LHCb : 香精物理学

Sergey Barsuk, LAL Orsay
on behalf of the LHCb collaboration

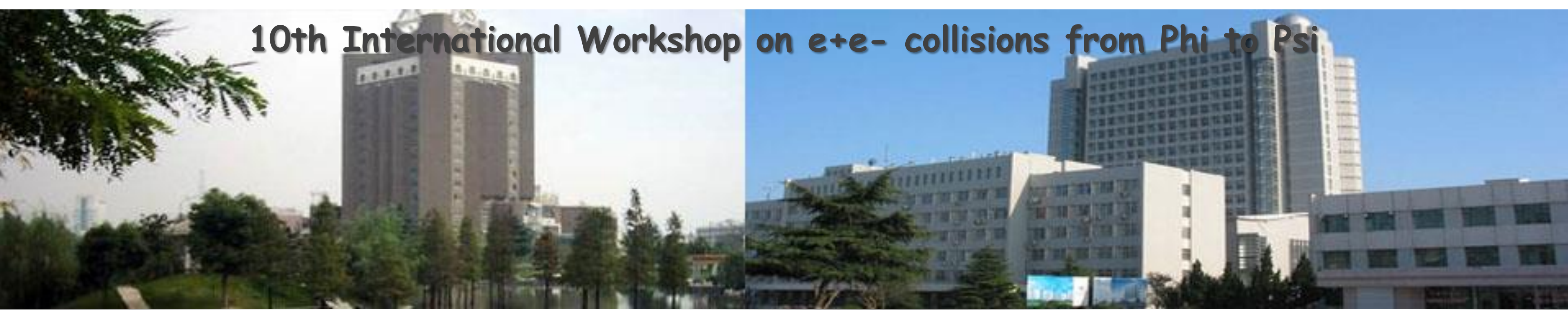
Selected **LHCb results** on

- LHCb as LHCb and LHCc, **key detector elements and data sample**
- **CP-parity violation**, involving or not CPV measurements
- **Rare decays**

very personal selection of results

Other new important LHCb results in the talk by Liming Zhang :

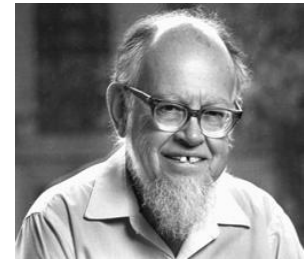
- New results on exotic baryon resonances at LHCb



CKM matrix, CP-parity violation and unitarity triangle

The Cabibbo-Kobayashi-Maskawa

in Wolfenstein



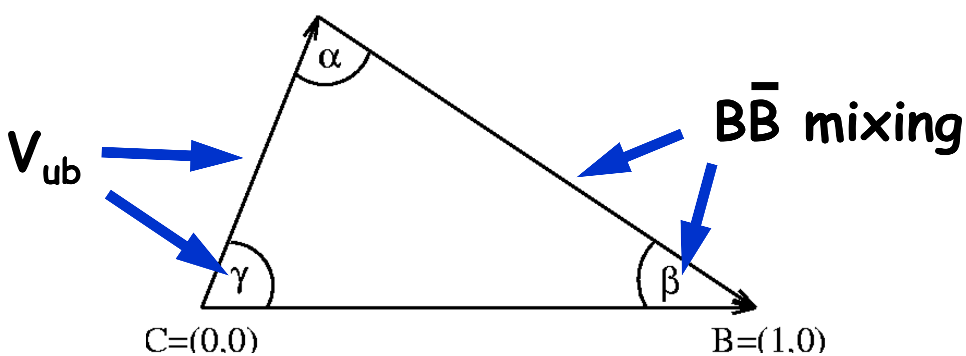
matrix

parametrization

$$V_{CKM} = \begin{array}{cc} \begin{matrix} u \\ c \\ t \end{matrix} & \begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+A^2\lambda^5(1/2-\rho-i\eta) & 1-\lambda^2/2-\lambda^4(1+4A^2)/8 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta)+A\lambda^5(\rho+i\eta)/2 & -A\lambda^2+A\lambda^4(1/2-\rho-i\eta) & 1-A^2\lambda^4/2 \end{pmatrix} \\ & \begin{matrix} d & \qquad\qquad s & \qquad\qquad b \end{matrix} \end{array} + O(\lambda^6)$$

η - CPV phase

- ❑ Beauty :



- ❑ Charm CPV : 2x2 Cabibbo matrix and V_{ub} via loops

SM: single CP-violating phase ➔ strong predictive power for CP asymmetries !

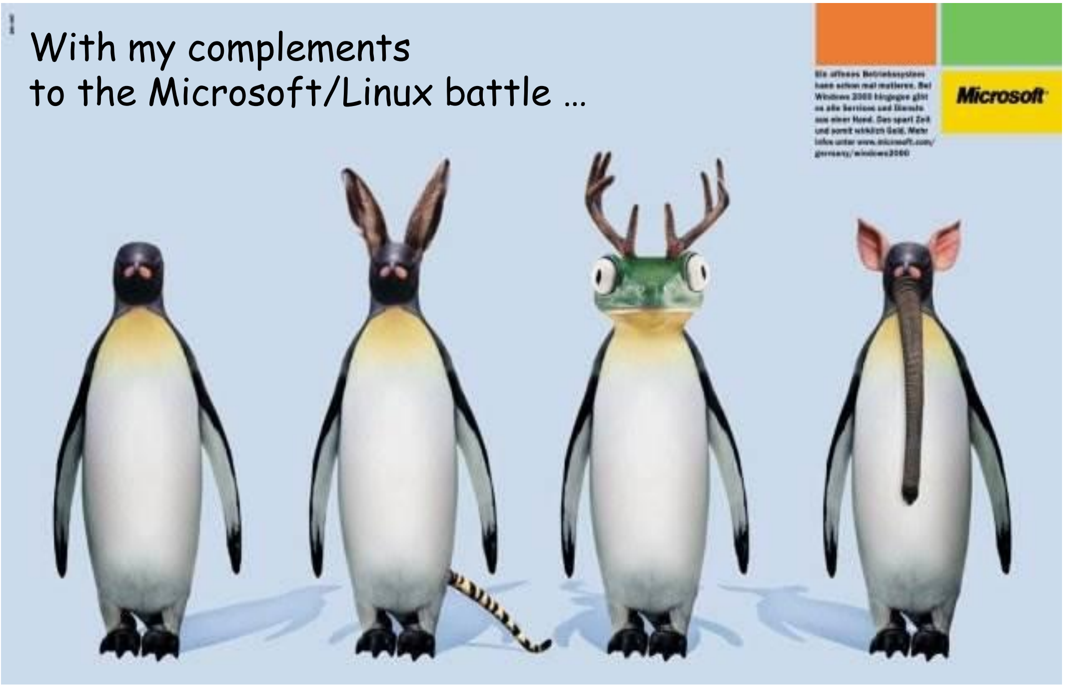
- Standard Model extremely successful for 40 years
- "New Physics" indications suppressed by scale and/or coupling
- Search for NP via two complementary approaches

Energy path – direct production – brutal force

or

Quantum path – indirect search via loops – intelligent

- In close collaboration with theorists who modify even a simple penguin to describe the measurements



- **Look at LoopS:** Search for contributions from effects not described by SM via **loop-mediated transitions** contributing to

Small asymmetries – CPV

Rare decays

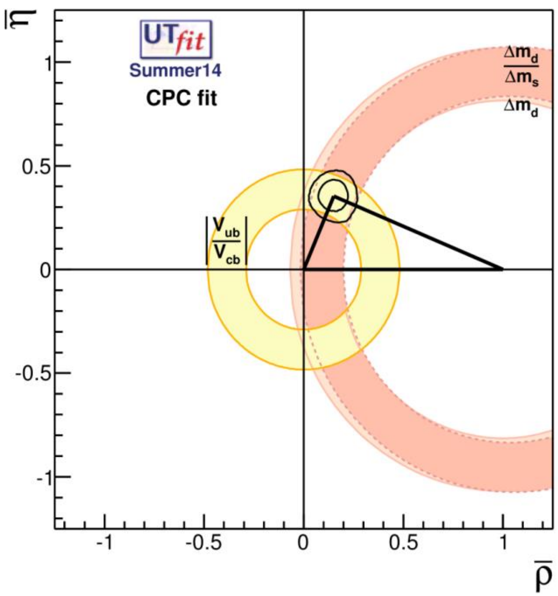
in **charm** and **beauty** sectors

- **Production** – mainly QCD tests
- Precision measurement of **CKM parameters** (e.g. via tree diagrams)

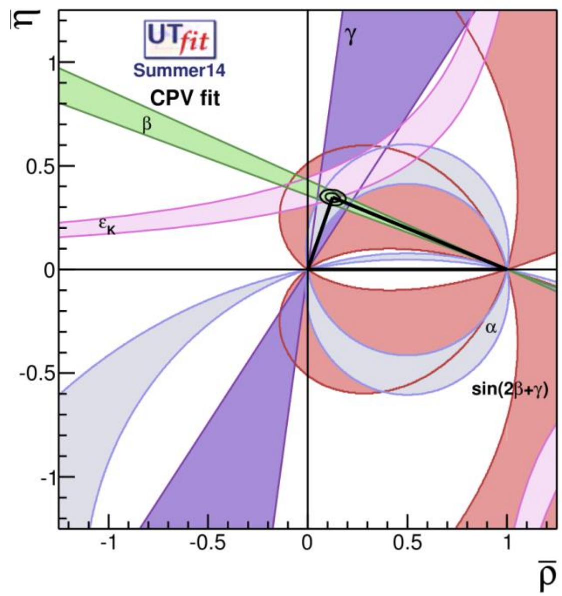
Constructing the unitarity triangle

- The UT can be constructed from non-CPV measurements
- The UT can be constructed from CPV measurements only
- Both construct the same UT

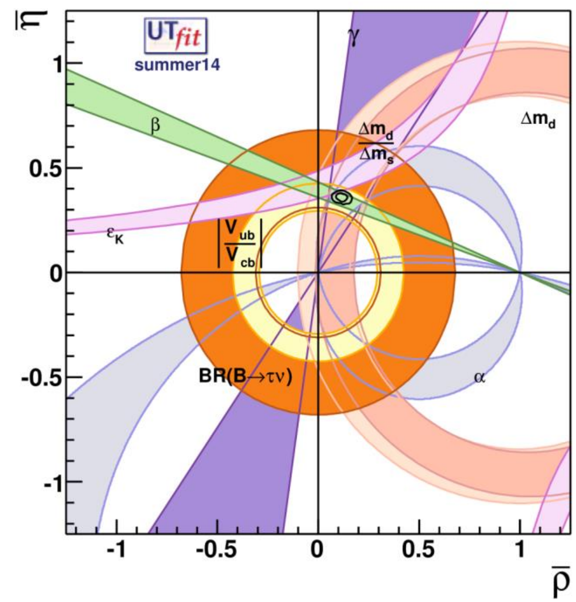
CPV from |Vub/Vcb| and B-mixing



CPV from angles



all included

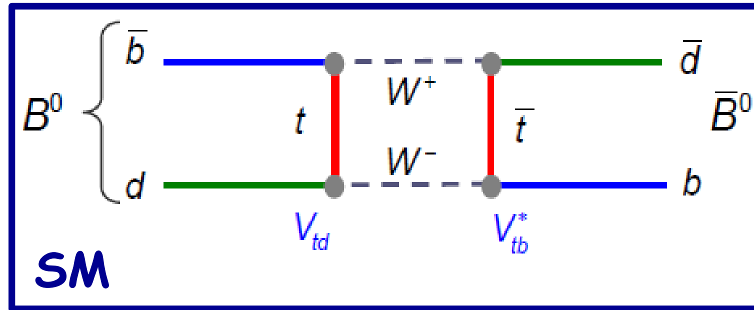


- All measurements are so far consistent with the same UT
- Single same CPV parameter for charm and beauty sector

How to quantify NP contribution

Flavour transitions probe high mass scales in quantum loops (e.g. FCNC)

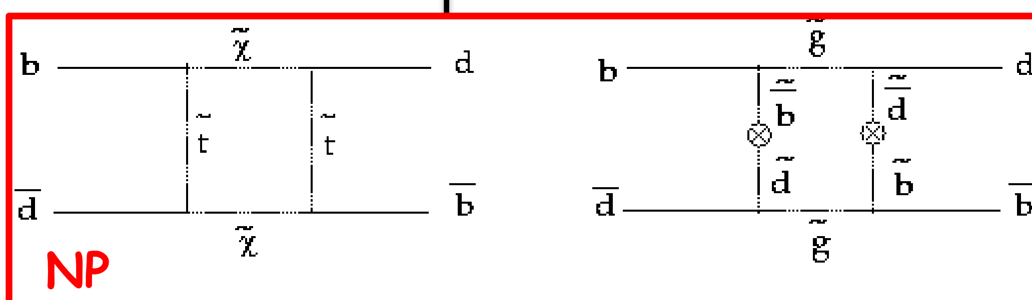
Standard Model scale and couplings (CKM matrix elements) :



$B\bar{B}$ mixing :

$$A_0 \left[\frac{C_{SM}}{M_W^2} + \frac{C_{NP}}{\Lambda_{NP}^2} \right]$$

New Physics scale and coupling :

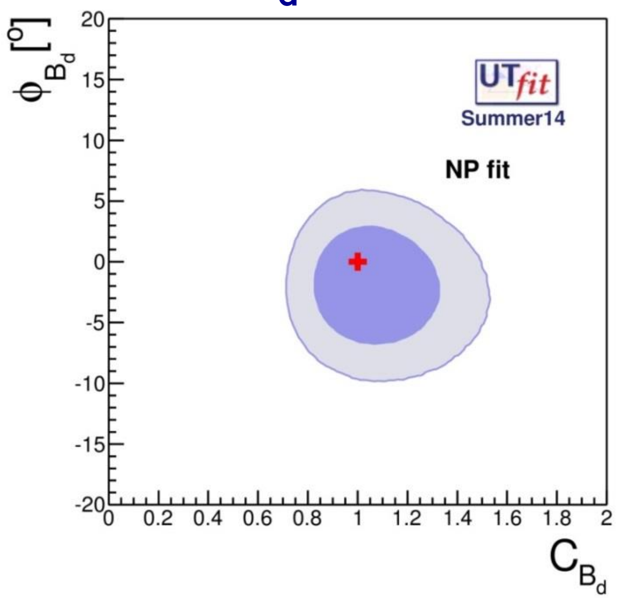


- For NP in ΔB=2 transitions :

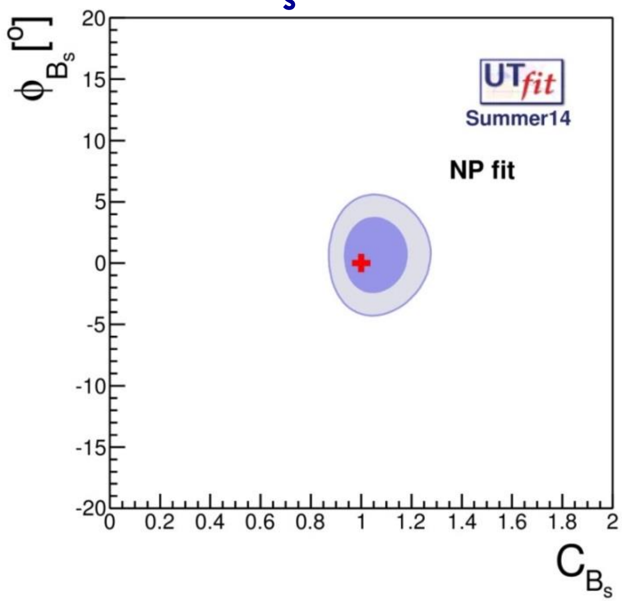
$$C_{B_q}\, e^{2i\phi_{B_q}} = \frac{\langle B_q^0 | H_{\rm eff}^{\rm full} | \bar{B}_q^0 \rangle}{\langle B_q^0 | H_{\rm eff}^{\rm SM} | \bar{B}_q^0 \rangle}\,,$$

$$\begin{aligned}
\Delta m_d^{\rm exp} &= C_{B_d} \Delta m_d^{\rm SM}\,,\\
\sin 2\beta^{\rm exp} &= \sin(2\beta^{\rm SM} + 2\phi_{B_d})\,,\\
\alpha^{\rm exp} &= \alpha^{\rm SM} - \phi_{B_d}\,,\\
\Delta m_s^{\rm exp} &= C_{B_s} \Delta m_s^{\rm SM}\,,\\
\phi_s^{\rm exp} &= (\beta_s^{\rm SM} - \phi_{B_s})\,,
\end{aligned}$$

B_d sector

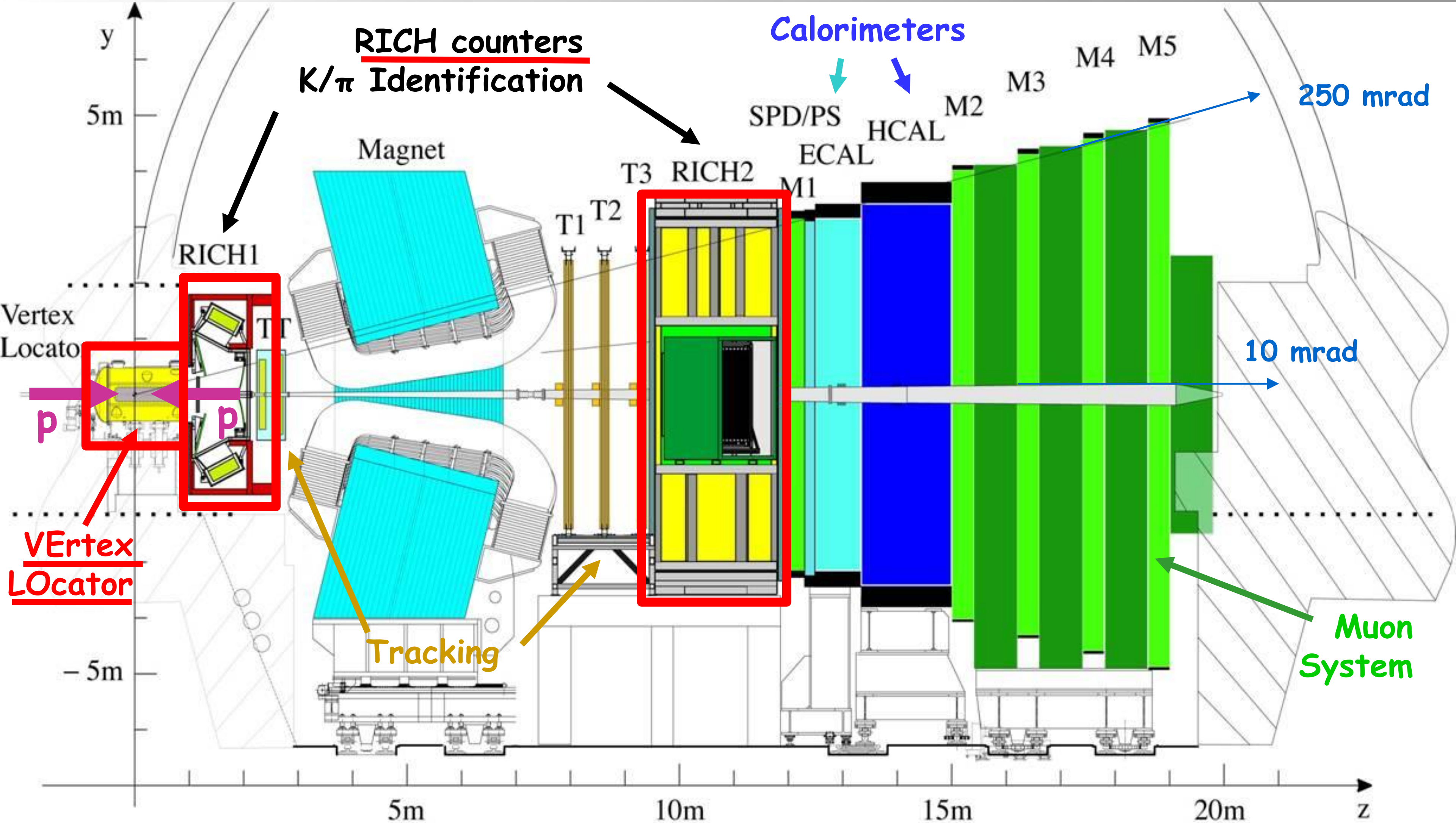


B_s sector



- **No sign of NP at the 10%-30% level …**

LHCb: key detector systems for precision flavour physics



Vertex reconstruction:
VELO

Kinematics:
Magnet
Tracker
Calorimeters

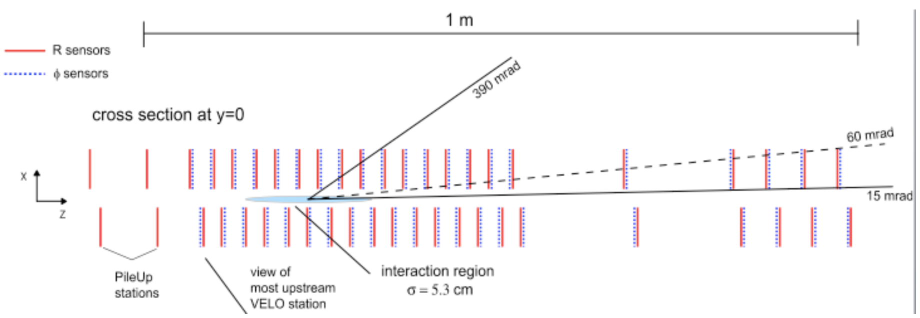
PID:
RICHs
Calorimeters
Muon Chambers

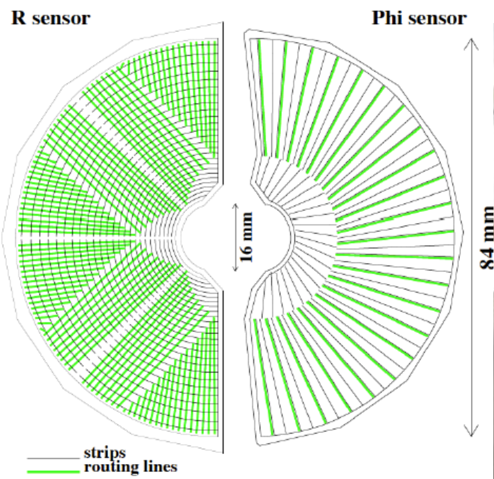
Trigger:
Muon Chambers
Calorimeters
Tracker

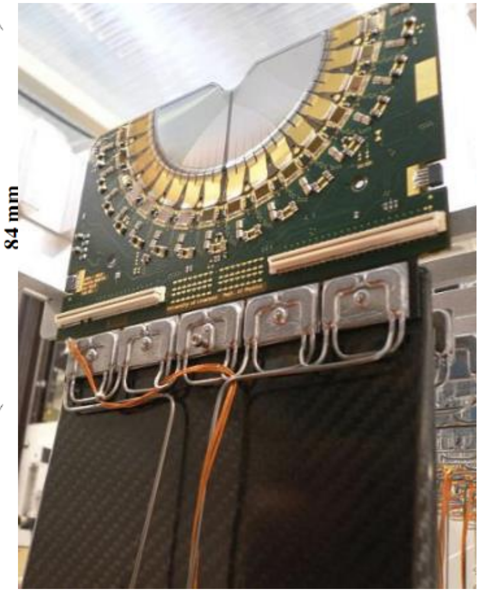
VELO: Vertex LOcator

JINST 8 (2013) P08002, arXiv:1405.7808

- 88 semi-circular **microstrip Si sensors**
- Double-sided, **R and φ** layout, in each module
- 300μ thick n-on-n sensors
- Strip pitches from 40 to 120μ



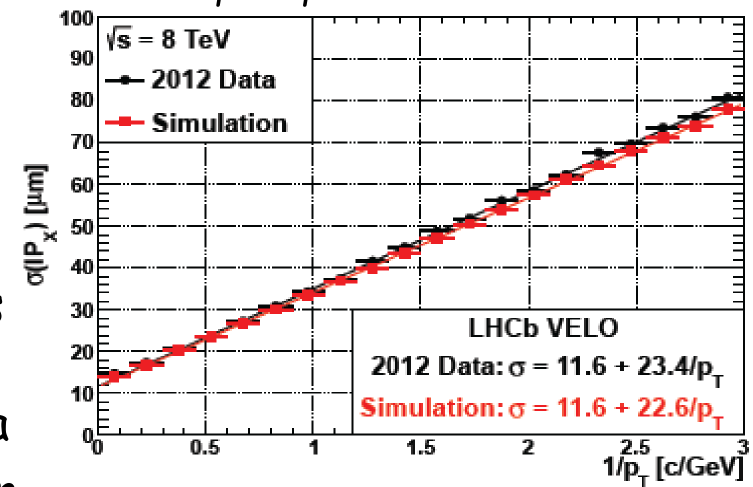




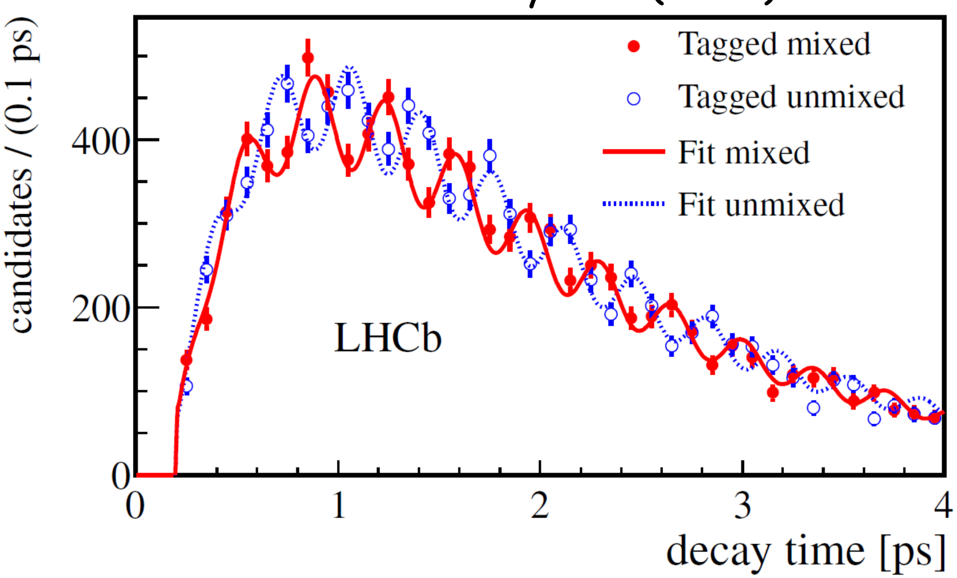
- **First active strip at 8.2mm from the beam axis**
- Moves away every fill and centers around the beam with self measured vertices

- Excellent **spatial resolution**, down to 4μ for single tracks
- Precise **impact parameter** measurement,
  $\sigma_{IP} = 11.6 + 23.4/pT \ \ [\mu]$
- Precise **primary vertex** reconstruction,
  $\sigma_x = \sigma_x = 13\mu$, $\sigma_z = 69\mu$ for a vertex of 25 tracks
- Detector understood, simulation describes data
- VELO provides excellent **proper time** resolution

Impact parameter resolution



New J. Phys. 15 (2013) 053021



- **Vertex resolution** allows to resolve fast (x~27) $B_s\overline{B}_s$ oscillations

$$B_s^0 \to D_s^- \pi^+ \qquad \begin{array}{l} D_s^- \to \phi(K^+K^-)\pi^- \\ D_s^- \to K^{*0}(K^+\pi^-)K^- \\ D_s^- \to K^+K^-\pi^- \text{ nonresonant} \\ D_s^- \to K^-\pi^+\pi^- \\ D_s^- \to \pi^-\pi^+\pi^- \end{array}$$

$$\boxed{\Delta m_s = 17.768 \pm 0.023\,(\text{stat}) \pm 0.006\,(\text{syst})\ \text{ps}^{-1}}$$

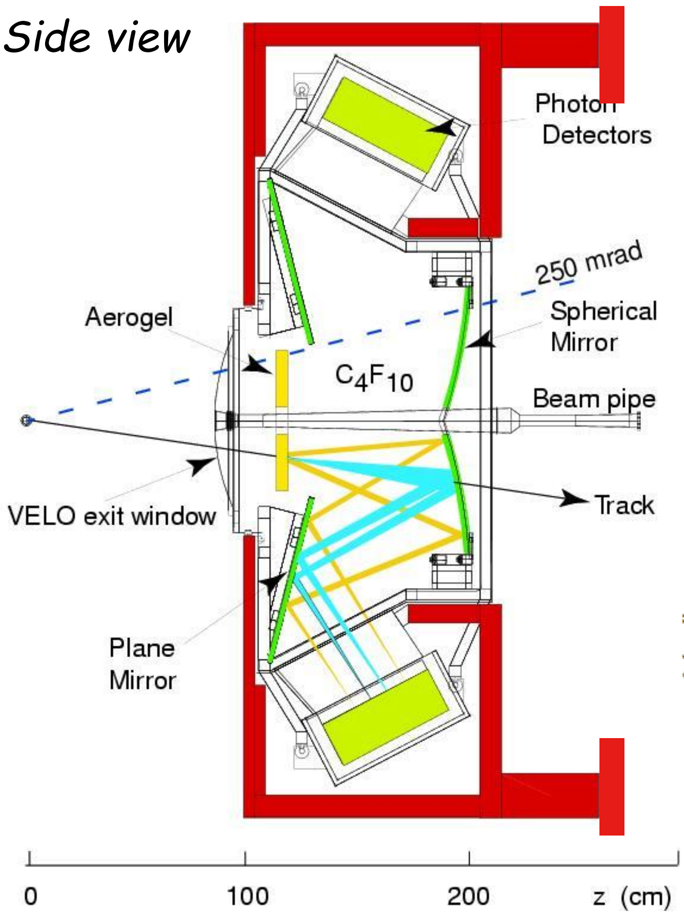
Charged hadron identification: RICH detectors

*2 **Ring Imaging Cherenkov Detectors (RICH)**: 3 **Radiators**, photons from Cerenkov cone focused onto rings recorded by **Hybrid Photon Detector** (HPD) arrays, out of acceptance*

RICH 1

Acceptance 25-300 mrad

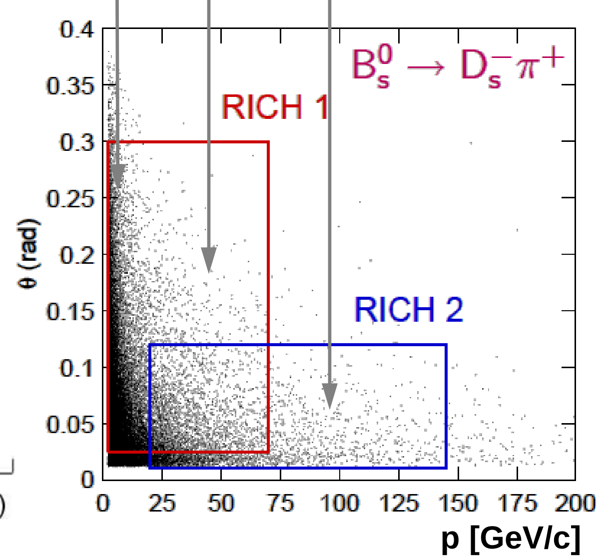
Side view



Silica Aerogel:
n=1.03
1-10 GeV/c

C_4F_{10}:
n=1.0014
Up to ~70 GeV/c

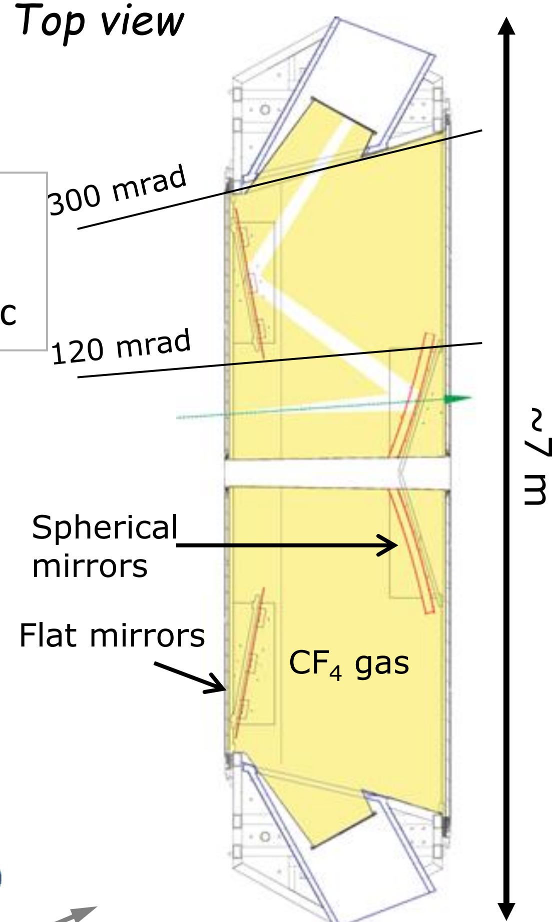
CF_4:
n=1.0005
Up to ~100 GeV/c



RICH 2

Acceptance 15-120 mrad

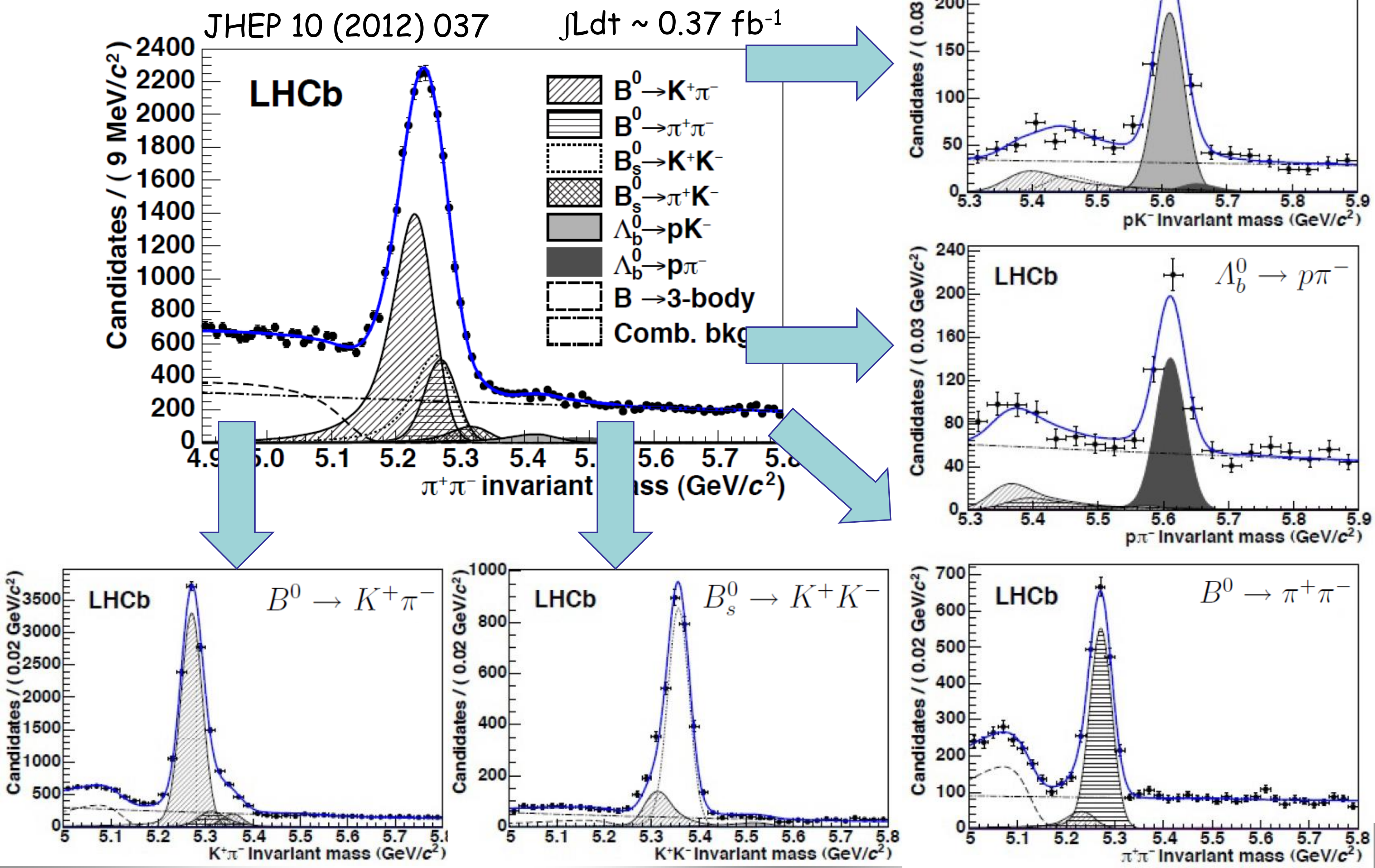
Top view

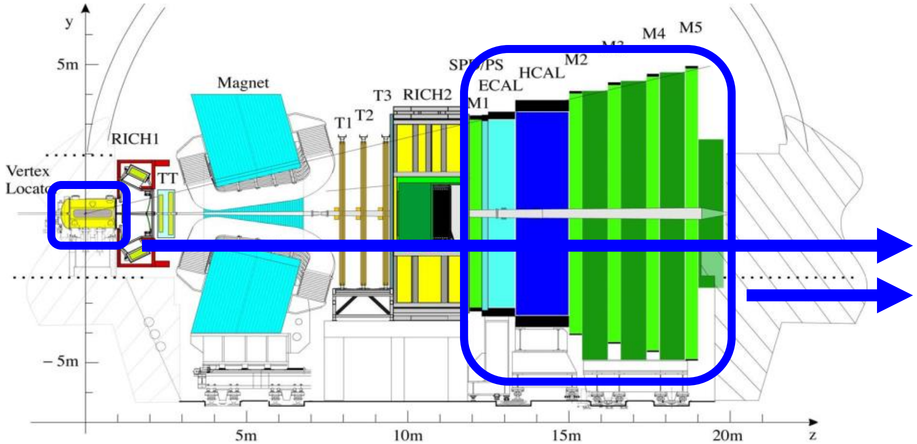


Note scale difference

Charged hadron ID with RICH : charmless two-body b-hadron decays

- *Split b→hh sample into specific modes using RICH detectors*





- Performant LHCb trigger: hardware **L0**, software **HLT**, and software **deferred trigger** implemented in 2012 to use the farm during the inter-fill periods

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz $h^\pm$	400 kHz $\mu/\mu\mu$	150 kHz e/γ

Software High Level Trigger

29000 Logical CPU cores

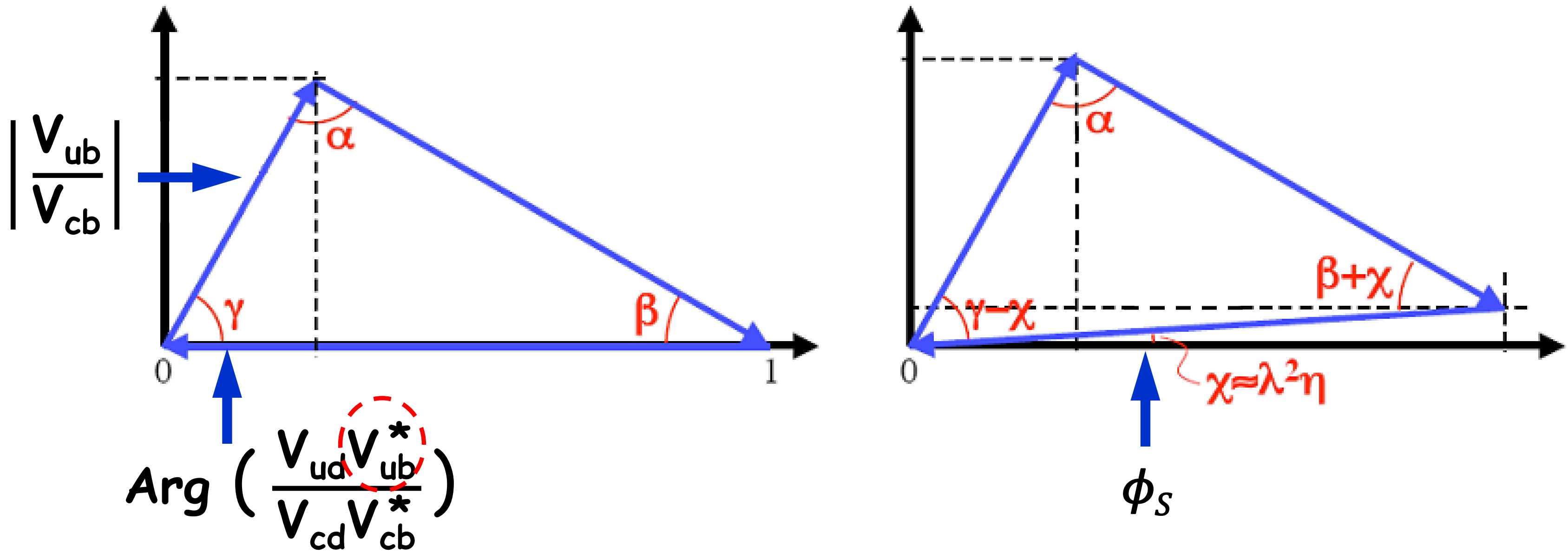
Offline reconstruction tuned to trigger time constraints

Mixture of exclusive and inclusive selection algorithms

5 kHz Rate to storage

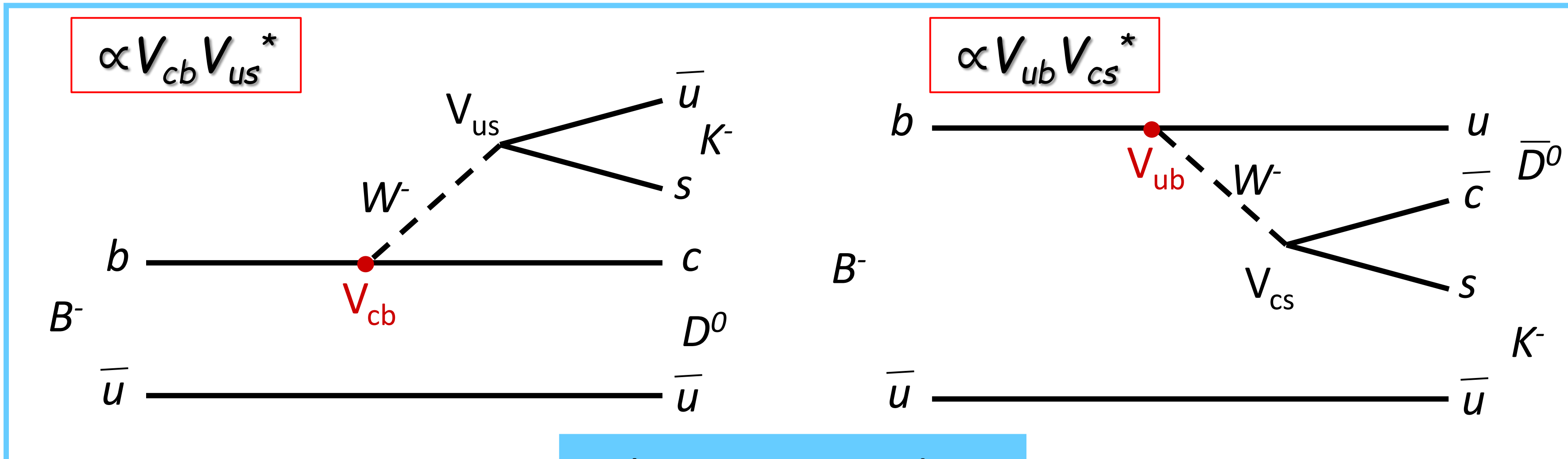
2 kHz Inclusive Topological	2 kHz Inclusive/ Exclusive Charm	1 kHz Muon and DiMuon

- **Angle** γ, new decay modes
- $|V_{ub}/V_{cb}|$ from $\Lambda_b \to p\mu\nu$ / $\Lambda_b \to \Lambda_c^+\mu\nu$
- Weak phase ϕ_s via $B_s \to J/\psi K^+K^-$



- Search for **CPV in charm sector**
  - Search for asymmetries in $D^0 \to hh$
  - Search for CPV in $D^0 \to \pi^+\pi^-\pi^0$ with Energy Test
- **Rare decays** $B \to \mu\mu$, $b \to s\,\mu\mu$, charm rare decays

- **Angle γ** can be measured **from tree diagrams alone** (probably the only such CPV parameter) → a reference point for SM
- A final state common to D^0 and $\bar{D}^0$ is required
- In B→Dh decays (and in $D^0\bar{D}^0$ mixing) effects from NP are considered to be small → benchmark test of CKM consistency



Relative magnitude r_B
relative phase δ_B-γ

1) Use a CP mode for the D^0

Parameters: r_B, γ, δ_B, (r_D = 1, δ_D=0)

GLW (Gronau, London, Wyler)
CP+ and CP- modes

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

$(K_S\pi^0, \phi K_S, \eta K_S, \rho K_S, \omega K_S)$

(Very) small Branching Ratios

2) Use CAD ($K^- \pi^+$) for the V_{ub} decay and DCSD ($K^- \pi^+$) for the V_{cb} decay

Parameters: r_B, γ, δ_B, r_D~0.06, δ_D

ADS
(Atwood, Dunietz, Soni)

$$\left\{ \begin{array}{l} D^0 \to K^-\pi^+ \\ D^0 \to K^-\pi^+\pi^0 \\ D^0 \to K^-\pi^+\pi^-\pi^+ \end{array} \right.$$

(Very) small Branching Ratios

Strong phase between the D^0 decays

3) Use Dalitz plot analysis of 3-body D^0 decay, e.g. $D^0 \to K_S\pi\pi$

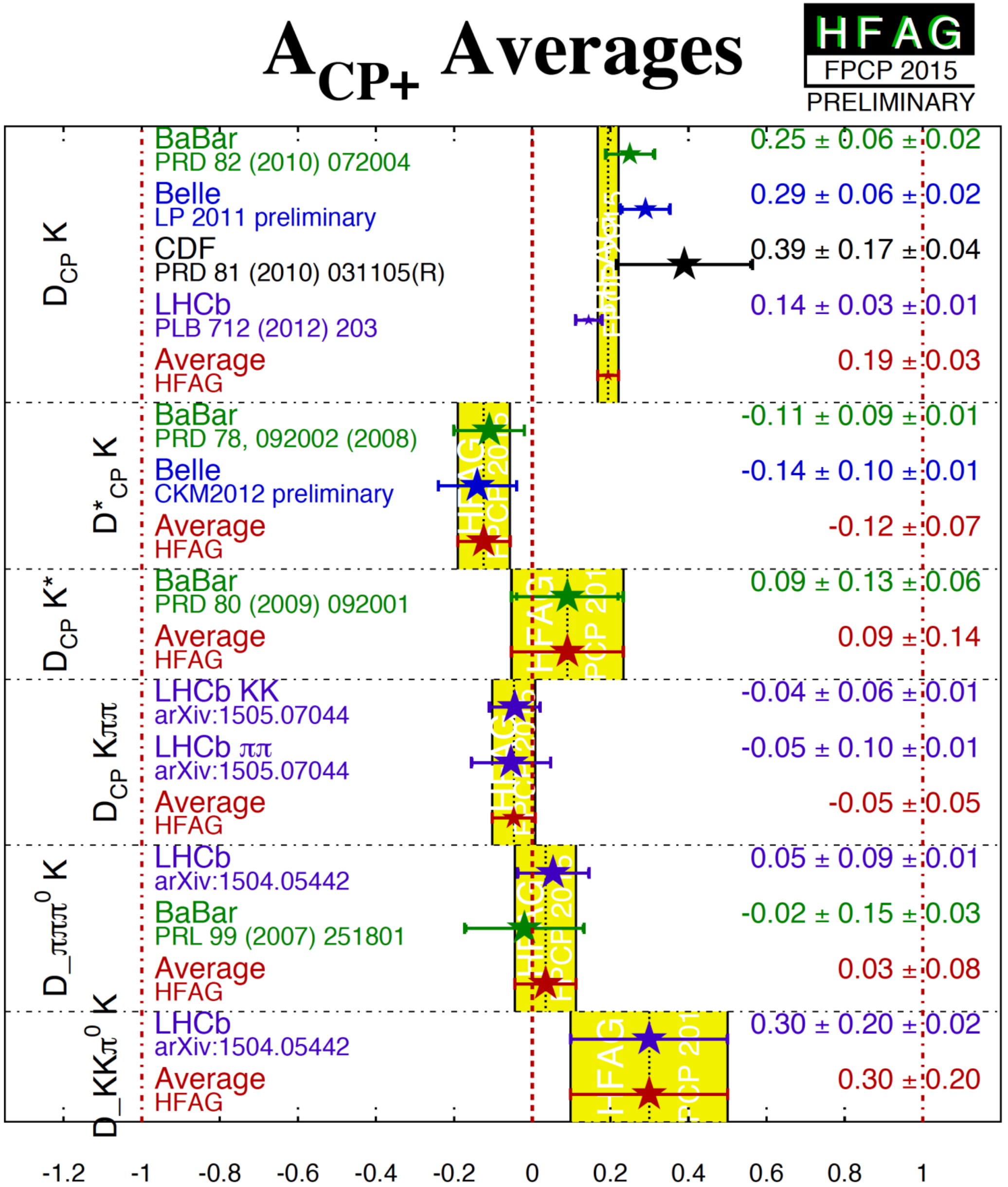
GGSZ (Giri, Grossman, Soffer, Zupan)

Dalitz plot description

- Most precise channel is $D_{CP}K$ (awaiting LHCb update with full Run I data sample)
- LHCb only combination, without latest results (but including measurements on DK^{*0} and time-dependent $D^{\pm}_sK^{\pm}$) :

  $$\gamma = (79^{+9}_{-10})^{\circ},$$

  best single-experiment result (CKM2014 update)
- New LHCb measurements with competitive sensitivity



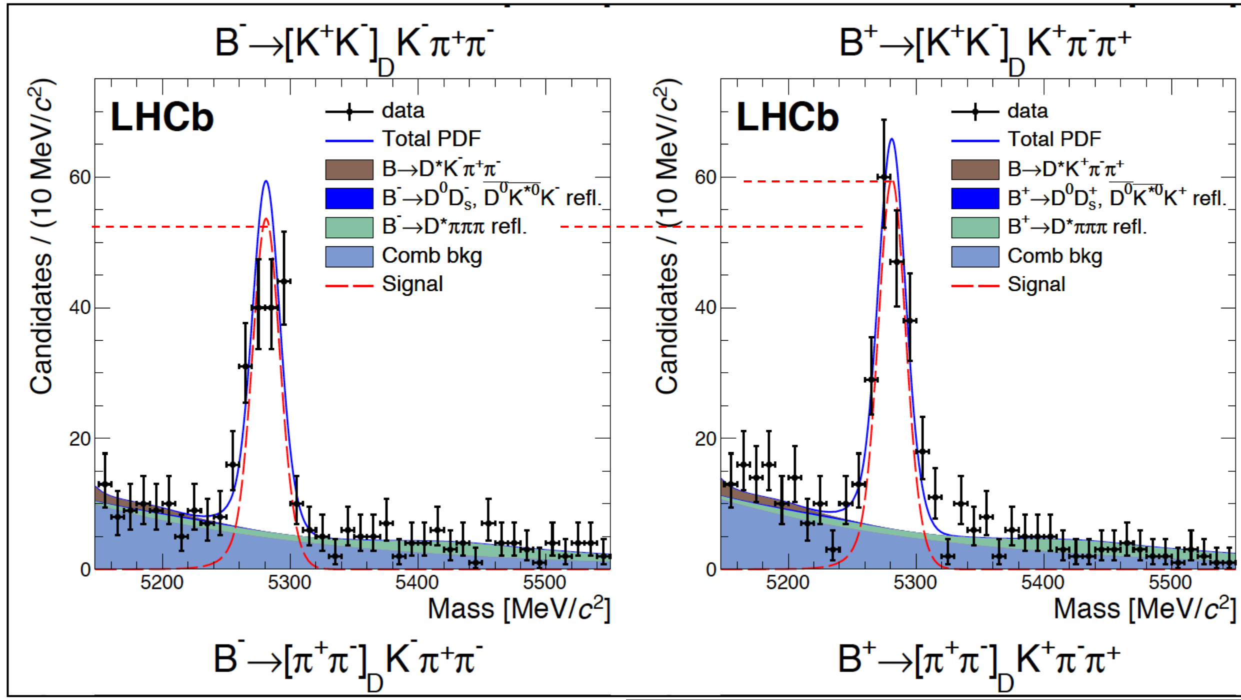
Angle γ, new decay modes

arXiv:1505.07044 3.0 fb^{-1}

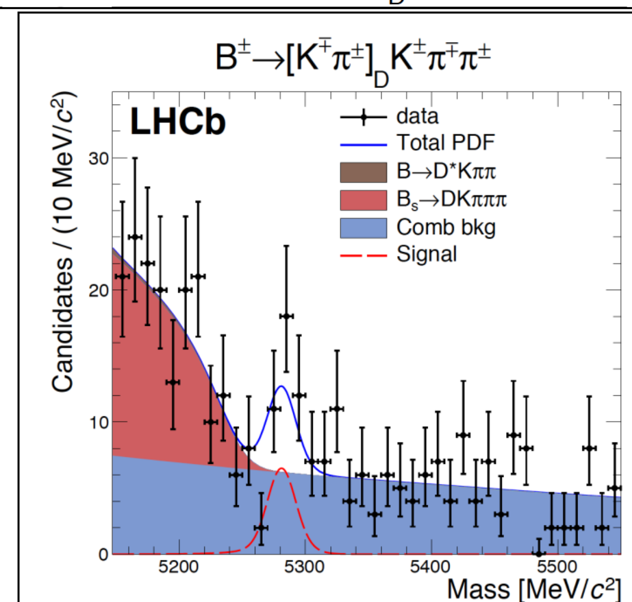
- Highly **significant signals in CP modes** $B^- \to DK^-\pi^+\pi^-$, $D \to K^+\pi^-, K^+K^-, \pi^+\pi^-$

- **New independent LHCb measurement:**

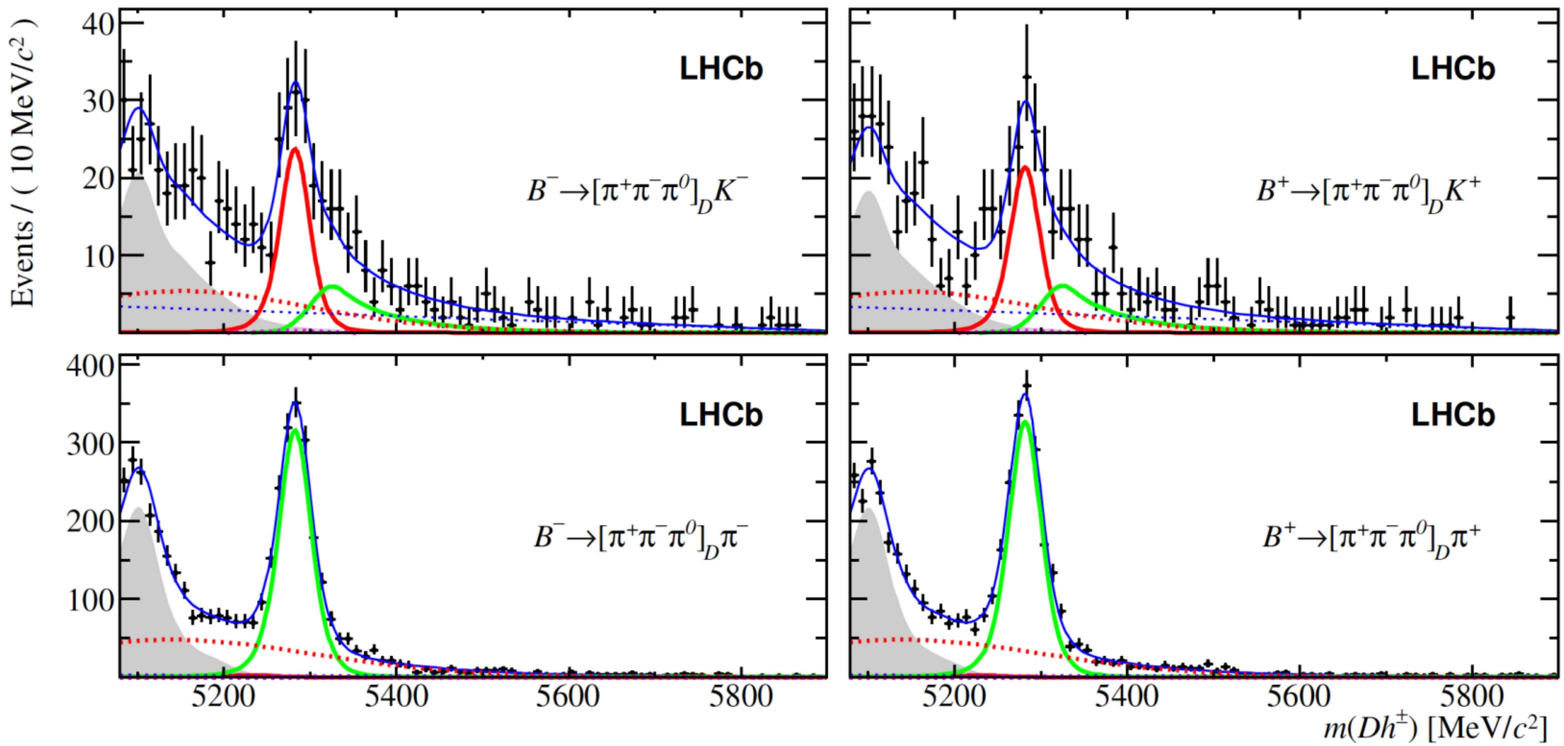
$$\gamma = (74^{+20}_{-18})^o$$



- First observation of **the suppressed ADS mode** $B^- \to (K^+\pi^-)_D K^-\pi^+\pi^-$, *very sensitive to γ*



- $B^- \to DK^-$ with D^0 modes including π^0 : PRD 91 (2015) 112014
  $D \to \pi^+\pi^-\pi^0$, $D \to K^+K^-\pi^0$ and $D \to K^-\pi^+\pi^0$ (ADS) 3.0 fb^{-1}



- Recent analysis of coherently produced DD at ψ(3770) : $D \to \pi^+\pi^-\pi^0$ very close to a CP-even eigenstate (CP-even fraction $F_+ = 0.968\pm0.017$)
  → γ analysis (so-called quasi-GLW) PLB 740 (2015) 1
- No evidence of CPV yet at LHCb, good consistency with other measurements

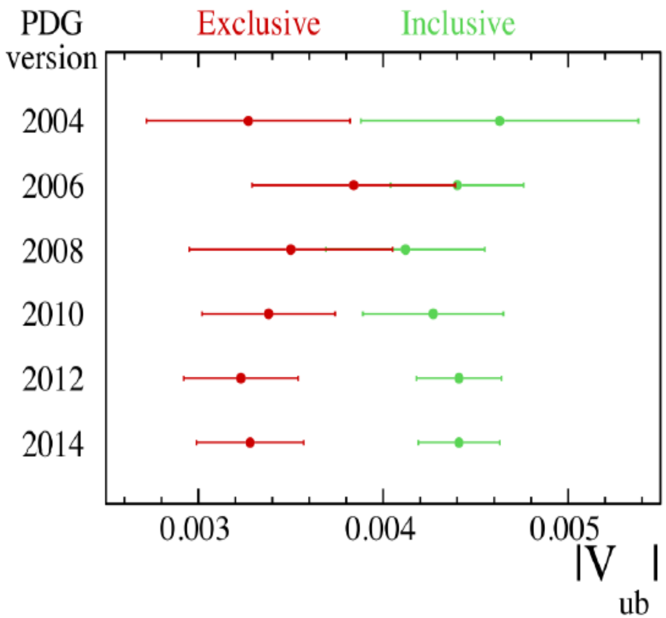
- Long standing **discrepancy between exclusive and inclusive measurements**, now at 3.8σ level:

  inclusive

  $|V_{cb}| = (42.4 \pm 0.9)\times10^{-3}$, $|V_{ub}| = (4.41 \pm 0.15)\times10^{-3}$

  exclusive

  $|V_{cb}| = (39.5 \pm 0.8)\times10^{-3}$, $|V_{ub}| = (3.23 \pm 0.31)\times10^{-3}$



- **NP RH coupling** to explain the discrepancy

$$\mathcal{L}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{ub}^{L} \left(\bar{u}\gamma_\mu P_L b + \epsilon_R \bar{u}\gamma_\mu P_R b\right)\left(\bar{\nu}\gamma^\mu P_L l\right) + h.c.$$

F. Bernlochner et al. PRD 90 (2014) 094003

- LHC provides rich sample of Λ_b :

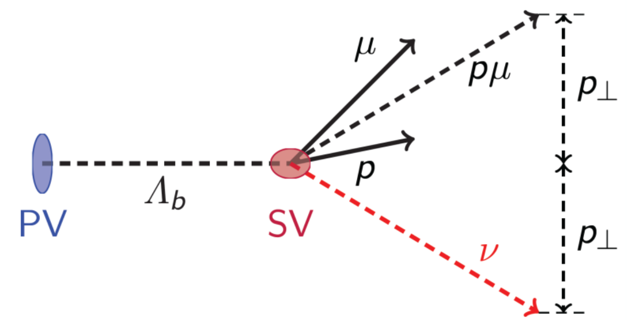
  Bd : Bs : Λ_b ~ 4 : 1 : 2 in LHCb acceptance

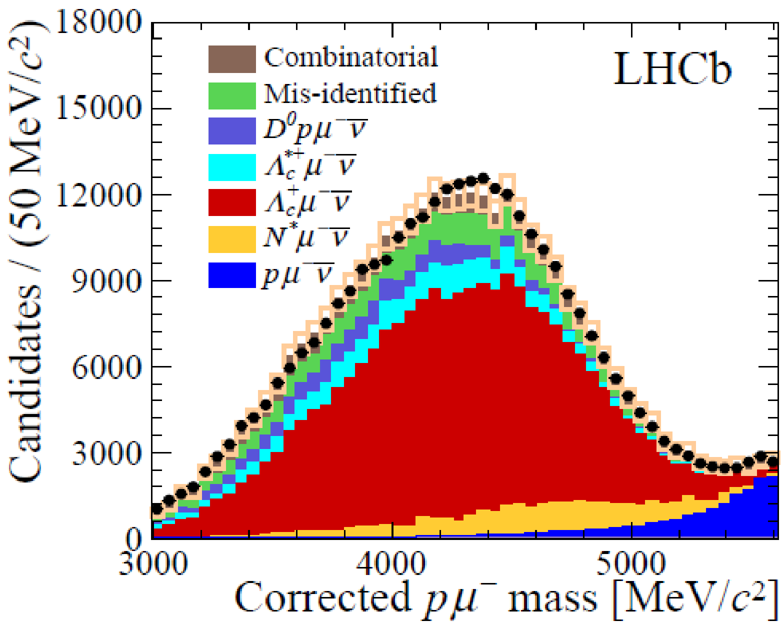
- Directly compare $\Lambda_b \to p\mu^-\bar{\nu}$ with $\Lambda_b \to \Lambda_c^+ (pK^-\pi^+)\, \mu^-\bar{\nu}$

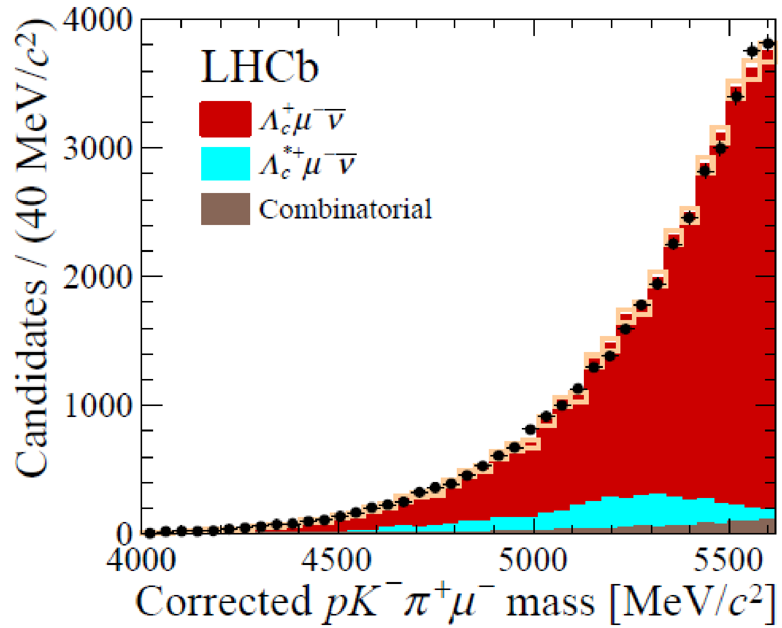
$|V_{ub}/V_{cb}|$ from $\Lambda_b \to p\mu\nu$ / $\Lambda_b \to \Lambda_c^+\mu\nu$

Nature Phys. 11 (2015) 743
2.0 fb^{-1}

- Lattice QCD form factors, needed in the calculation of $|V_{ub}|$, are most precise at high $q^2(\mu\nu)$, PRD 92 (2015) 3, 034503
  use $q^2(\mu\nu) > 15\ GeV^2$
- q^2 determined using Λ_b flight direction and mass, up to a two-fold ambiguity
- Vertex isolation is used, $\Lambda_c^+ \to pK^-\pi^+$ cross-feed is the main background
- Use **corrected mass**: $M_{corr} = \sqrt{M_{h\mu}^2 + p_\perp^2} + p_\perp$







$|V_{ub}/V_{cb}|$ from $\Lambda_b \to p\mu\nu$ / $\Lambda_b \to \Lambda_c^+\mu\nu$

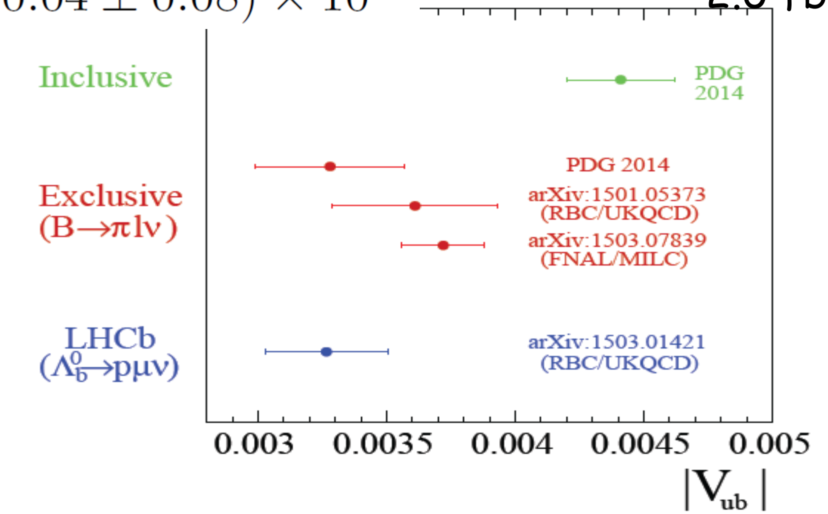
Nature Phys. 11 (2015) 743

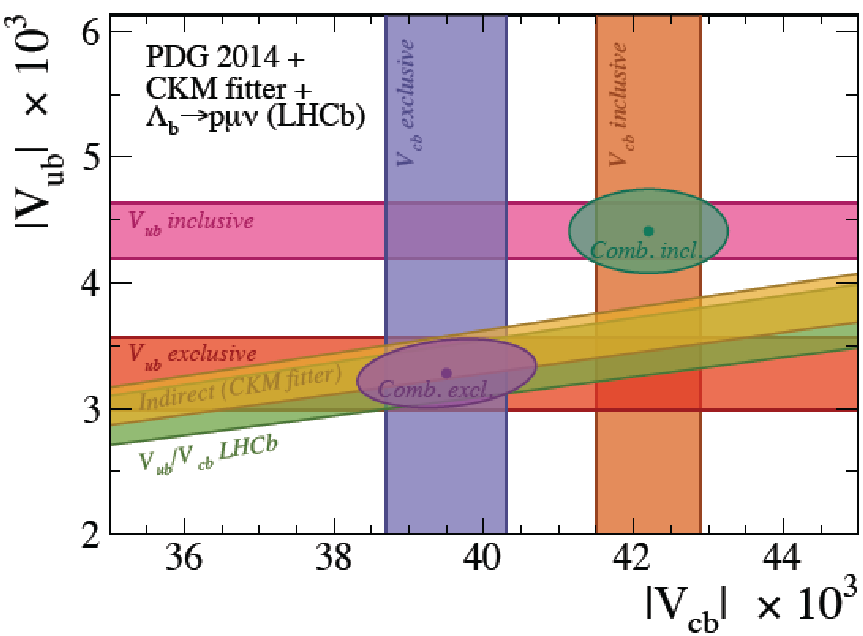
2.0 fb^{-1}

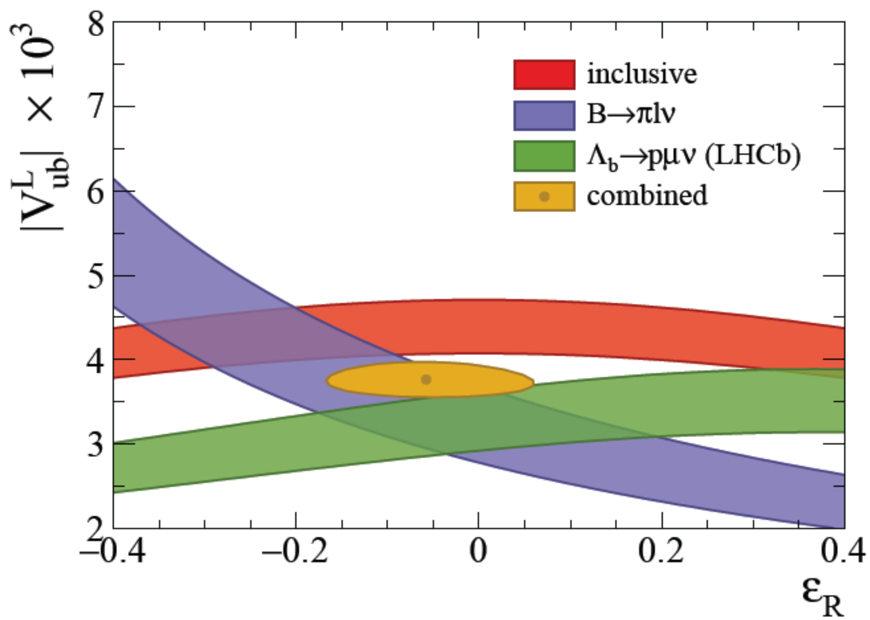
$$\frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}/c^2}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)_{q^2>7\,\mathrm{GeV}/c^2}} = (1.00 \pm 0.04 \pm 0.08) \times 10^{-2}$$

- First observation of $\Lambda_b \to p\mu\nu$

$$\boxed{\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004 \pm 0.004}$$

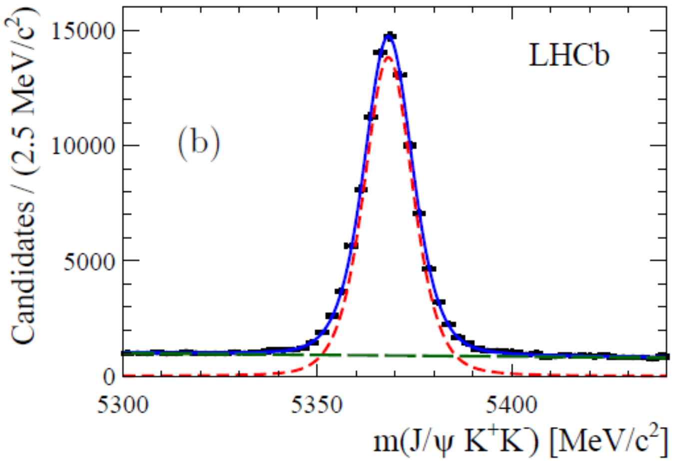


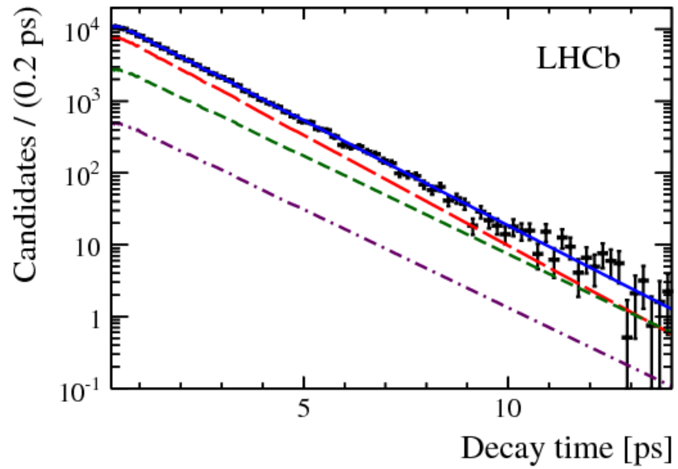




- LHCb results do not support RH currents, agree with exclusive

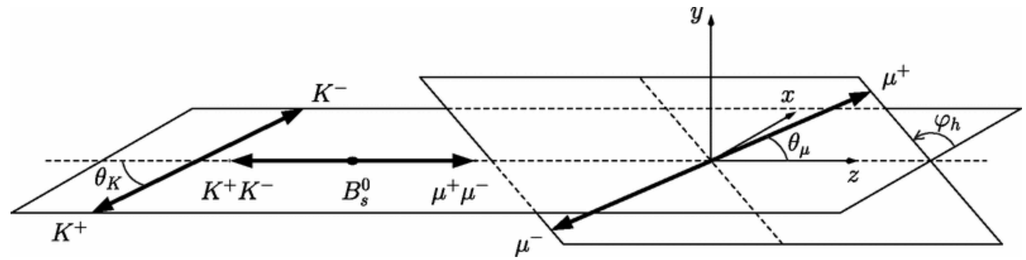
Weak phase ϕ_s via $B_s \to J/\psi K^+K^-$

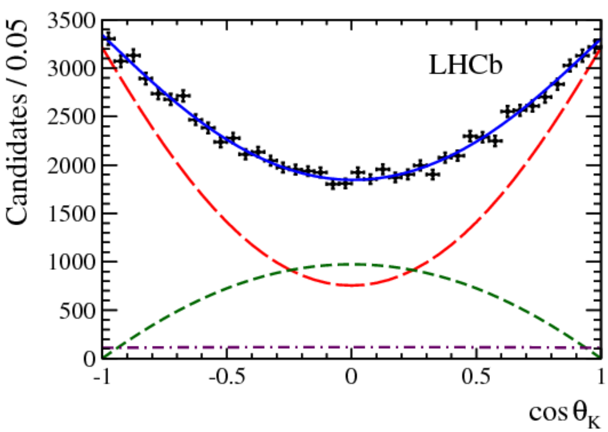


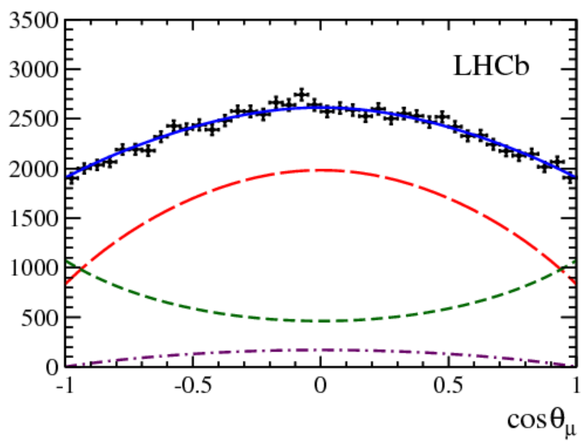


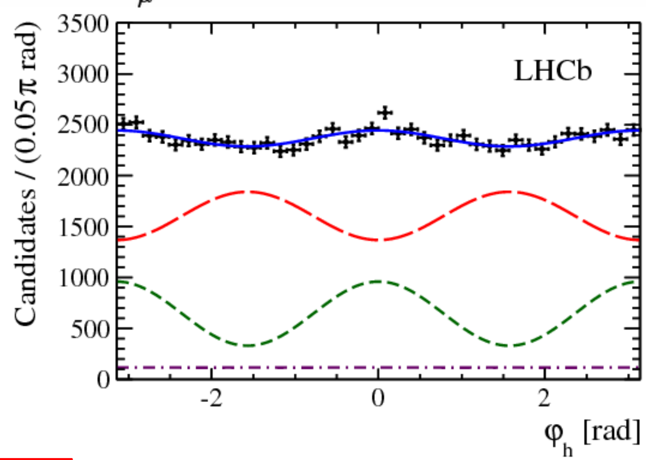
PRL 114 (2015) 041801
3.0 fb^{-1}

- Orbital angular momentum of the final state is mixture of CP-even and CP-odd components: L = 0, 1, 2
- **Disentangle CP even and CP odd amplitudes via time-dependent angular analysis**









$$\boxed{\phi_s = -0.058 \pm 0.049 \pm 0.006}$$

FIRST EVIDENCE OF NEW PHYSICS IN b ↔ s TRANSITIONS

(UT*fit* Collaboration)

arXiv:0803.0659v1

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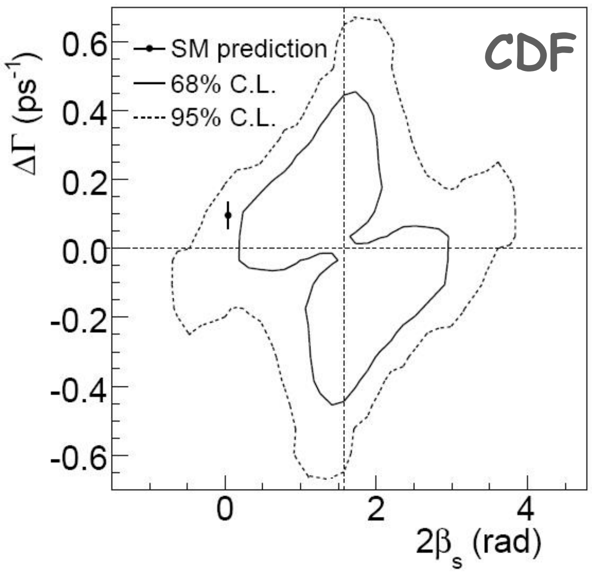
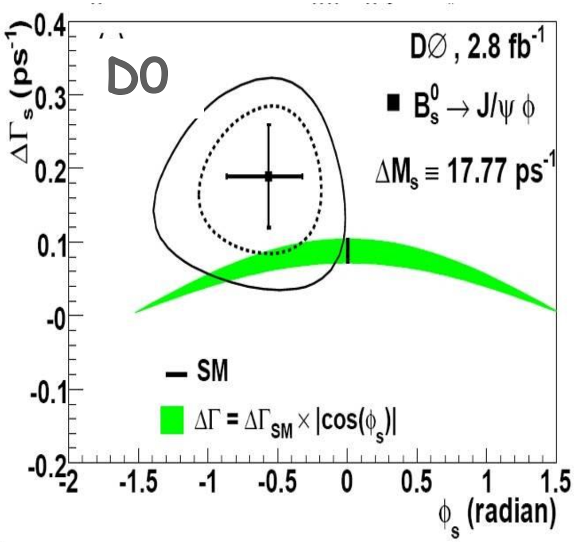
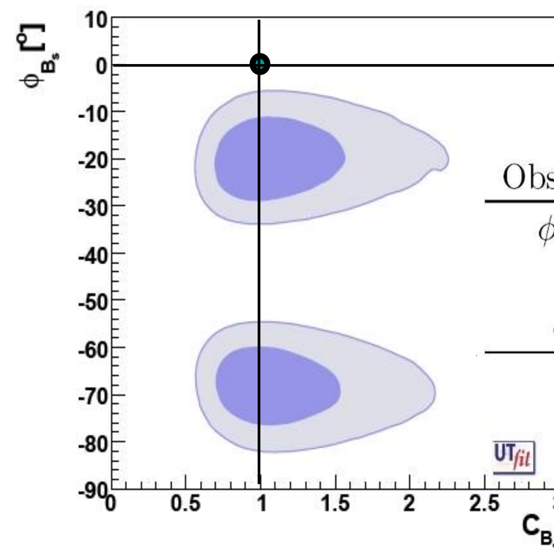
We combine all the available experimental information on B_s mixing, including the very recent tagged analyses of $B_s \to J/\Psi\phi$ by the CDF and DØ collaborations. We find that the phase of the B_s mixing amplitude deviates more than 3σ from the Standard Model prediction. While no single measurement has a 3σ significance yet, all the constraints show a remarkable agreement with the combined result. This is a first evidence of physics beyond the Standard Model. This result disfavours New Physics models with Minimal Flavour Violation with the same significance.



NP parameterization $C_{B_s}\, e^{2i\phi_{B_s}} = \dfrac{A_s^{\rm SM} e^{-2i\beta_s} + A_s^{\rm NP} e^{2i(\phi_s^{\rm NP}-\beta_s)}}{A_s^{\rm SM} e^{-2i\beta_s}} = \dfrac{\langle B_s | H_{\rm eff}^{\rm full} | \bar{B}_s\rangle}{\langle B_s | H_{\rm eff}^{\rm SM} | \bar{B}_s\rangle}$,

>3σ NP effect in φ_s





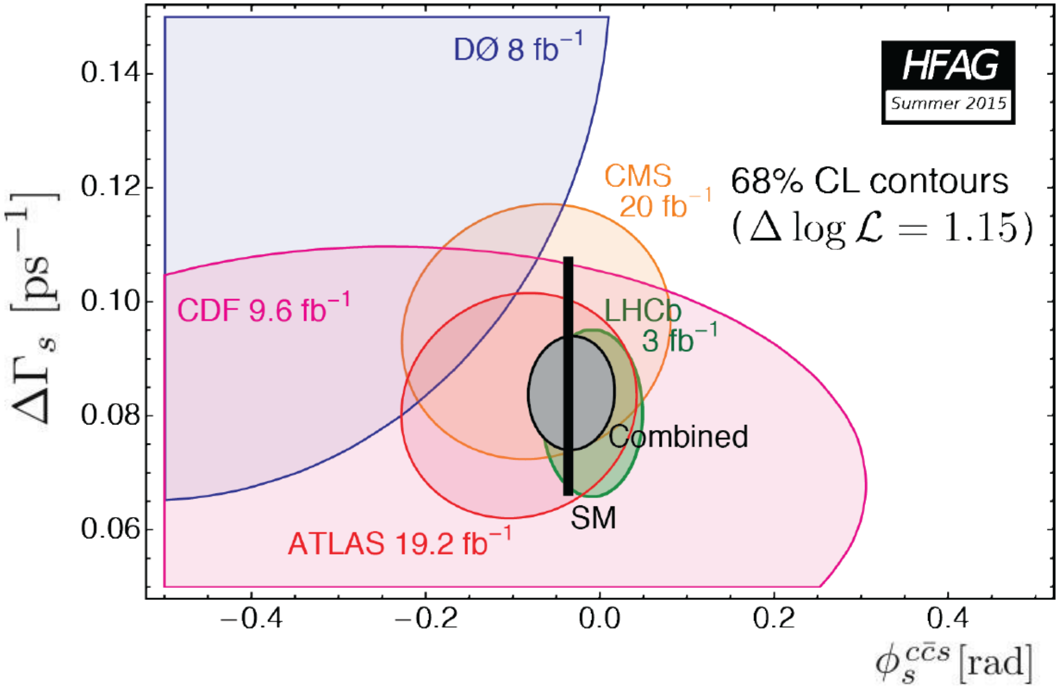
Observable	68% Prob.	95% Prob.
ϕ_{B_s} [°]	-19.9 ± 5.6	[-30.45,-9.29]
	-68.2 ± 4.9	[-78.45,-58.2]
C_{B_s}	1.07 ± 0.29	[0.62,1.93]

LHCb : $\sigma_{stat}(\varphi_s)$ ~0.02 (~1°) in one LHCb year (2 fb^{-1})

A slide from introduction to Moriond QCD 2008

Weak phase ϕ_s via $B_s \to J/\psi K^+K^-$ (ϕ)

Shown on EPS-HEP

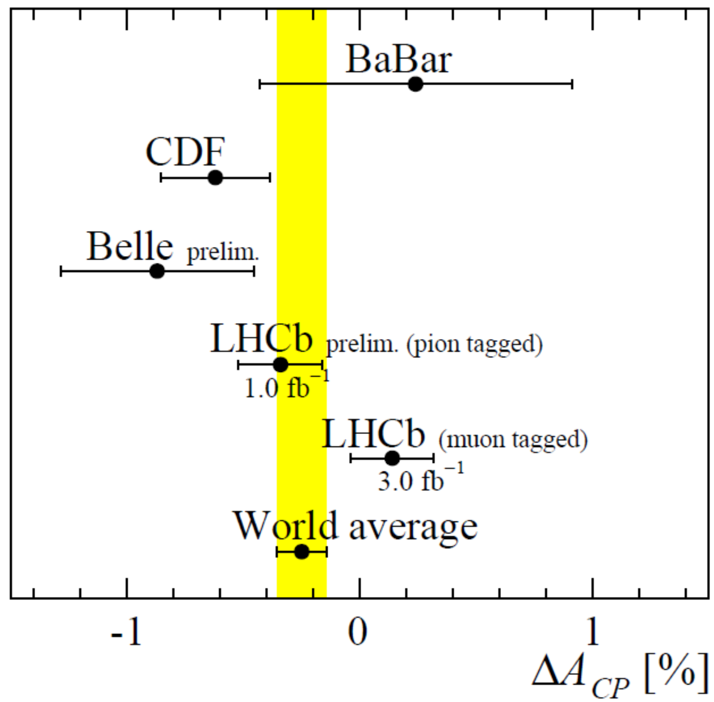


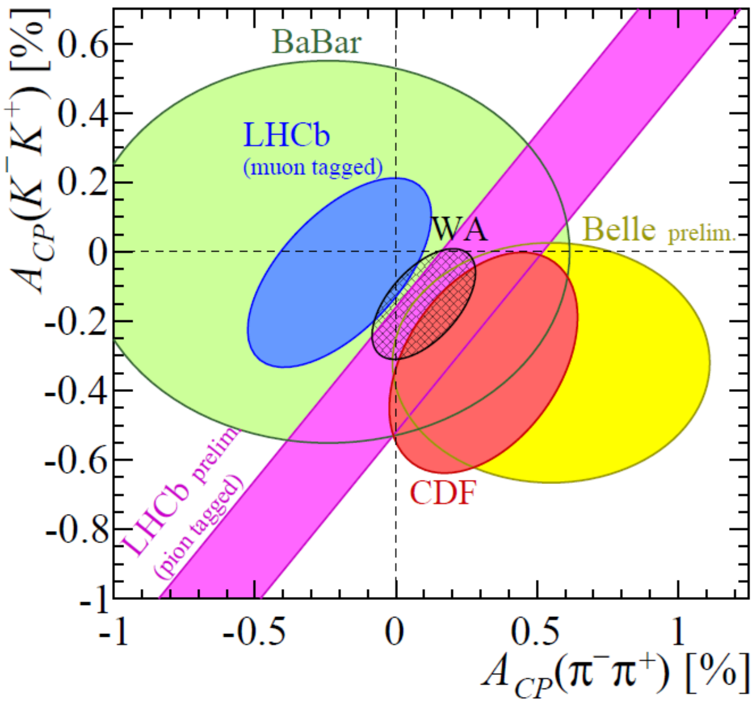
Combination of $B_s \to J/\psi K^+K^-$, $B_s \to J/\psi\, \pi^+\pi^-$ and $B_s \to D_s^+D_s^-$

- SM: $\phi_s = -\,0.0363\,^{+0.0014}_{-0.0012}$ rad
- Experiment: $\phi_s = -\,0.034 \pm 0.033$ rad

- Results consistent with SM
- Measurements statistically limited

- CPV in charm, 1% effects would mean NP



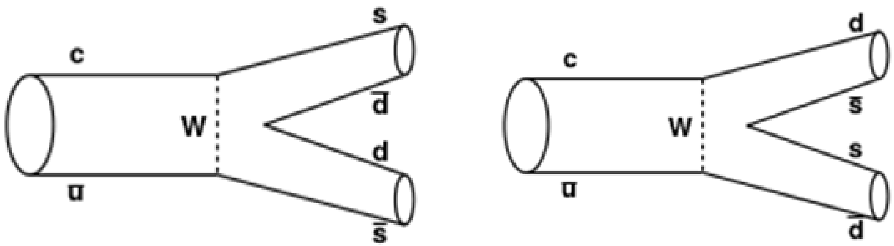


- $A_{CP}(K^+K^-) = (-0.016 \pm 0.012)\%$
- $A_{CP}(\pi^+\pi^-) = (-0.05 \pm 0.15)\%$
- $\Delta A_{CP} = (-0.253 \pm 0.104)\%$ [HFAG 2/2015]

CP asymmetry in $D^0 \rightarrow K^0_S K^0_S$

arXiv:1508.06087   3.0 fb^{-1}

- $D^0 \rightarrow K^0_S K^0_S$ proceeds via **two annihilation diagrams, in SM phases cancel**

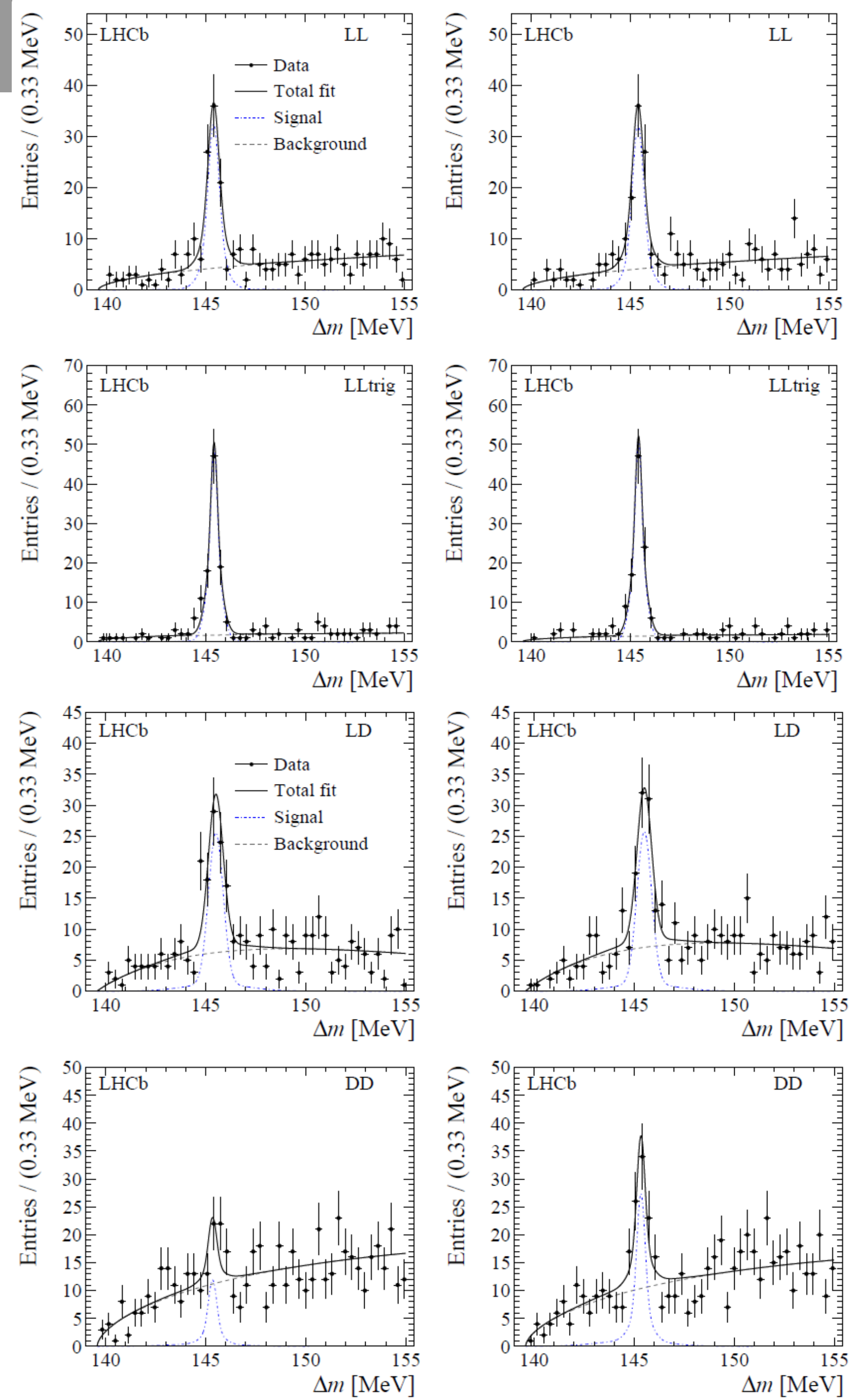


- Can only trigger on cases where both K^0_S decay in VELO ("LLtrig")
- Three other categories with 0 (DD), 1 (LD) or 2 (LL, but not triggered) K^0_S in VELO

  → 600 decays, tagged by D* charge

$$A_{CP} = -(2.9 \pm 5.2 \pm 2.2)\%$$

- Compatible with CP symmetry



$D^0 \to h^+h^-$: A_Γ with semileptonic decays

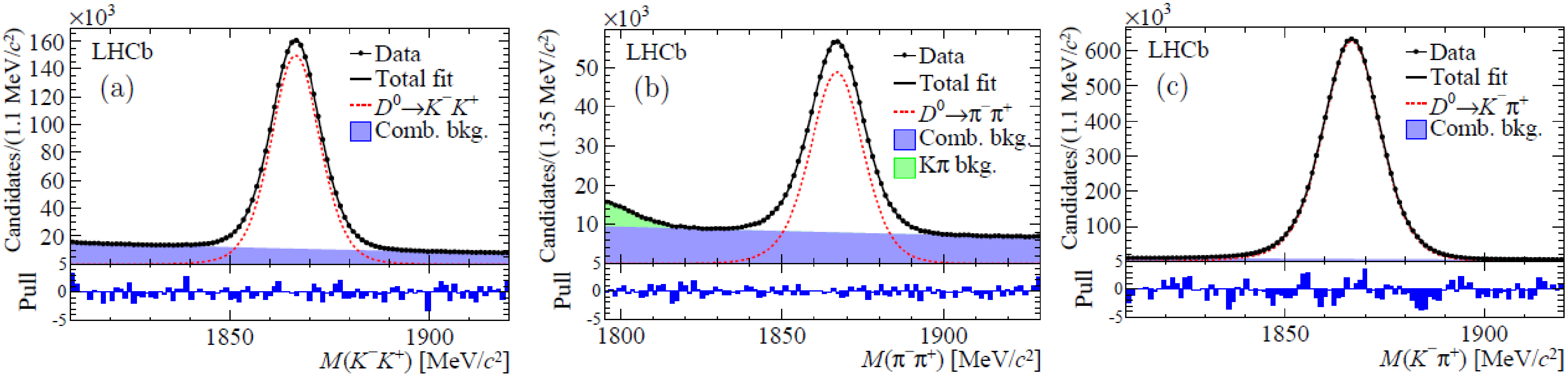
- Measurement of time-dependent CPV for $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$ and $D^0 \to \pi^+K^-$ from semileptonic B-decays

JHEP 1504 (2015) 043
3.0 fb^{-1}

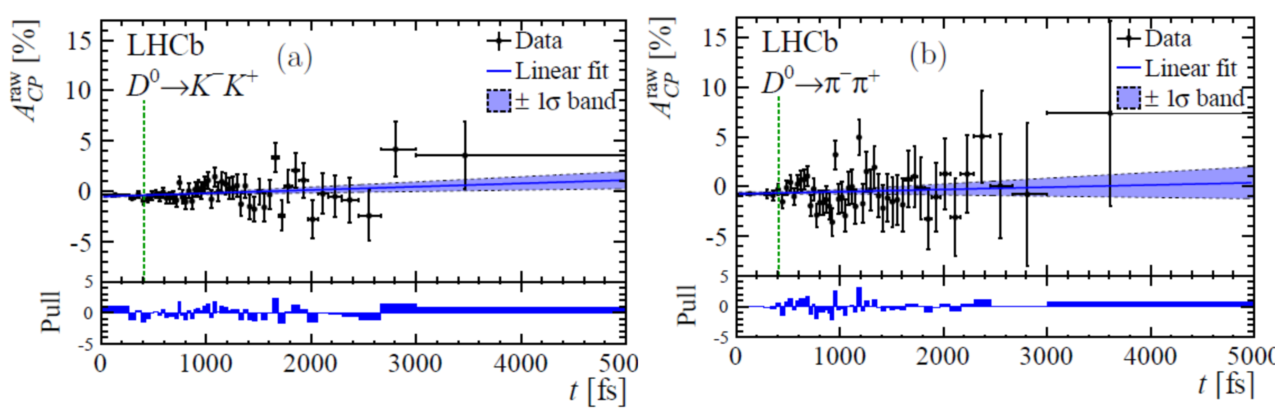
$$A_{CP}(t) \approx A_{CP}^{dir} - A_\Gamma \times t/\tau$$

- A_Γ is the asymmetry of effective lifetimes of D^0 and $\overline{D}^0$:

$$A_\Gamma \approx \left(\tfrac{1}{2} A_{CP}^{mix} - A_{CP}^{dir} \right) y \cos\phi - x \sin\phi$$



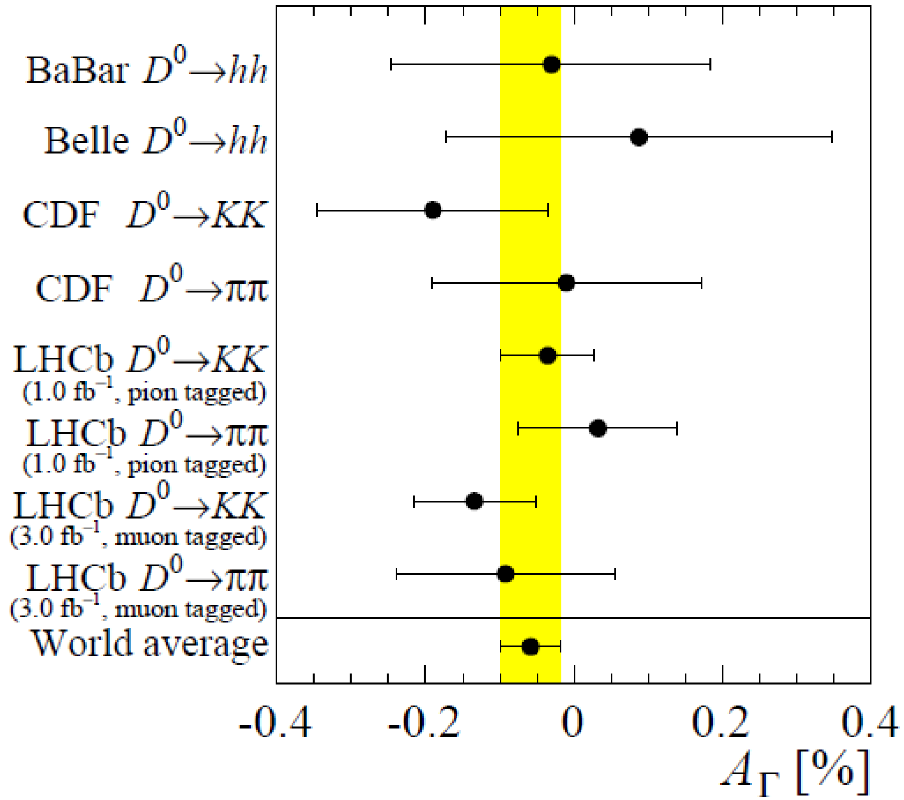
- Lifetime obtained from the $D^0\mu$ and $D^0 \to h^+h^-$ vertices



$D^0 \to h^+h^-$: A_Γ with semileptonic decays

JHEP 1504 (2015) 043 3.0 fb^{-1}

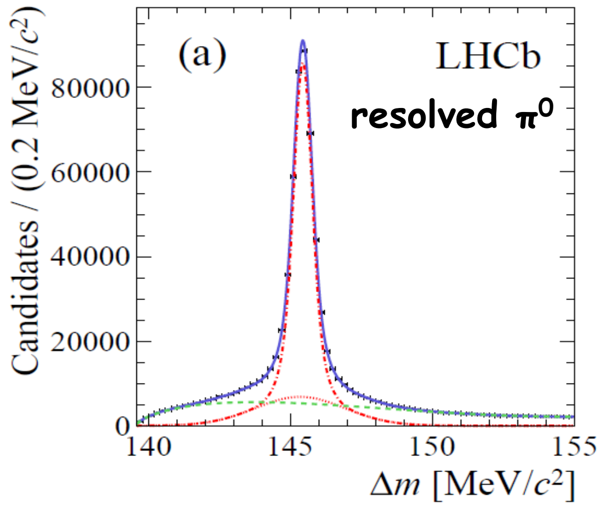
$$A_\Gamma(K^-K^+) = (-0.134 \pm 0.077\ ^{+0.026}_{-0.034})\%$$
$$A_\Gamma(\pi^-\pi^+) = (-0.092 \pm 0.145\ ^{+0.025}_{-0.033})\%$$

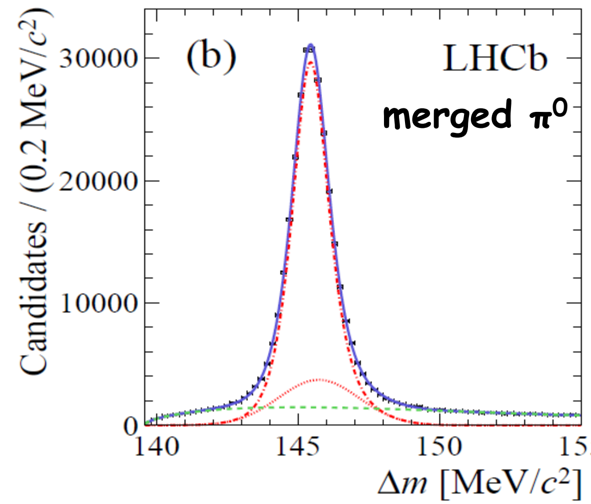


CPV in $D^0 \to \pi^+\pi^-\pi^0$ with Energy Test

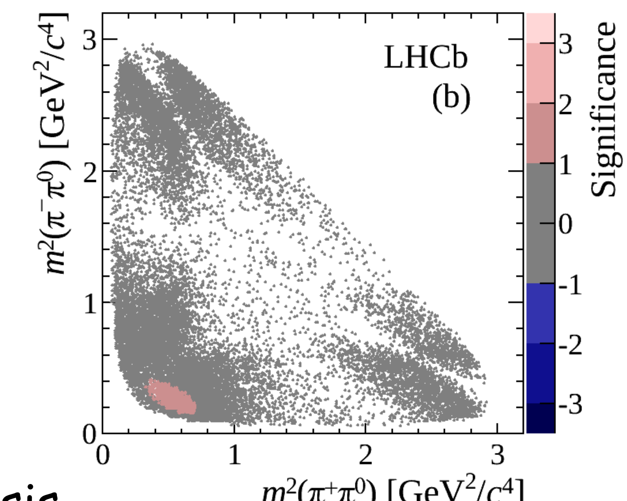
PLB 740 (2015) 158 2.0 fb^{-1}

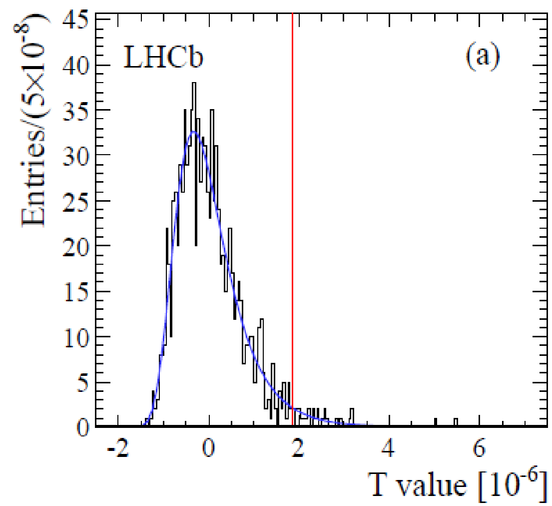
- ❑ Model-independent search for local CP asymmetry in tagged $D^0 \to \pi^+\pi^-\pi^0$ decays
- ❑ Use resolved (both γ seen) and merged π^0





- ❑ **Energy test**: Unbinned test of compatibility between D^0 and $\bar{D}^0$ Dalitz distributions
- ❑ Based on distance in phase-space of events
- ❑ **Sensitive to local asymmetries**
- ❑ The data are found to be consistent with the hypothesis of CP symmetry with a p-value of (2.6 ± 0.5).

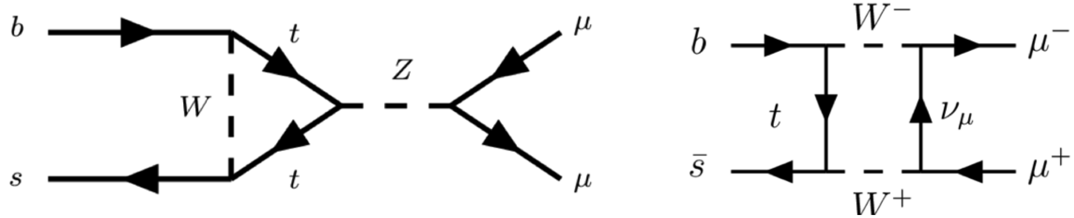




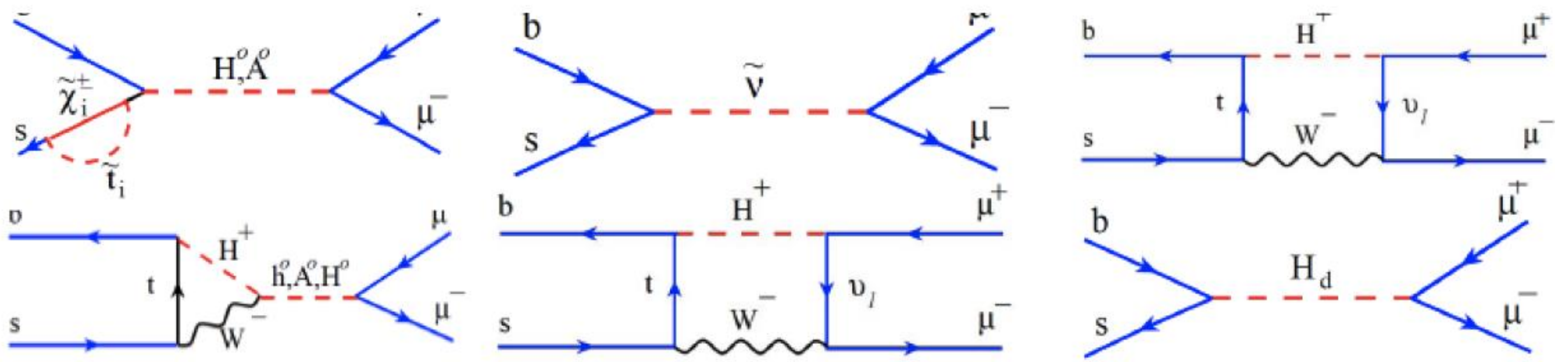
Rare decays: search for $B_{d,s} \to \mu\mu$

- Very rare in SM, CKM and helicity suppressed
- $BR(B_s \to \mu+\mu-)_{SM} = (3.66 \pm 0.23)\times10^{-9}$, $BR(B_d \to \mu+\mu-)_{SM} = (1.06 \pm 0.09)\times10^{-10}$

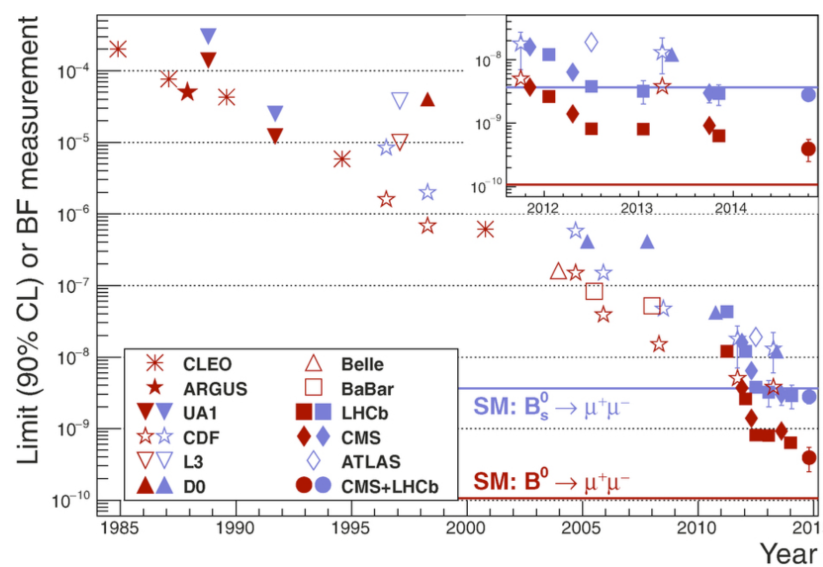
SM



NP

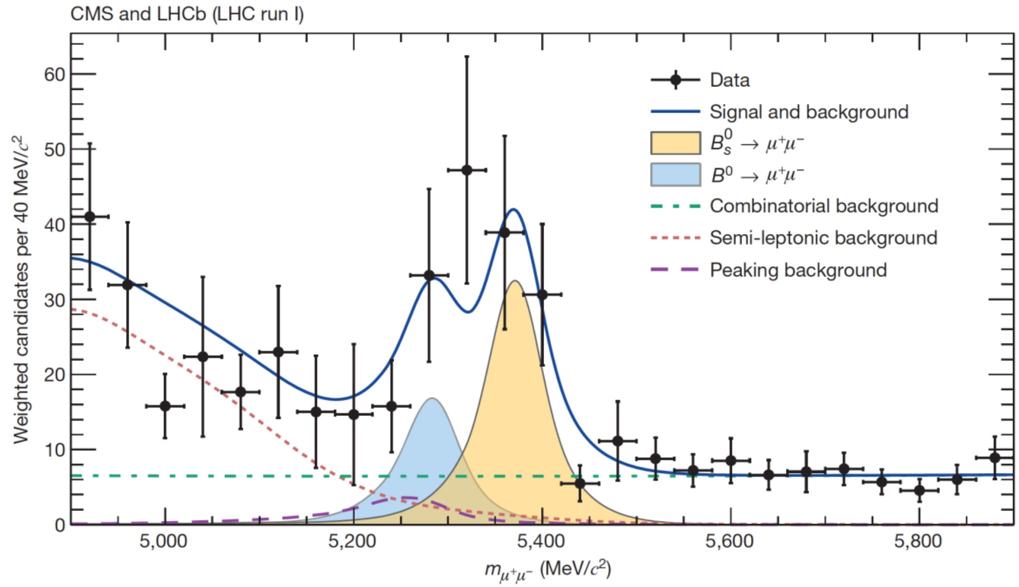


- Search for B_d and B_s: BRs could be modified differently by New Physics
- Exemplary sensitivity for SUSY: $B(Bs \to \mu+\mu-) \approx (\tan\beta)^6/M_{A0}$
- Improved by 6 orders of magnitude over 30 years …

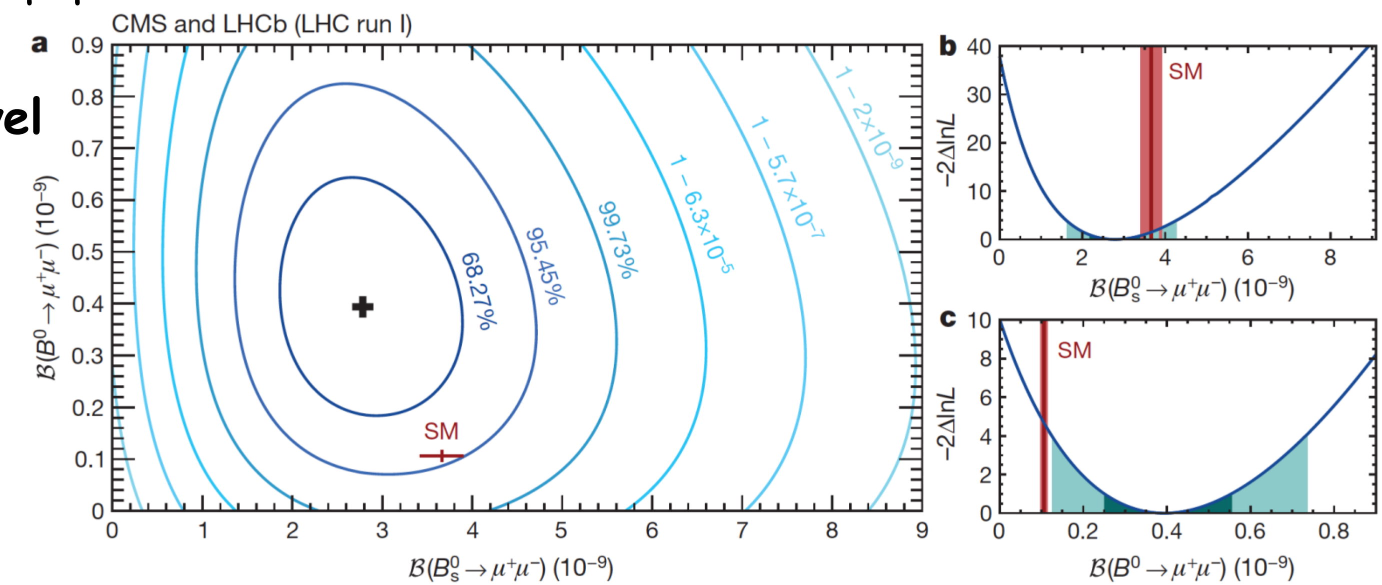


Nature Letter 522 (2015) 68

- Measurements by **LHCb and CMS**, complementary angular coverage, designed for different purposes
- CMS: higher instantaneous L
- LHCb: higher efficiency and dimuon mass resolution

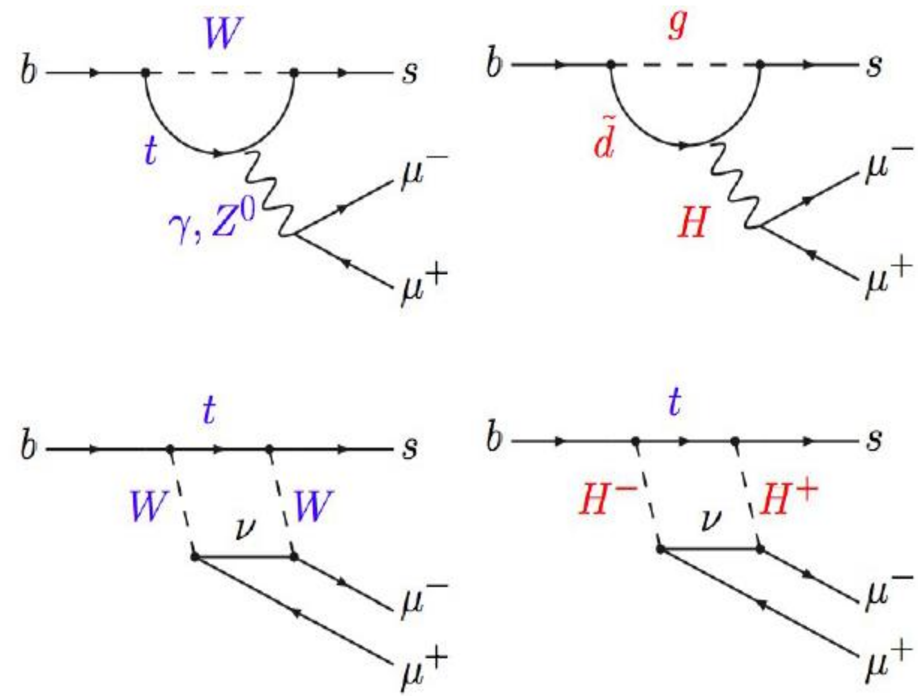


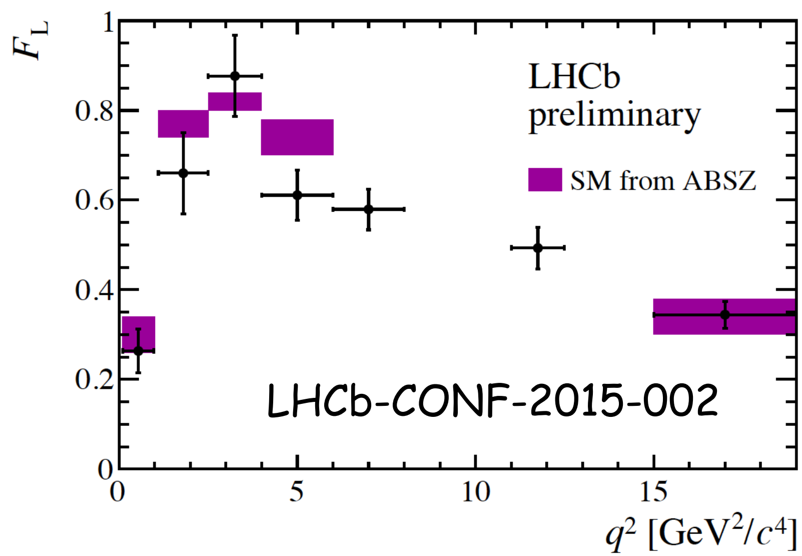
- Combination of CMS and LHCb
- Conclusive evidence for $B_s \to \mu^+\mu^-$
- 3σ effect for $B^0 \to \mu^+\mu^-$
- **Results consistent with SM at 2σ level**

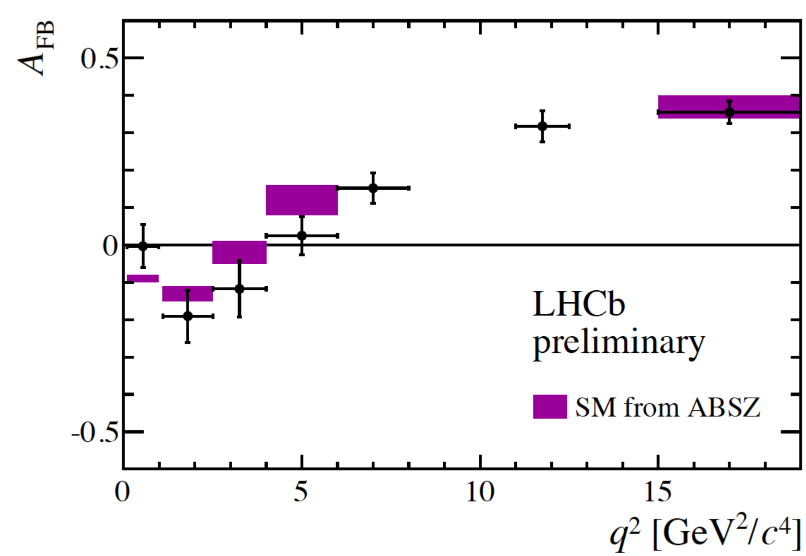


Angular analysis of $B_d \rightarrow K^{*0} \mu^+\mu^-$

- $b \rightarrow s \mu^+\mu^-$, FCNC transition
- SM: EW penguin, box diagrams
- Possible contribution from new heavy particles (Z', extra H...)
- Angular observables in $K^{*0}(K^+\pi^-)\mu^+\mu^-$ characterized by 6 amplitudes for K^{*0} helicities and $\mu^+\mu^-$ chiralities (L,R): $A_{0,\parallel,\perp}^{L,R}$
- Full set of 8 observables analised as function of $q^2(\mu^+\mu^-)$







- Zero crossing point q_0^2 sensitive to some MSSM models arXiv:0811.1214

- LHCb with 2011 dataset: local deviation from SM, >3σ significance for P'_5 observable PRL 111 (2013) 191801

- P'_5 is related to the L/R asymmetry of the interference between A_0 and $A_\perp$

$$P_5{}' = \sqrt{2} Re\left(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*}\right) / \sqrt{F_L(1-F_L)} = S_5 / \sqrt{F_L(1-F_L)}$$

$$F_L = |A_0^L|^2 + |A_0^R|^2$$

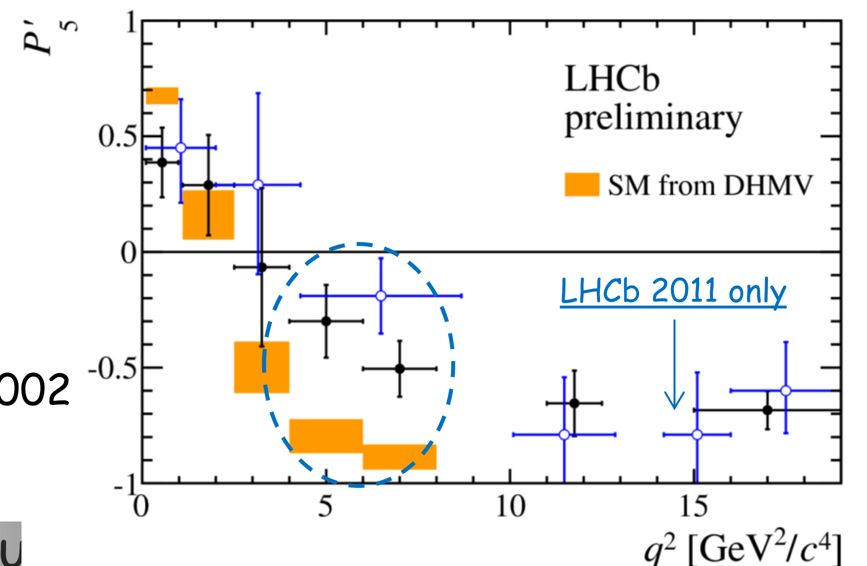
- **Sensitive to NP in VV or VA** (Wilson coefficient C_9)

S. Descotes-Genon, L. Hofer, J. Matias and J. Virto, arXiv:1407.8526

- Many interpretations of this discrepancy: over 13 papers in 2014.

- LHCb confirms a **3.7σ statistical discrepancy with 3 fb^{-1}**

LHCb-CONF-2015-002

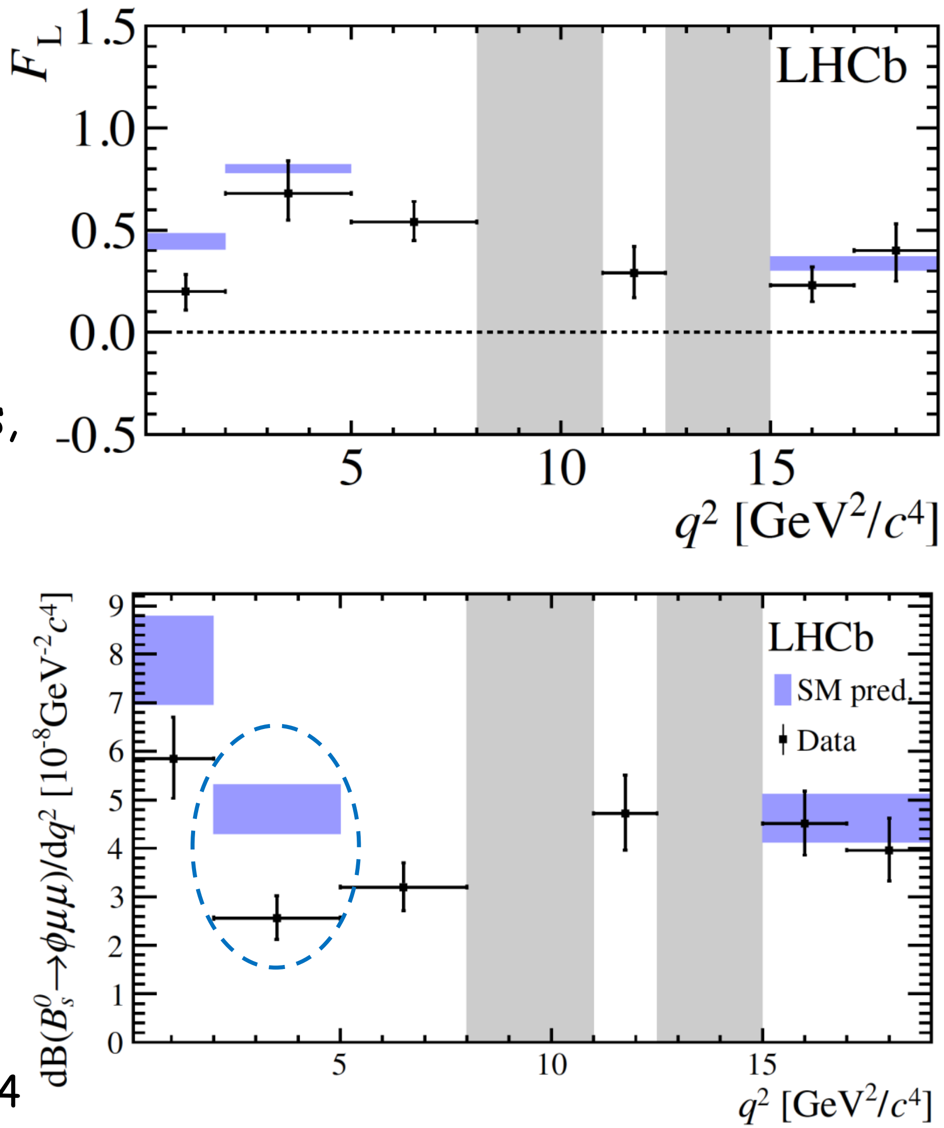


arXiv:1506.08777

- $B_s \rightarrow \Phi(K^+K^-)\ \mu^+\mu^-$ is not self-tagging
- Good complementarity (yield ≈ 1/6)
- Full angular analysis as function of $q^2(\mu^+\mu^-)$, all 8 observables determined for the first time
  - the observables are different from K* μμ (new CPV asymmetries, no S_5 or A_{FB})
- All **angular observables consistent with the SM**, but a local 3.3σ **tension in the BR**
  - a **similar trend** is also seen for the BRs of other $b \rightarrow s\ \mu^+\ \mu^-$ decays at LHCb:

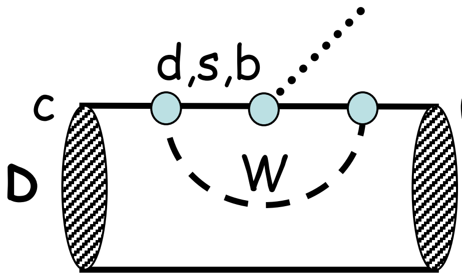
$B_d \rightarrow K(*)\ \mu^+\ \mu^-$, JHEP06 (2014) 133

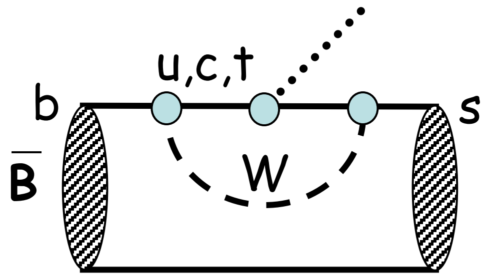
$B^+ \rightarrow K^+\ \pi^+\ \pi^-\ \mu^+\ \mu^-$, JHEP 10 (2014) 064



Rare charm decays

- Decays are suppressed in the SM (10^{-9}-10^{-10}), potential NP enhancement by an order of magnitude. E.g. beauty penguin wins due to t-quark contribution





Modes	Run I	Run II	Upgrade
$D^0 \to \mu^+\mu^-$	few 10^{-9}	fewer 10^{-9}	few 10^{-10}
$D^+ \to \pi^+\mu^+\mu^-$	few 10^{-8}	fewer 10^{-8}	few 10^{-9}
$D^+_s \to K^+\mu^+\mu^-$	few 10^{-7}	fewer 10^{-7}	few 10^{-8}
$D^0 \to h^+h'^{(-)}\mu^+\mu^-$	few 10^{-7}	fewer 10^{-7}	few 10^{-8}
$\Lambda_c \to p\mu\mu$	few 10^{-7}	fewer 10^{-7}	few 10^{-8}
$D^0 \to \mu e$	few 10^{-8}	fewer 10^{-8}	few 10^{-9}

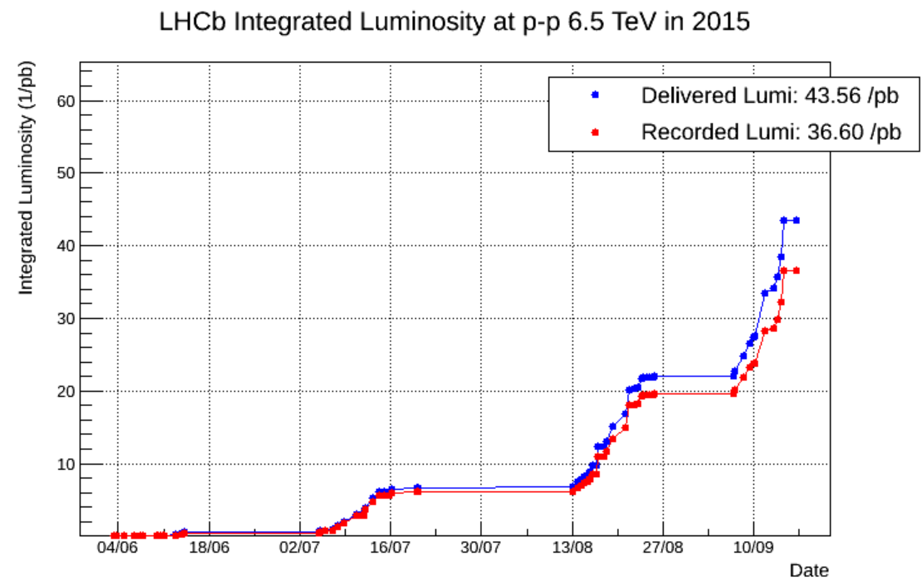
- Based on current result, scaling for luminosity and cross section
- Current studies. With more statistics, also NP-sensitive asymmetries

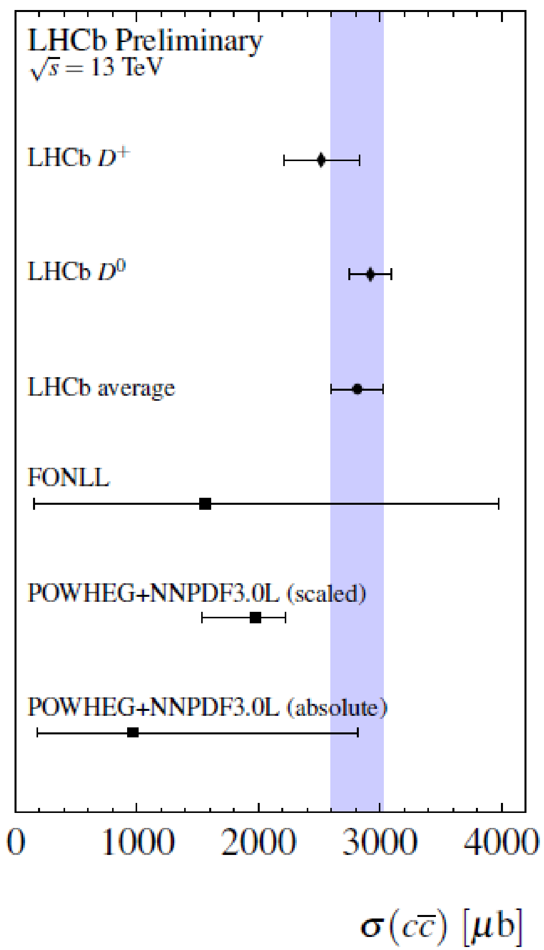
- These modes will benefit from a full-software trigger after LS2, with a gain >3 in efficiency (not included in prospects above)
- Theoretical framework to **combine rare charm** measurements needed

Status and outlook

- **LHCb, Run II** until 2018: $\sqrt{s}$ = 13 TeV, goal is L ~ 4 x 10^{32} cm^{-2} s^{-1}, bunch crossing spacing of 25 ns, μ = 1.4

- LHC is progressing to deliver nominal L





$b\bar{b}$ cross-section with 4π extrapolation*

arXiv:1509.00771

$$\sigma = 515 \pm 2(\text{stat}) \pm 53(\text{syst})\ \mu\text{b}$$

$c\bar{c}$ production cross-section

LHCb-PAPER-2015-041

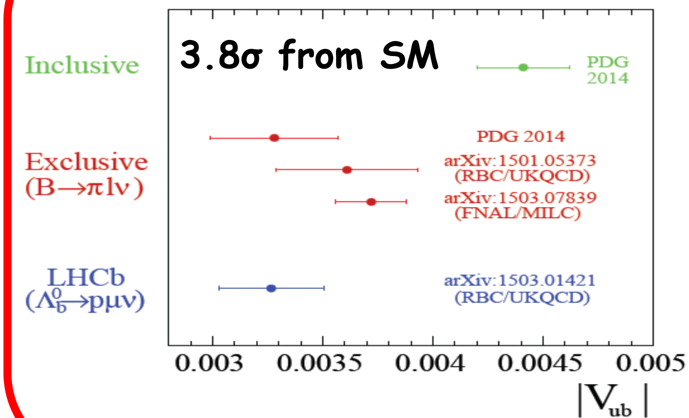
$$\sigma(c\bar{c}) = 2850 \pm 3(\text{stat}) \pm 180(\text{syst}) \pm 140(\text{frag})\ \mu\text{b}$$

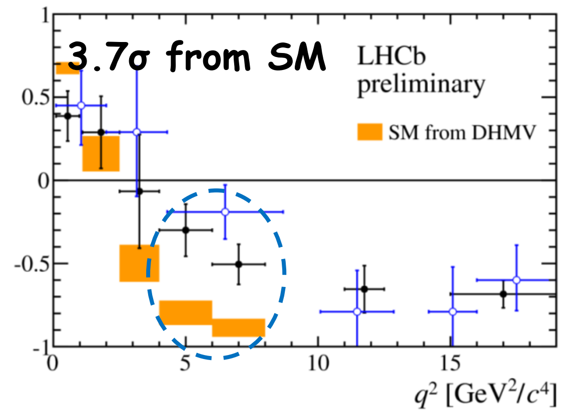
Collect and exploit data !

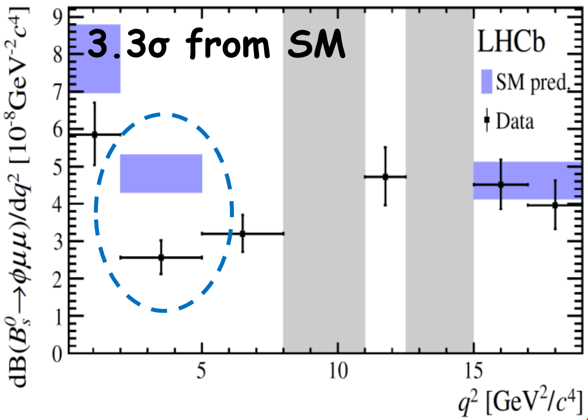
- **Upgraded LHCb, Run III** from 2019-2020 on: $\sqrt{s}$ = 14 TeV, L ~ 10^{33} cm^{-2} s^{-1} (newcoming detectors designed to operate at L ~ 2 x 10^{33} cm^{-2} s^{-1}), bunch crossing spacing of 25 ns, μ = 2, improved trigger efficiency, $\int Ldt$ ~ 5 fb^{-1} /year

- ❑ Do we start seeing signs of effects beyond SM ?

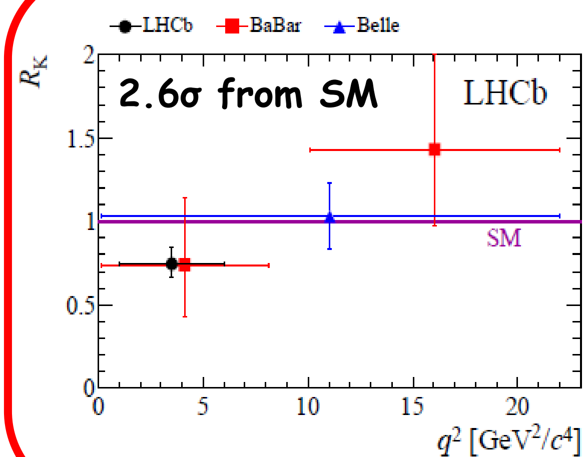
Promising differences in the studies covered in the talk

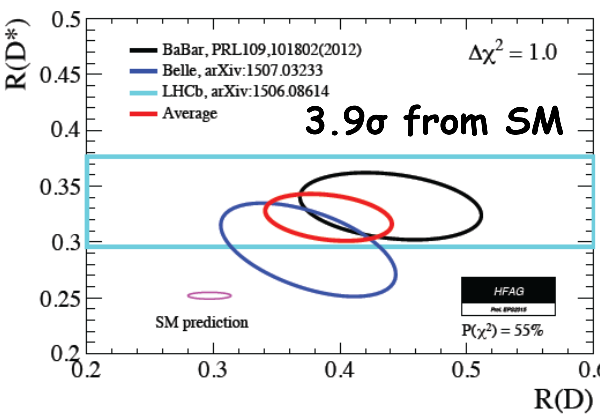






Differences in the studies left beyond the talk



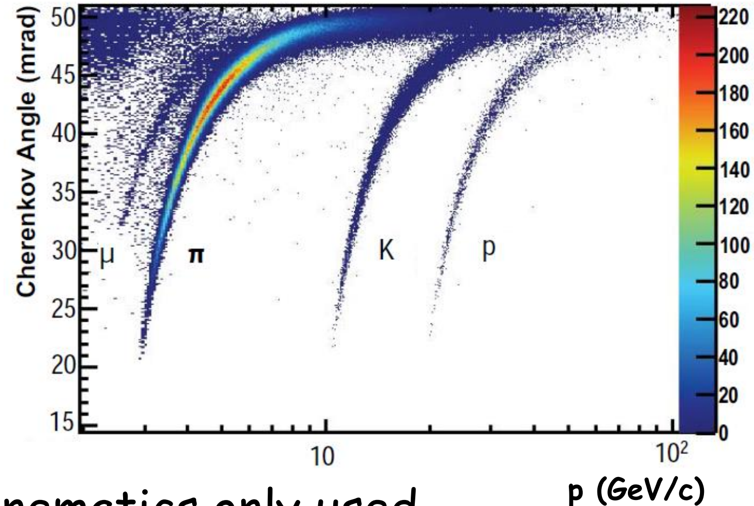


Backup

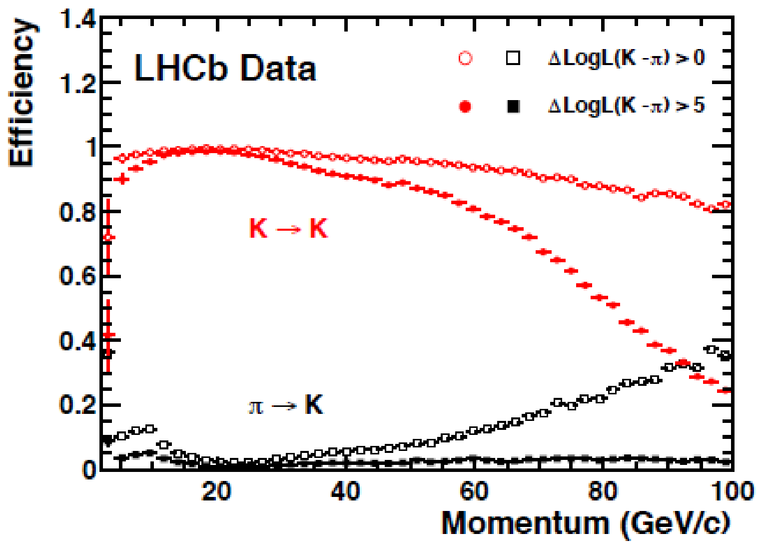
RICH detectors : charged particles identification performance

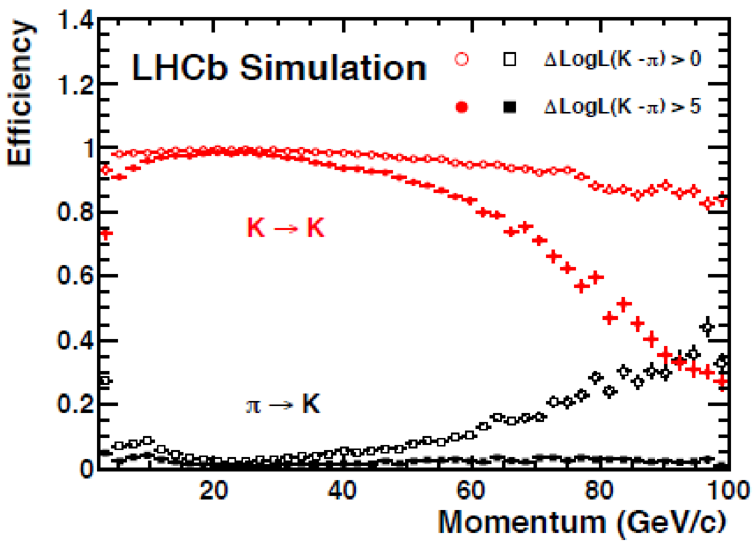
Eur. Phys. J. C73 (2013) 2431

- Reconstructed **Cherenkov angle for isolated tracks**, as a function of track momentum in the **C_4F_{10} radiator**

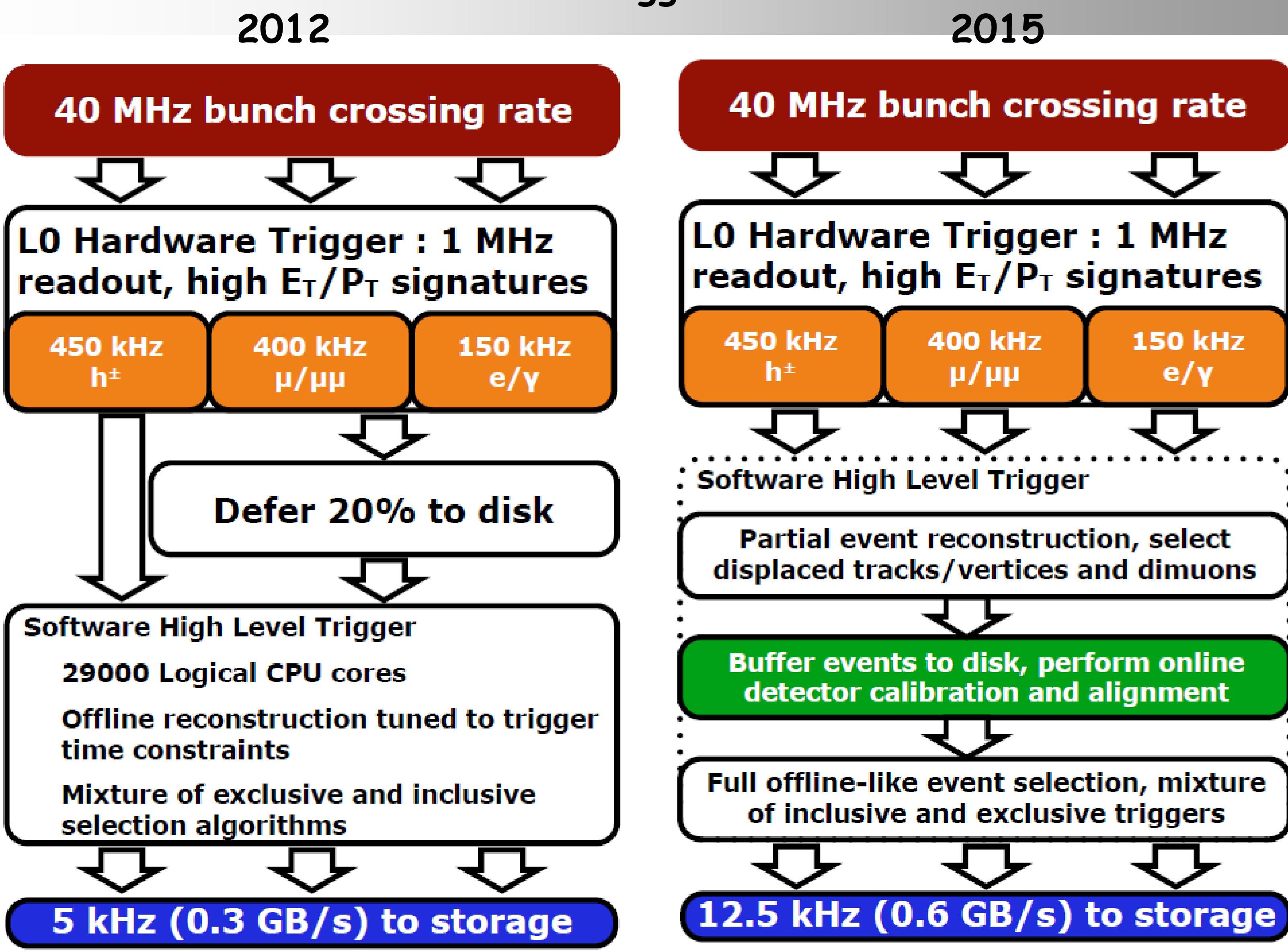


- Genuine π/K/p samples identified from kinematics only used to evaluate particle identification (PID) performance from data
- **Efficiency/rejection:** reasonable **agreement between data and simulation**



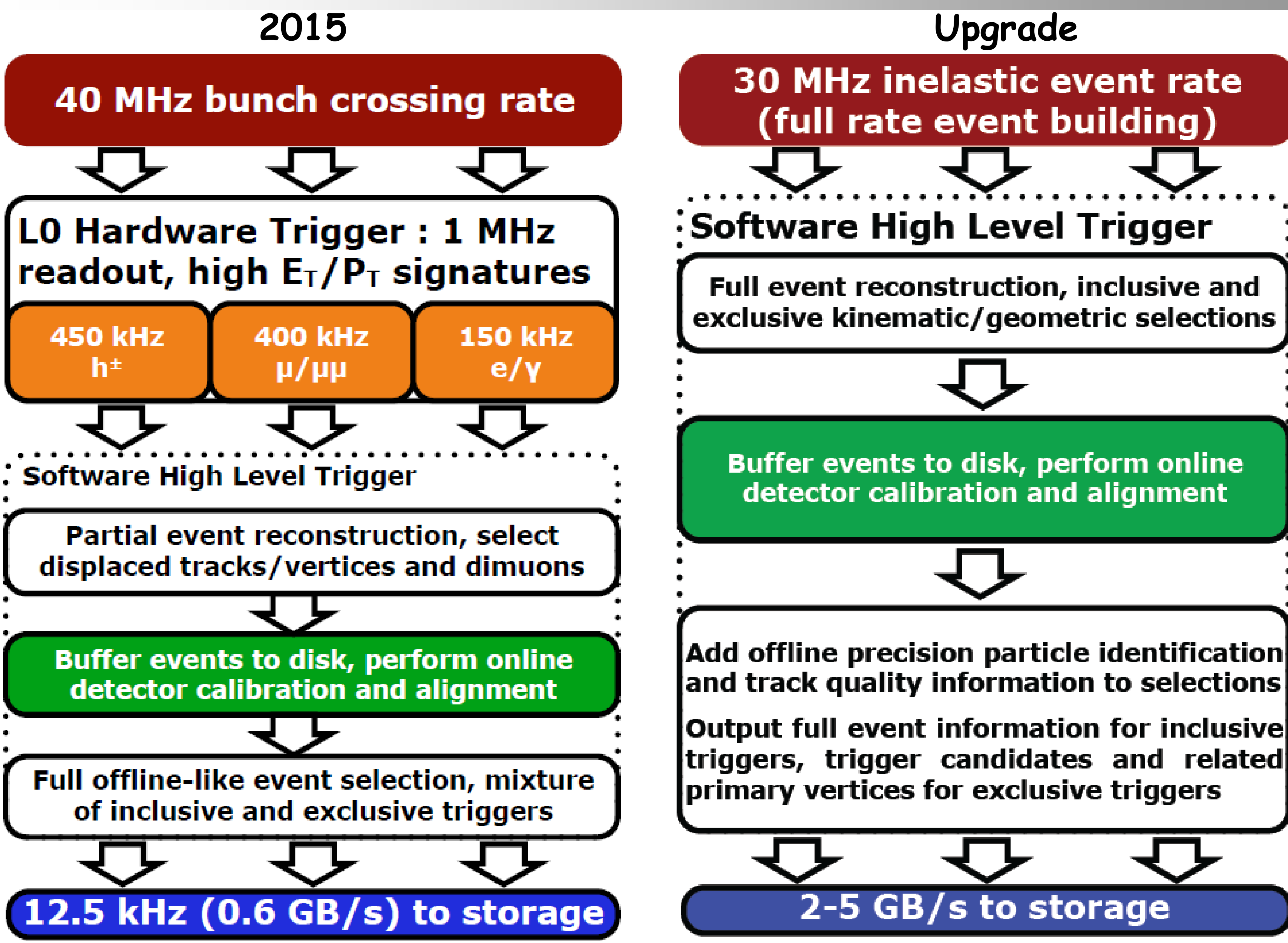


Trigger



- For 5 kHz of 12 kHz only trigger information saved
- Small events, fast analysis: high yield exclusive trigger lines

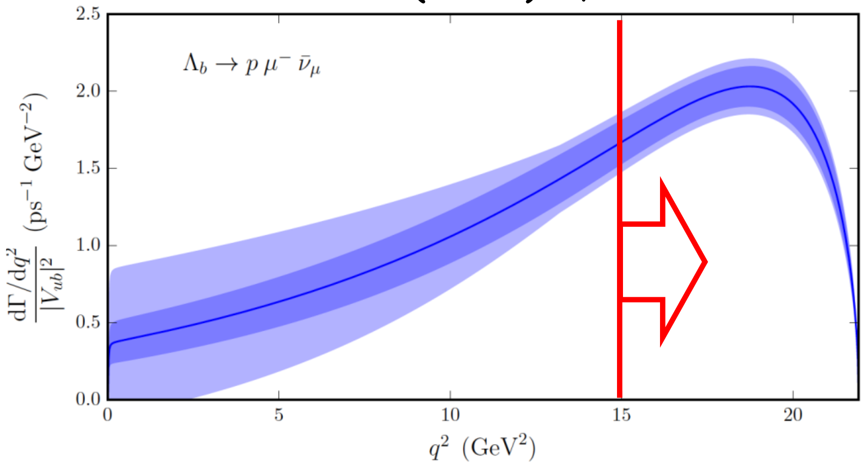
Trigger


2015
40 MHz bunch crossing rate
L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures
450 kHz $h^\pm$
400 kHz $\mu/\mu\mu$
150 kHz e/γ
Software High Level Trigger
Partial event reconstruction, select displaced tracks/vertices and dimuons
Buffer events to disk, perform online detector calibration and alignment
Full offline-like event selection, mixture of inclusive and exclusive triggers
12.5 kHz (0.6 GB/s) to storage
Upgrade
30 MHz inelastic event rate (full rate event building)
Software High Level Trigger
Full event reconstruction, inclusive and exclusive kinematic/geometric selections
Buffer events to disk, perform online detector calibration and alignment
Add offline precision particle identification and track quality information to selections
Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers
2-5 GB/s to storage

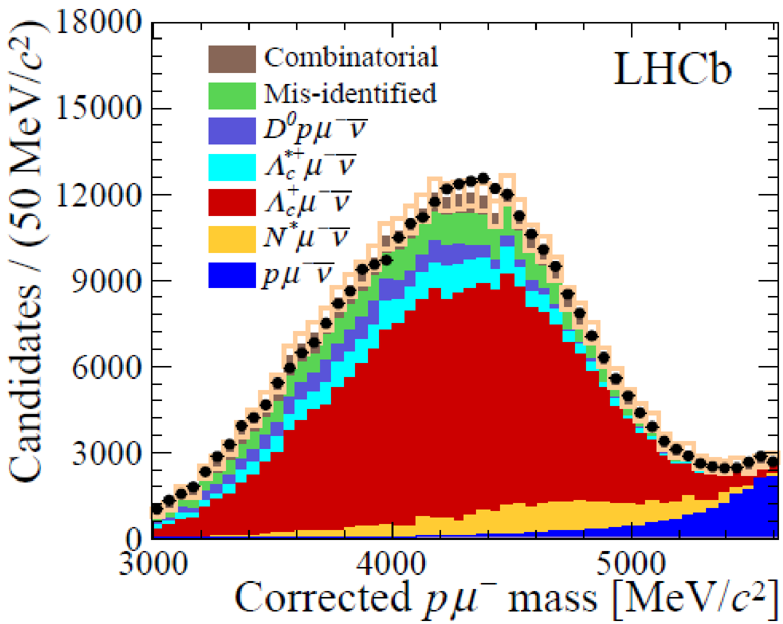
$|V_{ub}/V_{cb}|$ from $\Lambda_b \to p\mu\nu$ / $\Lambda_b \to \Lambda_c^+\mu\nu$

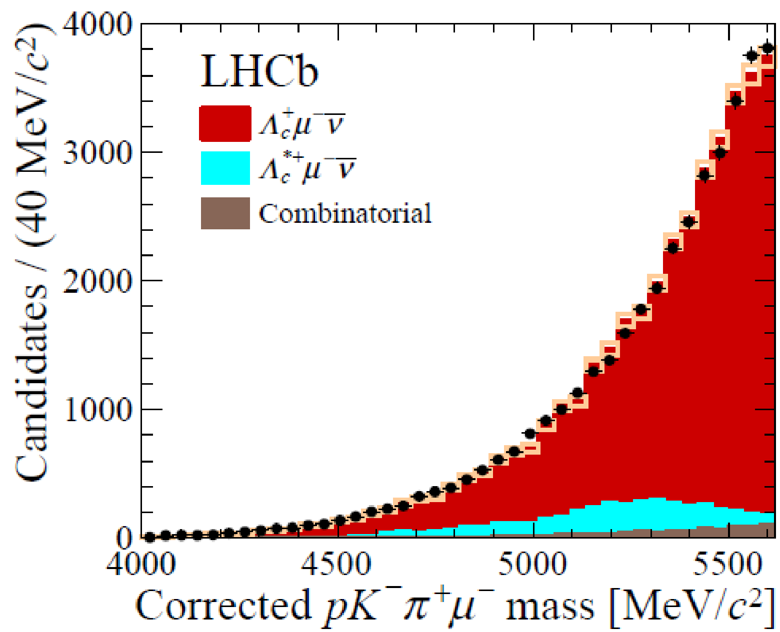
- Lattice QCD form factors, needed in the calculation of $|V_{ub}|$, are most precise at high q^2 ($\mu\nu$)
- q^2 determined using Λ_b flight direction and mass, up to a two-fold ambiguity
- Vertex isolation is used, $\Lambda_c^+ \to pK^-\pi^+$ cross-feed is the main background

PRD 92 (2015) 3, 034503



Nature Phys. 11 (2015) 743





- In SM ratios

PRL 113 (2014) 151601

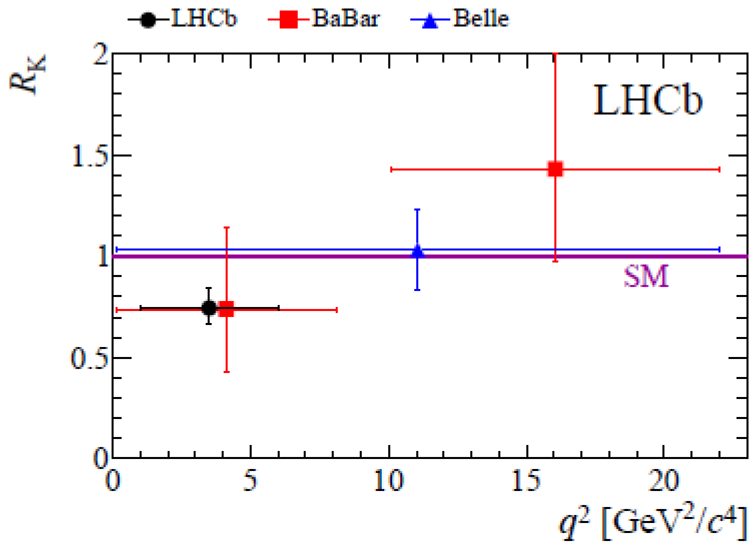
$$R_{\mathrm{K}} = \frac{\int \mathrm{d}\Gamma[B^+ \to K^+\mu^+\mu^-]/\mathrm{d}q^2 \cdot \mathrm{d}q^2}{\int \mathrm{d}\Gamma[B^+ \to K^+e^+e^-]/\mathrm{d}q^2 \cdot \mathrm{d}q^2}$$ and $$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu_\ell)}$$

are different from unity only due phase space difference

- LHCb, Run I :

$$\boxed{R_{\mathrm{K}} = 0.745\,^{+0.090}_{-0.074}\,^{+0.036}_{-0.036}}$$

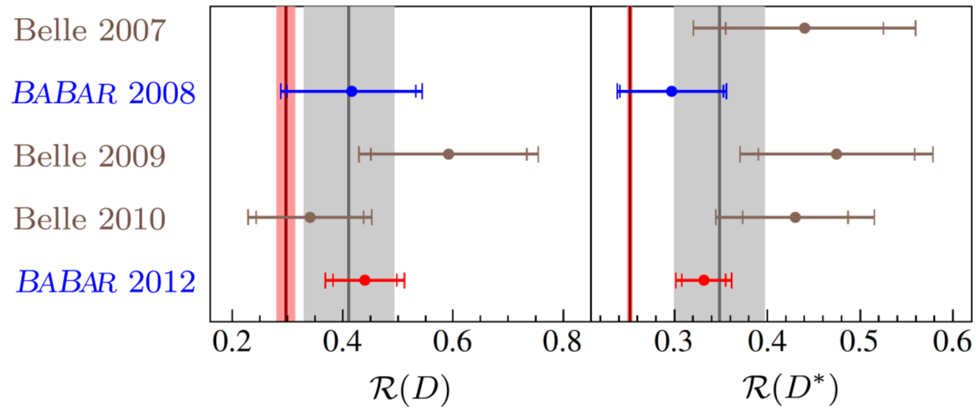
for $1 < q^2 < 6$ GeV^2, consistent with the SM at 2.6σ



B → D(*) τ ν

- Lepton universality can be broken by new physics with τ lepton   arXiv:1504.06339
- Ratios like R(D*)=*BR*(B → D(*)τν)/*BR*(B → D(*)μν) are sensitive to it
- In two Higgs doblet models (2HDM), the D/D* helicity amplitudes *Hs* : $H_s^{2HDM} \approx H_s^{SM}\left(1+(S_R \pm S_L)\dfrac{q^2}{m_\tau(m_b \mp m_c)}\right)$
- BaBar and Belle reported anomalous high values of R(D*) and R(D):

PRD 88 (2013) 072012, PRL 109 101802



- Those exclude 2HDM where S_L= 0 (type II, minimal SUSY) in the full tanβ-$m_{H\pm}$ plane, but are compatible with general 2HDM having $|S_R+S_L|<1.4$
- LHCb : First b → τ reco at a hadron collider, $\bar{B}^0 \to D^{*+}\,\tau^-\,\bar{\nu}_\tau$ and $B^0 \to D^{*+}\,\mu^-\,\bar{\nu}_\mu$

identical final state topologies with $D^{*+} \to D^0\,(\to K^-\pi^+)\,\pi^+$ and $\tau^- \to \mu^-\,\bar{\nu}_\mu\,\nu_\tau$

$$\boxed{R(D^*) = 0.336 \pm 0.027 \pm 0.030}$$

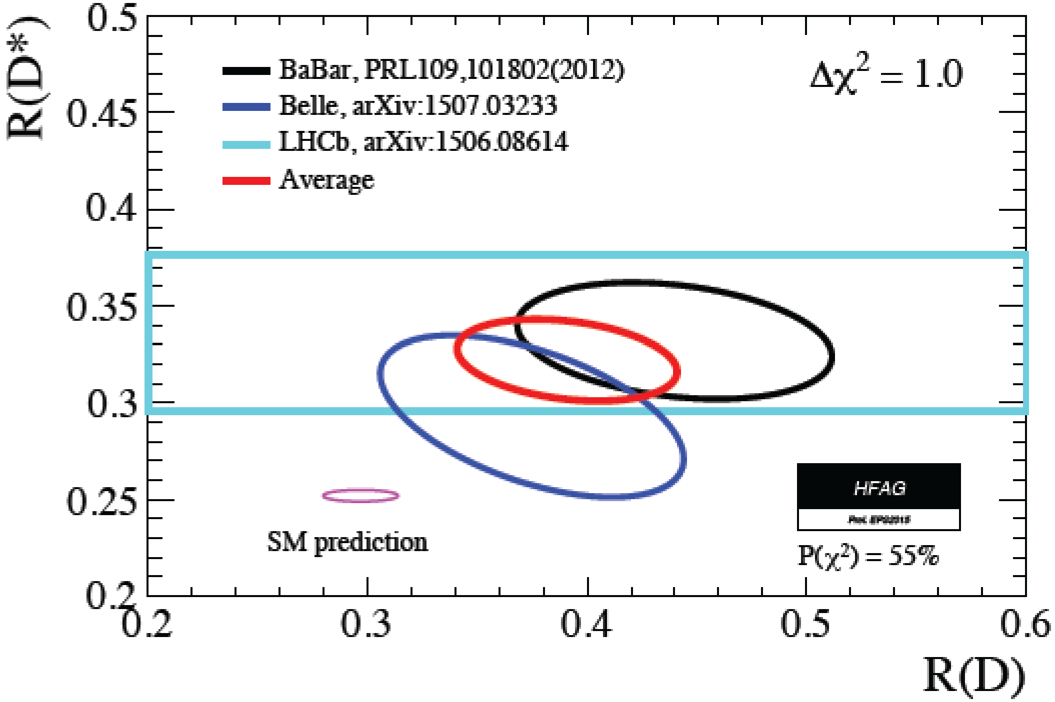
- LHCb result *confirms* the excess to the SM value 0.252±0.003

PRD 85 (2012) 094025

- Combination is **3.9**σ from the SM expectation:

$$R(D) = 0.297 \pm 0.017 \quad R(D^*) = 0.252 \pm 0.003$$

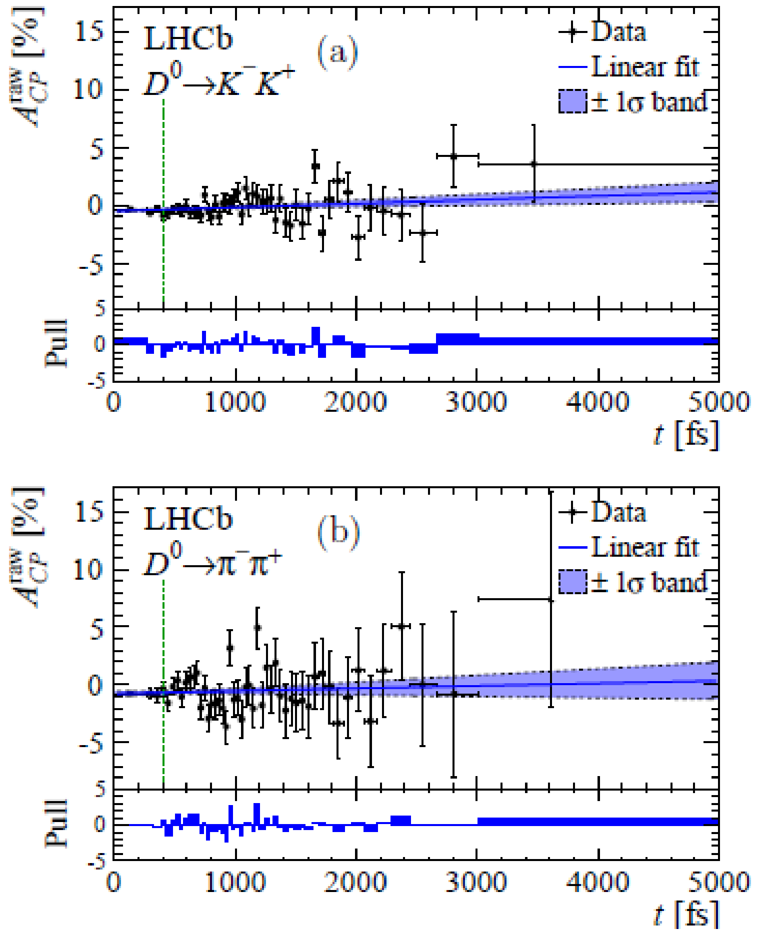
PRD 78 014003 (2008), PRD 85 094025 (2012)



$D^0 \rightarrow h^+h^-$: A_Γ with semileptonic decays

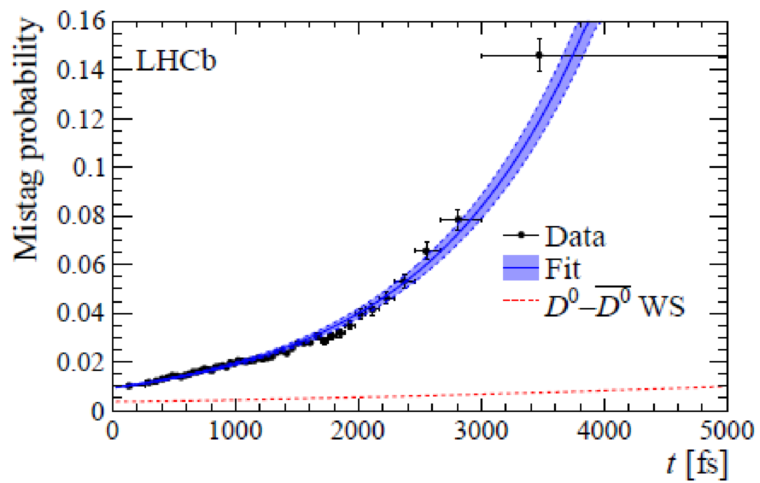
JHEP 1504 (2015) 043   3.0 fb^{-1}

- ❑ Lifetime obtained from $D^0\mu$ and $D^0 \rightarrow h^+h^-$ vertices



- ❑ Mistag asymmetry is the largest systematic uncertainty
- ❑ Mistag larger for larger lifetimes.

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



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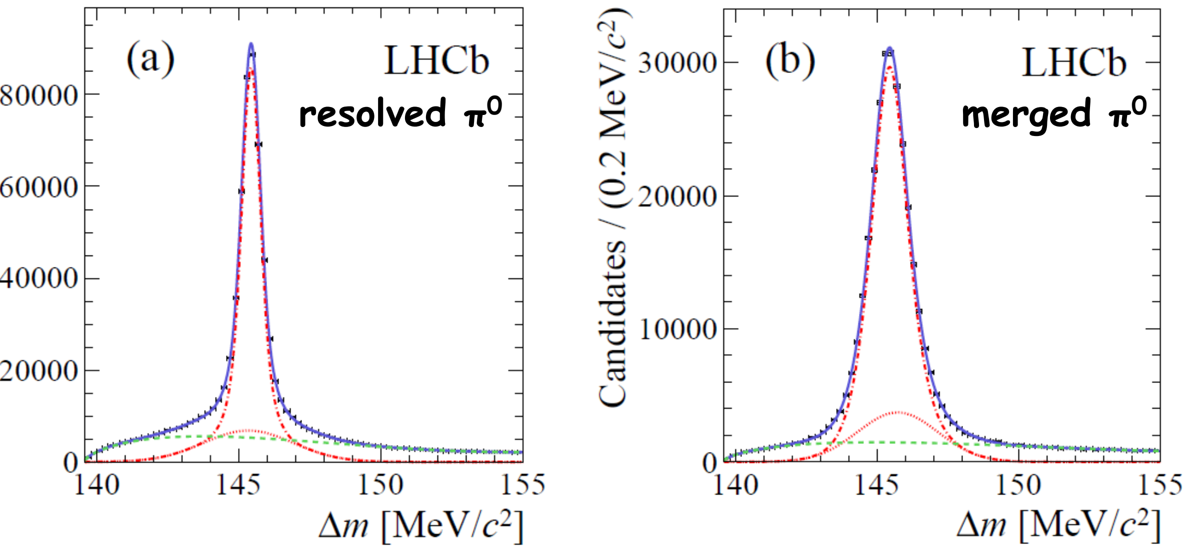
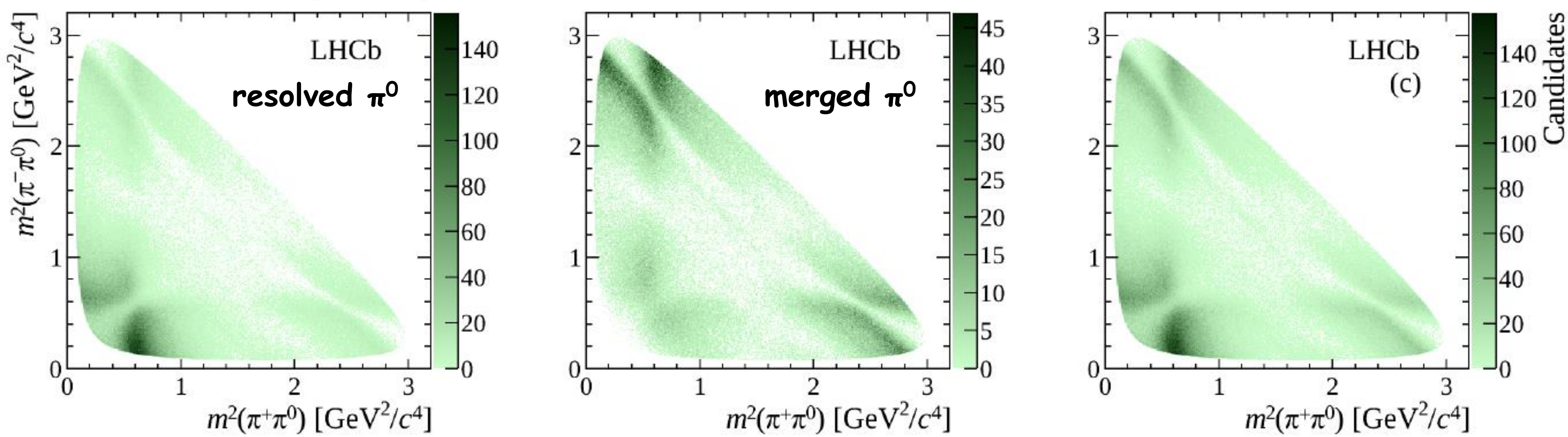
- Model-independent search for local CP asymmetry in tagged $D^0 \to \pi^+\pi^-\pi^0$ decays



- Use resolved (both γ seen) and merged π^0
- 2 fb^{-1} at 8 TeV



Energy test

- Test statistic to compare average distances in phase space

$$T = \sum_{i,j>i}^{n} \frac{\psi_{ij}}{n(n-1)} + \sum_{i,j>i}^{\overline{n}} \frac{\psi_{ij}}{\overline{n}(\overline{n}-1)} - \sum_{i,j}^{n,\overline{n}} \frac{\psi_{ij}}{n\overline{n}}$$

weighted average distance of events in one flavour sample to events of the opposite flavour sample

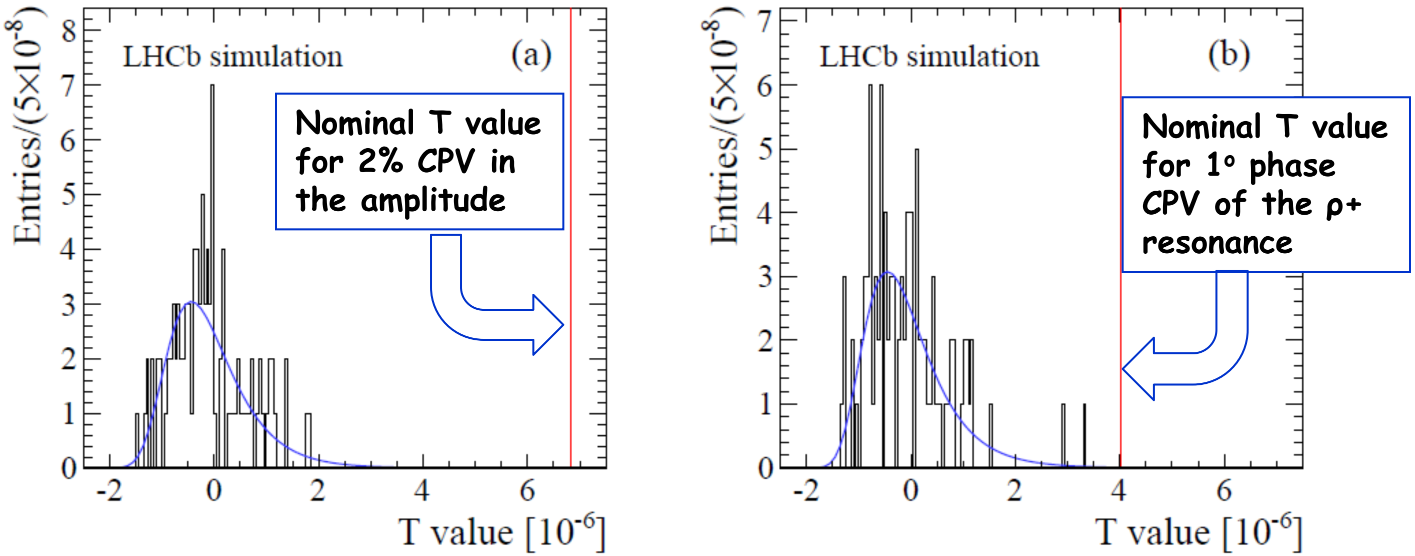
- Metric functions correspond to events i,j belonging to two samples of opposite flavour.
- Normalisation factors in the denominator remove impact of global asymmetries.
- If the distributions of events in both flavour samples are identical, T fluctuates around a value close to zero.
- Choose Gaussian metric $\psi_{ij} \equiv \psi(d_{ij}) = e^{-d_{ij}^2/2\sigma^2}$, that decreases with a distance to improve sensitivity to local asymmetries
- Remove dependence on the choice of Dalitz plot axes by choosing d_{ij} as

$$\Delta\vec{x}_{ij} = (m_{12}^{2,j} - m_{12}^{2,i}, m_{23}^{2,j} - m_{23}^{2,i}, m_{13}^{2,j} - m_{13}^{2,i})$$

- Larger CP asymmetries lead to larger T values → determine p-value under hypothesis of CP symmetry by comparing nominal T value from data to a distribution of T values from permutation samples, where the flavour of each candidate is randomly reassigned to simulate samples without CPV
- p-value for the no CPV hypothesis is obtained as the fraction of permutation T values greater than the nominal T value

Energy test

- Permutation T values fitted with a GEV function



- Visualisation of regions of significant asymmetry is obtained by assigning asymmetry significance to each event. Contributions to the total T value of a single event:
- one flavour :

$$T_i = \frac{1}{2n\,(n-1)} \sum_{j \neq i}^{n} \psi_{ij} - \frac{1}{2n\overline{n}} \sum_{j}^{\overline{n}} \psi_{ij},$$

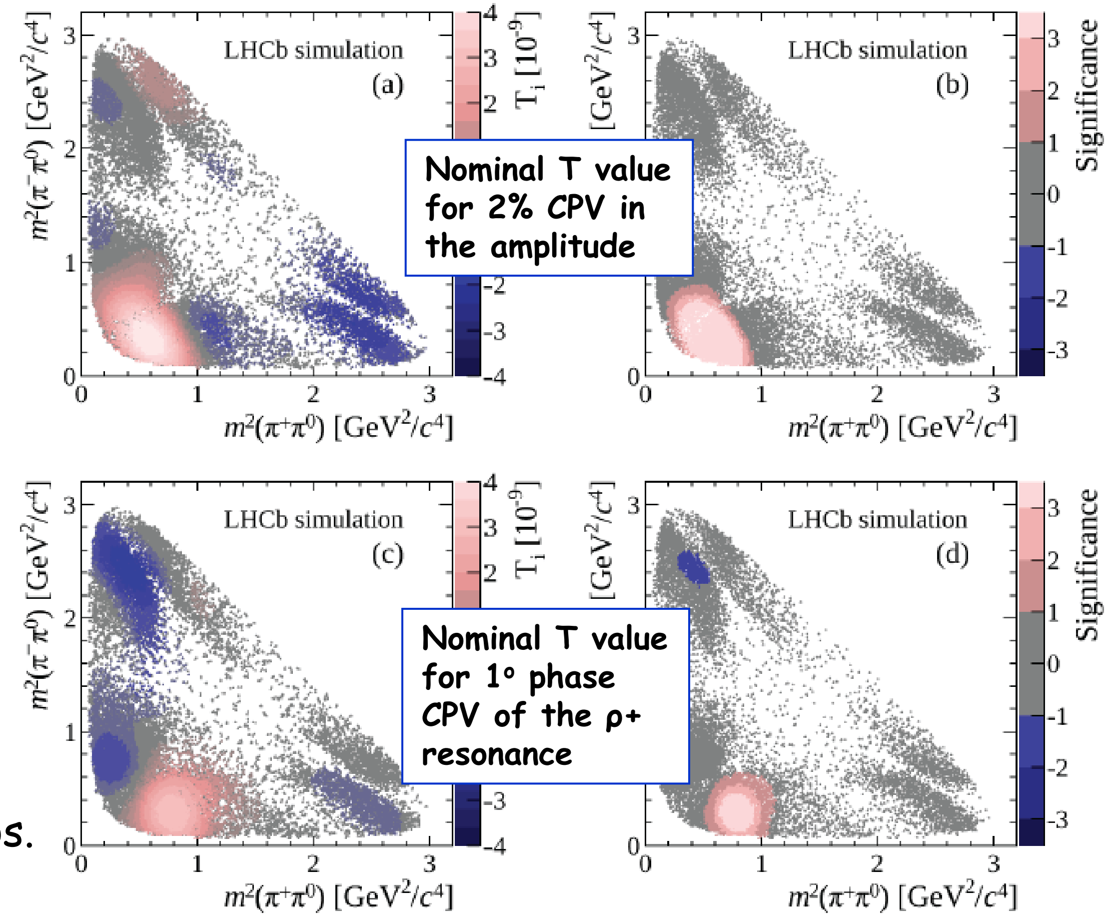
- opposite favour :

$$\overline{T}_i = \frac{1}{2\overline{n}\,(\overline{n}-1)} \sum_{j \neq i}^{\overline{n}} \psi_{ij} - \frac{1}{2n\overline{n}} \sum_{j}^{n} \psi_{ij}.$$

- Permutation method to define the level of significance, distributions of the smallest negative (T^{min}_i) and largest positive (T^{max}_i) T_i values of each permutation.
- Positive (negative) local asymmetry significances : T_i values greater (smaller) than the fraction of the T^{max}_i (T^{min}_i) distribution that corresponds to the significance level.
- Same procedure for anti-T_i distribution, Dalitz plot with an inverted asymmetry pattern.

Energy test

- Amplitude difference between CP-conjugate states of a resonance → region of significant asymmetry as a band around the mass of the resonance
- Phase difference → regions of positive and negative asymmetry around the resonance

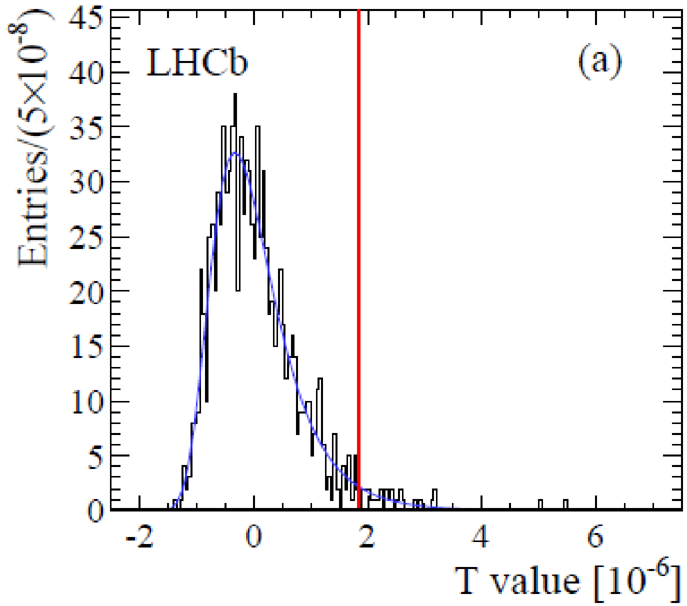


- Sensitivities to various CPV scenarios. ΔA and Δ φ: change in amplitude and phase of the resonance R

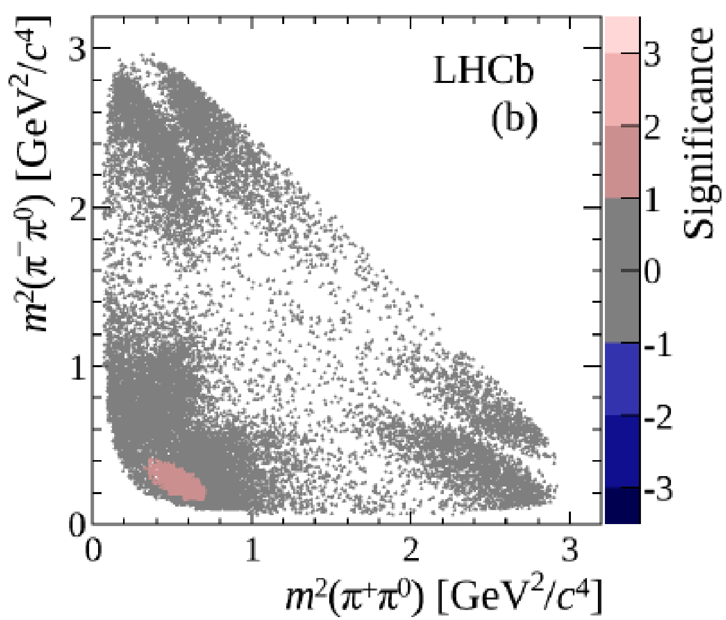
R (ΔA, $\Delta\phi$)	p-value (fit)	Upper limit
ρ^0 (4%, 0°)	$3.3^{+1.1}_{-3.3} \times 10^{-4}$	4.6×10^{-4}
ρ^0 (0%, 3°)	$1.5^{+1.7}_{-1.4} \times 10^{-3}$	3.8×10^{-3}
ρ^+ (2%, 0°)	$5.0^{+8.8}_{-3.8} \times 10^{-6}$	1.8×10^{-5}
ρ^+ (0%, 1°)	$6.3^{+5.5}_{-3.3} \times 10^{-4}$	1.4×10^{-3}
ρ^- (2%, 0°)	$2.0^{+1.3}_{-0.9} \times 10^{-3}$	3.9×10^{-3}
ρ^- (0%, 1.5°)	$8.9^{+22}_{-6.7} \times 10^{-7}$	4.2×10^{-6}

Energy test

Permutation T value distribution showing the fit function and the measured T value as a red line



Visualisation of local asymmetry significances.
Positive (negative) asymmetry significance : D^0 candidates having positive (negative) contribution to the measured T value



Results for various metric parameter values. The p-values are obtained with the counting method

σ [GeV^2/c^4]	p-value
0.2	$(4.6 \pm 0.6) \times 10^{-2}$
0.3	$(2.6 \pm 0.5) \times 10^{-2}$
0.4	$(1.7 \pm 0.4) \times 10^{-2}$
0.5	$(2.1 \pm 0.5) \times 10^{-2}$