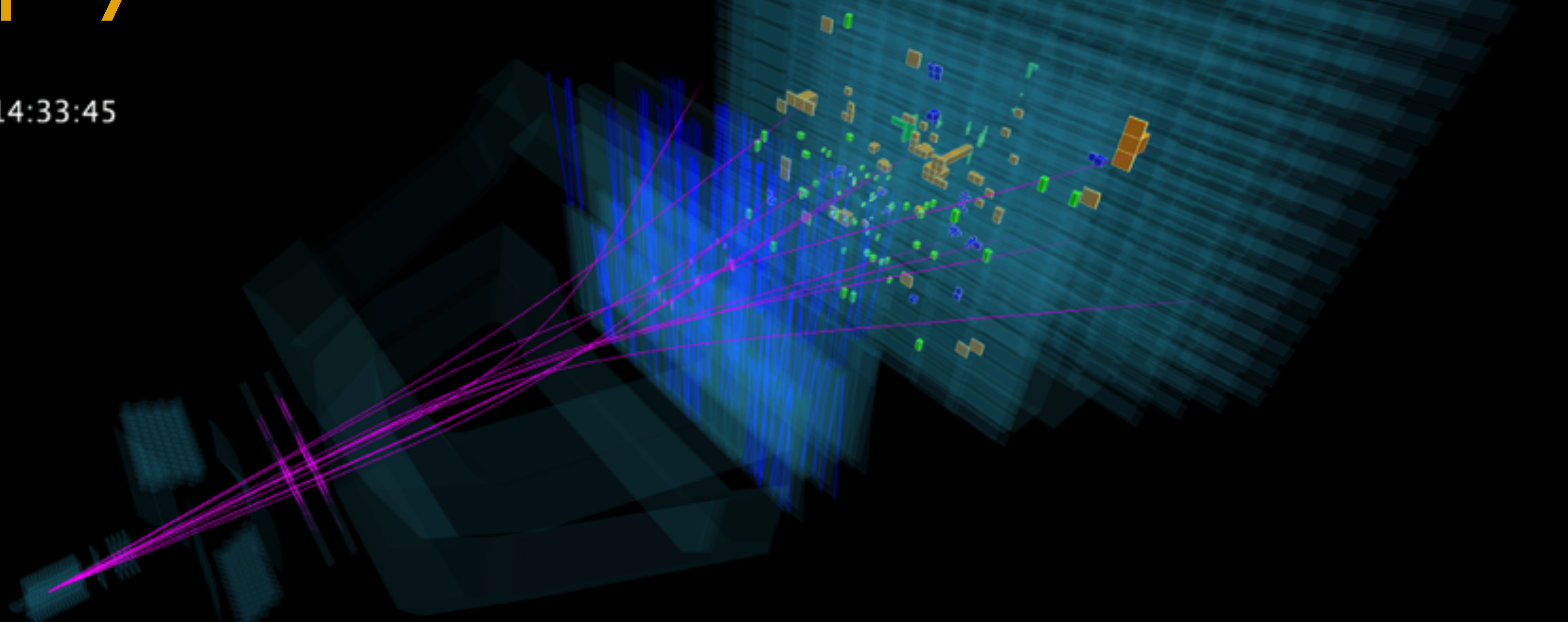
Recent results and prospects of quark flavour physics at LHCb

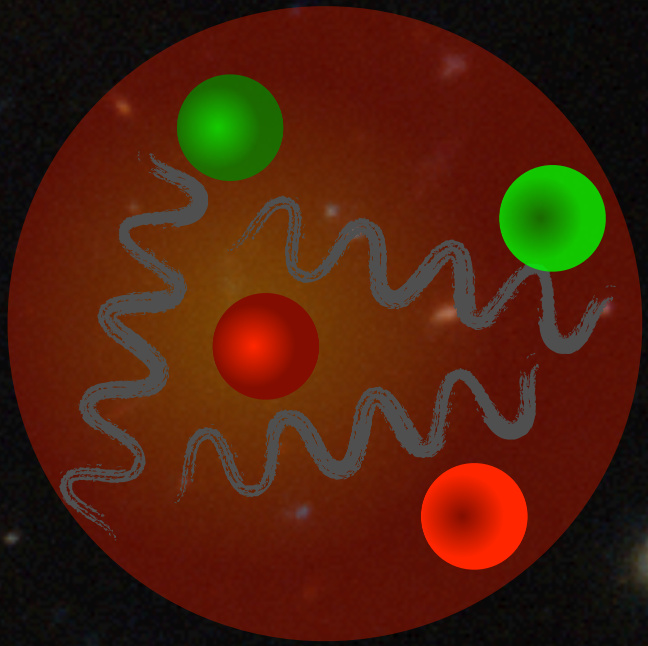


Marco Gersabeck (The University of Manchester)

Particle Physics Seminar, Birmingham, 16/11/2016

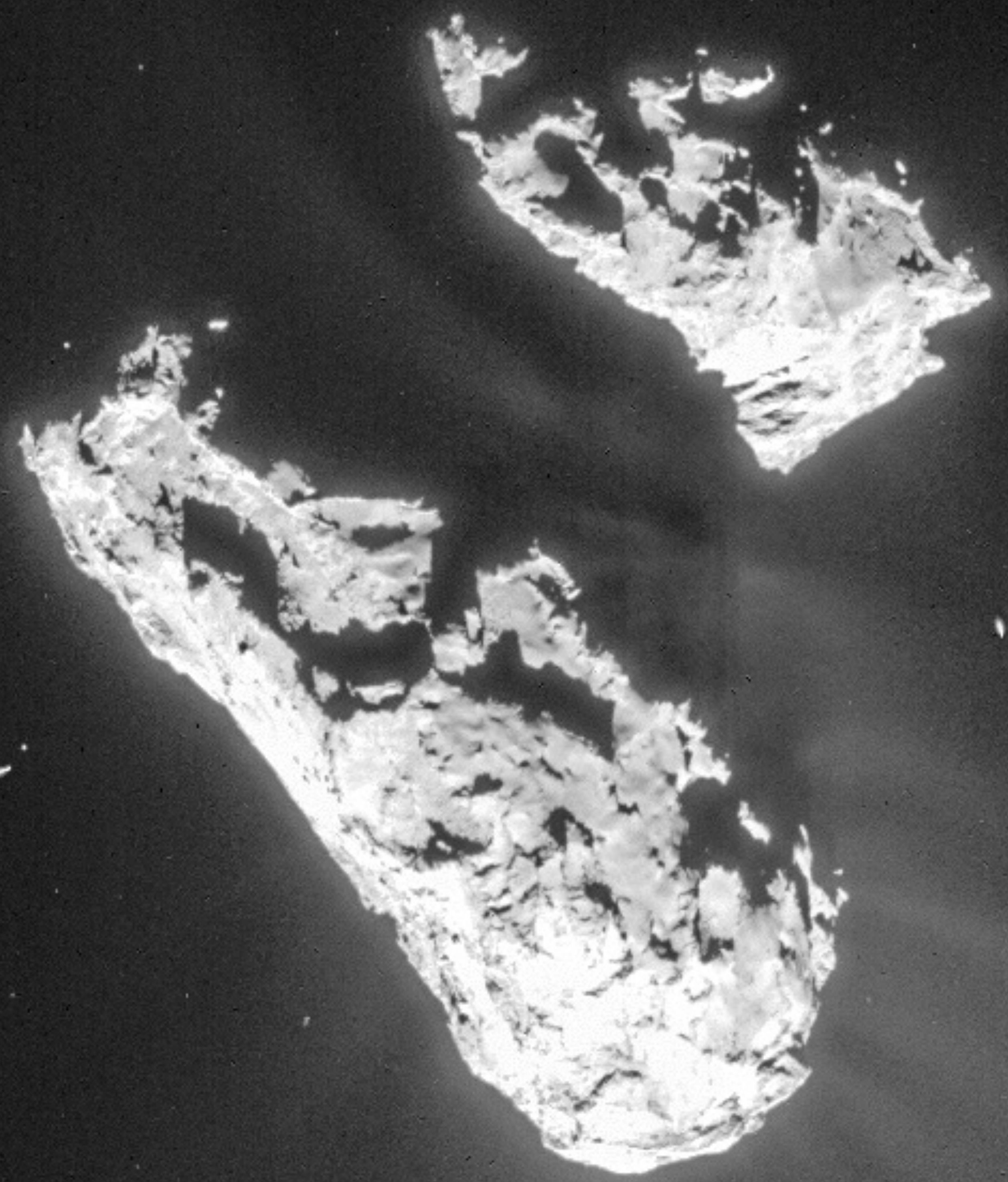
Two roads to discovery

New particles = New planets



ESA/Hubble

Direct searches

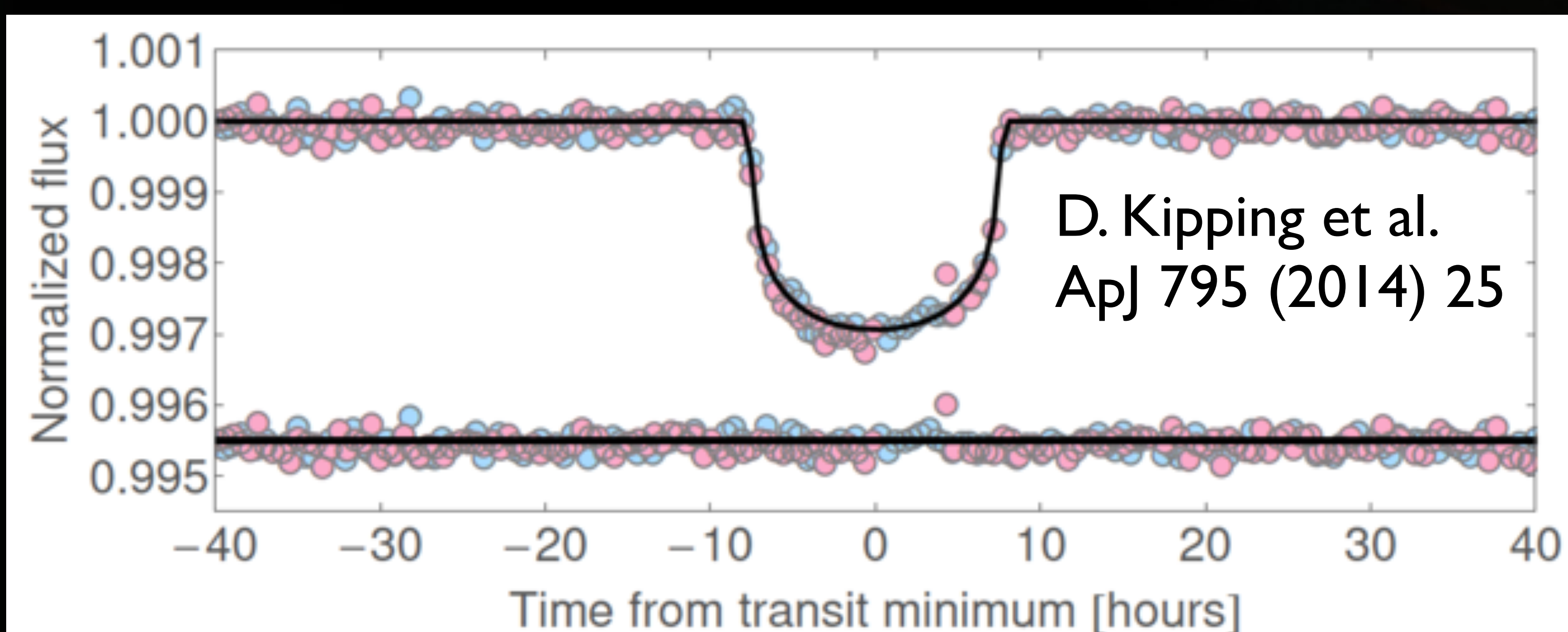


Reach limited by amount of fuel

ESA/Rosetta/NAVCAM

Indirect searches

Look for subtle deviations
in known processes



David A. Aguilar (CfA)

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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

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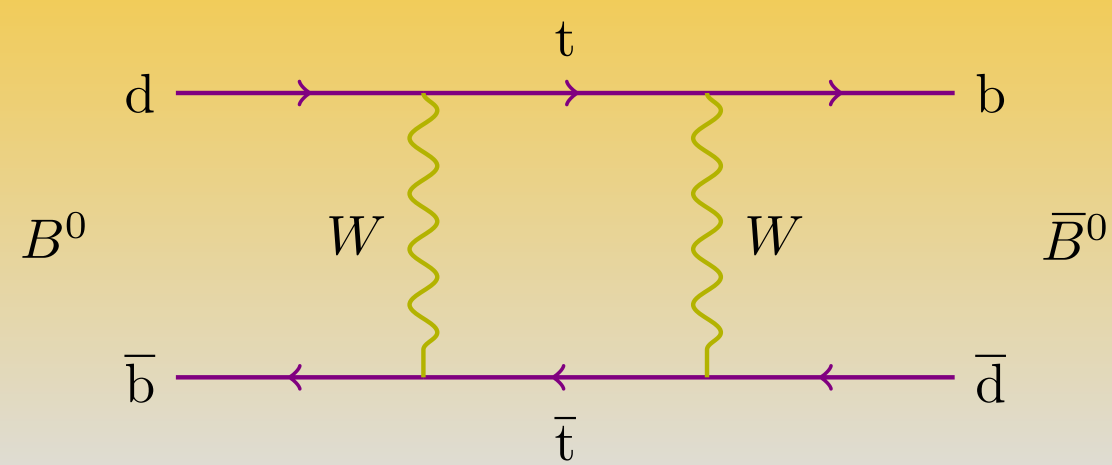
Flavour physics:
Fast-tracking discoveries

- K^0-$\overline{K}^0$ mixing
  - ➡ GIM mech
- Kaon CP viol
  - ➡ KM mecha

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

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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

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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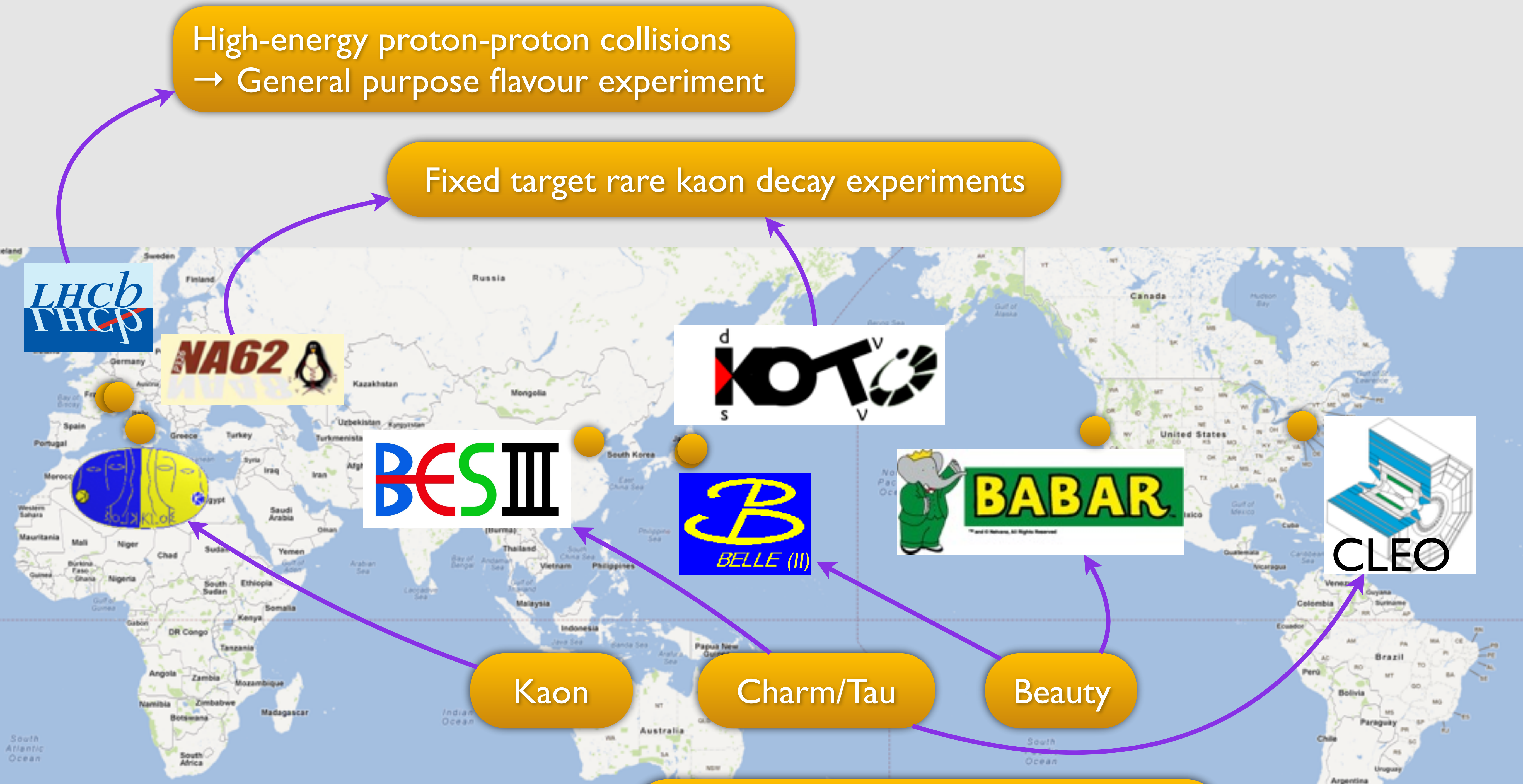
Flavourful experiments



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

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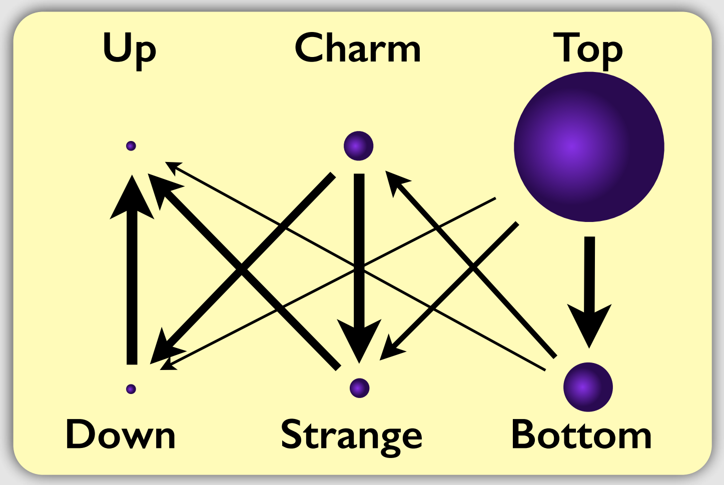
Outline

- CP violation
  - ➡ Selected highlights of small and large asymmetries
- The needles in the haystack
  - ➡ Rare decays
- A brief visit to the particle zoo
  - ➡ Other physics areas
- Future directions
  - ➡ Upgrade programmes

CKM matrix

- Unitary matrix combining flavour and mass eigenstates

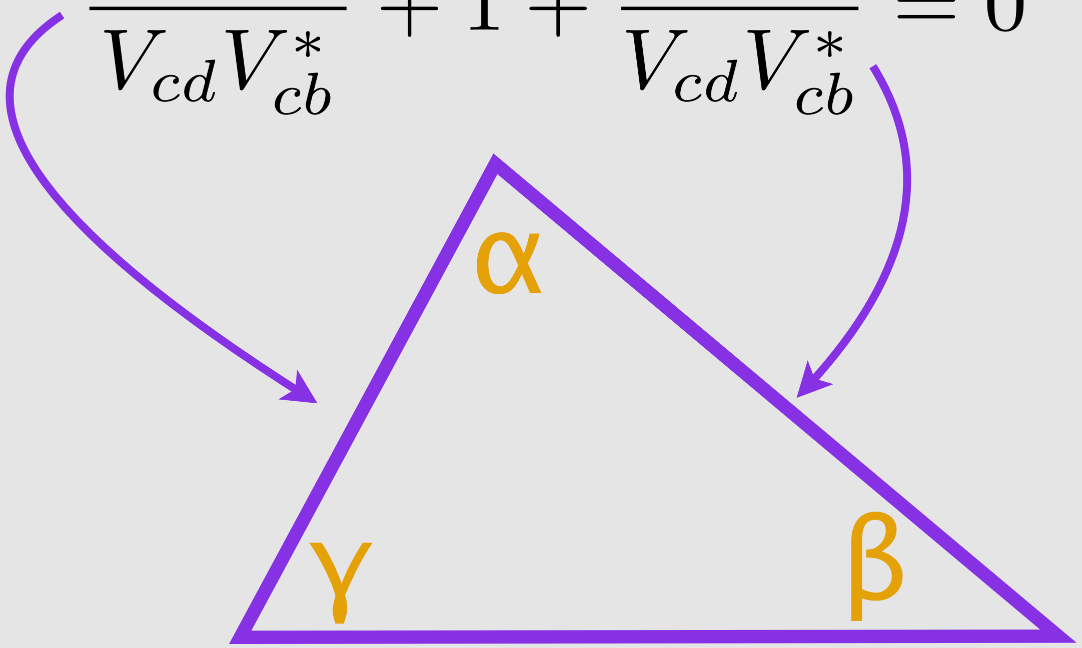
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



- Unitarity relations lead to triangles in complex plane

$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + 1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0$$

B_d triangle



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CKM matrix

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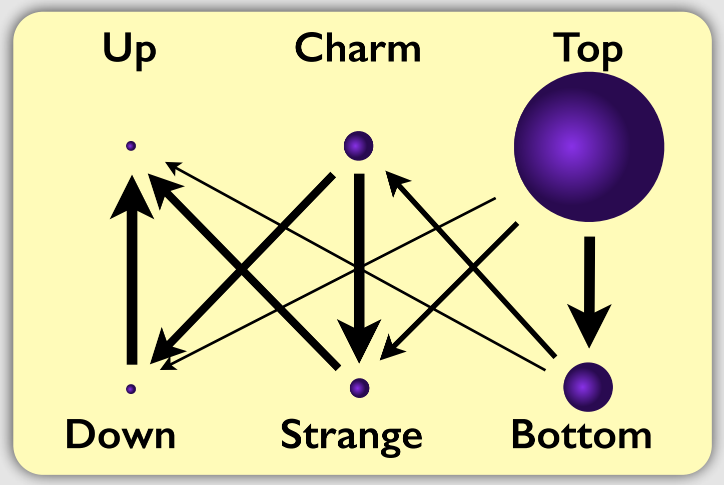

- Unitarity relations lead to triangles in complex plane

$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + 1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0$$ B_d triangle

$$\frac{V_{us}V_{ub}^*}{V_{cs}V_{cb}^*} + 1 + \frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*} = 0$$ B_s triangle

$$\frac{V_{ud}V_{cd}^*}{V_{us}V_{cs}^*} + 1 + \frac{V_{ub}V_{cb}^*}{V_{us}V_{cs}^*} = 0$$ D triangle

+ 3 more

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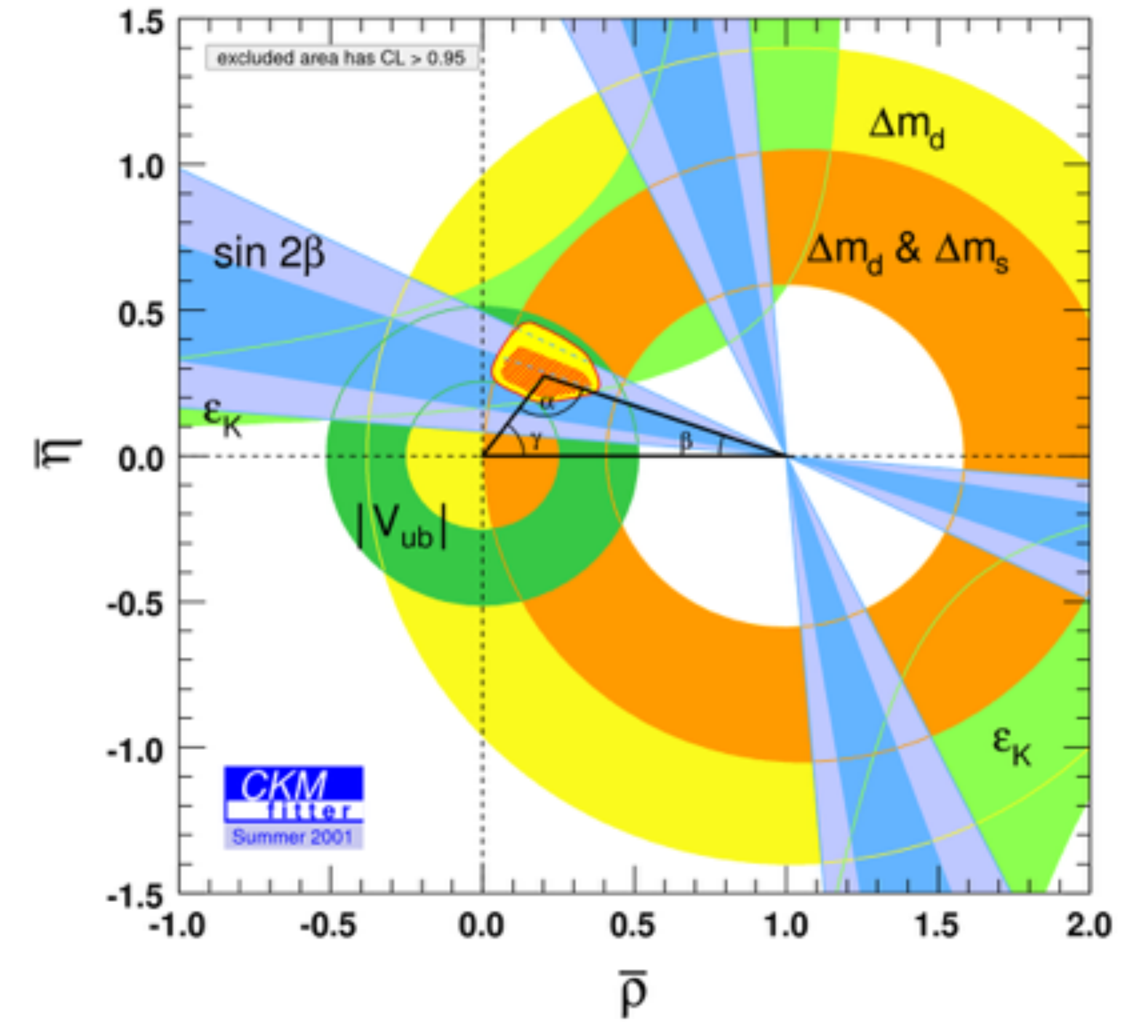
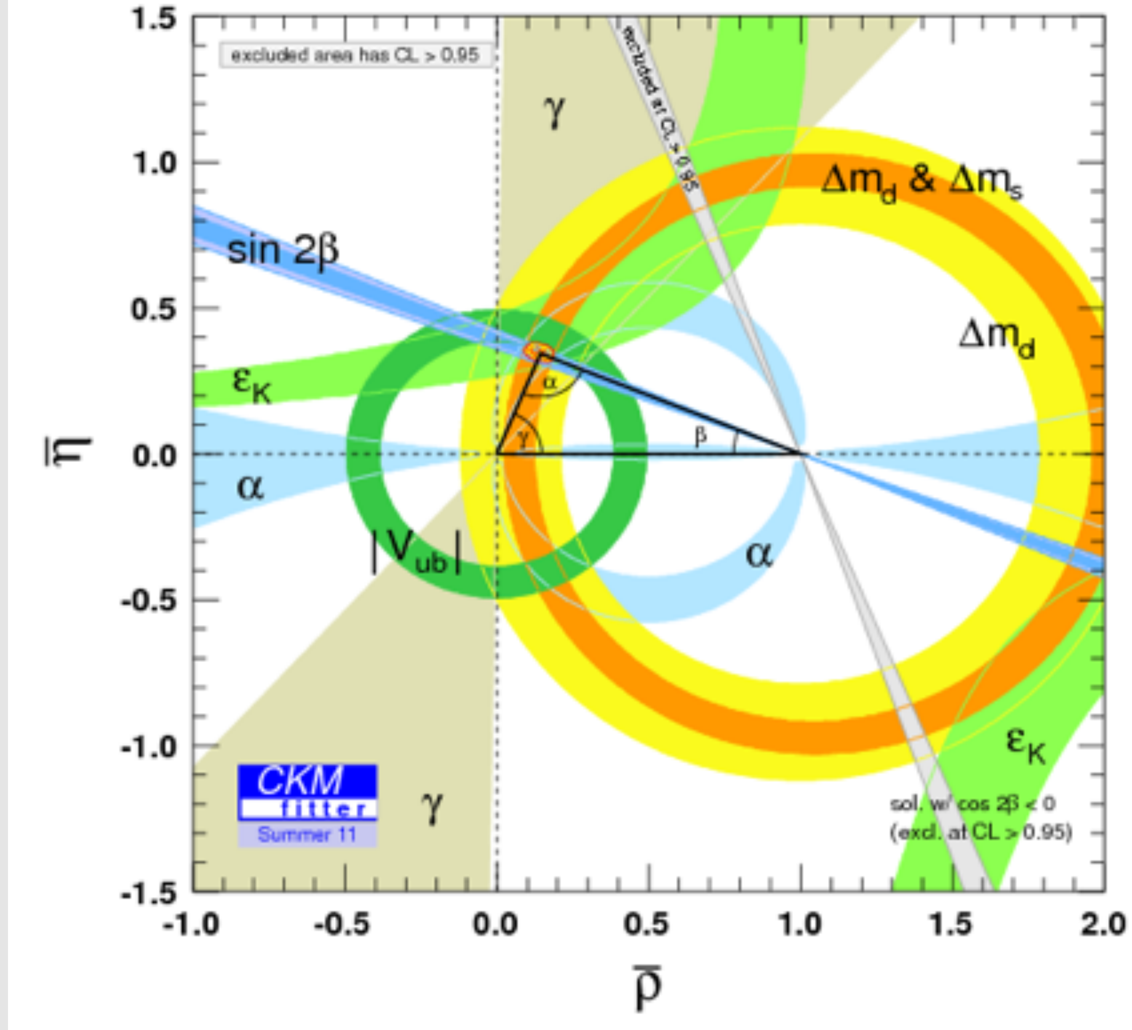
CKM and beyond

Summer 2001



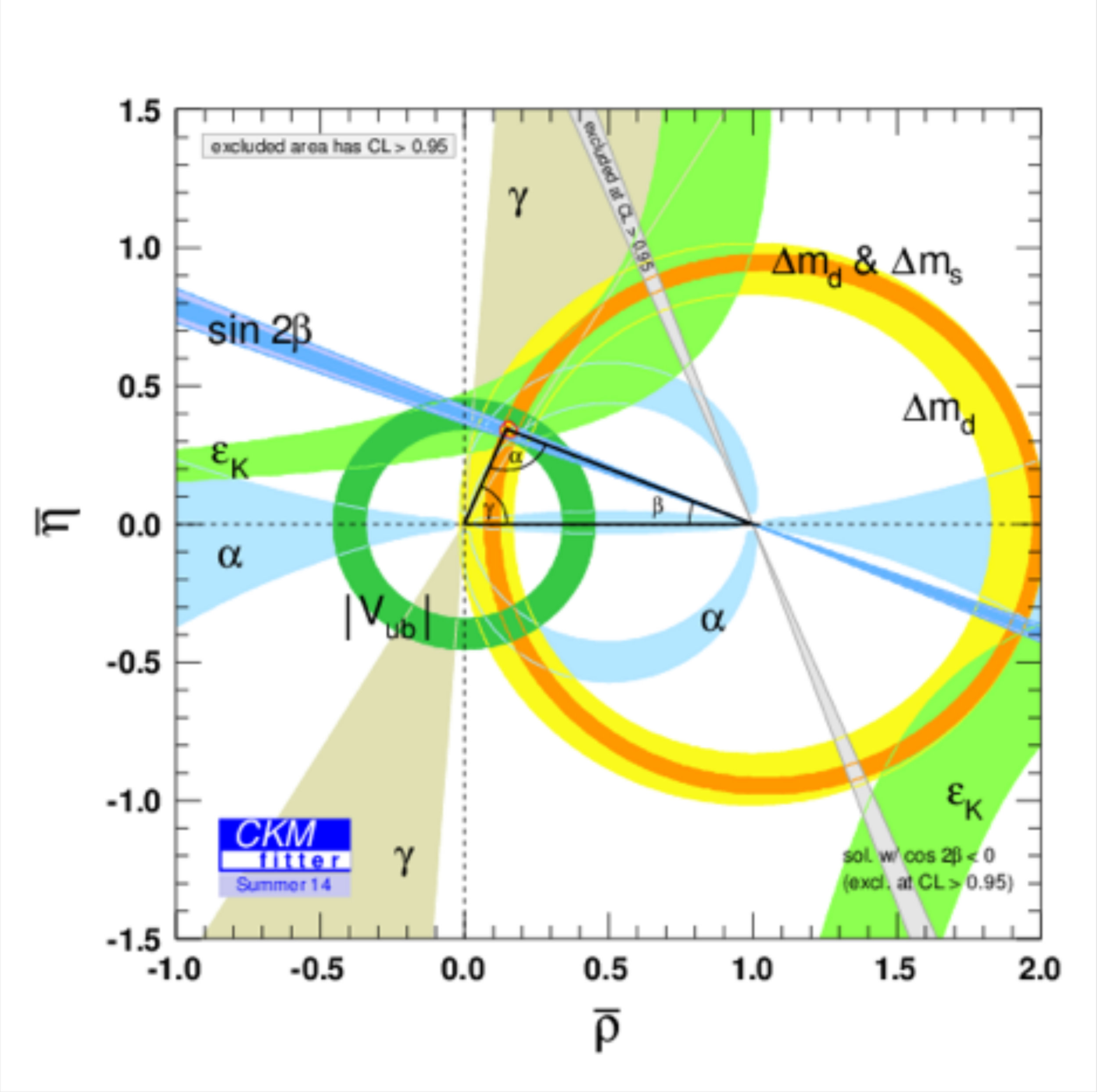
Summer 2011



- A decade of precision measurements
- Huge success for BaBar and Belle

CKM today

- 2010-2020
  ➡ Enter LHCb
- Looking for these little ripples caused by particles beyond the standard model



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Beauty CP violation

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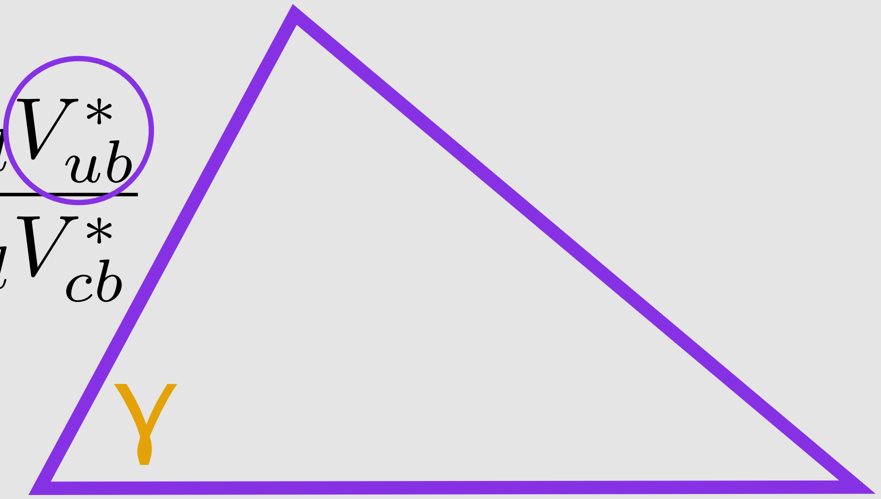
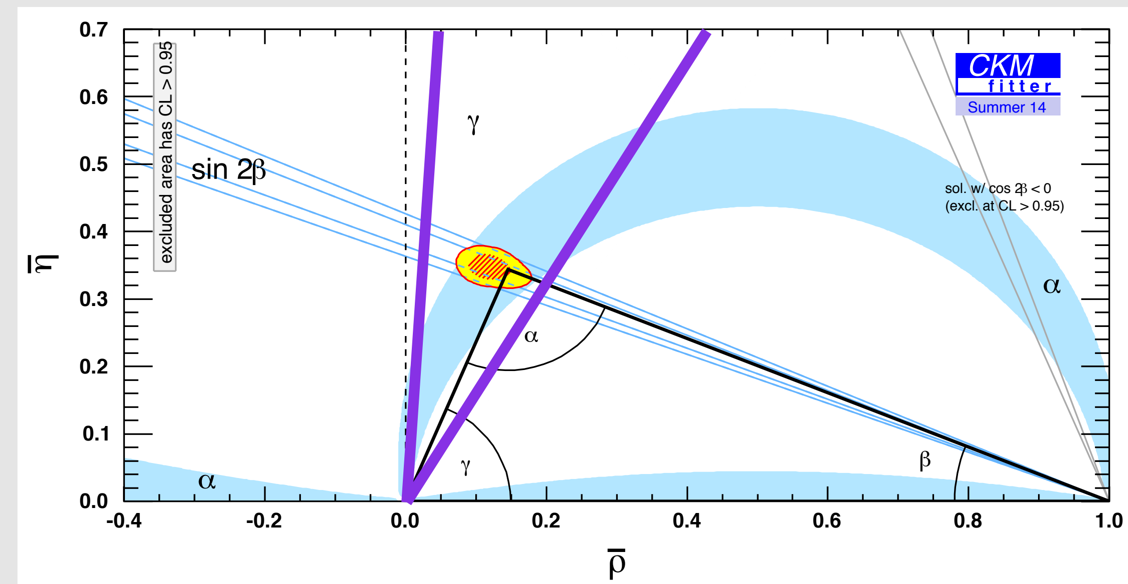
Measuring γ

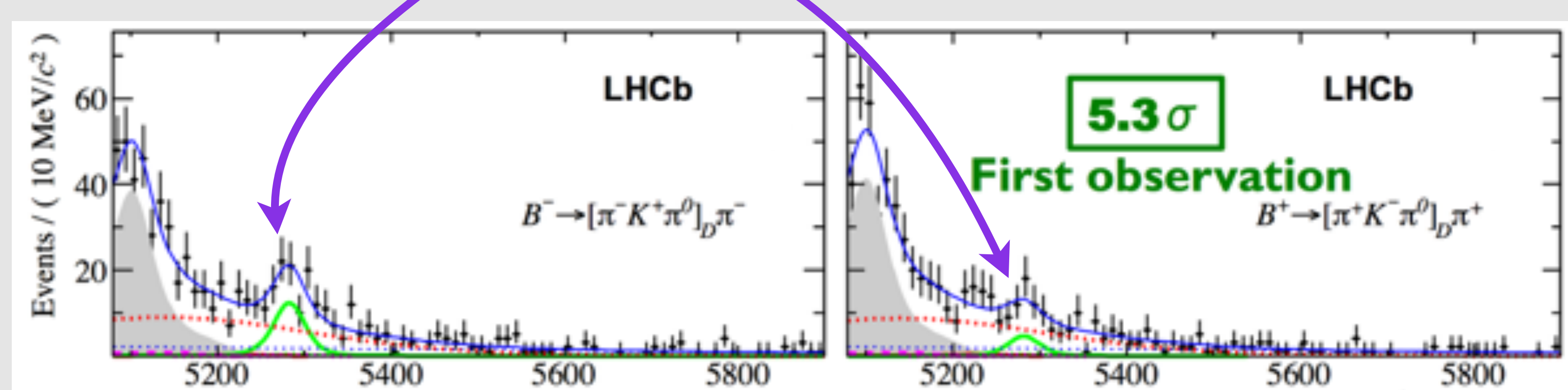
$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$



- Essentially measuring the phase of V_{ub}
- Least well measured CKM angle
- Measure CP violation in $B_{(s)} \to D_{(s)}hX$ decays
- CP violation requires the interference of two amplitudes
- Many different methods
  - ➡ Combinations of B and D decays
  - ➡ Time-integrated and time-dependent



CP violation in $B^- \to D(K^+\pi^-\pi^0)\pi^-$



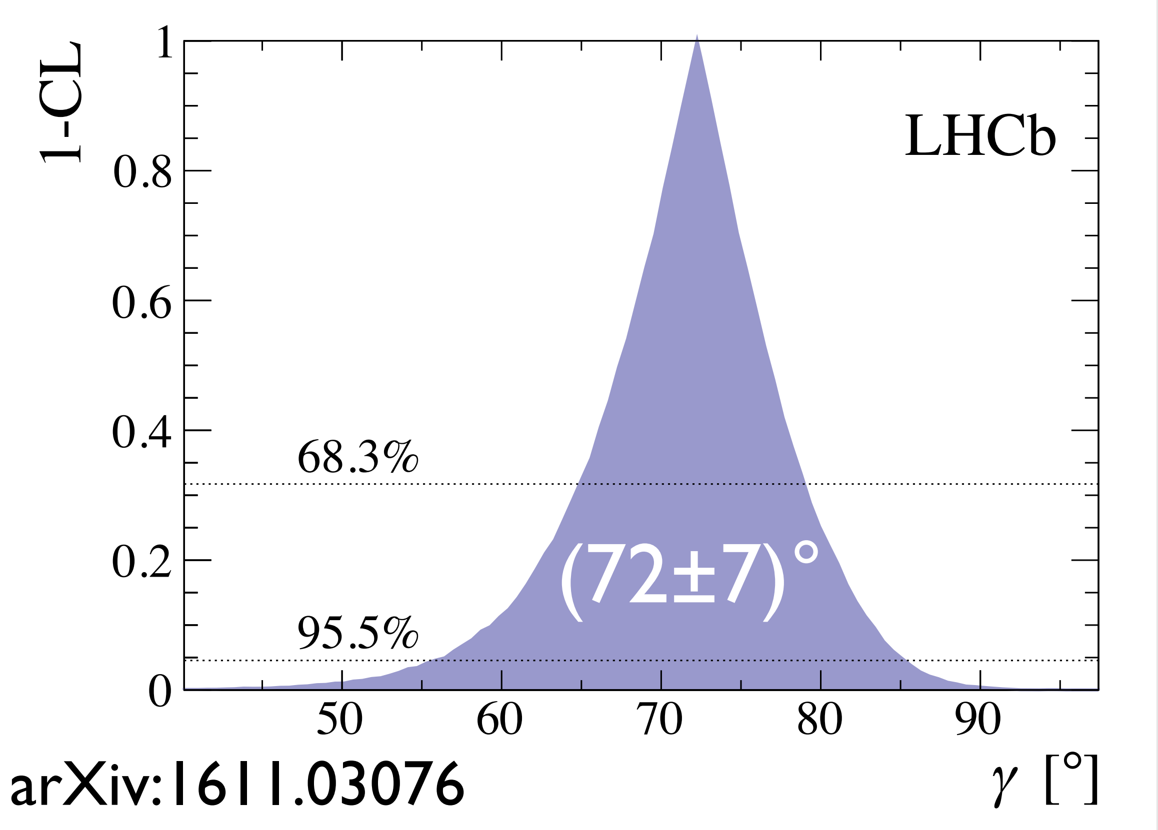
Phys. Rev. D91 (2015) 112014

A multitude of methods

- Methods for $B^{(0,-)} \to Dh$ ($h=\pi,K,K^*$) decays
  - ➡ Observables are time-integrated ratios of rates and rate asymmetries
- ADS
  - ➡ Measure favoured B decay with doubly Cabibbo-suppressed D decay and vice versa
- GLW
  - ➡ Measure favoured/suppressed B decays with D decaying into CP eigenstate
- GGSZ
  - ➡ Measure favoured/suppressed B decays with D decaying into multi-body final state including Dalitz analysis
- In addition using $B_s \to D_s K$ decays
  - ➡ Need to perform time-dependent measurement of rates and asymmetries

Improving γ precision

- Combining LHCb measurements of $B_{(s)} \to DK^{(*)}$ decays
- BaBar average*:
  - ➡ (70±18)°
- Belle average*:
  - ➡ (73±14)°
- LHCb improves by factor 2
- All based on tree decays
  - ➡ SM measurements
  - ➡ Access to beyond SM particles through loops in γ measurements using $B \to hh(h)$ decays



*CKMFitter Summer 2014

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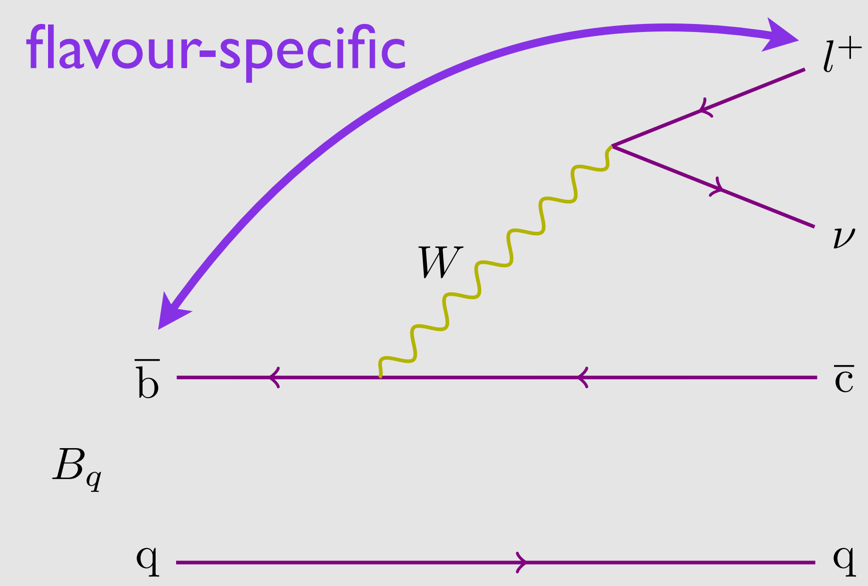
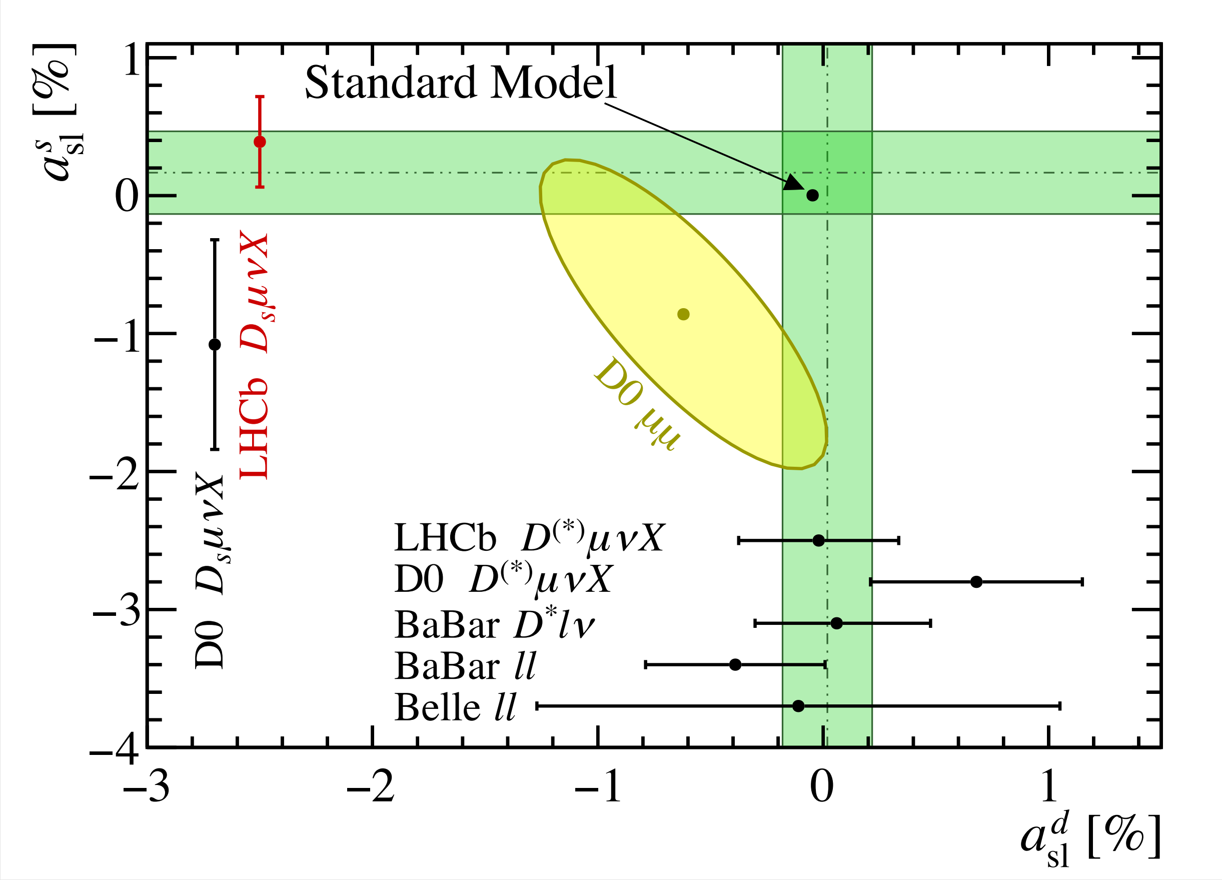
CP violation in mixing



- Look for $\bar{B} \to l^+$ decays
  - ➡ Forbidden directly, requires $\bar{B} \to B$ oscillation
- Measure asymmetry of $\bar{B} \to l^+$ and $B \to l^-$ rates
  - ➡ CP violation in mixing
- SM expectation far below current sensitivity
- Can measure this separately for B_d and B_s mesons
  - ➡ Separate access to $A_{sl}(B_d)$ & $A_{sl}(B_S)$
- Alternatively look for same-sign lepton pairs and compare l^+l^+ with l^-l^-
  - ➡ Measures combination of $A_{sl}(B_d)$ & $A_{sl}(B_S)$

Latest results

- D0 dimuon measurement differs from SM by about 3σ
  - ➡ Difficult to motivate by non-SM physics
- Direct measurements of $a_{sl}(B_d)$ & $a_{sl}(B_S)$ show agreement with SM
- Possible differences in SM contribution to observables?
- LHCb has best single measurement of $a_{sl}(B_d)$ and $a_{sl}(B_s)$
  - ➡ Latest: $a_{sl}(B_s)=(0.39\pm0.26\pm0.20)\%$ PRL 117 (2016) 061803



Charm CP violation

$$\frac{V_{ud}V_{cd}^*}{V_{us}V_{cs}^*} + 1 + \frac{V_{ub}V_{cb}^*}{V_{us}V_{cs}^*} = 0$$

D triangle

~1 1 ~0.002

Hardly a triangle

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Charm: hardly a triangle

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

D^0-$\overline{D}^0$ mixing

1000 TeV

Probing highest scales

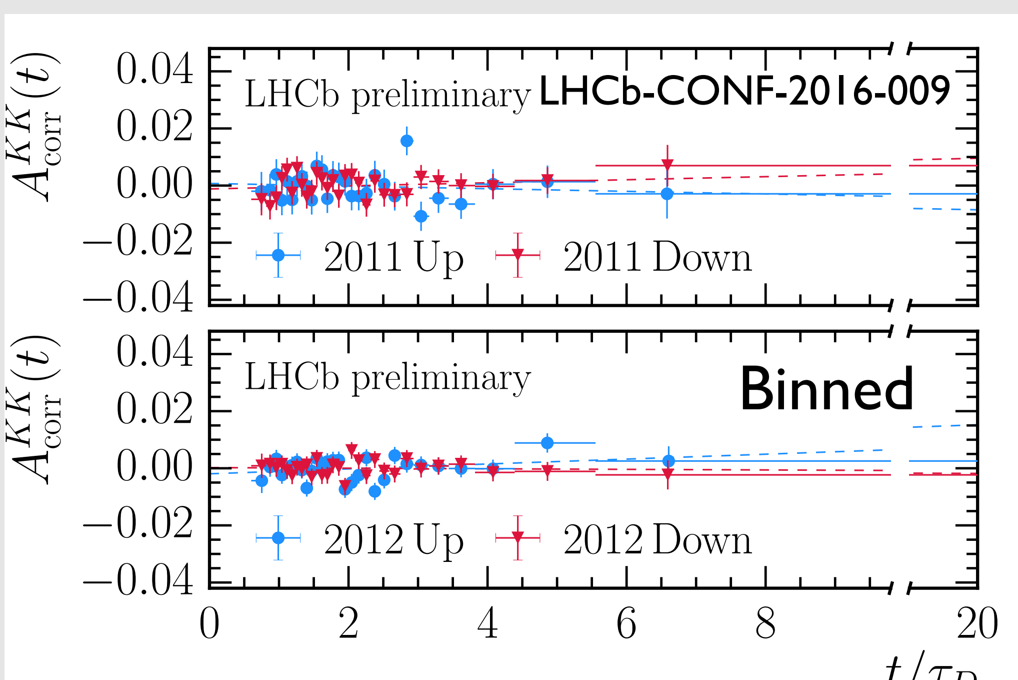
→ Isidori, Nir, Perez, ARNPS 60 (2010) 355

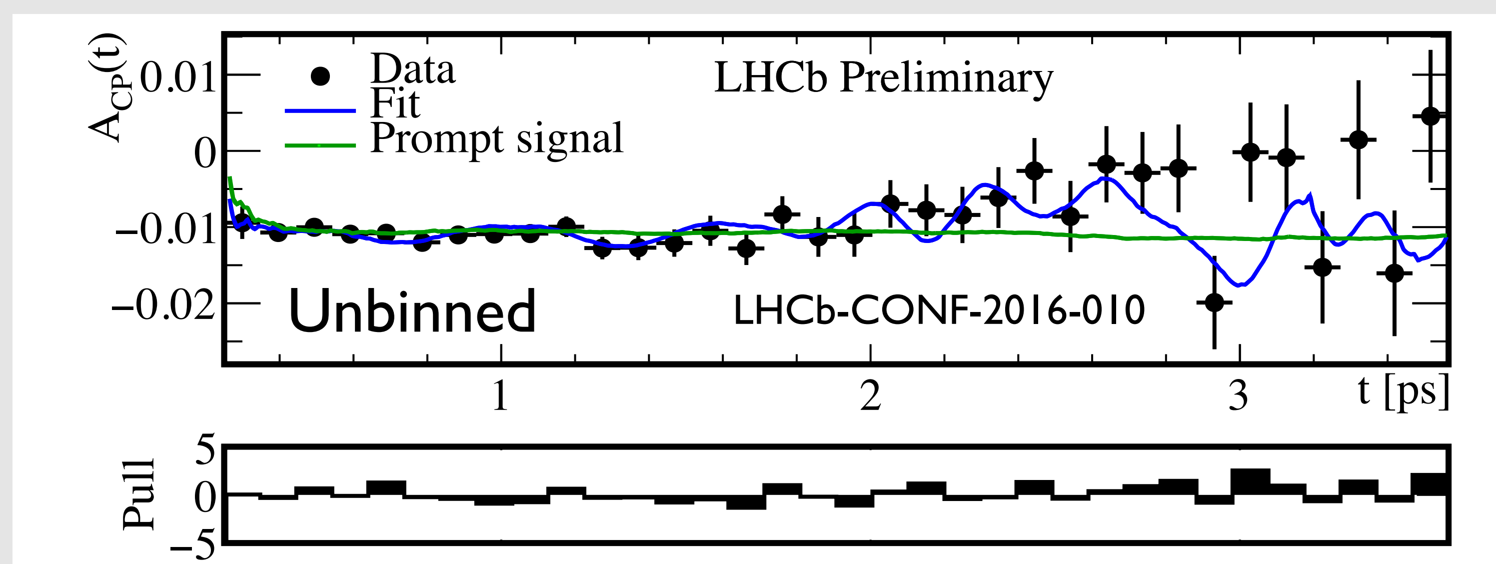
Need 1000 lifetimes to see a full D^0-$\overline{D}^0$ oscillation

→ Not enough charm in the universe!

Mixing-related CP violation

- Measurements based on $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ decays
- Measure asymmetries of effective lifetimes of decays to CP eigenstates:
  - ➡ $A_\Gamma \approx a_m\, y \cos\phi + x \sin\phi \equiv -a_{CP}^{ind}$
- Measures ability of both mass eigenstates to decay to CP eigenstate
- Prompt D^{*+}-tagged, 3 fb^{-1} [Preliminary, LHCb-CONF-2016-009+010]
  - ➡ $A_\Gamma(KK) = (-0.30 \pm 0.32 \pm 0.14) \times 10^{-3}$; $A_\Gamma(\pi\pi) = (0.46 \pm 0.58 \pm 0.16) \times 10^{-3}$
- D from semi-leptonic B decays, μ^+-tagged, 3 fb^{-1} [JHEP 04 (2015) 043]
  - ➡ $A_\Gamma(KK) = (-1.34 \pm 0.77 \pm 0.30) \times 10^{-3}$; $A_\Gamma(\pi\pi) = (-0.92 \pm 1.45 \pm 0.29) \times 10^{-3}$





The Δa_{CP} saga*

- What is Δa_{CP}?

$$\Delta a_{CP} \equiv a_{CP}(K^- K^+) - a_{CP}(\pi^- \pi^+) = a_{\rm raw}(K^- K^+) - a_{\rm raw}(\pi^- \pi^+).$$

- Interplay of CP violation in decay and mixing

$$\Delta a_{CP} = \Delta a_{CP}^{\rm dir}\left(1 + y_{CP}\frac{\overline{\langle t \rangle}}{\tau}\right) + \overline{A}_\Gamma \frac{\Delta\langle t \rangle}{\tau},$$

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

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

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

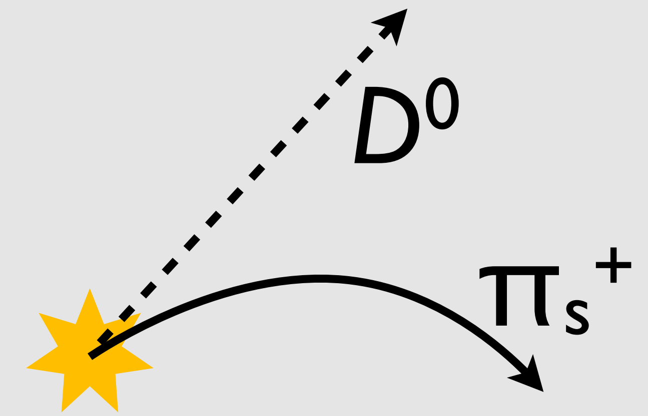
EPJC 73 (2013) 2373

Results

- D*-tagged (2011+12 data)

$$\Delta a_{CP} = (-0.10 \pm 0.08\ (\text{stat}) \pm 0.03\ (\text{syst}))\,\%$$

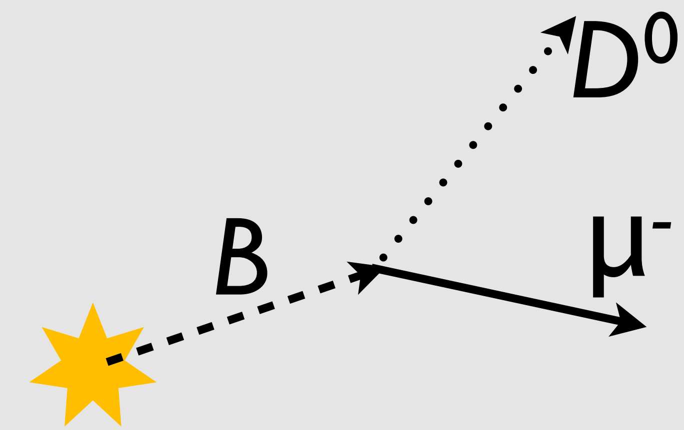
PRL 116 (2016) 191601



- muon-tagged (2011+12 data)

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

JHEP 07 (2014) 014



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Individual asymmetries

$$a_{raw}(K^-K^+) = a_{CP}(K^-K^+) + a_P(D^*) + a_D(\pi^+)$$

measure ← $a_{raw}(K^-K^+)$

want ← $a_{CP}(K^-K^+)$

Individual asymmetries

$$a_{raw}(K^-K^+) = a_{CP}(K^-K^+) + a_P(D^*) + a_D(\pi^+)$$

measure

want

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

Individual asymmetries

$$a_{raw}(K^-K^+) = a_{CP}(K^-K^+) + a_P(D^*) + a_D(\pi^+)$$

measure

want

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

$a_D(K^-\pi^+)$

Individual asymmetries

$$a_{raw}(K^-K^+) = a_{CP}(K^-K^+) + a_P(D^*) + a_D(\pi^+)$$

measure

want

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

$a_D(K^-\pi^+)$

$D^+ \to K^-\pi^+\pi^+$

Individual asymmetries

$$a_{raw}(K^-K^+) = a_{CP}(K^-K^+) + a_P(D^*) + a_D(\pi^+)$$

measure

want

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

$a_D(K^-\pi^+)$

$D^+ \to K^-\pi^+\pi^+$

$a_P(D^+)$, $a_D(\pi^+)$

Individual asymmetries

$$a_{raw}(K^-K^+) = a_{CP}(K^-K^+) + a_P(D^*) + a_D(\pi^+)$$

measure ($a_{raw}(K^-K^+)$)

want ($a_{CP}(K^-K^+)$)

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

$a_D(K^-\pi^+)$

$D^+ \to K^-\pi^+\pi^+$

$a_P(D^+)$, $a_D(\pi^+)$

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

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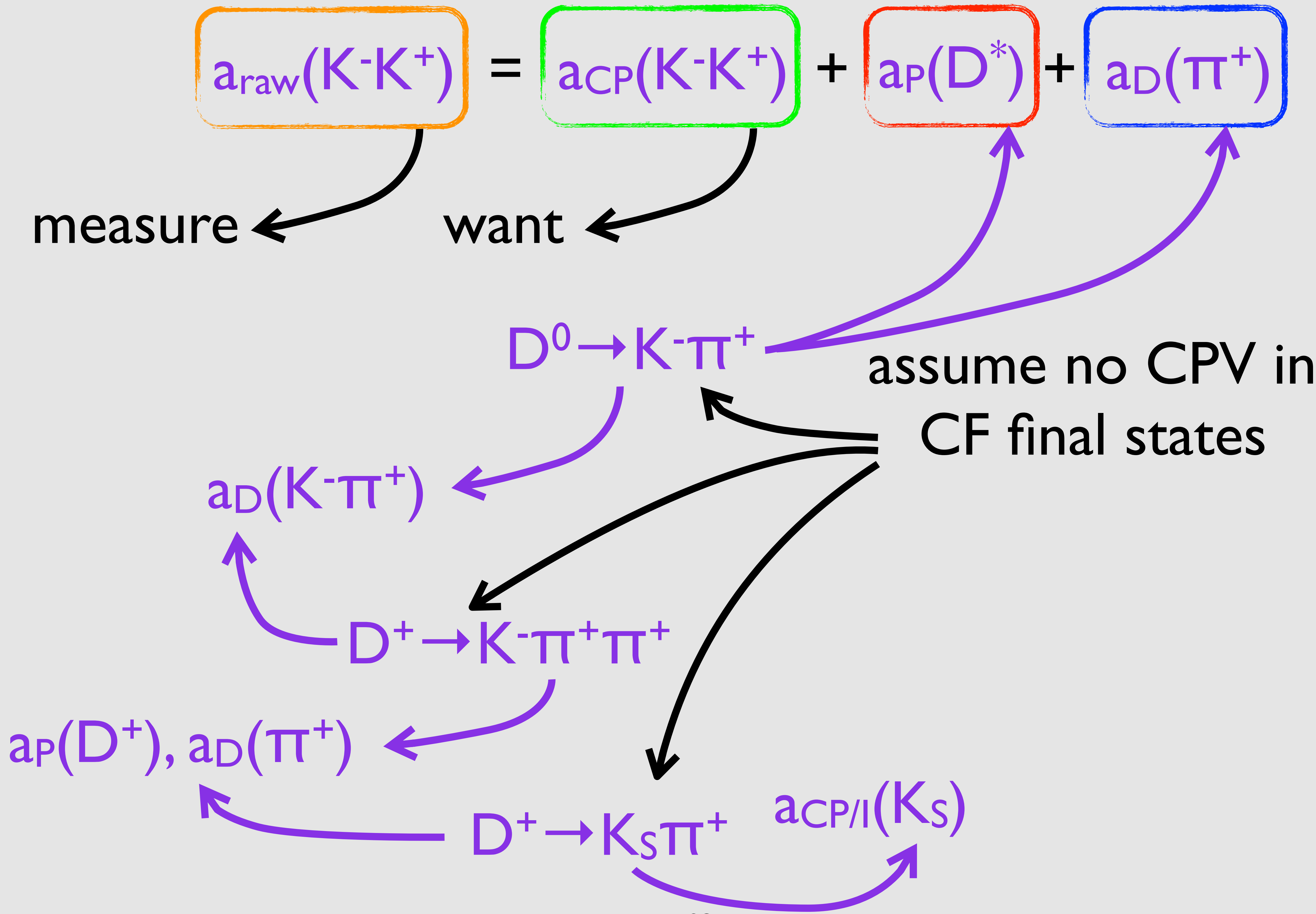
Individual asymmetries



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Individual asymmetries

$$a_{raw}(K^-K^+) = a_{CP}(K^-K^+) + a_P(D^*) + a_D(\pi^+)$$

measure

want

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

assume no CPV in CF final states

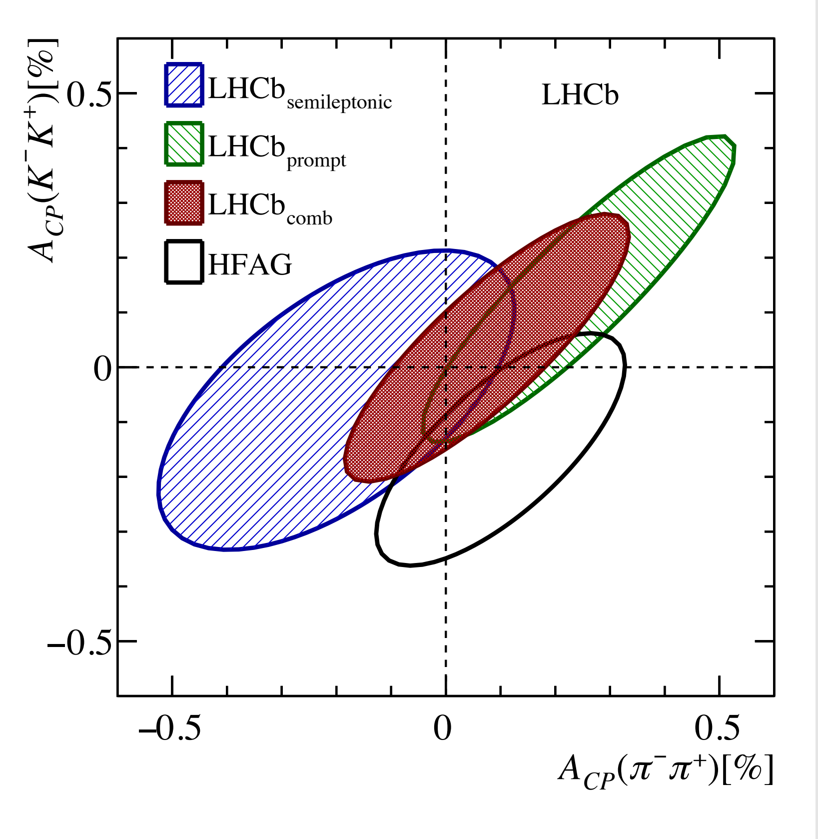
$a_D(K^-\pi^+)$

$D^+ \to K^-\pi^+\pi^+$

$a_P(D^+)$, $a_D(\pi^+)$

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

$a_{CP/I}(K_S)$



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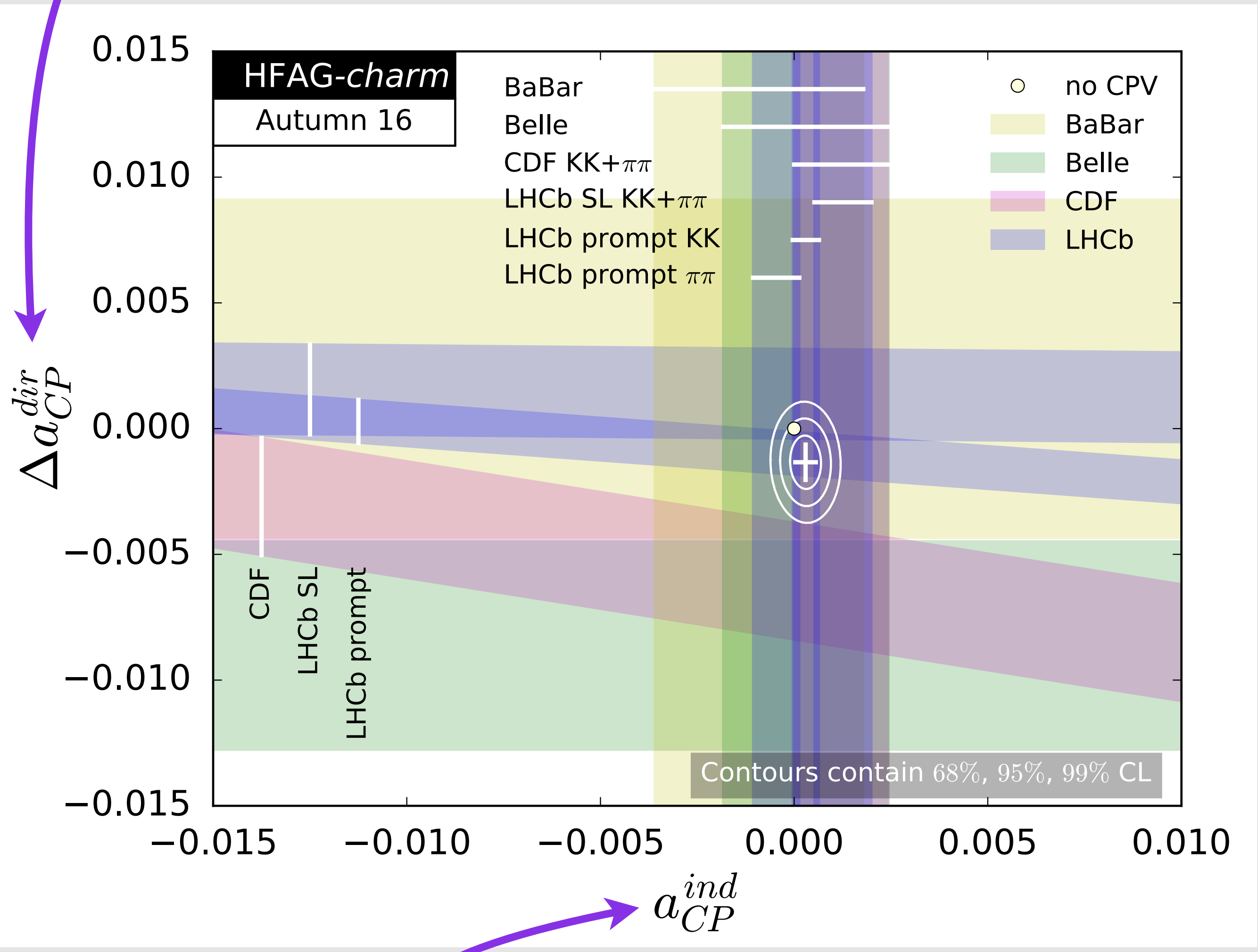
CP violation

- World's best precision on charm CP violation

  ➡ Approaching 10^{-4} precision

- LHCb dominating the picture
- Agreement with CP violation hypothesis at 9% level

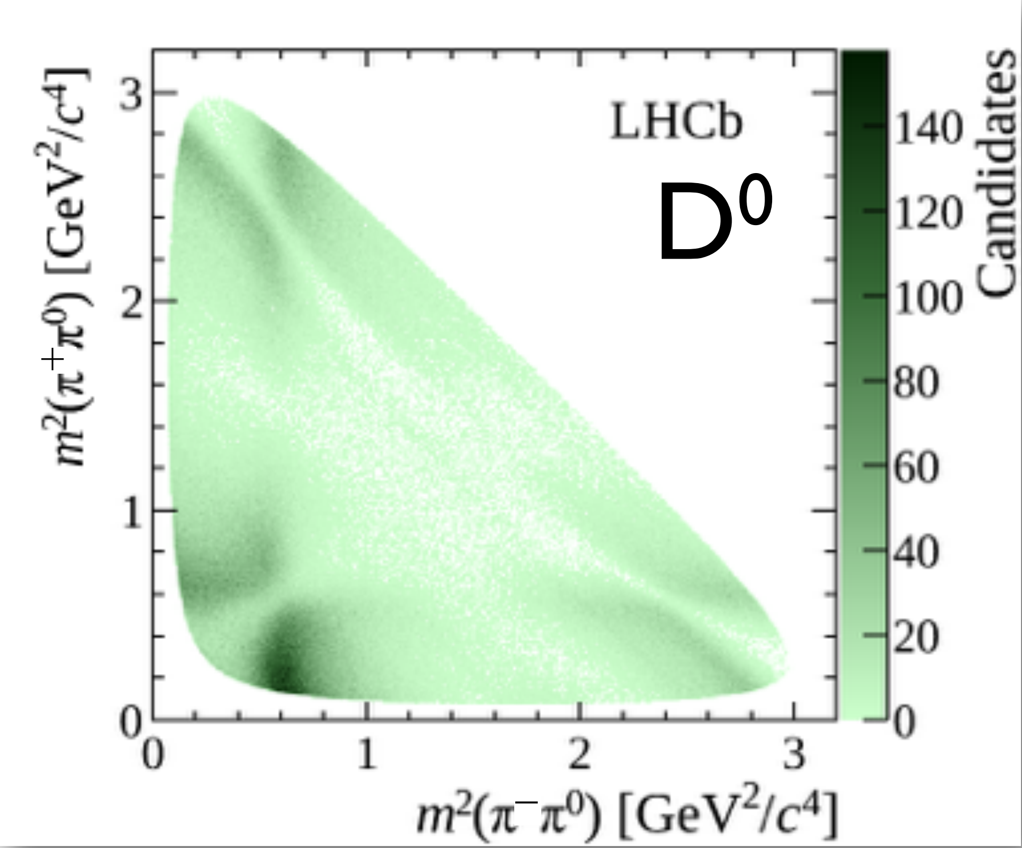
CP violation in decay

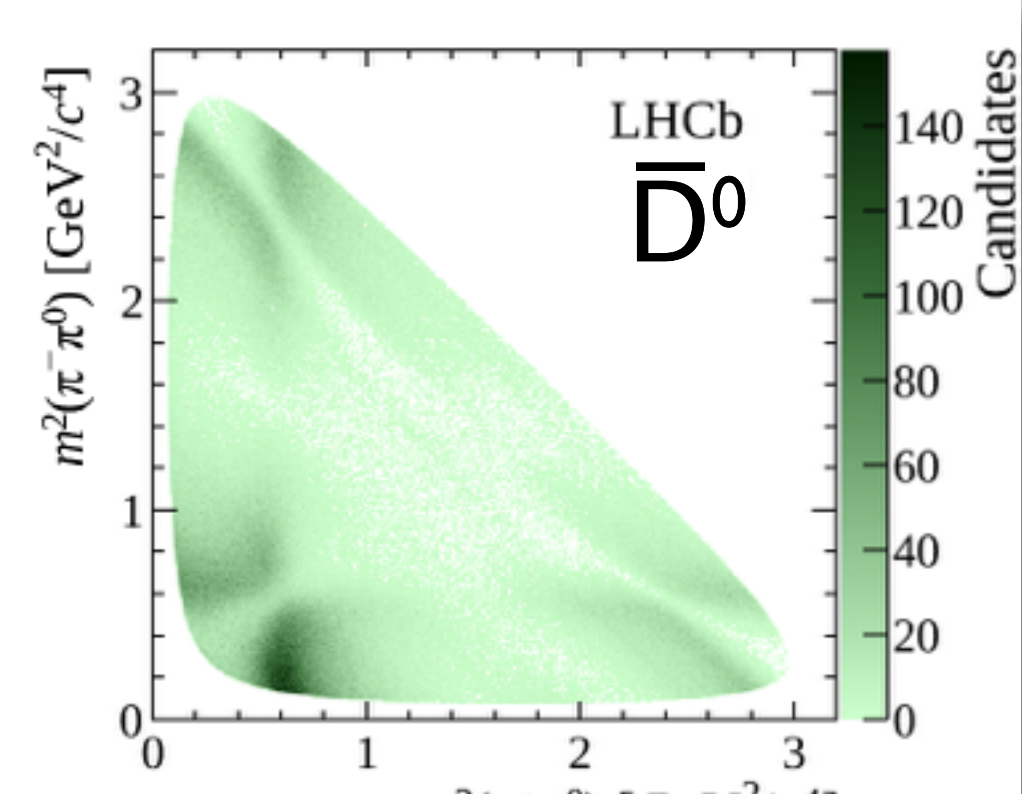


Mixing-related CP violation

CP violation in multi-body final states

- An unbinned approach
- Need to compare each event with every other
  - ➡ Computationally challenging for O(1M) events
  - ➡ Use GPUs to exploit massive parallelisation
  - ➡ Applied to $D^0 \to \pi^+\pi^-\pi^0$ decays
- Energy test (M. Williams, PRD 84 (2011) 054015)
  - ➡ Test statistic (T) comparing pairwise weighted distances in phase space
  - ➡ Compare
    - $D^0 \leftrightarrow D^0$
    - $\overline{D}^0 \leftrightarrow \overline{D}^0$
    - $D^0 \leftrightarrow \overline{D}^0$
  - ➡ Expect T~0 (no CPV) or T>0 (CPV)





PLB 740 (2015) 158

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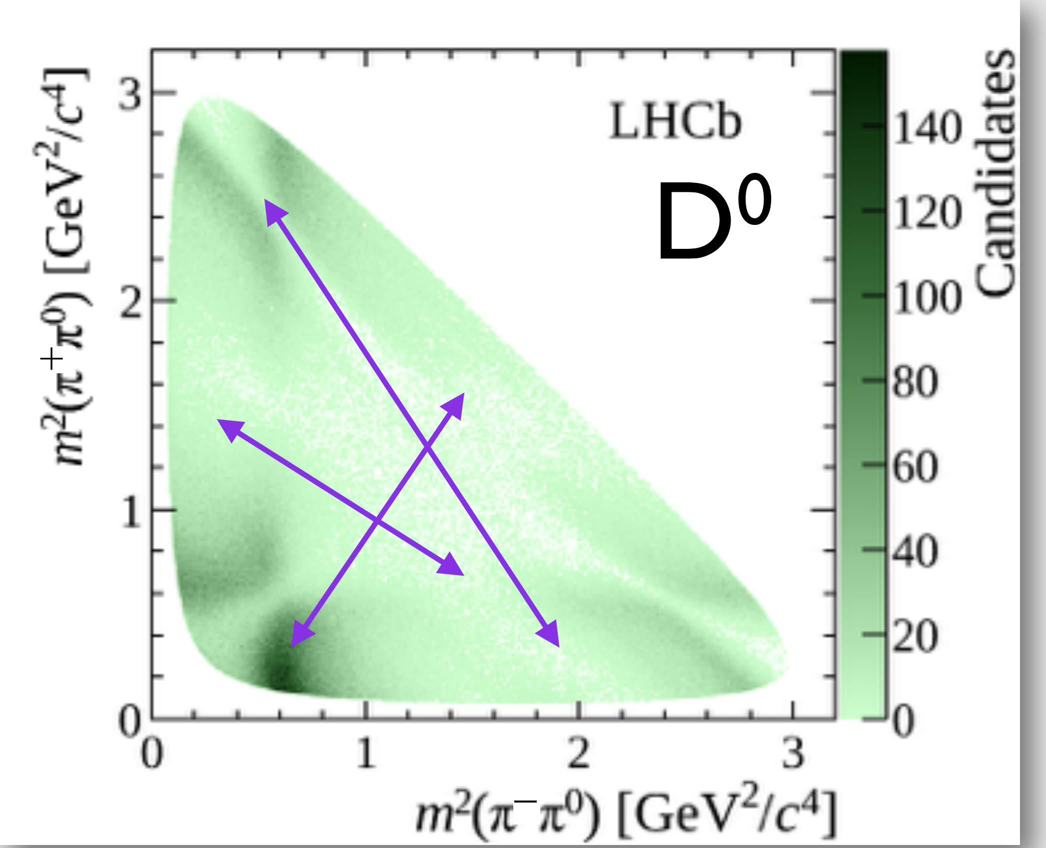

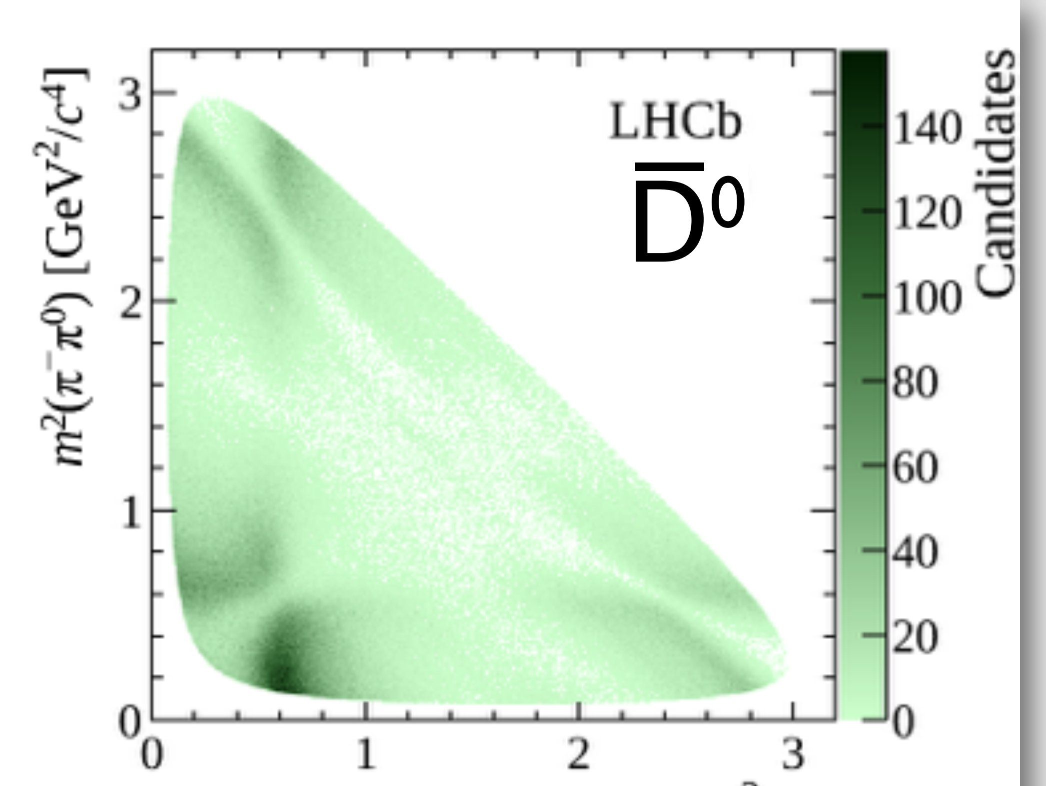

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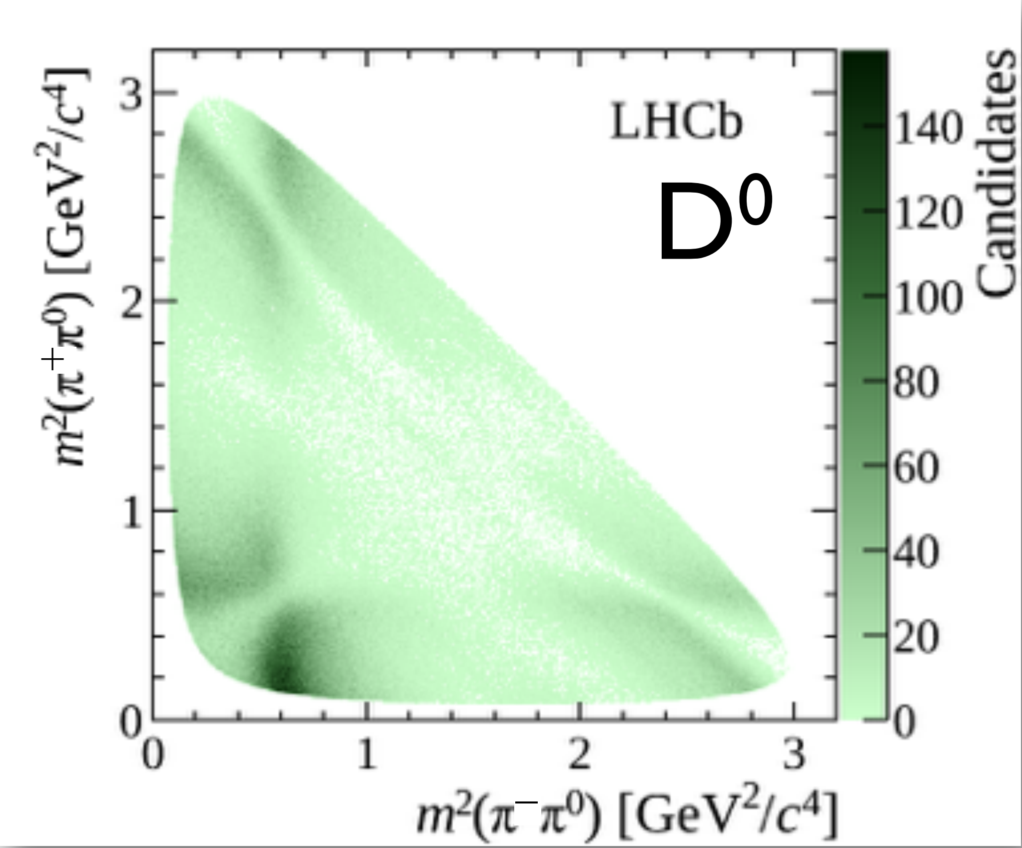

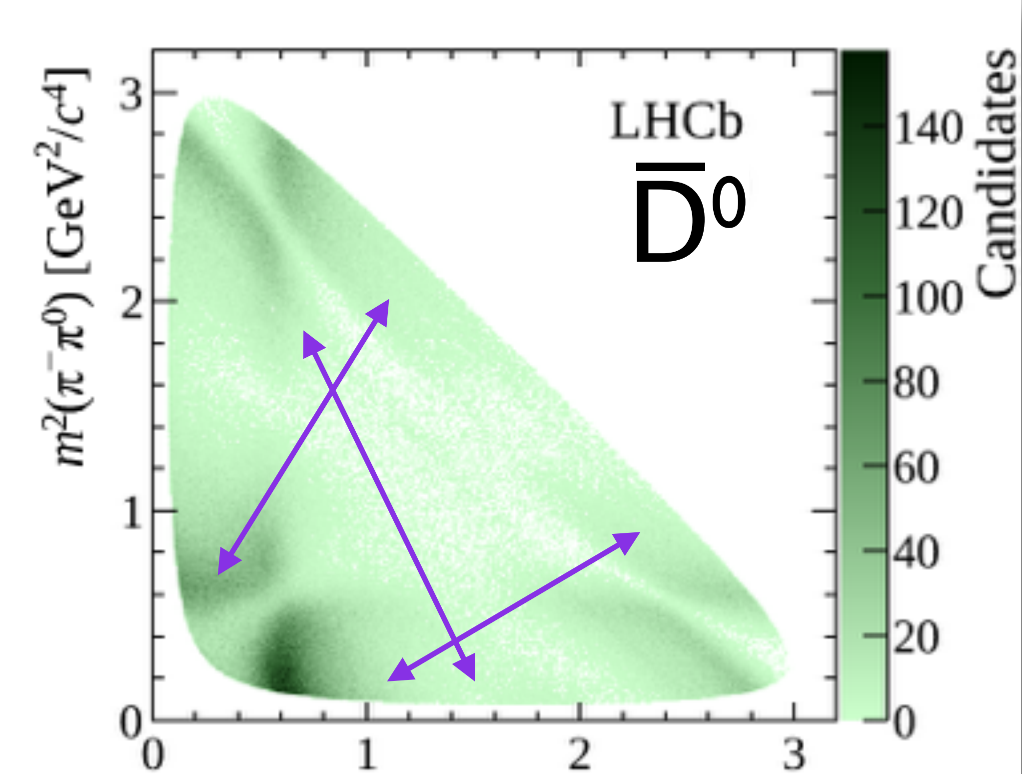

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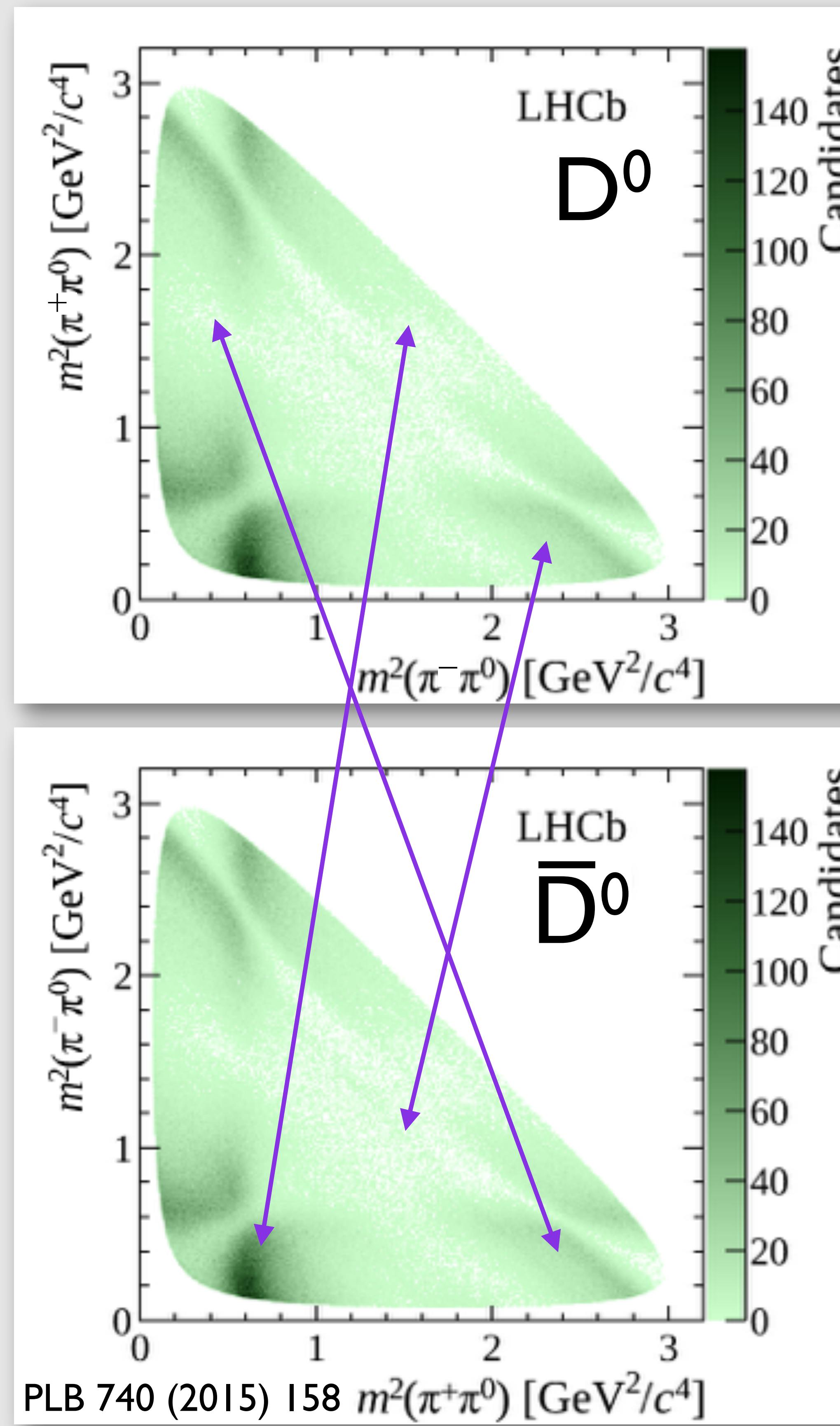

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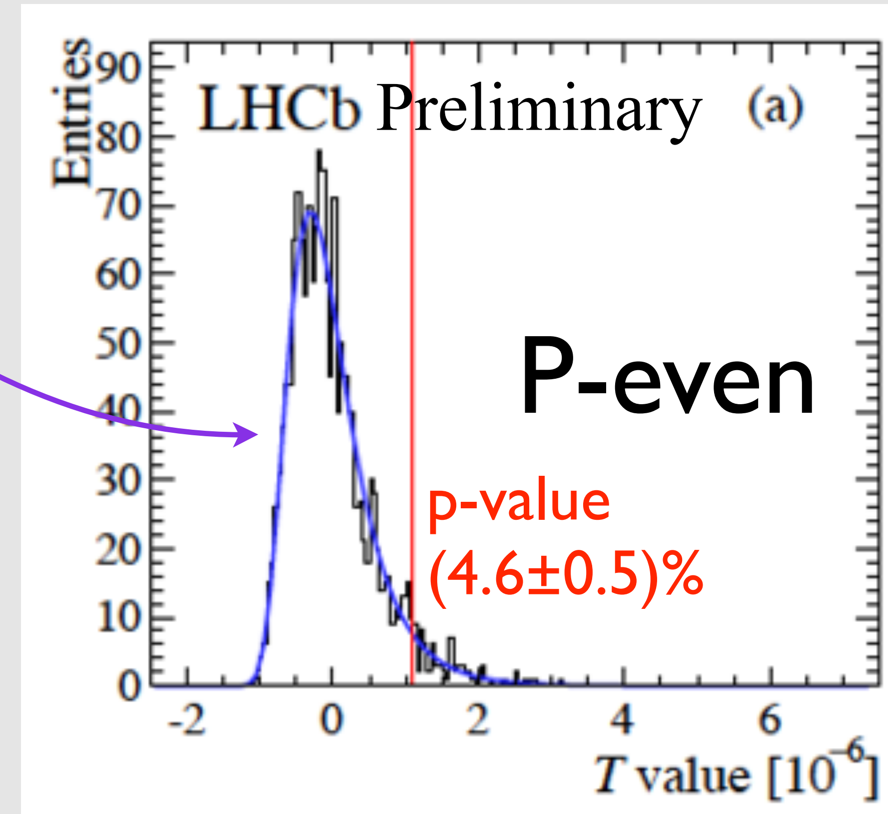
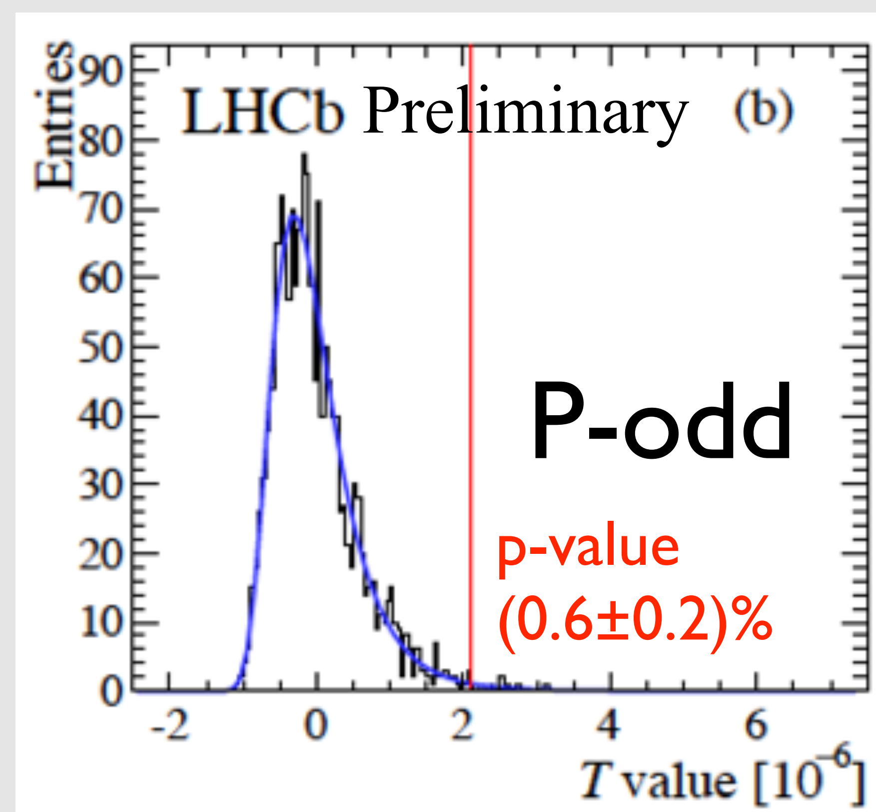
3→4 body

No-CPV hypothesis from permutations with randomised flavour tags

- $D^0 \to \pi^+\pi^-\pi^+\pi^-$
  - ➡ 5-dimensional phase-space
  - ➡ Split D^0 and $\overline{D}^0$ (P-even)
  - ➡ And by sign of decay planes (P-odd)
    - ▸ Only marginally compatible with no-CPV hypothesis





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More CP violation

arXiv:1609.05216

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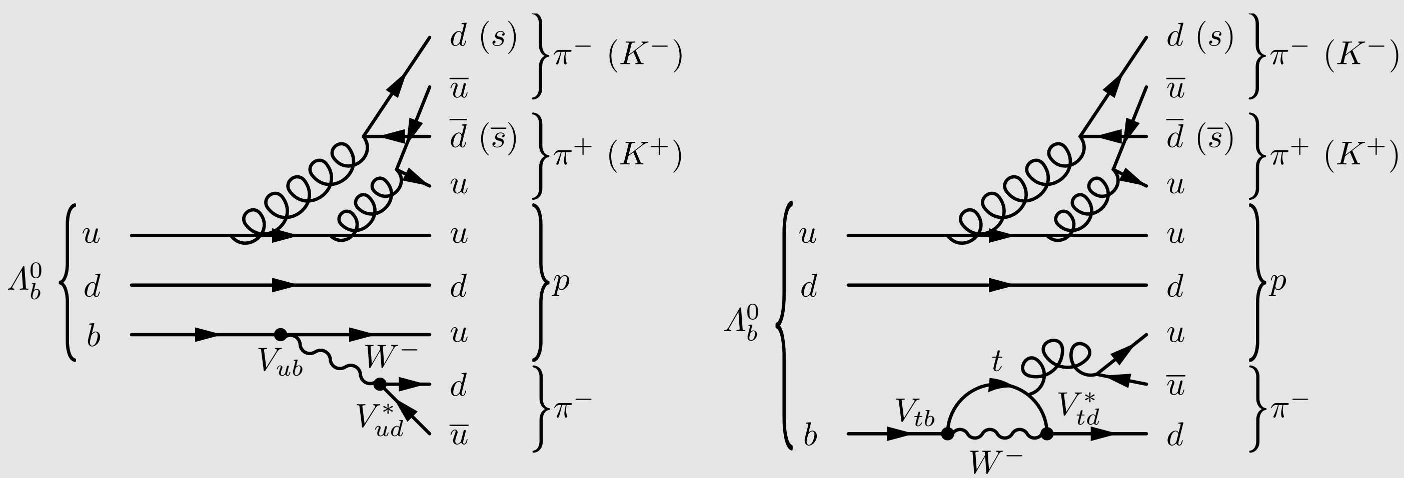
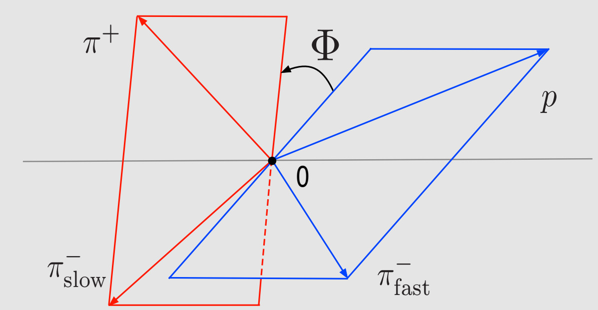
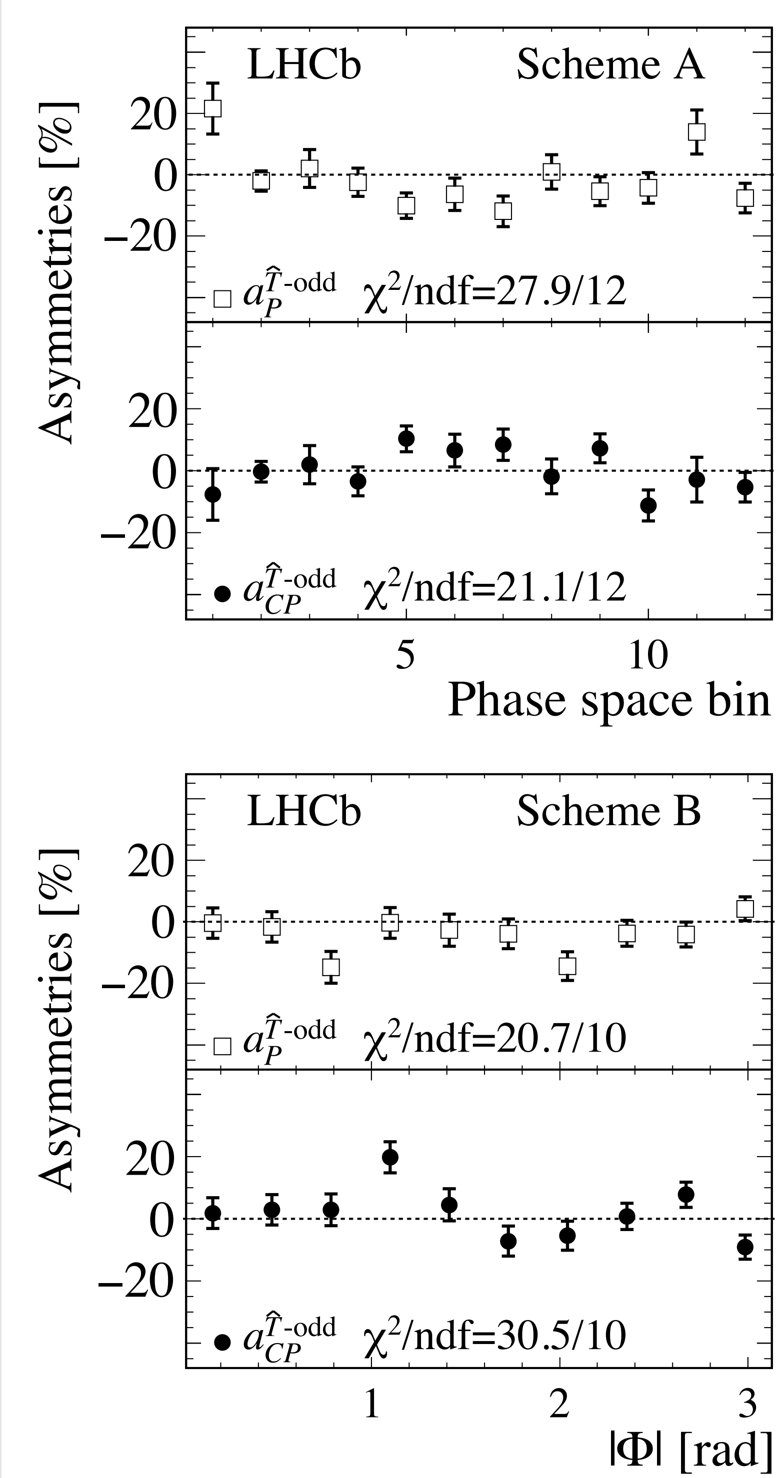
CP violation in Baryons





- CP violation has never been measured in baryons
- Study local triple-product asymmetries
  - ➡ in bins of phase space
  - ➡ in bins of decay-plane angle
- Triple-products are robust against systematic uncertainties
- Angular bins for $\Lambda_b \rightarrow p\pi^-\pi^+\pi^-$ show 3.3σ deviation from no-CPV hypothesis
- Weaker signals in phase-space binning and smaller $\Lambda_b \rightarrow p\pi^-K^+K^-$ sample



arXiv:1610.03666

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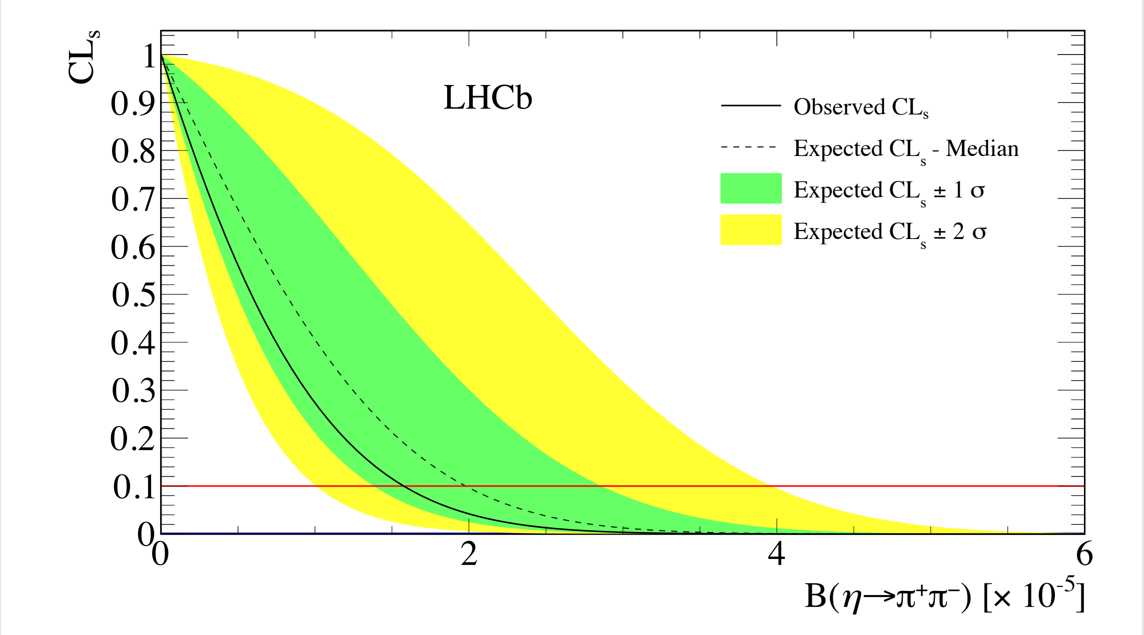
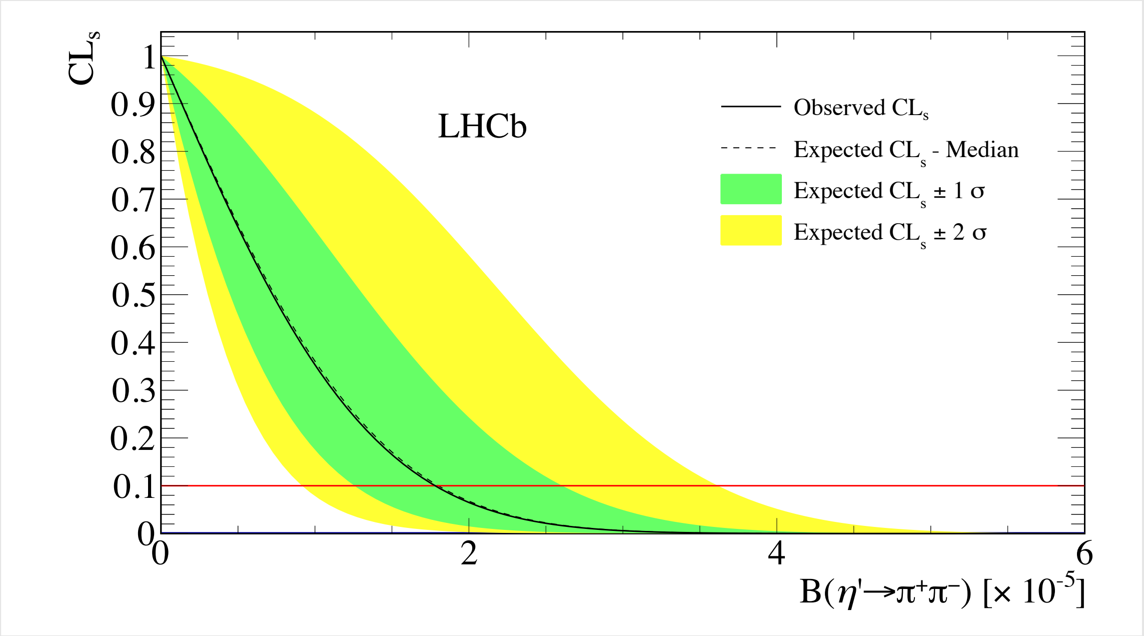
Strong CP violation

- Look for $\eta^{(\prime)}$ in $D_{(s)}^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decays
- BF in SM $\lesssim 10^{-27}$
- Constraints from nEDM $\lesssim 10^{-17}$
- Achieved world's best limit on η' and comparable to best limit on η
- Based on 2011+12+15 data including reconstruction at trigger level for 2015 data





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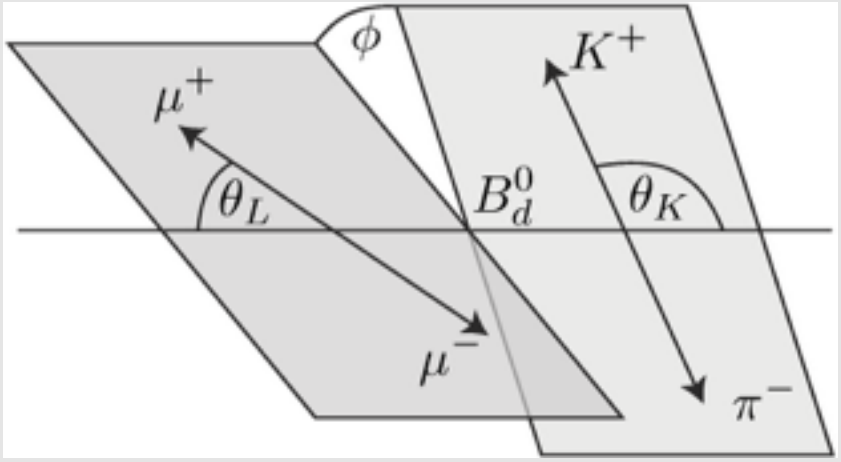
Rare decays

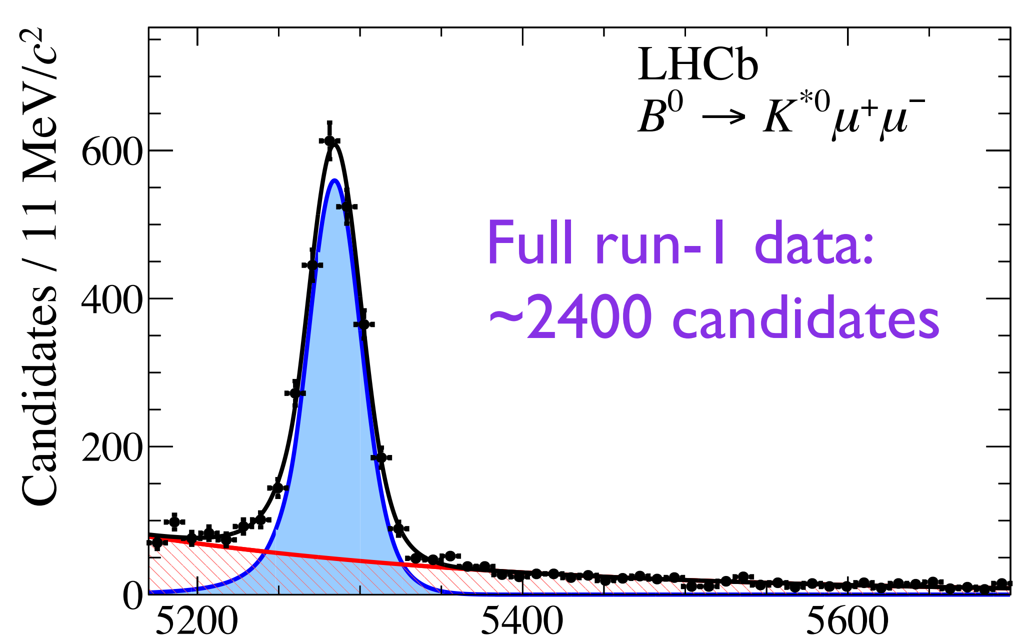
~~Needles in the haystack~~

Precision needle stack physics

$B_d \to K^* \mu^+ \mu^-$

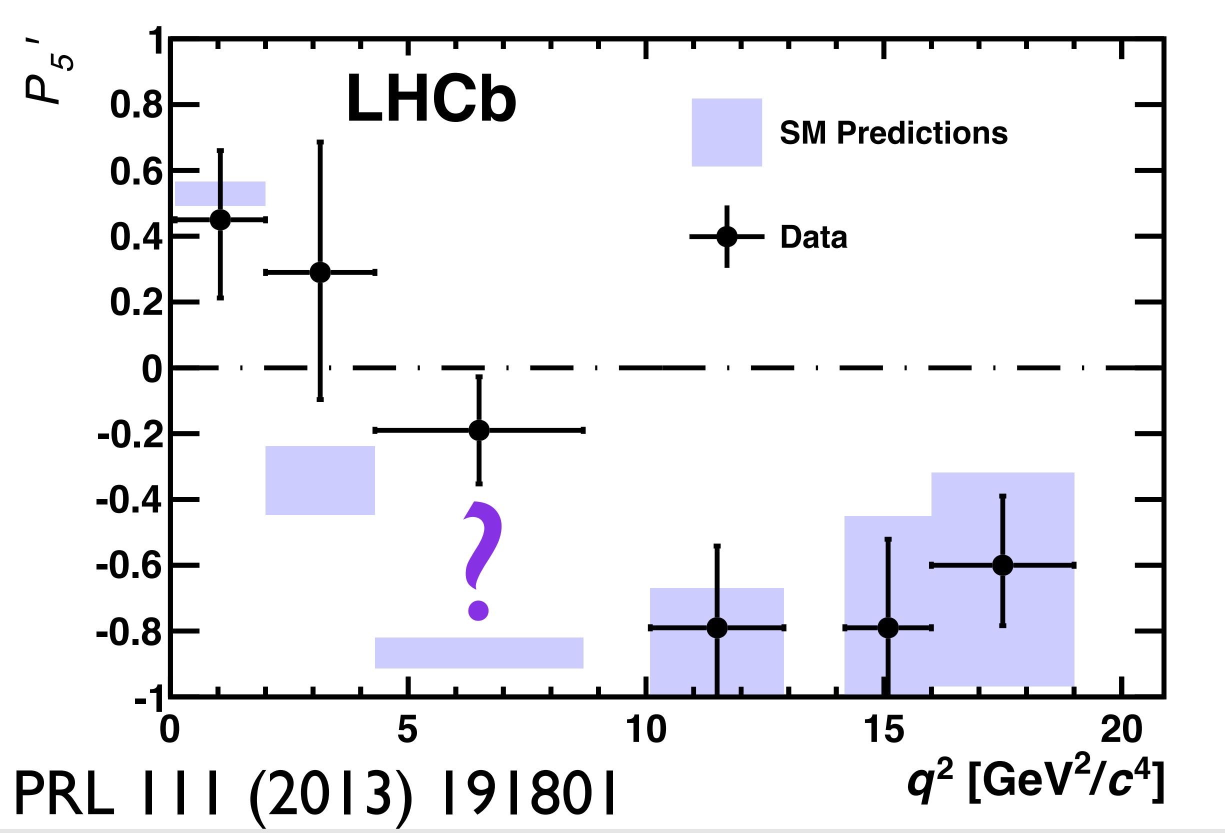


- Flavour-changing neutral current decay
  - ➡ Particular sensitivity to electromagnetic penguins
- Angular analysis can unravel contributions from different physics processes
  - ➡ Forward-backward asymmetry of muons, A_{FB}
  - ➡ Longitudinal polarisation fraction of K^*, $F_L \propto \cos^2\theta_K$
  - ➡ Further angular observables, S_i (i=3,4,5,6)
  - ➡ Derived observables with reduced form-factor dependence, $P_i' = S_i/\sqrt{F_L(1-F_L)}$



JHEP 02 (2016) 104

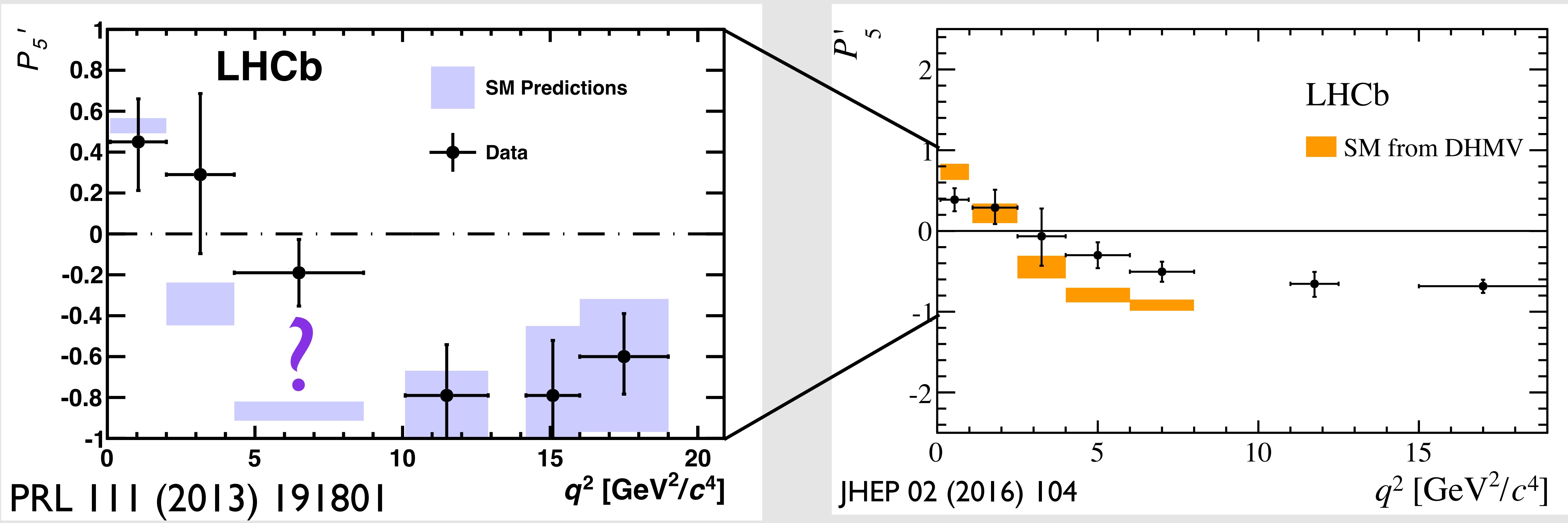
$B_d \to K^* \mu^+ \mu^-$ results



PRL 111 (2013) 191801

- Some slight surprise in P_5'

$B_d \rightarrow K^* \mu^+ \mu^-$ results



- Some slight surprise in P_5'
- Now measured at higher precision

SM prediction from Descotes-Genon, Hofer, Matias, Virto, JHEP 1412 (2014) 125

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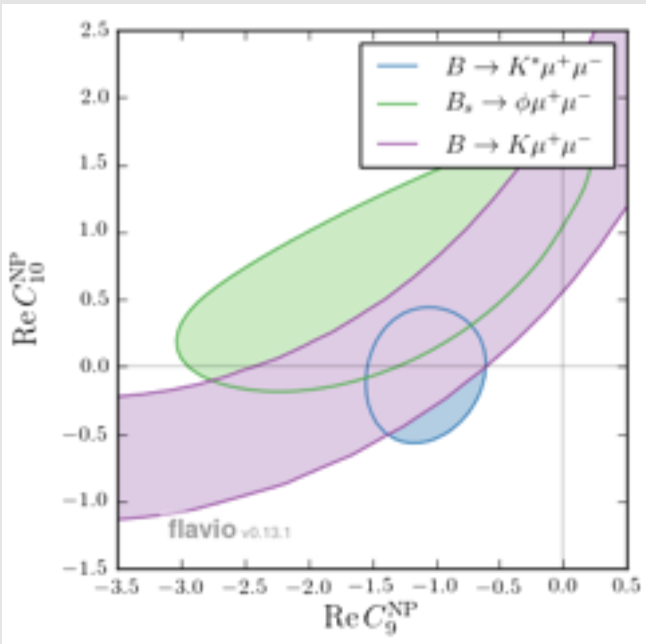
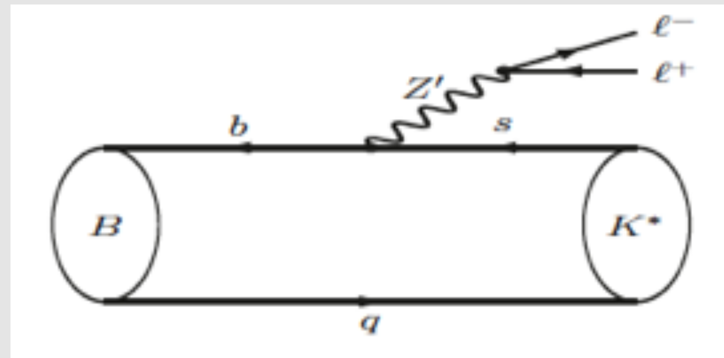
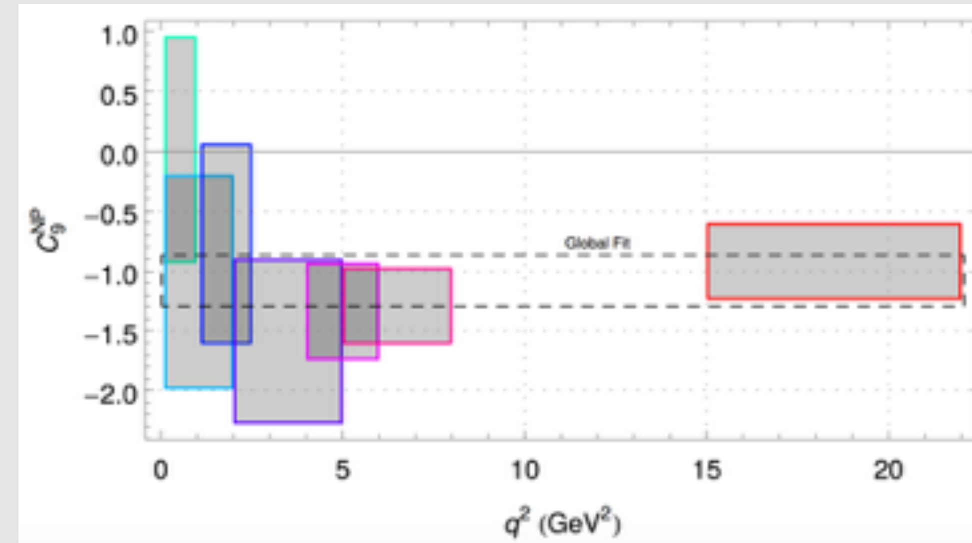
Theory perspective

Straub, LHCb Implications 2016





Z’ still possible within indirect and direct constraints



Descotes-Genon et al., JHEP 06 (2016) 092

- “All [New Physics model] consistency tests* we have done so far are nicely fulfilled with 3 fb^{-1} showing robustness of data.” (Matias @ Moriond EW 2015)
- “q^2 dependence indicates that (unexpectedly) huge charm effect mimicking $C_9^{NP} < 0$ at intermediate q^2 could solve the tensions as well.” (Straub @ Moriond EW 2015)

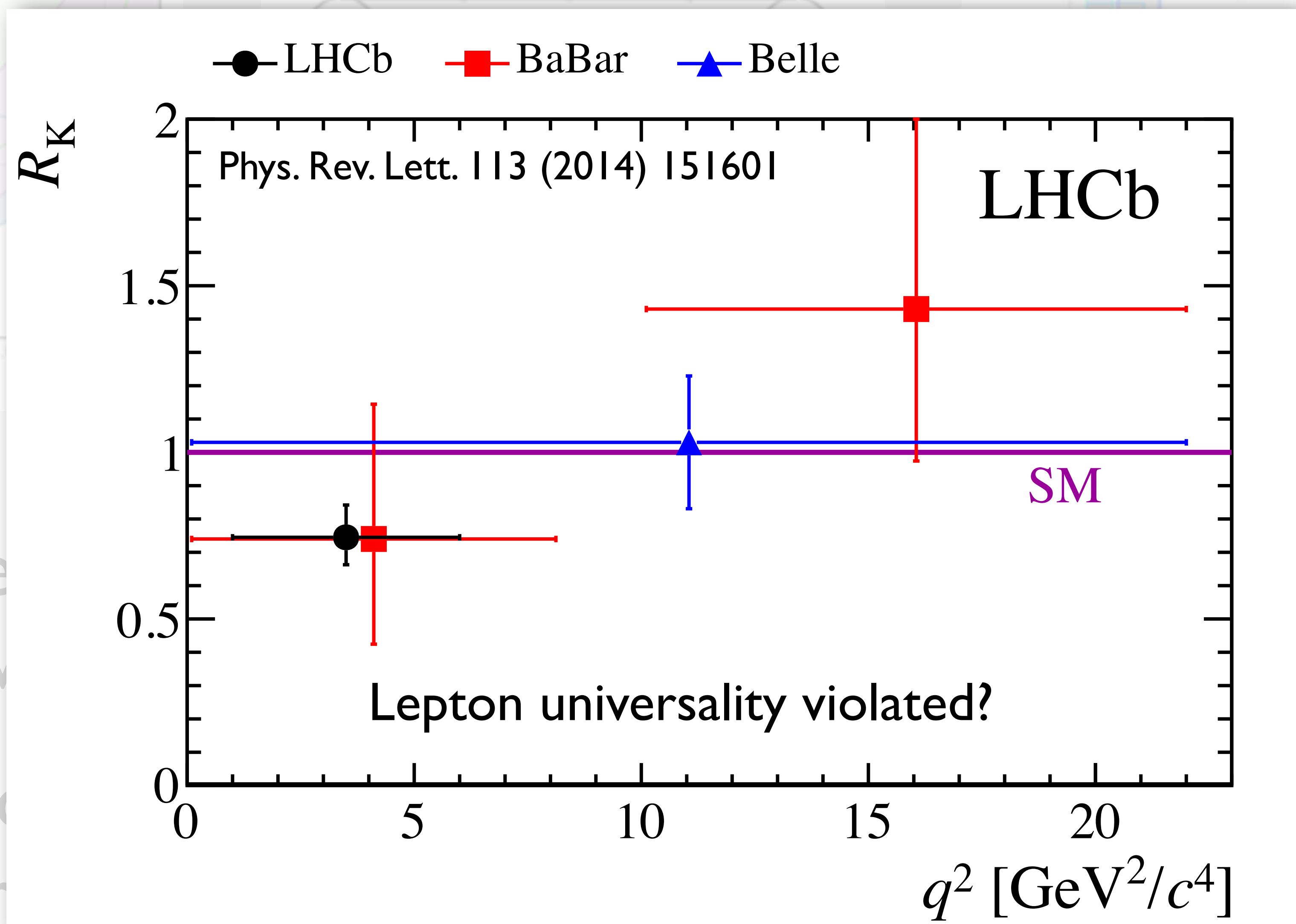
* **Relevant Observables included**: $B \to K^*\mu^+\mu^-$ ($P_{1,2}$, $P'_{4,5,6,8}$, F_L in all 5 large-recoil + low-recoil), $B^+ \to K^+\mu^+\mu^-$ and $B^0 \to K^0\mu^+\mu^-$, $\mathcal{B}_{B\to X_s\gamma}$, $\mathcal{B}_{B\to X_s\mu^+\mu^-}$, $\mathcal{B}_{B_s\to\mu^+\mu^-}$, $A_I(B \to K^*\gamma)$, $S_{K^*\gamma}$

Many more LHCb results adding to the picture!

Theory perspective

Straub, LHCb Implications 2016

... et al., JHEP 06 (2016) 092



- "All ... * we have ... b^{-1} show ... 2015)
- "q^2 ... y) huge char... ediate q^2 could solve the tensions as well." (Straub @ Moriond EW 2015)

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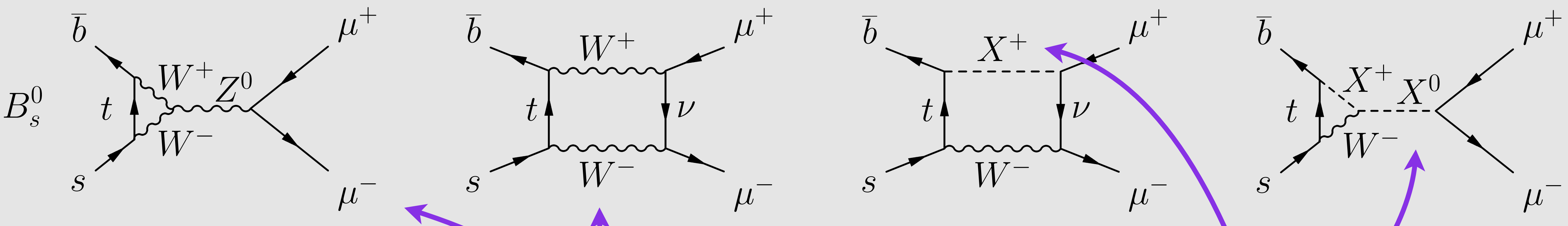
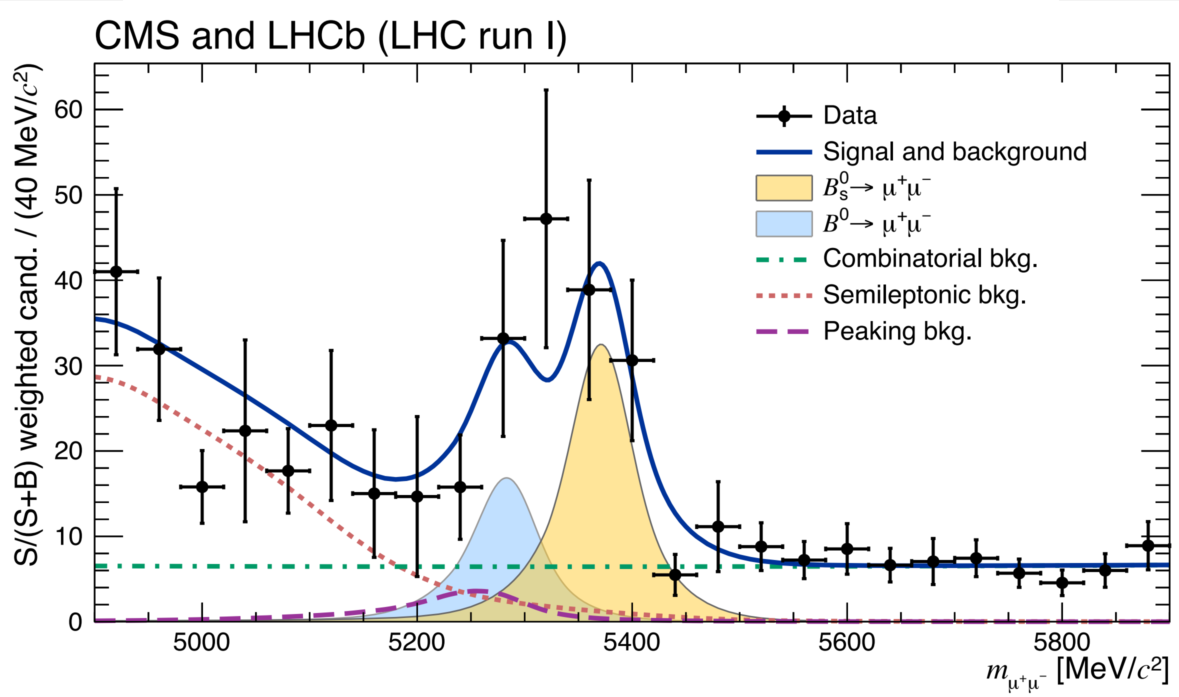
Many more LHCb results adding to the picture!

$B_{(s)} \to \mu^+\mu^-$



- Very rare decays
  - ➡ Precise SM predictions and high sensitivity to BSM physics
- Joint analysis by CMS and LHCb
- First observation of $B_s \to \mu^+\mu^-$
- First evidence for $B_d \to \mu^+\mu^-$
- No disagreement with SM
- Now measure B_d/B_s ratio, lifetime, …
  - ➡ Need much more data

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.8\,^{+0.7}_{-0.6}\right) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(3.9\,^{+1.6}_{-1.4}\right) \times 10^{-10}$$



CMS and LHCb, Nature 522 (2015) 68

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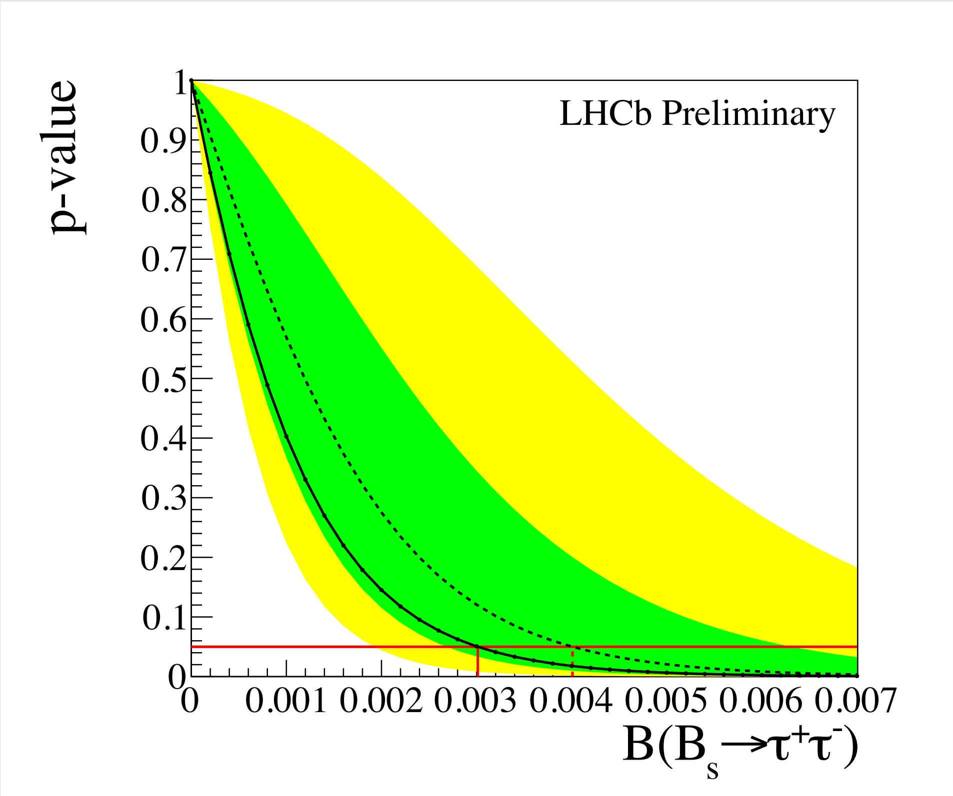
$B_{(s)} \to \tau^+\tau^-$

- $B_{(s)} \to \tau^+\tau^-$ can be enhanced w.r.t. $\mu^+\mu^-$ due to greater masses
- No existing limit for B_s
- Use $\tau^\pm \to \pi^\pm\pi^+\pi^-$ decays
- $\mathcal{B}(B_s \to \tau^+\tau^-) < 2.4\times10^{-3}$
- $\mathcal{B}(B_d \to \tau^+\tau^-) < 1.0\times10^{-3}$

at 90% CL

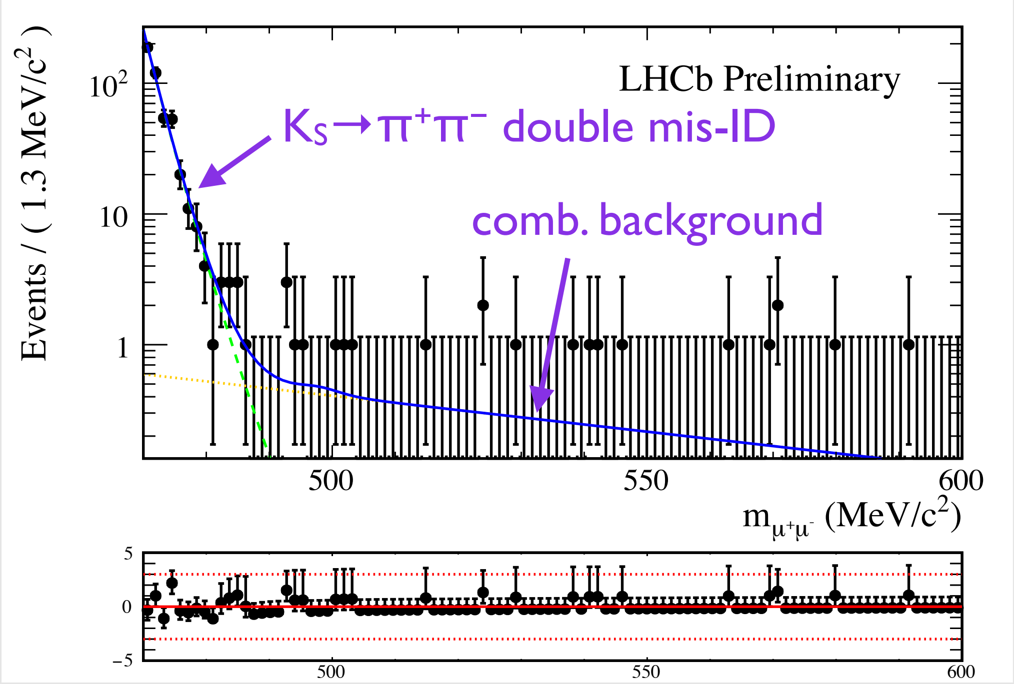


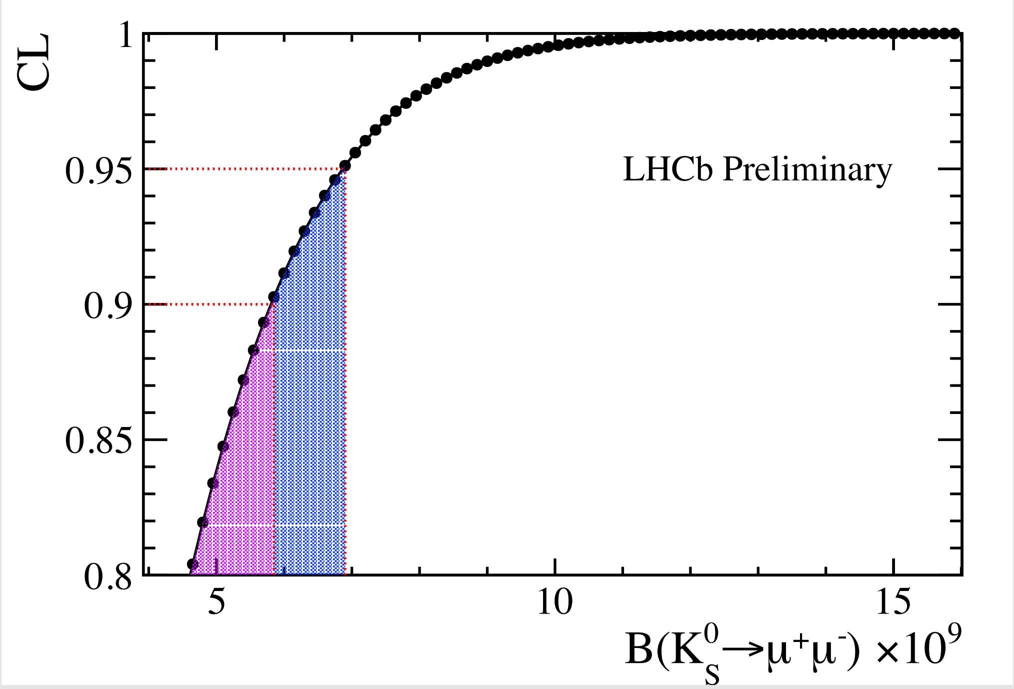
$K_S \to \mu^+\mu^-$

- Updated limit based on 2011+12 data
- Factor ~50 improvement over previous 40-year old limit

➡ 5.8×10^{-9} at 90% CL

- Headline result of a growing programme of strange physics at LHCb





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A brief visit to the particle zoo

Other physics areas

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Some examples

Exotica
- $Z(4430)^-$
- X(4140)
- X(3872)

Central exclusive production
- Improving HERA PDF measurements
- J/ψ, X(3872), Υ production
- Forward shower counters

. . .

Production & Spectroscopy
- $\Xi_b'^-$, Ξ_b^{*-}
- Hadron decays to Spin-3 state

Electroweak physics
- Associated W/Z production
- Forward energy flow
- Top production

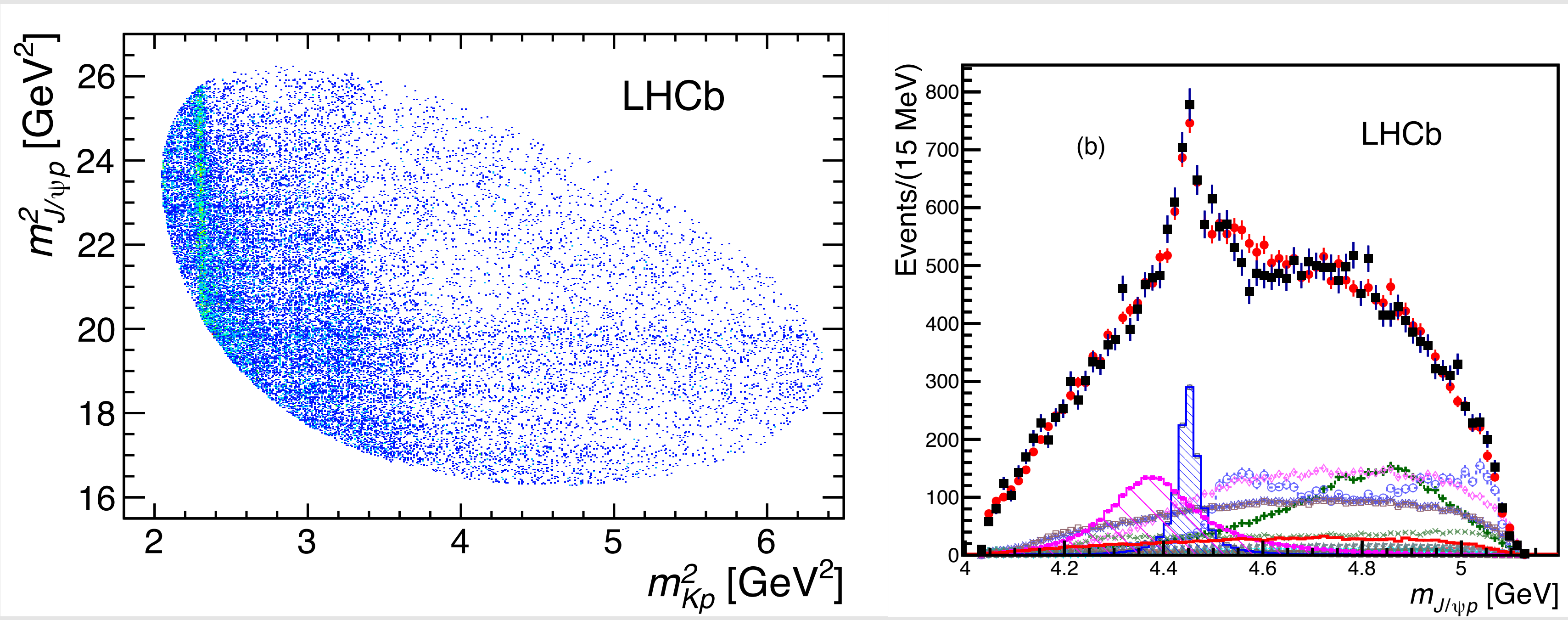
Heavy ion collisions
- Ridge analysis
- Production in p-Pb collisions

Forbidden decays
- Lepton-flavour violation
- τ decays

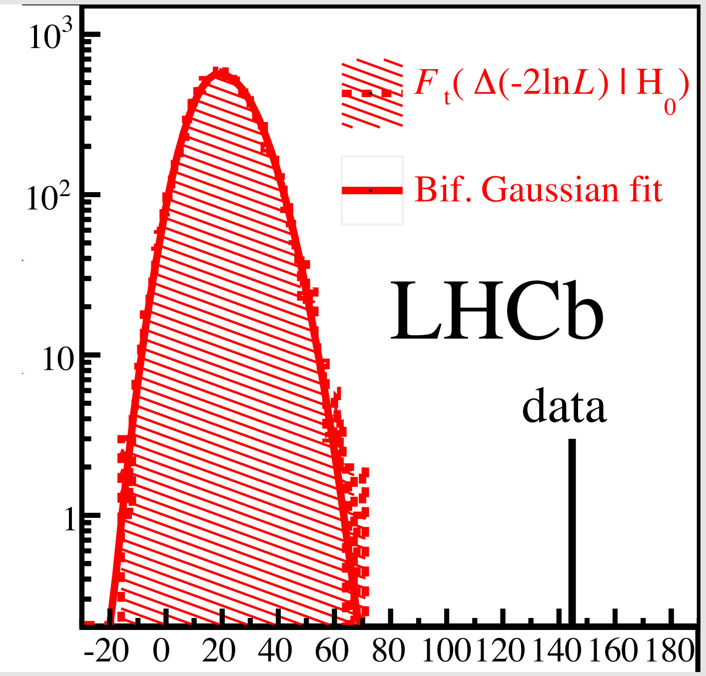
→ link to all >340 LHCb papers

Tetraquarks and Pentaquarks

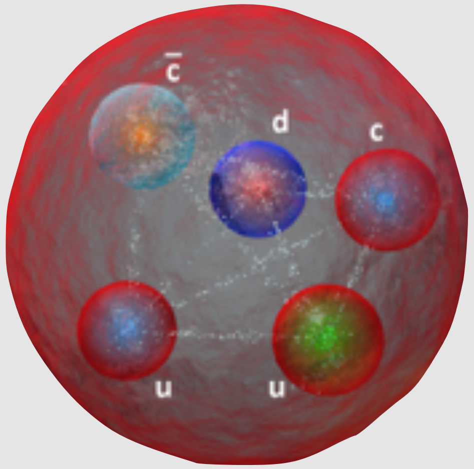
Phys. Rev. Lett. 115 (2015) 072001



PRL 117 (2016) 082002

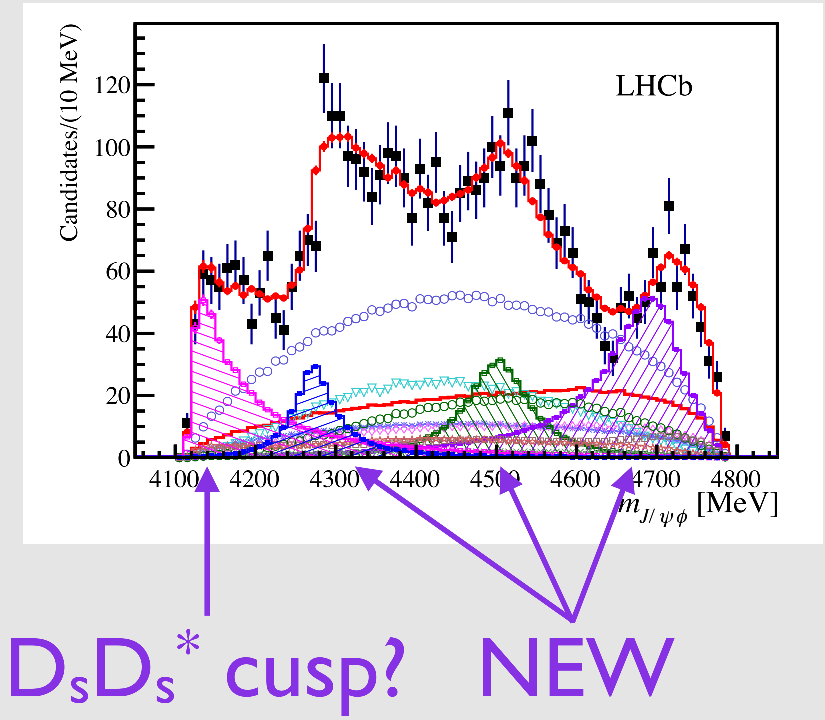


- Two pentaquark candidates discovered in 2015
  - ➡ Model-independent confirmation in 2016



- Four tetraquark candidates observed decaying to J/ψϕ
  - ➡ First full amplitude analysis
  - ➡ Three new states plus one known suspect

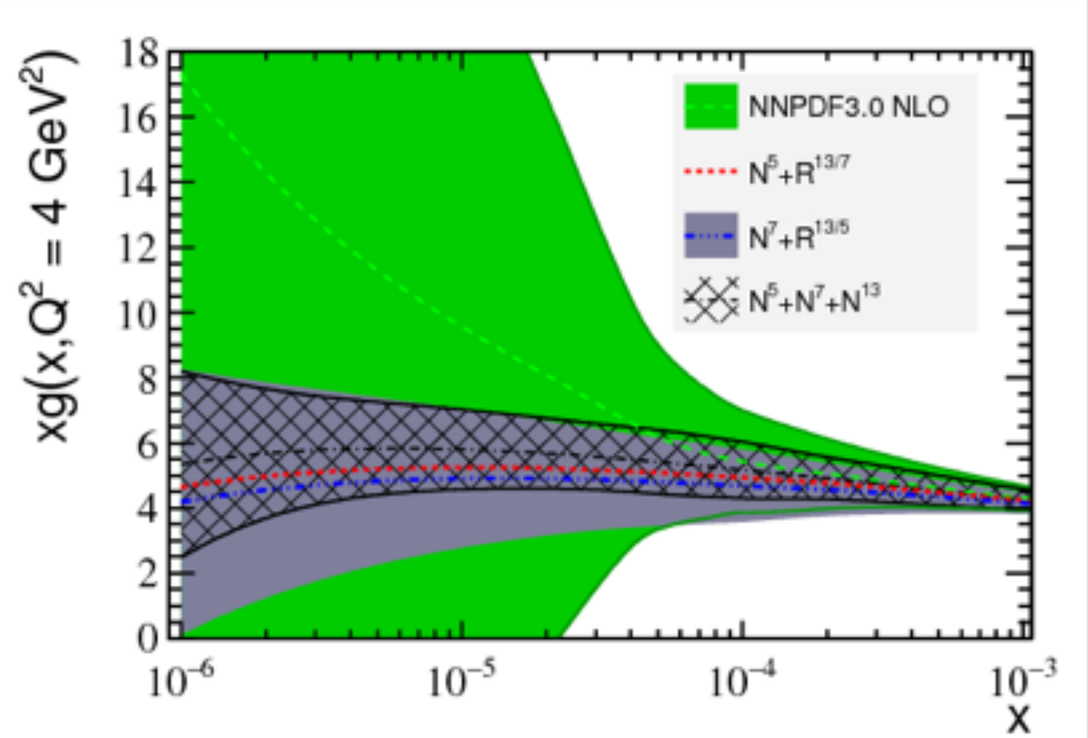
arXiv:1606.07895



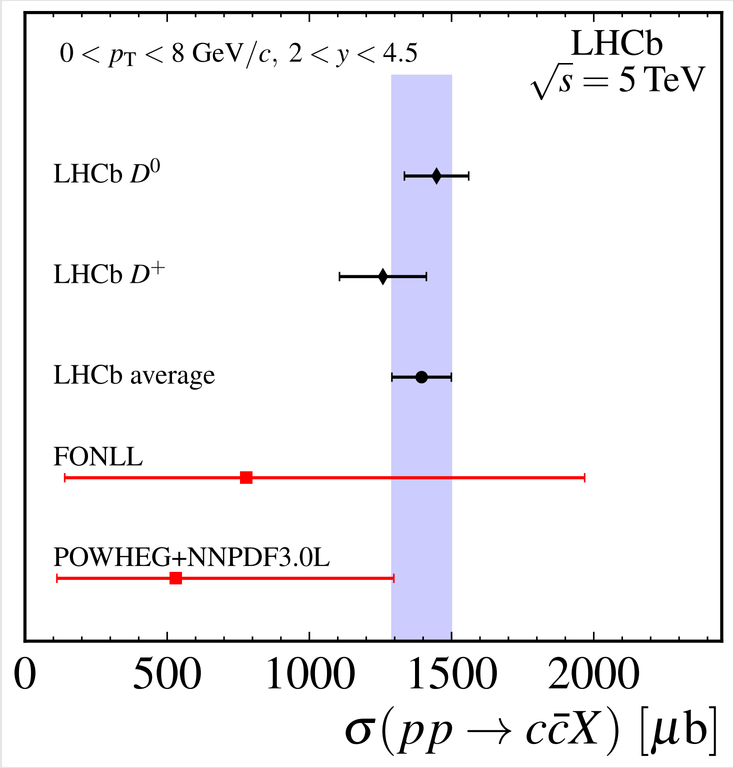
arXiv:1610.02230

Charm production

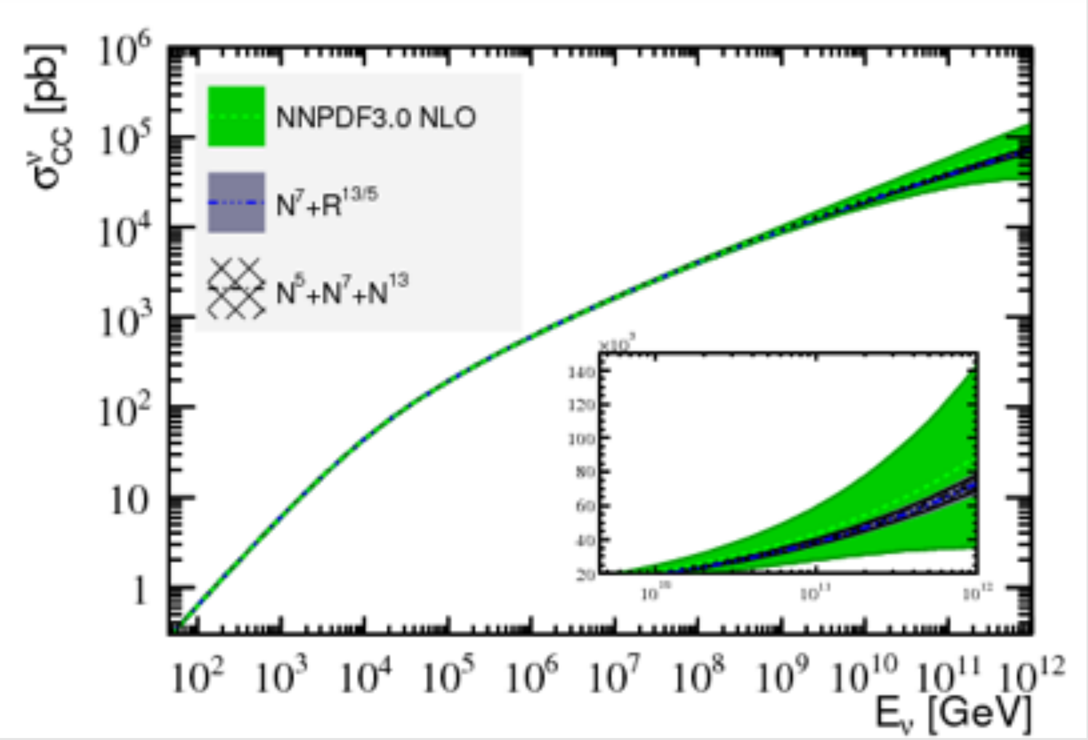
- Latest addition: 5 TeV
- Complements measurements at 7 TeV and 13 TeV
- Powerful constraints of gluon PDF at low x



Gauld, Rojo, arXiv:1610.09373



- Also improves atmospheric neutrino background prediction at very high energies



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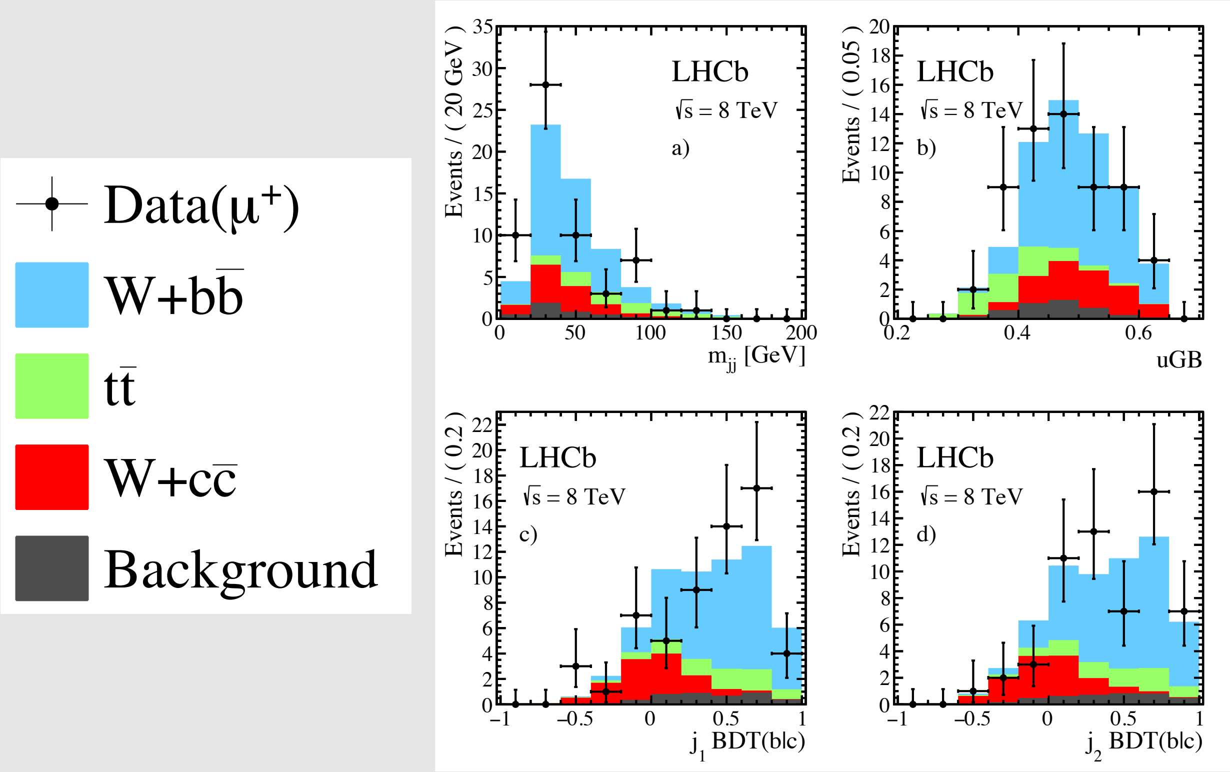
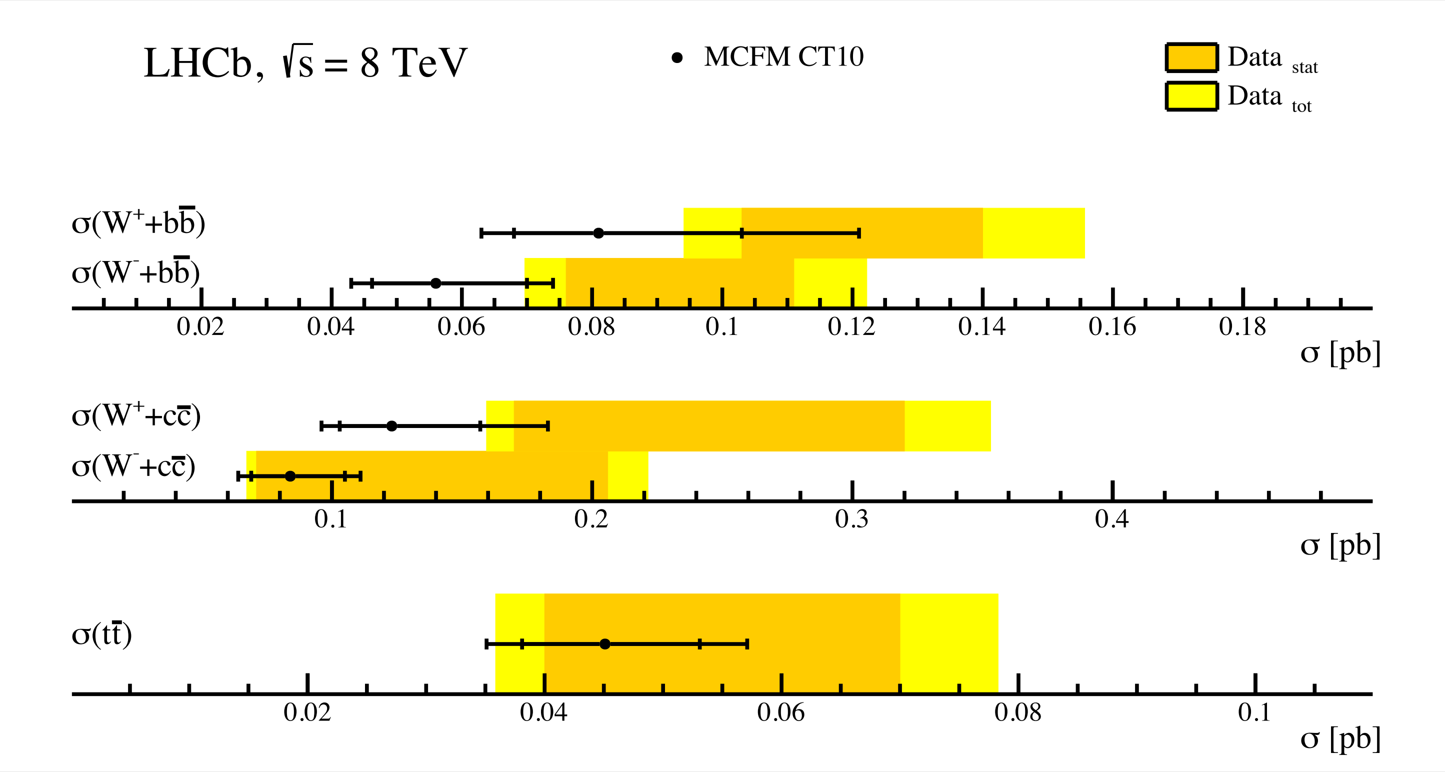
Top production

- New measurement of $t\bar{t}$ production in forward region
- Based on μ + b-jet reconstruction
- b and c jet tagging
  - ➡ 2 BDTs, secondary vertex detection, corrected mass JINST 10 P06013
- Combined with W+b,c production (asymmetry) measurement
- Uncertainties comparable to theory





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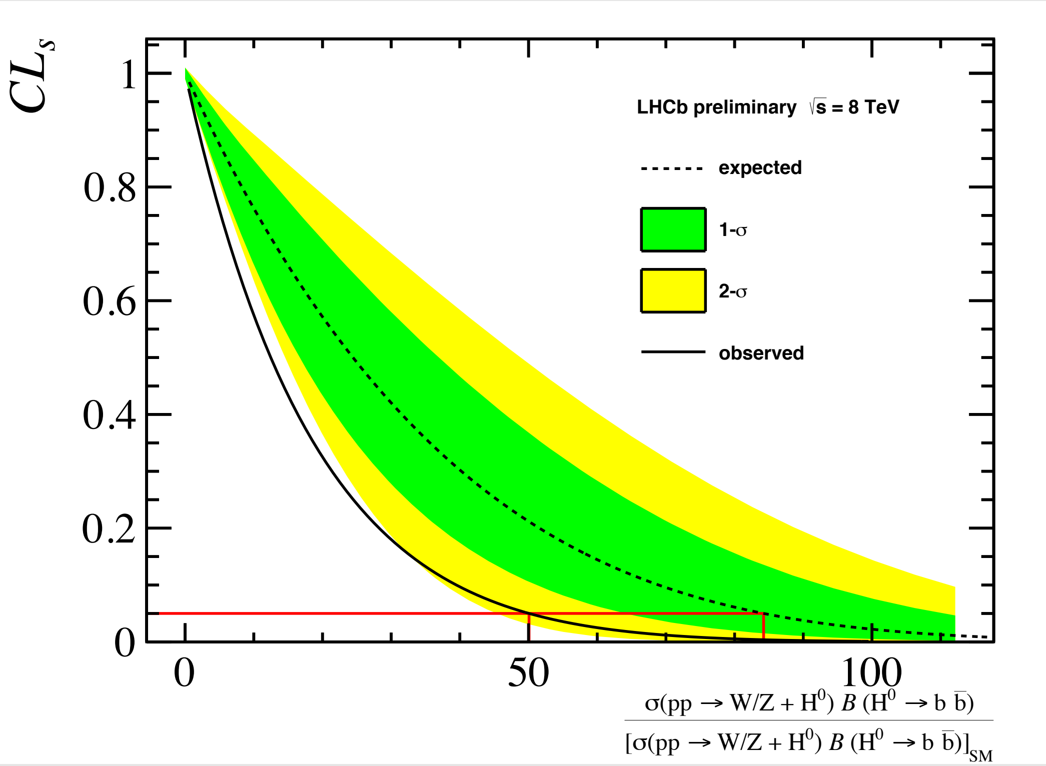
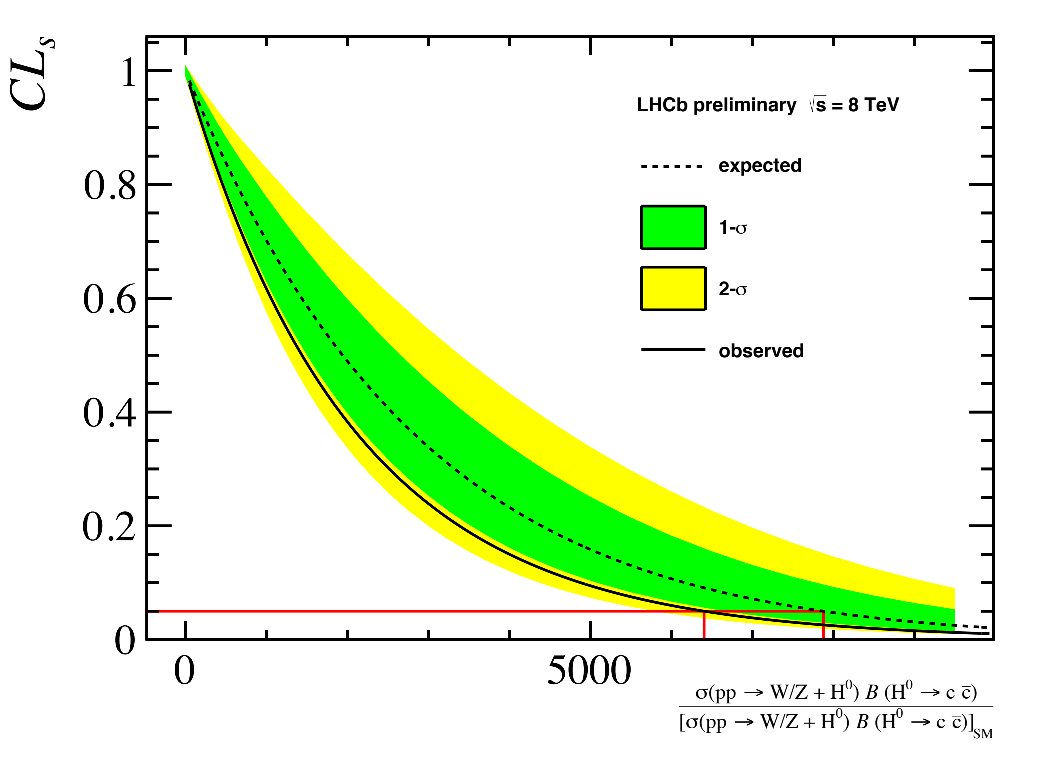
Higgs production

- Can LHCb see the Higgs?
  - ➡ One day maybe
- Searches in decays to $b\bar{b}$ and $c\bar{c}$
  - ➡ $b\bar{b}$ has potential with LHCb upgrade
  - ➡ $c\bar{c}$ in SM will be challenging
    - Still good chances for non-SM rates





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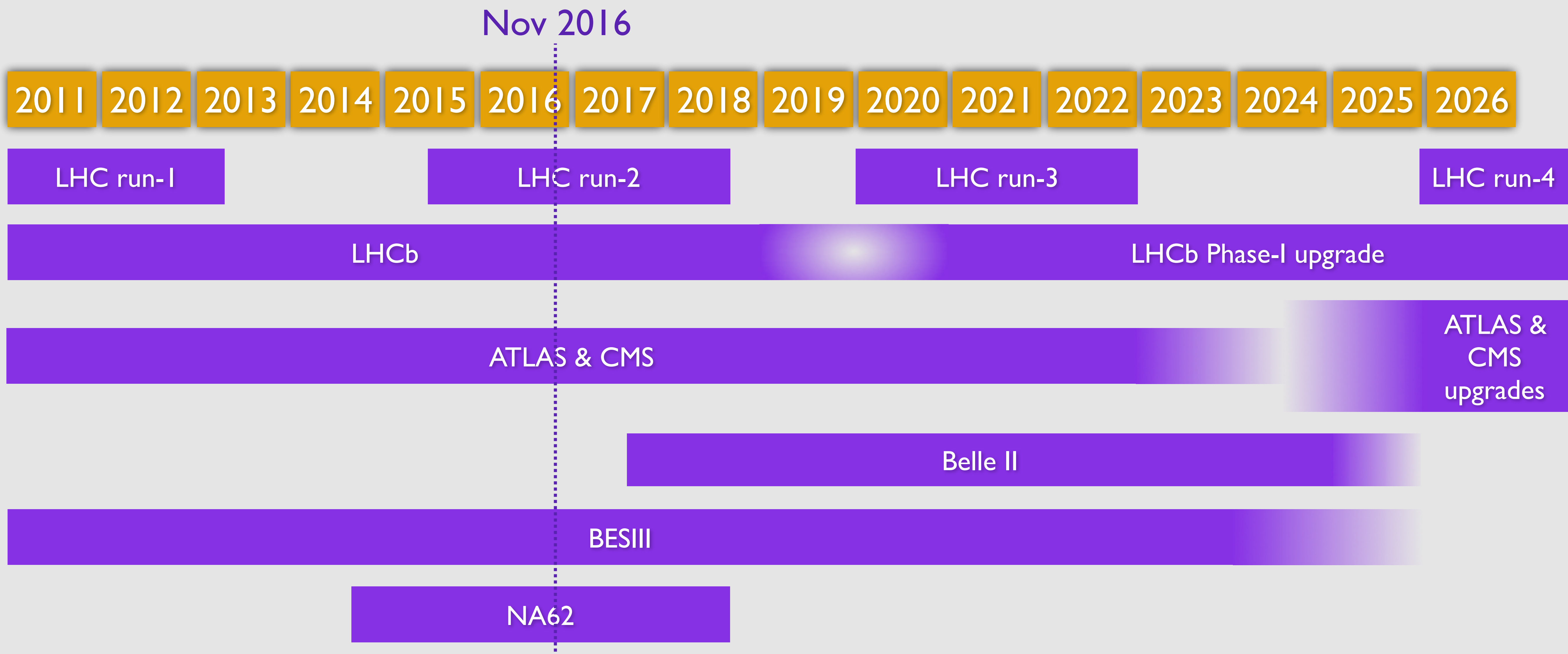
Future directions

Upgrading flavour experiments

A flavourful decade



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

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LHCb upgrade

2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024-26	2027	…

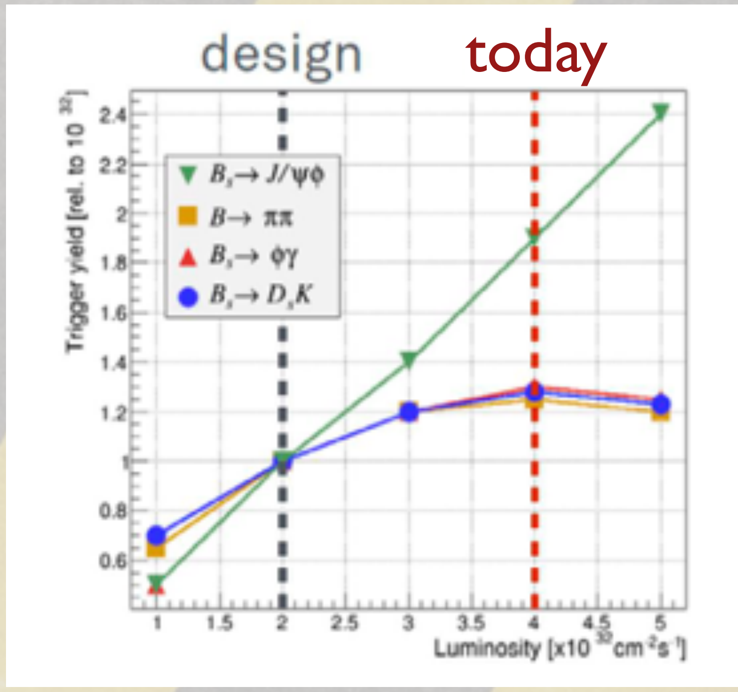
LHC run-1 | LHC run-2 | LHC run-3 | LHC run-4

LHCb | LHCb Phase-I upgrade

Nov 2016

Belle 2

- With increased luminosity hadron channels would saturate
  - ➡ Limited by hardware trigger
- Upgrade to allow full detector readout at 40 MHz and increased luminosity: collect ~8fb^{-1} per year
  - ➡ Requires several new detectors (all tracking plus RICH) and new readout electronics otherwise
- Full software trigger
  - ➡ Massively improved trigger efficiencies
  - ➡ Offline quality reconstruction in trigger
- Major construction project
  - ➡ Vertex Locator and RICH built in UK
- Maintain/improve current level of detector performance
- Phase-1b consolidation and Phase-II upgrade planned in LS3 and LS4

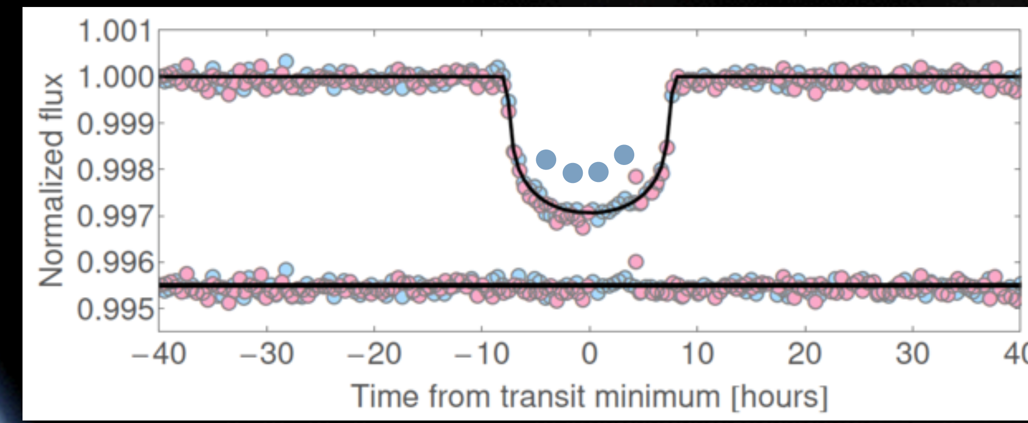


UNDER CONSTRUCTION

Conclusion

- LHC(b) now taken over leading role in flavour physics
- No smoking gun signal for physics beyond the SM
  - ➡ Several hints demand more precise and complementary measurements as well as advances on the theoretical side
- Good chance that strong signals will emerge with run-2
  - ➡ Stay tuned for latest updates at CKM
- Need LHCb upgrade to probe to Standard Model level precision
- Next decade will be flavourful
  - ➡ Belle II, BESIII, COMET, g-2, LHCb run-2, LHCb upgrade(s), MEG, mu2e, mu3e, NA62

Conclusion



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