Heavy flavour physics at the LHC

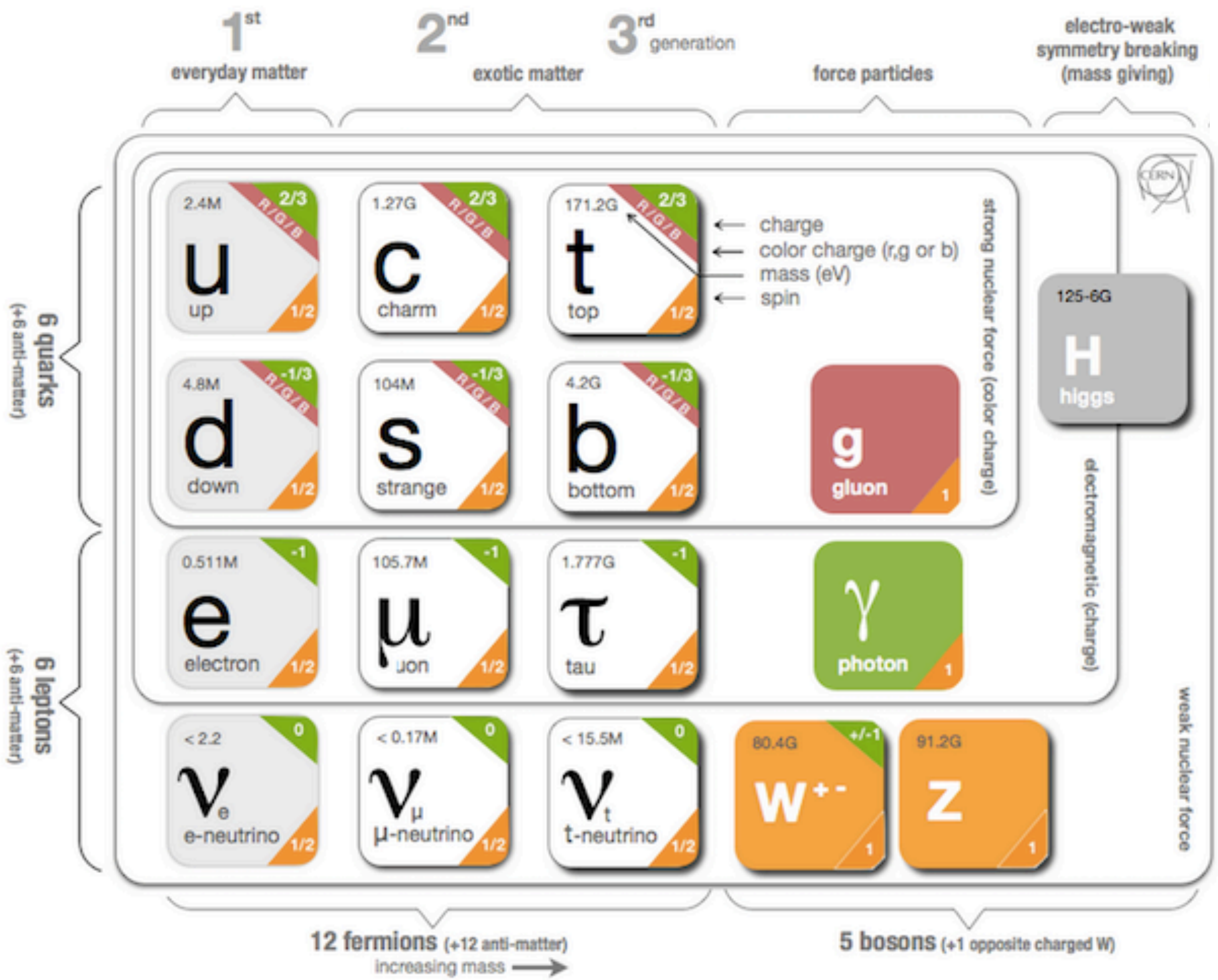
Sneha Malde

University of Oxford

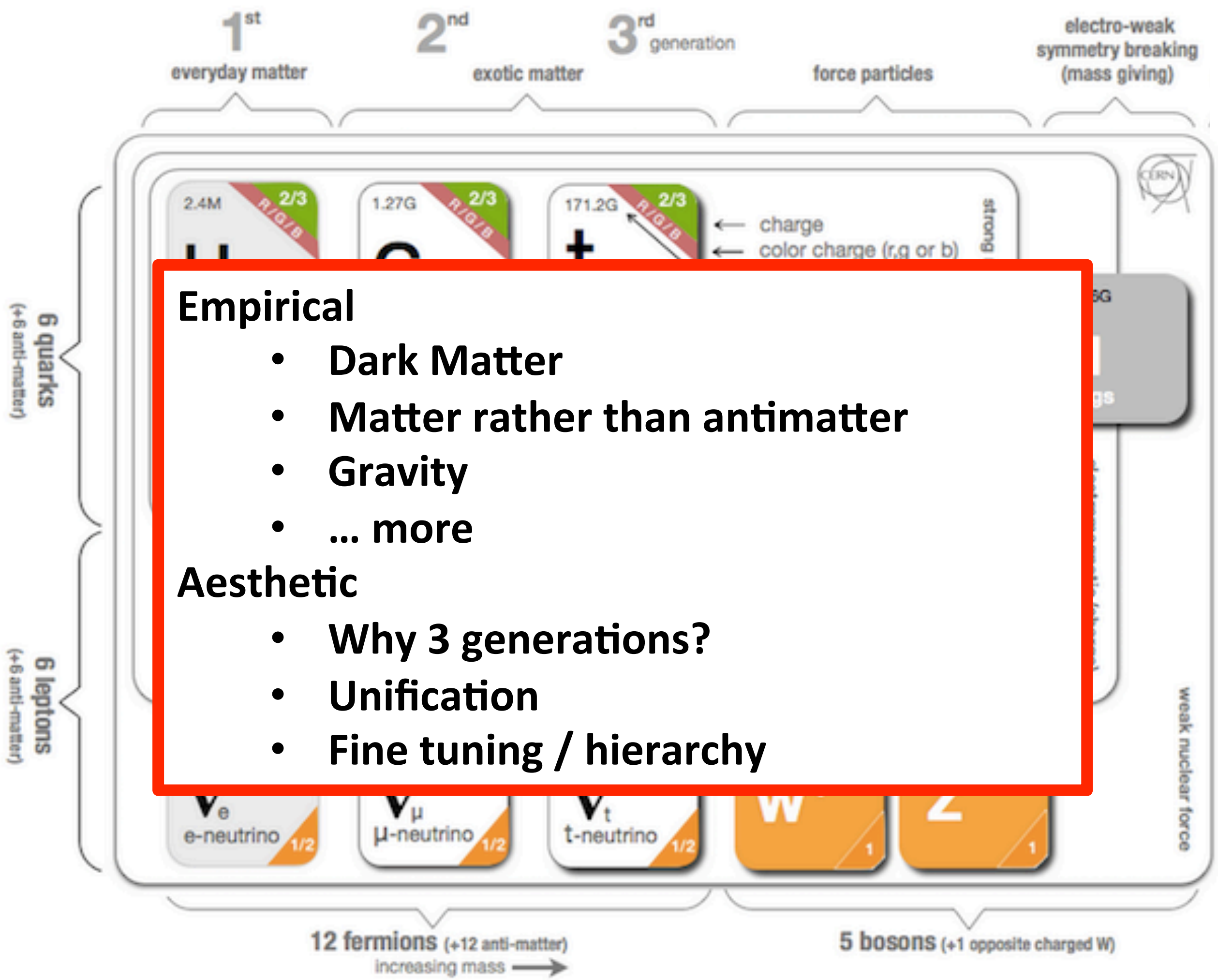
THE ROYAL SOCIETY

erc European Research Council

The Standard Model



The Standard Model



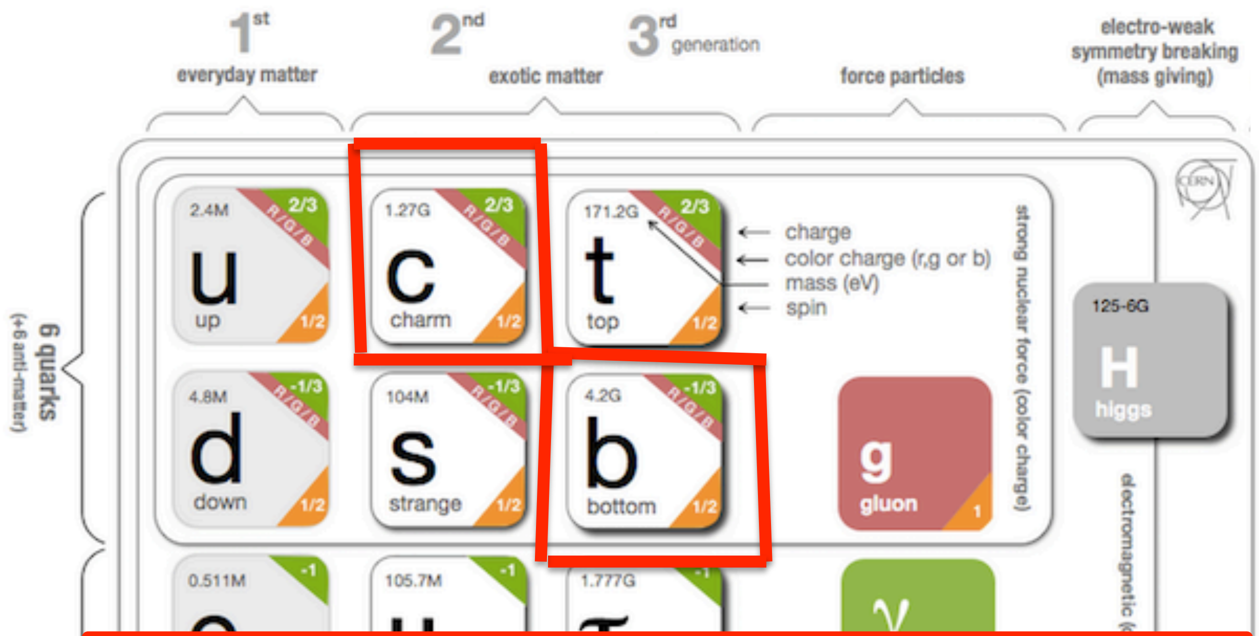
Empirical

- **Dark Matter**
- **Matter rather than antimatter**
- **Gravity**
- **… more**

Aesthetic

- **Why 3 generations?**
- **Unification**
- **Fine tuning / hierarchy**

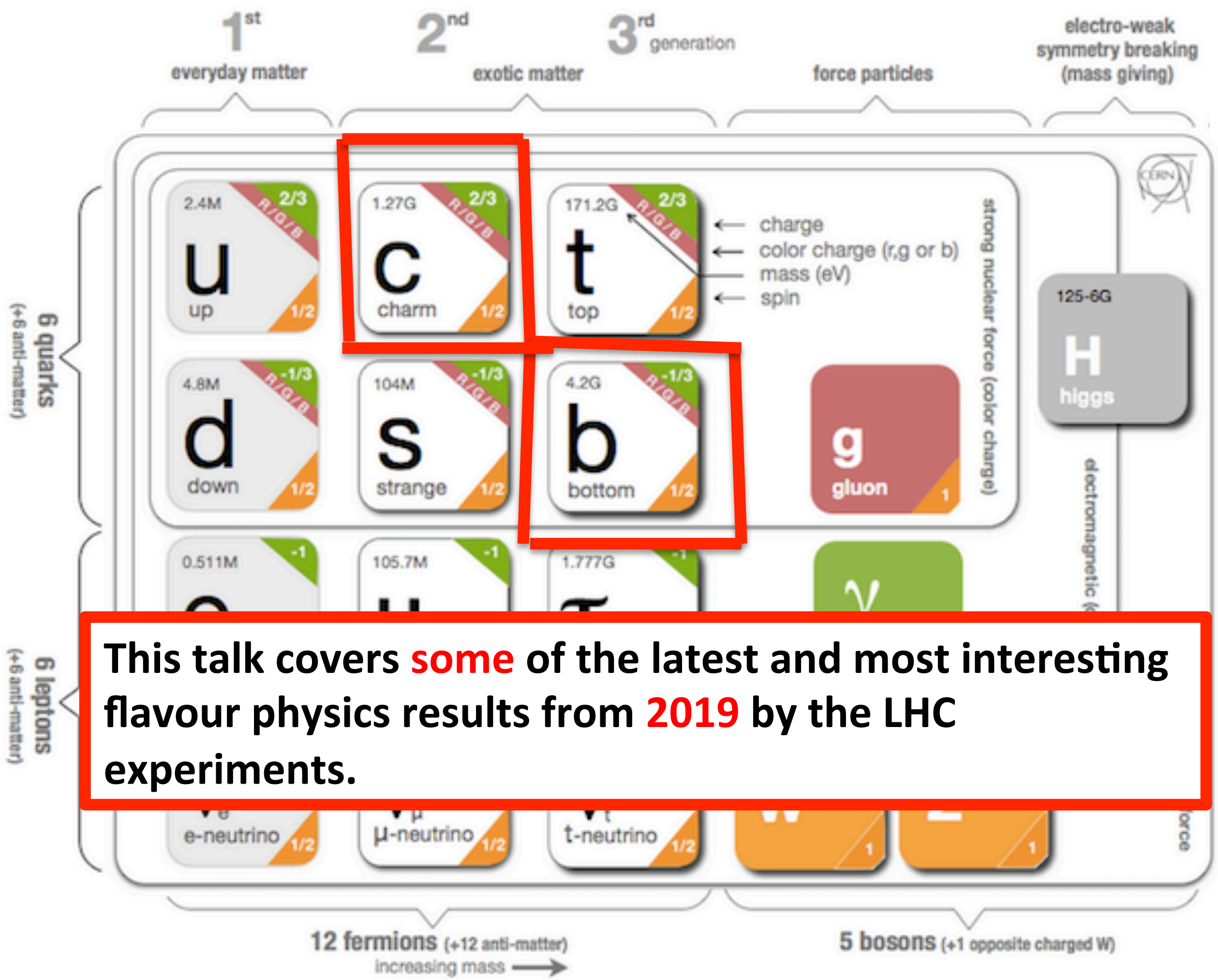
The Standard Model



Study of hadrons containing beauty and charm gives

- **Insights into the strong force**
- **Insights into the weak force**
- **Constraints on beyond the SM physics**
- **Observation of beyond the SM physics?**

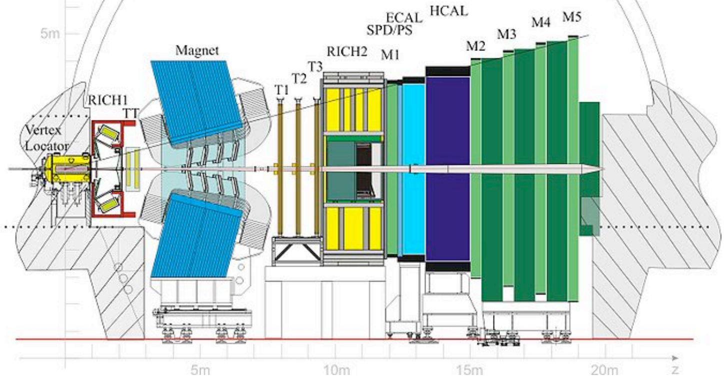
The Standard Model

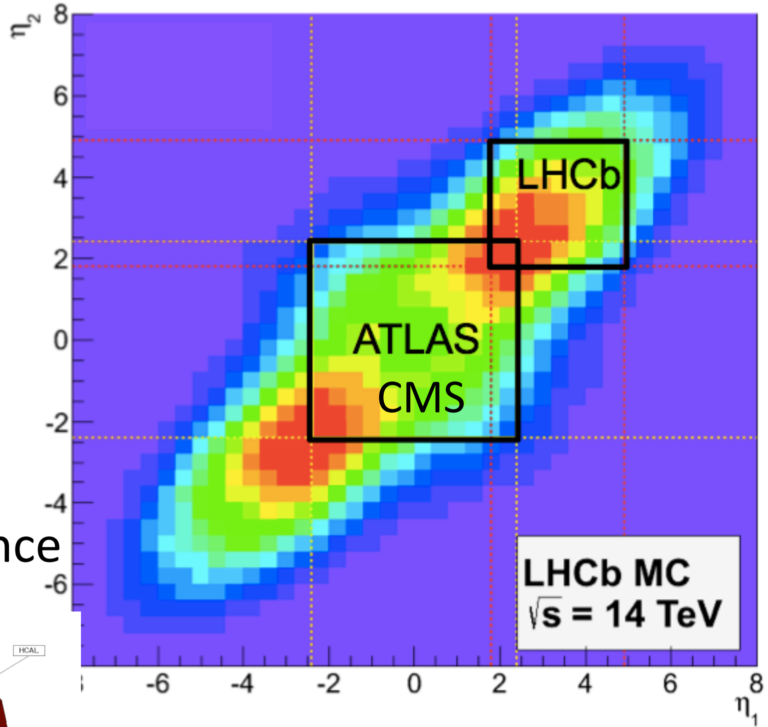


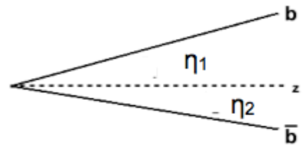
This talk covers some of the latest and most interesting flavour physics results from 2019 by the LHC experiments.

Flavour physics at the LHC

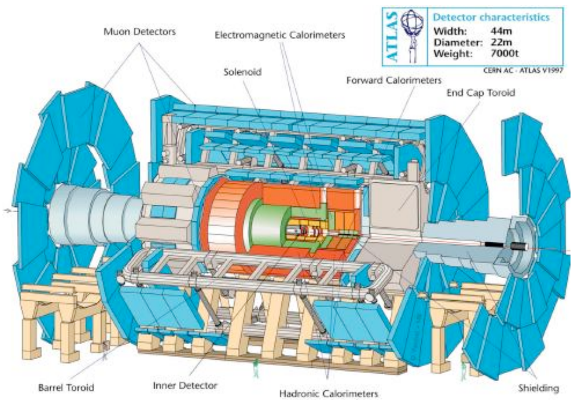
LHCb – A forward experiment optimised towards flavour physics

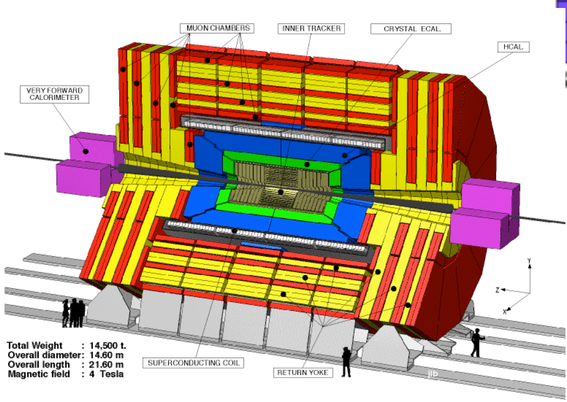




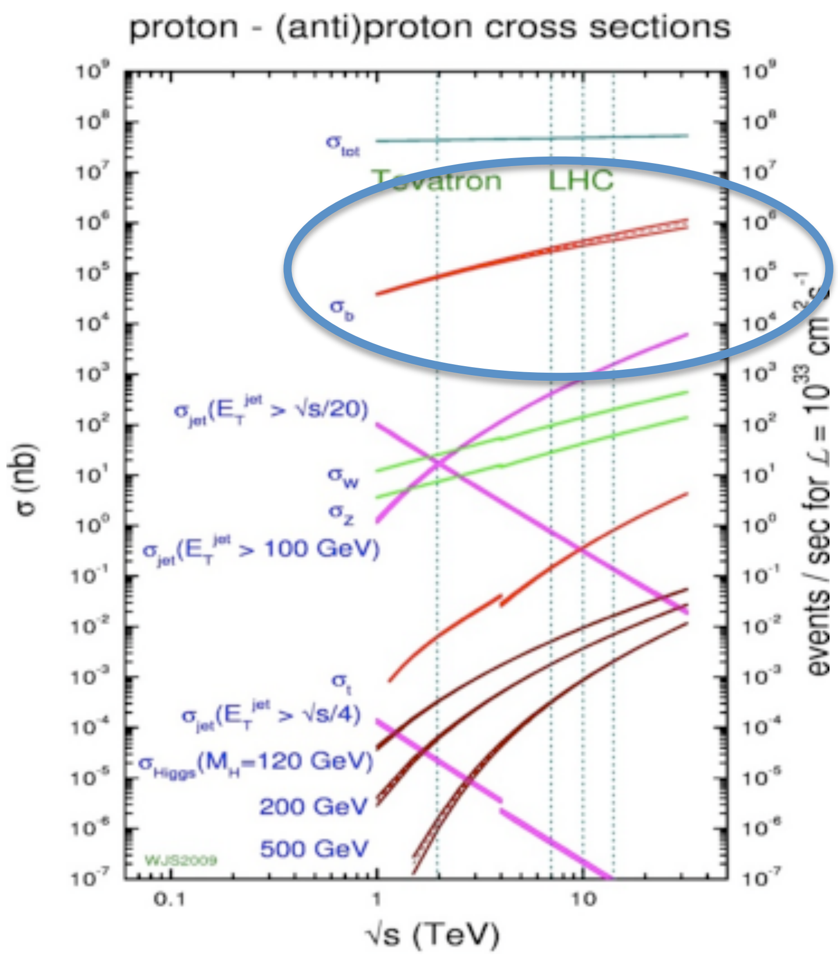


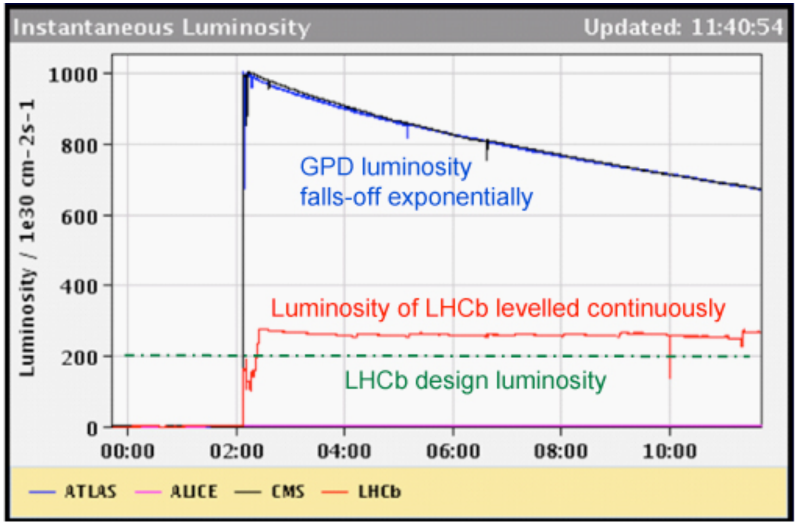
ATLAS & CMS – general purpose, central acceptance





Cross sections and triggers





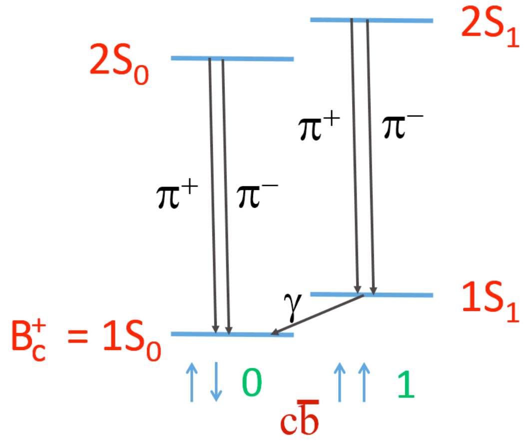
Beauty and charm are produced in abundance

GPDs : Mainly di-muon

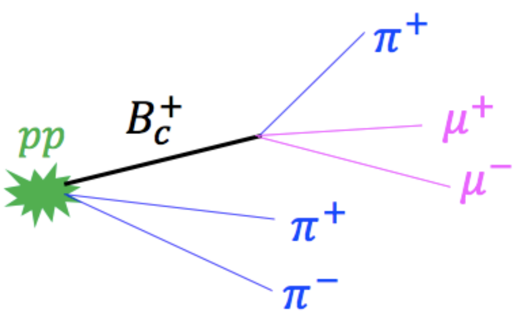
LHCb : array of different triggers

B_c spectroscopy

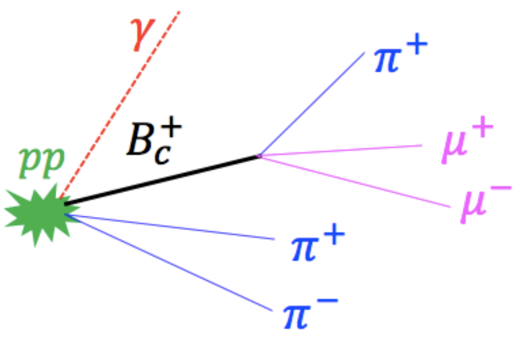
- Unique system of two heavy quarks in a bound state
- Production rate is low compared to other B mesons – lots to discover
- Allows tests of non-perturbative QCD.
- Search for excited states of the B_c studies states similar to bottomonium, charmonium

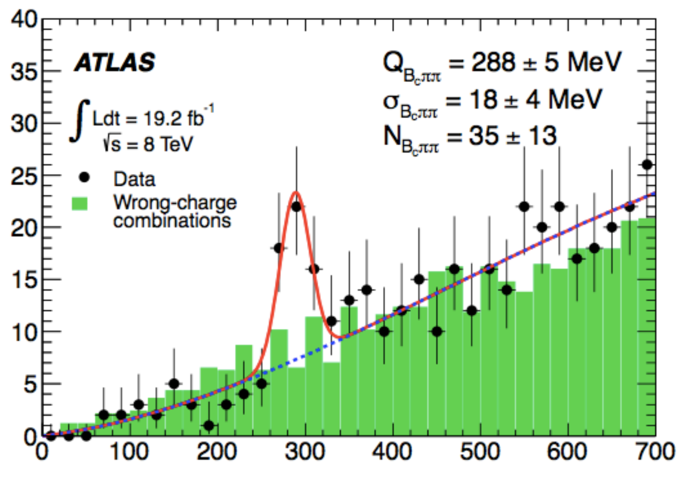


$B_c(2S)^+ \to B_c^+\pi^+\pi^-$



$B_c^*(2S)^+ \to B_c^{*+}(\to B_c^+\gamma)\pi^+$



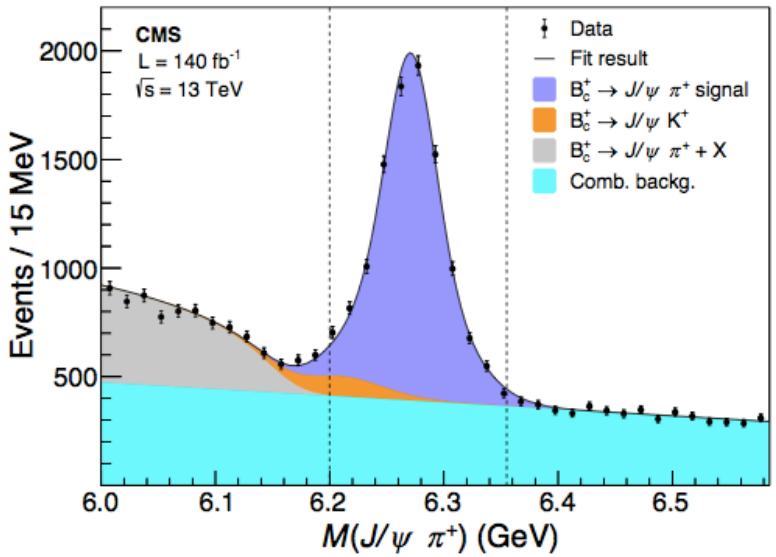


[PRL 113 (2014) 12004]

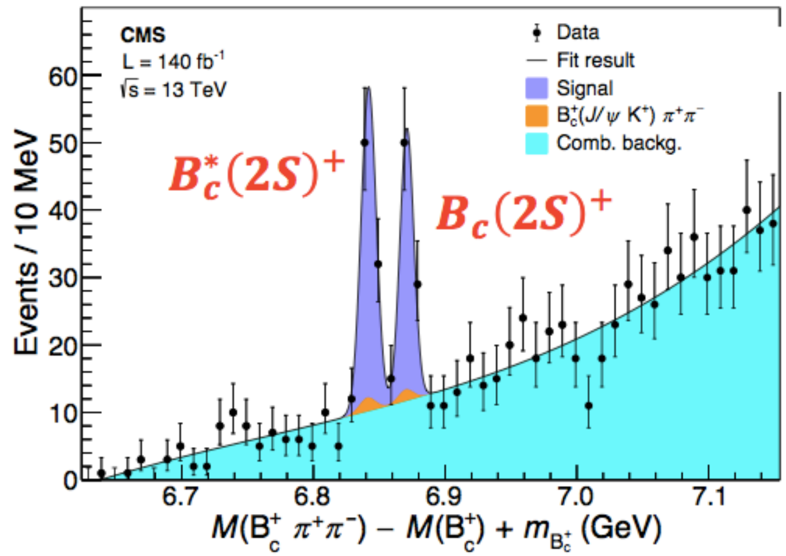
A peak was observed by ATLAS in 2014, but which state was it ?

$B_c^{(*)}(2S)^+$ at CMS

- CMS uses full Run 2 dataset 140 pb^{-1}
- Topological selection criteria key to reducing backgrounds
- $B_c^*(2S)^+$ and $B_c(2S)^+$ resolved for the first time > 5 σ
- $B_c^*(2S)^+$ lower in reconstructed mass due to missing photon



$7495 \pm 225\ B_c^+$ signals

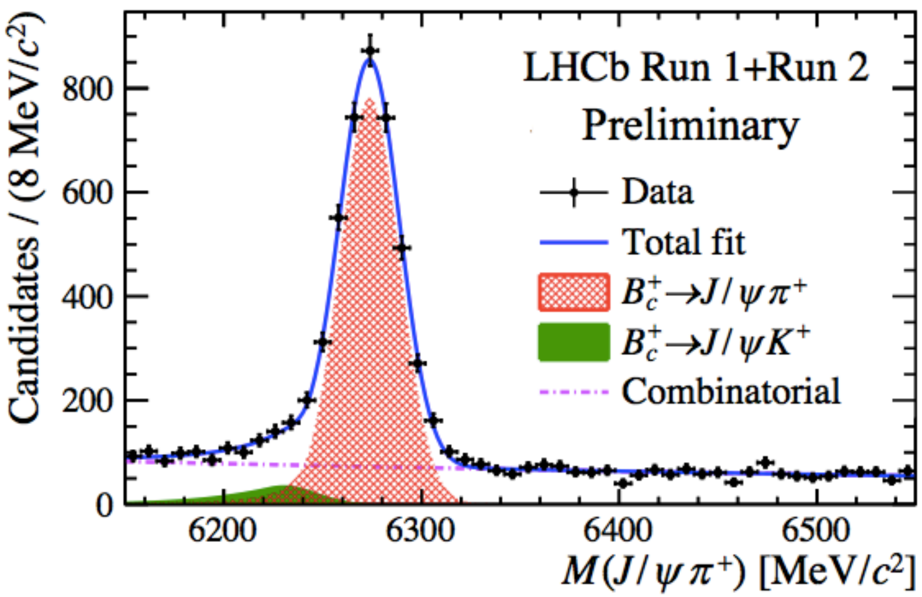


$66 \pm 10\ B_c^*(2S)^+$; $51 \pm 10\ B_c(2S)^+$

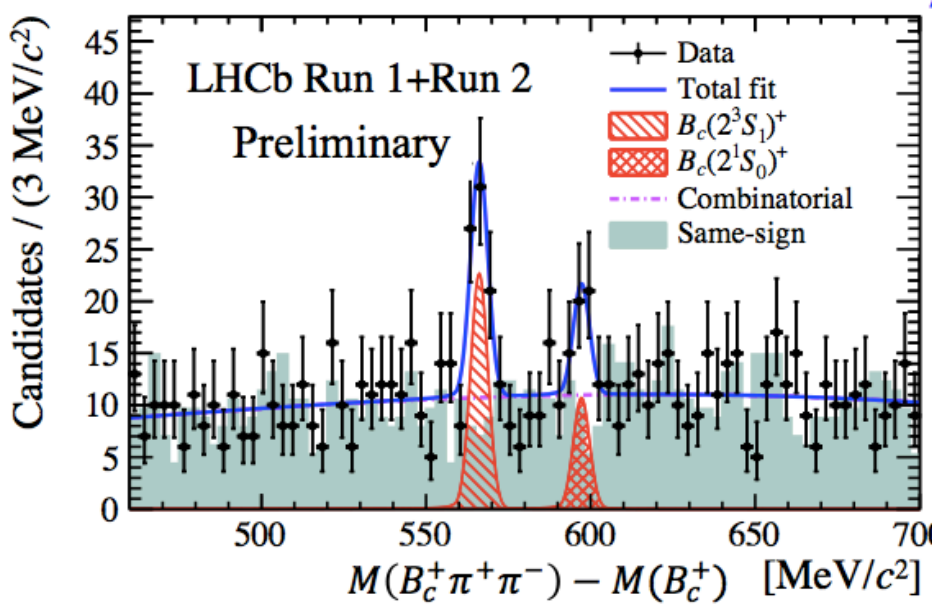
arXiv:1902.00571

$B_c^{(*)}(2S)^+$ at LHCb

- Run1 + Run2 dataset : 8.5 pb-1
- $B_c^*(2S)^+$ observed with greater than 5σ significance
- Hint of $B_c(2S)^+$



3785 ± 73 B_c^+ signals

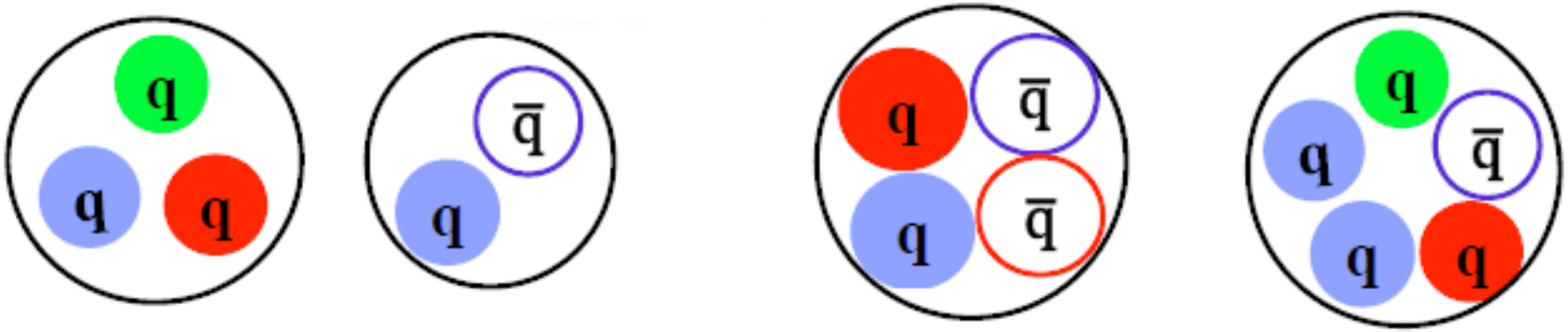


51 ± 10 $B_c^*(2S)^+$; **24 ± 9** $B_c(2S)^+$

LHCb-PAPER-2019-007

Exotic hadrons

Insight into QCD



Baryon **Meson** **Tetraquark** **Pentaquark**

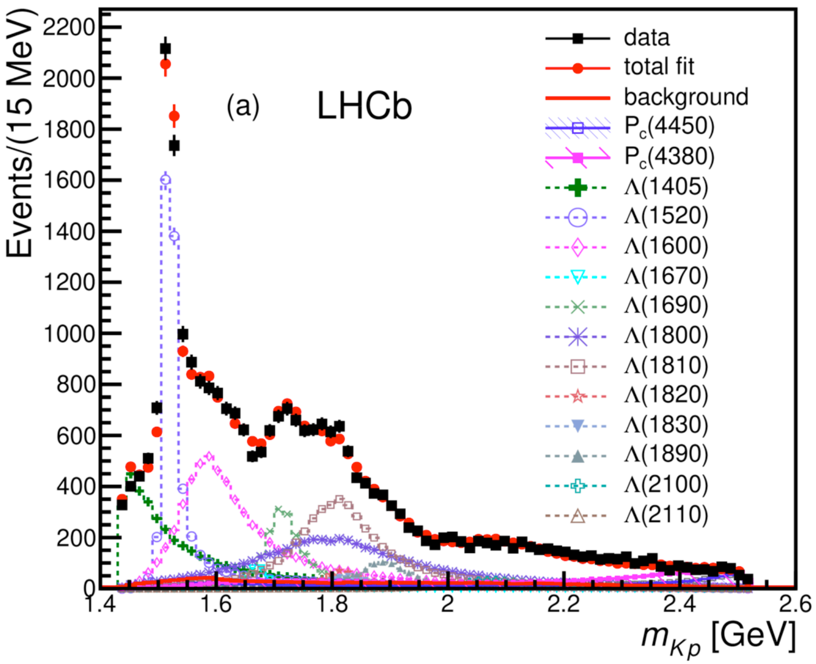
- Over the last decade tetraquarks and more recently pentaquarks have been discovered – despite their existence predicted in 1964

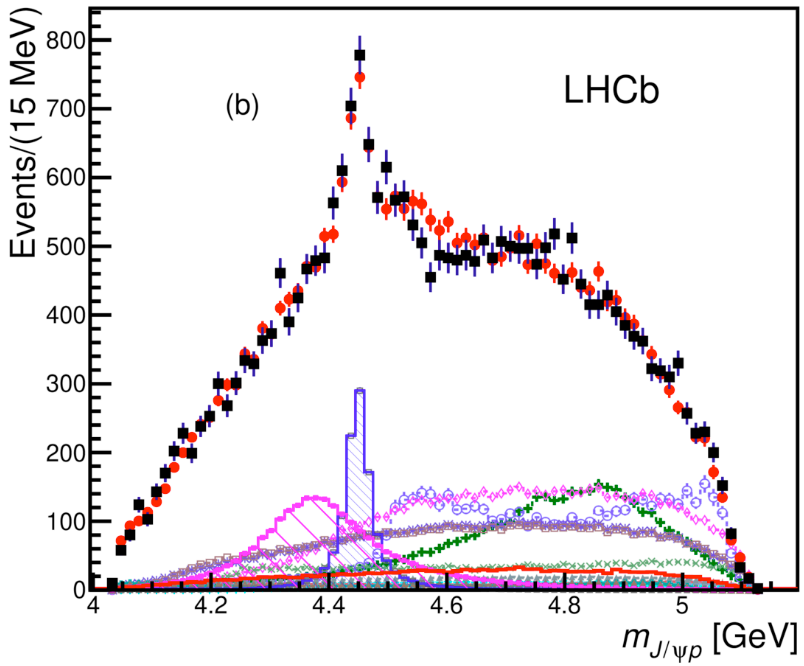
- How do quarks bind themselves?

Pentaquark observation in 2015

- Study of 2011 + 2012 data : 6-dim amplitude fit of the $\Lambda_b \rightarrow J/\psi\ p\ K$ decay
- All known Λ^* states and new ones tried
- The structure in the $J/\psi\ p$ spectrum cannot be a reflection

Observation of 2 pentaquark states

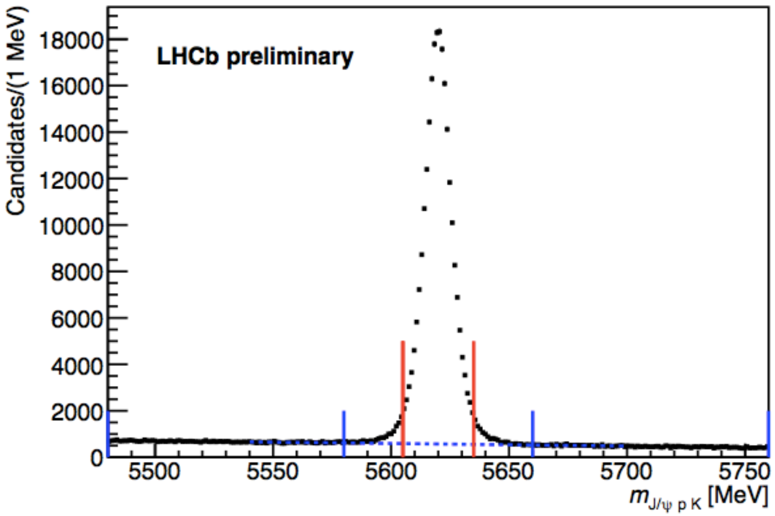




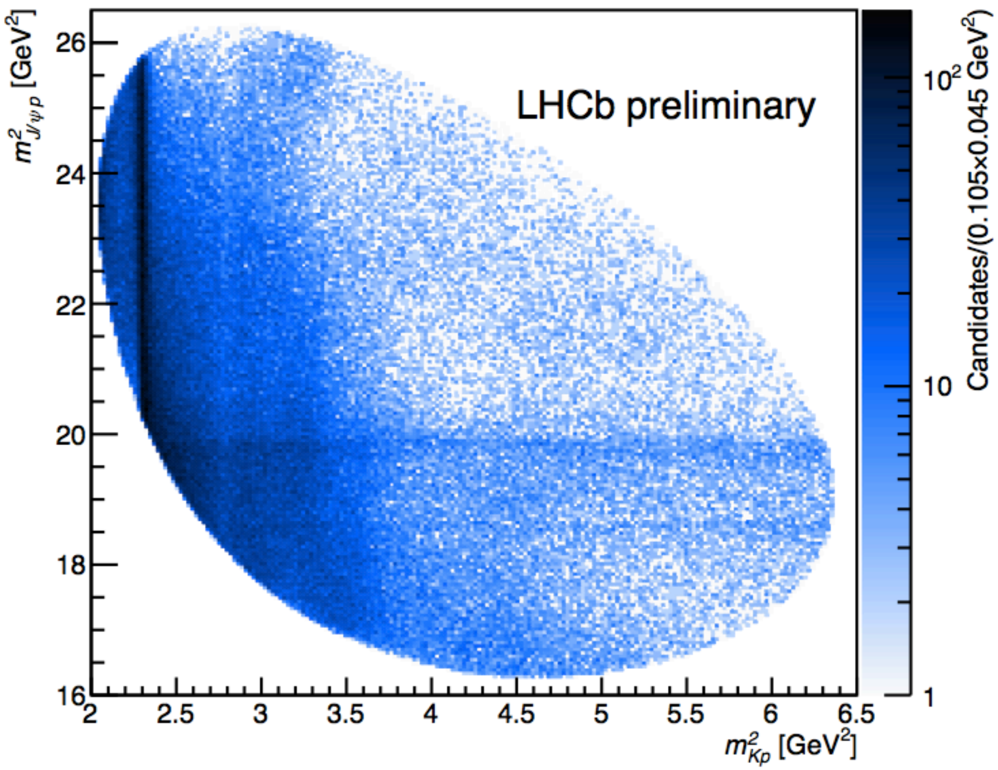
arXiv:1507.03414

New data

- Data : 2011 – 2018
- New selection with BDT including PID information.
- Signal efficiency doubled for same purity
- → **x9 previous signal yield**



246K $\Lambda_b \to J/\psi\ p\ K$ candidates

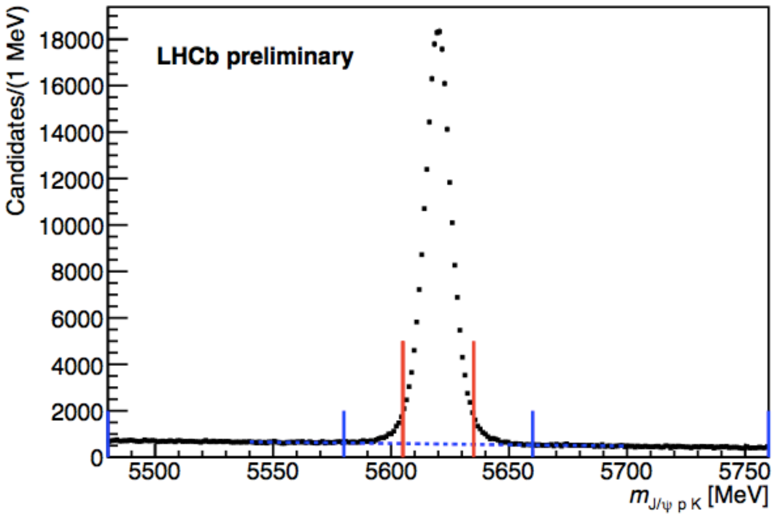


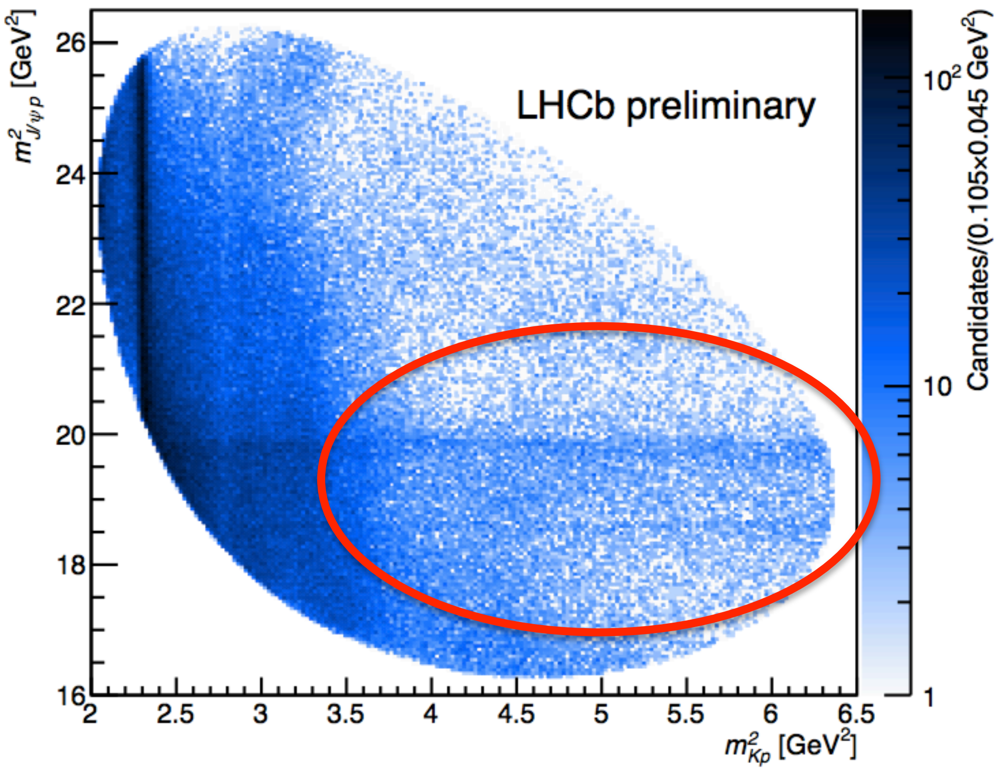
arXiv:1904.03947

New data

- Data : 2011 – 2018
- New selection with BDT including PID information.
- Signal efficiency doubled for same purity
- **→ x9 previous signal yield**

Pentaquark structure visible



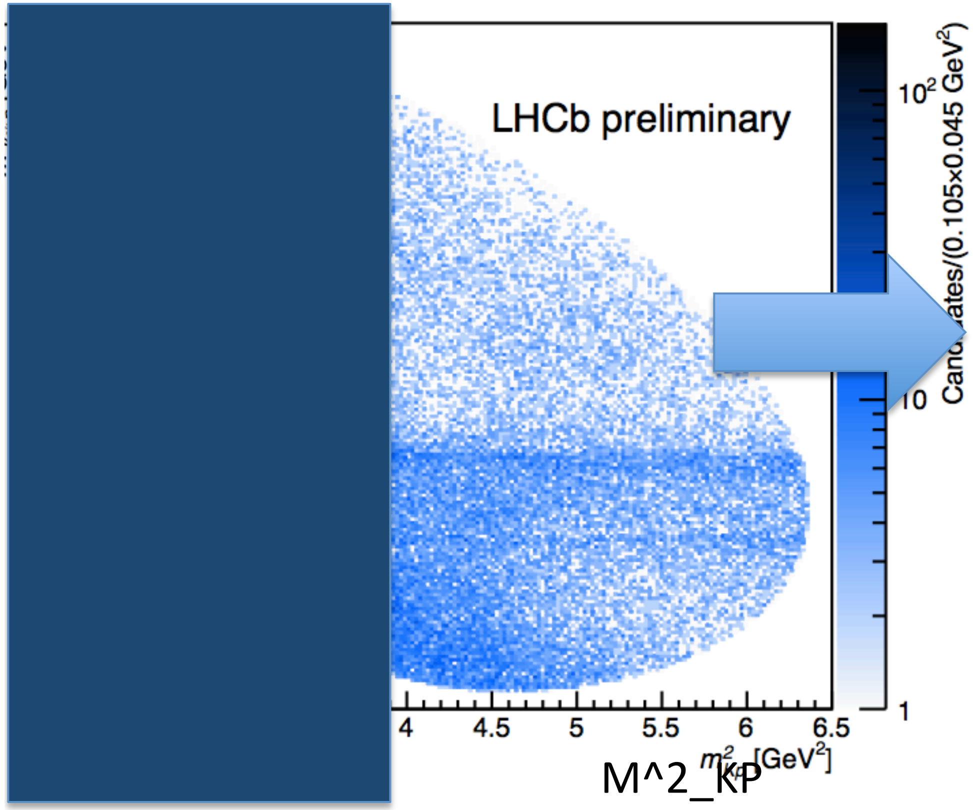


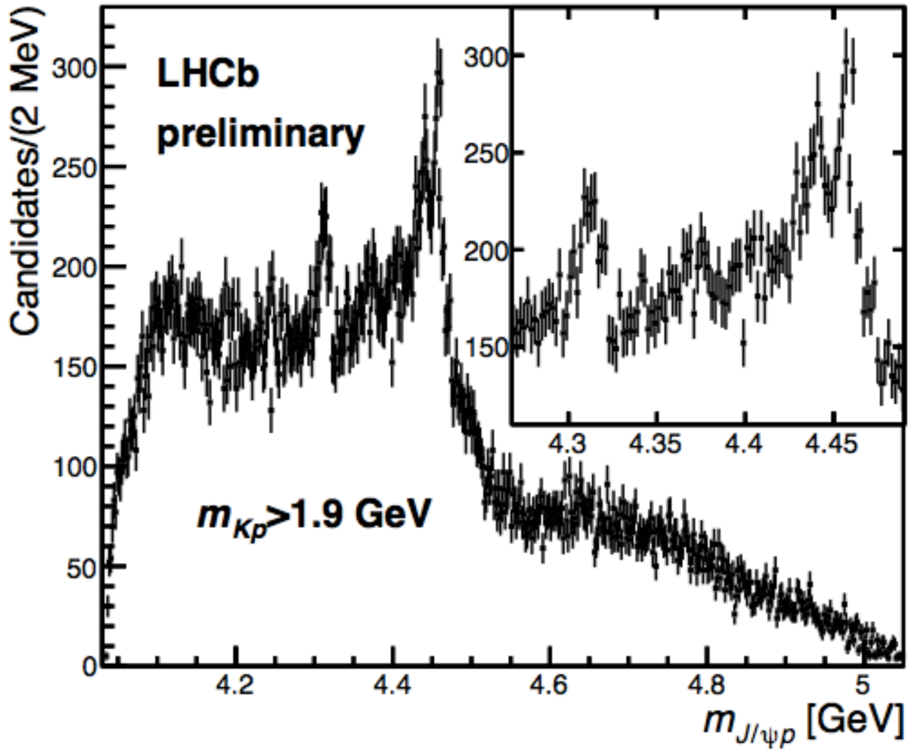
246K $\Lambda_b \rightarrow J/\psi\ p\ K$ candidates

arXiv:1904.03947

New strategy

- Narrow J/ψ p structures can be investigated without full model if data above 1.9 in m_{Kp} is selected.
- 3 narrow peaks seen. Previous broad peak can't be studied without amplitude analysis.

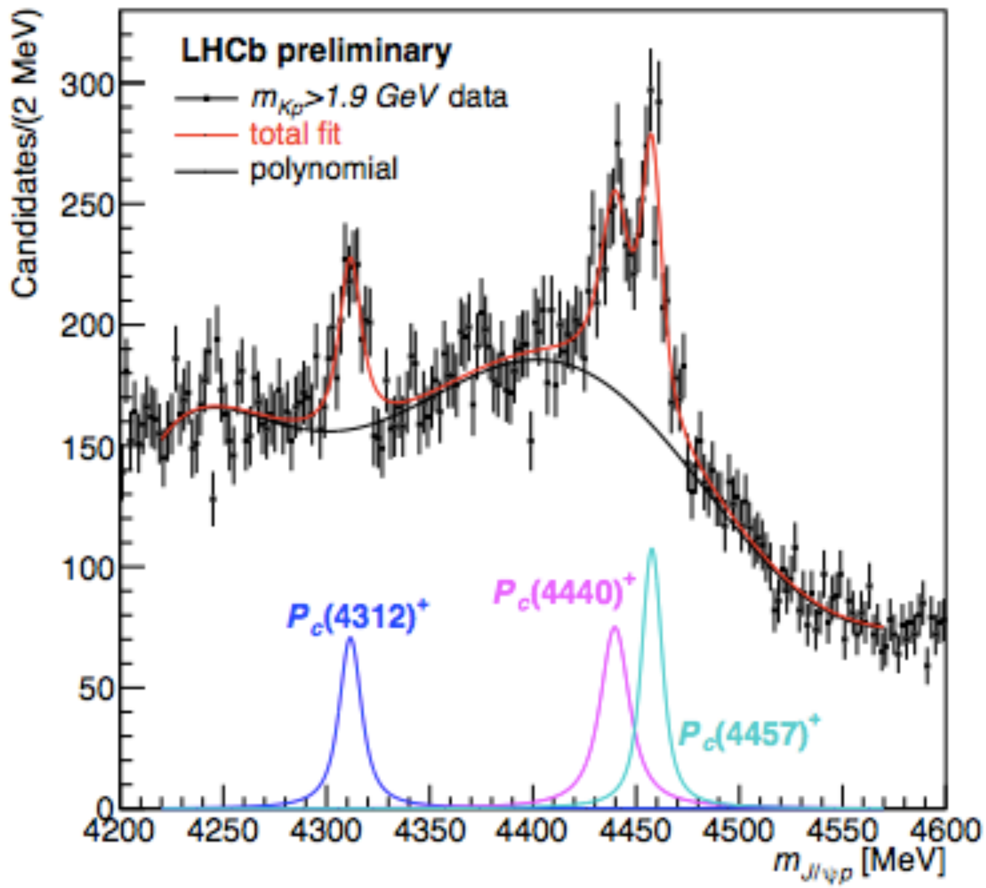




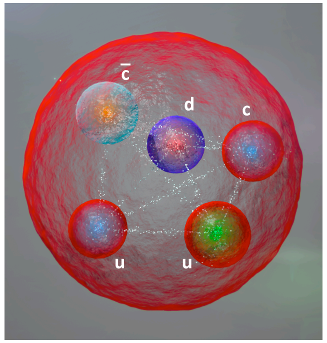
arXiv:1904.03947

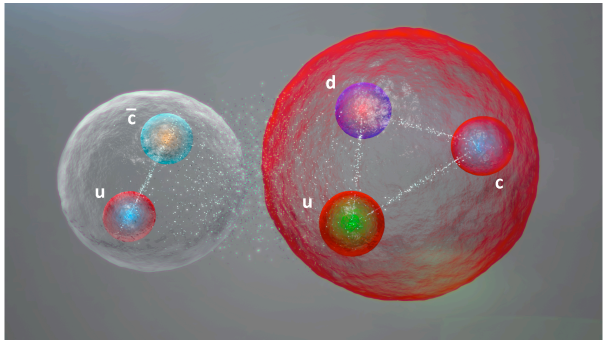
Introducing new pentaquarks

- Previous $P_c(4450)^+$ peak is resolved into two narrow states
- $P_c(4440)^+$ & $P_c(4457)^+$ with 5.4 σ significance
- A further state $P_c(4312)^+$ is discovered with 7.3σ significance



Possible interpretation

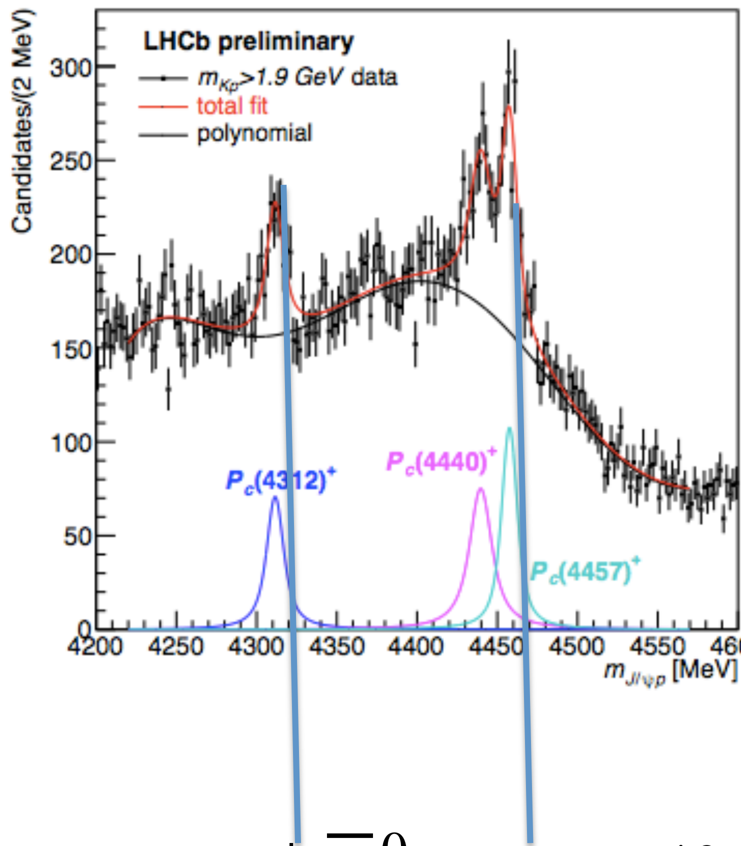




The Pentaquarks are found just below threshold by amounts that are plausible hadron-hadron binding energies.

They are narrow.

While it points to the molecular interpretation further experimental and theoretical required to confirm this.



$\Sigma_c^+ \overline{D}^0$ $\Sigma_c^+ \overline{D}^{*0}$

Flavour physics and CP violation

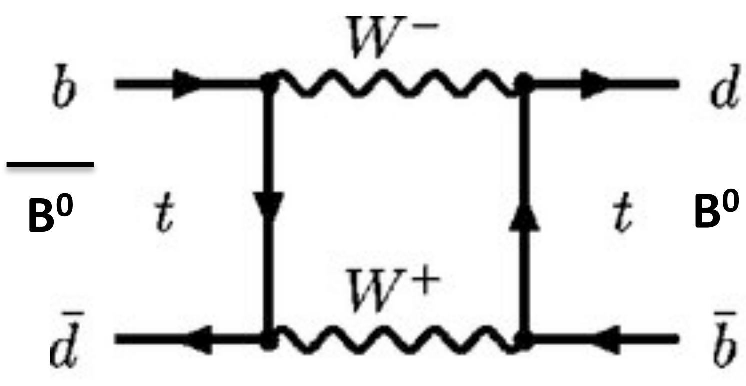
- The CKM matrix couples the weak and mass eigenstates of quarks
- 3 generations gives rise to one free phase which is the source of CP violation in the standard model
- Level of CP violation in the SM is orders of magnitude too small to explain our matter dominated universe → There must be other sources of CP violation.
- Flavour physics provides and excellent arena to study CP violation

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Flavour physics as a window to beyond the SM physics

- Throughout history precision flavour physics has resulted in the discovery of "new physics" of its time.
- CP violation, b quark, top quark
- Not only do we learn that something else exists but we can identify its properties.
- Flavour physics could be the key in answering the big questions surrounding the standard model.

Observation of B^0 mixing in 1987



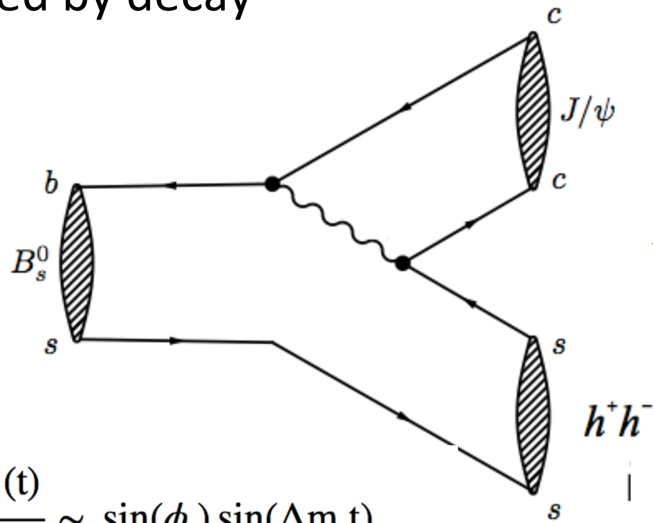
implied that $m_t > 50$ GeV

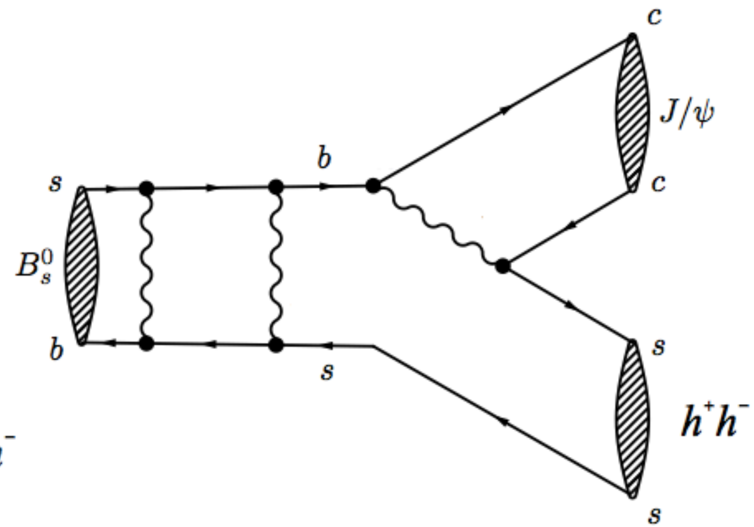
Top eventually discovered in 1995 with mass ~175 GeV

Low energy phenonmena is sensitive to heavy particles

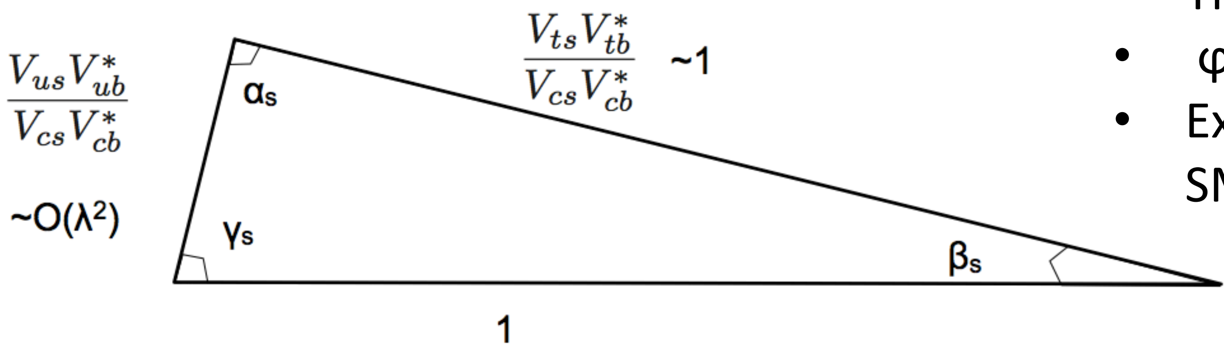
CP violation in $B_s \rightarrow J/\psi\ hh$ decays

CP violation in the Interference between direct decay, and mixing followed by decay



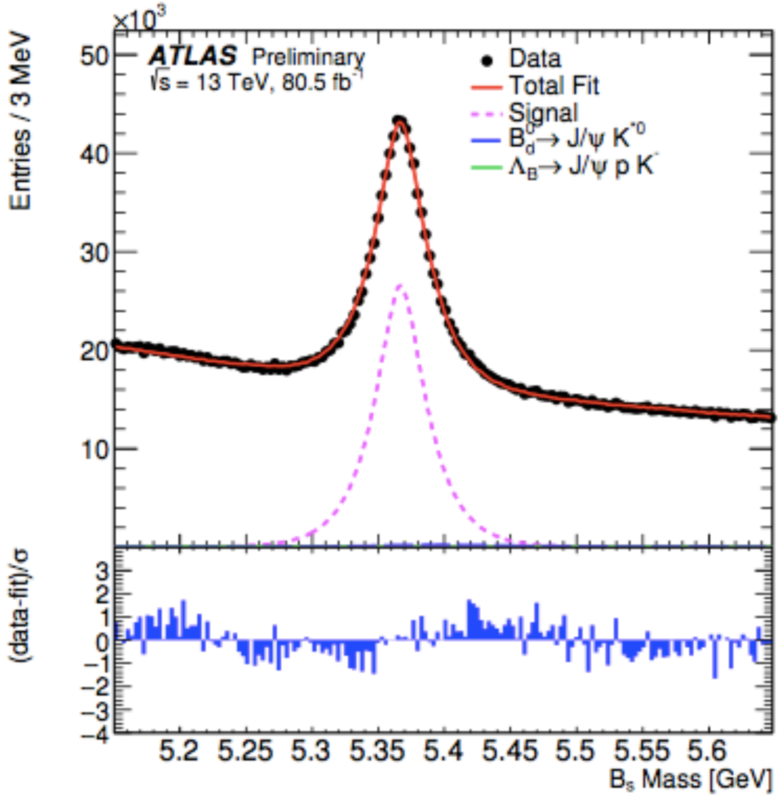


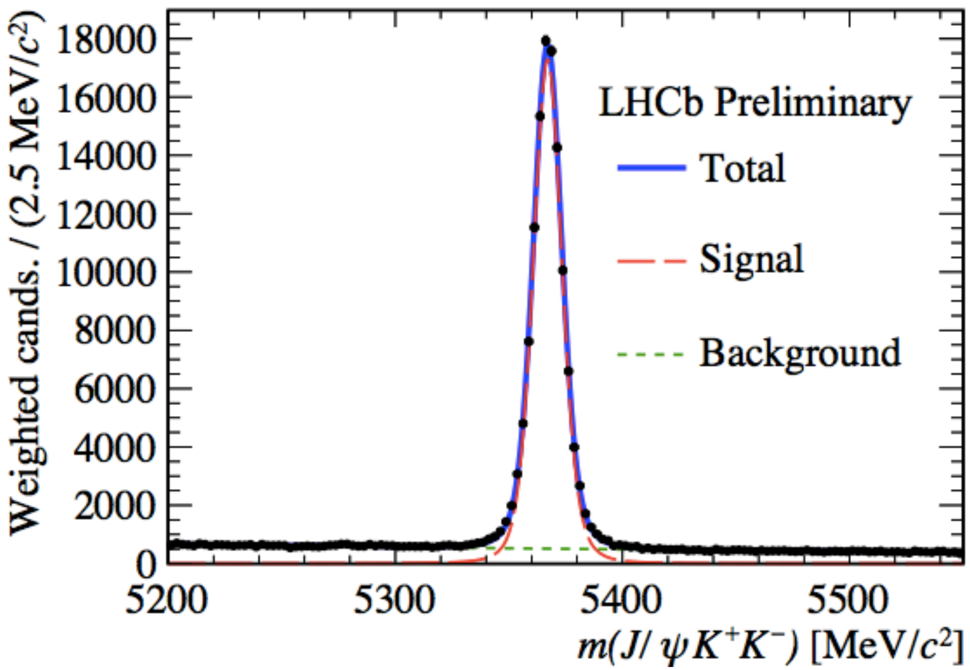
$$A_{CP}(t) = \frac{\Gamma_{\bar{B}_s^0 \to f}(t) - \Gamma_{B_s^0 \to f}(t)}{\Gamma_{\bar{B}_s^0 \to f}(t) + \Gamma_{B_s^0 \to f}(t)} \sim \sin(\phi_s)\sin(\Delta m_s t)$$



- The measured phase is φ_s.
- $\varphi_s \sim -2\beta_s$ (if no penguin)
- Expected to be very small in SM : $2\beta_s = 37.04 \pm 0.64$ mrad

Signal extraction





ATLAS 2015-2017 data

N (B_s→J/ψ ϕ) = 447,000

LHCb 2015 – 2016 data

N (B_s→/ψ KK) = 117,000

Signal extraction

$$A_{CP}(t) = \frac{\Gamma_{\bar{B}^0_s \to f}(t) - \Gamma_{B^0_s \to f}(t)}{\Gamma_{\bar{B}^0_s \to f}(t) + \Gamma_{B^0_s \to f}(t)} \sim \sin(\phi_s)\sin(\Delta m_s t)$$

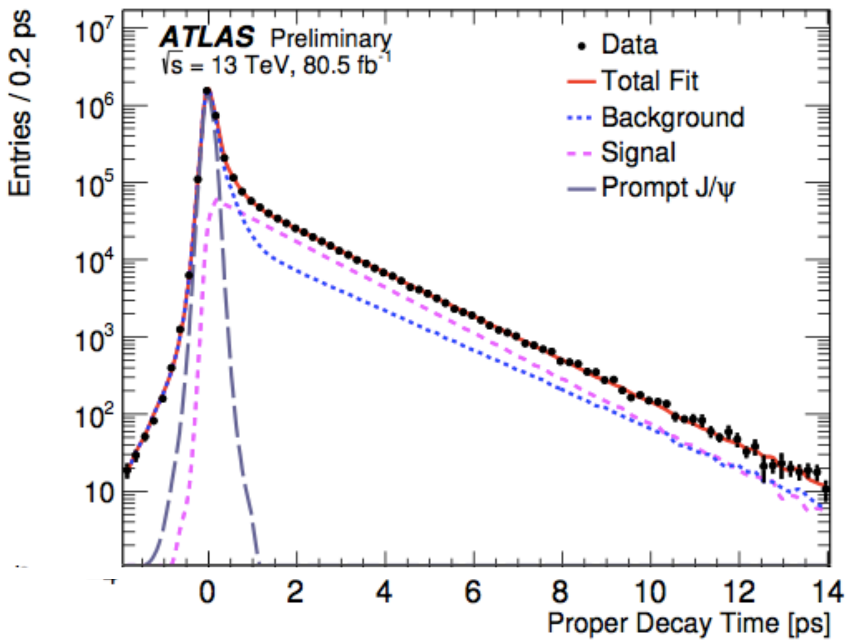
- Time dependent:

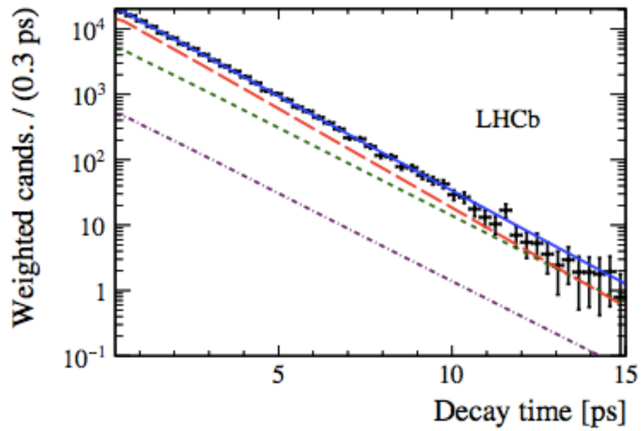
- ATLAS New: IBL layer
- Pixel layer close to the beam pipe
  - Decay time resolution from ~100 fs → ~70 fs

- LHCb resolution around ~ 45 fs – prompt signal removes from analysis

- Tagging power

- ATLAS: 1.65 %
- LHCb : 4.73 %

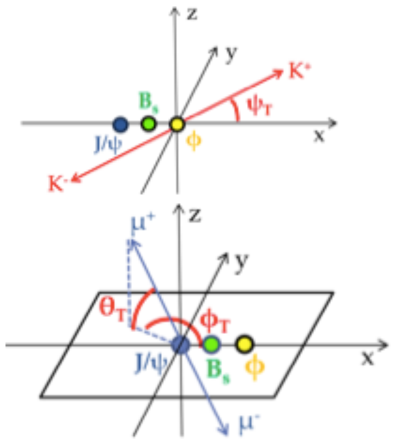




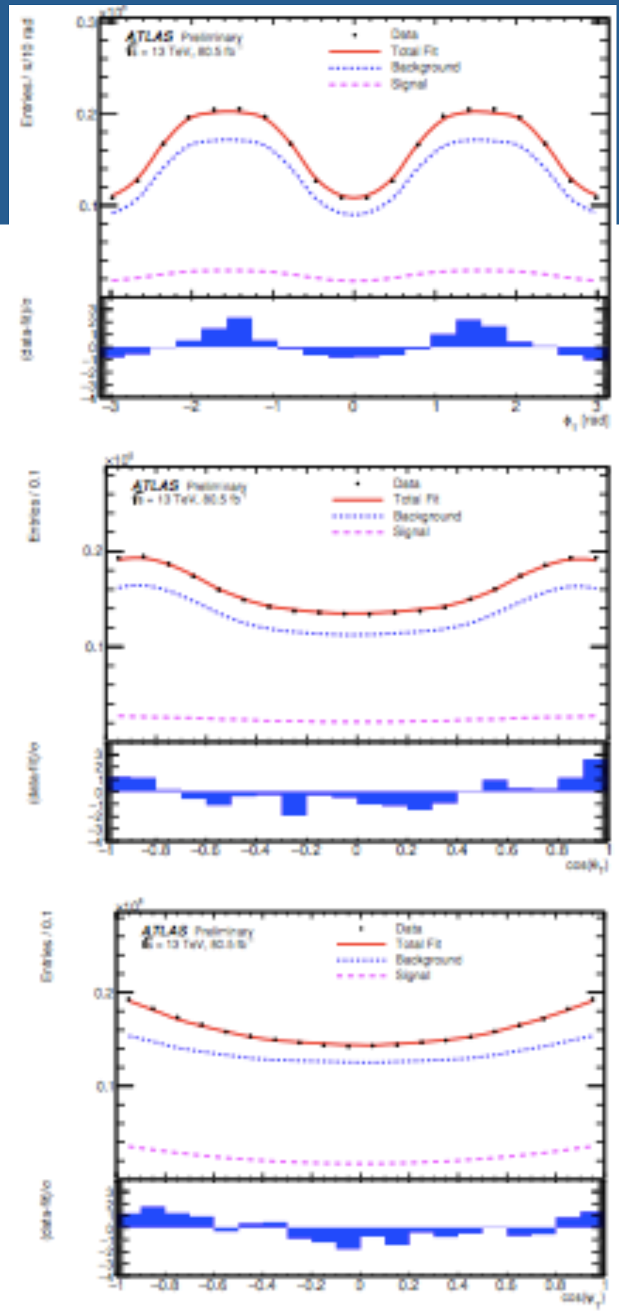
Full fit

$$A_{CP}(t) = \frac{\Gamma_{\bar{B}^0_s \to f}(t) - \Gamma_{B^0_s \to f}(t)}{\Gamma_{\bar{B}^0_s \to f}(t) + \Gamma_{B^0_s \to f}(t)} \sim \sin(\phi_s)\sin(\Delta m_s t)$$

- The final state has L = 0, 1, 2 between the J/ψ and φ, and also a non-φ S-wave component
- These must be disentangled by fitting the decay angle distributions

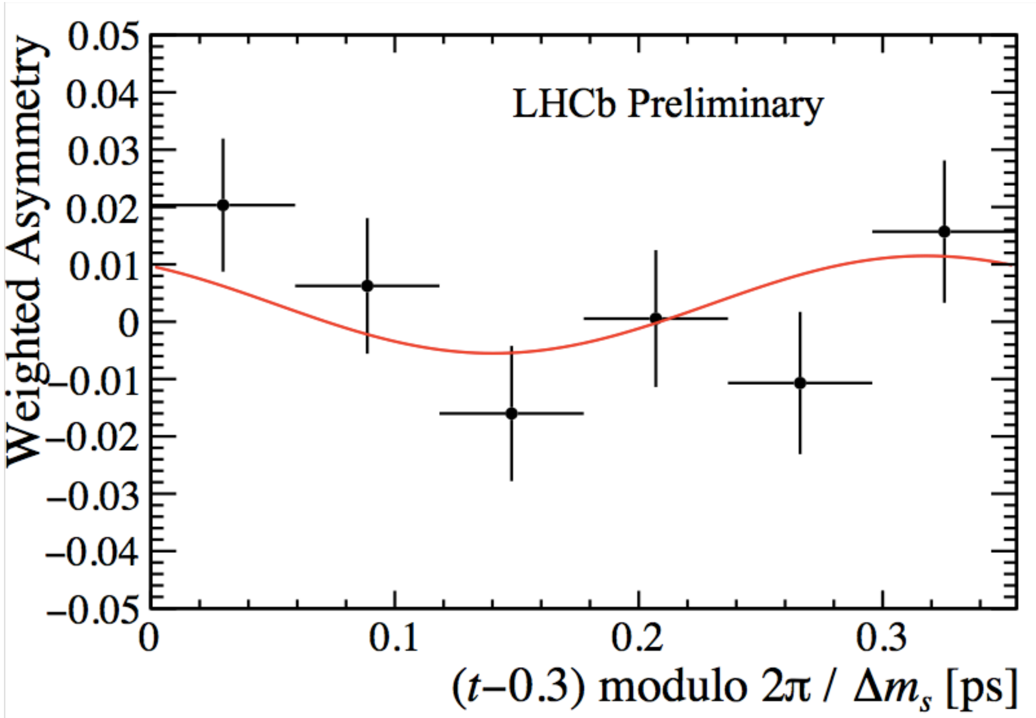


Full fit is a simultaneous fit to mass, decay time, tagging probability, and traversity angles



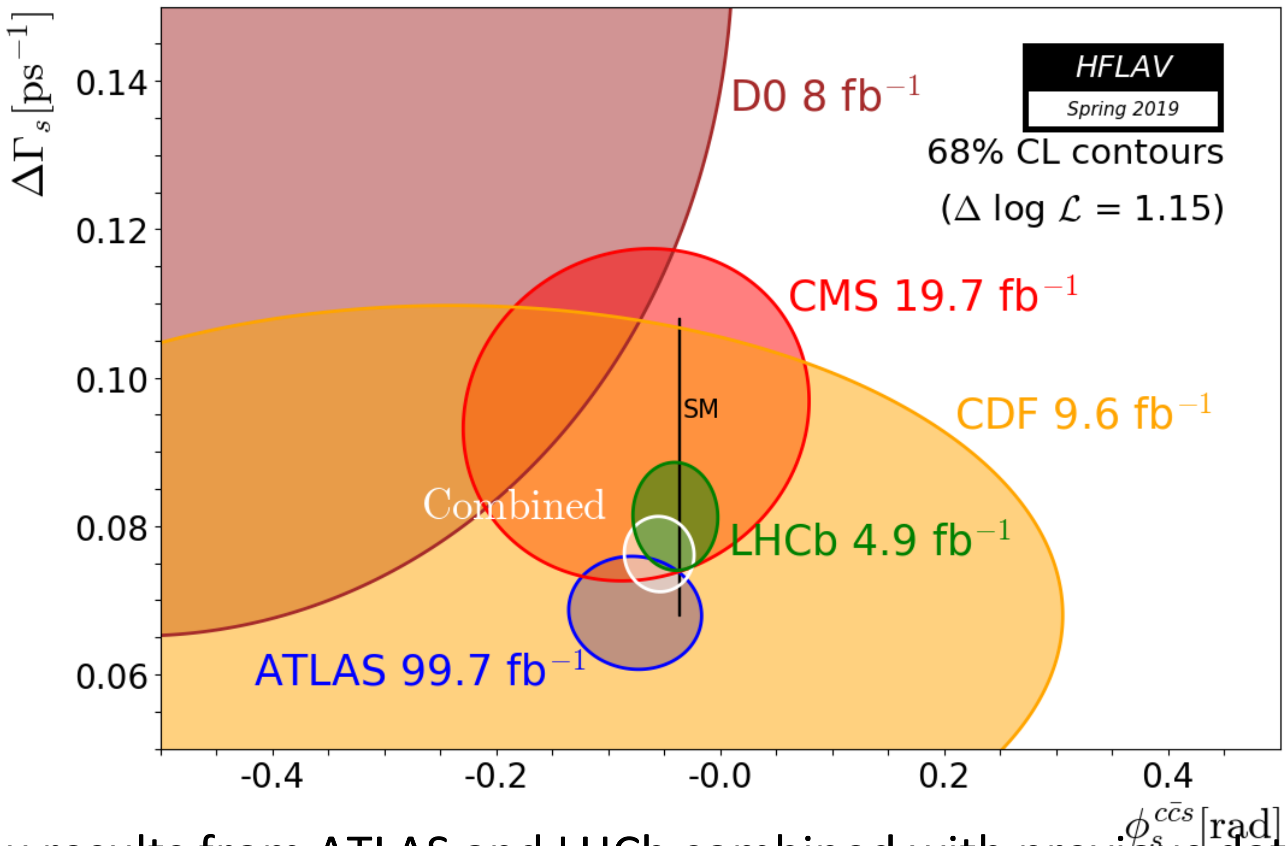
Time dependent asymmetry

$$A_{CP}(t) = \frac{\Gamma_{\bar{B}^0_s \to f}(t) - \Gamma_{B^0_s \to f}(t)}{\Gamma_{\bar{B}^0_s \to f}(t) + \Gamma_{B^0_s \to f}(t)} \sim \sin(\phi_s)\sin(\Delta m_s t)$$



- Full fit extracts φ_s and other parameters simultaneously
- This figure is an illustration
- As errors continue to shrink the oscillatory nature of the asymmetry will become clear

Results

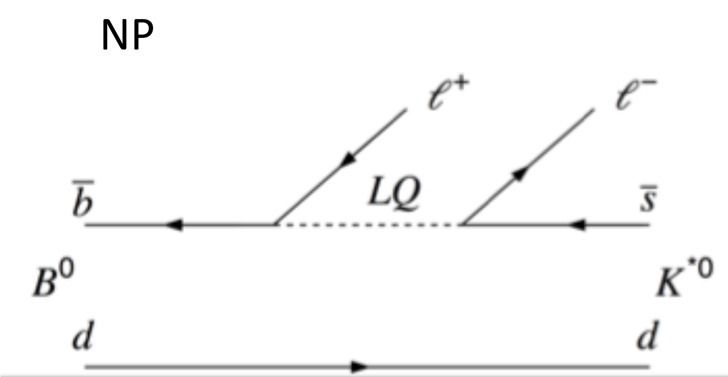


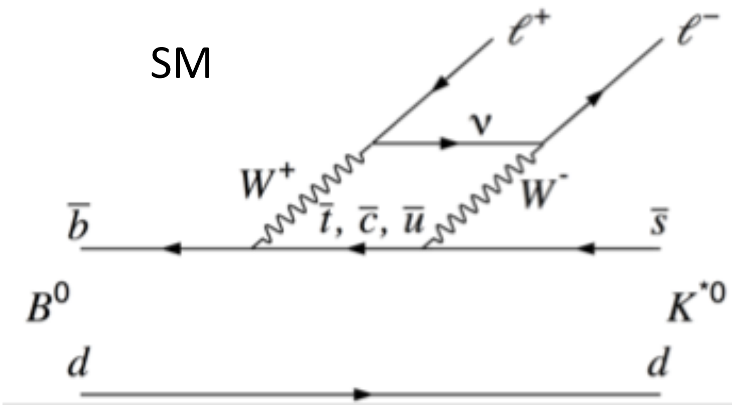
- New results from ATLAS and LHCb combined with previous data results (and from other modes on LHCb)
- ATLAS & LHCb results are competitive with each other
- While consistent with the SM, approaching a sensitivity to truly probe it.

Progress in LFU measurements

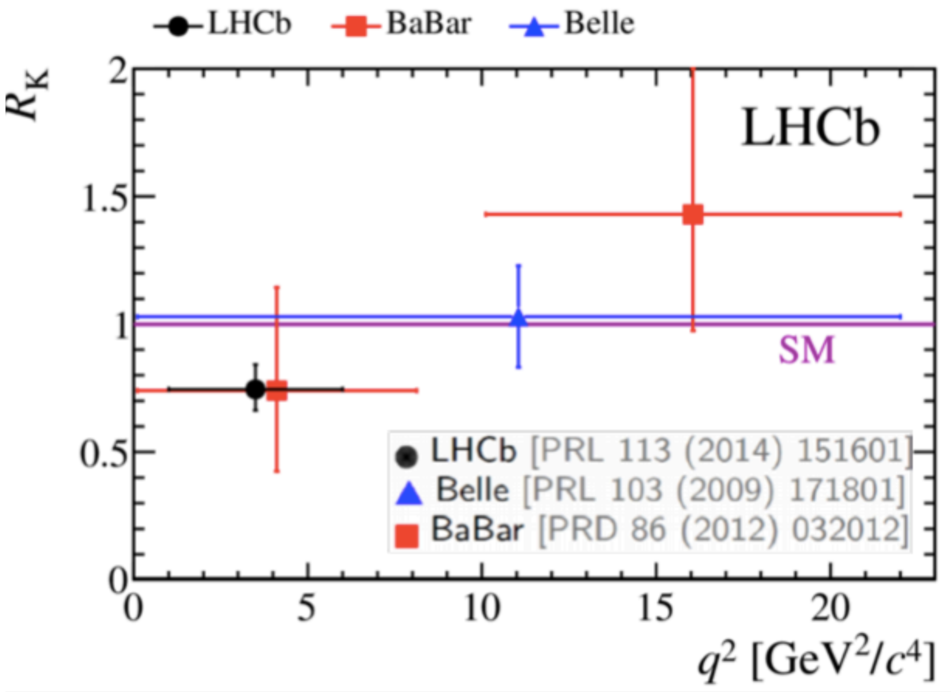
- For the SM e, μ, τ are the **same except for their masses**
- Very precise predictions for $R_h = \dfrac{\mathbf{B}(B \to h l_1 l_1)}{\mathbf{B}(B \to h l_2 l_2)}$
- **R_h ~ 1.0 for μ/e ; R_h ~ 0.3 for τ/μ** (away from phase space limits)

New particles at tree level can compete with SM loop diagrams and alter these ratios





Intriguing deviations

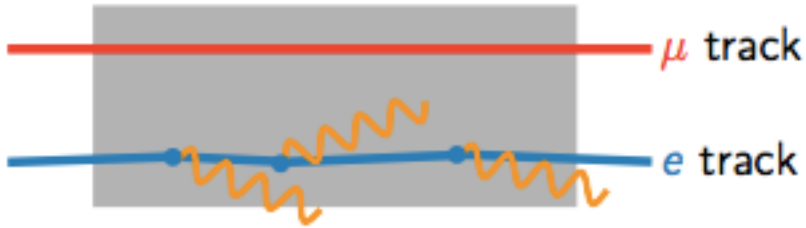


- R_K ~ 2.6σ significance deviation from SM
- Similar story elsewhere:
  - R_{K^*} 2.2 (2.4)σ for low (high) q^2
  - Combined significance of $R_{D(*)}$ ~ 3.1 σ

New results from Belle on R_{K^*}, $R_{K^{*+}}$, $R_{D(*)}$

Experimentally challenging

- Muon and Electron tracks are different in LHCb



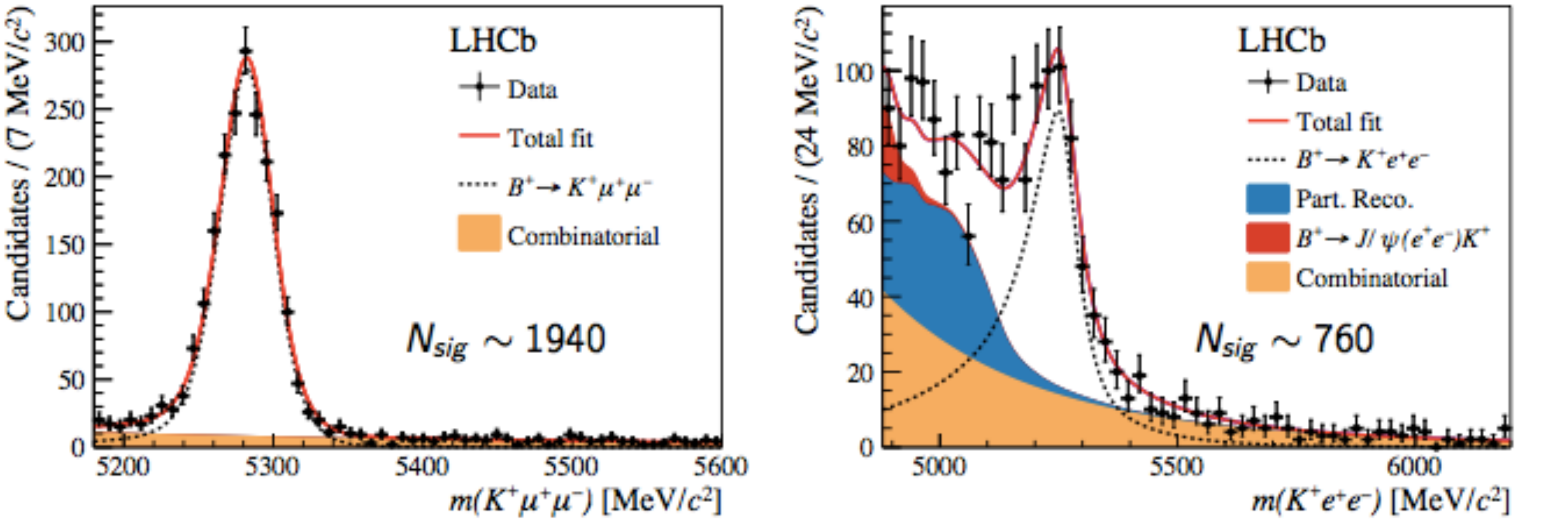
- Interactions with material and bremsstrahlung emission.
- Muons have better PID and trigger perfomances
- To measure R_K, require yields and efficiencies.
- Double ratio used to try and cancel most systematic uncertainties

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu\mu)}{\mathcal{B}(B^+ \to K^+ee)} \Big/ \frac{\mathcal{B}(B^+ \to K^+J/\psi(\mu\mu))}{\mathcal{B}(B^+ \to K^+J/\psi(ee))}$$

$$= \frac{N(K^+\mu\mu)}{N(K^+J/\psi(\mu\mu))} \cdot \frac{N(K^+J/\psi(ee))}{N(K^+ee)} \cdot \frac{\varepsilon(K^+J/\psi(\mu\mu))}{\varepsilon(K^+\mu\mu)} \cdot \frac{\varepsilon(K^+ee)}{\varepsilon(K^+J/\psi(ee))}$$

Simultaneous fit to $B^+ \rightarrow K^+\mu^+\mu^-$ and $B^+ \rightarrow K^+e^+e$

A single fit is performed to determine R_K, using 2011 – 2016 dataset



arXiv:1903.09252

Results with 2011 – 2016 data

Using 2011 and 2012 LHCb data R_K was:

$$R_K = 0.745^{+0.090}_{-0.074}(stat) \pm 0.036(syst)$$

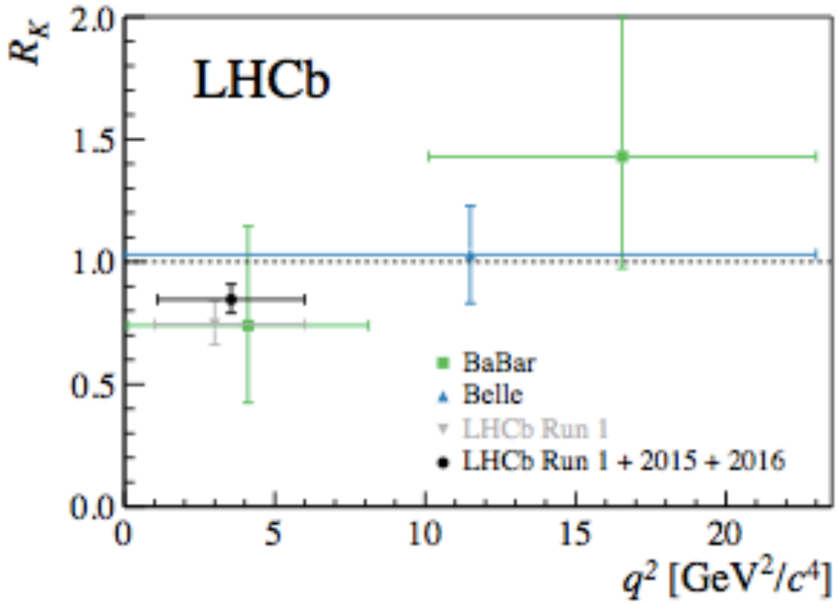
~2.6 σ from SM

Reanalysis of 2011,2012+ 2015 and 201(data R_K becomes:

$$R_K = 0.846^{+0.060}_{-0.054}(stat)^{+0.016}_{-0.014}(syst)$$

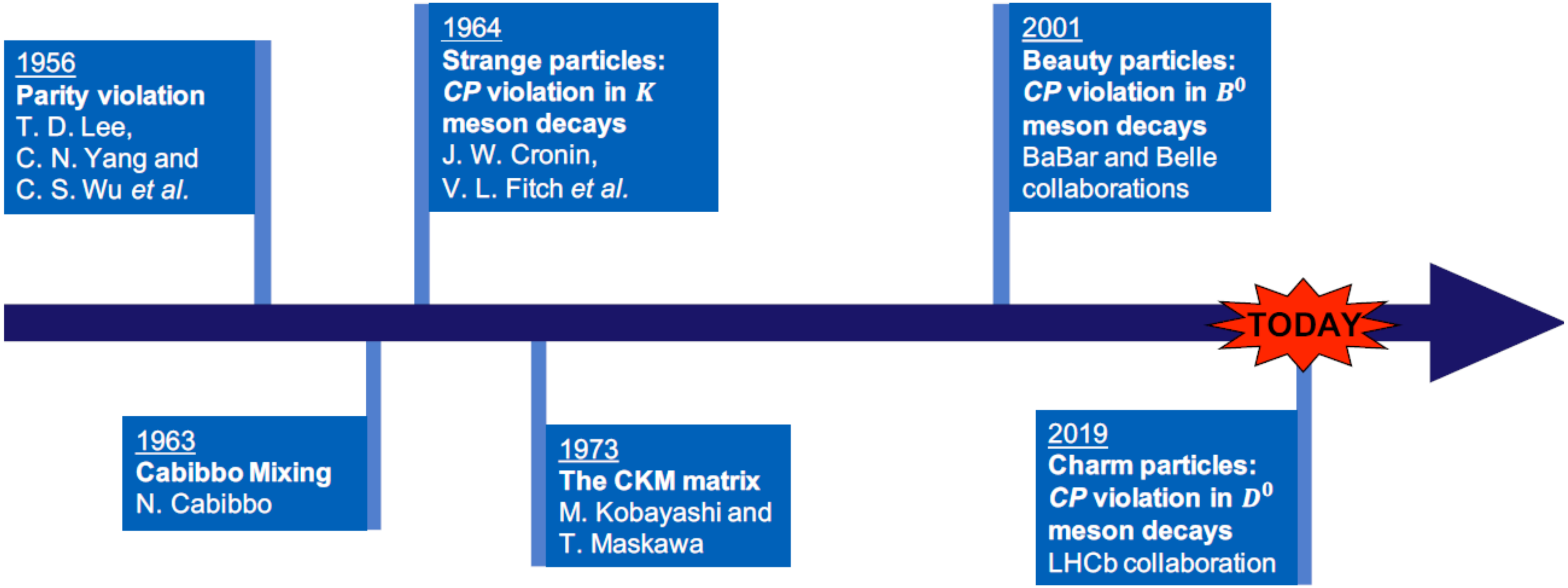
~ 2.5 σ from SM

Compatibility between new and old resu



- R_K is more precise. LFU breaking not confirmed …. nor ruled out!
- Look forward to update with full Run 2 and plenty of other measurements that probe LFU.

Timeline of CP violation



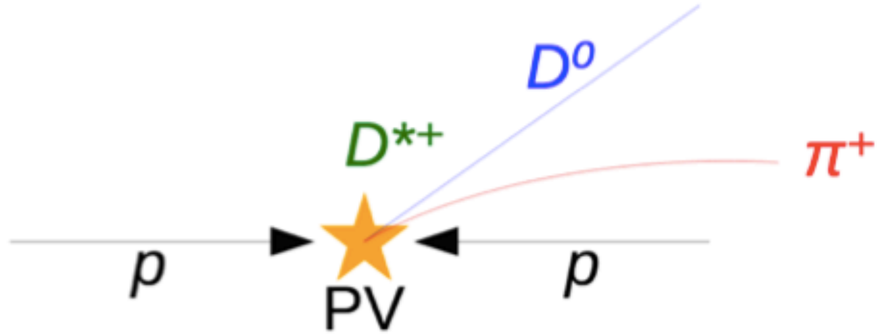
- CPV in Kaons and B mesons is well established – both are down type quarks
- Charm contains an up-type quark. SM predicts it to be at 10^{-3} - 10^{-4} level

CPV in charm is finally observed

Direct CPV

Direct CPV : $|A_f|^2 \neq |\bar{A}_{\bar{f}}|^2$

e.g $D^0 \rightarrow KK$ or $D^0 \rightarrow \pi\pi$

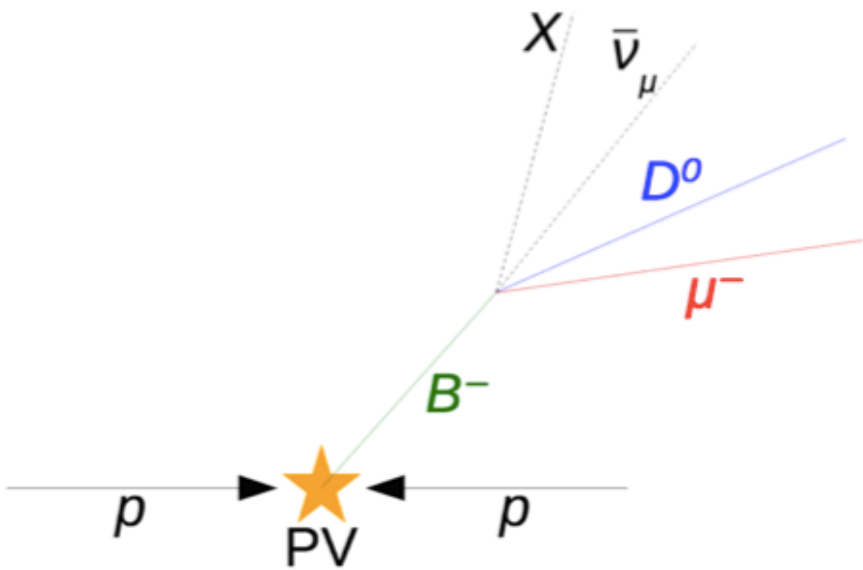


Necessary to know initial D meson state

Charge of the accompanying particle tags the production flavour

Prompt charm $D^{*+} \rightarrow D^0\pi^+$

Semileptonic charm $B \rightarrow D^0 \mu^- \upsilon X$



Detector effects contribute to measured asymmetry

$$A_{raw}(f) \cong A_{CP}(f) + A_D(f) + A_D(\pi_s) + A_P(D^{*+})$$

- $A_{raw}(f)$ → Observable
- $A_{CP}(f)$ → **Physical asymmetry**
- $A_D(f)$ → Detection asymmetry → 0 as the final states are symmetric
- $A_D(\pi_s)$, $A_P(D^{*+})$ → Soft π detection and production asymmetry. Independent of the subsequent decay (If the D* and π kinematics are reweighted to be the same)

Use the difference in the direct CPV in two decay modes to reduce systematic uncertainties (direct CPV is expected to be different in these decay modes)

$$\Delta A_{CP} = A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)$$

arXiv:1903.08726

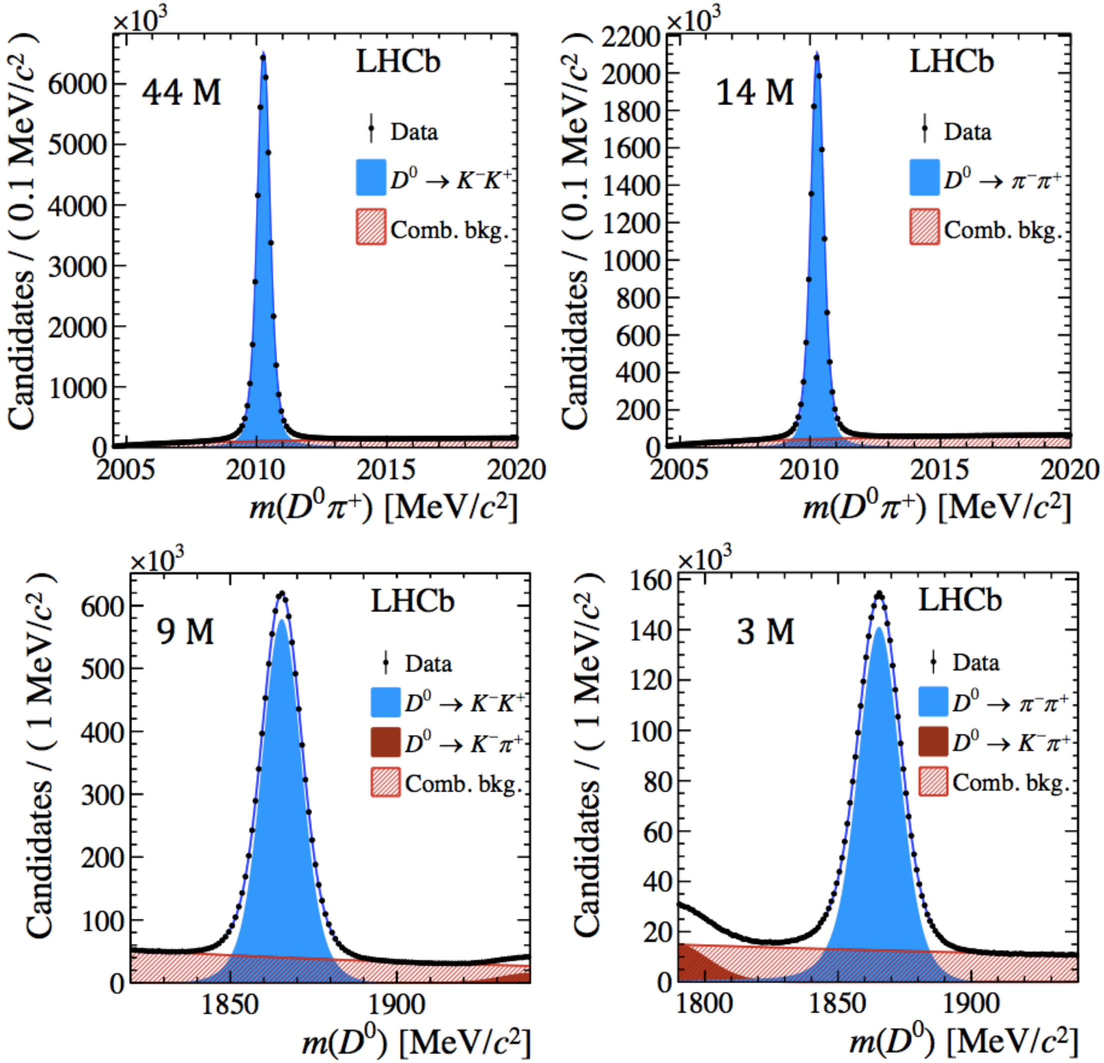
A_{raw} measurement

Prompt Sample

Very high yields

Secondary samples, lower yields but still substantial contribution

A_{raw} is a parameter of the fit shared between D^0 and $\bar{D}^0$ states



arXiv:1903.08726

Results

$$\Delta A_{CP}^{\pi-tag} = [-18.2 \pm 3.2(stat) \pm 0.9(syst)] \times 10^{-4}$$

$$\Delta A_{CP}^{\mu-tag} = [-9 \pm 8(stat) \pm 5(syst)] \times 10^{-4}$$

Compatible with Run 1 results . When combined together and with Run 1 results:

$$\Delta A_{CP} = (-15.4 \pm 2.9) \text{x} 10^{-4}$$

First observation of CPV in charm decays at 5.3σ significance

arXiv:1903.08726

Interpretation

$$\Delta A_{CP} \simeq \Delta a_{CP}^{\mathrm{dir}} \left(1 + \frac{\overline{\langle t \rangle}}{\tau(D^0)} y_{CP}\right) + \frac{\Delta \langle t \rangle}{\tau(D^0)} a_{CP}^{\mathrm{ind}}$$

Using other LHCb measurements for y_{cp} and $A_{\Gamma} \sim a_{CP}^{Ind}$

$$\Delta a_{CP}^{dir} = (-15.6 \pm 2.9)\mathrm{x}10^{-4}$$

- arXiv:1903.10490, arXiv:1903.10638, arXiv:1903.10952 – **NP or SM**?
- Further measurements with other charm decays along will theoretical improvements will help clarify the physics picture
- Establish whether this is consistent with SM or indicates the presence of new physics in the up-quark sector

arXiv:1903.08726

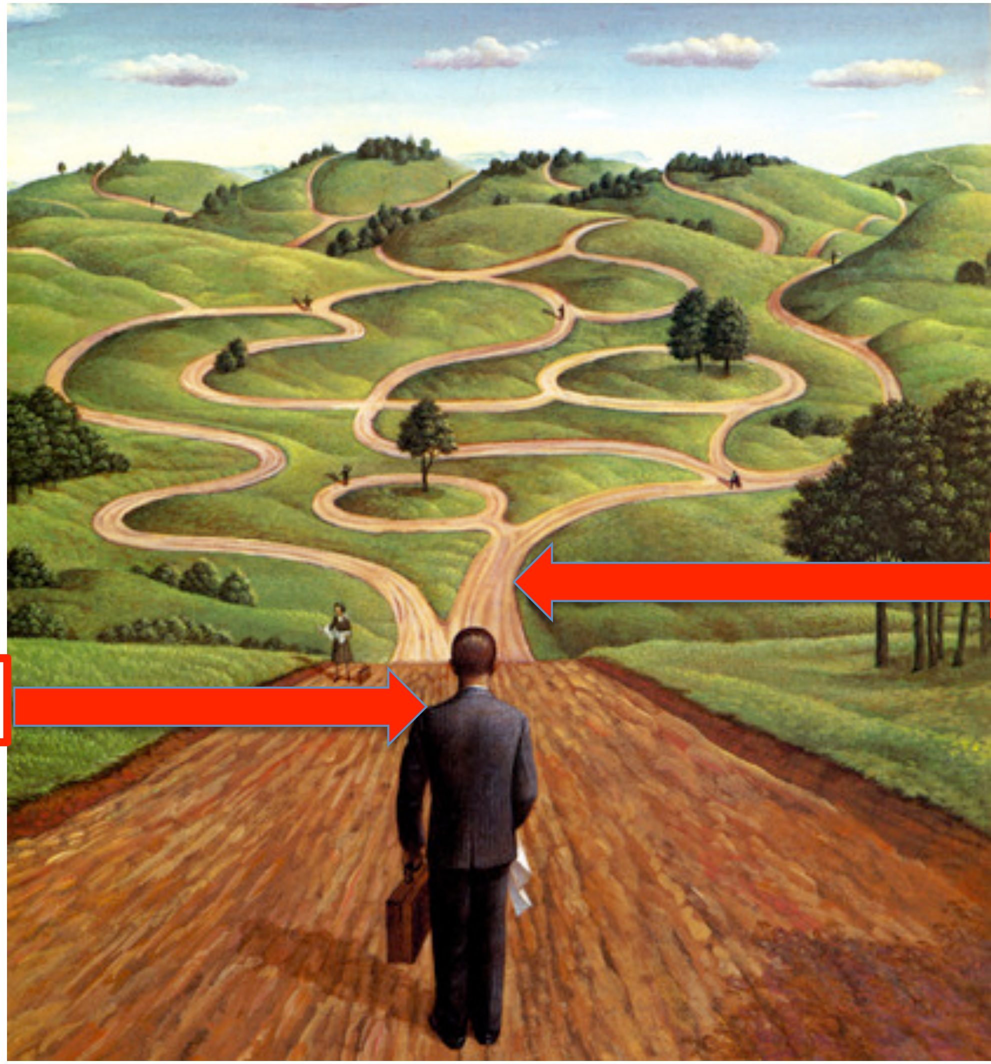
Summary

- **Last 2 months have been a very exciting time for flavour physics at the LHC** – plenty of <u>new</u> results were omitted here.

- Plenty of new information on QCD, CPV, rare processes

- No clear sign of new phyiscs

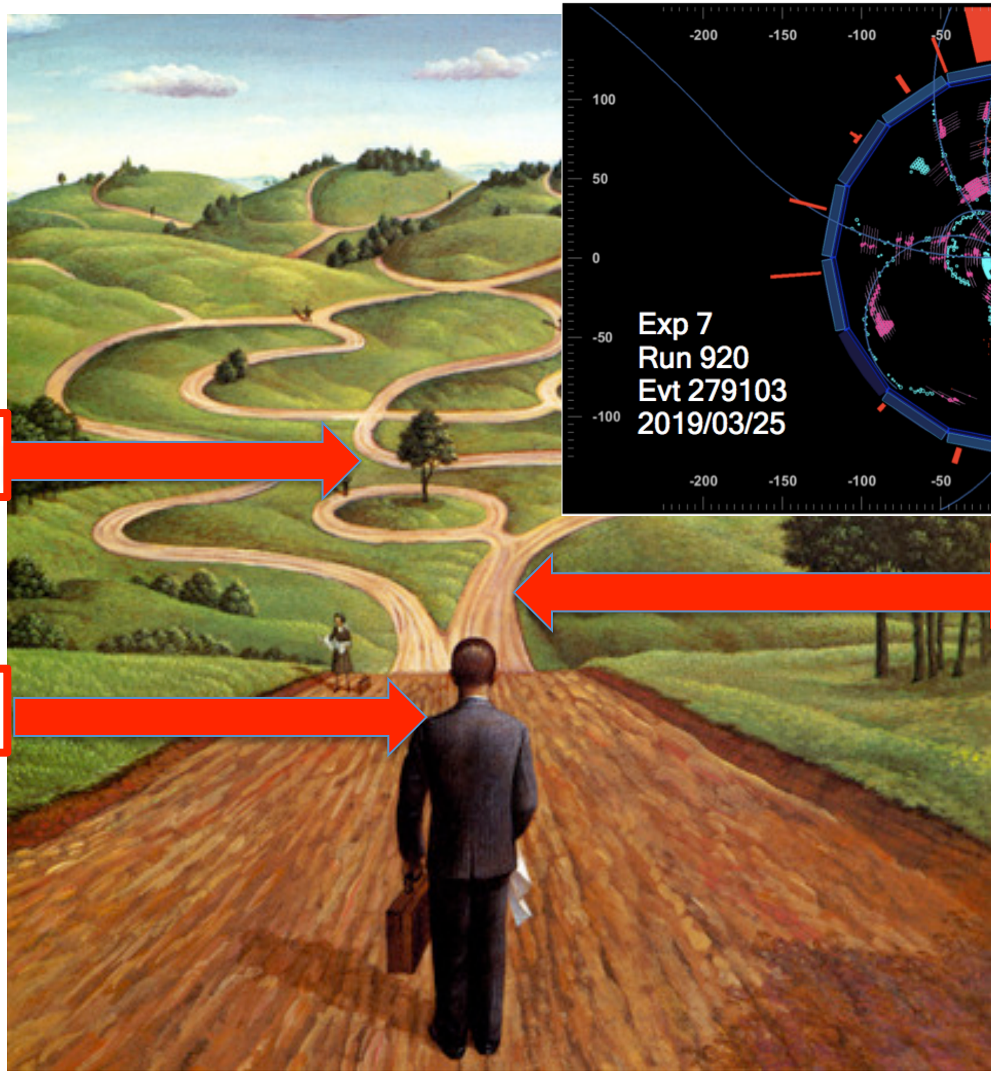
Outlook

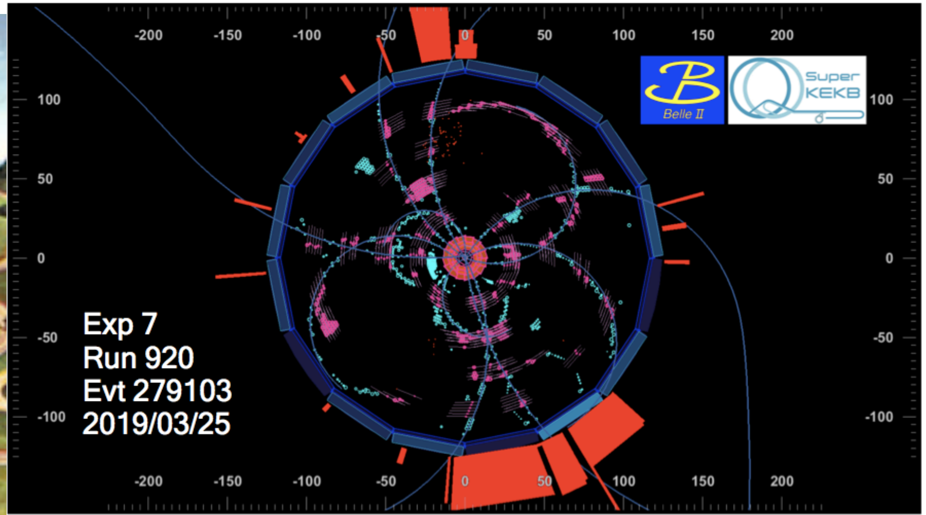


Full Run2 dataset

GPD Run3 data

Outlook



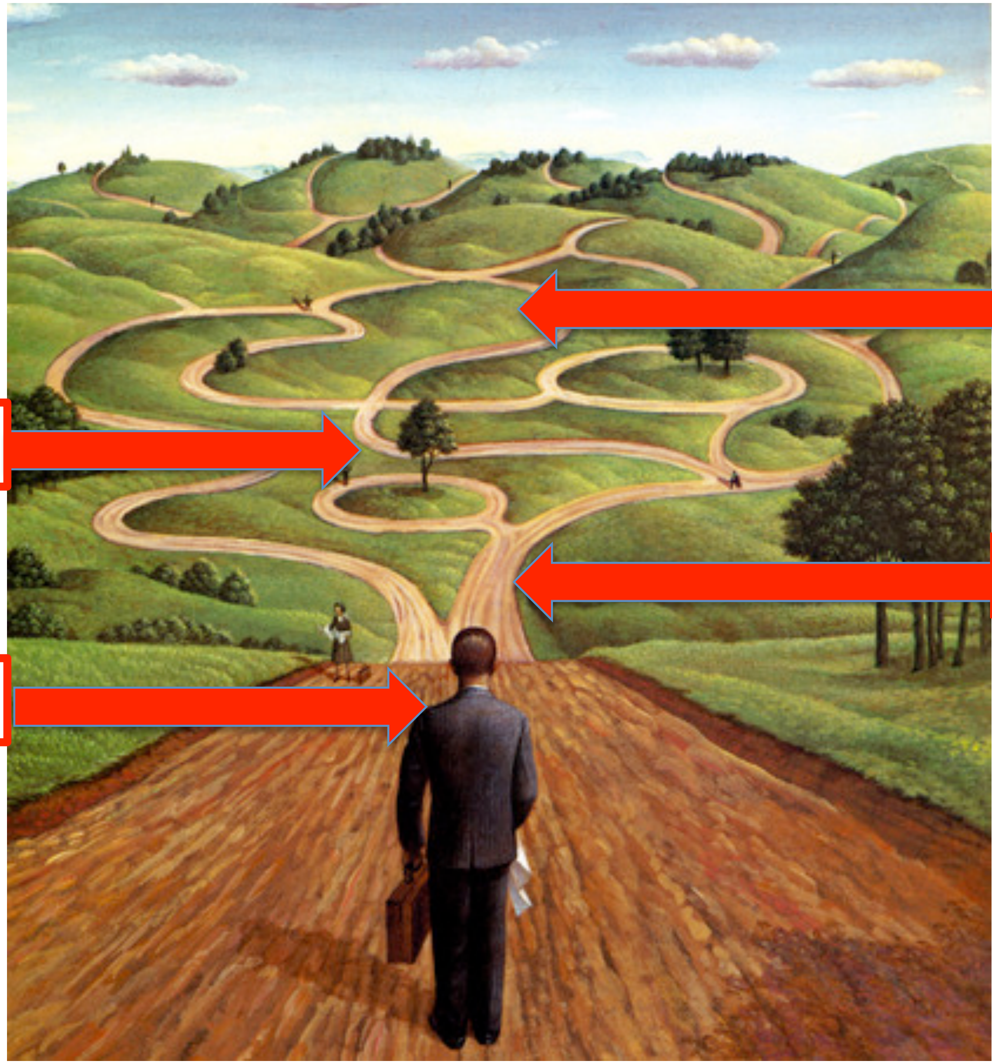


BELLE II

GPD Run3 data

Full Run2 dataset

Outlook



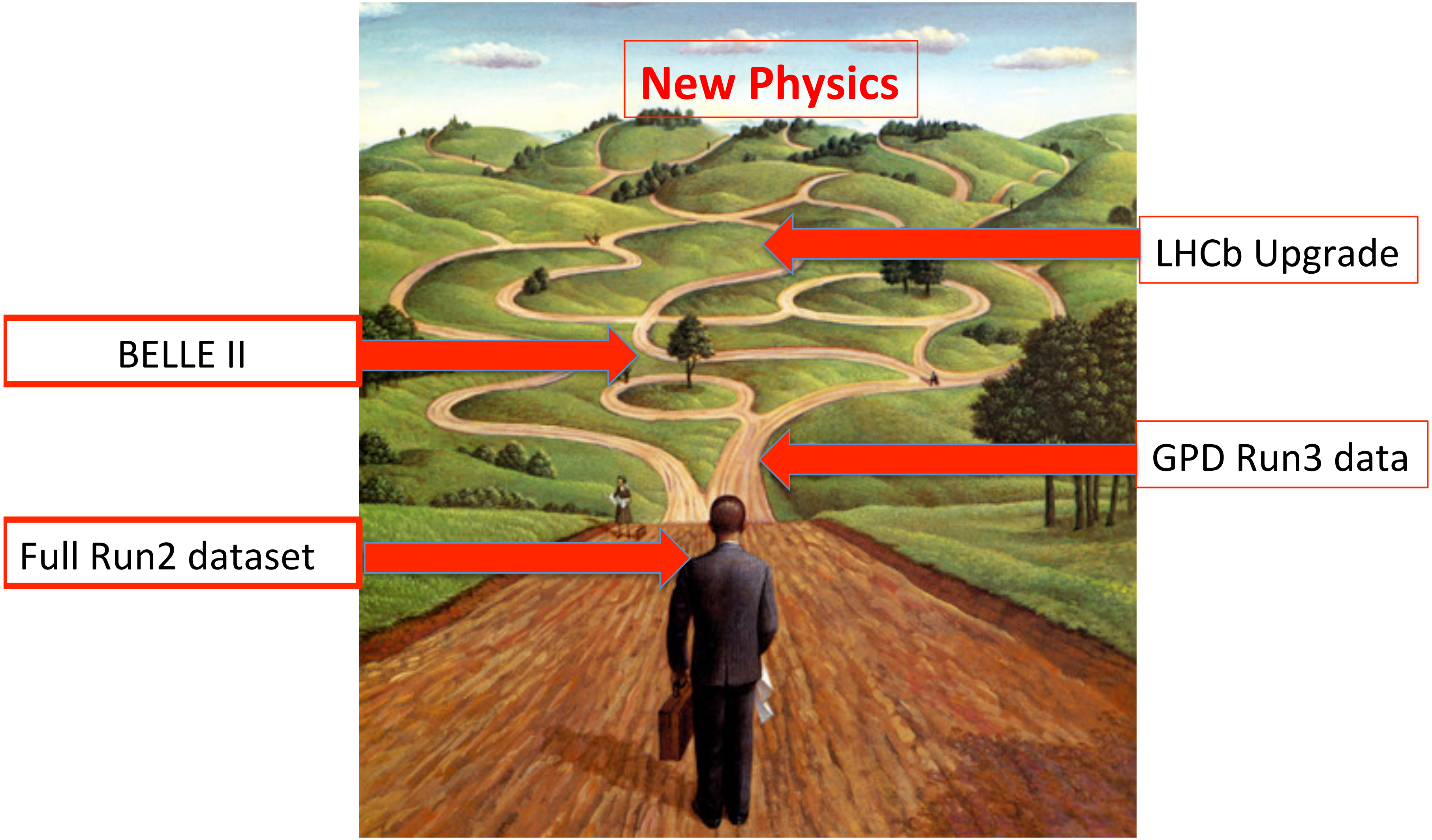
BELLE II

Full Run2 dataset

LHCb Upgrade

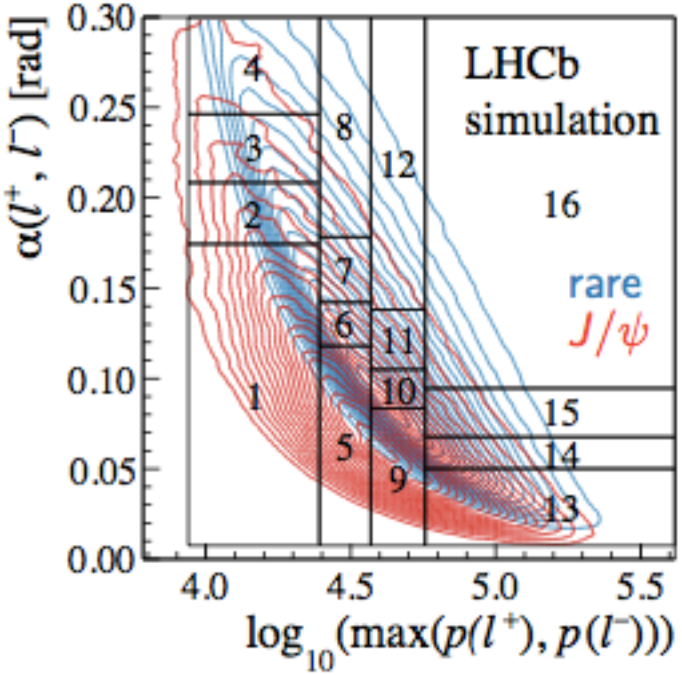
GPD Run3 data

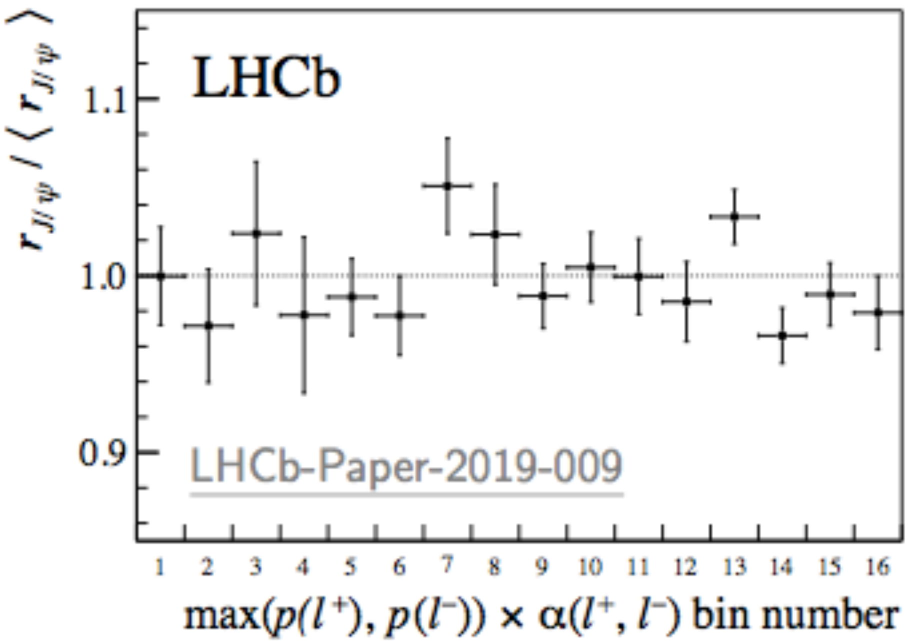
Outlook


New Physics
LHCb Upgrade
BELLE II
GPD Run3 data
Full Run2 dataset

Backup

R_J/ψ


LHCb
simulation
rare
J/ψ
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
0.30
0.25
0.20
0.15
0.10
0.05
0.00
4.0
4.5
5.0
5.5
α(l⁺, l⁻) [rad]
log10(max(p(l⁺), p(l⁻)))


LHCb
LHCb-Paper-2019-009
1.1
1.0
0.9
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
r_J/ψ / ⟨r_J/ψ⟩
max(p(l⁺), p(l⁻)) × α(l⁺, l⁻) bin number

ϕ_s analysis results

Parameter	Value
ϕ_s [rad]	$-0.080 \pm 0.041 \pm 0.006$
$\lvert\lambda\rvert$	$1.006 \pm 0.016 \pm 0.006$
$\Gamma_s - \Gamma_d$ [ps^{-1}]	$-0.0041 \pm 0.0024 \pm 0.0015$
$\Delta\Gamma_s$ [ps^{-1}]	$0.0772 \pm 0.0077 \pm 0.0026$
Δm_s [ps^{-1}]	$17.705 \pm 0.059 \pm 0.018$
$\lvert A_\perp\rvert^2$	$0.2457 \pm 0.0040 \pm 0.0019$
$\lvert A_0\rvert^2$	$0.5186 \pm 0.0029 \pm 0.0024$
$\delta_\perp - \delta_0$	$2.64 \pm 0.13 \pm 0.10$
$\delta_\parallel - \delta_0$	$3.061^{+0.084}_{-0.073} \pm 0.037$

LHCb