Experimental overview

Marco Gersabeck (The University of Manchester)

8th International Workshop on Charm Physics
Bologna, Italy
10 years and 3 months after CHARM@Beijing 2006

Outline

- Part I
  - From Past to present
    - Trying not to steal the show from other speakers
- Part II
  - Whereto next?

The very beginning

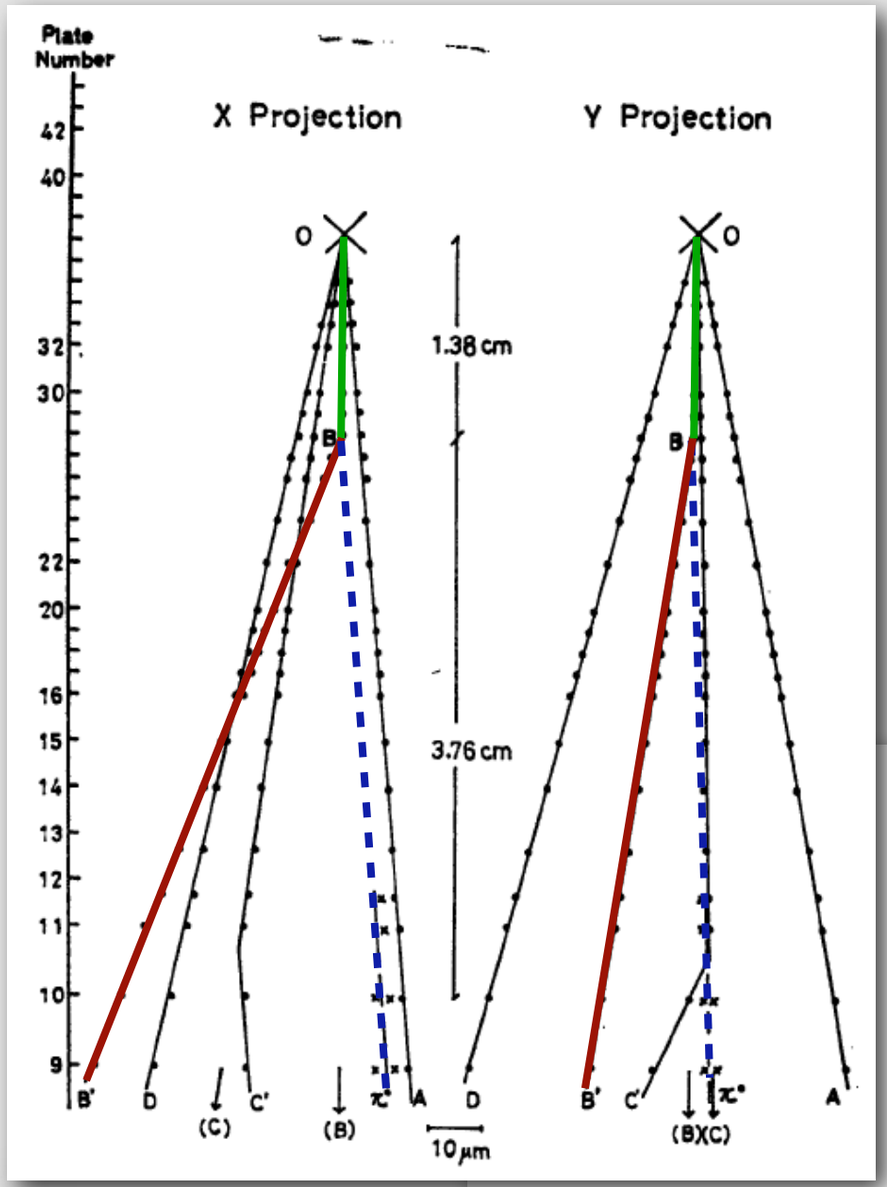
Prog. Theor. Phys. Vol. 46 (1971), No. 5

A Possible Decay in Flight of a New Type Particle

Kiyoshi NIU, Eiko MIKUMO and Yasuko MAEDA*

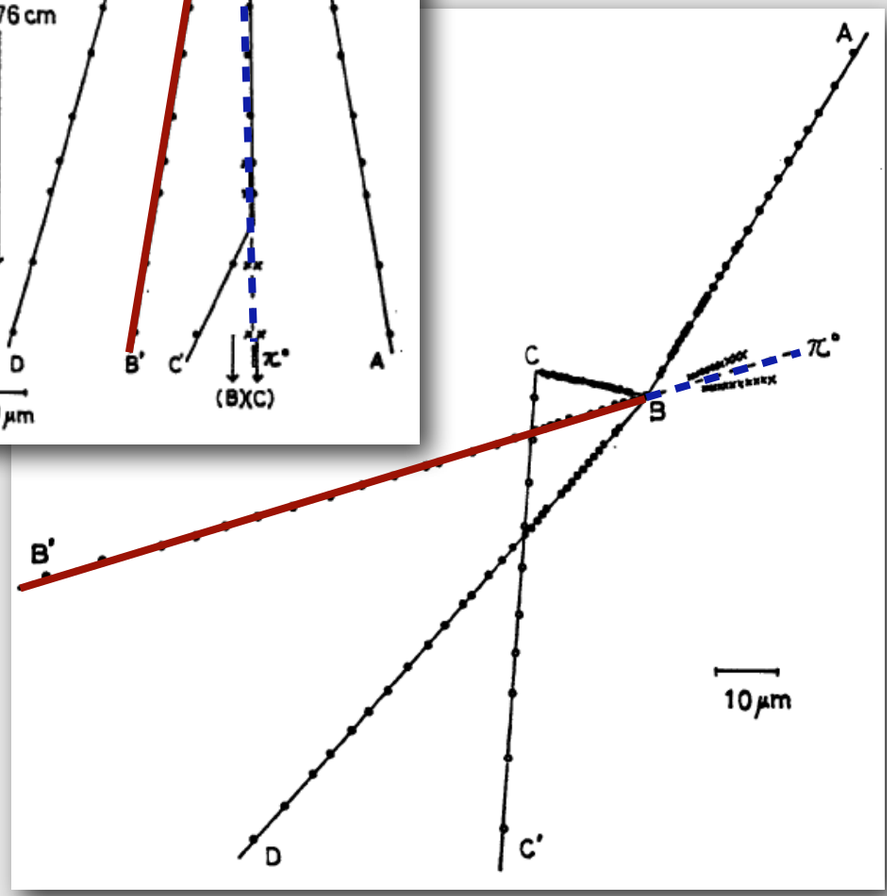
Institute for Nuclear Study
University of Tokyo
**Yokohama National University*

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}



The Nobel beginning

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

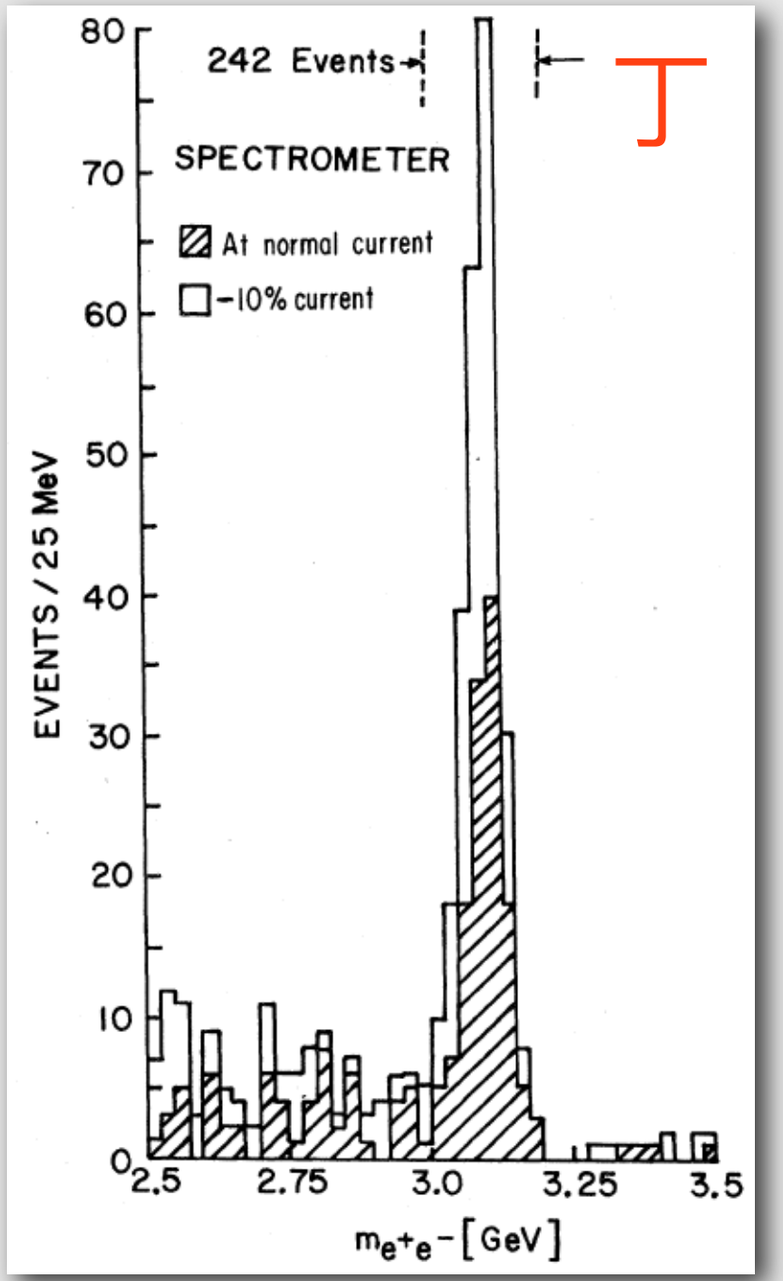
Y. Y. Lee
Brookhaven National Laboratory, Upton, New York 11973
(Received 12 November 1974)

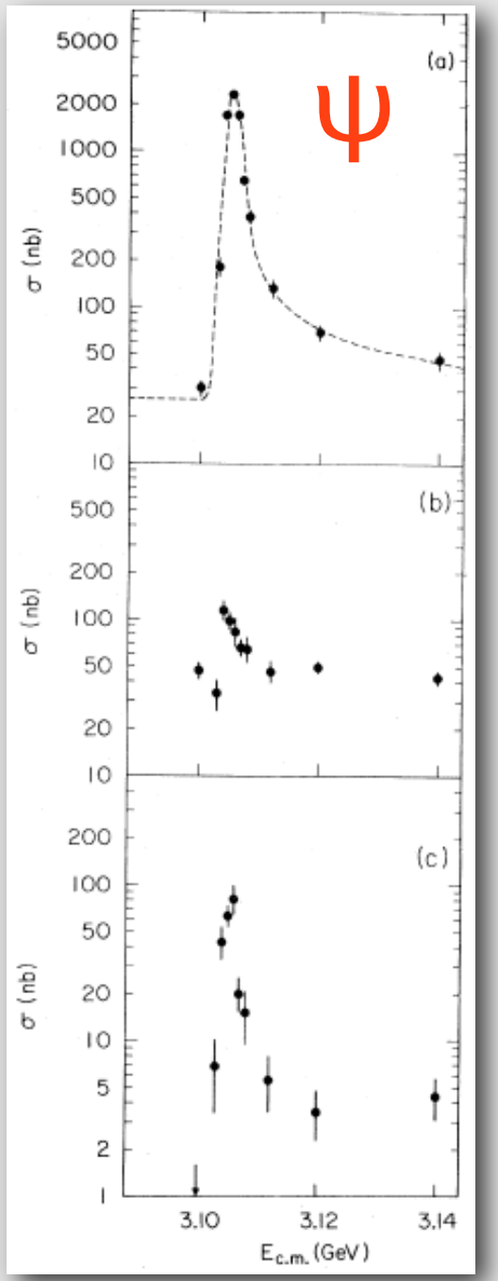
Discovery of a Narrow Resonance in e^+e^- Annihilation*

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)





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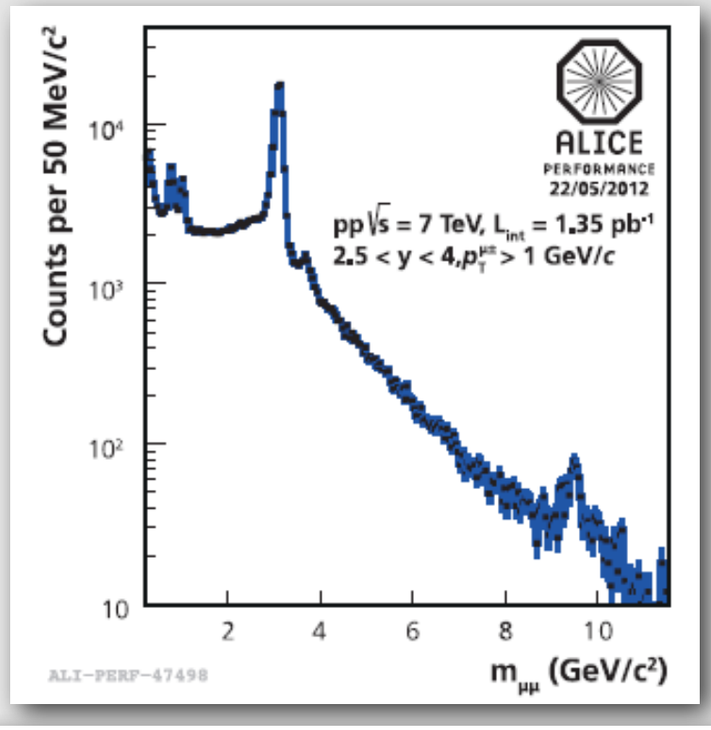
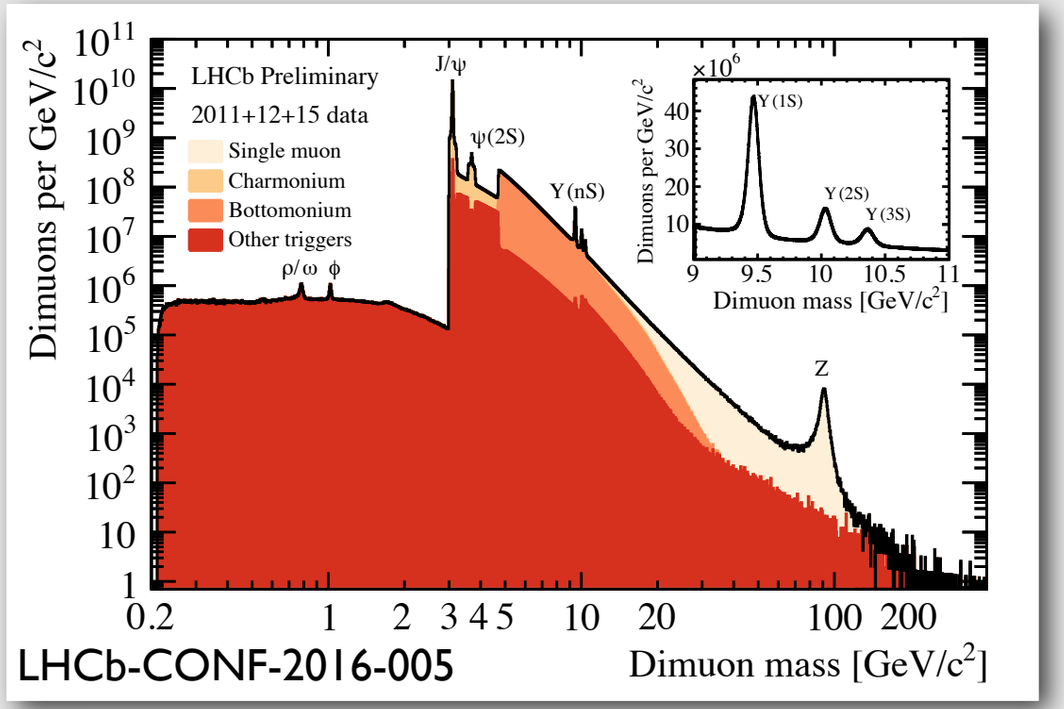
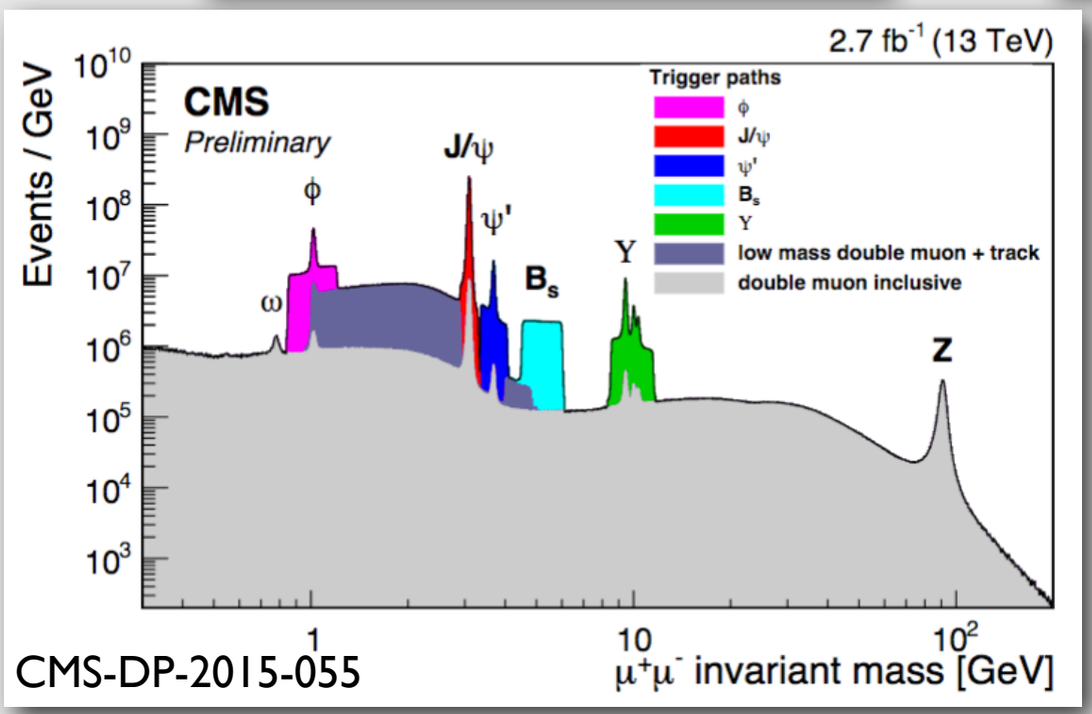
J/psi today





LHCb-CONF-2016-005



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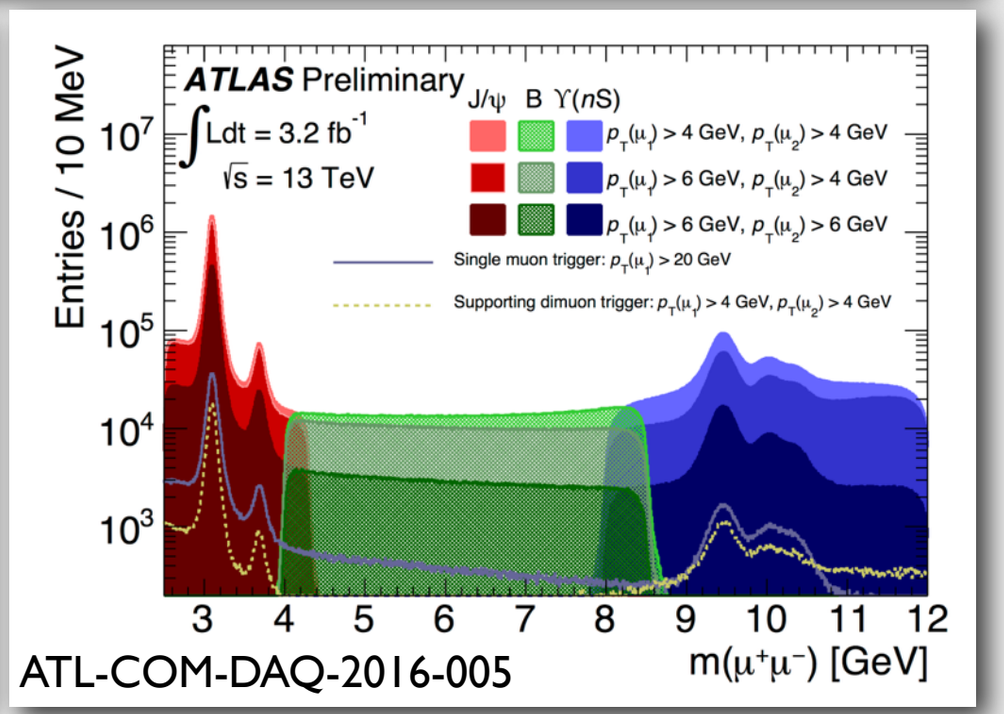

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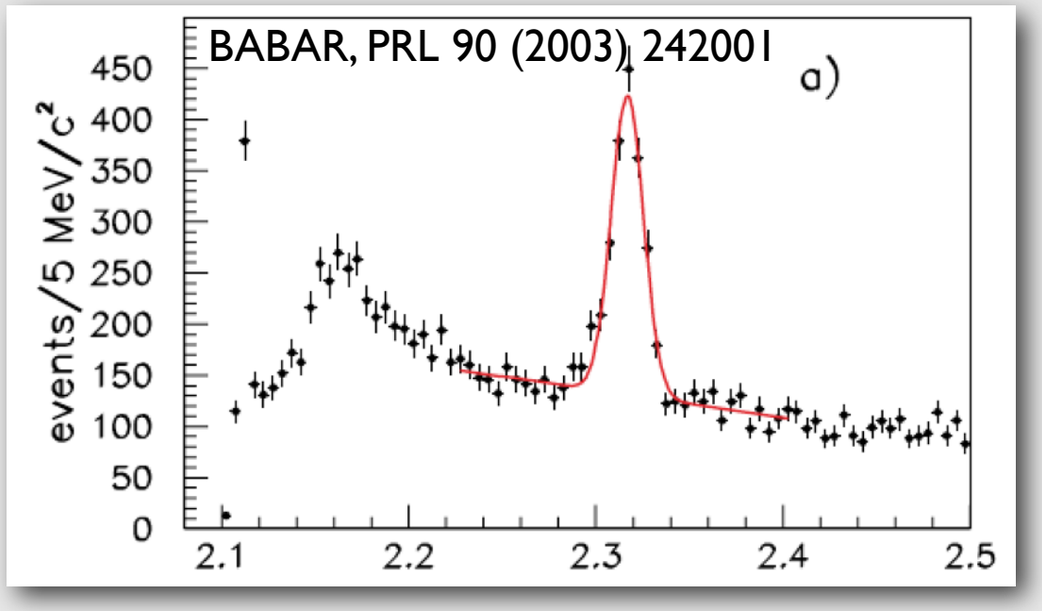
Spectroscopy

Friday morning



- Strange peaks started appearing in 2003/04
- Matching with quark model predictions still difficult
  - ➡ Many gaps in possible states
  - ➡ Some observed states may be exotics
- Different production mechanisms
  - ➡ Prompt vs B decays

$n\,^{2s+1}\ell_J$	J^{PC}	$I = \frac{1}{2}$ $c\bar{u}$, $c\bar{d}$; $\bar{c}u$, $\bar{c}d$	$I = 0$ $c\bar{s}$; $\bar{c}s$
$1\,^1S_0$	0^{-+}	D	$D_s^{\pm}$
$1\,^3S_1$	1^{--}	D^*	$D_s^{*\pm}$
$1\,^1P_1$	1^{+-}	$D_1(2420)$	$D_{s1}(2536)^{\pm}$
$1\,^3P_0$	0^{++}	$D_0^*(2400)$	$D_{s0}^*(2317)^{\pm\dagger}$
$1\,^3P_1$	1^{++}	$D_1(2430)$	$D_{s1}(2460)^{\pm\dagger}$
$1\,^3P_2$	2^{++}	$D_2^*(2460)$	$D_{s2}^*(2573)^{\pm}$
$1\,^3D_1$	1^{--}		$D_{s1}^*(2860)^{\pm\ddagger}$
$1\,^3D_3$	3^{--}		$D_{s3}^*(2860)^{\pm}$
$2\,^1S_0$	0^{-+}	$D(2550)$	
$2\,^3S_1$	1^{--}		$D_{s1}^*(2700)^{\pm\ddagger}$
$2\,^1P_1$	1^{+-}		
$2\,^3P_{0,1,2}$	$0^{++}, 1^{++}, 2^{++}$		
$3\,^3P_{0,1,2}$	$0^{++}, 1^{++}, 2^{++}$		

C. Amsler et al. in PDG2015

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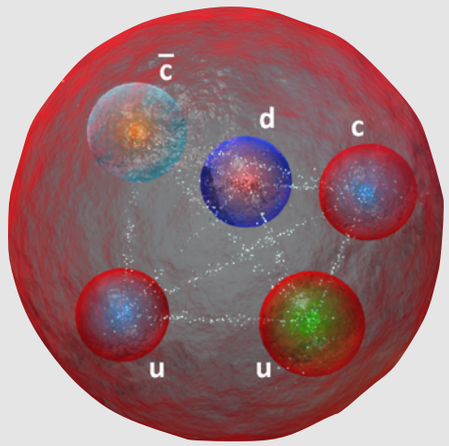
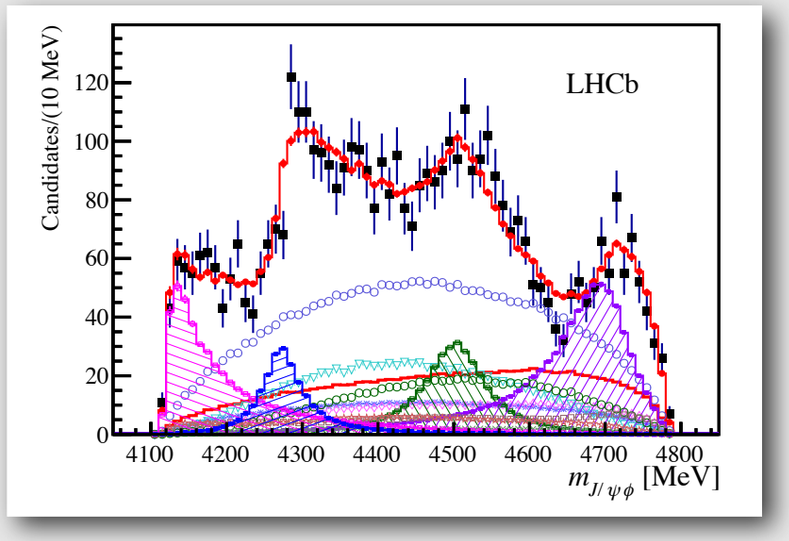
Exotica

Thursday morning

- What are they?
  - ➡ Different things
- Study various indicators
  - ➡ J^{PC}, mass, width, production, decay
- $Z_c(3900)^-$ was hot topic at Manchester
- Pentaquark with $c\bar{c}$ followed last year
- New insights on X(4140) will be discussed here
  - ➡ It was seen, then not, and again, and so on

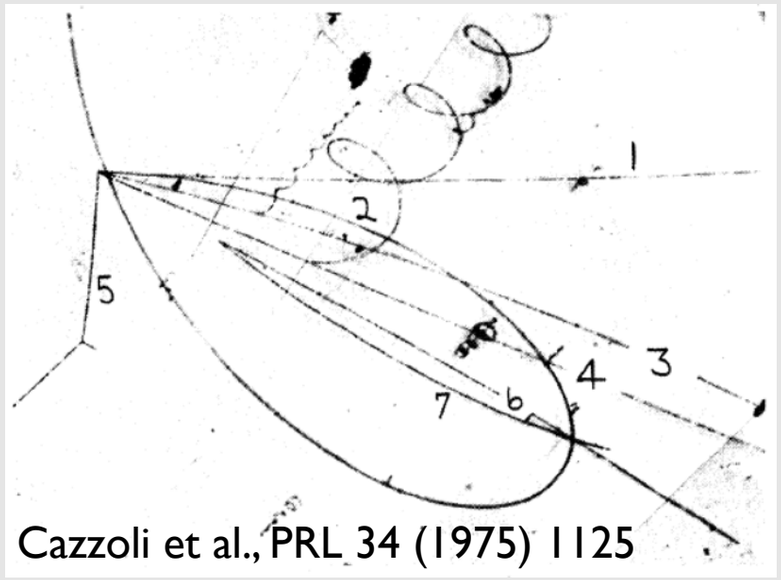


arXiv:1606.07895

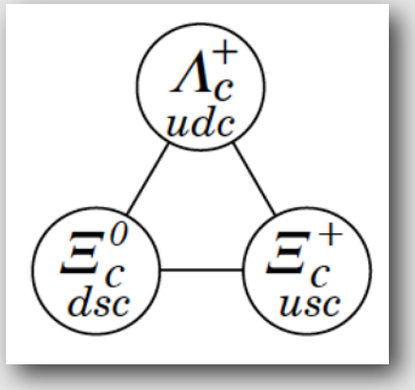


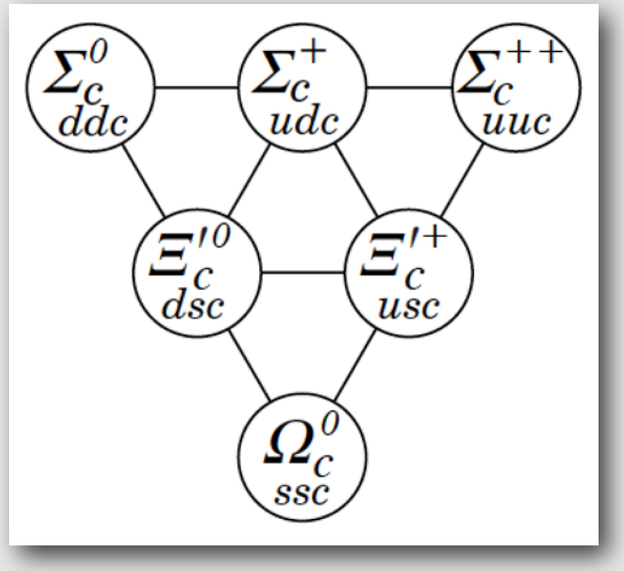
Baryons

Tuesday morning

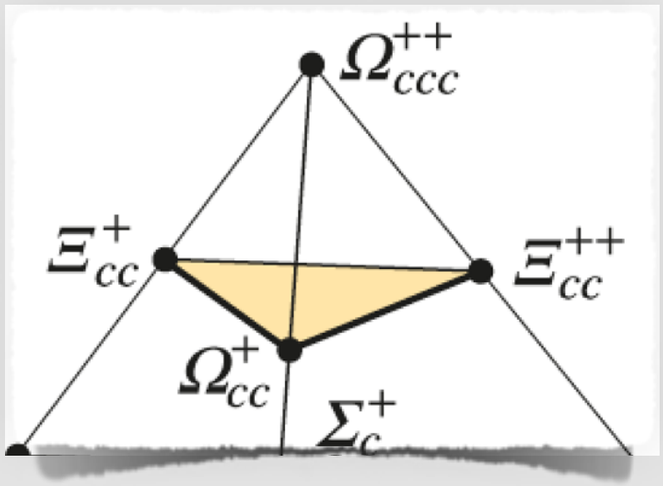


Cazzoli et al., PRL 34 (1975) 1125





- Ground state singly-charmed baryons known
  - ➡ Lifetimes between 3% and 17% uncertainties
- No established doubly-charmed baryon
  - ➡ Not to mention Ω_{ccc}
- What level of CPV should we expect?

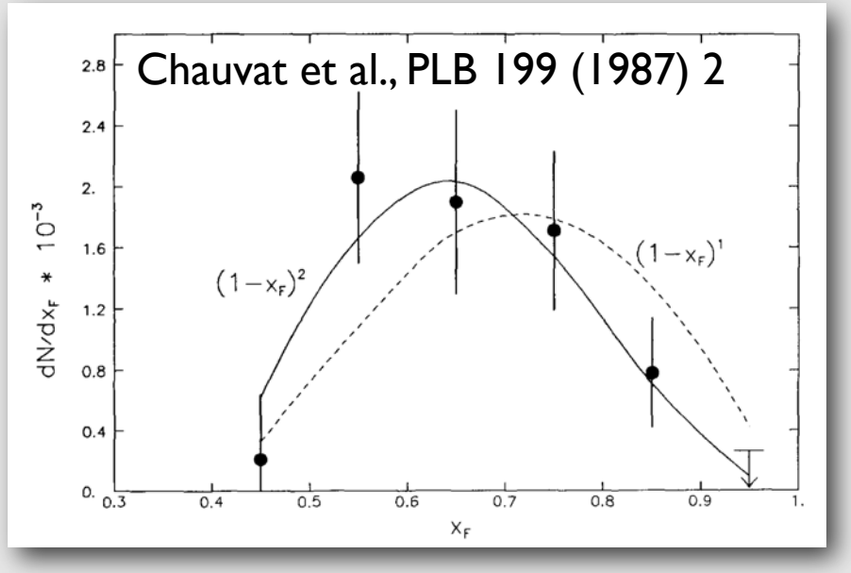


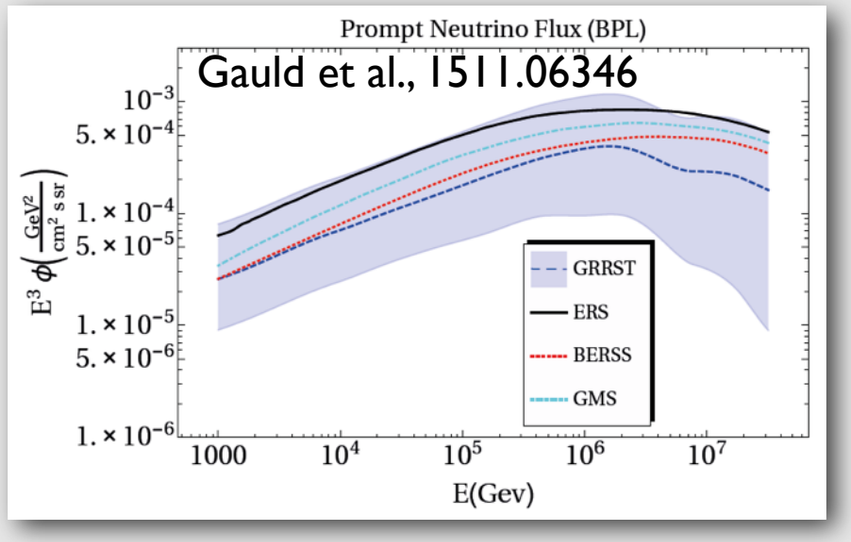
C.G.Wohl in PDG2014

Production

Monday afternoon
Thu+Fri morning

- Charm production as precision measurements
  - ➡ Constrain PDFs and QCD processes
    - Comparing e^+e^-, pp, $p\bar{p}$, ions, associated production
  - ➡ (Still) searching for intrinsic charm
  - ➡ Puts direct constraints on charm production in atmosphere
    - Crucial for high-energy neutrino background
- Production rates in different collisions are crucial input in identifying exotica





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IC@IC, Laha et al., arXiv:1607.08240

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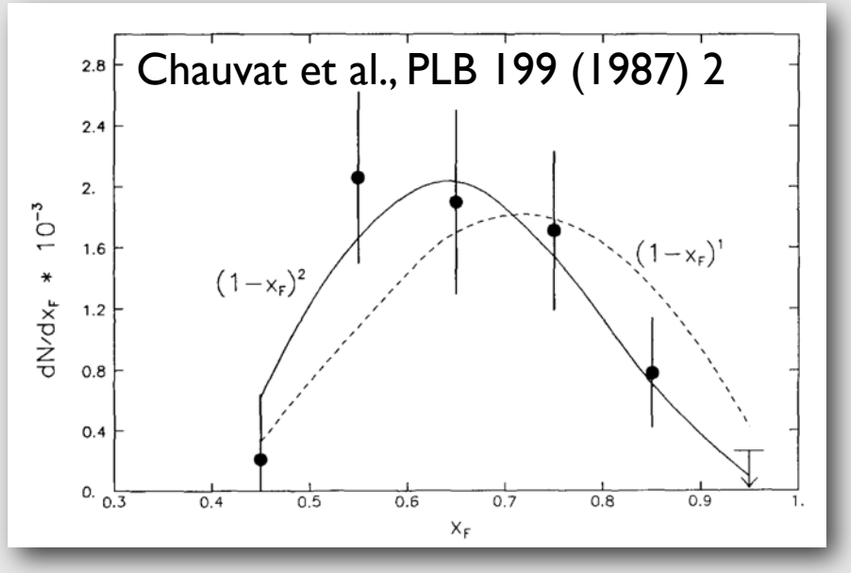

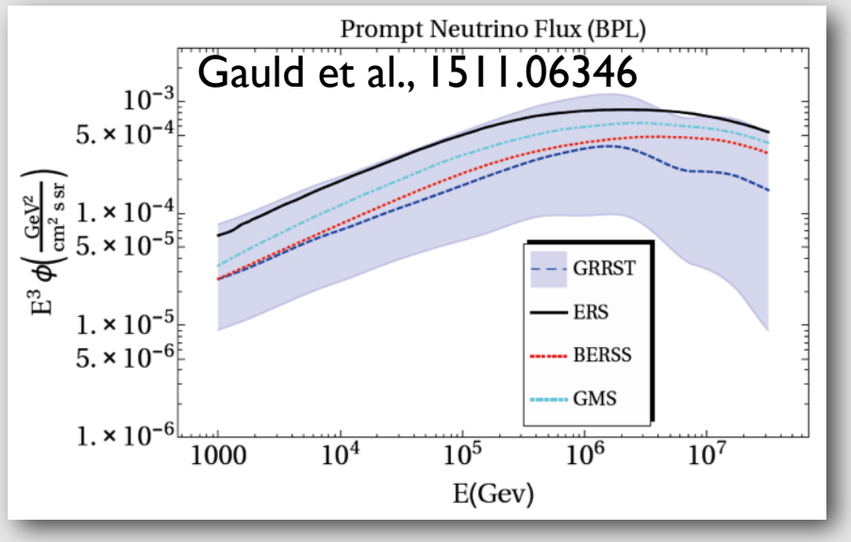

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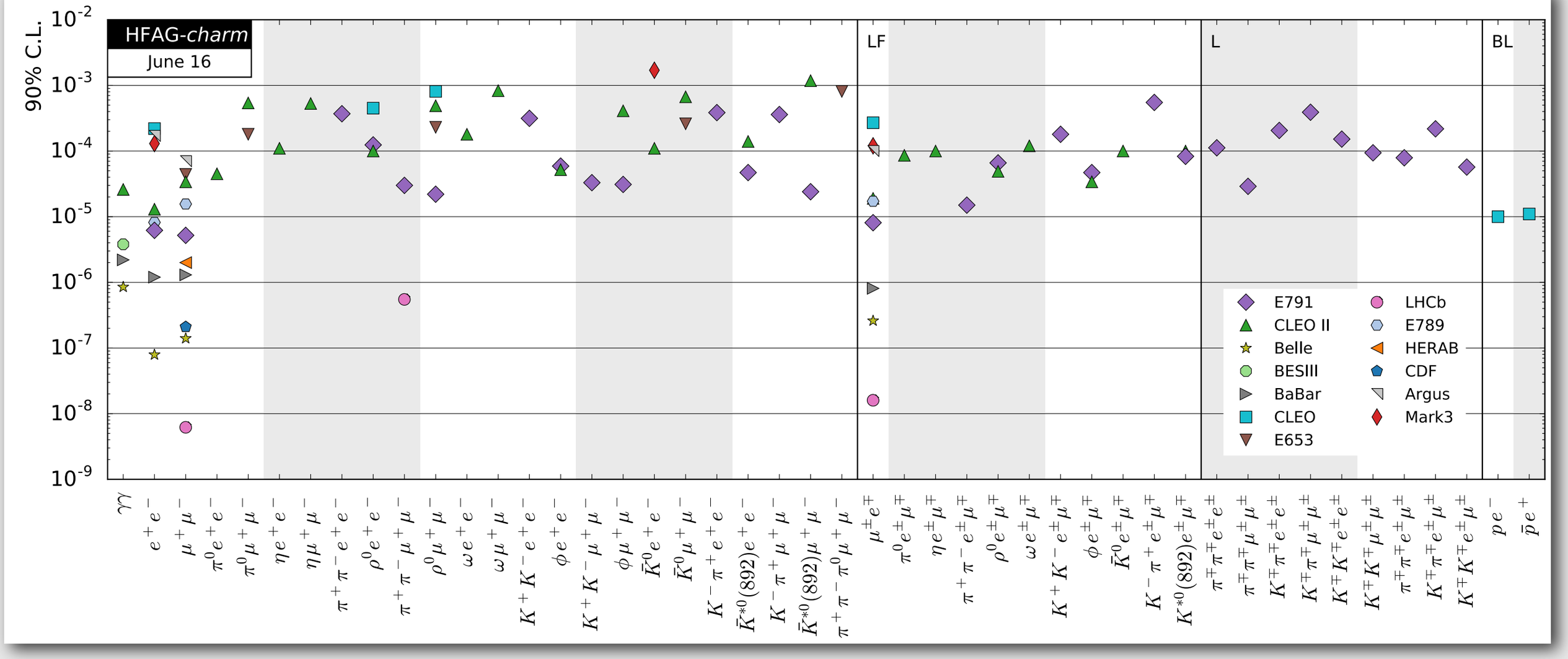
Rare decays

Tuesday morning



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

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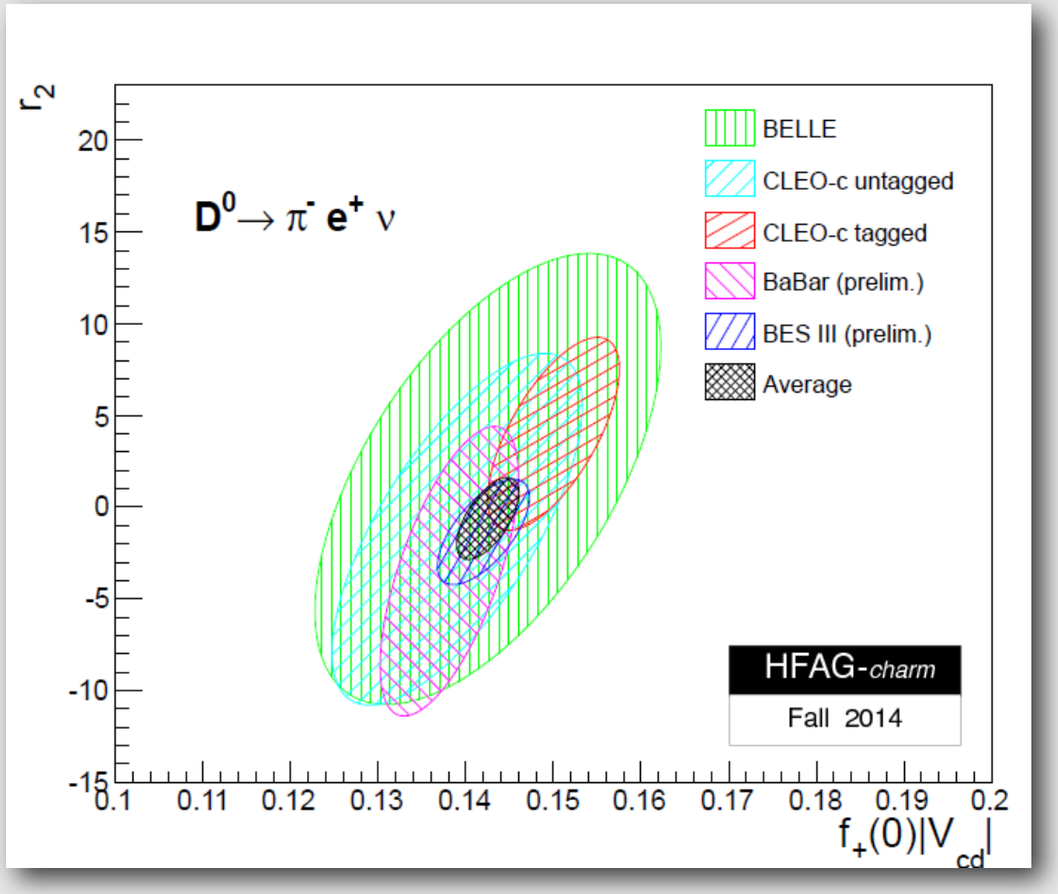
(Semi-)leptonic decays

Tuesday morning

- Measure
  - ➡ Decay constants
  - ➡ CKM elements
  - ➡ Form factors
- Also potential for
  - ➡ Mixing (requires loads of data, $R_M \approx 3\times10^{-5}$)
  - ➡ Lepton universality tests



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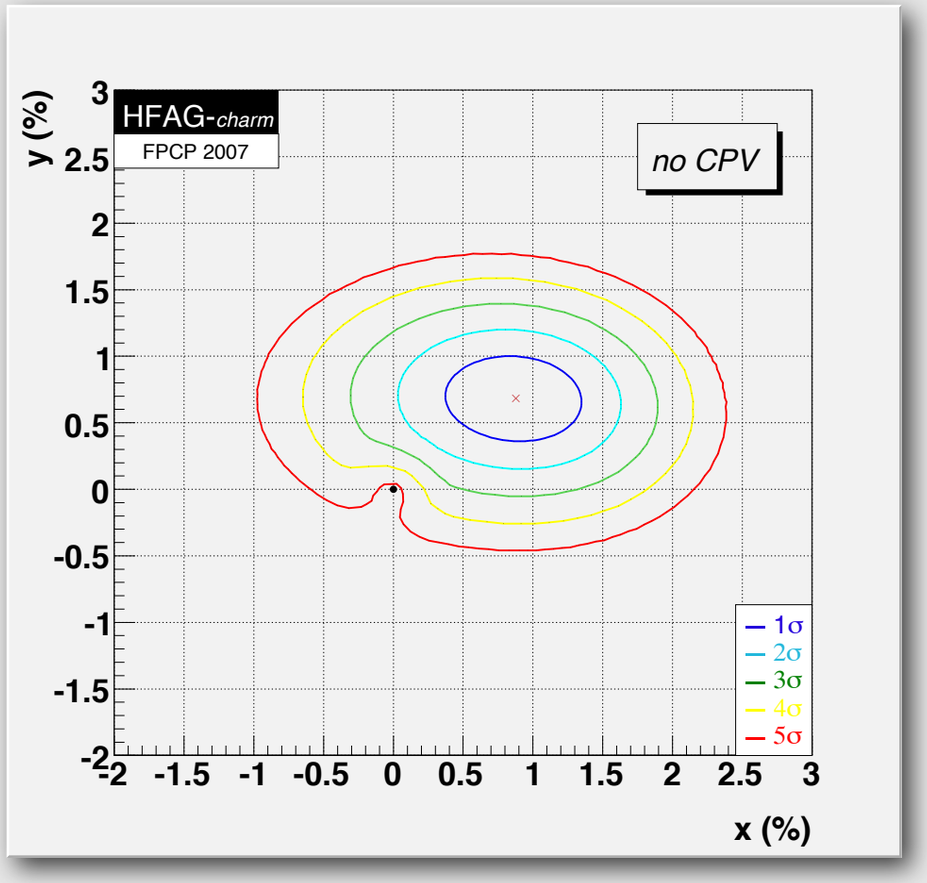
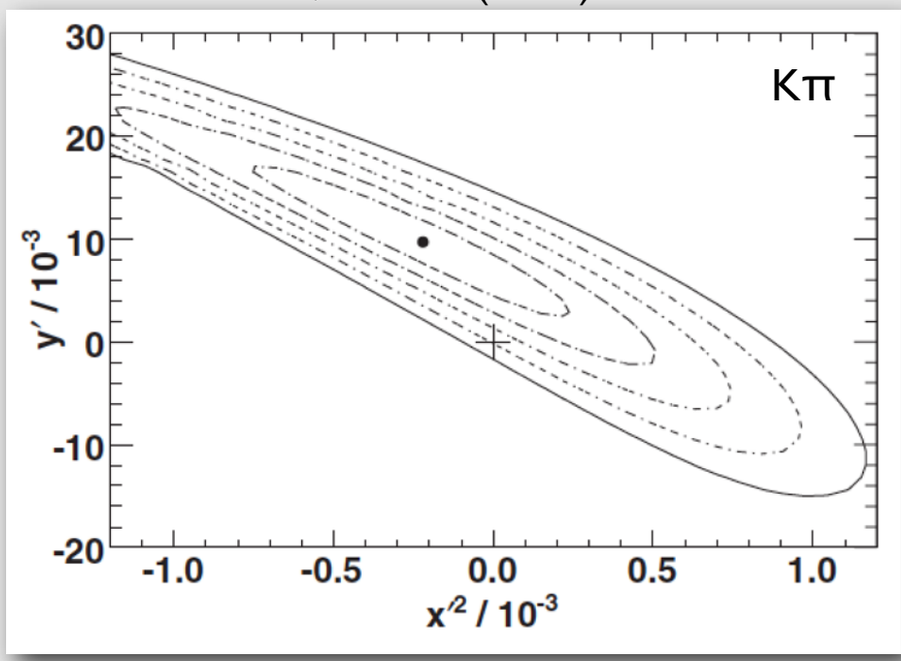
Mixing discovery

Thursday afternoon

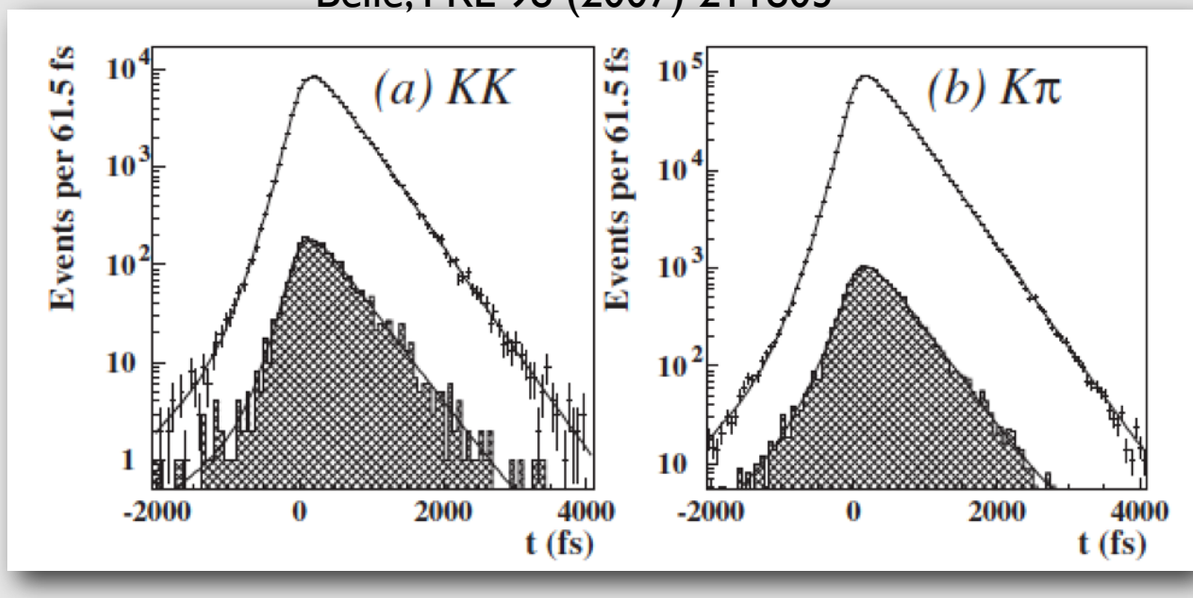


BABAR, PRL 98 (2007) 211802



- Discovery through combination of measurements

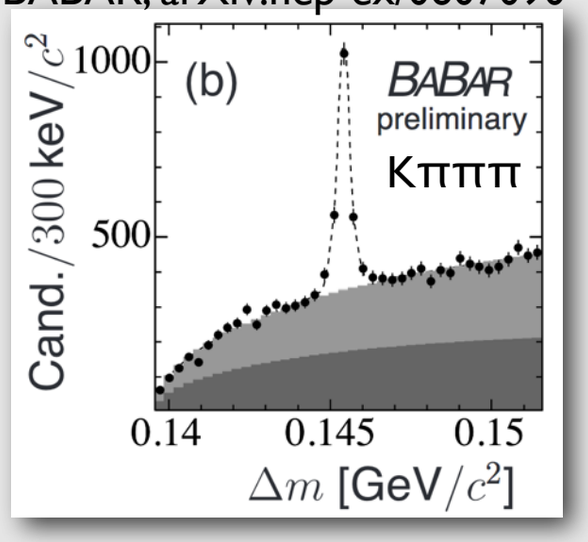
Belle, PRL 98 (2007) 211803



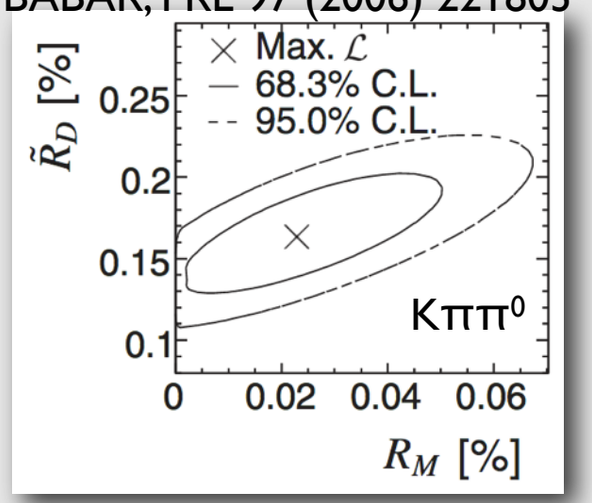
Mixing discovery

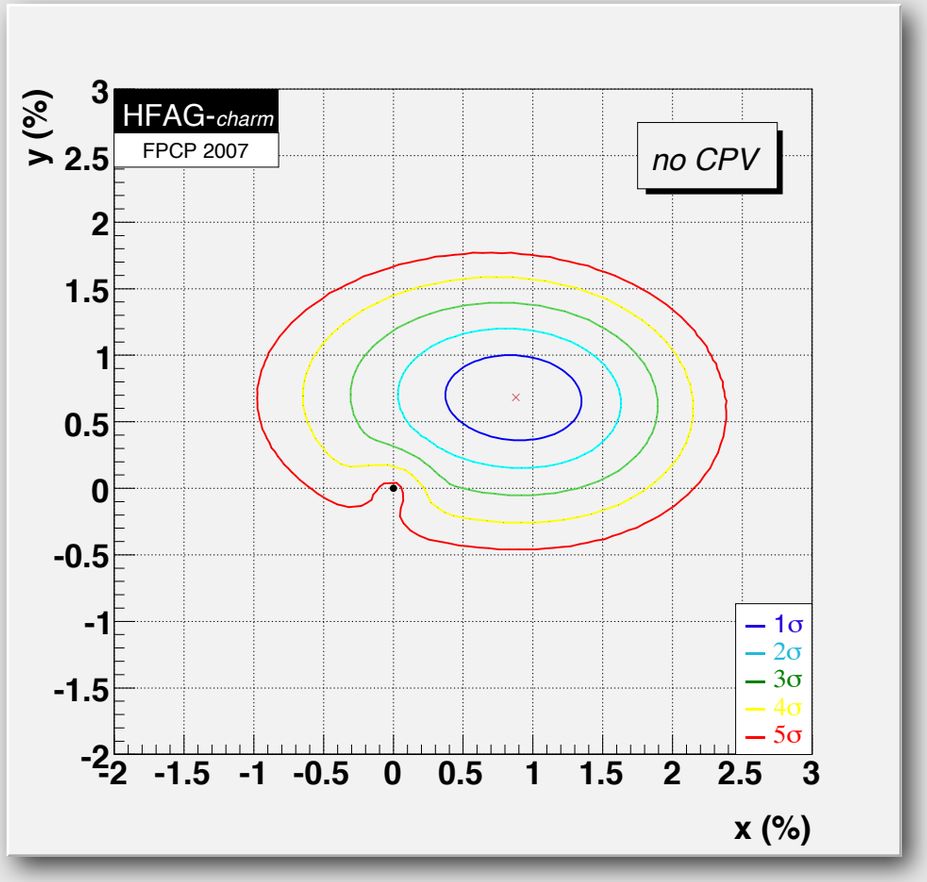
Thursday afternoon

BABAR, arXiv:hep-ex/0607090

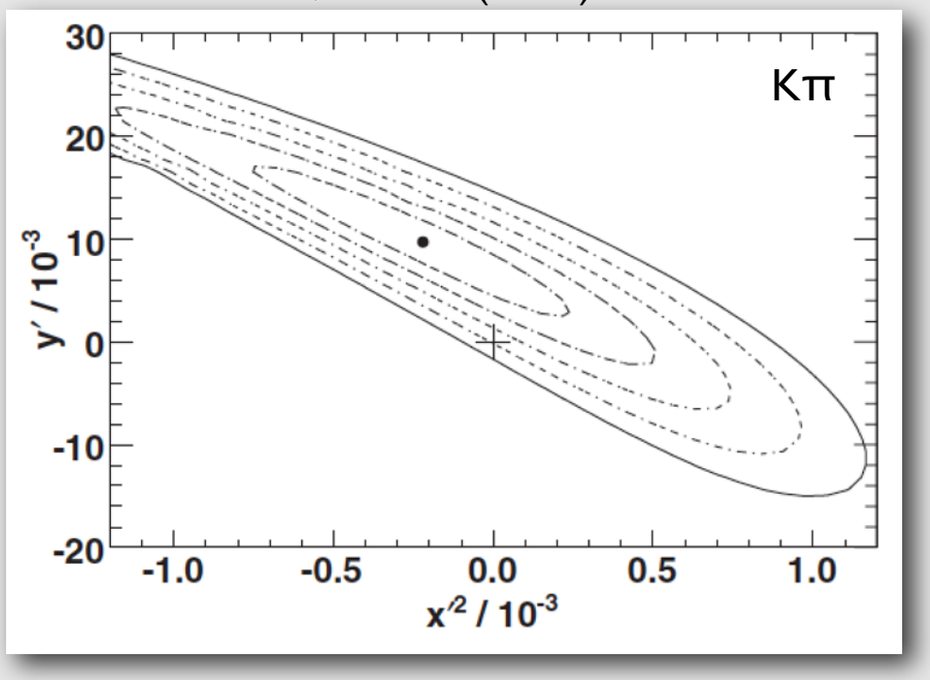


BABAR, PRL 97 (2006) 221803

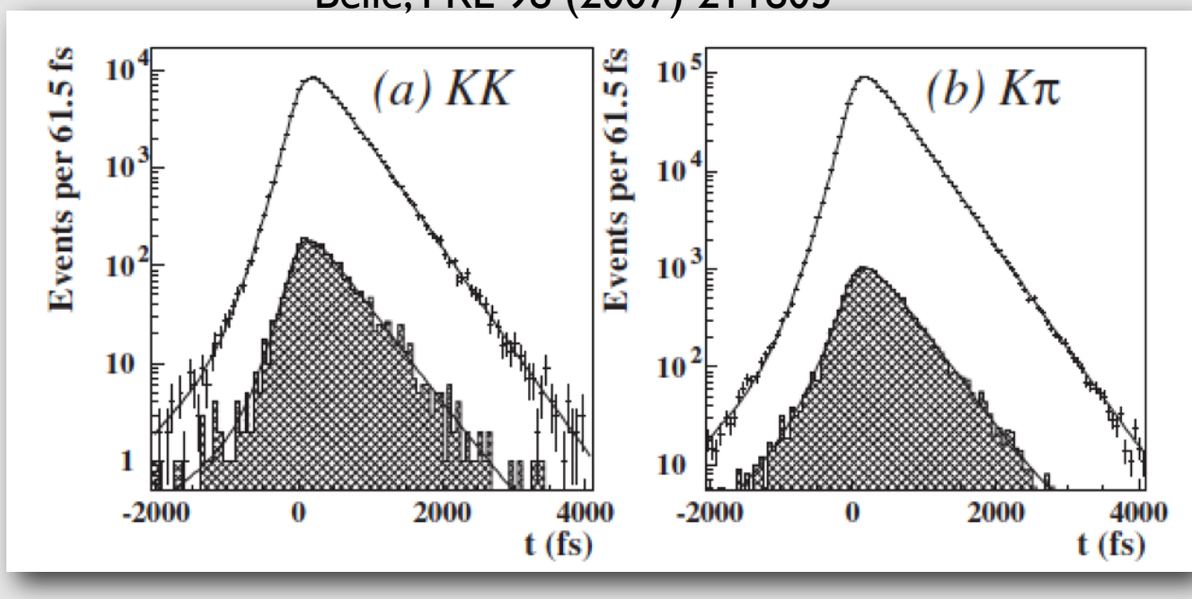




BABAR, PRL 98 (2007) 211802

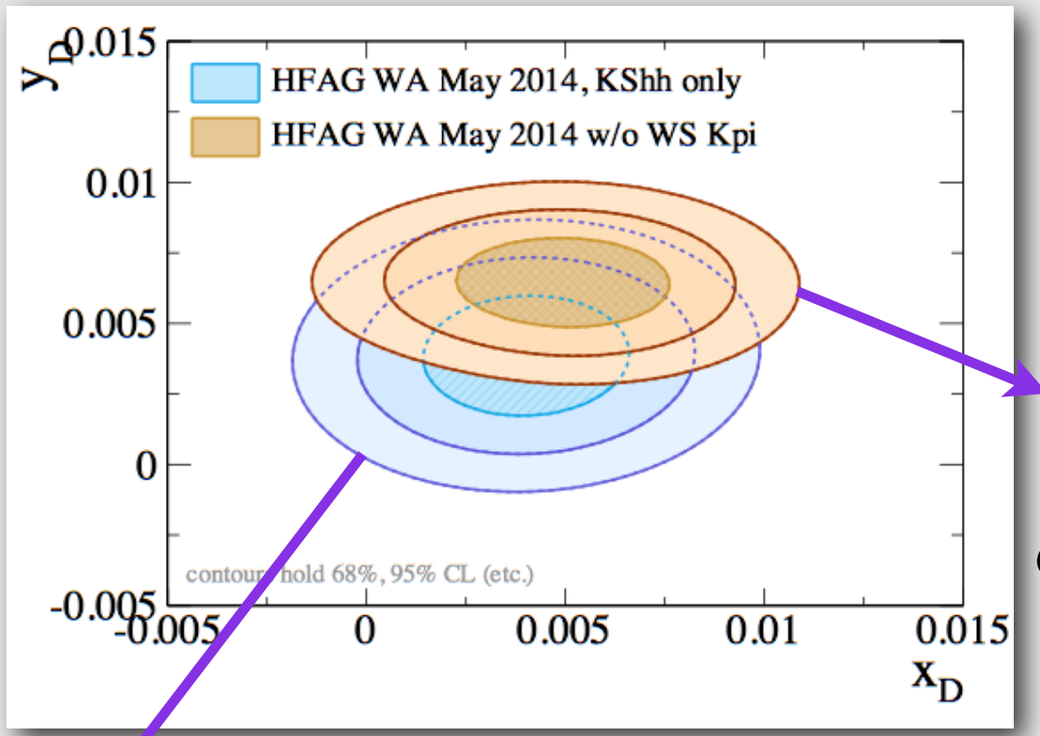


Belle, PRL 98 (2007) 211803



- Discovery through combination of measurements

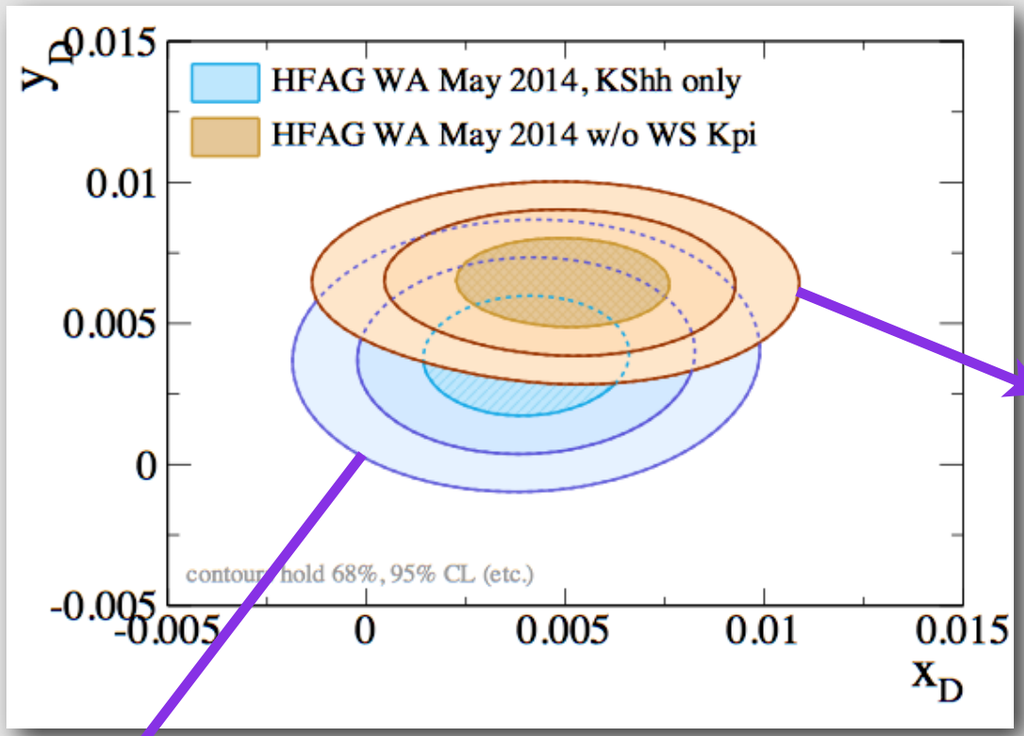
World average decoded



Adding y_{CP} mostly constrains y

x & y measured directly

World average decoded



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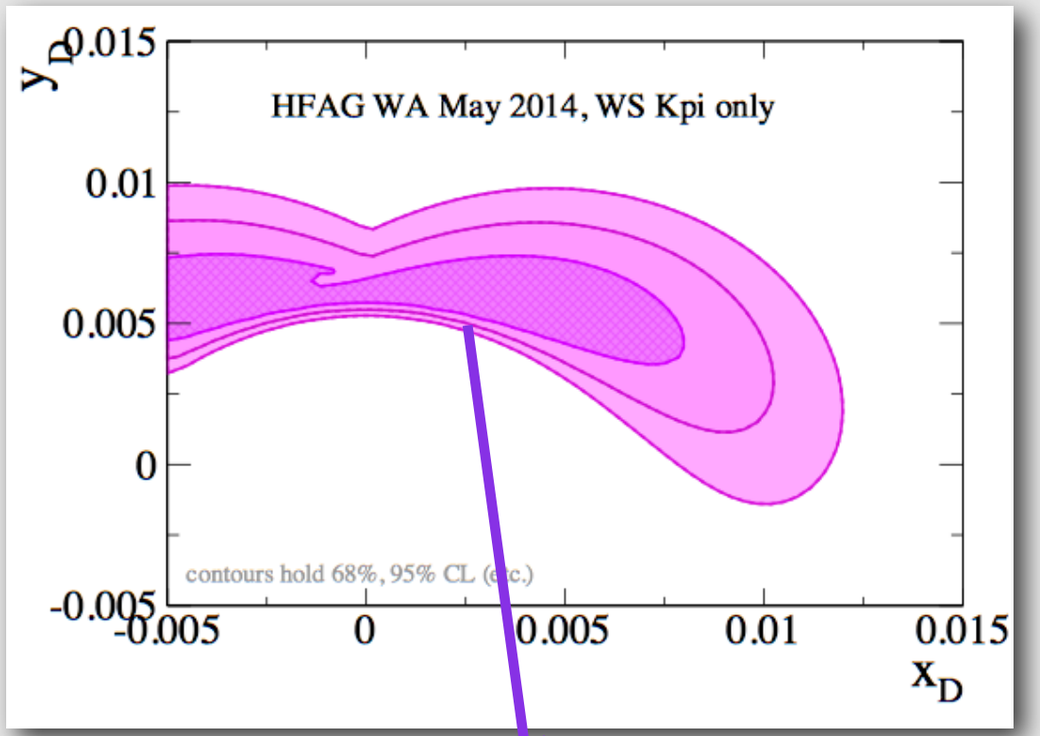
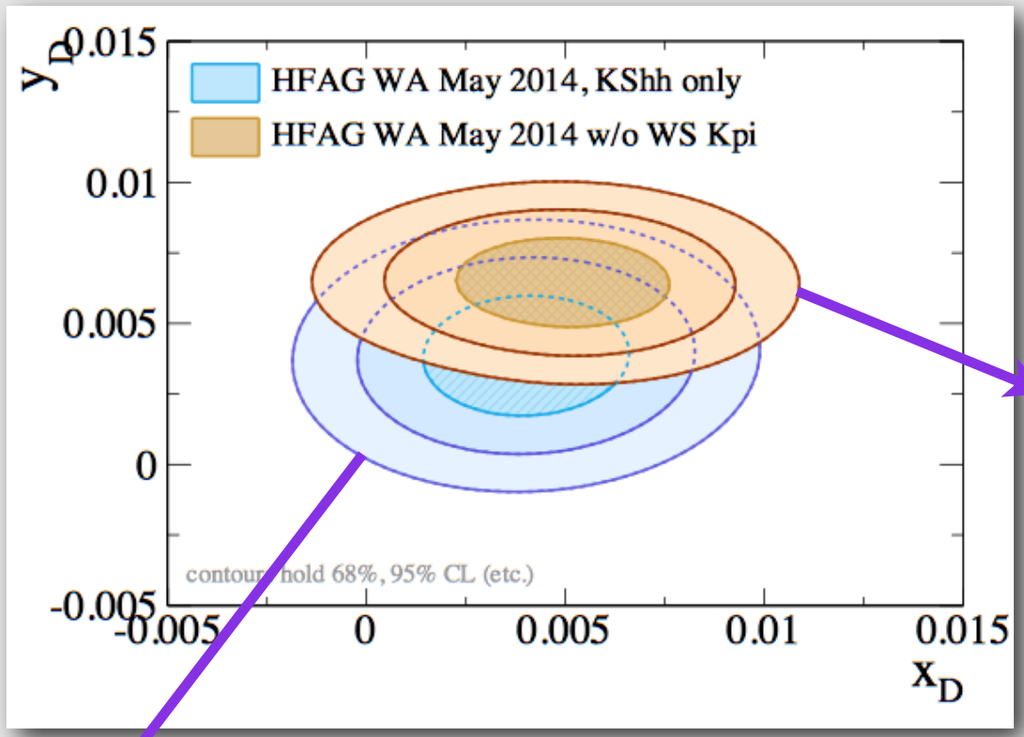


x^2+y^2 measures a ring
y′ mostly adds information on y ($\delta_{K\pi}$ near 0)

World average decoded



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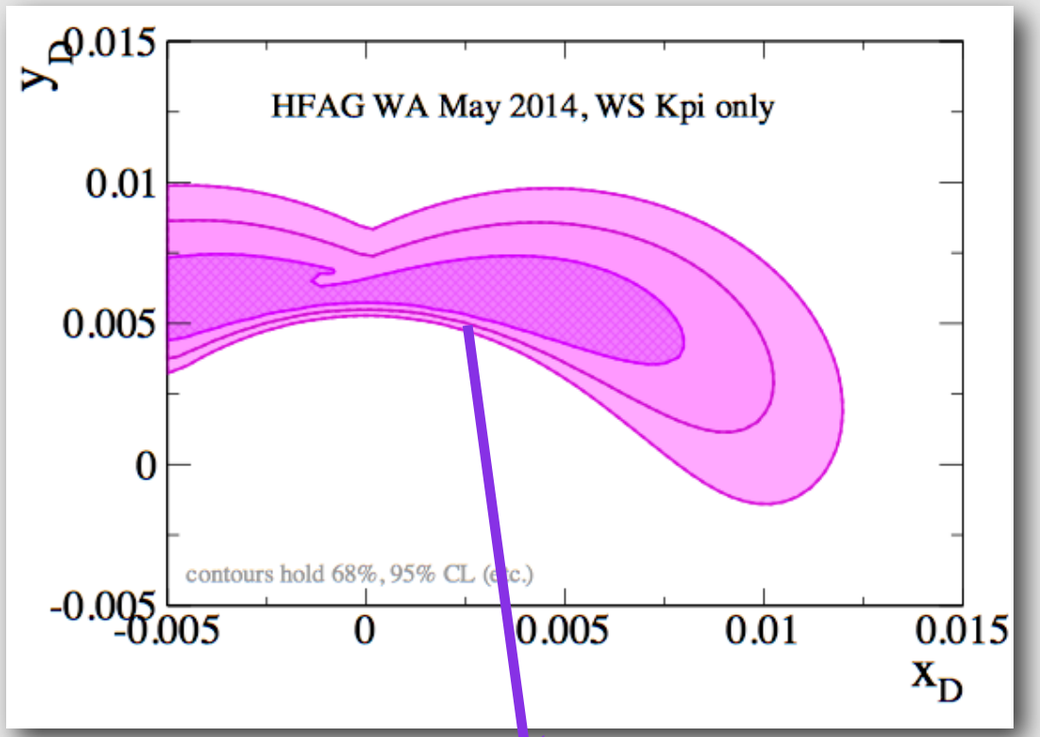

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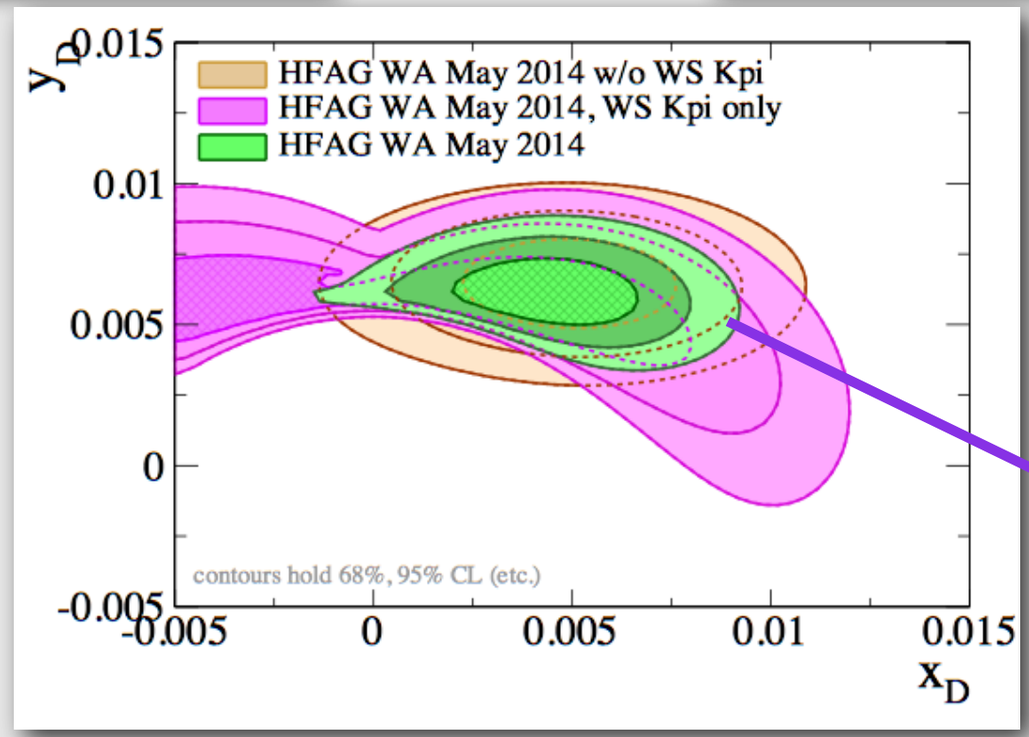
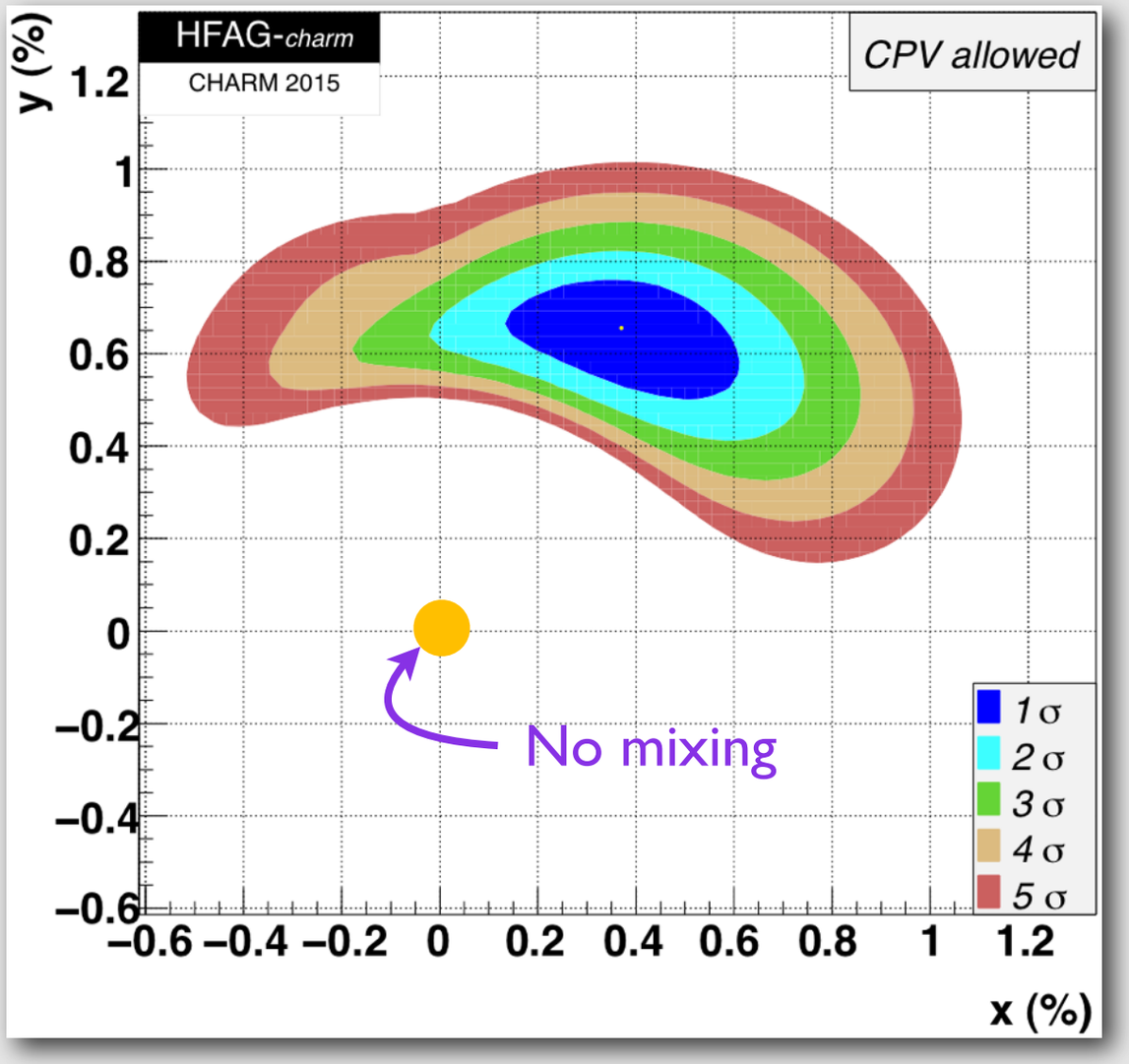


Full average following intersection of contours

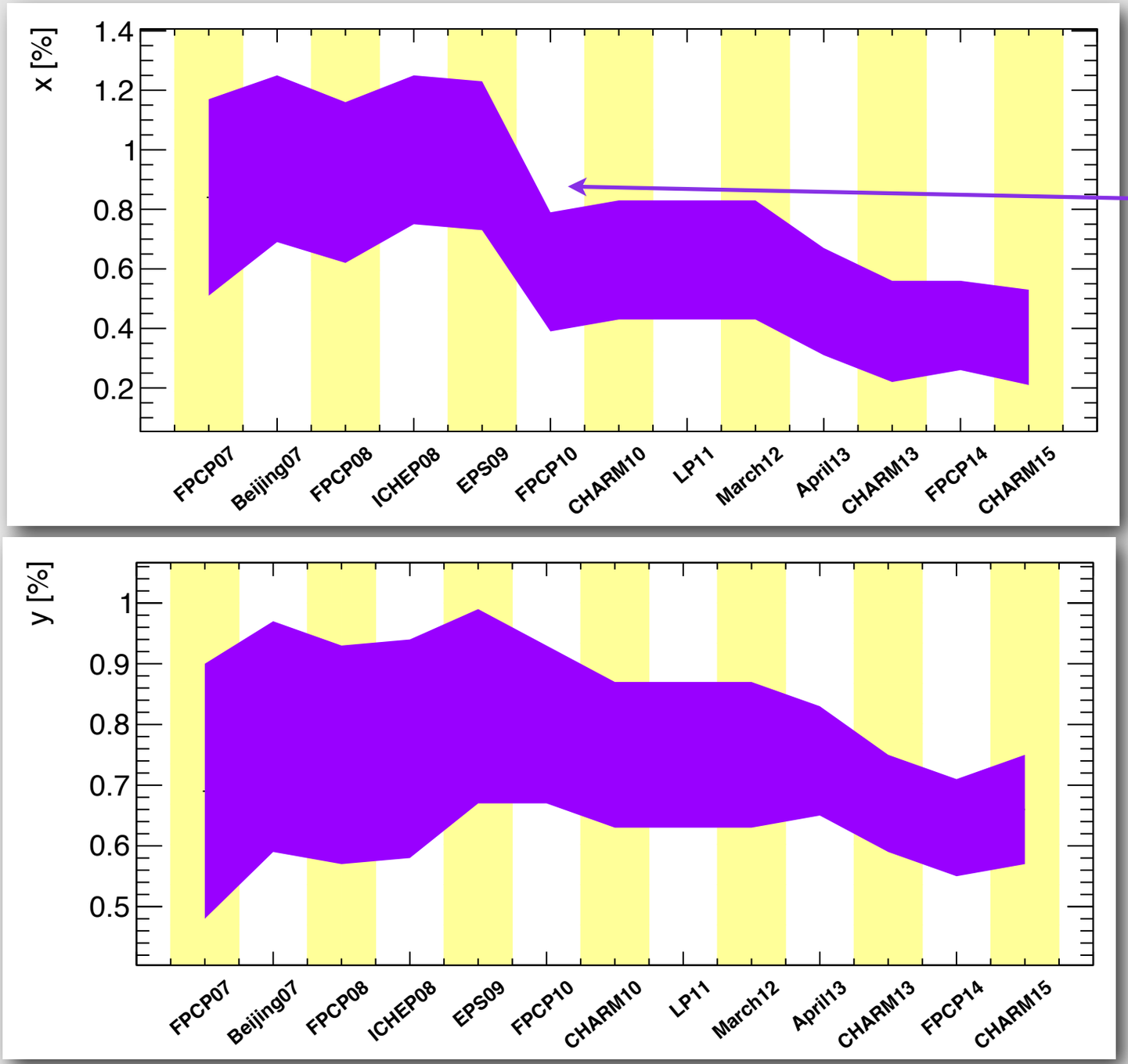
Mixing nowadays



- Mixing established

➡ x still unknown

Mixing evolution



BaBar 2010
$K_S hh$ analysis
full dataset

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Mixing-related CP violation

Thursday afternoon

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

Mixing:

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

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

CP violation:

$|q/p| \neq 0$

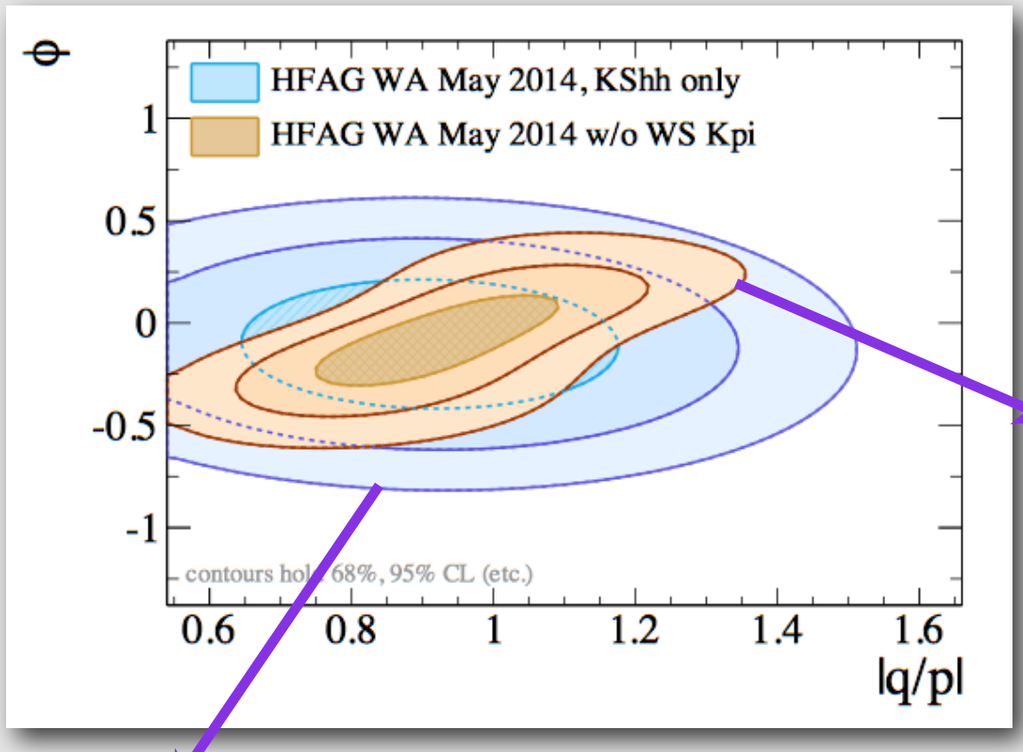
$\phi \equiv \arg(q/p) \neq 0, \pi$

Indirect CP violation:

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

with $a_m \approx \pm(|q/p|^2 - 1)$

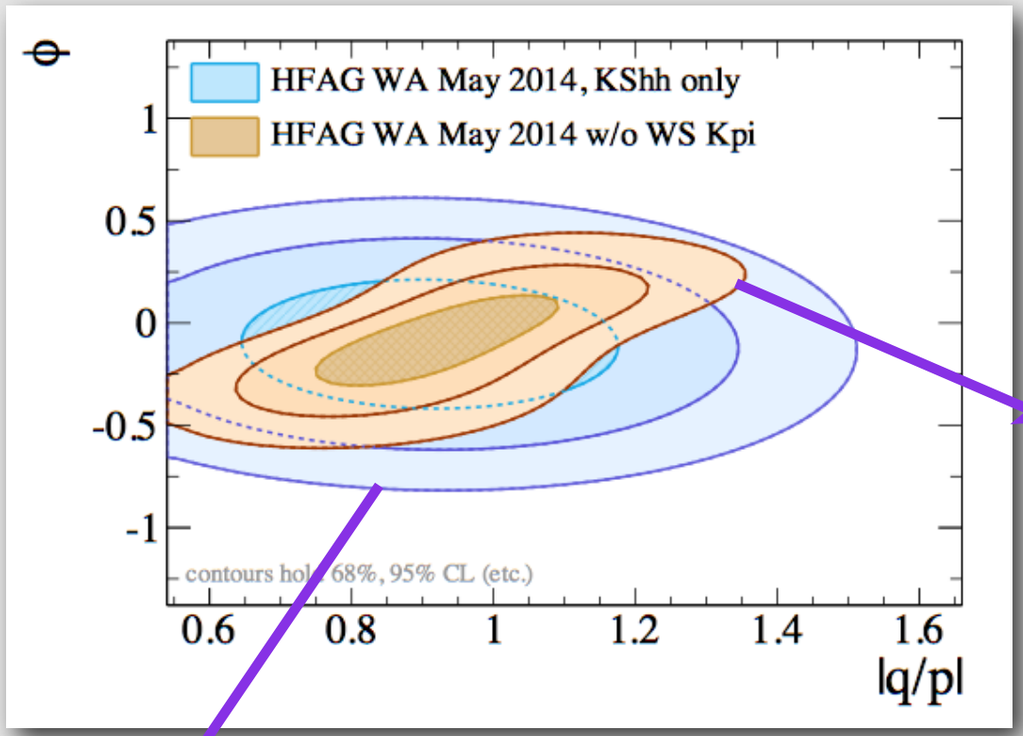
Contributions



Precise constraints if x and y provided, mostly from A_Γ

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

Contributions



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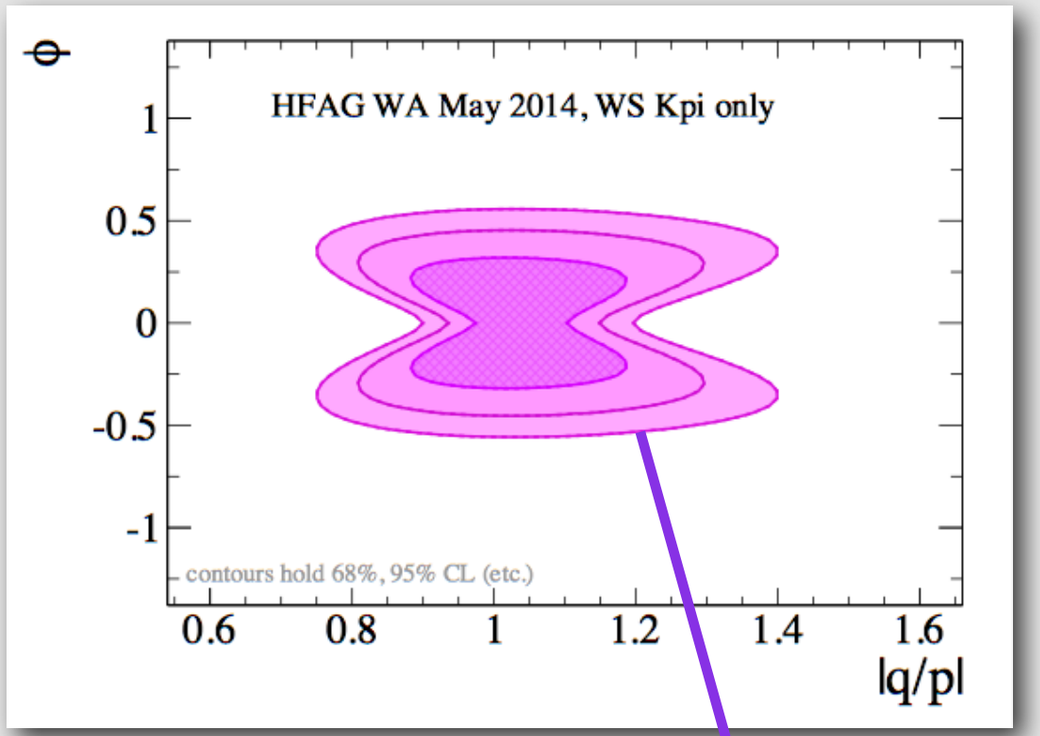
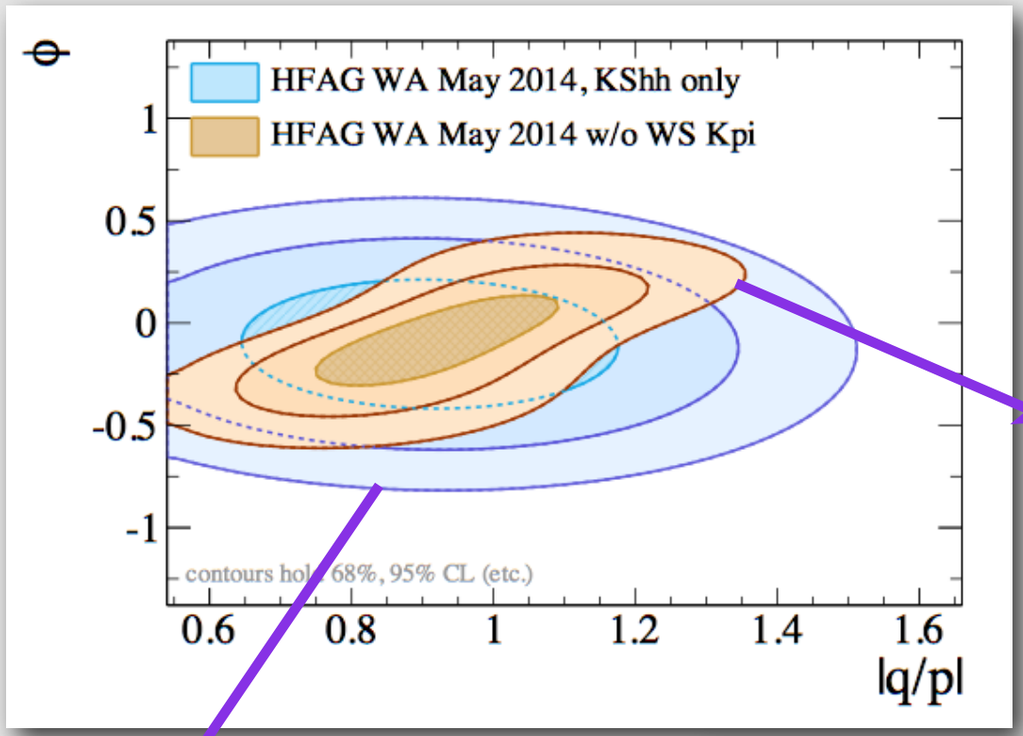


WS Kπ: symmetric in φ,

good sensitivity to |q/p| for small φ

Contributions



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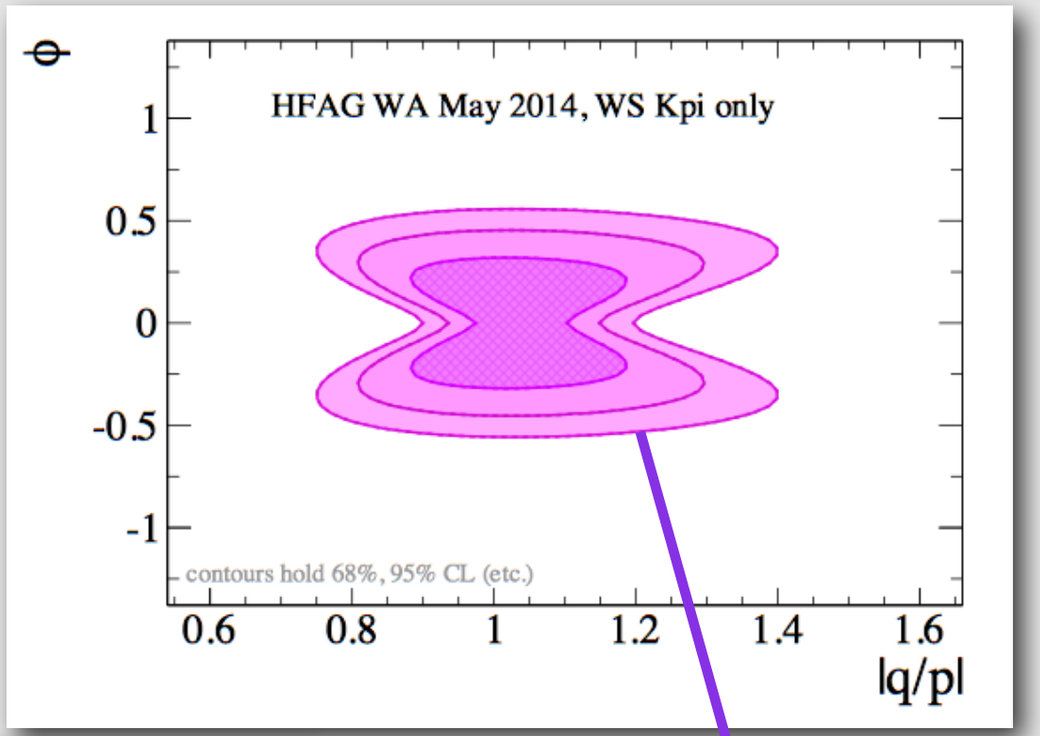
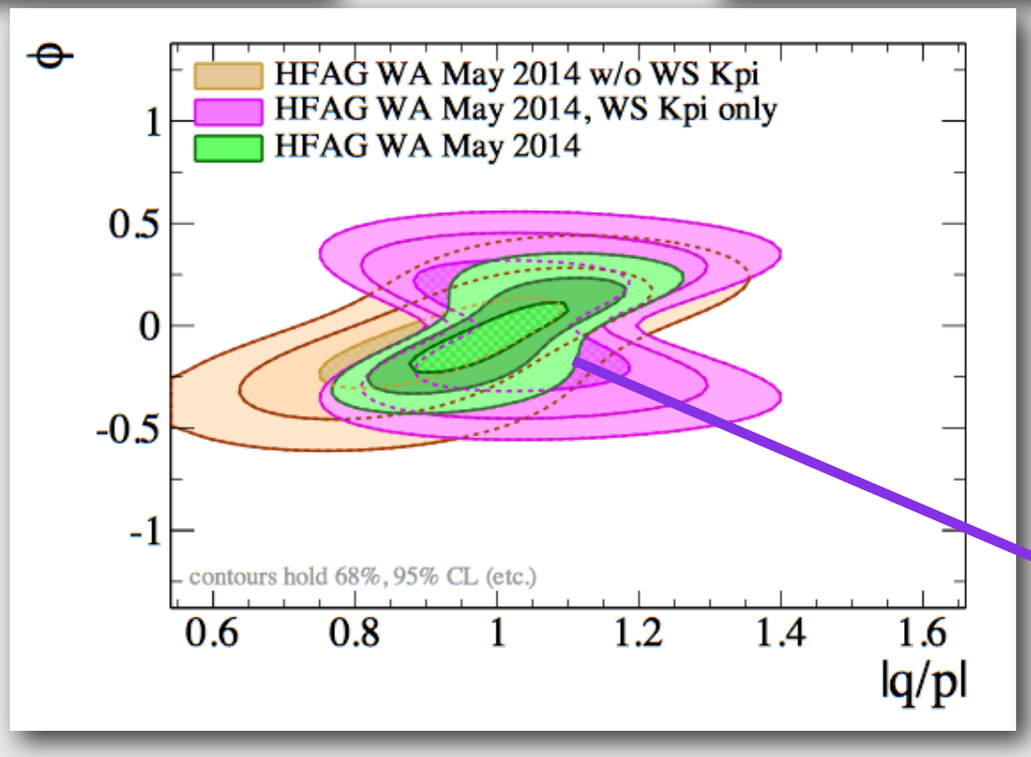


Direct access to |q/p| and φ from $K_S hh$



WS Kπ: symmetric in φ, good sensitivity to |q/p| for small φ

Full average following intersection of contours

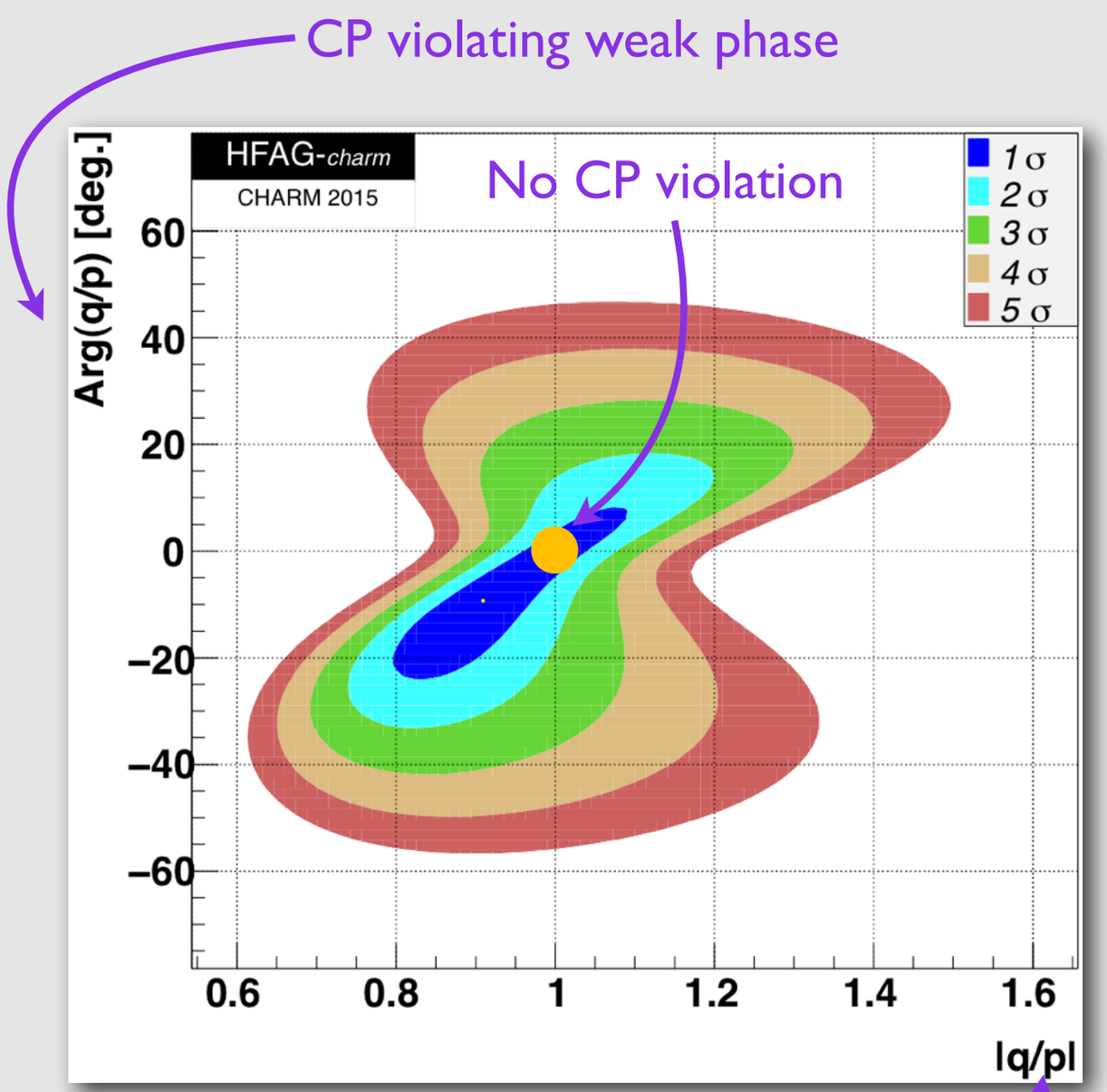
Multi-body decays

Mon+Thu afternoon

- Give access to full set of mixing and CP violation observables
  - ➡ In particular: sensitivity to x
  - ➡ Require amplitude models
  - ➡ Or quantum-correlated measurements
- In last ten years time-dependent measurements almost only in $D^0 \to K_S\pi\pi$
  - ➡ A missed opportunity?
  - ➡ Recent work by BABAR
- Can provide powerful input to CKM γ measurements

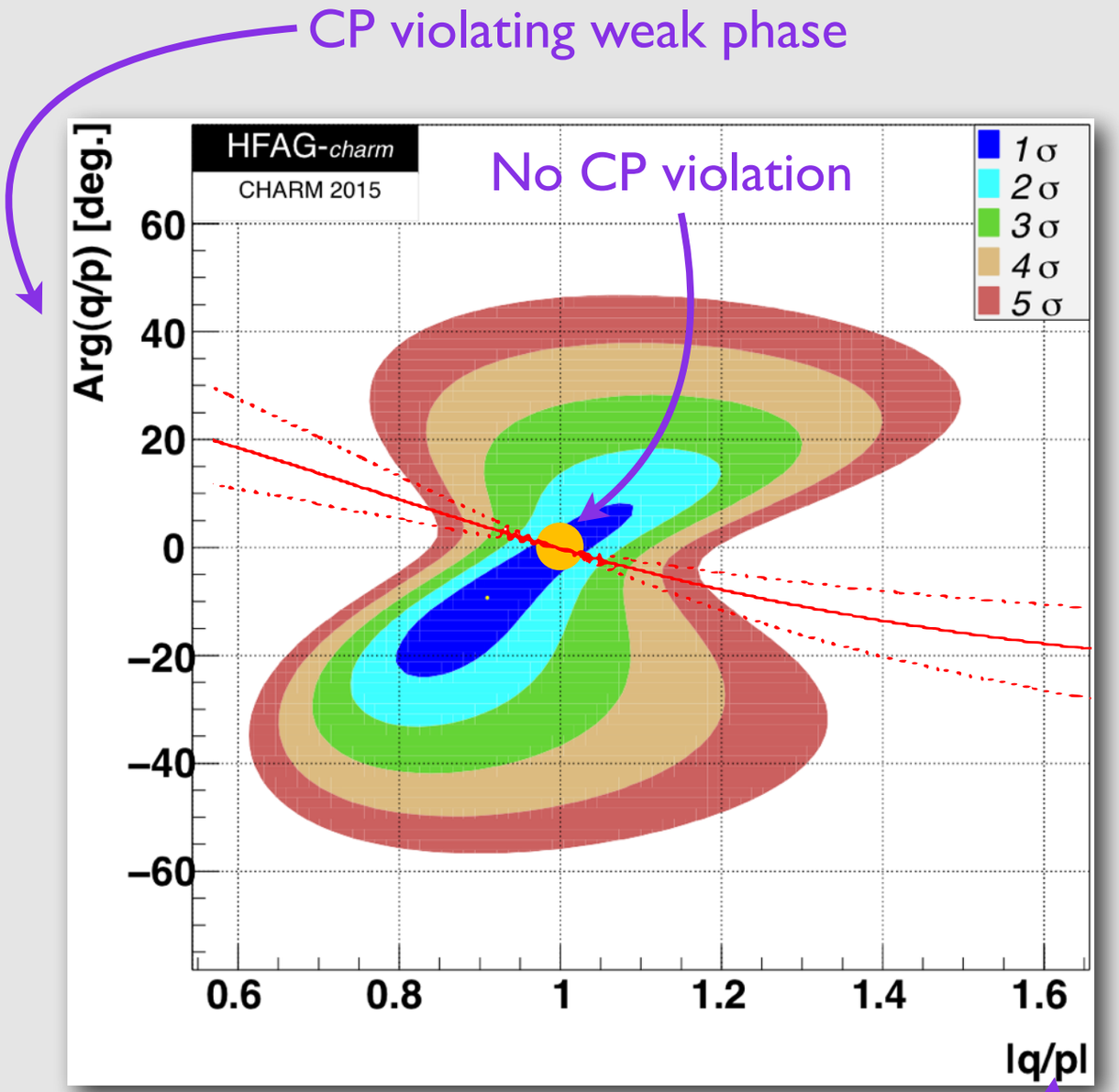
CP violation overview

- No sign of CP violation



Can we do better?

- Superweak constraint
  - ➡ Assumes no new 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
  - ➡ $\sigma(\Phi_{12}) = 1.7°$



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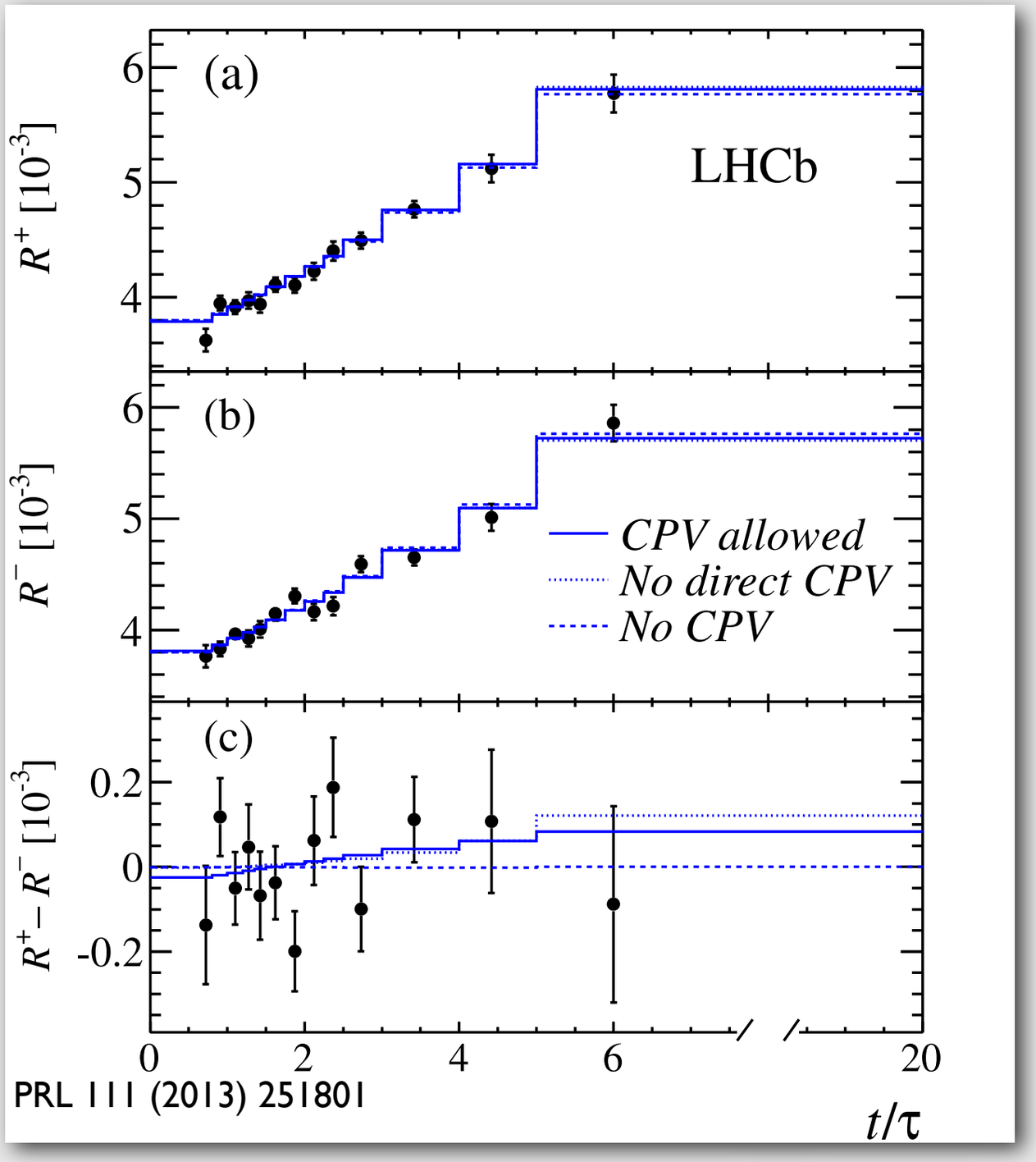

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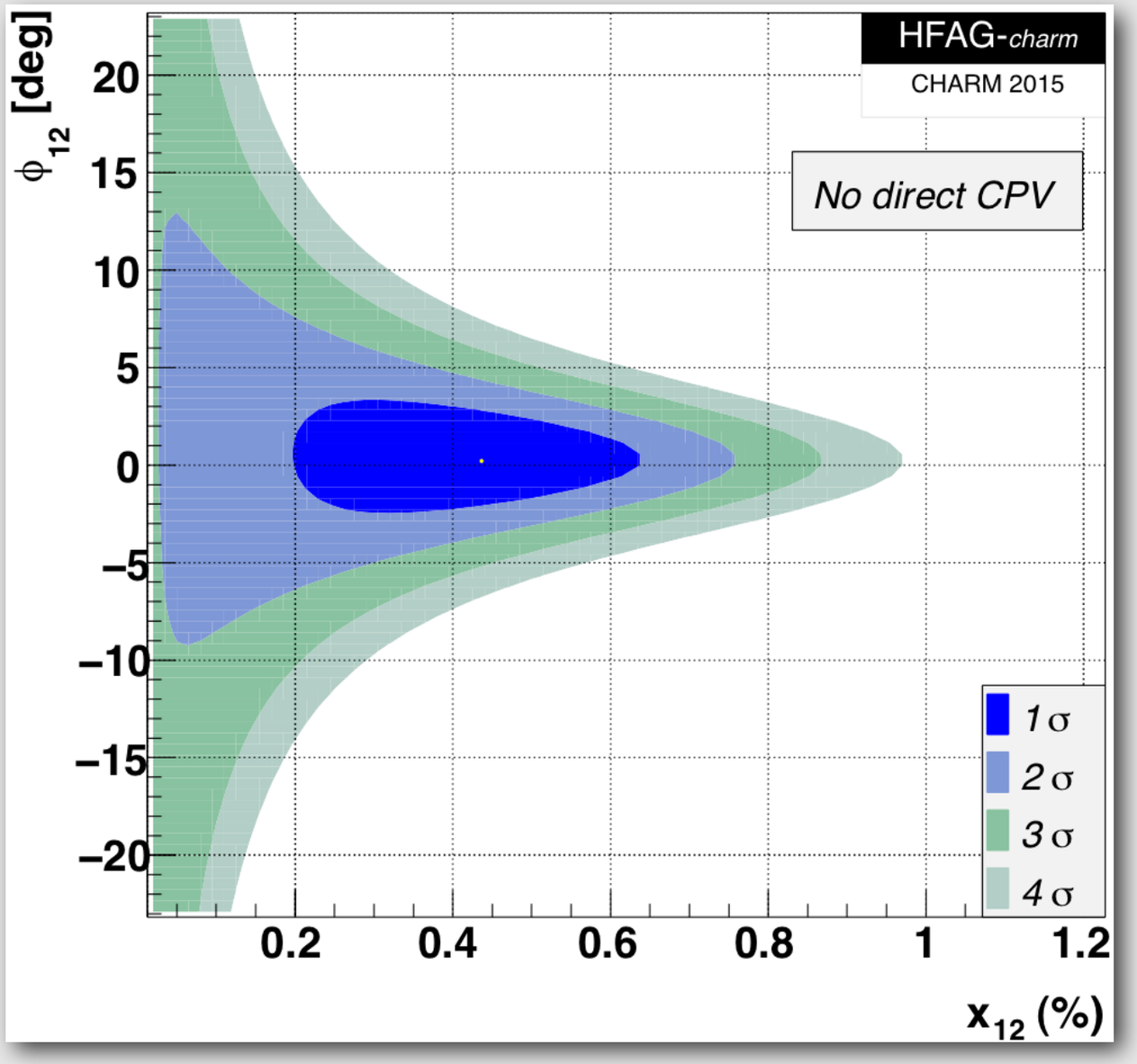
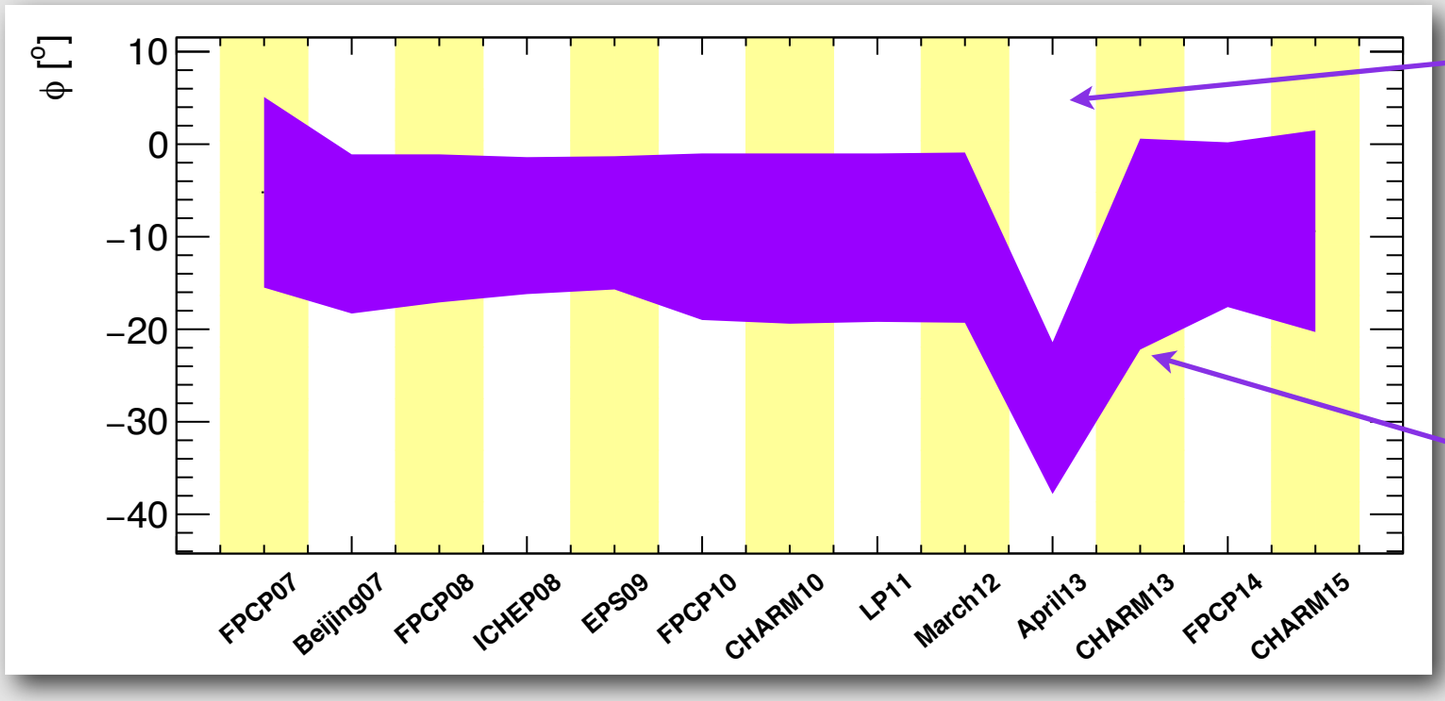


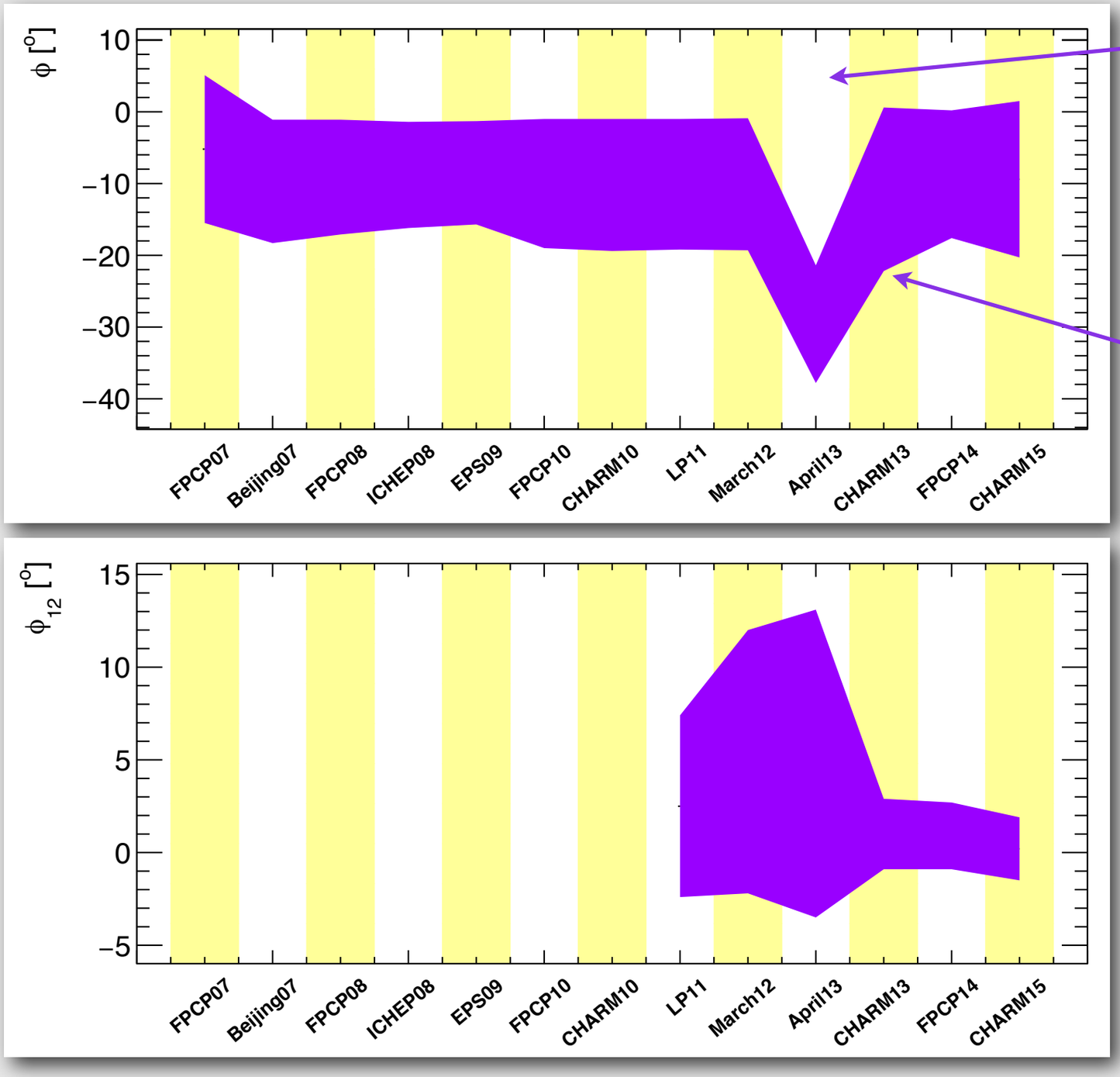
CPV evolution



LHCb 2011 & CLEO
WS Kπ analyses,
CDF DACP
Belle & BaBar AGamma

LHCb & CDF 2012
WS Kπ analyses,
LHCb 2011
A_Γ analysis

CPV evolution



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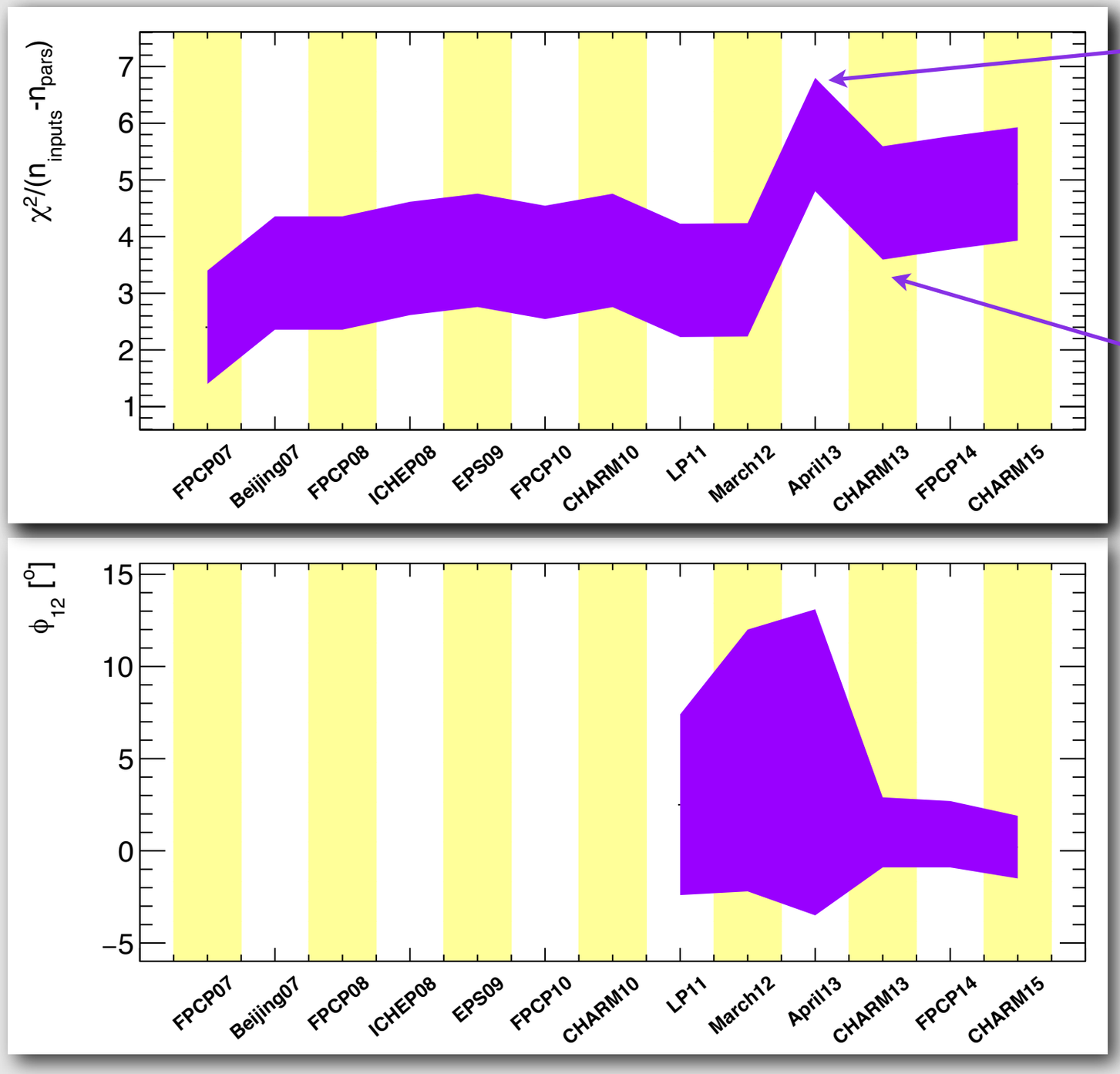

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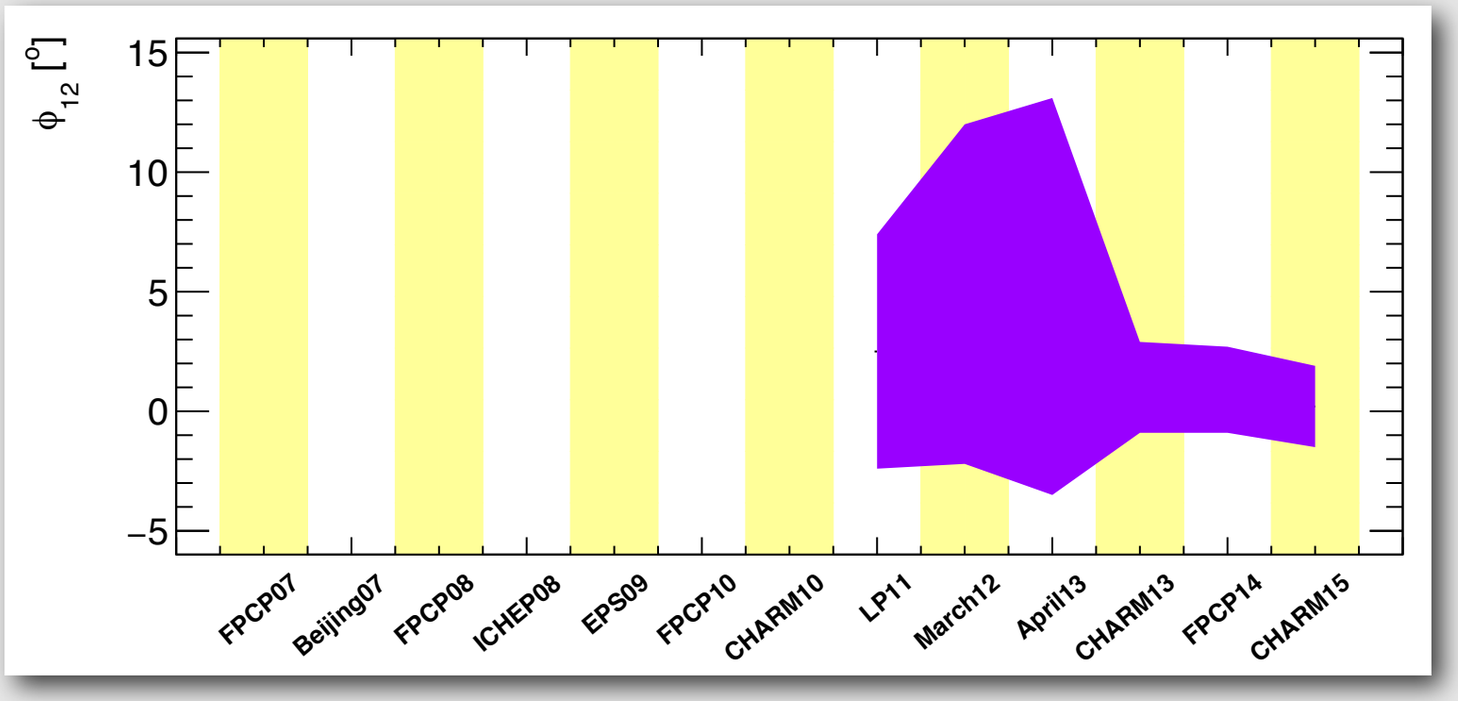


- Stunning precision on ϕ_{12}

  ➡ How long will it last?

- Impact of SM direct CPV may become relevant
- Should compare measurements from singly Cabibbo-suppressed and doubly CS decays

  ➡ DCS should be free of new weak phases

MANCHESTER 1824
The University of Manchester

Thursday afternoon

Direct CP violation

Direct CP violation:

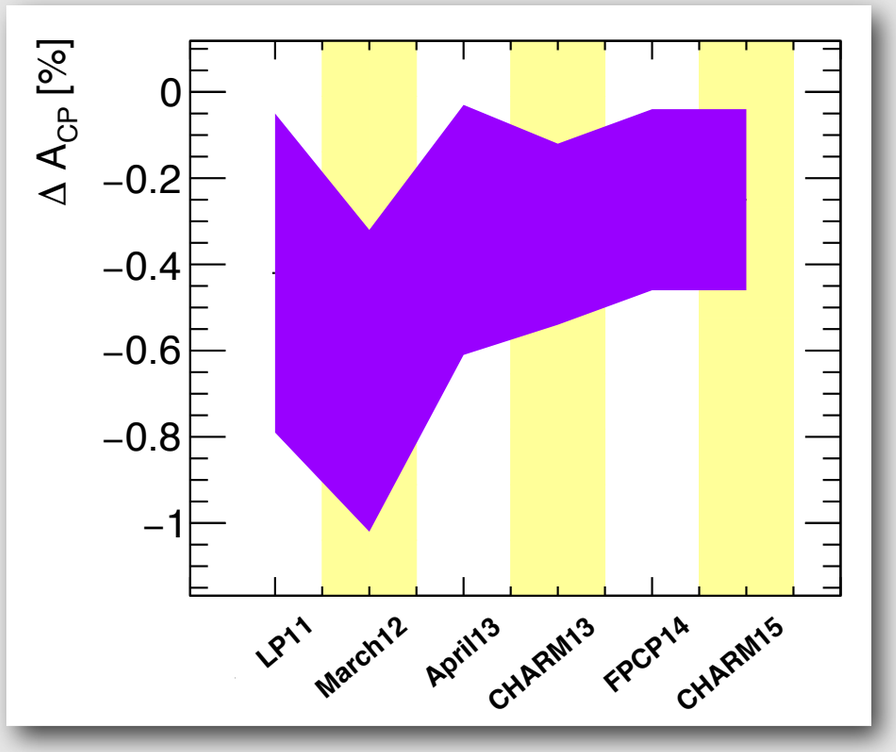
$$a_{CP}^{dir} \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}$$

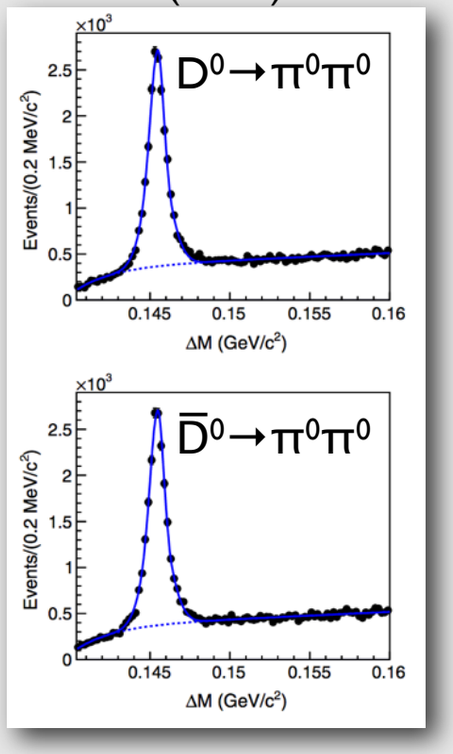
CPV in decay

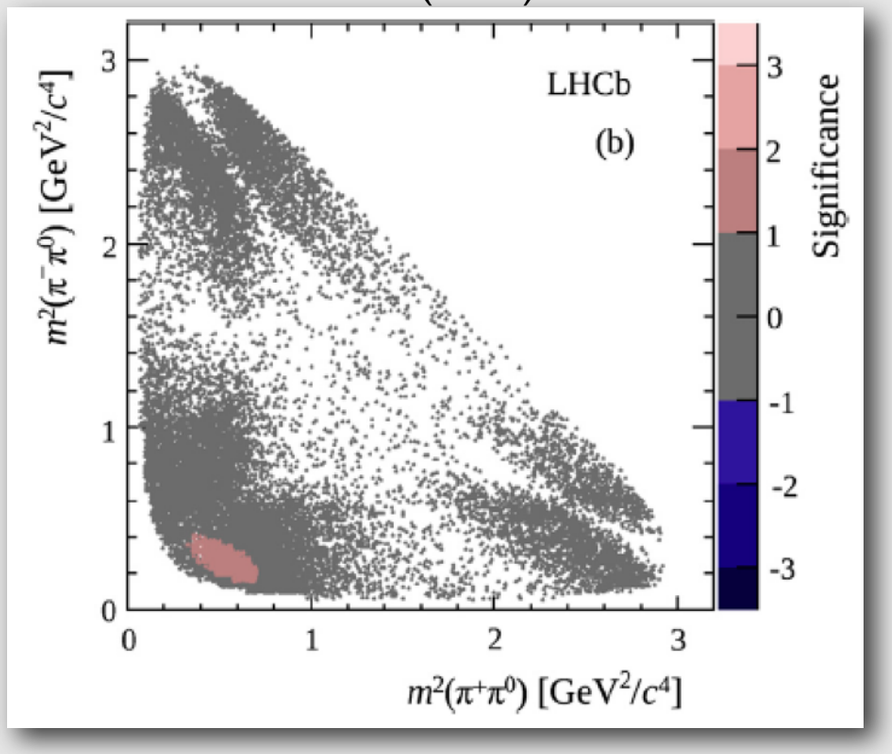
Thursday afternoon

BaBar,
PRL 112 (2014) 211601

LHCb,
PLB 740 (2015) 158







- Once upon a time, it looked like there was…
  - ➡ Updates at this conference
- 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, …

MANCHESTER 1824
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Outline

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

Outline

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

Echoes from the past

A: I would think it worthwhile to study the spectroscopy, decay modes, and production mechanisms of the charmed particles, assuming their masses are within reach at Fermilab, Super CERN and ISR, or at the next generation of accelerators like PEP, etc., even though I personally am not convinced of their existence.

B: Thanks, that's precisely what I am working on now.[2]

From a fictitious dialogue between two researchers —an enthusiast and a devil's advocate.
(Gaillard, Lee, Rosner 1975)

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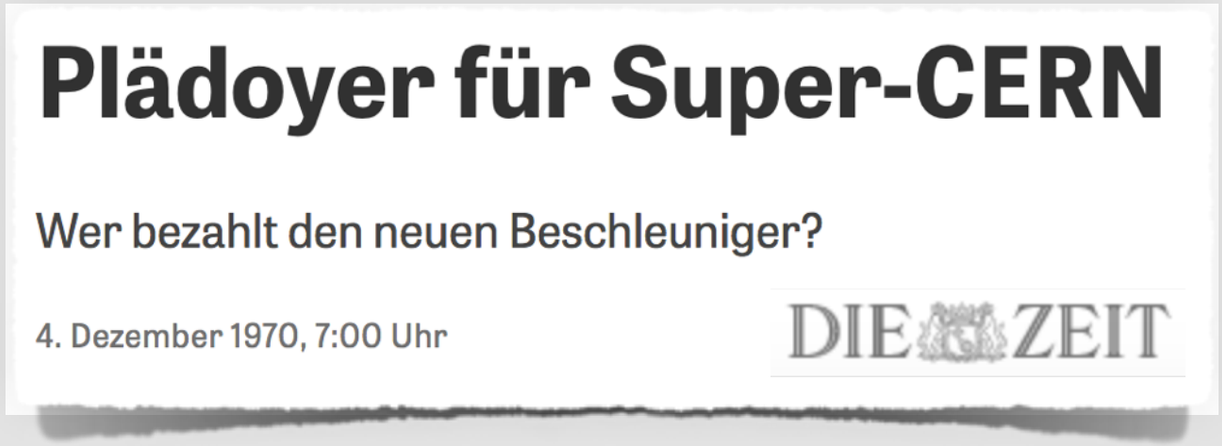

Plädoyer für Super-CERN

Wer bezahlt den neuen Beschleuniger?

4. Dezember 1970, 7:00 Uhr

DIE ZEIT

Echoes from the past

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Plädoyer für Super-CERN

Wer bezahlt den neuen Beschleuniger?

4. Dezember 1970, 7:00 Uhr DIE ZEIT

NOVEMBER 1, 2015 · 7:57 AM exopolitikschweiz

China baut ein Super-CERN

Where to now?

- 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

Yuval Grossman, Experimental Summary, CHARM 2012

Where to now?

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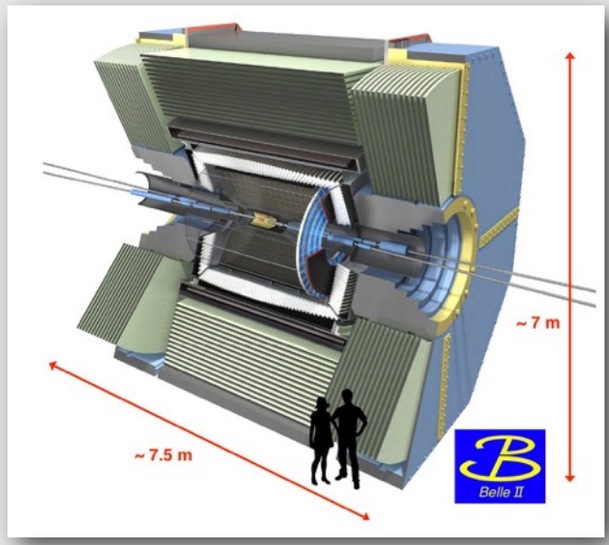
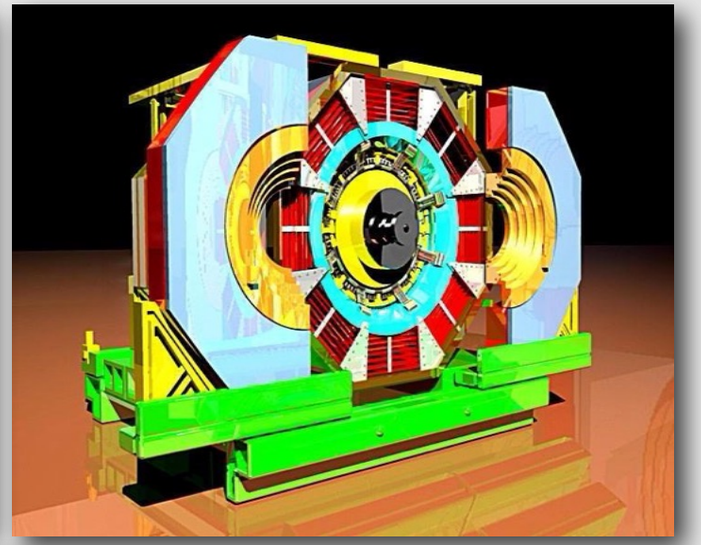
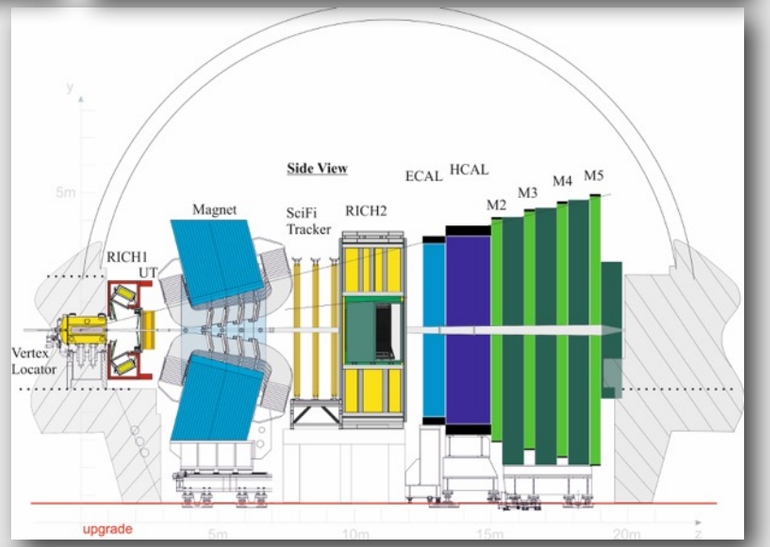
Yuval Grossman, Experimental Summary, CHARM 2012

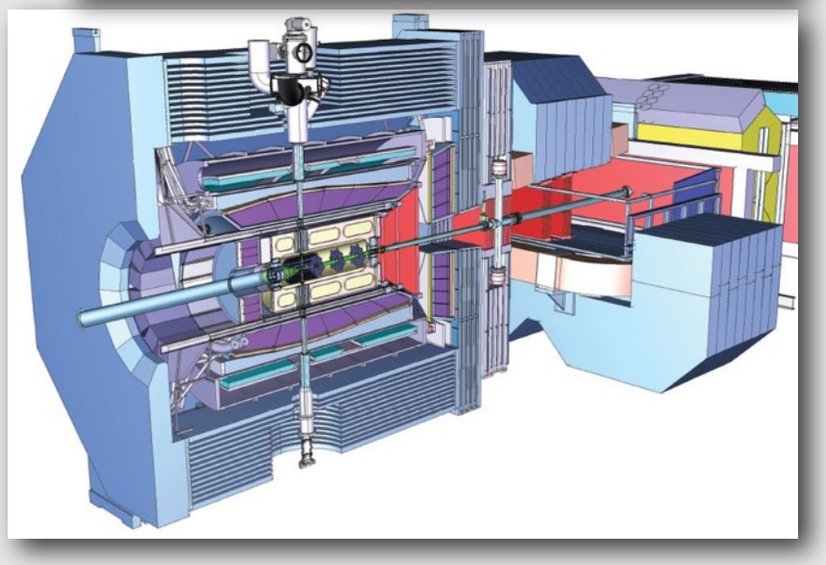
Which facilities?

- Safe bets
  - ➡ Belle II, BESIII, LHCb upgrade, PANDA
  - ➡ Expect also contributions from ATLAS and CMS









- What else?
  - ➡ LHCb @ HL-LHC
  - ➡ Super CERN (whether in China or around Salève)
  - ➡ Linear Collider
  - ➡ Tau-charm
- Will hear more on Friday

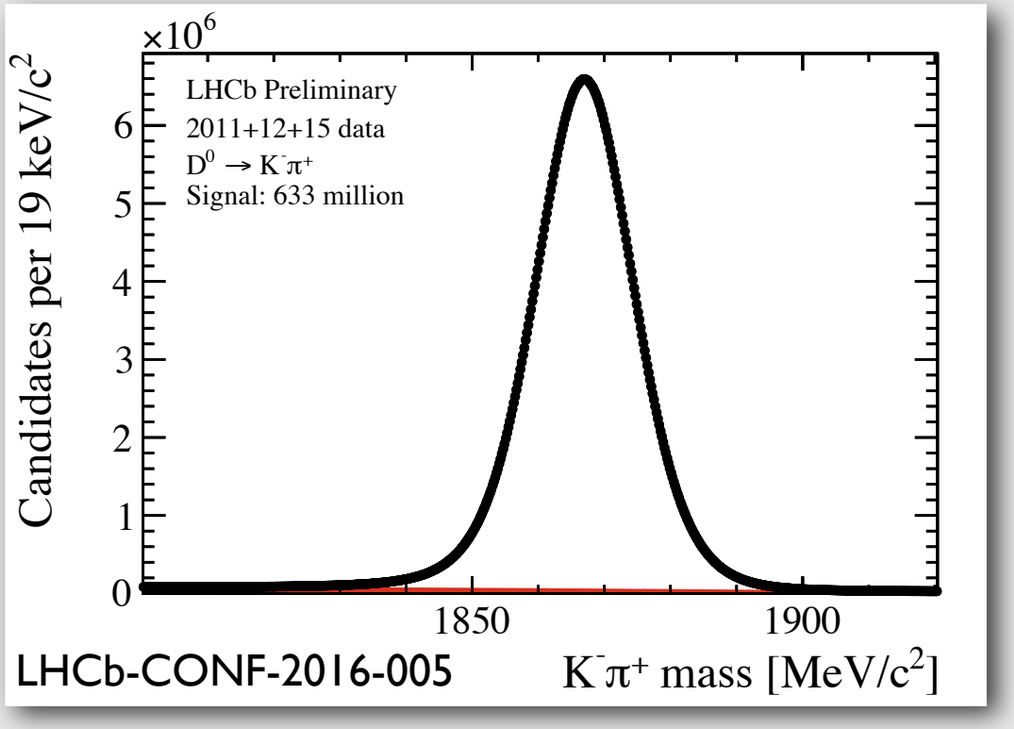
More than enough?

- $\sigma(pp \to c\bar{c})_{14TeV,\ LHCb\ acc.} \sim 3mb$
  - ➡ 15×10^{12} $c\bar{c}$ per year in Run 3 (assuming $5fb^{-1}/y$)
  - ➡ 0.6×10^{12} $D^0 \to K\pi$ per year in Run 3
  - ➡ Even accounting for reconstruction/selection efficiency and tagging still get up to 10^9 candidates per year
    - Factor ~20 compared to Run 1
    - Belle II should also get $>10^8$ candidates
  - ➡ Increasing luminosity at LHCb by a further order of magnitude being discussed

Charm the challenge champion

- Charm among the most abundant particles produced

  ➡ At LHC and e^+e^- running at $\Upsilon(4S)$



- Technical challenges therefore driven by charm

  ➡ Data selection/reconstruction/storage

  ➡ Simulation

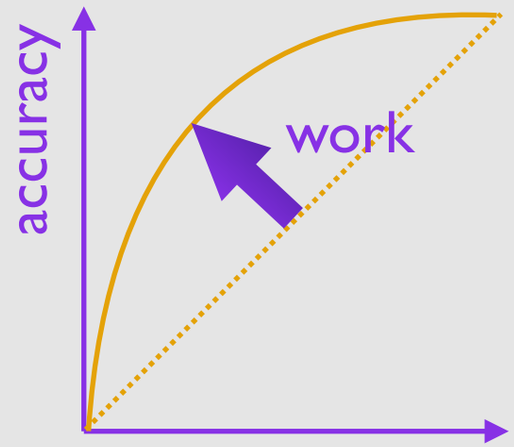
  ➡ Data analysis

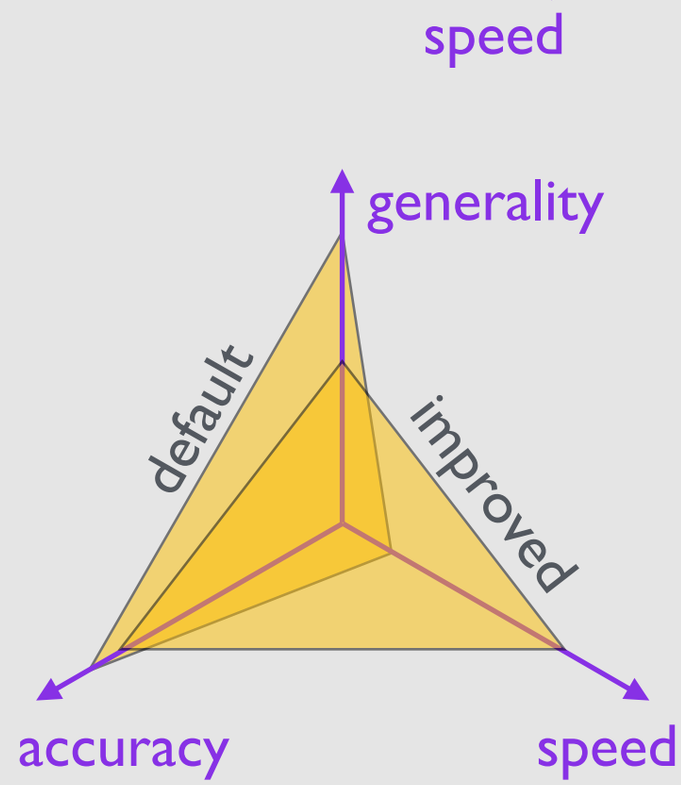
Data processing

- 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
- Minimise repetition in reconstruction steps to reduce CPU footprint
  - ➡ Repeated reconstruction is very expensive
- Can we afford storing reduced sets of information for analyses?
  - ➡ We have to if we want to exploit the full samples

Simulation

- Simulation used to extract efficiencies
  - ➡ Need particular detail for phase-space dependent analyses
- Want to simulate at least as many events as in data sample
  - ➡ Record with up to 100 Hz
  - ➡ Simulation can take up to O(100)s
    - 10^4 CPUs running full time for one analysis
- Need to cut corners without sacrificing precision
  - ➡ Need to maintain investment
- Some approaches surely applicable across experiments
  - ➡ E.g. parallelisation techniques





Data analysis

- Fitting large data sets is a growing challenge
  - ➡ Will need more and more sophisticated models
  - ➡ Unbinned fits likely to become impossible
- Data analysis is a perfect playground for parallelisation
  - ➡ Some analyses already run on GPUs
- In general will need to write efficient code
  - ➡ Training on this front will be increasingly important

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Thinking ahead

- Need to ensure to have highly efficient selections for most sensitive analyses

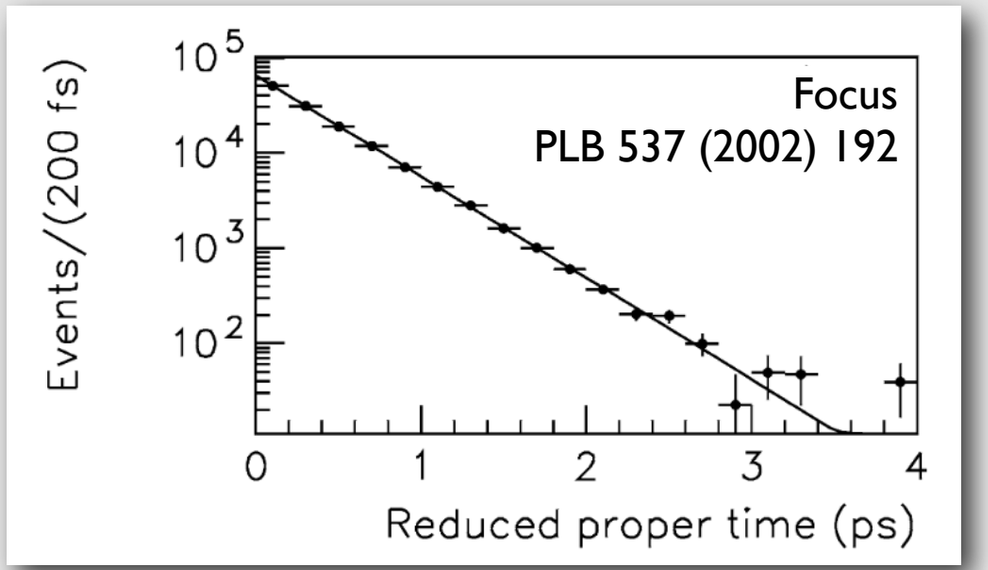
  ➡ In mixing/CPV, is there more to be had from yet-unexplored multi-body modes?

- Are there unexplored areas for charm?

  ➡ What can LHCb say about $H \to c\bar{c}$?

  ➡ Do we need new D lifetime measurements?

  ➡ Is there a chance to access intrinsic charm?



- Make sure to exploit complementarity optimally across experiments

Future collaborations

- Identify areas where inter-experiment collaboration is better than the independent/ competitive approach

➡ Development of amplitude models

➡ Exploit complementarity of quantum-correlated measurements (BESIII) with high statistics samples (Belle II & LHCb)

➡ Measurement of effective CP content, …

Conclusion

- Charm was discovered over 40 years ago
  - ➡ Spectroscopy evolved a lot, but still leaves open questions
- Mixing discovery almost 10 years ago
  - ➡ But can D^0 mesons change into $\overline{D}^0$ mesons?
- Now:
  - ➡ LHCb in full swing but also other facilities delivering many results
- Next:
  - ➡ New facilities: Belle II, LHCb upgrade, PANDA, …
- What will they bring?
  - ➡ Charm baryon spectrum?
  - ➡ More exotic states?
  - ➡ CP violation?
- Challenges ahead
  - ➡ Both technical and physics-related
  - ➡ Exploit synergies wherever possible
- Lots to discuss here in Bologna!

Thanks to:
Alberto Correa Dos Reis
Michael Creutz
Miriam Gandelman
Alex Lenz
Patrick Spradlin