Heavy flavor physics at LHCb

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On behalf of LHCb collaboration

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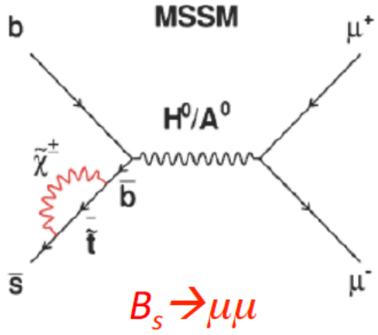
全国第十四届重味物理与CP破坏研讨会

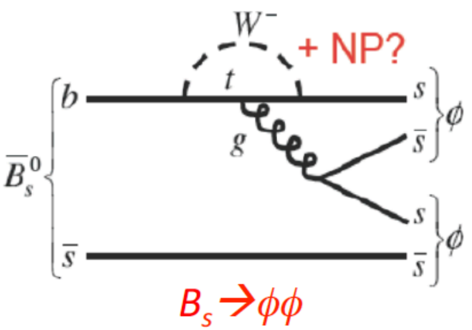
Outline

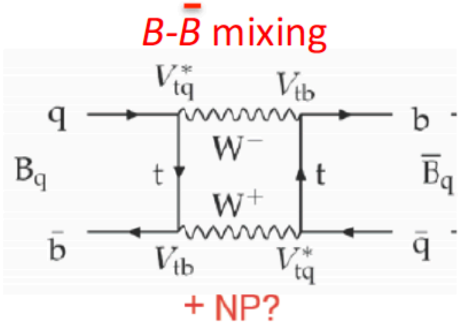
- Motivation and introduction of LHCb experiment
- Personal selected recent LHCb highlights
  - CP violation (CPV) measurements
  - Rare decays
  - Exotics
- Summary

Precision measurements of CPV and rare decays: why important?

- Instead of searching for NP particles directly produced, look for their indirect effects to low energy processes (e.g. *b*-hadron decays)



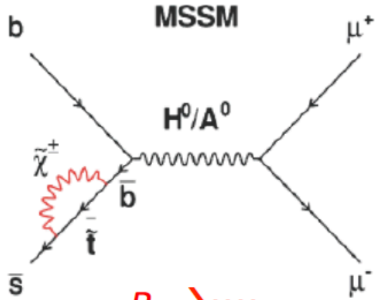




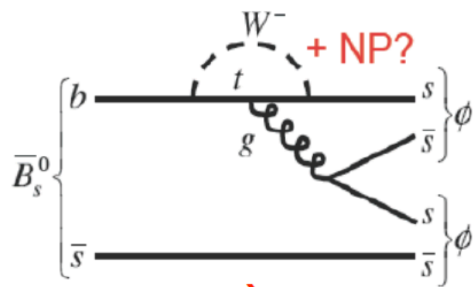
- NP may be more visible in these SM suppressed processes
- Studying CPV and flavor-changing processes => two fundamental tasks can be accomplished
  - Identify new symmetries (and their breaking) beyond the SM
  - Probe mass scales not accessible directly at nowadays colliders

Precision measurements of CPV and rare decays: why important?

- Instead of searching for NP particles directly produced, look for their indirect effects to low energy processes (e.g. *b*-hadron decays)

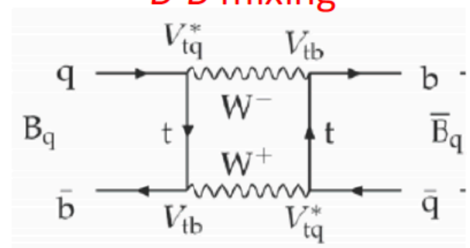


$B_s \rightarrow \mu\mu$



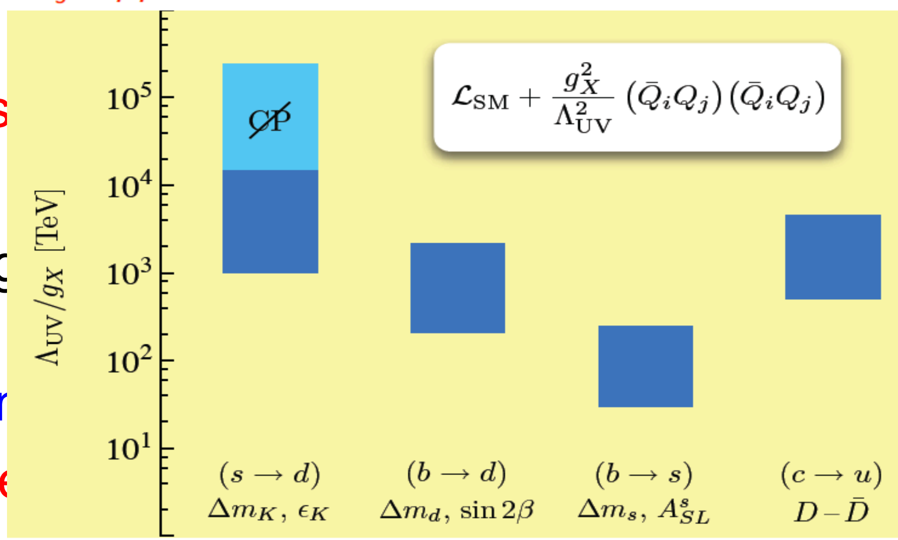
$B_s \rightarrow \phi\phi$

B-$\bar{B}$ mixing



+ NP?

- NP may be more visible in thes

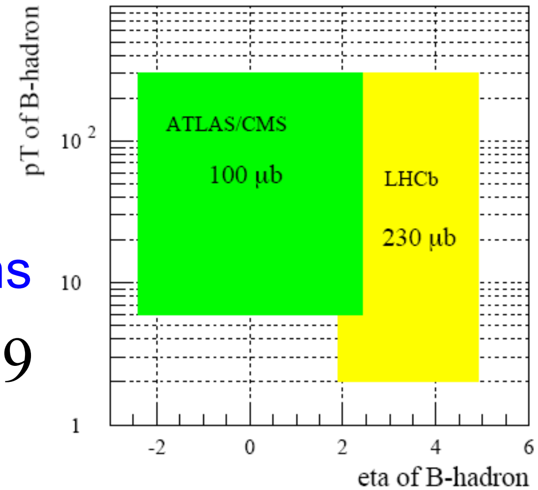


Generic bounds on New Physics scale (for g_X~1)

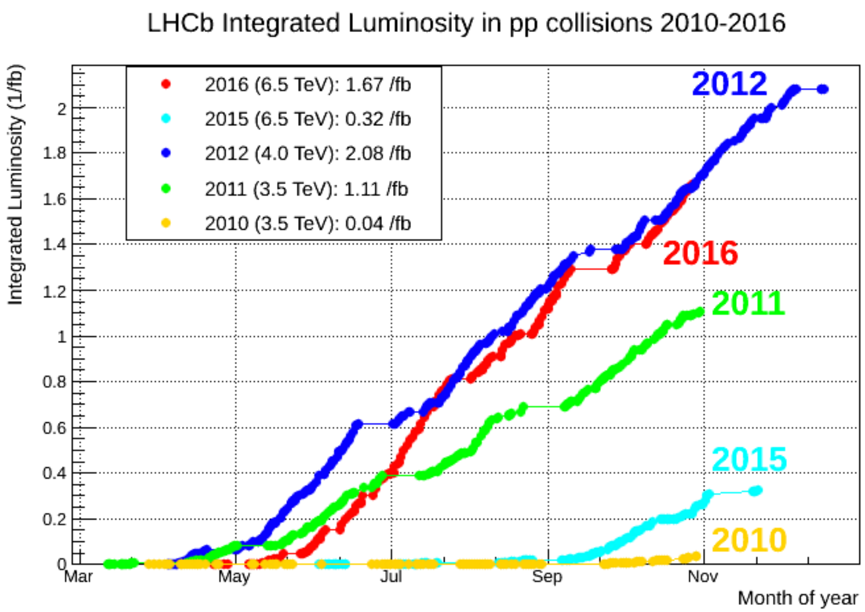
- Studying CPV and flavor-chang
  tasks can be accomplished
  - Identify new symmetries (ar
  - Probe mass scales not acce

The LHCb Experiment

- LHCb is a dedicated B and charm physics experiment at LHC
  - Large b production rate
  - Access to all b-hadrons: B^+, B^0, B_s, B_c, b-baryons
- Forward single arm spectrometer $1.9<\eta<4.9$



LHCb Integrated Luminosity in pp collisions 2010-2016



Fantastic progress for LHC this year

The effective dataset almost double with respect to Run-I at the end of 2016

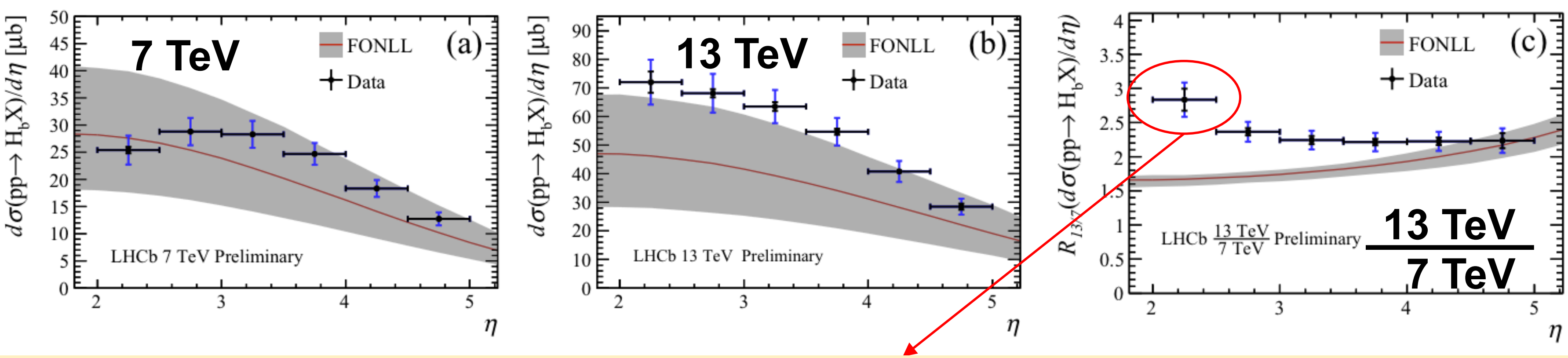
Results reported here based on RUN-I

RUN-II analysis is getting there

Production cross section

- The b production cross section $\sigma(pp \rightarrow H_b X)$ has been measured in the forward region $2 < \eta < 5$
- For sensitive test of QCD & constraints for PDFs
- Measured with b semileptonic decays
- Actually cross-section is larger than expected

Preliminary LHCb-PAPER-2016-031 in preparation



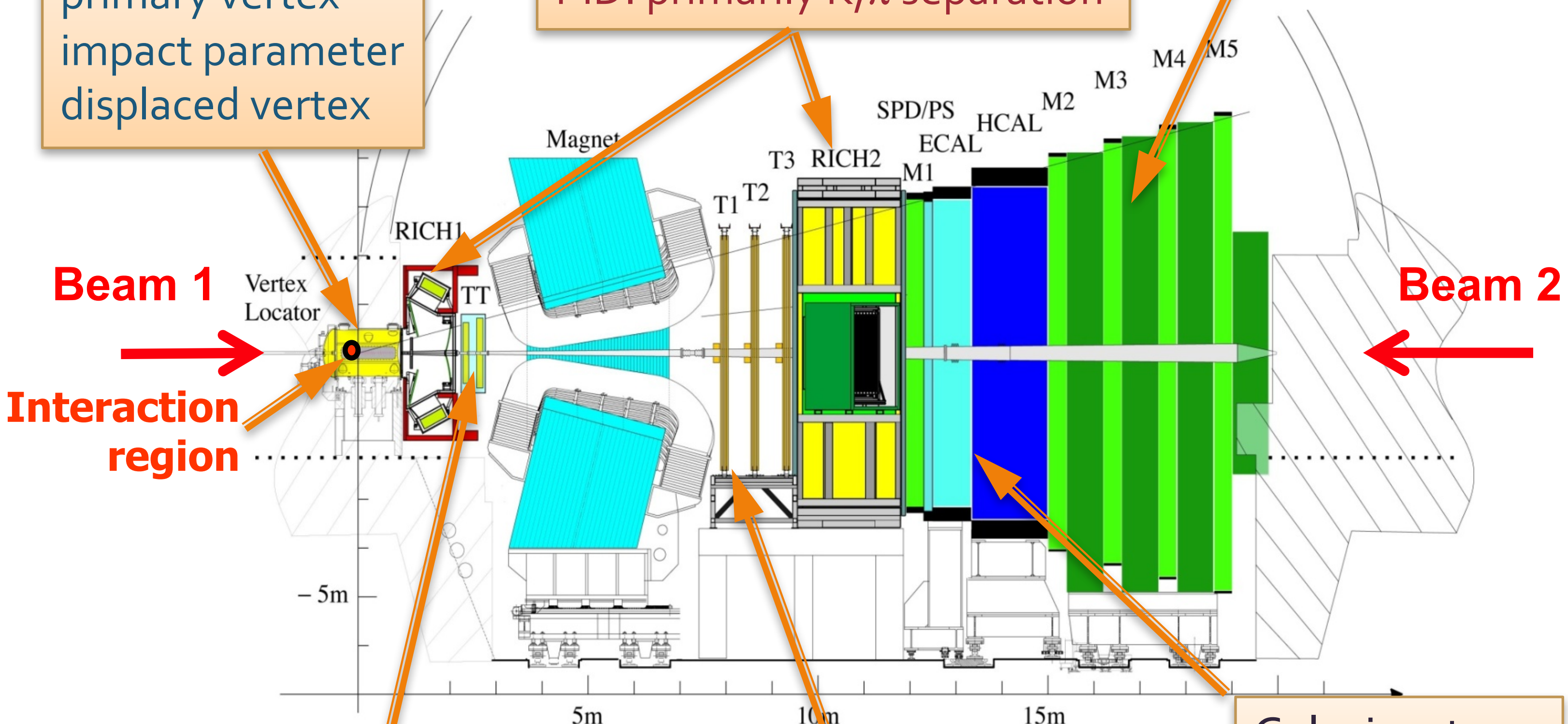
Deviate from the FONLL prediction at central region, while in experimental side, Validations ongoing to ensure reconstruction & trigger efficiencies are well understood

LHCb Detector

VELO:
primary vertex
impact parameter
displaced vertex

RICH:
PID: primarily K,π separation

Muon System



Tracking Station: p for lower energy tracks and long lived V° reconstruction

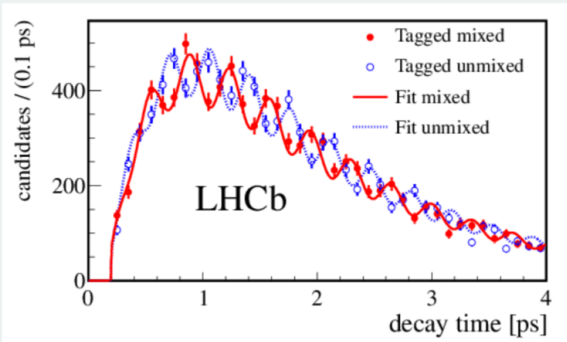
Tracking Stations:
p of charged particles that traverse the magnet

Calorimeters:
PID: h,e,γ, π°

Detector performance

Vertexing

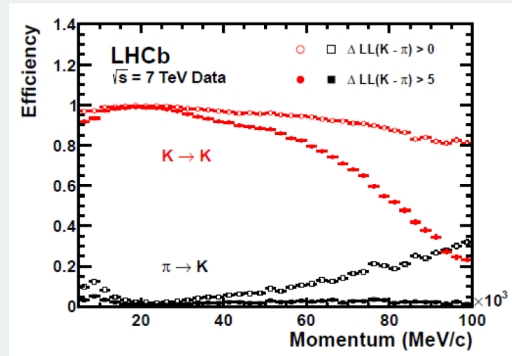
B_s^0 oscillations with $B_s^0 \to D_s \pi$



[New J. Phys. 15 (2013) 053021]

PID

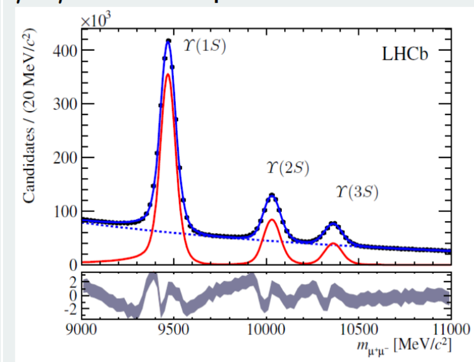
K/π ID efficiency and misID rate



[EPJ C73 (2013) 2431]

Tracking

$\mu^+\mu^-$ mass spectrum

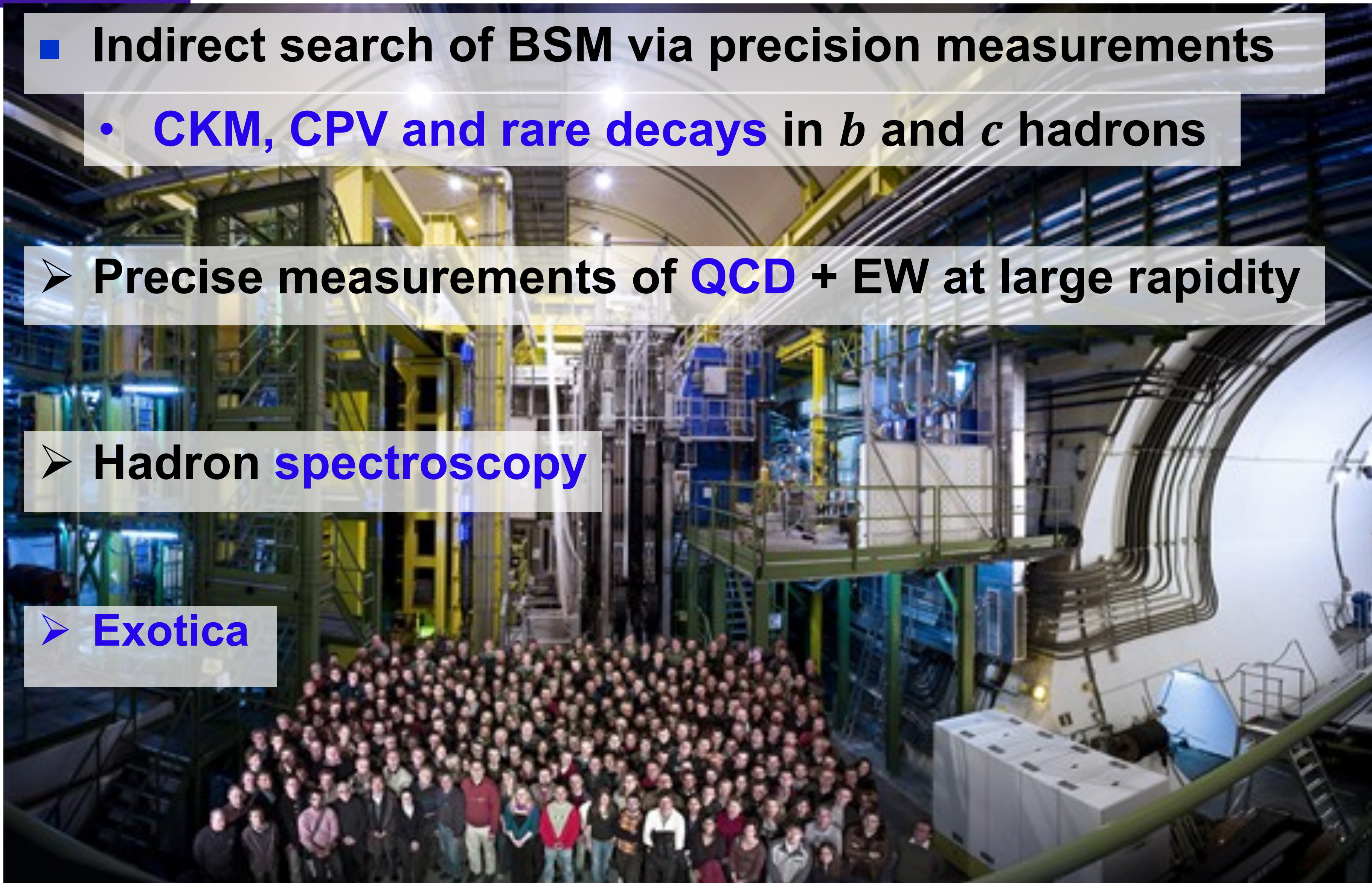


[PRL 111 (2013) 101805]

Int. J. Mod. Phys. A 30 (2015) 1530022

Impact parameter:	$\boldsymbol{\sigma_{IP} = 20\ \mu m}$
Proper time:	$\sigma_\tau = 45$ fs for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$
Momentum:	$\Delta p/p = 0.4 \sim 0.6\%$ $(5 - 100\ \mathrm{GeV}/c)$
Mass :	$\boldsymbol{\sigma_m = 8\ \mathrm{MeV}/c^2}$ **for** $\boldsymbol{B \to J/\psi X}$ **(constrained** $\boldsymbol{m_{J/\psi}}$**)**
RICH $K - \pi$ separation:	$\boldsymbol{\epsilon(K \to K) \sim 95\%}$ **mis-ID** $\boldsymbol{\epsilon(\pi \to K) \sim 5\%}$
Muon ID:	$\boldsymbol{\epsilon(\mu \to \mu) \sim 97\%}$ **mis-ID** $\boldsymbol{\epsilon(\pi \to \mu) \sim 1 - 3\%}$
ECAL:	$\Delta E/E = 1 \oplus 10\%/\sqrt{E(\mathrm{GeV})}$

Physics goals of LHCb



- Indirect search of BSM via precision measurements
  - CKM, CPV and rare decays in b and c hadrons
- Precise measurements of QCD + EW at large rapidity
- Hadron spectroscopy
- Exotica

LHCb and LHCb Chinese group

- 1151 Members, from 69 Institutes in 16 Countries

- 2000年 清华大学加入
- 2013年 华中师范加入
- 2015年 国科大加入
- 2016年 武汉大学加入

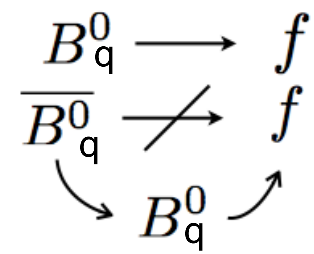
CP violation measurements

Semi-leptonic asymmetries

Semi-leptonic asymmetry $a_{\rm sl}^{q}$ quantifies *CPV* in mixing.

$a_{\rm sl}^{q}$ is precisely predicted to be tiny in SM: ~*O*(10^{-4}), can be enhanced by NP

$$a_{\rm sl} = \frac{N(\bar{B}\to B \to f) - N(B\to\bar{B} \to \bar{f})}{N(\bar{B}\to B \to f) + N(B\to\bar{B} \to \bar{f})}$$



(1) Measure time-integrated raw asymmetry

$$A_{\rm raw} = \frac{N(D_s^-\mu^+) - N(D_s^+\mu^-)}{N(D_s^-\mu^+) + N(D_s^+\mu^-)}$$

(2) Correct for detection asymmetry and background effect

$$a_{\rm sl}^{s} = \frac{2}{1-f_{\rm bkg}}(A_{\rm raw} - A_{\rm det} - f_{\rm bkg}A_{\rm bkg})$$

For B_d, also correct for production asymmetry

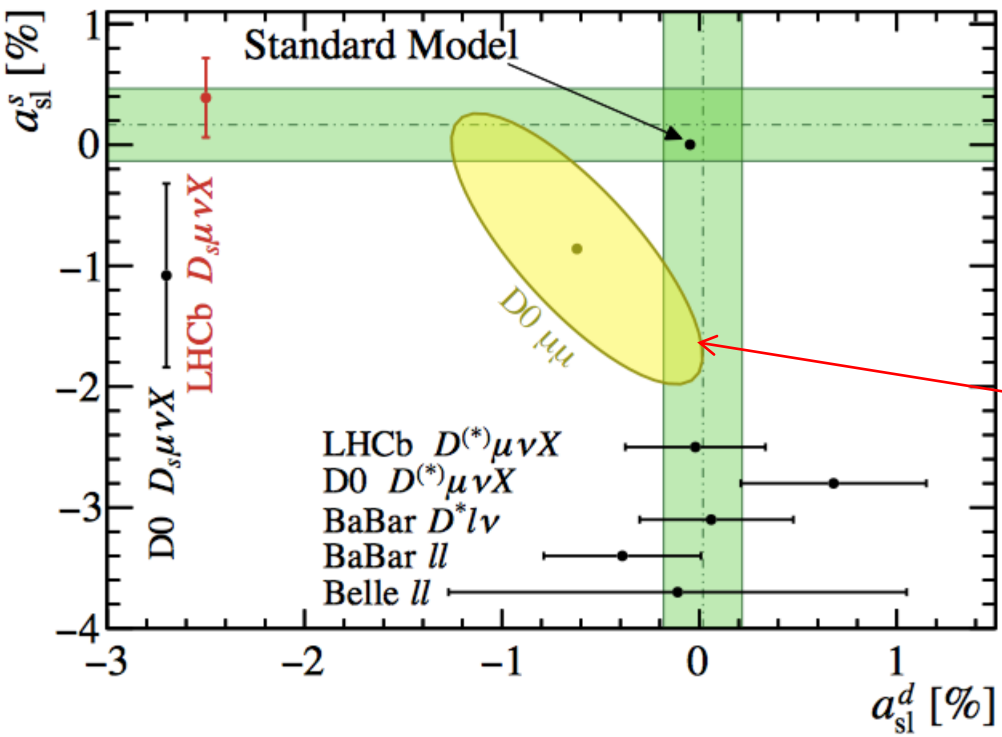
LHCb results of a_{sl}^q

$B_s \to D_s^- \mu^+ \overline{\nu}$: $a_{sl}^s = (0.39 \pm 0.26 \pm 0.20)$ %

LHCb, PRL 117 (2016) 061803

$B_d \to D^{(*)-} \mu^+ \overline{\nu}$: $a_{sl}^d = (-0.02 \pm 0.19 \pm 0.30)$ %

LHCb, PRL 114 (2014) 041601



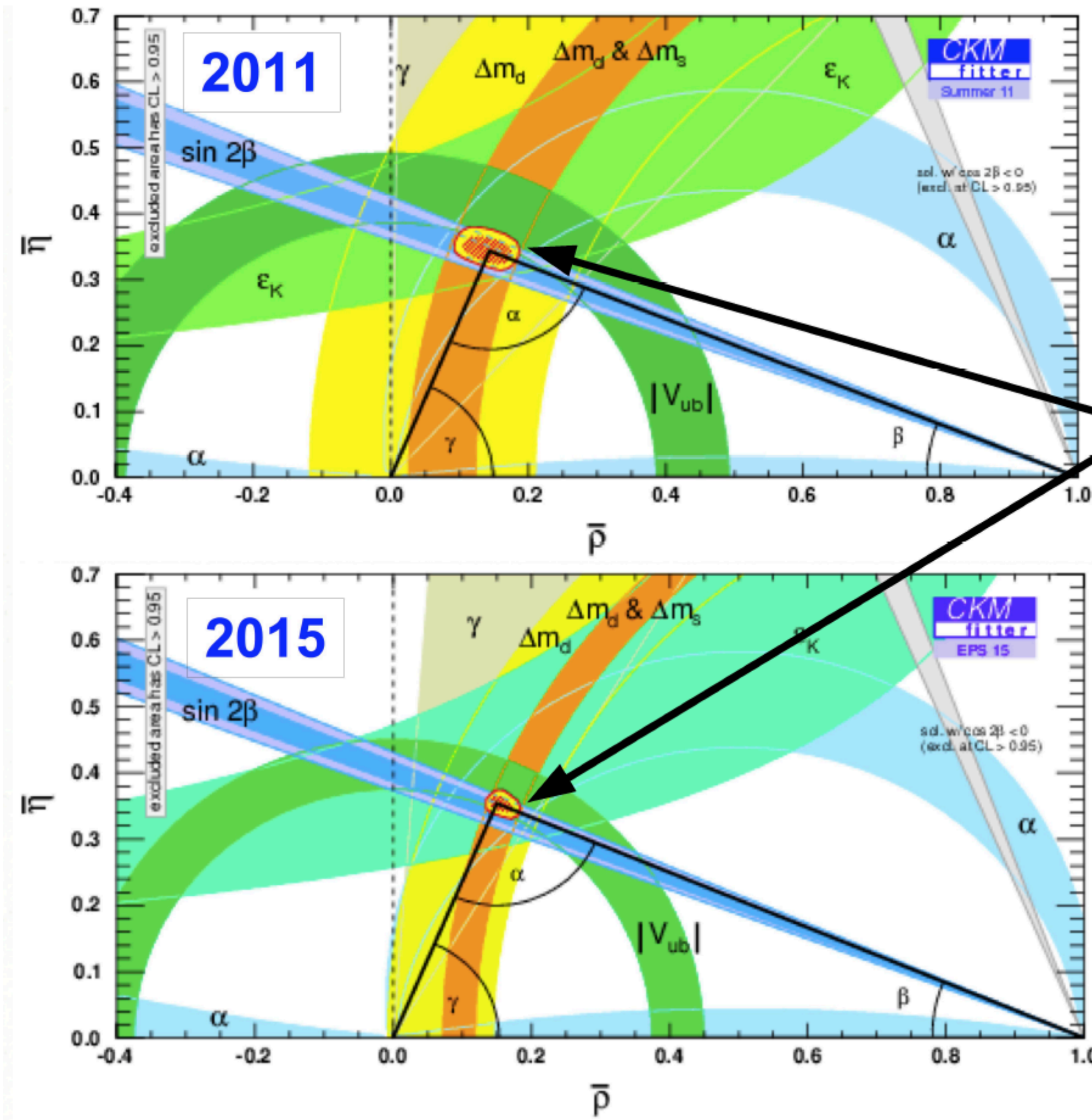
Consistent with SM prediction & CP conservation

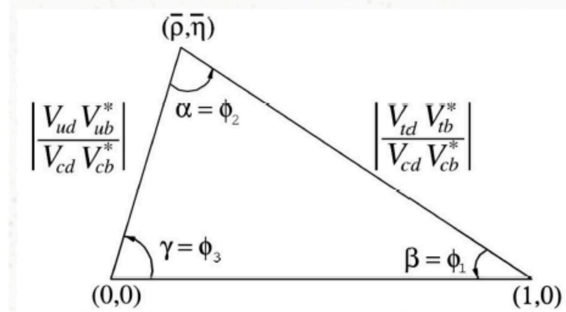
In tension with D0 dimuon asymmetry

$$A_{sl}^b = c_1\, a_{sl}^d + c_2\, a_{sl}^s = (0.957 \pm 0.251 \pm 0.146)\%$$

D0, PRL 105 (2010) 081801

CKM: before & after LHC



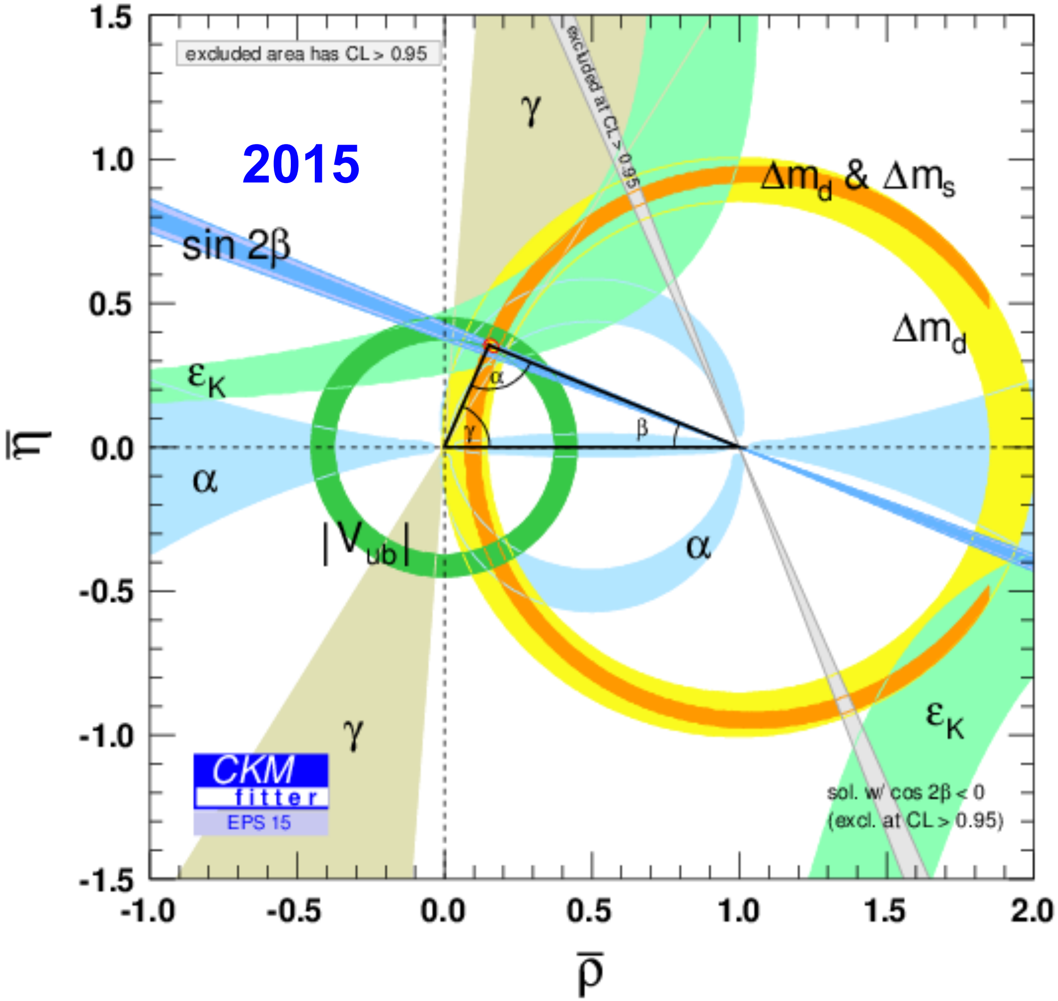


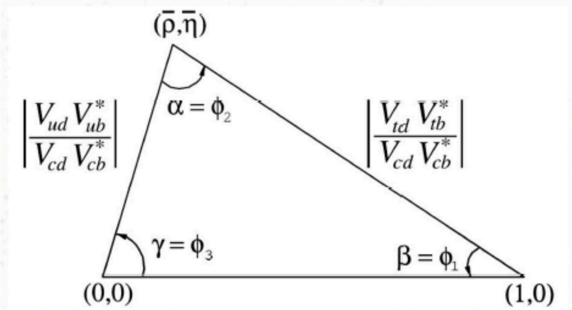
- 4x smaller area
- 4x better σ(J)
- 2x on angles (4x on γ)

Most of the improvement due to LHCb !

Further improvements after this plot (EPS'15)

CKM: before & after LHC





>

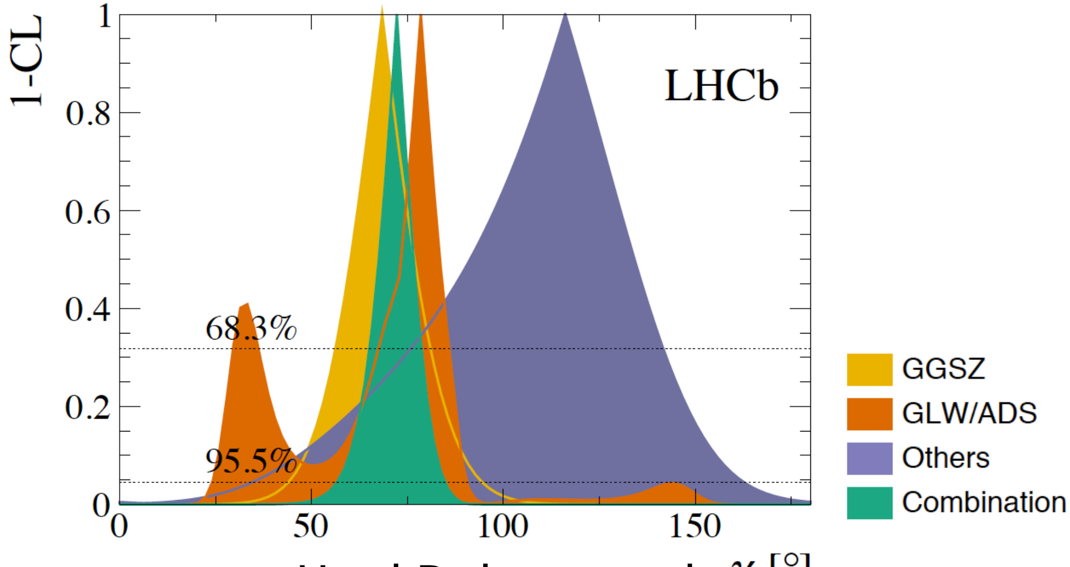
- 4x smaller area
- 4x better σ(J)
- 2x on angles (4x on γ)

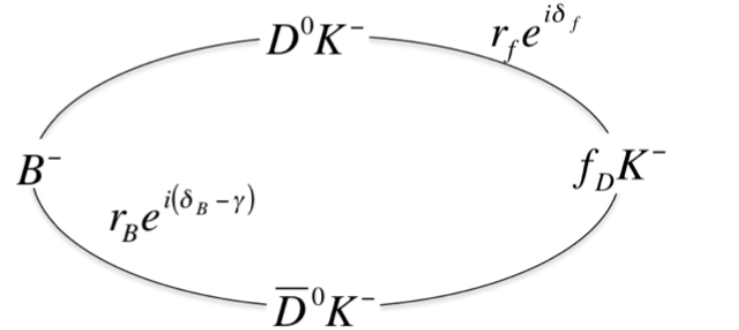
But γ precision is the worst one

γ combination at LHCb

Determine γ from CPV measurements

LHCb-PAPER-2016-032





$$\gamma = \left(72.2^{+6.8}_{-7.3}\right)^\circ$$ syst. included

BaBar: $\gamma = (70\pm18)^\circ$

Belle: $\gamma = (73^{+13}_{-15})^\circ$

Prospects

Sample	$\sigma_{\rm stat}(\gamma)^\circ$
Run 1	8
Run 2	4
Upgrade	∼ 1
Future upgrade	<0.5

Used D decay modes

GLW: $D\to K^+K^-$, $\pi^+\pi^-$, $K_S\pi^0$

ADS: $D\to \pi^-K^+$

quasi-ADS $D\to \pi^-K^+\pi^+\pi^-$, $\pi^-K^+\pi^0$

quasi-GLW $D\to \pi^+\pi^-\pi^+\pi^-$, $K^+K^-\pi^0$, $\pi^+\pi^-\pi^0$

GGSZ $D\to K_S\pi^+\pi^-$, $K_SK^+K^-$

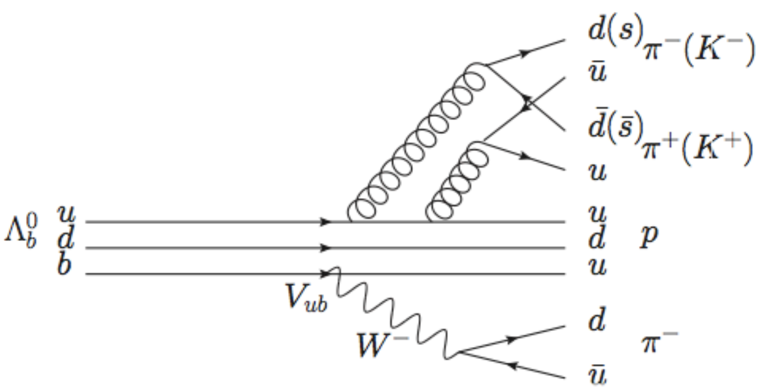
GLS $D\to K_SK^-\pi^+$, $K_S\pi^-K^+$

- **Current one syst. ~2° from CLEO strong phase measurements**
- **15-20 fb^{-1} ψ(3370) data from BESIII are desired to avoid syst. limitation for upgrade scenario**

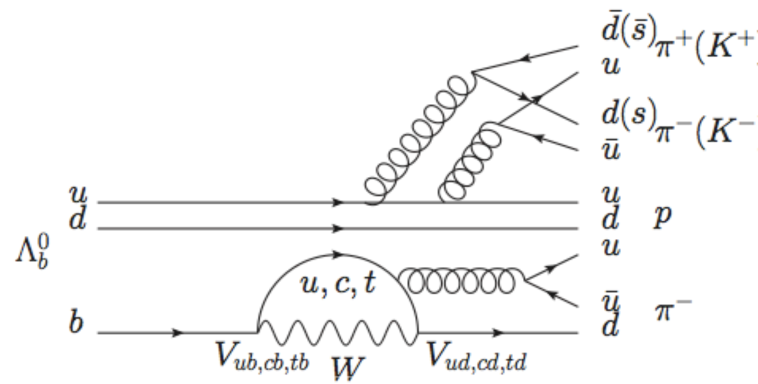
Baryon decays $\Lambda_b^0 \to p\pi^- h^+ h^-$

- CPV has never been observed in baryon sector
- $A_{CP} \sim 20\%$ expected in charmless Λ_b^0 decays in SM

  Y. K. Hsiao et al., PRD 91 (2015) 116007
- $\Lambda_b^0 \to p\pi^- h^+ h^-$ has comparable tree and loops contributions



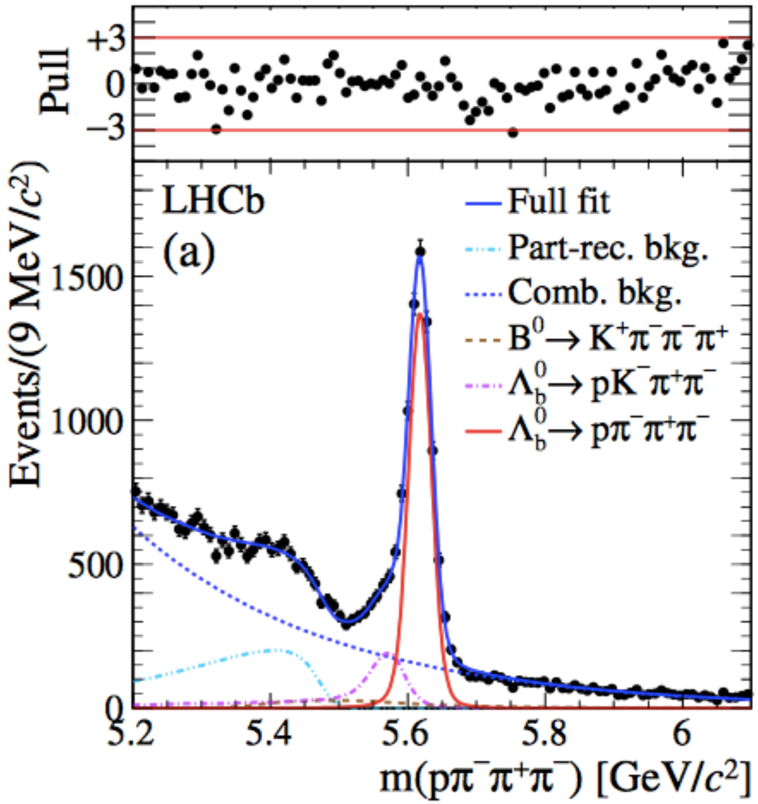
Tree $\propto |V_{ub}| \sim \lambda^3$

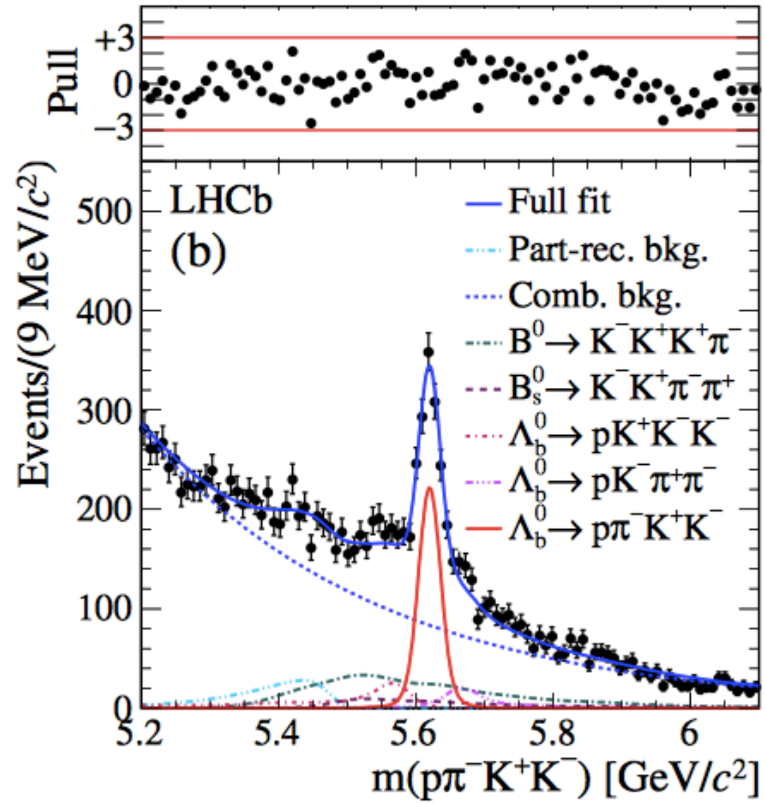


Penguin $\propto \sum_{x=u,c,t} V_{bx} V_{xd} \sim \lambda^3$

V_{ub} has large phase γ

$\Lambda_b \to p\pi^- h^+ h^-$: signal yields





$$N_{\Lambda_b^0 \to p\pi^-\pi^+\pi^-} = 6646 \pm 105(\text{stat}) \qquad N_{\Lambda_b^0 \to p\pi^- K^+ K^-} = 1030 \pm 56(\text{stat})$$

(full run-1 sample)

arXiv:1609.05216 (submitted to Nature Phys.)

Triple product asymmetry

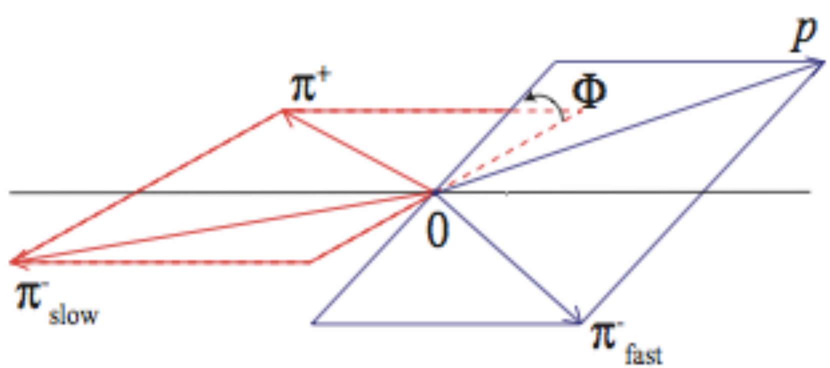
Search for CPV using triple product asymmetry (TPA)

Triple products in the Λ_b rest frame:

$$C_{\hat{T}} = \vec{p}_p \cdot (\vec{p}_{h^-} \times \vec{p}_{h^+}) \propto \sin\Phi$$
$$\overline{C}_{\hat{T}} = \vec{p}_{\overline{p}} \cdot (\vec{p}_{h^+} \times \vec{p}_{h^-}) \propto \sin\overline{\Phi}$$

$\hat{T}$-odd asymmetries:

$$A_{\hat{T}} = \frac{N_{\Lambda_b^0}(C_{\hat{T}}>0) - N_{\Lambda_b^0}(C_{\hat{T}}<0)}{N_{\Lambda_b^0}(C_{\hat{T}}>0) + N_{\Lambda_b^0}(C_{\hat{T}}<0)}$$
$$\overline{A}_{\hat{T}} = \frac{N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}}>0) - N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}}<0)}{N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}}>0) + N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}}<0)}$$



arXiv:1506.01346

CP-violating observable:

$$a_{CP}^{\hat{T}-\text{odd}} = \frac{1}{2}(A_{\hat{T}} - \overline{A}_{\hat{T}})$$

P-violating observable:

$$a_{P}^{\hat{T}-\text{odd}} = \frac{1}{2}(A_{\hat{T}} + \overline{A}_{\hat{T}})$$

CPV in baryon decays

Measurements integrated over phase space

– No significant CPV

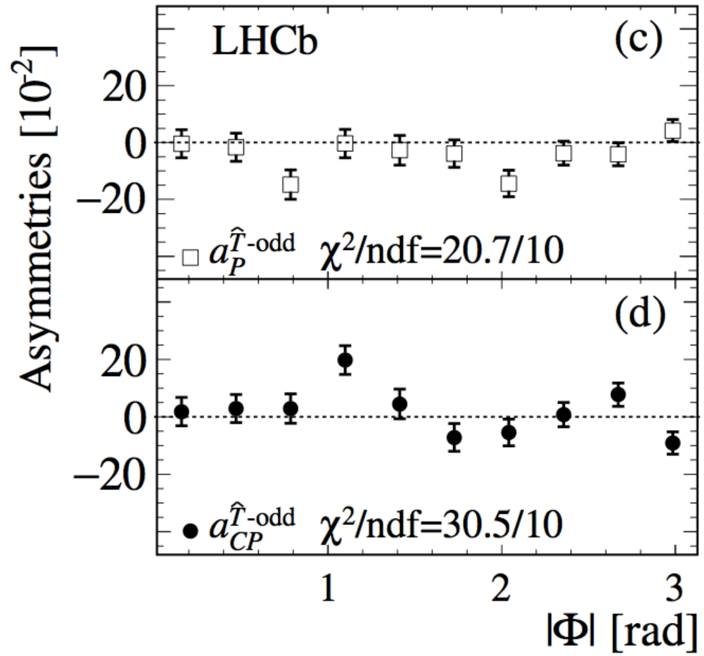
Λ_b^0 decay	$A_{\hat{T}}$ [%]	$\overline{A}_{\hat{T}}$ [%]	$a_{CP}^{\hat{T}\text{-odd}}$ ($a_P^{\hat{T}\text{-odd}}$) [%]
$p\pi^-\pi^+\pi^-$	$-2.56 \pm 2.06 \pm 0.45$	$-4.86 \pm 2.06 \pm 0.44$	$1.15(-3.71) \pm 1.45 \pm 0.32$
$p\pi^-K^-K^+$	$+2.68 \pm 6.76 \pm 0.85$	$+4.55 \pm 6.07 \pm 0.52$	$-0.93(+3.62) \pm 4.54 \pm 0.42$

Local Measurements

–Binning in $|\Phi|$

–3.3σ significance of localized CPV in $\Lambda_b \to p\pi^- \pi^+\pi^-$

–Compatible with SM



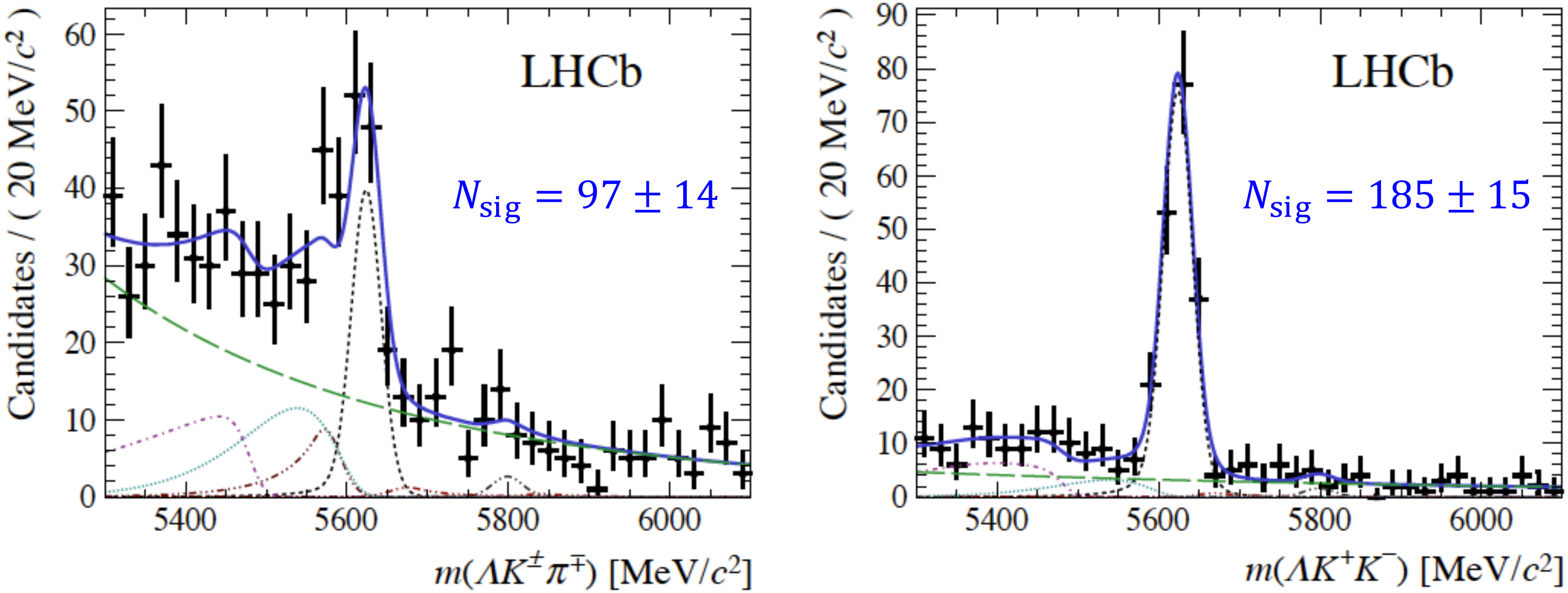
arXiv:1609.05216 (submitted to Nature Phys.)

First evidence of CPV in baryon decays!

CPV in baryon other decays

JHEP 05 (2016) 081

- First observations of $\Lambda_b^0 \to \Lambda K^+\pi^-$ and ΛK^+K^-



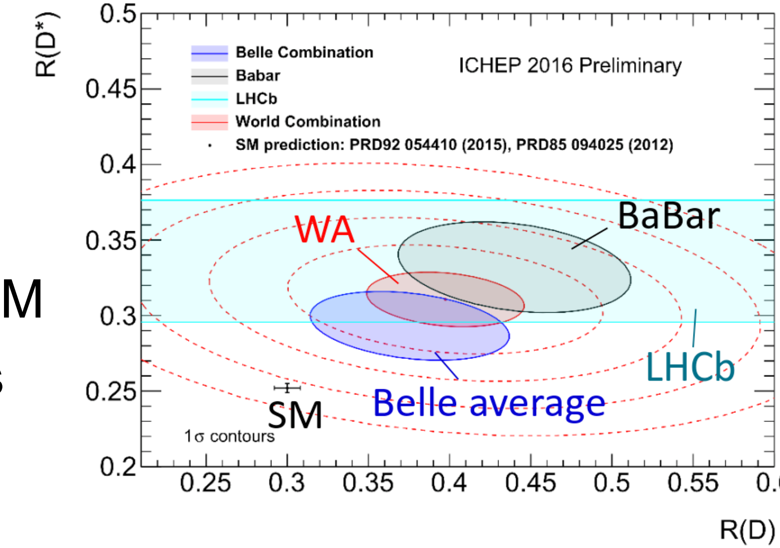
$$\mathcal{A}_{CP}(\Lambda_b^0 \to \Lambda K^+\pi^-) = -0.53 \pm 0.23 \pm 0.11$$
$$\mathcal{A}_{CP}(\Lambda_b^0 \to \Lambda K^+K^-) = -0.28 \pm 0.10 \pm 0.07$$

Rare decays

Flavor anomalies

$$R_{D^{(*)}} = \frac{\mathcal{B}(B\to D^{(*)}\tau\nu)}{\mathcal{B}(B\to D^{(*)}\mu\nu)}$$

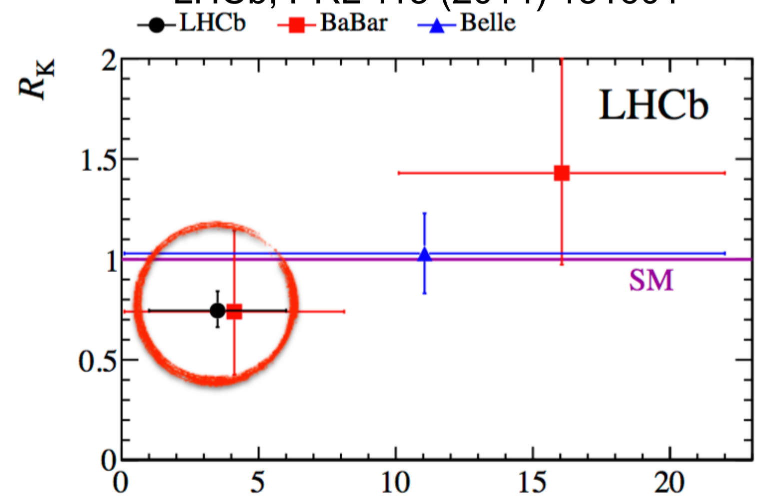
- Sensitive e.g. to charged Higgs
- Combined result from Babar, Belle and LHCb shows **4σ** discrepancy from the SM
- LHCb working on R_D and other τ modes



Ratio $R_K = \frac{\mathcal{B}(B^+\to K^+\mu^+\mu^-)}{\mathcal{B}(B^+\to K^+e^+e^-)}$

- Expected to be unity in the SM
- Observation of LFU violation would be a clear sign of NP
- LHCb observed a 2.6σ deviation from SM in the low q² region
- New results expected soon, e.g. R_{K^*}

LHCb, PRL 113 (2014) 151601

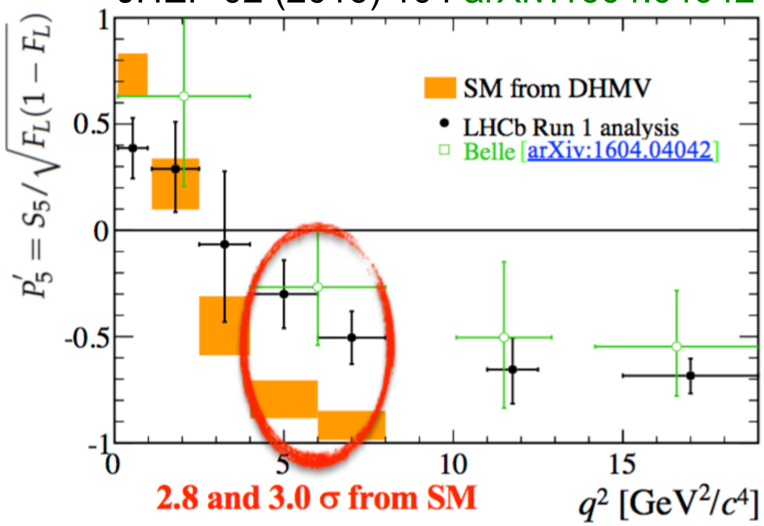


Flavor anomalies

Angular analysis of $B^0 \to K^* \mu^+ \mu^-$

- Angular distributions provide many observables sensitive to different sources of NP JHEP 05 (2013) 137
- Belle first angular analysis supports the deviation from SM expectation

JHEP 02 (2016) 104 arXiv:1604.04042



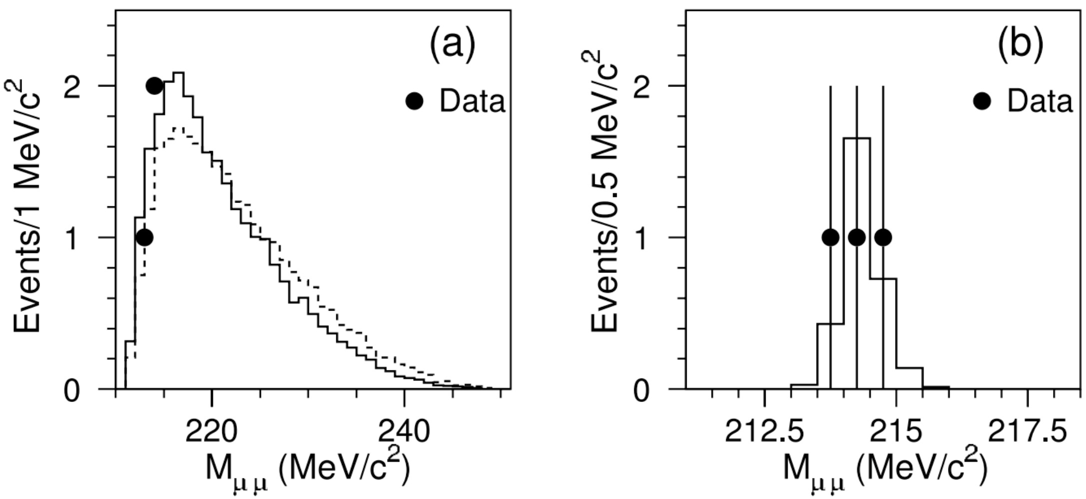
New results of rare decays

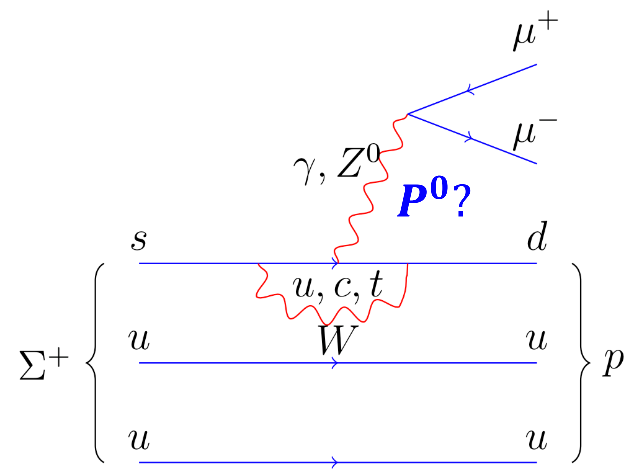
- $\Sigma^+ \to p\mu^+\mu^-$ NEW
- $B_s^0 \to \phi\gamma$
- $B_s^0 \to \tau^+\tau^-$ NEW

$\Sigma^+ \to p\mu^+\mu^-$

- Hint of a intermediate particle, $\Sigma^+ \to pP^0$, $P^0 \to \mu^+\mu^-$ with mass 214.3 MeV

HyperCP (E871)
PRL 94, 021801 (2005)





$\Sigma^+ \to p\mu^+\mu^-$

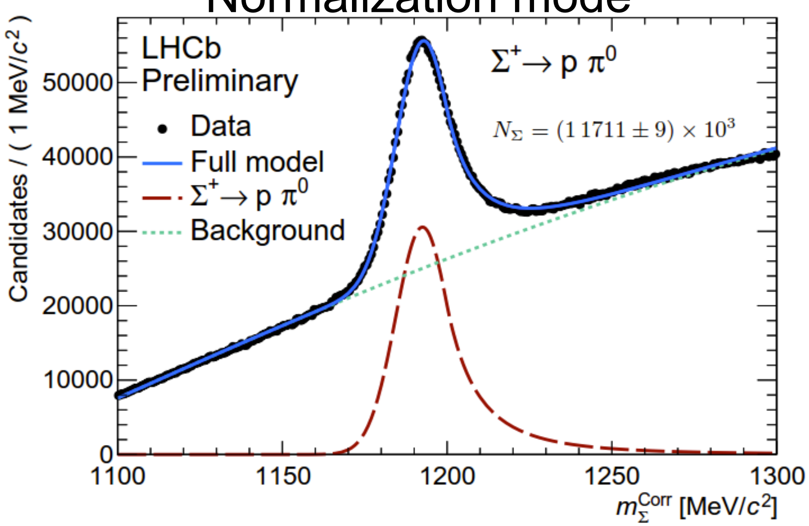
NEW

- LHCb has search for decay from prompt Σ^+
  - A challenge due to the small Q value of the decay and long lifetime of Σ^+

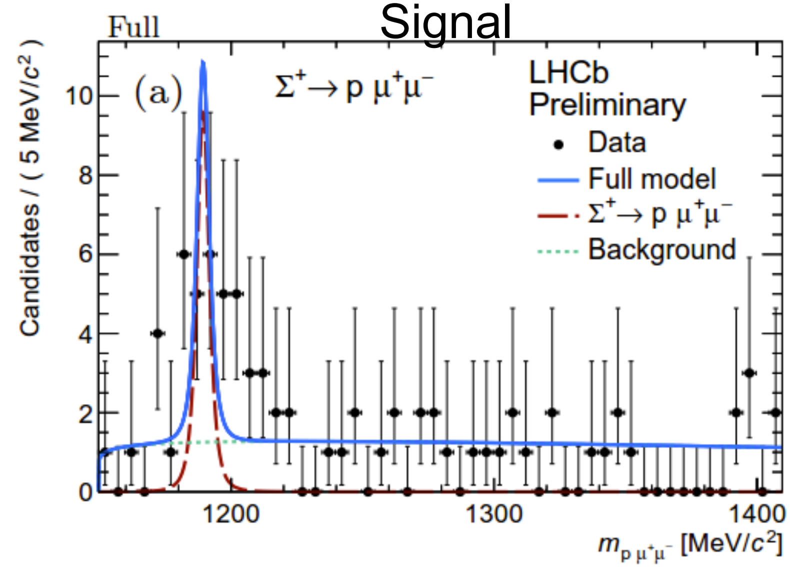
LHCb-CONF-2016-013

- A clear signal is seen with $12.9^{+5.1}_{-4.2}$ events. Significance 4 σ

Normalization mode



Signal



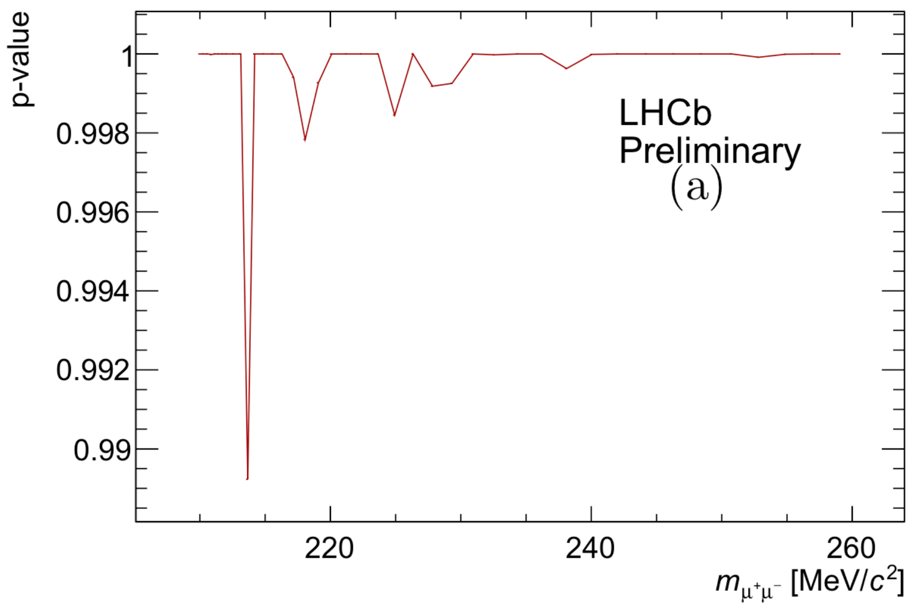
$\Sigma^+ \to p\mu^+\mu^-$ NEW

- Background subtracted data is fitted

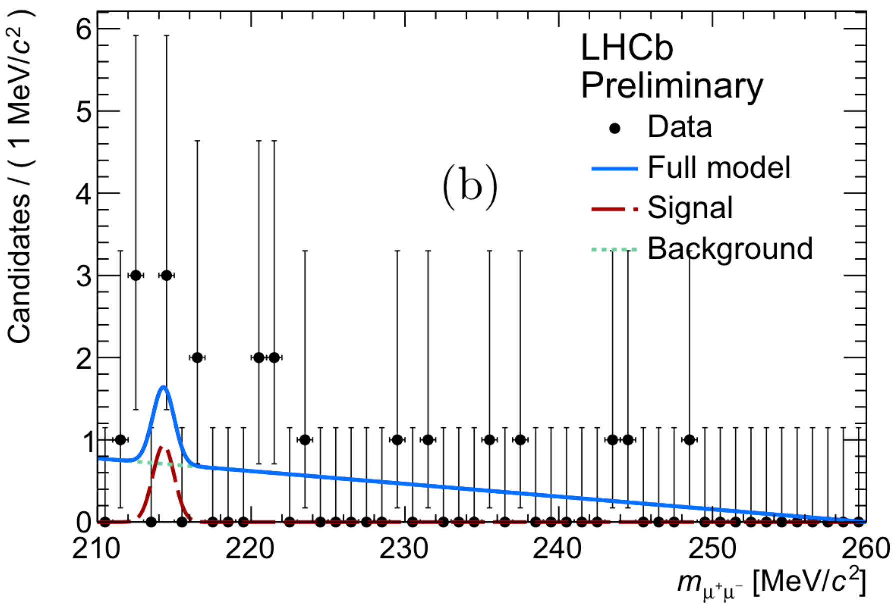
LHCb-CONF-2016-013

- No sign for a narrow peak

p-value of continuum-liked hypothesis



Fit with 214.3 MeV peak: N = 1.6 ± 1.9



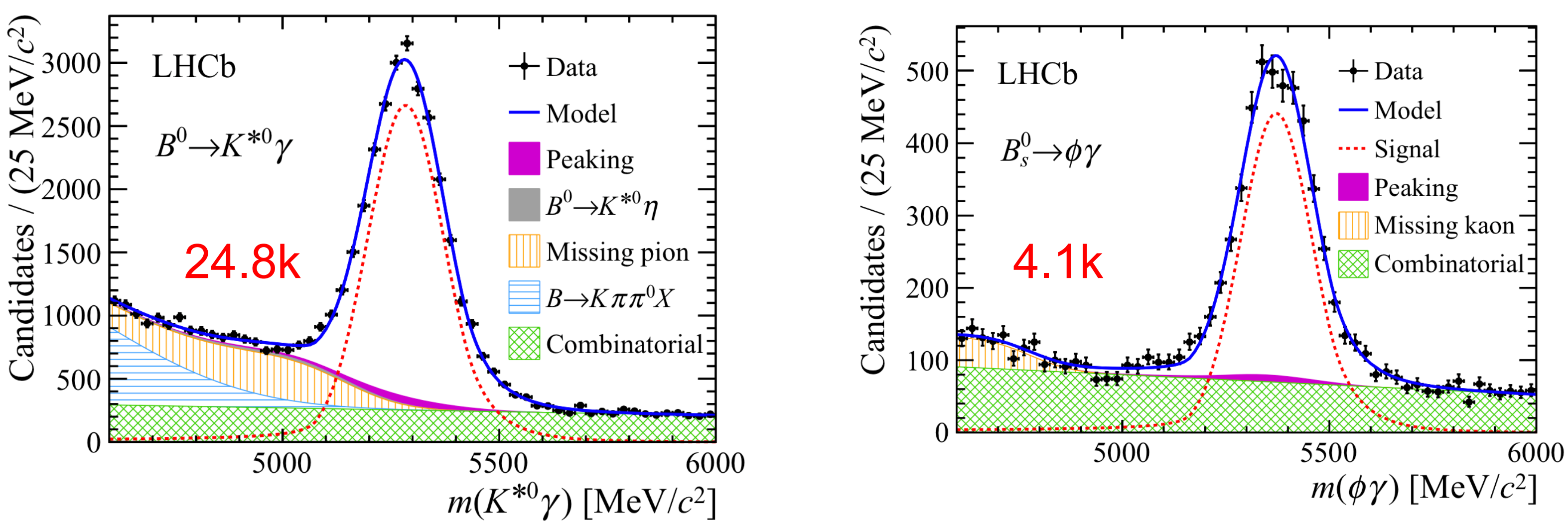
$B_s^0 \to \phi\gamma$

- Lifetime distribution can in principle reveal of the presence of right handed currents in the decay

$$\mathcal{P}(t) \propto e^{-\Gamma_s t}\{\cosh(\Delta\Gamma_s t/2) - \mathcal{A}^{\Delta}\sinh(\Delta\Gamma_s t/2)\}$$

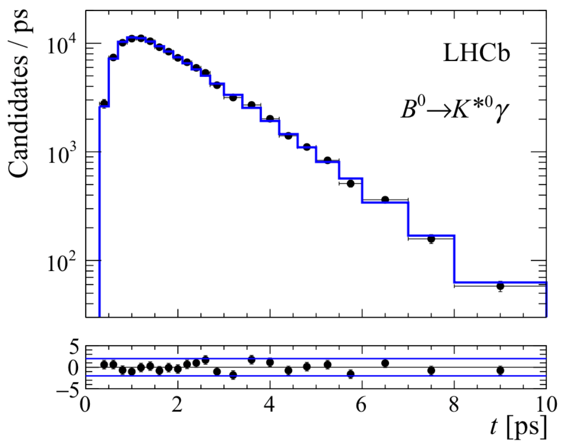
with $\mathcal{A}^{\Delta} \propto 2\frac{\gamma_R}{\gamma_L}$. $\mathcal{A}^{\Delta}_{SM} = 0.05 \pm 0.03$

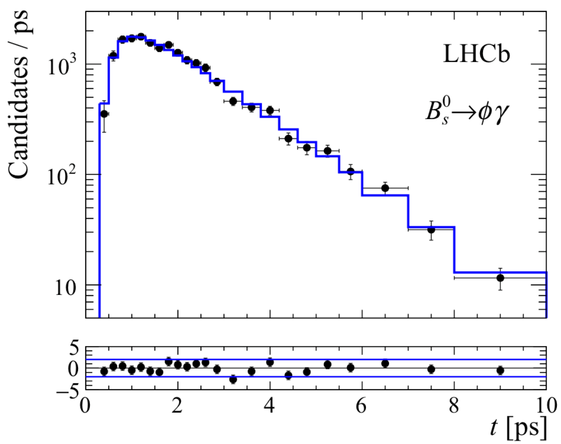
- $B^0 \to K^{*0}\gamma$ as control chancel for *t* acceptance



$B_s^0 \to \phi\gamma$

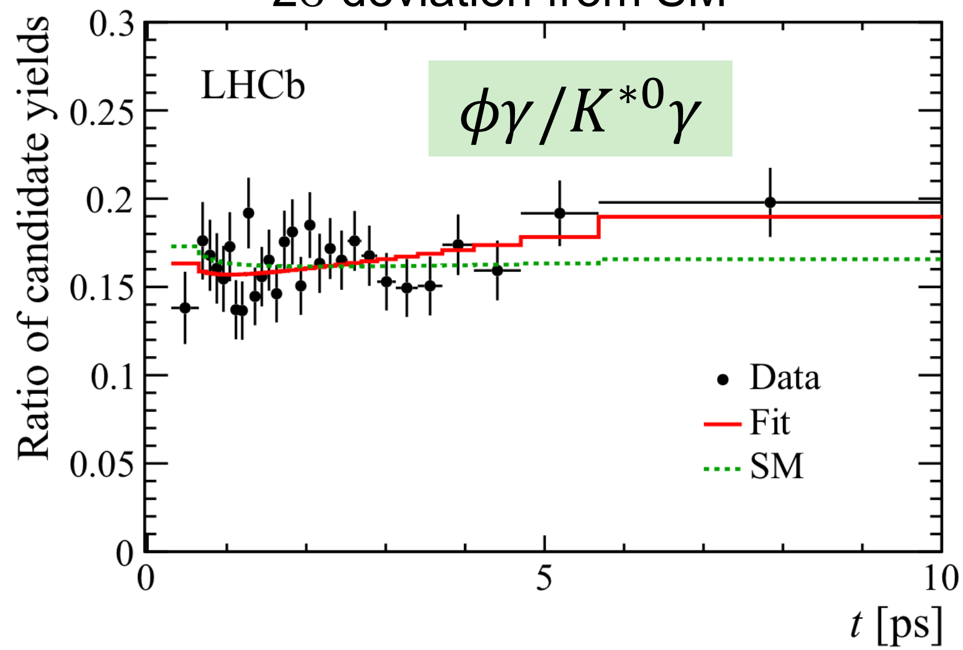
- An analysis of the lifetime distribution





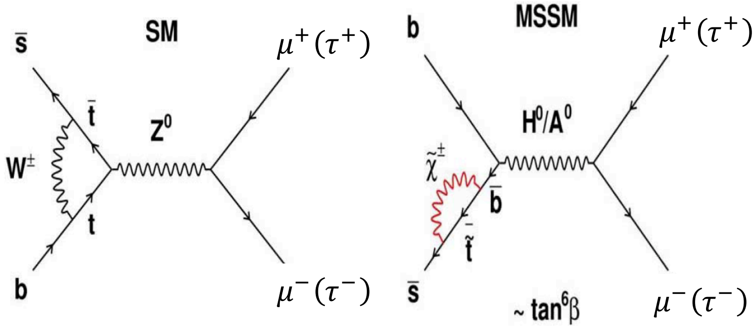
$$\mathcal{A}^{\Delta} = -0.98^{+0.46+0.23}_{-0.52-0.20}$$

2σ deviation from SM

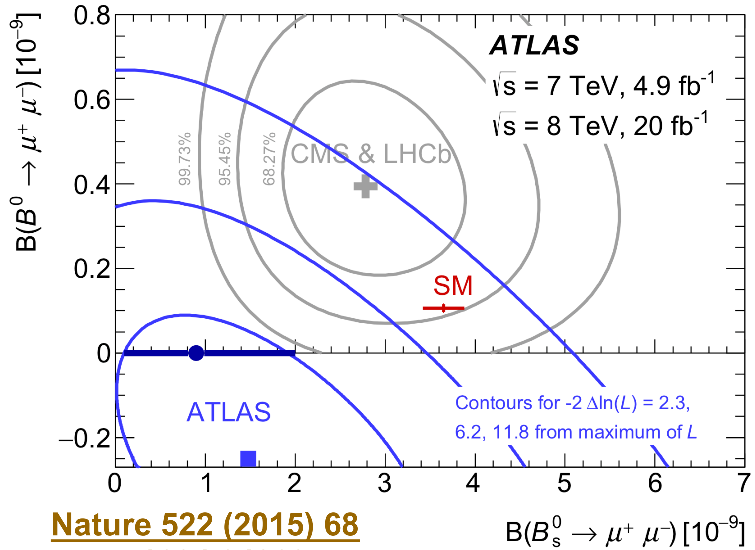


$B^0_{(s)} \to \ell^+\ell^-$

- $B^0_{(s)} \to \ell^+\ell^-$ very interesting

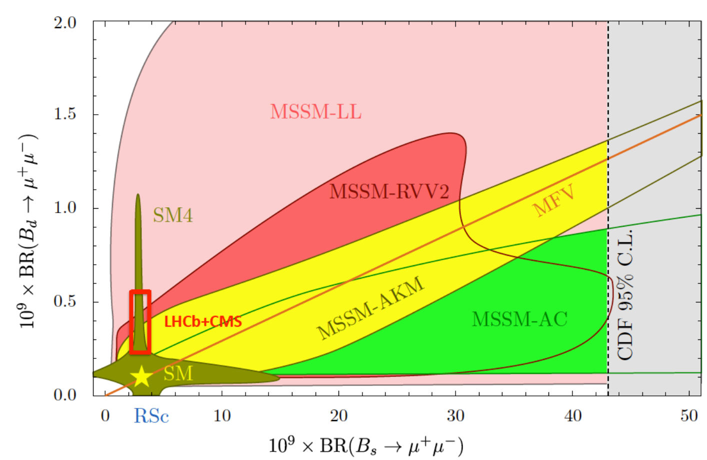


- $B^0_{(s)} \to \mu^+\mu^-$ consistent with SM prediction introduce strong constraints on NP models



Nature 522 (2015) 68
arXiv:1604.04263

$\mathcal{B}(B^0_q \to \mu^+\mu^-)$	$B^0_s(\times 10^{-9})$	$B^0_d(\times 10^{-10})$
SM prediction	(3.7 ± 0.2)	(1.06 ± 0.09)
CMS& LHCb	$(2.8^{+0.7}_{-0.6})$	$(3.9^{+1.6}_{-1.4})$
ATLAS	$(0.9^{+1.1}_{-0.8})$	< 4.2 @ 95% CL



$B^0_{(s)} \to \tau^+\tau^-$

- In the SM, $B^0_{(s)} \to \tau^+\tau^-$ is not helicity suppressed
- SM predicted $\mathcal{B}$ is ~200 larger than $B^0_{(s)} \to \mu^+\mu^-$

$$\mathcal{B}(B^0_s \to \tau^+\tau^-)_{SM} = (7.73 \pm 0.49) \times 10^{-7}$$
$$\mathcal{B}(B^0 \to \tau^+\tau^-)_{SM} = (2.22 \pm 0.19) \times 10^{-8}$$

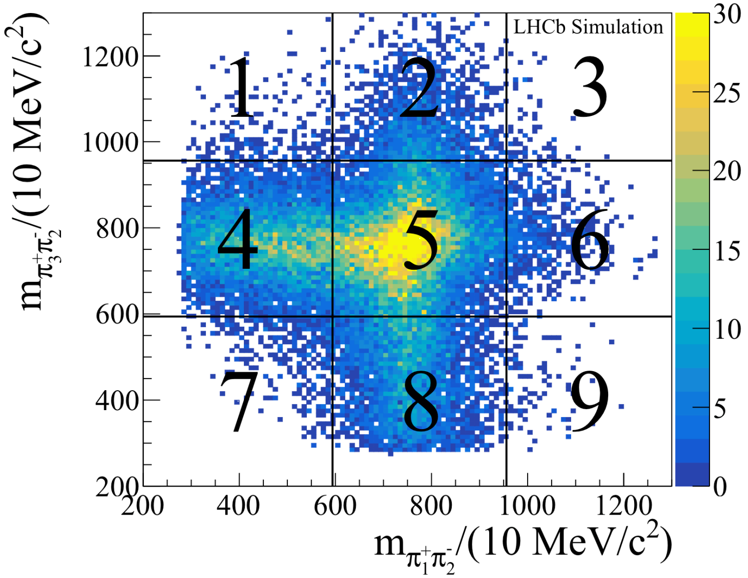
- $\mathcal{B}$ enhanced in many NP scenarios
- Current best limit from Babar

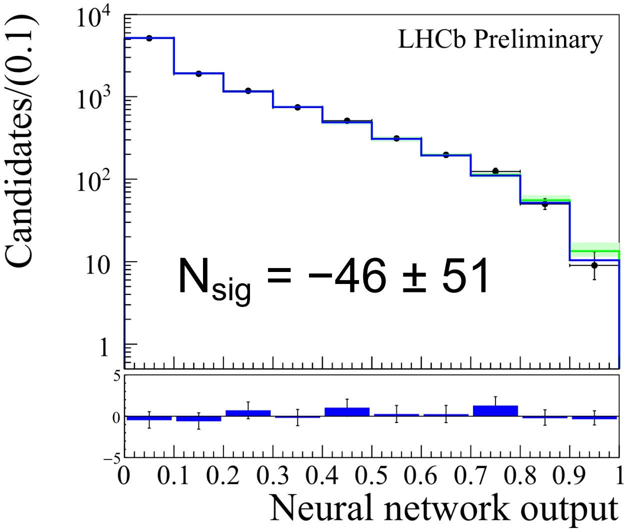
$$\mathcal{B}(B^0 \to \tau^+\tau^-) < 4.1 \times 10^{-3} \text{ at } 90\% \text{ C.L.}$$

$B^0_{(s)} \to \tau^+\tau^-$

NEW

- τ's reconstructed through hadronic $\tau^- \to \pi^-\pi^+\pi^-\nu$ mode
  - Fewer neutrinos in signal but more bkg from D^+ and D_s^+ decays
- Signal shape of NN is flat, bkg shape from control region
- Fit to $\tau^+\tau^- \in (5,5)$, the signal region





$$\mathcal{B}(B_s^0 \to \tau^+\tau^-) < 3.0 \times 10^{-3} \text{ at } 95\% \text{ C.L.}$$

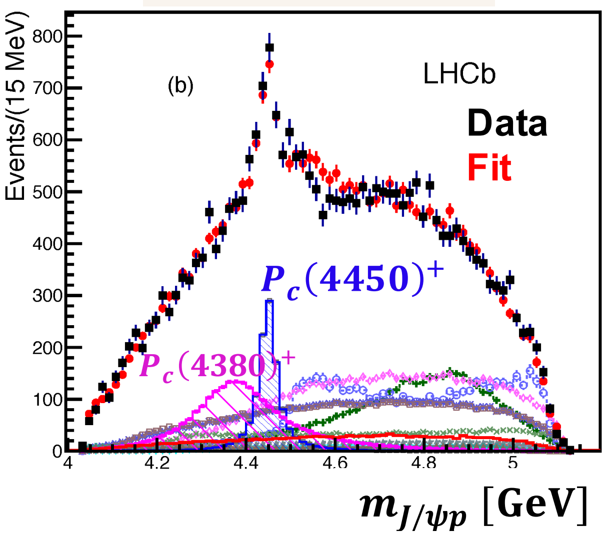
$$\mathcal{B}(B^0 \to \tau^+\tau^-) < 1.3 \times 10^{-3} \text{ at } 95\% \text{ C.L.}$$

Exotics

Pentaquarks

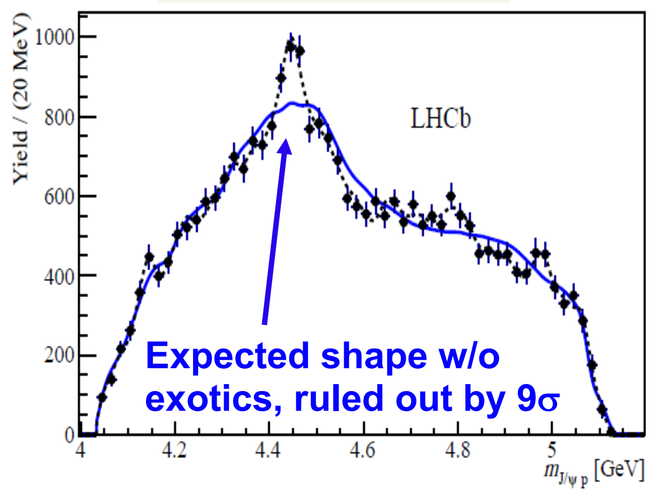
- In $\Lambda_b^0 \to J/\psi p K^-$, amplitude fits revealed two $J/\psi p$ states, consistent with $uudc\bar{c}$ pentaquarks
- Model-independent method confirmed the observations
- Amplitude fits to Cabibbo-suppressed $\Lambda_b^0 \to J/\psi p \pi^-$
  - Significance of the two P_c^+ and $Z_c(4200)^-$ together is 3.1σ; if assume production of $Z_c(4200)^-$is negligible, significance of two P_c^+ is 3.3σ
  - The two P_c^+ production rates is consistent with expectation

$\Lambda_b^0 \to J/\psi p K^-$



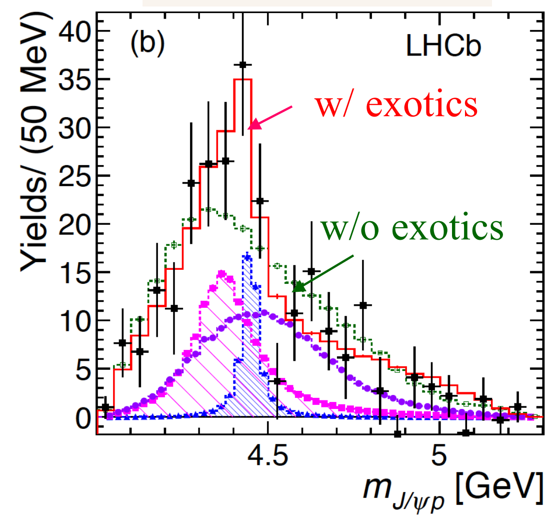
PRL 115 (2015) 072001

$\Lambda_b^0 \to J/\psi p K^-$



PRL 117 (2016) 082002

$\Lambda_b^0 \to J/\psi p \pi^-$

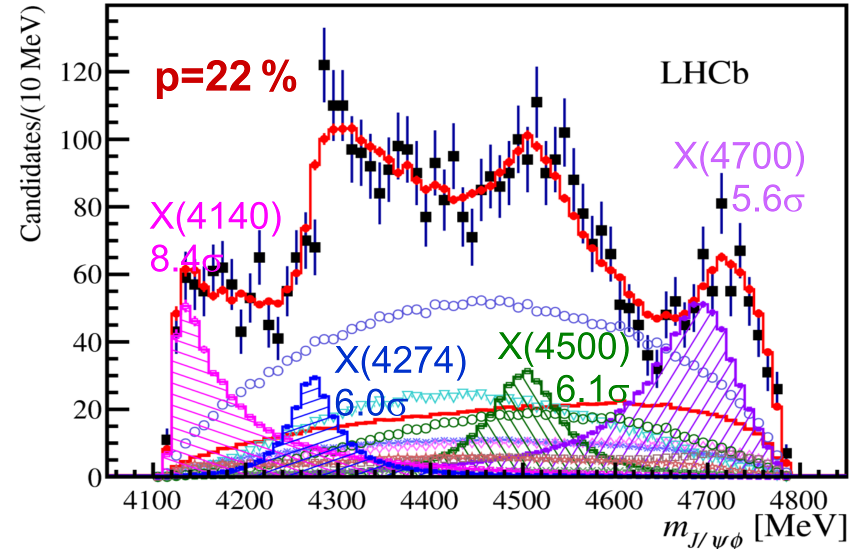


PRL 117 (2017) 082003

$J/\psi\phi$ states in $B^+ \to J/\psi\phi K^+$

arXiv: 1606.07898

- Observed four $X \to J/\psi\phi$ states
- J^{PC} are useful for interpretations of the states
  - First two identified as 1^{++} at $>5\sigma$
  - Last two as 0^{++} at $>4\sigma$



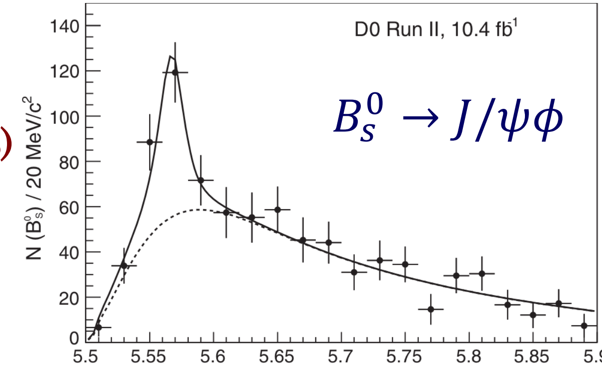
Contri-bution	sign. or Ref.	M_0 [MeV]	Γ_0 [MeV]	Fit results FF %
All $X(1^+)$				$16\pm3\ ^{+\ 6}_{-\ 2}$
$X(4140)$	8.4σ	$4146.5\pm4.5\ ^{+4.6}_{-2.8}$	$83\pm21\ ^{+21}_{-14}$	$13\pm3.2\ ^{+4.8}_{-2.0}$
Average other experiments		4143.4 ± 1.9	15.7 ± 6.3	
$X(4274)$	6.0σ	$4273.3\pm8.3\ ^{+17.2}_{-\ 3.6}$	$56\pm11\ ^{+\ 8}_{-11}$	$7.1\pm2.5\ ^{+3.5}_{-2.4}$
CDF	[28]	$4274.4\ ^{+8.4}_{-6.7}\pm1.9$	$32\ ^{+22}_{-15}\pm8$	
CMS	[25]	$4313.8\pm5.3\pm7.3$	$38\ ^{+30}_{-15}\pm16$	
All $X(0^+)$				$28\pm\ 5\pm\ 7$
$NR_{J/\psi\phi}$	6.4σ			$46\pm11\ ^{+11}_{-21}$
$X(4500)$	6.1σ	$4506\pm11\ ^{+12}_{-15}$	$92\pm21\ ^{+21}_{-20}$	$6.6\pm2.4\ ^{+3.5}_{-2.3}$
$X(4700)$	5.6σ	$4704\pm10\ ^{+14}_{-24}$	$120\pm31\ ^{+42}_{-33}$	$12\pm\ 5\ ^{+\ 9}_{-\ 5}$

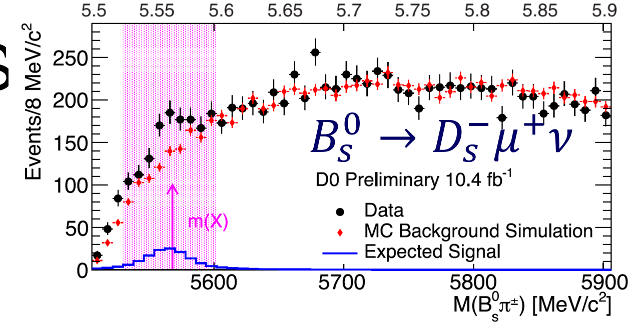
substantially larger

$X(5568)^{\pm} \to B_s^0 \pi^{\pm}$ state?

- Claimed by DØ in $p\bar{p}$ collision
  - M = $5567.8 \pm 2.9^{+0.9}_{-1.9}$ MeV
  - Γ = $21.9 \pm 6.4^{+5.0}_{-2.5}$ MeV
  - $\rho_X^{D\O}$ = (8.6 ±1.9 ± 1.4) %

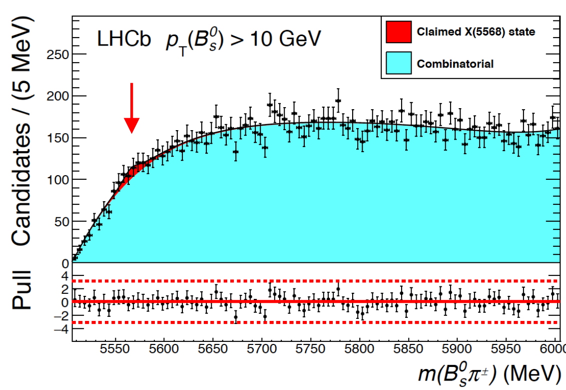
PRL 117, 022003 (2016)

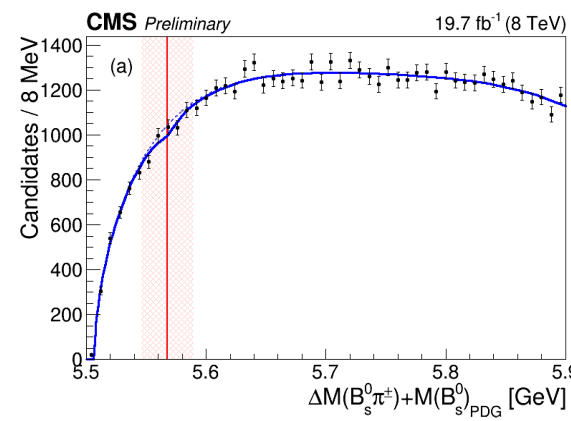




- No evidence seen by LHCb and CMS in pp collision
  - 20x larger and much cleaner B_s^0 sample
  - ρ_X < 2.4% (LHCb) & < 3.9% (CMS) @95% $C.L.$

$$\rho_X = \frac{\sigma(\overset{(-)}{pp} \to X + \text{anything};\ X \to B_s^0\pi^{\pm})}{\sigma(\overset{(-)}{pp} \to B_s^0 + \text{anything})} = \frac{N_X}{N_{B_s}} \frac{\varepsilon_{B_s}}{\varepsilon_X}$$





PRL 117 (2016) 152003

Summary

- LHCb has performed many measurements with unprecedented sensitivity in various aspects: CPV, rare decays… Generally agree with SM well
- A handful of $\mathbf{2-4\,\sigma}$ deviations from SM observed, and further investigations needed from both theory and experimental sides

Thanks!

Fit results

- Best fit has J^P=(3/2$^-$, 5/2$^+$), also (3/2$^+$, 5/2$^-$) & (5/2$^+$, 3/2$^-$) are preferred for low and high P_c^+

Resonance	Mass (MeV)	Width (MeV)	Significance	Fit fraction(%)
$P_c(4380)^+$	4380 ± 8 ± 29	205±18±86	**9 σ**	8.4 ± 0.7 ± 4.2
$P_c(4450)^+$	4449.8 ± 1.7 ± 2.5	39±5±19	**12 σ**	4.1 ± 0.5 ± 1.1

[PRL 115, (2015) 072001]

For $P_c(4380)^+$,

$$\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)\mathcal{B}(P_c^+ \to J/\psi p) = (2.66 \pm 0.22 \pm 1.33^{+0.48}_{-0.38})\times 10^{-5}$$

For $P_c(4450)^+$,

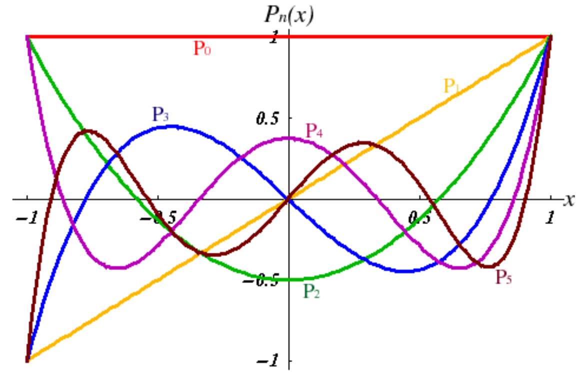
$$\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)\mathcal{B}(P_c^+ \to J/\psi p) = (1.30 \pm 0.16 \pm 0.35^{+0.23}_{-0.18})\times 10^{-5}$$

Chin. Phys. C40 (2016) 011001

Legendre moments

$$\frac{dN}{d\cos\theta} = \sum_{l=0}^{l_{\max}} \left\langle P_l^U \right\rangle P_l(\cos\theta) \qquad \theta = \theta_{K^*} \quad \text{or} \quad \theta_{\Lambda^*}$$

$$\left\langle P_l^U \right\rangle = \int_{-1}^{+1} \frac{dN}{d\cos\theta} P_l(\cos\theta) d\cos\theta \propto \sum_{i=1}^{n_{events}} \frac{1}{\varepsilon_i} P_l(\cos\theta_i)$$



Λ* can contribute only to low-order moments

Λ*-only hypothesis called H_0

$$l_{\max} = 2J_{\max}$$

***J_{max}* is the highest spin of Λ* resonance possible**

Reflections of exotic hadrons can contribute to low **and high** order moments:

– Detecting non-zero moments above $2J_{max}$ signals presence of exotics

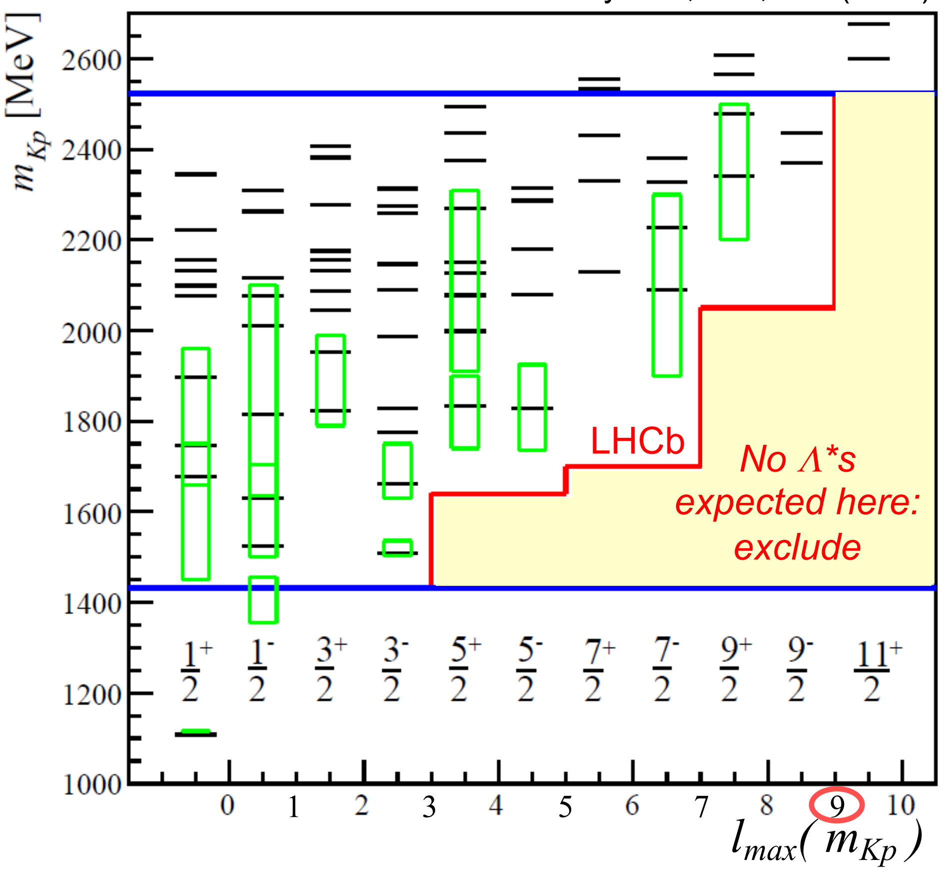
Moments coefficients as function of $m_{K\pi}$

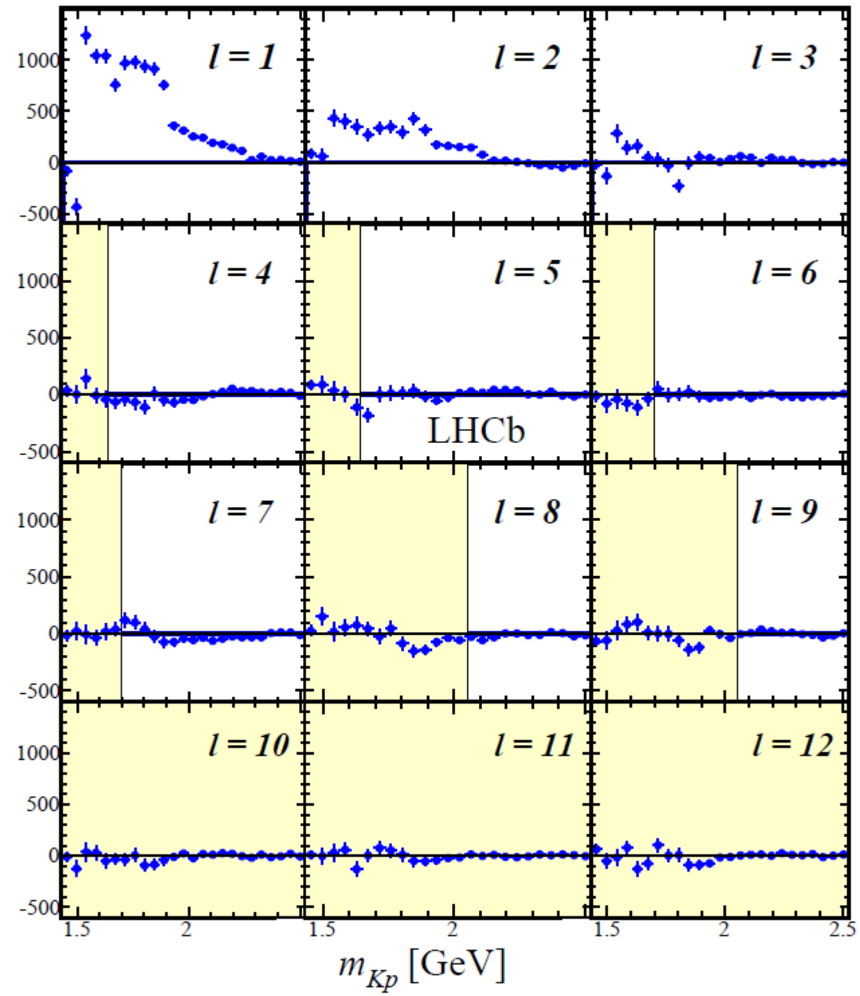
From **know Λ* resonances**, **quark model predictions** as a guide

Much fewer known states than predicted!

Known Λ* states: boxes $M_0 \pm \Gamma_0$

Λ* mass predictions by Loring-Metsch-Petry EPJ, A10, 447 (2001)

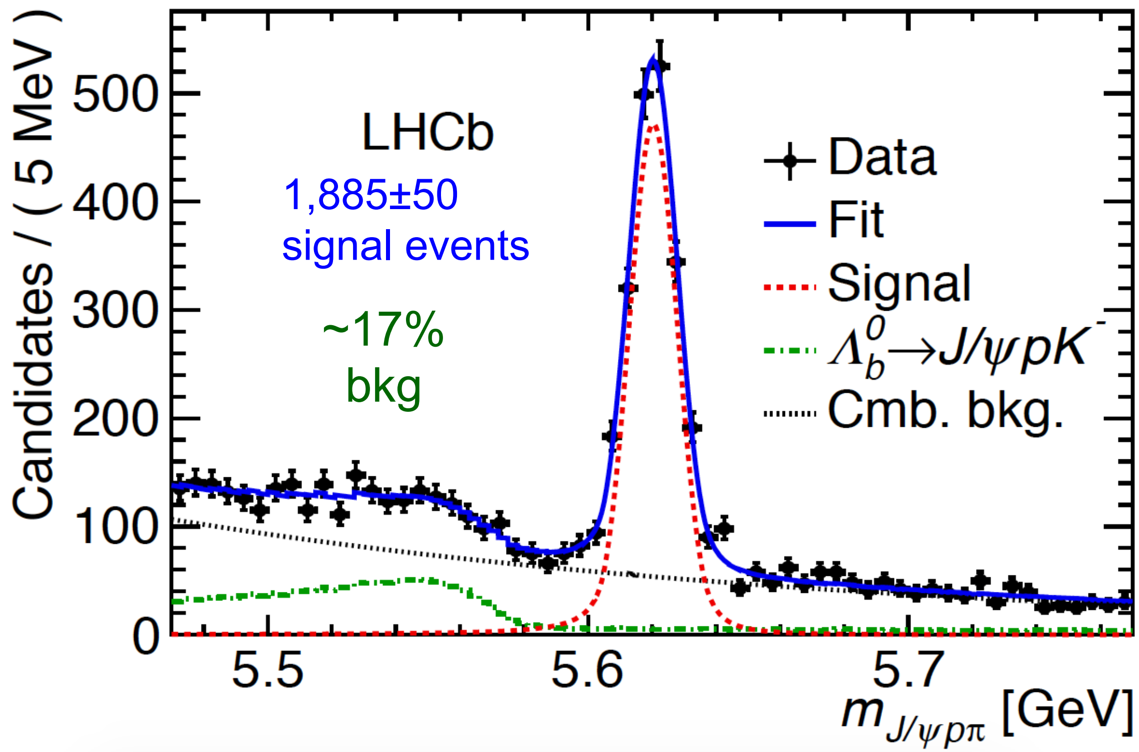




$\Lambda_b^0 \to J/\psi p \pi^-$

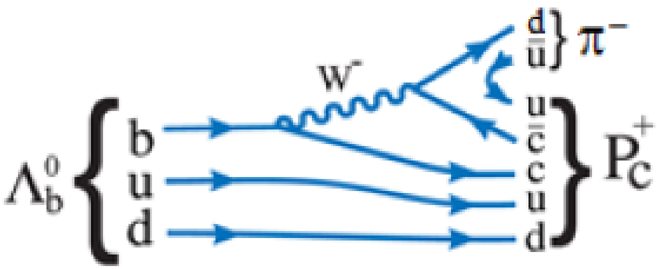
- Cabibbo-suppressed decay $\Lambda_b^0 \to J/\psi p \pi^-$
- $\mathcal{B}$ is ~8% of the favored $\Lambda_b^0 \to J/\psi p K^-$ decays

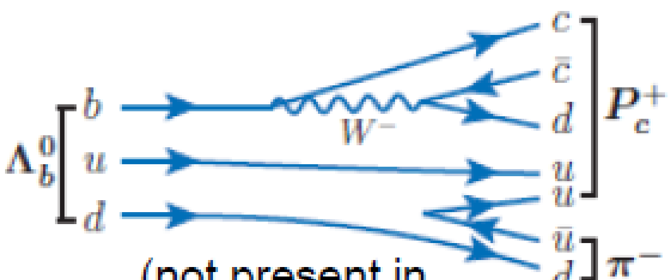
PRL 117 (2016) 082003



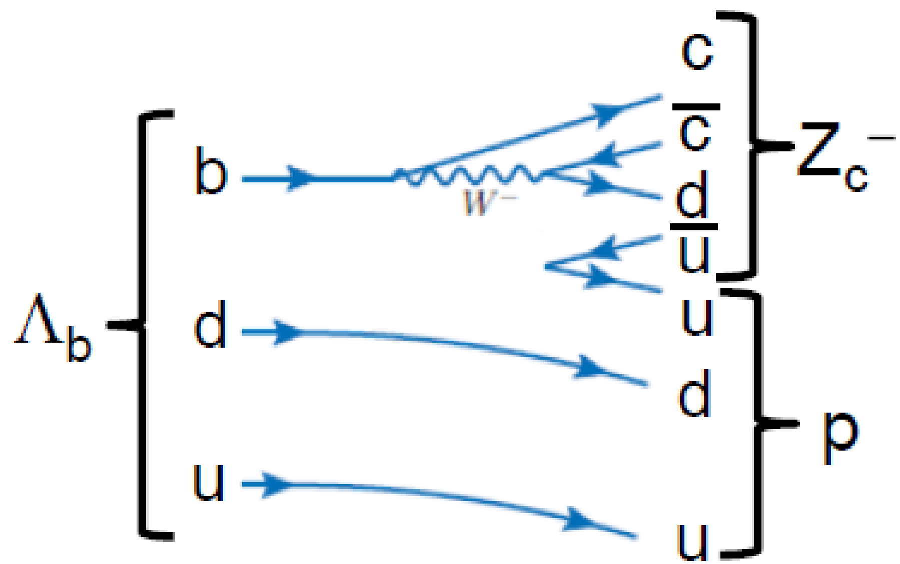
Possible exotic contributions

- $P_c(4380)^+$ and $P_c(4450)^+$ observed in the favored mode by LHCb
- $Z_c(4200)^- \to J/\psi\pi^-$ observed in $B^0 \to J/\psi\pi^- K^+$ by Belle





(not present in Cabibbo favored case)



N^* resonance models

State	J^P	Mass (MeV)	Width (MeV)	RM	EM
NR $p\pi$	$1/2^-$	-	-	4	4
$N(1440)$	$1/2^+$	1430	350	3	4
$N(1520)$	$3/2^-$	1515	115	3	3
$N(1535)$	$1/2^-$	1535	150	4	4
$N(1650)$	$1/2^-$	1655	140	1	4
$N(1675)$	$5/2^-$	1675	150	3	5
$N(1680)$	$5/2^+$	1685	130	-	3
$N(1700)$	$3/2^-$	1700	150	-	3
$N(1710)$	$1/2^+$	1710	100	-	4
$N(1720)$	$3/2^+$	1720	250	3	5
$N(1875)$	$3/2^-$	1875	250	-	3
$N(1900)$	$3/2^+$	1900	200	-	3
$N(2190)$	$7/2^-$	2190	500	-	3
$N(2300)$	$1/2^+$	2300	340	-	3
$N(2570)$	$5/2^-$	2570	250	-	3
Free parameters				40	106

← *LS* couplings

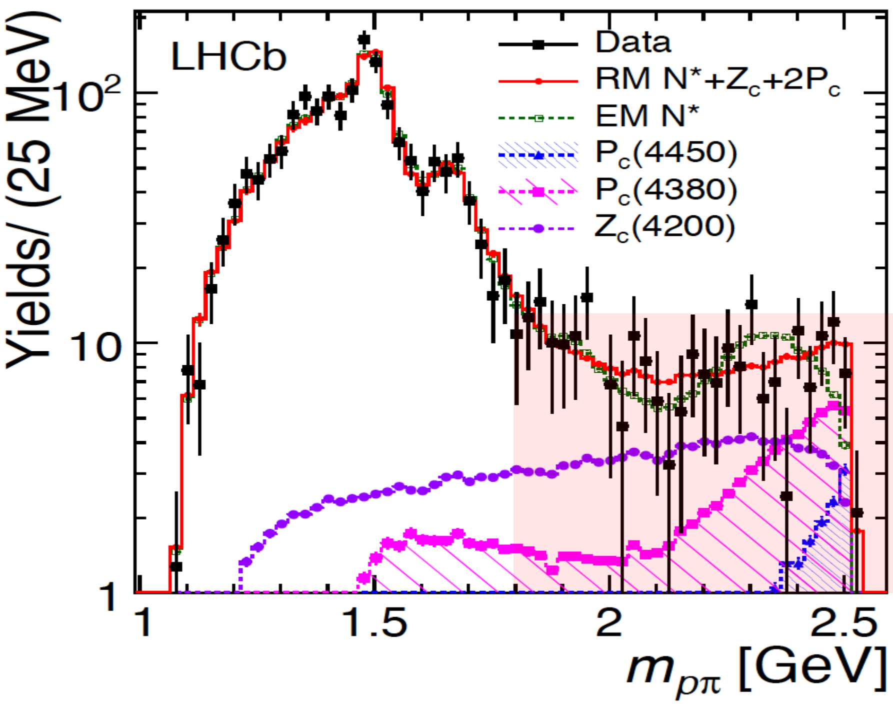
allow for reduction of the number of free parameters by excluding high *L* values

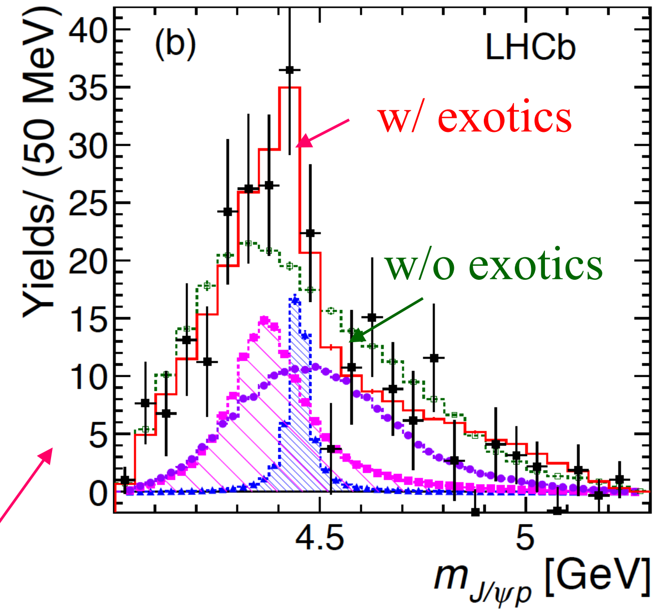
} BES-III ($N(2300)$, $N(2570)$)

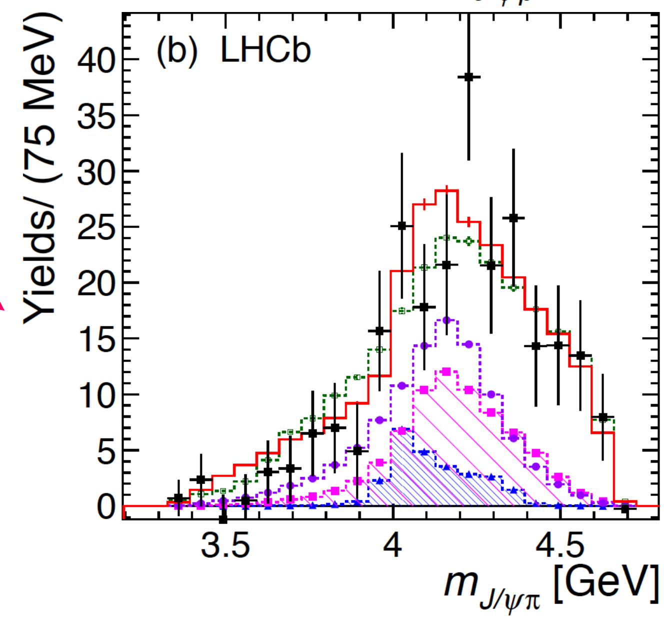
Reduce Model for central value, Extended model for significance and syst.

Full amplitude fits

- Significance of the two P_c^+ and $Z_c(4200)^-$ together is 3.1σ.
- **Evidence for exotic hadron contributions to $\Lambda_b^0 \to J/\psi p \pi^-$!**







PRL 117 (2016) 082003

Further results

- Individual exotic hadron contributions are not significant
  More data are needed
- If assume production of $Z_c(4200)^-$ is negligible, significance of two P_c^+ is 3.3σ

State	Fit fraction (%)	$R_{\pi/K} \equiv \mathcal{B}(\Lambda_b^0 \to P_c^+\pi^-)/\mathcal{B}(\Lambda_b^0 \to P_c^+K^-)$
$Z_c(4200)^-$	$7.7 \pm 2.8^{+3.4}_{-4.0}$	$-$
$P_c(4380)^+$	$5.1 \pm 1.5^{+2.1}_{-1.6}$	$0.050 \pm 0.016^{+0.020}_{-0.016} \pm 0.025$
$P_c(4450)^+$	$1.6^{+0.8}_{-0.6}{}^{+0.6}_{-0.5}$	$0.033^{+0.016}_{-0.014}{}^{+0.011}_{-0.009} \pm 0.025$

[H.-Y Cheng and C.-K Chua, PRD92 (2015) 096009]： $R_{\pi/K} = 0.07 \sim 0.08$

[Y. K. Hsiao and C. Q. Geng, PLB751 (2015) 572]： $R_{\pi/K} = 0.58 \pm 0.05$

$\Lambda_b^0 \to J/\psi p\pi^-$ are consistent with $\Lambda_b^0 \to J/\psi pK^-$ results

Physics (APS) Synopsis:

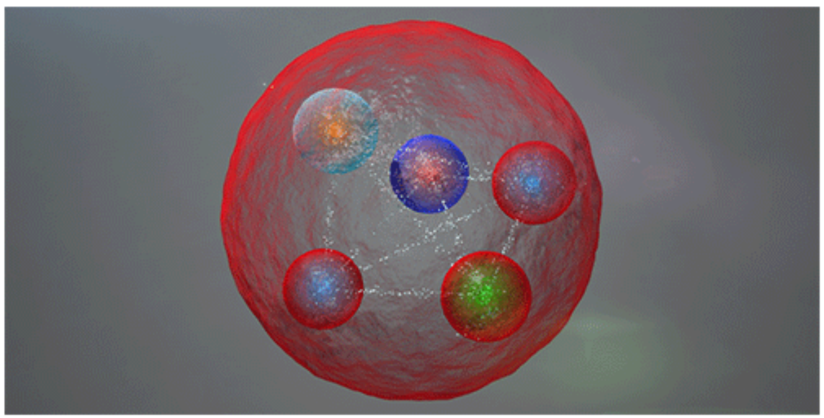
http://physics.aps.org/synopsis-for/10.1103/PhysRevLett.117.082003

Print

Synopsis: Pentaquark Discovery Confirmed

August 18, 2016

New results from the LHCb experiment confirm the 2015 discovery that quarks can combine into groups of five.



CERN

Pentaquarks are here to stay. Two new studies from the LHCb collaboration at CERN's Large Hadron Collider quash any remaining doubts about the discovery of the exotic five-quark particles that was announced last year (see 12 August 2015 Viewpoint). One study demonstrates that the evidence for pentaquarks in the discovery data is model independent. Another reports evidence for exotic hadronic particles—whose properties are consistent with those of

Evidence for Exotic Hadron Contributions to $\Lambda_b^0 \to J/\psi p \pi^-$ Decays

R. Aaij *et al.* (LHCb Collaboration)

Phys. Rev. Lett. 117, 082003 (2016)

Published August 18, 2016

Model-Independent Evidence for $J/\psi p$ Contributions to $\Lambda_b^0 \to J/\psi p K^-$ Decays

R. Aaij *et al.* (LHCb Collaboration)

Phys. Rev. Lett. 117, 082002 (2016)

Published August 18, 2016

Announcements

Neutrinos

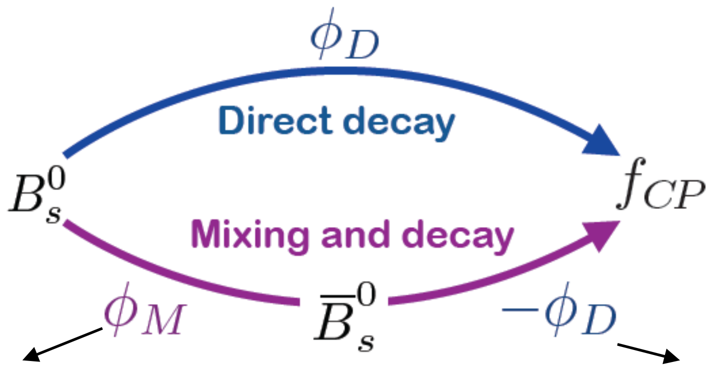
Find out more about research on neutrinos in this collection of articles from the archive of *Physics*.

More Announcements »

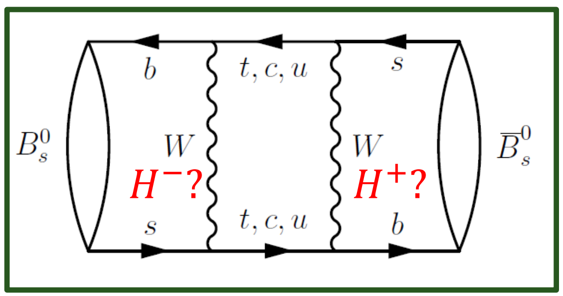
CPV phase ϕ_s

- Phase difference between interference of mixing and decay in B_s^0 system

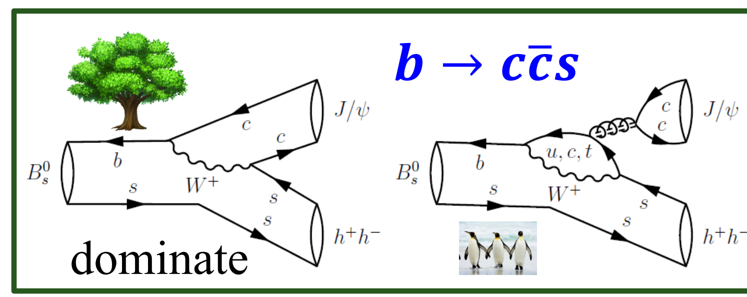
$$\phi_s = \phi_M - 2\phi_D$$



Mixing



Decay

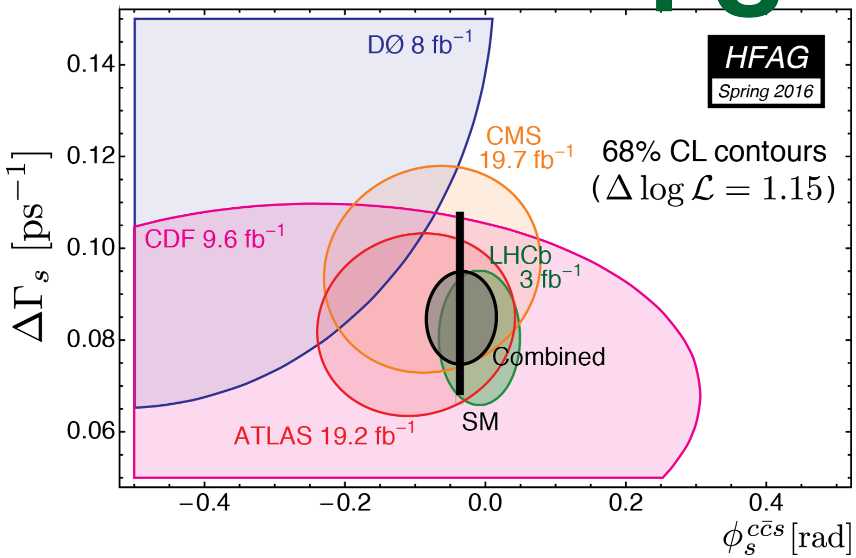


- Contributions to measured value [CKMFitter]

$$\phi_s^{\text{meas}} = \phi_s^{\text{SM}} + \Delta\phi_s^{\text{peng}} + \delta^{\text{NP}}$$

$$\phi_s^{\text{SM}} = -0.0376^{+0.0007}_{-0.0008}\ \text{rad}$$

ϕ_s results



LHCb, PRL 114 （2015） 041801

$B_s \to J/\psi\phi$, $J/\psi\pi^+\pi^-$:

ϕ_s = -0.010 ± 0.039 rad

In agreement with, much less precise than

ϕ_s^{SM} = -0.038 ± 0.001 rad

LHCb result most precise but still statistically limited

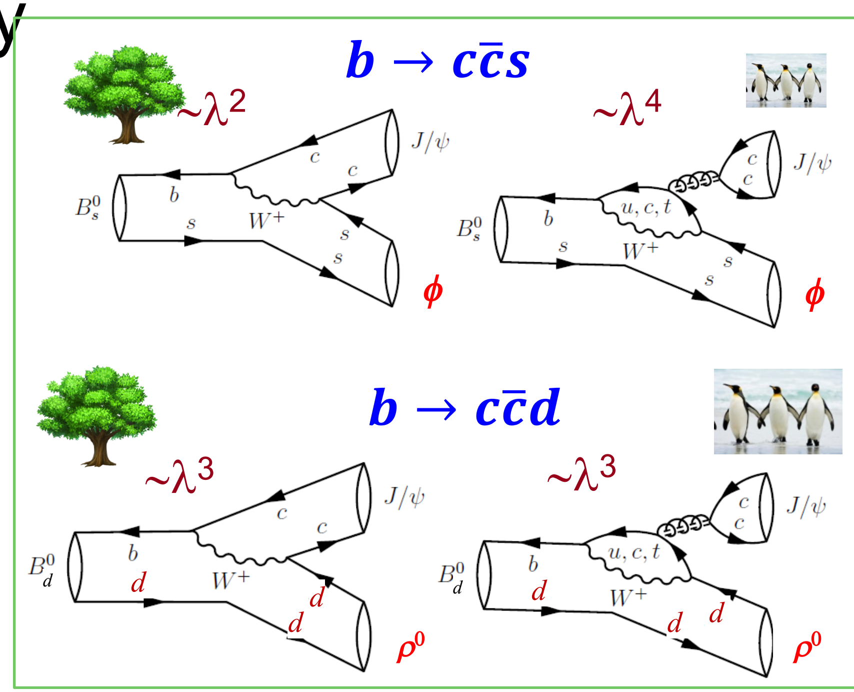
$m_{KK} < 1.05$ GeV

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)
All combined			-0.033 ± 0.033	$+0.084 \pm 0.007$	

Penguin pollution in ϕ_s

- $\phi_s^{\mathrm{meas}} = \phi_s^{\mathrm{SM}} + \Delta\phi_s^{\mathrm{peng}} + \delta^{\mathrm{NP}}$
- Penguin contribution is small, but cannot can't be calculated reliably from QCD
- To reveal NP, necessary to know $\Delta\phi_s^{\mathrm{peng}}$
- Penguin in $B_s^0 \to J/\psi\phi$ is doubly-suppressed; can be study in enhanced process: $B^0 \to J/\psi\rho^0$

$\lambda = |V_{us}| = 0.22$



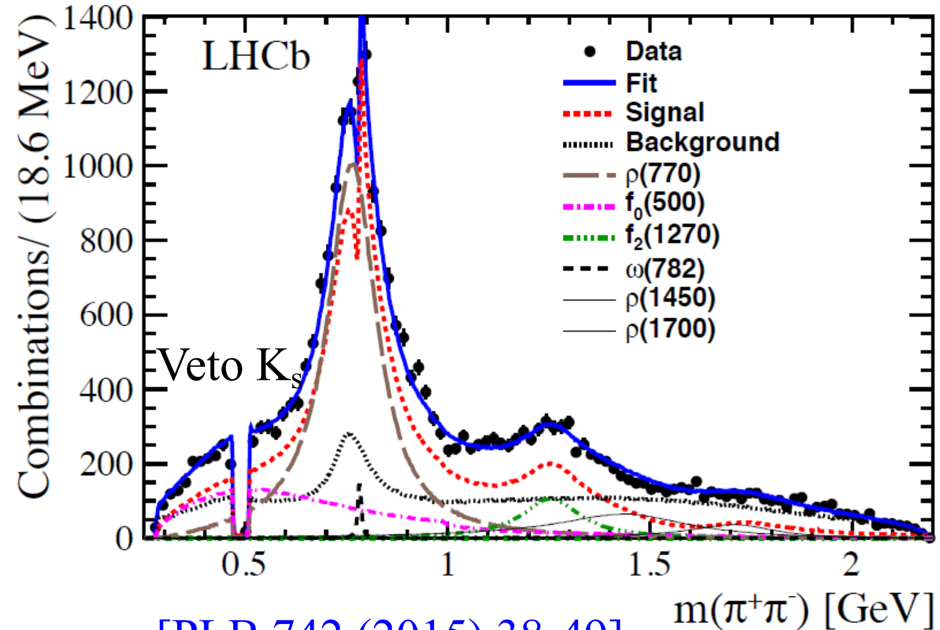
Measurement in $B^0 \to J/\psi\pi^+\pi^-$

- Time-dependent full amplitude analysis
- Large ρ^0 fraction ~65%

$$\phi_d^{J/\psi\rho^0} = \left(41.7 \pm 9.6^{+2.8}_{-6.3}\right)^\circ,$$

$$\Rightarrow \Delta\phi_d \equiv \phi_d^{J/\psi\rho^0} - \phi_d^{c\bar{c}s} = \left(-0.9 \pm 9.7^{+2.8}_{-6.3}\right)^\circ$$

$$\Delta\phi_s^{\text{peng}} = -\frac{\lambda^2}{1-\lambda^2}\Delta\phi_d$$



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Including theoretical uncertainty, $\Delta\phi_s^{peng}$ is limited in $\pm$18 mrad @ 68.3% CL. Better than $\sigma(\phi_s) = \pm$ 33 mrad

It becomes an important benchmark channel for LHCb upgrade

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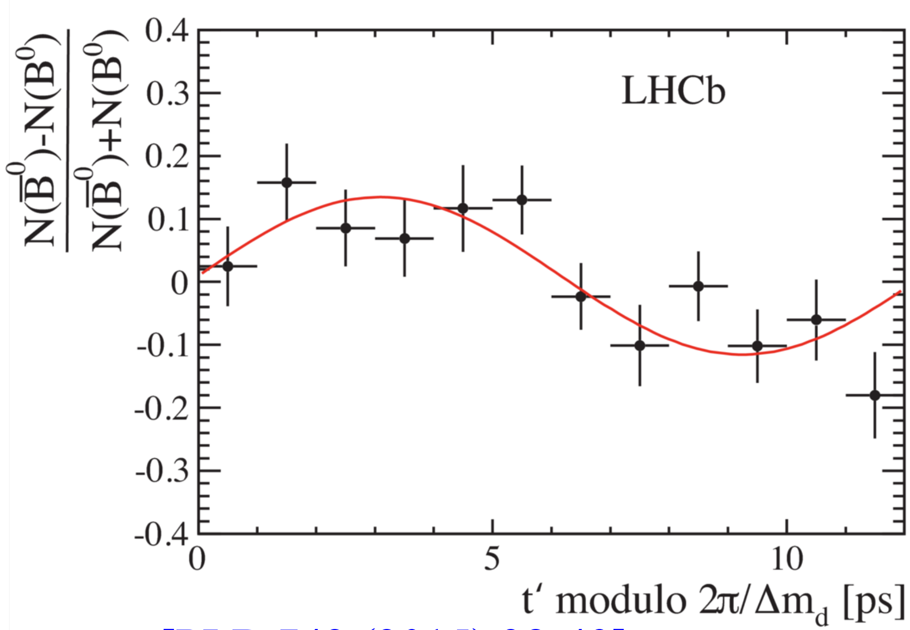

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LHCb goals

- Find or establish limits on physics beyond the standard model using CP violating & rare beauty & charm decays
- Rare: $B_{(s)}\to\mu^+\mu^-$, $B^0\to K^*\mu^+\mu^-$, $B^-\to Ke^+e^-/K\mu^+\mu^-$
- CP violation: determine $\angle$'s: γ, β, ϕ_s
  - γ measured with $B^-\to D^0 K^-$ decays
  - ϕ_s measured with $B_s\to J/\psi\phi$ & $J/\psi\pi^+\pi^-$ decays
  - All $B\to J/\psi\, \pi^+\pi^-$ & $J/\psi K^+K^-$ studied
  - In study of $B^0\to J/\psi K^+K^-$ [arXiv:1308.5916], $\Lambda_b\to J/\psi K^- p$ was suggested as a potential background