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Charming opportunities in flavour physics

Marco Gersabeck (The University of Manchester)

EPD Seminar

IHEP, Beijing, 24/8/2018

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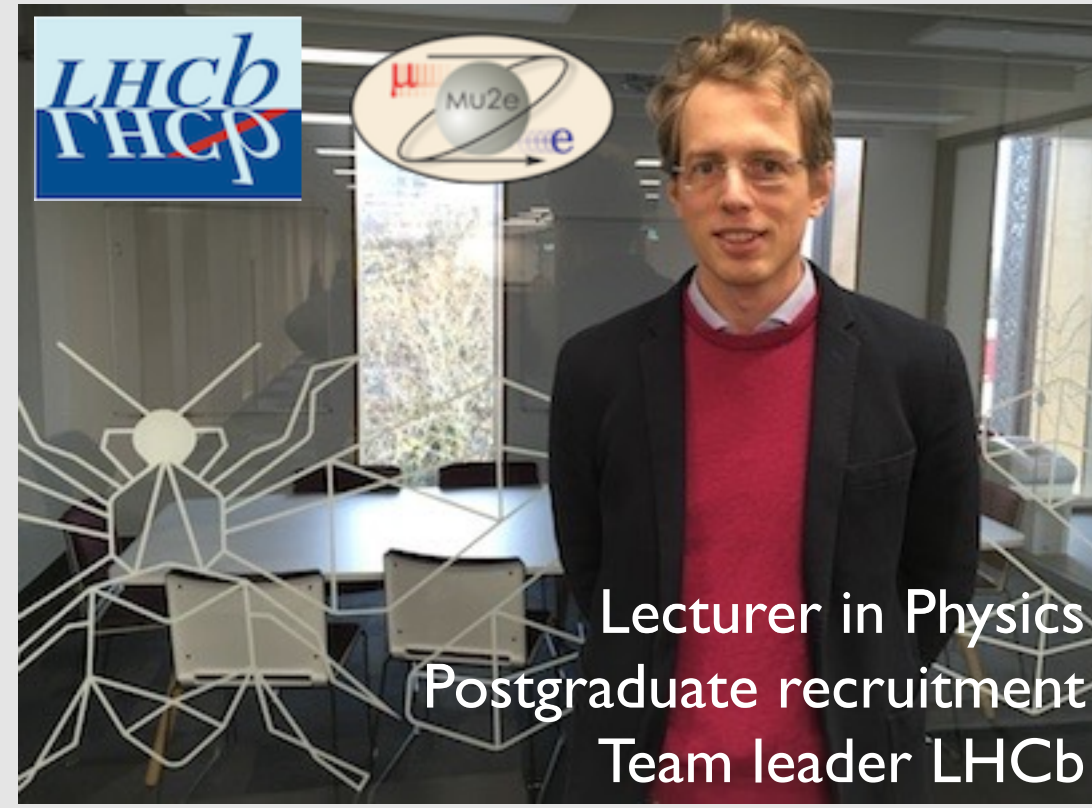
Your speaker



Research Associate on the LHCb experiment

Job Reference : S&E-12555
Location : Oxford Road, Manchester
Closing Date : 17/09/2018

ShanghaiRanking's Global Ranking of Academic Subjects 2018 - Physics 2018

Field: Natural Sciences **Subject:** Physics

ACADEMIC RANKING OF WORLD UNIVERSITIES SINCE 2003

World Rank	Institution*			
9	The University of Manchester	UK	305.5	67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Outline
• Part I
➡ From past to present
• Part II
➡ Where to next?

The very beginning

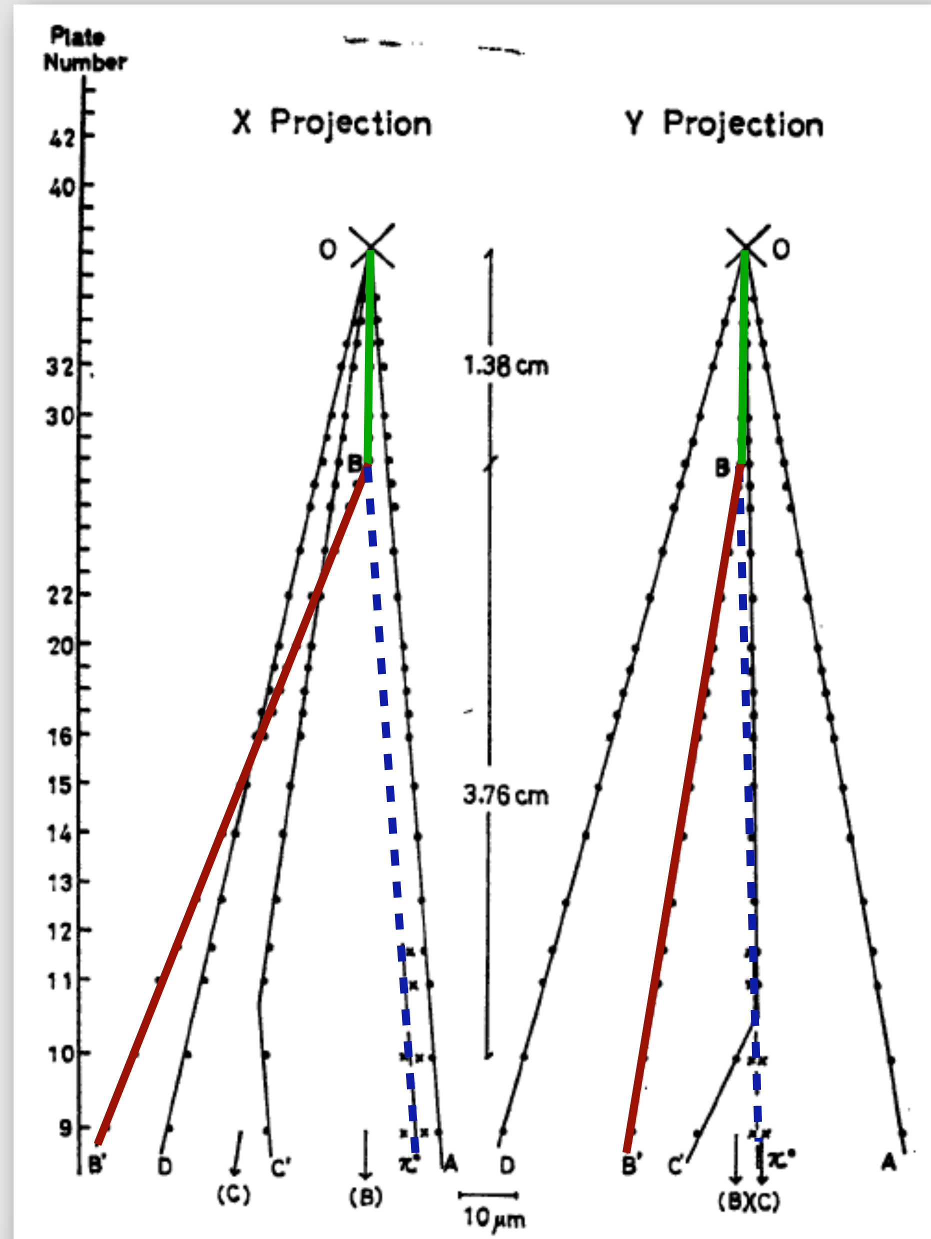
Prog. Theor. Phys. Vol. 46 (1971), No. 5

A Possible Decay in Flight of a New Type Particle

Kiyoshi NIU, Eiko MIKUMO and Yasuko MAEDA*

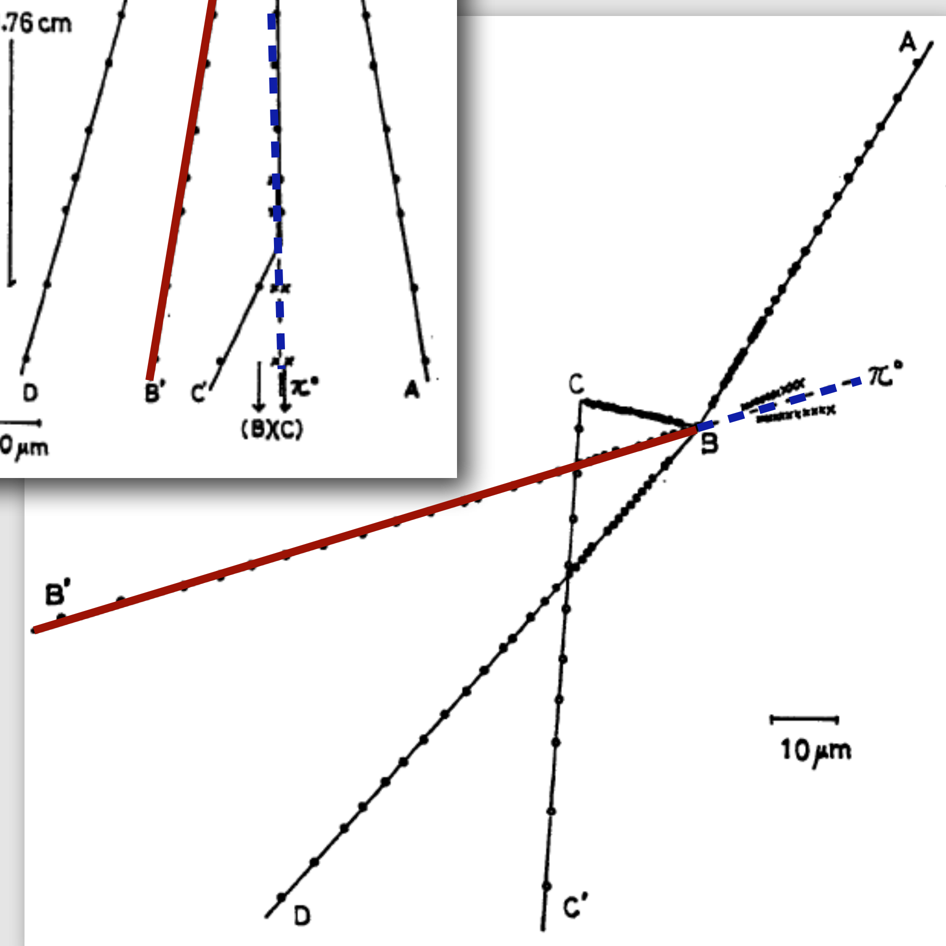
Institute for Nuclear Study University of Tokyo
**Yokohama National University*

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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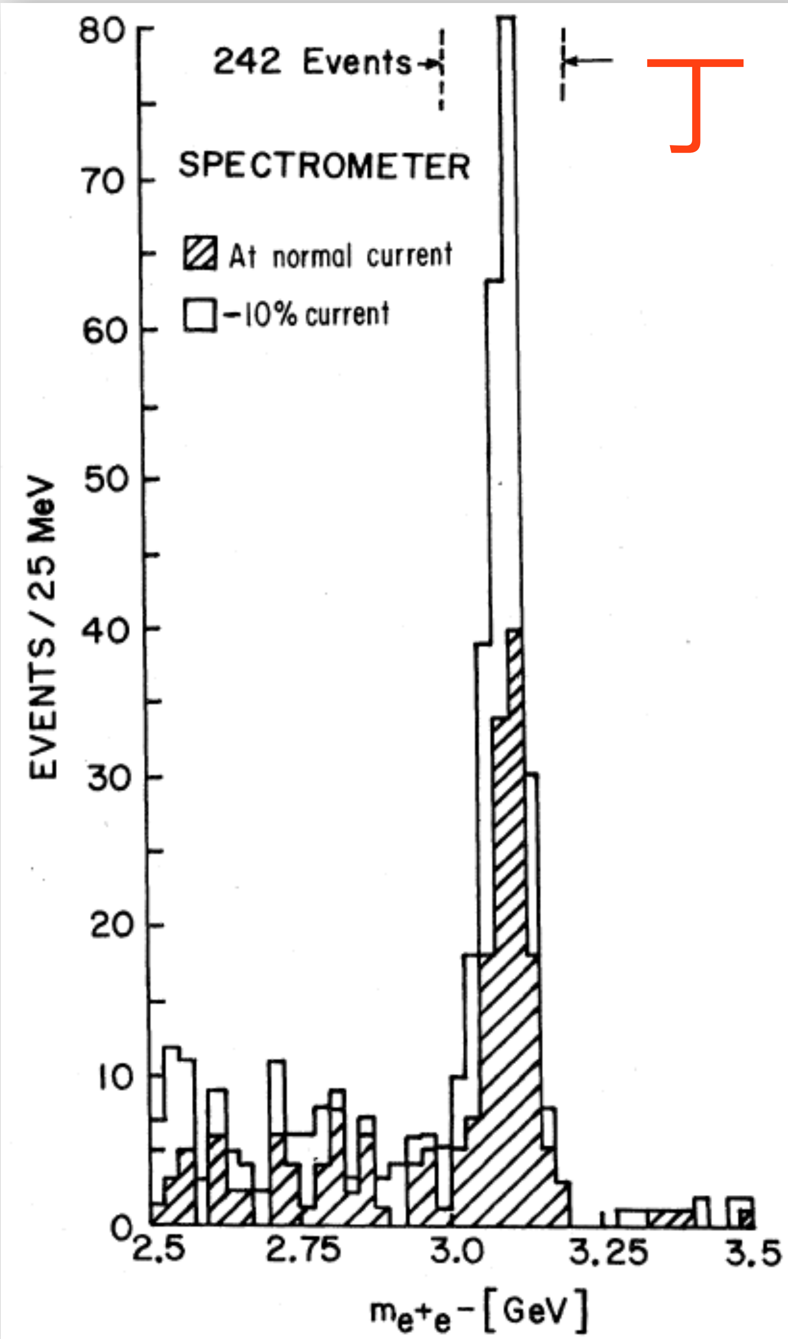
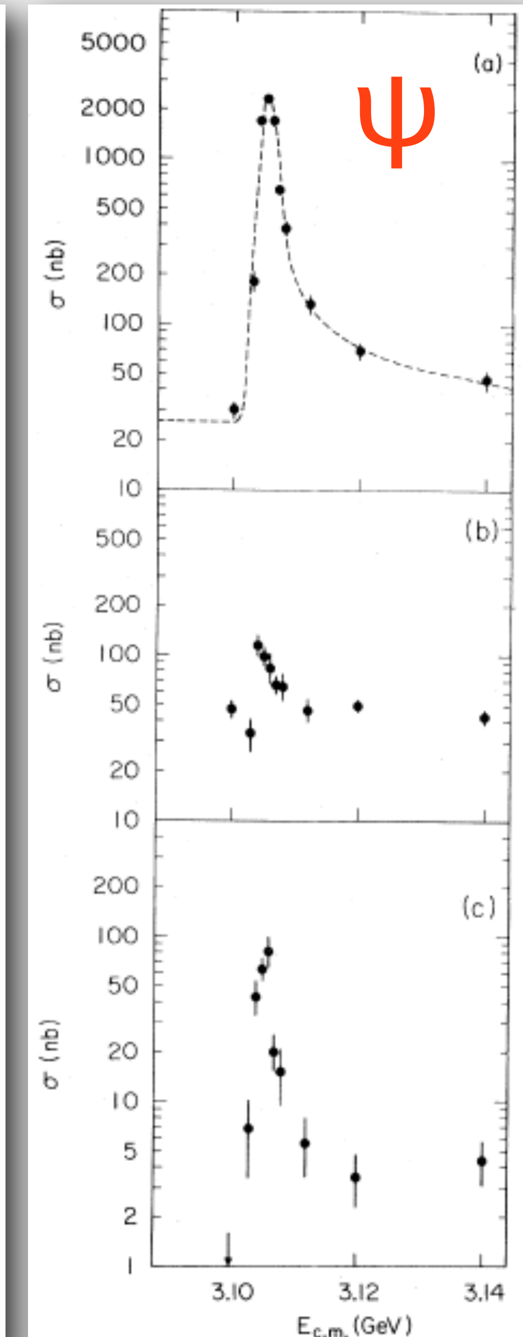
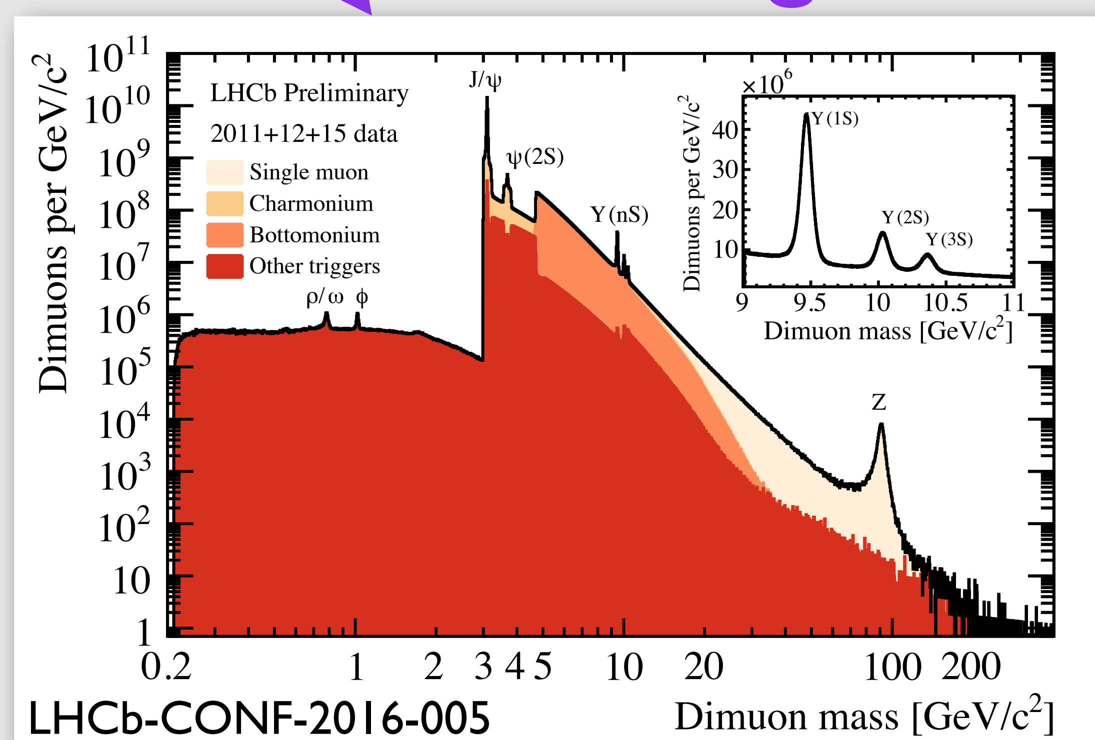
Charmonium





+42 years

+8 orders
of magnitude



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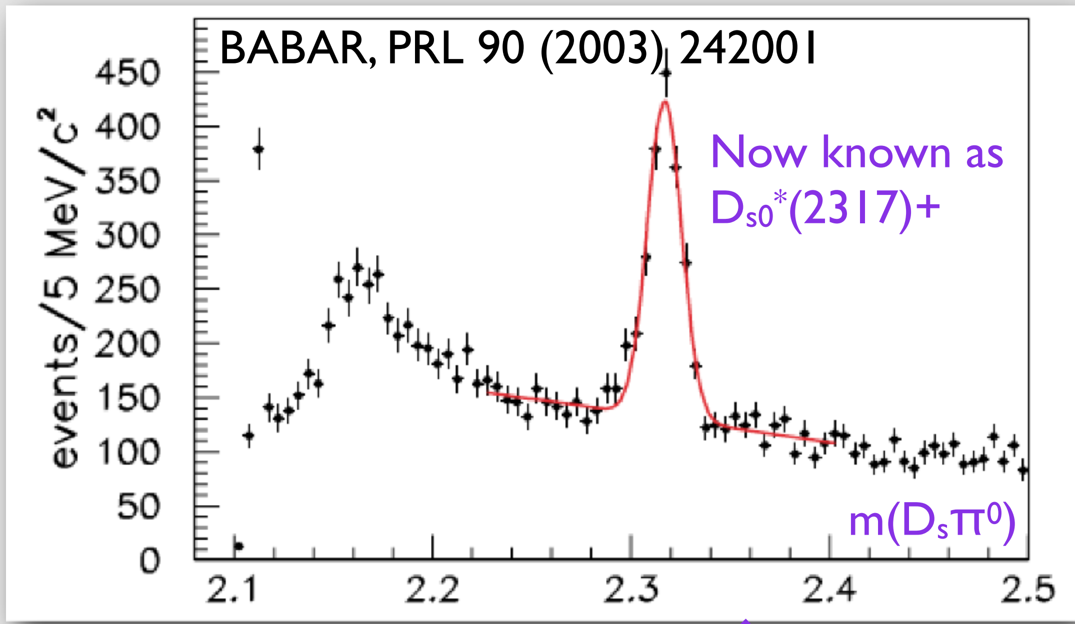
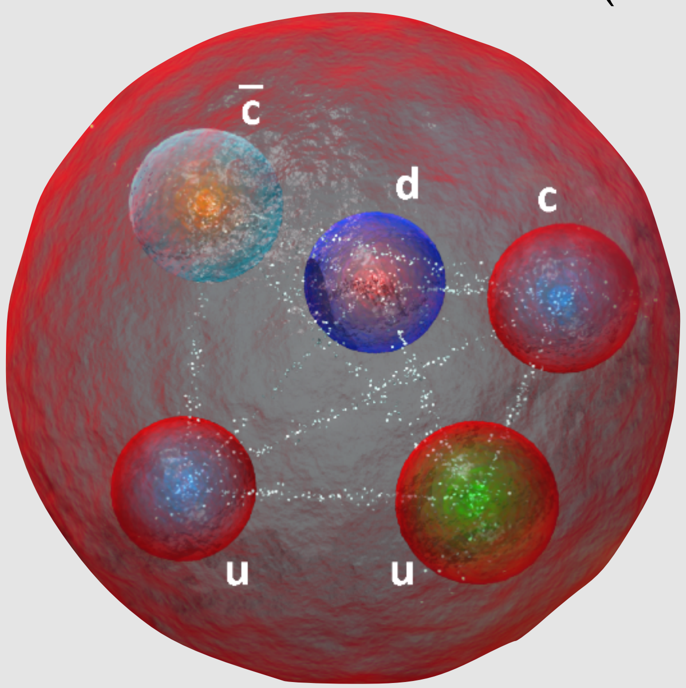
Spectroscopy

See Greig Cowan



12 years

PRL 115 (2015) 072001



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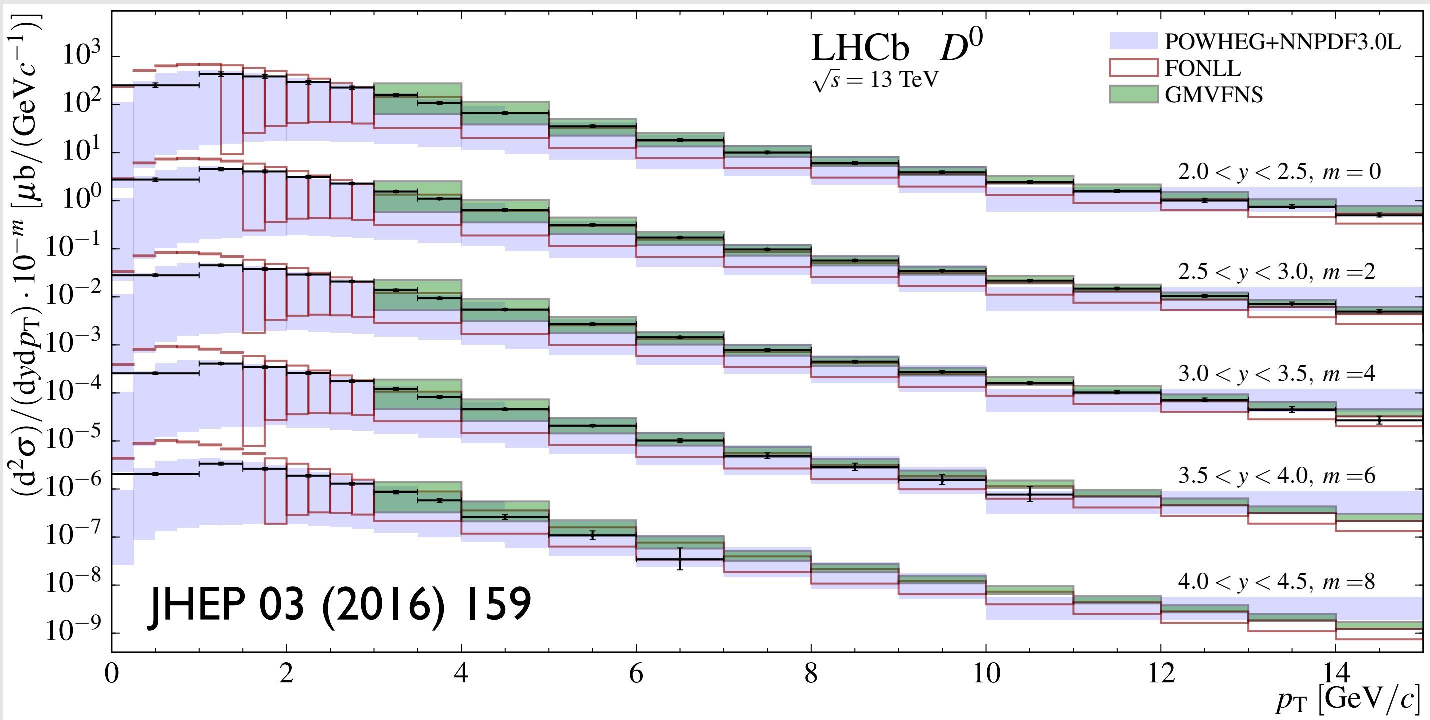
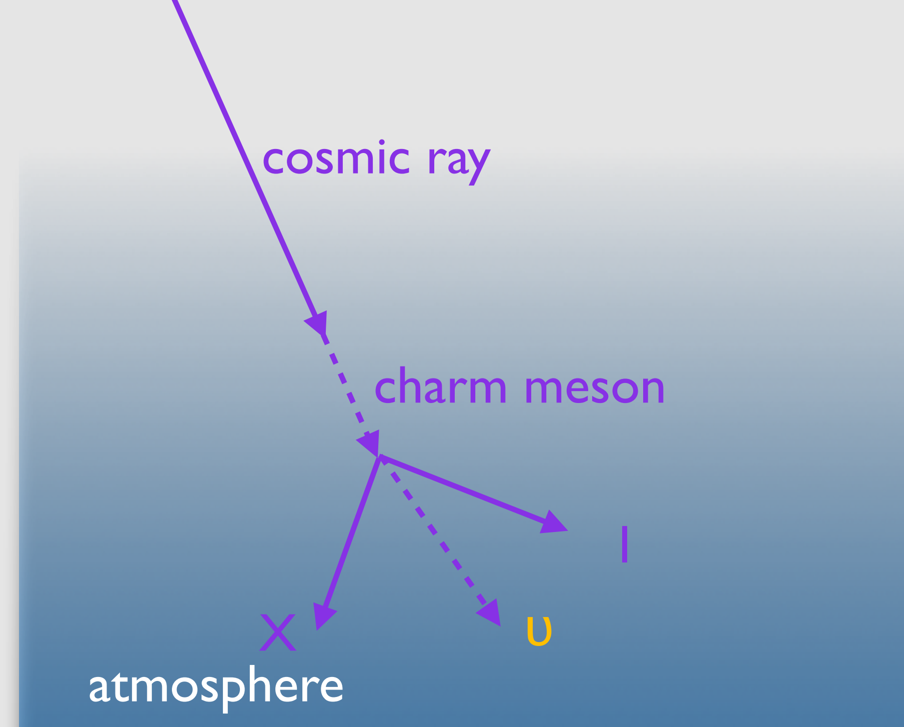
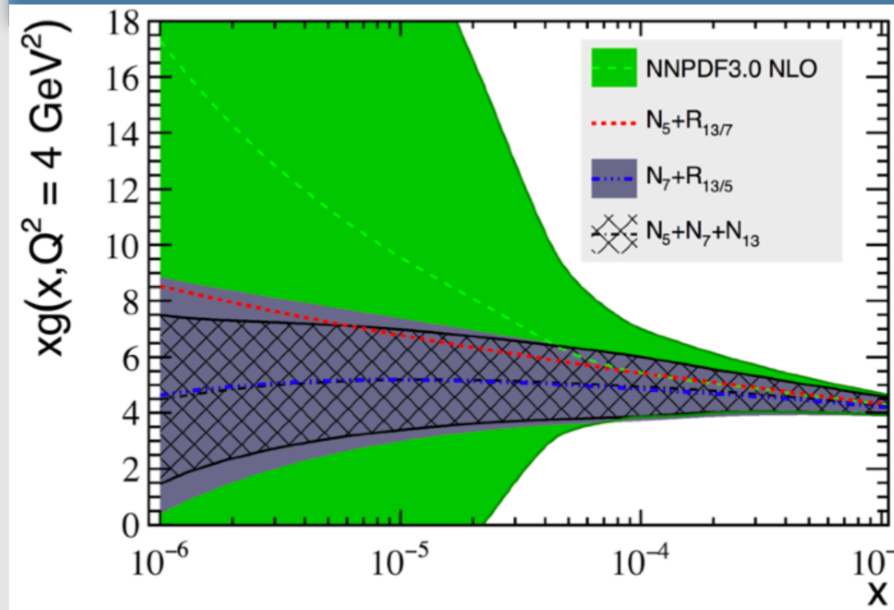
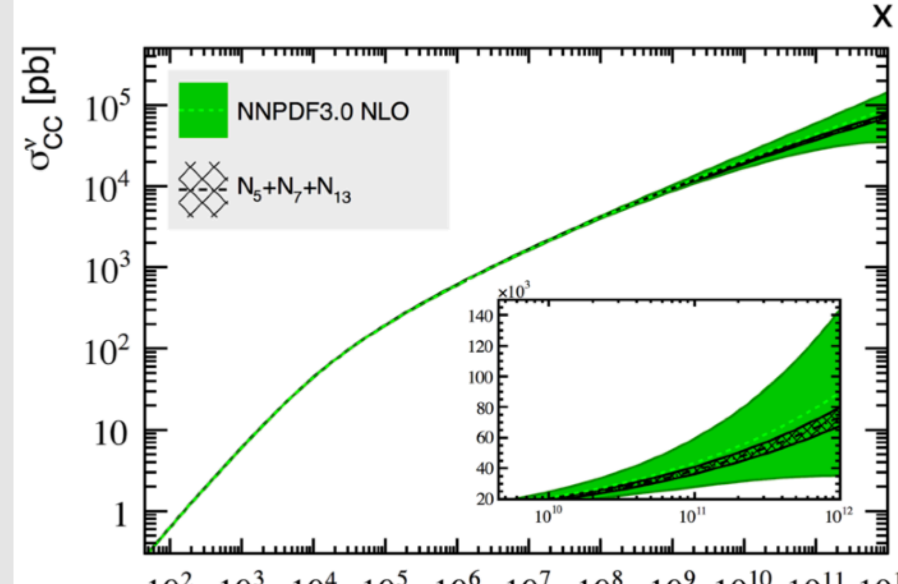
Production





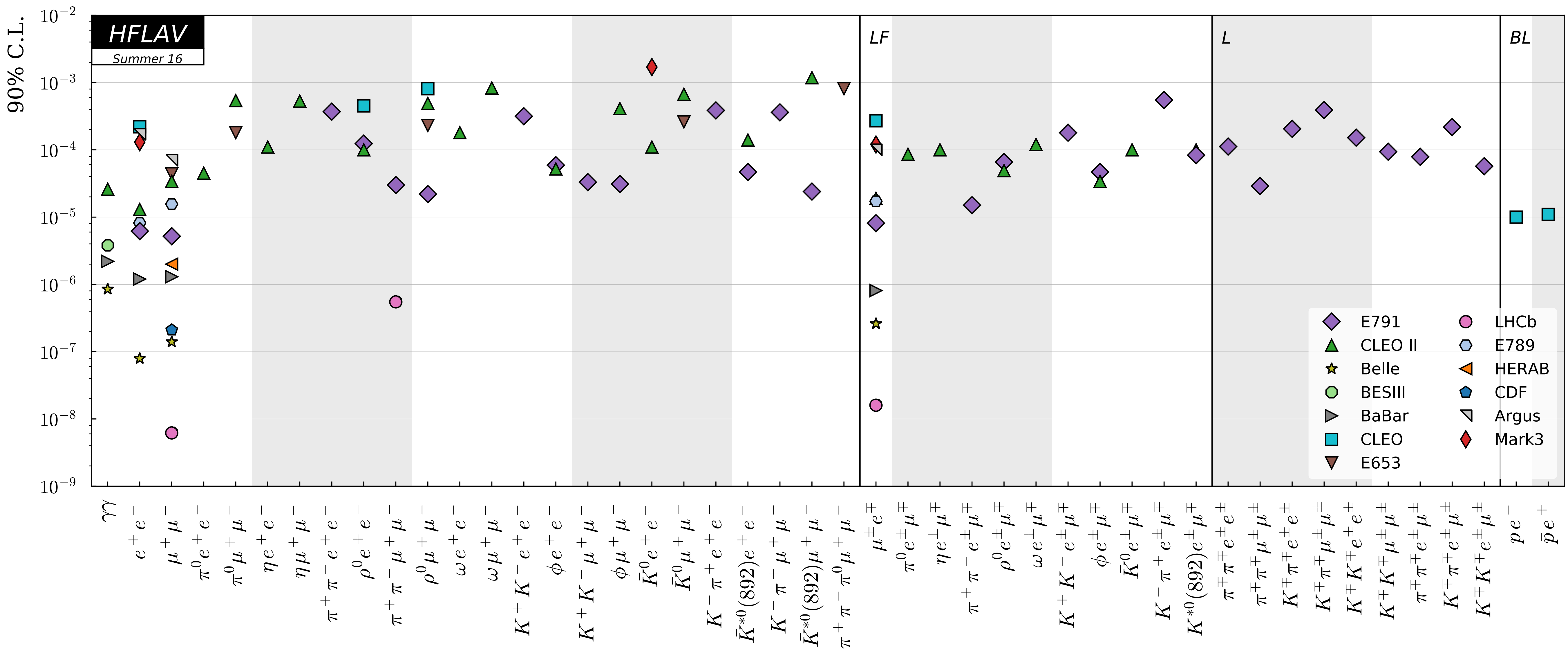




Gauld, Rojo, PRL 118 (2017) 072001

- 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

Rare decays

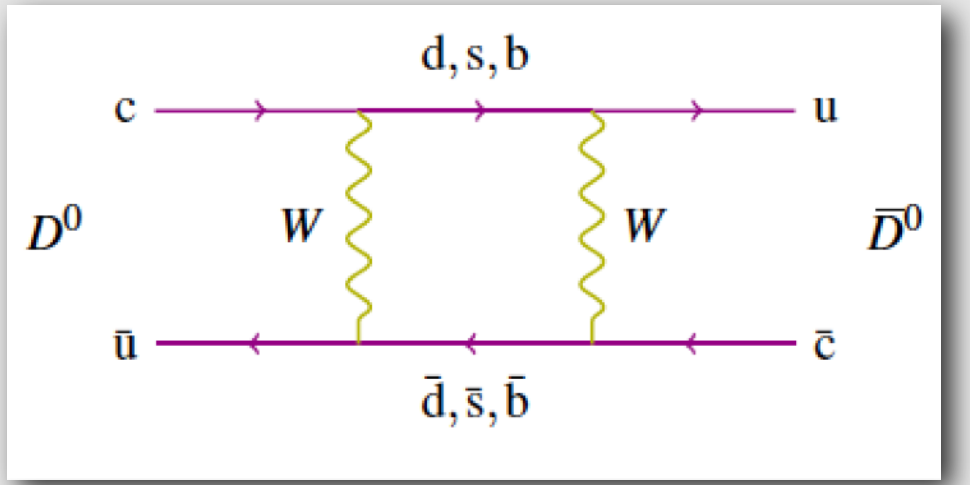


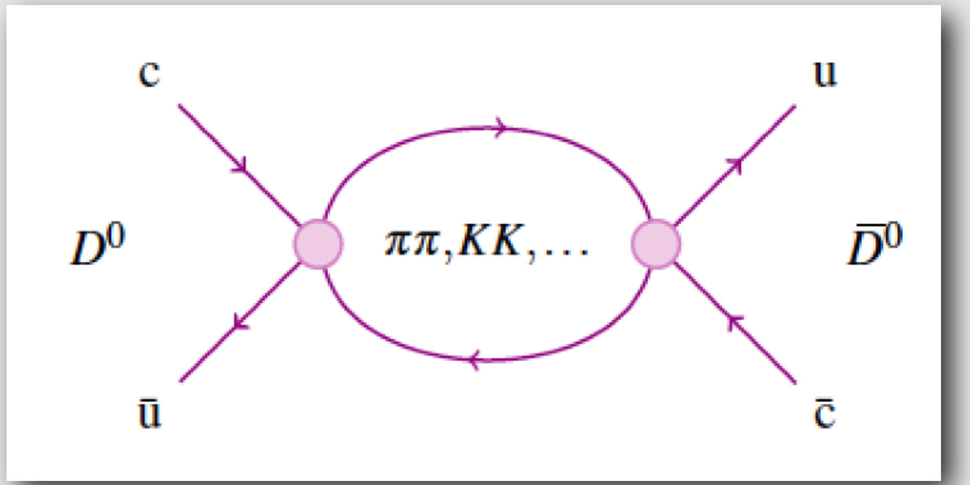
- Some recent progress
  - ➡ Many limits are very old, some >20 years
- No clear sign yet of non-resonant FCNC component*
- Keep searching also for LFV/LNV processes

*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





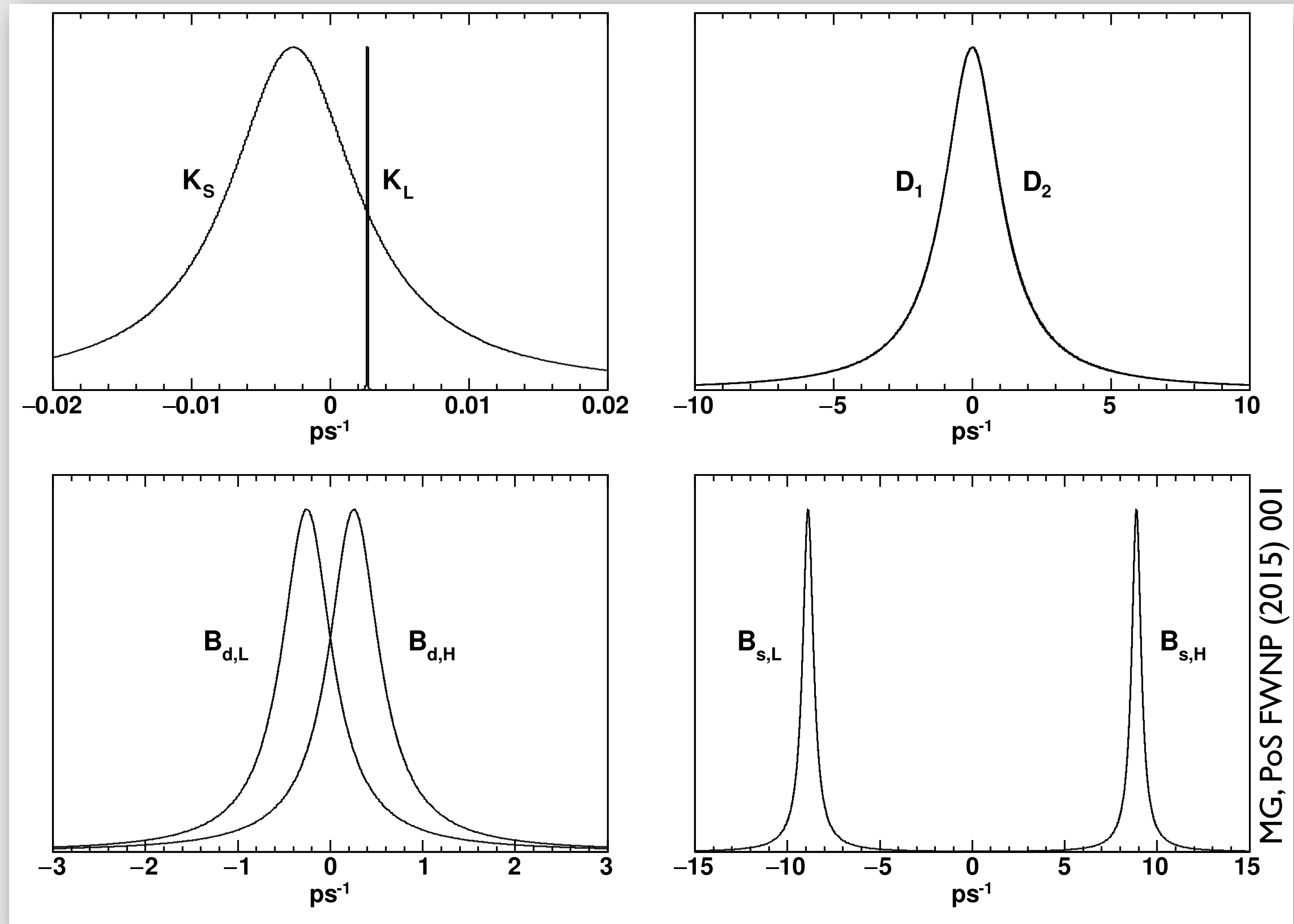
Probing highest scales

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

Mixing

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

Physical states — Flavour eigenstates



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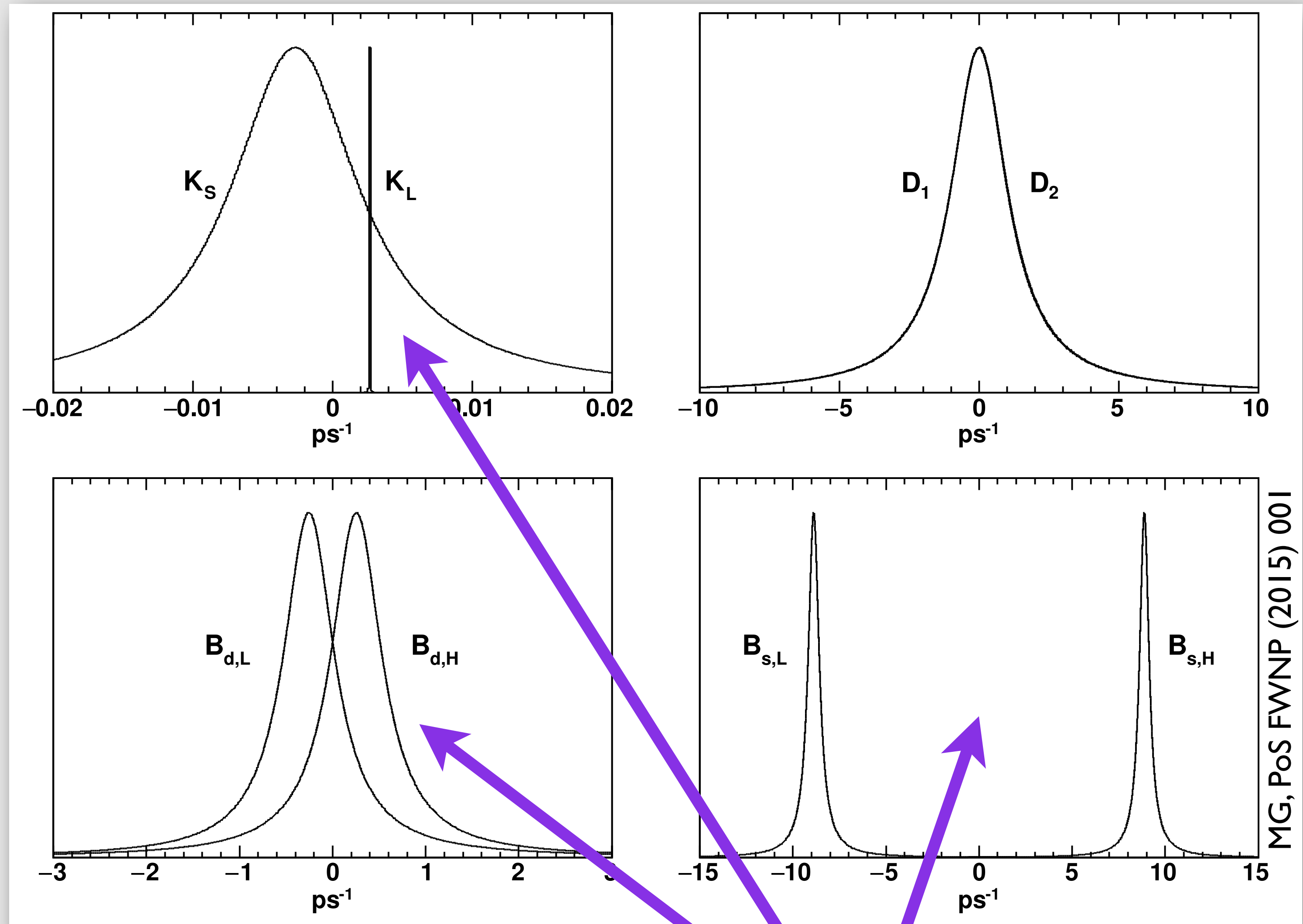
Physical states

Flavour eigenstates



Mass difference → Oscillation

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

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

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

Mixing

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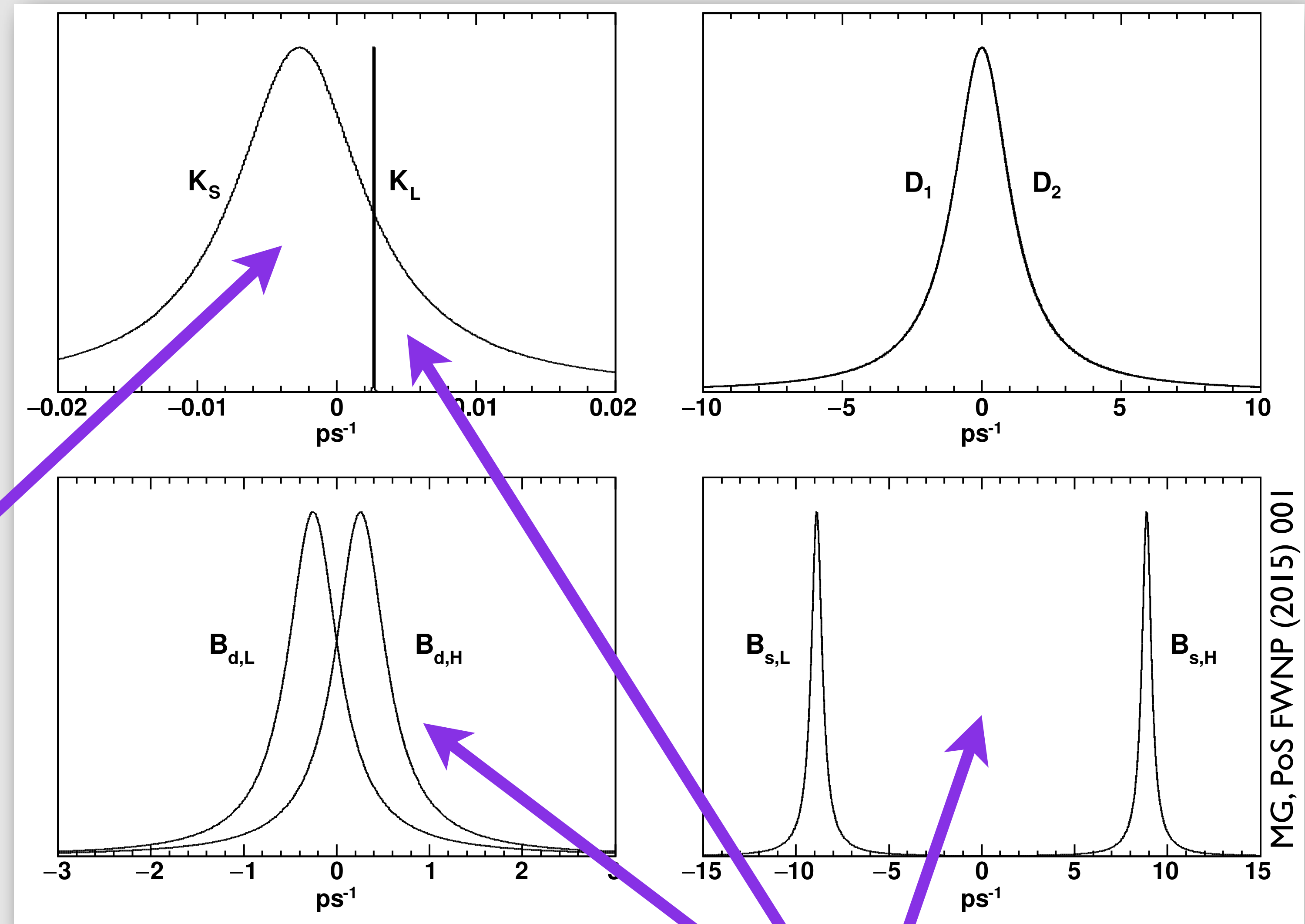
Physical states   Flavour eigenstates



Width difference

→ Lifetime difference

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

Mass difference

→ Oscillation

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

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

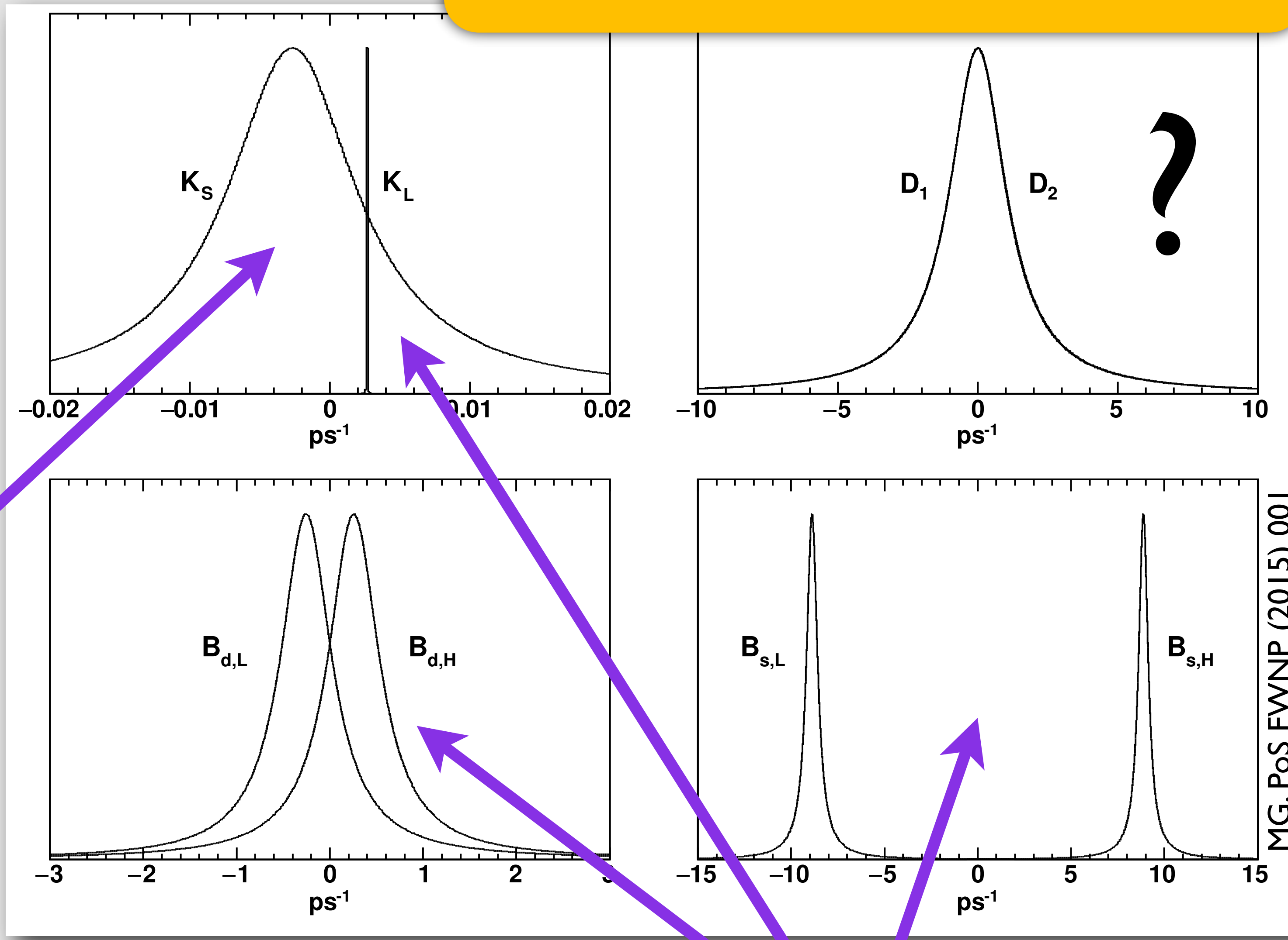
$$P(M^0 \to \overline{M}^0, t) = \frac{1}{2}\left|\frac{q}{p}\right|^2 e^{-\Gamma t}(\cosh(y\Gamma t) - \cos(x\Gamma t))$$

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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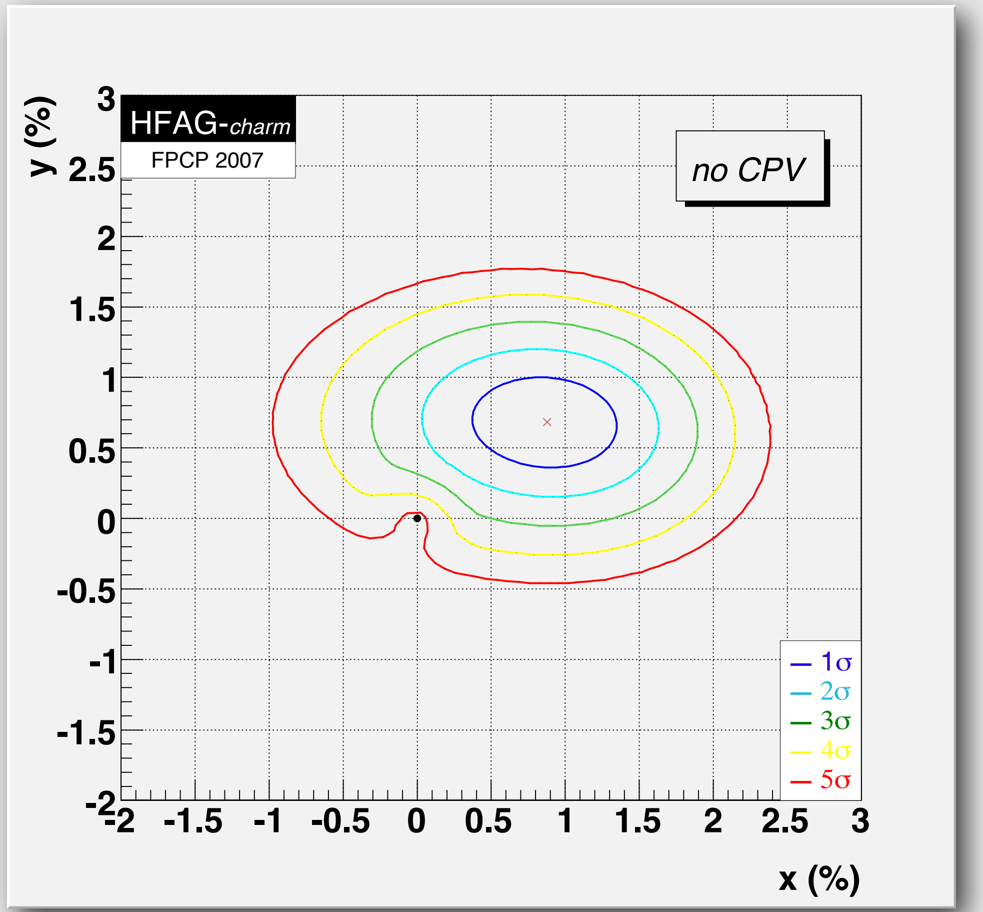
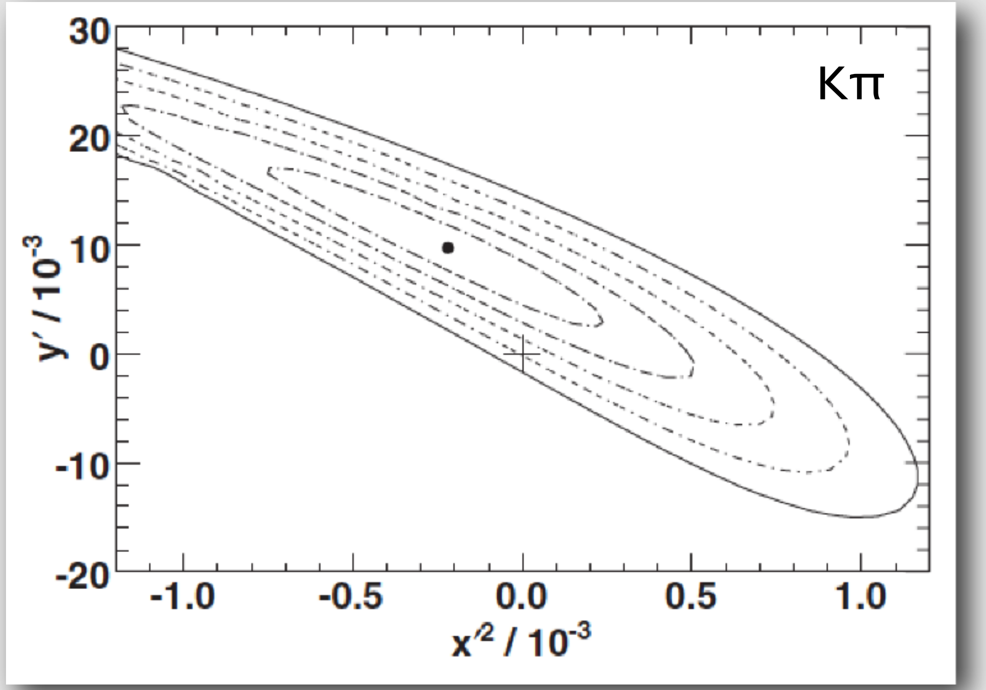
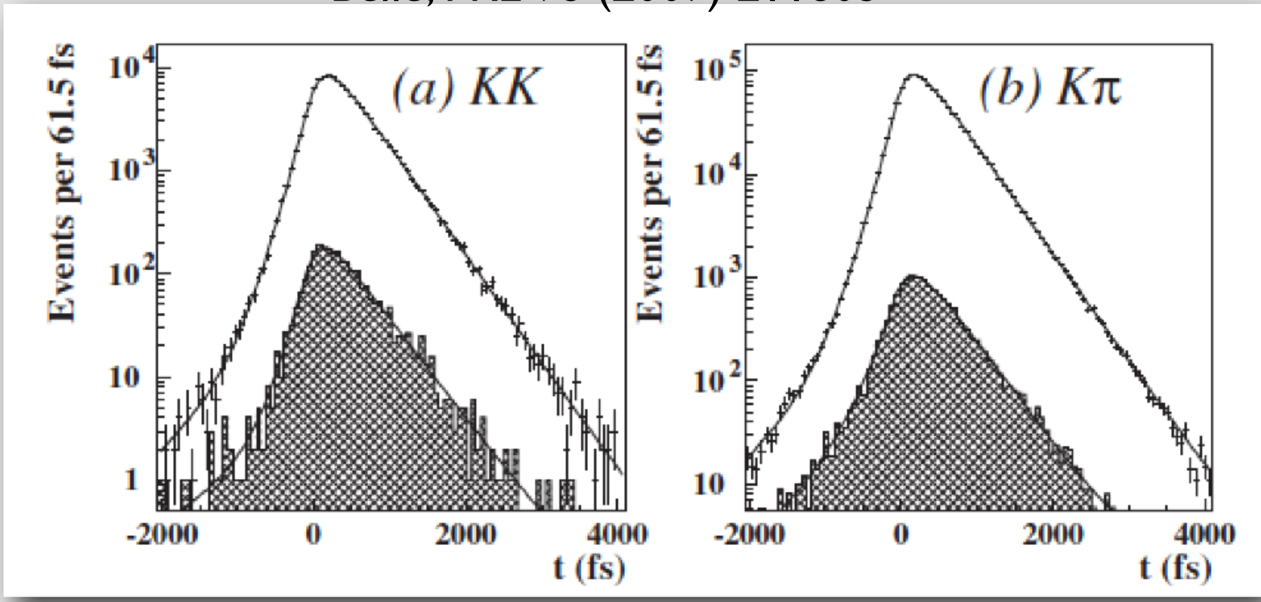
Mixing discovery



BABAR, PRL 98 (2007) 211802



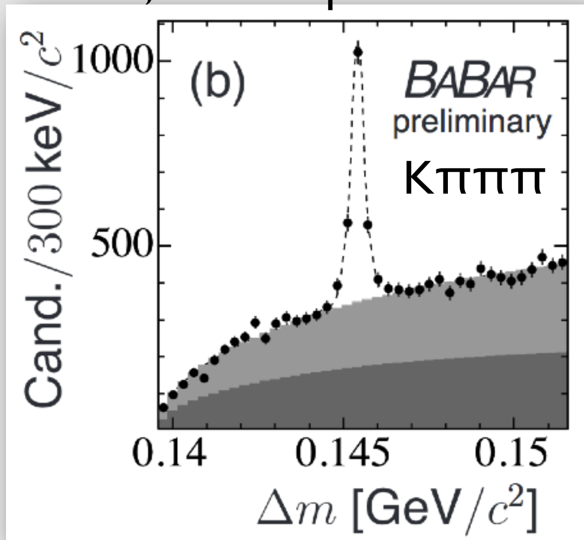
Belle, PRL 98 (2007) 211803



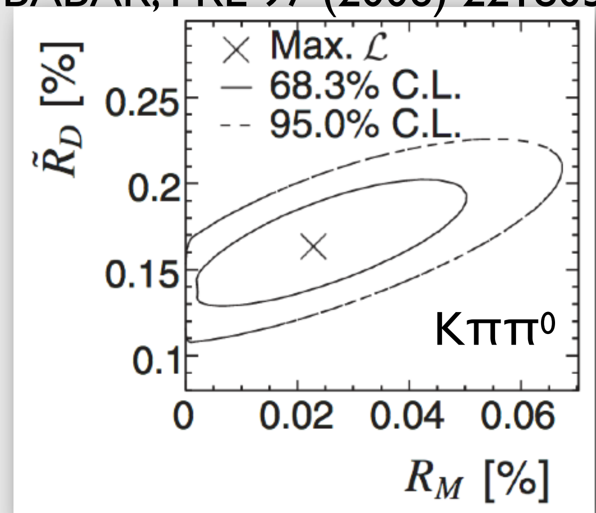
- Discovery through combination of measurements

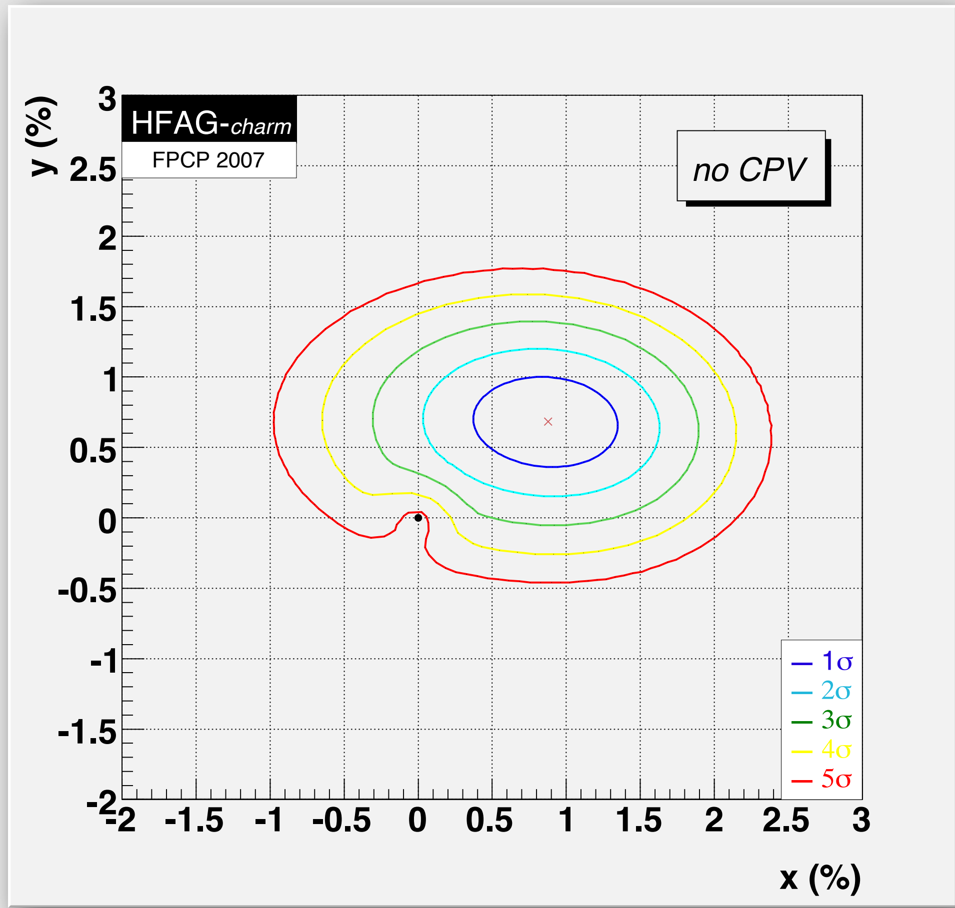
Mixing discovery

BABAR, arXiv:hep-ex/0607090

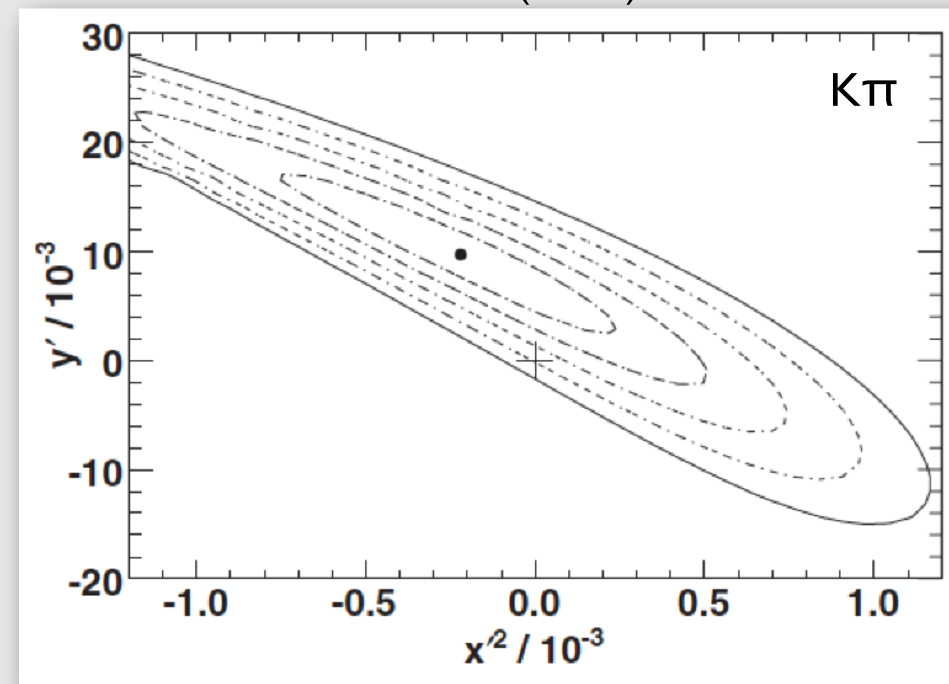


BABAR, PRL 97 (2006) 221803

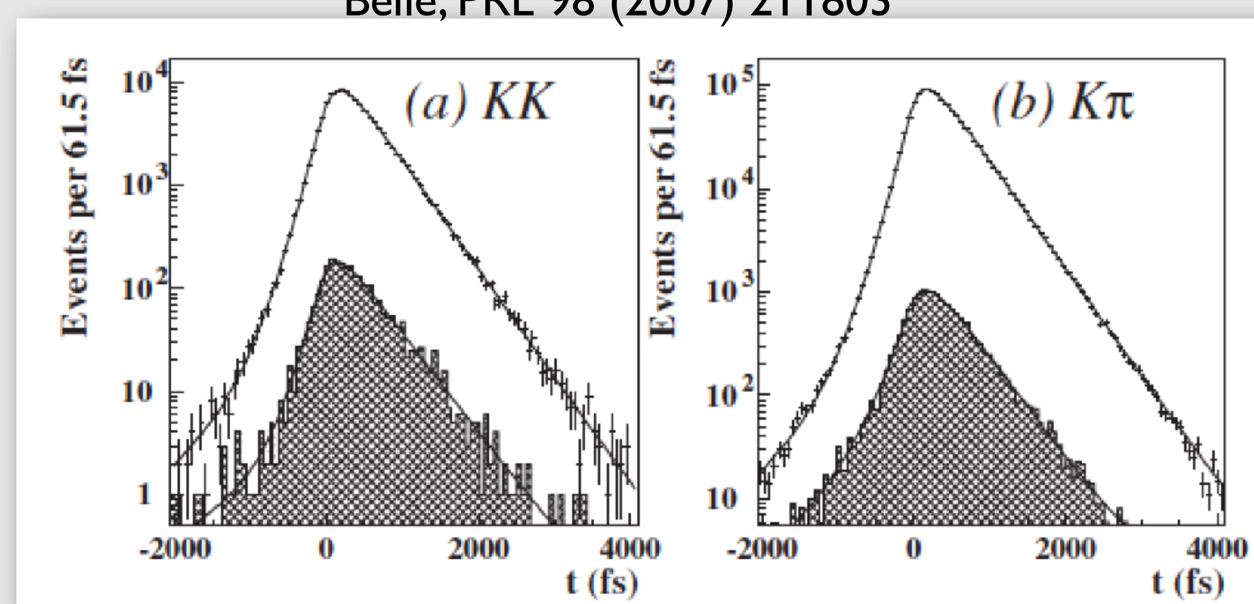




BABAR, PRL 98 (2007) 211802



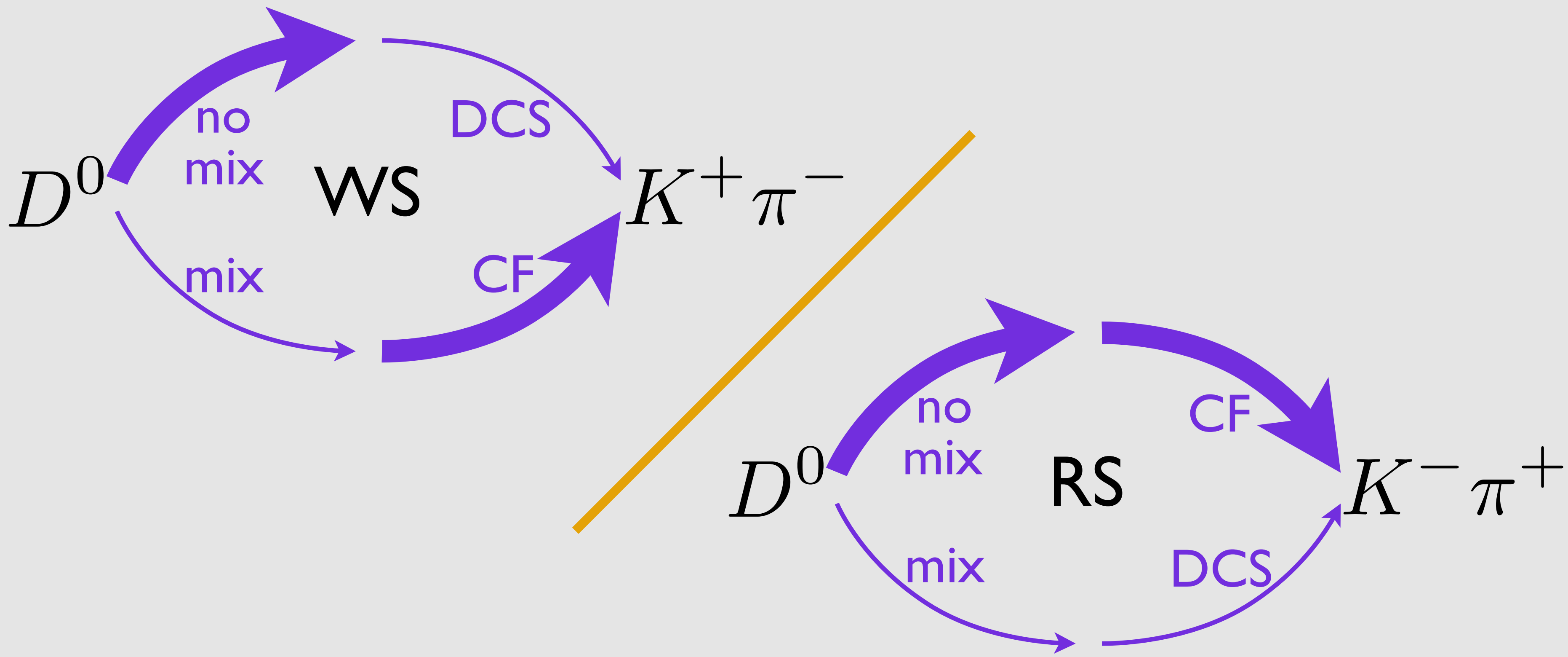
Belle, PRL 98 (2007) 211803



- Discovery through combination of measurements

Mixing discovery

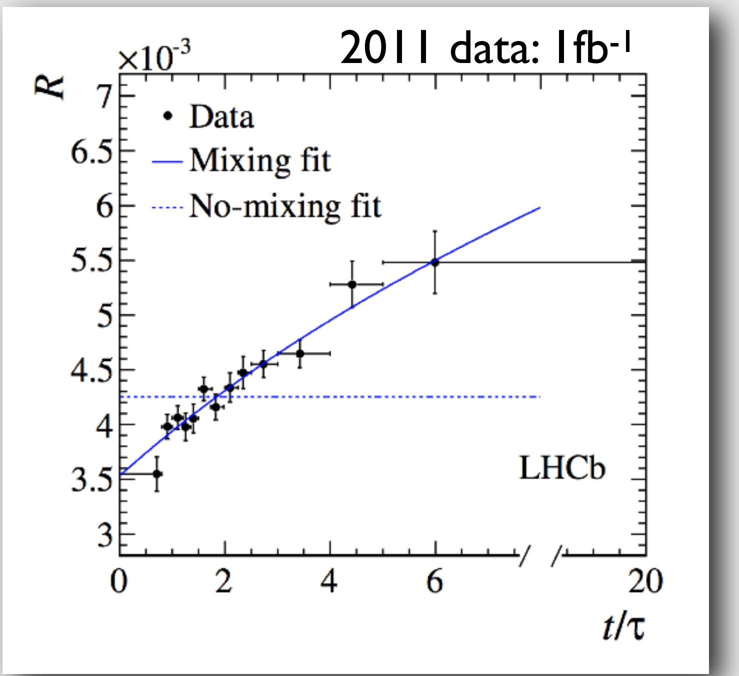
PRL 110 (2013) 101802



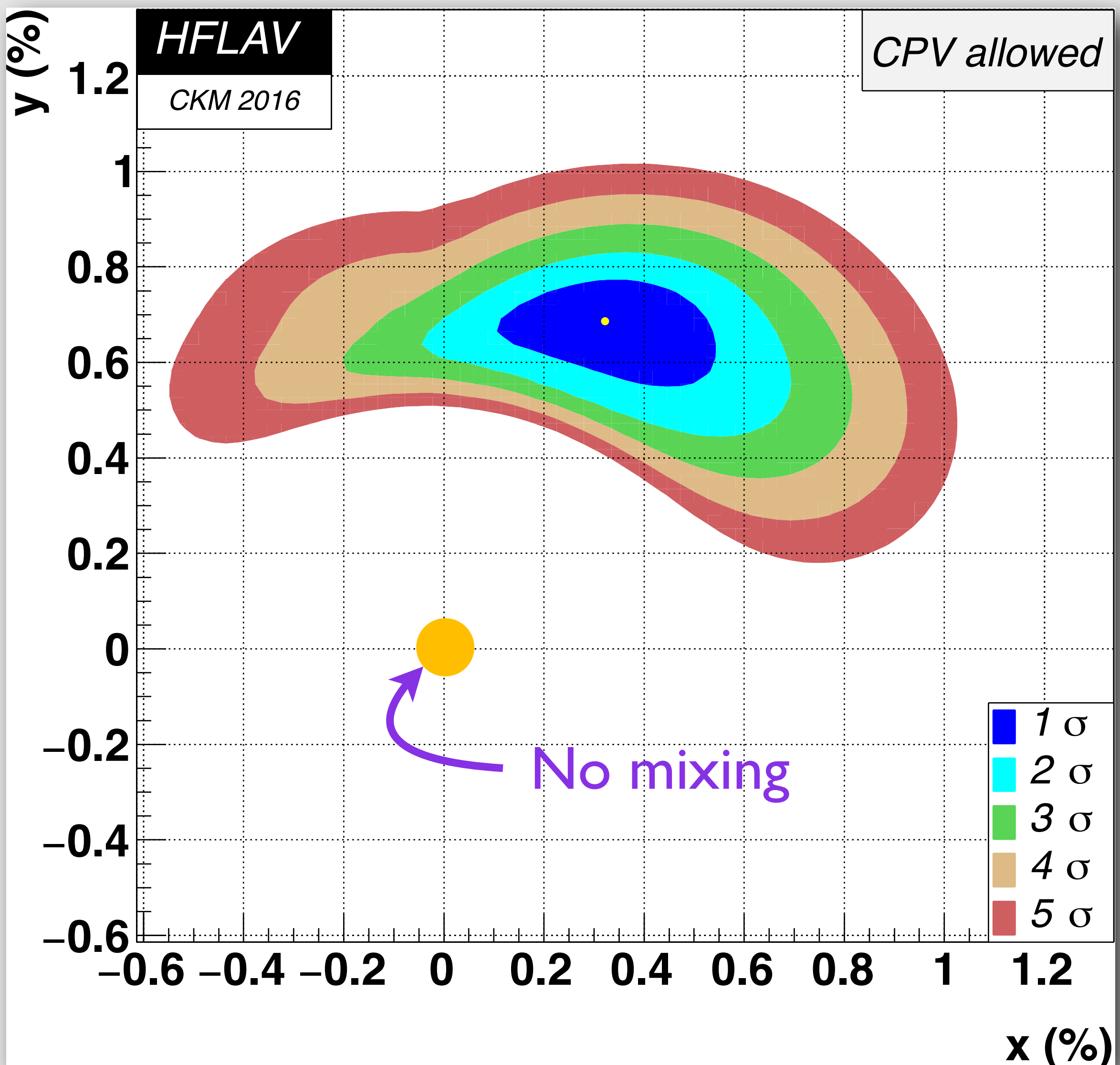
Using roughly 8.4×10^6 RS and 3.6×10^4 WS candidates

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

- 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:

$|q/p| \neq 1$

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

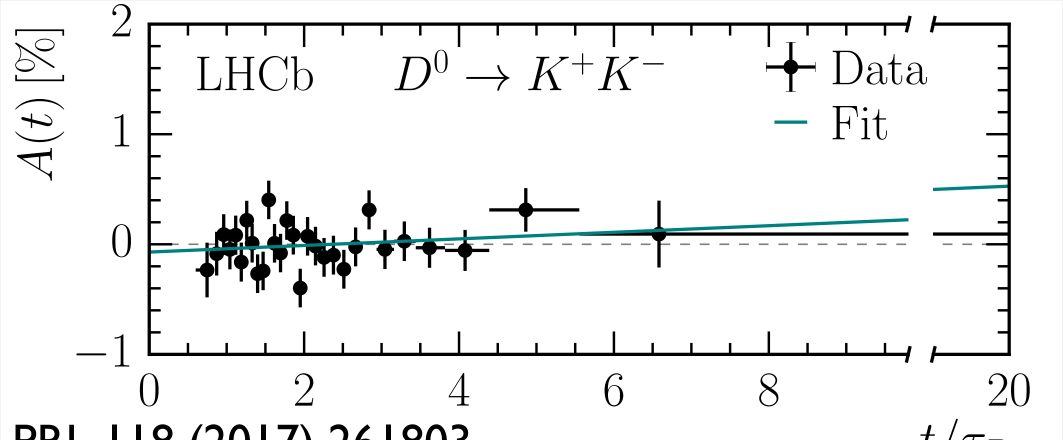
Indirect CP violation:

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

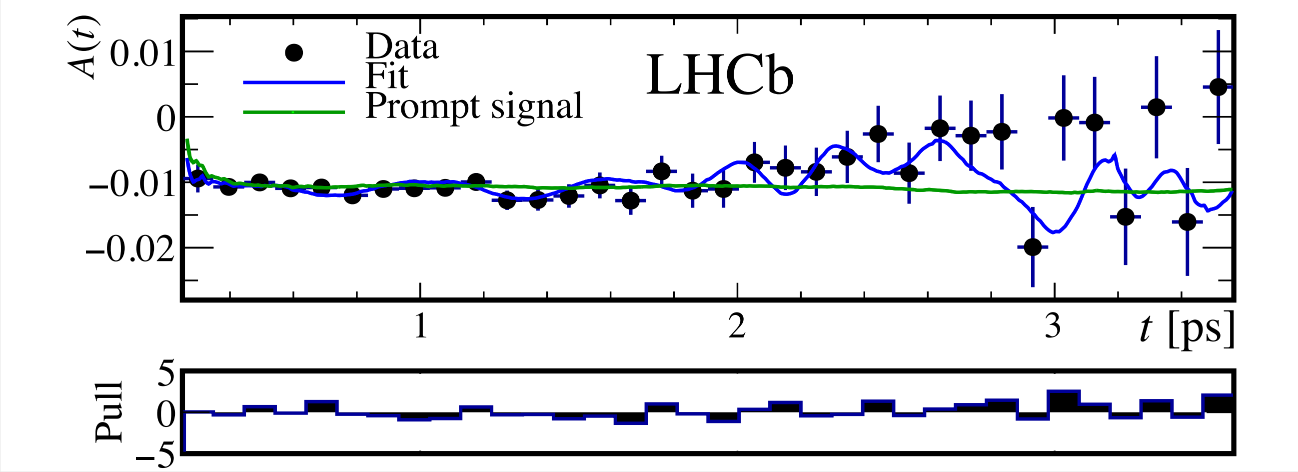
with $a_m \approx \pm(|{}^q/_p|^2 - 1)$

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

- 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
  - ➡ $A_\Gamma(K^+K^-)= (-0.30\pm0.32\pm0.10)\times10^{-3}$
  - ➡ $A_\Gamma(\pi^+\pi^-)= (+0.46\pm0.58\pm0.12)\times10^{-3}$



PRL 118 (2017) 261803



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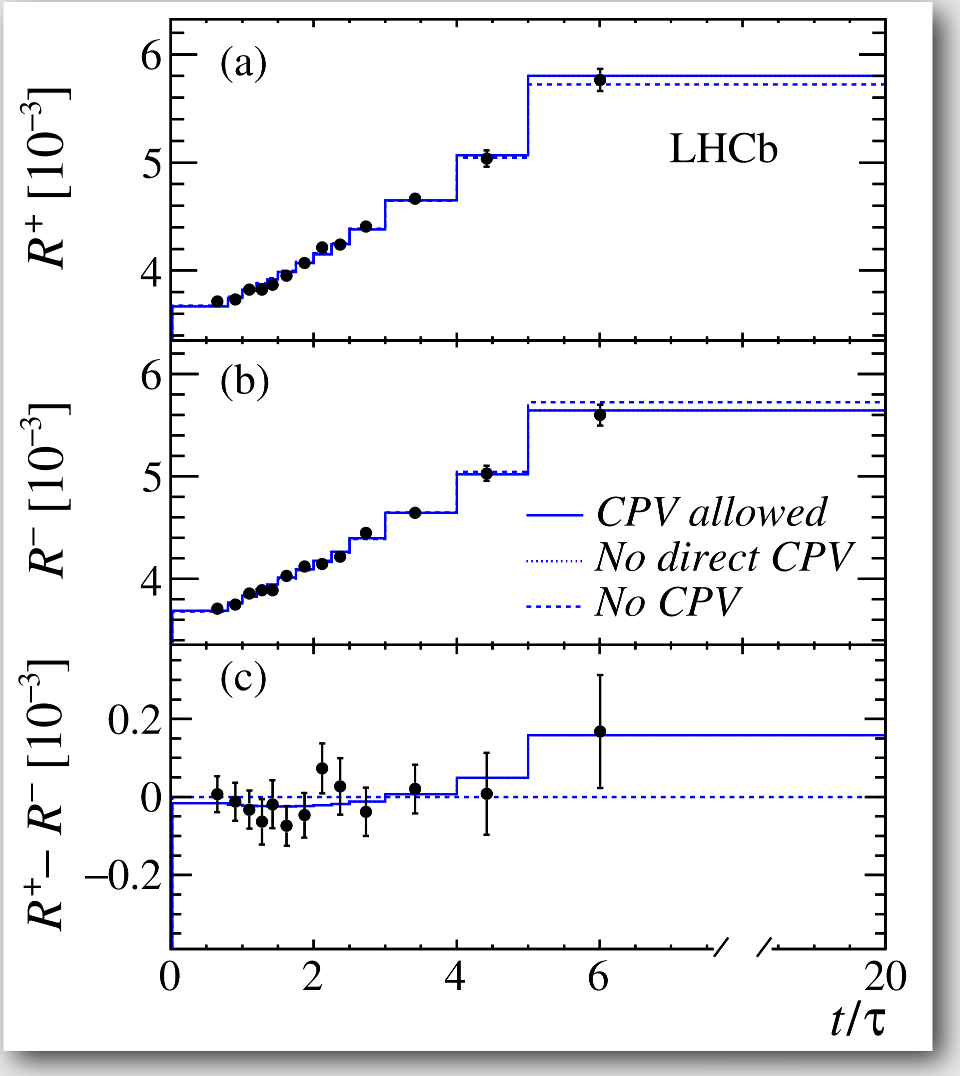
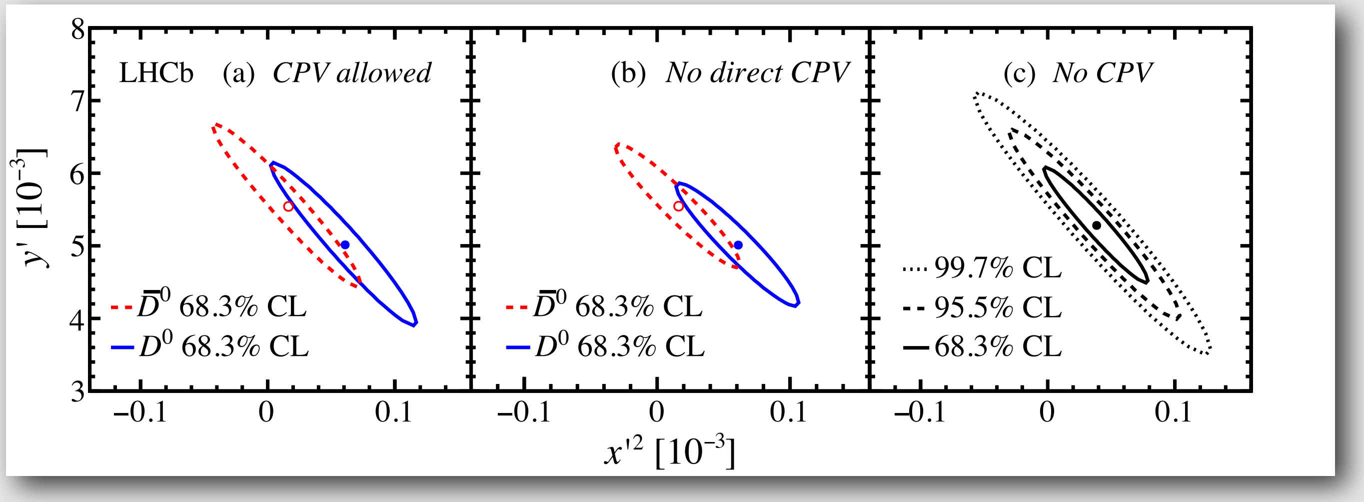
CPV in WS Kπ

PRD 97 (2018) 031101

- Split by flavour to search for CP violation
  - ➡ $x'^{\pm} = |q/p|^{\pm 1}(x' \cos\Phi \pm y' \sin\Phi)$
  - ➡ $y'^{\pm} = |q/p|^{\pm 1}(y' \cos\Phi \mp x' \sin\Phi)$
- Very good sensitivity to |q/p| for small ϕ
- 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



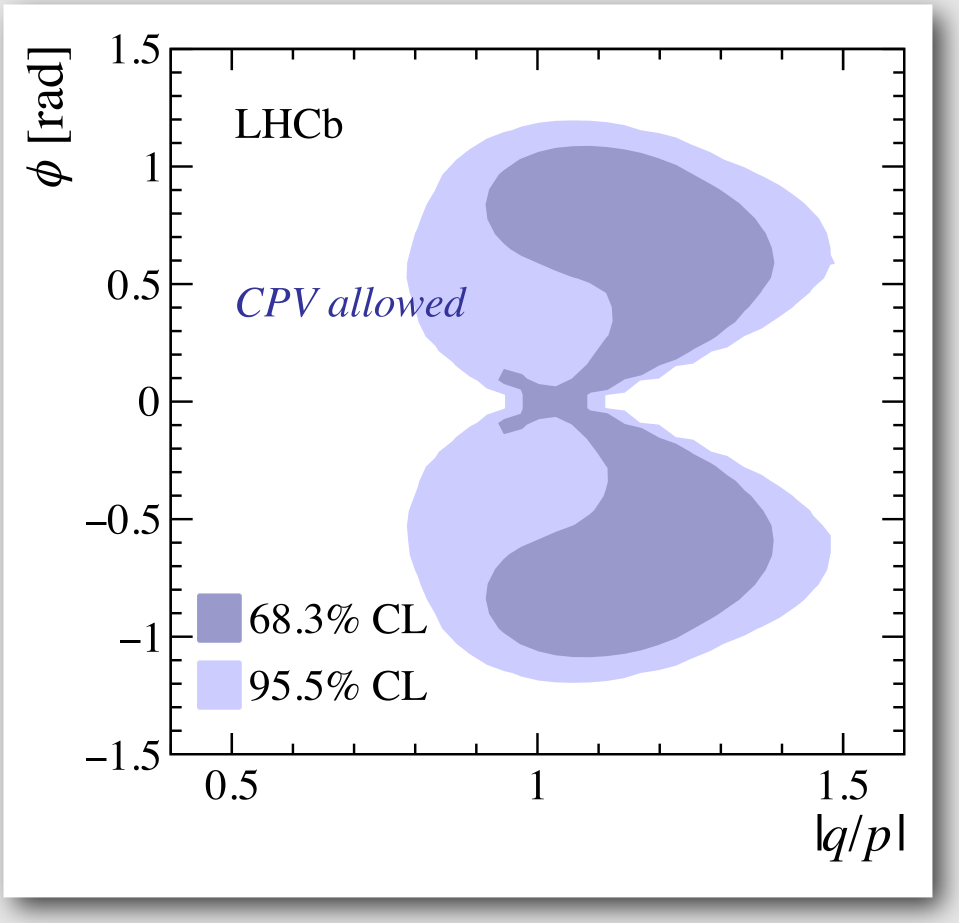


CPV in WS Kπ - II

- Results

Parameter	Results [10^{-3}] Value	Correlations					
Direct and indirect *CP* violation							
Parameter	Value	R_D^+	y'^+	$(x'^+)^2$	R_D^-	y'^-	$(x'^-)^2$
R_D^+	$3.454 \pm 0.040 \pm 0.020$	1.000	−0.935	0.843	−0.012	−0.003	0.002
y'^+	$5.01 \pm 0.64 \pm 0.38$		1.000	−0.963	−0.003	0.004	−0.003
$(x'^+)^2$	$0.061 \pm 0.032 \pm 0.019$			1.000	0.002	−0.003	0.003
R_D^-	$3.454 \pm 0.040 \pm 0.020$				1.000	−0.935	0.846
y'^-	$5.54 \pm 0.64 \pm 0.38$					1.000	−0.964
$(x'^-)^2$	$0.016 \pm 0.033 \pm 0.020$						1.000
No direct *CP* violation							
Parameter	Value	R_D	y'^+	$(x'^+)^2$	y'^-	$(x'^-)^2$	
R_D	$3.454 \pm 0.028 \pm 0.014$	1.000	−0.883	0.745	−0.883	0.749	
y'^+	$5.01 \pm 0.48 \pm 0.29$		1.000	−0.944	0.758	−0.644	
$(x'^+)^2$	$0.061 \pm 0.026 \pm 0.016$			1.000	−0.642	0.545	
y'^-	$5.54 \pm 0.48 \pm 0.29$				1.000	−0.946	
$(x'^-)^2$	$0.016 \pm 0.026 \pm 0.016$					1.000	
No *CP* violation							
Parameter	Value	R_D	y'	x'^2			
R_D	$3.454 \pm 0.028 \pm 0.014$	1.000	−0.942	0.850			
y'	$5.28 \pm 0.45 \pm 0.27$		1.000	−0.963			
x'^2	$0.039 \pm 0.023 \pm 0.014$			1.000			

PRD 97 (2018) 031101



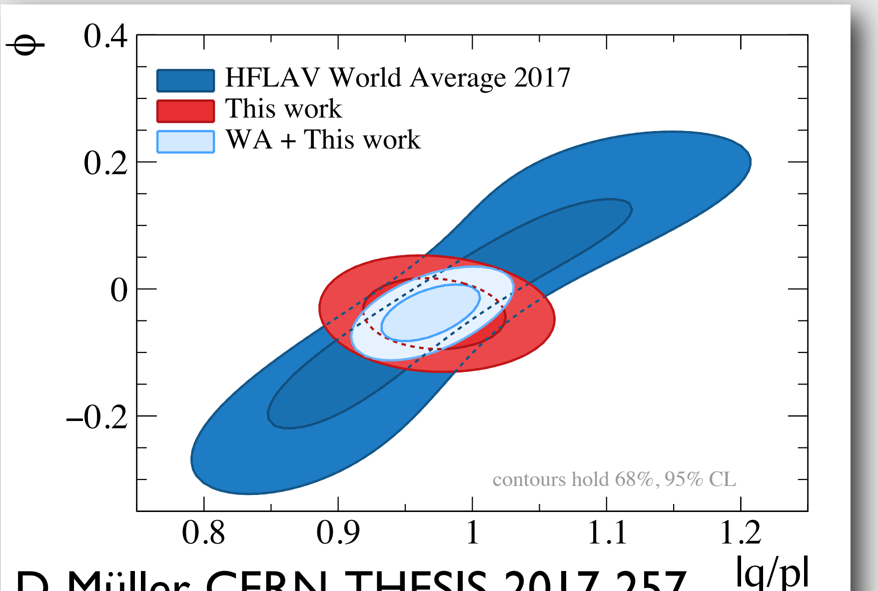
Multi-body decays

- 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
    - ▸ See Jim Libby's talk in this session

Realistically need both

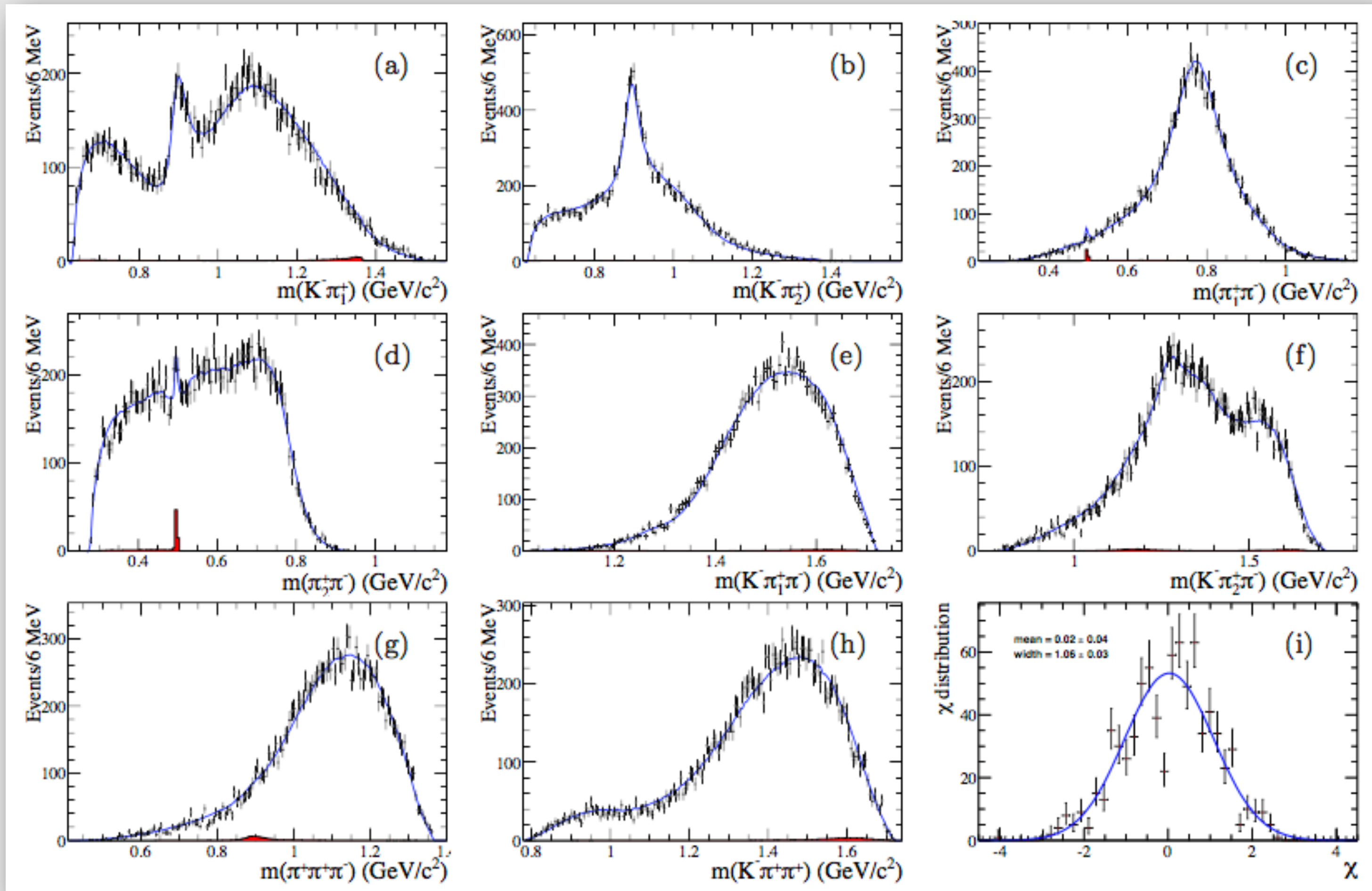
- In last ten years time-dependent measurements almost only in $D^0 \to K_S \pi^+ \pi^-$
  - ➡ A missed opportunity?
  - ➡ Recent work by BABAR on $D^0 \to \pi^+ \pi^- \pi^0$
  - ➡ Surely something for Belle II
  - ➡ Very promising studies at LHCb

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



D. Müller, CERN-THESIS-2017-257

$D^0 \to K^-\pi^+\pi^-\pi^+$ at BESIII



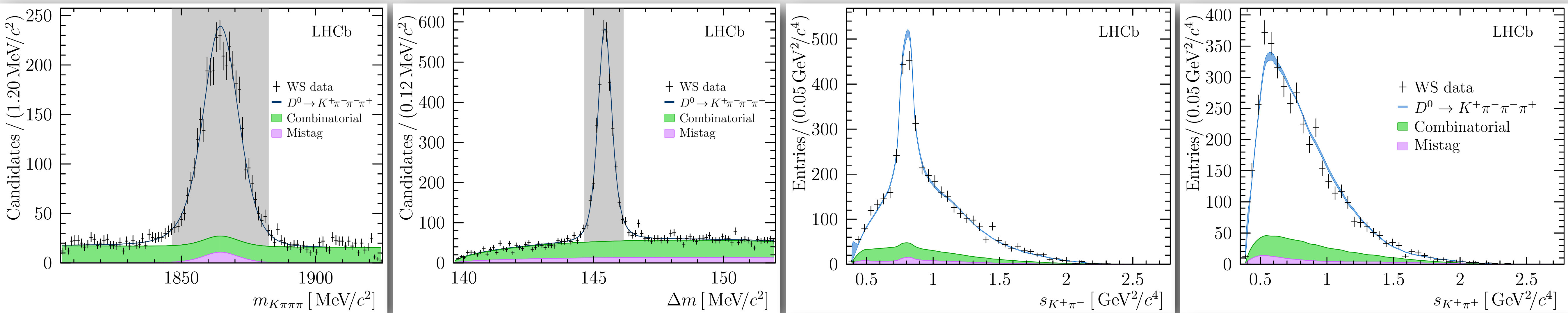
PRD 95 (2017) 072010

Amplitude	ϕ_i	Fit fraction (%)
$D^0[S] \to \bar{K}^*\rho^0$	$2.35 \pm 0.06 \pm 0.18$	$6.5 \pm 0.5 \pm 0.8$
$D^0[P] \to \bar{K}^*\rho^0$	$-2.25 \pm 0.08 \pm 0.15$	$2.3 \pm 0.2 \pm 0.1$
$D^0[D] \to \bar{K}^*\rho^0$	$2.49 \pm 0.06 \pm 0.11$	$7.9 \pm 0.4 \pm 0.7$
$D^0 \to K^- a_1^+(1260),\ a_1^+(1260)[S] \to \rho^0\pi^+$	0(fixed)	$53.2 \pm 2.8 \pm 4.0$
$D^0 \to K^- a_1^+(1260),\ a_1^+(1260)[D] \to \rho^0\pi^+$	$-2.11 \pm 0.15 \pm 0.21$	$0.3 \pm 0.1 \pm 0.1$
$D^0 \to K_1^-(1270)\pi^+,\ K_1^-(1270)[S] \to \bar{K}^{*0}\pi^-$	$1.48 \pm 0.21 \pm 0.24$	$0.1 \pm 0.1 \pm 0.1$
$D^0 \to K_1^-(1270)\pi^+,\ K_1^-(1270)[D] \to \bar{K}^{*0}\pi^-$	$3.00 \pm 0.09 \pm 0.15$	$0.7 \pm 0.2 \pm 0.2$
$D^0 \to K_1^-(1270)\pi^+,\ K_1^-(1270) \to K^-\rho^0$	$-2.46 \pm 0.06 \pm 0.21$	$3.4 \pm 0.3 \pm 0.5$
$D^0 \to (\rho^0 K^-)_A\pi^+,\ (\rho^0 K^-)_A[D] \to K^-\rho^0$	$-0.43 \pm 0.09 \pm 0.12$	$1.1 \pm 0.2 \pm 0.3$
$D^0 \to (K^-\rho^0)_P\pi^+$	$-0.14 \pm 0.11 \pm 0.10$	$7.4 \pm 1.6 \pm 5.7$
$D^0 \to (K^-\pi^+)_{S-wave}\rho^0$	$-2.45 \pm 0.19 \pm 0.47$	$2.0 \pm 0.7 \pm 1.9$
$D^0 \to (K^-\rho^0)_V\pi^+$	$-1.34 \pm 0.12 \pm 0.09$	$0.4 \pm 0.1 \pm 0.1$
$D^0 \to (\bar{K}^{*0}\pi^-)_P\pi^+$	$-2.09 \pm 0.12 \pm 0.22$	$2.4 \pm 0.5 \pm 0.5$
$D^0 \to \bar{K}^{*0}(\pi^+\pi^-)_S$	$-0.17 \pm 0.11 \pm 0.12$	$2.6 \pm 0.6 \pm 0.6$
$D^0 \to (\bar{K}^{*0}\pi^-)_V\pi^+$	$-2.13 \pm 0.10 \pm 0.11$	$0.8 \pm 0.1 \pm 0.1$
$D^0 \to ((K^-\pi^+)_{S-wave}\pi^-)_A\pi^+$	$-1.36 \pm 0.08 \pm 0.37$	$5.6 \pm 0.9 \pm 2.7$
$D^0 \to K^-((\pi^+\pi^-)_S\pi^+)_A$	$-2.23 \pm 0.08 \pm 0.22$	$13.1 \pm 1.9 \pm 2.2$
$D^0 \to (K^-\pi^+)_{S-wave}(\pi^+\pi^-)_S$	$-1.40 \pm 0.04 \pm 0.22$	$16.3 \pm 0.5 \pm 0.6$
$D^0[S] \to (K^-\pi^+)_V(\pi^+\pi^-)_V$	$1.59 \pm 0.13 \pm 0.41$	$5.4 \pm 1.2 \pm 1.9$
$D^0 \to (K^-\pi^+)_{S-wave}(\pi^+\pi^-)_V$	$-0.16 \pm 0.17 \pm 0.43$	$1.9 \pm 0.6 \pm 1.2$
$D^0 \to (K^-\pi^+)_V(\pi^+\pi^-)_S$	$2.58 \pm 0.08 \pm 0.25$	$2.9 \pm 0.5 \pm 1.7$
$D^0 \to (K^-\pi^+)_T(\pi^+\pi^-)_S$	$-2.92 \pm 0.14 \pm 0.12$	$0.3 \pm 0.1 \pm 0.1$
$D^0 \to (K^-\pi^+)_{S-wave}(\pi^+\pi^-)_T$	$2.45 \pm 0.12 \pm 0.37$	$0.5 \pm 0.1 \pm 0.1$

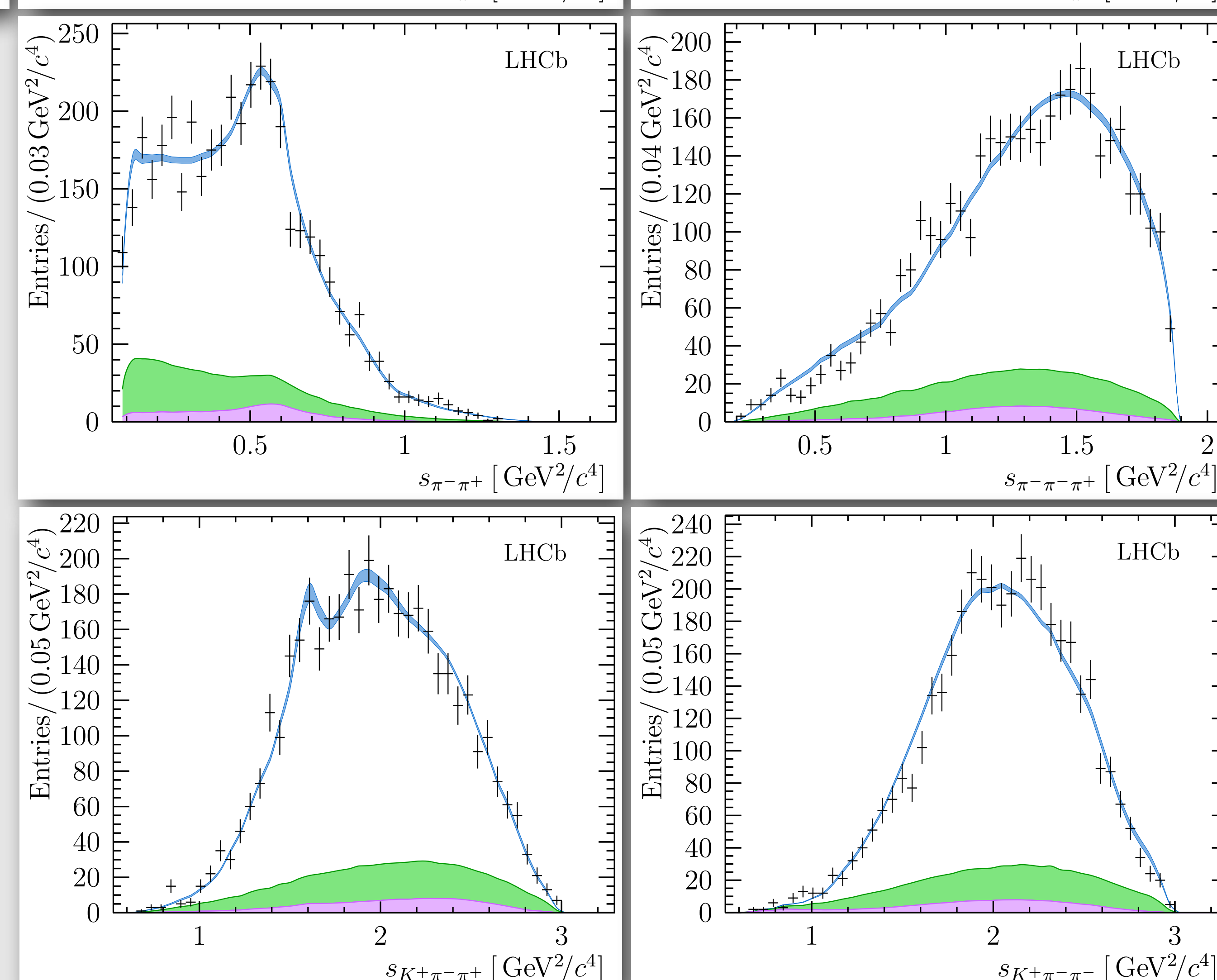
- Based on 16000 RS candidates (99.4% purity)
  - ➡ Double-tagged sample via $\bar{D}^0 \to K\pi$ decays
- First study of this decay in this millennium
- Paving the way for time-dependent amplitude analysis

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

EPJ C78 (2018) 443



- 2011+12 data (3 fb^{-1})
- Based on 2500 WS events (82.4% purity)
  - ➡ Suppressed by factor of ~300
  - ➡ Input to time-dependent analysis
- Also measured RS model with ~900k events (99.6% purity)
  - ➡ Broadly similar but some disagreement on NR contribution

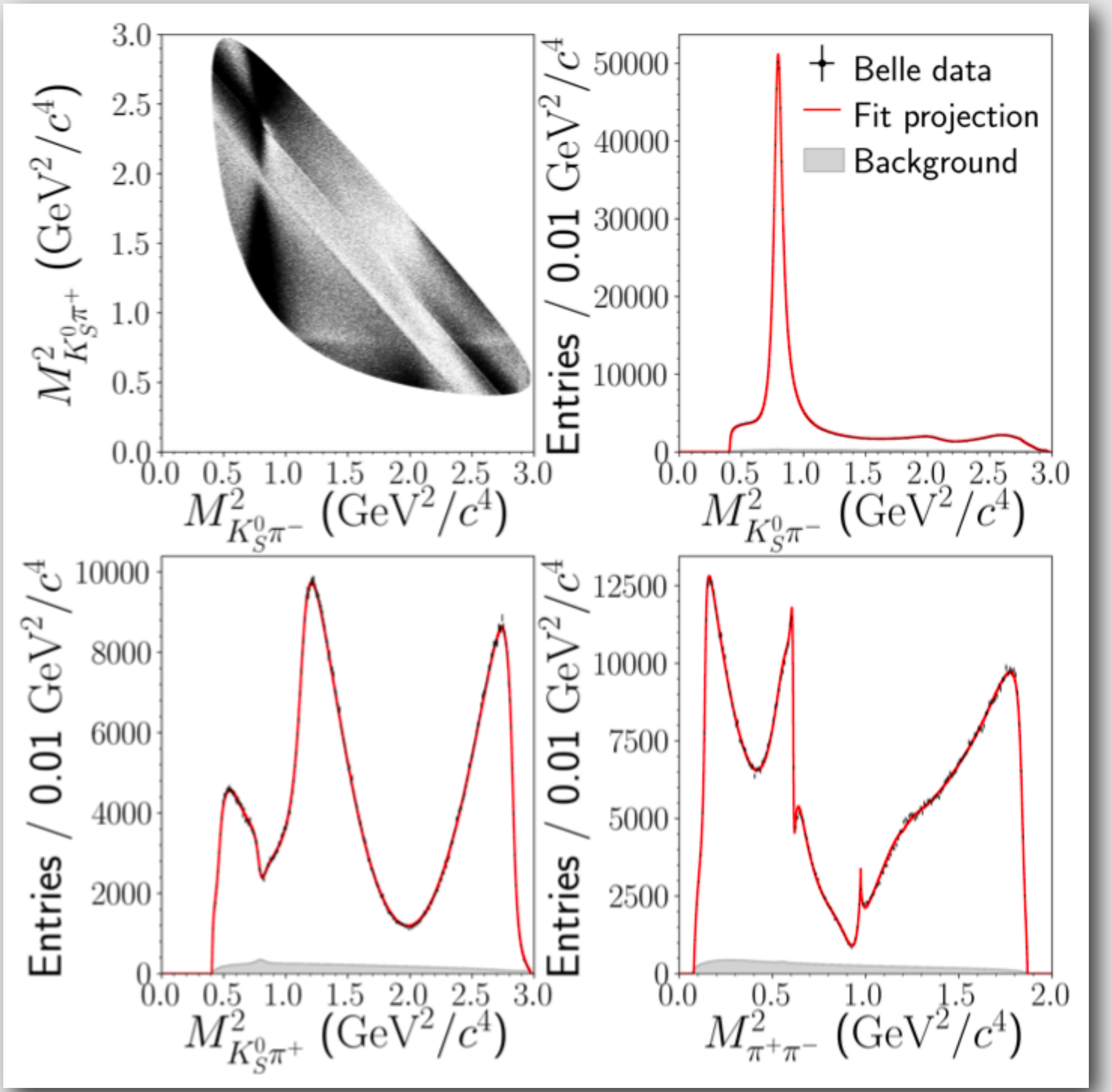


The golden mode

arXiv:1804.06152
arXiv:1804.06153

- Joint BaBar and Belle amplitude analysis of $D^0 \rightarrow K_S\pi\pi$
- 1.2M candidates
- Prime candidate to perform time-dependent analysis to measure x

➡ Feasible both for Belle II and LHCb



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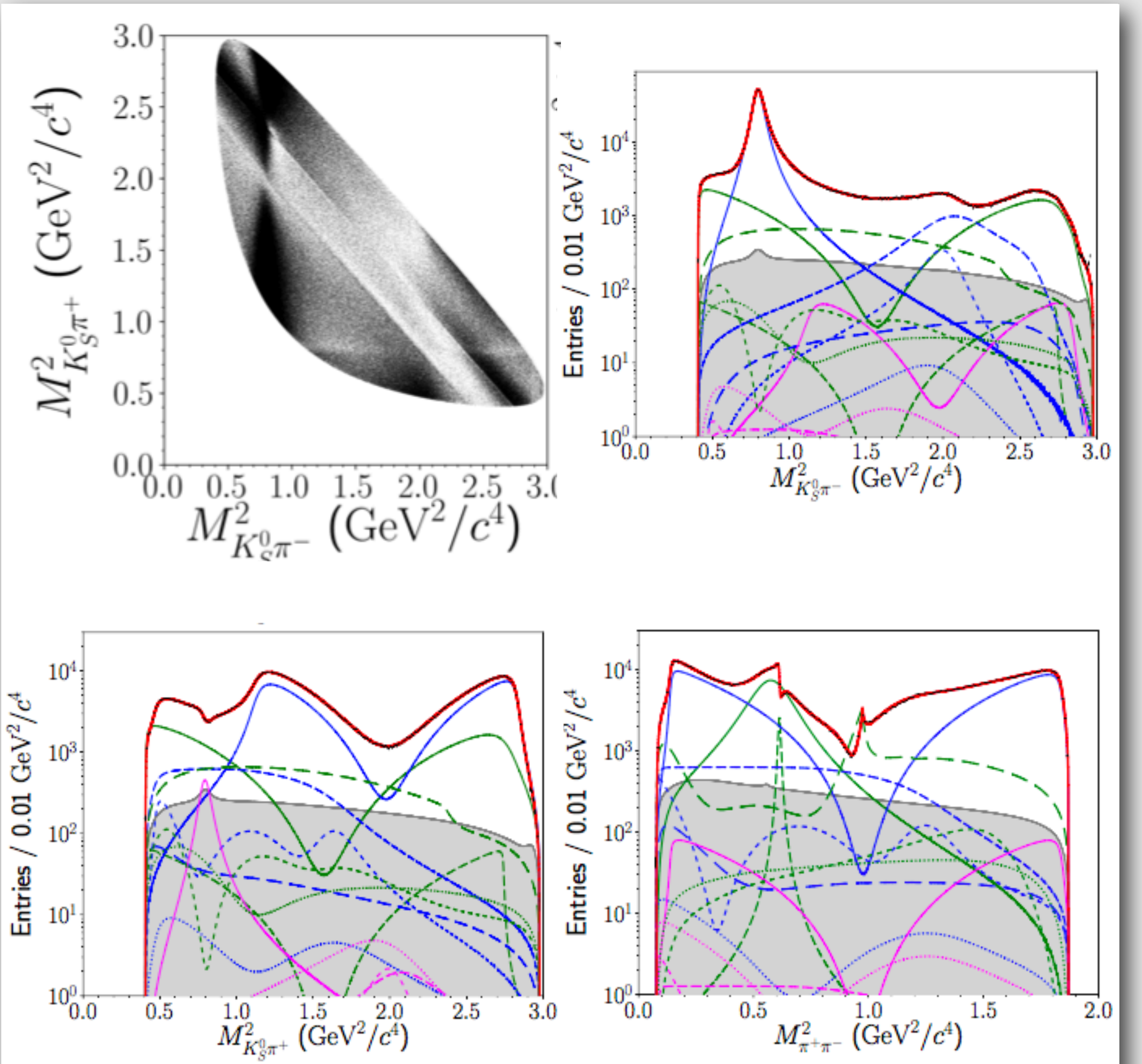
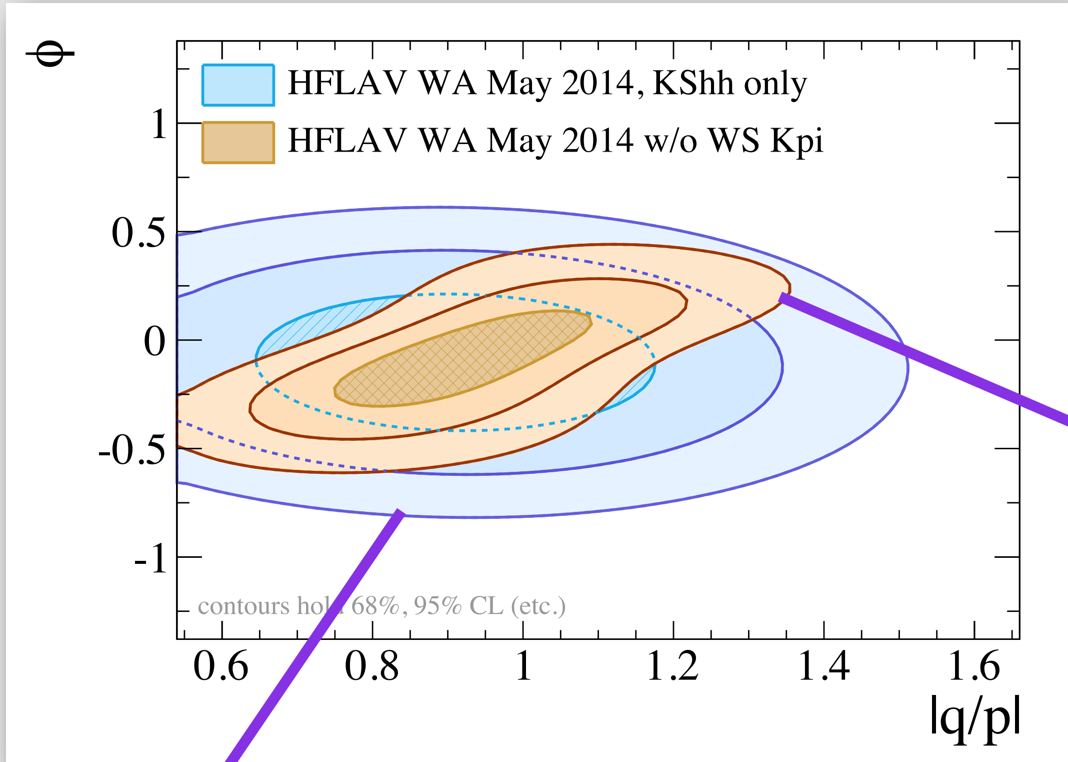
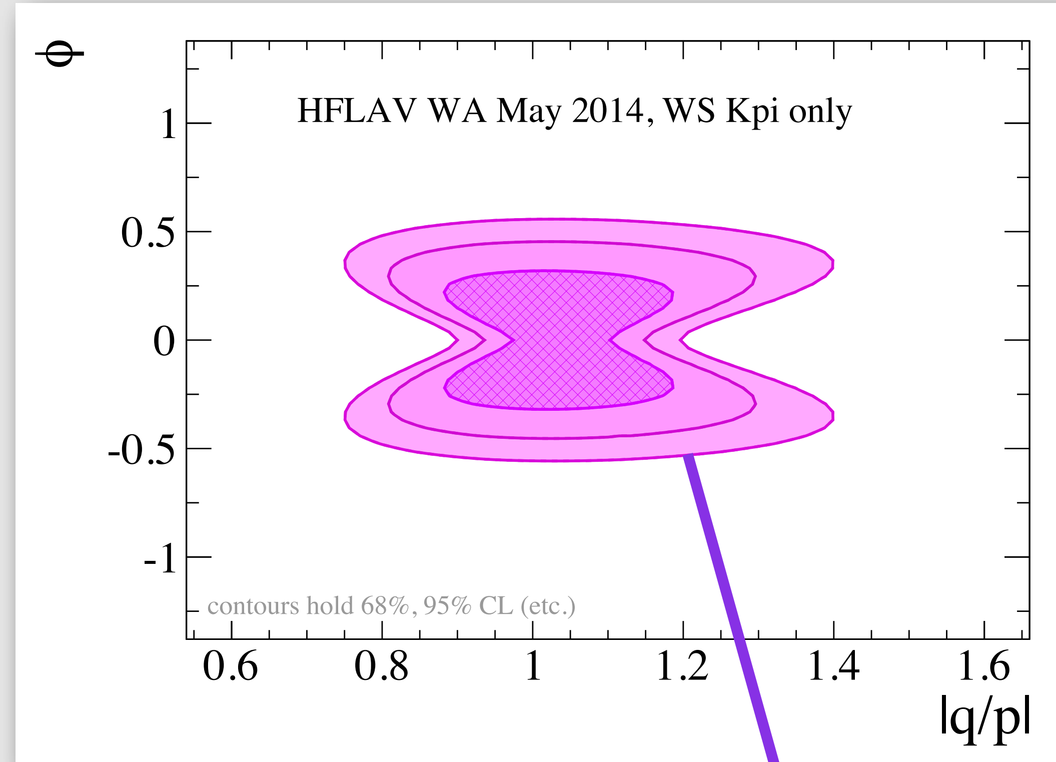


Individual fit contributions

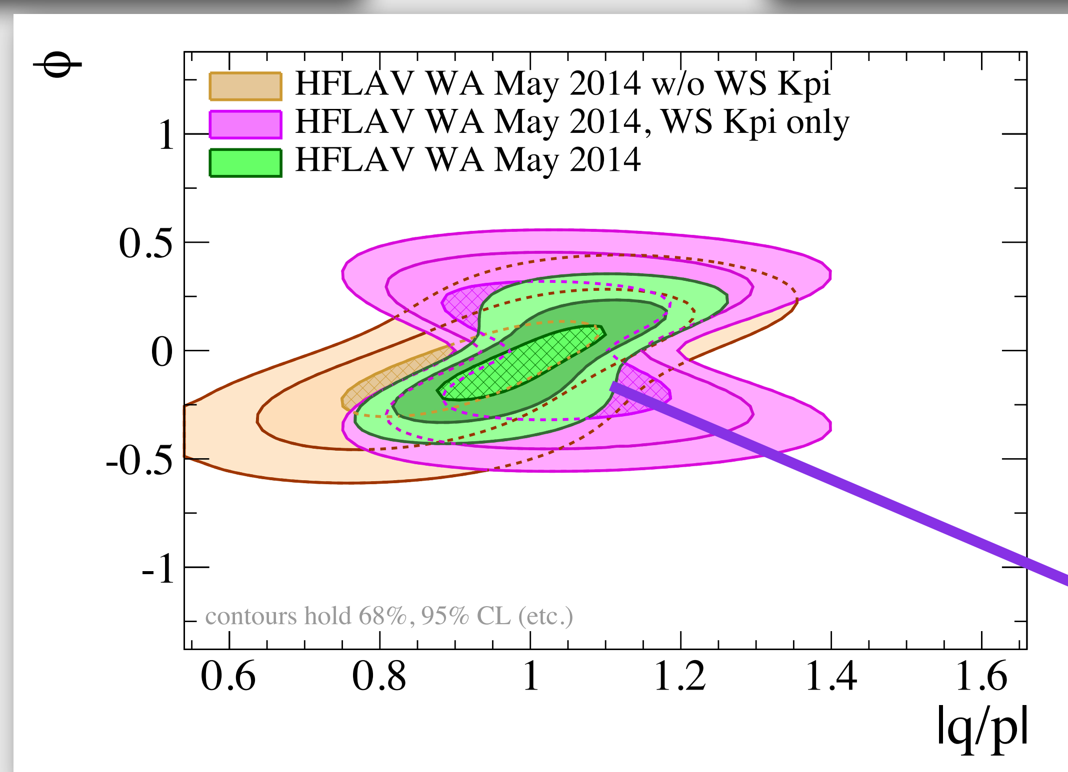
Contributions



Precise constraints if x and y provided, mostly from A_Γ



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



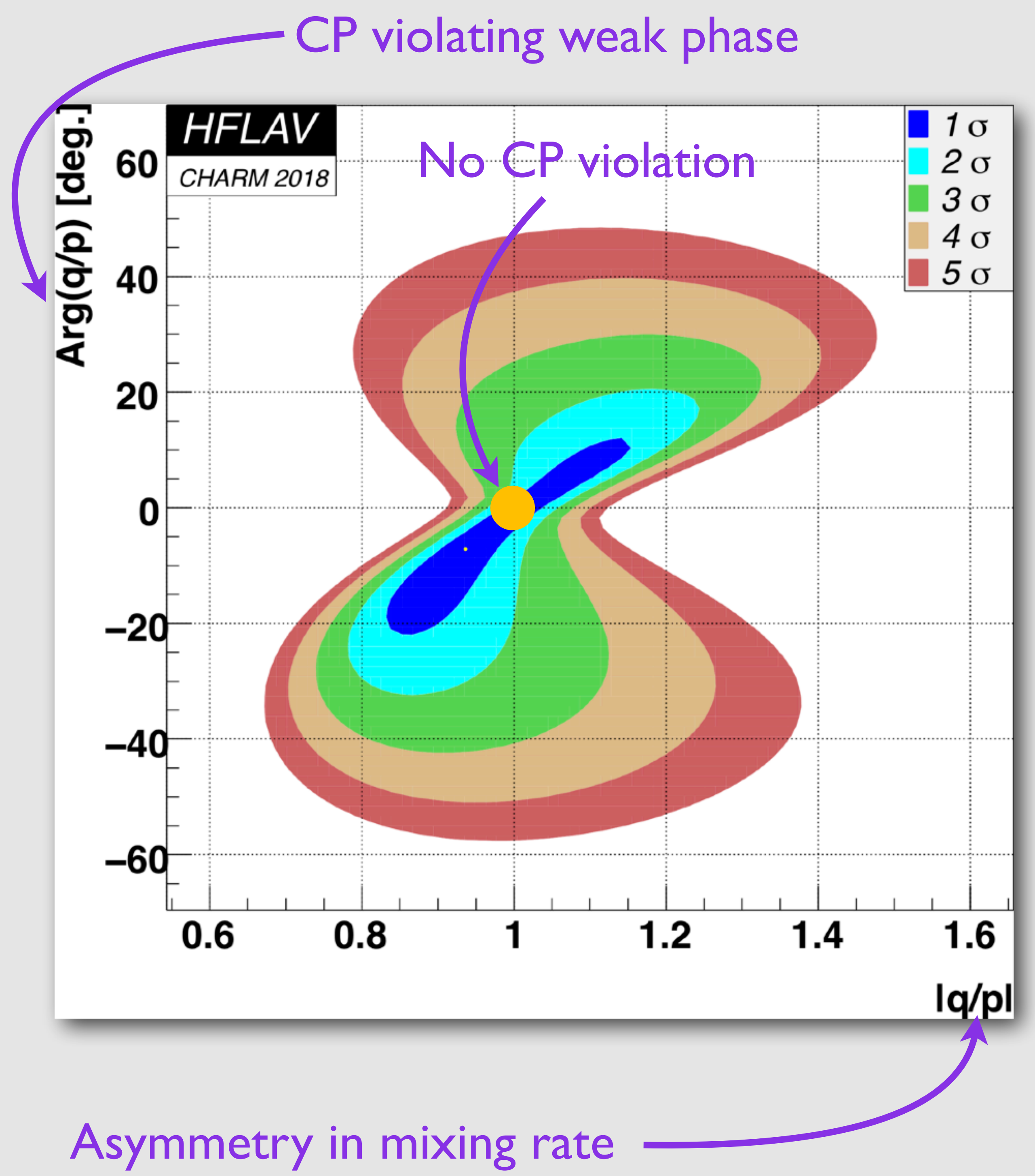
WS Kπ: symmetric in φ,

good sensitivity to |q/p| for small φ

Full average following intersection of contours

CP violation overview

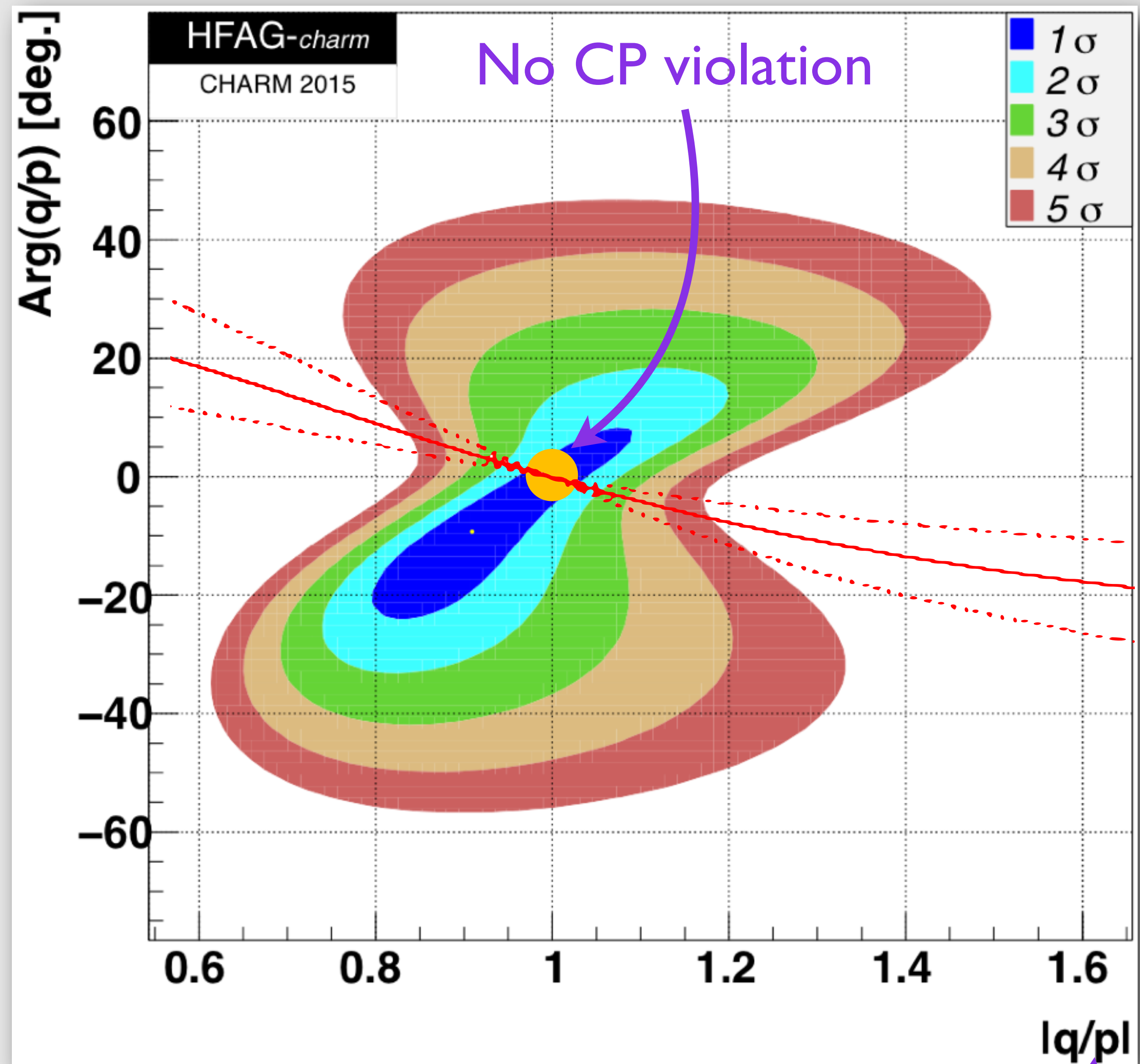
- No sign of CP violation
  …yet



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}, Φ_{12}
- Current sensitivity already very good
  - ➡ $\sigma(\Phi_{12}) = 1.7°$

CP violating weak phase



Asymmetry in mixing rate

Can we do better?

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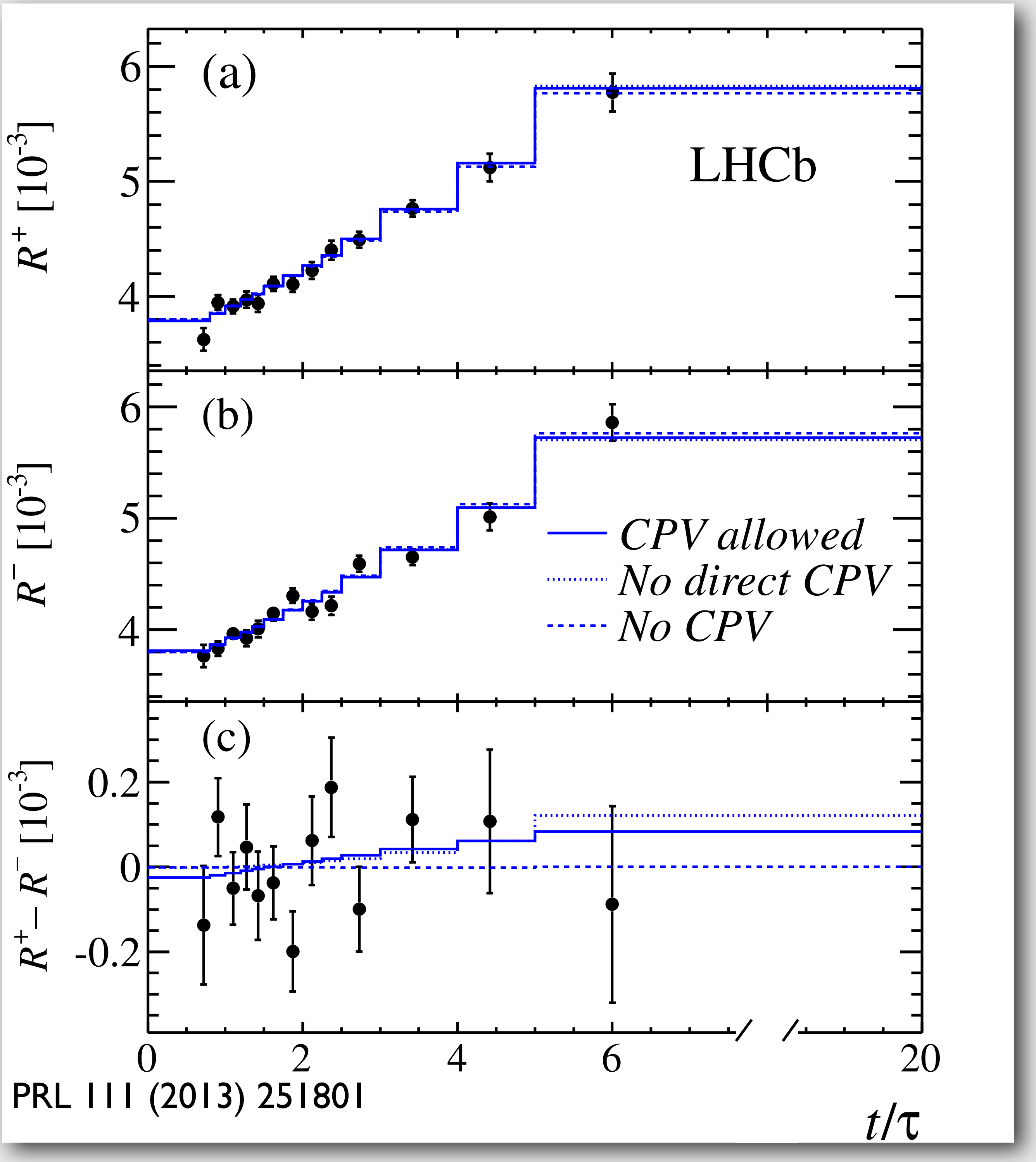

PRL 111 (2013) 251801

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  - ➡ $x_{12}, y_{12}, \Phi_{12}$
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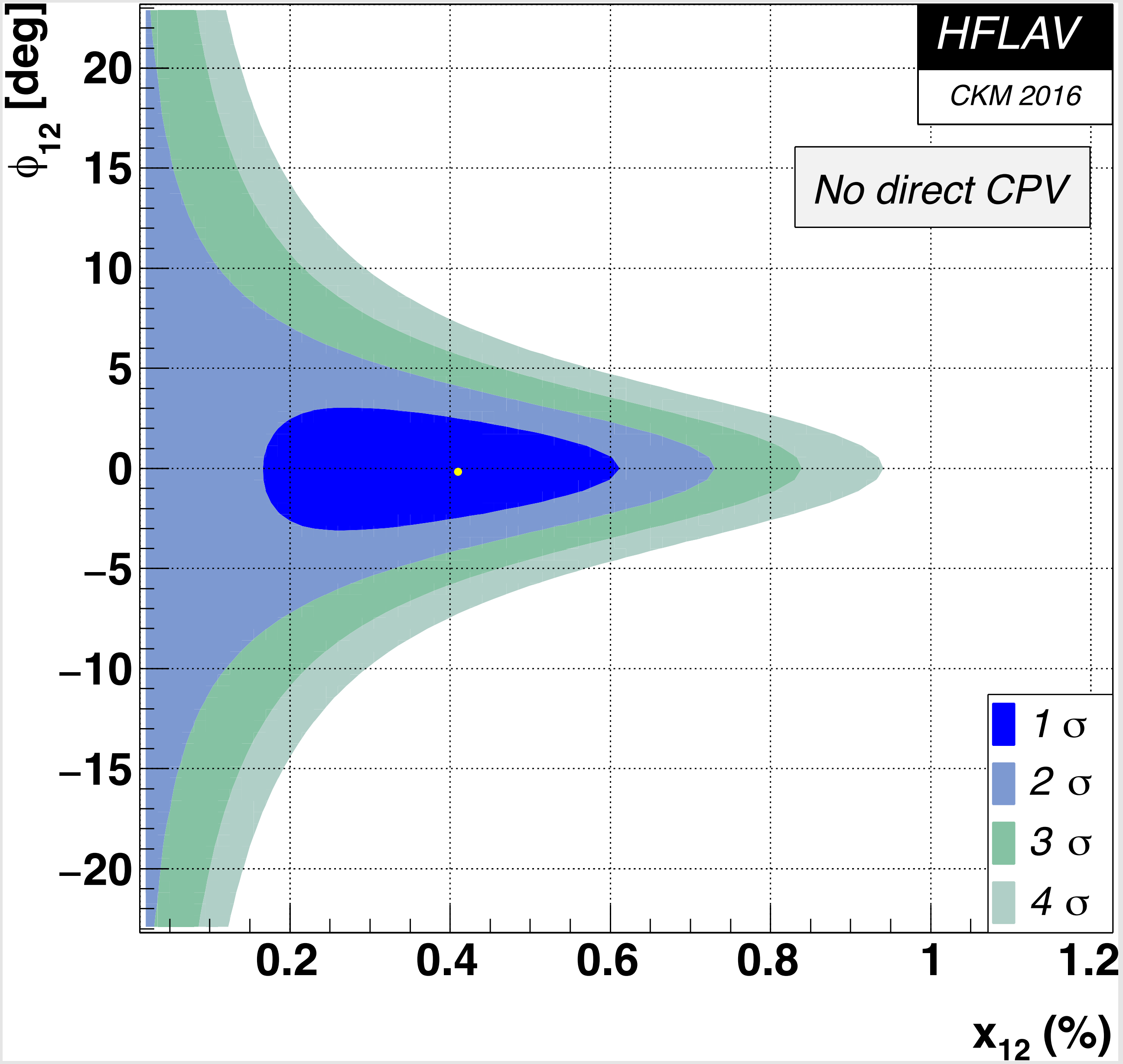

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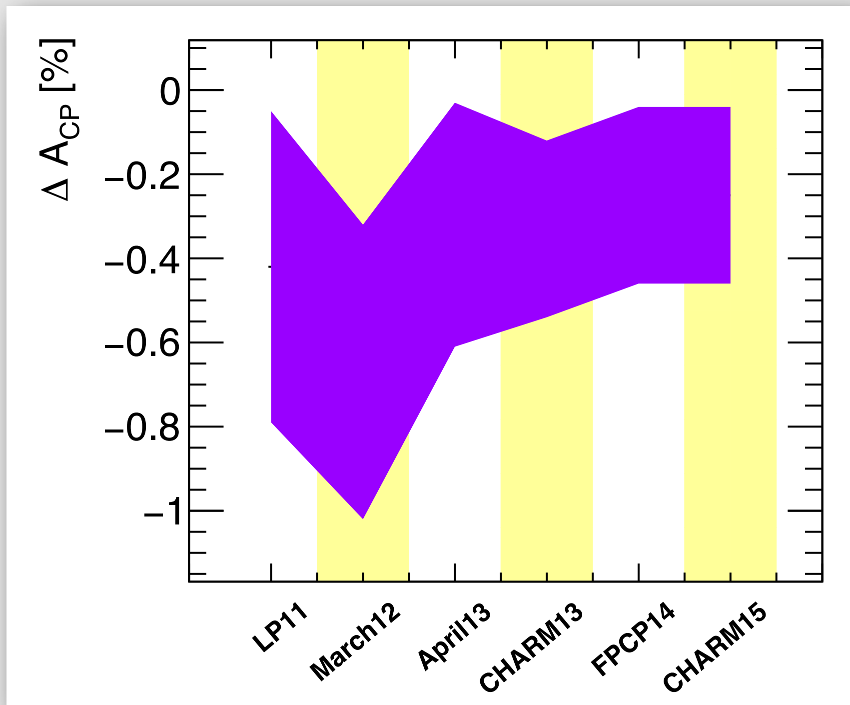
Direct CP violation

Direct CP violation:

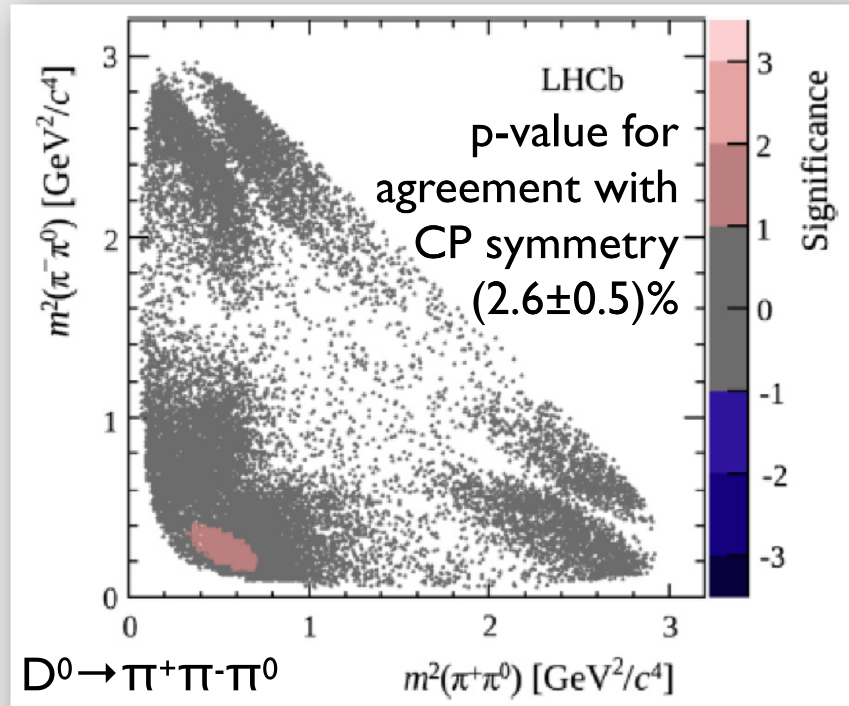
$$a_{CP}^{dir} \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}$$

CPV in decay

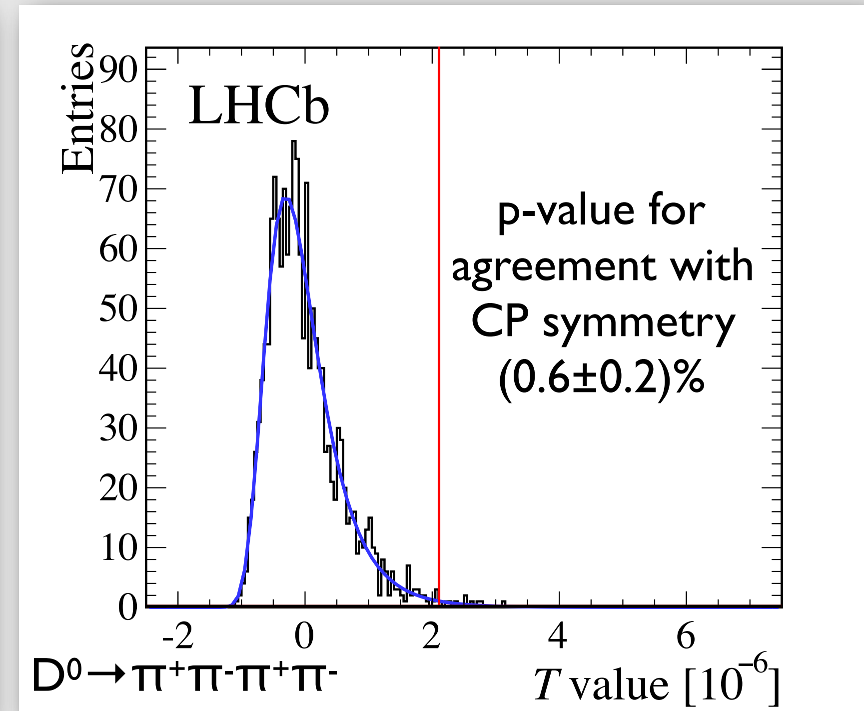
$A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$



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, …

$D^0 \rightarrow hh\mu\mu$

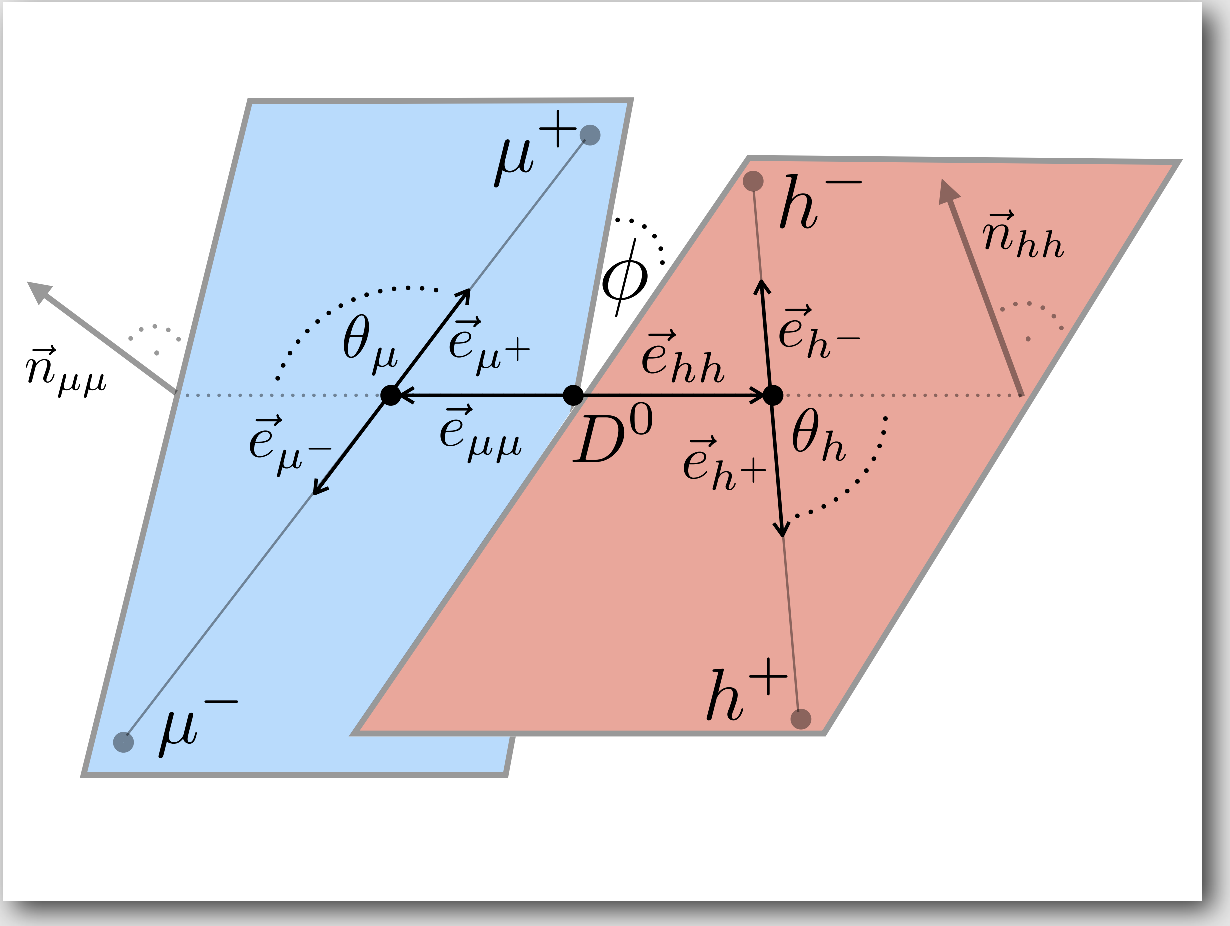
See talk by M. Chrzaszcz

- Four-body decays offer
  - ➡ Spectrum of interfering resonances
  - ➡ Several ways of searching for CPV
  - ➡ Rare decays may have larger interference effects = CP violation
- Measure:

$$A_{\rm FB} = \frac{\Gamma(\cos\theta_\mu > 0) - \Gamma(\cos\theta_\mu < 0)}{\Gamma(\cos\theta_\mu > 0) + \Gamma(\cos\theta_\mu < 0)},$$

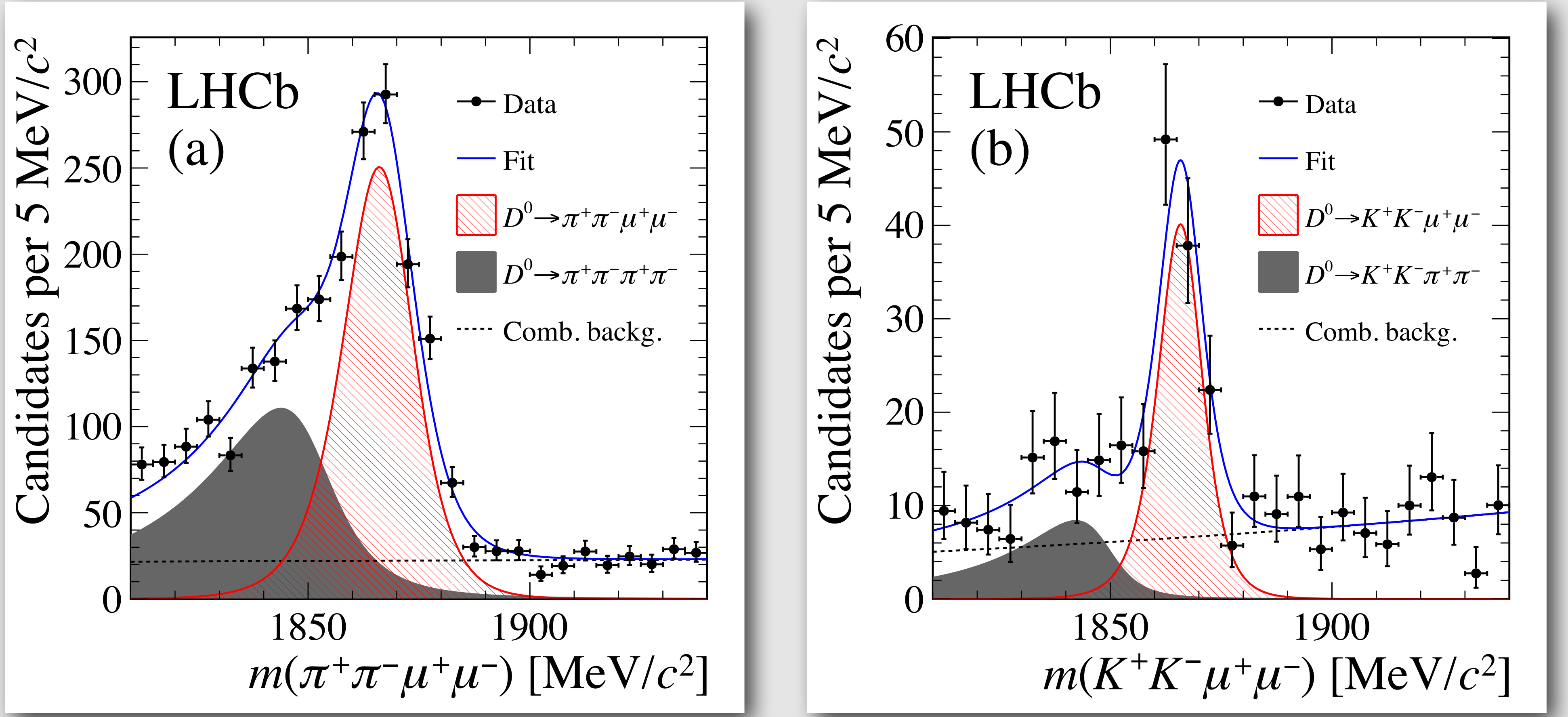
$$A_{2\phi} = \frac{\Gamma(\sin 2\phi > 0) - \Gamma(\sin 2\phi < 0)}{\Gamma(\sin 2\phi > 0) + \Gamma(\sin 2\phi < 0)},$$

$$A_{CP} = \frac{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) - \Gamma(\bar{D}^0 \to h^+h^-\mu^+\mu^-)}{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) + \Gamma(\bar{D}^0 \to h^+h^-\mu^+\mu^-)},$$



$D^0 \to hh\mu\mu$ - II

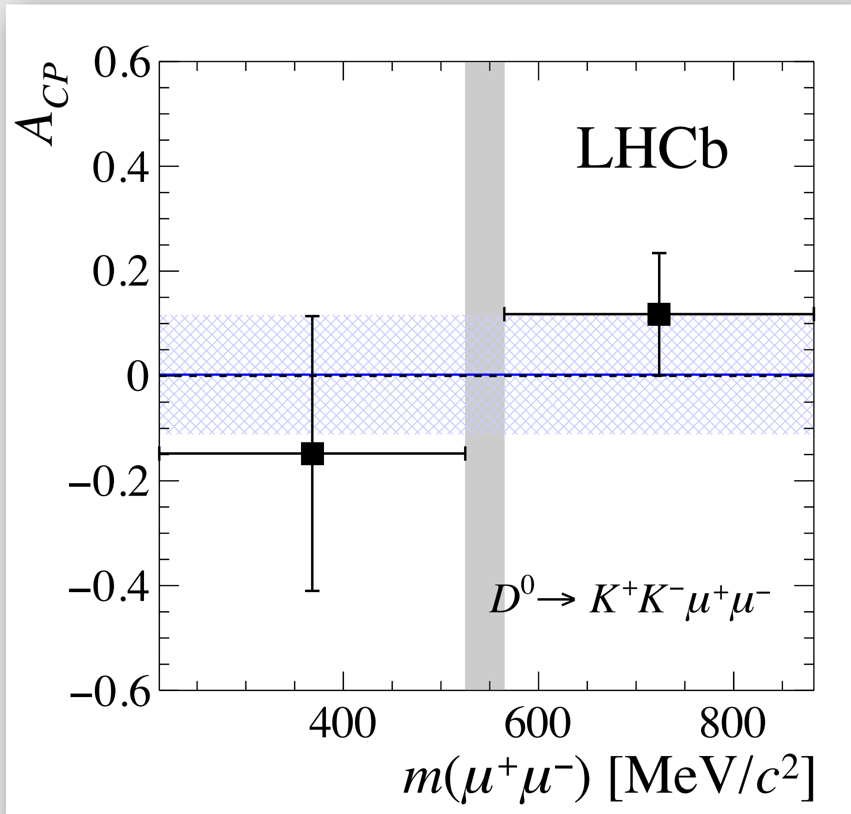
arXiv:1806.10793

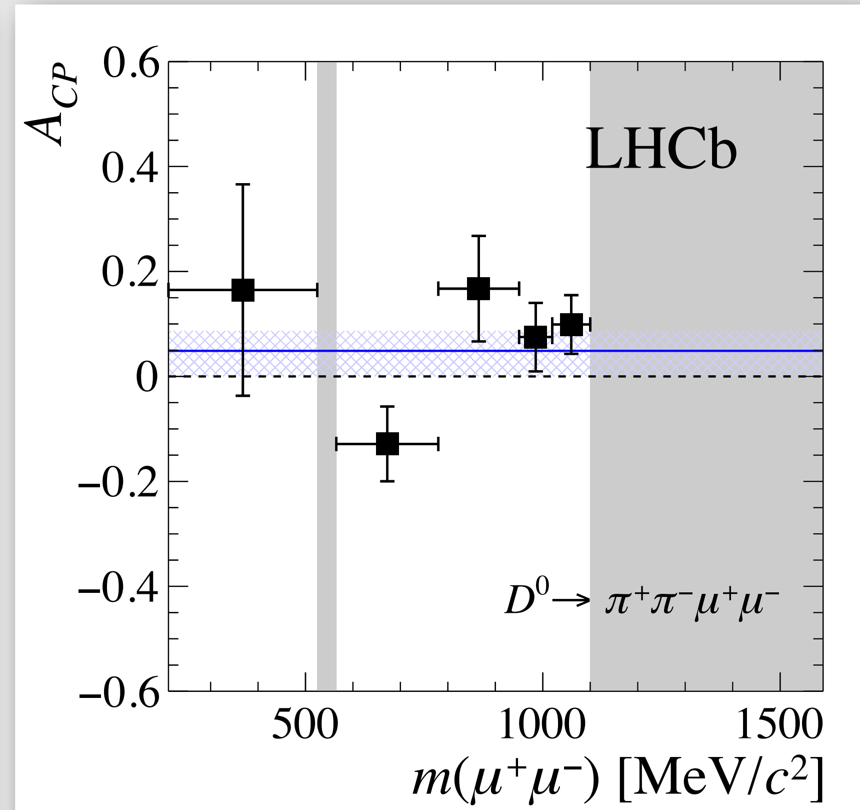


- LHCb 2011-16 data (5 fb^{-1})
- Includes significant signal in low-mass region (<525 MeV/c^2)
- A_{CP} normalised to $D^0 \to K^+K^-$

$D^0 \to hh\mu\mu$ - III

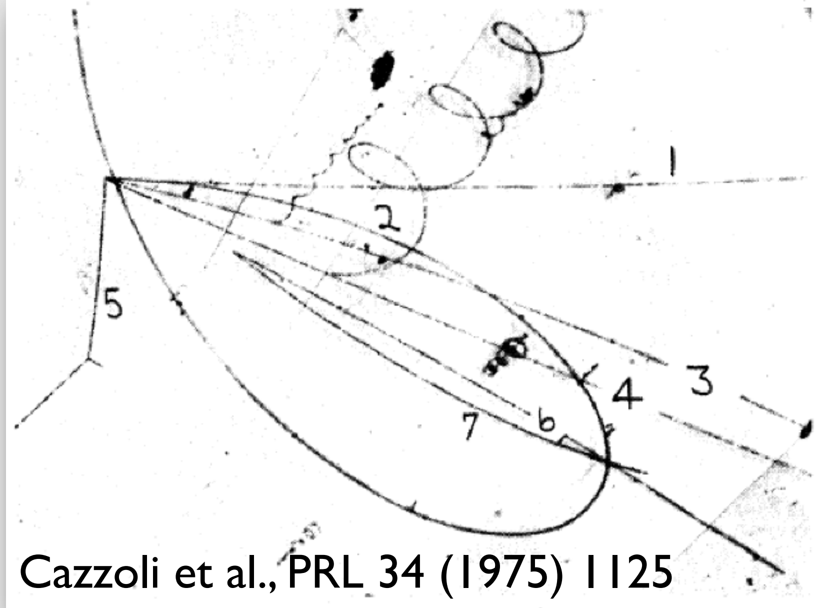
arXiv:1806.10793



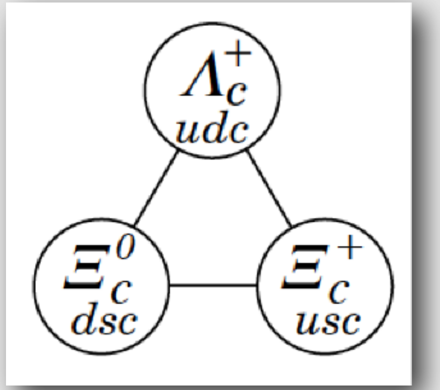


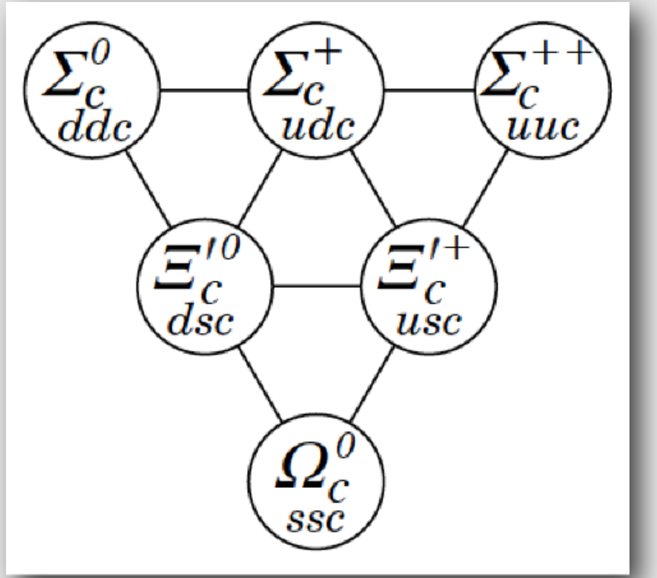
$m(\mu^+\mu^-)$ [MeV/c^2]	Efficiency-weighted yields: Signal	Misid. back.	Comb. back.	Signal asymmetries: A_{FB} [%]	$A_{2\phi}$ [%]	A_{CP} [%]
			$D^0 \to \pi^+\pi^-\mu^+\mu^-$			
< 525	90 ± 17	233 ± 25	108 ± 22	$2 \pm 20 \pm 2$	$-28 \pm 20 \pm 2$	$17 \pm 20 \pm 2$
525–565	–	–	–	–	–	–
565–780	326 ±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

Baryons



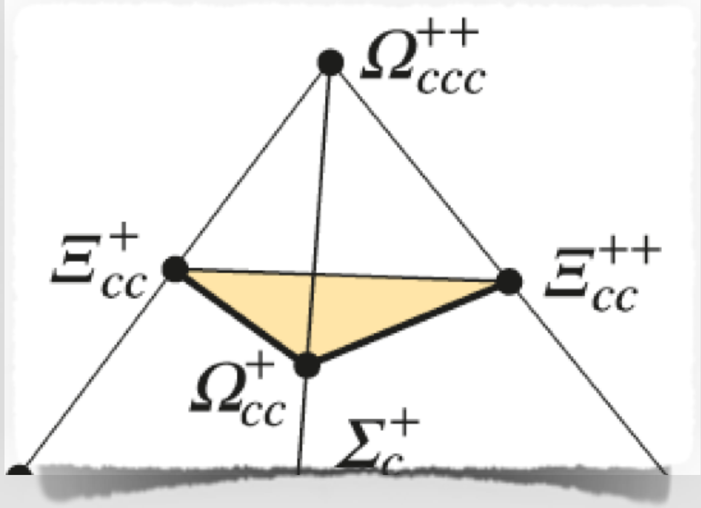
Cazzoli et al., PRL 34 (1975) 1125





- Ground state singly-charmed baryons known
  - ➡ Lifetimes between 3% and 17% uncertainties
- Picture of doubly-charmed baryons still evolving
  - ➡ Not to mention Ω_{ccc}
- What level of CP violation should we expect?

More in the next talk

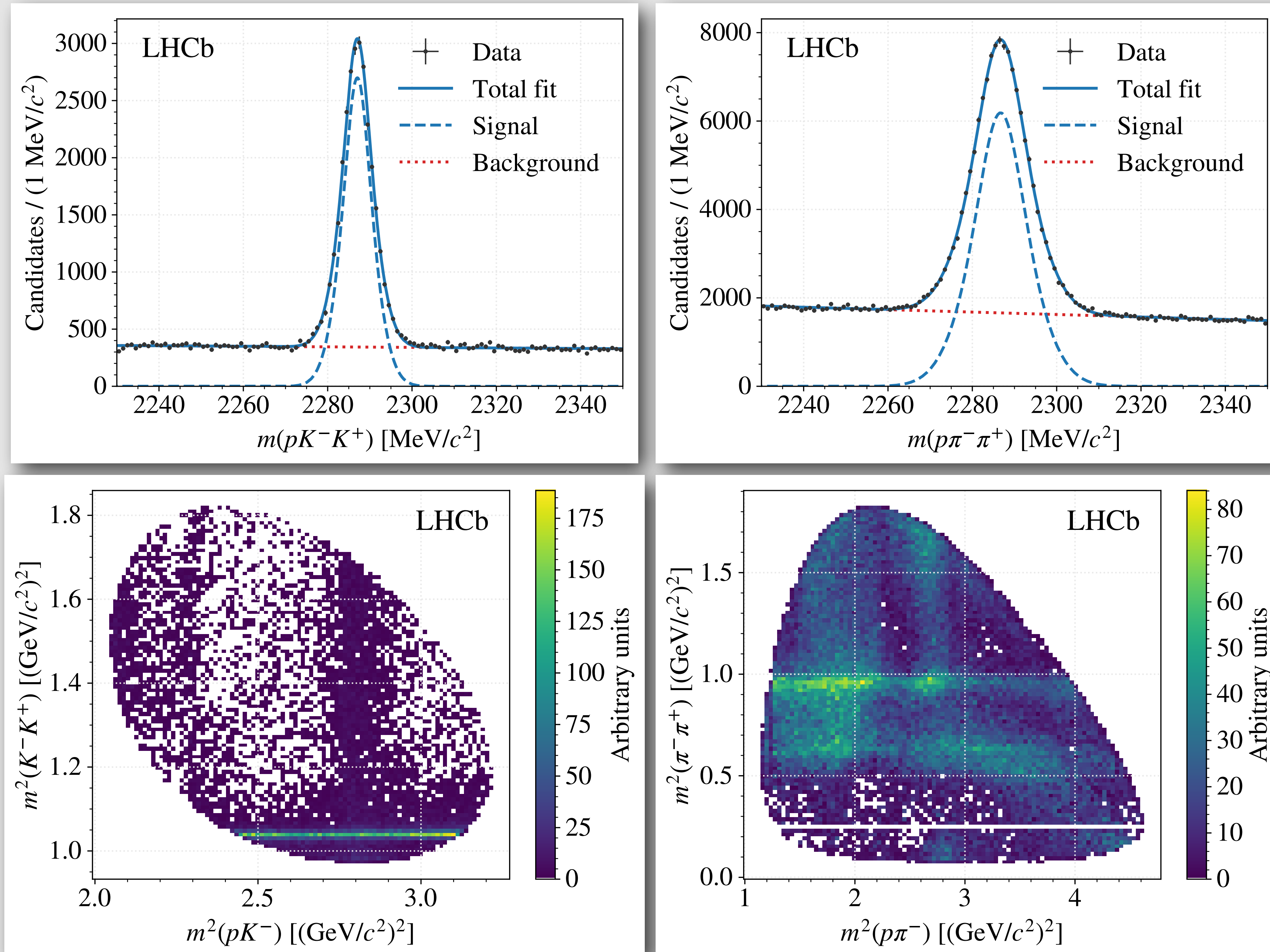


C.G.Wohl in PDG2014

$\Lambda_c \to phh$

Phys. Rev. D97 (2018) 091101

- 2011+12 data (3 fb^{-1})
- Measure difference in CP asymmetries
  - ➡ Cancel systematics
  - ➡ Apply reweighting to improve cancellation



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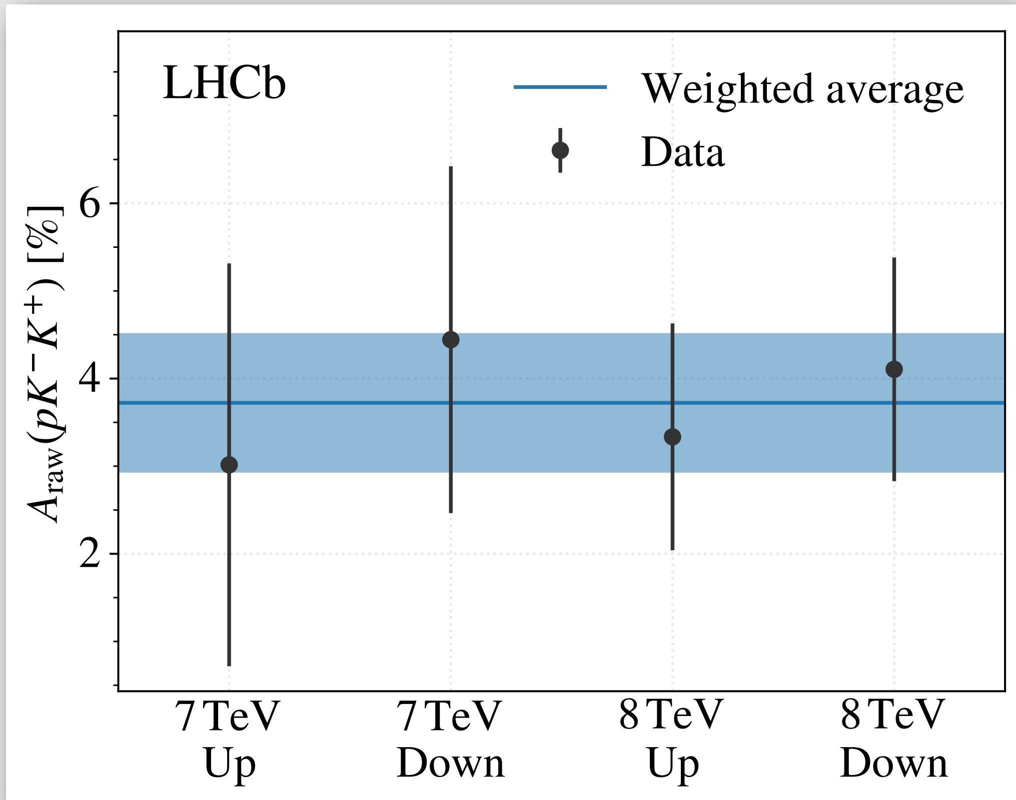
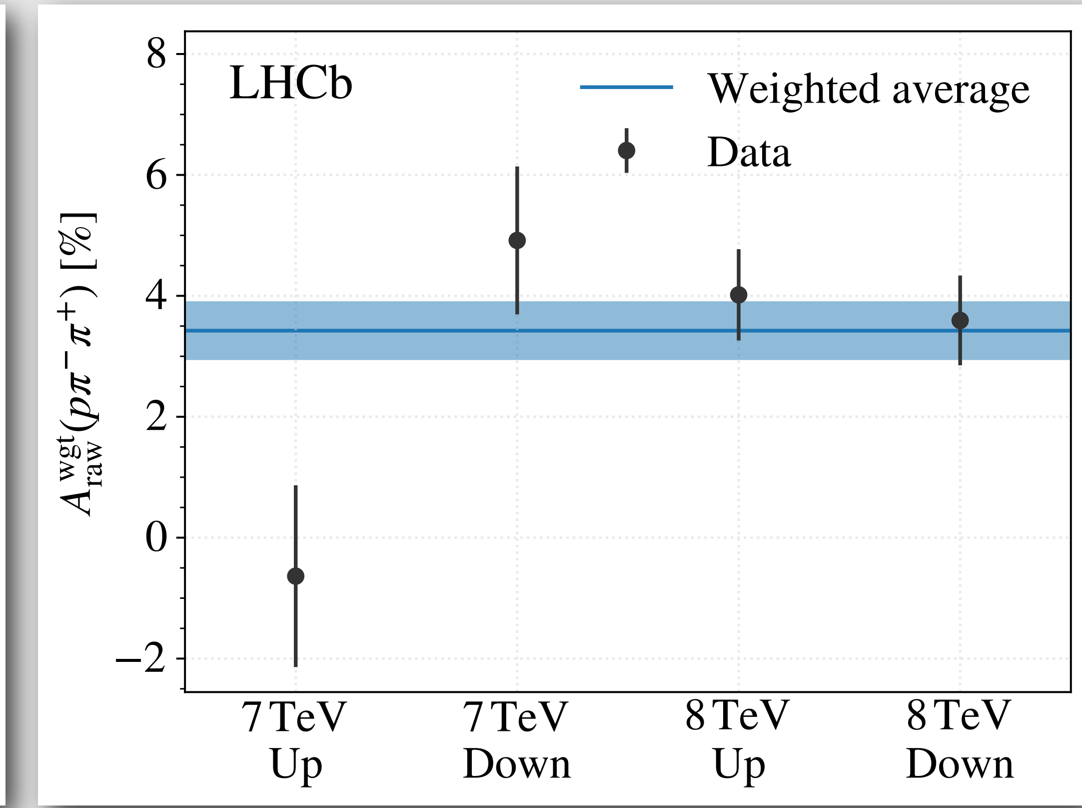
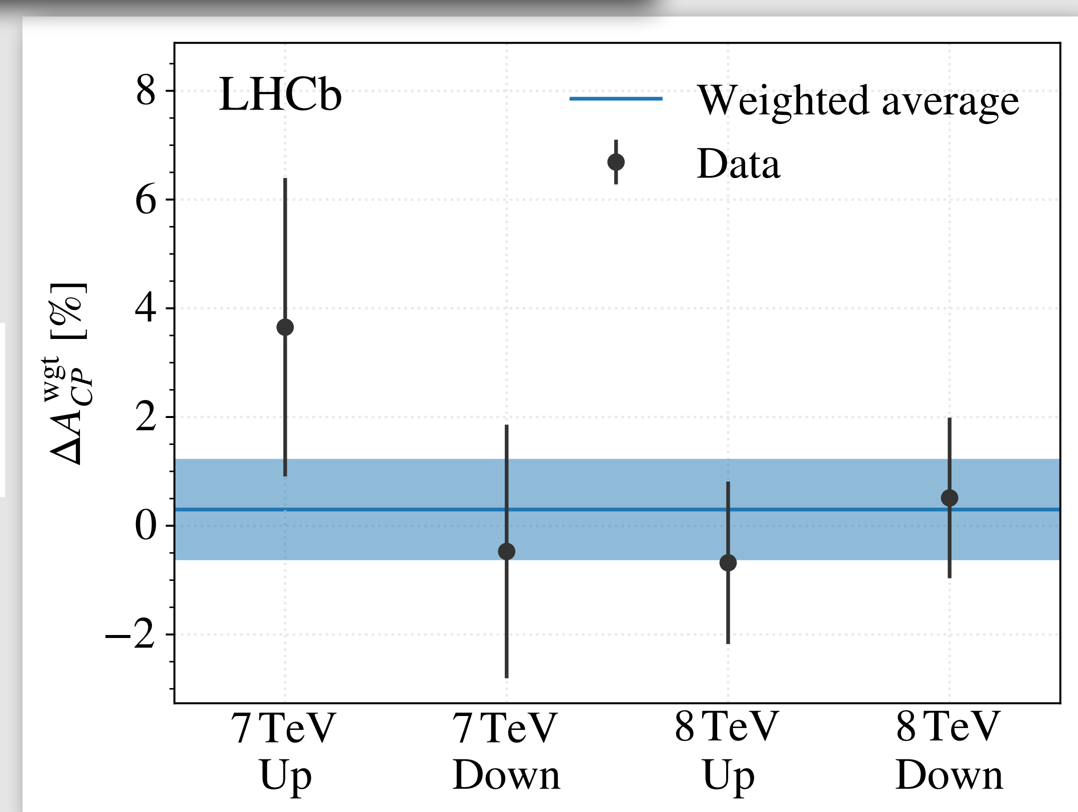
$\Lambda_c \to phh$ - II

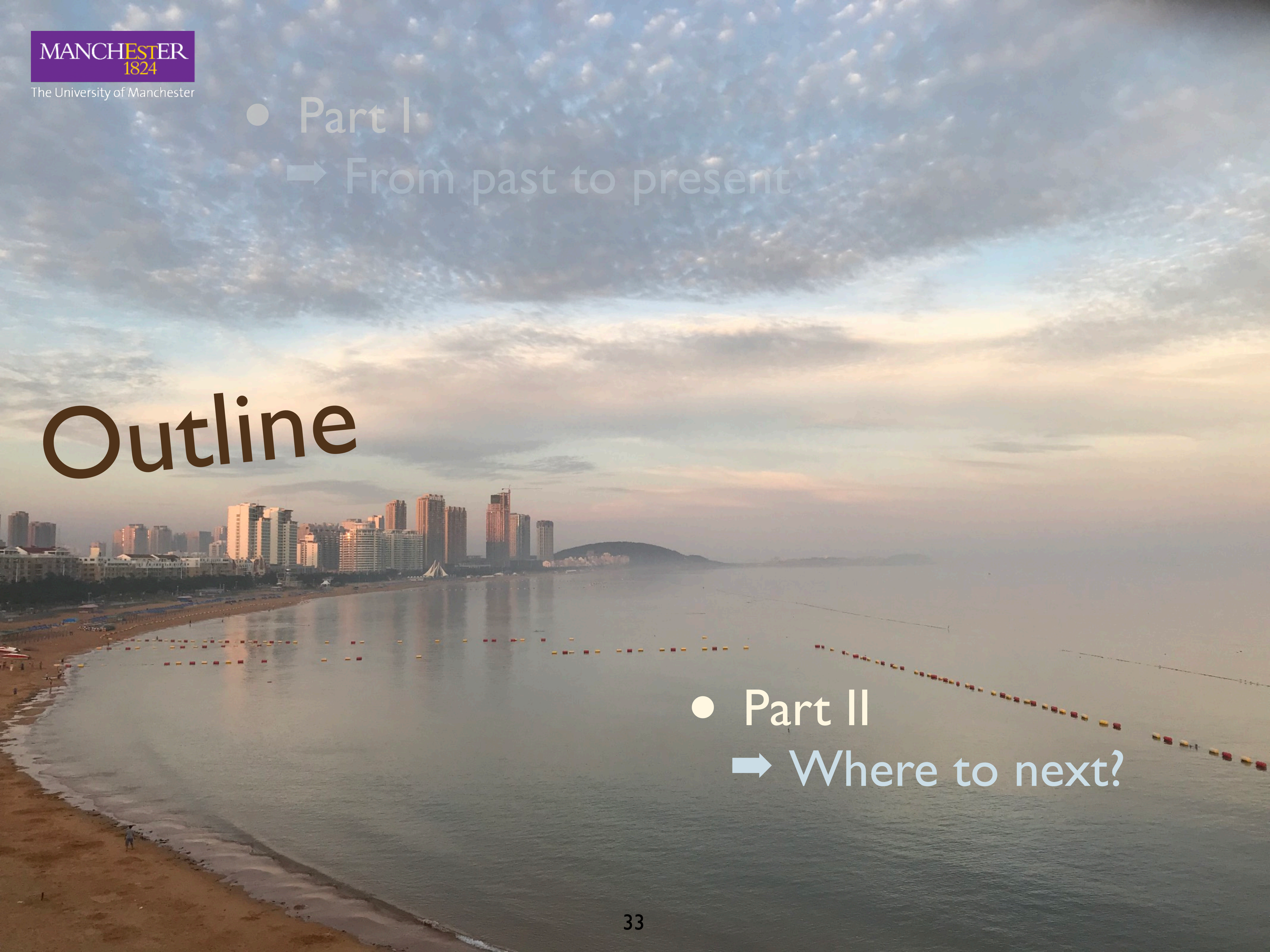
Phys. Rev. D97 (2018) 091101





$$\Delta A_{CP}^{\rm wgt} = A_{CP}(pK^-K^+) - A_{CP}^{\rm wgt}(p\pi^-\pi^+) = (0.30 \pm 0.91 \pm 0.61)\,\%,$$





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- Part I
  ➡ From past to present

Outline

- Part II
  ➡ 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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- The issue is how can we keep on checking

Who cares about bagels, it's lunch time!

Yuval Grossman, Experimental Summary, CHARM 2012

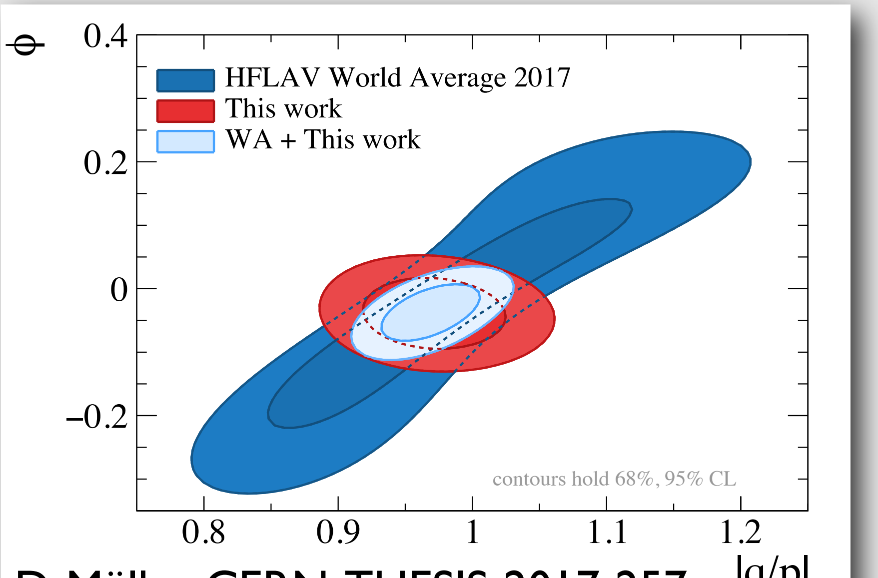
Multi-body decays

- 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

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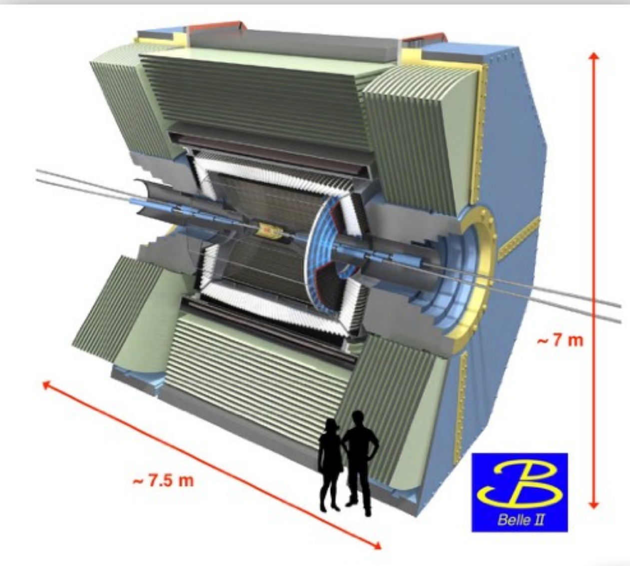
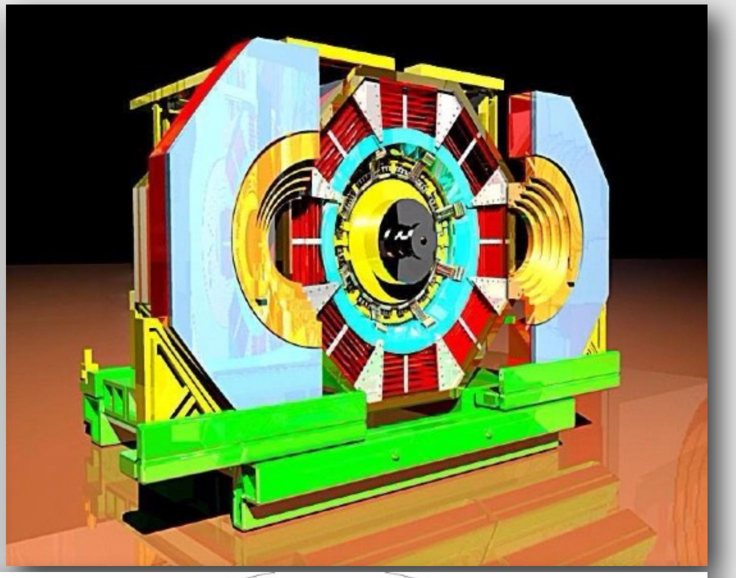
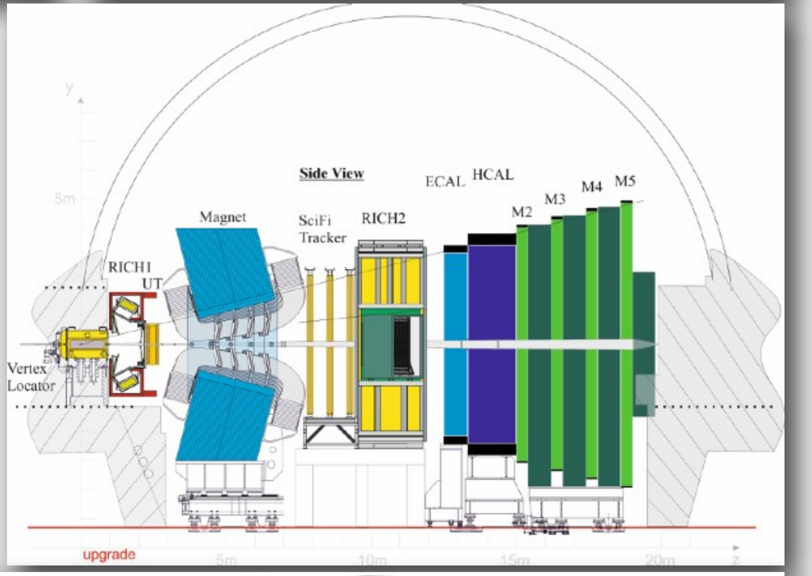
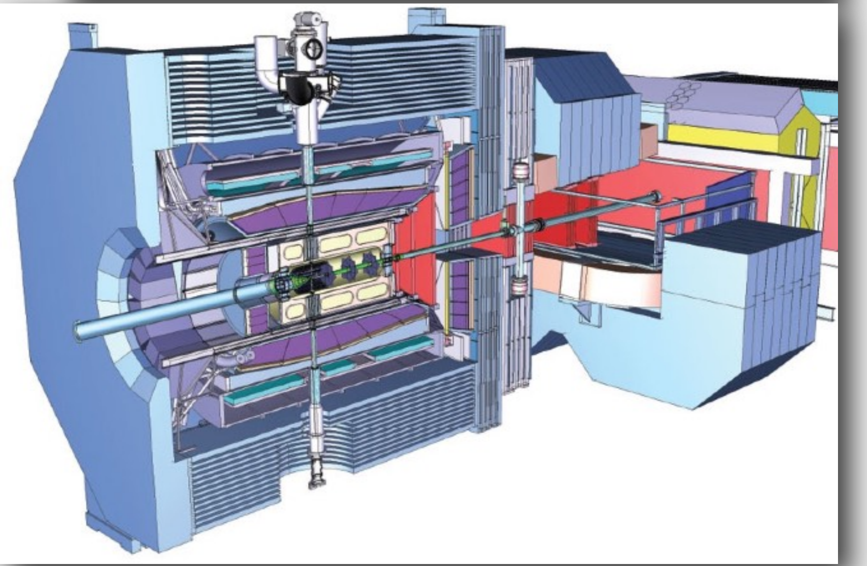
Which facilities?





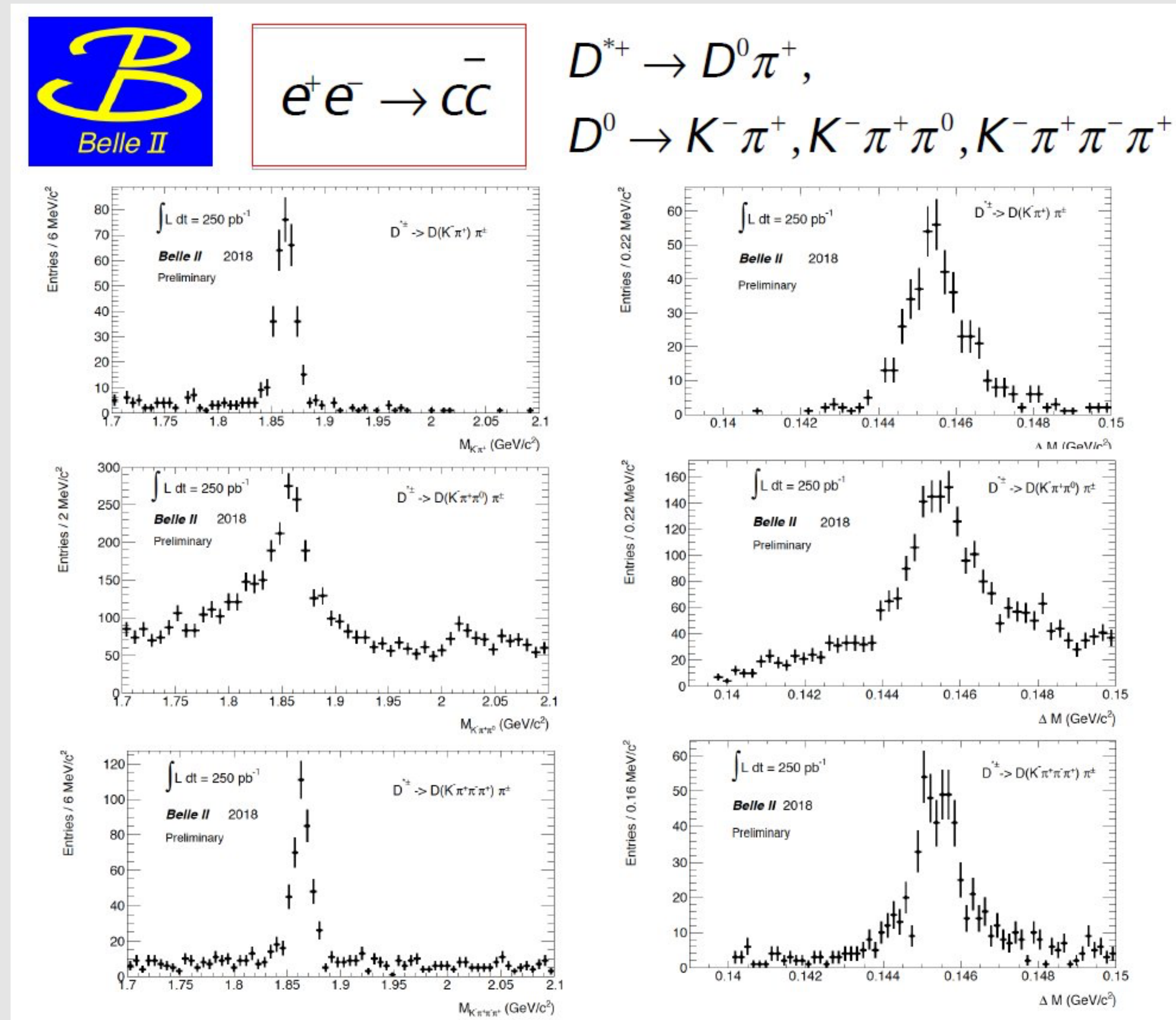




- Safe bets
  - ➡ Belle II, BESIII, LHCb upgrade, PANDA
  - ➡ Expect also contributions from ATLAS and CMS
- What else?
  - ➡ LHCb @ HL-LHC
  - ➡ Super CERN (whether in China or around Salève)
  - ➡ Linear Collider
  - ➡ Tau-charm

Belle II

- First charm signals seen at Belle II
- LHCb sensitivity on charged two-body decays not in reach
- Can exploit strengths with neutral final-state particles
- Multi-body decays may benefit from lower backgrounds

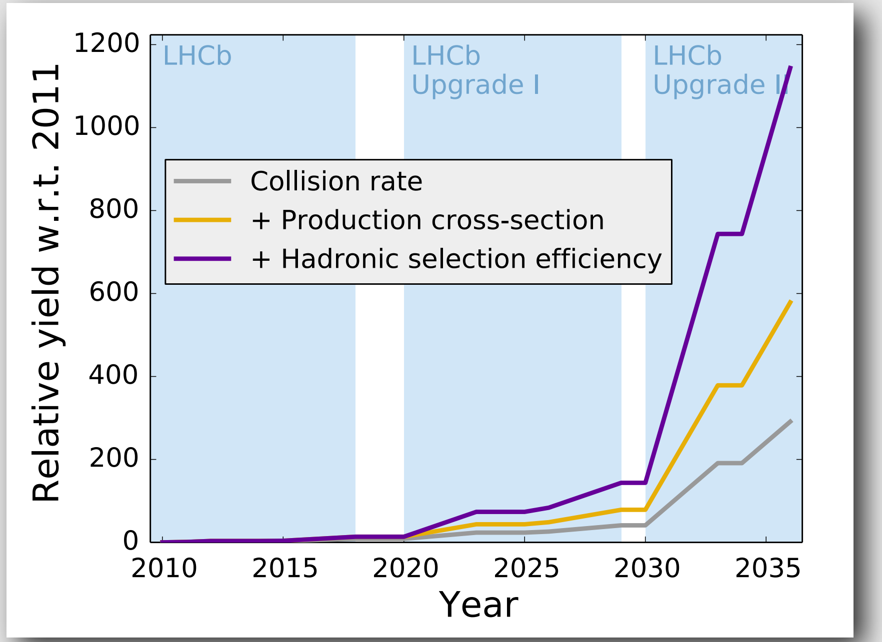


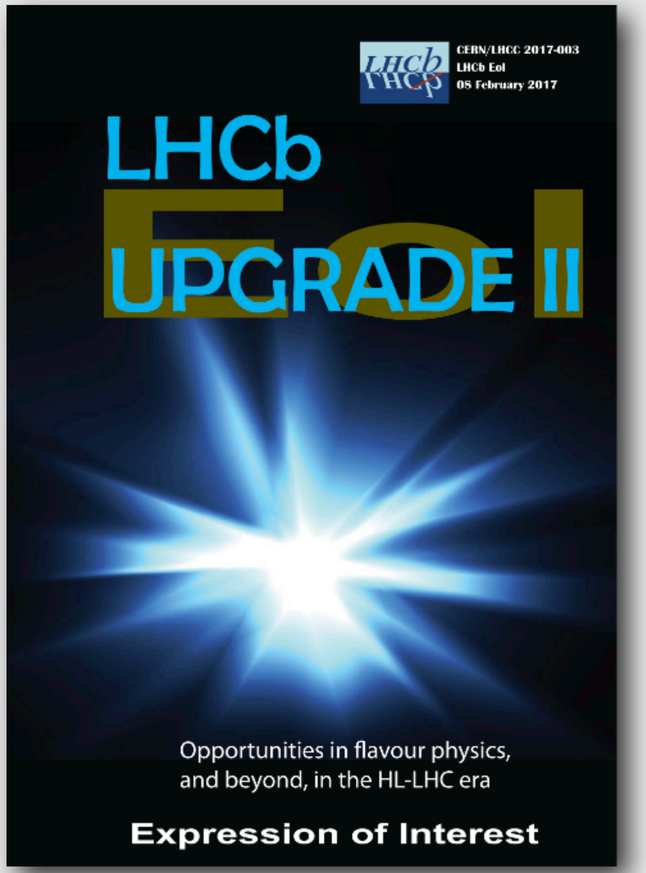
T. Browder at FPCP 2018

LHCb Upgrades

See talk by T. Szumlak

- LHCb Upgrade I in construction
- Will collect very high-rate real-time calibrated data
  - ➡ Huge potential for charm
- Need to dig a lot deeper to reach SM-level precision
  - ➡ LHCb Upgrade II
- LHCb is the best bet for charm for the foreseeable future
  - ➡ Best shot at BSM physics in the up-quark sector





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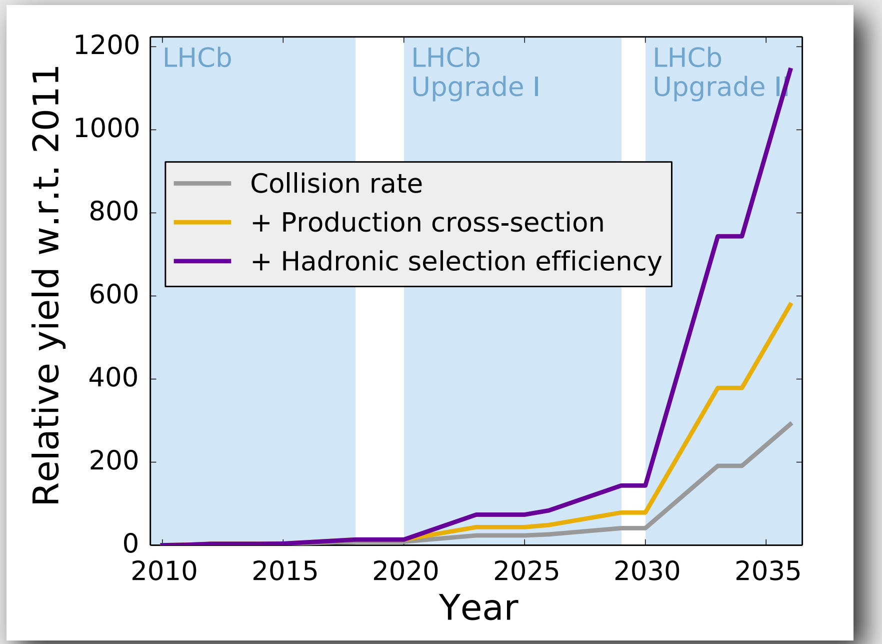
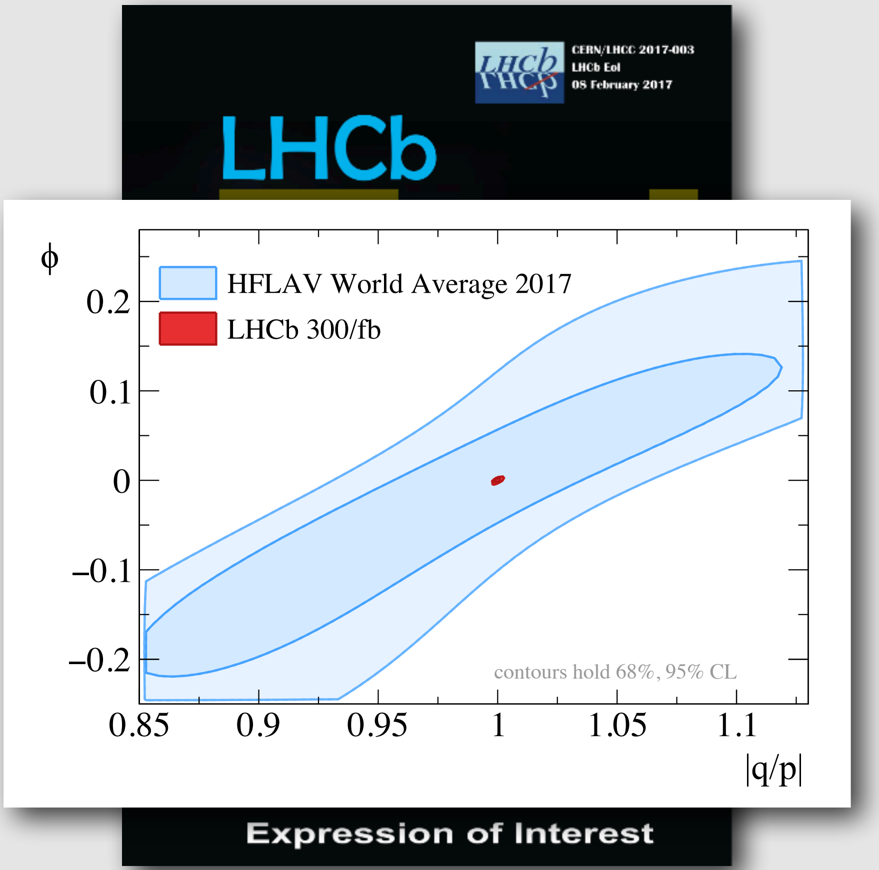
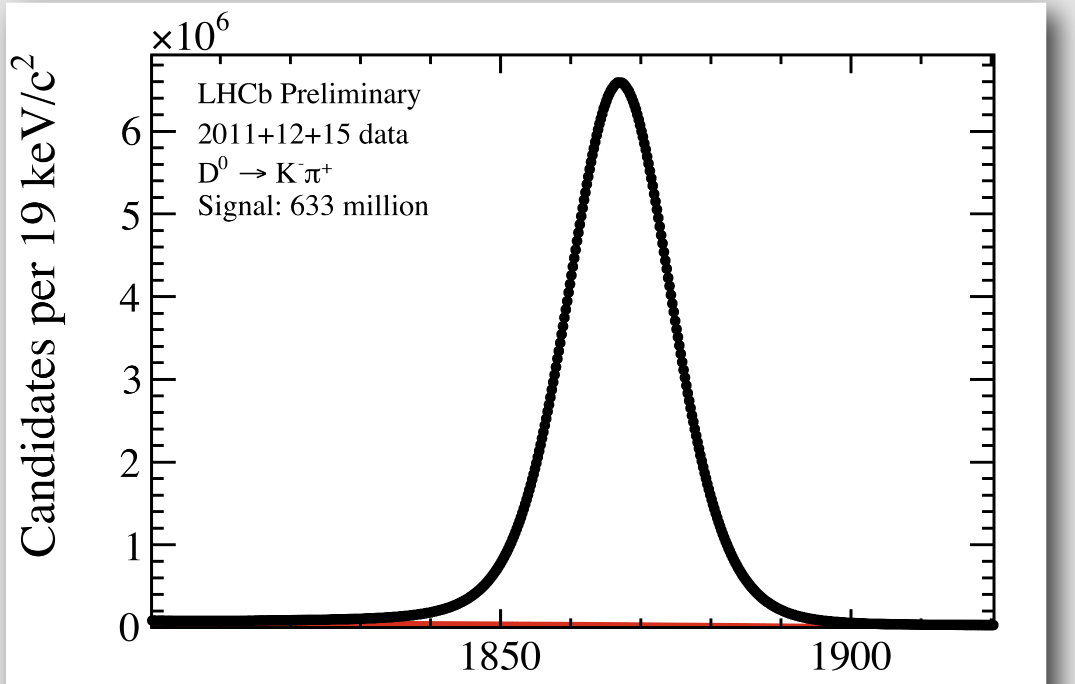




Charm the challenge champion

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



LHCb-CONF-2016-005

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

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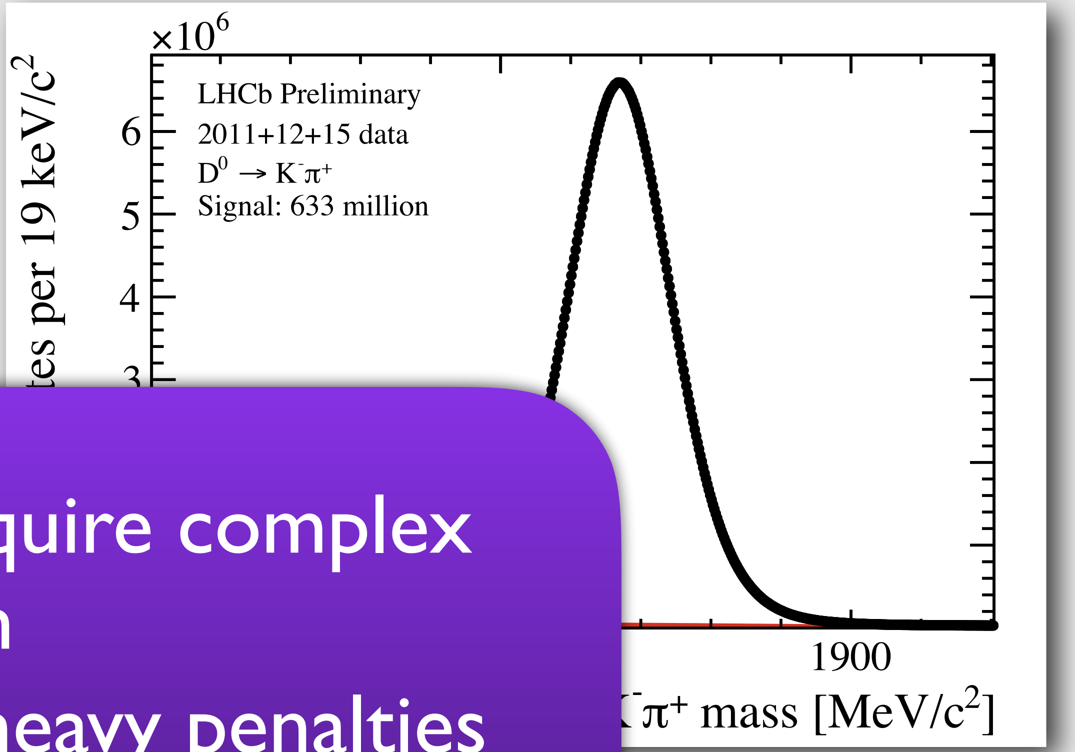
Charm the challenge champion

- 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

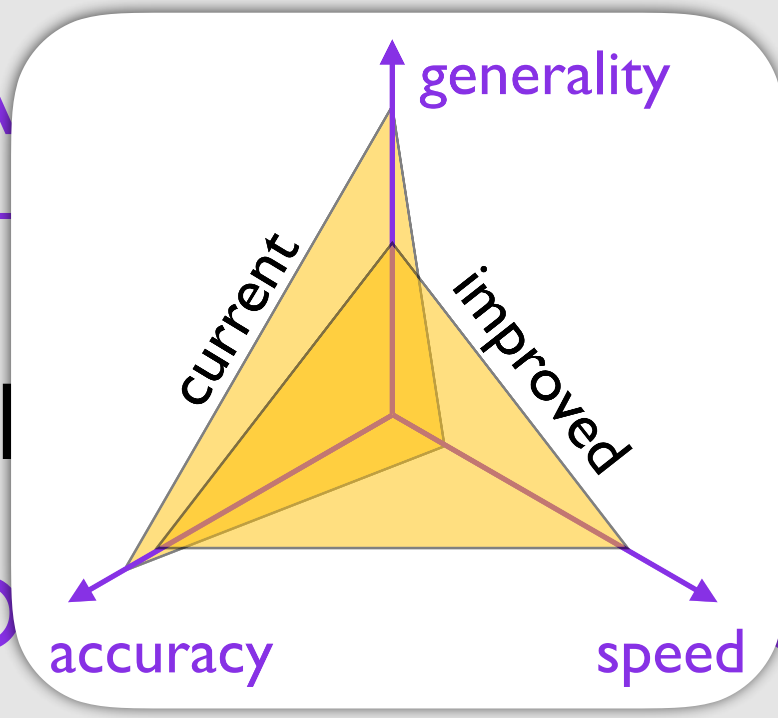
➡ Data selection/reconstruction/storage

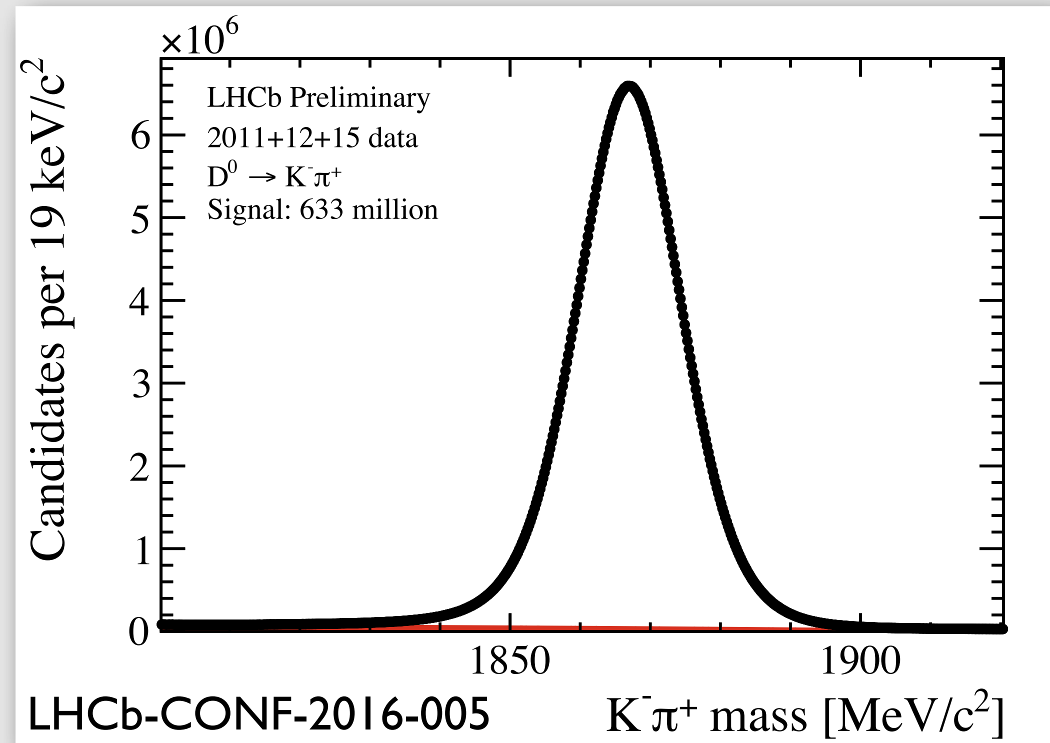
➡ Simulation

➡ Data analysis

Charm the challenge champion

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

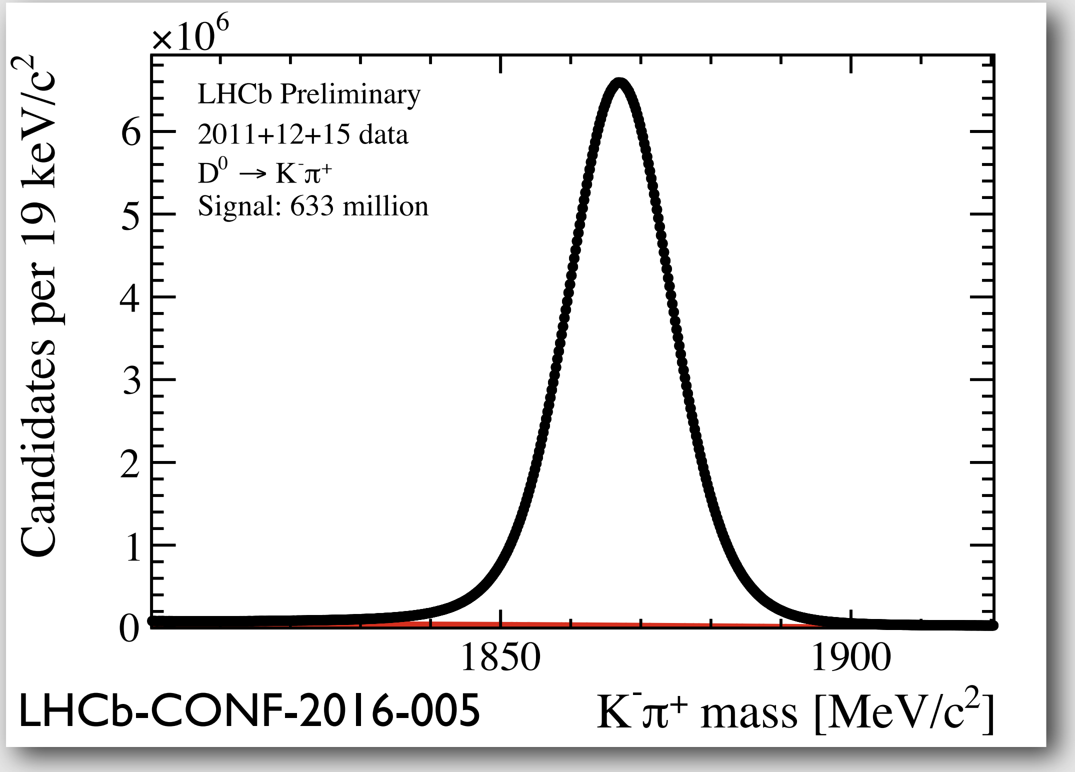




- Tec… therefore driven by charm
  - ➡ D… onstruction/storage
  - ➡ Simulation
  - ➡ Data analysis

Charm the challenge champion

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



- 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 $\bar{D}^0$ mesons oscillate, i.e. is $x\neq0$?
- 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