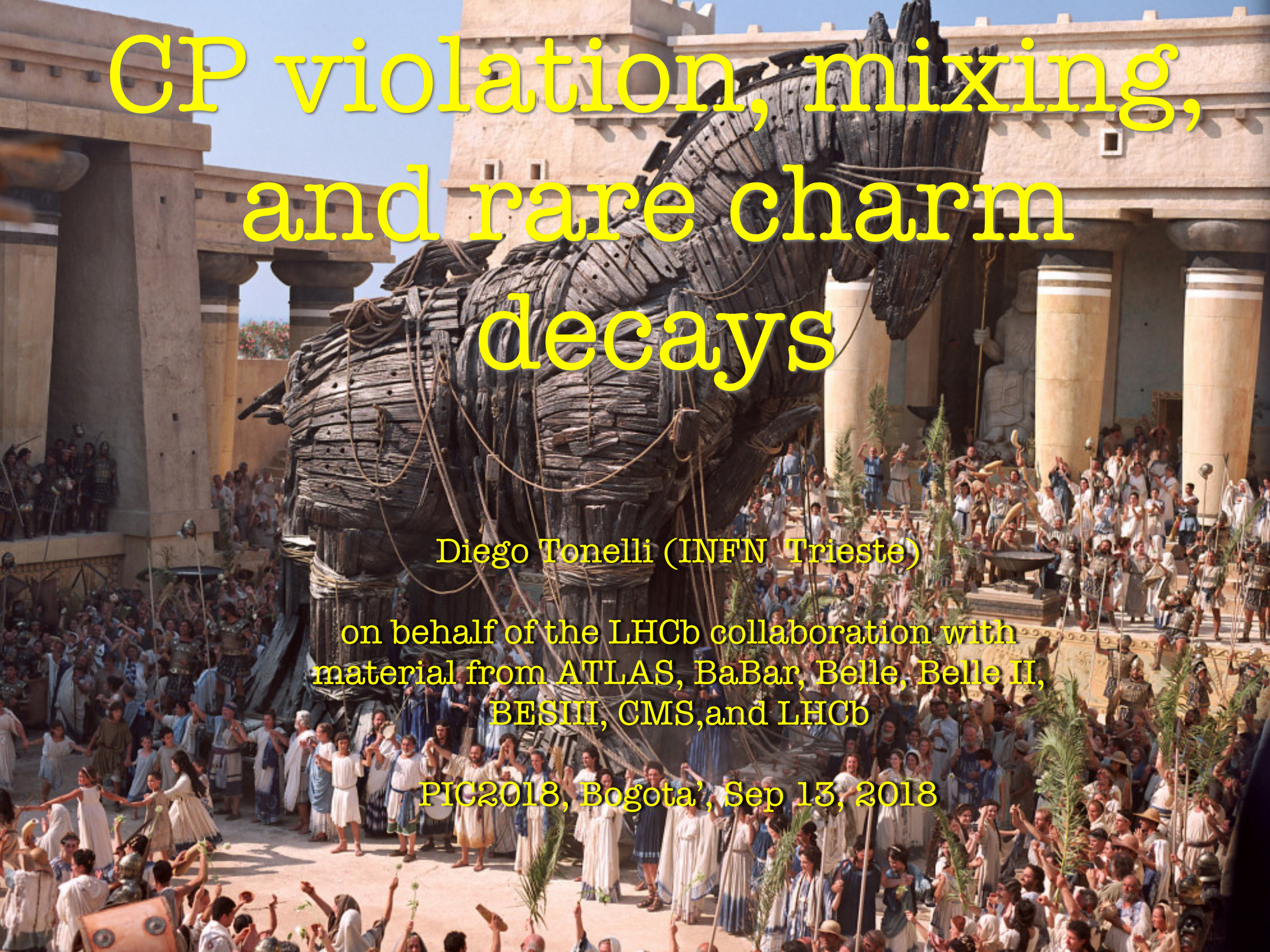


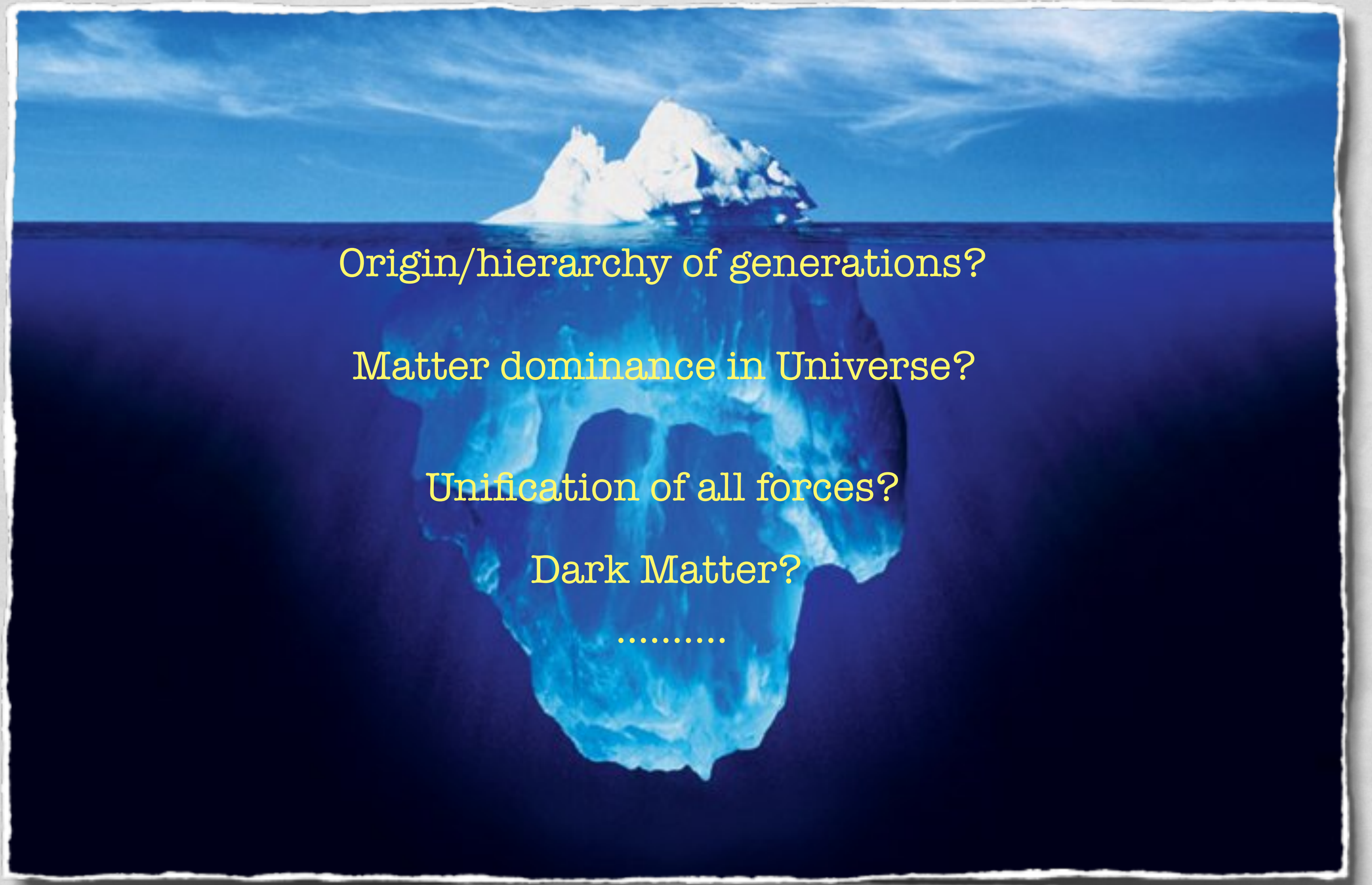
CP violation, mixing, and rare charm decays

Diego Tonelli (INFN Trieste)

on behalf of the LHCb collaboration with
material from ATLAS, BaBar, Belle, Belle II,
BESIII, CMS,and LHCb

PIC2018, Bogota', Sep 13, 2018

Incompleteness



Origin/hierarchy of generations?

Matter dominance in Universe?

Unification of all forces?

Dark Matter?

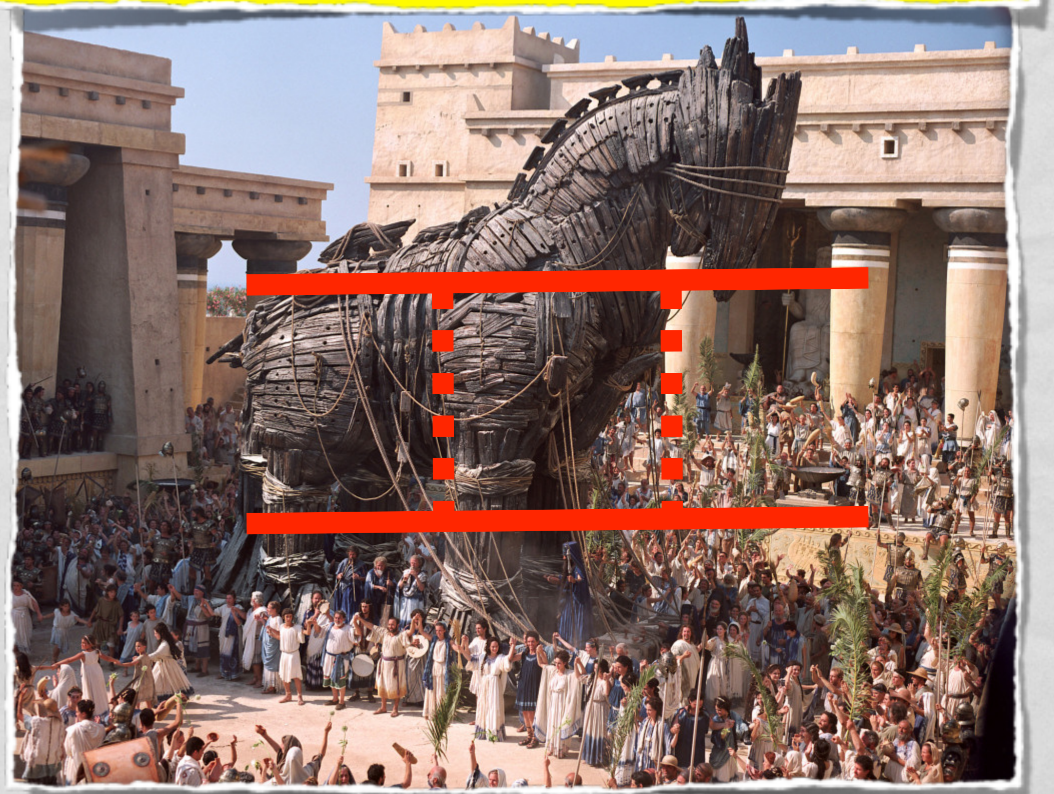
……….

Two ways out (hopefully)

A more powerful machine (unlikely soon)

HE production of new particles. Probe directly structure of matter and its interactions

Get smarter



LE precision measurements access effects of exchange of virtual new particles. Quantum-probe of higher energies than directly accessible

Here’s were brute force led us so far

Flavor

- Null results from direct searches so far
- No plans for more powerful colliders soon

Flavor's rich multipronged program make flavor dynamics best bet for the next decade and beyond to

Discover the particles that extend the SM - or tightly constrain their possible dynamic configurations.

(Hope to) Gain insight on some of the deepest questions and the intersection of particle physics and cosmology

CHARM QUARK

c

Heavier than a strange quark, but not as heavy as a bottom quark, the **CHARM QUARK** was discovered in 1974. Particles that contain charm and anticharm quarks are called "charmed matter."

Acrylic felt/fleece with a mix of poly beads and gravel for medium-heavy mass.

$10.49 PLUS SHIPPING

●●●●●●●●●●○○○

LIGHT HEAVY

The PARTICLE ZOO

Outline

(I will try to convince you that) Charm physics is a compelling, unique probe of BSM dynamics.

- Charm dynamics and its idiosyncrasies
- (Won't discuss the experiments, just a few) generalities of experimental techniques in charm-physics.
- Tests for lepton-flavor universality with rare D decays
- CP violation and oscillations to test for the presence of BSM phases

Will stick with BaBar/Belle(II)/BESIII/LHCb results since a year ago or newer: apologies for I had to skip many others

Outlin

(I will try to convince … physics … compelling, uniq… …ynamic…

- Charm … idiosy…
- … the exp… …st a few) … es … ntal tec… charm-p…
- Tests for l… universal… rare D decays
- CP … and oscill… …est for the presence of … ses

… stick … Belle(II)/BESIII/LHCb results since a year a… apologies for I had to skip many others

Spoiler alert: first showing of Belle II charm signals from the whole 2018 pilot run — hot off the press right for PIC2018!

Spoiler alert: new LHCb preliminary result on CP violation in mixing — hot off the press right for PIC2018!

Spoiler alert: new BESIII preliminary result on charm amplitude analysis —hot off the press right for PIC2018

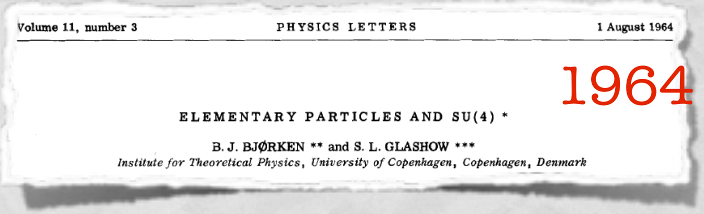
Why is charm charming?

Unique — charm quark is up-type. D dynamics sensitive to BSM models complementary to those probed by B/K.

Discovery tool — No triangles here, charm isn't a precision probe.

Challenging — Effects are $<10^{-3}$ due to dynamic suppressions: calls for O(>1M) yields and control over systematic uncertainties

Only recently experiments reached sensitivity to discern SM from non-SM effects


Volume 11, number 3 PHYSICS LETTERS 1 August 1964

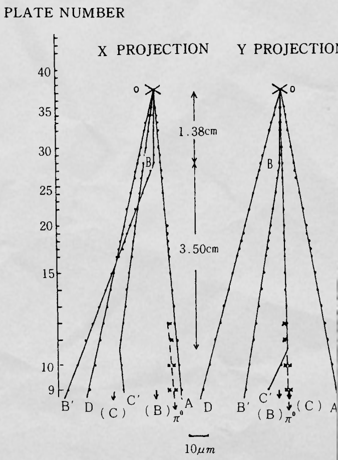
ELEMENTARY PARTICLES AND SU(4) *

B. J. BJØRKEN ** and S. L. GLASHOW ***

Institute for Theoretical Physics, University of Copenhagen, Copenhagen, Denmark

1964

1970



1971

1974

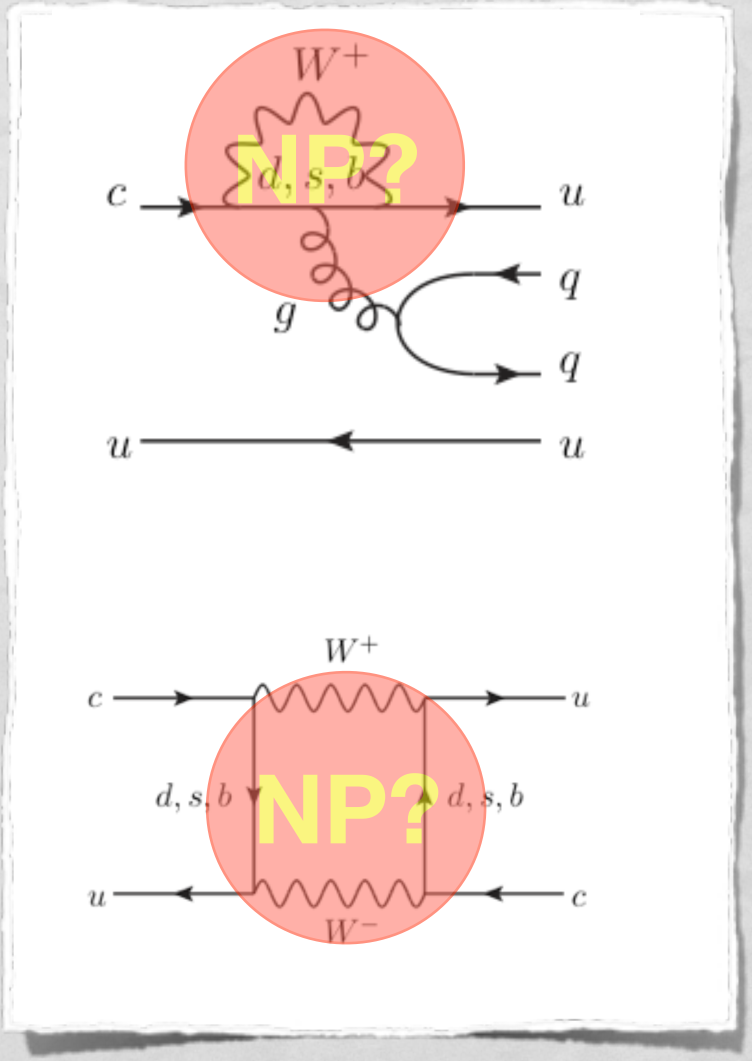
The name of the game

Target processes mediated by flavor-changing-neutral currents

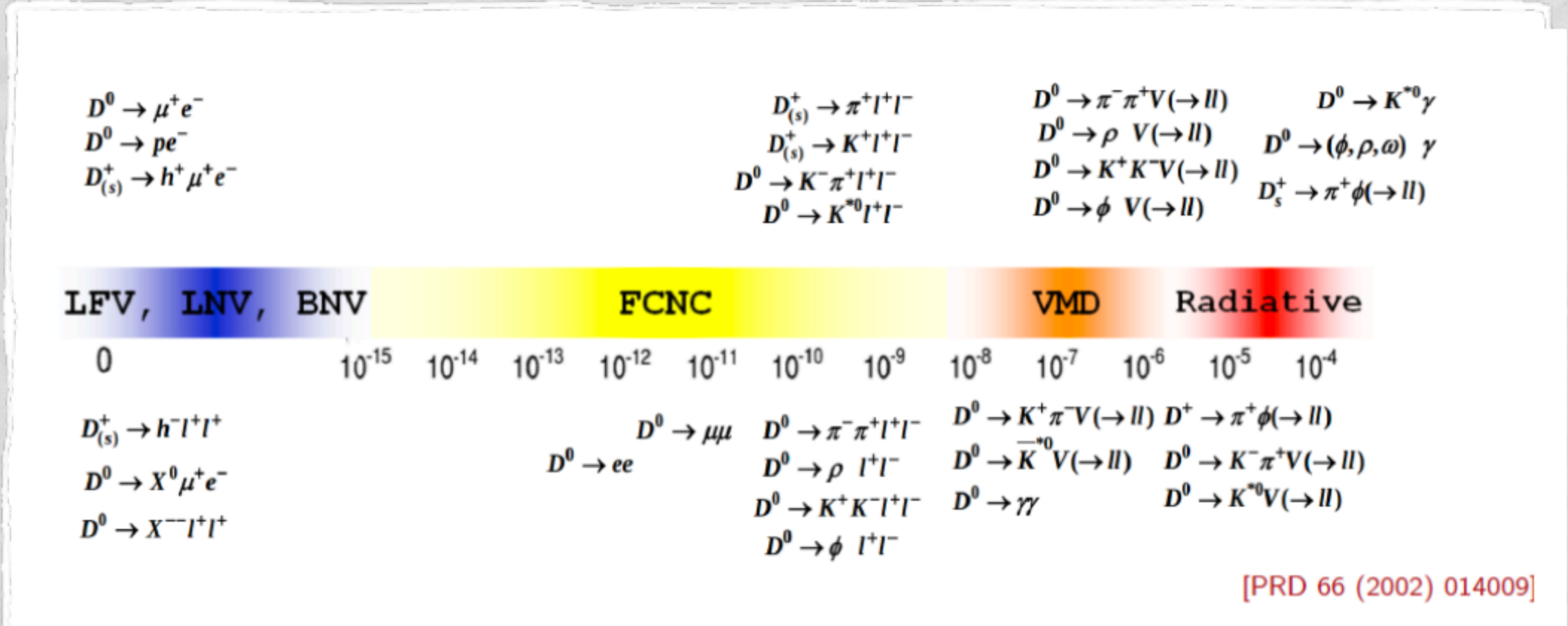
Any internal quark line can be replaced by non-SM particles, with no effect on initial/final states.

Detect BSM contributions from

- Altered rates (e.g., enhanced decay or oscillation rates)
- Altered phases, observed through interference of FCNC amplitudes with others (e.g., enhanced CPV asymmetries or changes in angular distributions)



Challenge#1 — small rates



[PRD 66 (2002) 014009]

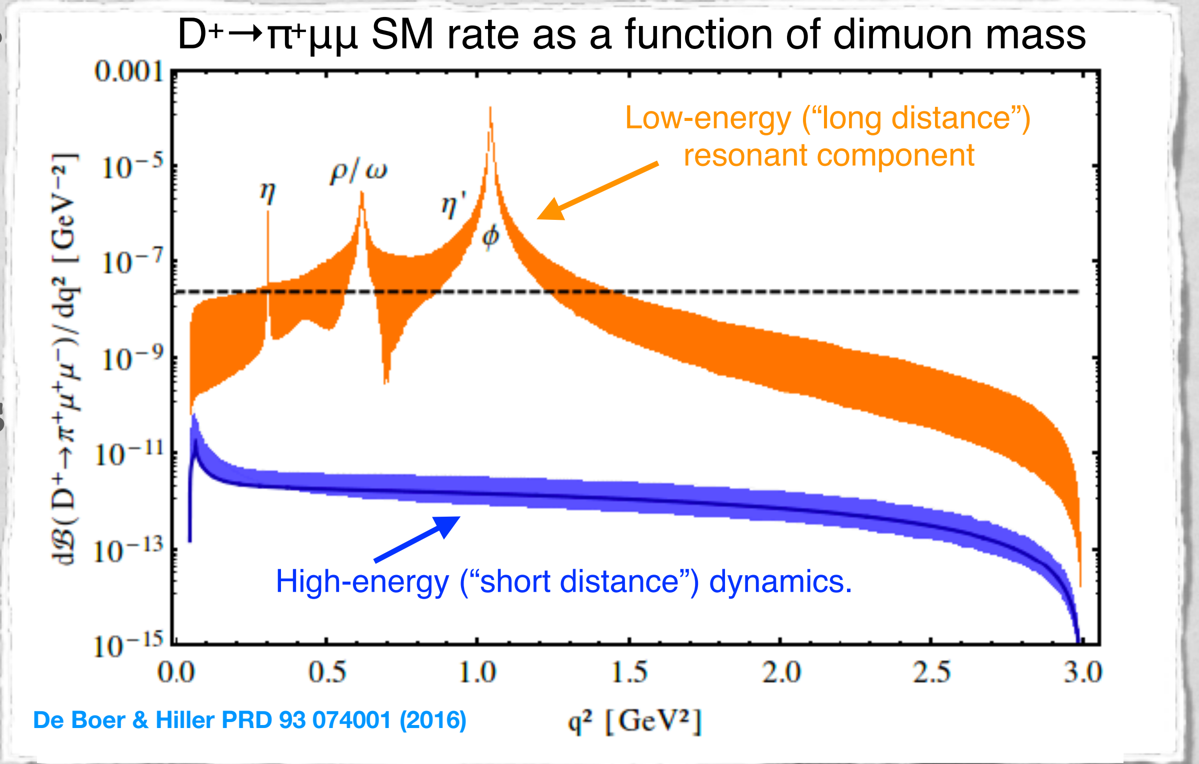
More accurate GIM cancellation than in B/K. Need large samples.

Hadron colliders favored over D/B factories. But online selection is hard: no intermediate J/ψ's like for B, need to trigger on tracks or low-momentum muons (hence fewer CMS/ATLAS results on charm)

Challenge#2 — SM noise

Intermediate charm-mass value ==> large nonperturbative effects:

- Predictions get harder (soft QCD often intractable)
- Measurements get harder: e.g, low-energy resonant SM-processes overshadow high-q^2 dynamics one wanna probe => spoils BSM sensitivity.



$D^+ \rightarrow \pi^+\mu\mu$ SM rate as a function of dimuon mass

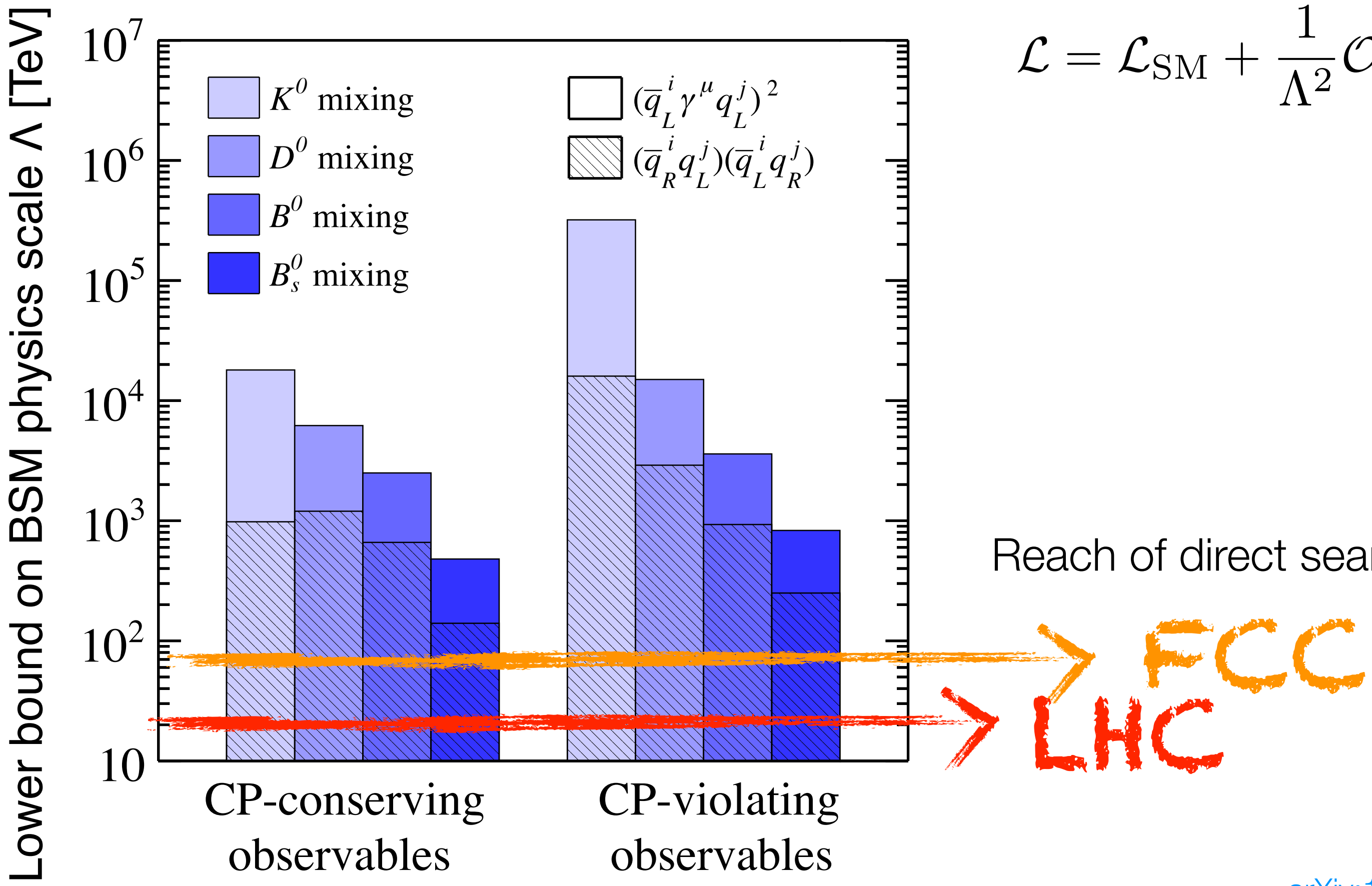
Low-energy ("long distance") resonant component

High-energy ("short distance") dynamics.

De Boer & Hiller PRD 93 074001 (2016)

Mitigate by exploiting dynamical cancellations through symmetries/correlations and/or getting away from the resonant peaks.

Reach



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

Reach of direct searches

arXiv:1302.0661

D is second only to K in probing the highest energies
(and D tests complementary dynamics)

Players

$2\times10^7\ c\bar{c}$

Coherent e⁺e⁻ → $c\bar{c}$ at ψ(3770): strong-phase measurements and flavor tagging. No backg. Strong in final states with e/neutrals. Low rate and no boost ==> no time-evolution

$8\times10^8\ c\bar{c}$

$13\times10^8\ c\bar{c}$

Incoherent e⁺e⁻ → $c\bar{c}$ at 10 GeV. Time evolution accessible. Strong in final states with e/neutrals

Incoherent pp → $c\bar{c}$ at 10 TeV. Large rates. Strong for time evolution studies. Weak in final states with e/neutrals

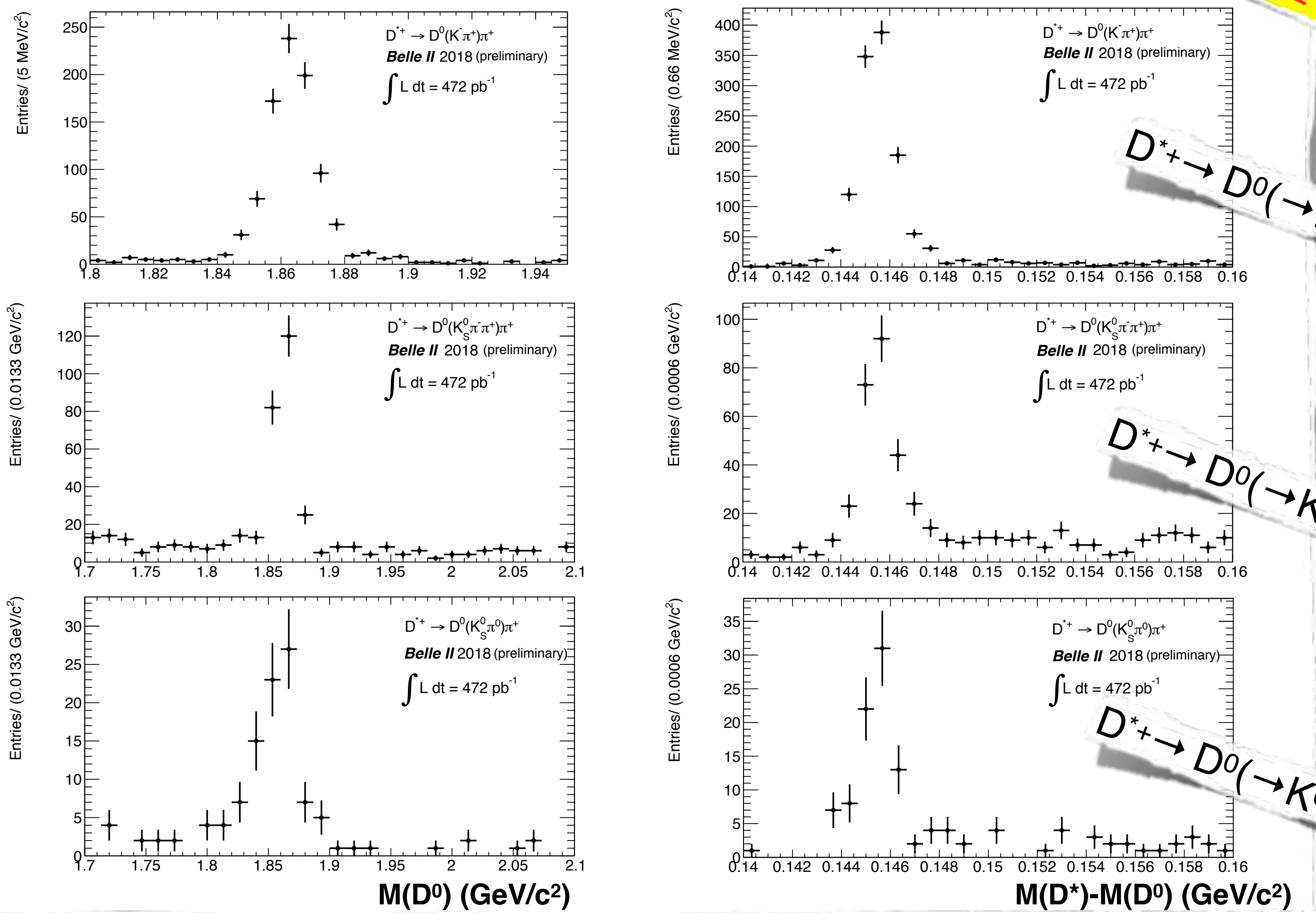
$$8\times10^{12}\ c\bar{c}$$

Getting published/analyzed now. Another nearly equal amount on disk

Welcome back!

Welcome back!

New for PIC2018



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

$D^{*+} \to D^0(\to K^0_S\pi^+\pi^-)\pi^+$

$D^{*+} \to D^0(\to K^0_S\pi^0)\pi^+$

Belle II D*-tagged D's from whole 2018 pilot-run data

Experimentally

- Signal selection and reconstruction
  - All: vertex/track quality, PID, mass of intermediate resonances
  - BaBar/Belle(II): high $p_T(D)$ enriches $e^+e^- \to c\bar{c}$, decay-length, D^*-tag
  - LHCb: triggers on muons and hadrons => tracks; decay length, D^*-tag.
- Was it a D^0 or anti-D^0 ?
  - BESIII: Look at the “other D” and use $\psi(3770)$ quantum correlation
  - BaBar/Belle(II)/LHCb: D^*-tag (introduces instrumental asymmetry)
- Efficiencies
  - All: simulation. LHCb mainly relative efficiences; BaBar/Belle(II)/ BESIII absolute too
- Production/instrumental asymmetries: All: control modes on data

Is there a c→u counterpart for the observed b→s μμ anomalies*?

Can charm tell us something new about lepton-flavor universality?

---

*See P. Chang talk

Nonresonant di-μ in $\Lambda_c^+ \to p\mu\mu$

Search for $\Lambda_c^+ \to p\mu\mu$ with nonresonant μ pair. 10^{-9} SM rate.

1/2 of LHCb sample.

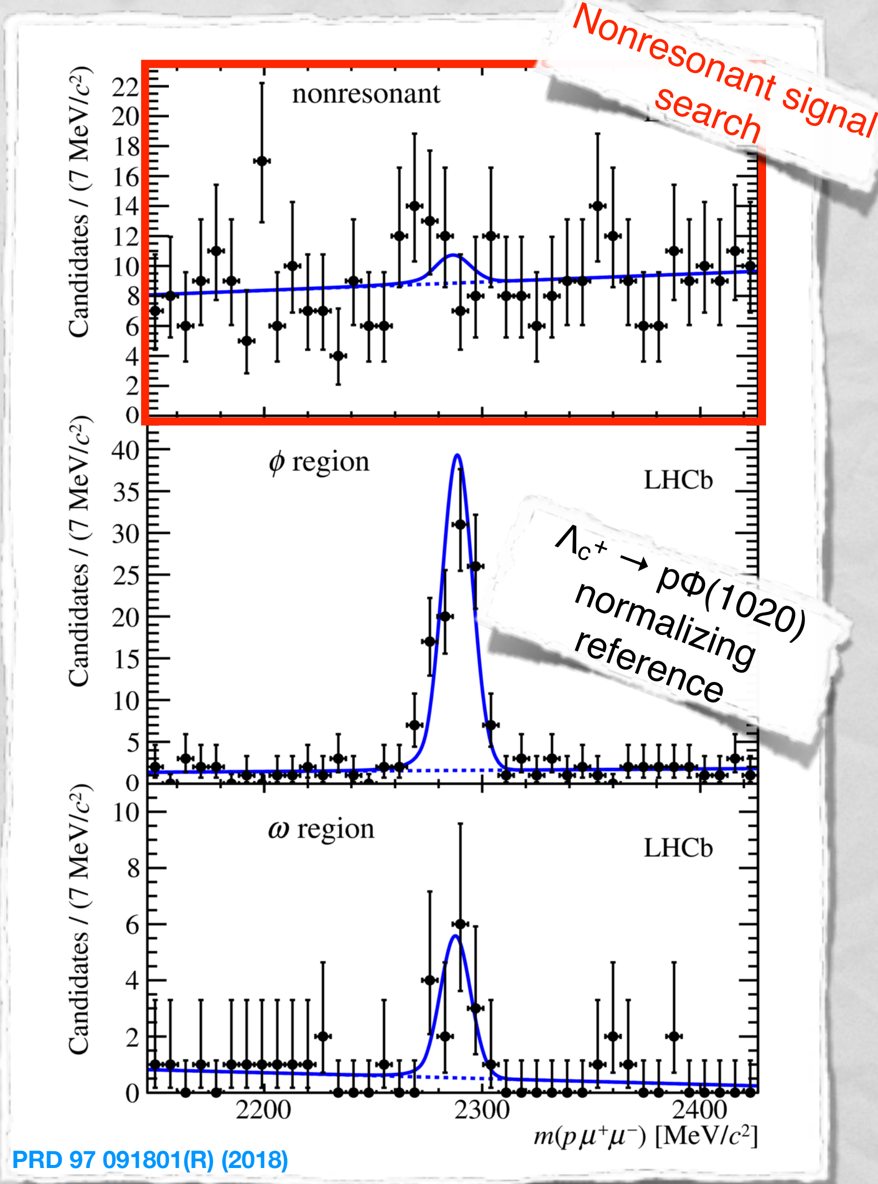
Challenge: suppress combinatorics. => combine in a BDT track/vertex quality, flight, PID, p/μ isolation.

~100 candidates with resonant dimuons, 13 in the ω (782) region: BF = $(9.4 \pm 3.9) * 10^{-4}$

No evidence for nonresonant di-μ

BF < $9.6 * 10^{-8}$ at 95% CL

100x better than previous limits



Nonresonant signal search

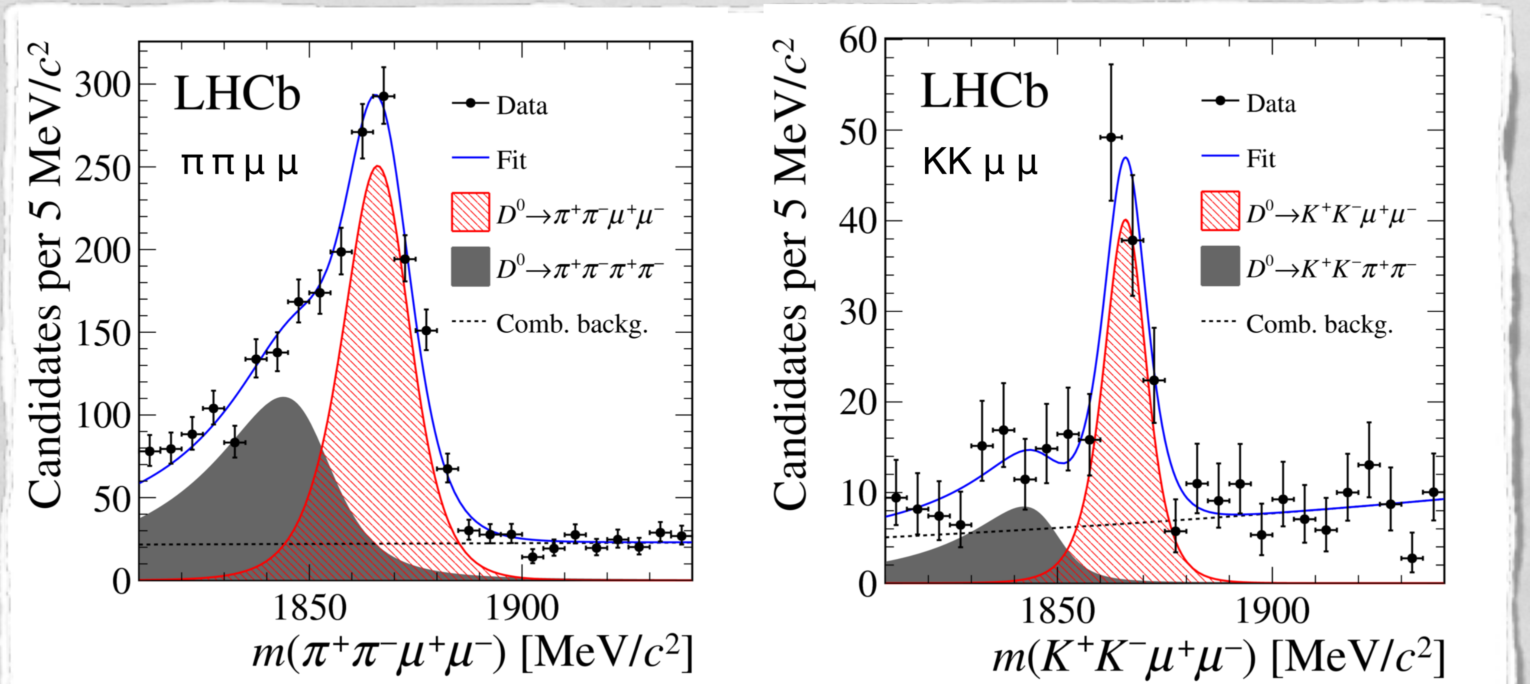
$\Lambda_c^+ \to p\Phi(1020)$ normalizing reference

PRD 97 091801(R) (2018)

$D^0 \to hh\mu\mu$ asymmetries

Observed $D^0 \to \pi\pi\mu\mu$ and $KK\mu\mu$ rates of $10^{-6} - 10^{-7} >> 10^{-9}$ short-distance SM rate ==> low-energy pollution PRL 119 181805 (2017)

Use 1/2 of LHCb sample to target asymmetries based on correlations that mitigate low-energy biases.



PRL 121 091801 (2018)

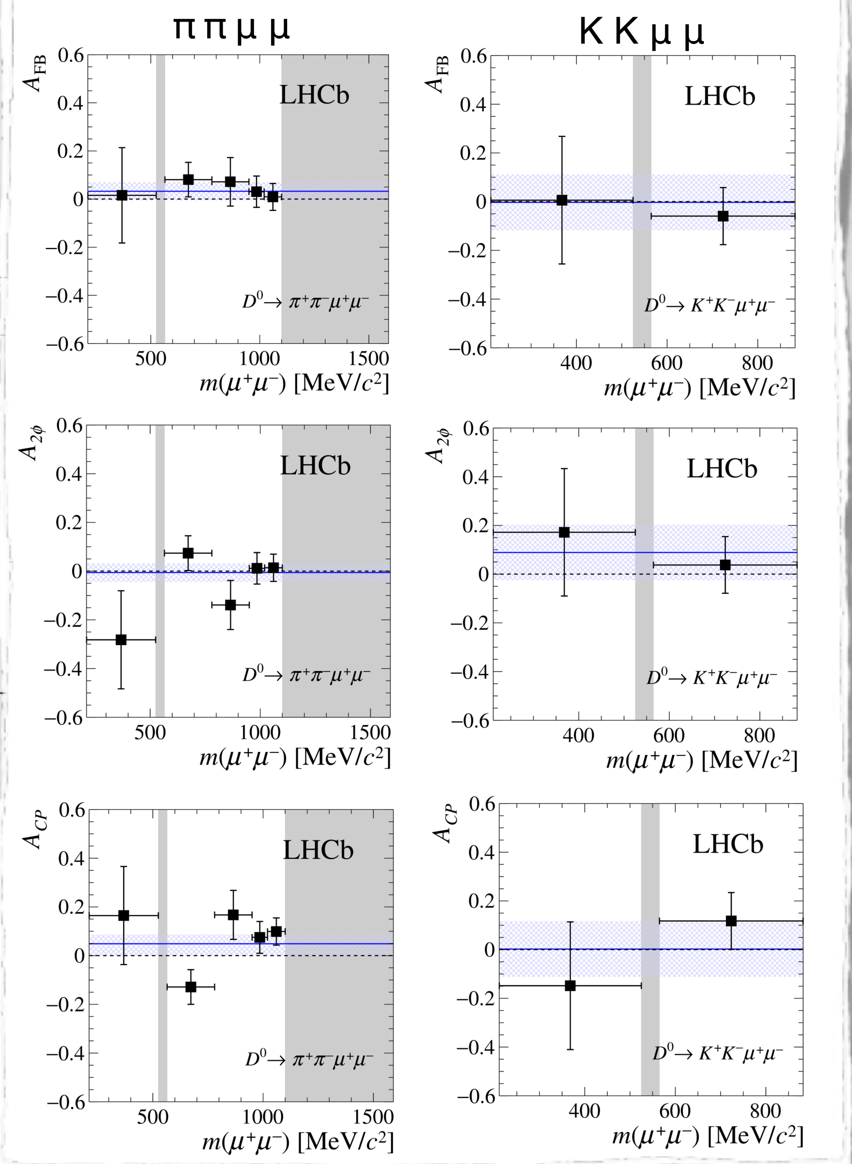
$D^0 \to hh\mu\mu$ asymmetries

Challenges: (i) comb. bckg and misID $D^0 \to hh\pi\pi$ (ii) instrumental and production asymmetries

$m(\mu^+\mu^-)$ [MeV/c^2]	Efficiency-weighted yields			Signal asymmetries		
	Signal	Misid. back.	Comb. back.	A_{FB} [%]	$A_{2\phi}$ [%]	A_{CP} [%]
$D^0 \to \pi^+\pi^-\mu^+\mu^-$						
< 525	90 ± 17	233 ± 25	108 ± 22	$2 \pm 20 \pm 2$	$-28 \pm 20 \pm 2$	$17 \pm 20 \pm 2$
525–565	–	–	–	–	–	–
565–780	326 ± 23	253 ± 24	145 ± 21	$8.1 \pm 7.1 \pm 0.7$	$7.4 \pm 7.1 \pm 0.7$	$-12.9 \pm 7.1 \pm 0.7$
780–950	141 ± 14	159 ± 15	89 ± 14	$7 \pm 10 \pm 1$	$-14 \pm 10 \pm 1$	$17 \pm 10 \pm 1$
950–1020	244 ± 16	63 ± 13	43 ± 9	$3.1 \pm 6.5 \pm 0.6$	$1.2 \pm 6.4 \pm 0.5$	$7.5 \pm 6.5 \pm 0.7$
1020–1100	258 ± 14	33 ± 9	44 ± 9	$0.9 \pm 5.6 \pm 0.7$	$1.4 \pm 5.5 \pm 0.6$	$9.9 \pm 5.5 \pm 0.7$
> 1100	–	–	–	–	–	–
Full range	1083 ± 41	827 ± 42	579 ± 39	$3.3 \pm 3.7 \pm 0.6$	$-0.6 \pm 3.7 \pm 0.6$	$4.9 \pm 3.8 \pm 0.7$
$D^0 \to K^+K^-\mu^+\mu^-$						
< 525	32 ± 8	5 ± 13	124 ± 20	$13 \pm 26 \pm 4$	$9 \pm 26 \pm 3$	$-33 \pm 26 \pm 4$
525–565	–	–	–	–	–	–
> 565	74 ± 9	39 ± 7	48 ± 8	$1 \pm 12 \pm 1$	$22 \pm 12 \pm 1$	$13 \pm 12 \pm 1$
Full range	110 ± 13	49 ± 12	181 ± 19	$0 \pm 11 \pm 2$	$9 \pm 11 \pm 1$	$0 \pm 11 \pm 2$

No anomalous dependences on dimuon mass

Integrated asymmetries are zero within 4% ($\pi\pi\mu\mu$) or 11% ($KK\mu\mu$) uncertainties dominated by sample size.



PRL 121 091801 (2018)

Searches for $D^0 \to hh'ee$

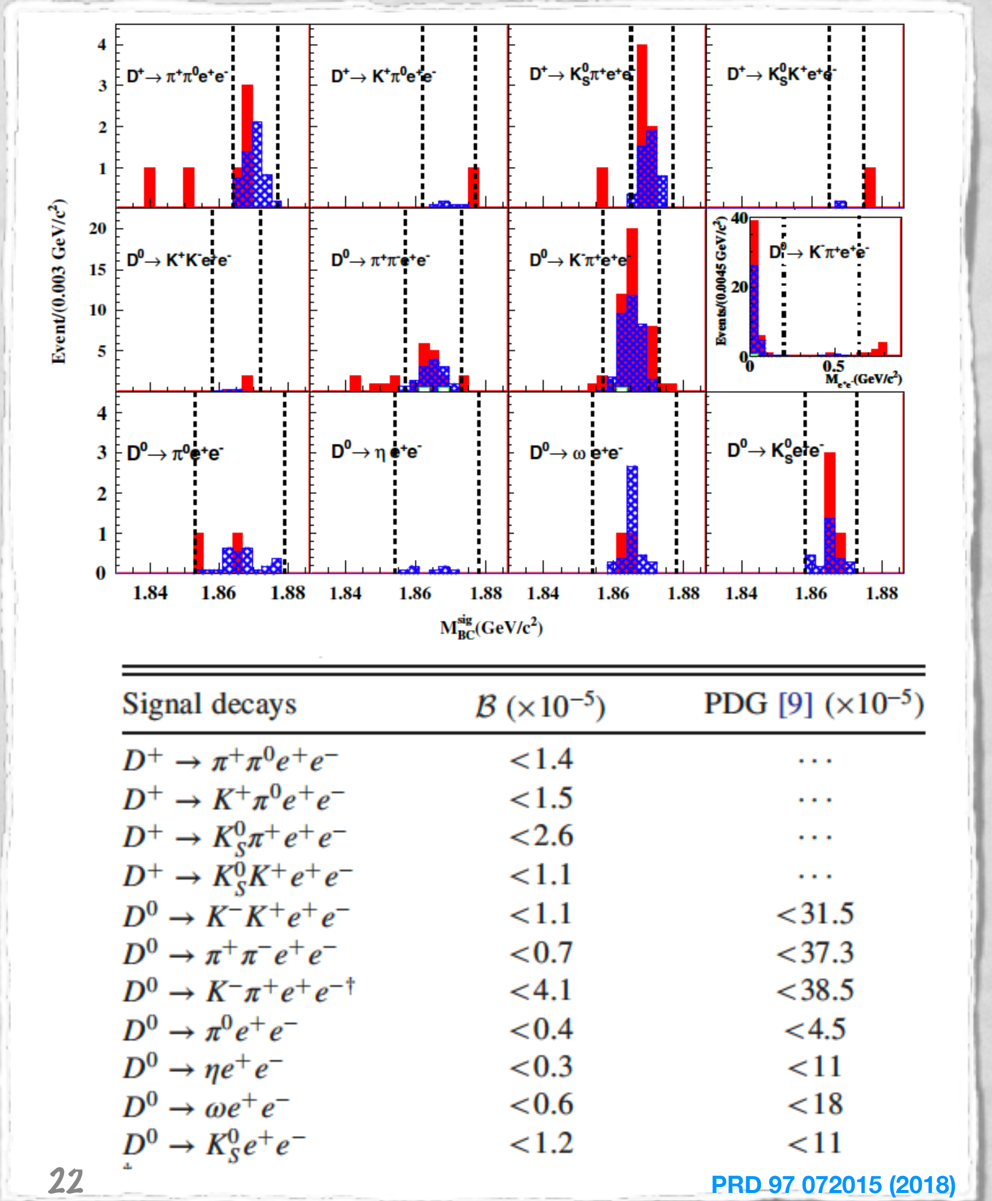
Search for 11 (!) decays involving dielectrons.

Small sample-size compensated by strong electron reconstruction

Misreconstruction backgrounds prevent from seing signals

10x improvements over previous limits

SM predictions still out of reach



Signal decays	$\mathcal{B}$ ($\times10^{-5}$)	PDG [9] ($\times10^{-5}$)
$D^+ \to \pi^+\pi^0 e^+e^-$	<1.4	...
$D^+ \to K^+\pi^0 e^+e^-$	<1.5	...
$D^+ \to K^0_S\pi^+ e^+e^-$	<2.6	...
$D^+ \to K^0_S K^+ e^+e^-$	<1.1	...
$D^0 \to K^-K^+ e^+e^-$	<1.1	<31.5
$D^0 \to \pi^+\pi^- e^+e^-$	<0.7	<37.3
$D^0 \to K^-\pi^+ e^+e^{-\dagger}$	<4.1	<38.5
$D^0 \to \pi^0 e^+e^-$	<0.4	<4.5
$D^0 \to \eta e^+e^-$	<0.3	<11
$D^0 \to \omega e^+e^-$	<0.6	<18
$D^0 \to K^0_S e^+e^-$	<1.2	<11

PRD 97 072015 (2018)

Testing LFU with $D^0 \to K^-\pi^+ ee$

Search Babar data for $D^0 \to K^-\pi^+ee$
Check universality wrt $D^0 \to K^-\pi^+\mu\mu$

D^0 from D^{*+} to enhance purity

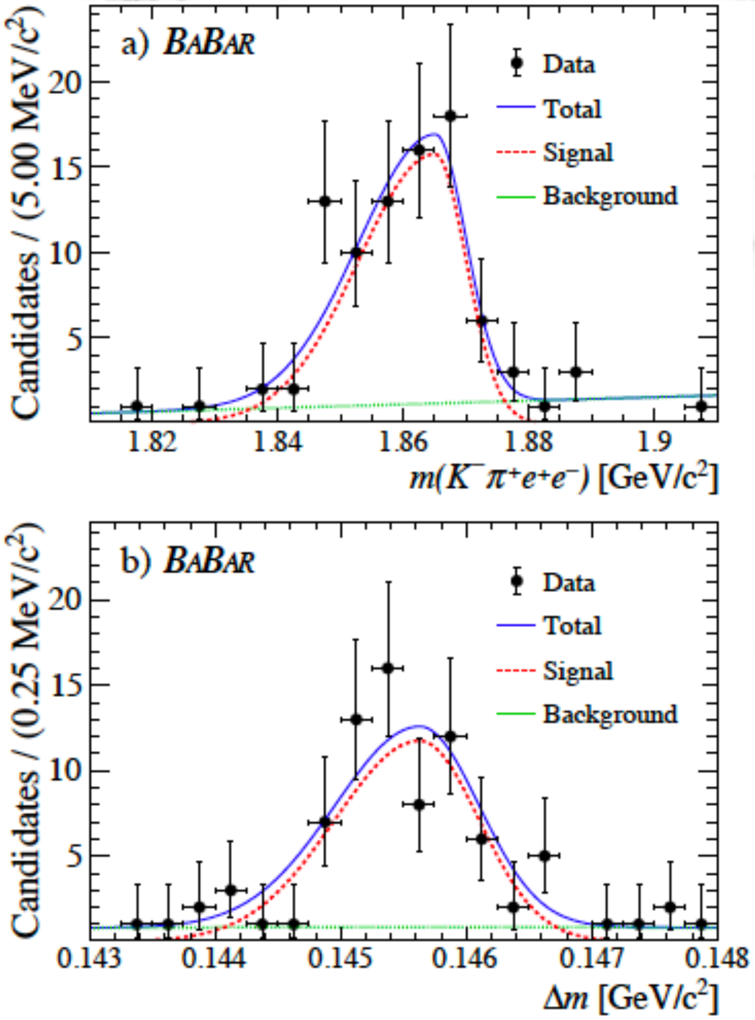
70 signal decays in the range
$m_{ee} = 0.675–0.875\ \mathrm{GeV}/c^2$

First observation with

$BF(D^0 \to K^-\pi^+ee) = (4.0 \pm 0.6) * 10^{-6}$

Consistent with $D^0 \to K^-\pi^+\mu\mu$

[$BF = (4.2 \pm 0.4) * 10^{-6}$ PLB 757 558 (2016)]



arxiv:1808.09680

Can we finally establish CP violation in charm?

(Assuming so) does that differ than predicted in the SM?

Direct CPV in $D^+ \to \pi^+\pi^0$

Robust SM prediction of zero asymmetry —firm nonzero result could be a big deal.

Combination with results from isospin-partner decays through "sum-rules" enhances the insight into BSM.

Time-integrated charge-asymmetry measurement (D+ minus D-) on full Belle data set: Υ(4S), Υ(5S), and off-peak.

Use samples 100k primary D^+ (more abundant, dirtier) with 6.5k secondary D^+ from D^{*+} (fewer, cleaner)

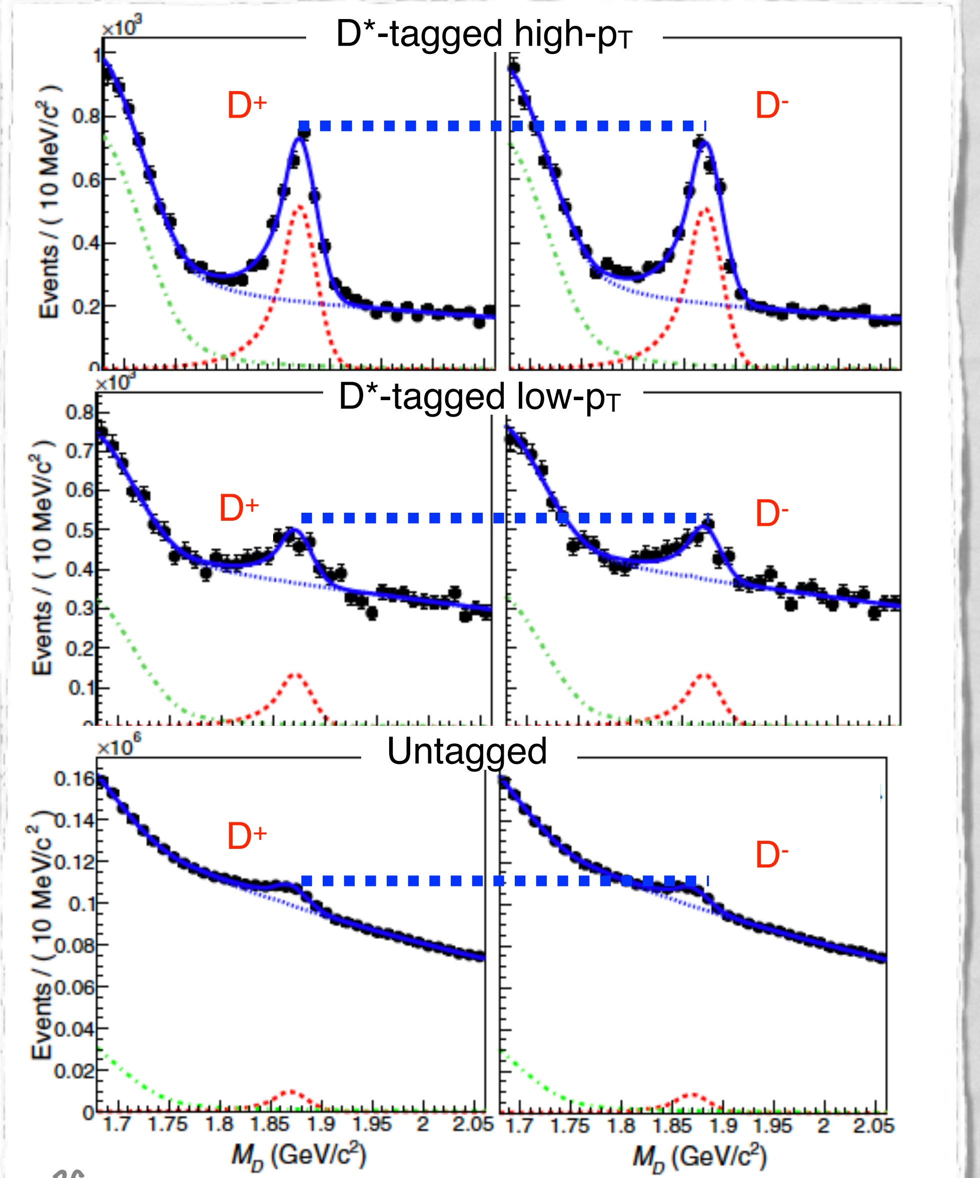
Direct CPV in $D^+ \to \pi^+\pi^0$

Subtract production and instrumental asymmetries by using $D^+ \to \pi^+ K^0_S$ as reference

Challenge: signal extraction: π^0 selection and fit model

$A_{CP} = (2.31 \pm 1.24 \pm 0.23)\%$

World best — not sufficient yet for conclusive SM test



PRD 97 011101(R) (2018)

Direct CPV in $D^0 \to K^0_s K^0_s$

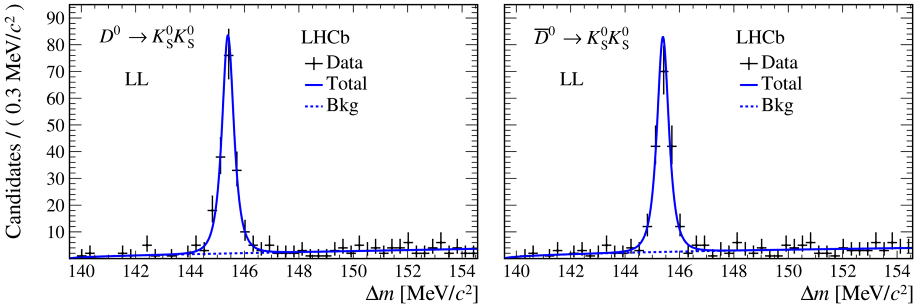
Up to 1% asymmetry in SM

D*-tagged D^0 from first 1/3 of data from current LHCb run — 20% of total.

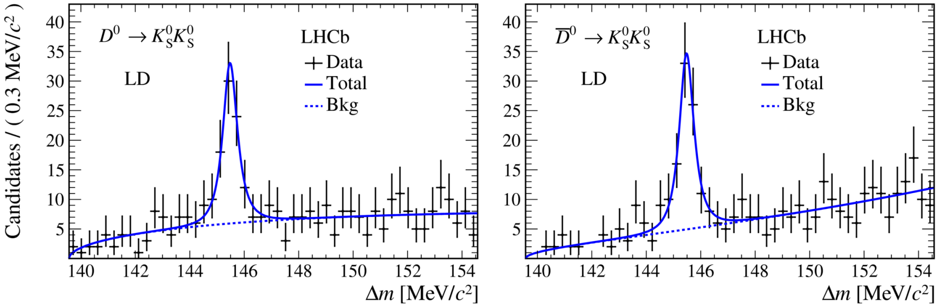
Subtract production and instrumental asymmetries by using $D^0 \to K^+K^-$ as a reference

Reject $D^0 \to K^0_s \pi\pi$ with correlation btw K^0_s flights

Both K^0_s decay inside the vertex detector



One K^0_s decays outside the vertex detector



arxiv:1806.01642

Combined with previous LHCb measurement yields
$A_{CP} = (2.0 \pm 2.9 \pm 1.0)\%$

Inferior to 1.5% Belle result — will match it when extended to full sample

First stab at baryons

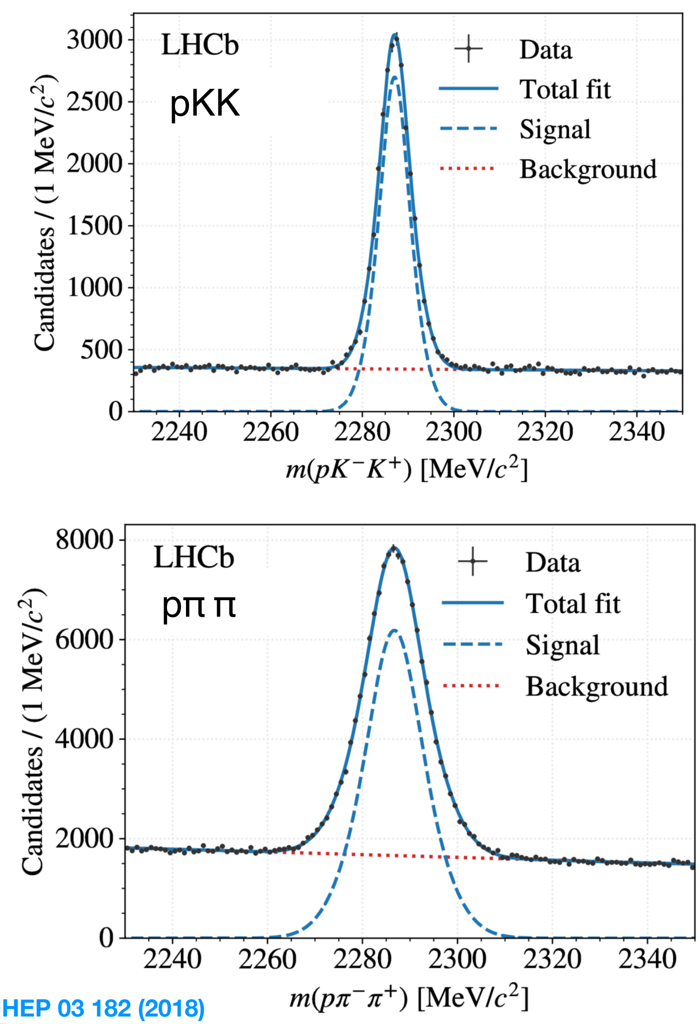
Difference of charge-asymmetries btw 25k pKK and 161k pππ Λ_c decays — inspired by now-gone indications of CPV in $D^0 \rightarrow h^+h^-$

1/3 of the LHCb sample

Production/instrumental asymmetries self-suppressed once kinematics is equalized across the two decays

$$\Delta A_{CP} = A_{CP}(pKK) - A_{CP}(p\pi\pi) =$$

$$(0.30 \pm 0.91 \pm 0.61)\%$$



JHEP 03 182 (2018)

Can we establish a mass difference between the D physical eigenstates ?

Will D oscillations bring us closer to see CPV in charm?

Oscillations

Transformation of matter into antimatter and back through a time-oscillating pattern.

Parametrized using normalized width and mass differences between the Hamiltonian eigenstates D^0_H and D^0_L

$$x = \frac{\Delta m}{\Gamma} = \frac{m_H - m_L}{(\Gamma_H + \Gamma_L)/2},$$

$$y = \frac{\Delta\Gamma}{2\Gamma} = \frac{\Gamma_H - \Gamma_L}{\Gamma_H + \Gamma_L}$$

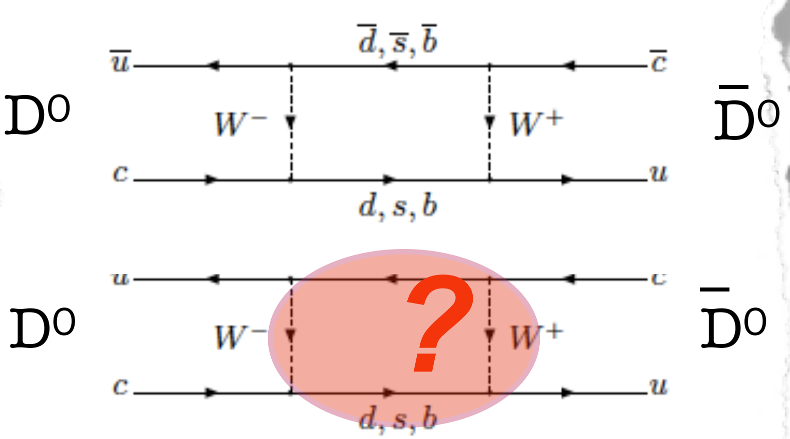
Behavior of Neutral Particles under Charge Conjugation

M. Gell-Mann,* *Department of Physics, Columbia University, New York, New York*

AND

A. Pais, *Institute for Advanced Study, Princeton, New Jersey*

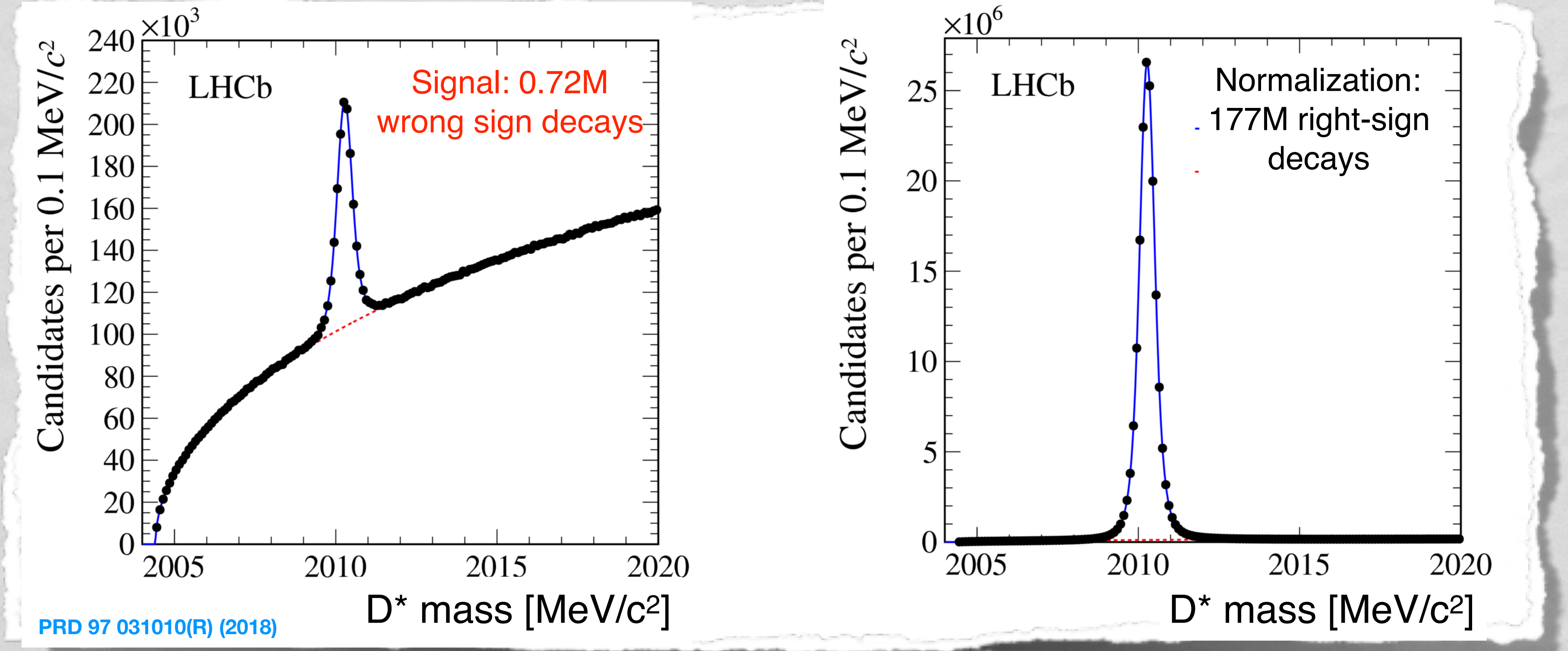
(Received November 1, 1954)



Established since 2007; x, y known with 0.1% absolute precision.
No evidence for nonzero x nor for CP violation.

Taking it easy — two-body

Modulation of the 'wrong-sign' $D^0 \to K^+\pi^-$ rate vs decay time implies oscillation. Differing patterns btw $\bar{D}^0$ and D^0 imply CPV. Straightforward, but has reduced sensitivity to mass difference x



PRD 97 031010(R) (2018)

1/2 of the LHCb data set. Fit signal and normalization yields in decay-time bins

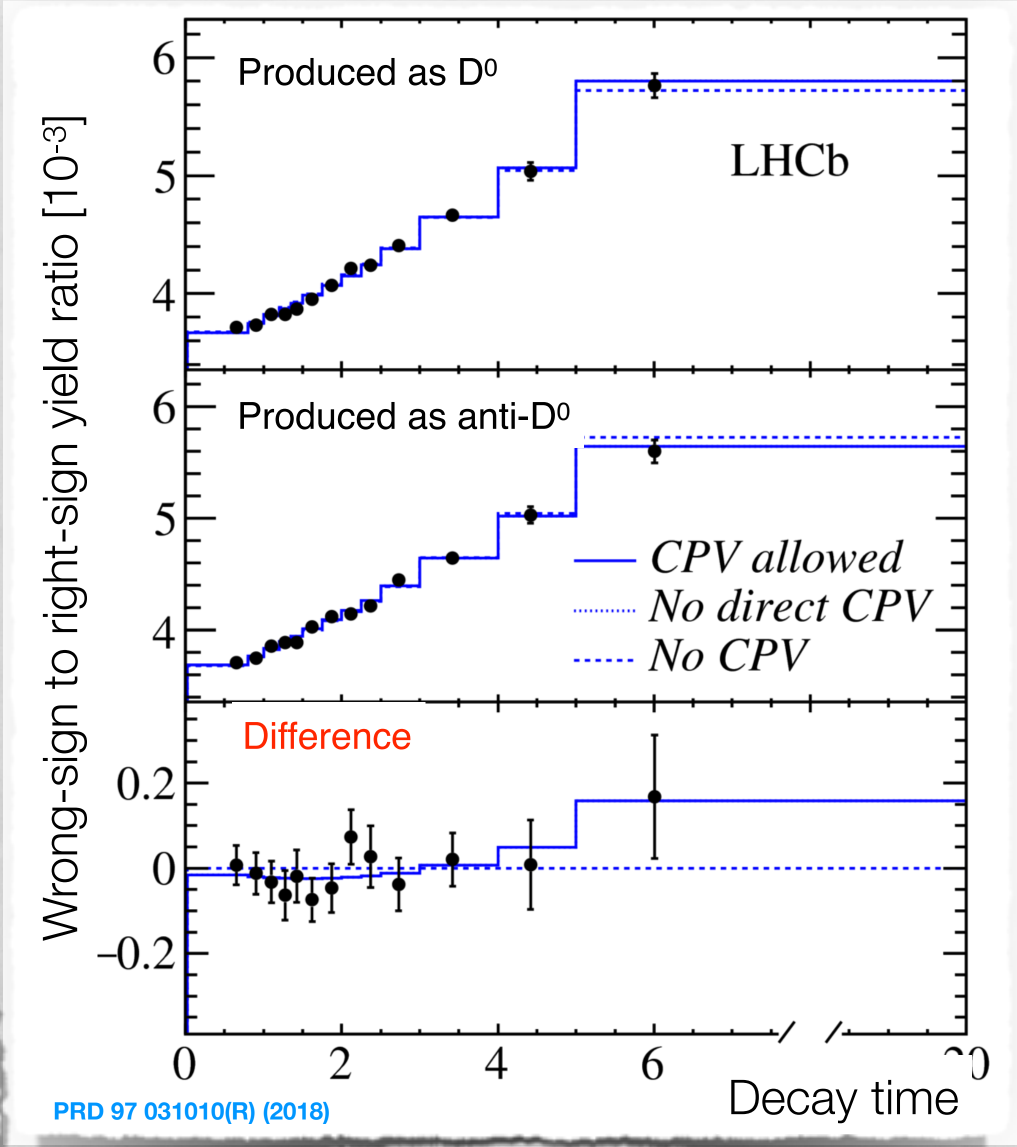
WS/RS ratios vs time

Plot signal/normalization (“WS/RS”) ratio as a function of decay time

Charm oscillates (we knew that…) but no measurable difference observed in oscillation rate between D^0 and anti-D^0

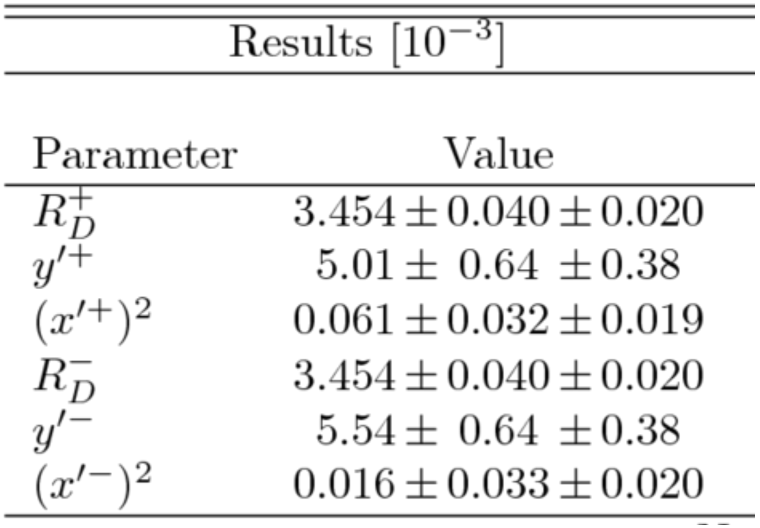
Fit these to extract the (rotated) mixing parameters x’, y’

$$R(t) \approx R_D + \sqrt{R_D}\, y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} \left(\frac{t}{\tau}\right)^2,$$

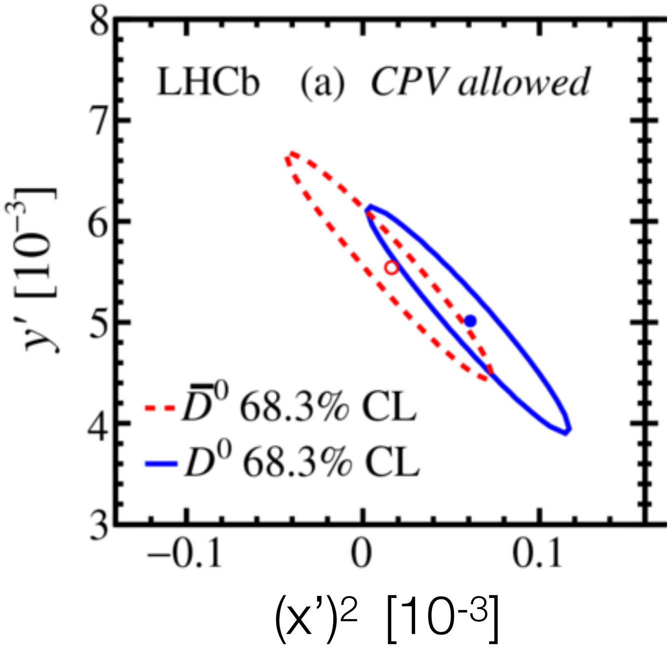


PRD 97 031010(R) (2018)

Results



Results $[10^{-3}]$	
Parameter	Value
R_D^+	$3.454 \pm 0.040 \pm 0.020$
y'^+	$5.01 \pm 0.64 \pm 0.38$
$(x'^+)^2$	$0.061 \pm 0.032 \pm 0.019$
R_D^-	$3.454 \pm 0.040 \pm 0.020$
y'^-	$5.54 \pm 0.64 \pm 0.38$
$(x'^-)^2$	$0.016 \pm 0.033 \pm 0.020$



PRD 97 031010(R) (2018)

D^0-vs-D^0bar mixing rate asymmetry $1.00 < |q/p| < 1.35$ at 68% CL

No evidence for CP violation.

World's best mixing parameters and constraints on CPV in mixing (uncertainties halved wrt previous results)

…less easy: y_{CP}

Compare D^0 width into CP-pure (KK, ππ) and CP-mix states (Kπ)

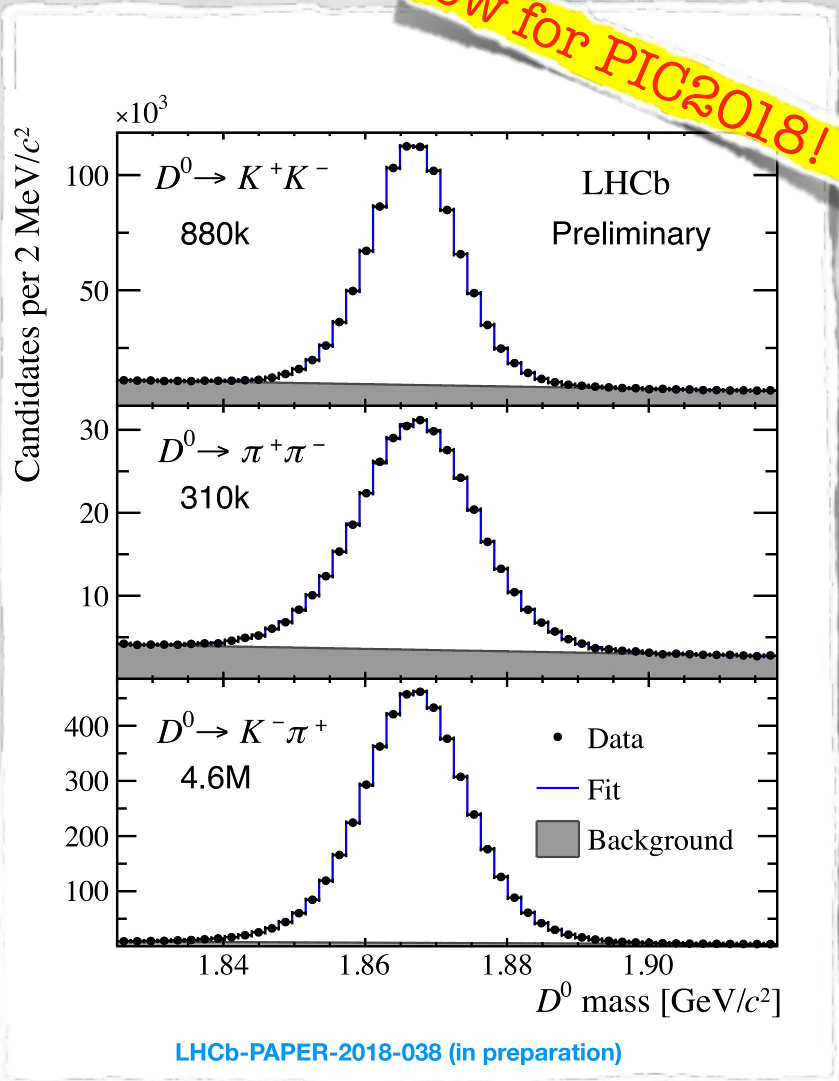
$$y_{CP} \equiv \frac{\Gamma_{CP}}{\Gamma} - 1$$

If $y_{CP} \neq y$ ==> CP is violated.

1/3 of LHCb sample. Fit KK/Kπ and ππ/Kπ yield ratios vs decay time

Challenge: trigger sculpting on decay-time acceptance
==> D^0 from $B \rightarrow D^0 \mu\nu$ decays triggered on the muon.

New for PIC2018!



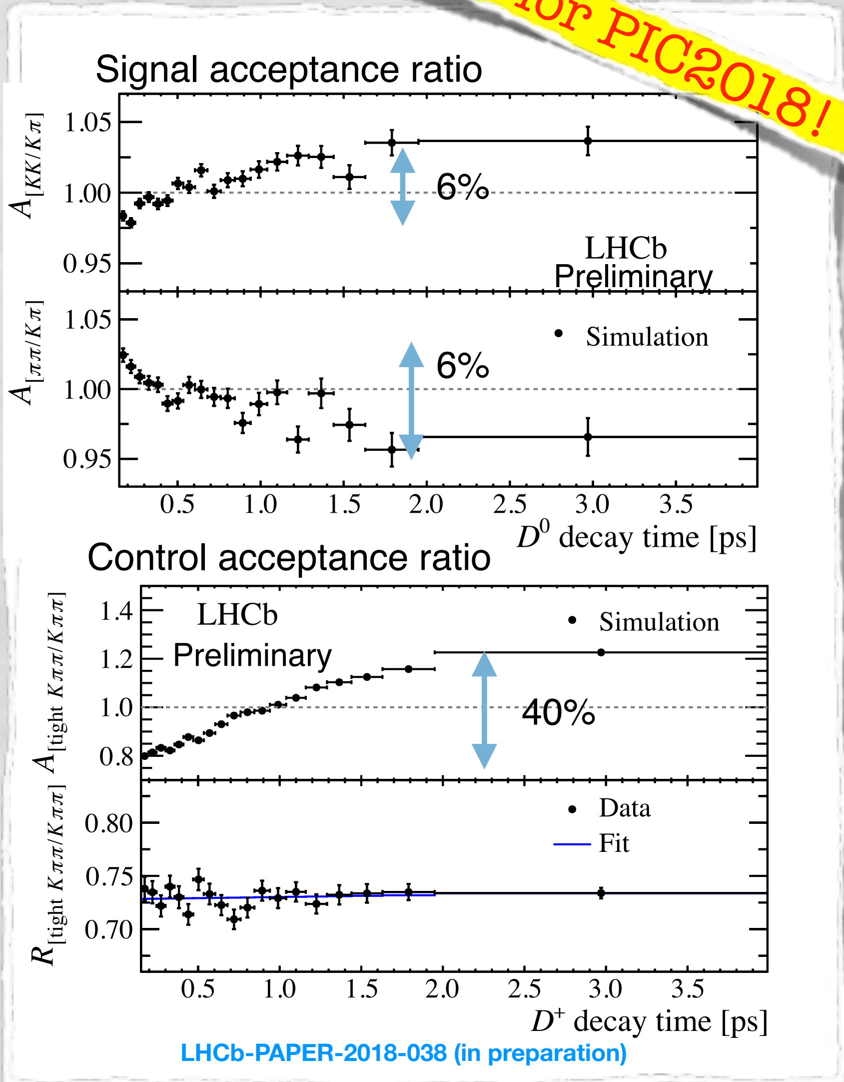
LHCb-PAPER-2018-038 (in preparation)

y_{CP} – decay-time acceptance

New for PIC2018!

Residual <6% biases on the ratios of KK/Kπ and ππ/Kπ decay-times corrected with simulation

Correction method validated in data known to have zero y_{CP} and much larger biases



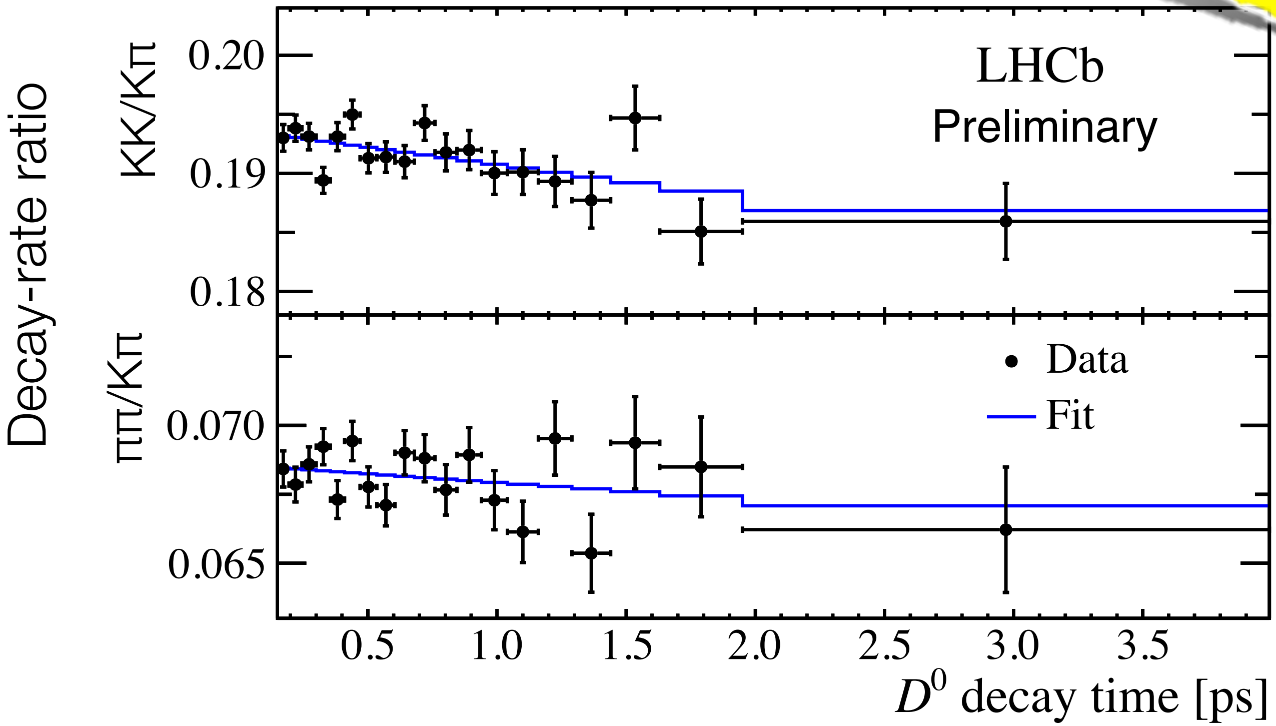
Signal acceptance ratio

Control acceptance ratio

LHCb-PAPER-2018-038 (in preparation)

y_{CP} – results

New for PIC2018!



LHCb-PAPER-2018-038 (in preparation)

Preliminary

$y_{CP}(KK) = (0.63 \pm 0.19)\%$ $y_{CP}(\pi\pi) = (0.38 \pm 0.32)\%$

$y_{CP}(KK+\pi\pi) = (0.57 \pm 0.16)\%$

Matches world-average precision and is consistent with y
==> no evidence for CP violation in D^0 mixing

The full thing — multibody

Decay-time dependent analysis of Dalitz plot in $D^0 \rightarrow K^0_S\pi^+\pi^-$

Rate at which an anti-D^0 component appears in the Dalitz space of initially produced D^0 (and viceversa) is function of the mixing parameters x and y.

However, x and y require knowledge of the CP-conserving (“strong”) phases of the decay amplitude, which vary across the Dalitz plot

- phases from a dedicated amplitude analysis
- phases externally input from meas. at the $\psi(3770)$

More complicated than two-body analyses. Access to genuine mixing parametersx and y and has greater sensitivity to mass difference x

$D^0 \to K^0_S\,\pi^+\pi^-$ amplitudes

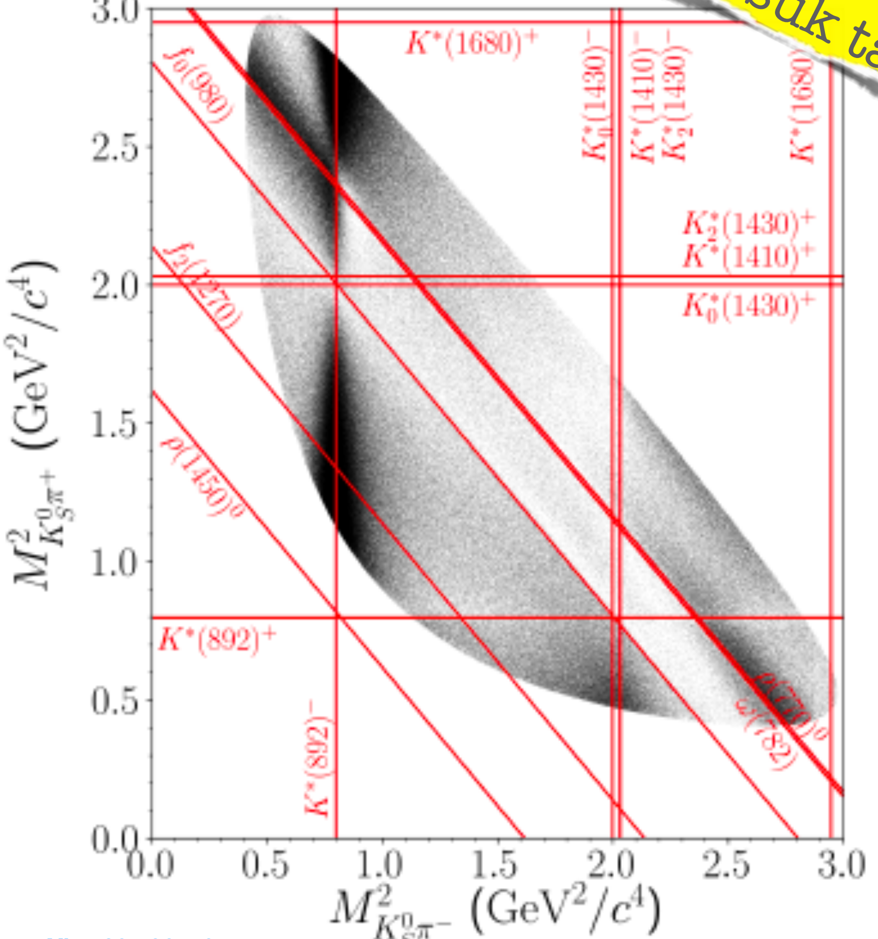
See also S. Barsuk talk

Joint analysis of combined full BaBar+Belle data sets to solve the sin2β ambiguity.

Amplitude analysis of the Dalitz plot is a prerequisite.

=> done on 1.2M candidates from Belle only, obtaining an improved amplitude model.

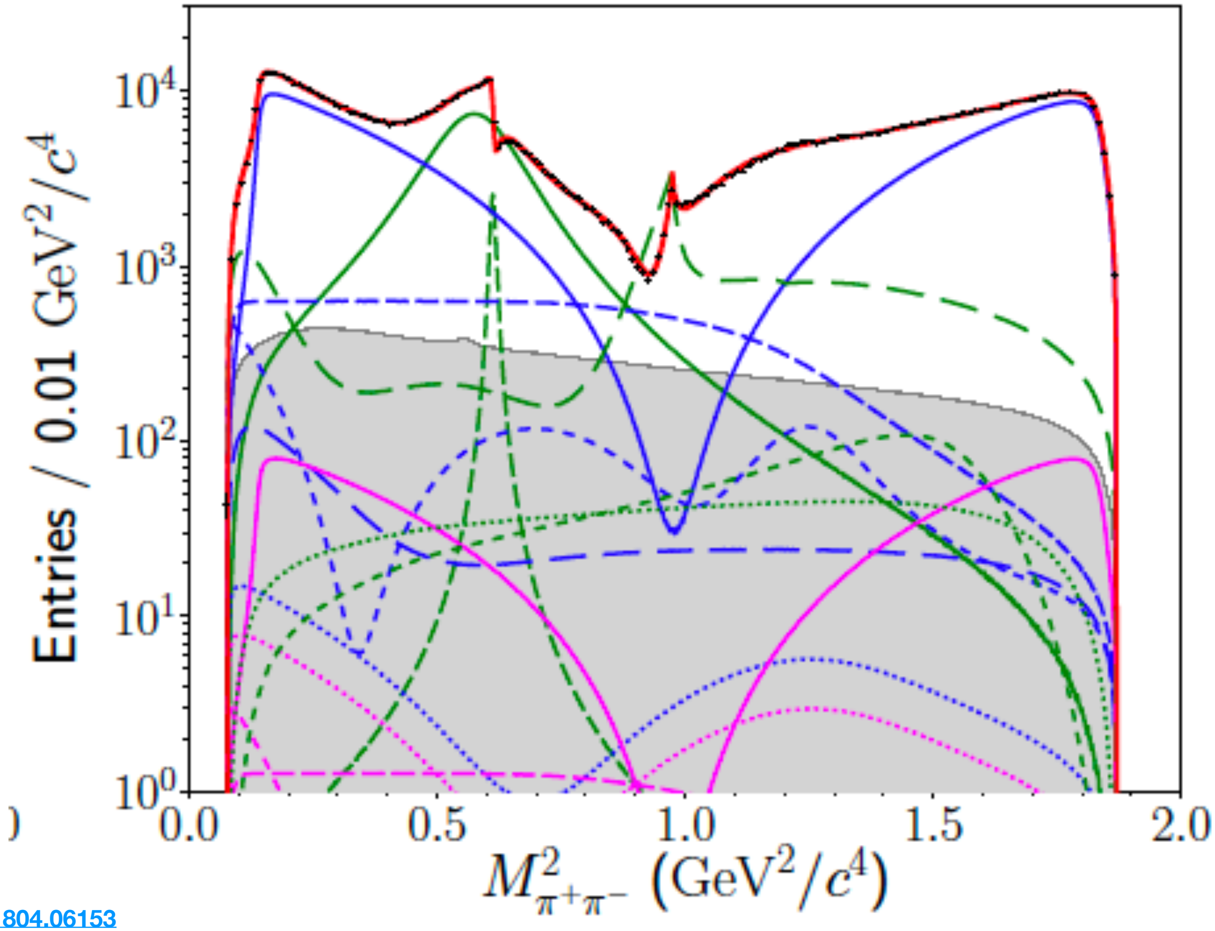
Foundation for decay-time dependent analysis



arXiv:1804.06153
arXiv:1804.06152

Not your vanilla fit

Fit projection in one of the dipion masses



arXiv:1804.06153
arXiv:1804.06152

Toward $D^0 \to K^+\pi^-\pi\pi$

Diversifying the portfolio

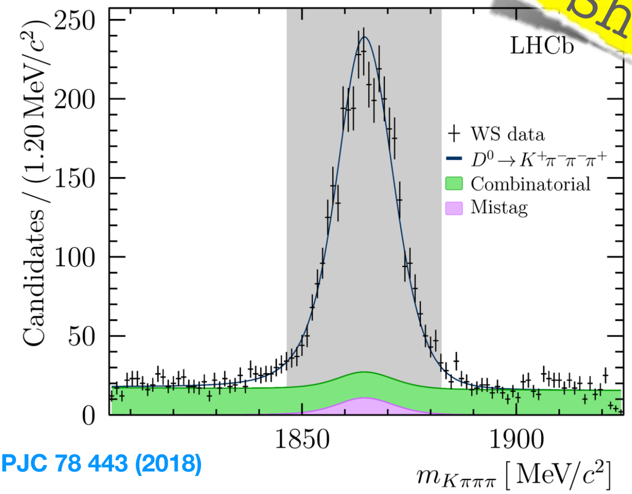
LHCb — 1st amplitude analysis of WS $D^0 \to K^+\pi^-\pi^+\pi^-$ decays. Double $B \to D^{*+}(\to D^0\, \pi^+)\ell\nu$ tag yields 4k very pure events.

BESIII— amplitude analysis of 6k RS $D^0 \to K^-\pi^+\pi^0\pi^0$ (BESIII) decays

BESIII Preliminary

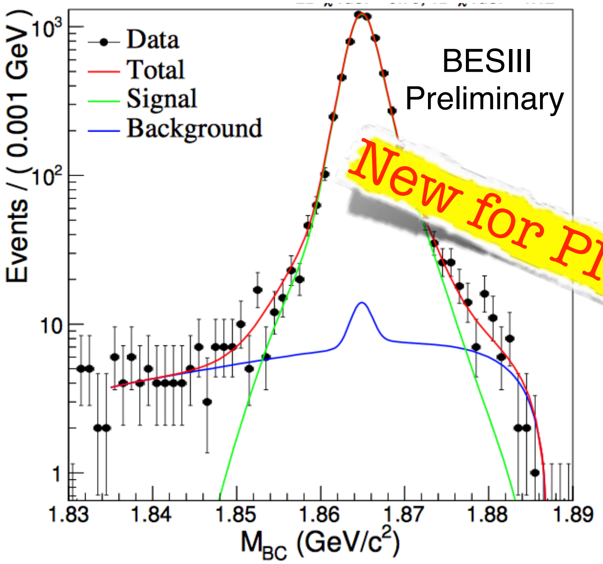
$BF(D^0 \to K^-\pi^+\pi^0\pi^0) = (9.00 \pm 0.4)\%$

Groundwork toward decay-time dependent mixing analyses



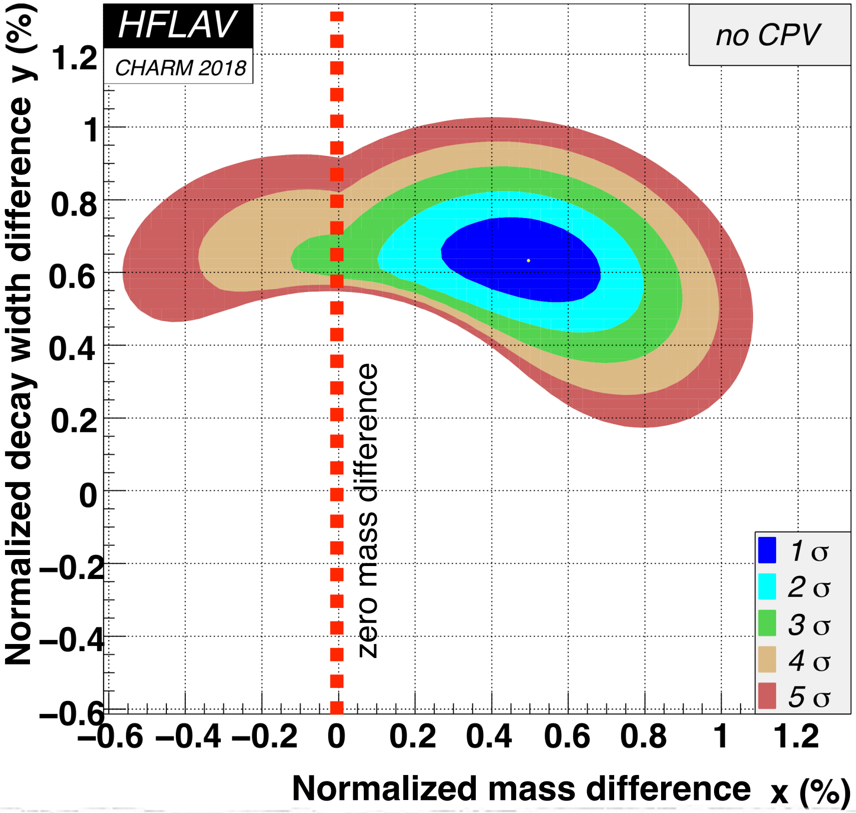
EPJC 78 443 (2018)

See also X. Shen talk

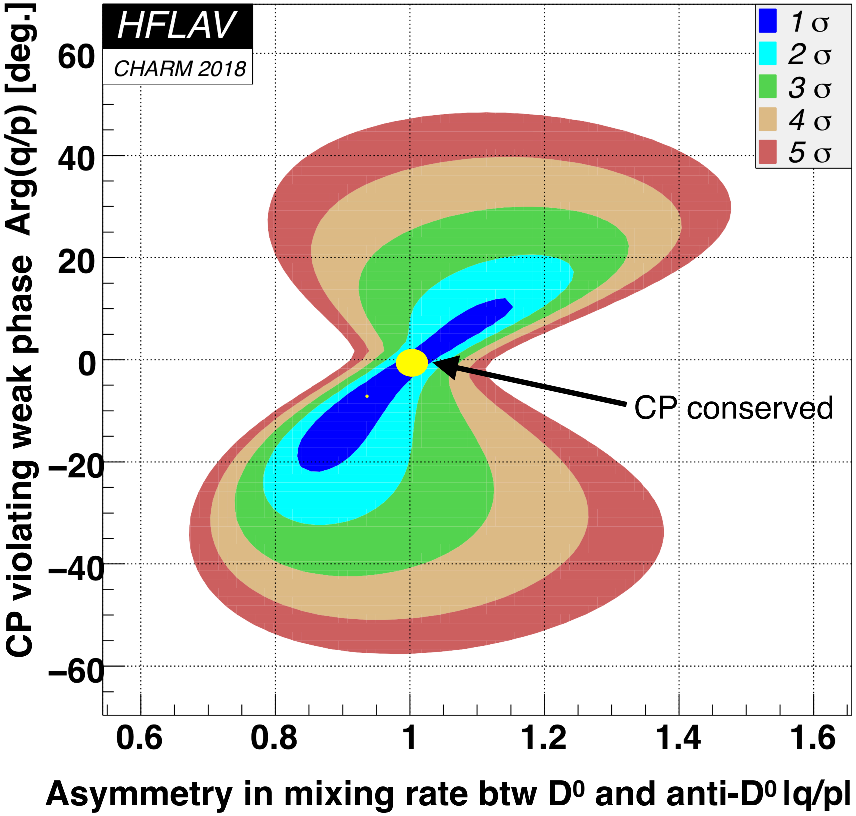


New for PIC2018!

Oscillations/CPV in mixing today

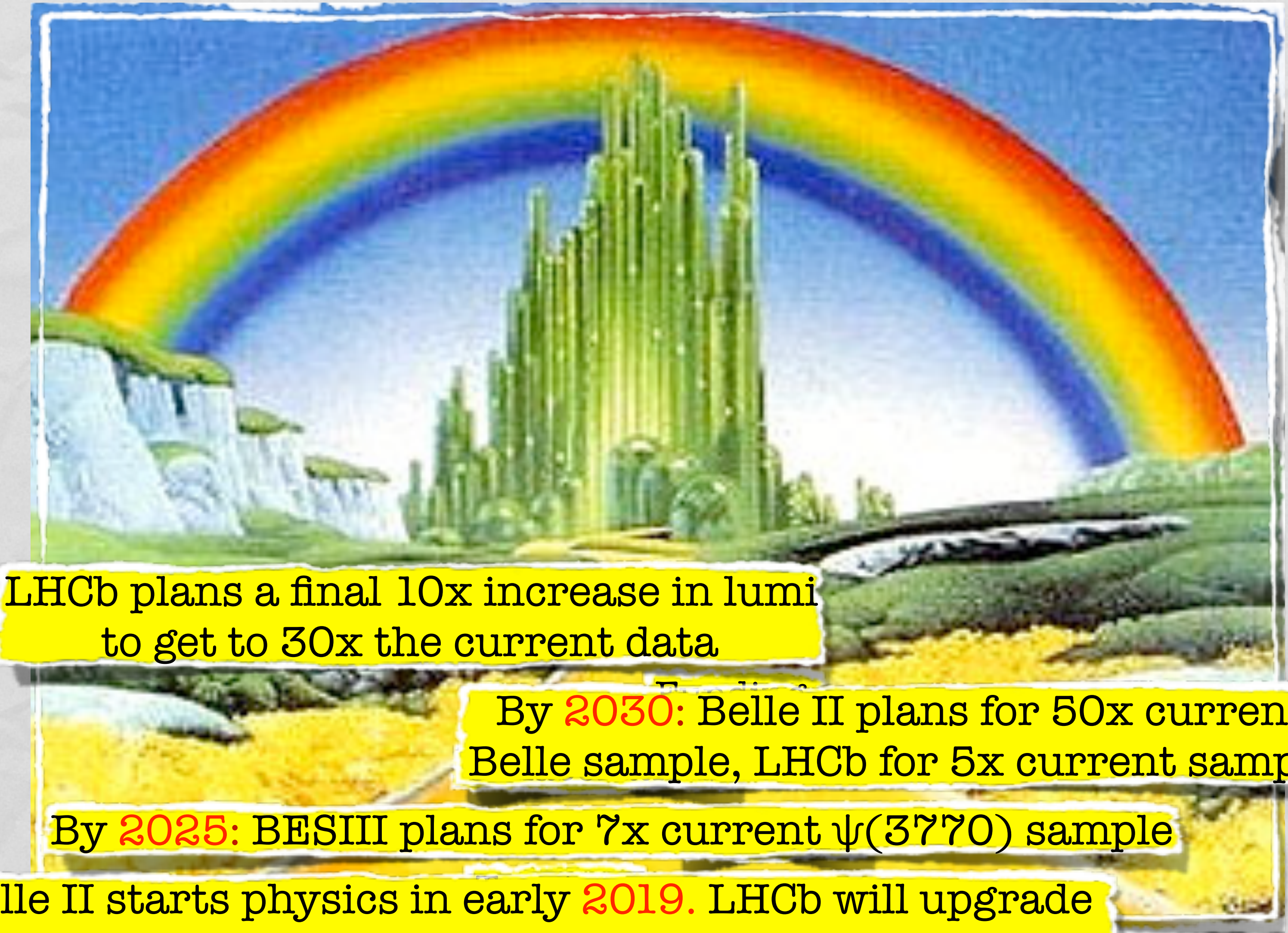


No evidence of nonzero mass difference



No evidence of CP violation

What next?



LHCb plans a final 10x increase in lumi to get to 30x the current data

By 2030: Belle II plans for 50x current Belle sample, LHCb for 5x current sample

By 2025: BESIII plans for 7x current $\psi(3770)$ sample

Belle II starts physics in early 2019. LHCb will upgrade for 2021 (20x instantaneous lumi with 40 MHz readout)

Summary

BSM reach of charm dynamics is unique — both in energies probed and BSM-dynamics tested.

Measurements are hard — competitive/synergic BaBar/Belle/BESIII/LHCb effort is steadily bringing major progresses.

Today: my choice of recent highlights on lepton universality, searches for CP violation, and oscillations — 2 results new for PIC!

The SM didn't crack.

Keep pushing: today's results use at best 1/2 of current LHCb data — and Belle II has just joined. Times seem particularly fitting: LHC expected exciting high-p_T physics and boring flavor — looks like it's going the other way around ;)

Flavor's getting more compelling than ever — our best (only?) probe for 10 –10^6 TeV energies in the next decade and beyond.

(Hopefully not) The end