Selected LHCb highlights

Complementary to Neville Harnew's lecture on "Measurement of the Unitarity Triangle with LHCb" and to Toni Pich's lecture on "Theory of flavour"

Monica Pepe Altarelli (CERN)

On behalf of LHCb collaboration

Summer School and Workshop on the Standard Model and Beyond

CORFU2016

The LHCb collaboration

- ~700 authors from 69 institutes in 16 countries
- >300 publications, some with very high impact

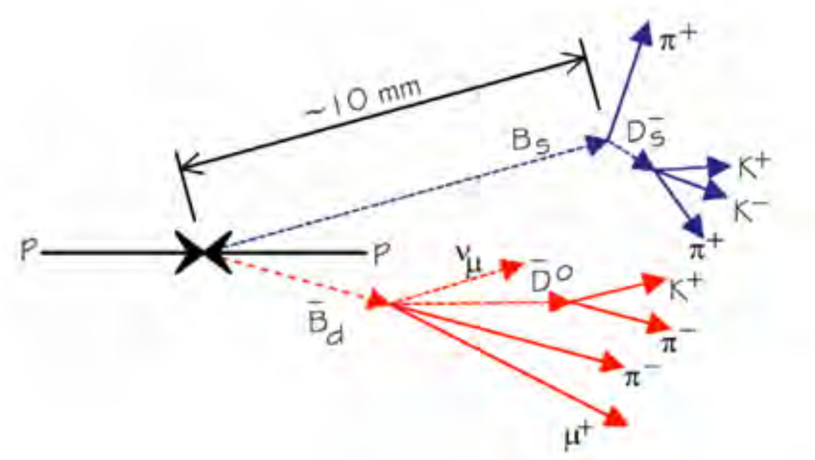
Why b? (I)

- The heaviest quark that binds in hadrons
- Many decay channels: a vast laboratory
- Heavy mass → more theoretically accessible
  - Asymptotic freedom: $\alpha_s(m_b) \approx 0.2$
  - Heavy Quark Effective Theory: $\Lambda_{QCD}/m_b \approx 0.1$
- Lifetime long enough for experimental detection
  - While the t quark lifetime is too short, the b and c quarks live long enough so that we can study their production and decay sequence in detail
  - $\tau_{beauty} \sim 1.5\ 10^{-12}$ s
  - $\tau_{charm} \sim 10^{-12}$ s
  - $\tau_{top} \sim 5\ 10^{-25}$ s

$\tau \sim 1/(m^5\ |V_{CKM}|^2)$

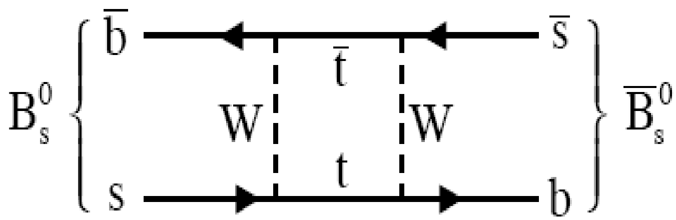
Lifetime long enough for experimental detection

- $\tau_{beauty} \sim 1.5\ 10^{-12}$ s $\qquad \tau \sim 1/(m^5\ |V_{cb}|^2)$
- $D = \beta\, \gamma\, c\, \tau$
- @LHC:
  - $\beta = v/c \sim 1$
  - $\gamma = E/mc^2 \sim 20$ (E: b energy)
- $D = 20 \bullet 3 \bullet 10^{10} \bullet 1.5 \bullet 10^{-12} \sim 1$cm



Why b? (II)

- Sizeable CP violation expected in many decays
  - Large CPV effects expected in processes which involve quarks from all three generations (quark mixing matrix cannot violate CP in a world with only two families!)
  - In fact top quark loops are not suppressed (neither GIM ($m_t > m_W$) nor CKM ($V_{tb}=1$))

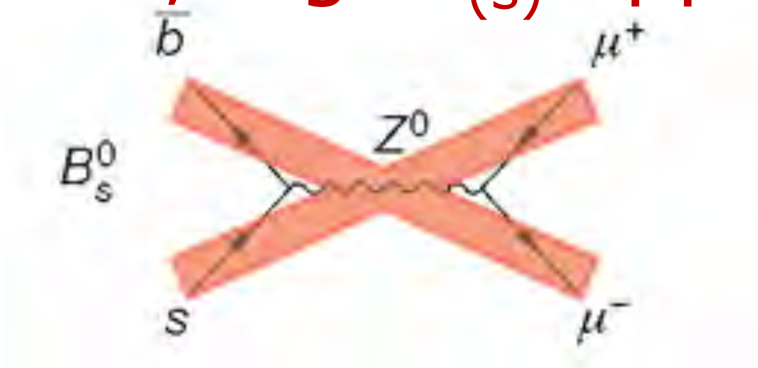


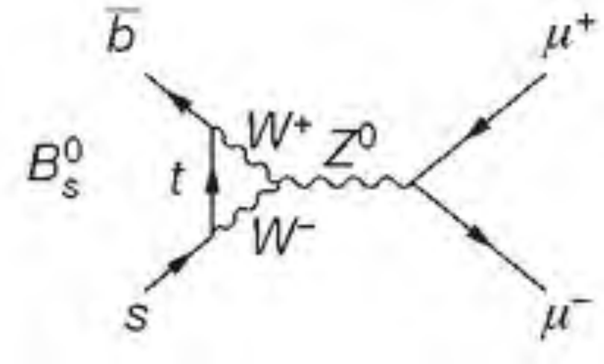
$$\begin{array}{ccc} \mathbf{1} & \mathbf{2} & \mathbf{3} \\ \begin{pmatrix} u \\ d \end{pmatrix} & \begin{pmatrix} c \\ s \end{pmatrix} & \begin{pmatrix} t \\ b \end{pmatrix} \end{array}$$

- Most TeV new physics contains new sources of CP and flavour violation
- The observed baryon asymmetry of the Universe requires CPV beyond the SM
  - Not necessarily in flavour changing processes, nor necessarily in quark sector, it could originate from lepton sector

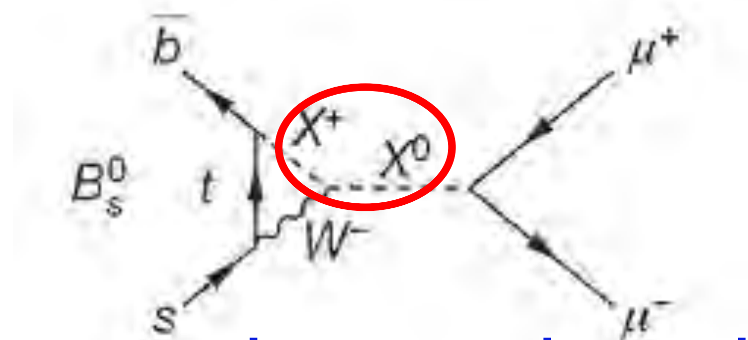
Why b? (III)

- Some rare decays can only proceed through loop diagrams, e.g. $B_{(s)} \rightarrow \mu\mu$





  – $Z^0 \rightarrow bs$ vertex does not exist! (No Flavour Changing Neutral Currents - FCNCs)



- A new particle X, too heavy to be produced at the LHC, can give sizeable effects when exchanged in a loop

B decays: a window on NP at high scales

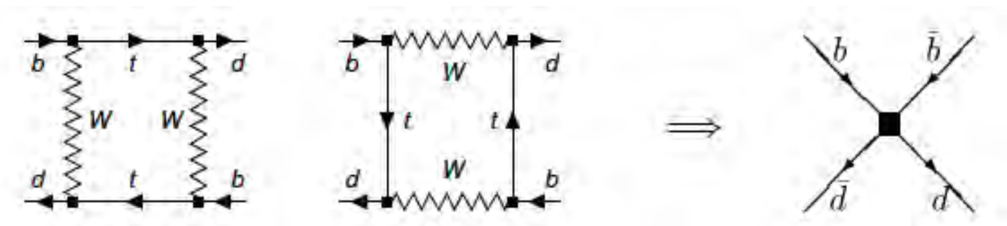
- New particles in the 1-10 TeV LHC range (there are reasons to believe they should exist!) would produce visible signals in rare B decays unless the NP is highly non generic (e.g. Minimal Flavour Violation, in which the flavour breaking structure of the SM also holds beyond the SM)
- In conclusion, precision studies of B decays offer a window on NP not accessible to direct production (even if the space for TeV NP is clearly reduced after the results of the LHC at 7, 8 and 13 TeV)

Strong limits on the scale of NP arise from flavour processes

- Assumption: generic NP effects in loop-mediated amplitudes, i.e. those from K^0,D^0, B_d, B_s, mixing ($\Delta F=2$)
- Bounds on scale of NP for different additional 4-fermion interactions O (with C = 1):

$$\frac{C}{\Lambda^2}O$$

	Operator	Bound on Λ [TeV] ($C=1$) Re	Im
K^0	$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4
	$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5
D^0	$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3
	$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4
B_d	$(\bar{b}_L\gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2
	$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3
B_s	$(\bar{b}_L\gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2
	$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2



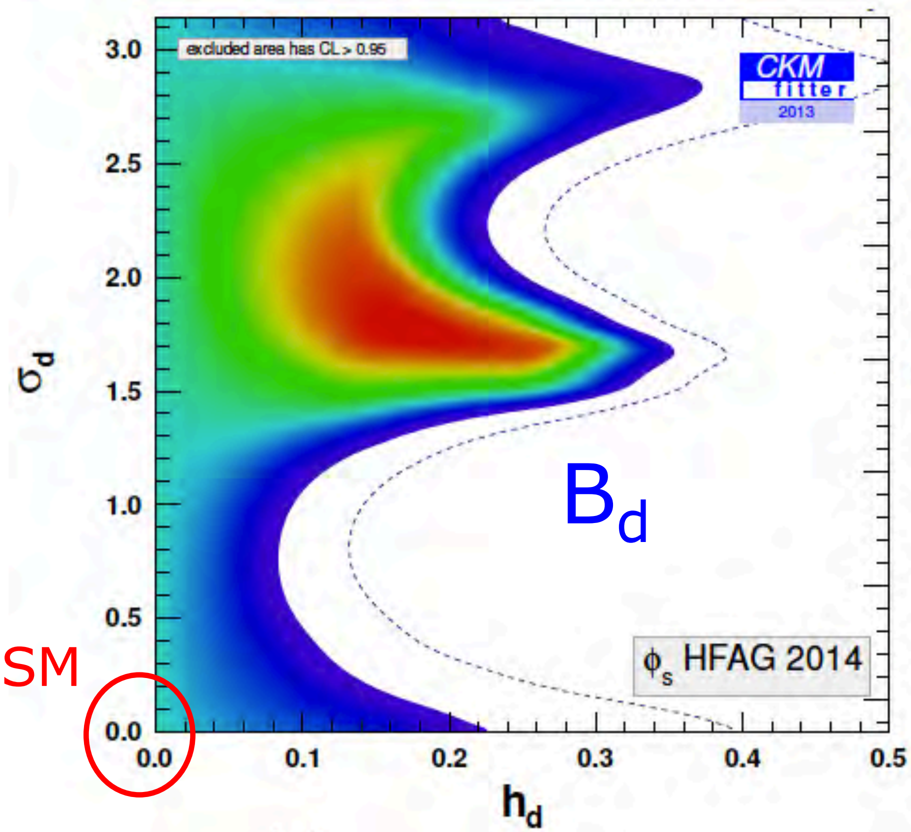
Isidori, arXiv:1302.0661

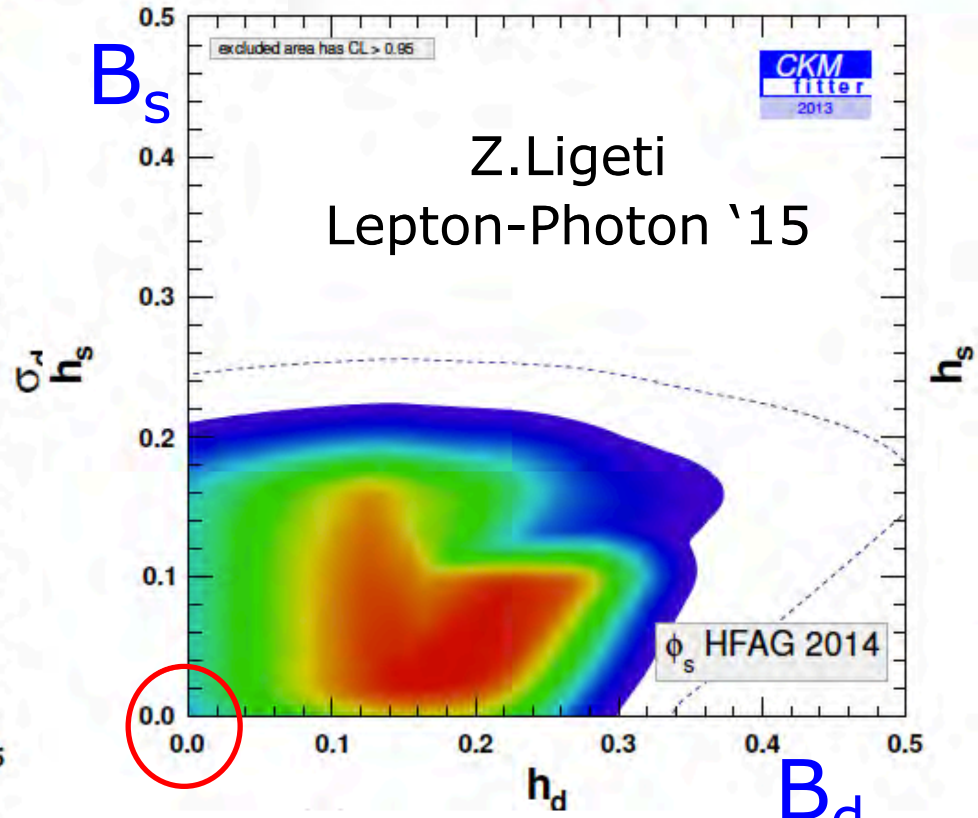
- These bounds on the scale of NP (up to ~10^5 TeV) go well beyond the direct production capabilities of new particles at the LHC (~few TeV)

Is there space left for NP in B_d and B_s mixing?

- Parameterize NP in B mixing as $M_{12} = M_{12}^{SM} \times (1 + h\, e^{2i\sigma})$

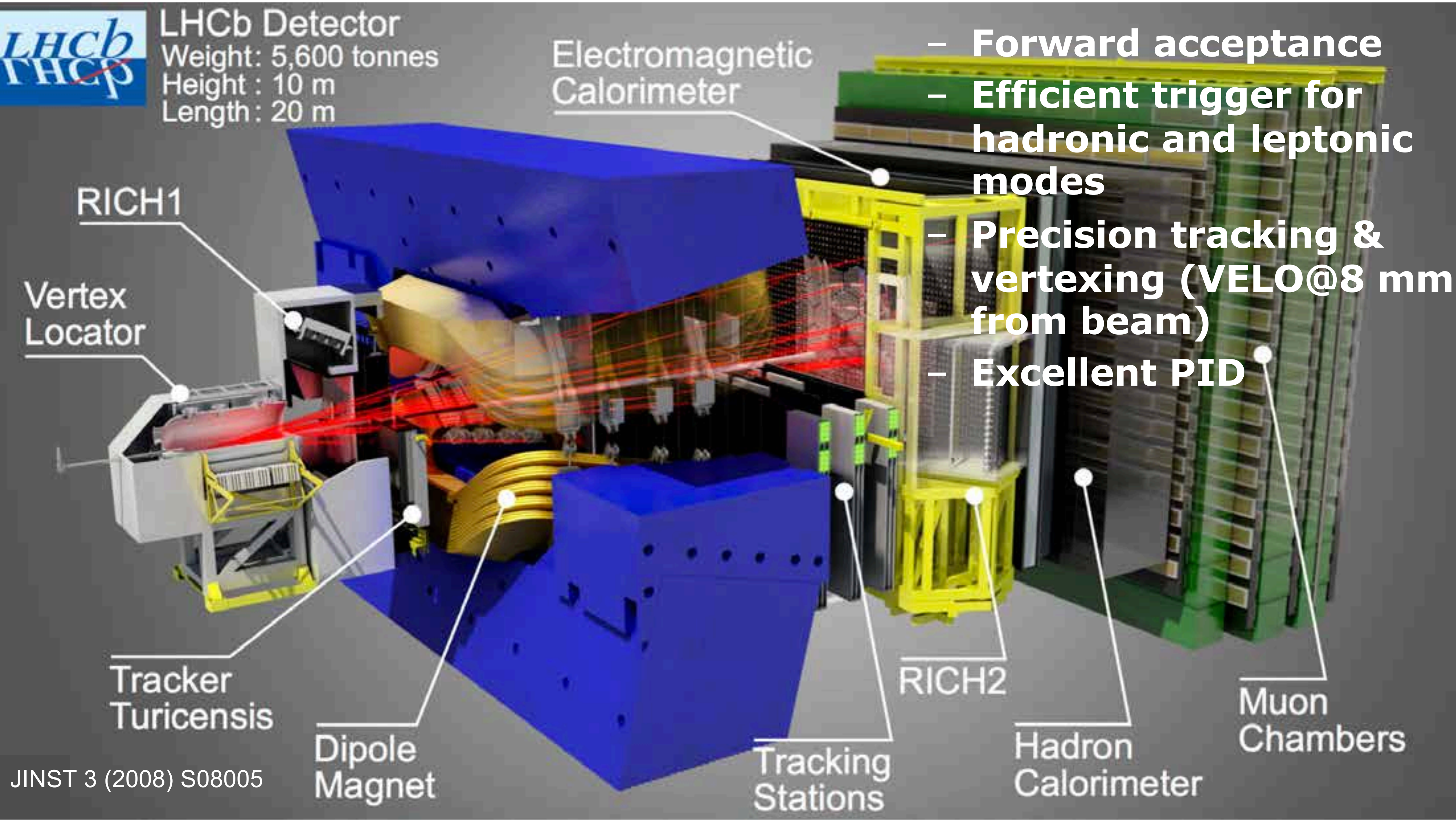
NP parameters





- Effects ~ 20 % (in amplitude) are still well possible from New Physics

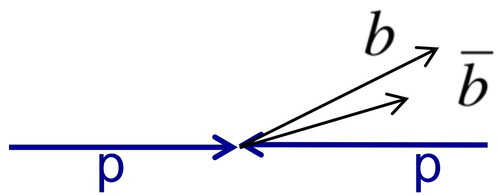
LHCb detector:the essentials

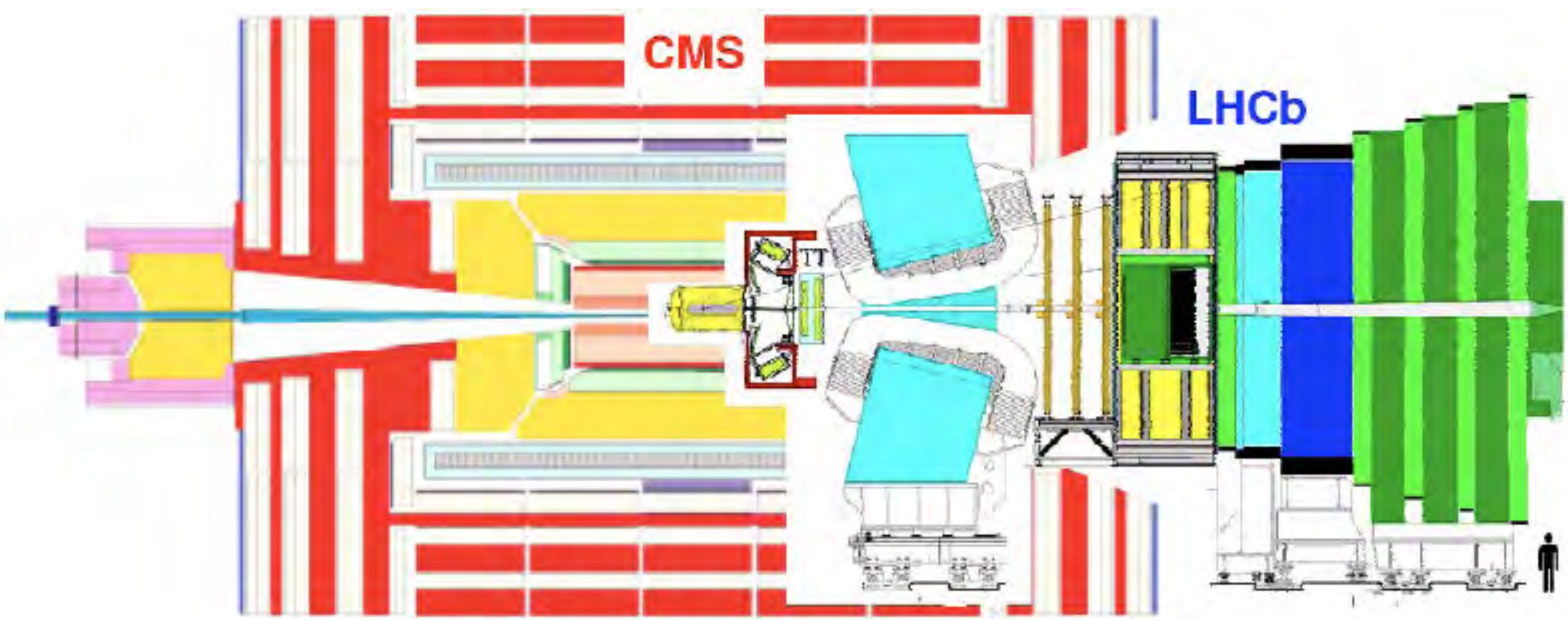


- **Forward acceptance**
- **Efficient trigger for hadronic and leptonic modes**
- **Precision tracking & vertexing (VELO@8 mm from beam)**
- **Excellent PID**

Why does LHCb look so different?

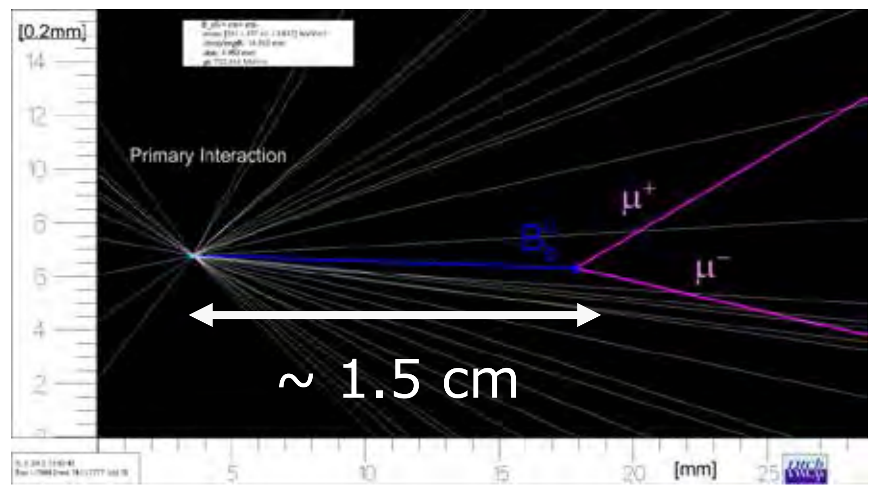
- The B mesons formed by the colliding proton beams (and the particles they decay into) stay close to the line of the beam pipe, and this is reflected in the design of the detector



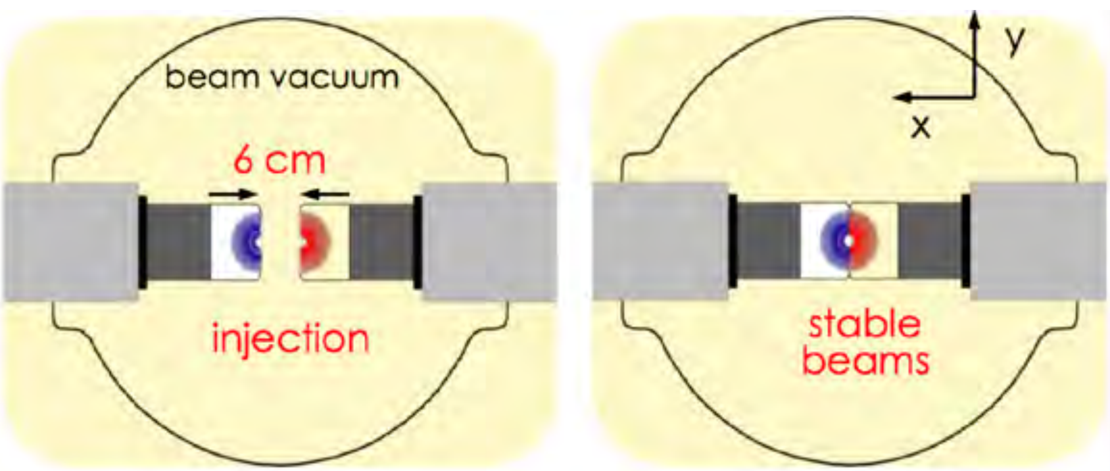


Vertex Locator (VELO)

- The VELO is a precise particle tracking detector, which surrounds the pp collision point inside LHCb
- It is composed of 21 stations, each made of two retractable silicon half disks with R-ϕ sensors
- It approaches within 8 mm of the beamline and reconstructs the b-hadron decay vertex precisely (Run 1 decay time resolution ~45 fs)

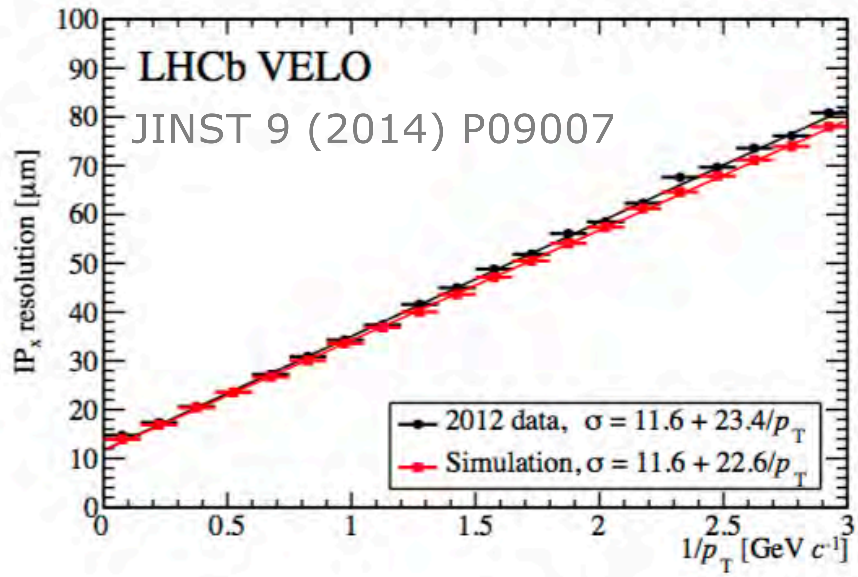


A reconstructed B-hadron decay vertex



VELO performance

- Excellent vertex resolution is essential: most analyses rely on impact paramenter (IP) cuts and on displaced vertex reconstruction
  - IP optimised by placing the sensors as close to the beam as possible, having small inter-strip pitch and minimising the material before the first measured hits in the VELO
  - IP resolution <35 μm for p_T>1GeV/c



- Excellent decay time resolution also essential to resolve fast $B_s^0 - \bar{B}_s^0$ oscillations
  - Decay time resolution evaluated for $B_s^0 \to J/\psi\ \phi$ is ~50 fs << 350 fs, B_s^0 oscillation period

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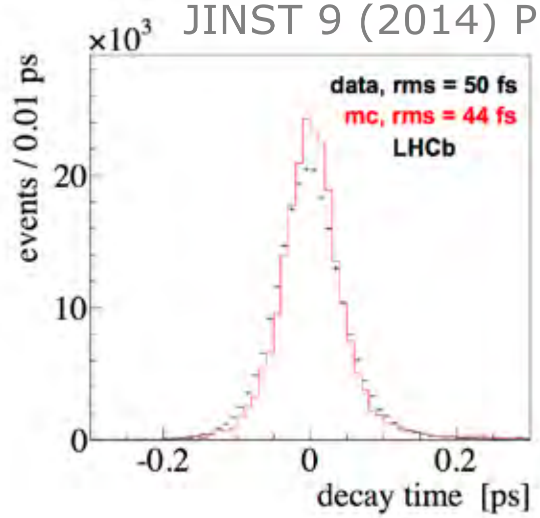
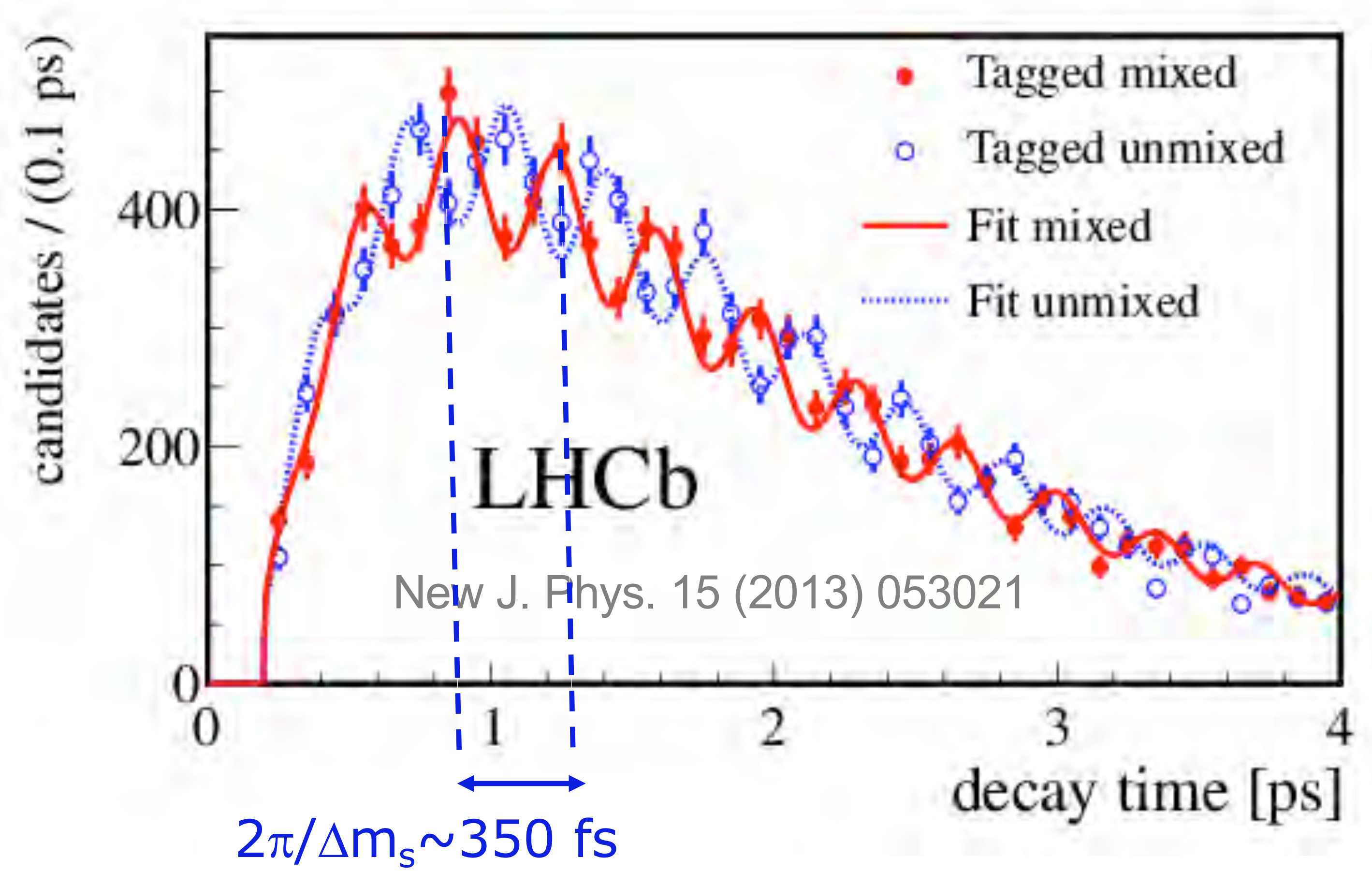


From selected prompt $J/\psi K^+K^-$

Precision measurement of the $B_s^0 - \bar{B}_s^0$ oscillation frequency

$B_s^0 \to D_s^- \pi^+$ with $D_s^- \to \phi(K^+K^-)\pi^-$, $K^{*0}(K^+\pi^-)K^-$, $K^+K^-\pi^-$, $K^-\pi^+\pi^-$, $\pi^-\pi^+\pi^-$



different flavour at decay and production

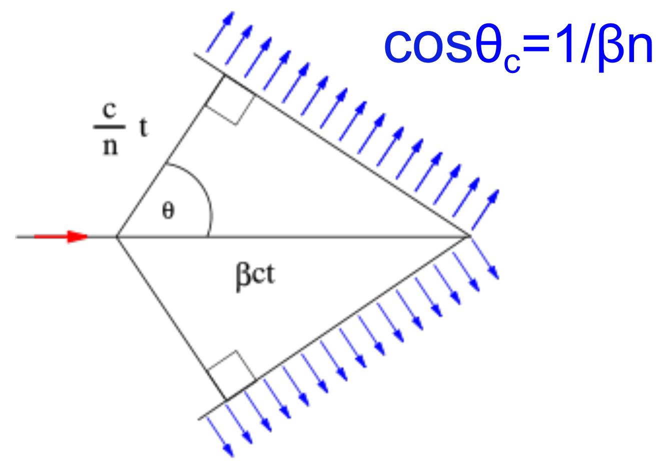
same flavour at decay and production

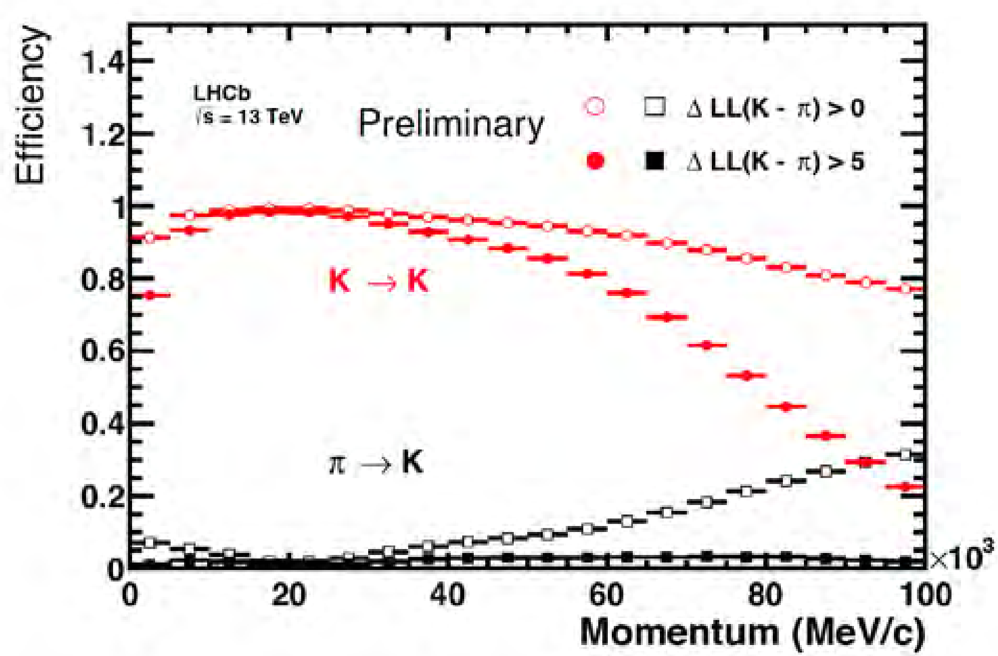
1 fb^{-1}, most precise to date

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

Ring Imaging Cherenkov (RICH) detectors

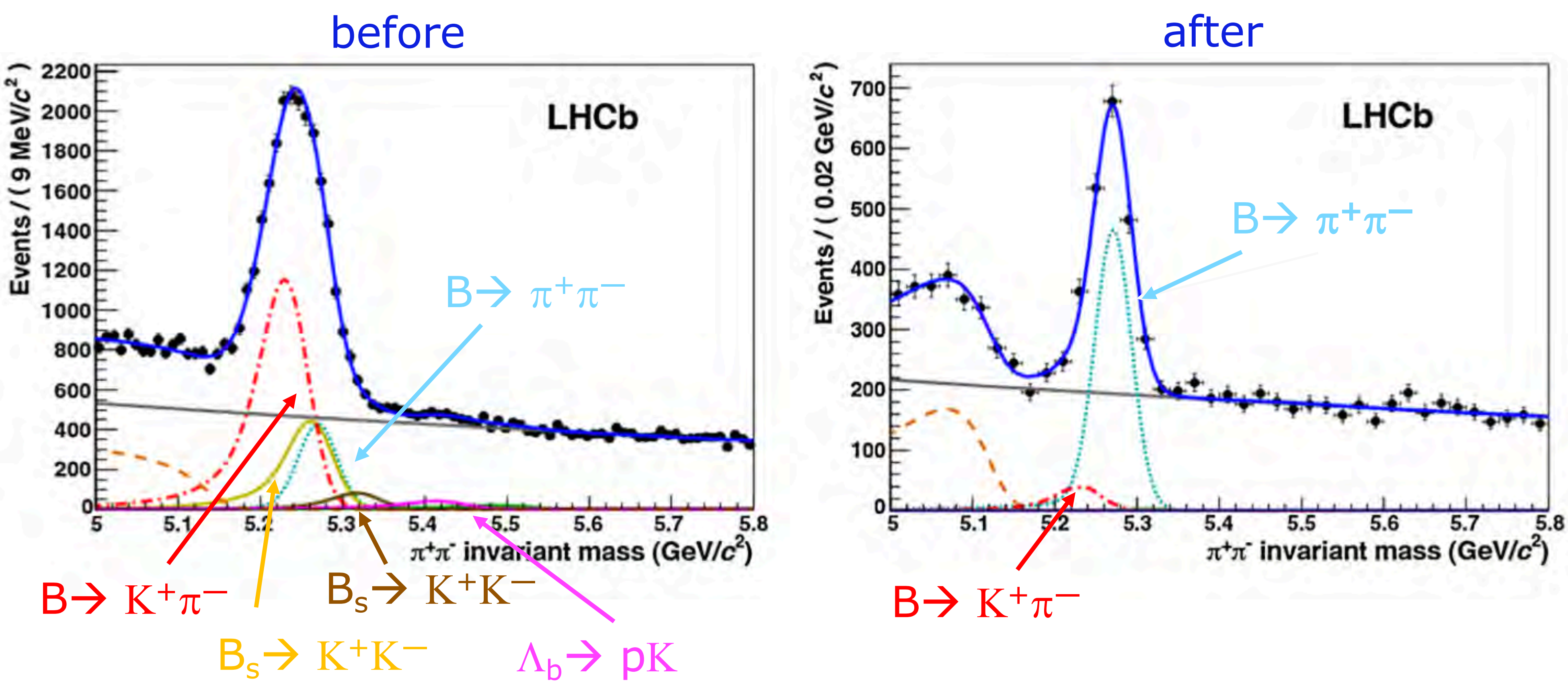
- RICH detectors work by measuring emissions of Cherenkov radiation. This occurs when a charged particle passes through a medium faster than light does ($v > c/n$, with n refractive index)
- The particle emits light in a cone with $\cos\theta_c = 1/\beta n$, which the RICH detectors reflect onto an array of sensors using mirrors
- By measuring θ_c the velocity β of the particle is found. With knowledge of its momentum, the mass of the particle can be found
- 2 separate detectors and 2 separate radiators
- Kaon id eff. ~95%, mis-id <1%





RICH Performance

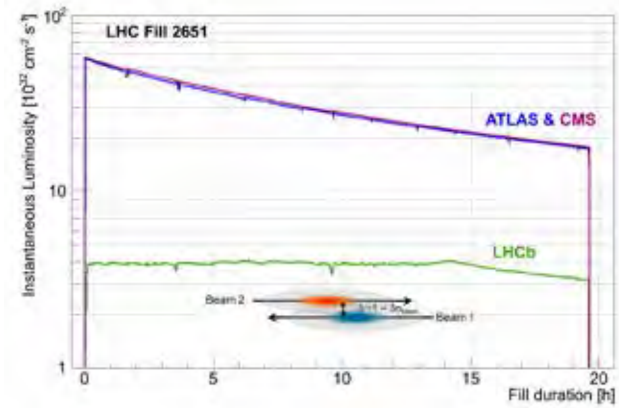
- Invariant mass distribution for $B \rightarrow h^+h^-$ ($h=\pi,K$) before and after use of the RICH information
- Signal under study is $B \rightarrow \pi^+\pi^-$



Eur.Phys.J.C(2013)73:2431

Running conditions

- LHCb designed to run at lower Lumi than ATLAS/CMS
  - Tracking, Particle Identification sensitive to pile-up
  - Mean number of interactions/bunch crossing ~1
- pp beams displaced to reduce instantaneous luminosity
  - $\mathcal{L} \sim 4.0\ 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$



- Huge heavy quark production cross-sections
  - $\sigma_{bb} \sim 500\ \mu b$ @$\sqrt{s}$=13 TeV (~1nb in e^+e^-@ $\Upsilon(4s)$)
  - σ_{cc} is ~ 20 times larger!

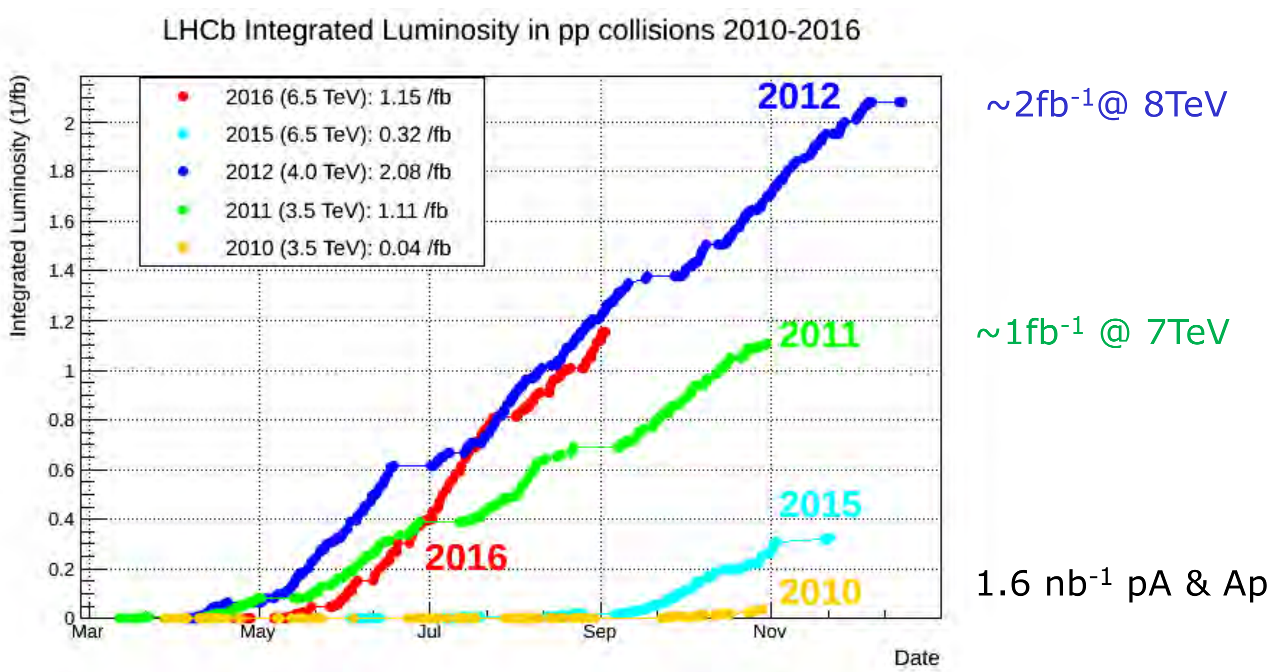
~10^{11} b decays/fb in acceptance

~10^{12} c decays/fb

- Going ahead with Run 2 (2015-2018) @13 TeV with several ambitious changes aimed at maximising physics output → completely revised trigger

Excellent LHC performance in 2016

- Several records beaten:
  - Fastest LHC start ever!
  - LHC reached design Luminosity of 1 x $10^{34}/cm^2/s$ (ATLAS/CMS)
  - Longest fill ever (fill 5045 was 37h in stable beams!)
  - Stunning availability with very short turnaround time (~4h)



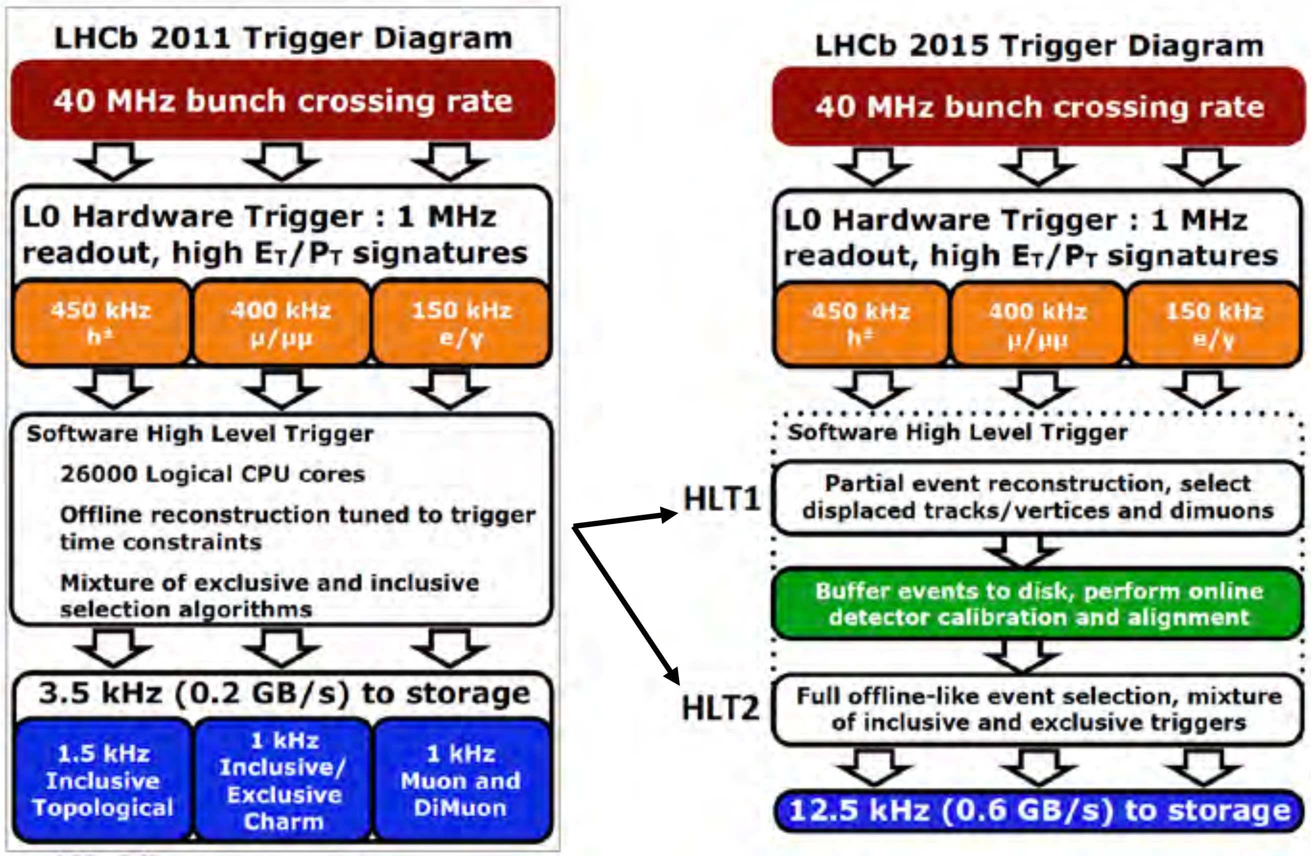
  - LHCb: ~$4fb^{-1}$ on tape

The Trigger

- For LHCb, more data more important than higher energy
  - Direct searches @ATLAS/CMS: more energy →new particles could appear above threshold
  - Indirect searches: precision measurements→ gain from increased production rates
- However, digesting more data is a true challenge
- At nominal Lumi, ~45k beauty and 1M charm hadrons pass through the detector/sec
- Most interesting b-hadron decays occur at 10^{-5} prob
- Big data challenge → Requires Powerful Trigger
- Three level trigger system – increasing complication:
  - hardware level L0 based on calo and muons: reduces rate from 40 MHz to 1 MHz, maximum allowed by front-end electronics
  - two software levels High Level Trigger (HLT): software application designed to reduce the event rate from 1 MHz to ~12 kHz, executed on a large computing cluster

The Trigger

- Evolving strategy for the High Level Trigger

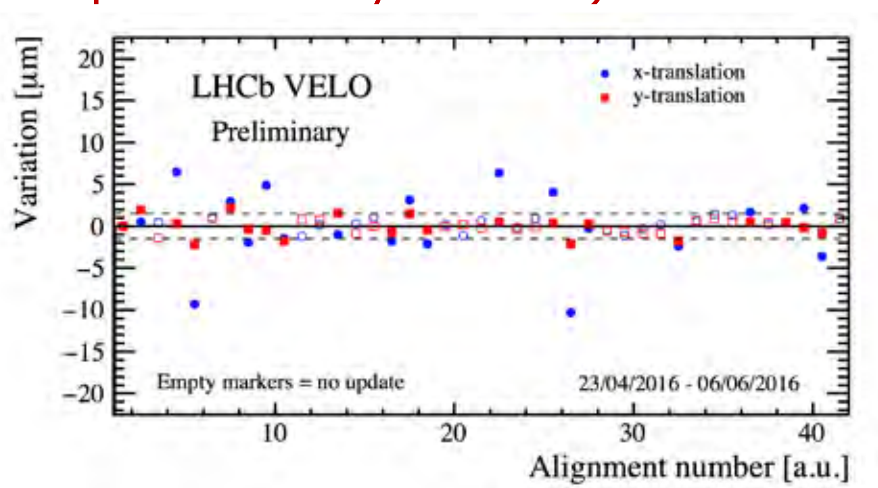


- 2015-2016 → Split HLT
  - All 1st stage (HLT1) output stored on disk (5PB in 2015, 10PB in 2016)
  - Enough time to perform online calibration & alignment before HLT2
  - Stage 2 (HLT2) uses offline-quality calibration → more discriminant trigger

Real-time alignment and calibration

- Tracking system: alignment of about 700 elements
  - Automatic evaluation at regular intervals, once per fill by minimising residuals of track fits

  - Tracking constants evaluated in a few minutes, updated only when necessary (VELO updates every 2-3 fills)



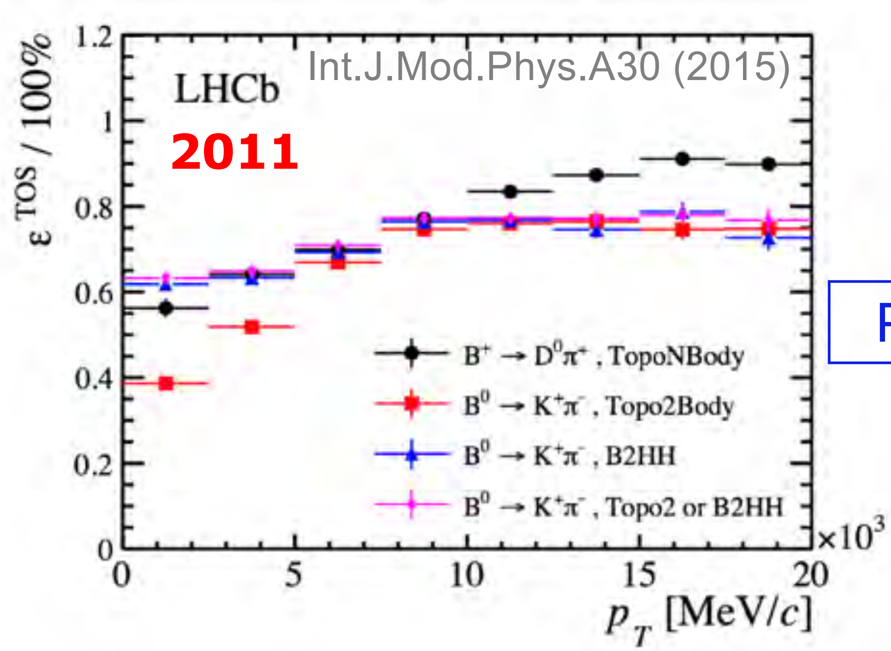
- RICH systems: alignment of 110 mirror pairs
  - Constants evaluated in ~20 minutes
  - Calibration of RICH refractive index

Trigger performance

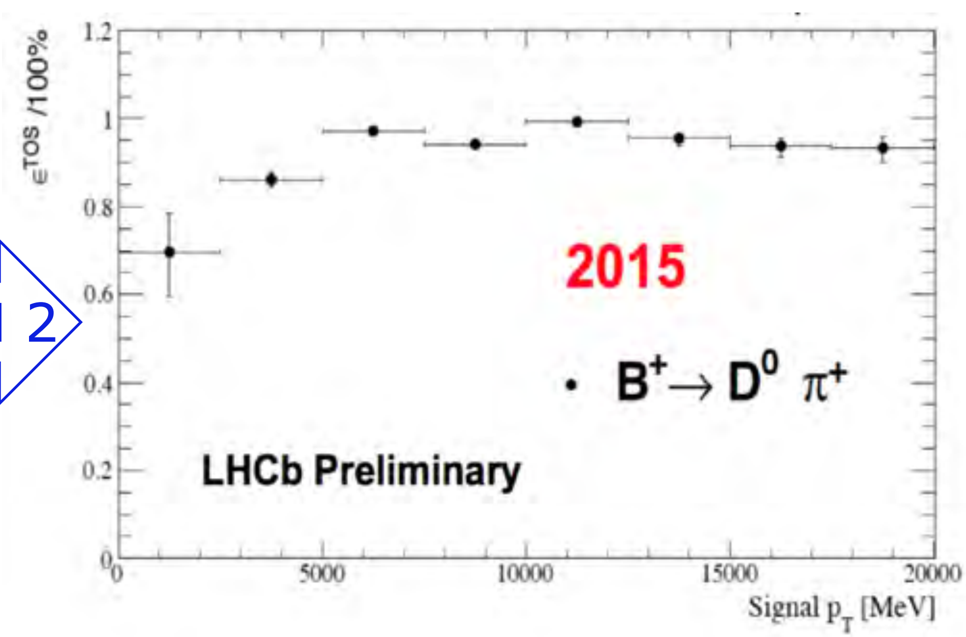
Fully calibrated & aligned detector
Offline-quality reconstruction
PID @trigger level

⇨ Improved trigger performance

- Efficiency for the HLT2 inclusive b trigger as a function of b-hadron p_T
  - Significant portion of events selected by inclusive 'topological lines': all b-hadron decays with at least 2 charged tracks and a displaced vertex
  - Efficiency for $B^+ \rightarrow D^0\pi^+$ went from ~75% to ~90%



RUN 2



The TURBO stream

- With offline-quality reconstruction up-front, no need to reconstruct offline
- Can perform physics analysis directly @ HLT level ("TURBO" stream)
  - Store full information of trigger candidates
  - Remove most of detector raw data
  - Save >~90% of space
  - Very quick turn around [24 h]
  - Smaller events means → analyse much higher rates
- Turbo publications with 13 TeV data!

J/psi production cross-section

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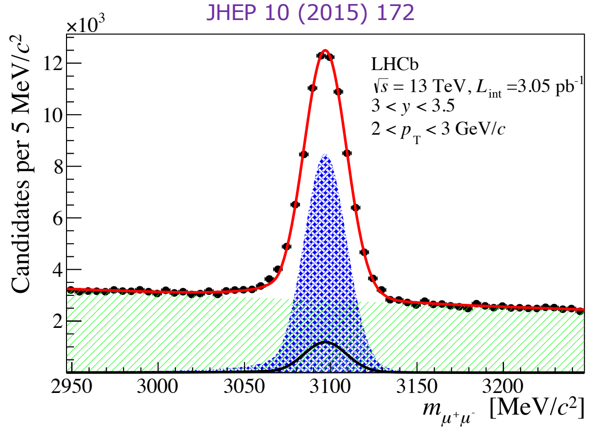

Prompt charm production cross-section

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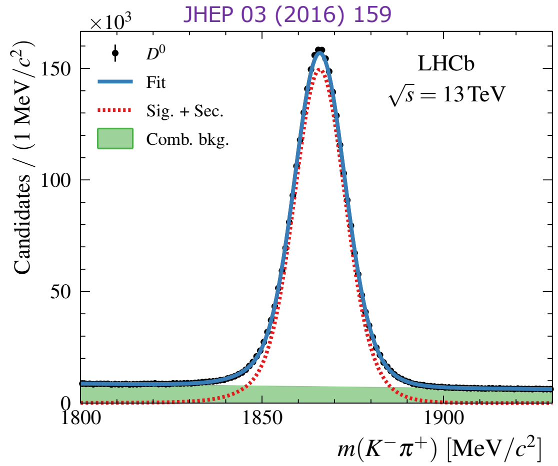
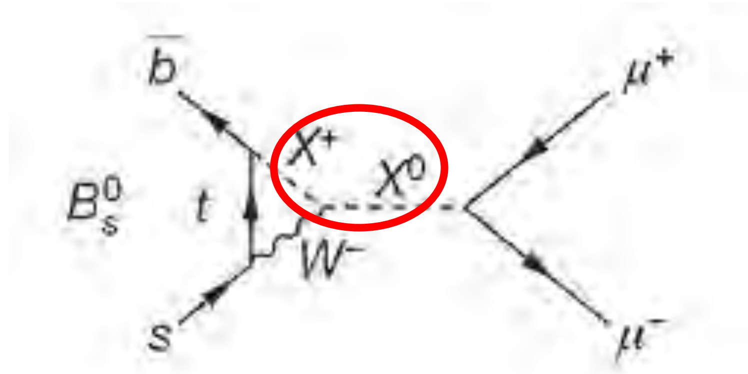


- For 2016 run, code sped up and made even more "offline-like"
- TURBO approach extended to analyses of higher complexity
- The higher output rates of the LHCb upgrade will make this approach increasingly necessary

Rare Decays

One of the milestones of flavour program: $B_{d,s} \rightarrow \mu^+\mu^-$

- Highly suppressed in SM
  - FCNC
  - Helicity suppressed $\sim(m_\mu/M_B)^2$
- Precisely predicted
  - $BR(B_s \rightarrow \mu^+\mu^-)_{SM} = 3.66 \pm 0.23 \times 10^{-9}$
  - $BR(B_d \rightarrow \mu^+\mu^-)_{SM} = 1.06 \pm 0.09 \times 10^{-10}$
- Sensitive to NP
  - in MSSM BR ~ $\tan^6\beta$

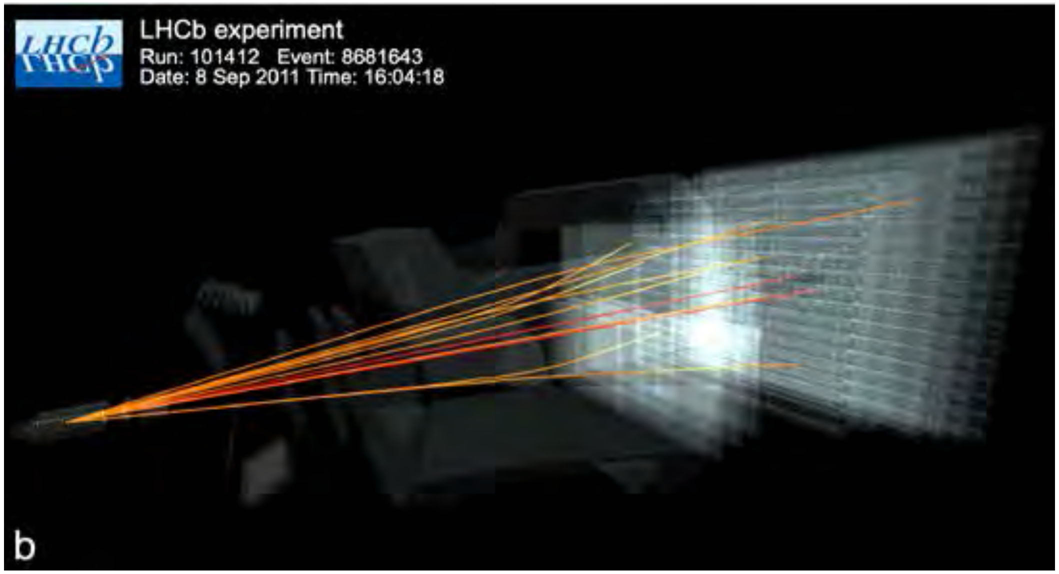


- Very clean signature
  - studied by all high-energy hadron collider experiments

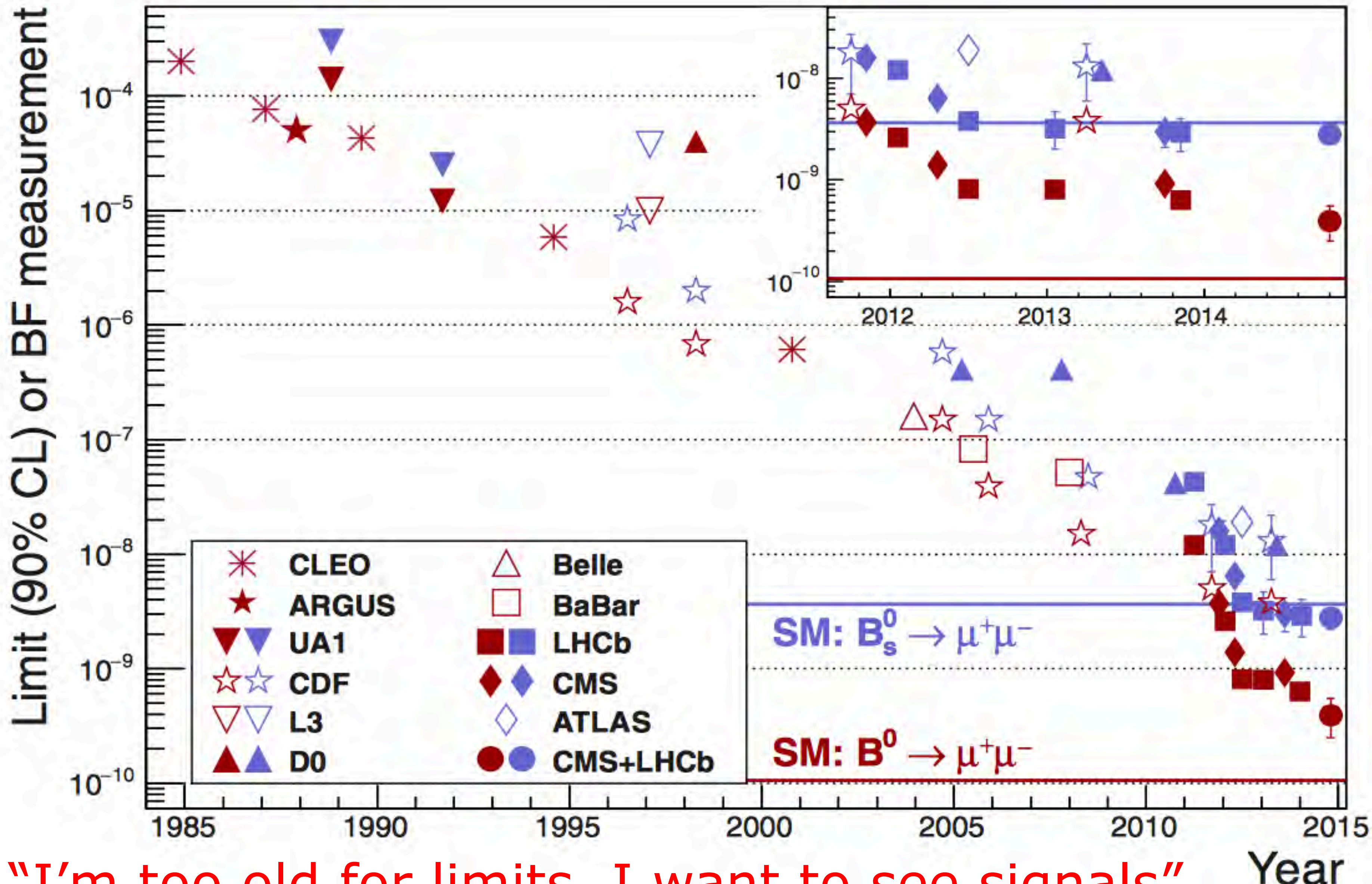
$B_{d,s} \to \mu^+\mu^-$: analysis features

- Use of control channels to calibrate selection avoiding dependence on simulation
- Use of multi-variant discriminants trained on data whenever possible (e.g. B candidate decay time, IP and p_T, isolation, etc)
- Use of normalisation channels with well-known BRs, same topology and/or trigger. Cancel uncertainties in ratios.
  - Normalise to large samples of $B^+ \to J/\psi K^+$ or $B^0 \to K^+\pi^-$
- Excellent mass resolution mandatory to separate B_s from B_d and from background (σ_B~25 MeV)
- Blind analysis: mass interval that includes $B_{d,s}$ signals blind until all selection criteria established

$B_s \to \mu^+\mu^-$ candidate



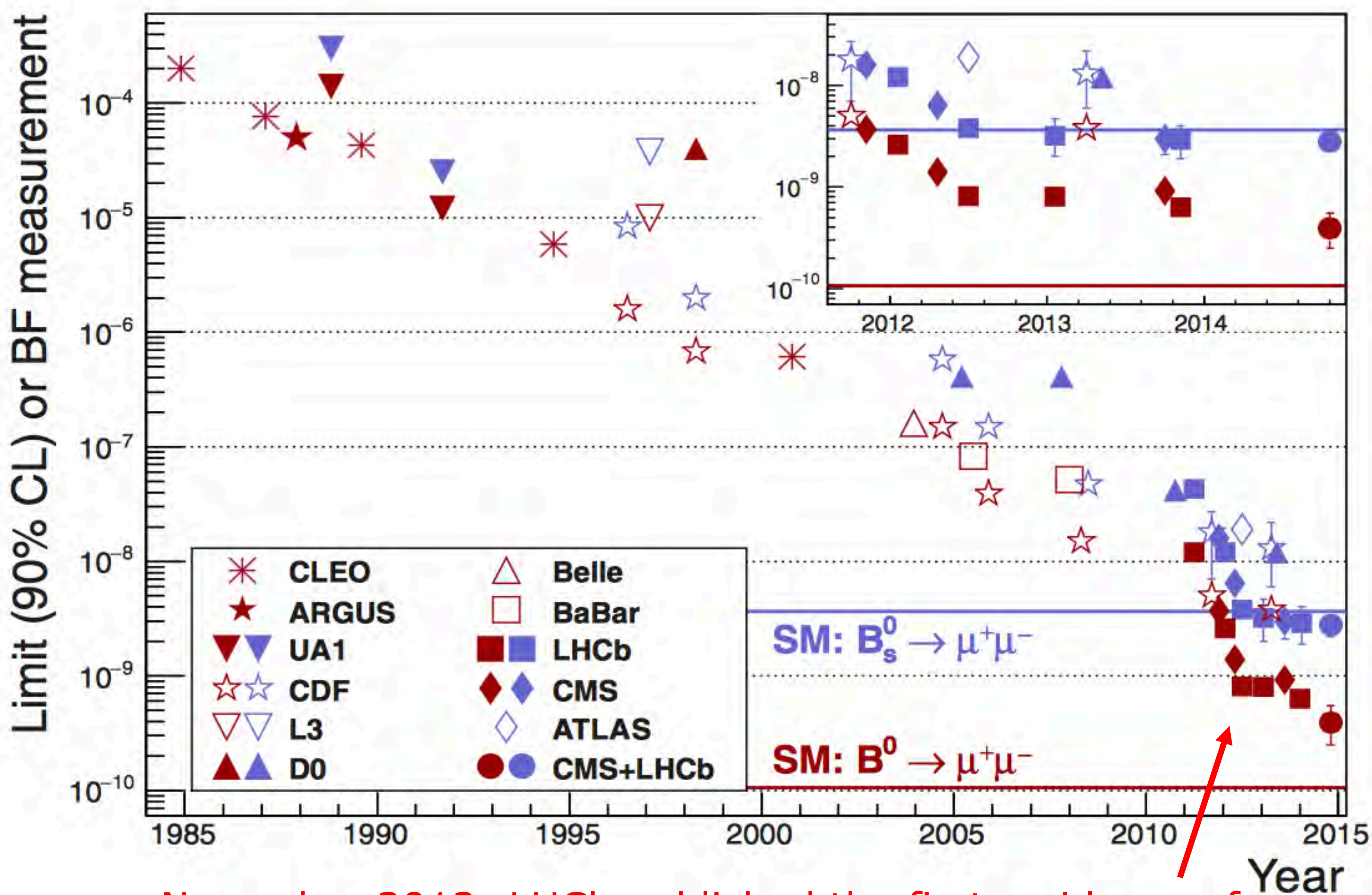
30 years of effort!



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

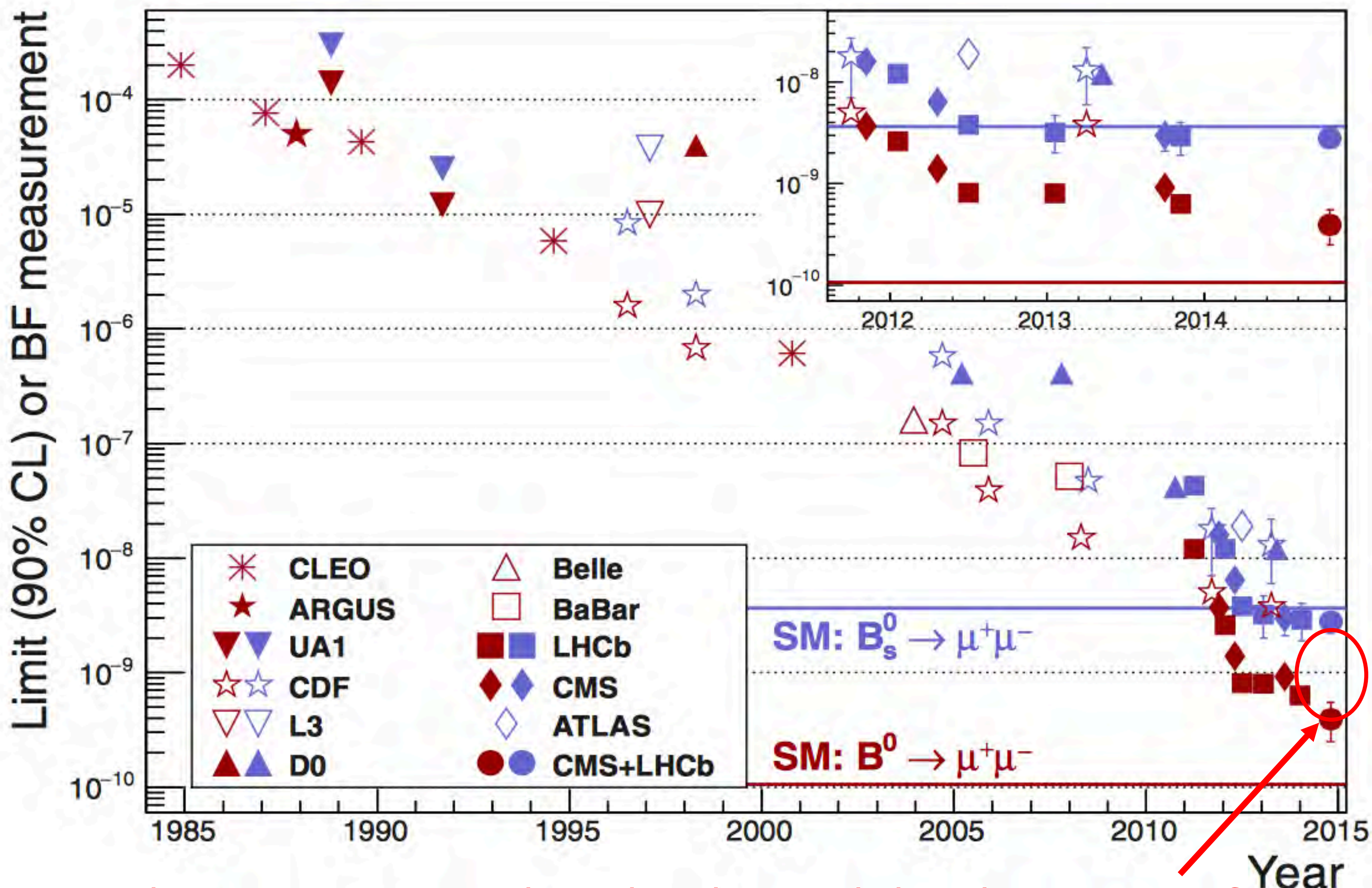
Francis Halzen (EPS '15)

30 years of effort!



November 2012: LHCb published the first evidence of the $B_s \rightarrow \mu\mu$ decays [PRL 110 (2013) 021801]

30 years of effort!



November 2014: CMS and LHCb submitted the observation of $B_s \rightarrow \mu\mu$ and the evidence for $B \rightarrow \mu\mu$ [Nature 522 (2015) 68]

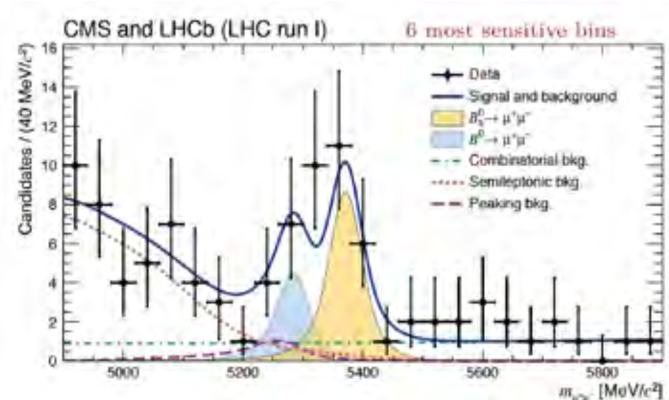
$B_{d,s} \to \mu^+\mu^-$ from LHCb and CMS

- Combined fit to full run 1 data set results in first observation of $B_s \to \mu^+\mu^-$ and first evidence for $B^0 \to \mu^+\mu^-$

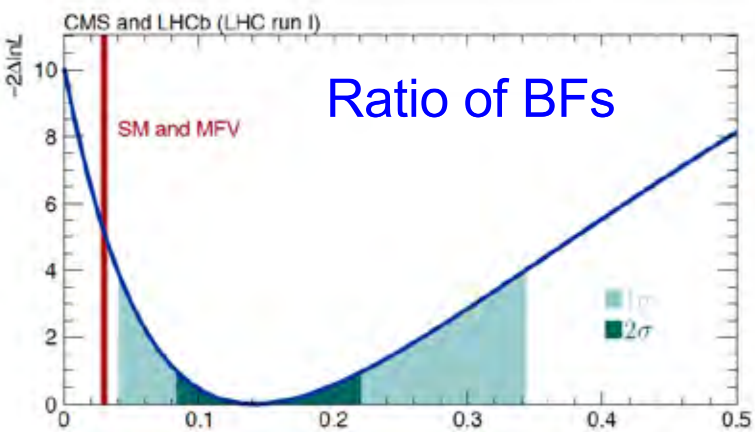
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 2.8\,^{+0.7}_{-0.6} \times 10^{-9}$$

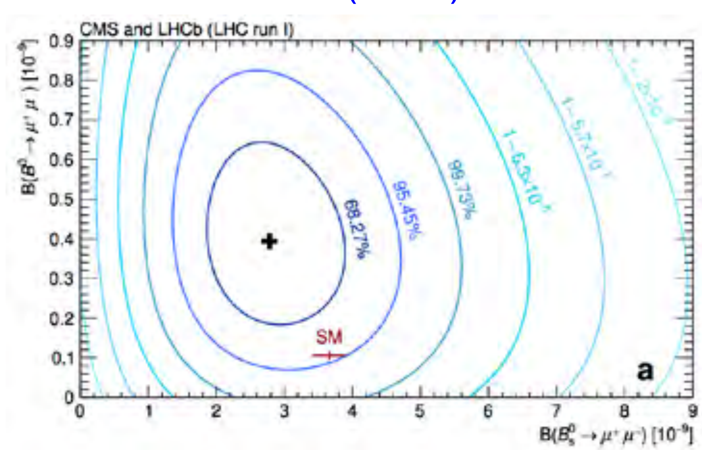
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.9\,^{+1.6}_{-1.4} \times 10^{-10}$$

$$\frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)} = 0.14\,^{+0.08}_{-0.06}$$



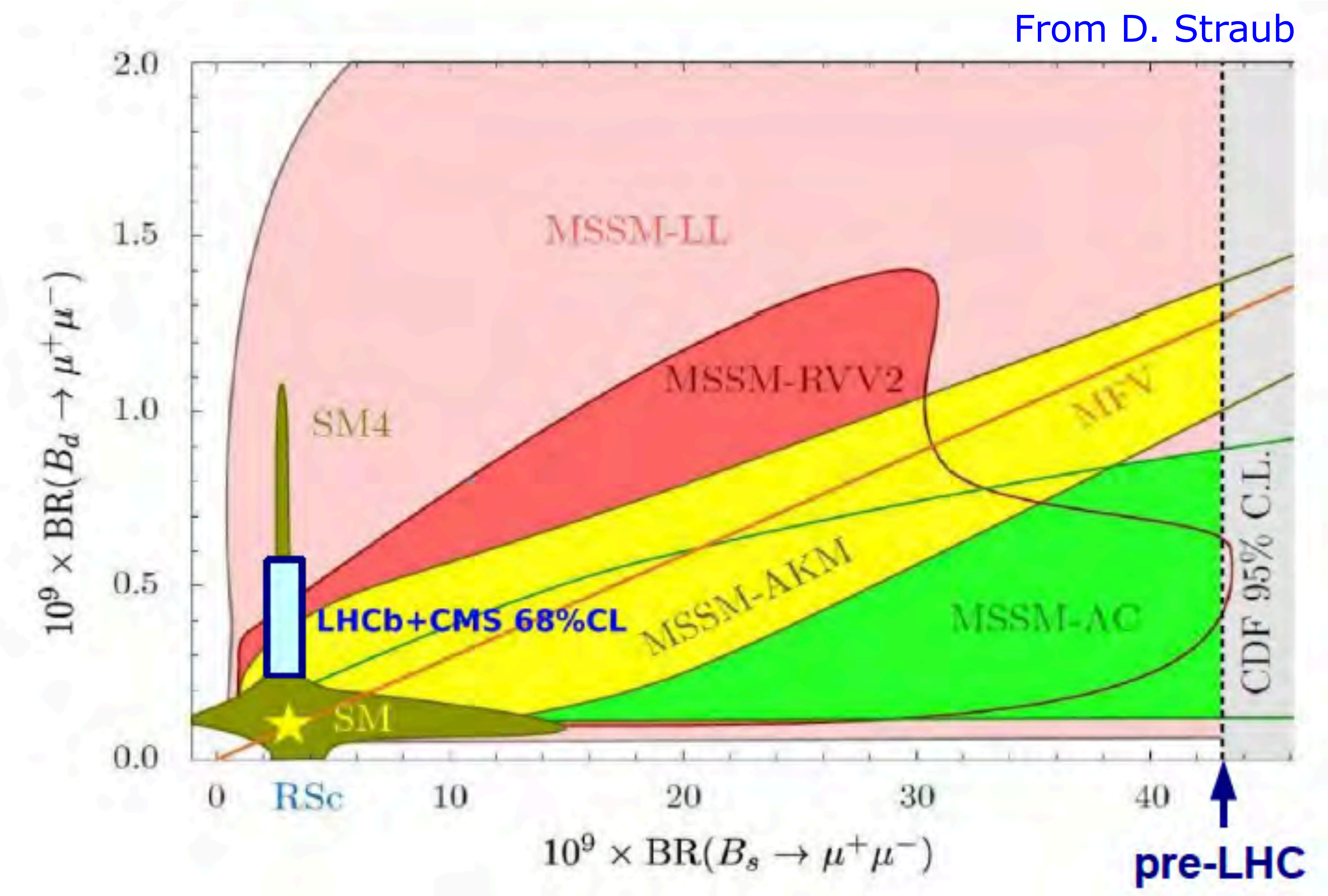
Nature 522 (2015) 68





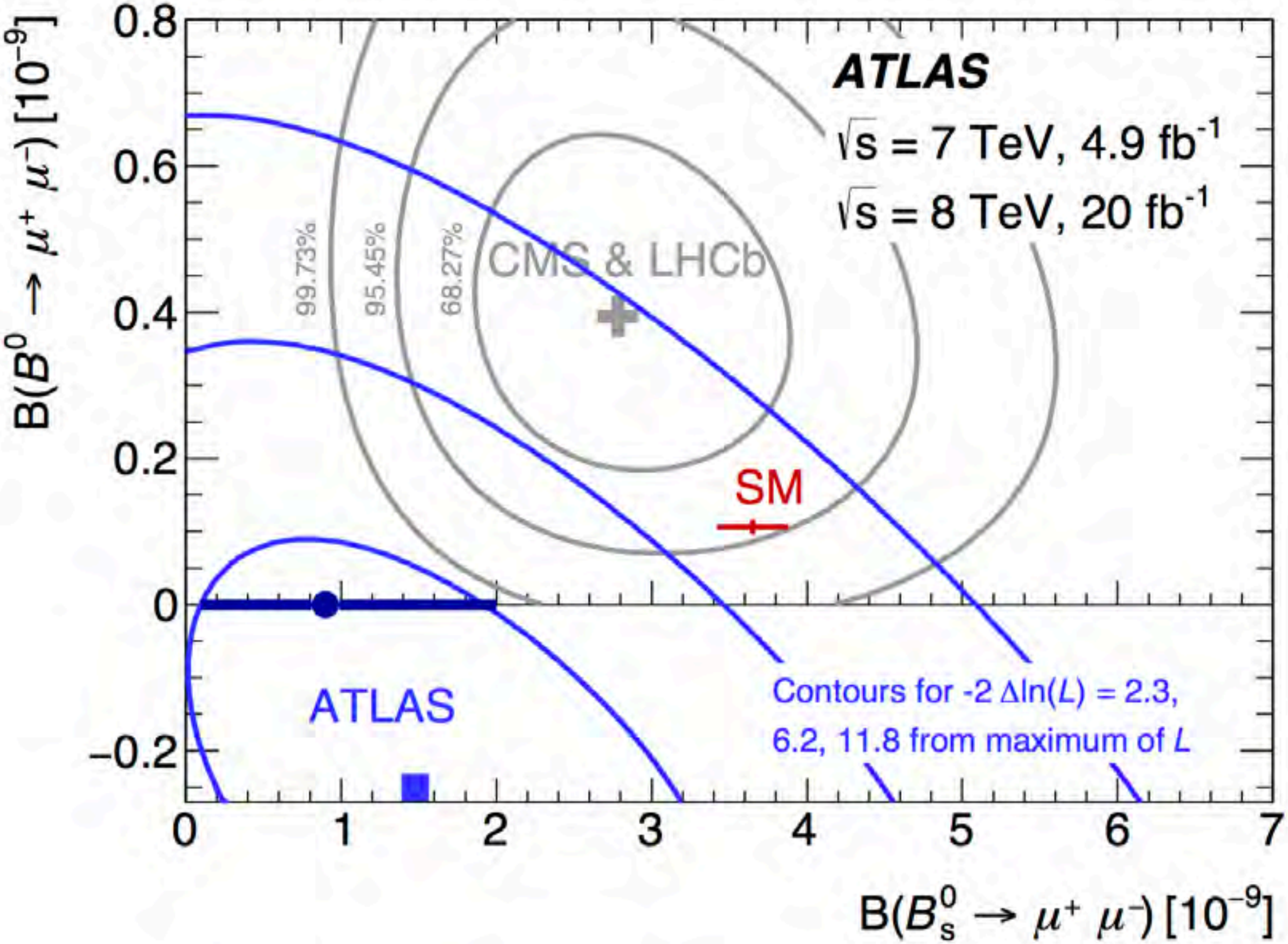
- Ratio of BFs provides powerful discriminations among BSM theories, compatible with SM at ~2σ level

The killer observables!



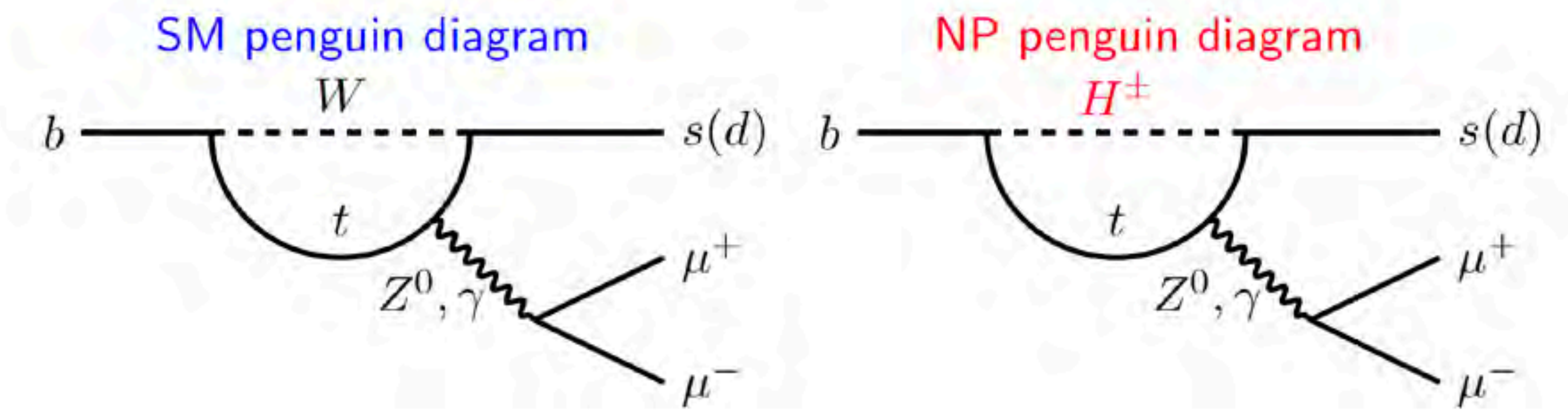
ATLAS entered the game

arXiv:1604.04263



Another interesting rare decay: $B^0 \to K^{*0} (\to K^+\pi^-)\mu^+\mu^-$

- $B^0 \to K^{*0}\mu^+\mu^-$ is a $b \to s$ transition that only proceeds via loops and boxes
- NP can be competitive with SM processes



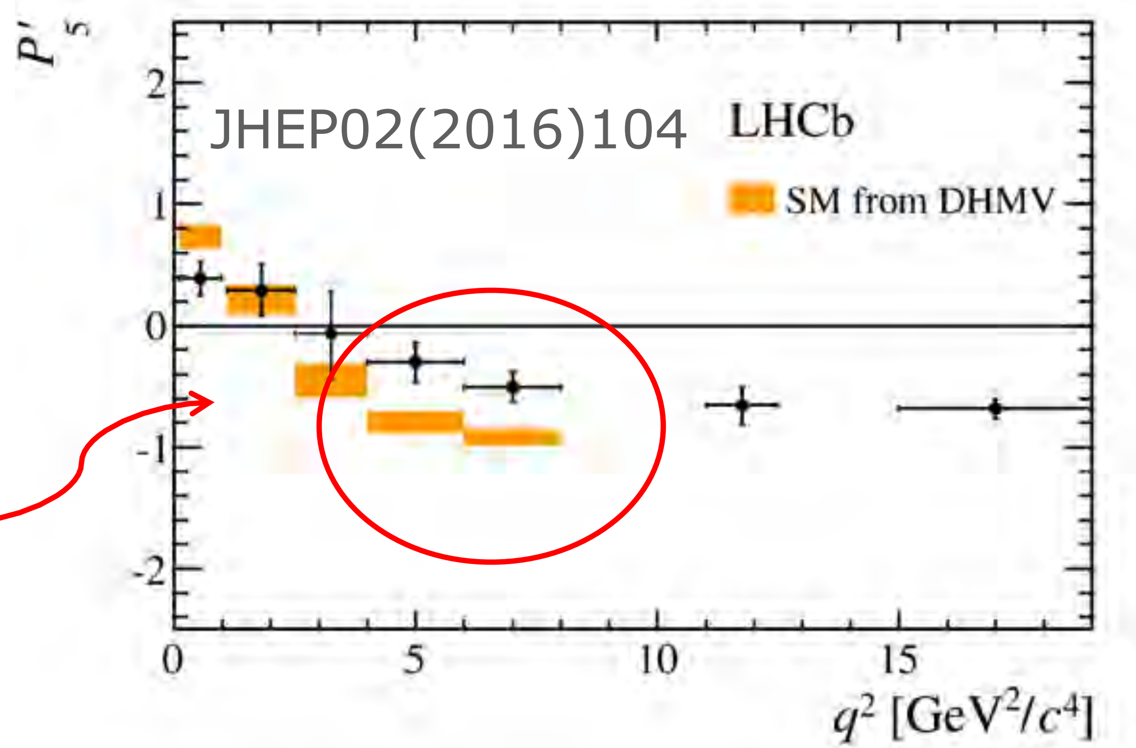
- Four final state particles with rich phenomenology, plethora of observables, which can be built from the measured amplitudes
- Rates, angular distributions and asymmetries sensitive to NP
- A lot of phenomenological work invested in defining observables with "clean" theoretical prediction

Question: how clean?

P'_5 anomaly

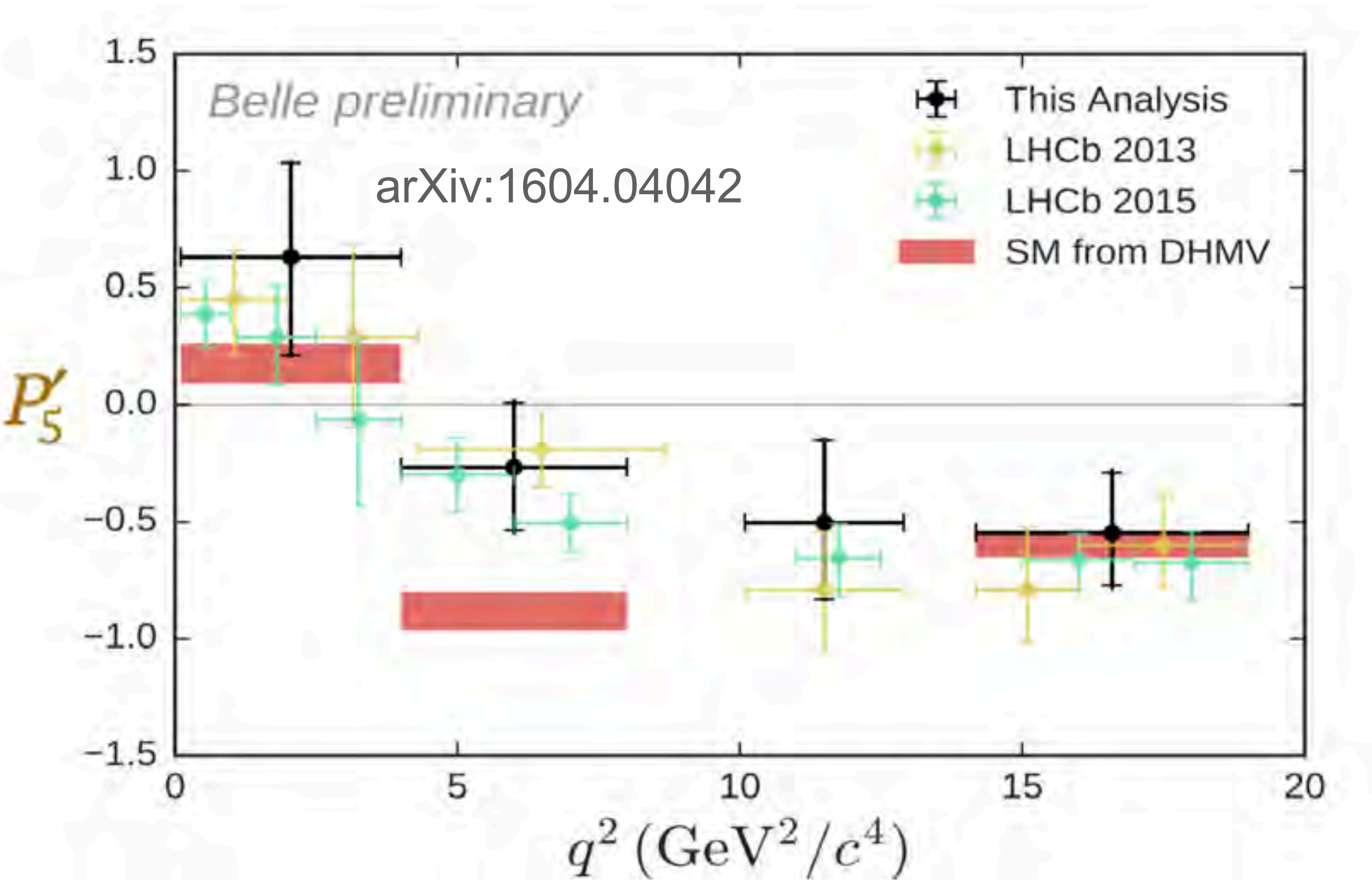
- One such observable is so-called P'_5 , not intuitive, but constructed from angular observables to be robust from 'form-factor uncertainties' and also easily relatable to short-distance physics

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



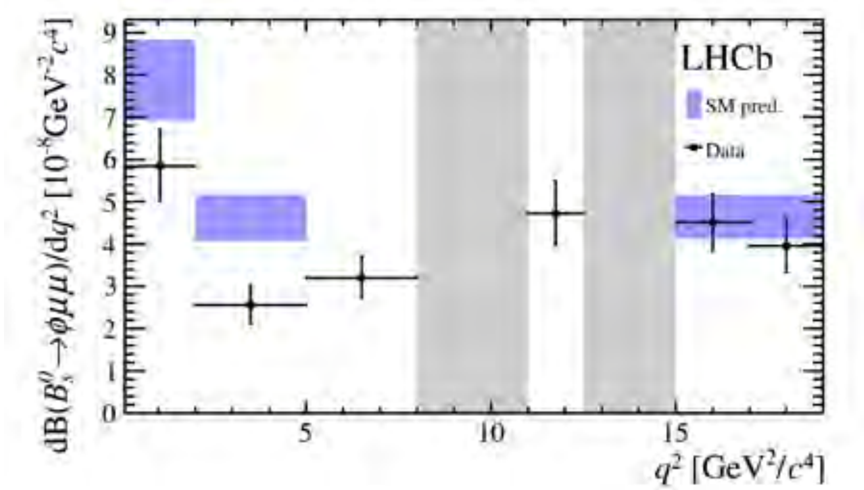
- Is SM prediction less precise than what is claimed?

New analysis from Belle

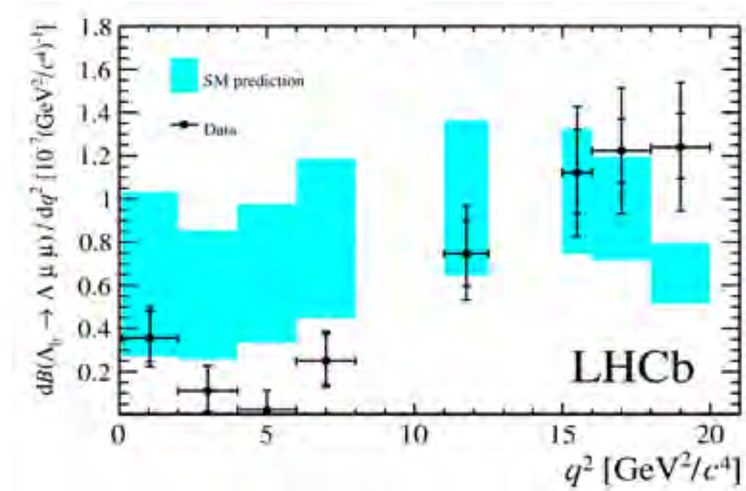


Intriguing set of results in differential branching fractions for b→sμμ transitions

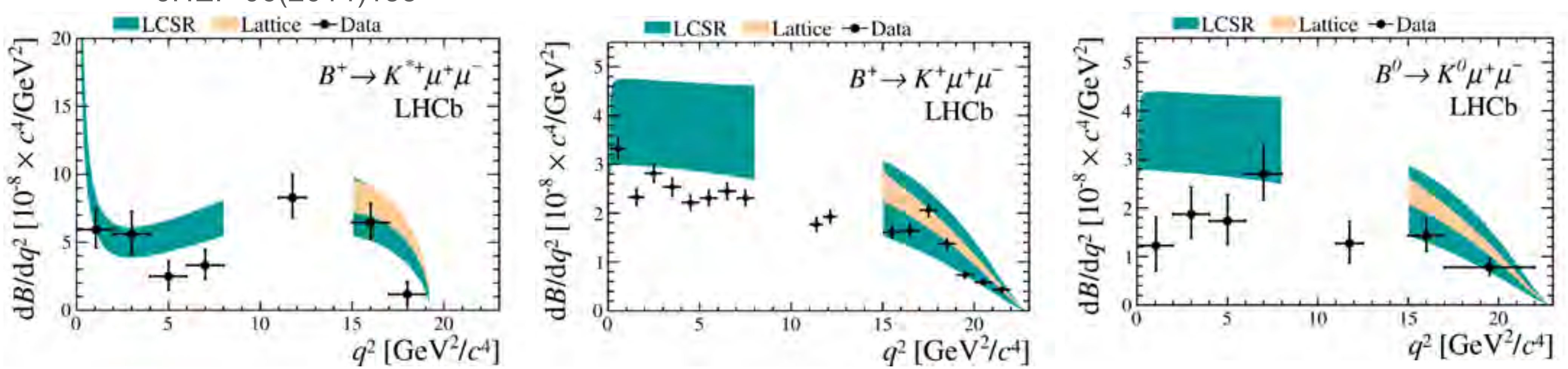
JHEP 09(2015)179



JHEP 06(2015)115



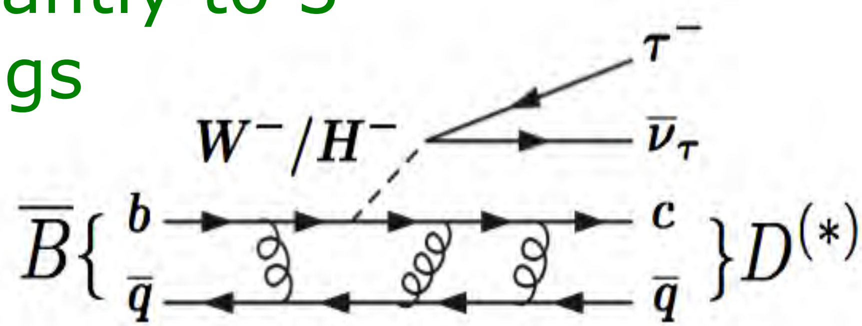
JHEP 06(2014)133



Other interesting deviations

Measurement of R(D*)

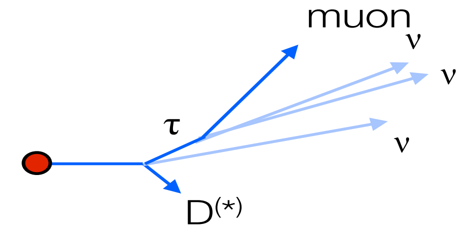
- $R(D^*) = B(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)/B(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)$
  - with $\tau^- \to \mu^-\nu_\mu\nu_\tau$
- Theoretically clean
  - In SM only difference is the mass of the lepton
  - $R(D^*)_{SM} = 0.252 \pm 0.003$
- Sensitive to NP coupled dominantly to 3rd generation, e.g. a charged Higgs



- Heightened interest
  - BaBar: ~3 σ tension (final data set)

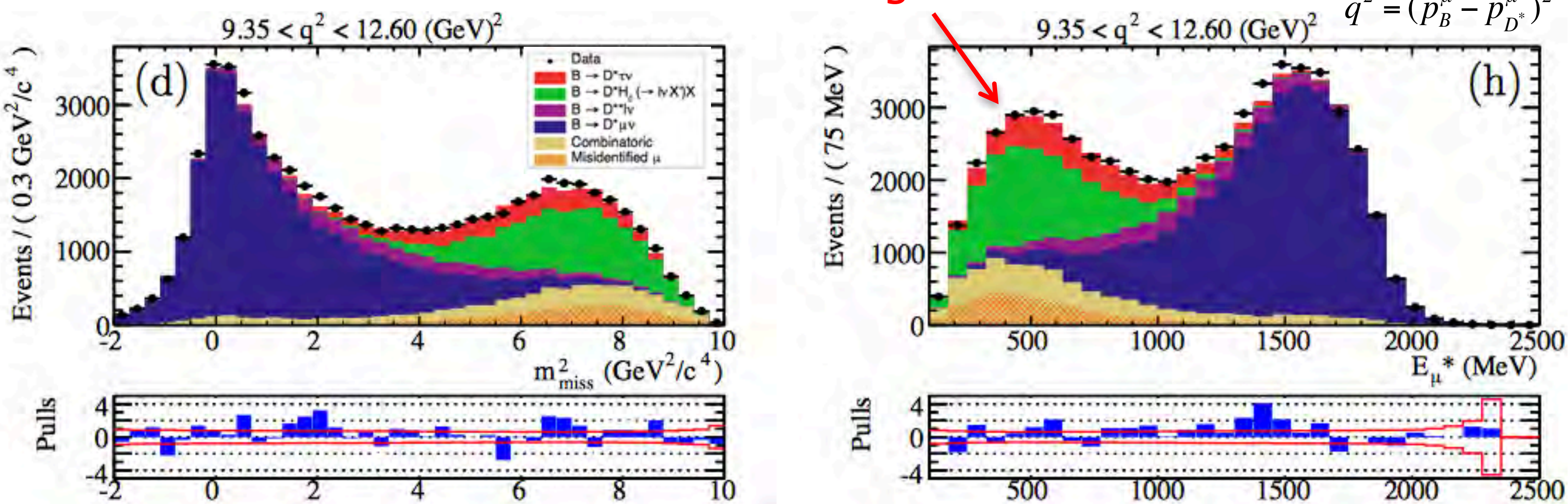
$R(D^*) = \mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)$

- Experimentally very difficult at LHC (considered unfeasible!) :
  - No kinematic constraints (as in B factories)
  - 3 ν final state, no peaking structure
  - Large background e.g. from partially reconstructed b decays



Signal

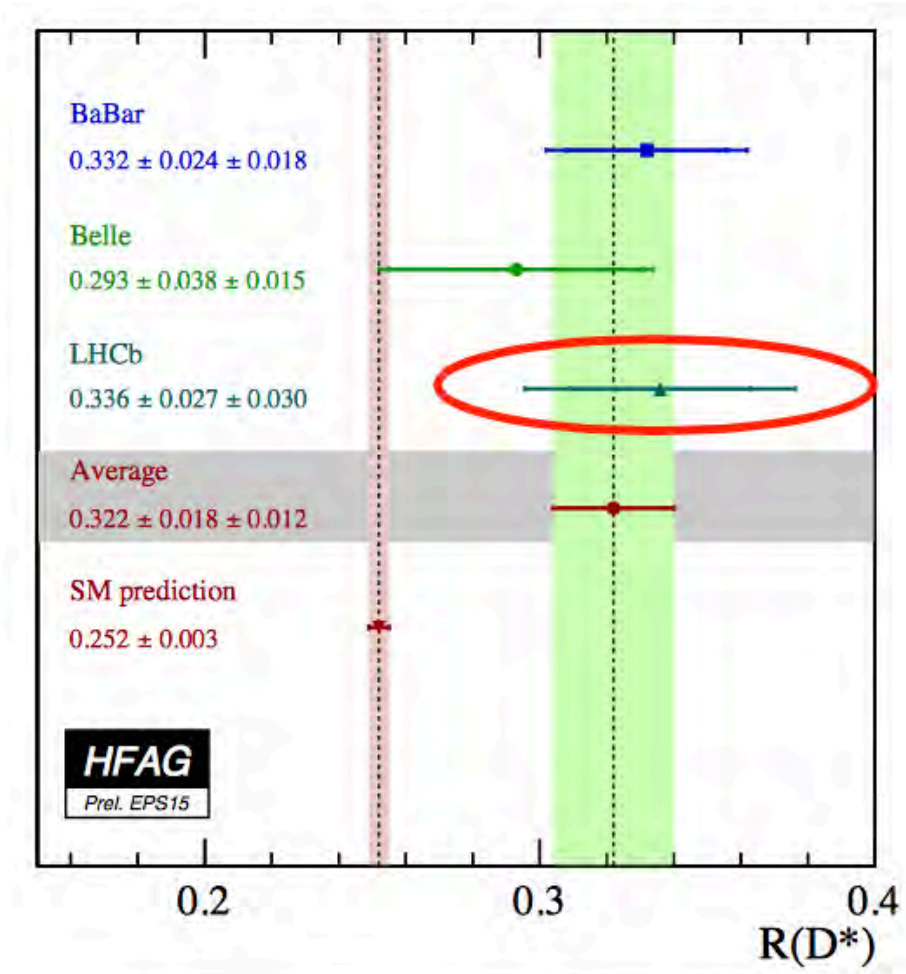
$q^2 = (p_B^\mu - p_{D^*}^\mu)^2$



PRL 115 (2015) 111803

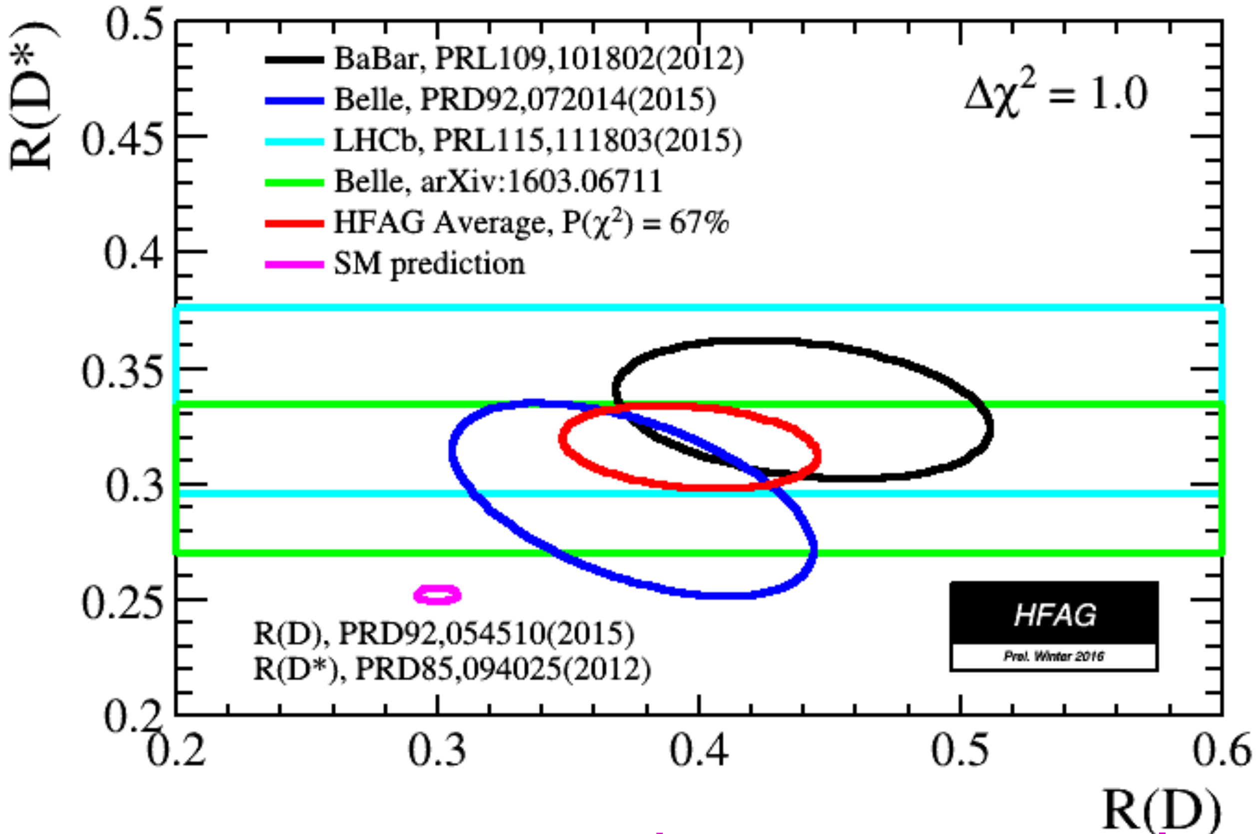
R(D*): Result

- R(D*)=0.336±0.027(stat)±0.030(syst)
  - in excellent agreement with previous measurements
  - in agreement with SM at 2.1σ level



EPS'16 HFAG average of R(D*) & R(D)

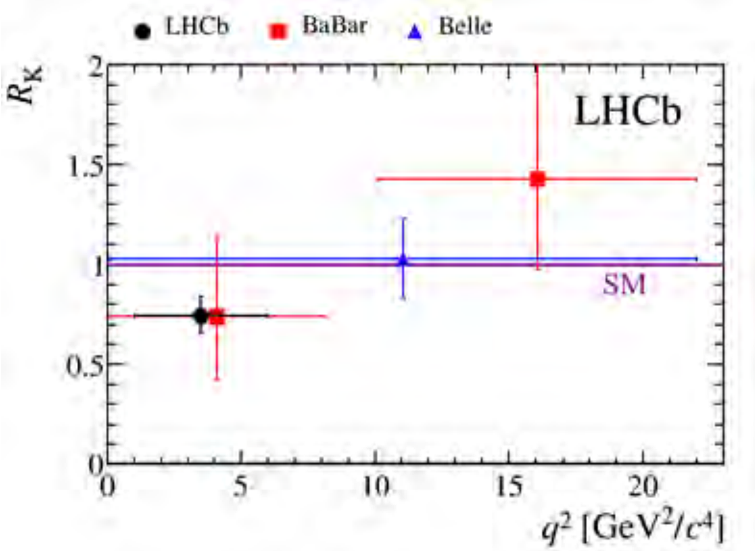
- Including new preliminary BELLE result (arXiv:1603.06711)



- Difference wrt SM predictions at 4 σ level !
- Similar studies with hadronic τ decays very advanced
- Work underway with other B hadrons ($B_s \to D_s \tau\nu$, $\Lambda_B \to \Lambda_c \tau\nu$)

Hints of lepton-flavour violation in $R_K = B(B^+ \to K^+\mu^+\mu^-)/B(B^+ \to K^+e^+e^-)$??

- Test of lepton universality : R_K ~1 in SM, with negligible theoretical uncertainties



LHCb, PRL 113 151601
Belle, PRL 103 171801
BaBar, PRD 86 032012

$$R_K(1 < q^2 < 6\ \mathrm{GeV}^2) = 0.745^{+0.090}_{-0.074}(\mathrm{stat}) \pm 0.036(\mathrm{syst})$$

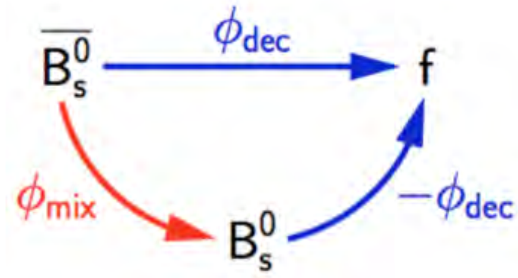
- Compatible with SM at 2.6σ
- Experimentally challenging
  - lower trigger efficiency for electrons, resolution deteriorated by bremsstrahlung
- Other modes suitable for same test: $B^0 \to K^{*0}\, l^+ l^-$, $B_s \to \phi\, l^+ l^-$, $\Lambda_B \to \Lambda\, l^+ l^-$

Selected results on CP Violation

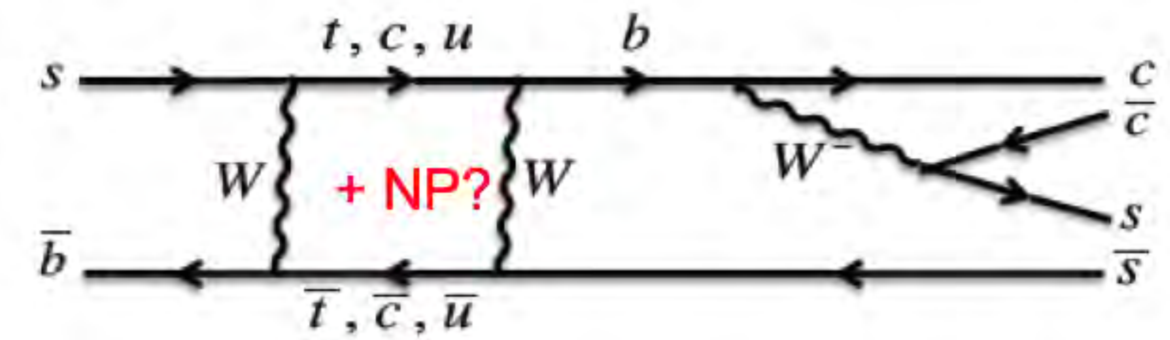
Extensively discussed by Neville Harnew in his lecture

CP violation in interference between B_s decays with or without mixing

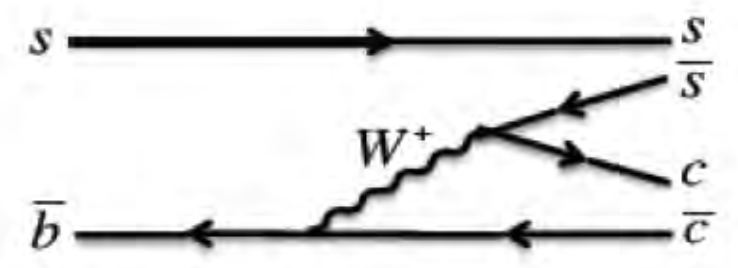
- Measurement of $B_s^0 - \bar{B}_s^0$ mixing phase difference $\phi_s = \phi_{mix}$ -2 ϕ_{dec} sensitive to NP effects in mixing



- Golden mode $B_s \to J/\psi(\mu^+\mu^-)\ \phi(K^+K^-)$ dominated by $b \to c\bar{c}s$ tree decay



Decay amplitude with mixing (ϕ_s)

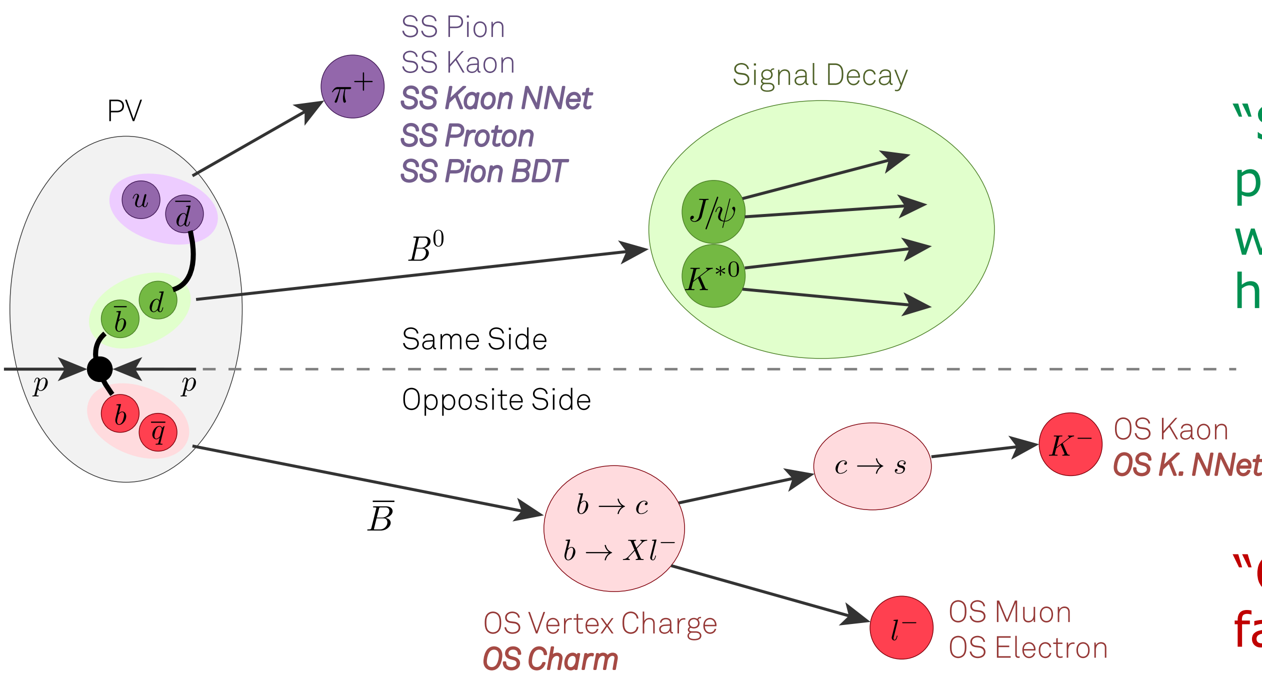


Amplitude with direct decay

- Theoretically and experimentally clean
  - $b \to c\bar{c}s$ tree dominance leads to precise prediction in the SM $\phi_s \cong -37 \pm 1$ mrad → very small!
  - Clean topology

$B_s \to J/\psi\ \phi$: key experimental ingredients

- Decay time resolution ~50 fs <<350 fs: B_S^0 oscillation period
- Tagging of the initial flavour ($B/\bar{B}$)
  - Effectiveness of flavour tagging is crucial as it increases the statistical power of the dataset collected

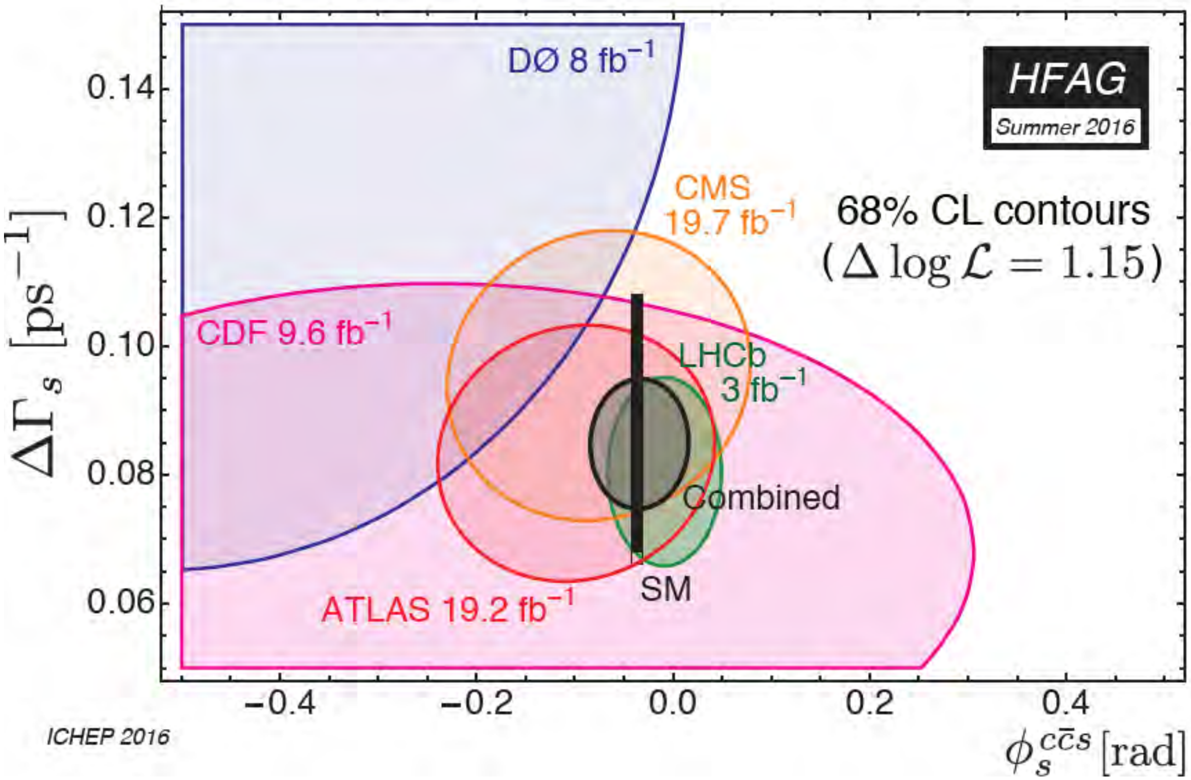


"Same Side" tag looks for particles produced in association with reconstructed B in hadronisation process

"Opposite Side" tag exploits the fact that b quarks are predominantly produced in $b\bar{b}$ pairs

- Tagging performance metric
  - ε=N(tagged)/Total
  - ω=N(wrong tag)/Total
  - Tagging power $\varepsilon_{eff}=\varepsilon\,(1-2\omega)^2=3.73\%$ PRL 114, 041801

ϕ_s combined



- Several measurements at Tevatron and LHC
- World average:
  $\phi_s = -30 \pm 33$ mrad
- Earlier hints from the Tevatron of significant deviations from the SM have gone!
- Excellent agreement with SM!
- Statistically 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)

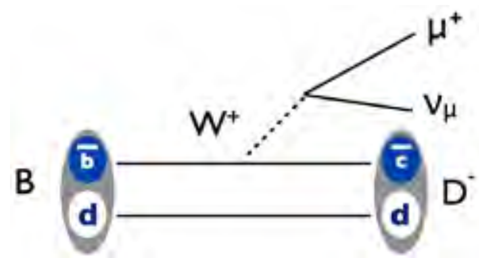
CP violation in $B_{(s)}$ mixing with semileptonic decays

- Asymmetry in the yield of mixed decays

$$B \to \bar{B} \to D^+\mu^-\bar{\upsilon}_\mu \text{ vs } \bar{B} \to B \to D^-\mu^+\upsilon_\mu$$

- Semileptonic decays expected to be both CP conserving and flavour specific (lepton charge identifies the flavour of the meson at decay time)

- $$a_{sl}^q = \frac{P(\bar{B}_q \to B_q) - P(B_q \to \bar{B}_q)}{P(\bar{B}_q \to B_q) + P(B_q \to \bar{B}_q)}$$

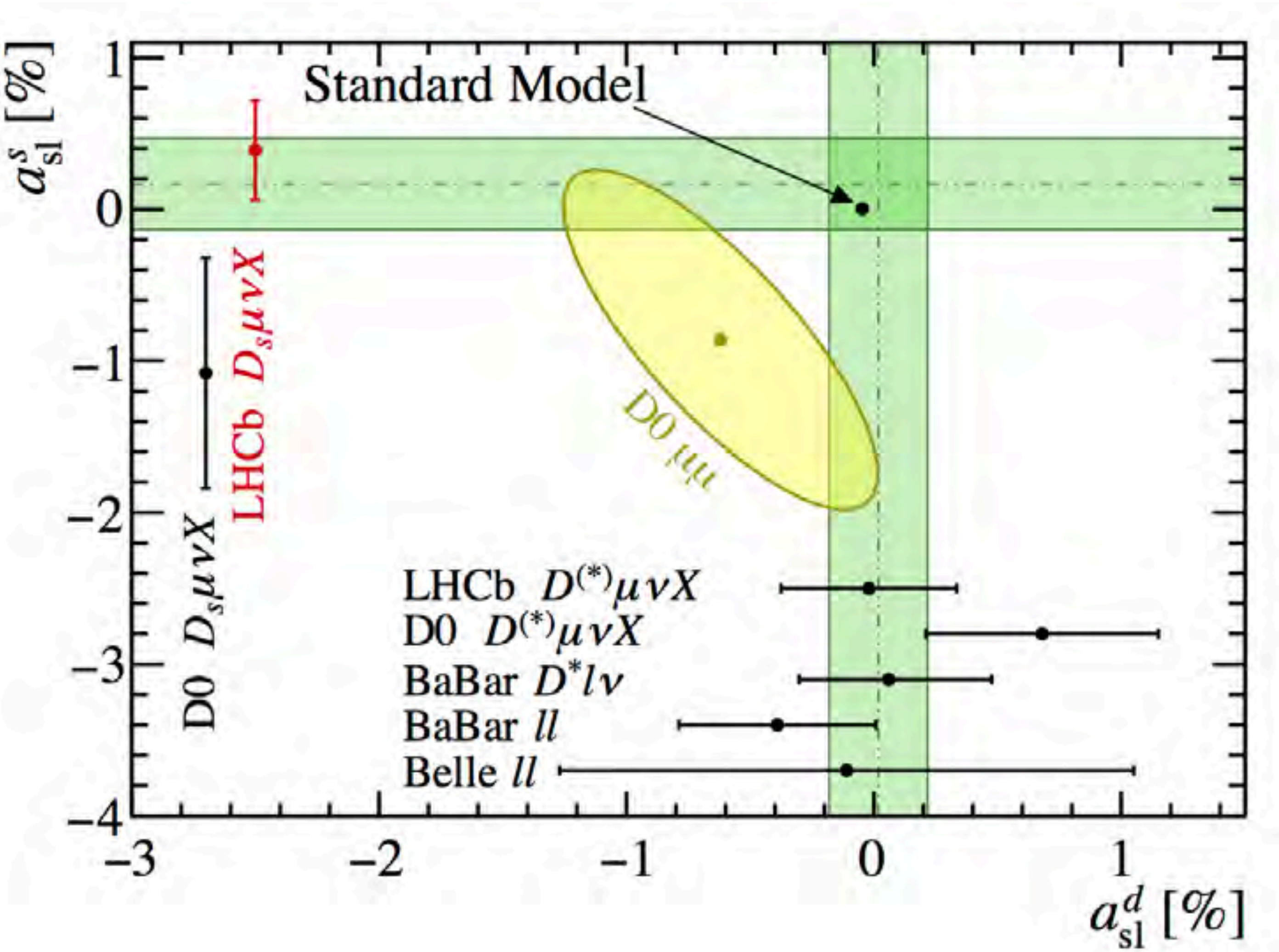


- Expected to be small in SM ~ $-5 \cdot 10^{-4}$ (B_d) and $2 \cdot 10^{-5}$ (B_s), but could be enhanced by NP in mixing

- Experimentally, for the B_s:

$$A_{raw} = \frac{N(D_s^- \mu^+) - N(D_s^+ \mu^-)}{N(D_s^- \mu^+) + N(D_s^+ \mu^-)} = \frac{a_{sl}^s}{2} + \text{corrections}$$

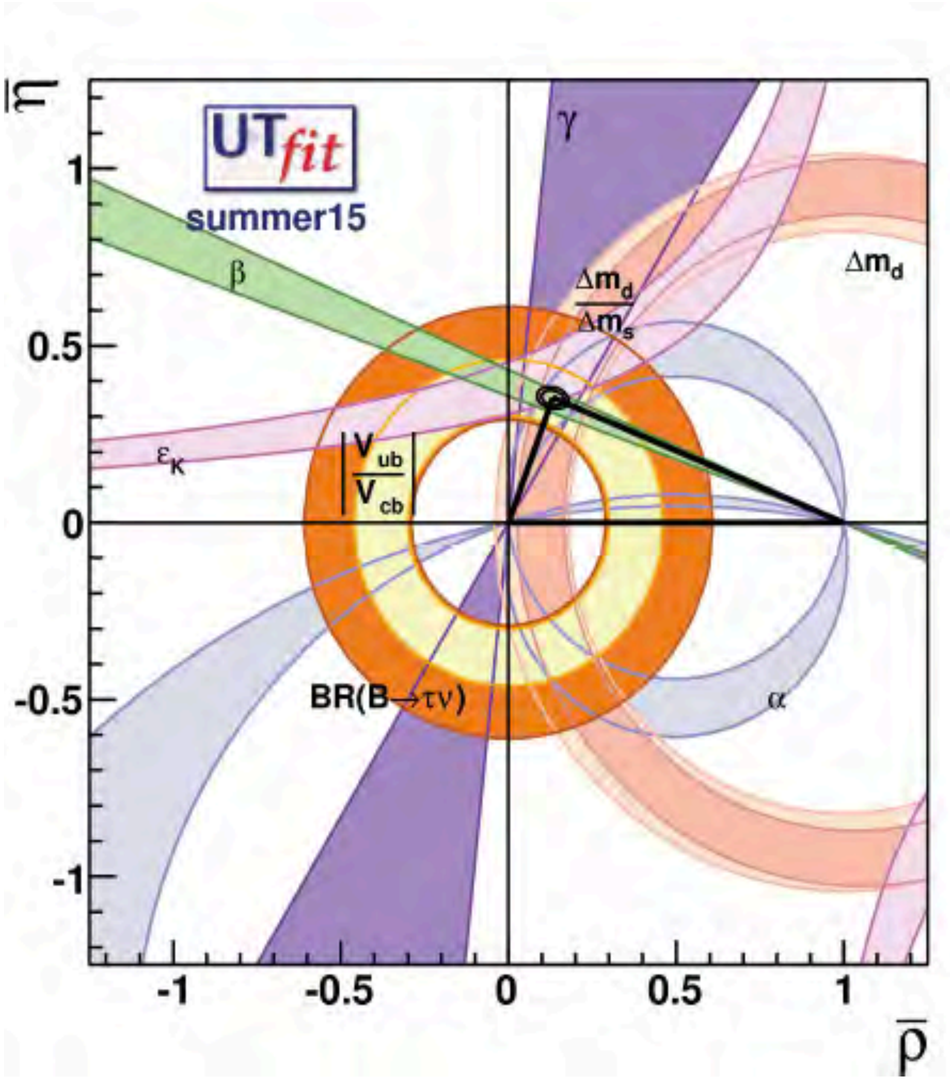
Results



$a_{sl}^{s} = (0.39 \pm 0.26(stat) \pm 0.20(syst))\%$ PRL117, 061803 (2016)

- Marginally compatible with D0 dimuon result
- Very much compatible with SM predictions
- Most precise measurement of CPV in B_s - statistically limited

Experimental success of CKM description

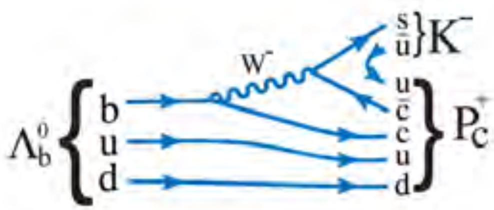


- Excellent overall consistency with the CKM paradigm
- The CKM mechanism is obviously at work at ~O(20%) but there is still room for NP (e.g. new sources of CPV in quark sector)
- Moving to the (high) precision era to look for signs of non-SM physics

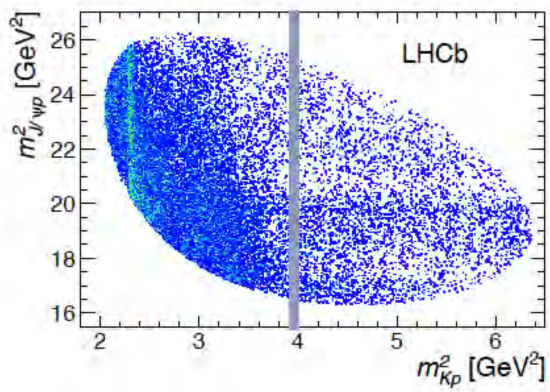
Exotic Spectroscopy

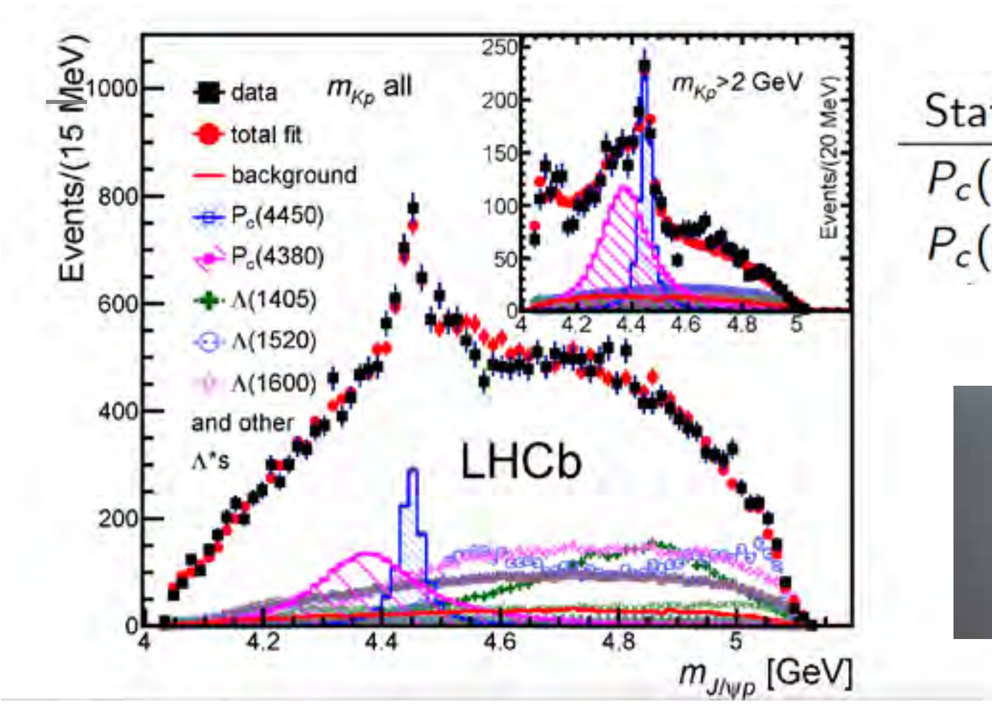
LHCb sees the pentaquark!

- Two charmonium pentaquark candidates in $\Lambda^0_b \rightarrow J/\psi p K^-$ decays!
  [PRL 115 (2015) 072001]

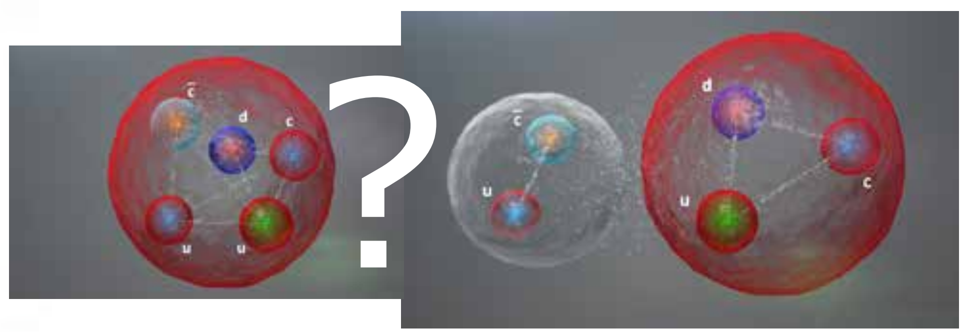


$uudc\bar{c}$





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

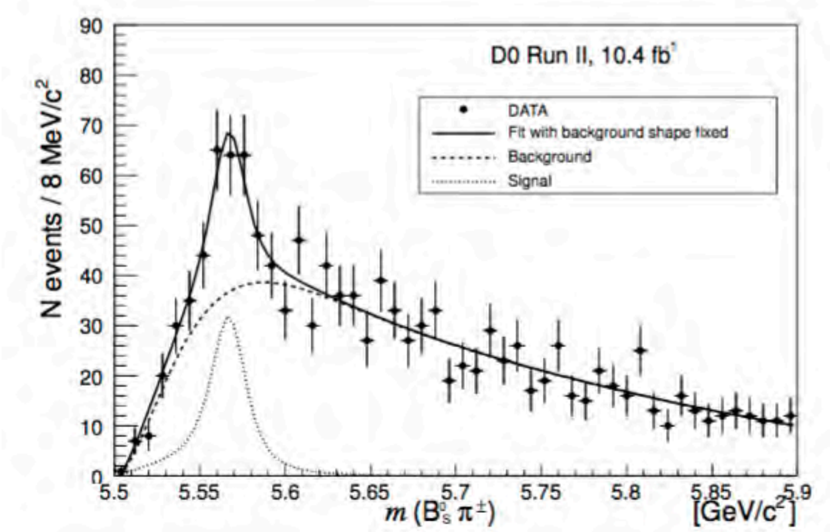


- Result confirmed by a model independent study [PRL 117 (2016) 082002]
  – $\Lambda^0_b \rightarrow J/\psi p K^-$ decays cannot be explained by $\Lambda^0_b \rightarrow J/\psi \Lambda^*$ with $\Lambda^* \rightarrow p K^-$
- Also supported by amplitude analysis of $\Lambda^0_b \rightarrow J/\psi p \pi^-$ decays [PRL 117 (2016) 082003]
  – More statistics needed

… does not confirm D0 tetraquark

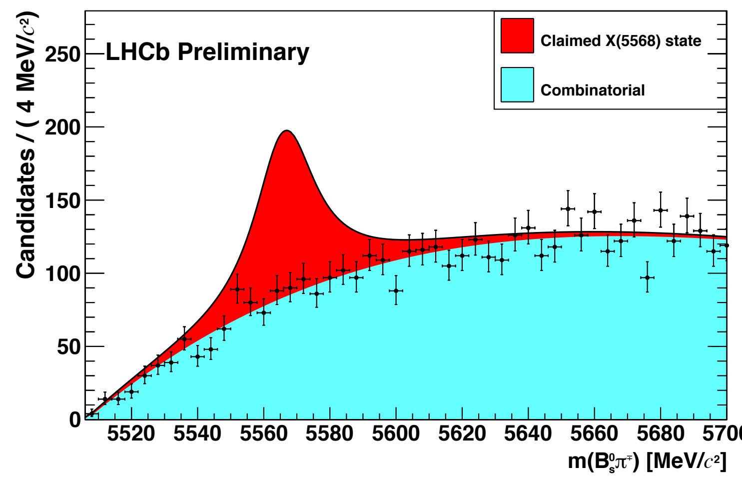
- Feb. 26th: D0 announces observation of exotic state $X(5568) \rightarrow B_s\pi$ with 5σ significance: (b,s,u,d) tetraquark state
- N_{B_S}~5500

PRL 117, 022003 (2016)



- LHCb responded very quickly, exploiting our fast analysis chain, ~110k ultra-clean B_s

arXiv:1608.00435

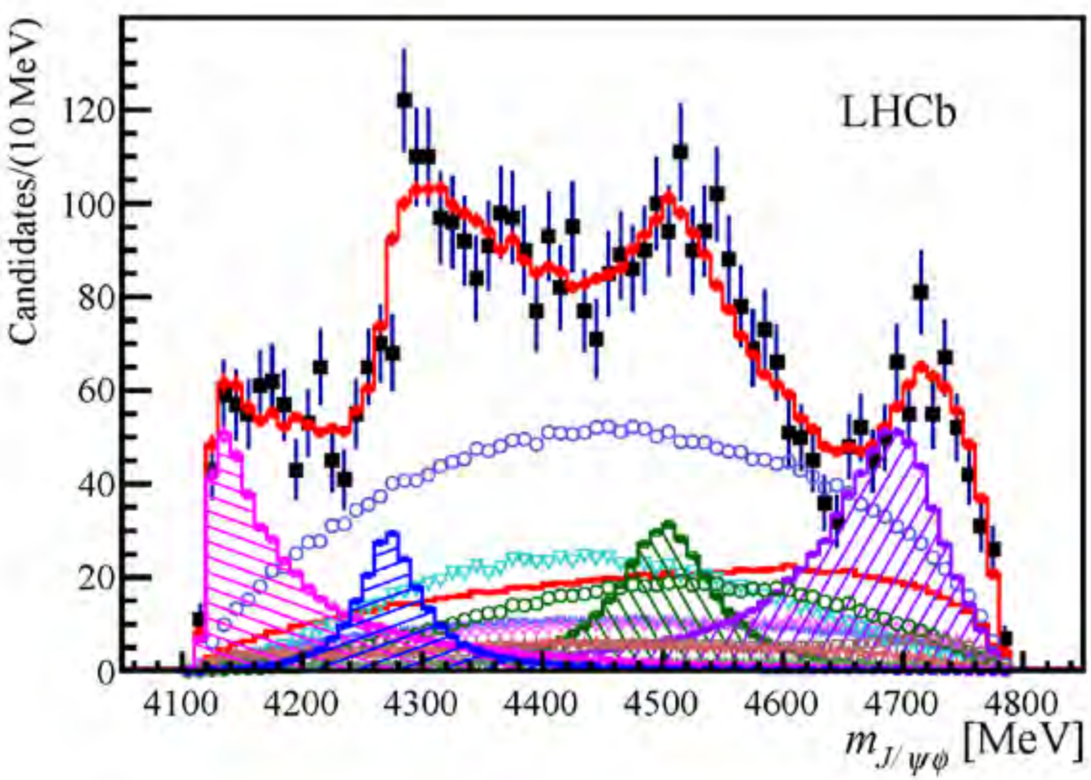


- What we should have seen

- Existence of X(5568) not confirmed → production upper limits set

Observation of exotic J/ψΦ structures from $B^+ \to J/\psi\Phi K^+$ decays

- Amplitude analysis of $B^+ \to J/\psi\Phi K^+$ decays with $J/\psi \to \mu^+\mu^-$, $\Phi \to K^+K^-$
  - Simultaneous analysis of $m_{J/\psi\Phi}$ and $m_{\Phi K}$ and decay angle distributions to show that J/ψΦ structures are not reflections of 'conventional states'



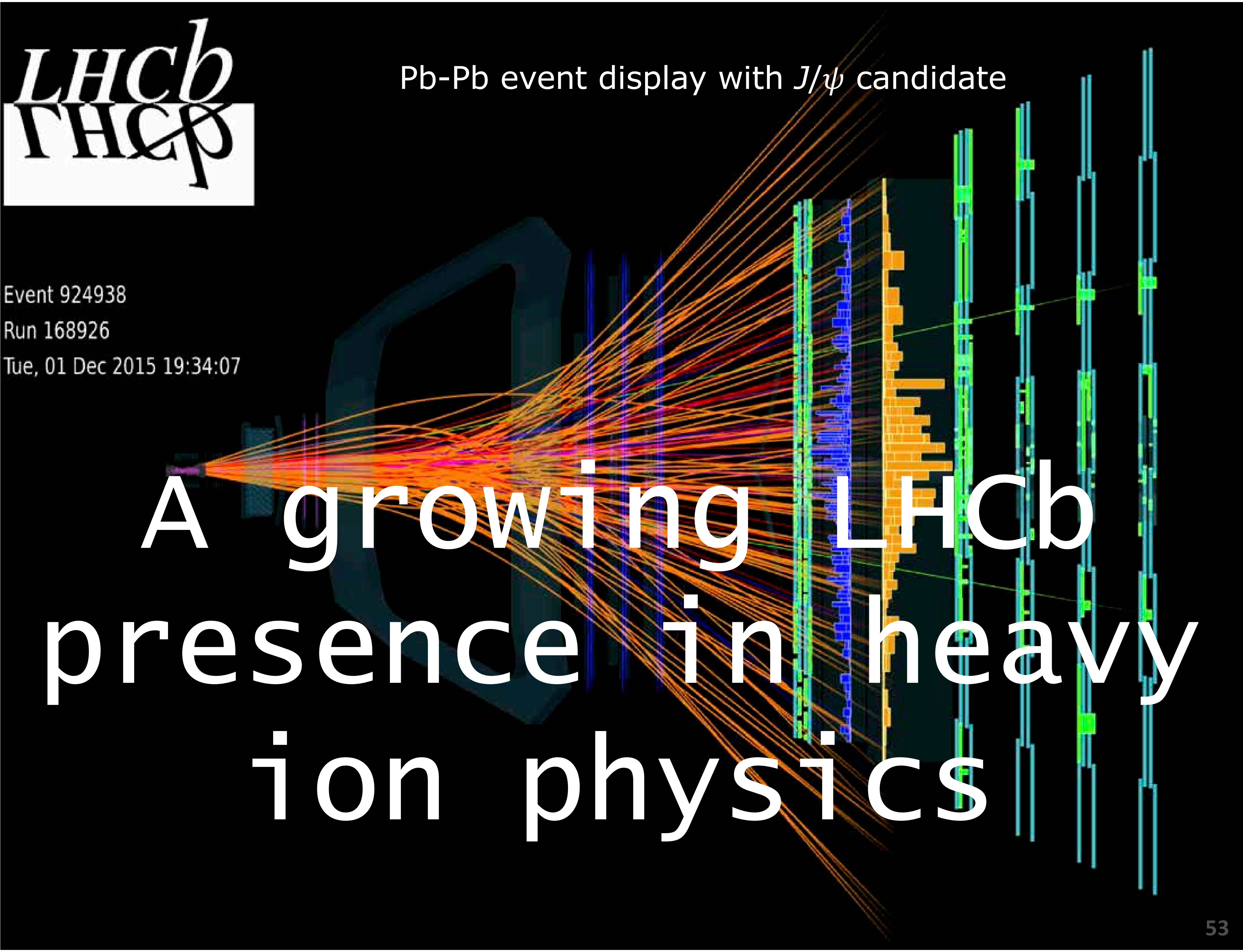
Evidence for X(4140) near-threshold J/ψΦ mass peak first announced by CDF, later confirmed by D0 and CMS. Searches by Belle and BaBar gave negative results

X(4140), X(4274)
X(4500), X(4700)

arXiv:1606.07895, arXiv:1606.07898

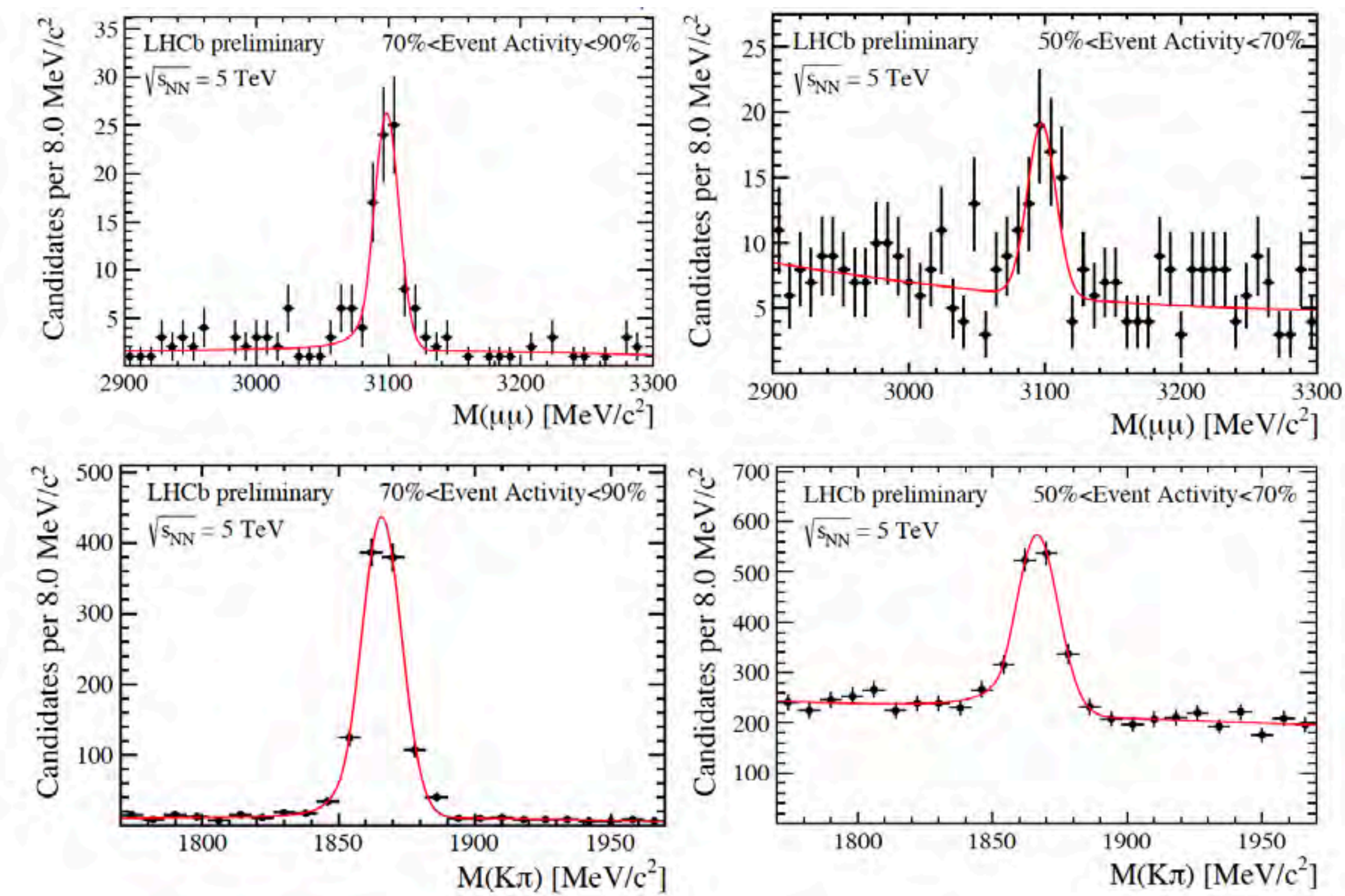
- Consistent with 4-quark particles $c\bar{c}s\bar{s}$, detail of binding mechanism not clear

A growing LHCb presence in heavy ion physics



First signals in Pb-Pb (2015)

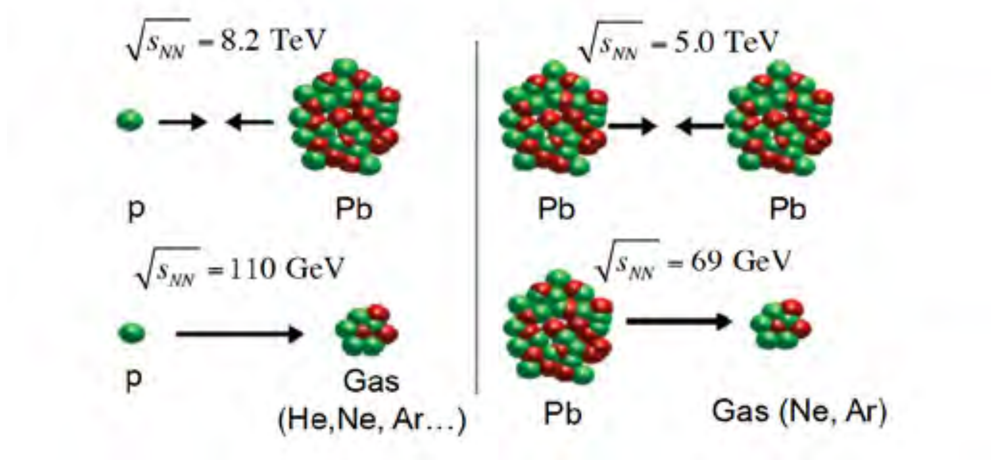
- First Pb-Pb data taking with 24 colliding bunches
- J/ψ, D^0 signals in bins of event activity in the electromagnetic calo



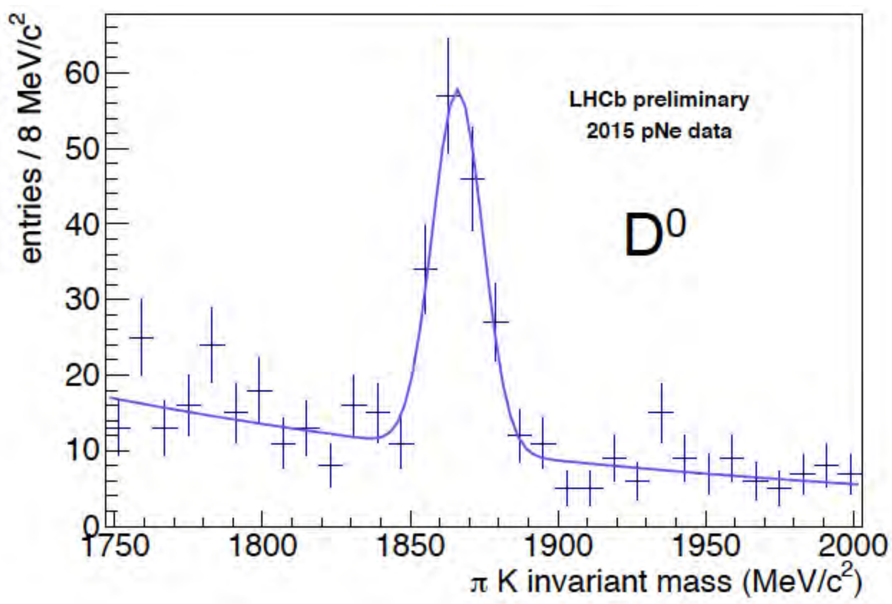
https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlots2015

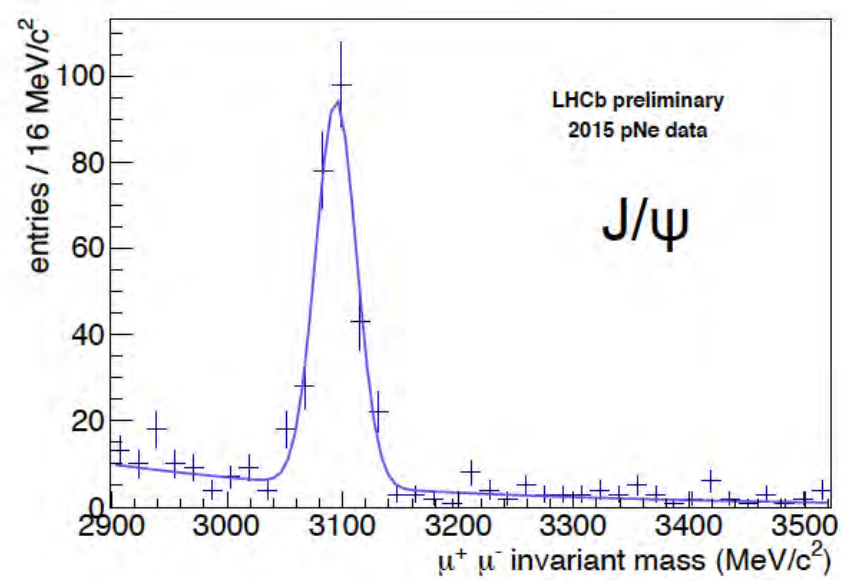
Several running modes

- LHCb can operate in parallel collider mode or fixed target mode
  - Fixed target mode (SMOG)
  - **S**ystem for **M**easuring **O**verlap with **G**as (M.Ferro-Luzzi, NIM A553(2005) 388)
    - Low density noble gas injected in interaction region (He, Ne, Ar)
    - Gas pressure ~2 orders of magnitude larger than vacuum pressure
      - Only local temporary degradation of LHC vacuum
    - Main use so far for precise $\mathcal{L}$ meas.



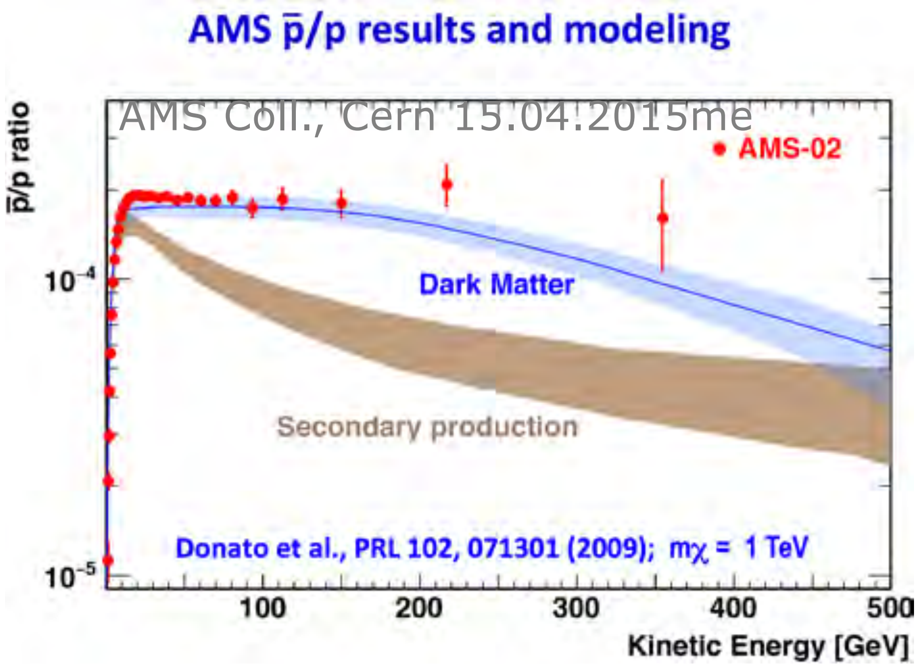
- p-Ne collisions at $\sqrt{S_{NN}} = 110\ \text{GeV}, \sim 12\ \text{h of data taking (2015)}$

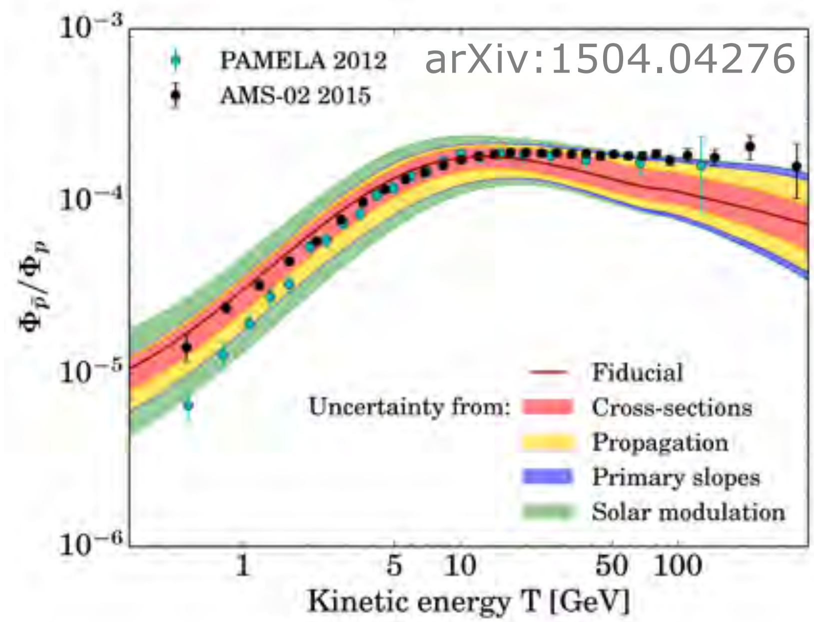




Link with other communities: cosmic ray physics

- Recent results from AMS-02 exhibit an antiproton excess with respect to expectations from secondary productions ($p + p \to \bar{p}$X and $p + He \to \bar{p}$X) in the interstellar medium, in the O(100 GeV) region
- Dark Matter contribution????

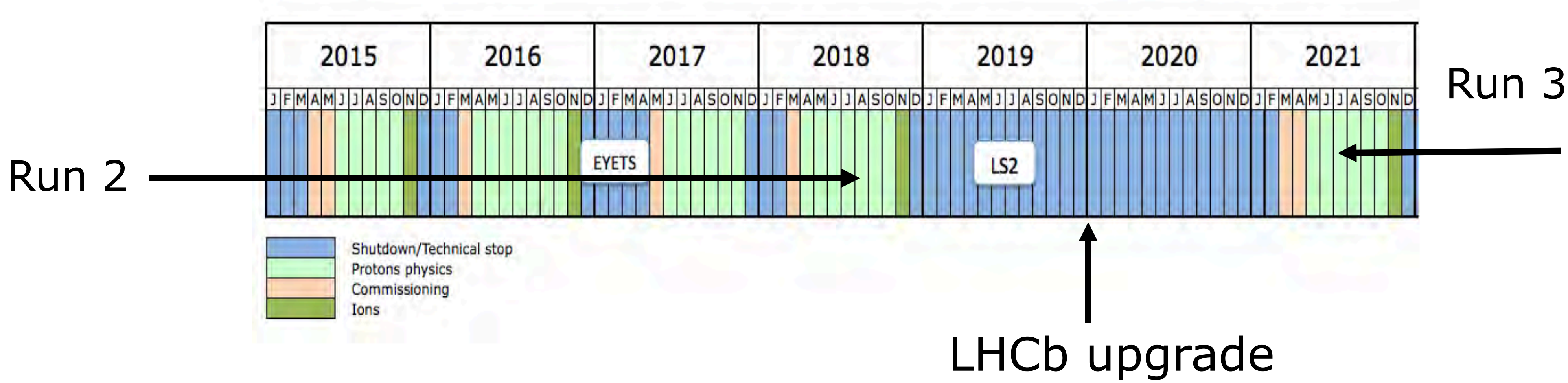




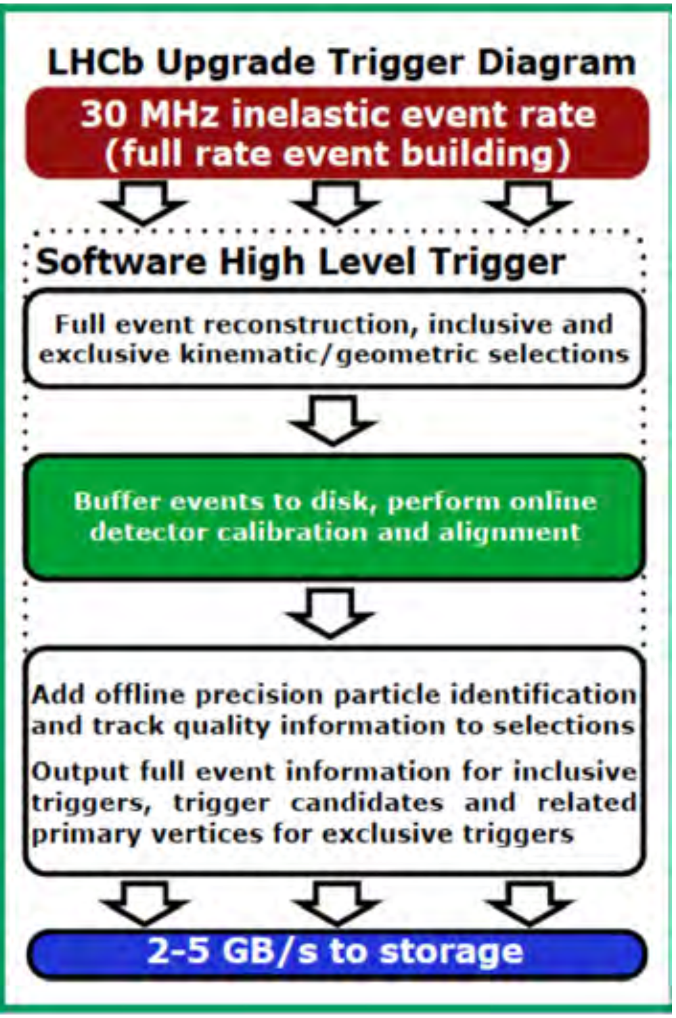
- More conservative estimates on the uncertainties indicate that the result could still fit with secondary productions
- Largest uncertainty from $\sigma(p + He \to \bar{p}$X)
- LHCb can measure this process with a 6.5 TeV p beam on He

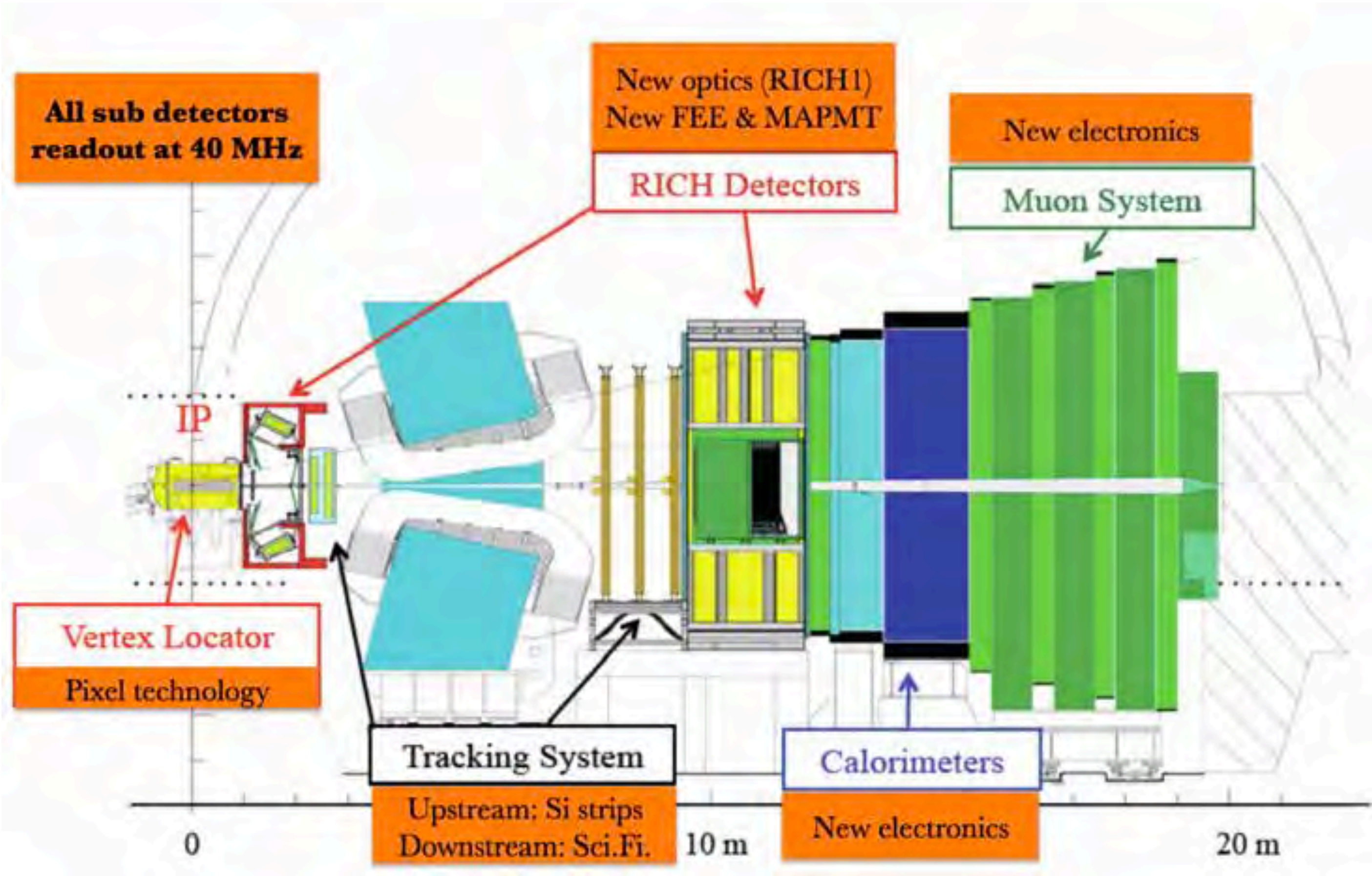
Looking forward: LHCb upgrade

- By the end of Run2, LHCb will have accumulated ~>8fb^{-1} (at $\mathcal{L} \sim 4\ 10^{32}$cm^{-2}s^{-1})
- Without modifications data doubling time after Long Shutdown 2 (LS2) would become too long → need significant increase in instantaneous luminosity
- Heavy Flavour physics still has large room for improvement with many measurements far from being limited by systematic uncertainties
- LHCb will be upgraded during LS2 to run at higher luminosity ($\mathcal{L} \sim 2\ 10^{33}$cm^{-2}s^{-1})
- First data taking in Run 3



Detector modifications for the upgrade





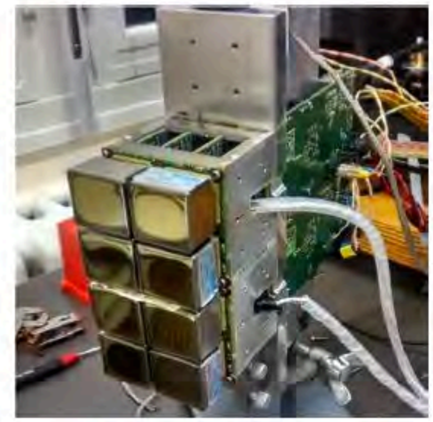
Upgrade progress

- LHCb upgrade is fully approved
- Intense ongoing activities on all sub-sytems, with many now entering production phase
- On schedule for installation in 2019-2020

Prototype 40 MHz readout board

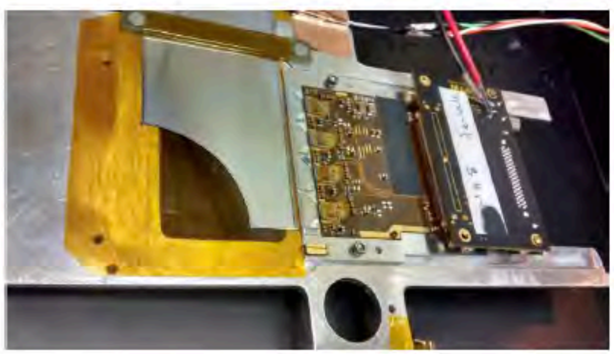
Prototype RF box for VELO

Mat production for SciFi

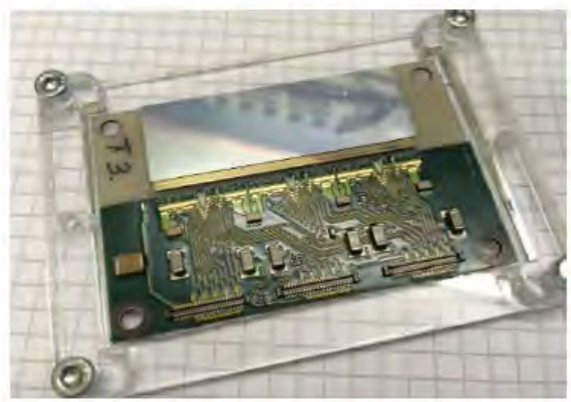


Photodetectors for RICH 1

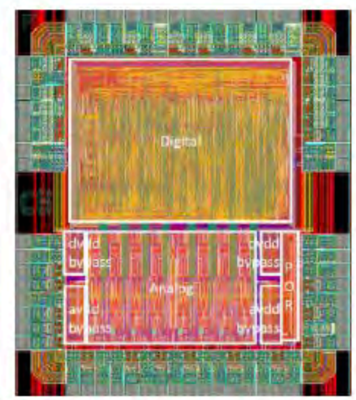
Spare production of muon chambers



Evaluation of Si modules of Upstream Tracker

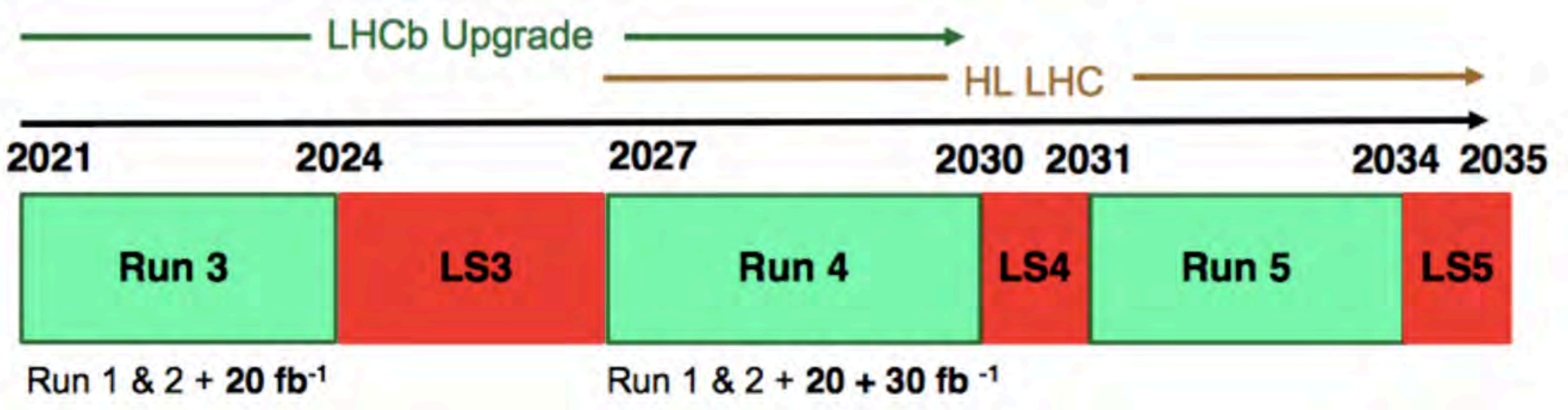


VELO sensor bump-bonded to ASICs + quarter hybrid



RICH ASIC

A future after the future



- While working for the upgrade, discussion started on what to do during the very long LS3 currently beginning in 2024
- Several ideas on the table to enhance LHCb with new capabilities that will bring extended physics opportunities in Run 4, & maybe lay the foundations for the further future
- Brainstorming on a phase-2 Upgrade with a target $\mathcal{L} \sim 2\ 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Machine studies already advanced and so far rather encouraging

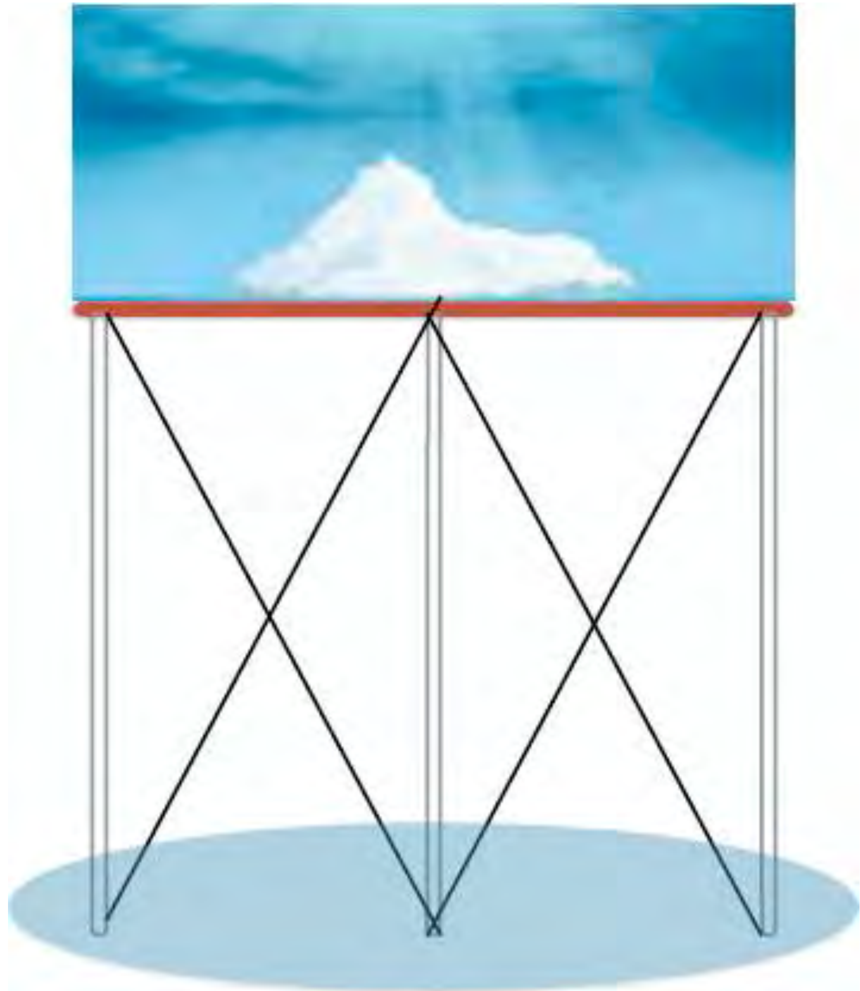
The SM as an emerging iceberg

What is under the water?

BSM in the multiTev region?

BSM in the multiTev region?

… or SM up to E>>TeVs



In the current uncertain situation of particle physics it is useful/necessary to have a diversified programme in which flavour plays an important role

Conclusions

- Wealth of LHCb results with the first 3/fb at "CERN's flavour factory" (and also from Run 2!)
  - Everything worked beautifully (detector, trigger, data analysis, ..)
  - Many world record results. For some topics we have moved from exploration to precision measurements.
  - Only very few highlights covered here (e.g. not covered charm, EW,…)
  - Many important results from run 1 still to come (e.g. R(D*), all the various R_K modes, more on charm,..)
- Some new territory already explored, some intriguing effects emerged, but in general SM still depressingly uncracked
- We'll keep on looking….
- We have shown to be ready for Run 2 and implemented many clever and innovative ideas
  - E.g. calibration and alignment of detector in real time
- Working hard to prepare for the future (LHCb Upgrade) and brainstorming on the future of the future