Flavour Physics circa 2013

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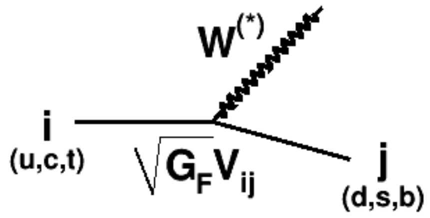
2 May 2013

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

Quark flavour mixing
a.k.a. CKM phenomenology



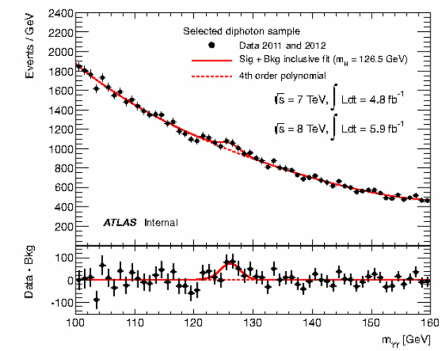
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}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

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
- 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



SM

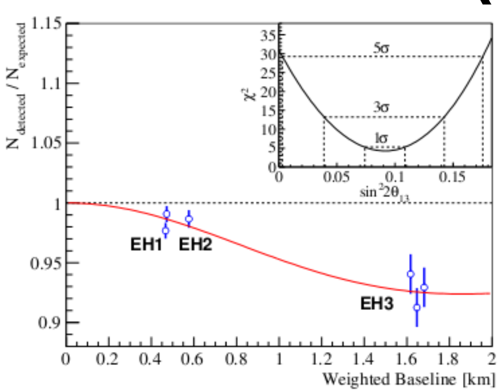
NP

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}

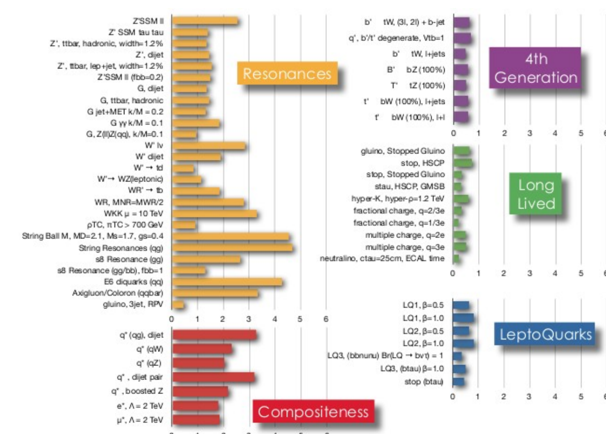


Rare decays

(strong theoretical arguments)

But

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



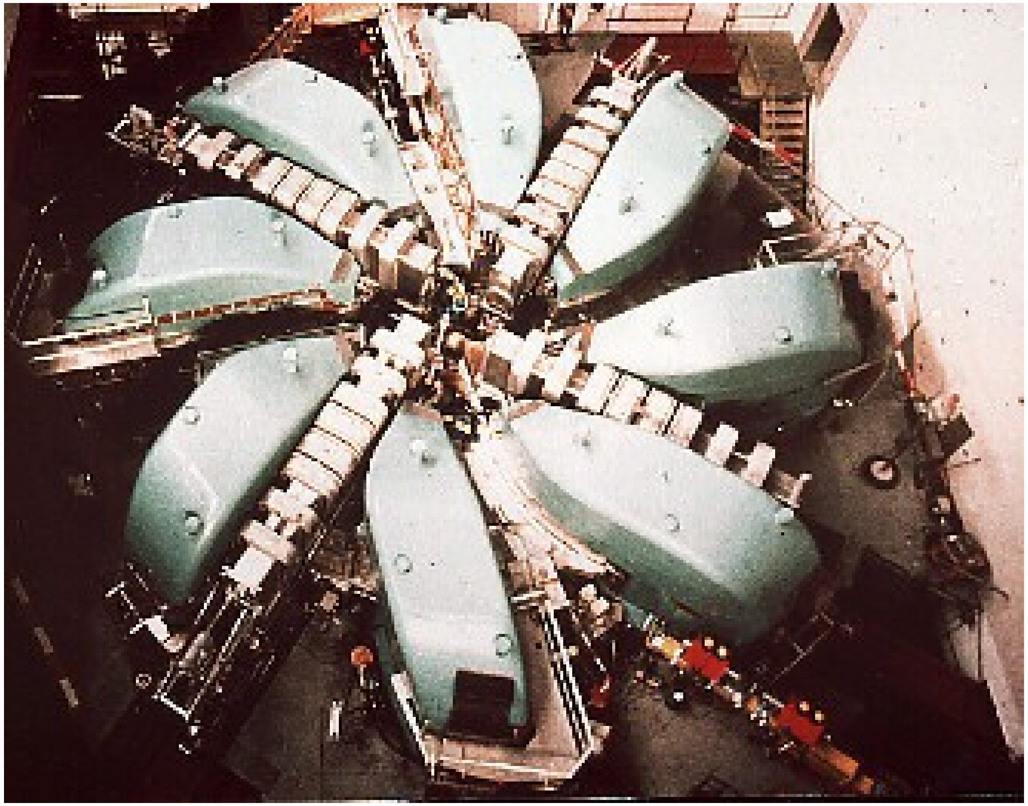
Absence of NP signals at ATLAS/CMS → argument for searches via rare decays stronger

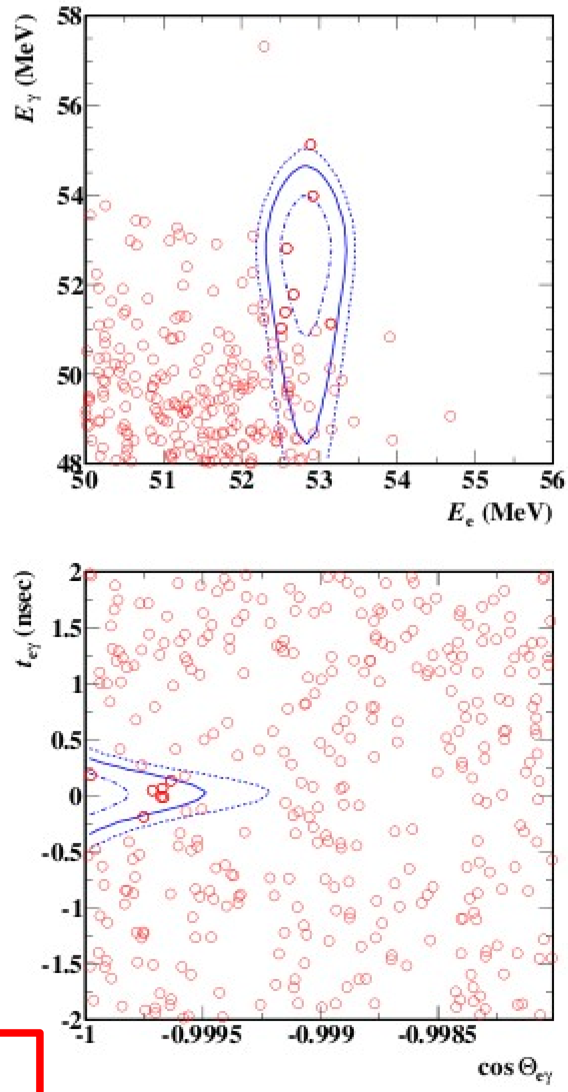
Search for $\mu^+ \rightarrow e^+\gamma$

$\mu^+ \rightarrow e^+\gamma$

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

MEG arXiv:1303.0754





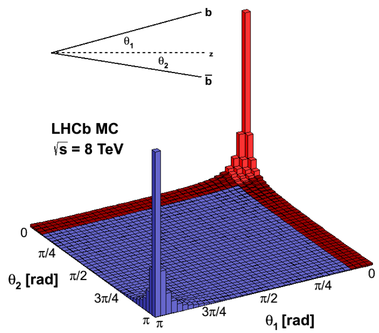
$B(\mu^+ \rightarrow e^+\gamma) < 5.7\ 10^{-13}$ @ 90% CL

Why flavour physics in the LHC era?

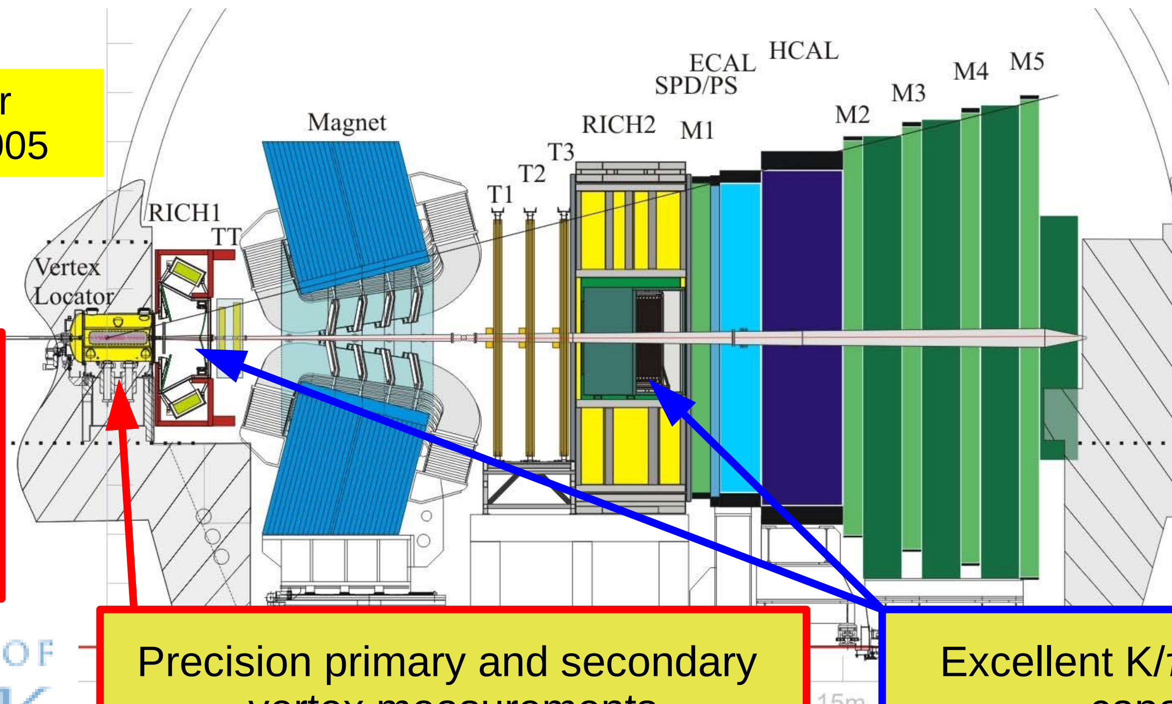
- There is still much physics to be done with the datasets of BaBar, Belle, CDF, D0, CLEO, BES, etc.
  - Discovery potential complementary to other experiments
  - New experiments in the charged lepton sector add additional potential
- LHC is the world's most copious source of heavy flavoured fermions
  - 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
  - Must also exploit the capability of ATLAS and CMS 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

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

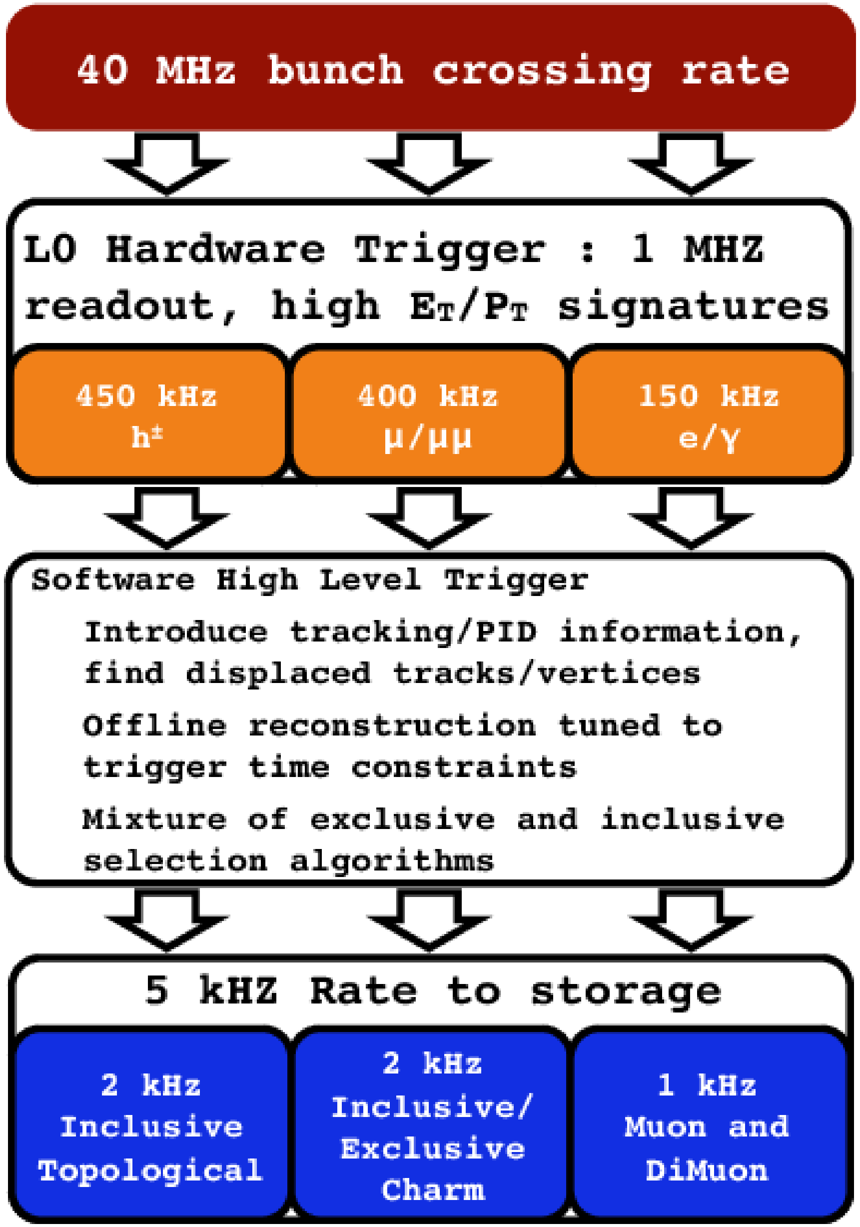
- to efficiently select most interesting B decays
- while maintaining manageable data rates

Main backgrounds

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

Handles

- high p_T signals (muons)
- displaced vertices



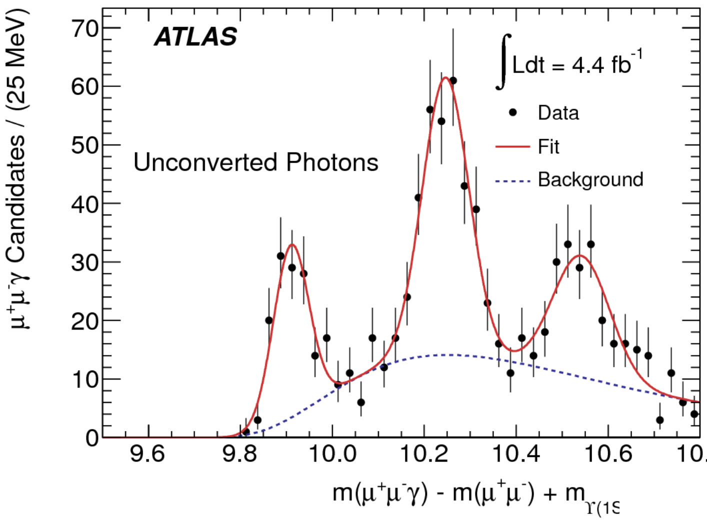
Selected highlights of results
Production and spectroscopy

Observations of new states

(no, not the Higgs)

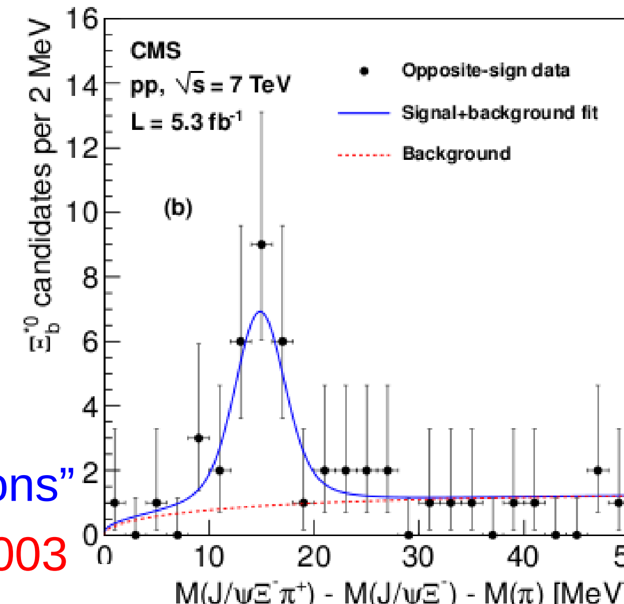
"Observation of a New χ_b State in Radiative Transitions to Υ(1S) and Υ(2S) at ATLAS"

Phys. Rev. Lett. 108 (2012) 152001



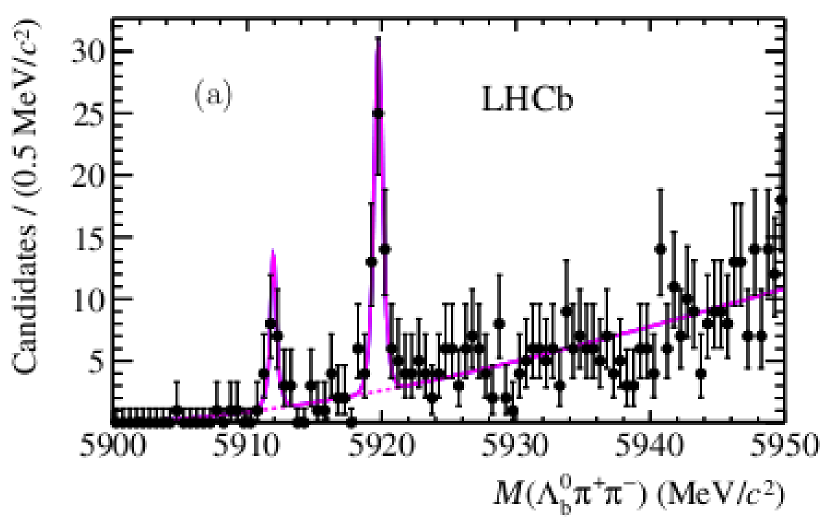
"Observation of a New Ξ_b Baryon"

Phys. Rev. Lett. 108 (2012) 252002



"Observation of excited Λ^0_b baryons"

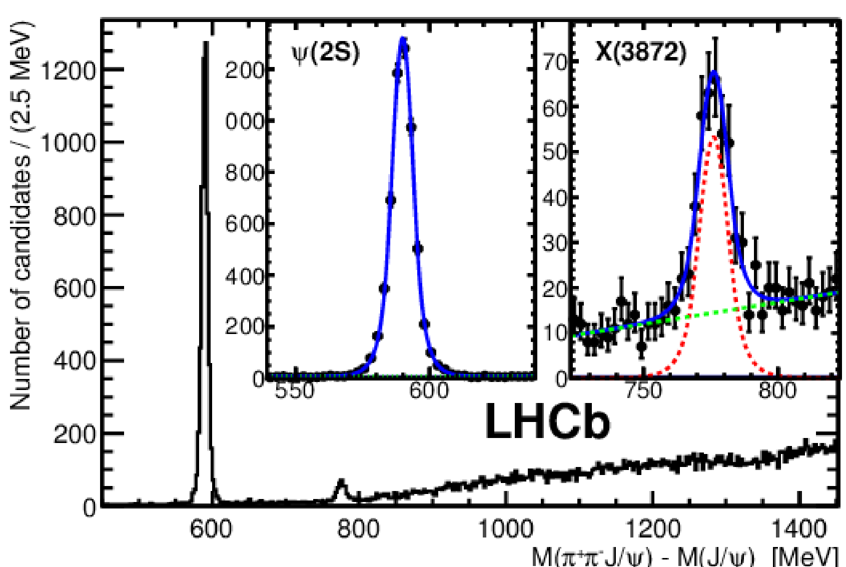
Phys. Rev. Lett. 109 (2012) 172003

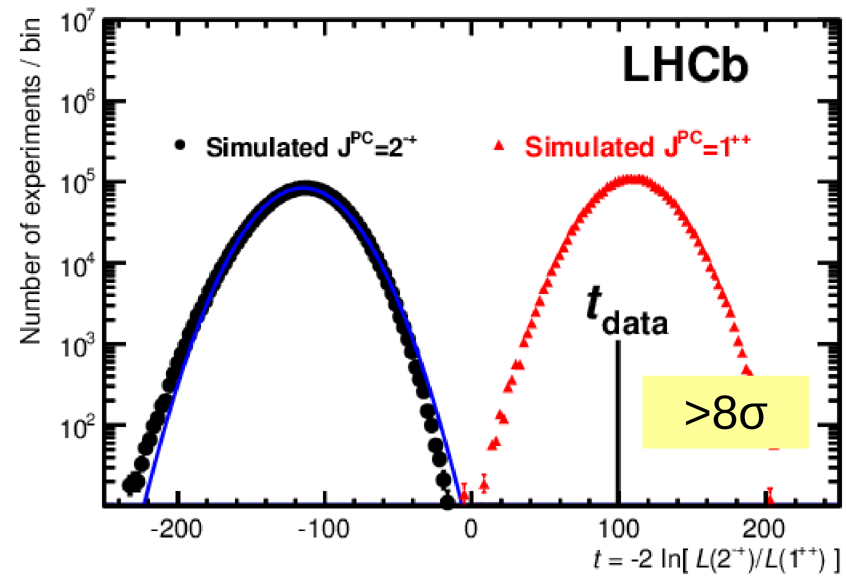


Unconventional states (I) X(3872)

LHCb arXiv:1302.6269

- X(3872) discovered in B→XK, with X→J/ψππ (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



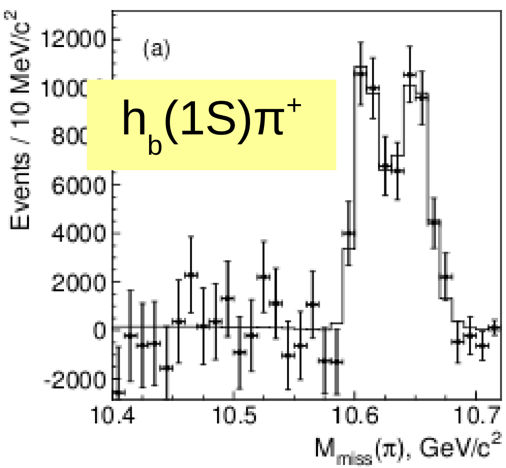


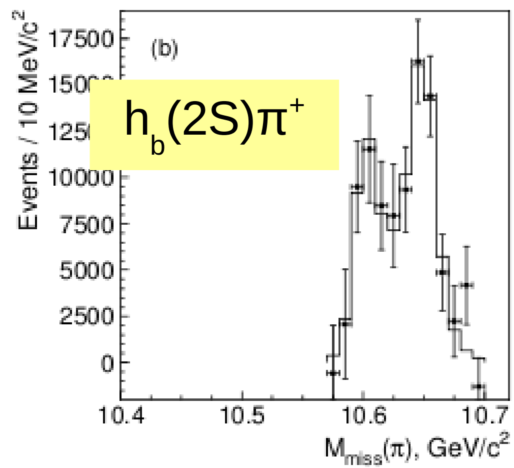
$J^{PC} = 1^{++}$ supports molecular interpretation of X(3872)
… but then how to explain production in hadron collisions?

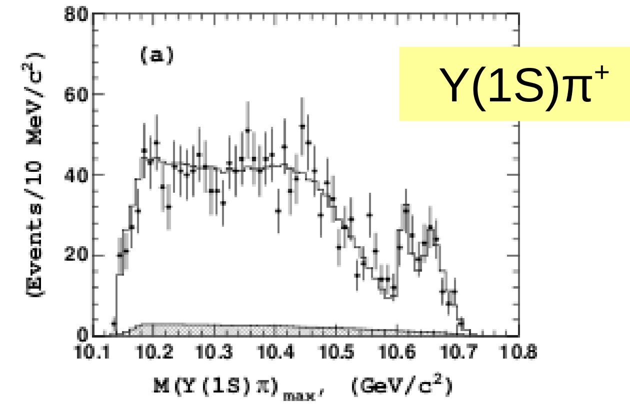
Unconventional states (II)
Charged bottomonium-like states

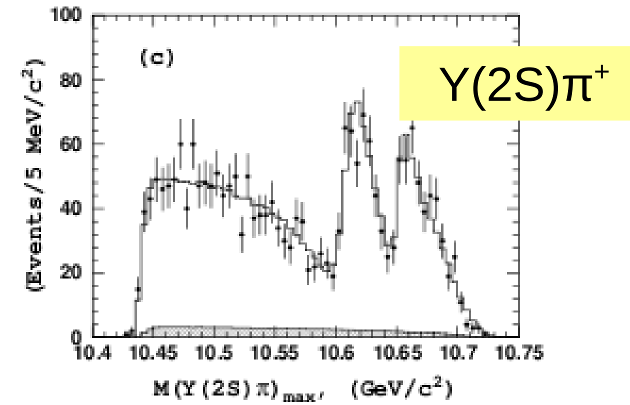
Belle
PRL 108 (2012) 122001

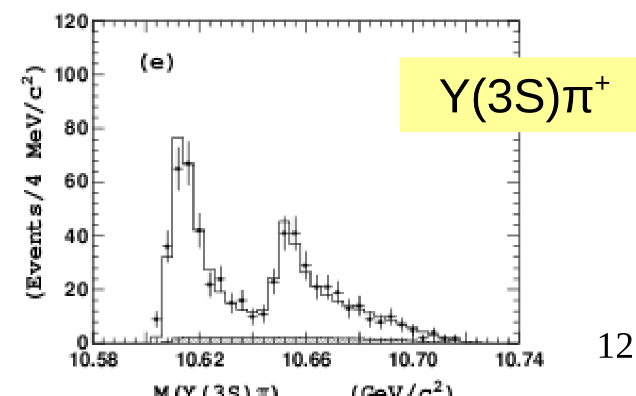
Studied in "Y(5S)"$\rightarrow (b\bar{b})\pi^+\pi^-$ amplitude analyses











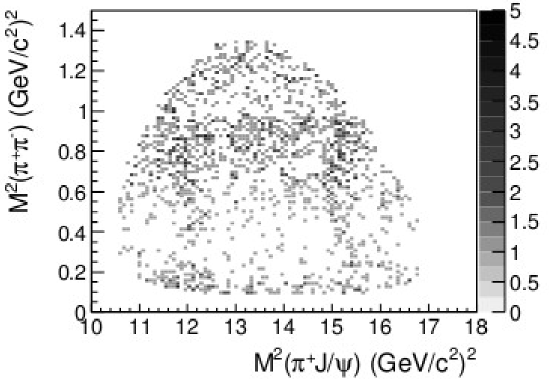
Final state	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$	$h_b(2P)\pi^+\pi^-$
$M[Z_b(10610)]$, MeV/c^2	$10611 \pm 4 \pm 3$	$10609 \pm 2 \pm 3$	$10608 \pm 2 \pm 3$	$10605 \pm 2^{+3}_{-1}$	10599^{+6+5}_{-3-4}
$\Gamma[Z_b(10610)]$, MeV	$22.3 \pm 7.7^{+3.0}_{-4.0}$	$24.2 \pm 3.1^{+2.0}_{-3.0}$	$17.6 \pm 3.0 \pm 3.0$	$11.4\,^{+4.5+2.1}_{-3.9-1.2}$	$13\,^{+10+9}_{-8-7}$
$M[Z_b(10650)]$, 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}	$181^{+65+74}_{-105-109}$

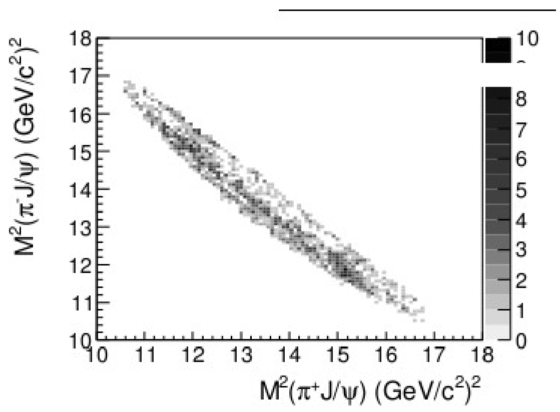
Interpretation of Z_b^+ states as $B^{(*)}B^*$ molecules

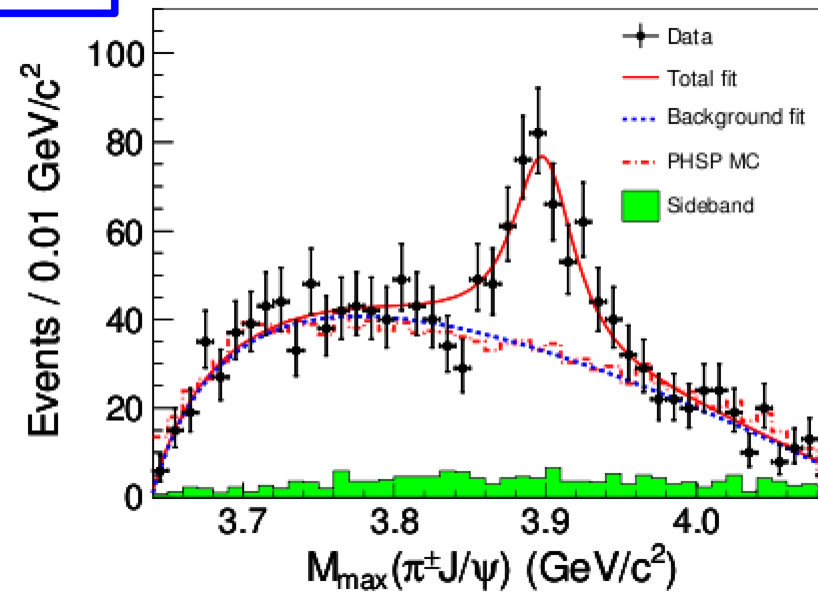
Unconventional states (III)
Charged charmonium-like states

BESIII arXiv:1303.5949
also Belle arXiv:1304.0121

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?

Selected highlights of results
CP violation and the Unitarity Triangle

The Unitarity Triangle

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

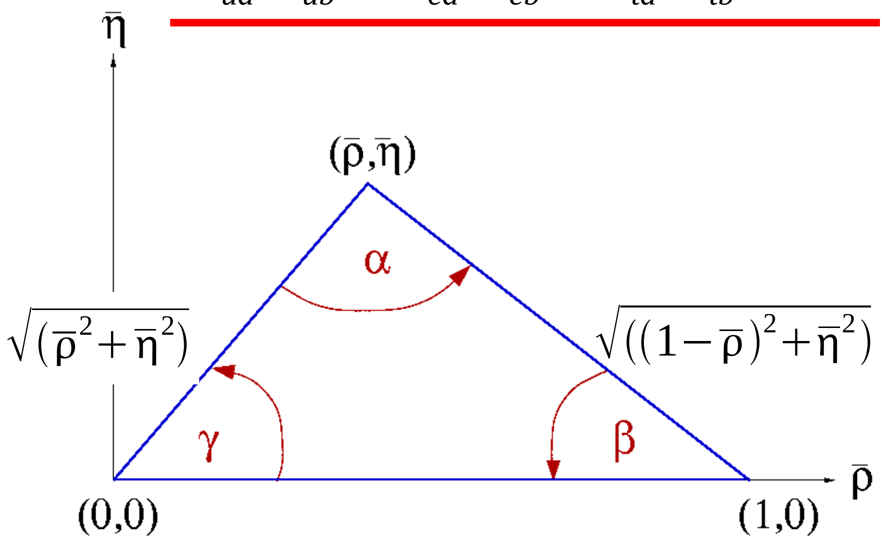
- The CKM matrix must be unitary

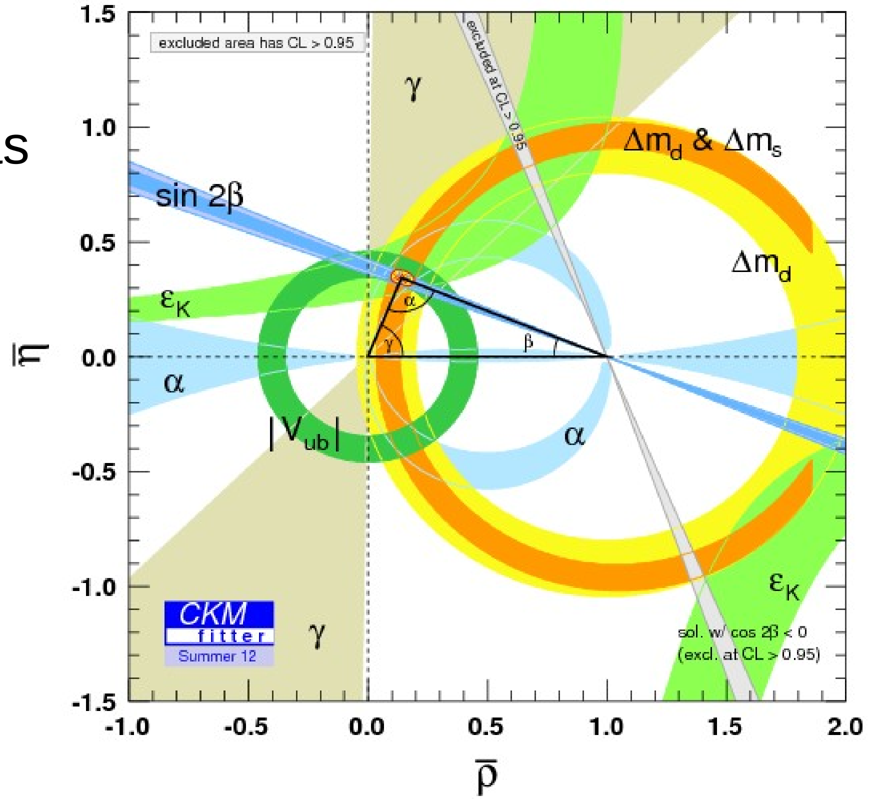
$$V_{CKM}^{+} V_{CKM} = V_{CKM} V_{CKM}^{+} = 1$$

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

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

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

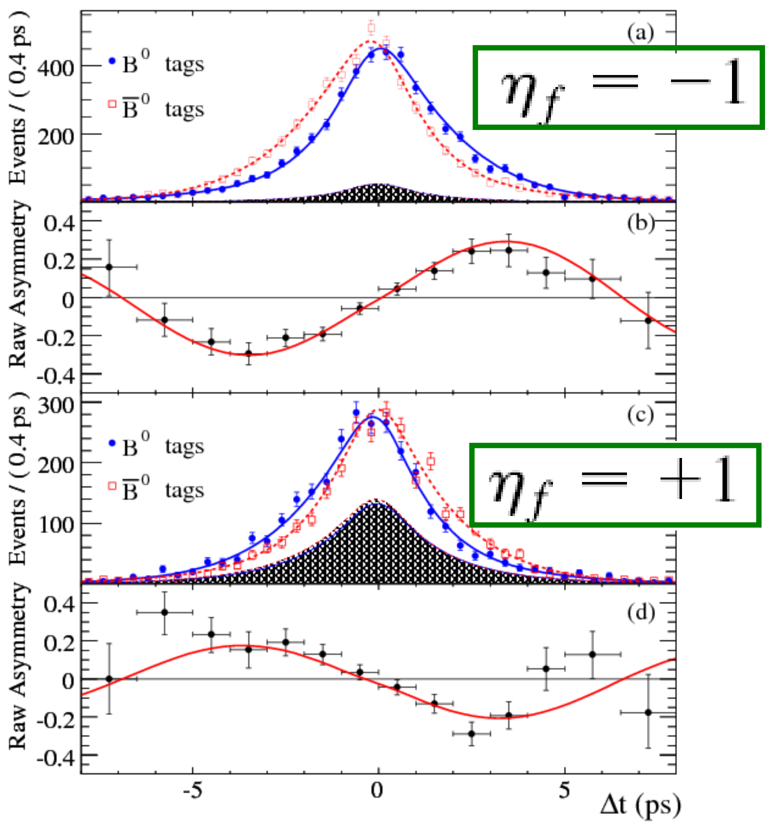




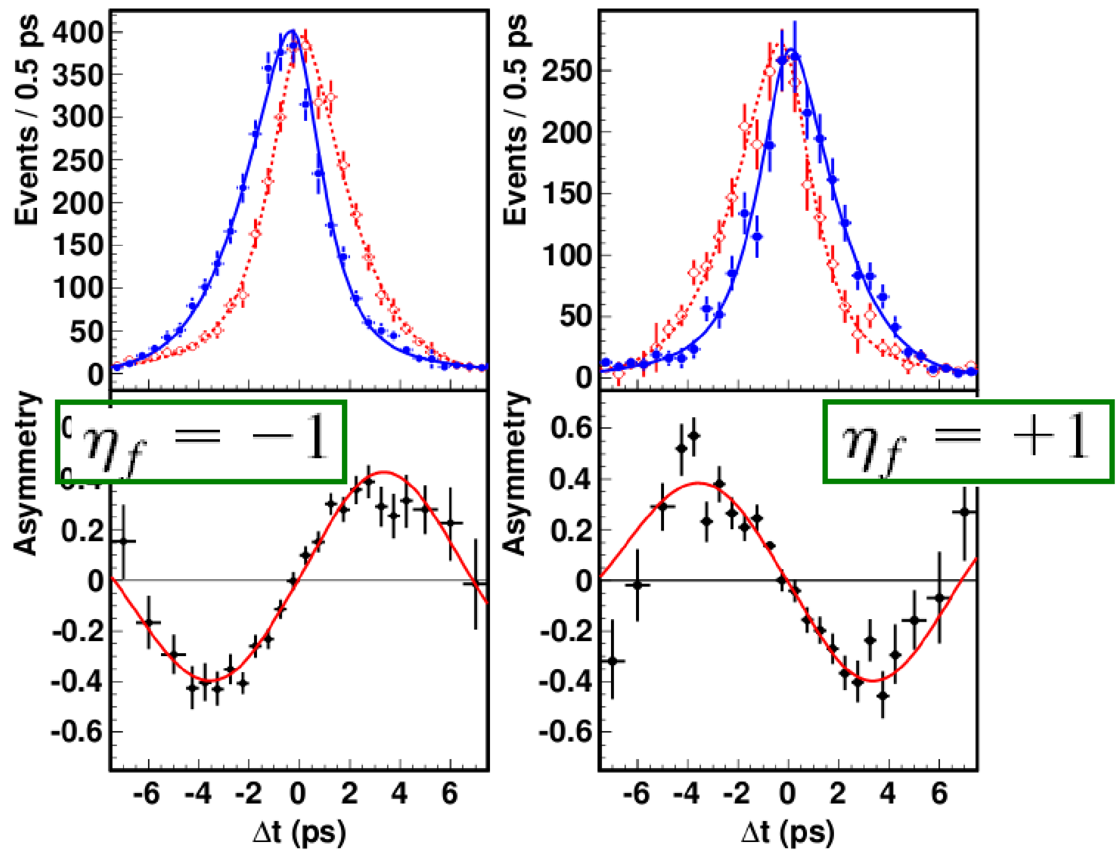
Consistency of measurements tests the Standard Model and provides model-independent constraints on New Physics

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

BABAR **BELLE**



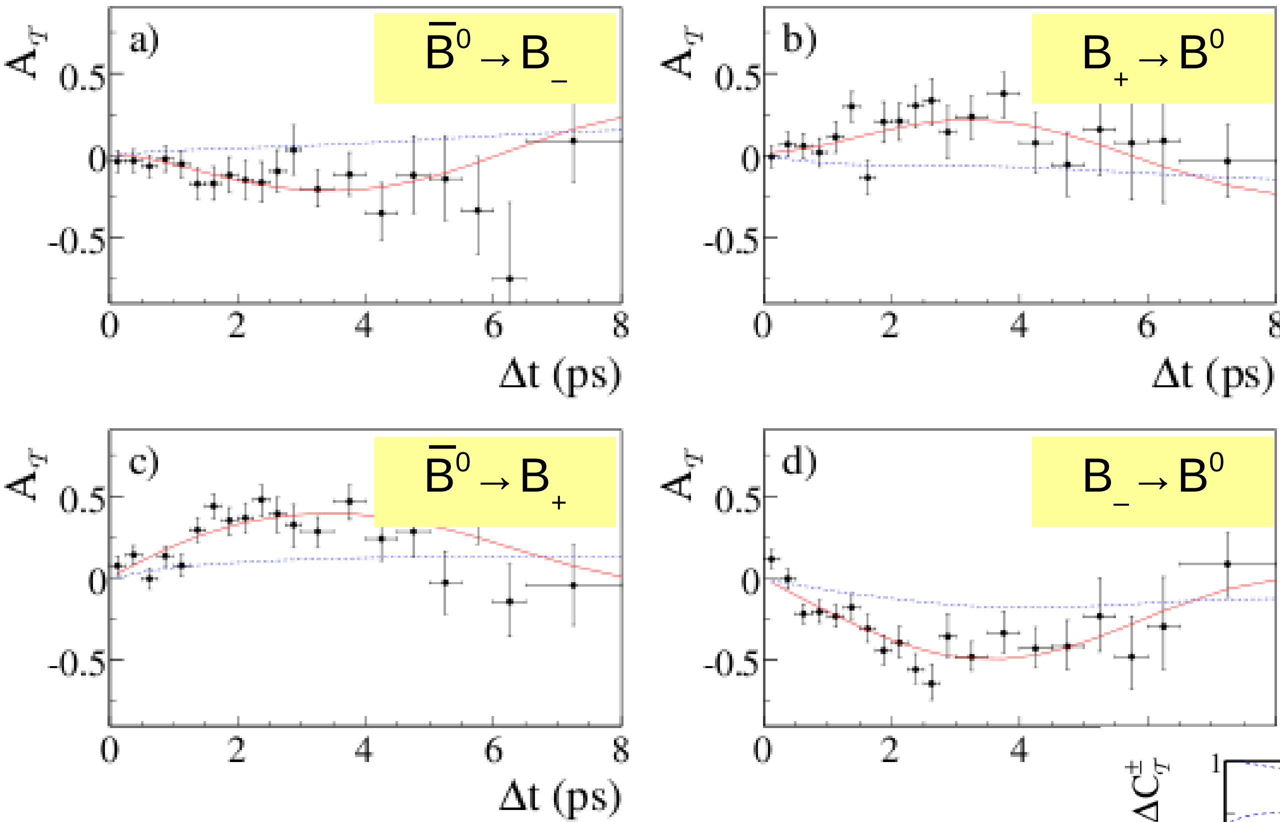
PRD 79 (2009) 072009



PRL 108 (2012) 171802

World average: $\sin(2\beta) = 0.679 \pm 0.020$

… and T is also violated, as expected

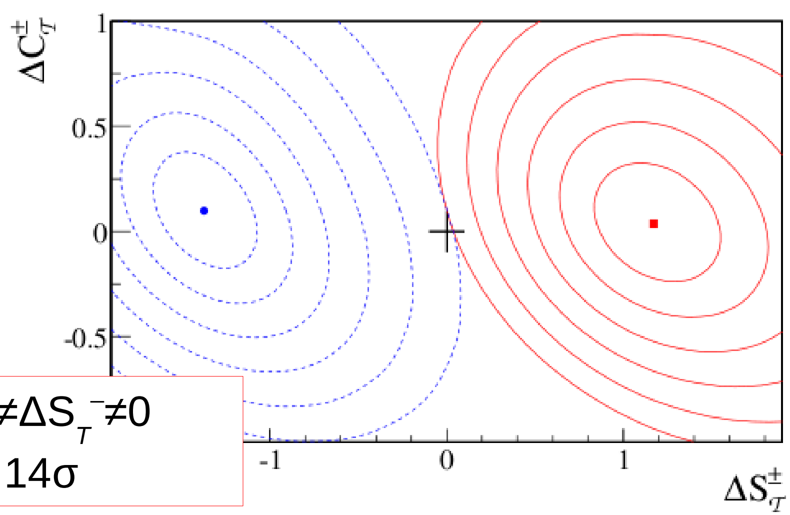


BaBar
PRL 109 (2012) 211801

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, $J/\psi K_L$, $\Delta t<0$)
$\sim ½(\Delta S_T^+ \sin(\Delta m_d \Delta t) + \Delta C_T^+ \cos(\Delta m_d \Delta t))$

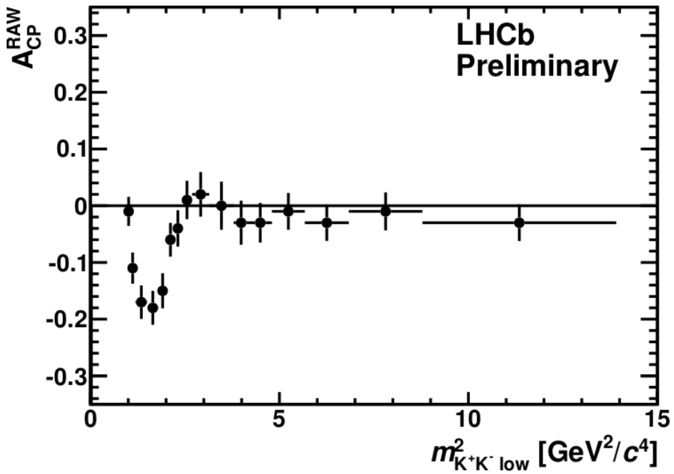


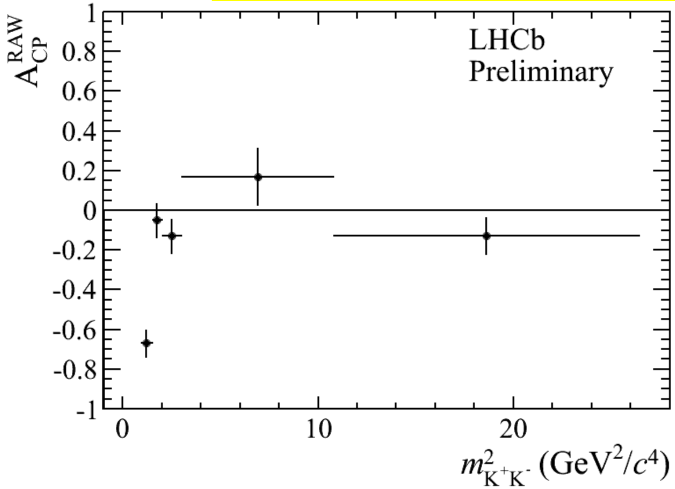
Contours show $\Delta S_T^+ \neq \Delta S_T^- \neq 0$
→ T violation at 14σ

Large *direct* CP violation effects also exist

LHCb-CONF-2012-018, -028

$B \to KKK$

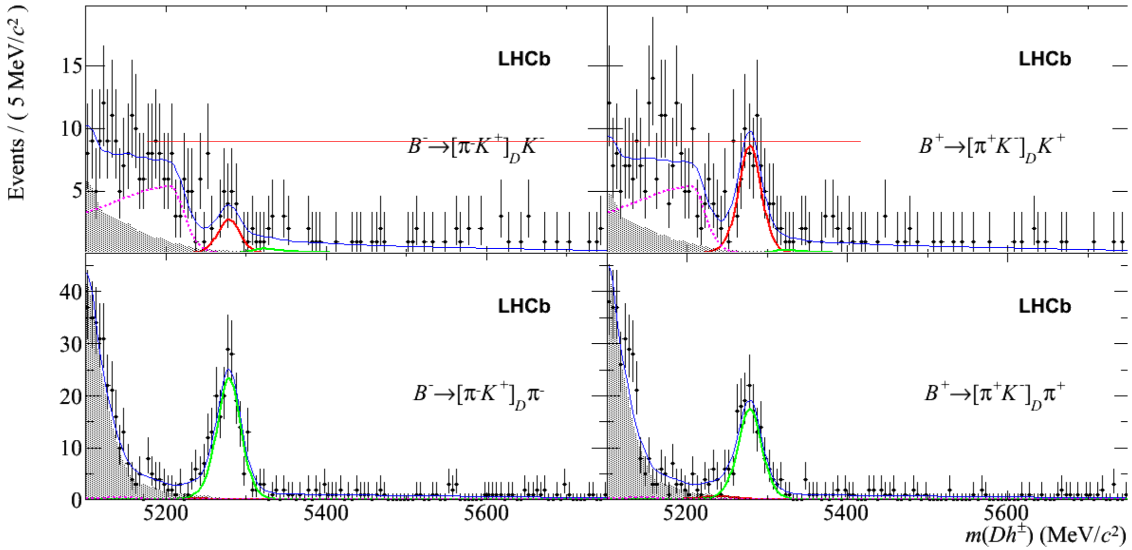




$B \to KK\pi$

Large CP violation effects with strong variation across the Dalitz plot
Detailed studies in progress to understand origin of these effects

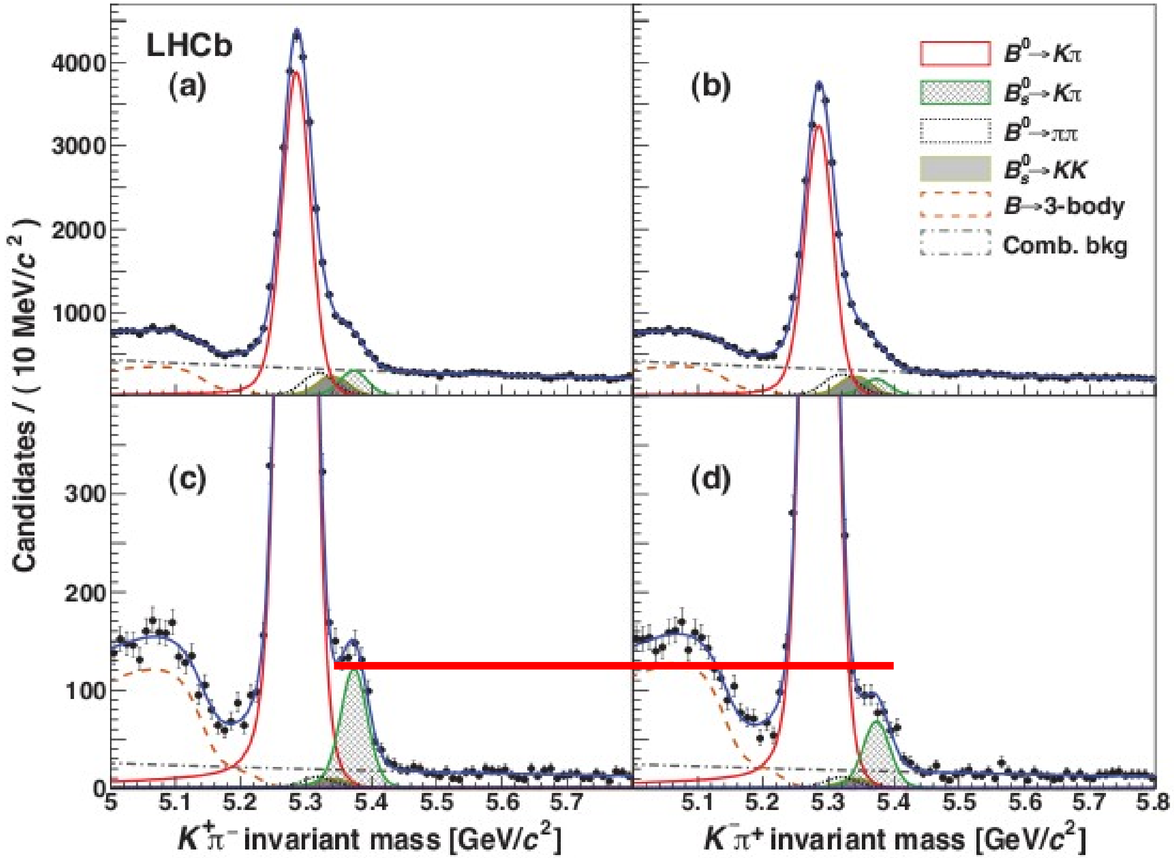
PLB 712 (2012) 203



$B \to D_{ADS}K$

… also in B_s^0 decays

LHCb arXiv:1304.6173



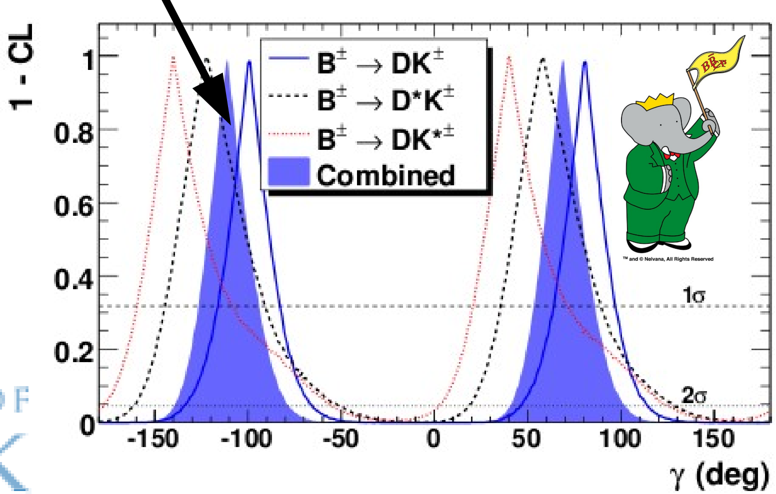
$$A_{CP}(B_s^0 \to K^-\pi^+) = 0.27 \pm 0.04\,(\text{stat}) \pm 0.01\,(\text{syst}).$$

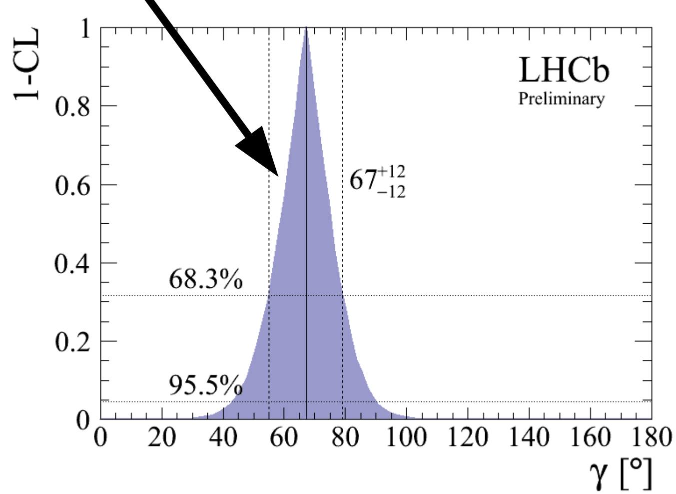
5σ observation of CP violation in $B_s \to K\pi$ decays

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

BaBar PRD 87 (2013) 052015
Belle CKM2012 preliminary
LHCb-PAPER-2013-020
& 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°



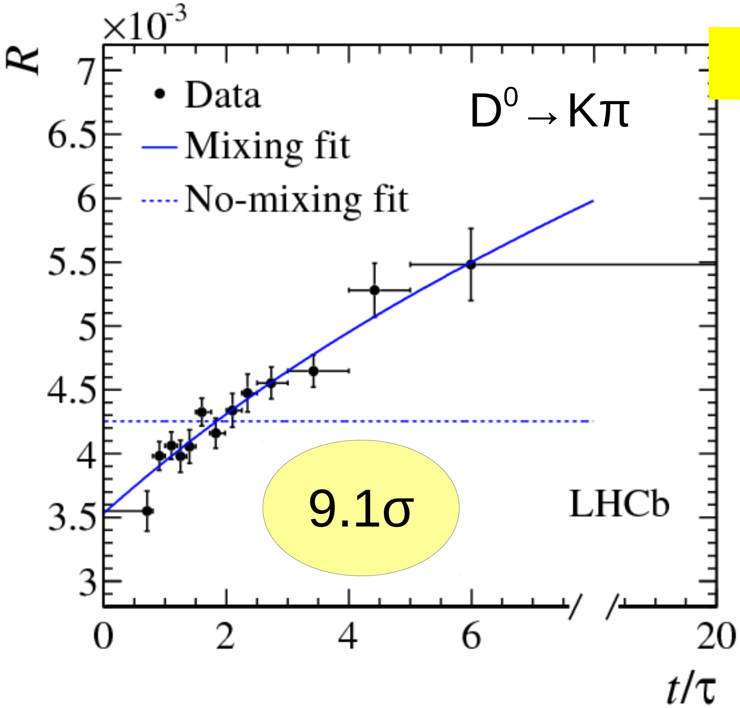


Neutral meson mixing –

oscillation phenomena over 4 orders in magnitude

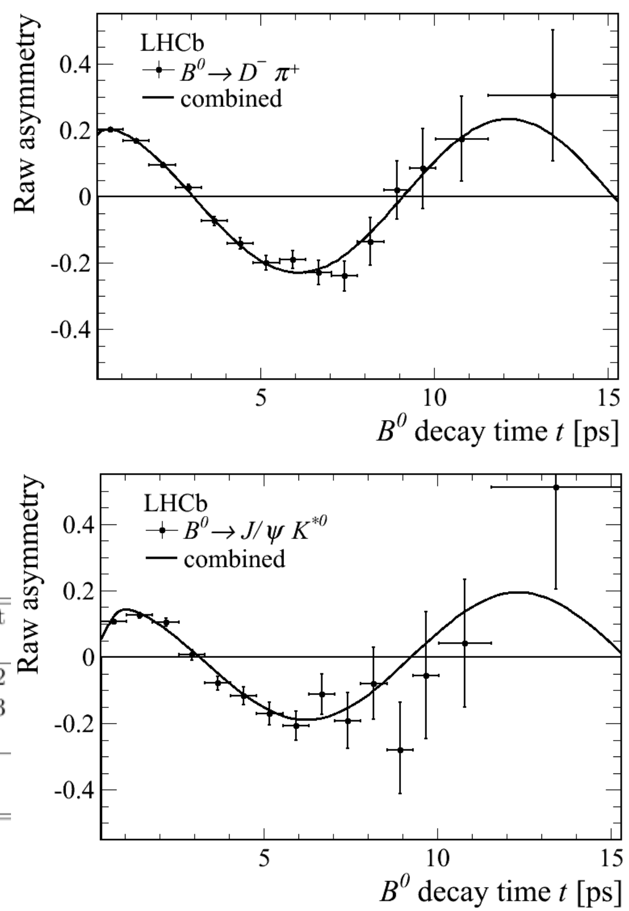
LHCb PRL 110 (2013) 101802

LHCb arXiv:1304.4741



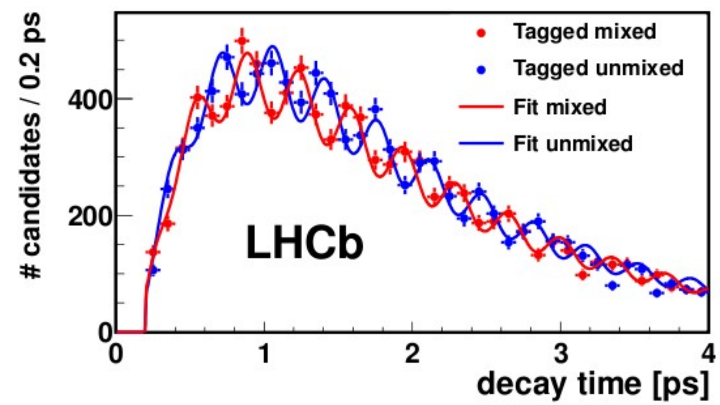
Fit type (χ^2/ndf)	Parameter	Fit result (10^{-3})	Correlation coefficient R_D	y'	x'^2
Mixing (9.5/10)	R_D	3.52 ± 0.15	1	-0.954	$+0.882$
	y'	7.2 ± 2.4		1	-0.973
	x'^2	-0.09 ± 0.13			1
No mixing (98.1/12)	R_D	4.25 ± 0.04			

LHCb PLB 719 (2013) 318



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

$B_s^0 \to D_s \pi$



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

Is there CP violation in B *mixing*?

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

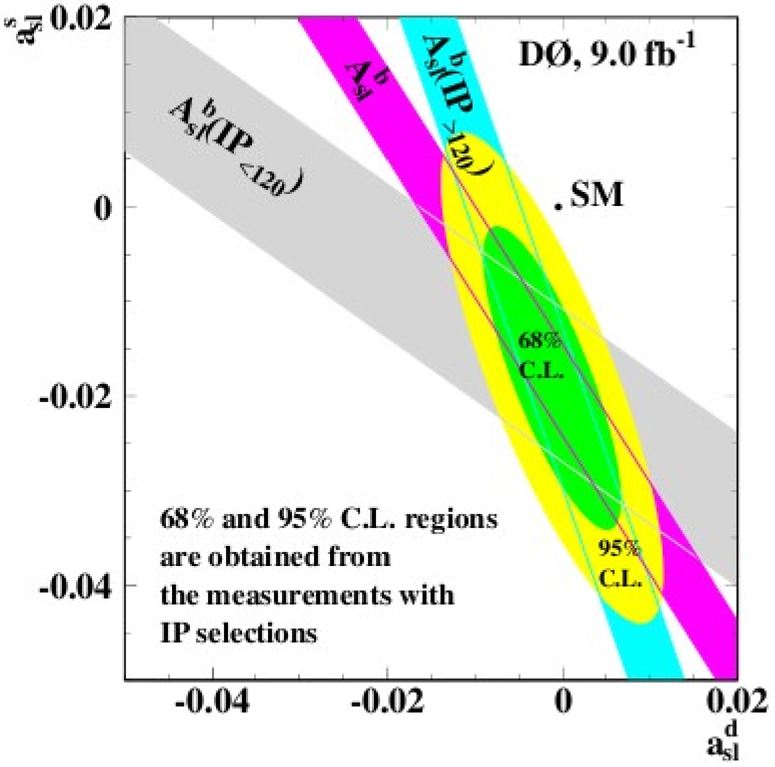
D0 PRD 84 (2011) 052007

Results of inclusive dimuon asymmetry analysis 3.9σ from SM

Systematics reduced by magnet polarity inversions, and from use of control samples, such as single muon sample

$$A_{sl}^{b} = (0.594 \pm 0.022)\, a_{sl}^{d} + (0.406 \pm 0.022)\, a_{sl}^{s}$$

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



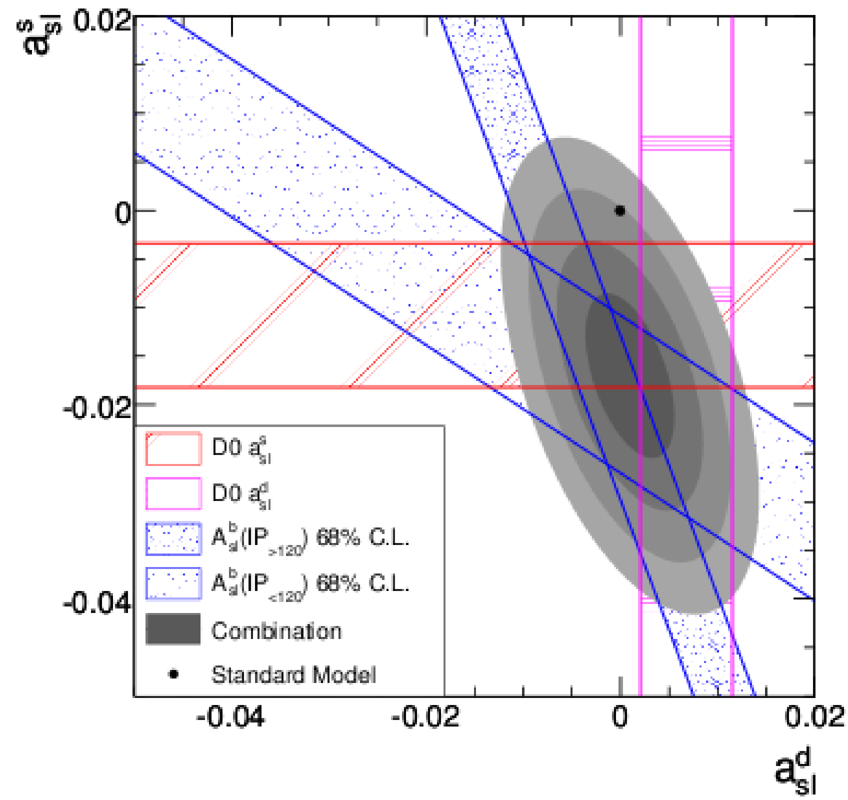
Is there CP violation in B *mixing*?

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

D0 PRD 84 (2011) 052007,
PRL 110 (2013) 011801,
PRD 86 (2012) 072009

Results of inclusive dimuon asymmetry analysis 3.9σ from SM

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 2.9σ from SM



Is there CP violation in B *mixing*?

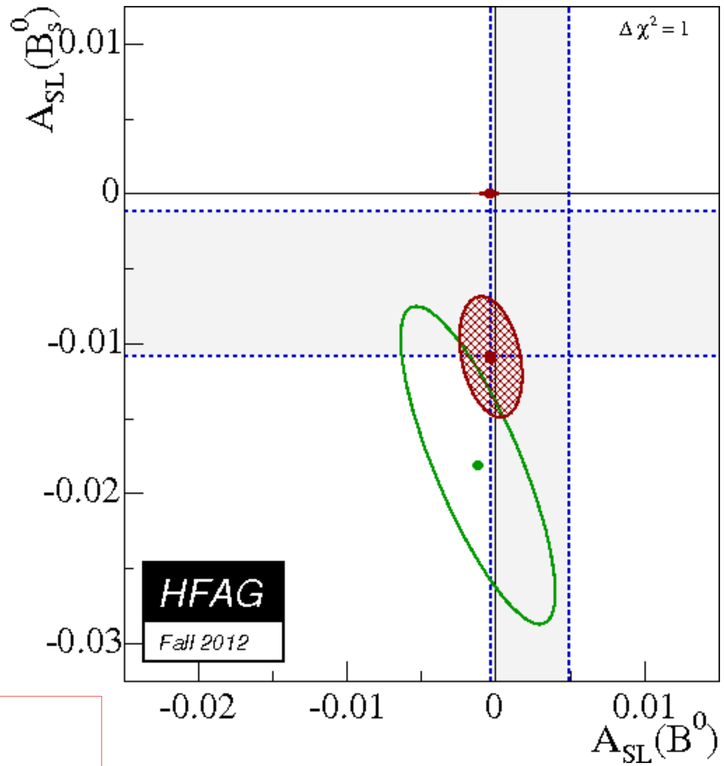
Semileptonic asymmetries in both B_d and B_s systems negligibly small in the SM

D0 PRD 84 (2011) 052007,
PRL 110 (2013) 011801,
PRD 86 (2012) 072009
LHCb-CONF-2012-022
BaBar CKM2012 preliminary

Results of inclusive dimuon asymmetry analysis 3.9σ from SM

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 2.9σ from SM

Including B factory a_{sl}^{d} and LHCb a_{sl}^{s} results give average 2.4σ from the SM



Warning: scale changed from previous slide

Situation unclear – improved measurements needed

Must prepare for
‰ level measurements

Improved measurements of B_s oscillations and CP violation

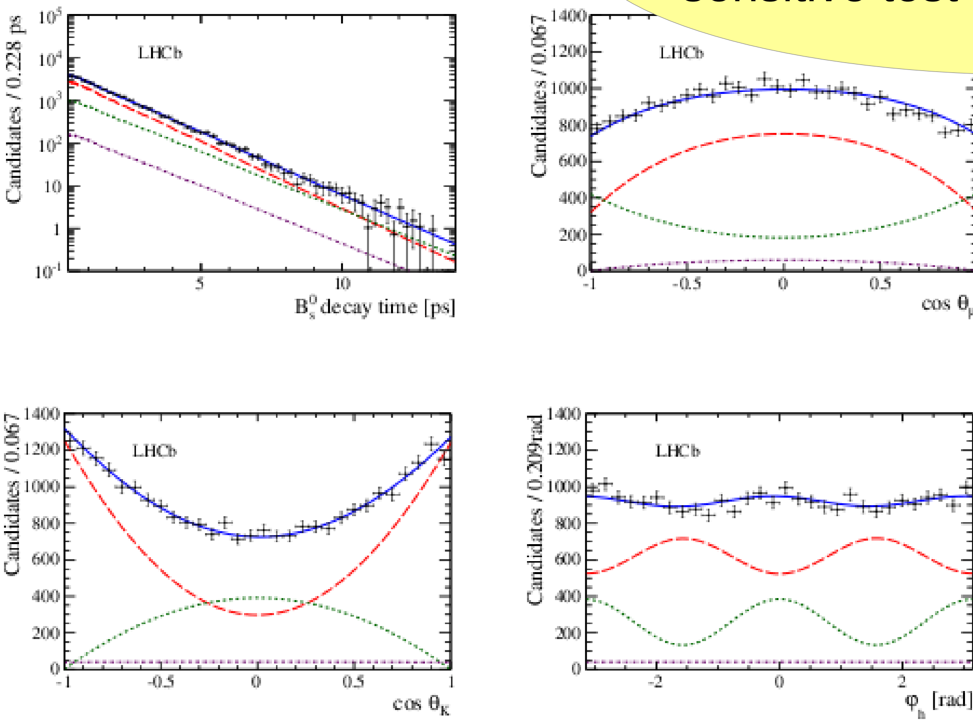
LHCb arXiv:1304.2600

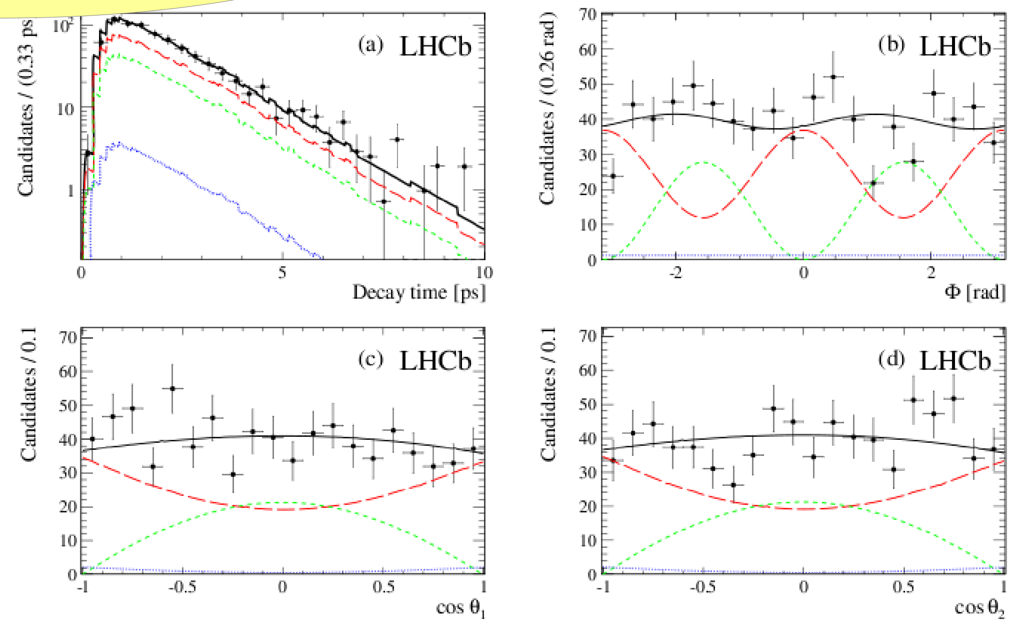
$B_s \to J/\psi KK$ (& $J/\psi\pi\pi$)

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

LHCb arXiv:1303.7125

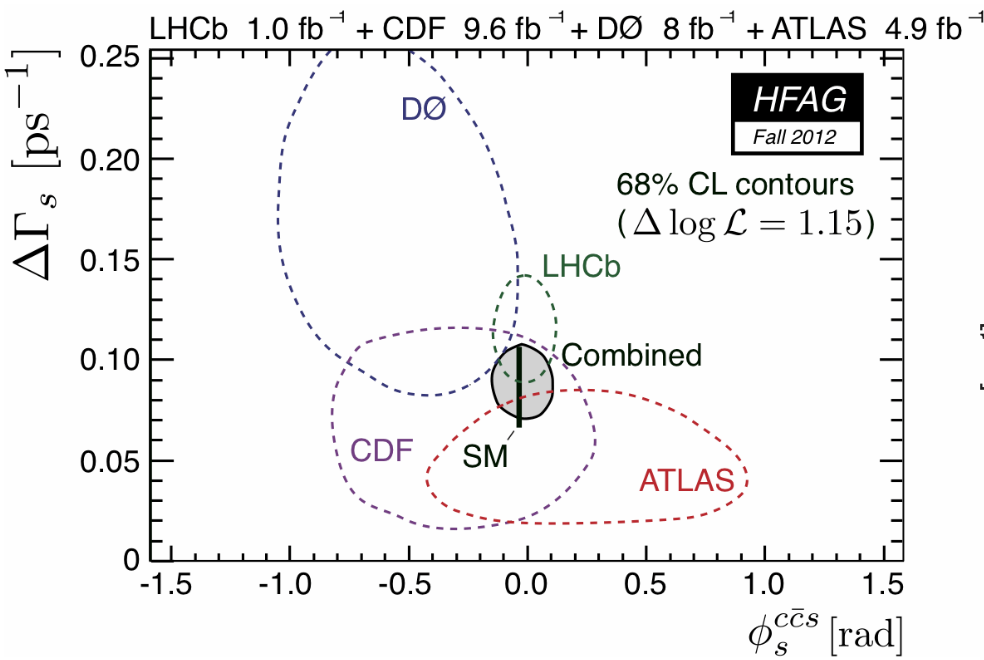
$B_s \to \phi\phi$



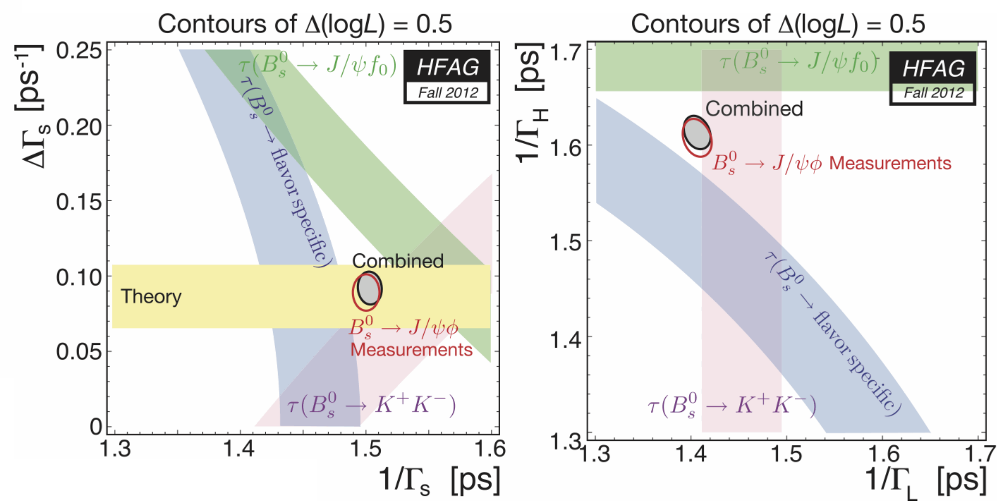


$$\phi_s = 0.01 \pm 0.07 \text{ (stat)} \pm 0.01 \text{ (syst) rad},$$
$$\Gamma_s = 0.661 \pm 0.004 \text{ (stat)} \pm 0.006 \text{ (syst) ps}^{-1},$$
$$\Delta\Gamma_s = 0.106 \pm 0.011 \text{ (stat)} \pm 0.007 \text{ (syst) ps}^{-1}.$$

Improved measurements of B_s lifetimes and CP violation

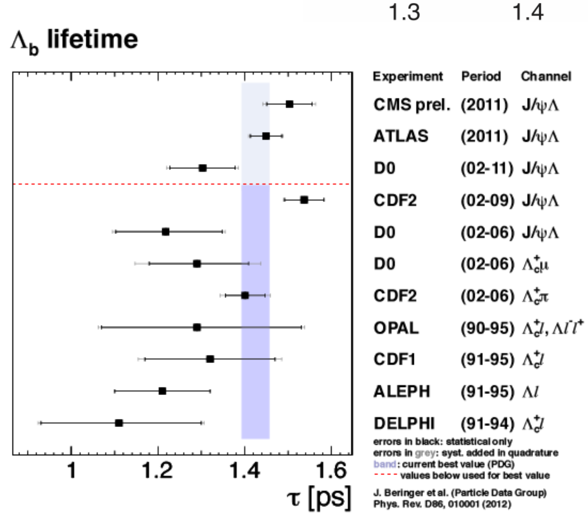


LHCb arXiv:1304.2600
CDF PRD 85 (2012) 072002
D0 PRD 85 (2012) 032006
ATLAS JHEP 12 (2012) 072 &
ATLAS-CONF-2013-039



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

D0 PRD 85 (2012) 112003
ATLAS PRD 87 (2013) 032002
CMS arXiv:1304.7495



… tensions with expectations reduced

Tim Gershon
Flavour Physics circa 2013

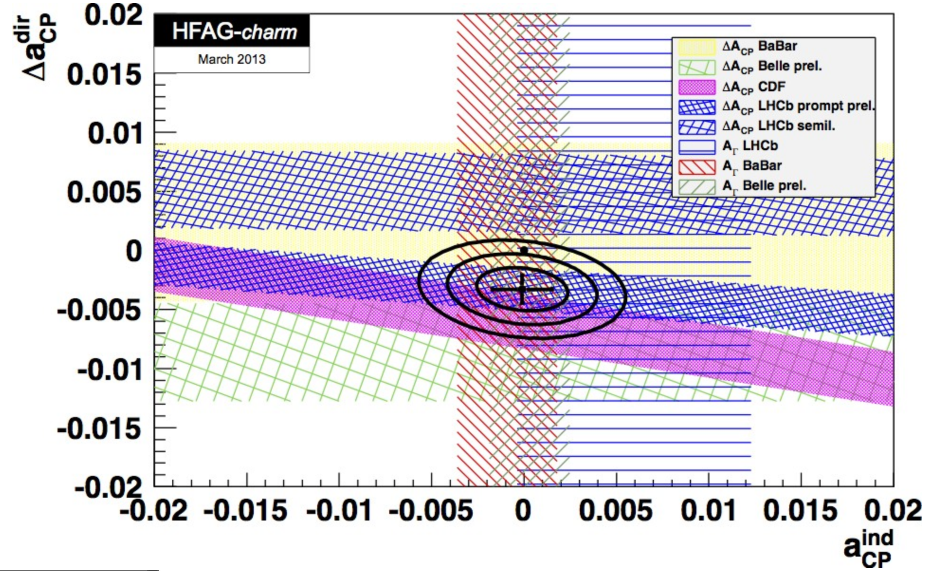
Is there CP violation in the charm system?

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

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

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

LHCb arXiv:1303.2614, LHCb-CONF-2013-003
CDF PRL 109 (2012) 111801
Belle ICHEP preliminary

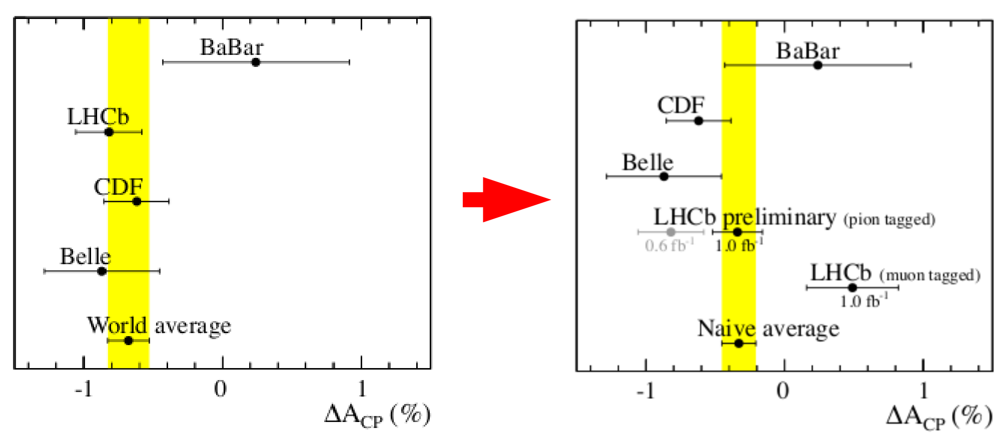


ΔA_{CP} related mainly to direct CP violation

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

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

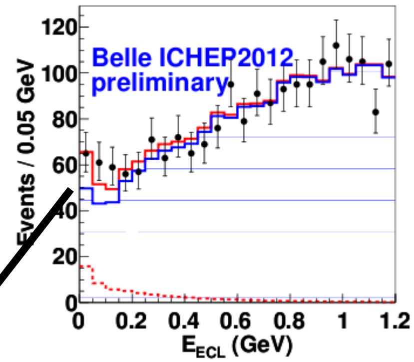
Previous evidence for CPV not confirmed
Need more precise measurements



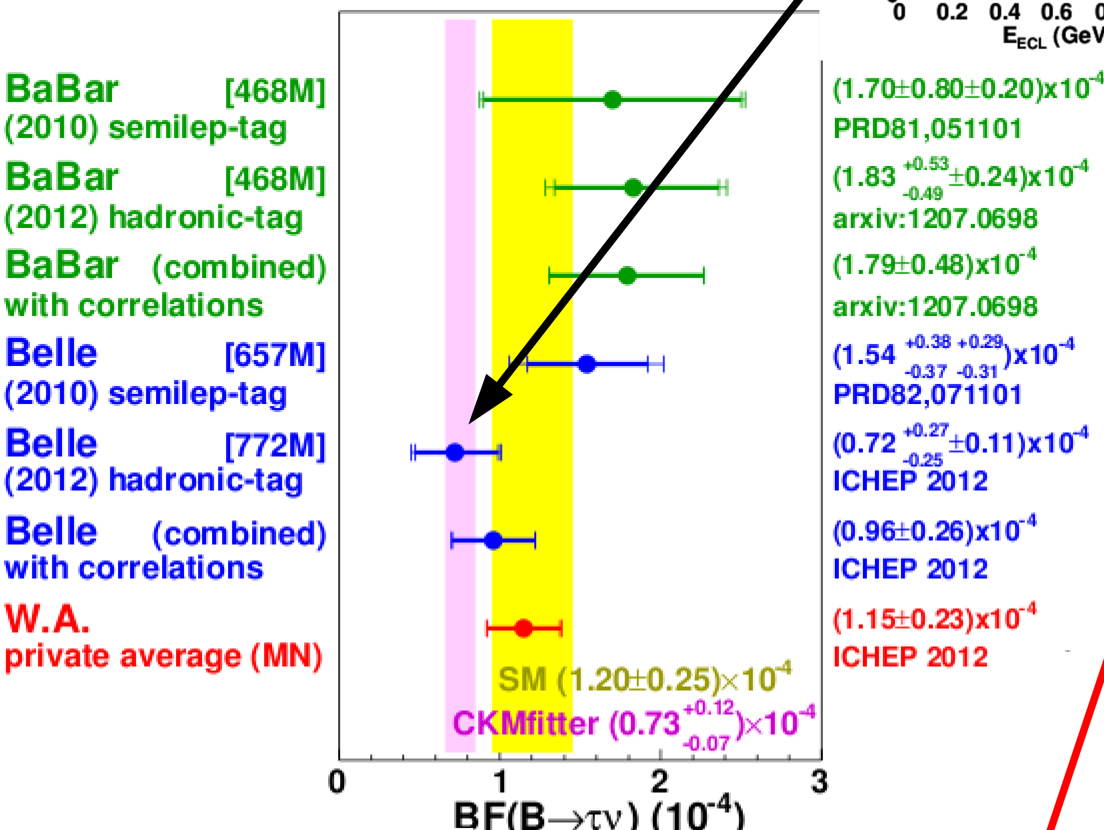
All shifts consistent with being statistical in origin

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

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



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



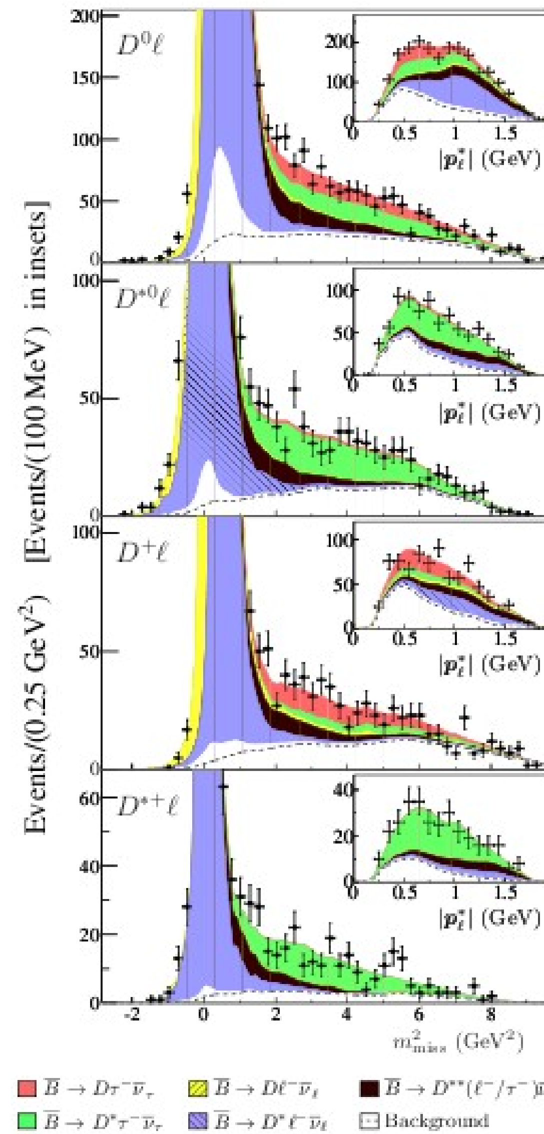
2.3σ

3.8σ

3.6σ

3.0σ

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



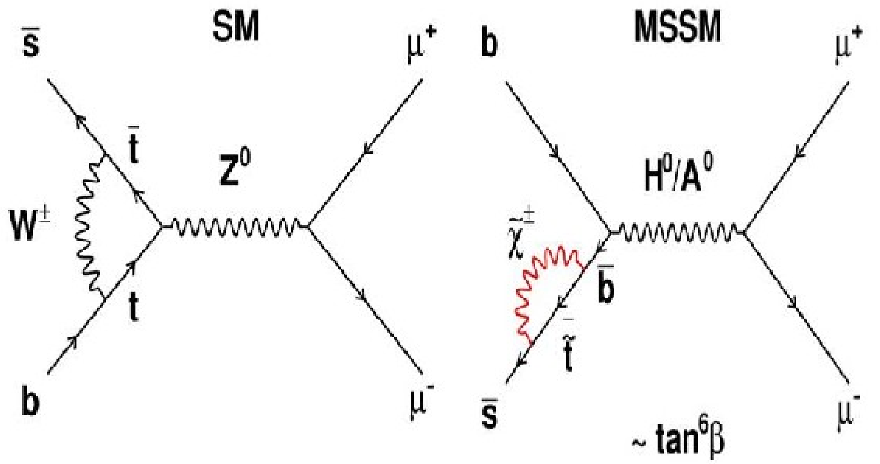
BaBar rates 3.4σ above the SM, and inconsistent with 2HDM

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

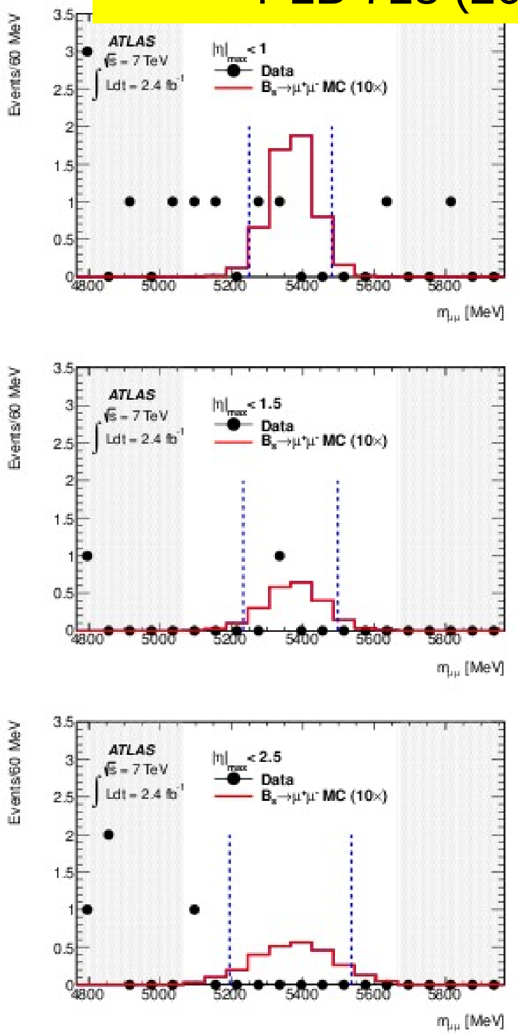


$\mathcal{B}(B_s \to \mu^+\mu^-)^{SM} = (3.2 \pm 0.3) \times 10^{-9}$ $\mathcal{B}(B_s \to \mu^+\mu^-)^{MSSM} \sim \tan^6\beta / M^4_{A0}$

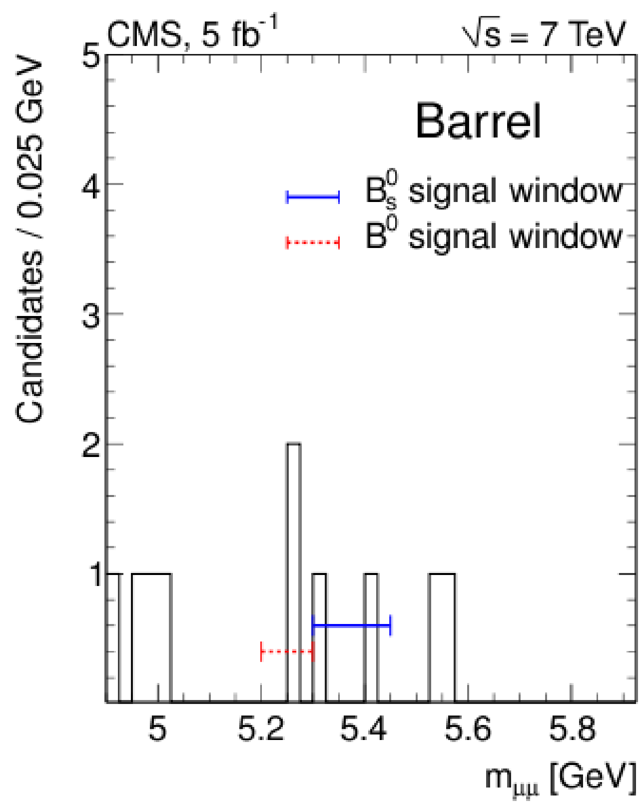
Buras et al, EPJ C72 (2012) 2172
N.B. Should be corrected up by 9% since measurement is of the time-integrated branching fraction (PRL 109 (2012) 041801)

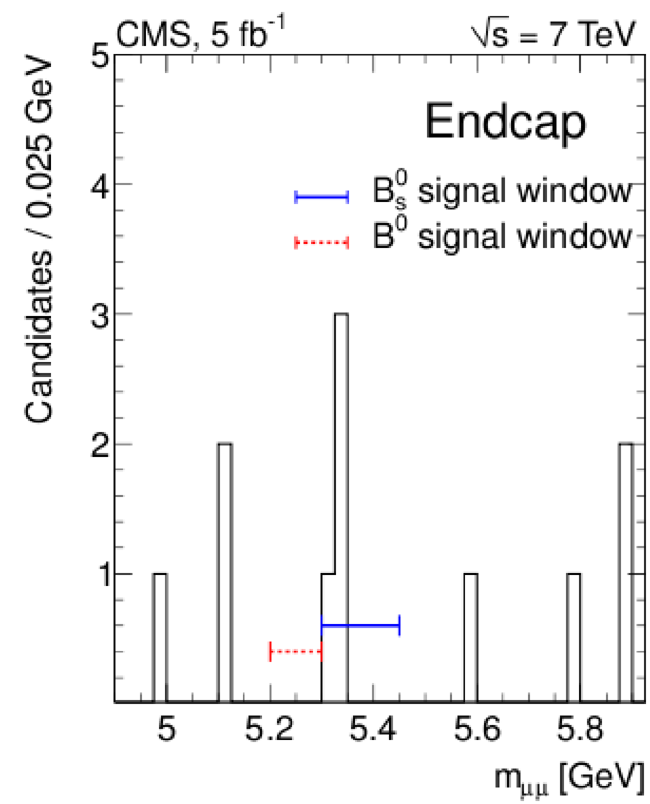
Latest results on $B_s \to \mu^+\mu^-$

ATLAS (2.4/fb)
PLB 713 (2012) 387



CMS (5/fb)
JHEP 04 (2012) 033



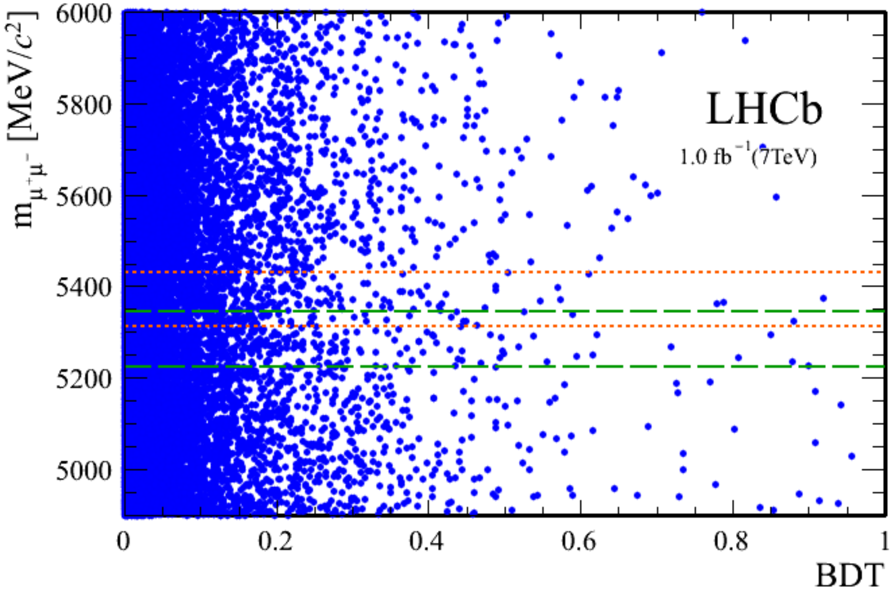


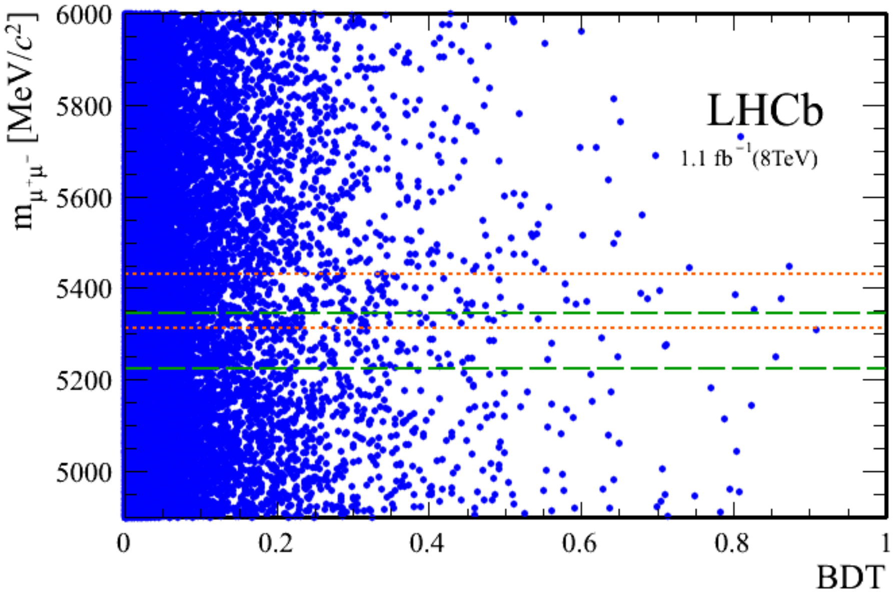
ATLAS $B(B_s \to \mu^+\mu^-) < 2.2\ (1.9) \times 10^{-8}$ @ 95% (90%) CL

CMS $B(B_s \to \mu^+\mu^-) < 7.7\ (6.4) \times 10^{-9}$ @ 95% (90%) CL

See also CDF arXiv:1301.7048
& D0 arXiv:1301.4507

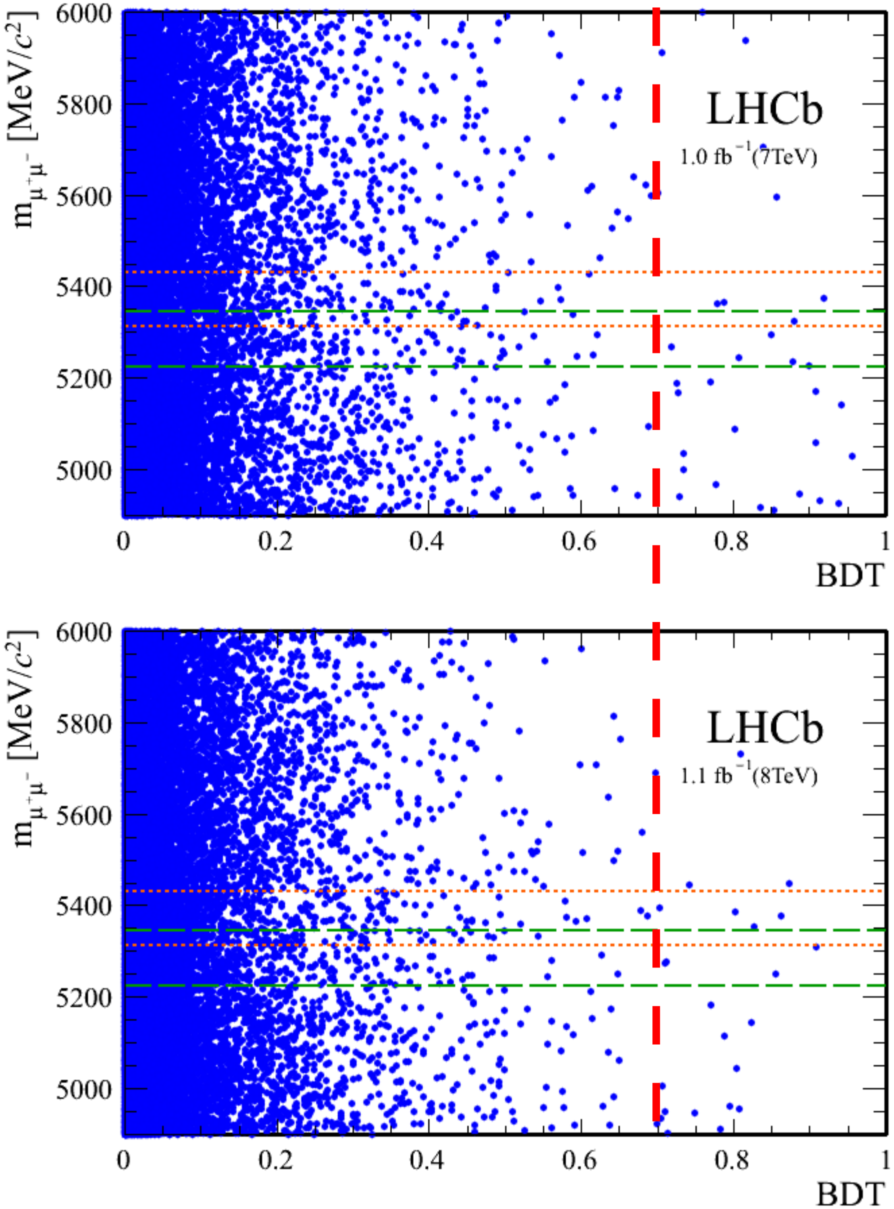
Latest results on $B_s \to \mu^+\mu^-$



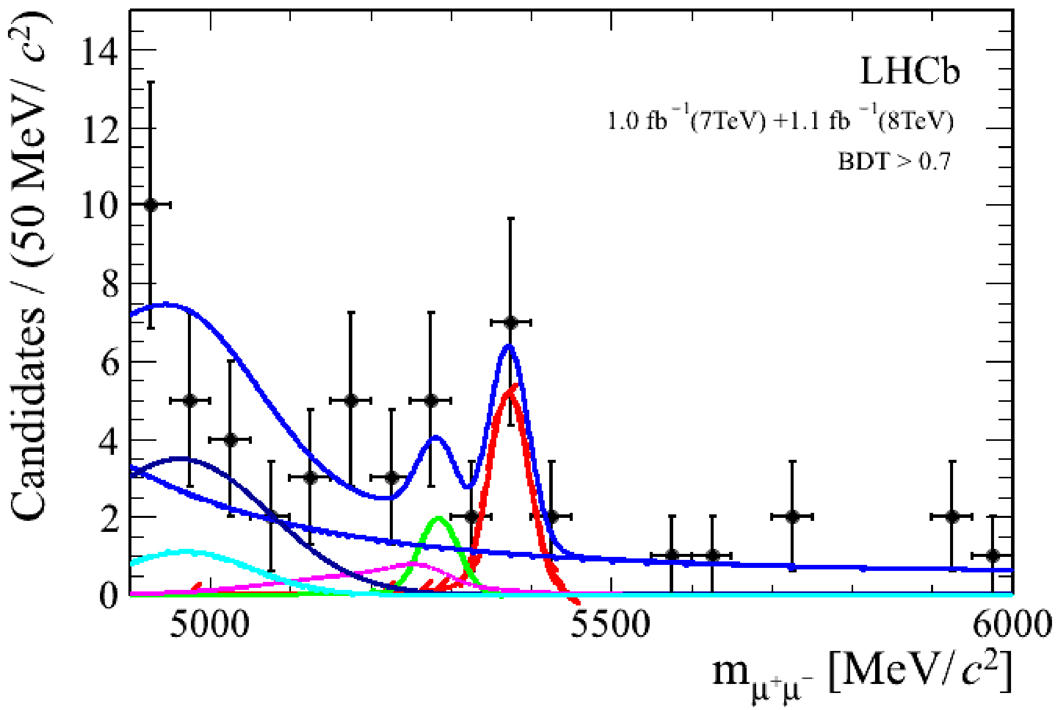


LHCb (2/fb)
PRL 110 (2013) 021801

Latest results on $B_s \to \mu^+\mu^-$



LHCb (2/fb)
PRL 110 (2013) 021801

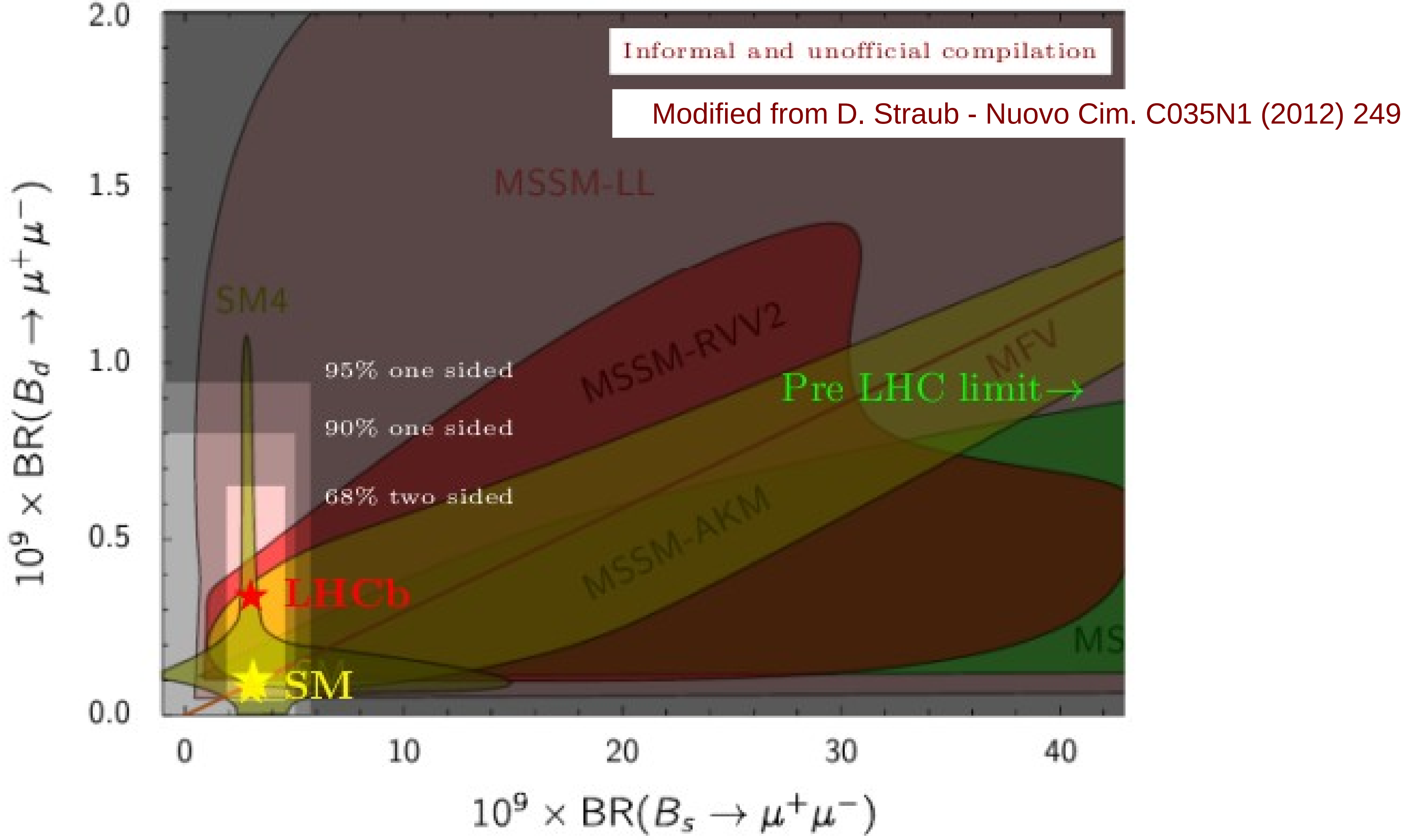


$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.2\,^{+1.4}_{-1.2}(\text{stat})\,^{+0.5}_{-0.3}(\text{syst})) \times 10^{-9}$$

3.5σ

Updates from ATLAS, CMS & LHCb keenly anticipated

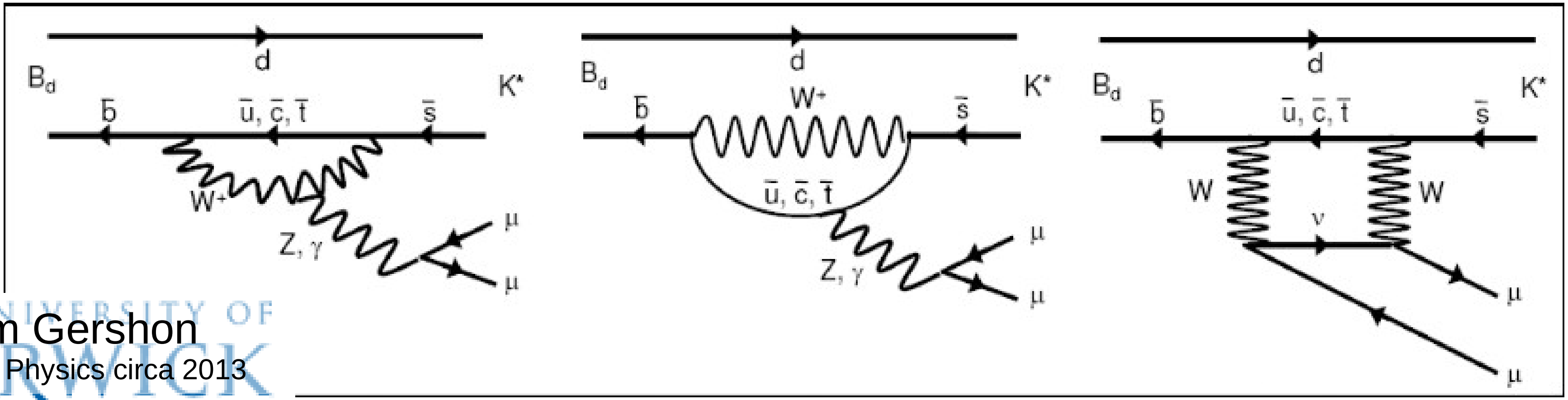
Impact of $B_s \to \mu^+\mu^-$



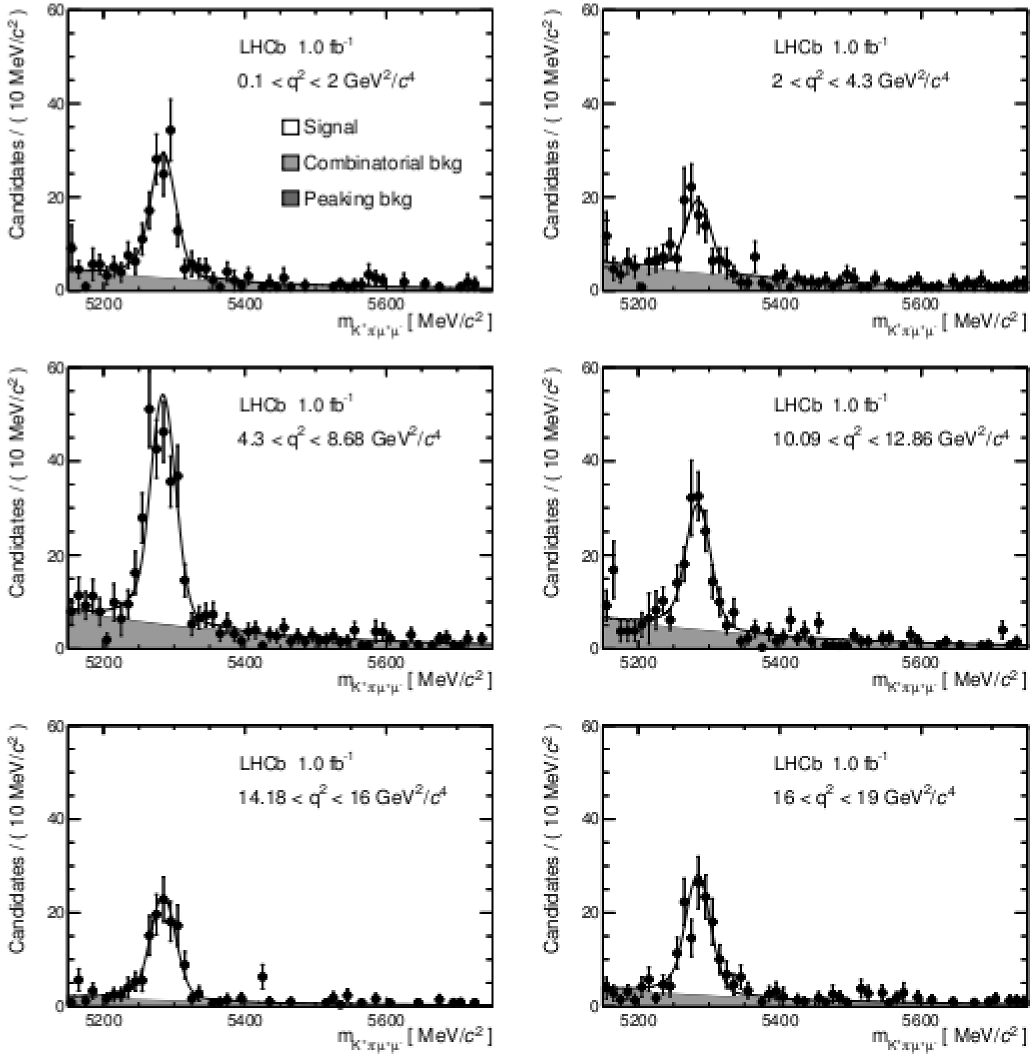
Updates from ATLAS, CMS & LHCb keenly anticipated

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

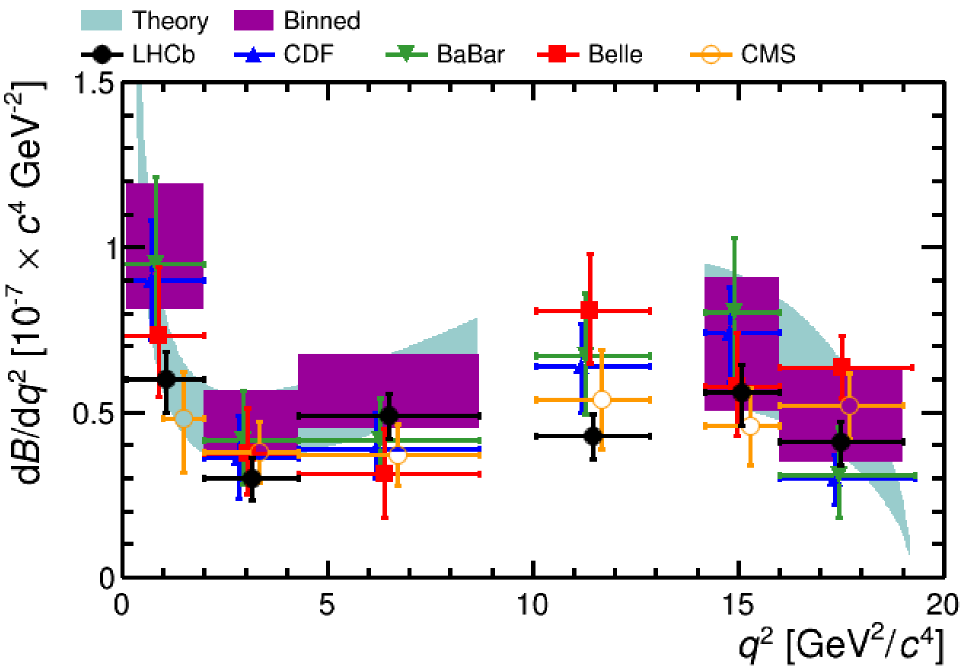
- $B_d \to K^{*0}\mu^+\mu^-$ provides complementary approach to search for new physics in $b \to sl^+l^-$ FCNC processes
  - rates, angular distributions and asymmetries sensitive to NP
  - superb laboratory for NP tests
  - experimentally clean signature
  - many kinematic variables …
  - … with clean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



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



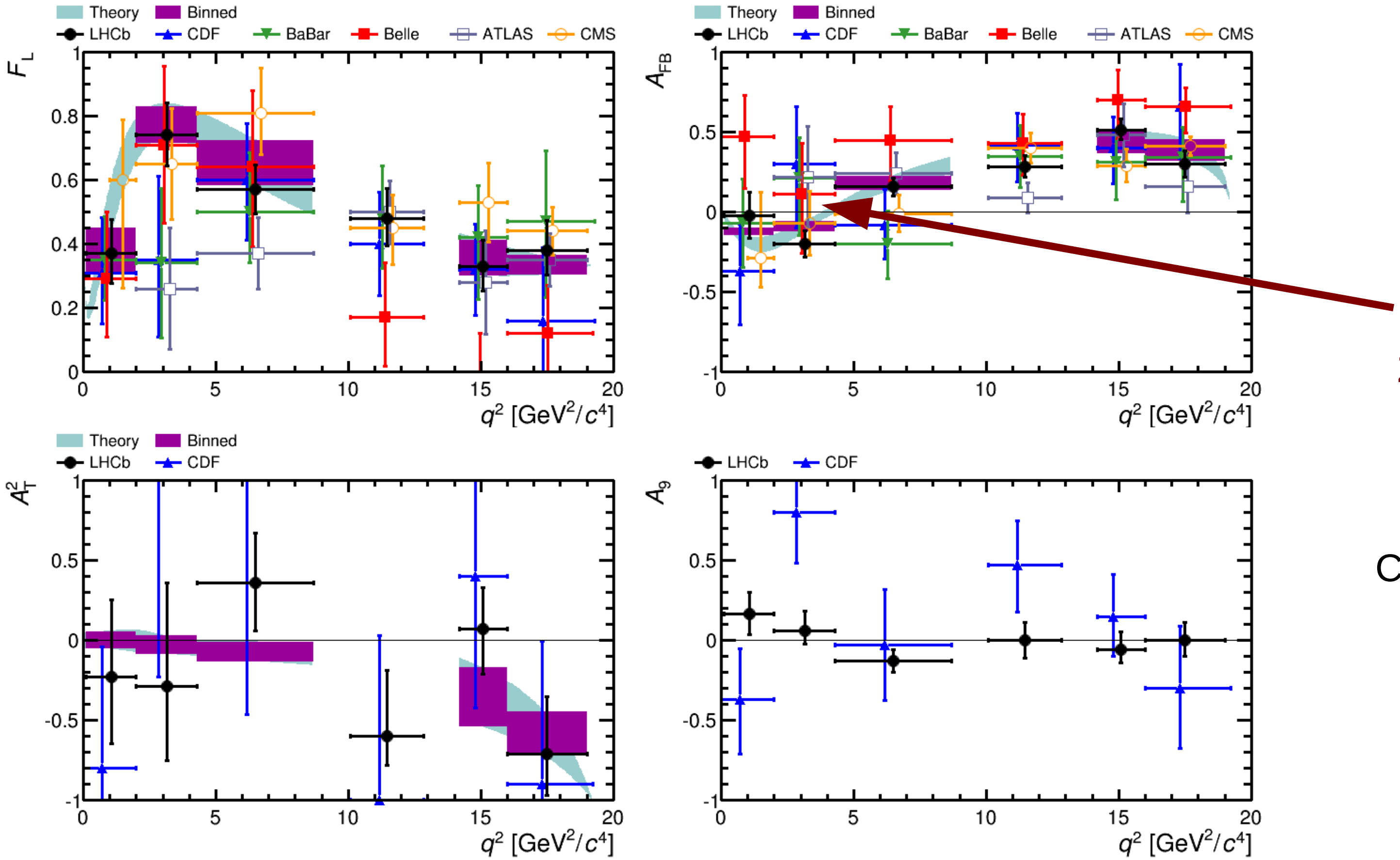
LHCb arXiv:1304.6325
See also CDF PRL 108 (2012) 081807
BaBar PRD 86 (2012) 032012
ATLAS-CONF-2013-038 & CMS BPH-11-009



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

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

LHCb arXiv:1304.6325
See also CDF PRL 108 (2012) 081807
BaBar PRD 86 (2012) 032012
ATLAS-CONF-2013-038 & CMS BPH-11-009



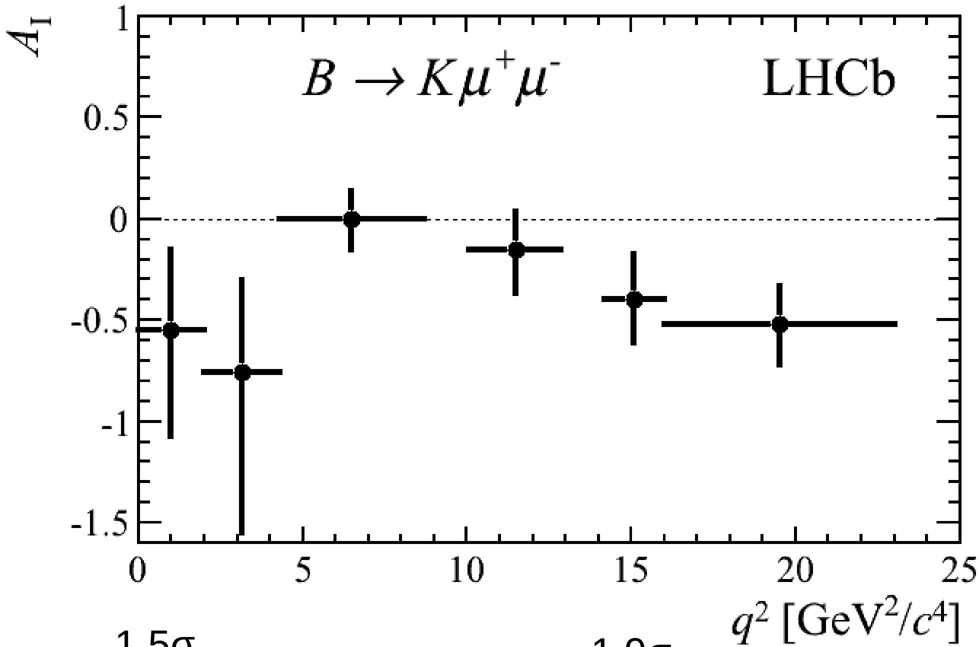
First measurement of zero-crossing point of A_{FB}

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

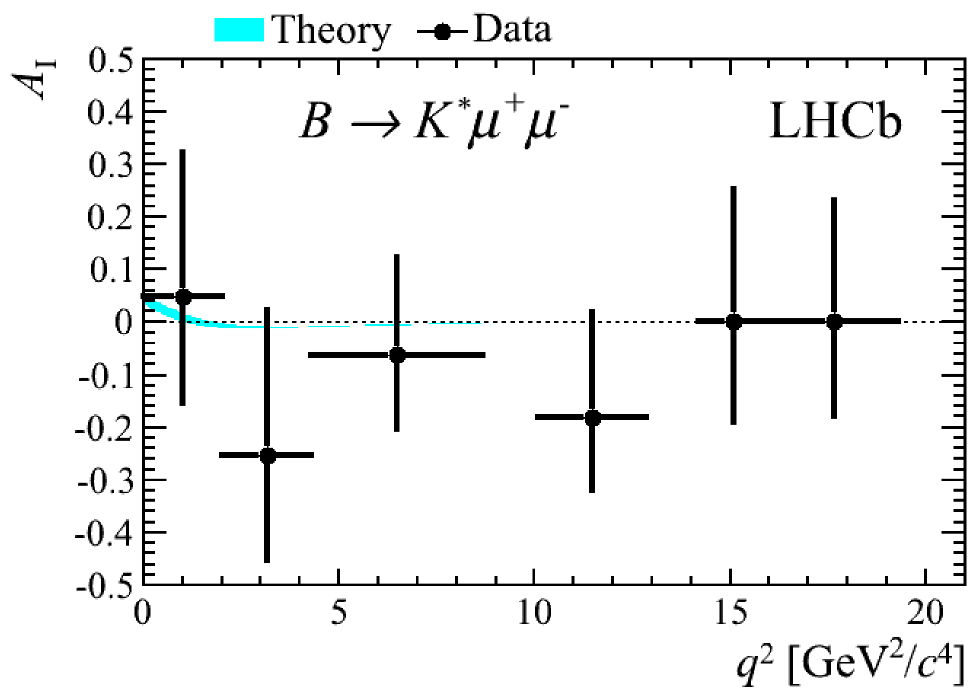
Consistent with SM expectation

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

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)

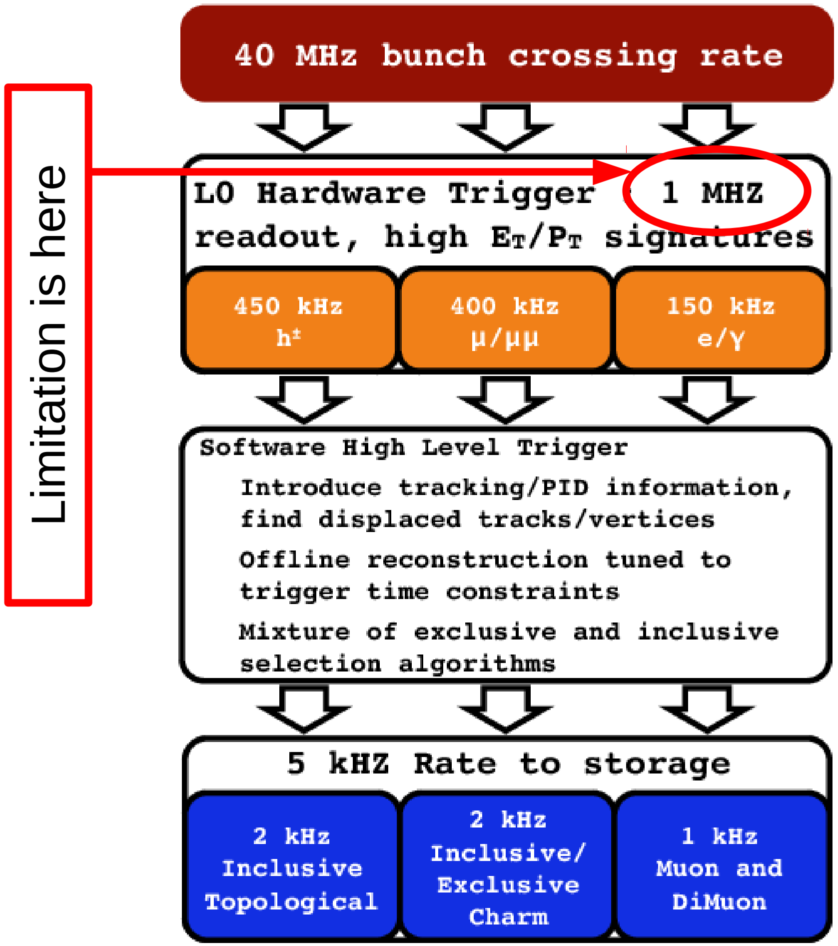
Food for thought ...

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

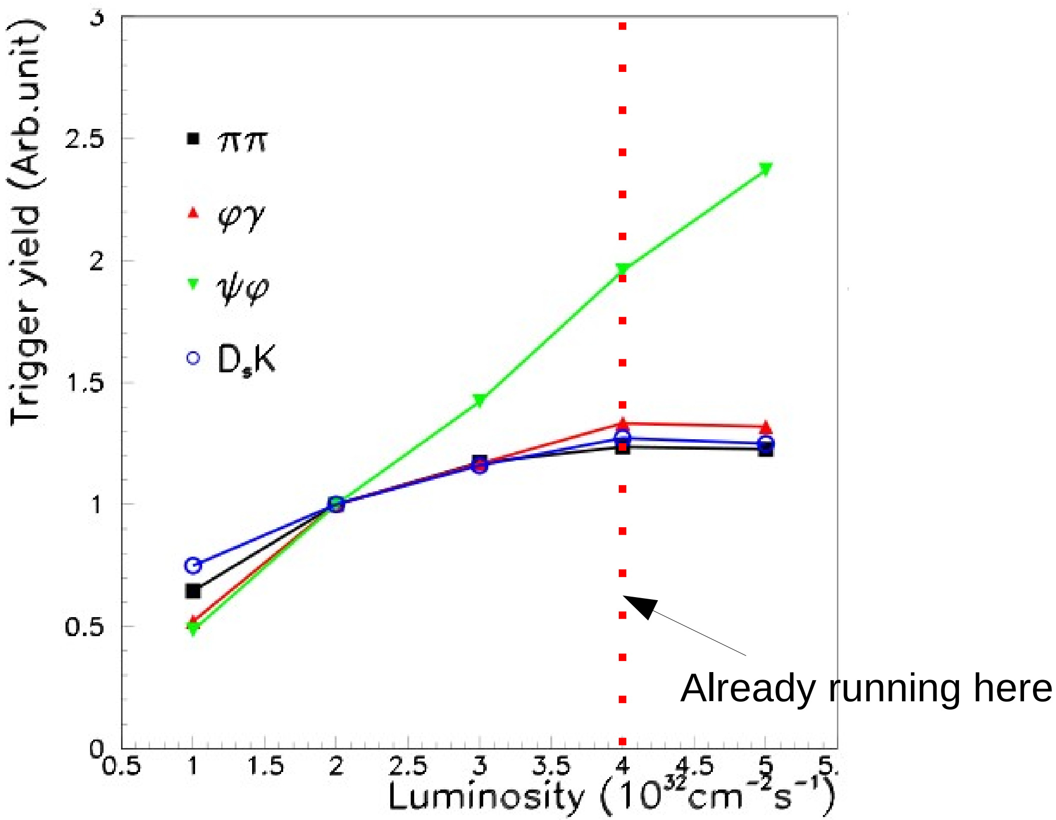
LHC upgrade and the all important trigger



higher luminosity

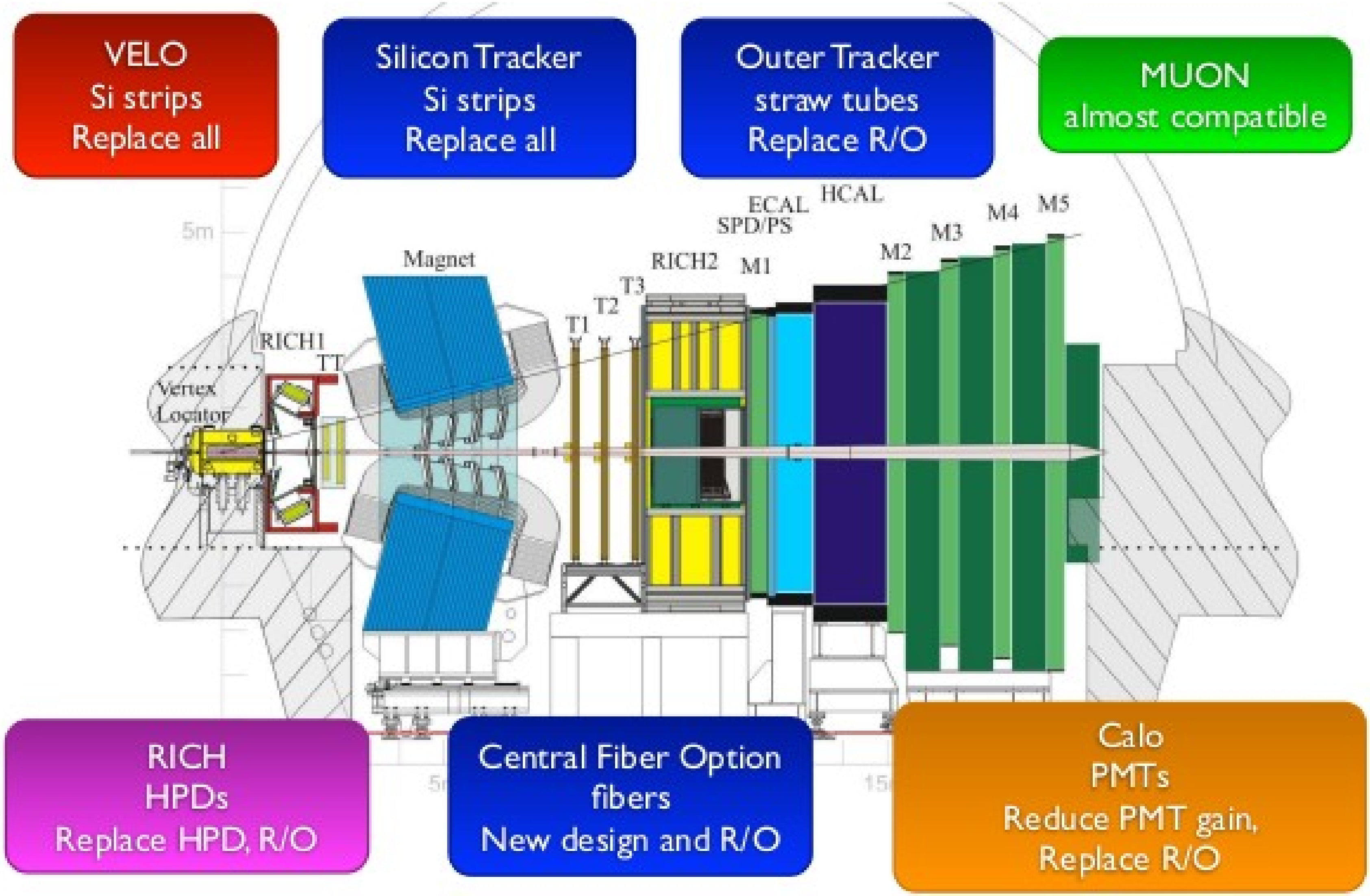
→ need to cut harder at L0 to keep rate at 1 MHz

→ 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



Several options still under study (e.g. strips/pixels for VELO)
Decisions to be made soon with TDRs available ~end 2013

LHCb upgrade timeline

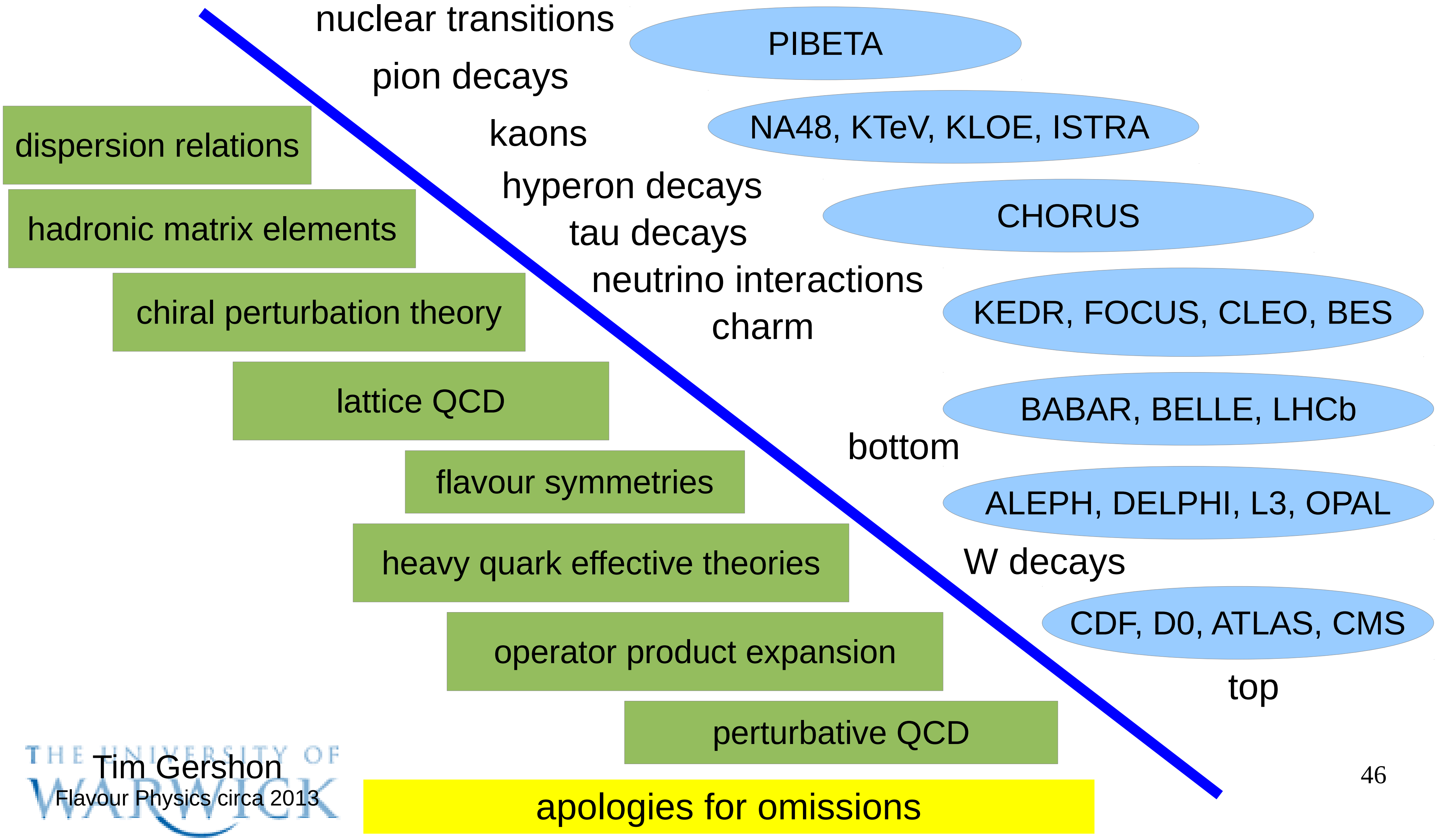
- 2011
  - Letter of Intent: CERN-LHCC-2011-001
- 2012
  - Framework TDR: CERN-LHCC-2012-007
    - Endorsed by LHCC and approved by CERN Research Board (minutes)
    - LHCb upgrade features prominently in draft European Strategy for Particle Physics
  - See also arXiv:1208.3355 for physics discussion
- 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)

Summary

- Huge recent progress in quark-flavour physics
  - many important new results from BaBar, Belle, BES, CDF, D0, …
  - and in particular, LHCb, which has definitively proved the concept of a forward spectrometer at a hadron collider
- Standard Model still survives
  - several "tensions" alleviated with improved measurements
  - further investigation still needed in many areas (a_{sl}, $B \to D^{(*)}\tau\nu$, etc.)
  - not a cause for depression! Now probing regions where "realistic" new physics effects might appear
- Exciting short- and mid-term prospects
  - next generation experiments in kaon, charm and B physics
  - LHCb upgrade confirmed as a core component of LHC exploitation

Back up

Range of CKM phenomena



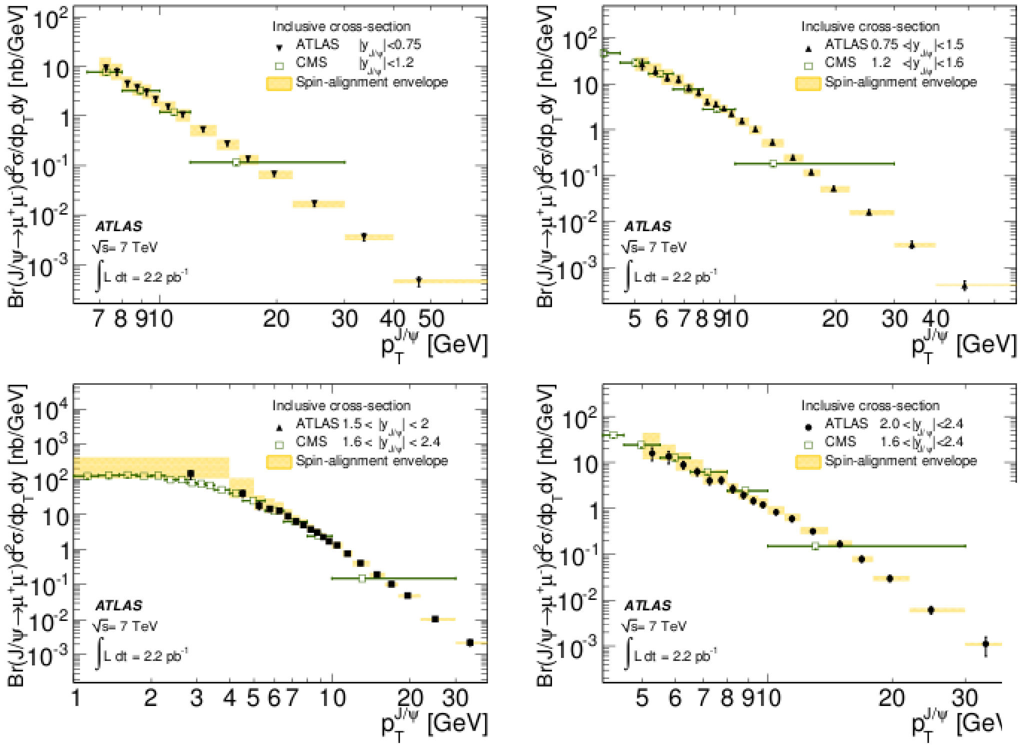
CP violation and the matter-antimatter asymmetry

- 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

Heavy flavour production @ ATLAS

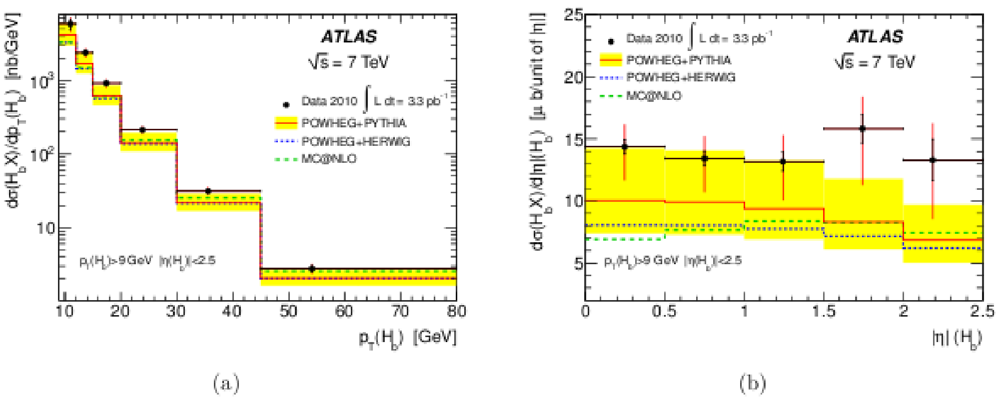
“Measurement of the differential cross-sections of inclusive, prompt and non-prompt J/ψ production in proton-proton collisions at √s = 7 TeV”

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”

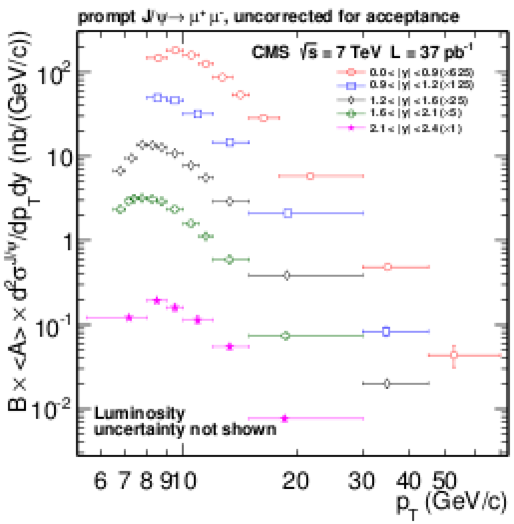
Nucl. Phys. B 864 (2012) 341

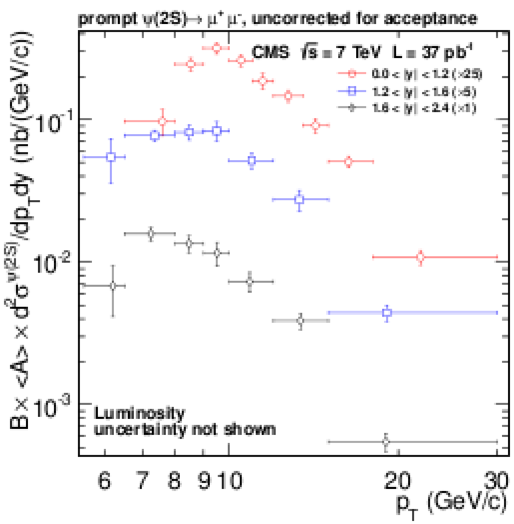


Heavy flavour production @ CMS

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

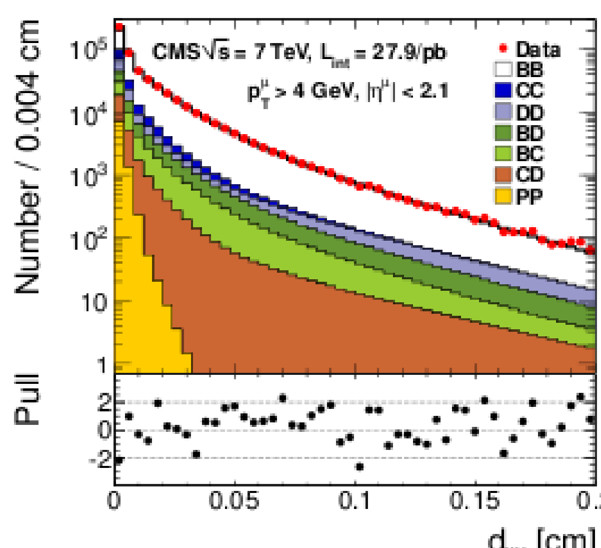
J. High Energy Phys. 02 (2012) 011

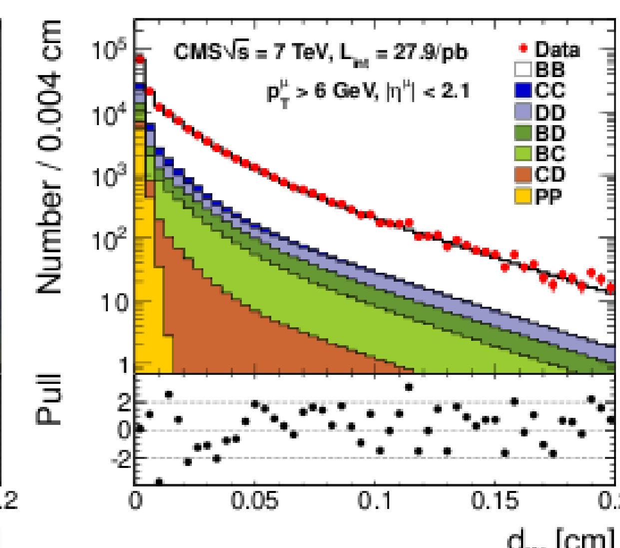




“Measurement of the cross section for production of b b-bar X, decaying to muons in pp collisions at s√=7 TeV”

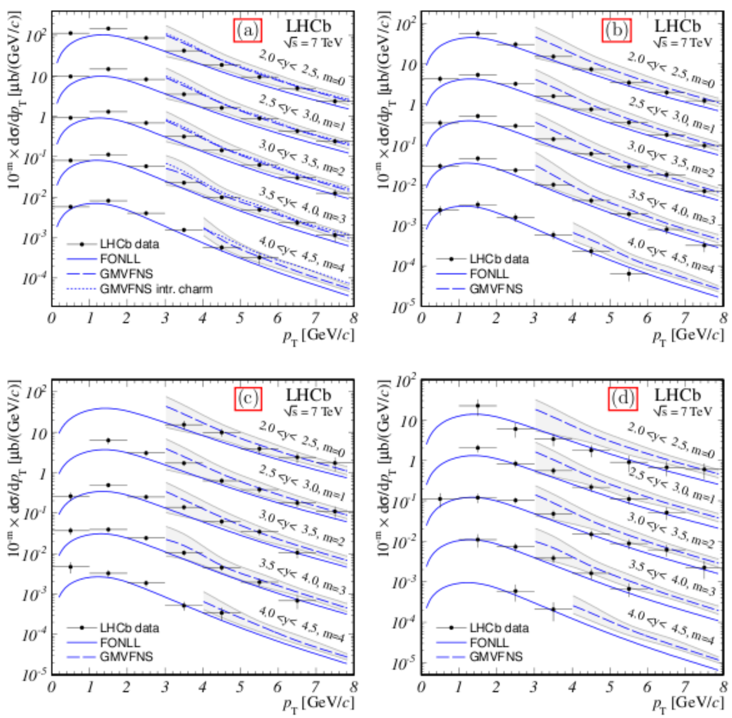
J. High Energy Phys. 06 (2012) 110





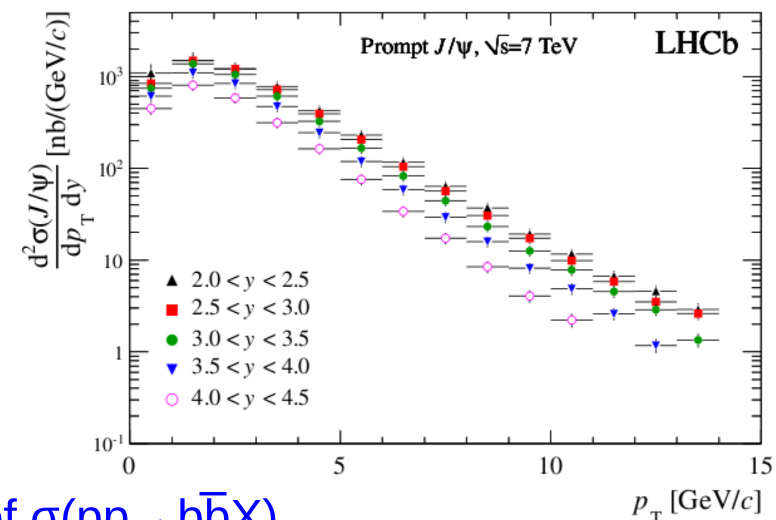
Heavy flavour production @ LHCb

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

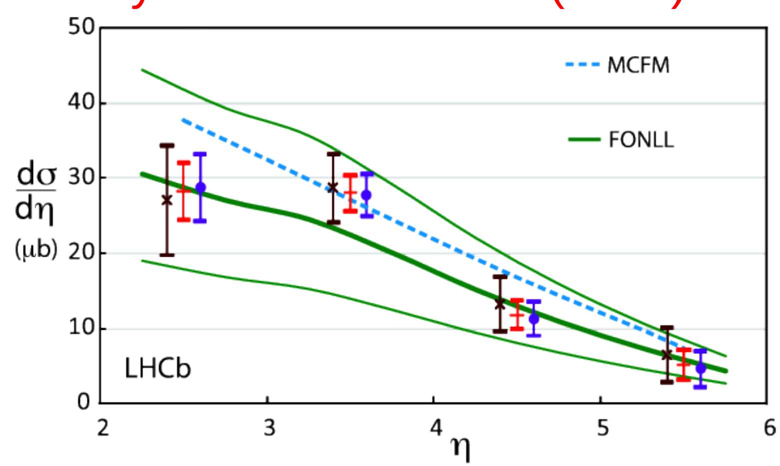


(a) D^0, (b) D^+, (c) D^{*+}, (d) D_s^+

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



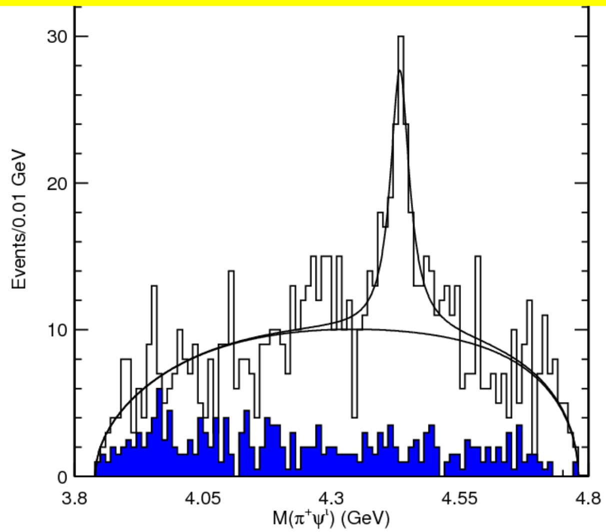
"Measurement of $\sigma(pp \to b\bar{b}X)$ at √s = 7 TeV in the forward region"
Physics Letters B 694 (2010) 209



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

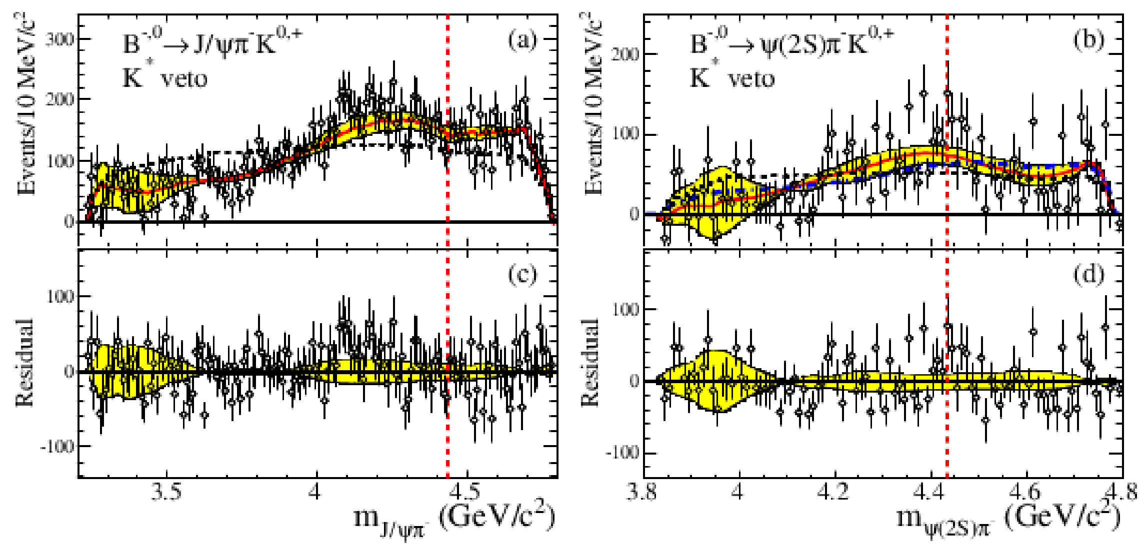
$B^0 \to Z(4430)^- K^+$, $Z(4430)^- \to \psi' \pi^-$

Belle PRL 100 (2008) 142001



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

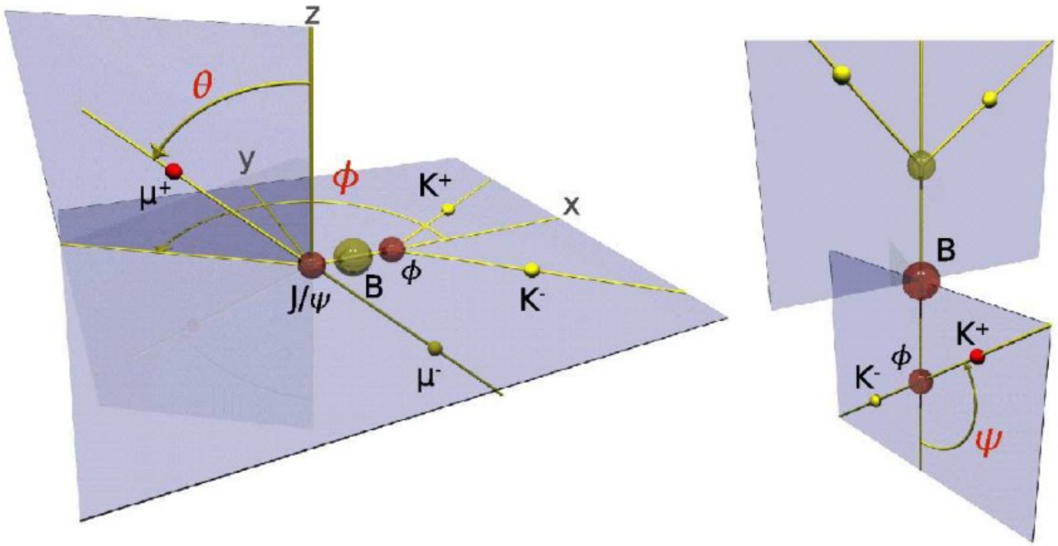
BABAR PRD 79 (2009) 112001



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)

$\Phi_s = -2\beta_s$ ($B_s \to J/\psi\varphi$)



- VV final state

  three helicity amplitudes

  → mixture of CP-even and CP-odd

  disentangled using angular & time-dependent distributions

  → additional sensitivity

  many correlated variables

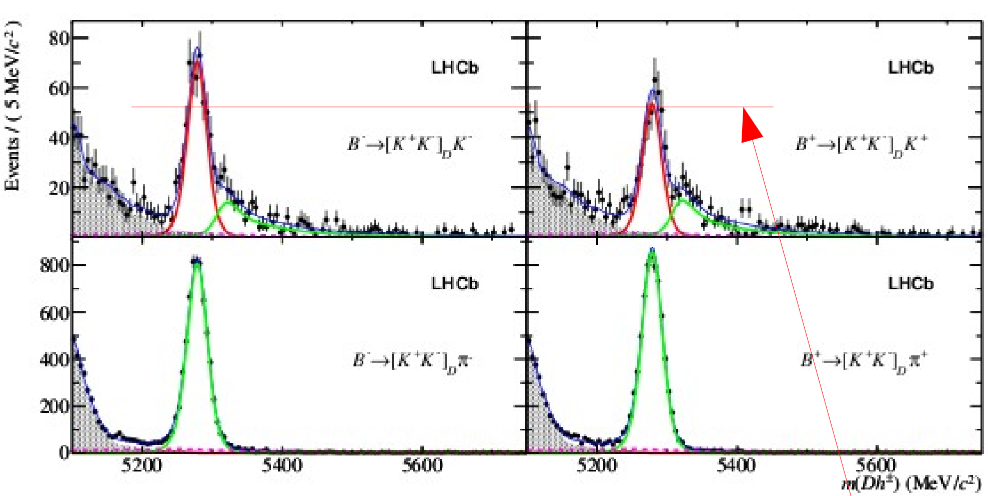
  → complicated analysis

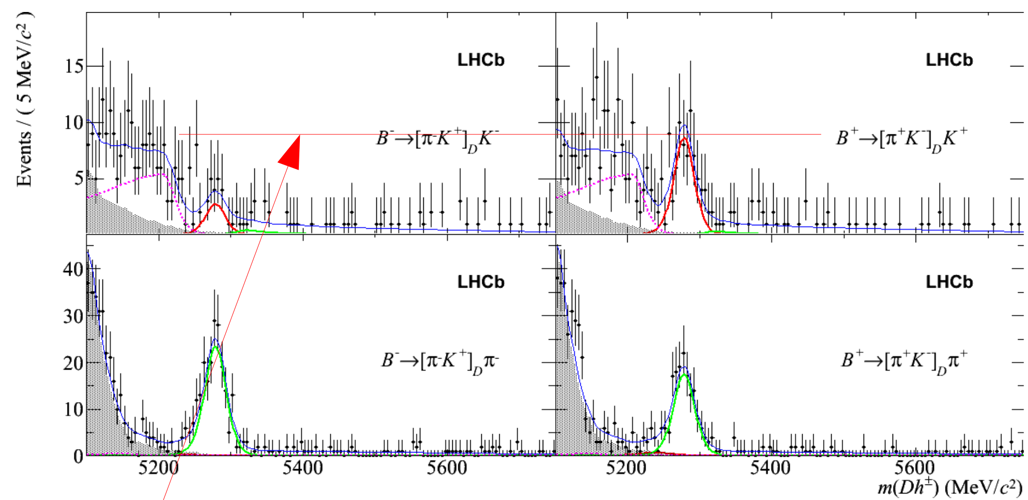
- LHCb also uses $B_s \to J/\psi f_0$ ($f_0 \to \pi^+\pi^-$)
  - CP eigenstate; simpler analysis
  - fewer events; requires input from $J/\psi\varphi$ analysis (Γ_s, $\Delta\Gamma_s$)

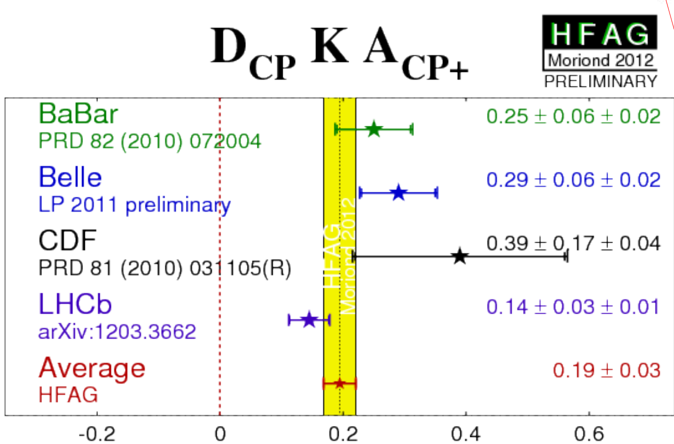
B → DK decays
"GLW" and "ADS" methods

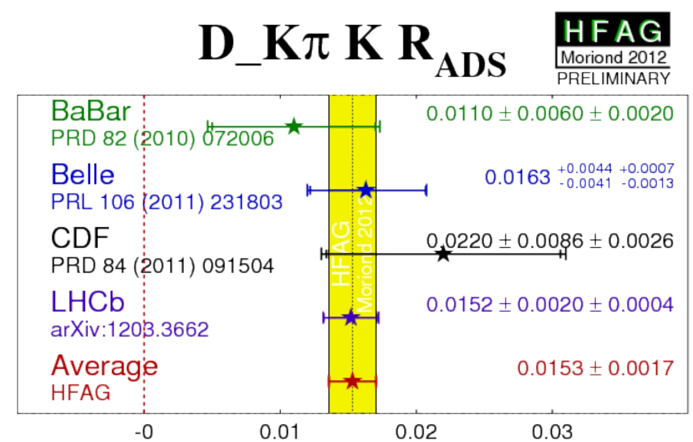
B → DK decays
give theoretically clean
way to measure
CKM phase γ

LHCb
Phys. Lett. B 712 (2012) 203









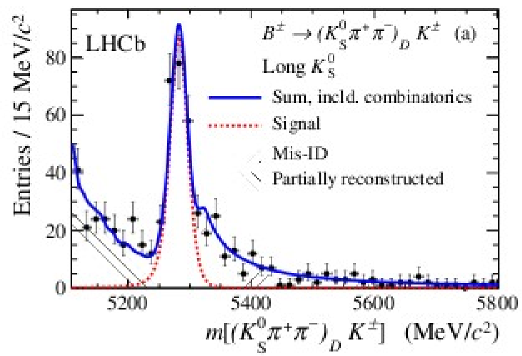
Observation of CP violation in B → DK decays

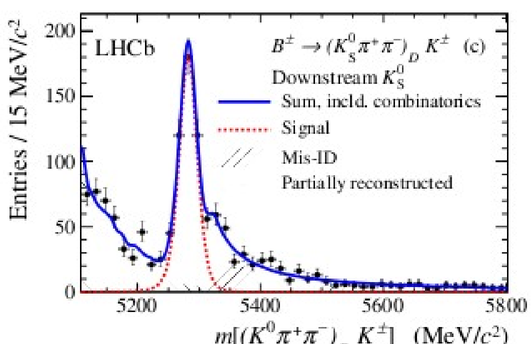
γ from $B^+ \to DK^+$, $D \to K^0_S h^+h^-$

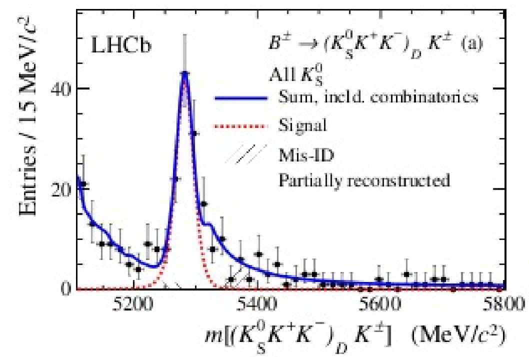
LHCb (1/fb)
Phys. Lett. B 718 (2012) 43

- 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





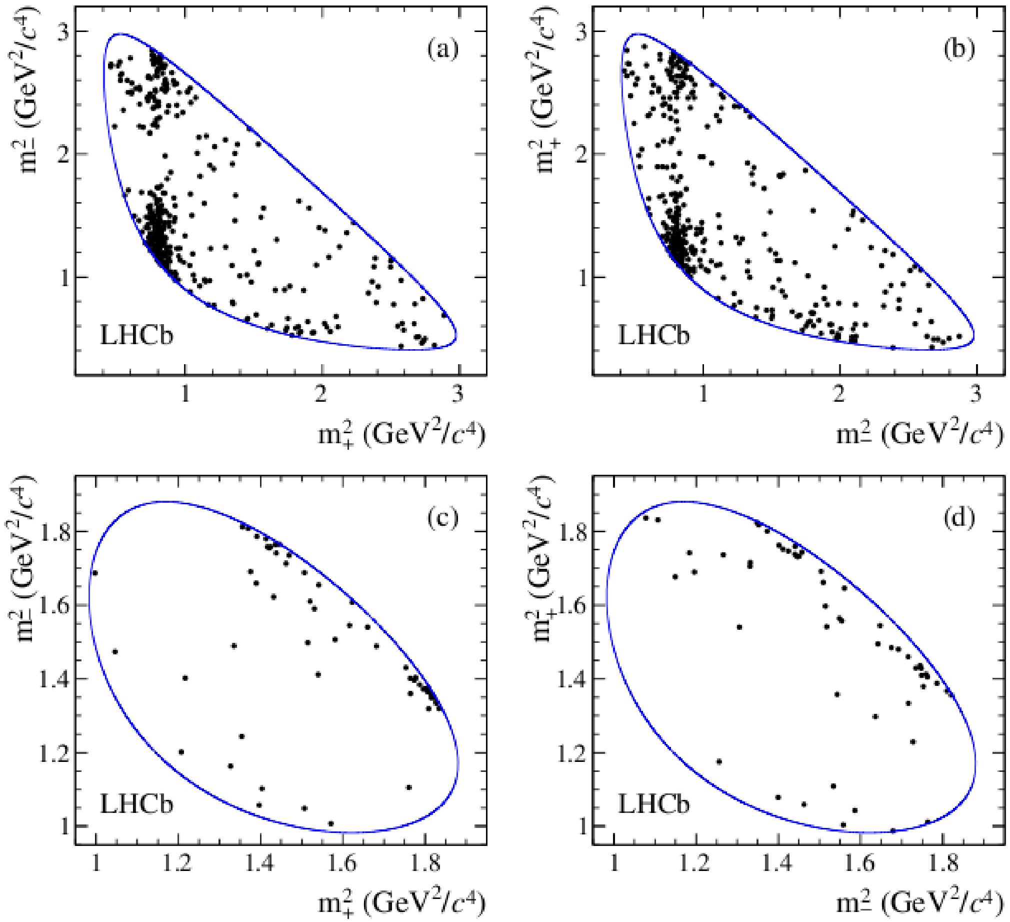


$K^0_S K^+K^-$ (all combined)

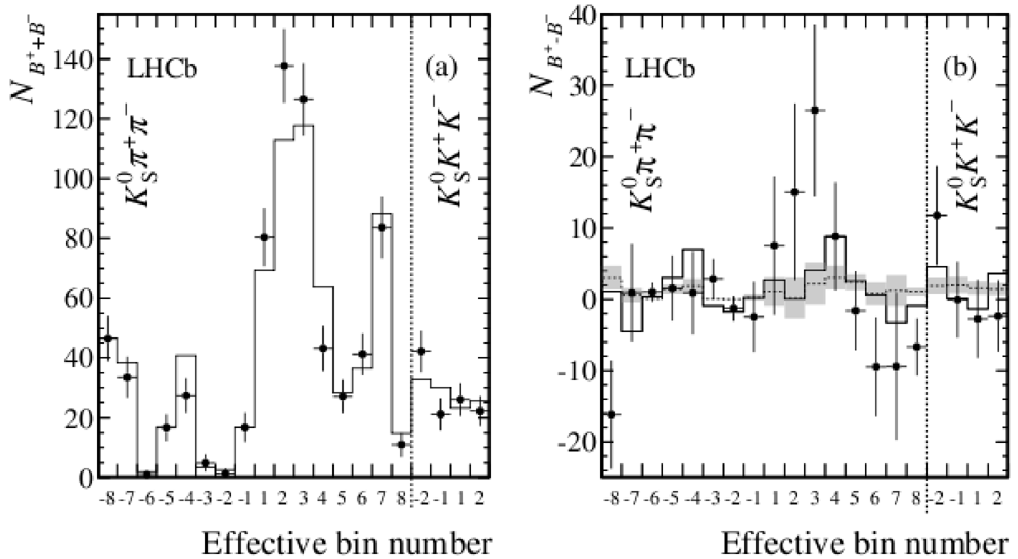
γ from $B^+ \to DK^+$, $D \to K^0_S h^+h^-$

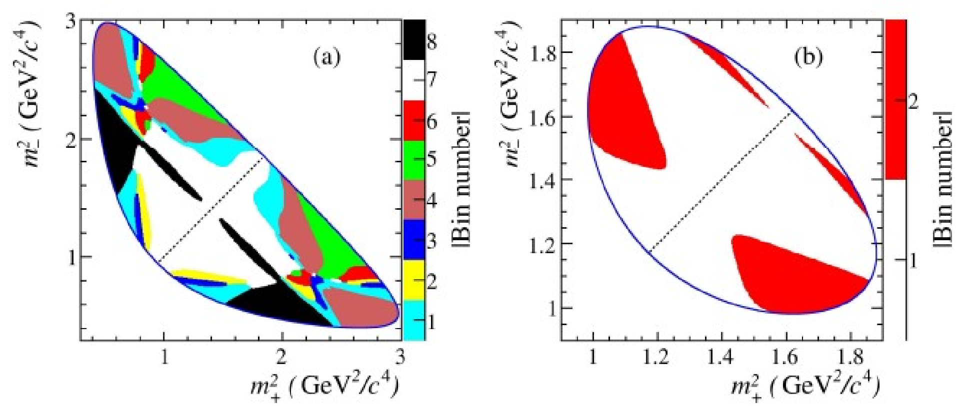
LHCb (1/fb)
Phys. Lett. B 718 (2012) 43

Reconstruct Dalitz plot distributions ...



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

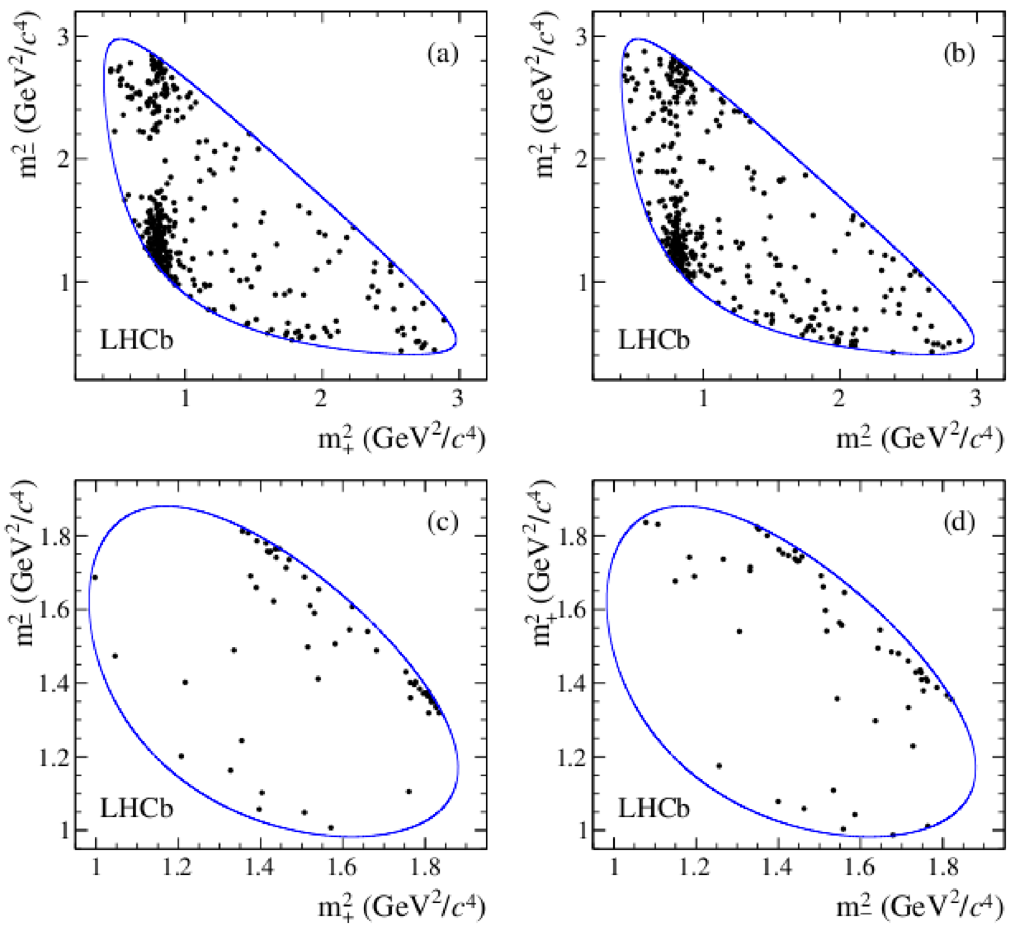




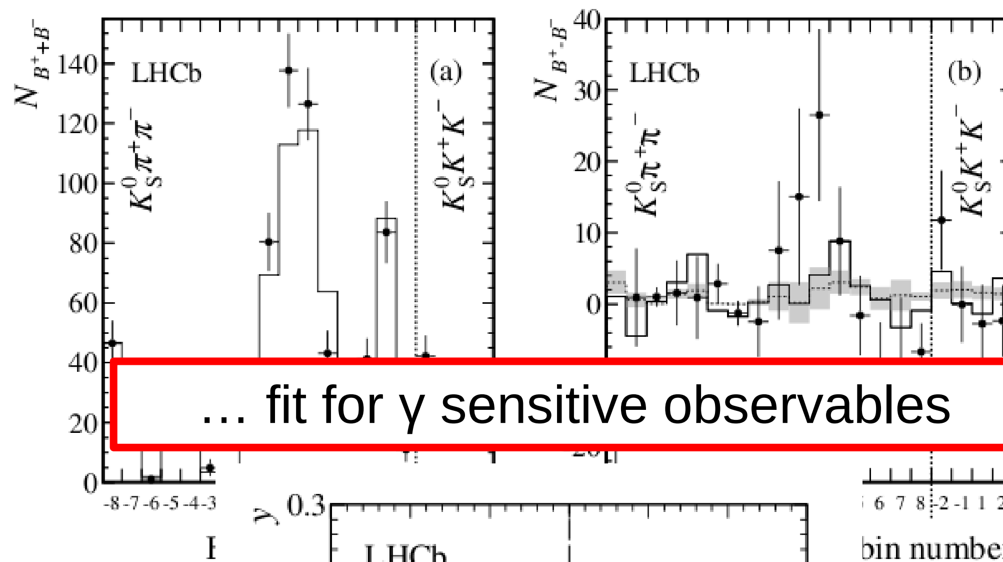
γ from $B^+ \to DK^+$, $D \to K^0_S h^+h^-$

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

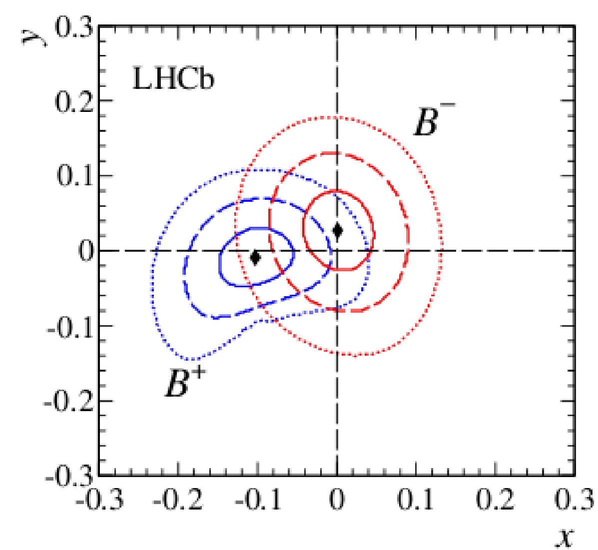
Reconstruct Dalitz plot distributions ...



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

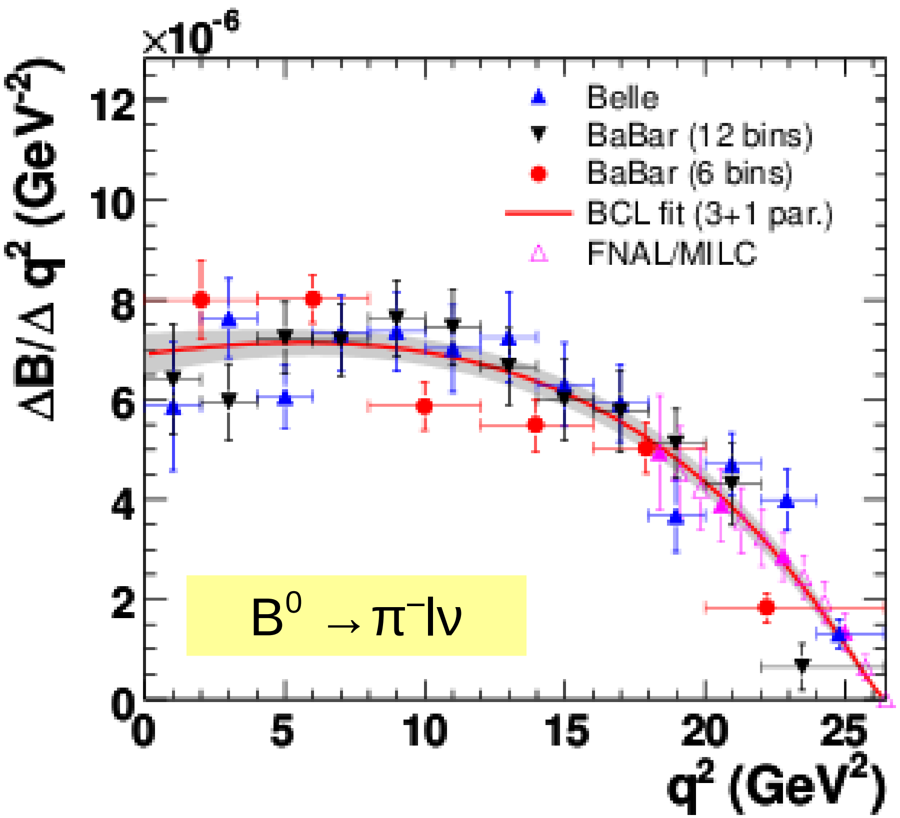


… fit for γ sensitive observables



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

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



$B^0 \to \pi^- l \nu$

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

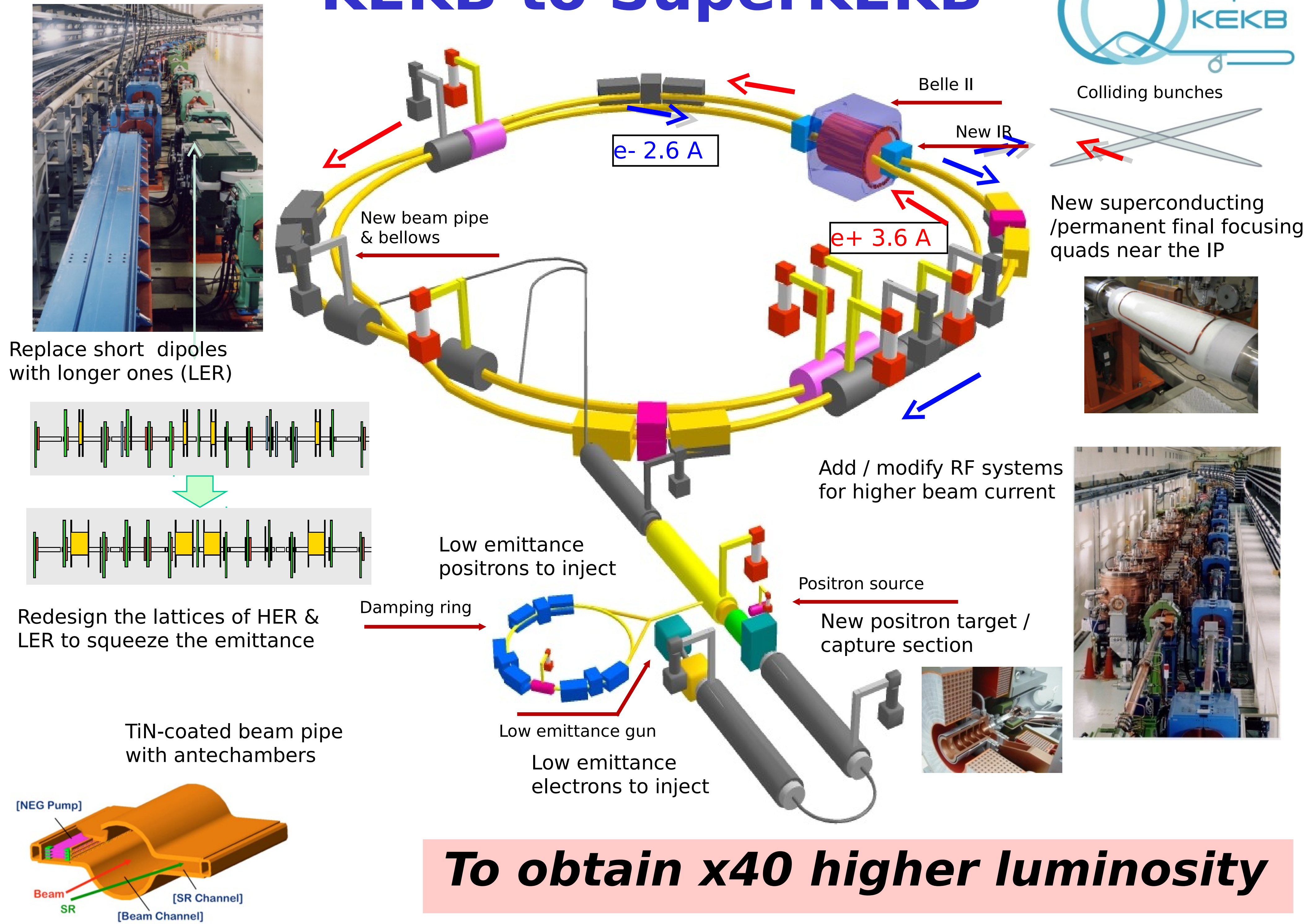
Upgrade – expected sensitivities

Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\text{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s$ ($B_s^0 \to J/\psi\ \phi$)	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s$ ($B_s^0 \to J/\psi\ f_0(980)$)	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\text{fs}}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\text{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\text{eff}}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\text{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\ A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\text{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	$\sim 10\,\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	$\sim 100\,\%$	$\sim 35\,\%$	$\sim 5\,\%$
Unitarity triangle angles	γ ($B \to D^{(*)}K^{(*)}$)	~ 10–12° [19, 20]	4°	0.9°	negligible
	γ ($B_s^0 \to D_s K$)	–	11°	2.0°	negligible
	β ($B^0 \to J/\psi\ K_S^0$)	0.8° [18]	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

Table 1: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the current sensitivity is compared to that which will be achieved by LHCb before the upgrade, and that which will be achieved with $50\,\text{fb}^{-1}$ by the upgraded experiment. Systematic uncertainties are expected to be non-negligible for the most precisely measured quantities.

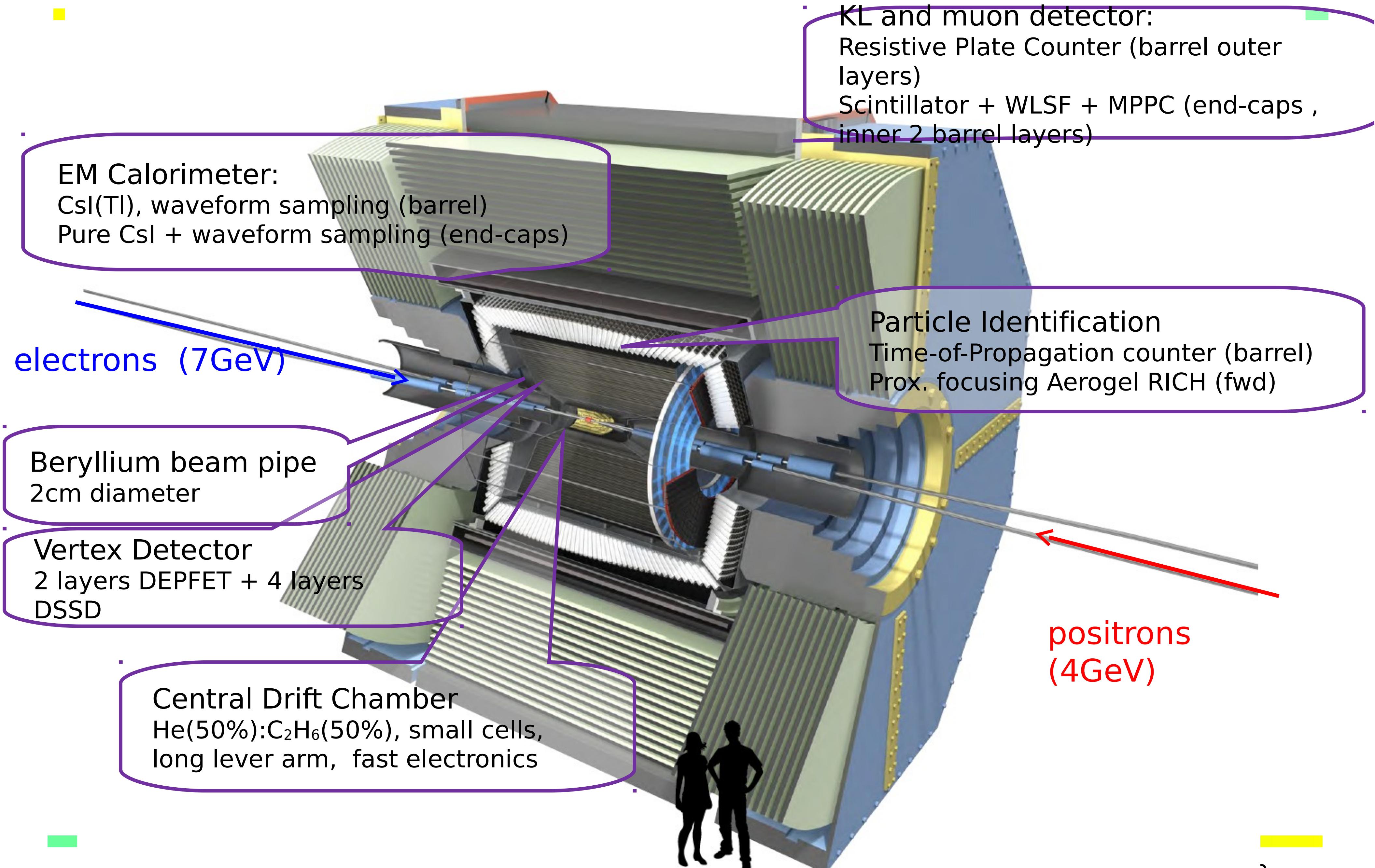
- sample sizes in most exclusive B and D final states far larger than those collected elsewhere
- no serious competition in study of B_s decays and CP violation

KEKB to SuperKEKB

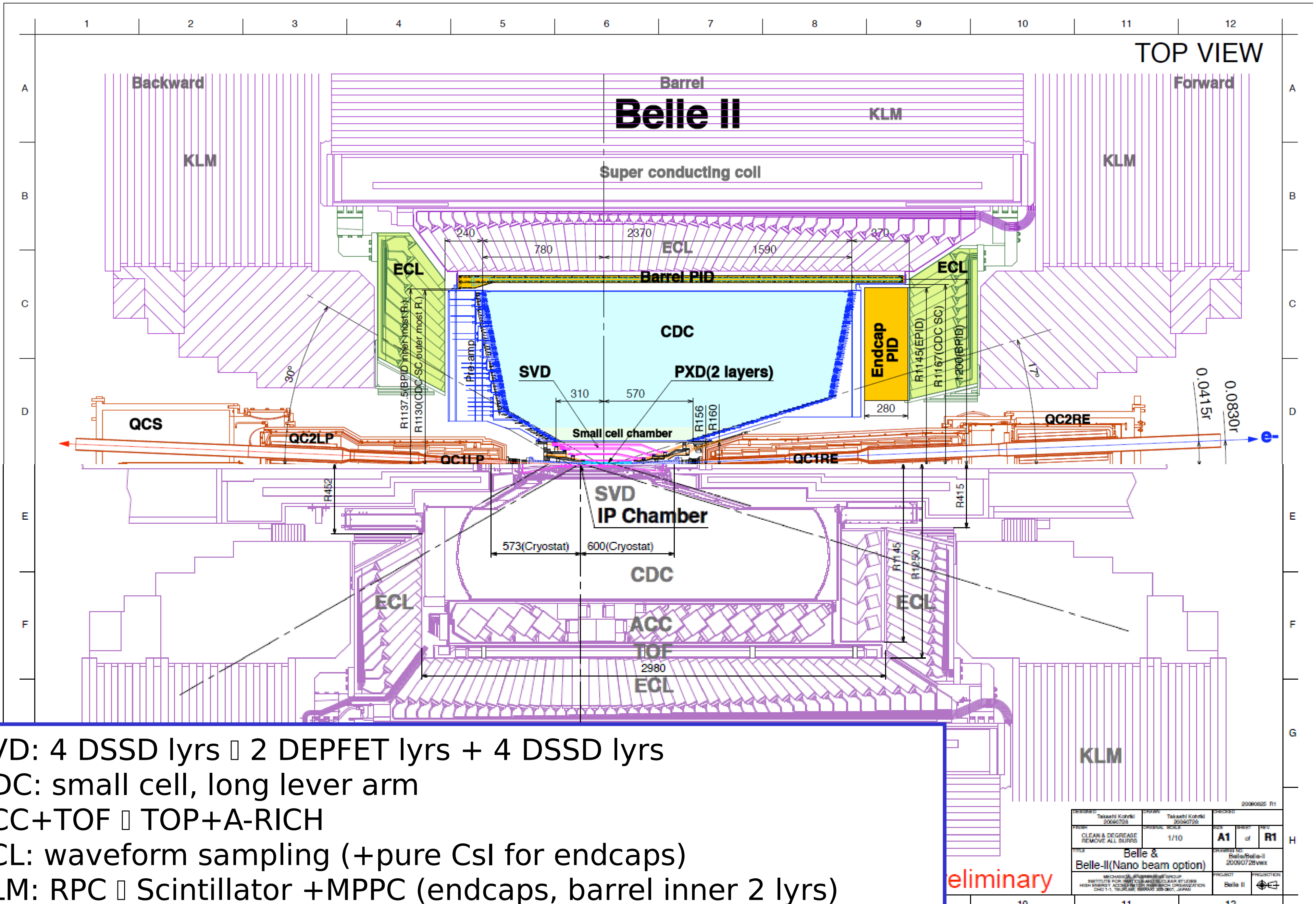


To obtain x40 higher luminosity

Belle II Detector

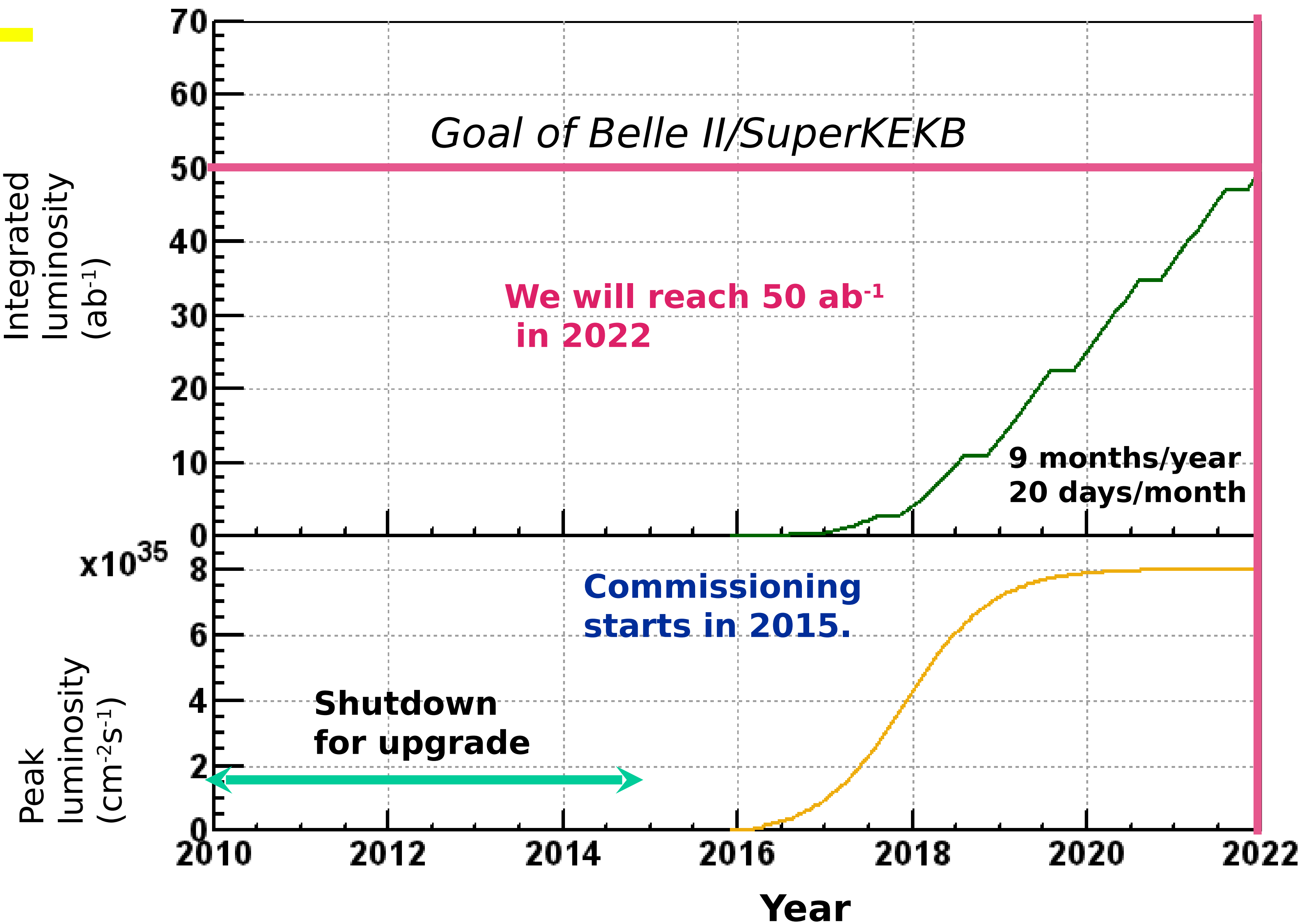


Belle II Detector (in comparison with Bell



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.

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