Heavy Flavour Physics at the LHC

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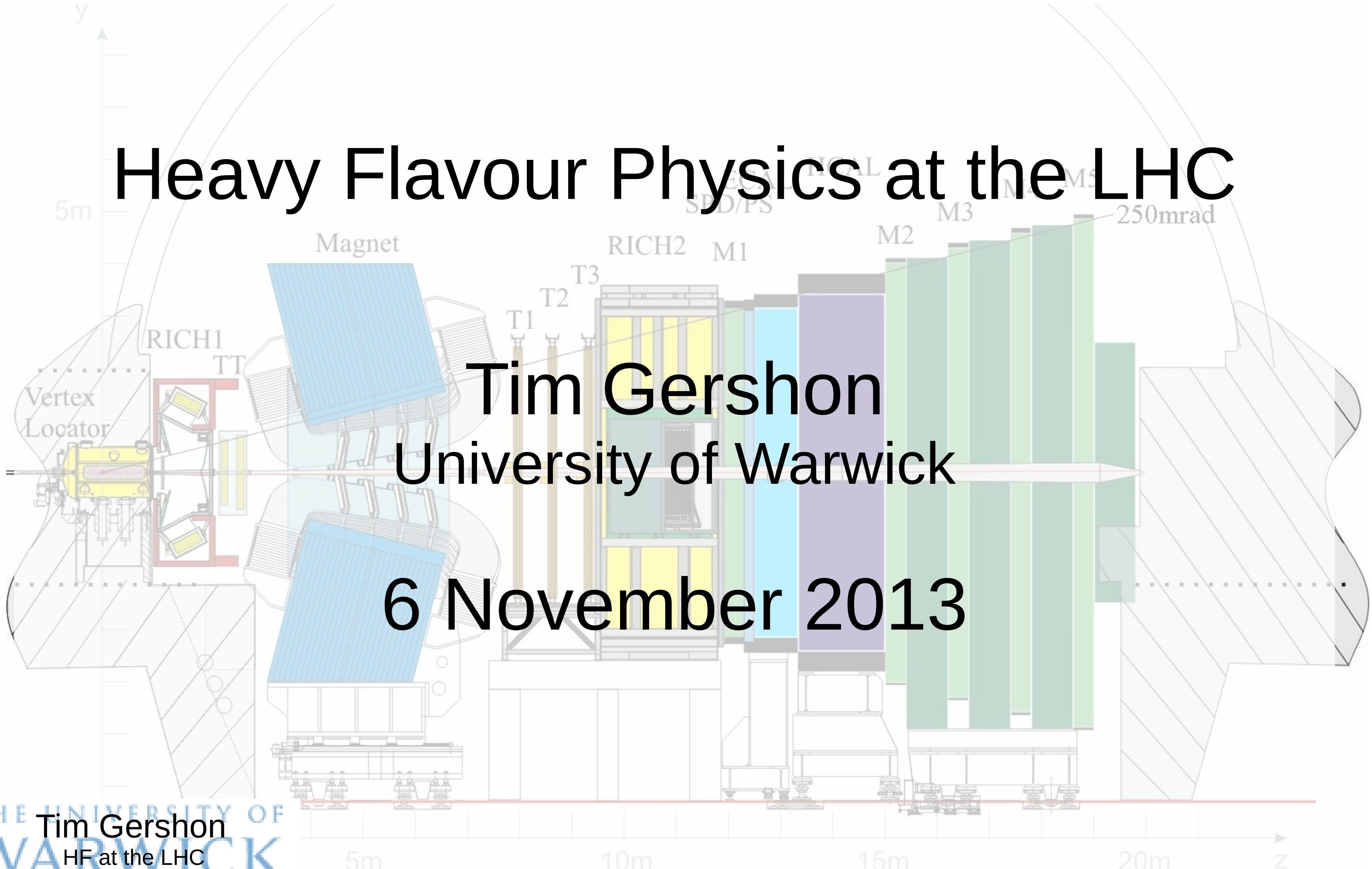
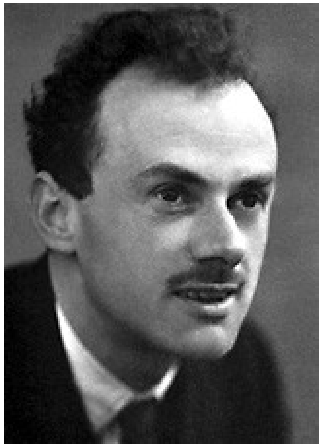


Outline

- Why flavour physics in the LHC era?
- Selected highlights of recent results
  - Production and spectroscopy
  - CP violation and the Unitarity Triangle
  - Rare decays
- Future prospects

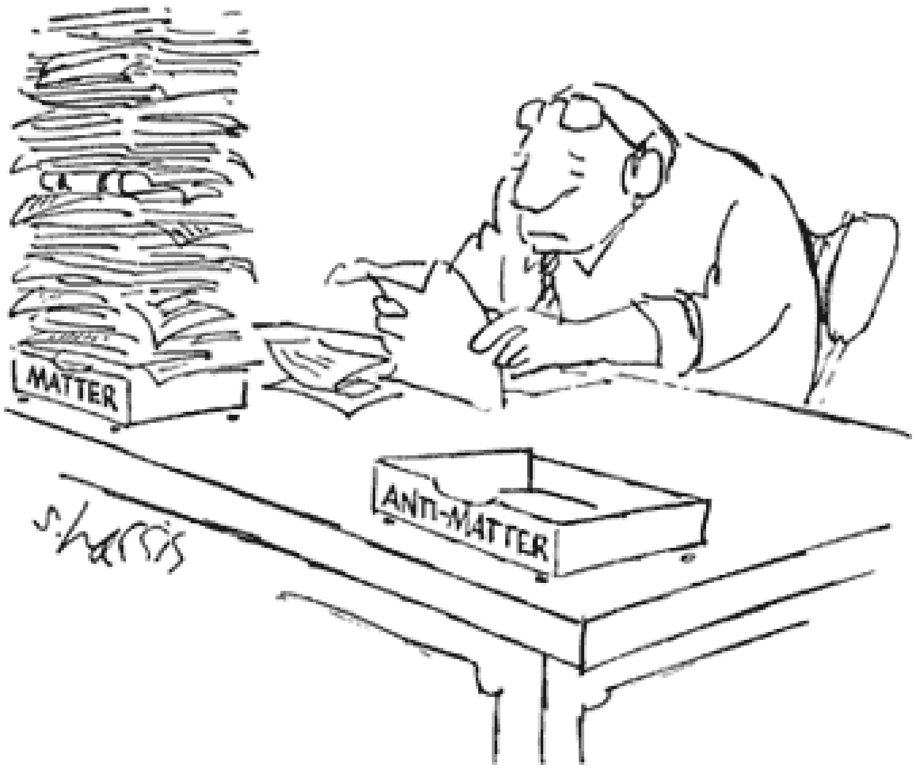
Dirac's prescience



Concluding words of 1933 Nobel lecture

"If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods."

Where is the antimatter?



CP violation and the matter-antimatter asymmetry

- Two widely known facts
  1) CP violation is one of 3 “Sakharov conditions” necessary for the evolution of a baryon asymmetry in the Universe
  2) The Standard Model (CKM) CP violation is not sufficient to explain the observed asymmetry
- Therefore, there must be more sources of CP violation in nature … but where?
  - extended quark sector, lepton sector (leptogenesis), supersymmetry, anomalous gauge couplings, extended Higgs sector, quark-gluon plasma, flavour-diagonal phases, …
- Testing the consistency of the CKM mechanism provides the best chance to find new sources of CP violation today

What causes the difference between matter and antimatter?

- In the SM, fermion masses arise from the Yukawa couplings of the quarks and charged leptons to the Higgs field (taking m_ν=0)
- The CKM matrix arises from the relative misalignment of the Yukawa matrices for the up- and down-type quarks

$$V_{CKM} = U_u U_d^+$$

U matrices from diagonalisation of mass matrices

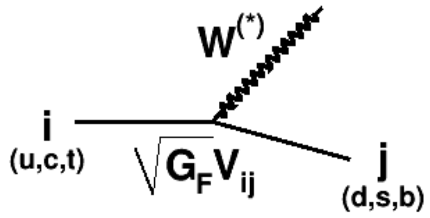
- It is a 3x3 complex unitary matrix
  - described by 9 (real) parameters
  - 5 can be absorbed as phase differences between the quark fields
  - 3 can be expressed as (Euler) mixing angles
  - the fourth makes the CKM matrix complex (i.e. gives it a phase)
    - weak interaction couplings differ for quarks and antiquarks
    - CP violation

The Cabibbo-Kobayashi-Maskawa Quark Mixing Matrix

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- A 3x3 unitary matrix
- Described by 4 real parameters – allows CP violation
  - PDG (Chau-Keung) parametrisation: θ_{12}, θ_{23}, θ_{13}, δ
  - Wolfenstein parametrisation: λ, A, ρ, η
- Highly predictive

Quark flavour mixing
a.k.a. CKM phenomenology



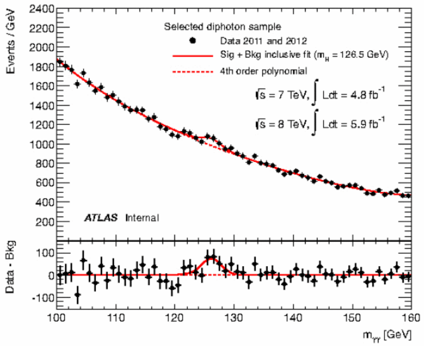
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

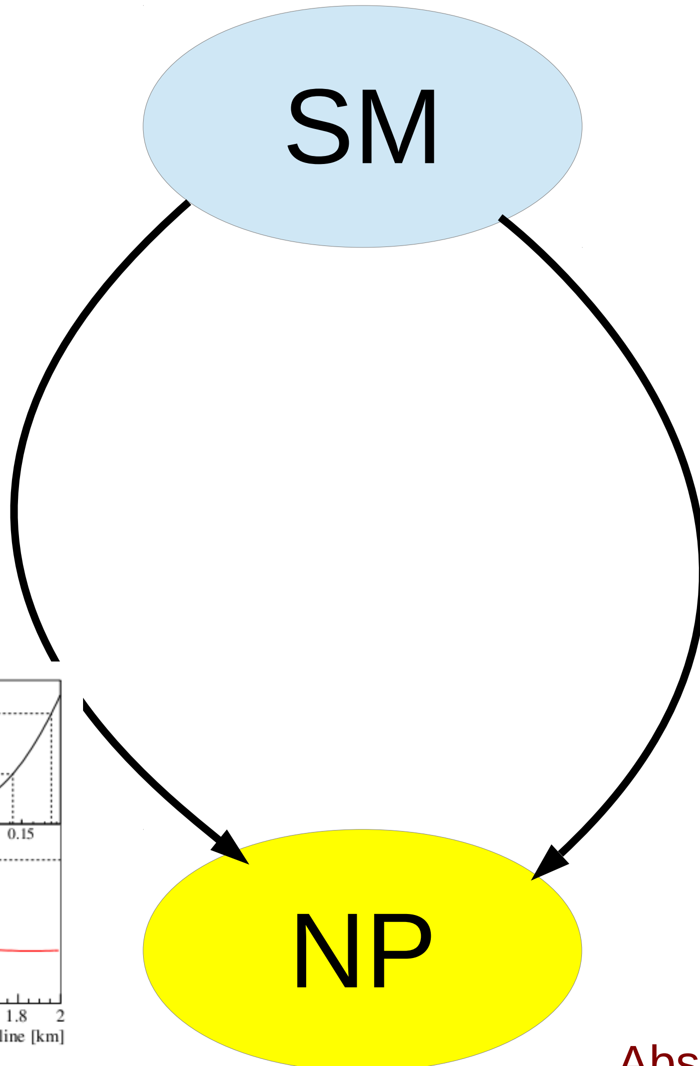
N.B. V_{ts} has imaginary part at $O(\lambda^4)$

- CKM theory is highly predictive
  - huge range of phenomena over a massive energy scale predicted by only 4 independent parameters (+ QCD)
- CKM matrix is hierarchical
  - theorised connections to quark mass hierarchies, or (dis-)similar patterns in the lepton sector
    - origin of CKM matrix from diagonalisation of Yukuwa (mass) matrices after electroweak symmetry breaking
  - distinctive flavour sector of Standard Model not necessarily replicated in extended theories → strong constraints on models
- CKM mechanism introduces CP violation
  - only source of CP violation in the Standard Model ($m_\nu = \theta_{QCD} = 0$)

Two routes to heaven

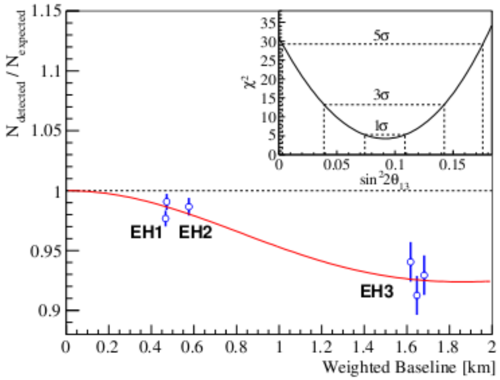
for flavour physics





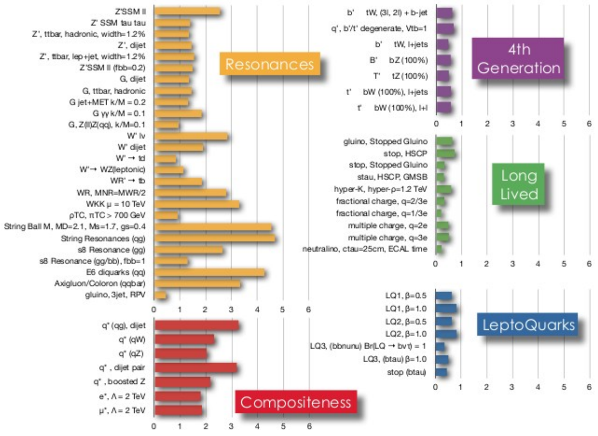
CP violation
(extra sources must exist)

But
- No guarantee of the scale
- No guarantee of effects in the quark sector
- Realistic prospects for CPV measurement in νs due to large θ_{13}



Rare decays
(strong theoretical arguments)

But
- How high is the NP scale?
- Why have FCNC effects not been seen?



Absence of NP signals at ATLAS/CMS → argument for searches via rare decays stronger

New Physics Flavour Problem

- Limits on NP scale at least 100 TeV for generic couplings
  - model-independent argument, also for rare decays
- But we need NP at the "TeV scale" to solve the hierarchy problem (and to provide DM candidate, etc.)
- So we need NP flavour-changing couplings to be small
- Why?
  - minimal flavour violation?
    - perfect alignment of flavour violation in NP and SM
  - some other approximate symmetry?
  - flavour structure tells us about physics at very high scales
- Many important observables are not sufficiently well-tested

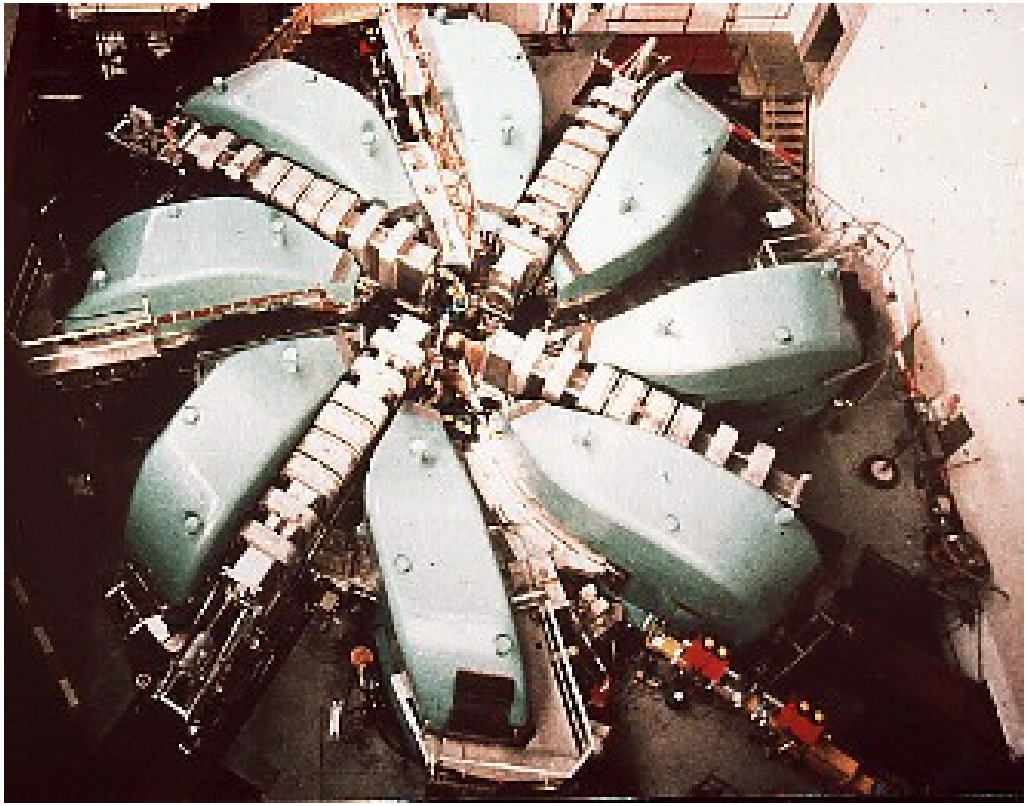
NPB 645 (2002) 155

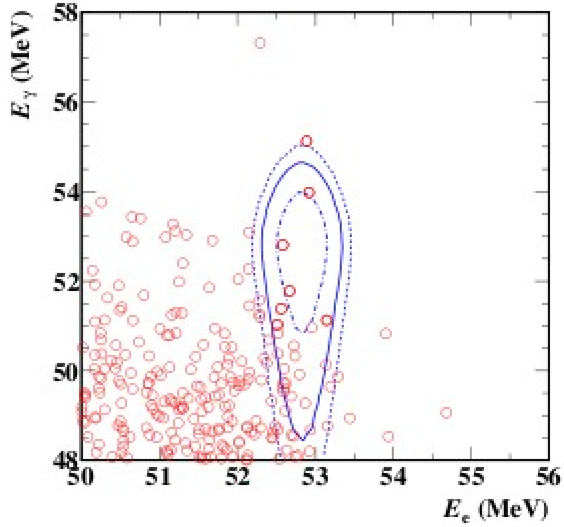
Search for $\mu^+ \to e^+\gamma$

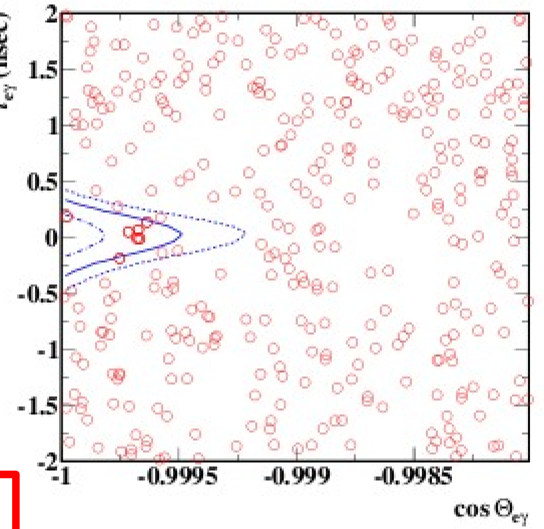
MEG arXiv:1303.0754

$\mu^+ \to e^+\gamma$

- positive muons $\to$ no muonic atoms
- continuous (DC) muon beam at PSI $\to$ minimise accidental coincidences







$B(\mu^+ \to e^+\gamma) < 5.7\ 10^{-13}$ @ 90% CL

Why flavour physics in the LHC era?

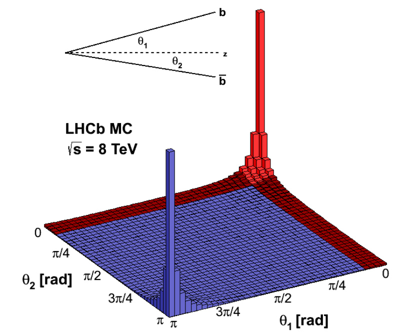
- There is still much physics to be done with the datasets of BaBar, Belle, CDF, D0, CLEO, BES, etc.
  - Discovery potential complementary to other experiments
  - New experiments in the charged lepton sector add additional potential
- LHC is the world's most copious source of heavy flavoured fermions
  - LHCb experiment instruments the forward region for best b & c physics capability
    - extends the physics reach of the LHC programme, exploring *beyond* the energy frontier
  - ATLAS and CMS experiments also have some capability in this sector
- In addition to studying flavour-changing phenomena, excellent opportunities to study unresolved issues in QCD
  - Puzzles concerning heavy flavour production and spectroscopy

Flavour physics at hadron colliders

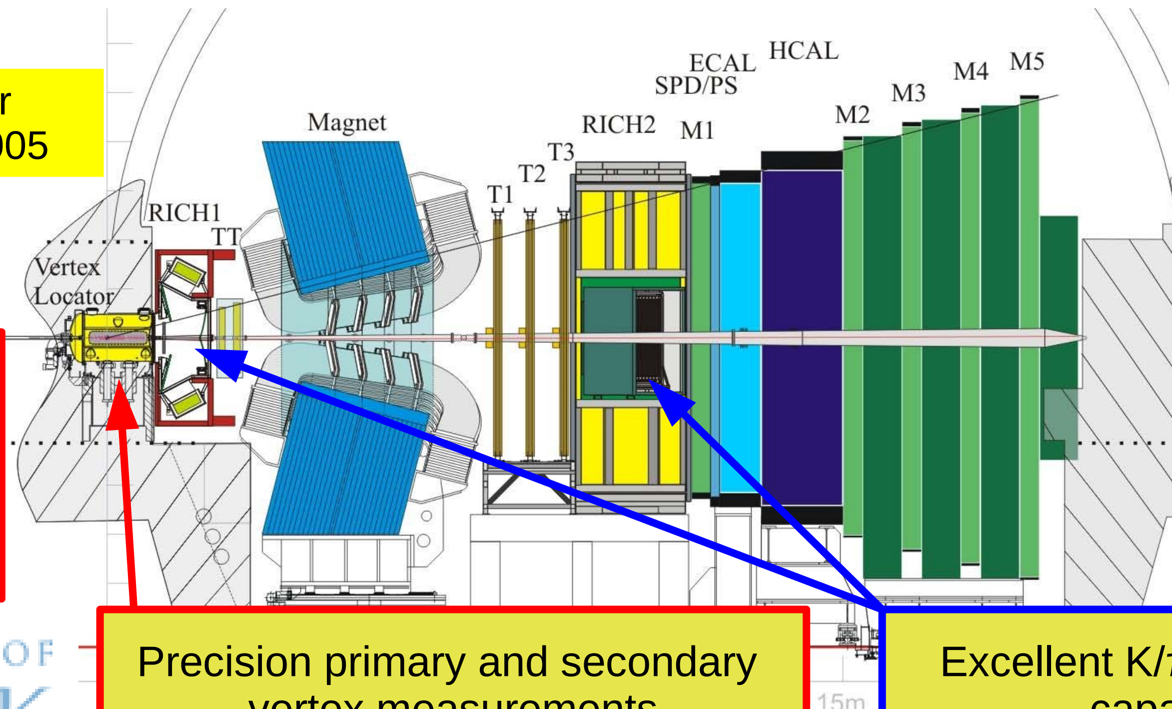
	$e^+e^- \to \Upsilon(4S) \to B\bar{B}$ PEP-II, KEKB	$p\bar{p} \to b\bar{b}X$ ($\sqrt{s} = 2\,\mathrm{TeV}$) Tevatron	$pp \to b\bar{b}X$ ($\sqrt{s} = 14\,\mathrm{TeV}$) LHC
Production cross-section	$1\,\mathrm{nb}$	$\sim 100\,\mu\mathrm{b}$	$\sim 500\,\mu\mathrm{b}$
Typical $b\bar{b}$ rate	$10\,\mathrm{Hz}$	$\sim 100\,\mathrm{kHz}$	$\sim 500\,\mathrm{kHz}$
Pile-up	0	1.7	0.5–20
b hadron mixture	B^+B^- (50%), $B^0\bar{B}^0$ (50%)	B^+ (40%), B^0 (40%), B_s^0 (10%), Λ_b^0 (10%), others ($< 1\%$)	
b hadron boost	small ($\beta\gamma \sim 0.5$)	large ($\beta\gamma \sim 100$)	
Underlying event	$B\bar{B}$ pair alone	Many additional particles	
Production vertex	Not reconstructed	Reconstructed from many tracks	
B^0–$\bar{B}^0$ pair production	Coherent (from $\Upsilon(4S)$ decay)	Incoherent	
Flavour tagging power	$\varepsilon D^2 \sim 30\%$	$\varepsilon D^2 \sim 5\%$	

The LHCb detector

- In high energy collisions, $b\bar{b}$ pairs produced predominantly in forward or backward directions
- LHCb is a forward spectrometer
  - a new concept for HEP experiments



The LHCb Detector
JINST 3 (2008) S08005



Precision primary and secondary vertex measurements

Excellent K/π separation capability

The LHCb trigger

JINST 8 (2013) P04022

Challenge is

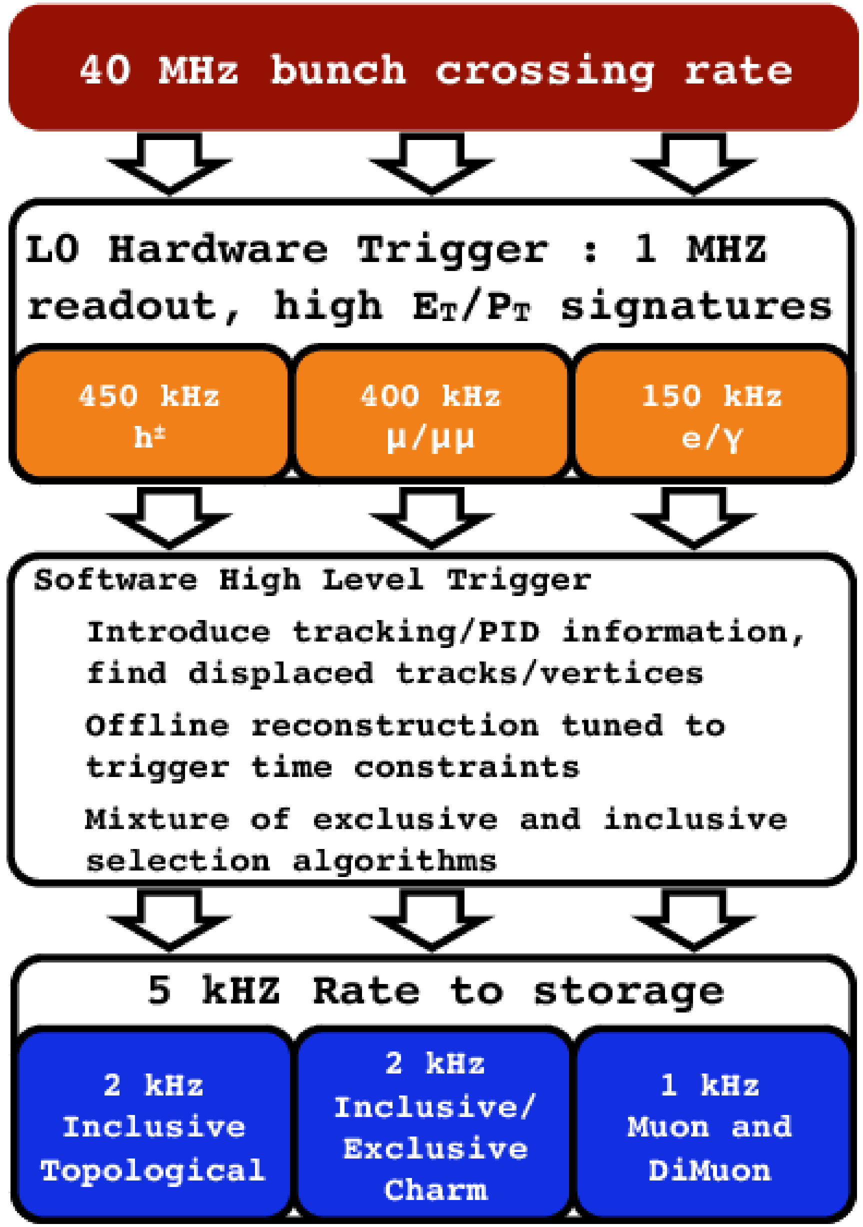
- to efficiently select most interesting B decays
- while maintaining manageable data rates

Main backgrounds

- “minimum bias” inelastic pp scattering
- other charm and beauty decays

Handles

- high p_T signals (muons)
- displaced vertices



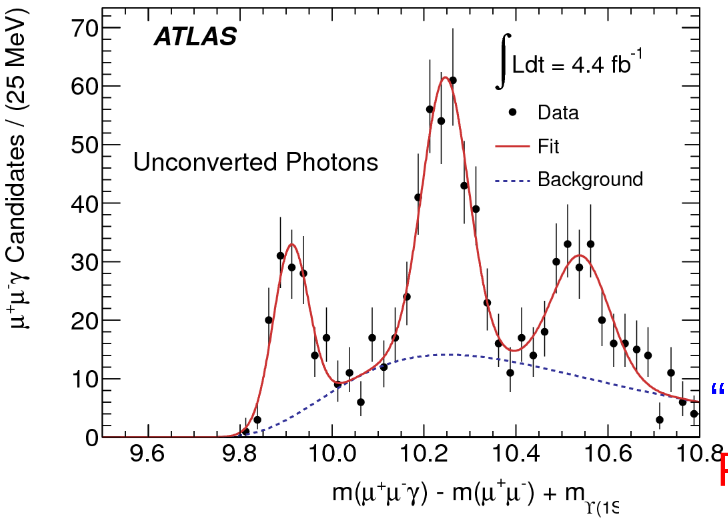
Selected highlights of results
Production and spectroscopy

Observations of new states

(no, not the Higgs)

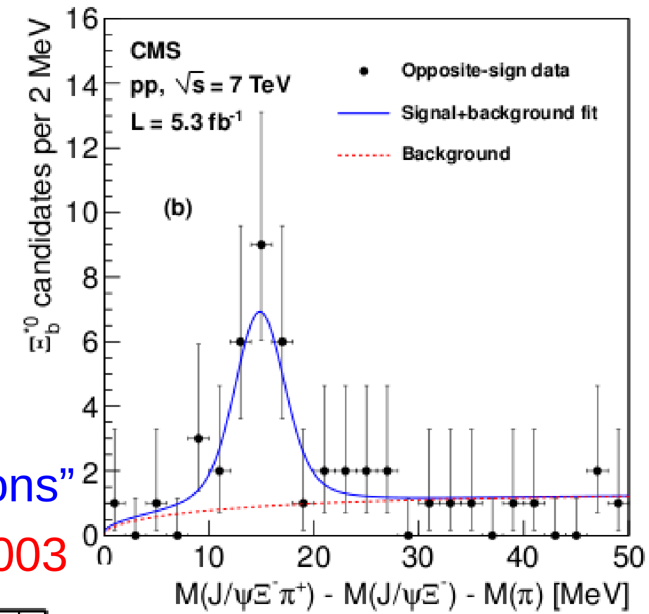
"Observation of a New χ_b State in Radiative Transitions to $\Upsilon(1S)$ and $\Upsilon(2S)$ at ATLAS"

Phys. Rev. Lett. 108 (2012) 152001



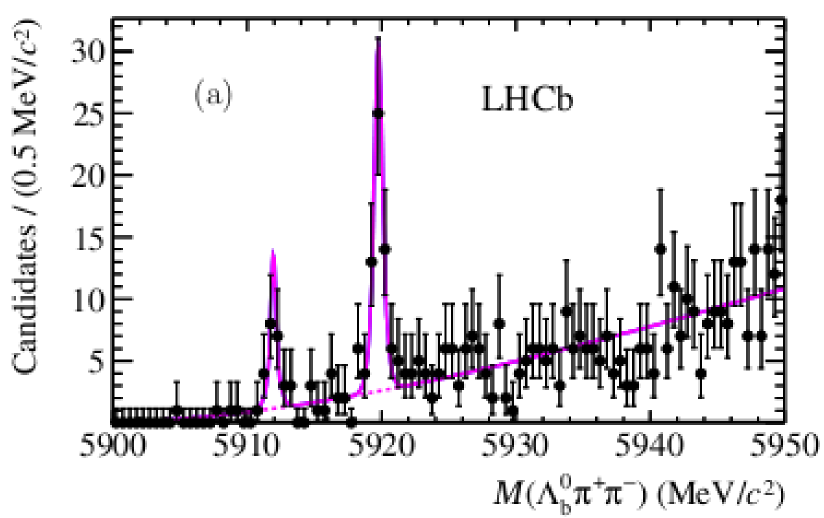
"Observation of a New Ξ_b Baryon"

Phys. Rev. Lett. 108 (2012) 252002



"Observation of excited Λ^0_b baryons"

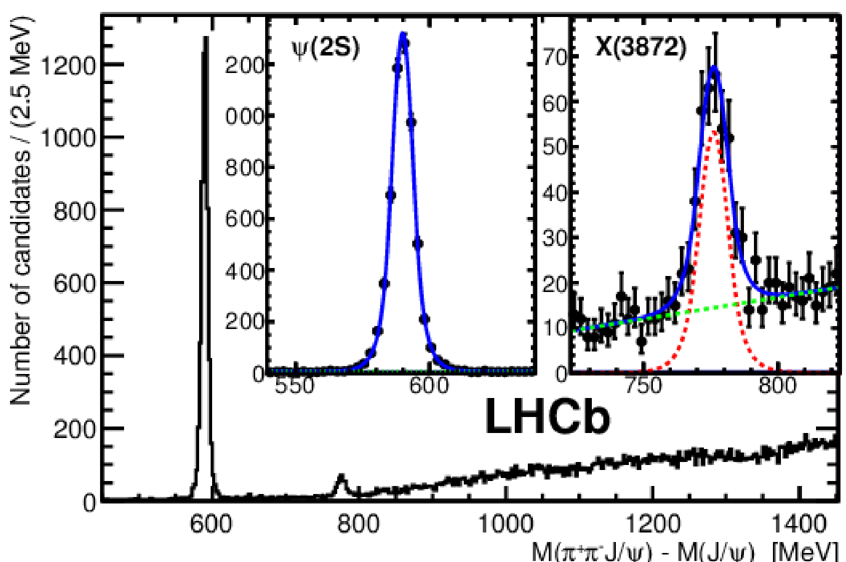
Phys. Rev. Lett. 109 (2012) 172003

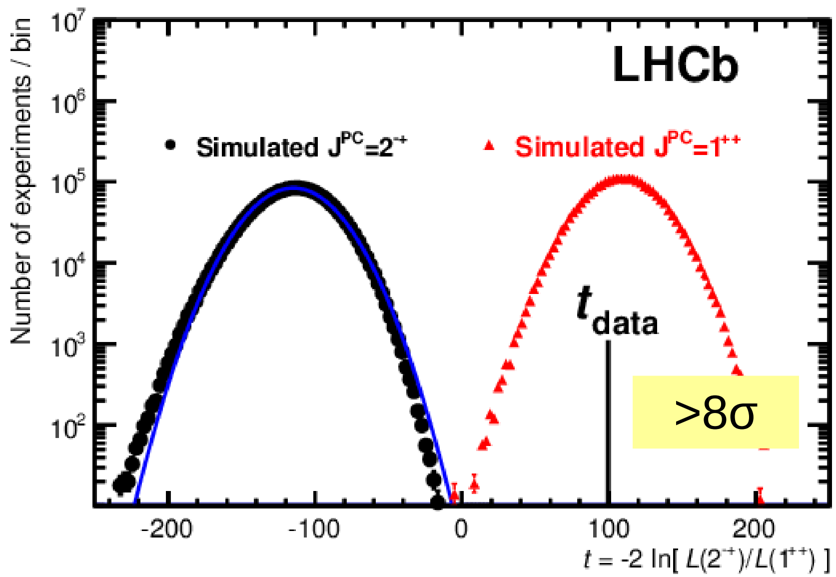


Quantum numbers of the X(3872)

LHCb PRL 110 (2013) 222001

- X(3872) discovered in $B \to XK$, with $X \to J/\psi\pi\pi$ (Belle PRL 91 (2003) 262001)
- Does not fit well with expectations for conventional states
  - above open charm threshold but narrow
- J^{PC} limited to 1^{++} or 2^{-+} by previous analyses (CDF PRL 98 (2007) 132002)
- LHCb analysis uses production from B decay, and full (5D) angular distribution of decay chain (assuming $J^{PC}(\pi\pi) = 1^{--}$; see also CMS arXiv:1302.3968)
- Likelihood ratio test used to compare hypotheses





>8σ

$J^{PC} = 1^{++}$ supports molecular interpretation of X(3872)
… but then how to explain production in hadron collisions?

Selected highlights of results
CP violation and the Unitarity Triangle

The Unitarity Triangle

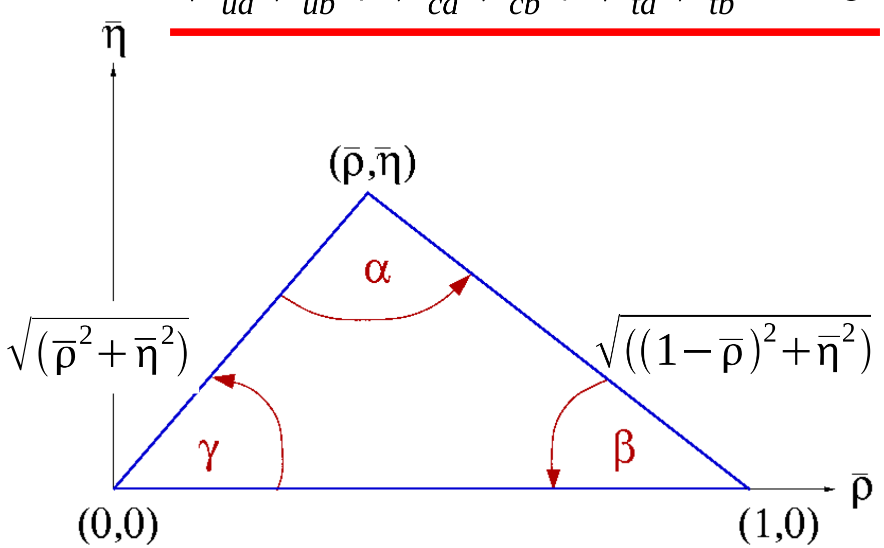
- The CKM matrix must be unitary

$$V_{CKM}^{+} V_{CKM} = V_{CKM} V_{CKM}^{+} = 1$$

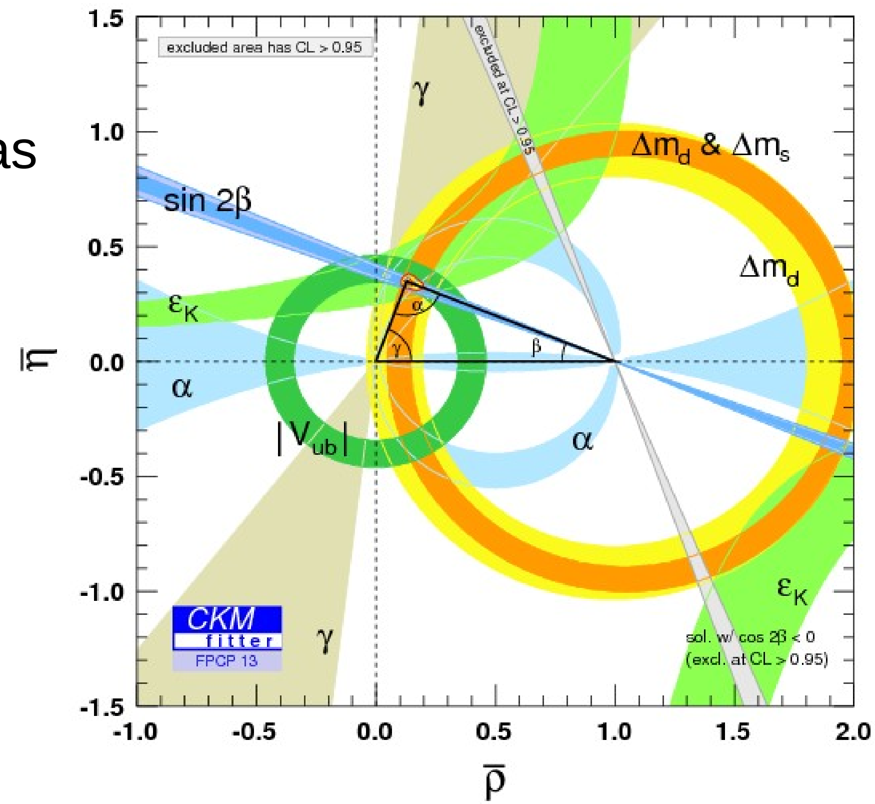
- Provides numerous tests of constraints between independent observables, such as

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

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



http://ckmfitter.in2p3.fr
see also http://www.utfit.org

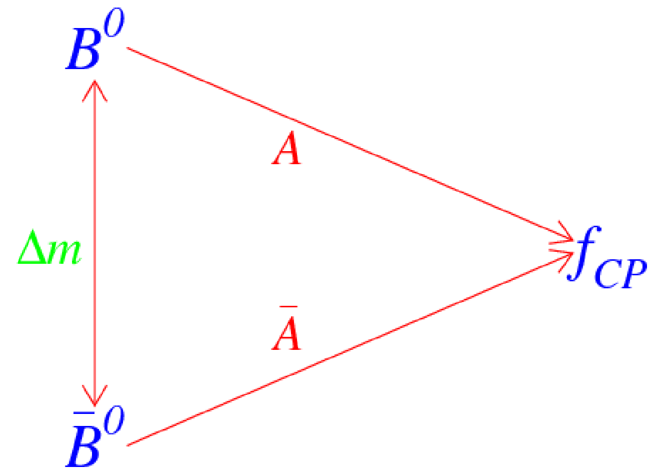


Consistency of measurements tests the Standard Model and provides model-independent constraints on New Physics

Categories of CP violation

- Consider decay of neutral particle to a CP eigenstate

$$\lambda_{CP} = \frac{q}{p}\frac{\overline{A}}{A}$$



$$\left|\frac{q}{p}\right| \neq 1$$

CP violation in mixing

$$\left|\frac{\overline{A}}{A}\right| \neq 1$$

CP violation in decay (direct CPV)

$$\Im\left(\frac{q}{p}\frac{\overline{A}}{A}\right) \neq 0$$

CP violation in interference between mixing and decay

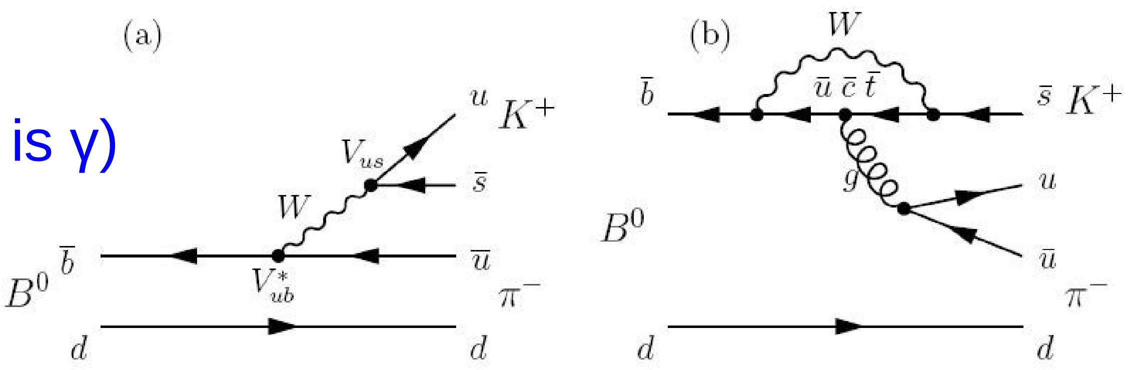
Direct CP violation

- Condition for DCPV: $|\bar{A}/A| \neq 1$
- Need $\bar{A}$ and A to consist of (at least) two parts
  - with different weak (φ) and strong (δ) phases
- Often realised by “tree” and “penguin” diagrams

$$A = |T| e^{i(\delta_T - \phi_T)} + |P| e^{i(\delta_P - \phi_P)} \qquad \bar{A} = |T| e^{i(\delta_T + \phi_T)} + |P| e^{i(\delta_P + \phi_P)}$$

$$A_{CP} = \frac{|\bar{A}|^2 - |A|^2}{|\bar{A}|^2 + |A|^2} = \frac{2\,|T||P| \sin(\delta_T - \delta_P) \sin(\phi_T - \phi_P)}{|T|^2 + |P|^2 + 2\,|T||P| \cos(\delta_T - \delta_P) \cos(\phi_T - \phi_P)}$$

Example: B→Kπ
(weak phase difference is γ)



Feynman tree (a) and penguin (b) diagrams for the $B_d^0 \to K^+\pi^-$ decay

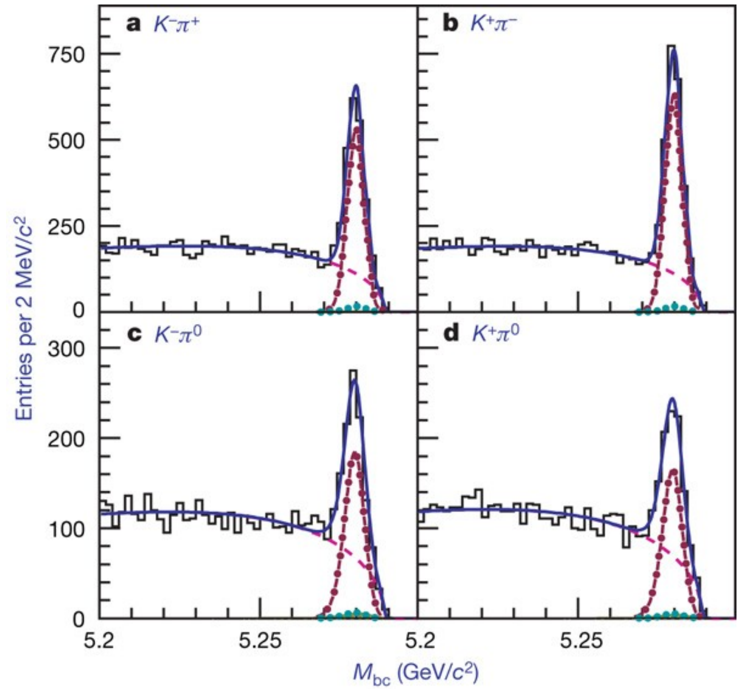
Direct CP violation in B→Kπ

- Direct CP violation in B→Kπ sensitive to γ

  too many hadronic parameters ⇒ need theory input

NB. interesting deviation from naïve expectation

Belle Nature 452 (2008) 332



"Kπ puzzle"

$A_{CP}(K^-\pi^+) = -0.082 \pm 0.006$

$A_{CP}(K^-\pi^0) = +0.040 \pm 0.021$

HFAG averages

Could be a sign of new physics …
… but first need to rule out possibility of
larger than expected QCD corrections

How to rule out large QCD corrections?

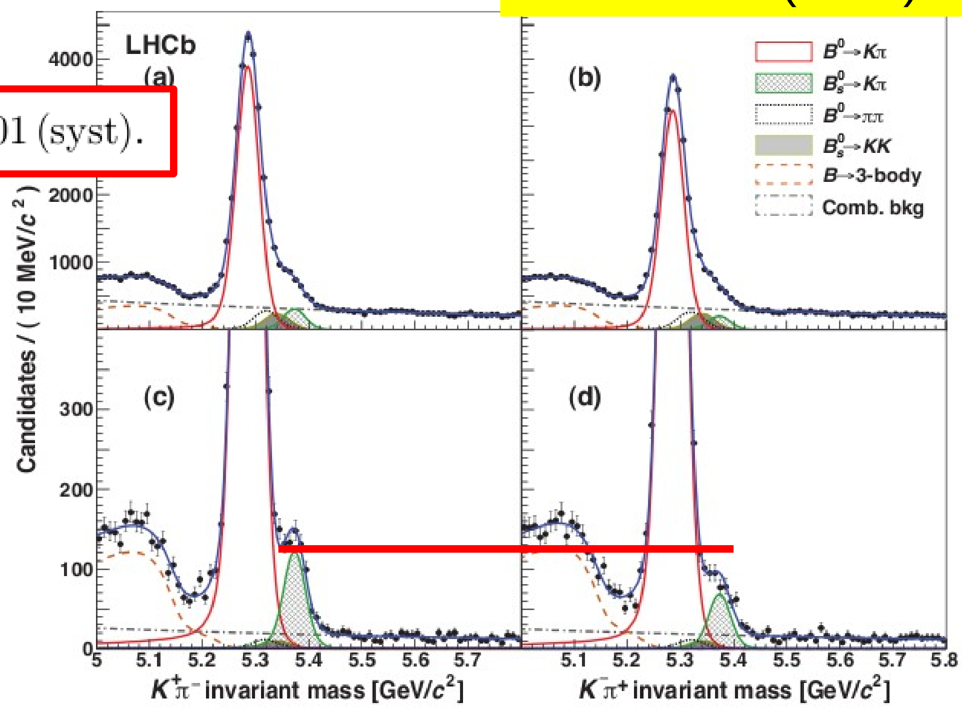
- Measure more $B_{u,d} \to K\pi$ decays & relate by isospin
- Perform similar analysis on $B \to K^*\pi$ &/or $B \to K\rho$
- Measure $B_s \to KK$ decays & relate by U-spin

PRL 110 (2013) 221601

$$A_{CP}(B_s^0 \to K^-\pi^+) = 0.27 \pm 0.04\,(\text{stat}) \pm 0.01\,(\text{syst}).$$

consistent with SM expectation

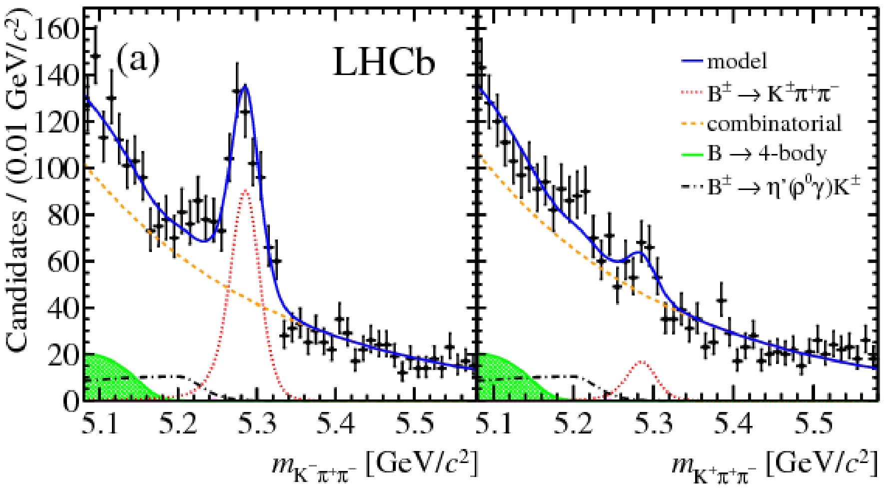
5σ observation of CP violation in $B_s \to K\pi$ decays

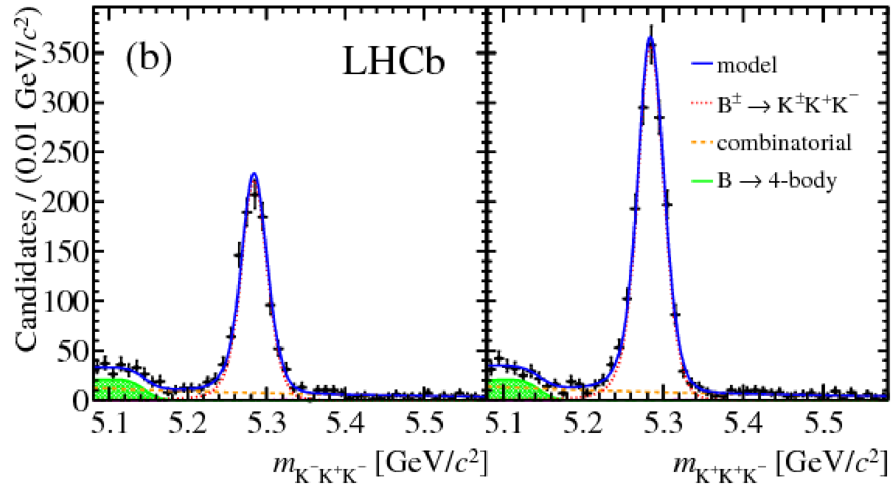


Surprisingly large *direct* CP violation effects

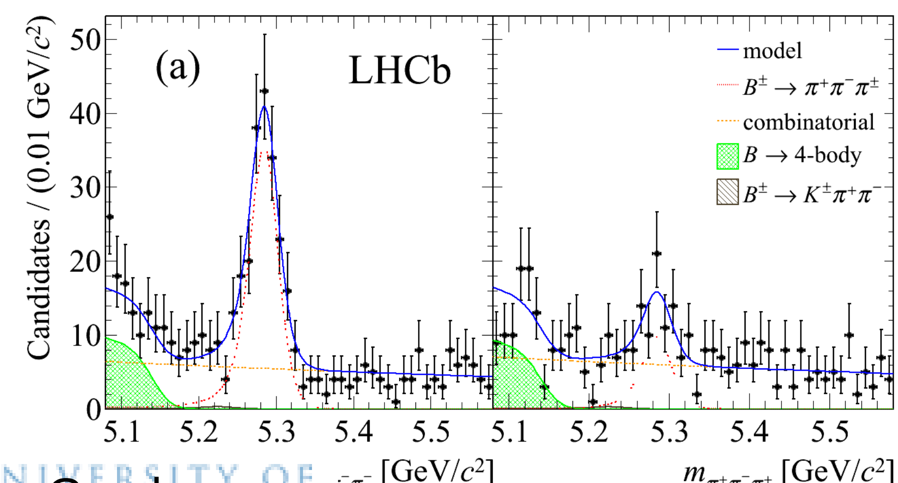
In regions of phase space of $B^+ \to 3h$ decays

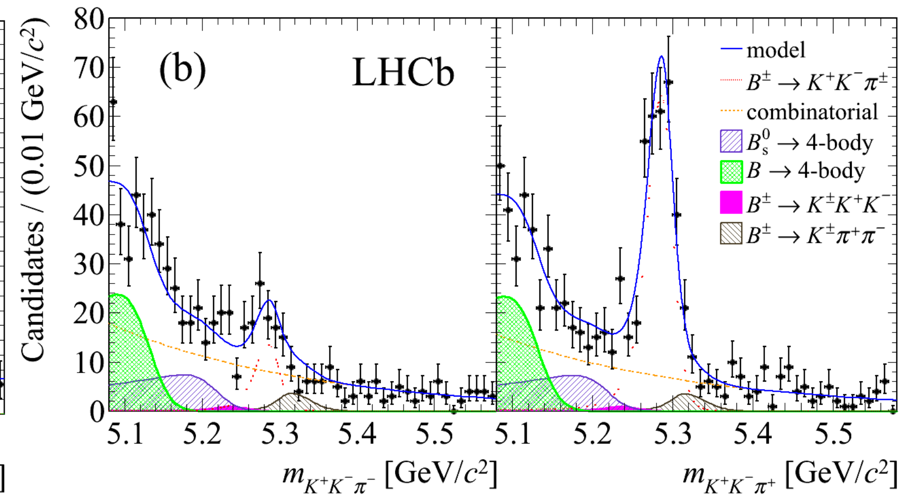
PRL 111 (2013) 101801





arXiv:1310.4740





Importance of γ from B→DK

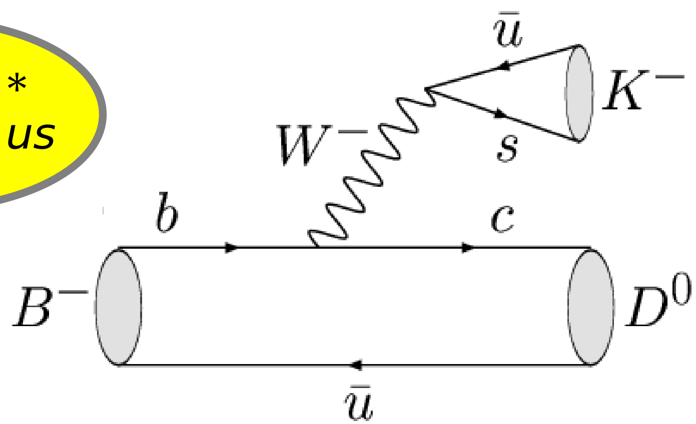
- γ plays a unique role in flavour physics

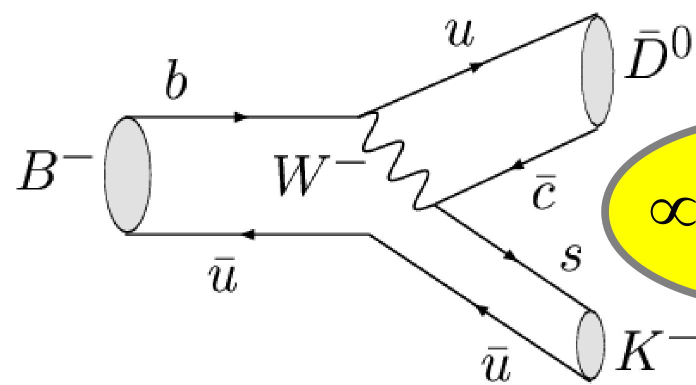
the only CP violating parameter that can be measured through tree decays only (*)

(*) more-or-less

- A benchmark Standard Model reference point
  - doubly important after New Physics is observed

$\propto V_{cb} V_{us}^{*}$



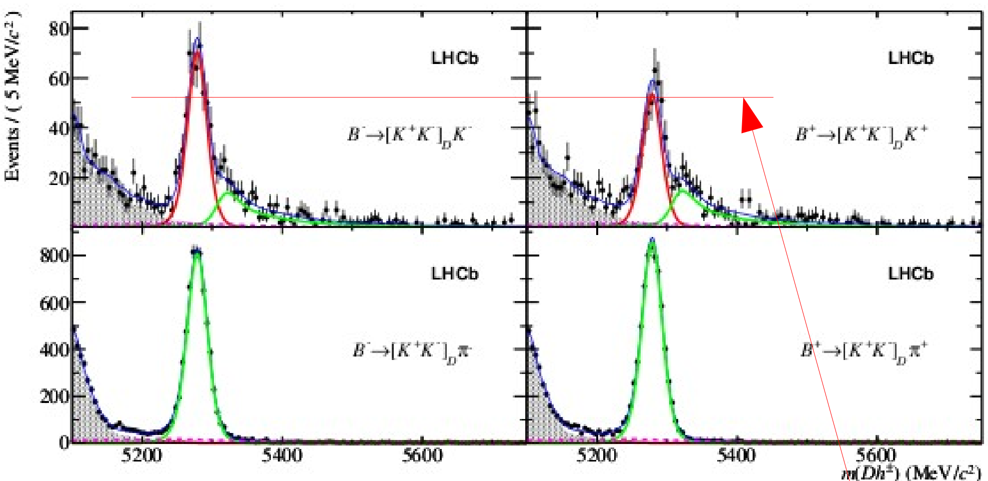


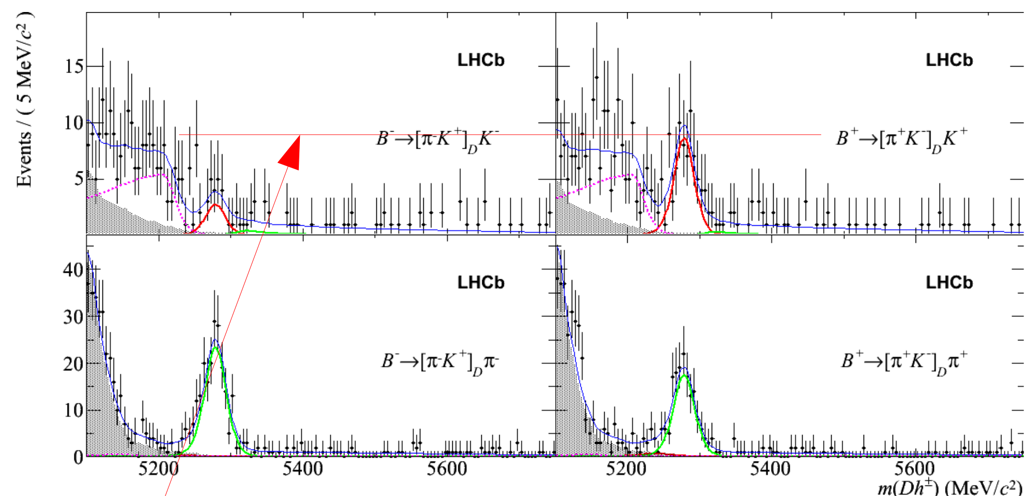
$\propto V_{ub} V_{cs}^{*}$

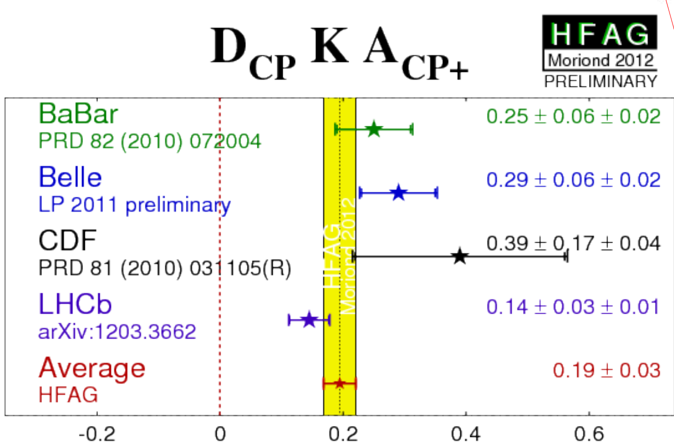
Variants use different B or D decays
require a final state common to both D^0 and $\bar{D}^0$

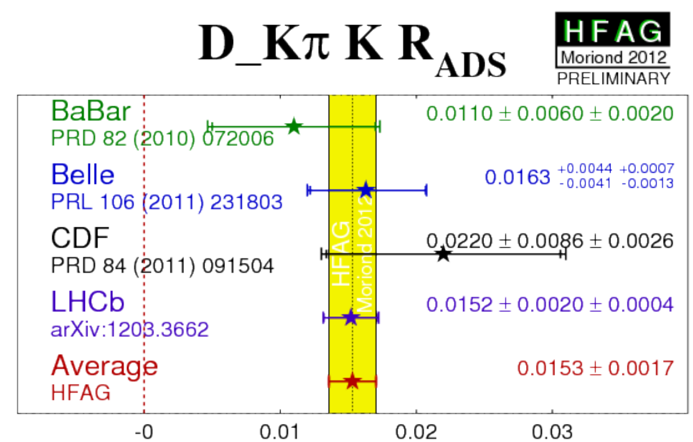
B → DK decays
"GLW" and "ADS" methods

PLB 712 (2012) 203







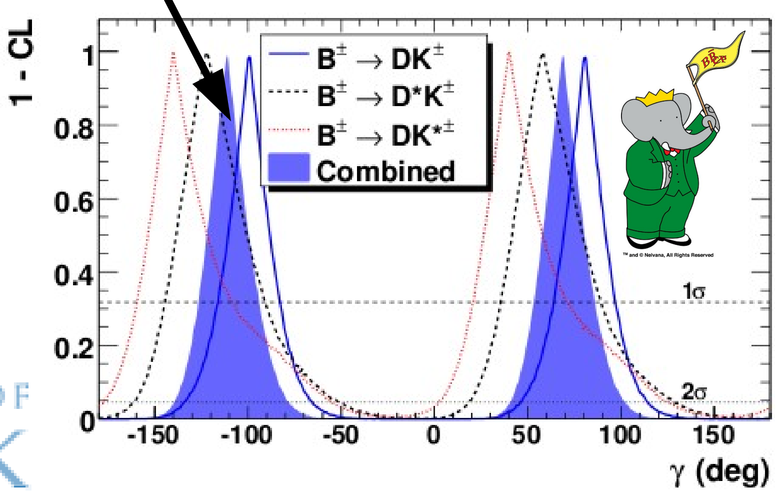


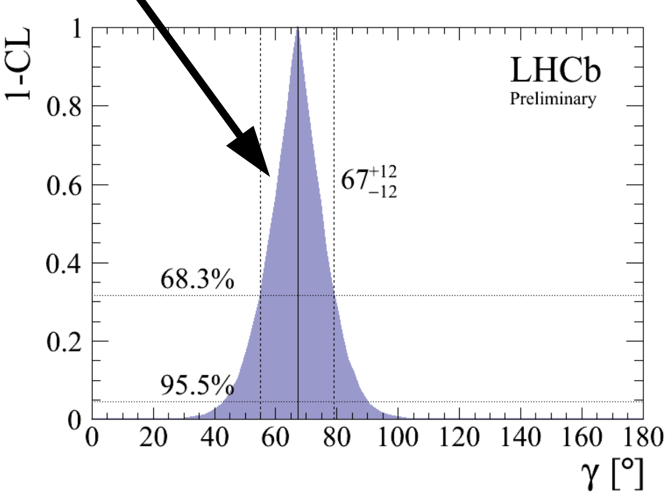
Observation of CP violation in B → DK decays

γ from combination of $B^+ \to DK^+$ modes

BaBar PRD 87 (2013) 052015
Belle CKM2012 preliminary
PLB 726 (2013) 151
& LHCb-CONF-2013-006

- All direct CP violation effects caused by γ in the Standard Model
- Only those in $B \to DK$ type processes involve only tree-level diagrams
  - enable determination of γ with negligible theoretical uncertainty
- Several different B and D decays can be used
- Combination includes results from GLW/ADS ($D \to hh$) & GGSZ ($D \to K_S hh$)
- Sensitivity: BaBar & Belle each ~16°; latest LHCb ~12°





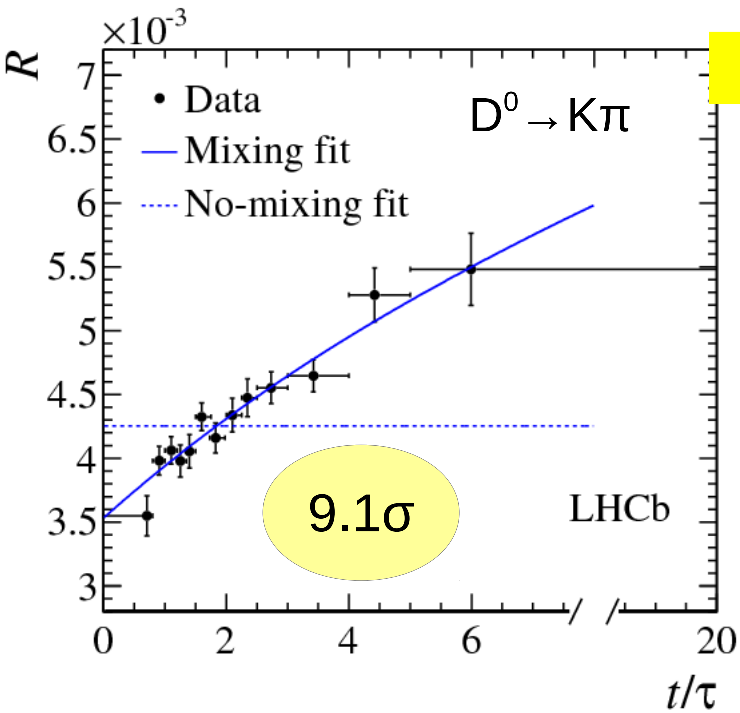
CP violation in neutral meson mixing

Neutral meson mixing –
oscillation phenomena over 4 orders in magnitude

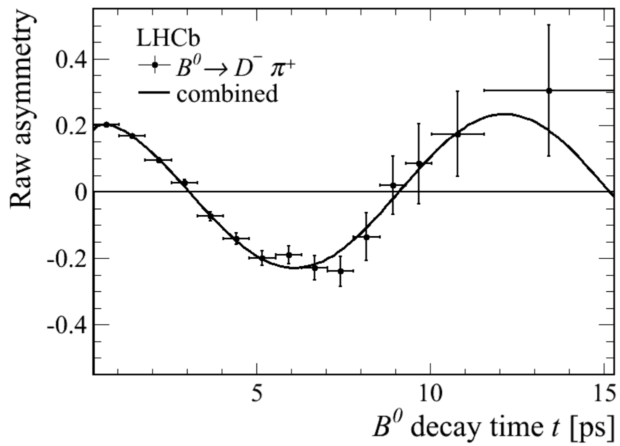
PRL 110 (2013) 101802

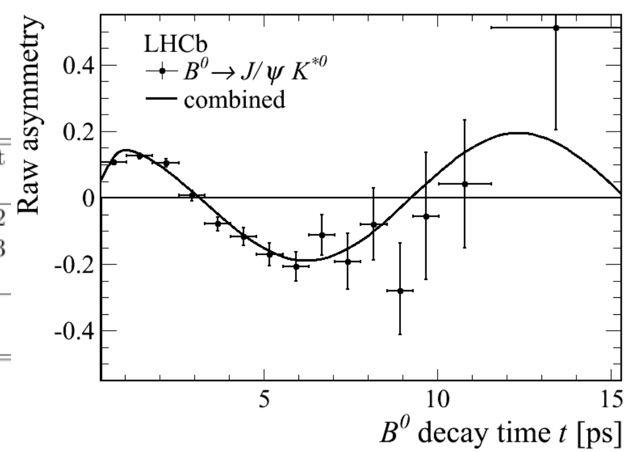
NJP 15 (2013) 053021

PLB 719 (2013) 318



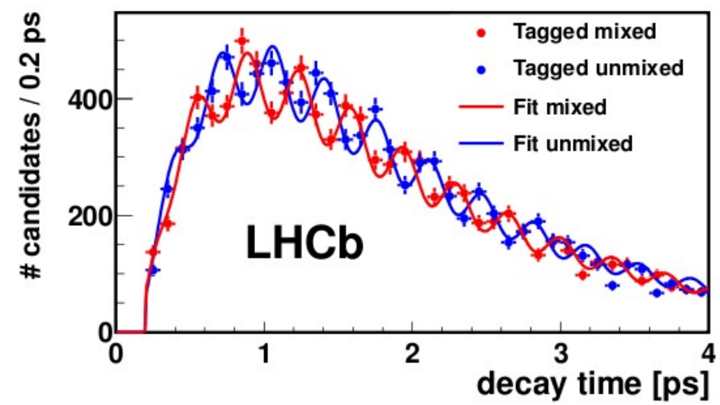
Fit type (χ^2/ndf)	Parameter	Fit result (10^{-3})	Correlation coefficient R_D	y'	x'^2
Mixing (9.5/10)	R_D	3.52 ± 0.15	1	-0.954	$+0.882$
	y'	7.2 ± 2.4		1	-0.973
	x'^2	-0.09 ± 0.13			1
No mixing (98.1/12)	R_D	4.25 ± 0.04			





$$\Delta m_d = 0.5156 \pm 0.0051\,(\mathrm{stat.}) \pm 0.0033\,(\mathrm{syst.})\ \mathrm{ps}^{-1}$$

$B_s^0 \to D_s \pi$



Δm_s = (17.768 ± 0.023 (stat) ± 0.006 (syst)) ps^{-1}
O(‰) precision & still statistically limited

Tim Gershon
HF at the LHC

Is there CP violation in B *mixing*?

Semileptonic asymmetries in both B_d and B_s systems negligibly small in the SM

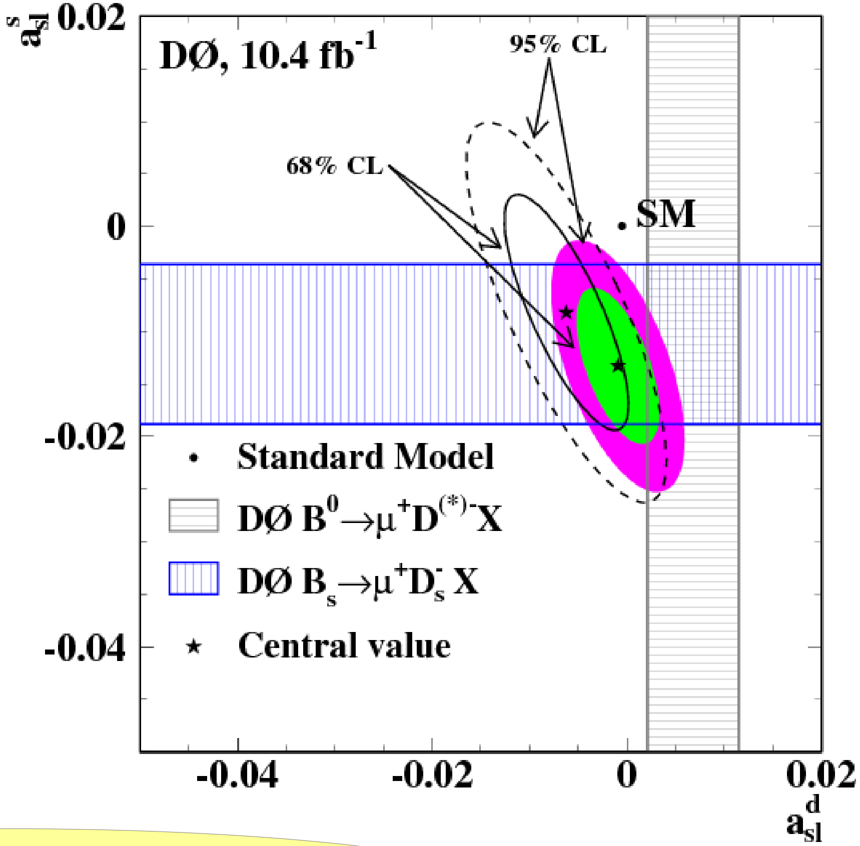
D0 arXiv:1310.0447,
PRL 110 (2013) 011801,
PRD 86 (2012) 072009

Results of inclusive dimuon asymmetry analysis 3.6σ from SM

Constraint in a_{sl}^d–a_{sl}^s plane obtained from oscillated B_d or B_s enriched samples (cutting on impact parameter)

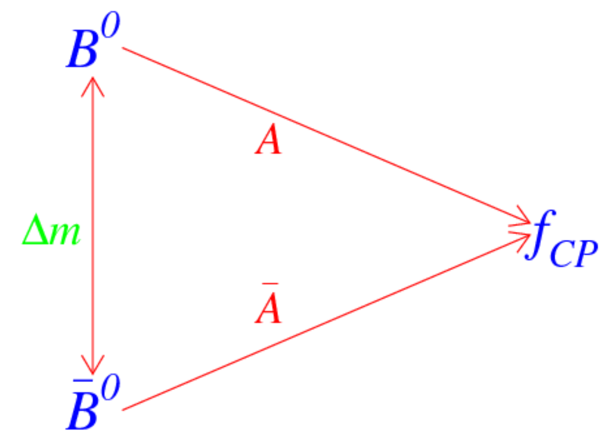
Including results on a_{sl}^d and a_{sl}^s individually (from $D^{(*)+}\mu^-\nu X$ and $D_s^+\mu^-\nu X$ samples) puts combination at 3.1σ from SM

Results on a_{sl}^d and a_{sl}^s from B factories and LHCb consistent with SM but not inconsistent with D0



Situation unclear – improved measurements needed

CP violation in mixing-decay interference

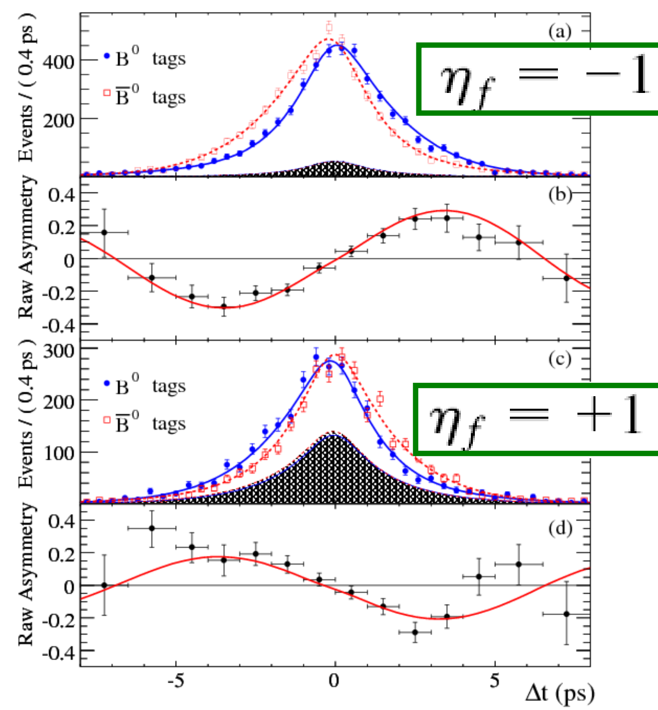


When both particle and anti-particle can decay to the same final state, the oscillations act as an interferometer to measure the relative phase

Used very productively for $B^0 \to J/\psi\, K_S$ decays to measure sin(2β) at BaBar & Belle

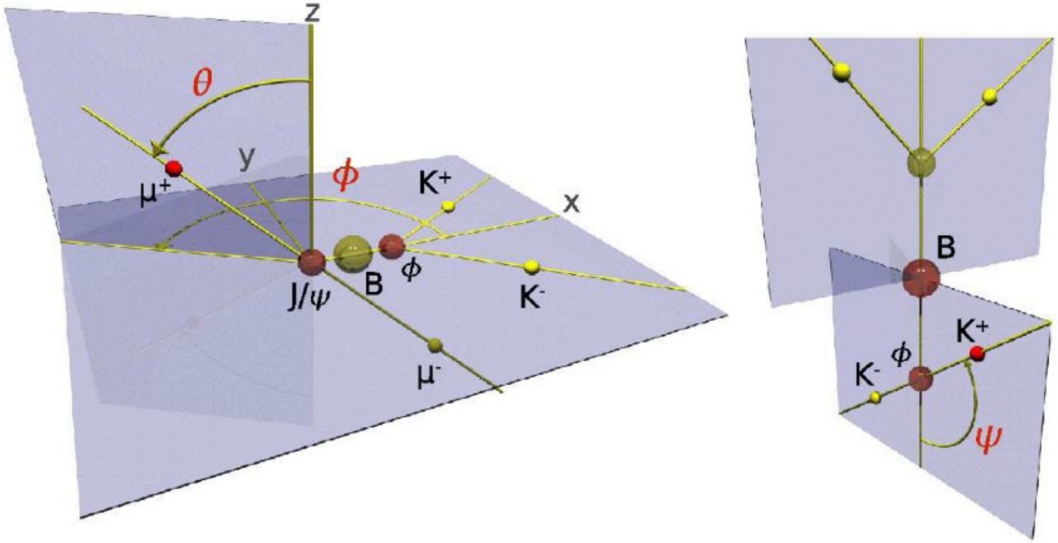
Exploit the same idea to measure the B_s^0 oscillation phase (ϕ_s), which is very small in the Standard Model → provides a null test

BABAR



PRD 79 (2009) 072009

$\Phi_s = -2\beta_s$ ($B_s \rightarrow J/\psi\phi$)



- VV final state
  three helicity amplitudes
  → mixture of CP-even and CP-odd
  disentangled using angular & time-dependent distributions
  → additional sensitivity
  many correlated variables
  → complicated analysis
- LHCb also uses $B_s \rightarrow J/\psi f_0$ ($f_0 \rightarrow \pi^+\pi^-$)
  - CP eigenstate; simpler analysis
  - fewer events; requires input from $J/\psi\phi$ analysis (Γ_s, $\Delta\Gamma_s$)

Improved measurements of B_s oscillations and CP violation

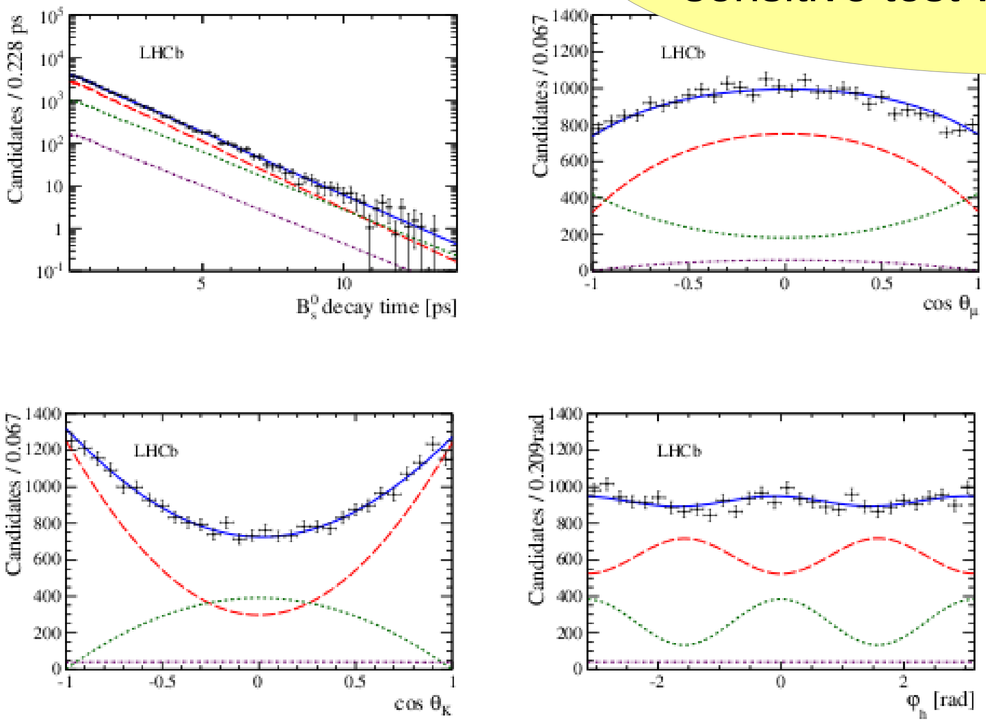
LHCb PRD 87 (2013) 112010

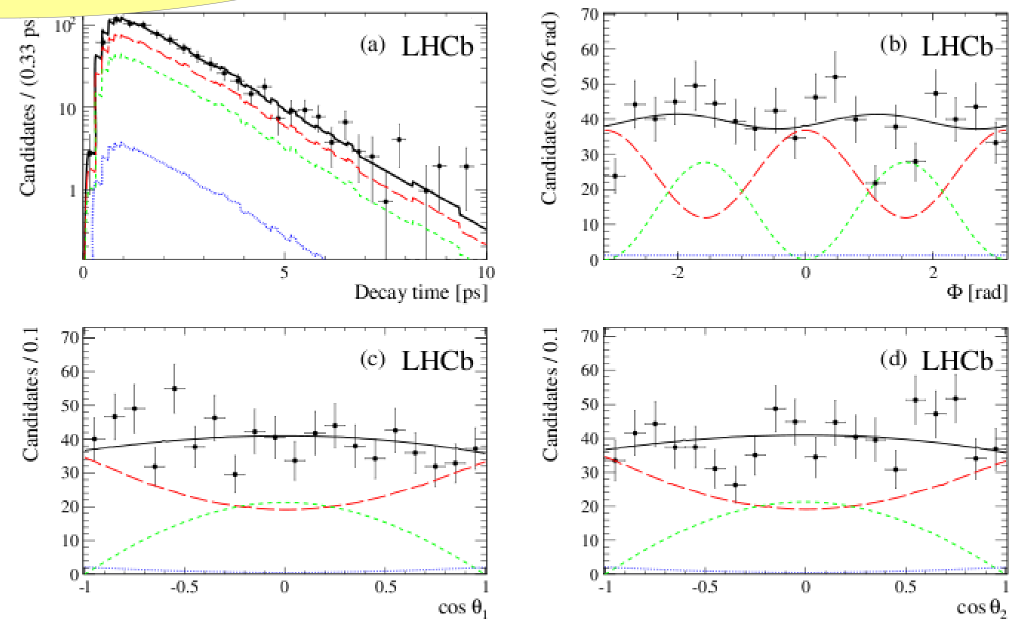
$B_s \to J/\psi KK$ (& $J/\psi\pi\pi$)

Start to compare tree-level decays with much rarer penguin processes → sensitive test with higher statistics

LHCb PRL 110 (2013) 241802

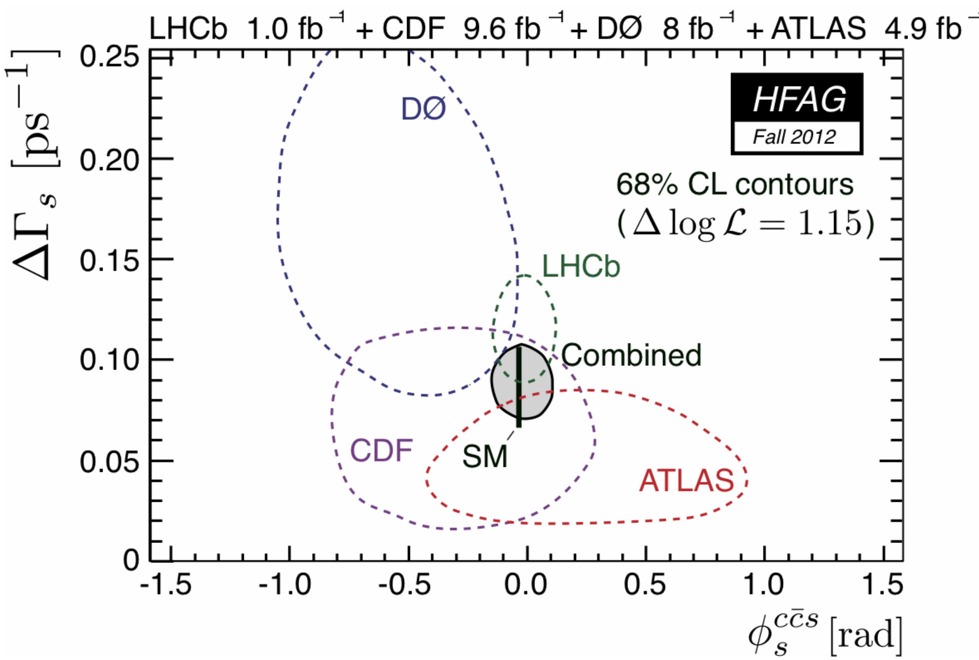
$B_s \to \varphi\varphi$



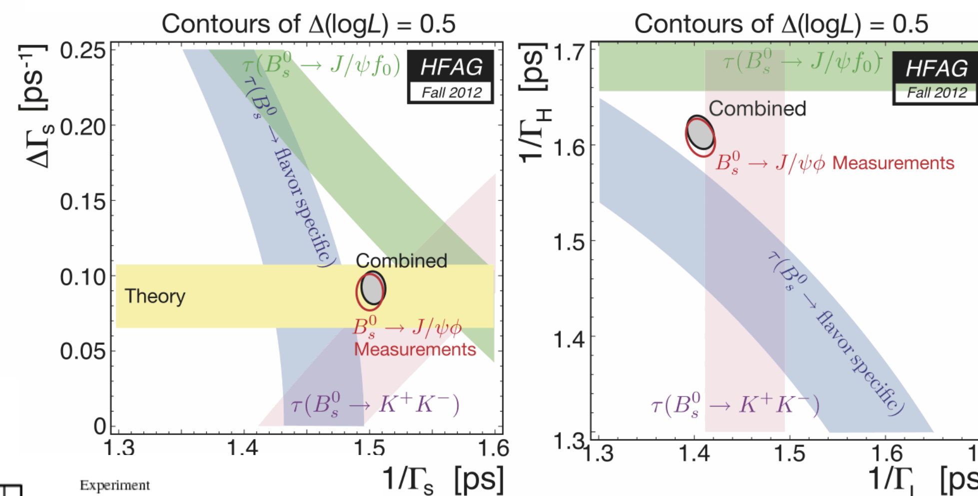


$$
\begin{aligned}
\phi_s &= 0.01 \pm 0.07\ (\text{stat}) \pm 0.01\ (\text{syst})\ \text{rad},\\
\Gamma_s &= 0.661 \pm 0.004\ (\text{stat}) \pm 0.006\ (\text{syst})\ \text{ps}^{-1},\\
\Delta\Gamma_s &= 0.106 \pm 0.011\ (\text{stat}) \pm 0.007\ (\text{syst})\ \text{ps}^{-1}.
\end{aligned}
$$

Improved measurements of B_s lifetimes and CP violation

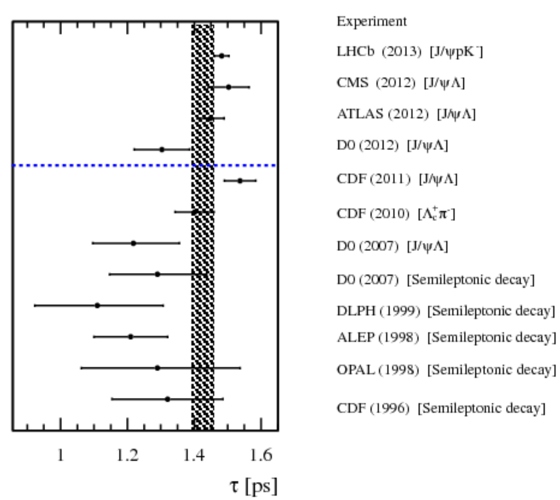


LHCb PRD 87 (2013) 112010
CDF PRD 85 (2012) 072002
D0 PRD 85 (2012) 032006
ATLAS JHEP 12 (2012) 072 &
ATLAS-CONF-2013-039



N.B. Improved Λ_b lifetime measurements of great interest:

D0 PRD 85 (2012) 112003
ATLAS PRD 87 (2013) 032002
CMS JHEP 07 (2013) 163
LHCb PRL 111 (2013) 102003



… tensions with expectations reduced

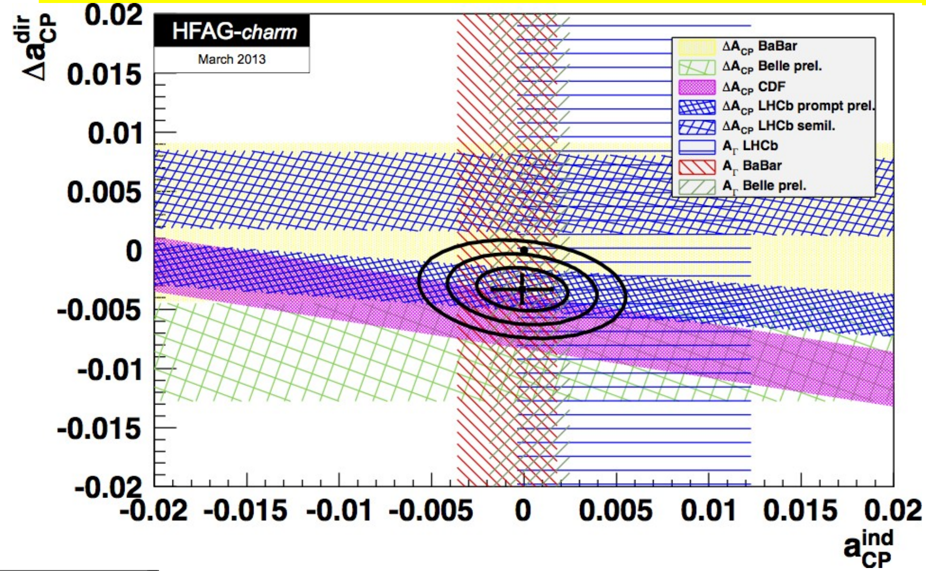
Is there CP violation in the charm system?

(and if so, where does it come from?)

LHCb PLB 723 (2013) 33,
LHCb-CONF-2013-003
CDF PRL 109 (2012) 111801
Belle ICHEP preliminary

To reduce systematics and (perhaps) enhance CP violation effect, experiments measure

$$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$
$$= \left[a_{CP}^{\rm dir}(K^-K^+) - a_{CP}^{\rm dir}(\pi^-\pi^+)\right] + \frac{\Delta\langle t\rangle}{\tau} a_{CP}^{\rm ind}.$$

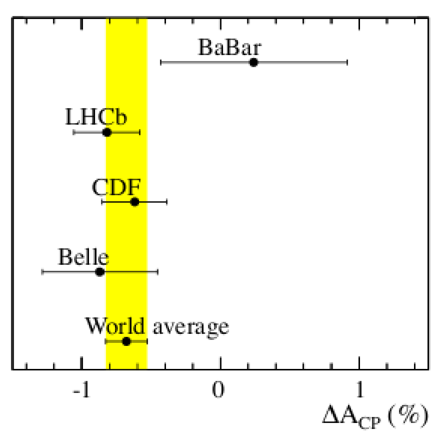


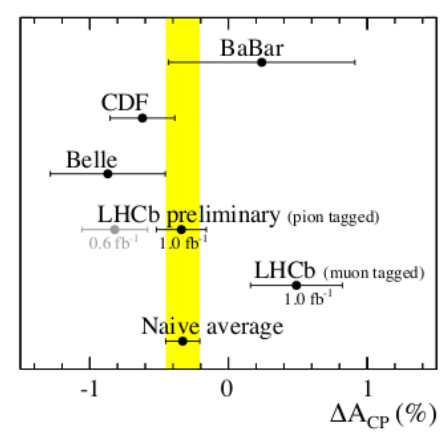
ΔA_{CP} related mainly to direct CP violation

(contribution from indirect CPV suppressed by difference in mean decay time)

$\Delta a_{CP}^{dir} = (-0.33 \pm 0.12)\%$

Previous evidence for CPV not confirmed
Need more precise measurements





All shifts consistent with being statistical in origin

Selected highlights of results
Rare Decays

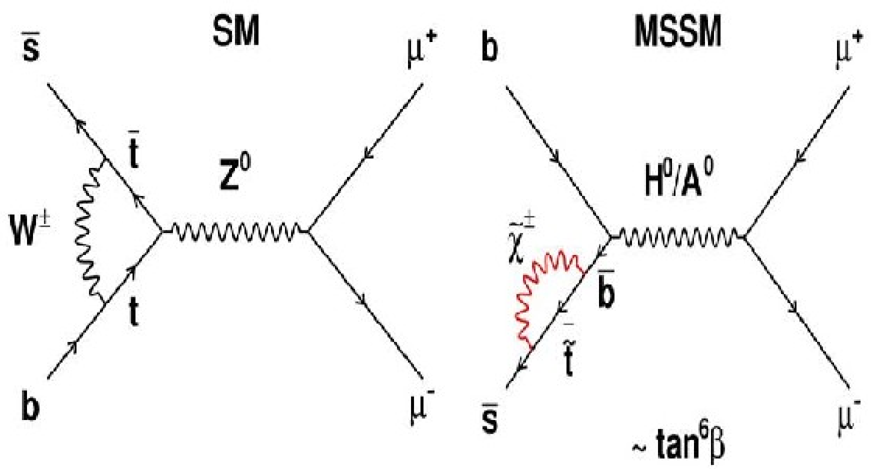
$B_s \to \mu^+\mu^-$

Killer app. for new physics discovery

Very rare in Standard Model due to

- absence of tree-level FCNC
- helicity suppression
- CKM suppression

… all features which are not necessarily reproduced in extended models



$$\mathcal{B}(B_s \to \mu^+\mu^-)^{SM} = (3.2 \pm 0.3) \times 10^{-9}$$

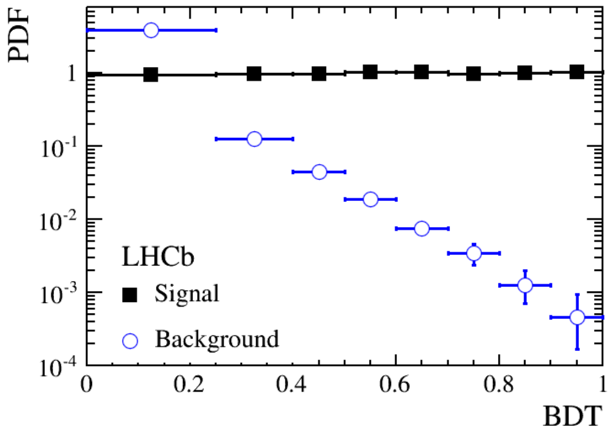
$$\mathcal{B}(B_s \to \mu^+\mu^-)^{MSSM} \sim \tan^6\beta / M^4_{A0}$$

Buras et al, EPJ C72 (2012) 2172

N.B. Should be corrected up by 9% since measurement is of the time-integrated branching fraction (PRL 109 (2012) 041801)

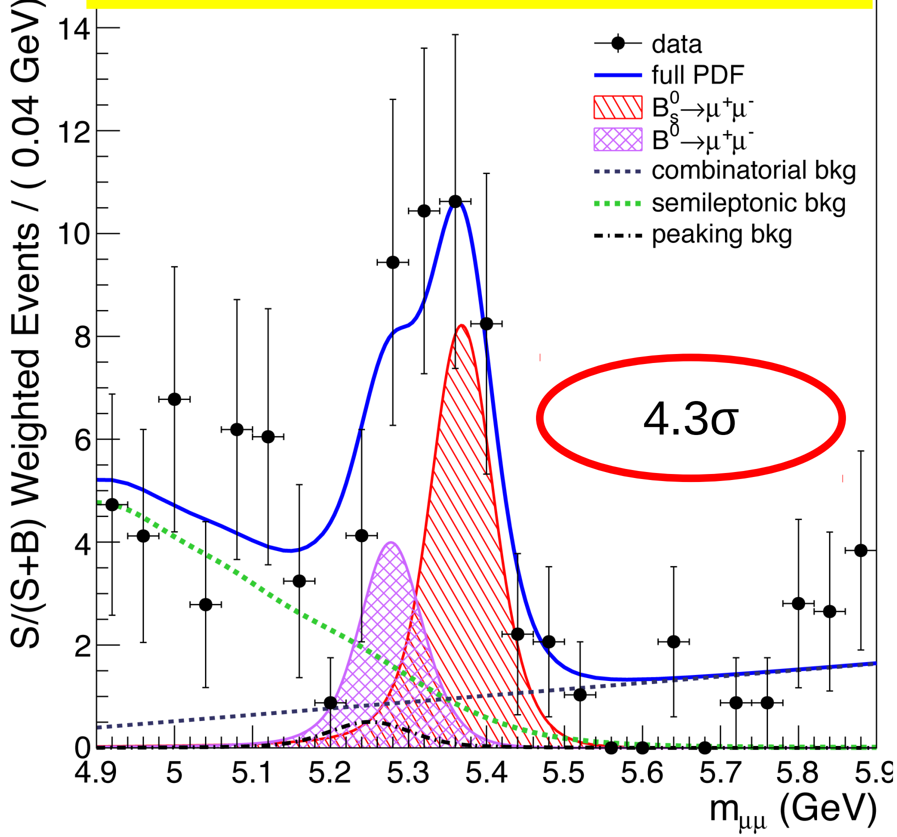
$B_{(s)}^0 \to \mu^+\mu^-$ – analysis ingredients

- Produce a very large sample of B mesons
- Trigger efficiently on dimuon signatures
- Reject background
  - excellent vertex resolution (identify displaced vertex)
  - excellent mass resolution (identify B peak)
    - also essential to resolve B^0 from B_s^0 decays
  - powerful muon identification (reject background from B decays with misidentified pions)
  - typical to combine various discriminating variables into a multivariate classifier
    - e.g. Boosted Decision Trees algorithm



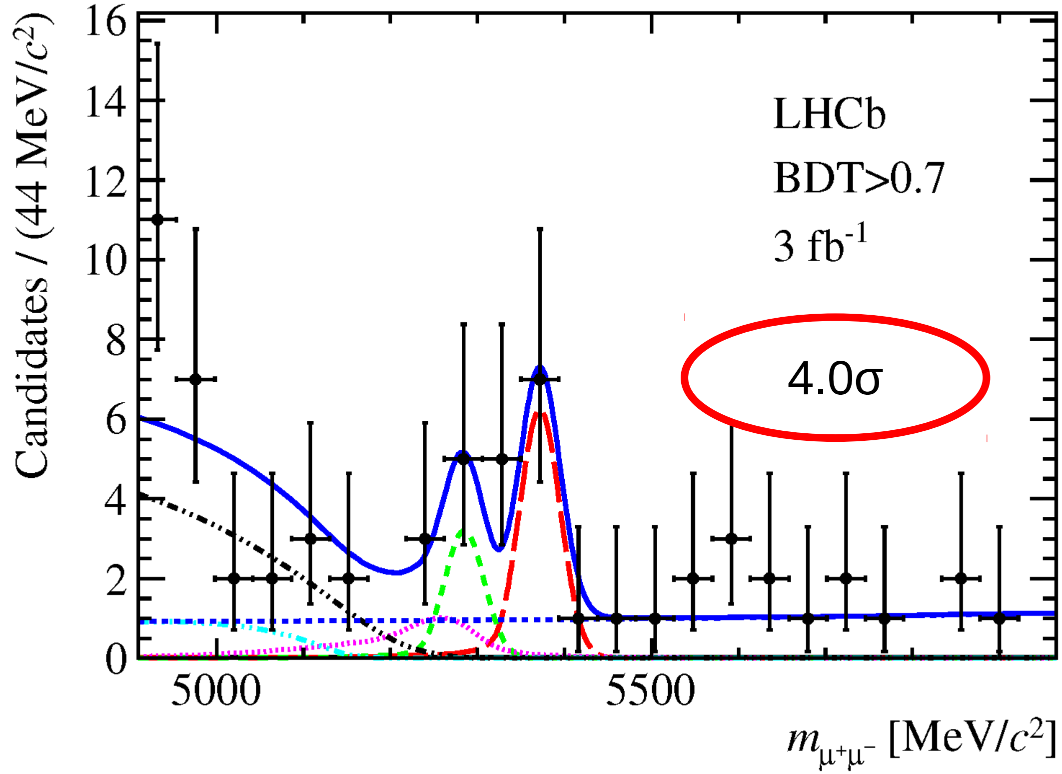
$B_{(s)}^0 \to \mu^+\mu^-$

CMS
PRL 111 (2013) 101804



Events weighted by S/(S+B)

LHCb
PRL 111 (2013) 101805

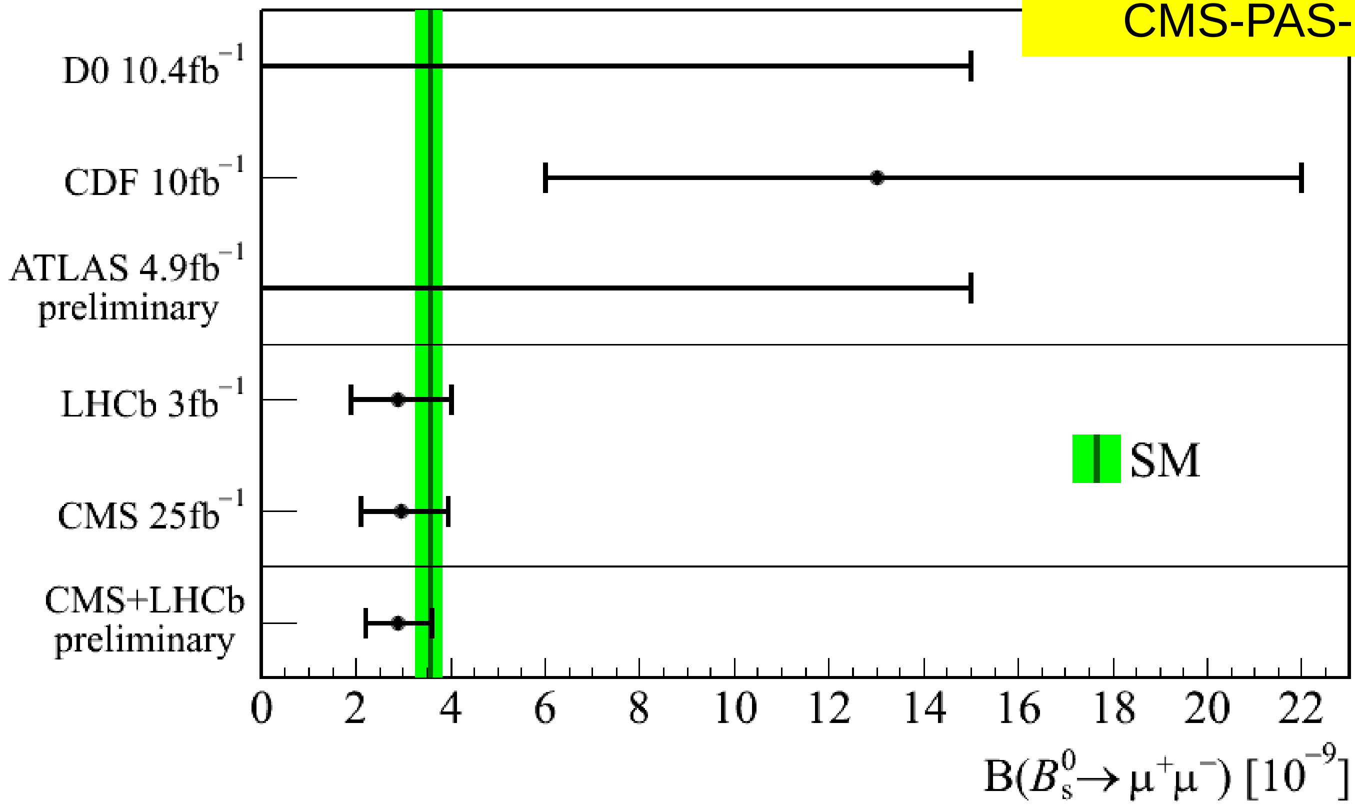


Only events with BDT > 0.7

Updated results confirm earlier evidence from LHCb
(PRL 110 (2013) 021801)

$B_{(s)}^0 \to \mu^+\mu^-$ – combined results

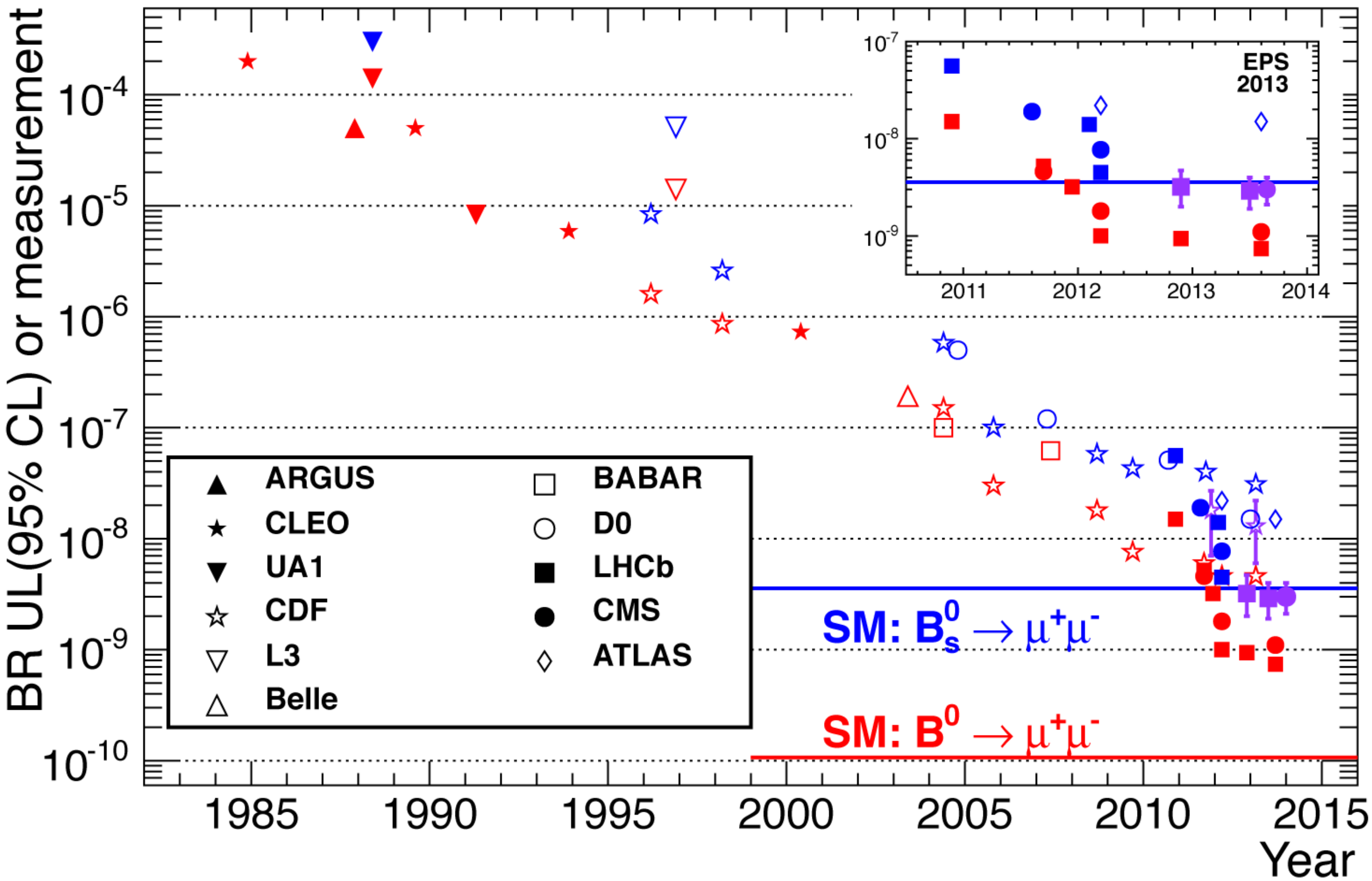
LHCb-CONF-2013-012
CMS-PAS-BPH-13-007



$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$

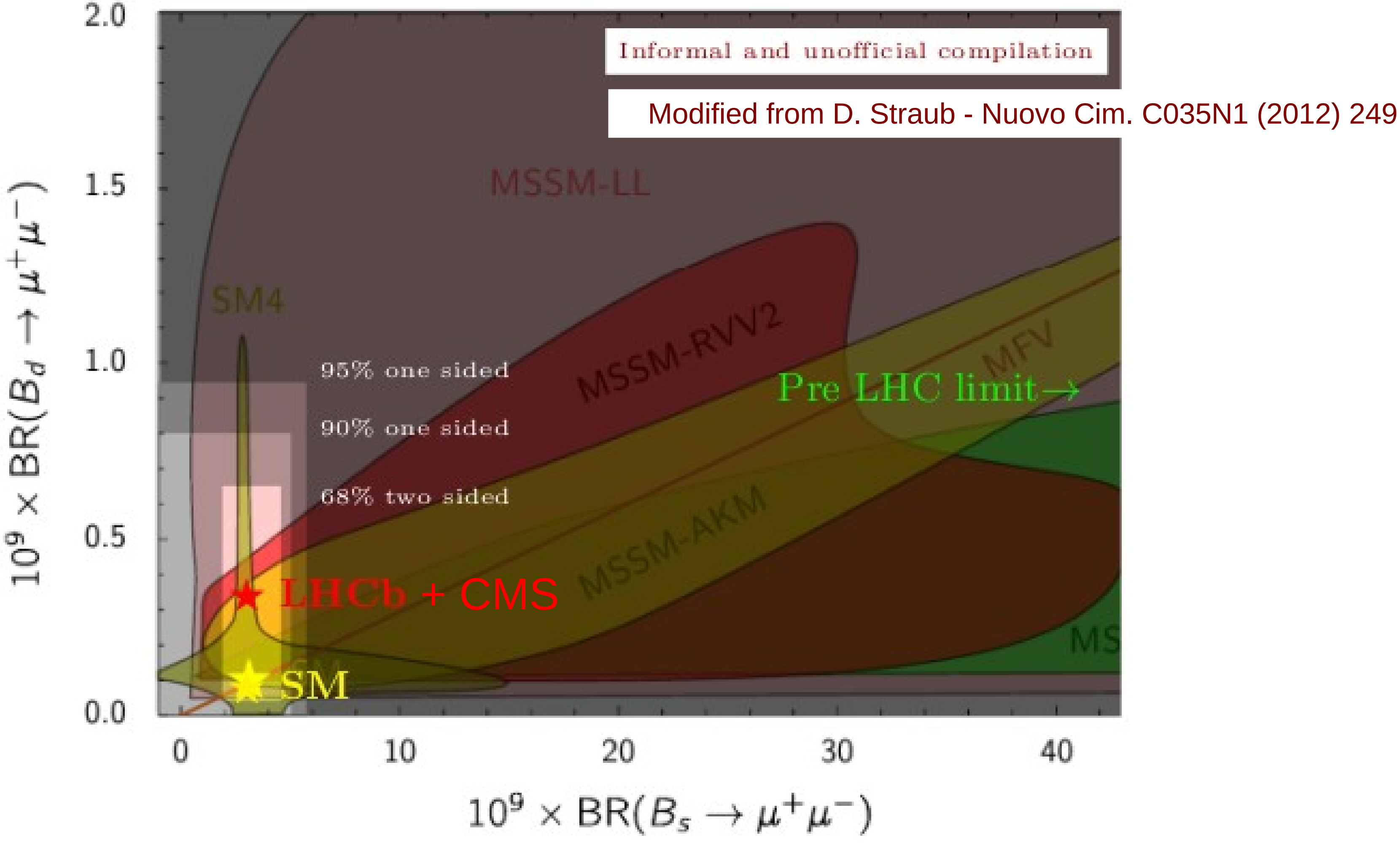
Observed!

$B_{(s)}^0 \to \mu^+\mu^-$



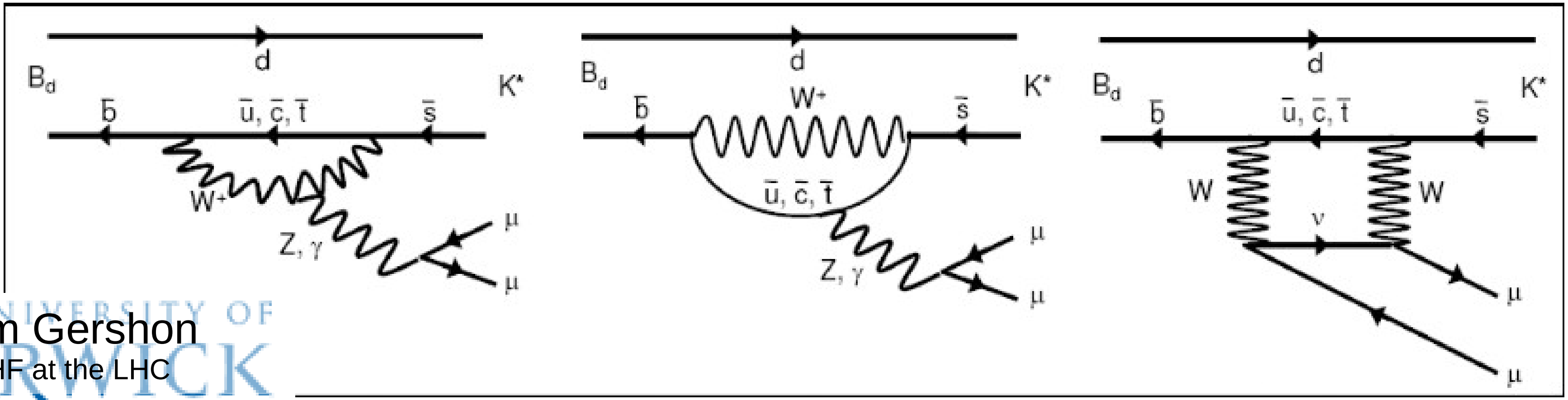
Searches over 30 years

Impact of $B_s \to \mu^+\mu^-$

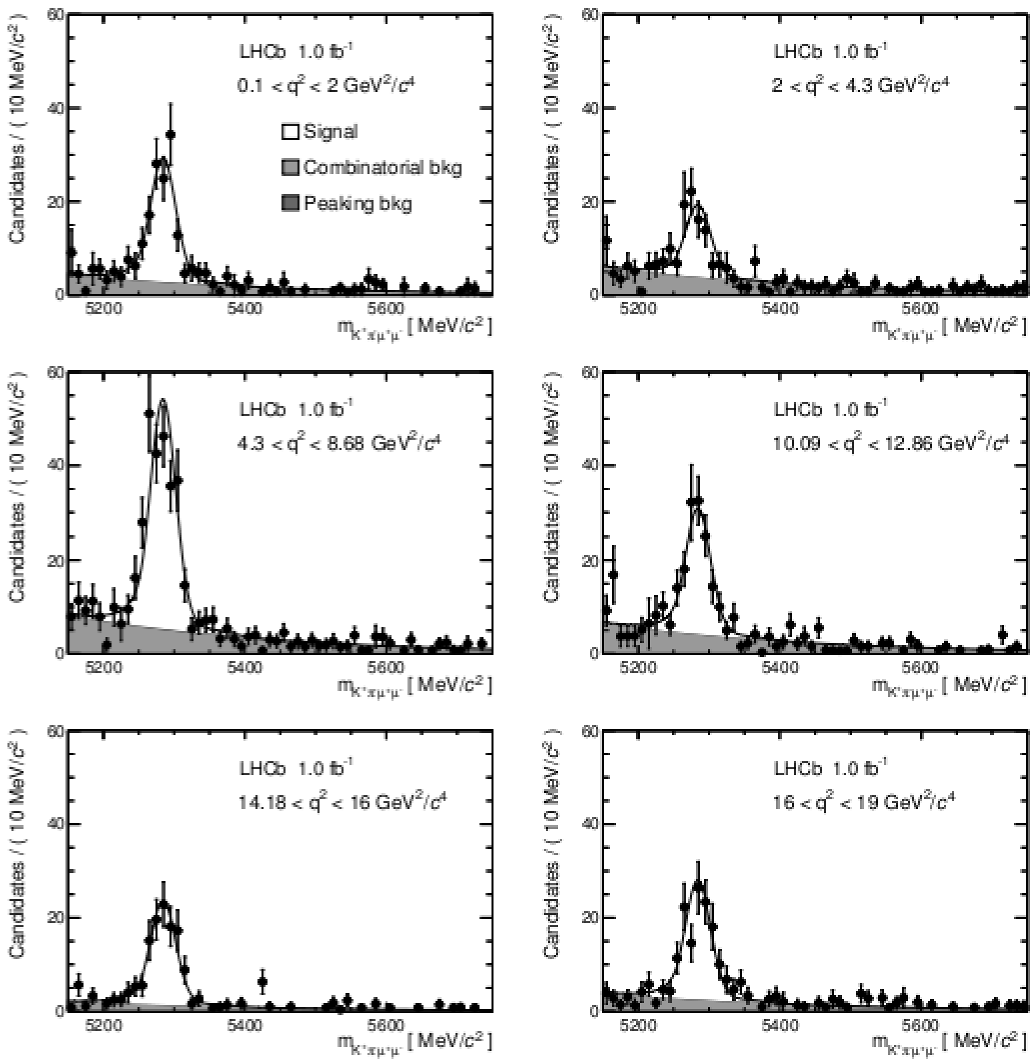


$B \to K^{*}\mu^{+}\mu^{-}$

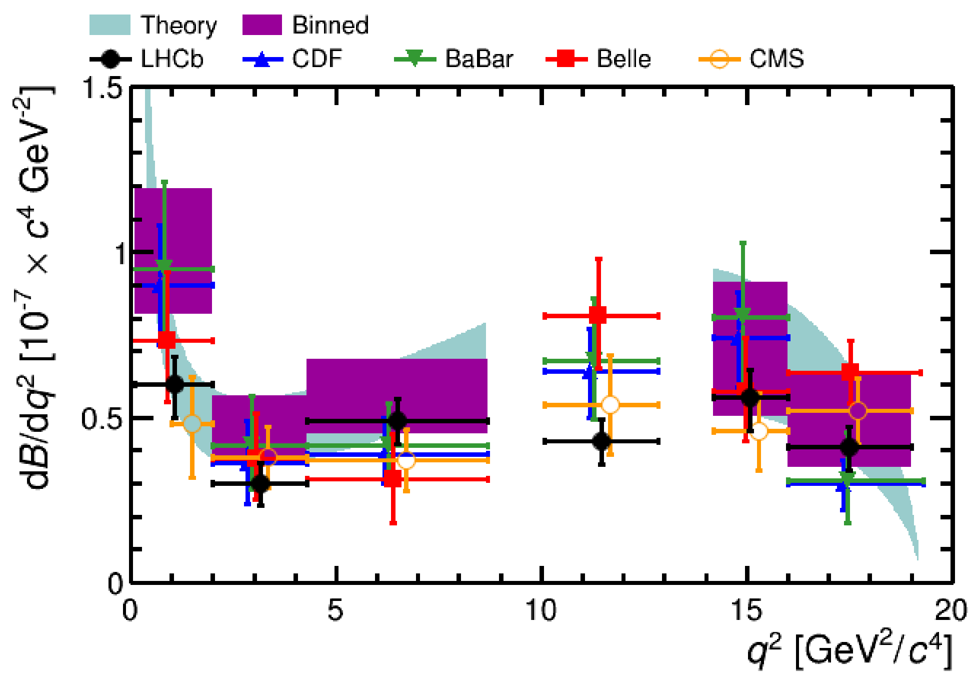
- $B_d \to K^{*0}\mu^+\mu^-$ provides complementary approach to search for new physics in $b \to sl^+l^-$ FCNC processes
  - rates, angular distributions and asymmetries sensitive to NP
  - superb laboratory for NP tests
  - experimentally clean signature
  - many kinematic variables …
  - … with clean theoretical predictions



Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$



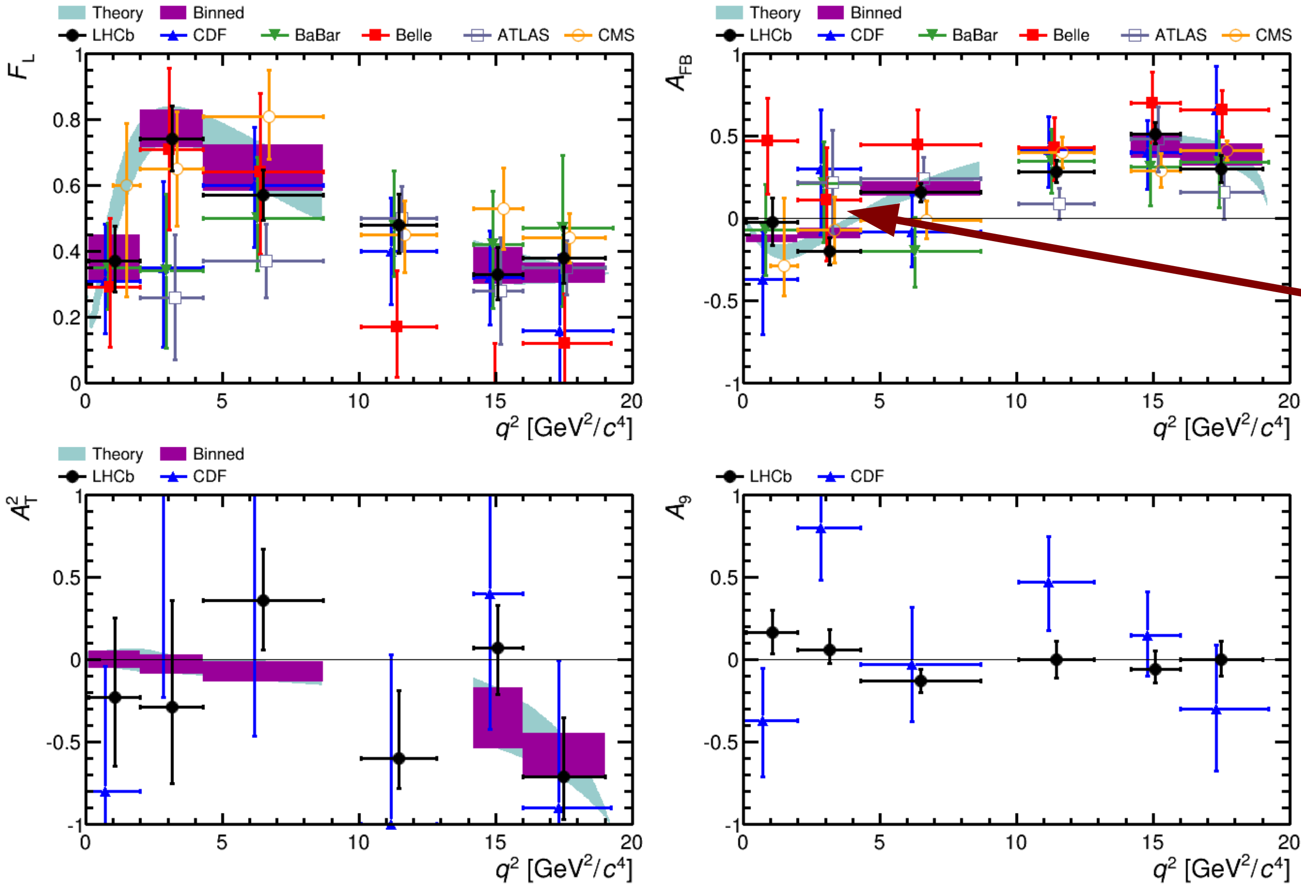
LHCb JHEP 08 (2013) 131
See also CDF PRL 108 (2012) 081807
BaBar PRD 86 (2012) 032012
ATLAS-CONF-2013-038 & CMS BPH-11-009



Analysis performed in bins of dimuon invariant mass squared (q^2)

Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$

LHCb JHEP 08 (2013) 131
See also CDF PRL 108 (2012) 081807
BaBar PRD 86 (2012) 032012
ATLAS-CONF-2013-038 & CMS BPH-11-009



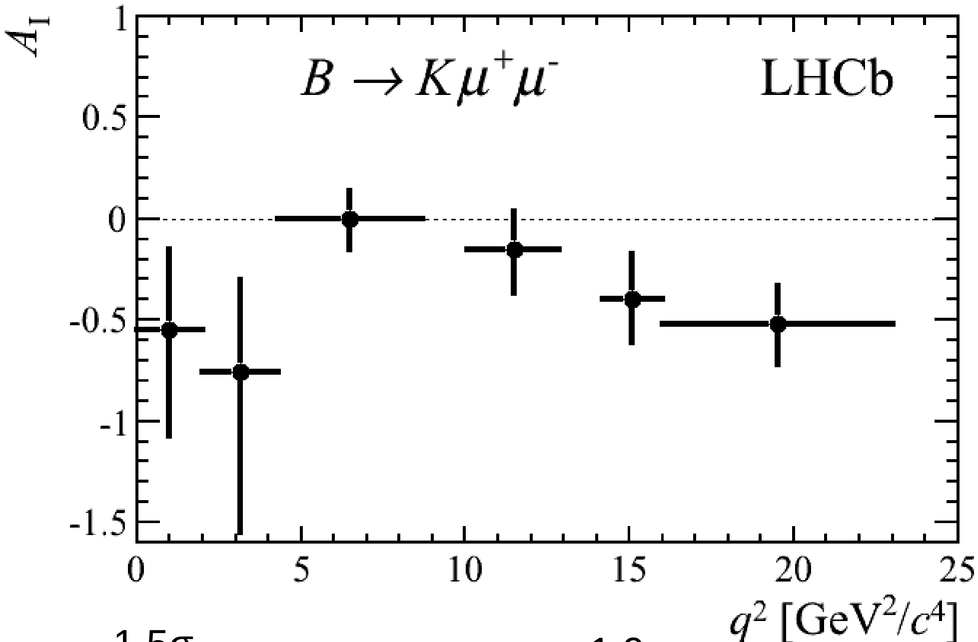
First measurement of zero-crossing point of A_{FB}

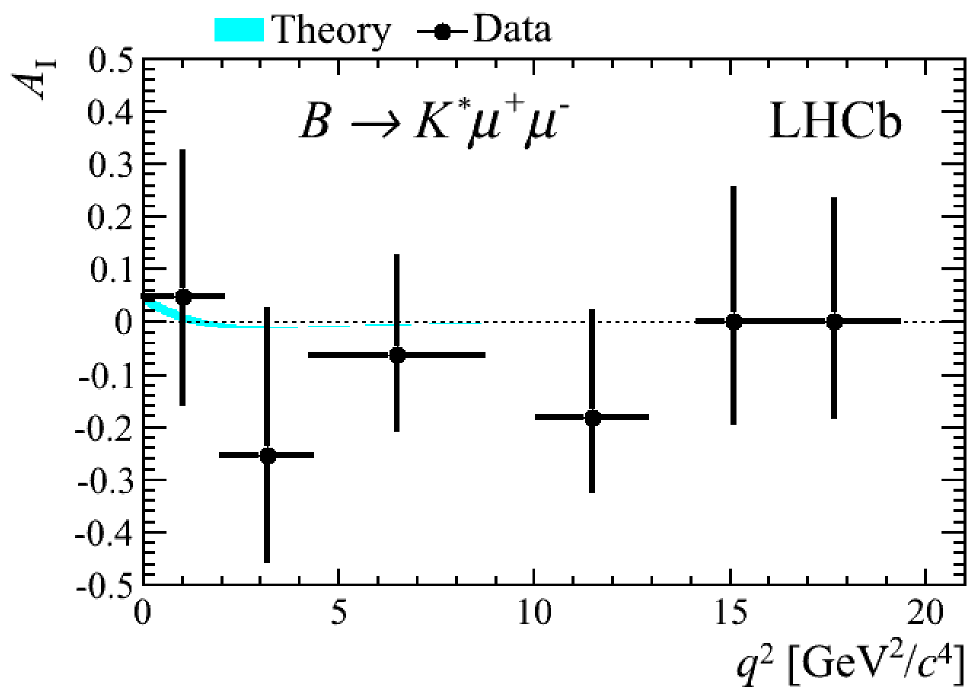
$q^2_0 = (4.9 \pm 0.9)$ GeV^2/c^4

Consistent with SM expectation

Isospin asymmetry in $B \to K^{(*)}\mu\mu$

LHCb JHEP 07 (2012) 133





1.5σ

1.9σ

1.9σ

3.0σ

Deviation from zero integrated over q^2 ~ 4.4σ
Consistent with previous measurements (BaBar, Belle, CDF)

Consistent with zero & with SM prediction
Consistent with previous measurements (BaBar, Belle, CDF)

Food for thought ...

New observables in $B^0 \to K^{*0}\mu^+\mu^-$

PRL 111 (2013) 191801

Full angular distribution (B^0 and $\bar{B}^0$ averaged):

$$\frac{1}{\mathrm{d}\Gamma/dq^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell - F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],$$

Previously measured (LHCb-PAPER-2013-019; JHEP 08 (2013) 131) F_L, S_3, $A_{FB} \sim S_6$, $A_9 \sim S_9$

New analysis measures remaining terms, but in a basis with reduced form-factor uncertainty

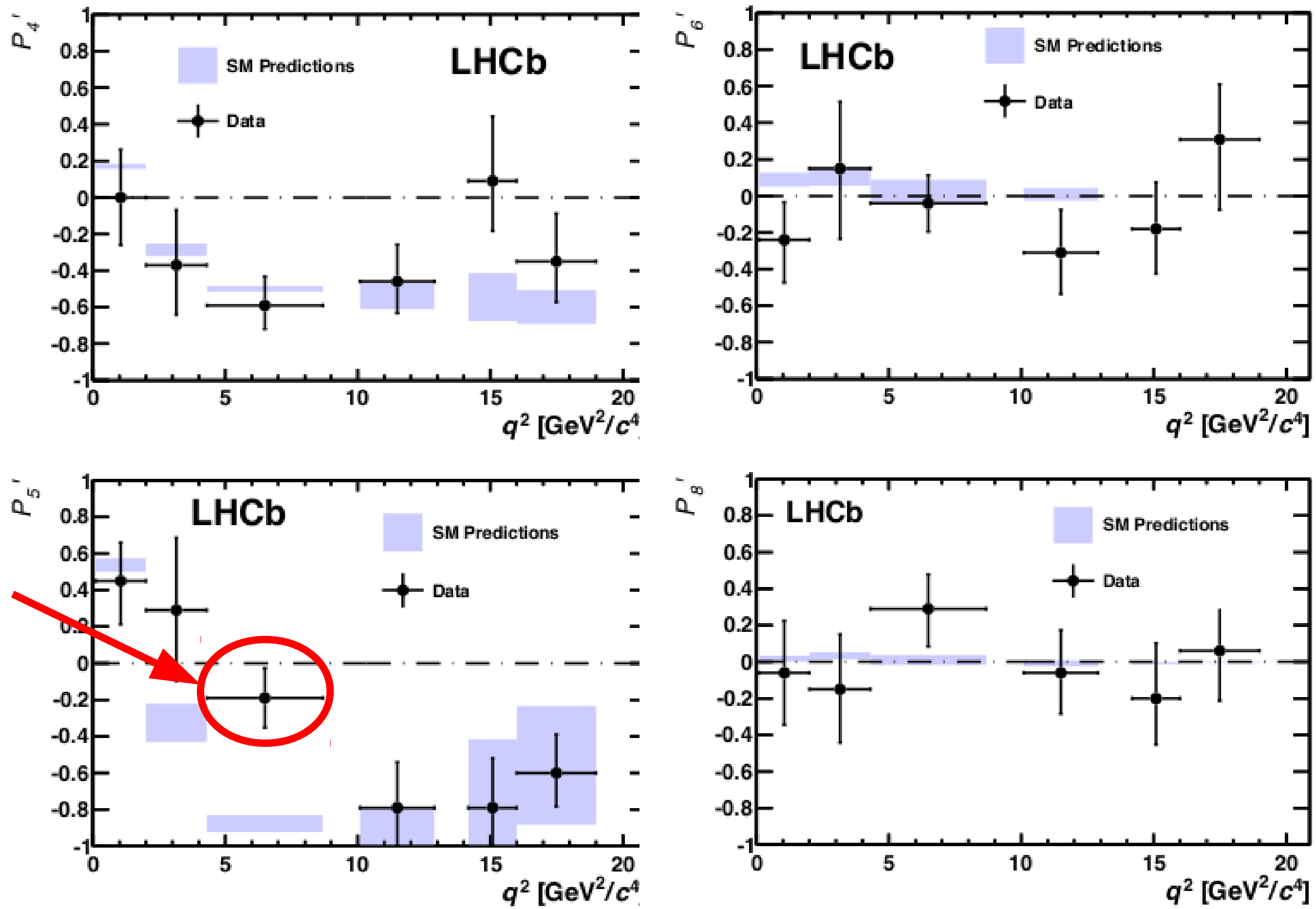
$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}.$$

Key point is that each observable corresponds to a different angular distribution
Therefore each is sensitive to different combinations of operators →
enhanced sensitivity to possible sources of new physics

New observables in $B^0 \to K^{*0}\mu^+\mu^-$

PRL 111 (2013) 191801

Interesting tension with the SM prediction

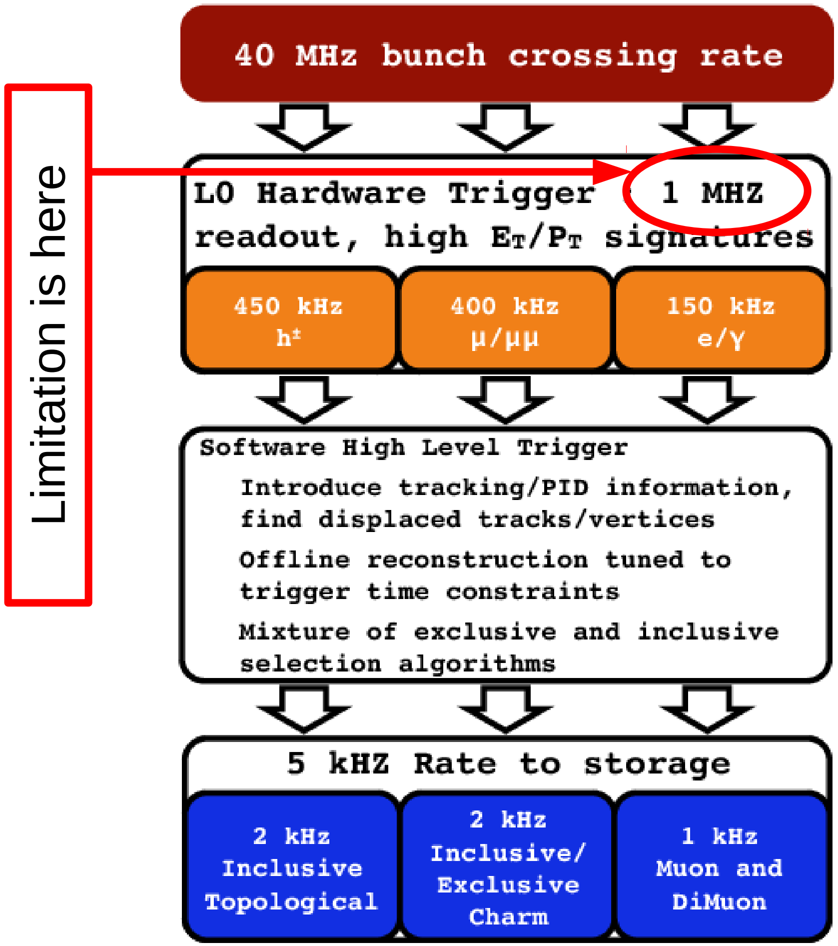


Future prospects

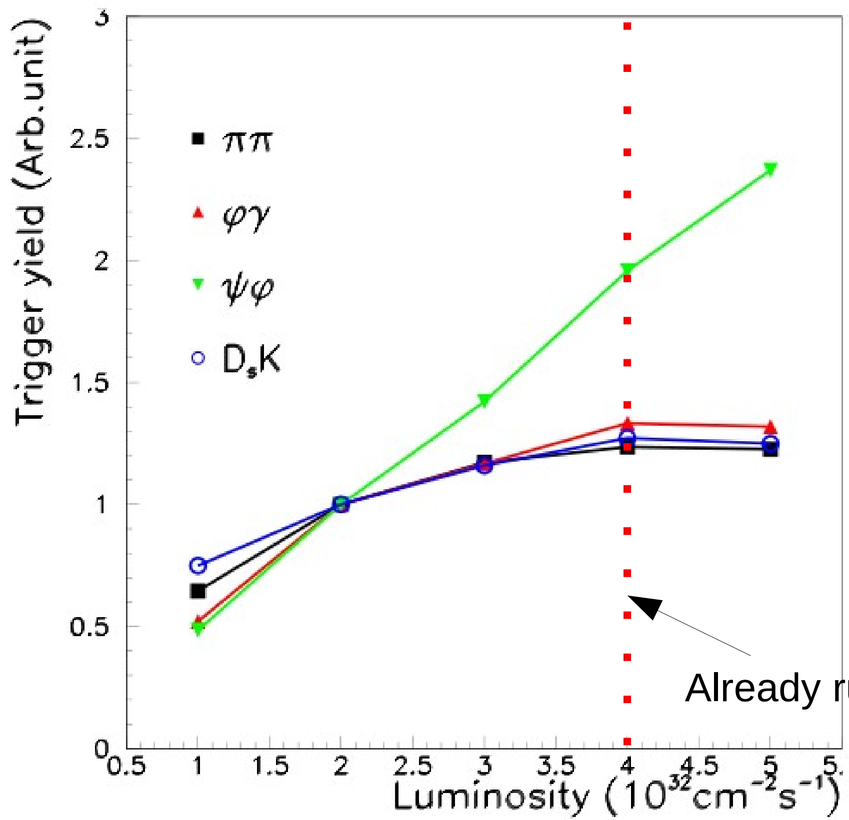
Quark flavour physics: short and mid-term projects

- Good short-term prospects with existing experiments
  - LHCb & BES taking new data plus final analyses from completed experiments
  - NA62 and K0T0 coming online to probe $K \to \pi\nu\nu$ decays
- In the second half of this decade will transition to next generation experiments → very exciting future!
  - Belle2 (start 2016/7) & LHCb upgrade (start 2019)
  - possibilities for τ-charm factories in Russia, Turkey, Italy
    - SuperB unfortunately cancelled, however
  - K0T0 phase II, ORKA, possible extension of NA62

LHC upgrade and the all important trigger

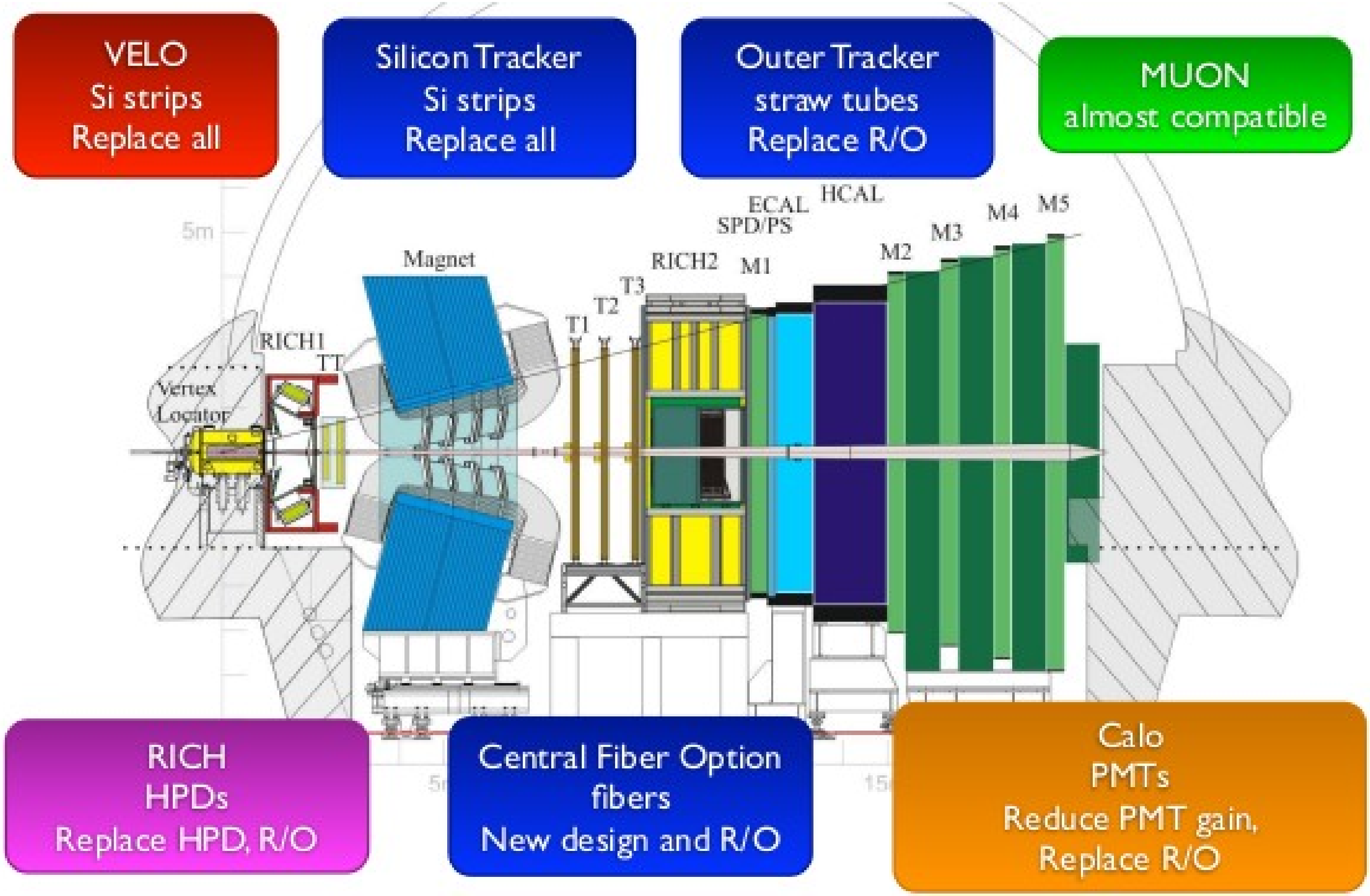


higher luminosity
→ need to cut harder at L0 to keep rate at 1 MHz
→ lower efficiency



- readout detector at 40 MHz
- implement trigger fully in software → efficiency gains
- run at L_{inst} up to 2 10^{33}/cm^2/s

LHCb detector upgrade



Subdetector TDRs available ~end 2013!

Upgrade – expected sensitivities

Table 3: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the expected sensitivity is given for the integrated luminosity accumulated by the end of LHC Run 1, by 2018 (assuming $5\,\mathrm{fb}^{-1}$ recorded during Run 2) and for the LHCb Upgrade ($50\,\mathrm{fb}^{-1}$). An estimate of the theoretical uncertainty is also given – this and the potential sources of systematic uncertainty are discussed in the text.

Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.05	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\, f_0(980))$ (rad)	0.09	0.05	**0.016**	~ 0.01
	$A_{\mathrm{sl}}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$ (rad)	0.18	0.12	**0.026**	0.02
	$\phi_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.04**	0.02
Right-handed currents	$\phi_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	0.20	0.13	**0.030**	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.8%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\, A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.14	0.07	**0.024**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\,\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**1.1°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.4°**	negligible
	$\beta(B^0 \to J/\psi\, K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm CP violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.5**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.12**	–

- sample sizes in most exclusive B and D final states far larger than those collected elsewhere
- no serious competition in study of B_s decays and CP violation

LHCb upgrade timeline

- 2011
  - Letter of Intent: CERN-LHCC-2011-001
- 2012
  - Framework TDR: CERN-LHCC-2012-007
    - Endorsed by LHCC and approved by CERN Research Board (minutes)
    - LHCb upgrade features prominently in draft European Strategy for Particle Physics
  - See also arXiv:1208.3355 for physics discussion
- 2013
  - Sub-detector TDRs ← preparation of TDRs already started
- 2014-17
  - Final R&D, production and construction
- 2018 (LS2)
  - Installation of upgraded LHCb detector (requires 18 months)

A lesson from history

- New physics shows up at precision frontier before energy frontier
  - GIM mechanism before discovery of charm
  - CP violation / CKM before discovery of bottom & top
  - Neutral currents before discovery of Z
- Particularly sensitive – loop processes
  - Standard Model contributions suppressed / absent
  - flavour changing neutral currents (rare decays)
  - CP violation
  - lepton flavour / number violation / lepton universality

The need for more precision

- "Imagine if Fitch and Cronin had stopped at the 1% level, how much physics would have been missed"

  – A.Soni

- "A special search at Dubna was carried out by Okonov and his group. They did not find a single $K_L^0 \to \pi^+\pi^-$ event among 600 decays into charged particles (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the lab. The group was unlucky."

  – L.Okun

(remember: $B(K_L^0 \to \pi^+\pi^-) \sim 2\ 10^{-3}$)

Summary

- Huge recent progress in quark-flavour physics
  - in particular with results from LHCb, which has definitively proved the concept of a forward spectrometer at a hadron collider
- Standard Model survives
  - several "tensions" alleviated with improved measurements
  - further investigation still needed in many areas (a_{sl}, $K^*\mu\mu$, $B \to D^{(*)}\tau\nu$, etc.)
  - now probing regions where "realistic" new physics effects might appear
  - looking forward to many new results on full Run 1, and then Run 2, data sets
- Exciting short- and mid-term prospects
  - LHCb upgrade confirmed as a core component of LHC exploitation

Back up

Range of CKM phenomena

nuclear transitions

PIBETA

pion decays

dispersion relations

kaons

NA48, KTeV, KLOE, ISTRA

hadronic matrix elements

hyperon decays

CHORUS

tau decays

chiral perturbation theory

neutrino interactions

KEDR, FOCUS, CLEO, BES

charm

lattice QCD

BABAR, BELLE, LHCb

bottom

flavour symmetries

ALEPH, DELPHI, L3, OPAL

heavy quark effective theories

W decays

CDF, D0, ATLAS, CMS

operator product expansion

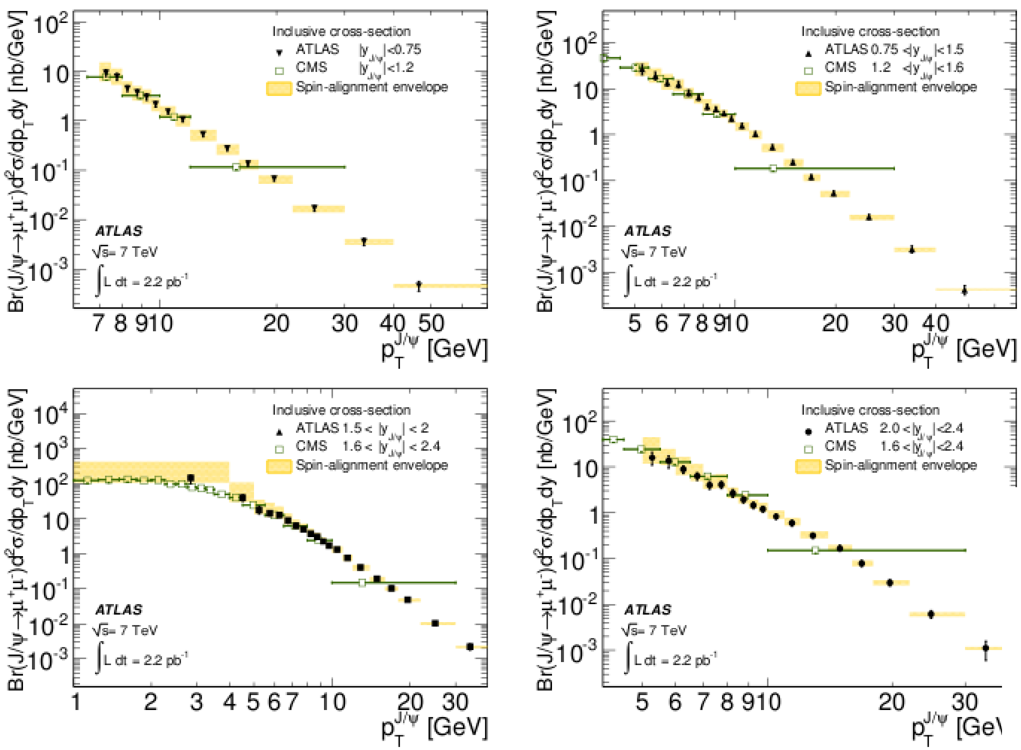
top

perturbative QCD

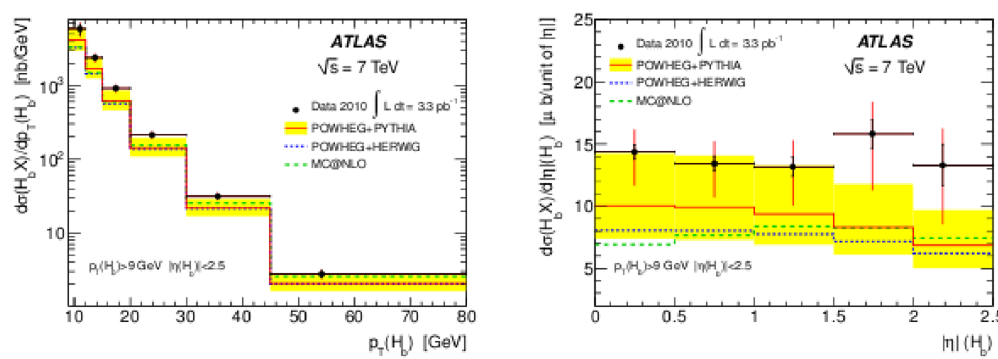
apologies for omissions

Heavy flavour production @ ATLAS

"Measurement of the differential cross-sections of inclusive, prompt and non-prompt J/ψ production in proton-proton collisions at √s = 7 TeV"
Nucl. Phys. B 850 (2011) 387



"Measurement of the b-hadron production cross section using decays to D*+ μ- X final states in pp collisions at √s = 7 TeV with the ATLAS detector"
Nucl. Phys. B 864 (2012) 341



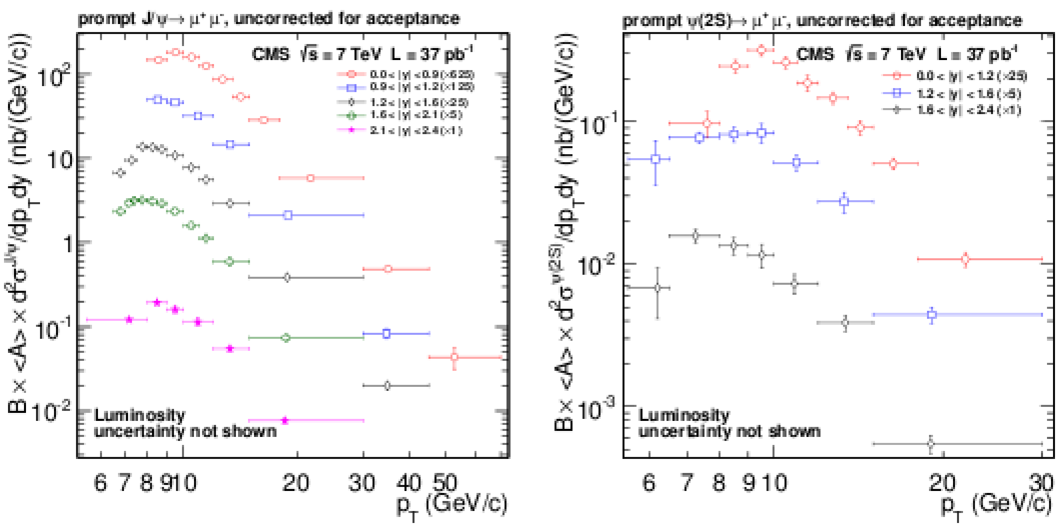
(a)

(b)

Heavy flavour production @ CMS

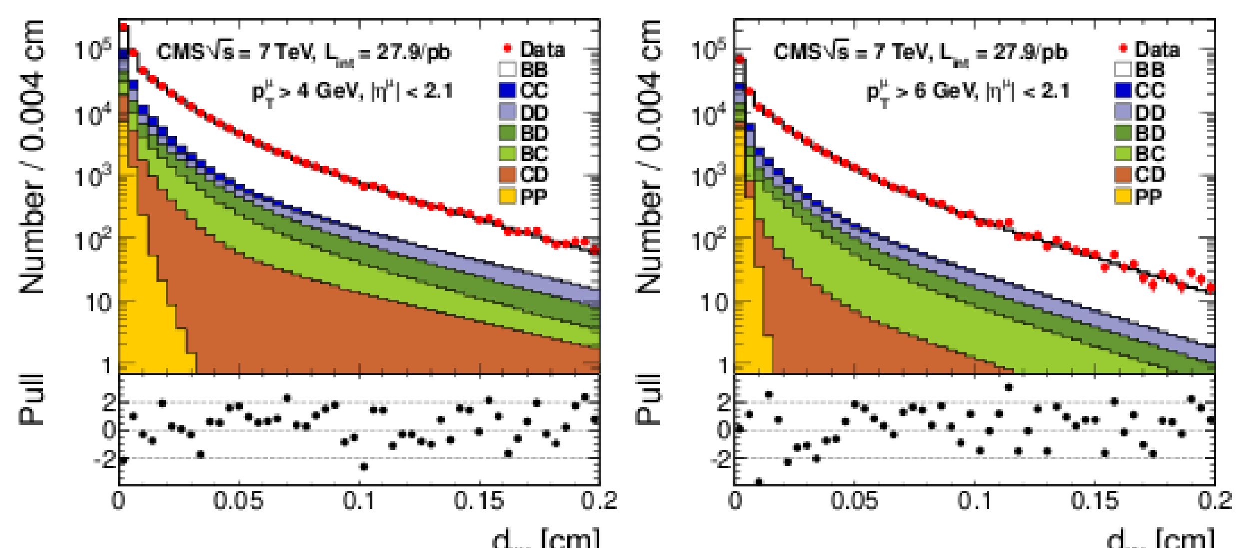
“J/ψ and ψ(2S) production in pp collisions at √s = 7 TeV ”

J. High Energy Phys. 02 (2012) 011



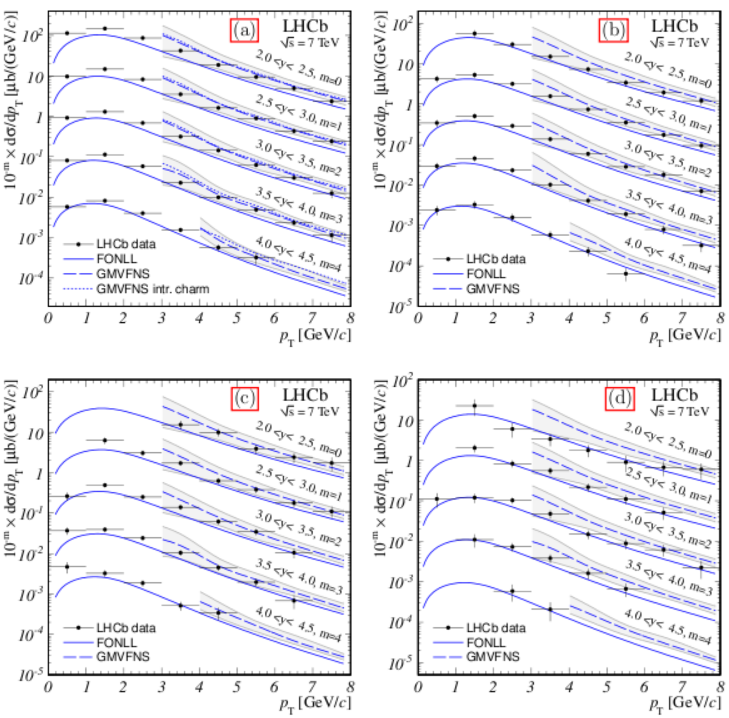
“Measurement of the cross section for production of b b-bar X, decaying to muons in pp collisions at s√=7 TeV”

J. High Energy Phys. 06 (2012) 110



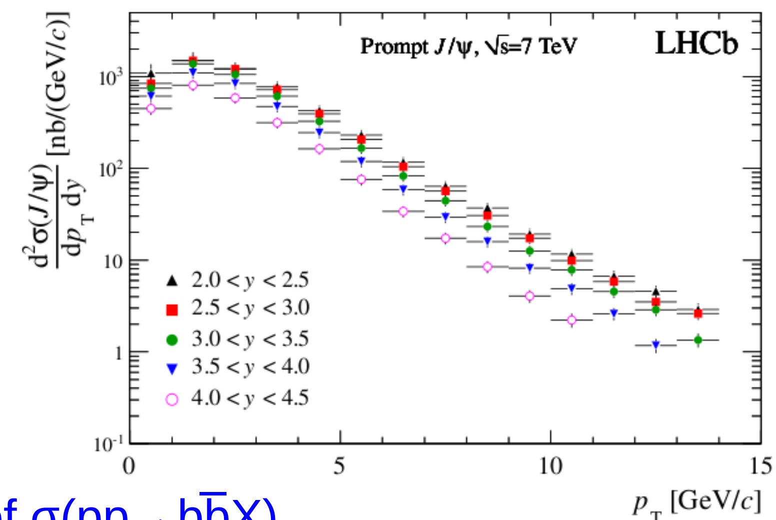
Heavy flavour production @ LHCb

“Prompt charm production in pp collisions at √s = 7 TeV”
LHCb-PAPER-2012-041

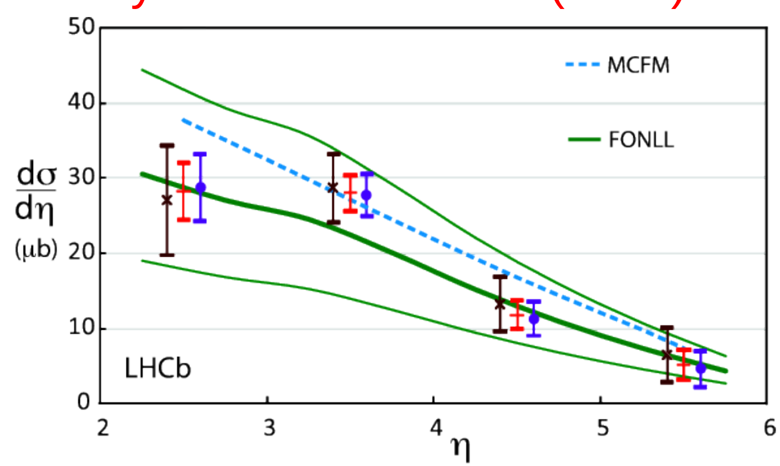


(a) D^0, (b) D^+, (c) D^{*+}, (d) D_s^+

“Measurement of J/ψ production in pp collisions at √s = 7 TeV”
Eur. Phys. J. C 71 (2011) 1645



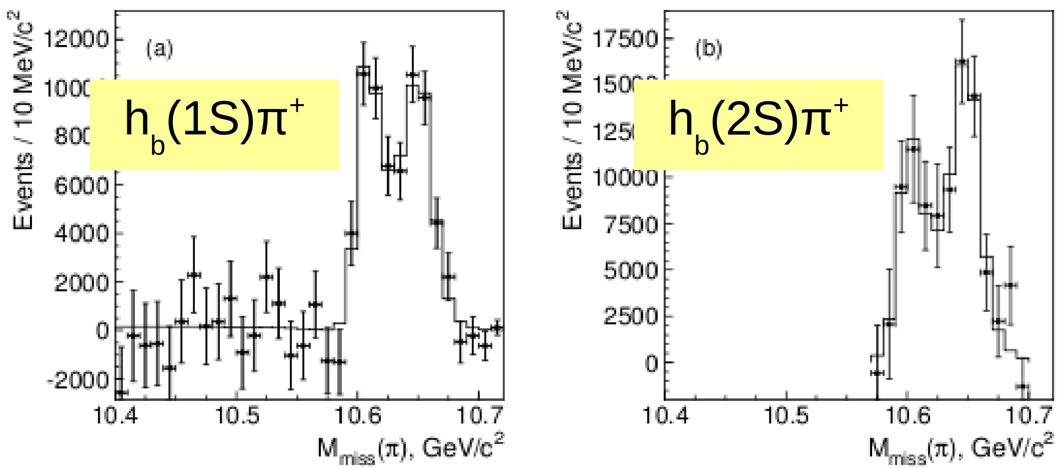
"Measurement of $\sigma(pp \to b\bar{b}X)$ at √s = 7 TeV in the forward region"
Physics Letters B 694 (2010) 209



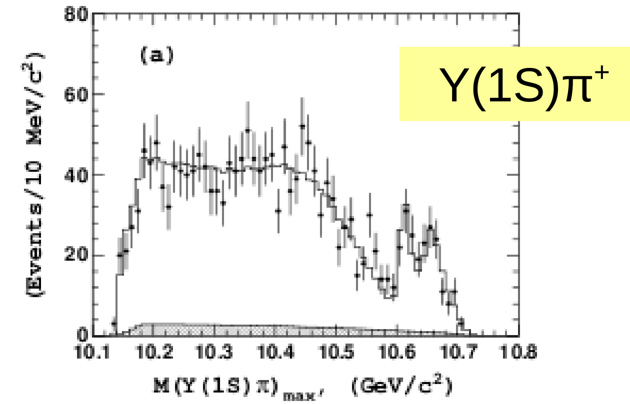
Unconventional states (II)
Charged bottomonium-like states

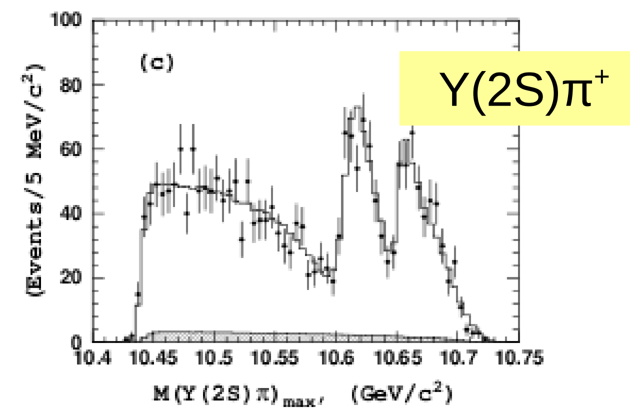
Belle PRL 108 (2012) 122001

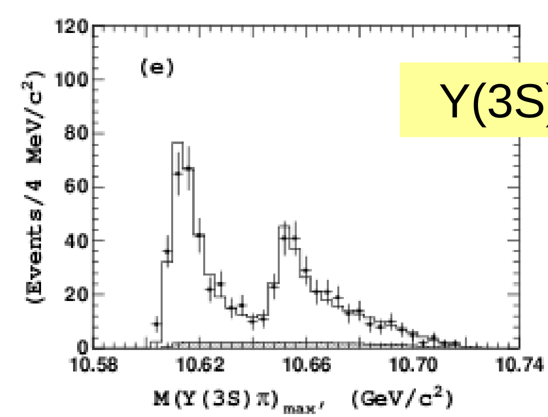
Studied in "Υ(5S)"→$(b\bar{b})\pi^+\pi^-$ amplitude analyses



Final state	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$	$h_b(2P)\pi^+\pi^-$
$M[Z_b(10610)]$, MeV/c^2	$10611 \pm 4 \pm 3$	$10609 \pm 2 \pm 3$	$10608 \pm 2 \pm 3$	$10605 \pm 2^{+3}_{-1}$	10599^{+6+5}_{-3-4}
$\Gamma[Z_b(10610)]$, MeV	$22.3 \pm 7.7^{+3.0}_{-4.0}$	$24.2 \pm 3.1^{+2.0}_{-3.0}$	$17.6 \pm 3.0 \pm 3.0$	$11.4\,^{+4.5+2.1}_{-3.9-1.2}$	$13\,^{+10+9}_{-8-7}$
$M[Z_b(10650)]$, MeV/c^2	$10657 \pm 6 \pm 3$	$10651 \pm 2 \pm 3$	$10652 \pm 1 \pm 2$	$10654 \pm 3\,^{+1}_{-2}$	10651^{+2+3}_{-3-2}
$\Gamma[Z_b(10650)]$, MeV	$16.3 \pm 9.8^{+6.0}_{-2.0}$	$13.3 \pm 3.3^{+4.0}_{-3.0}$	$8.4 \pm 2.0 \pm 2.0$	$20.9\,^{+5.4+2.1}_{-4.7-5.7}$	$19 \pm 7\,^{+11}_{-7}$
Rel. normalization	$0.57 \pm 0.21^{+0.19}_{-0.04}$	$0.86 \pm 0.11^{+0.04}_{-0.10}$	$0.96 \pm 0.14^{+0.08}_{-0.05}$	$1.39 \pm 0.37^{+0.05}_{-0.15}$	$1.6^{+0.6+0.4}_{-0.4-0.6}$
Rel. phase, degrees	$58 \pm 43^{+4}_{-9}$	$-13 \pm 13^{+17}_{-8}$	$-9 \pm 19^{+11}_{-26}$	187^{+44+3}_{-57-12}	$181^{+65+74}_{-105-109}$





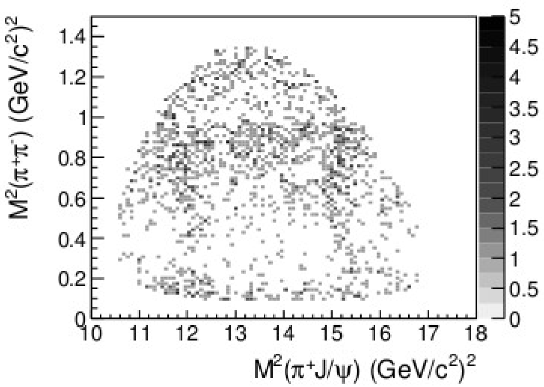


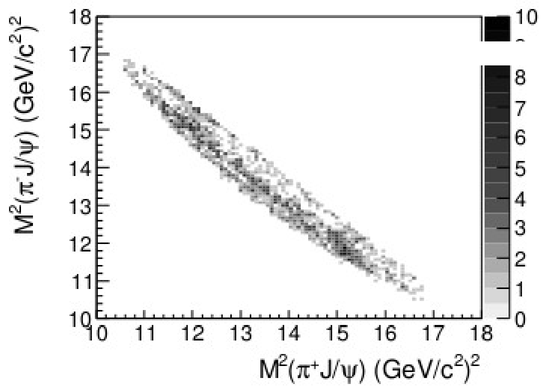
Interpretation of Z_b^+ states as $B^{(*)}B^*$ molecules

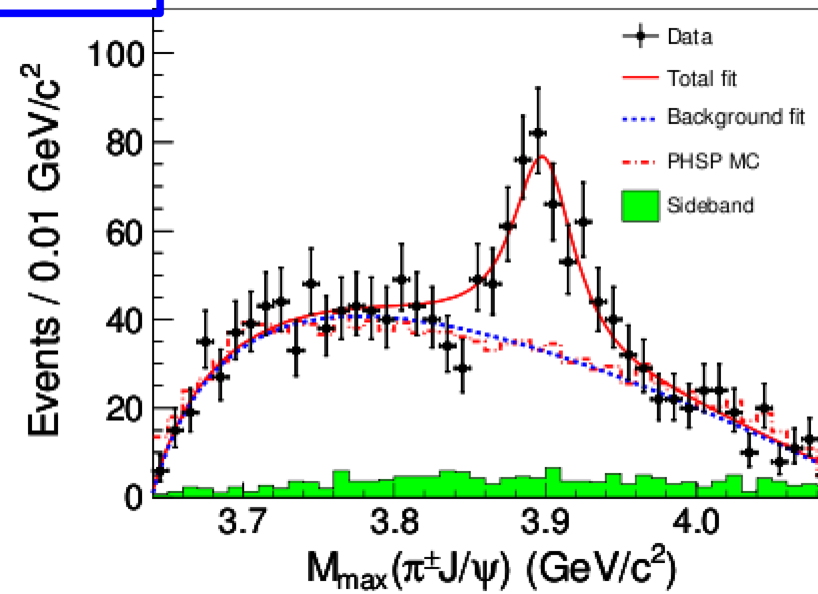
Unconventional states (III)
Charged charmonium-like states

BESIII PRL 110 (2013) 252001
& Belle PRL 110 (2013) 252002

Studied in $Y(4260) \to J/\psi\pi^+\pi^-$
not amplitude analysis







$Z_c(3900)$ adds to a list of claimed charged charmonium-like states

($Z(4430)$ in $\psi'\pi^+$, $Z_1(4050)$, $Z_2(4250)$ in $\chi_{c1}\pi^+$)

Independent confirmations (or refutations) needed …

Careful amplitude analyses are necessary to understand broad peaks

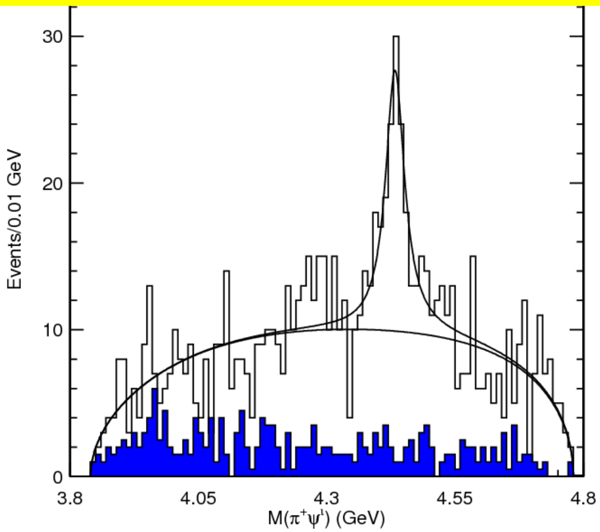
"The story of the pentaquark shows how poorly we understand QCD" – F. Wilczek, 2005

→ are we approaching understanding beyond $q\bar{q}$ and qqq?

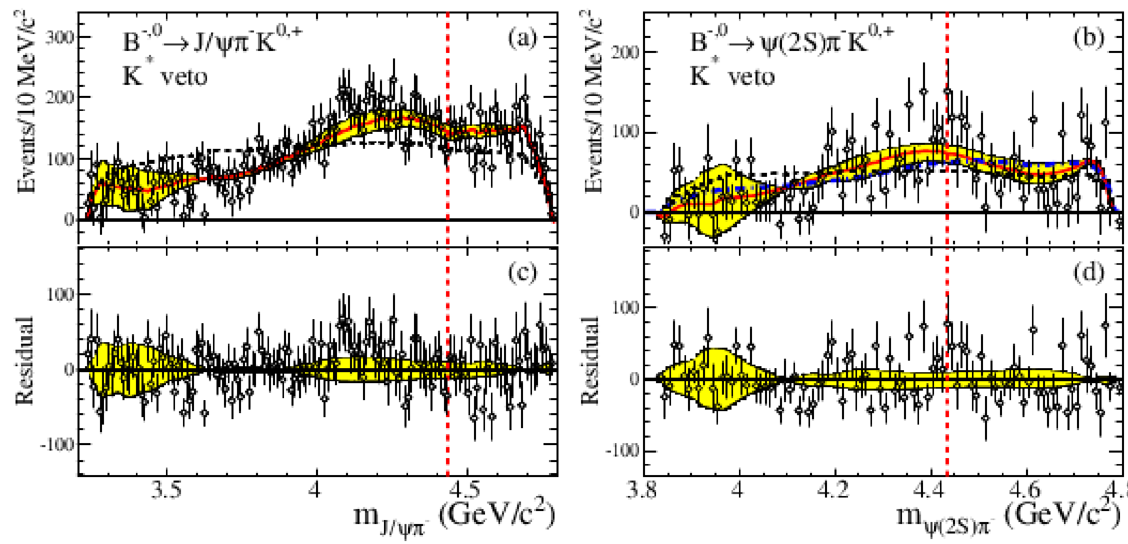
The smoking gun exotic hadron: A charged charmonium-like state

$B^0 \to Z(4430)^- K^+$, $Z(4430)^- \to \psi' \pi^-$

Belle PRL 100 (2008) 142001



BABAR PRD 79 (2009) 112001



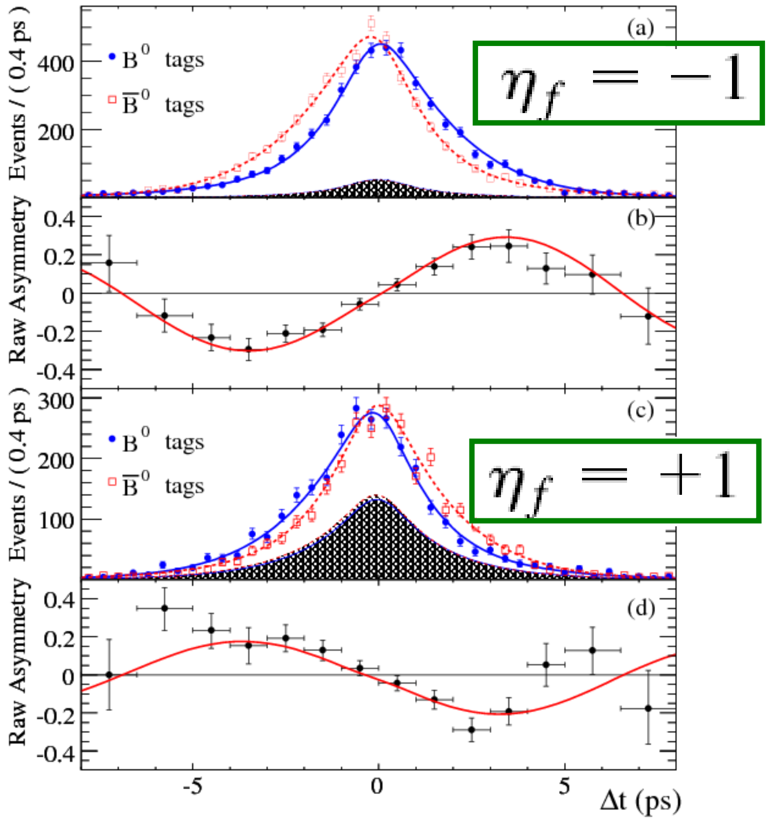
Clear peak
Still there in more detailed analysis
PRD 80 (2009) 031104

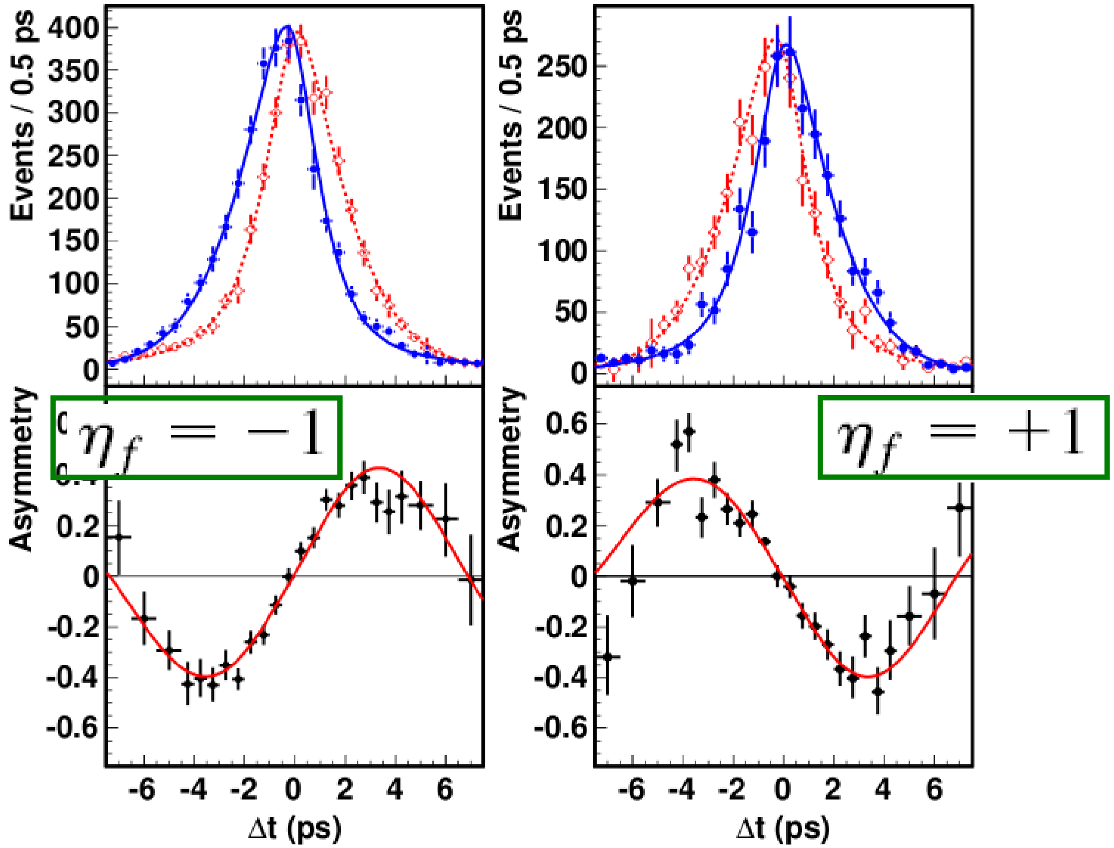
Data consistent with Kπ reflections
Slight peak but no evidence for new state
But also consistent with Belle

Need more experimental input
(CDF, D0, ATLAS, CMS or LHCb)

Large CP violation effects exist
sin(2β) from $B^0 \rightarrow J/\psi K^0_S$

BABAR **BELLE**



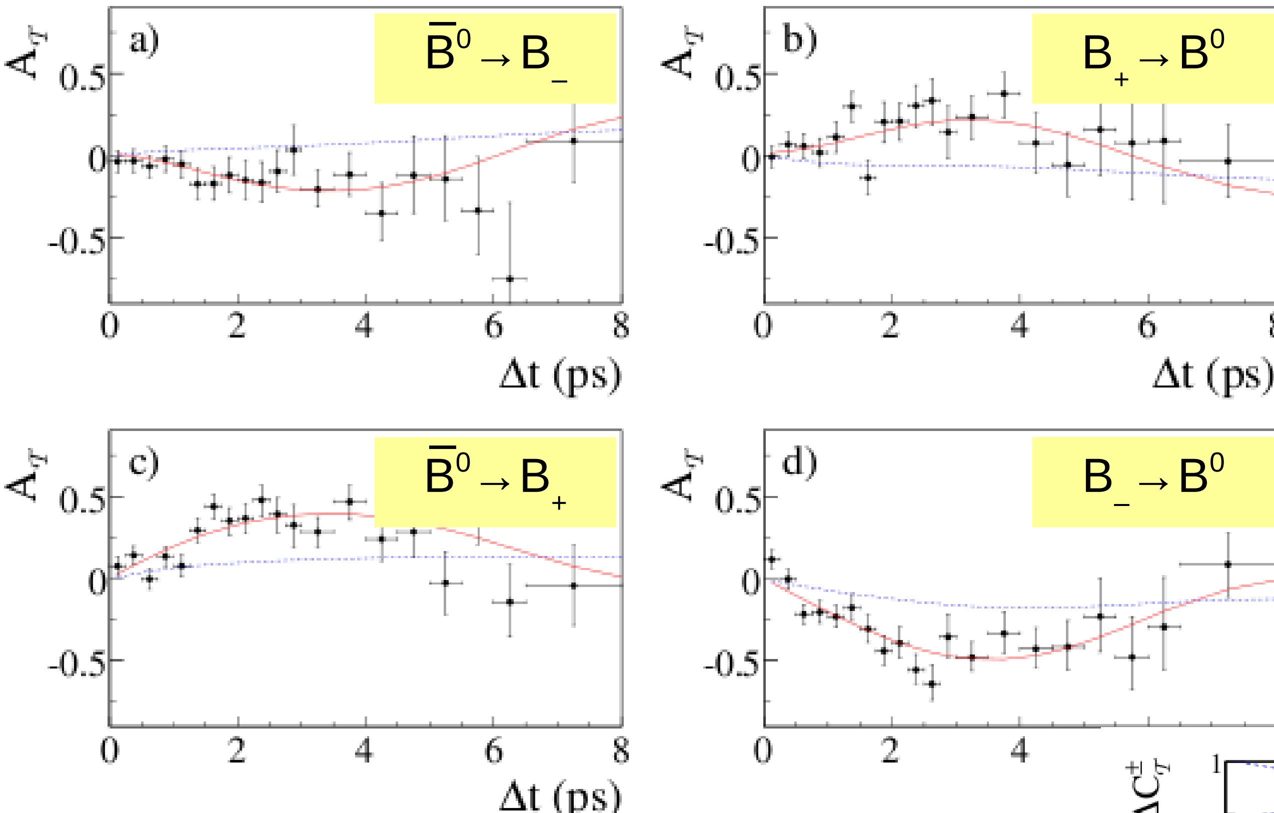


PRD 79 (2009) 072009

PRL 108 (2012) 171802

World average: sin(2β) = 0.679 ± 0.020

… and T is also violated, as expected



BaBar
PRL 109 (2012) 211801

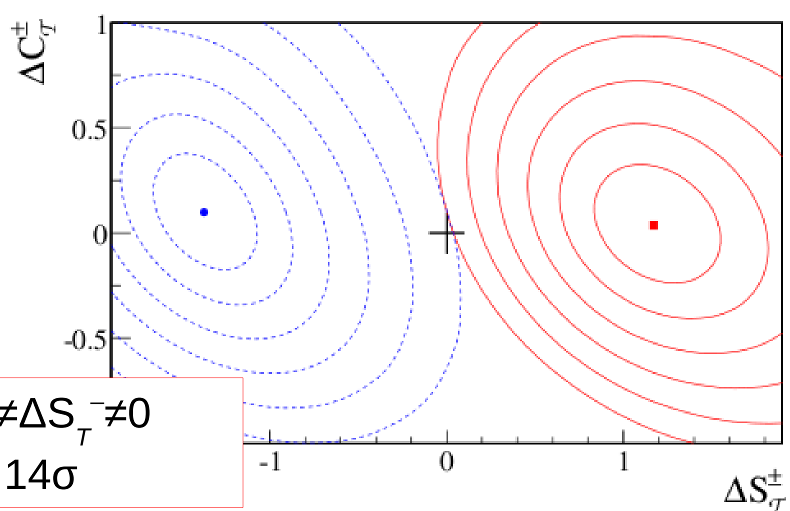
Generalisation of usual sin(2β) analysis allowing for separate CP, T and CPT violating terms

No significant sign of CPT violation in any test

e.g. $A_T(\bar{B}^0 \to B_-)$ between (l^- tag, $J/\psi K_S$, $\Delta t>0$)

and (l^+ tag, $J/\psi K_L$, $\Delta t<0$)

$\sim \frac{1}{2}(\ \Delta S_T^{\ +}\sin(\Delta m_d \Delta t) + \Delta C_T^{\ +}\cos(\Delta m_d \Delta t)\ )$



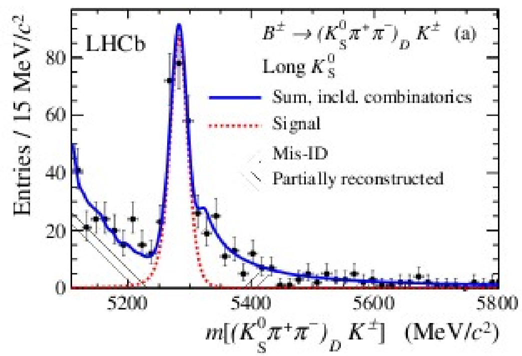
Contours show $\Delta S_T^{\ +} \neq \Delta S_T^{\ -} \neq 0$
→ T violation at 14σ

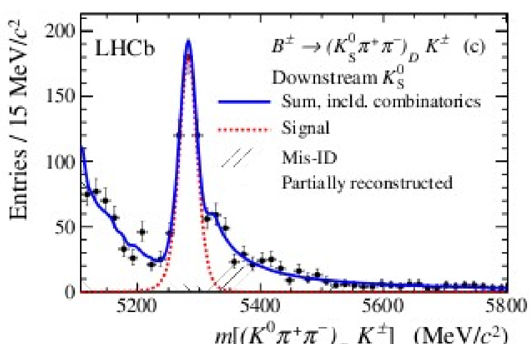
γ from $B^+ \to DK^+$, $D \to K^0_S h^+ h^-$

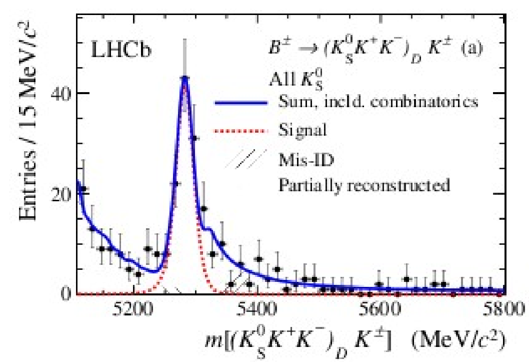
LHCb (1/fb)
Phys. Lett. B 718 (2012) 43

- Results from "GGSZ" mode very important to break ambiguities in determination of γ
- Model-independent approach using $D \to K^0_S \pi^+\pi^-$ and (world first) $D \to K^0_S K^+K^-$

$K^0_S \pi^+\pi^-$ in two K^0_S categories





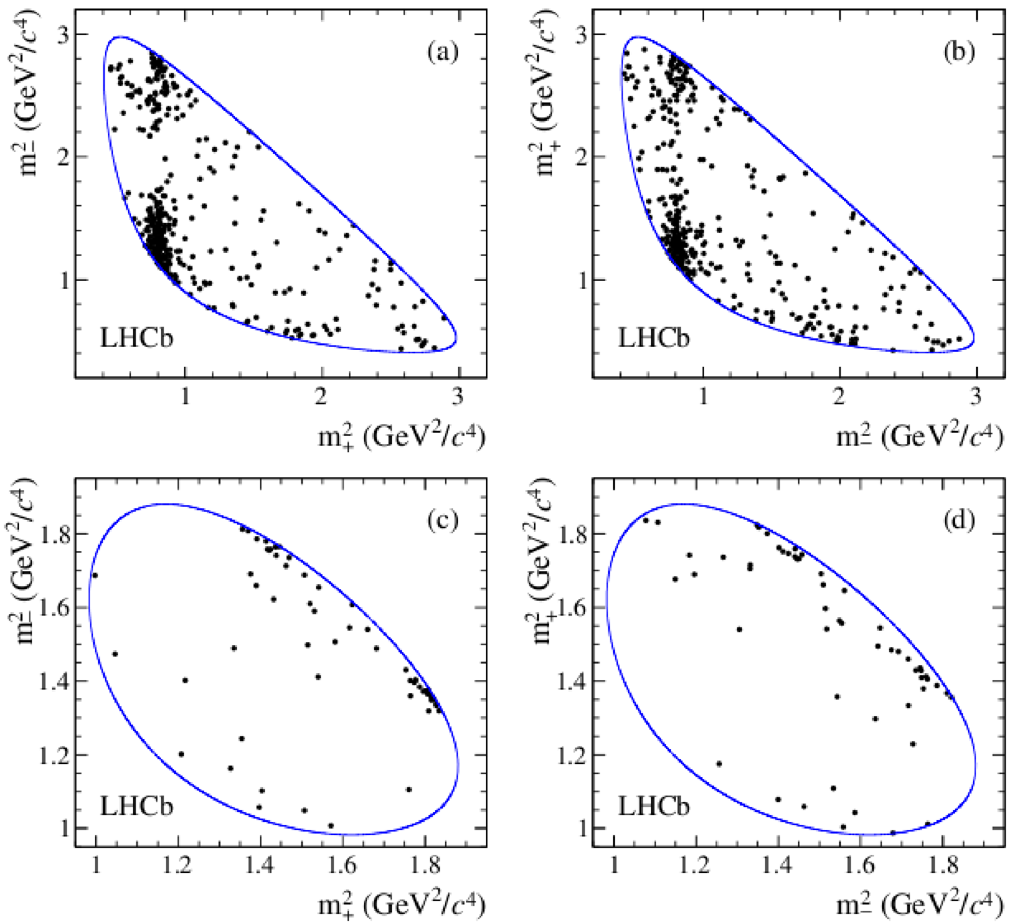


$K^0_S K^+K^-$ (all combined)

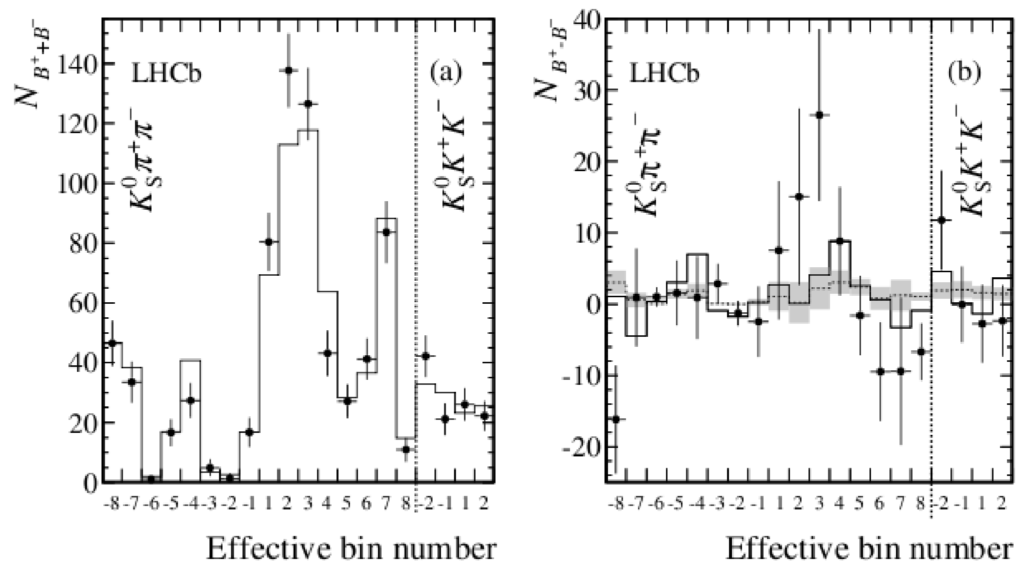
γ from $B^+ \to DK^+$, $D \to K^0_S h^+ h^-$

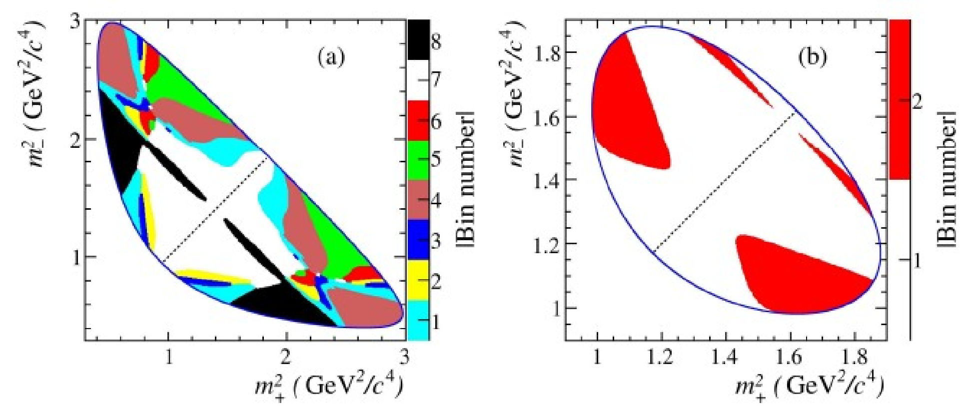
LHCb (1/fb)
Phys. Lett. B 718 (2012) 43

Reconstruct Dalitz plot distributions ...



... bin them ...
(in complicated but ~optimal way)

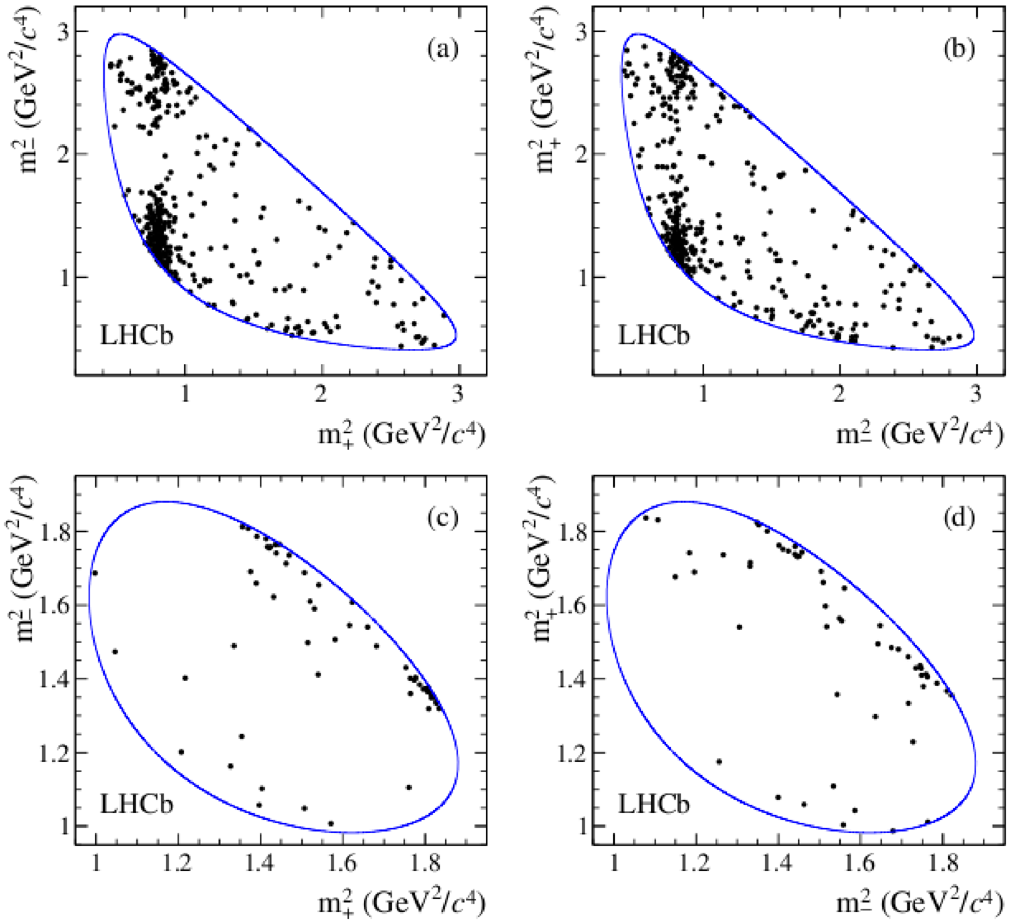




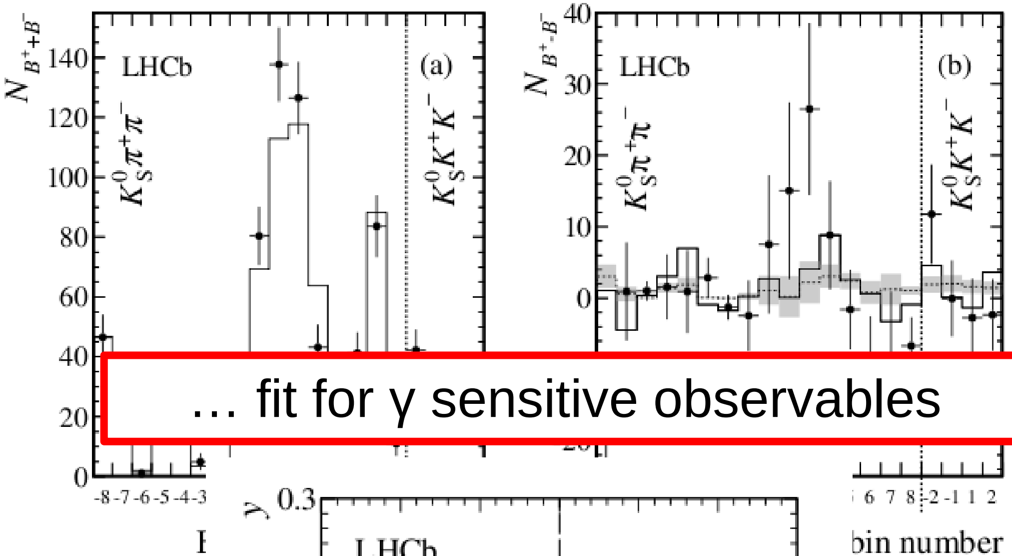
γ from $B^+ \to DK^+$, $D \to K^0_S h^+h^-$

LHCb (1/fb)
Phys. Lett. B 718 (2012) 43

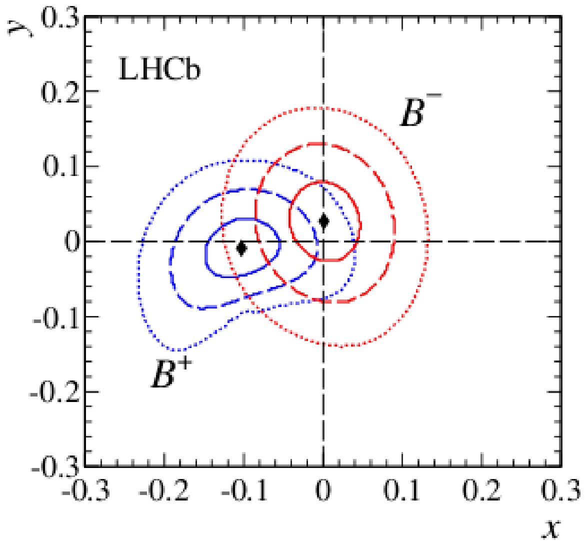
Reconstruct Dalitz plot distributions ...



... bin them ...
(in complicated but ~optimal way)

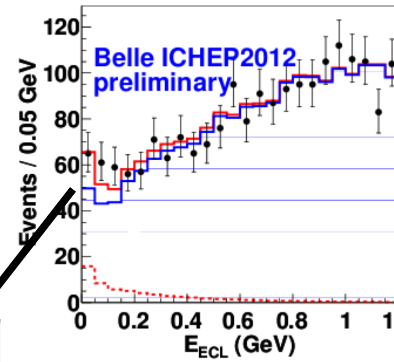


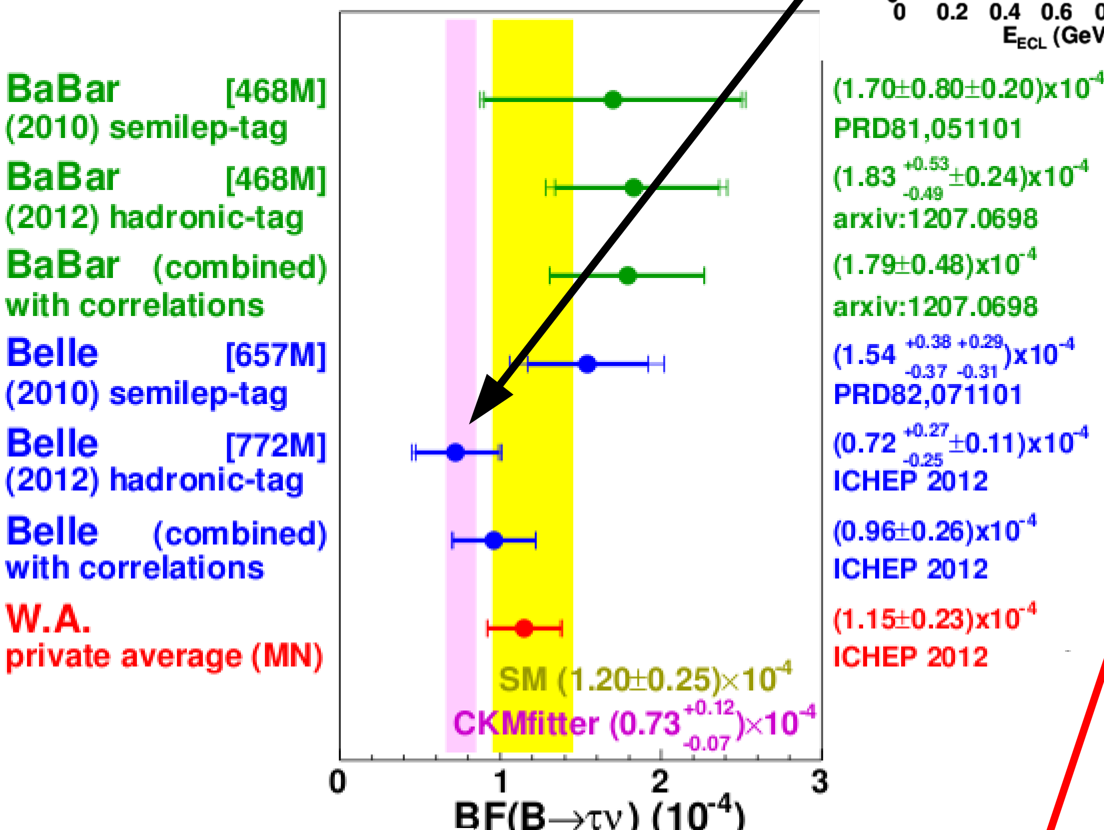
... fit for γ sensitive observables



$B \to \tau\nu$ & $B \to D^{(*)}\tau\nu$

BaBar arXiv:1207.0698
Belle arXiv:1208.4678
M. Nakao @ ICHEP 2012





2.3σ

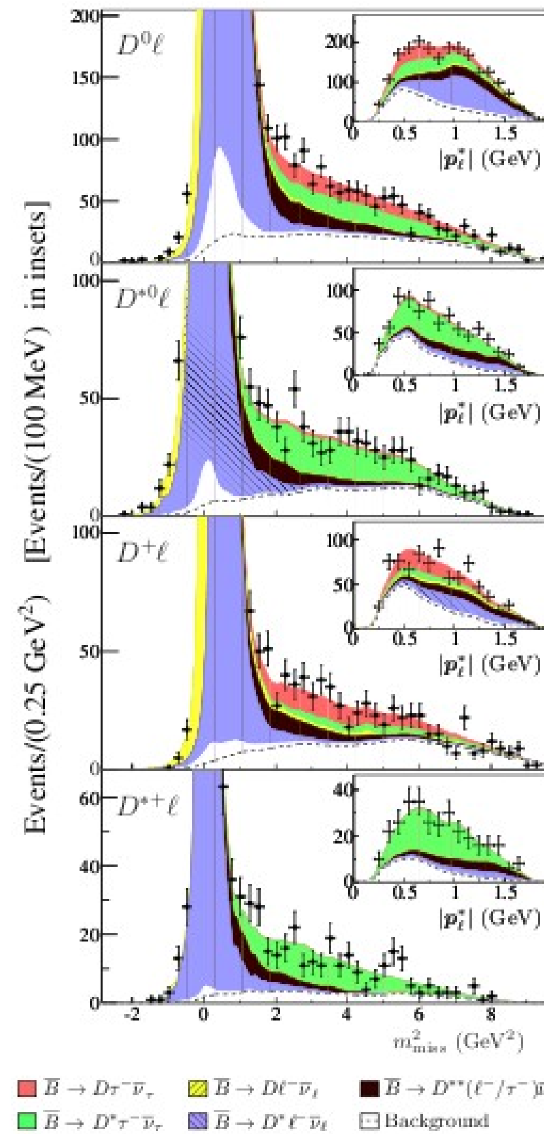
3.8σ

3.6σ

3.0σ

Significance (from 0) below the usual threshold to claim observation

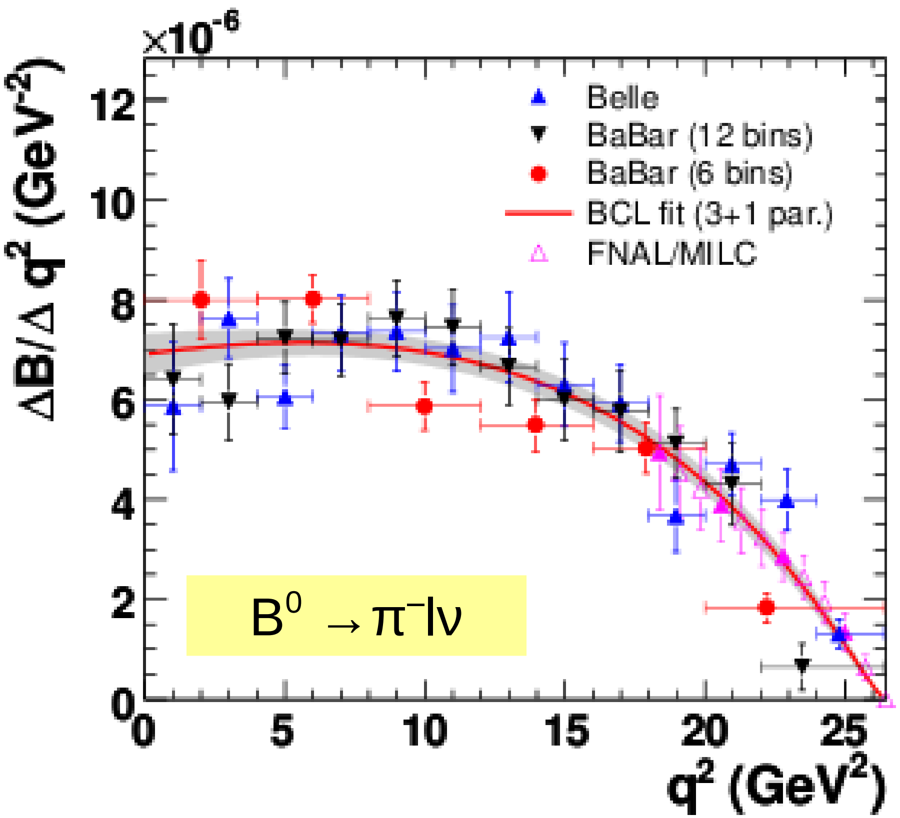
BaBar PRL 109 (2012) 101802
Belle PRD 82 (2010) 072005



BaBar rates 3.4σ above the SM, and inconsistent with 2HDM

$|V_{ub}|$ from {in,ex}clusive semileptonic decays

PBFLB based on
BaBar PRD 83 (2011) 052011 &
PRD 83 (2011) 032007
Belle PRD 83 (2011) 071101(R)



Some tension between exclusive and inclusive results. PBFLB concludes:

$$|V_{ub}|_{excl} = [3.23\ (1 \pm 0.05_{exp} \pm 0.08_{th})] \times 10^{-3}$$
$$|V_{ub}|_{incl} = [4.42\ (1 \pm 0.045_{exp} \pm 0.034_{th})] \times 10^{-3}.$$

This average has a probability of $P(\chi^2) = 0.003$. Thus we scale the error by $\sqrt{\chi^2} = 3.0$ and arrive at

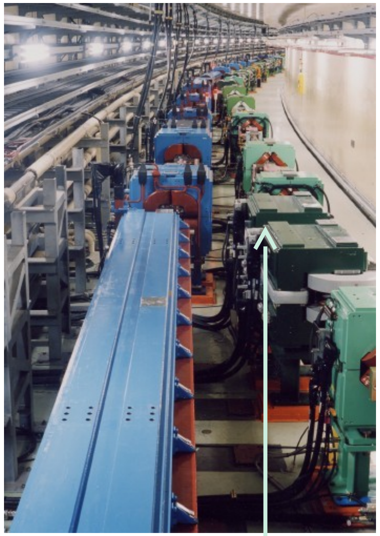
$$|V_{ub}| = [3.95\ (1 \pm 0.096_{exp} \pm 0.099_{th})] \times 10^{-3}$$

Similar tension also for $|V_{cb}|$

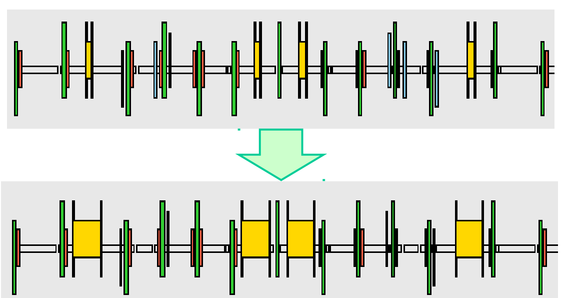
Better understanding needed to reduce uncertainty

lattice uncertainty

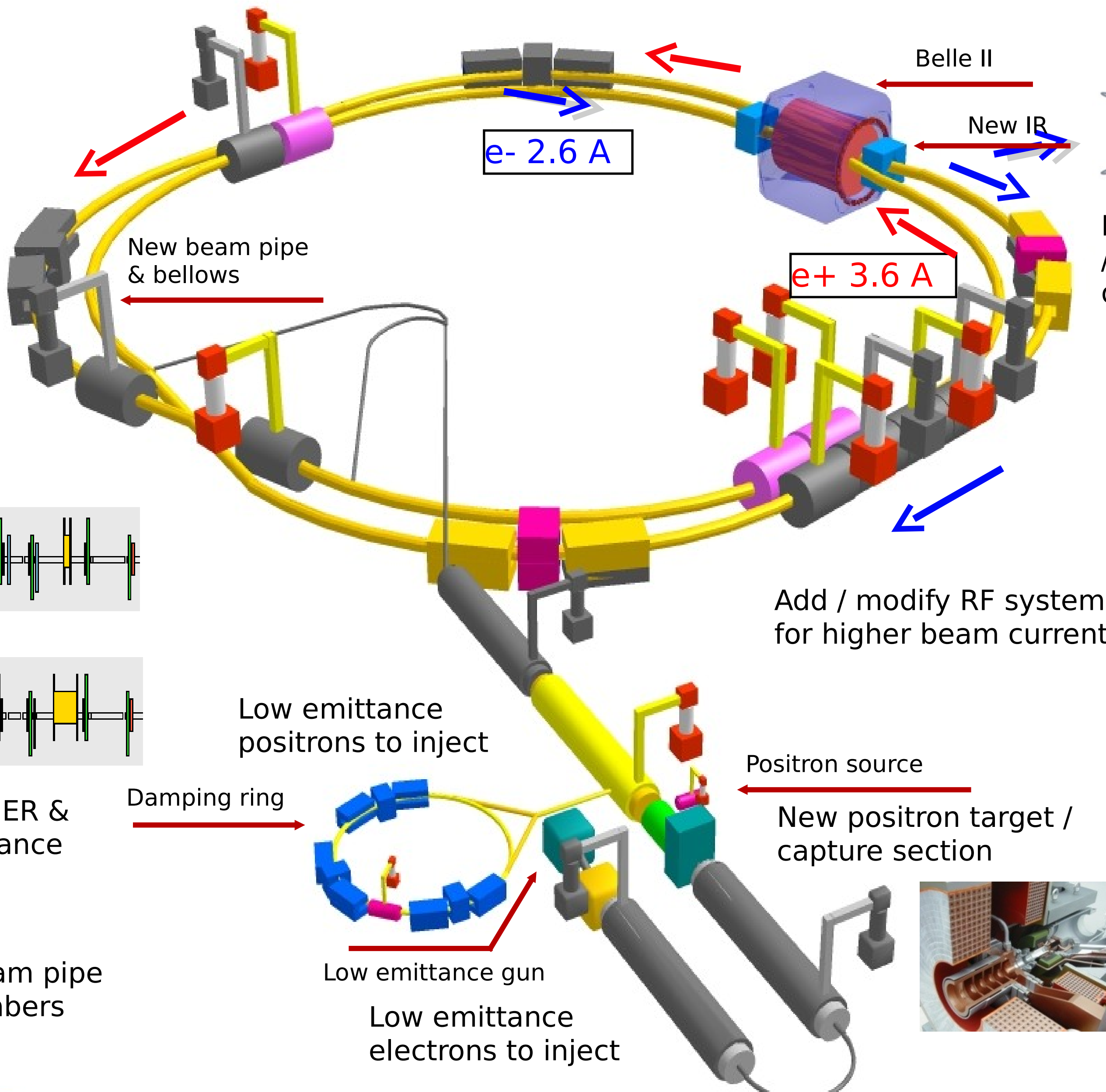
KEKB to SuperKEKB



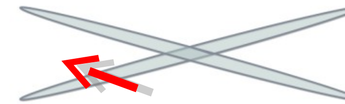
Replace short dipoles with longer ones (LER)



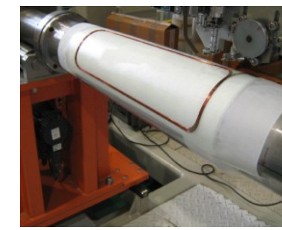
Redesign the lattices of HER & LER to squeeze the emittance



Colliding bunches



New superconducting /permanent final focusing quads near the IP



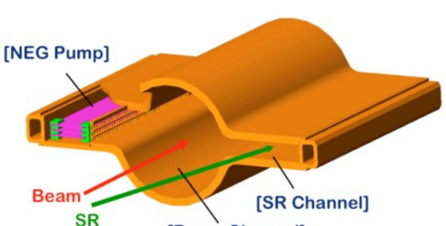
Add / modify RF systems for higher beam current

Low emittance positrons to inject

New positron target / capture section

Low emittance electrons to inject

TiN-coated beam pipe with antechambers



To obtain x40 higher luminosity

Belle II Detector

KL and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps , inner 2 barrel layers)

EM Calorimeter:
CsI(Tl), waveform sampling (barrel)
Pure CsI + waveform sampling (end-caps)

electrons (7GeV)

Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)

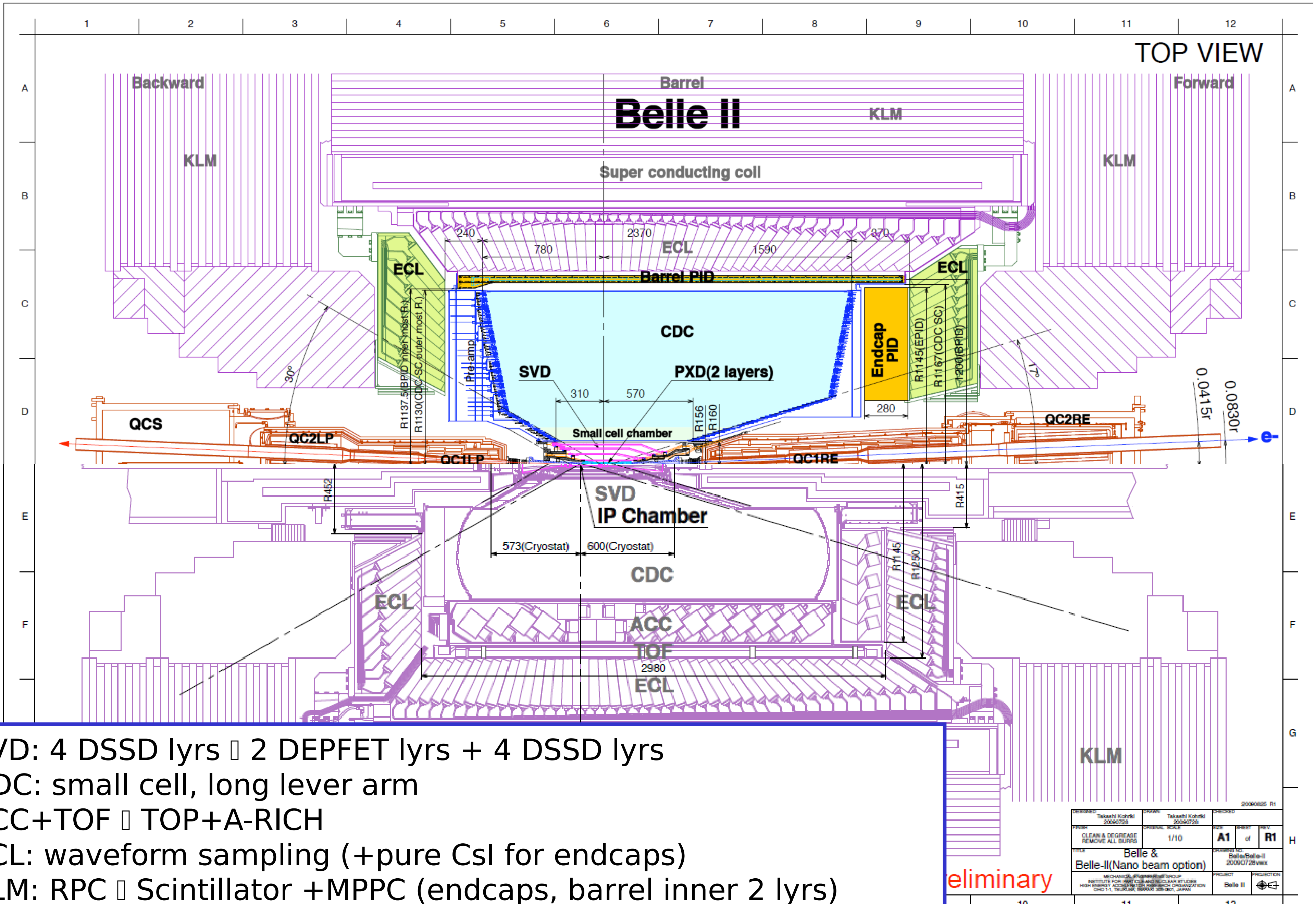
Beryllium beam pipe
2cm diameter

Vertex Detector
2 layers DEPFET + 4 layers DSSD

Central Drift Chamber
He(50%):C_2H_6(50%), small cells, long lever arm, fast electronics

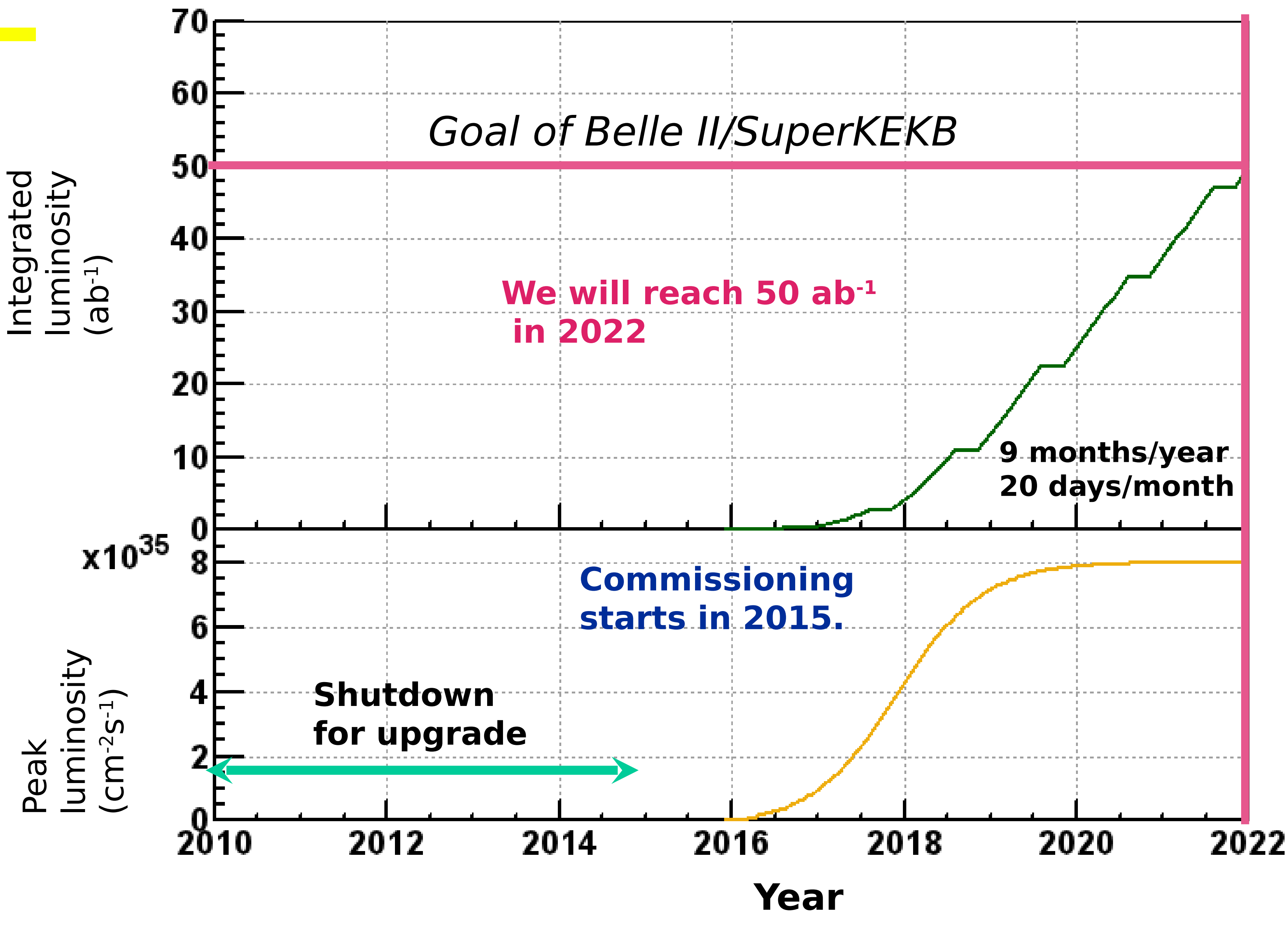
positrons (4GeV)

Belle II Detector (in comparison with Bell



SVD: 4 DSSD lyrs 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF TOP+A-RICH
ECL: waveform sampling (+pure CsI for endcaps)
KLM: RPC Scintillator +MPPC (endcaps, barrel inner 2 lyrs)

Schedule



The schedule is likely to shift by a few months because of a new construction/commissioning strategy for the final quads.