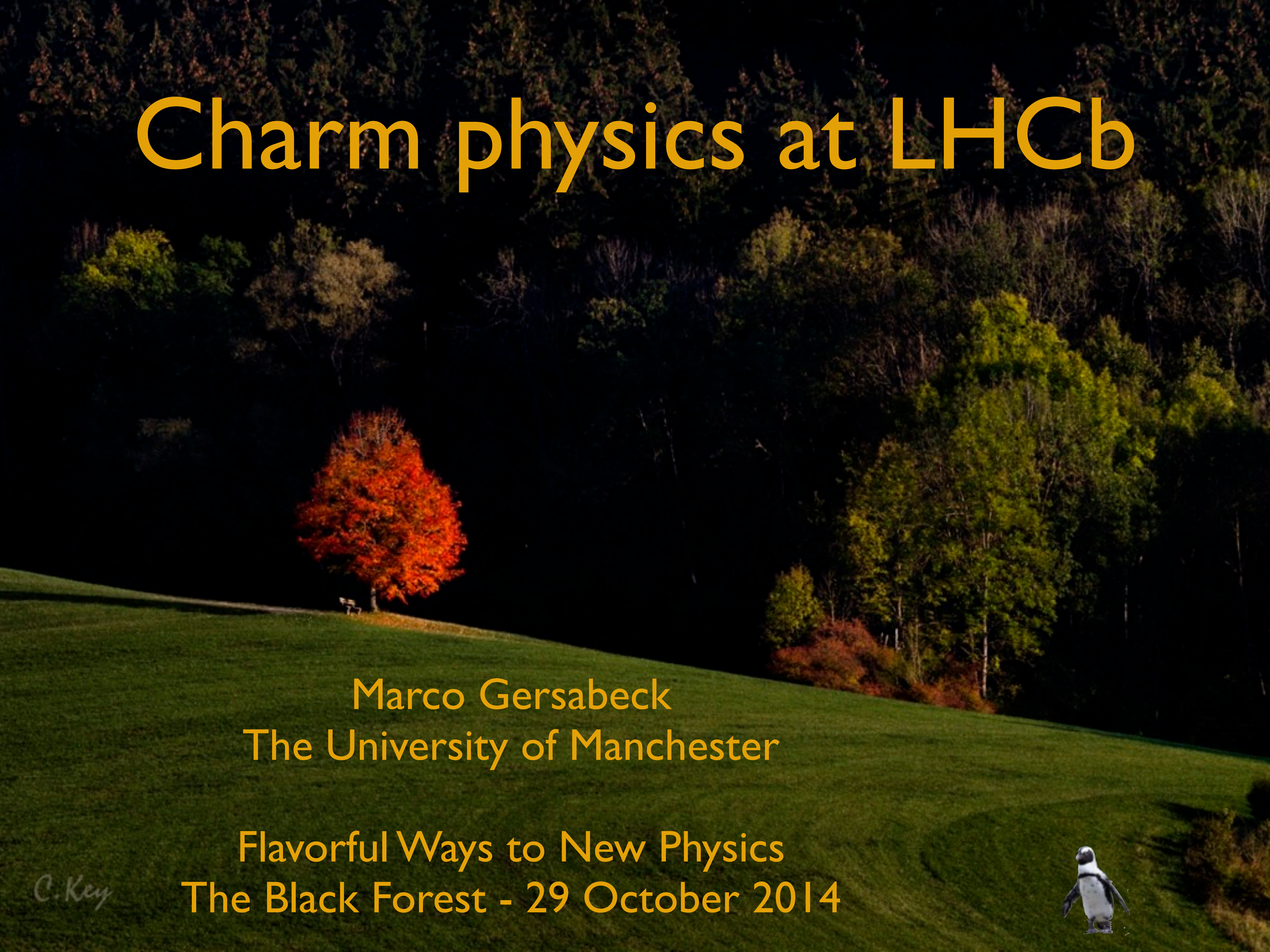
Charm physics at LHCb

Marco Gersabeck
The University of Manchester

Flavorful Ways to New Physics
The Black Forest - 29 October 2014



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Outline

- Charm discovery
- Measuring charm
- Exotic charm
- Direct CP violation
- Mixing & indirect CP violation
- Interplay
- Future potential

To begin

The very beginning

Prog. Theor. Phys. Vol. 46 (1971), No. 5

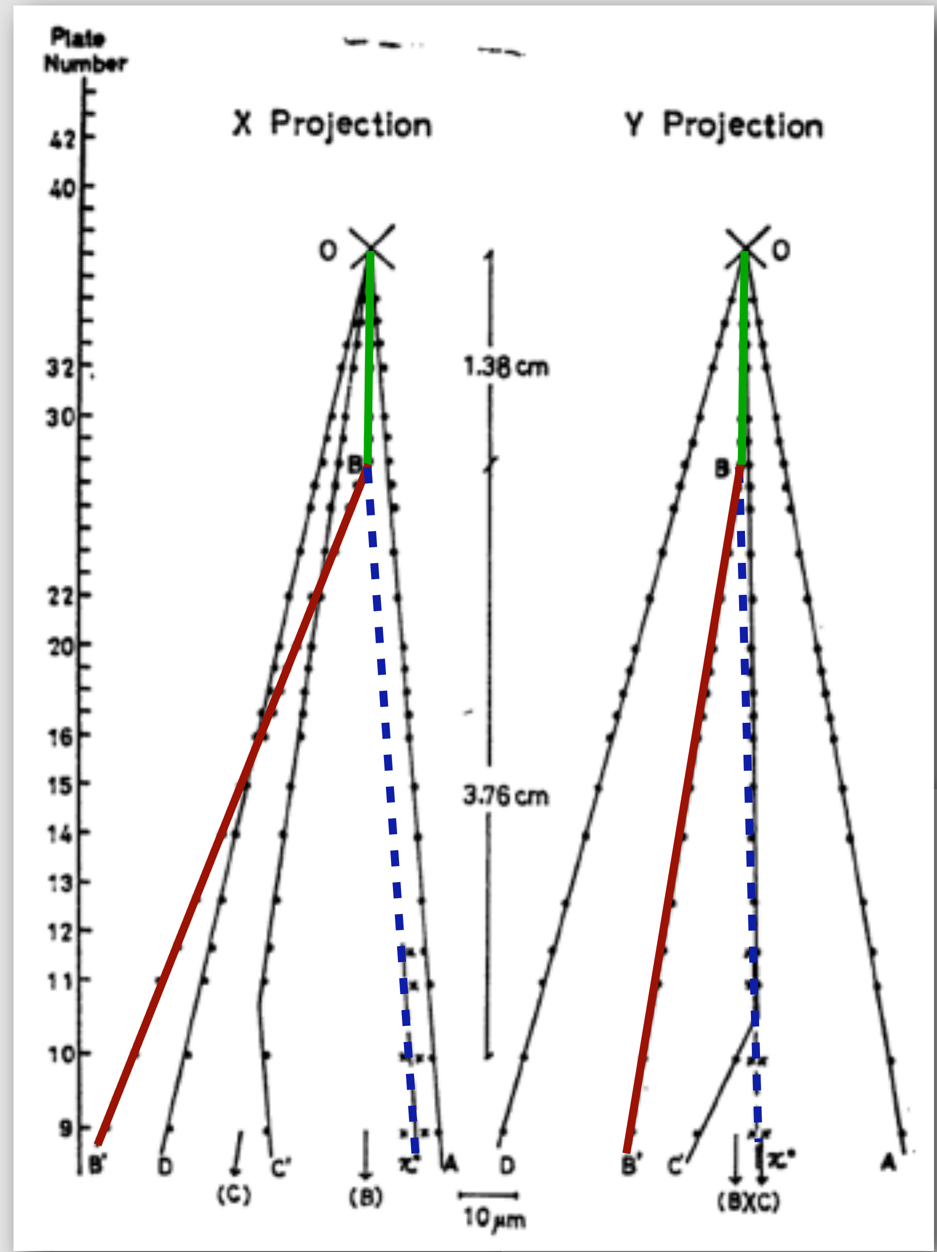
A Possible Decay in Flight of a New Type Particle

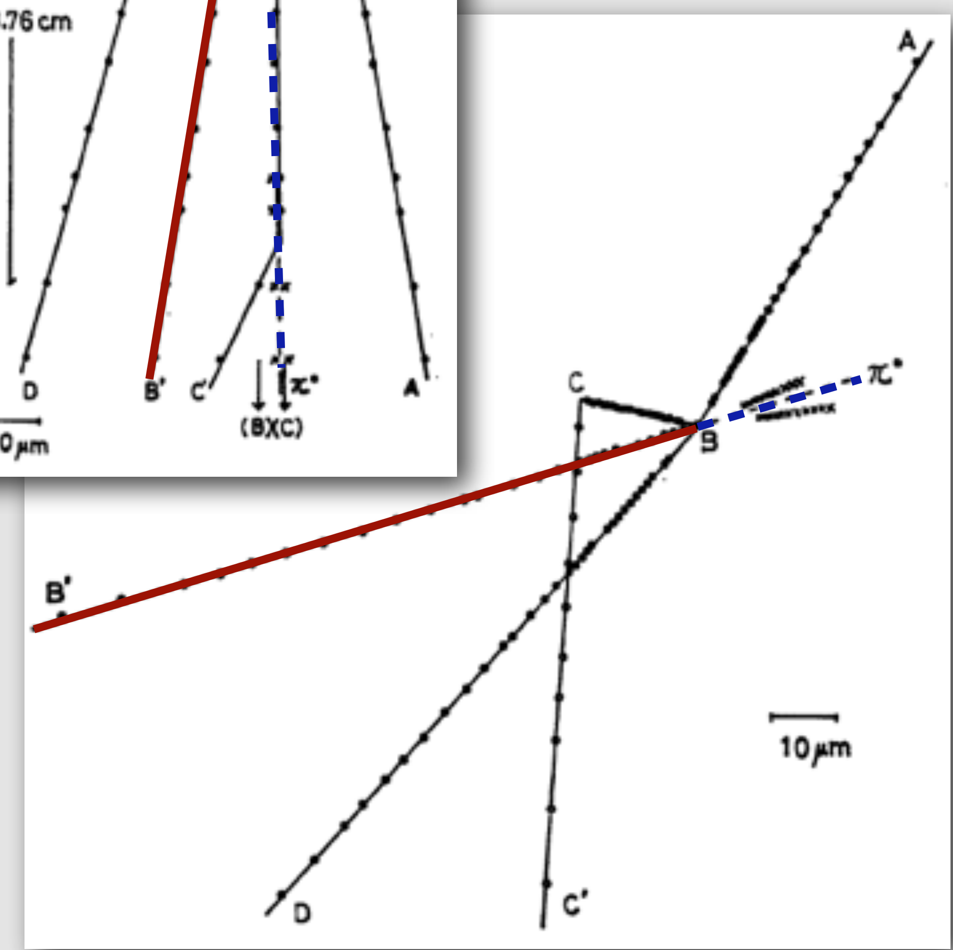
Kiyoshi NIU, Eiko MIKUMO and Yasuko MAEDA*

Institute for Nuclear Study
University of Tokyo
**Yokohama National University*

August 9, 1971

- Cosmic showers
- Observed in emulsion chambers
- 500 hours aboard a cargo plane





Assumed decay mode	M_x GeV	T_x sec
$X \to \pi^0 + \pi^\pm$	1.78	2.2×10^{-14}
$X \to \pi^0 + p$	2.95	3.6×10^{-14}

The Nobel beginning

VOLUME 33, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 1974

Experimental Observation of a Heavy Particle J†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, 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

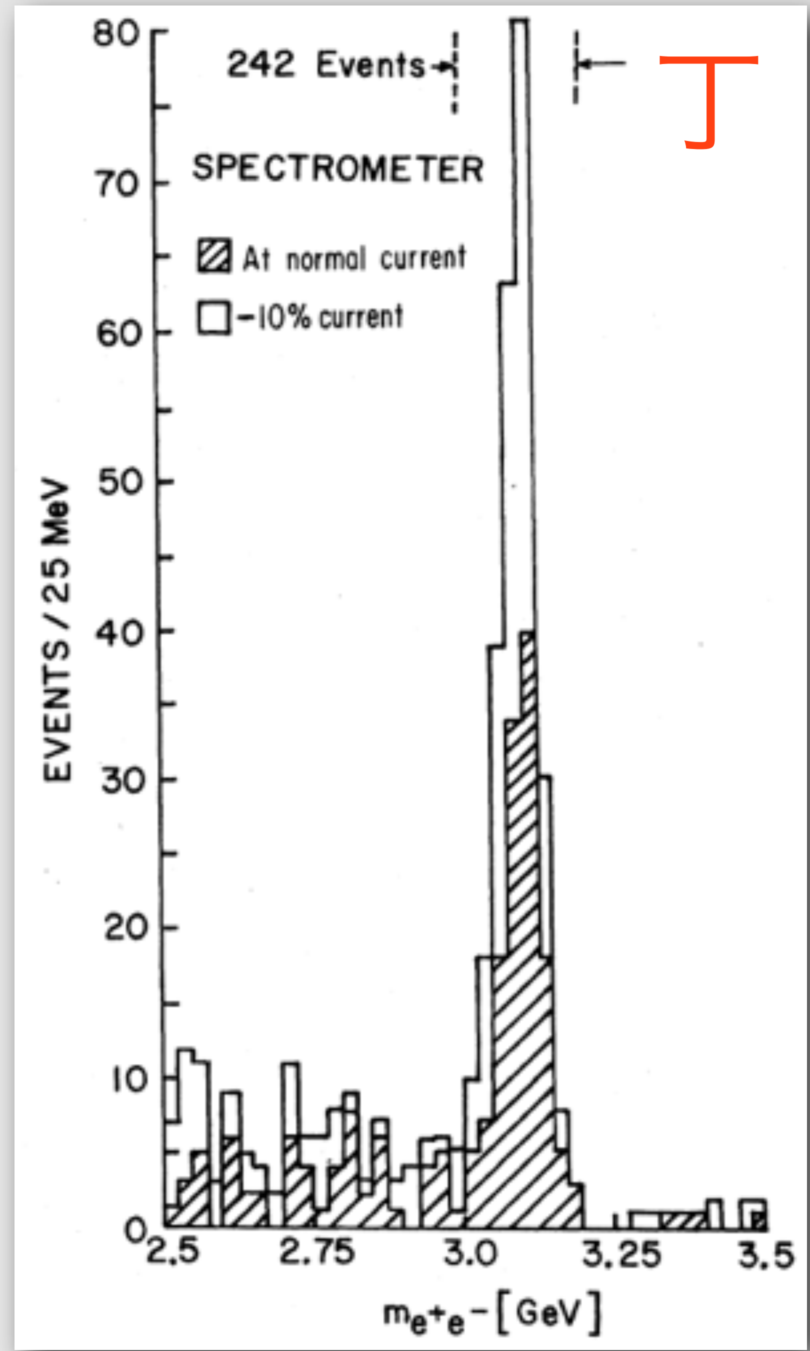
Y. Y. Lee
Brookhaven National Laboratory, Upton, New York 11973
(Received 12 November 1974)

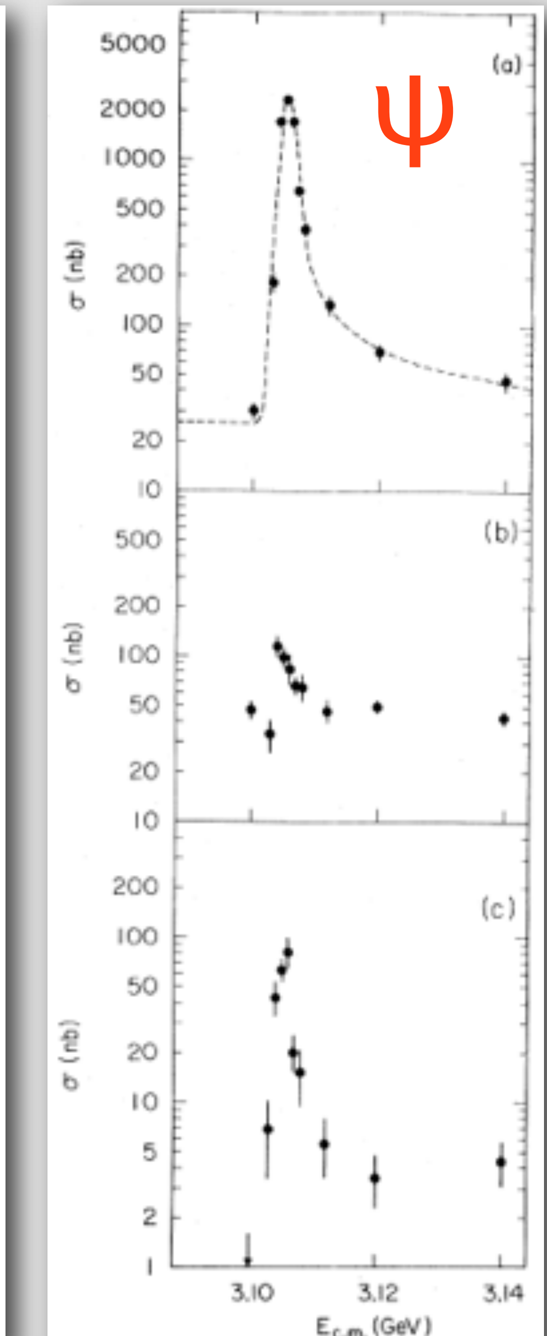
Discovery of a Narrow Resonance in e^+e^- Annihilation*

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

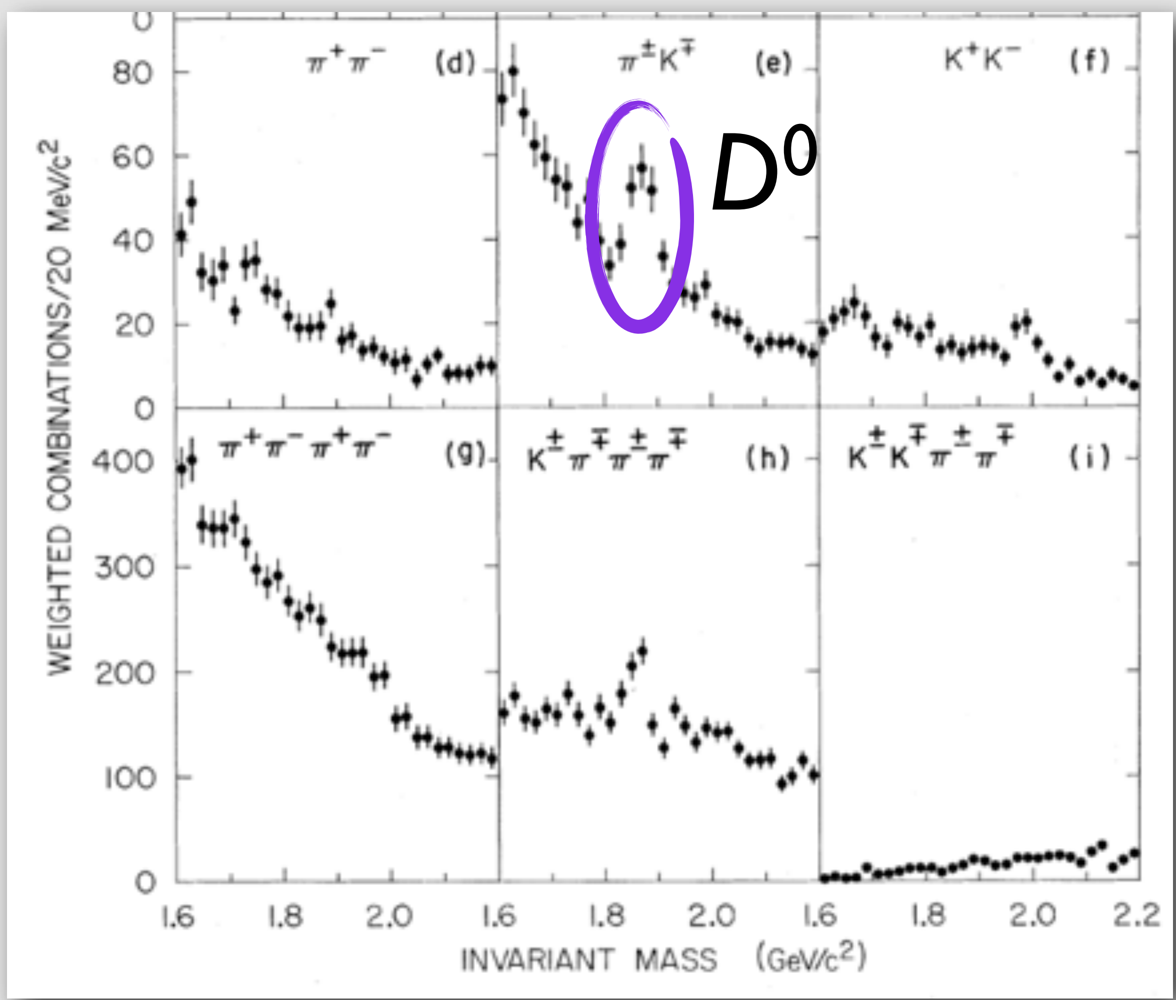
G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720
(Received 13 November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



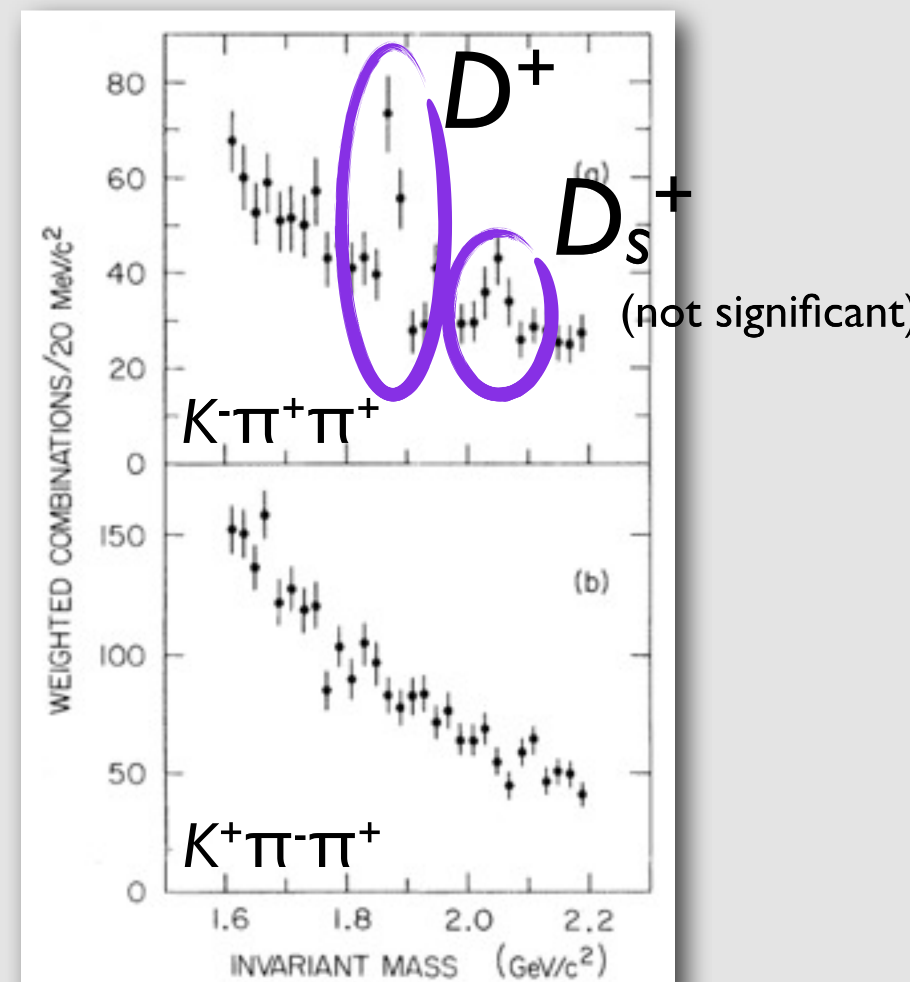


Enter open charm

- MARK-I experiment at SPEAR/SLAC
- 4π detector at e^+e^- collider



PRL 37 (1976) 255



PRL 37 (1976) 569

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Measuring charm

at 40 MHz

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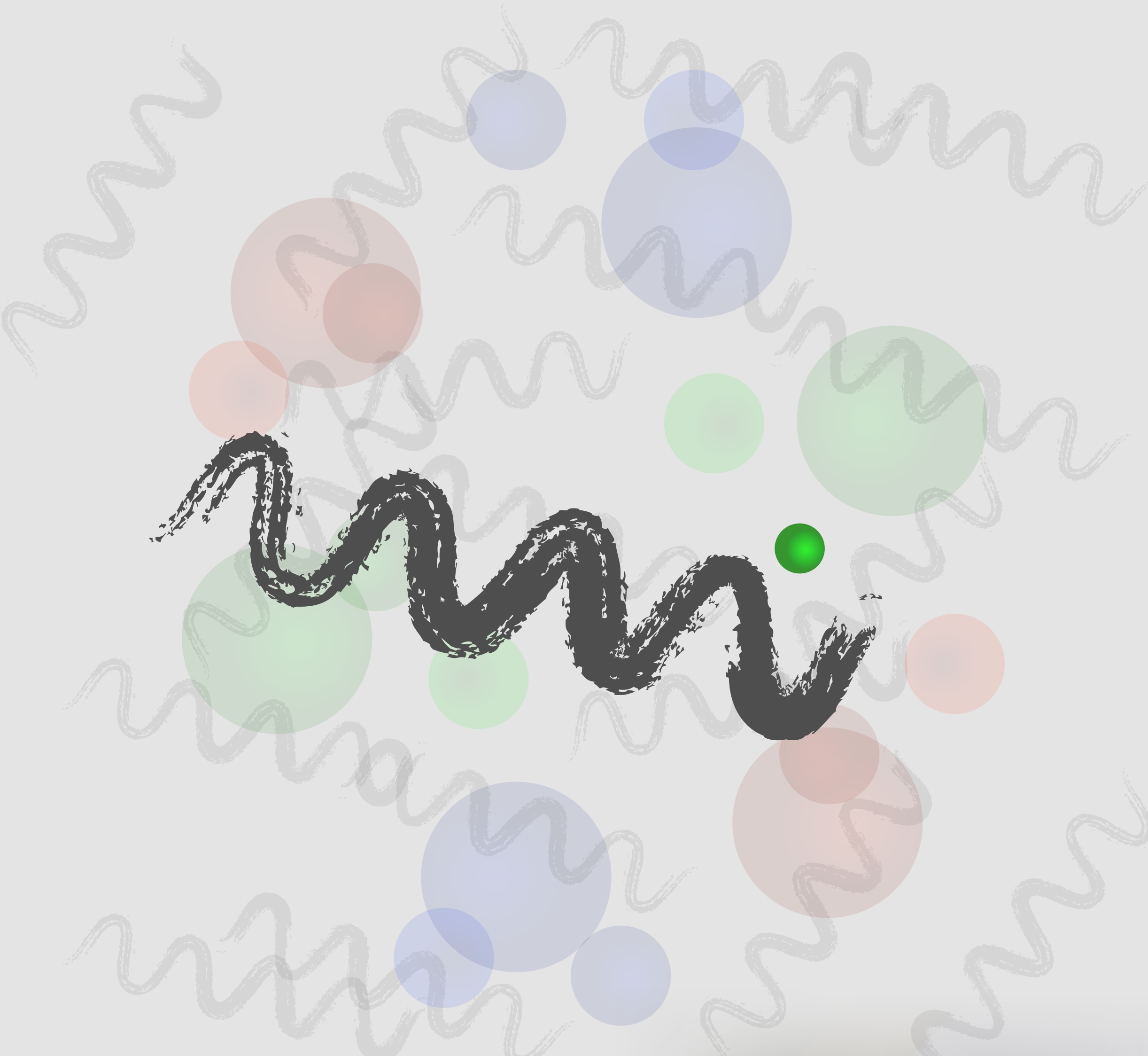
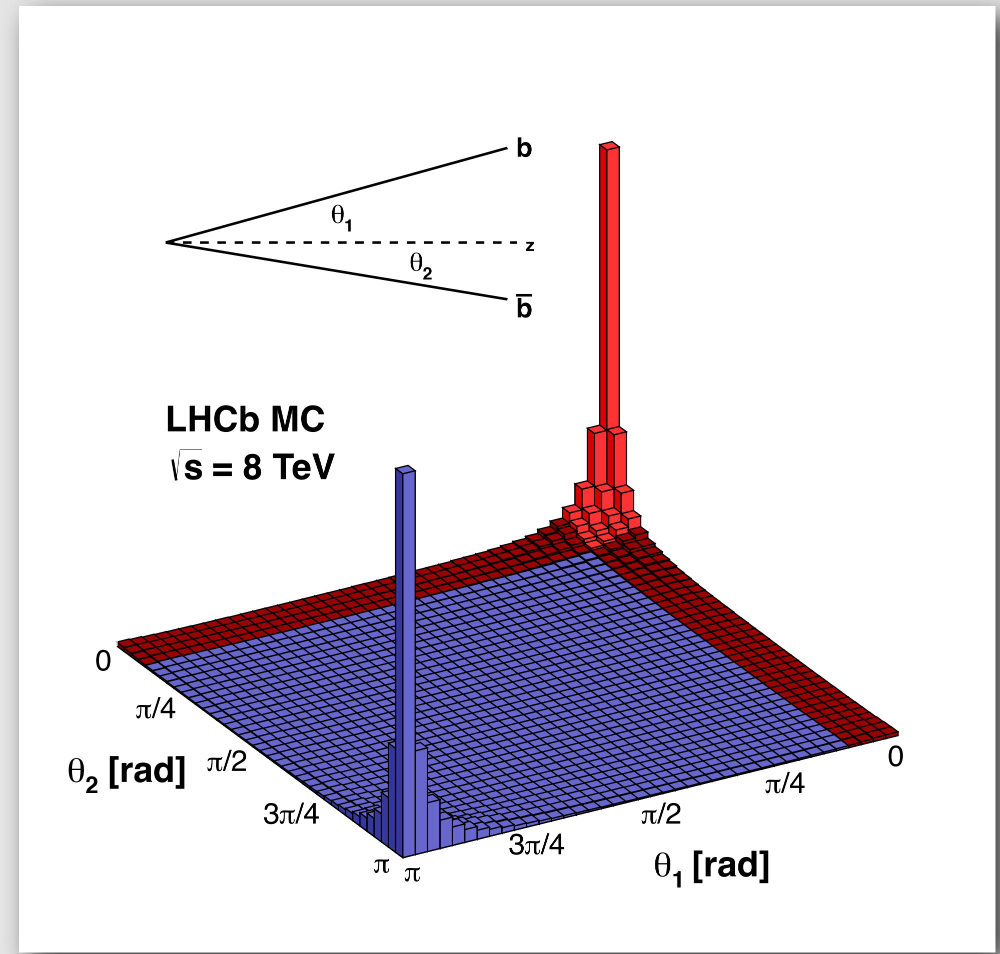
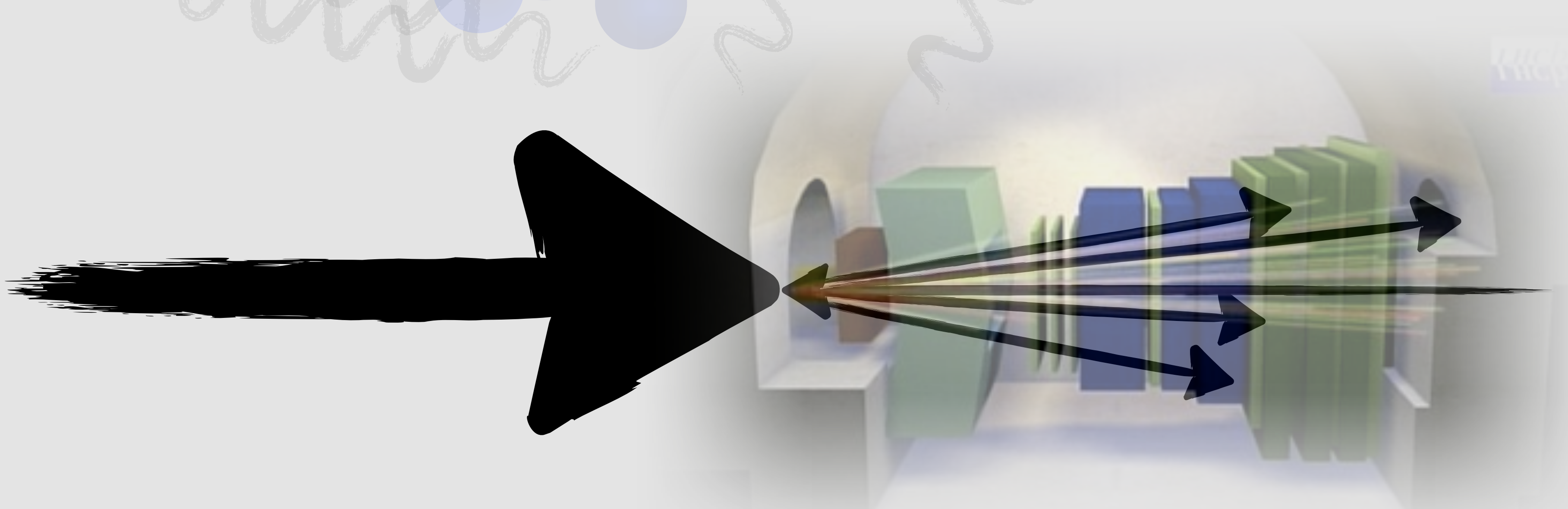
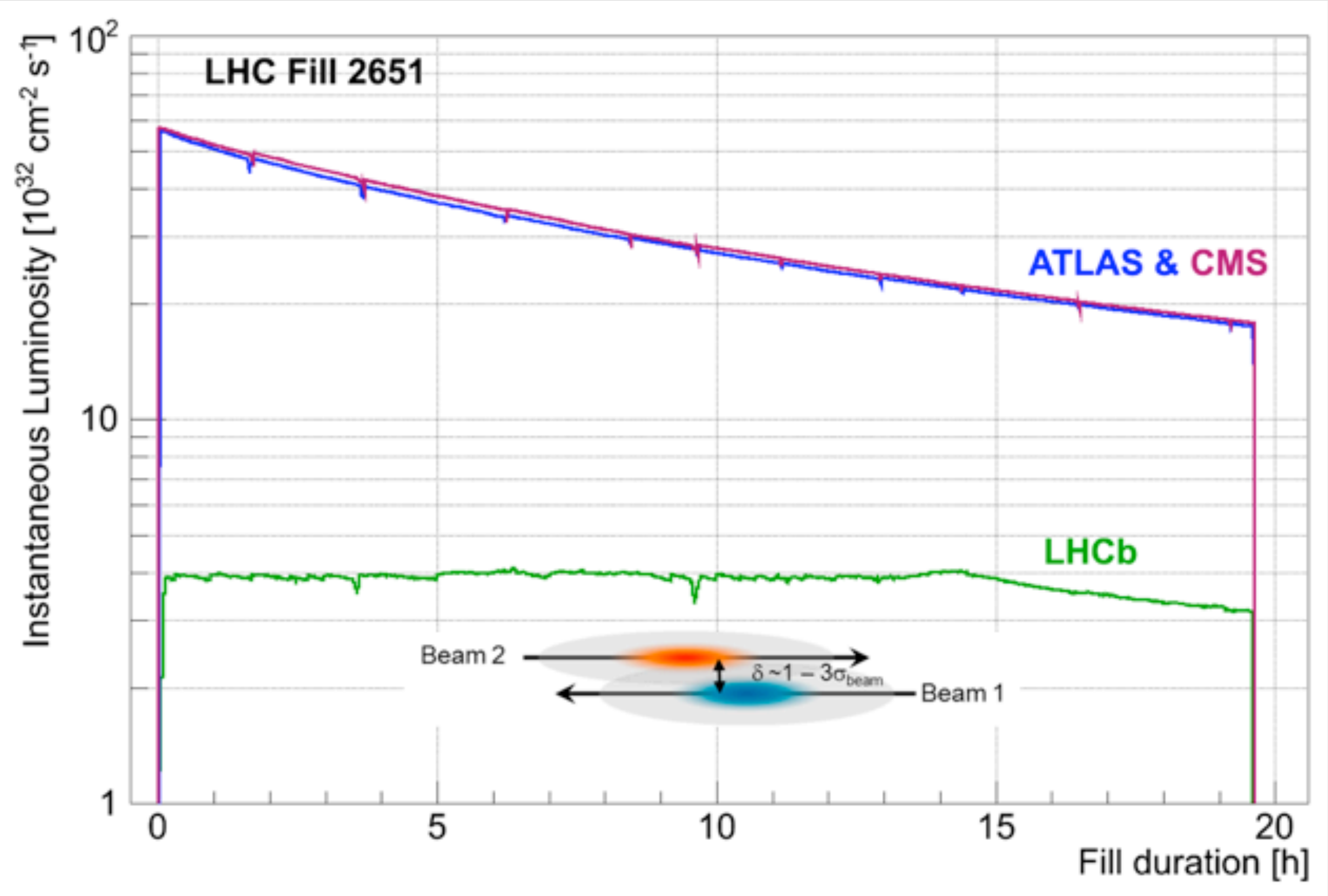
Asymmetric collisions







Constant luminosity



- In total so far:
  - ➡ 2010 peanuts
  - ➡ 2011 1 fb^{-1}
  - ➡ 2012 2 fb^{-1}

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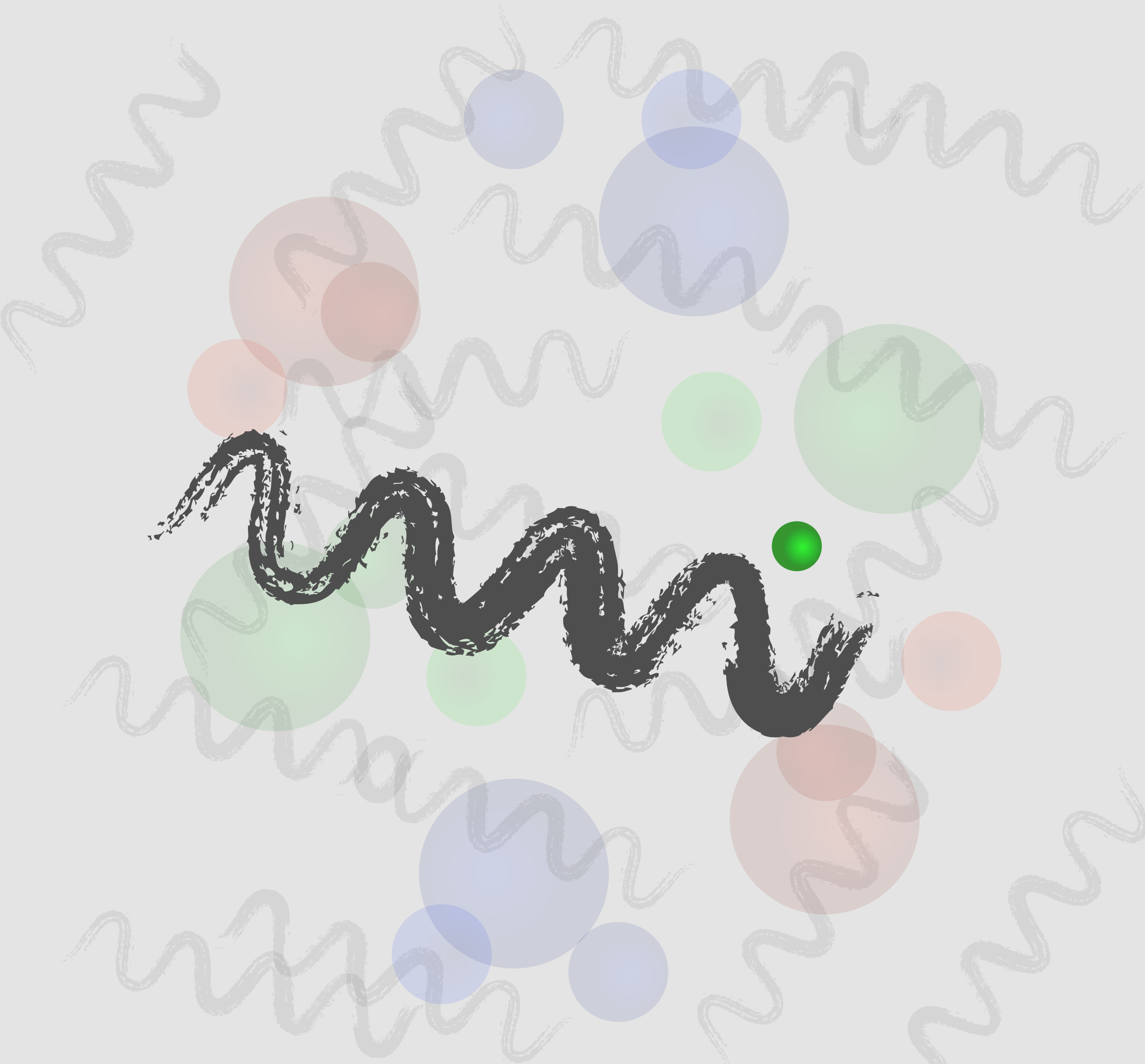
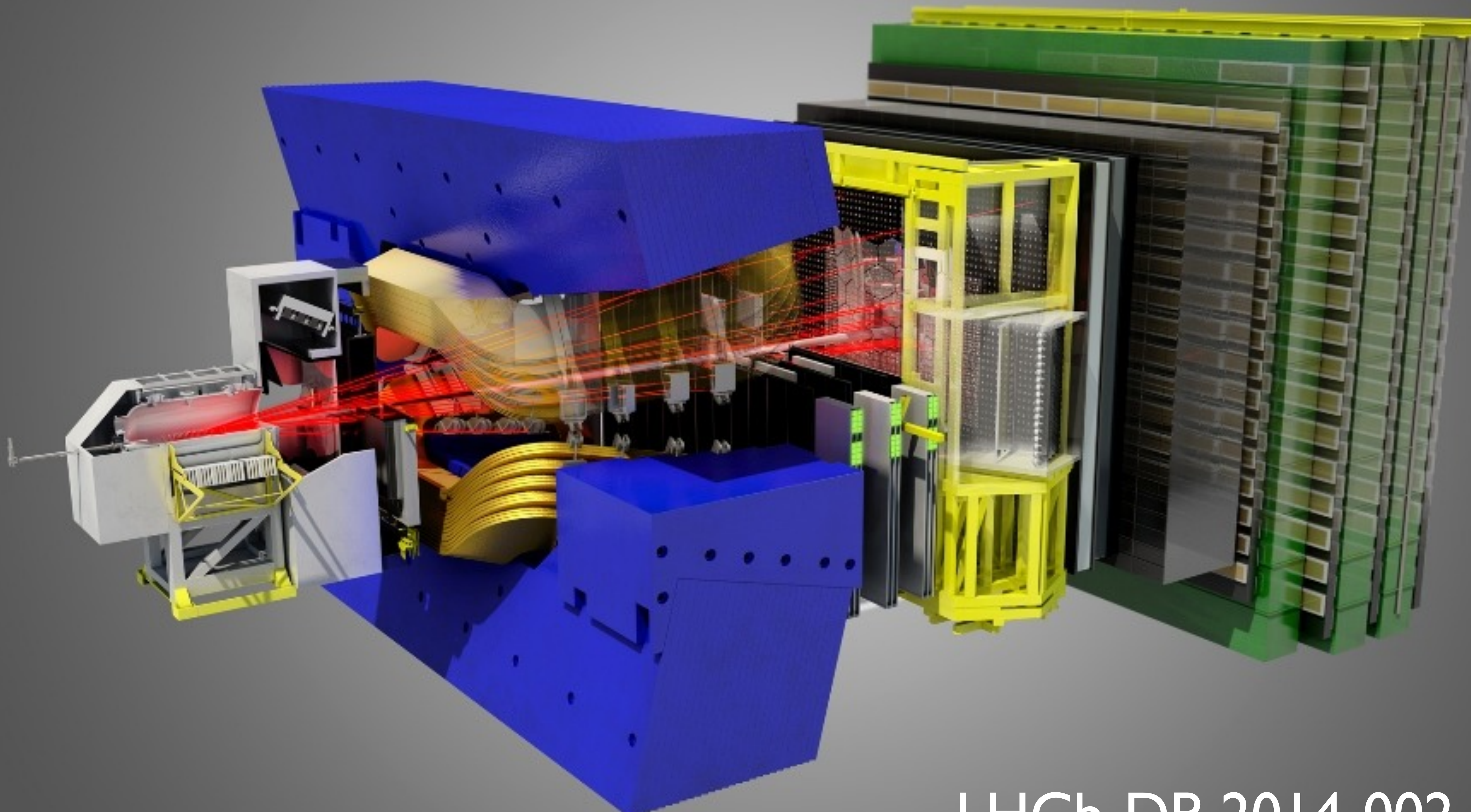
Matter dominance



- pp collisions
- Matter-antimatter asymmetric
- Causes production asymmetries
  - ➡ Not present at Tevatron or B-factories

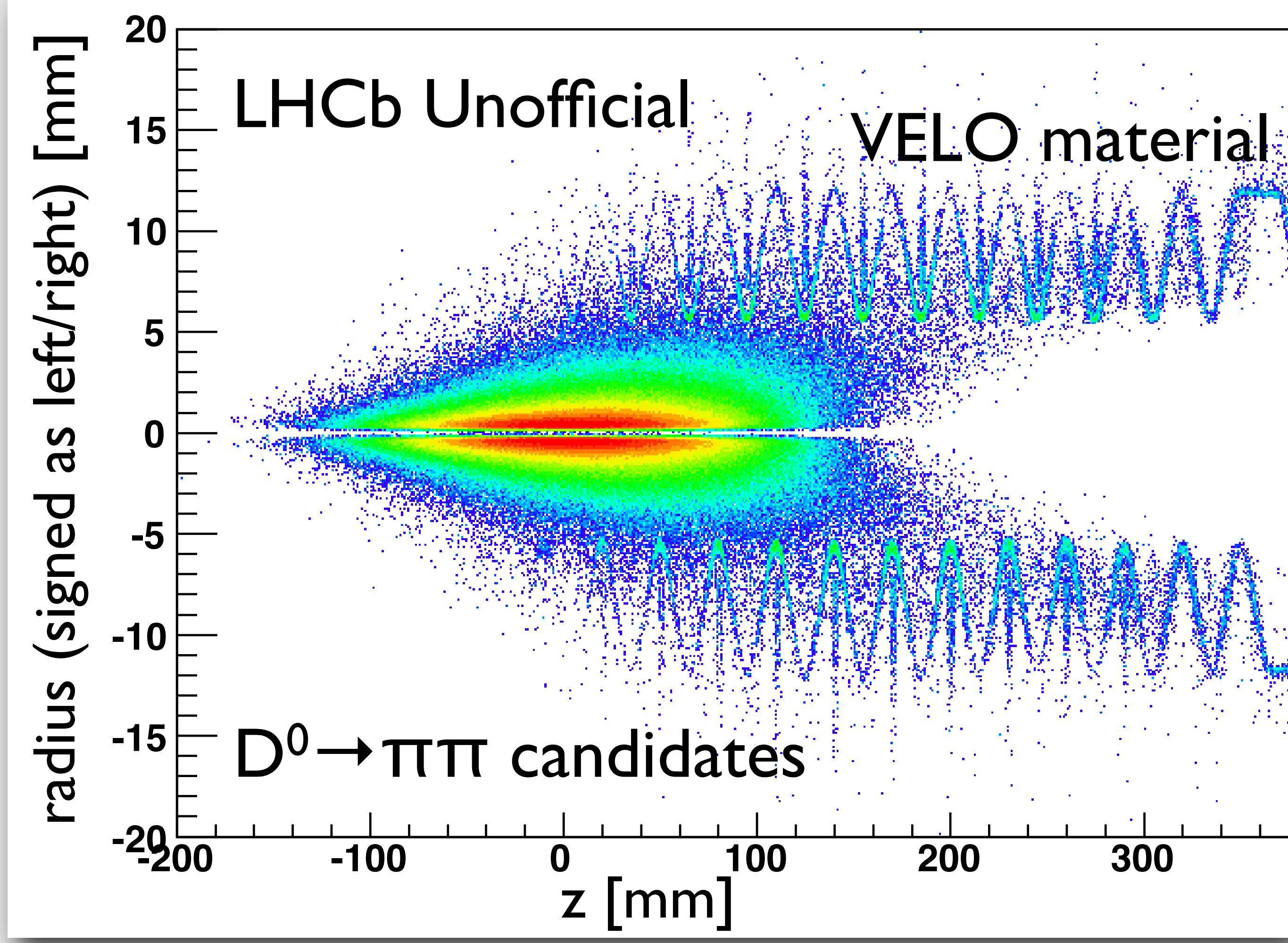
Enter LHCb



LHCb-DP-2014-002

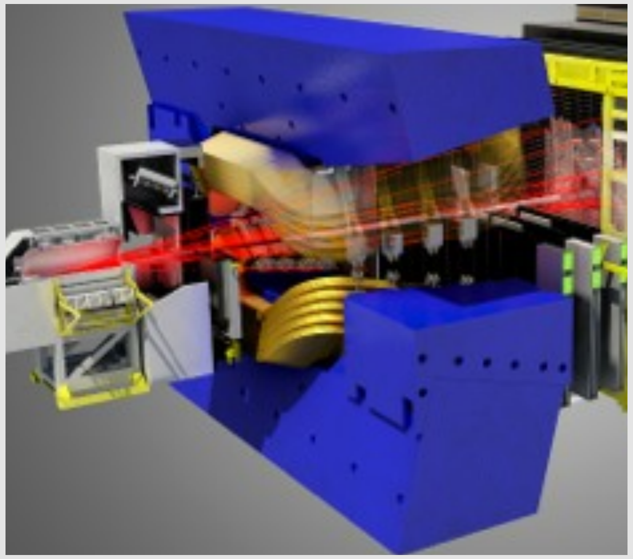
Boost

- Average $\beta\gamma$
  - ➡ LHCb: O(10)
  - ➡ BaBar/Belle: ~1
- Heavy flavour particles fly few mm

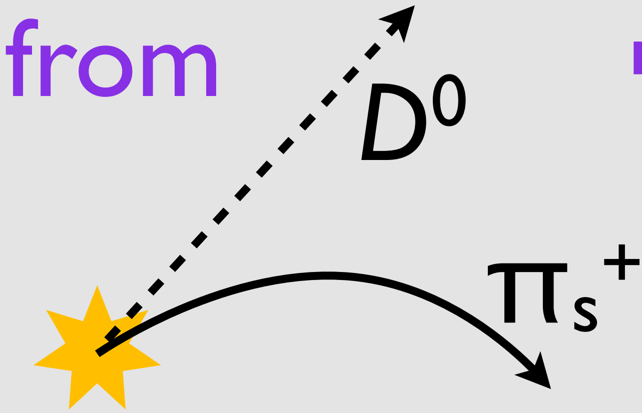


- First material at 5mm radius
- Decay time resolution ~0.1τ_D

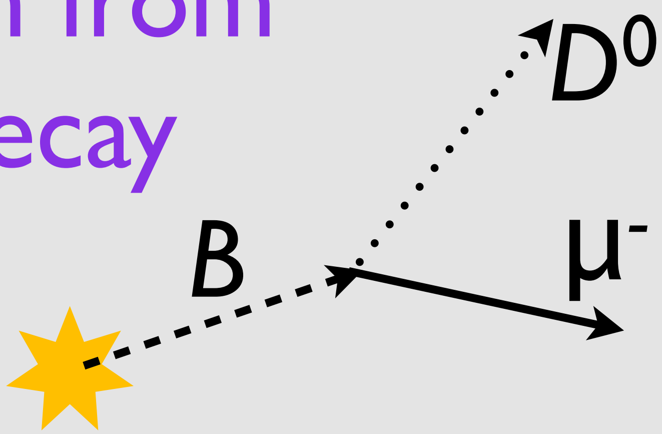
Flavour tagging



- Can distinguish D^0 from $\bar{D}^0$ in two ways
  - ➡ Charge of soft pion from strong decay $D^{*+} \to D^0 \pi_s^+$



  - ➡ Charge of muon from semi-leptonic decay $B \to D^0 \mu^- X$



- 4 Tm dipole magnet
  - ➡ Need ~2 GeV/c momentum
  - ➡ σ(p)/p 0.4% - 0.6% @5-100 GeV/c momentum

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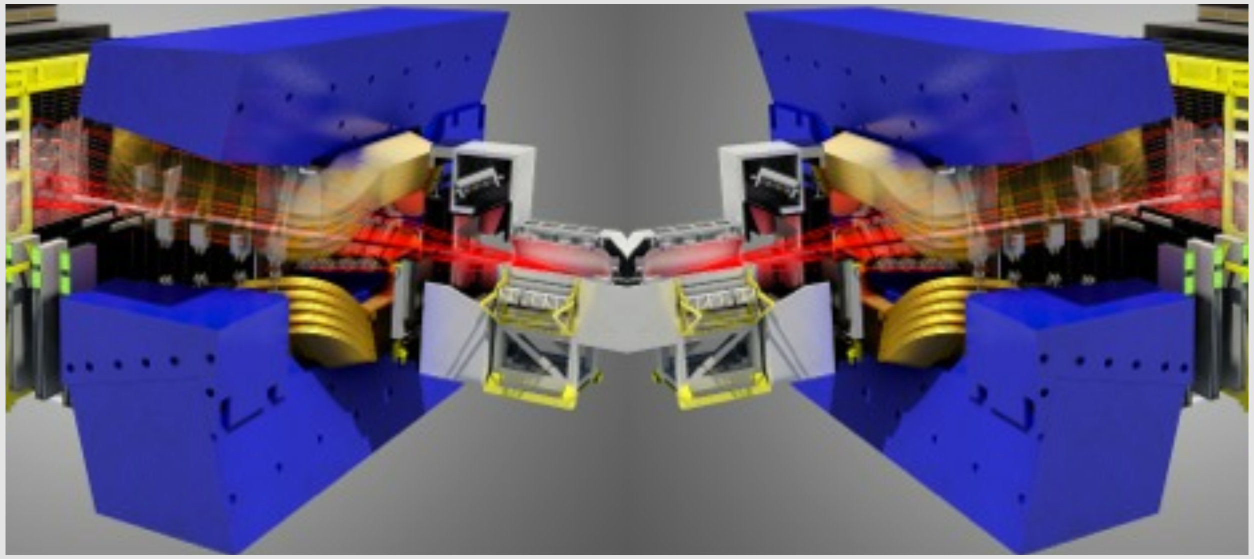
Particle detection



- Excellent charged particle ID
  - ➡ But you know that
- But even the best detector can challenge you
  - ➡ Detector asymmetries
    - Cancel left-right asymmetries by swapping dipole field
  - ➡ Interaction asymmetries
    - Measure through control modes

see Suzanne's talk after coffee

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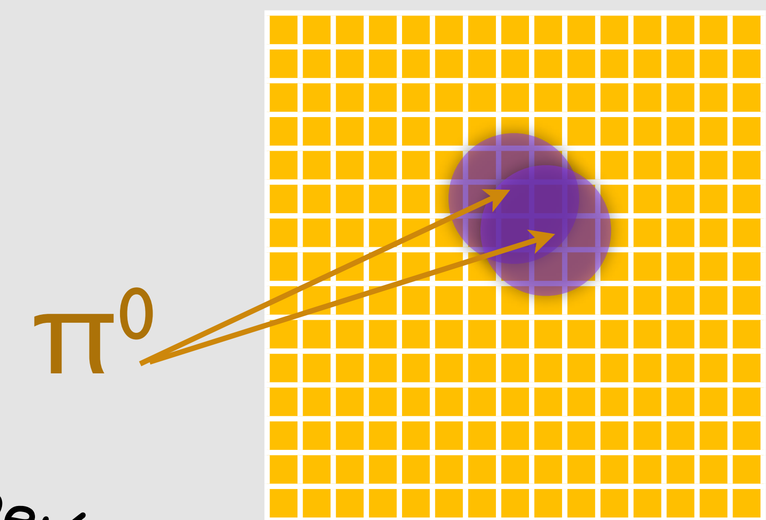
Neutral particles

Yes, we can!

- Need ⩾2 charged particles to define decay vertex
- Additional challenges from neutrals
- K_S and Λ
  - ➡ Long flight distance: Most escape VELO acceptance
- π^0
  - ➡ Coarse granularity: Calorimeter clusters not always separated
- γ
  - ➡ Busy calorimeter: Probability of confusion with electrons or π^0



see Shanzhen's talk on Thursday

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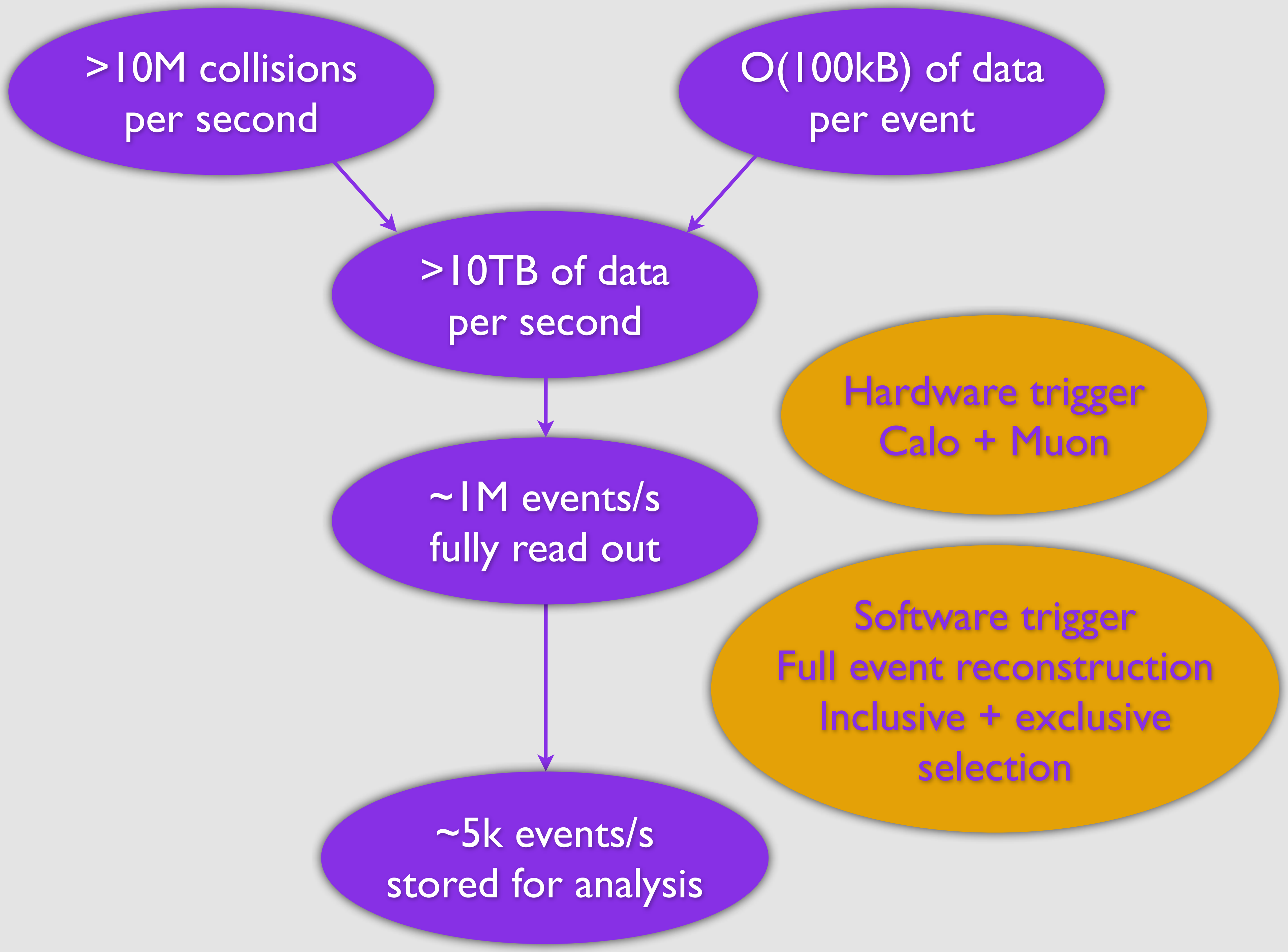
Trigger



Tough choices:
About 10% of all events before triggering contain charm particles

Seemingly plenty:
About 2kHz of charm events written out
→10^{10} per year

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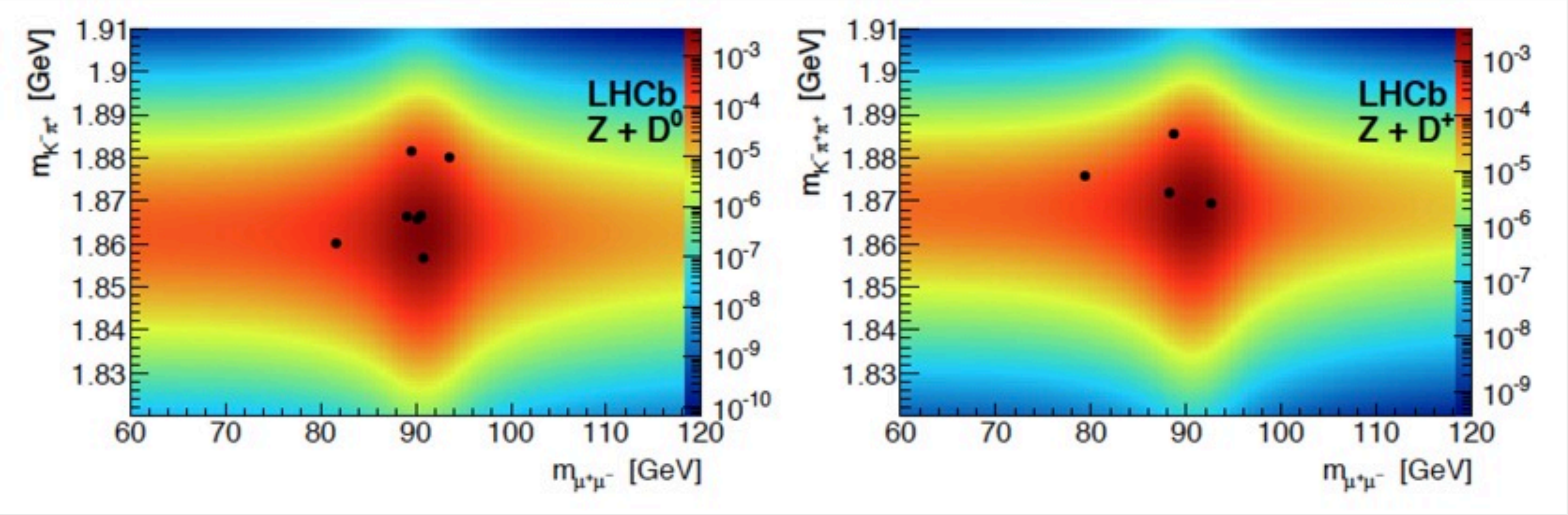
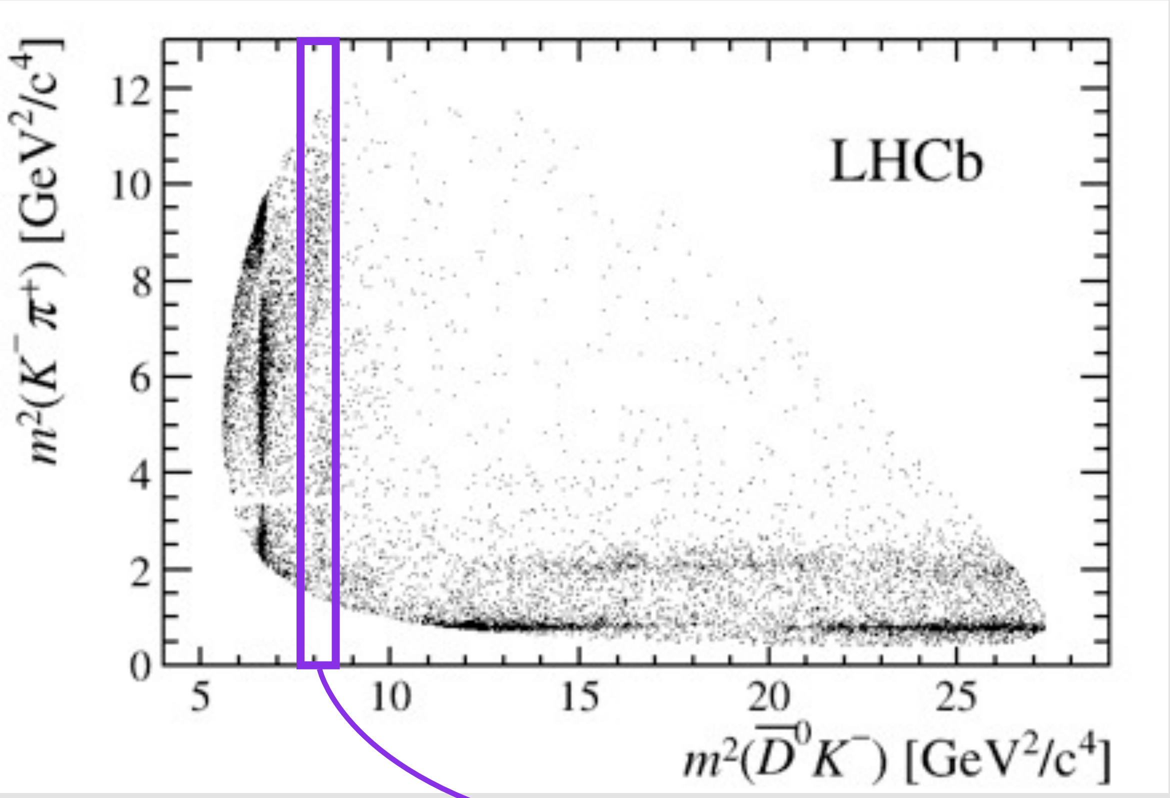
Exotic charm

or all the things the LHC can produce

JHEP 1404 (2014) 091

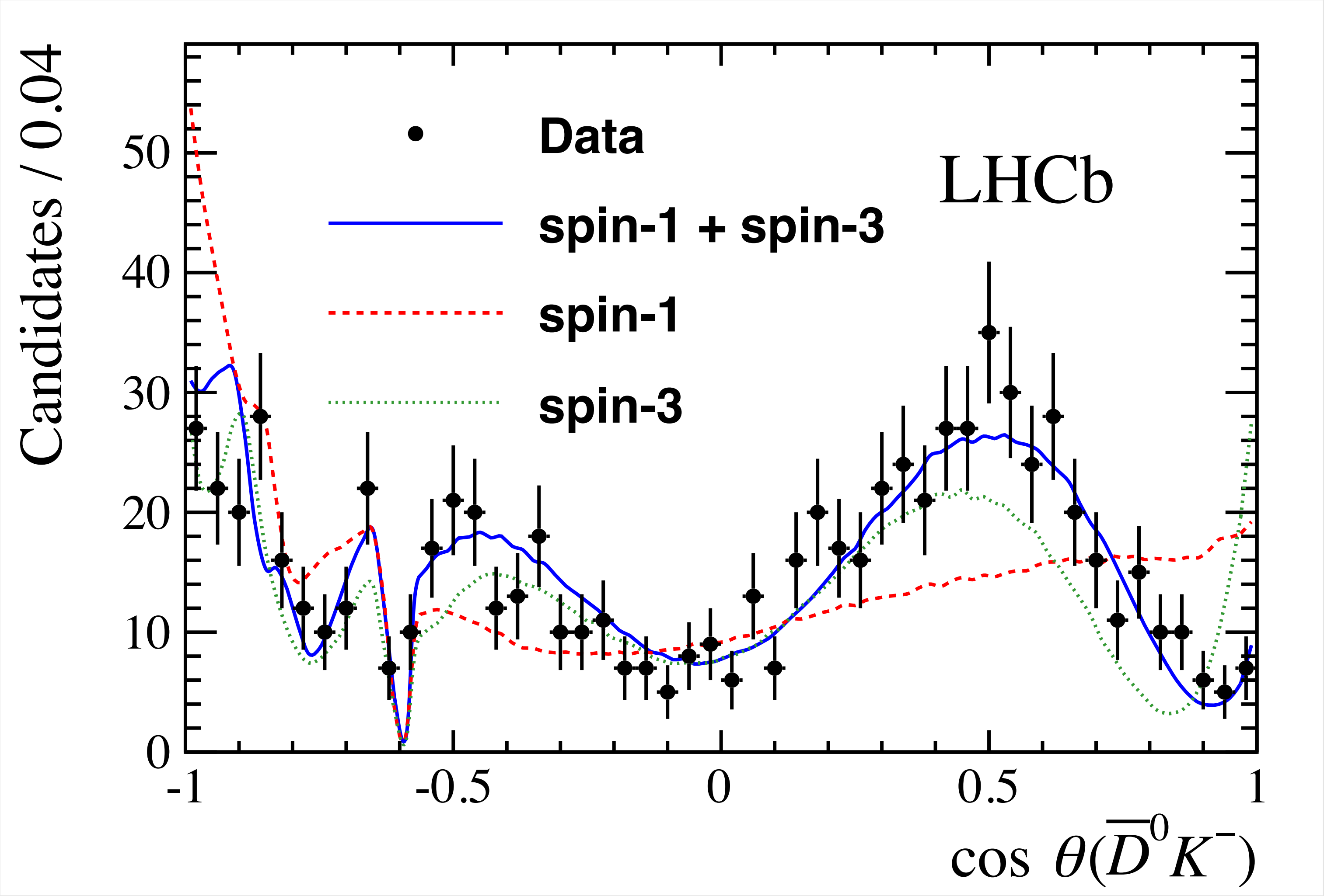


Buy 1 get 2



$D^*_{sJ}(2860)^+$ first seen in 2006 by BaBar and confirmed since by BaBar, Belle, and LHCb

PRL 97 (2006) 222001, PRL 100 (2008) 092001, PRD 80 (2009) 092003, JHEP 10 (2012) 151



Now confirmed by LHCb to be two states with spin-1 and spin-3

PRL 113 (2014) 162001

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CP violation in charm decays

≡ direct CP violation

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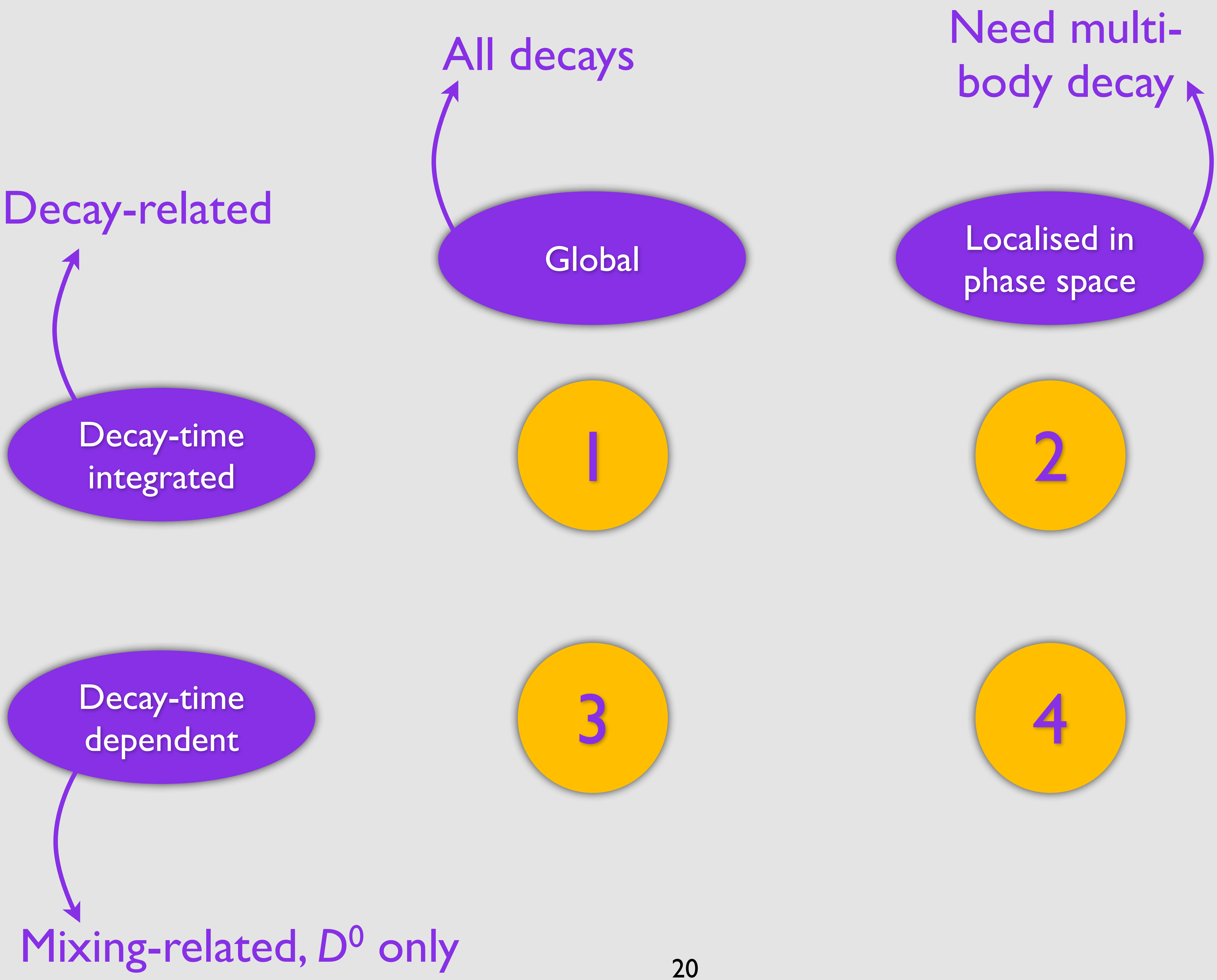
Asymmetries

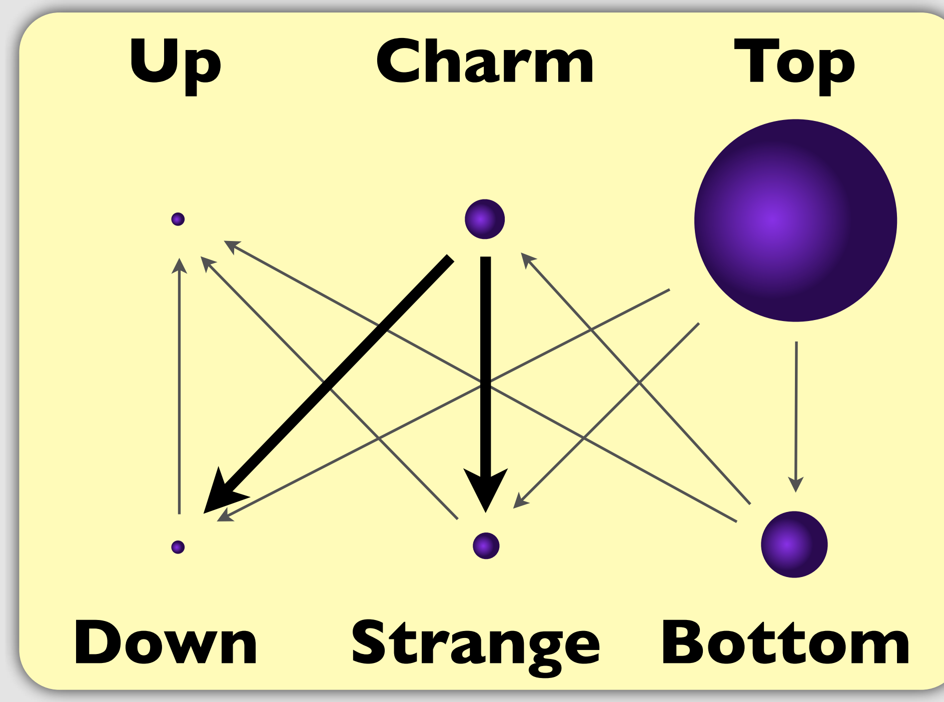


Asymmetries

	Global	Localised in phase space
Decay-time integrated	1	2
Decay-time dependent	3	4

Charm decays

- Only weak up-type quark decay from a bound system
- Quasi two-generation system
  - ➡ No CP violation in decay at first order
- Imaginary part of V_{cd} very small

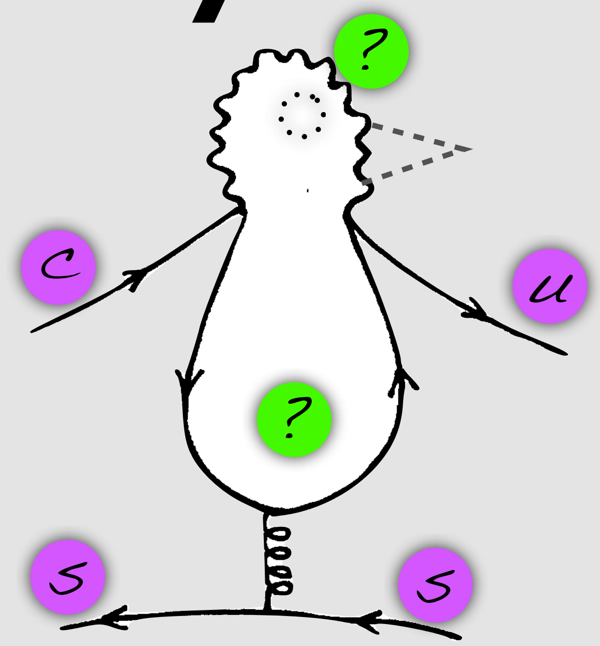


$$V_{CKM} \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda-iA^2\lambda^5\eta & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\hat{\rho}-i\hat{\eta}) & -A\lambda^2-iA\lambda^4\eta & 1 \end{pmatrix}$$

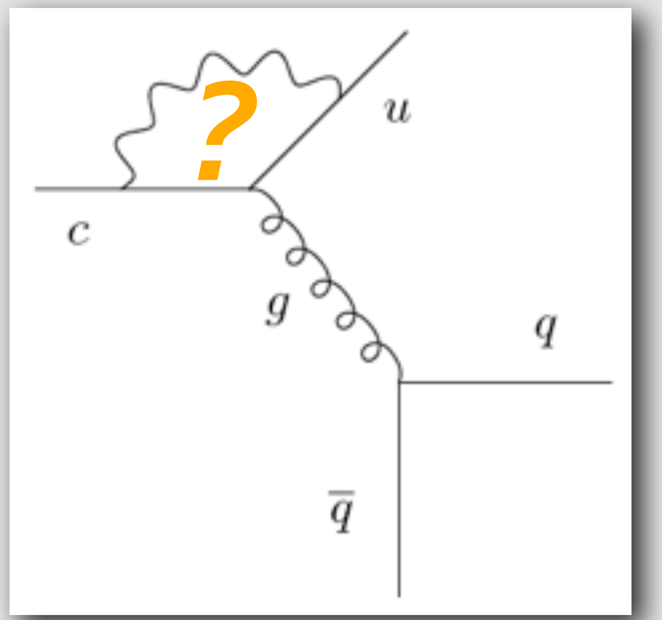
CP violation in decay

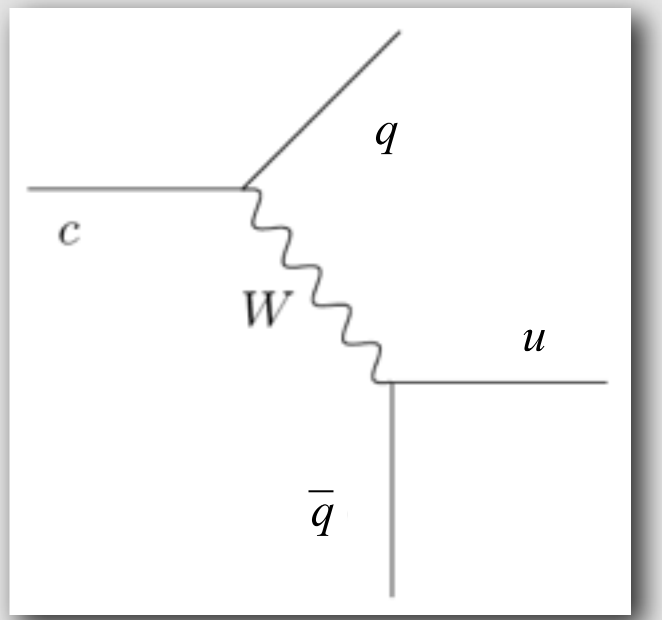
- Divide amplitudes into leading and sub-leading parts:
  $A(D \to f) = C(1+re^{i(\delta+\phi)})$
  $A(\bar{D} \to f) = C(1+re^{i(\delta-\phi)})$
- r is the ratio of sub-leading over leading amplitude
- CP violation requires difference in strong (δ) and weak phase (ϕ):
  $a_{CP} \equiv [\Gamma(D \to f)-\Gamma(\bar{D} \to f)] / [\Gamma(D \to f)+\Gamma(\bar{D} \to f)]$
  $= 2\, r \sin(\delta) \sin(\phi)$
  with $\Gamma(D \to f) = {}_0\int^\infty \Gamma(D(t) \to f)\, dt \propto |A|^2$

CP violation in decay



- CP violation in decays requires interference of several amplitudes
- Example:
  - ➡ singly Cabibbo-suppressed (SCS) decays
    $c \to d\bar{d}u$ ($D^0 \to \pi^-\pi^+$) or $c \to s\bar{s}u$ ($D^0 \to K^-K^+$)
- Only SCS decays have gluonic penguin contributions (need $q\bar{q}$)
- Penguins can carry strong and weak phase w.r.t. trees





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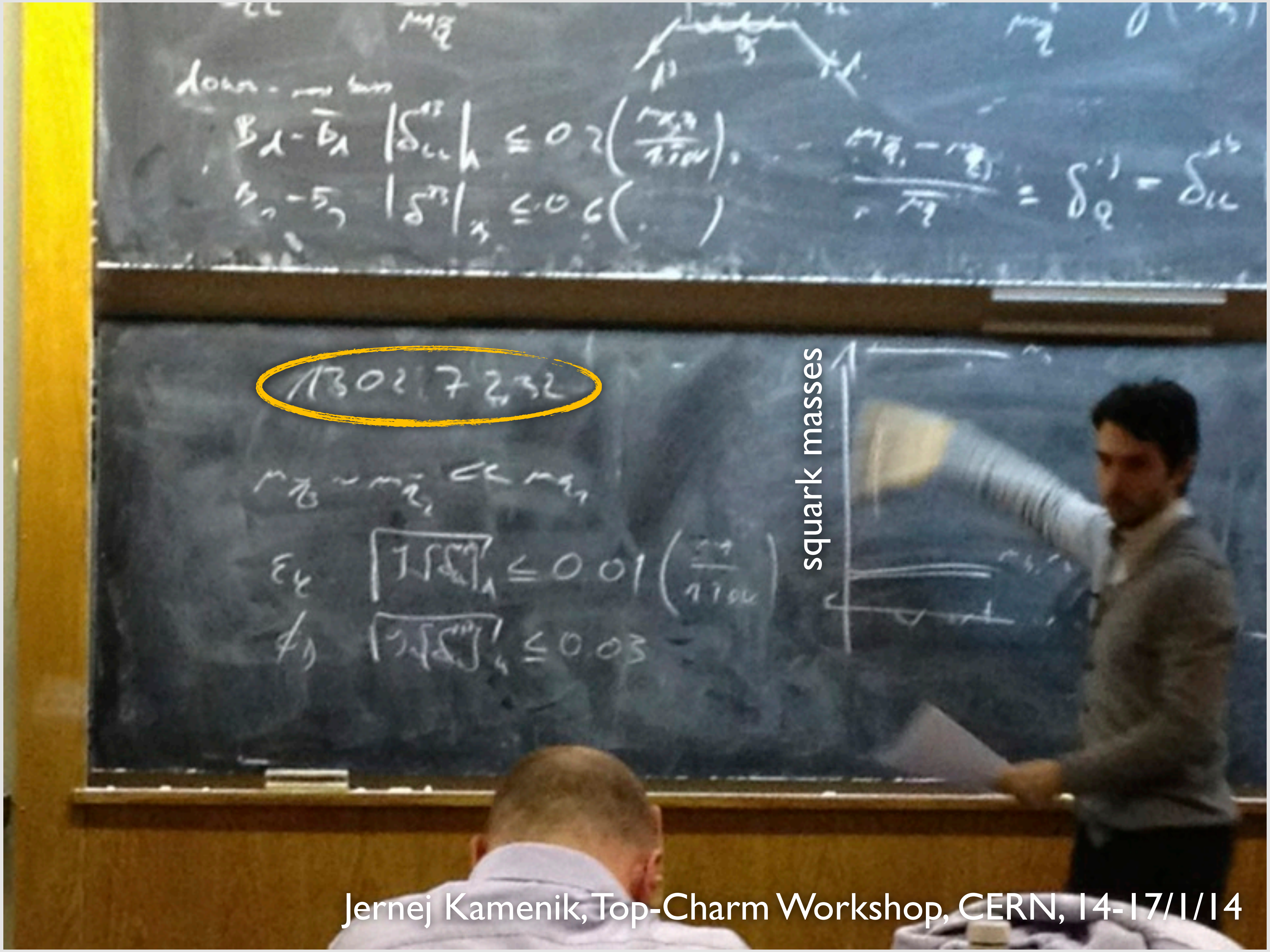
Is it new physics?



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CP violation in two-body charm decays

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Asymmetries

	Global	Localised in phase space
Decay-time integrated	1	2
Decay-time dependent	3	4

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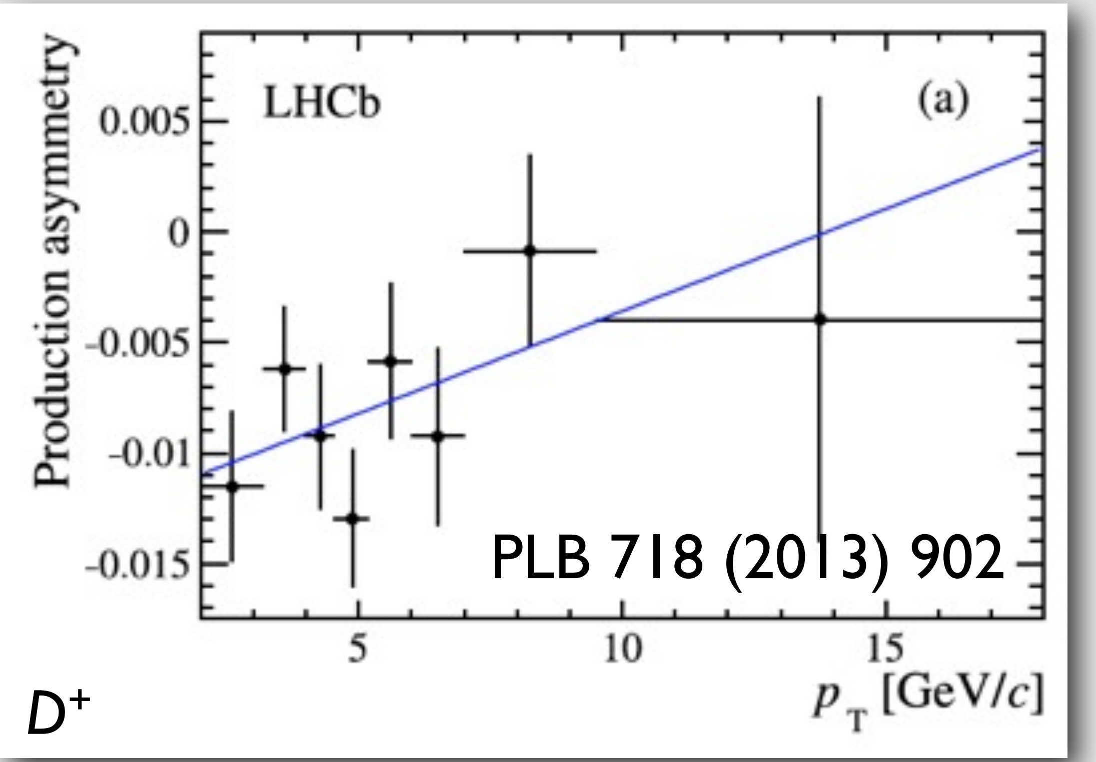
Measured asymmetries

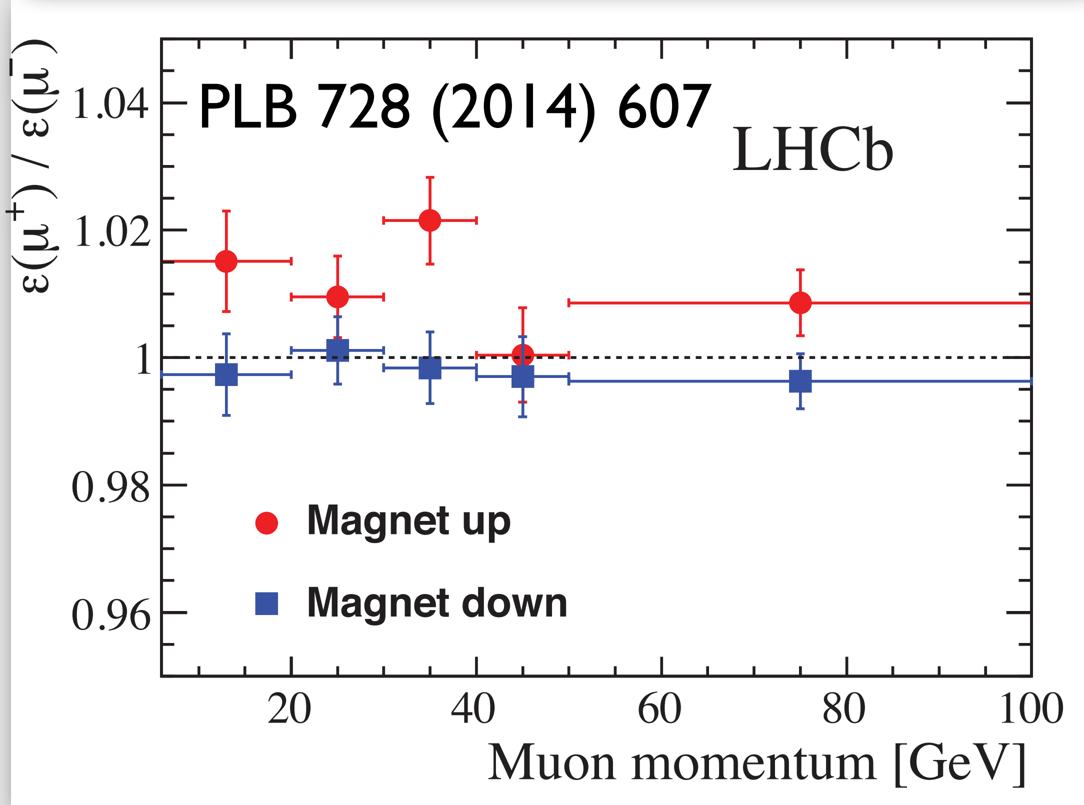
- Measure
  - ➡ $A_{raw}(D \to f) = [N(\bar{D} \to \bar{f}) - N(D \to f)]/[N(\bar{D} \to \bar{f}) + N(D \to f)]$
- Get to first order
  - ➡ $A_{raw}(D \to f) = A_{CP}(D \to f) + A_{prod}(D) + A_{det}(tag) + A_{det}(f)$
- Need to constrain
  - ➡ Production asymmetry
  - ➡ Detection asymmetry
- General idea
  - ➡ Use similar Cabibbo-allowed processes and assume $A_{CP}(D \to f) = 0$

In more detail

see Suzanne's talk after coffee

- Production and detection asymmetries can be momentum dependent
- Need to ensure kinematic overlap to guarantee cancellation from control mode
  - ➡ Split measurement in sufficiently small kinematic bins
  - ➡ Use re-weighting techniques to equalise distributions
  - ➡ All methods have some cost in statistical precision





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First example

- Measurement

$$\mathcal{A}_{\rm meas}^{D^\pm_{(s)}\to K^0_{\rm S}h^\pm} = \frac{N_{\rm sig}^{D^+_{(s)}\to K^0_{\rm S}h^+} - N_{\rm sig}^{D^-_{(s)}\to K^0_{\rm S}h^-}}{N_{\rm sig}^{D^+_{(s)}\to K^0_{\rm S}h^+} + N_{\rm sig}^{D^-_{(s)}\to K^0_{\rm S}h^-}},$$

$$\mathcal{A}_{\rm meas}^{D^\pm_{(s)}\to K^0_{\rm S}h^\pm} \approx \mathcal{A}_{CP}^{D^\pm_{(s)}\to K^0_{\rm S}h^\pm} + \mathcal{A}_{\rm prod}^{D^\pm_{(s)}} + \mathcal{A}_{\rm det}^{h^\pm} + \mathcal{A}_{K^0/\overline{K}^0},$$

- Extract CP asymmetries using control modes

$$\mathcal{A}_{CP}^{D^\pm_s\to K^0_{\rm S}\pi^\pm} = \mathcal{A}_{\rm meas}^{D^\pm_s\to K^0_{\rm S}\pi^\pm} - \mathcal{A}_{\rm meas}^{D^\pm_s\to \phi\pi^\pm} - \mathcal{A}_{K^0}.$$

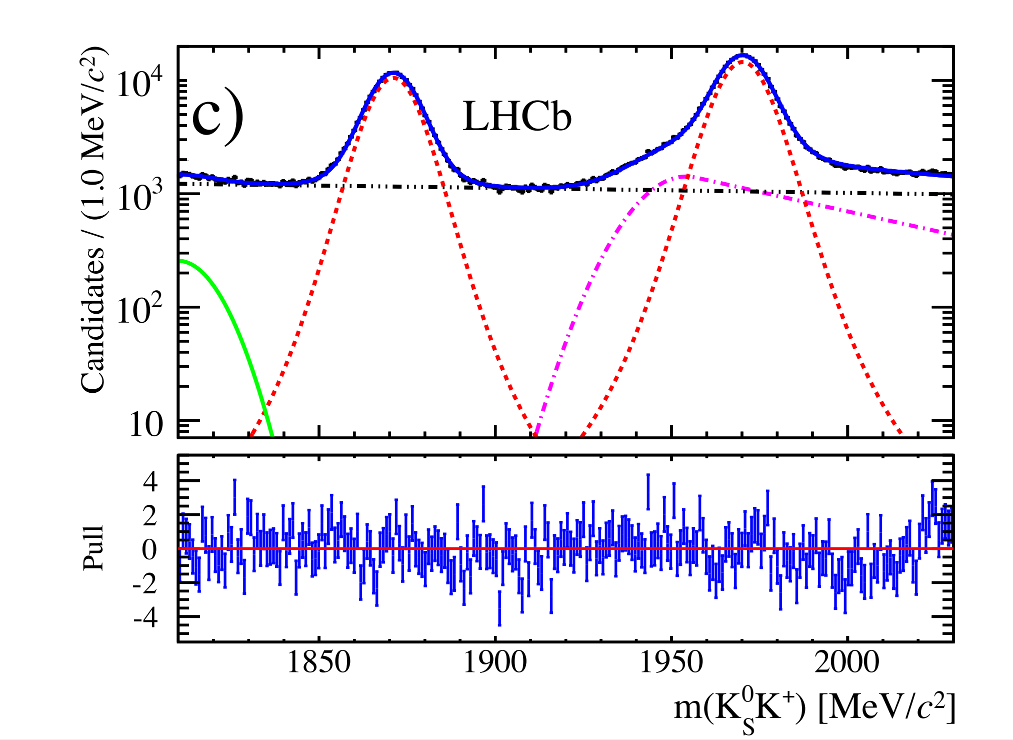
$$\mathcal{A}_{CP}^{D^\pm\to K^0_{\rm S}K^\pm} = \left[\mathcal{A}_{\rm meas}^{D^\pm\to K^0_{\rm S}K^\pm} - \mathcal{A}_{\rm meas}^{D^\pm_s\to K^0_{\rm S}K^\pm}\right] - \left[\mathcal{A}_{\rm meas}^{D^\pm\to K^0_{\rm S}\pi^\pm} - \mathcal{A}_{\rm meas}^{D^\pm_s\to \phi\pi^\pm}\right] - \mathcal{A}_{K^0}$$

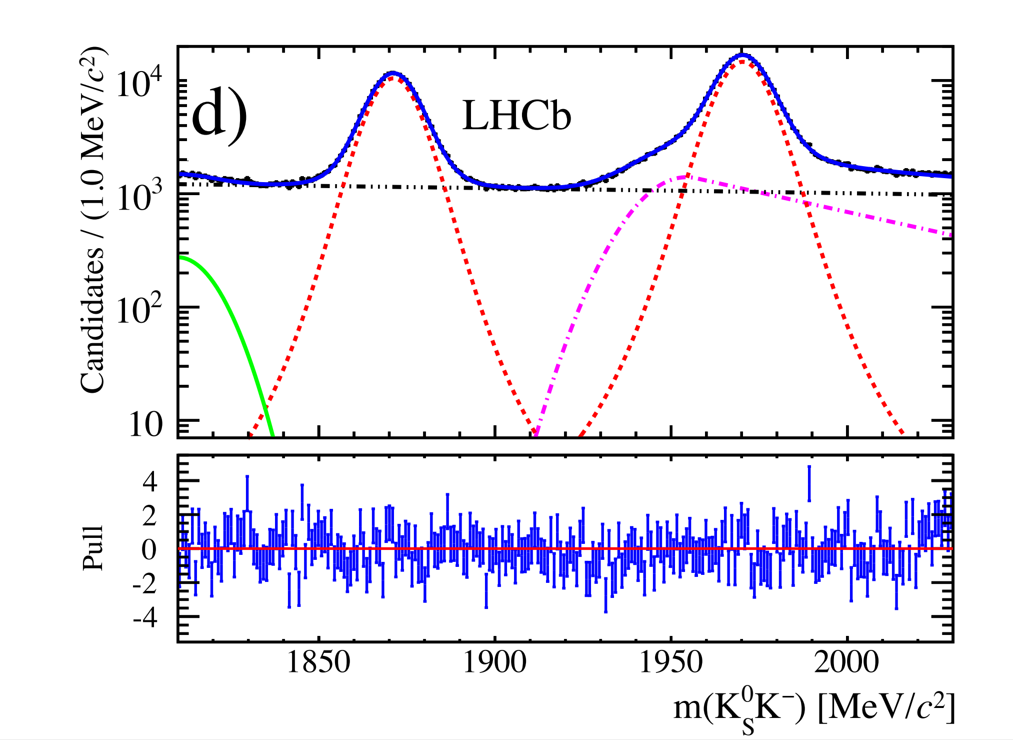
JHEP 10 (2014) 025

Results for $K_S h$

- Charged D two-body modes are challenging due to neutral particles involved
- Measurement based on 3 fb^{-1}
- Uses weighted control mode kinematics and average of dipole magnet polarities
- All approximately zero

$$\mathcal{A}_{CP}^{D^\pm \to K_S^0 K^\pm} = (+0.03 \pm 0.17 \pm 0.14)\%$$
$$\mathcal{A}_{CP}^{D_s^\pm \to K_S^0 \pi^\pm} = (+0.38 \pm 0.46 \pm 0.17)\%,$$





JHEP 10 (2014) 025

The ΔA_{CP} saga*

- Measure time-integrated CP asymmetries in $D \rightarrow hh'$ decays

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

- Decays to CP eigenstates: $f = K^-K^+, \pi^-\pi^+$
- A_{CP} is a sum of direct and indirect CP violation, leading to

$$\begin{aligned} \Delta A_{CP} &\equiv A_{CP}(KK) - A_{CP}(\pi\pi) \\ &\approx \Delta a_{CP}^{dir} (1 + y_{CP} \overline{\langle t \rangle} / \tau) + a_{CP}^{ind} \Delta \langle t \rangle / \tau \end{aligned}$$ §

- Need to measure asymmetries and time distributions
- Expected $a_{CP}^{dir} < 10^{-3}$ in SM and $a_{CP}^{dir} < 10^{-2}$ with NP**

*after A. Lenz @ CHARM 2013, arXiv:1311.6447

**uncontroversial statement made at Beauty in April

§MG et al., JPhysG 39 (2012) 045005

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Observables

$$A_{CP}^{RAW}(KK)^* = A_{CP}(KK) + A_D(\pi_s) + A_P(D^*)$$

$$A_{CP}^{RAW}(\pi\pi)^* = A_{CP}(\pi\pi) + A_D(\pi_s) + A_P(D^*)$$

2 observables | 2 CP asymmetries | 1 detection asymmetry | 1 production asymmetry

Construct observable without external input:

$$A_{CP}(KK) - A_{CP}(\pi\pi) = A_{CP}^{RAW}(KK)^* - A_{CP}^{RAW}(\pi\pi)^*$$

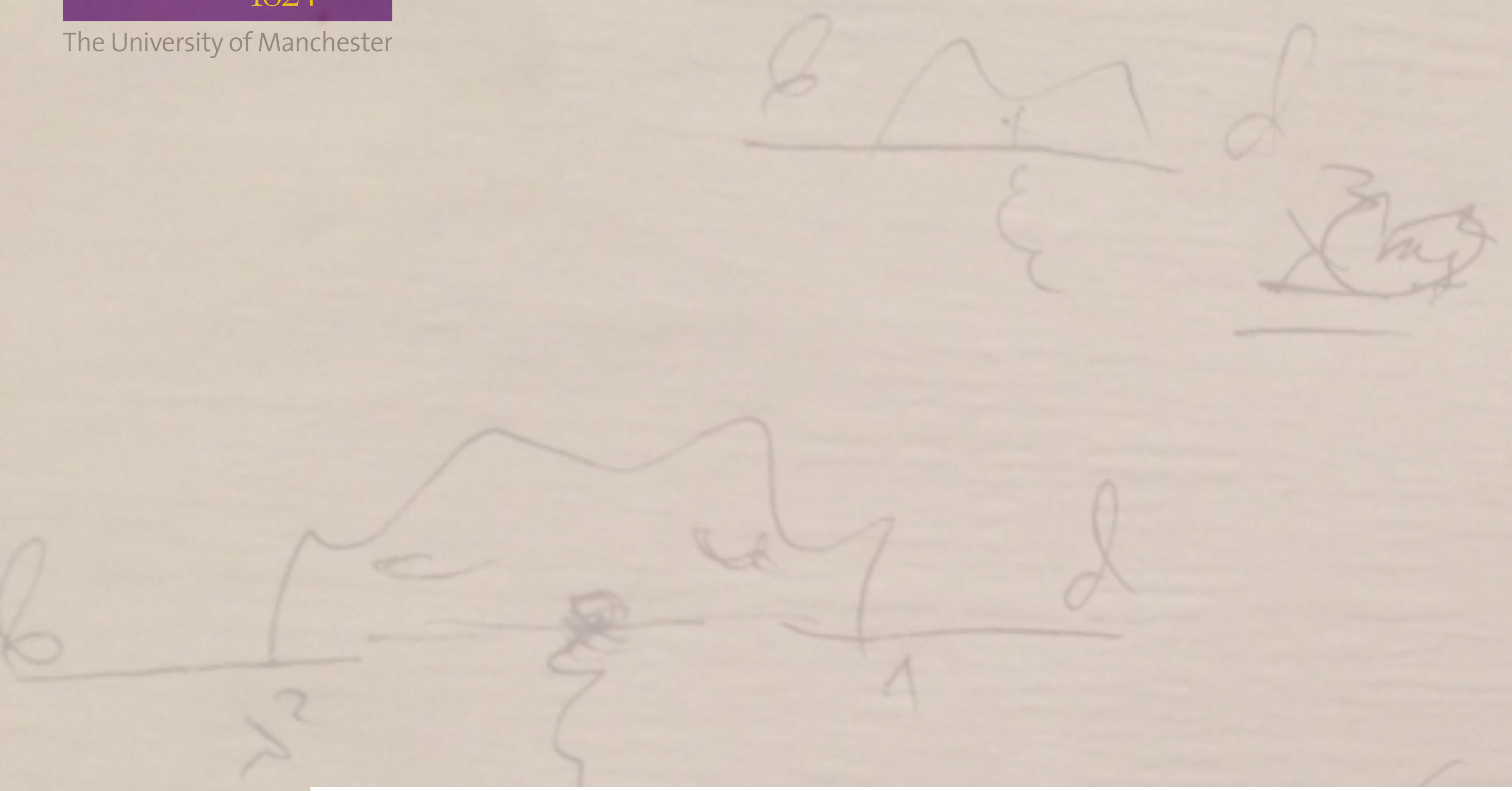
Expect indirect CP violation to cancel in difference as caused by common mixing process

Direct CP violation expected to differ for different final states

Expect non-zero result in presence of direct CP violation

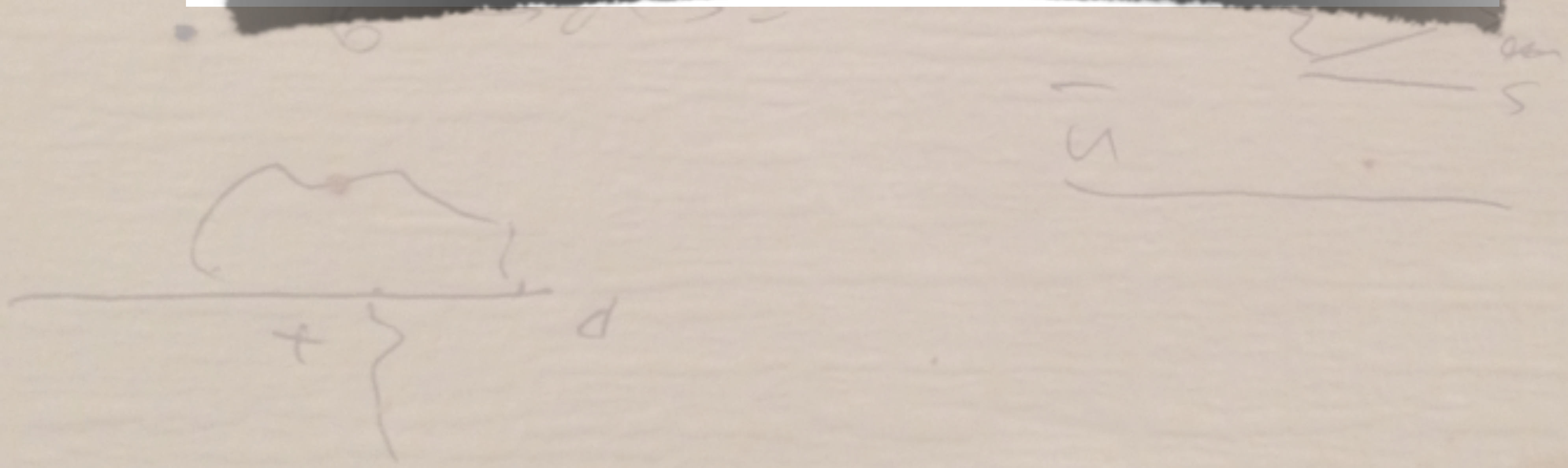
Complementary New Physics search to A_Γ measurement

→later



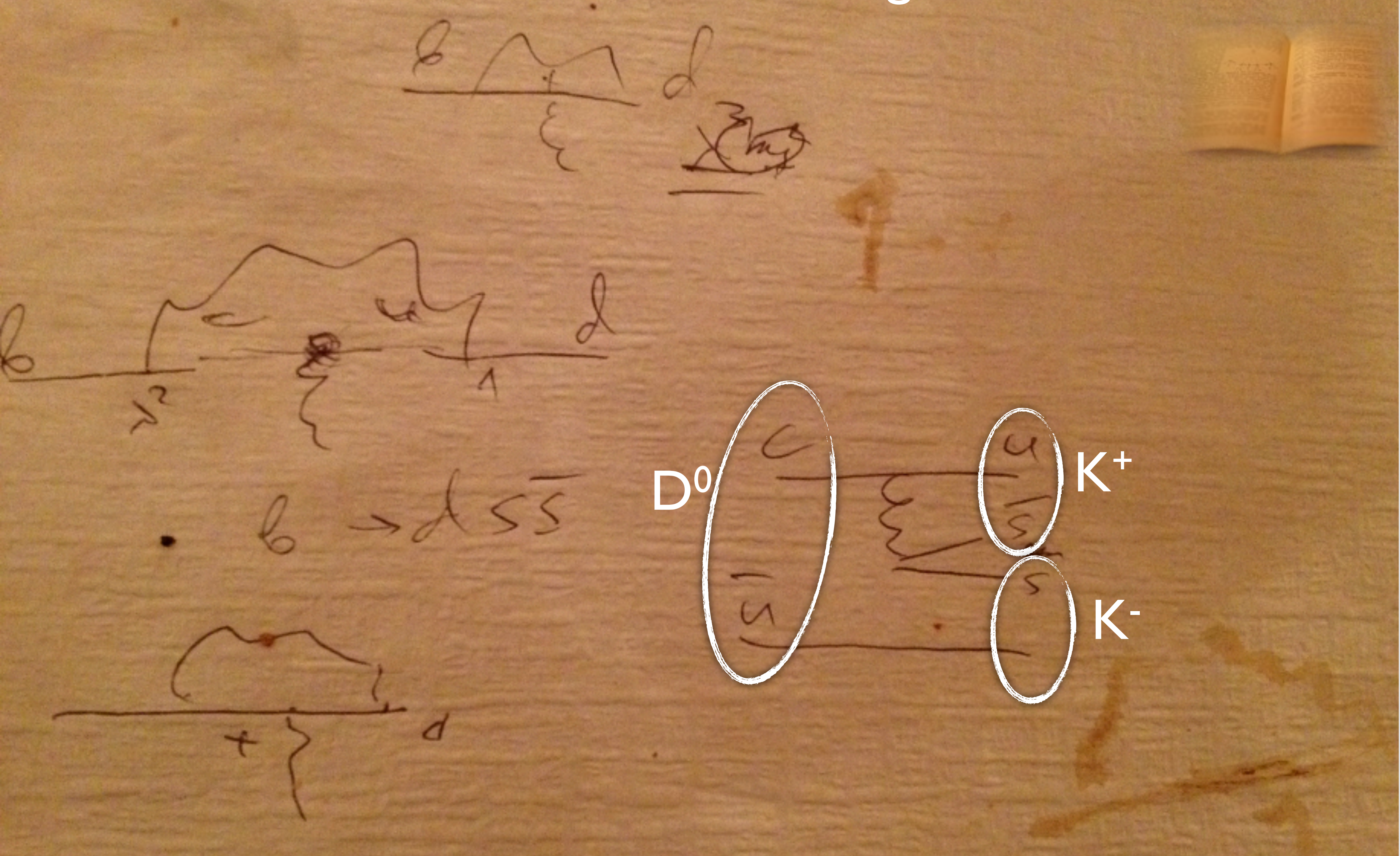
$$\Delta A_{CP} = [-0.82 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})]\,\%$$

PRL 108 (2012) 111602



(November 9, 2011, Pizzeria de la Place, Meyrin)

November Revolutions, Zoltan Ligeti, Charm 2012



(November 9, 2011, Pizzeria de la Place, Meyrin)

CHARM 2012: the summary

- Zoltan: "While the central value of Δa_{CP} is much larger than what was expected in the SM, we cannot yet exclude that it may be due to a huge hadronic enhancement in the SM"
- Yuval: "While the central value of Δa_{CP} fits nicely in the SM, we cannot yet exclude that it may be due to NP"

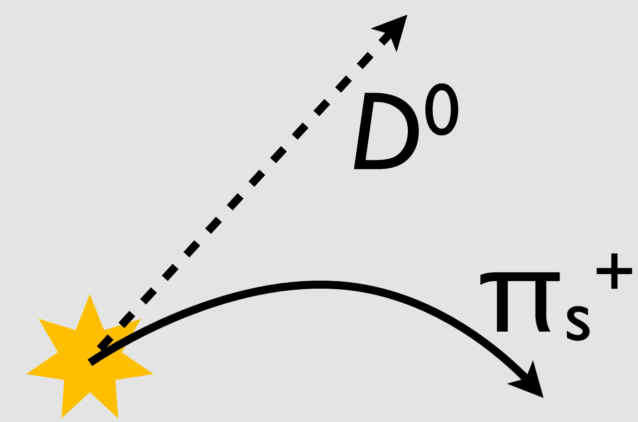
- Topologically the above two statements are equivalent
- Just like a bagel and a mug are
- Yet, to emphasize, whether Zoltan, me, or anyone else is the bagel is not the issue
- The issue is how can we keep on checking

Latest results

- D*-tagged (2011 data)

$$\Delta A_{CP} = (-0.34 \pm 0.15\,(\text{stat.}) \pm 0.10\,(\text{syst.}))\%\,.$$

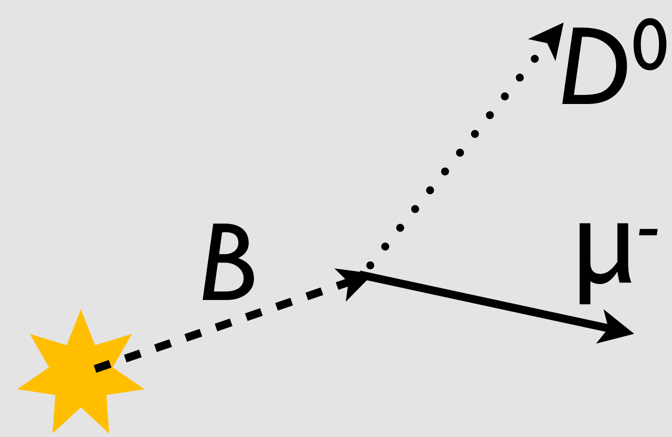
LHCb-CONF-2013-003



- muon-tagged (2011+12 data)

$$\Delta A_{CP} = (+0.14 \pm 0.16\,(\text{stat}) \pm 0.08\,(\text{syst}))\%\,,$$

JHEP 07 (2014) 014



Individual asymmetries

- What makes ΔA_{CP} non-zero?

$$\Delta \mathcal{A}_{CP} \equiv \mathcal{A}_{CP}(D^0 \to K^- K^+) - \mathcal{A}_{CP}(D^0 \to \pi^- \pi^+)$$

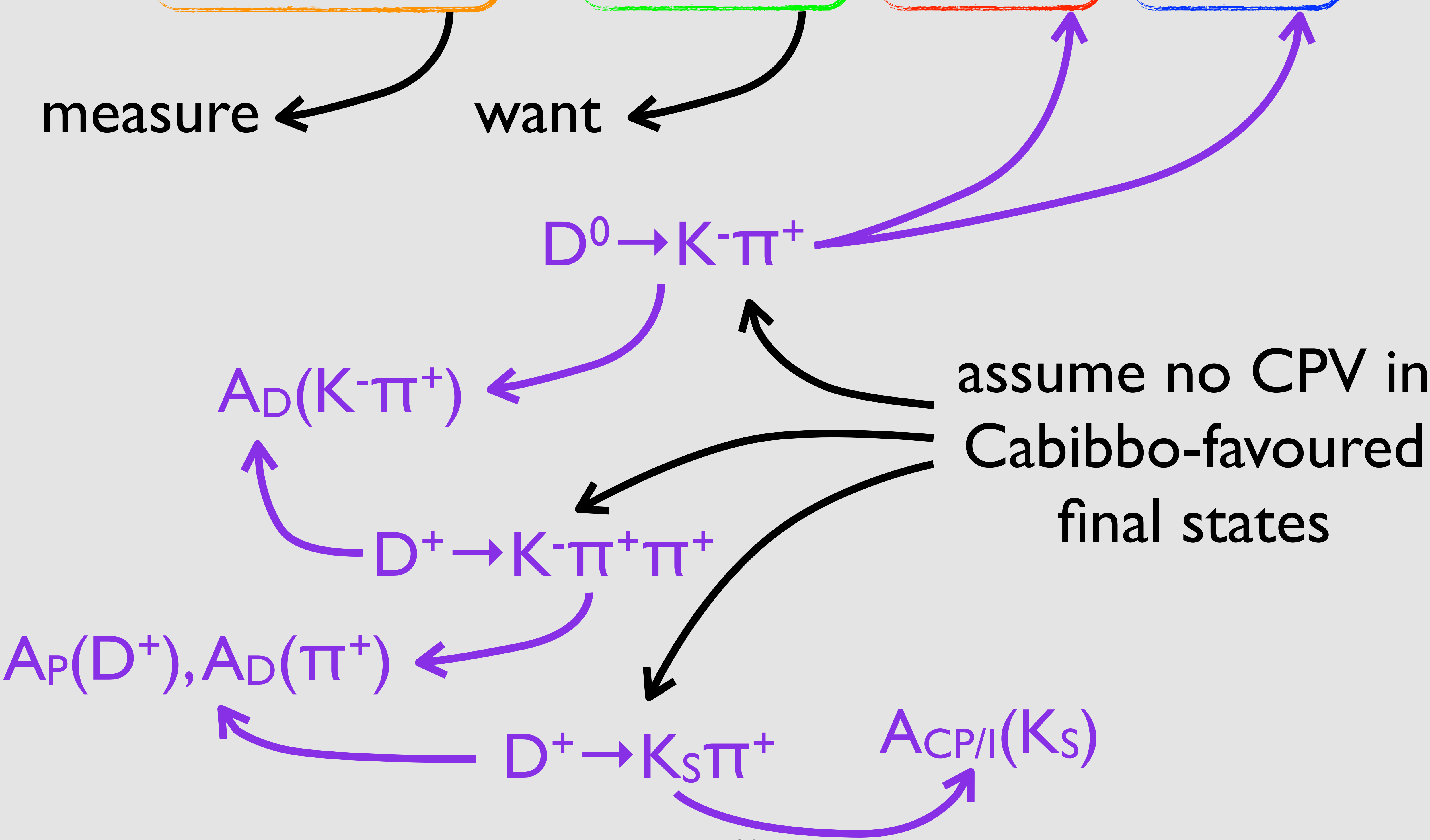
- Individual asymmetries are expected to have opposite sign due to CKM structure

$$A(\overline{D}^0 \to \pi^+\pi^-, K^+K^-) = \mp\tfrac{1}{2}\left(V_{cs}V_{us}^* - V_{cd}V_{ud}^*\right)(T \pm \delta S) - V_{cb}V_{ub}^*\left(P \mp \tfrac{1}{2}\delta P\right),$$

EPJC 73 (2013) 2373

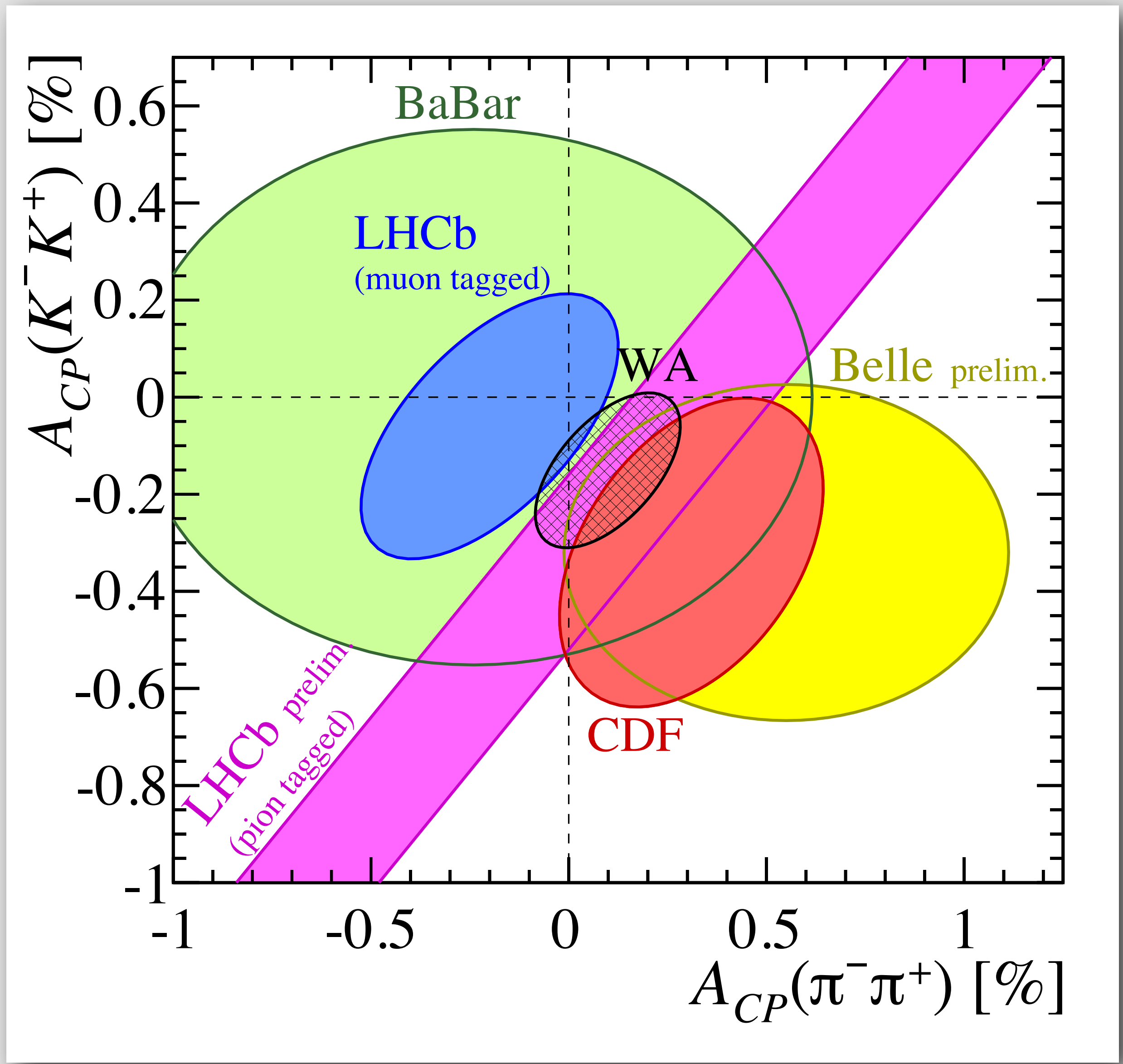
Individual asymmetries

$$A_{CP}^{RAW}(KK)^* = A_{CP}(KK) + A_D(\pi_s) + A_P(D^*)$$



(Δ)ACP results

- Ignoring contribution from indirect CPV*



$$A_{CP}(K^-K^+) = (-0.06 \pm 0.15\,(\text{stat}) \pm 0.10\,(\text{syst}))\%\,,$$

JHEP 07 (2014) 014

*more on this later

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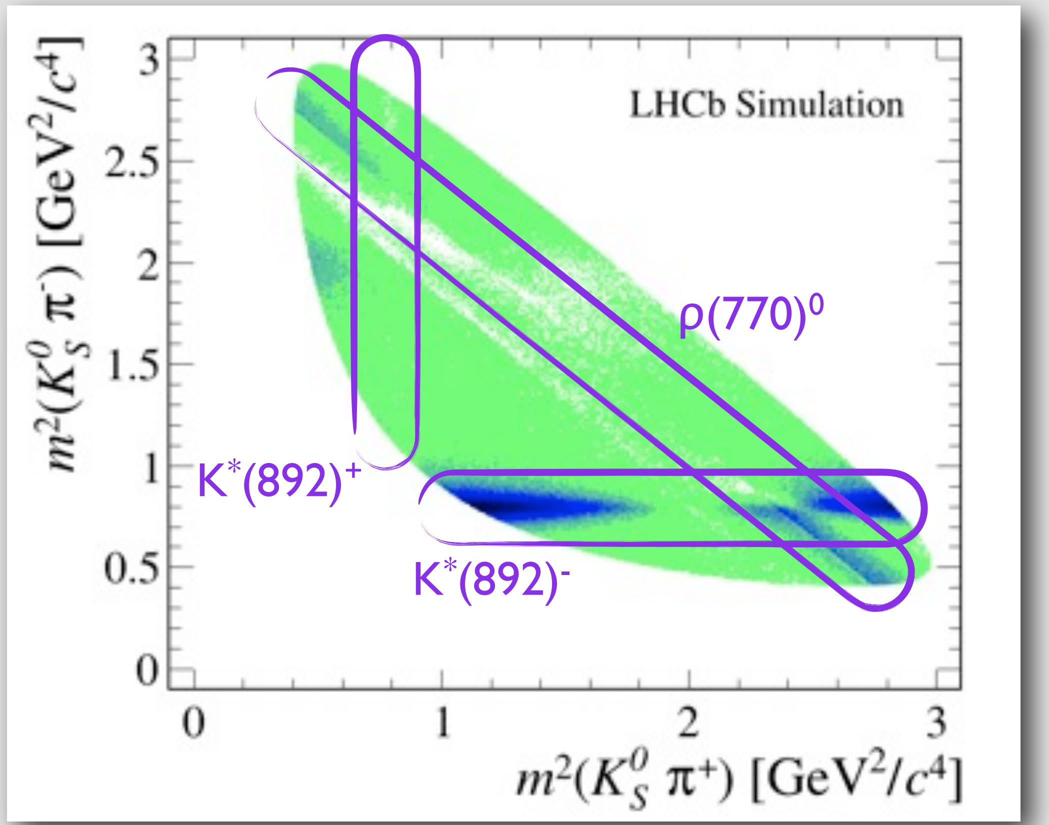
CP violation in multi-body charm decays

Asymmetries

	Global	Localised in phase space
Decay-time integrated	1	2
Decay-time dependent	3	4

On Dalitz plots

- Many ways to reach multi-body final states through intermediate resonances
- Resonances interfere and can carry different strong phases
  - ➡ Superb playground for CP violation
- Look for local asymmetries
  - ➡ Model-dependent:
    Fit all contributions to phase-space and look for differences in fit parameters
  - ➡ Model-independent:
    Look for asymmetries in regions of phase space by "counting"



Courtesy of S. Reichert

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On Dalitz plots

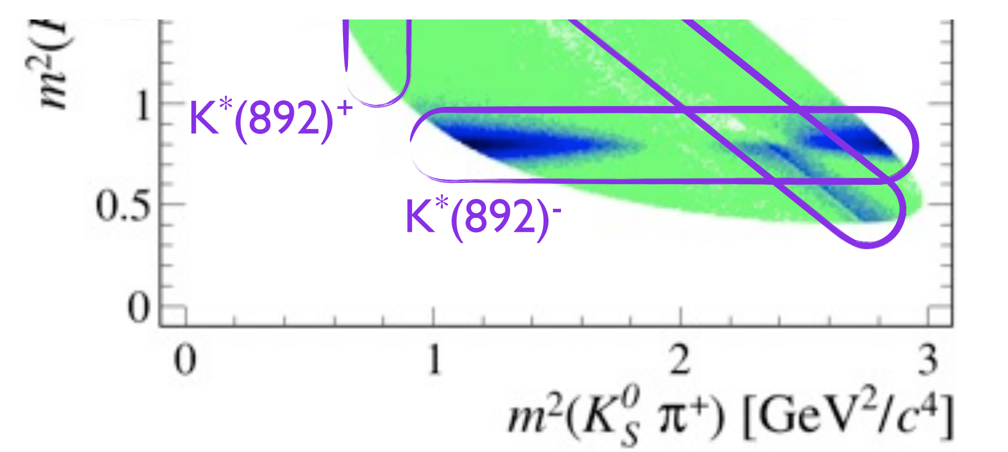
I.I. Bigi, *Could Charm's "Third Time" Be the Real Charm? – A Manifesto*, arXiv:0902.3048

2.3.2 Dalitz Plot Studies

Final states with three pseudoscalar mesons can be treated in a 'Catholic' style: there is a single path to 'heaven' provided by the Dalitz plot. The challenge we face here can be summarized as follows: we look for probably smallish asymmetries in subdomains of the Dalitz plot, which is shaped by nonperturbative dynamics. Large statistics are necessary, yet not sufficient. As far as pattern recognition is concerned, we can learn a lot from astronomers. They regularly face the problem of searching for something they do not quite know what it is at a priori unknown locations and having to deal with background sources that are all too often not really understood.

look for differences in fit parameters

➡ Model-independent:
Look for asymmetries in regions of phase space by "counting"



Courtesy of S. Reichert

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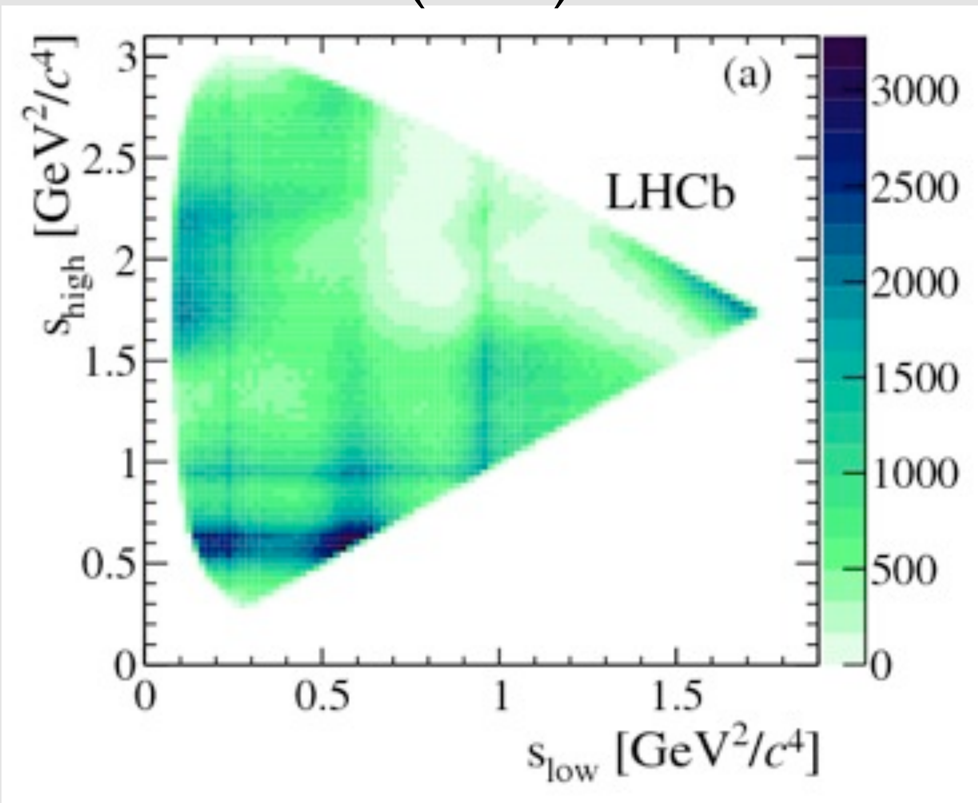
PLB 728 (2014) 585-595

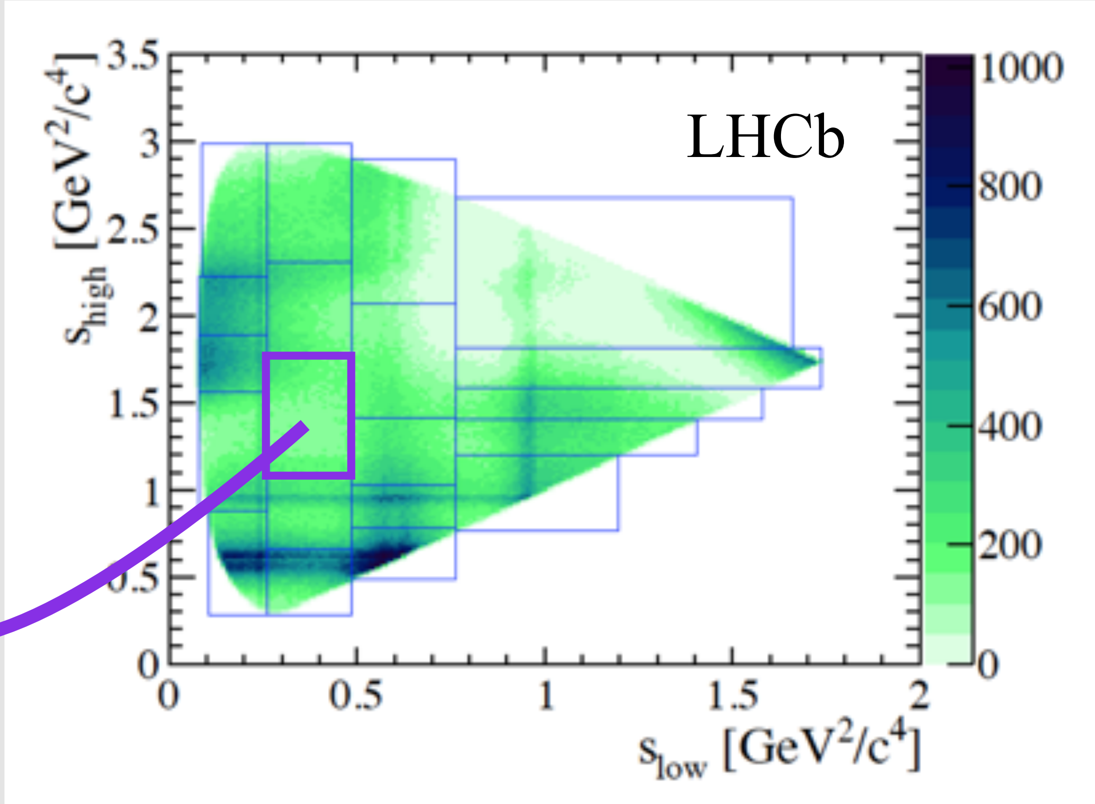


$D^+ \rightarrow 3\pi$

- Model-independent searches for CP violation
  - ➡ Over 3M D^+ & D^- decays in 1 fb^{-1}
  - ➡ Search for asymmetry significances in bins of phase space
  - ➡ Search for local asymmetries through un-binned comparison with nearest neighbours

PLB 728 (2014) 585-595

Binned method



$$\mathcal{S}^i_{CP} = \frac{N^i(D^+) - \alpha N^i(D^-)}{\sqrt{N^i(D^+) + \alpha^2 N^i(D^-)}}$$

$$\alpha = \frac{N_{\rm tot}(D^+)}{N_{\rm tot}(D^-)}$$

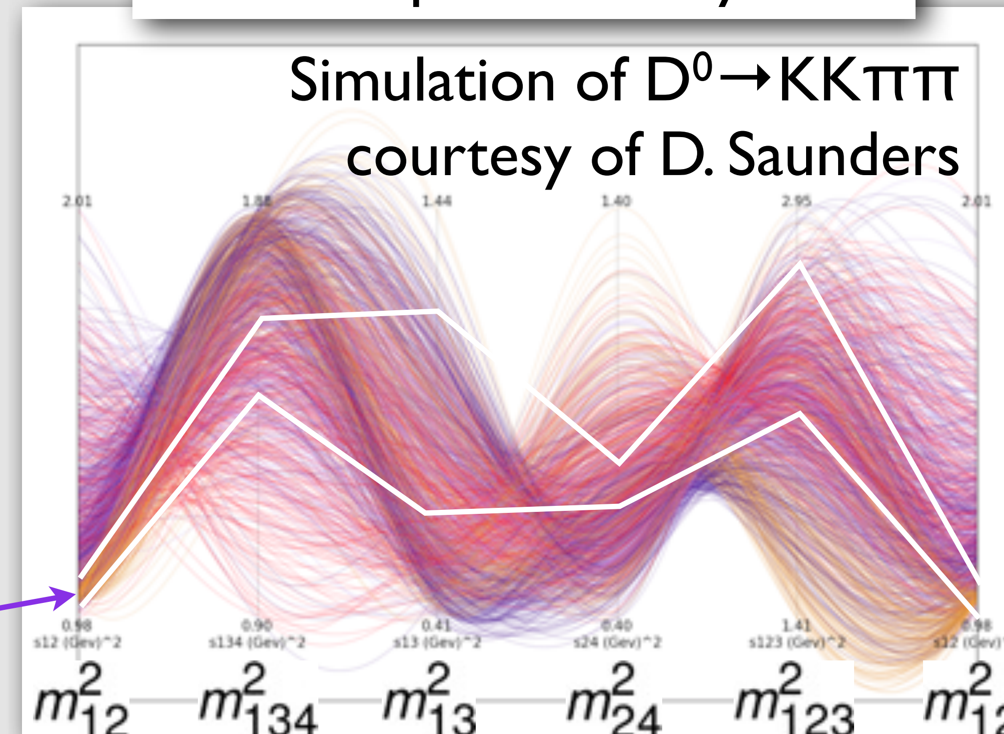
removes sensitivity to global asymmetries

$$\chi^2 = \sum (\mathcal{S}^i_{CP})^2$$

p-values for no-CPV hypothesis > 50% for different binnings

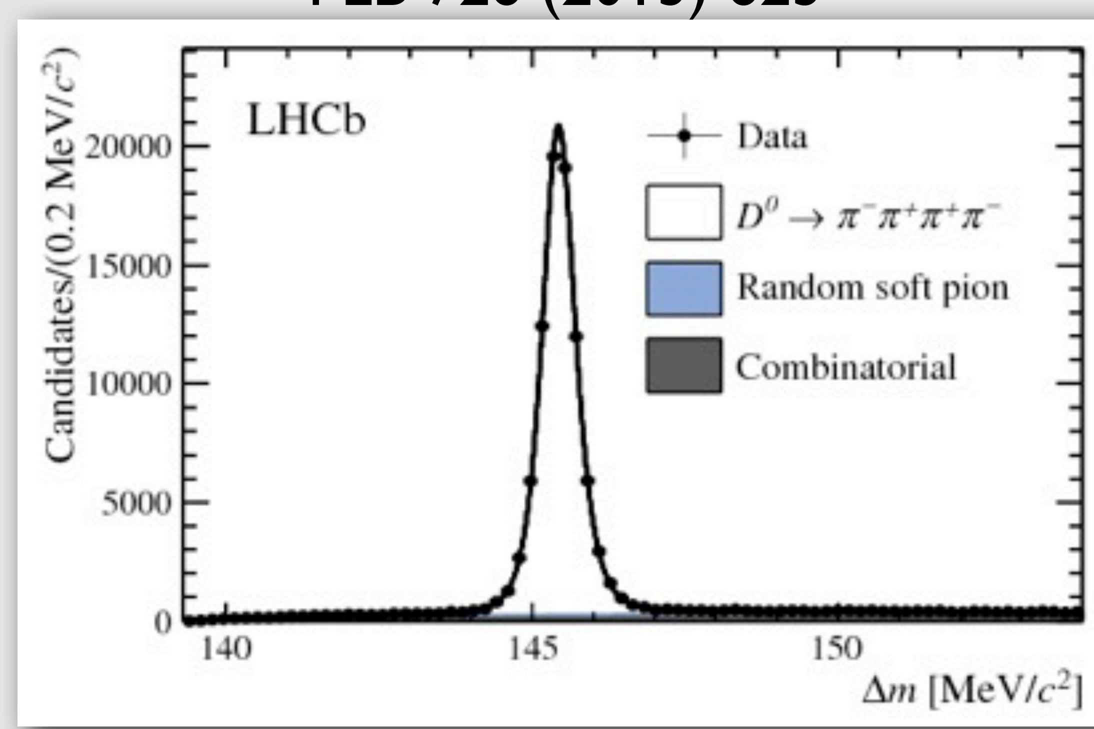
$D^0 \to 4h$

Parallel axes: 5D "Dalitz" plot
Events represented by lines



- 4-body phase space has 5 dimensions!
  - ➡ Bin in 5D hypercubes
- Analyse 1 fb^{-1} of $D^0 \to 4\pi/KK\pi\pi$ decays
  - ➡ Use search for asymmetry significances in 128/32 bins of 5D phase space
  - ➡ p-values for no CPV hypothesis are 9.1% for $KK\pi\pi$ and 41% for 4π

PLB 726 (2013) 623



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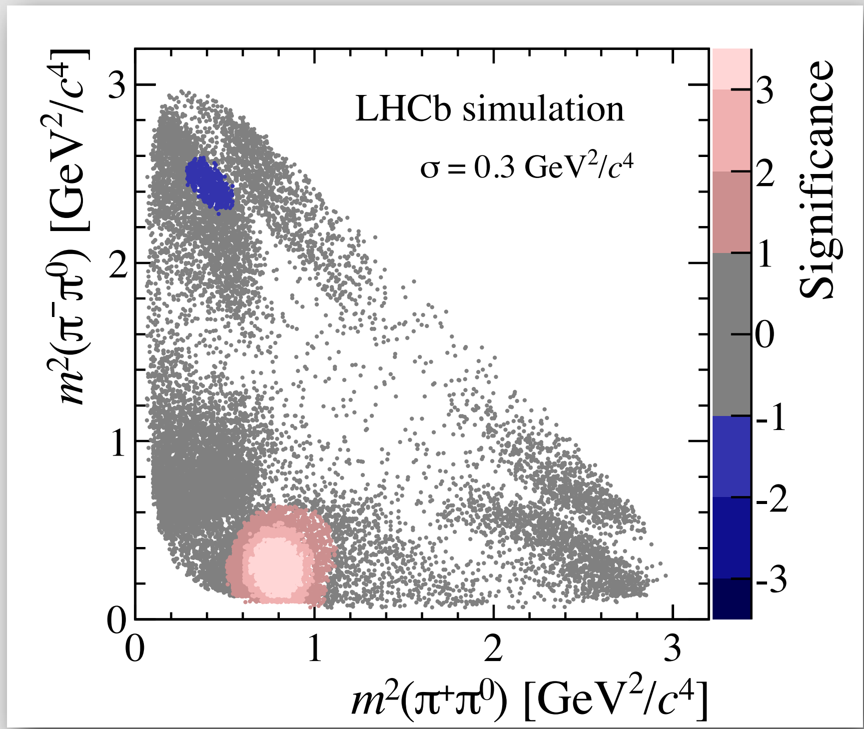
Why not un-binned?

- Need to compare each event with every other
  - ➡ Computationally challenging for O(1M) events
- Combine this with reconstructing π^0
  - ➡ Additional challenge with LHCb detector
- But it can be done
  - ➡ See Shanzhen's talk on Thursday!



LHCb-PAPER-2014-054

CP violation in decay

- Range of new measurements with increasing precision in several decay modes
- Route forward:
  - ➡ Need measurements in several modes to identify potential sources of CP violation
  - ➡ Model-independent measurements are discovery strategies
  - ➡ Need model-dependent measurements for quantitative interpretation

Mixing and indirect CP violation

Asymmetries

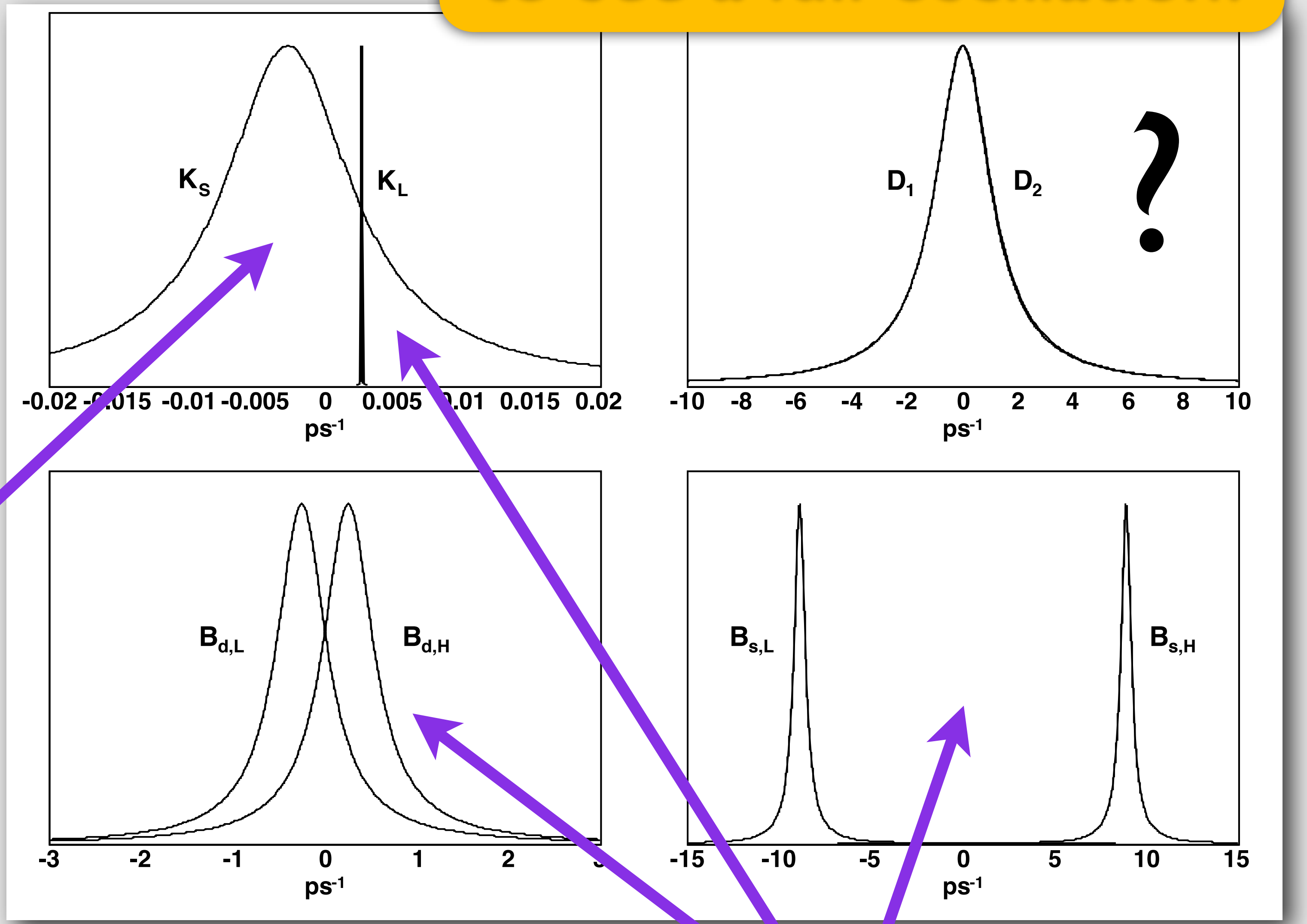
	Global	Localised in phase space
Decay-time integrated	1	2
Decay-time dependent	3	4

Mixing

Charm mixing:
Need ~1000 lifetimes to see a full oscillation!

$$|M_{1,2}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle$$

Mass eigenstates   Flavour eigenstates



Width difference
→ Lifetime difference

$\Delta\Gamma \equiv \Gamma_2 - \Gamma_1$ $y \equiv \Delta\Gamma/(2\Gamma)$

Mass difference
→ Oscillation

$\Delta m \equiv m_2 - m_1$

$x \equiv \Delta m/\Gamma$

$$P(M^0 \to \overline{M}^0, t) = \frac{1}{2}\left|\frac{q}{p}\right|^2 e^{-\Gamma t}(\cosh(y\Gamma t) - \cos(x\Gamma t))$$

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Mixing

Convention in charm differs from B system

$\Delta\Gamma \equiv \Gamma_2 - \Gamma_1$

$\Delta m \equiv m_2 - m_1$

Based on $CP|D^0\rangle = -|\overline{D}^0\rangle$

Leading to $D_{1,2}$ being CP even/odd

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CP violation in mixing

- CP conservation implies that mass eigenstates are CP eigenstates

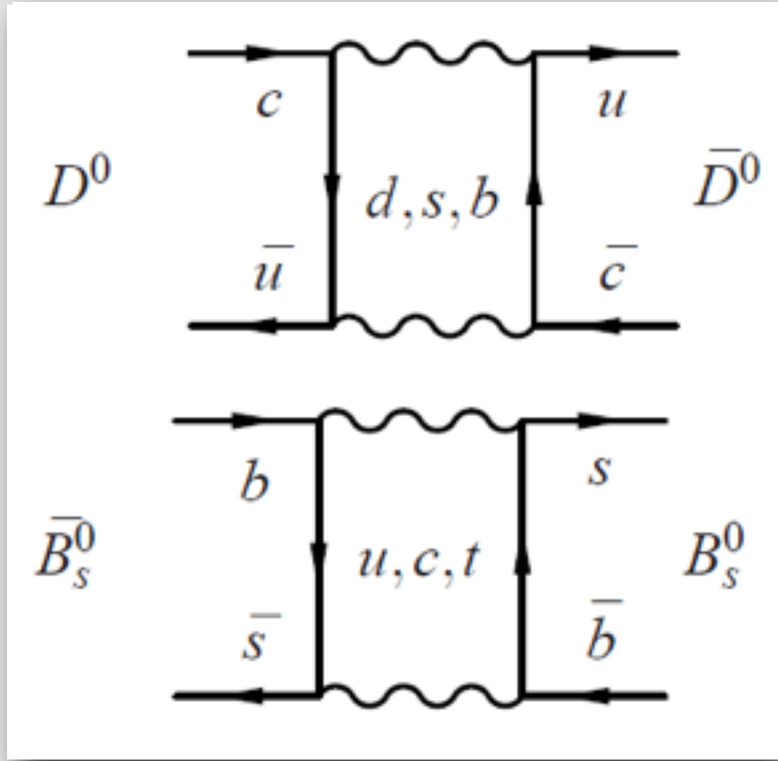
$\mathcal{CP}|M_{1,2}\rangle = \pm|M_{1,2}\rangle$ $|M_{1,2}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle$

- CP violation in mixing if $q \neq \pm p$
- Two possibilities $|q/p| \neq 1$ $\Im(q/p) \neq 0$

→ $\phi \equiv \arg(q/p) \neq 0,\pi$

- Mass eigenstates and CP eigenstates no longer the same $\mathcal{CP}|M_{1,2}\rangle \neq \pm|M_{1,2}\rangle$
- Decays to CP eigenstates now possible from both mass eigenstates

D^0 mixing theory



- Mixing box contains down-type quarks
- No dominance of top mass as in B sector
- CKM-suppression balances GIM cancellation
- Charm mass neither small nor large
- Huge cancellations
  - ➡ Long-distance effects become important
- Over 1000 lifetimes for 1 full oscillation
- Difficult to measure
  - ➡ CP violation even more tricky to discover

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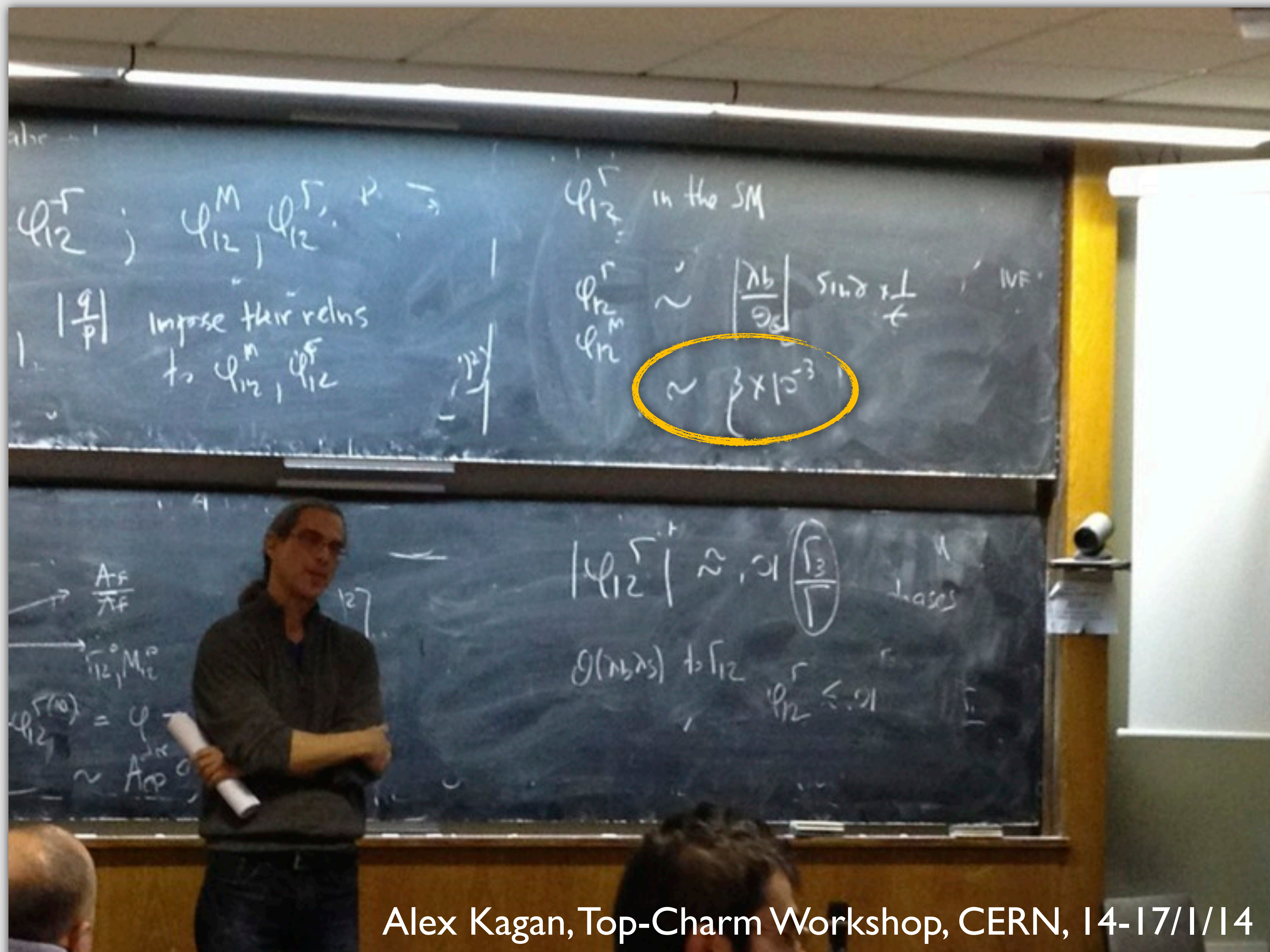
Expert advice



Alex Kagan, Top-Charm Workshop, CERN, 14-17/1/14

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Asymmetries

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Measuring mixing

$$P(M^0 \to \overline{M}^0, t) = \frac{1}{2}\left|\frac{q}{p}\right|^2 e^{-\Gamma t}\left(\cosh(y\Gamma t) - \cos(x\Gamma t)\right)$$

$$\approx \frac{1}{2}(x^2 + y^2)(\Gamma t)^2 - \frac{1}{24}(x^4 - y^4)(\Gamma t)^4$$

current world averages → 3×10^{-5} -7×10^{-11}

need $t > 200\tau$ for a 10% contribution of this term

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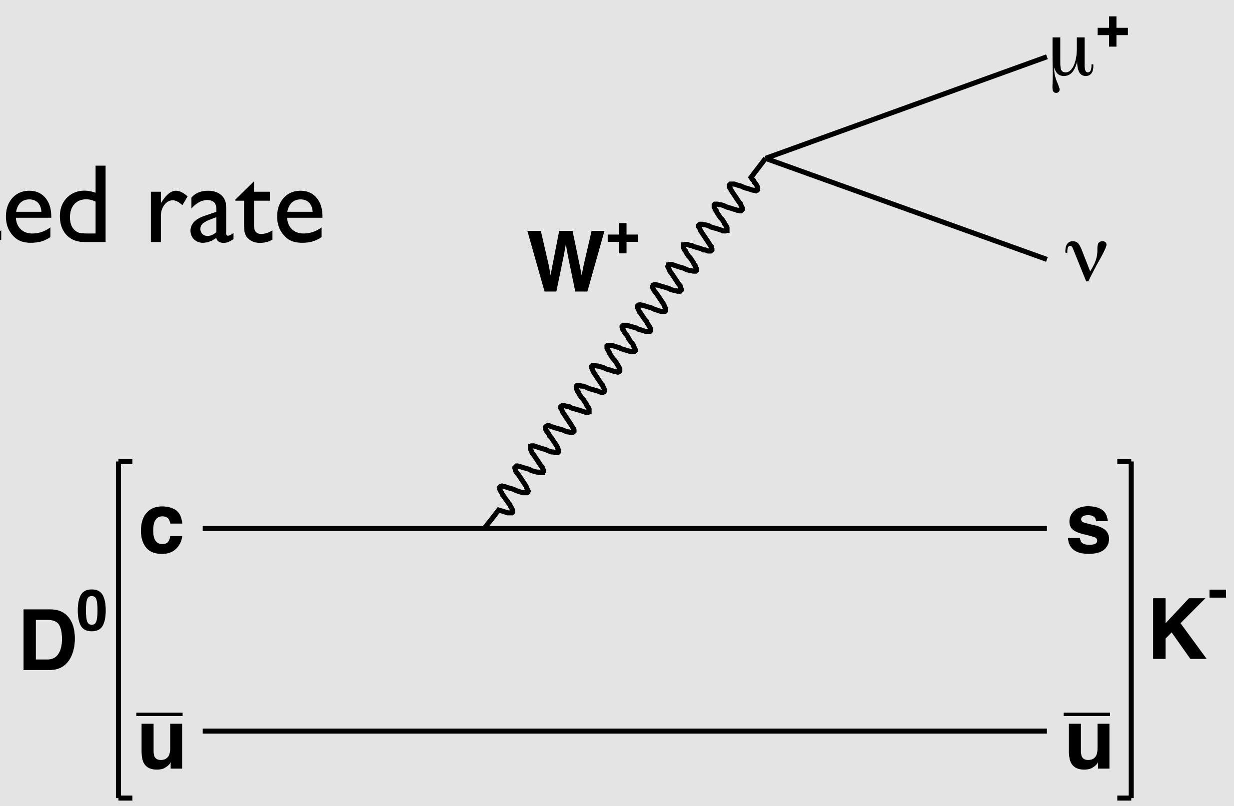
$D^0 \to K^+ \mu^- \nu$

- Semileptonic decay is flavour tagging
- Charge-conjugate final state only accessible through mixing
- Measure time-integrated rate
  - ➡ Proportional to mixing probability

$$\frac{1}{2}(x^2 + y^2)(\Gamma t)^2$$

$\approx 3\times10^{-5}$



$D^0 \to K^+ \mu^- \nu$

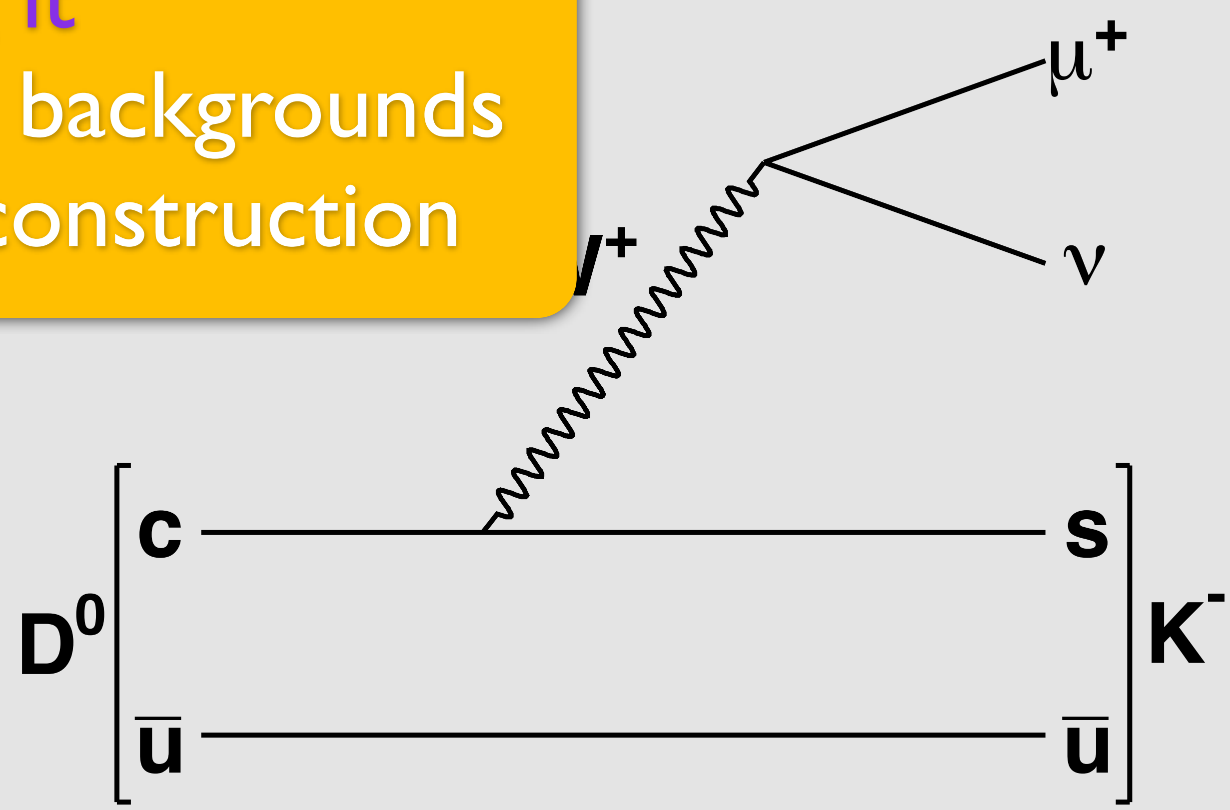
- Semileptonic decay is flavour tagging
- Char... ...ccessible throu...
- Meas...

Main challenge:
Finding it
Low rate and high backgrounds
due to partial reconstruction

➡ Proportional to mixing probability

$$\frac{1}{2}(x^2 + y^2)(\Gamma t)^2$$

$\approx 3\times10^{-5}$



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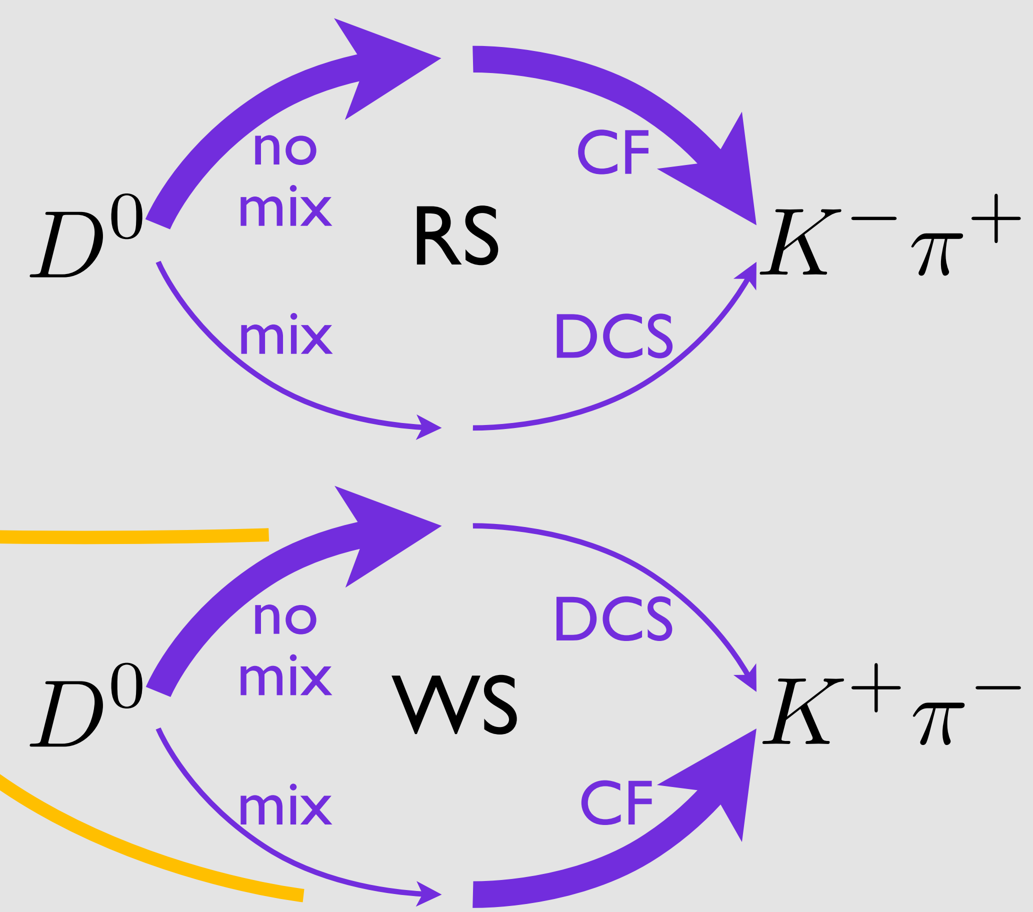
Mixing discovery

$$R(t) \equiv \frac{N_{WS}(t)}{N_{RS}(t)} \approx R_d + \sqrt{R_D}y'\frac{t}{\tau} + \frac{x'^2 + y'^2}{4}(\frac{t}{\tau})^2$$



Interference

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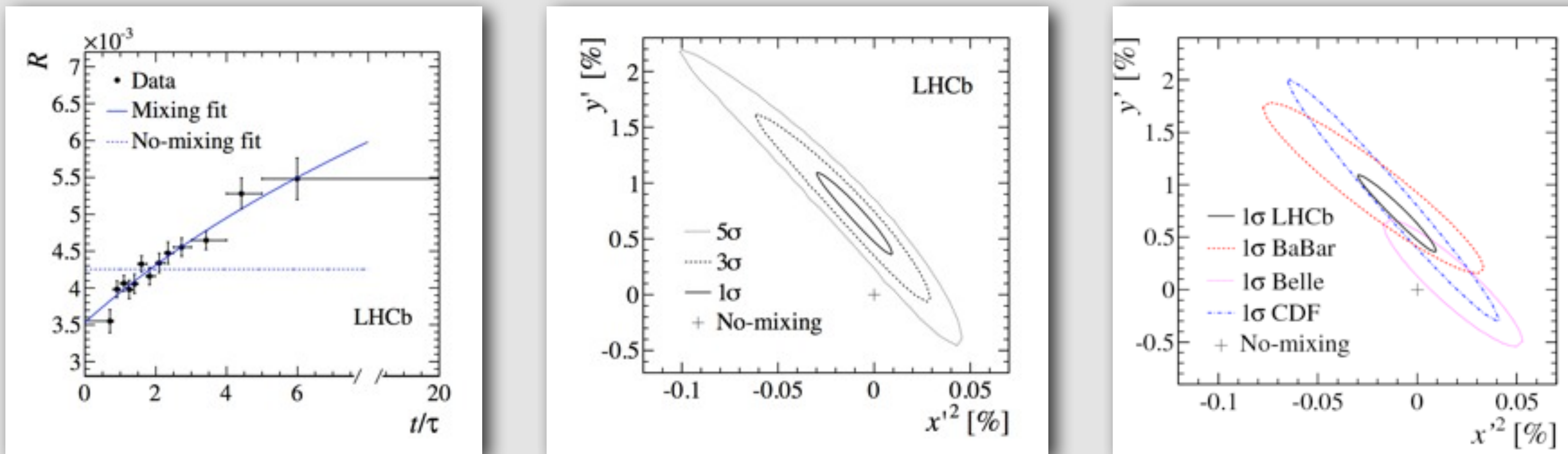
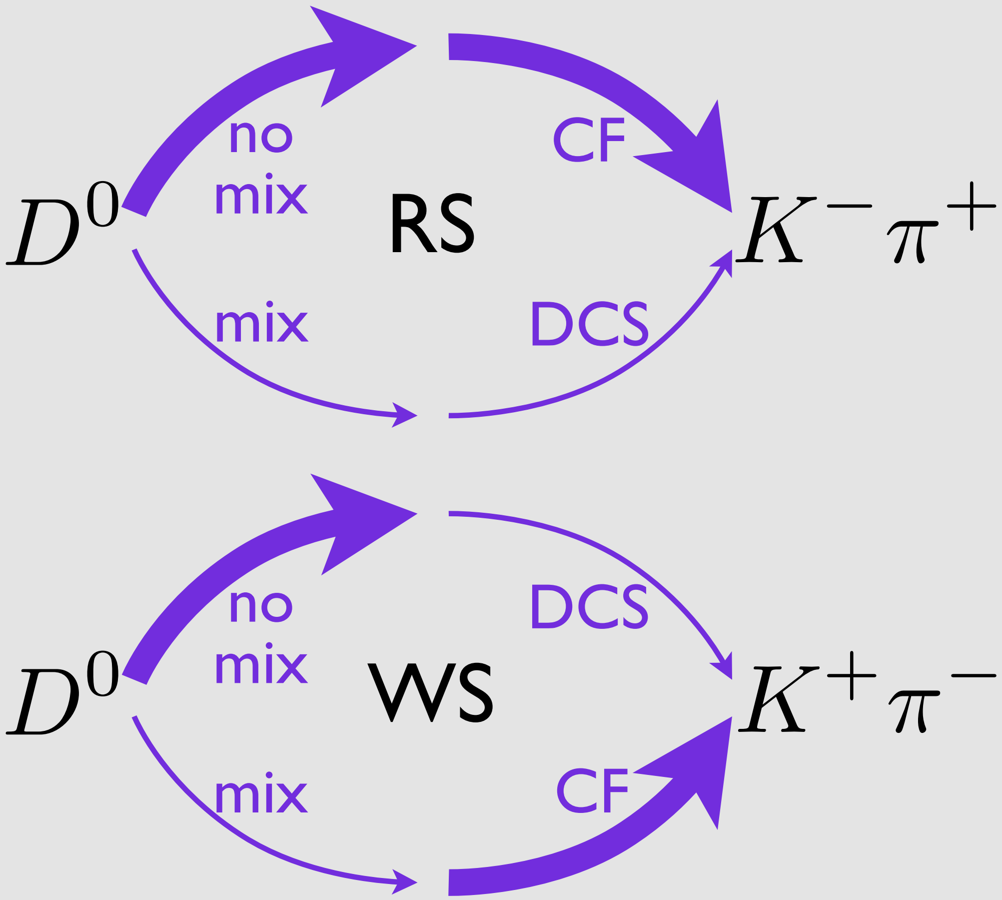
Mixing discovery



$$R(t) \equiv \frac{N_{WS}(t)}{N_{RS}(t)} \approx R_d + \sqrt{R_D}y'\frac{t}{\tau} + \frac{x'^2 + y'^2}{4}(\frac{t}{\tau})^2$$

- First single-experiment measurement >5σ significance
- Rotation of mixing parameters by strong phase difference



Phys. Rev. Lett. 110, 101802 (2013)

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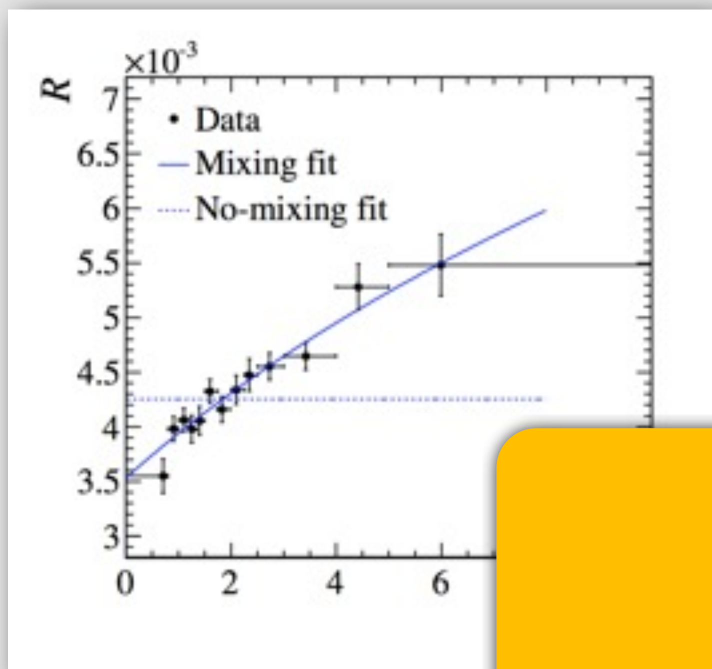
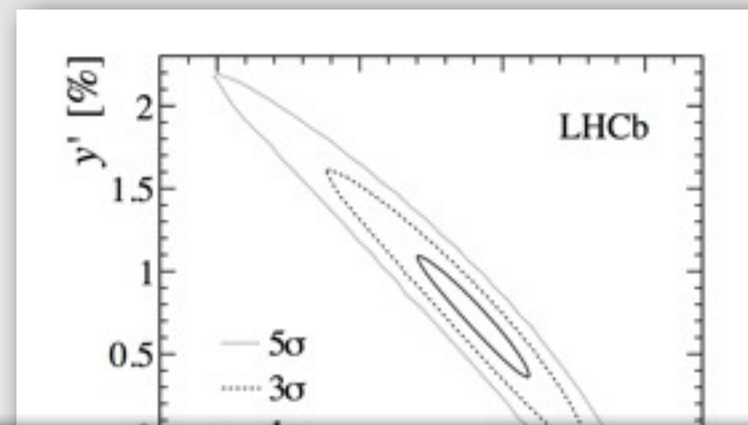
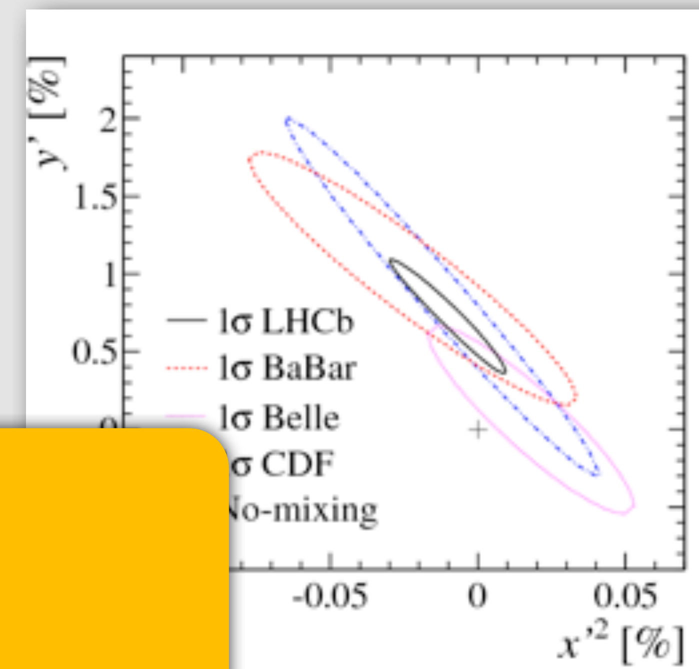
Mixing discovery

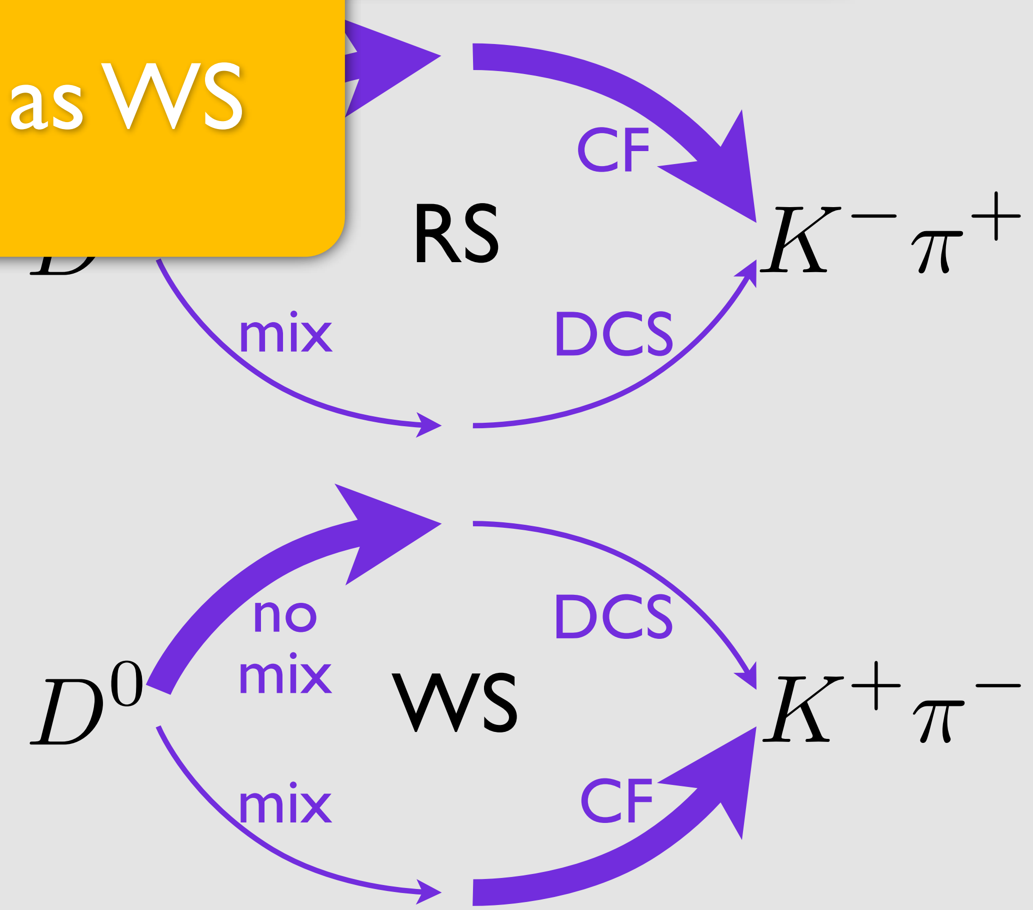






Main challenge:
Double mis-ID
RS decay mis-identified as WS

$$R(t) \equiv \frac{N_{WS}(t)}{N_{RS}(t)} \approx$$



- First single-experiment measurement >5σ significance
- Rotation of mixing parameters by strong phase difference

Phys. Rev. Lett. 110, 101802 (2013)

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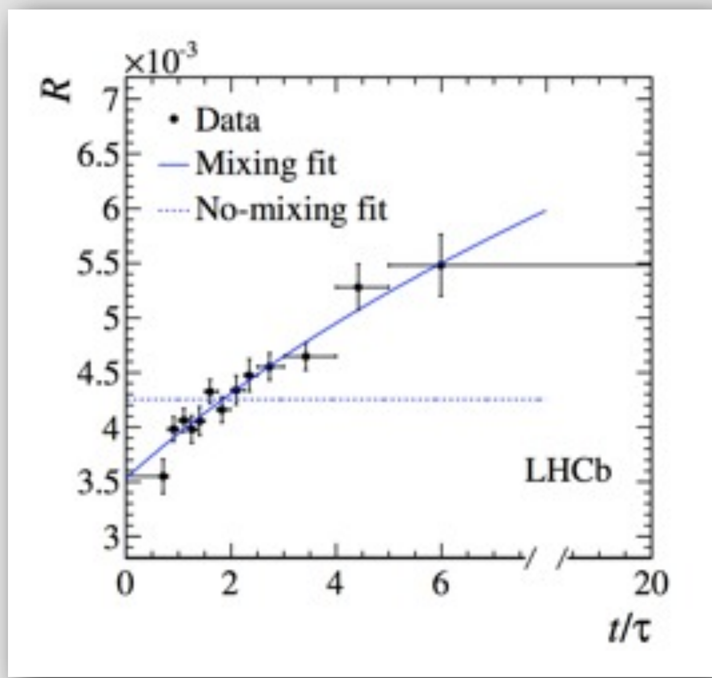
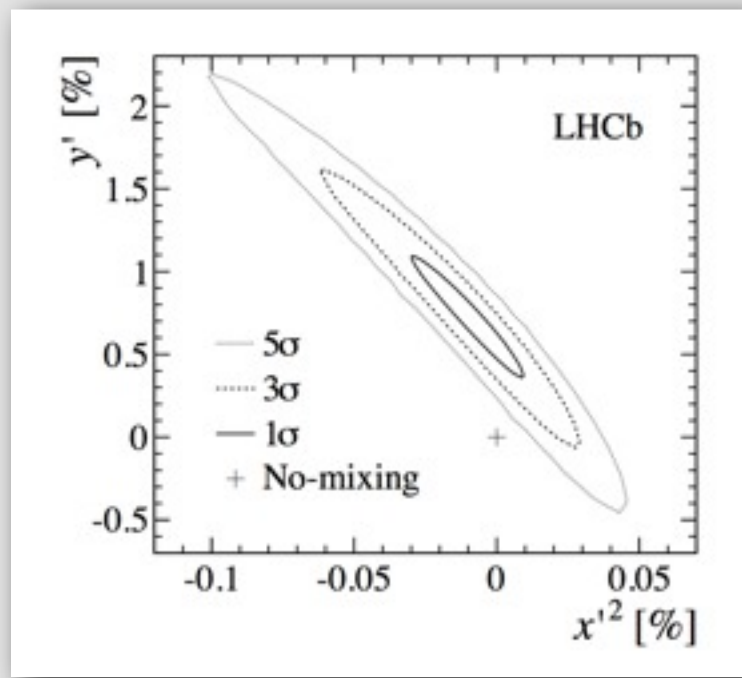
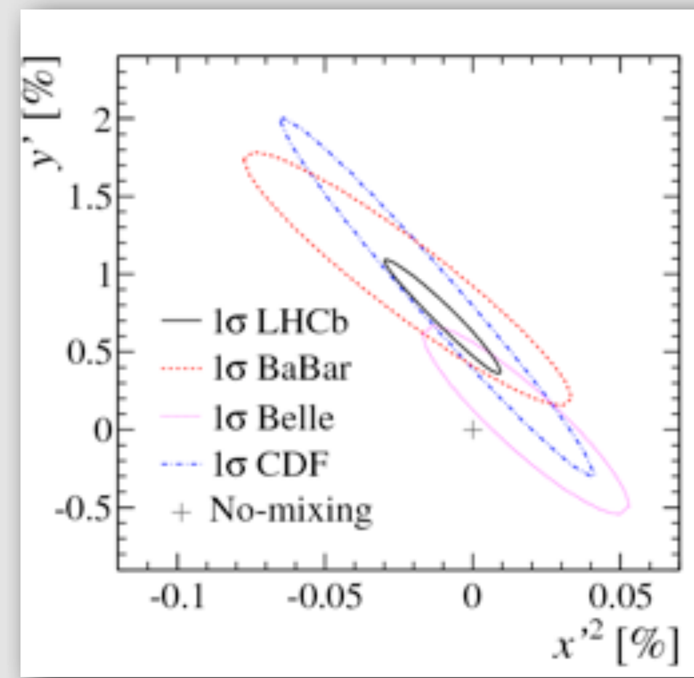
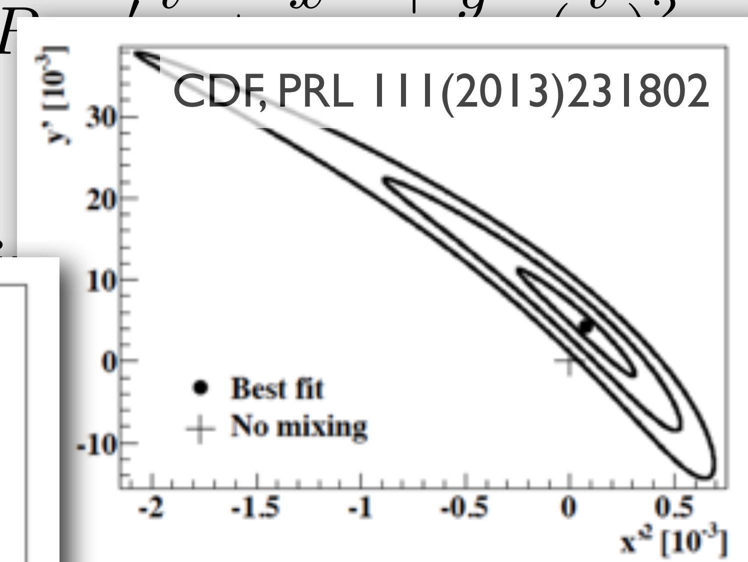
Mixing discovery



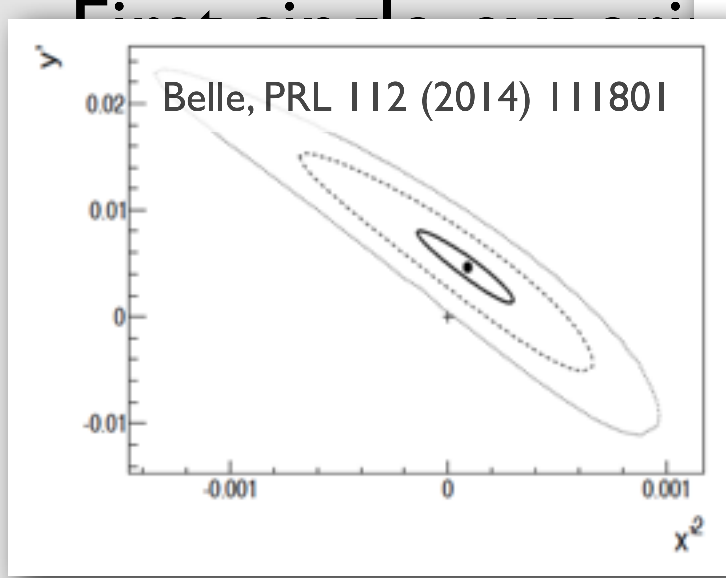


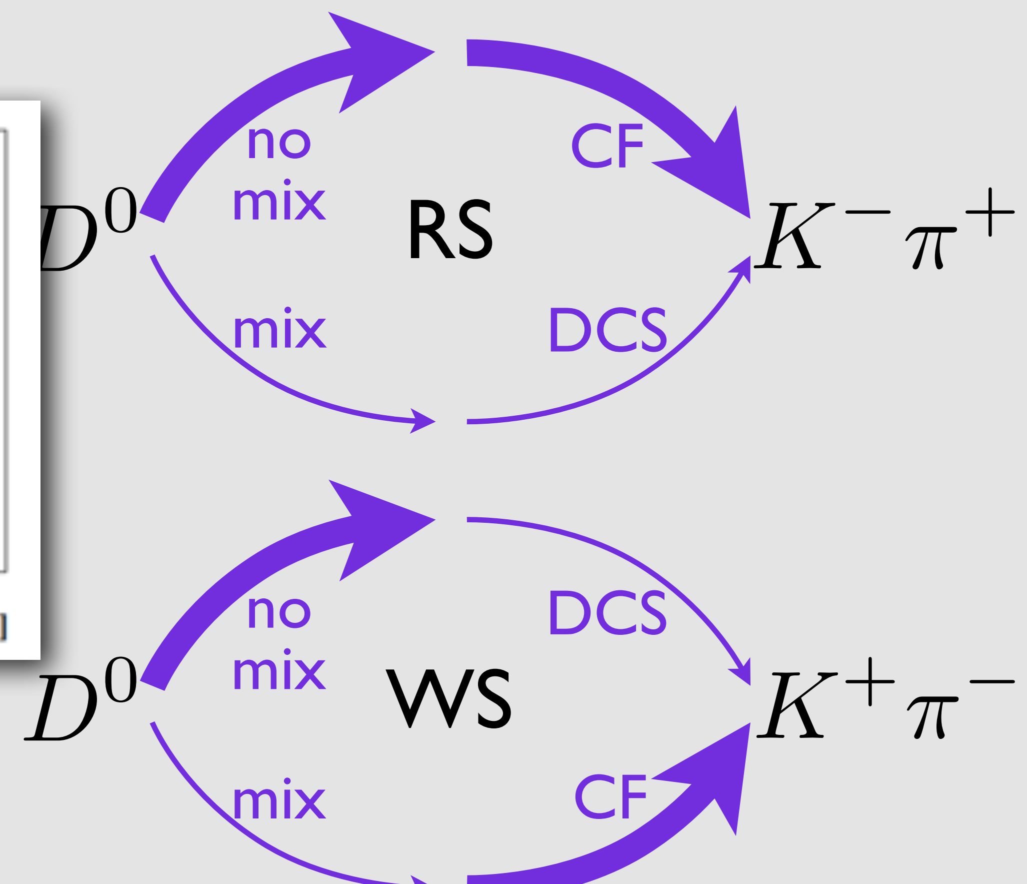


$$R(t) \equiv \frac{N_{WS}(t)}{N_{RS}(t)} \approx R_d + \sqrt{R \ldots}$$



- First single-experi...
- ...ence





Phys. Rev. Lett. 110, 101802 (2013)

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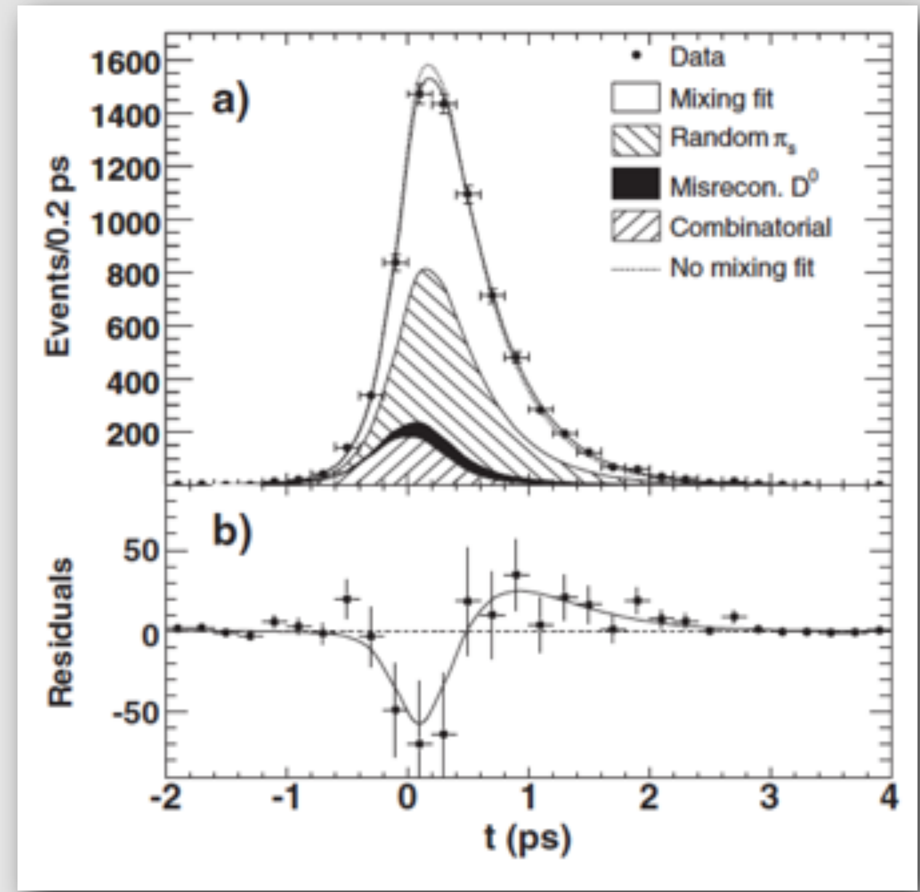
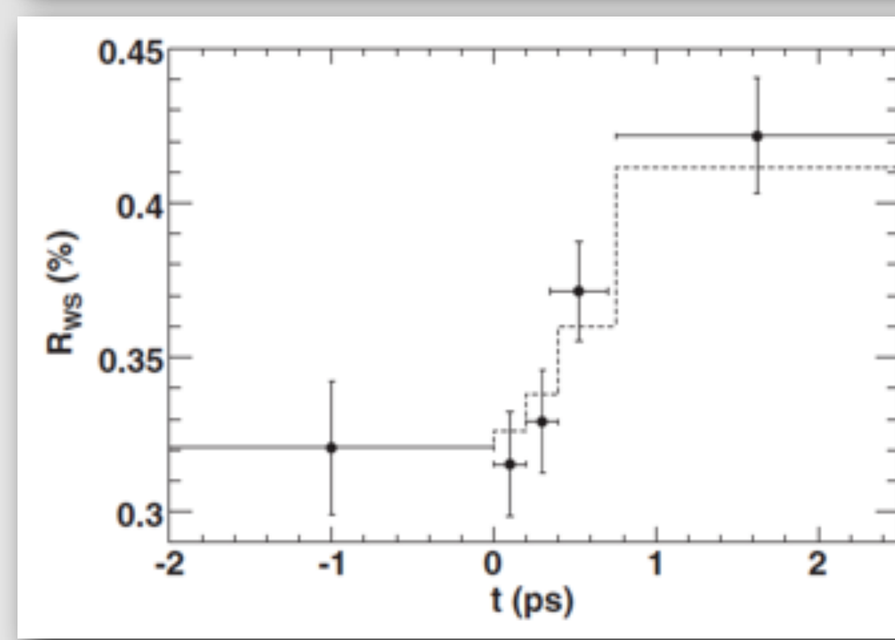
Two methods

- Measure effective lifetime of RS and WS samples
  - ➡ Use full statistical power
  - ➡ More complicated as need to model time distribution
  - ➡ Need to account for decay-time resolution (mostly B-factories) and acceptance (mostly hadron colliders)
- Measure ratio of RS and WS yields in bins of decay time
  - ➡ Only need yield extraction
  - ➡ Price in statistical precision limited for very large samples
  - ➡ Harder to exploit correlation of fit parameters across time bins
  - ➡ Assume cancellation of acceptance effects





BaBar, PRL 98 (2007) 211802

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Measuring lifetimes

- Many measurements based on measurements of lifetime ratios/ asymmetries
  - ➡ But no D^0 lifetime measurement published
- Demonstrates the challenge in controlling systematics
  - ➡ LHCb has statistical power to reduce WA uncertainty by factor 40

2014 Review of Particle Physics.
Please use this CITATION: K.A. Olive *et al.* (Particle Data Group), Chin. Phys. C, **38**, 090001 (2014).

D^0 MEAN LIFE

Measurements with an error > $10E - 15$s have been omitted from the average.

Value (10^{-15} s)	EVTS	Document ID		TECN	Comment
$(41.01 \pm 0.15) \times 10^1$	OUR AVERAGE				
$409.6 \pm 1.1 \pm 1.5$	210k	LINK	2002F	FOCS	γ nucleus, $\approx$ 180 GeV
$407.9 \pm 6.0 \pm 4.3$	10k	KUSHNIRENKO	2001	SELX	$K^- \pi^+$, $K^- \pi^+ \pi^+ \pi^-$
$413 \pm 3 \pm 4$	35k	AITALA	1999E	E791	$K^- \pi^+$
$408.5 \pm 4.1 ^{+3.5}_{-3.4}$	25k	BONVICINI	1999	CLE2	$e^+ e^- \approx \Upsilon(4S)$
$413 \pm 4 \pm 3$	16k	FRABETTI	1994D	E687	$K^- \pi^+$, $K^- \pi^+ \pi^+ \pi^-$

Measuring lifetimes

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- Theoretically challenging as well... on measurements of lifetime ratios/ asymmetries
  - ➡ Bu
- Dem
  - ➡ Ll ... factor 40

Measurements with an error > $10E-15$ s have be

and Lenz, Rauh, Phys.Rev. D88 (2013) 034004

Value (10^{-15} s)	EVTS	Document ID		TECN	Comment
$(41.01 \pm 0.15) \times 10^1$	OUR AVERAGE				
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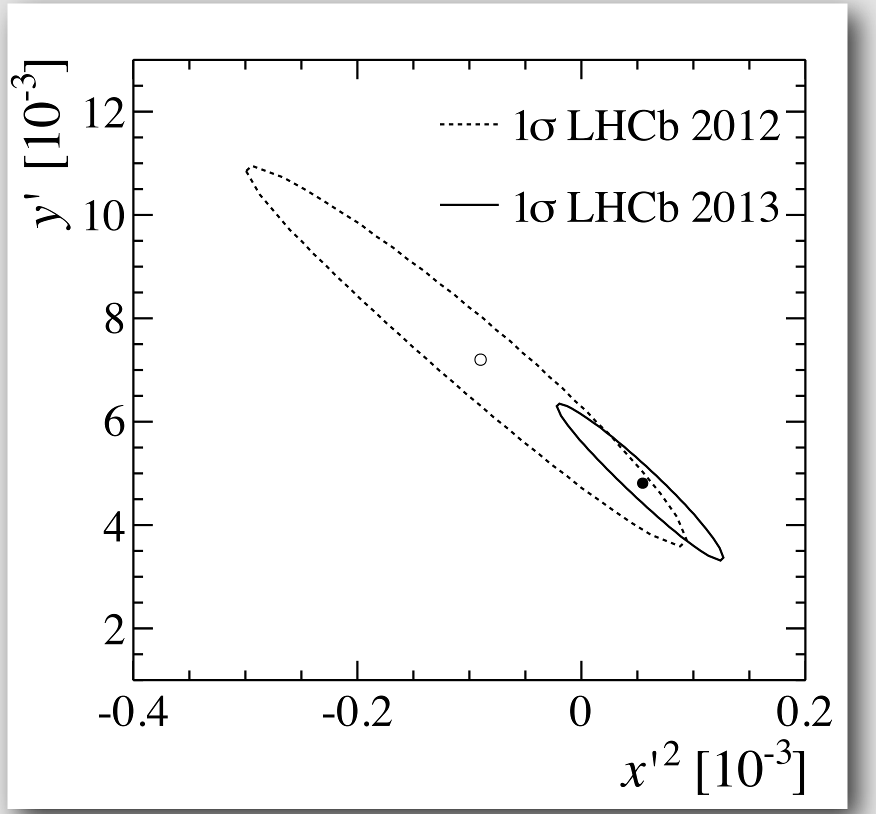
$413 \pm 4 \pm 3$	16k	FRABETTI	1994D	E687	$K^- \pi^+$, $K^- \pi^+ \pi^+ \pi^-$

Mixing and CP violation

- Update with 3 fb^{-1}
- Split by flavour to search for CP violation
  - ➡ $x'^{\pm} = |q/p|^{\pm 1}(x' \cos\Phi \pm y' \sin\Phi)$
  - ➡ $y'^{\pm} = |q/p|^{\pm 1}(y' \cos\Phi \mp x' \sin\Phi)$
- No indication for CP violation



PRL 111 (2013) 251801

R_D^+	$[10^{-3}]$	$3.545 \pm 0.082 \pm 0.048$
y'^+	$[10^{-3}]$	$5.1 \pm 1.2 \pm 0.7$
x'^{2+}	$[10^{-5}]$	$4.9 \pm 6.0 \pm 3.6$
R_D^-	$[10^{-3}]$	$3.591 \pm 0.081 \pm 0.048$
y'^-	$[10^{-3}]$	$4.5 \pm 1.2 \pm 0.7$
x'^{2-}	$[10^{-5}]$	$6.0 \pm 5.8 \pm 3.6$

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y_{CP}

- Comparison of decay-time dependence of decays to CP eigenstates (e.g. KK, ππ) to Cabibbo-favoured decays (RS Kπ)
  - ➡ $y_{CP} \equiv \tau_{K\pi}/\tau_{hh} - 1$
- Approximate
  - ➡ Mass eigenstates = CP eigenstates
- Measure
  - ➡ ΔΓ or y (width difference of mass eigenstates)
- Including CP violation
  - ➡ $y_{CP} \approx y \cos\phi + A_M \times \sin\phi$
    - $A_M \equiv (|q/p|-|p/q|) / (|q/p|+|p/q|)$

y_{CP}

- Comparison of decay-time dependence of decays to CP eigenstates (e.g. KK, ππ) to Cabibbo-favoured decays (RS Kπ)
  - ➡ y_{CP}
- Appro
  - ➡ Mas
- Measu
  - ➡ ΔΓ or y (width difference of mass eigenstates)
- Including CP violation
  - ➡ $y_{CP} \approx y \cos\phi + A_M\, x \sin\phi$
    - $A_M \equiv (|q/p|-|p/q|) / (|q/p|+|p/q|)$

Main challenge:
Time acceptance
Lifetime ratio of two different final states

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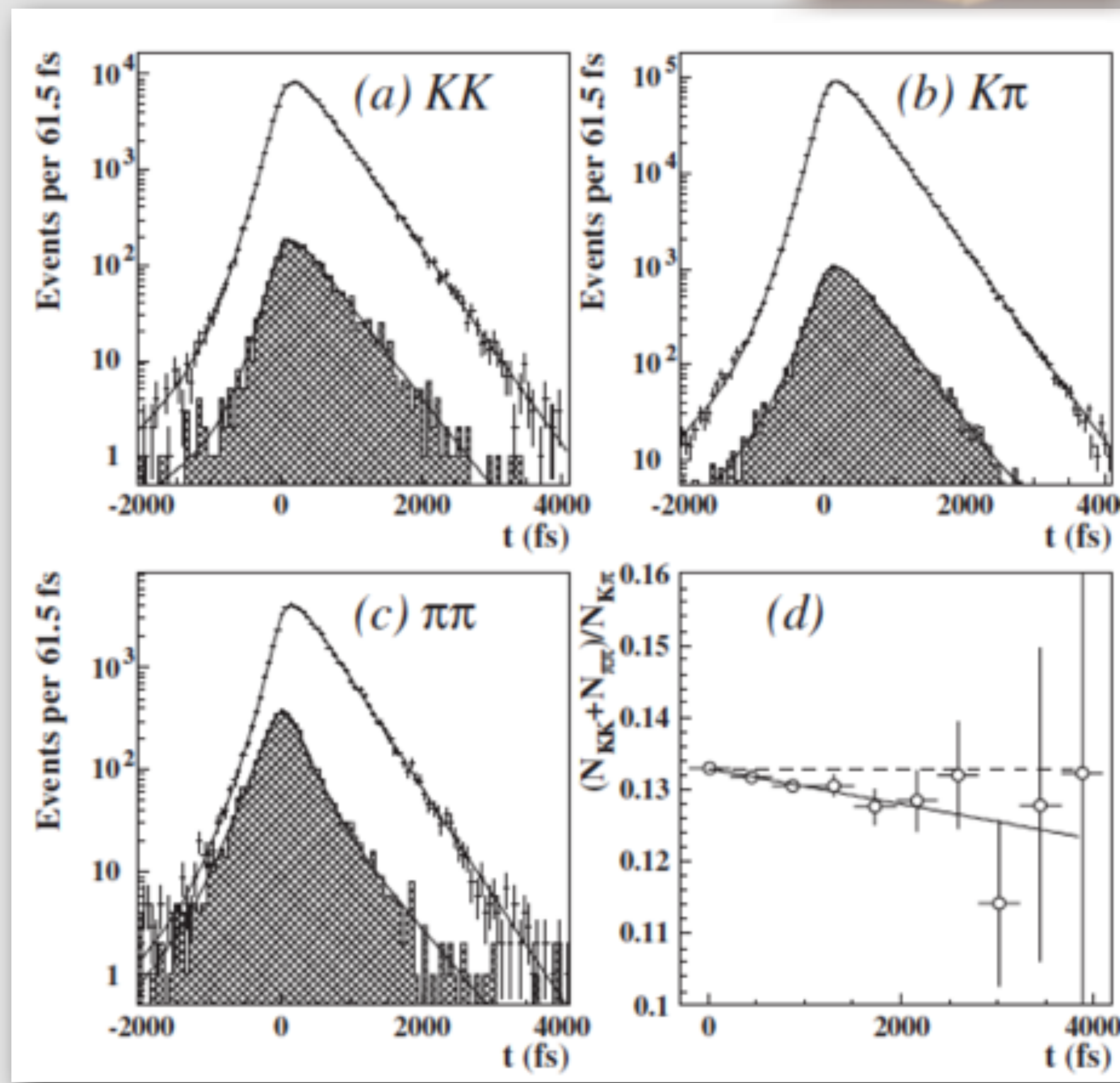
First evidence

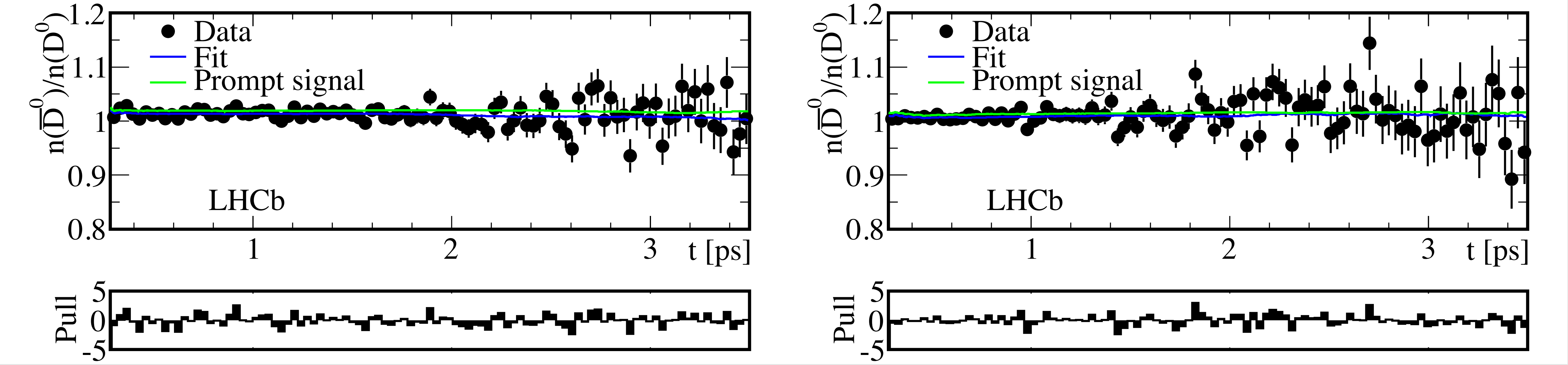
- Provided first evidence for charm mixing
  - ➡ Together with BaBar WS Kπ
- Method of choice
  - ➡ Effective lifetime fits
- Ratio method not reported as cross-check



Belle, PRL 98 (2007) 211803

Indirect CP violation

- Measure asymmetries of effective lifetimes of decays to CP eigenstates:
  - ➡ $A_\Gamma \approx A_M\, y \cos\phi + x \sin\phi \equiv -a_{CP}^{ind}$
- Measures ability of both mass eigenstates to decay to CP eigenstate
- Measurements use $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays (1 fb^{-1})
  - ➡ $A_\Gamma(KK) = (-0.35 \pm 0.62 \pm 0.12) \times 10^{-3}$
  - ➡ $A_\Gamma(\pi\pi) = (0.33 \pm 1.06 \pm 0.14) \times 10^{-3}$



PRL 112 (2014) 041801

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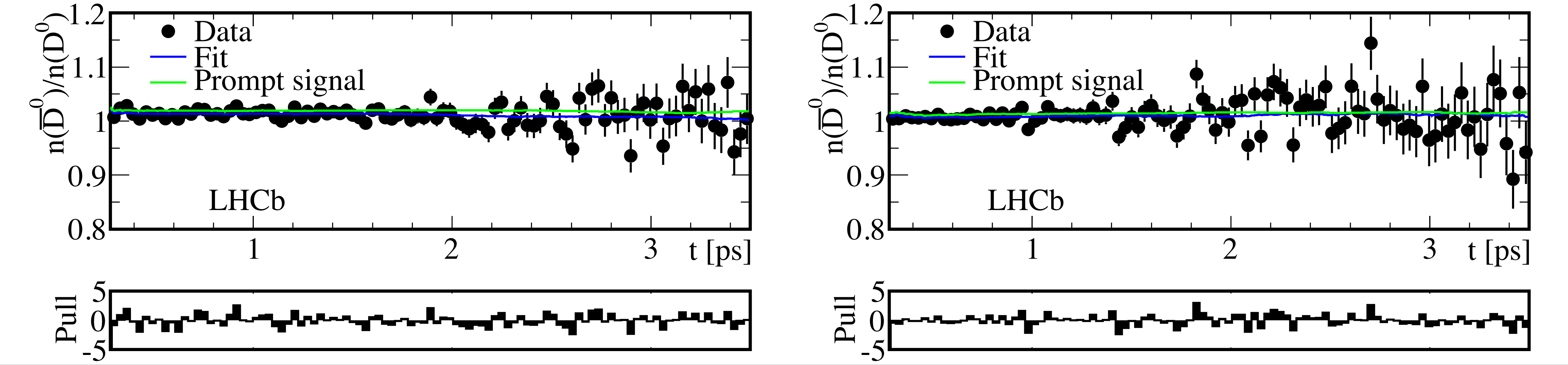
Indirect CP violation

- Measure asymmetries of effective lifetimes of decays to CP eigenstates:
  - ➡ $A_\Gamma \approx A_M\, y \cos\phi + x \sin\phi \equiv -a_{CP}^{ind}$
- Measures [obscured] CP eigenstate
- Measurem[obscured] (1 fb^{-1})
  - ➡ $A_\Gamma(KK)$ [obscured]
  - ➡ $A_\Gamma(\pi\pi$ [obscured]

Main challenge:
Beautiful charm
D originating from B decays
distort the decay-time distribution



PRL 112 (2014) 041801

Asymmetries

	Global	Localised in phase space
Decay-time integrated	1	2
Decay-time dependent	3	4

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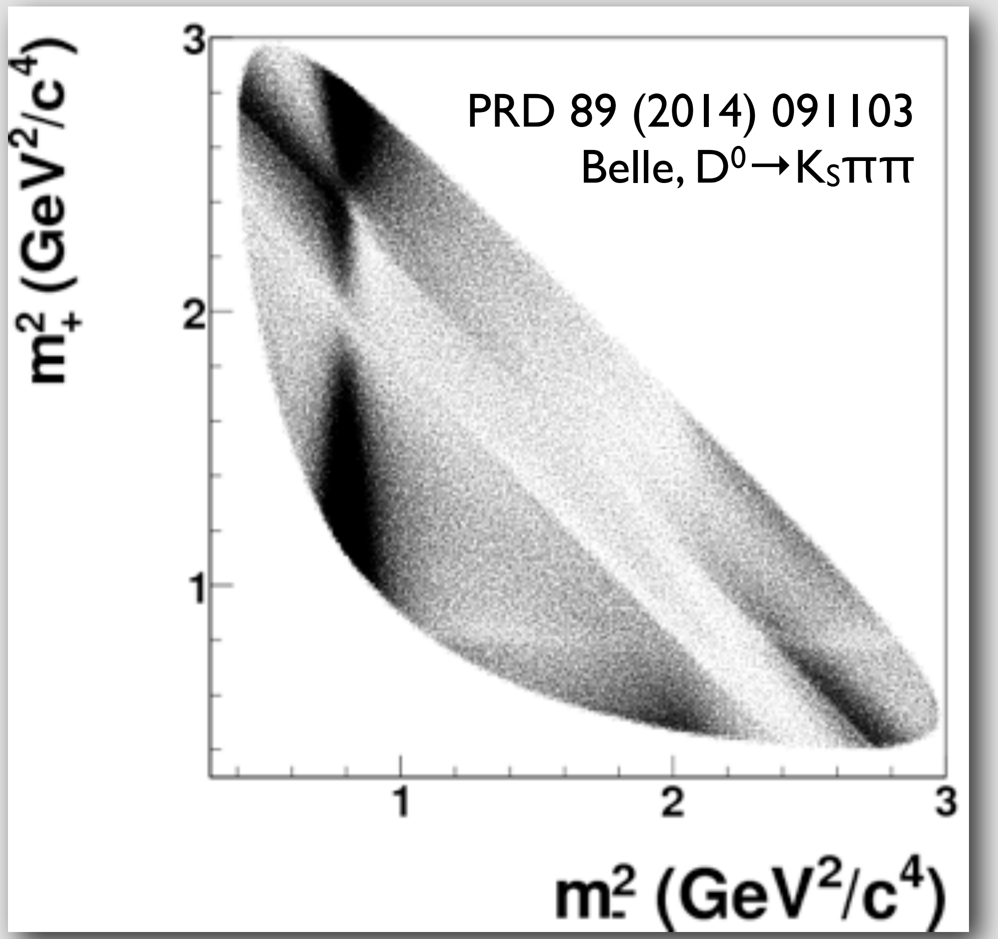
$D^0 \to K_S hh$



- $K_S K^- K^+$ and $K_S \pi^- \pi^+$
  - ➡ Complex assembly of different resonances
  - ➡ Including flavour and CP eigenstates
- Study decay-time dependence of resonances
  - ➡ Decay-time dependent Dalitz-plot analysis
- Access to individual mixing and CPV parameters
  - ➡ x, y, $|q/p|$, ϕ

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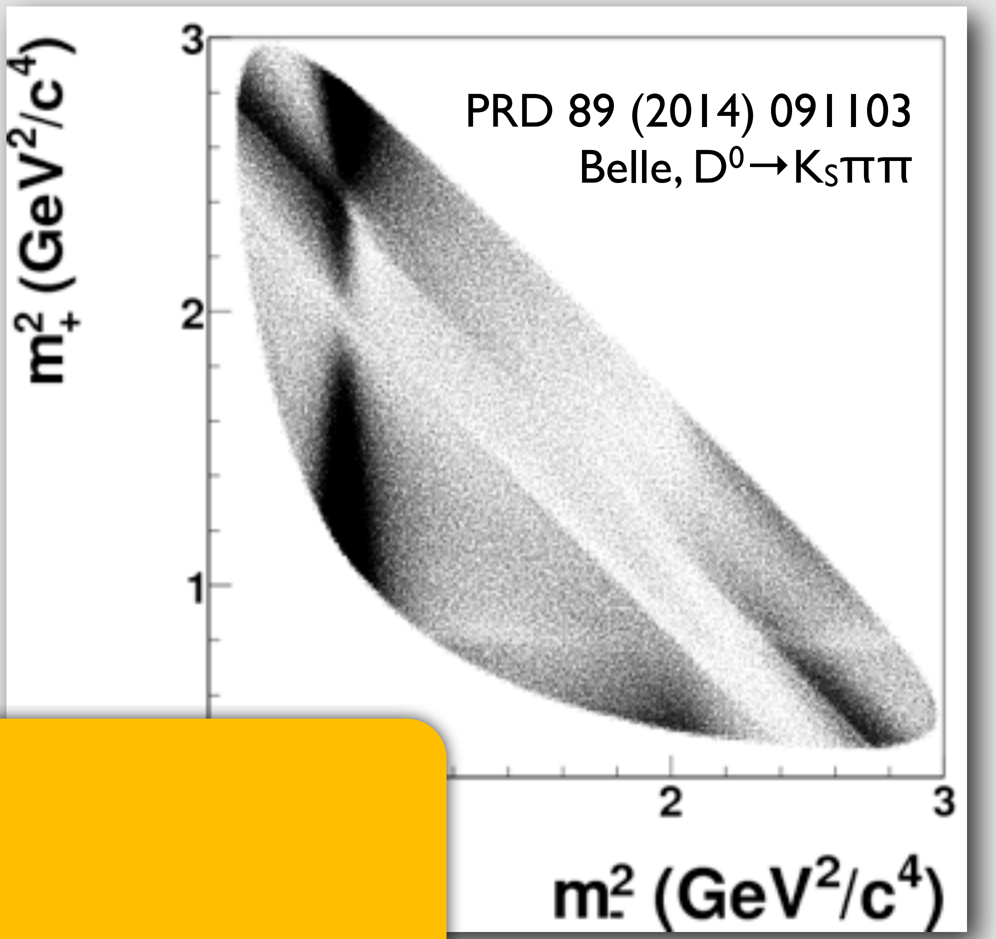
$D^0 \rightarrow K_S hh$



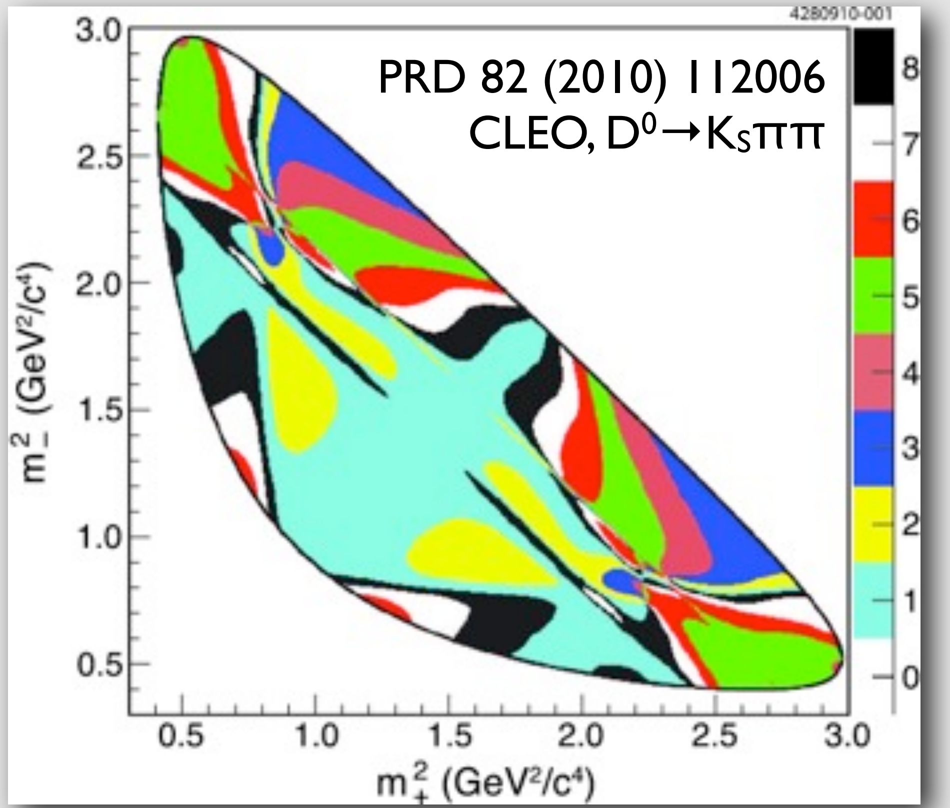
- $K_S K^- K^+$ and $K_S \pi^- \pi^+$
  - ➡
  - ➡

Main challenge:
All of it
Efficiencies varying as function of position in phase space and decay time

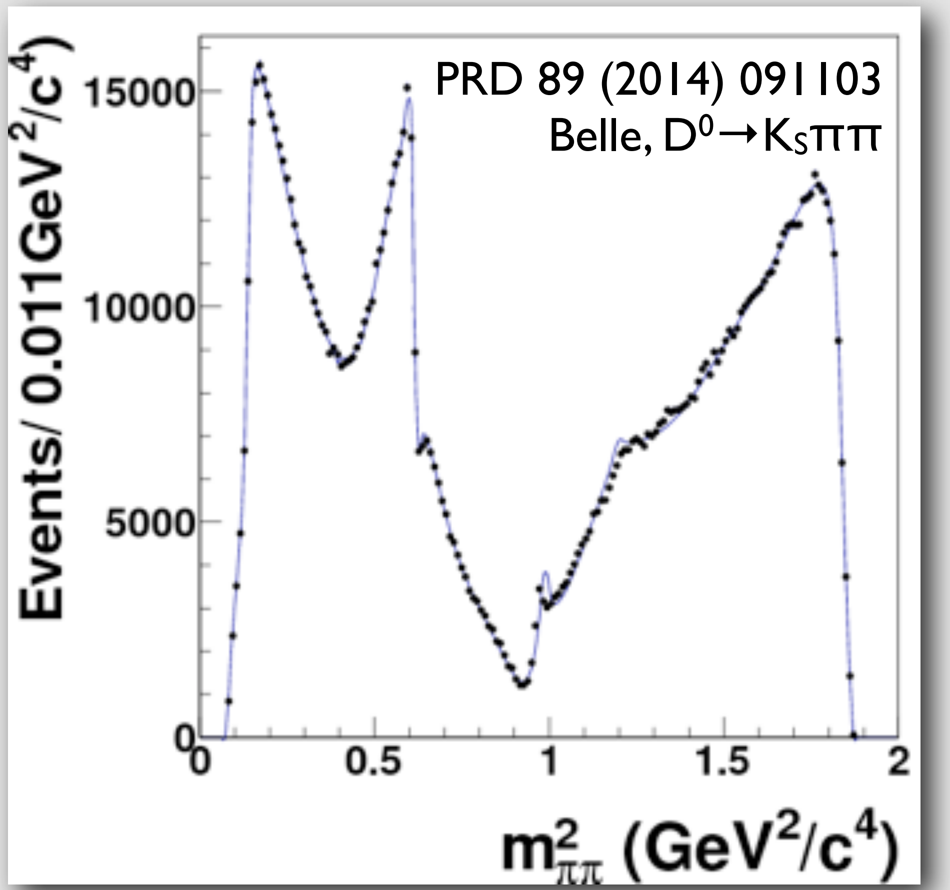
- Study decay-time dependence of resonances
  - ➡ Decay-time dependent Dalitz-plot analysis
- Access to individual mixing and CPV parameters
  - ➡ x, y, $|q/p|$, ϕ

Techniques

- Model-independent
  - ➡ Study decay-time evolution in bins of similar strong phase difference



- Model-dependent
  - ➡ Measure effective lifetime of individual resonances



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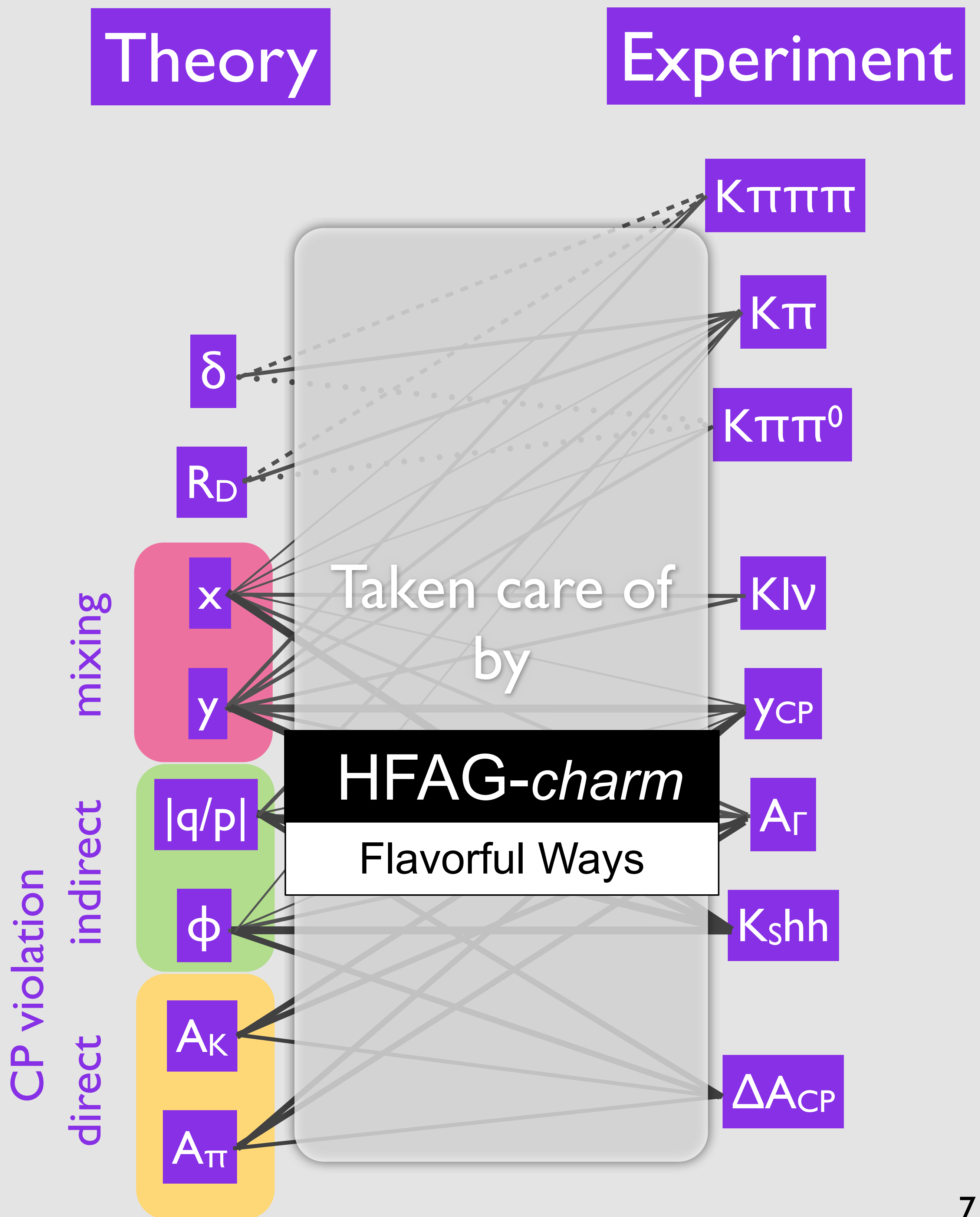
Mixing and indirect CPV

- Mixing by now well established
  - ➡ $y > 0$: CP-even eigenstate is shorter lived than CP-odd
  - ➡ $x > 0$?: mass splitting not yet clear
- CP violation
  - ➡ Powerful constraints without hints for CPV
  - ➡ Now entering regime of BSM predictions

Interplay

Interplay



- Loads of measurements
- Few with trivial connection to underlying theory parameters
- Strong phases obscure access to mixing parameters

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

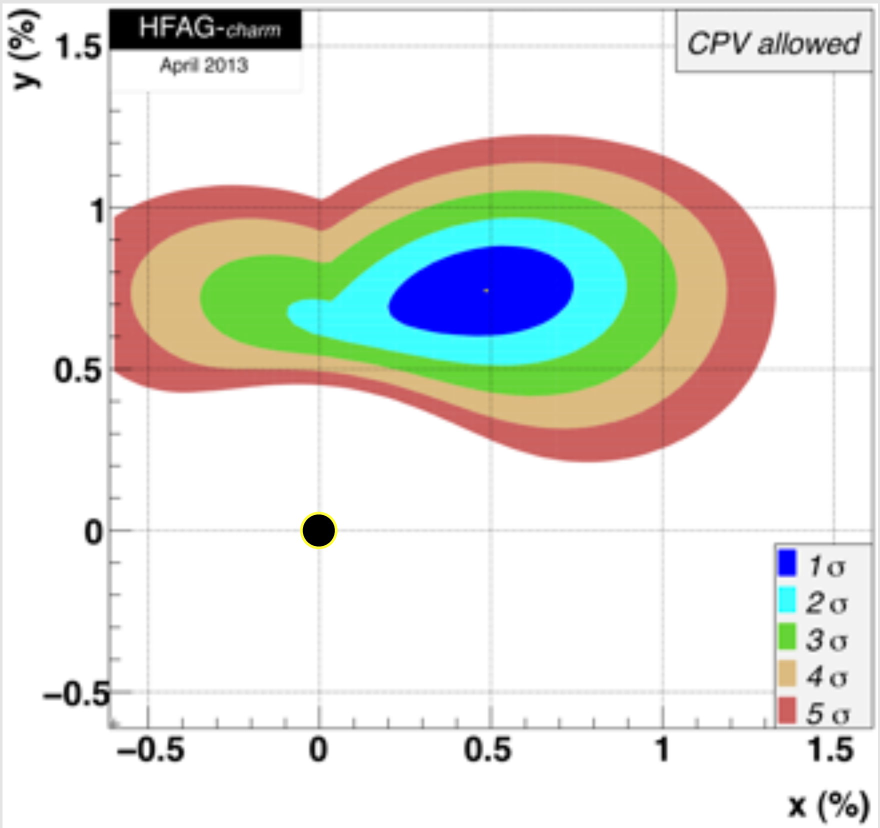
- Interplay of direct and indirect CP violation

$$a_f \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D^0} \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D^0} \to f)} = a_f^d + a^m + a^i$$

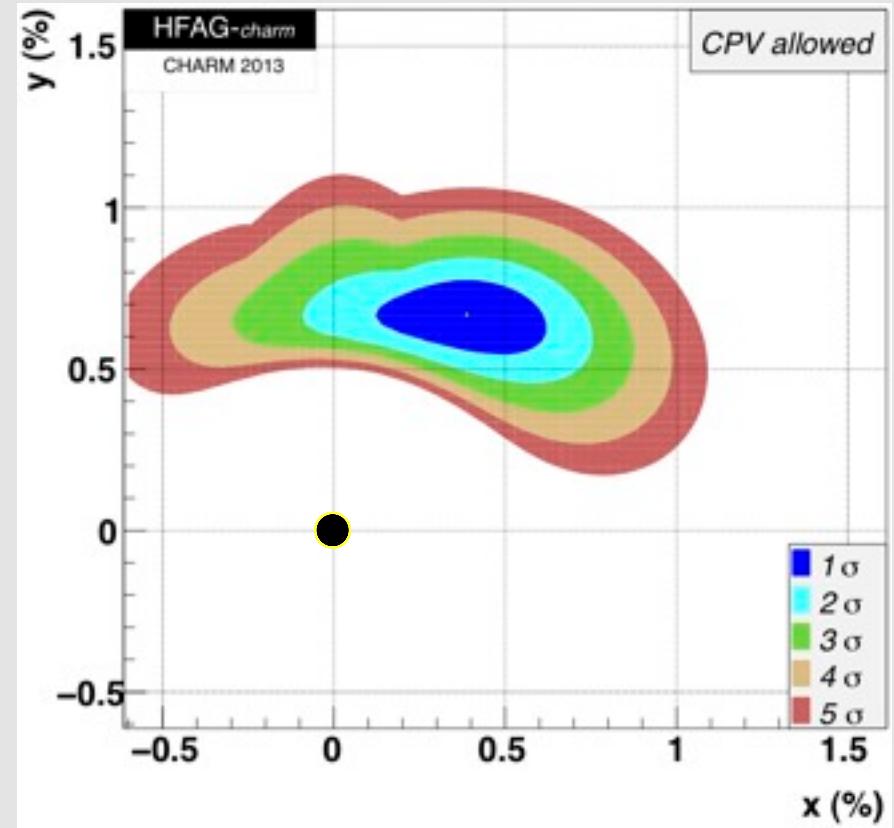
Kagan, Sokoloff

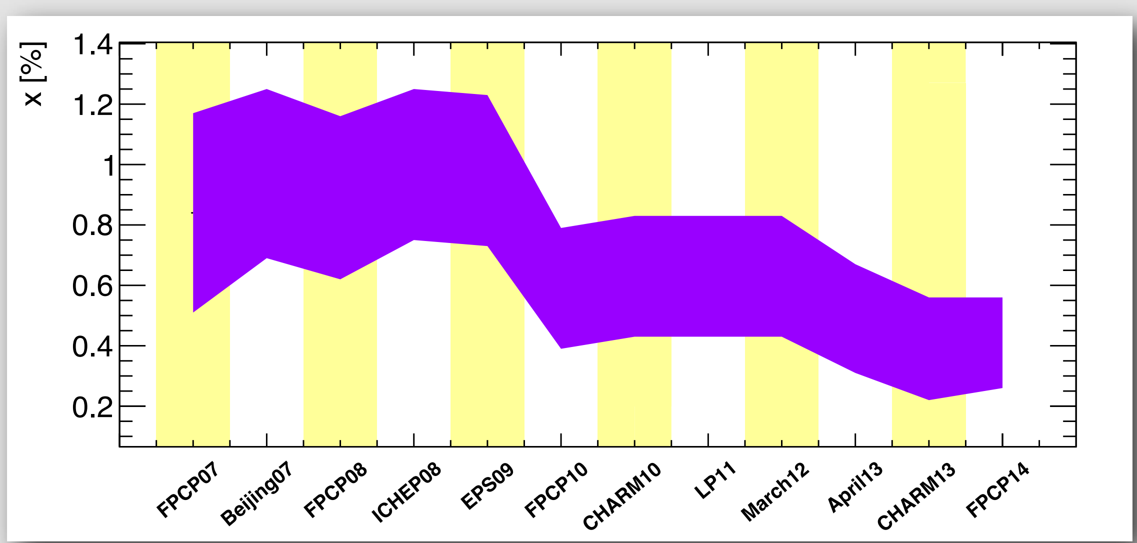
CHARM (r)evolution mixing

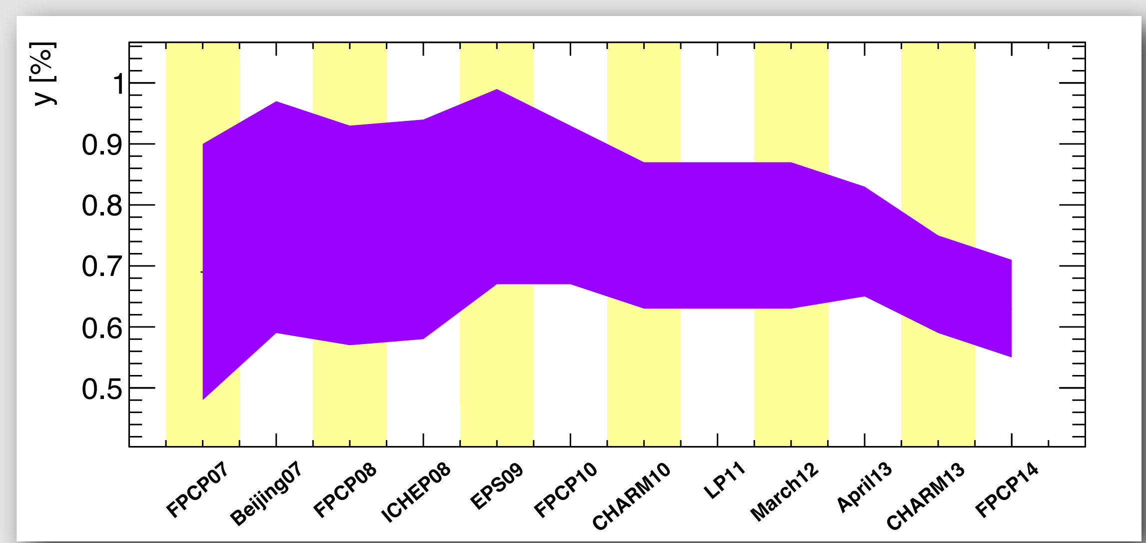
BEFORE



AFTER







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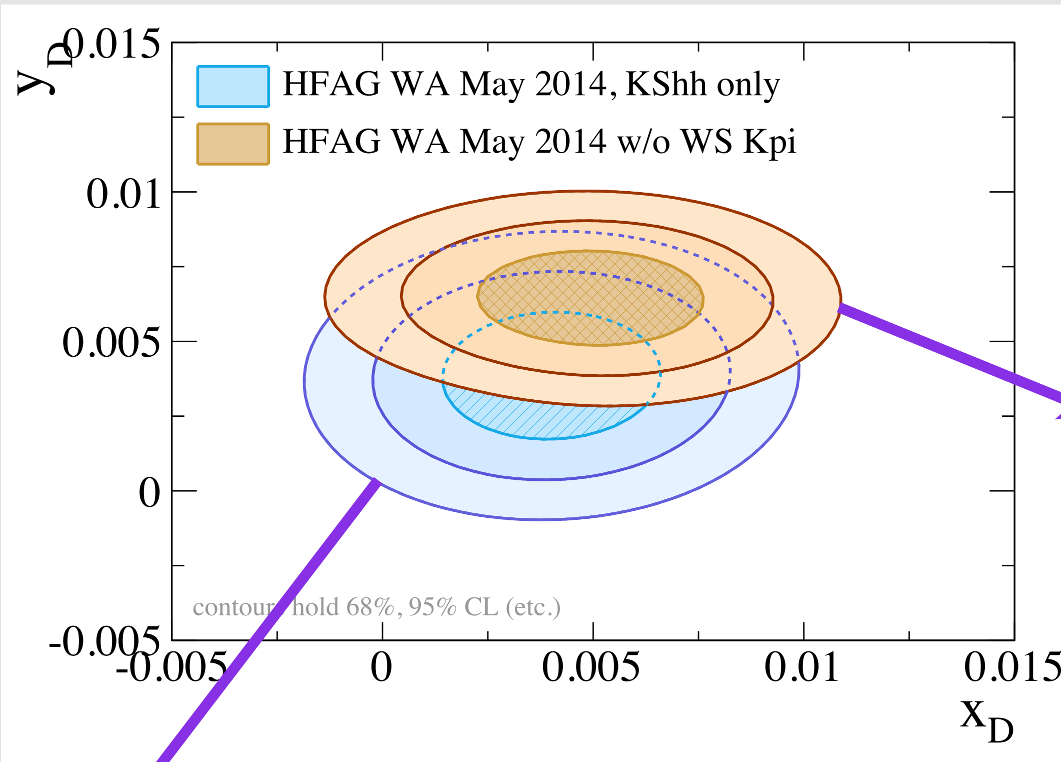
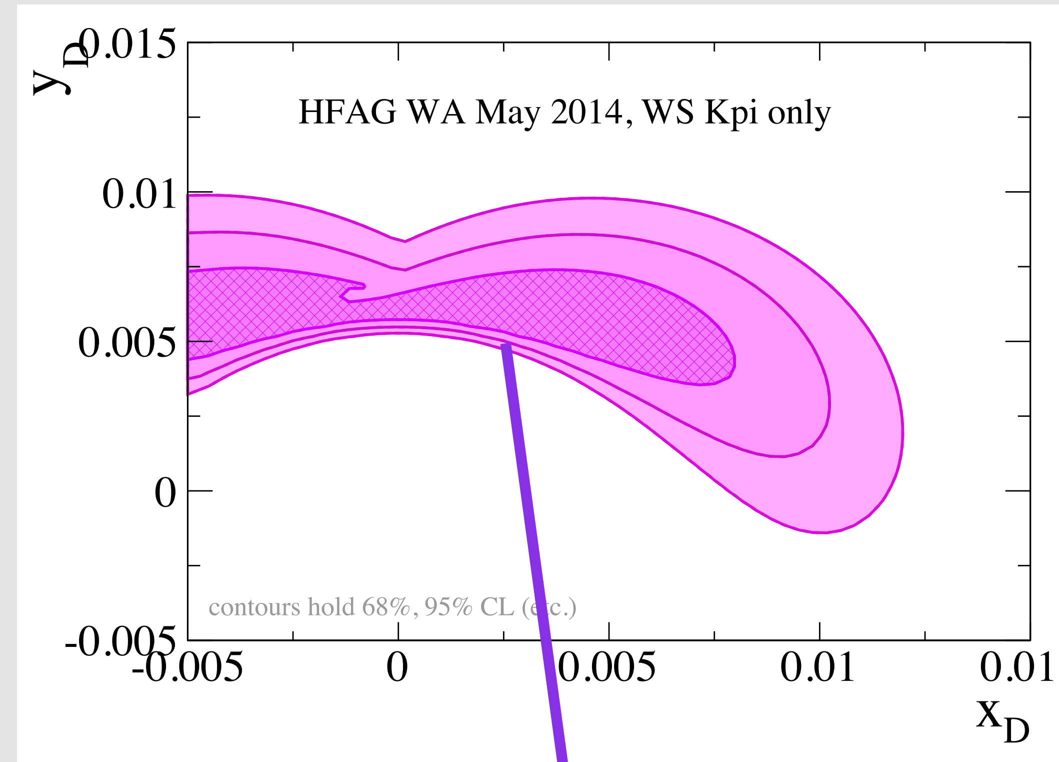
Contributions



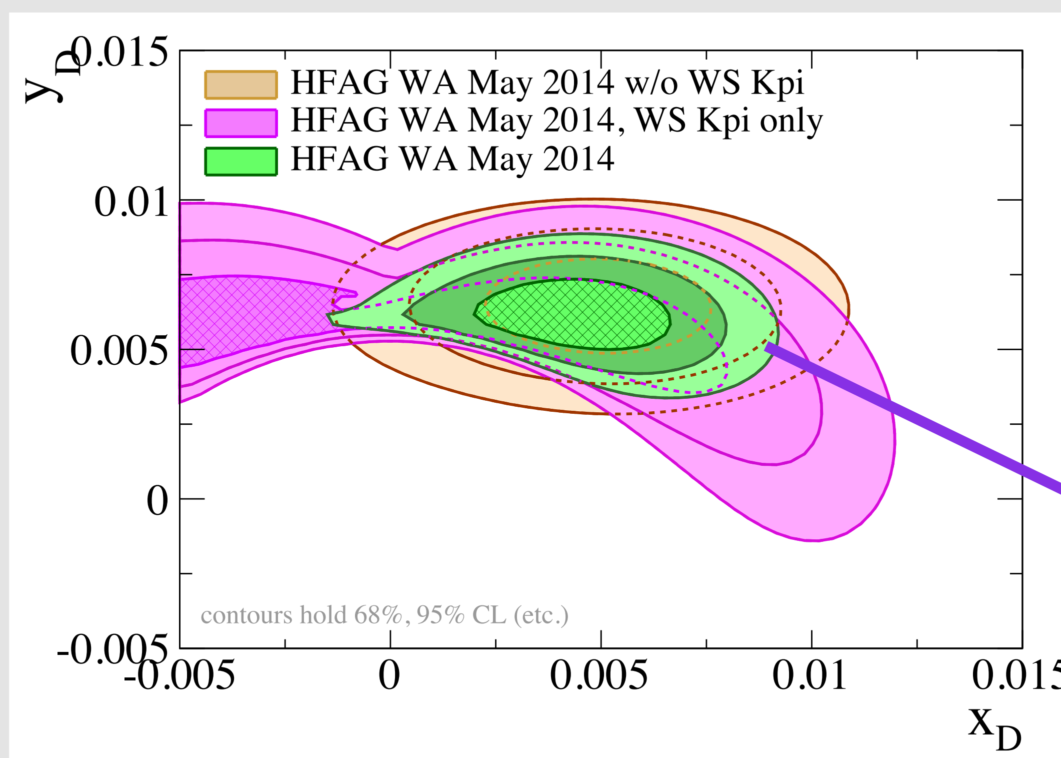


Adding y_{CP} mostly constrains y

x & y measured directly

x^2+y^2 measures a ring

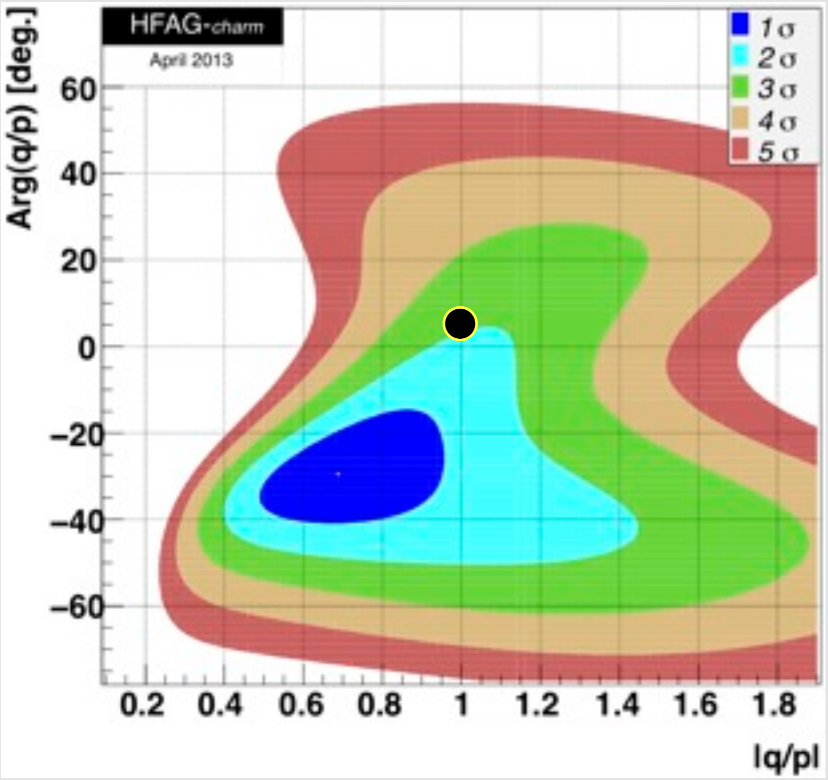
y′ mostly adds information on y ($\delta_{K\pi}$ near 0)



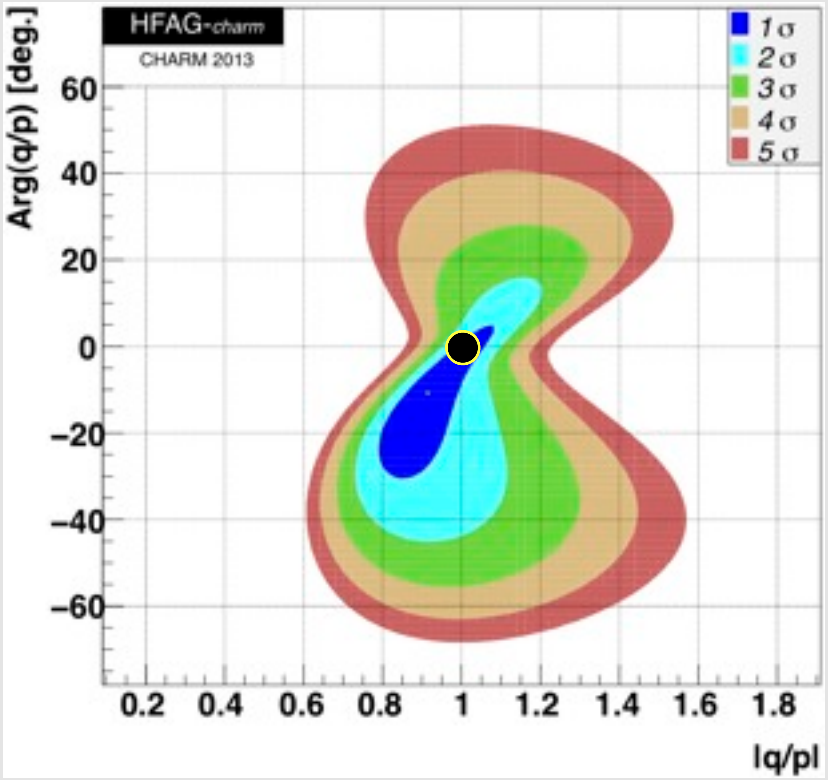
Full average following intersection of contours

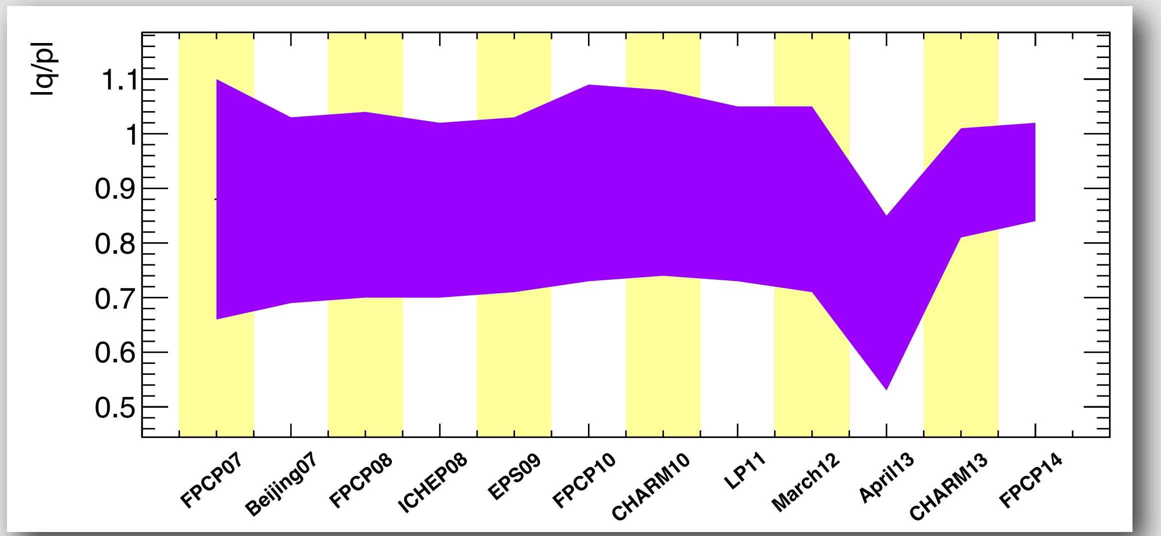
CHARM (r)evolution indirect CPV

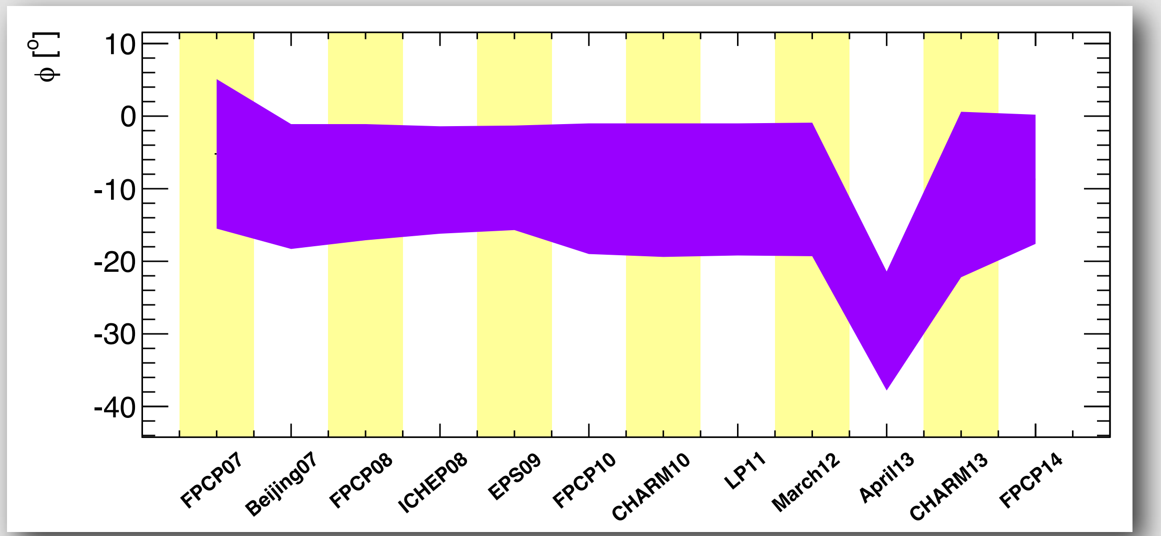
BEFORE



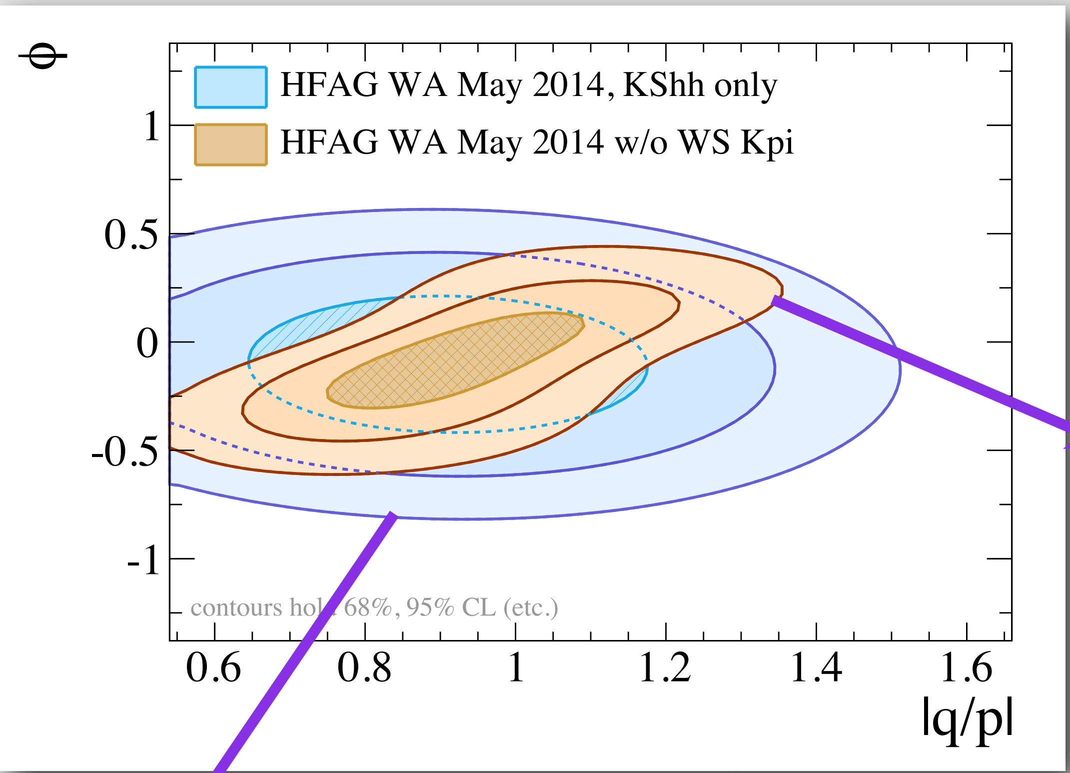
AFTER

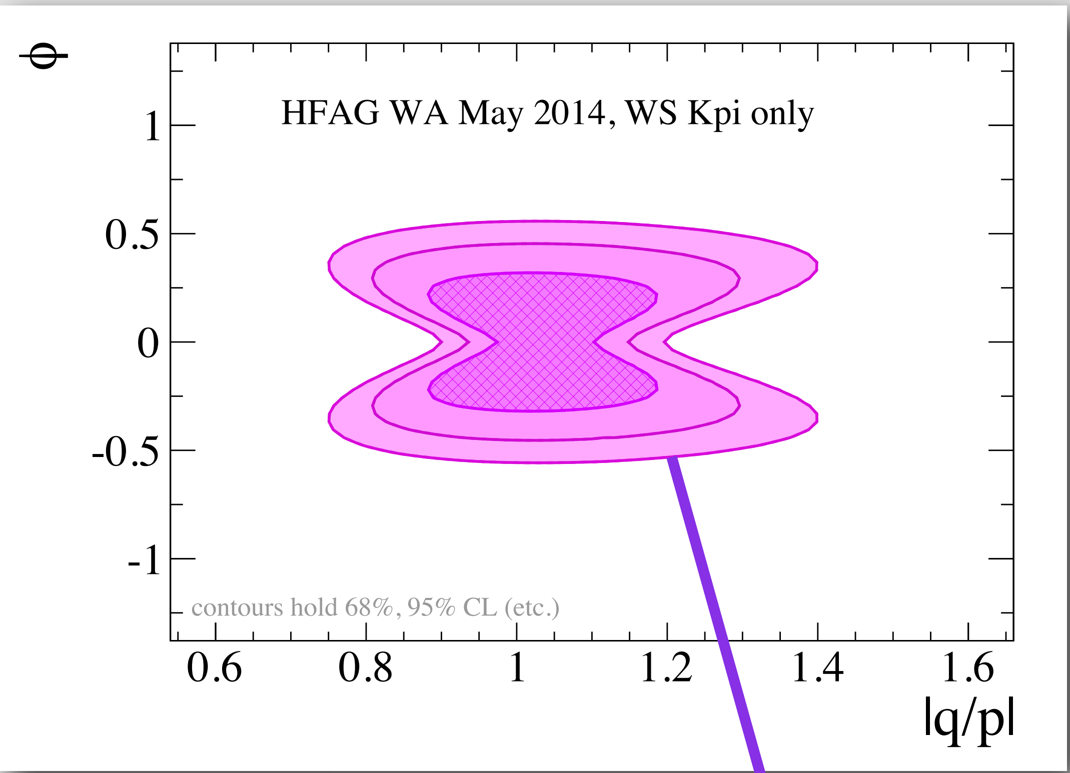






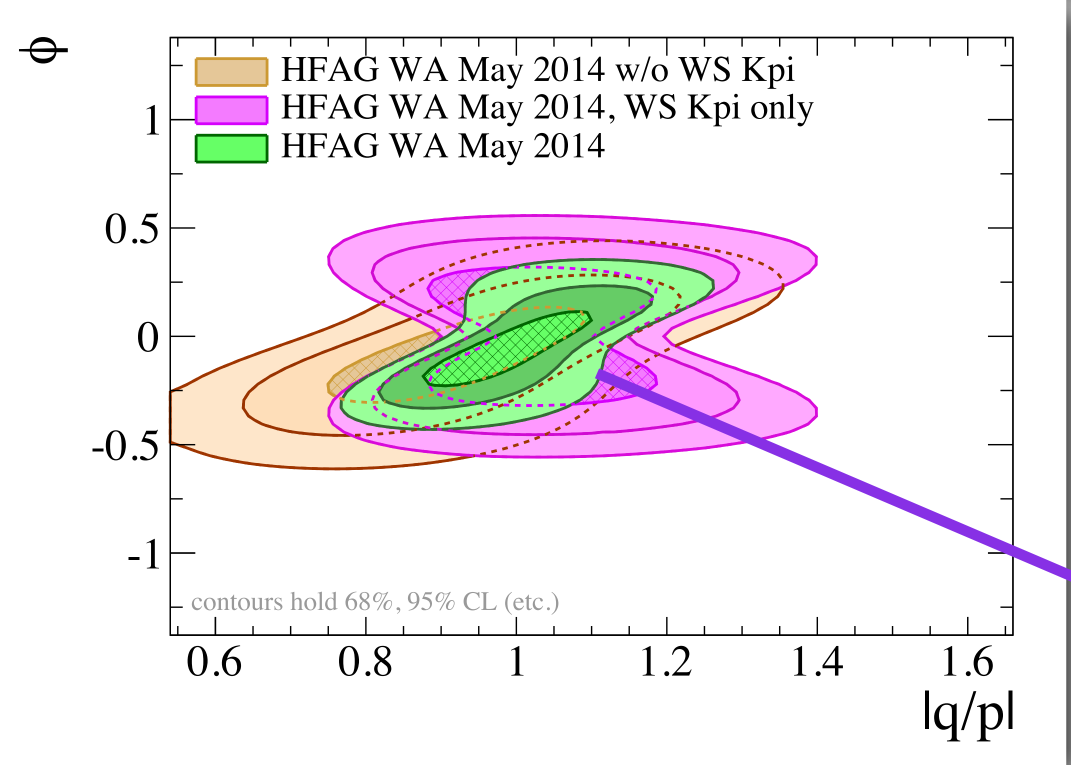
Contributions





Precise constraints if x and y provided, mostly from A_Γ

Direct access to |q/p| and φ from K_Shh



WS Kπ: symmetric in φ,

good sensitivity to |q/p| for small φ

Full average following intersection of contours

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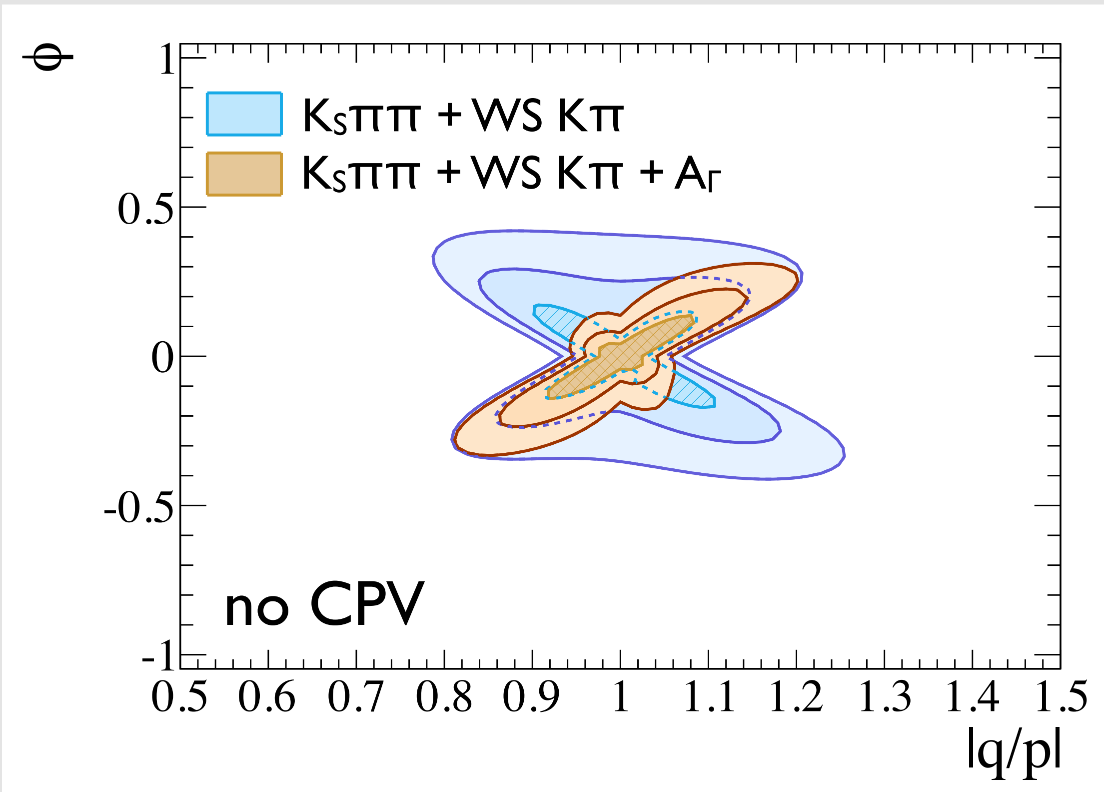
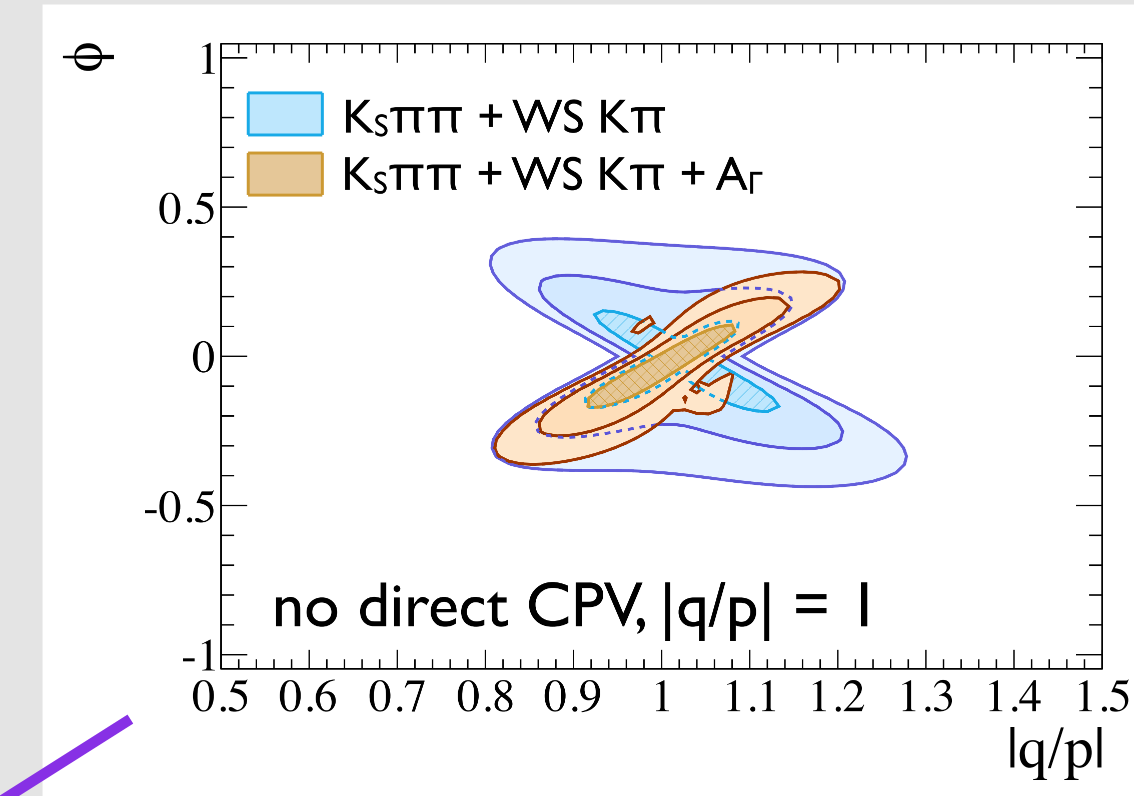
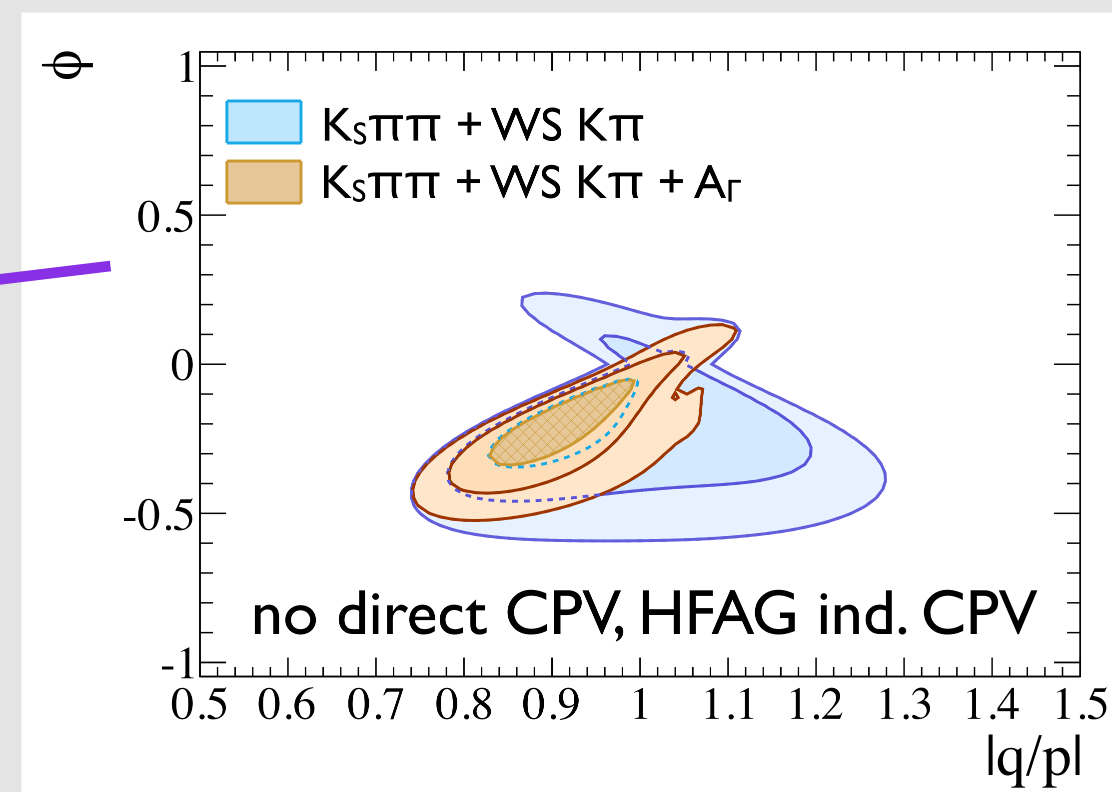
Different central values

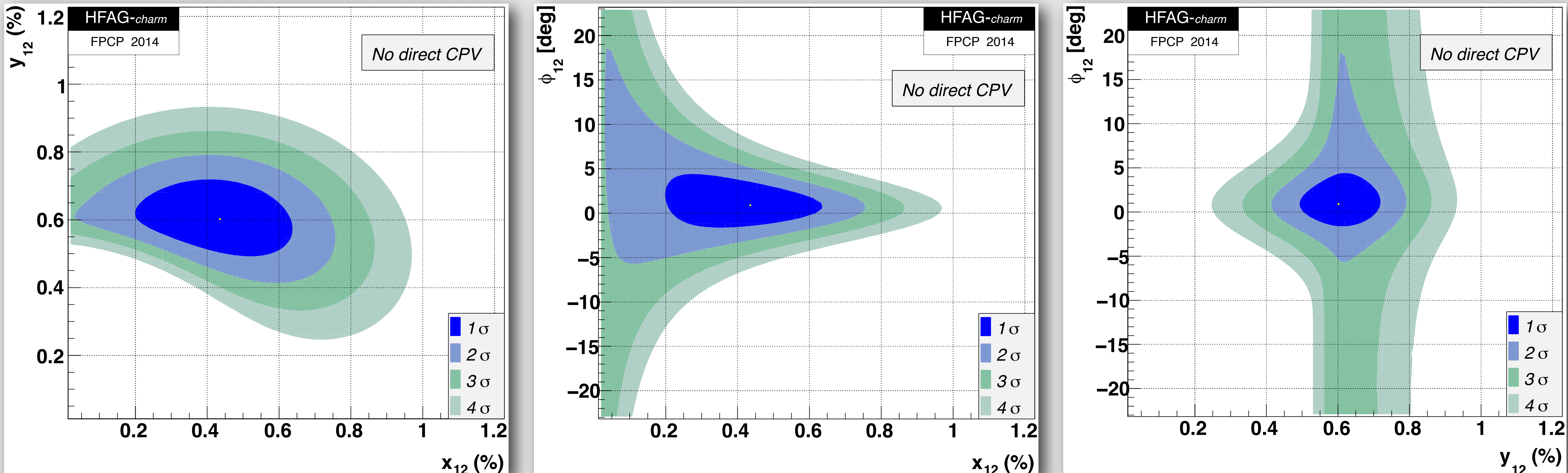






same central values for A_Γ

Super-weak approximation



- Assume no direct CPV in DCS decays
- Can reduce 4 observables to 3 using
  - ➡ $\tan\varphi = (1-|q/p|^2)/(1+|q/p|^2) \times (x/y)$
- Gives much improved sensitivity
  - ➡ $\sigma(q/p)$ reduced from 8.7% to 1.4%
  - ➡ $\sigma(\varphi)$ reduced from 8.9° to 0.6°
  - ➡ Still no sign of indirect CP violation

Alternatively re-write set of parameters as x_{12}, y_{12}, φ_{12} as shown in plots

x_{12} (%)	$0.43^{+0.14}_{-0.15}$
y_{12} (%)	0.60 ± 0.07
$\phi_{12}(°)$	$0.9^{+1.9}_{-1.7}$

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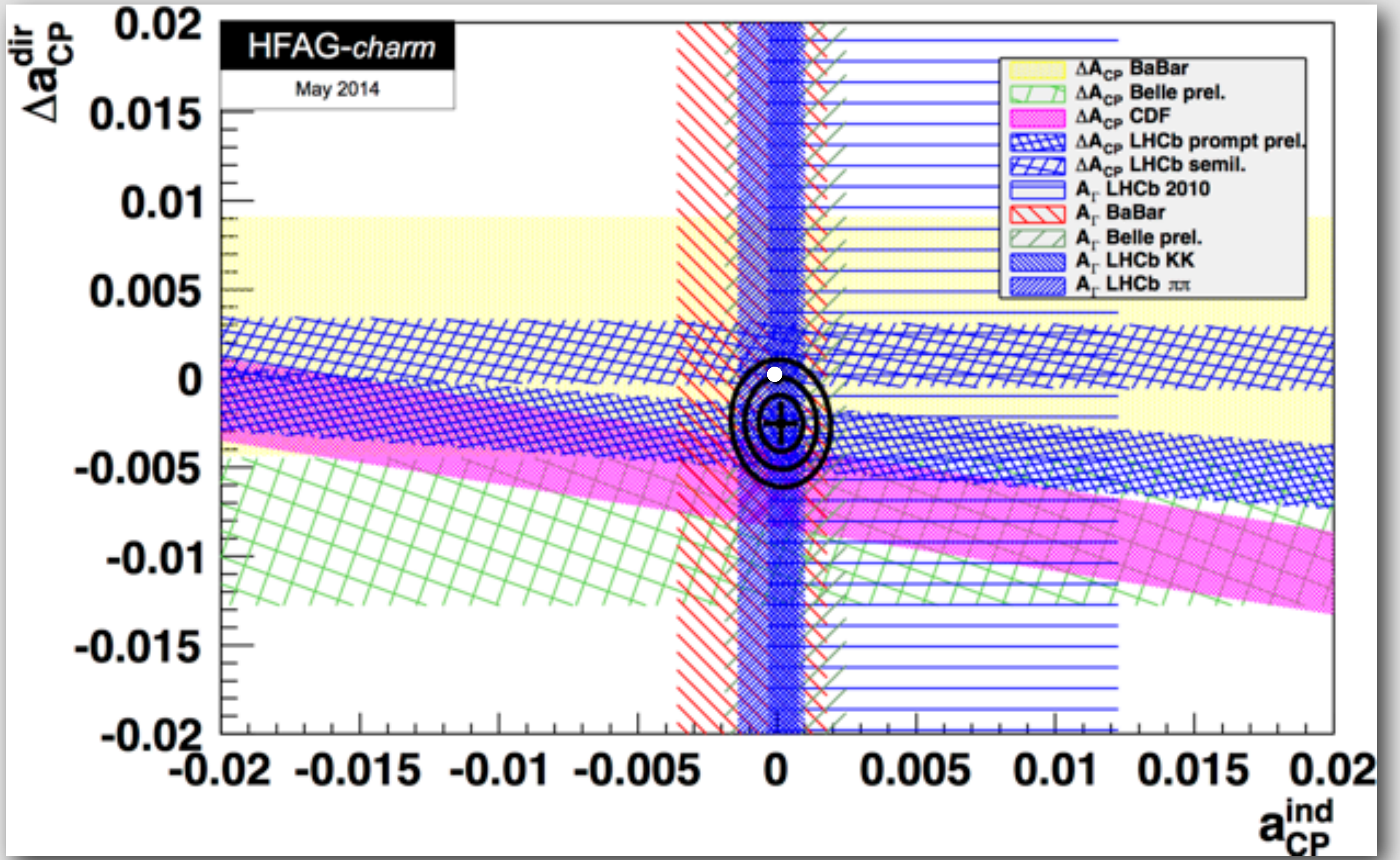
Direct vs indirect



- Results:
  - ➡ $a_{CP}^{ind} = (0.013 \pm 0.052)\%$; $\Delta a_{CP}^{dir} = (-0.253 \pm 0.104)\%$
  - ➡ no CPV $\Delta\chi^2 = 5.9$; corresponds to CL of 5.1×10^{-2}

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Towards a charming future

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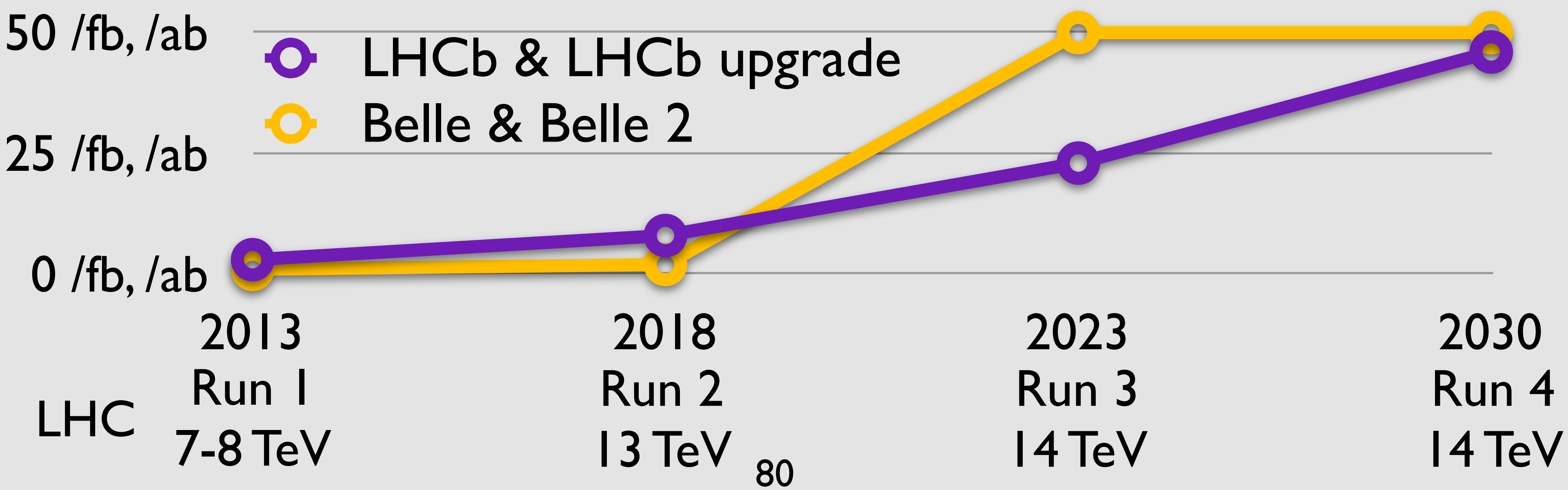
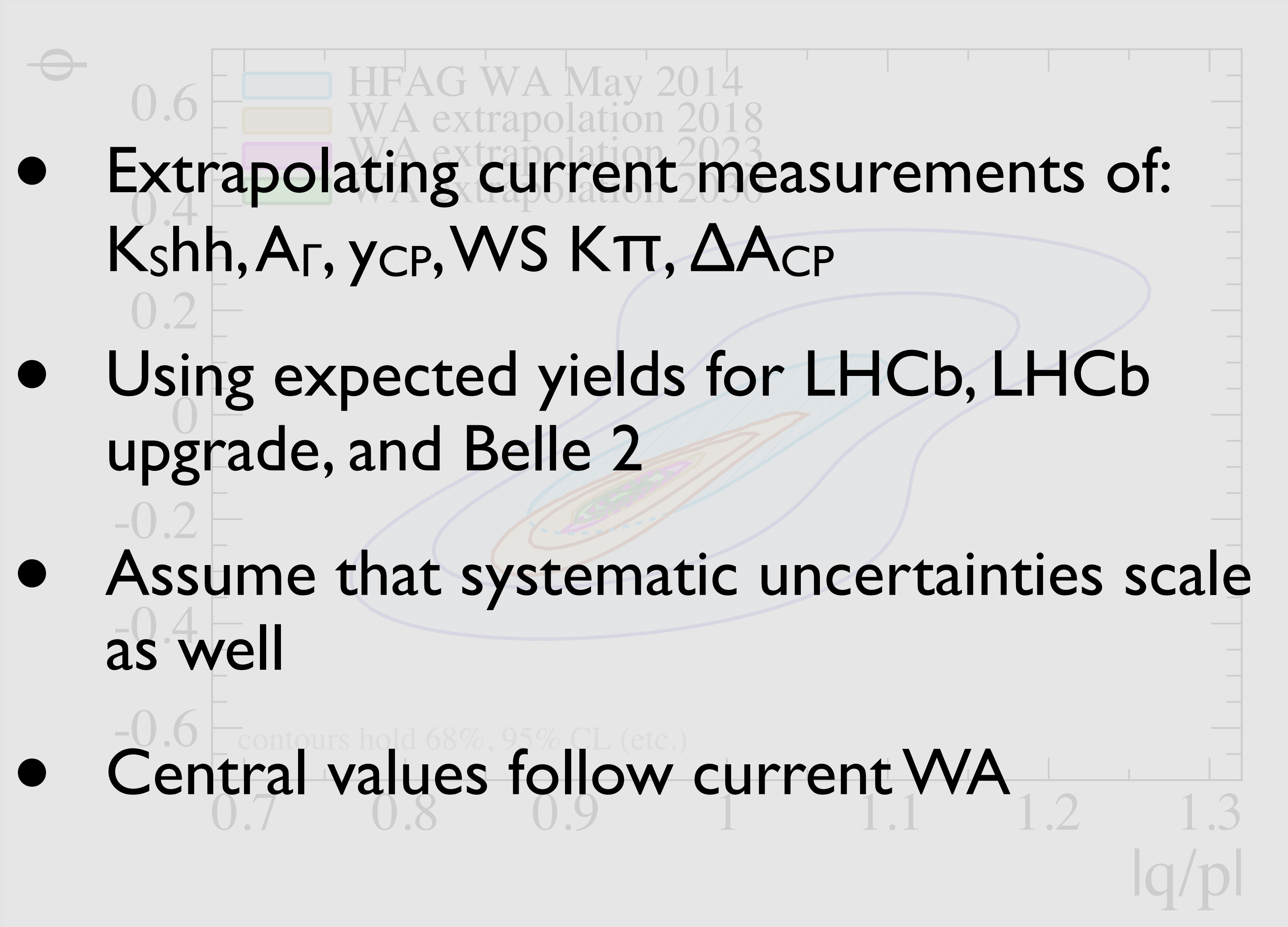
The agenda

- Charm physics has proven to be successful at both e^+e^- and hadron colliders
- Expect most measurements to be statistics limited and most question to remain open
- Next generation experiments: precision charm physics
  - ➡ Belle 2 construction underway →see talk by P. Krizan tomorrow
  - ➡ LHCb upgrade in R&D stage

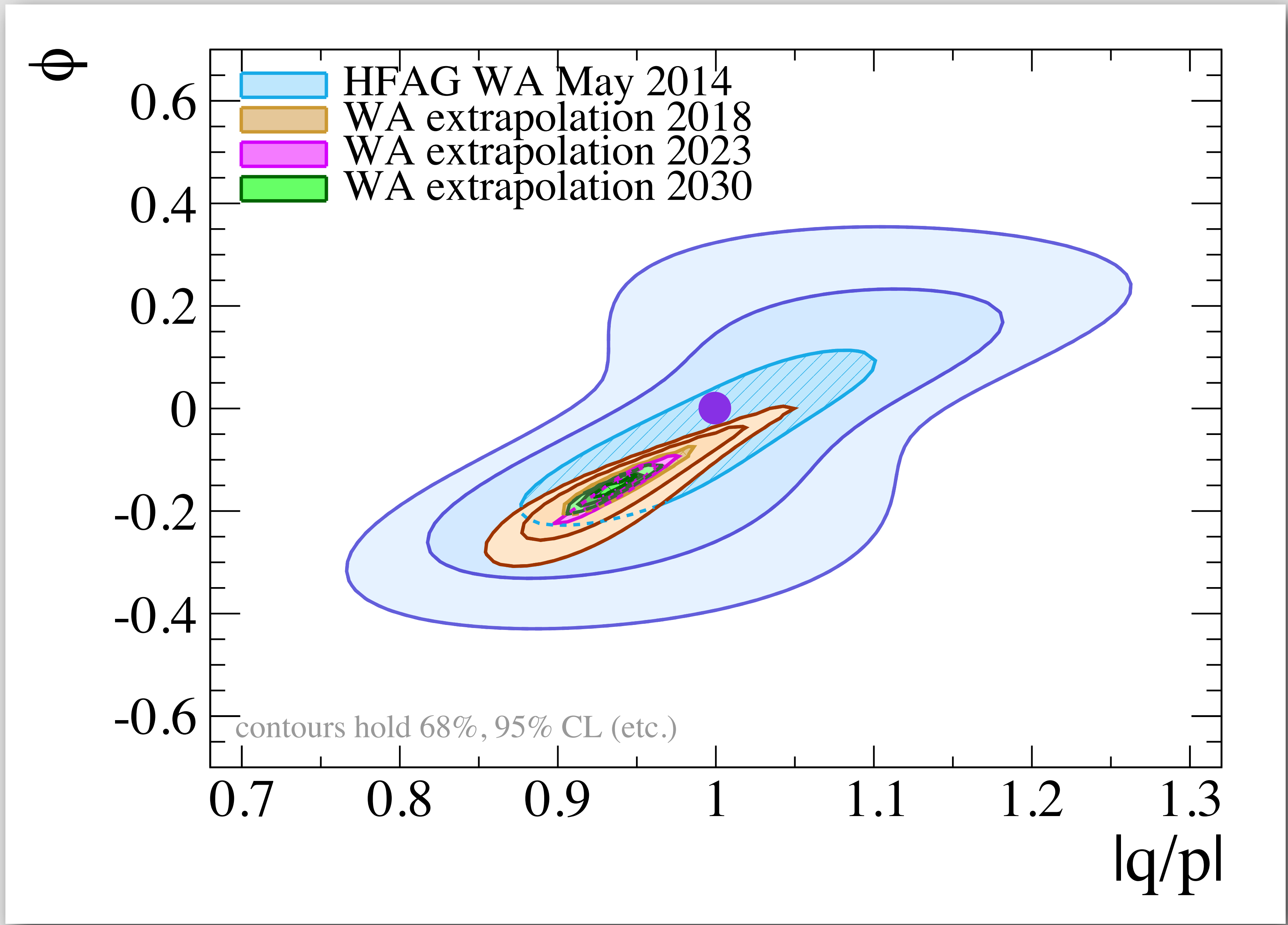


Future

- Extrapolating current measurements of: $K_S hh$, A_Γ, y_{CP}, WS $K\pi$, ΔA_{CP}
- Using expected yields for LHCb, LHCb upgrade, and Belle 2
- Assume that systematic uncertainties scale as well
- Central values follow current WA

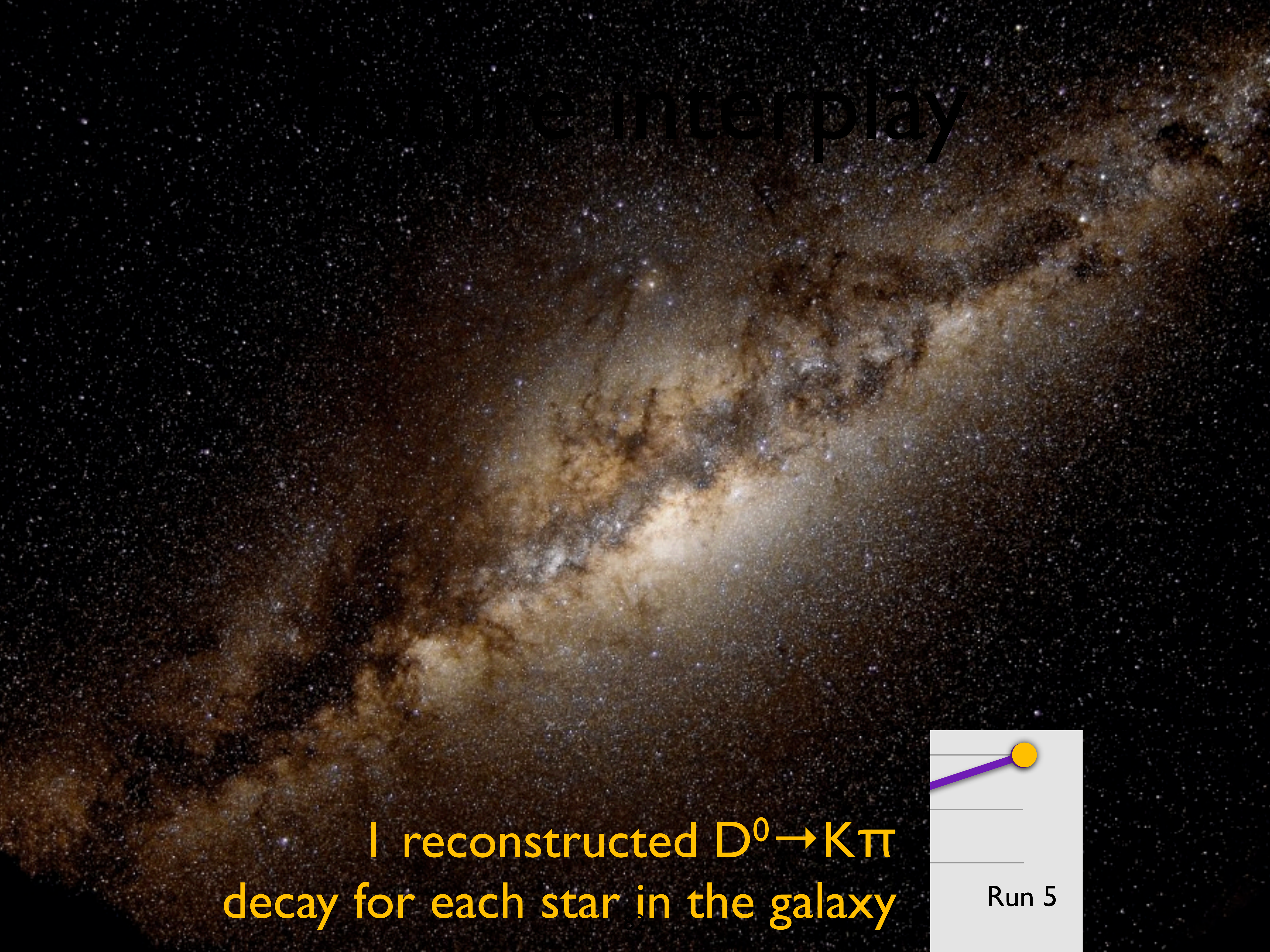


Future



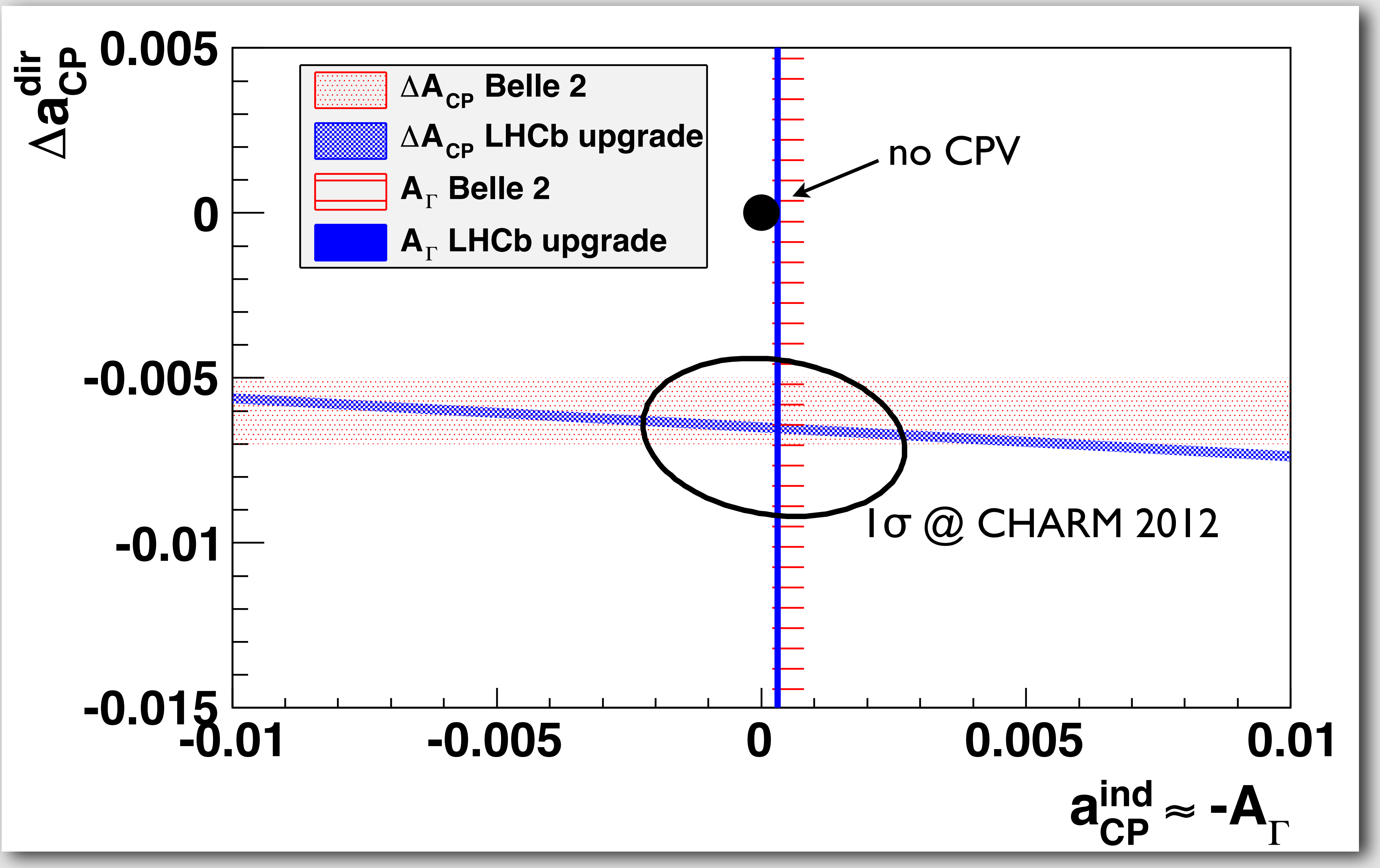
- No indirect CPV 2014: $\Delta\chi^2 = 1.3$
- No indirect CPV 2030: $\Delta\chi^2 = {\sim}670$

interplay



1 reconstructed $D^0 \rightarrow K\pi$
decay for each star in the galaxy

Future interplay - II



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Conclusions

- Charm physics has received precision input from hadron colliders
- Large advances in searches for CP violation
  - ➡ Reached sub-10^{-3} precision
  - ➡ Also large numbers of charm baryons available
- Need combination of measurements to
  - ➡ Extract mixing and indirect CPV parameters
  - ➡ Identify source of possible direct CPV
- Experimental upgrade programmes, particularly LHCb upgrade, vital for charm physics

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Further reading

- Review articles
  - ➡ MG, *Brief review of charm physics*, MPLA 27 (2012) 1230026
  - ➡ M.J. Morello, *Measurement of CP Violation in $D^0/\overline{D}^0$*, MPLA 27 (2012) 1230039
  - ➡ A. Correa Dos Reis, E. Polycarpo, *Review of Recent Results on Charm Mixing and CP violation*, IJMPA (2014)
- Textbooks
  - ➡ M.S. Sozzi, *Discrete symmetries and CP violation: From experiment to theory*, OUP (2008)
  - ➡ I.I. Bigi, A.I. Sanda, *CP violation*, 2nd edition, CUP (2009)

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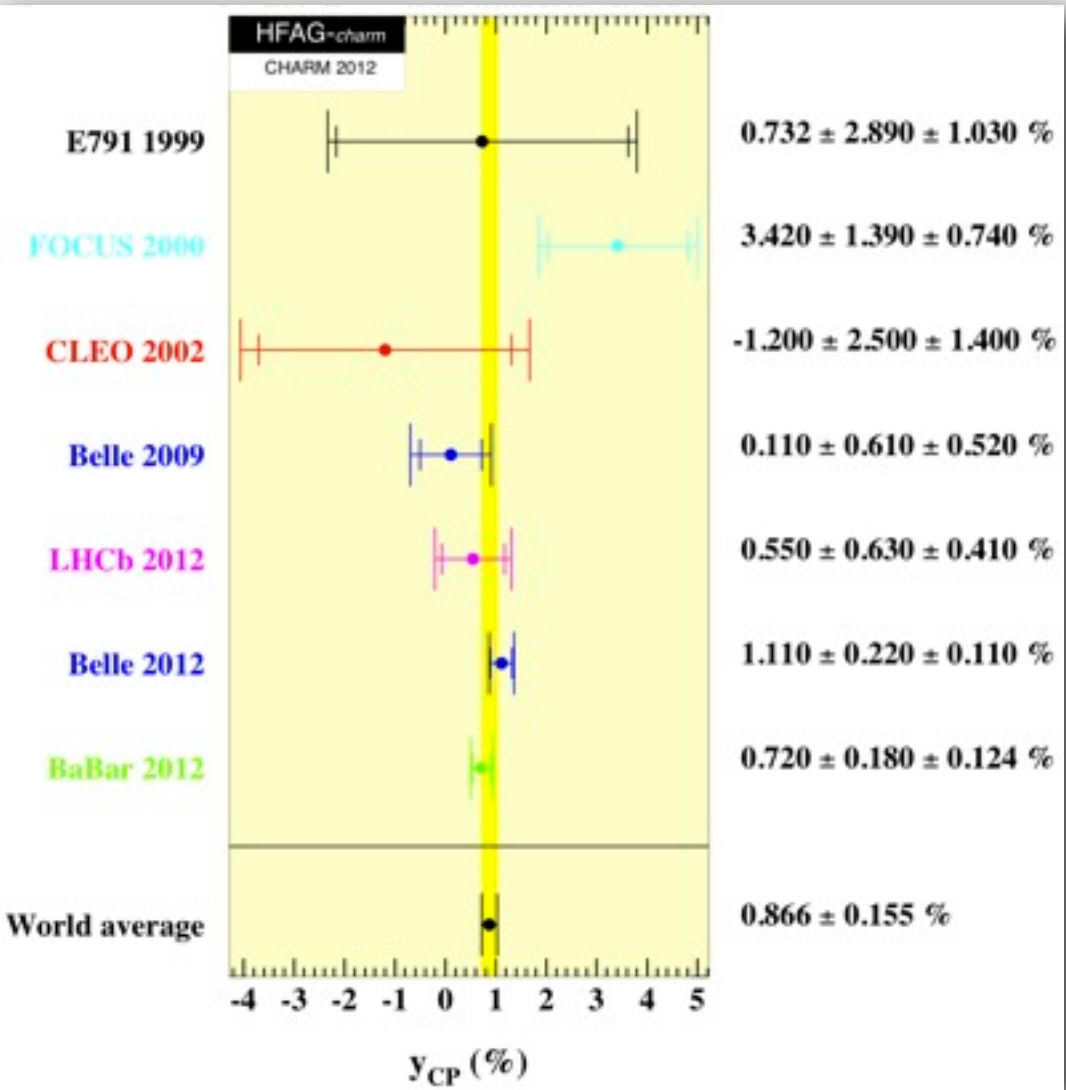
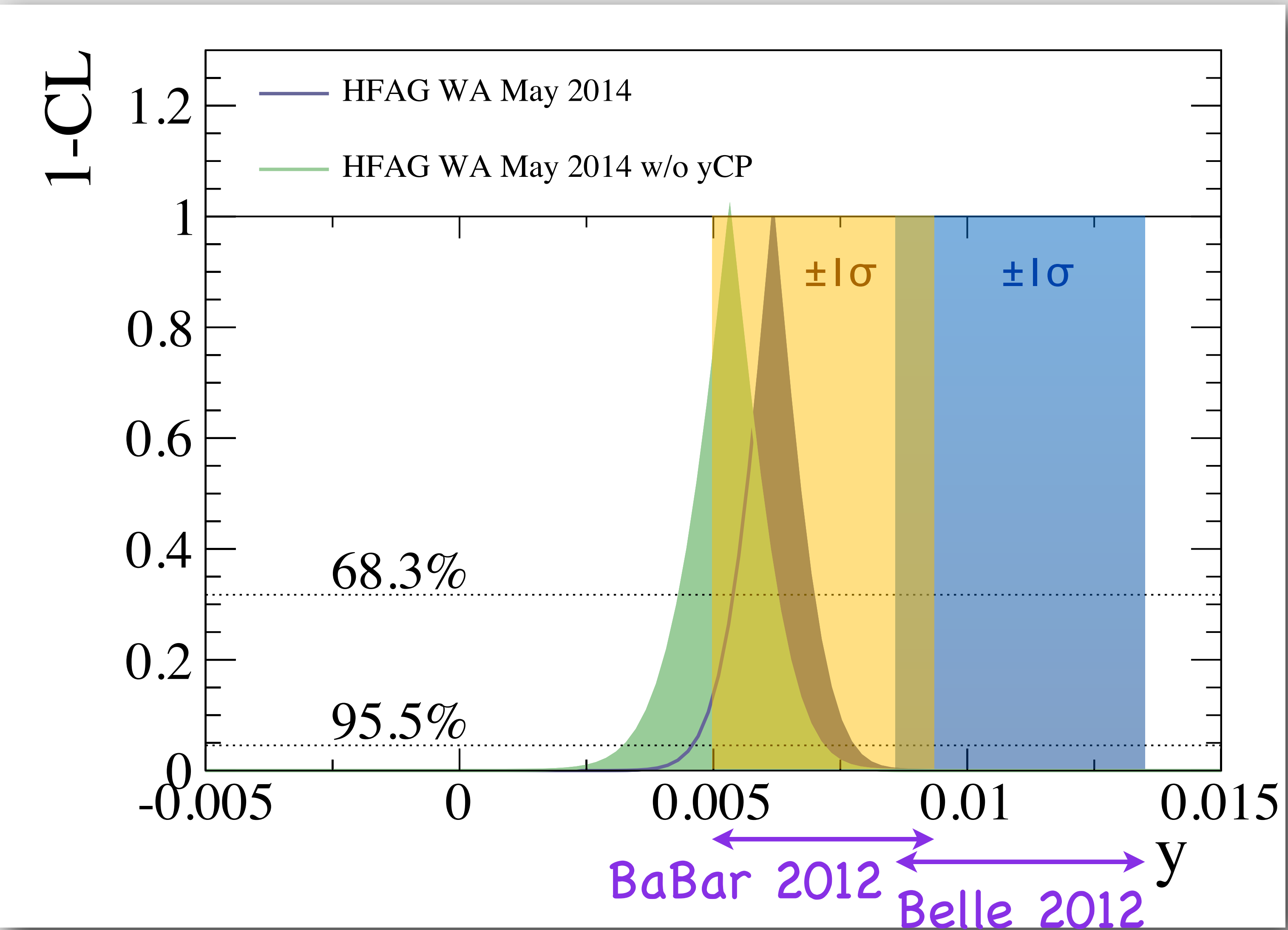
BACKUP

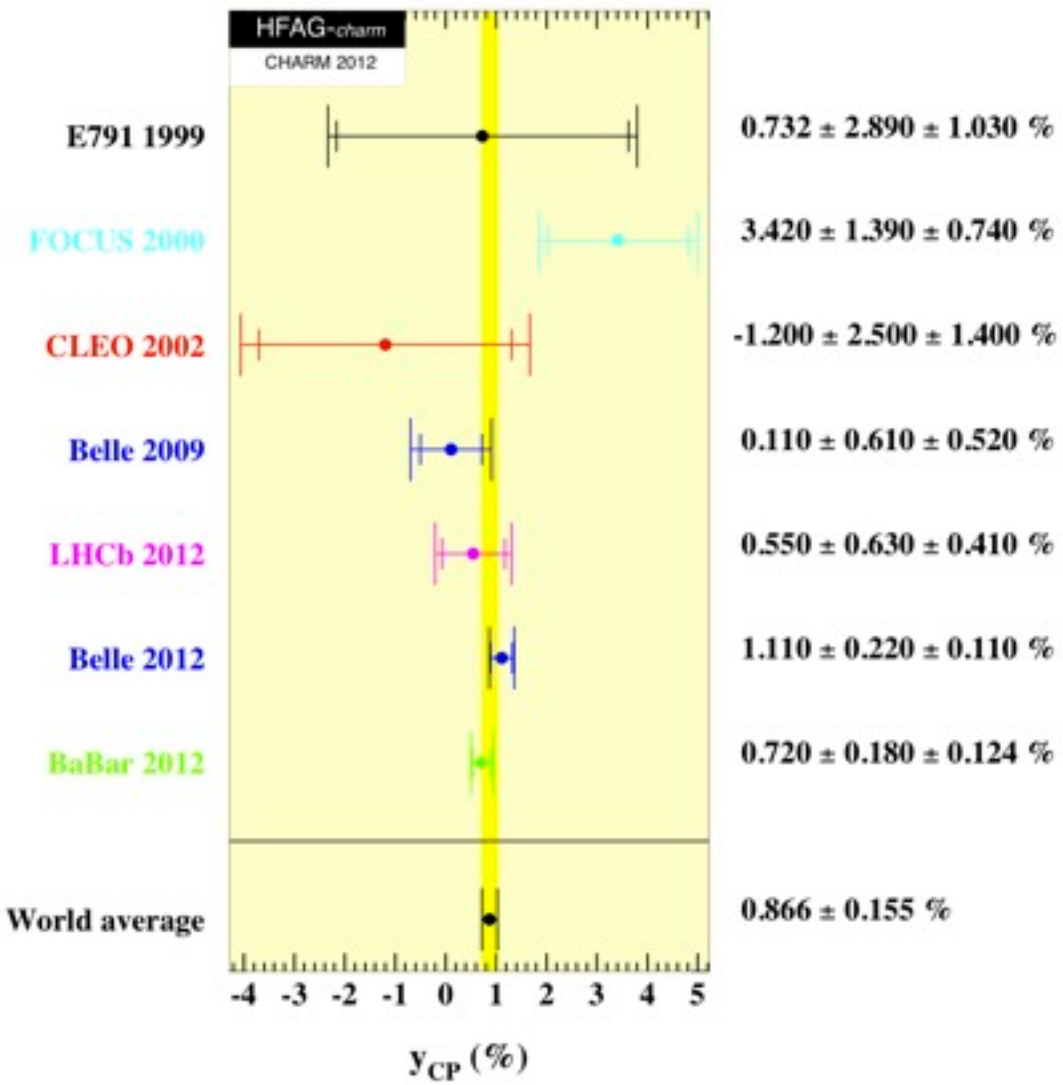
Is $y_{CP} > y$?

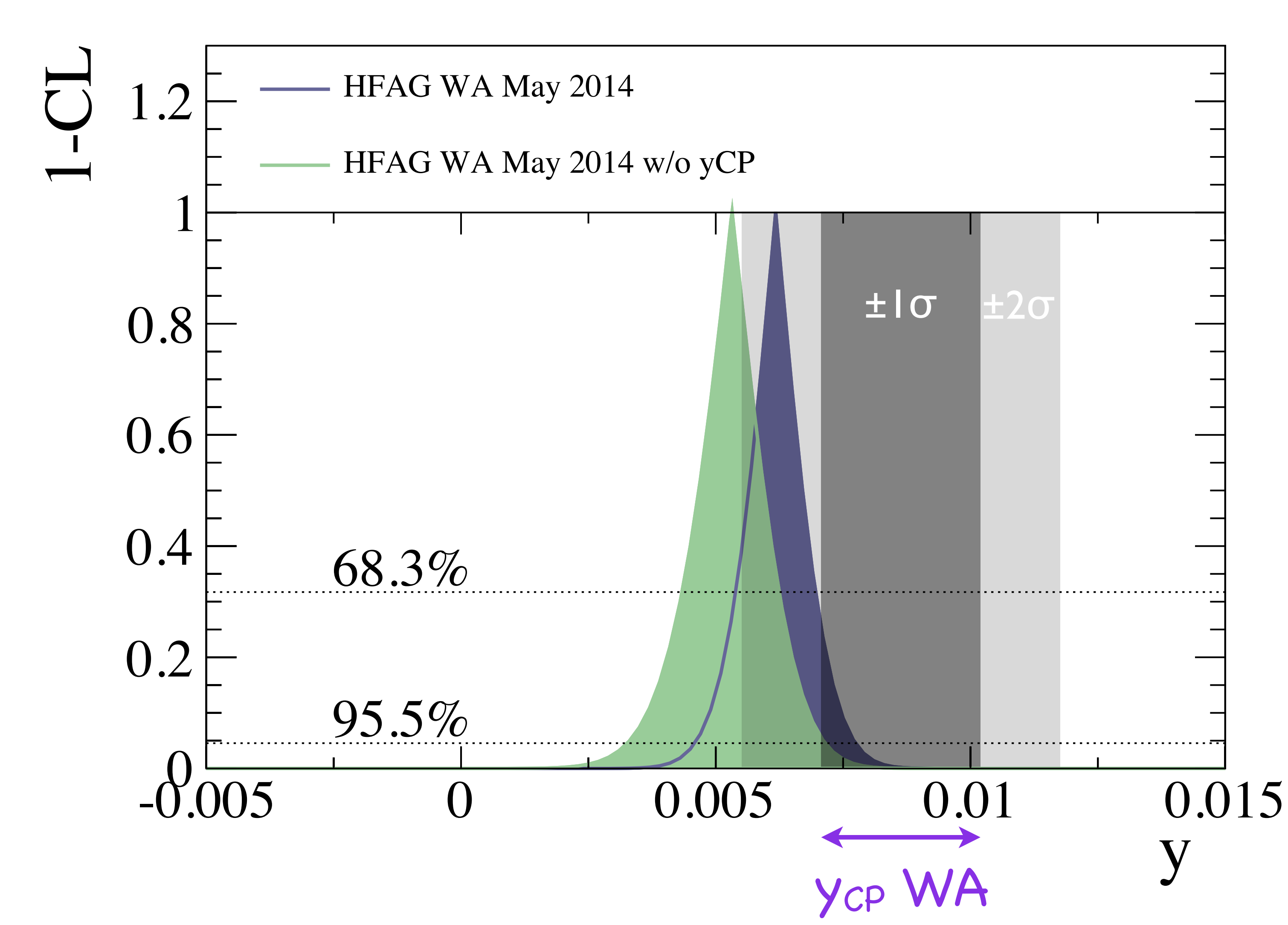




- Not significantly
- Largest tension ~2.2σ between Belle y_{CP} and WA of y without using y_{CP}

Is $y_{CP} > y$?





- Not significantly
- Largest tension ~2.2σ between Belle y_{CP} and WA of y without using y_{CP}