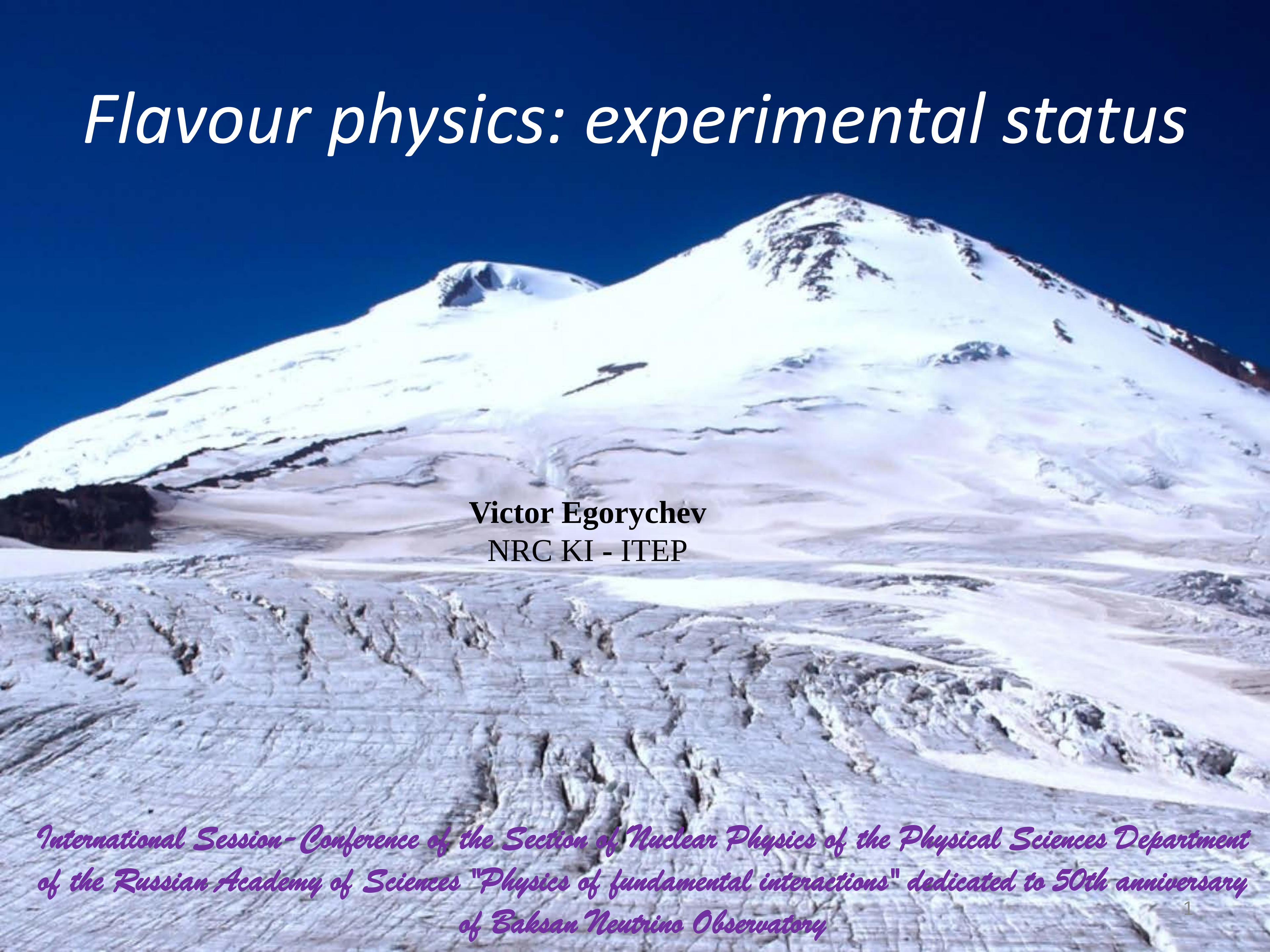


Flavour physics: experimental status

Victor Egorychev
NRC KI - ITEP

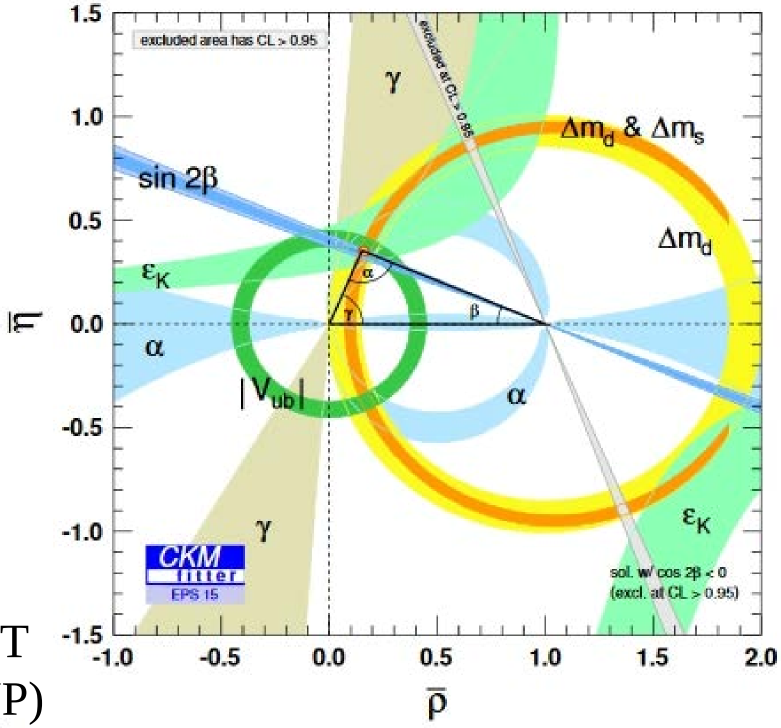
International Session-Conference of the Section of Nuclear Physics of the Physical Sciences Department of the Russian Academy of Sciences "Physics of fundamental interactions" dedicated to 50th anniversary of Baksan Neutrino Observatory

NP search: Direct vs Indirect

- CKM model gives a remarkably consistent description of experimental results

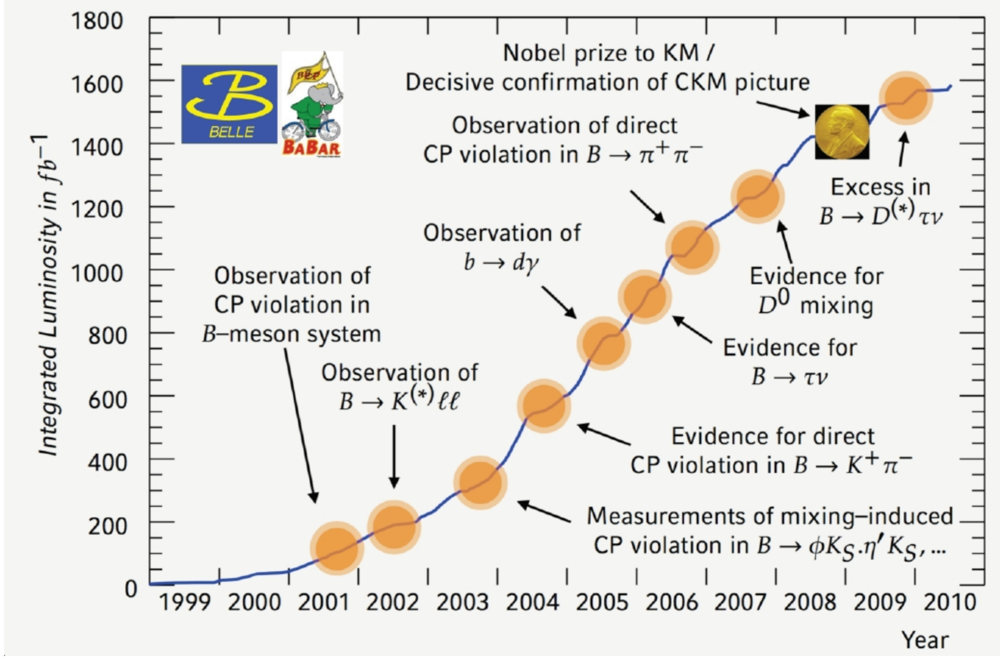
- The most precise tests come from either tree-level B decays or from B mixing

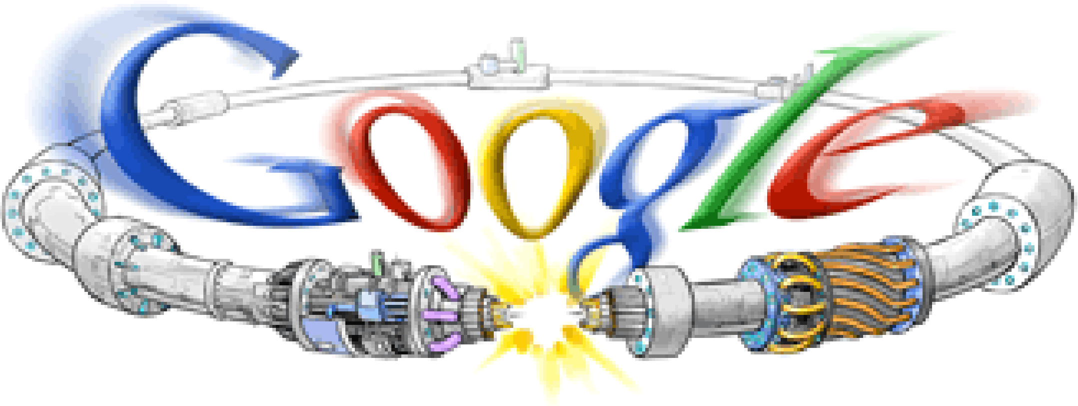
- Where is the New Physics?



  - ✓ CP violation (any inconsistencies in the UT construction will indicate the present of NP)
  - ✓ Rare decays
    - ✓ new particle to be produced and observed as real particles at energy frontier machines (e.g LHC)
    - ✓ virtual new particles (in loop processes) may alter the decay rate, CP-asymmetry and other observable quantities
    - ✓ rare B decays, where penguin amplitudes play a dominate role, are excellent places to look for NP

NP search: Direct vs Indirect





BaBar & Belle were astonishingly successful experiments.

Most importantly, they demonstrated that CKM mechanism drives CP-violation.

If the energy of the particle collisions is high *enough*, we can discover NP detecting the production of real new particles

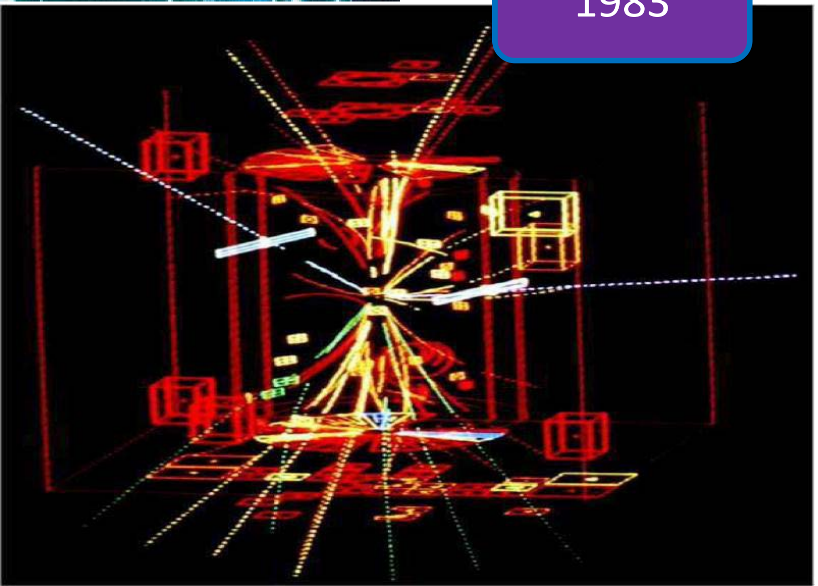
If the precision of the measurement is high *enough*, we can discover NP due to the effect of virtual new particles in loops

Indirect approach

1973

- sensitive to NP effects
- third quark family
  - ✓ inferred by Kobayashi and Maskawa (1973) to explain small CP violation measured in kaon mixing (1964)
  - ✓ directly observed in 1977 (b-quark) and 1995 (t-quark)

1983



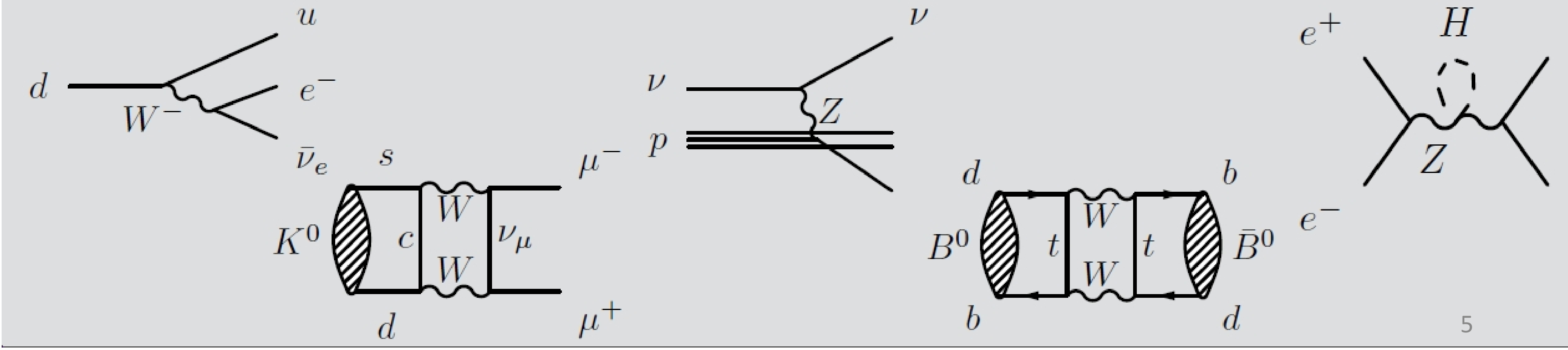
- Neutral current (the Z-boson discovery)
  - ✓ $\nu + N \rightarrow \nu + N$ discovered in 1973
  - ✓ Real Z-boson observed in 1983

1973

The Gargamelle (bubble chamber), now on display at CERN Microcosm museum science garden

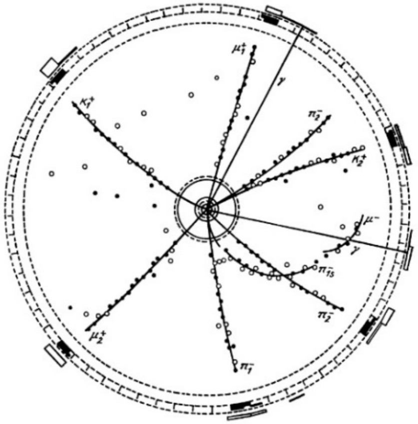
Direct vs Indirect

Particle	Indirect approach			Direct approach		
ν	β decay		1932	Reactor νCC	Cowan, Reines	1956
W	β decay		1932	$W \rightarrow e\nu$	UA1, UA2	1983
c-quark	$K^0 \rightarrow \mu^+\mu^-$	GIM	1970	J/ψ	Richter, Ting	1974
b-quark	CPV $K^0 \rightarrow \pi^+\pi^-$	CKM, 3^e generation	1964/ 1972	Υ	Ledermann	1977
Z	ν-NC	Gargamelle	1973	$Z \rightarrow e^+e^-$	UA1	1983
t-quark	B-mixing	Argus	1987	$t \rightarrow Wb$	D0, CDF	1995
H	e^+e^-	EW fit, LEP	2000	$H \rightarrow 4\mu/2\gamma$	ATLAS, CMS	2012



Direct vs Indirect

ARGUS experiment



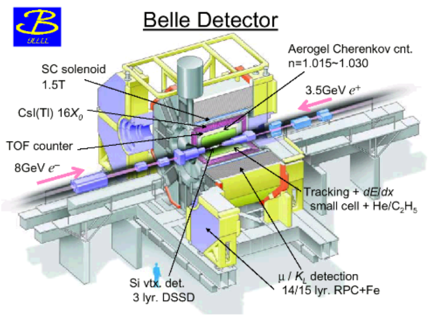
Henning Schröder

Yuri Zaitsev

W.K.H. Panofsky Prize in Experimental Particle Physics

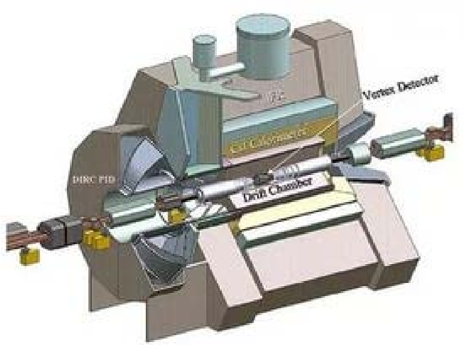
"For their leading role in the first demonstration of mixing in the B0 – antiB0 system. The unexpectedly ***large value of the mixing parameter provided indirect evidence for a large top quark mass*** *and has greatly enhanced the possibility for studying CP violation in B meson decays. This capability has encouraged a worldwide effort to determine whether the small CP violation in K decay is a reflection of a fundamental parameter characterizing transitions of quarks among the three generations."*

Main players in heavy flavor physics

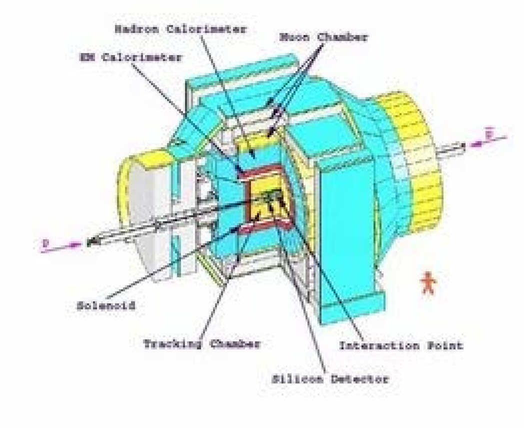


e^+e^- machines, B-factories

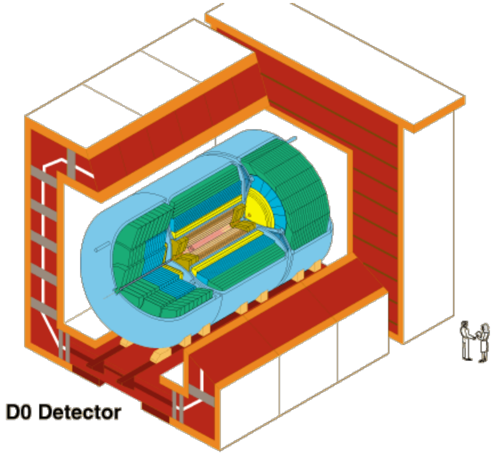
- ✓ BaBar, Belle experiments
- ✓ operated in the 2000’s
- ✓ mainly B^0 and B^+ physics



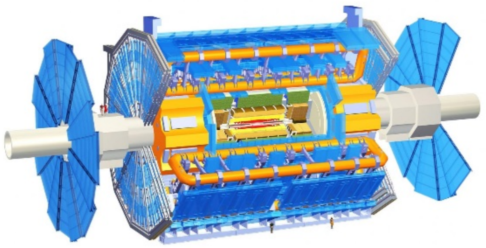
Tevatron collider



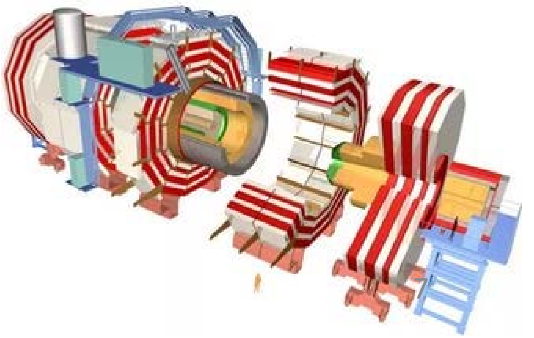
- ✓ CDF, D0 experiments
- ✓ general purpose detectors
- ✓ important early B^0_s and b-hadron studies



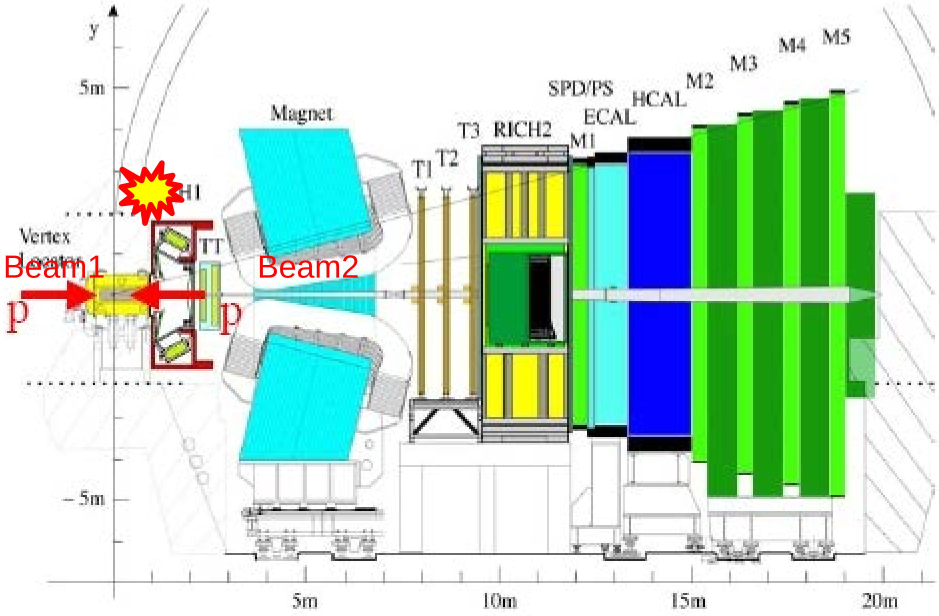
LHC



- ✓ ATLAS, CMS experiments
- ✓ Their excellent instrumentation gives them great capabilities in certain b-physics channels, especially those with dilepton final states



LHCb – a flavour physics experiment at the LHC



An experiment to search for physics beyond the Standard Model, through flavour studies of beauty- and charm- hadrons (but also general 'forward physics')

A collaboration of ~1200 members from 72 institutes in 16 countries

Russian groups involved in LHCb

NRC KI

IHEP

ITEP

INR RAS

PNPI

LHCb

TPU

SCHOOL OF DATA ANALYSIS

BINP

MSU

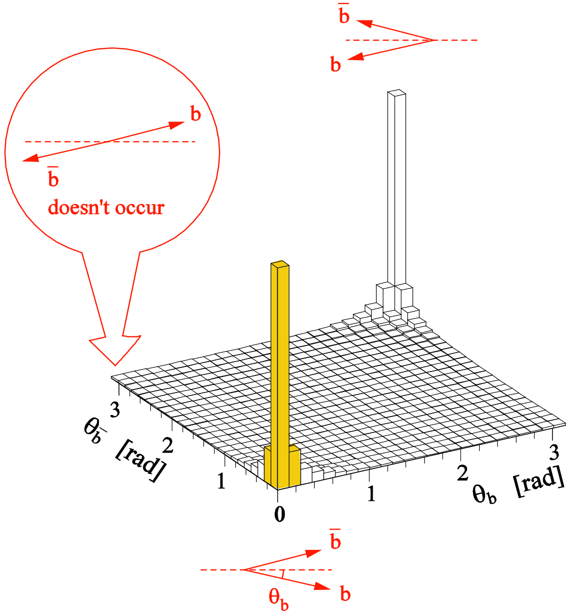
LHCb experiment

- Advantages of beauty physics at hadron colliders:
  - high value of *bb* cross section at LHC

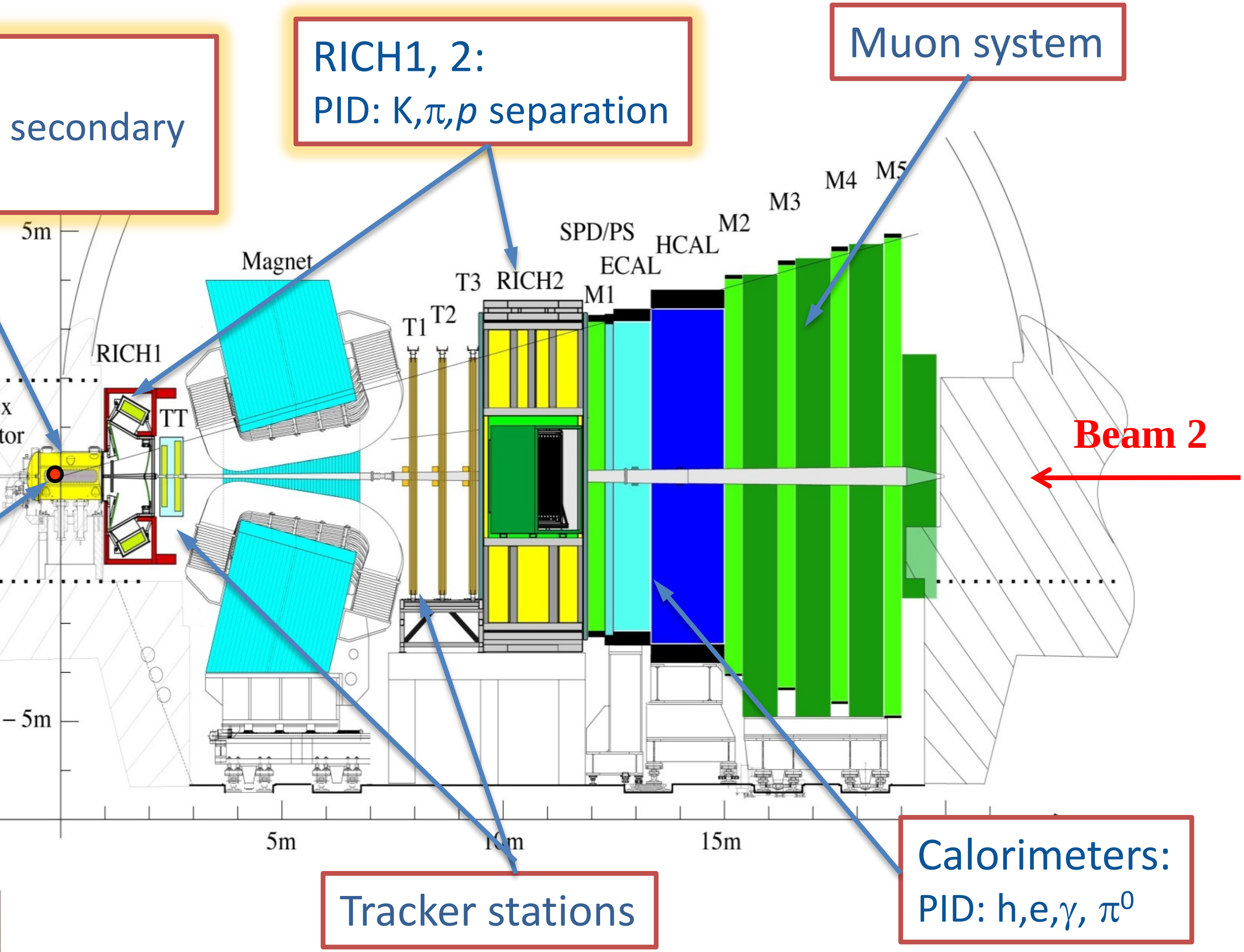
    $\sigma_{bb} \sim 600\ (280)\ \mu b$ @ $\sqrt{s}=13\ (7)$ TeV
    (e^+e^- machine $\sigma_{bb} \sim 1$ nb @ $\Upsilon(4S)$)

  - access to all quasi-stable *b*-flavoured hadrons : $B^{\pm}$, B^0, B^0_s, $B^{\pm}_c$, Λ^0_b , …
- Challenge:
  - multiplicity of tracks (~30 tracks per rapidity unit)
  - rate of background events: $\sigma_{inel} \sim 100$ mb
- LHCb nominal running conditions:
  - luminosity limited $\mathcal{L} \sim 3\text{-}4 \times 10^{32}\ \mathrm{cm^{-2}\ s^{-1}}$ by not focusing the beam as much as ATLAS and CMS
  - maximize the probability of single interaction per bunch crossing
- acceptance
  - $2 < \eta < 5 \rightarrow |\eta| < 2.5$ @ ATLAS/CMS
  - 10-300 mrad

The B mesons formed by the colliding proton beams (and the particles they decay into) stay close to the line of the beam pipe, and this is reflected in the design of the detector



LHCb detector



VELO:
Primary and secondary vertex

RICH1, 2:
PID: K,π,*p* separation

Muon system

Beam 1

Beam 2

Interaction point

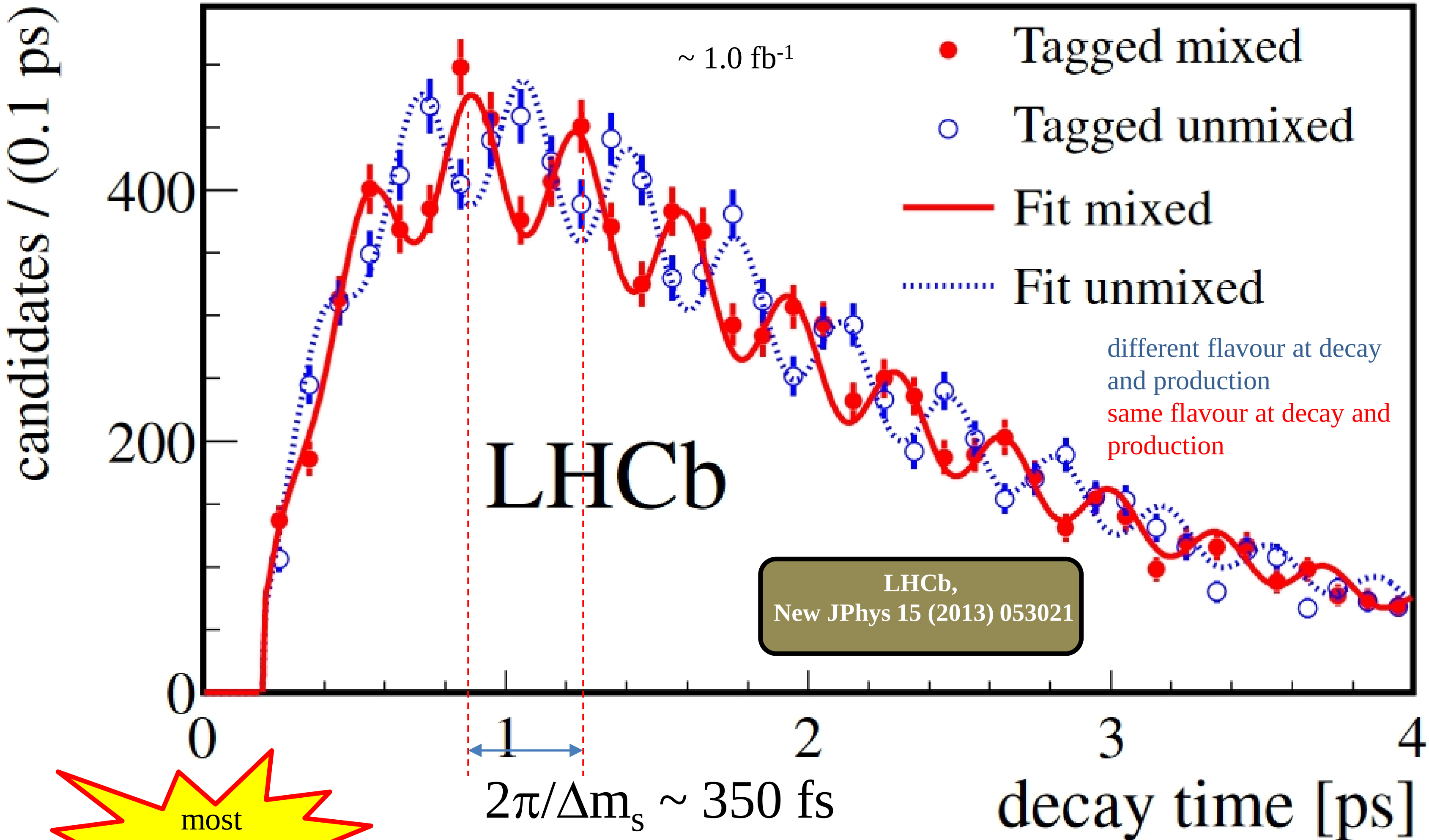
Tracker stations

Calorimeters:
PID: h,e,γ, π^0

flavour physics experiment at the LHC

B_s mixing

$B^0_s \rightarrow D^-_s\pi^+$, $D^-_s \rightarrow \phi(K^+K^-)\pi^-$, $K^{*0}(K^+\pi^-)K^-$, $K^+K^-\pi^-$, $K^+\pi^+\pi^-$, $\pi^-\pi^+\pi^-$



different flavour at decay and production

same flavour at decay and production

LHCb,
New JPhys 15 (2013) 053021

$2\pi/\Delta m_s \sim 350$ fs

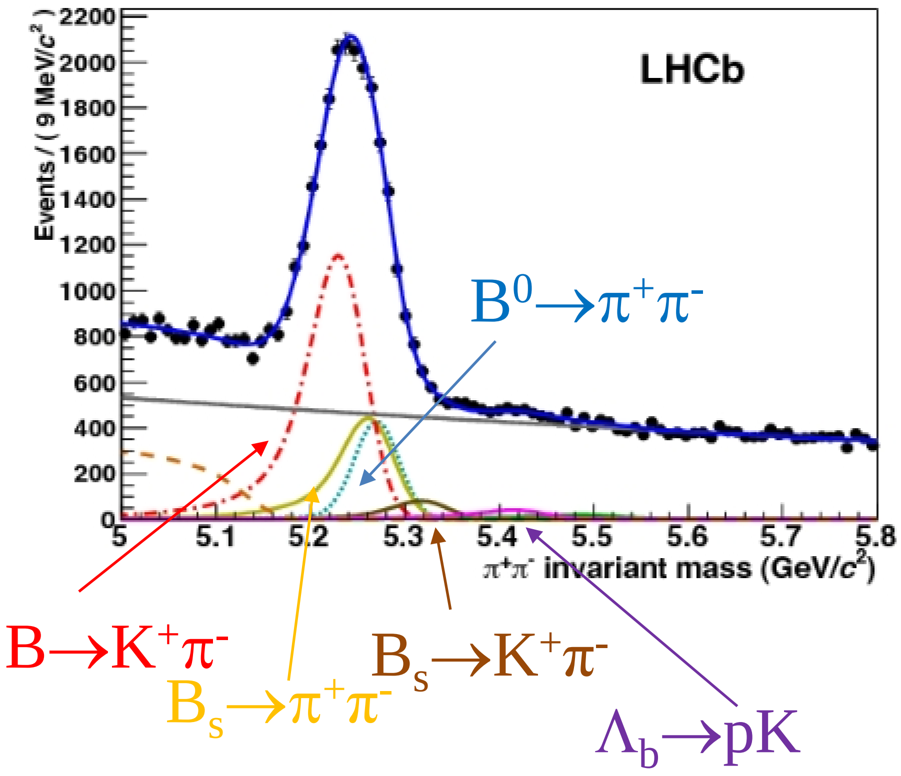
most precise to date

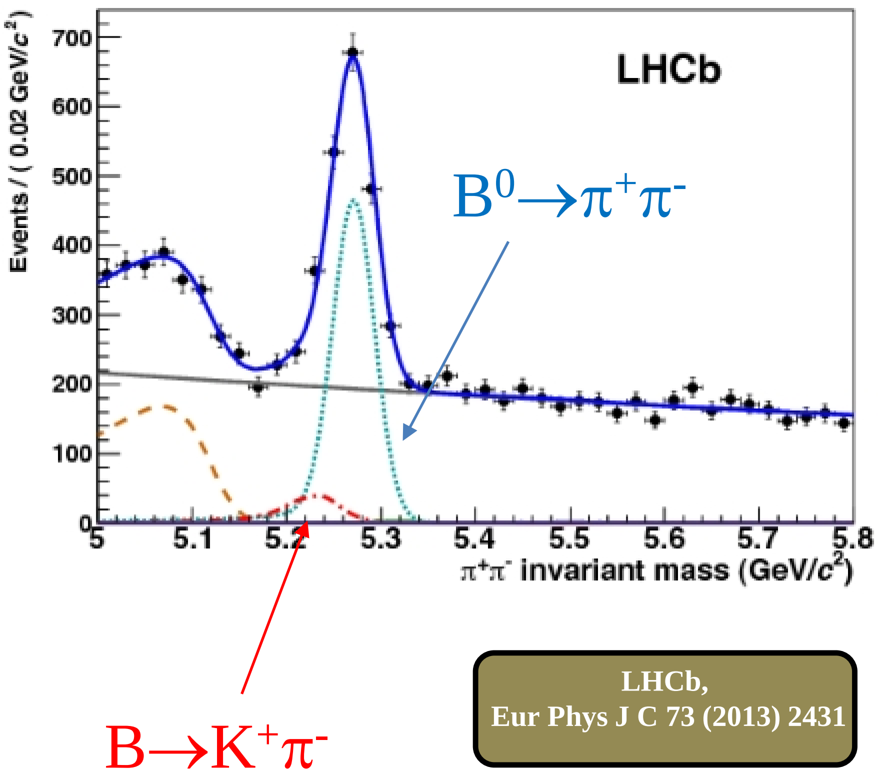
$\Delta m_s \sim 17.768 \pm 0.023 \pm 0.006\ \mathrm{ps}^{-1}$

Particle identification

RICH detectors

Invariant mass distribution for $B^0 \rightarrow h^+h^-$ ($h = K, \pi$) decays with and without RICH

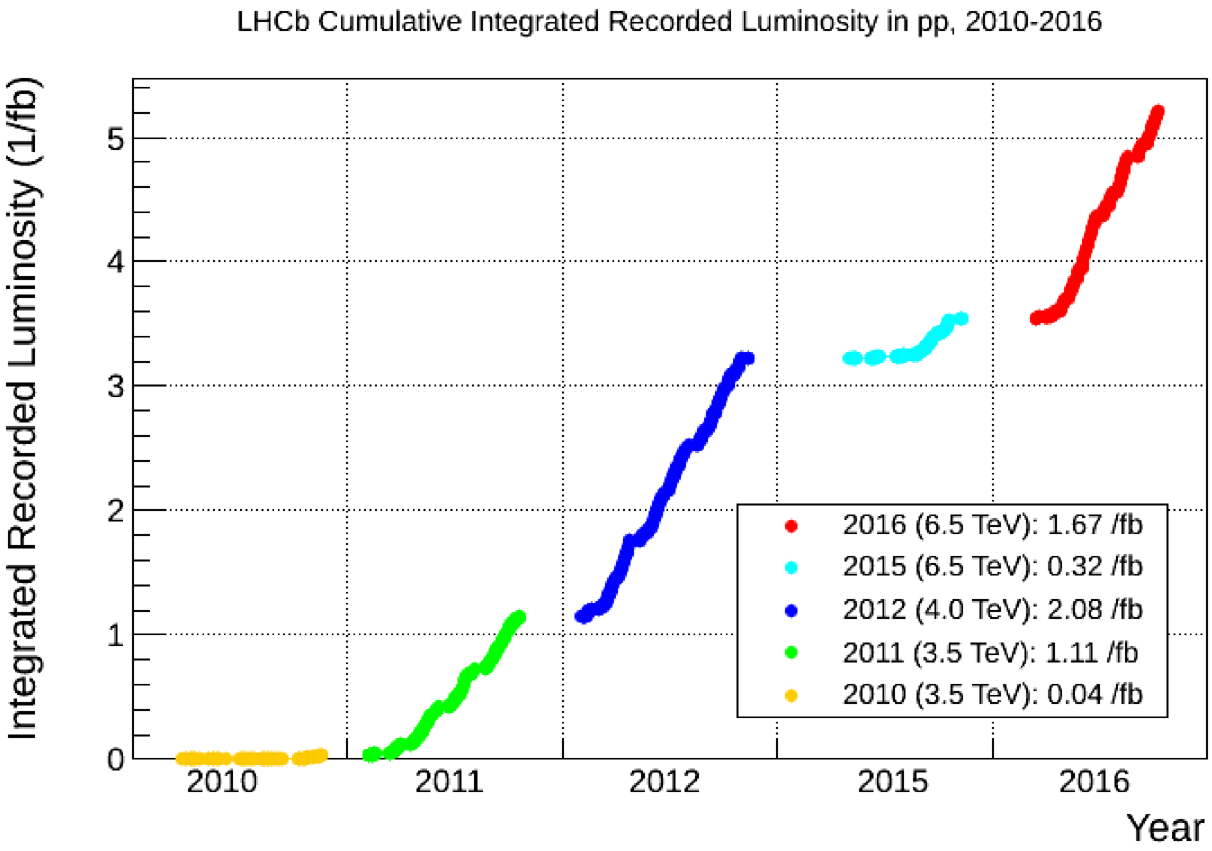




LHCb,
Eur Phys J C 73 (2013) 2431

Running conditions

LHC run-I went from 2010 to 2012, during which LHCb collected 3 fb^{-1} of data (this corresponds to ~3 x 10^{11} *b anti-b* pairs being produced within LHCb)

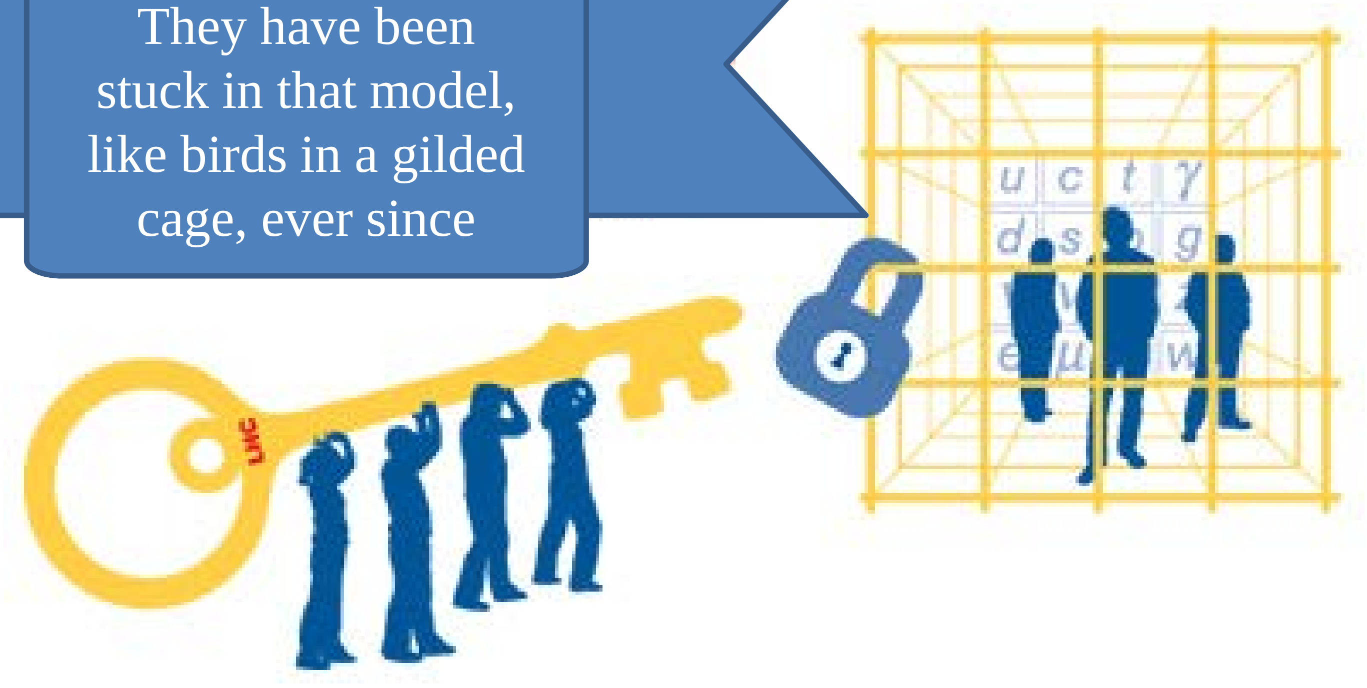


Now embarking on second ‘production year’ of run-II (after a ‘start-up’ year in 2015). Operating at higher energy and at 25 ns bunch - crossing (+ detector improvements).

Run-II will go to end of 2018 – expect to increase the beauty sample by x3 or more.

But physicists are hoping for something bizarre…

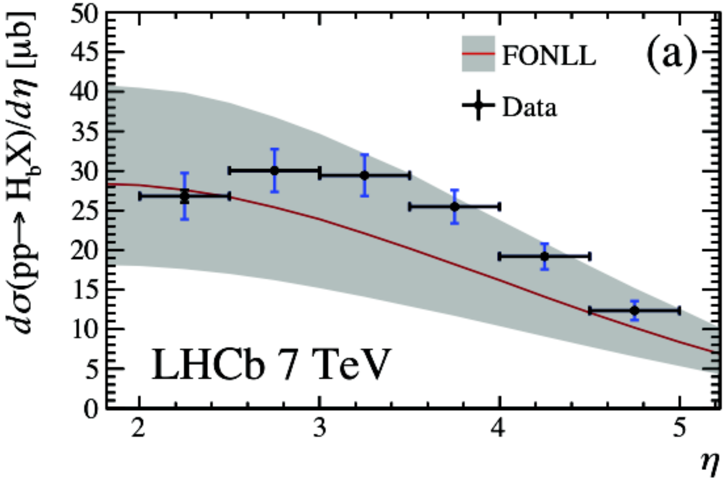
They have been stuck in that model, like birds in a gilded cage, ever since

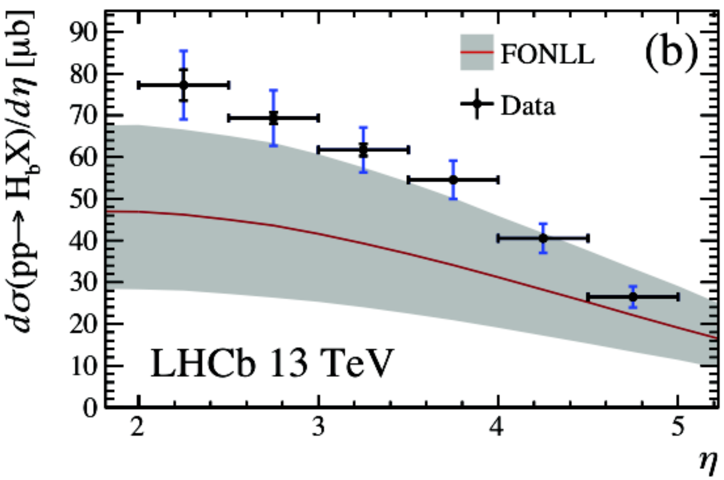


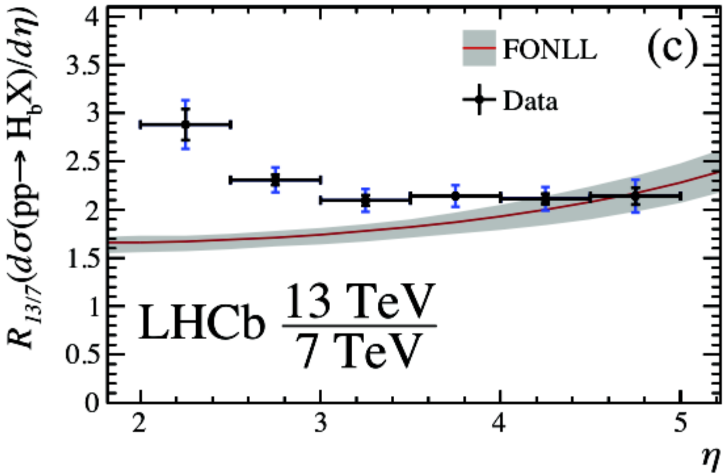
b-quark production

Cross-section as function of η

2 < η < 5







LHCb,
LHCb-PAPER-2016-031

A striking difference between measurement and theory is observed at low η values corresponding to b-hadron production at larger θ angles.

$B^0 \to D^{*-}\tau^+\nu$

$|V_{ub}| / |V_{cb}|$

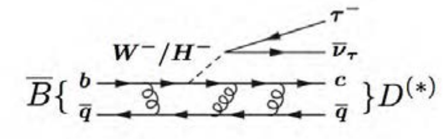
$B^0 \rightarrow D^{*-}\tau^+\nu$

Measurement of R(D*) = $BR(B^0 \rightarrow D^{*-}\tau^+\nu)/BR(B^0 \rightarrow D^{*-}\mu^+\nu)$

Theoretically clean

- ✓ in CM only difference is the mass of the lepton
- ✓ R(D*) = 0.252±0.003

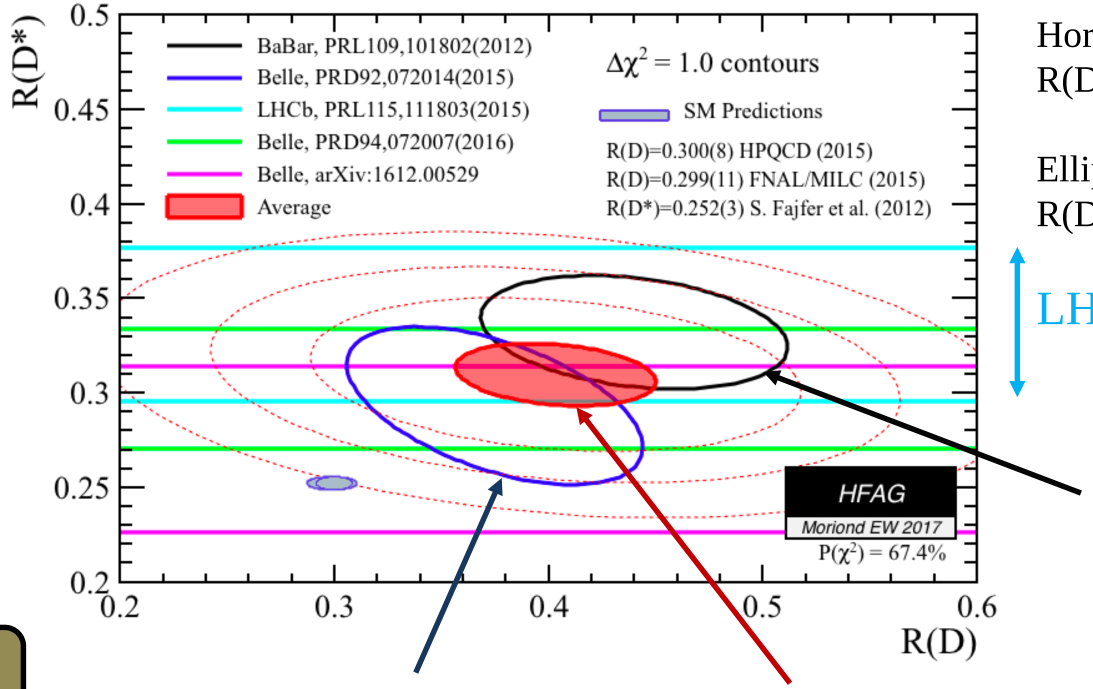
Sensitive to NP coupled dominantly to 3rd generation, e.g. a charged Higgs



BaBar ~3σ tension

$$R(D^*) = \frac{BR(\overline{B^0} \rightarrow D^{*+}\tau^-\overline{\nu_\tau})}{BR(\overline{B^0} \rightarrow D^{*+}\mu^-\overline{\nu_\mu})}$$

difference wrt SM predictions at 3.9σ level



Horizontal bands refer to R(D*)

Ellipses refer to both R(D*, D)

LHCb

BaBar

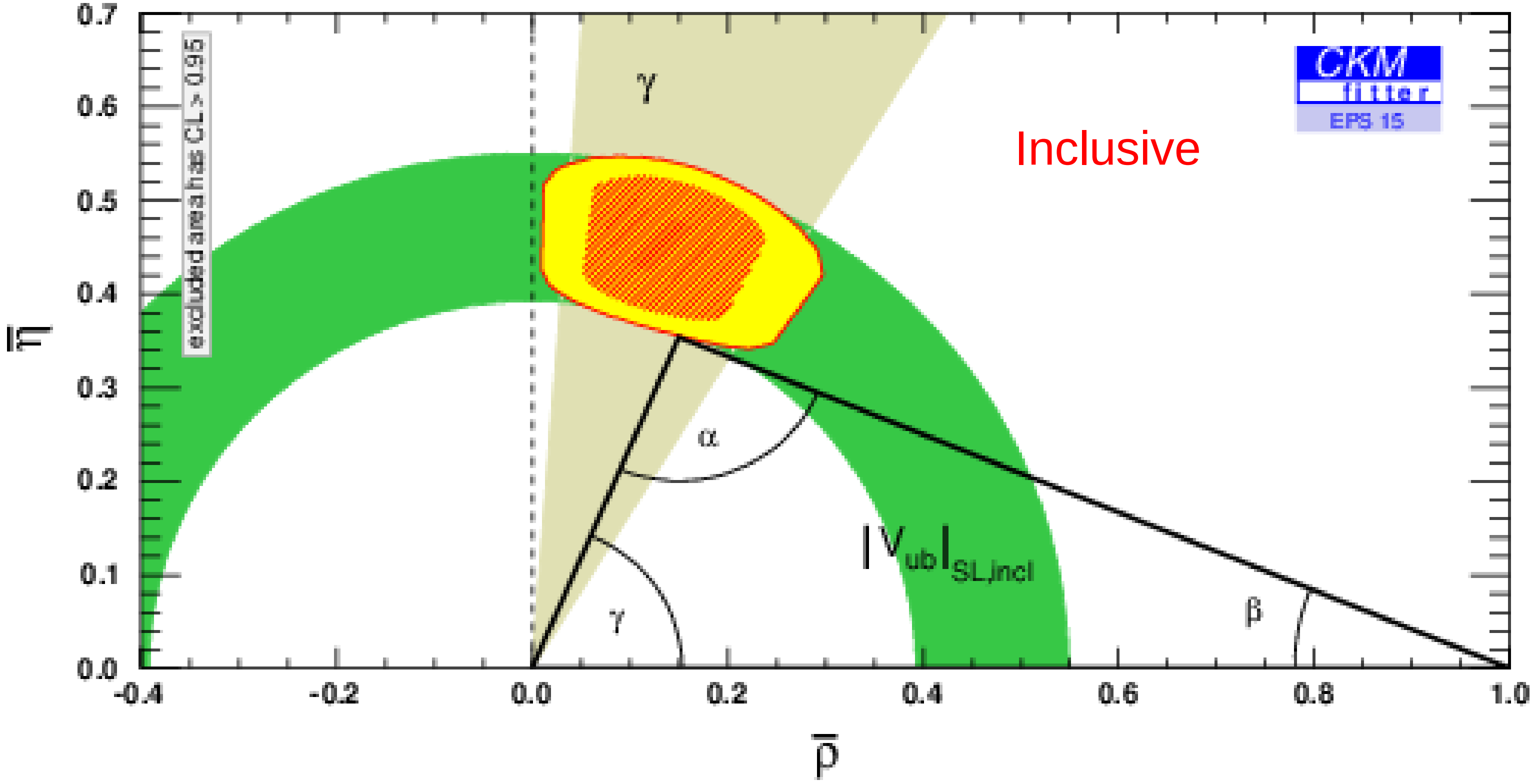
Belle

WA

LHCb,
PRL 115 (2015) 111803

$|V_{ub}|$ / $|V_{cb}|$

There has been a long standing discrepancy between the value of $|V_{ub}|$ determined from exclusive B→πlν and inclusive b→ulν decays.

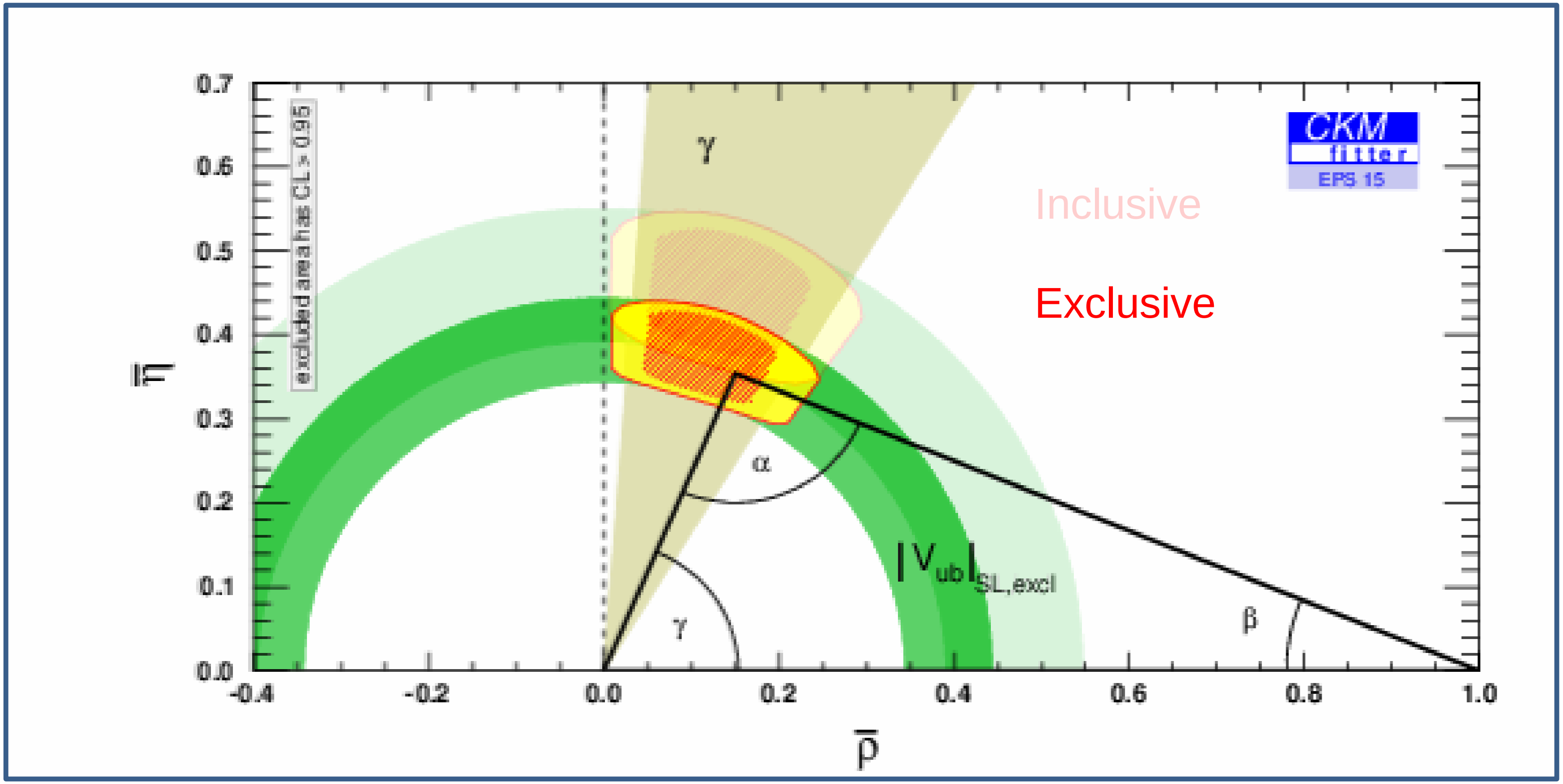


Inclusive

V_{ub} (incl) = $(4.40 \pm 0.22) \times 10^{-3}$

$|V_{ub}| / |V_{cb}|$

There has been a long standing discrepancy between the value of $|V_{ub}|$ determined from exclusive B→πlν and inclusive b→ulν decays.



V_{ub} (incl) = $(4.40 \pm 0.22) \times 10^{-3}$ V_{ub} (excl) = $(3.69 \pm 0.14) \times 10^{-3}$

~2.7 σ

$|V_{ub}| / |V_{cb}|$

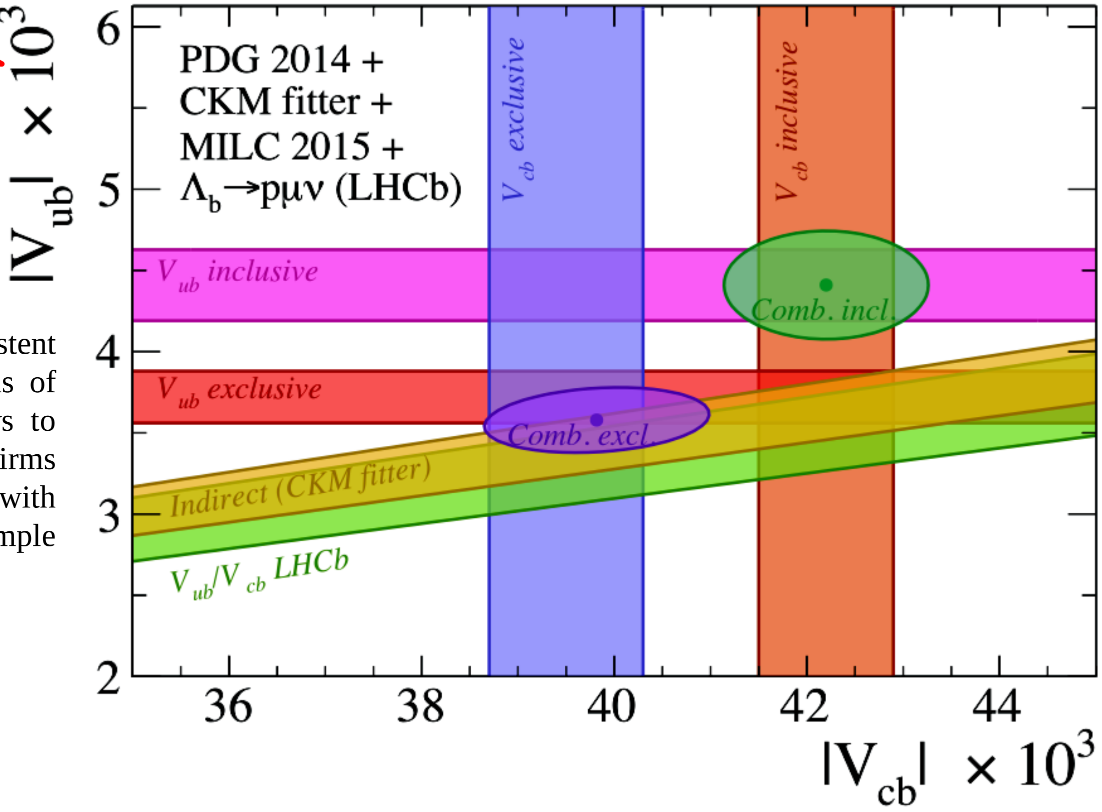
LHCb

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004(\text{stat}) \pm 0.004(\text{syst})$$

LHCb,
Nature 10 (2015) 1038

First time in a baryonic decays

$\Lambda_b \to p\mu\nu$ и $\Lambda_b \to \Lambda_c^+\mu\nu$



This measurement is consistent with previous determinations of |*Vub*| using *B* meson decays to specific final states and confirms the existing incompatibility with those using an inclusive sample of final states.

disagrees with the inclusive measurement at a significance level of 3.5σ

Rare decays

$B^0_s \rightarrow \mu^+ \mu^-$

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

$B^+ \rightarrow K^+ \mu^+ \mu^-$ and $B^+ \rightarrow K^+ e^+ e^-$

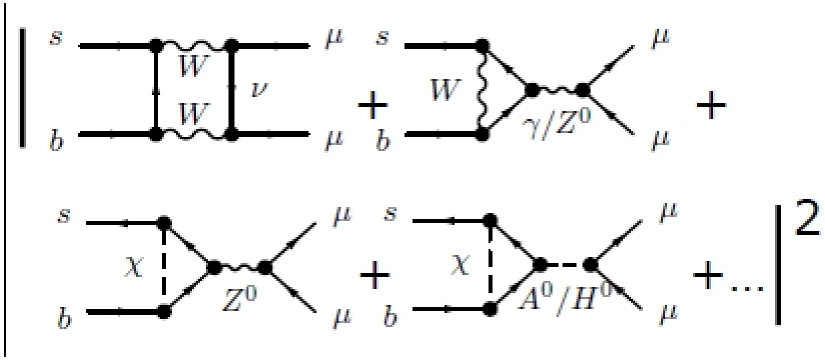
$B^0_s \rightarrow \mu^+\mu^-$

Very rare decay, well described in the SM

✓ FCNC
✓ Helicity suppressed ~ $(m_\mu/M_B)^2$

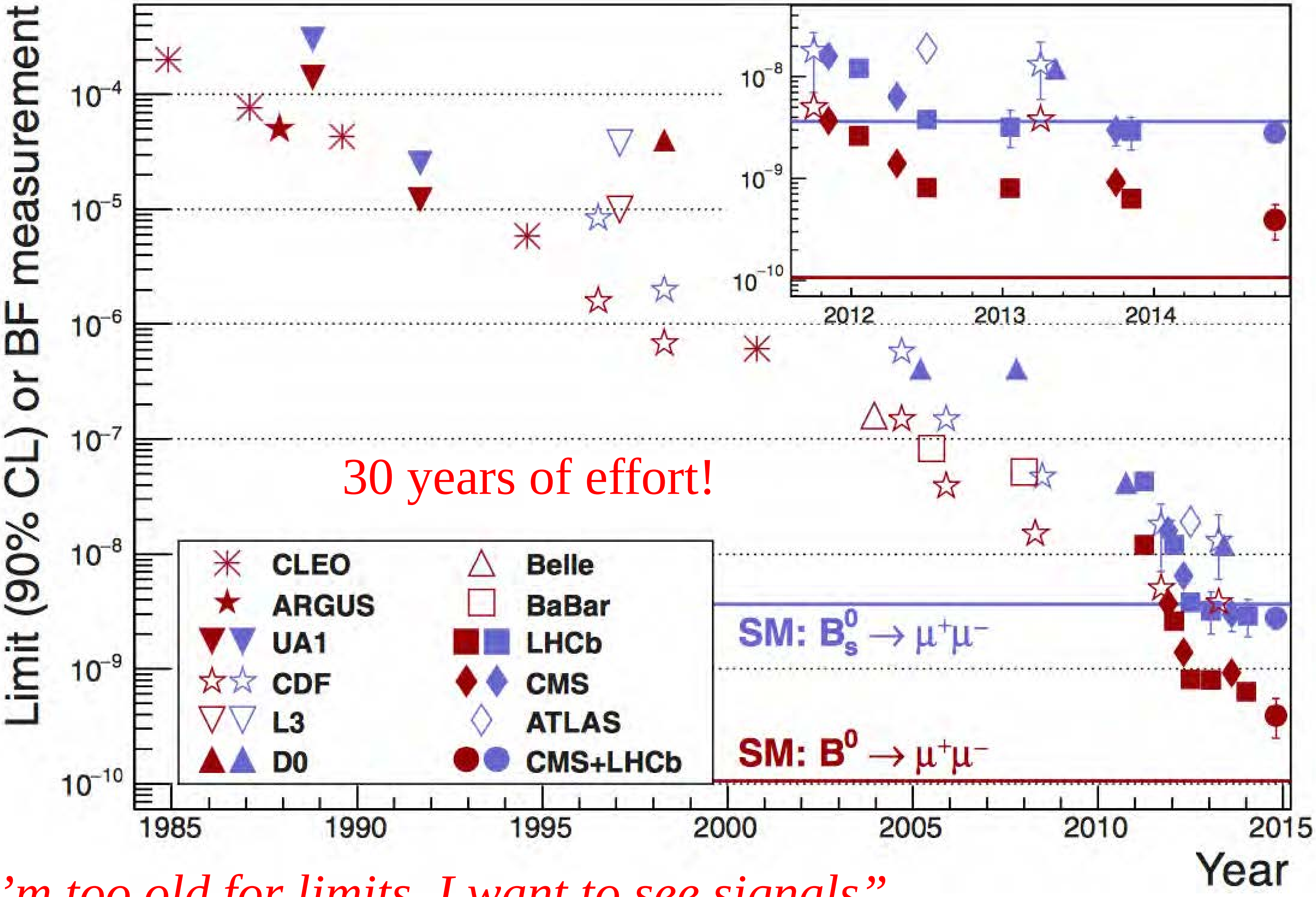
$BR(B^0_s \rightarrow \mu^+ \mu^-) = (3.66 \pm 0.23) \times 10^{-9}$
$BR(B^0_d \rightarrow \mu^+ \mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

Very sensitive to NP,
e.g. Minimal Susy Models (BR ~ $\tan^6\beta$)



Very clean signature
Studied by all high-energy hadron collider experiments (~30 years)

$B^0_s \rightarrow \mu^+\mu^-$



30 years of effort!

"I'm too old for limits, I want to see signals"

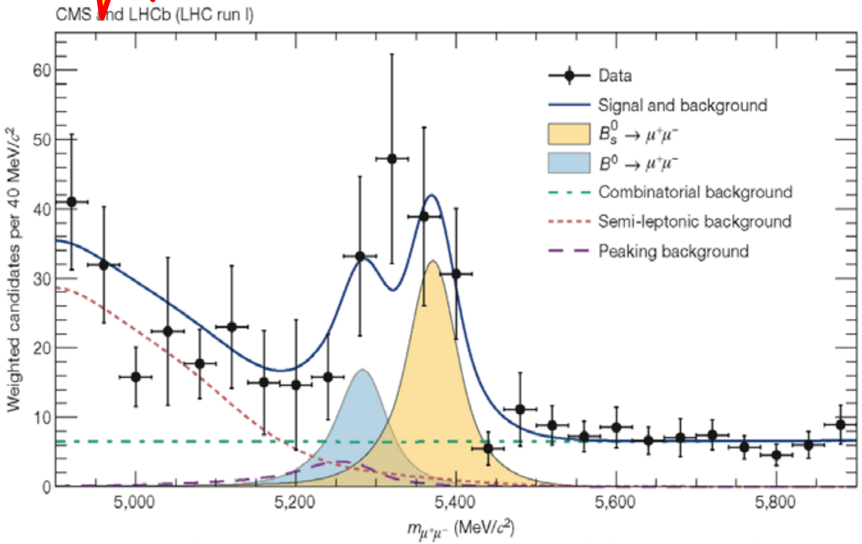
Francis Halzen (EPS '15)

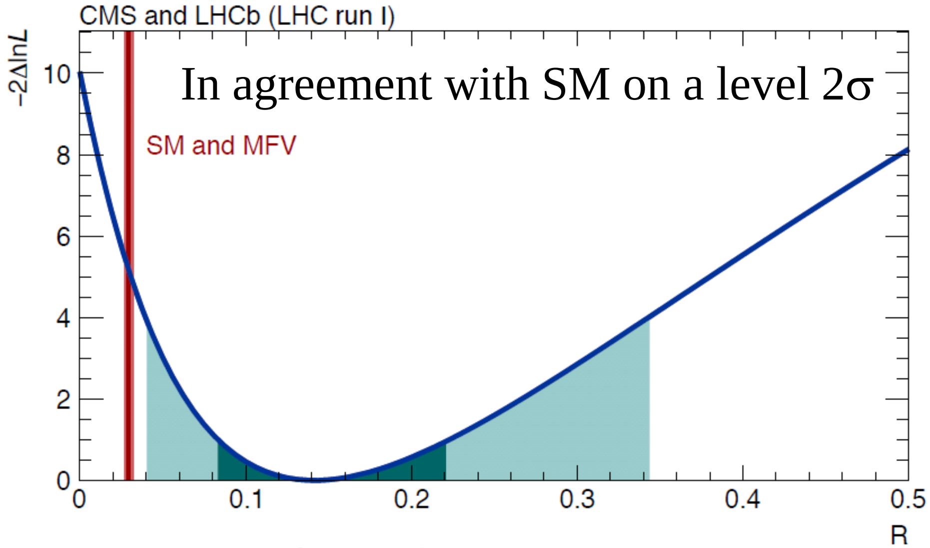
2015

$B^0_s \to \mu^+\mu^-$

LHCb and CMS combination

LHCb, Nature 552 (2015) 68



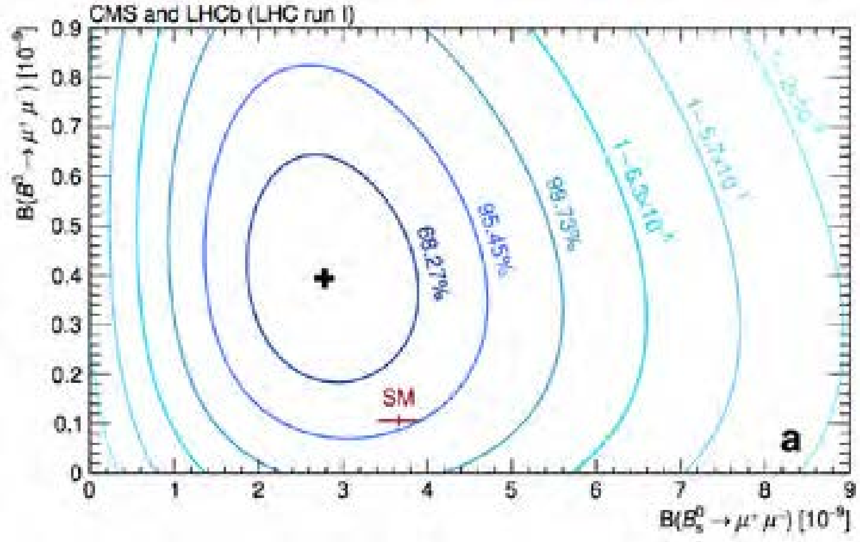


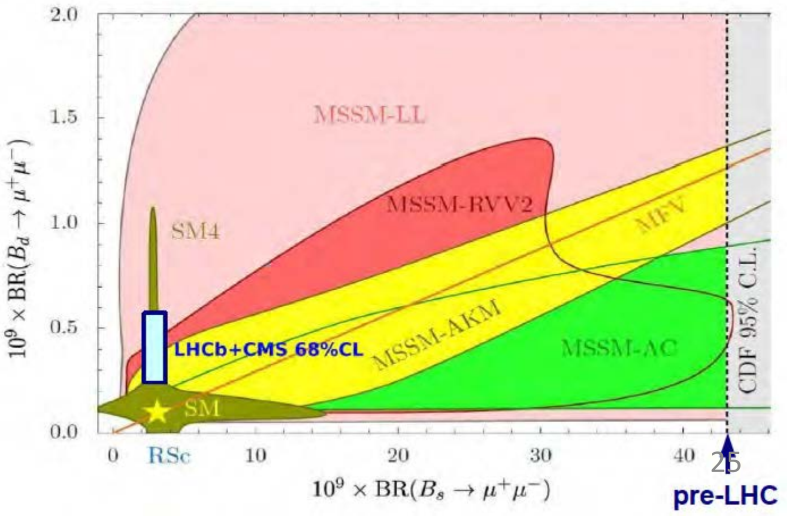
In agreement with SM on a level 2σ

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (2.8\,^{+0.7}_{-0.6}) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.9\,^{+1.6}_{-1.4}) \times 10^{-10}$$

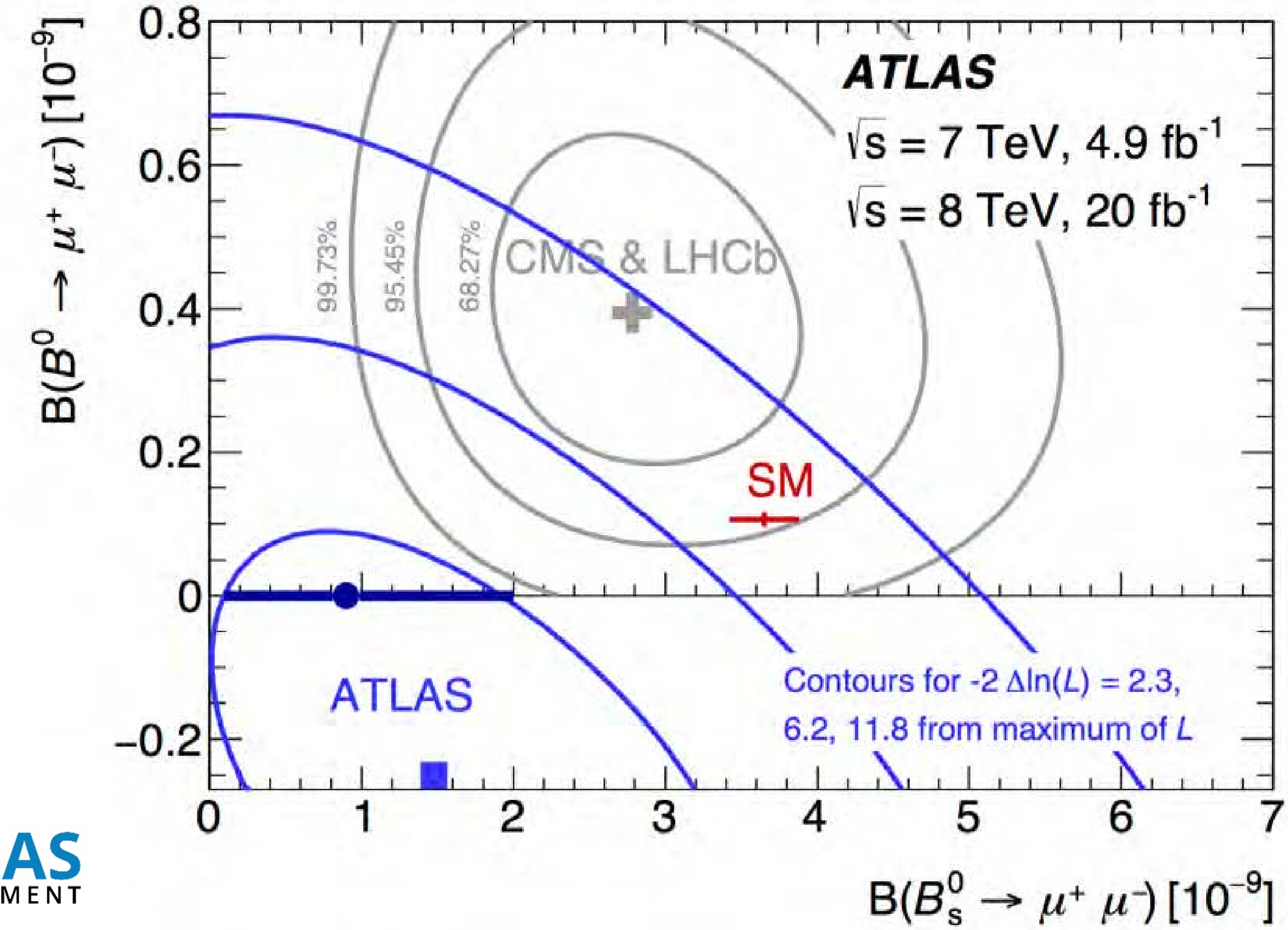
$$\frac{BR(B^0 \to \mu^+\mu^-)}{BR(B^0_s \to \mu^+\mu^-)} = 0.14^{+0.08}_{-0.06}$$





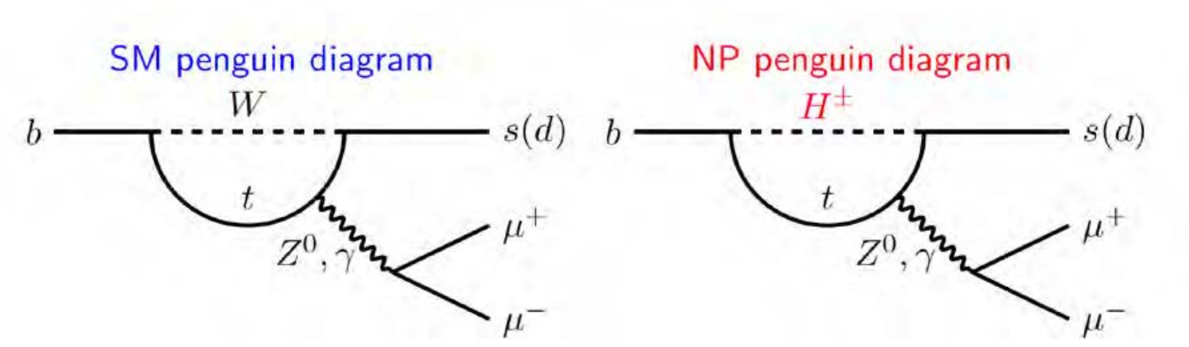
$B^0_s \rightarrow \mu^+\mu^-$

from 2016 also with ATLAS contribution



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

$b \to sl^+l^-$ transition



✓ only proceeds via loops and boxes → sensitive to NP

- Supersymmetry, Any 2HDM, Fourth generation, Extra dimensions, Axions . . .

✓ ideal place to look for new physics

- rates, angular distributions and asymmetries sensitive to NP

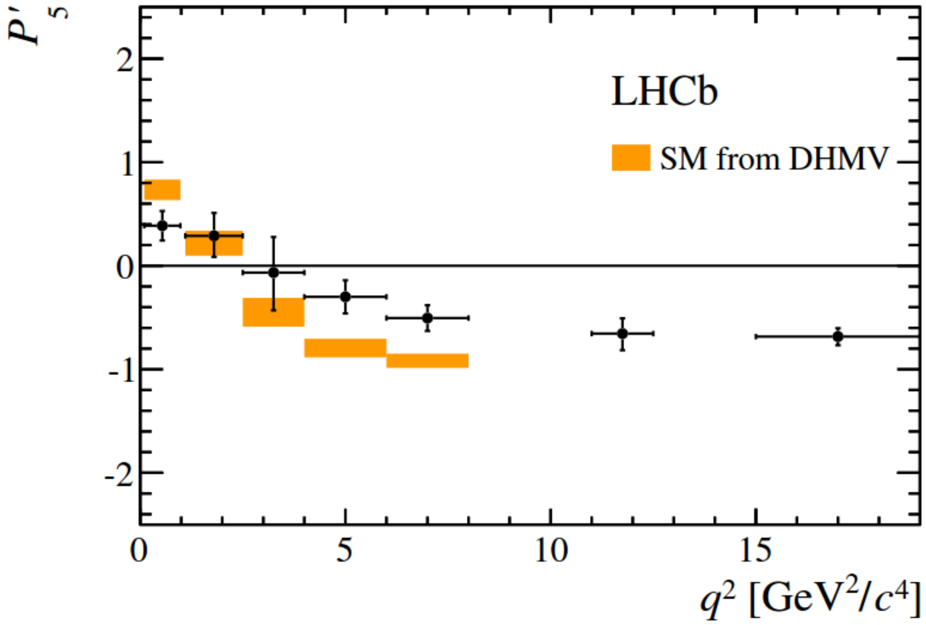
✓ a lot of phenomenological work invested in defining observables with "clean" theoretical prediction

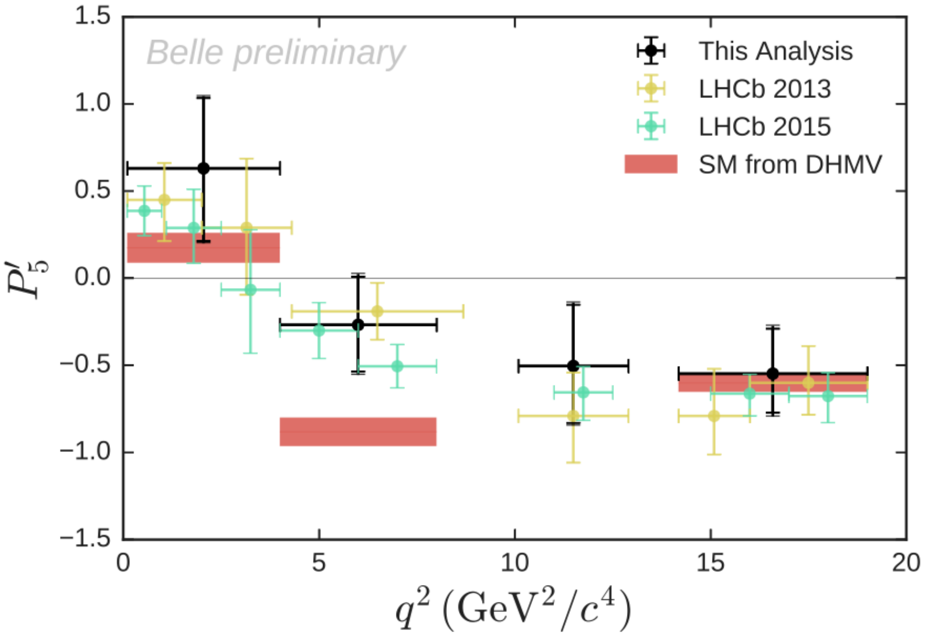
Question: how clean?

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

LHCb,
JHEP 02 (2016) 104

arXiv 1604:040402





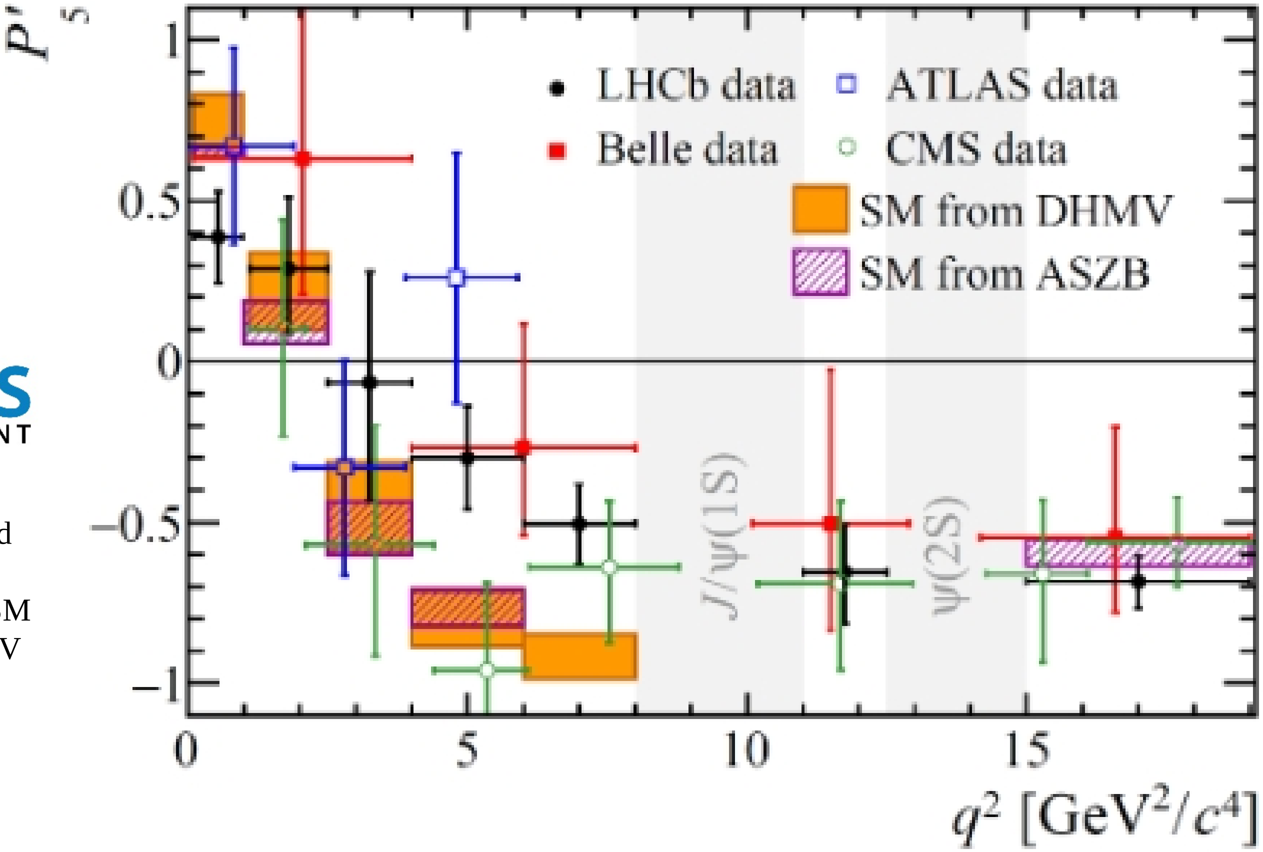
Local naïve significance of ~3σ using full Run 1 statistics

Belle result (di-electron mode) is in agreement with LHCb

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

with ATLAS and CMS results

new



LHCb, Belle and ATLAS show deviations from SM in 4< $q^2_{\mu\mu}$< 8 GeV

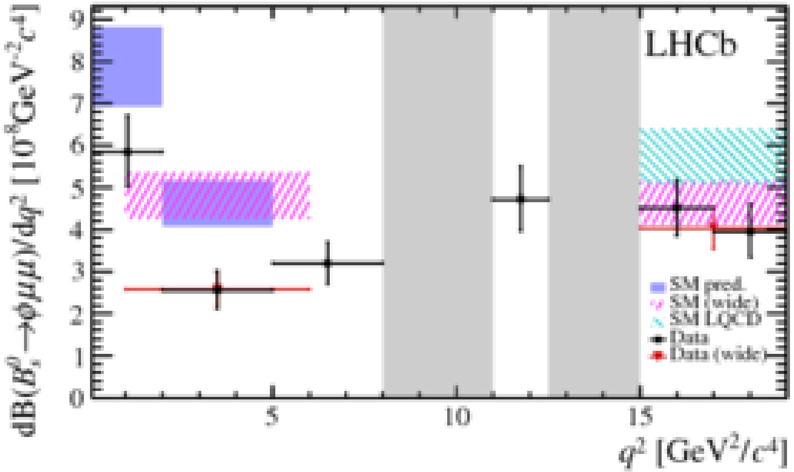
The measurement are in agreement with standard model predictions

ATLAS-CONF-2017-023
(March 2017)

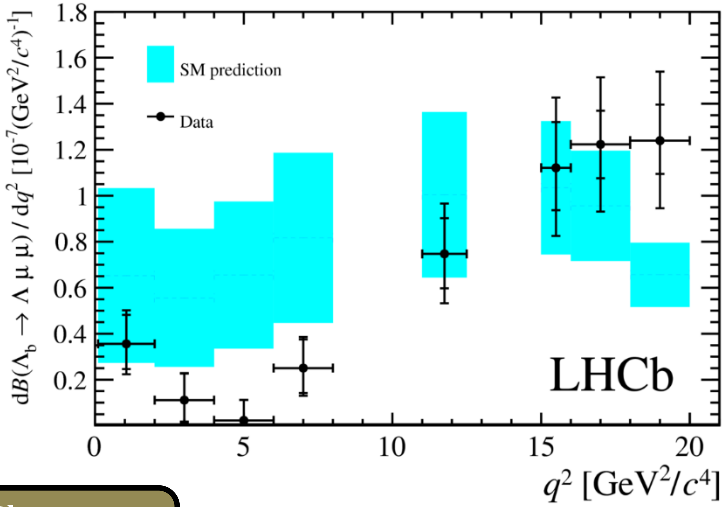
CMS PAS BPH-15-008
(March 2017)

BRs too low in $b \to s\mu^+\mu^-$ decays?

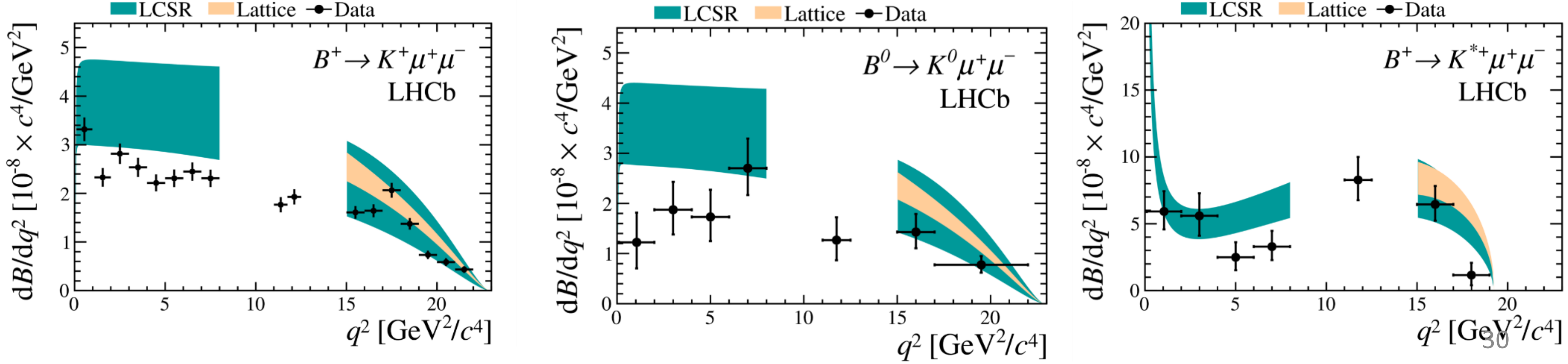
LHCb,
JHEP 09 (2015) 179



LHCb,
JHEP 06 (2015) 115



LHCb,
JHEP 06 (2014) 133

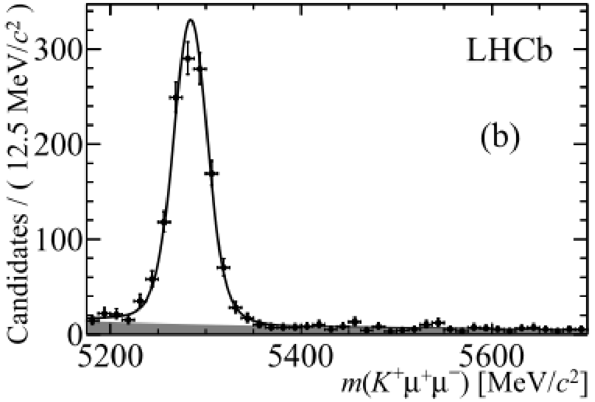


$B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$

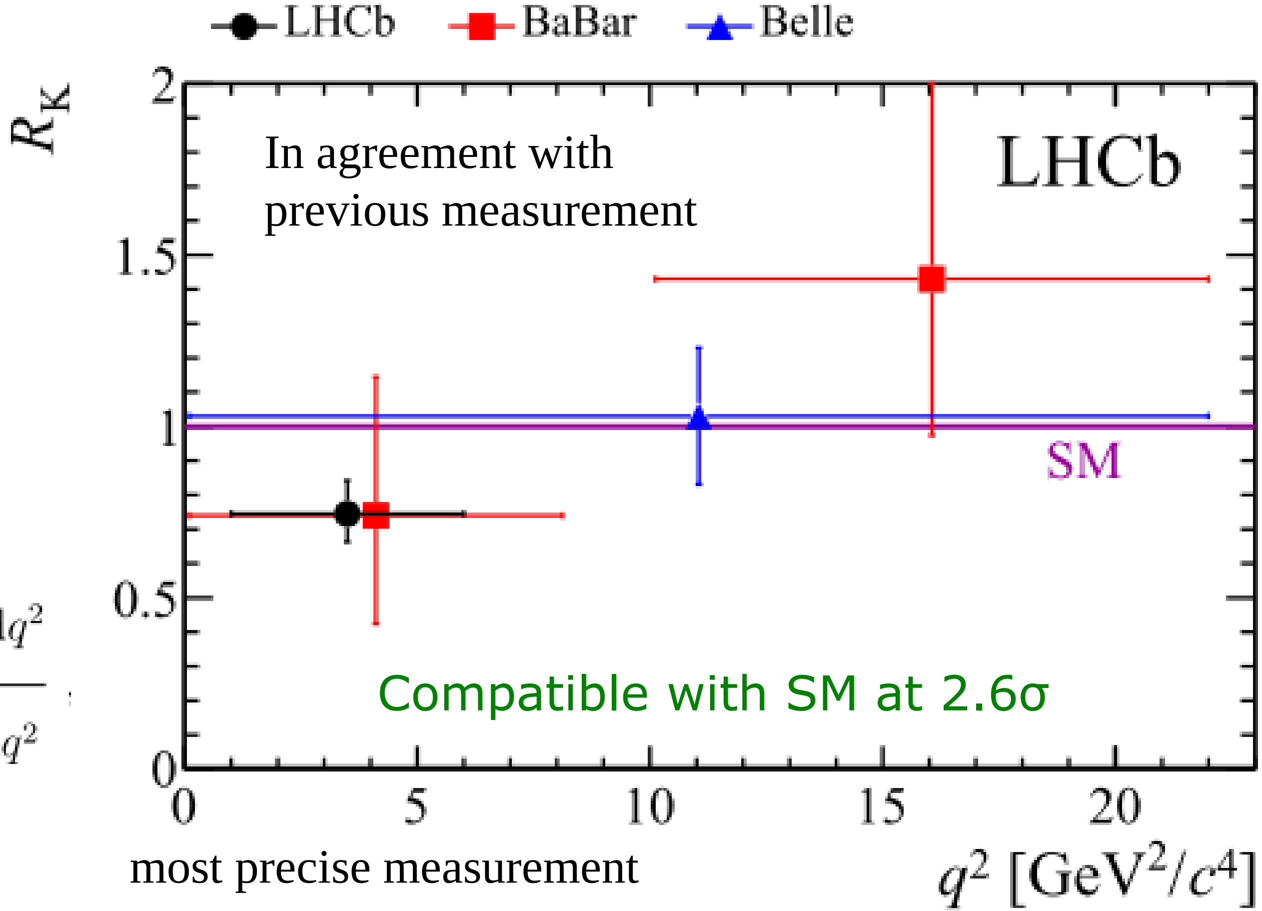
Test of lepton universality – key aspect of SM

Ratio ~1 in SM, with negligible theoretical uncertainties

LHCb,
PRL 113 (2014) 15160



$$R_K = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma[B^+ \to K^+\mu^+\mu^-]}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma[B^+ \to K^+e^+e^-]}{dq^2} dq^2}$$



In agreement with previous measurement

Compatible with SM at 2.6σ

most precise measurement

LHCb

$$R_k = 0.745^{+0.090}_{-0.074}\,(stat) \mp 0.036\,(syst)$$

$B^0 \rightarrow K^{*0}\mu^+\mu^-$ and $B^0 \rightarrow K^{*0}e^+e^-$

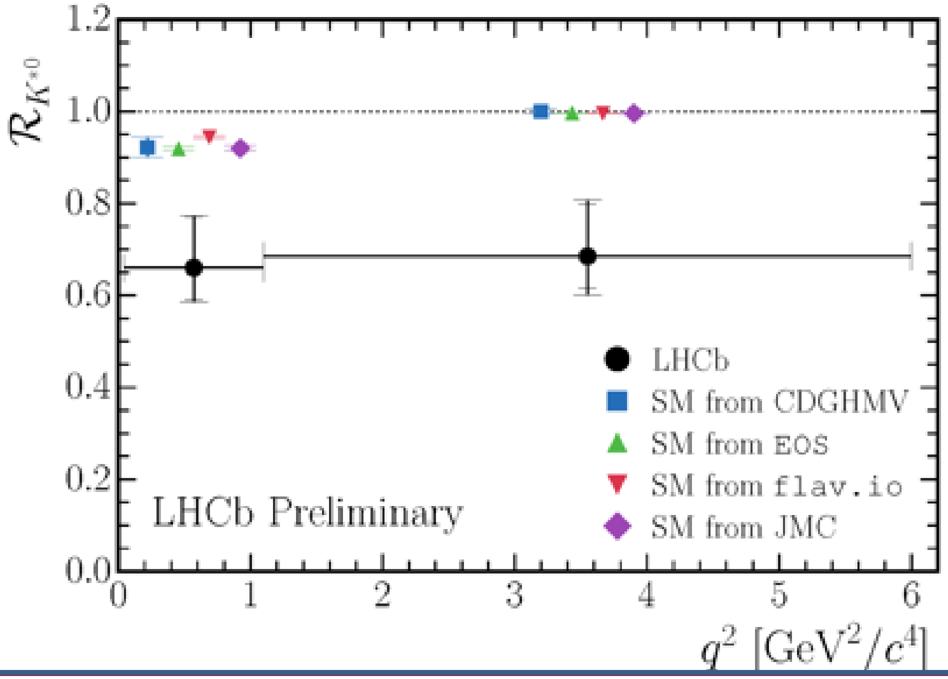
Test of lepton universality – key aspect of SM

Ratio ~1 in SM, with negligible theoretical uncertainties

LU means that leptons (e.g., electrons e and muons μ) behave in the same way, i.e., they have the same couplings to gauge bosons

2.1-2.3σ and 2.4-2.5σ away from SM at low and central-q^2, respectively.

new

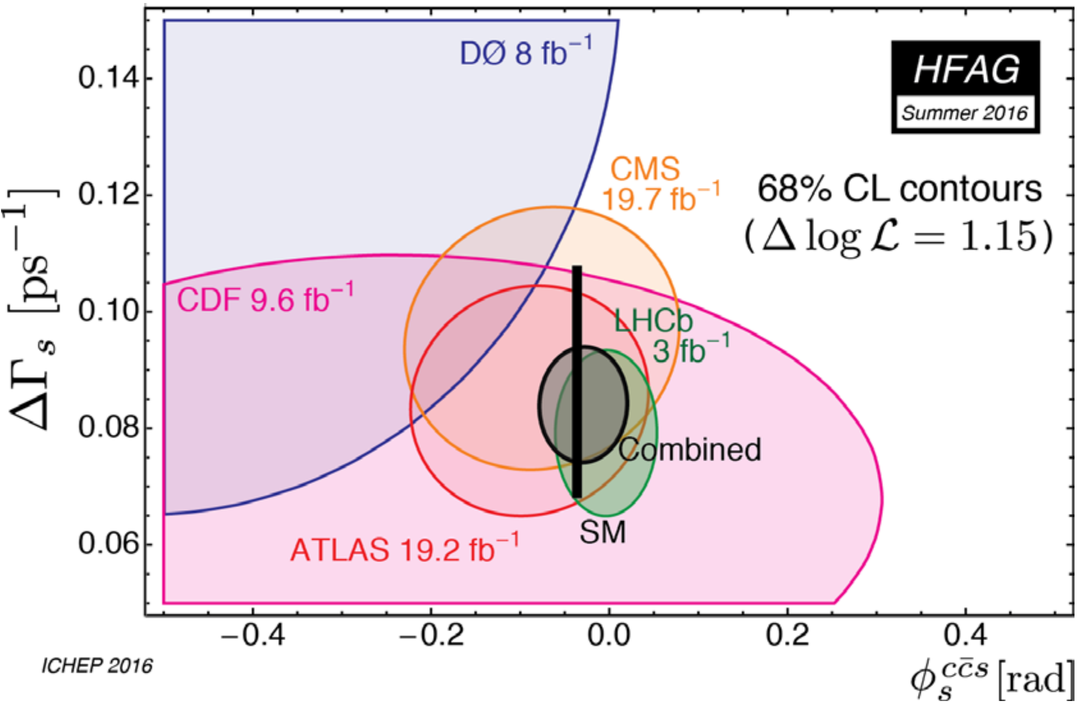


arXiv, 1705.05802

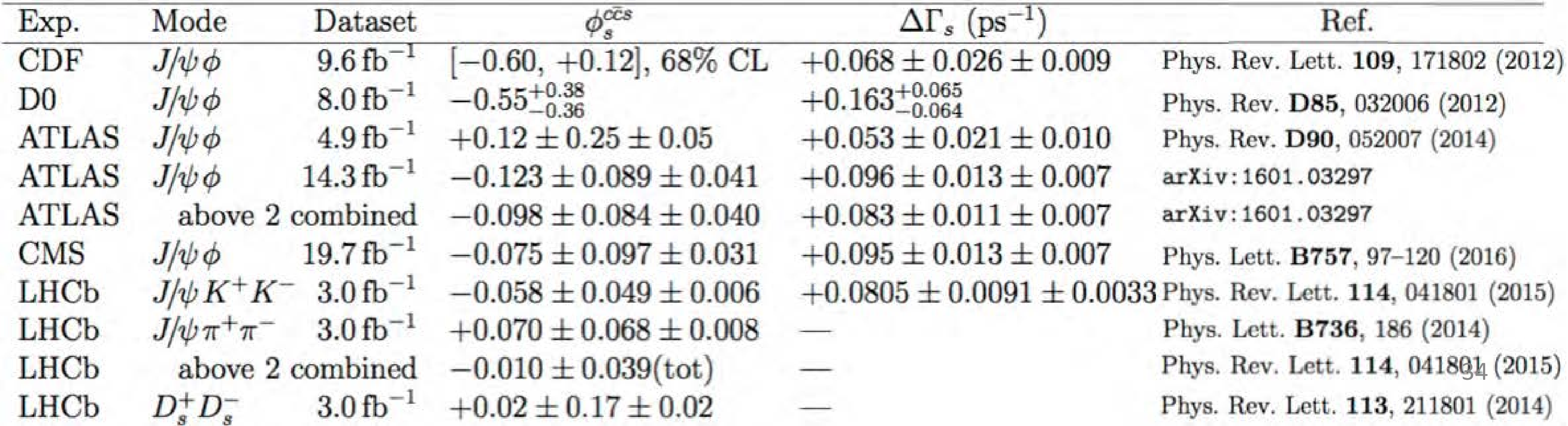
$$R_{K^{*0}} = \begin{cases} 0.660^{+0.110}_{-0.070} \pm 0.024 & \text{for } 0.045 < q^2 < 1.1\ \text{GeV}^2/c^4 \\ 0.685^{+0.113}_{-0.069} \pm 0.047 & \text{for } 1.1 < q^2 < 6.0\ \text{GeV}^2/c^4 \end{cases}$$

CP violation

B_s mixing



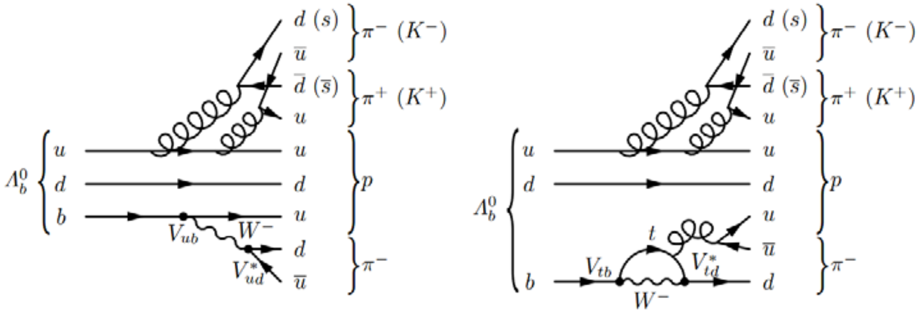
- ✓ Several measurements at Tevatron and LHC
- ✓ World average:
  ϕ_s = -34 ± 33 mrad
- ✓ Combination of
  - $B^0_s \rightarrow J/\psi K^+K^-$
  - $B^0_s \rightarrow J/\psi \pi^+\pi^-$
  - $B^0_s \rightarrow D_s^+D_s^-$
- ✓ Excellent agreement with SM
- ✓ Statistical limited

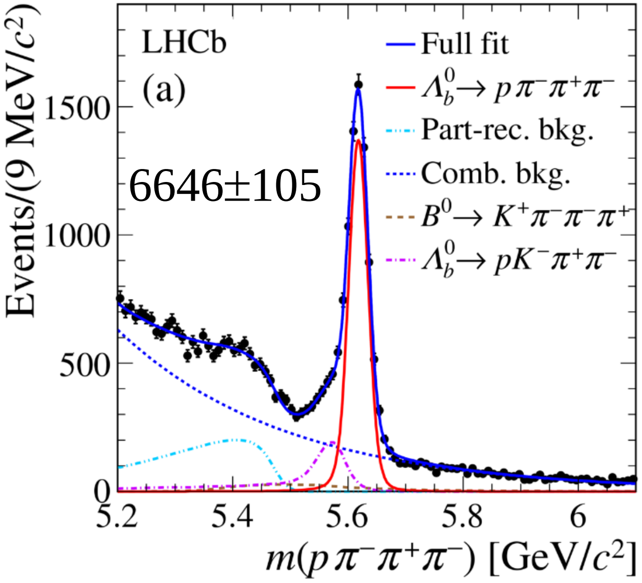


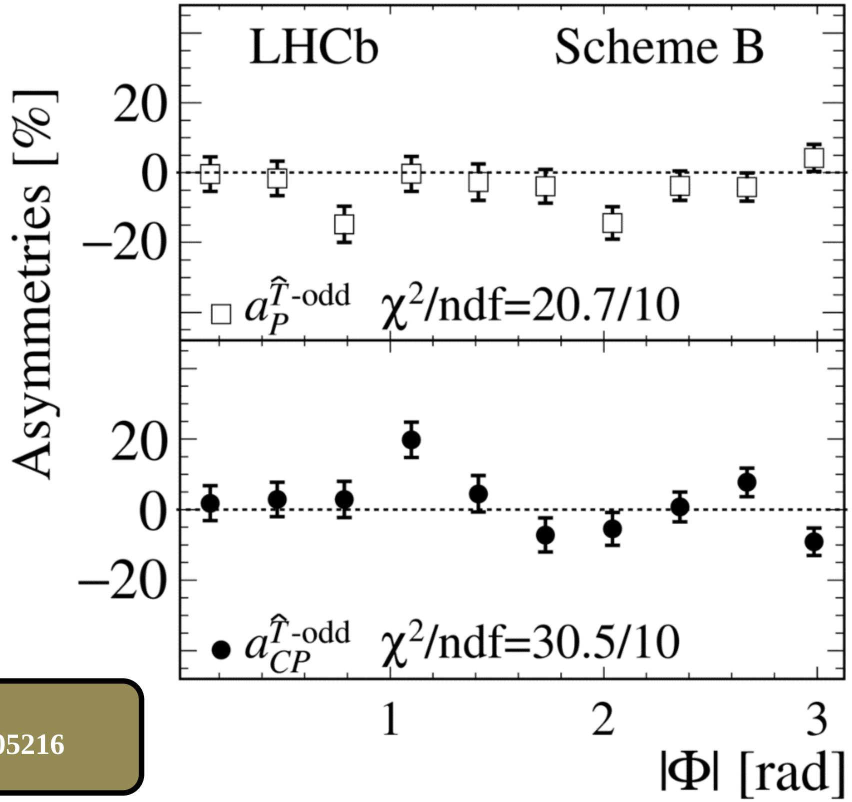
Exp.	Mode	Dataset	$\phi_s^{c\bar{c}s}$	$\Delta\Gamma_s$ (ps^{-1})	Ref.
CDF	$J/\psi\phi$	9.6 fb^{-1}	[−0.60, +0.12], 68% CL	$+0.068 \pm 0.026 \pm 0.009$	Phys. Rev. Lett. **109**, 171802 (2012)
D0	$J/\psi\phi$	8.0 fb^{-1}	$-0.55^{+0.38}_{-0.36}$	$+0.163^{+0.065}_{-0.064}$	Phys. Rev. **D85**, 032006 (2012)
ATLAS	$J/\psi\phi$	4.9 fb^{-1}	$+0.12 \pm 0.25 \pm 0.05$	$+0.053 \pm 0.021 \pm 0.010$	Phys. Rev. **D90**, 052007 (2014)
ATLAS	$J/\psi\phi$	14.3 fb^{-1}	$-0.123 \pm 0.089 \pm 0.041$	$+0.096 \pm 0.013 \pm 0.007$	`arXiv:1601.03297`
ATLAS	above 2 combined		$-0.098 \pm 0.084 \pm 0.040$	$+0.083 \pm 0.011 \pm 0.007$	`arXiv:1601.03297`
CMS	$J/\psi\phi$	19.7 fb^{-1}	$-0.075 \pm 0.097 \pm 0.031$	$+0.095 \pm 0.013 \pm 0.007$	Phys. Lett. **B757**, 97–120 (2016)
LHCb	$J/\psi K^+K^-$	3.0 fb^{-1}	$-0.058 \pm 0.049 \pm 0.006$	$+0.0805 \pm 0.0091 \pm 0.0033$	Phys. Rev. Lett. **114**, 041801 (2015)
LHCb	$J/\psi\pi^+\pi^-$	3.0 fb^{-1}	$+0.070 \pm 0.068 \pm 0.008$	—	Phys. Lett. **B736**, 186 (2014)
LHCb	above 2 combined		-0.010 ± 0.039(tot)	—	Phys. Rev. Lett. **114**, 041801 (2015)
LHCb	$D_s^+D_s^-$	3.0 fb^{-1}	$+0.02 \pm 0.17 \pm 0.02$	—	Phys. Rev. Lett. **113**, 211801 (2014)

CP-violation in baryon decays

CP-violation has been observed in K^0, B^0 and B^0_s decays
BUT not yet in any baryon decay
First evidence for CP violation in baryon decays ($\Lambda^0_b \to p\pi^-\pi^+\pi^-$)



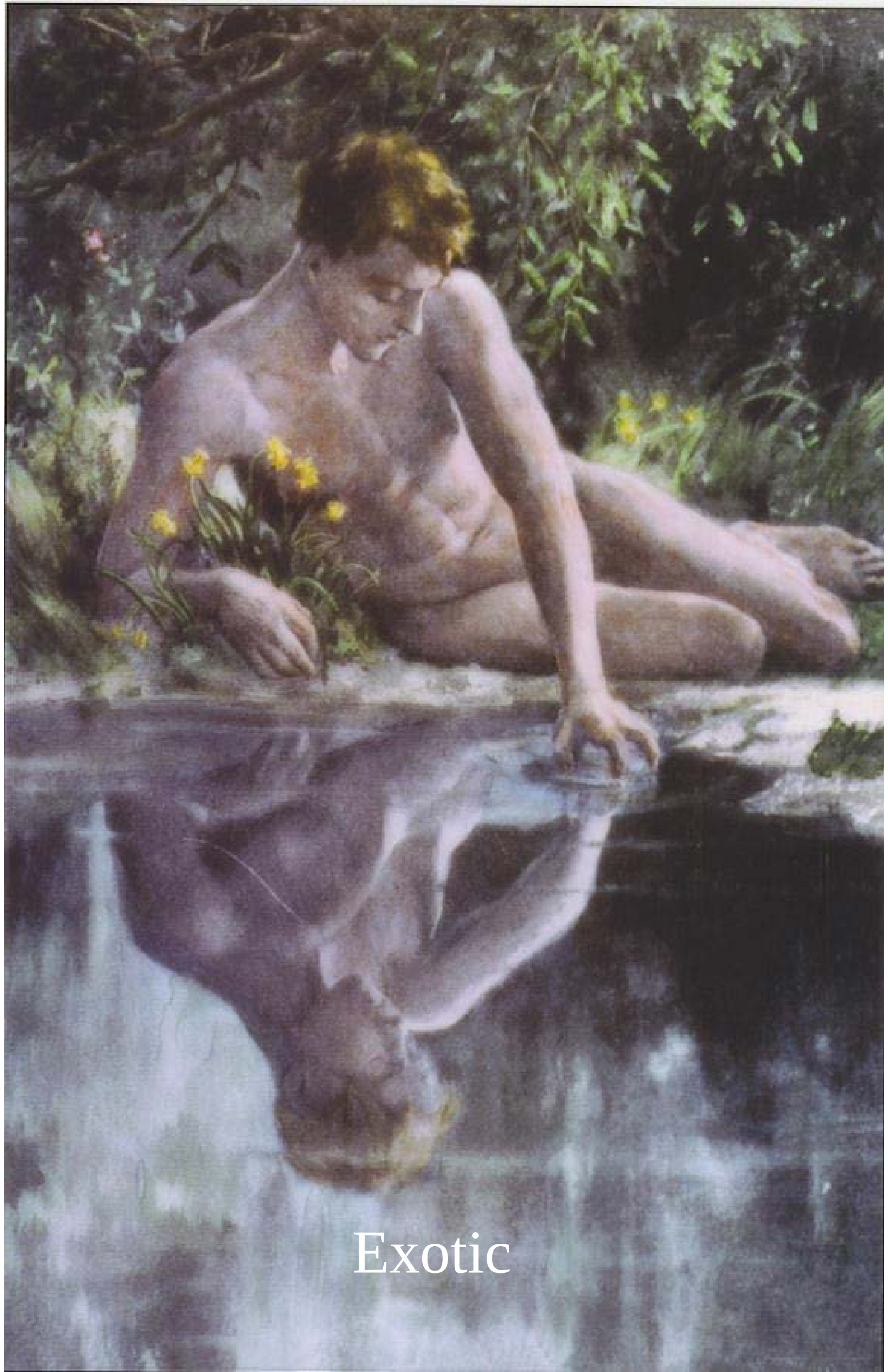




**LHCb,
arXiv 1609.05216**

The statistical significance of these asymmetries differing from zero is 3.3σ

Chamonium



Charmonium-like states

Exotic

Pentaquark, tetraquark …

Quark model

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" 1-3), we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone 4). Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

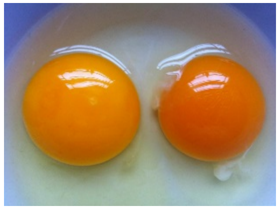
Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means of dispersion theory, there are still meaningful and important questions regarding the algebraic properties of these interactions that have so far been discussed only by abstracting the properties from a

ber $n_t - n_{\bar t}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

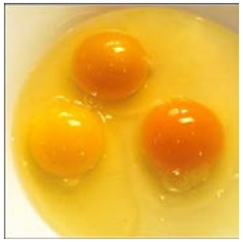
A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

A formal mathematical model based on field theory can be built up for the quarks exactly as for p, n, Λ in the old Sakata model, for example 3) with all strong interactions ascribed to a neutral

meson



baryon



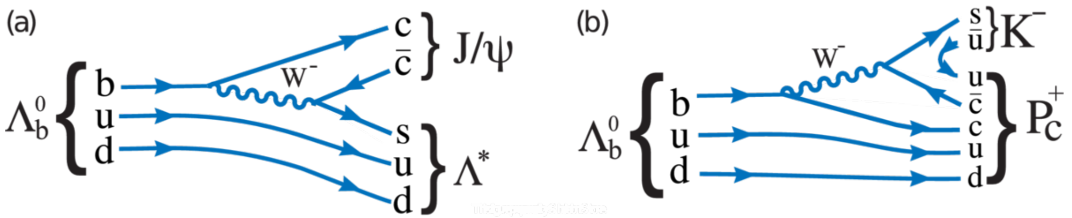
tetraquark

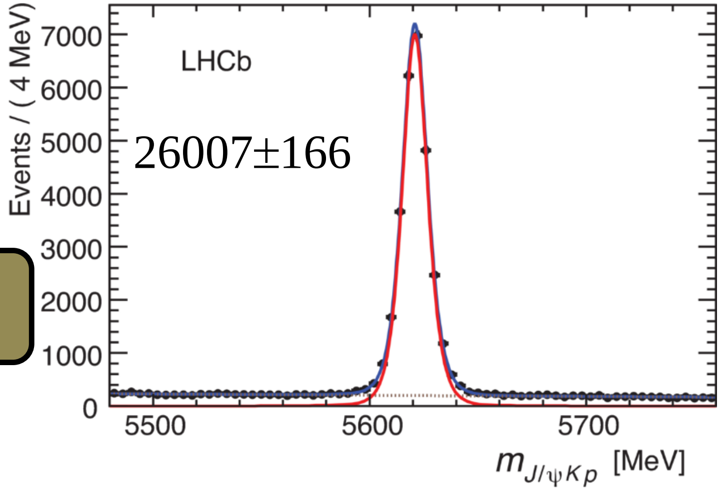
pentaquark

Pentaquarks in $\Lambda_b \to J/\psi p K^-$ decays

Two pentaquark-charmonium states decaying into a J/ψ meson and a proton p

$uudc\bar{c}$

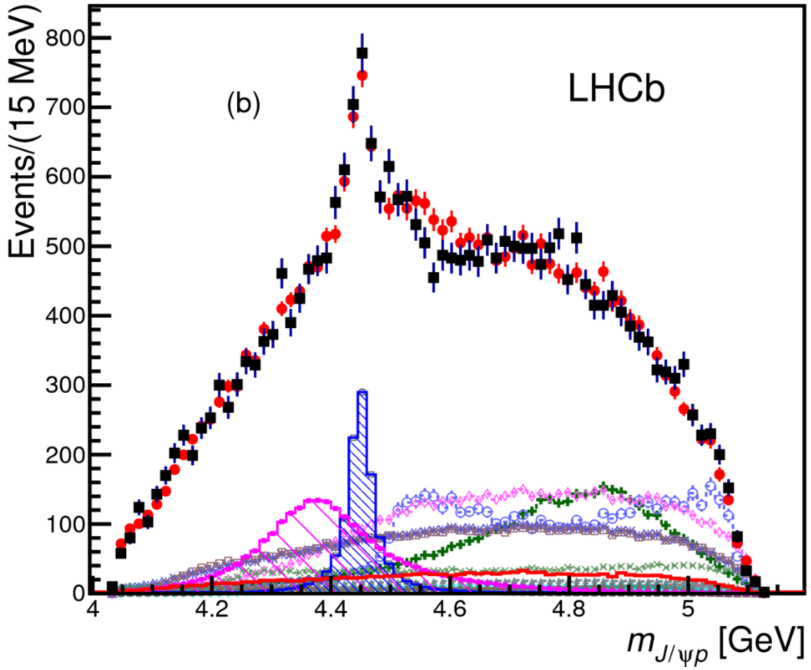




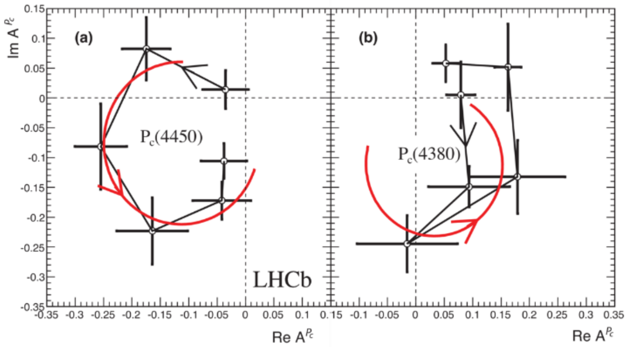
26007±166

LHCb,
PRL 115 (2015) 072001

statistical significance 9σ and 12σ



State	J^P	Mass [MeV/c^2]	Width [MeV]
$P_c(4380)^+$	$\frac{3}{2}^-$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$
$P_c(4450)^+$	$\frac{5}{2}^+$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$



Tetraquark Z(4430)$^-$

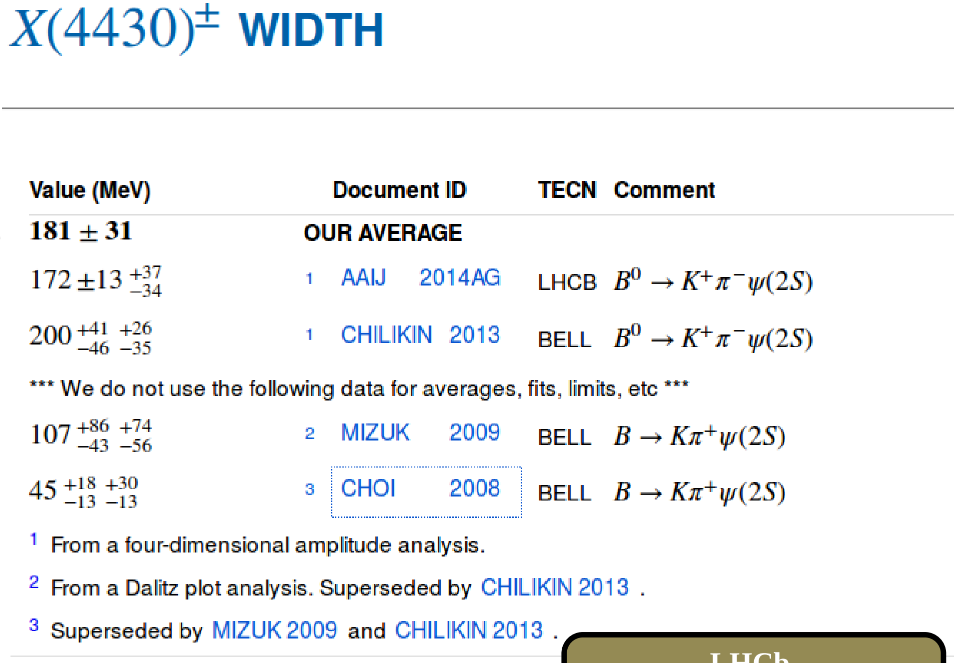
$B^0 \rightarrow \psi(2S)\,\pi^- K^+$

First result from Belle

BaBar did not confirm Z(4430)$^-$ in B sample comparable to Belle
Did not numerically contradict the Belle results
$BR(B^0 \rightarrow Z^- K^+) \times BR(Z^- \rightarrow \pi^- \psi(2S)) < 3.1\times10^{-5}$

Next analysis in Belle

LHCb observed the Z(4430) particle and established its quantum numbers which make it the first confirmed unambiguous tetraquark $(cu\overline{cd})$



$X(4430)^{\pm}$ WIDTH

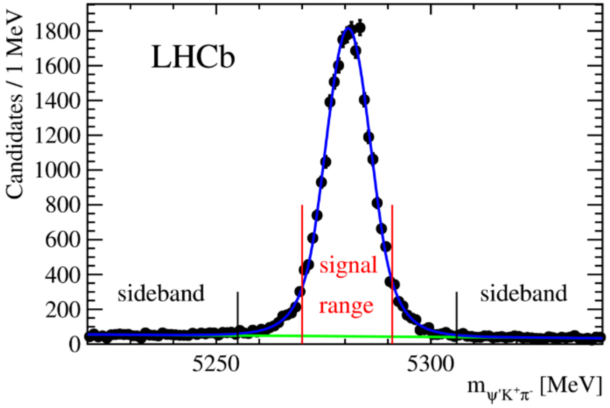
Value (MeV)		Document ID	TECN	Comment
181 ± 31		**OUR AVERAGE**		
$172 \pm 13\,^{+37}_{-34}$	[1]	AAIJ 2014AG	LHCB	$B^0 \rightarrow K^+\pi^-\psi(2S)$
$200\,^{+41}_{-46}\,^{+26}_{-35}$	[1]	CHILIKIN 2013	BELL	$B^0 \rightarrow K^+\pi^-\psi(2S)$
*** We do not use the following data for averages, fits, limits, etc ***				
$107\,^{+86}_{-43}\,^{+74}_{-56}$	[2]	MIZUK 2009	BELL	$B \rightarrow K\pi^+\psi(2S)$
$45\,^{+18}_{-13}\,^{+30}_{-13}$	[3]	CHOI 2008	BELL	$B \rightarrow K\pi^+\psi(2S)$

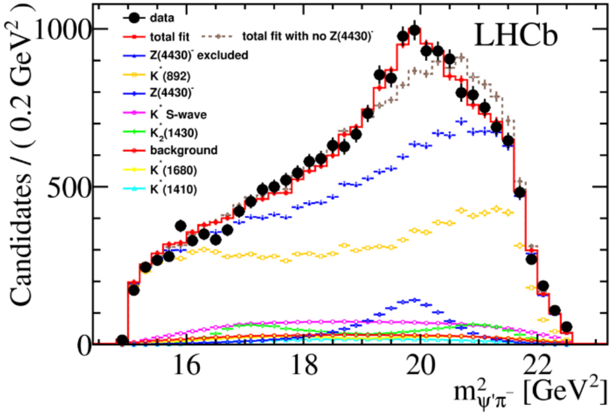
[1] From a four-dimensional amplitude analysis.

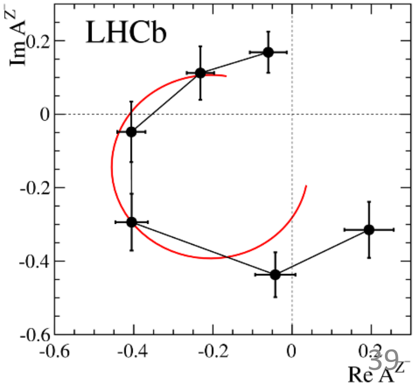
[2] From a Dalitz plot analysis. Superseded by CHILIKIN 2013 .

[3] Superseded by MIZUK 2009 and CHILIKIN 2013 .

LHCb,
PRL 112 (2014) 222002







D0 tetraquark

LHCb,
PRL 117 (2016) 152003

PRL 117 (2016) 022003 (February 2016)

D0 announces observation of exotic state

(b,s,u,d) $X(5568) \to B_s\pi^+$

$N(B_s) \sim 5500$

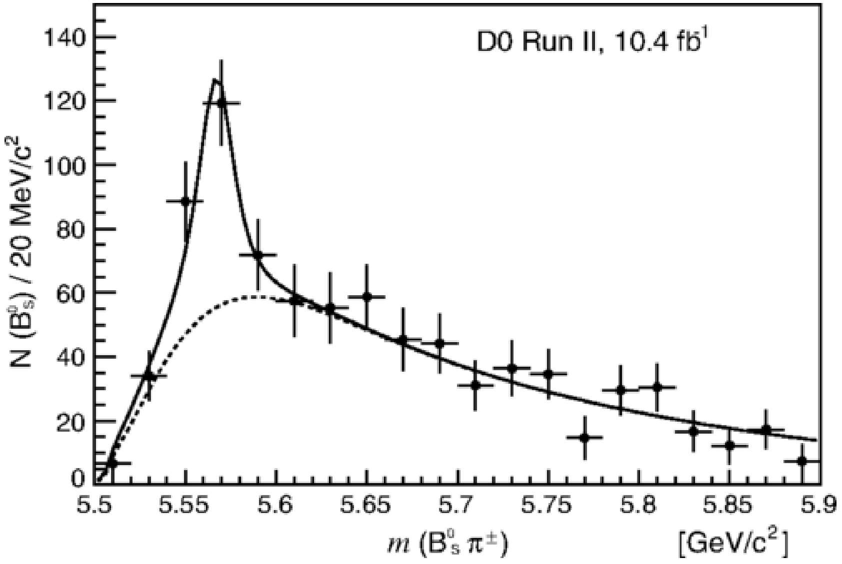
arXiv 1608:00435 (April 2016)

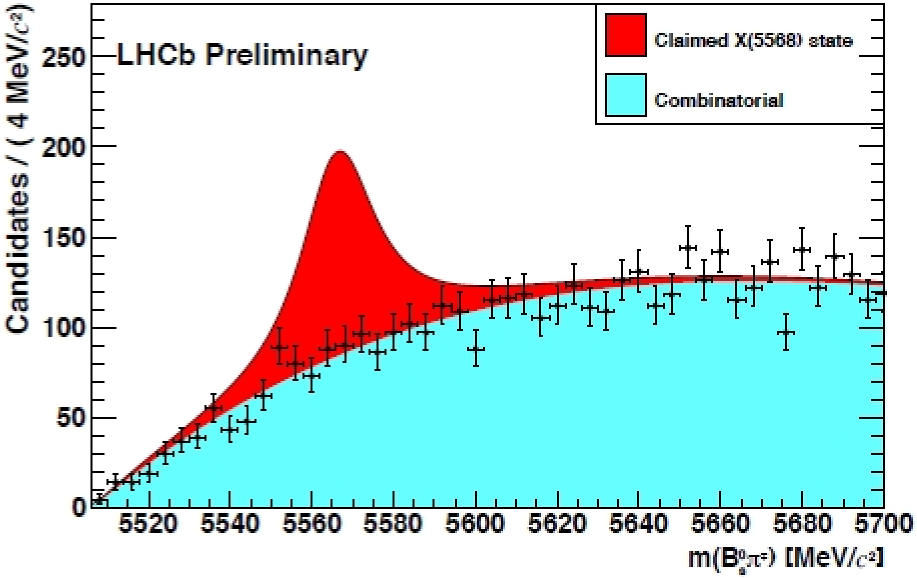
LHCb: Phys. Rev. Lett. 117, 152003 (2016)

Existence of X(5568) not confirmed

$N(B_s) \sim 110$ k

What we should have seen





$B_s \to J/\psi\phi$

$\rho_X = (8.6 \pm 1.9 \pm 1.4)\%$

production rate wrt B_s

ρ_X ($p_T(B_s)$> 5 GeV/c) < 0.011 (0.012)

ρ_X ($p_T(B_s)$>10 GeV/c) < 0.021 (0.024)

ρ_X ($p_T(B_s)$>15 GeV/c) < 0.018 (0.020)

90% (95%) CL

D0 tetraquark

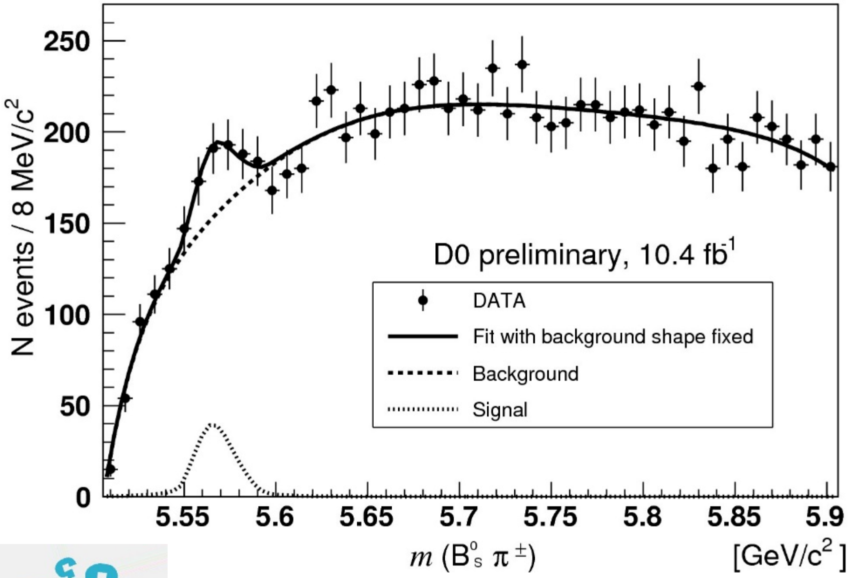
D0 conference note 6496 (March 2017)

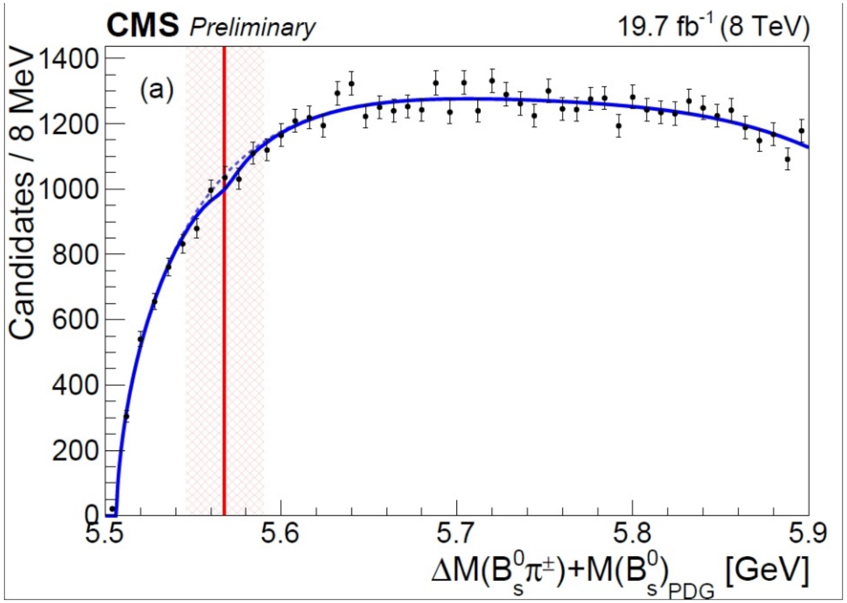
Confirmation of the X(5568) with semileptonic decays of the B_s mesons

CMS physics analysis summary 16-002 (August 2016)

Search for the X(5568) state in $B_s\pi^+$ decays

$N(B_s) \sim 48000$



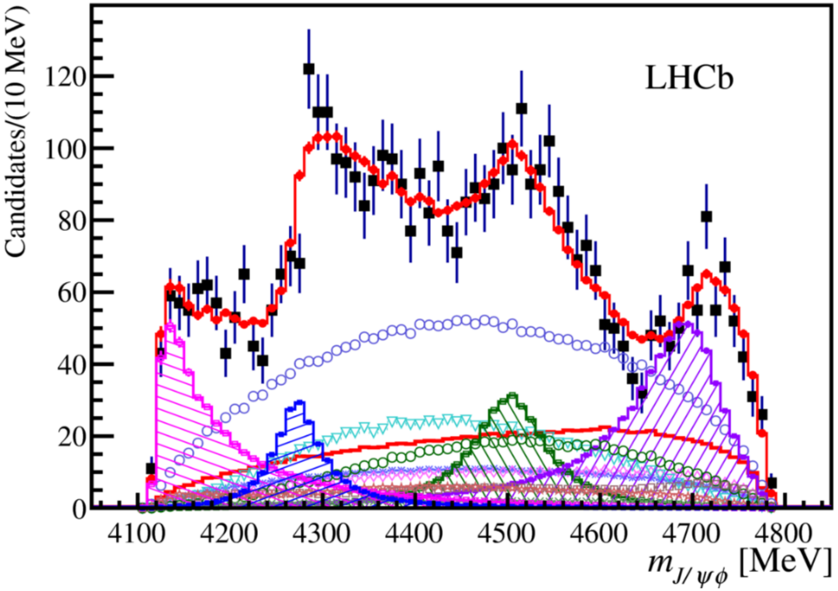


ρ_X (CMS) < 3.9% @ 95 CL

Observation of exotic $J/\psi\phi$ *structures in* $B^+ \rightarrow J/\psi\phi K^+$

Amplitude analysis of $B^+ \rightarrow J/\psi\phi K^+$ decays with $\phi \rightarrow K^-K^+$

- ✓ Simultaneous analysis of $M(J/\psi\phi)$, $M(\phi K^+)$ and decay angle distributions



Evidence for X(4140) near threshold $J/\psi\ \phi$ mass peak first announced by CDF, later confirmed by D0 and CMS

Searches by Belle and BaBar gave negative results

**LHCb,
PRL 118 (2017) 022003**

Consistent with 4-quark particles $c\bar{c}s\bar{s}$

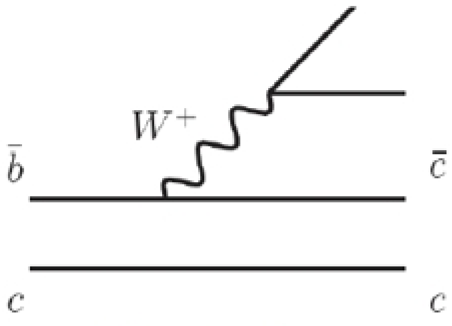
	signif	M, MeV/c²	width
X(4140)	8.4σ	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$
X(4274)	6.0σ	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56 \pm 11^{+8}_{-11}$
X(4500)	6.1σ	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$
X(4700)	5.6σ	$4706 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$

LHC – new era for B^+_c physics

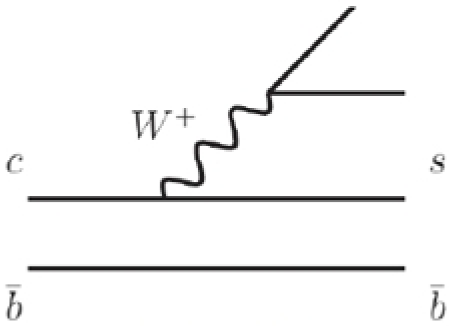
Beauty **charm**

Features

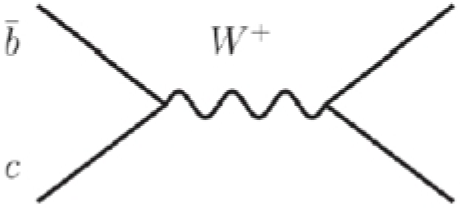
- ✓ Only meson consisting of two heavy quarks of different flavours
- ✓ From the spectroscopy view system is the heavy quarkonium
- ✓ Unique probe of both strong and weak interactions
- ✓ The heaviest meson that decays through weak interactions with either c- or b-quark decaying or through their weak annihilation
- ✓ Discovered in 1998 by the CDF ($B_c^+ \to J/\psi\pi^+$)
- ✓ No possibility to study at current e+e- machine
- ✓ Lifetime is almost three times smaller than that of other beauty mesons pointing to the important role of the c-quark in weak B_c^+ decays
- ✓ In PDG2013 $\tau(B_c^+) = 0.452 \pm 0.033$ ps (while $\tau(B^+) < 0.7\%$)



$B_c^+ \to J/\psi\, \ell^+ \upsilon$
$B_c^+ \to J/\psi\pi^+$



$B_c^+ \to B_s^0\, \ell^+ \upsilon$
$B_c^+ \to B_s^0 \pi^+$

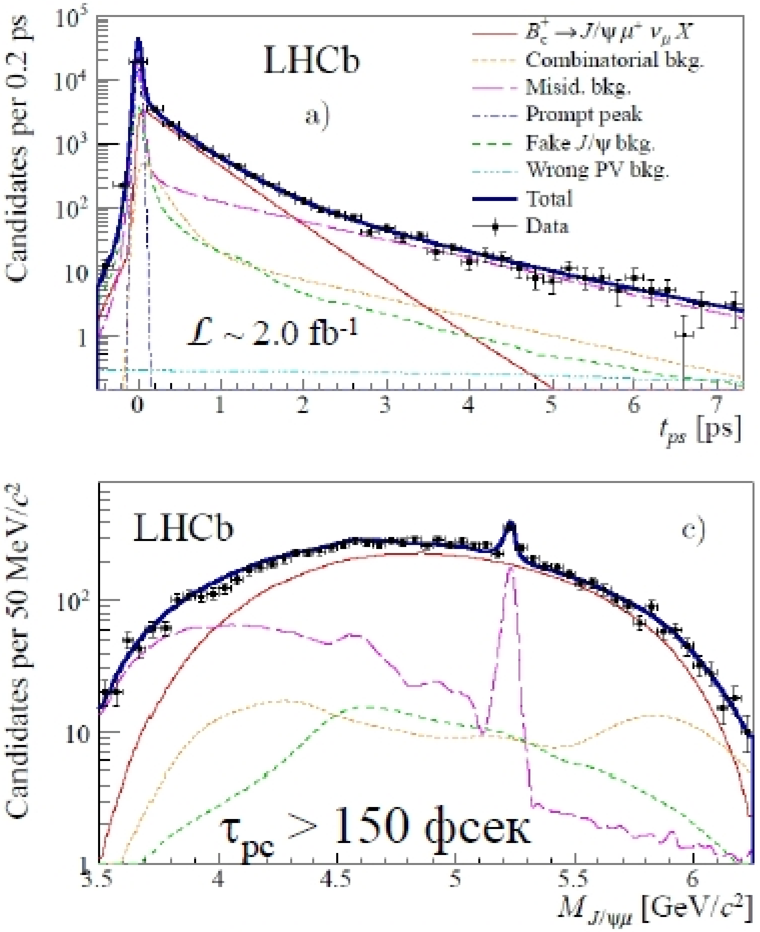


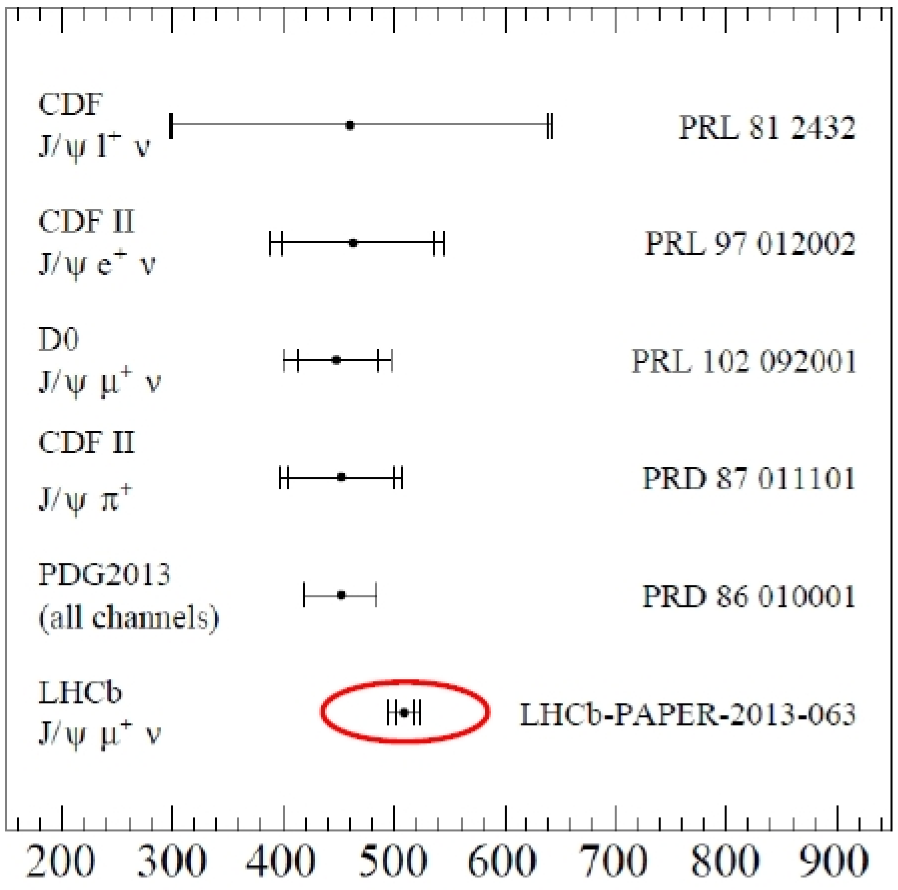
$B_c^+ \to \tau^+ \upsilon$

Lifetime measurement

LHCb,
EPJC 74 ((2014) 2839

semileptonic decays





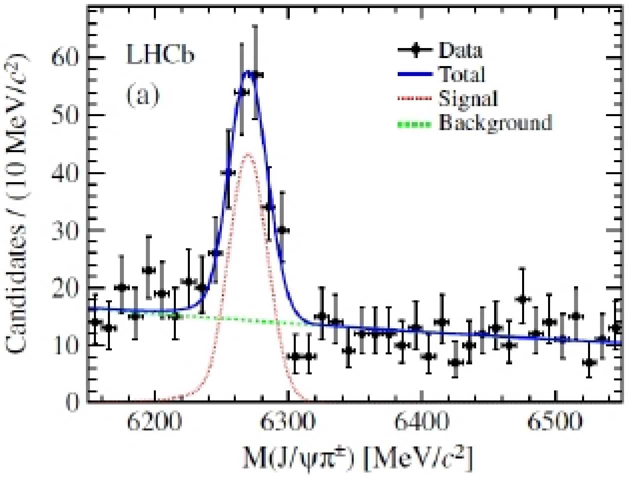
LHCb:

$\tau(B_c^+)$ = 509 ± 8(stat) ± 12(syst) fs

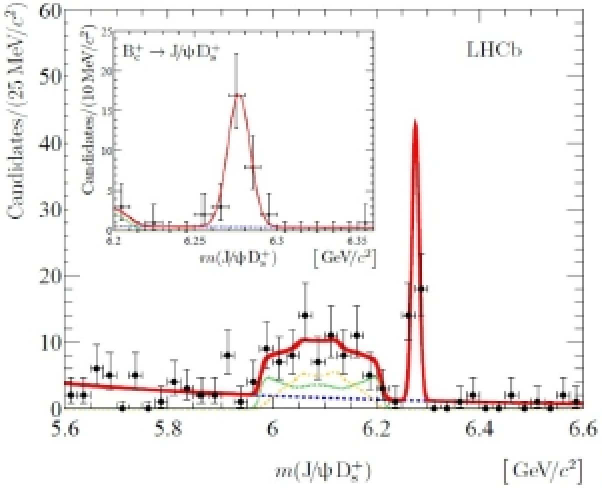
Mass measurement

CDF and D0 average: 6277 ± 6 MeV/c^2

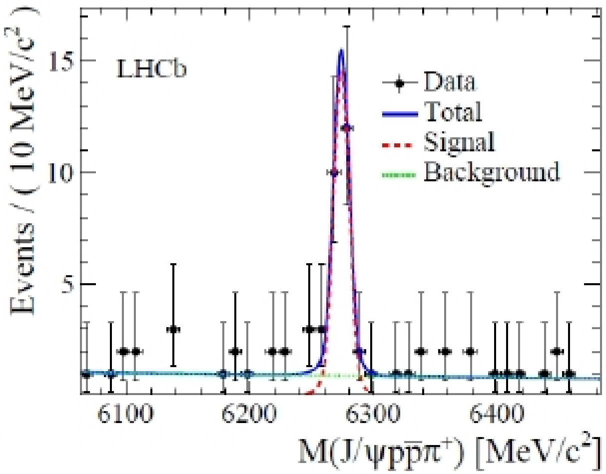
$\mathcal{L} \sim 0.37\ \text{fb}^{-1}$



$\mathcal{L} \sim 3.0\ \text{fb}^{-1}$



$\mathcal{L} \sim 3.0\ \text{fb}^{-1}$



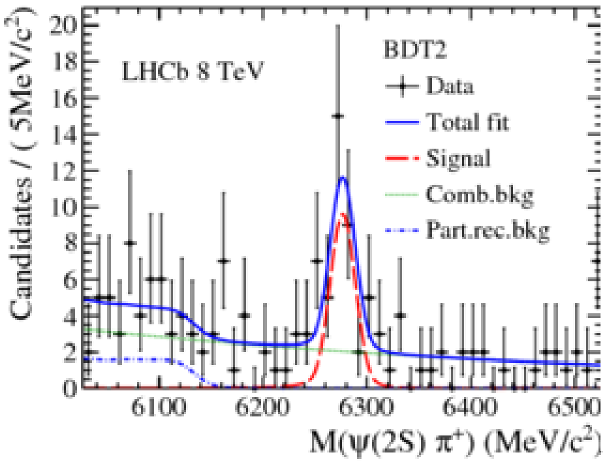
Decay mode	Mass, MeV/c^2
$B_c^+ \rightarrow J/\psi\pi^+$	6273.7 ± 1.3 (stat) ± 1.6 (syst)
$B_c^+ \rightarrow J/\psi D_s^+$	6276.28 ± 1.44 (stat) ± 0.36 (syst)
$B_c^+ \rightarrow J/\psi p\bar{p}\pi^+$	6274.0 ± 1.8 (stat) ± 0.4 (syst)

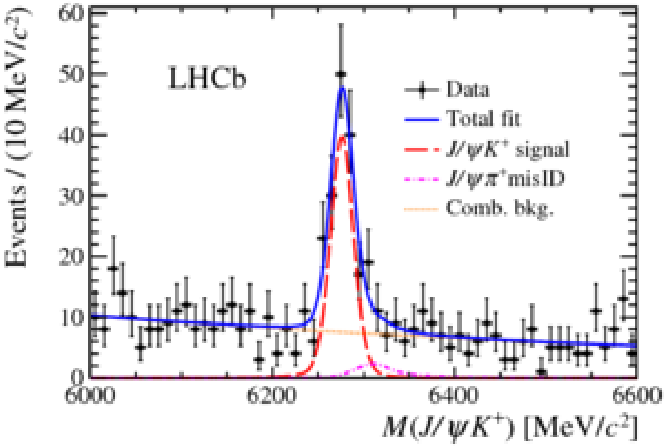
LHCb:

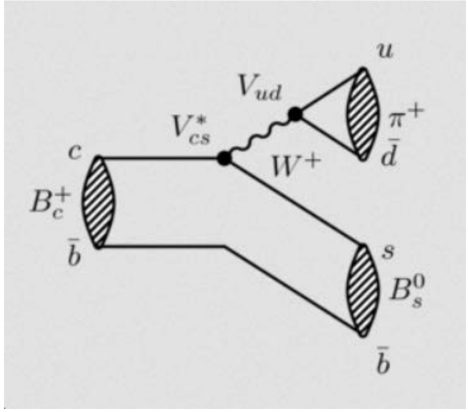
$M(B_c^+) = 6274.7 \pm 0.9(\text{stat}) \pm 0.8(\text{syst})\ \text{MeV}/c^2$

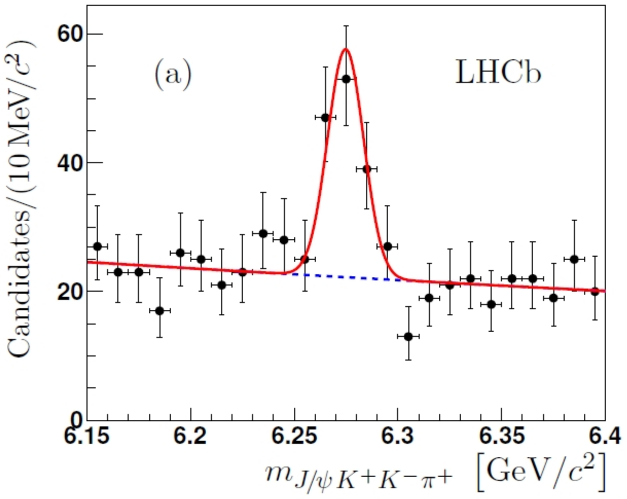
New decays

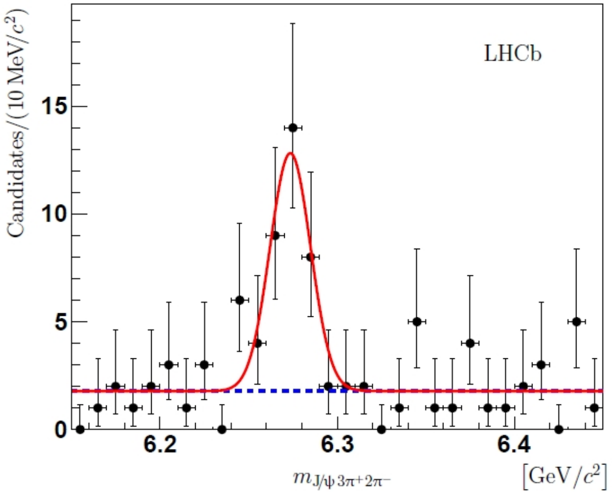
First observation of *B* meson decaying to another *B* meson via weak interaction

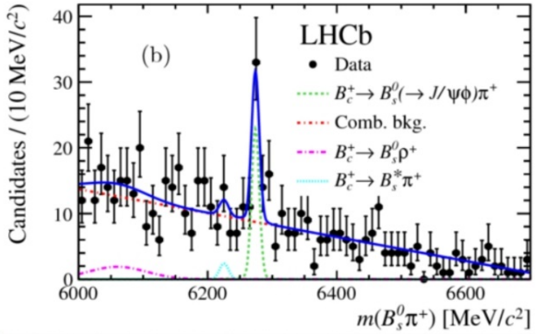




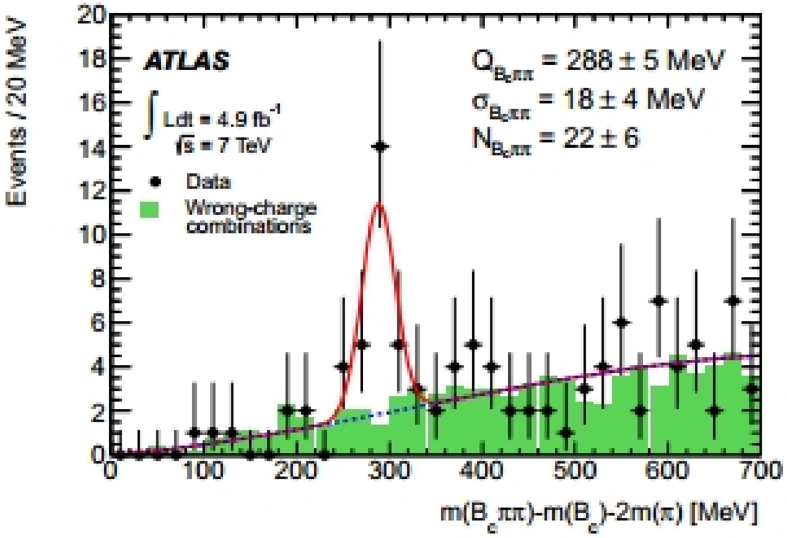


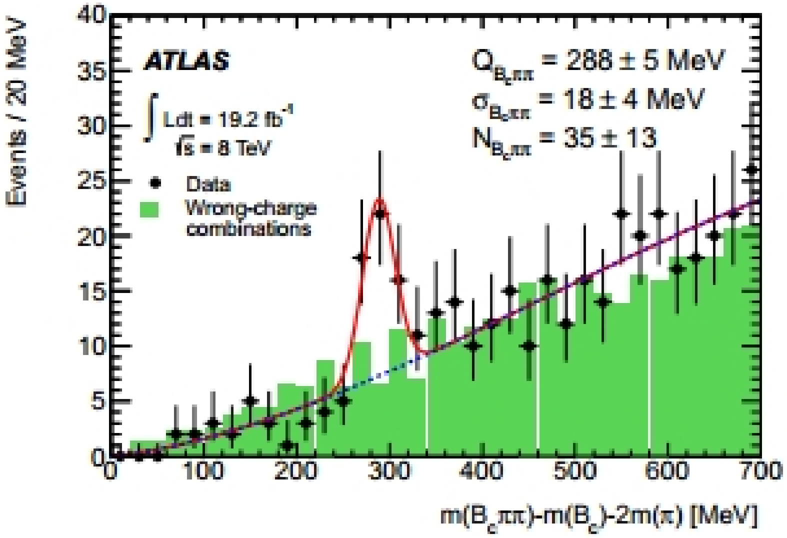






Excited B_c^+ meson state





$$B_c(2S)^+ \to B_c^+\,\pi^+\,\pi^-$$

$$B_c^+ \to J/\psi\,\pi^+$$

observed with 5.2 σ

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$$M(B_c(2S)^+) = 6842\ \pm 4 \pm 5$$

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PRL 113 (2014) 212004

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