Charming your way to New Physics

Angelo Di Canto (CERN)

A simple question

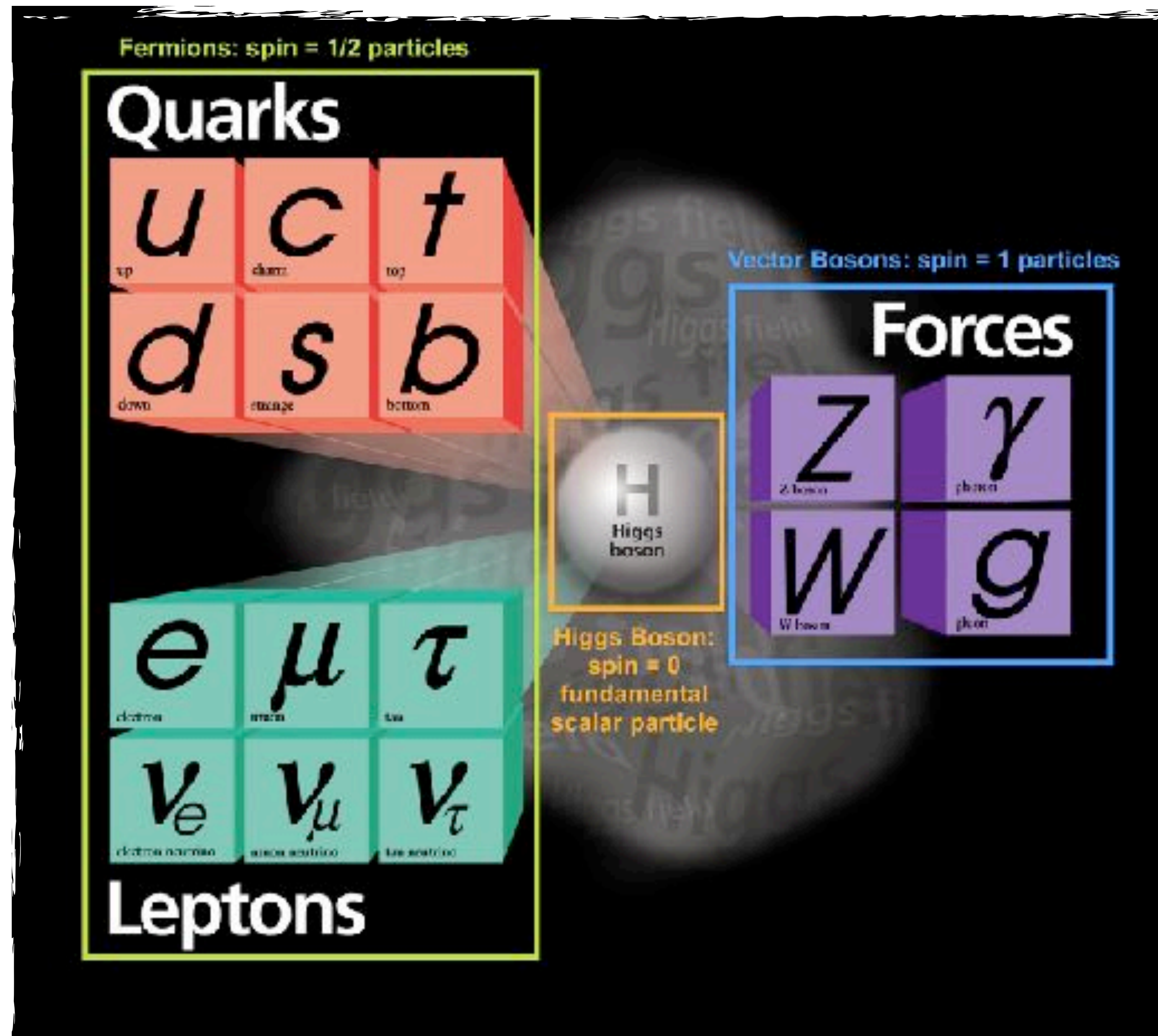
$$\mathcal{L} = ?$$

$$
\begin{aligned}
\mathcal{L}_{SM} = &-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
&M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
&igs_w(\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
&W^-_\nu \partial_\nu W^+_\mu)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
&Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w (A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - \tfrac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \\
&\beta_h\left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - \\
&g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
&\tfrac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) - \\
&gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \\
&\tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
&\tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
&M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - \\
&W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
&\tfrac{1}{4}g^2W^+_\mu W^-_\mu\left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu\left(H^2 + (\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-\right) - \\
&\tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- + \\
&W^-_\mu\phi^+) + \tfrac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - \\
&g^2s_w^2A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\lambda^a_{ij}(\bar q^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar e^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar\nu^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar u^\lambda_j(\gamma\partial + \\
&m^\lambda_u)u^\lambda_j - \bar d^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_wA_\mu\left(-(\bar e^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar u^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar d^\lambda_j\gamma^\mu d^\lambda_j)\right) + \\
&\tfrac{ig}{4c_w}Z^0_\mu\{(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar e^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar d^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2-1-\gamma^5)d^\lambda_j) + \\
&(\bar u^\lambda_j\gamma^\mu(1-\tfrac{8}{3}s_w^2+\gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar\nu^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar u^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \\
&\tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar e^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar d^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
&\tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar\nu^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar\nu^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa\right) + \\
&\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar e^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar e^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa\right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M}H(\bar\nu^\lambda\nu^\lambda) - \\
&\tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar e^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar\nu^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar e^\lambda\gamma^5 e^\lambda) - \tfrac{1}{4}\bar\nu_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat\nu_\kappa - \\
&\tfrac{1}{4}\overline{\bar\nu_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat\nu_\kappa} + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar u^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar u^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j\right) + \\
&\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar u^\lambda_j u^\lambda_j) - \\
&\tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar d^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar u^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar d^\lambda_j\gamma^5 d^\lambda_j) + \bar G^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar G^a G^b g^c_\mu + \\
&\bar X^-(\partial^2 - M^2)X^+ + \bar X^-(\partial^2-M^2)X^- + \bar X^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar Y\partial^2 Y + igc_wW^+_\mu(\partial_\mu\bar X^0 X^- - \\
&\partial_\mu\bar X^+ X^0) + igs_wW^+_\mu(\partial_\mu\bar Y X^- - \partial_\mu\bar X^+ Y) + igc_wW^-_\mu(\partial_\mu\bar X^- X^0 - \\
&\partial_\mu\bar X^0 X^+) + igs_wW^-_\mu(\partial_\mu\bar X^- Y - \partial_\mu\bar Y X^+) + igc_wZ^0_\mu(\partial_\mu\bar X^+ X^+ - \\
&\partial_\mu\bar X^- X^-) + igs_wA_\mu(\partial_\mu\bar X^+ X^+ - \\
&\partial_\mu\bar X^- X^-) - \tfrac{1}{2}gM\left(\bar X^+X^+H + \bar X^-X^-H + \tfrac{1}{c_w^2}\bar X^0X^0H\right) + \tfrac{1-2c_w^2}{2c_w}igM\left(\bar X^+X^0\phi^+ - \bar X^-X^0\phi^-\right) + \\
&\tfrac{1}{2c_w}igM\left(\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-\right) + igMs_w\left(\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-\right) + \\
&\tfrac{1}{2}igM\left(\bar X^+X^+\phi^0 - \bar X^-X^-\phi^0\right).
\end{aligned}
$$

The Standard Model

- **Symmetry**, local gauge
- **Simplicity**, few parameters
- **Anarchy**, whatever is not forbidden is allowed

Remarkable predictive power, it explains (almost) all observed phenomena at the elementary particle level



Just the tip…

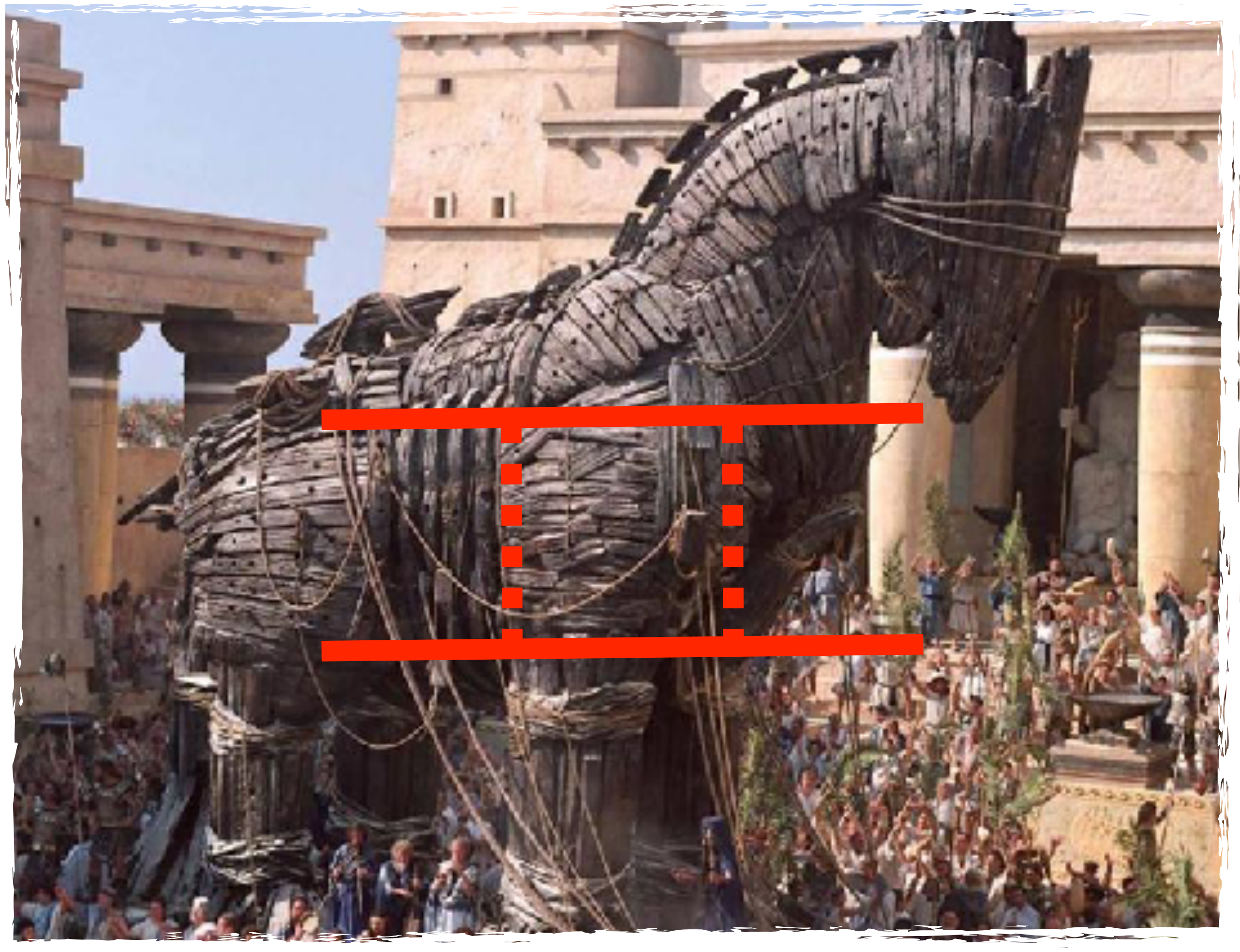
- Several questions remain unanswered: origin of generations, dark matter, matter-antimatter asymmetry, gravity, …
- Strong prejudice in favor of a higher-energy extension of the theory (ultraviolet completion)
- Will involve new particles and interactions at energy scales not (yet) explored

Probing the next scale

High-energy production
of new particles

Probe directly the structure of matter and its interactions

Low-energy precision
measurements

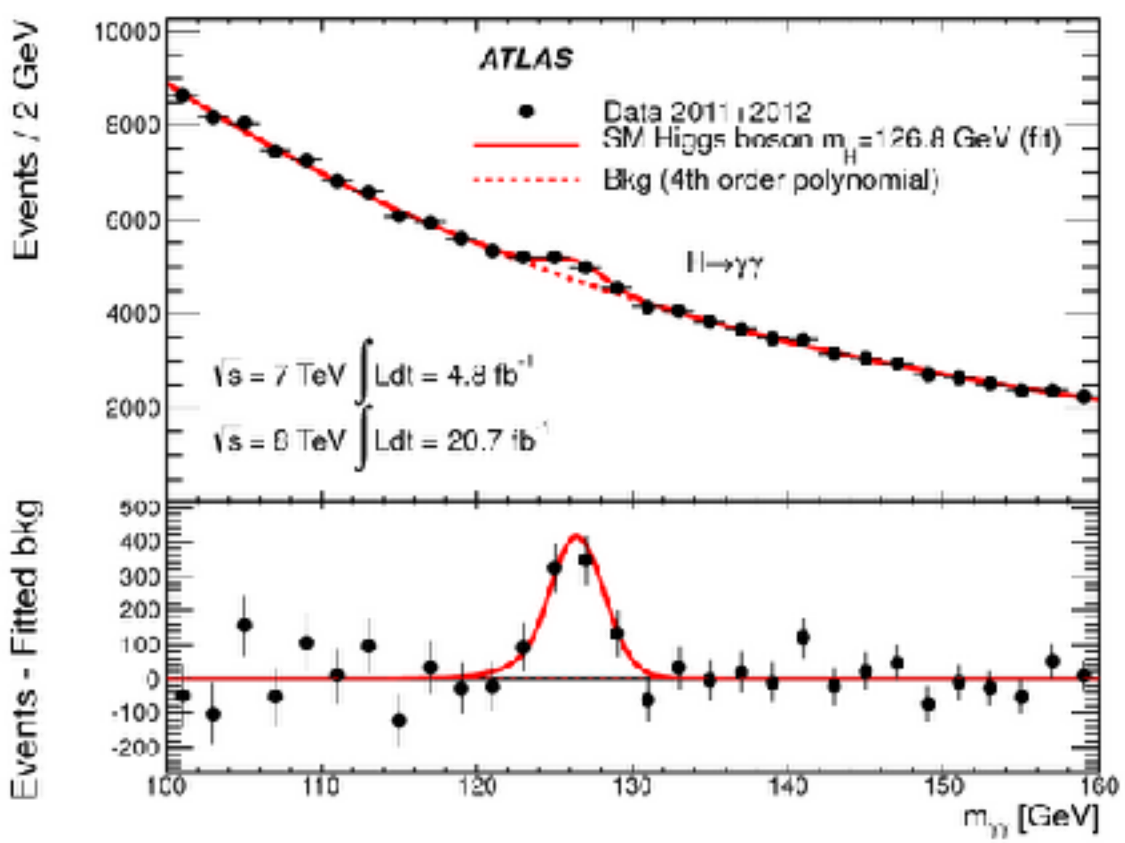


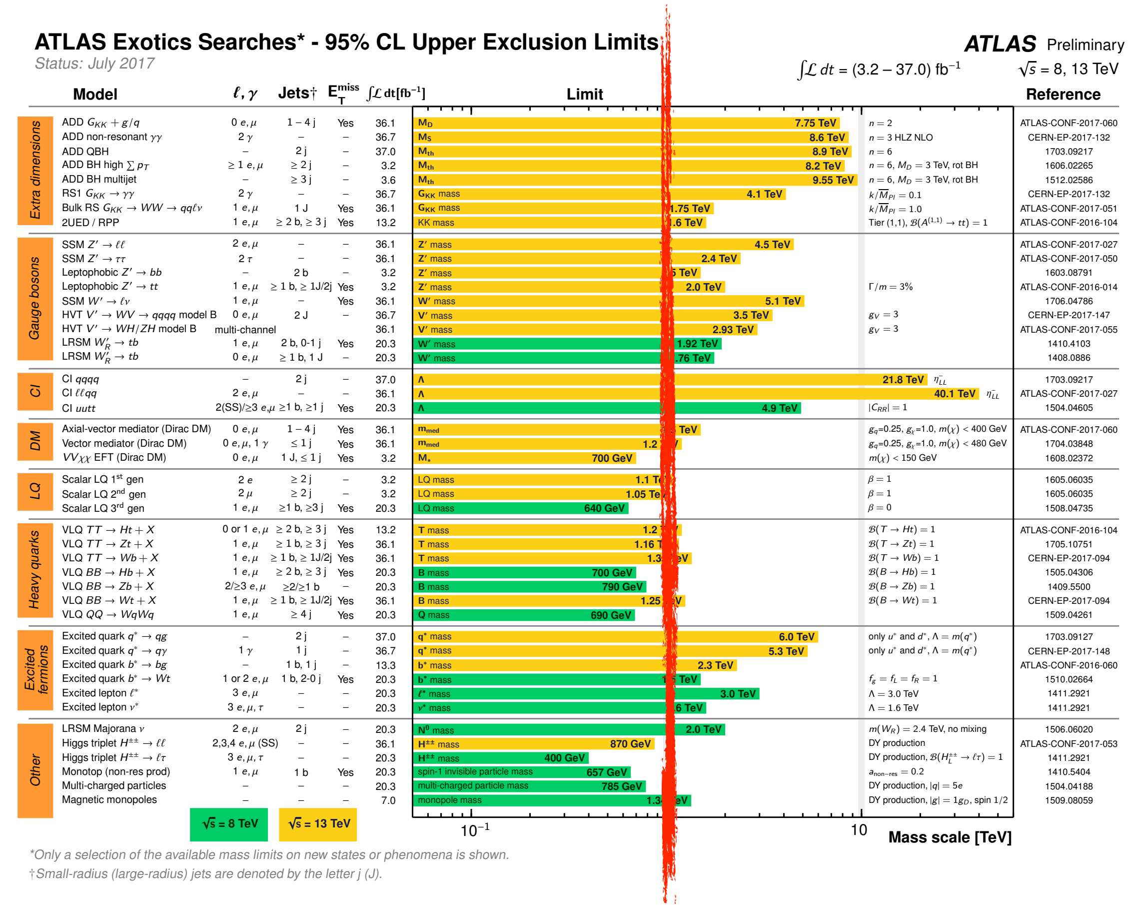
Look for the effects of exchange of virtual new particles. Quantum-probe of higher energies than directly accessible

The high-energy frontier

Discovery of a spin-0 boson consistent with the Higgs particle…

…and null results from direct searches probing masses >1 TeV



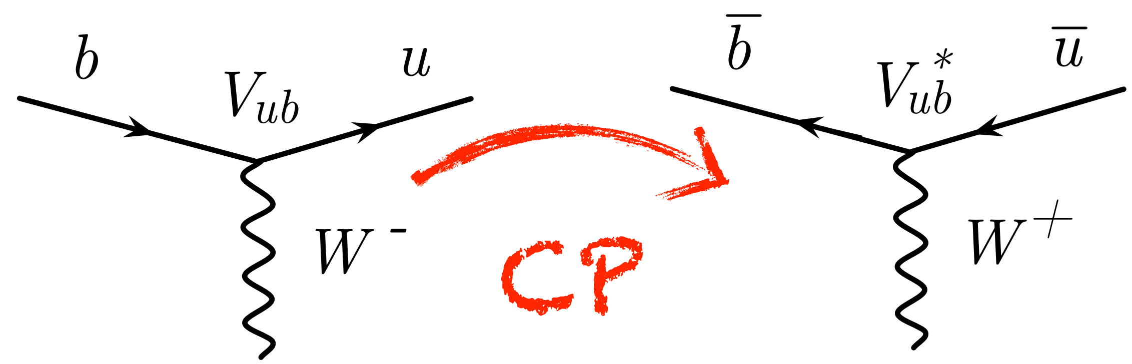


ATLAS shown for illustrative purposes only. Similar results hold for CMS

New particles or interactions are unlikely to be directly accessible at the energies probed by the LHC

(Quark) Flavor matters

- The physics of matter at its most fundamental level. Deals with masses and transitions of fermions
- Added bonus: dynamics is not invariant for mirror-reversal of the spatial arrangement and replacement of particles with antiparticles (*CP* violation)
- The richness of this phenomenology offers multiple ways to test the SM

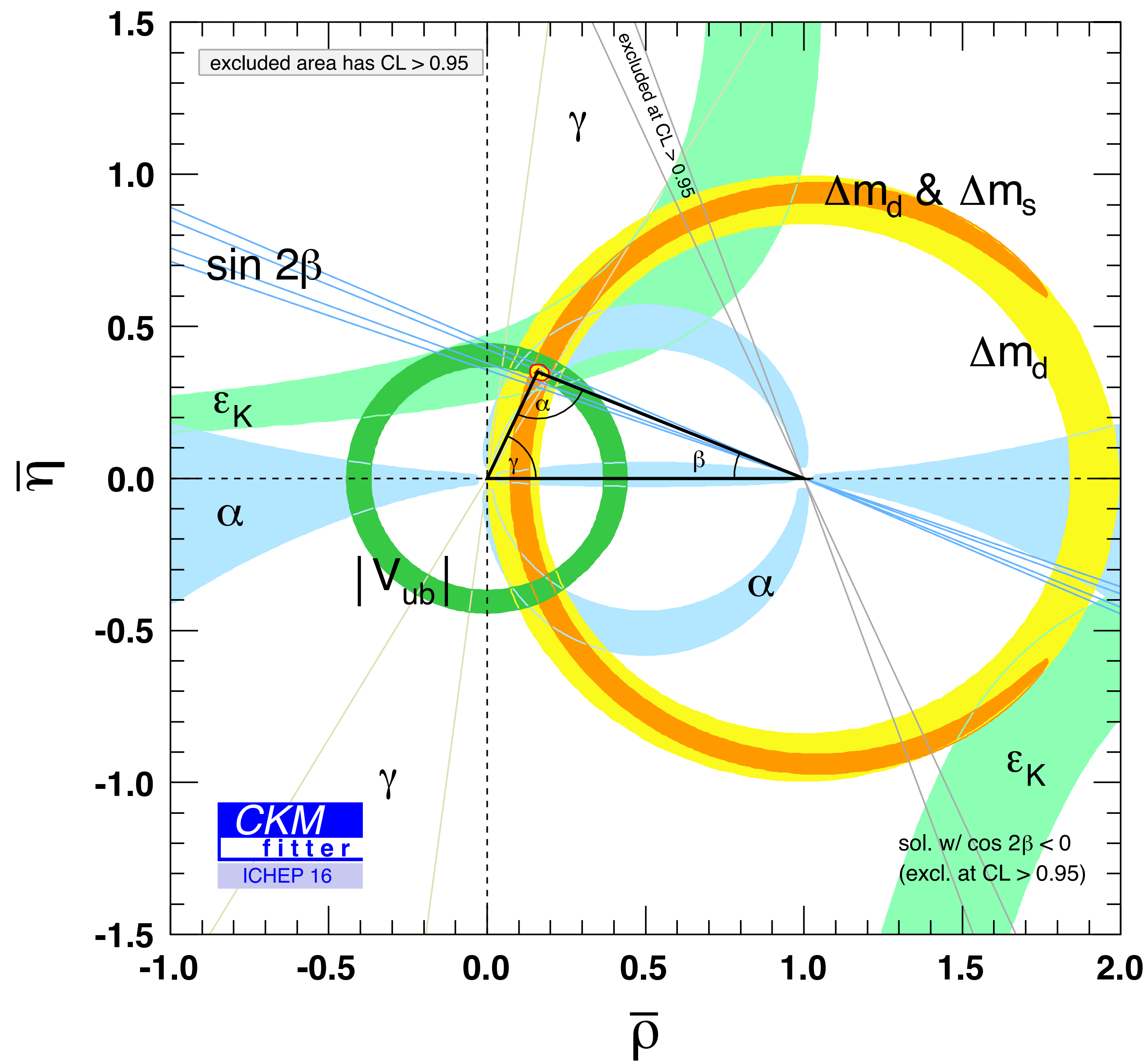


$$
\begin{array}{cccc}
 & d & s & b \\
V \approx & \begin{pmatrix} 1 & \lambda & \lambda^3 e^{i\varphi} \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 e^{-i\varphi} & -\lambda^2 & 1 \end{pmatrix} & & \begin{array}{c} u \\ c \\ t \end{array}
\end{array}
$$

$$\lambda \approx 0.22$$

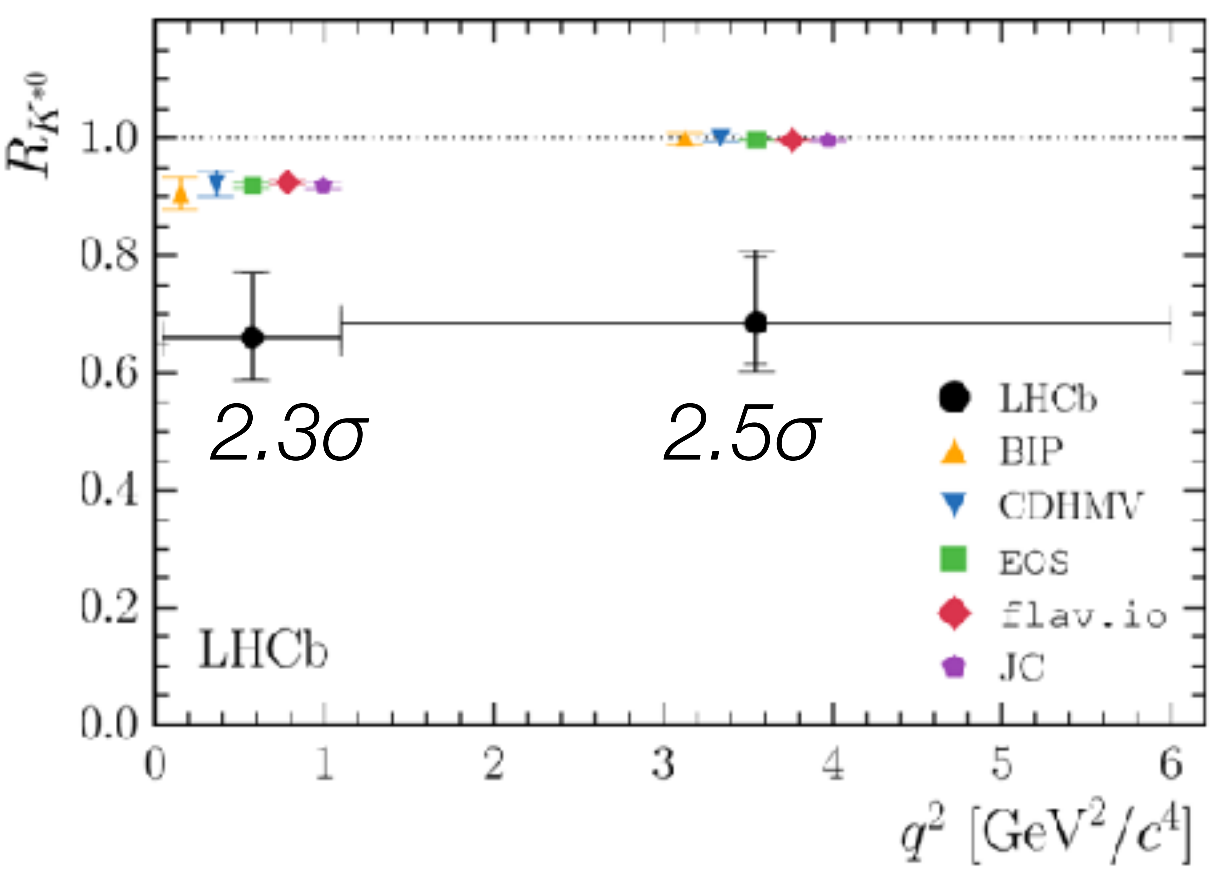
All consistent…

- A global campaign of O(1000) measurements conducted in the past 20+ years to experimentally explore the quark-flavor sector
- The SM is sufficient to accommodate all quark-flavor phenomena observed so far (*e.g.* CKM picture of *CP* violation is self consistent)
- Impressive, but let's not overstate the implications: up to 20% deviations still unconstrained in most of the suppressed processes
- LHCb and Belle II need to push the precision to the next level

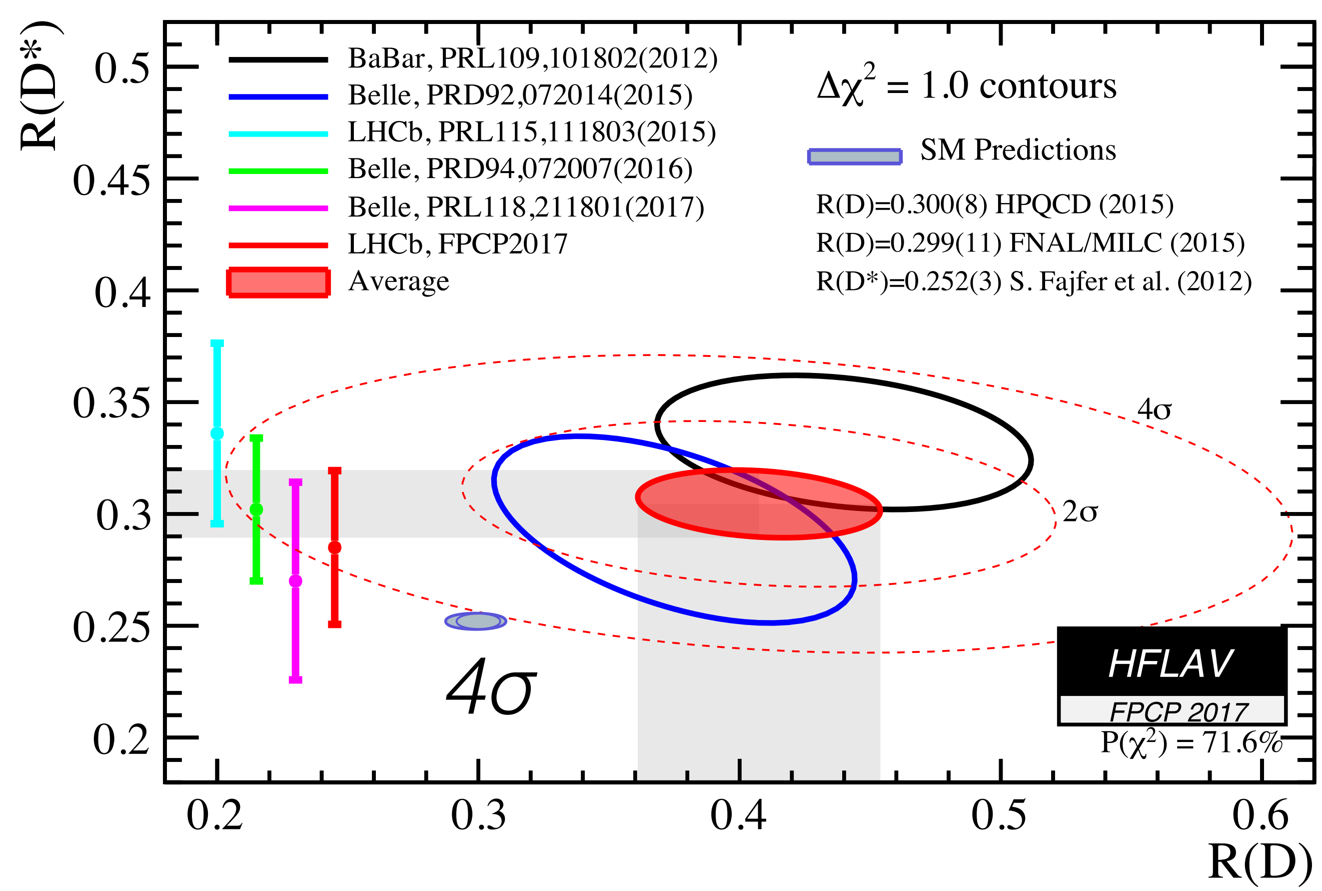


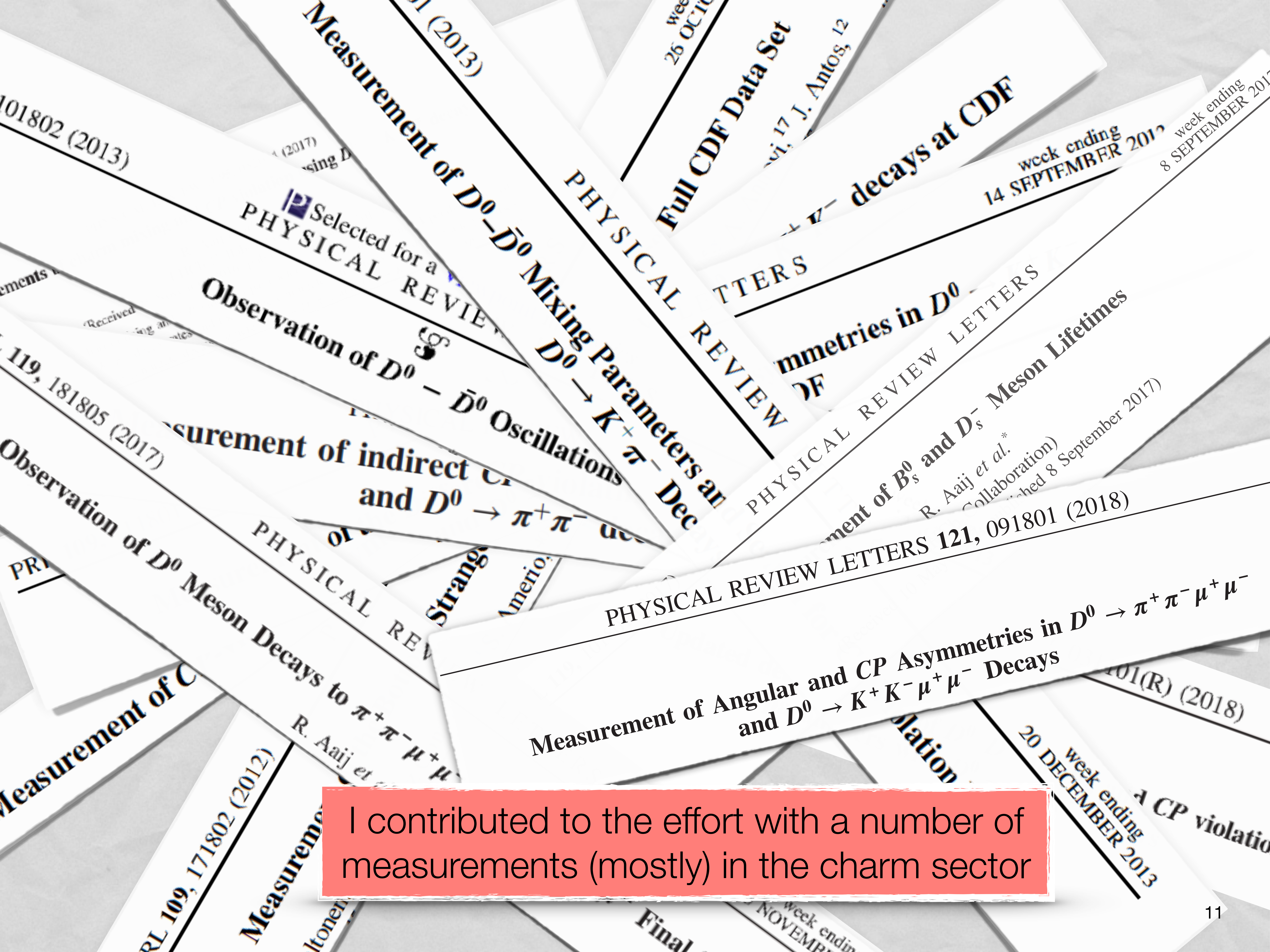
…or maybe not?

$(B\to K^{*}\mu^{+}\mu^{-})/(B\to K^{*}e^{+}e^{-})$

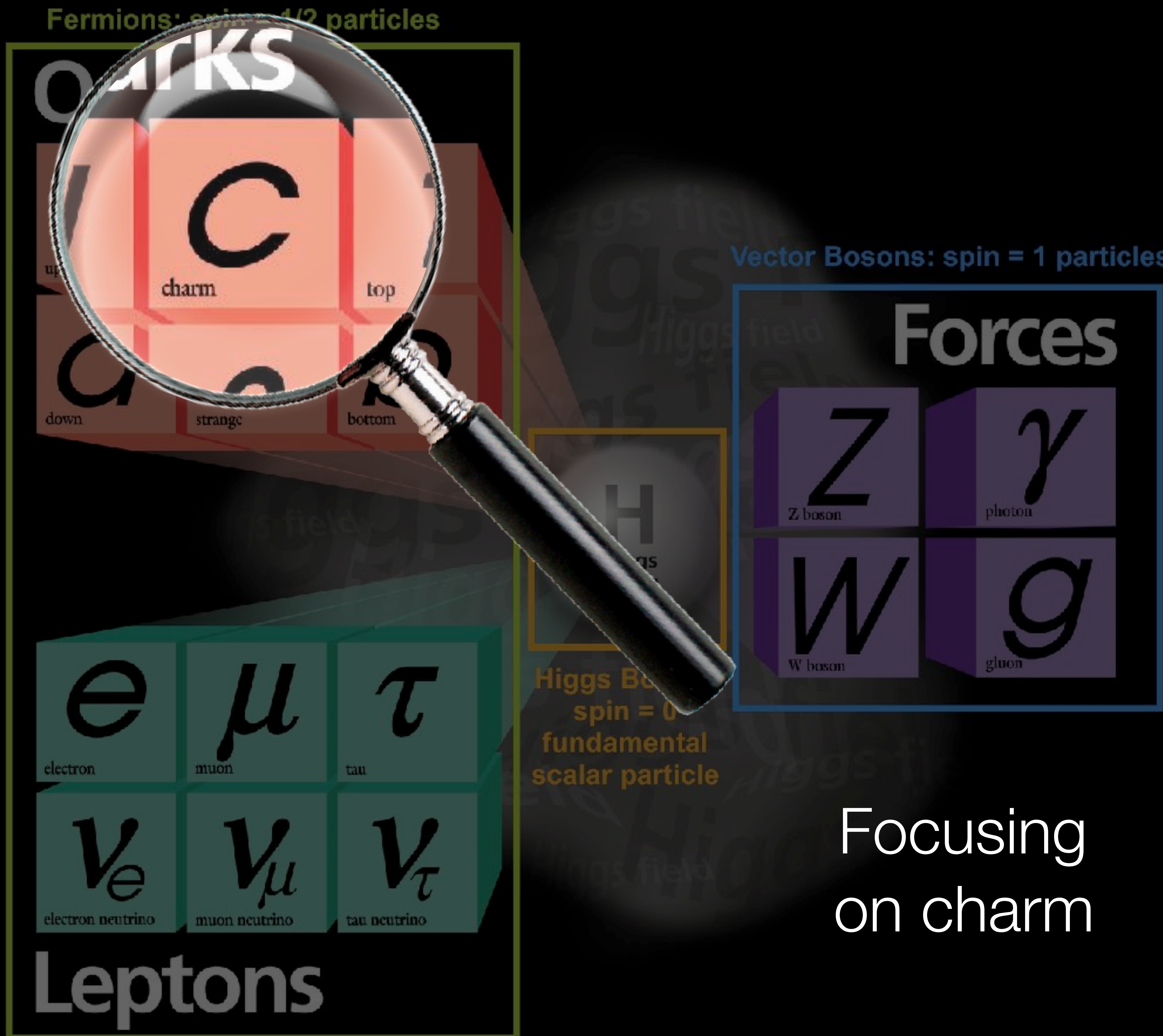


$(B\to D^{(*)-}\tau^{+}\nu)/(B\to D^{(*)-}\mu^{+}\nu)$





I contributed to the effort with a number of measurements (mostly) in the charm sector



Focusing on charm

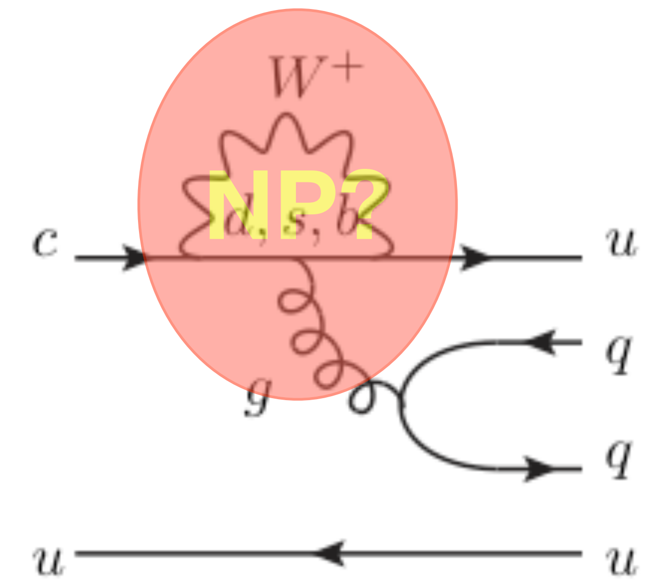
Why is charm charming?

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

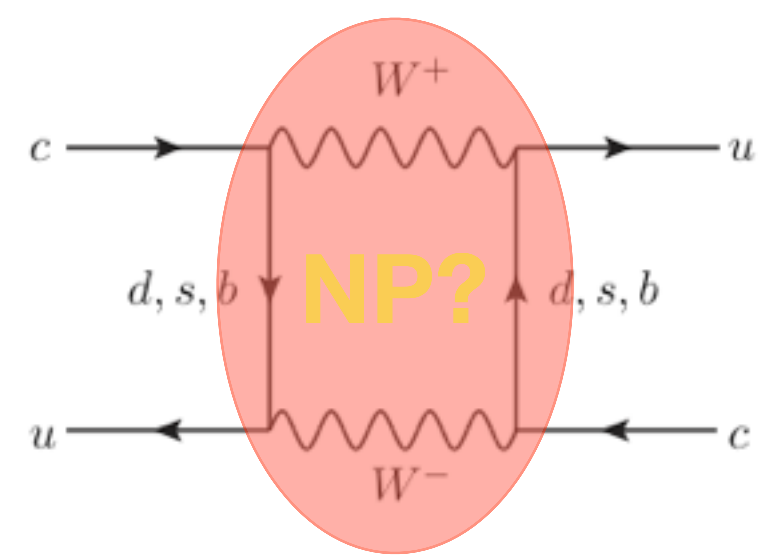
Discovery tool, SM effects are <10^{-3} or smaller, but predictions are difficult. Charm is not a precision probe

Challenging, need >1M yields and control over systematic uncertainties

Only recently reached sensitivity to discern SM from possible new physics effects

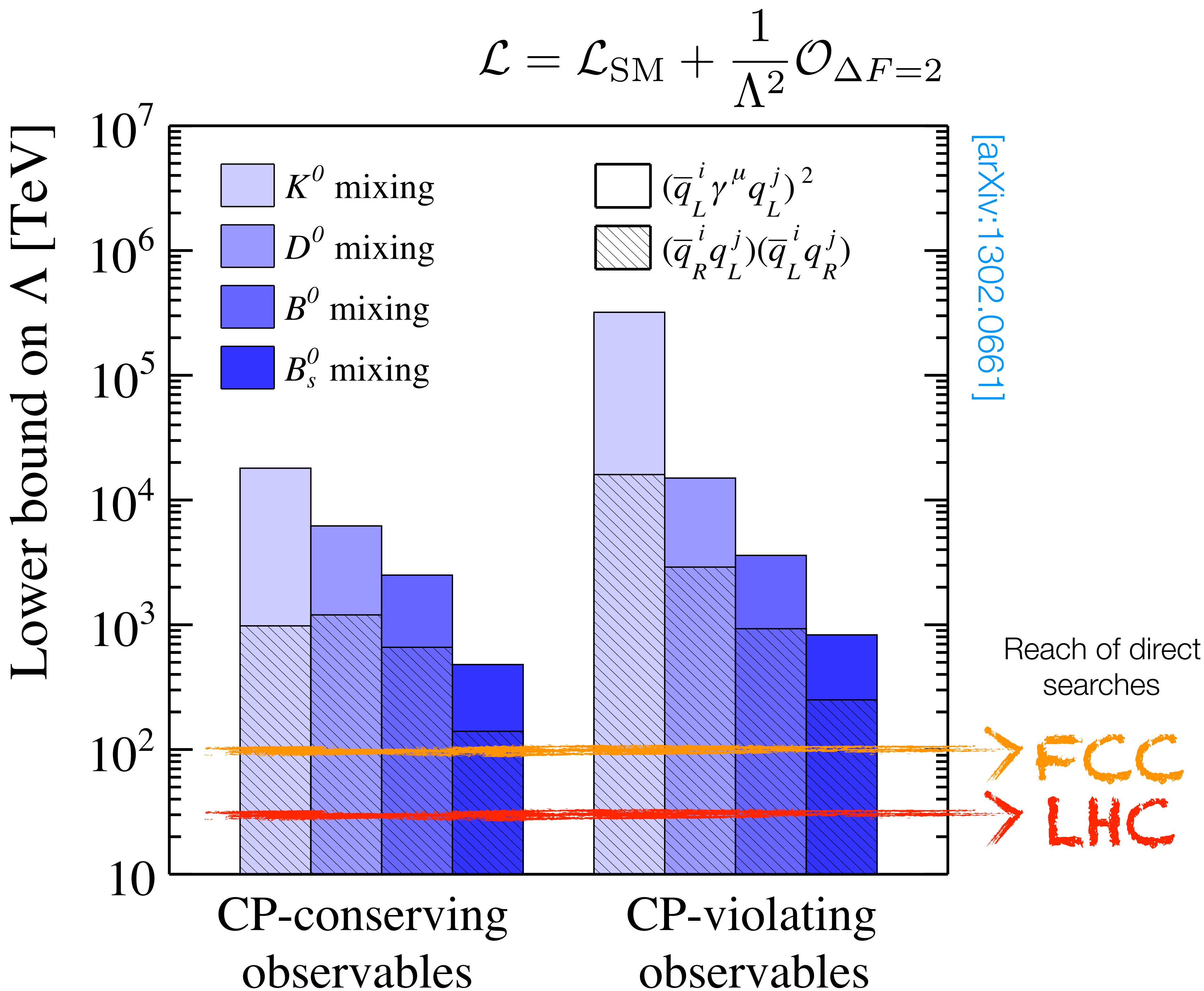


ΔC=1



ΔC=2

Reach



$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\mathcal{O}_{\Delta F=2}$
Lower bound on Λ [TeV]
10^7
10^6
10^5
10^4
10^3
10^2
10
K^0 mixing
D^0 mixing
B^0 mixing
B^0_s mixing
$(\bar{q}^i_L \gamma^\mu q^j_L)^2$
$(\bar{q}^i_R q^j_L)(\bar{q}^i_L q^j_R)$
CP-conserving observables
CP-violating observables
[arXiv:1302.0661]
Reach of direct searches
FCC
LHC

PHYSICAL REVIEW D **97,** 031101(R) (2018)

Rapid Communications

Updated determination of D^0–$\bar{D}^0$ mixing and *CP* violation parameters with $D^0 \to K^+\pi^-$ decays

R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 8 December 2017; published 22 February 2018; corrected 26 March 2018)

We report measurements of charm-mixing parameters based on the decay-time-dependent ratio of $D^0 \to K^+\pi^-$ to $D^0 \to K^-\pi^+$ rates. The analysis uses a data sample of proton-proton collisions corresponding to an integrated luminosity of 5.0 fb^{-1} recorded by the LHCb experiment from 2011 through 2016. Assuming charge-parity (*CP*) symmetry, the mixing parameters are determined to be $x'^2 = (3.9 \pm 2.7) \times 10^{-5}$, $y' = (5.28 \pm 0.52) \times 10^{-3}$, and $R_D = (3.454 \pm 0.031) \times 10^{-3}$. Without this assumption, the measurement is performed separately for D^0 and $\bar{D}^0$ mesons, yielding a direct *CP*-violating asymmetry $A_D = (-0.1 \pm 9.1) \times 10^{-3}$, and magnitude of the ratio of mixing parameters $1.00 < |q/p| < 1.35$ at the 68.3% confidence level. All results include statistical and systematic uncertainties and improve significantly upon previous single-measurement determinations. No evidence for *CP* violation in charm mixing is observed.

DOI: 10.1103/PhysRevD.97.031101

I. INTRODUCTION

The mass eigenstates of neutral charm mesons are linear

mixing parameters, $x = (4.6^{+1.4}_{-1.5}) \times 10^{-3}$ and $y = (6.2 \pm 0.8) \times 10^{-3}$ [16], although neither a nonzero value for the

Latest measurement of *CP* violation in charm oscillations

Oscillations

- The eigenstates of the neutral-meson systems are a mixture of the flavor states and can have different masses and lifetimes

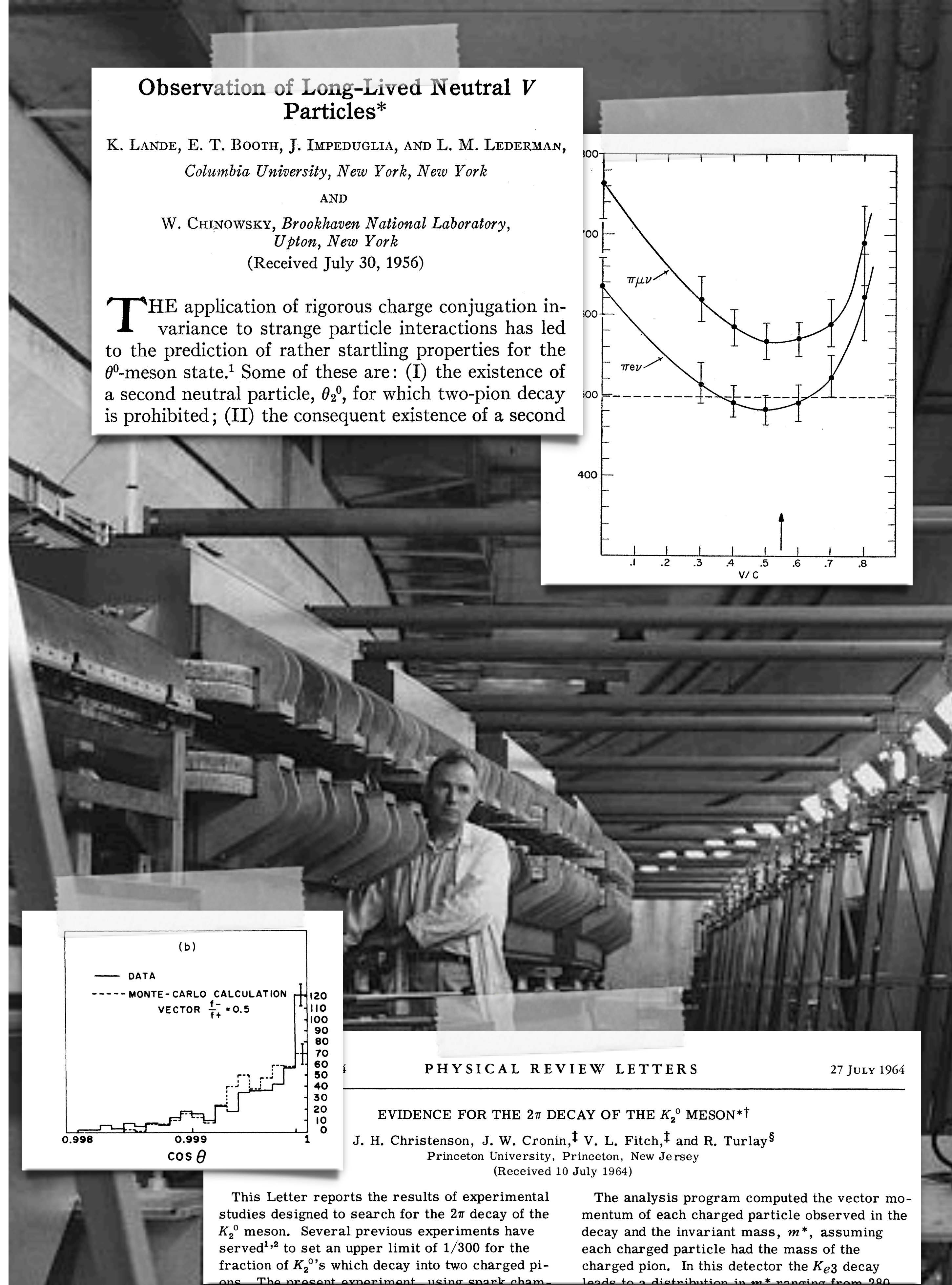
$$|P_{1,2}\rangle = p\,|P^0\rangle \pm q\,|\bar{P}^0\rangle$$

$$x = \frac{\Delta m}{\Gamma} = \frac{2(m_1 - m_2)}{\Gamma_1 + \Gamma_2}$$

$$y = \frac{\Delta \Gamma}{2\Gamma} = \frac{\Gamma_1 - \Gamma_2)}{\Gamma_1 + \Gamma_2}$$

- An initially produced P^0 meson can then “oscillate” into a $\bar{P}^0$ (and vice-versa) before it decays

- If q and p are real, P_1 and P_2 are CP eigenstates and the oscillation rates for $P^0 \rightarrow \bar{P}^0$ and $P^0 \rightarrow \bar{P}^0$ are the same

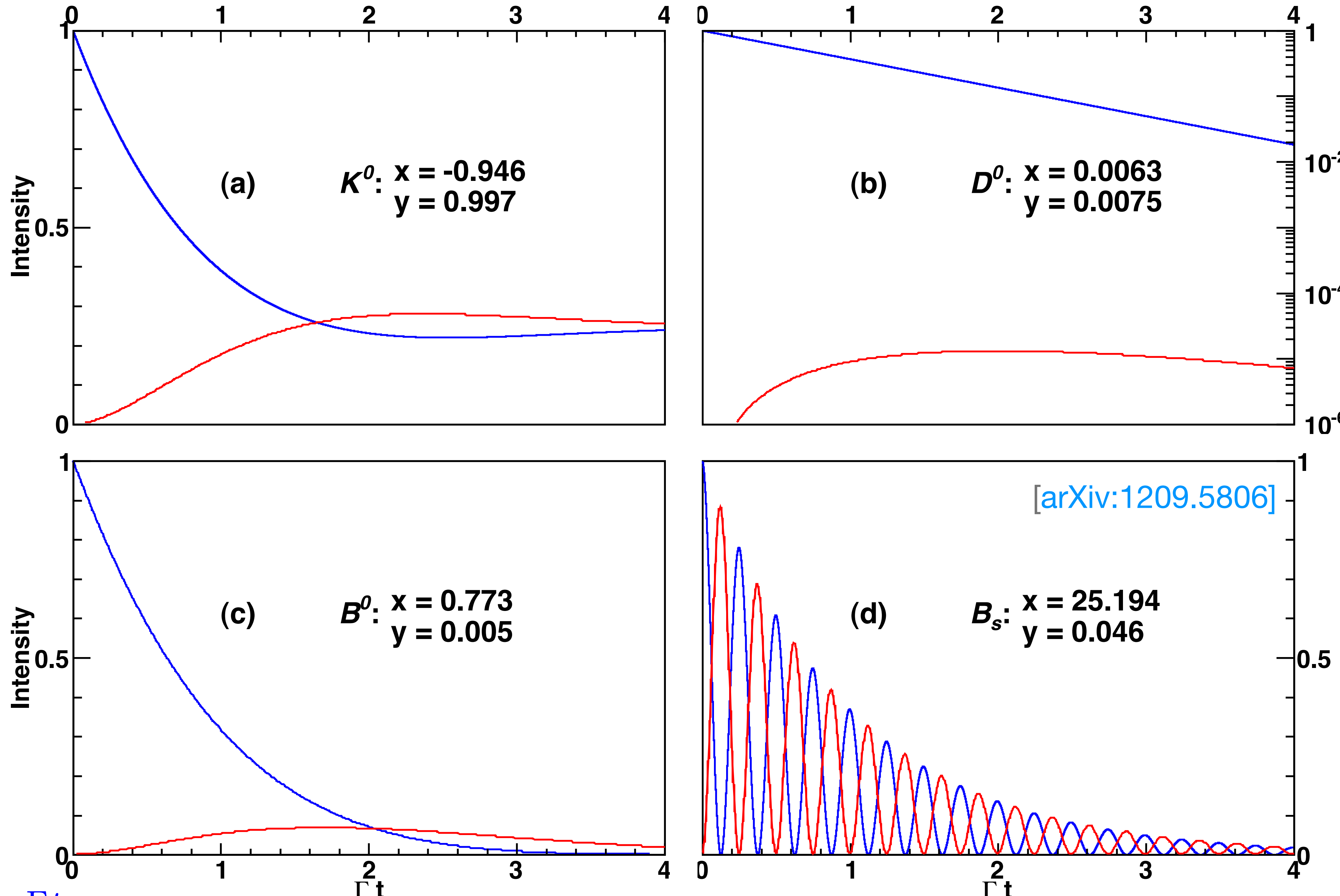


The Alternating Gradient Synchrotron at BNL in 1959

Phenomenology

Blue line:
given a P^0, at t=0, the probability of finding a P^0 at t

Red Line:
given a P^0, at t=0, the probability of finding a $\overline{P}^0$ at t



$$|\langle P^0(0)|P^0(t)\rangle|^2 \propto e^{-\Gamma t}\left[\cosh(y\Gamma t) + \cos(x\Gamma t)\right]$$

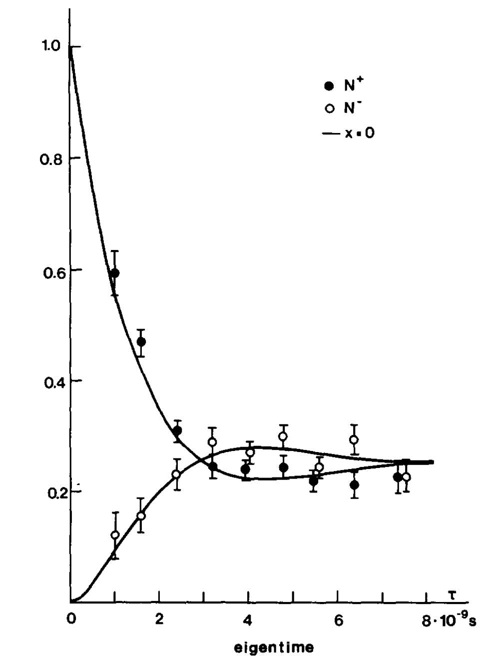
$$|\langle P^0(0)|\overline{P}^0(t)\rangle|^2 \propto e^{-\Gamma t}\left[\cosh(y\Gamma t) - \cos(x\Gamma t)\right]$$

Phenomenology

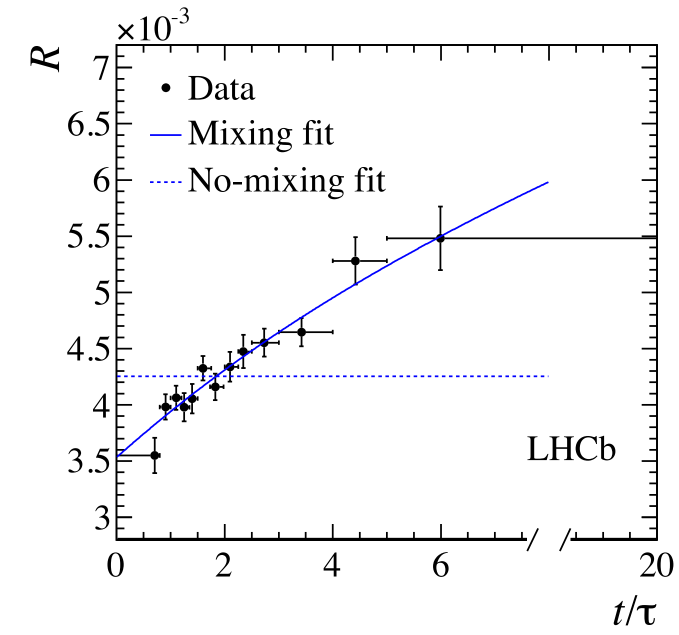
Blue line:
given a P^0, at t=0, the probability of finding a P^0 at t

Red Line:
given a P^0, at t=0, the probability of finding a $\overline{P}^0$ at t

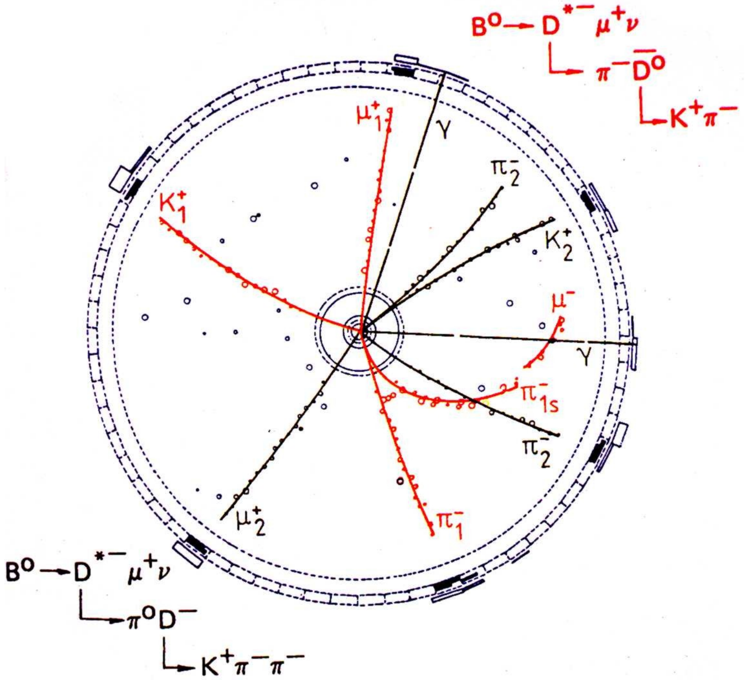
Phys. Lett. B 49 (1974) 103

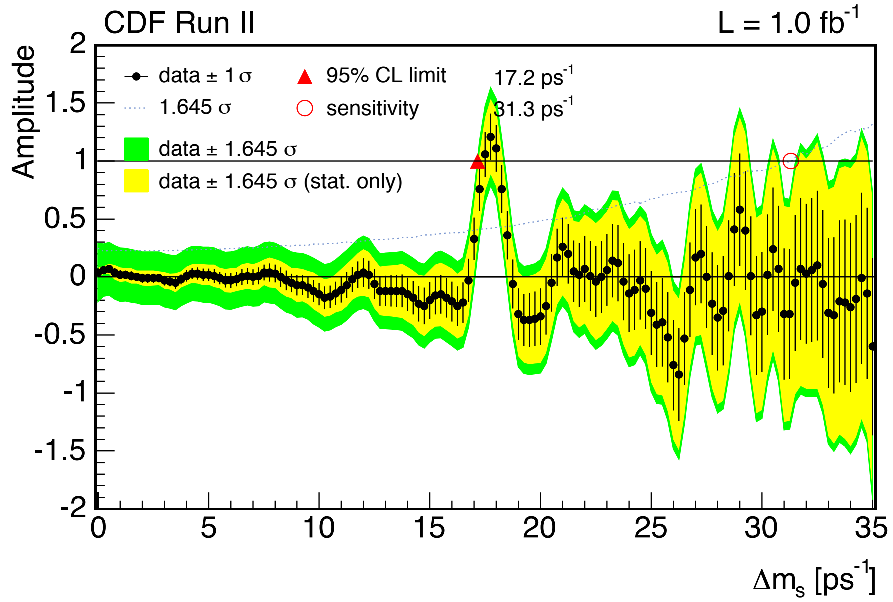


Phys. Rev. Lett. 110 (2013) 101802



Phys. Lett. B 192 (1987) 245

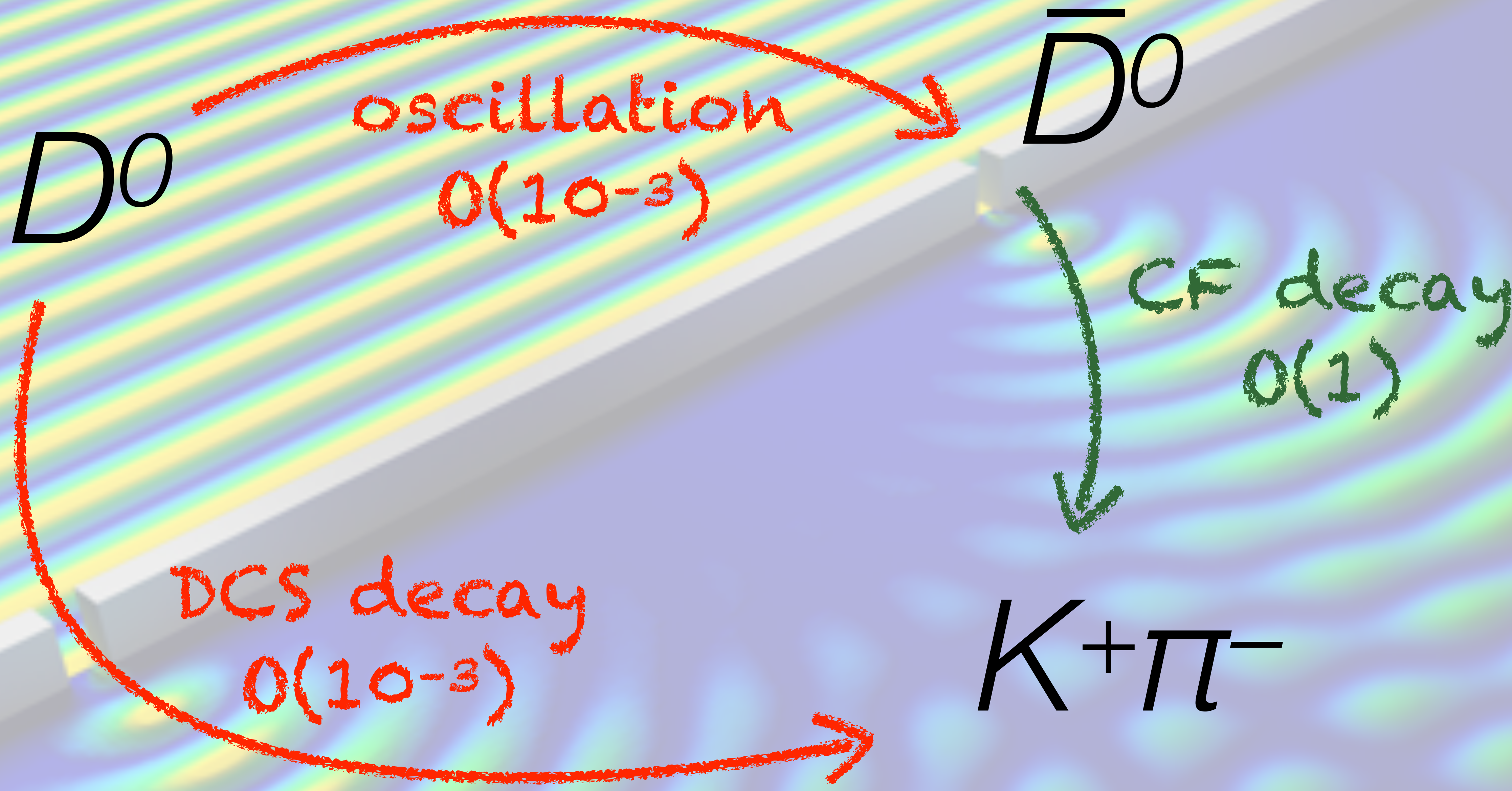


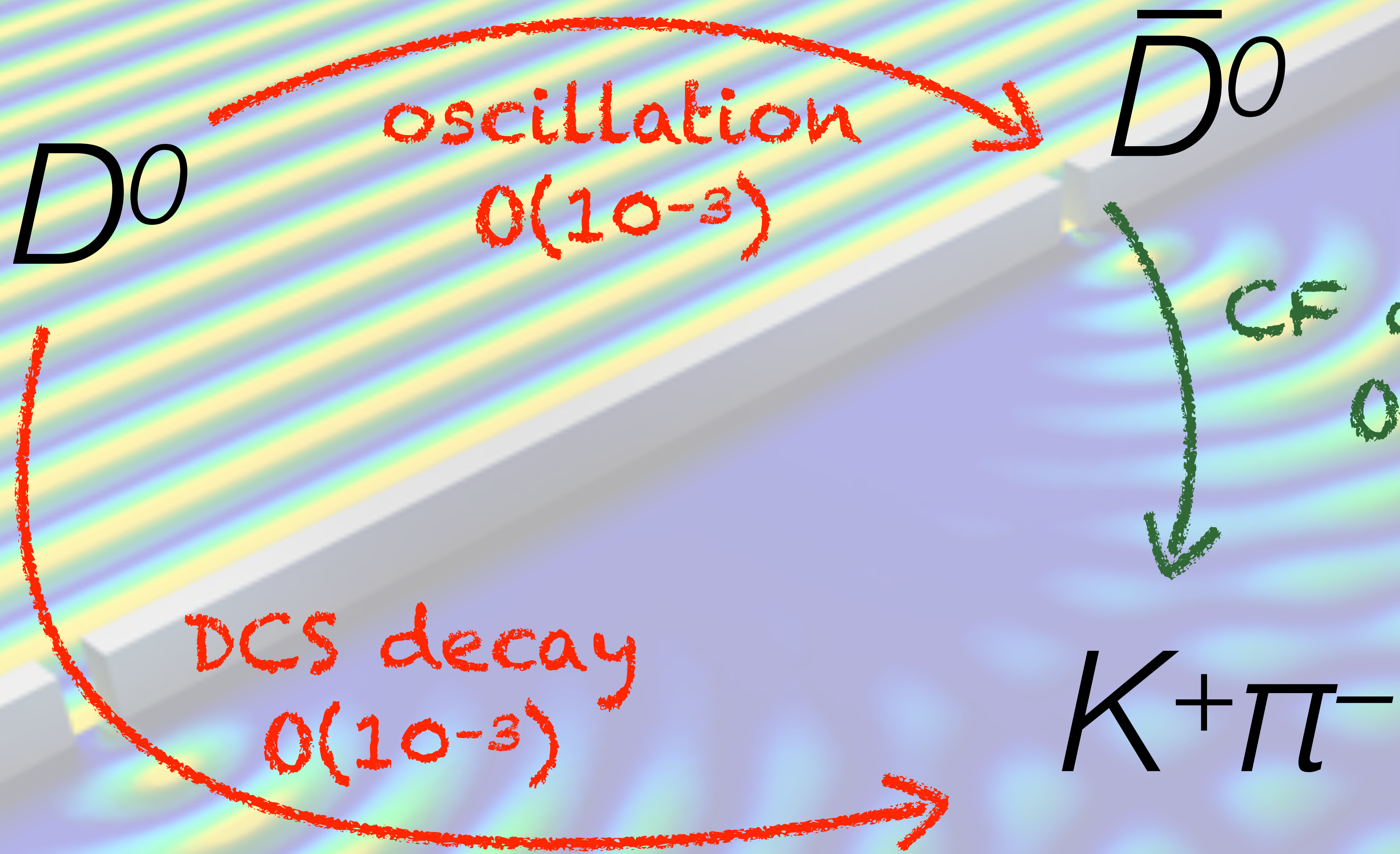


Phys. Rev. Lett. 97 (2006) 242003

$$|\langle P^0(0)|P^0(t)\rangle|^2 \propto e^{-\Gamma t}\,[\cosh(y\Gamma t)+\cos(x\Gamma t)]$$

$$|\langle P^0(0)|\overline{P}^0(t)\rangle|^2 \propto e^{-\Gamma t}\,[\cosh(y\Gamma t)-\cos(x\Gamma t)]$$


D^0
oscillation
$O(10^{-3})$
$\bar{D}^0$
CF decay
$O(1)$
DCS decay
$O(10^{-3})$
$K^+\pi^-$



Ratio of wrong-sign to right-sign rates:

$$x' = x\cos\delta + y\sin\delta$$
$$y' = y\cos\delta - x\sin\delta$$

$$R(t) = \frac{\Gamma(D^0 \to K^+\pi^-|t)}{\Gamma(D^0 \to K^-\pi^+|t)} \approx R_D + \sqrt{R_D}y'\left(\frac{t}{\tau}\right) + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2$$

Search for *CP* violation

- Measure separately the oscillation rates of initially produced D^0 (+) and $\bar{D}^0$ (–) mesons

$$R^{\pm} = R_D^{\pm} + \sqrt{R_D^{\pm}} y'^{\pm} t + \frac{x'^{2\pm} + y'^{2\pm}}{4} t^2$$

direct CPV

$$R_D^{+} \neq R_D^{-}$$

CPV in mixing or interference

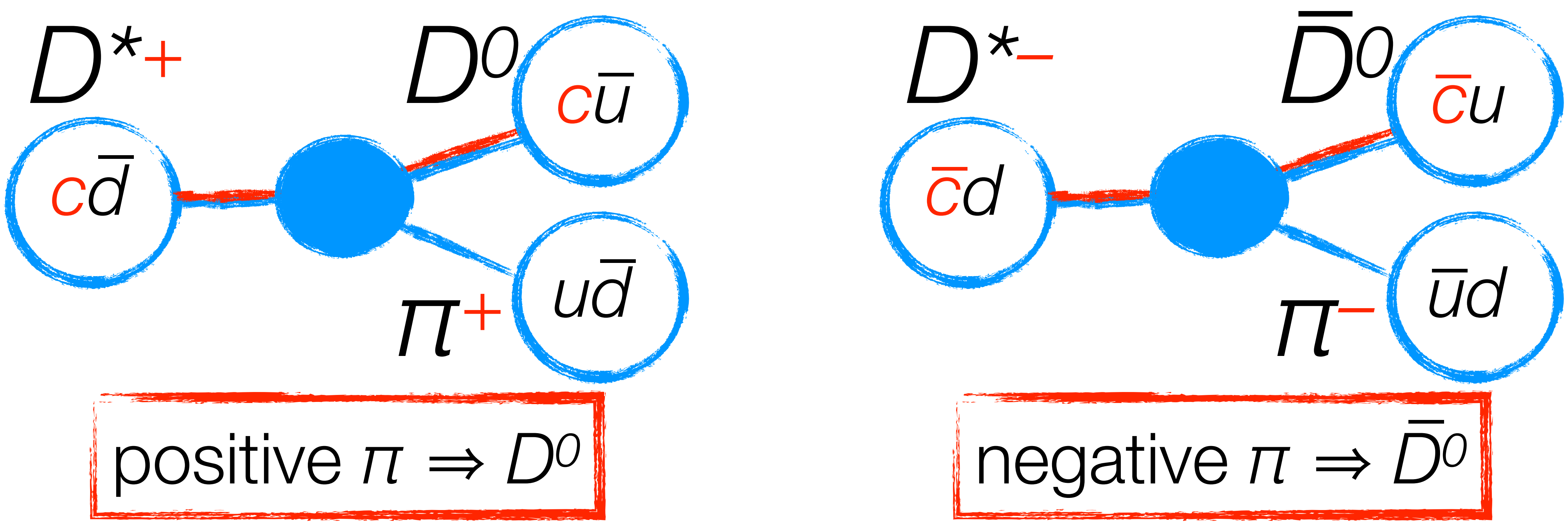
$$x'^{\pm} = |q/p|^{\pm 1} (x' \cos\phi \pm y' \sin\phi)$$

$$y'^{\pm} = |q/p|^{\pm 1} (y' \cos\phi \mp x' \sin\phi)$$

- Different offsets reveal *CP* violation in DCS decay, different slopes reveal mixing-induced *CP* violation

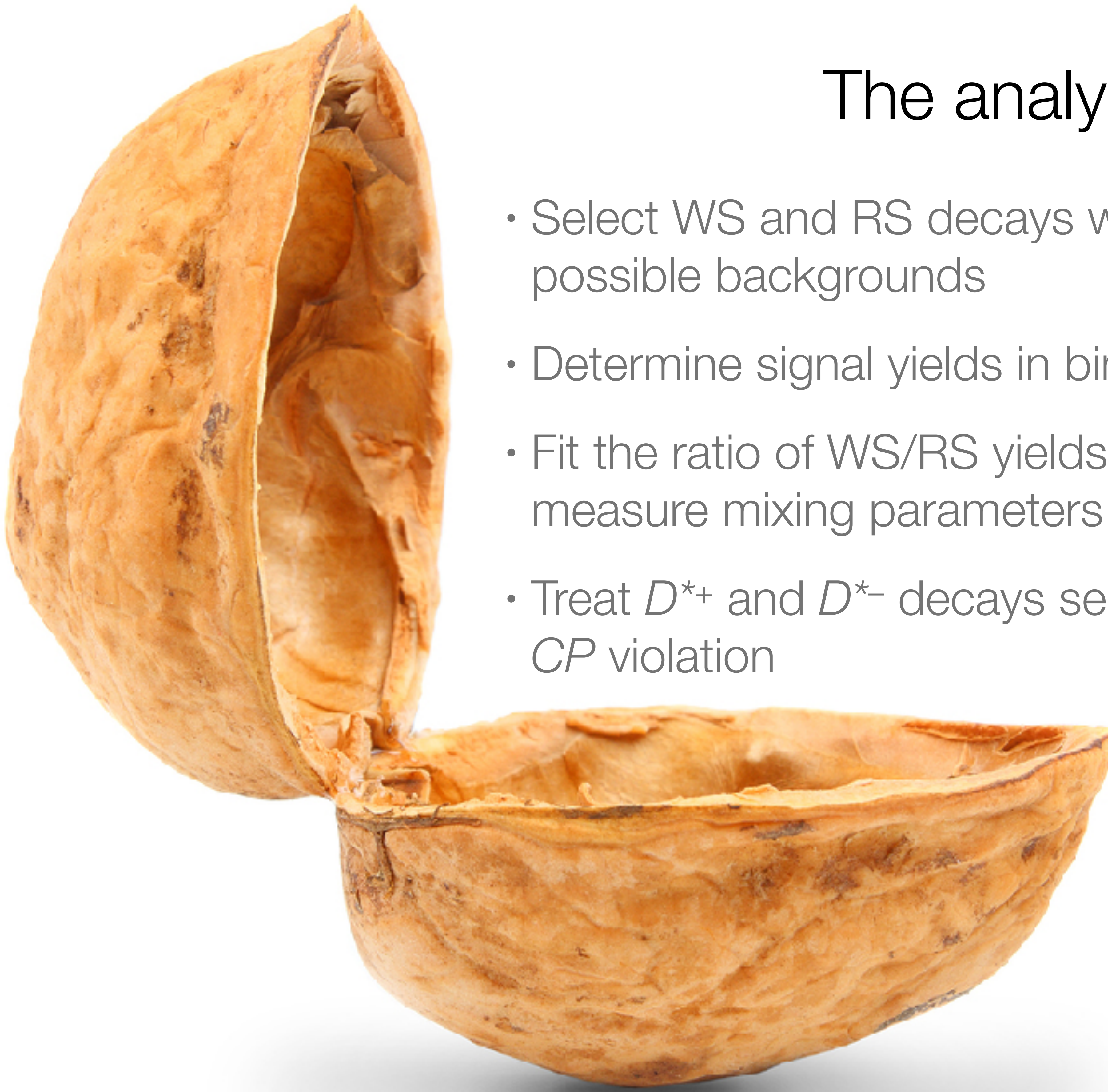
Flavor at production

- How do I know if a D^0 or a $\bar{D}^0$ was produced?
- Profit from strong-interaction decay of $D^*(2010)^+$ mesons



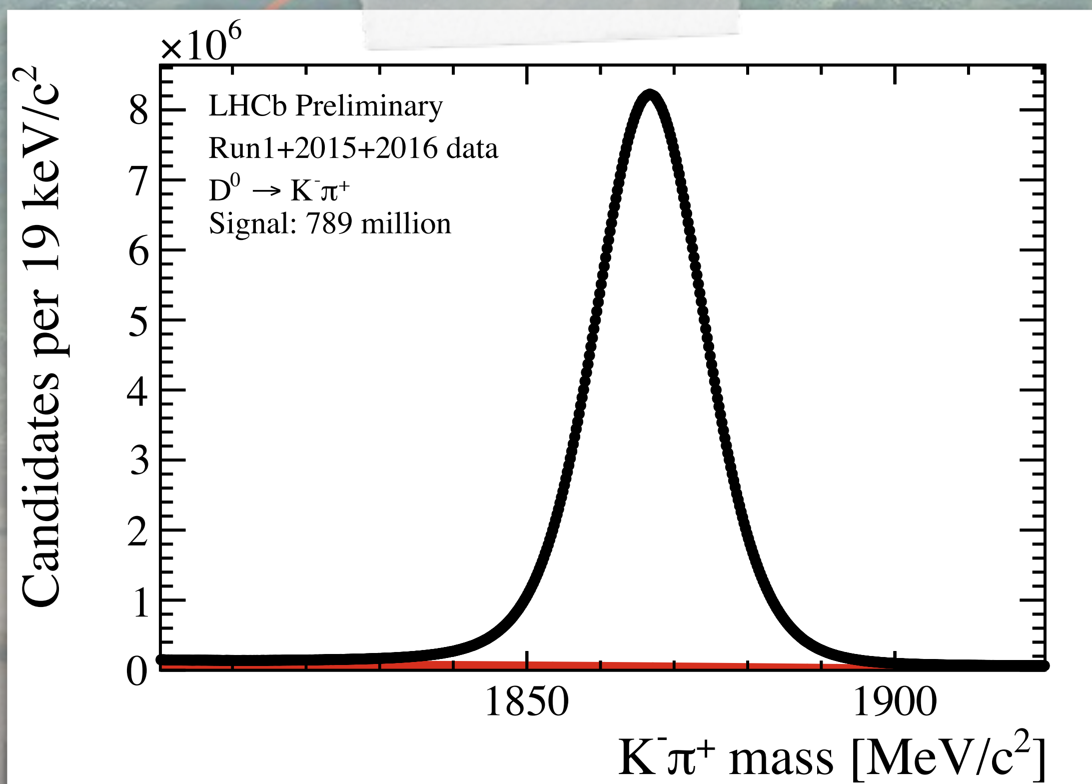
- Sacrifice ~85% in sample size, but gain flavor information and background rejection (because of the small Q-value)

The analysis in a nutshell



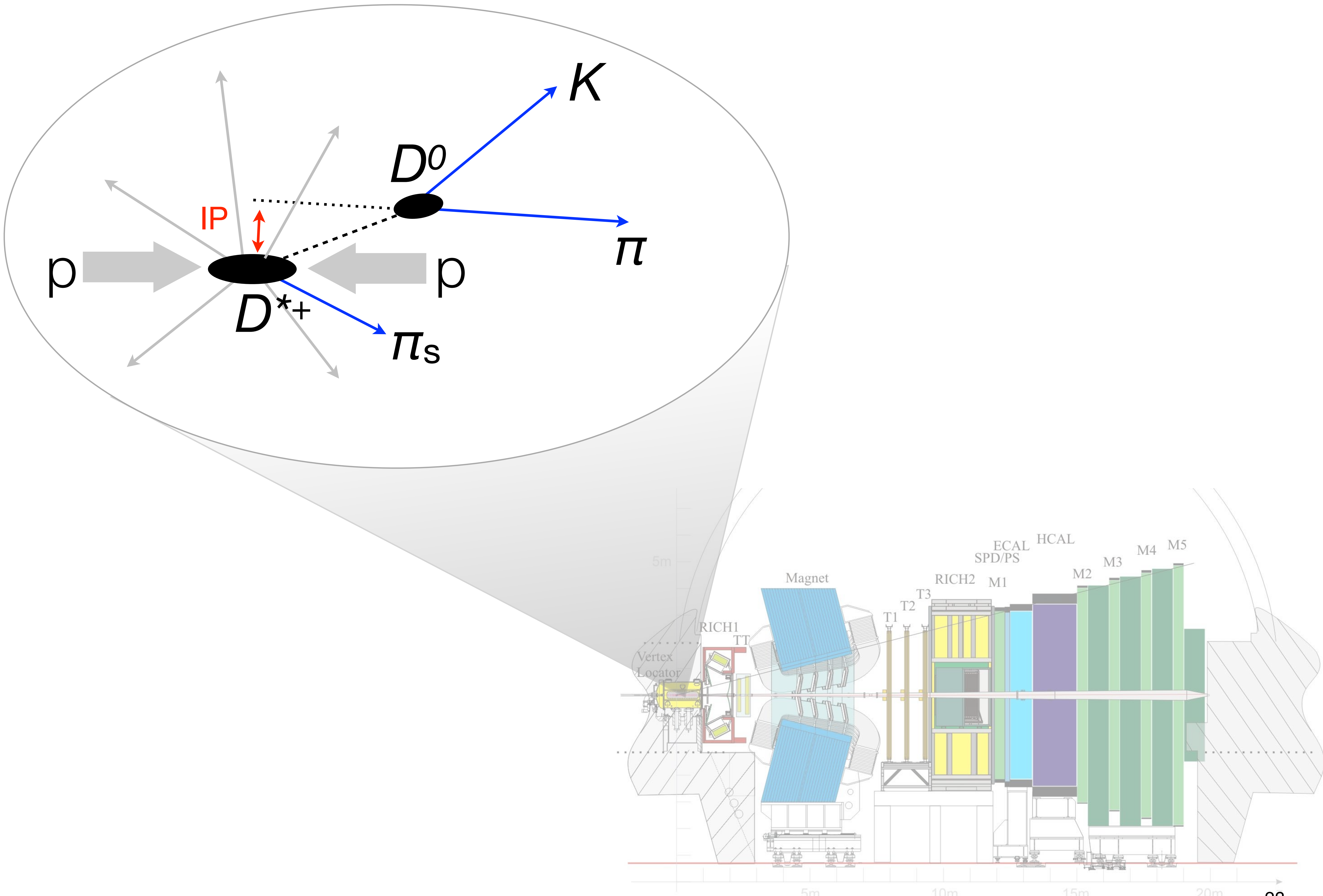
- Select WS and RS decays while suppressing all possible backgrounds
- Determine signal yields in bins of decay time
- Fit the ratio of WS/RS yields vs decay time to measure mixing parameters
- Treat D^{*+} and D^{*-} decays separately to search for *CP* violation

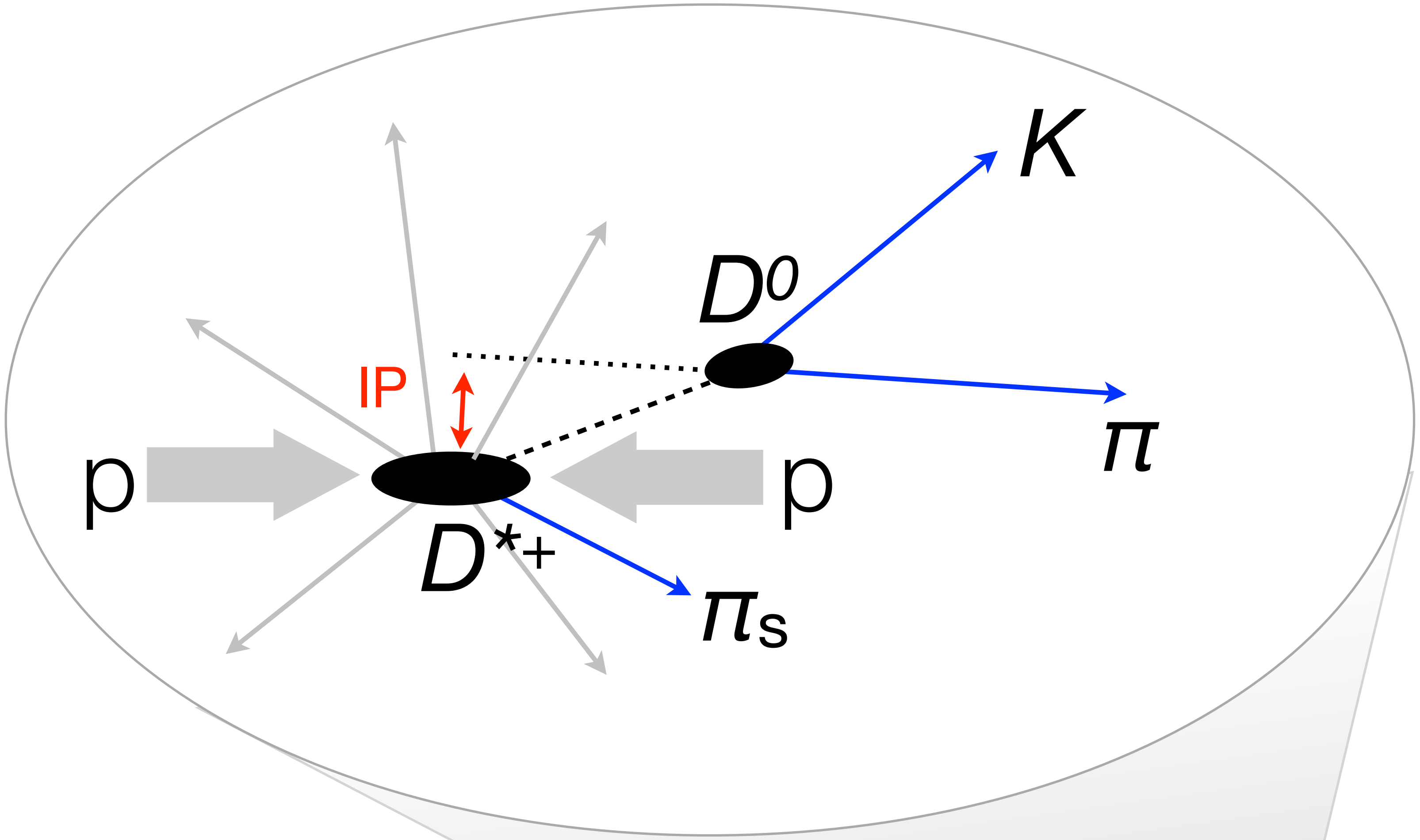
Charm at LHCb



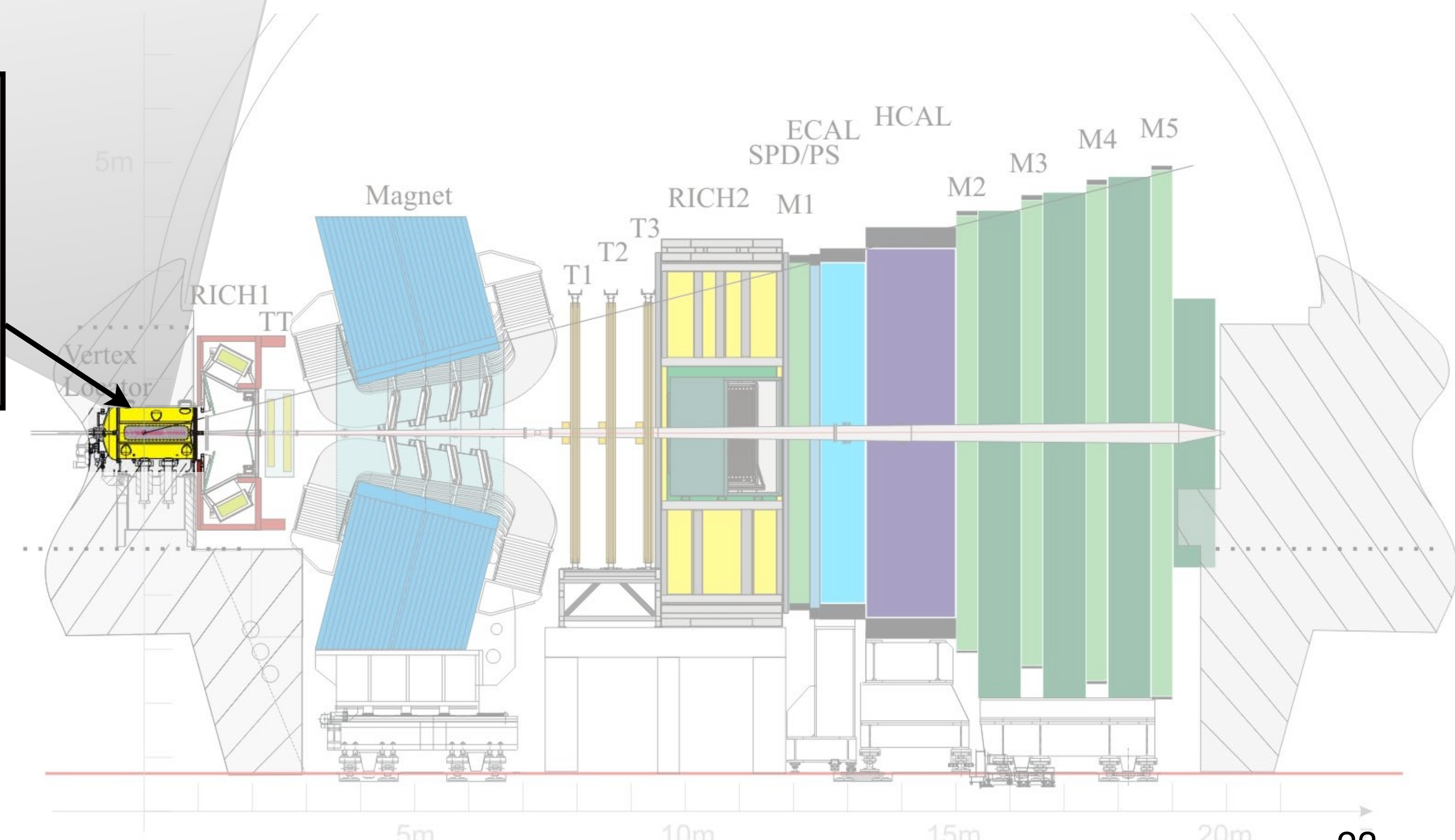
Billions of charm decays!

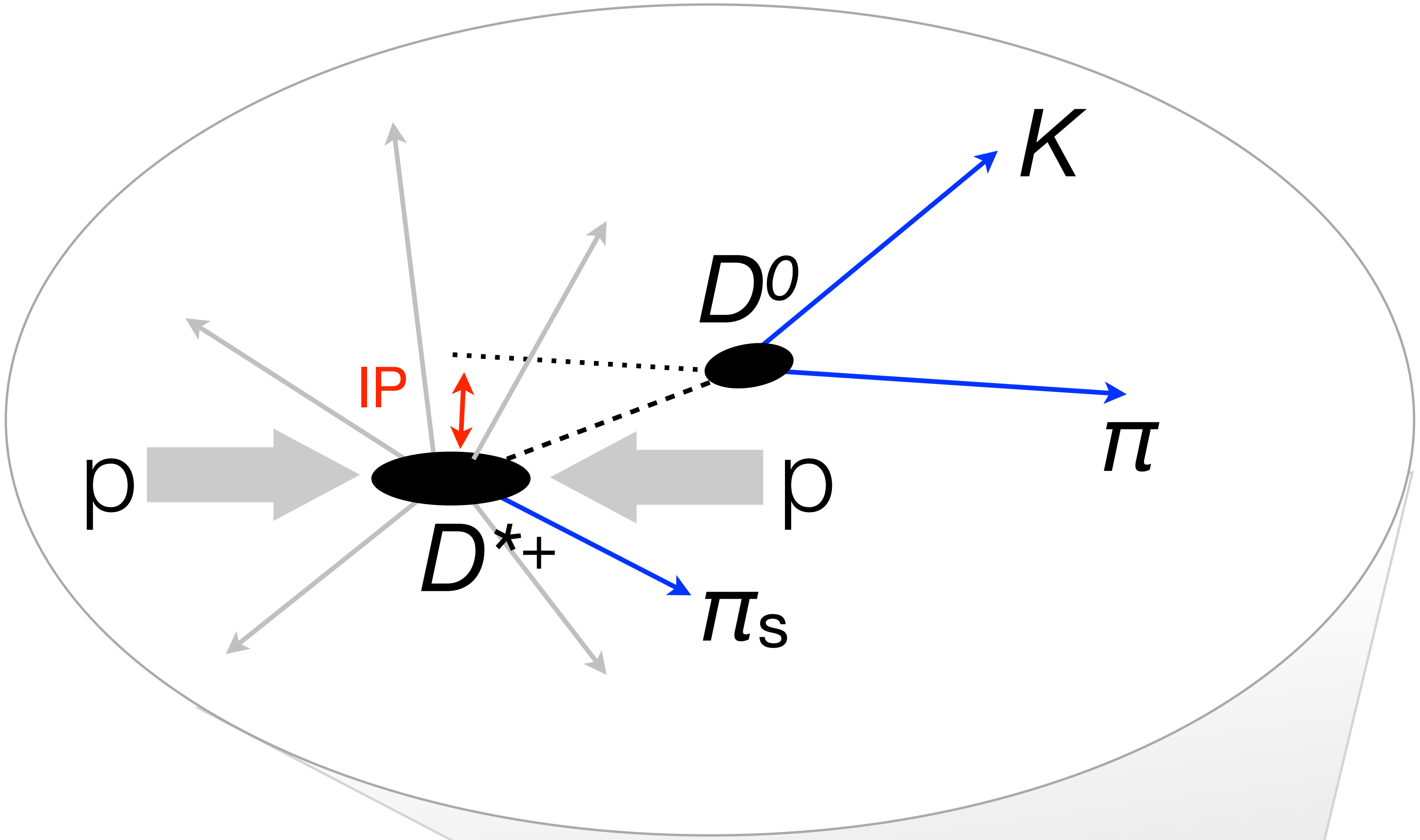
- 5 years of 7 to 13 TeV proton-proton collisions at 40 MHz
- About 10% of collisions yield a $c\bar{c}$ pair, $O(10^4)$ per second are reconstructible and interesting for physics
- Store 10-20% of them for analysis


K
D0
IP
π
p
p
D*+
πs
Magnet
ECAL
SPD/PS
HCAL
M1
M2
M3
M4
M5
RICH1
RICH2
TT
T1
T2
T3
Vertex
Locator
5m
10m
15m
20m



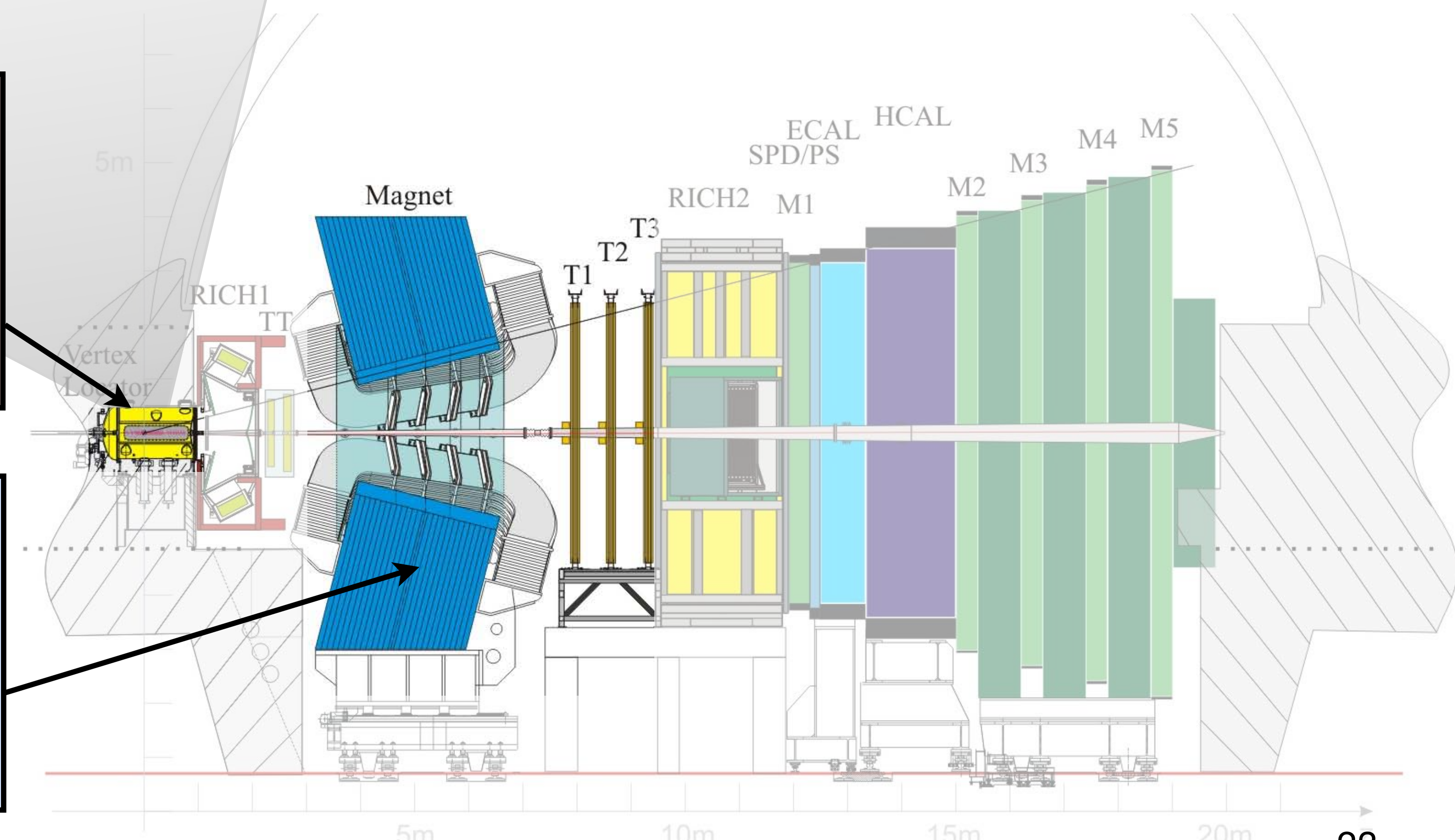
Silicon Vertex Locator:
20 μm impact parameter resolution, corresponding to ~0.1τ decay-time resolution for a 2-body charm decay

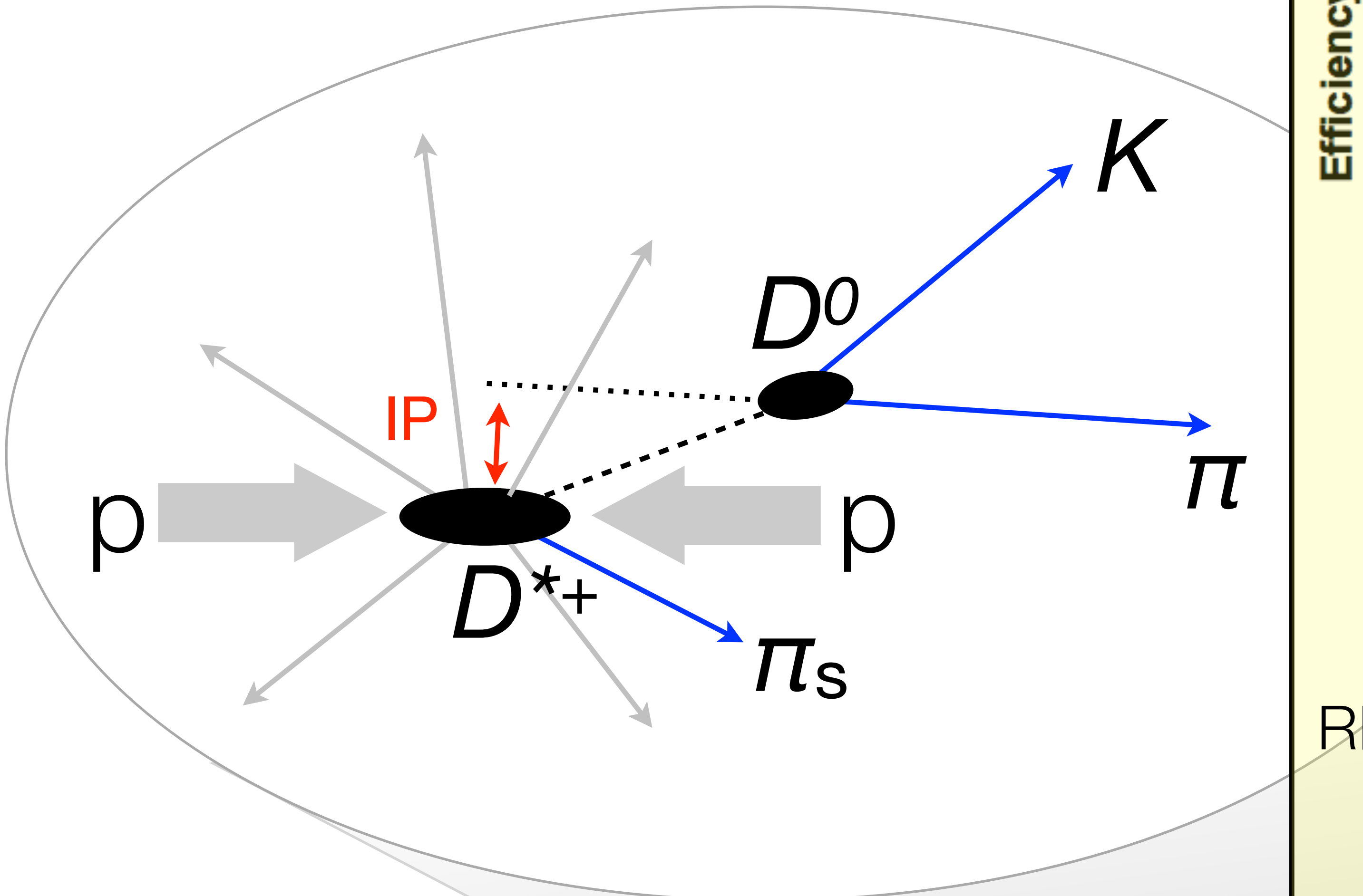


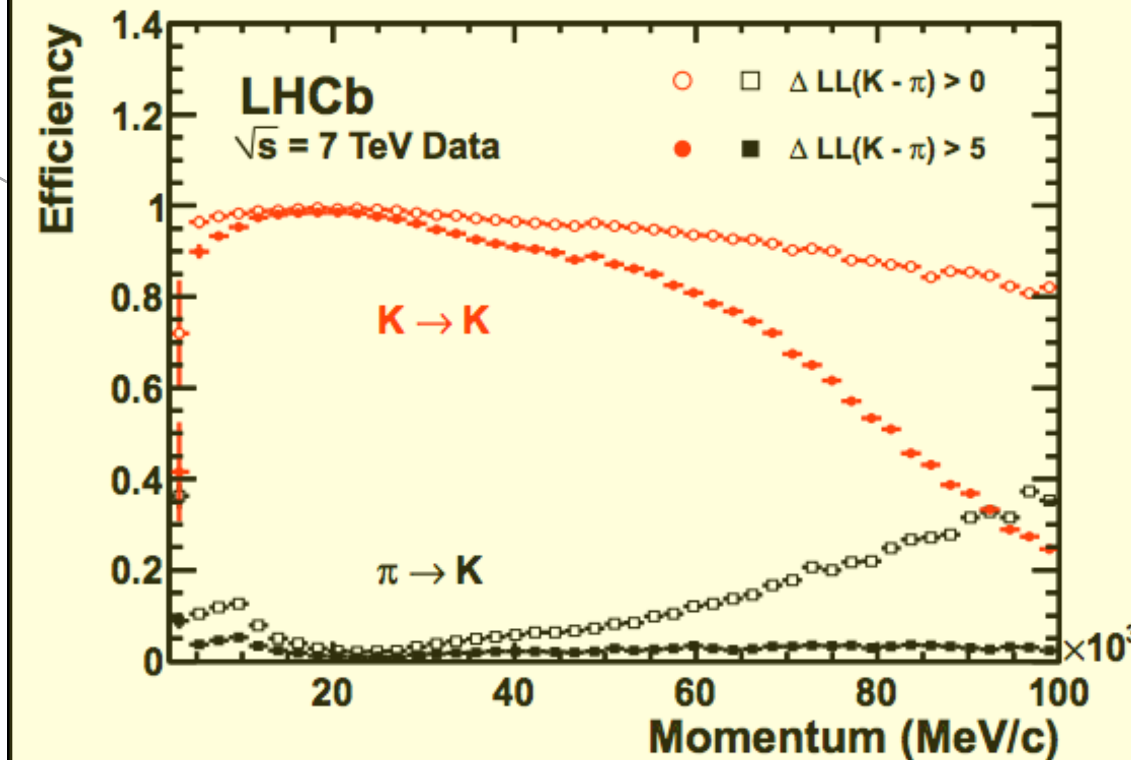


Silicon Vertex Locator:
20 μm impact parameter resolution, corresponding to ~0.1τ decay-time resolution for a 2-body charm decay

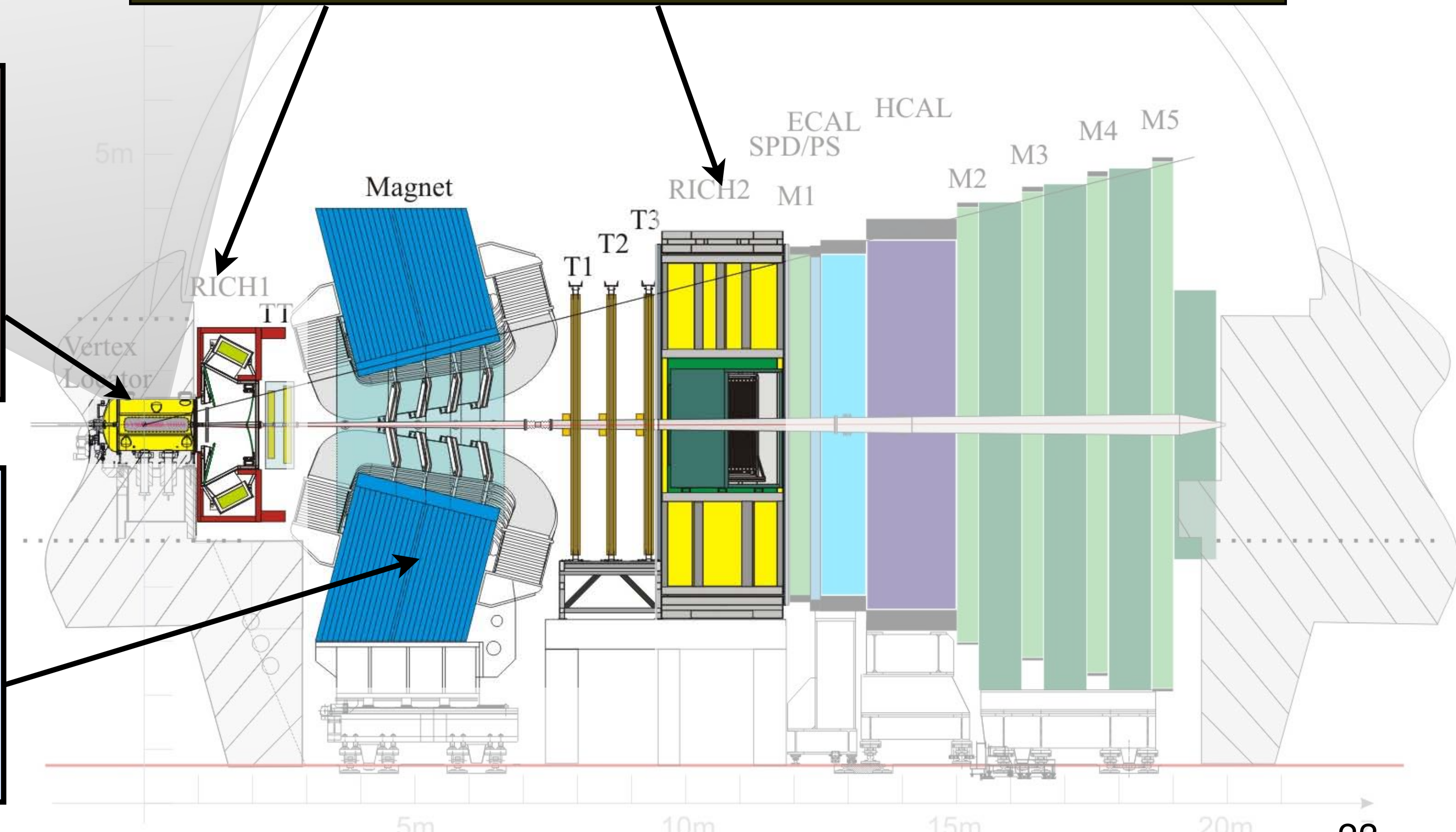
Excellent tracking:
$\Delta p/p$ = 0.4-0.6% at 5-100 GeV/c, corresponding to ~8 MeV/c^2 mass resolution for a 2-body charm decay







RICH detectors:
K-*π* separation in wide range of momentum



Silicon Vertex Locator:
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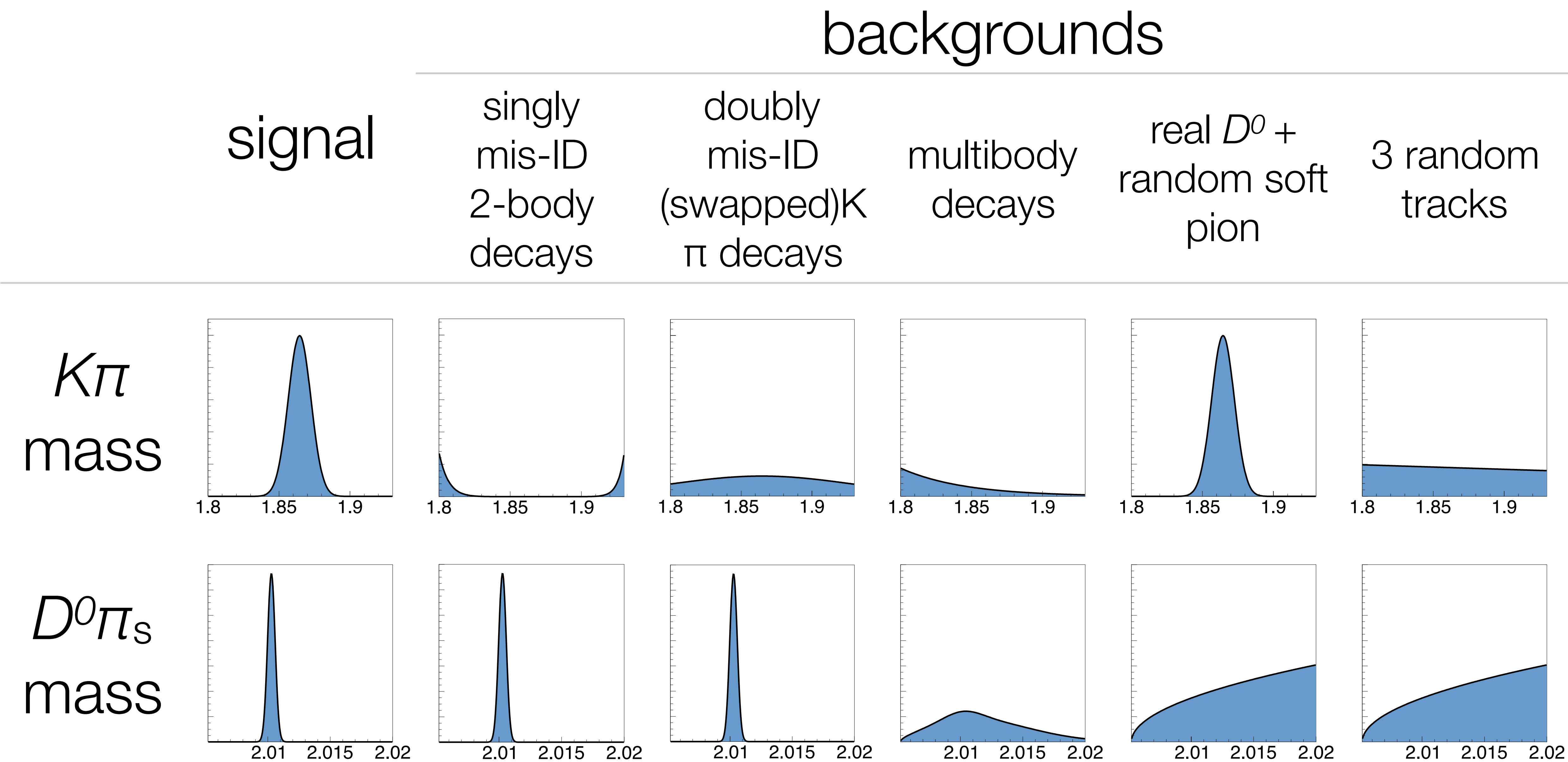
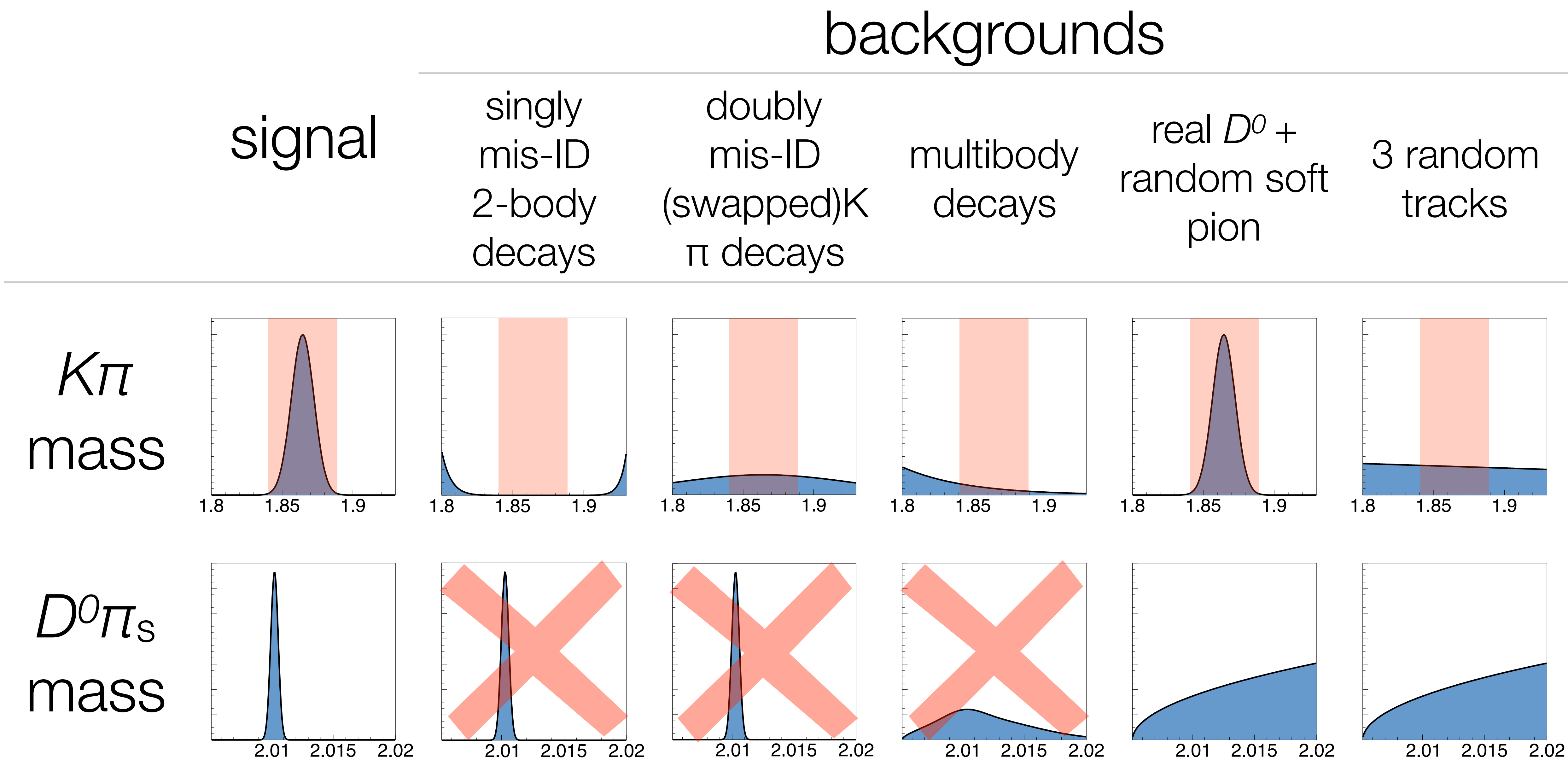
$D^* \to D^0(\to K\pi)\pi_s$ signal vs backgrounds



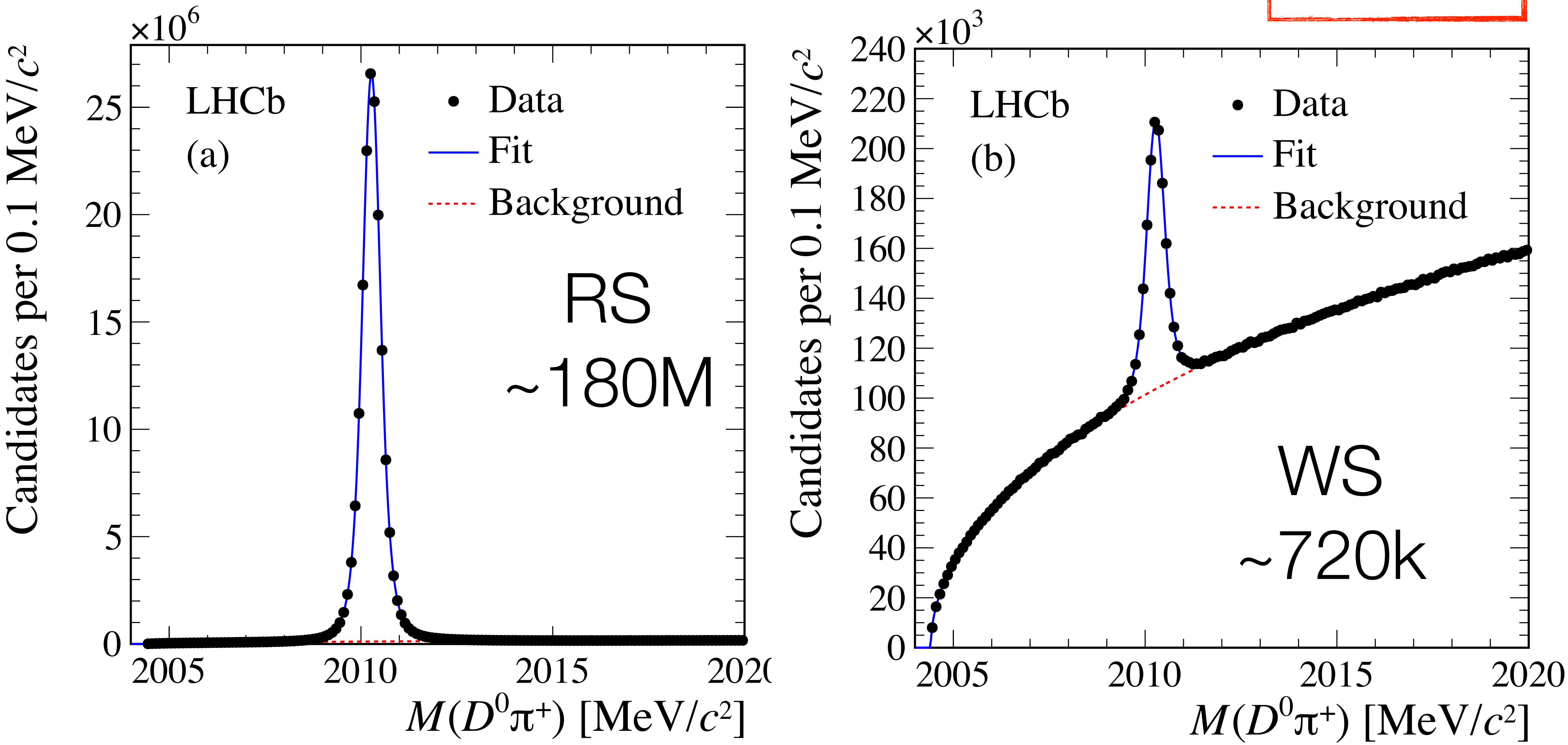
$D^* \rightarrow D^0(\rightarrow K\pi)\pi_s$ signal vs backgrounds



Cut tight on PID and D^0 mass to reduce physics bkg and fit $D^0\pi_s$ mass, then consider only signal and random pions in the fit

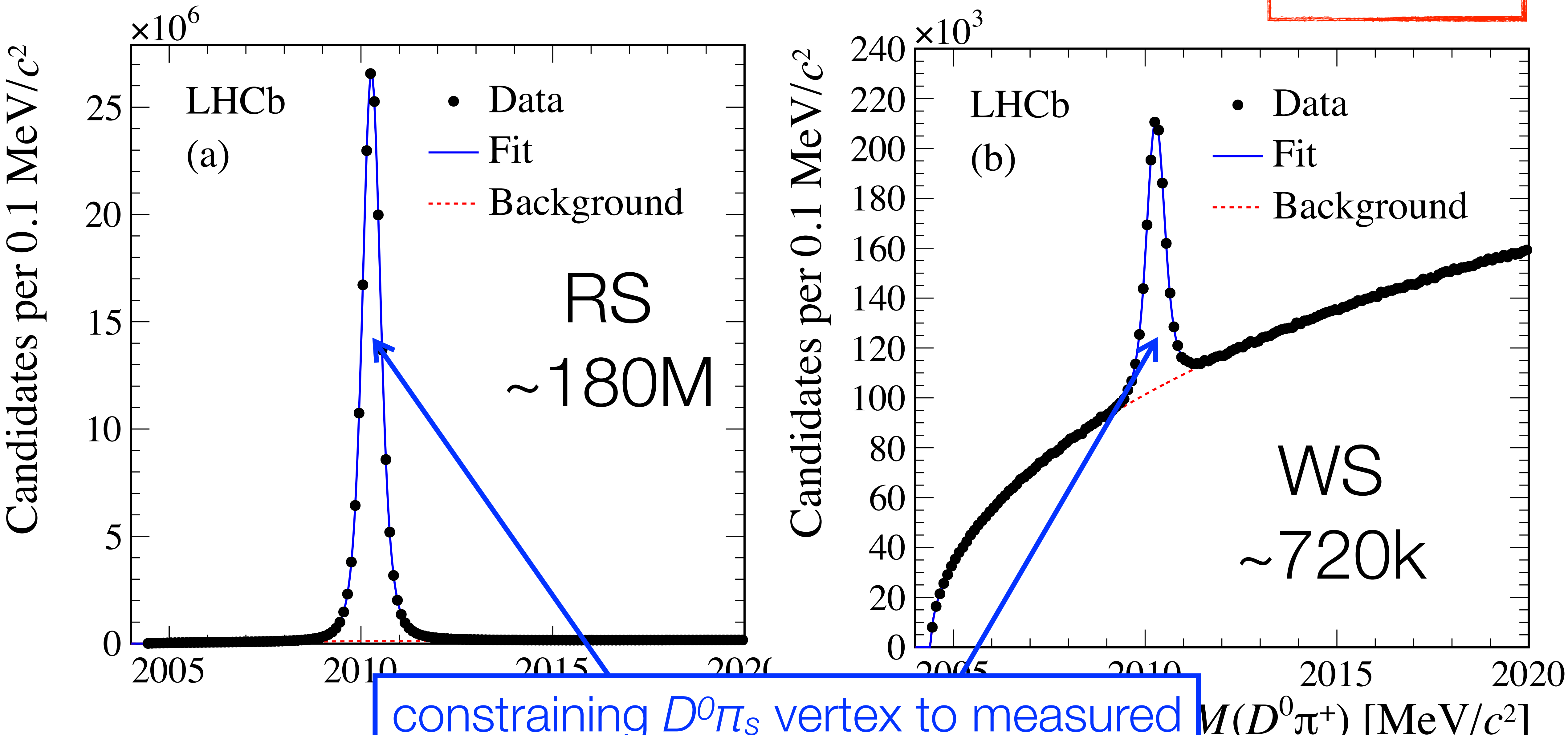
Time-integrated yields

LHCb 5 fb^{-1}



Time-integrated yields

LHCb 5 fb^{-1}

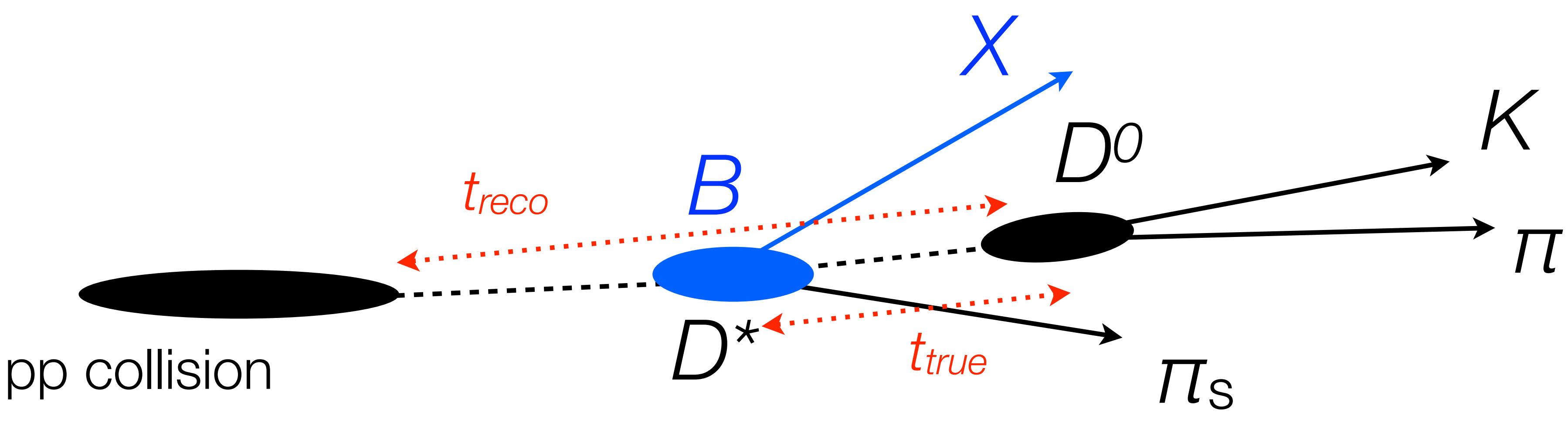


constraining $D^0\pi_s$ vertex to measured position of primary vertex allows mass resolution of ~0.3 MeV/c^2

Charm from beauty

- Once every 20 charm pairs a $b\bar{b}$ pair is produced. A large fraction of *B* decays into *D*, mimicking our signal

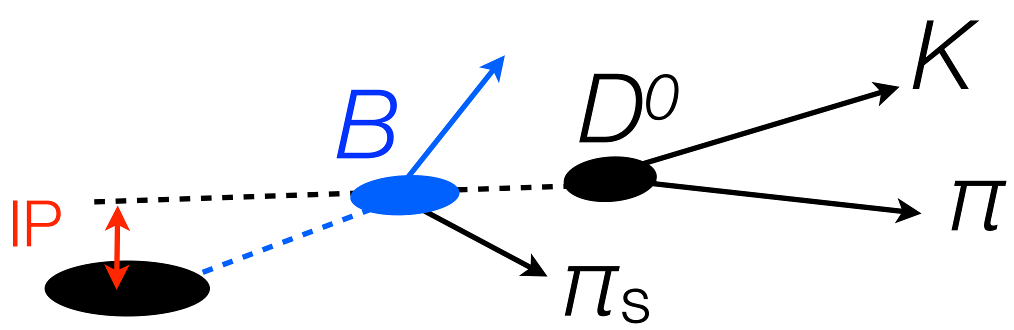
- Secondary charm have a larger observed decay time because the *B* lifetime gets folded in

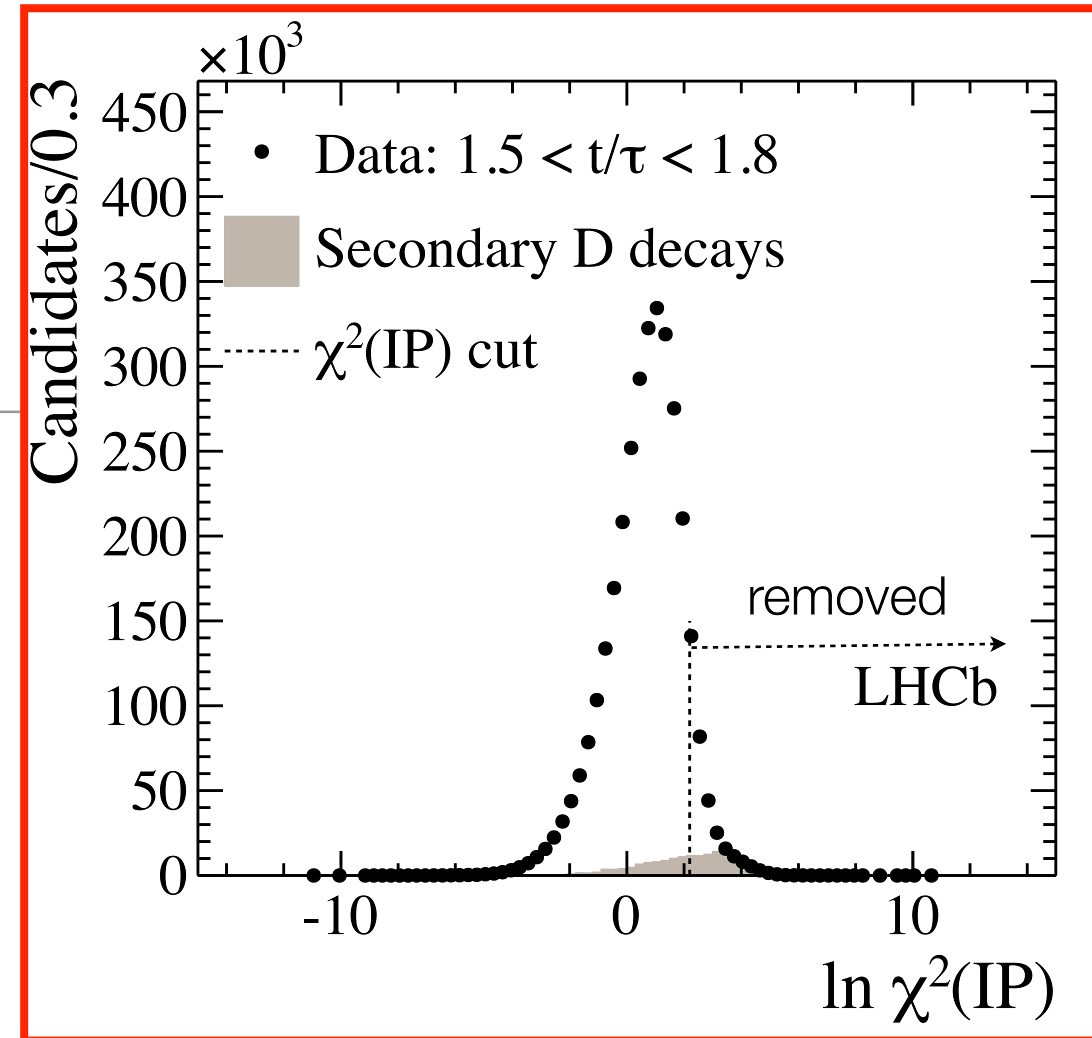


- Introduce a bias that dilutes the oscillations

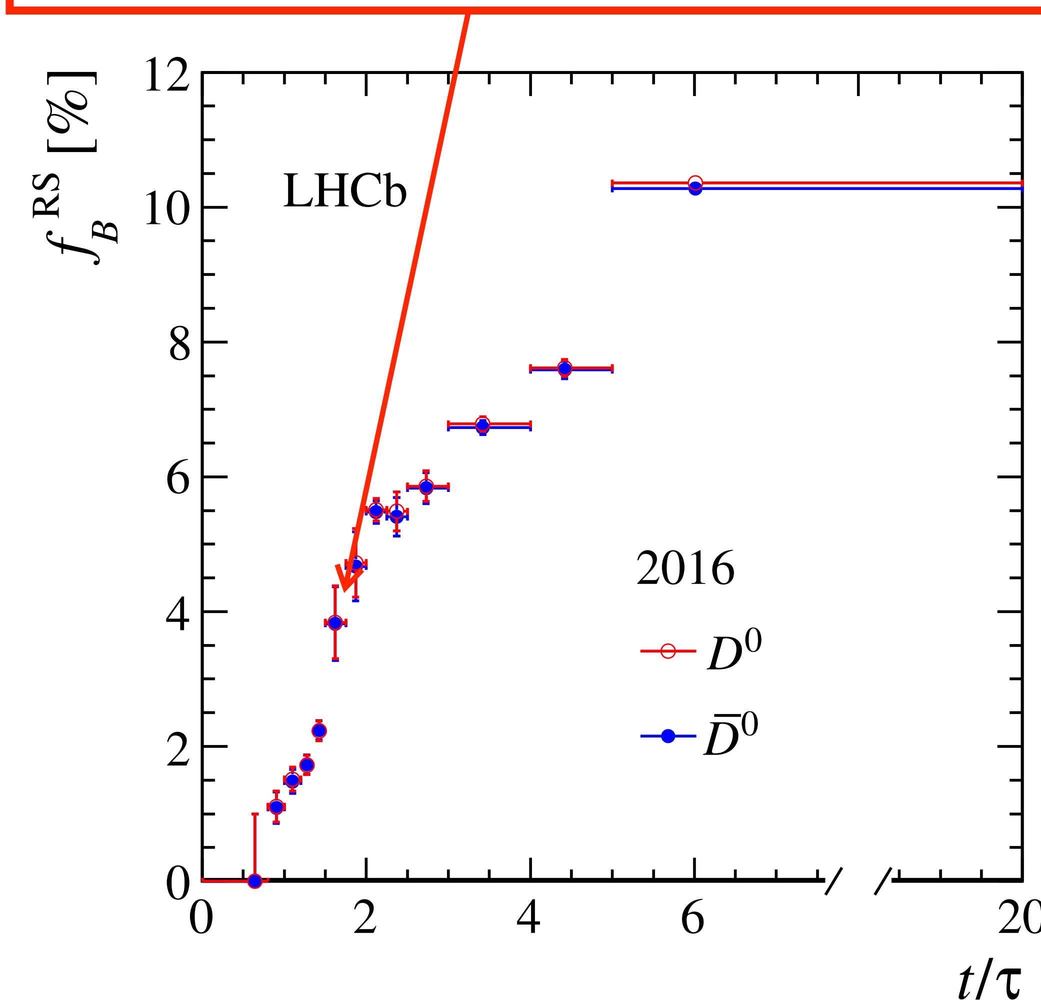
Charm from beauty

- *D* from *B* have non-zero impact parameter





- A pointing requirement reduces the secondary fraction to 1-10% depending on decay time

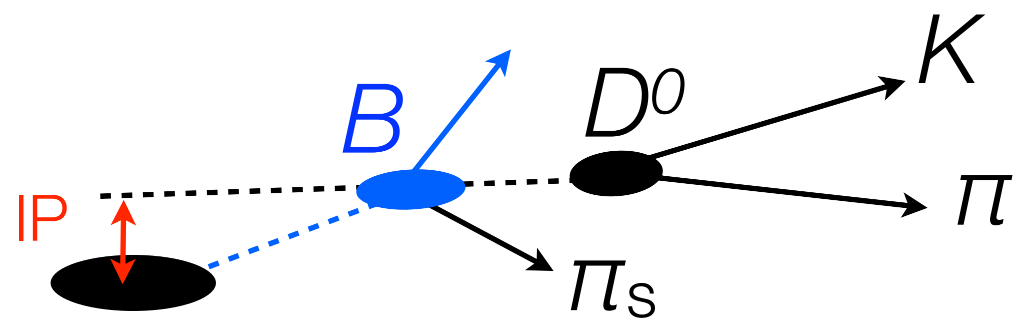


- A systematic uncertainty corresponding to the maximum possible bias on the mixing is propagated to the result

- Contamination is charge symmetric, effects on *CP* violation are marginal

Charm from beauty

- *D* from *B* have non-zero impact parameter



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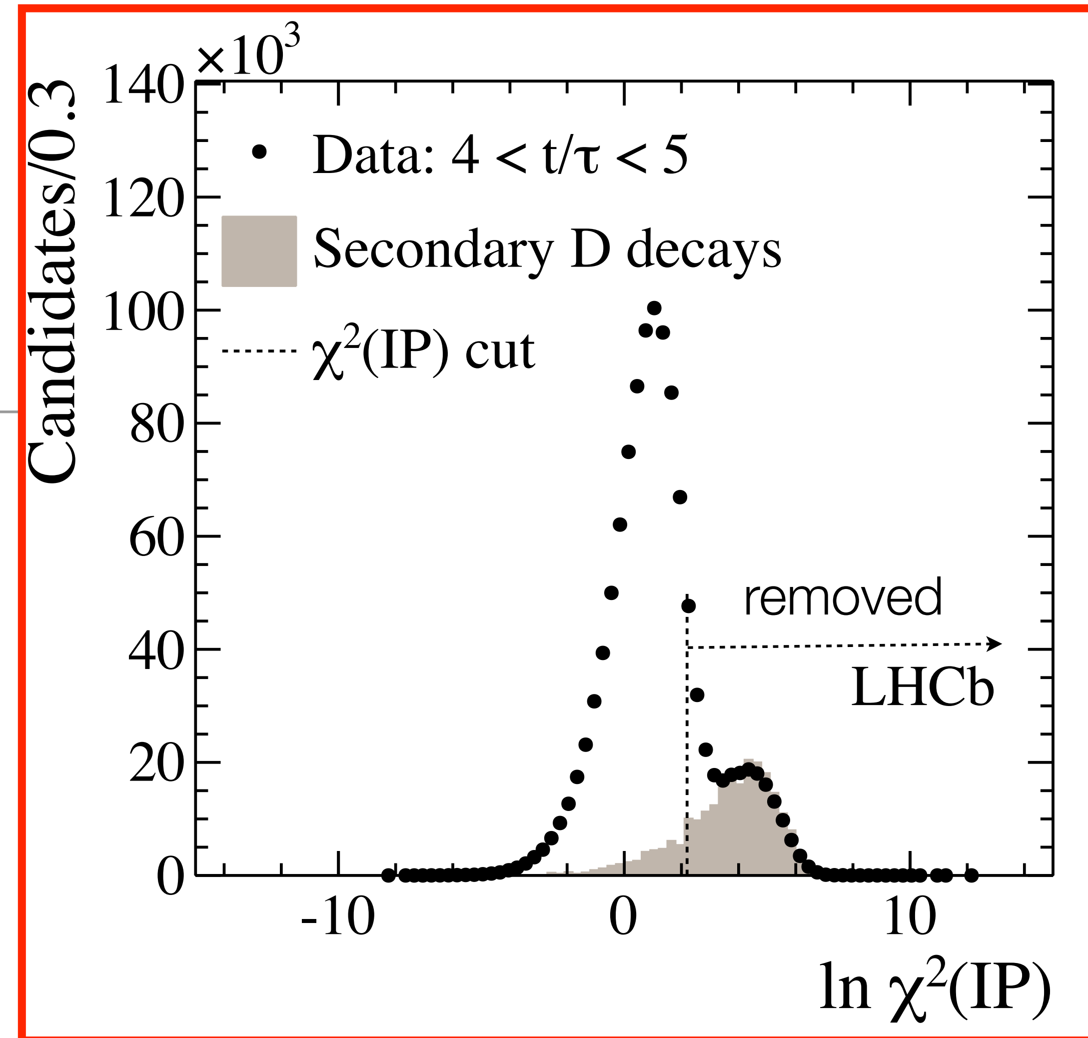
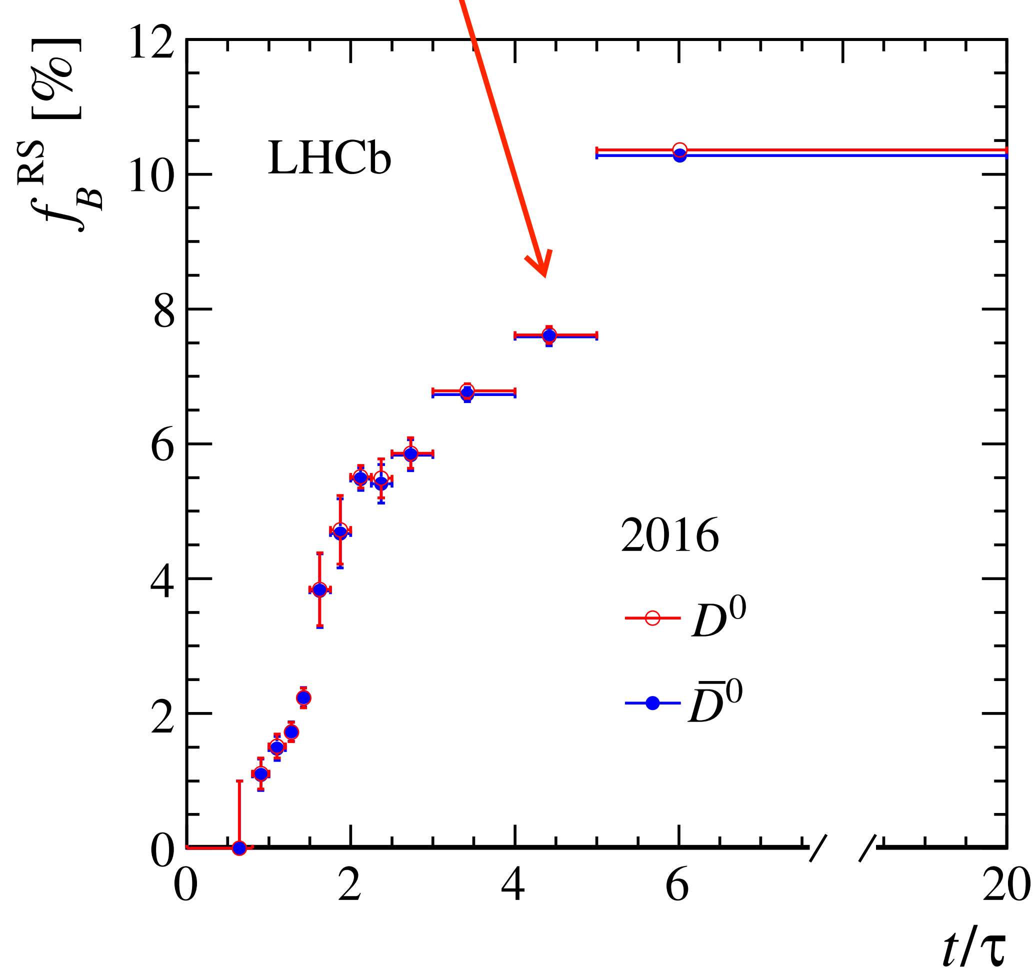




Peaking background

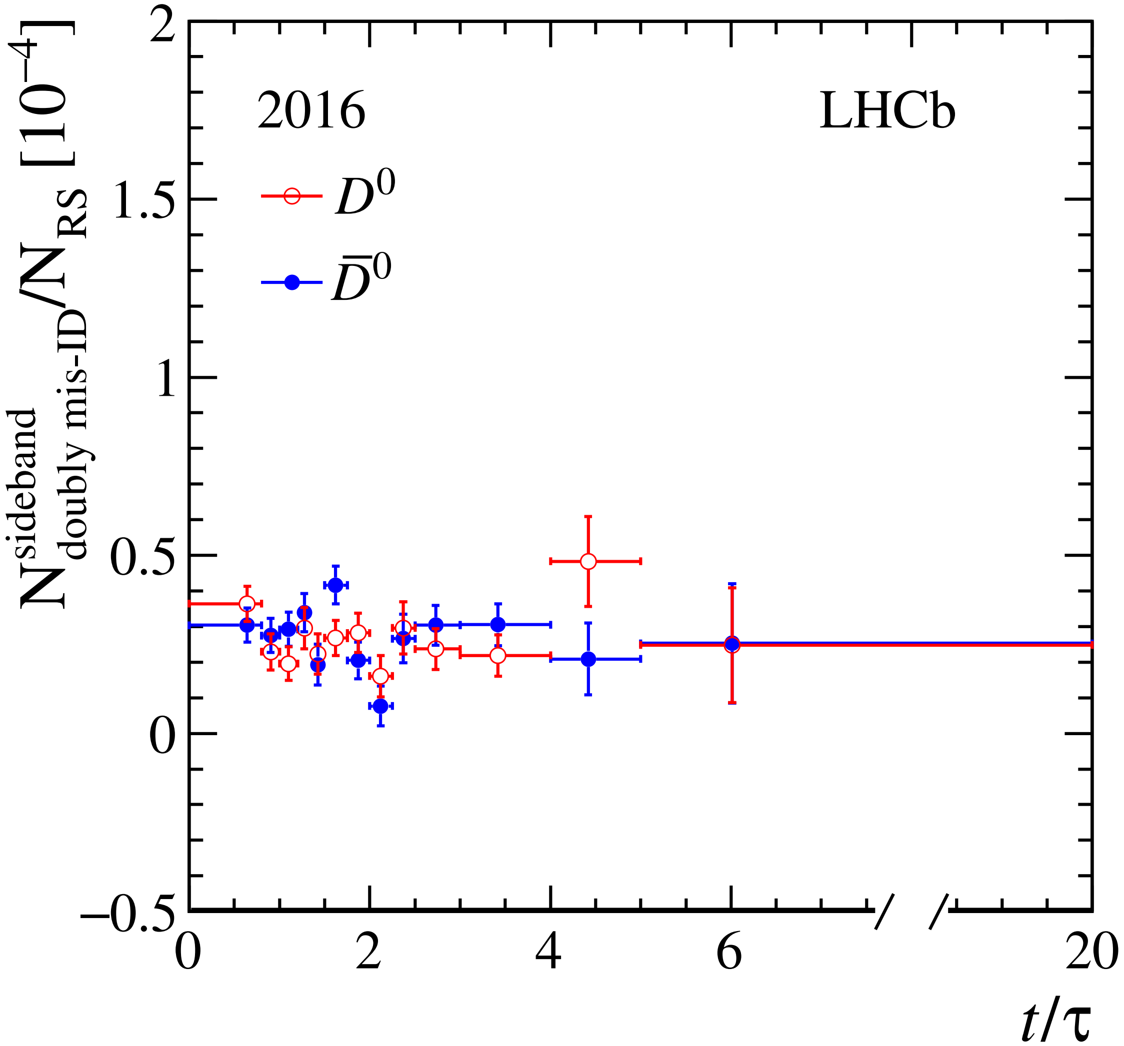
- Mass fits do not distinguish between signal and backgrounds which peak in $D^0\pi_s$ mass

- Such backgrounds are highly suppressed by tight PID requirements and reduced D^0 mass window

- Dominant residual contamination is from ~0.3% doubly mis-identified RS events in the WS sample

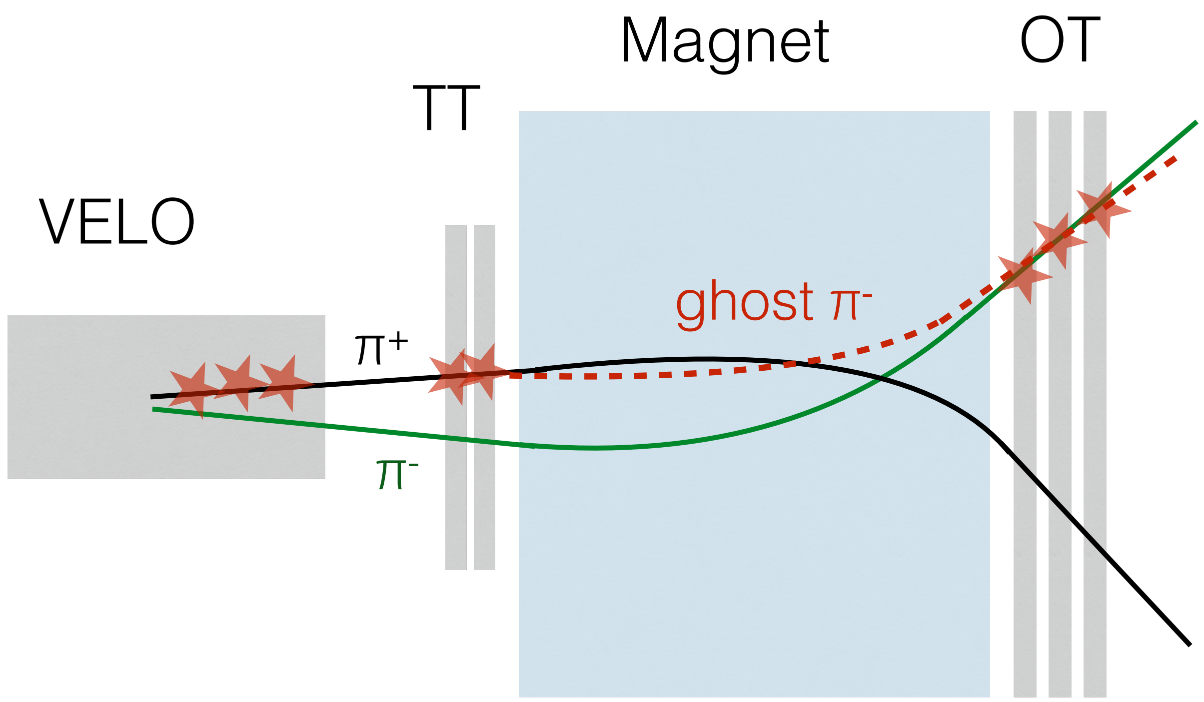
- (Un)observed time-dependence is included as a possible bias in the fit

data sideband enriched in doubly mis-identified events

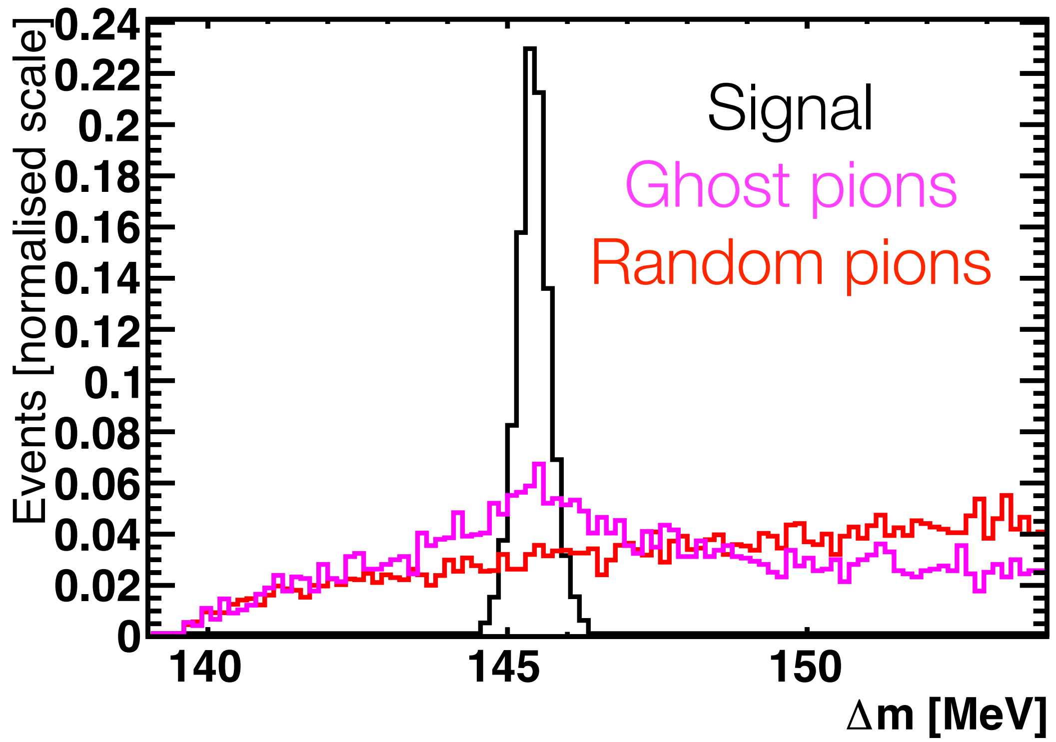


Ghost soft pions

- Soft pions made of correctly matched clusters in the VELO+TT and unrelated clusters downstream of the magnet
- Correct direction, but wrong momentum, cause a broad peaking structure at the D^{*+} mass
- Also the charge is wrong ~50% of the times, which makes a RS candidate become a WS
- Suppressed to 3% of the WS signal using a multivariate classifier based on low-level variables associated with track reconstruction



LHCb simulation



Instrumental asymmetries

- $K^+\pi^-$ and $K^-\pi^+$ final states are reconstructed with different efficiencies (mainly) because of the different interaction cross section with matter of K^+ and K^-

- Ratio of efficiencies constrained from external measurement of kinematically weighted Cabibbo-favored D^+ samples

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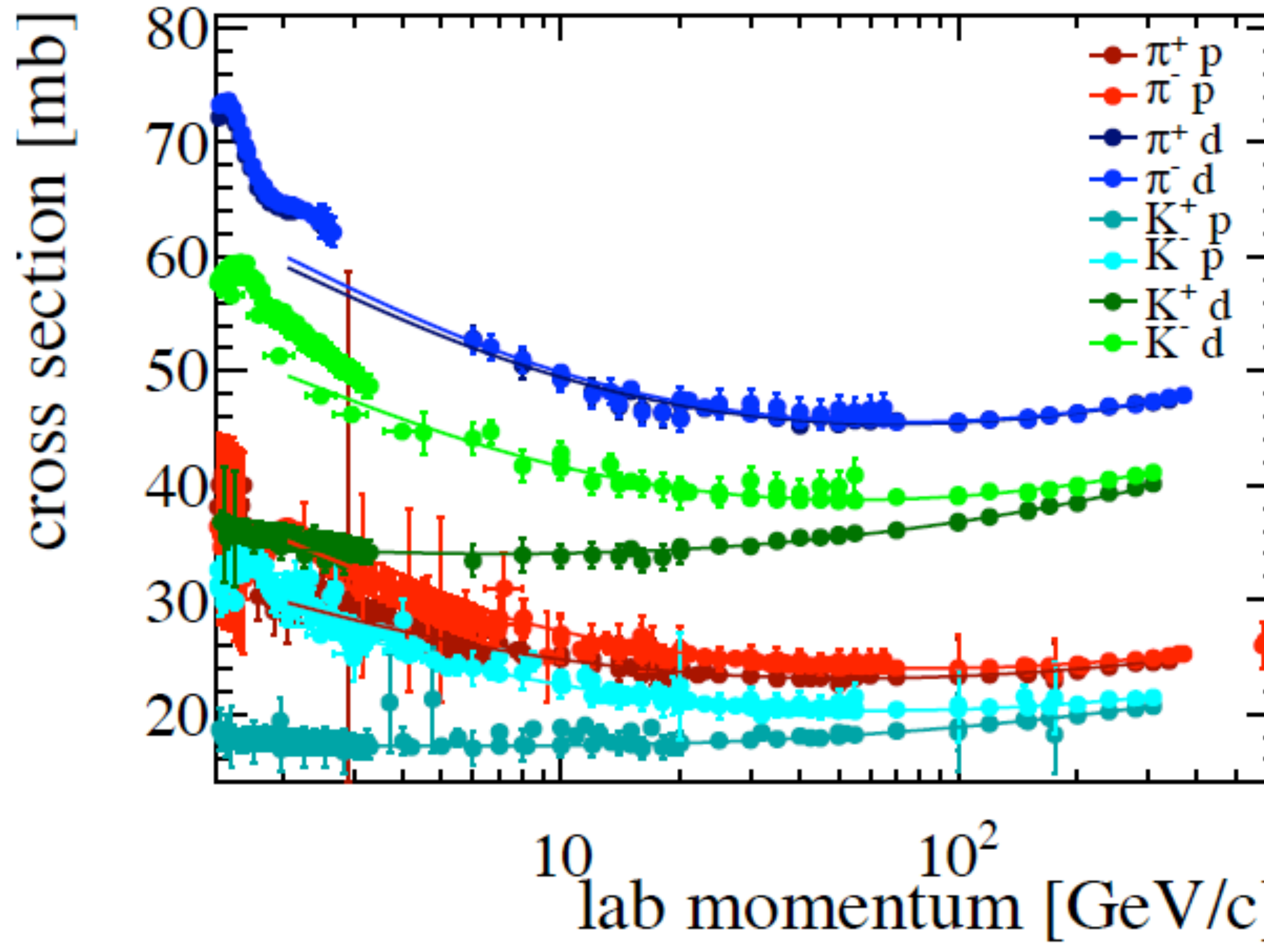
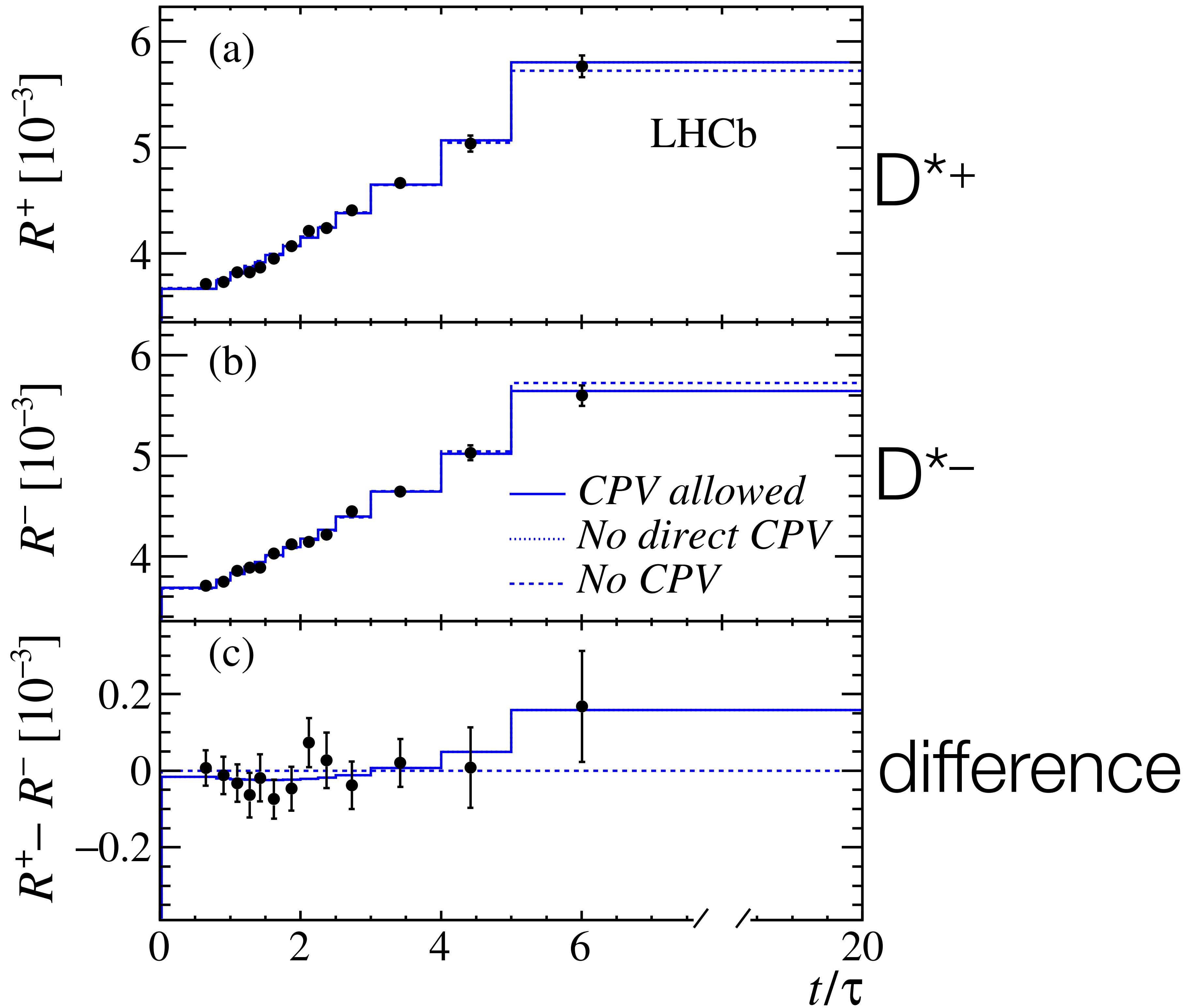


$$\frac{\epsilon(K^+\pi^-)}{\epsilon(K^{=}\pi^+)} = \frac{N(D^- \to K^+\pi^-\pi^-)}{N(D^+ \to K^-\pi^+\pi^+)} \times \frac{N(D^+ \to \overline{K}^0\pi^+)}{N(D^- \to K^0\pi^-)}$$

Time-dependent WS/RS ratio



Results

- World's tightest bound on *CP* violation in mixing

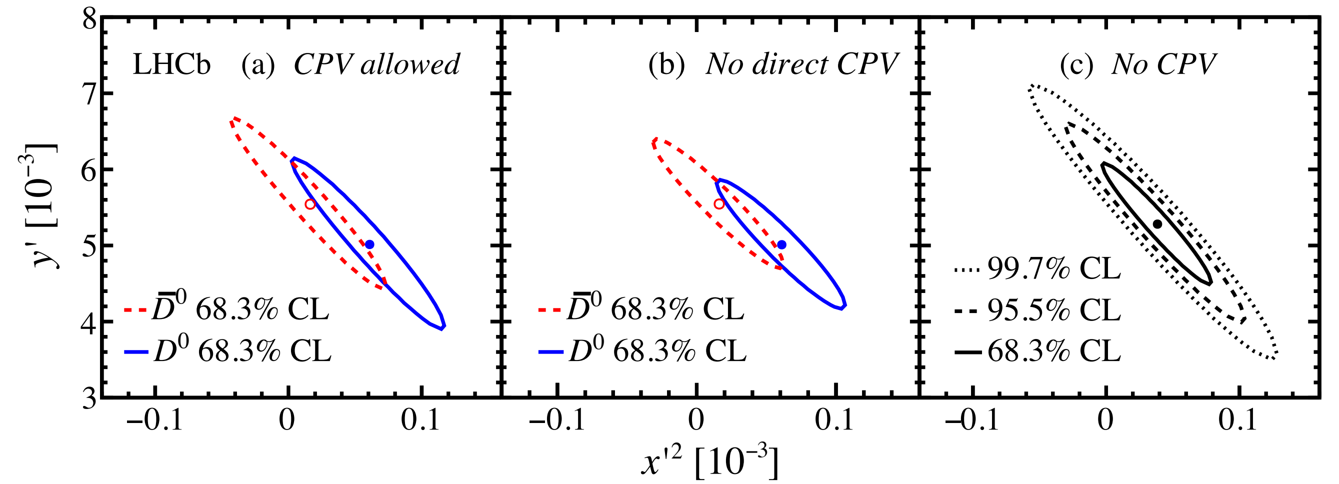
$$1.00 < |q/p| < 1.35 \quad @\ 68\% CL$$

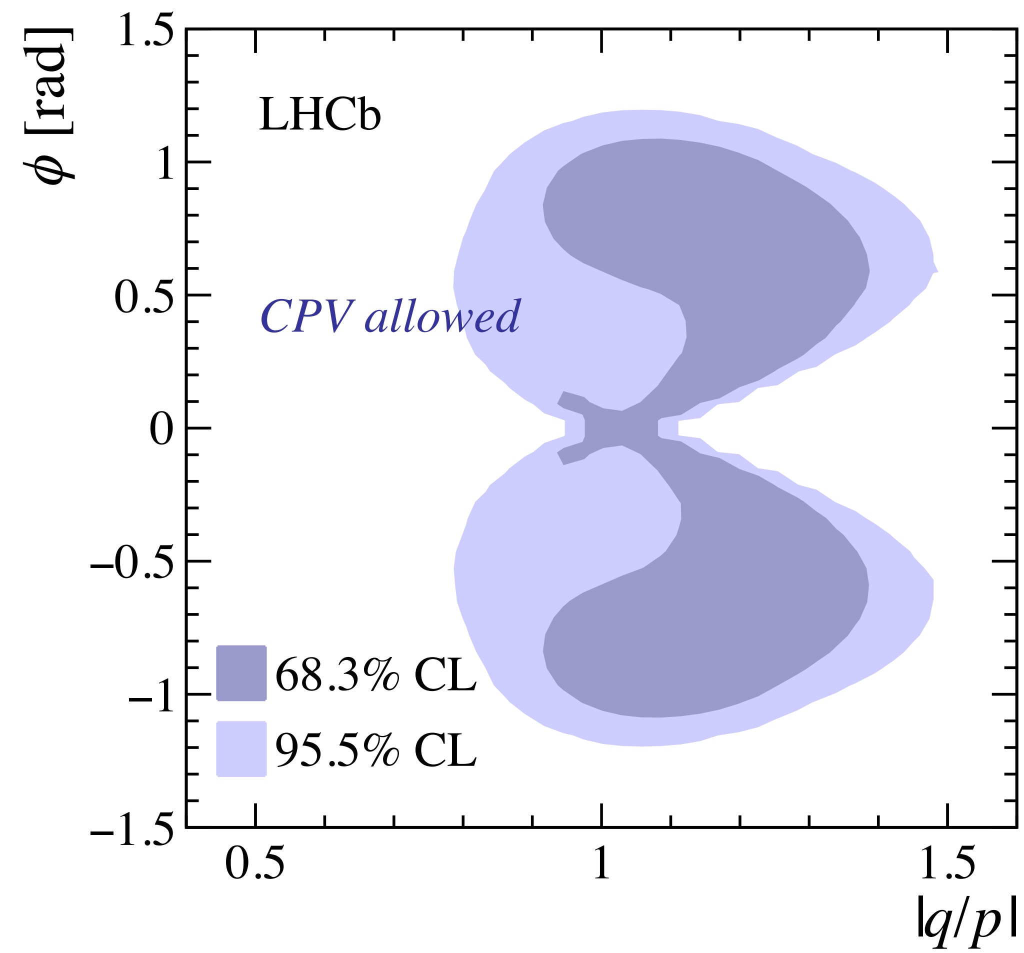
and on direct *CP* violation in DCS decays

$$A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-} = (-0.1 \pm 9.1) \times 10^{-3}$$

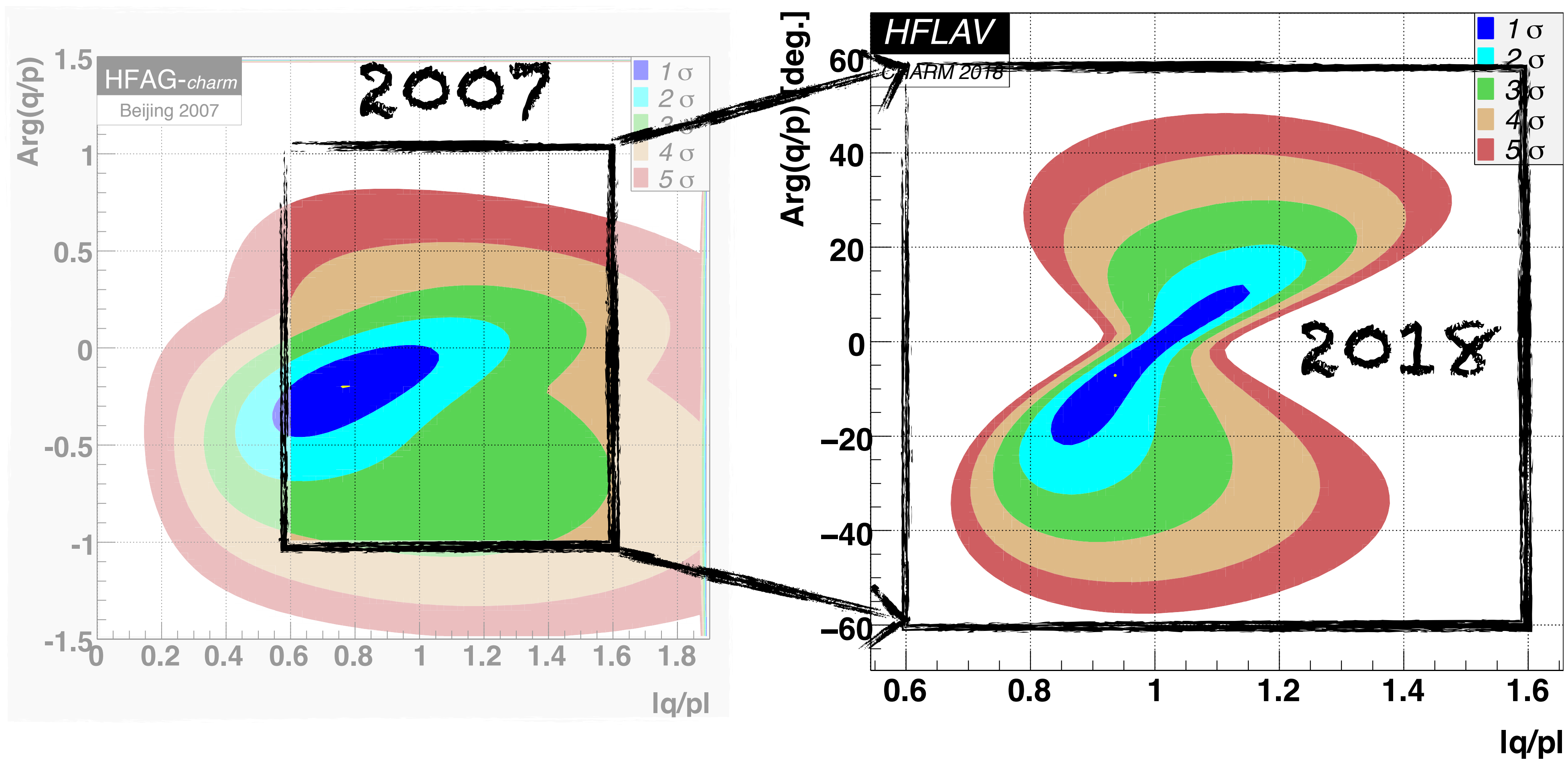
- Assuming no *CP* violation

Parameter	Value
R_D	$3.454 \pm 0.028 \pm 0.014$
y'	$5.28 \pm 0.45 \pm 0.27$
x'^2	$0.039 \pm 0.023 \pm 0.014$





Impact on world average

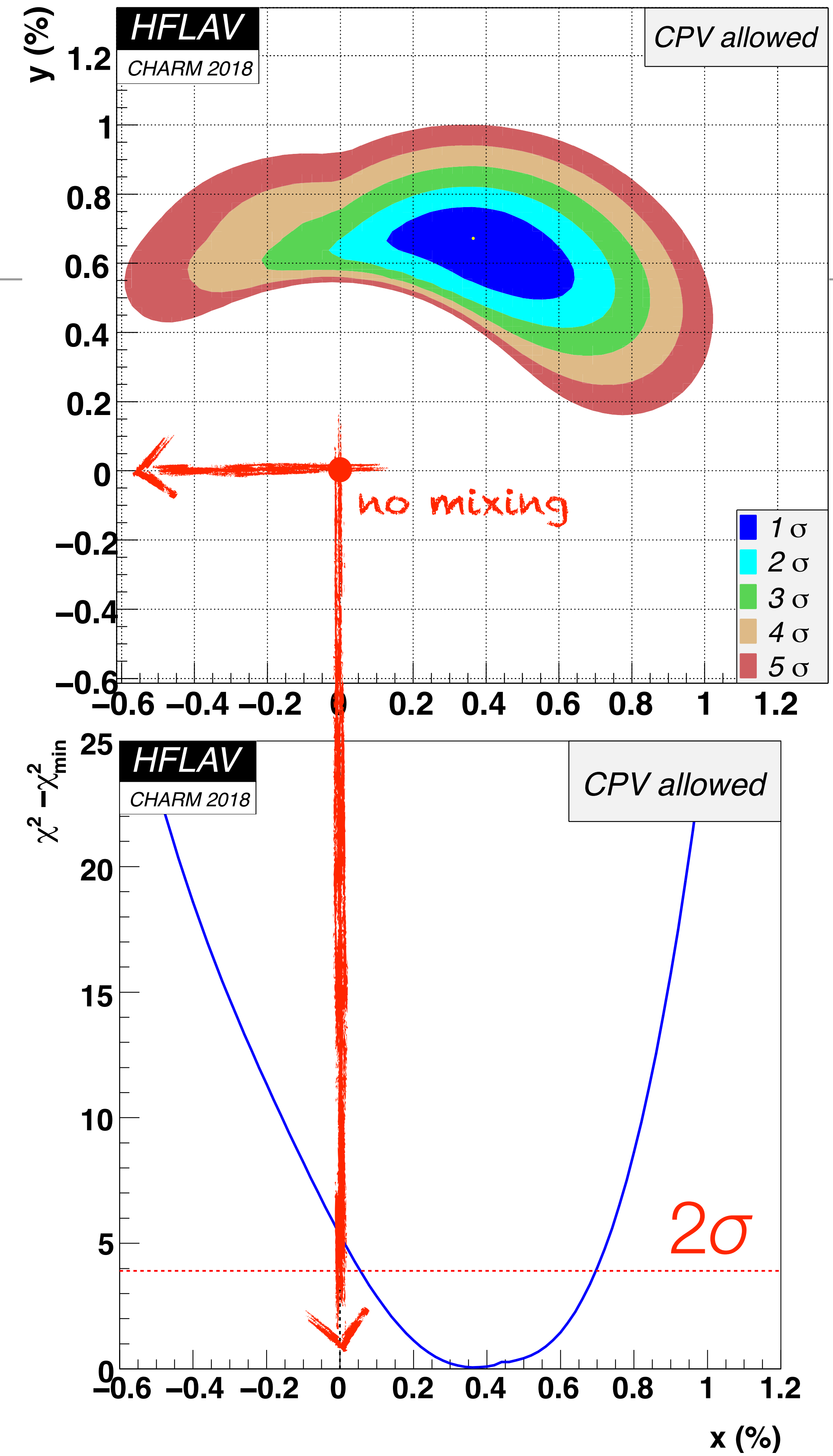


Plenty of progress in the last few years, mostly entirely driven by my measurements of WS $D^0 \to K\pi$ decays


What next?

x is the key

- Available mixing measurements are mostly based on decays to two-body final states
- These are primarily sensitive to y ($\delta_{K\pi}$~10 deg) $\Longrightarrow$ $x\leq 0$ cannot be excluded
- It is crucial to improve sensitivity on x as CP-violation observables are proportional to $x \sin\phi$
- Need more measurements with multi-body final states



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

- Multiple interfering amplitudes enhance the sensitivity to mixing and allows to measure directly *x* and *y*

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

- Requires a time-dependent Dalitz-plot analysis
- Pioneered by CLEO in 2005, then followed by *B* factories with larger yields
  - Belle $D^0 \to K_S\pi^+\pi^-$ result represents the best determination of *x* currently available
  - No precise measurement from LHCb yet (quite challenging at hadron colliders)

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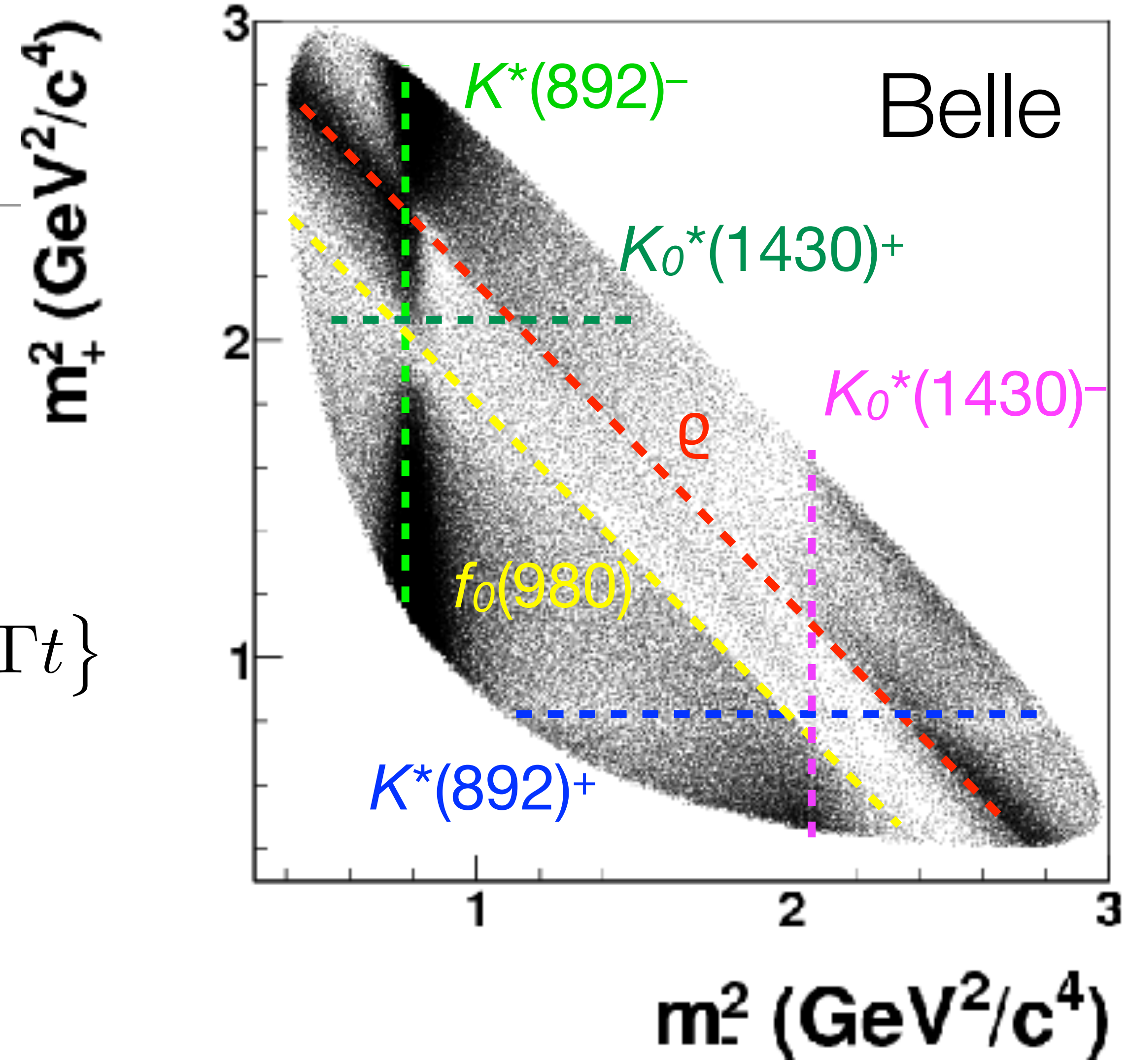
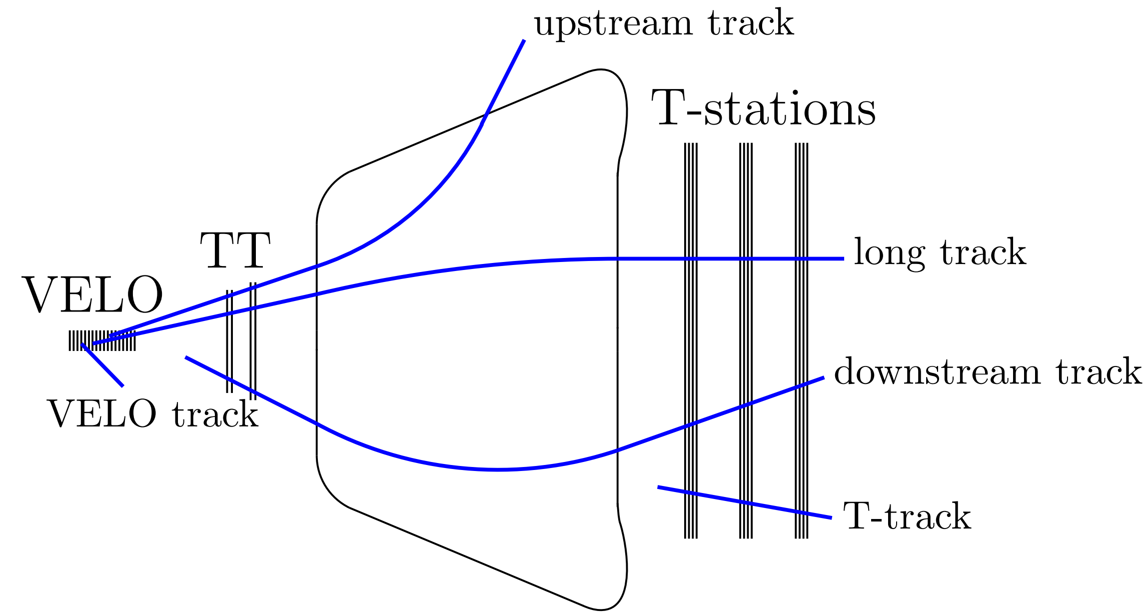
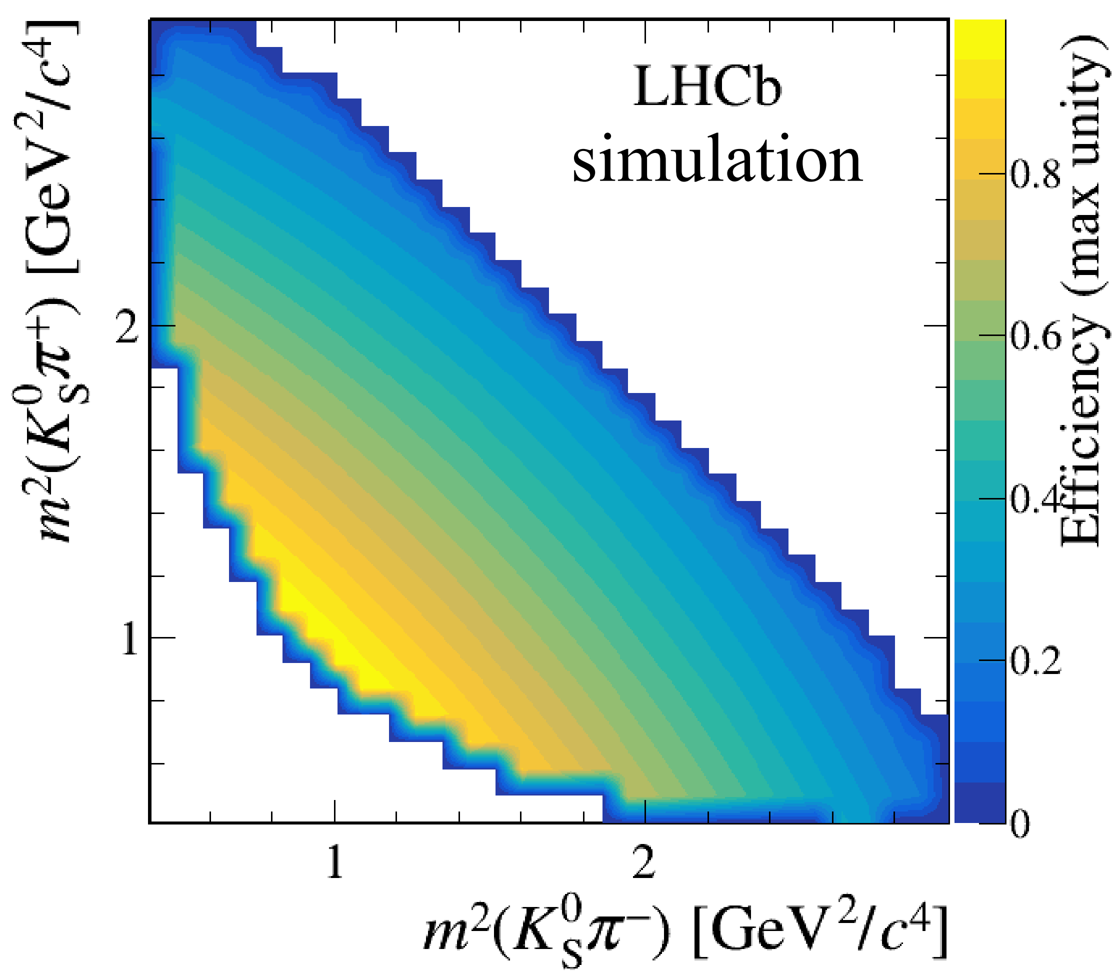


Fit type	Parameter	Fit result
No CPV	$x(\%)$	$0.56 \pm 0.19^{+0.03}_{-0.09}{}^{+0.06}_{-0.09}$
	$y(\%)$	$0.30 \pm 0.15^{+0.04}_{-0.05}{}^{+0.03}_{-0.06}$
CPV	$x(\%)$	$0.56 \pm 0.19^{+0.04}_{-0.08}{}^{+0.06}_{-0.08}$
	$y(\%)$	$0.30 \pm 0.15^{+0.04}_{-0.05}{}^{+0.03}_{-0.07}$
	$\|q/p\|$	$0.90^{+0.16}_{-0.15}{}^{+0.05}_{-0.04}{}^{+0.06}_{-0.05}$
	$\arg(q/p)(^\circ)$	$-6 \pm 11 \pm 3^{+3}_{-4}$

$D^0 \to K_S \pi^+ \pi^-$ at LHCb

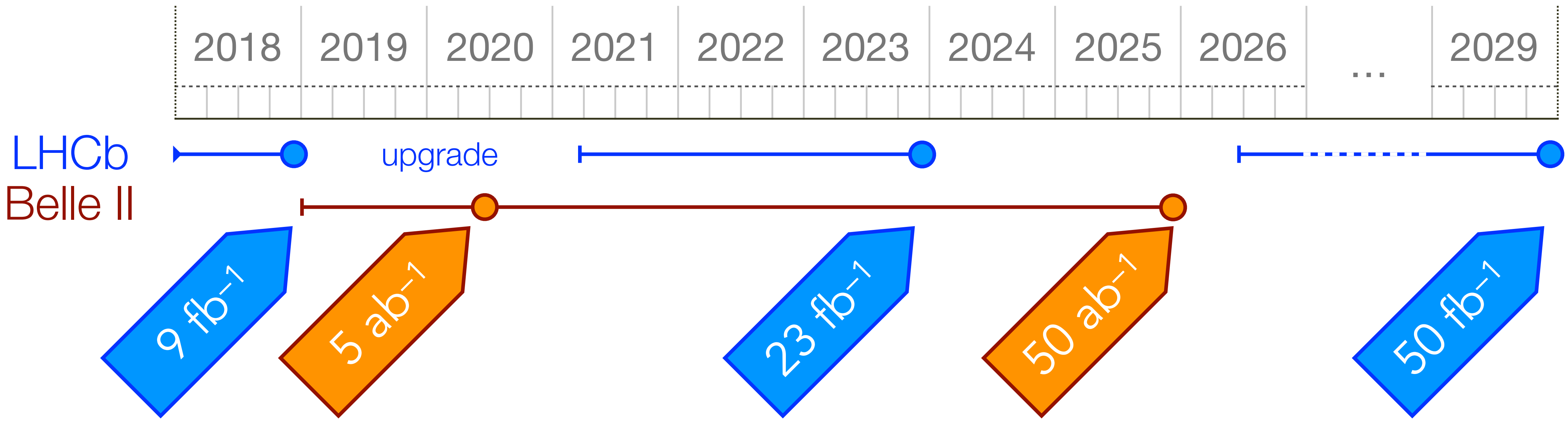
- $K_S \to \pi^+ \pi^-$ are difficult to reconstruct in LHCb
    - In the early stages of the trigger only K_S decaying inside the VELO ($t < 0.5\ \tau_{K_S}$) can be reconstructed
    - Trigger relies mostly on the two pions from the D^0 decay $\Longrightarrow$ non-uniform efficiency over the Dalitz plot (which is also correlated with the D^0 decay time)
- Could be overcome using D^0 from semitonic b-hadron decays (where the muon charge provides the flavor tag) $\Longrightarrow$ reduced efficiency and larger background levels
- A time-dependent amplitude analysis is very challenging at LHCb, Belle II seems much better suited for these kind of measurements





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

[LHCb-PUB-2018-009]
[The Belle II Physics Book]



- Projected statistical uncertainties assuming that LHCb can overcome the analysis challenges and that the current K_S efficiency is kept during the upgrade
- Systematic uncertainties due to the amplitude model are likely to limit the precision

	LHCb		Belle II	
	$9\ \mathrm{fb}^{-1}$	$23\ \mathrm{fb}^{-1}$	$5\ \mathrm{ab}^{-1}$	$50\ \mathrm{ab}^{-1}$
$\sigma(x)$ [%]	0.05	0.02	0.08	0.03
$\sigma(y)$ [%]	0.05	0.02	0.06	0.02
$\sigma(\|q/p\|)$ [%]	4	2	7	2
$\sigma(\phi)$ [deg]	2	1	5	1

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

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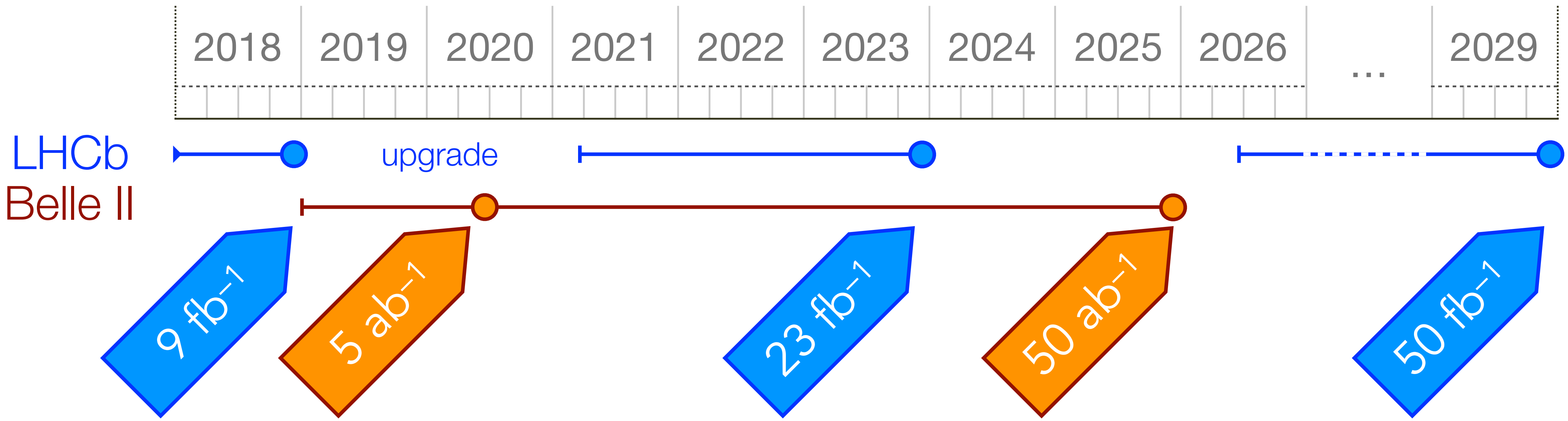

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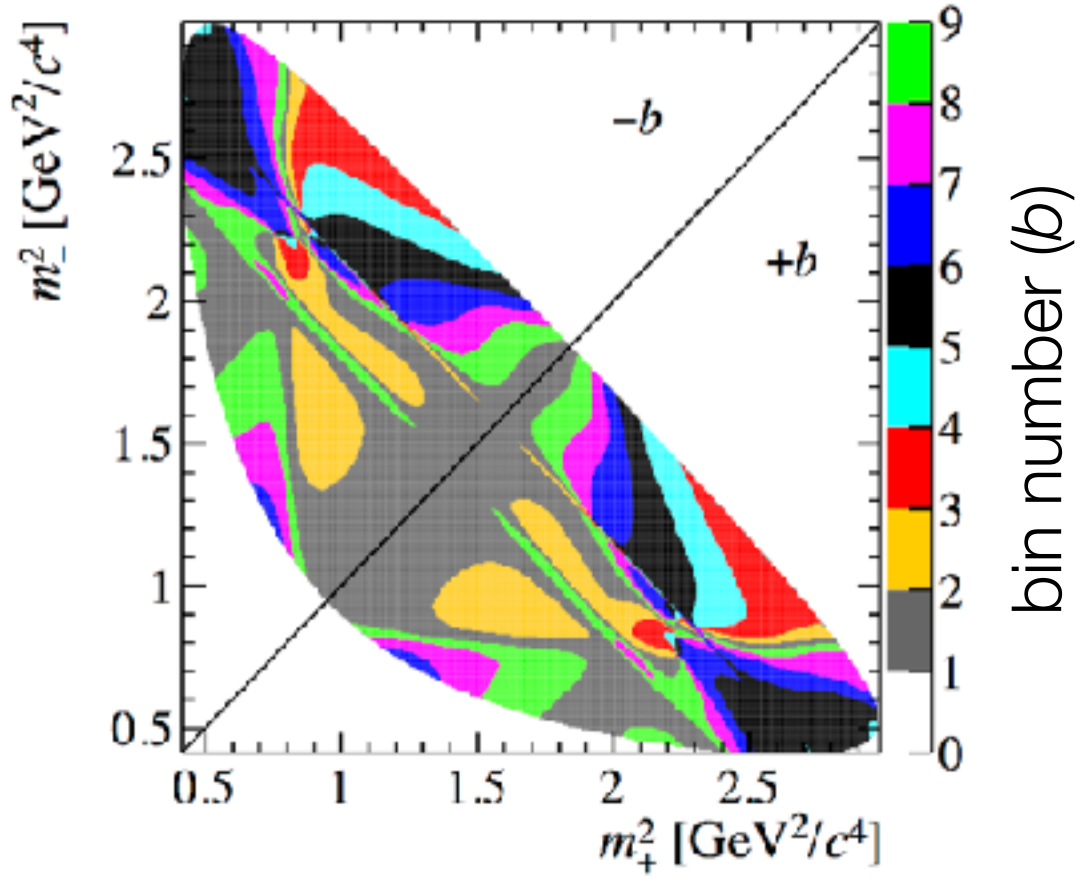
- Systematic uncertainties due to the amplitude model are likely to limit the precision

	LHCb		Belle II		Model
	$9\ fb^{-1}$	$23\ fb^{-1}$	$5\ ab^{-1}$	$50\ ab^{-1}$	syst.
$\sigma(x)$ [%]	0.05	0.02	0.08	0.03	0.07
$\sigma(y)$ [%]	0.05	0.02	0.06	0.02	0.05
$\sigma(\|q/p\|)$ [%]	4	2	7	2	6
$\sigma(\phi)$ [deg]	2	1	5	1	4

$D^0 \to K_S \pi^+ \pi^-$ with a model-independent approach

- Avoid amplitude analysis by integrating over Dalitz-plot bins with constant strong-phase variation

$$\mathcal{P}_{D^0} \propto e^{-\Gamma t}\left[F_b - \sqrt{F_b F_{-b}}(c_b\, y - s_b\, x)\Gamma t\right]$$



- Constrain hadronic parameters (c_b, s_b) using measurements with quantum-correlated $D^0\bar{D}^0$ pairs, *i.e.* at CLEO and BESIII

$$F_b = \int_b |\mathcal{A}_{D^0}|^2 dm_+^2 dm_-^2$$

$$c_b - i s_b \propto \int_b \mathcal{A}^*_{D^0} \mathcal{A}_{\bar{D}^0} dm_+^2 dm_-^2$$

A novel approach for measuring charm-mixing parameters using $D \to K^0_S\pi^+\pi^-$ decays

A. Contu[1], A. Di Canto[2], J. Garra Ticó[3], T. Gershon[4], N. Jurik[5], M. Martinelli[2], S. Stahl[2], D. Tonelli[6]

[1] *INFN Cagliari*, [2] *CERN*, [3] *University of Cambridge*, [4] *University of Warwick*, [5] *University of Oxford*, [6] *INFN Trieste*

Abstract

We propose a novel method to measure charm-mixing and *CP*-violation parameters using $D \to K^0_S\pi^+\pi^-$ decays. The approach does not require a fit of the decay amplitudes and achieves an efficient suppression biases due to nonuniform decay-time acceptance. We fit the ratios of signal yields observed in regions of the

New idea, to be submitted for publication soon

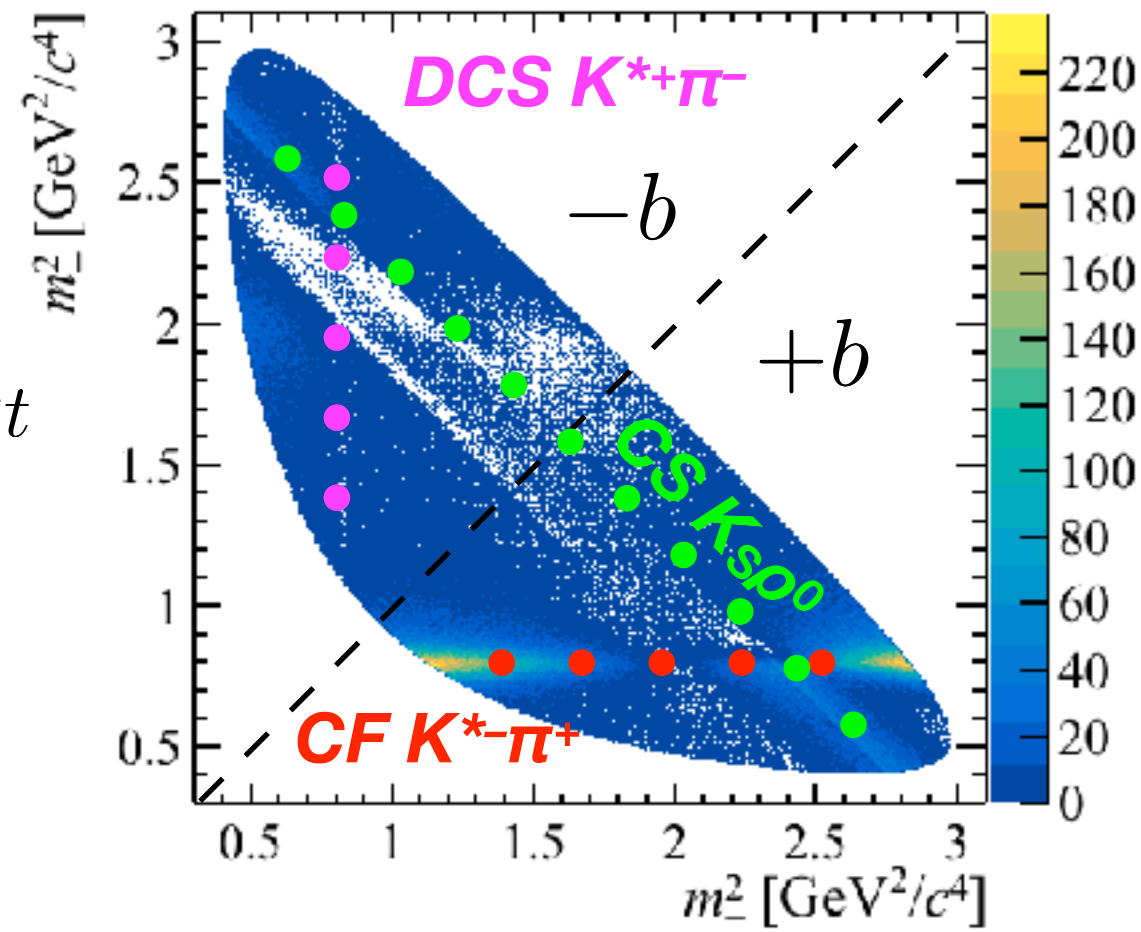
Bin-flip method

- Inspired by the WS $D^0 \to K\pi$ analysis: ratio of events in bin $-b$ to events in bin b to suppress effects due to non-uniform efficiency variations

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

- Model-independent and (potentially) completely data driven
- Comes with the price of degraded sensitivity to mixing effects from *CP*-even/odd amplitudes

Pseudodata based on BaBar amplitude model [PRL 105 (2010) 081803]



$$r_b = \frac{F_{-b}}{F_b}$$

Sensitivity study

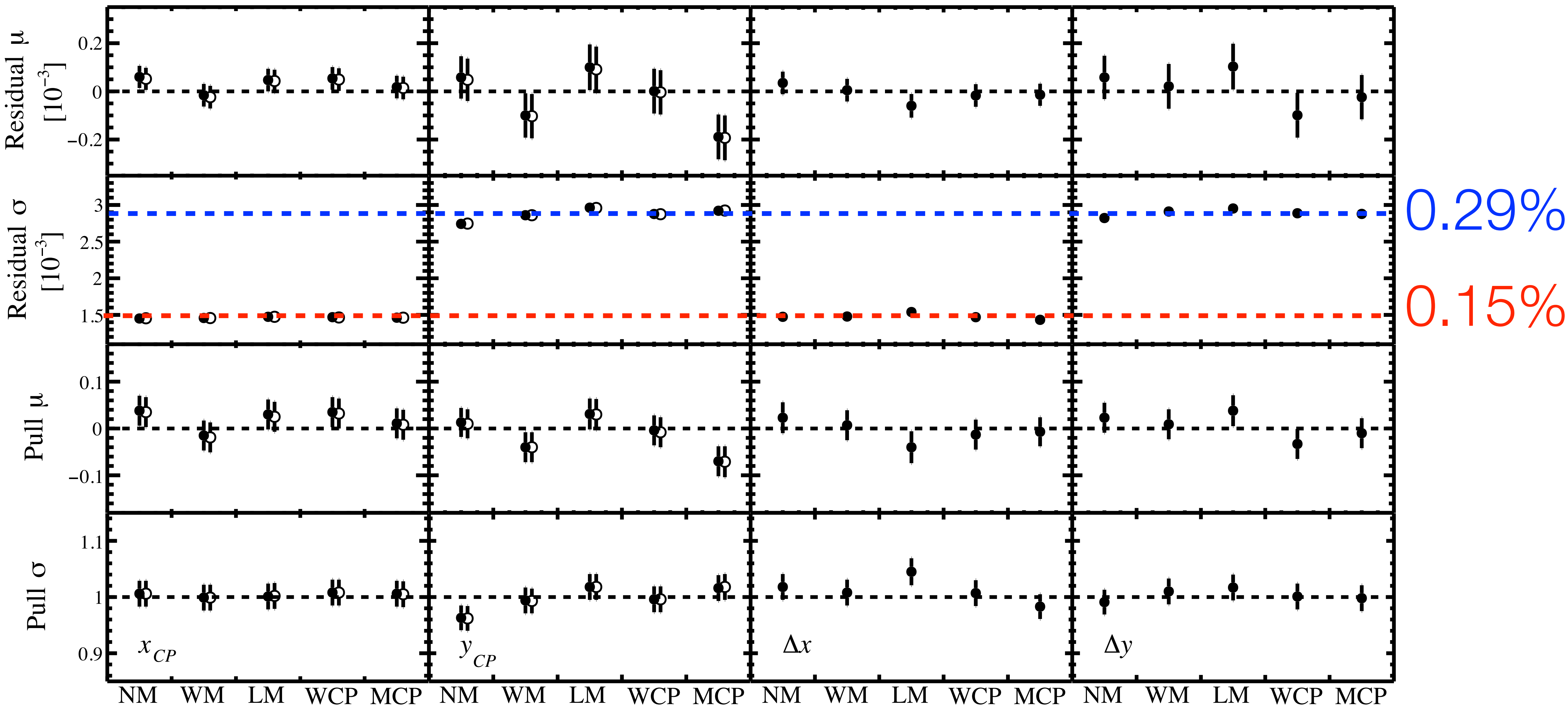
- Generated 1M signal-only $D^0 \to K_S\pi^+\pi^-$ decays using the BaBar amplitude model and compared sensitivity to x and y with different analysis methods (all other nuisance parameters fixed)

Analysis method	$\sigma(x)$	$\sigma(y)$
Model-dependent	0.11%	0.10%
Original model-independent	0.20%	0.18%
Bin-flip model-independent	0.15%	0.29%

- Bin-flip method gives better sensitivity to x than the original model-independent method
- Fit mixing parameters separately for D^0 and $\overline{D}^0$ decays to search for *CP* violation

$$x \longrightarrow x^{\pm} = x_{CP} \pm \Delta x$$
$$y \longrightarrow y^{\pm} = y_{CP} \pm \Delta y$$

Sensitivity study



NM = no mixing, WM = world-average mixing, LM = large mixing
WCP = WM + world average CPV, MCP = WM + CPV in mixing only

Releasing the nuisance parameters

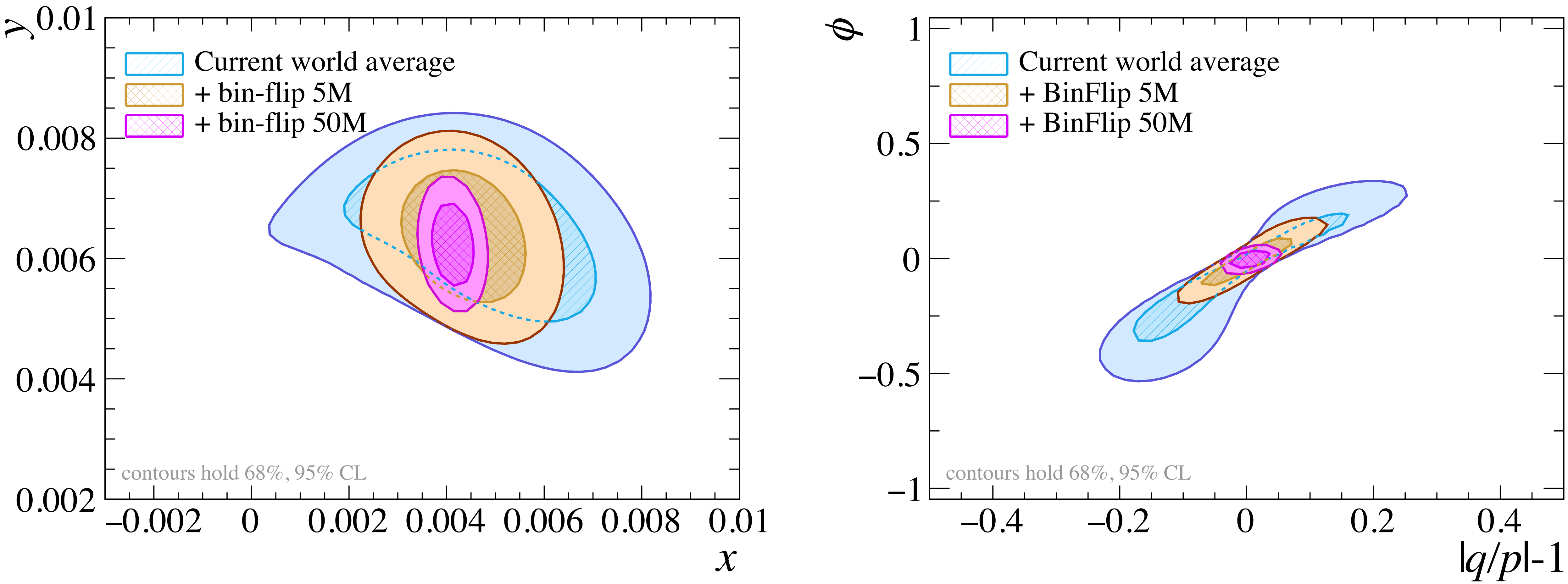
- So far shown results when only *x* and *y* are free to float in the fit, but in real life one would need to fit also for r_b, c_b and s_b

Fit configuration	$\sigma(x_{CP})$	$\sigma(y_{CP})$	$\sigma(\Delta x)$	$\sigma(\Delta y)$
r_b, (c_b, s_b) fixed	0.15%	0.29%	0.15%	0.29%
r_b free, (c_b, s_b) fixed	0.21%	0.41%	0.15%	0.29%
r_b fixed, (c_b, s_b) constrained	0.16%	0.30%	0.16%	0.31%
r_b free, (c_b, s_b) constrained	0.22%	0.43%	0.16%	0.31%

- Uncertainties on the external inputs from CLEO (c_b, s_b) have a marginal impact on the results (with *CP*-violation parameters practically unaffected) with O(1M) signal yields
- BESIII has already ~3.5× CLEO statistics and expects to collect at least a factor 3 more within the next 2-3 years (10 fb^{-1} in total)

Expected impact on world average

- Assuming a bin-flip analysis with 5-50M signal decays (*i.e.* ~5-50ab^{-1} of Belle II data) and improved BESIII measurement of (c_b, s_b)



Conclusions

Final remarks

- Quark-flavor physics allows to explore some of the deepest questions at the intersection of particle physics and cosmology
- Focused mostly on charm because of its unique reach
  - The SM didn't crack… but I'm contributing to further its understanding (while having quite some fun)
- Keep pushing the reach with novel measurements and ideas
  - 10× more precise results at Belle II and LHCb in the next decade may reveal unambiguous signs of beyond-SM physics
- Time seems particularly fitting: LHC expected exciting high-p_T physics and boring flavor physics. Looks like it's going the other way around…
- Flavor is more compelling than ever. Our best (only?) probe for 10–10^6 TeV energies in the next decade and beyond


Any
Questions!