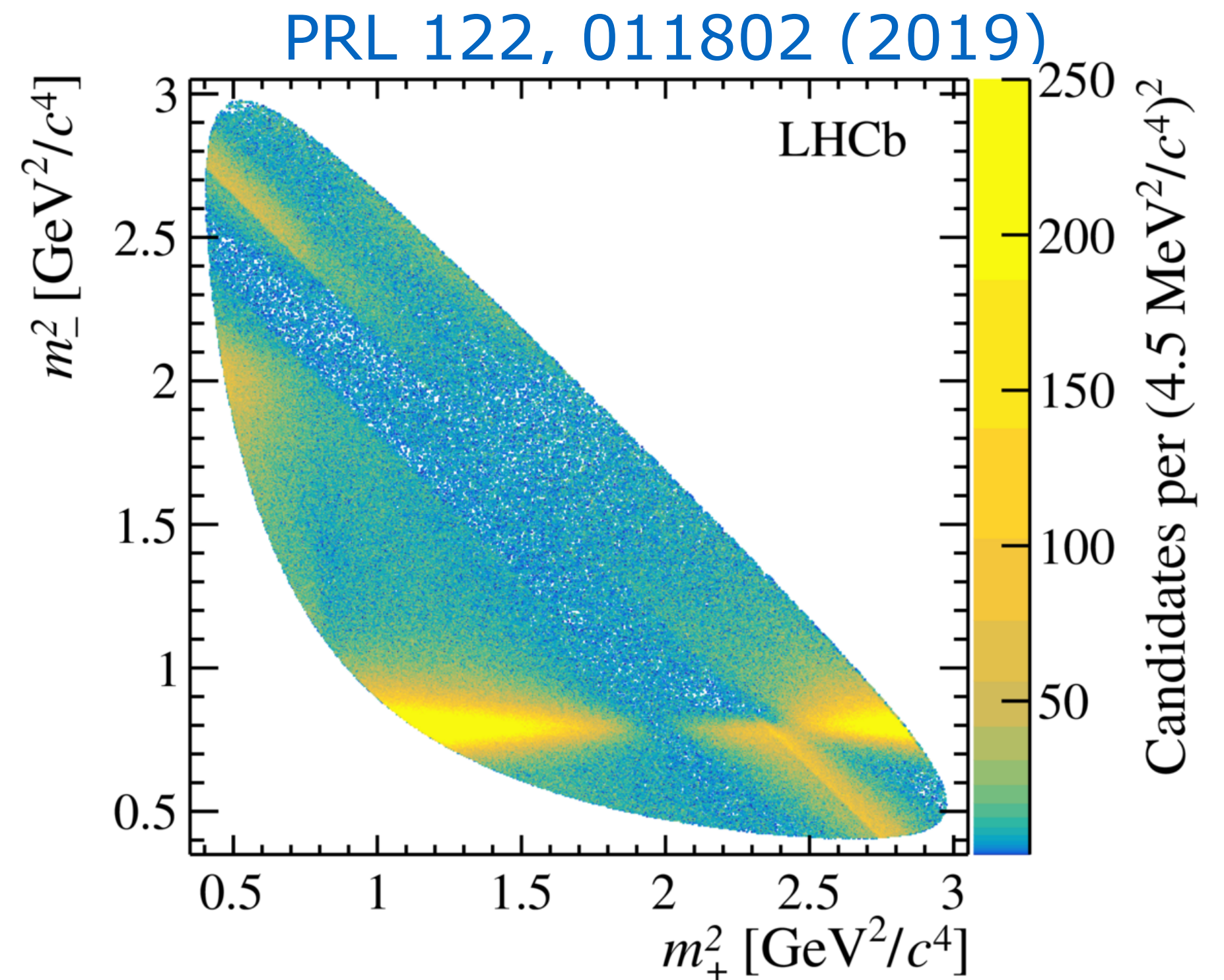
- Estensione della misura di mixing tramite decadimenti WS a decadimenti a molti corpi



$$x' = x \cos \delta_{K\pi} + y \sin \delta_{K\pi}$$

$$y' = y \cos \delta_{K\pi} - x \sin \delta_{K\pi}$$

$$R_{K\pi} \approx R_{K\pi} + \sqrt{R_{K\pi}} y' (\Gamma t) + \frac{x'^2 + y'^2}{4} (\Gamma t)^2$$



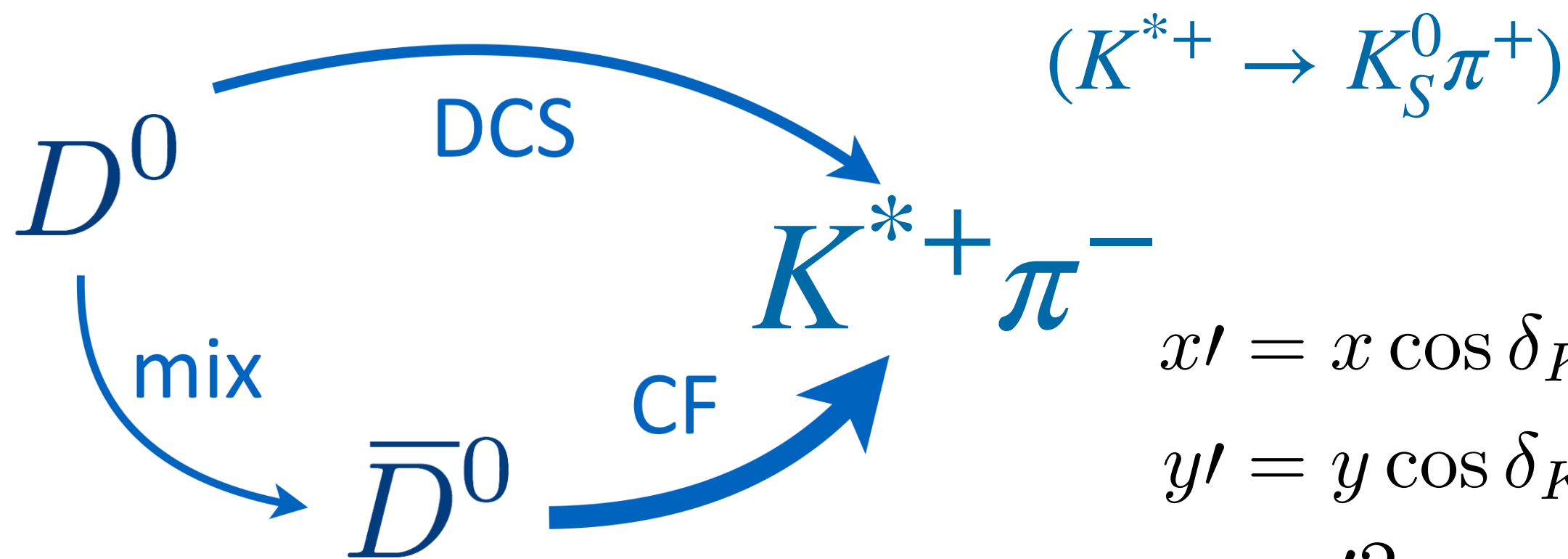
Violazione di CP e Mixing in un'unica misura: $D^0 \rightarrow K_S^0 \pi^+ \pi^-$

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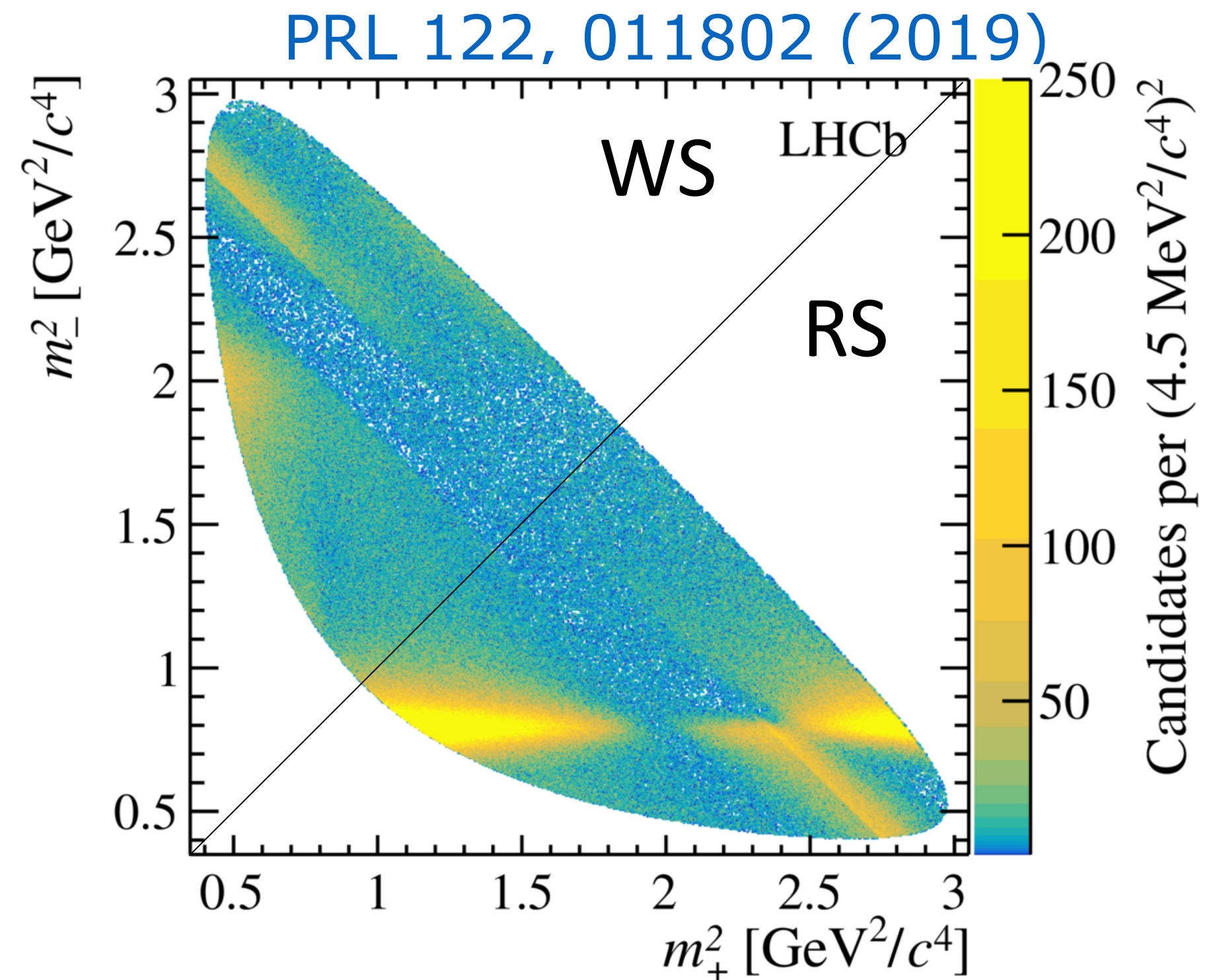
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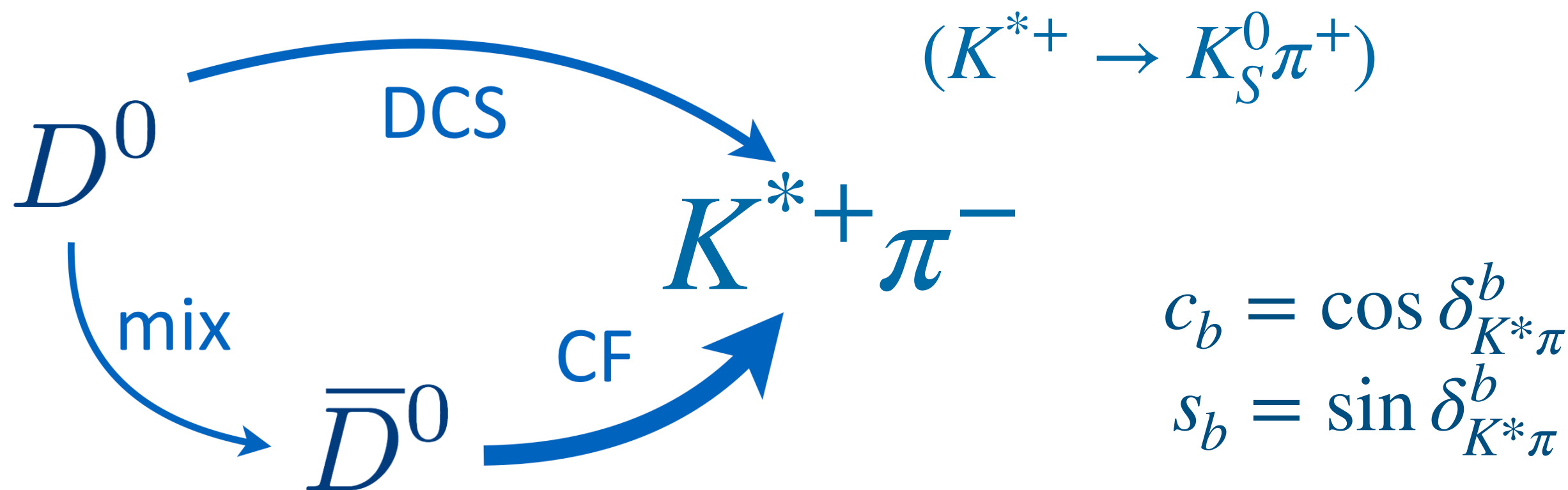
Violazione di CP e Mixing in un'unica misura: $D^0 \rightarrow K_S^0 \pi^+ \pi^-$

Mixing e Violazione di CP indiretta

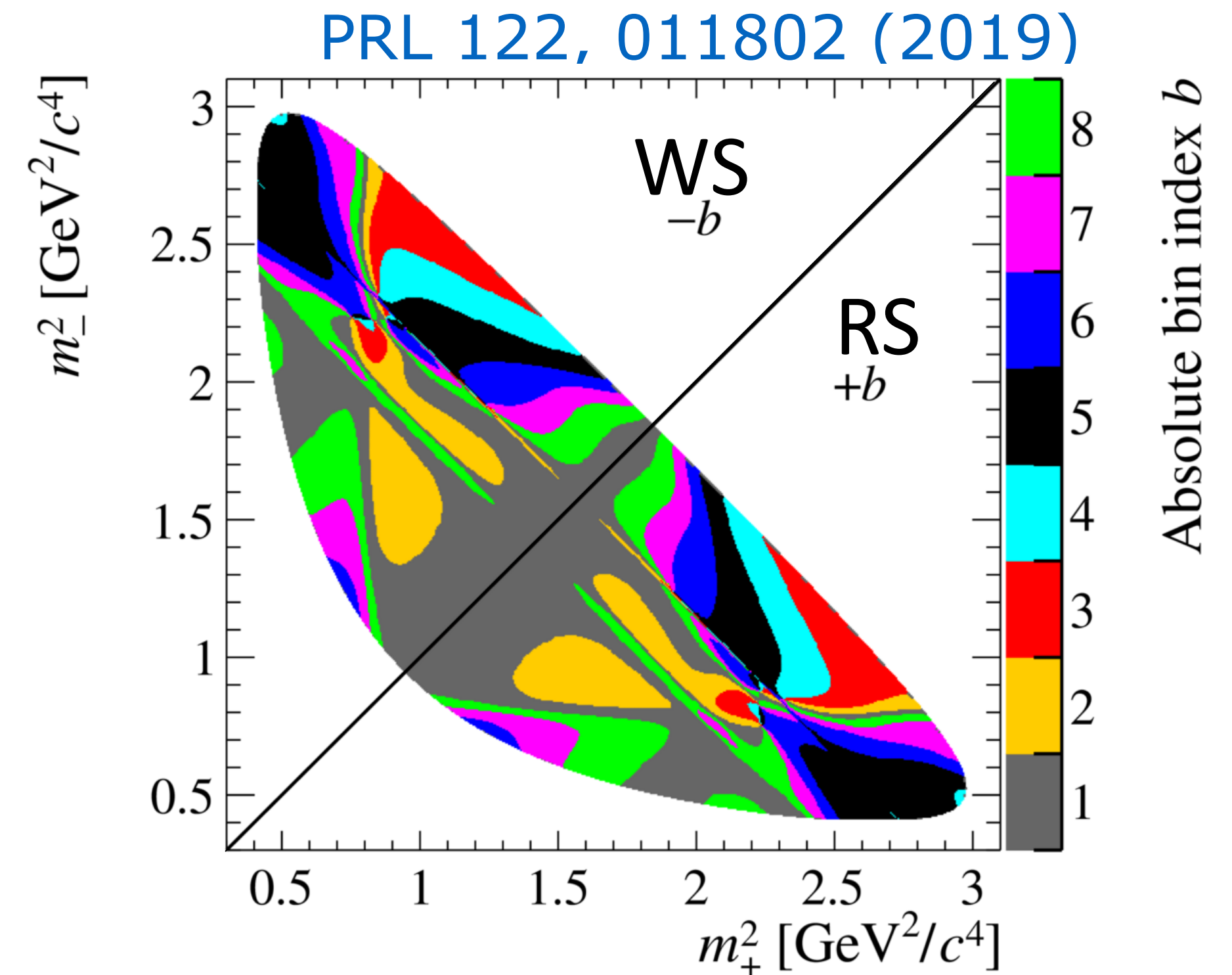
- Permette di misurare direttamente x e y
- Misure di violazione di CP indirect da q/p

Approccio di Analisi: Binflip PRD 99, 012007 (2019)

- Estensione della misura di mixing tramite decadimenti WS a decadimenti a molti corpi



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



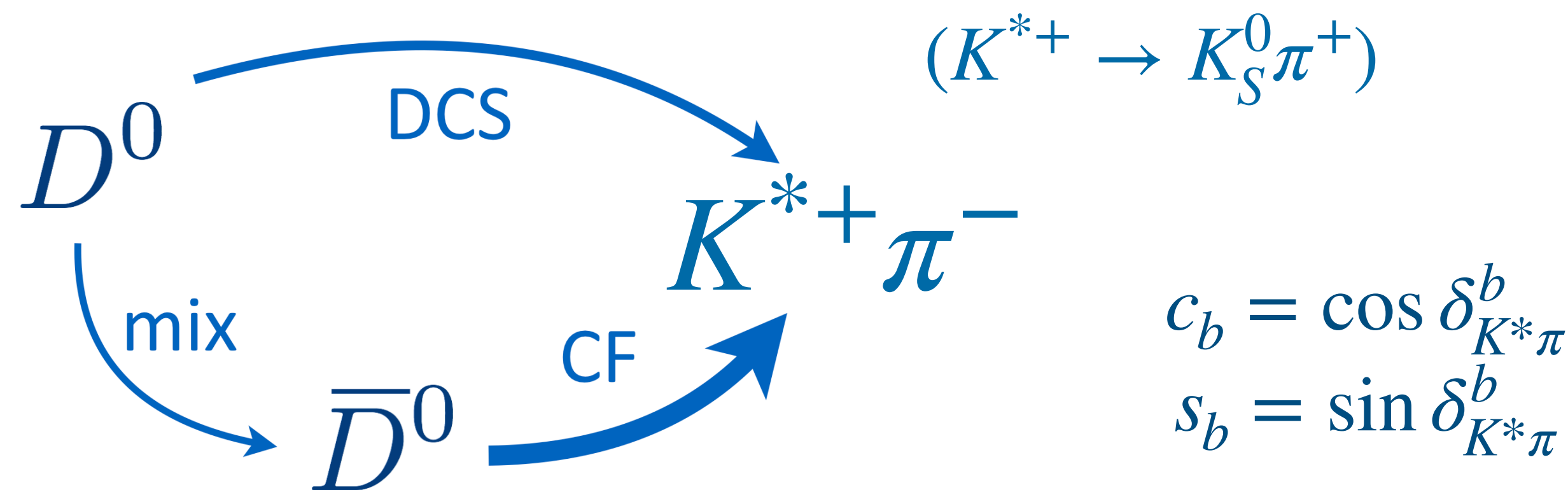
Violazione di CP e Mixing in un'unica misura: $D^0 \rightarrow K_S^0 \pi^+ \pi^-$

Mixing e Violazione di CP indiretta

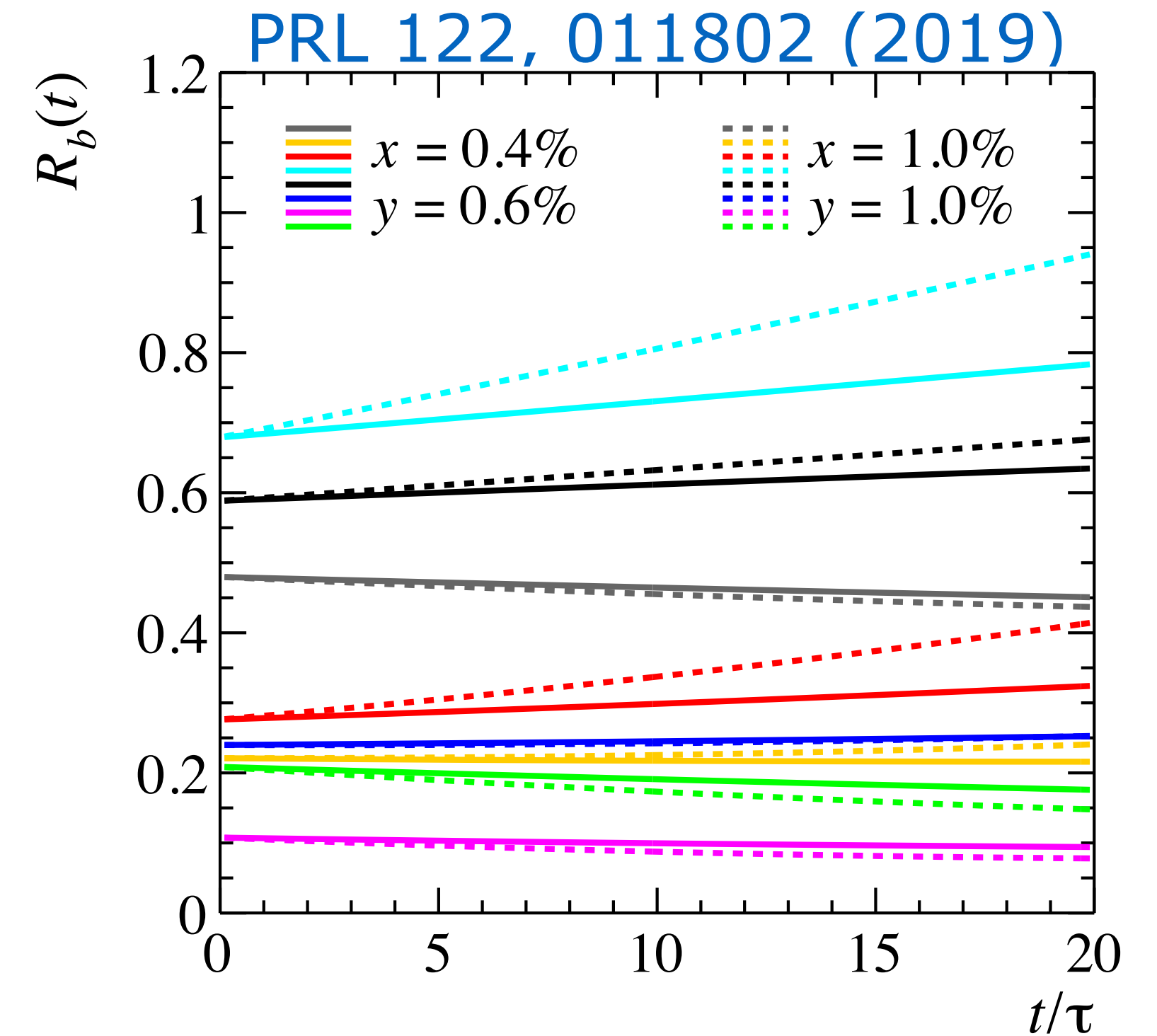
- Permette di misurare direttamente x e y
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Approccio di Analisi: Binflip PRD 99, 012007 (2019)

- Estensione della misura di mixing tramite decadimenti WS a decadimenti a molti corpi

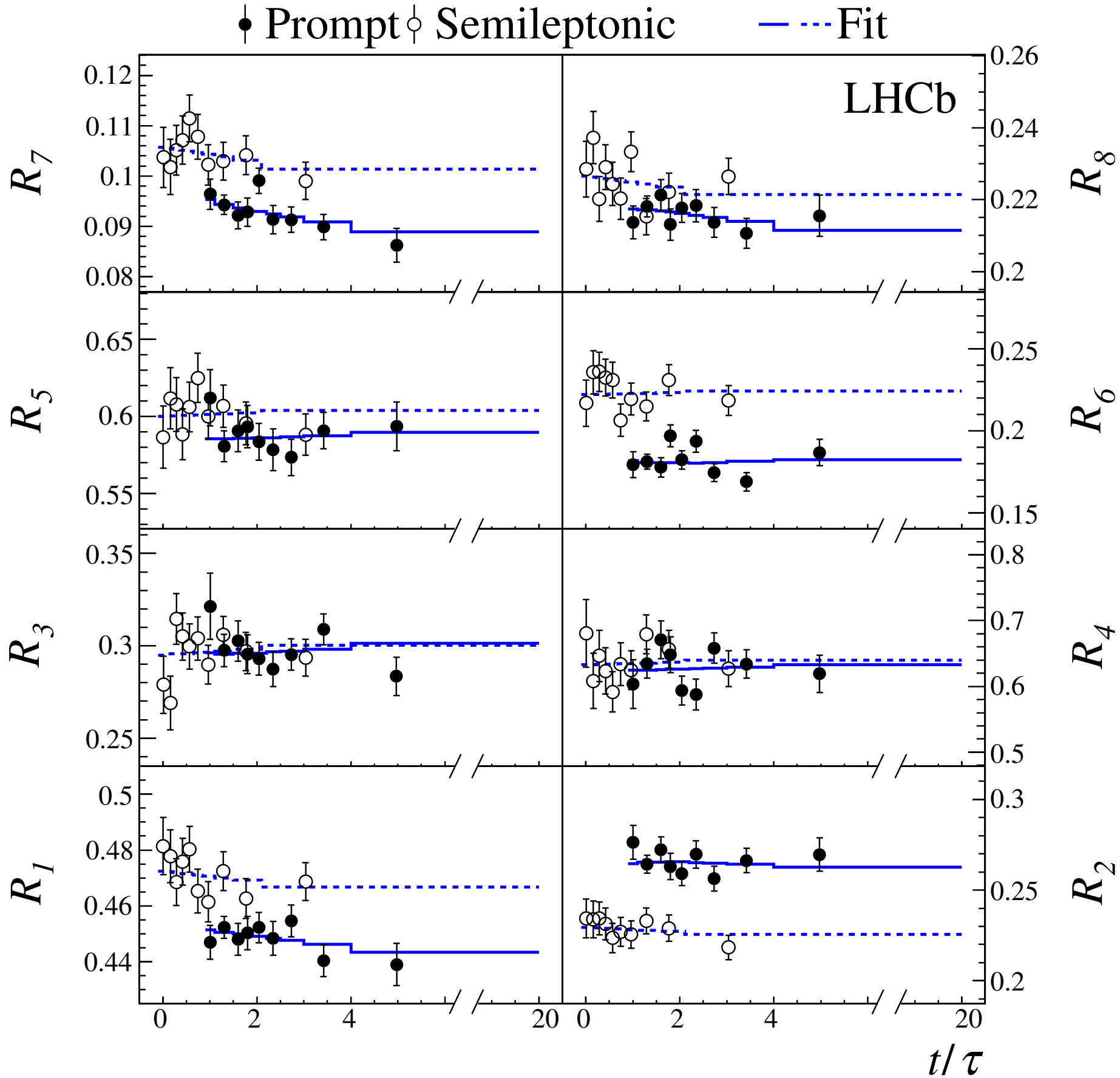


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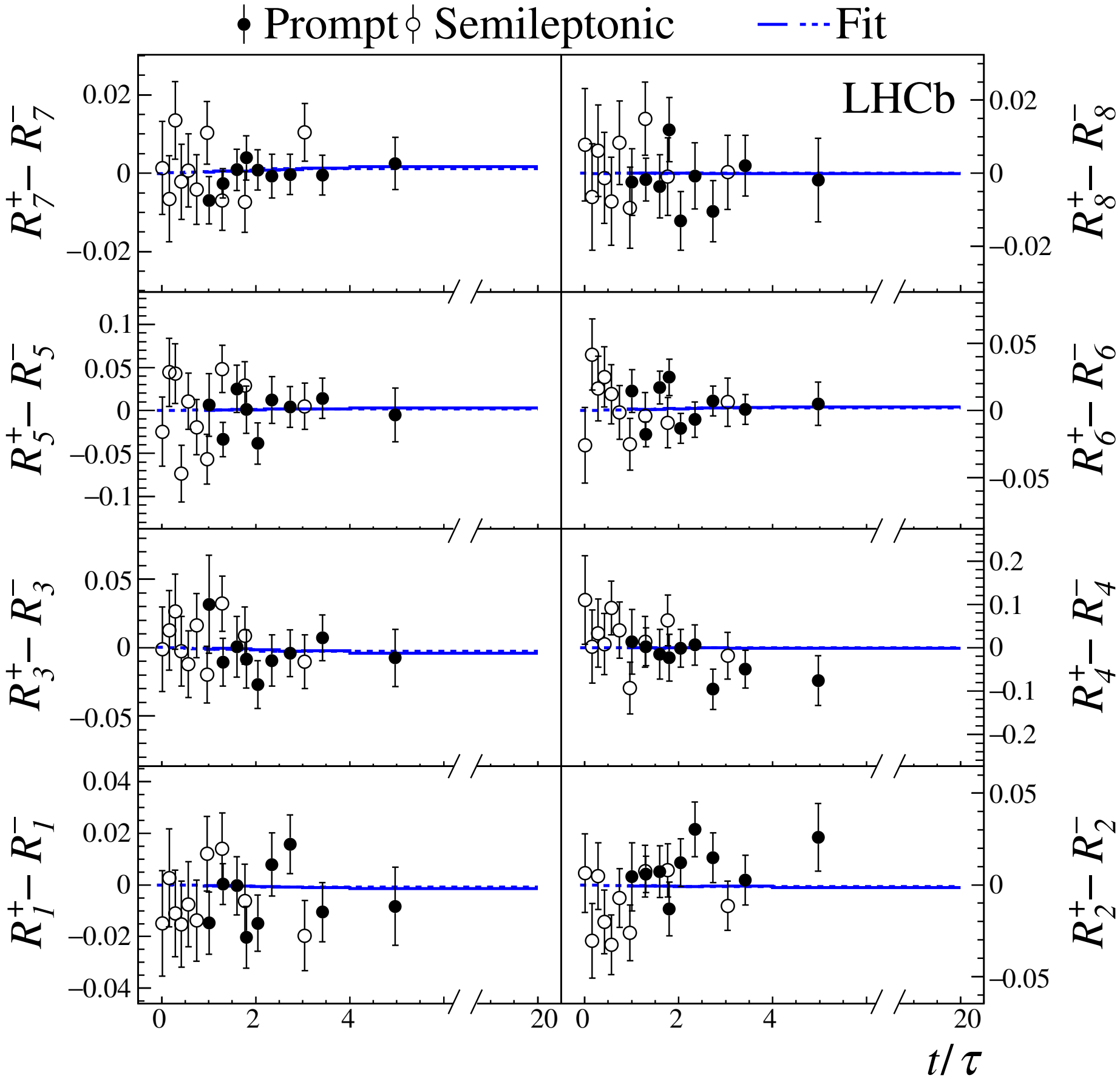


Risultati Bin-Flip $D^0 \rightarrow K^0_s \pi^+ \pi^-$

PRL 122, 011802 (2019)



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

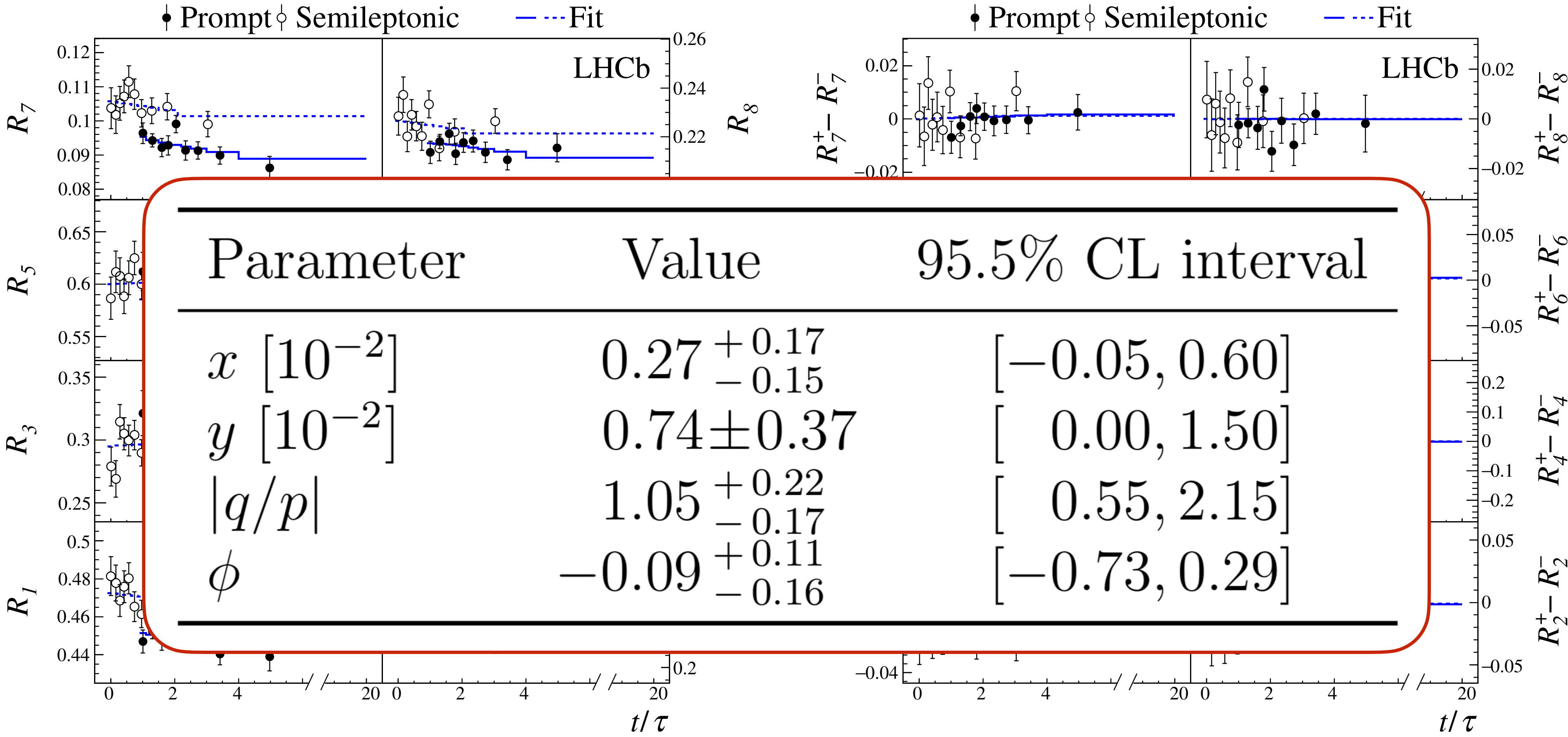


CPV: $D^0 - \bar{D}^0$

Run1 Data
 $N_{\text{prompt}}=1.3\text{M}$
 $N_{\text{semileptonic}}=1\text{M}$

Risultati Bin-Flip $D^0 \rightarrow K^0_s \pi^+ \pi^-$

PRL 122, 011802 (2019)



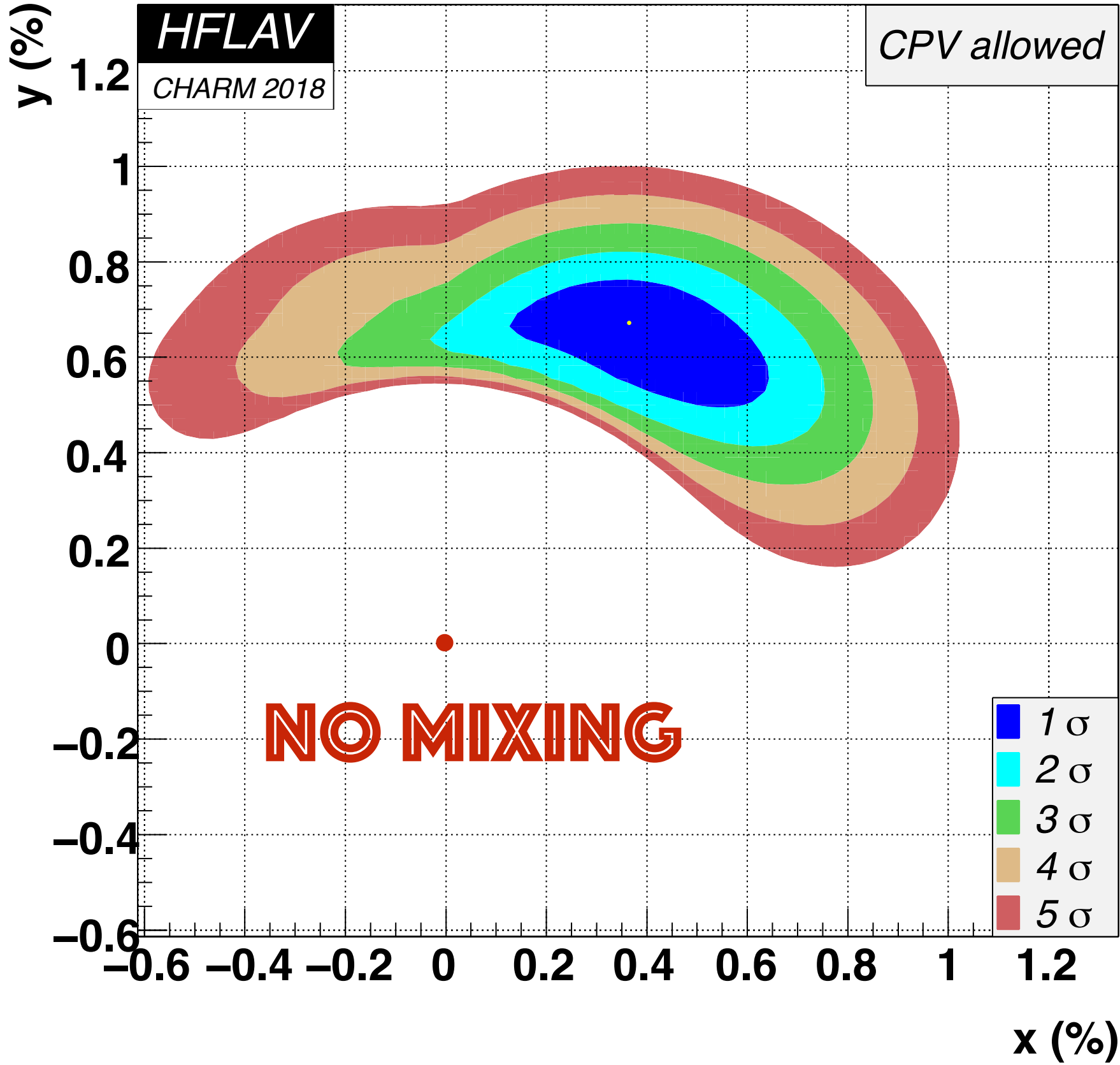
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 $N_{\text{prompt}}=1.3\text{M}$
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Mixing: $D^0 + \bar{D}^0$

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

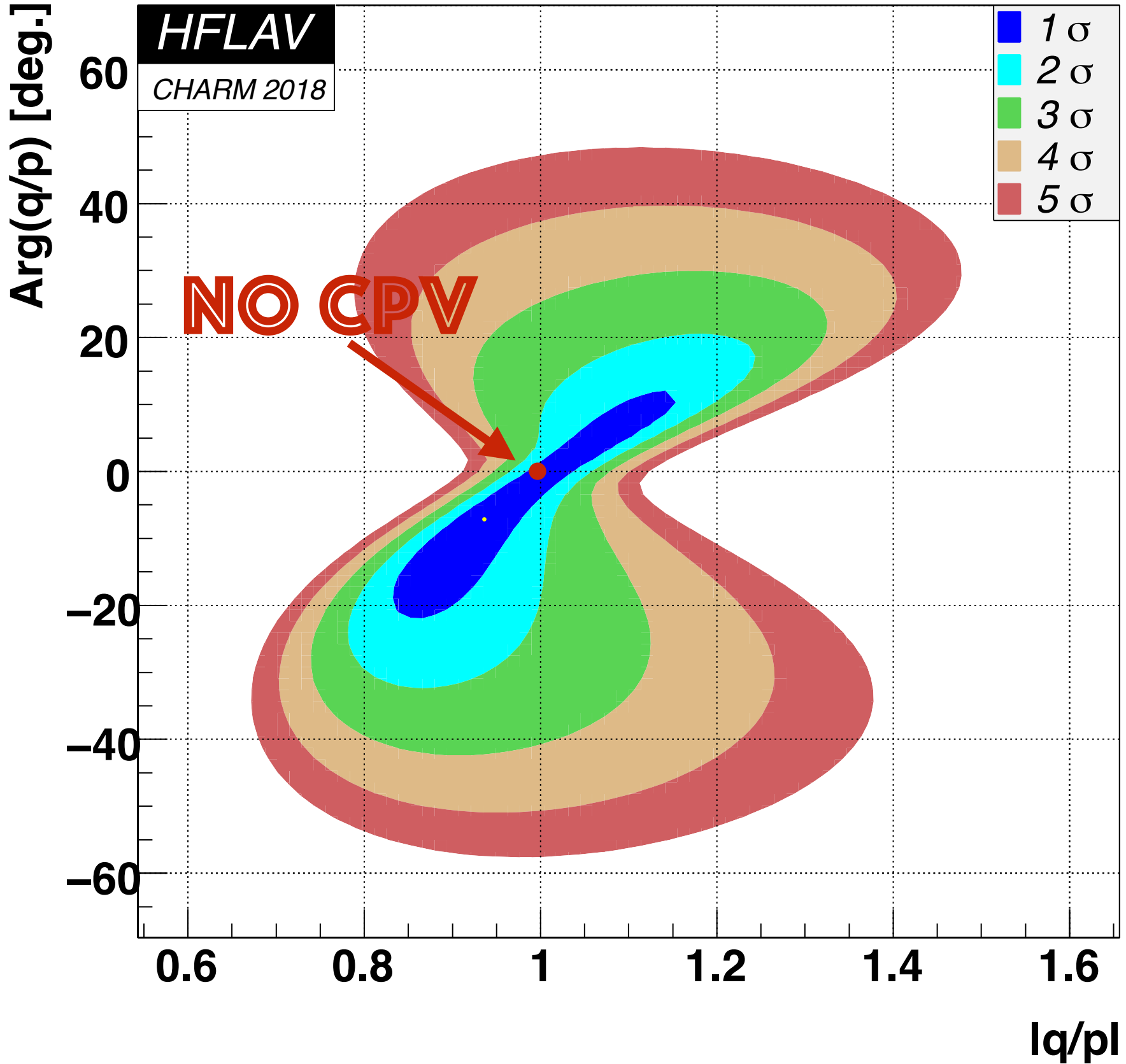
Misura attualmente più precisa di x , $|q/p|$, and ϕ

Impatto sulla Media Mondiale



$$x = (0.39^{+0.11}_{-0.12}) \%$$

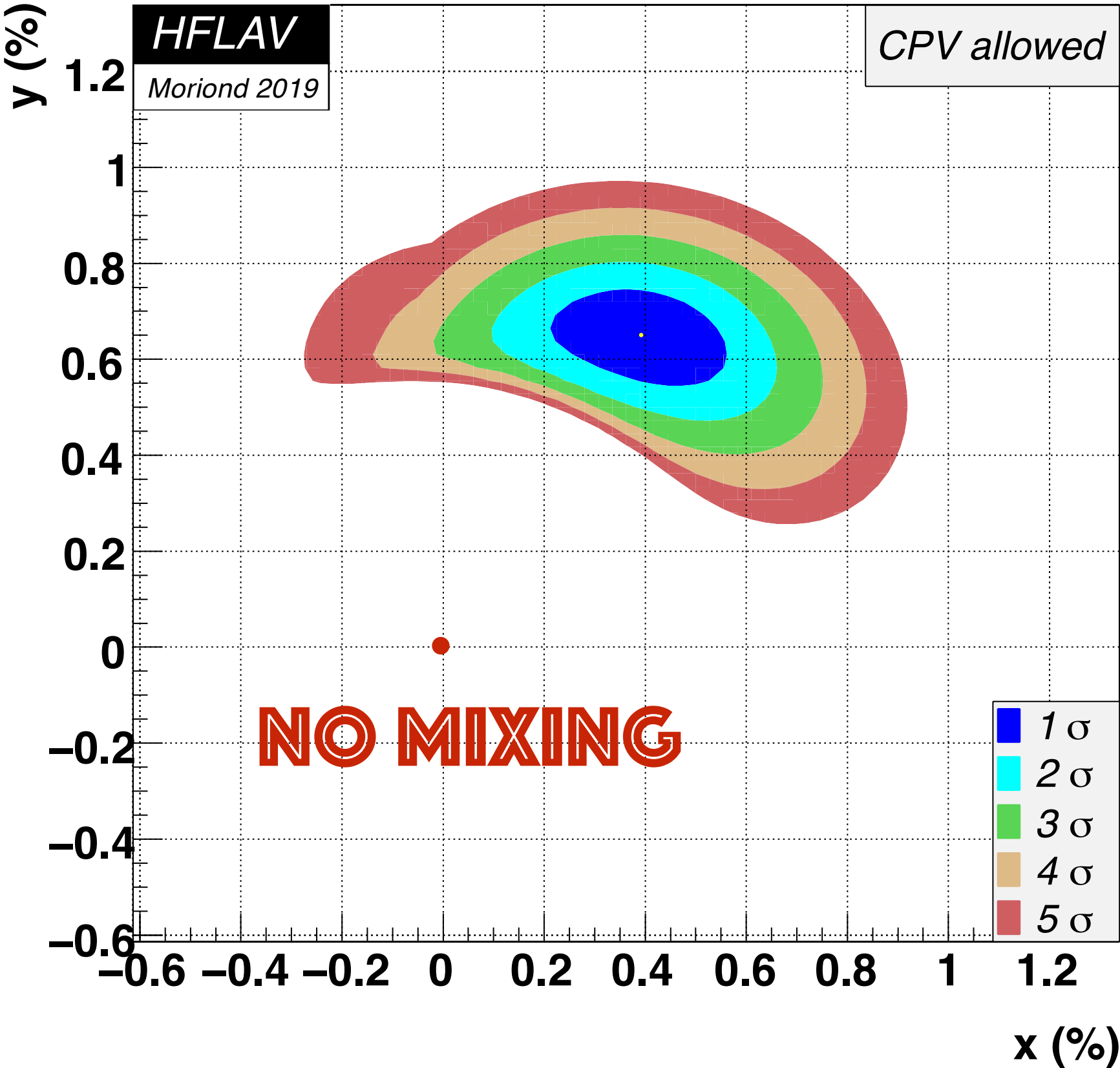
$$y = (0.651^{+0.063}_{-0.069}) \%$$



$$|q/p| = (0.969^{+0.050}_{-0.045})$$

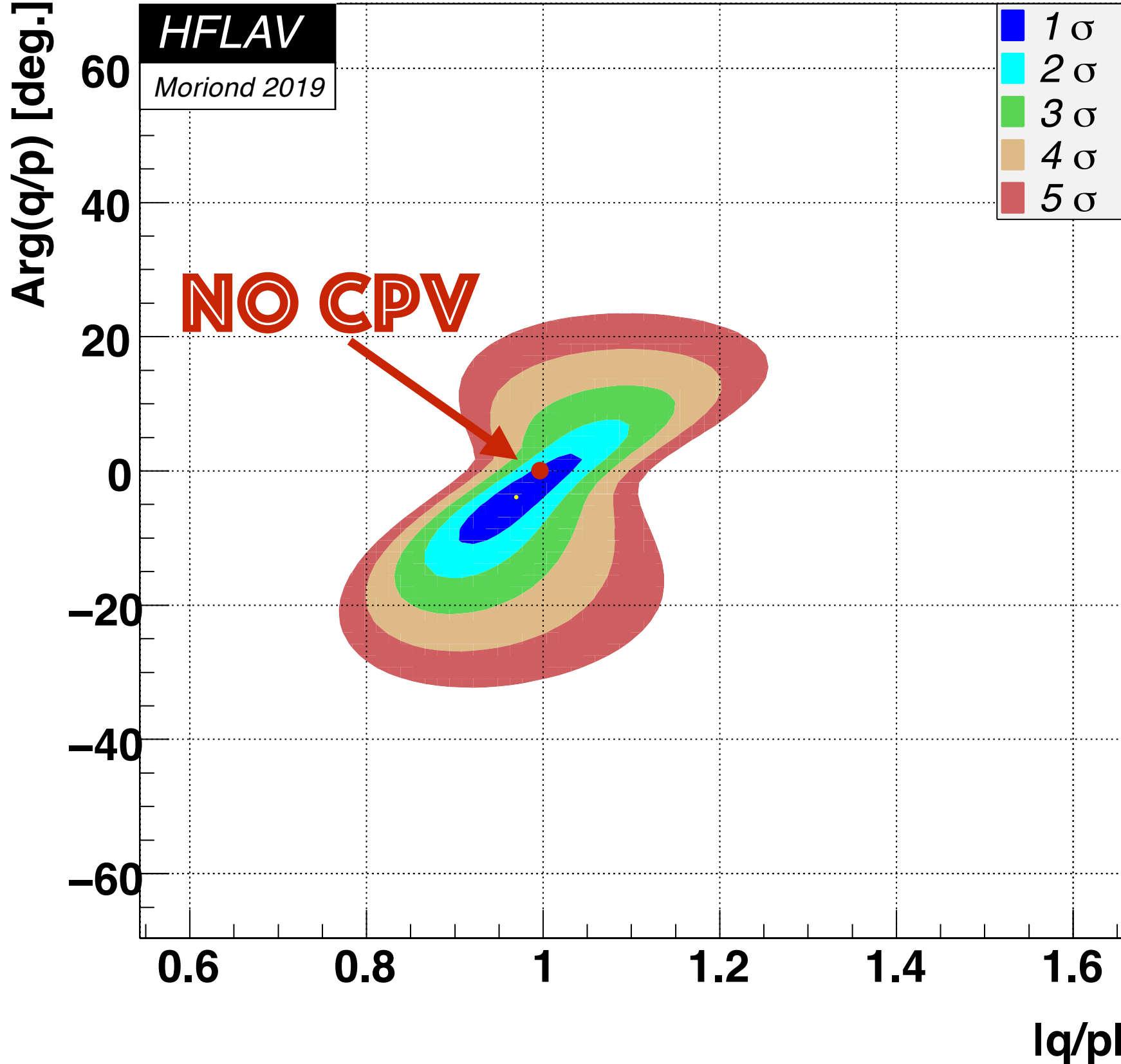
$$\phi = (-3.9^{+4.5}_{-4.6})^\circ$$

Impatto sulla Media Mondiale



$$x = (0.39^{+0.11}_{-0.12}) \%$$

$$y = (0.651^{+0.063}_{-0.069}) \%$$



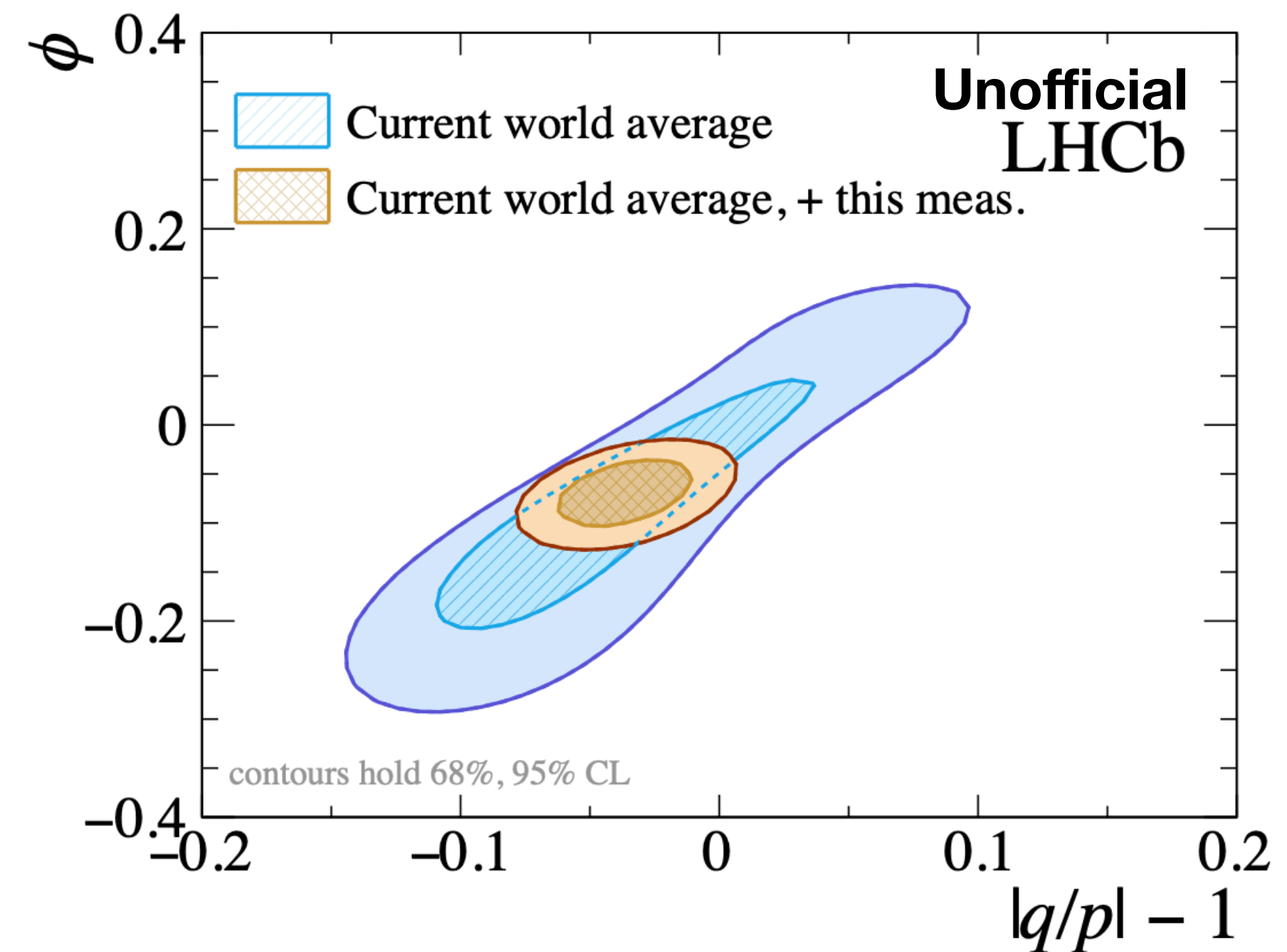
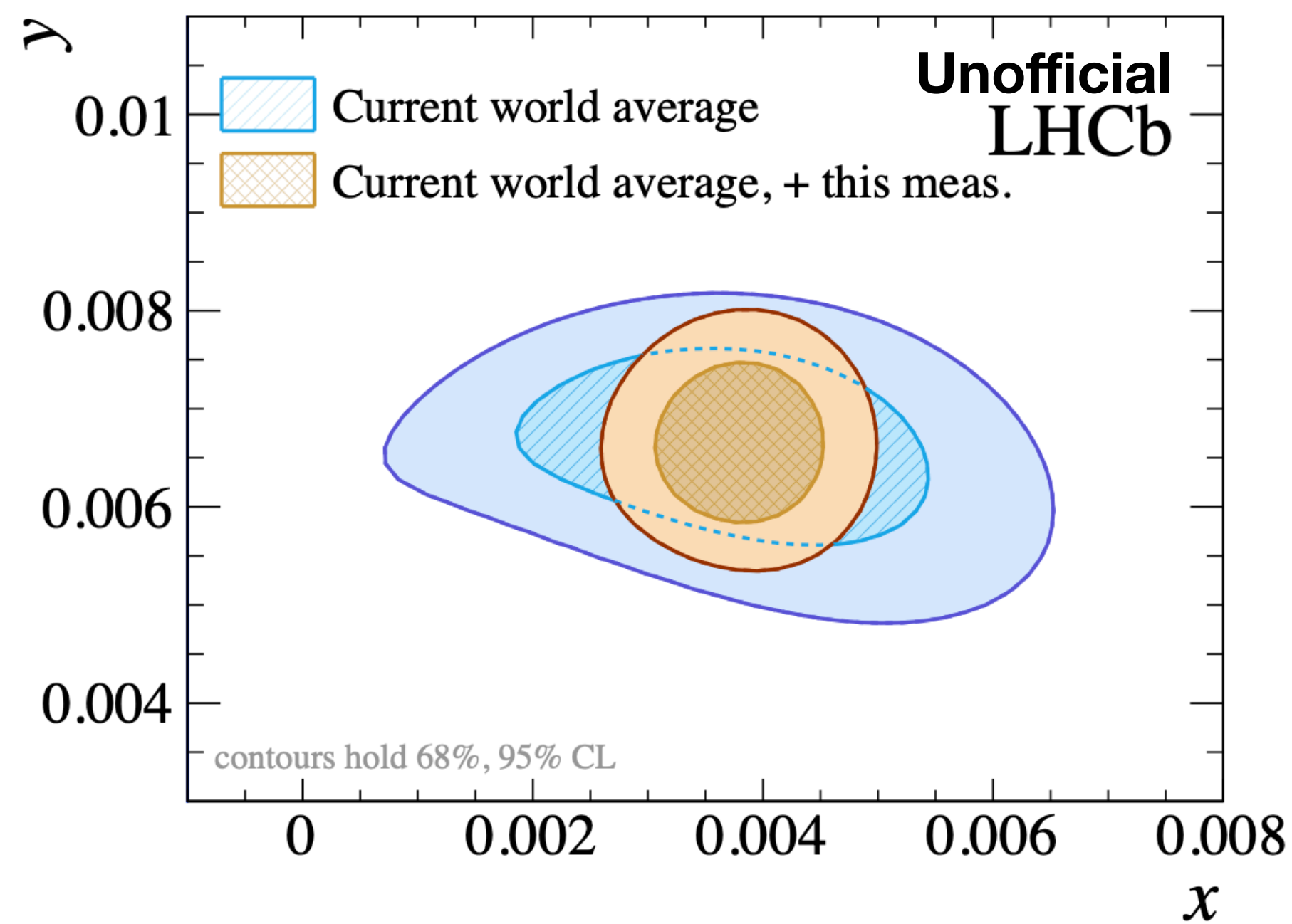
$$|q/p| = (0.969^{+0.050}_{-0.045})$$

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

Analisi di $D^0 \rightarrow K^0_S \pi^+ \pi^-$ nel Run2

Incremento del Dataset

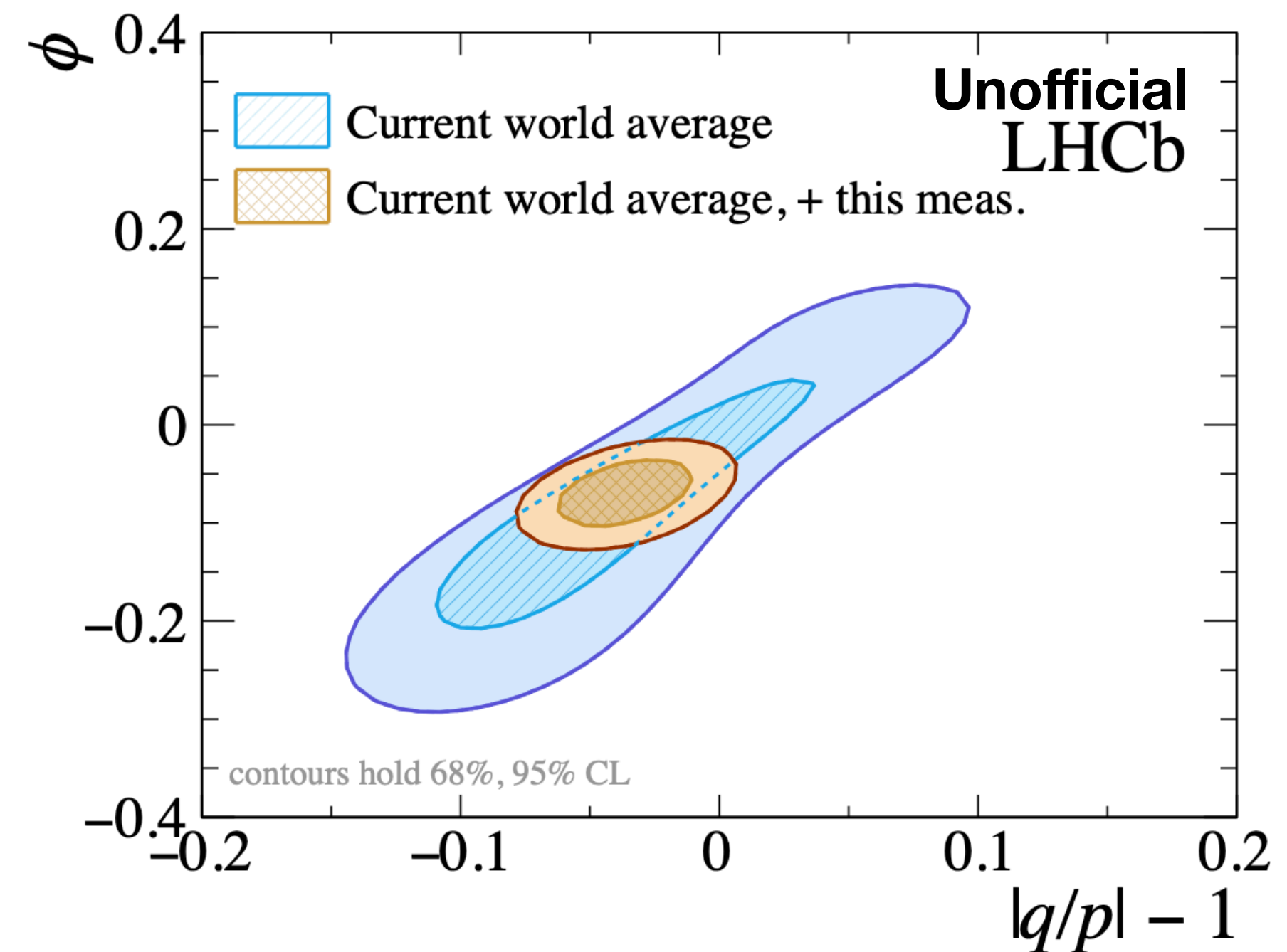
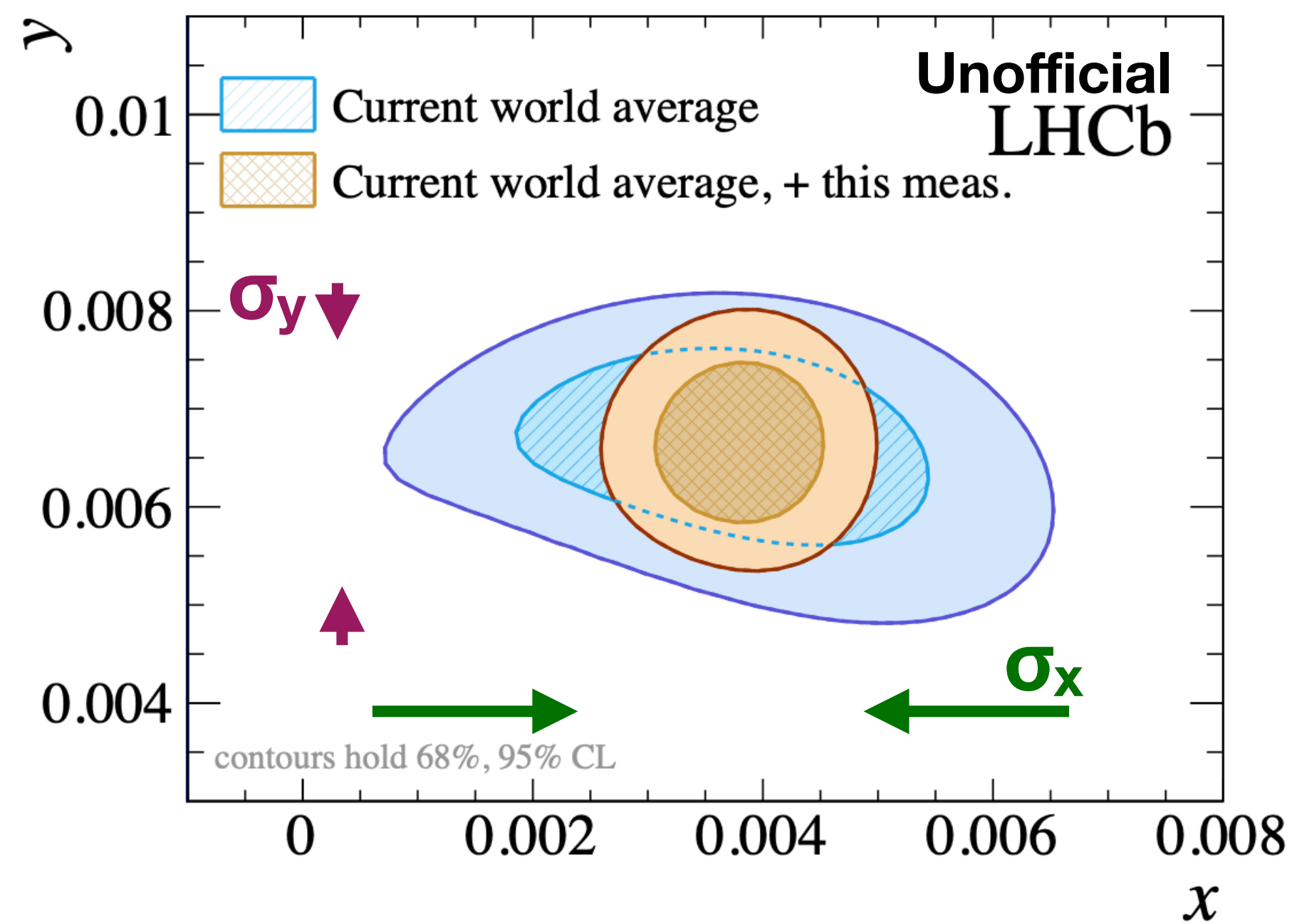
- Run1 \rightarrow Run2 : 32x eventi di segnale prompt
 - 2x incremento della sezione d'urto cc da 7-8 a 13 TeV
 - 16x miglioramento della selezione a livello di trigger (Turbo stream)



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Misura di y

Recuperare Sensività su y

- La tecnica del binflip ha scarsa sensitività su y per costruzione
 y influisce sul rapporto dei decadimenti autostati di CP (e.g.: $D^0 \rightarrow K^0_S \rho$)

Rapporto CP-dispari/CP-pari nel Tempo

$$N_{\text{ON}}(t) = f_{\text{ON}} a_1(s_0) e^{-\frac{t}{\tau}(1+y)} + (1 - f_{\text{ON}}) a_2(s_0) e^{-\frac{t}{\tau}(1-y)}$$

$$N_{\text{OFF}}(t) = f_{\text{OFF}} a_1(s_0) e^{-\frac{t}{\tau}(1+y)} + (1 - f_{\text{OFF}}) a_2(s_0) e^{-\frac{t}{\tau}(1-y)}$$



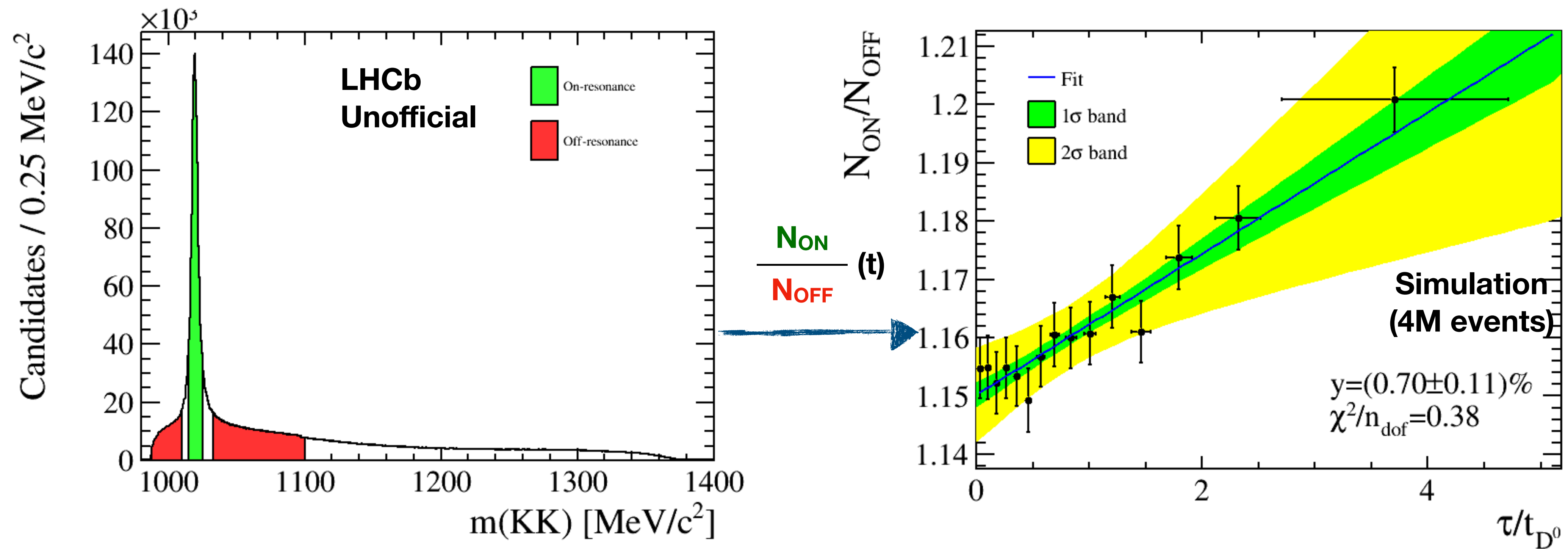
$$\frac{dN_{\text{ON}}}{dN_{\text{OFF}}}(t) = 1 - 2(f_{\text{ON}} - f_{\text{OFF}}) \frac{t}{\tau} y + O(y^2)$$

$f_{\text{ON/OFF}}$ = frazione CP-dispari (a_1) su totale (a_1+a_2)

Misura di y in $D^0 \rightarrow K^0_s K^+ K^-$

Struttura Risonante Ideale per la Misura

- La struttura risonante di $D^0 \rightarrow K^0_s \pi^+ \pi^-$ è complicata, è molto più semplice in $D^0 \rightarrow K^0_s K^+ K^-$
Sono predominanti $D^0 \rightarrow K^0_s \phi$ (CP-odd) e $D^0 \rightarrow K^0_s (K^+ K^-)_{\text{onda-s}}$ (CP-even)



Misura di y in $D^0 \rightarrow K^0_s K^+ K^-$ - Challenges

Efficienza di Ricostruzione

- Varia con il tempo di decadimento del D^0 a causa dei tagli in momento e parametro di impatto imposti su K^+ e K^- a livello di trigger
- Può introdurre un errore sistematico su y se non corretta
- In Bicocca stiamo studiando il trigger del Run3 di LHCb, basato su algoritmi per GPU, per ovviare a questo problema

Modello di Decadimento

- f_{ON} e f_{OFF} sono determinati da modelli di decadimento ottenuti da misure antecedenti (BaBar, Belle, BESIII)
- Le variazioni di questi parametri possono influire sulla misura introducendo un errore sistematico

Possibili tesi di laurea

LHCb Upgrade

LHCb Upgrade

Effetti Oltre il Modello Standard

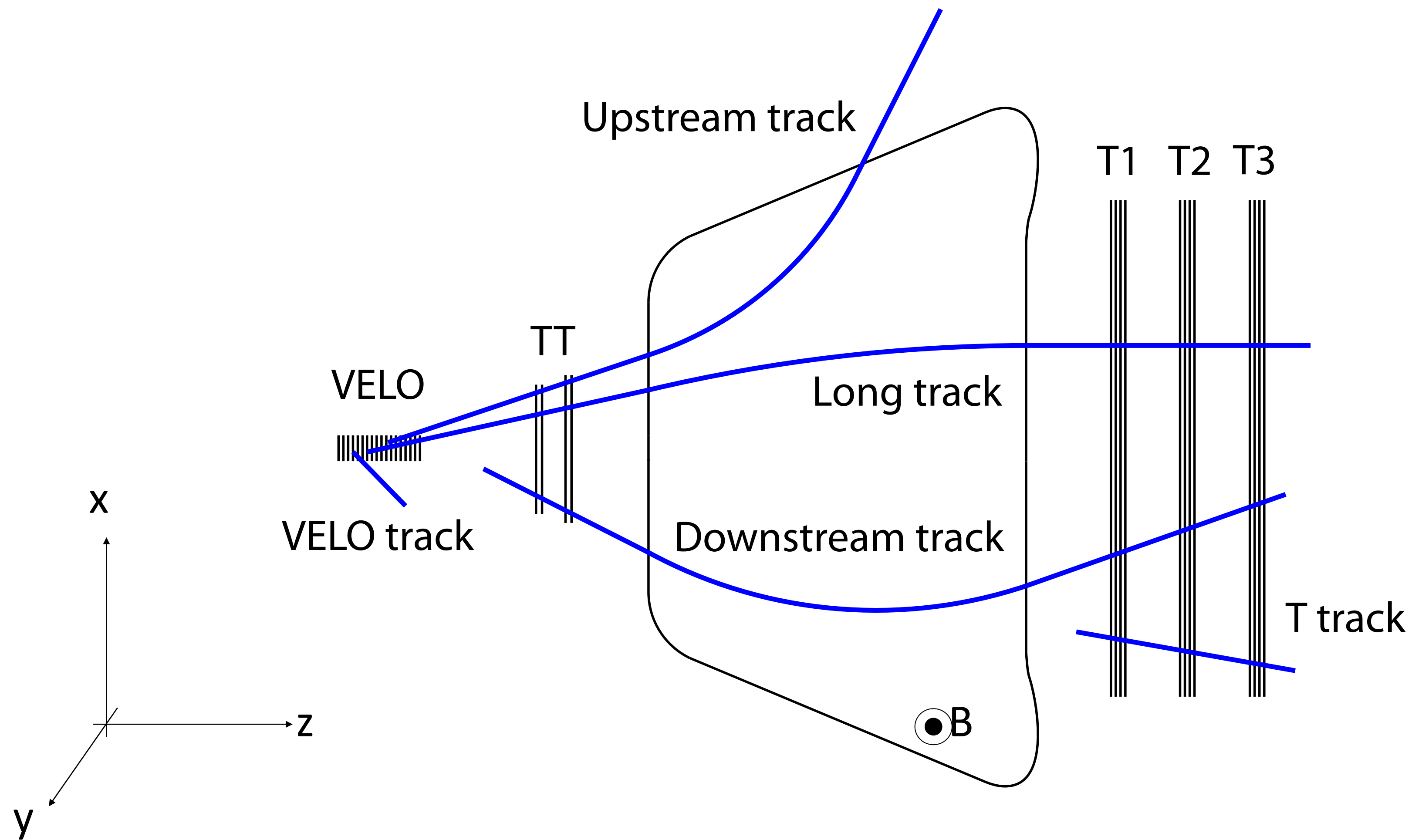
- La sensibilità dell'Upgrade di LHCb (2021-2029) raggiungerà i 10^{-5} per la ricerca di violazione di CP diretta e indiretta nel Charm
- Per la violazione di CP indiretta in particolare si potrebbero evidenziare effetti non contemplati dal Modello Standard ($a_{CP}^{ind(th)}=10^{-5}$)
- Misure più accurate e in ulteriori canali chiariranno la natura della violazione di CP diretta

Saranno anni molto "charmant"!

*Spare*s

Tracks Reconstruction at LHCb

JINST 10 (2015) P02007



Tracking Asymmetries

Sources of Inefficiency

- **Material Interactions**
15% nuclear interaction length before the end of the tracker
- **Geometry**
Trajectories through dead-channels, beam-pipe or out of the detector
- **Tracking**
High-occupancy, low p_T

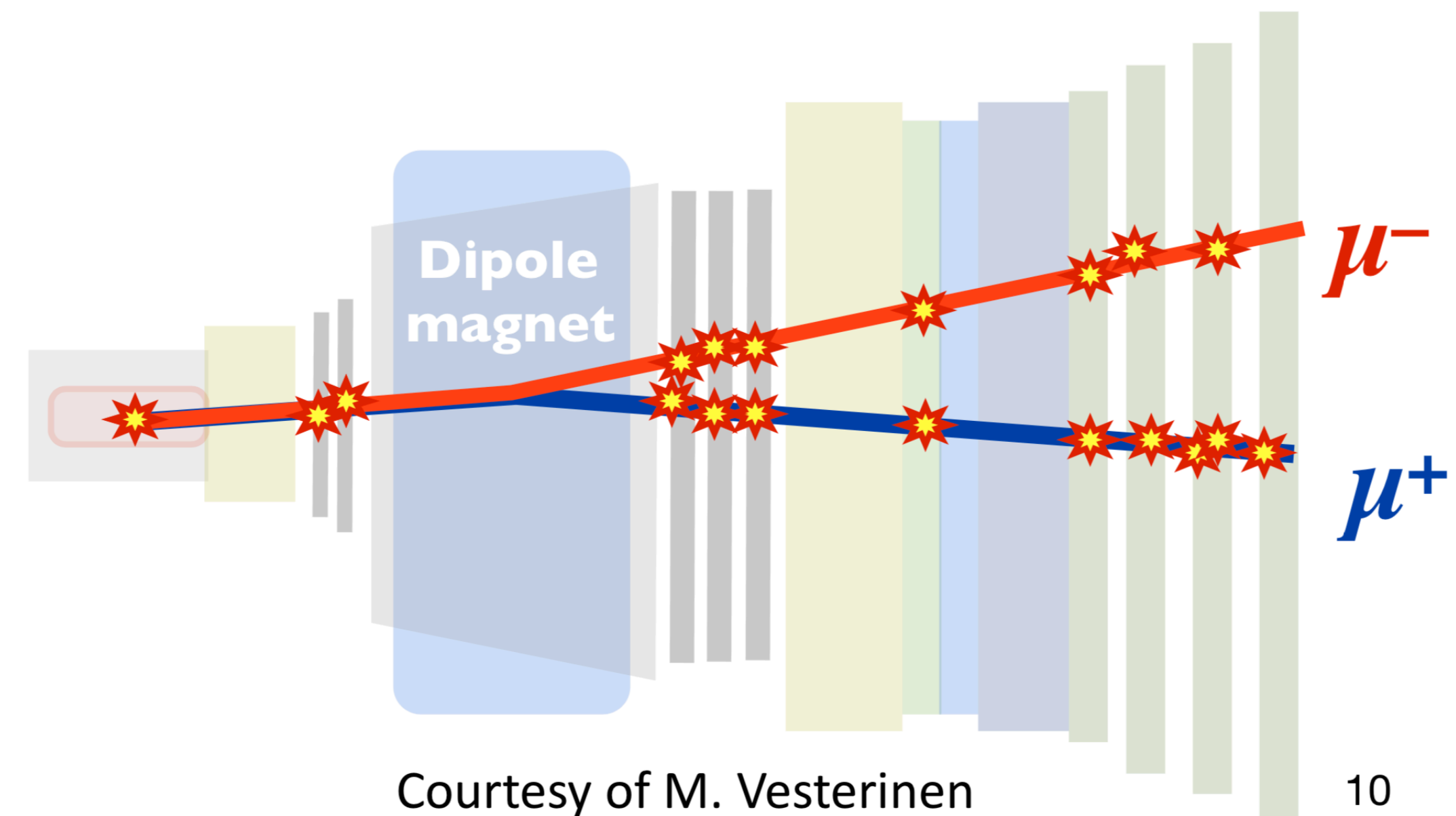
Depend on charge
(+kinematics, detector/machine conditions)

Uncertainty

- 10% on material budget, detector conditions over time, beam position, detector simulation

Strategies

- **Avoidance**
Use observables non-sensitive to detection asymmetries (e.g. ΔA_{CP})
- **Calibration**
Measure the correct asymmetries
- **Ignore it**
When statistical uncertainty much larger than residual asymmetry after averaging the two polarities



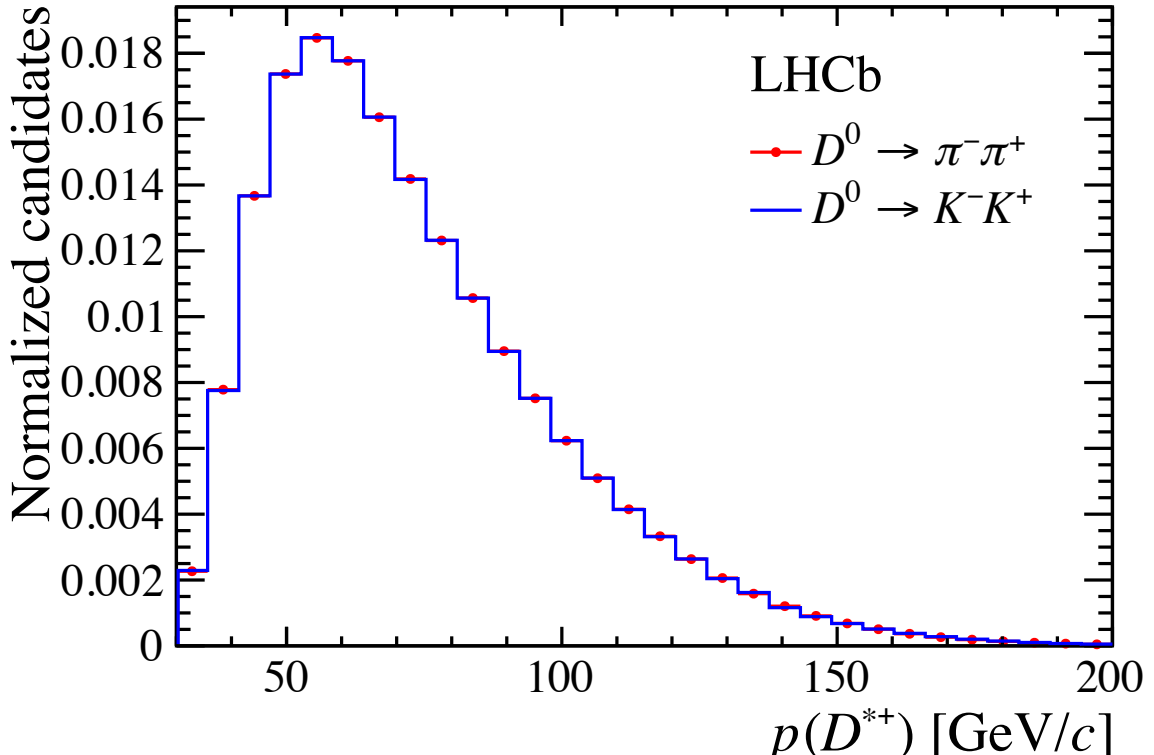
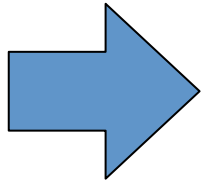
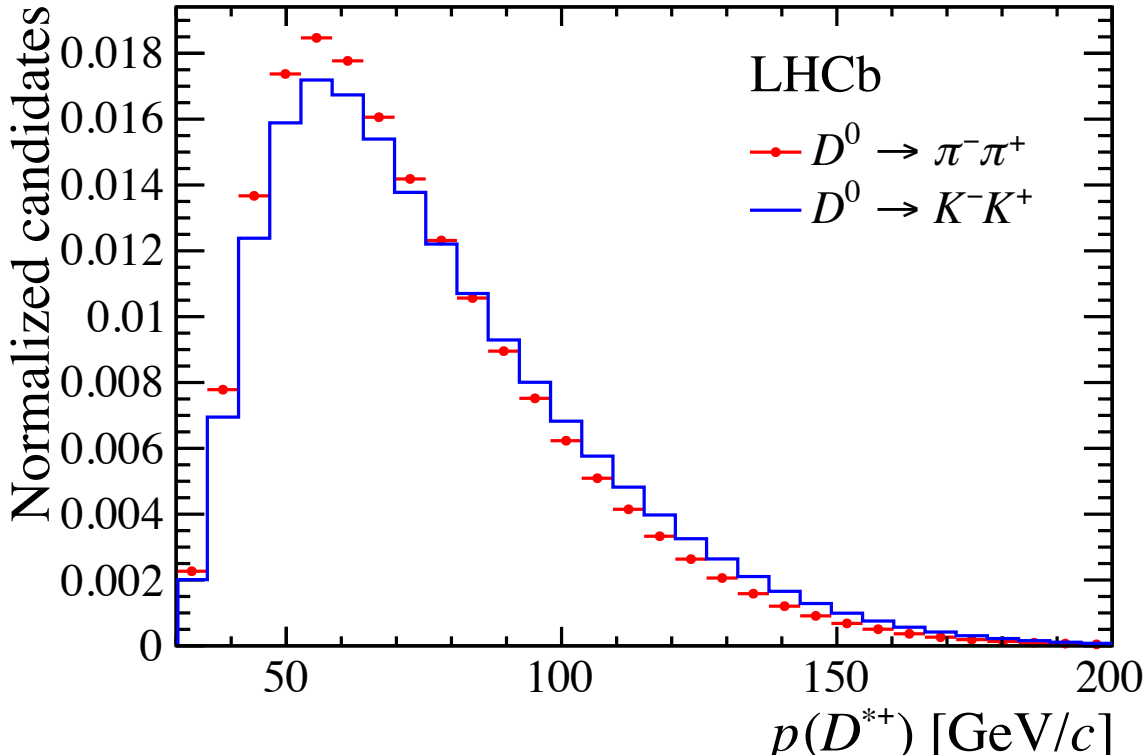
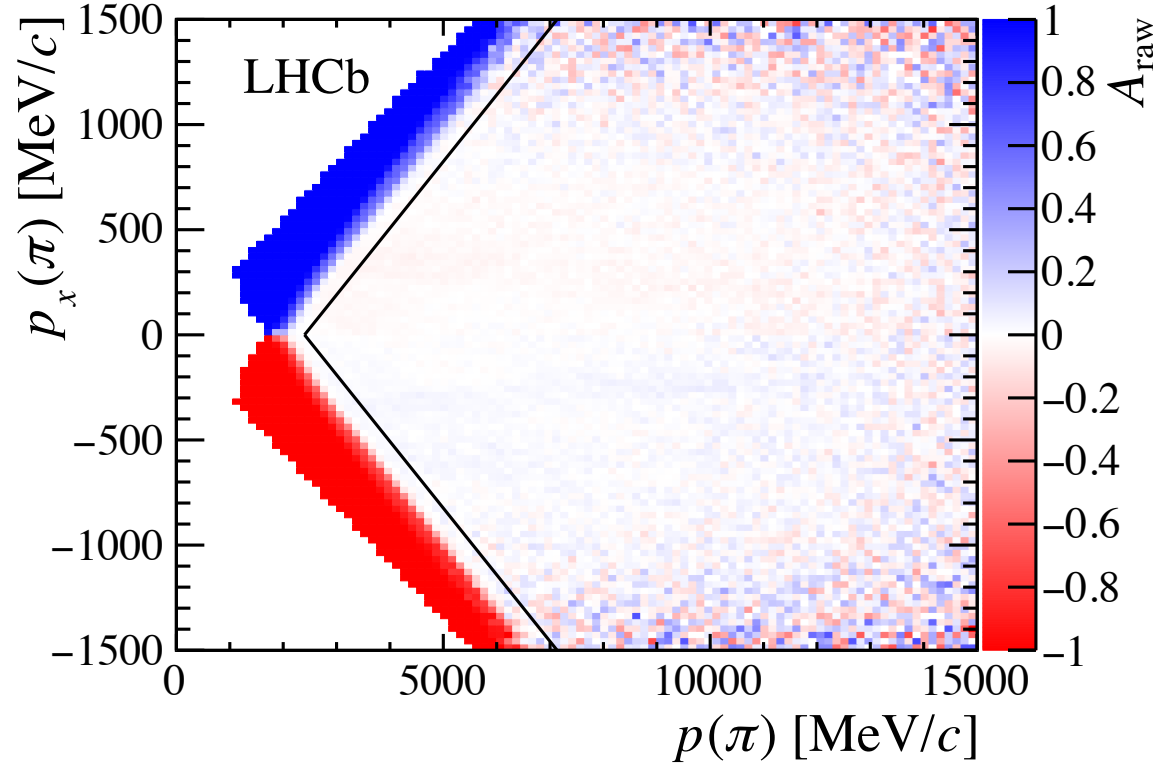
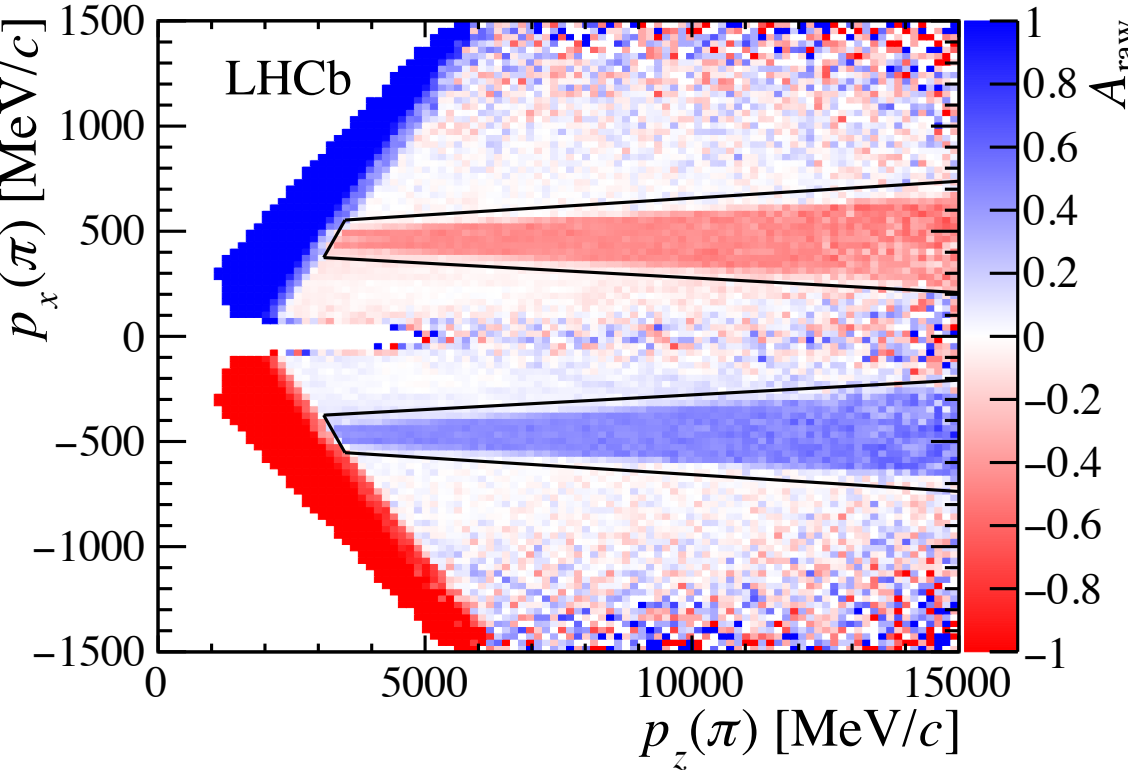
Correcting Tracking Asymmetries

Remove Areas with Large Asymmetries

- Regions in which only D^{*+} or D^{*-} are possible since low momentum pion escapes detection
- Break the assumption that A_{hh} is small

Reweigh by Momenta Distributions

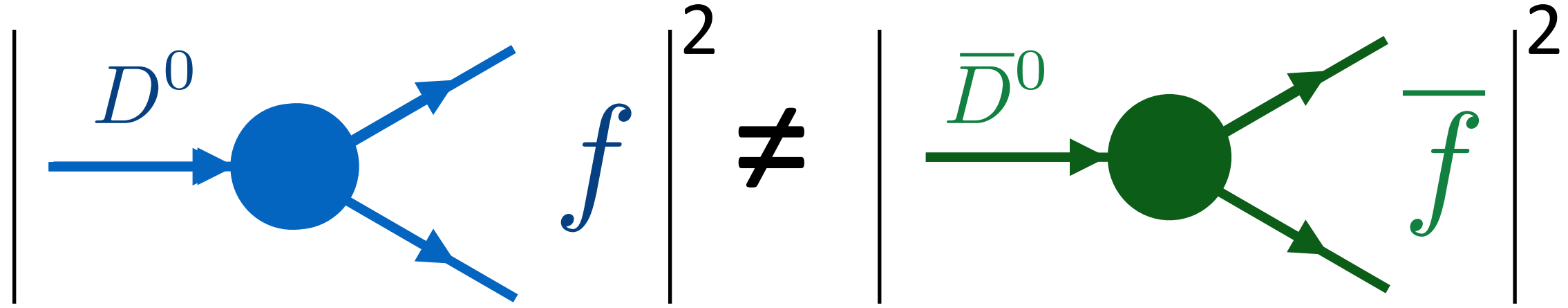
- Detection and production asymmetries dependent on kinematics of the reconstructed particles
- Typical Variables (p , p_T , ϕ) for D^{*+} and D^0



CP Violation in Charm

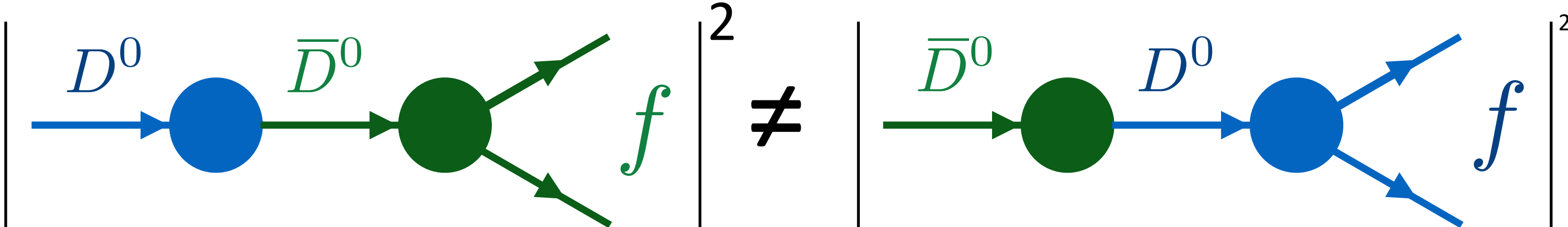
Decay

Direct

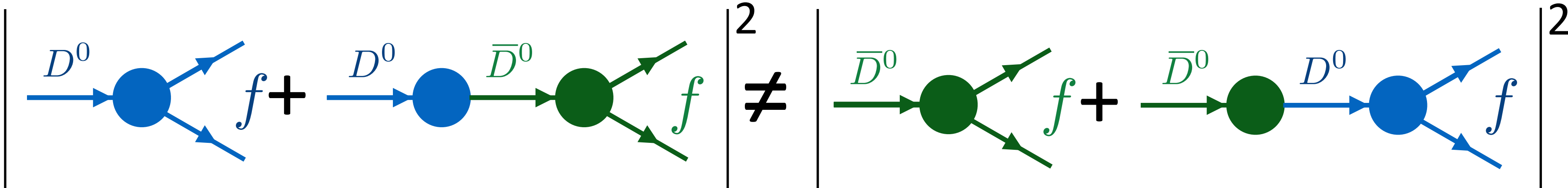


Mixing

Indirect



Interference Mixing and Decay



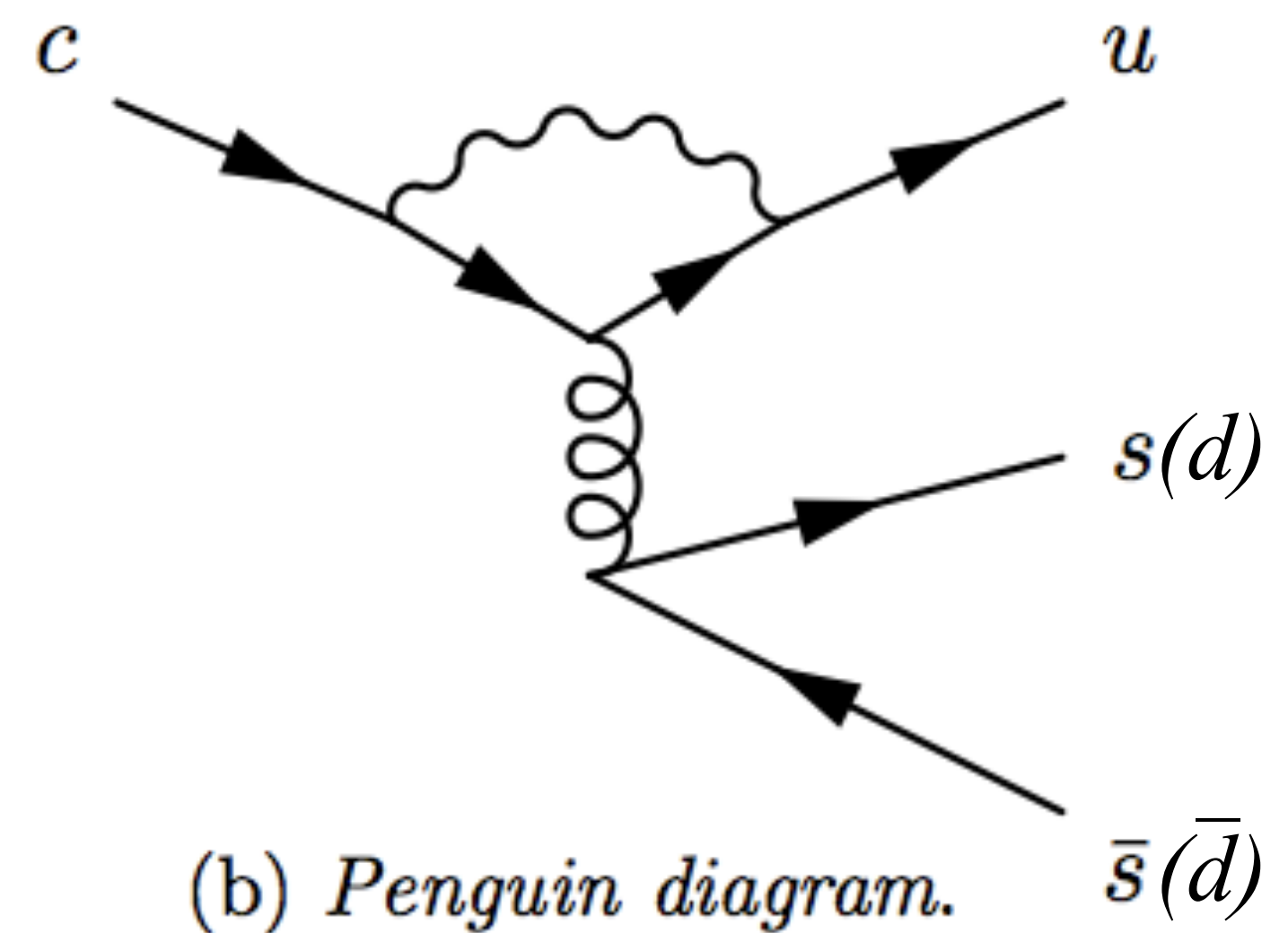
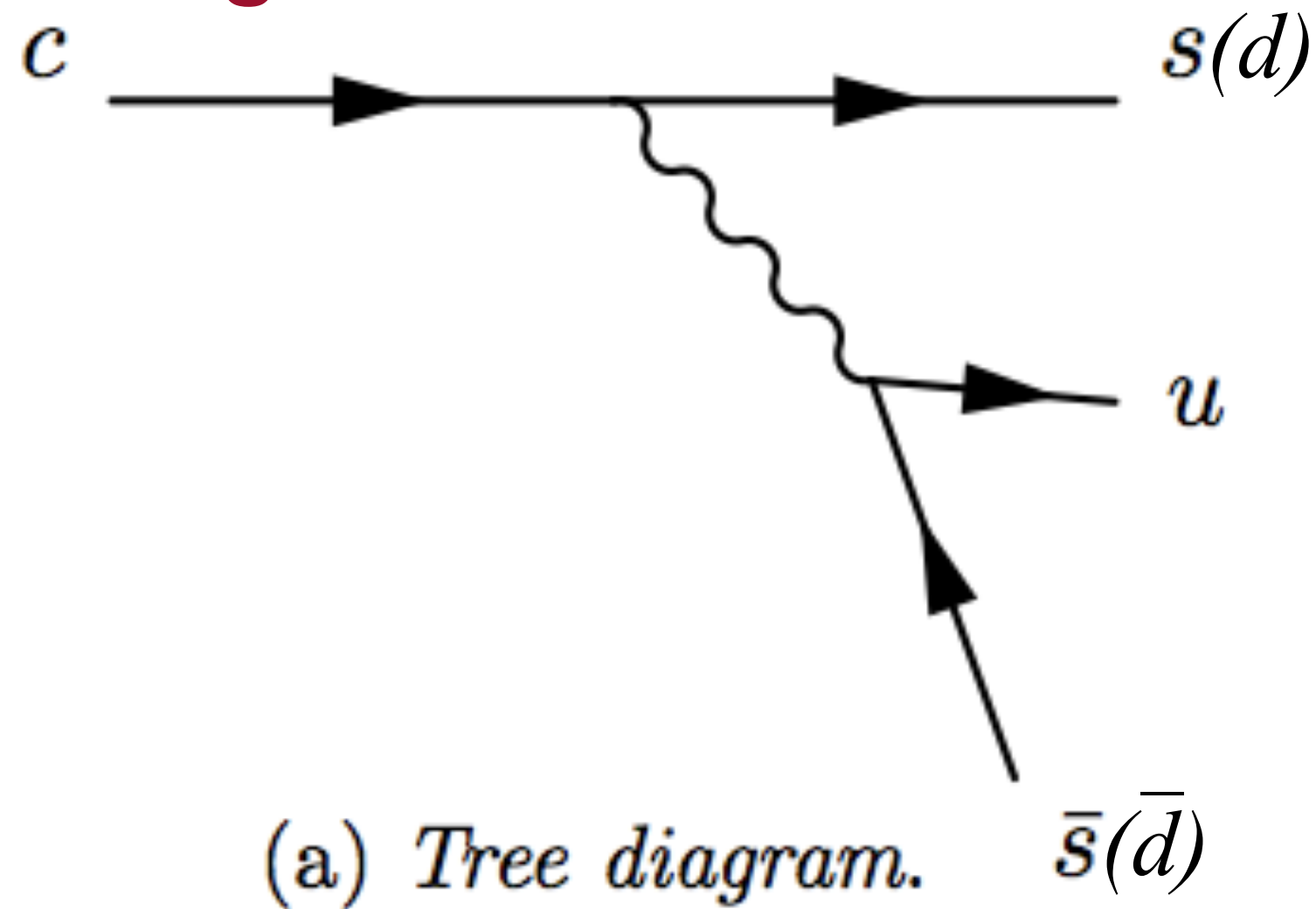
Why is $\Delta A_{CP} \neq 0$?

Phys. Lett. B774 (2017) 235-242

Phys. Rev. D75 (2007) 036008

Phys. Lett. B712 (2012) 81

CPV Arising from Interference



SU(3) Symmetry

- In this limit, $A_{CP}(K^+K^-)$ and $A_{CP}(\pi^+\pi^-)$ are equal and opposite in sign, resulting in $\Delta A_{CP} \sim 10^{-3}$
Naively: $V_{cd} \sim -V_{us}$

Why is $\Delta A_{CP} \neq 0$?

SU(3) Symmetry

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Rescattering

Luca Silvestrini @ LHCb Week, 19/6/2019

TOWARDS A SM PREDICTION

E. Franco, G. Martinelli, A. Paul & L.S., *in progress*

- Neglect all short-distance contributions to decay matrix elements except for emissions:
 - $A_{SD}(D \rightarrow \pi\pi) \approx \lambda_d \langle \pi\pi | Q^{dd} | D \rangle_{T,C}$
 - $A_{SD}(D \rightarrow KK) \approx \lambda_s \langle KK | Q^{ss} | D \rangle_{T,C}$
- Long-distance contributions to matrix elements due to rescattering:
 - $A(D \rightarrow \pi\pi) \approx A_{SD}(D \rightarrow \pi\pi) A(\pi\pi \rightarrow \pi\pi) + A_{SD}(D \rightarrow KK) A(KK \rightarrow \pi\pi)$
 - $A(D \rightarrow KK) \approx A_{SD}(D \rightarrow KK) A(KK \rightarrow KK) + A_{SD}(D \rightarrow \pi\pi) A(\pi\pi \rightarrow KK)$

n.b. One of the hypotheses on the table

LHCb week, 19/6/19

Different weak phase

Luca Silvestrini

Different strong phase

6

Time-Dependent CP Asymmetry in $D^0 \rightarrow h^+h^-$

Effects on ΔA_{CP}

- Even integrating over decay time, time-dependent effects can contribute

$$\Delta A_{CP} \simeq \Delta A_{CP}^{\text{dir}} - \frac{\Delta \langle t \rangle}{\tau_{D^0}} A_{\Gamma}$$

~10%

- Indirect CPV can be determined from

$$A_{\Gamma} = \frac{\hat{\Gamma}(D^0 \rightarrow h^+h^-) - \hat{\Gamma}(\bar{D}^0 \rightarrow h^+h^-)}{\hat{\Gamma}(D^0 \rightarrow h^+h^-) + \hat{\Gamma}(\bar{D}^0 \rightarrow h^+h^-)}$$

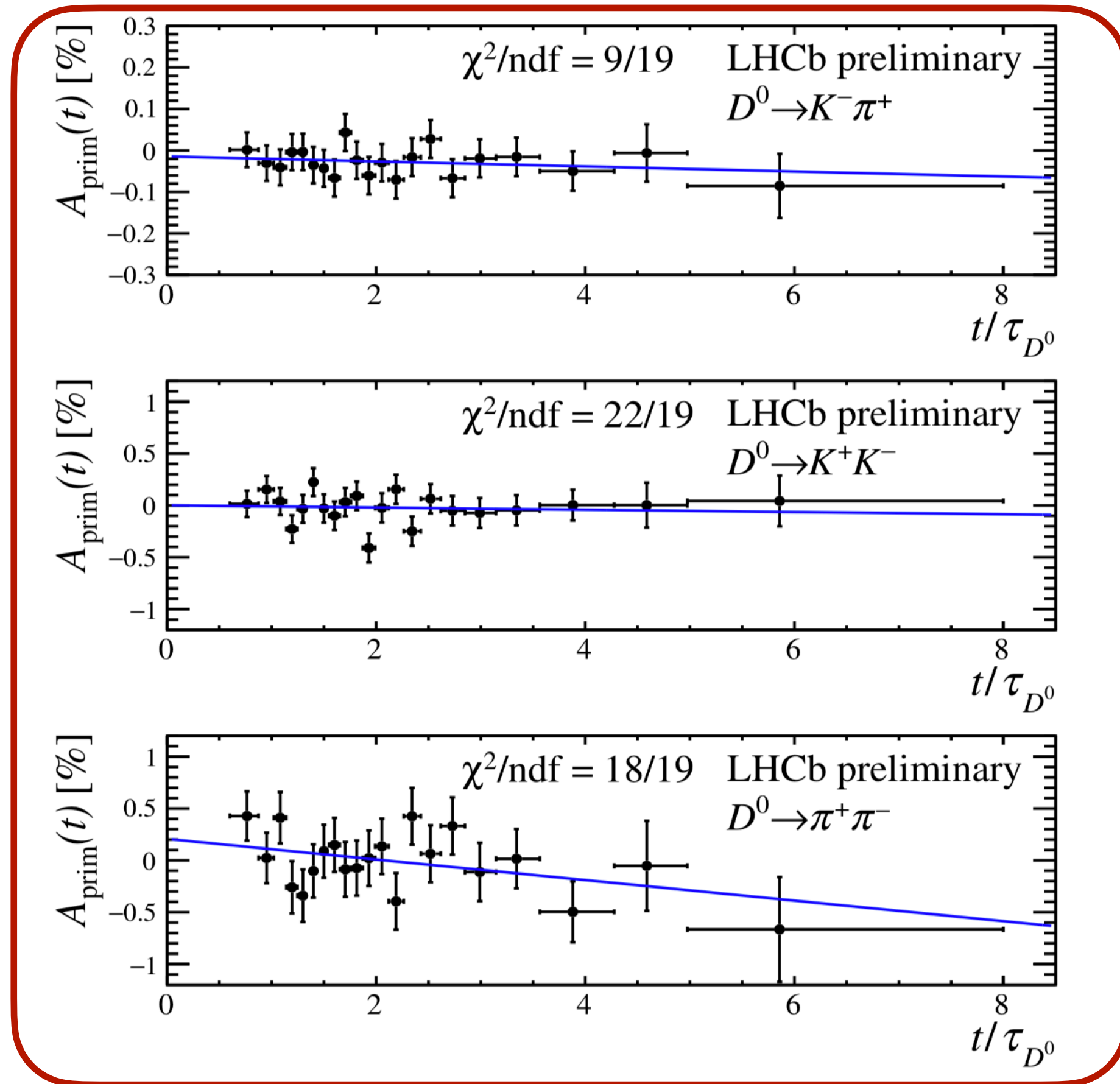
- SM expectations $\sim 10^{-5}$

A_Γ Measurements at LHCb

LHCb-CONF-2019-001
PRD 101, 012005 (2020)

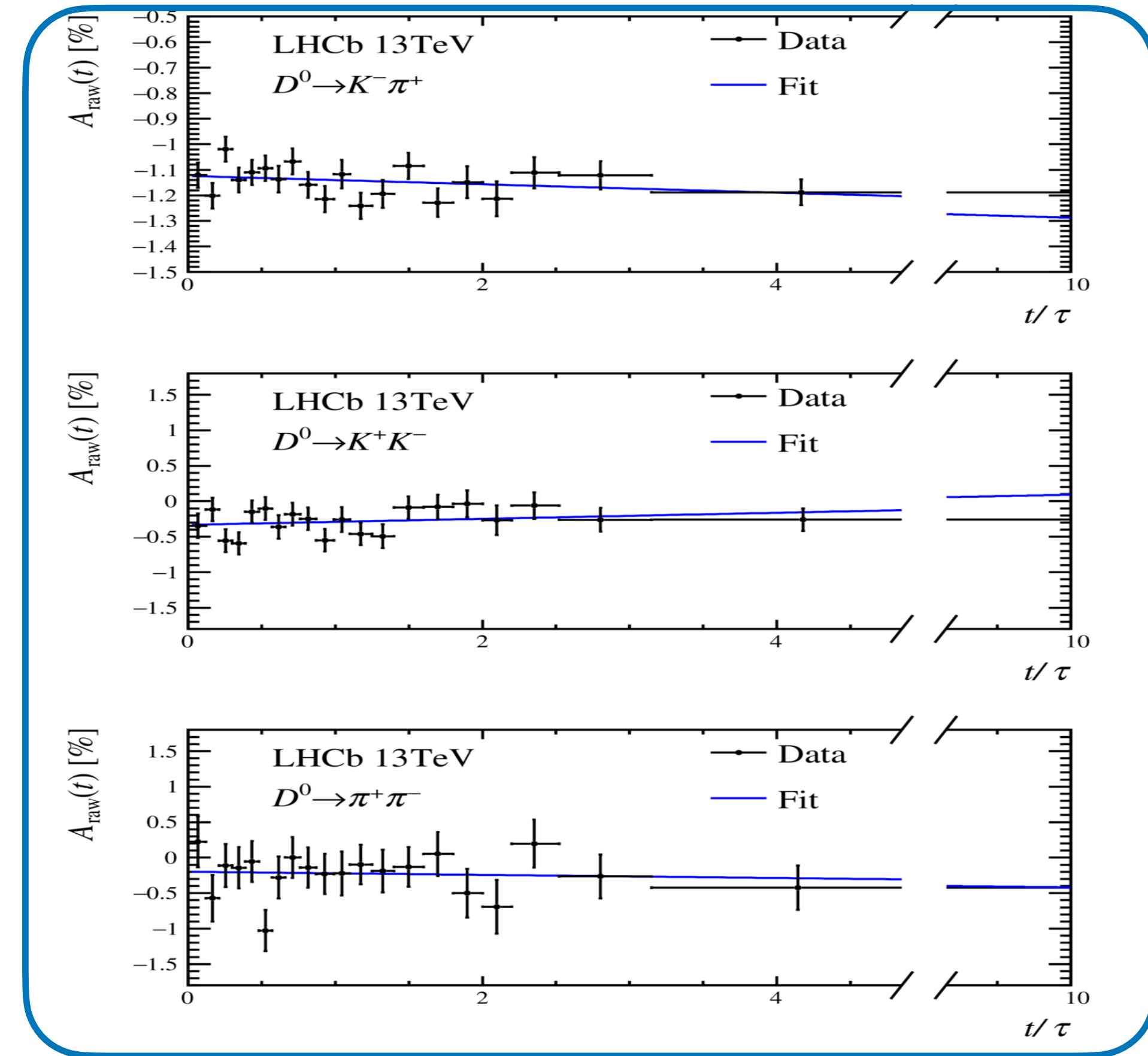
(π -tagged)

1.9/fb Run2



(μ -tagged)

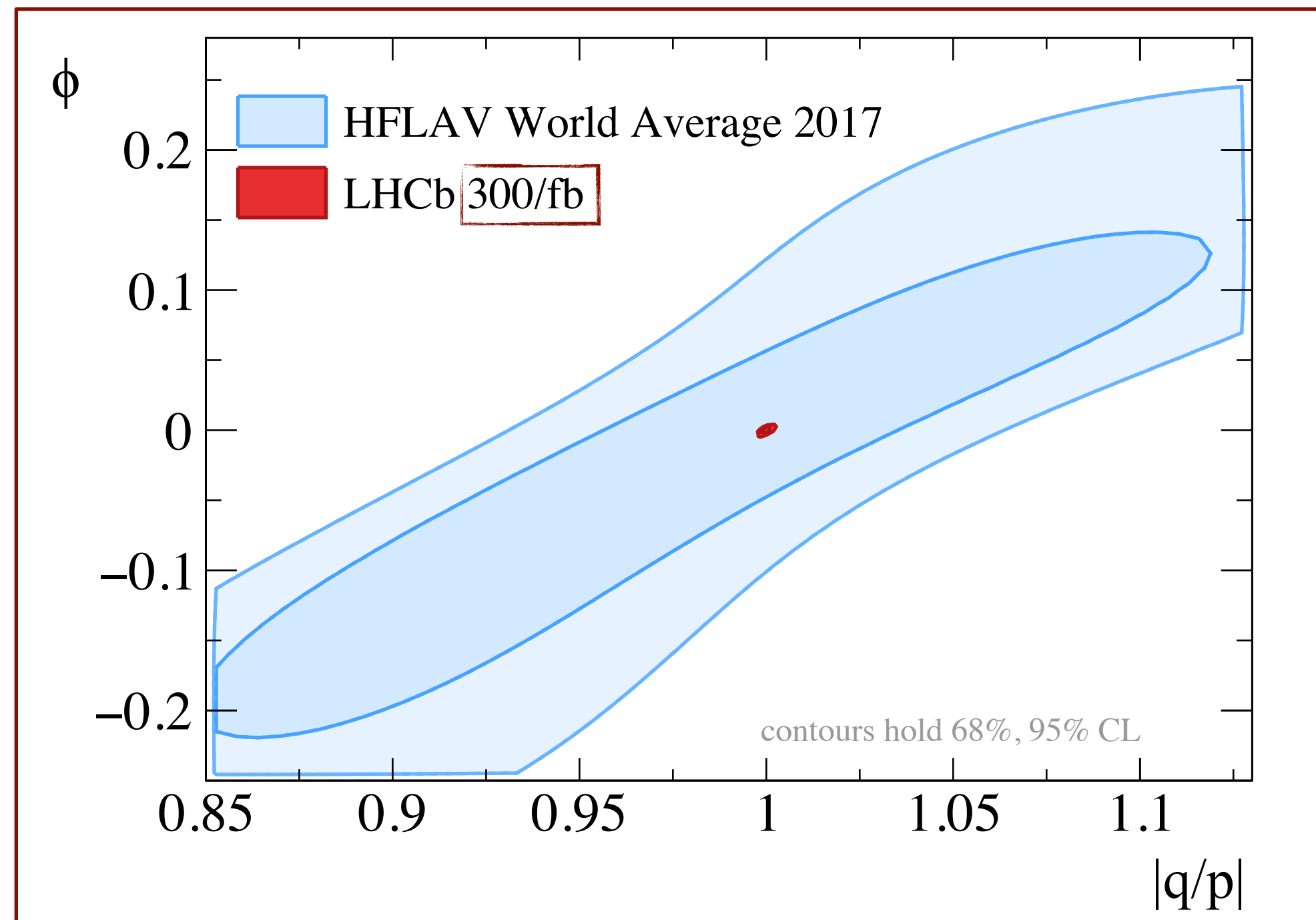
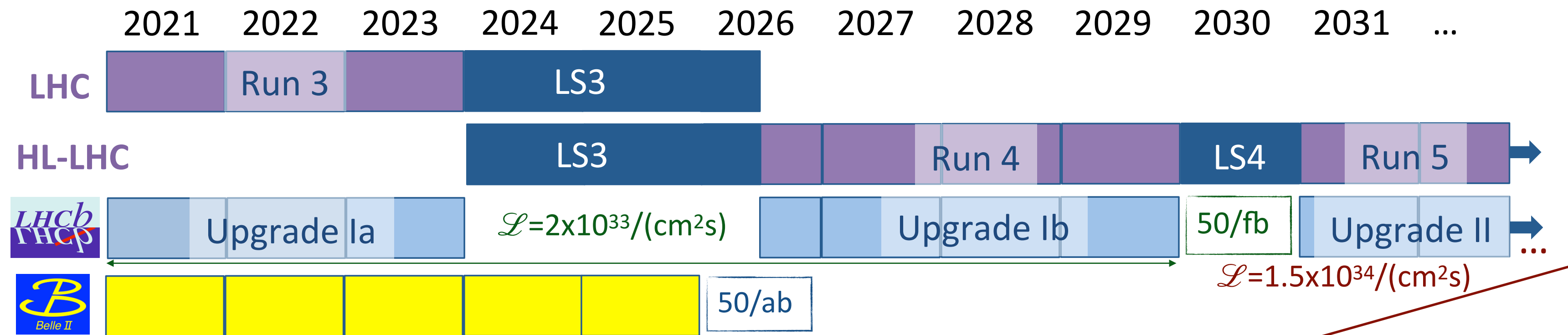
5.4/fb Run2



$$A_\Gamma = \left(-1.1 \pm 1.7(\text{stat}) \pm 0.5(\text{syst}) \right) \times 10^{-4}$$

Preliminary combination of Run1 and Run2 results (includes [PRL 118 \(2017\) 261803](#), [JHEP 04 \(2015\) 043](#))

Towards Ultimate Precision



LHCb Upgrade II Physics Case
(arXiv:1808.08865)