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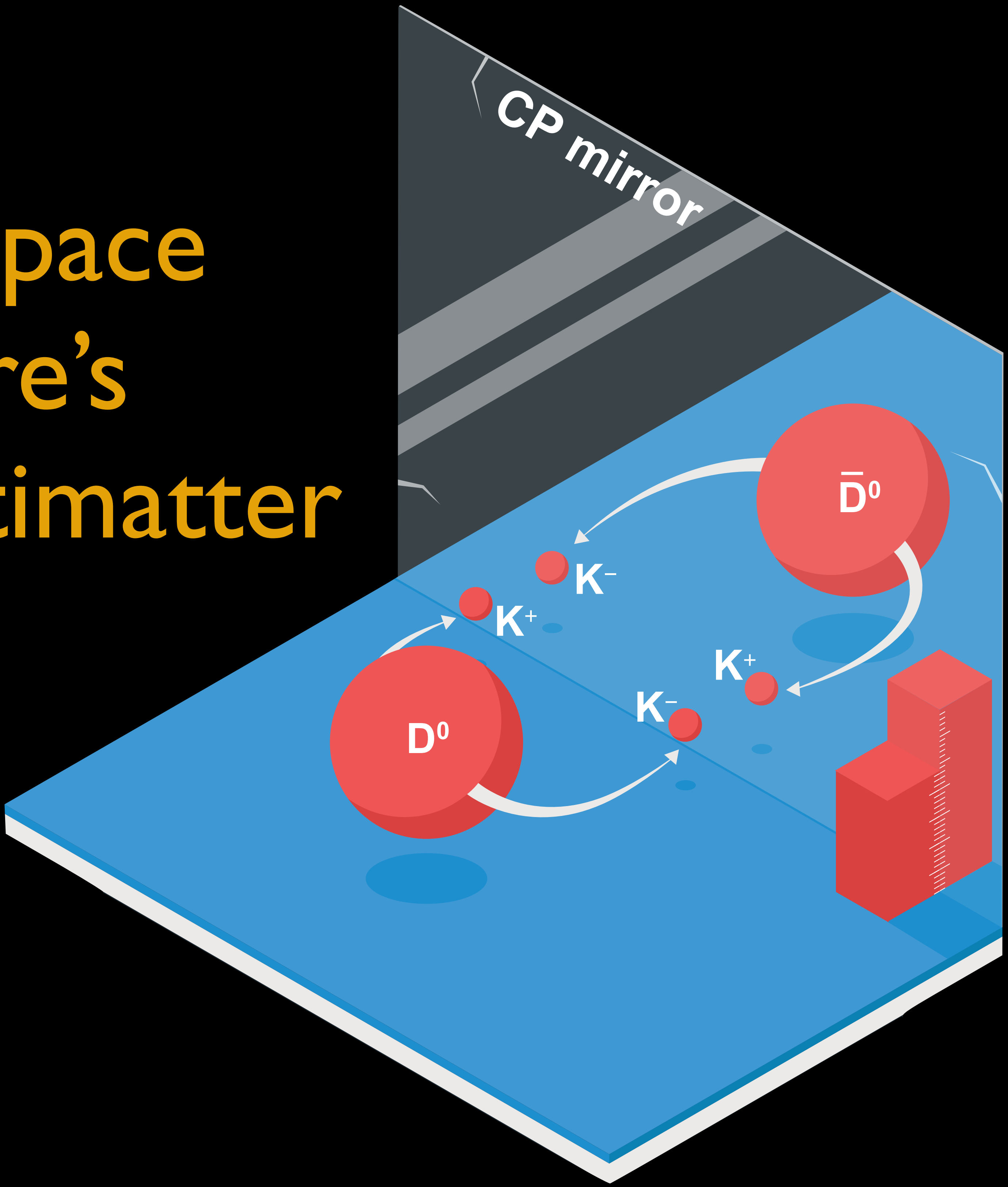
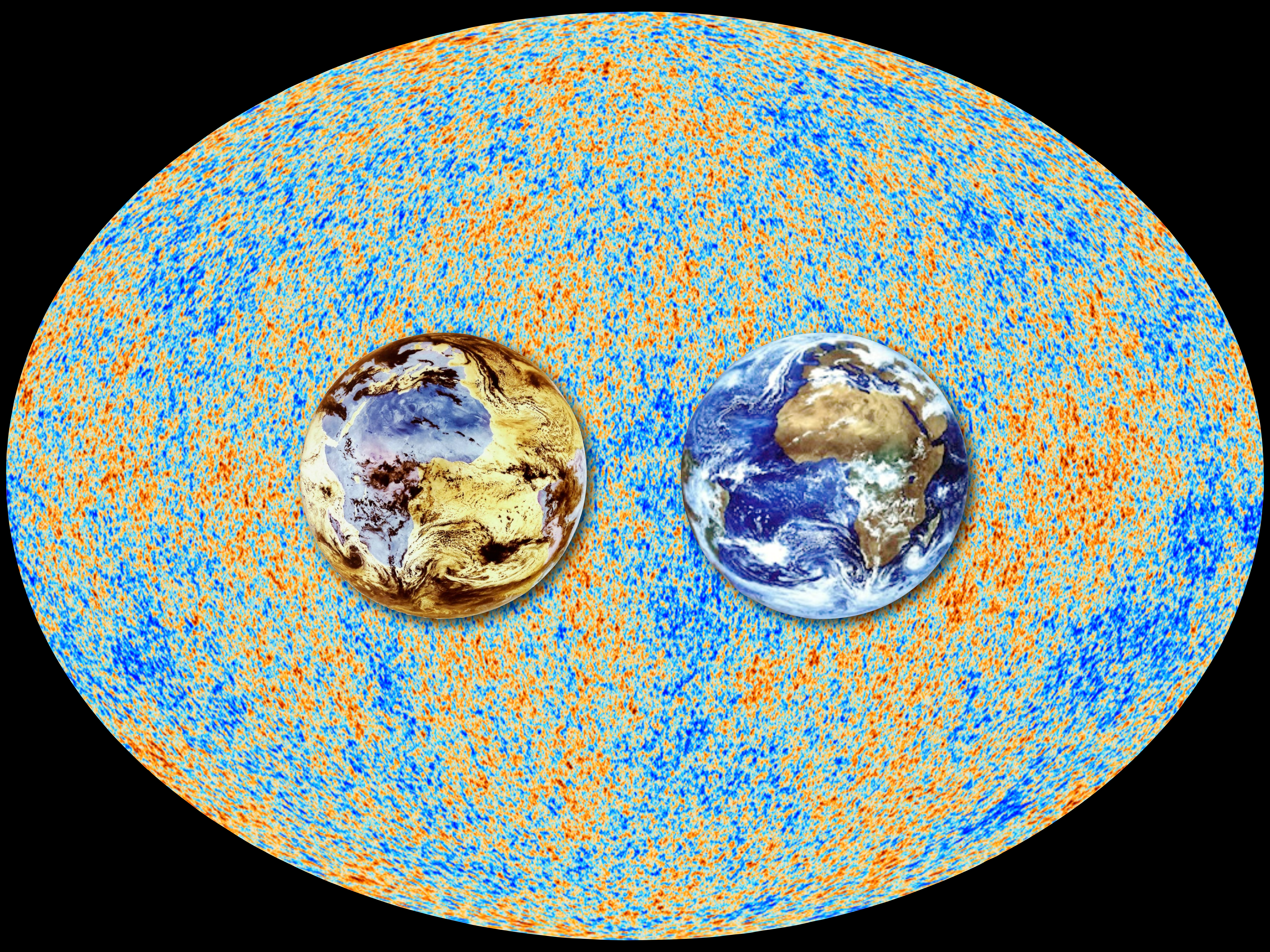
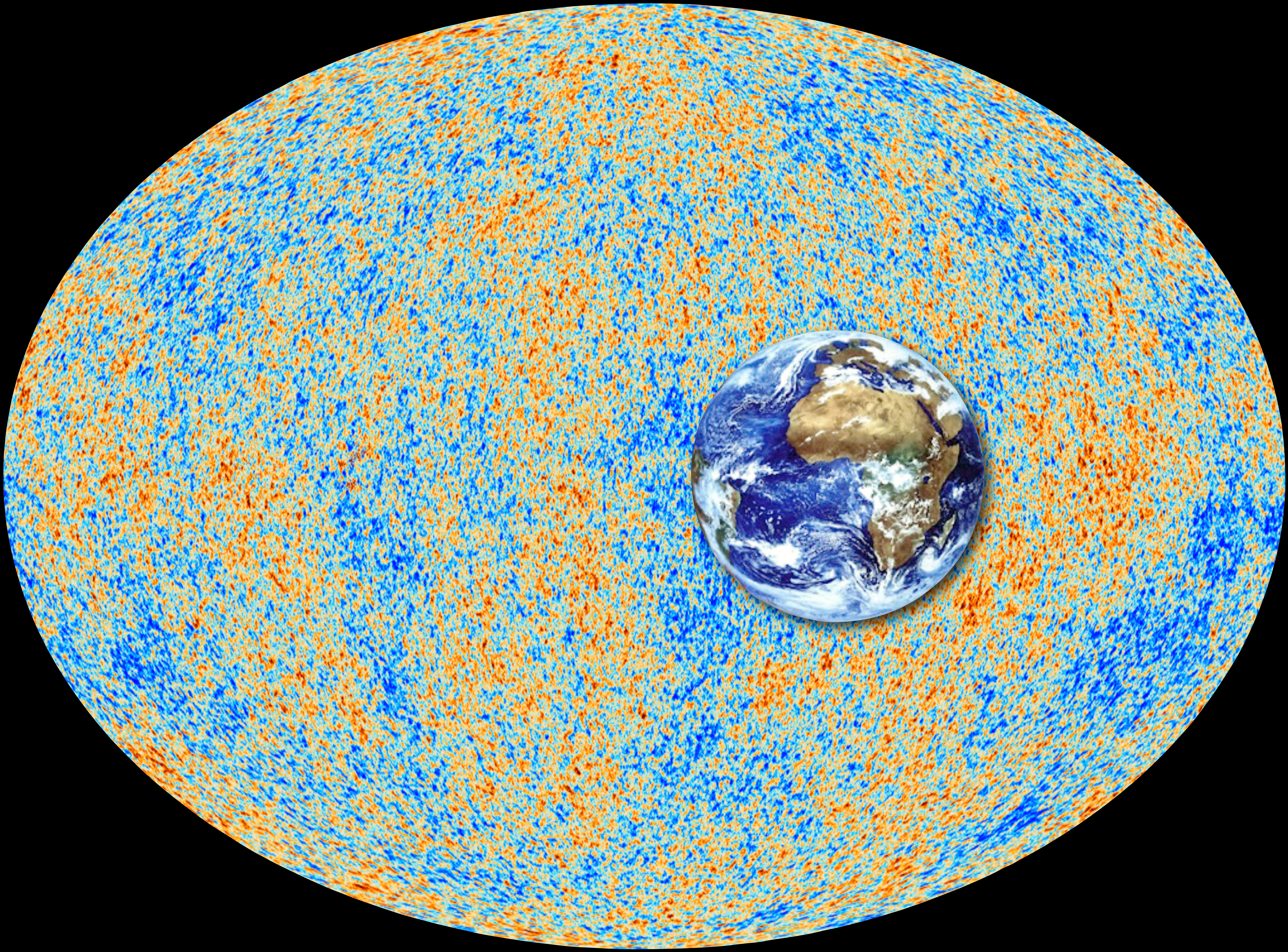
Ripples in Flavour Space — Unlocking Nature's Secrets with Antimatter

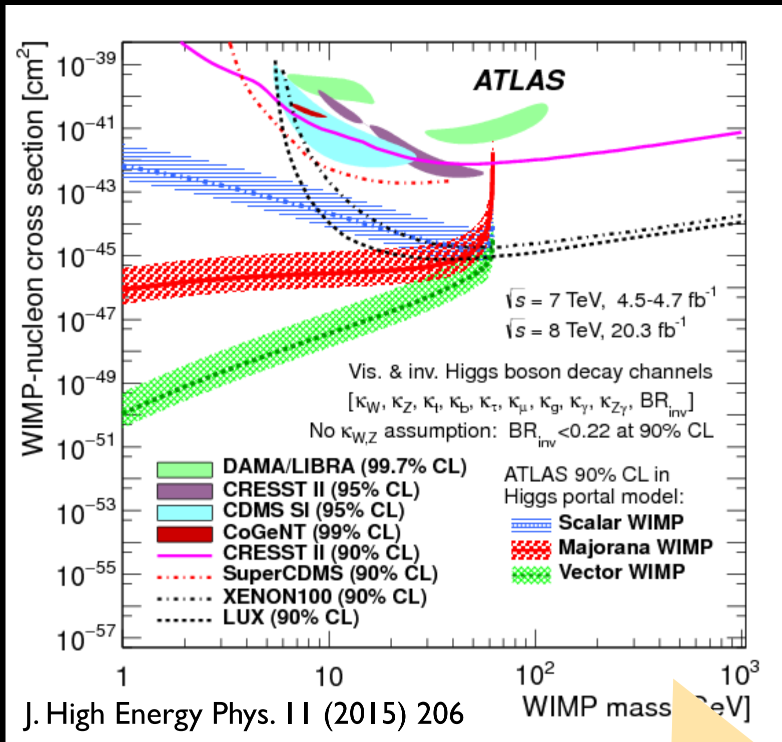


Marco Gersabeck (The University of Manchester)

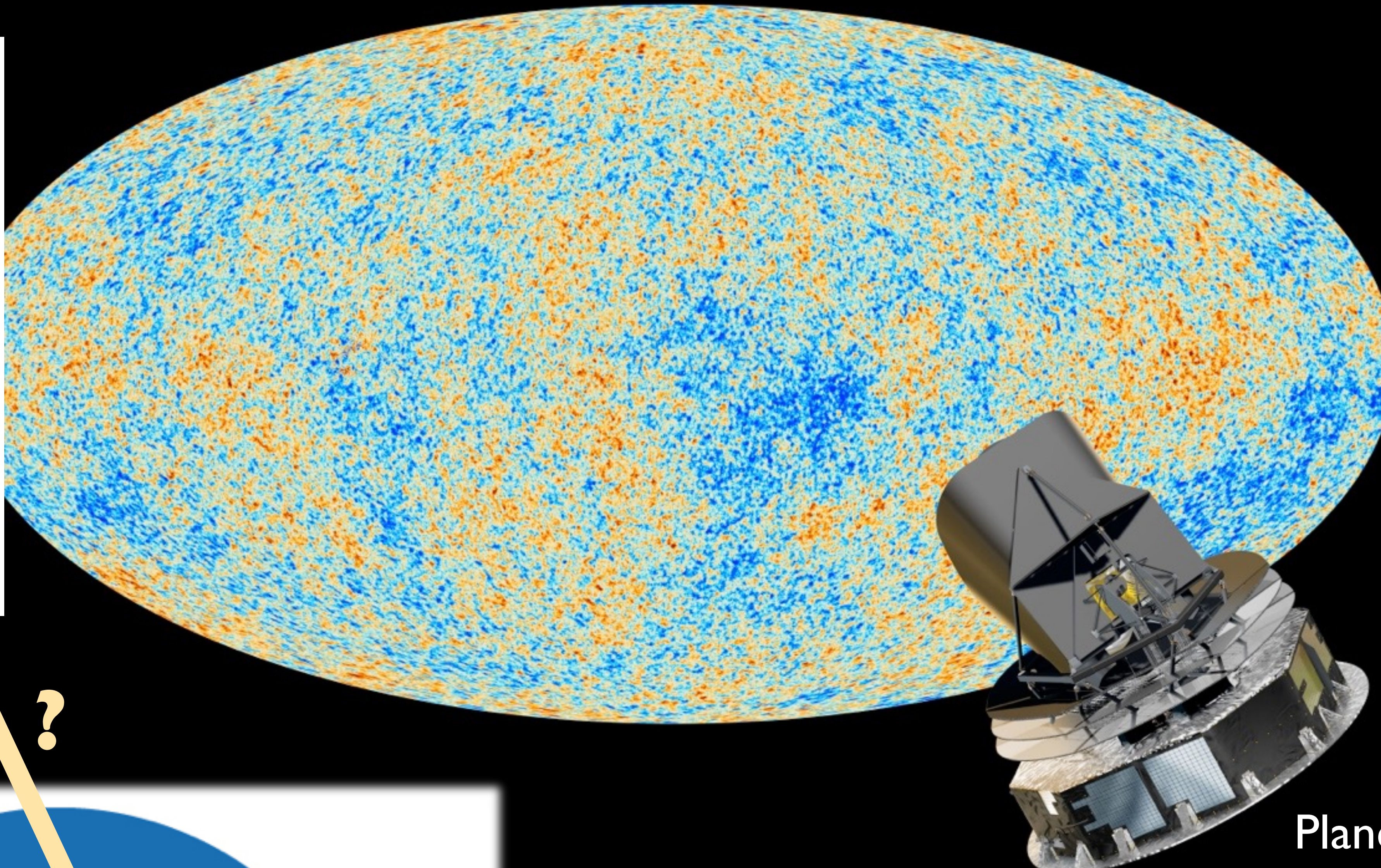
DESY Kolloquium, Hamburg, 2/7/2019



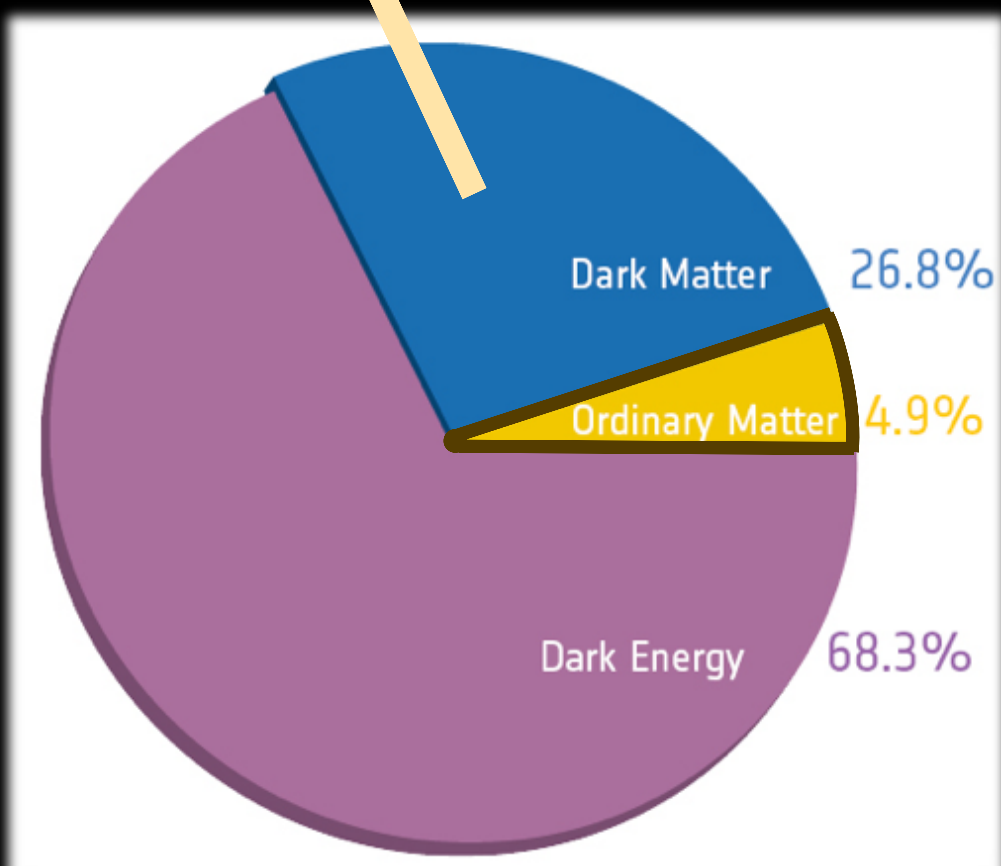



ATLAS
WIMP-nucleon cross section [cm²]
WIMP mass [GeV]
√s = 7 TeV, 4.5-4.7 fb⁻¹
√s = 8 TeV, 20.3 fb⁻¹
Vis. & inv. Higgs boson decay channels
No κW,Z assumption: BRinv<0.22 at 90% CL
DAMA/LIBRA (99.7% CL)
CRESST II (95% CL)
CDMS SI (95% CL)
CoGeNT (99% CL)
CRESST II (90% CL)
SuperCDMS (90% CL)
XENON100 (90% CL)
LUX (90% CL)
ATLAS 90% CL in Higgs portal model:
Scalar WIMP
Majorana WIMP
Vector WIMP
J. High Energy Phys. 11 (2015) 206

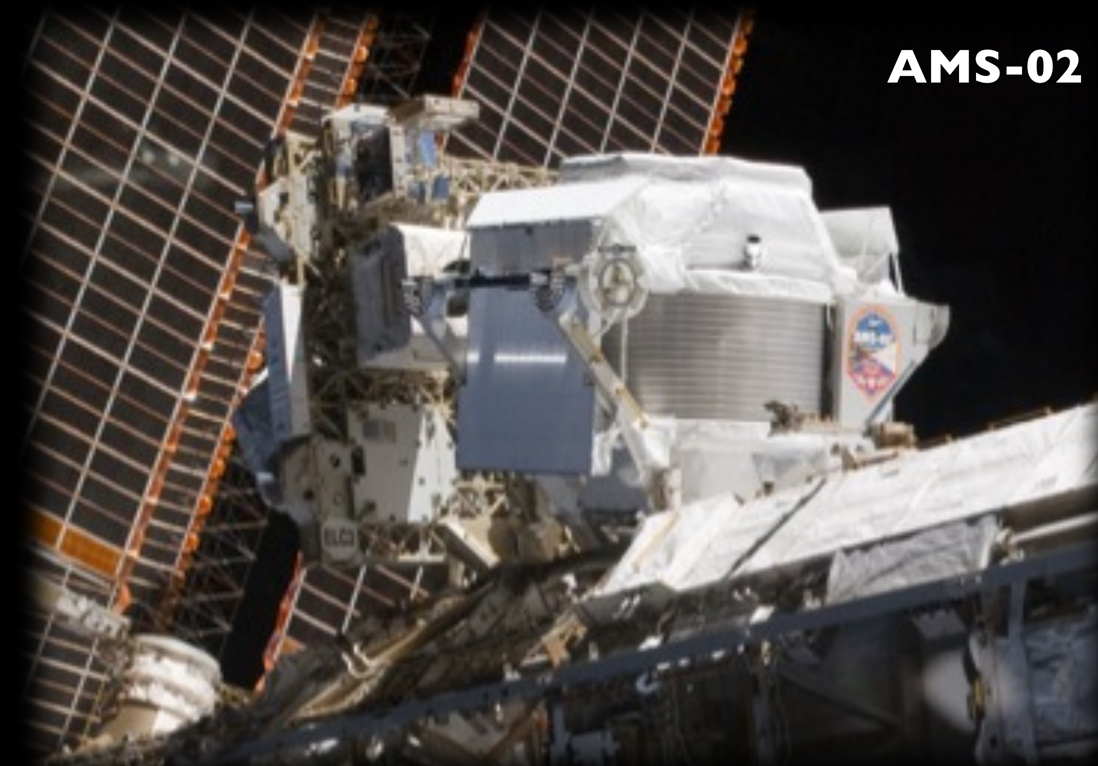
?



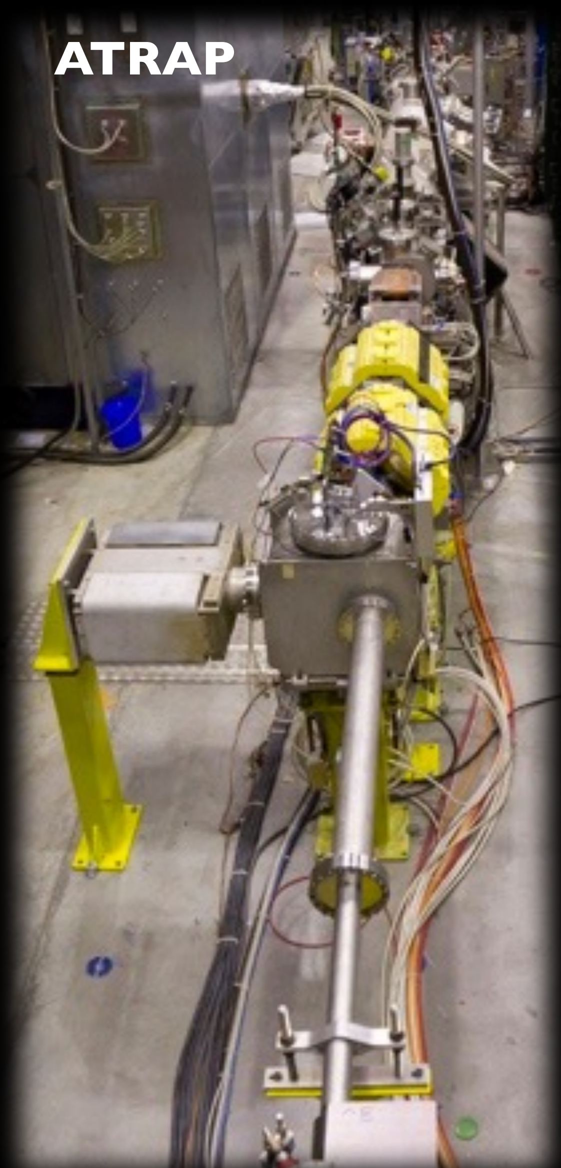
Planck


Dark Matter
26.8%
Ordinary Matter
4.9%
Dark Energy
68.3%

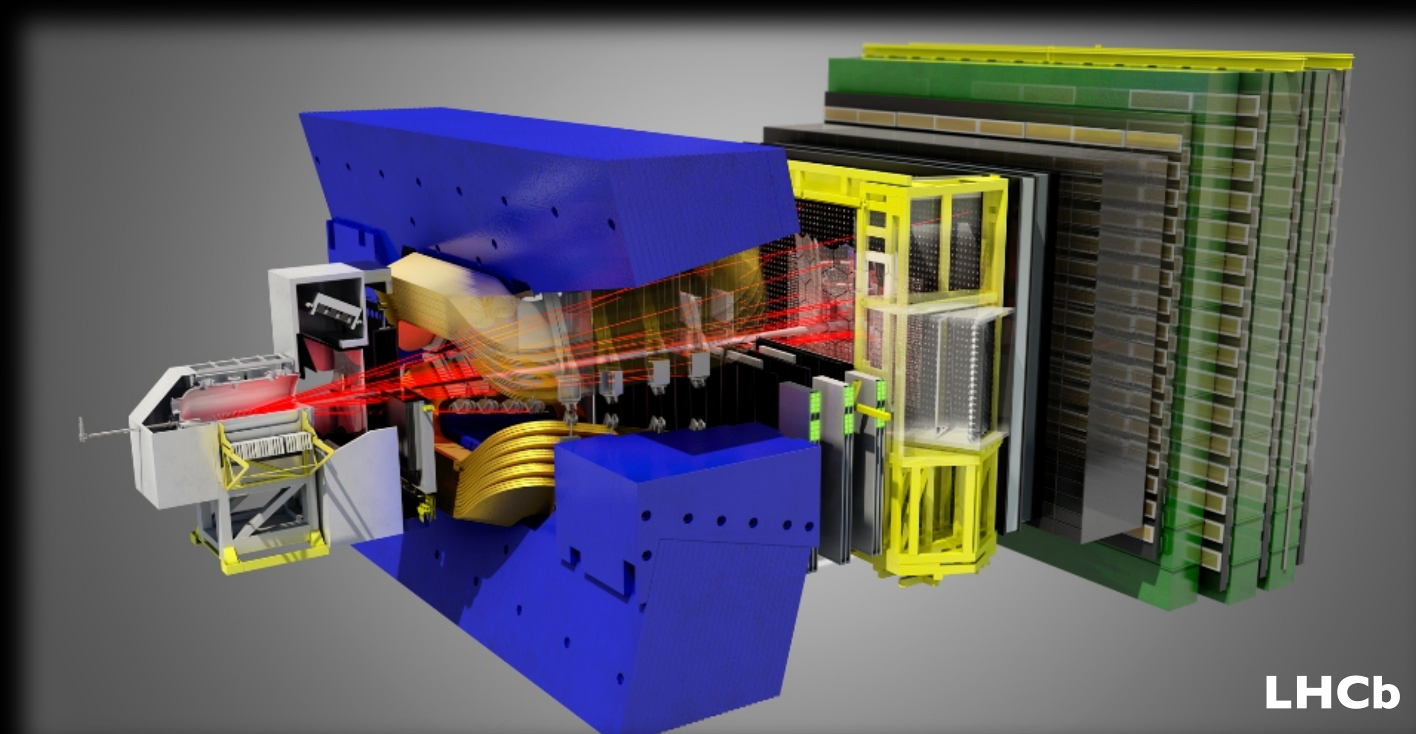
Understanding antimatter



Cosmic antimatter



Antimatter atoms



Antimatter elementary particles

Building blocks of matter

Quarks

	Up	Charm	Top
$+\frac{2}{3}e$			
$-\frac{1}{3}e$			
	Down	Strange	Bottom

Leptons

Electron	Muon	Tau	
			-1e
			0e
Electron-Neutrino	Muon-Neutrino	Tau-Neutrino	

Interactions and exchange particles

Electromagnetic

Photon

Strong

Gluon

Weak

$Z^0, W^\pm$ Bosons

Gravitation

Graviton???

Building blocks of matter

Quarks

	Up	Charm	Top
+⅔e			
-⅓e			
	Down	Strange	Bottom

Leptons

Electron	Muon	Tau	
			-1e
			0e
Electron-Neutrino	Muon-Neutrino	Tau-Neutrino	

Interactions and exchange particles

Electromagnetic

Photon

Strong

Gluon

Weak

$Z^0, W^\pm$ Bosons

Gravitation

Graviton???

Higgs

Antimatter

Identical mass

Opposite electrical charge

Matter-antimatter annihilation releases energy

$E=mc^2$

Bound matter

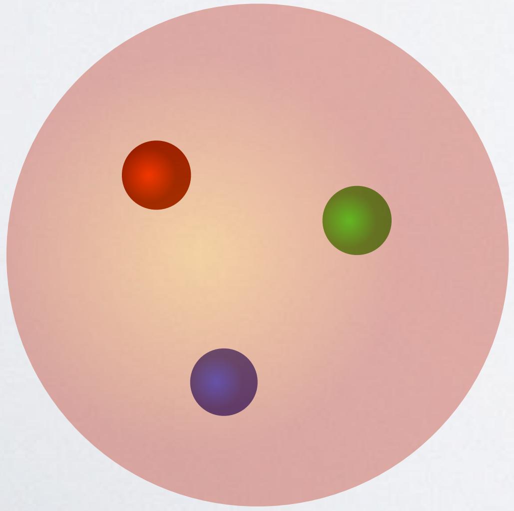
Baryons **3 Quarks**

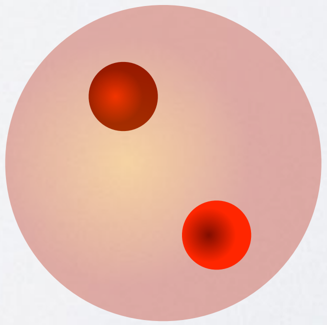
Proton: Up-Up-Down

Neutron: Up-Down-Down

Mesons **Quark-Antiquark pairs**

Pion: Up-Antiup, Up-Antidown, ...





Antimatter

Identical mass

Opposite electrical charge

Matter-antimatter annihilation releases energy

$E=mc^2$

Bound matter

Baryons 3 Quarks

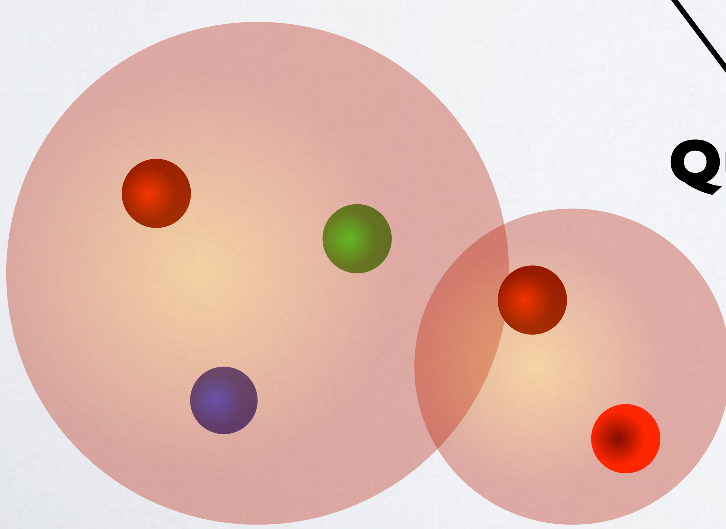
Proton: Up-Up-Down

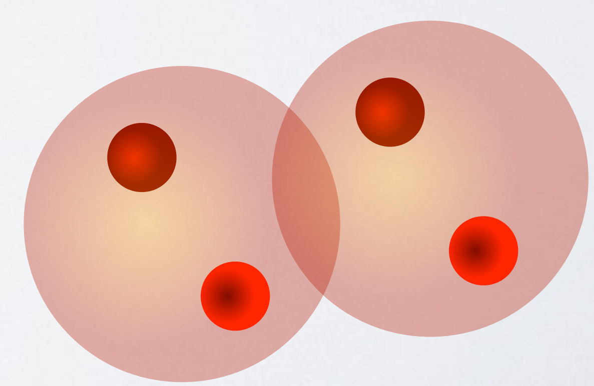
Neutron: Up-Down-Down

Mesons Quark-Antiquark pairs

Pion: Up-Antiup, Up-Antidown, ...

plus additional
Quark-Antiquark pairs





Not enough

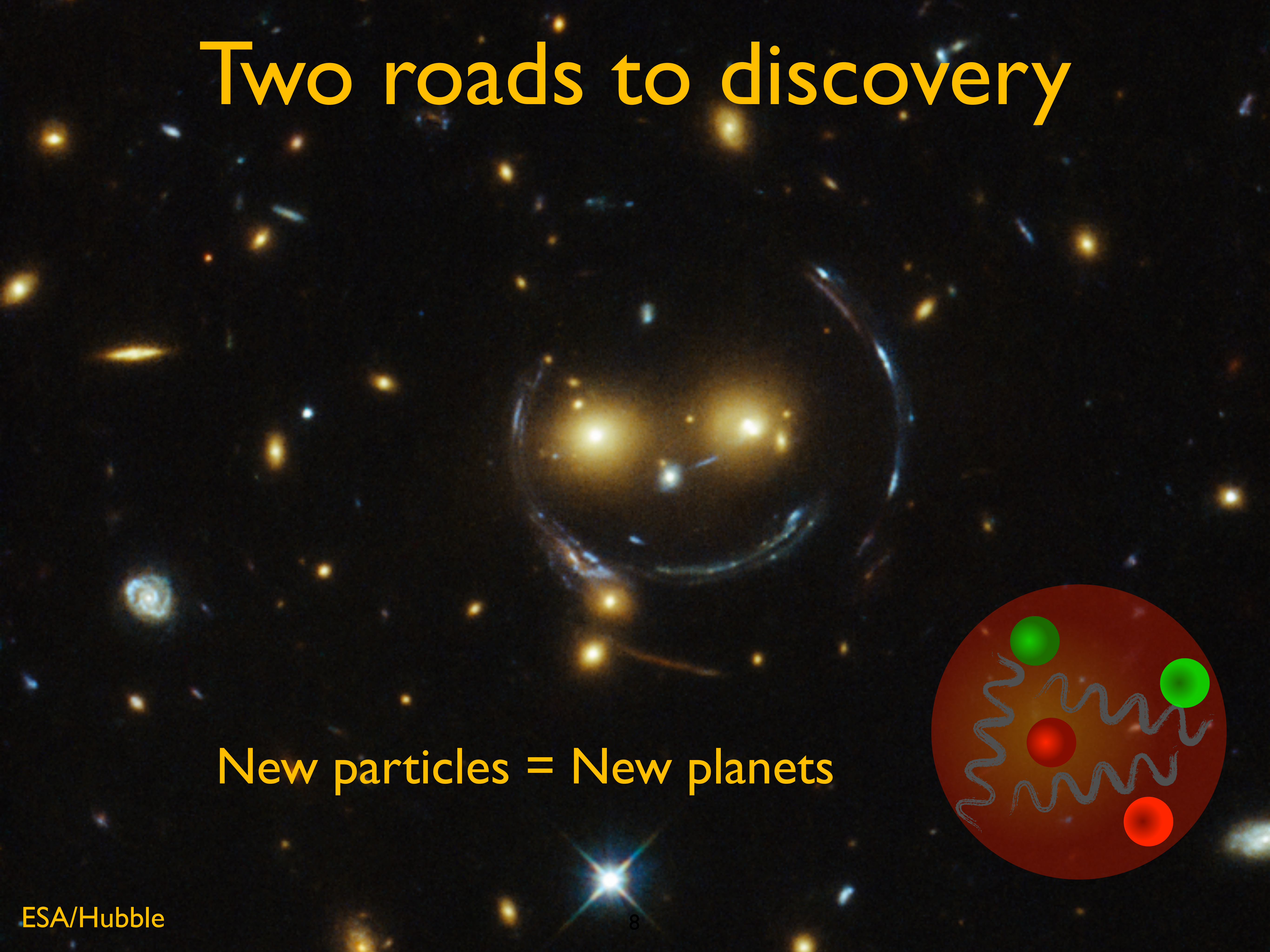
- What happened to all the antimatter?
- What is the nature of dark matter?
- Is there a reason for the mass hierarchy?

Not enough

- What happened to all the antimatter?
- What is the nature of dark matter?
- Is there a reason for the mass hierarchy?

- Answer
  - ➡ There must be more
  - ➡ Main quest:
    - Identify new particles

Two roads to discovery



New particles = New planets

ESA/Hubble

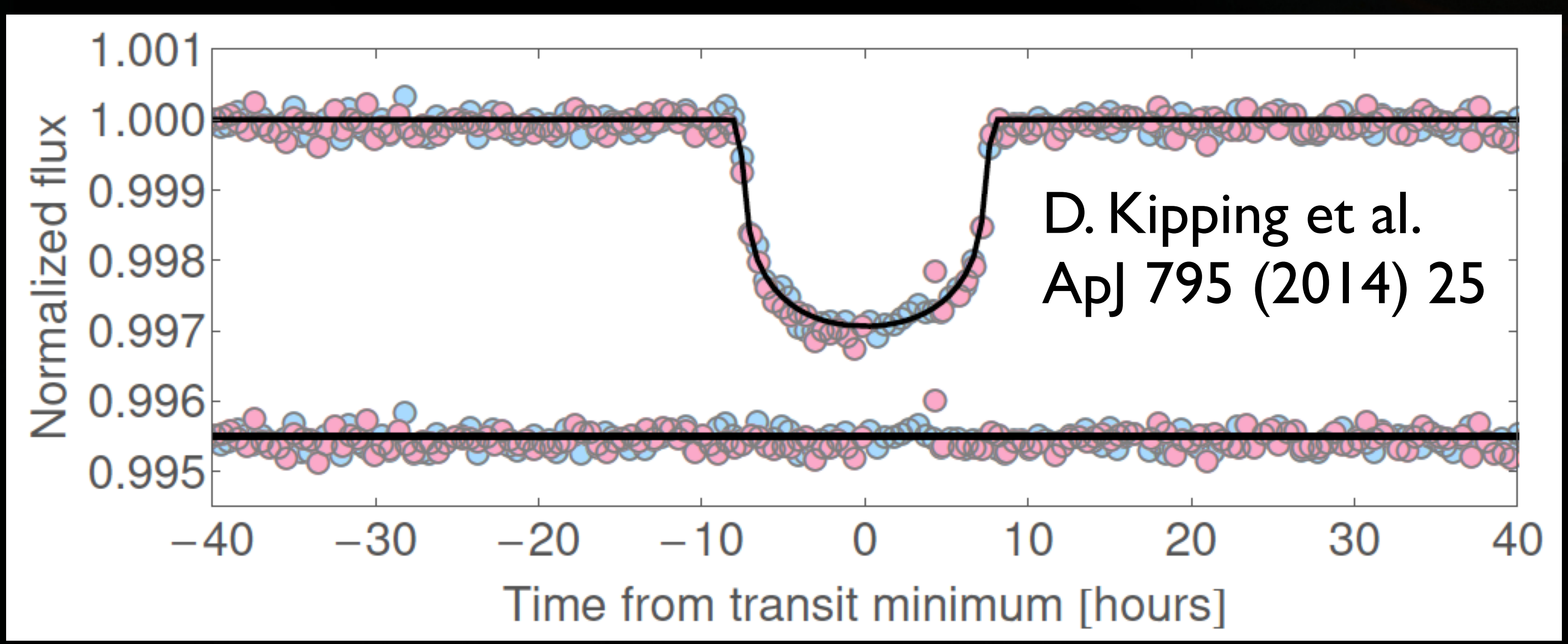
Direct searches

Reach limited by amount of fuel

NASA/JHUAPL/SwRI/Thomas Appéré

Indirect searches

Look for subtle deviations
in known processes



David A. Aguilar (CfA)

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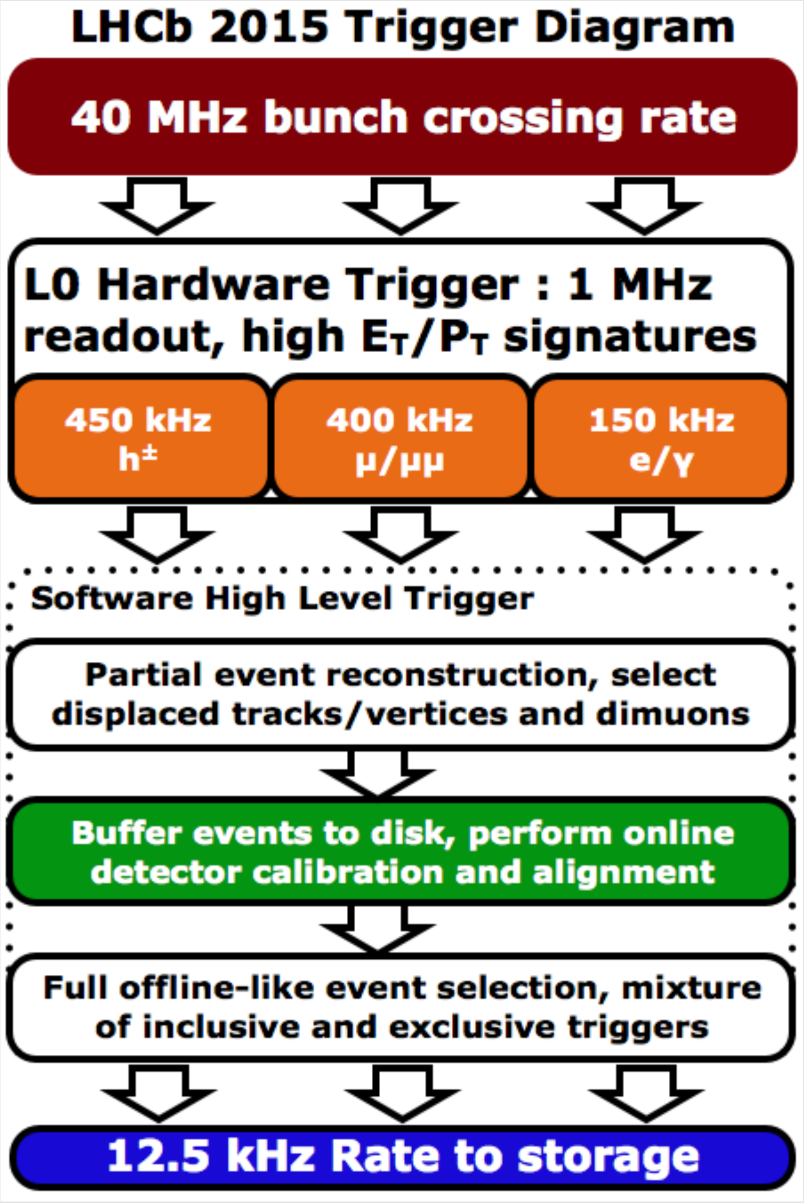
Precision physics

- How to achieve precision particle physics measurements?
  - ➡ Repeat many times
    - e.g. measure many particle decays of the same type
- Two uncertainties
  - ➡ Statistical
    - Generally scales with $1/\sqrt{N}$
  - ➡ Systematic
    - Depends on external sources:
      Limitations of methodology and tools
    - A priori independent on N
- How to achieve per-mille level precision?

Triggering is key



- Select 1 in ~3000 collisions to keep
  - ➡ Other data are lost: choose carefully
- Still over 60×10^9 events per year
  - ➡ Several Petabytes in storage
  - ➡ Fully online calibrated data
  - ➡ Processing on the world-wide grid
  - ➡ Need similar amount of simulated data

Indirect searches

- Two routes to success
  - ➡ Rare processes
    - Rare and forbidden decays
    - Small asymmetries
  - ➡ High-precision measurements of well-known processes
    - Large asymmetries
    - Symmetry tests: e.g. lepton universality
- New particles can contribute in quantum loops

Small new effects can cause large relative changes

Small new effects can cause large changes w.r.t. precision of prediction

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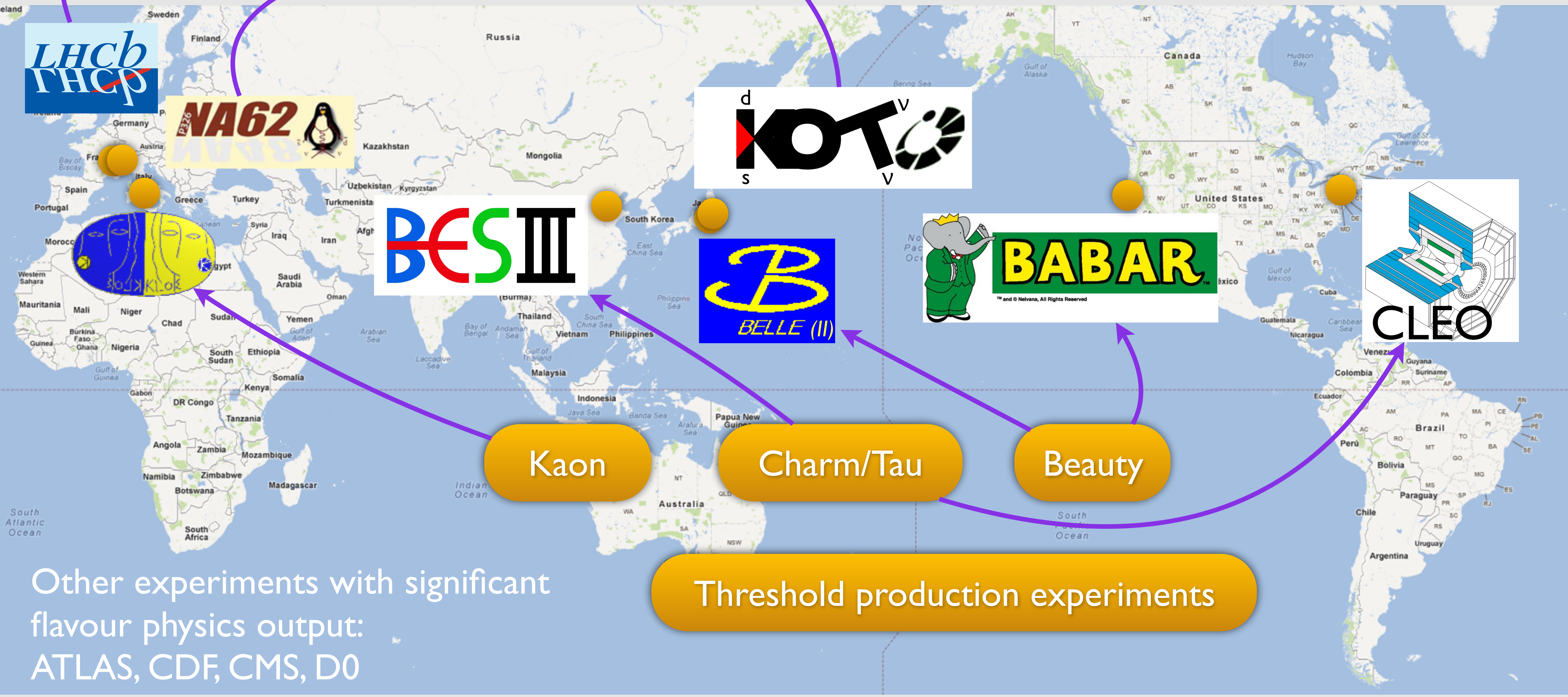
Flavourful experiments

High-energy proton-proton collisions
→ General purpose flavour experiment

Fixed target rare kaon decay experiments



Kaon

Charm/Tau

Beauty

Threshold production experiments

Other experiments with significant flavour physics output:
ATLAS, CDF, CMS, D0

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Outline

- Matter-antimatter asymmetries
  - ➡ The bigger picture

C H A R M

1. Production
   - ➡ The source of precision
2. Mixing
   - ➡ The need for precision
3. CP violation
   - ➡ Uncover the mysteries of the up-quark sector
4. Multi-body decays
   - ➡ Interference reveals the details

- Future directions
  - ➡ Upgrade programmes

Enter antimatter

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LETTERS TO THE EDITOR

[*The Editor does not hold himself responsible for opinions expressed by his correspondents. Neither can he undertake to return, or to correspond with the writers of, rejected manuscripts intended for this or any other part of* NATURE. *No notice is taken of anonymous communications.*]

Potential Matter.—A Holiday Dream.

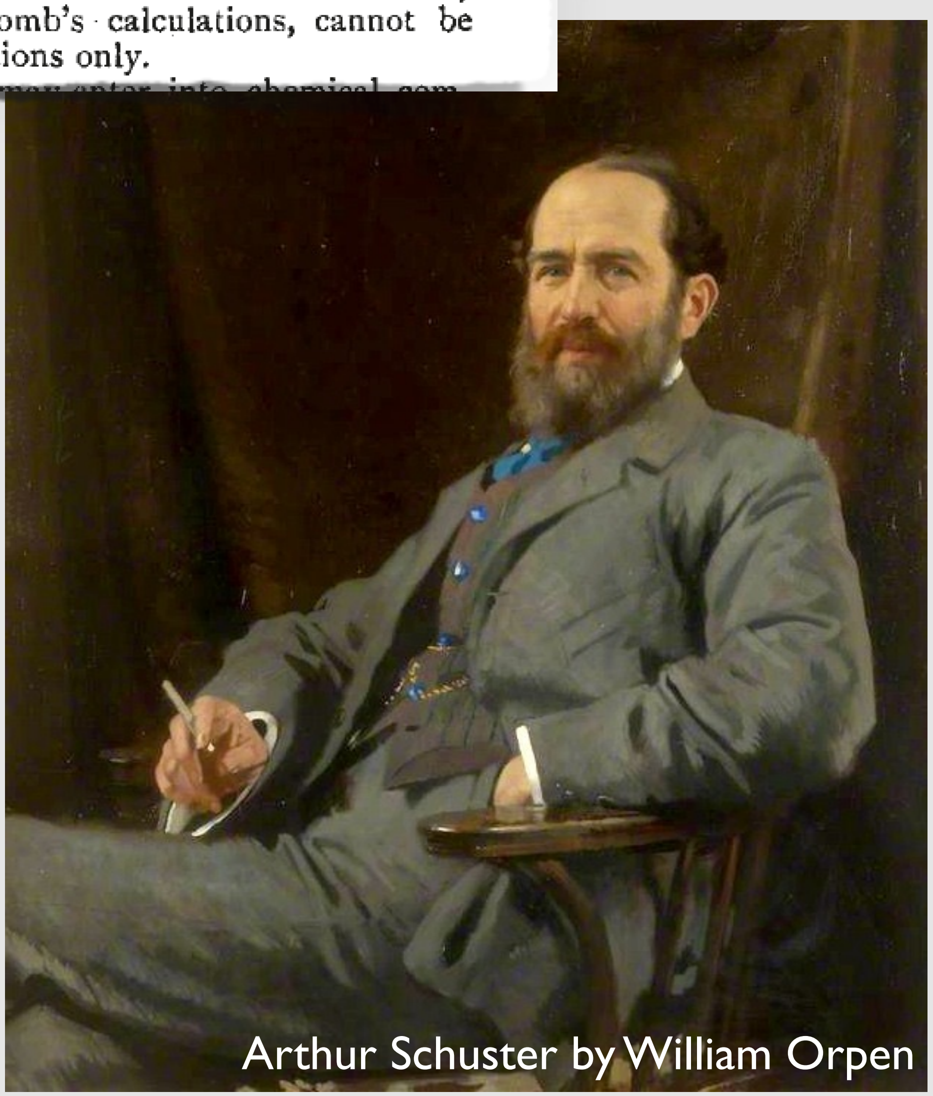
WHEN the year's work is over and all sense of responsibility has left us, who has not occasionally set his fancy free to dream

tional velocity of our solar and of many stellar systems, which cannot be self-generated. Unless we threw our laws of dynamics overboard, or imagine the rotation to have been impressed by creation, we must conclude that some outside body or system of bodies is endowed with an equal and opposite angular momentum. What has become of that outside body, and how could it have parted company with our solar system, if attractive forces only were acting? Another unexplained fact is found in the large velocities of some of the fixed stars, which, according to Prof. Newcomb's calculations, cannot be explained by gravitational attractions only.

undistinguishable in fact from them until they are brought into each other's vicinity. If there is negative electricity, why not negative gold, as yellow and valuable as our own, with the same boiling point and identical spectral lines; different only in so far that if brought down to us it would rise up into space with an acceleration of 981. The fact that we are not acquainted with such matter does not prove its non-existence; for if it ever

Astronomy, the oldest and yet most juvenile of sciences, may still have some surprises in store. May anti-matter be commended to its care! But I must stop—the holidays are nearing their end—the British Association is looming in the distance; we must return to sober science, and dreams must go to sleep till next year.

Do dreams ever come true? ARTHUR SCHUSTER.


Arthur Schuster by William Orpen

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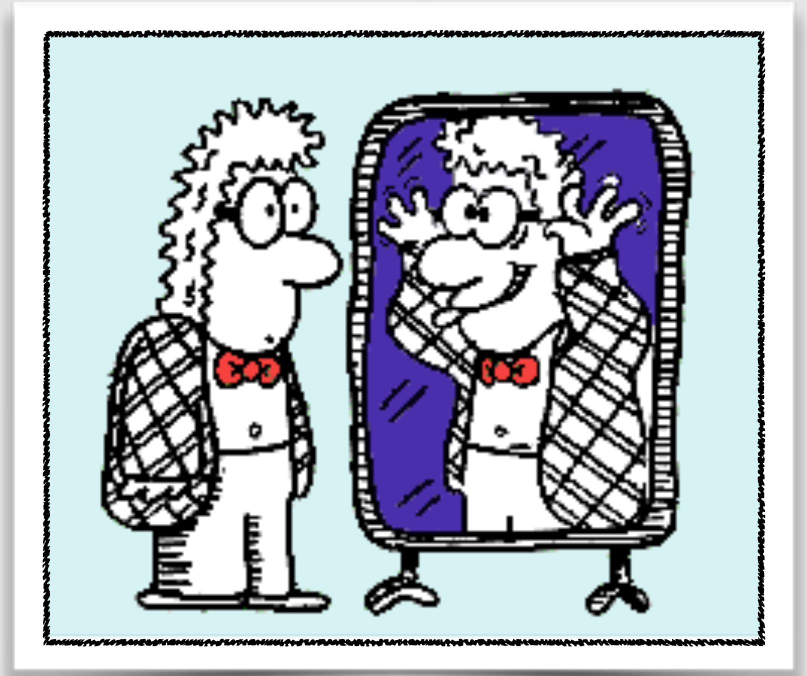
Matter-antimatter asymmetry



Charge
Parity

- CP symmetry:
  Particle ↔ Anti-particle exchange

CP violation

CP violation in decay

matter $D^0 \longrightarrow K^-K^+$

antimatter $\overline{D}^0 \longrightarrow K^-K^+$

↕ Interference

CP violation in mixing

$D^0 \longrightarrow \overline{D}^0 \longrightarrow D^0 \longrightarrow \overline{D}^0 \longrightarrow$

Direct CP violation

→ depends on decay mode
→ independent of decay time

Indirect CP violation

→ independent of decay mode
→ effect varies as function of decay time

CP violation

CP violation in decay

matter $D^0 \longrightarrow K^- K^+$

antimatter $\overline{D}^0 \longrightarrow K^- K^+$

↕ Interference

CP violation in mixing

$D^0 \longrightarrow \overline{D}^0 \longrightarrow D^0 \longrightarrow \overline{D}^0 \longrightarrow$

Direct CP violation

→ depends on decay mode
→ independent of decay time

Indirect CP violation

→ independent of decay mode
→ effect varies as function of decay time

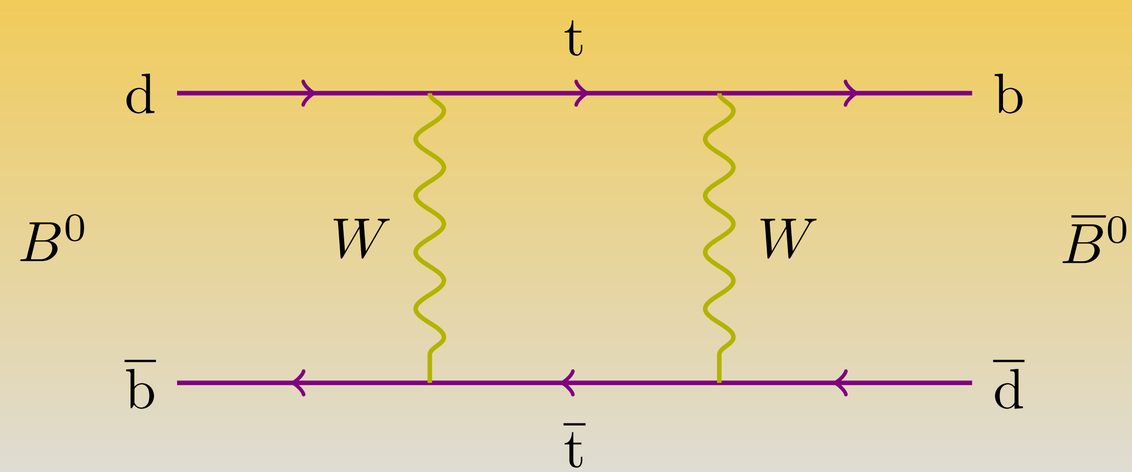
Flavour physics:
Fast-tracking discoveries

- K^0-$\overline{K}^0$ mixing and smallness of $K^0 \rightarrow \mu^+\mu^-$
  - ➡ GIM mechanism predicts charm quark in 1970
- Kaon CP violation
  - ➡ KM mechanism predicts bottom and top quarks in 1973
    - Charm & bottom quarks discovered: 1974+1977
- B^0-$\overline{B}^0$ oscillations discovered in 1987
  - ➡ Requires m_{top} > 50 GeV to deactivate GIM cancellation
    - Top quark discovered: 1995

Flavour physics:
Fast-tracking discoveries

- K^0-$\overline{K}^0$ mixin
  - ➡ GIM mec
- Kaon CP vi
  - ➡ KM mech

Then: ARGUS, 10^5 $B\overline{B}$ decays, probing 0.1 TeV
Now: LHCb, 10^{11} $B\overline{B}$ decays, probing 100 TeV



- B^0-$\overline{B}^0$ oscillations discovered in 1987
  - ➡ Requires m_{top} > 50 GeV to deactivate GIM cancellation
    - Top quark discovered: 1995

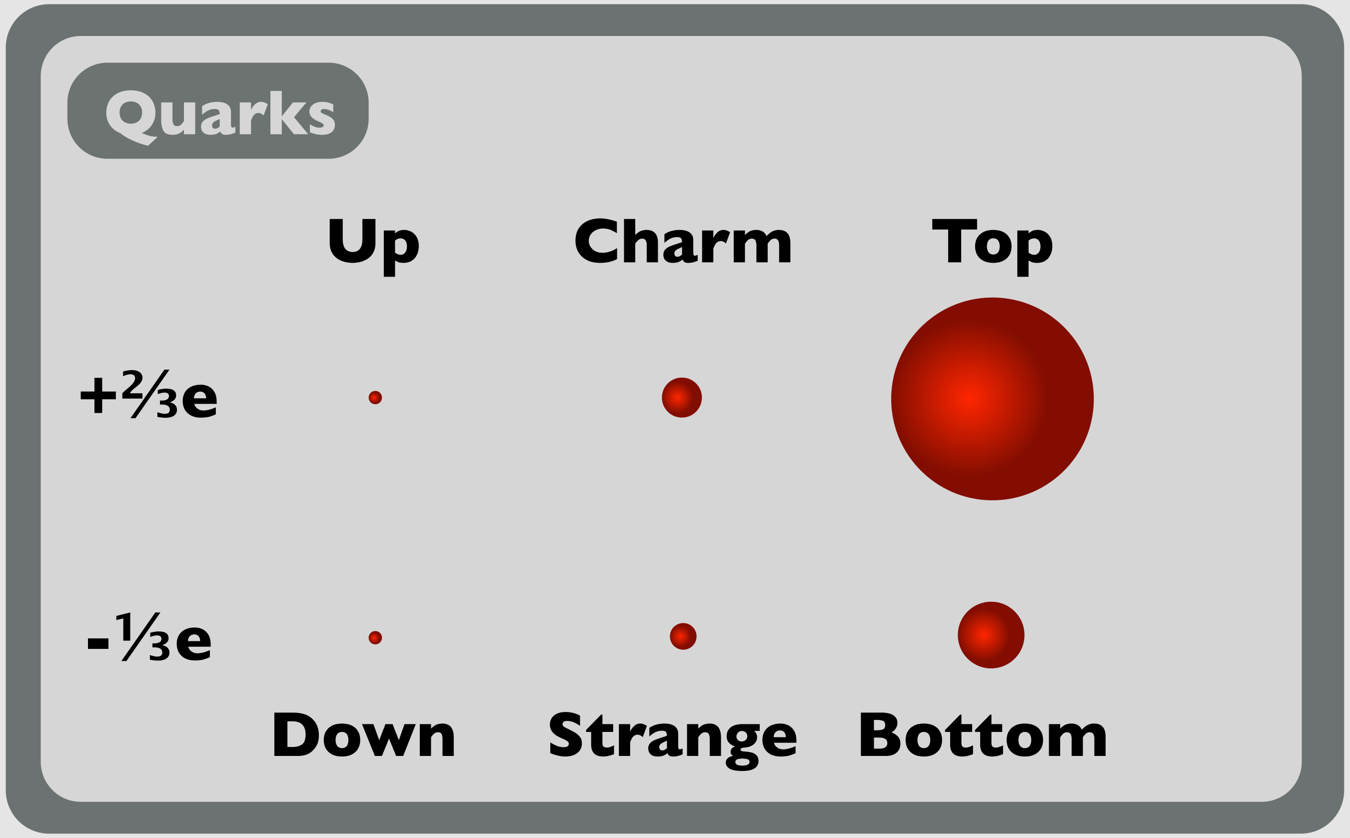
Flavour physics:
Fast-tracking discoveries

Then: ARGUS, 10^5 $B\bar{B}$ decays, probing 0.1 TeV
Now: LHCb, 10^{11} $B\bar{B}$ decays, probing 100 TeV

- K^0-$\bar{K}^0$ mixin
  - ➡ GIM mec
- Kaon CP vi
  - ➡ KM mech
- B^0-$\bar{B}^0$ oscillations discovered in 1987
  - ➡ Requires m_{top} > 50 GeV to deactivate GIM cancellation
    - Top quark discovered: 1995

4 flavoured neutral mesons

- K^0: $d\bar{s}$
- B^0: $d\bar{b}$
- D^0: $c\bar{u}$
- B_s: $s\bar{b}$



Mesons Quark-Antiquark pairs

Pion: Up-Antiup, Up-Antidown, ...

The flavour of the weak interaction

- Mesons have defined flavour eigenstates
  - ➡ Determines quark content

$$F\begin{pmatrix}|M^0\rangle\\0\end{pmatrix}=+\begin{pmatrix}|M^0\rangle\\0\end{pmatrix},\qquad F\begin{pmatrix}0\\|\overline{M}^0\rangle\end{pmatrix}=-\begin{pmatrix}0\\|\overline{M}^0\rangle\end{pmatrix}$$

- Eigenstates of weak Hamiltonian differ
  - ➡ Determines mass and lifetime

$$\mathscr{H}\begin{pmatrix}|M_1\rangle\\0\end{pmatrix}=\lambda_1\begin{pmatrix}|M_1\rangle\\0\end{pmatrix},\qquad \mathscr{H}\begin{pmatrix}0\\|M_2\rangle\end{pmatrix}=\lambda_2\begin{pmatrix}0\\|M_2\rangle\end{pmatrix}$$

- Each set is a linear combination of the other

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

1 — Production

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The very beginning

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

A Possible Decay in Flight of a New Type Particle

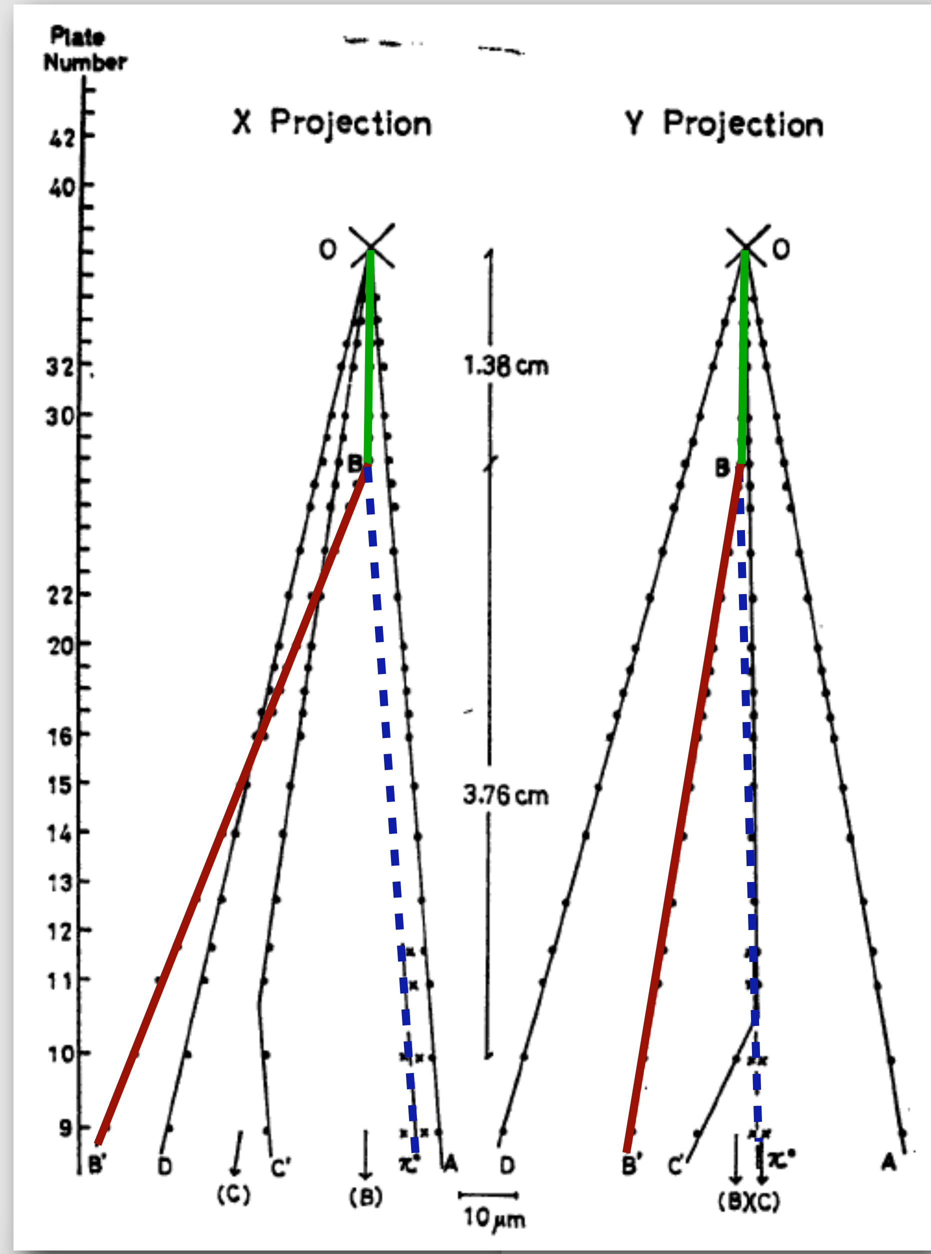
Kiyoshi NIU, Eiko MIKUMO and Yasuko MAEDA*

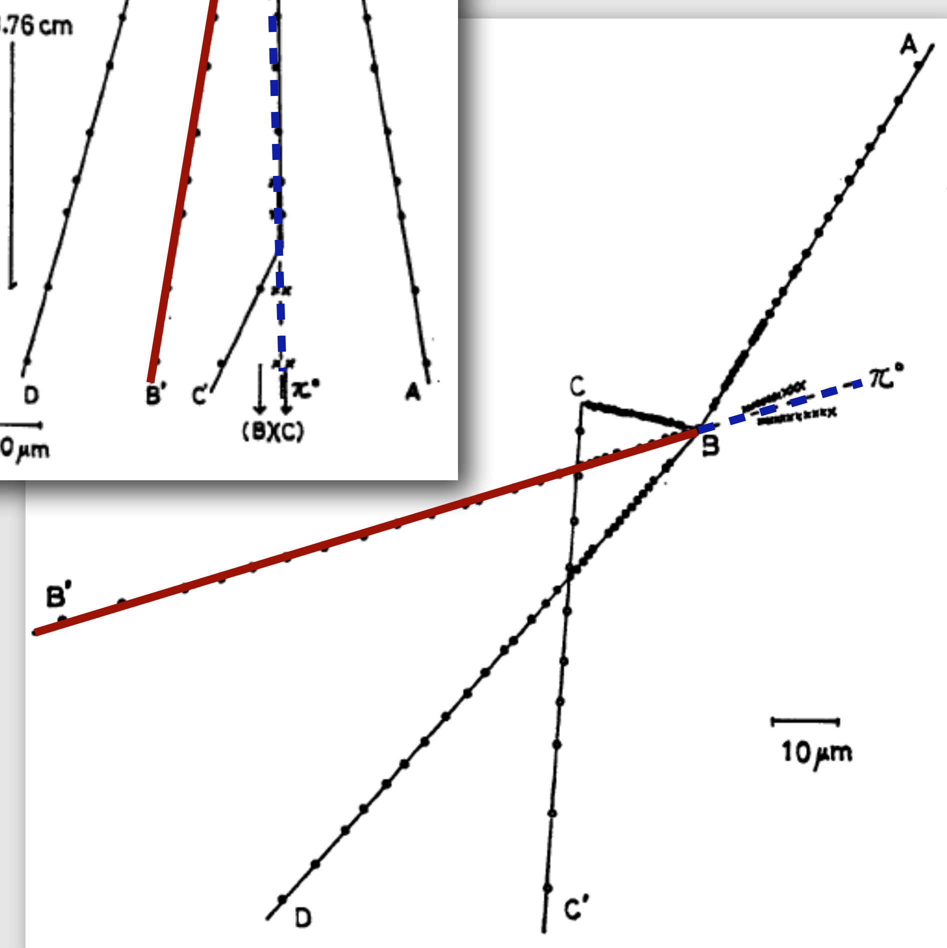
Institute for Nuclear Study
University of Tokyo
**Yokohama National University*

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}





Charmonium

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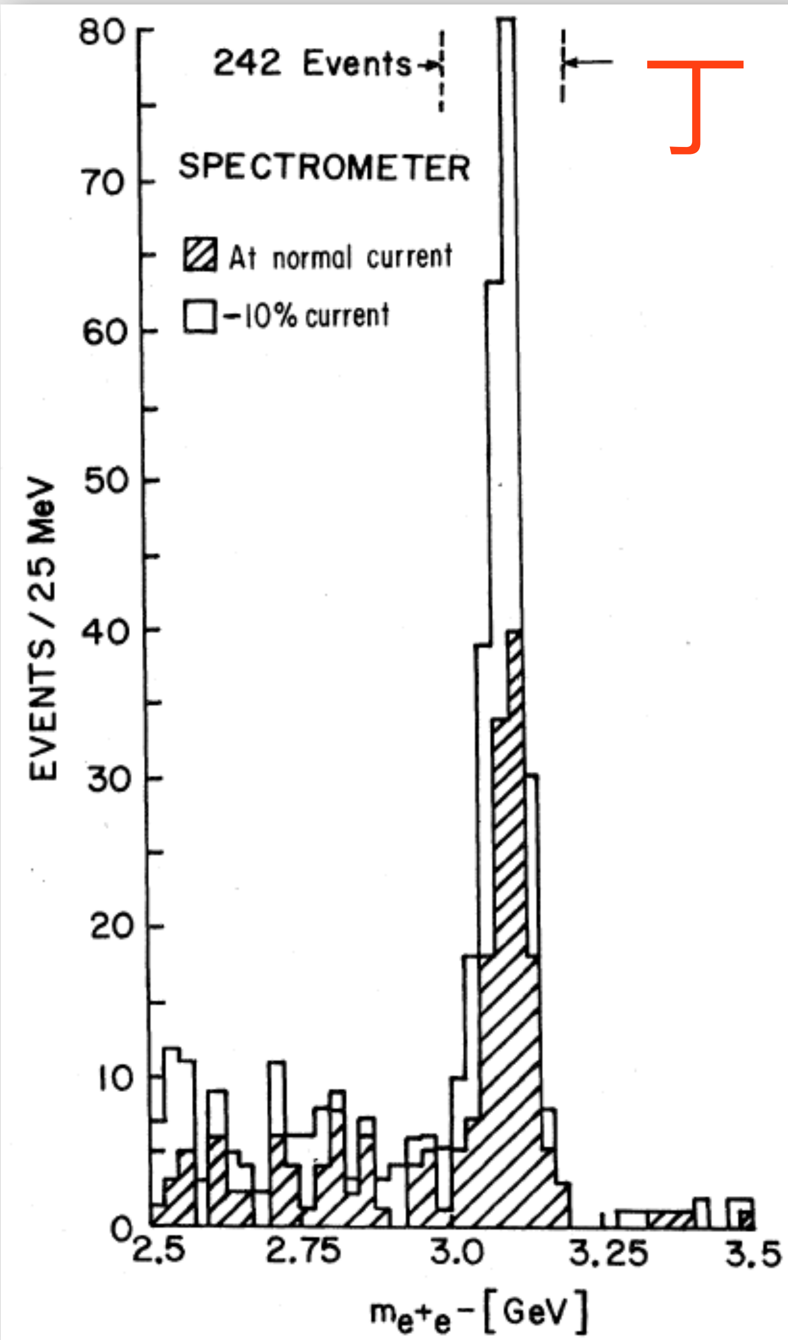
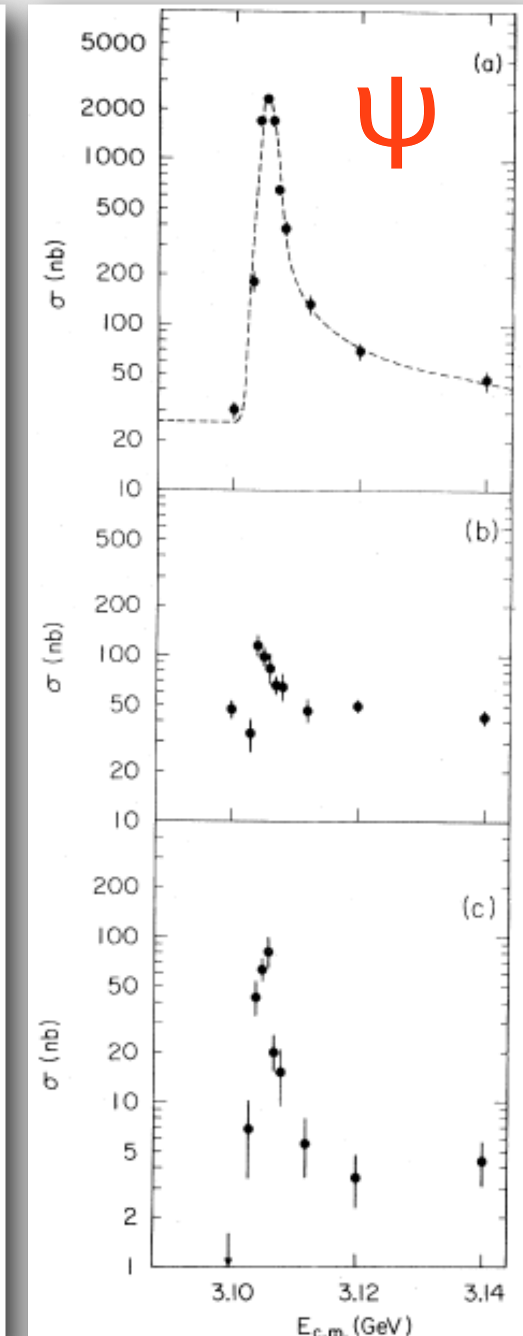
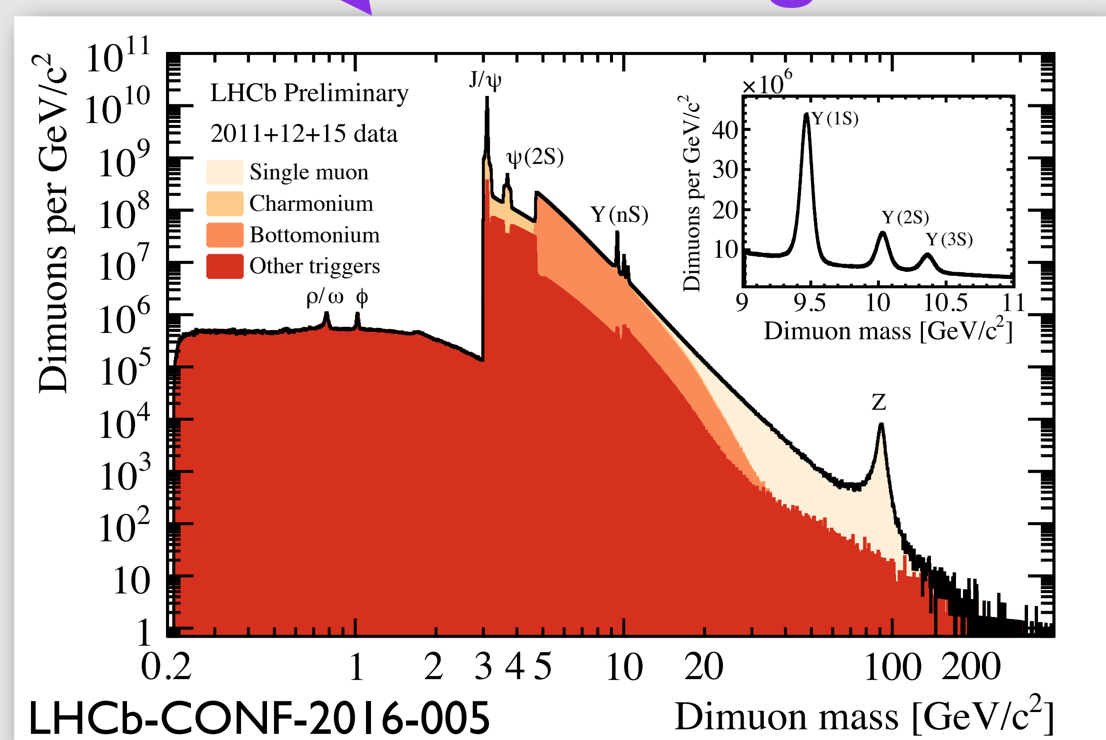




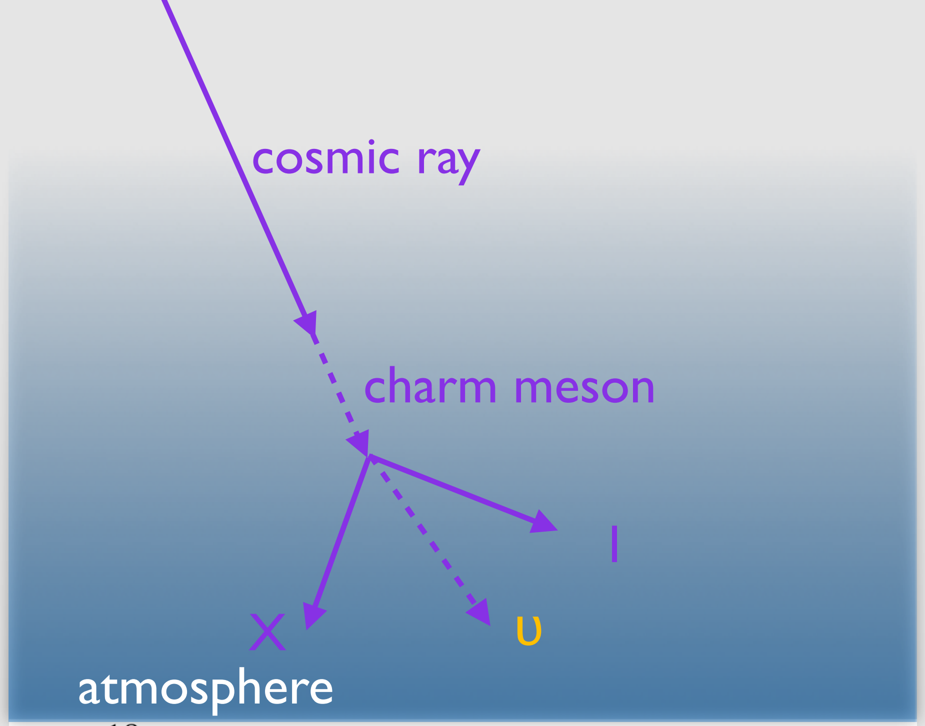
+42 years

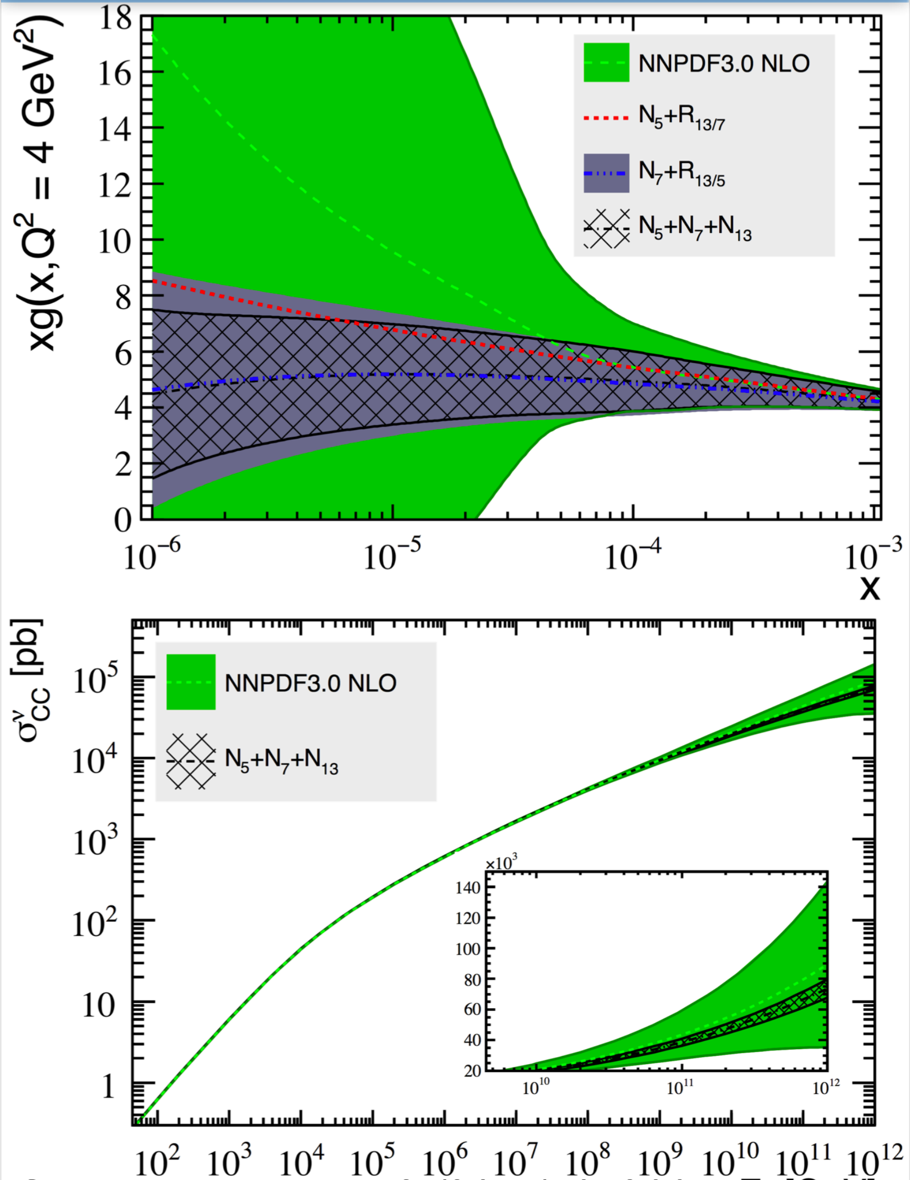
+8 orders of magnitude



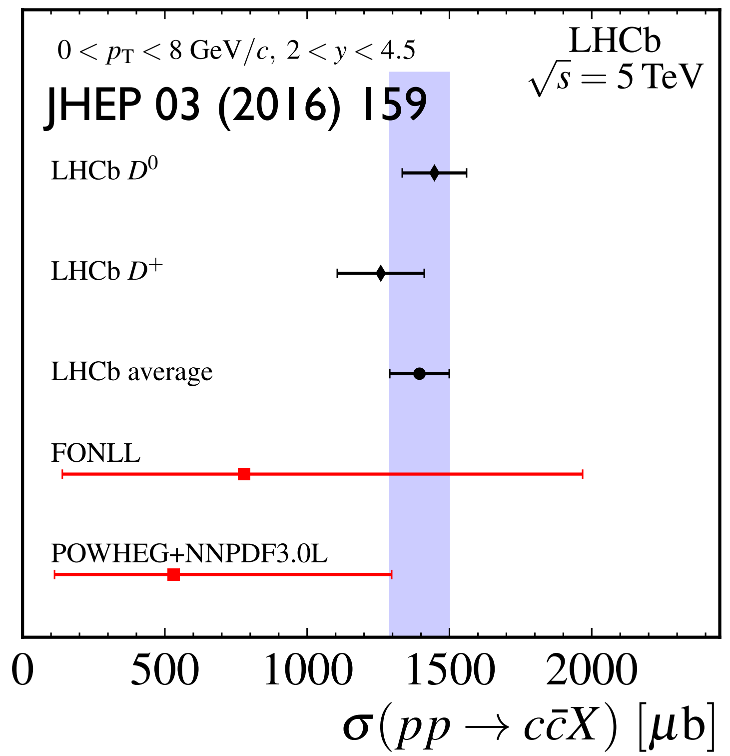
Production

- Charm production as precision measurements
  - ➡ Constrain gluon parton distribution function
  - ➡ Constrains on charm production in atmosphere
    - High-energy neutrino background, e.g. for IceCube





Gauld, Rojo, PRL 118 (2017) 072001



JHEP 03 (2016) 159

- At LHCb
  - ➡ >1 mb cross-section
  - ➡ 2 fb^{-1} luminosity per year
  - ➡ $>10^{12}$ $c\bar{c}$ pairs per year

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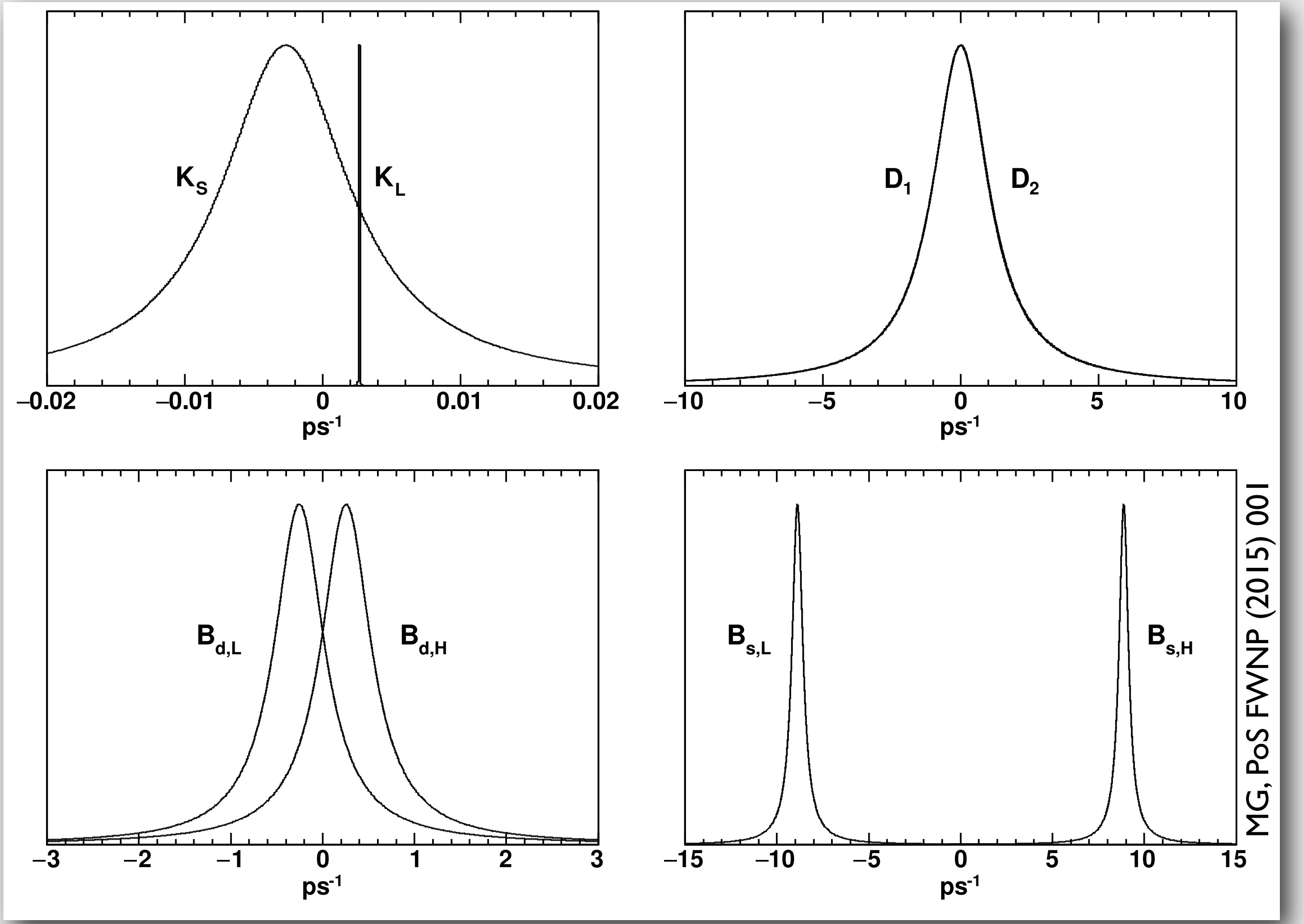
2 — Mixing

Mixing

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

Hamiltonian eigenstates

Flavour eigenstates



Mixing

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Hamiltonian eigenstates

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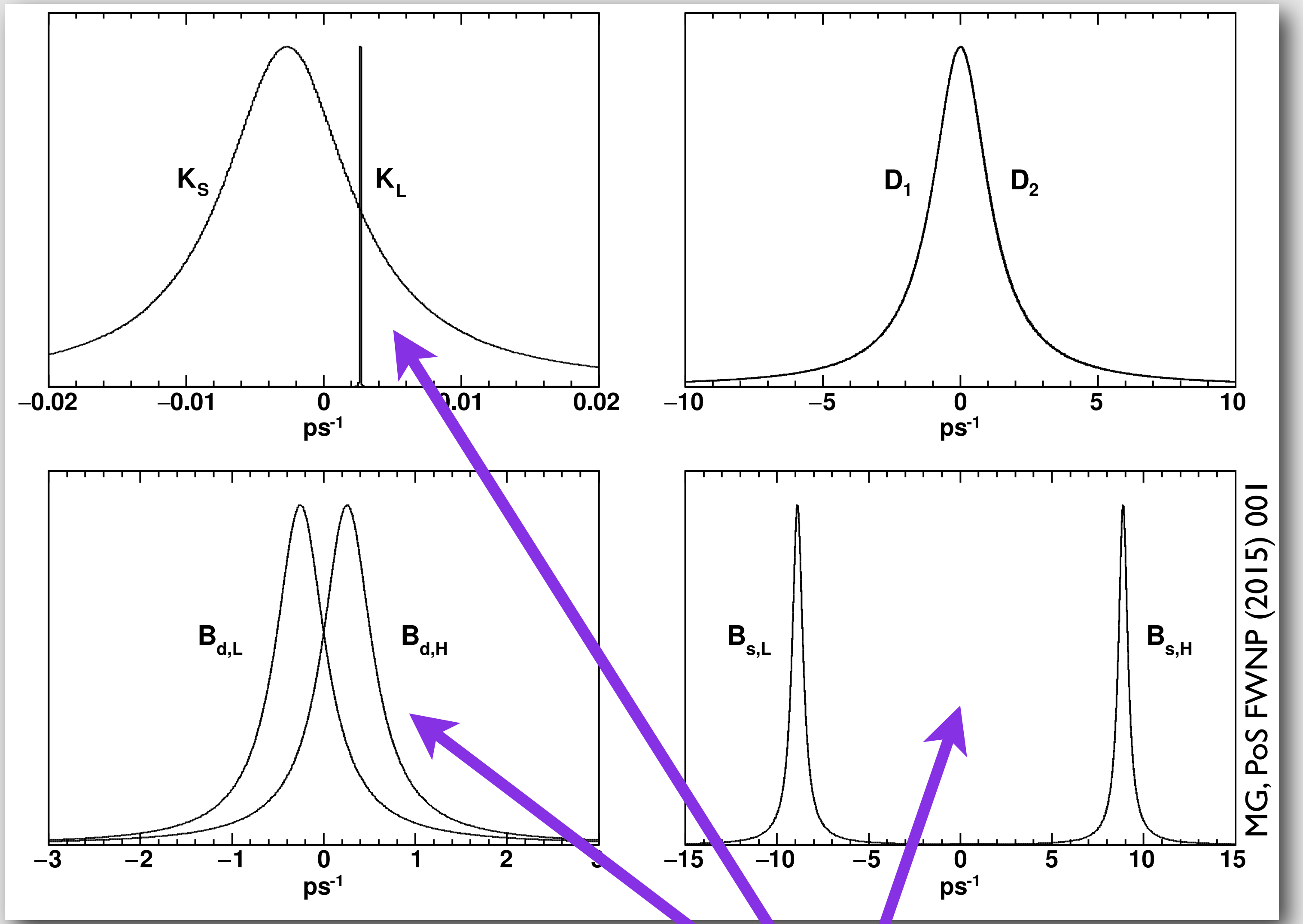


Mass difference

→ Oscillation

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

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

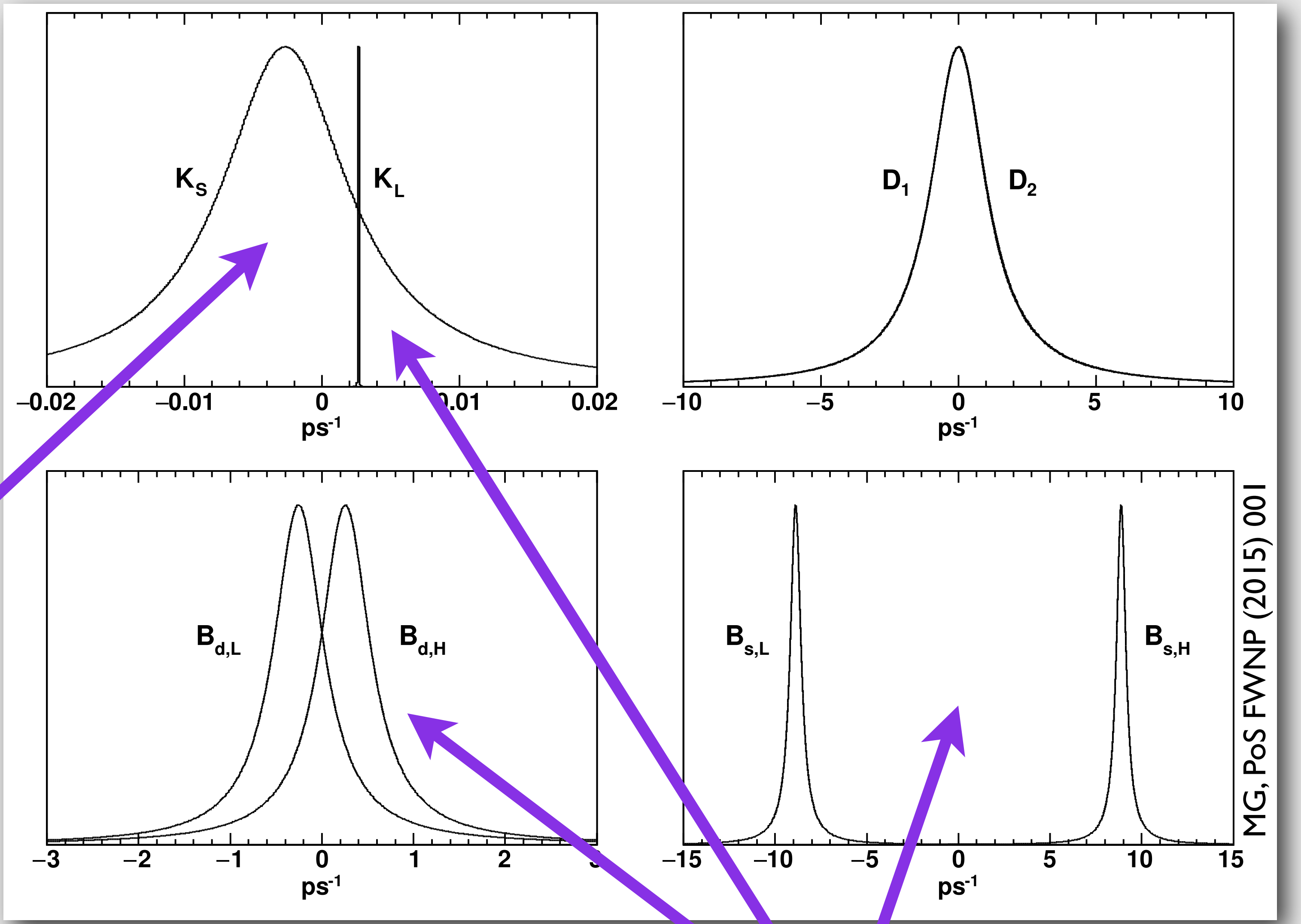
$$x \equiv \Delta m / \Gamma$$

Mixing

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

Hamiltonian eigenstates

Flavour eigenstates



Width difference

→ Lifetime difference

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

Mass difference

→ Oscillation

$\Delta m \equiv m_2 - m_1$

$x \equiv \Delta m/\Gamma$

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

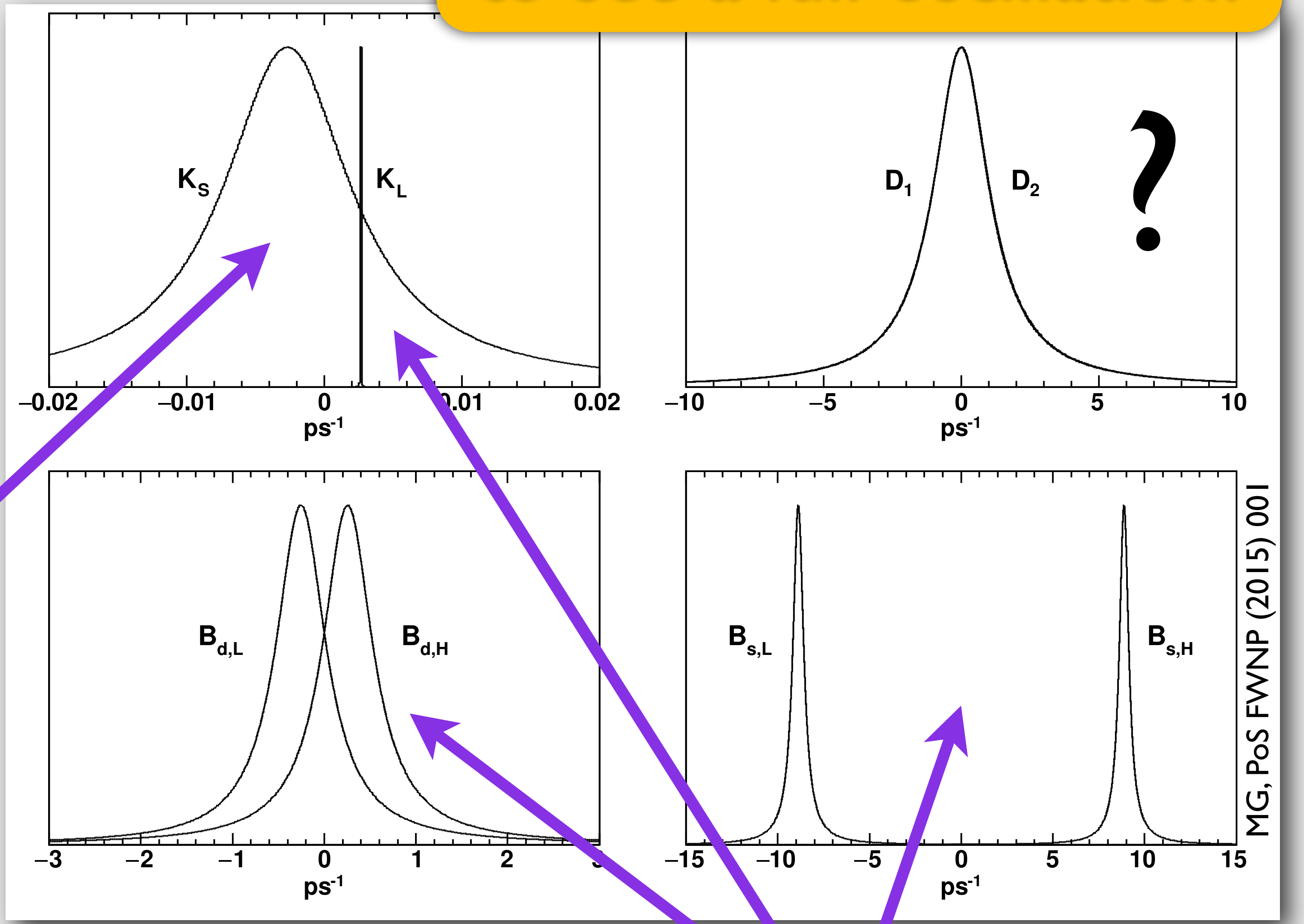
Mixing

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

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

Hamiltonian eigenstates

Flavour eigenstates



Width difference
→ Lifetime difference

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

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

Mass difference
→ Oscillation

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

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

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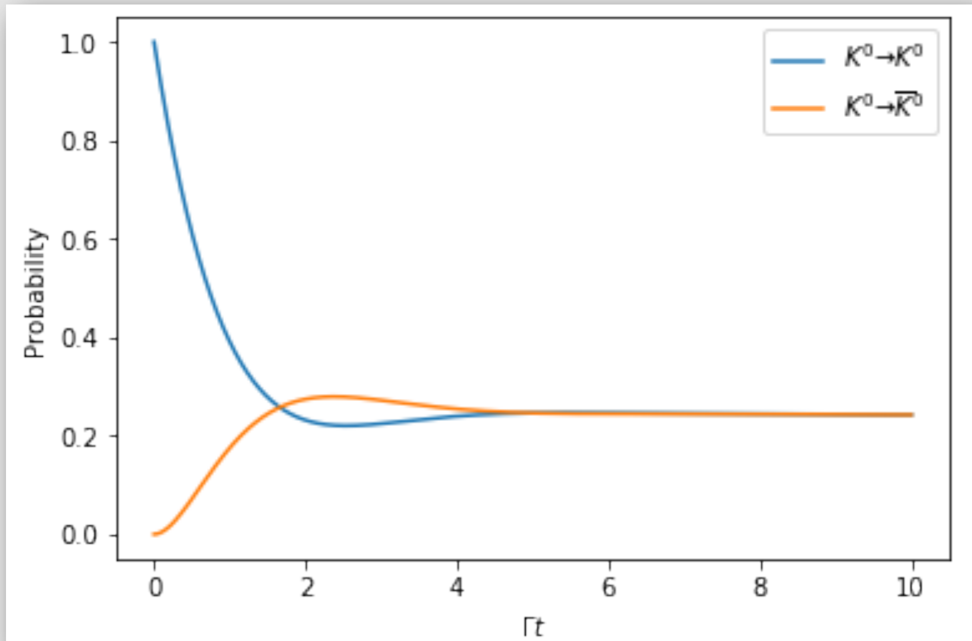
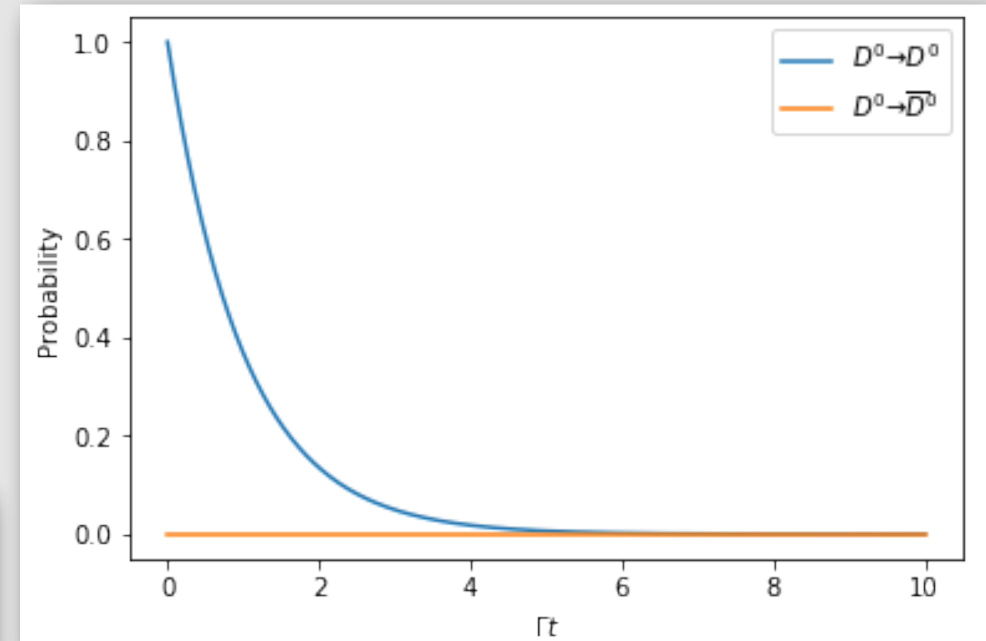
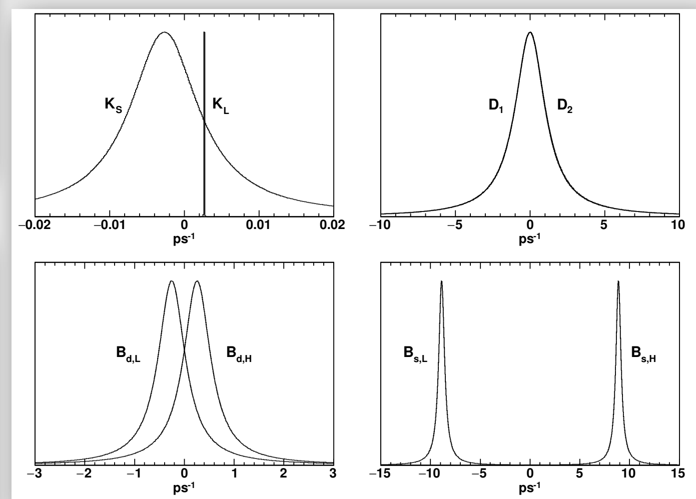
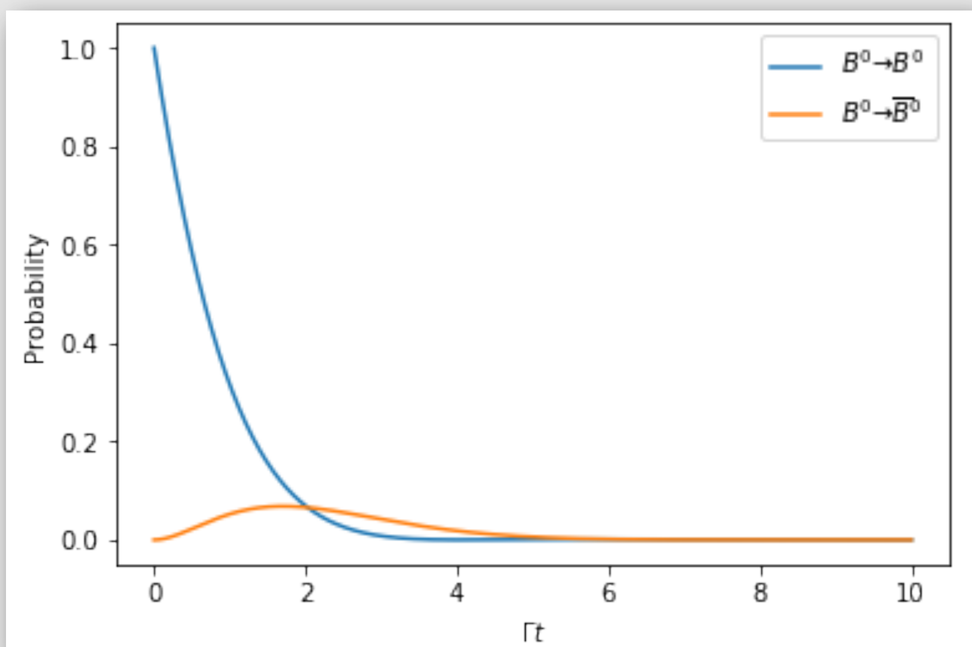
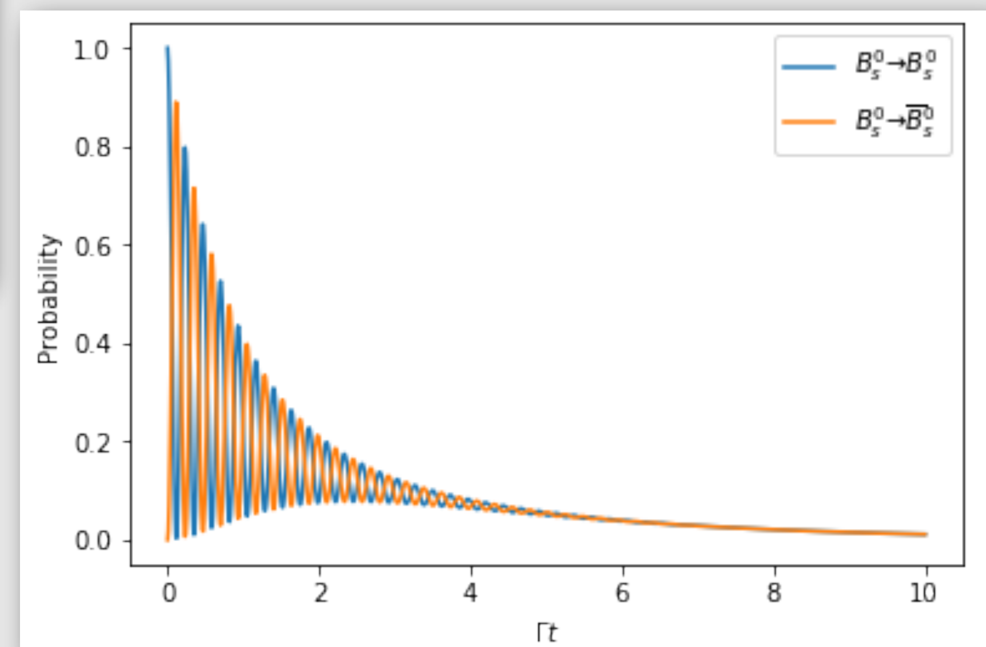
Mixing







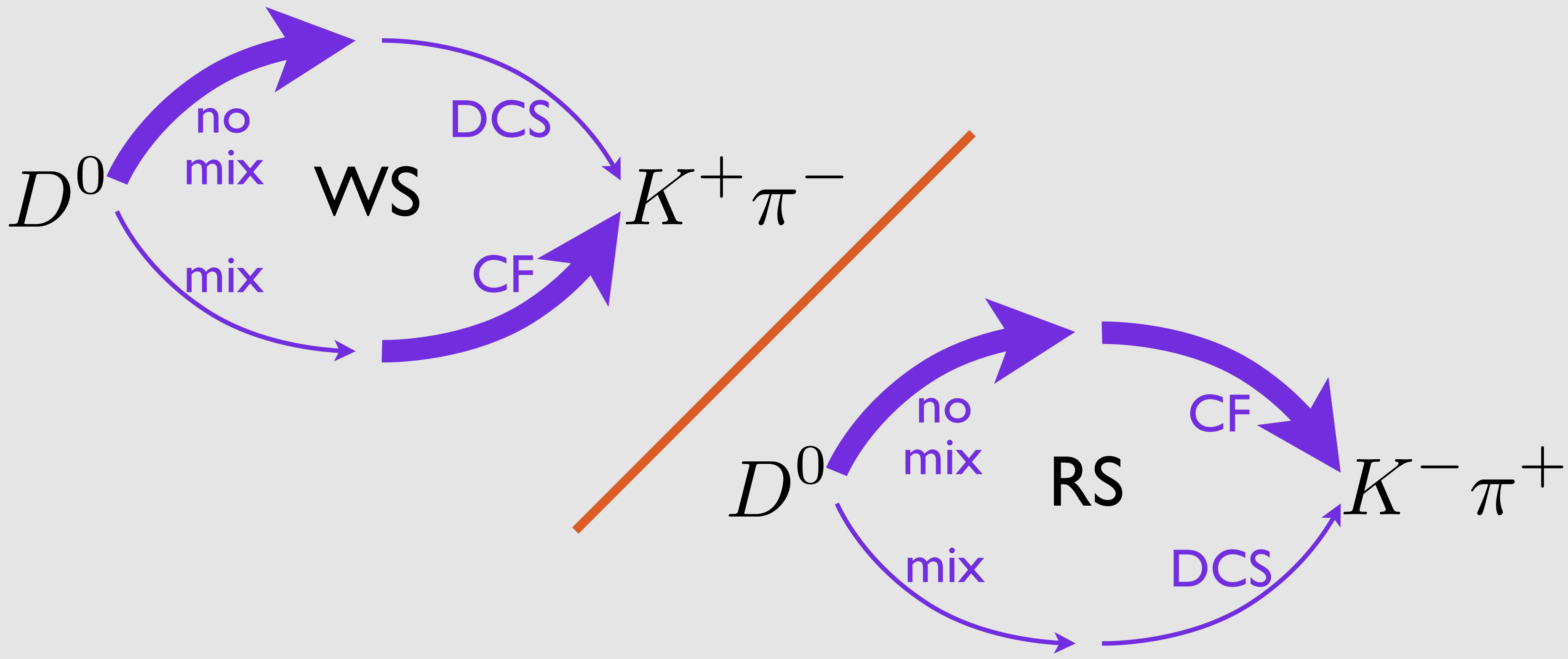




$$P(M^0 \to \overline{M}^0, t) = \frac{1}{2}\left|\frac{q}{p}\right|^2 e^{-\Gamma t}(\cosh(y\Gamma t) - \cos(x\Gamma t))$$

Mixing discovery

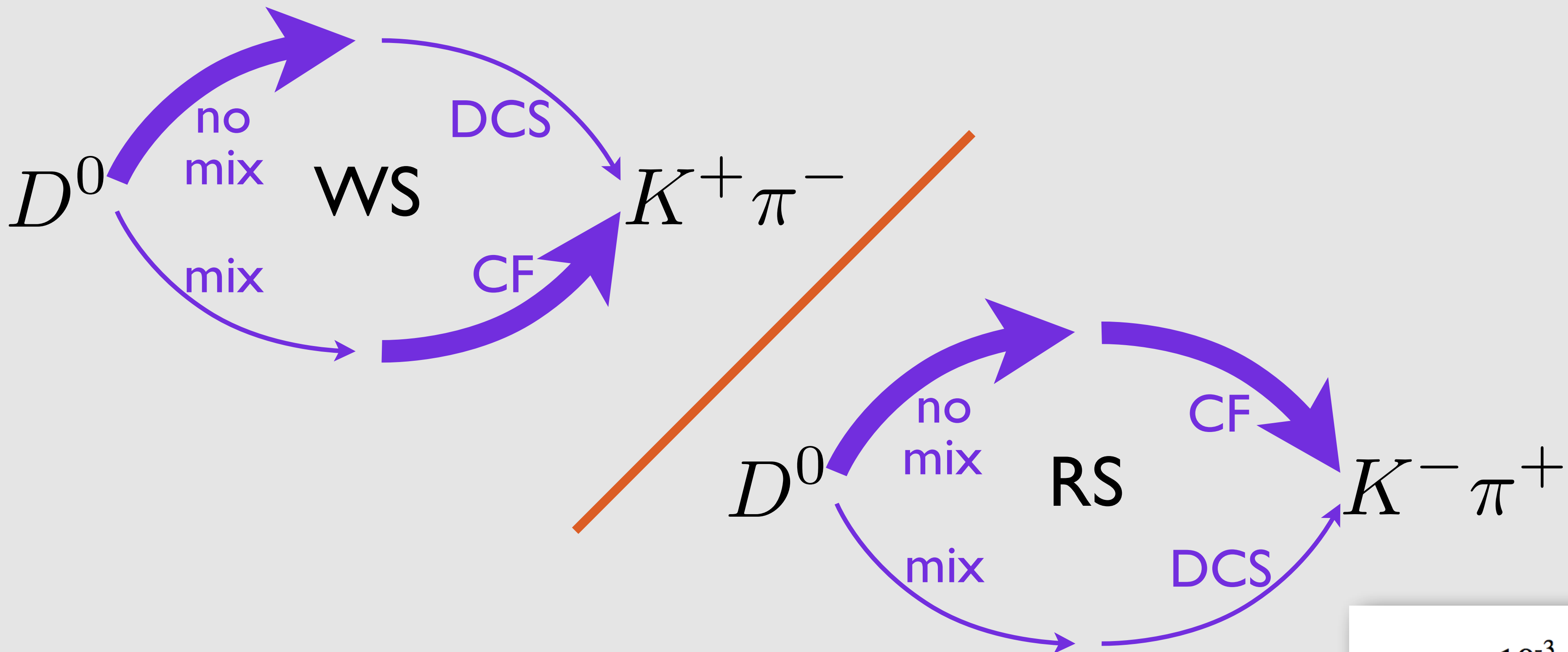
PRL 110 (2013) 101802



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

Mixing discovery

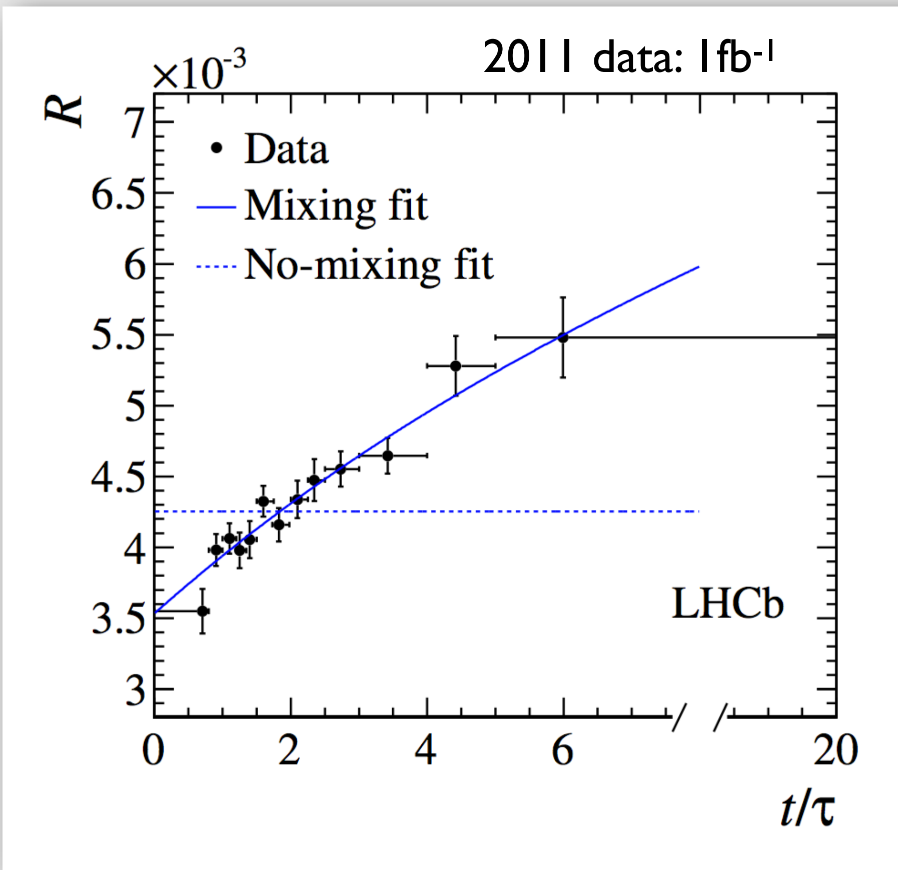
PRL 110 (2013) 101802



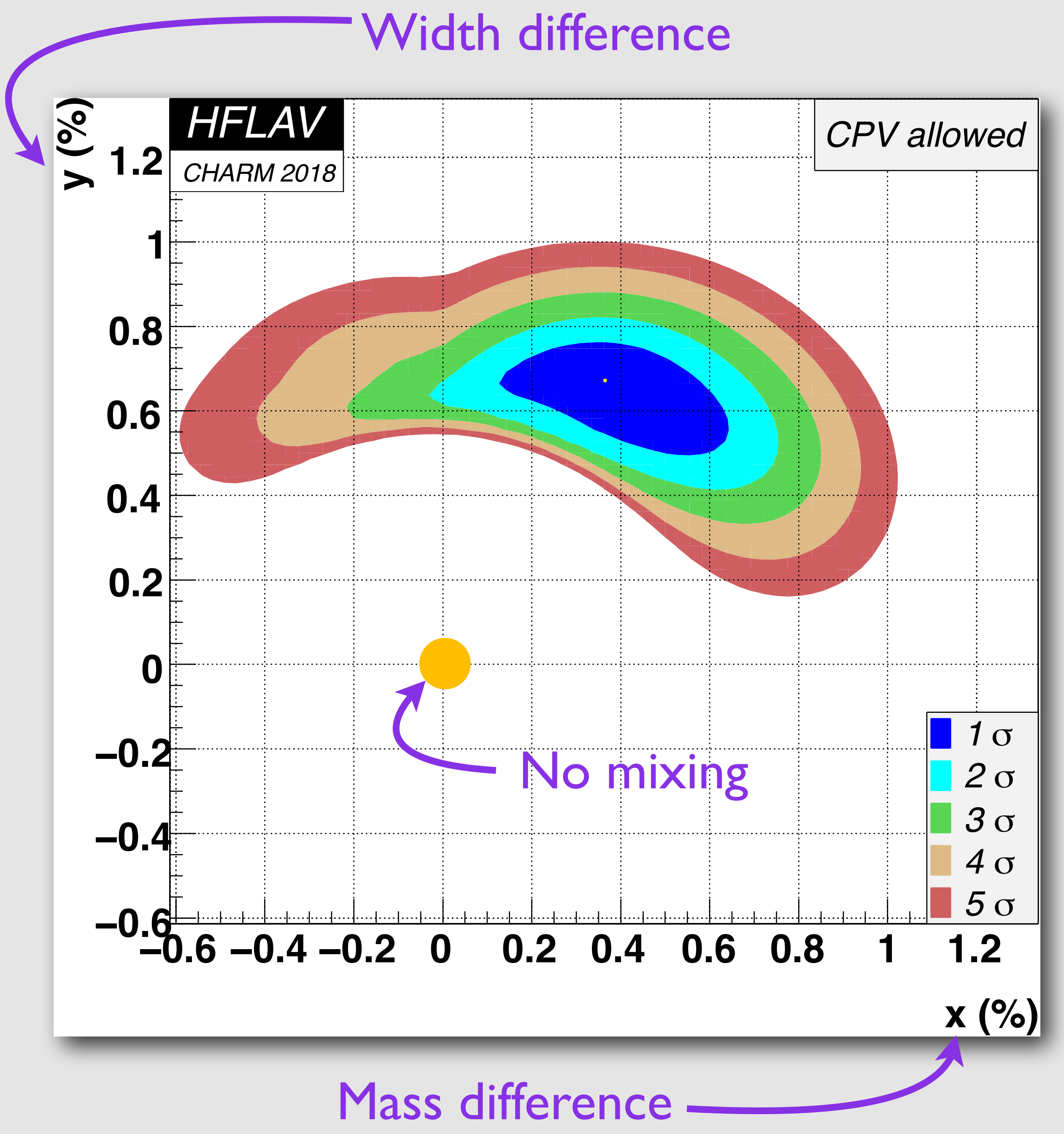
Using roughly 8.4×10^6 RS and 3.6×10^4 WS candidates

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

- Rotation of mixing parameters by strong phase difference between CF and DCS amplitudes: x,y → x',y'

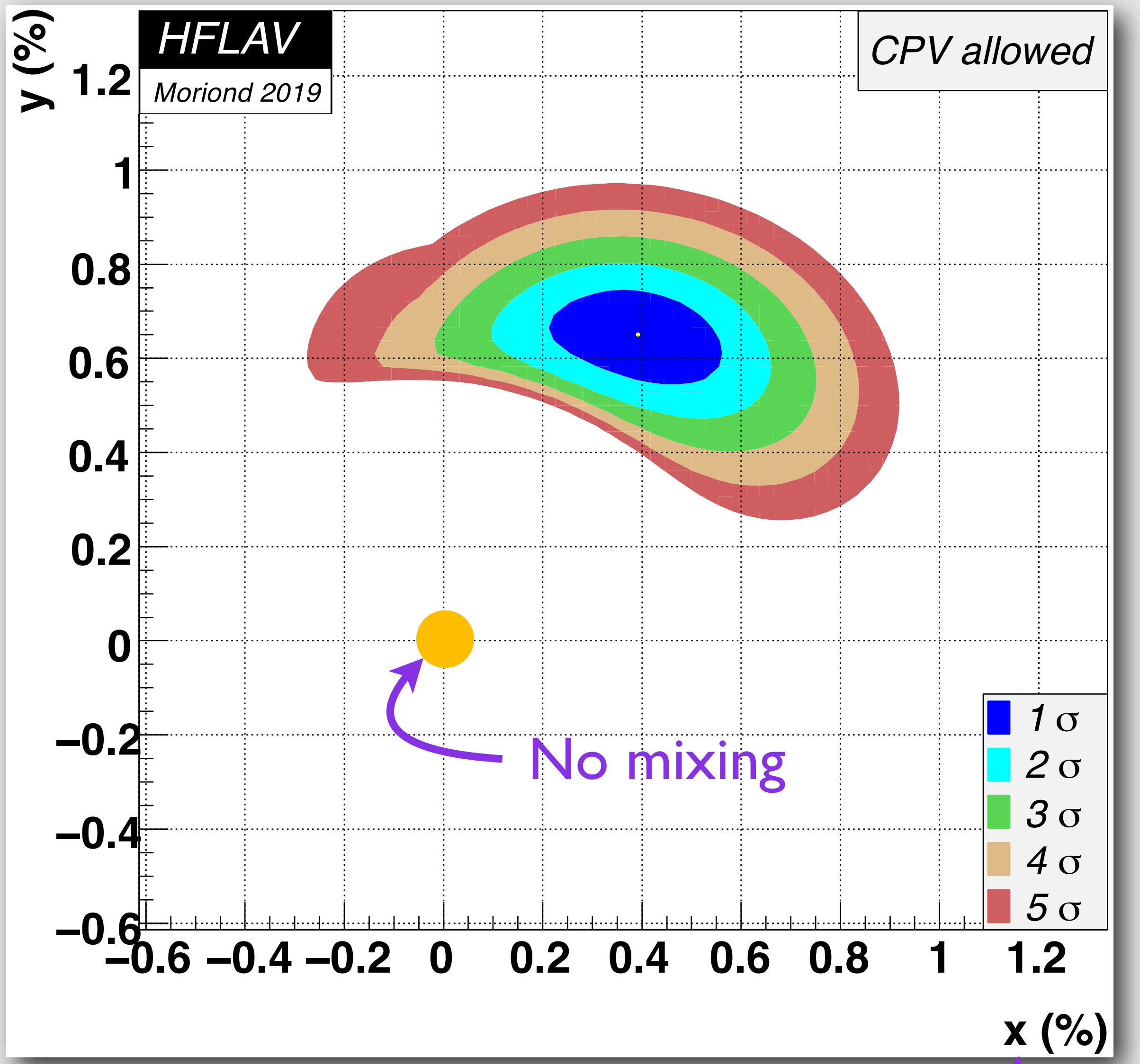


Mixing nowadays



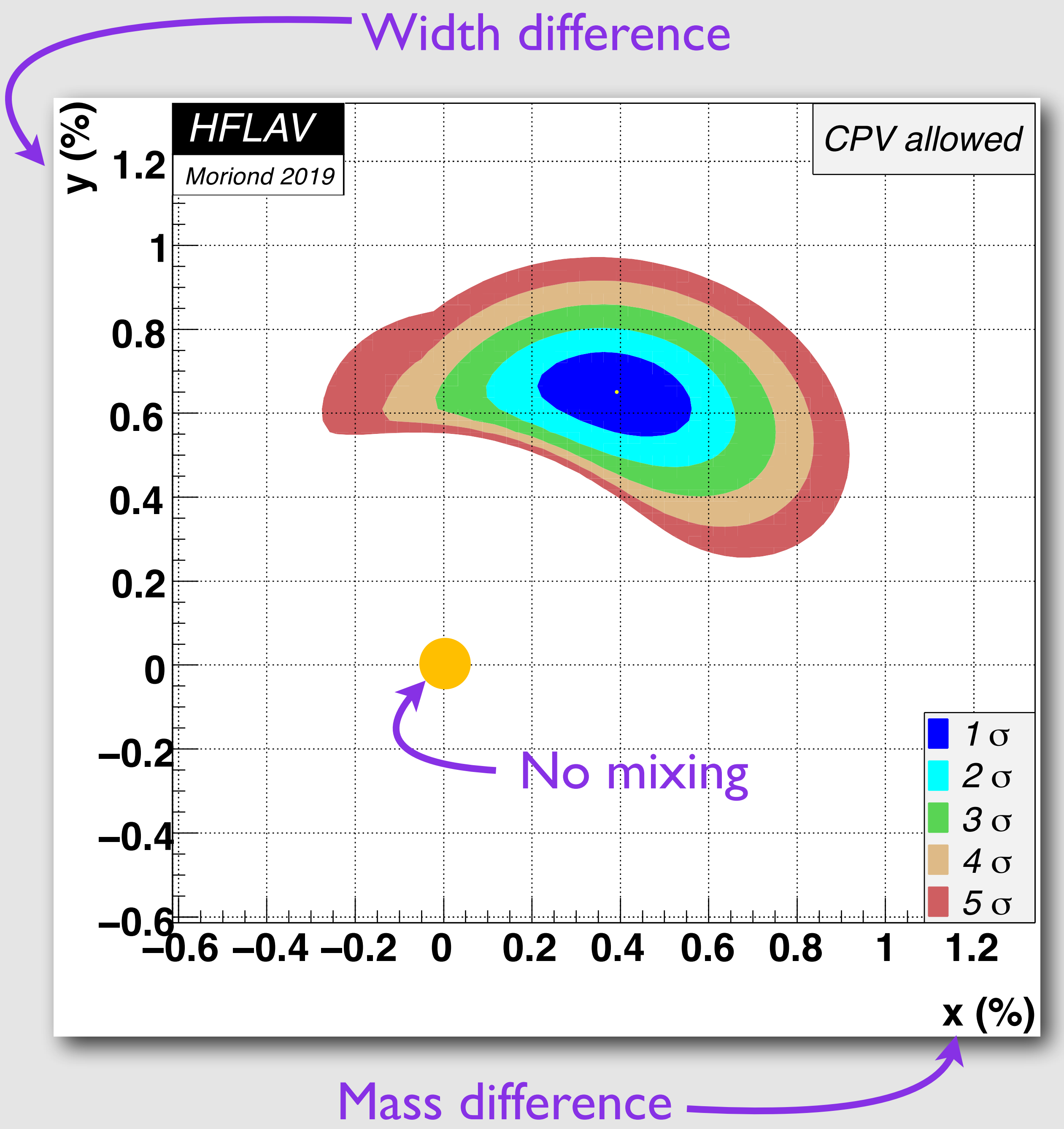
Mixing nowadays

Width difference



Mass difference

Mixing nowadays



- Evidence for x>0

3 — CP violation

Mixing-related CP violation = indirect CP violation

Hamiltonian eigenstates:

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

CP symmetry:

$q = \pm p$

CP violation:

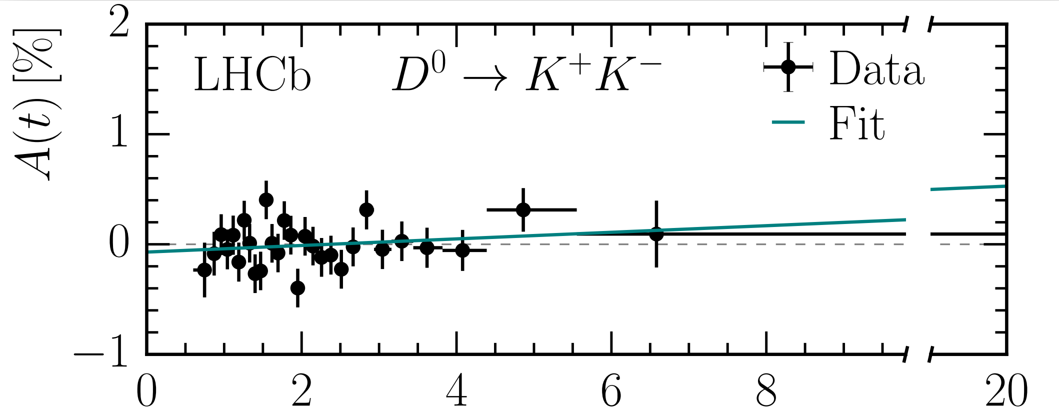
$|q/p| \neq 1$

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

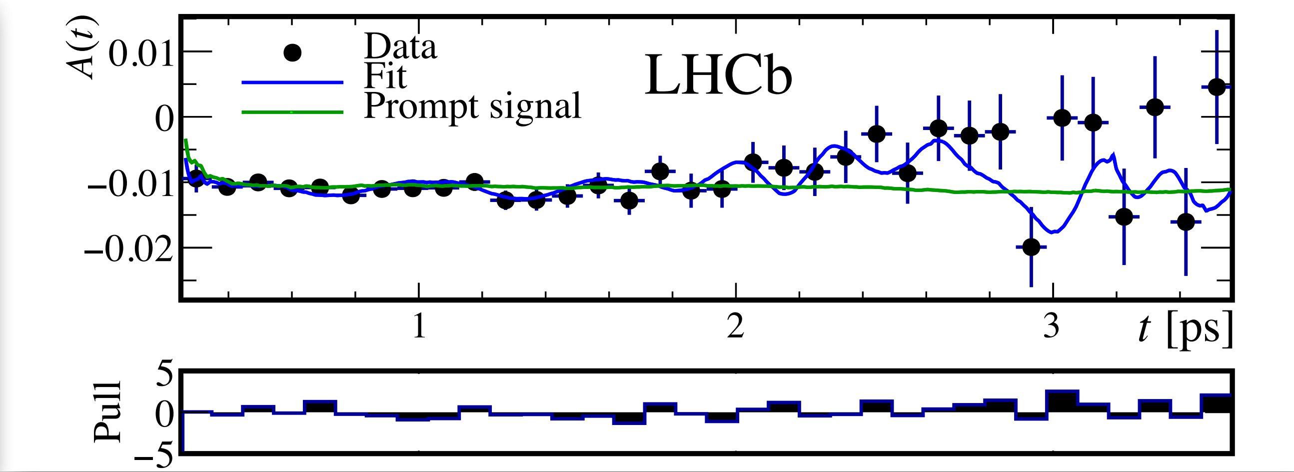
$A_\Gamma = -a_{CP}^{ind}$

- 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 (2011-12 data, 3 fb^{-1})
  - ➡ $A_\Gamma(K^+K^-)= (-0.30\pm0.32\pm0.10)\times10^{-3}$
  - ➡ $A_\Gamma(\pi^+\pi^-)= (+0.46\pm0.58\pm0.12)\times10^{-3}$
- Preliminary update (2015-16 data, 1.9 fb^{-1})
  - ➡ $A_\Gamma(K^+K^-)= (+0.13\pm0.35\pm0.07)\times10^{-3}$
  - ➡ $A_\Gamma(\pi^+\pi^-)= (+1.13\pm0.69\pm0.08)\times10^{-3}$

LHCb-CONF-2019-001



PRL 118 (2017) 261803



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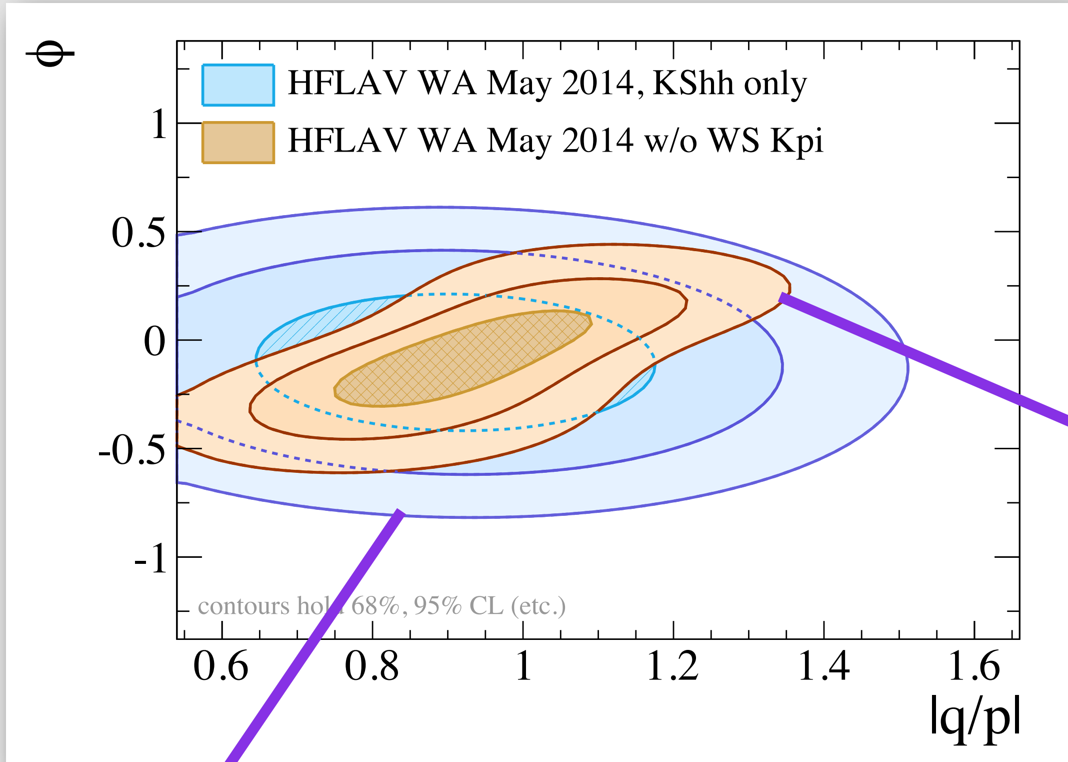
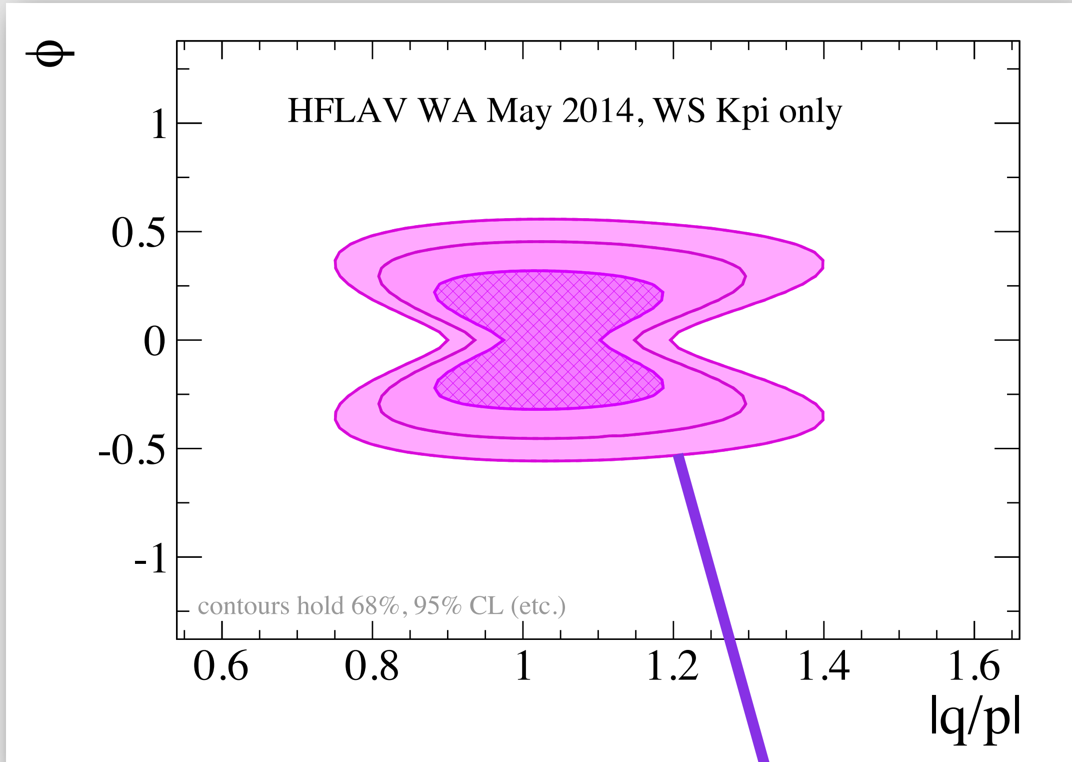
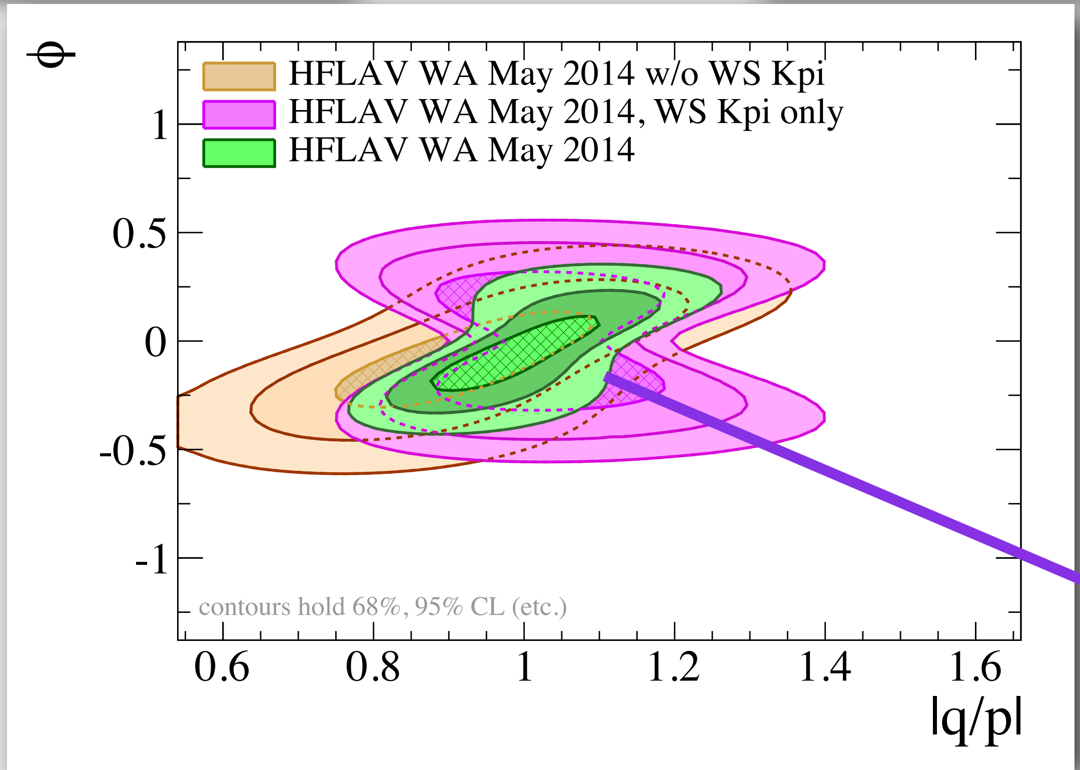
Contributions



Precise constraints if x and y provided, mostly from A_Γ



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



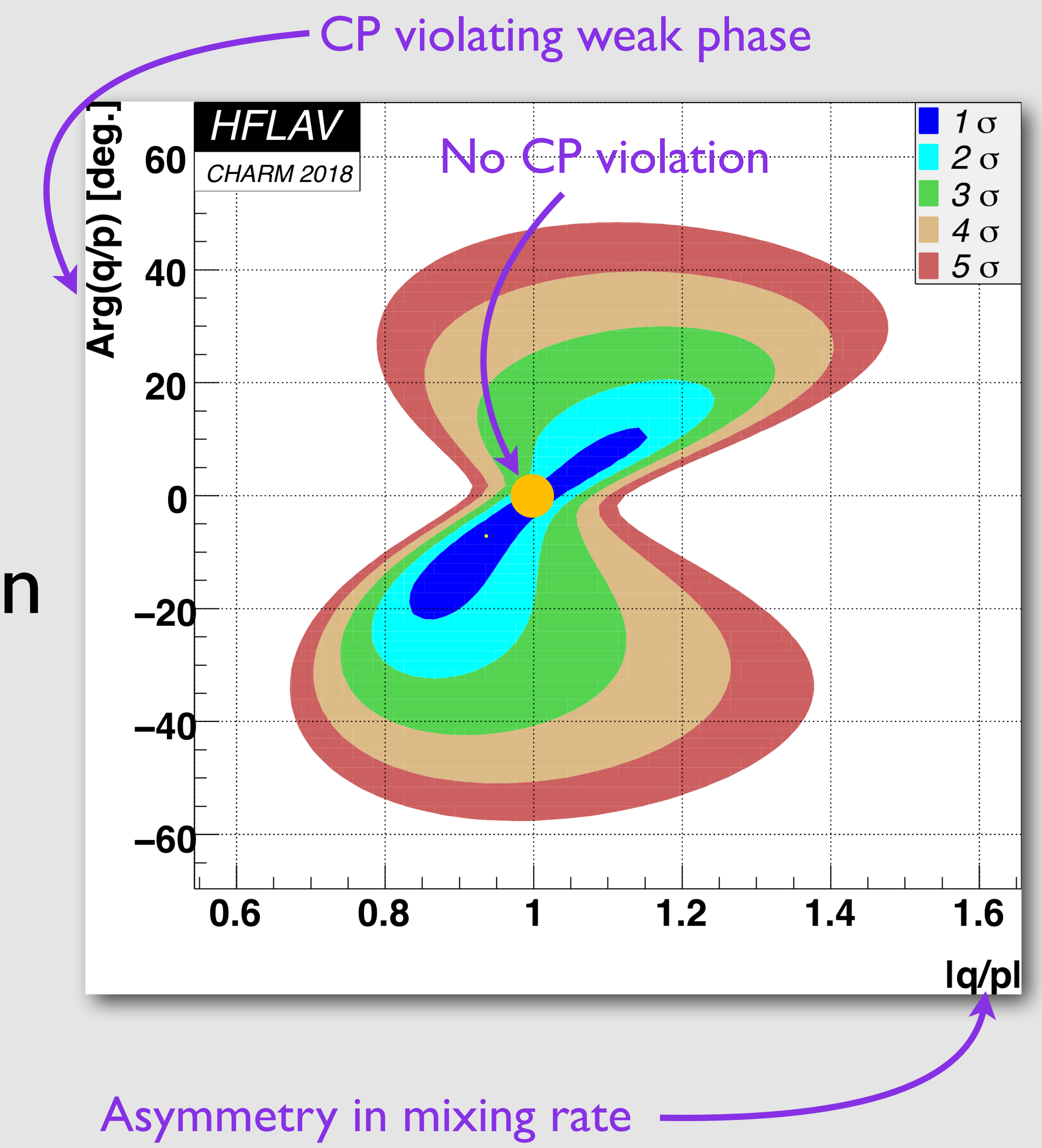
WS Kπ: symmetric in φ,

good sensitivity to |q/p| for small φ

Full average following intersection of contours

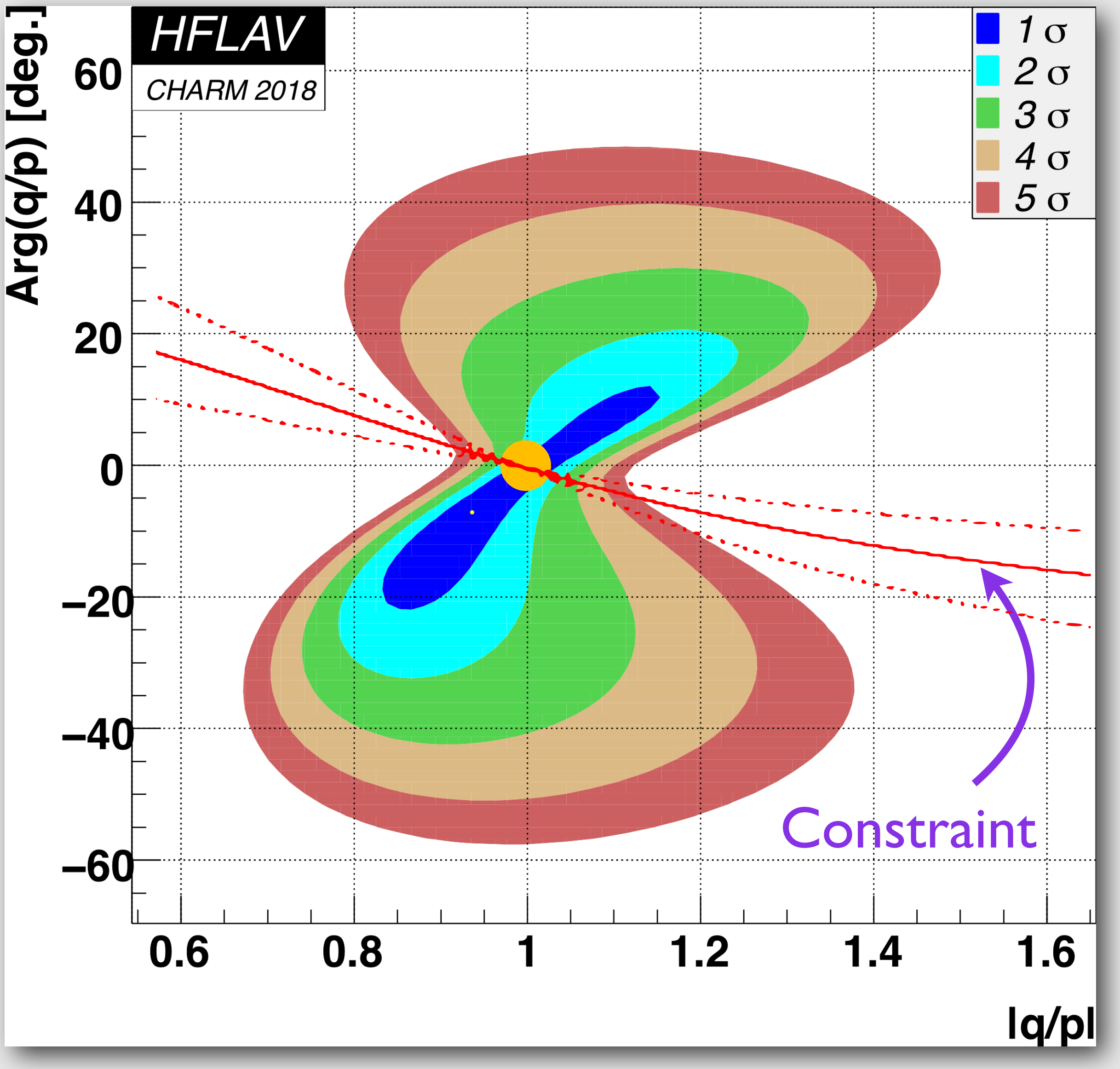
CP violation overview

- No sign of CP violation …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
  - ➡ $\tan\Phi \approx (1-|q/p|)x/y$
  - ➡ Huge improvement in precision



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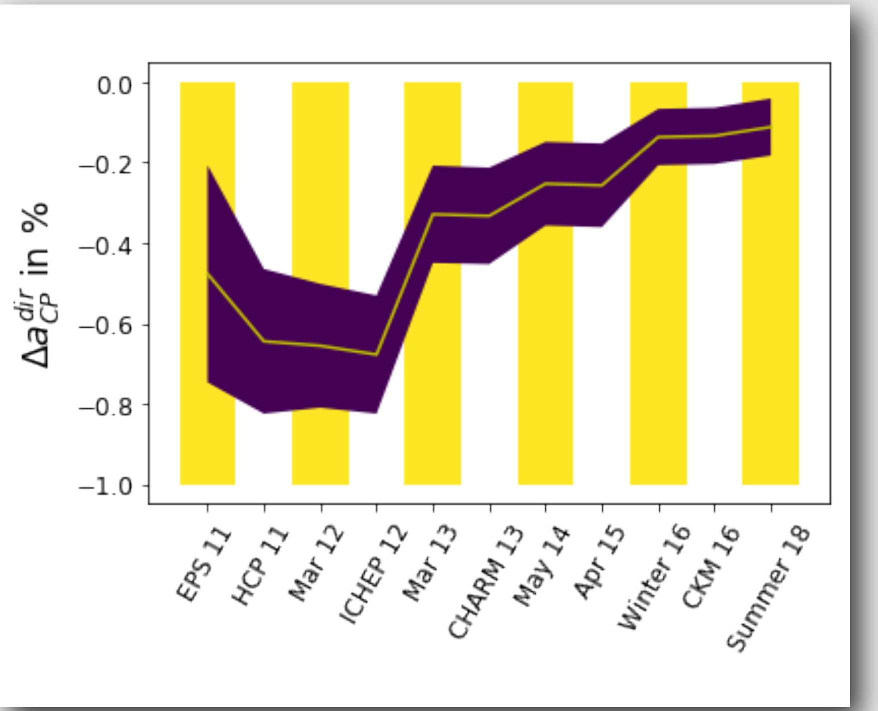
Direct CP violation

Decay rate asymmetry:

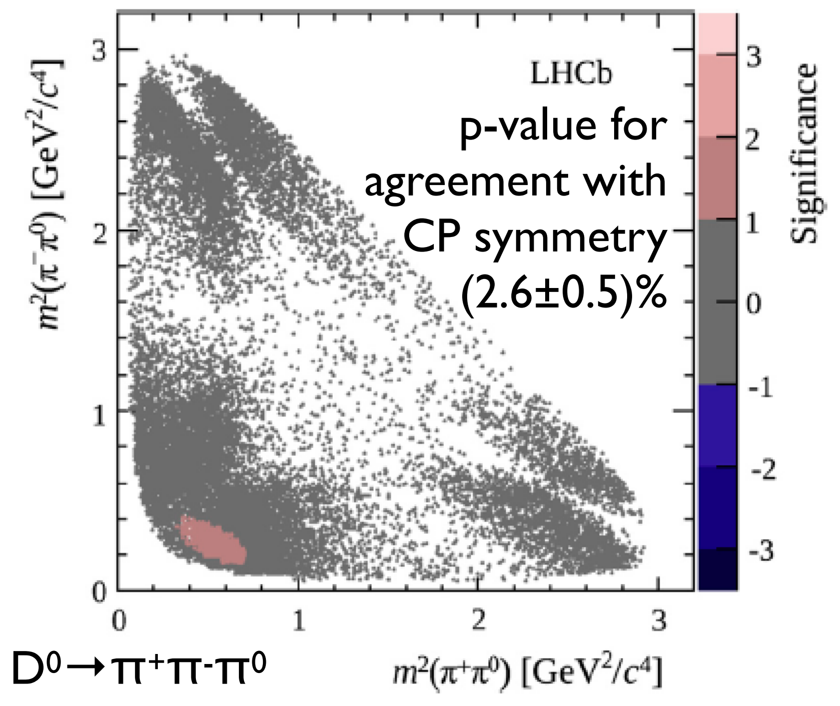
$$a_{CP}^{dir} \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}$$

CPV in decay

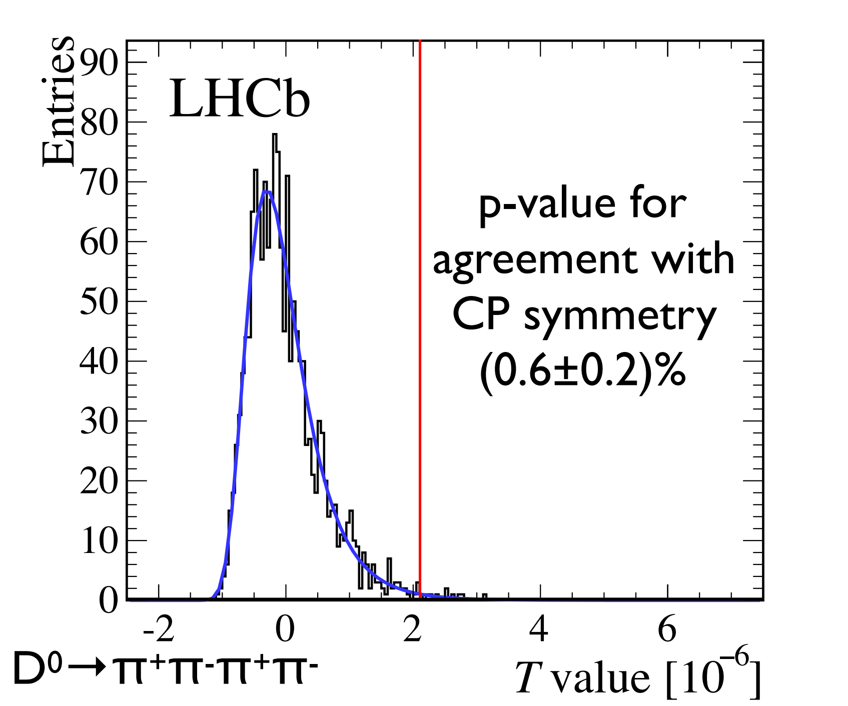
$A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$



PLB 740 (2015) 158



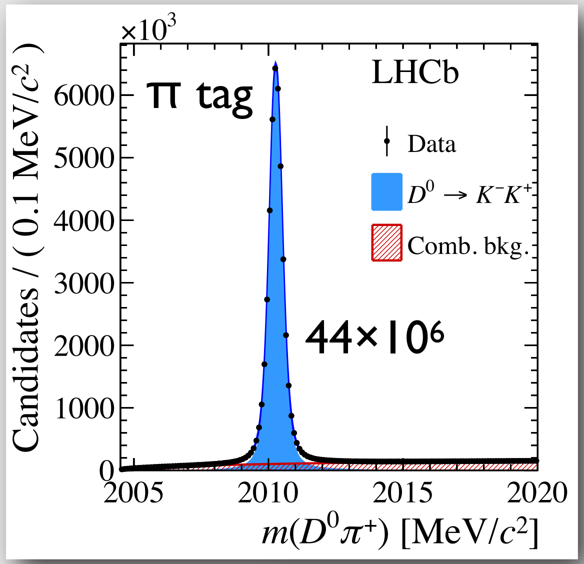
PLB 769 (2017) 345

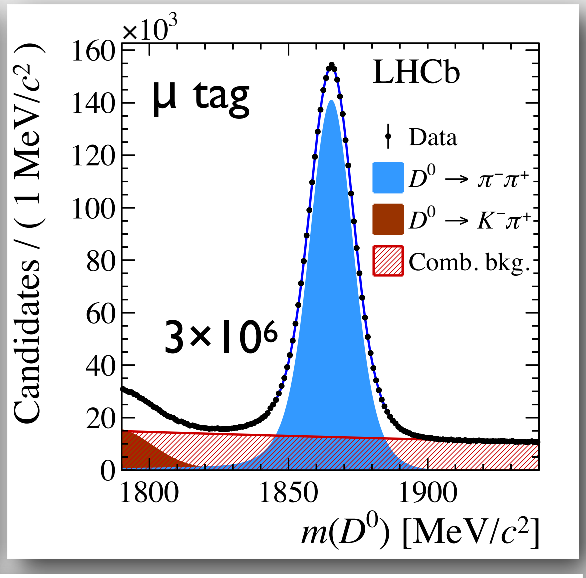


- Once upon a time, it looked like there was…
  - ➡ … but that saga got seemingly discontinued
- A growing number of decay modes explored
  - ➡ Phase-space integrated vs resonance structures
- A number of methods explored
  - ➡ Model-(in)dependent, (un)binned, triple products, …

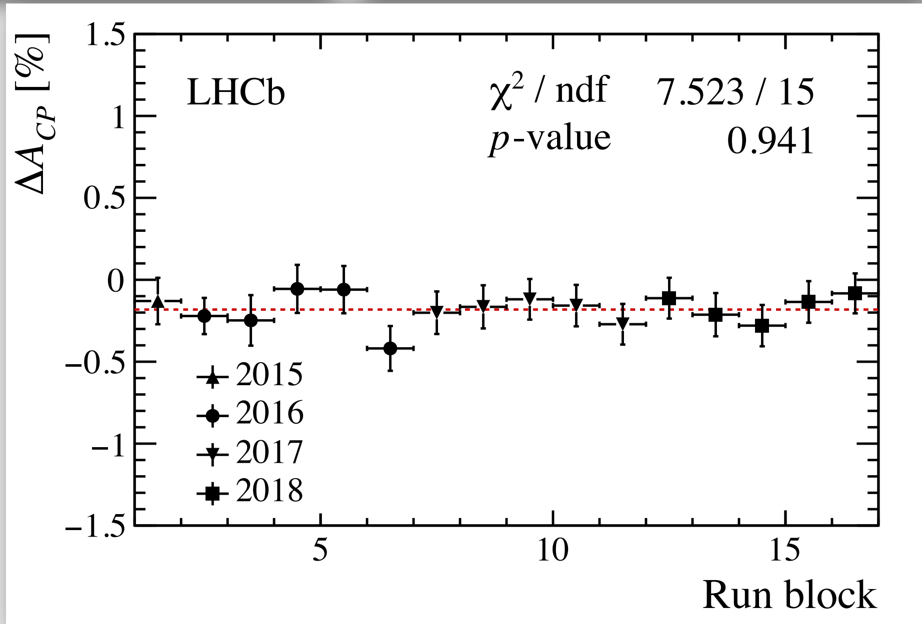
ΔA_{CP} returns

LHCb, Phys. Rev. Lett. 122 (2019) 211803

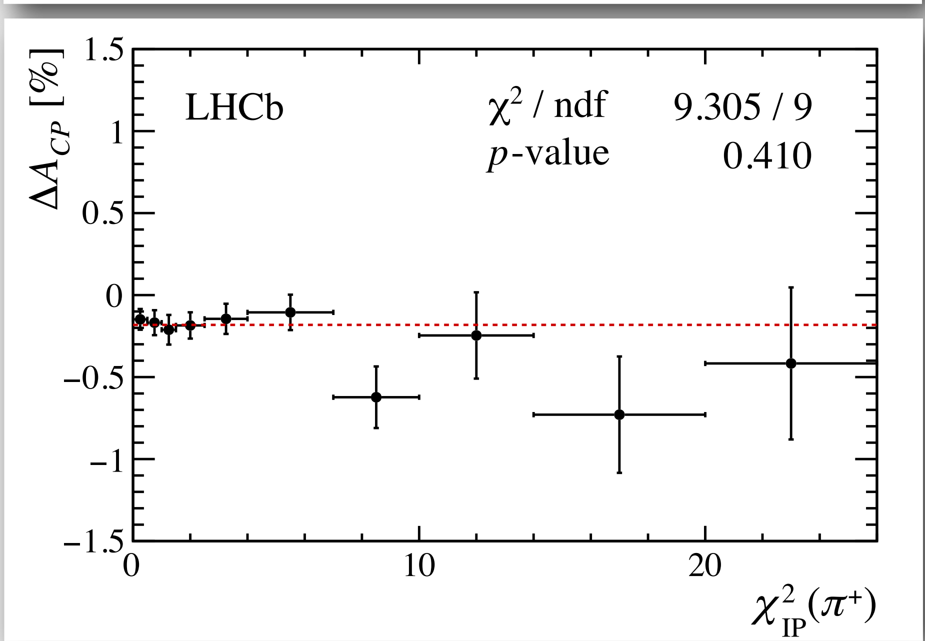




- Measure difference in time-integrated CP asymmetry between K^+K^- and $\pi^+\pi^-$ decays
  - ➡ Expect improved sensitivity due to sign flip in CKM structure and cancellation of systematic uncertainties
    - $V_{us} \sim -V_{cd}$



- Full Run 1+2 result (9 fb^{-1}) determined from prompt charm (π tag) and charm from B decays (μ tag)
  - ➡ $\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$
- First observation of CPV in charm decays



Theory perspective*

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$$\Delta A_{CP}^{\mathrm{Exp.}} = (-15.6 \pm 2.9) \times 10^{-4}$$

Physics Letters B 774 (2017) 235–242

$$\left|\Delta a_{CP}^{dir}\right| < 0.020 \pm 0.003\%$$

Direct CP asymmetry in $D \to \pi^-\pi^+$ and $D \to K^-K^+$ in QCD-based approach

Alexander Khodjamirian [a], Alexey A. Petrov [a,b,c,*]
[a] Theoretische Physik 1, Naturwissenschaftlich-Technische Fakultät, Universität Siegen, D-57068 Siegen, Germany
[b] Department of Physics and Astronomy, Wayne State University, Detroit, MI 48201, USA
[c] Michigan Center for Theoretical Physics, University of Michigan, Ann Arbor, MI 48196, USA

BSM!

ΔA_{CP} within the Standard Model and beyond

Mikael Chala, Alexander Lenz, Aleksey V. Rusov and Jakub Scholtz

BSM! **Z'?**

$$|\Delta A_{CP}^{\mathrm{SM}}| \leq 3 \times 10^{-4}$$

The Emergence of the $\Delta U = 0$ Rule in Charm Physics

Yuval Grossman* and Stefan Schacht†
D... of Physics, LEPP, Cornell University, Ithaca, NY 14853, USA

SM

"in SM requires mild non-perturbative enhancement due to rescattering amplitudes"

Implications on the first observation of charm CPV at LHCb

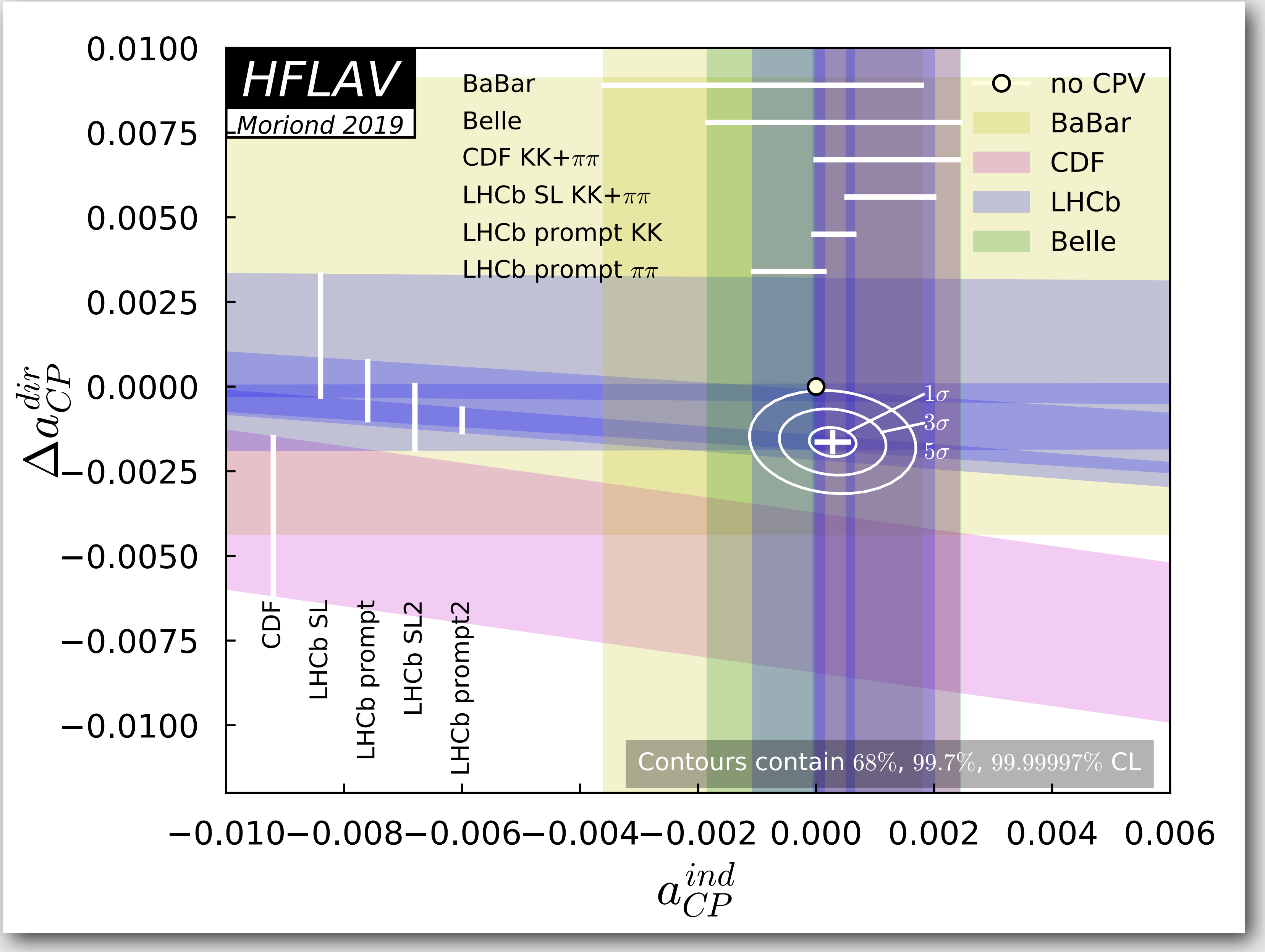
Hsiang-nan Li[1*], Cai-Dian Lü[2†], Fu-Sheng Yu[3‡]
[1] Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China
Lanzhou 730000, People's Republic of China

SM

$$\Delta A_{CP}^{\mathrm{SM}} = (-0.57 \sim -1.87) \times 10^{-3}$$

*a brief snapshot that cannot do justice to the amount of work done here

CP violated in charm!

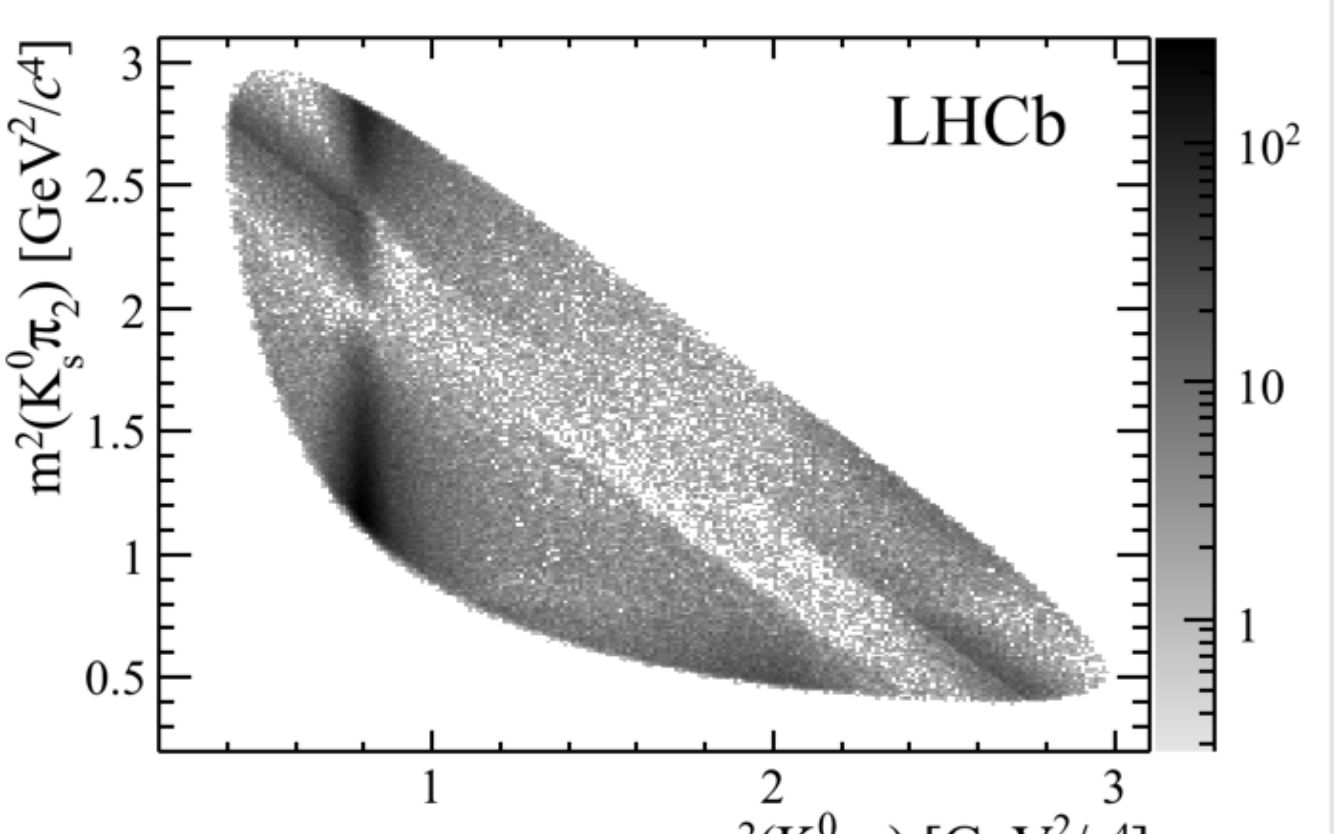


- Direct CPV in charm
- No hint for indirect CPV
- SM or BSM?
  - ➡ Open question for now
- Need theoretical advances <u>and</u> more measurements

4 — Multi-body decays

Dalitz plots

$D^0 \rightarrow K_S \pi^- \pi^+$

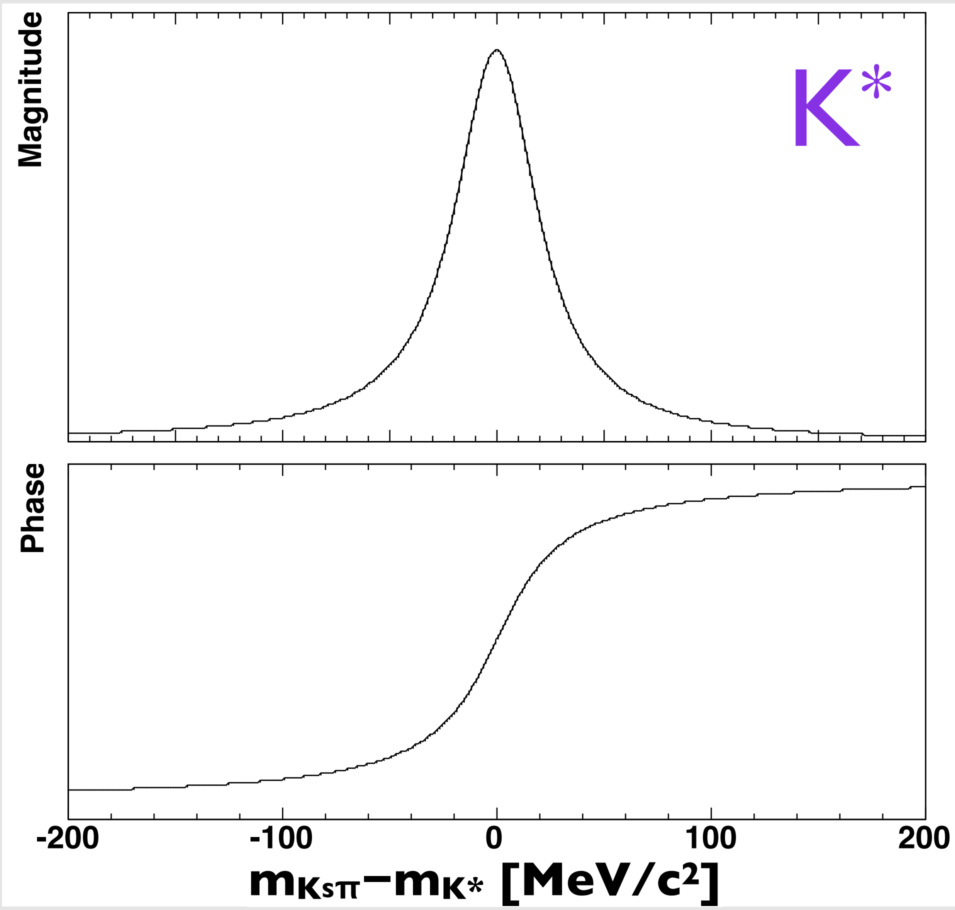


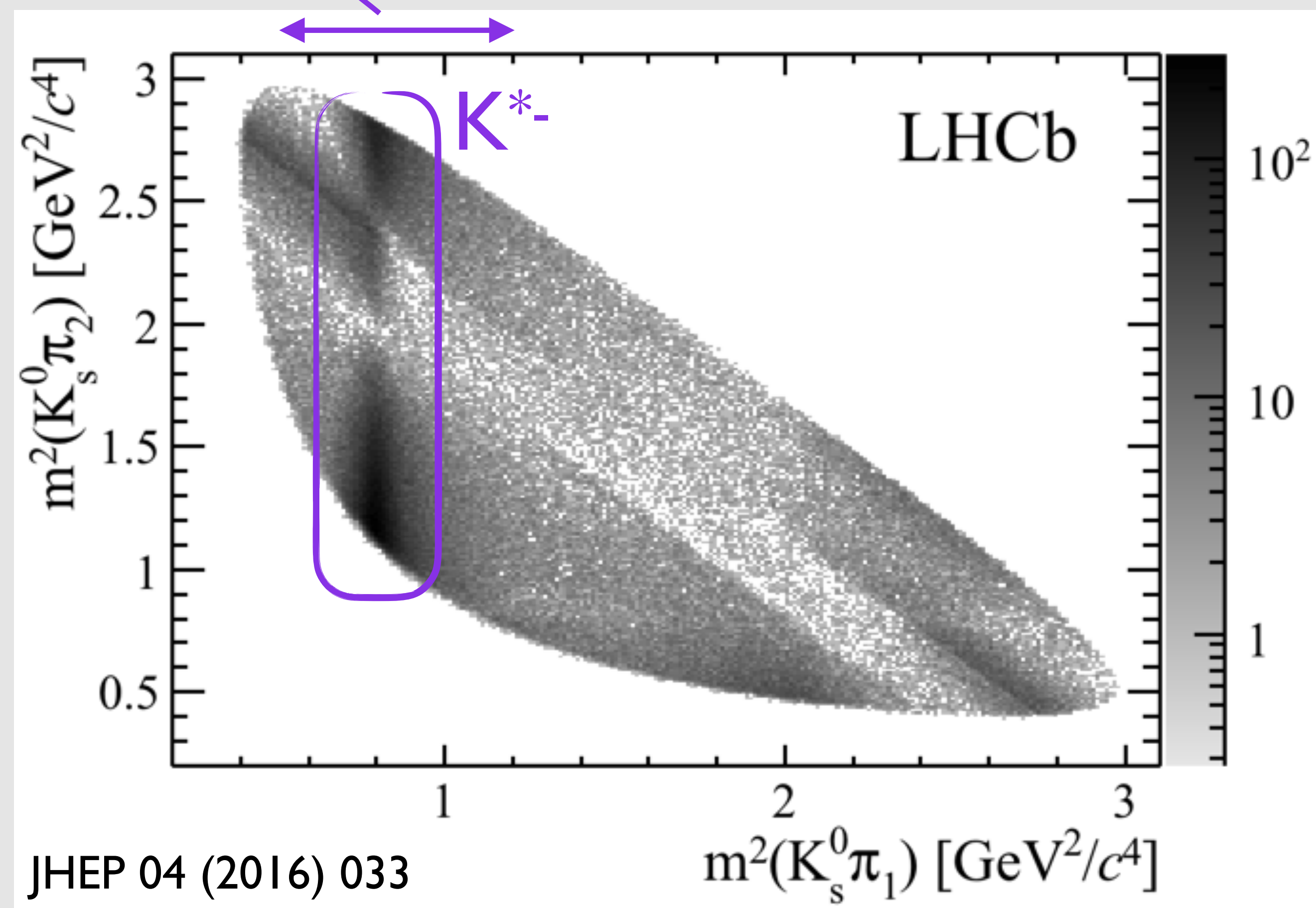
JHEP 04 (2016) 033

Dalitz plots

$D^0 \to K^{*-}(\to K_S\pi^-)\pi^+$

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





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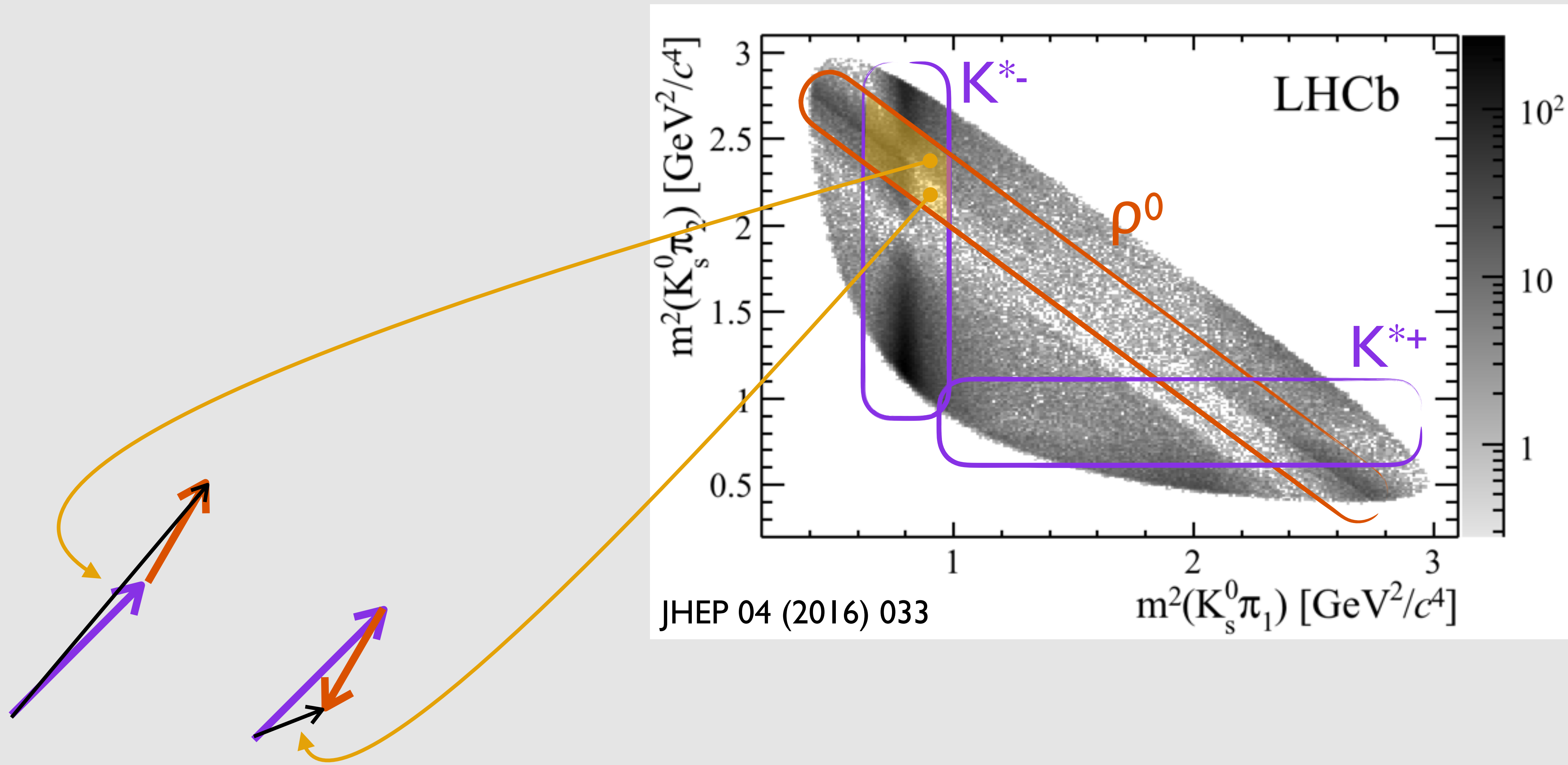
Dalitz plots

$D^0 \rightarrow K_S \pi^- \pi^+$



- Dalitz plot density is modulus squared of a sum of complex amplitudes $|A_{tot}|^2 = |\sum A_{resonance}|^2$
- Interference regions contain rapid phase variation

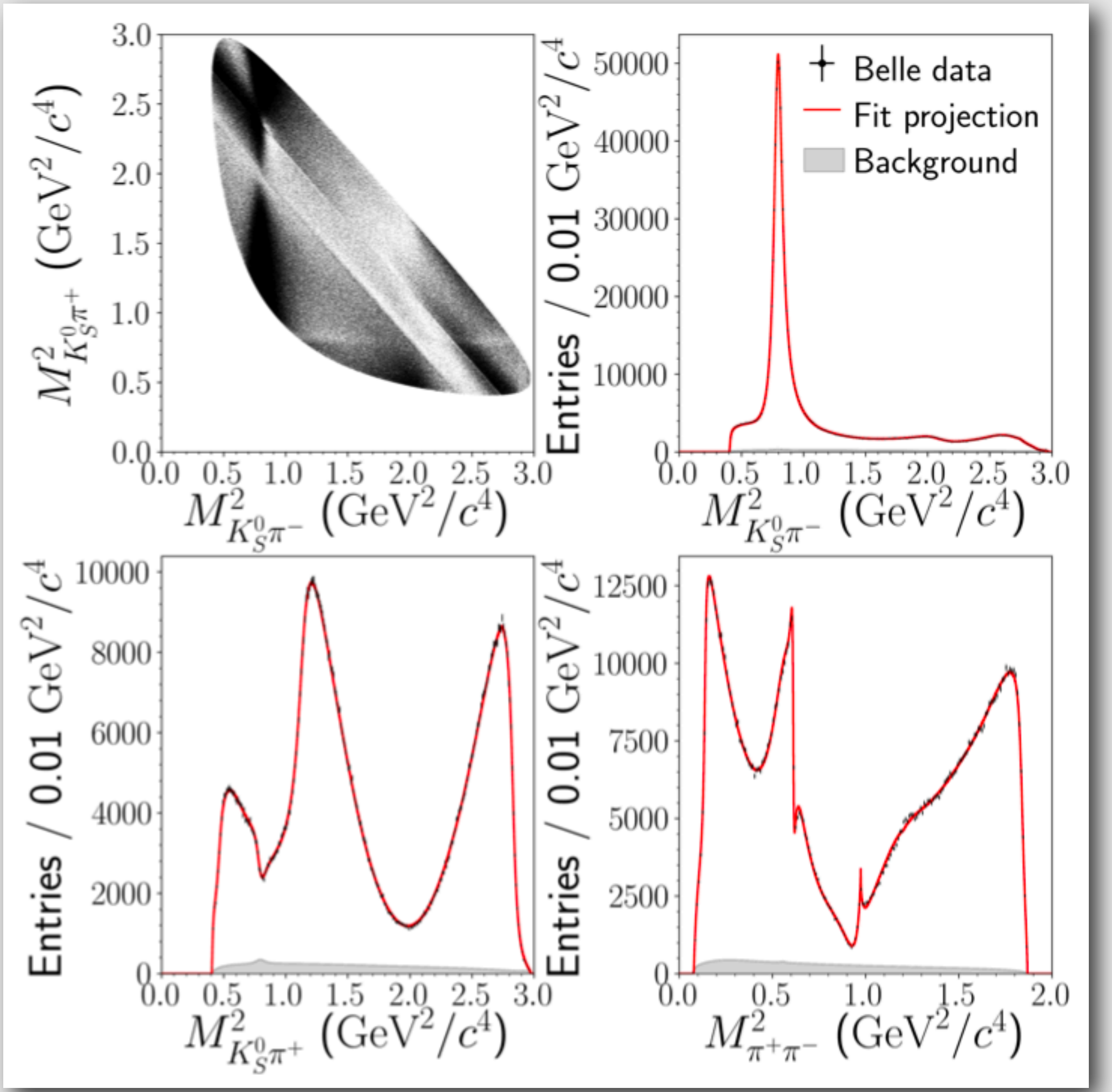
➡ Superb playground for CP violation

Latest model

Phys. Rev. Lett. 121, 261801 (2018)
Phys. Rev. D 98, 112012 (2018)

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

➡ Feasible both for Belle II and LHCb



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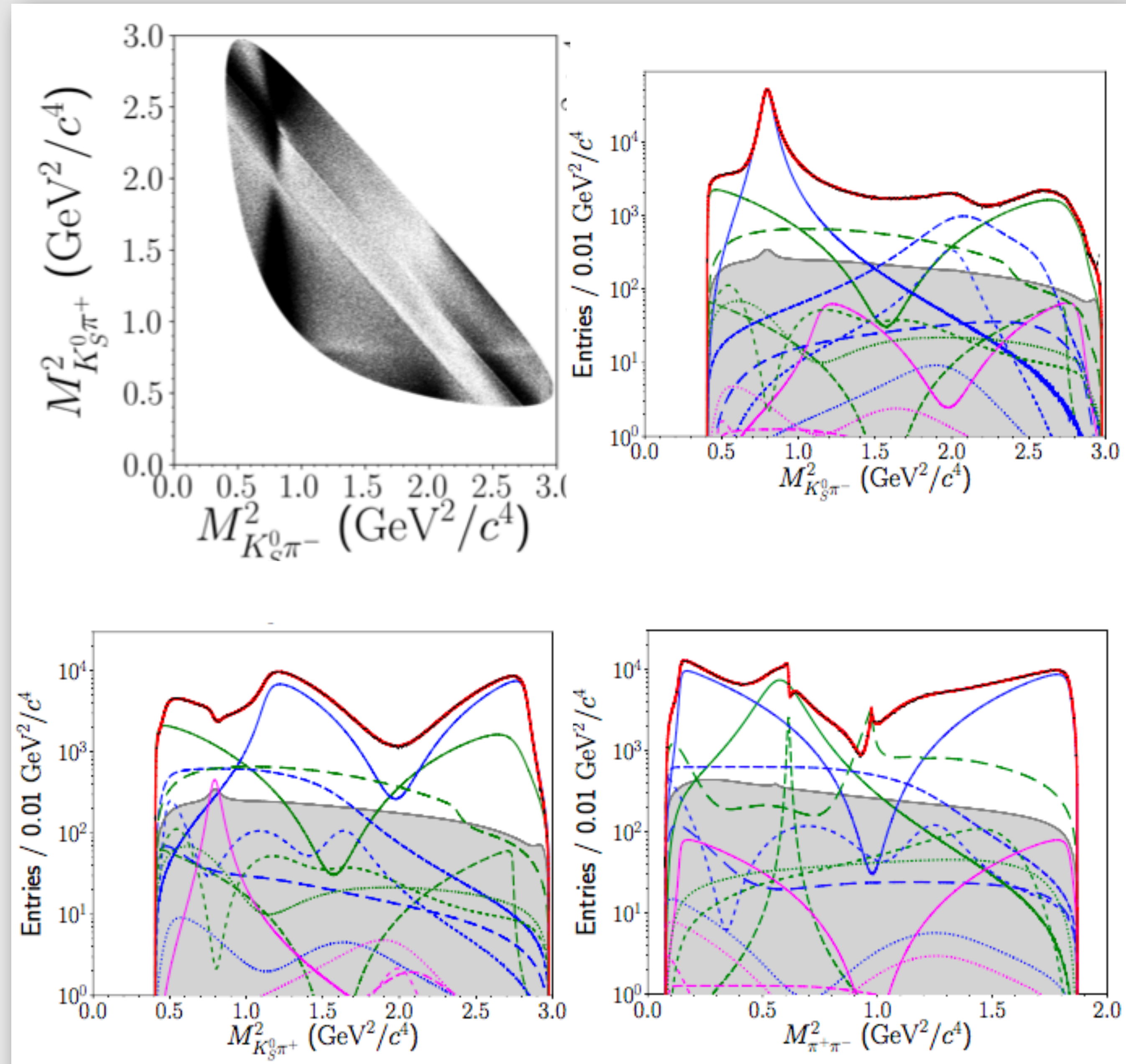


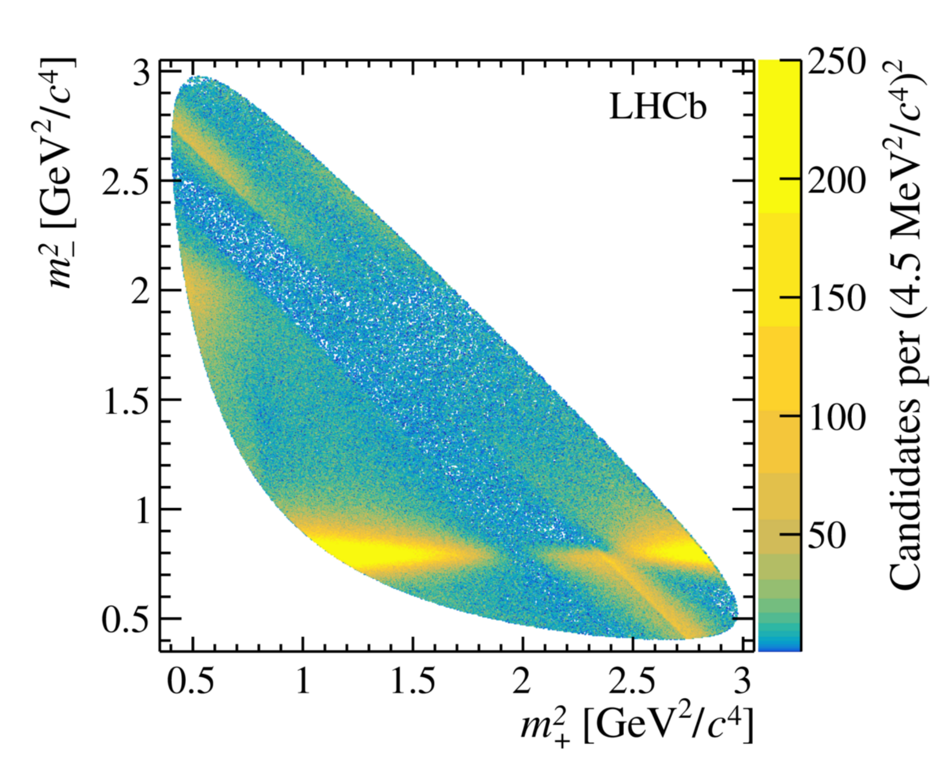
Individual fit contributions

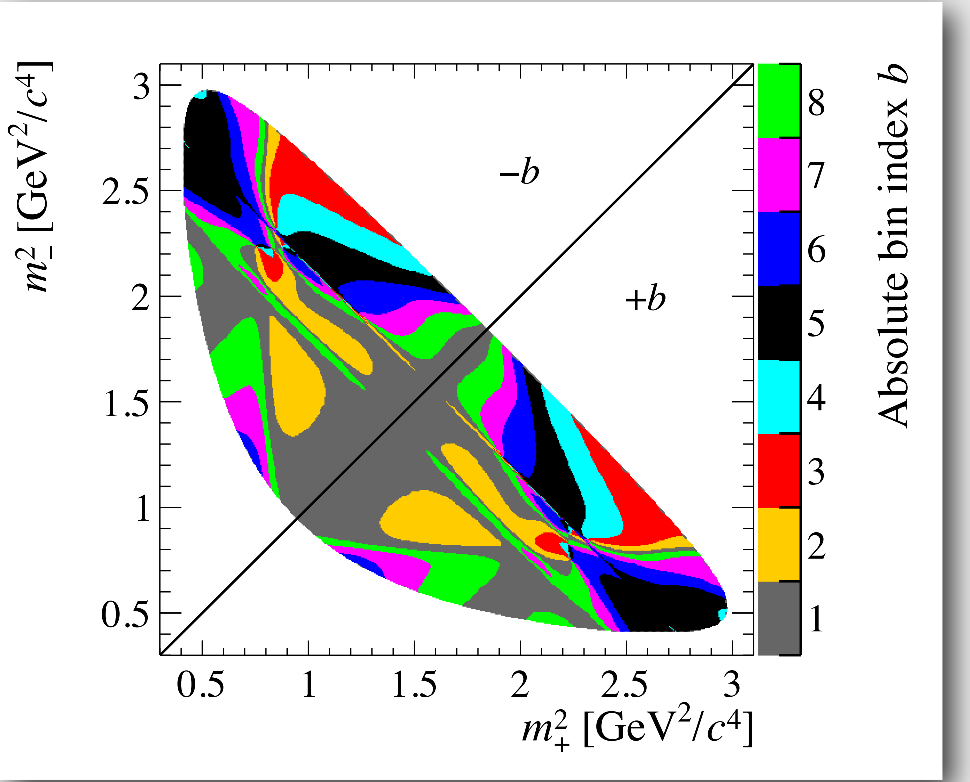
Latest measurement

- $D^0 \to K_S\pi^+\pi^-$ requires time-dependent amplitude analysis
  - ➡ Gives access to mixed and unmixed rates and strong phase differences
    - Measures individual mixing (x,y) and CPV parameters ($|q/p|$, ϕ)
  - ➡ Measurement based on lifetime ratios in bins with similar strong-phase difference (3 fb^{-1})

Parameter	Value $[10^{-3}]$
x_{CP}	$2.7 \pm 1.6 \pm 0.4$
y_{CP}	$7.4 \pm 3.6 \pm 1.1$
Δx	$-0.53 \pm 0.70 \pm 0.22$
Δy	$0.6 \pm 1.6 \pm 0.3$

LHCb, arXiv:1903.08726





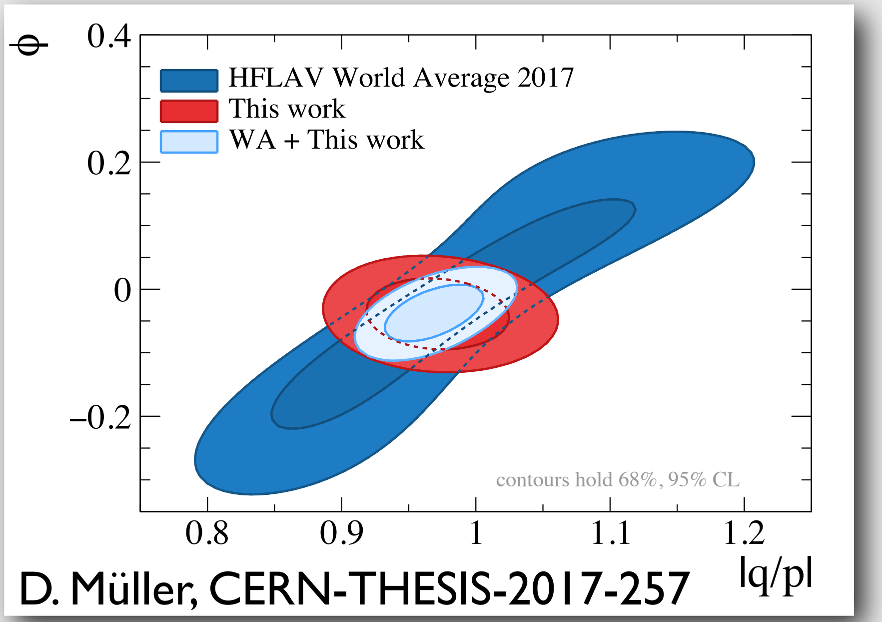
Multi-body decays

- 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
    - ‣ BESIII experiment can provide these

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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Future directions

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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

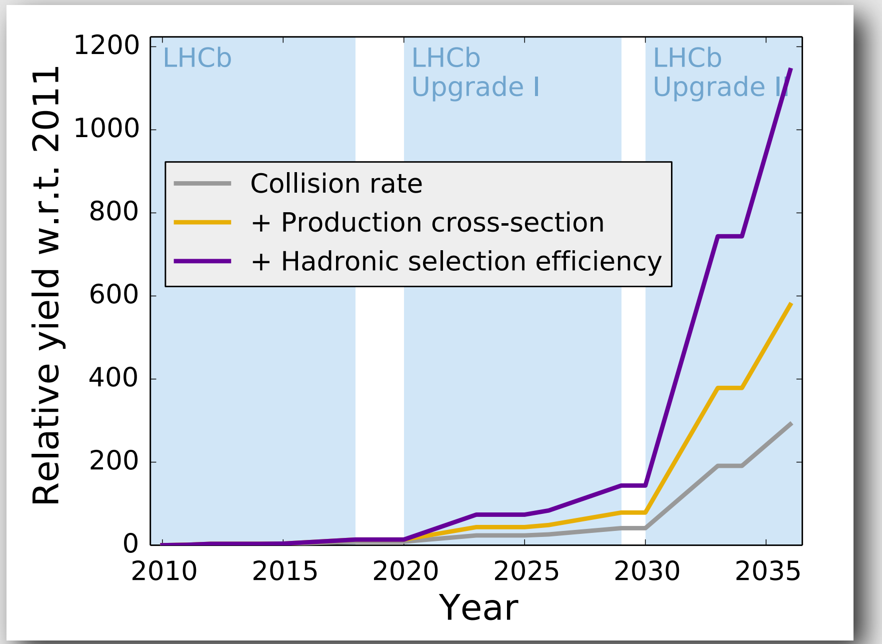
- Yuval: "While the central value of Δa_{CP} fits nicely in the SM, we cannot yet exclude that it may be due to NP"

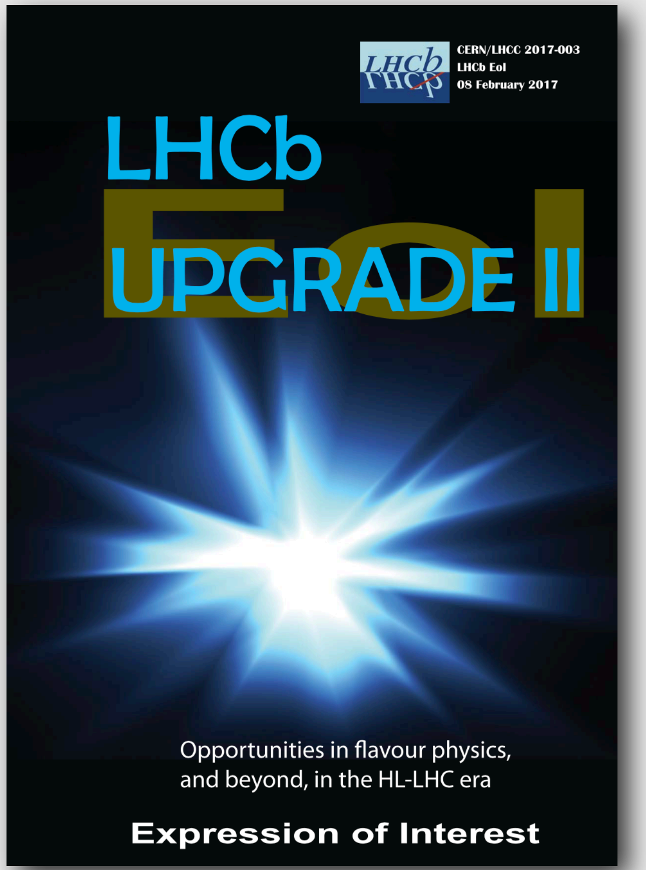
- Topologically the above two statements are equivalent
- Just like a bagel and a mug are
- Yet, to emphasize, whether Zoltan, me, or anyone else is the bagel is not the issue
- The issue is how can we keep on checking

Yuval Grossman, Experimental Summary, CHARM 2012

LHCb Upgrades

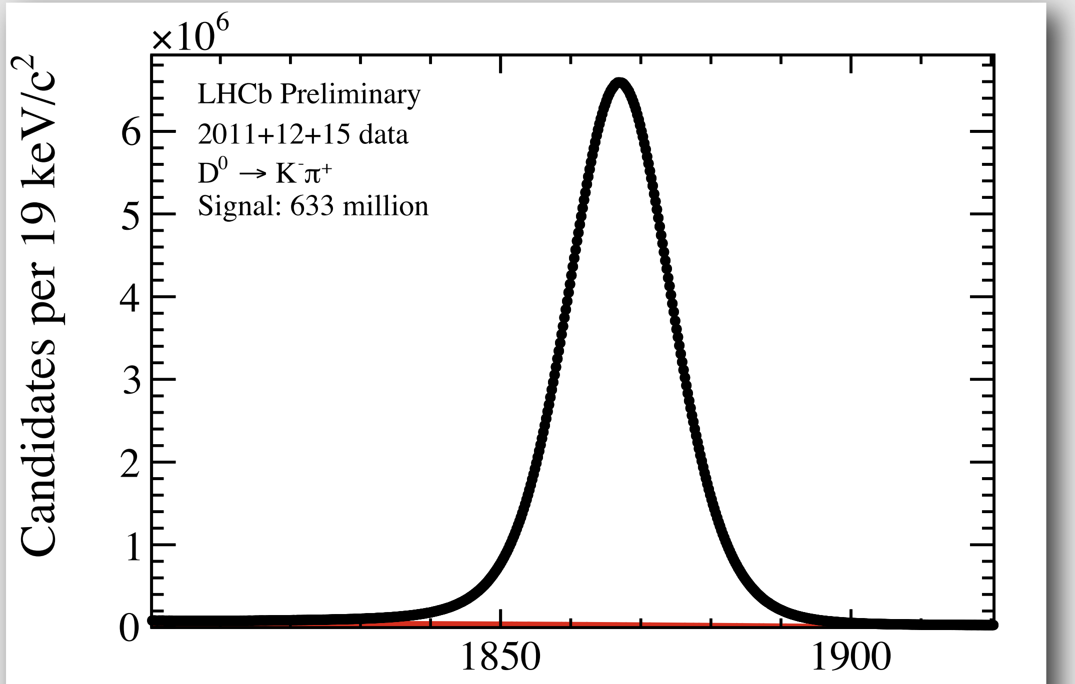
- Charm CP violation has been discovered in decays
  - ➡ What about indirect CP violation?
- Will require much more data to
  - ➡ Identify underlying sources
  - ➡ Challenge SM level in both direct and indirect CPV
- LHCb is the best bet for charm for the foreseeable future
  - ➡ Best shot at BSM physics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





Charm the challenge champion

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

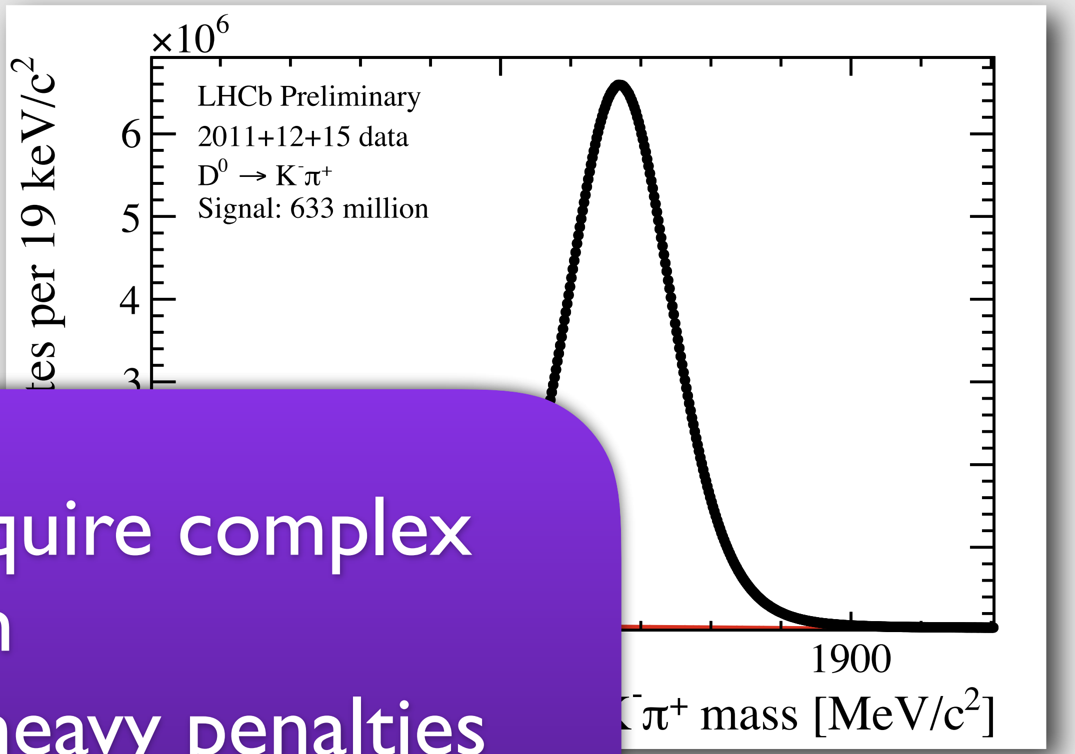


LHCb-CONF-2016-005

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

Charm the challenge champion

- Charm among the most abundant particles produced

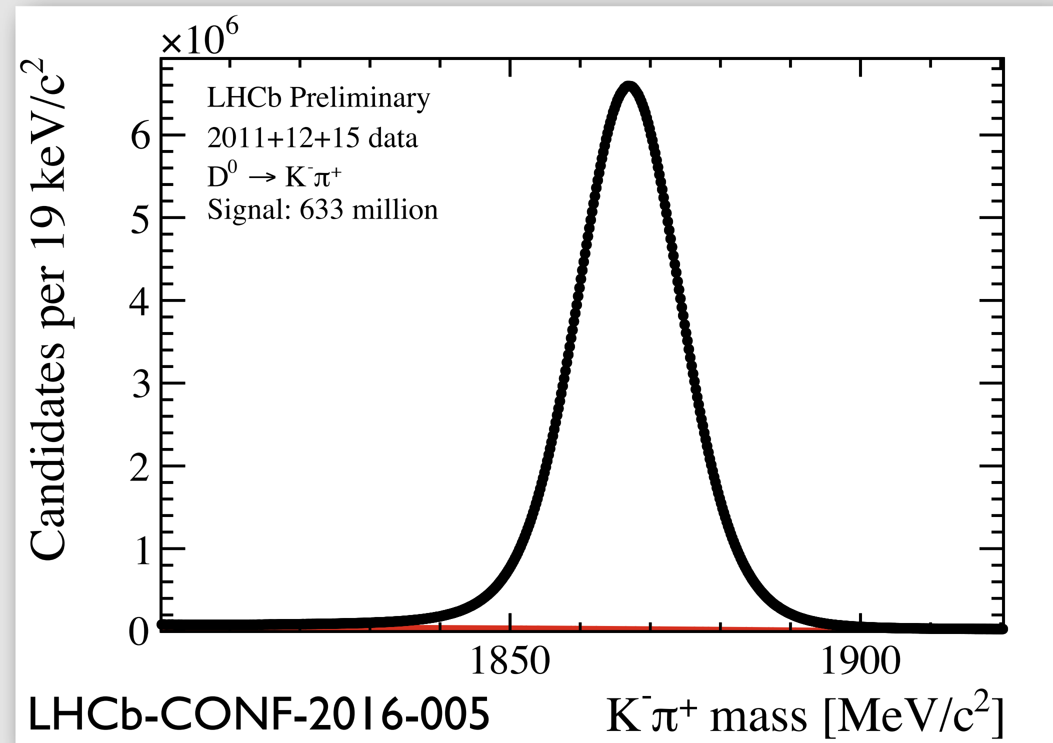


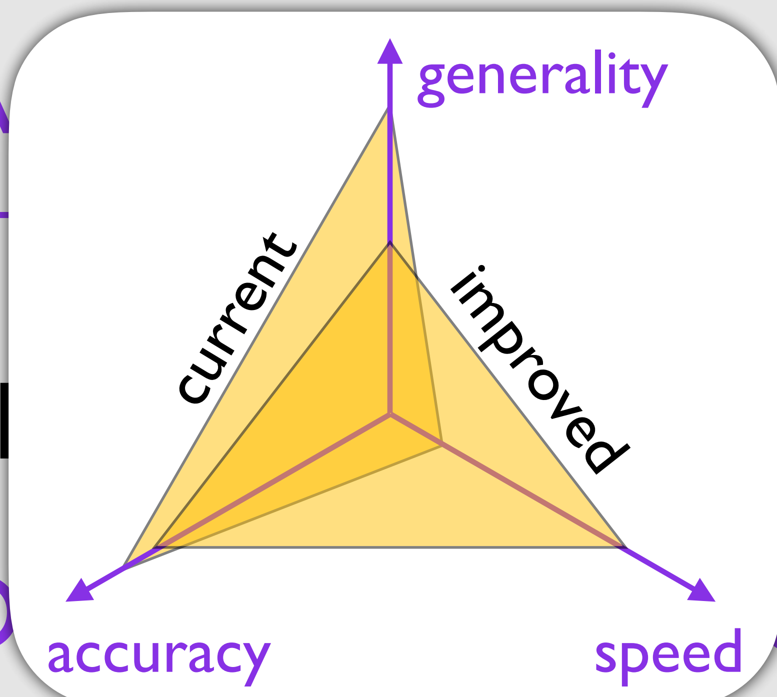
High rates of low p_T particles require complex decisions early on in trigger chain
→ Coarse decisions come with heavy penalties
→ Need to avoid burning detectors for little gain

- 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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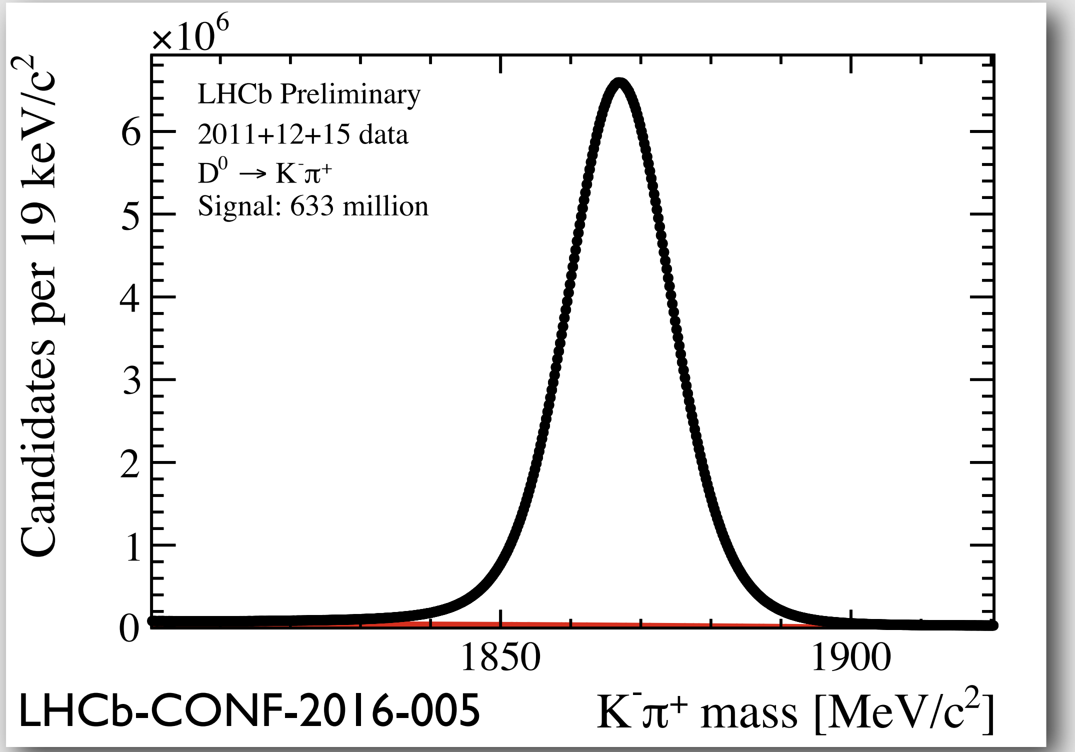
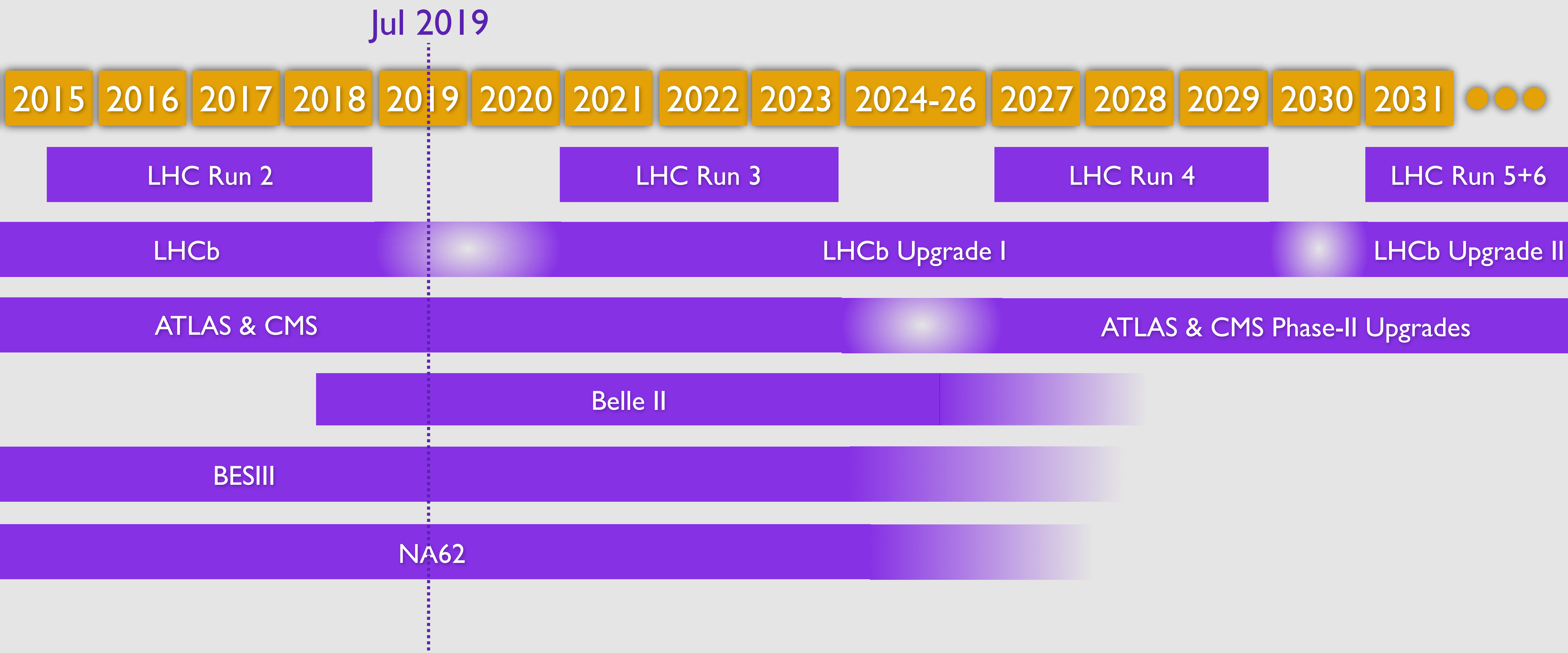


- Technical c
  - ➡ Data s
  - ➡ Simula
  - ➡ Data analysis

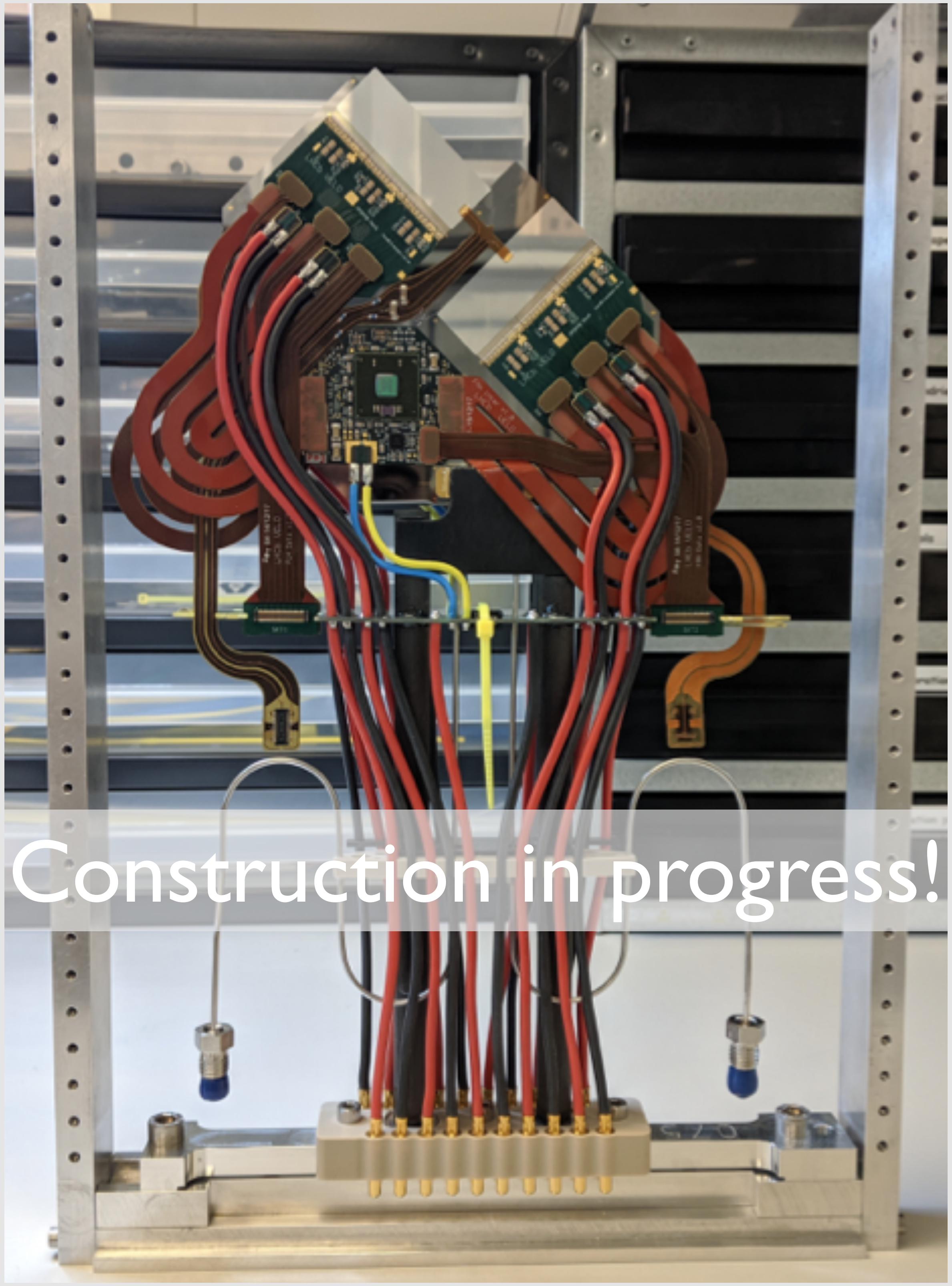
Fitting large data sets is a growing challenge
→ Will need more and more sophisticated models
→ Playground for new approaches, e.g. with GPUs

A flavourful decade



- Plus lots of activity on charged lepton flavour
  - ➡ MEG, mu3e, mu2e, COMET, g-2, …

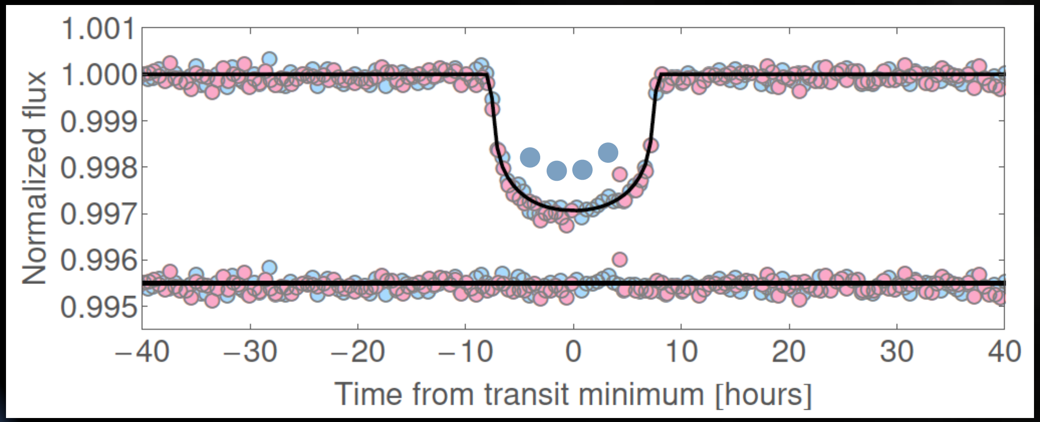
LHCb Upgrade I



Conclusion

- LHCb now taken over leading role in charm physics
- Production
  - ➡ The source of precision
- Mixing
  - ➡ First evidence for positive mass difference
- CP violation
  - ➡ Discovered in direct CP violation: is it SM?
- Multi-body decays
  - ➡ Interference reveals the details
- Need LHCb upgrades to probe to Standard Model level precision
- Next decade will be flavourful
  - ➡ Belle II, BESIII, COMET, g-2, LHCb upgrades, MEG, mu2e, mu3e, NA62

Conclusion



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