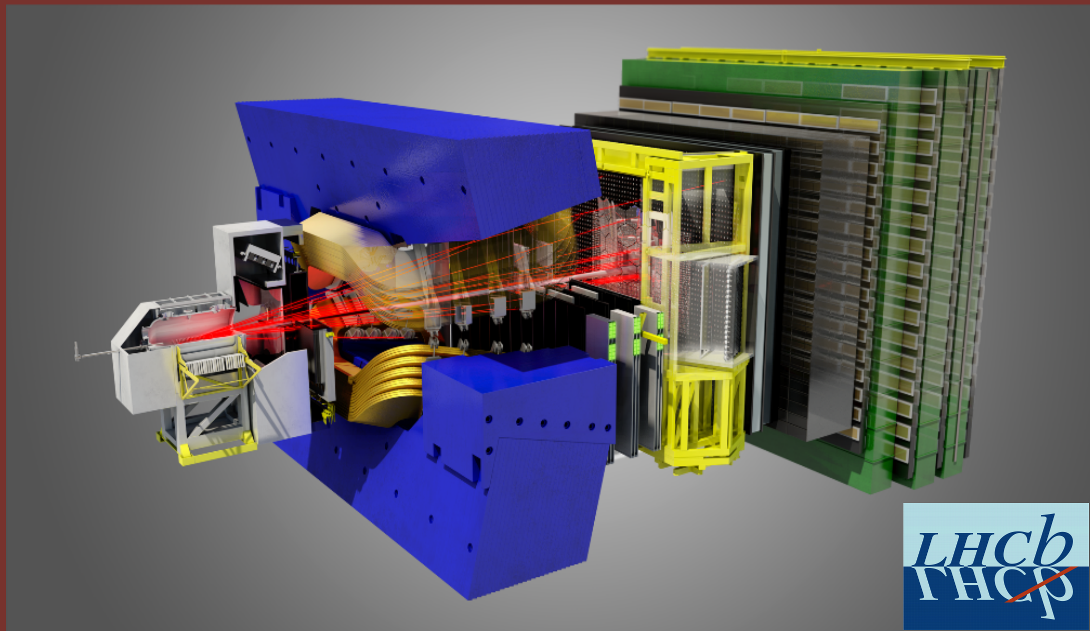
ETAT DE L'ART EN PHYSIQUE DU *b*



Francesco Polci

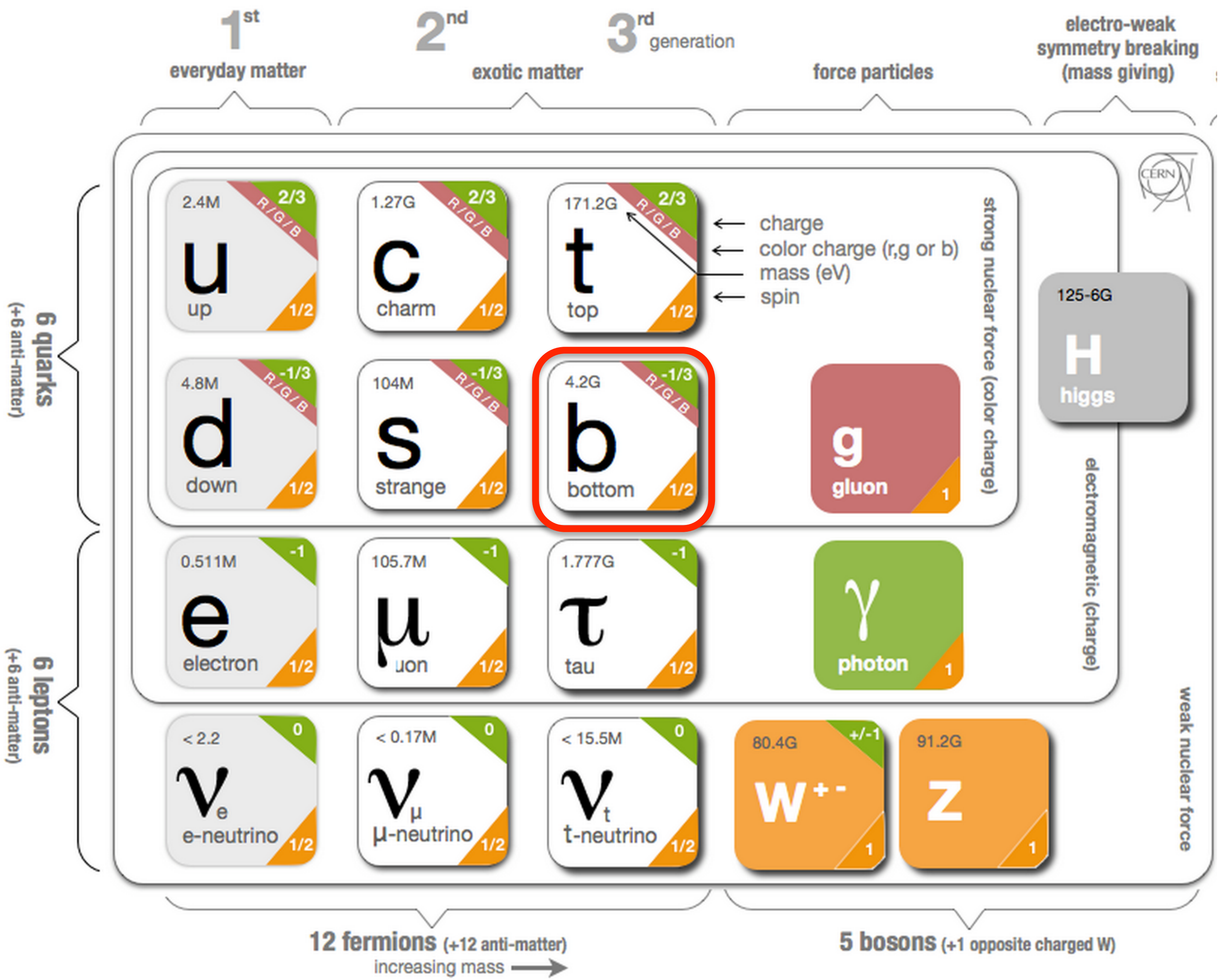
(LPNHE - CNRS/IN2P3 and Université Pierre et Marie Curie, Paris)

COLLOQUIUM LPSC Grenoble - 16 JUIN 2015

OUTLINE
OF A BIASED AND INCOMPLETE
VUE OF *b* PHISICS

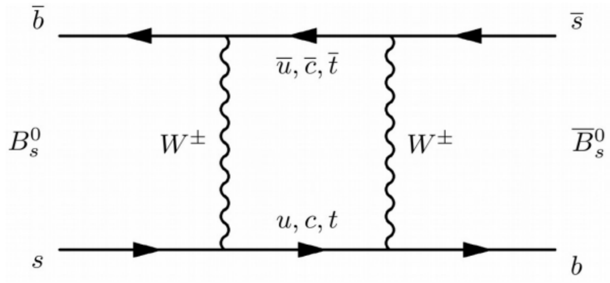
- *The strategy and role of flavor physics*
- *A detector dedicated to flavor physics: LHCb*
- *A selection of LHCb results from run1*
- *Perspectives for run2 and for the upgrade*

THE *b* QUARK IN THE STANDARD MODEL

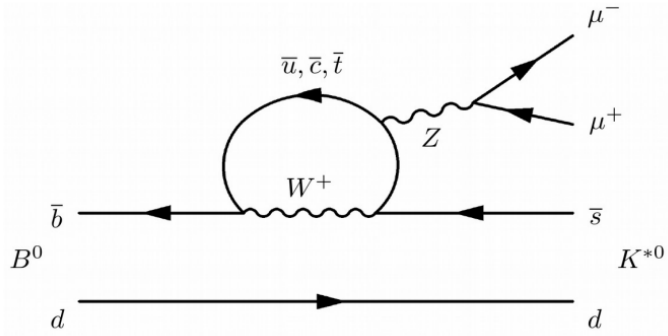


THE STRATEGY OF FLAVOR PHYSICS

- most New Physics models predict the existence of <u>new heavy particles</u>
  - these can enter in <u>internal loops</u> and have <u>sizeable effect</u> on observables
  - <u>*CP* violating phases</u>, <u>rare FCNC decays</u>



- B^0 and B^0_s systems are an <u>ideal hunting ground</u>
  - rich phenomenology, <u>precise SM predictions</u>
  - confront predictions with <u>precision measurements</u> $\Rightarrow$ LHCb



- indirect searches for New Physics are sensitive to <u>higher mass scales</u> than direct searches for new particles
- the <u>pattern of deviations</u> can hint at the <u>structure of the New Physics</u>

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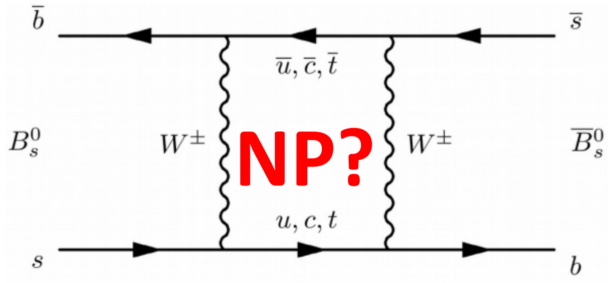

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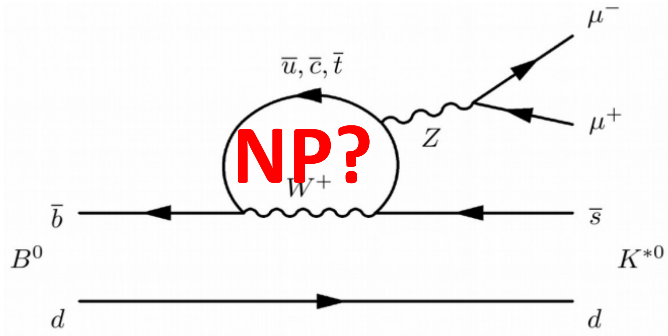
  - confront predictions with precision measurements ⇒ LHCb



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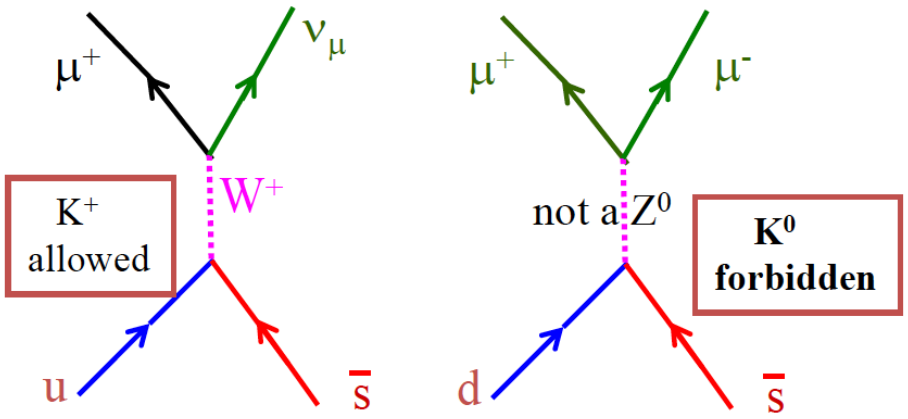
EXAMPLE FROM THE PAST: CHARM PREDICTION



$$\frac{BR(K^0 \to \mu^+\mu^-)}{BR(K^+ \to \mu^+\nu_\mu)} = \frac{7\times10^{-9}}{0.64} \approx 10^{-8}$$

SM with *u,d,s* only was predicting 10^{-4} ….

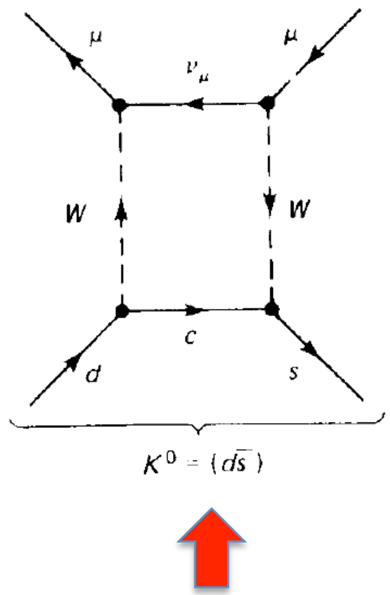
1970: Glashow, Iliopoulos, Maiani (GIM) proposent une solution

$\Rightarrow$ Pas de courant neutre qui change la saveur (FCNC)

$\Rightarrow$ Les FCNC sont supprimés via des diagrammes en boucles

$\Rightarrow$ prediction du quark charmé

Directement observé 1973

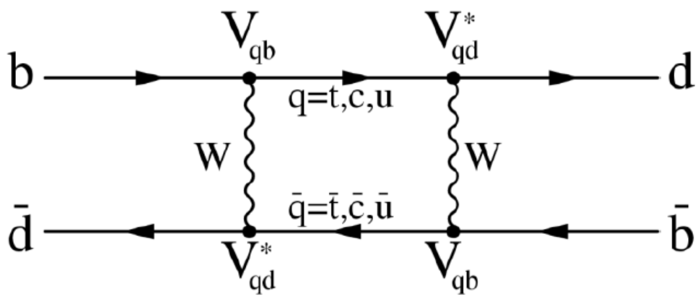


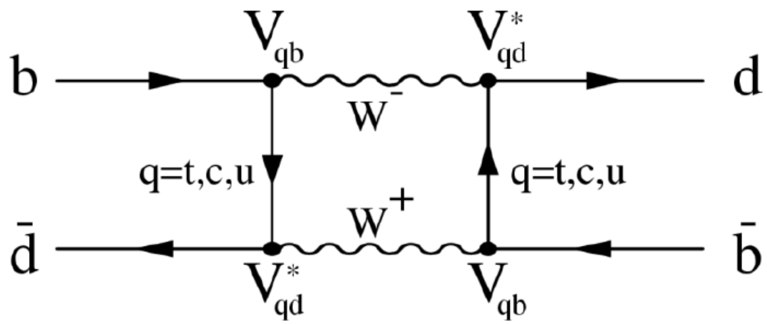
EXAMPLE FROM THE PAST: THIRD QUARK FAMILY

- 1964: observation de la violation de CP dans les Kaons. En 1973 Kobayashi et Maskawa demontrent qu'elle peut être expliquée si il y a 3 générations

  $\Rightarrow$ prediction de la 3ème famille, directement observée en 1977

- 1987: oscillation des mésons B



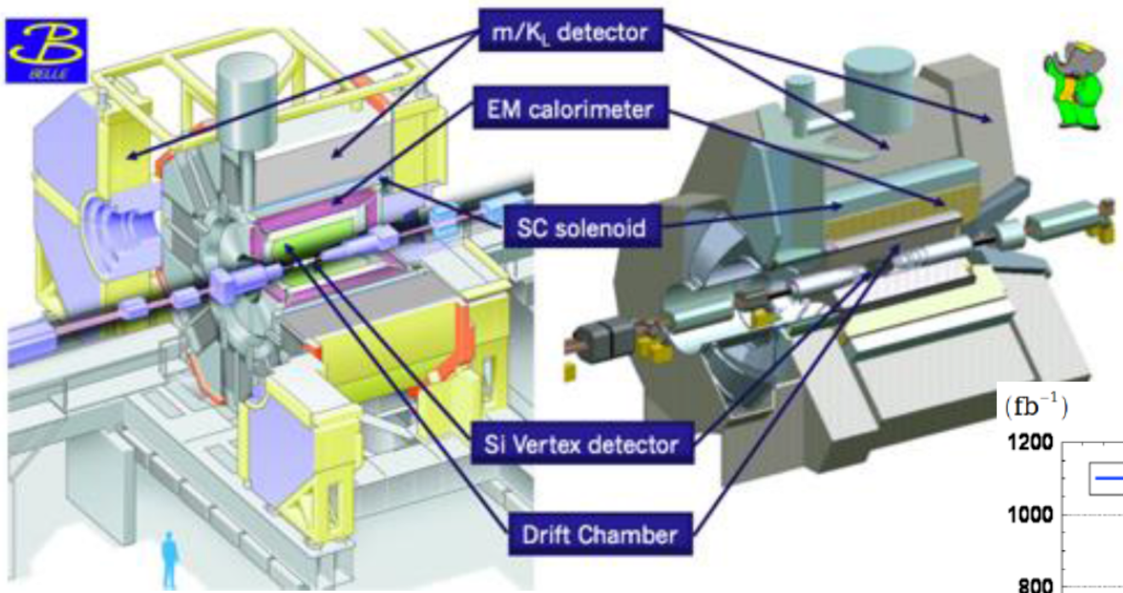


Argus mesure
$$\Delta m_B \approx 0.00002 \cdot \left(\frac{m_t}{\mathrm{GeV}/c^2} \right)^2 \mathrm{ps}^{-1}$$
$$\approx 0.5 \mathrm{ps}^{-1}$$

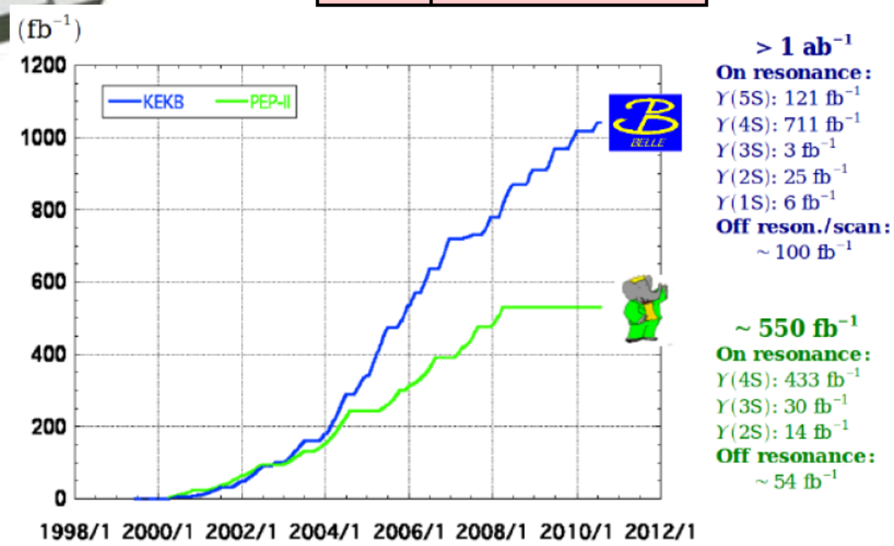
Premier indice de la masse elevé du quark top, découvert en 1995

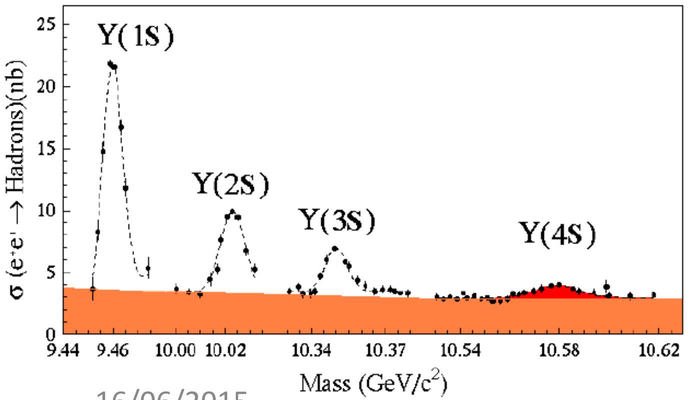
5

2000s : THE KINGDOM OF THE B-FACTORIES…



$e^+e^- \to$	Section efficace (nb)
uu	1,39
dd	0,35
ss	0,35
cc	1,30
bb	1,10

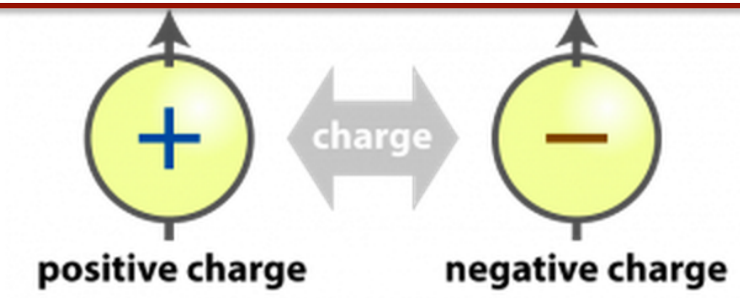




771M + 463M bb pairs accumulated

Only B_d and B_u produced, but very clean events

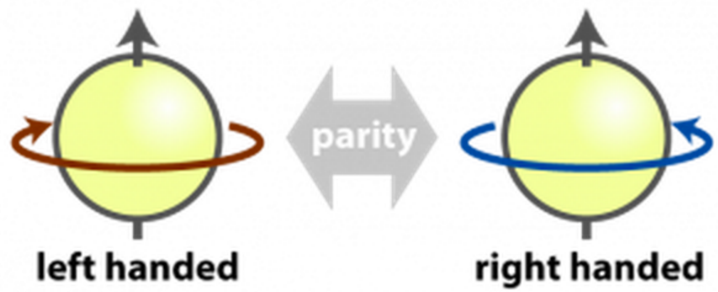
THE *C* AND *P* OPERATORS

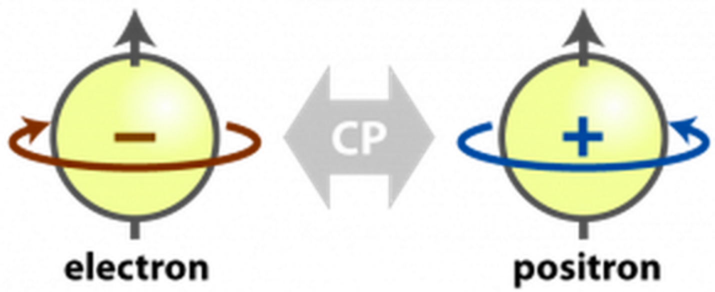


If we take a particle with positive charge, C reverses the charge, meaning the particle will now have negative charge, and vice versa.

Note that if we start with a neutral particle, C will have no effect, since it has no charge.

P is a little harder to explain, though more intuitive, as we encounter a symmetry of spatial coordinates every time we look into a mirror. I am right-handed, but when I look into a mirror, my reflection is left-handed. This almost a perfect analogy to the P symmetry in particle physics, which transforms left-handed particles to right-handed ones.





So the combination of CP on a left-handed, negatively-charged particle would transform it into a right-handed, positively-charged particle.

Source: http://www.quantumdiaries.org/2011/11/14/what-exactly-is-cp-violation/

CP VIOLATION IN THE DECAY

Measure:

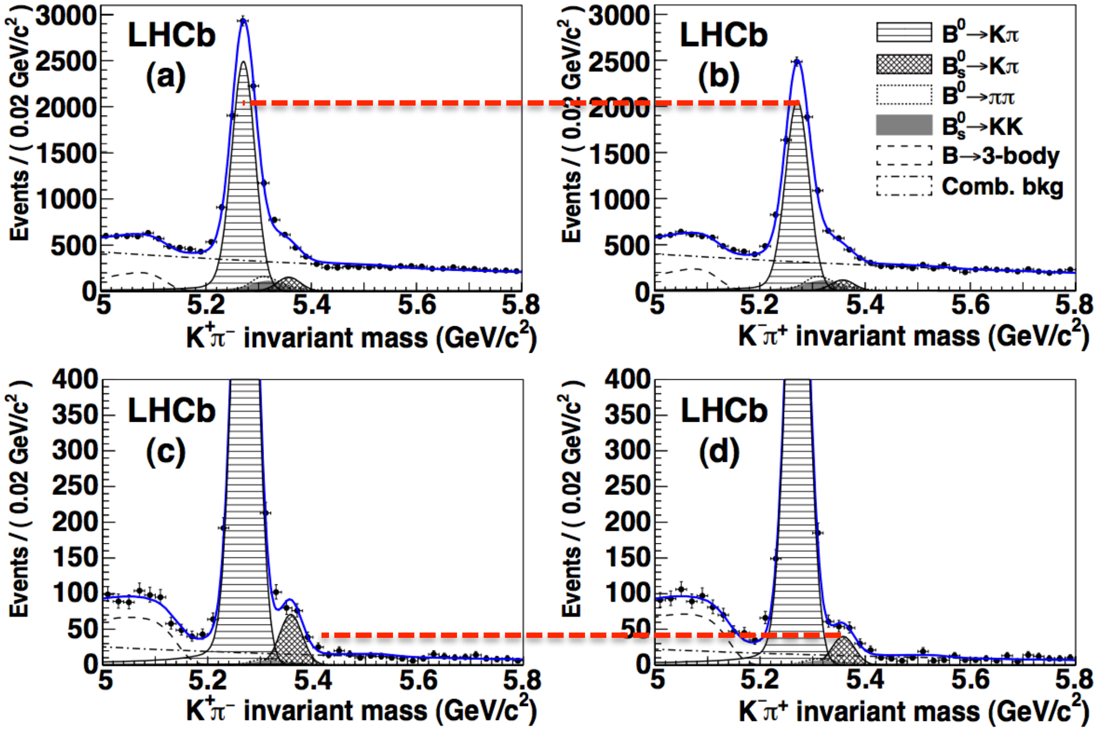
$$A_f = < f|\mathcal{H}|B^0 >$$
$$\bar{A}_{\bar{f}} = < \bar{f}|\mathcal{H}|\bar{B}^0 >$$

If: $\left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| \neq 1$

CP is violated!

24 April 2013: First observation of CP violation in the decays of B^0_s mesons.

[$A_{CP}(B^0_s \to K^- \pi^+) = +0.27 \pm 0.04 \pm 0.01$]
[$A_{CP}(B^0 \to K^+ \pi^-) = -0.080 \pm 0.007 \pm 0.003$]

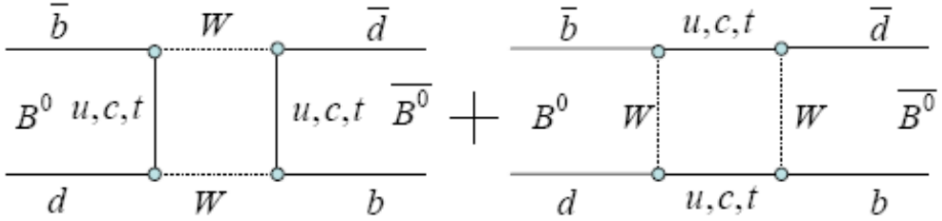


CP violation in the decay is the only one possible for charged mesons

CP VIOLATION IN THE MIXING

Standard Model predicts oscillations of neutral Mesons:

$$B_d^0 \Leftrightarrow \overline{B_d^0}$$



Transition can be described by matrix element: $\langle \overline{B_d^0} | H_W | B_d^0 \rangle$

For a generic neutral meson *P* *(K⁰, D⁰, B⁰)*

$|P_L\rangle = p|P^0\rangle + q|\overline{P^0}\rangle$ with m_L, Γ_L

$|P_H\rangle = p|P^0\rangle - q|\overline{P^0}\rangle$ with m_H, Γ_H

$|p|^2 + |q|^2 = 1$ complex coefficients

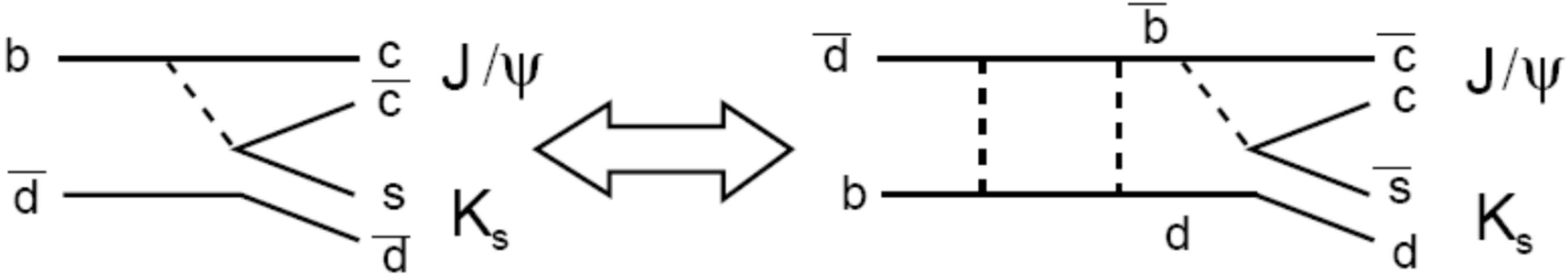
$$P(B^0 \to \overline{B^0}) = \frac{1}{4}\left|\frac{q}{p}\right|^2 \left[e^{-\Gamma_L t} + e^{-\Gamma_H t} - 2e^{-(\Gamma_L+\Gamma_H)t/2}\cos\Delta m t\right]$$

$$P(\overline{B^0} \to B^0) = \frac{1}{4}\left|\frac{p}{q}\right|^2 \left[e^{-\Gamma_L t} + e^{-\Gamma_H t} - 2e^{-(\Gamma_L+\Gamma_H)t/2}\cos\Delta m t\right]$$

$$P(B^0 \to \overline{B^0}) \neq P(\overline{B^0} \to B^0) \Rightarrow \left|\frac{q}{p}\right| \neq 1$$

Arises from masse eigenstates being different from flavor eigenstates

CP VIOLATION IN THE MIXING AND DECAY



$$\mathcal{A}(t) = \frac{\Gamma(\bar{B} \to J/\psi K_s)(t) - \Gamma(B \to J/\psi K_s)(t)}{\Gamma(\bar{B} \to J/\psi K_s)(t) + \Gamma(B \to J/\psi K_s)(t)}$$

$$= \sin 2(\phi_{mix} + \phi_{J/\psi K_s}) * \sin(\Delta m_d t)$$

$$\phi_{mix} = arg(V_{td} V_{tb}^*)$$

$$\phi_{J/\Psi K_s} = arg((V_{cb} V_{cd}^*)(V_{us} V_{ud}^*))$$

CP VIOLATION IN THE STANDARD MODEL

- **quark eigenstates of charged-current weak interaction ≠ mass eigenstates**

$$L_{\mathrm{cc}} = -\frac{g}{\sqrt{2}} \overline{u}_i \gamma^\mu (1-\gamma_5) V_{ij} d_j W^+_\mu + \mathrm{h.c.}$$

- **three quark families → 3 × 3 mixing matrix**

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

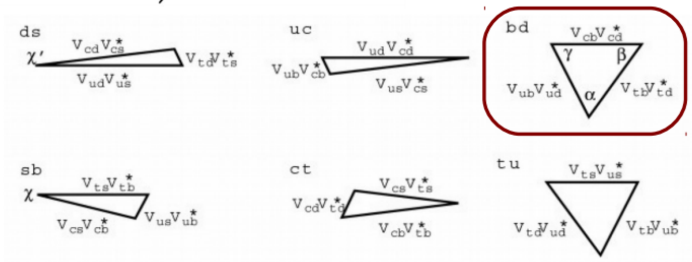
- **18 – 9 – 5 = 4 independent parameters → complex phase → *CP* violation**
  - Wolfenstein parametrization: ($\lambda = \sin\theta_c$, A, ρ, η)

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O\left(\lambda^5\right)$$

- **unitarity → six orthogonality conditions, e.g.**

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

- **visualize as triangles in the complex plane**

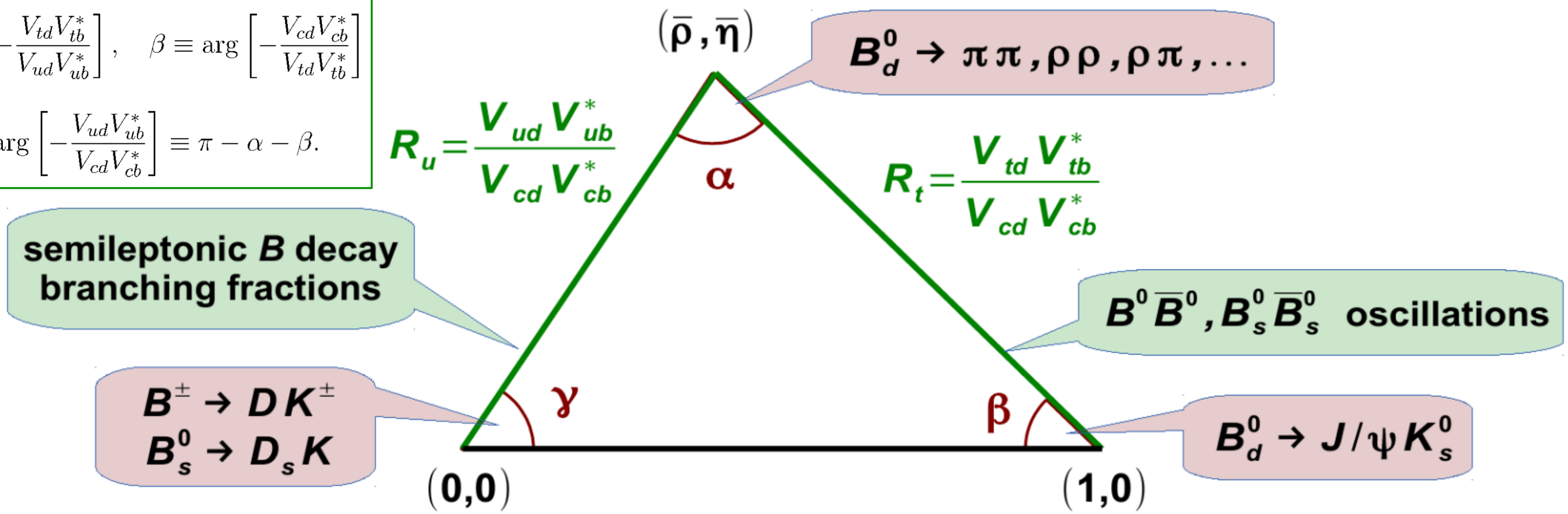


THE UNITARITY TRIANGLE

- **sides and angles of Unitarity Triangle are related to measurable observables**

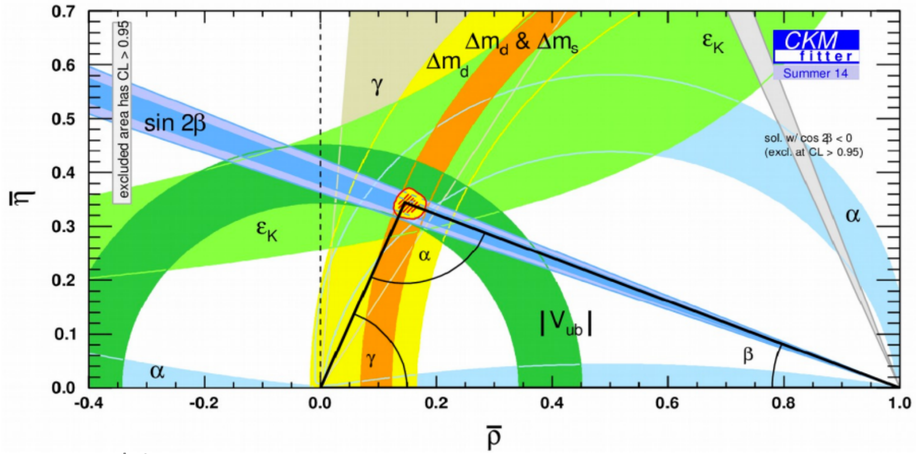
$$\alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right], \quad \beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

$$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right] \equiv \pi - \alpha - \beta.$$

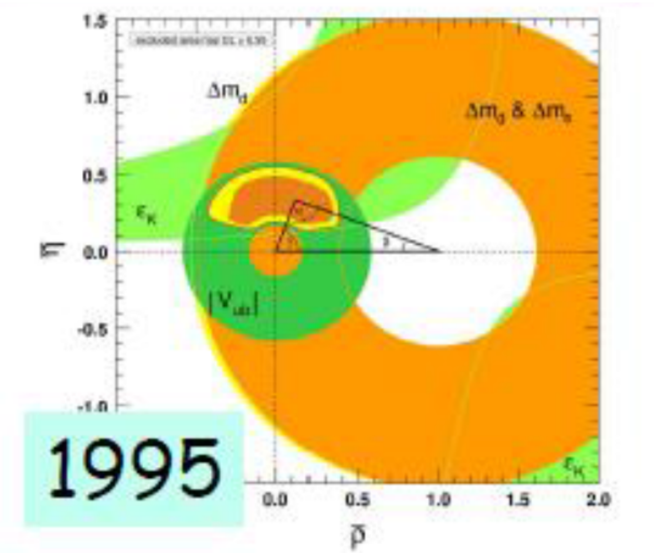


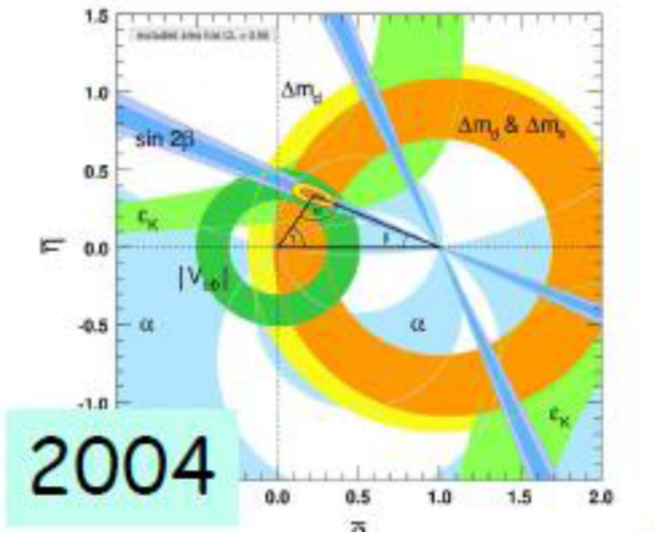
- sides: *CP* conserving observables
- angles: *CP* violating observables

- **consistency of measurements provides test of Standard Model**
  - global fits by UTFit, CKMfitter groups

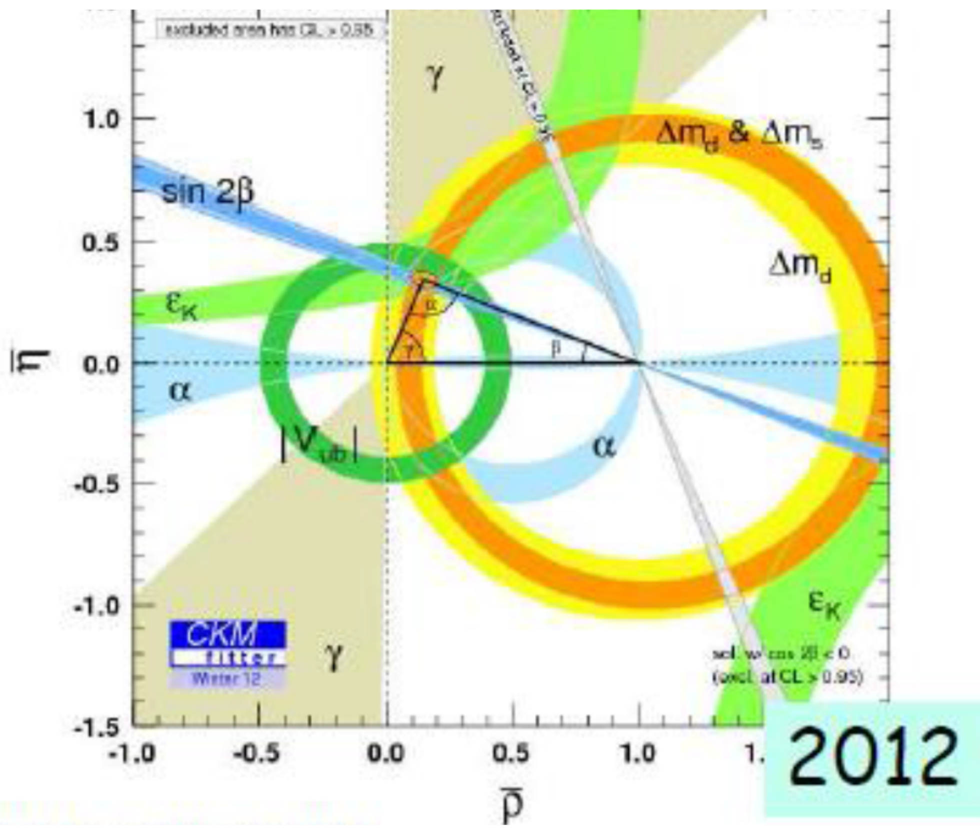


A GROWING PRECISION, A STRONGER TEST





- Importance des fits globaux (CKM fitter, UTfit)
- Necessitent des inputs théoriques: Lattice QCD



…LEADING TO A NOBEL PRIZE

The Nobel Prize in Physics 2008

Photo: University of Chicago

Yoichiro Nambu

Prize share: 1/2

© The Nobel Foundation Photo: U. Montan

Makoto Kobayashi

Prize share: 1/4

© The Nobel Foundation Photo: U. Montan

Toshihide Maskawa

Prize share: 1/4

The Nobel Prize in Physics 2008 was divided, one half awarded to Yoichiro Nambu *"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"*, the other half jointly to Makoto Kobayashi and Toshihide Maskawa *"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"*.

THE ROLE OF THE FLAVOR TODAY

- NP contribution can be expressed as a perturbation to the SM lagrangian

$$\boxed{\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{c_{NP}}{\Lambda^2}}$$

NP coupling

NP scale

- Considering the present experimental constraints in flavour physics:
  - if C=1, $\Lambda \sim O(100\text{TeV})$
  - If $\Lambda \sim 1$TeV (quantum stabilization of electroweak scale), C ~ $O(10^{-7})$. Where is this suppression coming from ?

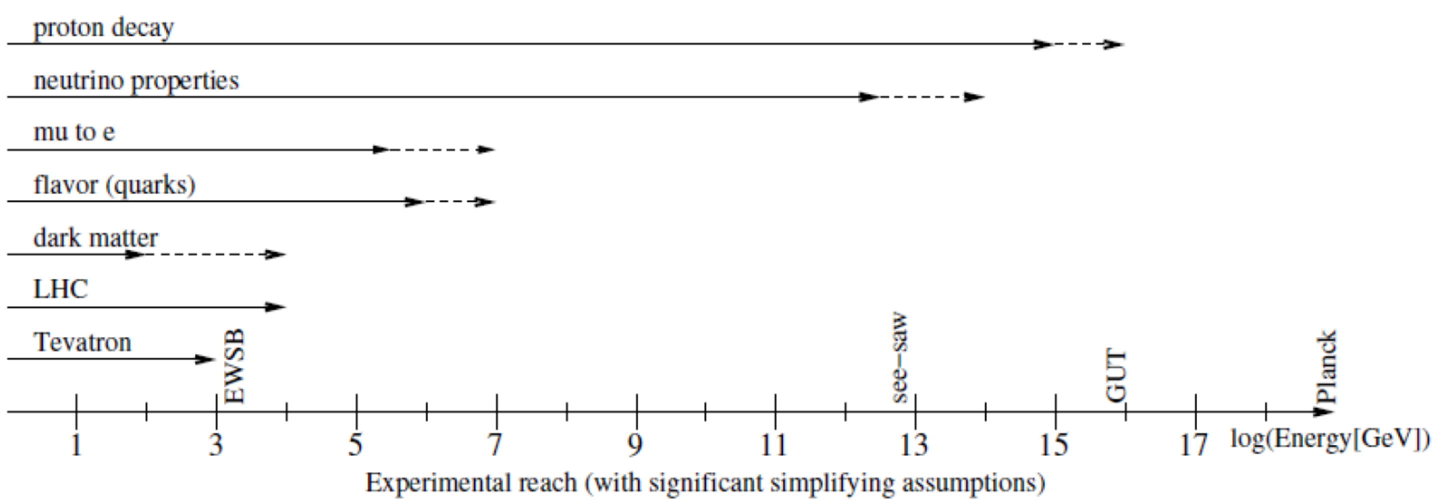
$\Rightarrow$ This is the NP flavour problem. The flavour strucure of NP should be highly non trivial.

DO WE STILL NEED FLAVOR PHYSICS? YES!

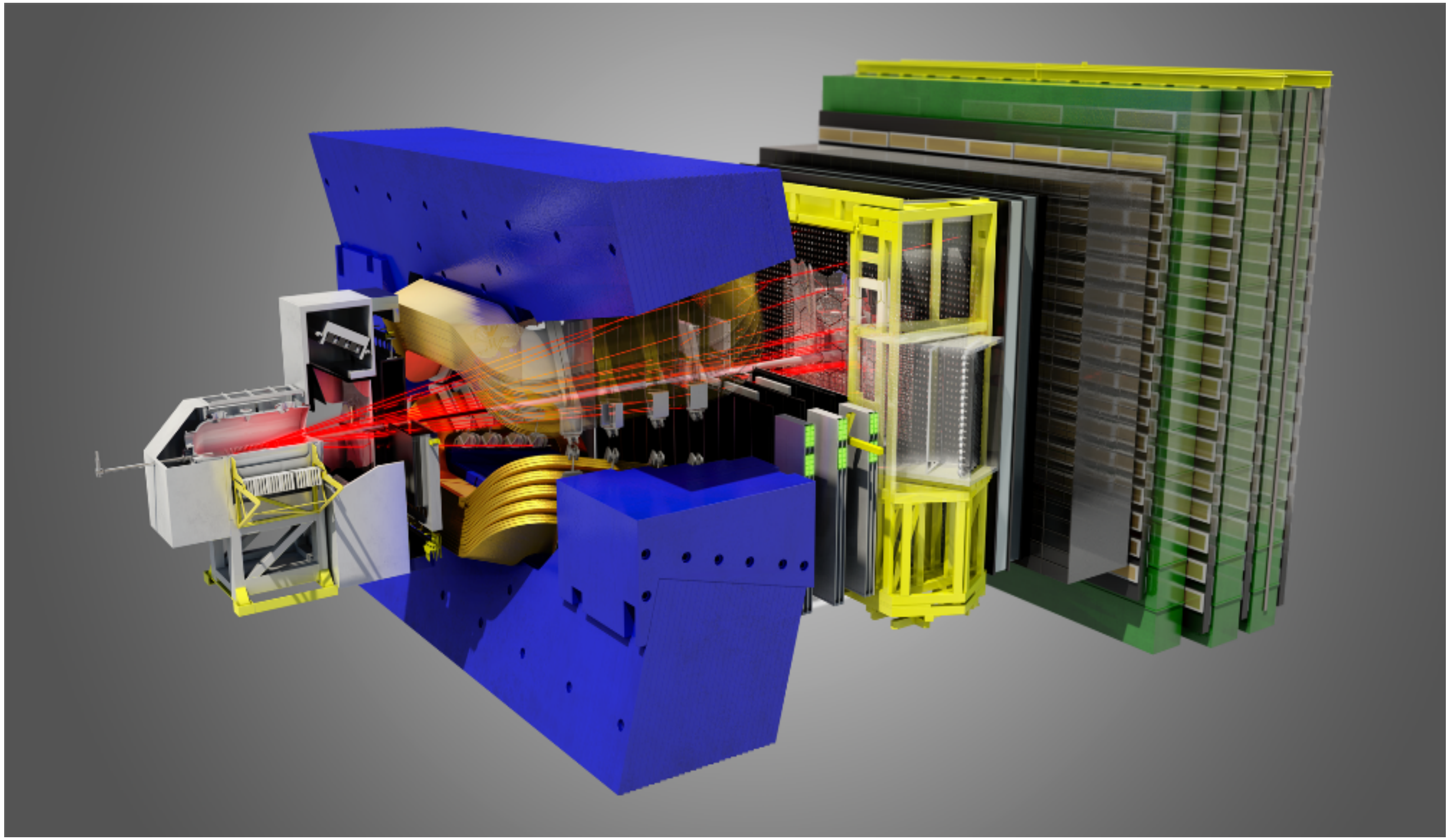
GPDs directly observe new physics?

→ YES → Need to measure flavour structure to differentiate NP models → FLAVOUR STUDIES REQUIRED

→ NO → Flavour sets scale of NP and guides design of future direct searches → FLAVOUR STUDIES REQUIRED



A DETECTOR DEDICATED TO FLAVOR PHYSICS : LHCb



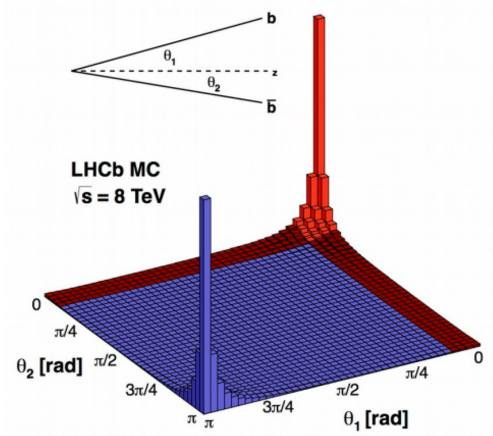
EXPLOITING LHC AS AN HEAVY FLAVOR FACTORY

$\sigma_{b\bar{b}} = (75.3 \pm 14.1)\ \mu\text{b}$ [Phys.Lett. B694 (2010)] in acceptance

- ***$b\bar{b}$* production at the LHC peaks at small polar angles:**

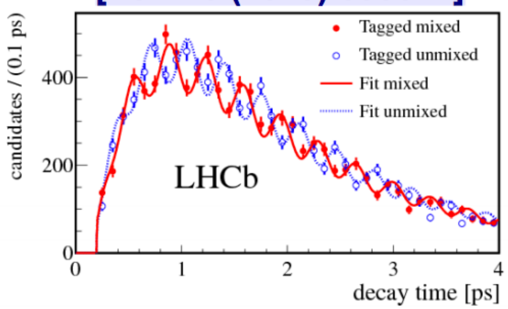
  ≈ 25 % of produced *$b\bar{b}$* pairs inside LHCb acceptance

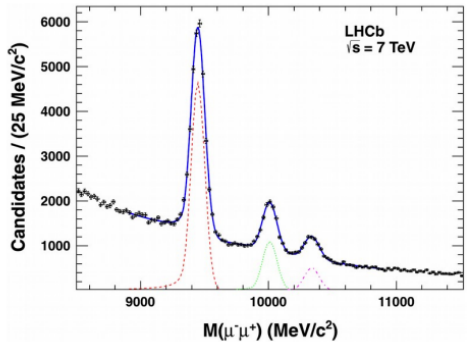
  - c.f. ≈ 40 % inside ATLAS/CMS acceptance



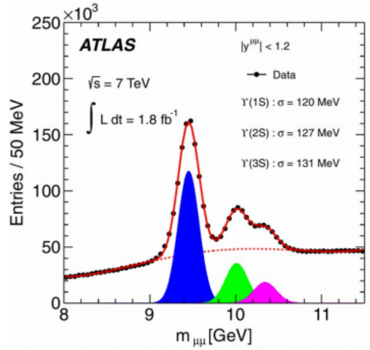
- **additional advantages:**
  - higher momentum at the same p_T → lower p_T thresholds possible
  - larger Lorentz boost of *b* hadrons → better decay time resolution
  - move dead material outside acceptance → less multiple scattering, better momentum and invariant-mass resolution
  - accessibility of detector components → installation / maintenance / repairs

[NJP 15 (2013) 053021]





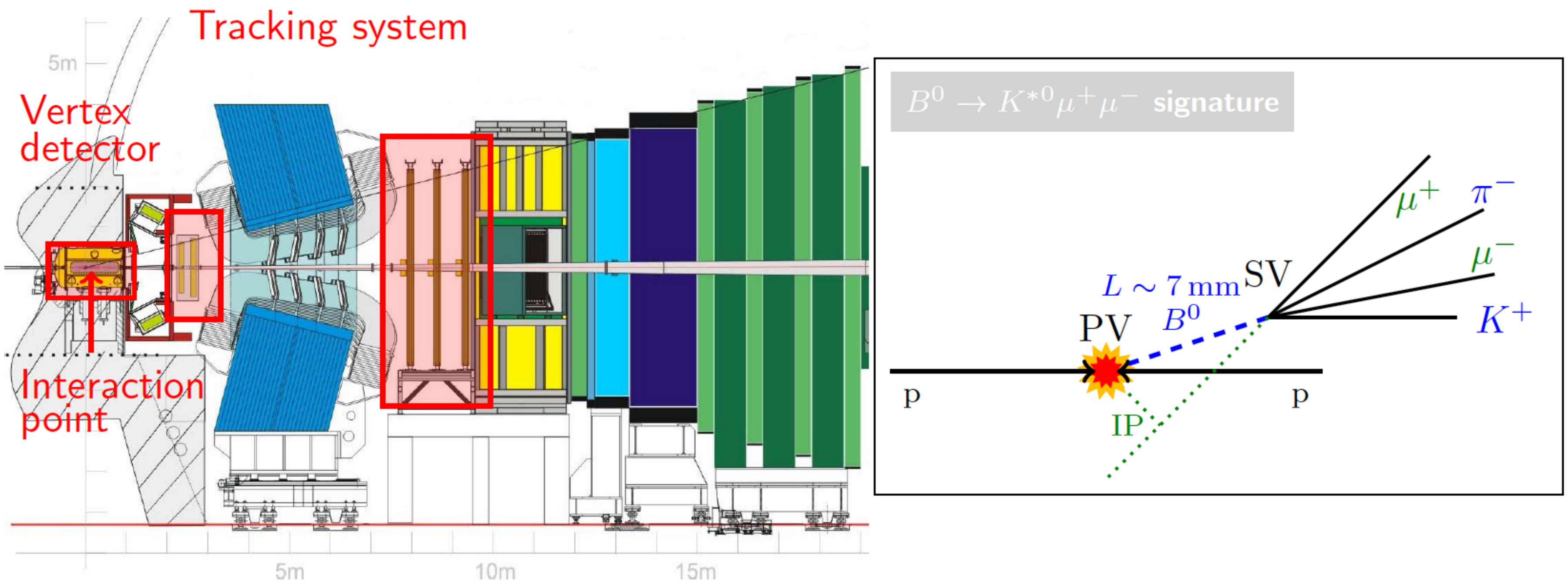
[EPJ C72 (2012) 2025]



[PRD (2013) 052004]

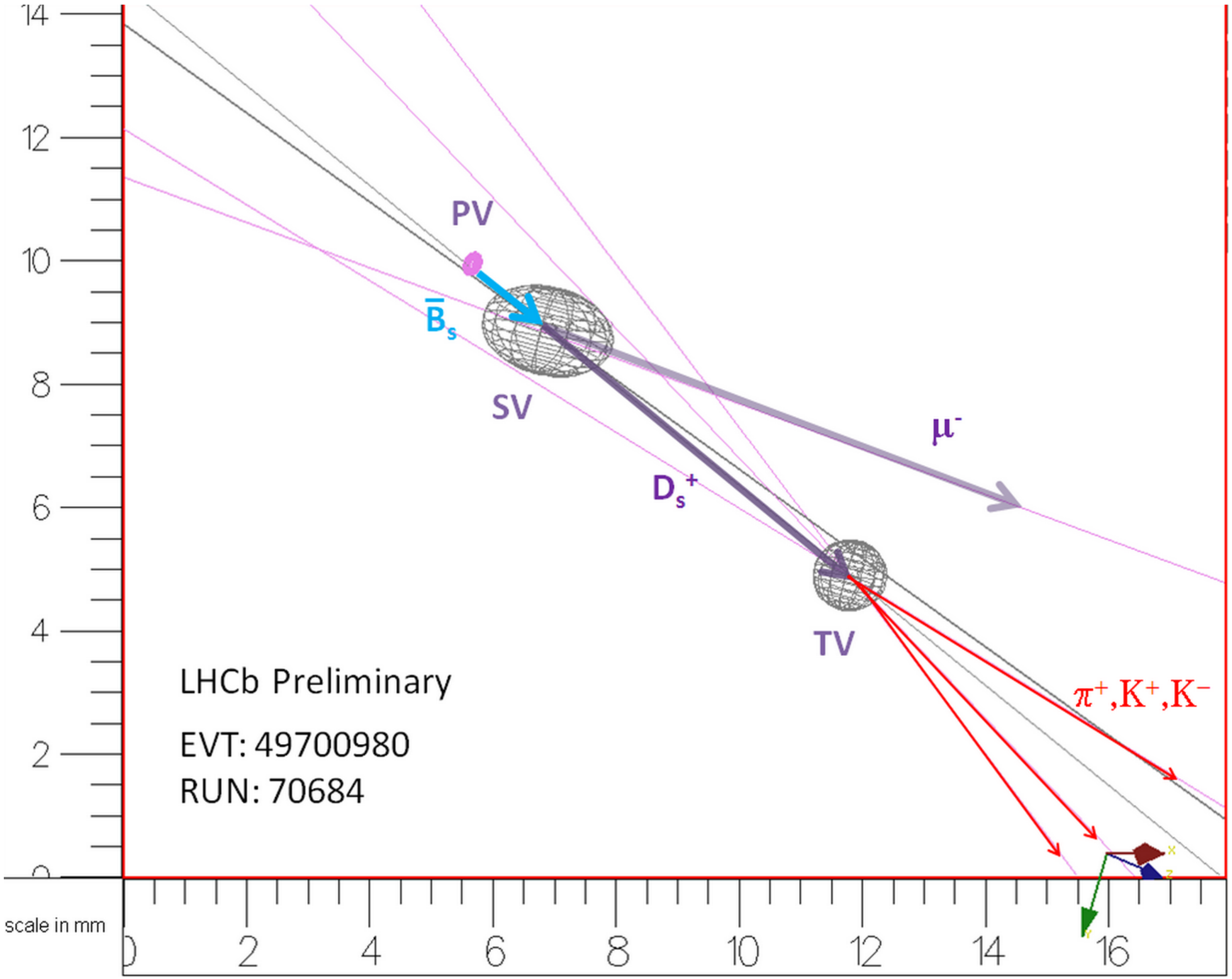
- **extra benefit: unique potential for production studies in forward direction**

LHCb: THE TRACKING SYSTEM

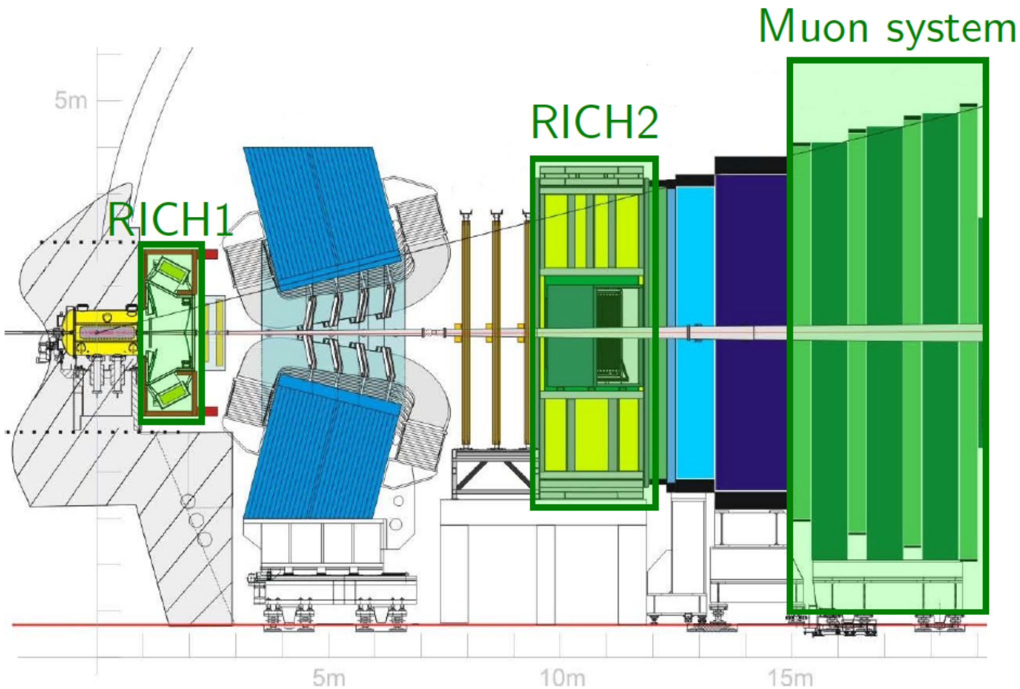


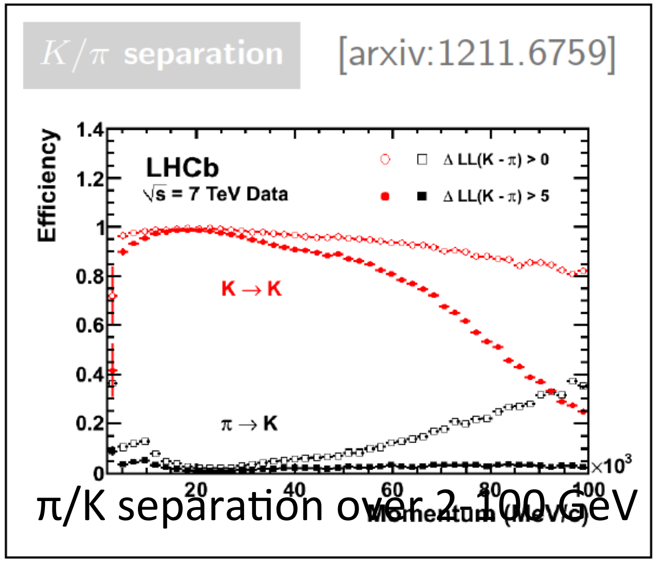
- Excellent Impact Parameter (IP) resolution ($20\,\mu\mathrm{m}$)
  $\rightarrow$ Identify secondary vertices from heavy flavour decays
- Proper time resolution $\sim 40\,\mathrm{fs}$
  $\rightarrow$ Good separation of primary and secondary vertices
- Excellent momentum ($\delta p/p \sim 0.4 - 0.6\%$) and inv. mass resolution
  $\rightarrow$ Low combinatorial background

THE POWER OF THE VELO



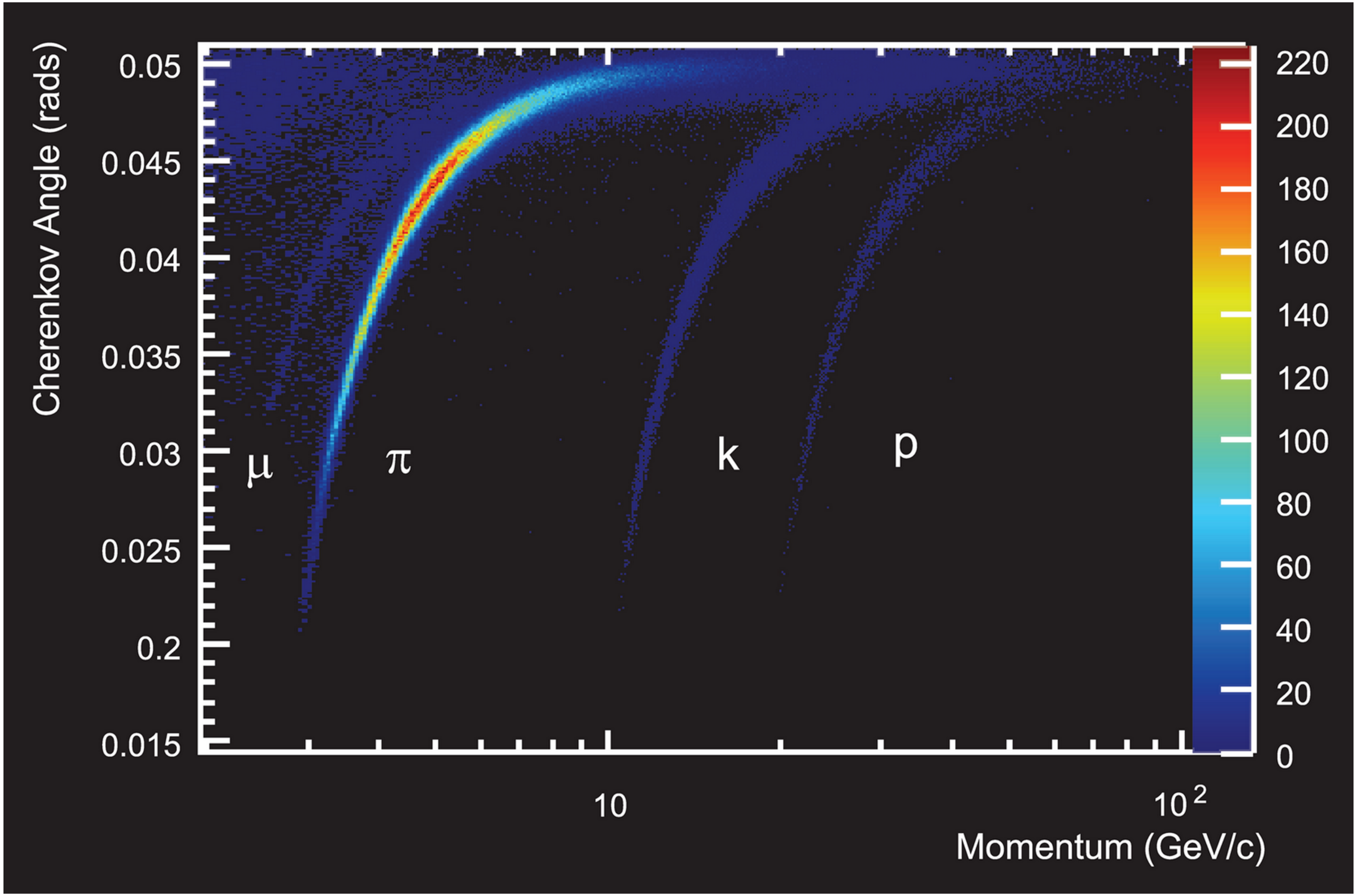
LHC: PARTICLE IDENTIFICATION



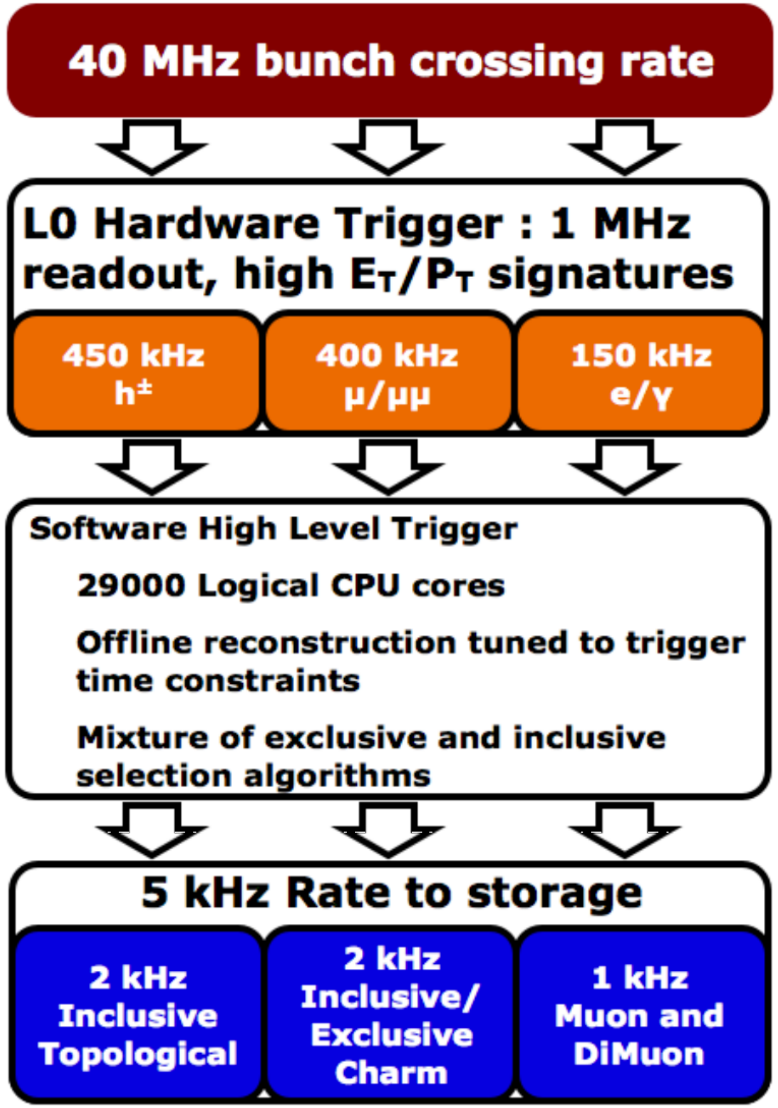


- Excellent Muon identification $\epsilon_{\mu\to\mu} \sim 97\%$ $\epsilon_{\pi\to\mu} \sim$ 1-3%
- Good $K\pi$ separation via RICH detectors $\epsilon_{K\to K} \sim 95\%$ $\epsilon_{\pi\to K} \sim 5\%$
  $\to$ Reject peaking backgrounds

THE POWER OF THE RICH



THE TRIGGER SYSTEM



Hardware level (L0):

- maximum output rate 1 MHz
- typical thresholds

  $E_T(e/\gamma) > 2.7$ GeV

  $E_T(h) > 3.6$ GeV

  $p_T(\mu) > 1.4$ GeV

Software level (HLT):

event reconstruction similar to offline

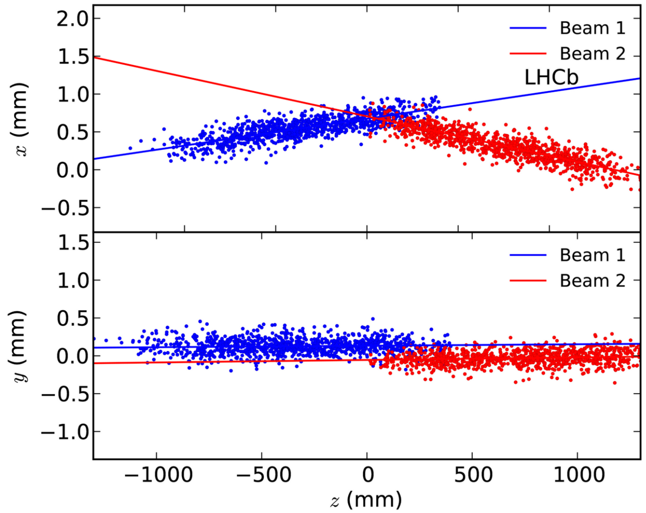
Combined efficiency L0+HLT (2012):

~ 90 % for di-muon channels ($J/\psi\ X$)

~ 30 % for multi-body hadronic final states

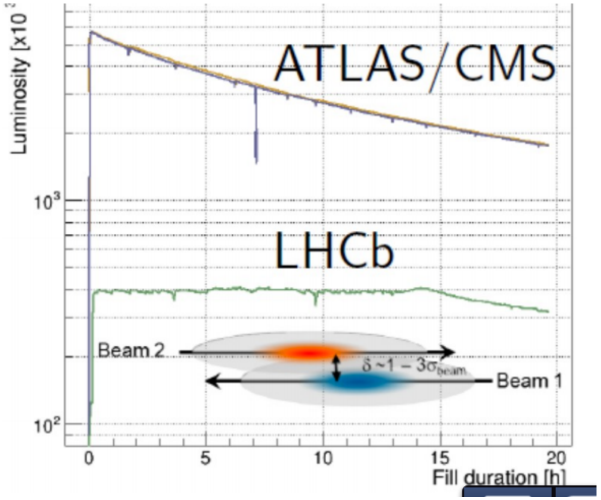
PERFORMANCES IN RUN1

- **LHCb designed to operate at lower instantaneous luminosity than ATLAS/CMS**
  - avoid too high particle density in forward region
  - large number of *pp* interaction vertices can affect reconstruction of decay length, flavour tagging



- **achieved by focussing and relative displacement of the two LHC beams in the LHCb interaction point**
  - luminosity leveling: adjust displacement throughout fill → operate at constant instantaneous luminosity
  - optimal use of beams + stable operation conditions

2011:	**1 fb^{-1} *pp* at 7 TeV**
2012:	**2 fb^{-1} *pp* at 8 TeV**
2013:	**1.6 nb^{-1} *pPb* / *Pbp***



- **data taking efficiency > 93 %**

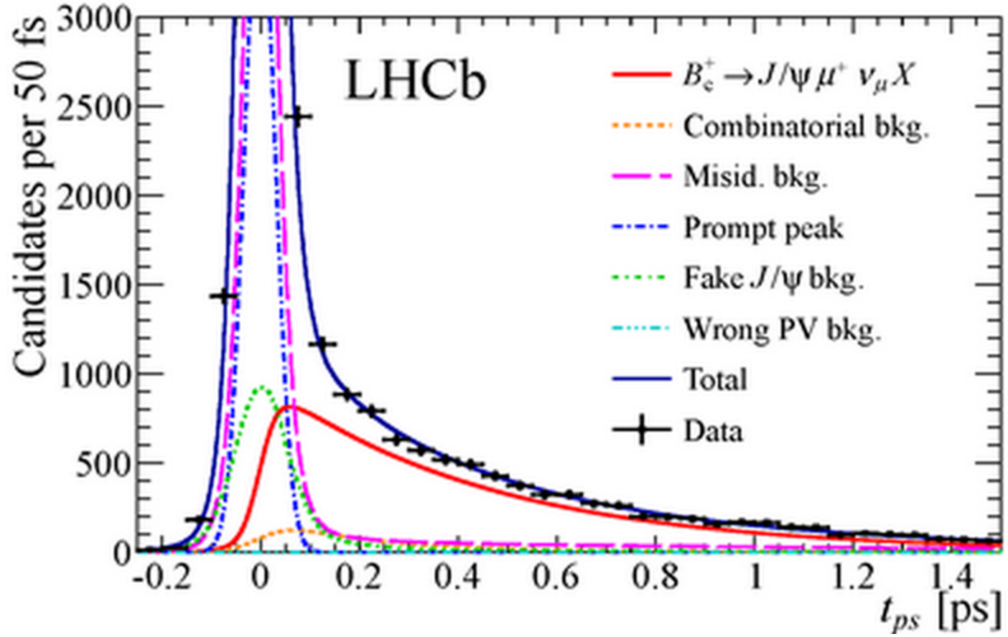
WHICH KIND OF PHYSICS WE DO WITH LHCb?

Large spectrum for the physics program:

- ***Rare B, D, K decays***
- ***CP parameters measurements***
- ***Charm physics***
- ***Spectroscopy and exotic states***
- ***Forward electroweak physics***

28 January 2014: How long can beauty and charm live together?

[$\tau(B_c^+)$ = 509 ± 8 ± 12 fs]

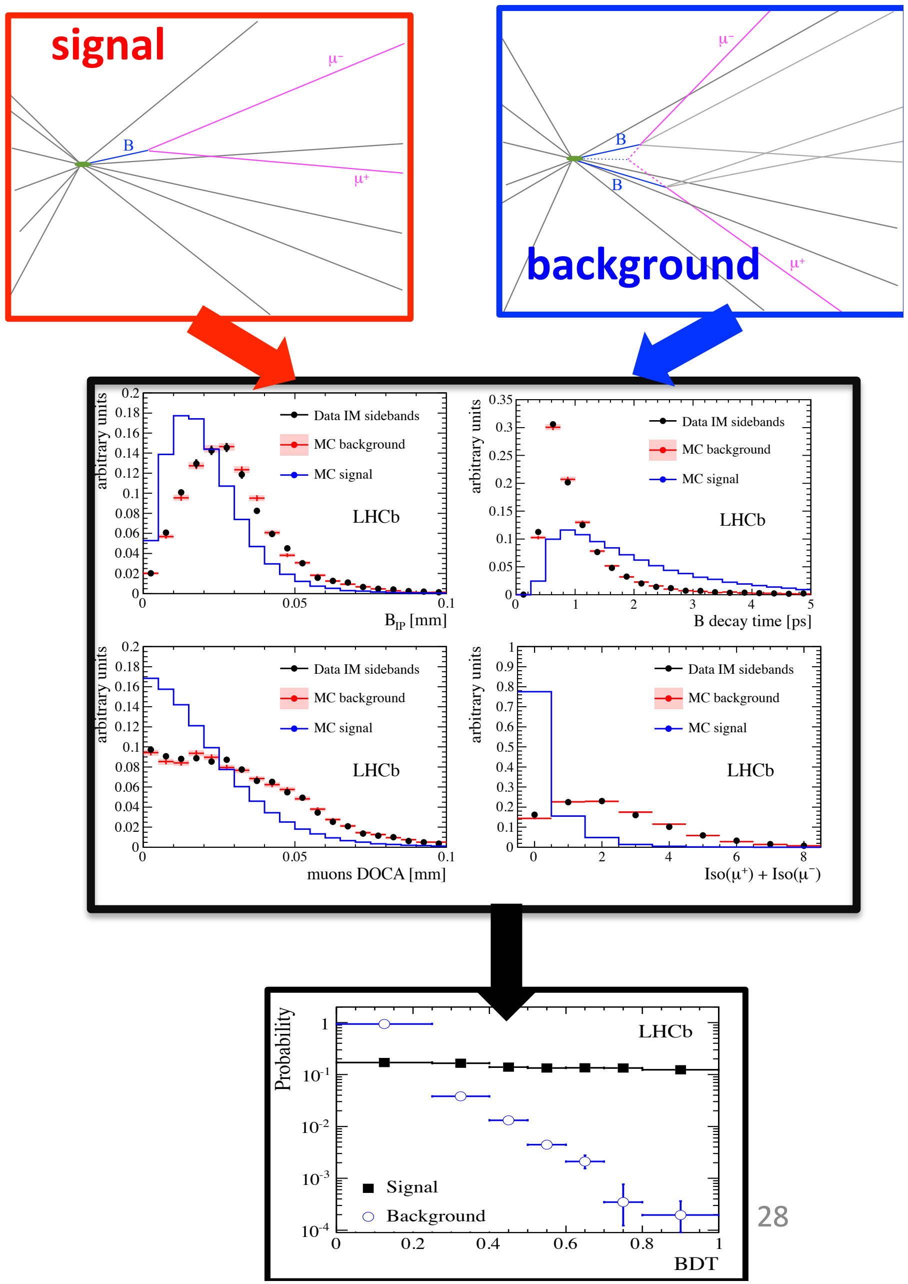


- We have not only B, but B_s, B_c, b-hadrons (Λ_b)
- Channels with muons are easier to trigger on and cleaner, but we learning working with electrons, taus and even channels containing neutrinos.
- K_s and other neutral reconstructions has improved

A TYPICAL ANALYSIS AT LHCb

Common features of many analysis at *LHCb*:

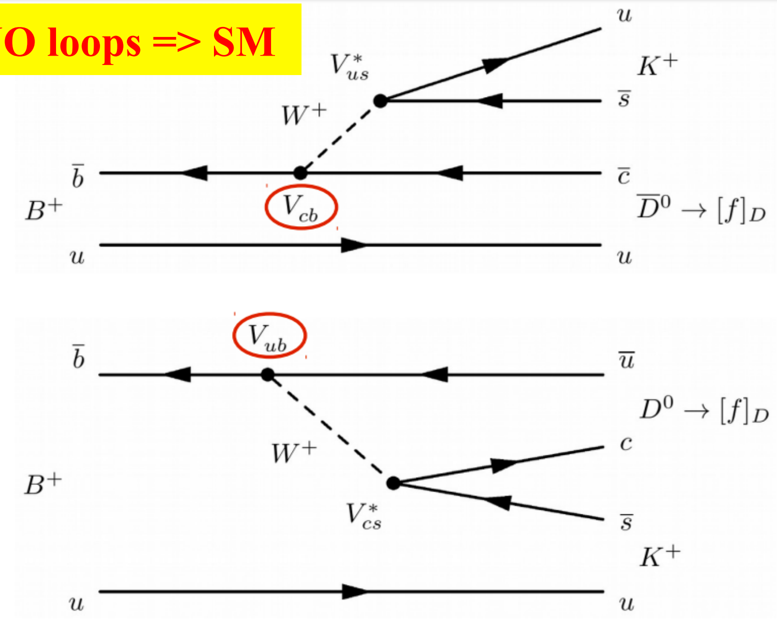
- **Dedicated trigger** (if **muons** in the final state: clean signature, easy to trigger on)
- **"stripping"**, i.e. central preselection
- Combinatorial background suppression based on **multivariate techniques** exploiting information from **kinematic variables**
- **Specific vetoes** to remove or reduce peaking backgrounds
- Particle **Id**entification requirements
- **Control channels** whenever possible to not rely on simulations only
- **Normalization channels** to reduce systematics (no absolute BR measurements)
- **Statistical methods (likelihood fit, method of moments)** to be applied on final set of discriminating variables and/or physics properties (mass, proper time, angular distributions,…)

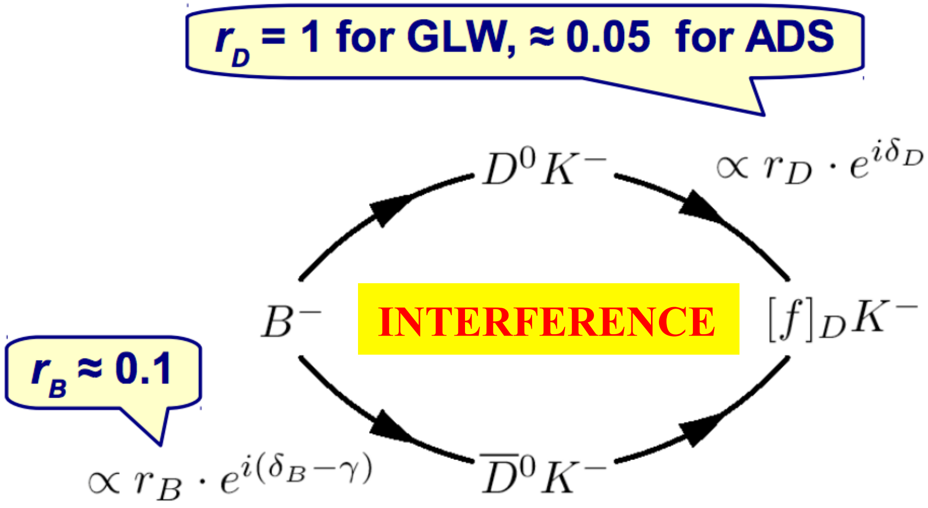


LET'S START WITH SOME GREAT CLASSICS IN FLAVOR.....

THE γ ANGLE FROM GLW and ADS

NO loops => SM



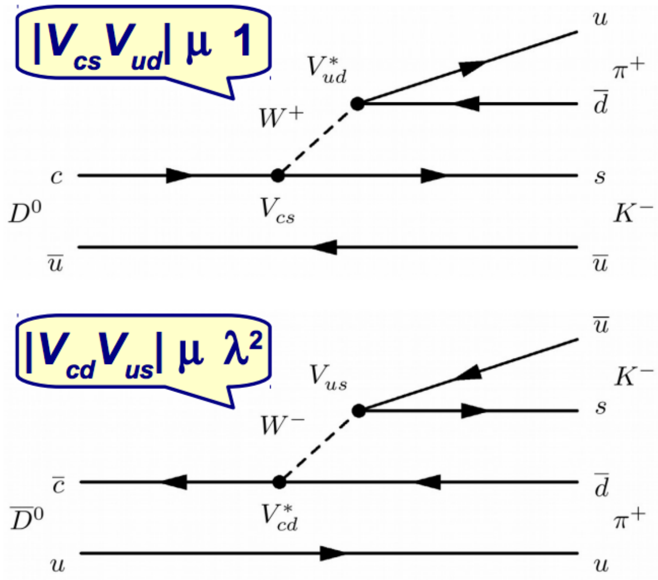


- **GLW: *CP* eigenstates $D^0 \to K^+K^-, \pi^+\pi^-$**
  - $r_B \approx 0.1 \to$ small interference limits sensitivity to γ

    [PLB 253(1991)483, PLB 265(1991)172]

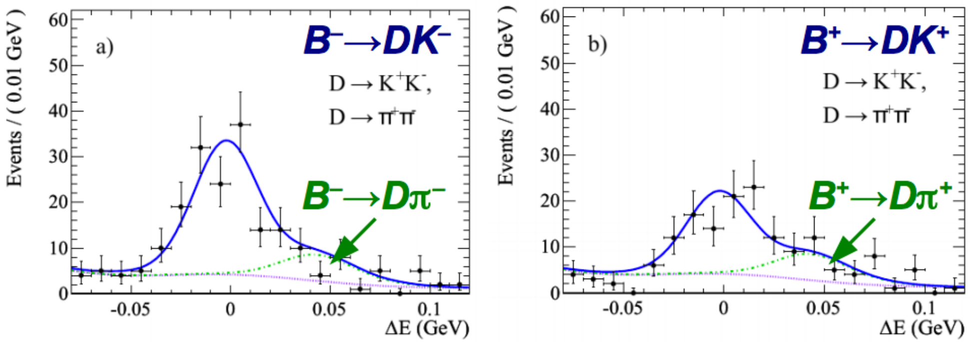
- **ADS: favoured $D^0 \to K^-\pi^+$ / suppressed $D^0 \to K^+\pi^-$**
  - small r_D compensates for $r_B \to$ larger interference
  - but very small *BF* for suppressed modes

    [PRL 78 (1997) 257, PRD 63 (2001) 036005]

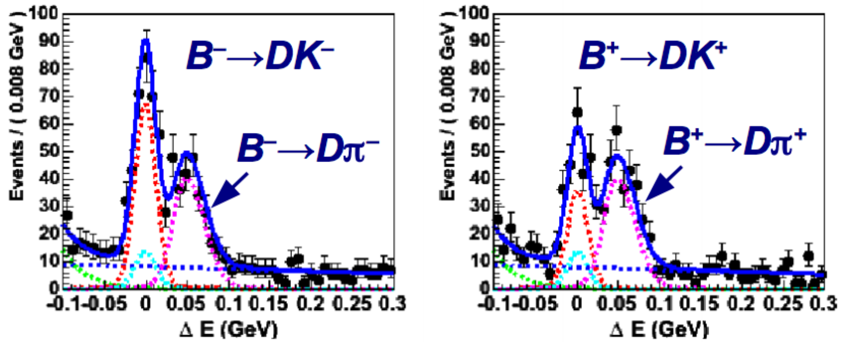


GLW MODES

- **Babar / Belle measurements based on full data sets** (467M / 772M $B\bar{B}$ pairs)

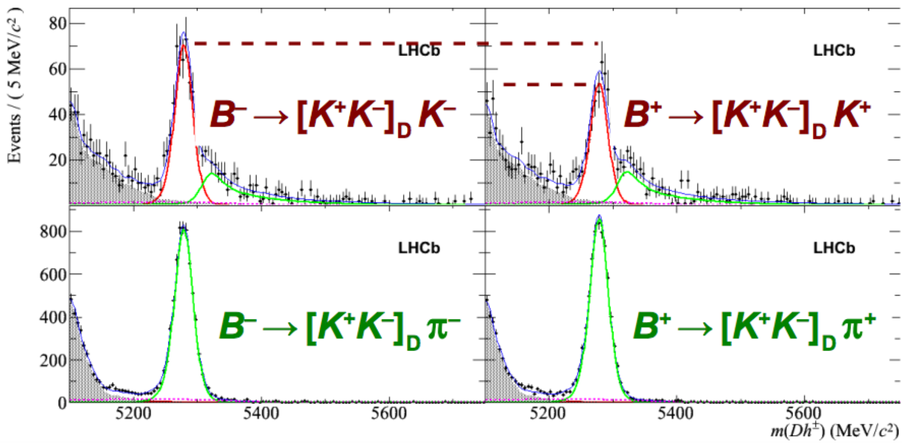


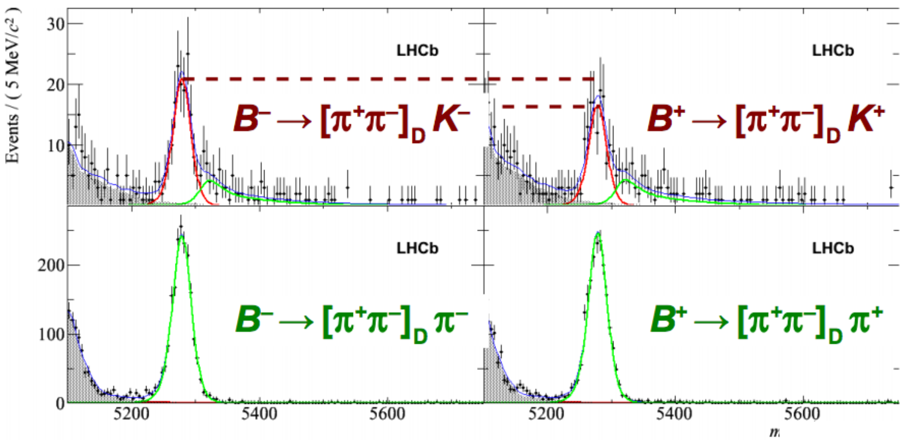
[PRD 82(2010)072004]



[arXiv:1112.1984]

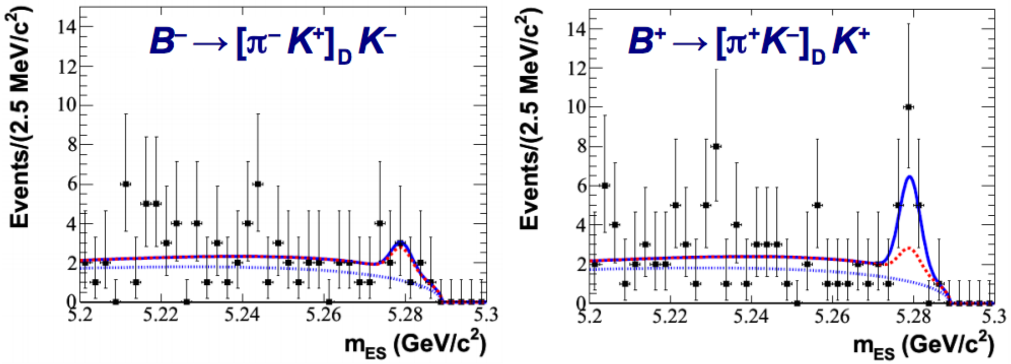
- **LHCb measurement based on 2011 data (1 fb^{-1})** [PLB 713(2012)351]
  - note the excellent suppression of $B^{\pm}\to D\pi^{\pm}$ contamination in $B^{\pm}\to DK^{\pm}$ samples !



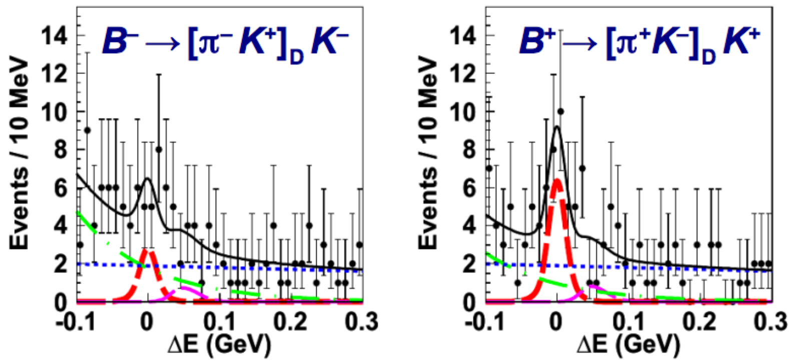


ADS MODES

- **Babar / Belle measurements based on full data sets** (467M / 772M $B\bar{B}$ pairs)

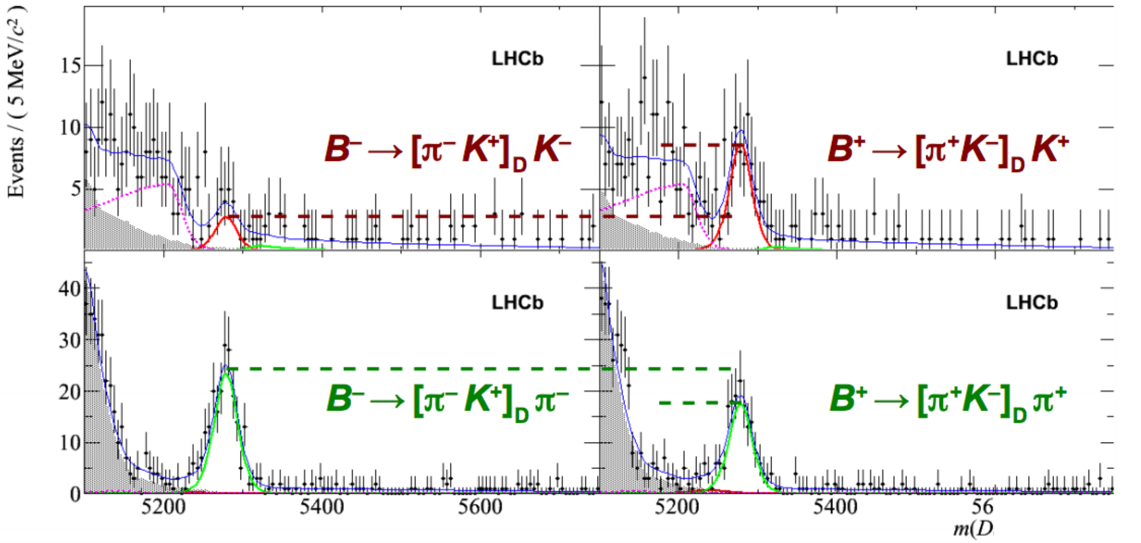


[PRD 82(2010)072006]



[PRL 106(2011)231803]

- **LHCb measurement based on 2011 data (1 fb^{-1})** [PLB 712(2012)203]
  - first observation of the doubly Cabibbo suppressed mode (10 σ significance)
  - evidence for *CP* asymmetry in $B^\pm \to DK^\pm$ (4 σ)
  - hint of an asymmetry also in $B^\pm \to D\pi^\pm$ (2.4 σ)



γ FROM DALITZ-PLOT ANALYSES

- **study $D \to K^0_S\pi^+\pi^-$ decay amplitude as a function of the invariant masses**

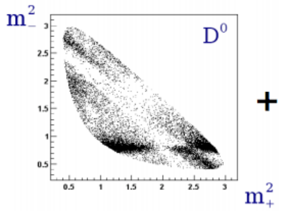
$$m_+^2 \equiv m^2(K^0_S\pi^+) \quad \text{and} \quad m_-^2 \equiv m^2(K^0_S\pi^-)$$

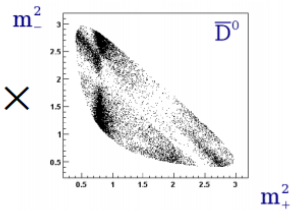
[PRD 68 (2003) 054018]
[PRD 70 (2004) 072003]

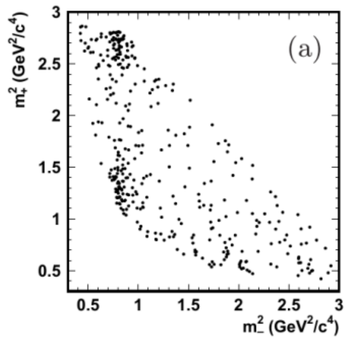
- **neglecting *CP* violation in $D^0\overline{D}^0$ mixing and decay** (known to be very small)**:**

$$f_{\overline{D}^0}(m_+^2, m_-^2) = f_{D^0}(m_-^2, m_+^2)$$

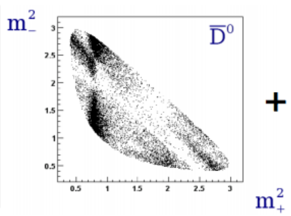
- **for $B^- \to [K^0_S\pi^+\pi^-]_D K^-$**

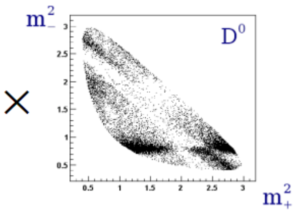
$$\Gamma_{B^-}(m_+^2, m_-^2) \propto \Bigg|$$


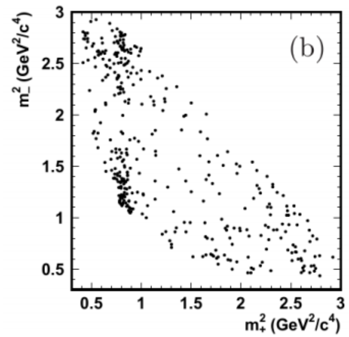
$$+\; \boxed{r_B} \cdot e^{i(\boxed{\delta_B} - \boxed{\gamma})} \times$$


$$\Bigg|^2 \Rightarrow$$


- **for $B^+ \to [K^0_S\pi^+\pi^-]_D K^+$ $(f_{D0} \leftrightarrow f_{\overline{D}0}, -\gamma \leftrightarrow +\gamma)$**

$$\Gamma_{B^+}(m_+^2, m_-^2) \propto \Bigg|$$


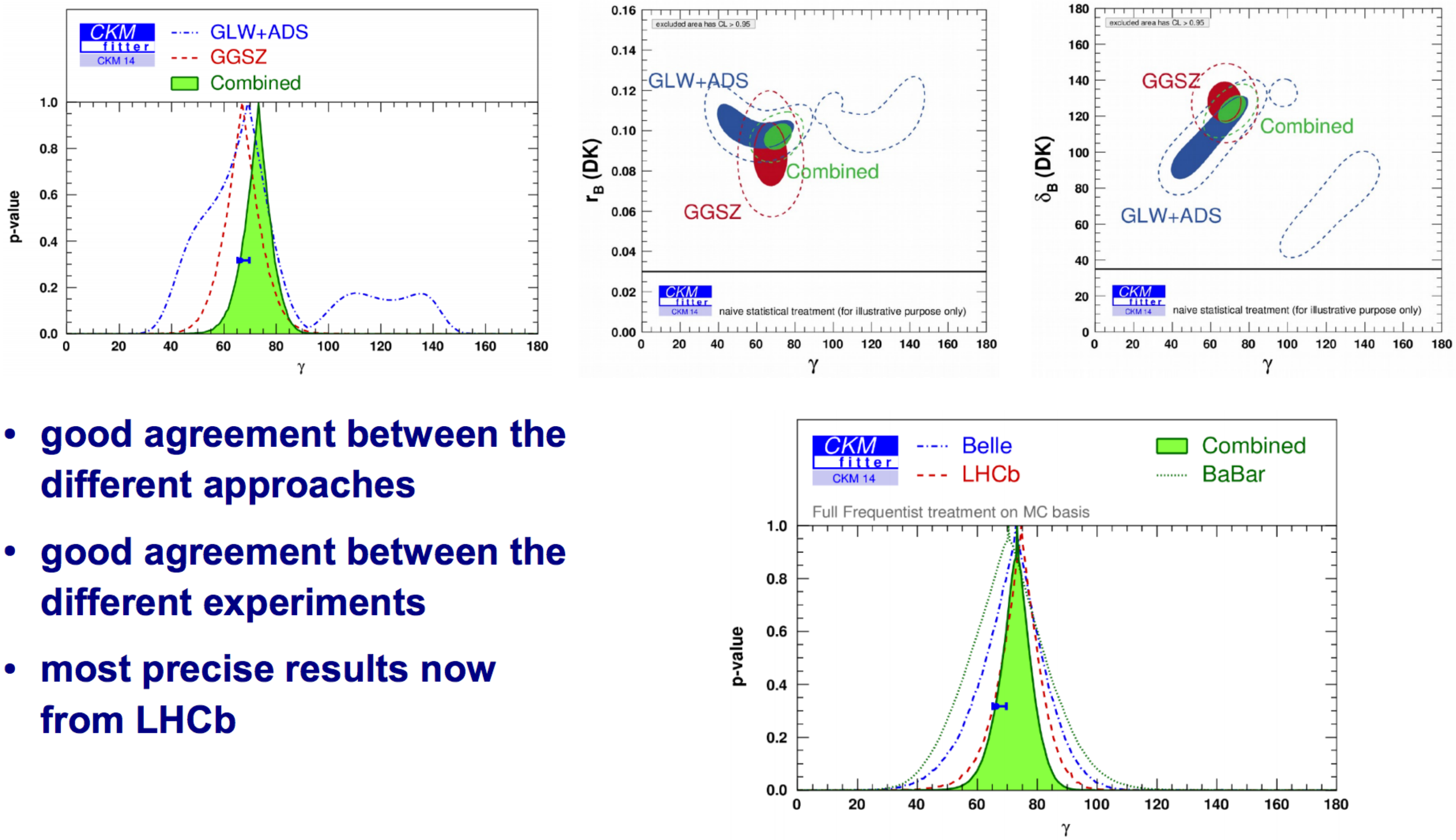
$$+\; \boxed{r_B} \cdot e^{i(\boxed{\delta_B} + \boxed{\gamma})} \times$$


$$\Bigg|^2 \Rightarrow$$


Belle, [PRD 81 (2010) 112002]

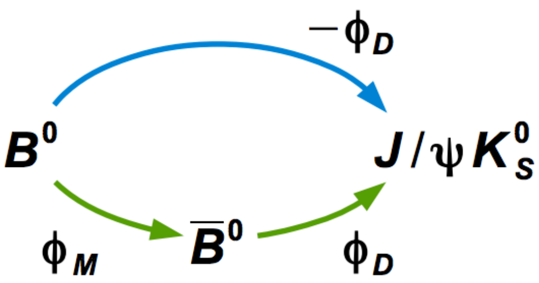
- **dominate precision on γ from the *B* factories**

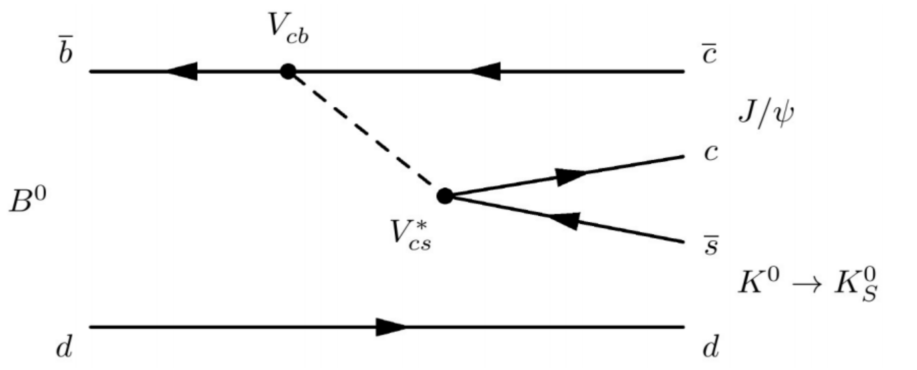
γ COMBINATIONS



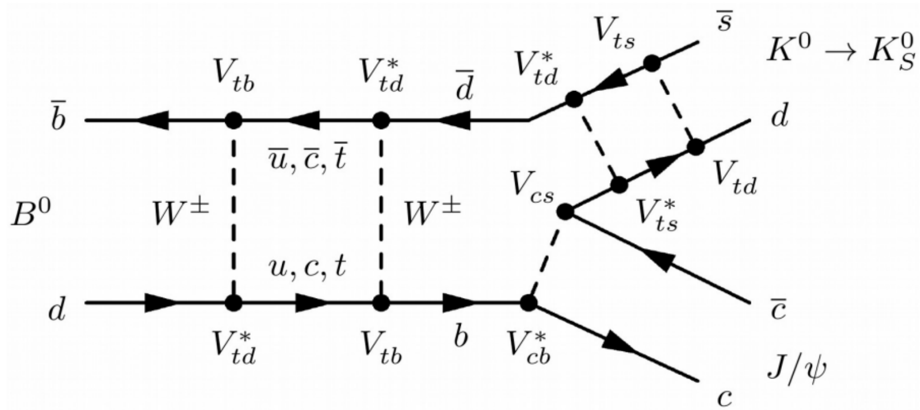
- **good agreement between the different approaches**
- **good agreement between the different experiments**
- **most precise results now from LHCb**

- "golden" decay mode $B^0 \to J/\psi\ K^0_S$
- time–dependent *CP* asymmetry due to "interference of mixing and decay"





$$a_{CP}(t) = \frac{\Gamma(B^0 \to J/\psi K^0_S) - \Gamma(\overline{B}^0 \to J/\psi K^0_S)}{\Gamma(B^0 \to J/\psi K^0_S) + \Gamma(\overline{B}^0 \to J/\psi K^0_S)}$$
$$= \sin(2\beta)\sin(\Delta m_d t)$$



- clean event signature from $J/\psi \to \mu^+\mu^-$ and $K^0_S \to \pi^+\pi^-$
- small theory uncertainty on extraction of sin 2β from measured asymmetry
- *the* flagship measurement of the *B* factories
- the best measured UT parameter to date

$\boxed{\sin 2\beta = 0.691 \pm 0.017}$

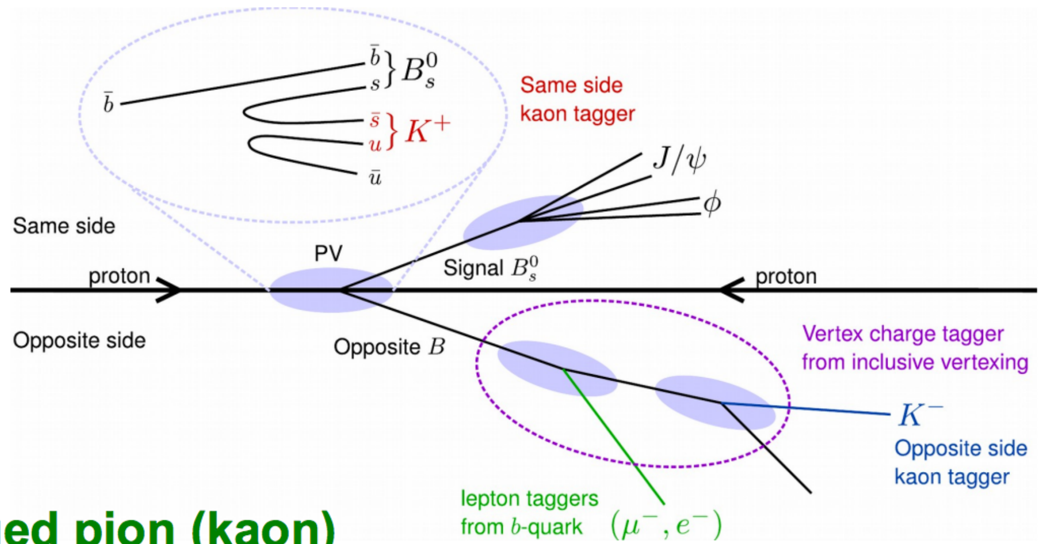
[HFAG, Winter 2015]

FLAVOR TAGGING AT LHCb

- ***pp* collisions produce $b\bar{b}$ quark pairs in an uncorrelated state**
  - each hadronizes independently into any type of *b* or $\bar{b}$ hadron

    B^0 (40 %), B^+ (40 %), B^0_s (10 %), B^+_c (few %), Λ^0_b (10 %)

- **opposite-side flavour tagging: imply initial flavour of signal *B* meson from decay products of the second *b* hadron**
  - charged lepton from $b \rightarrow c\, \ell^- \bar{\nu}_\ell$
  - charged kaon from $b \rightarrow c \rightarrow s$
  - inclusive vertex charge



- **same-side tagging: look for charged pion (kaon) close in phase space to the signal B^0 (B^0_s) meson**
  - from $\bar{b} \rightarrow B$ hadronization chain or from $B^{+**} \rightarrow B^0\pi^+$ decays

- **combined tagging power ≈ 3 %** (c.f. 30 % at *B* factories)
  - wrong tags due to underlying event; oscillation of opposite-side B^0 or B^0_s

FLAVOR TAGGING AT LHCb

Difficult at LHC because of:

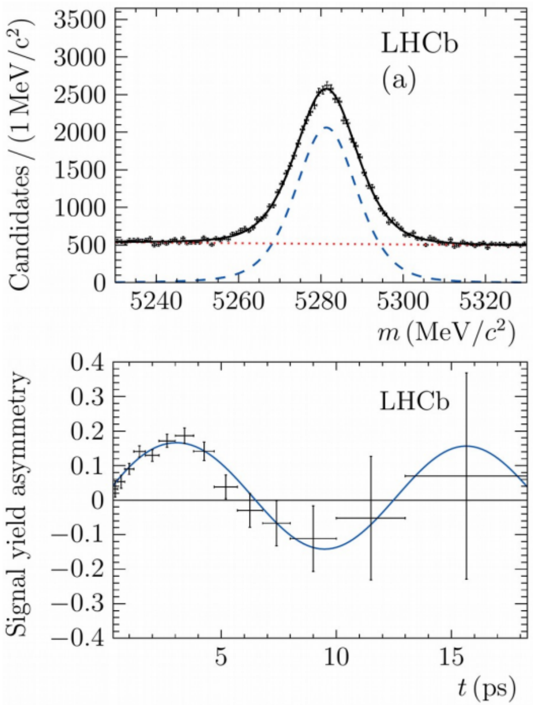
- high pion background from primary vertices (PVs)
- few PVs per event
- many fragmentation tracks (hadronic environment)
- need of particle identification at low momenta

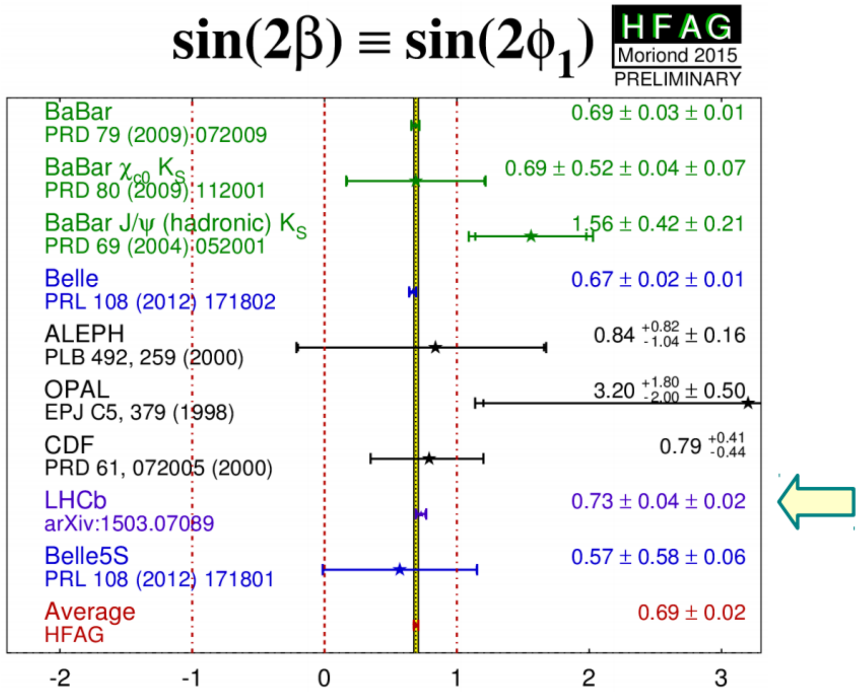
Typical effective efficiencies:

- Same Side Kaon Tagging: ~1.5%
- All taggers: ~3.5%

sin 2β AT LHCB

- **Moriond 2015: LHCb measurement based on run-I data set (3 fb^{-1})**



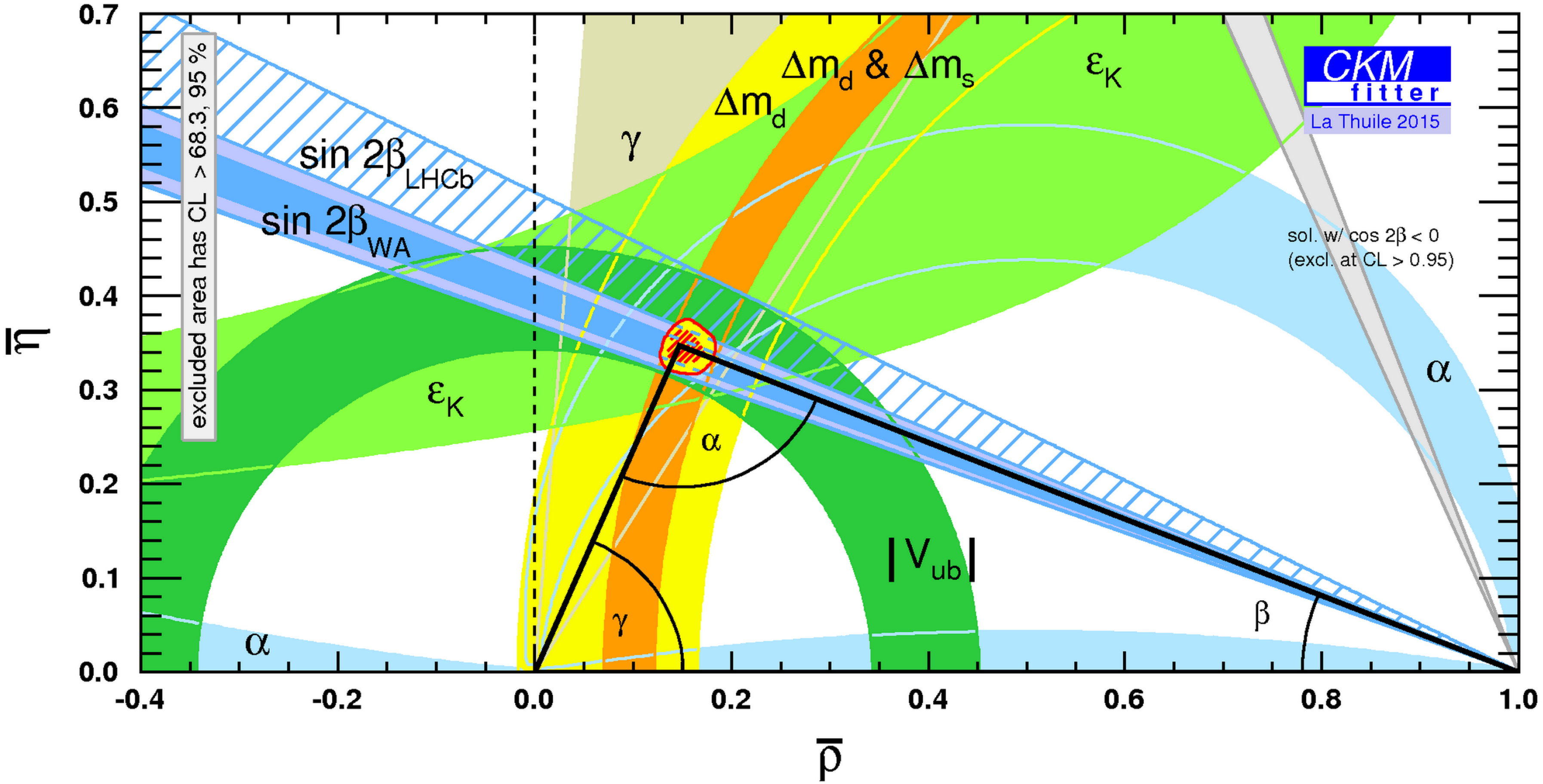


$$\sin 2\beta = 0.731 \pm 0.035\ (\text{stat}) \pm 0.020\ (\text{syst})$$

[arXiv:1503.07089]

- **systematic uncertainty dominated by effects related to flavour tagging**

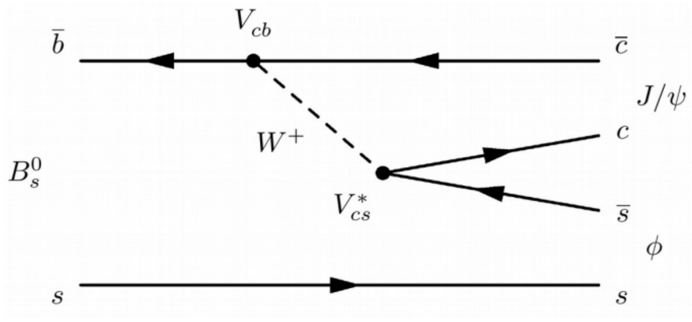
sin 2β FROM LHCB INTO THE GLOBAL FIT



CP VIOLATING PHASE ϕ_s

- "golden" decay mode $B^0_s \to J/\psi\ \phi$
- time-dependent *CP* asymmetry from interference between mixing and decay

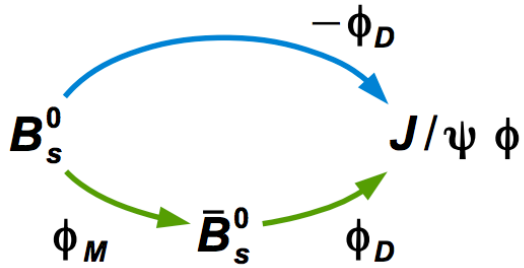
$$\phi_s = \boxed{\phi_M} - \boxed{2\phi_D}$$



- predicted to be very small in Standard Model

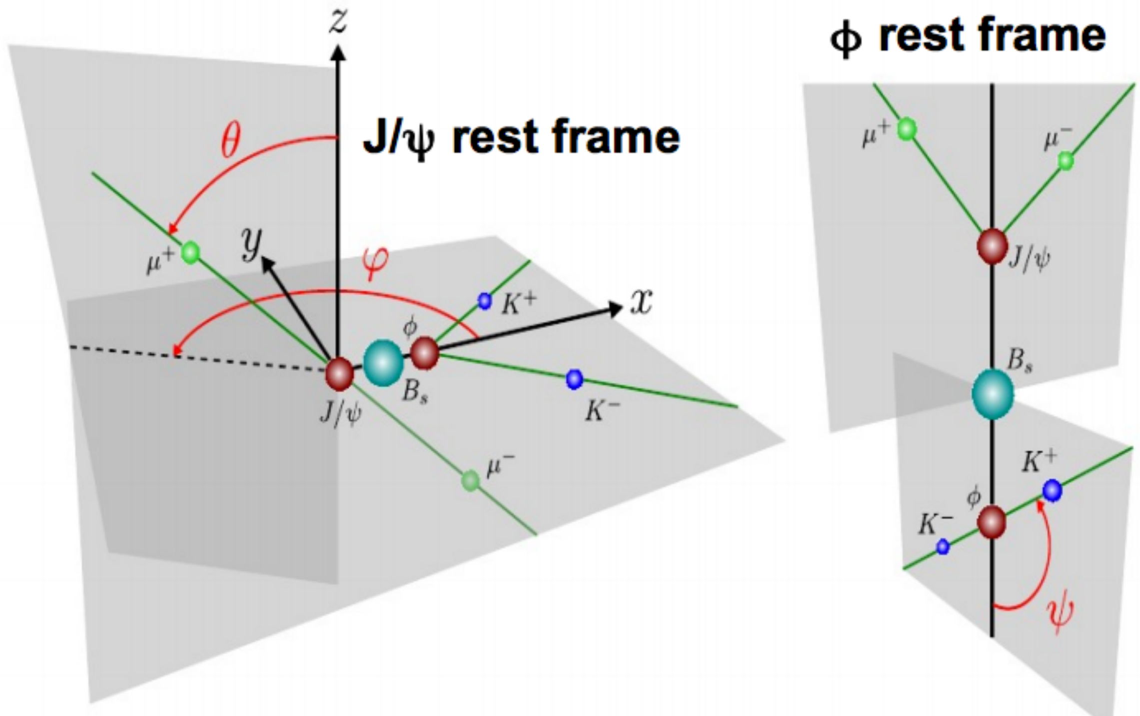
$$\boxed{\phi_s = 0.0364 \pm 0.0016 \text{ rad}}$$

[CKMfitter]



- sensitive to New Physics contributions in B^0_s–$\bar{B}^0_s$ mixing
- need to resolve fast B^0_s–$\bar{B}^0_s$ oscillations → excellent decay-time resolution
- significant decay-width difference $\Delta\Gamma_s$ between the mass eigenstates
  - need to measure simultaneously with ϕ_s
- *J/ψ φ* can have relative angular momentum *L* = 0,1 or 2 → not a *CP* eigenstate
  - time-dependent angular analysis to disentangle even and odd *CP* contributions

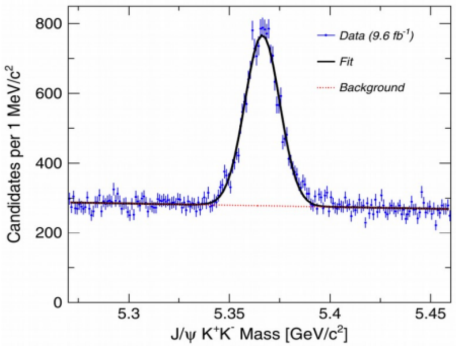
CP VIOLATING PHASE ϕ_s

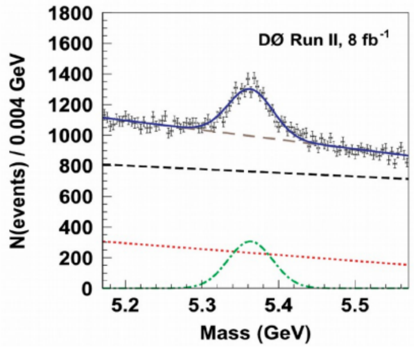


$$\Omega \equiv (\theta = \theta_\mu, \psi = \theta_K, \varphi = \phi_h)$$

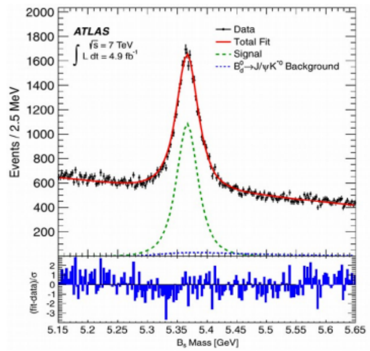
CP VIOLATING PHASE ϕ_s

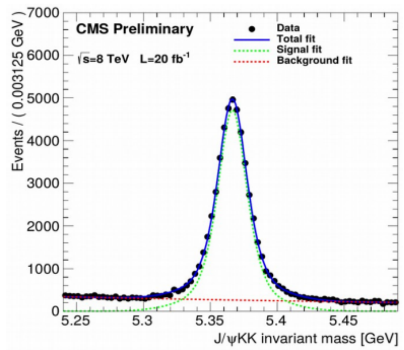
- **measurements by CDF, D0, ATLAS, CMS**



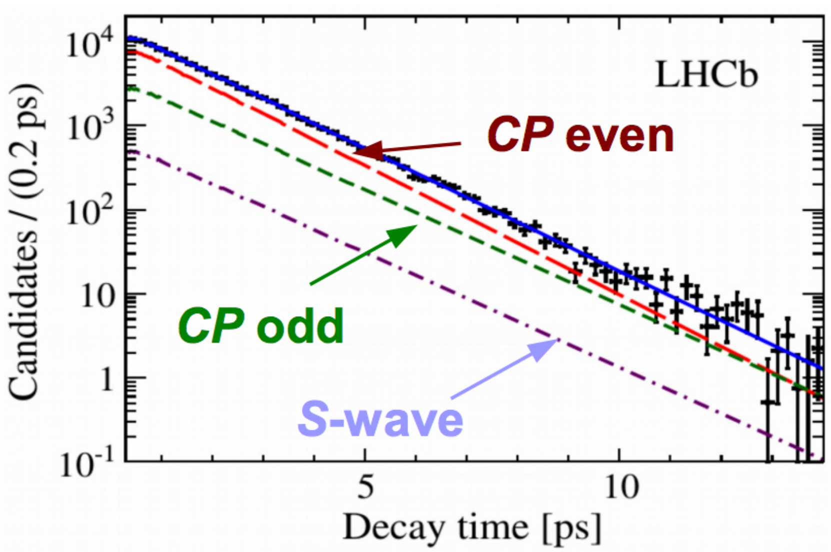


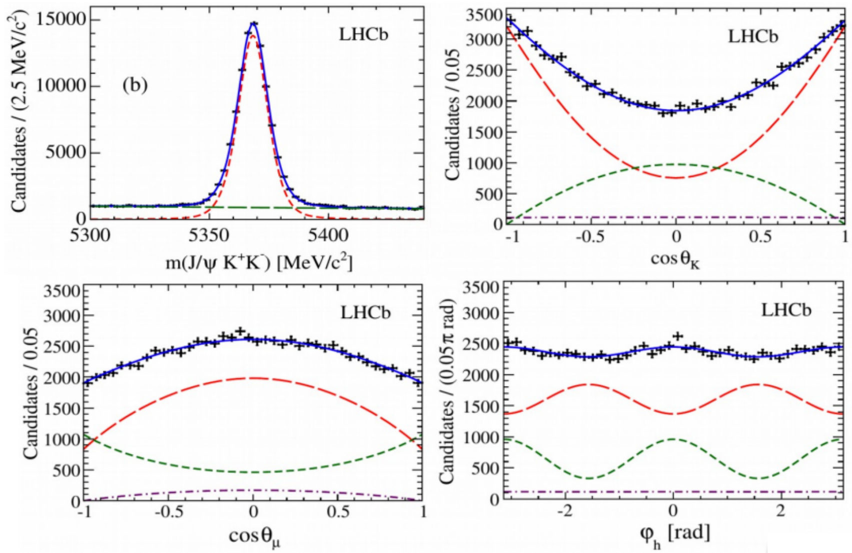
[PRL 109(2012)171802] [PRD 85(2012)032006]





- **LHCb measurement based on run-I data set** (3 fb^{-1}) [PRL 114(2015)041801]





CP VIOLATING PHASE ϕ_s

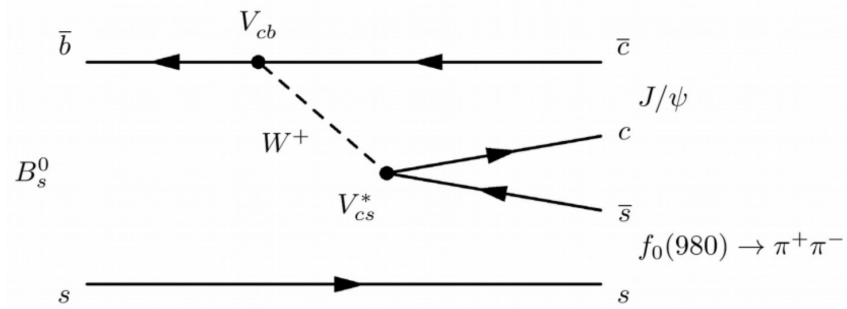
- **LHCb measurement also in $B^0_s \to J/\psi\, \pi^+\pi^-$**
  - (almost pure) *CP* eigenstate → no need for angular analysis
  - but lower branching fraction
- **combined LHCb result**

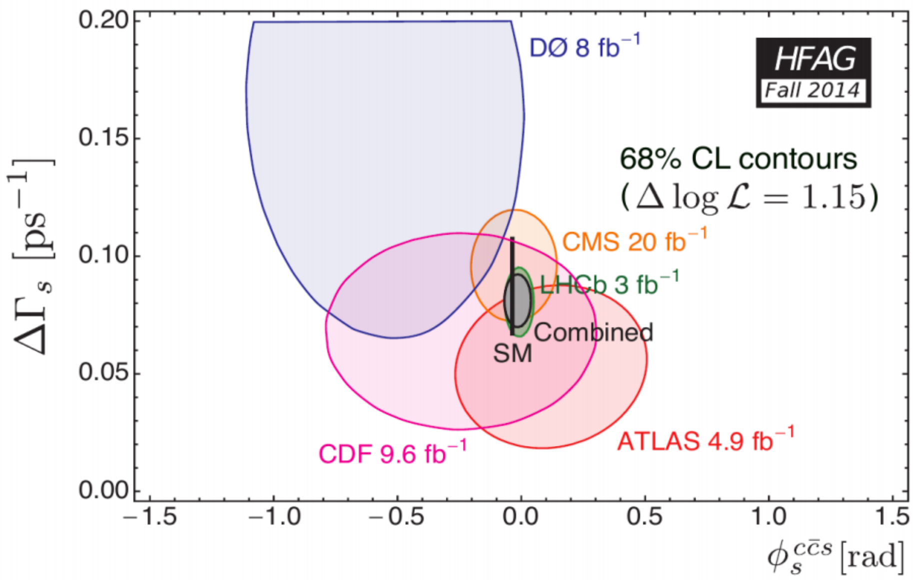
$$\boxed{\phi_s = -0.010 \pm 0.039 \text{ rad}}$$

[PRL 114(2015)041801]

most precise measurement to date

- **all measurements in good agreement with Standard Model prediction**





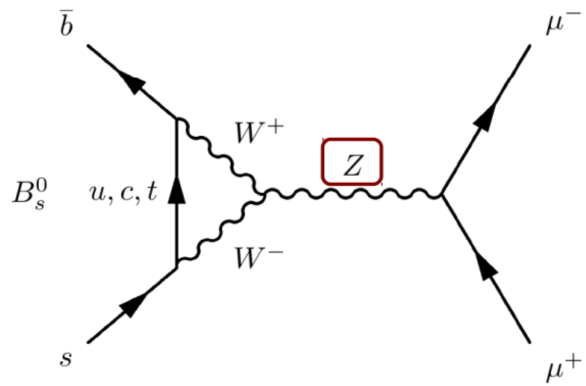
$B_{(s)} \rightarrow \mu\mu$

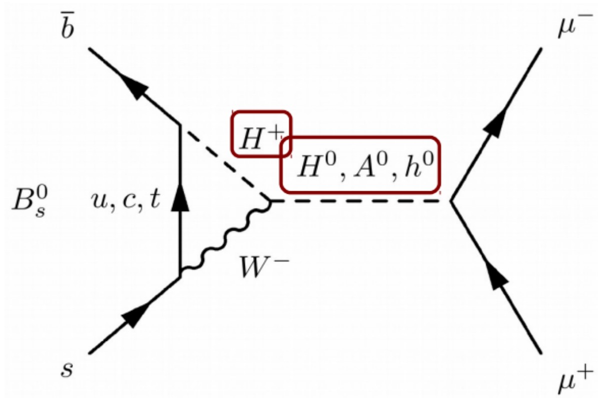
- **Flavour-Changing Neutral-Current $b \rightarrow s(d)$ transition**
  - can only proceed through loop diagrams
  - in addition helicity suppressed in Standard Model
- **branching fractions predicted to be very small**

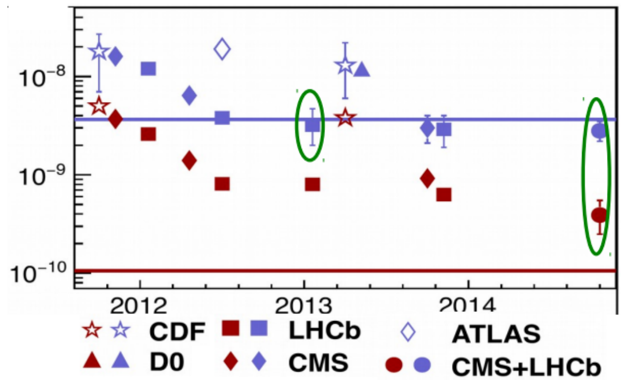
$$BF\,(B^0_s \rightarrow \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$
$$BF\,(B^0 \rightarrow \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

[PRL 112(2014)101801]

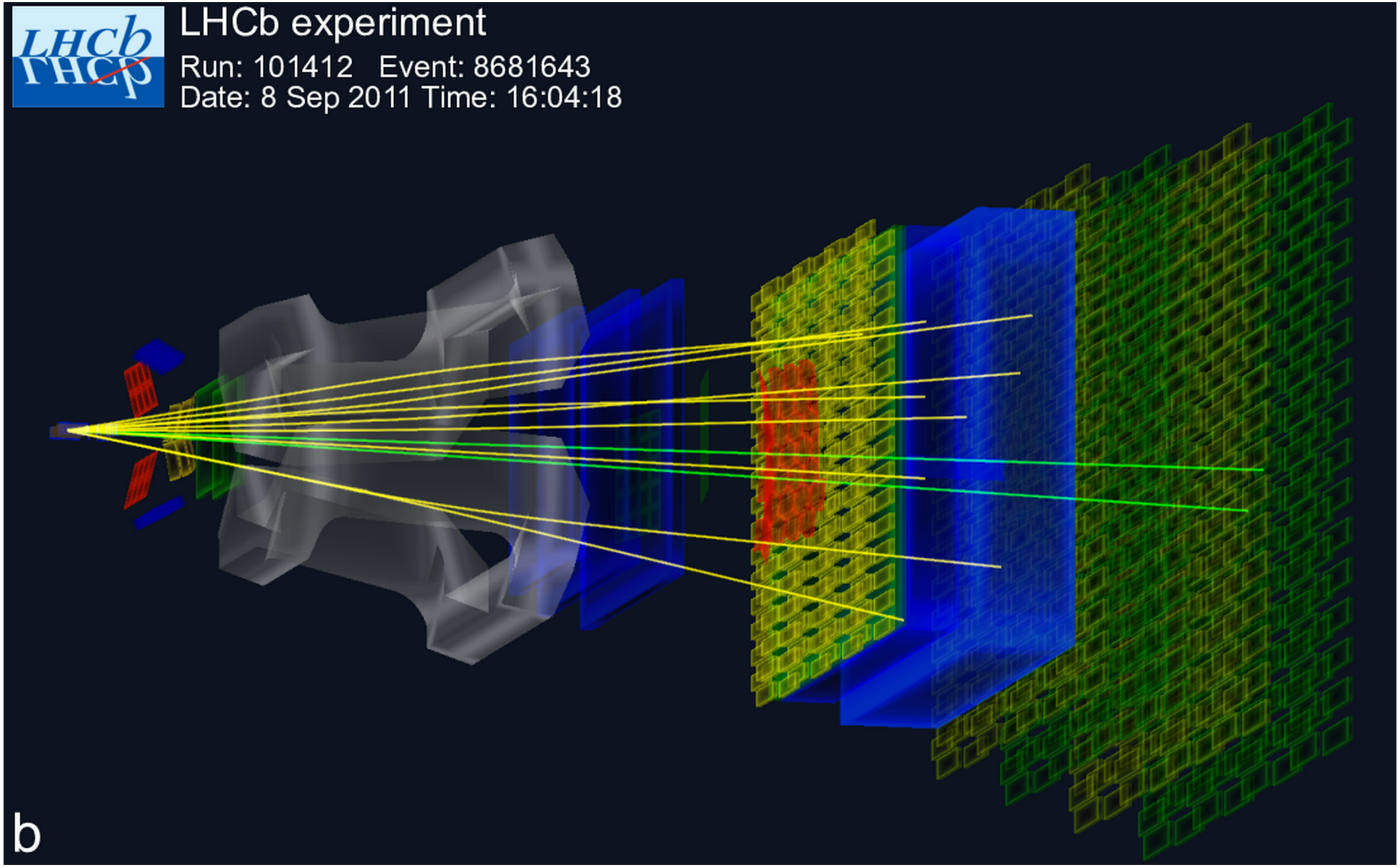
- **sensitive to possible New Physics**
  - in particular models with extended Higgs sector and large values of tan β
- **recent searches at CDF, D0, ATLAS, CMS, LHCb**
  - first $B^0_s \rightarrow \mu^+\mu^-$ evidence from LHCb analysis of 2 fb^{-1}
  - first $B^0_s \rightarrow \mu^+\mu^-$ observation, $B^0 \rightarrow \mu^+\mu^-$ evidence from combined LHCb/CMS analysis of full run-I data sets







A CANDIDATE FOR $B_{(s)} \rightarrow \mu\mu$



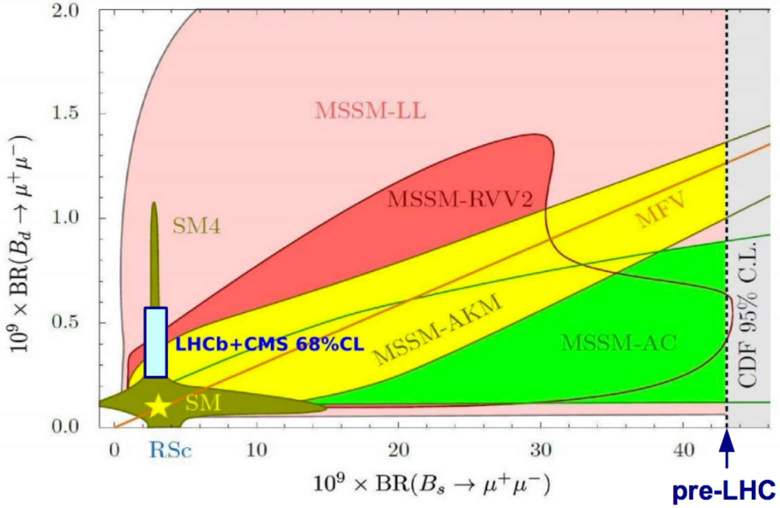
$B_{(s)} \rightarrow \mu\mu$: A COMBINED ANALYSIS WITH CMS

- **combination with CMS measurement**

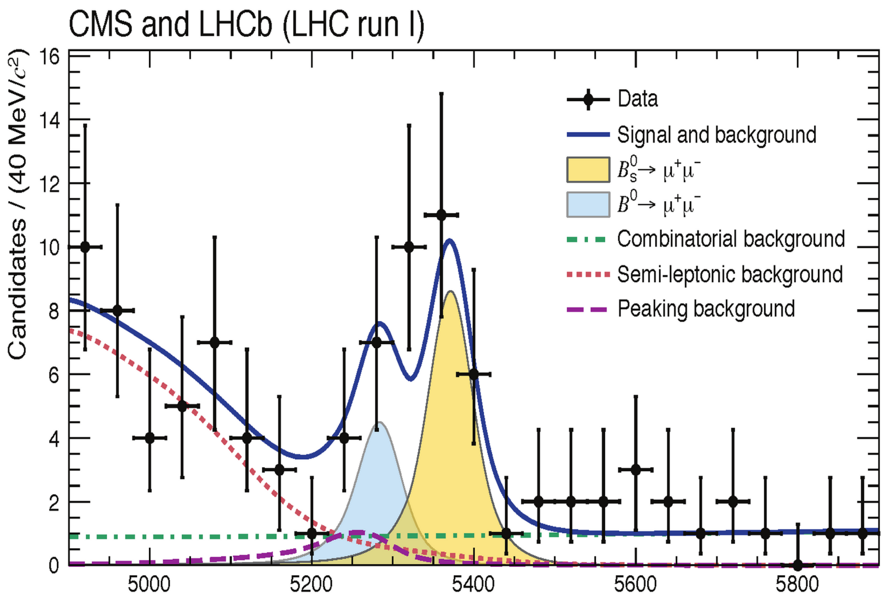
$$BF\,(B^0_s \rightarrow \mu^+\mu^-) = (2.8\,^{+0.7}_{-0.6}) \times 10^{-9}$$
$$BF\,(B^0 \rightarrow \mu^+\mu^-) = (3.9\,^{+1.6}_{-1.4}) \times 10^{-10}$$

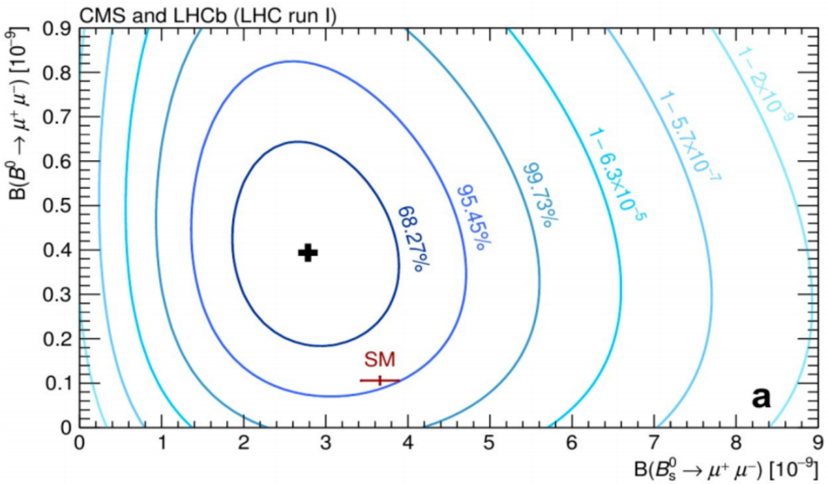
[arXiv:1411.4413]

- **$B^0_s \rightarrow \mu^+\mu^-$ agrees with Standard Model**
- **$B^0 \rightarrow \mu^+\mu^-$ 2.2 σ above Standard Model**



modified from [NC C035N1(2012)249]

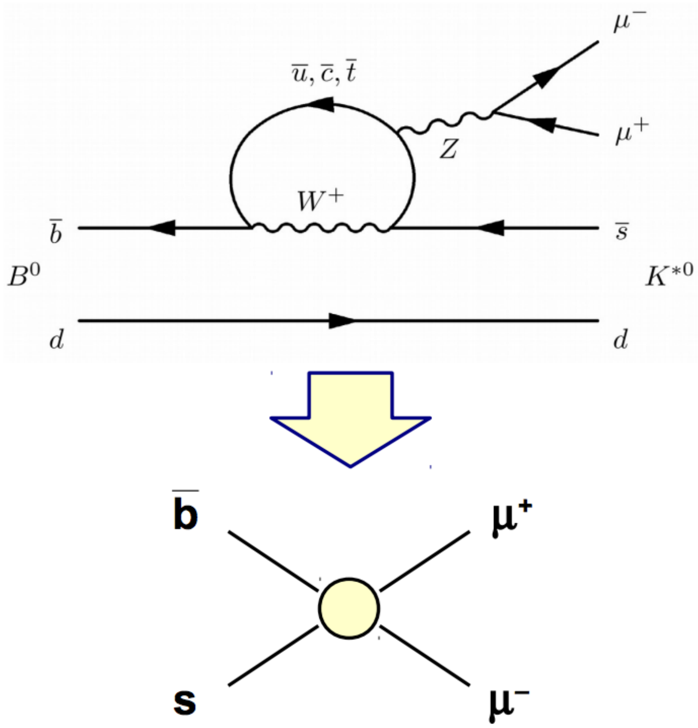




AND NOW LET'S SPICE IT UP!

$B \rightarrow K^{*}\mu\mu$

- **another Flavour-Changing Neutral Current decay mediated by loop diagrams**
  - physics beyond Standard Model can affect angular distributions of final-state particles
- **theoretical treatment: effective Hamiltonian**



$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \sum_i \Big[\underbrace{C_i(\mu) O_i(\mu)}_{\text{left-handed part}} + \underbrace{C_i'(\mu) O_i'(\mu)}_{\substack{\text{right-handed part} \\ \text{suppressed in SM}}} \Big]$$

i = 1,2	Tree
i = 3 – 6,8	Gluon penguin
i = 7	Photon penguin
i = 9,10	Electroweak penguin
i = S	Higgs (scalar) penguin
i = P	Pseudoscalar penguin

- operators O_i: non-perturbative long-distance effects
- Wilson coefficients C_i: perturbative short-distance effects

} factorization scale μ

- **$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ dominated by O_9 μ $(\bar{b}s)_{V\text{-}A}(\mu^+\mu^-)_V$ and O_{10} μ $(\bar{b}s)_{V\text{-}A}(\mu^+\mu^-)_A$**
- **physics beyond Standard Model can affect the values of Wilson coefficients (C_9 , C_{10}) or add contributions from other operators (e.g. O_9')**

$B \to K^*\mu\mu$ ANGULAR ANALYSIS

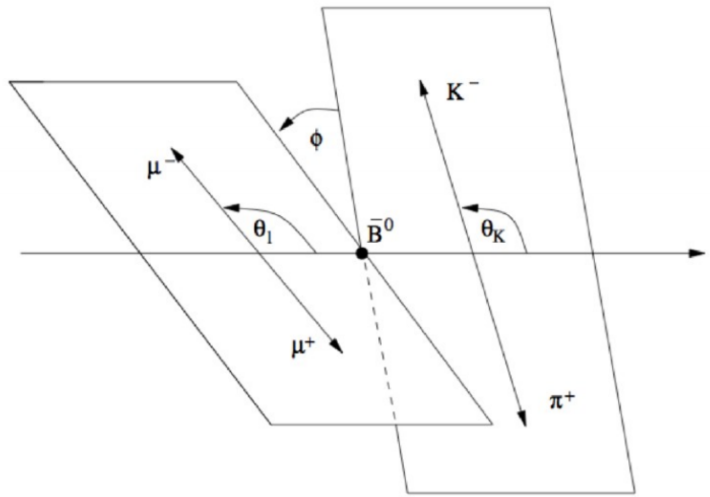
- **four final-state particles → three decay angles (θ_K, θ_ℓ, ϕ)**
- **angular distribution fully described by eight independent observables**

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

- **$F_L(q^2)$ and $S_j(q^2)$ are functions of the underlying Wilson coefficients**
- **but uncertainties from hadronic form factors**
- **define combinations of F_L and S_j in which form factors cancel to leading order, e.g.**

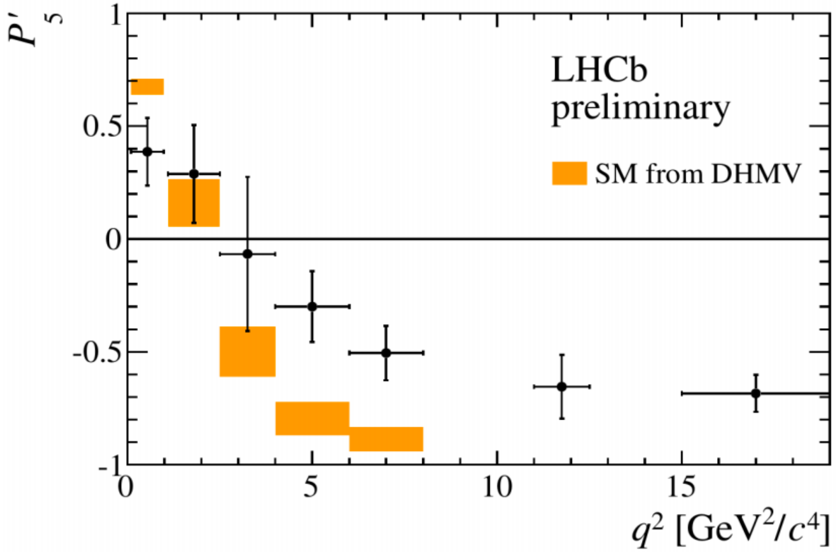
$$P'_5 \equiv \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

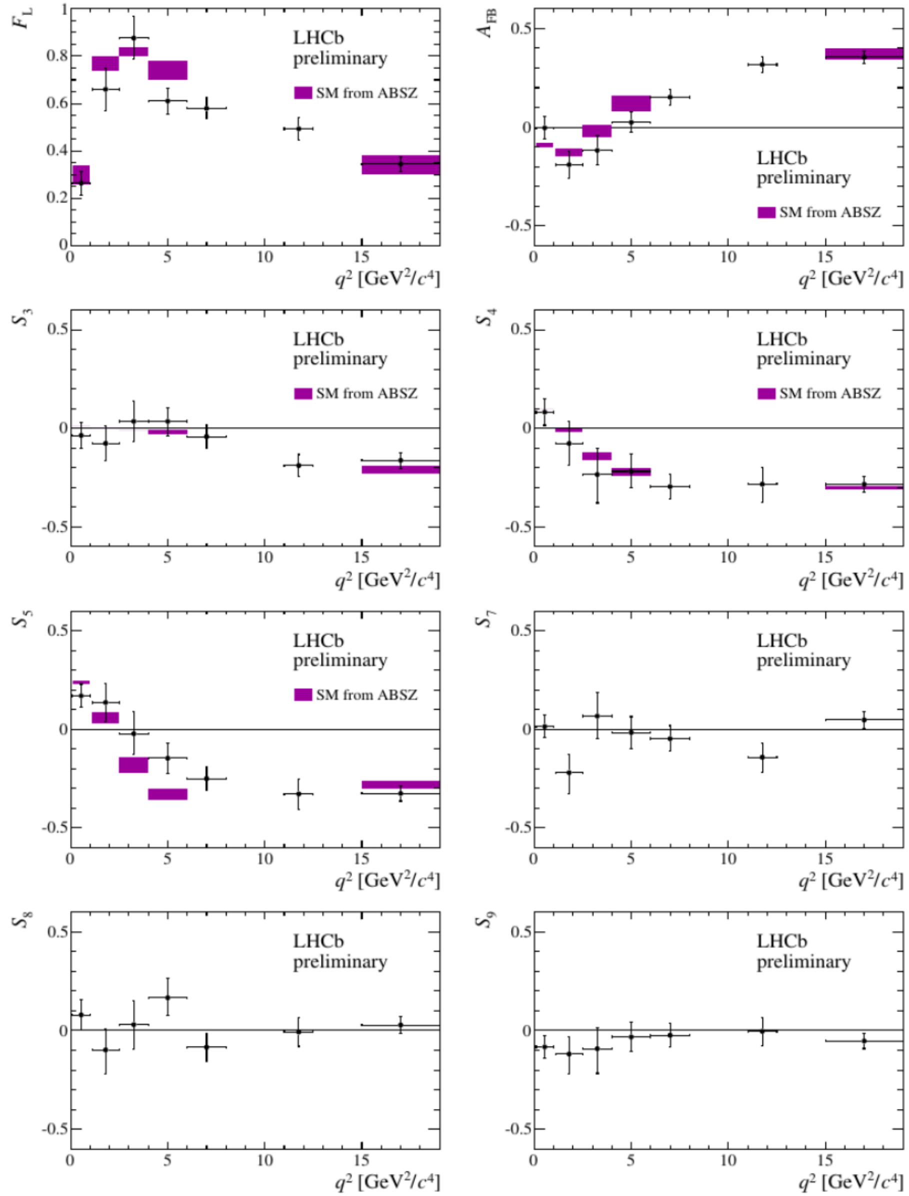
[JHEP 1305(2013)137]



$B \rightarrow K^*\mu\mu$ WITH 3fb-1

- **new results consistent with the earlier LHCb measurements**
  - in particular, discrepancy from Standard Model in P_5' is confirmed
  - significance again 3.7 σ

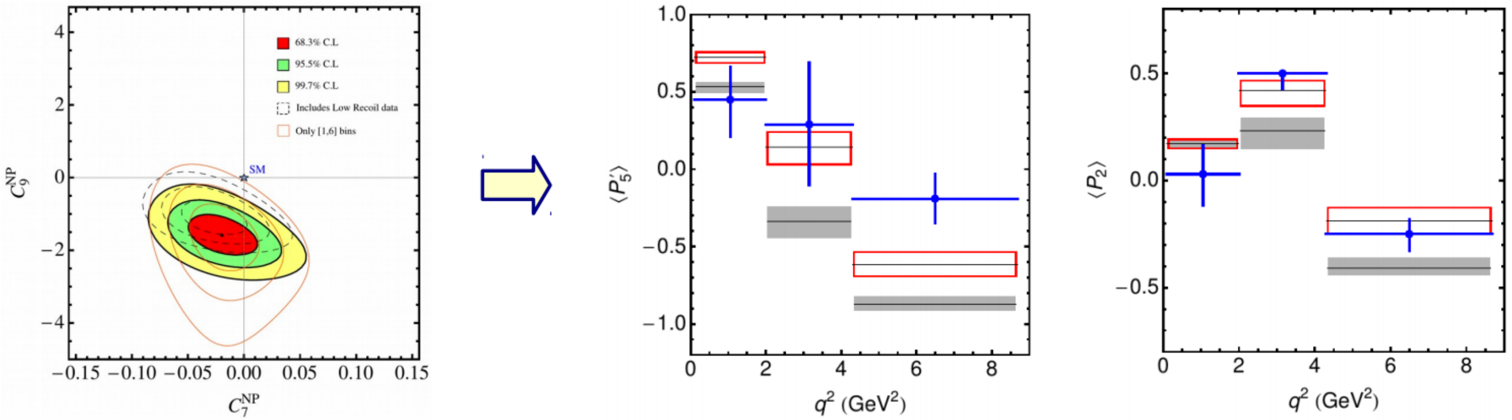




- **publication in preparation …**

$B \to K^*\mu\mu$: THEORISTS GETS EXCITED!

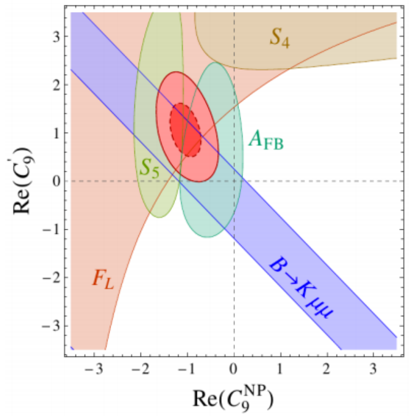
- **possible sign for New Physics contribution in Wilson coefficient C_9 ?**
  - yields slight improvement also in other observables (e.g. P_2)



[PRD 88(2013)074002]

- **combined fits to LHCb results and measurements from other experiments also seem to hint at possible New Physics contribution in C_9 and C_9' or C_{10}'**
  - explicit interpretations in terms of a Z' (mass > 7 TeV)

[PRD 84(2011)115006] [JHEP 11(2014)121] [PRD 89(2014)095033]



[EPJ C73(2013)2646]

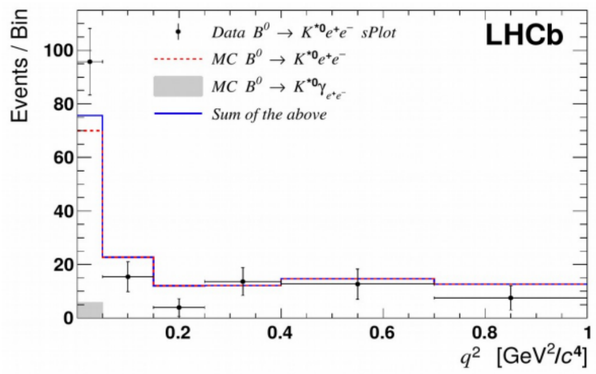
- **or larger uncertainties due to QCD effects than assumed?**
  - e.g. Standard Model predictions neglect virtual $c\bar{c}$ loops

[arXiv:1406.0566]

$B \rightarrow K^*ee$ SAME GAME WITH THE ELECTRONS!

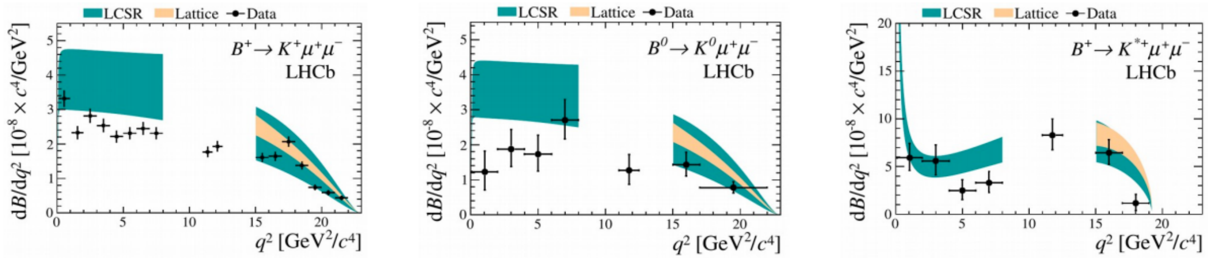
- **angular analysis in $B^0 \rightarrow K^{*0} e^+e^-$ (3 fb^{-1})**
  - $m_e < m_\mu \rightarrow$ can go to lower q^2 than in $K^{*0}\mu^+\mu^-$
  - higher sensitivity to operator O_7 via $B^0 \rightarrow K^{*0}[e^+e^-]_\gamma$
  - but lower yields than in $K^{*0}\mu^+\mu^-$
- **measure four of the angular observables at low q^2**
  - results agree with Standard Model predictions

[JHEP 1504 (2015) 064]



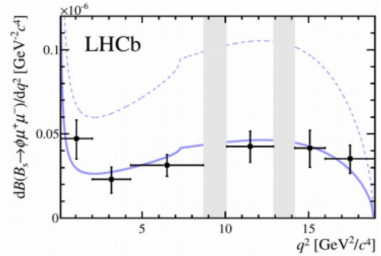
OTHER RARE DECAYS

- **measurements of differential branching fractions**
  - $B^+ \to K^+ \mu^+ \mu^-$
  - $B^0 \to K^0_S \mu^+ \mu^-$ $\Bigg\}$ ($3\ \mathrm{fb}^{-1}$)
  - $B^+ \to K^{*+} \mu^+ \mu^-$
  - $\Lambda_b \to \Lambda \mu^+ \mu^-$ ($3\ \mathrm{fb}^{-1}$)
  - $B^0_s \to \phi \mu^+ \mu^-$ ($1\ \mathrm{fb}^{-1}$)

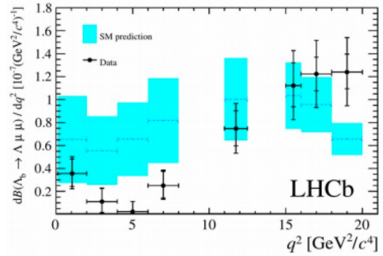


[JHEP 1406(2014)133]

- **tend to be lower than Standard Model**
  - but theory uncertainties not negligible

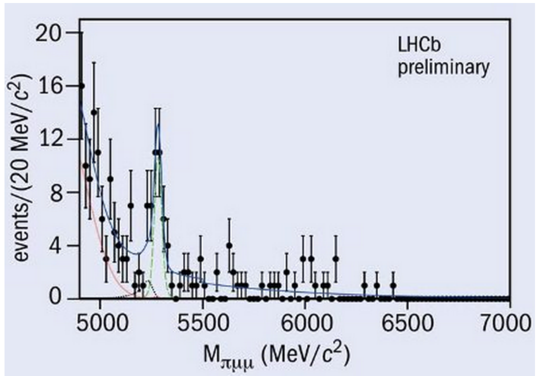


[JHEP 1307(2013)084]



[arXiv:1503.07138]

- ***B -> $\pi\mu\mu$:* the rarest B decay observed**
  => start testing de b->dll transitions

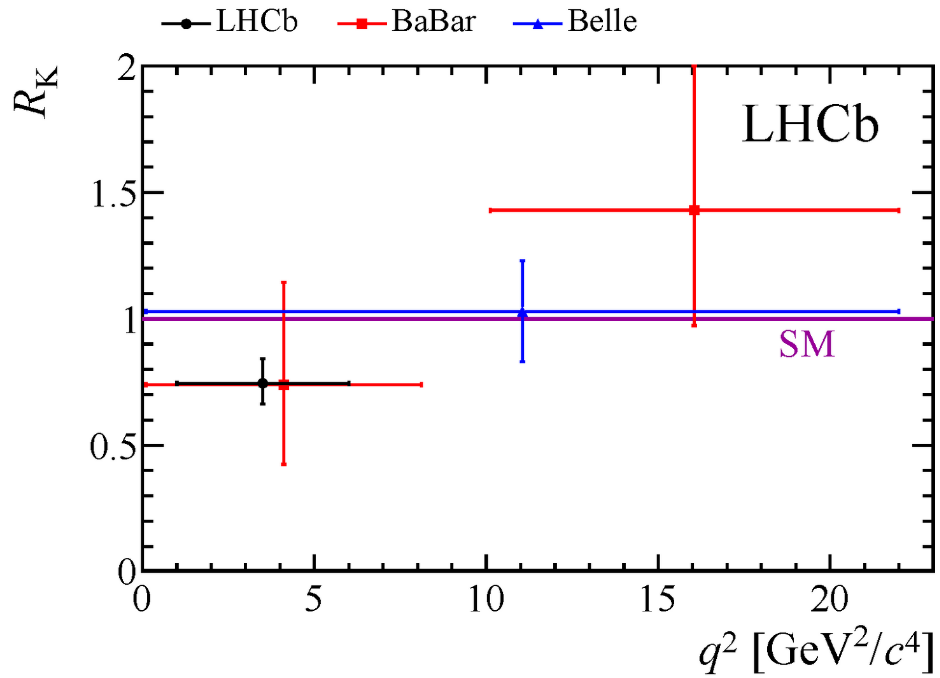


R(K*): QUESTIONING LEPTON FLAVOR UNIVERSALITY

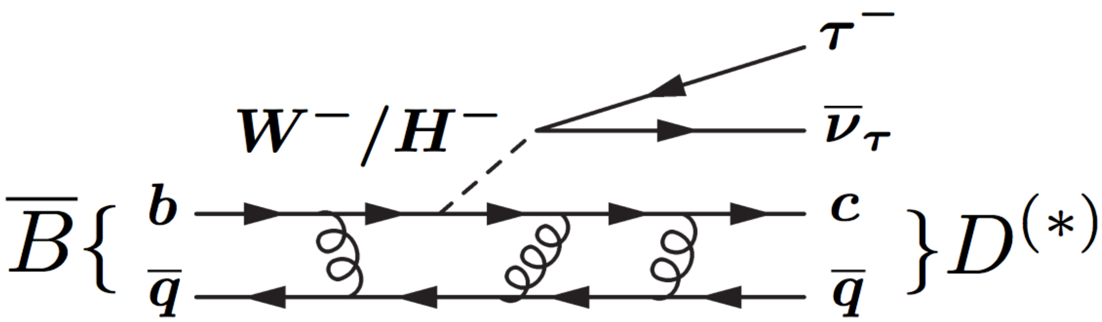
- **measurement of $R_K \equiv BF(B^+ \to K^+ \mu^+ \mu^-) \,/\, BF(B^+ \to K^+ e^+ e^-)$** [JHEP 0712(2007)040]

$$\boxed{R_K = 0.745\,^{+0.090}_{-0.074}\,(\text{stat}) \pm 0.036\,(\text{syst})} \quad (3\ \text{fb}^{-1},\ 1 < q^2 < 6)$$

- **Standard Model prediction: $R_K = 1.0003 \pm 0.0001$** [PRL 113(2014)151601]
- **2.6 σ deviation → violation of lepton universality ???**

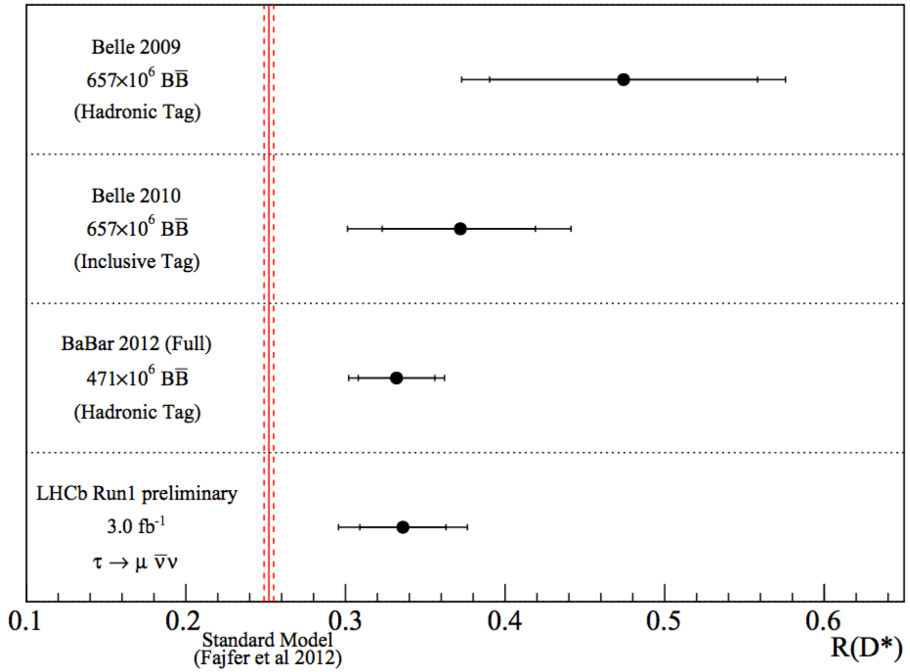


R(D*) = B -> D* τ ν / B -> D* μ ν



- In the Standard model, the only difference between $B \rightarrow D^{(*)}\tau\nu$ and $B \rightarrow D^{(*)}\mu\nu$ is the mass of the lepton
  - Theoretically clean - $\sim$ 2% uncertainty for D^* mode
- Ratio R($D^{(*)} = \mathcal{B}(B \rightarrow D^{(*)}\tau\nu)$ / $\mathcal{B}(B \rightarrow D^{(*)}\mu\nu)$ is sensitive to charged Higgs
  - Or non-MFV couplings favouring τ

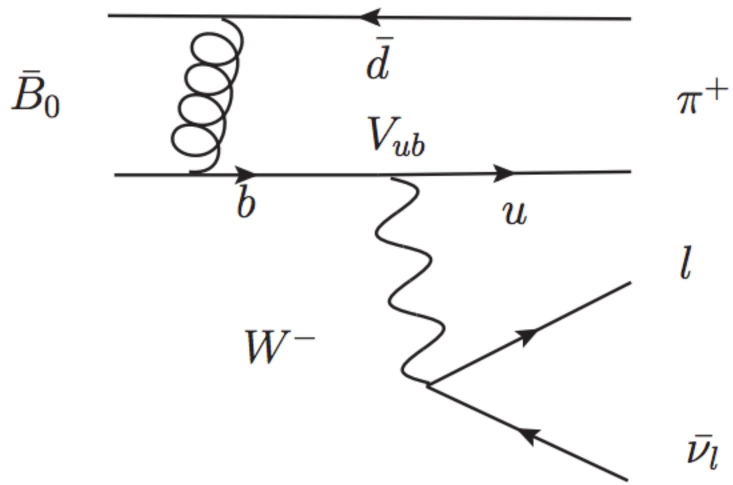
R(D*) = B -> D* $\tau\,\nu$ / B -> D* $\mu\,\nu$



- We measure $\mathcal{R}(D^*) = 0.336 \pm 0.027 \pm 0.030$
  - In good agreement with past measurements
  - Agreement with SM at 2.1σ level
- Measurement will improve with more data: largest systematic uncertainties depend on control samples (or simulation size)
- Paper (LHCB-PAPER-2015-025) to come in a few weeks

THE EXCLUSIVE MEASUREMENT OF V_{ub}

- Semi-leptonic decays can be used to make precise measurements of $|V_{ub}|$



Having a ground state hadron, such as a pion, is useful to control theoretical uncertainties.

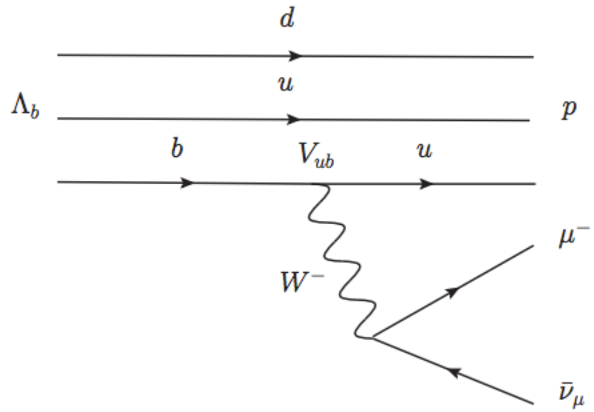
- Factorise electroweak and strong parts of the decay:

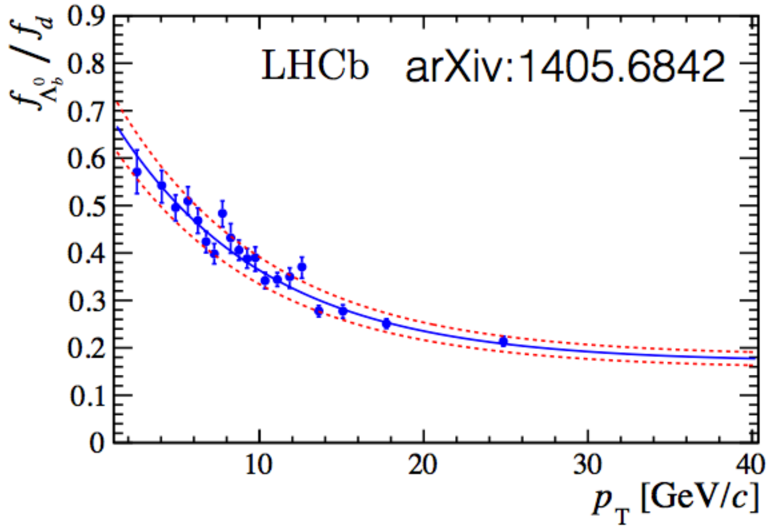
$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{ub}|^2 p_\pi^3}{24\pi^3} |f^+(q^2)|^2$$

QCD part encompassed by form-factor.

V_{ub} FROM Λ_b -> $p\,\mu\,\nu$

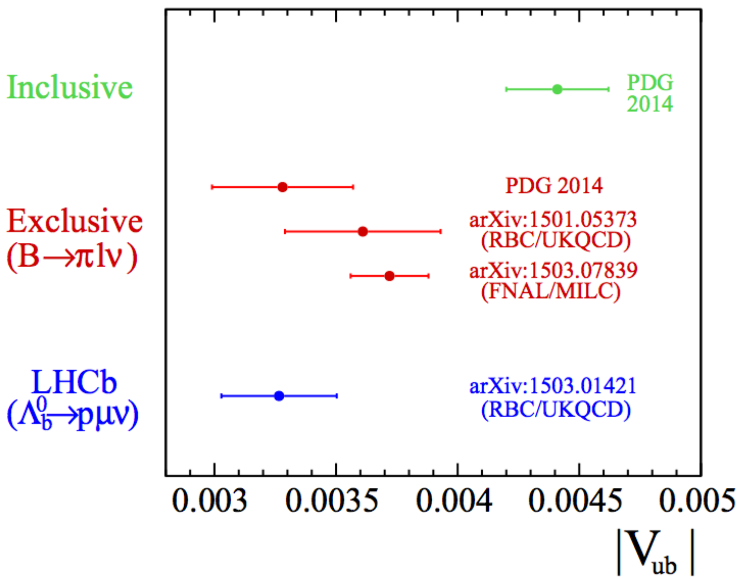
- The decay $\Lambda_b^0 \to p\mu\nu$ is the baryonic version of $B \to \pi\ell\nu$.
- Cleaner at LHCb as protons are rarer than kaons/pions.
- Λ_b baryons not produced at BaBar or Belle experiments but at the LHC produced half as often as B mesons.

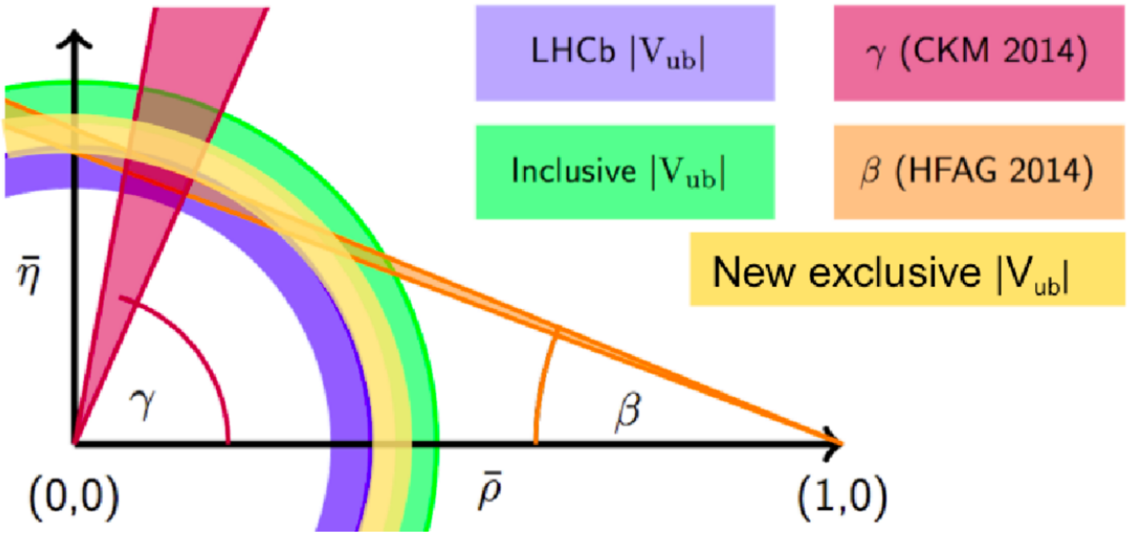




- Signature in detector: displaced muon-proton vertex.

FIRST LHCb V_{ub} EXCLUSIVE MEASUREMENT



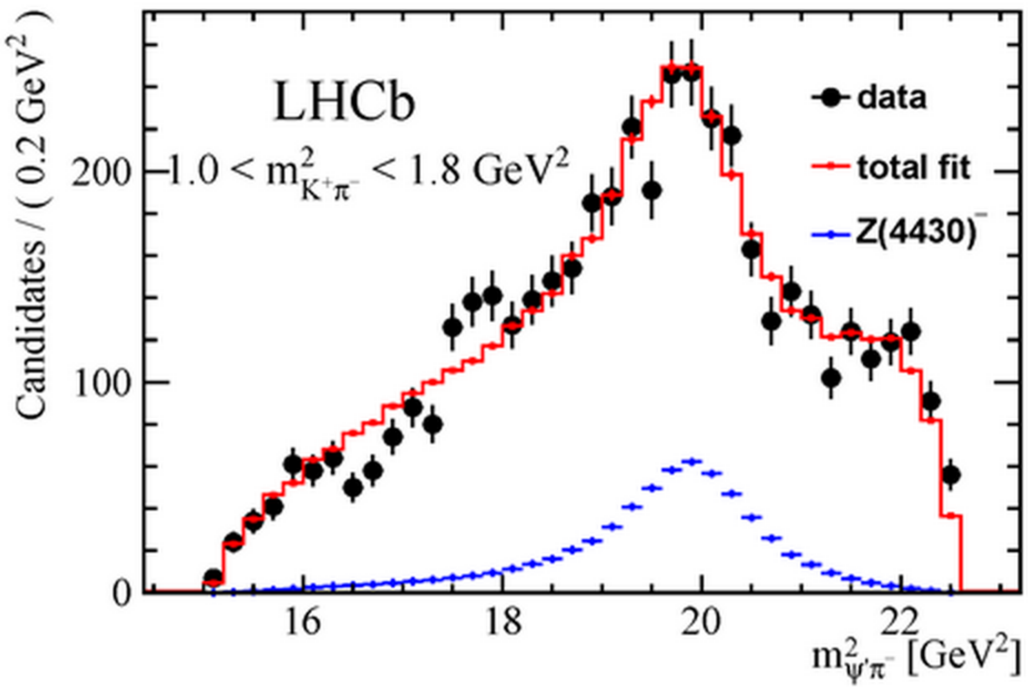


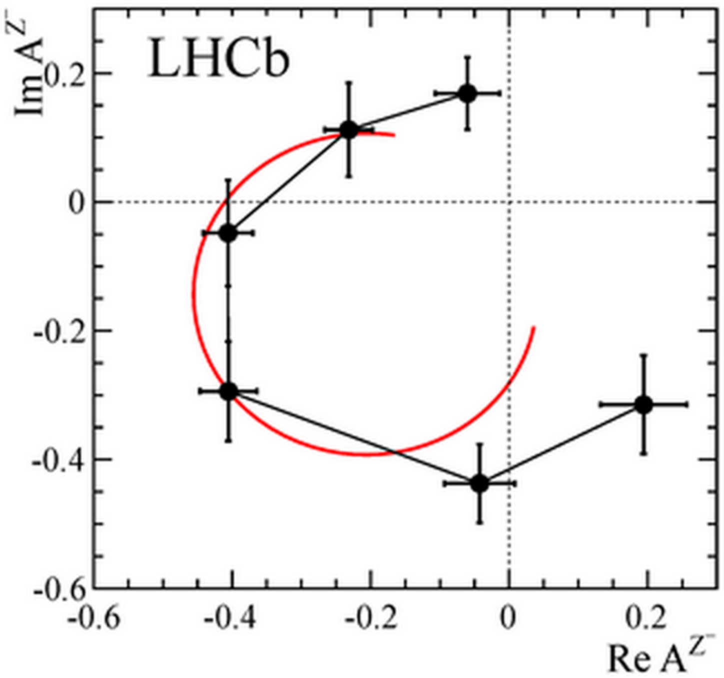
- $|V_{ub}| = 3.27 \pm 0.15(exp) \pm 0.17(theory) \pm 0.06(|V_{cb}|)$
- Result in good agreement with past exclusive $|V_{ub}|$ measurements
- 3.5σ below inclusive measurements
- Implications for CKM fit shown
- LHCB-PAPER-2015-013

BUT THIS EXPERIMENT IS RATHER A FOUR SEASONS

SPECTROSCOPY: THE Z(4430) $^-$

- An exotic particle which cannot be classified within the traditional quark model
- Observed by Belle in 2008
- Not confirmed nor excluded by BaBar
- LHCb confirms Belle results and measurement of $J^P = 1^+$ with large significance
- LHCb establish its resonance structure, proving it is a particle, and specifically a state c cbar d ubar



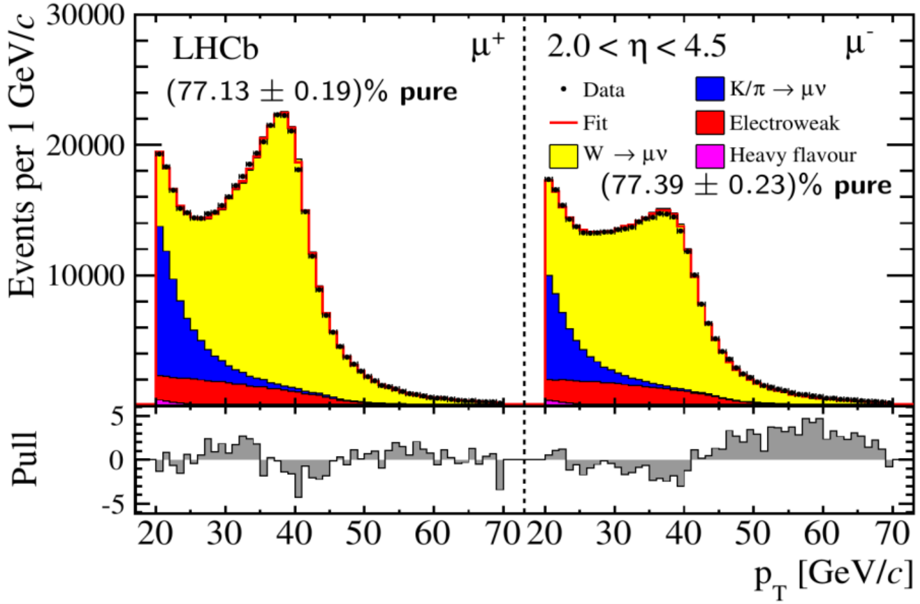


Z AND W PRODUCTION IN pp COLLISIONS

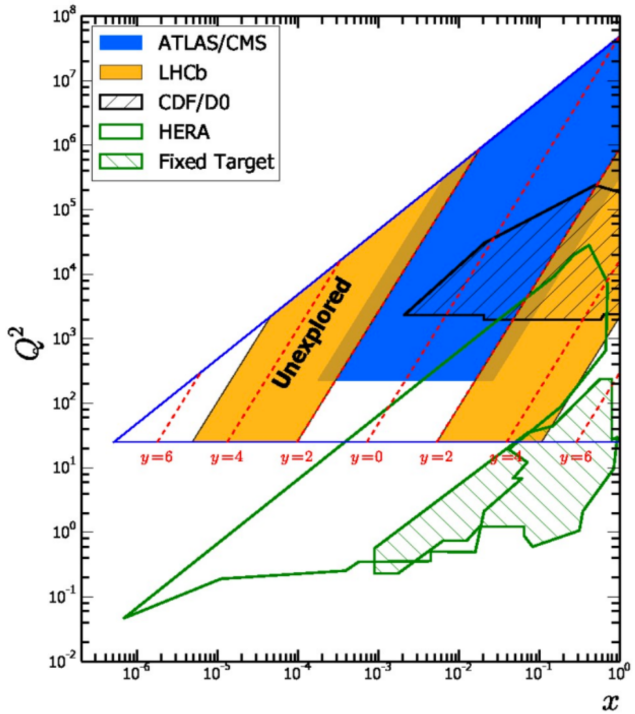
- **LHCb acceptance**

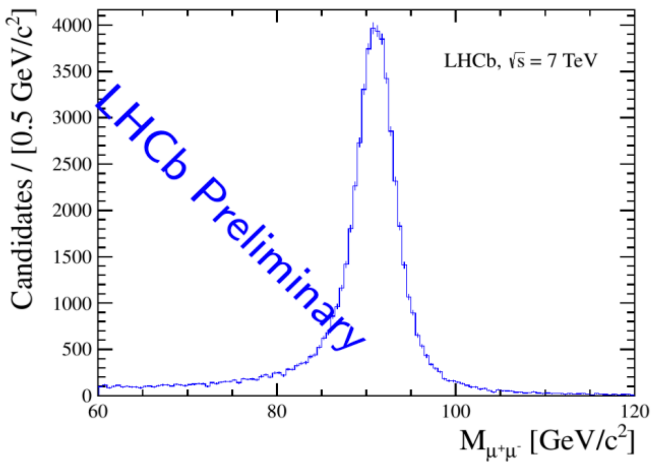
$2 < \eta < 4.5$

- **complementary to other experiments**
- **unexplored region in q^2, Bjorken-x**
- **potential to derive interesting constraints on parton density functions of the proton**



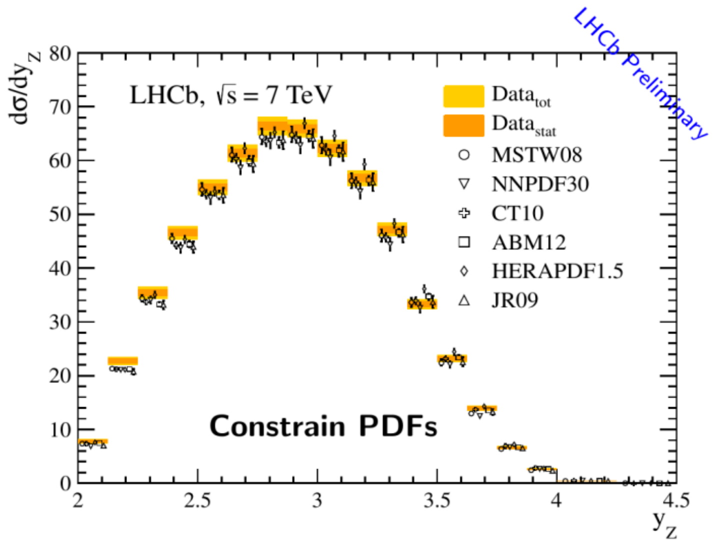
[JHEP 1412(2014)079]

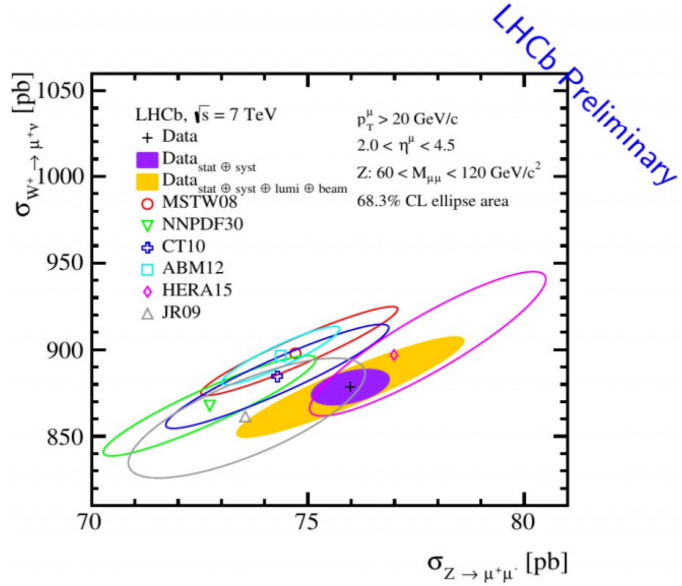




[LHCb-PAPER-2015-001]

Z AND W SEEN BY LHCb

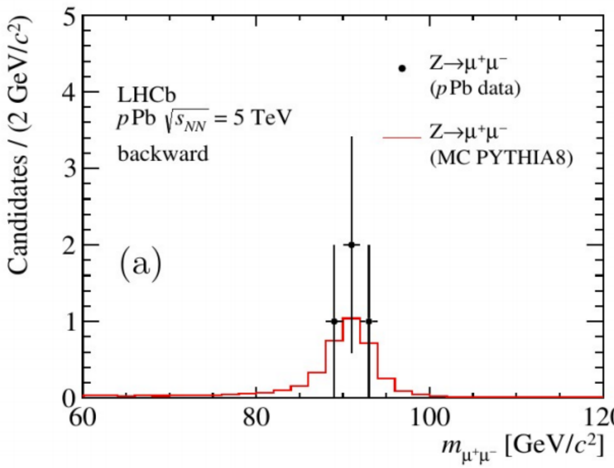


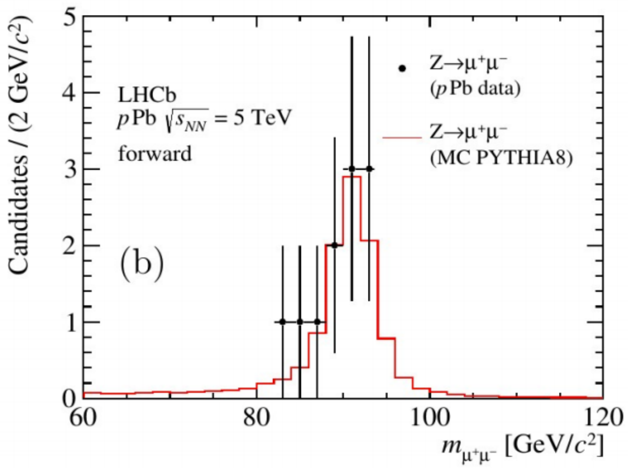


[LHCb-PAPER-2015-001]

- **also: *Z* + jet, *Z* + *b*-jet**
- **also: *Z* production in *p-Pb* and *Pb-p***

[JHEP 1409(2014)030]





EVEN HIGGS IS SEEN AT LHCb!!!

8 October: 2013 Nobel prize in Physics.

The Nobel Prize committee of the Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to François Englert and Peter Higgs for "the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".

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Congratulations to François Englert and Peter Higgs.

The image shows LHCb spokesperson Pierluigi Campana showing the LHCb detector to Peter Higgs on December 18th, 2012.

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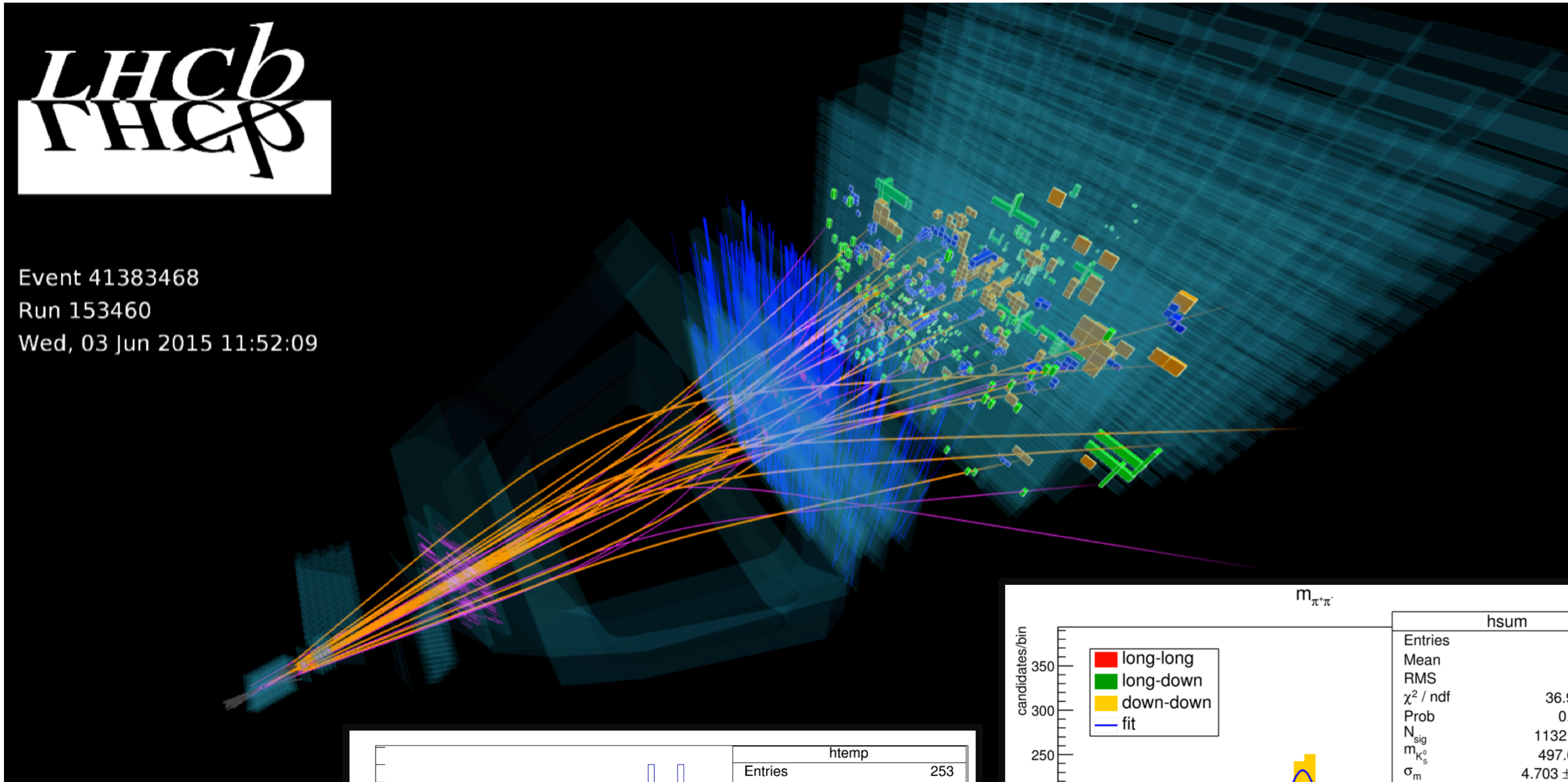
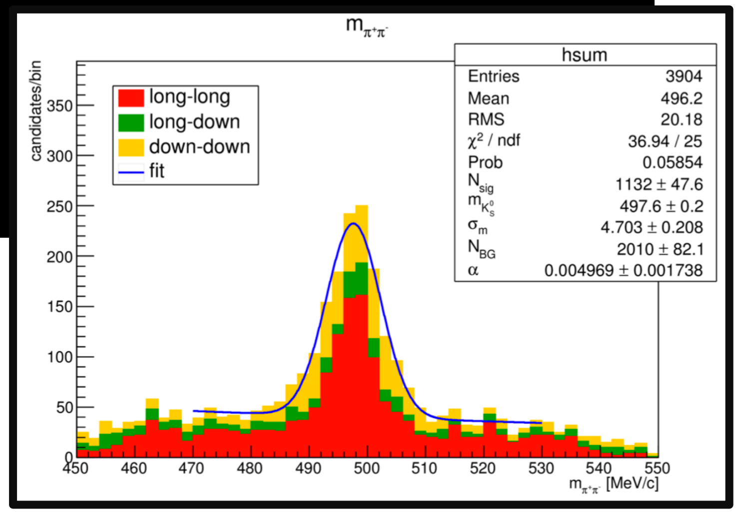
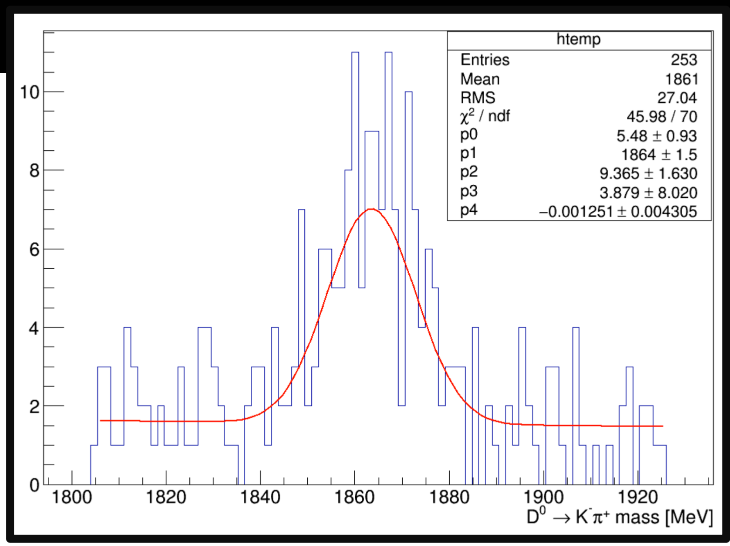
click the image for higher resolution

FIRST COLLISIONS IN JUNE 2015





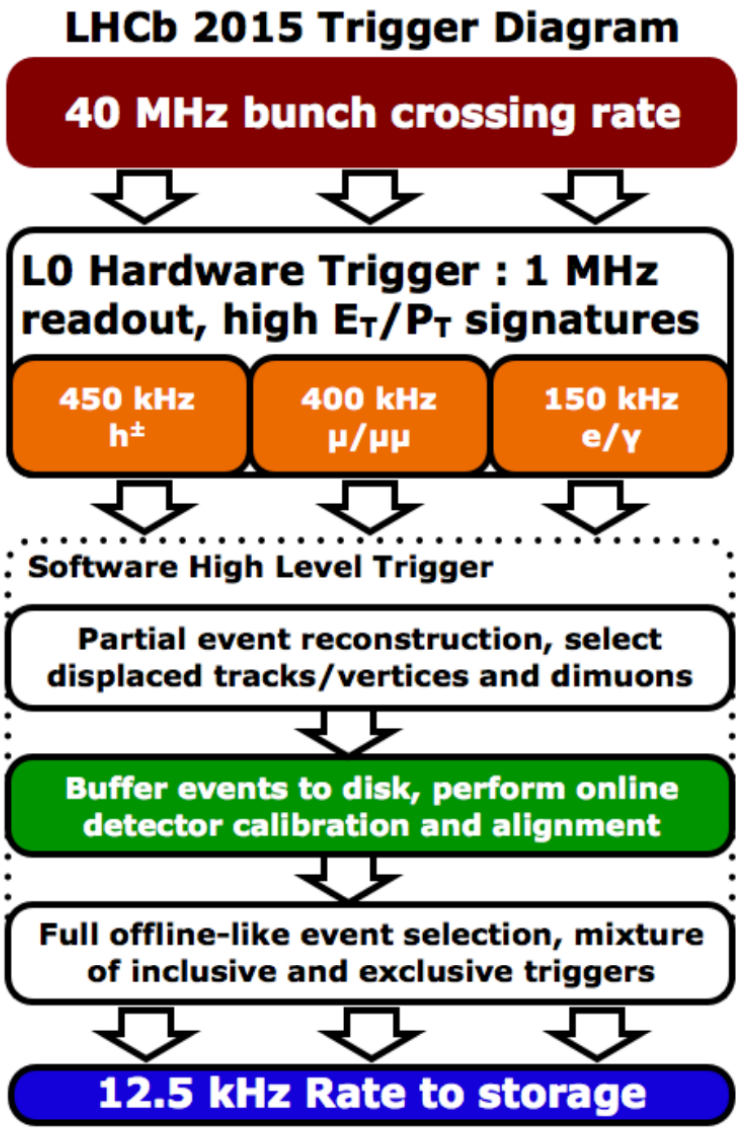


RUN2 CHALLENGES

- **changing operating conditions for run II may require re-adjustment of some detector operation parameters**
- **collision energy 8 TeV → 13 TeV**
  - expect higher particle densities per collision
- **bunch spacing 50 ns → 25 ns**
  - need less "pile-up" (average number of *pp* collisions per bunch crossing) to achieve the same luminosity
  - but more "spill-over" (signal remainders from interactions in the previous bunch crossing) in some detectors
- **Stay at $L=4\times10^{32}cm^{-2}s^{-1}$**

SPLIT HLT

- **no major hardware changes in LS1**
- **but new trigger concept: “split HLT”**
  - **run only first stage of software trigger (HLT1) synchronous with collisions**
  - **store all accepted events on local disks**
  - **use a subset of these data to perform quasi-online calibration and alignment**
  - **apply full event reconstruction and second-level software trigger algorithms (HLT2) using updated constants**
  - allows to use the same calibration/alignment constants in HLT2 as in offline reconstruction
  - allows to employ RICH particle identification information in HLT2 algorithms
- **additional advantage: use resources of the HLT computer farm also when no collisions**



PHYSICS PERSPECTIVES FOR RUN2

Lots of new data:

- **cross sections *bb* and *cc* x 1.6**
- **improved triggers**

The physics programs continues on the already designed pattern:

- **Improve precision on CP measurement, expecially γ**
- **Understand the current deviations from theory:**
  - **B->K*μμ anomaly**
- **Lepton flavor universality tests**
  - **Searches for charged lepton flavor violating decays**
- **Also rare kaon decays**
- **Plus: new particles, forward physics, etc…**

Channels with electrons, taus and neutrals are expected to play a larger role than before.

UPGRADING THE DETECTOR

[CERN-LHCC-2011-001]

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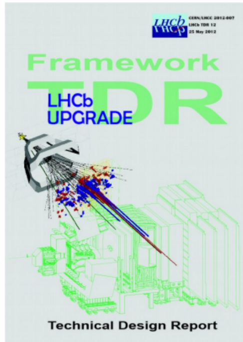

[CERN-LHCC-2012-007]

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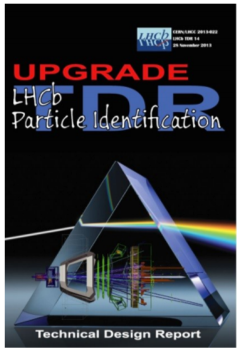

[CERN-LHCC-2013-001]

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[CERN-LHCC-2013-021]

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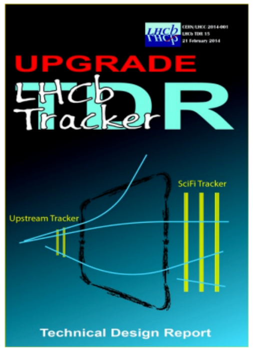

[CERN-LHCC-2014-001]

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[CERN-LHCC-2014-016]

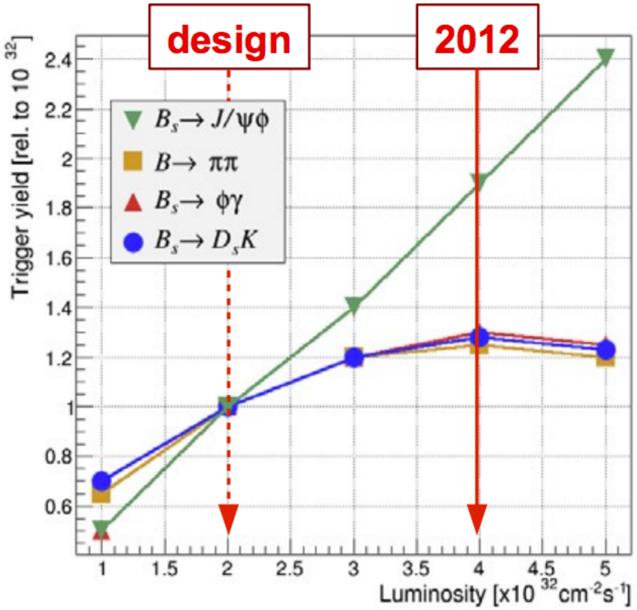
WHY WE NEED AN UPGRADE?

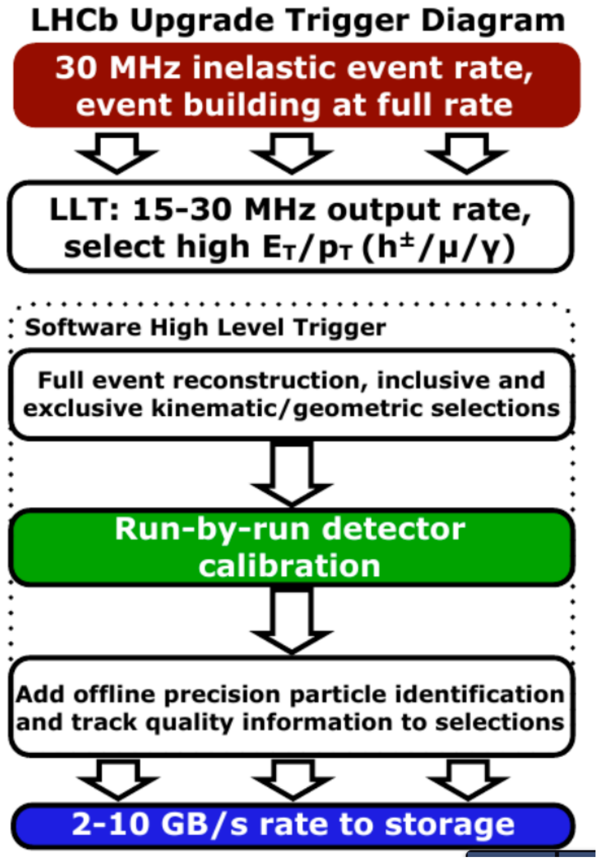
- current precision of measurements in the flavour sector still leaves ample room for sub-dominant contributions from New Physics
- almost all LHCb results are completely dominated by statistical uncertainties
  - leading systematic uncertainties will in many cases also decrease with increasing statistics
- assuming a total of 8 fb^{-1} by the end of run 2, it will then take another ≈ 15 years at current rate to quadruple statistics and halve uncertainties
- LHCb upgrade for LS 2:
  - operate at up to 5× higher luminosity
  - increase trigger efficiencies for hadronic final states, read out full detector at LHC bunch-crossing frequency

2010	run 1	0.037 fb^{-1} @ 7 TeV
2011		1 fb^{-1} @ 7 TeV
2012		2 fb^{-1} @ 8 TeV
2013	LS 1	minor maintenance work
2014		
2015	run 2	5 fb^{-1} @ 13 TeV
2016		
2017		
2018	LS 2	LHCb upgrade
2019		
2020	run 3	15 fb^{-1} @ 14 TeV with increased trigger efficiency
2021		
2022		
2023	LS 3	?
2024		
2025		
2026 ++	run 4	5 fb^{-1} / y @ 14 TeV

TRIGGER UPGRADE

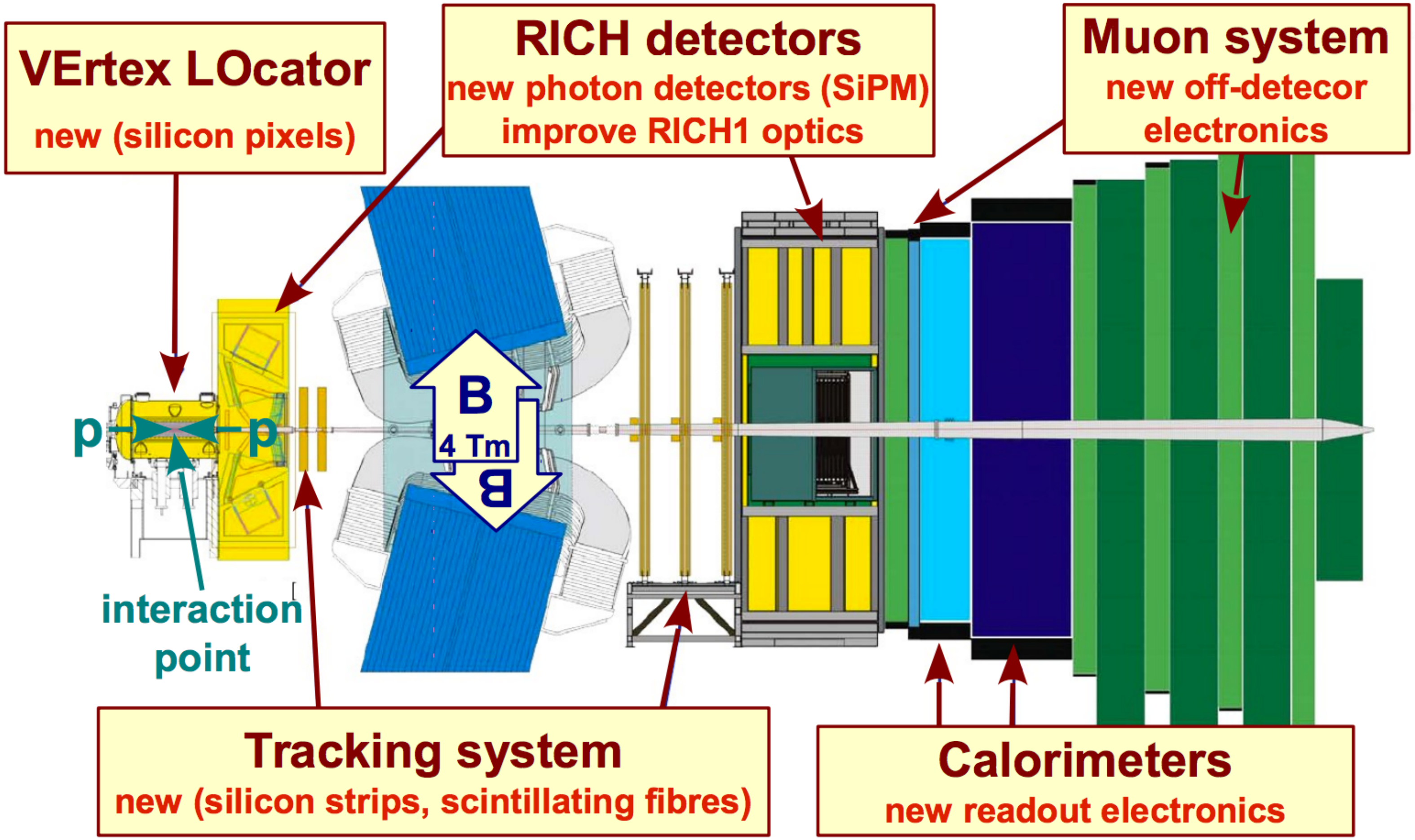
- to collect 5 fb^{-1} / year: operate at up to 5 × higher instantaneous luminosity
- final states with muons: event yields scale linearly with luminosity
- fully hadronic final states: in current trigger scheme have to increase p_T thresholds to stay within 1 MHz limit of L0 trigger → no further gain in yield





readout full detector at 40 MHz
full software trigger with 20 kHz output rate

DETECTOR UPGRADE



- 40 MHz readout → replace sub-systems with embedded front-end electronics
- 5 × higher luminosity → adapt detector technology where needed to maintain excellent performance

PHYSICS POTENTIAL

Erreurs statistiques

Framework TDR for the LHCb upgrade: Technical Design Report

Type	Observable	LHC Run 1 (~3/fb)	LHCb 2018 (~8/fb)	LHCb upgrade (~50/fb)	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
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.18	0.12	**0.026**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.04**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$	0.20	0.13	**0.030**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.8%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\ A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	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**	–

- Actuellement presque toutes les mesures sont limitées statistiquement.
- Incertitudes 10 fois plus petites après 10 ans d'upgrade
- Les incertitudes seront très proches des erreurs théoriques après l'upgrade.
- Le défi deviendra réduire les incertitudes systématiques.

COMPARISON WITH OTHER EXPERIMENTS

ECFA *(octobre 2013, Aix les Bains)*

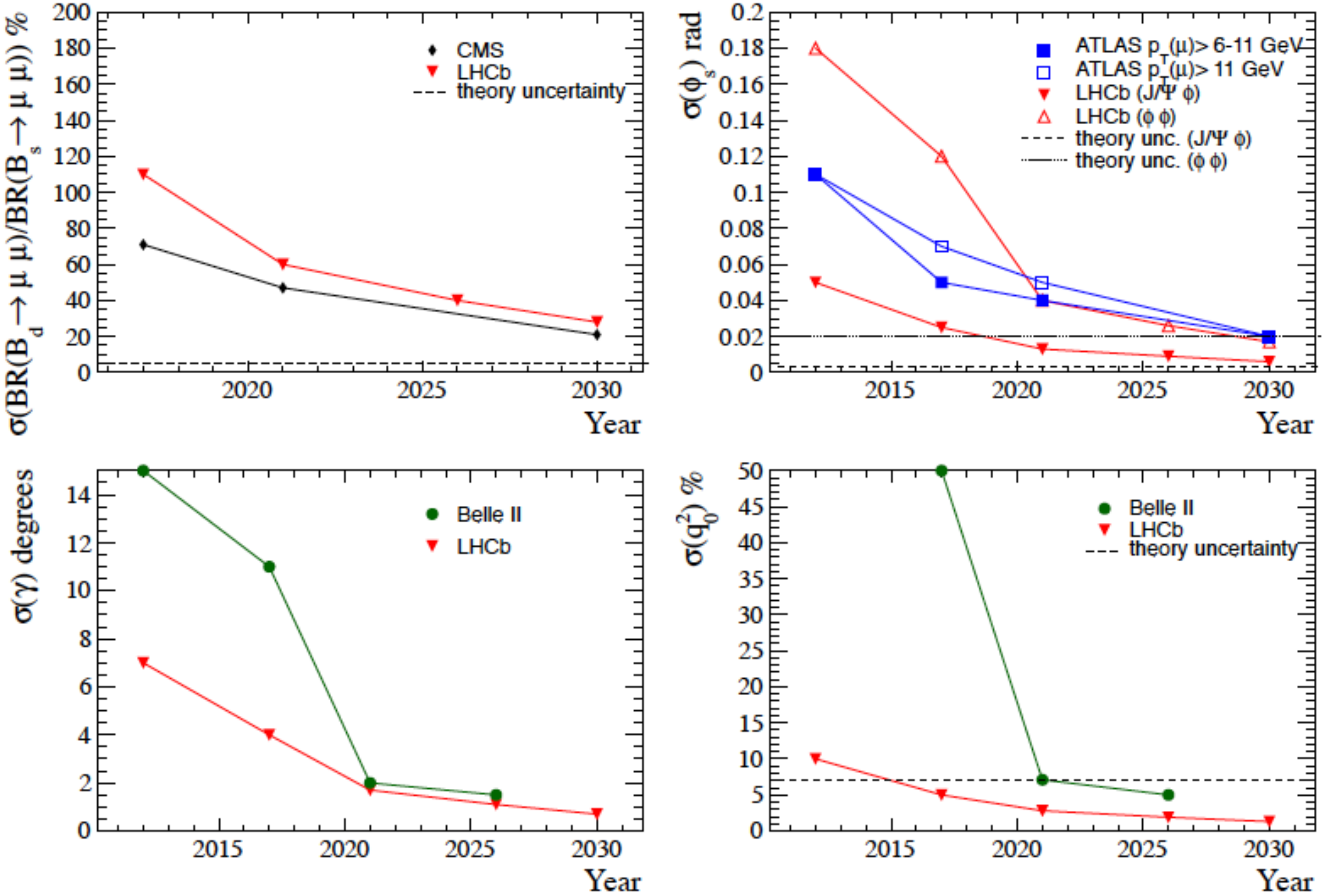


Fig. 2.1: Comparaison des précisions attendues pour les expériences ATLAS, CMS, LHCb et Belle-II pour $\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$, $\phi_s(B^0_s \to J/\psi\,\phi)$ et $\phi_s(B^0_s \to \phi\phi)$, l'angle γ et $q_0^2\ A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$. Une estimation des incertitudes théoriques est indiquée par les lignes pointillées. Les incertitudes théoriques dans le cas de l'angle γ sont négligeables.

CONCLUSION

- **B physics has a strong potential of unveiling new physics phenomena.**
- **The indirect searches paradigm, complementary to direct search, has been proved successful in the past and is still providing important constraints to the theories or interesting puzzles to solve.**
- **At the LHC we have a clear and long flavor research program ahead.**

…and maybe we are not so far from catching the cat hiding among the penguins….

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