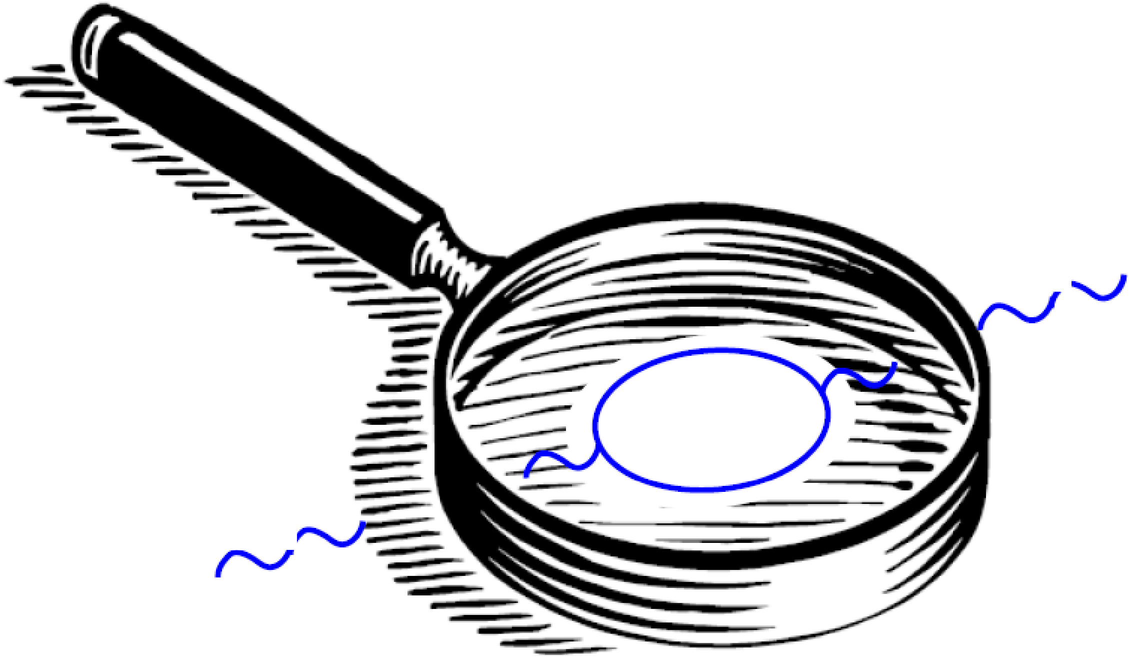
KSETA, Durbach, 20. 2. 2020

With "beautyful" quarks to new phenomena in particle physics



Outline:
- Introduction to beauty quarks
- Search for *new phenomena*
- LHC and LHCb experiment
- Test of quantum-loops
- New hadronic states

Supported by Bundesministerium für Bildung und Forschung

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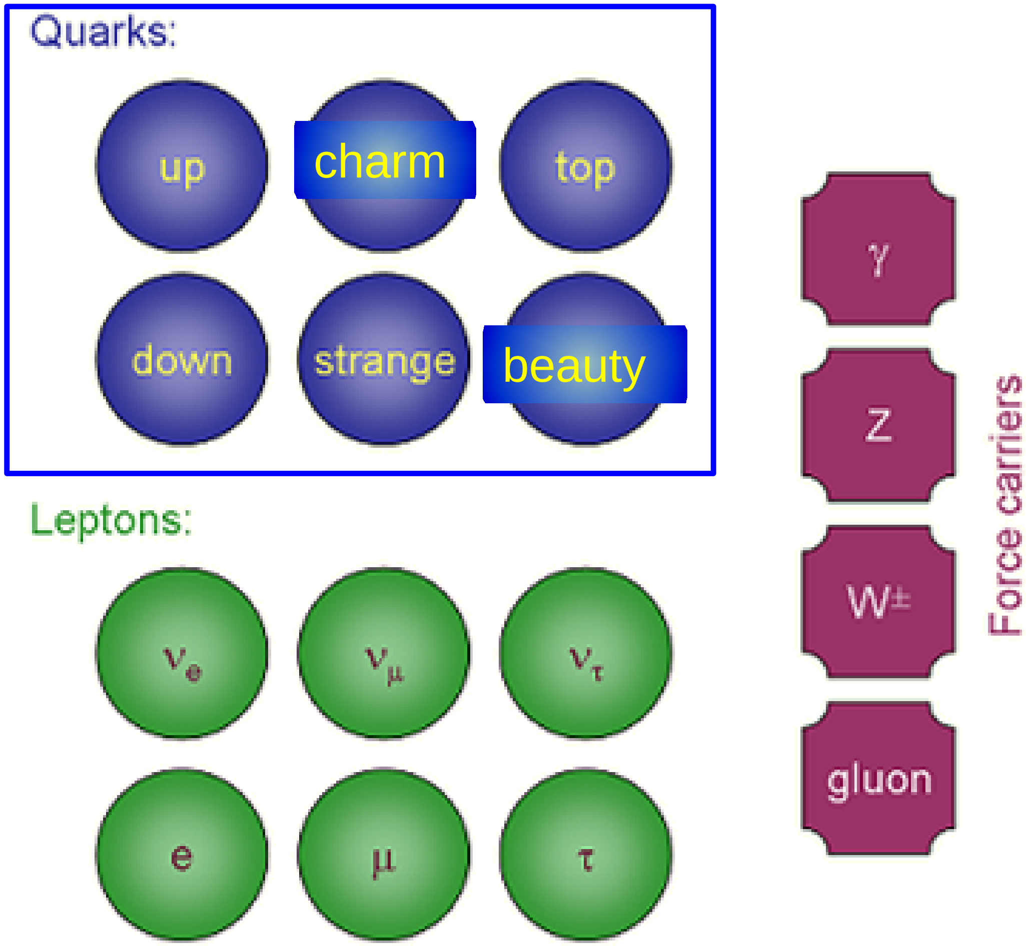
Standard Model

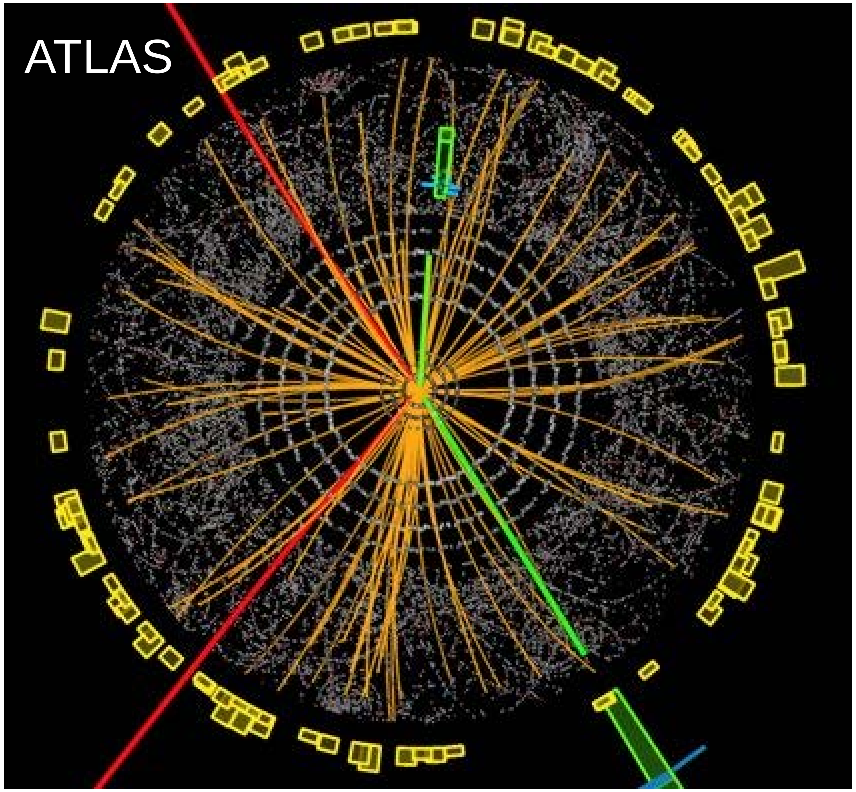


Despite its successes model is incomplete: e.g. DM and BAU.
$\rightarrow$ New phenomena at higher energies

http://www.physics.gla.ac.uk/ppt/research.htm

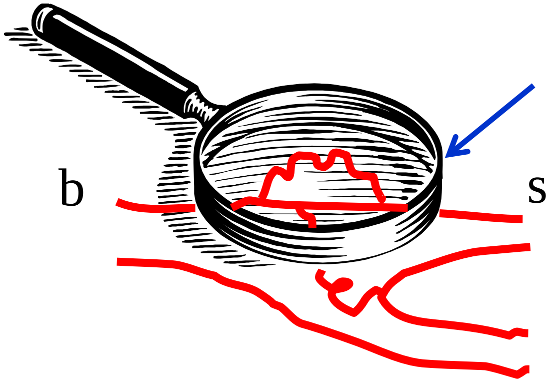
Searches for New Phenomena

Exploring highest energies



Direct searches at LHC $\rightarrow$ < 10 TeV

Precision experiments



Muon (g-2)

Electrical dipole-moments

Lepton-flavor violation

*K- , **c-** and **b-hadron** decays*

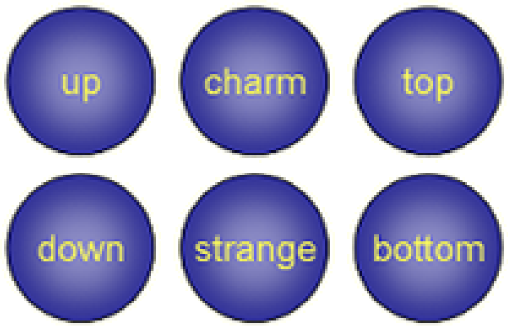
Indirect searches $\rightarrow$ > O(100 TeV)

Quark Sector

Q/e

$+\frac{2}{3}$

$-\frac{1}{3}$

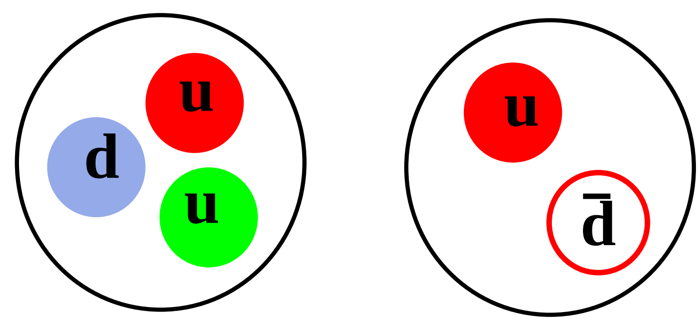


masses

u	d	s	
2.3	4.8	95	MeV/c^2
c	b	t	
1270	4200	173500	MeV/c^2

- Quarks carry color charge r g b: charge of strong interaction.
- Quarks do not exist free but are confined in colorless hadrons: baryons qqq and mesons $q\bar{q}$.

Baryon Meson



p π^+

Hadrons with "Heavy Quarks"

Mesons |q$\bar{q}$>

s	$K^+ = \|u\bar{s}\rangle$	$K^0 = \|d\bar{s}\rangle$
c	$D^+ = \|c\bar{d}\rangle$	$D^0 = \|c\bar{u}\rangle$
b	$B^+ = \|u\bar{b}\rangle$	$B^0 = \|d\bar{b}\rangle$
	$B_c^+ = \|c\bar{b}\rangle$	$B_s = \|s\bar{b}\rangle$

Anti-Mesons

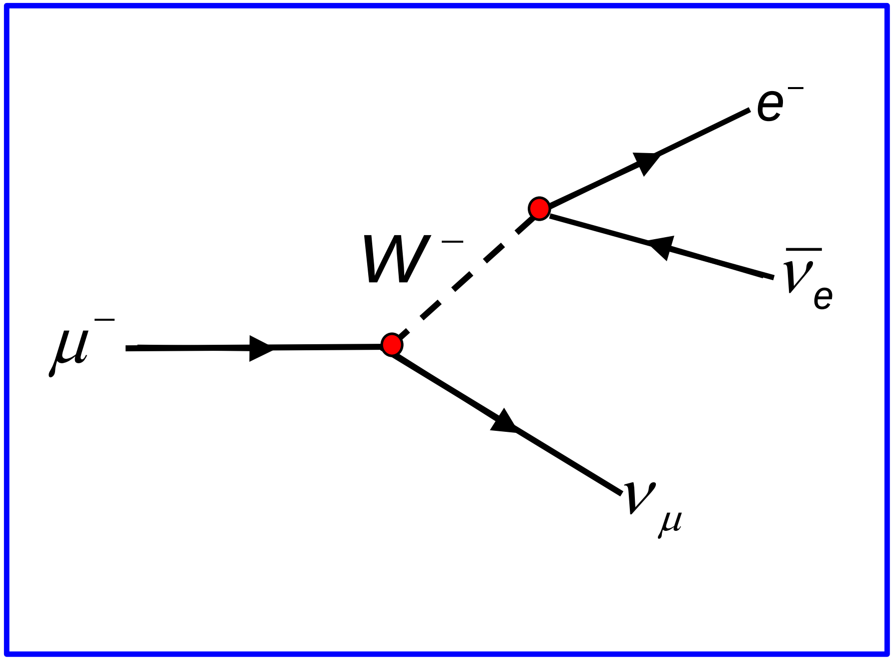
$\bar{K}^0 = \|\bar{d}s\rangle$	$K^- = \|\bar{u}s\rangle$
$\bar{D}^0 = \|\bar{c}u\rangle$	$D^- = \|\bar{c}d\rangle$
$\bar{B}^0 = \|\bar{d}b\rangle$	$B^- = \|\bar{u}b\rangle$
$\bar{B}_s = \|\bar{s}b\rangle$	$B_c^- = \|\bar{c}b\rangle$

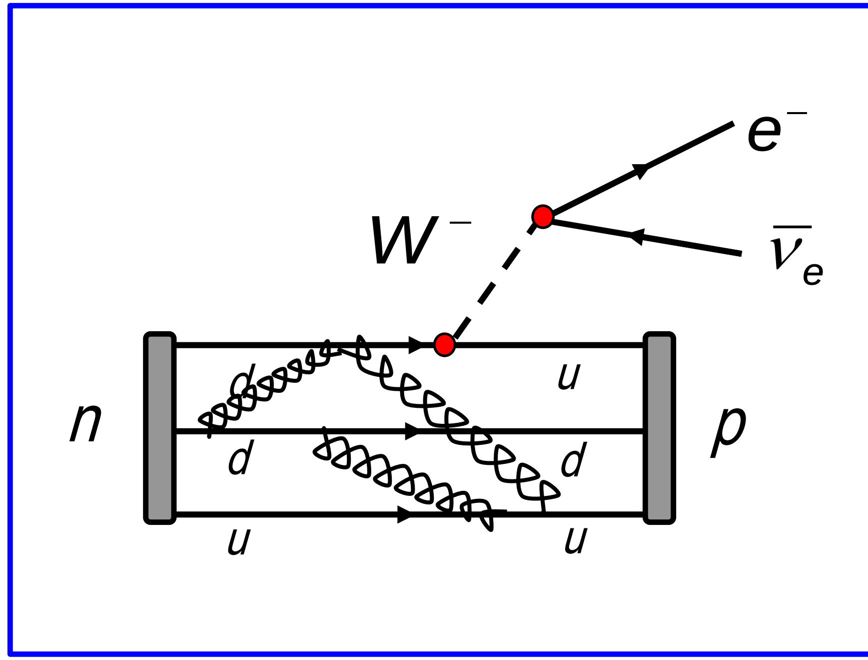
Baryons |qqq>

$\Lambda = |uds\rangle$ $\Lambda_c^+ = |udc\rangle$ $\Lambda_b = |udb\rangle$

	m [GeV/c²]	τ [ps]
D	2	0.4
B	5…6	1.5

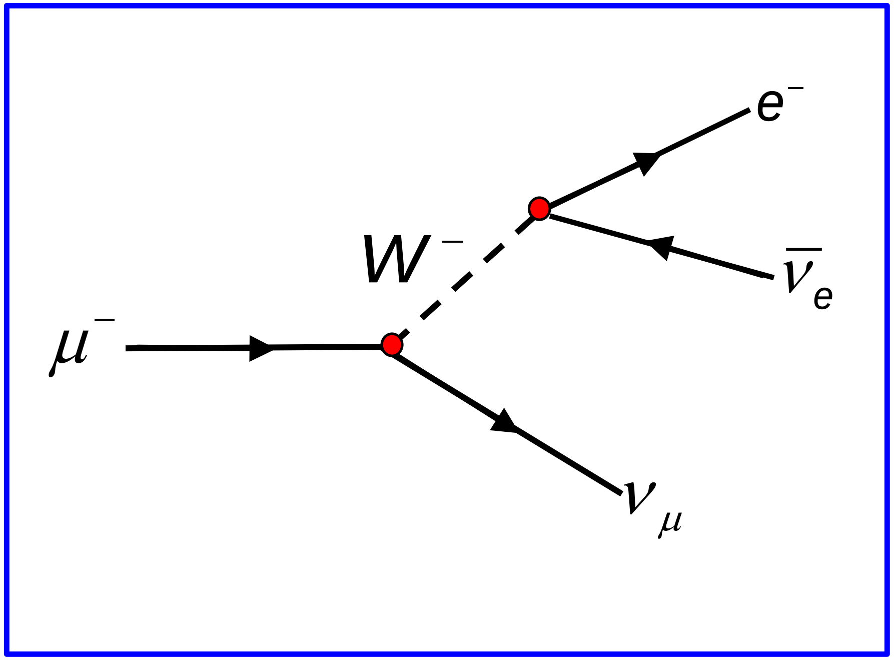
β-decays

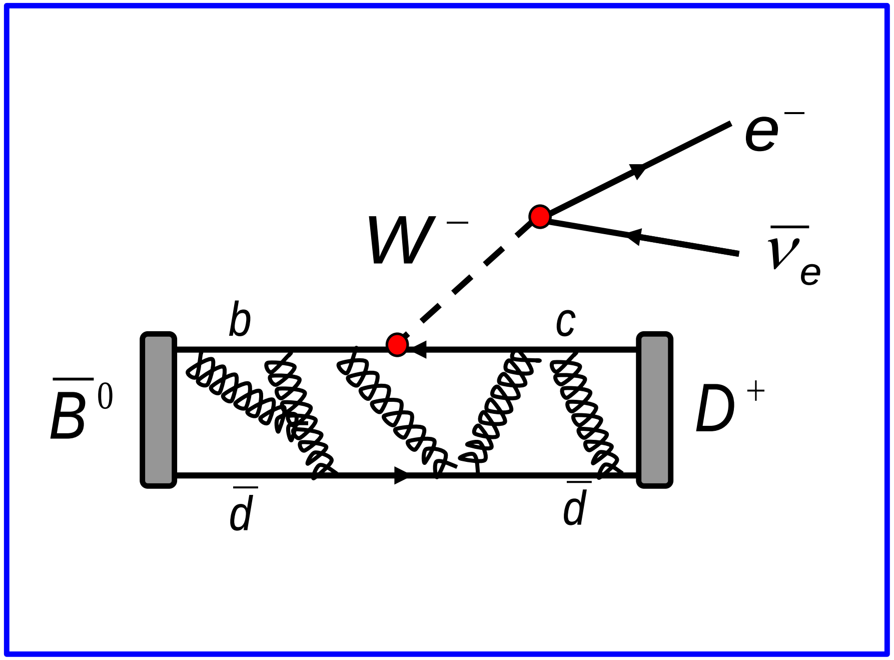




$$\begin{pmatrix} \nu_\mu \\ \uparrow \\ \mu^- \end{pmatrix} \qquad \begin{pmatrix} u \\ \uparrow \\ d \end{pmatrix}$$

Weak Decays of b-Hadrons

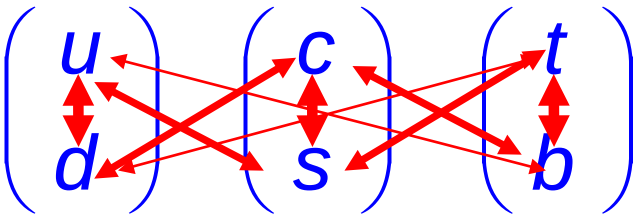




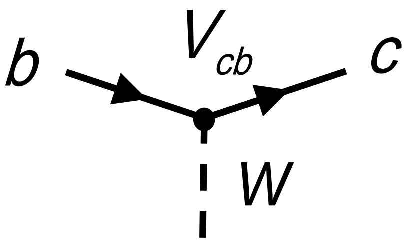
$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix} \qquad\qquad \begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

Quark Mixing and CKM-Matrix

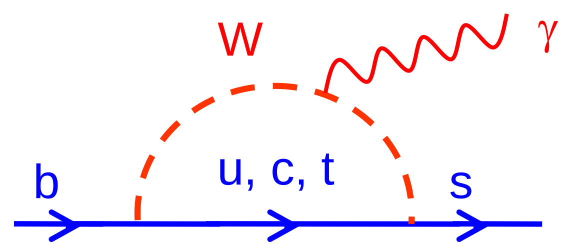
N.Cabibbo (1963), M.Kobayashi & T.Maskawa (1973)



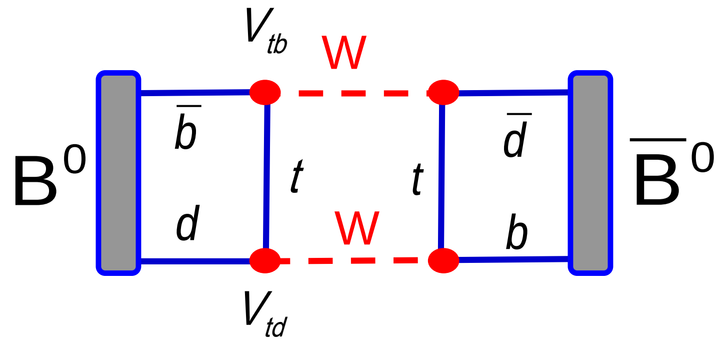
Kopplung: $\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$



Interesting quantum-loop corrections:
Flavor-Changing Neutral Currents



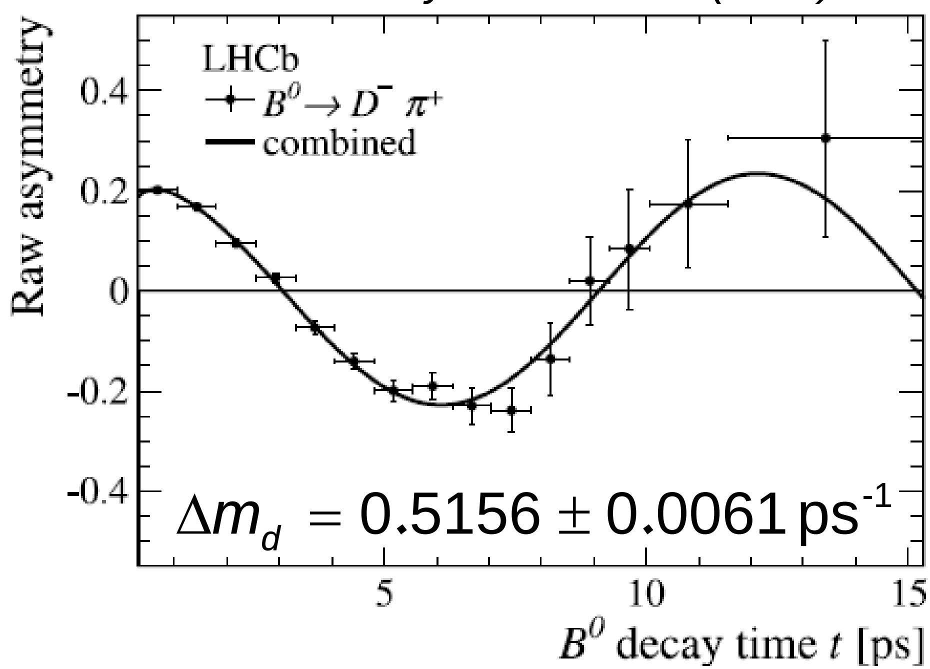
Effect of Quark Mixing



Observed by ARGUS (DESY), 1987

Phys. Lett. B 719 (2013) 318.

B^0
$\updownarrow$
$\bar{B}^0$



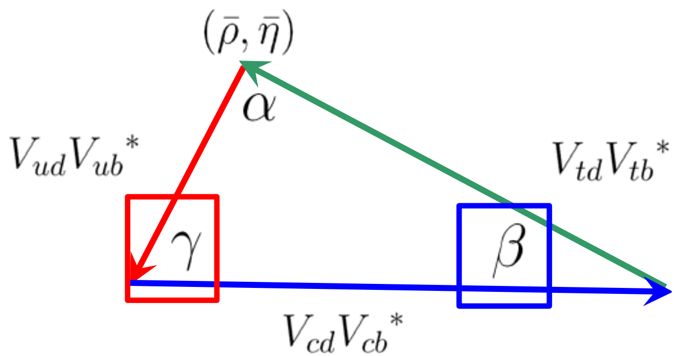
CKM-Matrix - Unitarity

$$V_{ub} = |V_{ub}| e^{-i\gamma}$$

$$V_{td} = |V_{td}| e^{-i\beta} \quad \begin{pmatrix} V_{ud} & V_{us} & \boxed{V_{ub}} \\ V_{cd} & V_{cs} & V_{cb} \\ \boxed{V_{td}} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}^{\dagger} = 1$$

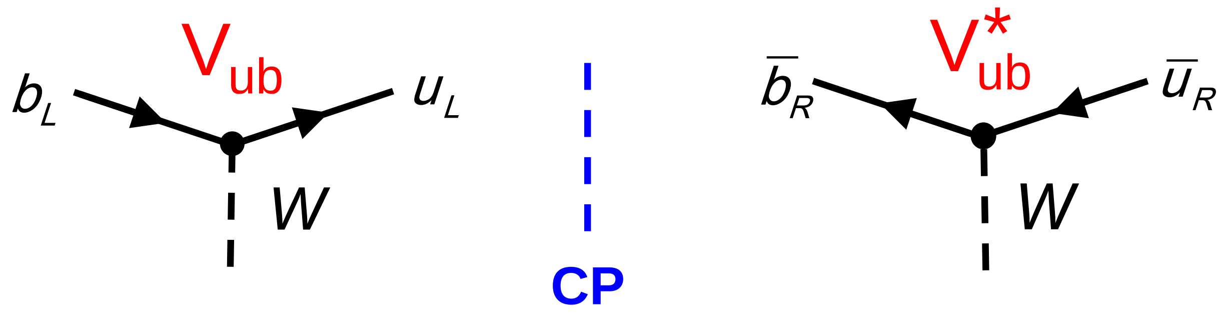
Complex elements: 3 real parameters + 1 phase

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



Unitarity Triangle can be explored using B mesons.

CP-Violation

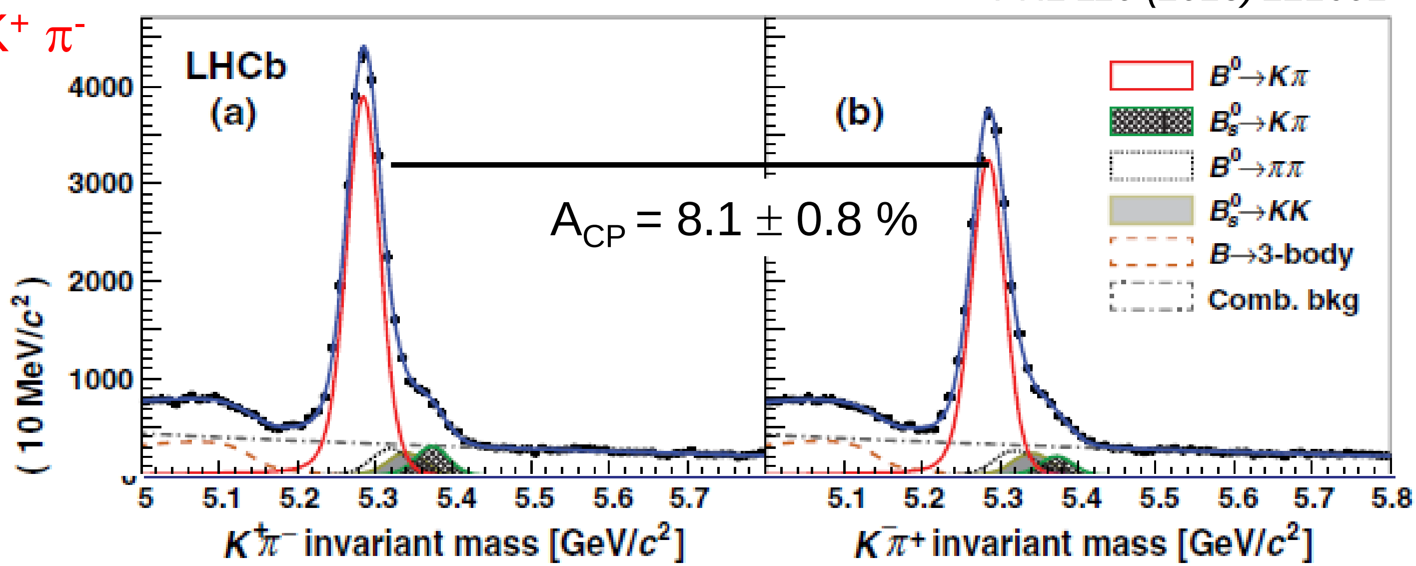


$\rightarrow$ Violation of particle anti-particle symmetry

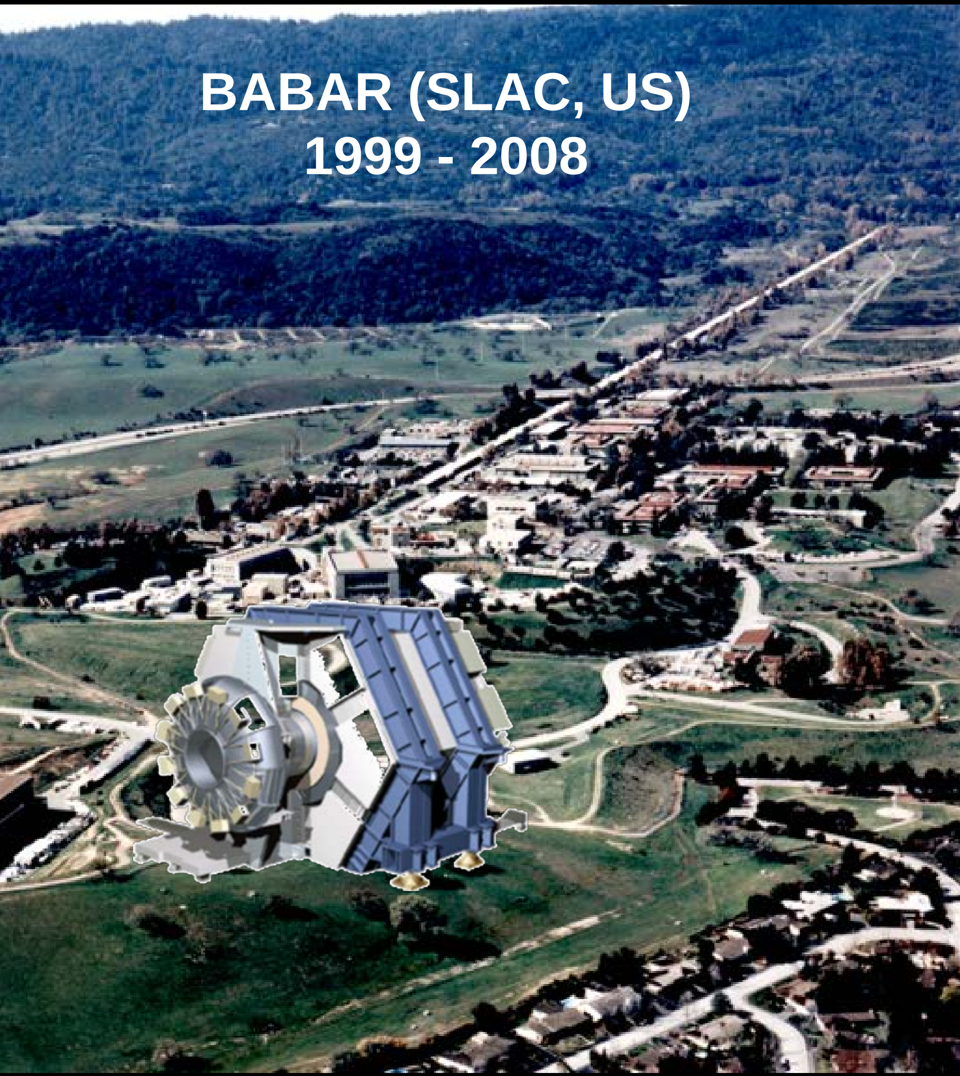
PRL 110 (2013) 221601

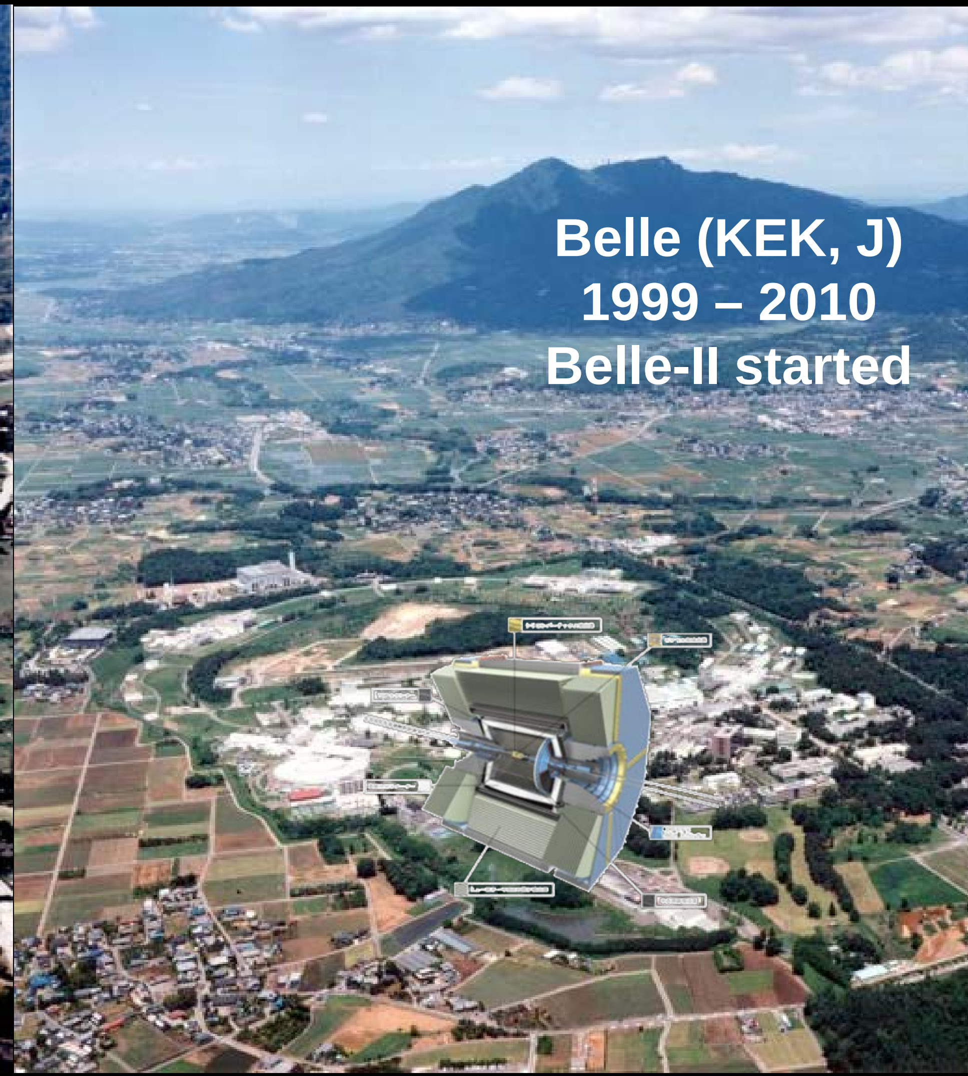
$B^0 \rightarrow K^+ \pi^-$

$\bar{B}^0 \rightarrow K^- \pi^+$



B-factories to explore the CKM paradigm

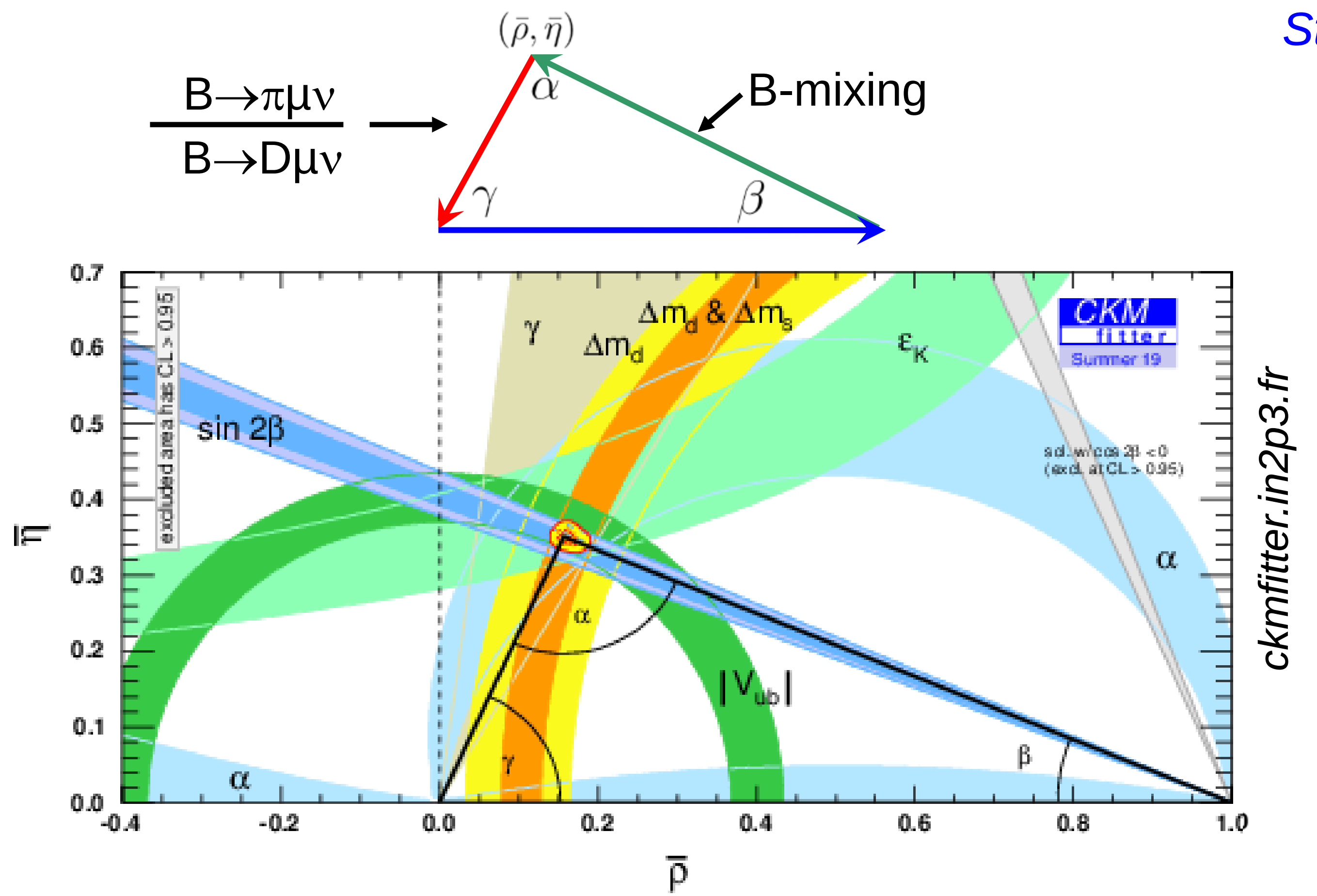




$$e^+ e^- \rightarrow \Upsilon(4S) \rightarrow B\,\bar{B} \qquad \sim 10^9$$

Experimental Test of CKM-Paradigm

Status 2019

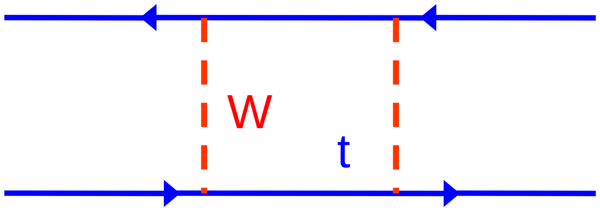


- Impressive confirmation of the quark mixing mechanism:
  Nobel prize 2008 for *M.Kobayashi & T.Maskawa*
- Effects of *New Physics* only as corrections to Standard Model

“New Phenomena” in Quantum-Loops

Standard Model

New Phenomena



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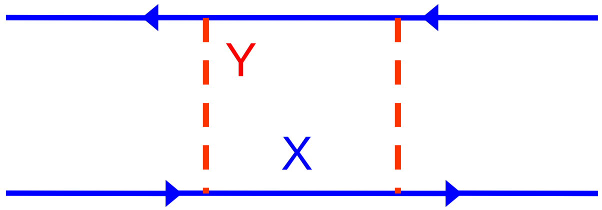
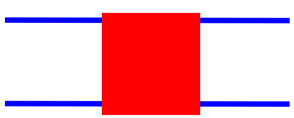


$$\mathcal{A}_{SM} \quad + \quad \mathcal{A}_{NP}$$



$|\mathcal{A}|^2 \rightarrow$ rates

Phase $\rightarrow$ CP-violation

Lorentz-structure $\rightarrow$ angular distr.

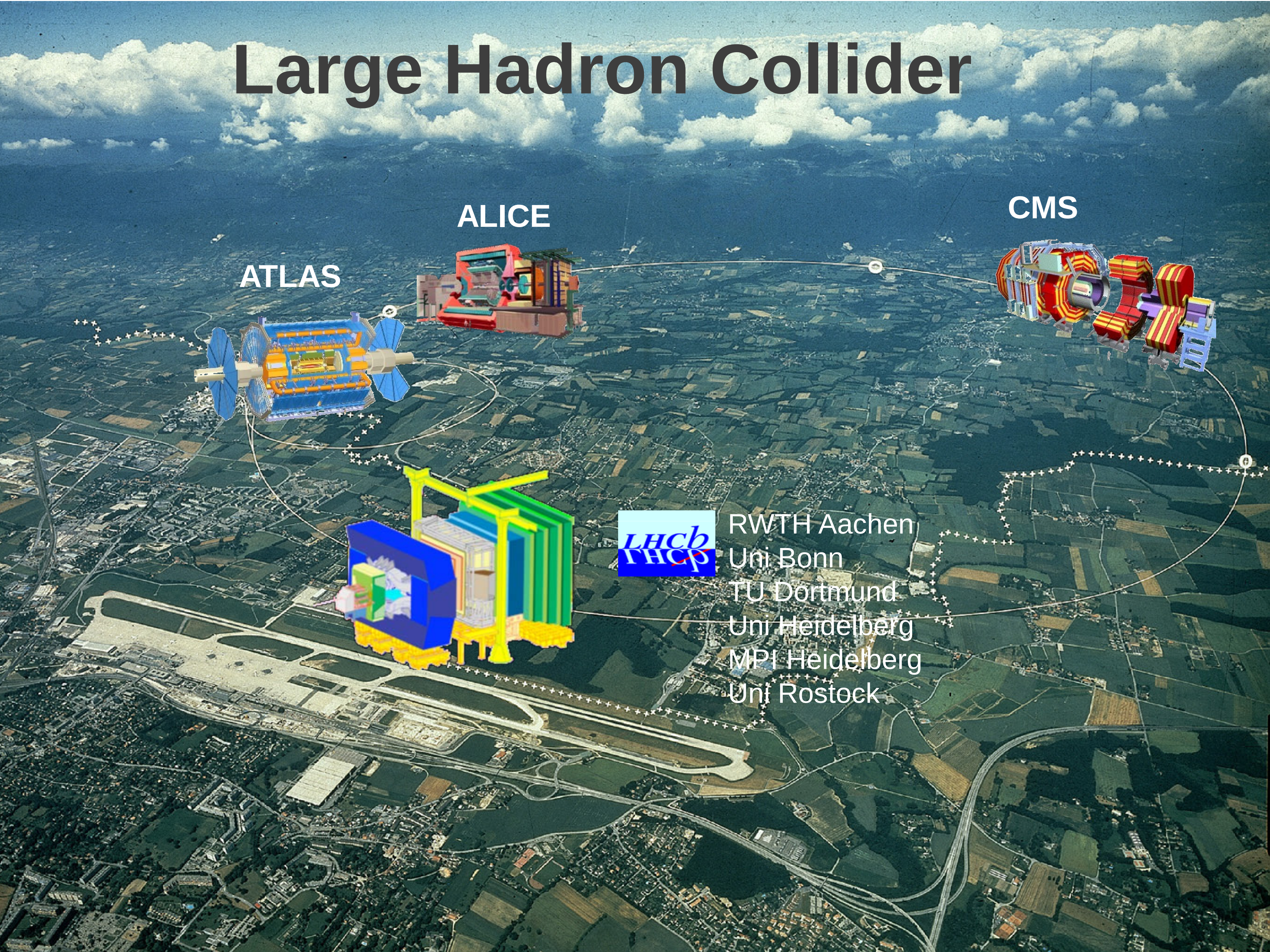
For c_{NP}=1:
NP > O(100 TeV)

Search for deviations from Standard Model predictions:

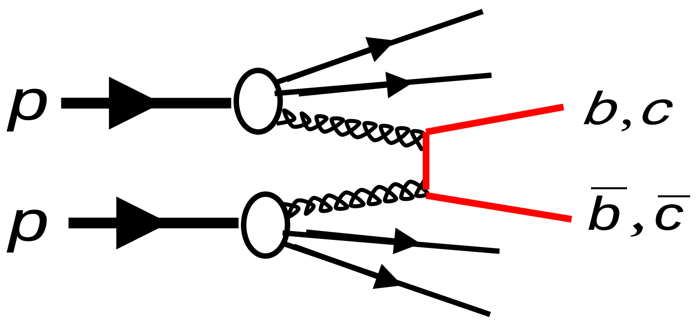
Suppressed processes, observables w/ small theoretical errors

High-rate experiments to maximize sensitivity: **LHC(b) / Belle-2**

Large Hadron Collider



b-quark production at LHC(b)

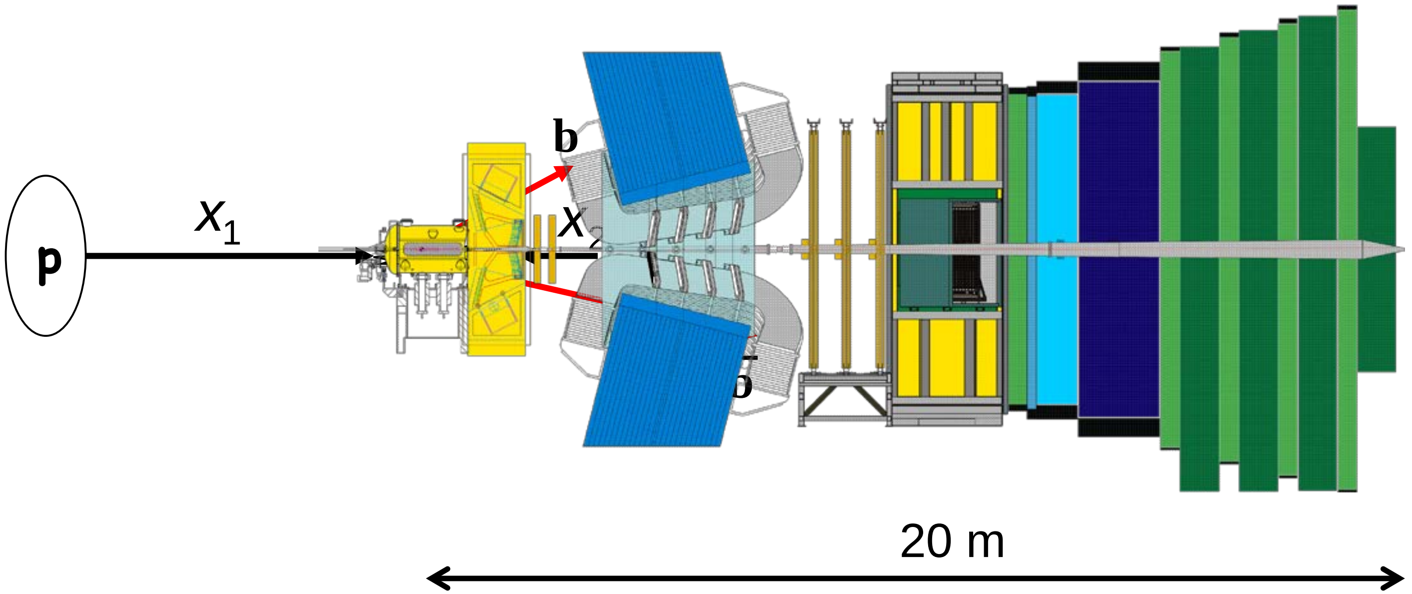


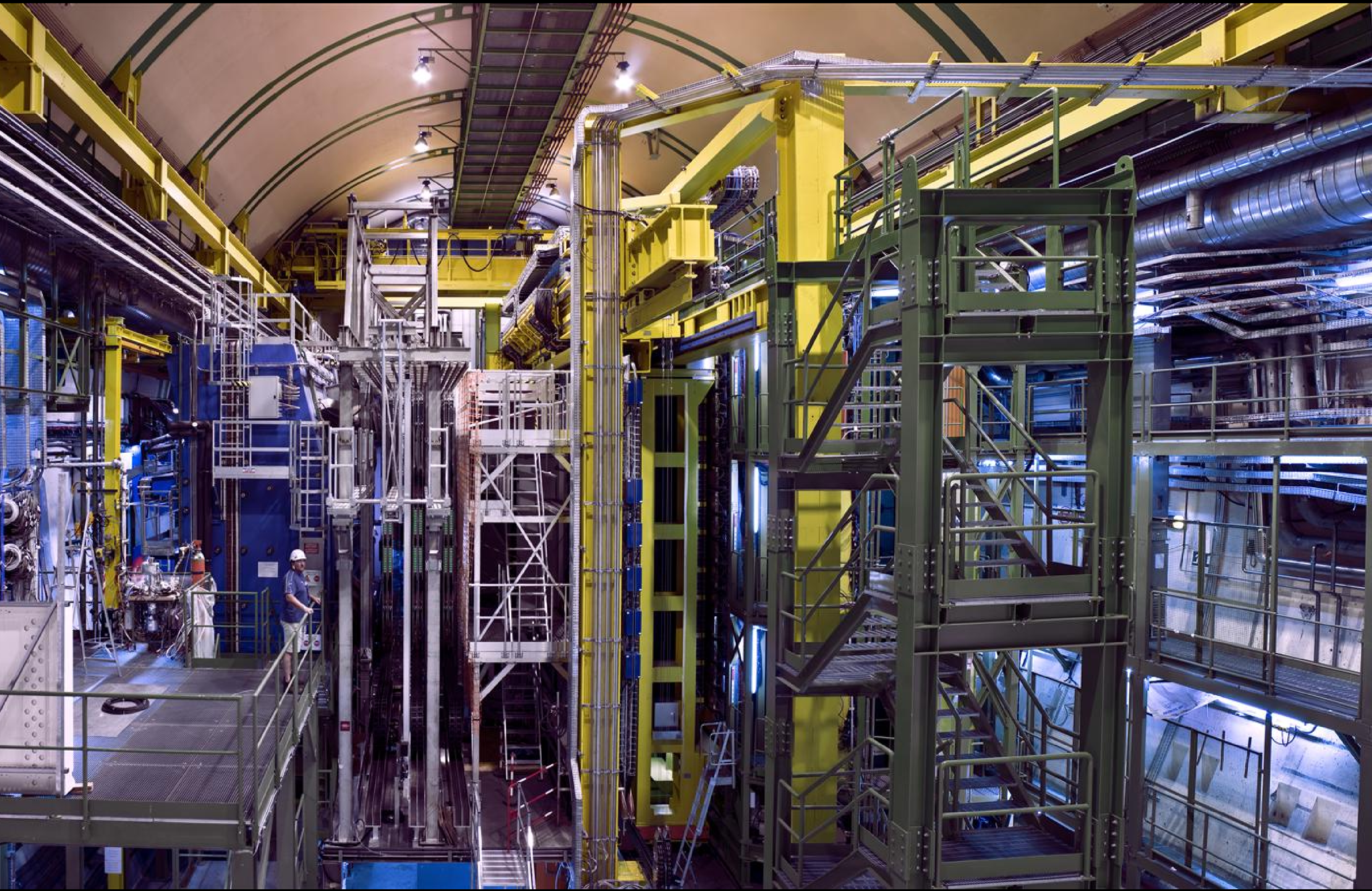
Run 2010-2012: 3 fb^{-1} (LHCb)

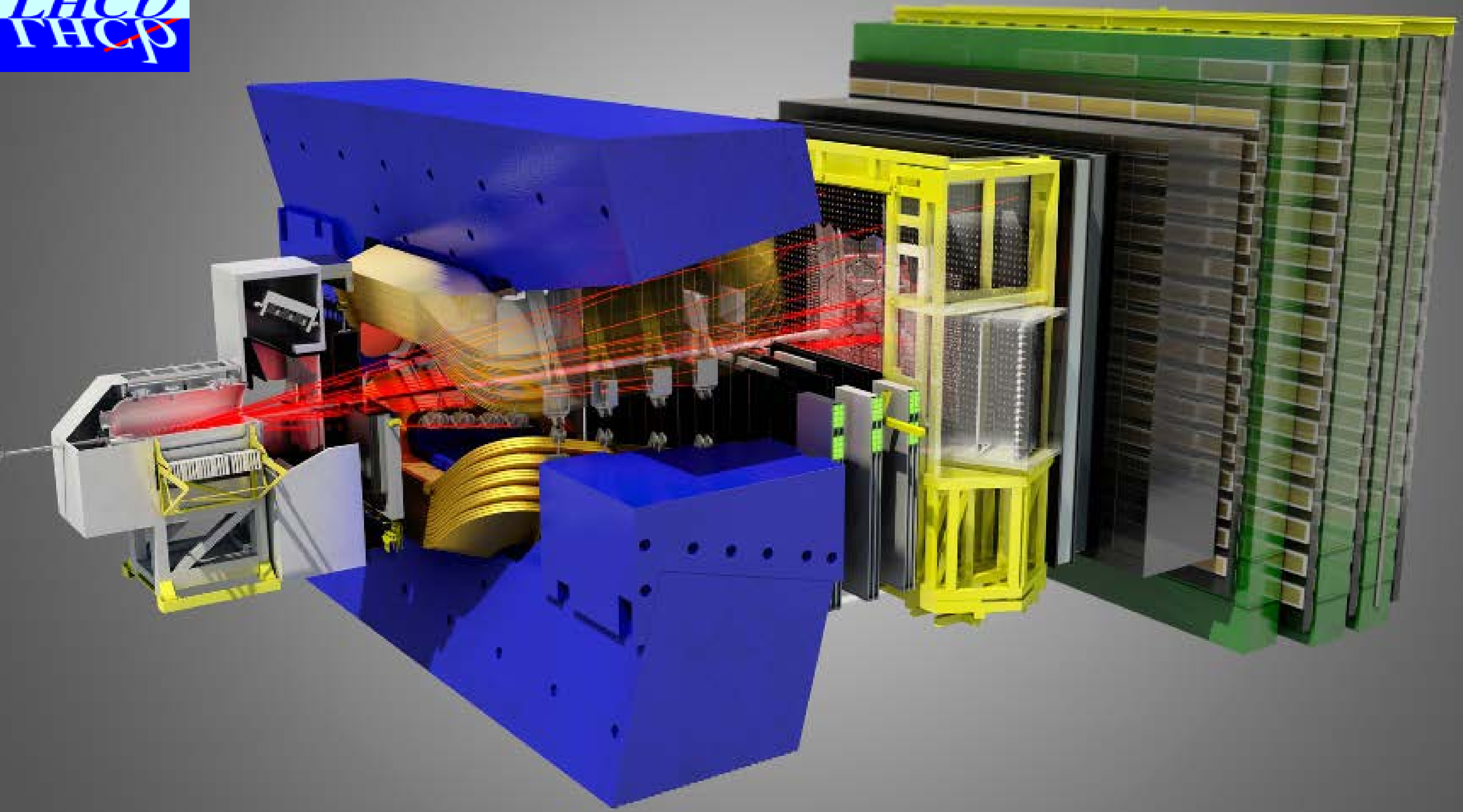
200 kHz $b\bar{b}$ $\rightarrow$ 2.6×10^{11} $b\bar{b}$

4MHz $c\bar{c}$ $\rightarrow$ 5.9×10^{12} $c\bar{c}$

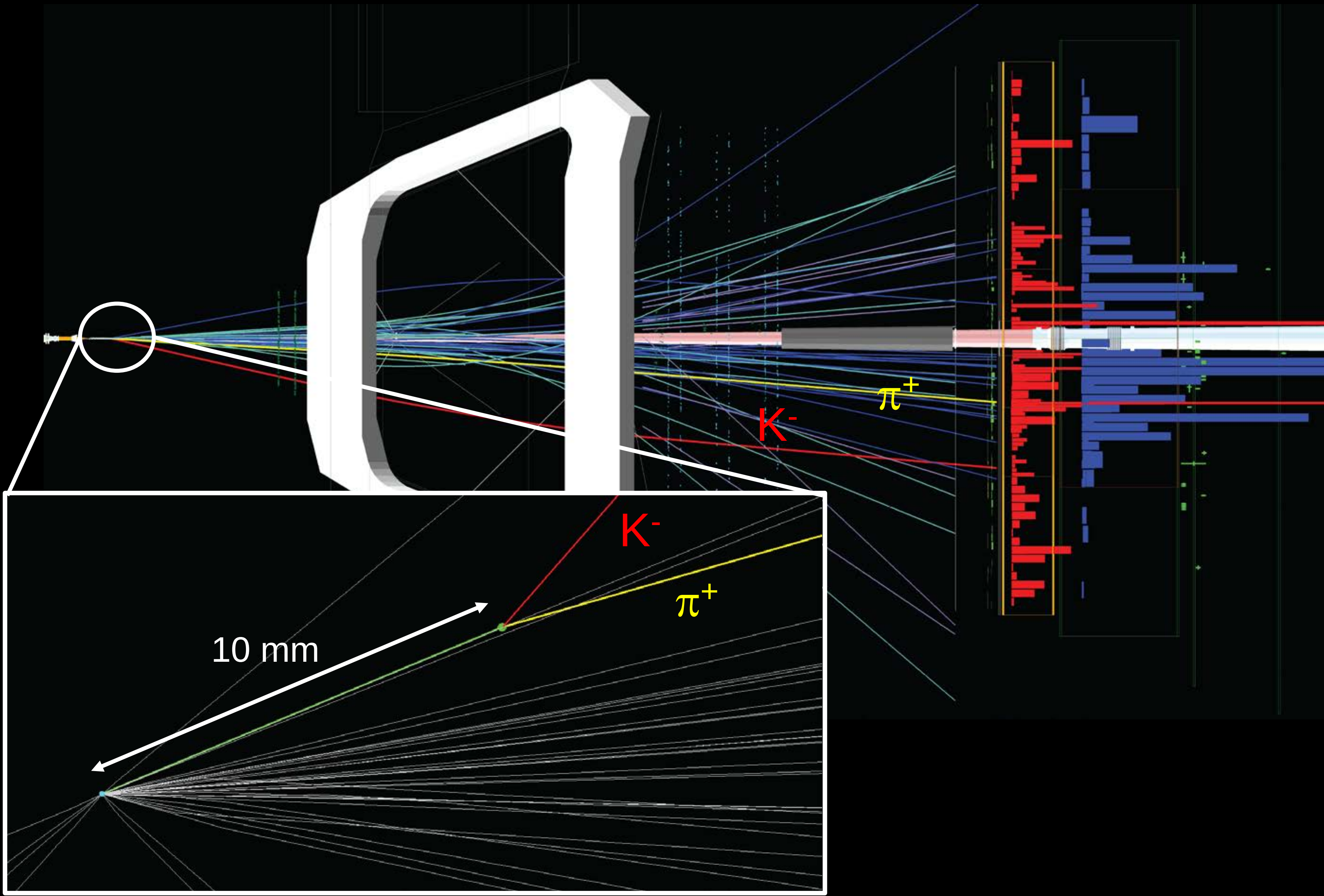
Run 2015 - 2018: 5.7 fb^{-1}







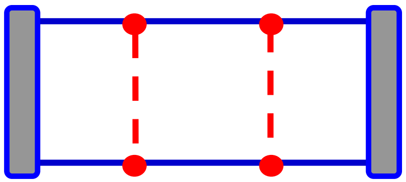
$B_s \to K^- \pi^+$



Searches for *New Effects with* LHCb

Meson - Mixing

$$\mathcal{A}_{mix} = \left|\mathcal{A}_{mix}\right| e^{-i\phi_{mix}}$$

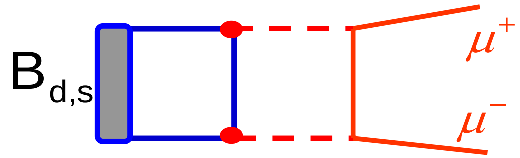


Mixing + CP violation

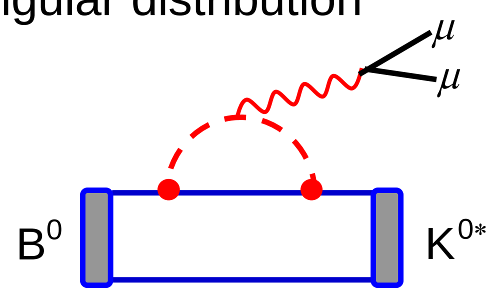
First observation of CPV in D mesons

Very rare decays

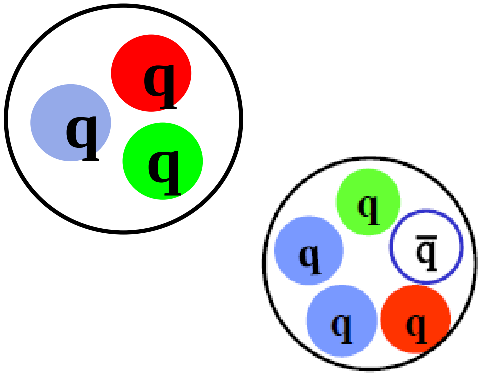
Rates



Angular distribution

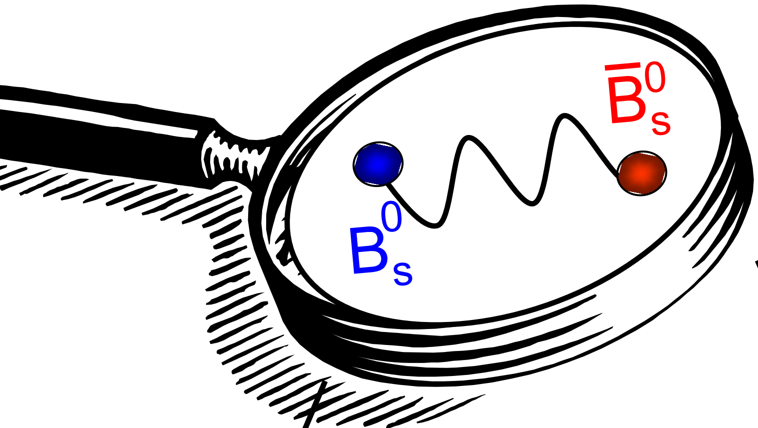


New and exotic hadrons

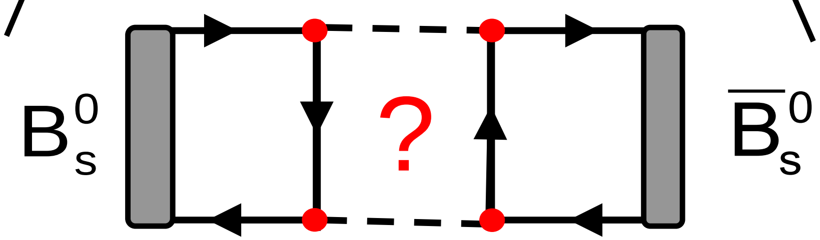


Masses & angular distributions

B_s-Mixing



$$\mathcal{A}_{mix} =$$



$$= \left|\mathcal{A}_{mix}\right| \cdot e^{i\phi_s}$$

Two state system:

mass states $\Leftrightarrow$ flavor states

Mass eigenstates:

$$\boxed{\tau = \hbar/\Gamma}$$

$$\left|B_L\right\rangle = p\left|B^0\right\rangle + q\left|\overline{B^0}\right\rangle \quad \text{mit } m_L, \Gamma_L$$

$$\left|B_H\right\rangle = p\left|B^0\right\rangle - q\left|\overline{B^0}\right\rangle \quad \text{mit } m_H, \Gamma_H$$

$\Downarrow$

Observables:

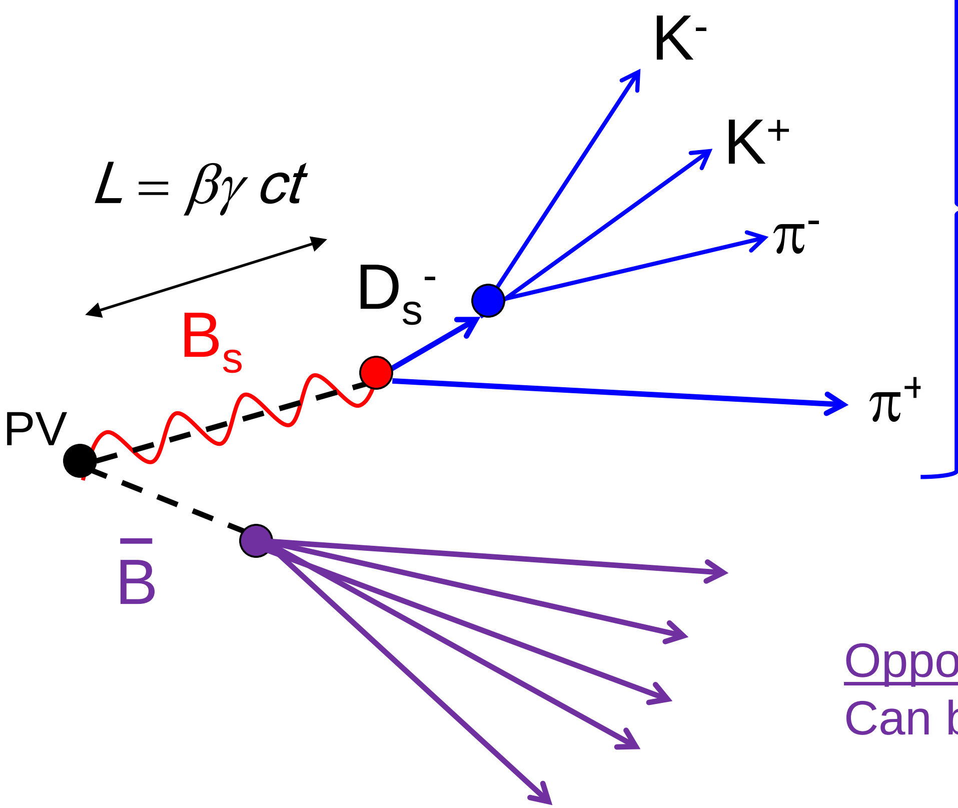
m_s, Γ_s aver. mass, lifetime

$\Delta m_s = \Delta m_H - \Delta m_L$ mixing frequ.

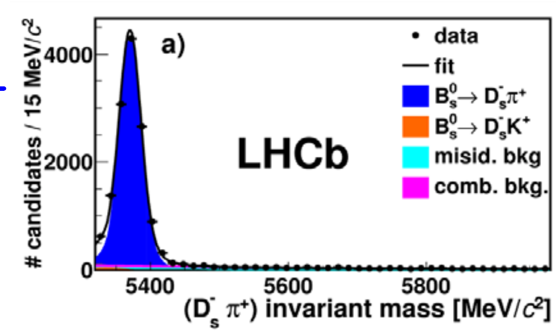
$\Delta\Gamma_s = \Gamma_L - \Gamma_H$

ϕ_s (as phase difference)

B_s Mixing Measurement in a Nutshell



Signal B
(flavor specific decay)



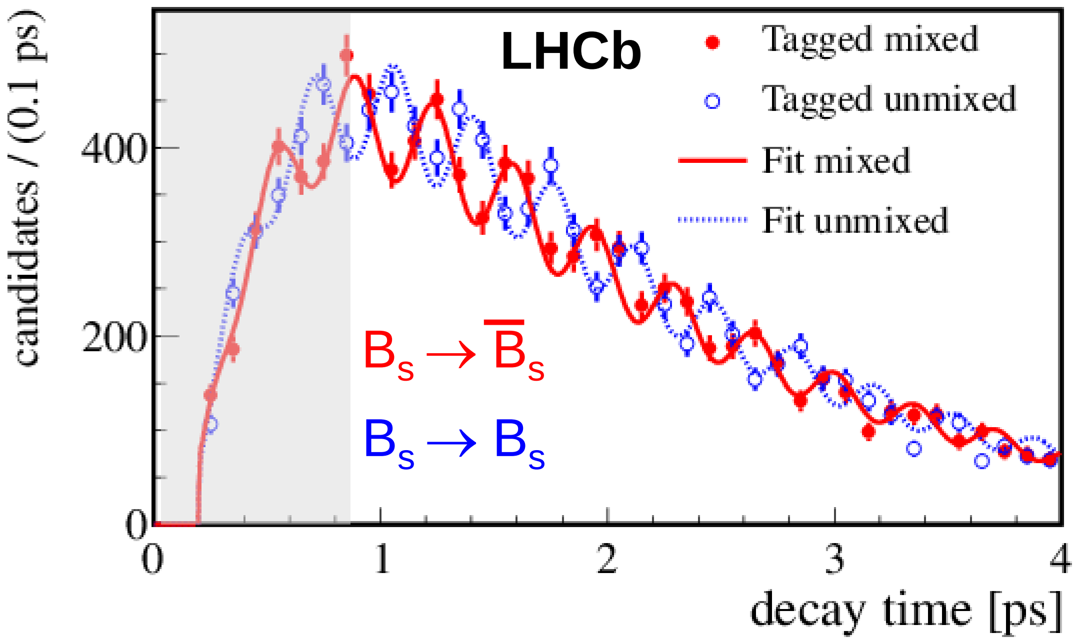
Invariant mass: $m^2 = \left(\sum p_i\right)^2$

Opposite B
Can be used for flavor tagging

$$PDF(B,t) \propto \left[e^{-\Gamma t} \cdot \left(1 \underset{B \to \bar{B}}{\overset{B \to B}{\pm}} \cos(\Delta m \cdot t) \right) \right]$$

B_s-Mixing

New J. Phys. 15 (2013) 053021



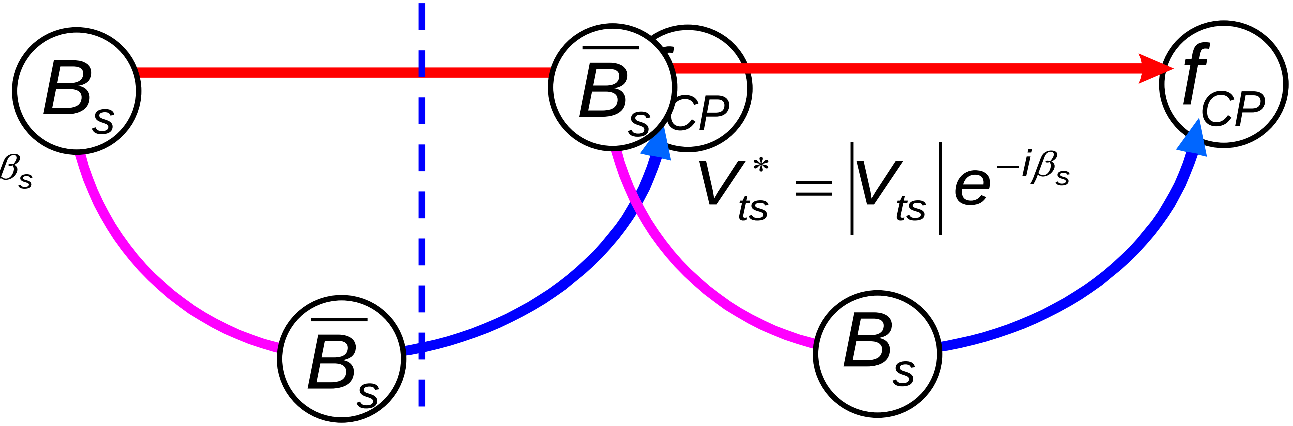
Δm_s = 17.768± 0.023 ± 0.006 ps^{-1}

Theory *(U.Nierste, 2012)*
Δm_s = 17.3± 1.5 ps^{-1}

Unsatisfying: Hadronic uncertainties limit the theoretical prediction

Time dependent CP Violation

$$V_{ts} = |V_{ts}| e^{i\beta_s}$$



$$V_{ts}^{*} = |V_{ts}| e^{-i\beta_s}$$

$$\boxed{V_{ts} = |V_{ts}| e^{i\beta_s}}$$

$$\Gamma(t) \sim e^{-\Gamma t}\left[1 - \sin 2\beta_s \sin(\Delta m_s t)\right]$$

$$\Gamma(t) \sim e^{-\Gamma t}\left[1 + \sin 2\beta_s \sin(\Delta m_s t)\right]$$

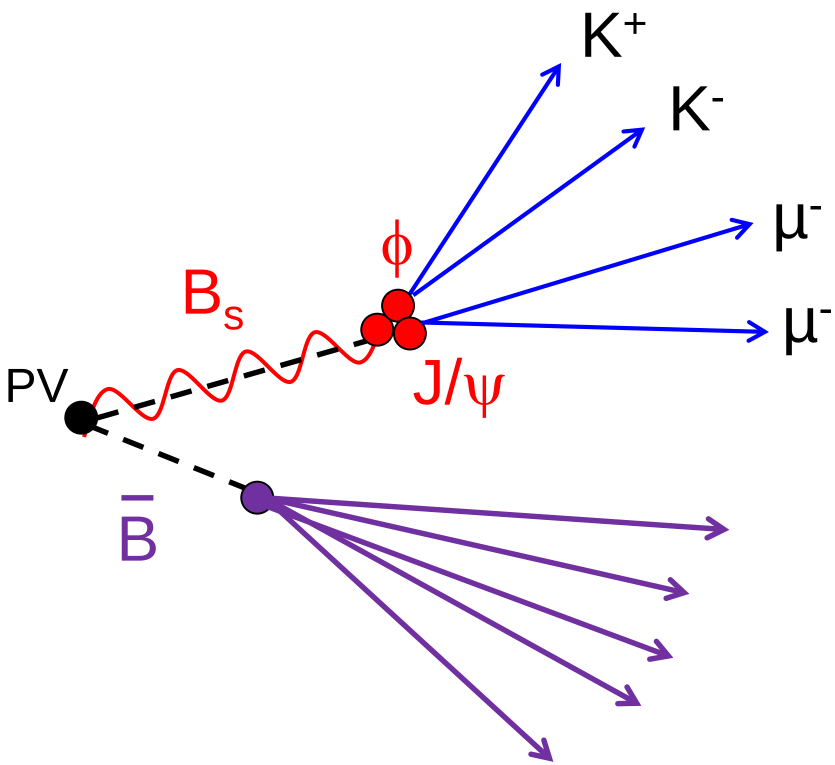
CP

$= -\phi_s$

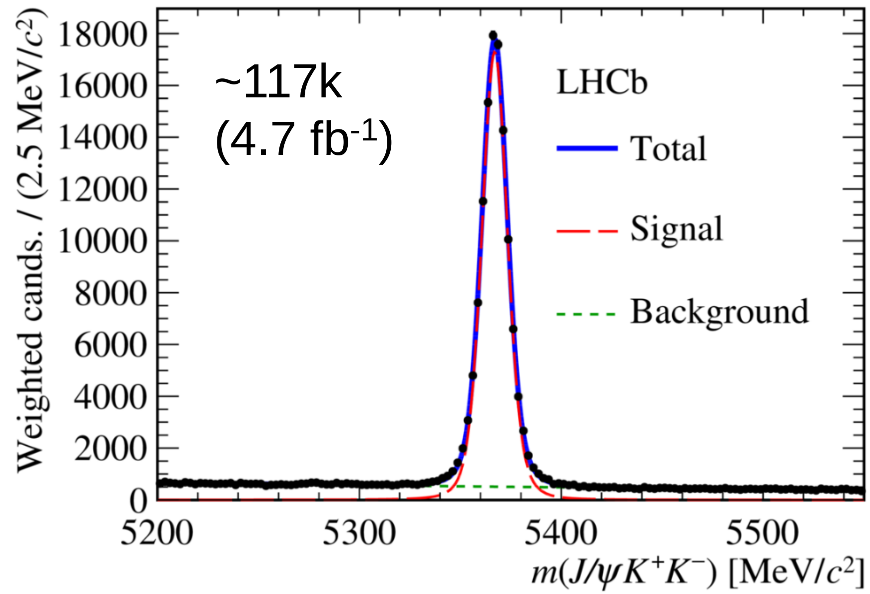
$$A_{CP}(t) = \frac{\Gamma(\overline{B}_s \to f)(t) - \Gamma(B_s \to f)(t)}{\Gamma(\overline{B}_s \to f)(t) + \Gamma(B_s \to f)(t)} = \sin \boxed{2\beta_s} \sin(\Delta m_s t)$$

"Golden" Decay: $B_s \to J/\psi\phi$

$c\bar{c}$ $s\bar{s}$



Eur. Phys. J. C 79 (2019) 706

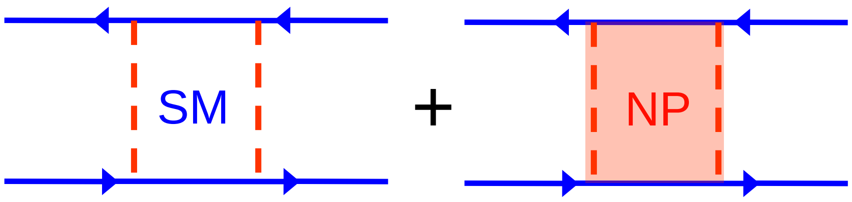


Theory predicts very small CP violation: $\phi_s = -0.036 \pm 0.0013$ → "Null" test

$\phi_s = -0.041 \pm 0.025$ Eur. Phys. J. C 79 (2019) 706

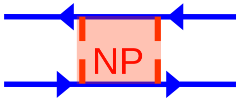
(stat. dominated)

Constraints for *New Physics*

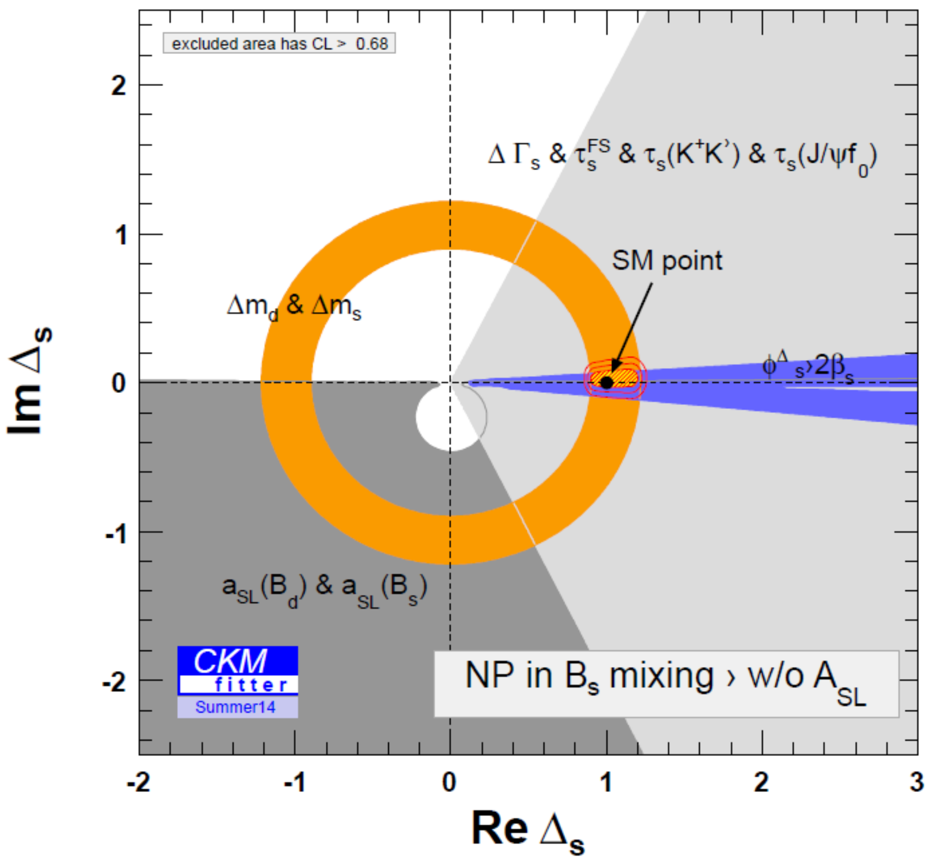


$$\mathcal{A}_{mix} = \mathcal{A}_{mix}^{SM} + \mathcal{A}_{mix}^{NP}$$
$$= \mathcal{A}_{mix}^{SM} \cdot \Delta$$

$B_s^0\ (\bar{b}s)$ < 15%

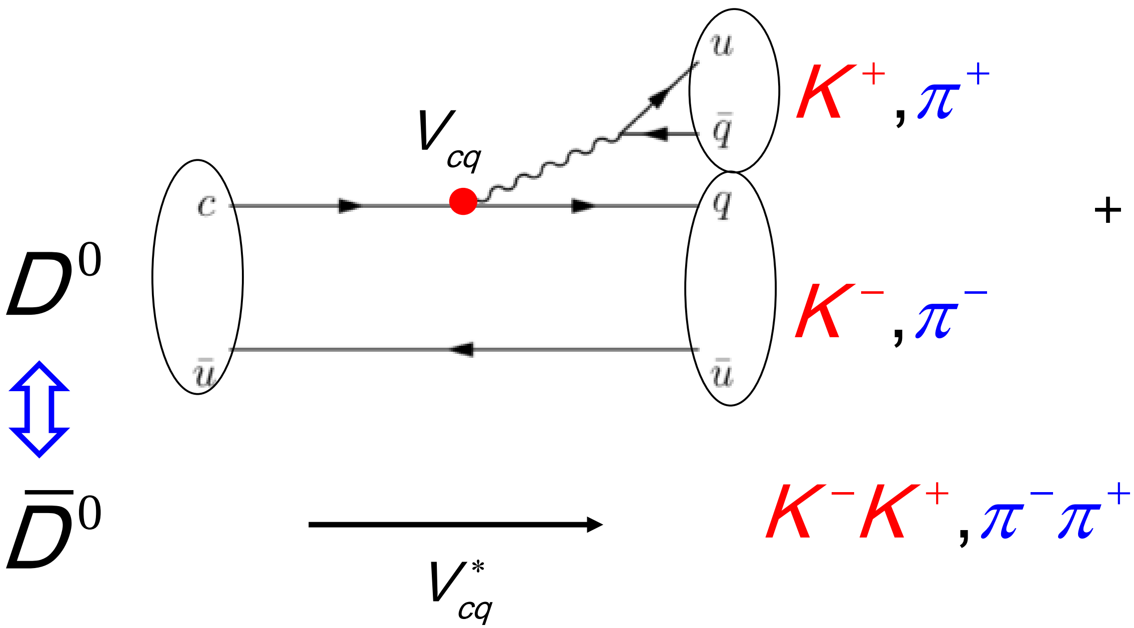


A.Lenz, U.Nierste & ckmfitter.in2p3.fr



error δφ=±0.025 (today) →δφ < 0.010 (2026, 50 fb^{-1})

The Beauty of Charm Decays

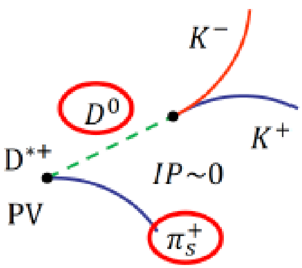


+ loops + $D^0 \to \bar{D}^0 \to KK$,

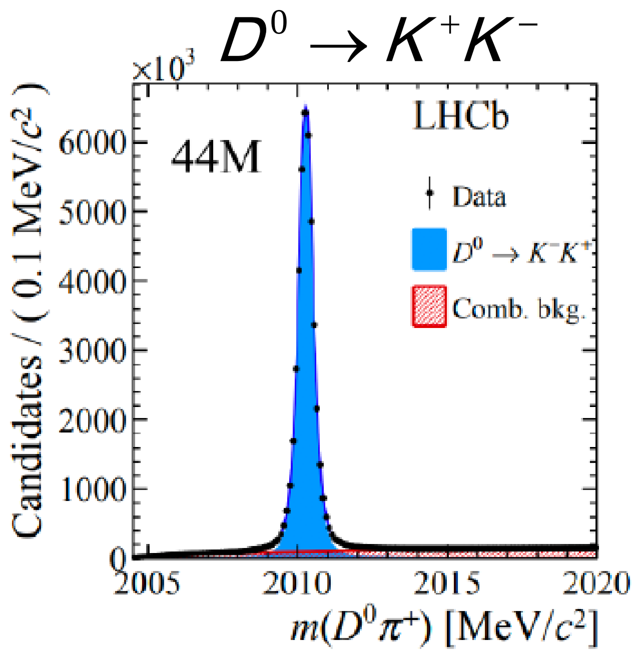
$$\boxed{A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to \bar{f})}}$$

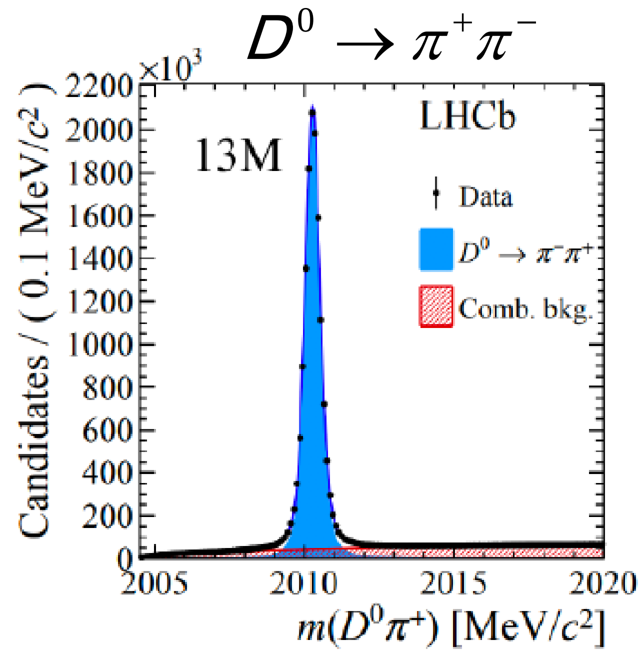
Only way to probe CP violation in *mesons w/ up-type quark decays.*
Complementary to K and B meson measurements.
SM expectation: $A_{CP} \approx 10^{-3} \ldots 10^{-4}$ (possibly large effects from NP)

CPV in D-Mesons



pion tag





Experimental trick

$$A_{raw}(f) = A_{CP}(f) + \overbrace{A_D(\pi_s) + A_{Prod}(D^0) + \cancel{A_D(f)}}^{\text{experimental asymmetries are large}}$$

$$\Delta A_{CP} \equiv A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)$$

First Observation of CPV in Charm

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

dominated by π-tagged sample

$\sigma_{syst} \approx 0.9 \times 10^{-4}$

Deviates by 5.3σ from zero:

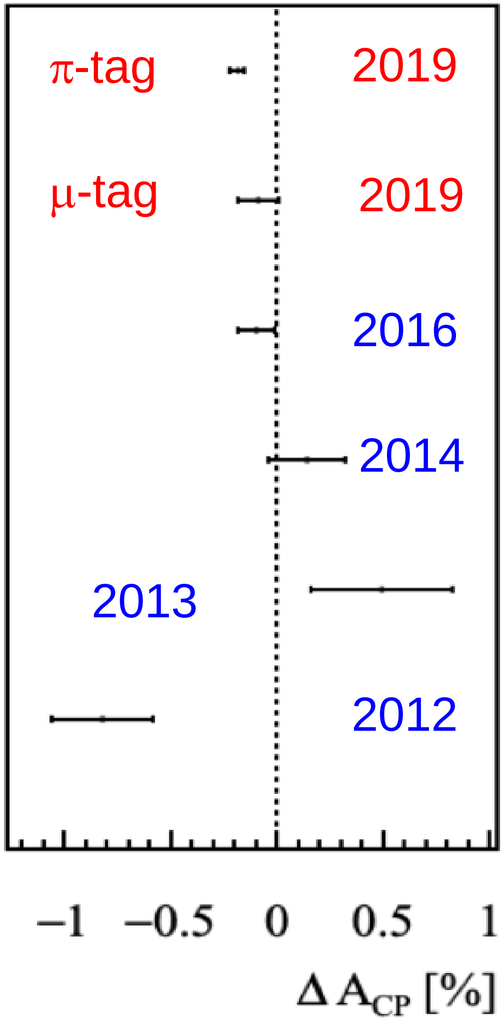
First observation of CP violation in the decay of charmed hadrons.

<u>History of CP violation:</u>

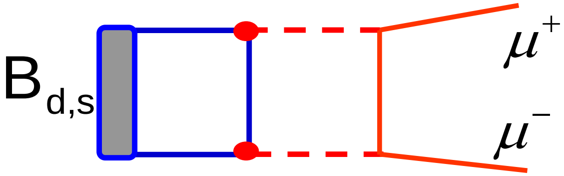
1964 CPV in K-mesons

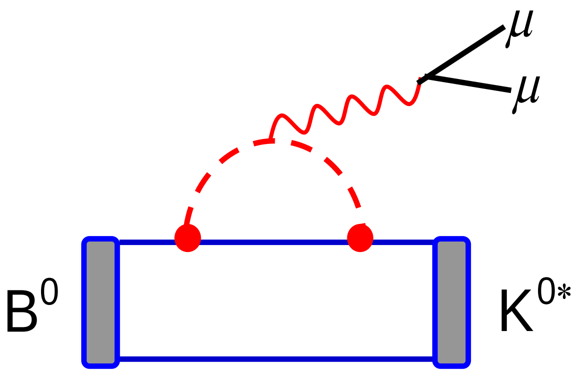
2001 CPV in B-mesons

2019 CPV in D-mesons



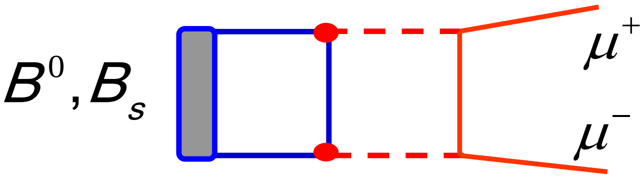
Rare (FCNC) B Decays





Very rare decays $B^0, B_s \to \mu^+ \mu^-$

Standard Model:

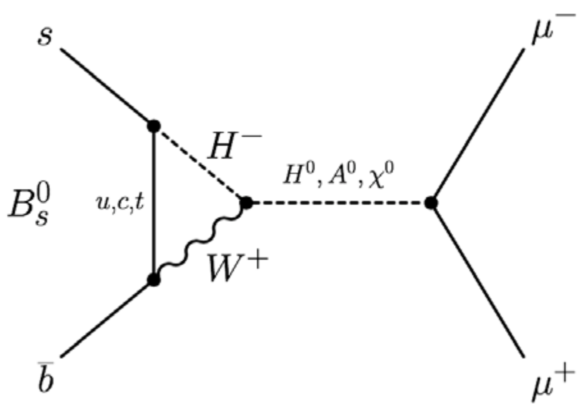


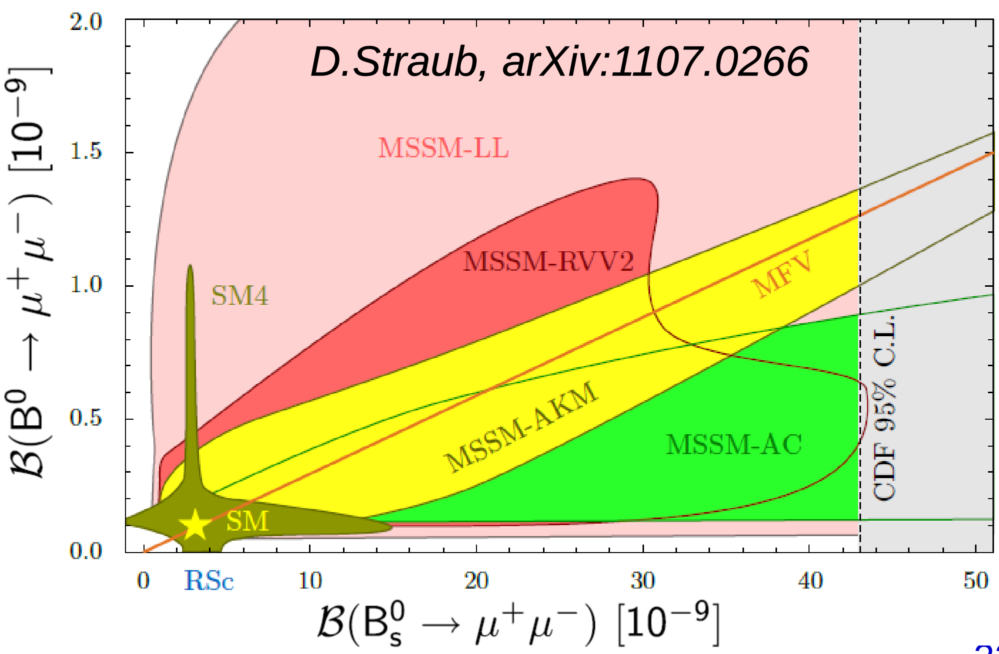
SM prediction: *PRL 112 (2014) 101801*

$BR(B_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$

$BR(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

Sensitive to *New Physics:*
(pseudo) scalar interactions

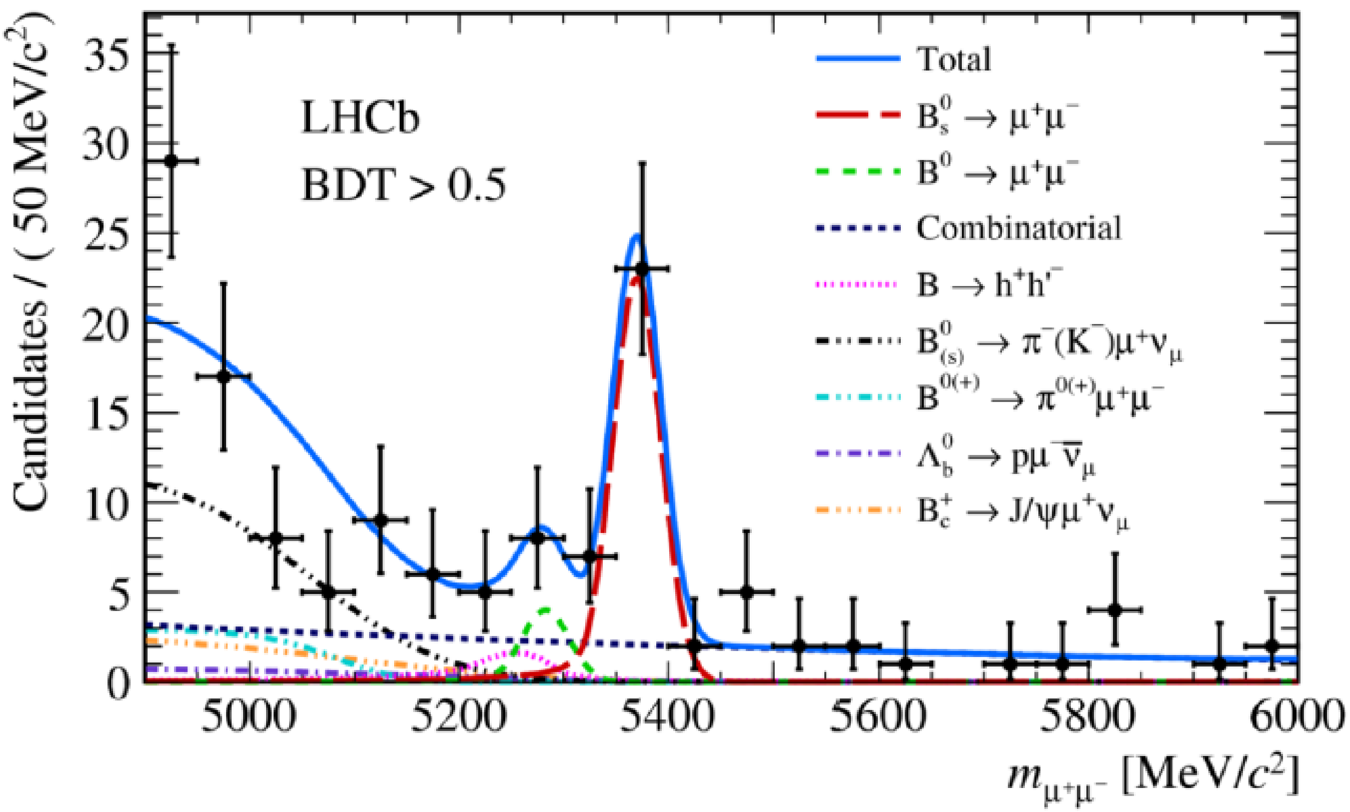




First "single" experiment observation

PRL118(2017)191801 (3+1.4 fb^{-1})

$$BR(B_s \to \mu\mu) = (3.0 \pm 0.6\,^{+0.3}_{-0.2}) \times 10^{-9}$$
$$BR(B^0 \to \mu\mu) < 3.4 \times 10^{-10}\ @95\%\ C.L.$$

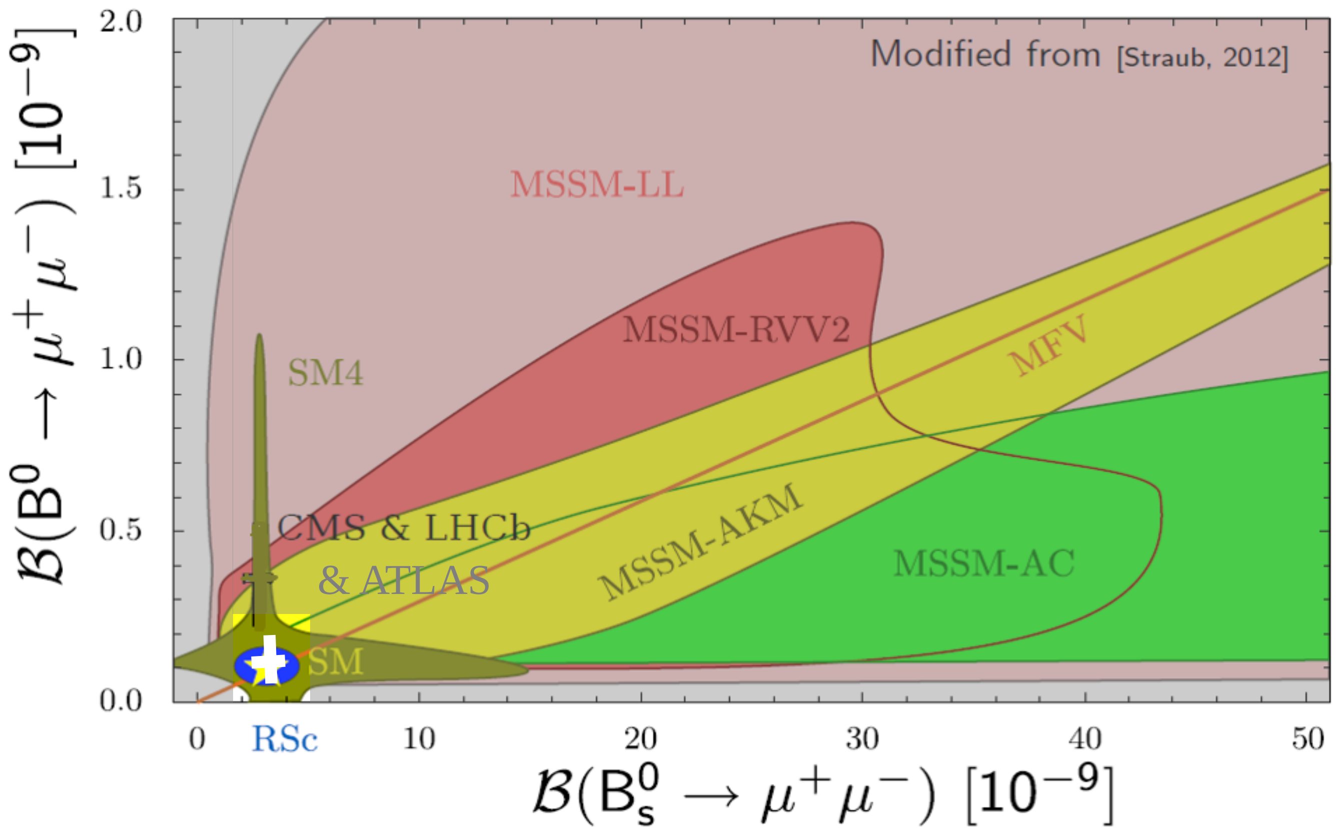


Constraints for *New Physics*

Combination;
ATLAS, CMS, LHCb

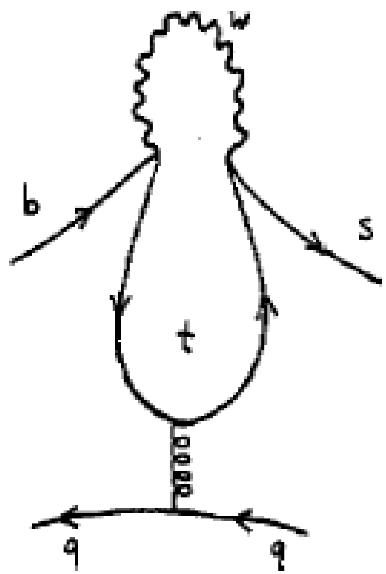
$$\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-) = (2.67^{+0.45}_{-0.35}) \times 10^{-9}$$
$$\mathrm{BR}(B^0 \to \mu^+\mu^-) = (1.00^{+0.86}_{-0.57}) \times 10^{-10}$$

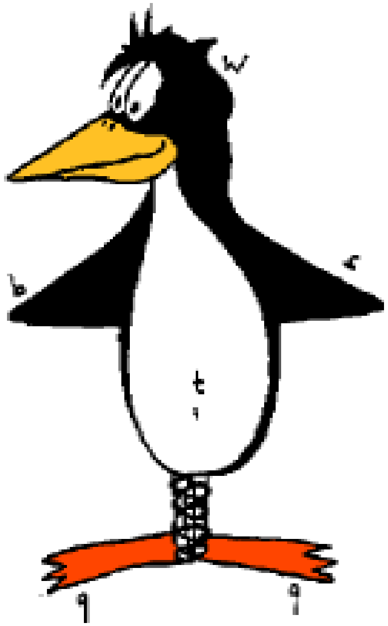
ATLAS: 1812.03017
CMS: PRL111(2013)101804
LHCb: PRL118(2017)191801



~~FCNC~~ decays

Penguin

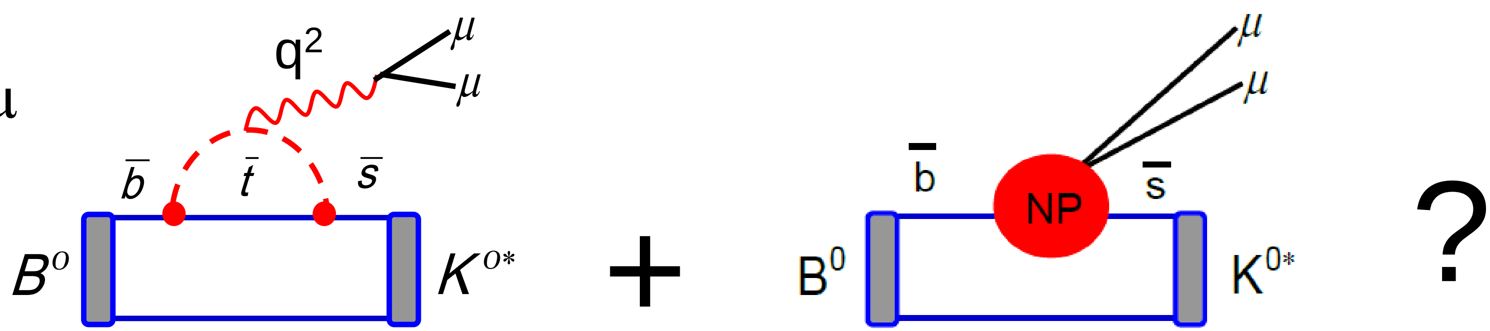




by A. Lenz

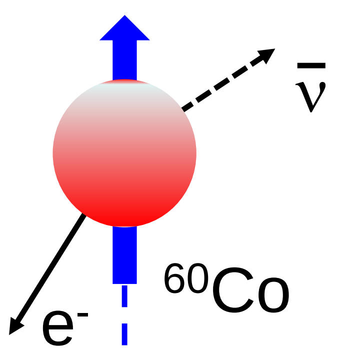
New Physics in "Penguin Decays" ?

$B^0 \to K^* \mu\mu$



⇨ modifies rates
modifies Lorentz structure

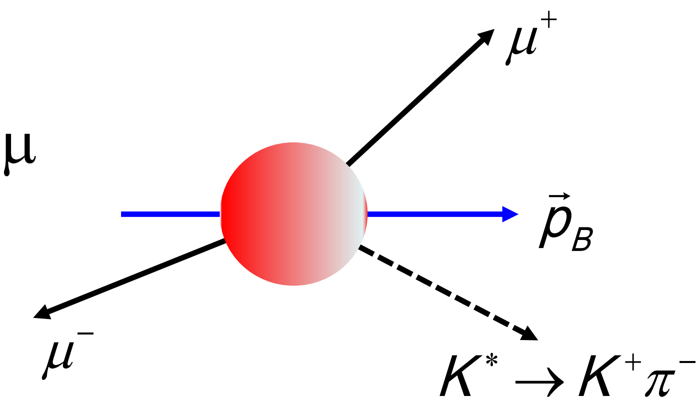
$^{60}Co \to {}^{60}Ni + e^- \bar{\nu}$



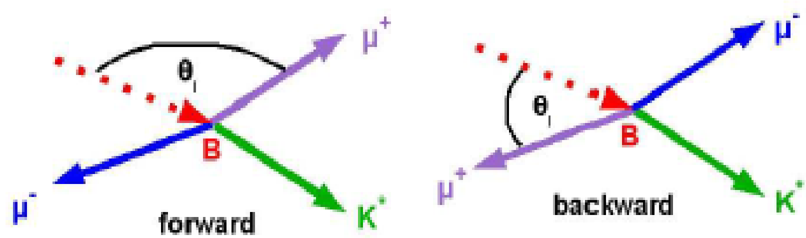
"Wu-experiment" to test
Lorentz structure of β-decay

"Wu-Experiment" for B-Mesons

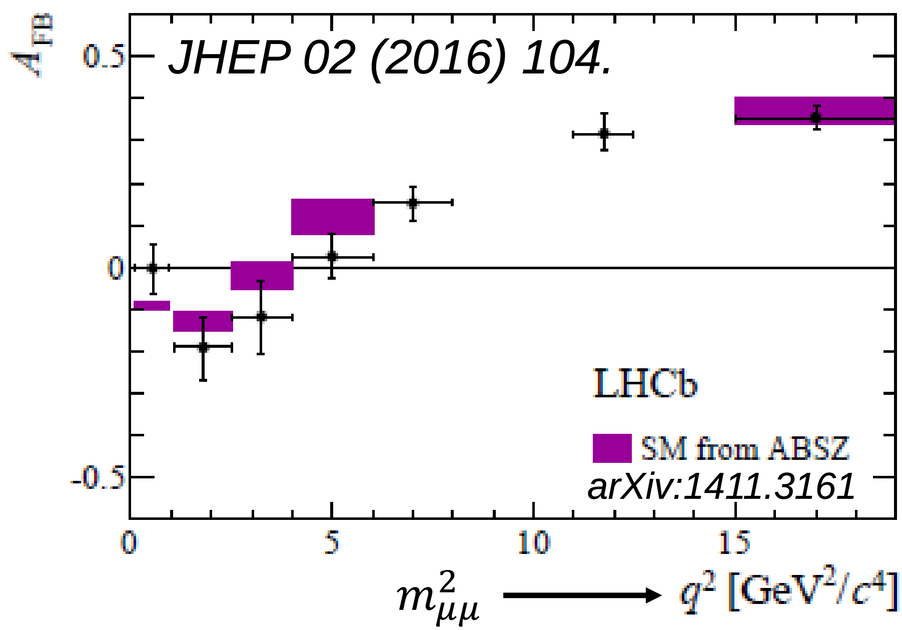
$B^0 \rightarrow K^* + \mu\mu$



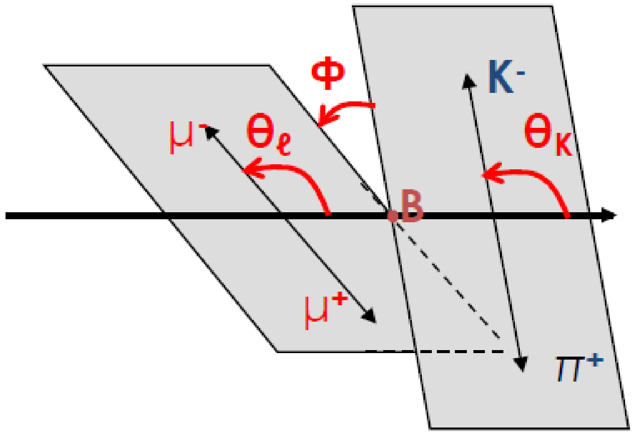
Forward-backward asymmetry:



$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

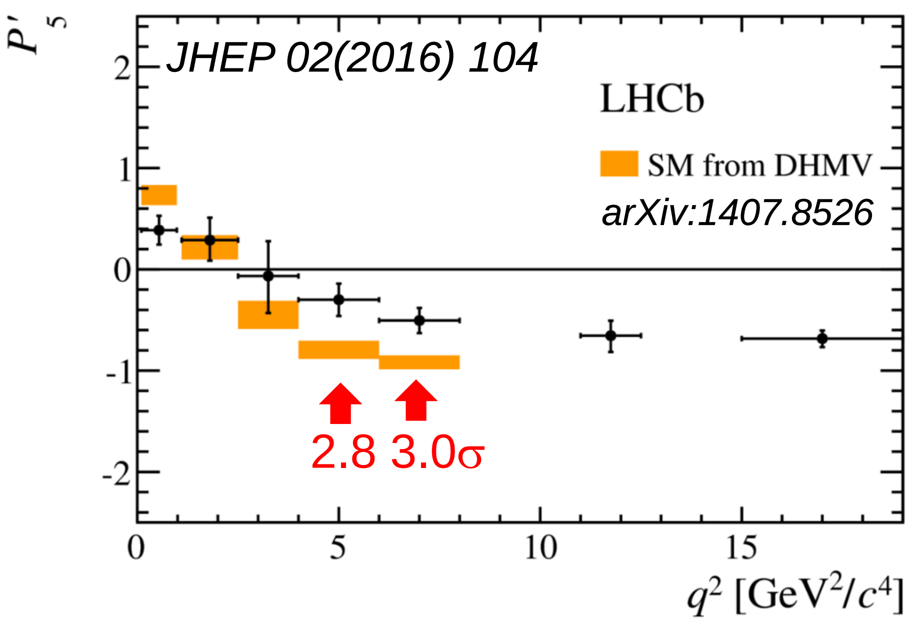


Full angular analysis



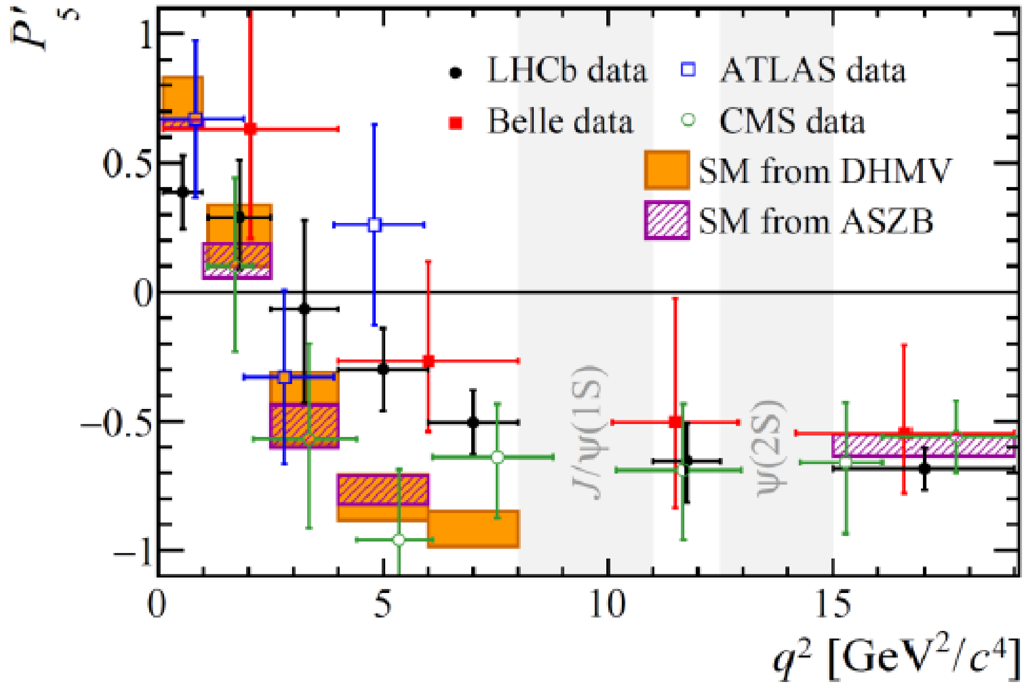
Differential angular distribution:

$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell \, d\cos\theta_K \, d\phi \, dq^2} = \sum_i \underbrace{\mathcal{J}_i(q^2)\,\Omega_i(\theta_\ell,\theta_K,\phi)}_{\text{11 angular terms}}$$



One angular coefficient deviates significantly from theory prediction

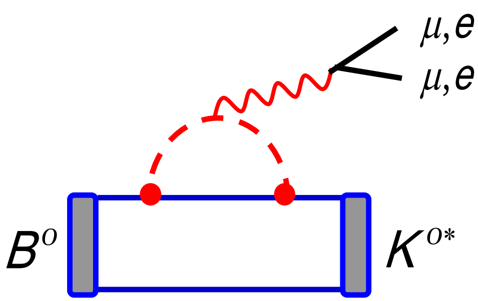
Confirmed by other Experiments



Belle, arXiv:1604.0402
ATLAS-CONF-2017-023
CMS-PAS-BPH-15-007

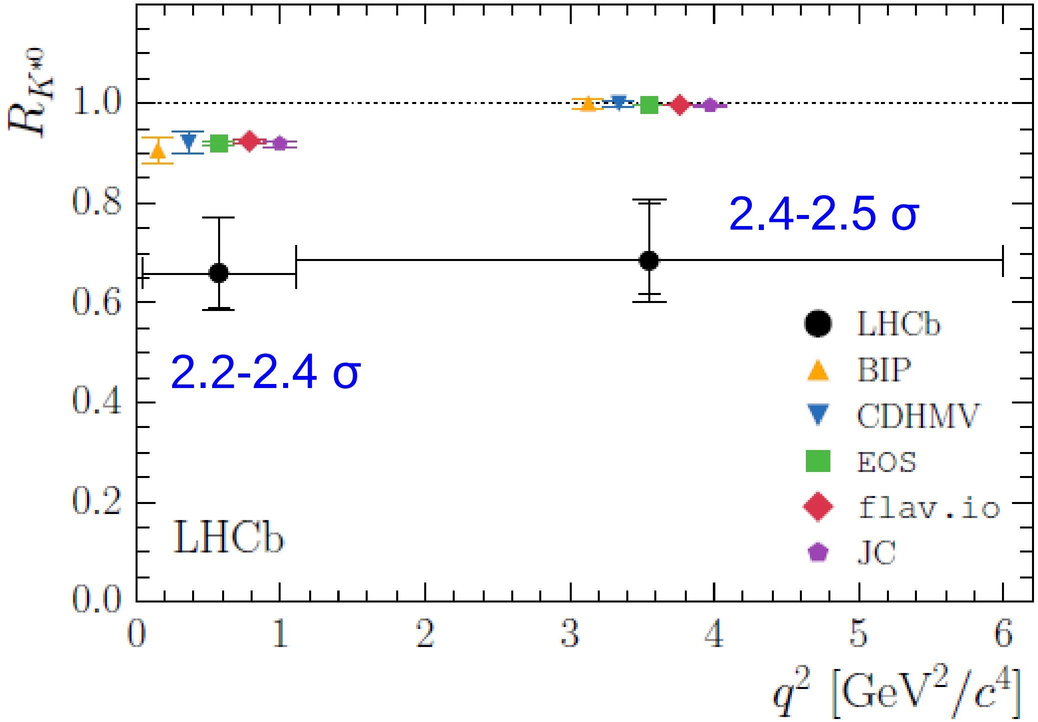
- LHCb has measured other ($b \to s\mu\mu$) channels: branching ratios for $B^+ \to K^+\mu\mu$, $B_s \to \phi\mu\mu$ and $\Lambda_b \to \Lambda\mu\mu$ lower than expectation.
- What about ($b \to see$) channels? Difficult with LHCb, but we tried.

$$R_{K^*} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu\mu)}{\mathcal{B}(B^0 \to K^{*0}ee)}$$



$R_{K^*} \approx 1$

lepton-universality:



Unexpected!

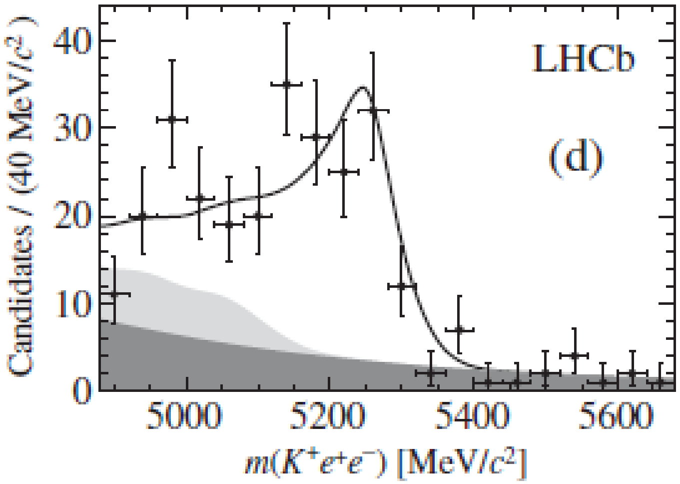
Lepton universality violated?

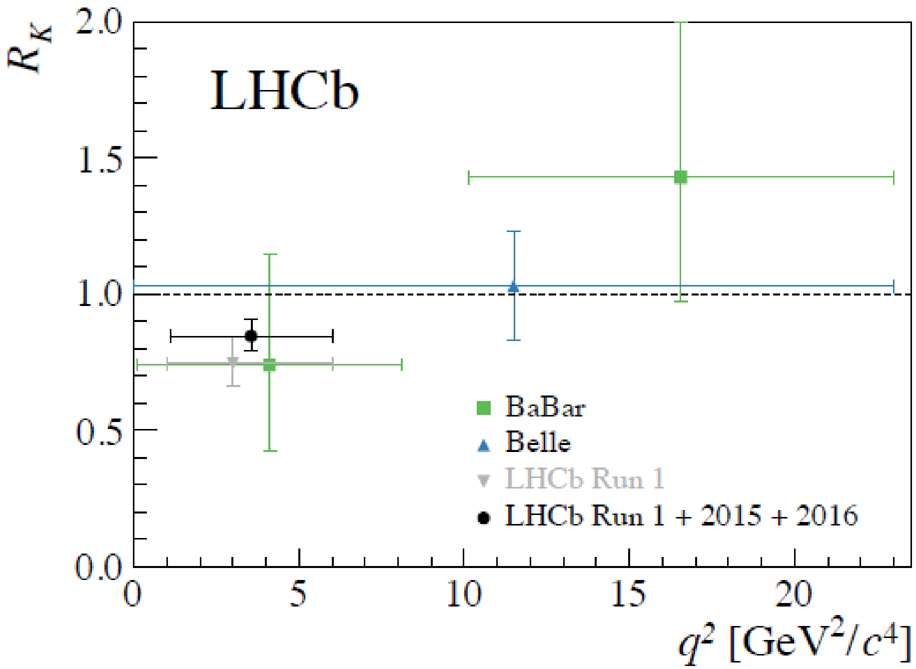
$B^+ \to K^+\mu^+\mu^-$ / $B^+ \to K^+e^+e^-$

PRL 113, 151601 (2014)

PRL 122, 191801 (2019)

$$R_K = \frac{\mathcal{B}(B^\pm \to K^\pm \mu\mu)}{\mathcal{B}(B^\pm \to K^\pm ee)} \overset{\text{SM}}{=} 1$$





Unexpected!

Both measurements consistent w/ smaller branching ration for the μμ-final state.

Violation of lepton universality?

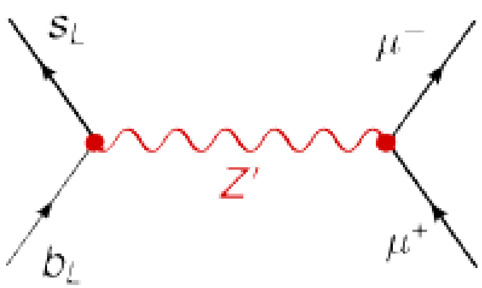
Interpretation

Global data fit:

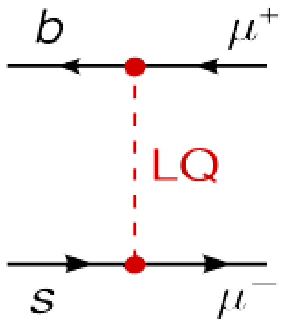
- Effective coupling (C_9) shows 5…6σ deviation wrt to Standard Model
- Lepton flavor universality (LFU) violation favored at 3.3 σ
- Additional observable with >4σ deviation: $B(B\to D^*\tau\nu)$ / $B(B\to D^*\mu\nu)$

Proposed *New Physics* explanations: *(e.g. arXiv:1704.05340)*

Z′ - boson



Leptoquark

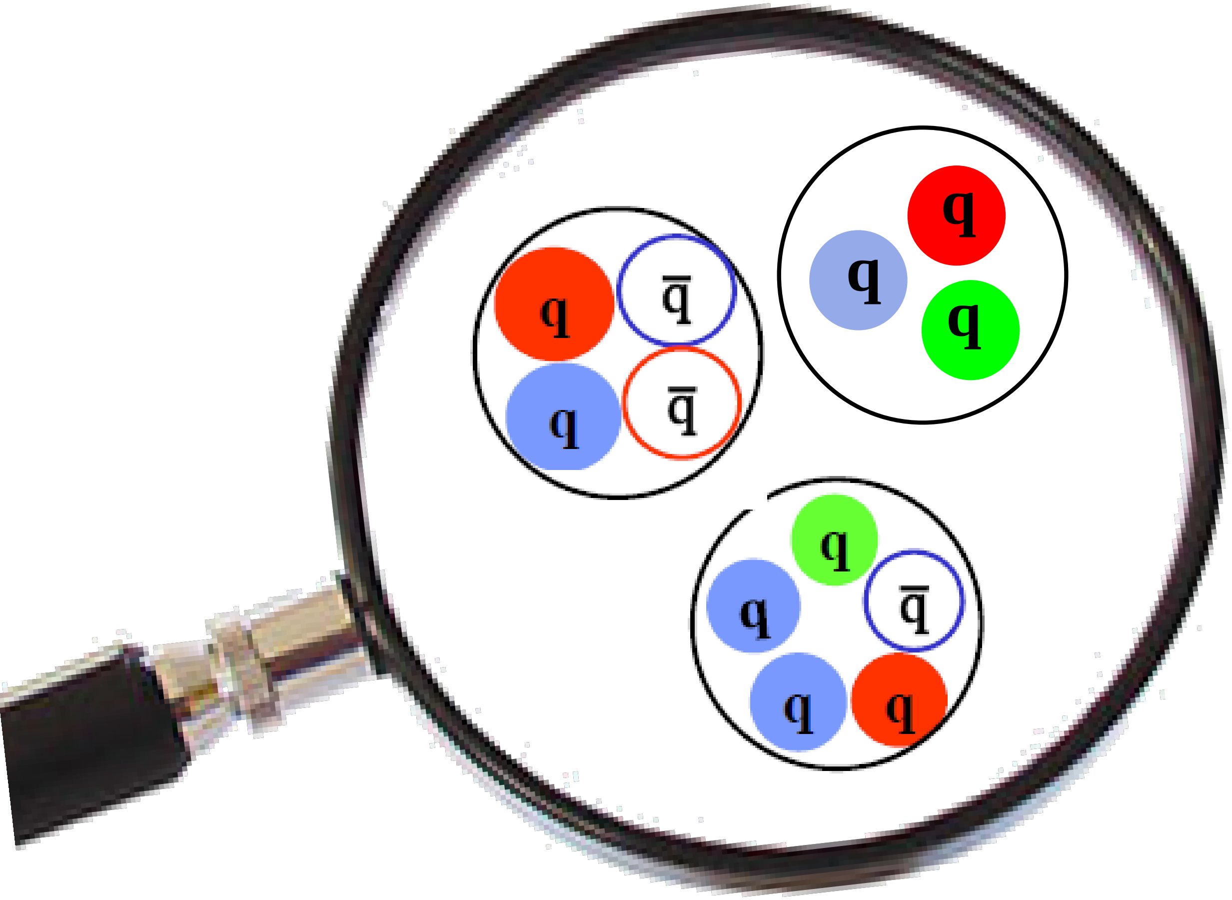


Very intriguing - more work needed:

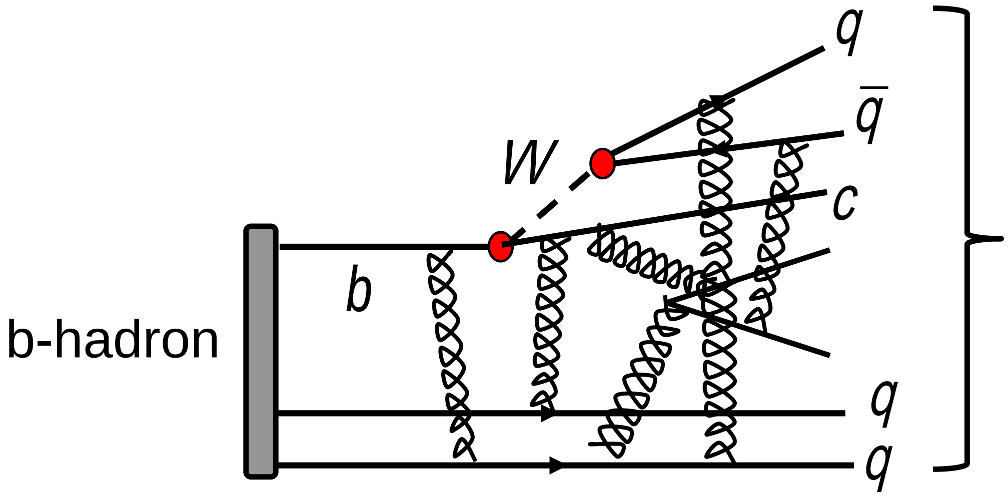
Theory: theoretical error of observables.

Experiment: LHCb Run-2 updates on R_K, R_{K^*} and even R_φ

New Hadron States - Spectroscopy

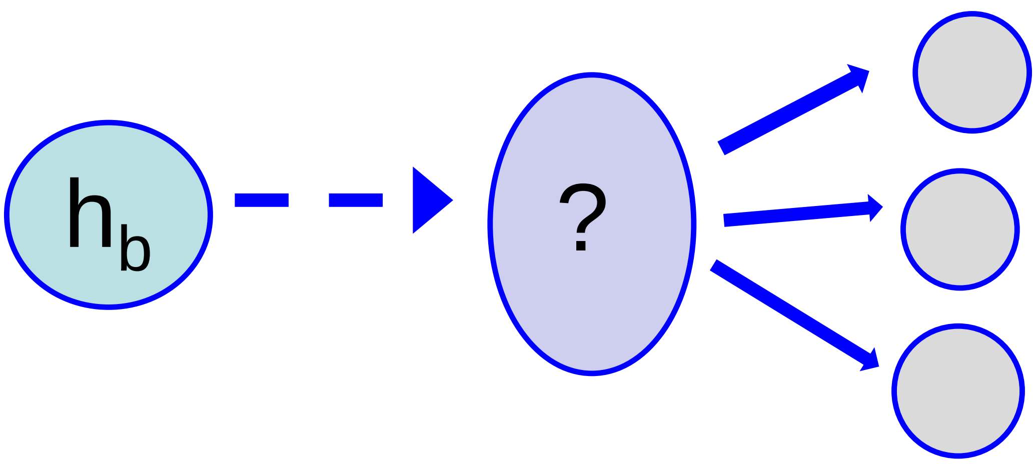


Hadron spectroscopy with b-hadrons

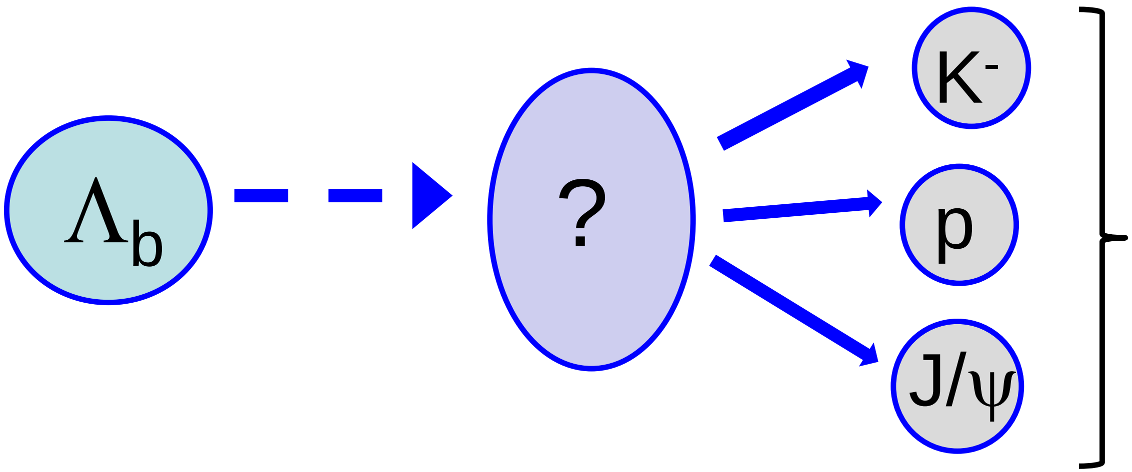


Final state = complex hadronic system

Hadronic states:
Invariant masses
Angular distributions

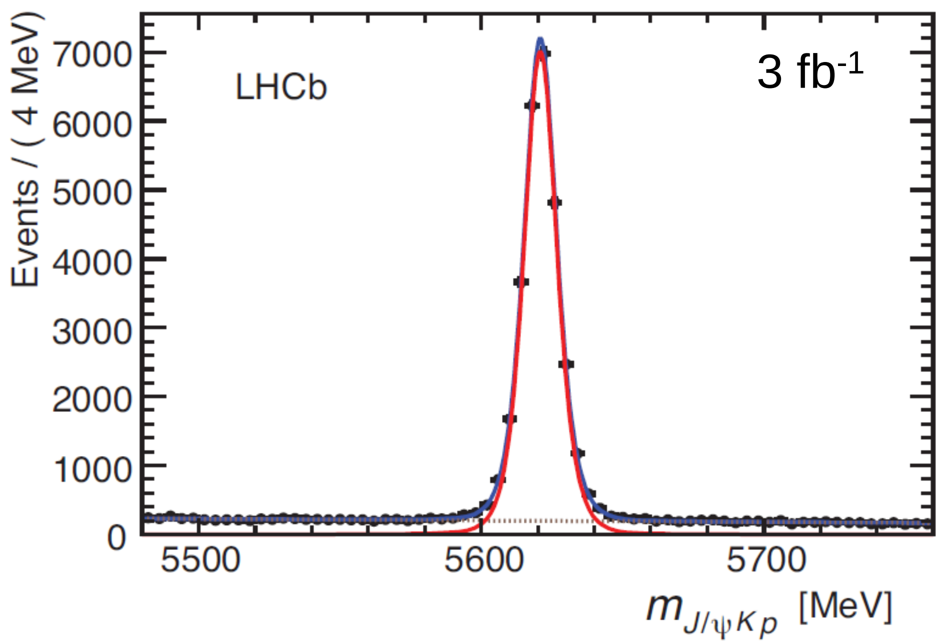


Λ_b decays



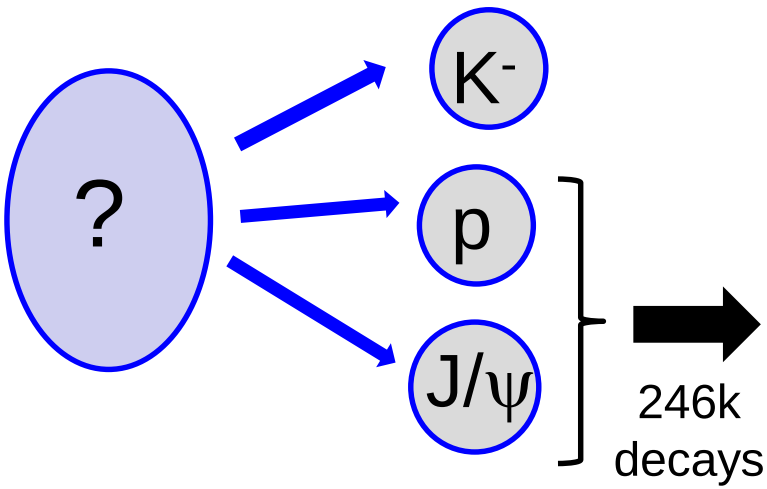
First observation of decay by LHCb

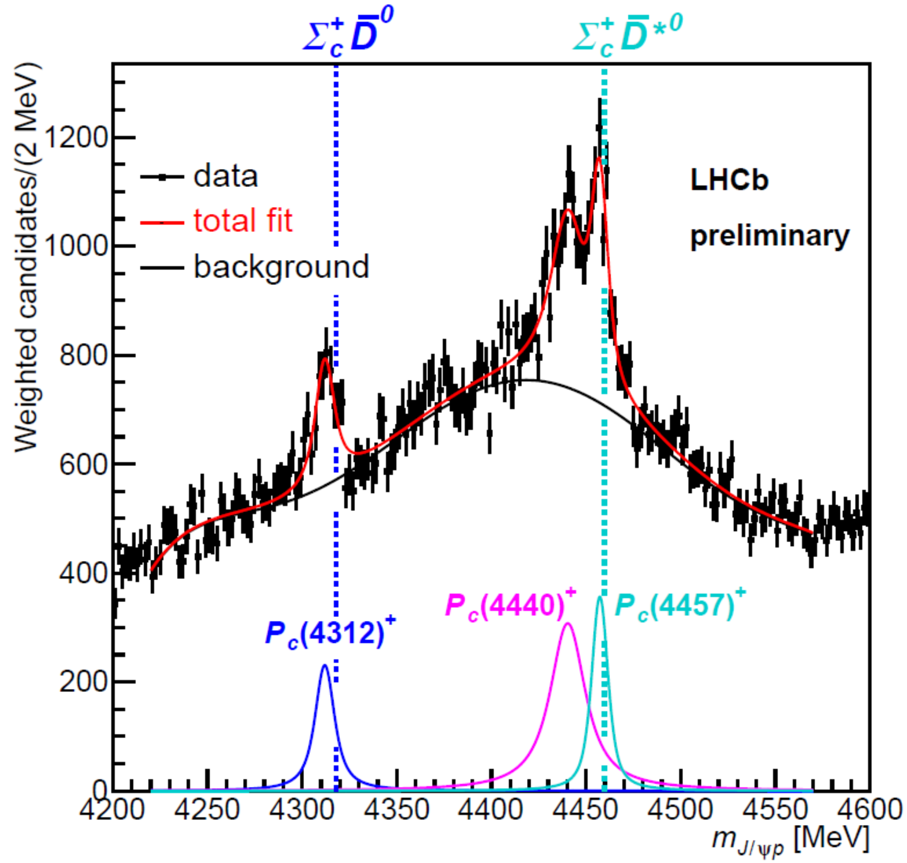
PRL 115, 07201, arXiv:1507.03414

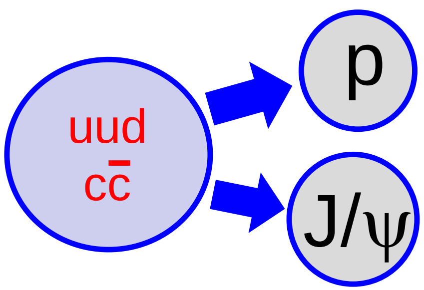


New resonances – Pentaquarks?

Phys. Rev. Lett.122 (2019) 222001
(Run 1+2).







Strongly bound pentaquark?
Molecular "pentaquarks" favored.

Pentaquark analysis w/ 10× statistic:

- Earlier reported Pc(4450)+ structure is resolved at 5.4σ into new narrow states: Pc(4440) and Pc(4457).
- New state Pc(4312)+ discovered. 7.3σ.
- No sensitivity to broad P_c(4380).

Physics with b-Hadrons

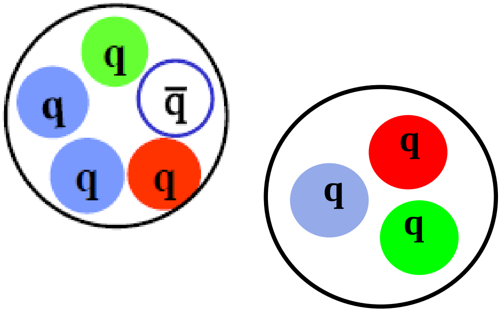
High production rates at LHC / LHCb allow
precision measurements of b-hadrons

Test of quantum-corrections

Test physics at high scales:

- many measurements confirm Standard Model
- Significant "tensions" in $b \to s\ \mu\mu$ and in $B \to D^* \tau\nu$

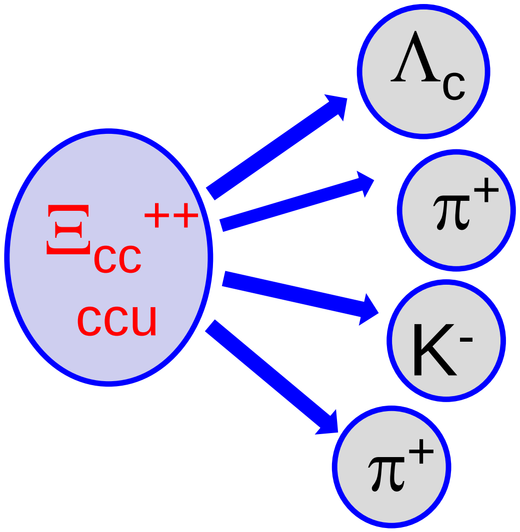
Hadron spectroscopy



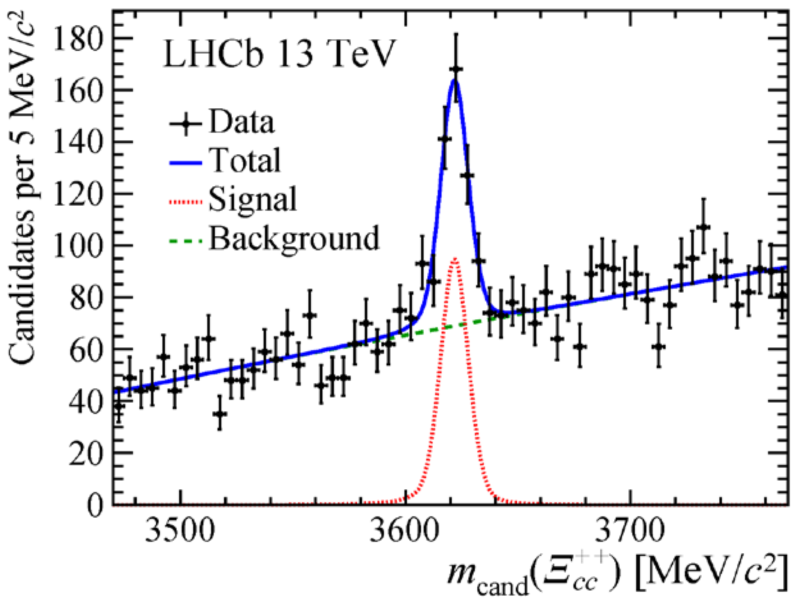
QCD at low scales:
New „conventional“ and „exotic“ states. Interpretation still open.

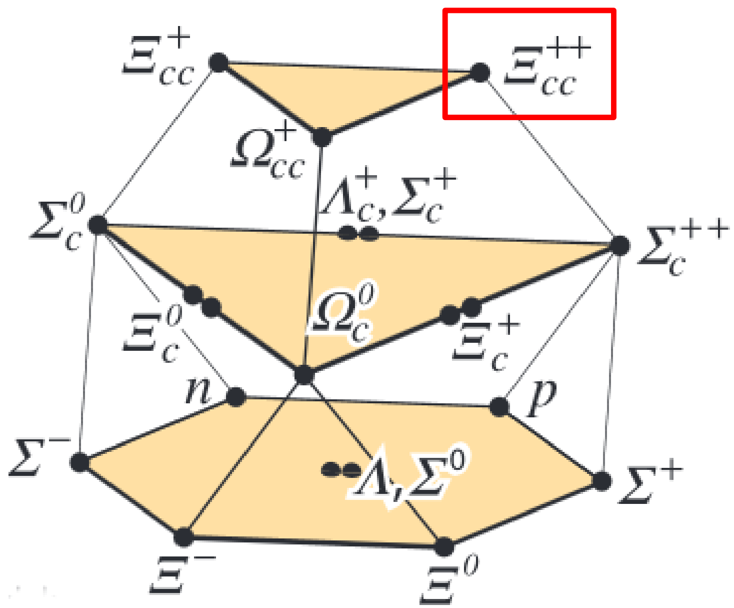
Future: upgraded LHCb in 2021, Belle-II started in 2018

Observation of doubly charmed baryon



arXiv:1710.04921





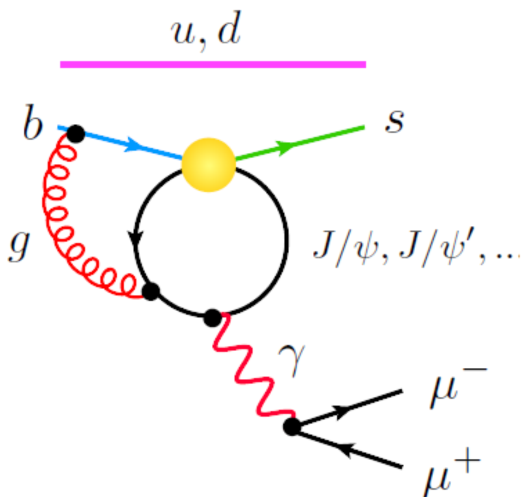
$m(\Xi_{cc}^{++}) = 3621.40 \pm 0.78$ MeV/c^2

Lattice QCD: *arXiv:1704.02647*

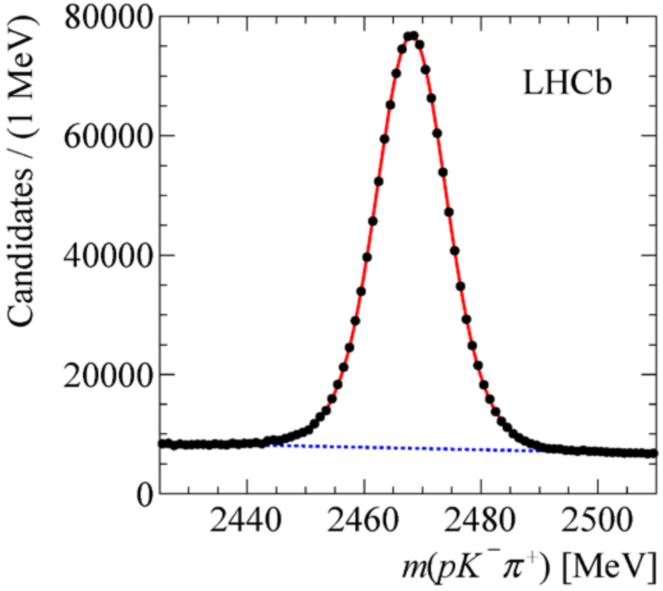
$m(\Xi_{cc}^{++}) = 3606 \pm 14$ MeV/c^2

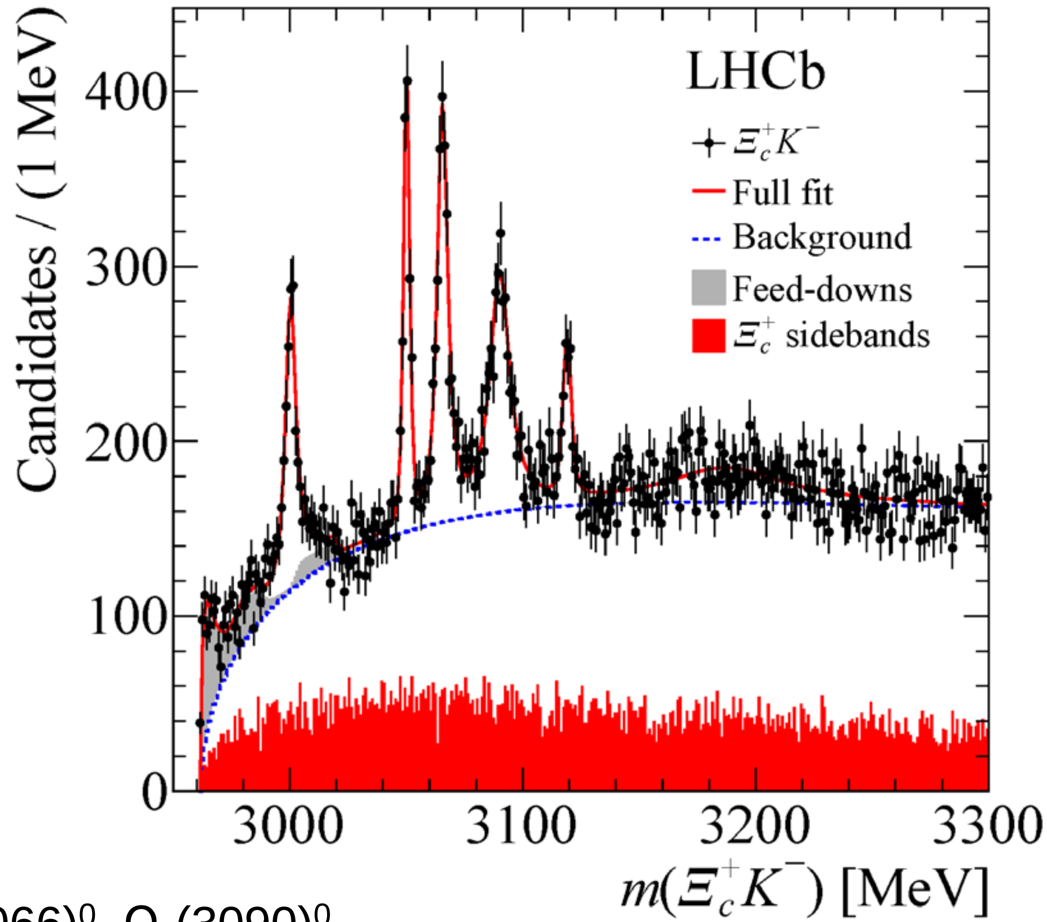
Interpretation

Underestimation of cc-loop?



However this should leave the ratios R_K and R_{K^*} unaffected.





$\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$ and $\Omega_c(3119)^0$

Beauty- und Charm-Physik

- LHC / LHCb erlauben einmalige Präzisionsmessungen im B- und D-System
- Vielzahl von “Loop”-Observablen getestet: Mit Standardmodell verträglich („Tensions“).

  Mehr: Plenar-Vortrag, M.Gersabeck, Di, 08:30

- Messungen alle statistisch limitiert. Mehr Daten um B- und D-Potenzial zu nutzen:
  - Run-2 + LHCb plant Detektor-Upgrade in 2018
  - Belle-2 an Super-B-Fabrik in Japan startet 2016
    s.a. Plenar-Vortrag, S.Lange, Fr, 09:10

Gefördert im Rahmen der BMBF Verbundforschung

Bundesministerium für Bildung und Forschung

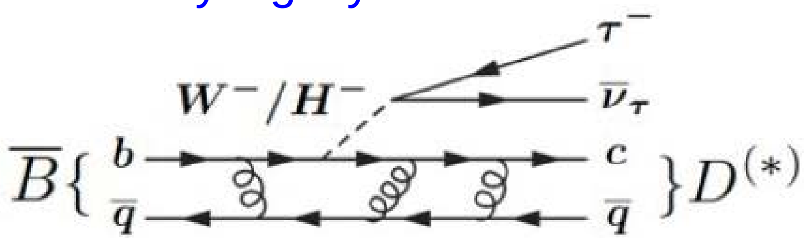
Other Hints for LFV

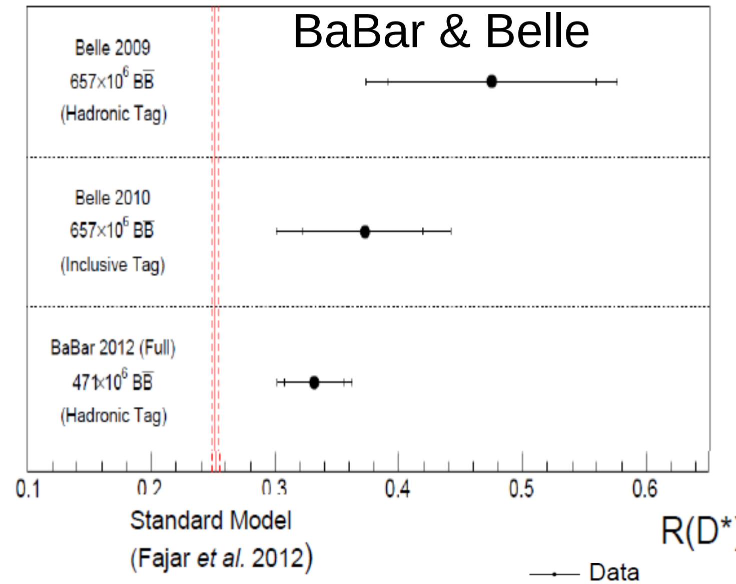
PRL 115 (2015) 111803

$$R(D^*) \equiv \mathcal{B}(B\to D^*\tau\nu) \,/\, \mathcal{B}(B\to D^*\mu\nu)$$

$B\to D^*\tau\nu$:

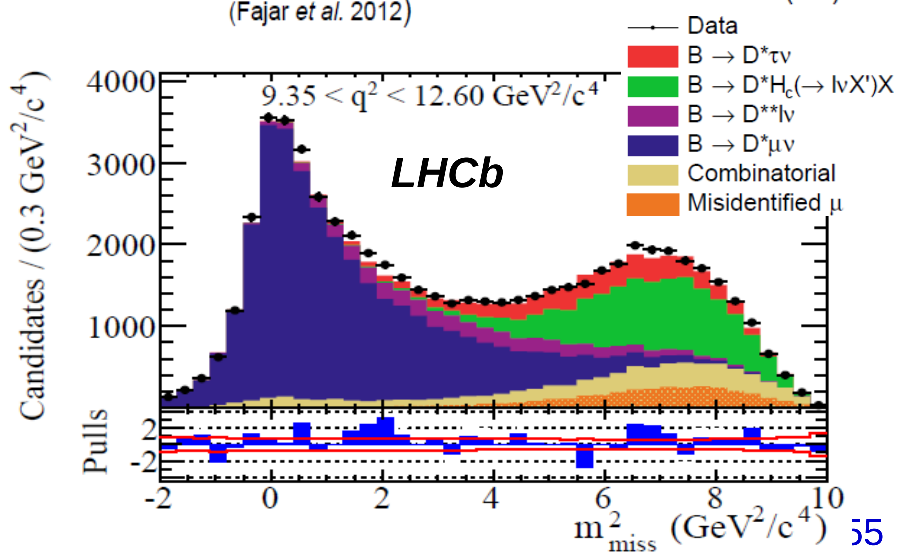
- Tree decay, not rare, only difficult
- sensitivity to possible charged Higgs
- *B*-factory legacy





Was thought to be impossible at LHCb (cannot reconstructing full event):

- Reconstruct $\tau\to\mu\nu\nu$
- disentangle signal from $B^0\to D^*\mu\nu$ and other backgrounds by fitting E_μ^* and m^{*2}_{miss} (rest frame of B) in bins of q^2



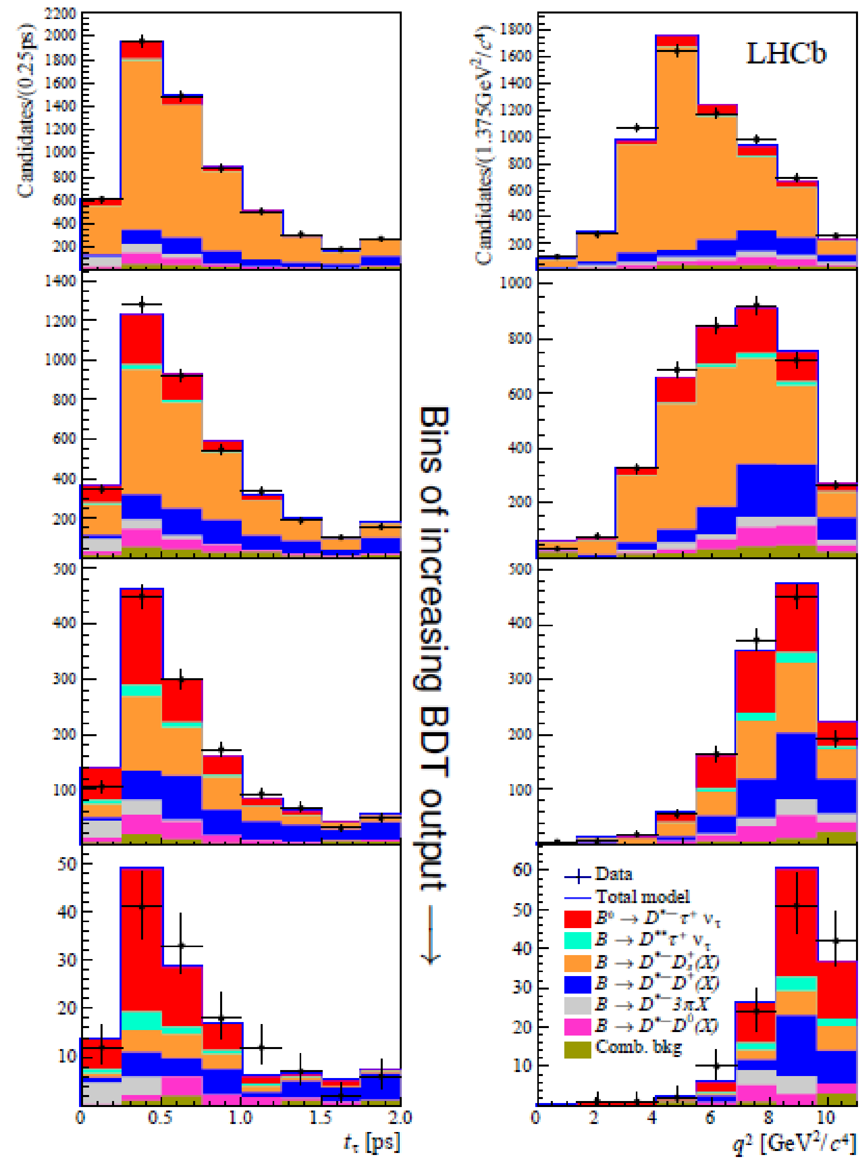
$R(D^*)$ hadronic ($\tau \to 3\pi\nu_\tau$) [arXiv:1708.08856]

- $N(B^0 \to D^{*-}\tau^+\nu_\tau)$ from 3D binned fit on BDT output, τ decay time and q^2
- Templates extracted from simulation and data control samples
- $N(B^0 \to D^{*-}\tau^+\nu_\tau) = 1300 \pm 85$

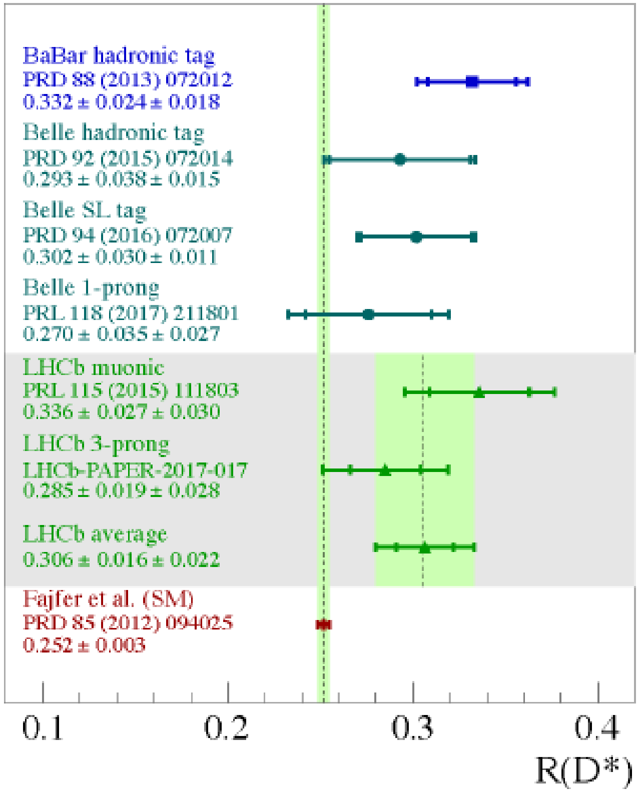
$$R(D^*) = 0.285 \pm 0.019(\mathrm{stat}) \pm 0.025(\mathrm{syst}) \pm 0.015(\mathrm{ext})$$

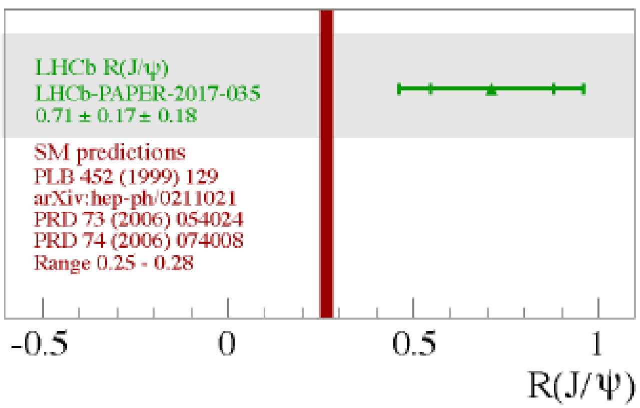
1.0σ above SM

- Dominant systematics: size of simulation samples and external BR

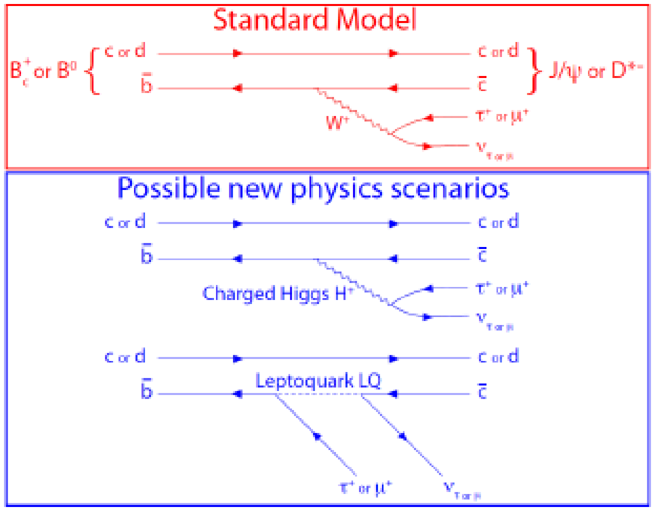


R_{D^*}





ALL $R(D^*)$ and $R(J/\psi)$ measurements lie ABOVE the SM expectations!



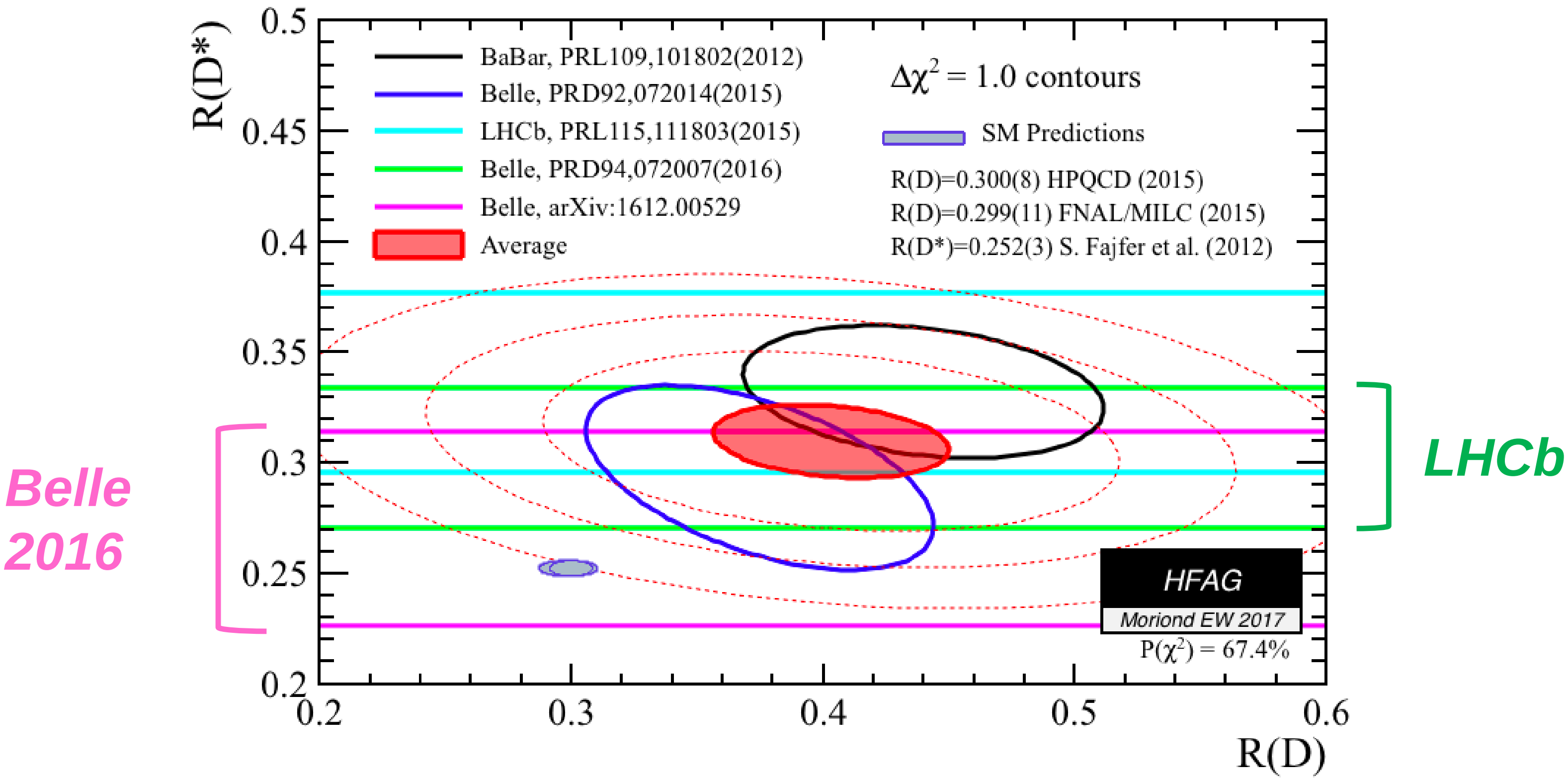
$R(D^*) \equiv \mathcal{B}(B \to D^*\tau\nu)\ /\ \mathcal{B}(B \to D^*\mu\nu)$

PRL 115 (2015) 111803

+2.1σ above SM

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

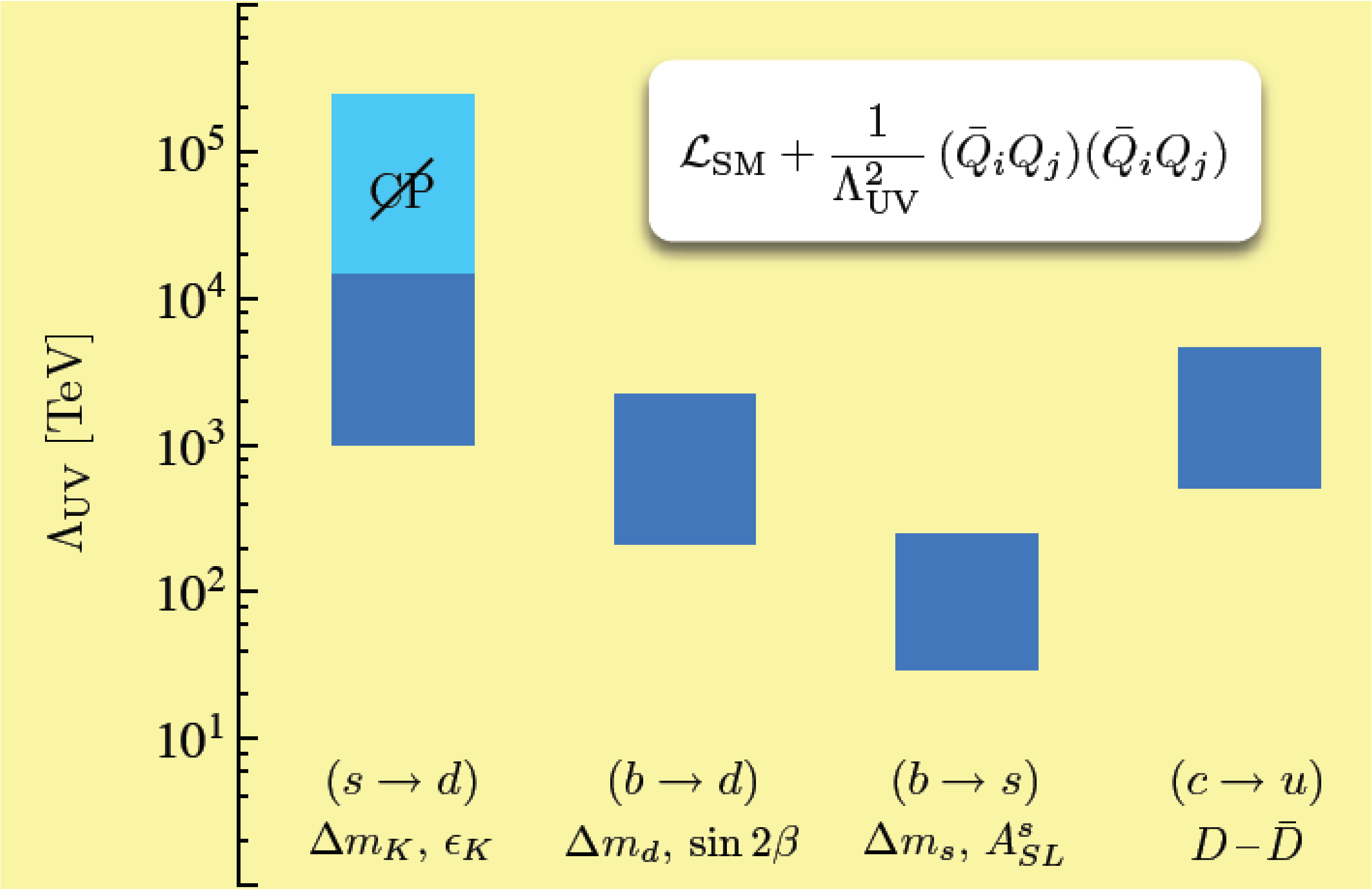
Systematics dominated by model uncertainties.



- New HFAG average 3.9σ away from SM prediction (0.252±0.003).
- New measurements including *R(D*)* w/ *τ→πππν* will come soon

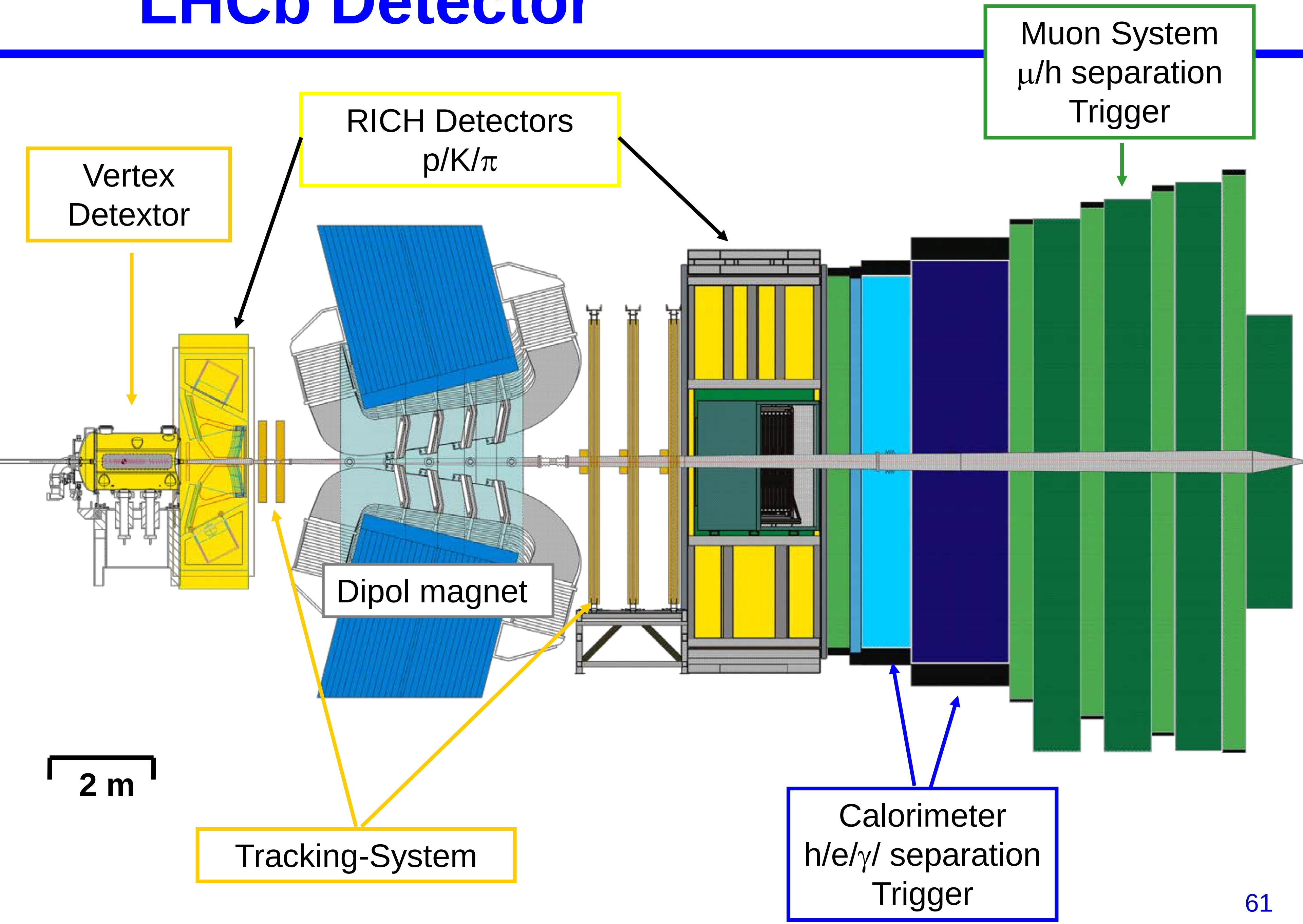
Probing New Physics

Transparency by M.Neubert (EPS 2011)

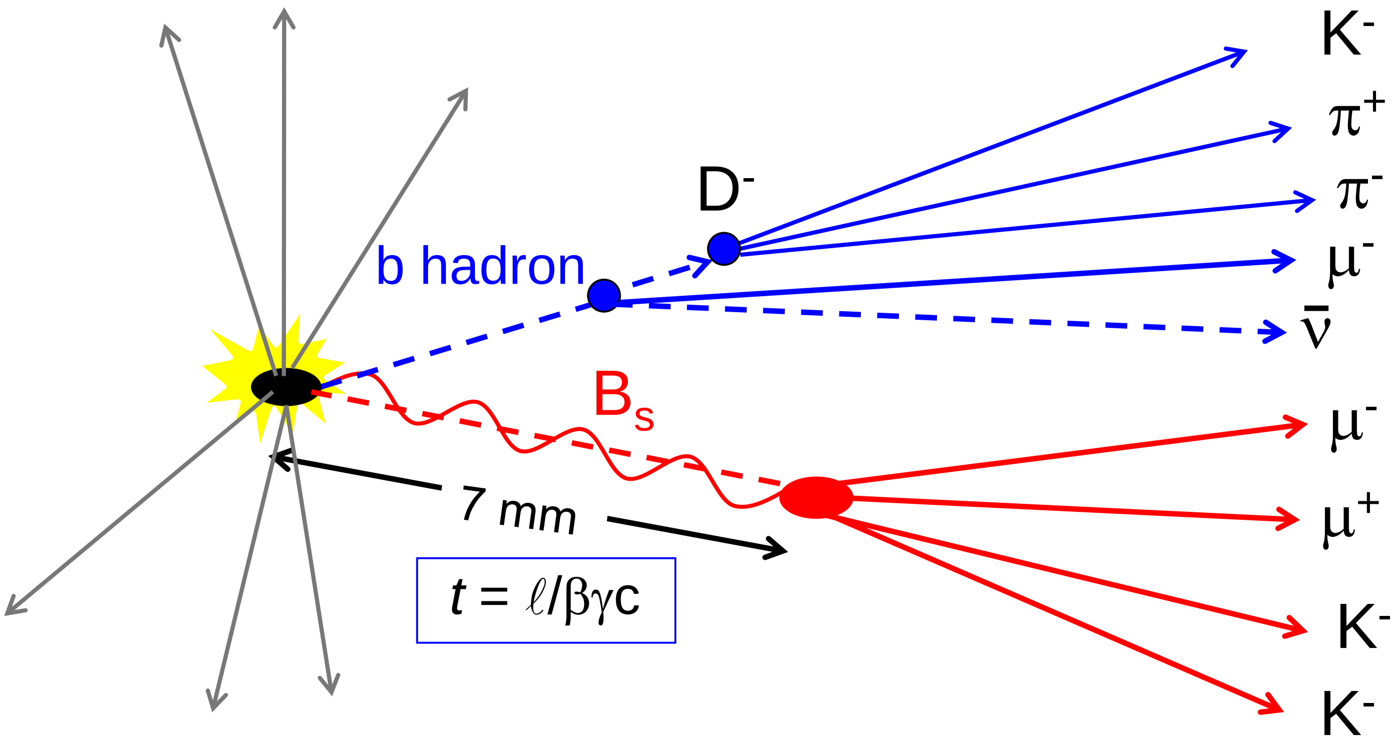


Generic bounds without a flavor symmetry

LHCb Detector



Typical $b\bar{b}$ event



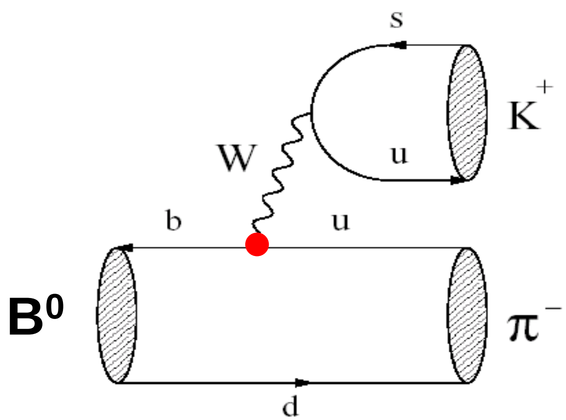
Detector requirements:

- excellent vertex reconstruction
- excellent momentum and mass resolution
- excellent particle identification (π/K/p and μ)

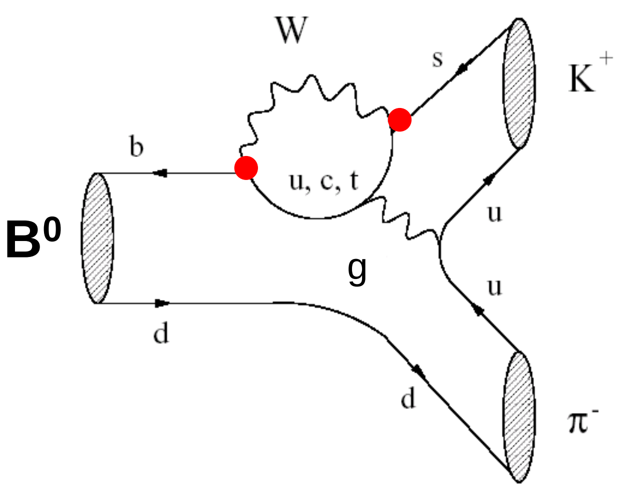
CP Violation

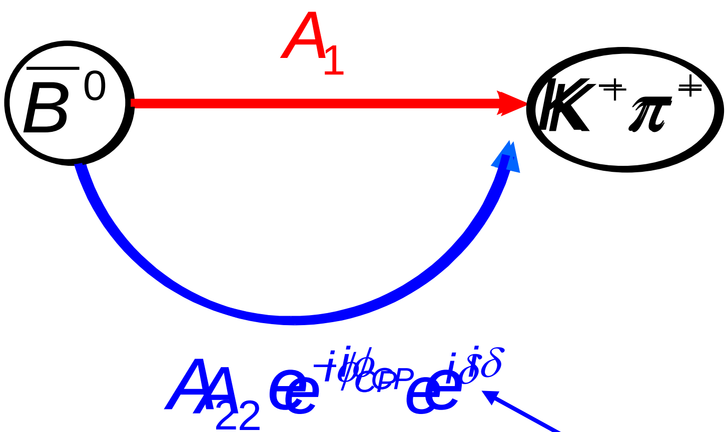
Direct CP Violation

Tree



Penguin





Strong phase: difficult to predict

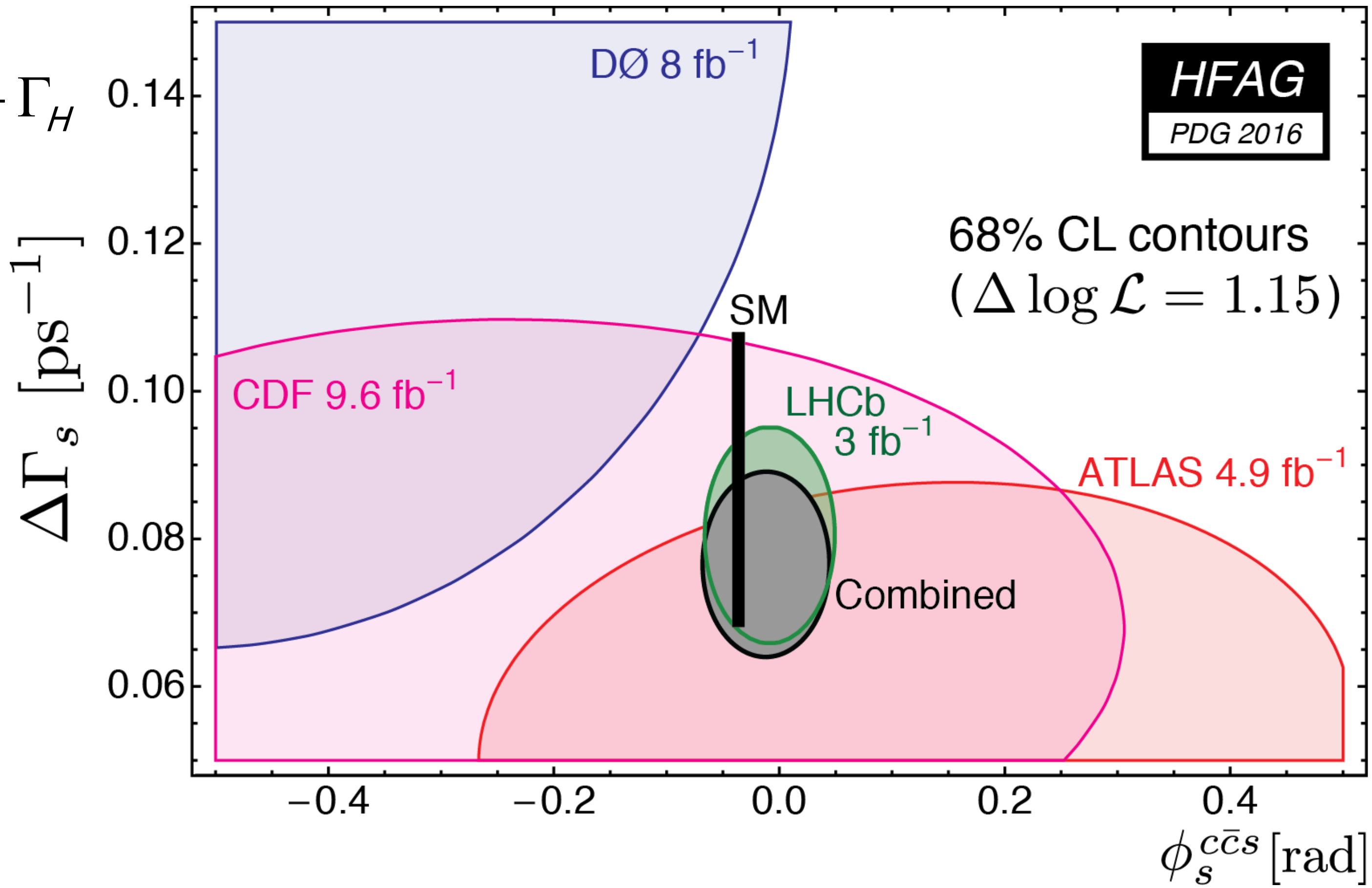
$$\boxed{A_{CP}(B \to f) = \frac{\Gamma(\overline{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\overline{B} \to \bar{f}) + \Gamma(B \to f)} \sim \sin(\phi_{CP})\sin(\delta)}$$

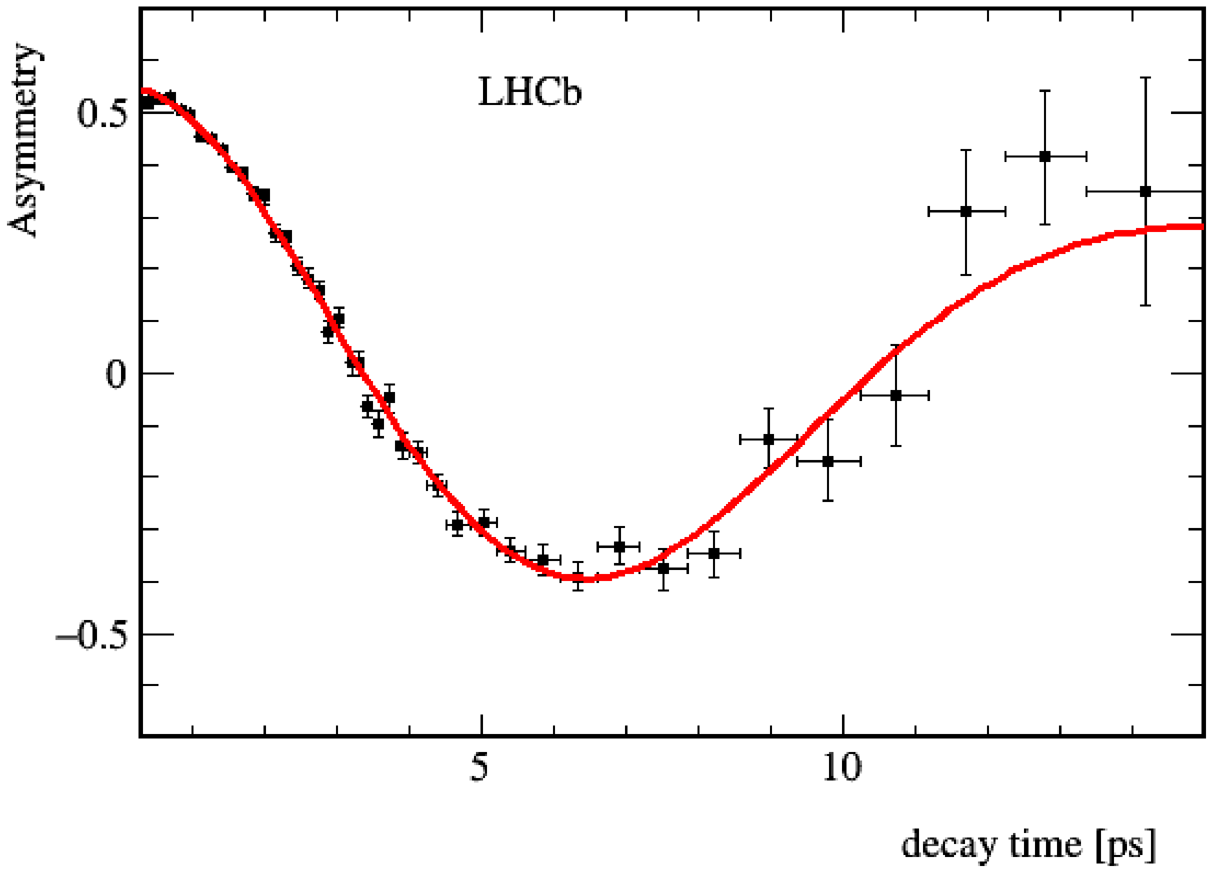
B_s – Mixing Phase

LHCb $\phi_s = 0.010 \pm 0.039$ PRL 114 (2015) 041801

www.slac.stanford.edu/xorg/hfag

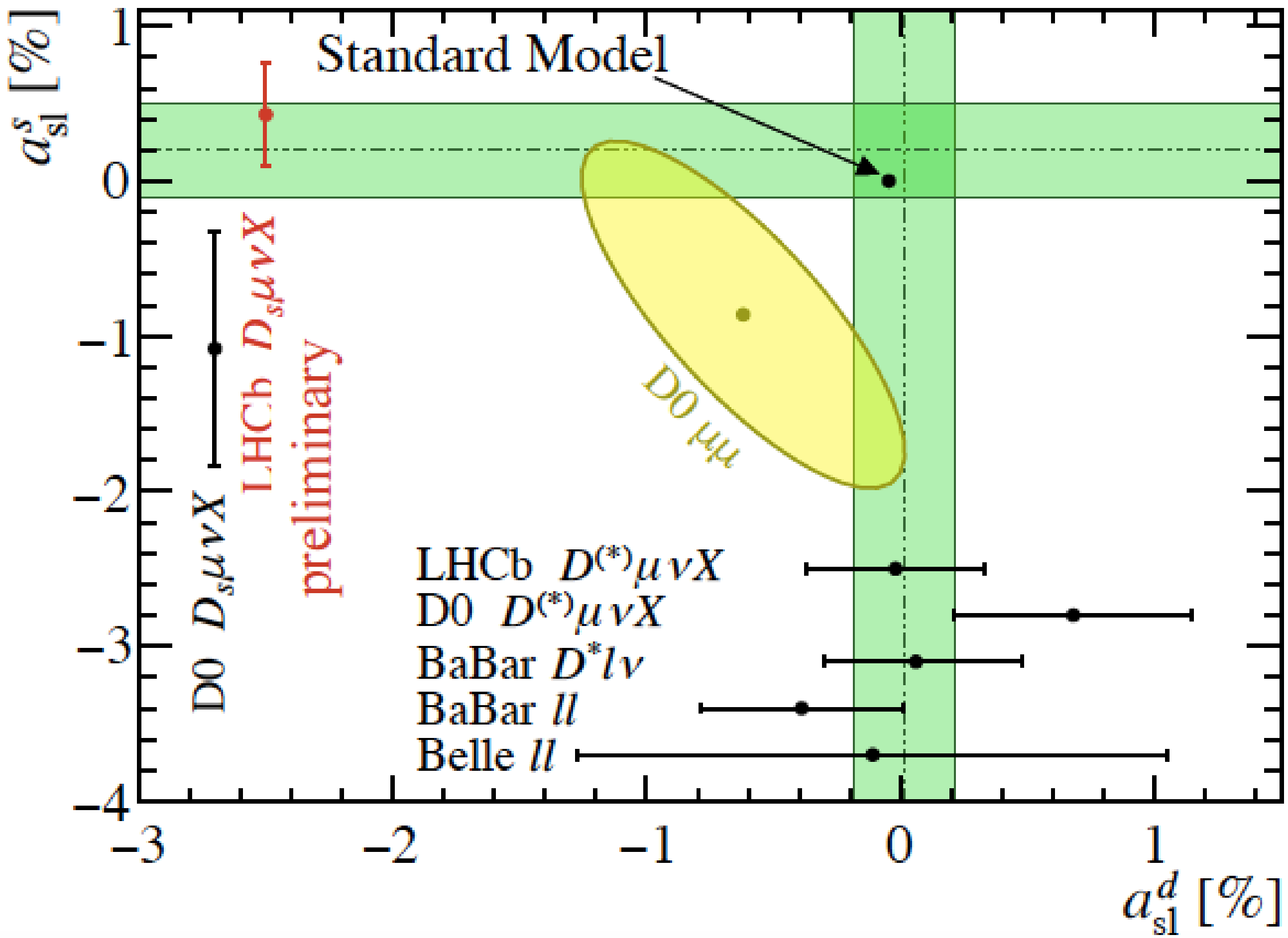
$\Delta\Gamma_s = \Gamma_L - \Gamma_H$



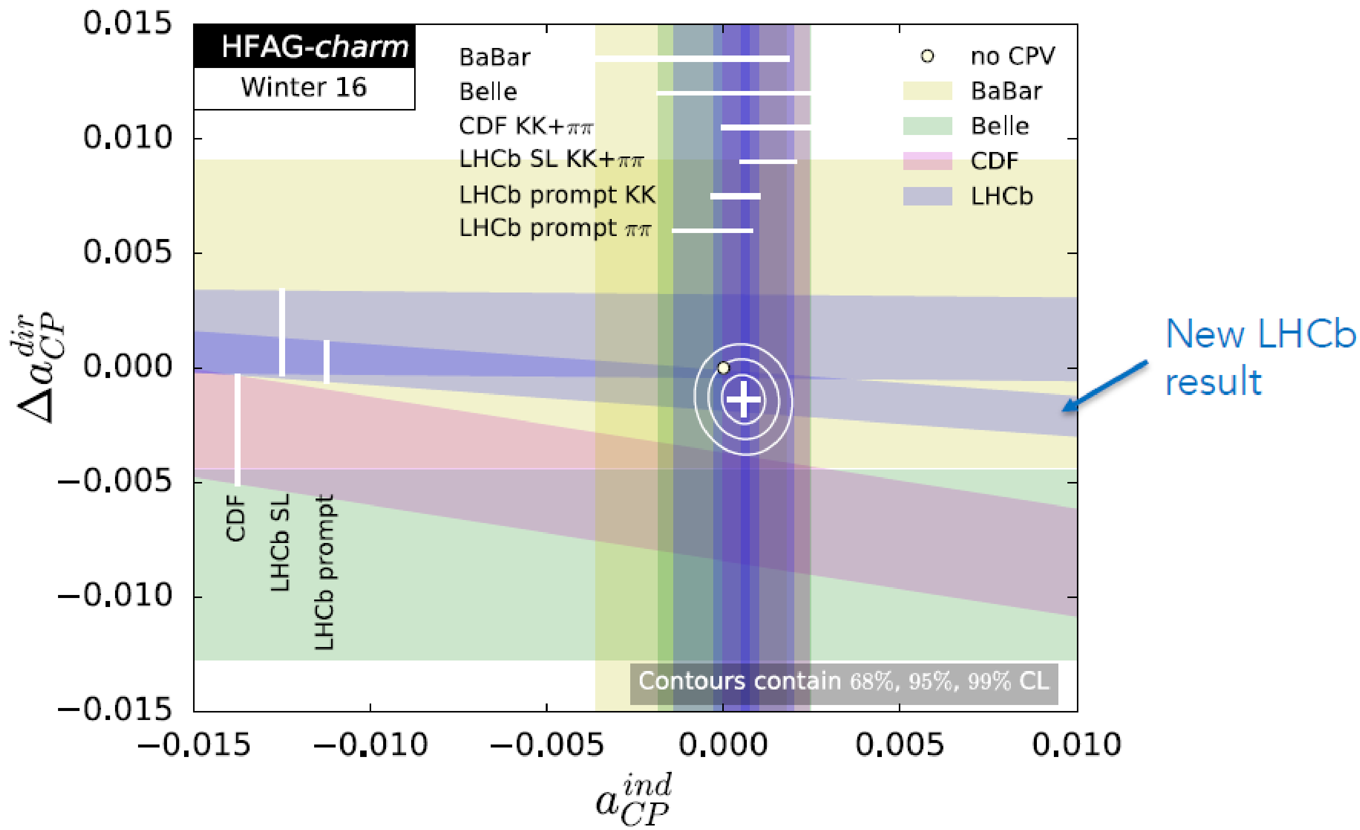


Δm_d=(505.0±2.1±1.0) ns^{-1}

CP Violation in B-Mixing



CPV in Charm

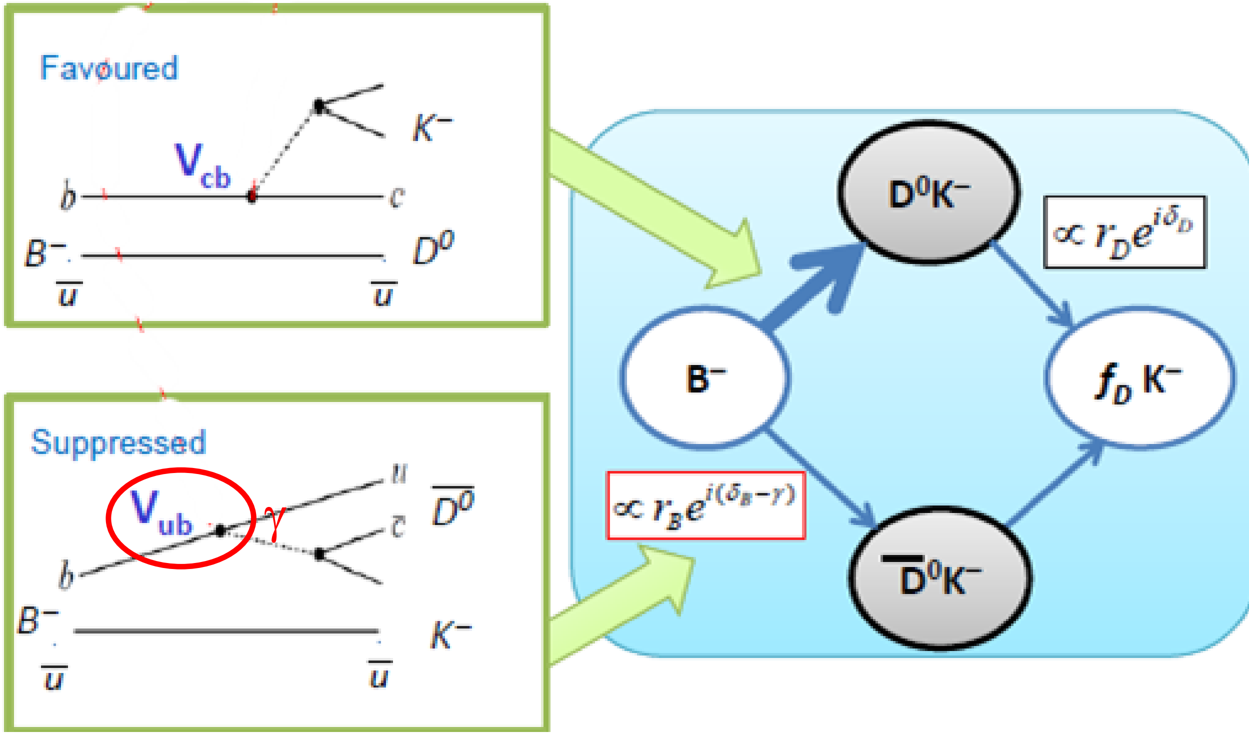


a_{CP}^{ind} = (0.056 ± 0.040)%

Δa_{CP}^{dir} = (−0.137 ± 0.070)%

Data consistent with no CP violation at 6.5 % CL

Sensitivity of B→DK decays to γ



$$r_B e^{i(\delta_B-\gamma)} \equiv \frac{A(B^- \to \overline{D}^0 K^-)}{A(B^- \to D^0 K^-)}$$

$$r_D e^{i\delta_D} \equiv \frac{A(D^0 \to f_D)}{A(\overline{D}^0 \to f_D)}$$

All unknowns from data

⇒ No hadronic uncertainties

Gronau, London, Wyler (GLW)

f_D = KK, ππ (CP state)

Atwood, Dunietz, Soni (ADS)

f_D = Kπ and πK

Giri, Grossman, Soffer, Zupan (GGSZ)

Self conjugated Dalitz modes

LHCb 1 fb^{-1}

- $B^\pm \to D(KK)\ K^\pm$
- $B^\pm \to D(\pi\pi)\ K^\pm$
- $B^\pm \to D(KK)\ \pi^\pm$
- $B^\pm \to D(\pi\pi)\ \pi^\pm$

LHCb 1 fb^{-1}

- $B^\pm \to D(\pi^+K^-)\ K^\pm$
- $B^\pm \to D(K^+\pi^-)\ K^\pm$
- $B^\pm \to D(\pi^+K^-)\ \pi^\pm$
- $B^\pm \to D(K^+\pi^-)\ \pi^\pm$

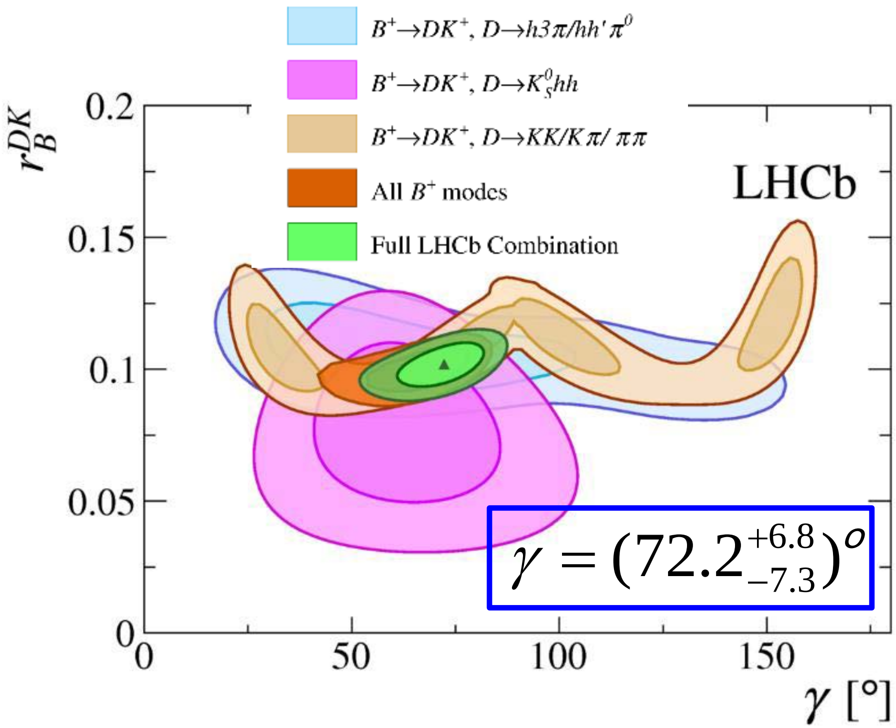
LHCb 1 fb^{-1} + 2 fb^{-1}

Combination of γ (B→DK)

JHEP 12 (2016) 087

B decay	D decay	Method
$B^+ \to Dh^+$	$D \to h^+h^-$	GLW/ADS
$B^+ \to Dh^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS
$B^+ \to Dh^+$	$D \to h^+h^-\pi^0$	GLW/ADS
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ
$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	GLS
$B^+ \to Dh^+\pi^-\pi^+$	$D \to h^+h^-$	GLW/ADS
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	TD

time dependent



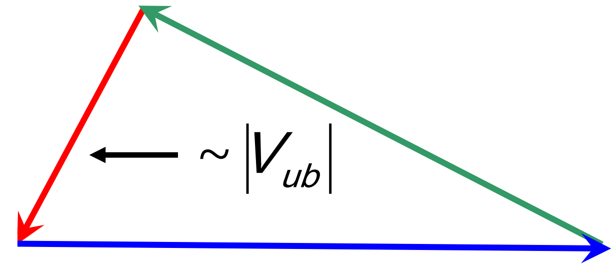
$$\gamma = (72.2^{+6.8}_{-7.3})^o$$

Agrees with BaBar and Belle and with prediction from CKM fits

BaBar	$\gamma = (69^{+17}_{-16})^o$	PRD 87, 052015 (2013)
Belle	$\gamma = (68^{+15}_{-14})^o$	arXiv:1301.2033 (2013)
Indirect	$\gamma = (65.3^{+1.0}_{-2.5})^o$	CKM Fitter 2006

Aim for 3 - 4° uncertainty after Run-2.
The LHCb-Upgrade will allow for even higher sensitivity (~1°).

Unitarity Triangle : $|V_{ub}|$



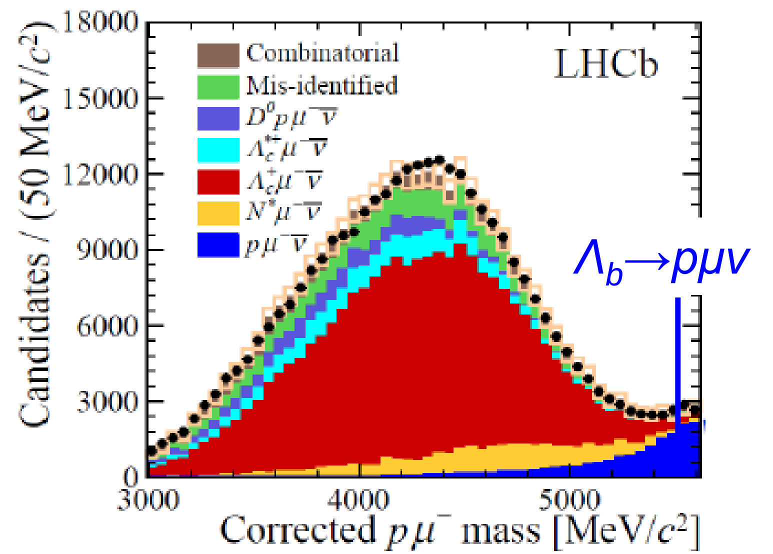
V_{ub} measurement thought impossible at LHC

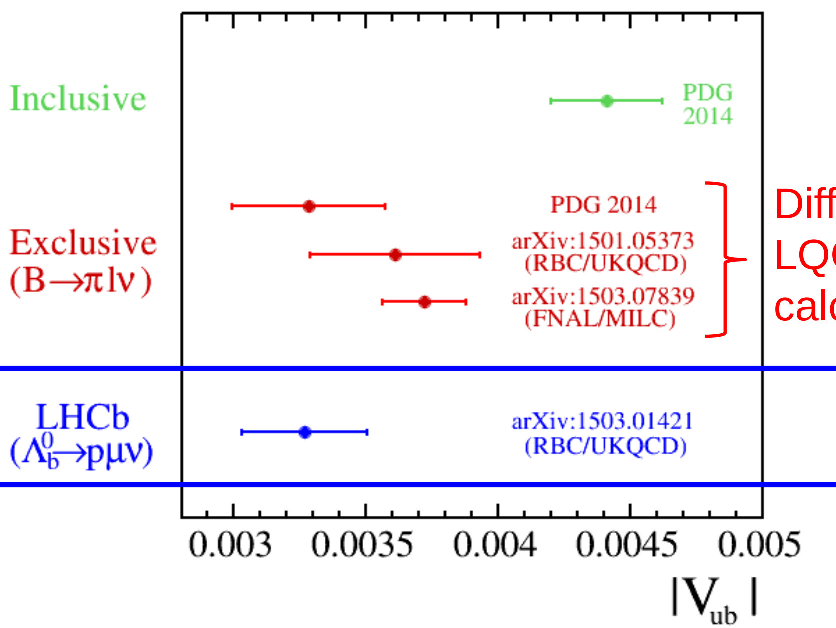
Nature Physics 10 (2015) 1038

- Use baryon decay $\Lambda_b \to p\mu\nu$, benefit from RICH & vertexing capabilities.
- Normalize to $\Lambda_b \to \Lambda_c \mu\nu$ and use lattice QCD to interpret result.

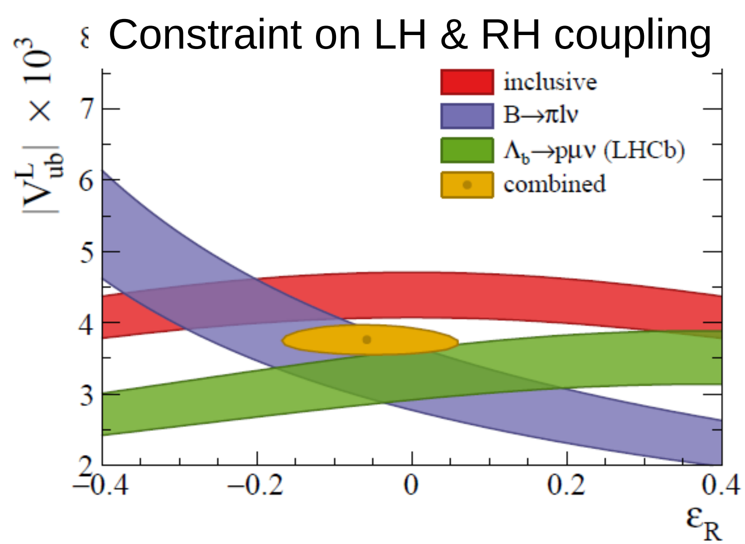
$$|V_{ub}| = (3.27 \pm 0.15 \pm 0.16 \pm 0.06) \times 10^{-3}$$

errors: exp LQCD from V_{cb}



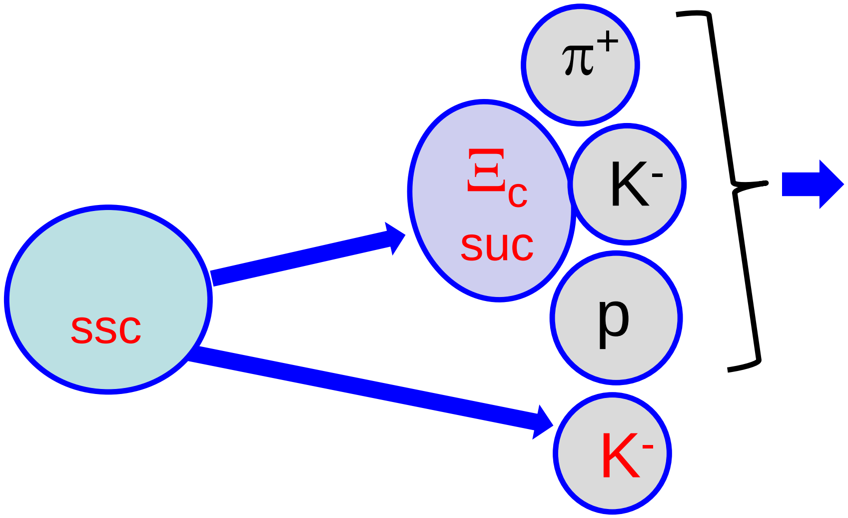


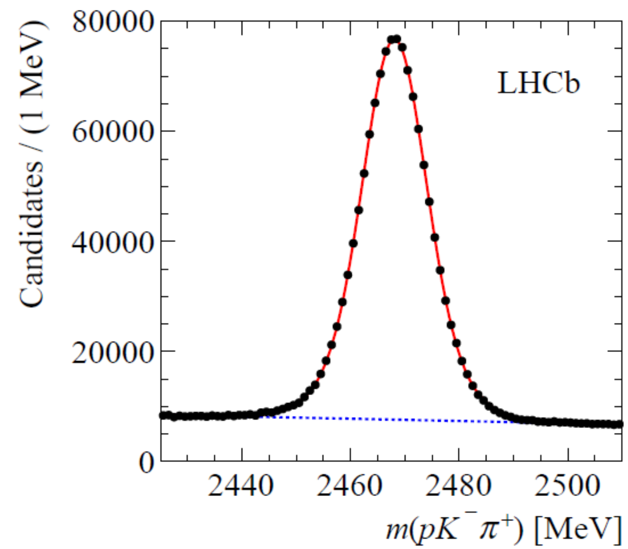
Different LQCD calculations

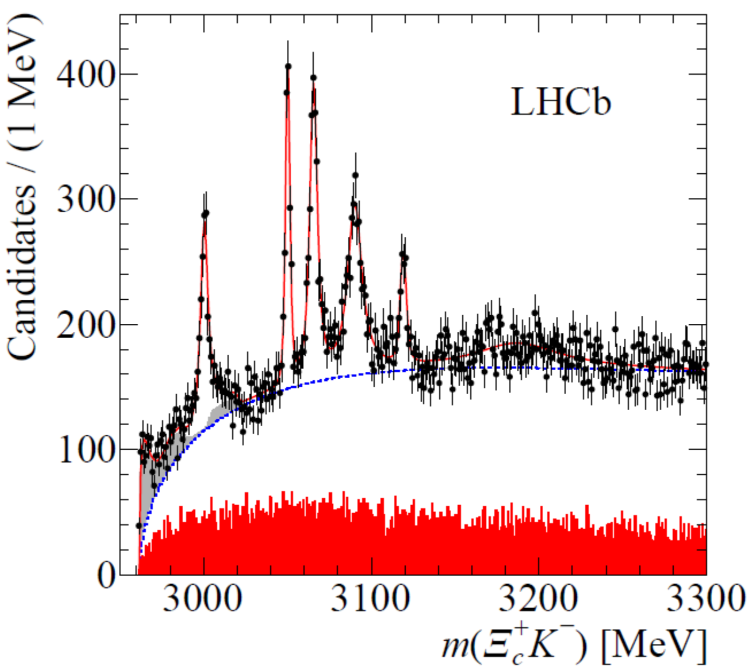


Spectroscopy

New Charmed Baryons





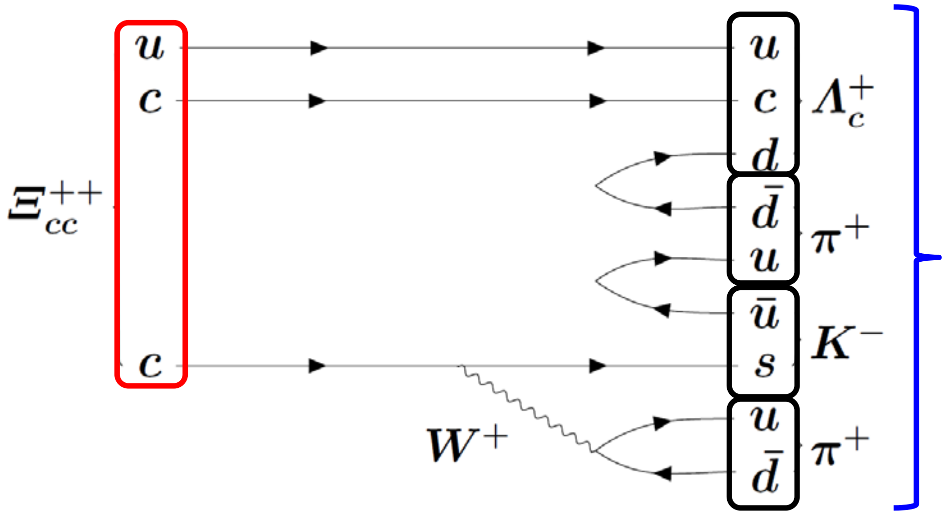


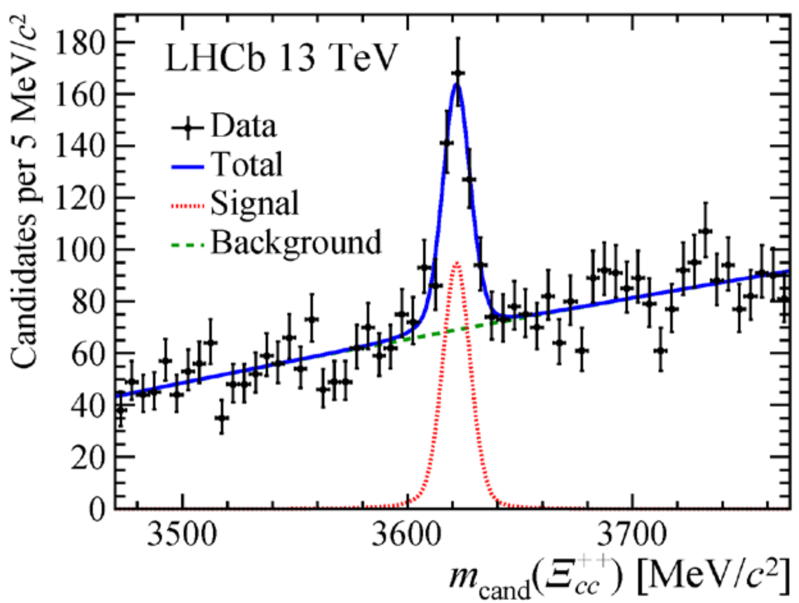
5 new excited Ω_c (ssc) states:

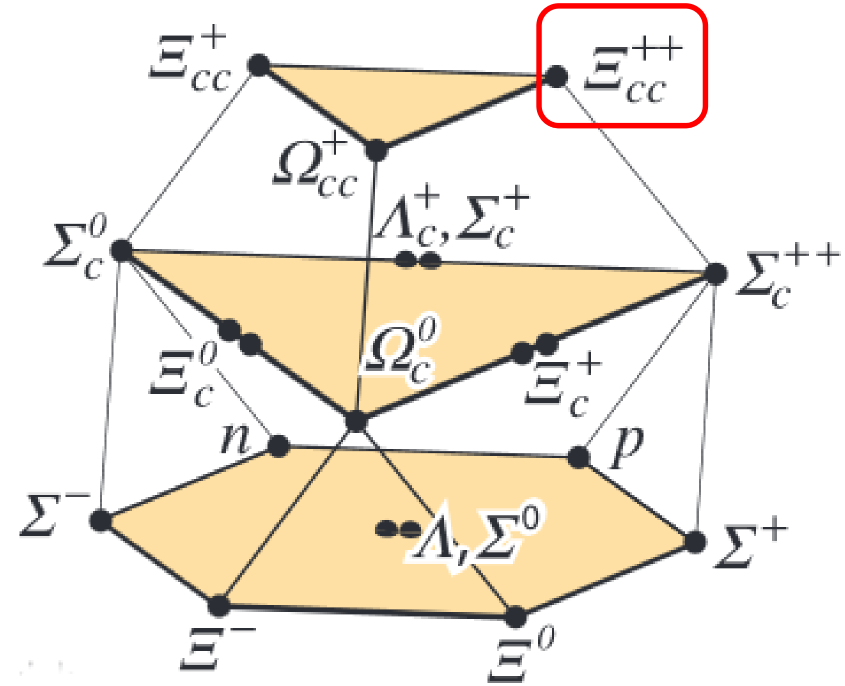
Ω_c^0 (3000), Ω_c^0(3050), Ω_c^0 (3066), Ω_c^0 (3090) and Ω_c^0 (3119)^0

Known so far Ω_c^0 (2695) ($J^p = ½^+$) and Ω_c^0 (2770) (J^P $3/2^+$)

New Doubly Charmed Baryon



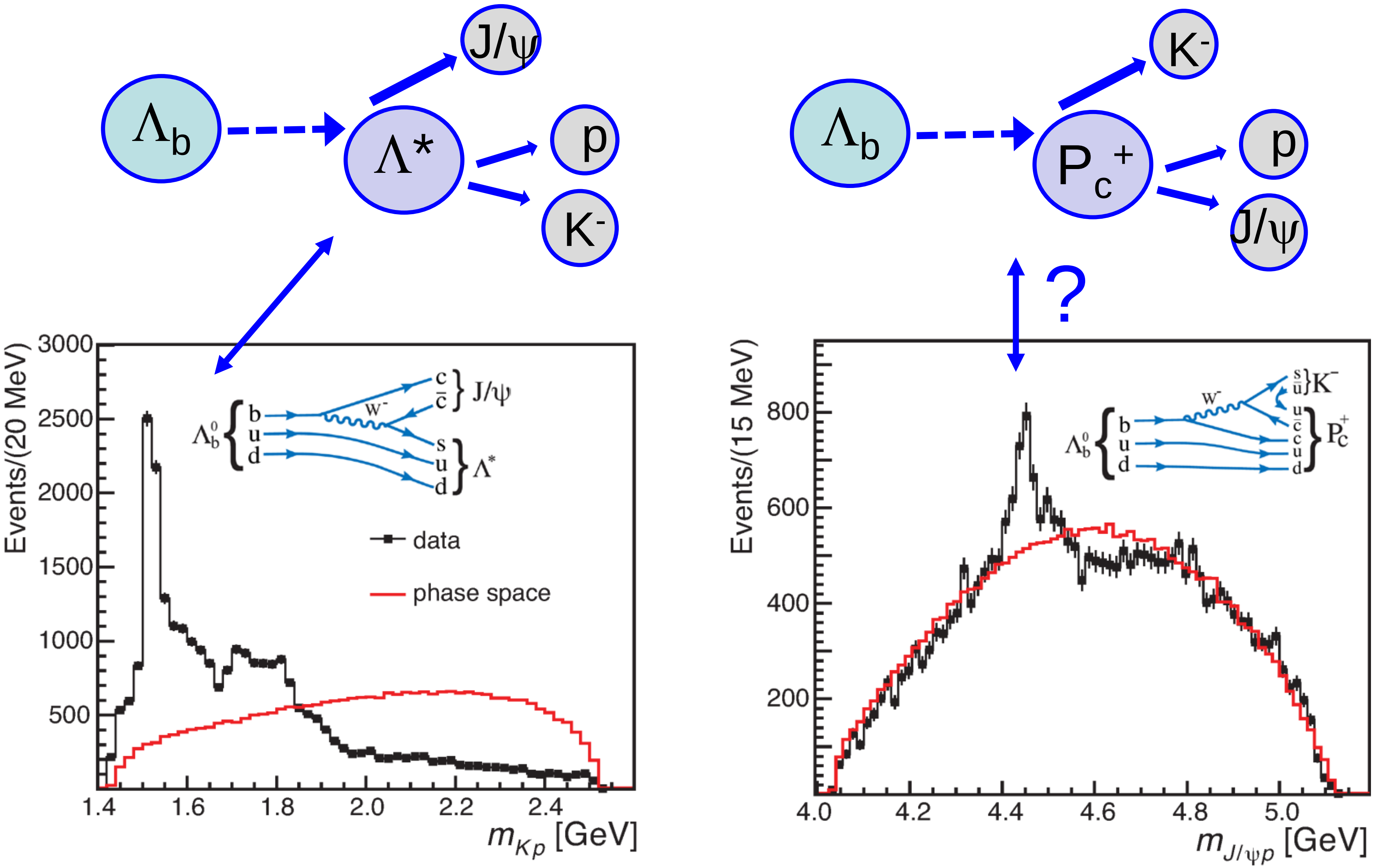




$m(\Xi_{cc}^{++})$ = 3621.40±0.72±0.27±0.14 MeV/c^2

Dalitz-Projections

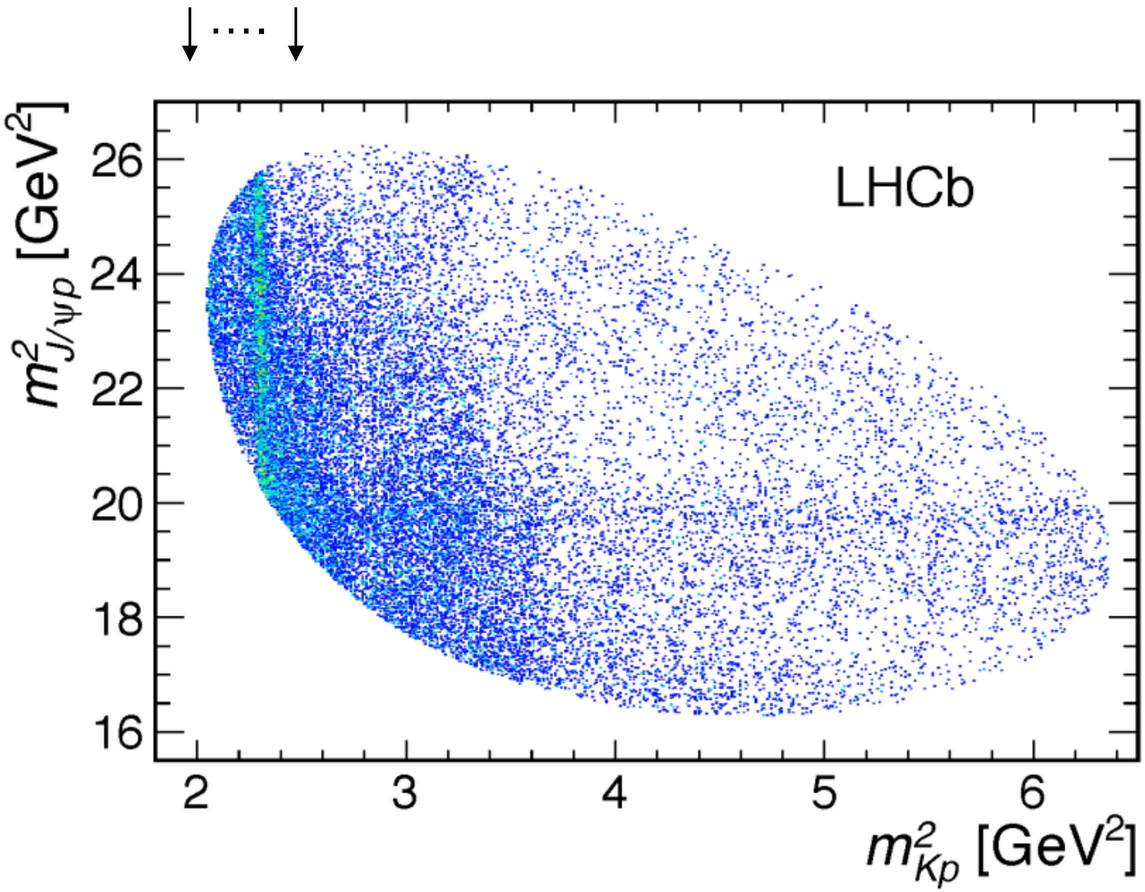
PRL 115, 07201, arXiv:1507.03414



Dalitz-Plot

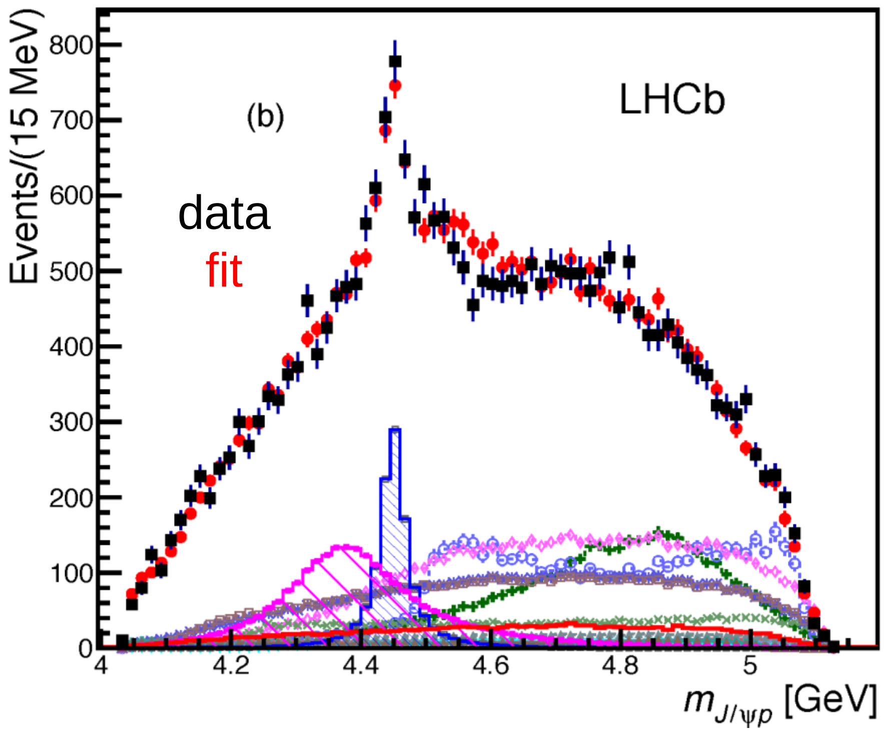
PRL 115, 07201, arXiv:1507.03414

Known Λ^*'s



Unexpected ?

Two new ($J/\psi p$)-Resonances



$J/\psi p$ spectrum cannot be described by known Λ^* amplitudes: new resonances

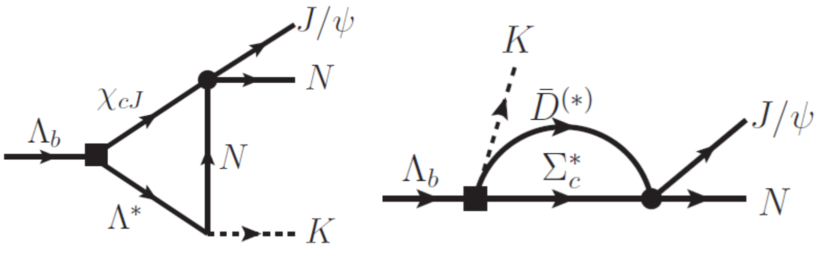
	State	Mass (MeV)	Width (MeV)
9σ	$P_c(4380)^+$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$
12σ	$P_c(4450)^+$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$

Best fit (m_{Kp} + 5 decay angles): $J^P=(3/2^-, 5/2^+)$, $J^P=(3/2^+, 5/2^-)$ and $J^P=(5/2^+, 3/2^-)$ also possible.

Possible Interpretation

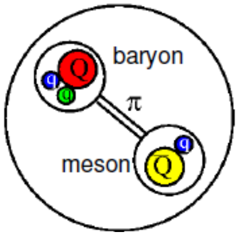
- Rescattering w/ threshold effects

  e.g. arXiv:1507.04950, 1507.05359, 1507.06552, 1507.07478



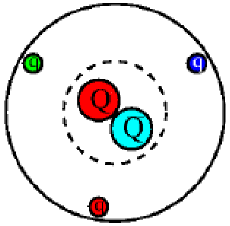
- Molecule of baryon and meson

  e.g. arXiv:1507.03717, 1507.03704, 1507.05200, 1507.04249, 1508.00924



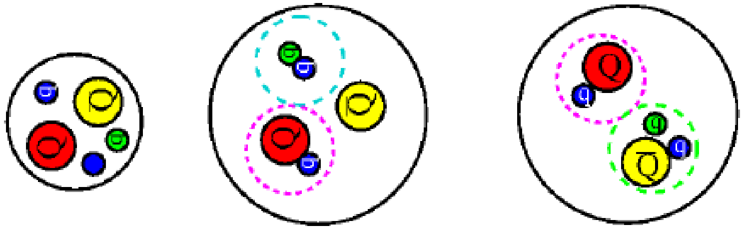
- Baryo-charmonia

  e.g. arXiv:1508.00888



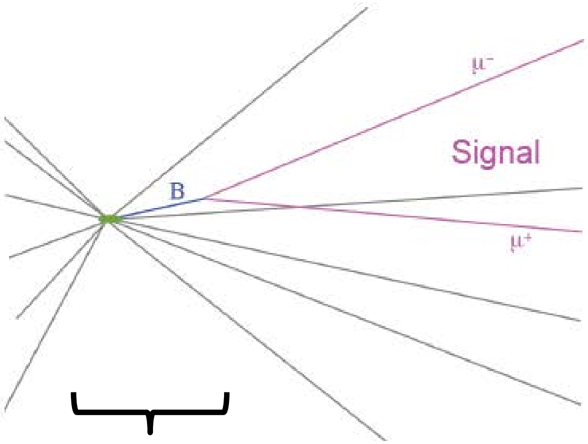
- "Strongly" bound penta-quark

  e.g. arXiv:1201.0807, 1507.04980, 1507.07652, 1508.00356, 1507.05867, 1507.08252, 1508.01468, 1508.04189

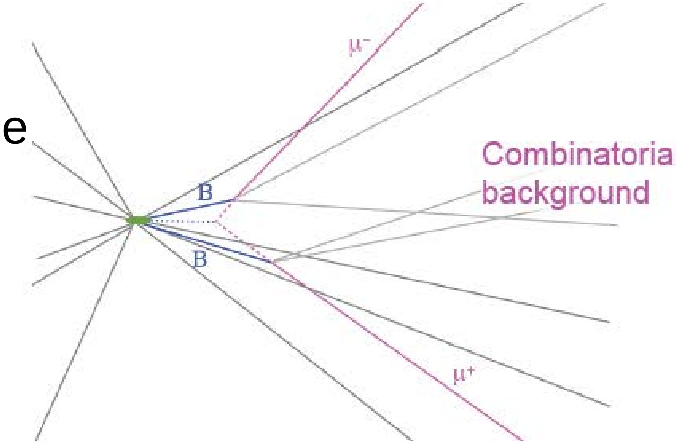


Rare decays

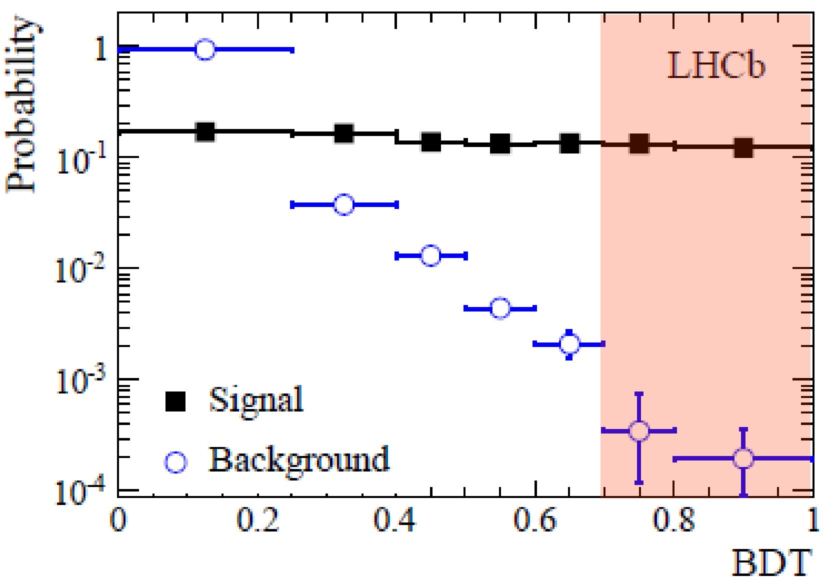
Experimental challenge B→μμ

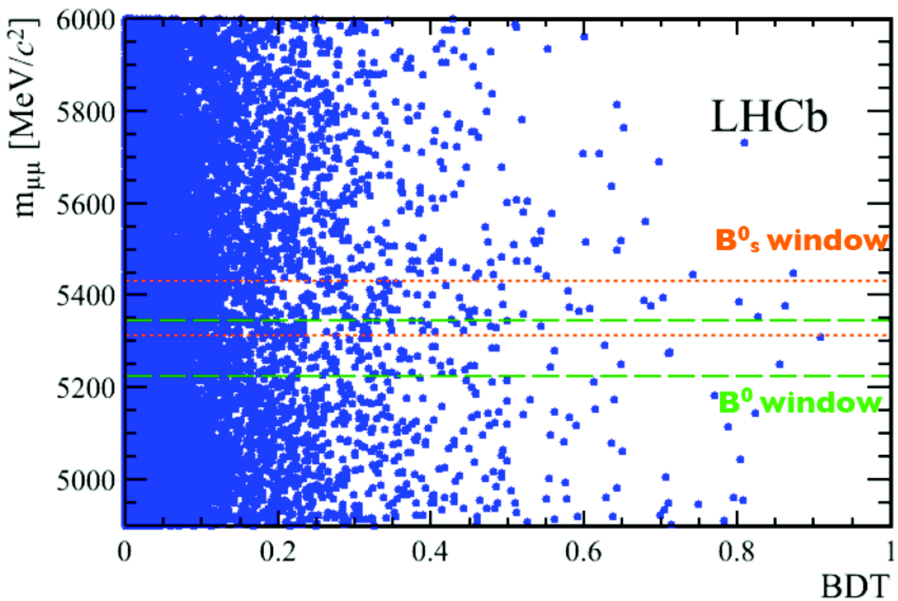


inv. Masse

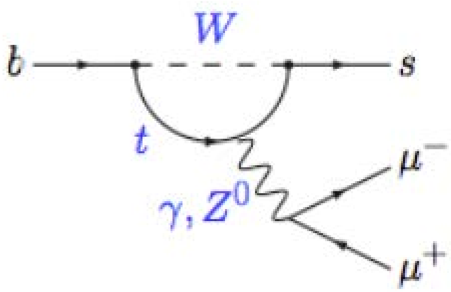


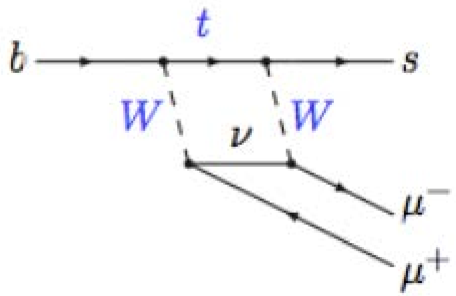
Topologie (BDT)

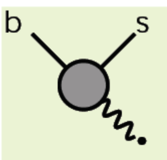




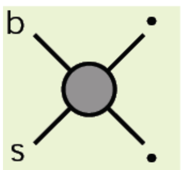
FCNC decays & Effective Field Theory







O_7



O_9 O_{10}

Standard Model:

$$\mathcal{O}_7 \sim m_b(\bar{s}_L \sigma^{\mu\nu} b_R)F_{\mu\nu}$$

$$\mathcal{O}_9 \sim (\bar{s}_L \gamma^\mu b_L)(\bar{\ell}\gamma_\mu \ell)$$

$$\mathcal{O}_{10} \sim (\bar{s}_L \gamma^\mu b_L)(\bar{\ell}\gamma_5\gamma_\mu \ell)$$

$$\mathcal{O}_{S,P} \sim (\bar{s}b)_{S,P}(\bar{\ell}\ell)_{S,P}$$

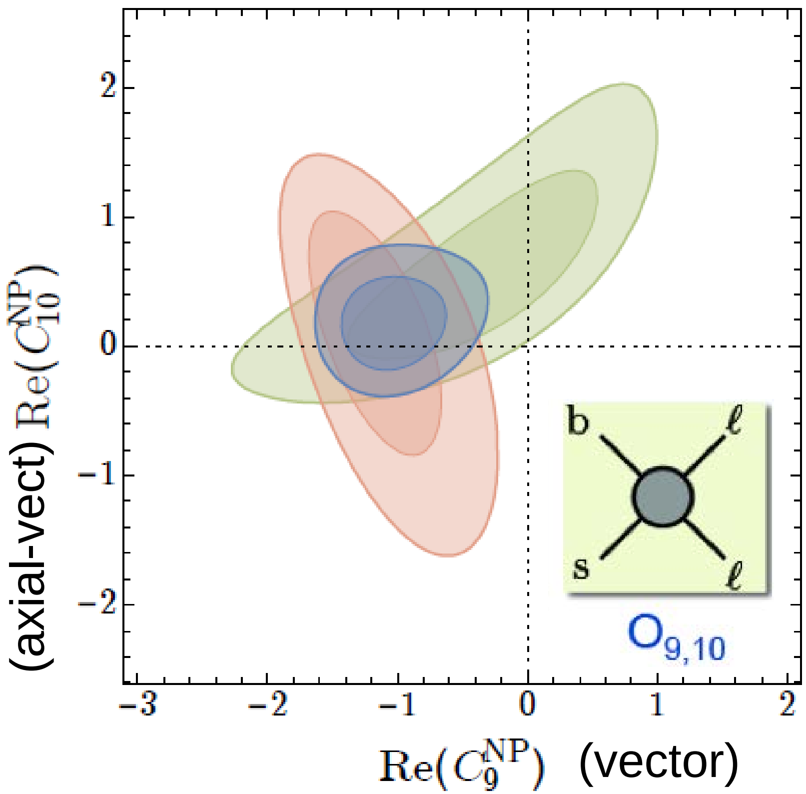
Operator product expansion

$$H = \frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum (C_i^{SM} \qquad)O_i^{SM}$$

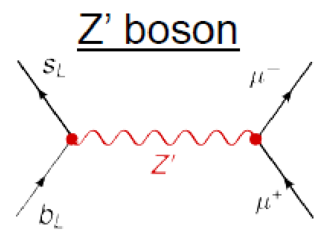
New Physics can lead to new operators with new Lorentz structure or can modify the Wilson coefficients → modifies the angular distribution

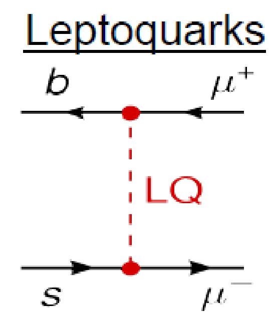
Interpretation of b→s results

Altmannshofer, Straub arXiv:1503.06199

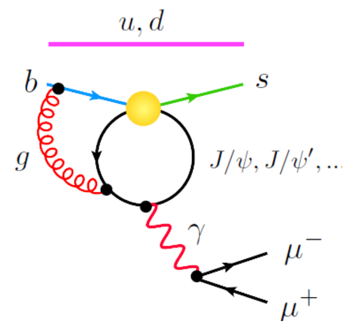


Modified vector coupling C_9 at ~4σ:



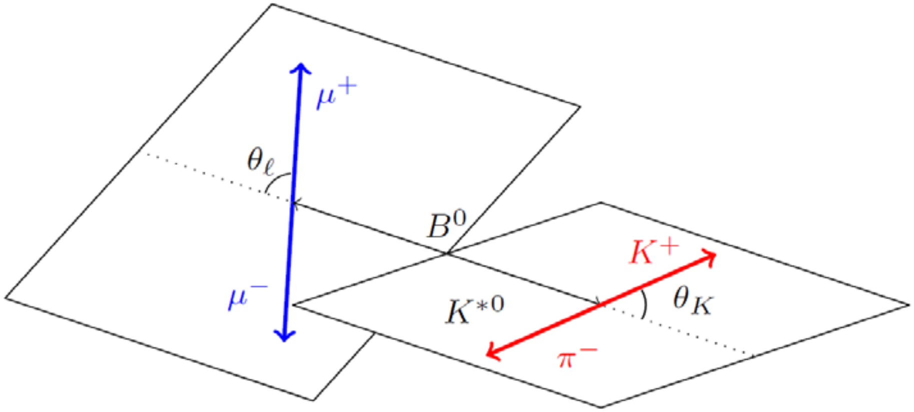


Underestimation of cc –loops:



Full angular analysis

$B^0 \to K^* (K\pi)\ \mu\mu$



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

$$\boxed{S_6^s = \frac{3}{4}A_{FB}}$$

Observables F_L and S_i are functions of Wilson coefficients.
Significant uncertainties from form-factor dependence

Different Parameterization

Different set of observables with reduced uncertainties proposed:

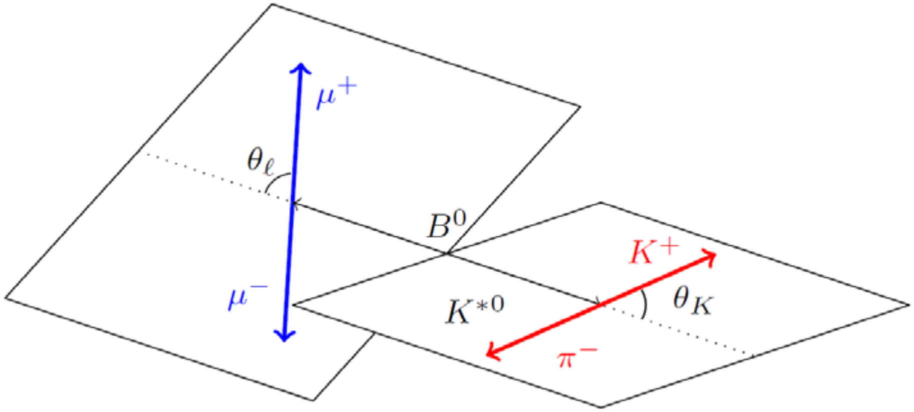
$$\boxed{A_T^{(2)} = \frac{2S_3}{(1-F_L)}} \qquad \boxed{P'_4 = \frac{S_4}{\sqrt{(1-F_L)F_L}}} \qquad P'_6 = \frac{S_7}{\sqrt{(1-F_L)F_L}}$$

$$A_T^{Re} = \frac{S_6}{(1-F_L)} \qquad P'_5 = \frac{S_5}{\sqrt{(1-F_L)F_L}} \qquad P'_8 = \frac{S_8}{\sqrt{(1-F_L)F_L}}$$

Kruger-Matias (2005), Matias et al. (2012), Egede-Matias-Hurth-Ramon-Reece (2208), Bobeth-Hiller-VanDyk (2010-11), Beciveric-Schneider (2012)

Full angular analysis

$B^0 \to K^* (K\pi)\ \mu\mu$



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

$$\boxed{S_6^s = \frac{3}{4}A_{FB}}$$

Observables F_L and S_i are functions of Wilson coefficients.
Significant uncertainties from form-factor dependence

Different Parameterization

Different set of observables with reduced uncertainties proposed:

$$\boxed{A_T^{(2)} = \frac{2S_3}{(1-F_L)}} \qquad \boxed{P_4' = \frac{S_4}{\sqrt{(1-F_L)F_L}}} \qquad P_6' = \frac{S_7}{\sqrt{(1-F_L)F_L}}$$

$$A_T^{Re} = \frac{S_6}{(1-F_L)} \qquad P_5' = \frac{S_5}{\sqrt{(1-F_L)F_L}} \qquad P_8' = \frac{S_8}{\sqrt{(1-F_L)F_L}}$$

Kruger-Matias (2005), Matias et al. (2012), Egede-Matias-Hurth-Ramon-Reece (2208), Bobeth-Hiller-VanDyk (2010-11), Beciveric-Schneider (2012)

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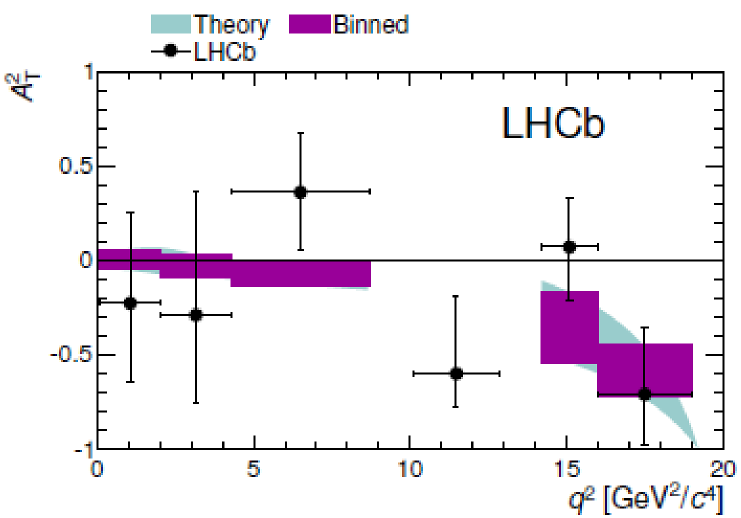
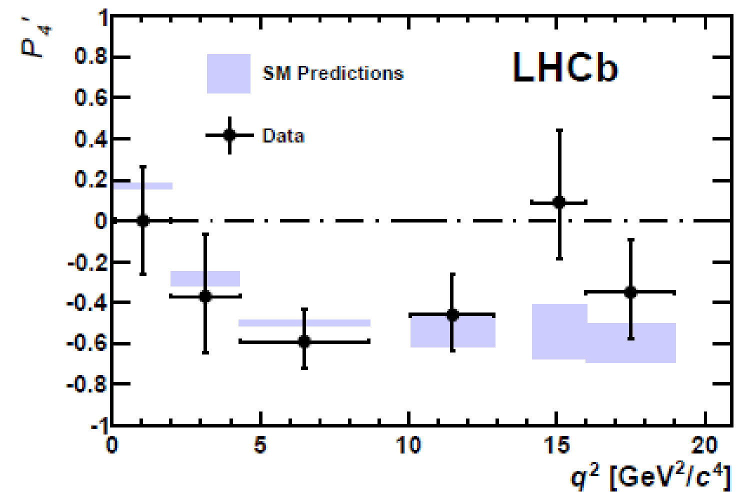


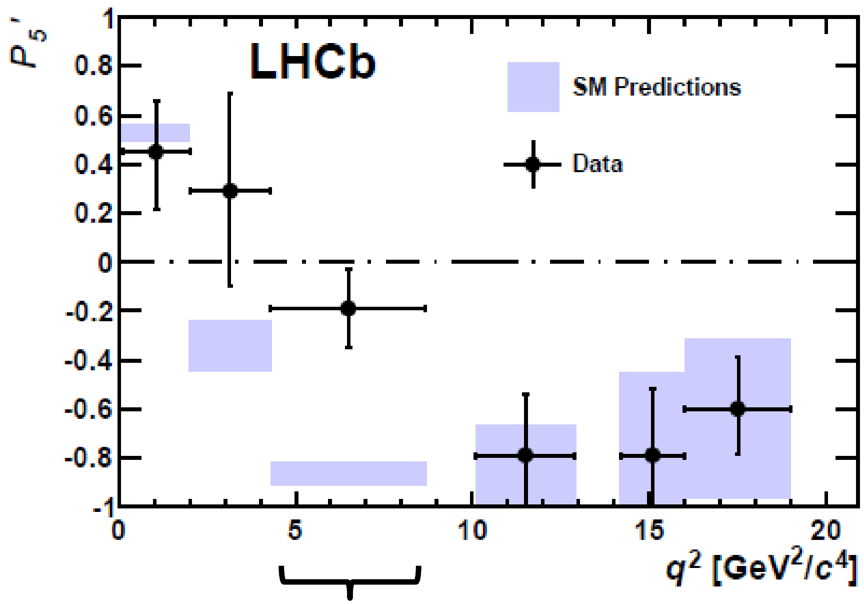


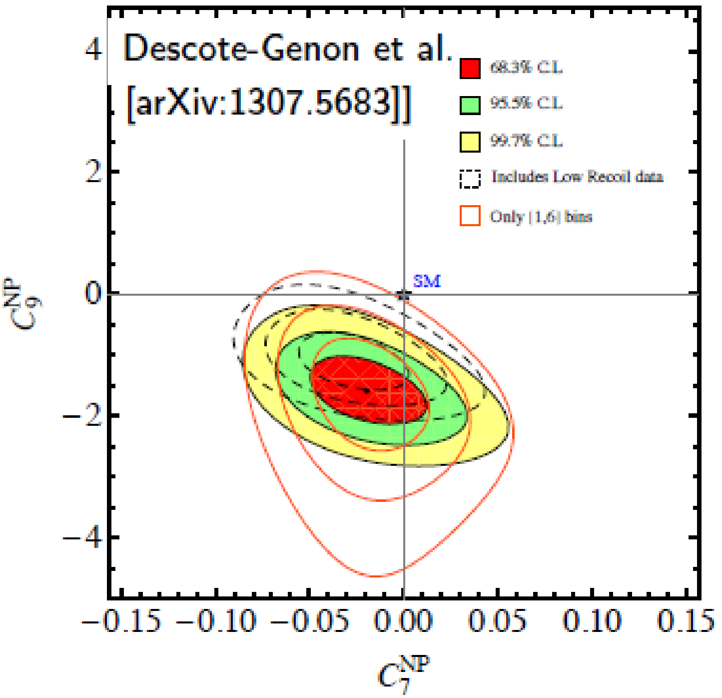
PRL 111, 191801 (2013)

In general good agreement with theory prediction … but ….

Deviation for P_5'

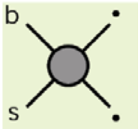
PRL 111, 191801 (2013)
arXiv:1308:1707





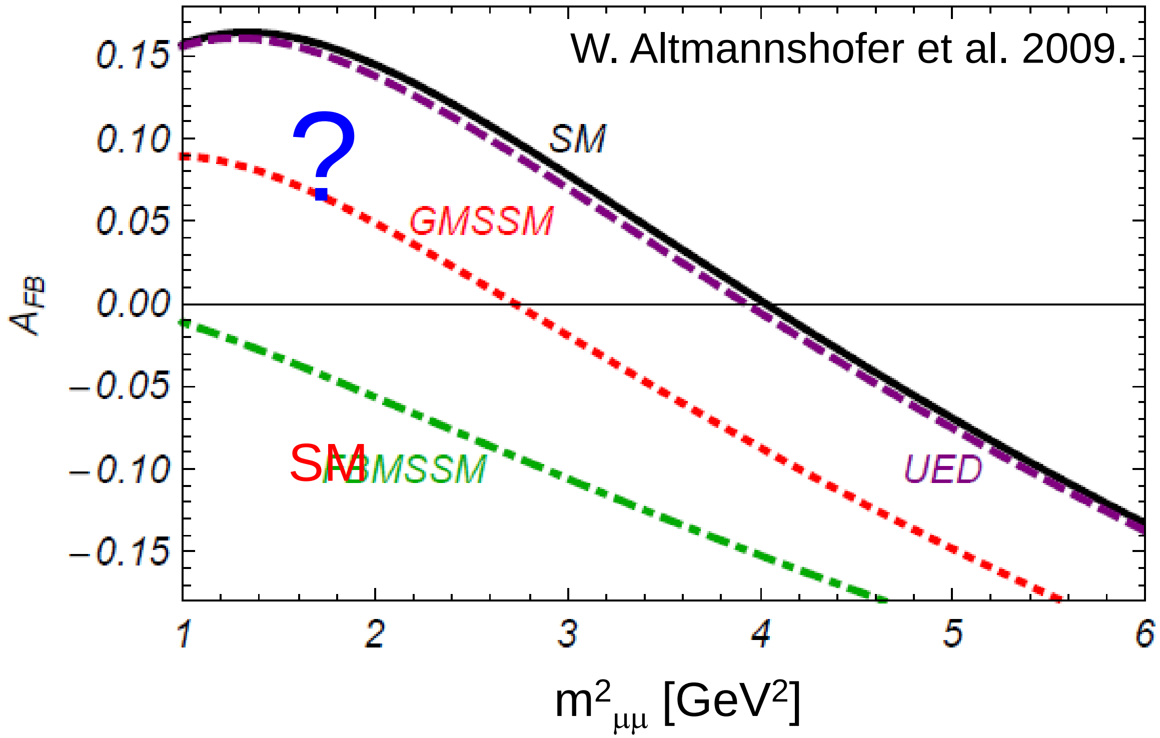
- P_5' shows deviation of 3.7σ from SM ($4.3 < q^2 < 8.68$ GeV^2/c^4)
- 2.5σ for $1 < q^2 < 6$ GeV^2/c^4 (theoretically favored region)

Possible interpretation: deviation in di-lepton vector operator C_9



But: only 1 / 24 bins (0.5% probability)

New Physics Models and $B^0 \rightarrow K^*\mu^+\mu^-$



<u>Status 2011</u>

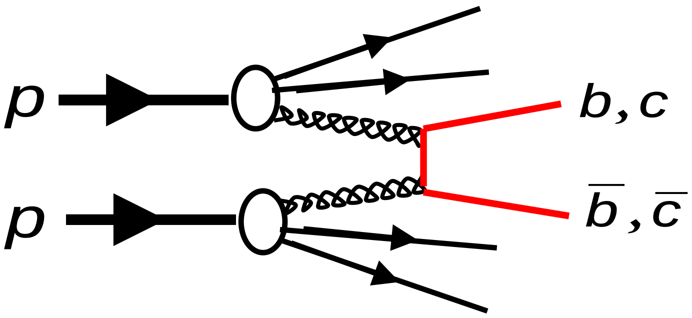
BABAR 100 Evts
BELLE 250 Evts
CDF 100 Evts

10 years

FBMSSM Flavor Blind MSSM
GMSSM: Non Minimal Flavor Violating MSSM
UED: One universal extra dimension

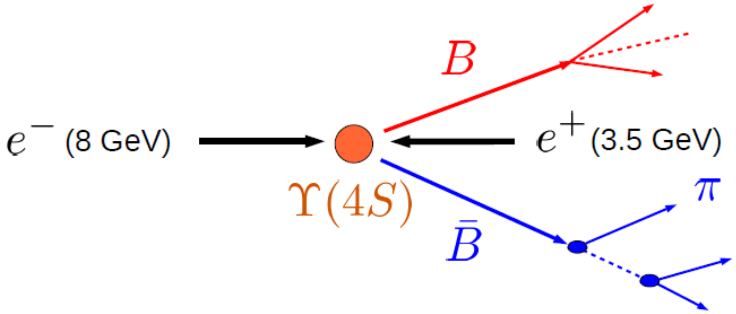
B-Physics at the Intensity Frontier

LHC @ 14 (13) TeV



$$\sigma_{bb}(14\ TeV) \approx 500\ \mu b$$
$$\rightarrow 10^{10}\ b\bar{b}\ \text{events/fb}^{-1}$$

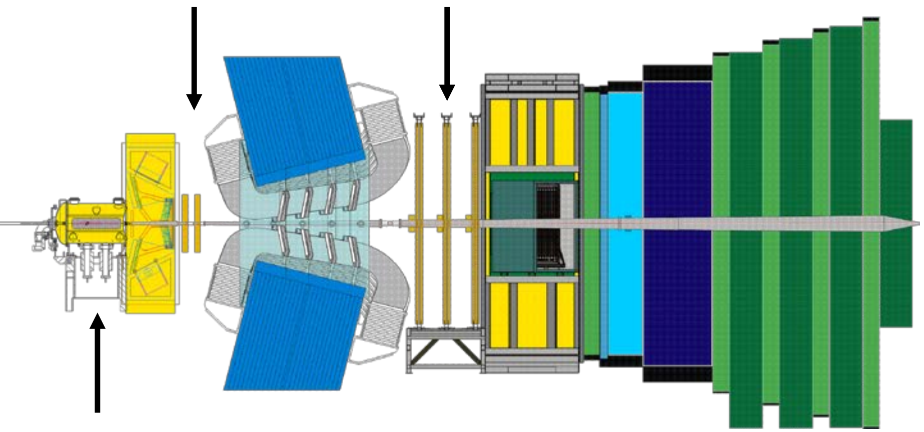
SuperKEKB & Belle II



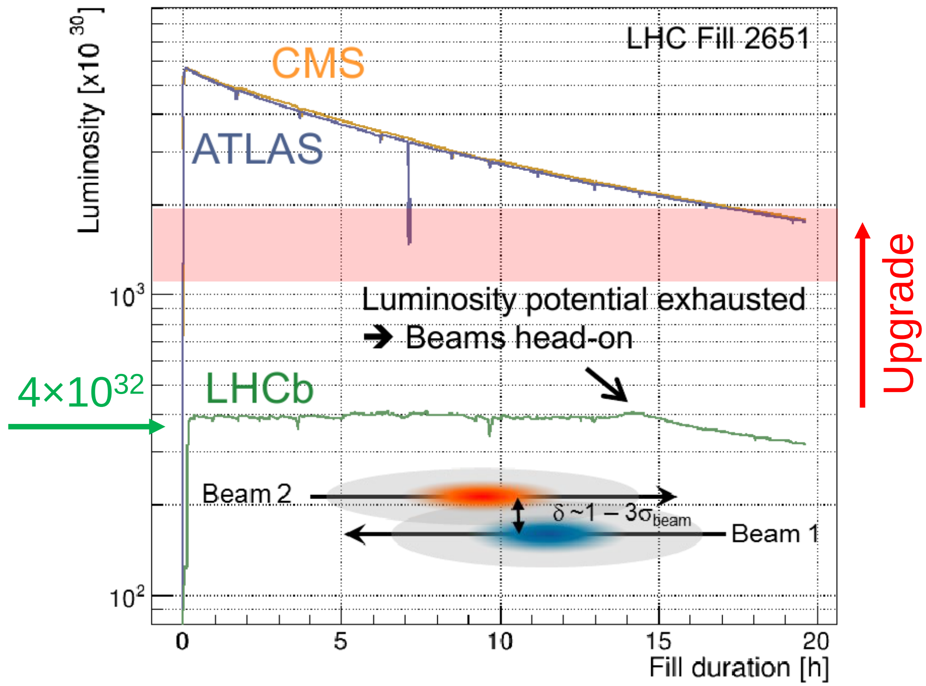
$$\sigma_{BB} \approx 1\ nb$$
$$\rightarrow 10^{9}\ B\bar{B}\ \text{events/ab}^{-1}$$

	LHC era		High-lumi LHC era		
	2010-2012	2015-2018	2020-2022	2025-2028	2030+
ATLAS & CMS	25 fb^{-1}	100 fb^{-1}	300 fb^{-1}	→	3000 fb^{-1}
LHCb	3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	100 fb^{-1}
Belle II		0.5 ab^{-1}	25 ab^{-1}	50 ab^{-1}	-

Upgrade-Project



40 MHz readout for RICHs, Calo, Muon System



See also talk by Wander Baldini

LHCb Upgrade:

- Increase levelled luminosity up to 2×10^{33} $cm^{-2}s^{-1}$ (pile-up ~8):
- Fully flexible & efficient software trigger up to 40 MHz input
- Record 20 – 100 kHz
- Upgrade VELO and Tracker (adapt to higher occupancy and radiation load)

Physics Complementarity*)

LHCb

ATLAS & CMS

- Rare decays: $B_{d,s} \to \mu\mu$
- B_s system
- b-baryons
- Spectroscopy
- CKM phases (β, γ)
- Gluonic penguins
- EW penguins
- Charm physics
- Semileptonics: Mixing, A_{SL}
- Semileptonics: V_{xb}
- $B \to \tau\nu$, $D\tau\mu$,
- $B \to K^*\nu\nu$
- τ-physics

Some only LHCb, some only Belle II

On-going

Belle II

*) Caveat: I am probably missing "your" favored channel/field

Ausblick - LHCb Upgrade

Obervable	LHCb 2018 (7 fb^{-1})	Upgrade (+ 50 fb^{-1})	Theory Uncertainty
B_s Mixing phase ϕ_s	0.025	0.008	~0.003
$BR(B_s \to \mu\mu)$ $BR(B_d \to \mu\mu)$ / $BR\ B_s \to \mu\mu$	0.5×10^{-9} ~100%	0.15×10^{-9} ~35%	0.3×10^{-9} ~5%
CKM angle γ	4^o	0.9^o	small
CPV in D (ΔA_{CP})	0.7×10^{-3}	0.1×10^{-3}	