Charm physics

Marco Gersabeck (The University of Manchester)

IoP HEPP Group Prize talk

IoP HEPP Group Meeting, Bristol, 28/3/2018

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Outline

- Part I
  - ➡ From past to present
- Part II
  - ➡ Where to next?

The very beginning

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

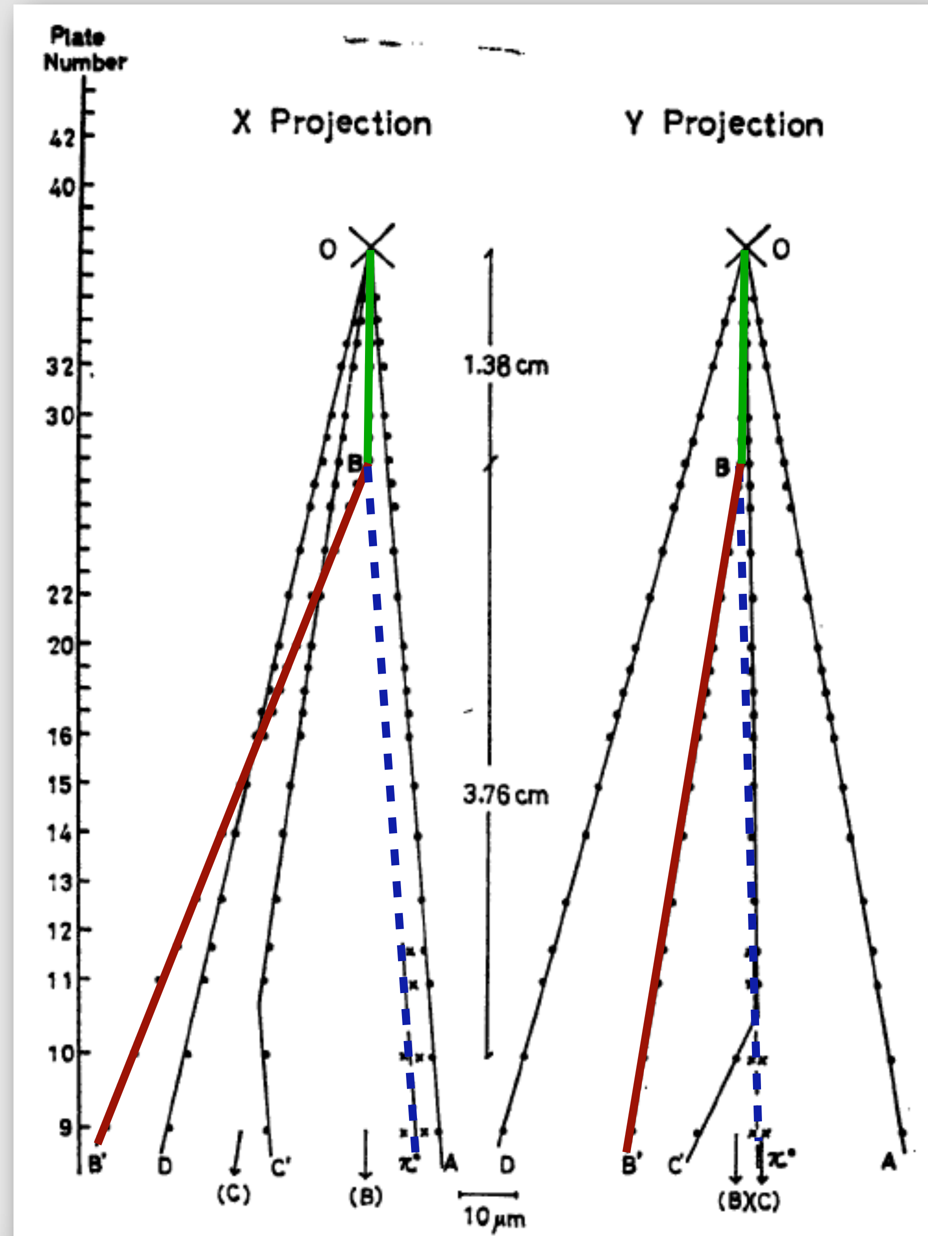
A Possible Decay in Flight of a New Type Particle

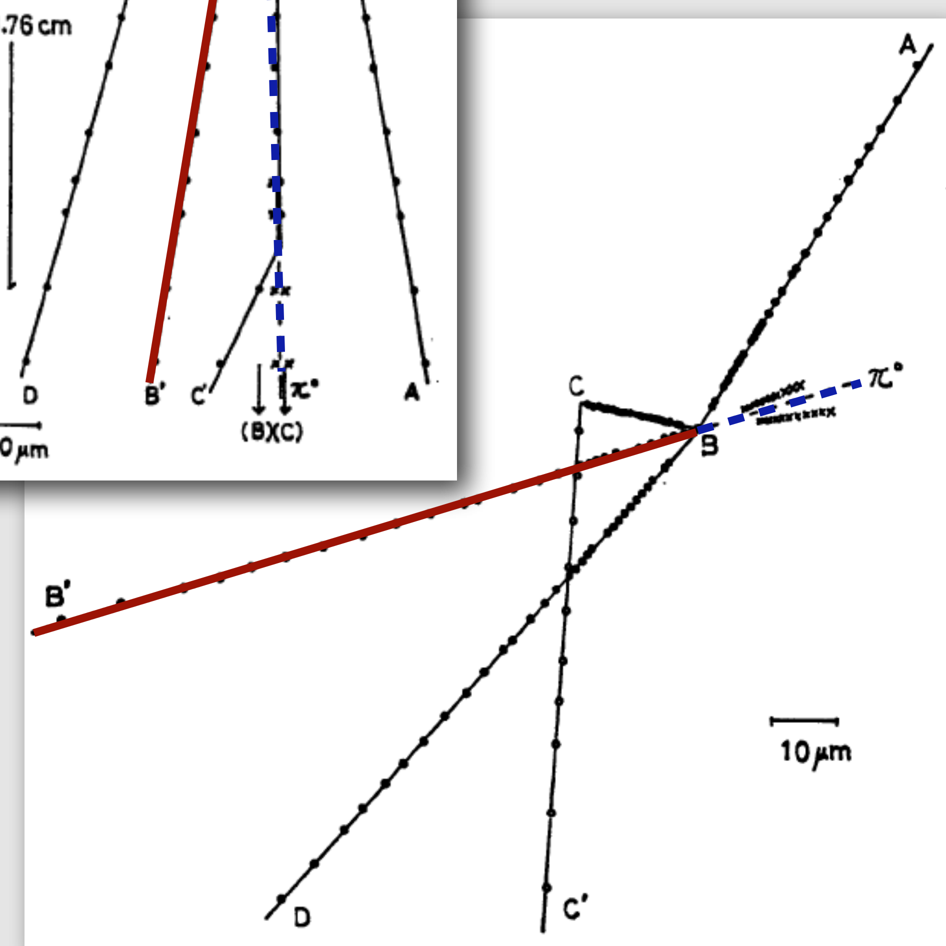
Kiyoshi NIU, Eiko MIKUMO and Yasuko MAEDA*

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}

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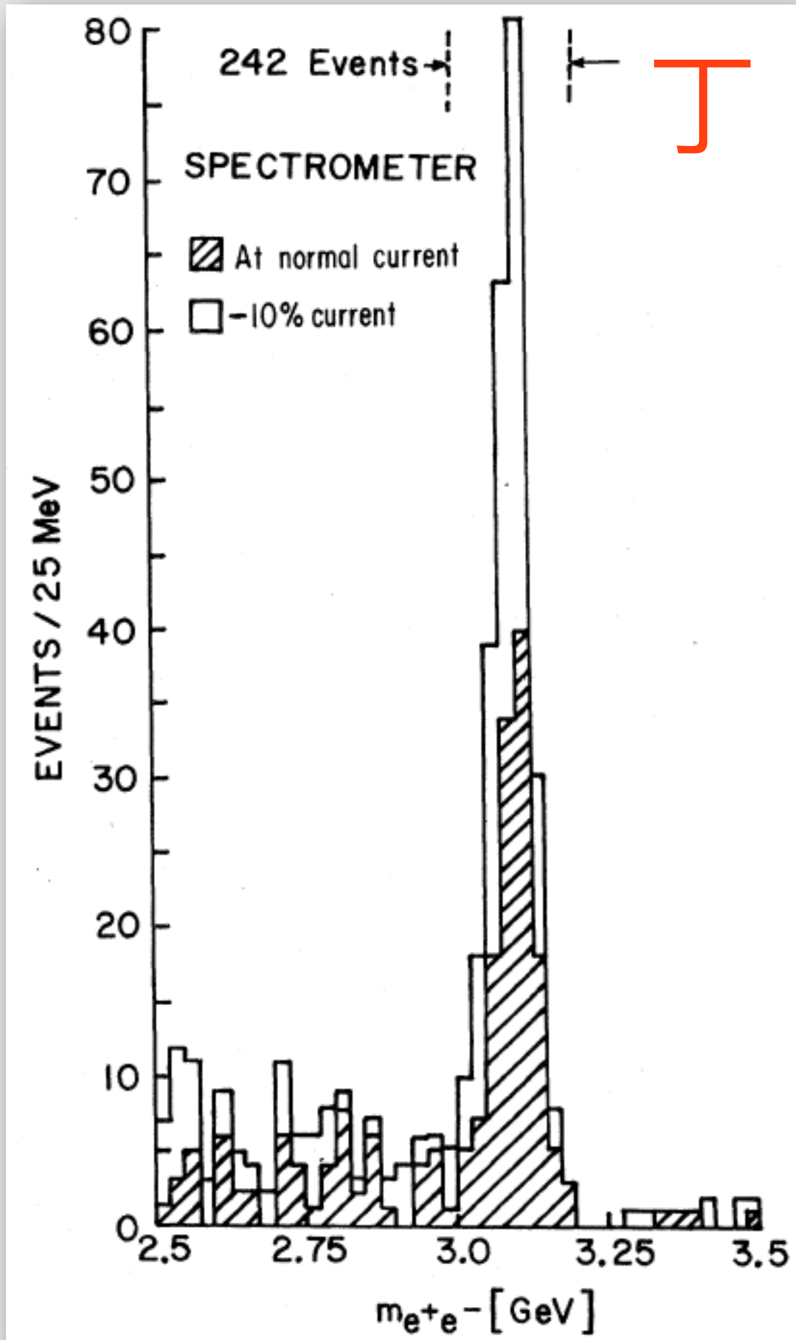
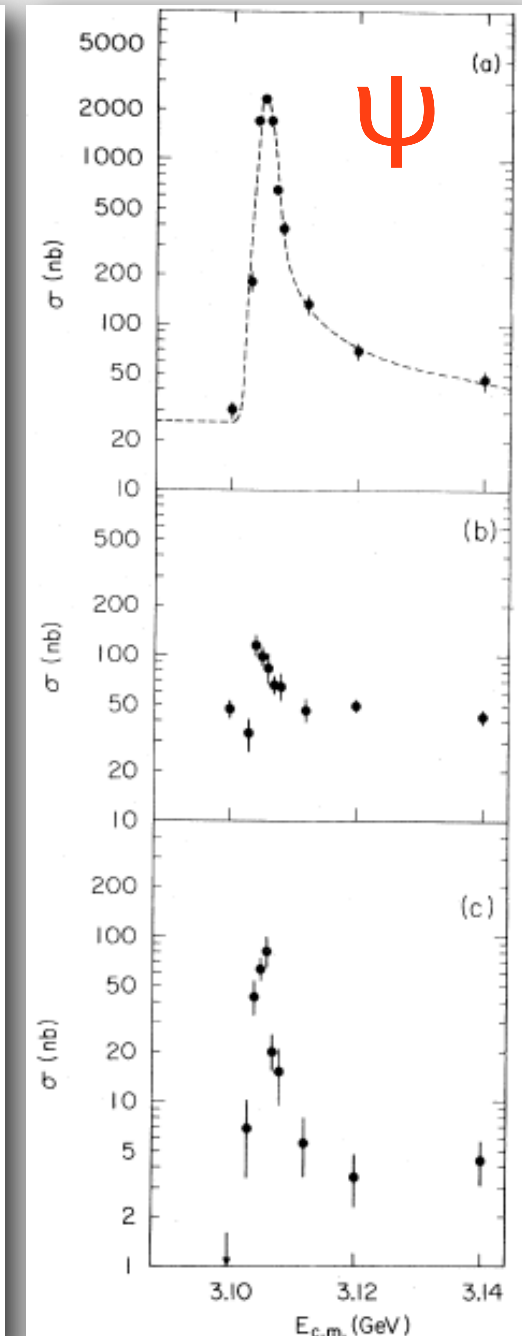
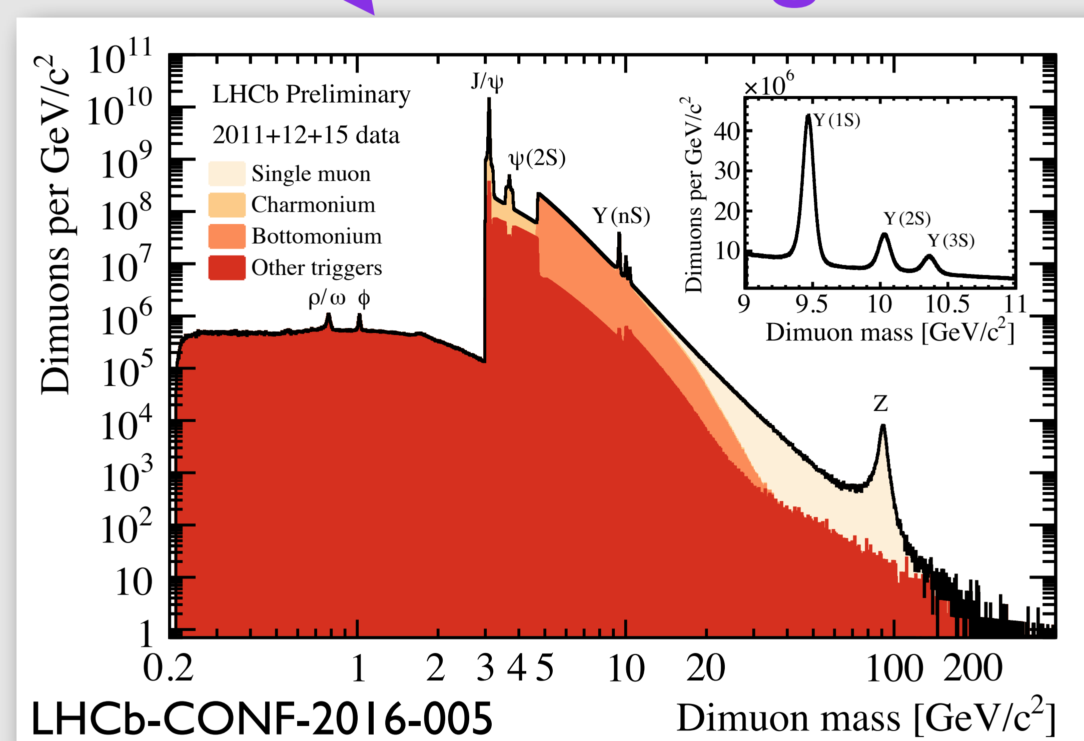
Charmonium





+42 years

+8 orders of magnitude



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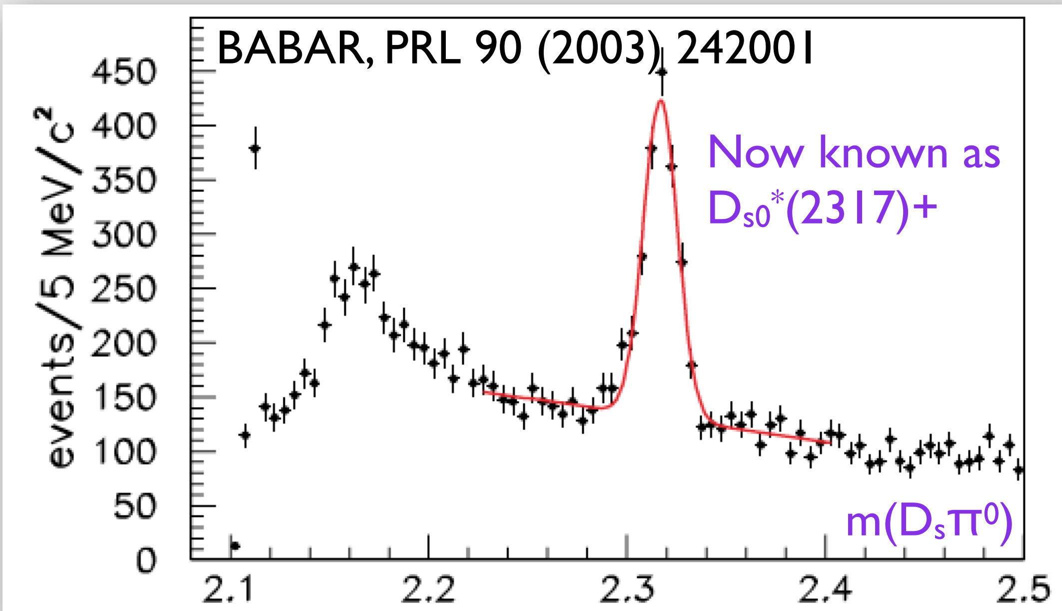
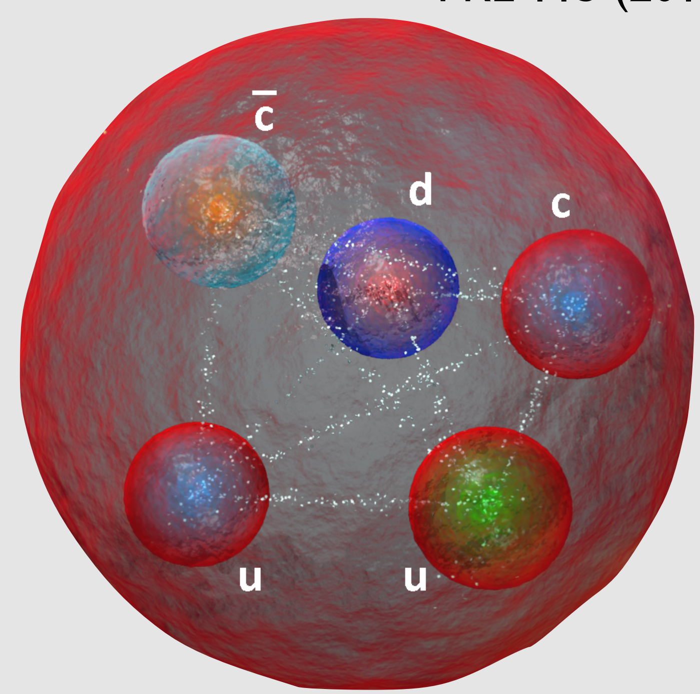
Spectroscopy

See Greig Cowan

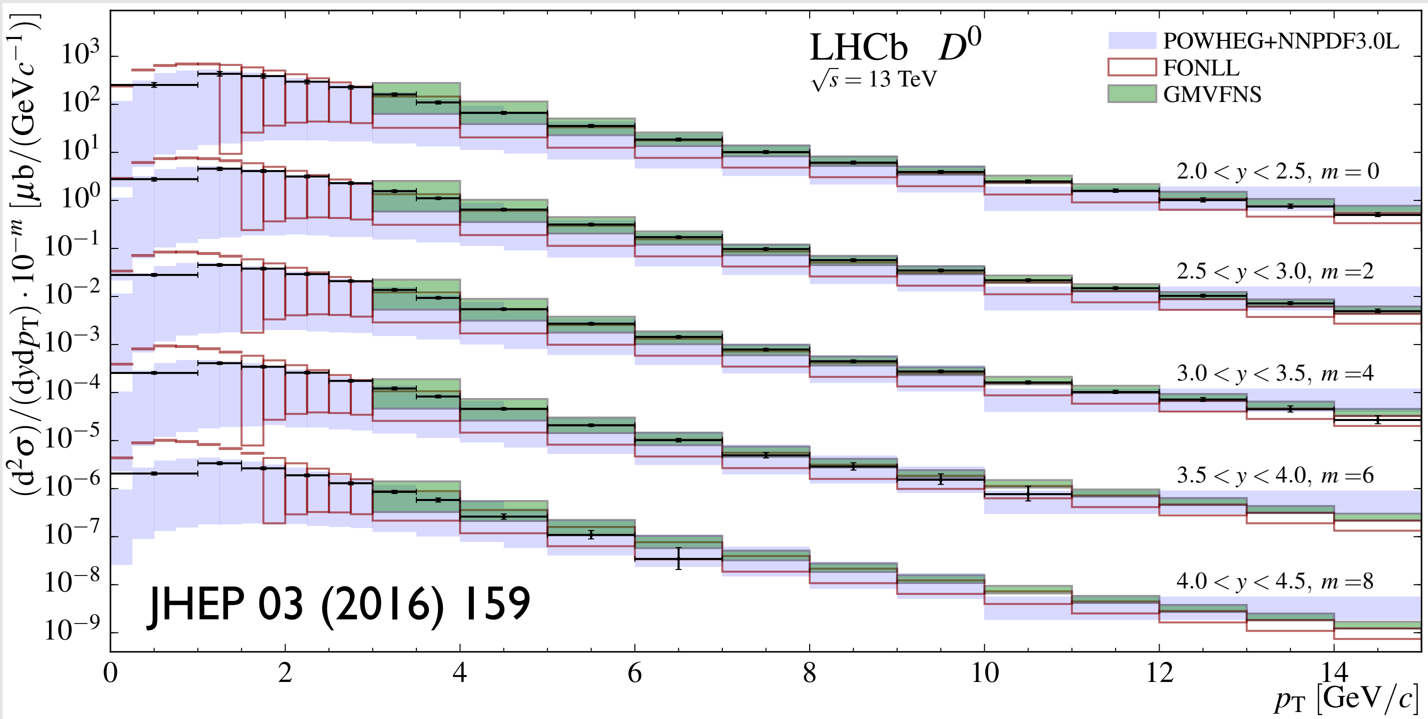


12 years

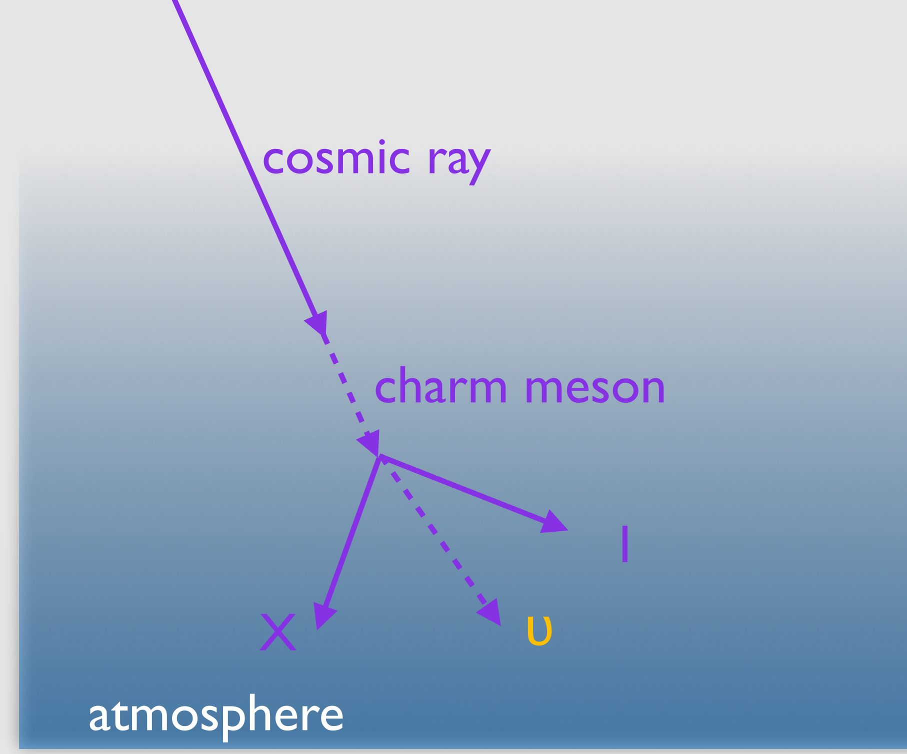
PRL 115 (2015) 072001

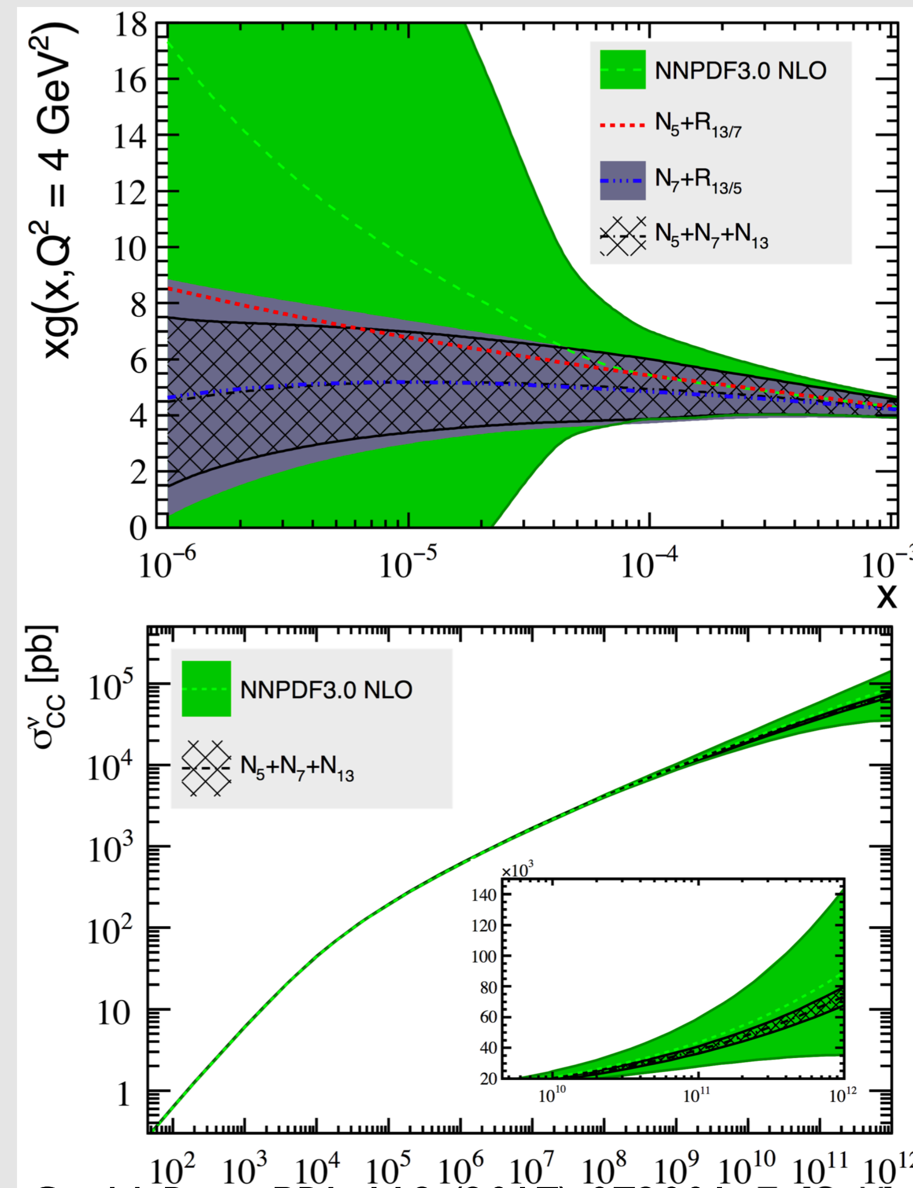


Production



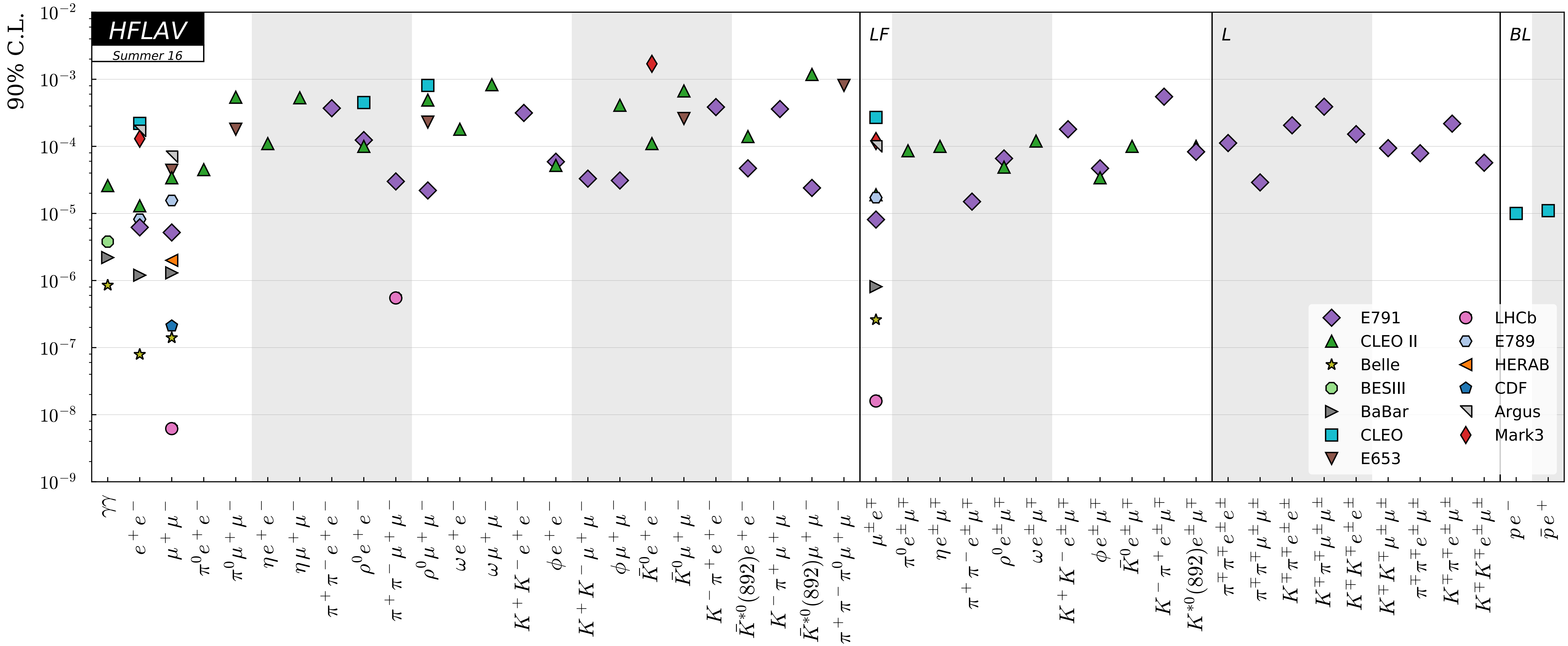
- Charm production as precision measurements
  - ➡ Constrain PDFs and QCD processes
  - ➡ Puts direct constraints on charm production in atmosphere
    - High-energy neutrino background, e.g. for IceCube
- Production in different collisions crucial in identifying exotica





Gauld, Rojo, PRL 118 (2017) 072001

Rare decays

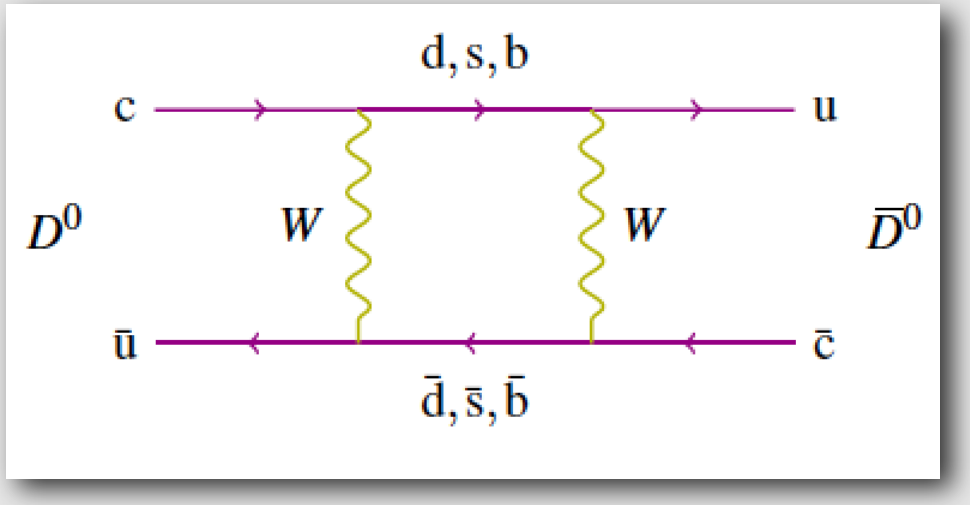


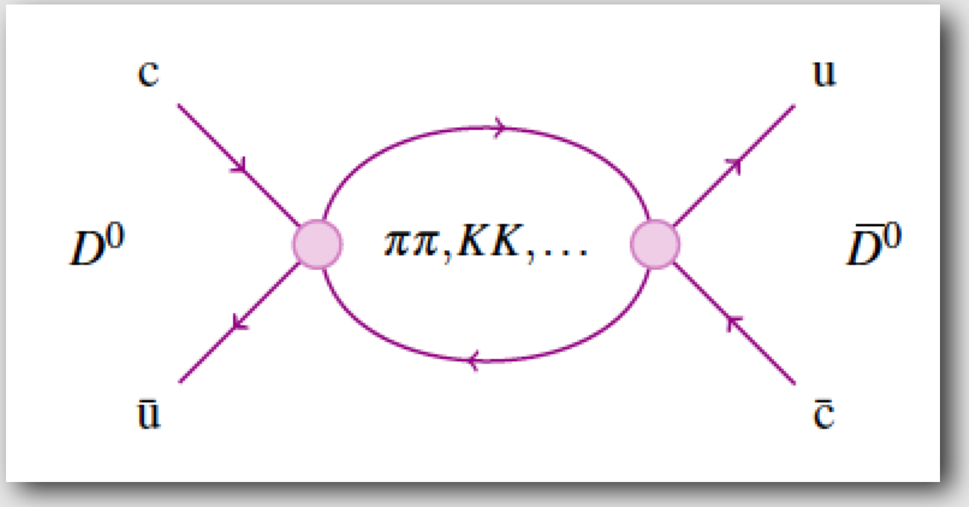
- Some recent progress
  - ➡ Many limits are very old, some >20 years
- No clear sign yet of non-resonant FCNC component*
- Keep searching also for LFV/LNV processes

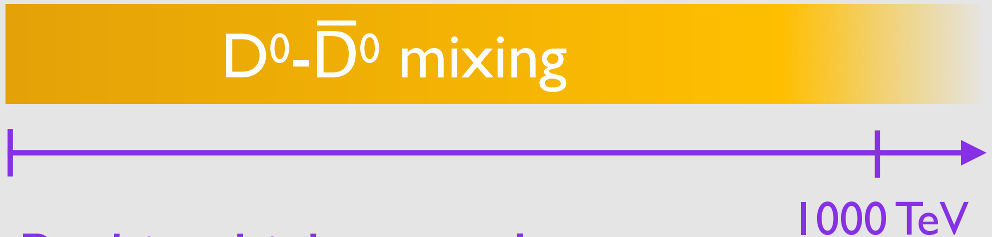
*but see LHCb, PRL 119 (2017) 181805

Charm: hardly a CKM triangle

- Mixing
  - ➡ Huge cancellations
  - ➡ Theoretically difficult
- CP violation
  - ➡ Predictions even smaller
- Only up-type quark to form weakly decaying hadrons
  - ➡ Unique physics access
- Need highest precision
- Huge LHCb dataset
  - ➡ Blessing and a curse







Probing highest scales

→ Isidori, Nir, Perez, ARNPS 60 (2010) 355

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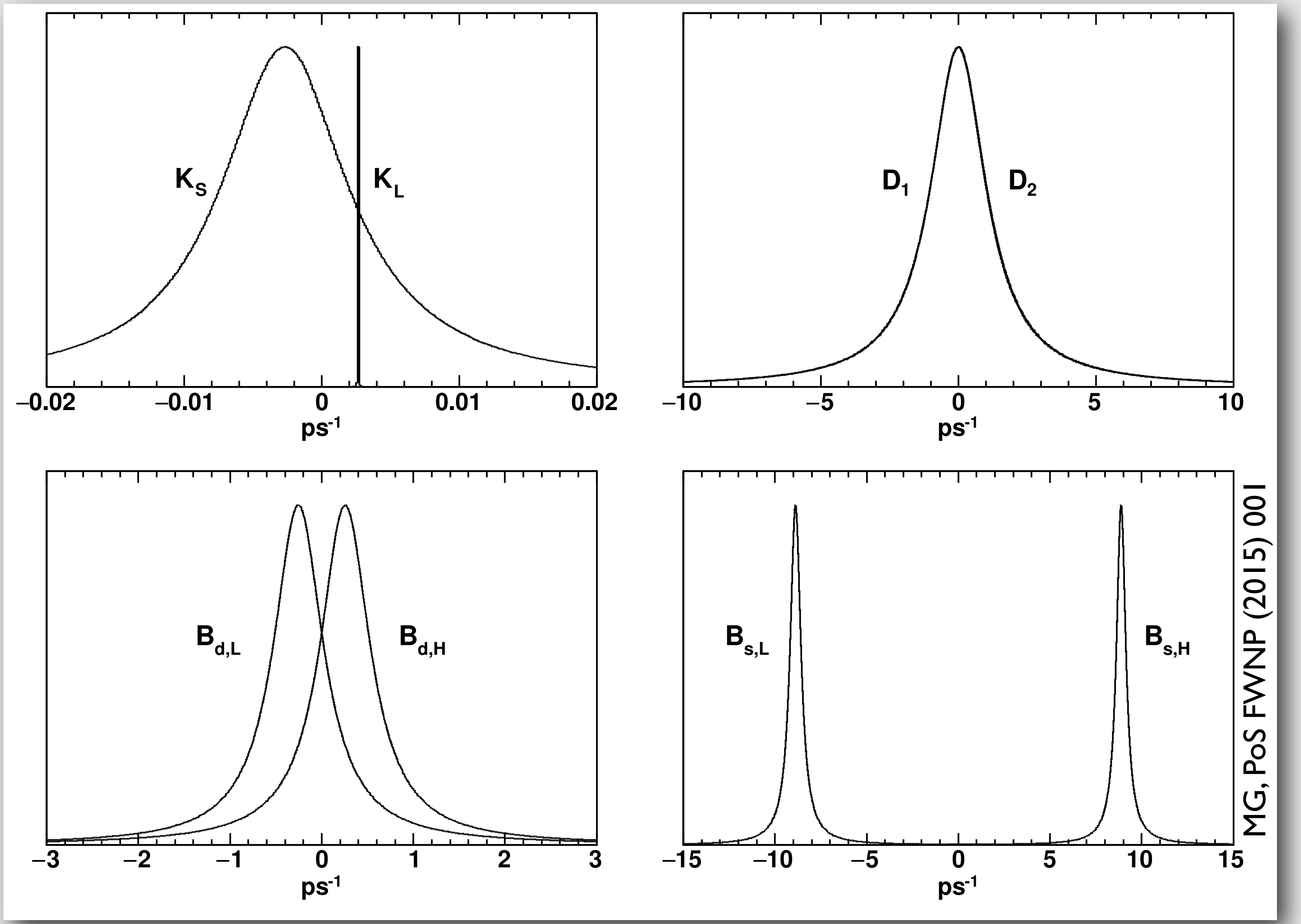
Mixing

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

Physical states

Flavour eigenstates



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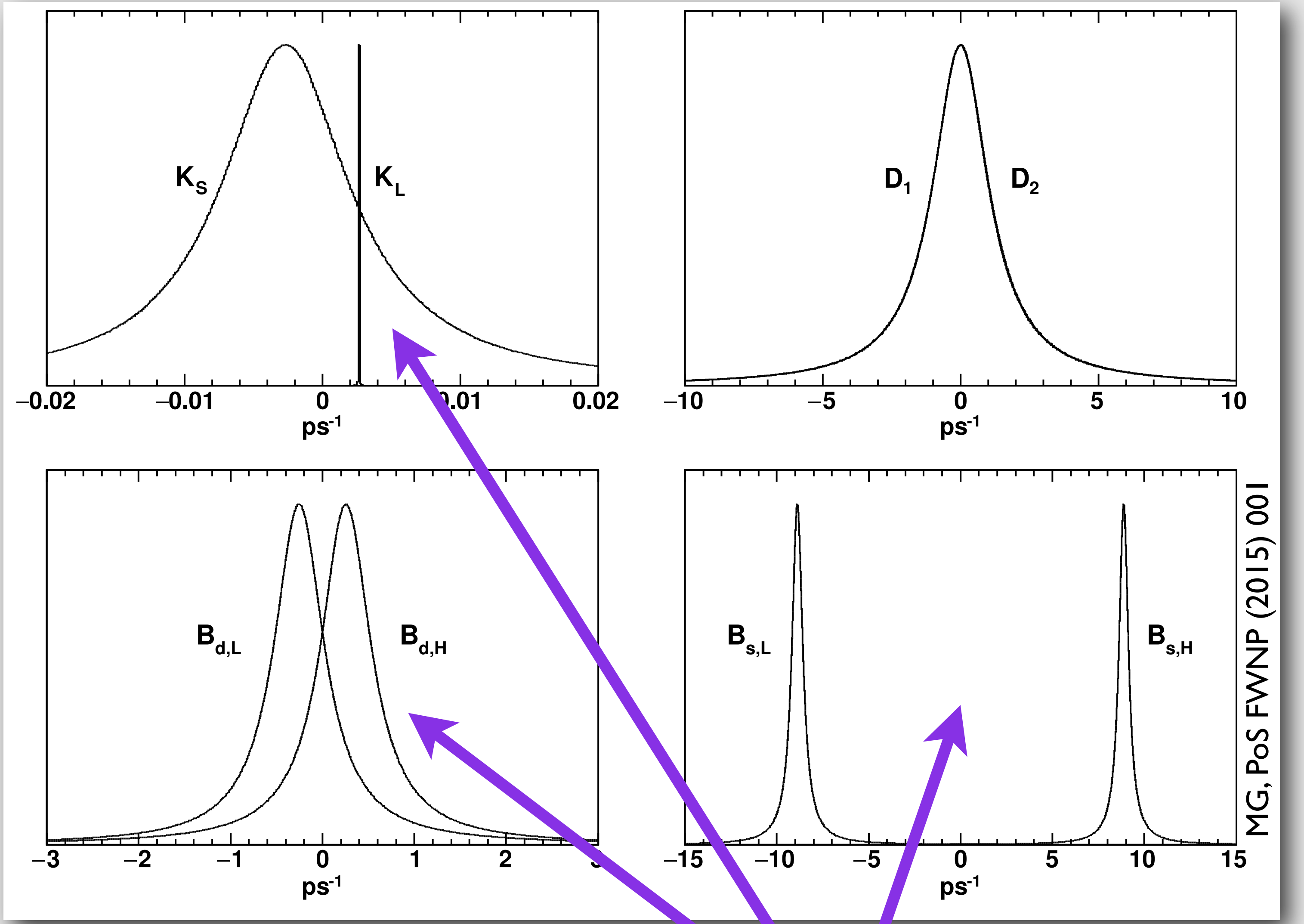

Mass difference

→ Oscillation

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

$$\Delta m \equiv m_2 - m_1$$

$$x \equiv \Delta m/\Gamma$$

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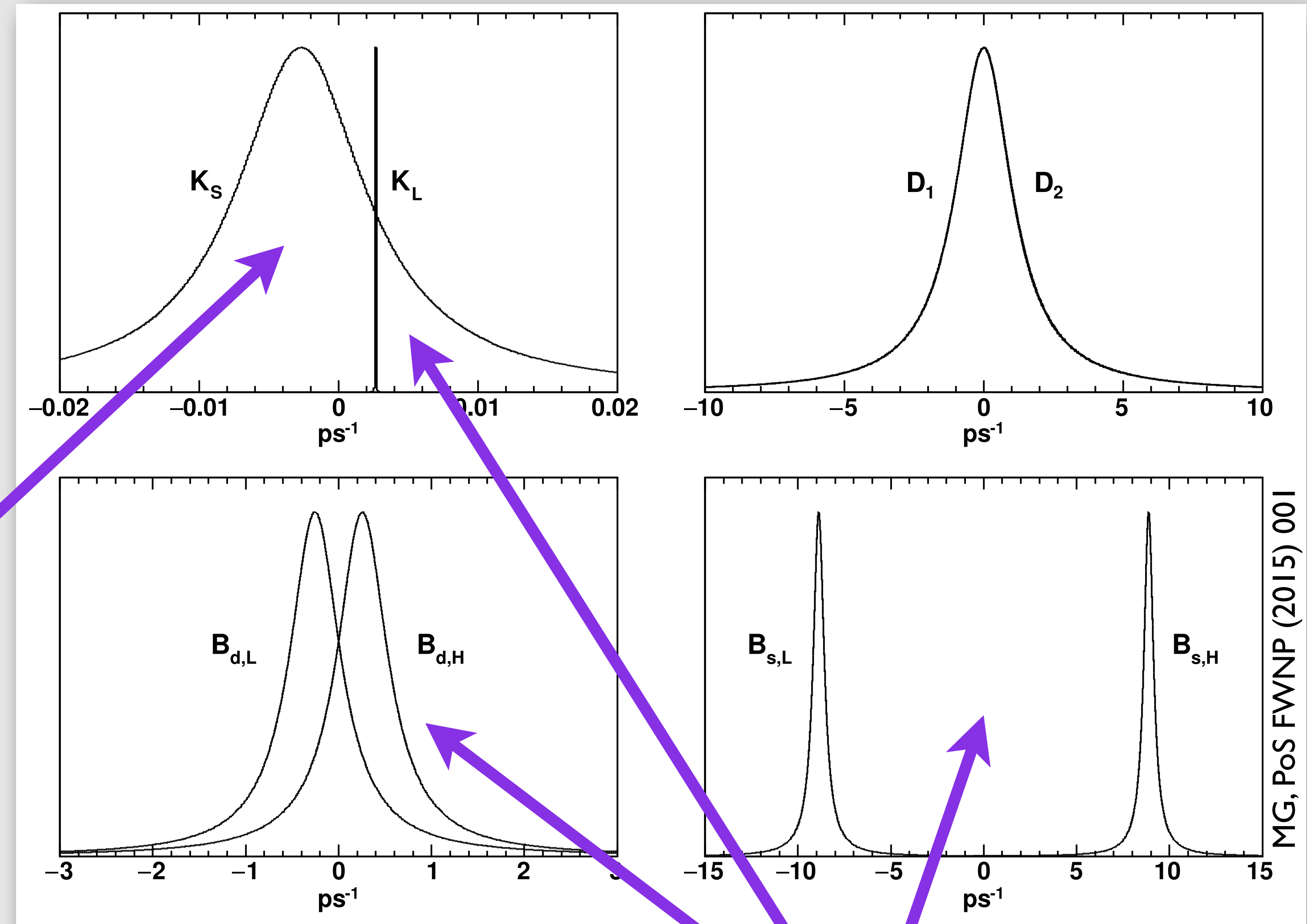

Width difference

→ Lifetime difference

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

$$y \equiv \Delta\Gamma/(2\Gamma)$$

Mass difference

→ Oscillation

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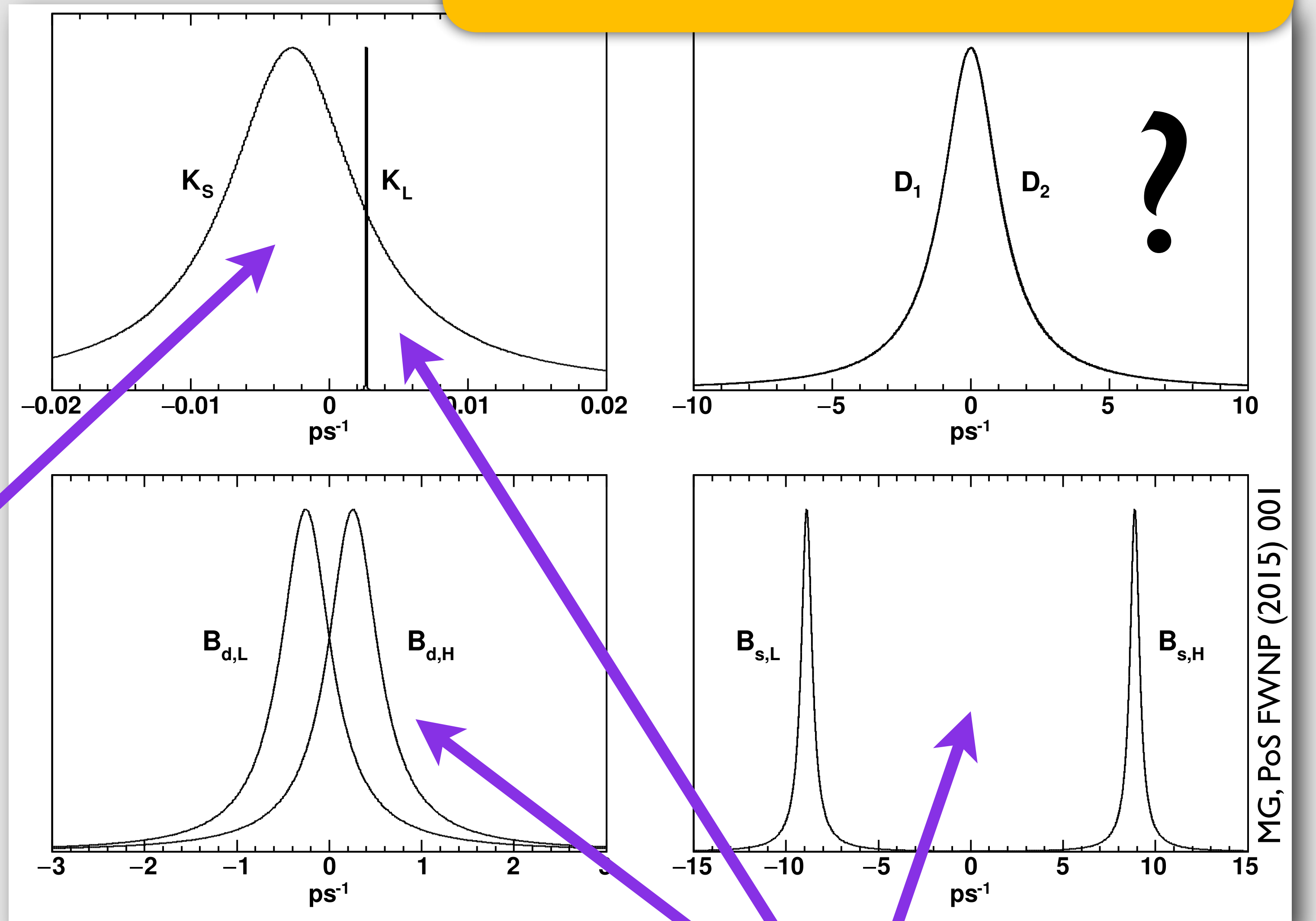
$$P(M^0 \to \overline{M}^0, t) = \frac{1}{2}\left|\frac{q}{p}\right|^2 e^{-\Gamma t}(\cosh(y\Gamma t) - \cos(x\Gamma t))$$

Mixing

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

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

Physical states — Flavour eigenstates



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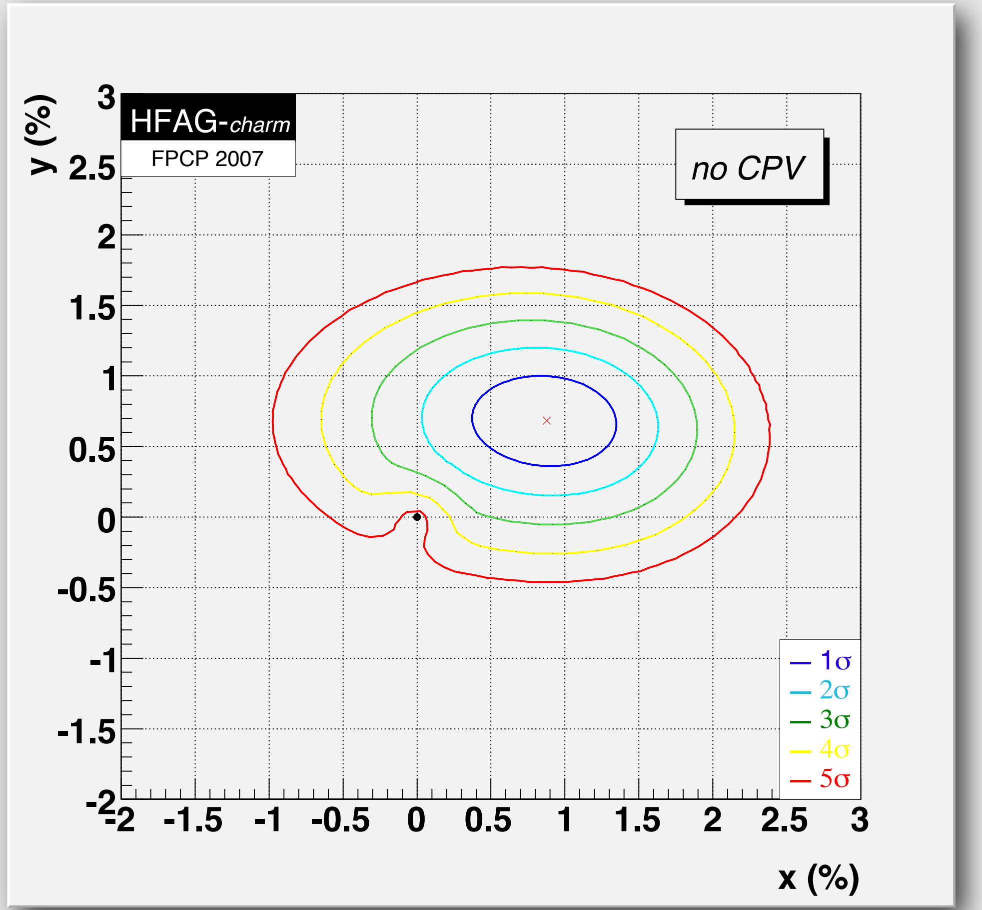
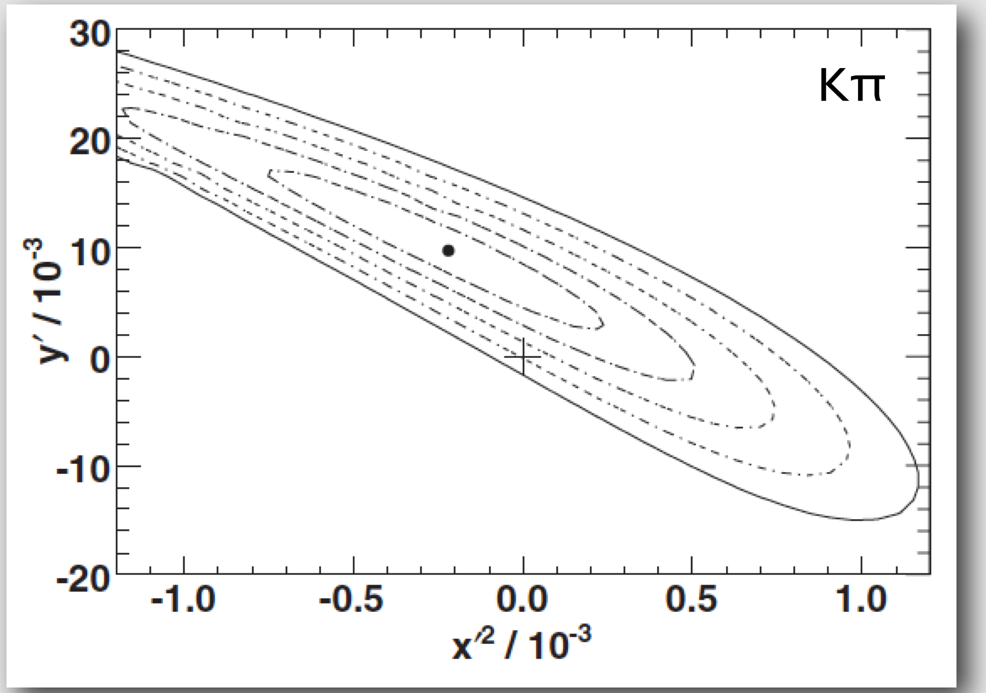
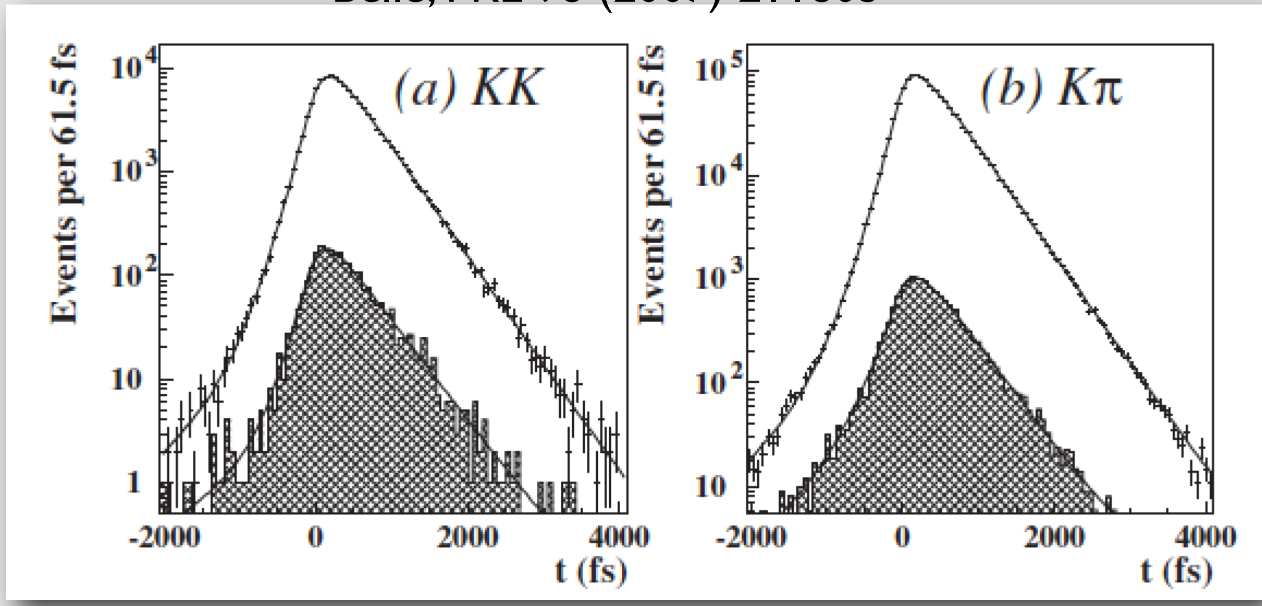
Mixing discovery



BABAR, PRL 98 (2007) 211802



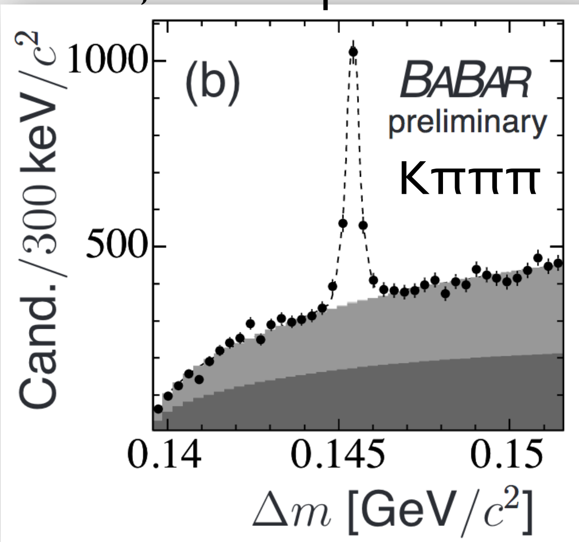
Belle, PRL 98 (2007) 211803



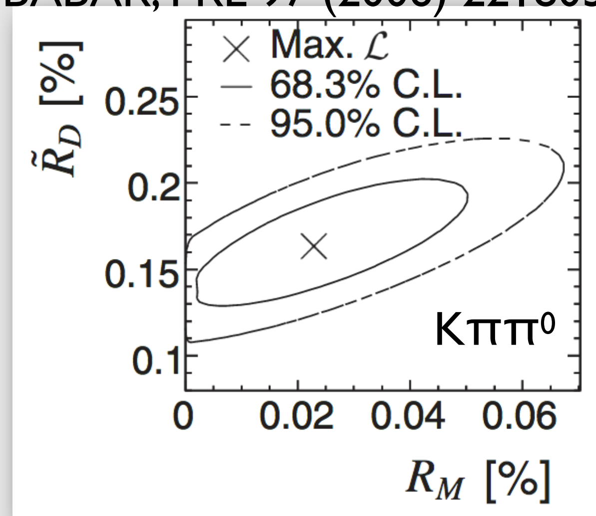
- Discovery through combination of measurements

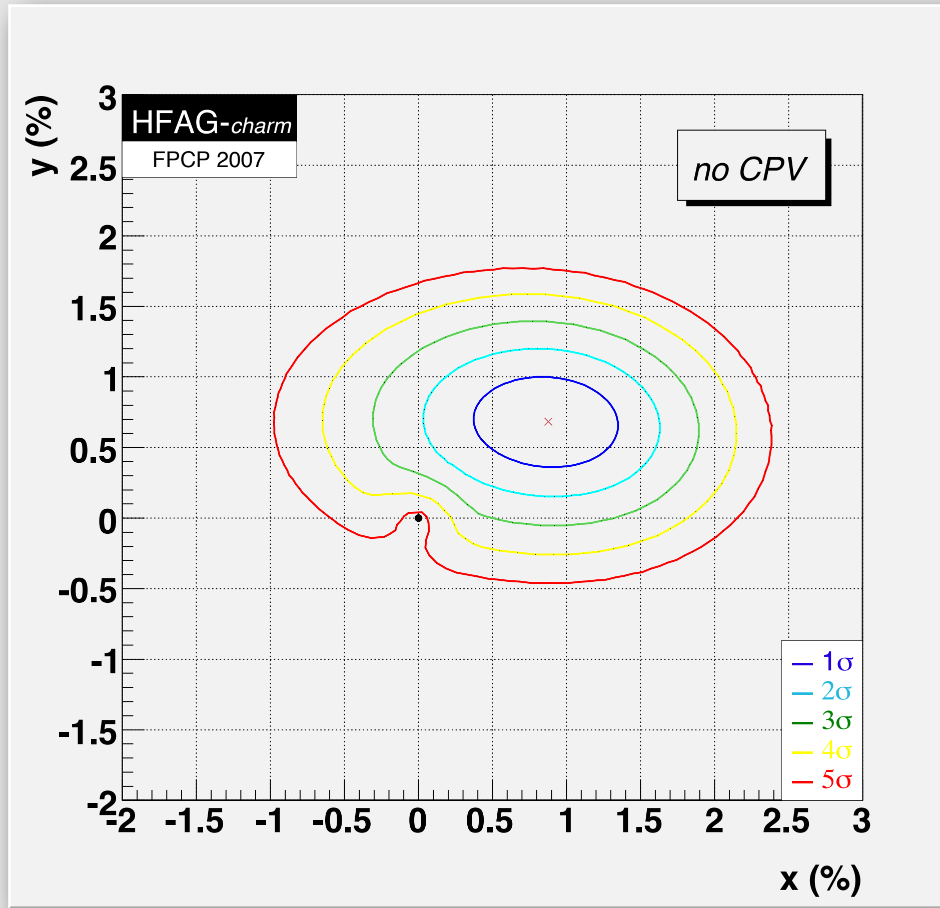
Mixing discovery

BABAR, arXiv:hep-ex/0607090

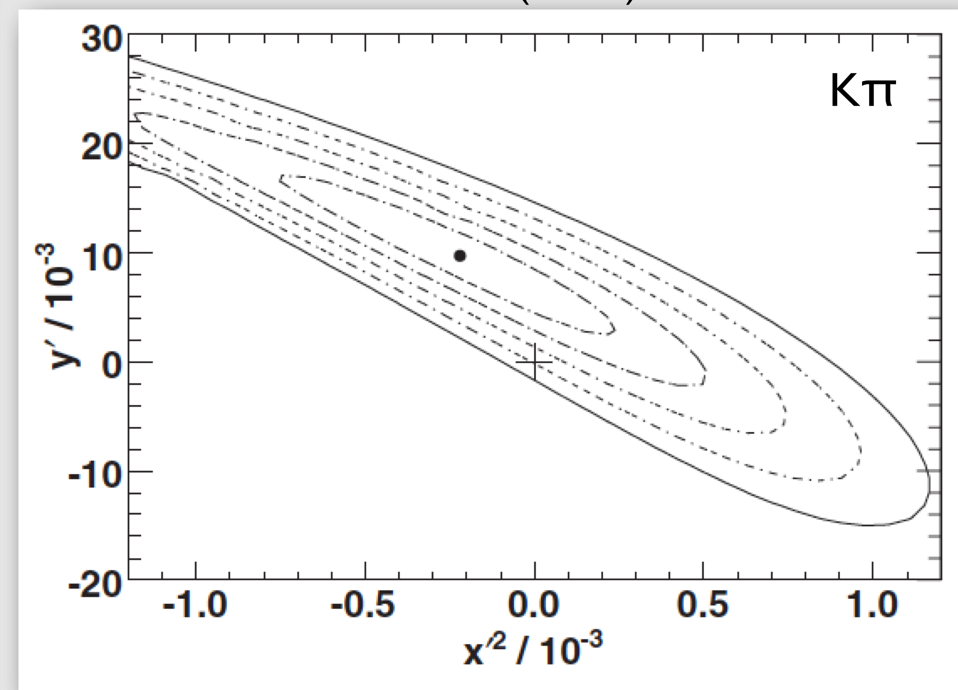


BABAR, PRL 97 (2006) 221803

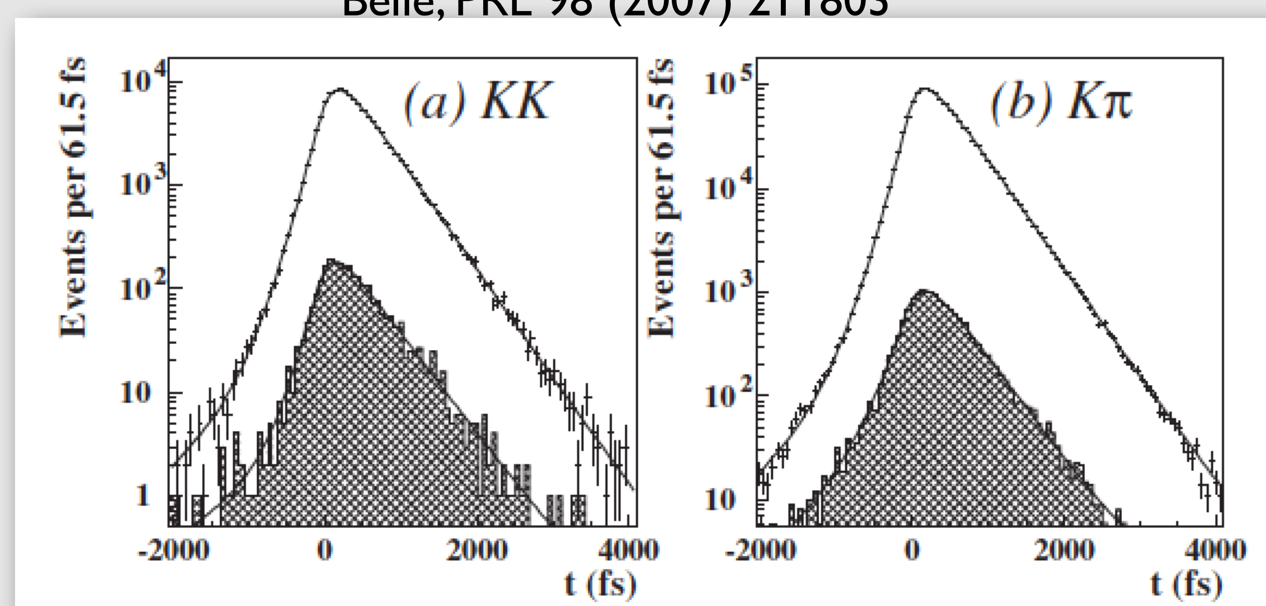




BABAR, PRL 98 (2007) 211802



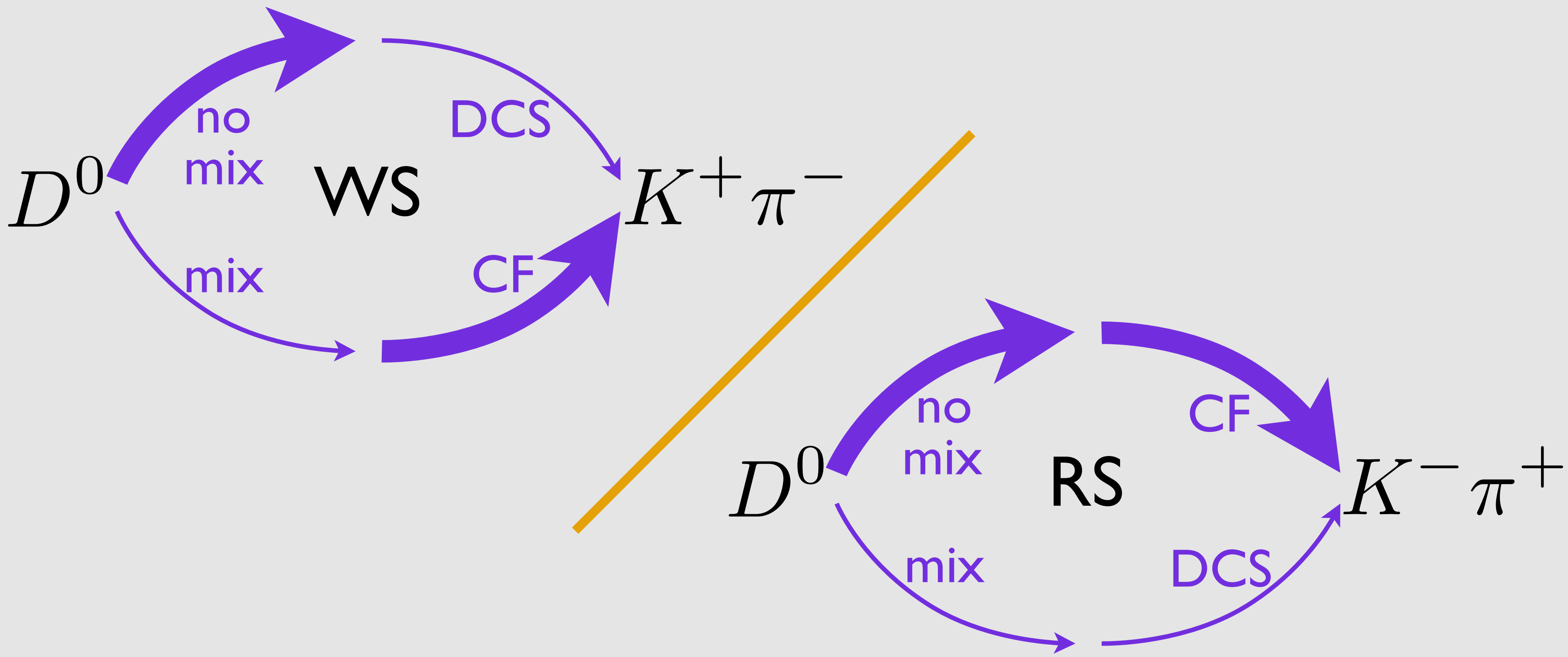
Belle, PRL 98 (2007) 211803



- Discovery through combination of measurements

Mixing discovery

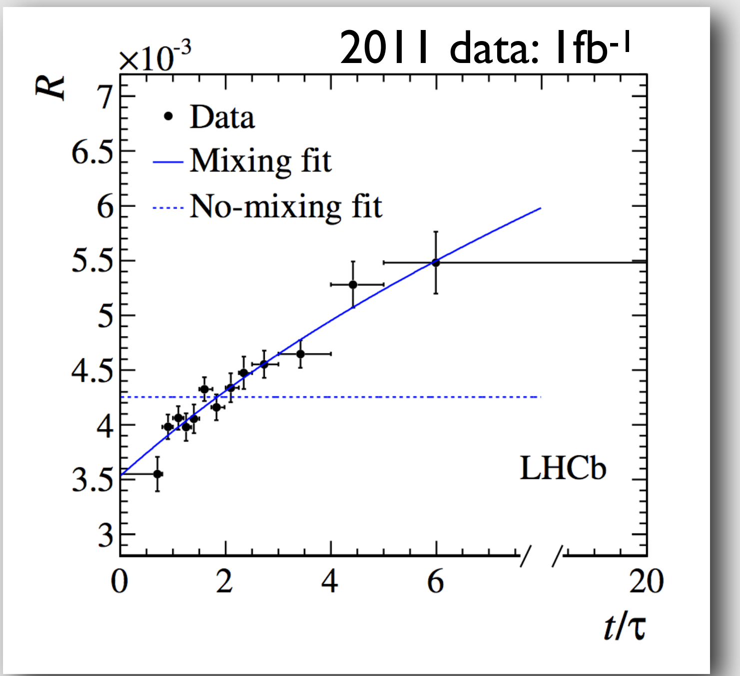
PRL 110 (2013) 101802



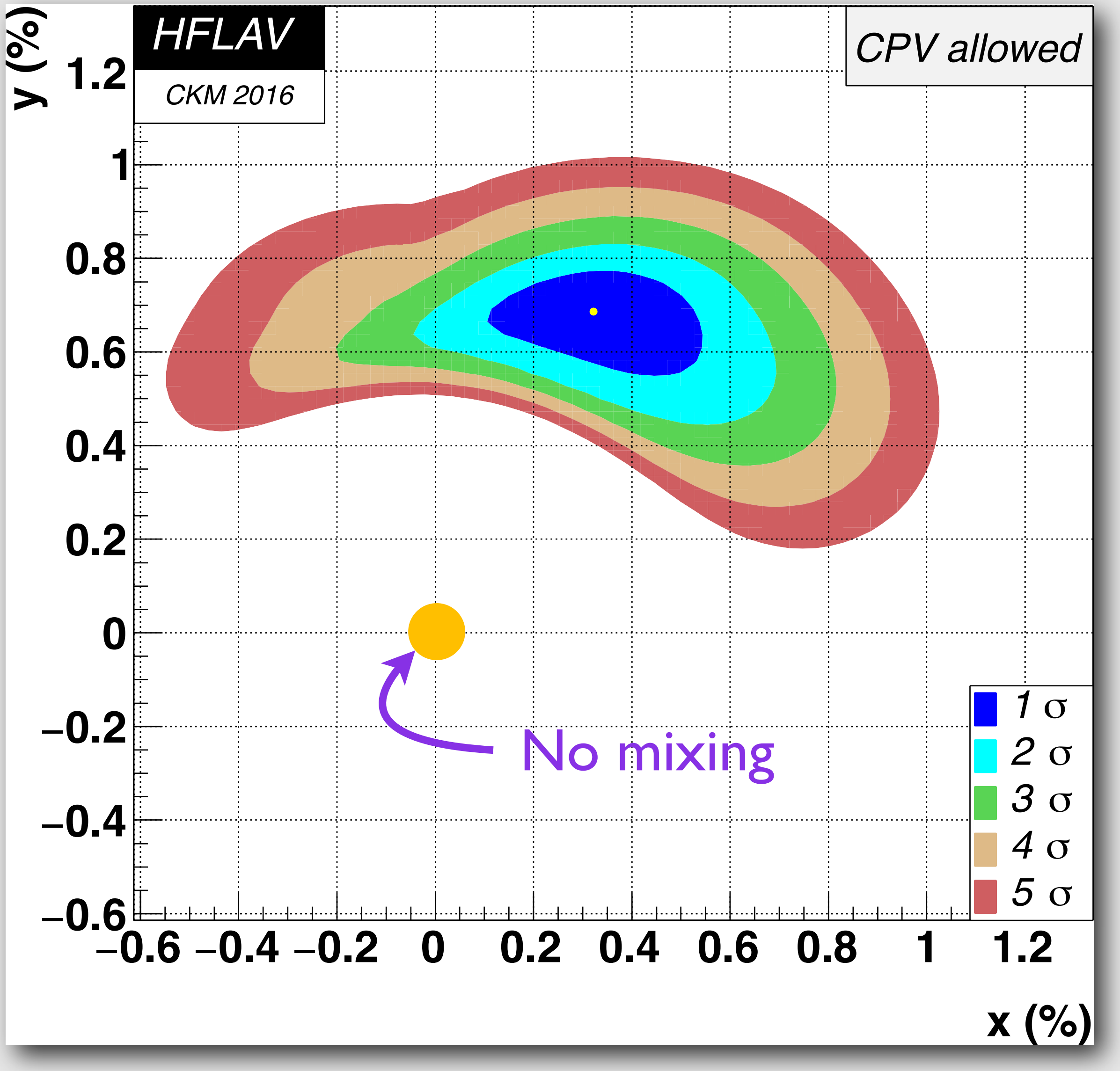
Using roughly 8.4×10^6 RS and 3.6×10^4 WS candidates

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

- First single-experiment measurement >5σ significance
- Rotation of mixing parameters by strong phase difference between CF and DCS amplitudes: x,y → x',y'



Mixing nowadays



- Mixing established

➡ $x \neq 0$ still open question

Mixing-related CP violation

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

Mixing:

$x \equiv (m_2 - m_1)/\Gamma$

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

CP violation:

$|q/p| \neq 1$

$\phi \equiv \arg(q/p) \neq 0, \pi$

Indirect CP violation:

$$a_{CP}^{ind} = -a_m \, y \cos\phi - x \sin\phi$$

with $a_m \approx \pm(|{}^q/_p|^2 - 1)$

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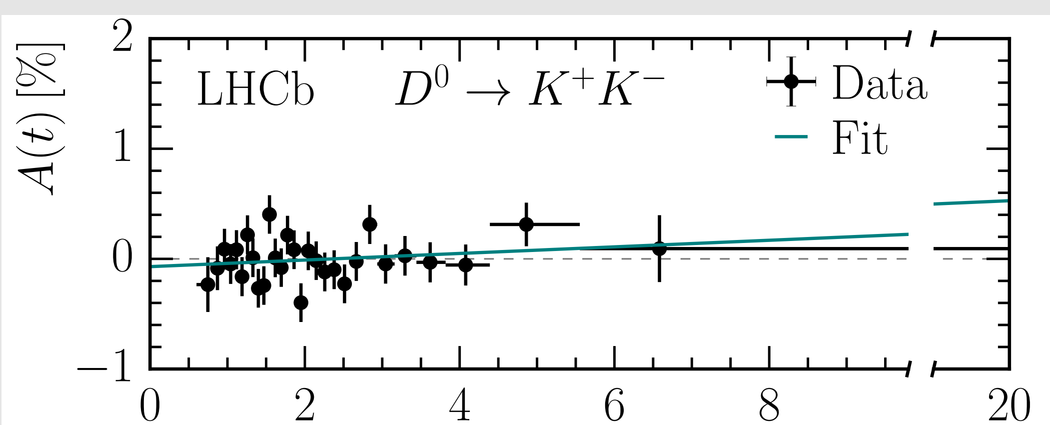
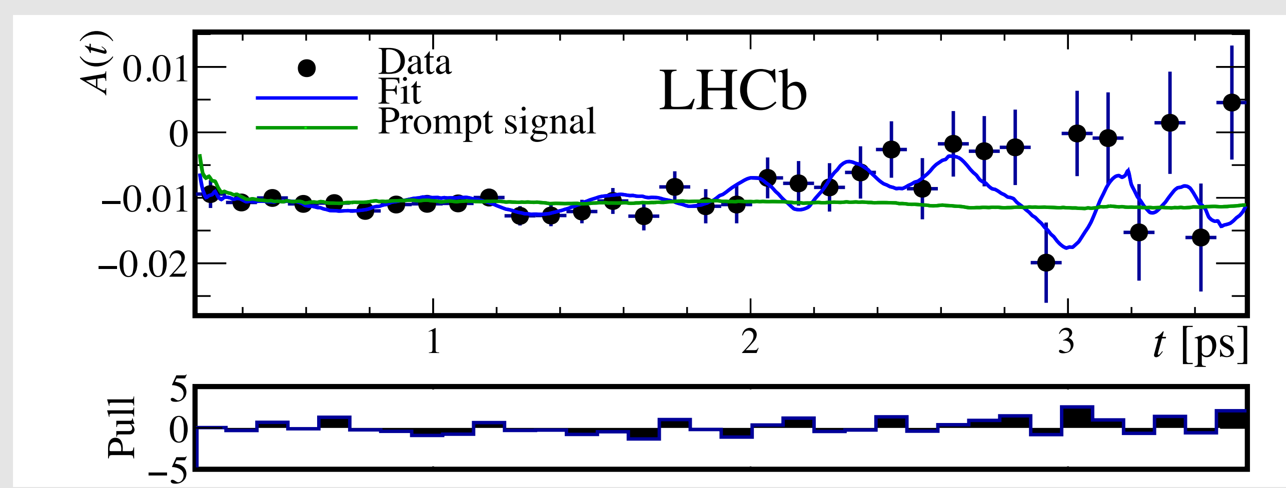
$A_\Gamma = -a_{CP}^{ind}$

- Measure asymmetry of effective lifetimes of D^0 and $\overline{D}^0$ decays to CP eigenstate
  - ➡ =0 if physical states are CP eigenstates
  - ➡ ≠0 implies CP violation
- Two methods, two final states, one result
  - ➡ $A_\Gamma(K^+K^-) = (-0.30 \pm 0.32 \pm 0.10) \times 10^{-3}$
  - ➡ $A_\Gamma(\pi^+\pi^-) = (+0.46 \pm 0.58 \pm 0.12) \times 10^{-3}$

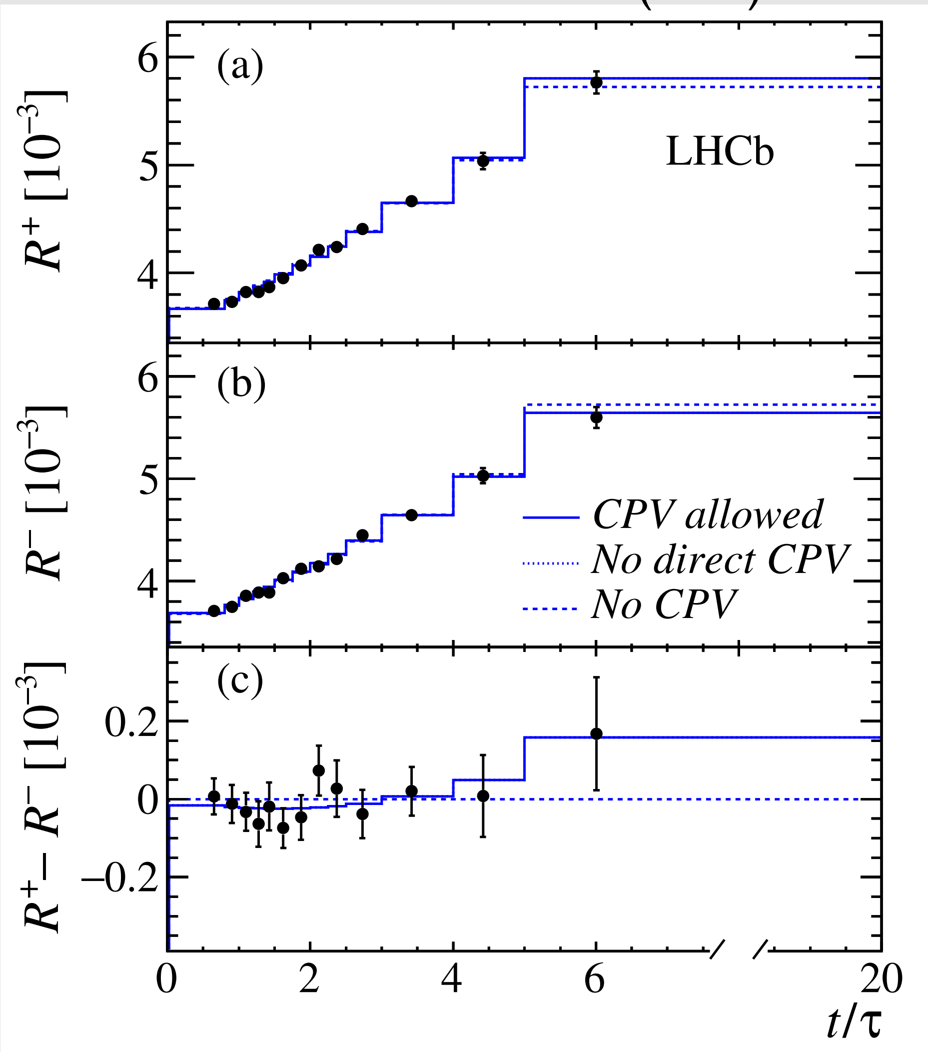


PRL 118 (2017) 261803

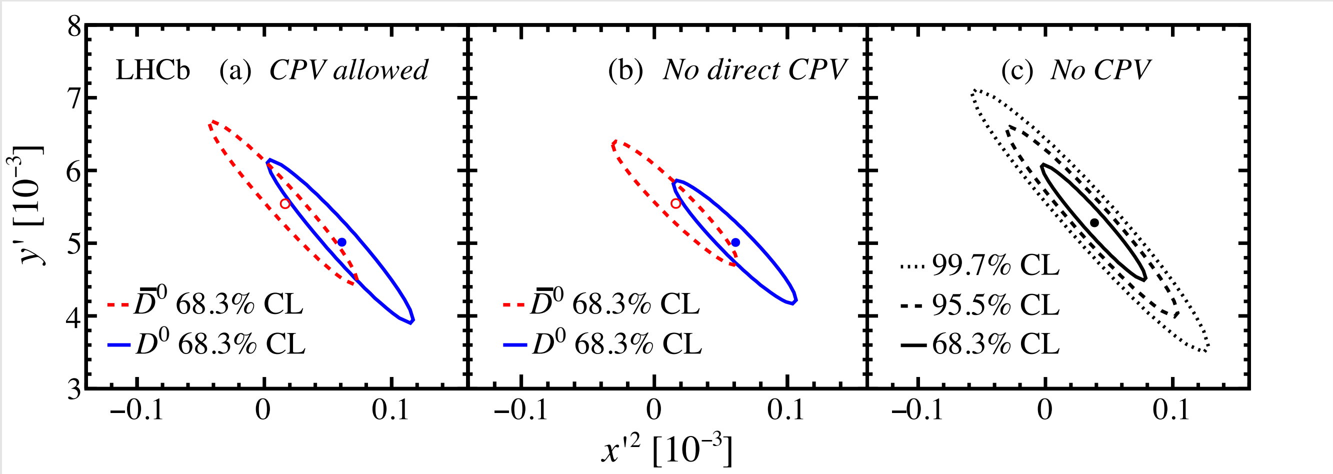


New WS Kπ

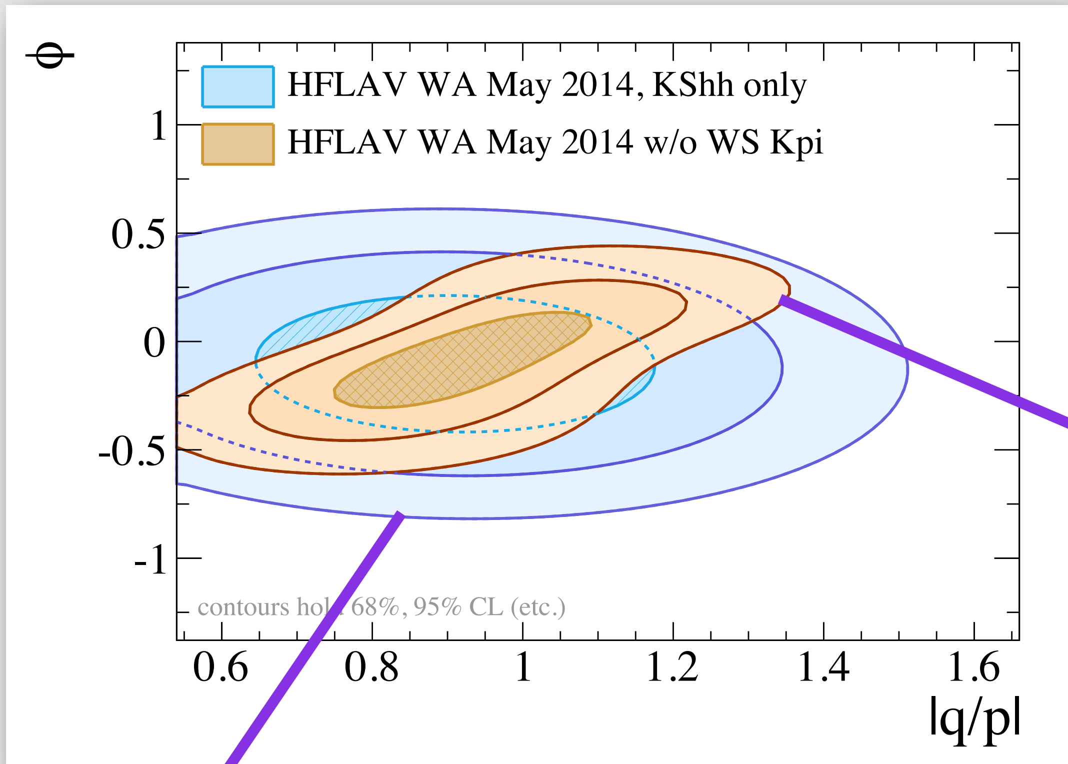
PRD 97 (2018) 031101

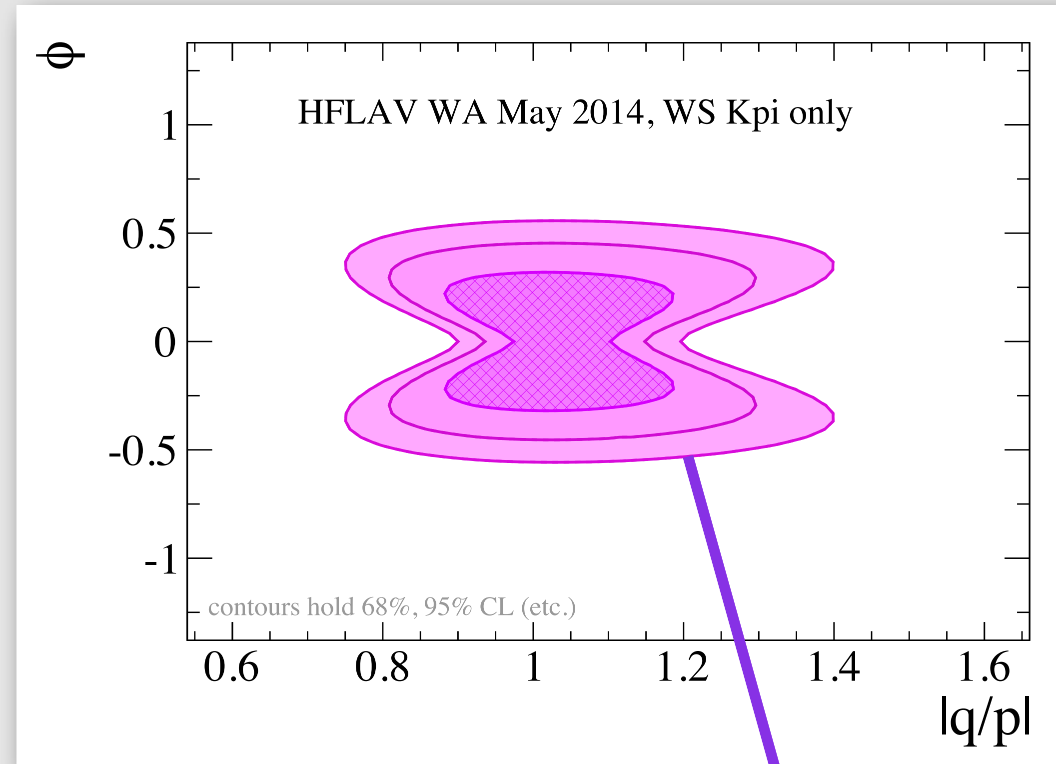


- Latest measurement based on 2011-2016 data
  - ➡ 180M favoured and 0.7M suppressed decays
- Twice as precise as previous results
- Still no sign for CPV



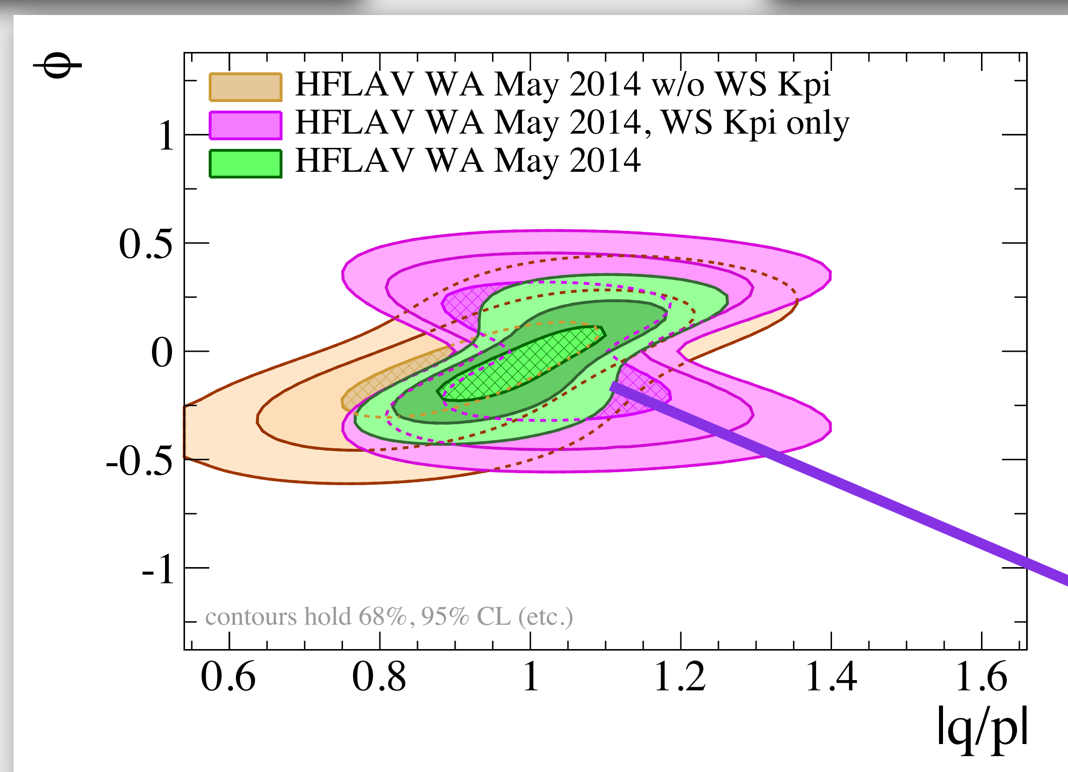
Contributions





Precise constraints if x and y provided, mostly from A_Γ

Direct access to |q/p| and φ from $K_S hh$



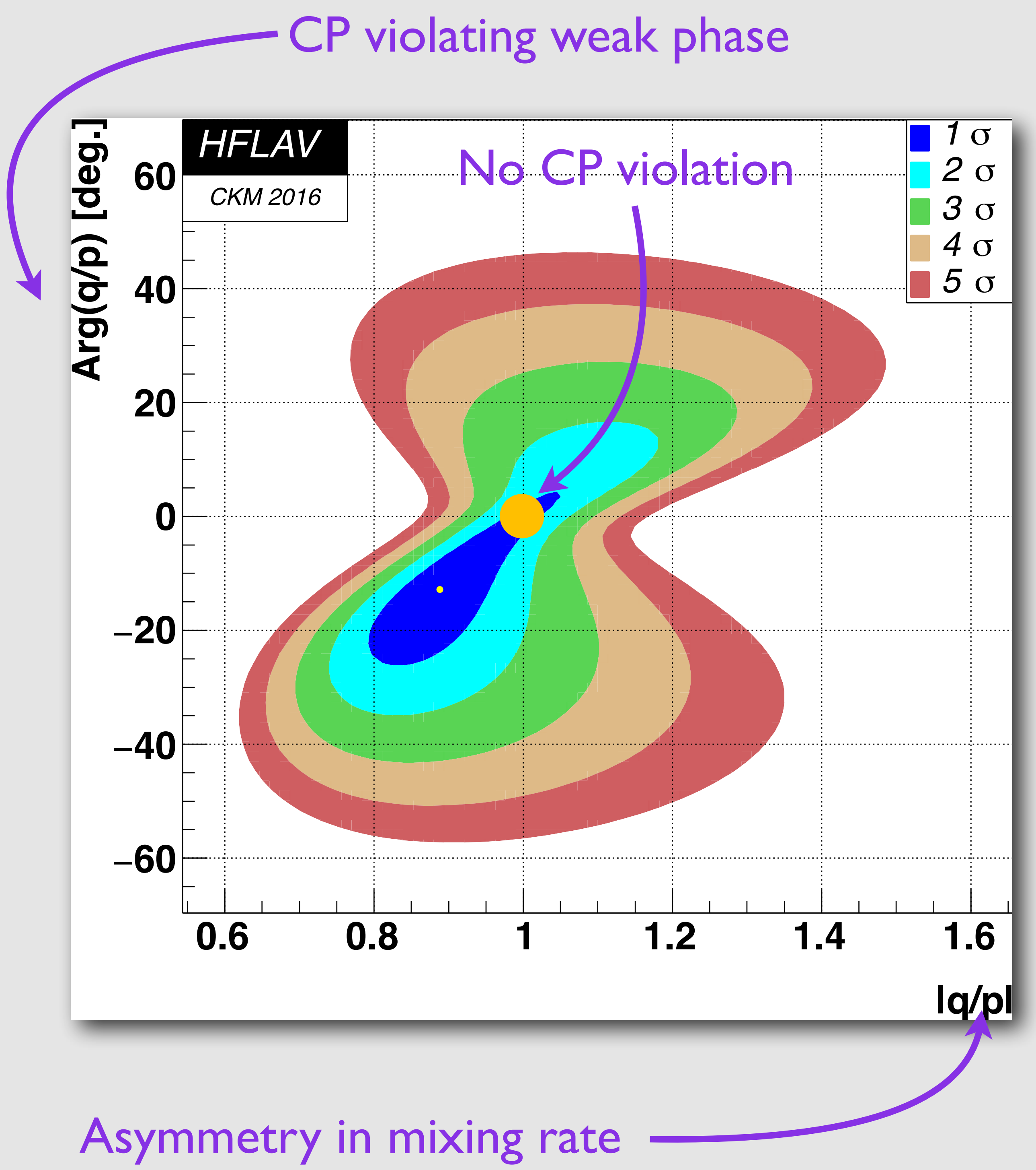
WS Kπ: symmetric in φ,

good sensitivity to |q/p| for small φ

Full average following intersection of contours

CP violation overview

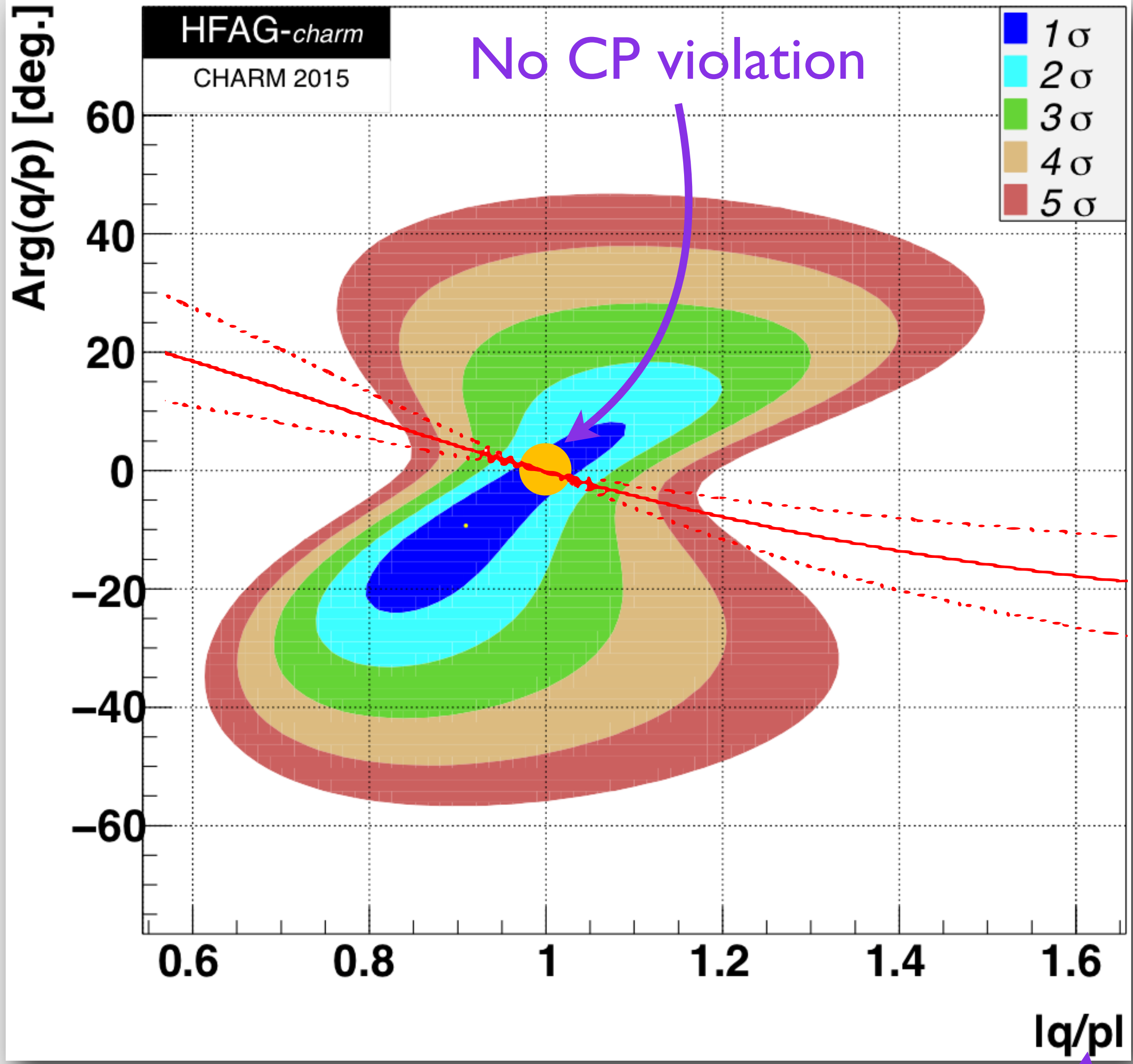
- No sign of CP violation



Can we do better?

- Superweak constraint
  - ➡ Assumes no new decay-specific weak phase
  - ➡ Cuichini et al. (2007)
  - ➡ Kagan, Sokoloff (2009)
- Reducing to 3 parameters
  - ➡ $\tan\Phi \approx (1-|q/p|)x/y$
- Consider WS measurement with $\Phi \approx 0$
  - ➡ $y'^{\pm} = |q/p|^{\pm 1}(y' \cos\Phi \mp x' \sin\Phi)$
- Different parametrisation
  - ➡ $x_{12}, y_{12}, \Phi_{12}$
- Current sensitivity already very good
  - ➡ $\sigma(\Phi_{12}) = 1.7°$

CP violating weak phase



Asymmetry in mixing rate

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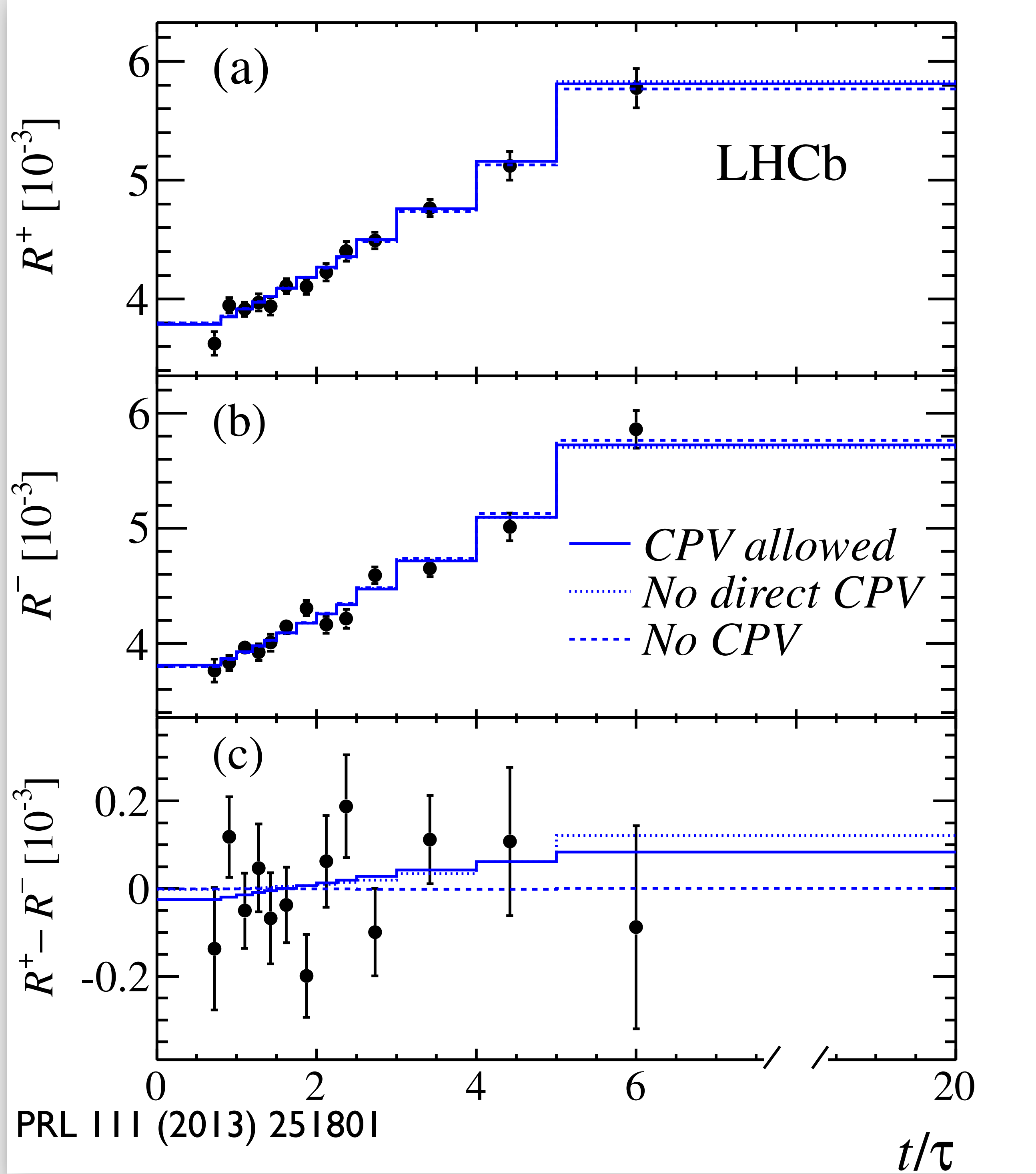

PRL 111 (2013) 251801

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  - ➡ x_{12}, y_{12}, Φ_{12}
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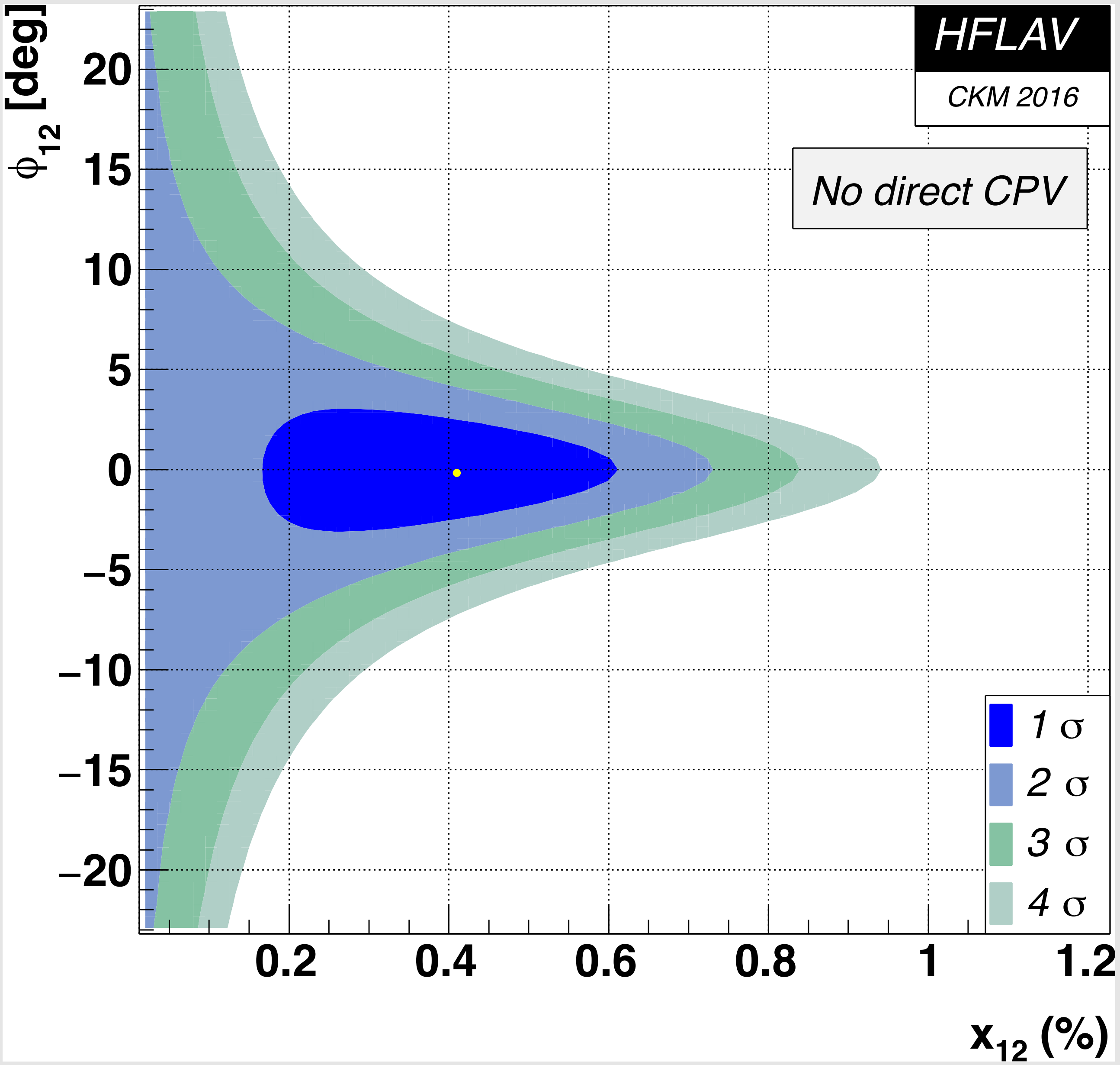

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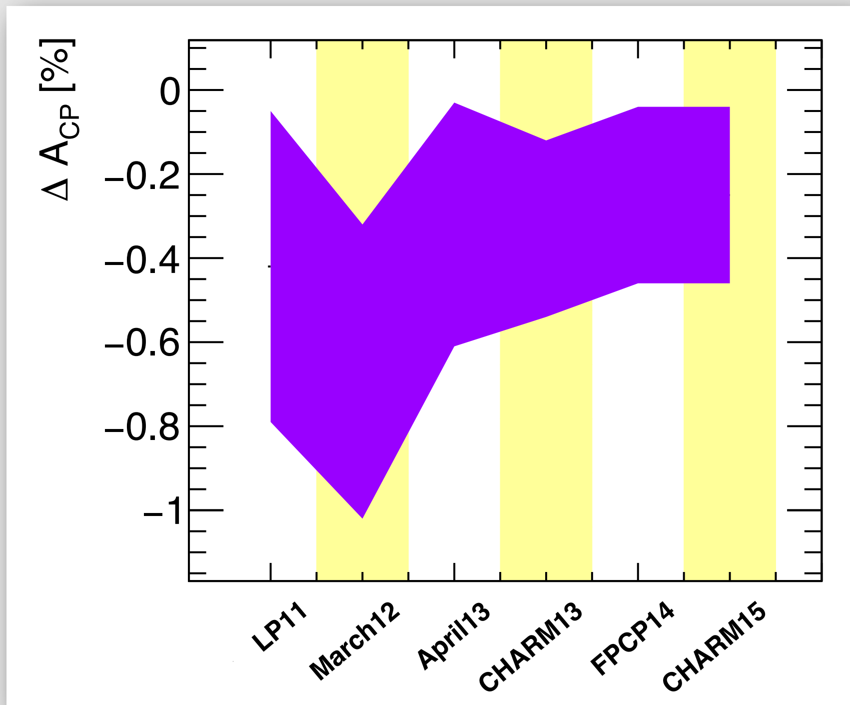
Direct CP violation

Direct CP violation:

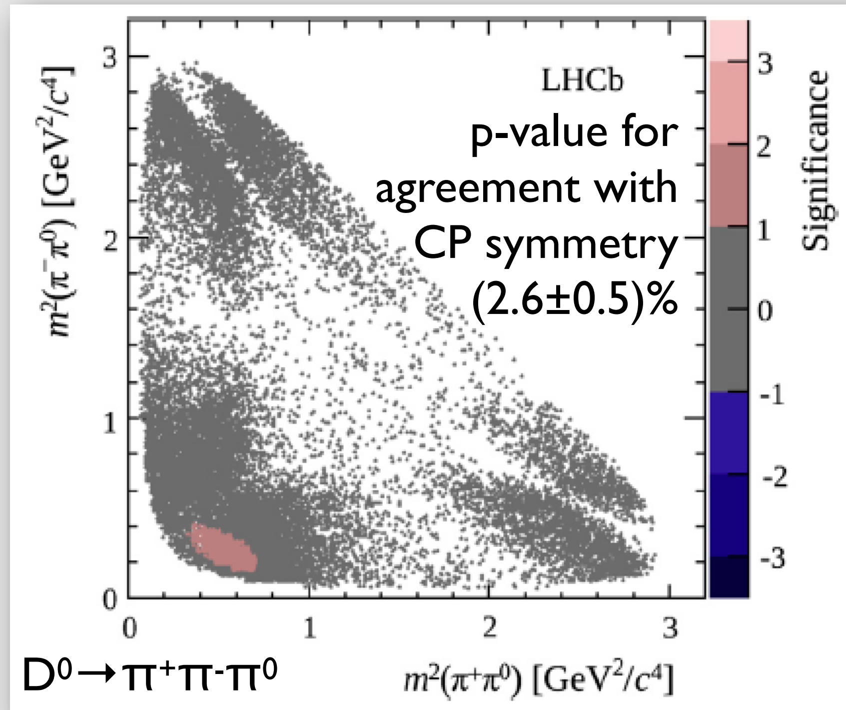
$$a_{CP}^{dir} \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}$$

CPV in decay

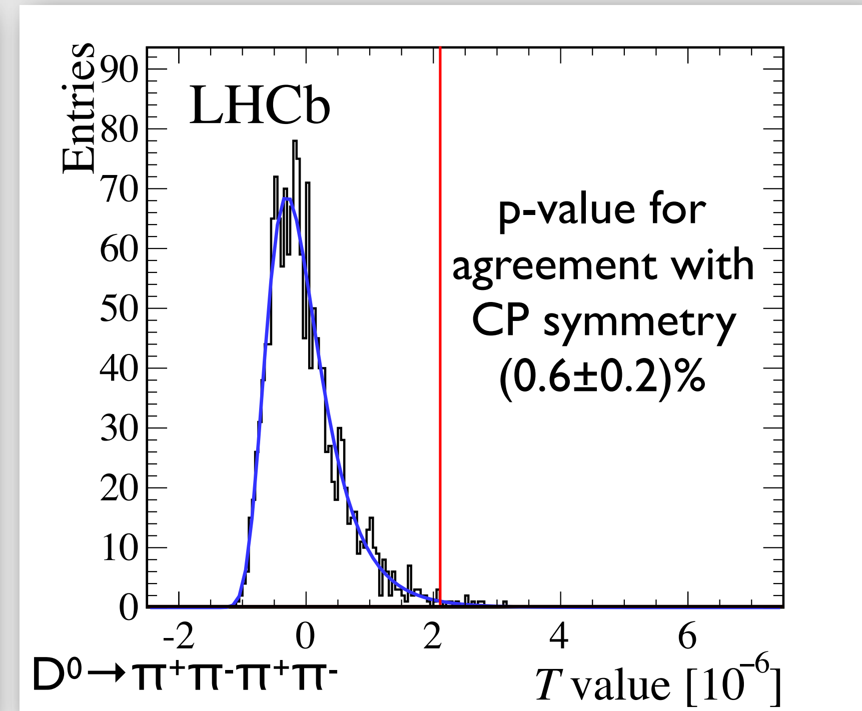
$A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$



PLB 740 (2015) 158



PLB 769 (2017) 345



- Once upon a time, it looked like there was…
  - ➡ … but that saga got discontinued
- A growing number of decay modes explored
  - ➡ Phase-space integrated vs resonance structures
- A number of methods explored
  - ➡ Model-(in)dependent, (un)binned, triple products, …

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Outline

- Part I
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  ➡ Where to next?

Where to now?

Looks like BSM,
can't rule out SM effects

Ligeti

- 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"

Looks like SM,
can't rule out BSM effects

Grossman

- 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

Yuval Grossman, Experimental Summary, CHARM 2012

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Who cares about bagels, it's lunch time!

Yuval Grossman, Experimental Summary, CHARM 2012

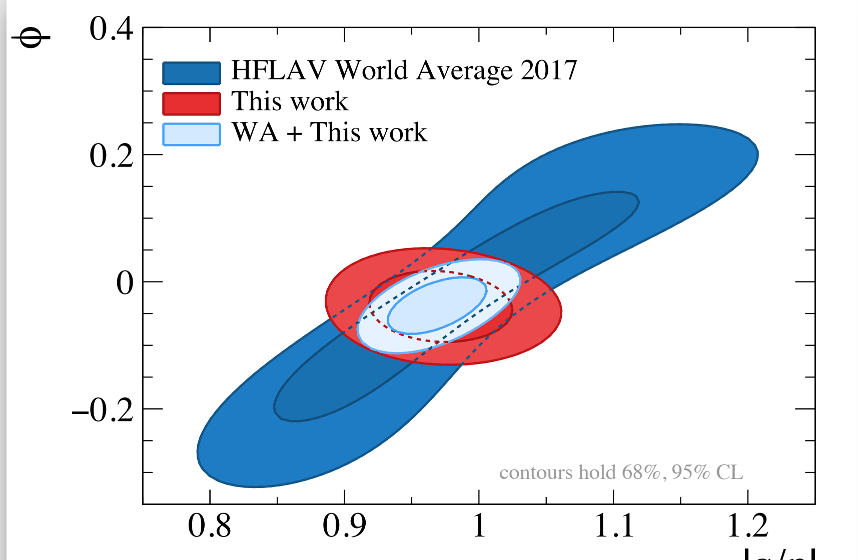
Multi-body decays

- Give access to full set of mixing and CP violation observables
  - ➡ In particular: sensitivity to x
  - ➡ Require amplitude models
    - ▸ Liaise with theory community on new techniques
  - ➡ Or quantum-correlated measurements
    - ▸ UK now has two BESIII members (Manchester, Oxford)

Realistically need both

- In last ten years time-dependent measurements almost only in $D^0 \to K_S \pi^+ \pi^-$
  - ➡ A missed opportunity?
  - ➡ Recent work by BABAR on $D^0 \to \pi^+ \pi^- \pi^0$
  - ➡ Surely something for Belle II
  - ➡ Very promising studies at LHCb

Potential of $D^0 \to K^{\pm} \pi^{\mp} \pi^+ \pi^-$ at LHCb

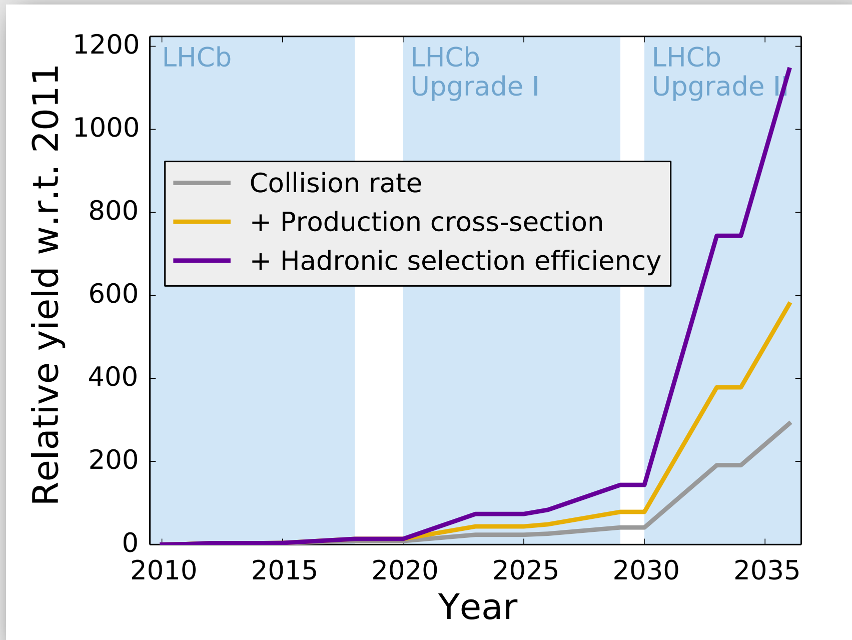


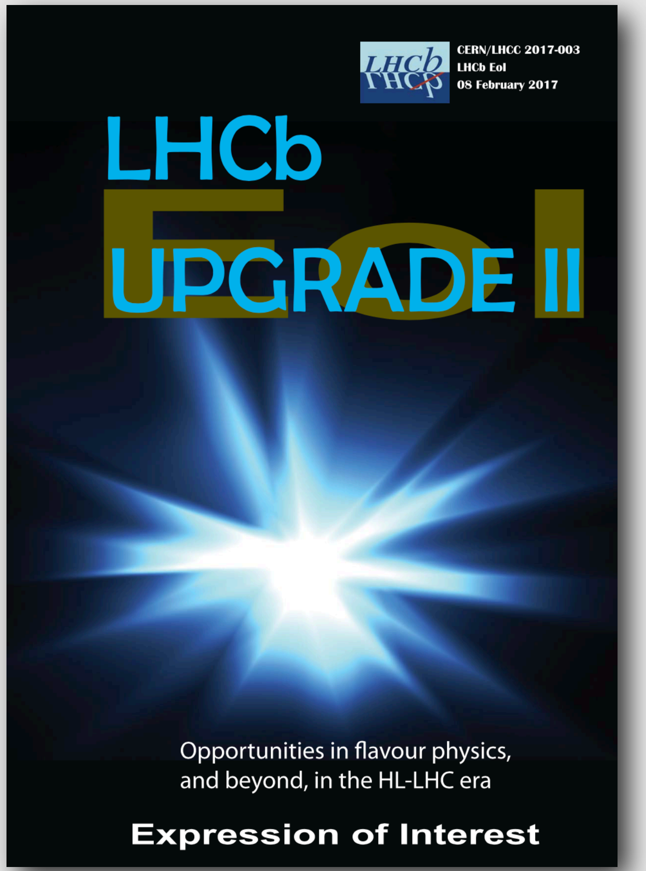
D. Müller, CERN-THESIS-2017-257

LHCb Upgrades

See Greig Cowan

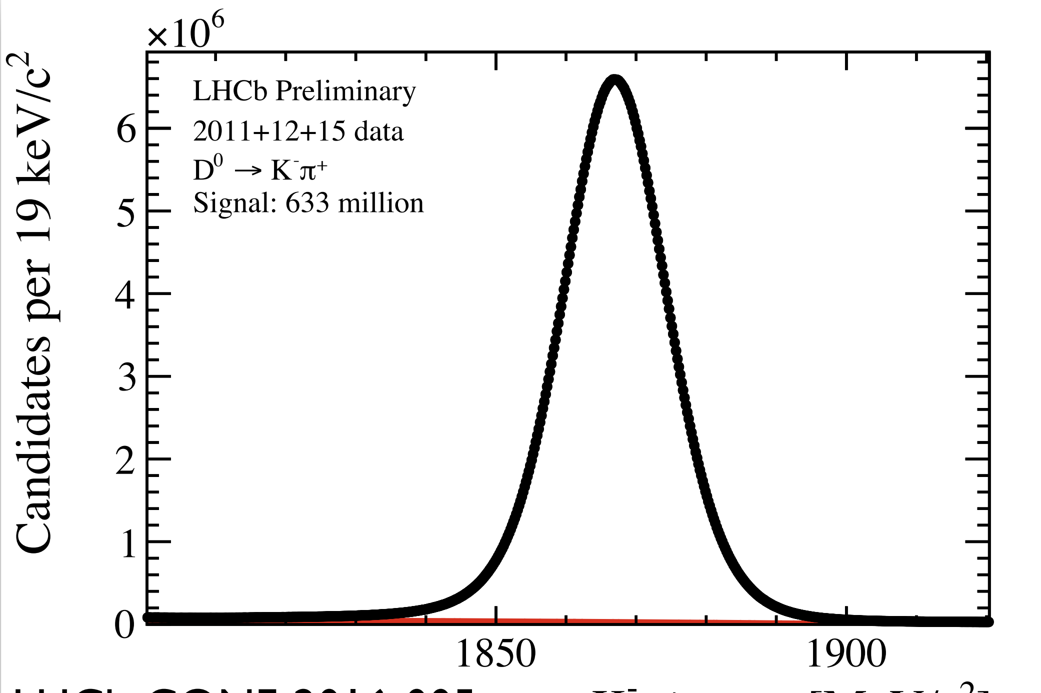
- Charm CP violation may well be discovered soon
- Will require much more data to
  - ➡ Identify underlying sources
  - ➡ Challenge SM level in both direct and indirect CPV
- LHCb is the best bet for charm for the foreseeable future
  - ➡ Best shot at BSM physics in the up-quark sector





Charm the challenge champion

- Charm among the most abundant particles produced
  - ➡ At LHC and e^+e^- running at $\Upsilon(4S)$



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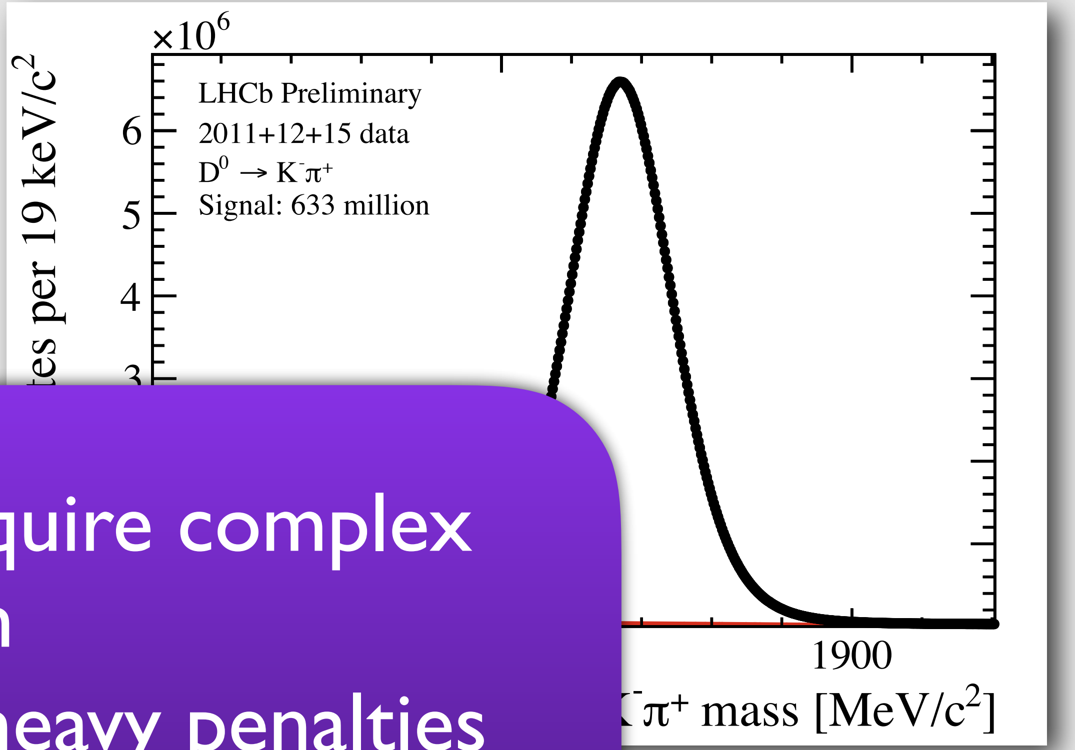
- Technical challenges therefore driven by charm
  - ➡ Data selection/reconstruction/storage
  - ➡ Simulation
  - ➡ Data analysis

Charm the challenge champion

- Charm among the most abundant particles produced



High rates of low p_T particles require complex decisions early on in trigger chain

→ Coarse decisions come with heavy penalties

→ Need to avoid burning detectors for little gain

- charm

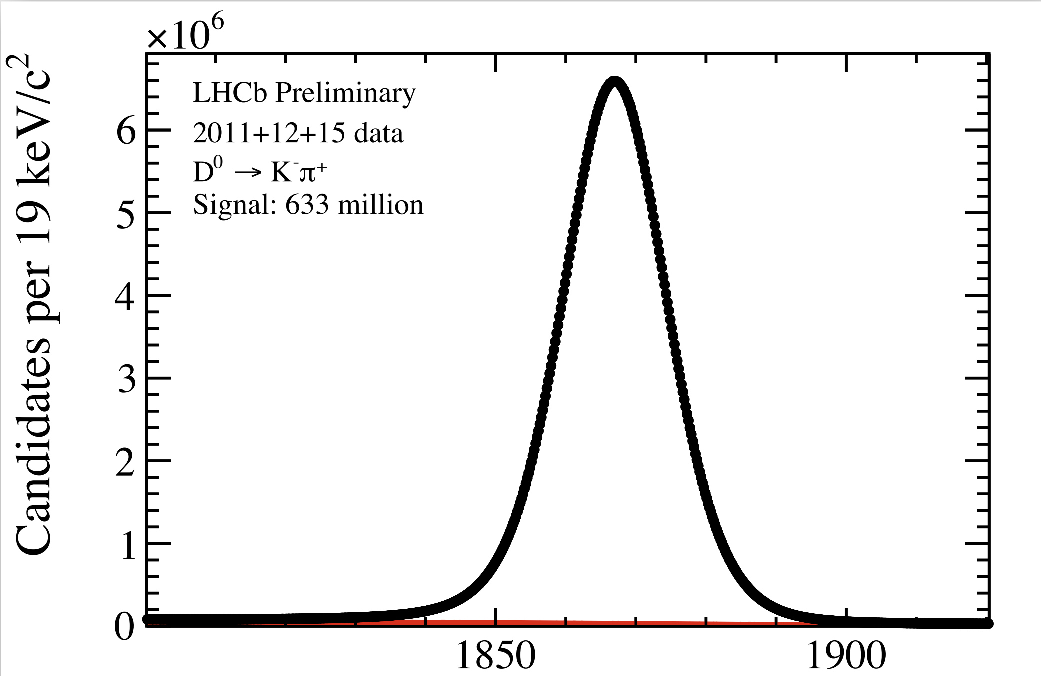
➡ Data selection/reconstruction/storage

➡ Simulation

➡ Data analysis

Charm the challenge champion

- Charm among the most abundant particles produced
  - ➡ A… e… …4S)



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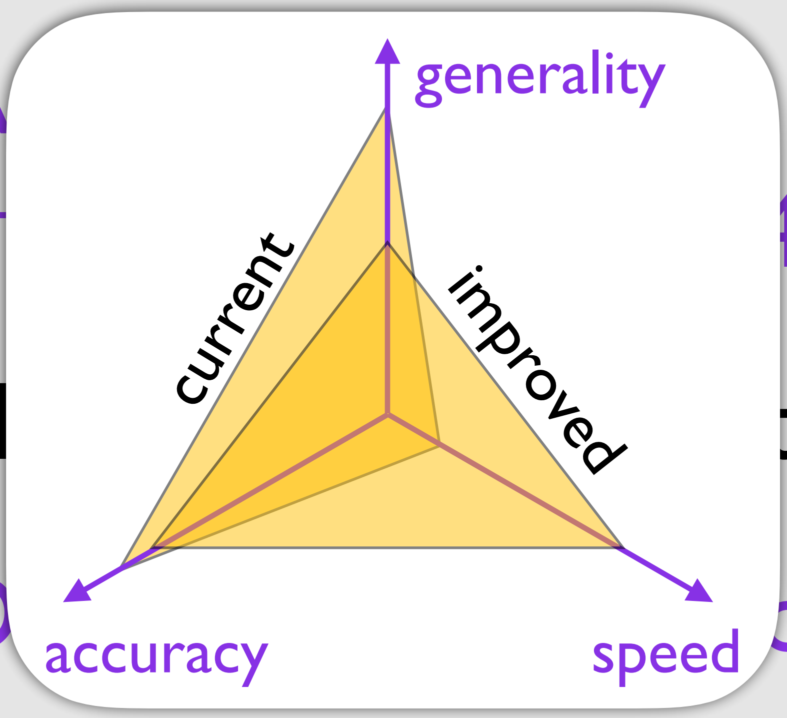

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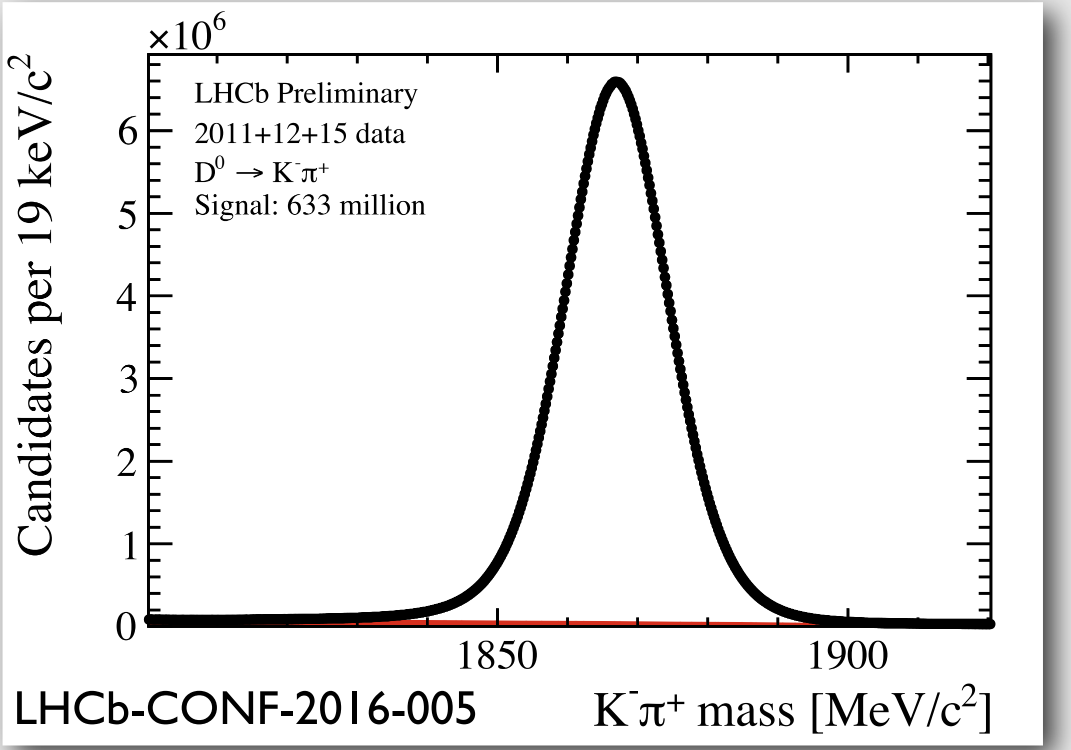

- Technical
  - ➡ Data s
  - ➡ Simula
  - ➡ Data analysis

Fitting large data sets is a growing challenge
→ Will need more and more sophisticated models
→ Playground for new approaches, e.g. with GPUs

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Conclusion

- Charm was discovered over 40 years ago
  - ➡ Spectroscopy evolved a lot, but still leaves open questions
- Mixing discovery over 10 years ago
  - ➡ But do D^0 and $\overline{D}^0$ mesons oscillate, i.e. is $x \neq 0$?
- Now:
  - ➡ LHCb in its last year of data taking, BESIII, (and still BaBar, Belle)
- Next:
  - ➡ New facilities: Belle II, LHCb upgrades, PANDA, …
- What will they bring?
  - ➡ Charm baryon spectrum?
  - ➡ More exotic states?
  - ➡ CP violation?
- Challenges ahead
  - ➡ Both technical and physics-related
  - ➡ Exploit synergies wherever possible