Recent selected LHCb highlights

Monica Pepe Altarelli (CERN)

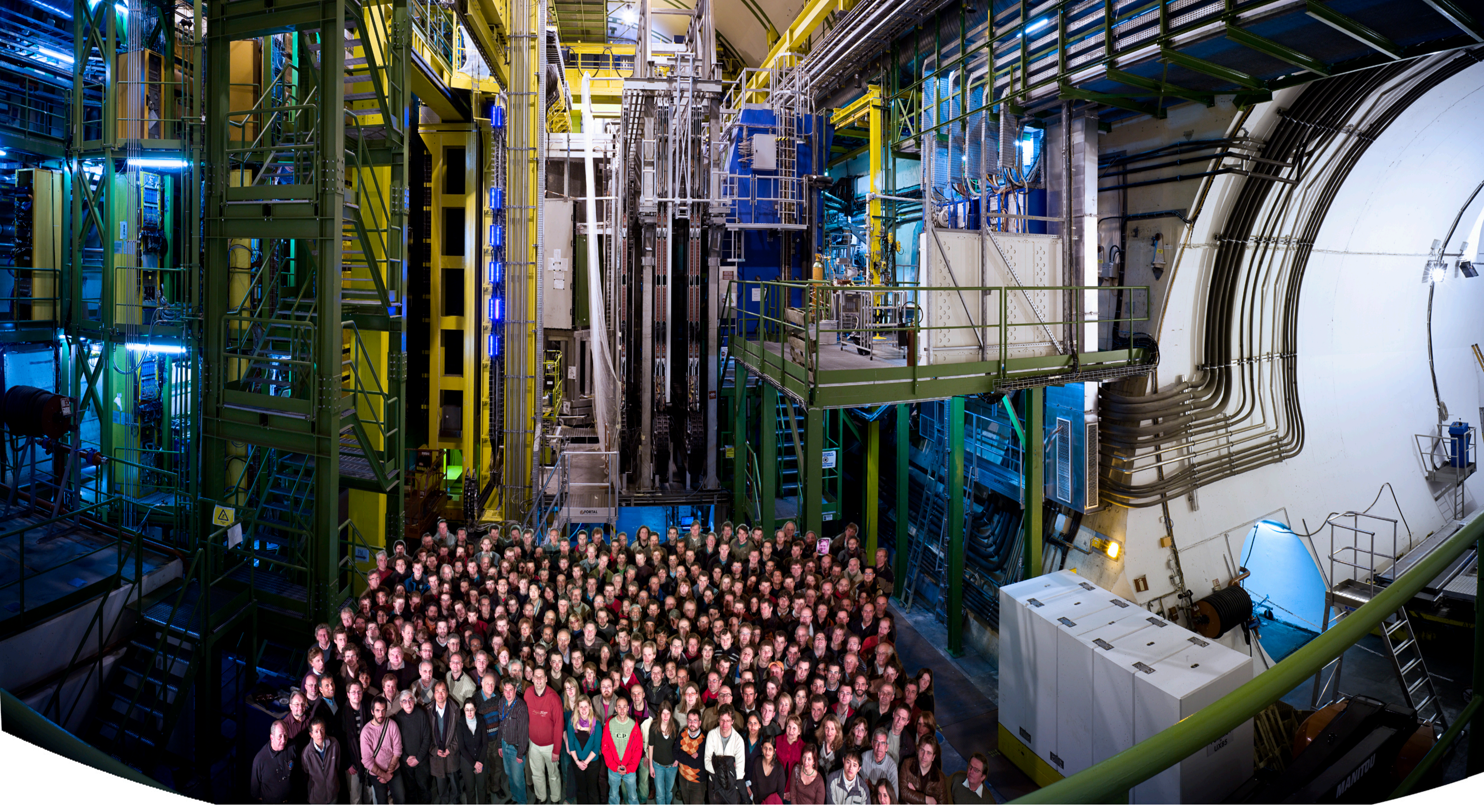
On behalf of LHCb collaboration

Vulcano Workshop 2016,

Frontier Objects in Astrophysics and Particle Physics

The LHCb collaboration

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

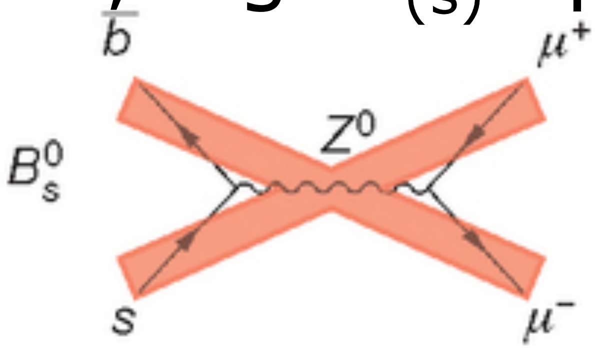


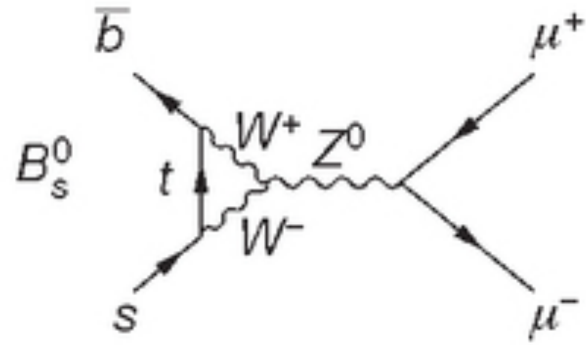
Why b? (I)

- The heaviest quark that binds in hadrons
- Many decay channels: a vast laboratory
- Heavy mass → more theoretically accessible
- Lifetime long enough for experimental detection:
  - $\tau_{beauty} \sim 1.5\ 10^{-12}$ s
- 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!)
- 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 flavor changing processes, nor necessarily in quark sector, it could originate from lepton sector

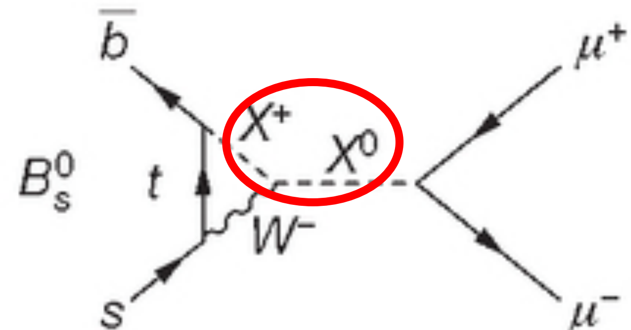
Why b? (II)

- 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 (e.g. modify BRs, angular distributions,..)

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 reduced after the results of the LHC at 7 and 8 TeV)

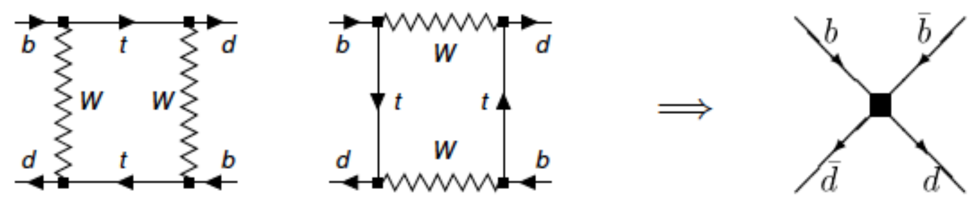
Strong limits on the scale of NP arise from flavour processes

- 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

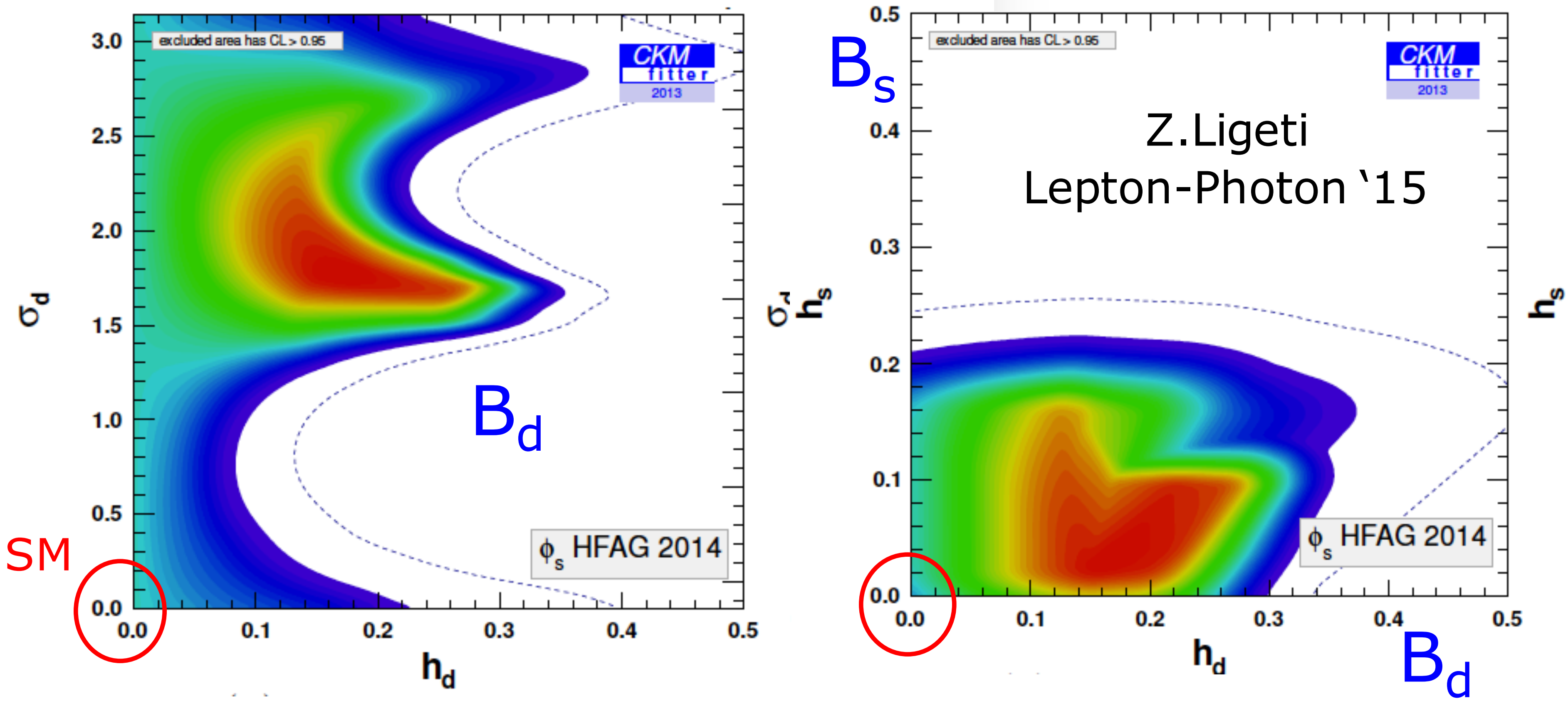


- These bounds on the scale of NP (up to $\sim10^5$ TeV) go well beyond the direct production capabilities of new particles at the LHC (~few TeV)

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

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

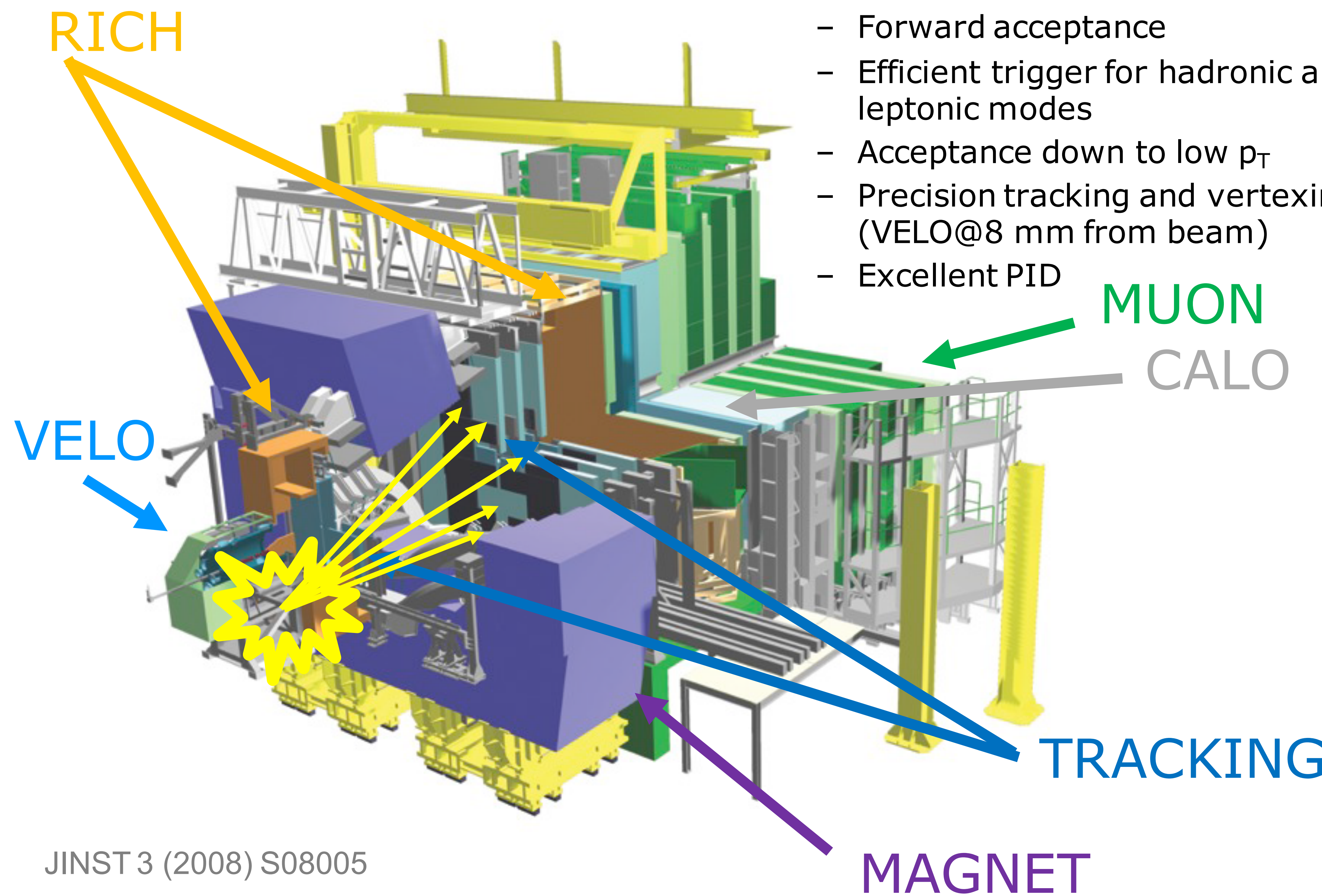
NP parameters



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

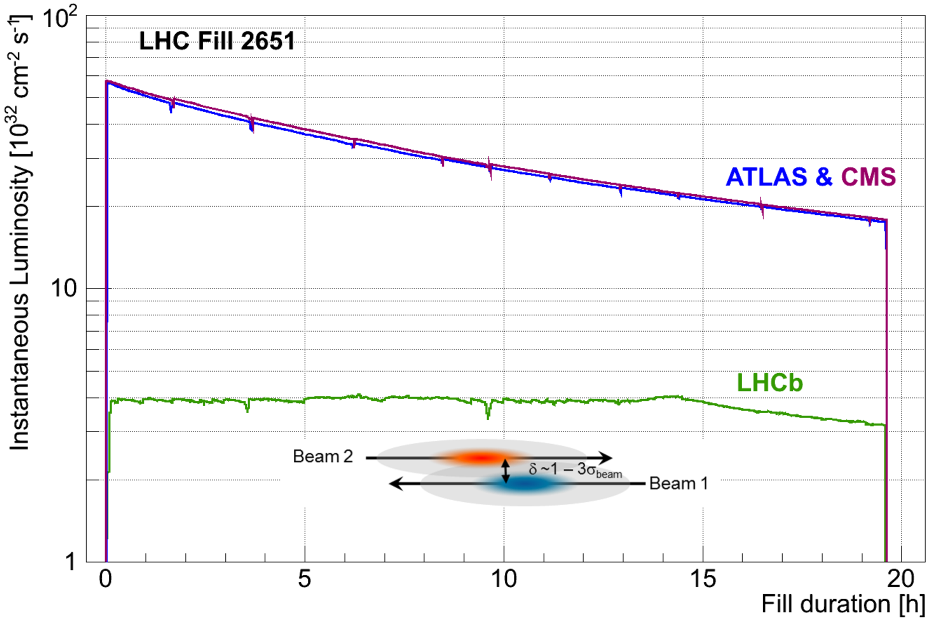
LHCb detector: the essentials

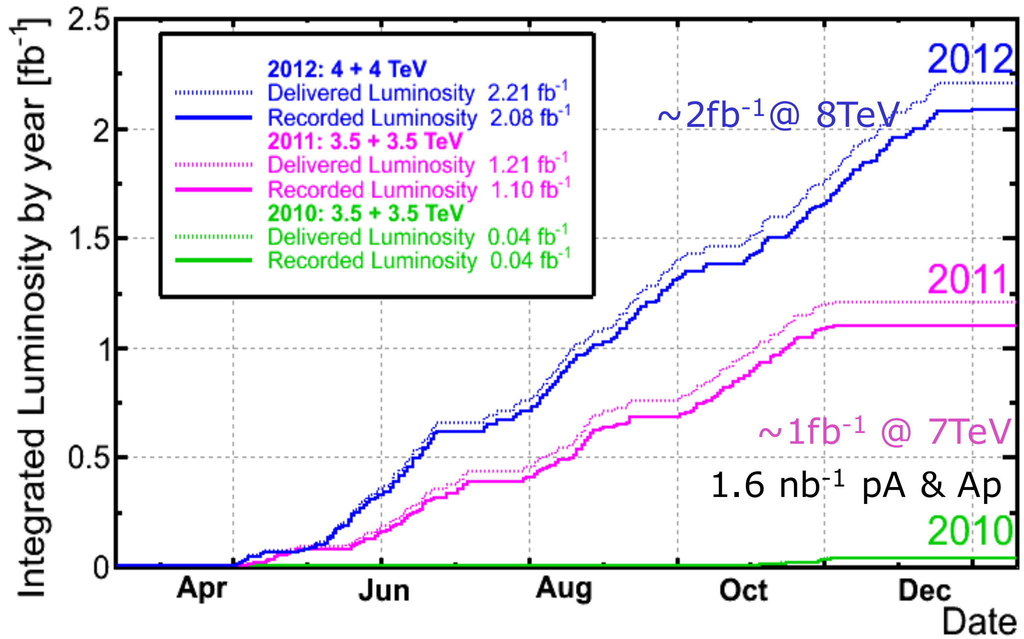
- Forward acceptance
- Efficient trigger for hadronic and leptonic modes
- Acceptance down to low p_T
- Precision tracking and vertexing (VELO@8 mm from beam)
- Excellent PID



JINST 3 (2008) S08005

Running conditions





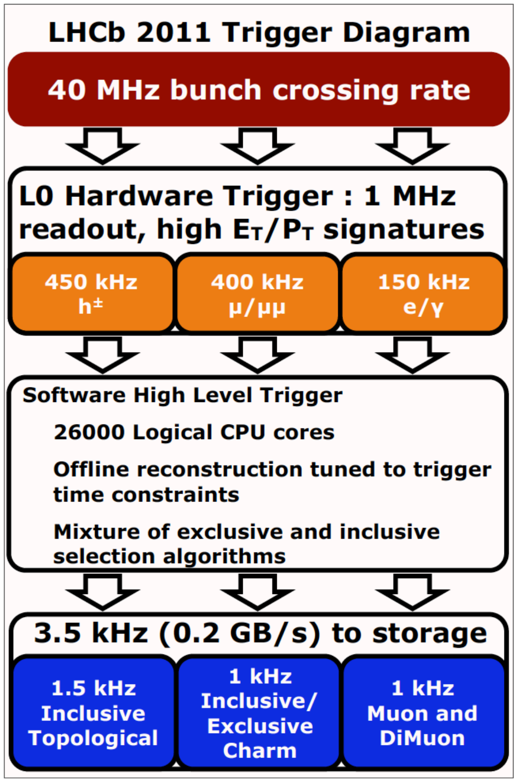
- LHCb designed to run at lower luminosity than ATLAS/CMS
  - Tracking, PID sensitive to pile-up
  - Mean number of interactions/bunch crossing ~1
- pp beams displaced to reduce instantaneous luminosity
  - $\mathcal{L} \sim 4.0\ 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Huge heavy quark production cross-sections
  - $\sigma_{bb} \sim 500\ \mu b$ @$\sqrt{s}$=13 TeV (~1nb in e^+e^-@ $\Upsilon(4s)$)
  - σ_{cc} is ~ 20 times larger!
- Resuming now with run 2 (2015-2018) @13 TeV with several ambitious changes aimed at maximising physics output

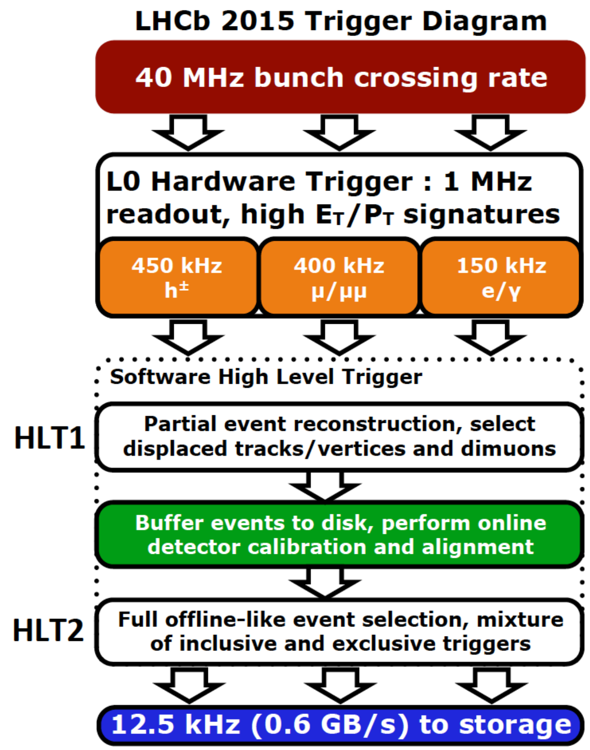
~10^{11} b decays/fb in acceptance

~10^{12} c decays/fb

Gearing up for 2016 – the trigger

- Evolving strategy for the High Level Trigger (HLT – software application designed to reduce the event rate from 1 M to ~10 k events/s, executed on a large computing cluster)





- 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
  - HLT2 uses offline-quality calibration → more discriminant trigger
  - With offline-quality reconstruction up-front, no need to reconstruct offline
  - Can perform physics analysis directly @ HLT level ("TURBO" stream)

The TURBO stream

- Online has offline quality→ Use it for physics!
  - 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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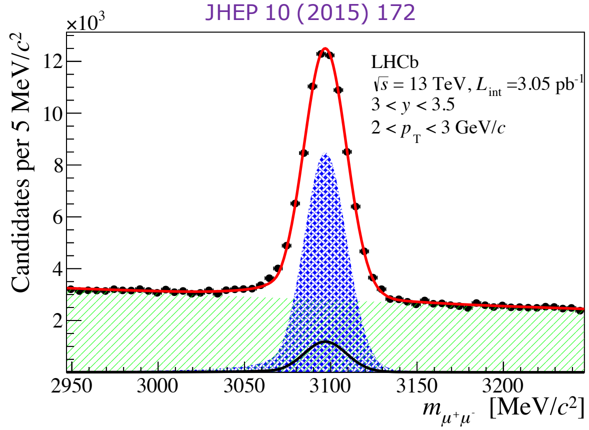
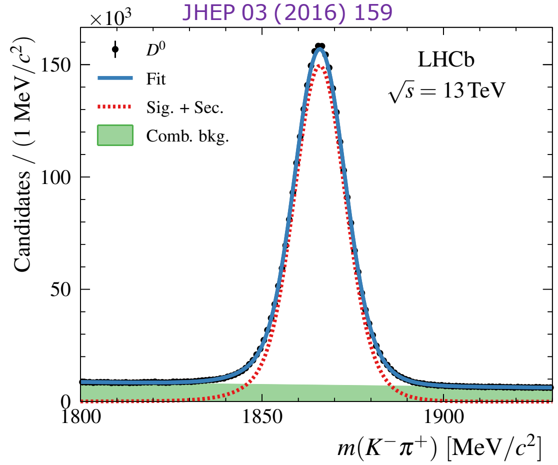


Prompt charm production cross-section

JHEP 03 (2016) 159

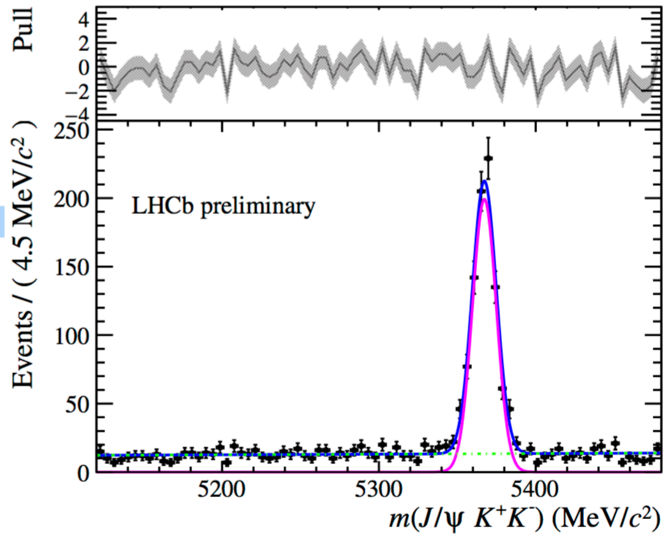


- For 2016 run, code sped up and made even more "offline-like"
- TURBO approach extended to analyses of higher complexity
- The higher output rates of the LHCb upgrade will make the approach increasingly necessary (→Pierluigi's talk)

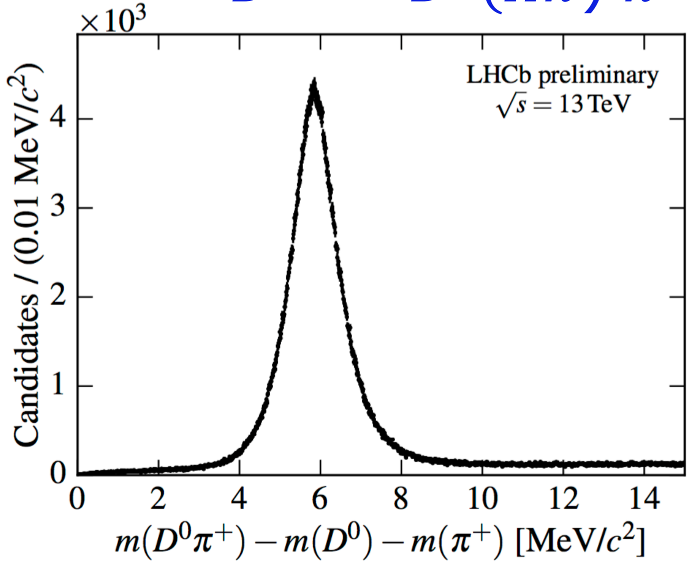
2016:Turbo++ stream

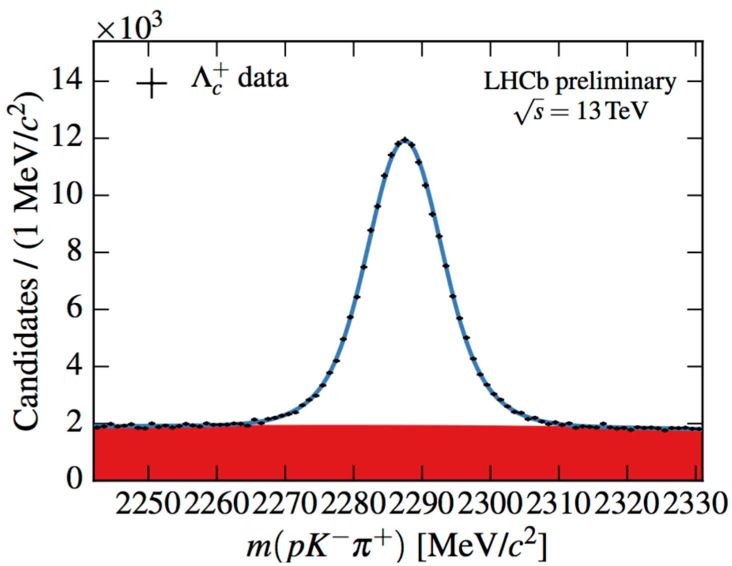
- 2016 HLT is even better, allowing qualitatively new analyses
- Can now save HLT candidates + any reconstructed particles

$B_s \to J/\psi K^+ K^-$



$D^{*+} \to D^0(K\pi)\,\pi^+$



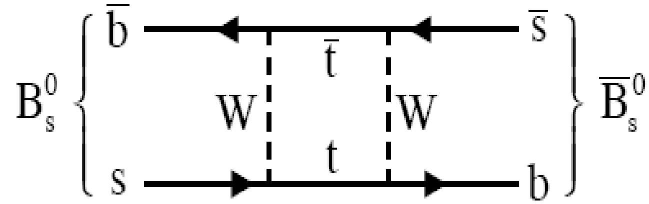


$\Lambda_c^+ \to pK^-\pi^+$

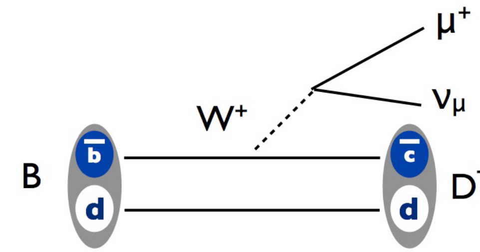
- Run 2 : a demonstrator for the upgrade!!!

Selected results on CP Violation

CP violation in B_s mixing



- $P(B_q \to \bar{B}_q) \neq P(\bar{B}_q \to B_q)$ $(q = d, s)$
- Use semileptonic final state $\bar{B}_s^0 \to D_s^+ \mu^- \bar{\nu}_\mu X$
  - Flavour specific → lepton charge identifies meson at the time of its decay



- $$a_{sl}^q = \frac{P(\bar{B}_q \to B_q) - P(B_q \to \bar{B}_q)}{P(\bar{B}_q \to B_q) + P(B_q \to \bar{B}_q)} \approx \frac{\Delta\Gamma}{\Delta m} \tan\phi_{12}$$

Semileptonic

Difference in mass and width of mass eigenstates

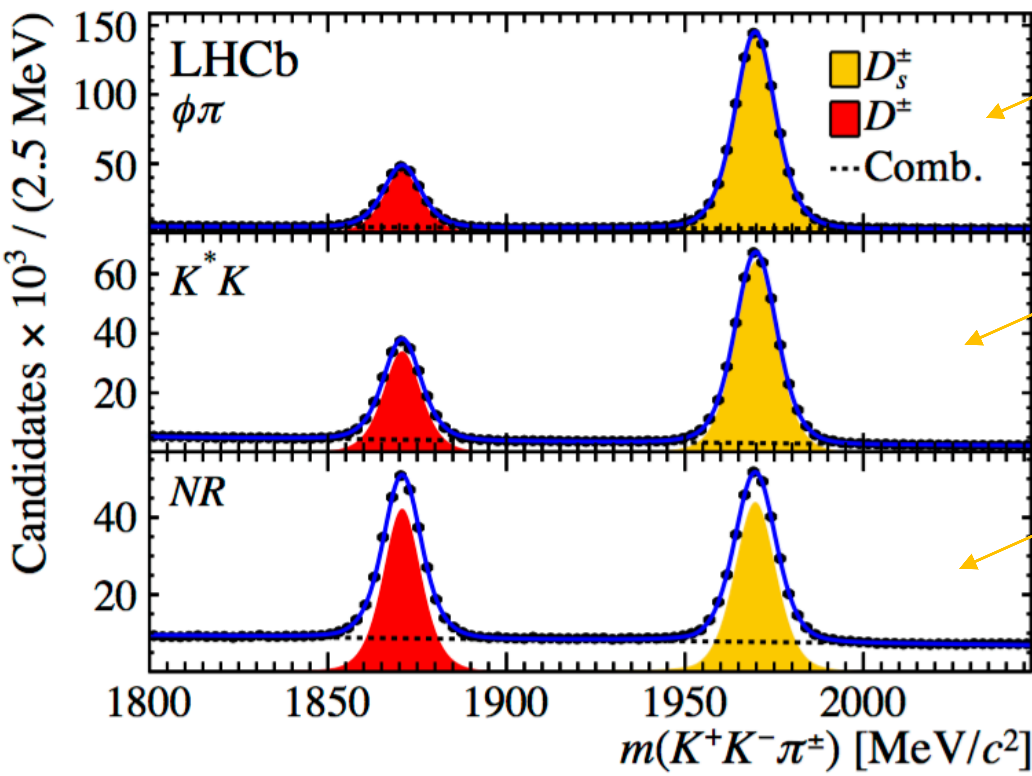
CPV phase

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

Results (full run 1)

- Use $D_s \to KK\pi$ in full Dalitz region: $\phi\pi, K^*K$, non-resonant

LHCb-PAPER-2016-013



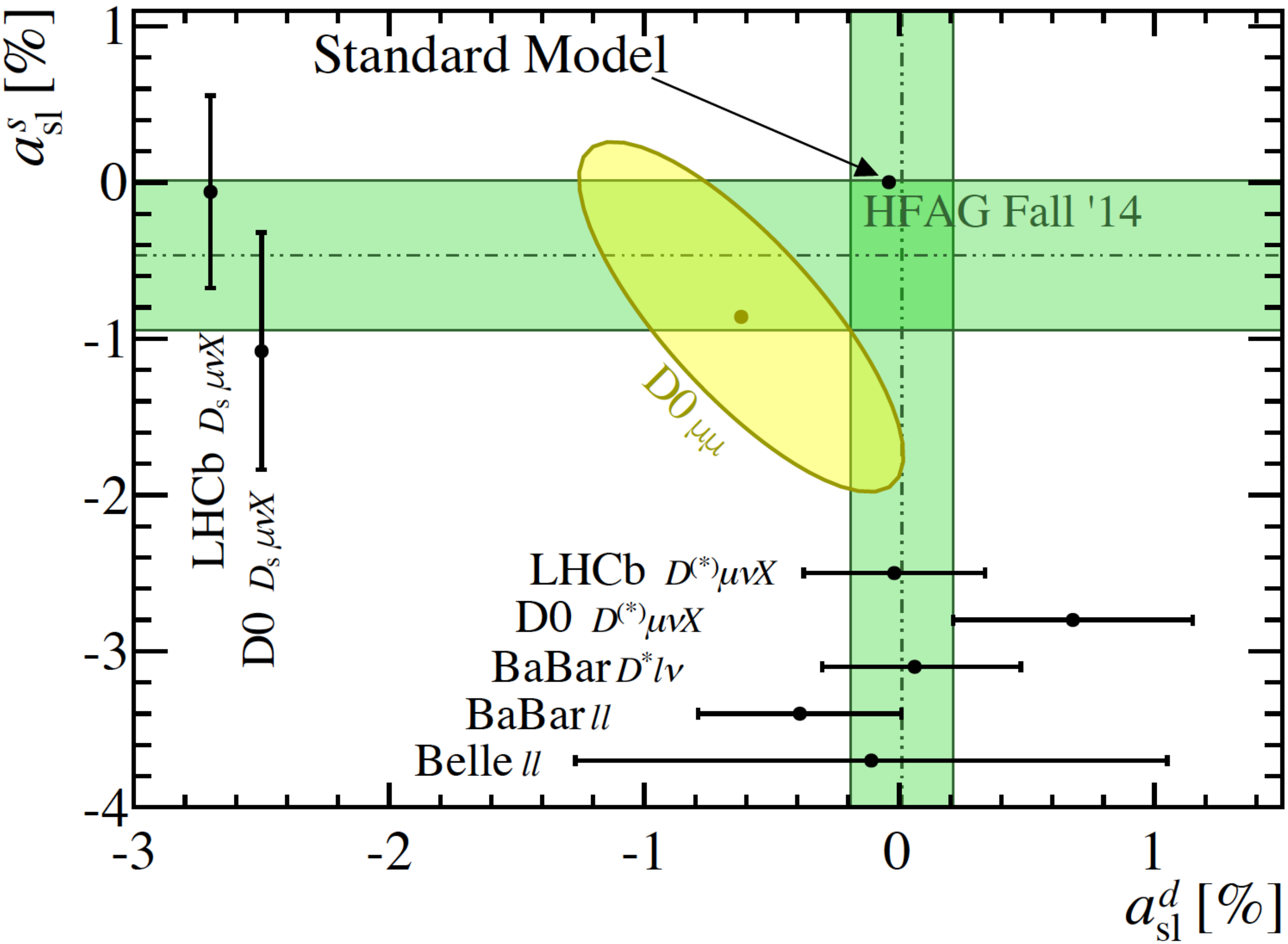
899 10^3

413 10^3 Prompt D_s removed

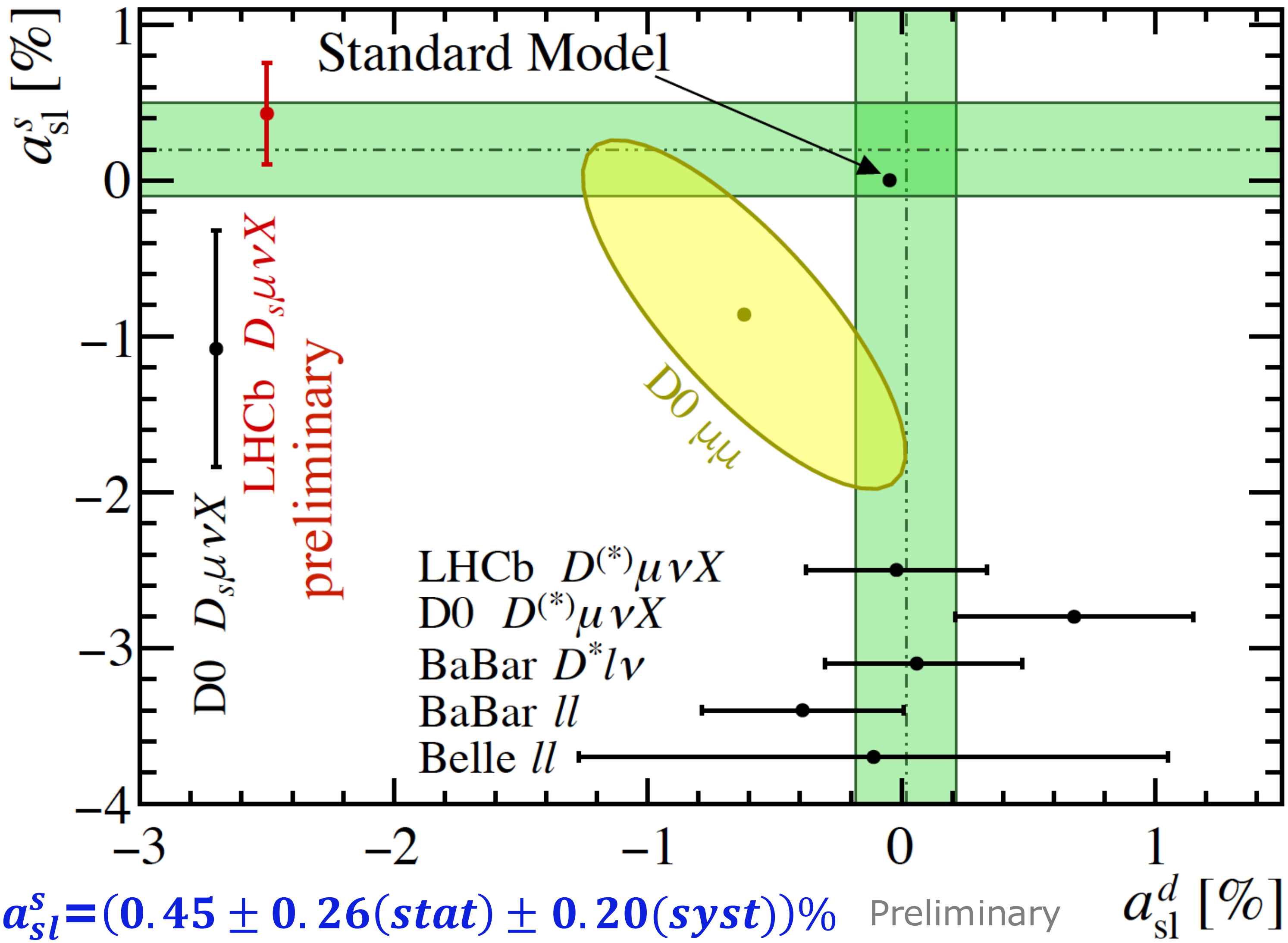
280 10^3

- $a_{sl}^s = (0.45 \pm 0.26 \pm 0.20)\%$ Preliminary, Beauty2016

The story so far



The story now



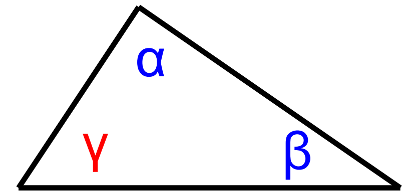
LHCb-PAPER-2016-013

$a^s_{sl}=(0.45 \pm 0.26(stat) \pm 0.20(syst))\%$ Preliminary

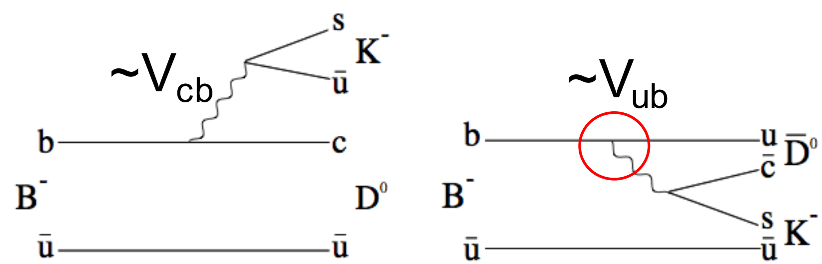
- Marginally compatible with D0 dimuon result
- Very much compatible with SM predictions
- Most precise measurement of CPV in B_s - statistically limited

γ from tree-level decays as "standard candle"

- $\gamma \approx -\arg(V_{ub})$ least well measured angle of Unitarity Triangle (~7°)
  - To be compared to ~3° for α and <1° for β



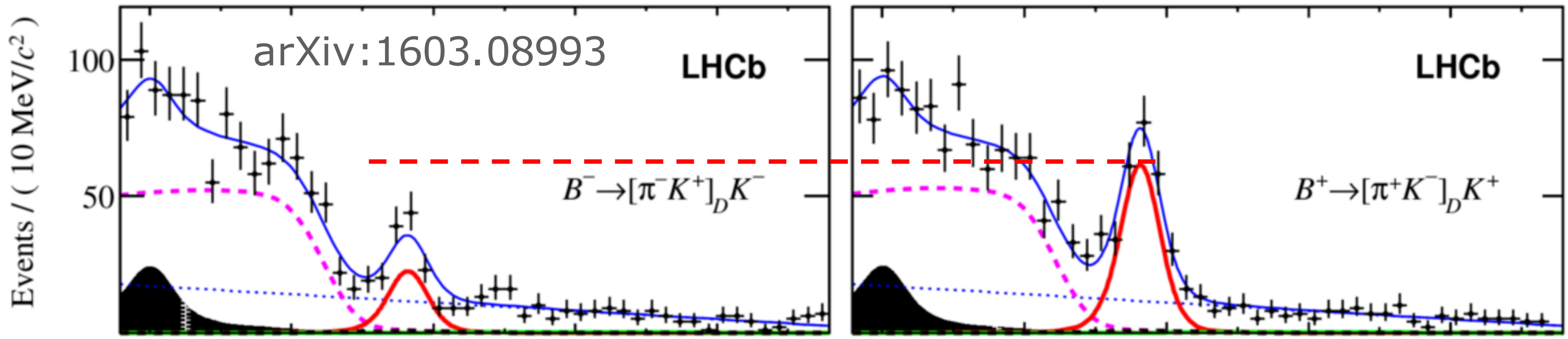
- Measurable in interference between two amplitudes to same final state
  - Sensitivity to γ through final states accessible to both D^0 and $\overline{D}^0$ leading to interference



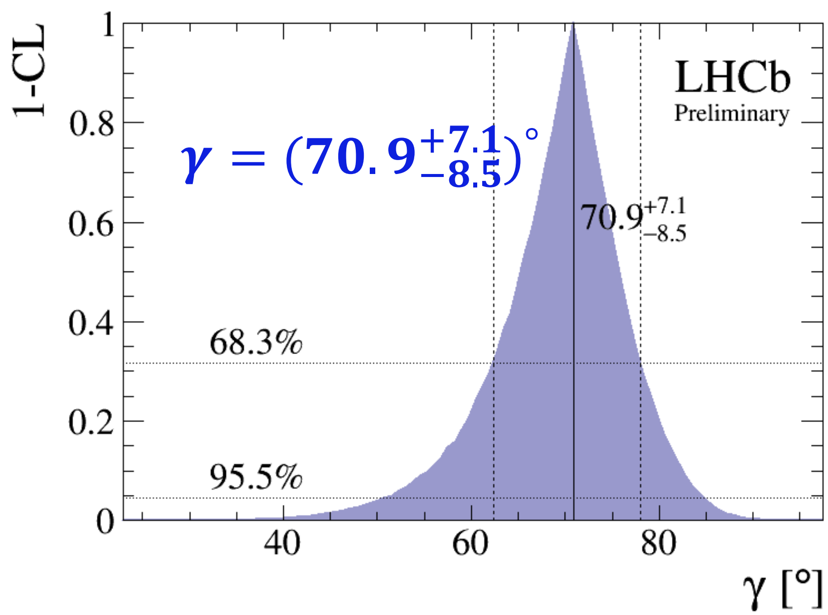
- Small theory uncertainty on γ from tree-level decays is crucial to identify NP
- Combining several independent decay modes is key to achieve ultimate precision

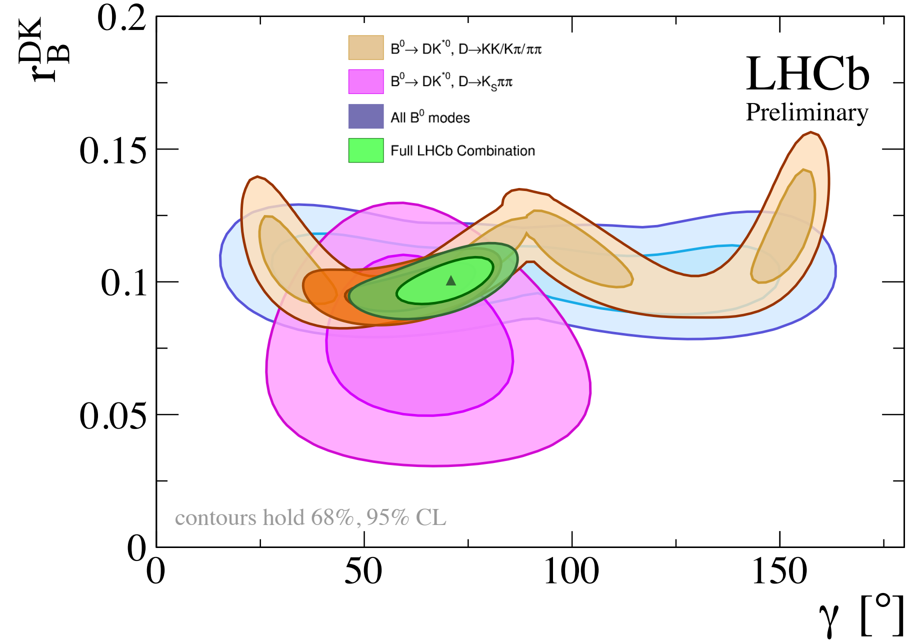
γ from trees: Results

- New precise *CPV* measurements in very rare (BR~10^{-7}) channels



- When combined with LHCb results from similar studies in B→DK allows for the world's most precise measurement of the angle γ

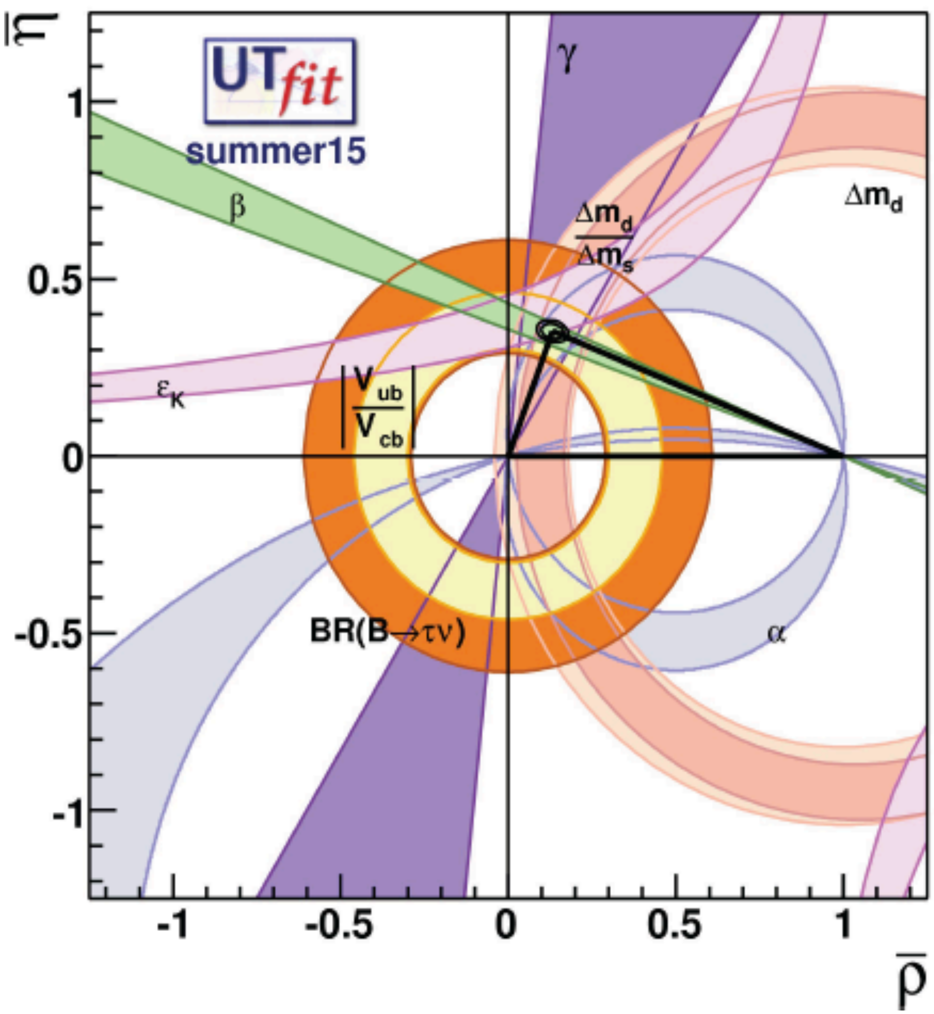




LHCb-CONF-2016-001

- Excellent progress on the road to ~1° precision with LHCb upgrade

Experimental success of CKM description

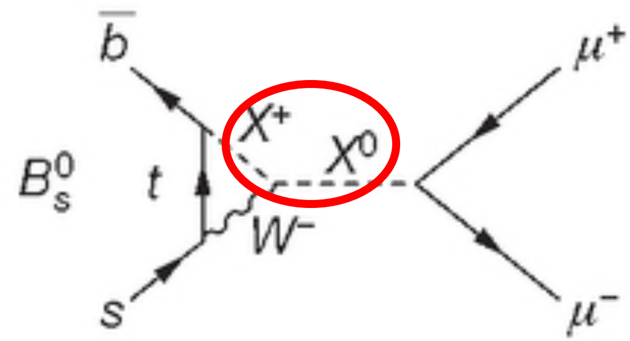


- Excellent overall consistency with the CKM paradigm
- The CKM mechanism is obviously at work at ~O(20%) but there is still room for NP (e.g. new sources of CPV in quark sector)
- Moving to the (high) precision era to look for signs of non-SM physics

Rare Decays

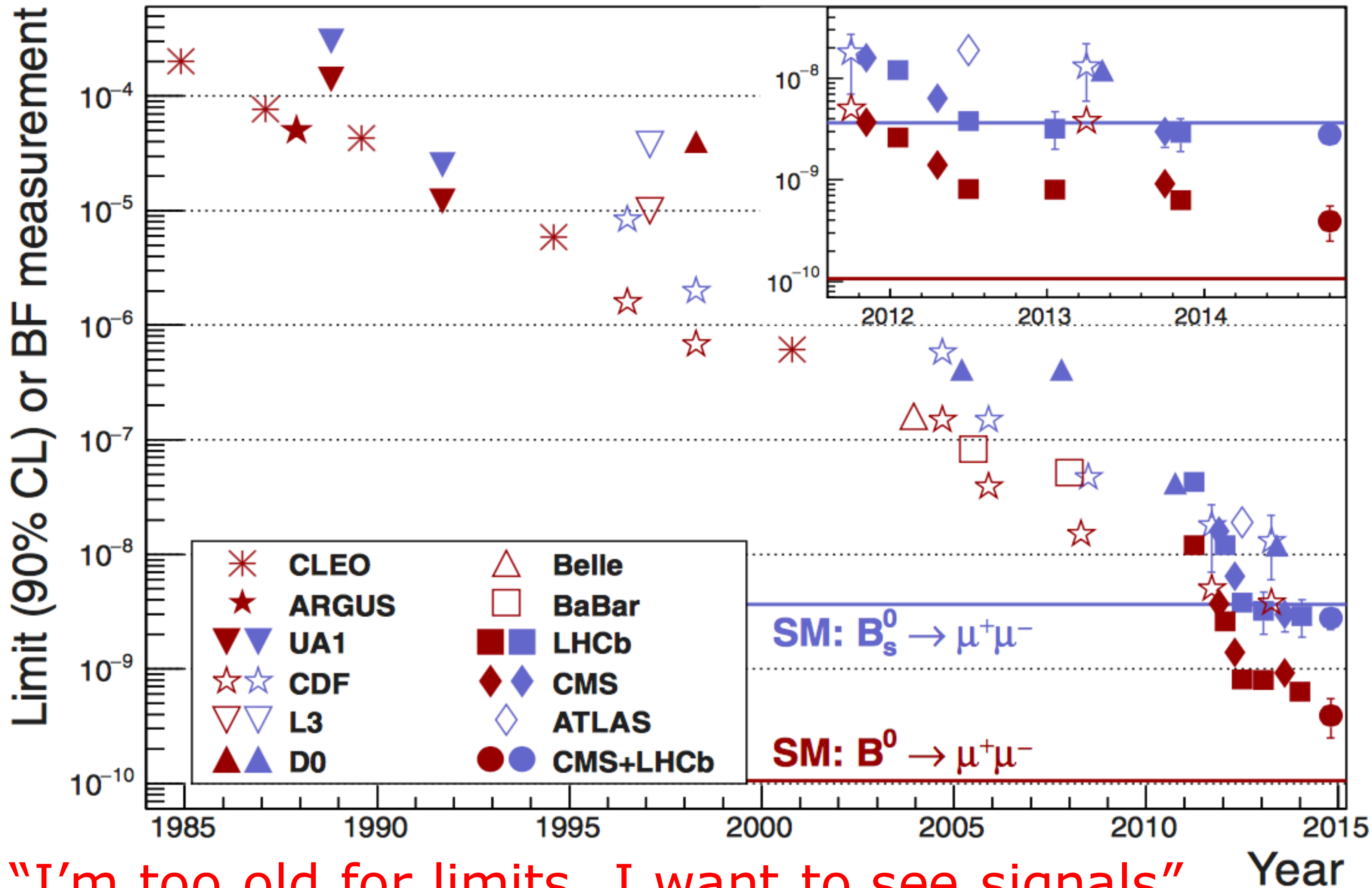
One of the milestones of flavour program: $B_{d,s} \rightarrow \mu^+\mu^-$

- 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 $\sim \tan^6\beta$



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

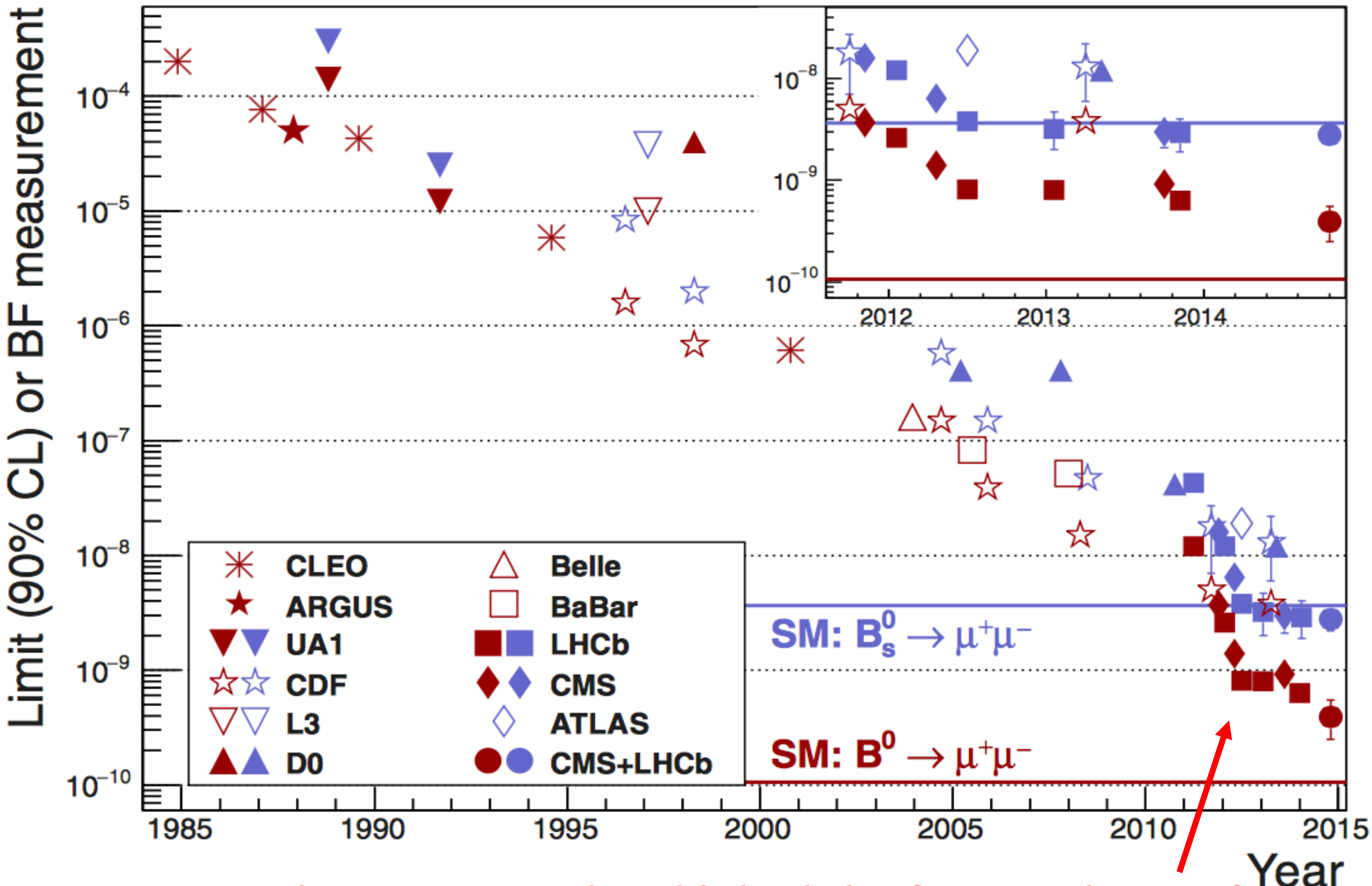
30 years of effort!



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

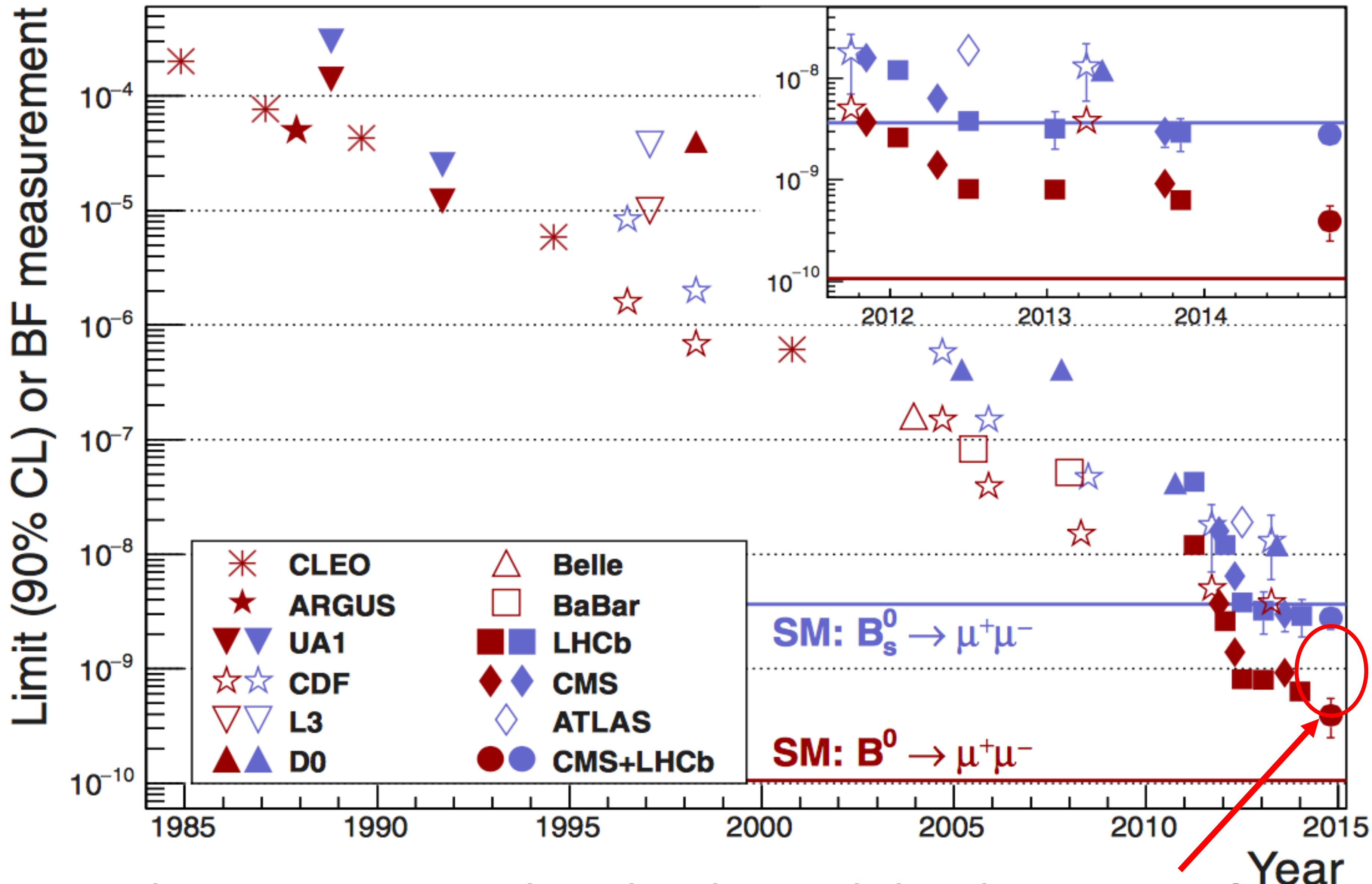
Francis Halzen (EPS '15)

30 years of effort!



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

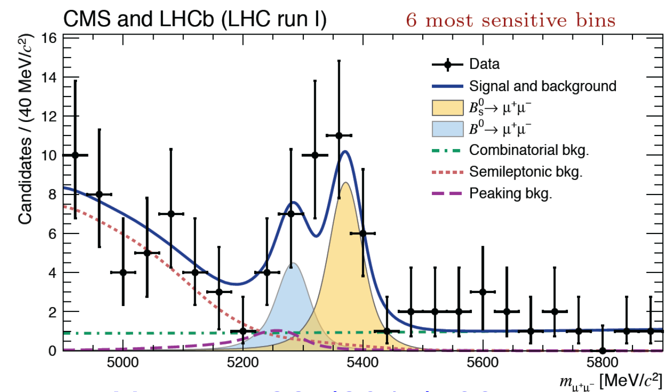
30 years of effort!



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

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

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



Nature 522 (2015) 68

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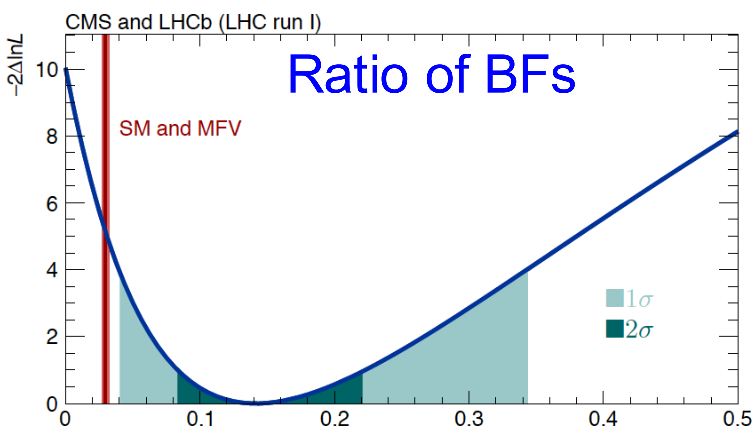
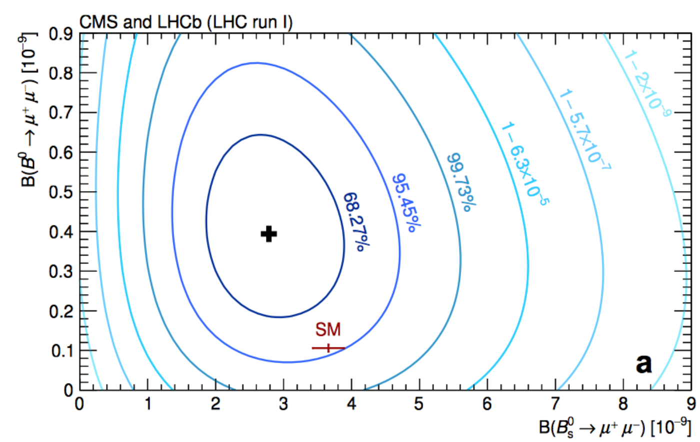
$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \cdot 10^{-9}$$

$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = 3.9^{+1.6}_{-1.4} \cdot 10^{-10}$$

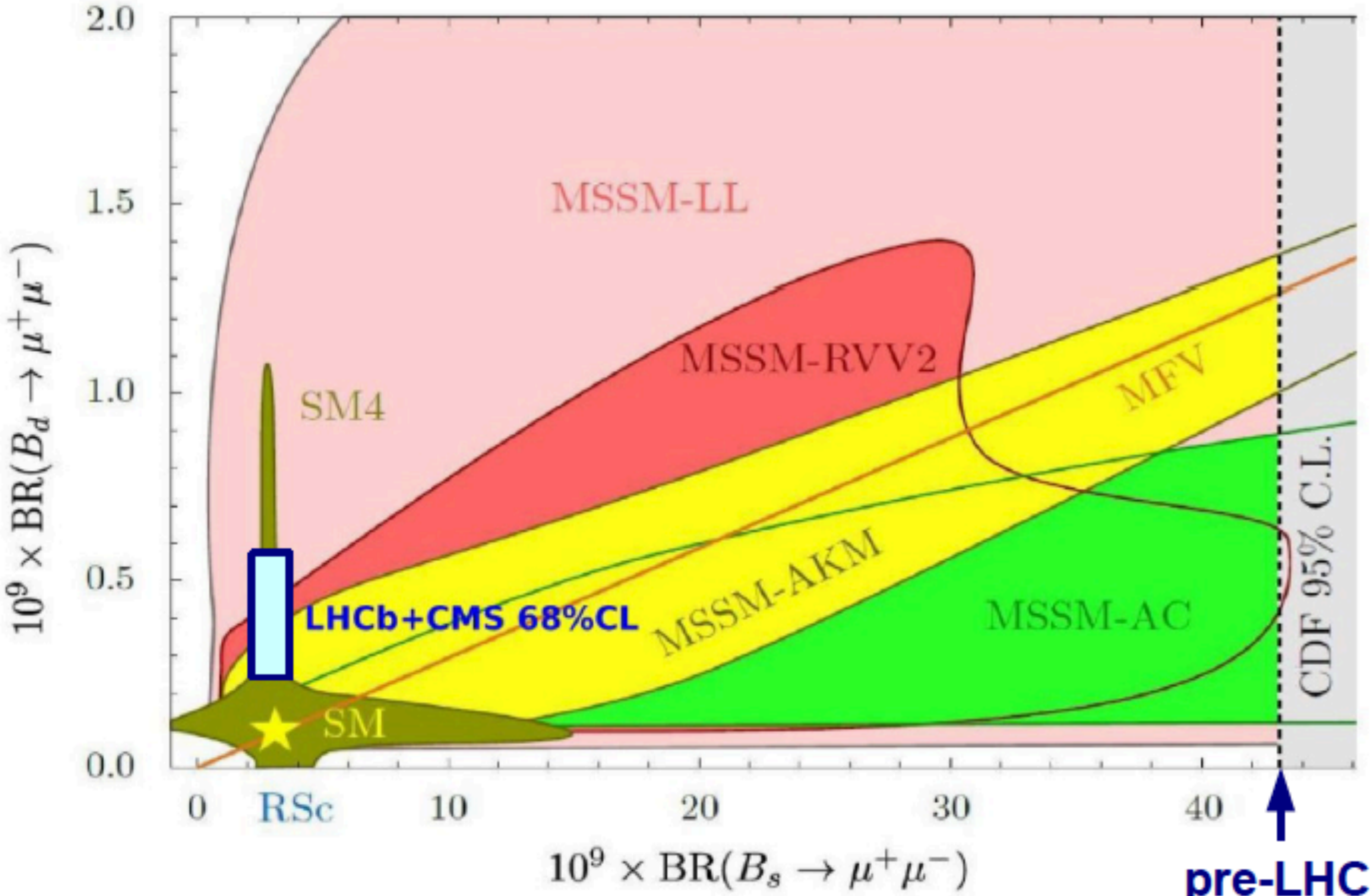




- Ratio of BFs provides powerful discriminations among BSM theories, compatible with SM at ~2σ level

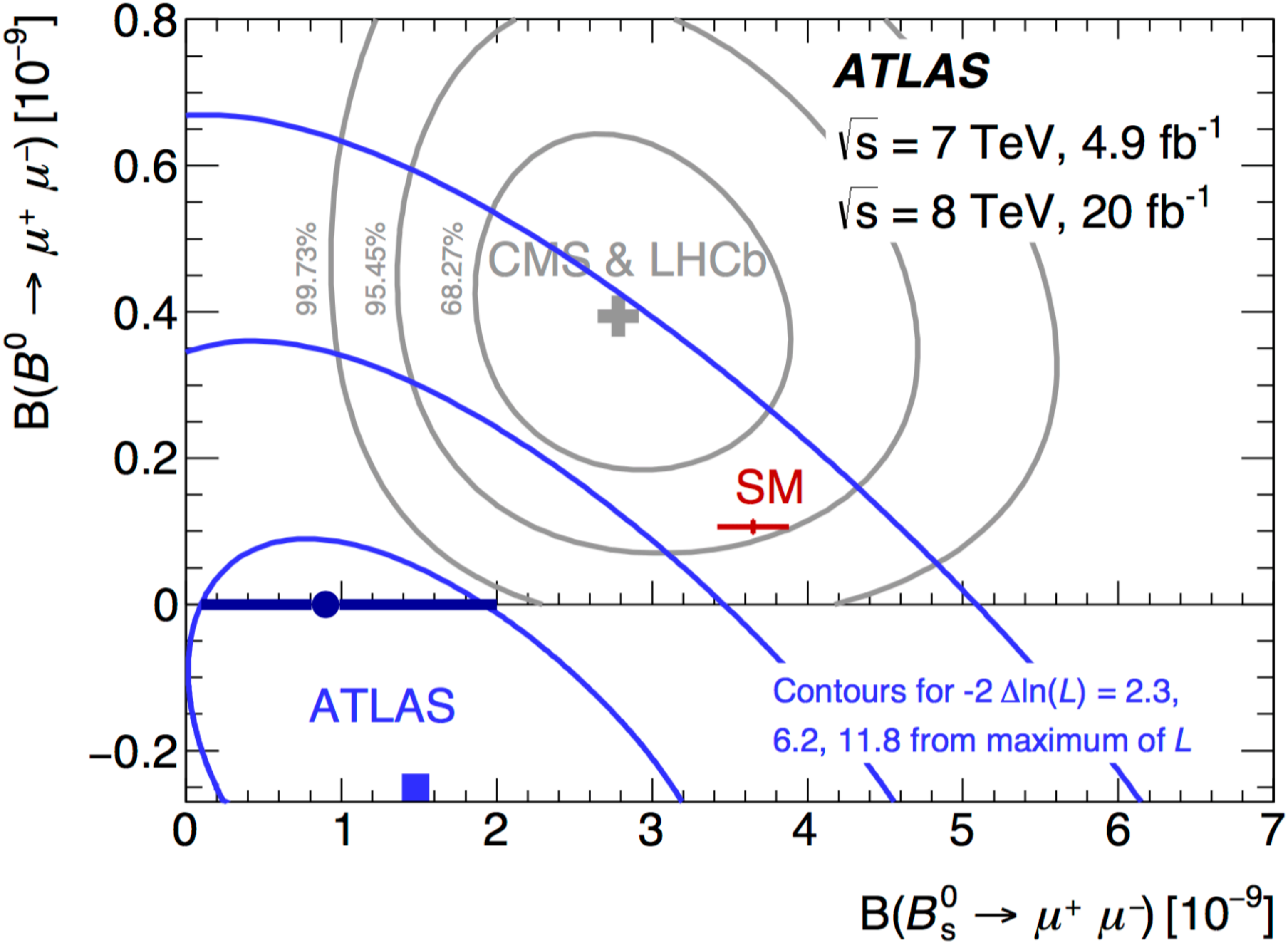
The killer observables!

From D. Straub



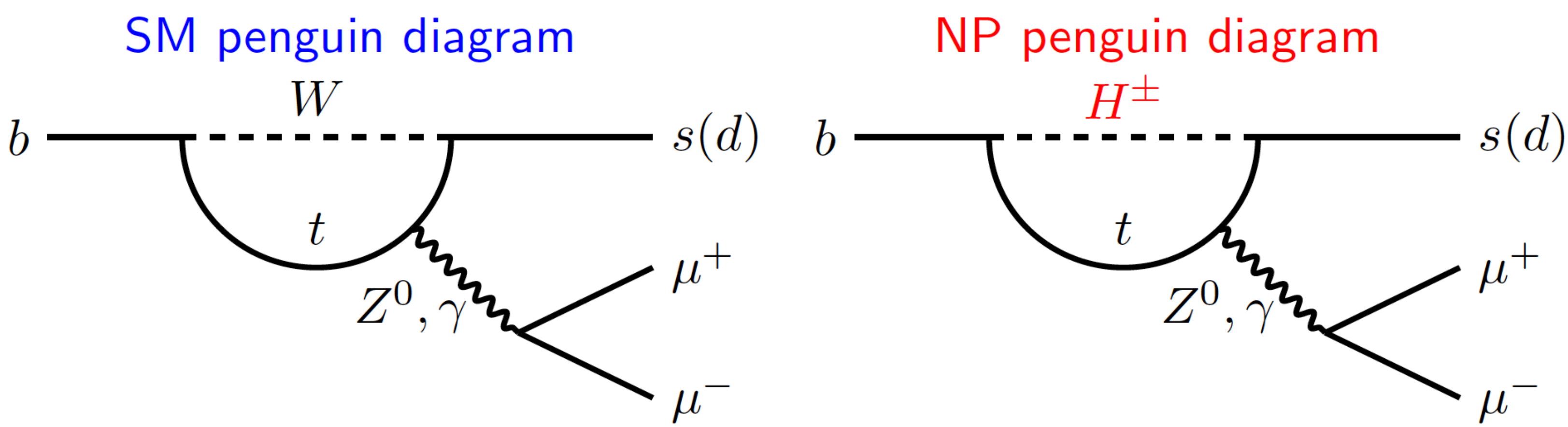
ATLAS entered the game

arXiv:1604.04263



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

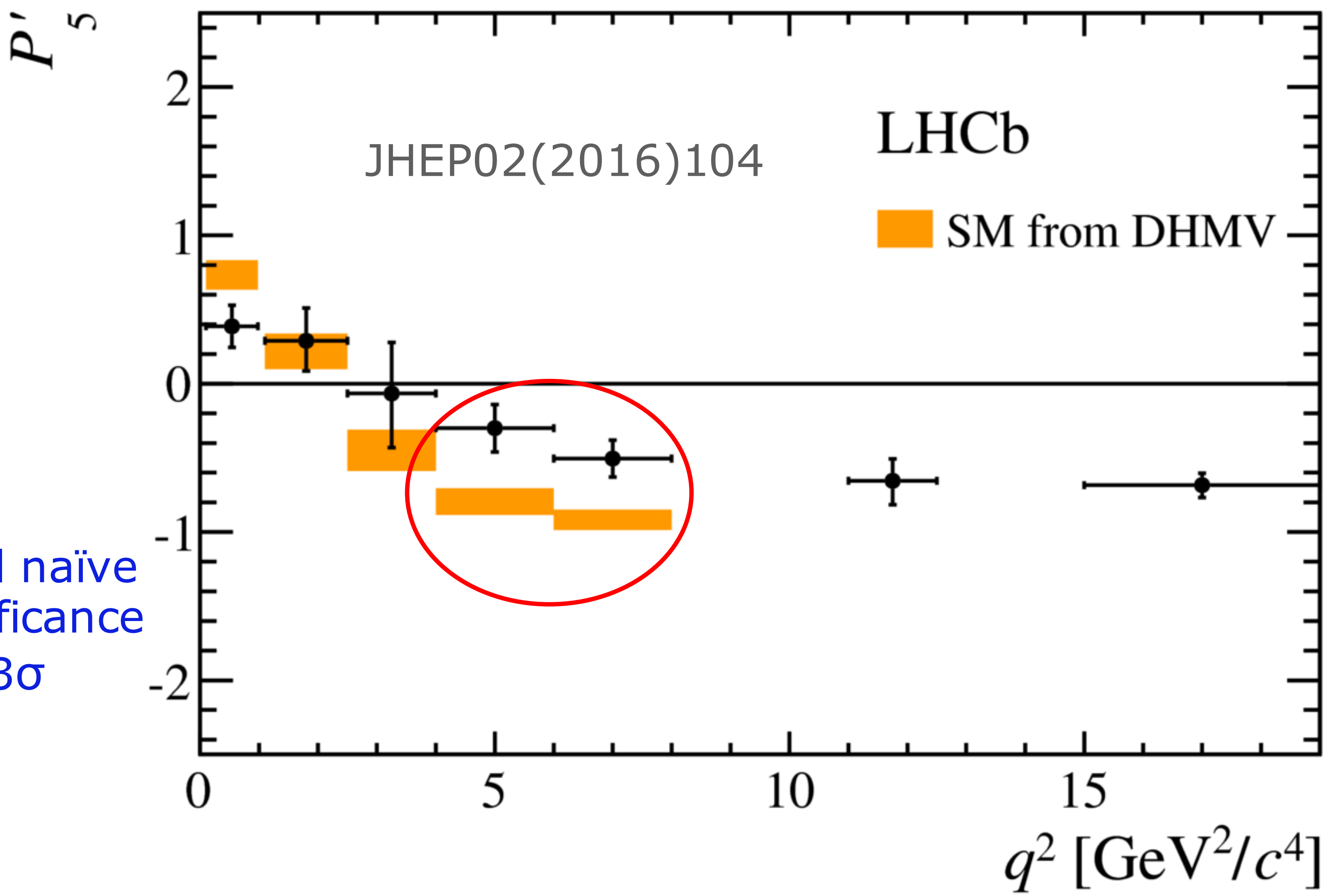
- $B^0 \to K^{*0}\mu^+\mu^-$ is a $b \to s$ transition that only proceeds via loops and boxes
- NP can be competitive with SM processes



- Four final state particles with rich phenomenology, plethora of observables
- Rates, angular distributions and asymmetries sensitive to NP
- A lot of phenomenological work invested in defining observables with "clean" theoretical prediction

Question: how clean?

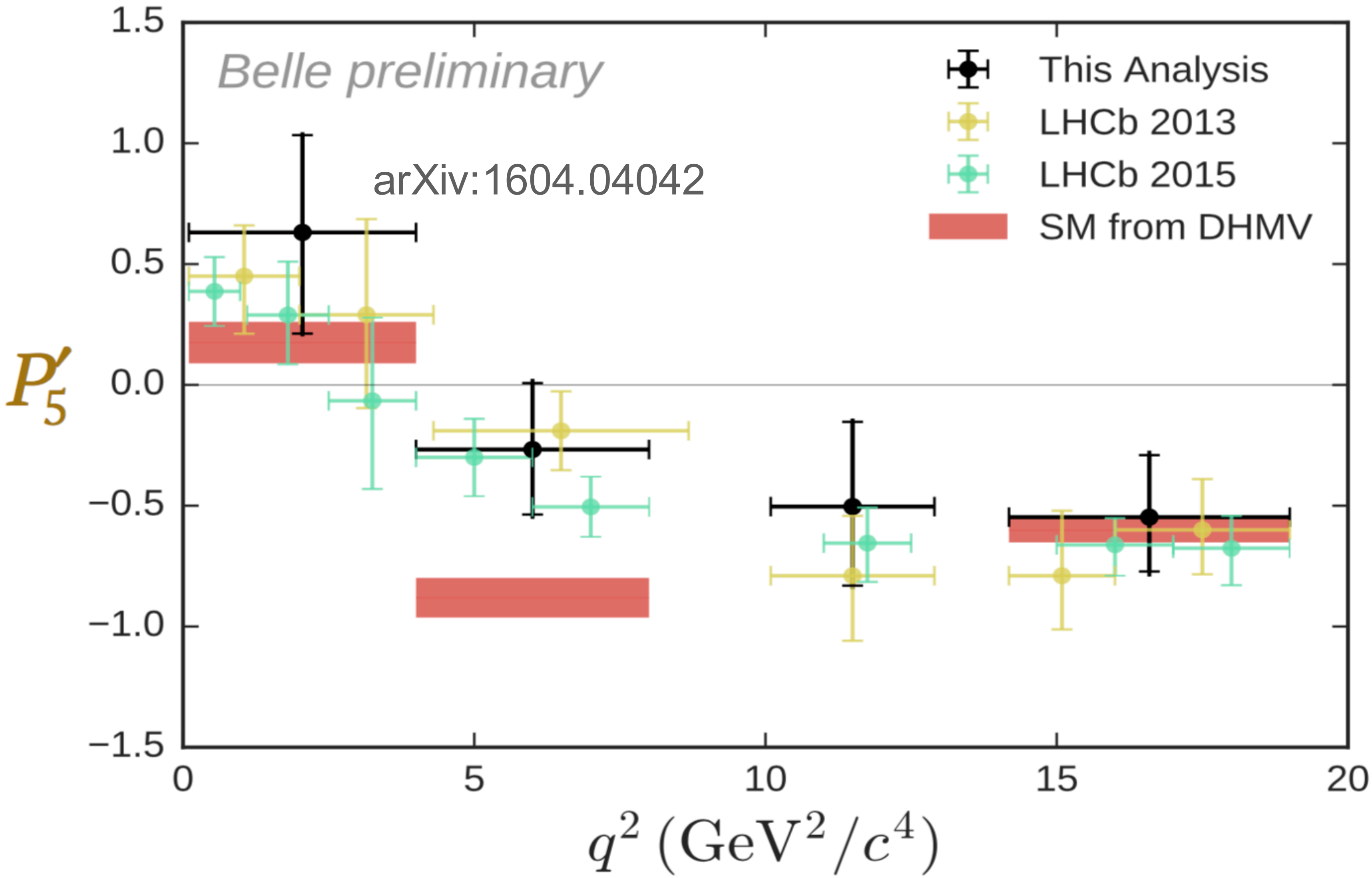
P'_5 anomaly



Local naïve significance of ~3σ

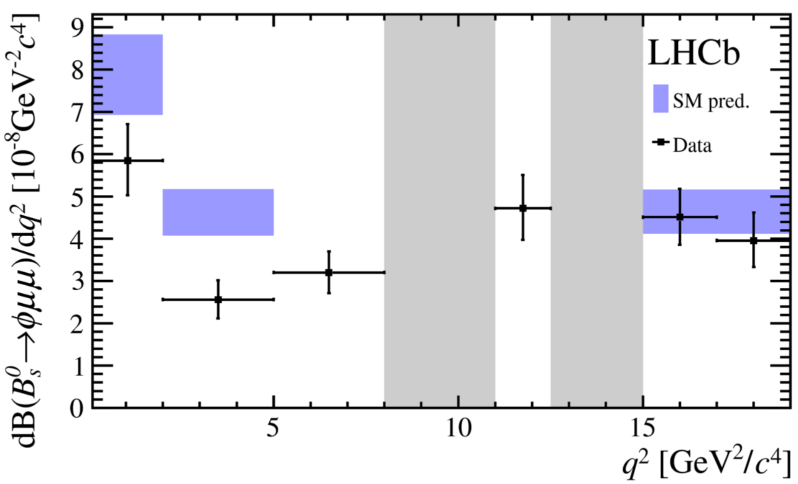
- Is SM prediction less precise than what is claimed?

New analysis from Belle

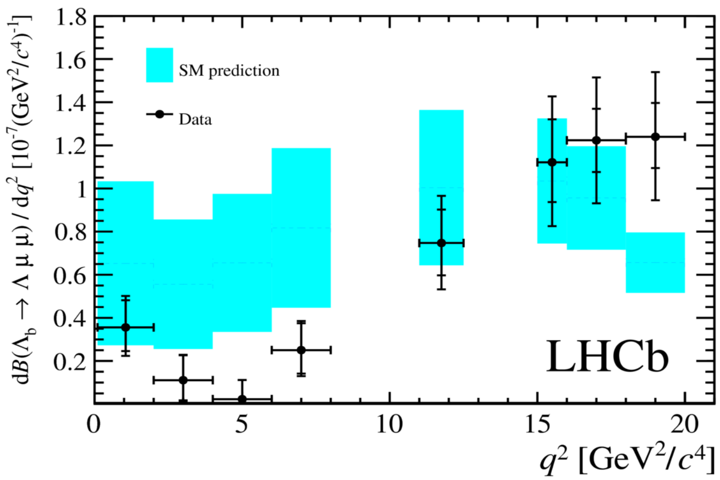


Intriguing set of results in differential branching fractions for b→sμμ transitions

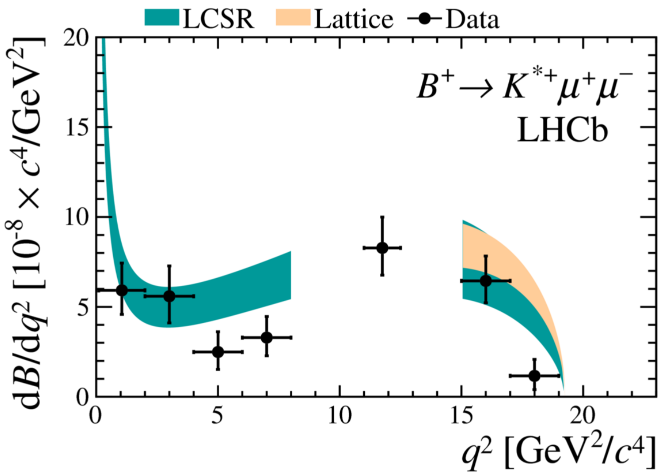
JHEP 09(2015)179

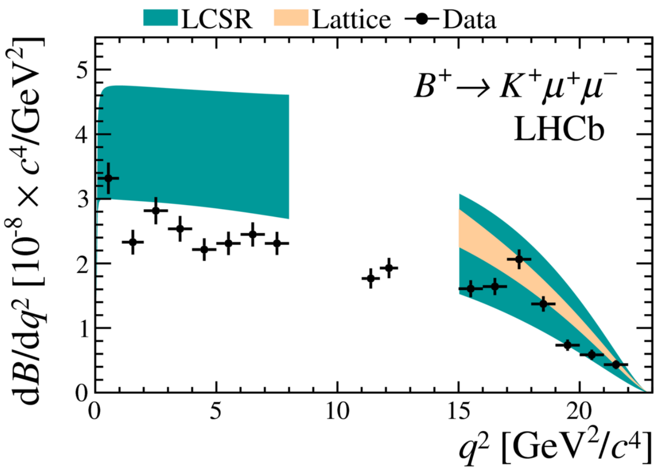


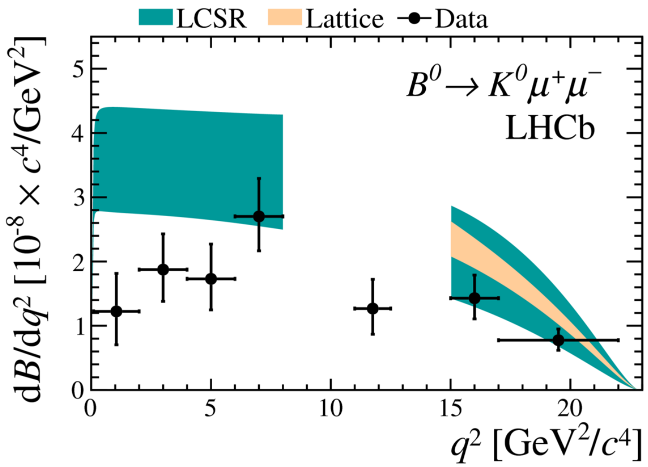
JHEP 06(2015)115



JHEP 06(2014)133







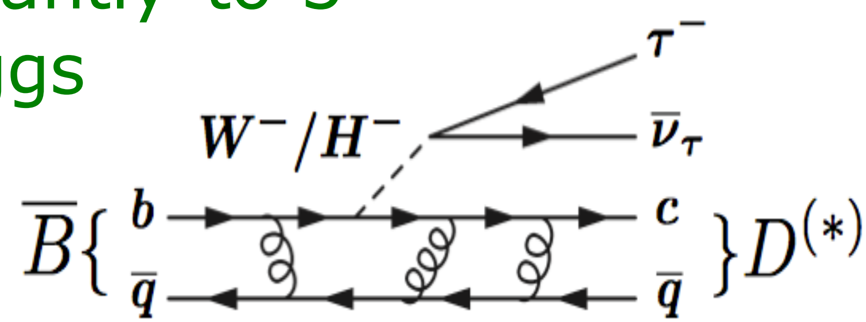

Other
interesting
deviations

Measurement of R(D*)

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

- Theoretically clean
  - In SM only difference is the mass of the lepton
  - $R(D^*)_{SM}=0.252\pm0.003$

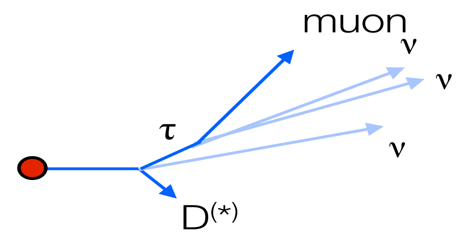
- Sensitive to NP coupled dominantly to 3rd generation, e.g. a charged Higgs

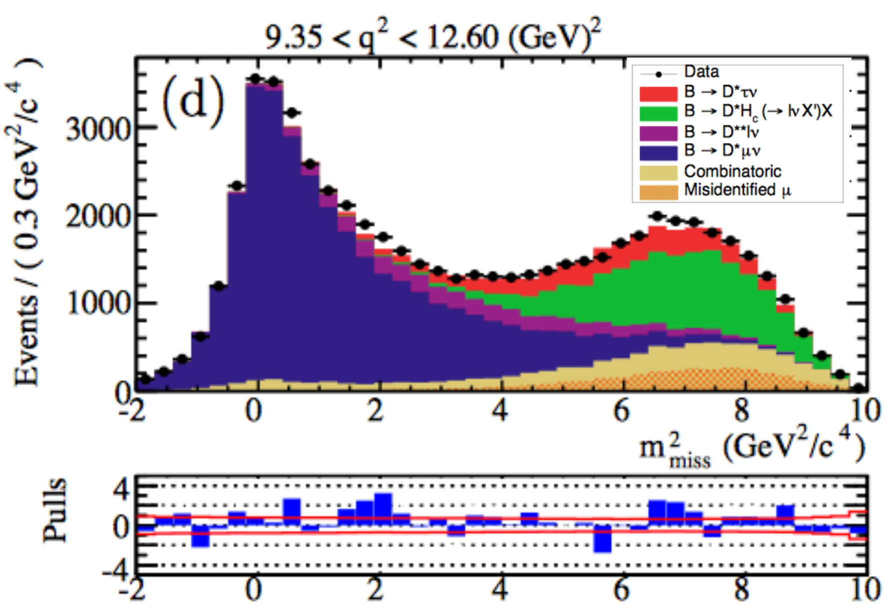


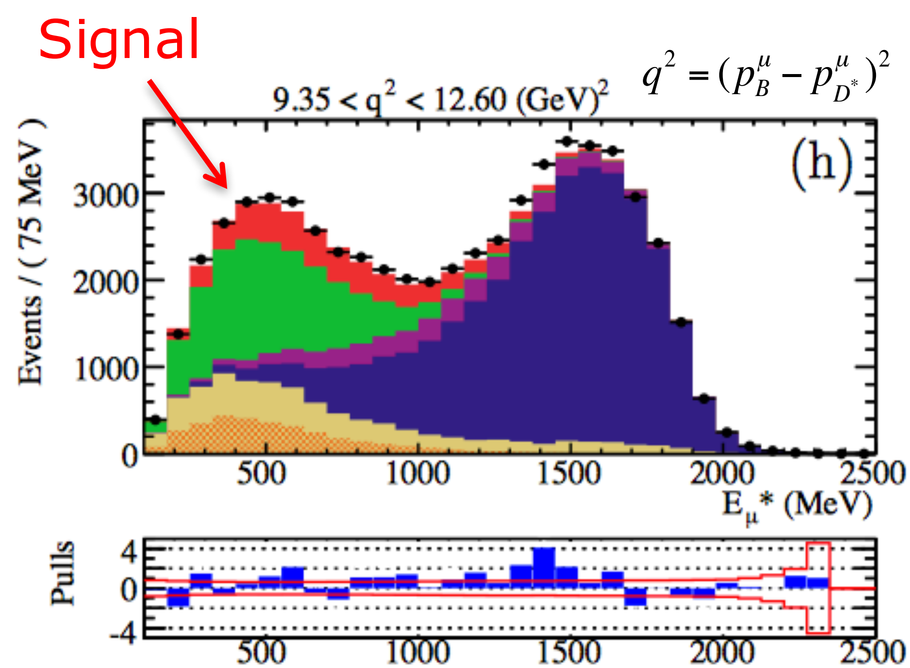
- Heightened interest
  - BaBar: ~3 σ tension (final data set)

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

- 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



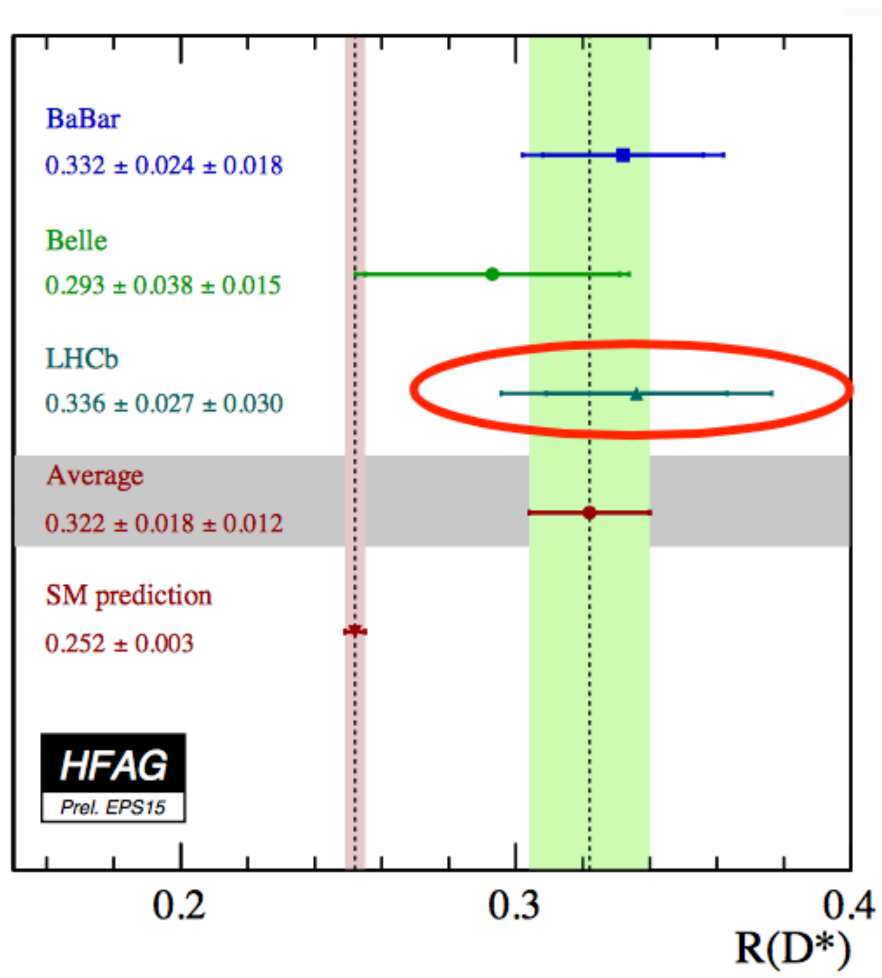




PRL 115 (2015) 111803

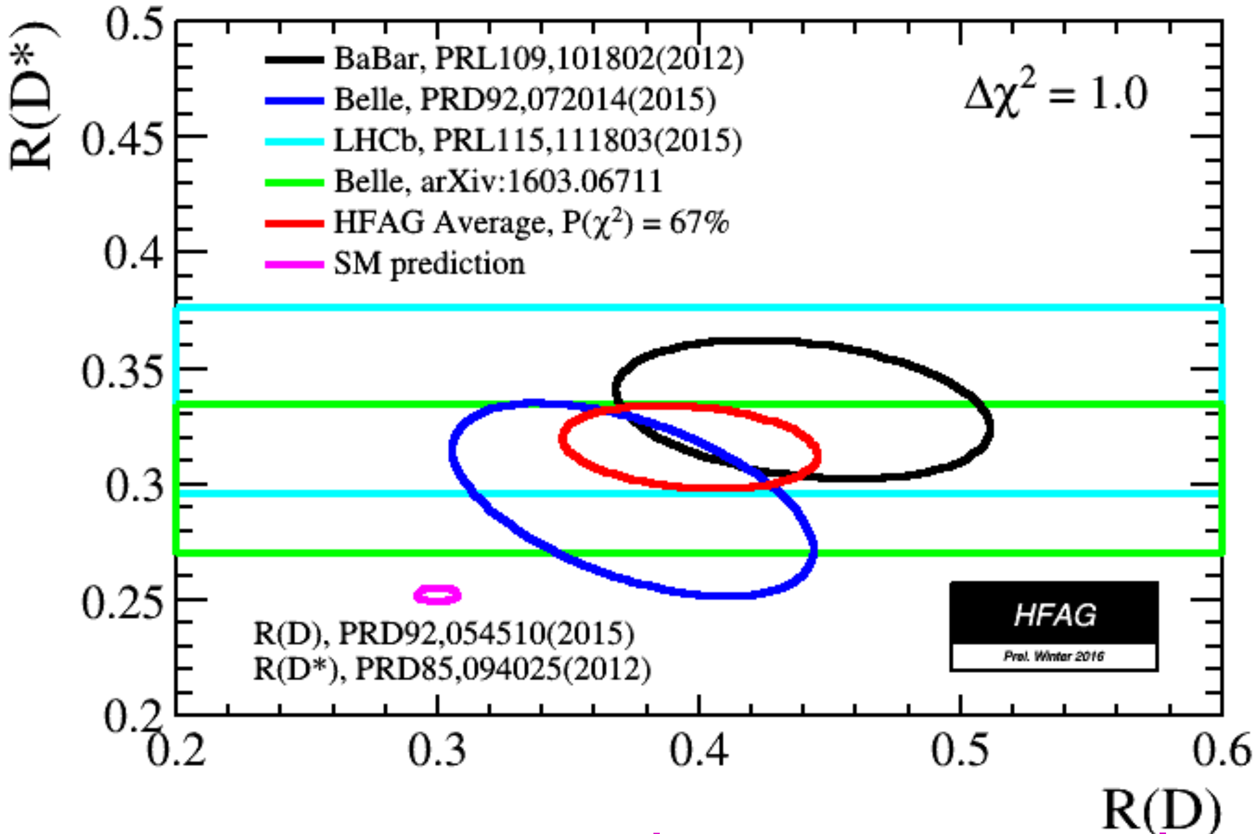
R(D*): Result

- $R(D^*) = 0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst})$
  - 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 ($B_s \to D_s \tau \nu$, $\Lambda_B \to \Lambda_c \tau \nu$)

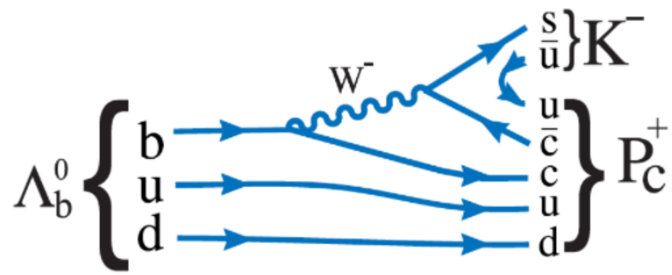

Many results on
spectroscopy

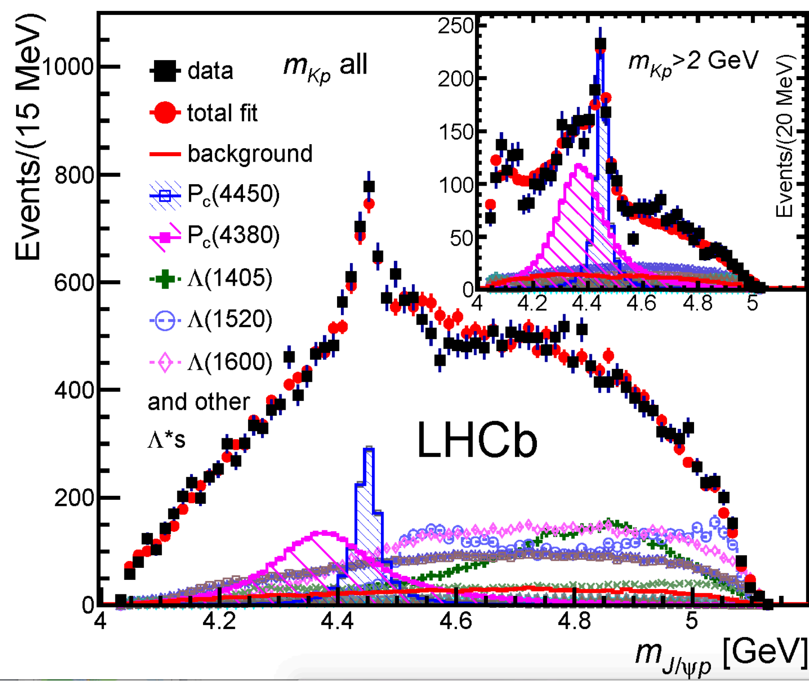
LHCb sees the pentaquark!

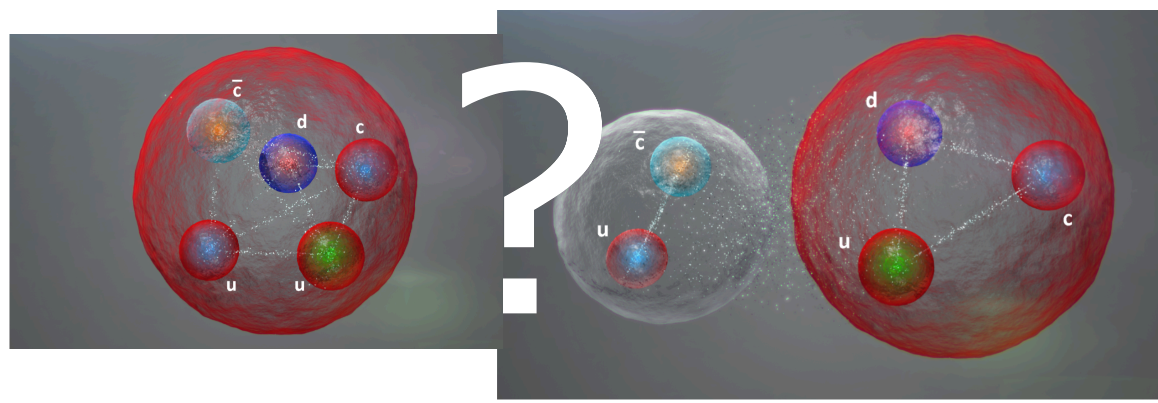
- Two charmonium pentaquark candidates in $\Lambda^0_b \to J/\psi p K^-$ decays! [PRL 115 (2015) 072001]

Mass (MeV)	Width (MeV)
$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$
$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$

$uudc\bar{c}$





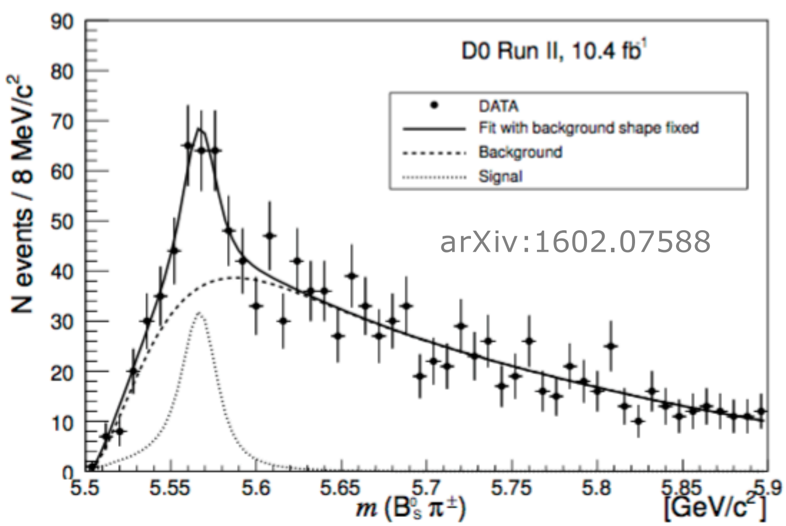


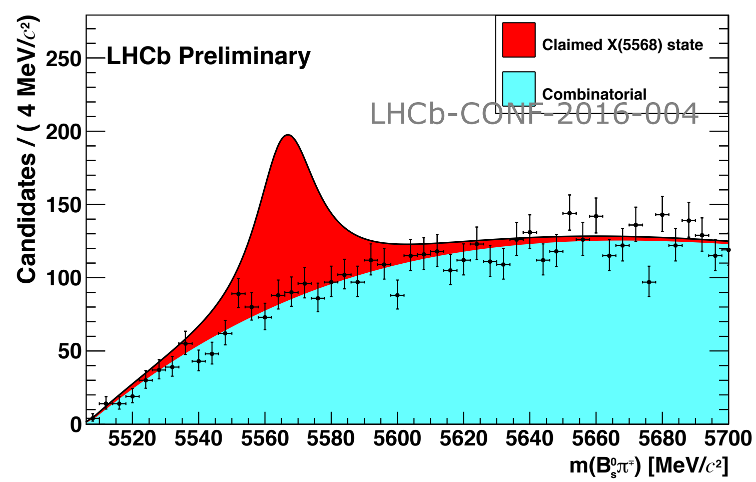
- Result confirmed by model independent study [arXiv:1604.05708]
  - $\Lambda^0_b \to J/\psi p K^-$ decays cannot be explained by $\Lambda^0_b \to J/\psi \Lambda^*$ with $\Lambda^* \to p K^-$

...but does not confirm D0 tetraquark

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

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





- What we should have seen

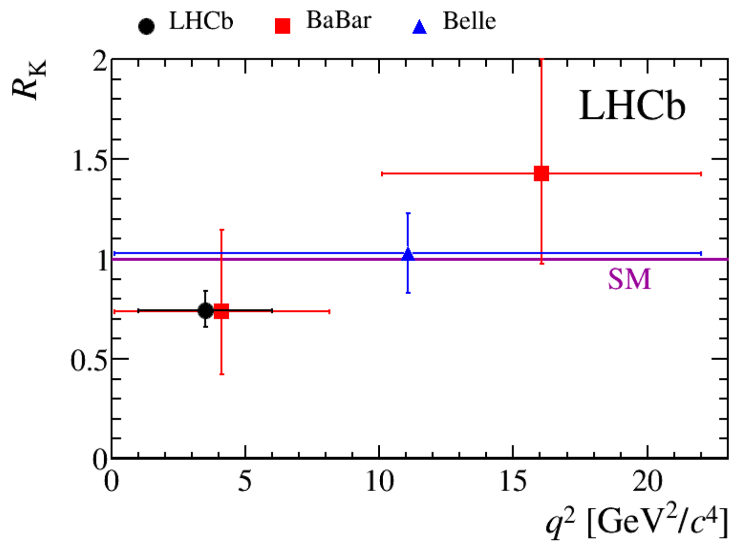
- Existence of X(5568) not confirmed → production upper limits set

Conclusions

- Wealth of LHCb results with the first 3/fb at "CERN's flavour factory" (and also from Run 2!)
  - Everything worked beautifully (luminosity leveling, 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, heavy-ions,…)
  - 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)

Reminder: $R_K = B(B^+ \to K^+\mu^+\mu^-)/B(B^+ \to K^+e^+e^-)$

- Test of lepton universality : $R_K \sim 1$ 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: $B^0 \to K^{*0}\, l^+ l^-$, $B_s \to \phi\, l^+ l^-$, $\Lambda_B \to \Lambda\, l^+ l^-$