Rare decays and exotic states in quark flavour physics

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On behalf of:

EPSHEP 2017

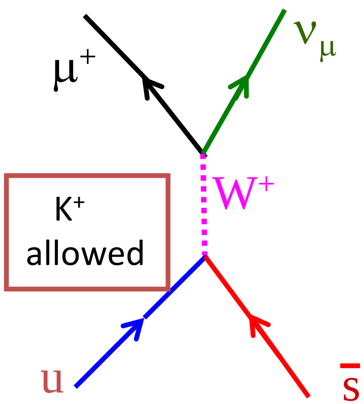
Outline

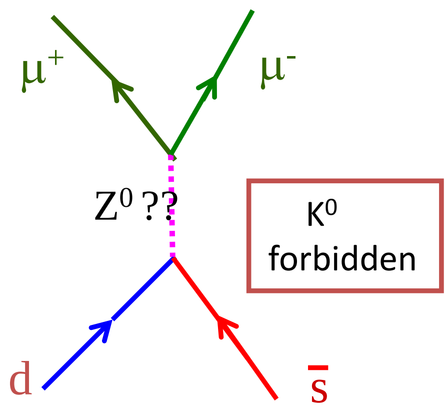
- Rare decays
  - Motivations
  - Beauty : $b \to s\ell\ell$ processes
  - Charm
  - Strange
- Exotic states
- Prospects

Why rare decays ?

- To look for new physics effects, in an *indirect* way

- Back to the 70's : Kaon semileptonic branching fractions





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

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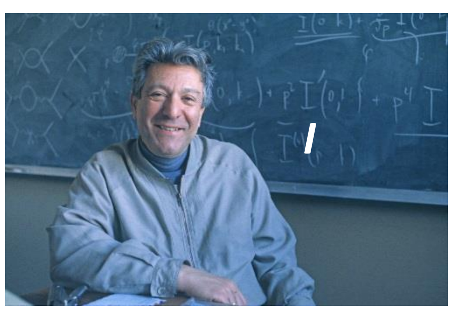

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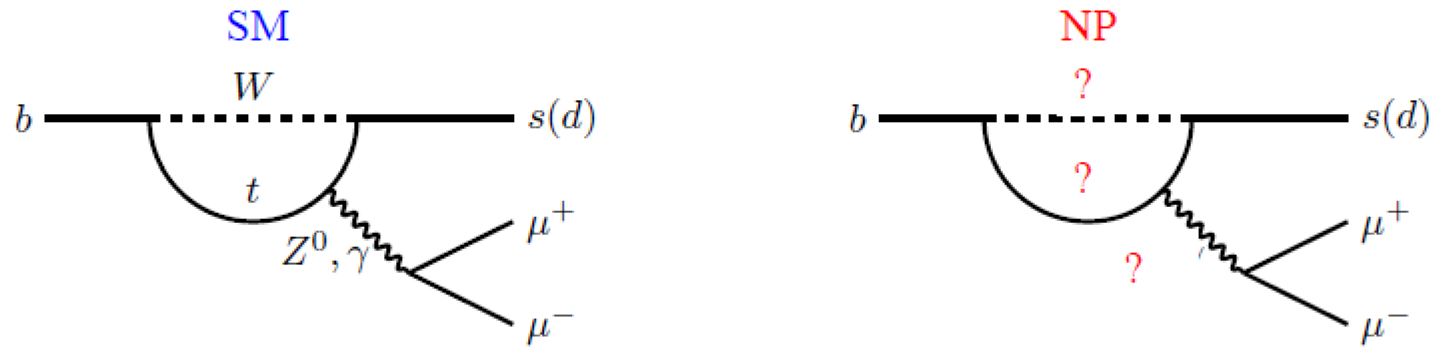
Flavour Changing Neutral Currents are heavily suppressed in the Standard Model

$\Rightarrow$ charm quark prediction

Why rare decays ?

- Flavour Changing Neutral Currents are forbidden at the tree level in the SM, they can only proceed through loop diagrams.



- NP virtual particles can enter the loop and modify observables such as branching ratios, CP asymmetries, angular distributions,…

- Complementary to direct searches as rare decays can probe a very high scale

Which rare decays ?

- The ones that have precise SM predictions and can be precisely measured

$\Rightarrow$ need statistics so high intensity experiments

e+e- : Belle, Babar, BES

pp: LHCb, ATLAS, CMS, D0, CDF

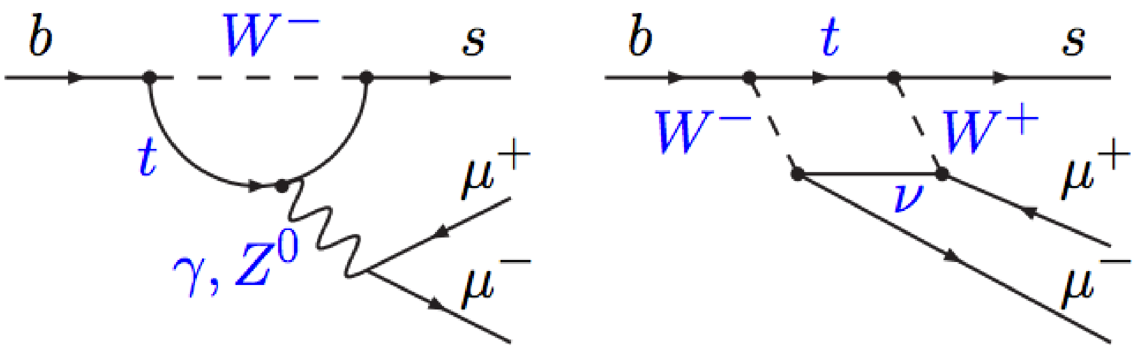
Dedicated experiments : NA62, KOTO, MEG, …

- The correlations between the observables allows to identify the type of new physics involved

$\Rightarrow$ important to measure all possible observables

- How rare ? Typical branching ratios are from 10^{-6} down to ~0 for forbidden decays (lepton flavour violation, lepton number violation,….)

$b \to s\ell\ell$



Phenomenology of b → sℓℓ

- b → sℓℓ decays can theoretically be described by effective hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i (C_i \mathcal{O}_i + C_i' \mathcal{O}_i')$$

left-handed part ($C_i \mathcal{O}_i$)

right-handed part suppressed in SM ($C_i' \mathcal{O}_i'$)

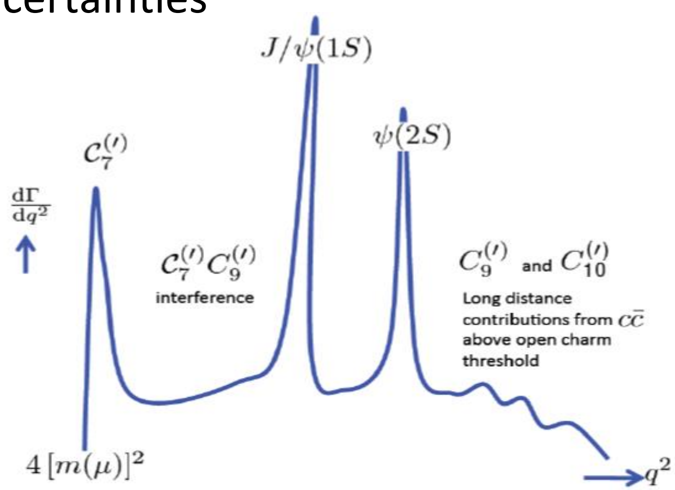
i=7 : photon

i=9 : vector current

i=10 : axial-vector current

i= S,P : scalar, pseudo scalar operators

- Wilson coefficient C_i describe short distance effects, they are sensitive to NP
- Operators O_i depends on hadronic form factors, which usually dominate theoretical uncertainties



- $B \to \ell\ell : C_{10}\, C_S\, C_P$
- $B \to X_s \gamma : C_7$
- $B \to K^* \ell\ell : C_7\, C_9\, C_{10}$

$q^2 = m_{\ell\ell}^2$

$B_{(s)} \to \ell^+\ell^-$

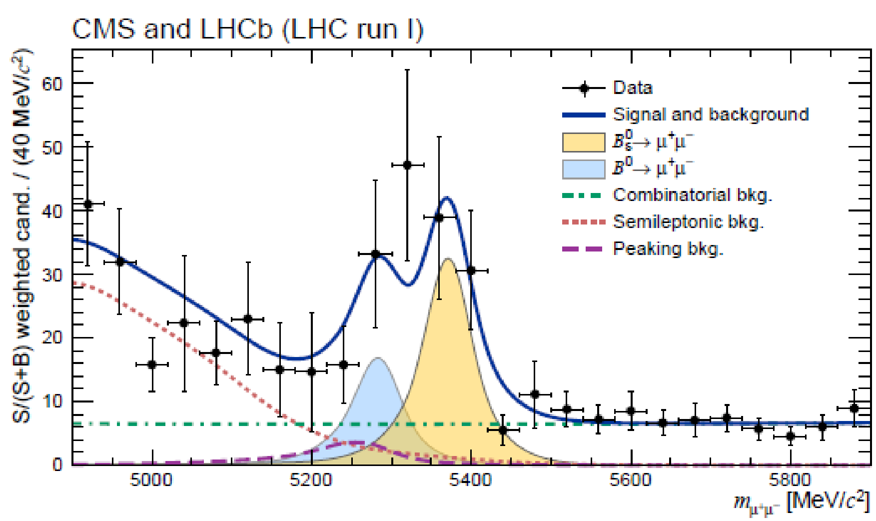
SM predictions for branching ratios:

	ee	μμ	ττ
B^0	$(2.48\pm0.21)\ 10^{-15}$	$(1.06\pm0.09)\ 10^{-10}$	$(2.22\pm0.19)\ 10^{-8}$
B_s	$(8.54\pm0.55)\ 10^{-14}$	$(3.65\pm0.23)\ 10^{-9}$	$(7.73\pm0.49)\ 10^{-7}$

PRL112(2014)101801

$B_{(s)} \to \mu^+\mu^-$:

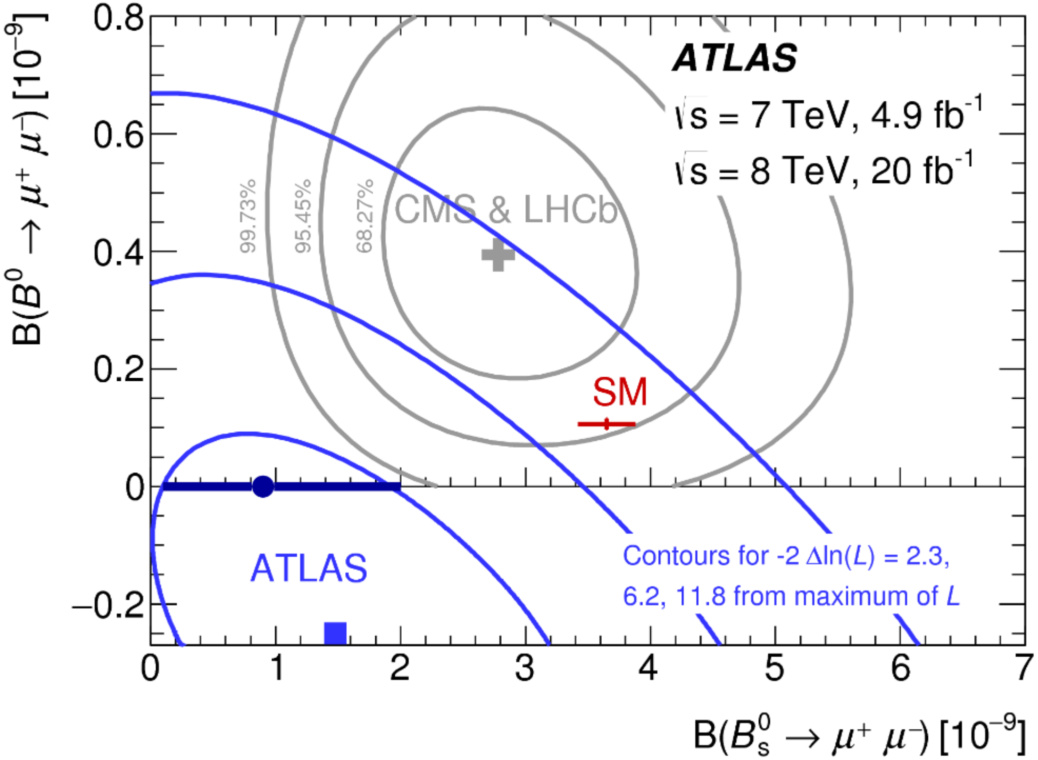
- Searched for 30 years
- First evidence of B_s decay in LHCb with $1fb^{-1}$
- Observation from CMS+LHCb combined Run1 analysis
- Good agreement with SM



Nature 522 (2015) 68

$B_{(s)} \rightarrow \mu^+\mu^-$

- ATLAS result with 25 fb^{-1} of Run1 data:



EPJC 76 (2016) 513

$$BR(B_S^0 \rightarrow \mu^+\mu^-) = (0.9^{+1.1}_{-0.8}) \times 10^{-9} \qquad BR(B^0 \rightarrow \mu^+\mu^-) < 4.2 \times 10^{-10} \quad \text{(95\%CL)}$$

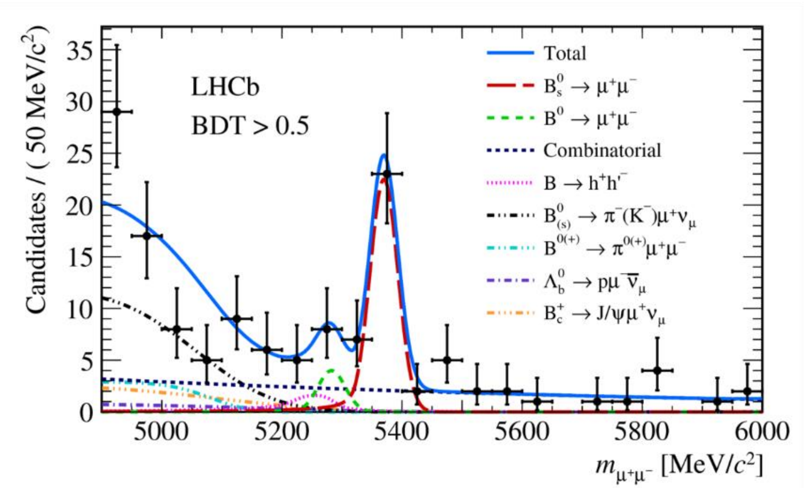
B_s signal significance is 1.4 σ, compatible with SM at 2σ

$B_{(s)} \rightarrow \mu^+\mu^-$

- New LHCb analysis : 3fb^{-1} Run1 + 1.4 fb^{-1} Run2

$$BR(B_S^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$

$$BR(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} \qquad \text{(95\%CL)}$$



- First single experiment observation (7.8σ)

- First measurement of effective lifetime

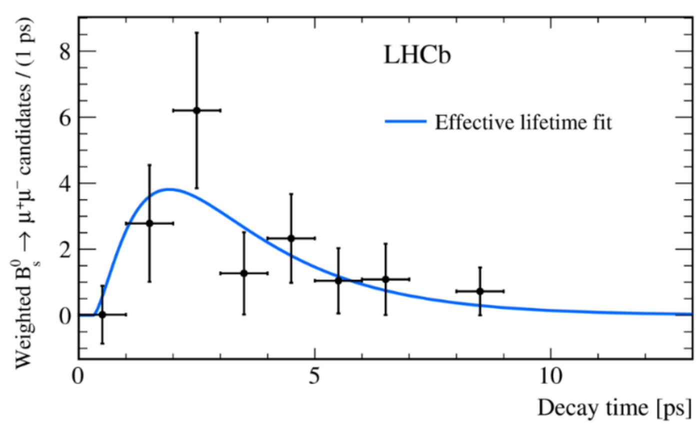
$$\tau_{\mu\mu} = \frac{\tau_{B_S}}{(1-y_s^2)} \frac{1+2y_s A_{\Delta\Gamma} + y_s^2}{1+y_s A_{\Delta\Gamma}}$$

$$A^f_{\Delta\Gamma} = \frac{\Gamma(B_{s,H} \to f) - \Gamma(B_{s,L} \to f)}{\Gamma(B_{s,H} \to f) + \Gamma(B_{s,L} \to f)}$$

SM predicts $A_{\Delta\Gamma} = 1$

$$\boxed{\tau(B_S^0 \to \mu^+\mu^-) = (2.04 \pm 0.44 \pm 0.05)\, ps}$$

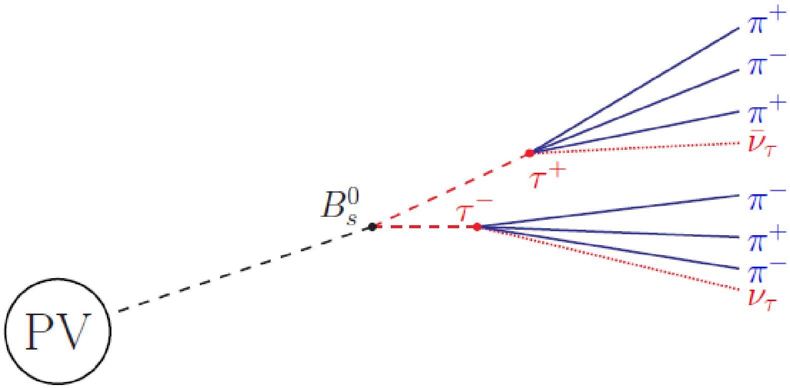
Not yet sensitive to $A_{\Delta\Gamma}$, but will become interesting with future runs!

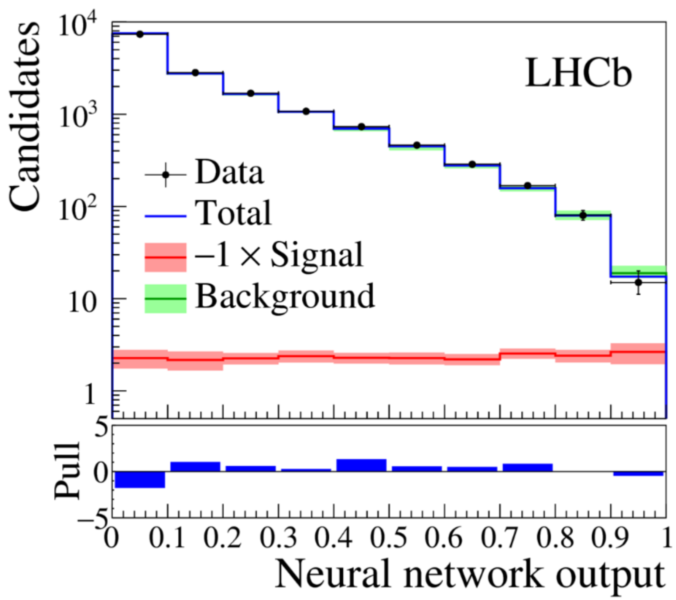


PRL 118 (2017) 191801

$B_{(s)} \to \tau^+\tau^-$

- Experimentally very challenging due to final state neutrinos
- LHCb uses $\tau^- \to \pi^- \pi^+ \pi^- \nu$ decay
- Fit the output of a NN using Run1 data





- First experimental result on the B_s

$$BR(B_s^0 \to \tau^+\tau^-) < 6.8 \times 10^{-3} \quad \text{(95\%CL)}$$

- Best limit on B^0

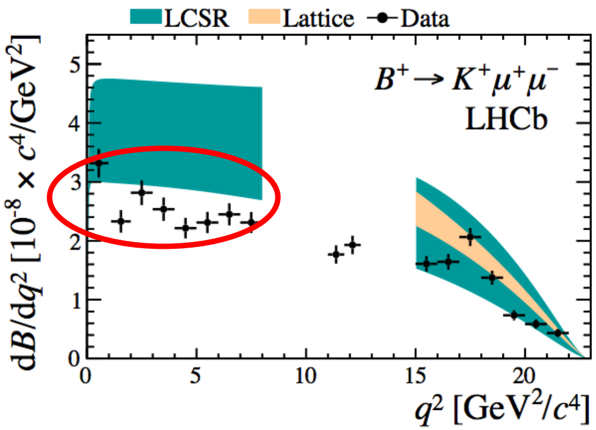
$$BR(B^0 \to \tau^+\tau^-) < 2.1 \times 10^{-3} \quad \text{(95\%CL)}$$

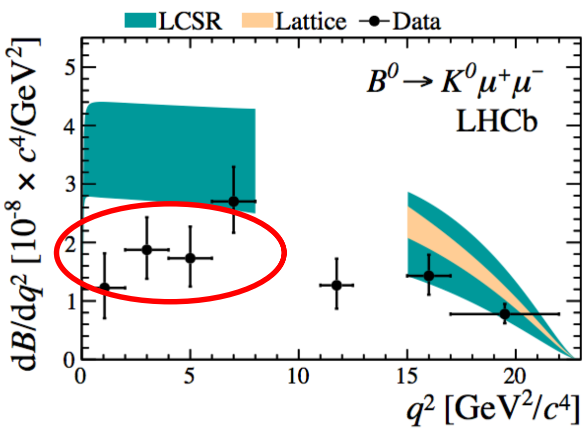
- Still orders of magnitude above SM but proof of concept that rare decays into taus can be done at hadron collider

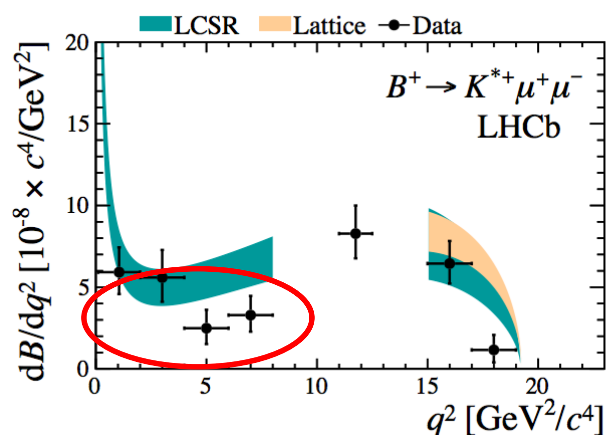
PRL118(2017)251802

b → sμμ branching ratios

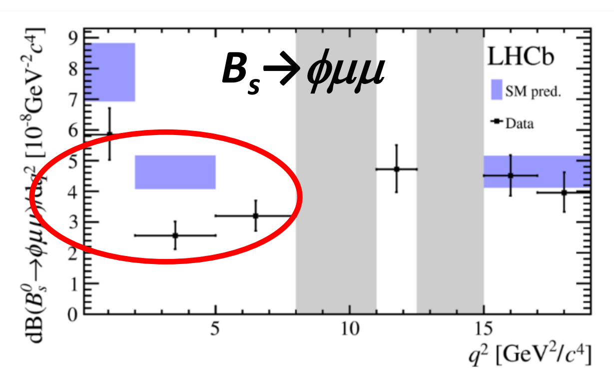
Measured BR are consistently lower than predicted in SM







JHEP 06 (2014)133



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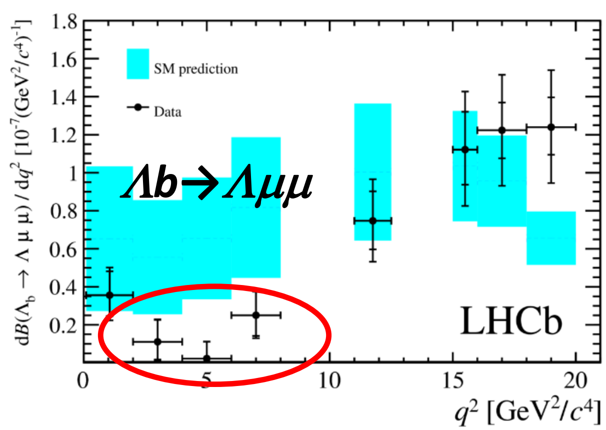
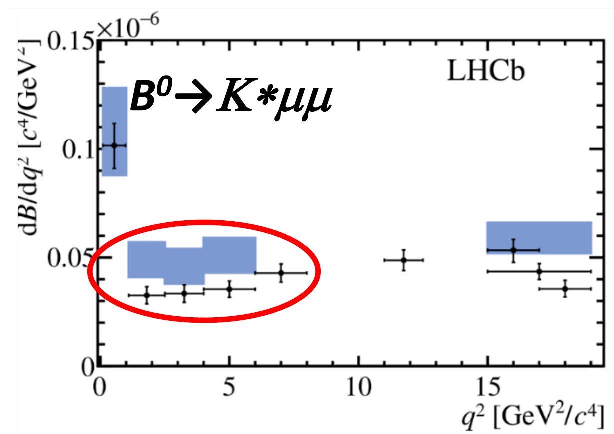


JHEP 06 (2015) 115

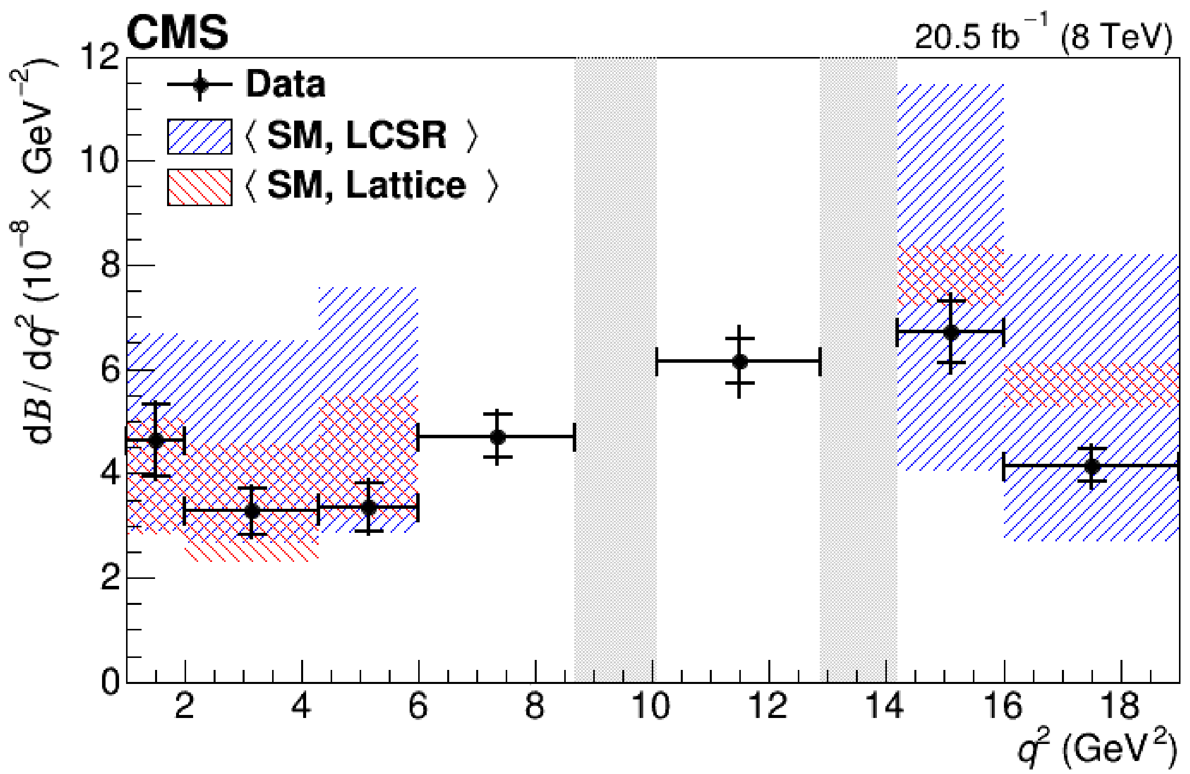


JHEP 11(2016)047
JHEP 04(2017)142

b → sμμ branching ratios

Measured BR are consistently lower than predicted in SM

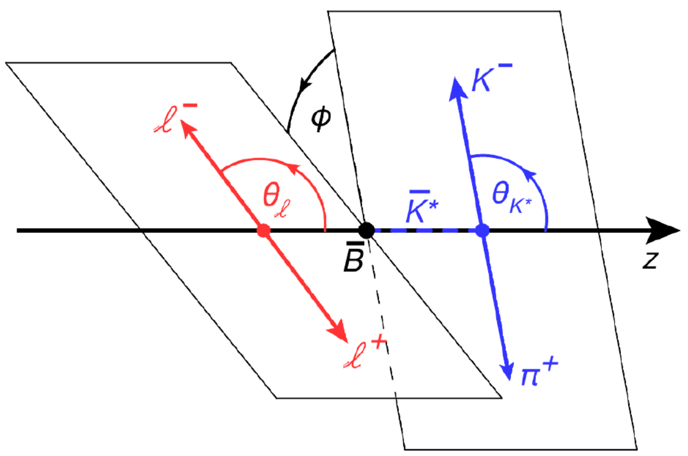
Same trend seen by CMS in $B^0 \to K^* \mu\mu$



PLB 753 (2016) 424

B →K*ℓℓ angular observables

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+\frac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\frac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big].$$



Observables (A_{FB}, F_L and S_j) are function of the Wilson coefficients.

A cleaner set of observables, where hadronic form factor uncertainties cancel at the leading order, can be defined

$$P_5' \equiv \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

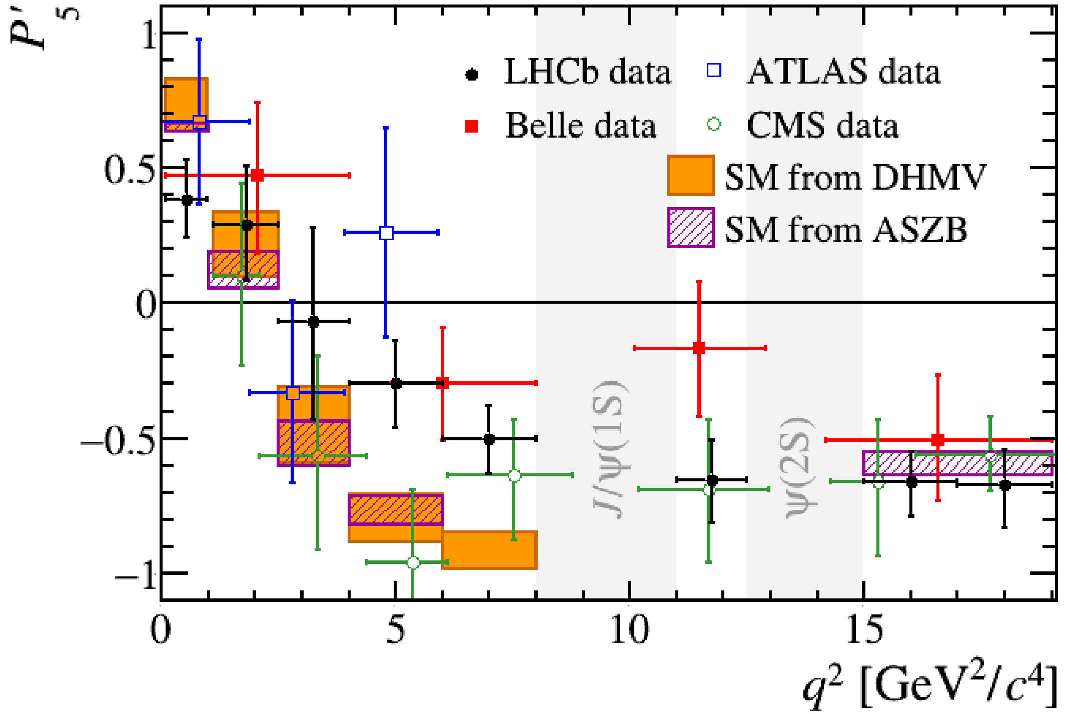
B →K*ℓℓ literature

	dataset	Angles and modes used	Measured obervables	Reference
	8TeV data (20.3 fb^{-1})	(θ_l, θ_K,ϕ) with folding technique, ℓ=μ	F_L , S_j , P'_i	*ATLAS-CONF-2017-023*
	Run1 data (3fb^{-1})	Full angular analysis (θ_l, θ_K,ϕ), ℓ=μ*	A_{FB}, F_L , S_j, P'_i	*JHEP 02 (2016) 104*
	8TeV data (20.5 fb^{-1})	(θ_l, θ_K,ϕ) with folding technique ℓ=μ	P'_5,P_1 A_{FB}, F_L measured in a previous paper	*CMS-PAS-BPH-15-008* *PLB 753 (2016) 424*
	All	(θ_l, θ_K), also B^+ modes ℓ=e,μ	A_{FB}, F_L	*PRD 93 (2016) 052015*
	All	(θ_l, θ_K,ϕ) with folding technique, also B^+ modes, ℓ=e,μ	A_{FB}, F_L , S_j, P'_i, and also Qi	*PRL 118 (2017) 111801*

*Angular analysis for e modes also performed at low q2 in JHEP04(2015)064

$B^0 \rightarrow K^{*0}\mu\mu$ results

Overall good agreement with SM predictions for the angular observables.
The main exception:



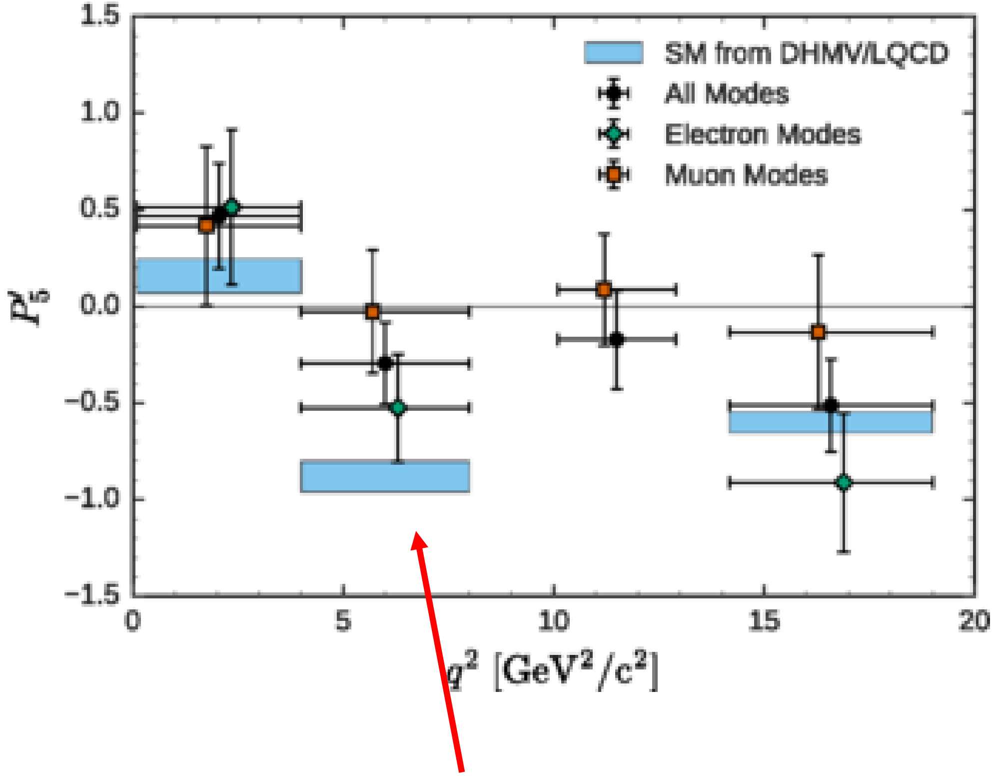
FF from LQSR (JHEP 08 (2016) 98) and LQCD (arXiv:1501.00367)

LHCb, Belle and ATLAS show deviations from the SM in the P'_5 observable in $4<q^2<8$ GeV^2

$\Rightarrow$ Points toward an anomaly in the Wilson coefficient C_9

Test of lepton universality in angular observables

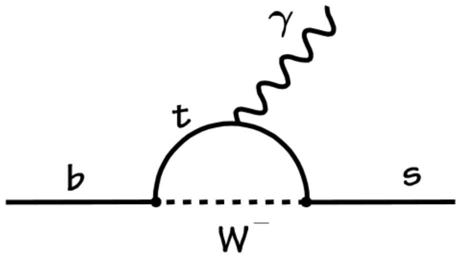
Belle split electron and muon modes :



PRL 118 (2017) 111801

tension at 2.6σ for the muons
tension at 1.1σ for the electrons

$B \rightarrow K^*\gamma$



- Isospin asymmetry

$$\Delta_{0+} = \frac{\Gamma(B^0 \to K^{*0}\gamma) - \Gamma(B^+ \to K^{*+}\gamma)}{\Gamma(B^0 \to K^{*0}\gamma) + \Gamma(B^+ \to K^{*+}\gamma)}$$

- CP asymmetry, very small in the SM

$$A_{CP} = \frac{\Gamma(\bar{B} \to \bar{K}^*\gamma) - \Gamma(B \to K^*\gamma)}{\Gamma(\bar{B} \to \bar{K}^*\gamma) + \Gamma(B \to K^*\gamma)}$$

New Belle measurement:

$$\Delta_{0+} = (+6.2 \pm 1.5 \pm 0.6 \pm 1.2)\%$$

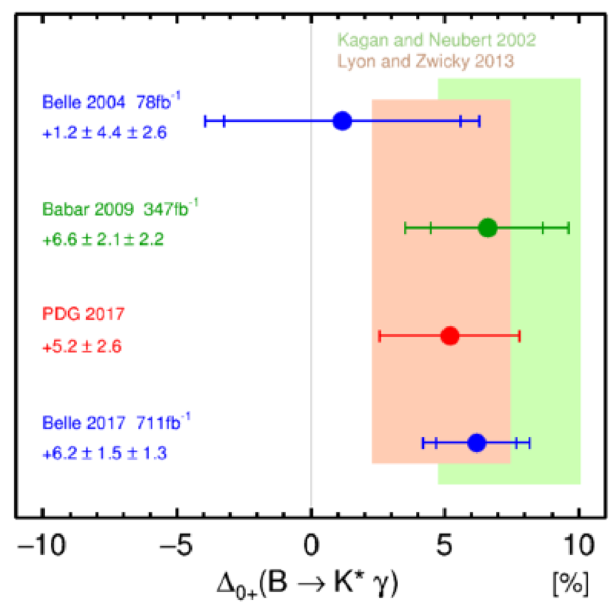
First evidence of isospin asymetry at 3.1σ, compatible with SM

A_{cp} compatible with SM:

$$A_{CP}(K^{*0}\gamma) = (-1.3 \pm 1.7 \pm 0.4)\%$$

$$A_{CP}(K^{*+}\gamma) = (+1.1 \pm 2.3 \pm 0.3)\%$$

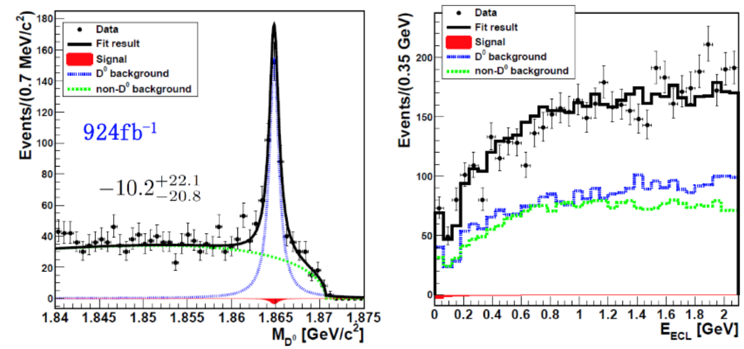
$$A_{CP}(K^{*}\gamma) = (-0.4 \pm 1.4 \pm 0.3)\%$$



arXiv:1707.00394

Rare charm decays

- $D^0 \to \nu\nu$ predicted BR ~10^{-30}, NP models (dark matter final states) may enhance BR to ~10^{-15}
  First search by Belle:
  BR($D^0 \to$ invisible) < 8.8×10^{-5} @90%C.L.

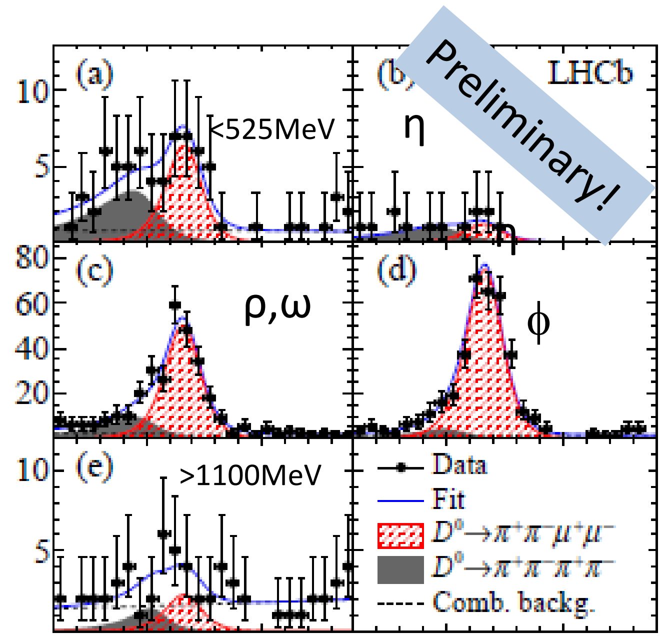


PRD95(2017)011102

- $D^0 \to \pi\pi\mu\mu$ and $D^0 \to KK\mu\mu$ are FCNC, expected BR ~10^{-9}
  Intermediate $\mu\mu$ resonances can have BR ~10^{-6}

  Integrated BR measured by LHCb :
  $B(D^0 \to \pi\pi\mu\mu)=(9.64\pm0.48\pm0.51\pm0.96)\times10^{-7}$
  $B(D^0 \to KK\mu\mu)=(1.54\pm0.27\pm0.09\pm0.16)\times10^{-7}$

  Rarest charm decays ever observed!



LHCb-PAPER-2017-019

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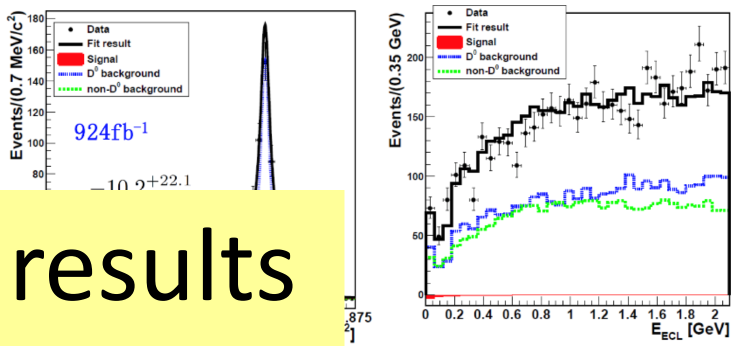

PRD95(2017)011102

Many other results in charm sector available by Babar, Belle, LHCb, BES…

- $D^0 \rightarrow \pi\pi\mu\mu$ and $D^0 \rightarrow$
  BR ~10^{-9}
  Intermediate μμ reso

  Integrated BR measured by LHCb :
  $B(D^0 \rightarrow \pi\pi\mu\mu) = (9.64 \pm 0.48 \pm 0.51 \pm 0.96) \times 10^{-7}$
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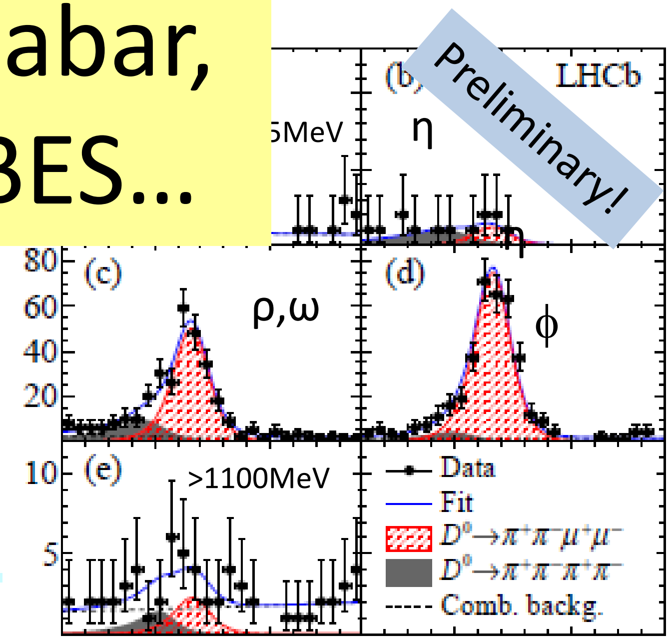
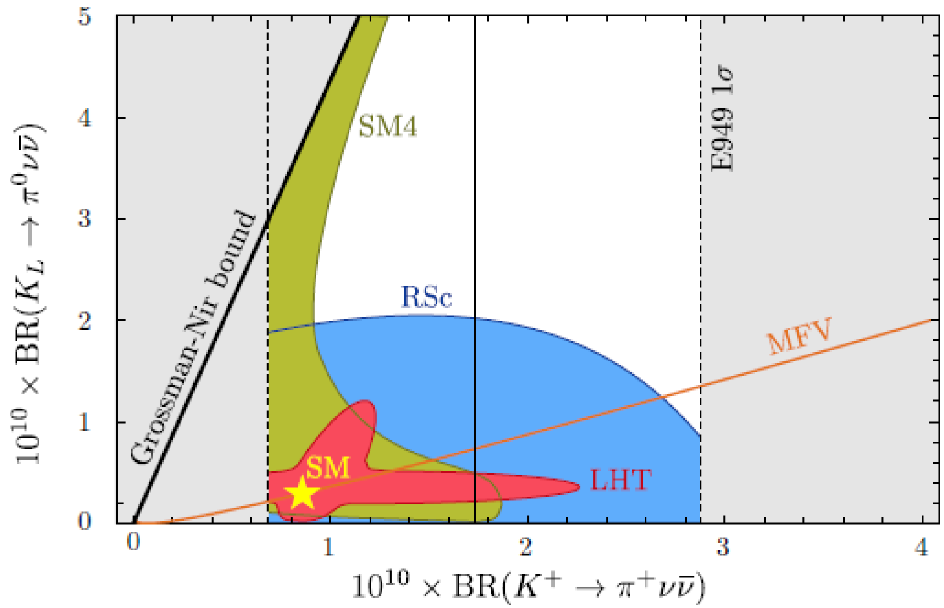


LHCb-PAPER-2017-019

Rare kaon decays: K → πνν

KOTO at JPARC

- Previous result (2013)
  BR < 5.1 × 10^{-8} (90%CL)
  arXiv:1609.03637
- Upgrade of the detector ongoing
- Expect to reach standard model sensitivity by 2021



arXiv:1012.3893

NA62 at CERN

- 10^{12} K^{+} collected in 2016
- ~ 100 SM K^{+} → π^{+}νν events before end of 2018
- Much more physics can be done: LFV/LNV decays, search for long-lived dark sector particles, heavy neutral lepton searches,….

Rare kaon decays: K → πνν

At JPARC

- Previous result (20
  BR < 5.1 × 10⁻⁸ (90
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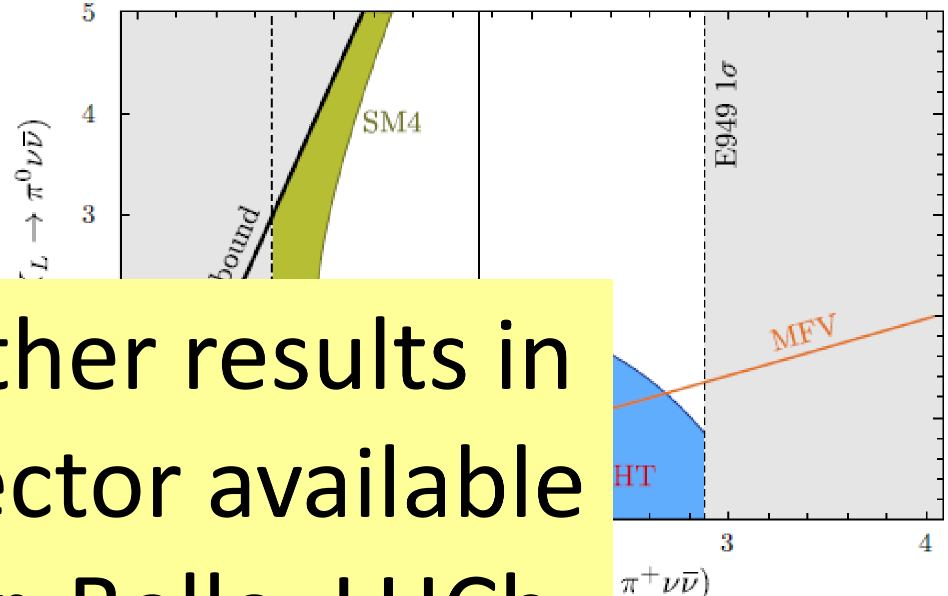


arXiv:1012.3893

Many other results in kaons sector available by Babar, Belle, LHCb, …

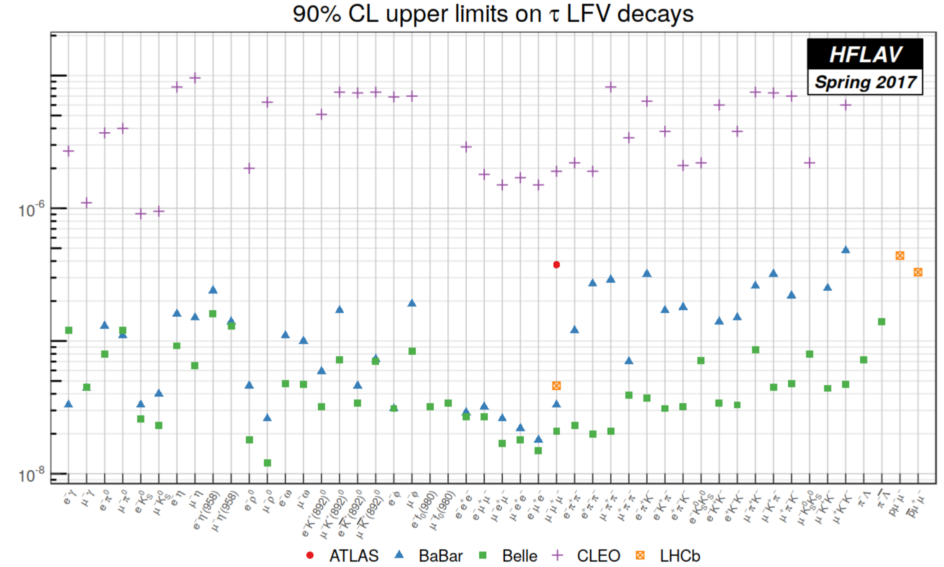
at CERN

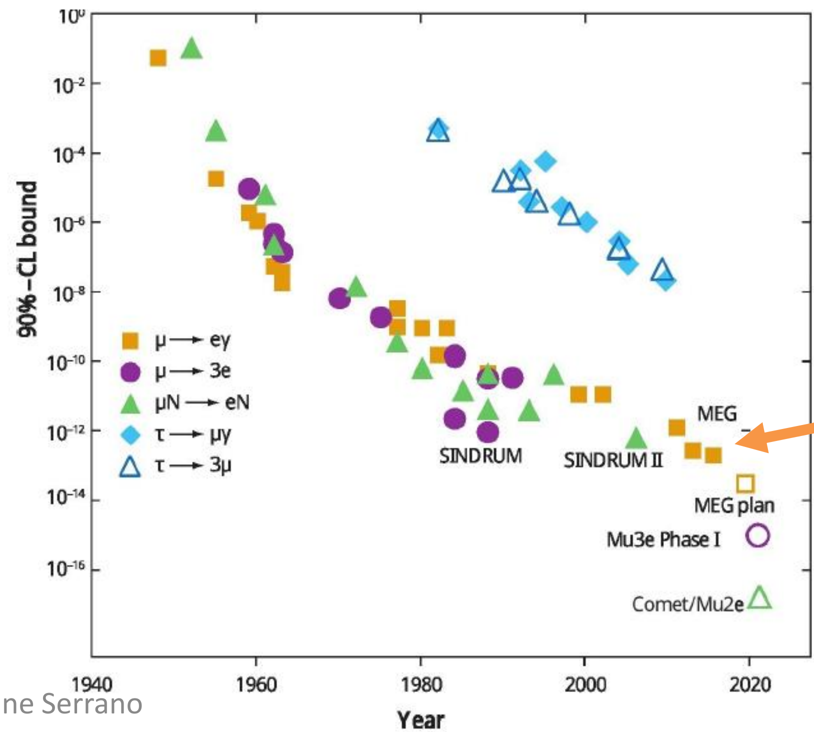
- 10^{12} K^+ collected in 2016
- ~ 100 SM $K^+ \to \pi^+\nu\nu$ events before end of 2018
- Much more physics can be done: LFV/LNV decays, search for long-lived dark sector particles, heavy neutral lepton searches,….

Lepton flavour violation

- Lot of tau LFV decay searches performed by Belle/Babar/LHCb Limits in the range 10^{-8} to $2x10^{-7}$

$\Rightarrow$ Expect improvements from Belle 2

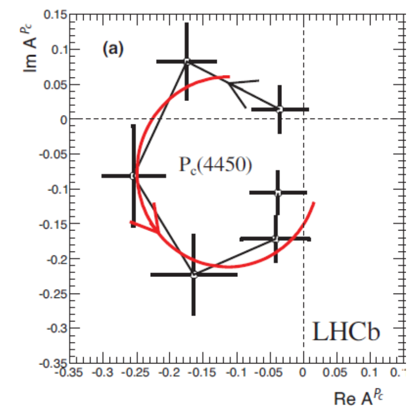




- Muon LFV searches by dedicated experiments
- Final MEG upper limit B(μ→eγ) < 4.2 10^{-13} @90% CL *EPJC 76 (2016) 434*
- Exciting times ahead with MEGII, Mu2e, COMET, Mu3e

Exotic states

Exotic states



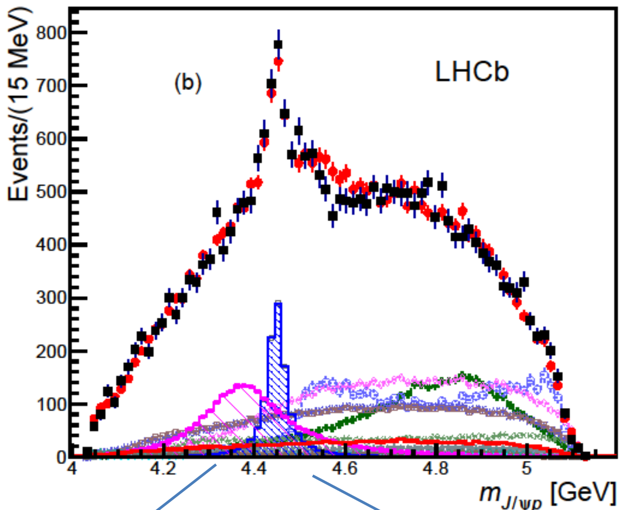
- What? all hadrons that are not mesons ($q\bar{q}$) or baryons (qqq)
  Tetraquarks, pentaquark, glueballs, hybrid mesons..
- How do we know they are exotic states?
  - Argand diagrams tells you it's a resonance
  - Unconventional J^{PC} quantum numbers (e.g. quark model can not account for 0^{--} states)
  - Unconventional charge or quark content (e.g. meson of charge 2+)
  - Conventional J^{PC} but supernumerary
  - Conventional J^{PC} but non expected production or decay modes
- About ~30 observed states so far, mainly in $c\bar{c}$ and $b\bar{b}$ sector

  charmoniumlike *bottomiumlike*

- They are labelled *X, Y, Z, P*... according to some not-always-followed rules:
  - X = neutral resonance appearing in B decays
  - Y = states produced in ISR processes
  - Z = charged charmonium like states (and their isospin partner)
  - P = pentaquark

Pentaquark in $\Lambda_b \to J/\psi pK$ decays

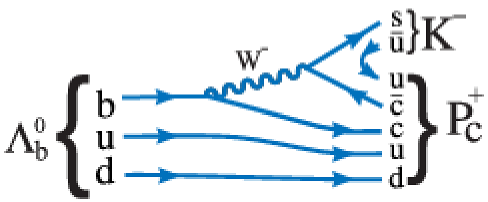
Amplitude analysis in 6 dimensions (decay angles and m_{Kp})
2 P_c states needed to describe the data



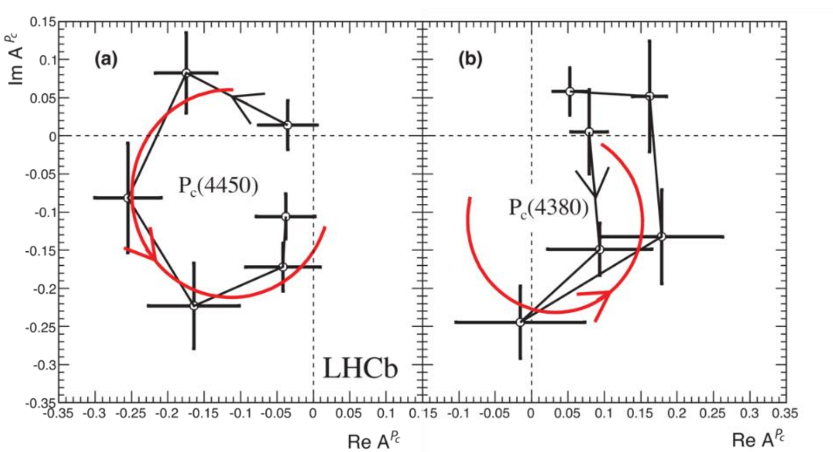
$P_c(4380)$	$P_c(4450)$
9 σ	12 σ
$J^P = 3/2^-$	$J^P = 5/2^+$

J^P also compatible with $(3/2^+, 5/2^-)$ and $(5/2^+, 3/2^-)$

Minimal quark content: $c\bar{c}uud$



Argand diagrams:



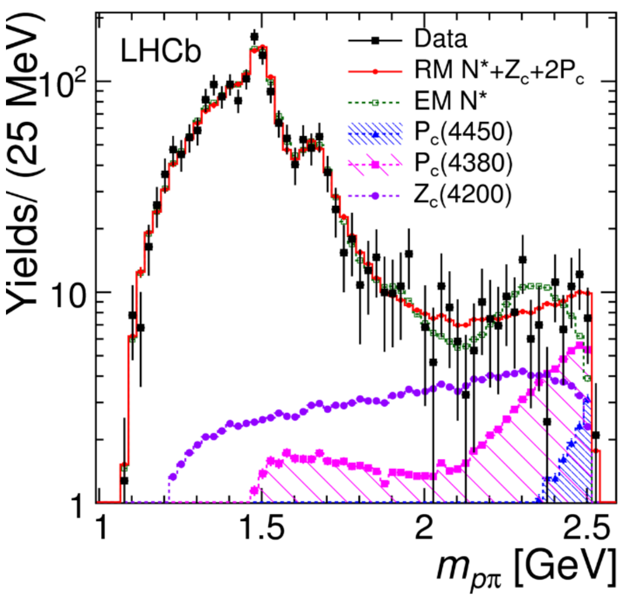
PRL 115 (2015) 072001

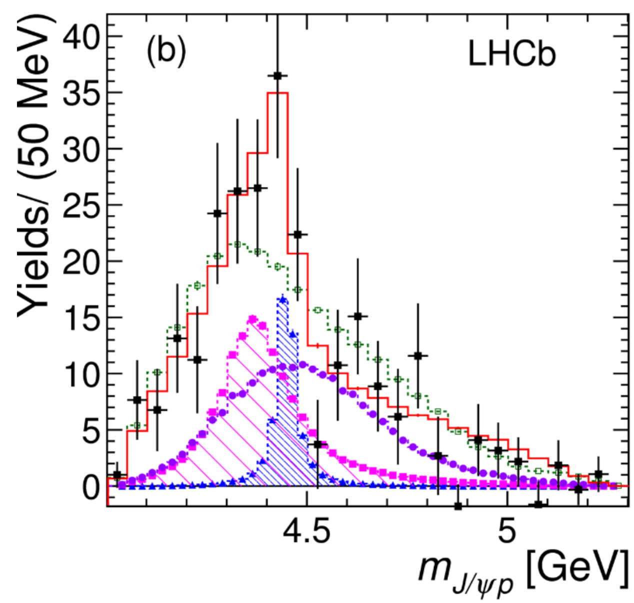
Pentaquark in $\Lambda_b \to J/\psi p\pi$ decays

Search for these states in $\Lambda_b \to J/\psi p\pi$ decays in order to test hypothesis of threshold effects

Angular analysis indicates the need for exotic states at 3.3σ, but can't tell which (the two P_c or $Z_c(4200)$).

Run 2 will help!



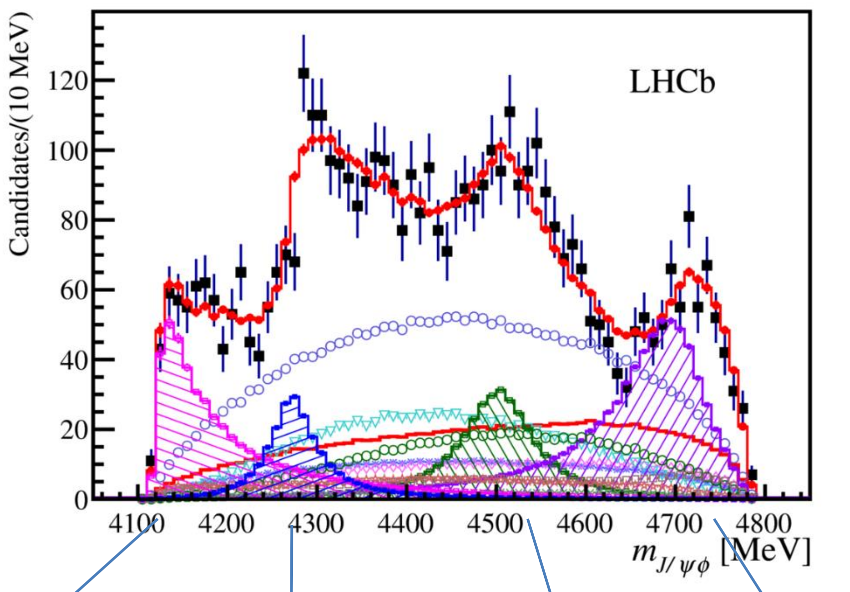


PRL 117 (2016) 082003

Other decays are also under study : $\Lambda_b \to \chi_{c(1,2)} pK$ *(arXiv:1704.07900)*, $\Xi_b \to J/\psi \Lambda K$ *(PLB 772 265)*, $B_{(s)} \to J/\psi pp$ *(JHEP 09(2013)006)* ,..

Tetraquark in B →J/ψϕK

- Looking at the J/ψϕ spectrum, a narrow state X(4140)^0 reported by CDF, D0, CMS but not seen by Belle. Hints of X(4274) also seen by CDF and CMS
- LHCb amplitude analysis of B →J/ψϕK ⇒ confirmed these 2 + 2 new states

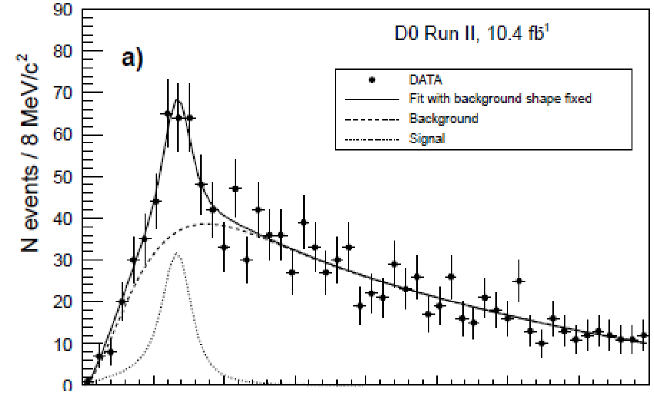


PRL 118 (2017) 022003

X(4140)	X(4274)	X(4500)	X(4700)
8.4 σ	5.8 σ	6.1 σ	5.6 σ
$J^{PC}= 1^{++}$	$J^{PC}= 1^{++}$	$J^{PC}= 0^{++}$	$J^{PC}= 0^{++}$

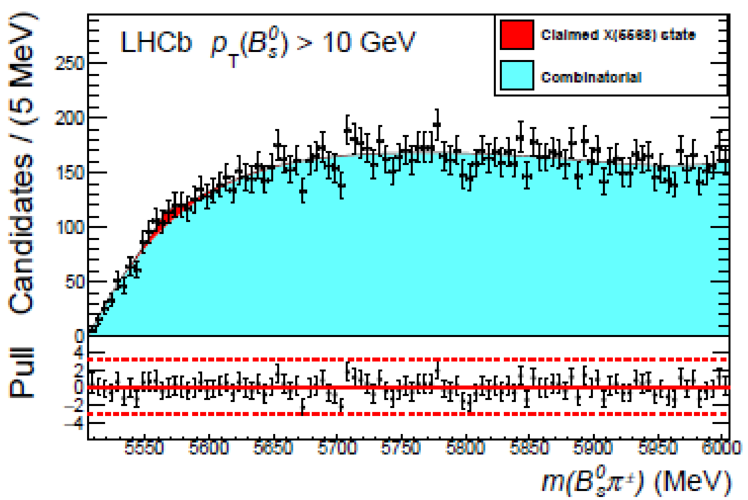
X(5568) ?

- D0 report a peak in the $B_s\pi$ mass distribution
  Local significance 5.1σ (after cone cut)
  Also confirmed in semileptonic decays
  D0 conf note 6496



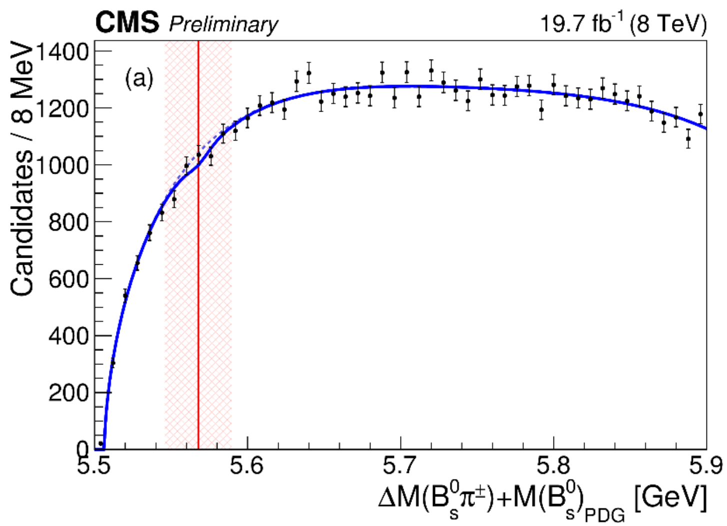
PRL117(2016)022003

- LHCb looked for it using 20 times more B_s than D0 but did not find signal



PRL117(2016)152003

- CMS preliminary search also turned out to be negative



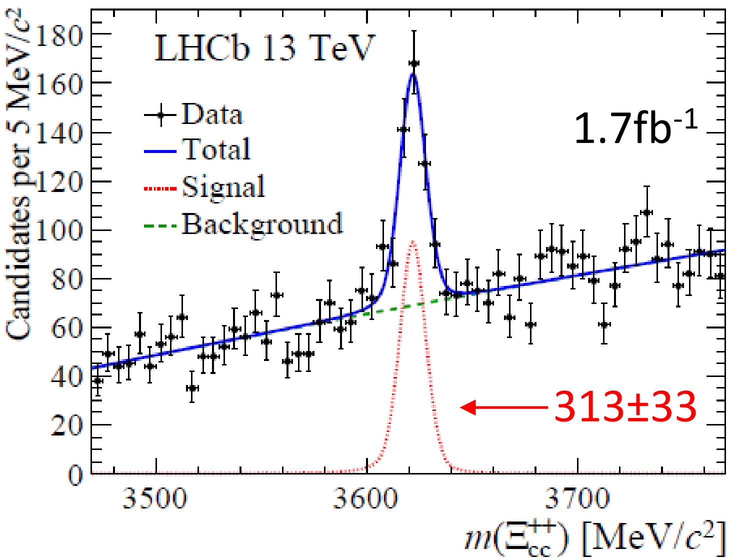
CMS-PAS-BPH-16-002

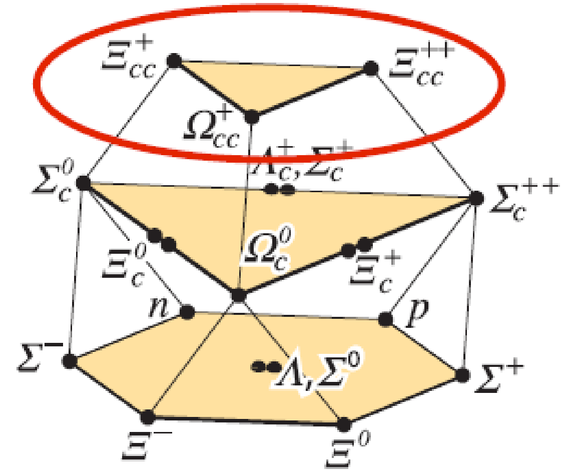
Charmed baryons

3 states expected from quark model:

Ξ_{cc}^{++}= ccu, Ξ_{cc}^{+}= ccd, Ω_{cc}^{+}= ccs

Ξ_{cc}^{+} observation reported by the SELEX experiment (*PRL89(2002)112001, PRB628(2005)18*)





SU(4) flavor multiplets, PDG Review of Particle Physics, Phys.Rev. D86, 010001.

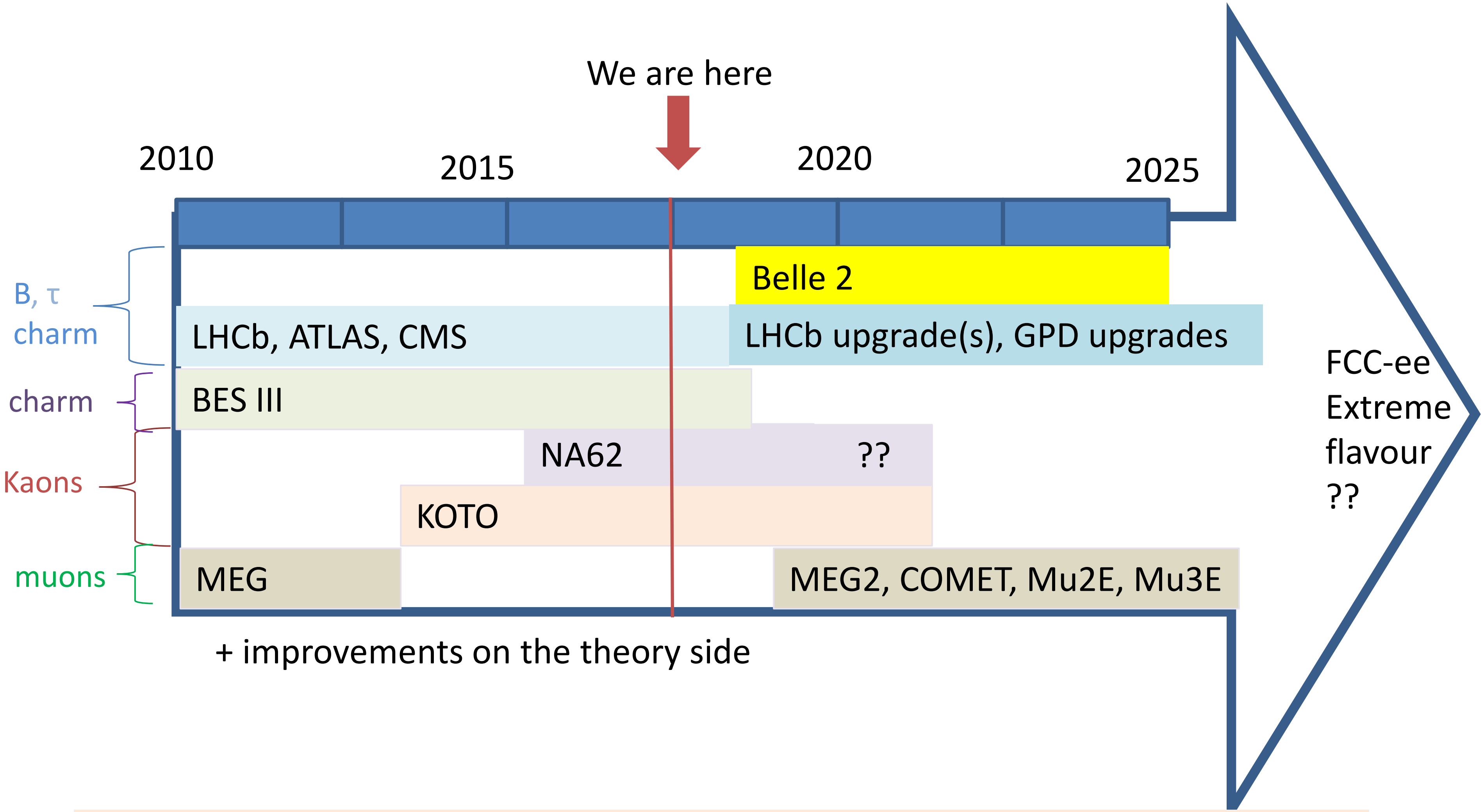
First observation of Ξ_{cc}^{++}

Mass ~100 MeV larger than the one reported by SELEX for Ξ_{cc}^{+}, disfavouring the Ξ_{cc}^{+} hypothesis of SELEX

arXiv:1707.01621

First observation of a baryon containing two heavy quarks
Provides a very interesting tool to probe QCD

Prospects



+ improvements on the theory side

Broad flavour physics program for the next decade, with complementary experiments that will be able to drastically constrain new physics phase space OR discover it!

Thanks for your attention

More details in parallel sessions

- flavour & symmetry :

Tom Blake, Simon Whele, Albert Puig, Carla Benito, Stefano Lacaprara, Elisa Manoni, Umberto De Sanctis, Saskia Falke, Jiangchuan Chen, Dominik Mitzel, Eduardo Rodrigues, Francesco Renga, Giuseppe Ruggiero, Miguel Pernas, Stefano Miscetti,…

- QCD and hadronic physics:

Patrick Spradlin, Sergey Polykarpov, Olaf Steinkamp, Bruce Hoeneisen,…

- Dark matter:

Youngjoon Kwon,..


Back up

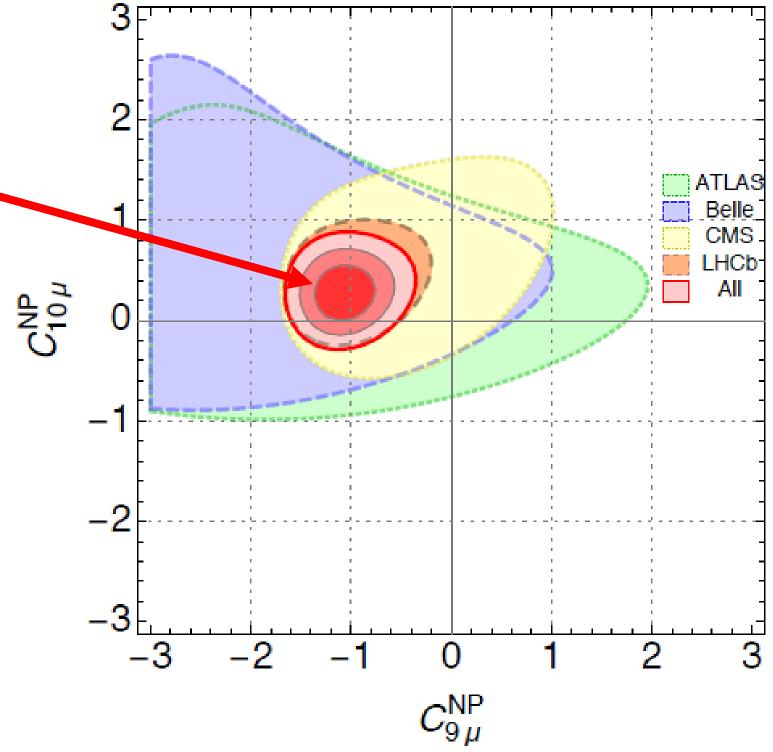
b → sℓℓ interpretation

- A lot of activity in the theory side to interpret these results
- Just one example of global model-independent fit of Wilson coefficients (*arXiv: 1704.05340*):

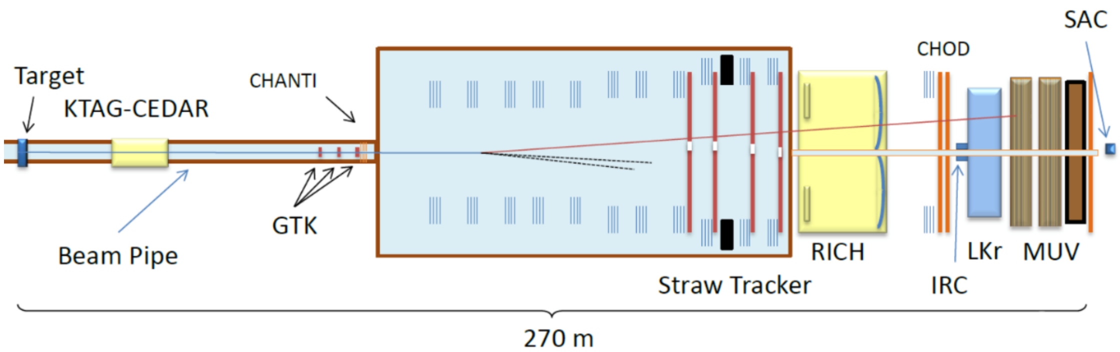
$C_i = C_i^{SM} + C_i^{NP}$

If NP allowed in C_9 and C_{10}, C_9^{NP} ~-1 with high significance

This can then be interpreted in terms of different models: leptoquark, Z',…

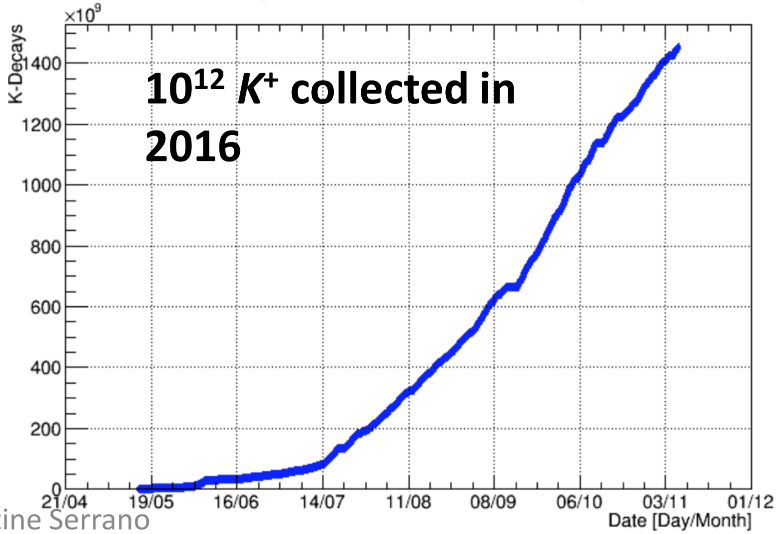


Rare kaon decays: $K^+ \rightarrow \pi^+\nu\nu$



- ~100 ps timing for K^+-π^+ association
- EM calorimeters to veto γs
- Hadron calorimeters to veto μs
- Very light, high-rate trackers to reconstruct K^+ and π^+
- Full particle identification

- SM prediction: $BR(K^+ \rightarrow \pi^+\nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$
- best result by E949: $BR(K^+ \rightarrow \pi^+\nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$



- 10^{13} K^+ will be collected before LS2
- ~ 100 SM $K^+ \rightarrow \pi^+\nu\nu$ events
- Much more physics can be done: LFV/LNV decays, search for long-lived dark sector particles, heavy neutral lepton searches,….

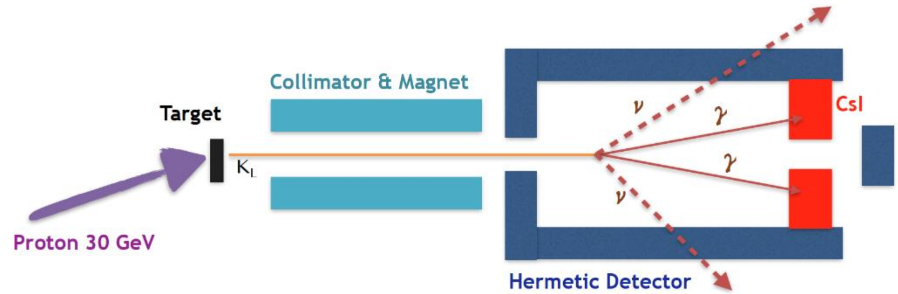
Rare kaon decays: $K^0 \rightarrow \pi^0 \nu\nu$

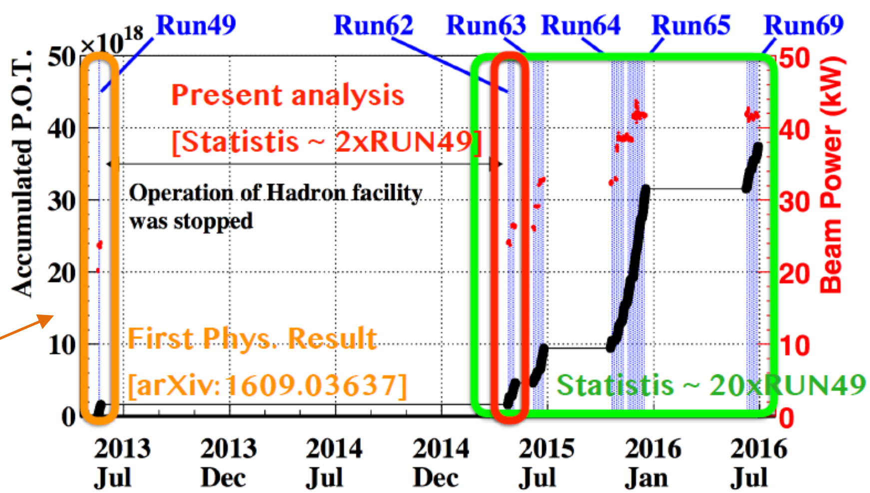
SM prediction :

$$BR(K^0 \rightarrow \pi^0 \nu \bar{\nu}) = (3.0 \pm 0.30) \times 10^{-11}$$

Best limit by E391a

$$BR(K^0 \rightarrow \pi^0 \nu \bar{\nu}) < 2.6 \times 10^{-8}$$





Using early 2015 data:

SES = 5.9 × 10^{-9} (90%CL)

Previous result (2013)

BR < 5.1 × 10^{-8} (90%CL)

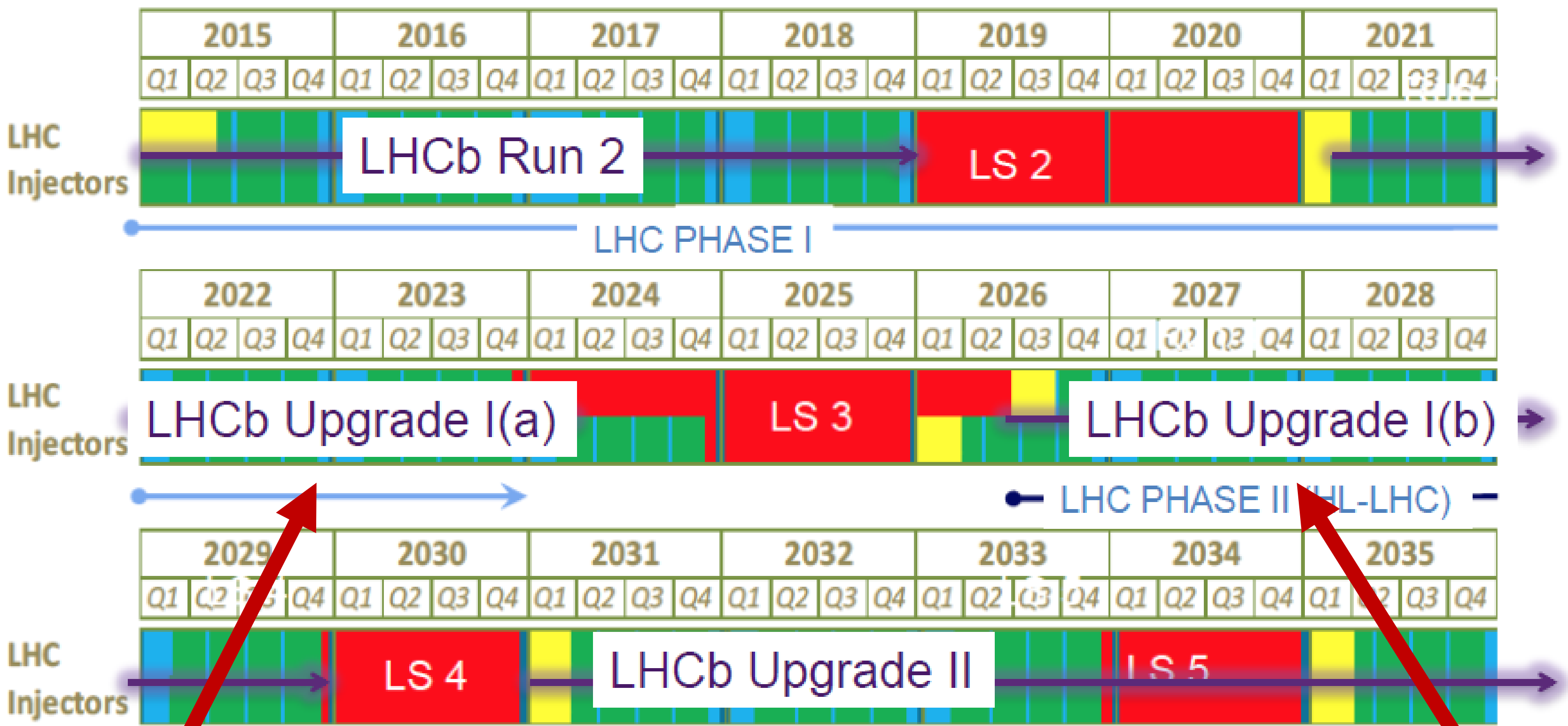
arXiv:1609.03637

Various improvements to reduce background before 2015-2016 run

Continuing upgrades to reduce background

Reach standard model sensitivity by 2021

- Future LHCb upgrades under study



40MHz readout, software trigger only, acquire 5fb-1 per year

New detector to benefit from HL-LHC and record >50 fb-1 per year. Total > 300fb-1 ?

Improve detector (add tracking station, improve ECAL,...) ?

- Several μ LFV experiments will start in 2017-2019 :
  - MEGII (PSI): improve resolution by a factor 2
  - COMET (J-PARK): μ-e conversion in atoms, target ~10^{-17}
  - Mu2e (FNAL): μ-e conversion in atoms, target ~10^{-17}
  - Mu3e (PSI): previous result from 1988 at 10^{-12}, goal is to reach 10^{-15} in a first phase, then 10^{-16}