Rare decays of beauty baryons

penguins: wikimedia commons; photo: VL

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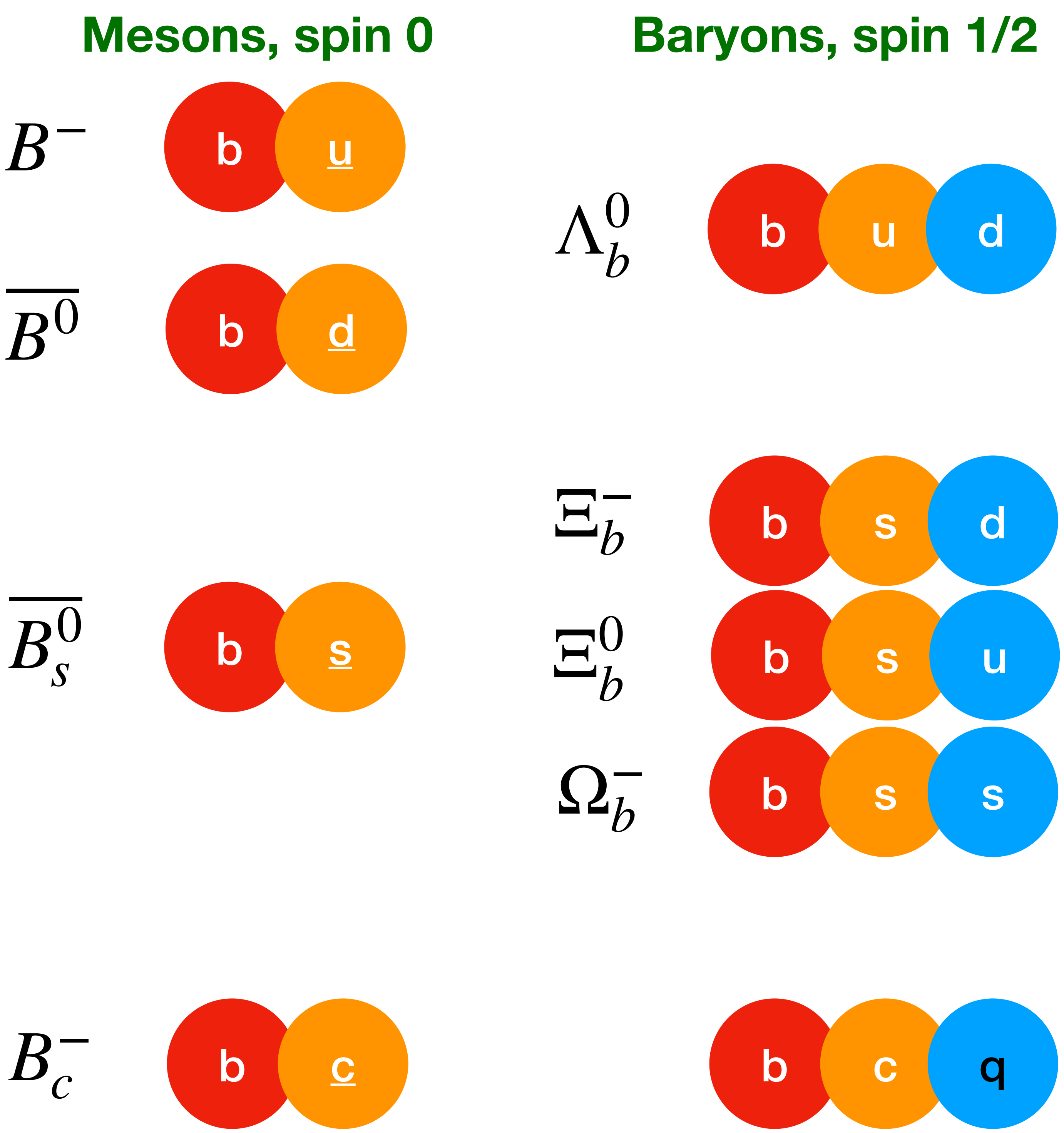
European Research Council

Jahrestreffen der deutschen LHCb-Gruppen
Bonn, 6 October 2020

Welcome to our zoo

- Weakly-decaying beauty hadrons:



There are many heavier states which decay strongly/EM to these listed states.

q = u,d,s,c,b

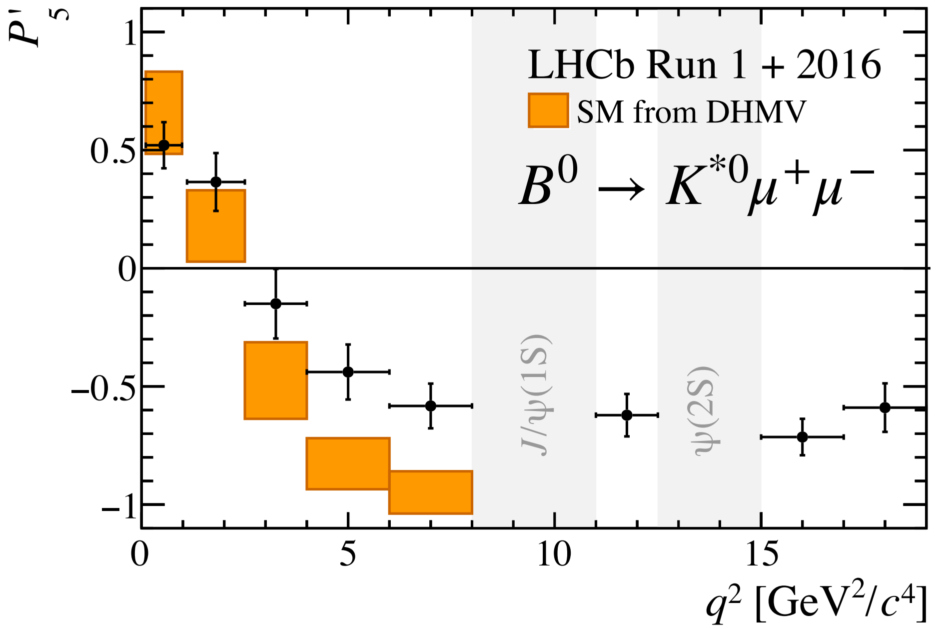
not yet discovered!

Anomalies in $b \to s\ell^+\ell^-$ decays

- Nice overview in yesterday's talks: anomalies in rare B-meson decays

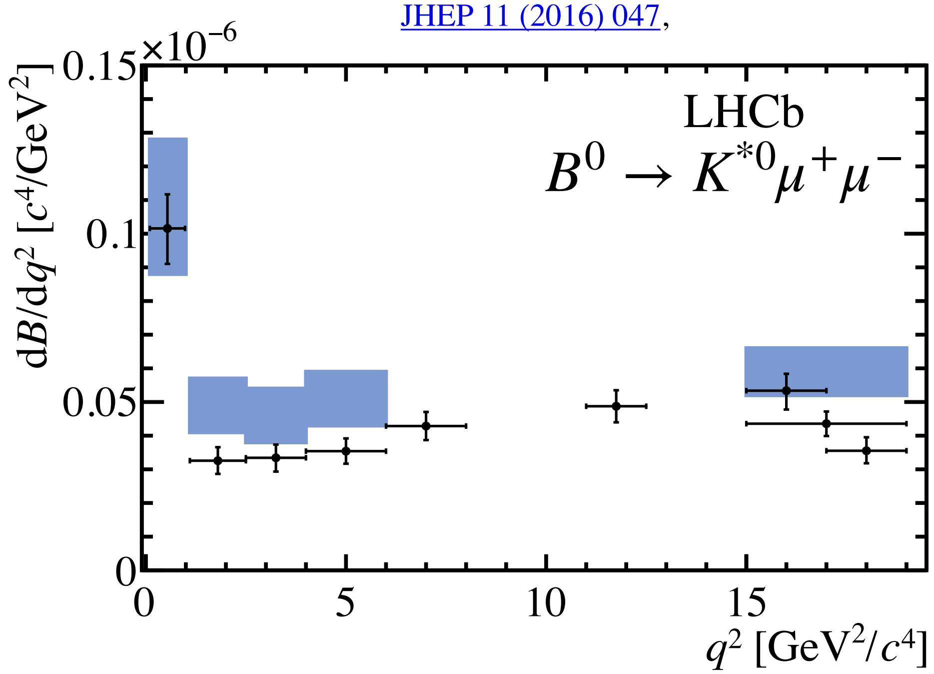
Angular observables

Phys. Rev. Lett. 125 (2020) 011802



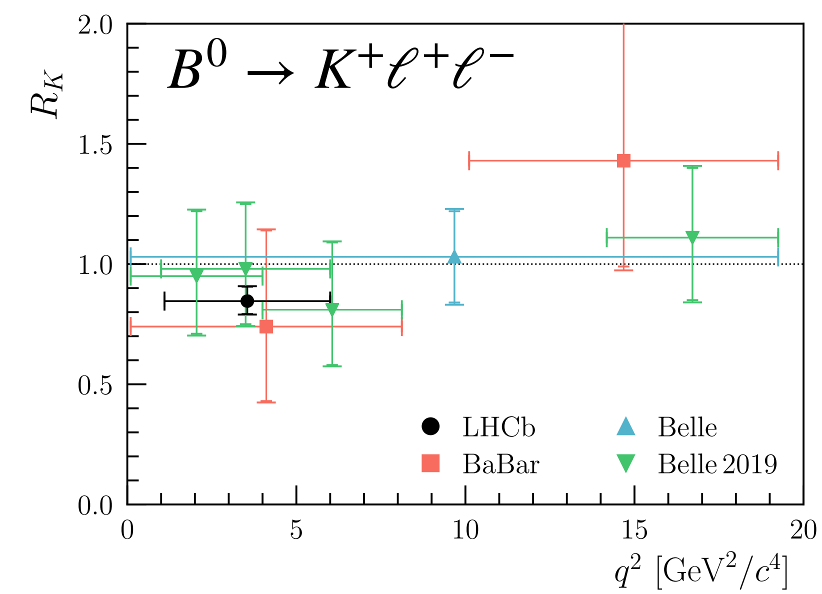
Differential rates

JHEP 11 (2016) 047,



Lepton Universality

Phys. Rev. Lett. 122 (2019) 191801

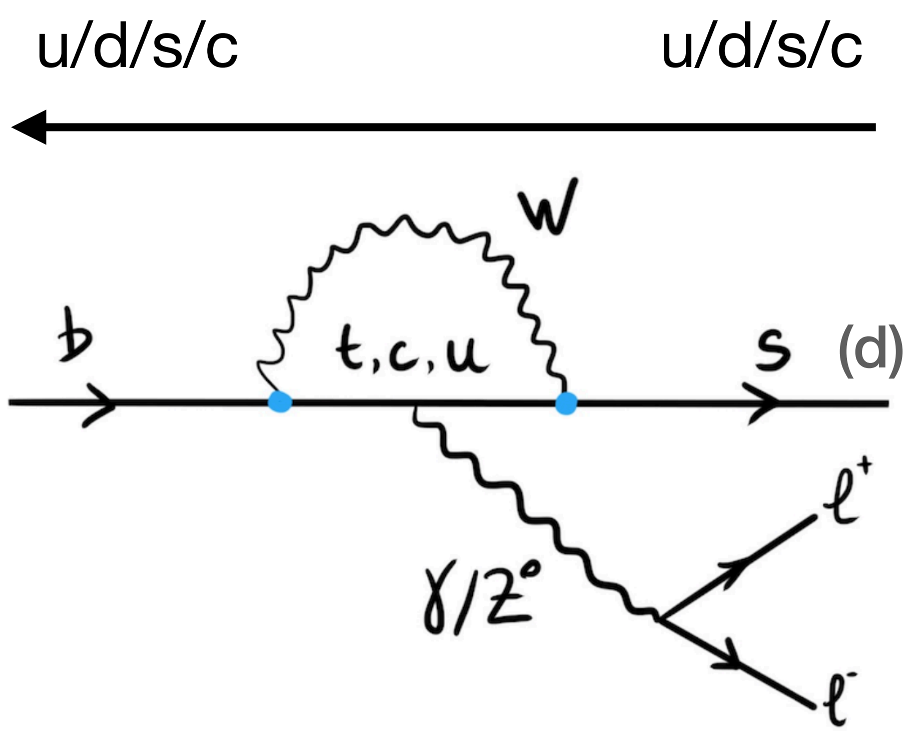


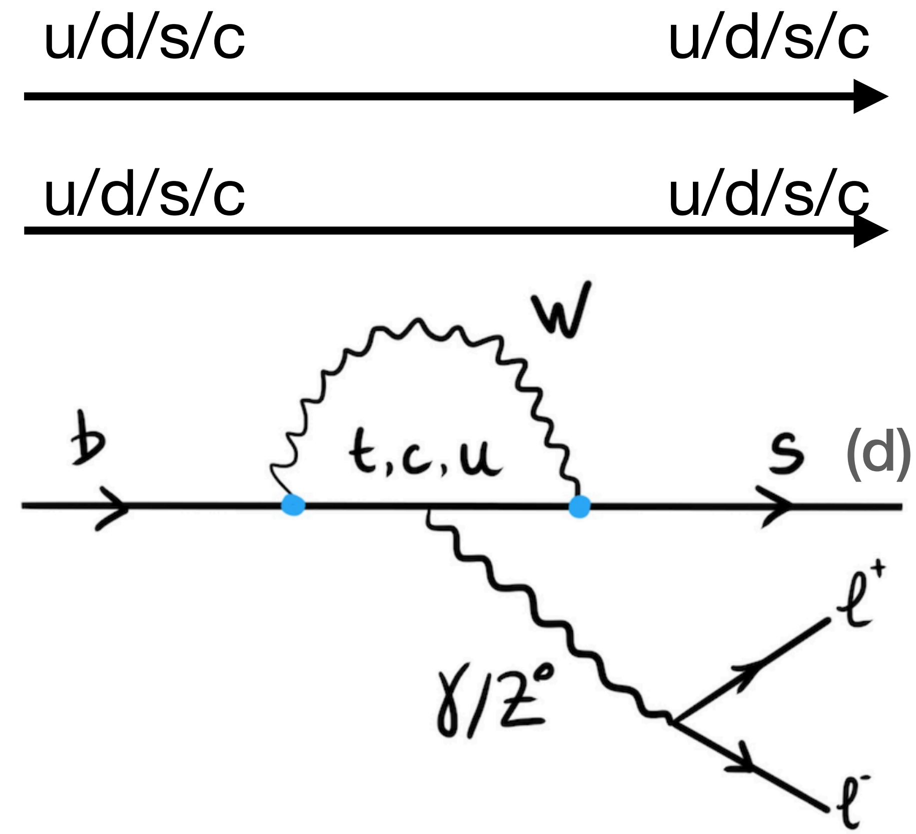
- Beauty **baryons** historically got much less attention: they cannot be produced at B factories
  - Studied at Tevatron and LHC
  - Still, at LHCb: only ~12% publications on rare decays study baryons.
  - This talk: will show the possibilities in baryon decays

I will mostly be talking about $b \to s\ell^+\ell^-$ transitions, opening the scope towards the end of my talk.

$b \to s\ell^+\ell^-$ and baryons

Rare $b \to s\ell^+\ell^-$ transition:





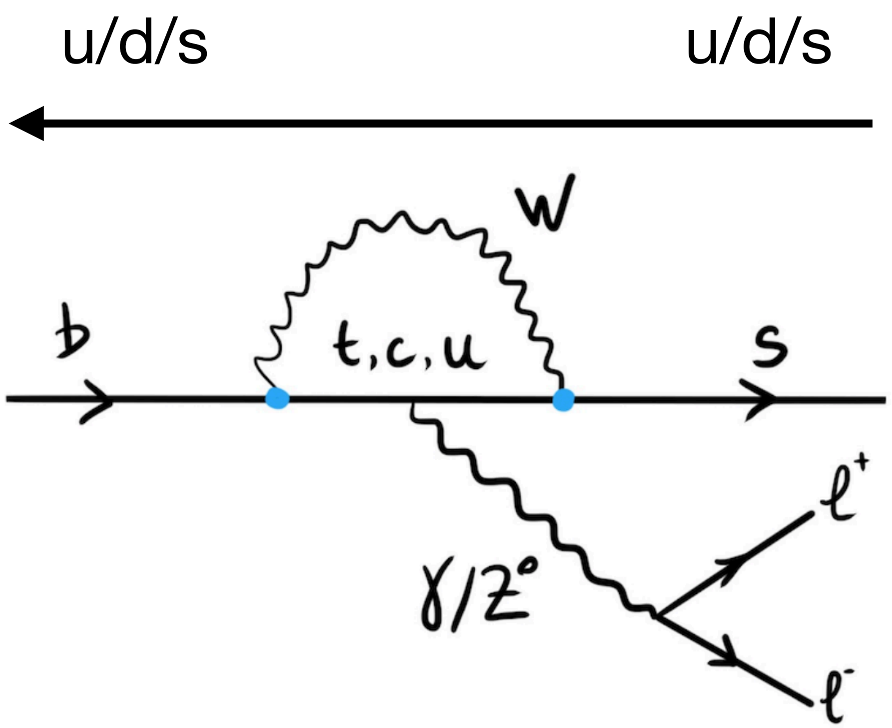
drawing by Y.Amhis

Can baryons bring additional knowledge?

- **Spin of the initial b-baryon is always 1/2**
  - All weakly-decaying B mesons are spin-0: **baryons bring more observables**
  - **Rich angular structure**, especially in cascade decays
  - Baryons can be produced polarised (not easy at the LHC, it seems)
- **Complementarity to B-meson decays:**
  - Expect similar deviations from SM as in meson sector
  - We can test if BSM couplings are spin-dependent
  - But: spectator system is a diquark -> **different hadronic uncertainties**
  - **Different experimental backgrounds** & challenges
- Our world is made of baryons, we should study them!

Which rare decays?

- **Mesons:**



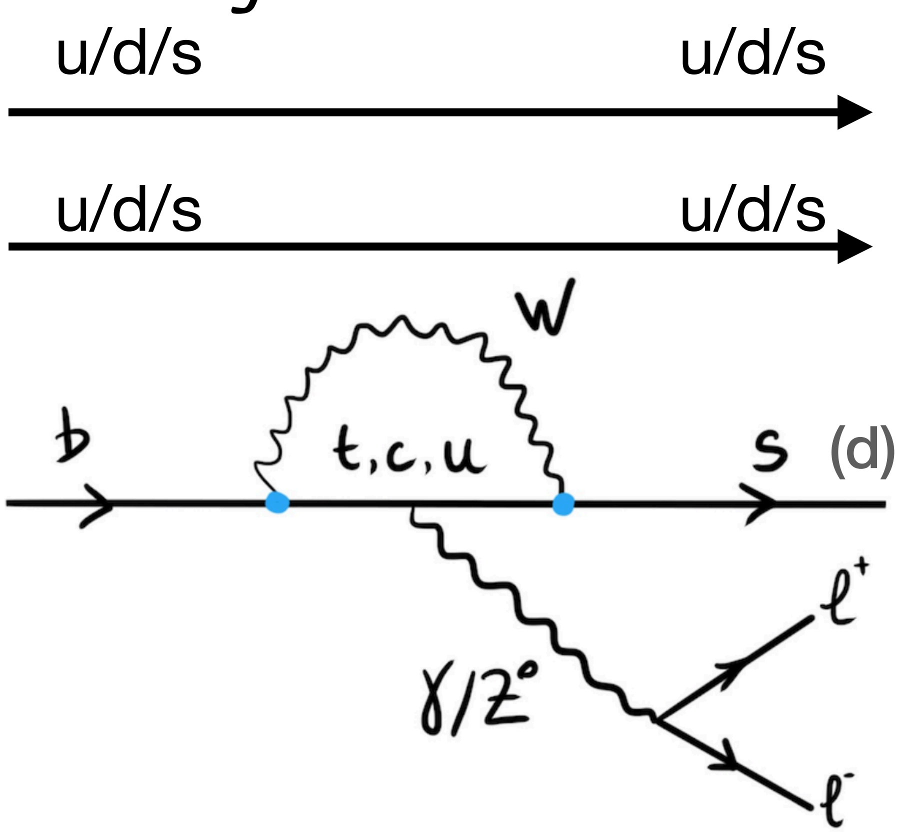
meson spin transitions:

$0 \to 0$	$0 \to 1$	$0 \to 2$
$B \to K\ell^+\ell^-$	$B \to K^*\ell^+\ell^-$	$B \to K_2^*(1430)\ell^+\ell^-$
$B_s \to f_0(980)\ell^+\ell^-$	$B_s \to \phi\ell^+\ell^-$	$B_s \to f_2'(1525)\ell^+\ell^-$

'narrow' final state meson = easy to select
'broad' = difficult **interferences** with overlapping states

Weakly-decaying final state: easier theoretical interpretation

- **Baryons:**

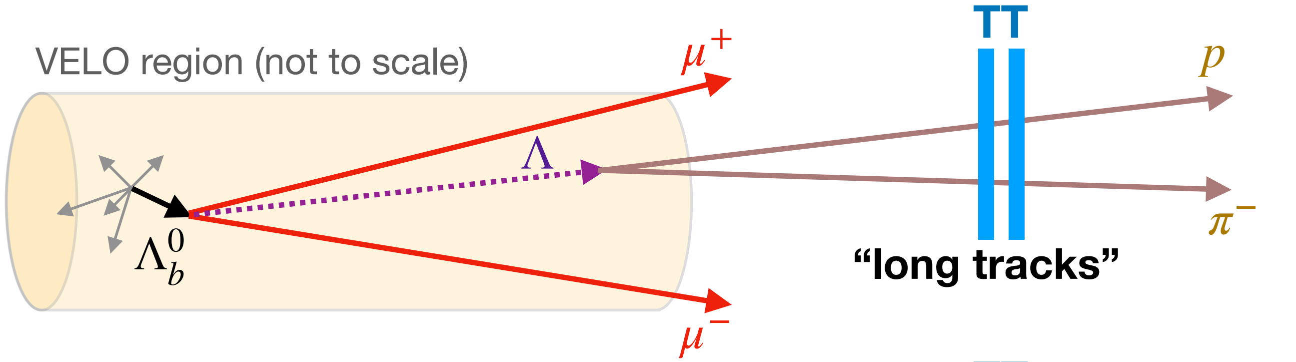


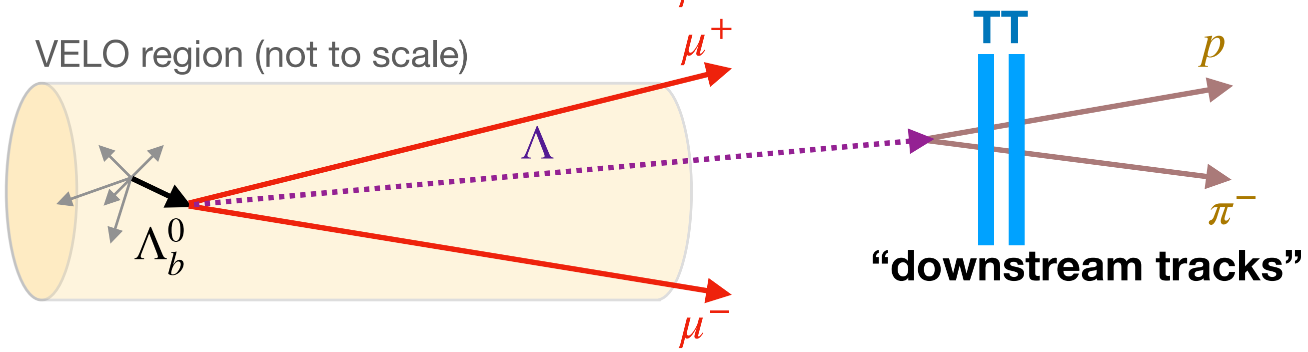
baryon spin transitions:

$1/2 \to 1/2$	$1/2 \to 3/2$	$1/2 \to 5/2$
$\Lambda_b^0 \to \Lambda\ell^+\ell^-$	$\Lambda_b^0 \to \Lambda^*(1520)\ell^+\ell^-$	$\Lambda_b^0 \to \Lambda^*(1820)\ell^+\ell^-$
$\Xi_b \to \Xi\ell^+\ell^-$	$\Xi_b \to \Xi^*(1820)\ell^+\ell^-$	
	$\Omega_b \to \Omega\ell^+\ell^-$	

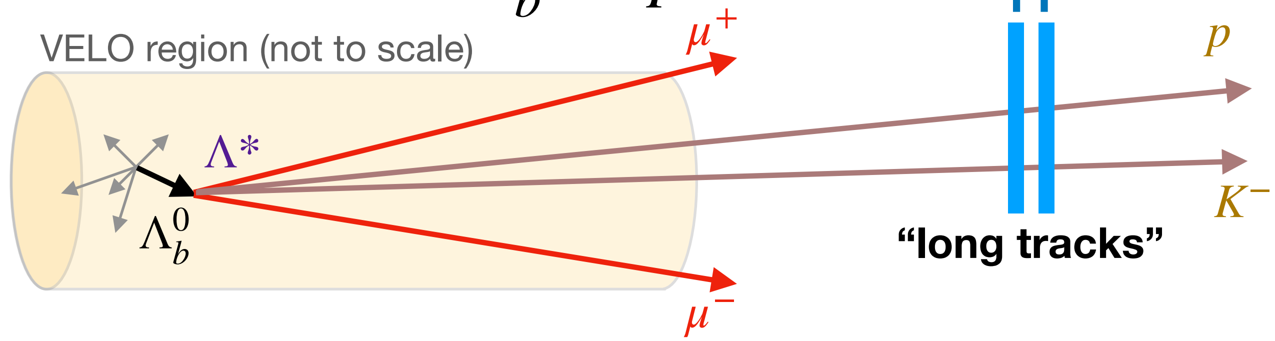
Make your choice (at LHCb)

$$\Lambda_b^0 \to \Lambda \ell^+ \ell^-$$





$$\Lambda_b^0 \to \Lambda^* \ell^+ \ell^-$$
$$\equiv \Lambda_b^0 \to pK \ell^+ \ell^-$$



Λ : ground state, decays weakly, long lifetime

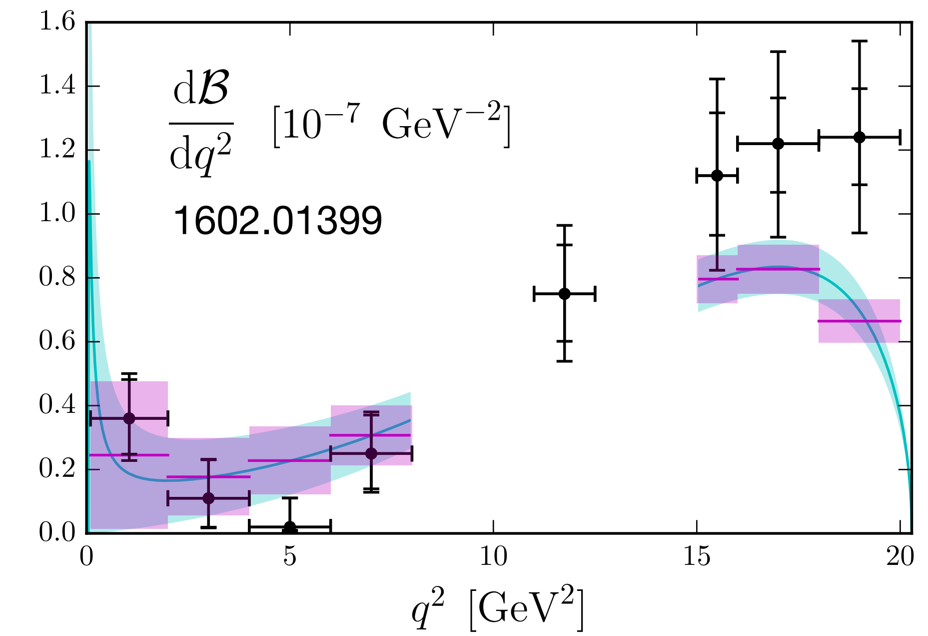
- ✔ unique topology = smaller background
- ✘ lower efficiency to detect in acceptance
- ✘ lower efficiency to reconstruct the vertex
- ✔ clean narrow state
- ✔ easier theoretical predictions

Λ^*: excited state, decays strongly (immediately)

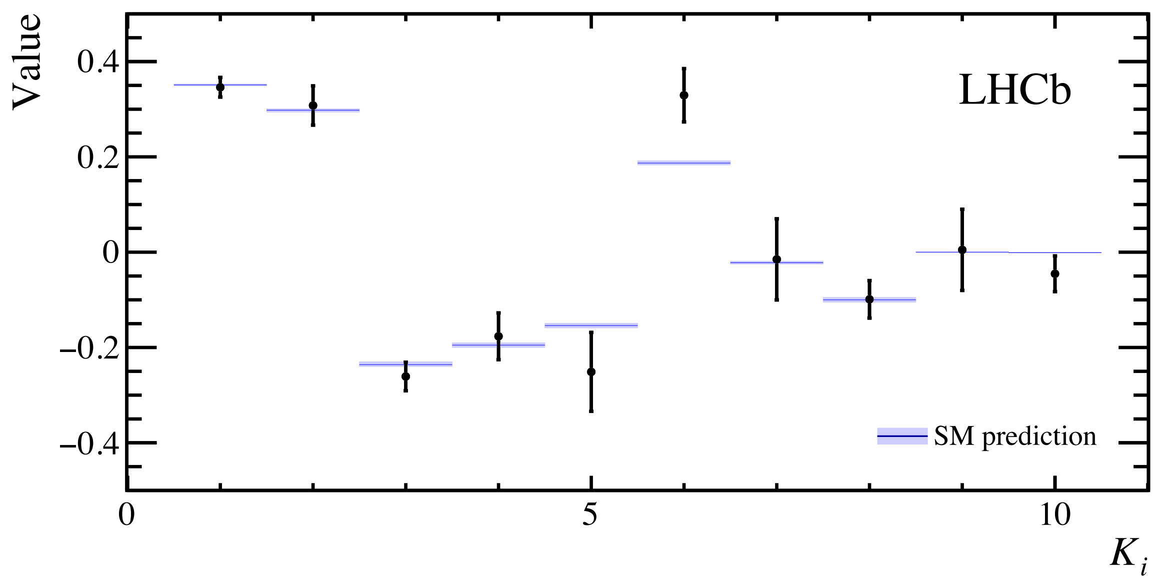
- ✘ larger background — needs hadron PID
- ✔ Λ^* always decays in acceptance
- ✔ easy to reconstruct the vertex
- ✘ interferences with other resonances
- ✘ more difficult theoretical interpretation

Only rare decays of the Λ_b have been studied experimentally so far.

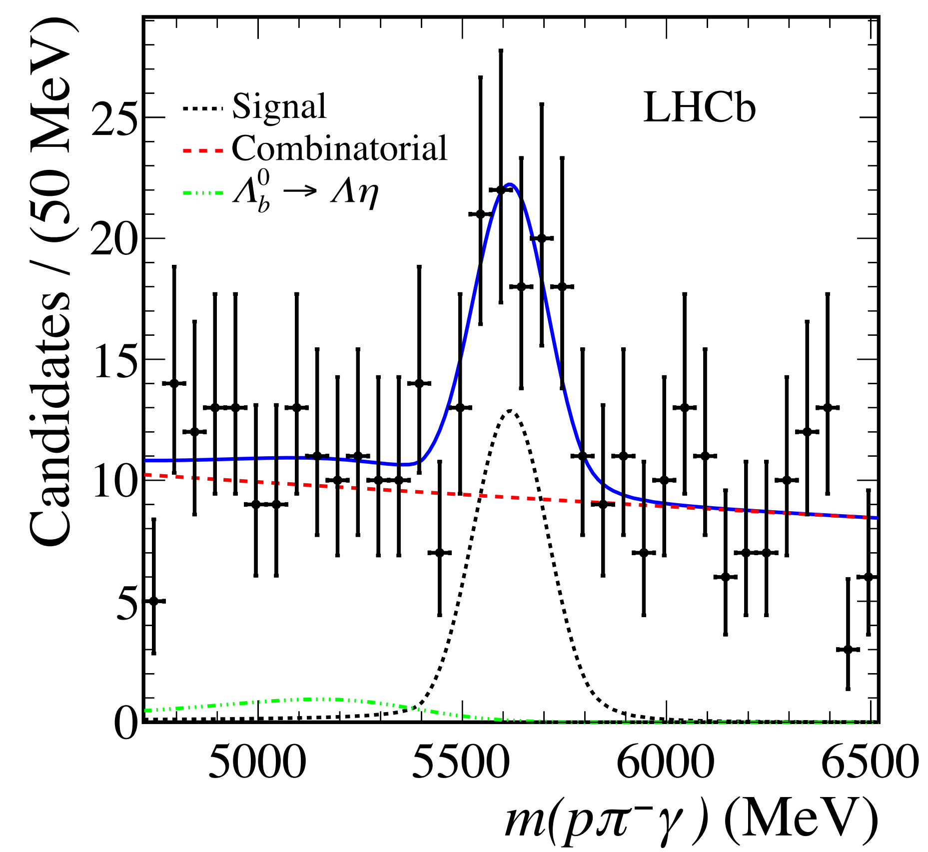
- $\Lambda_b \to \Lambda \mu^+ \mu^-$ studied by CDF and LHCb
- Differential decay rate [JHEP 06 (2015) 115]
  - syst.uncertainty: $\mathscr{B}(\Lambda_b \to J/\psi \Lambda)$



- Angular analysis [JHEP 09 (2018) 146]



- LHCb also observed $\Lambda_b \to \Lambda \gamma$ [PRL 123 (2019) 031801]



$\Lambda_b \to \Lambda \ell^+ \ell^-$

- A lot of theoretical feedback on LHCb results:
  - $\Lambda_b \to \Lambda \mu^+ \mu^-$ results included in the global fits (e.g. 1903.10434)
  - Improved form-factor calculations available
  - Improved predictions for SM and NP scenarios

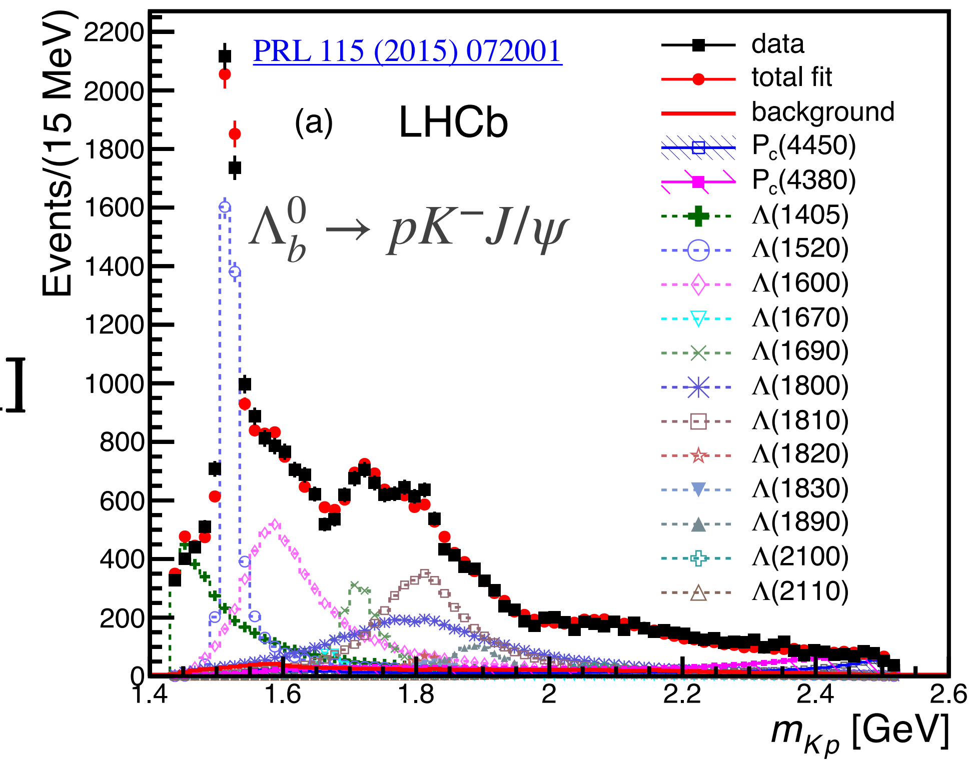
- Prospects:
  - Update of differential BF and angular analysis with full LHCb dataset
  - Precise measurement of $\mathscr{B}(\Lambda_b \to J/\psi \Lambda)$ at LHCb
  - Search for $\Lambda_b \to \Lambda e^+ e^-$ and LFU test R_Λ
  - Measurement of photon polarisation with $\Lambda_b \to \Lambda \gamma$

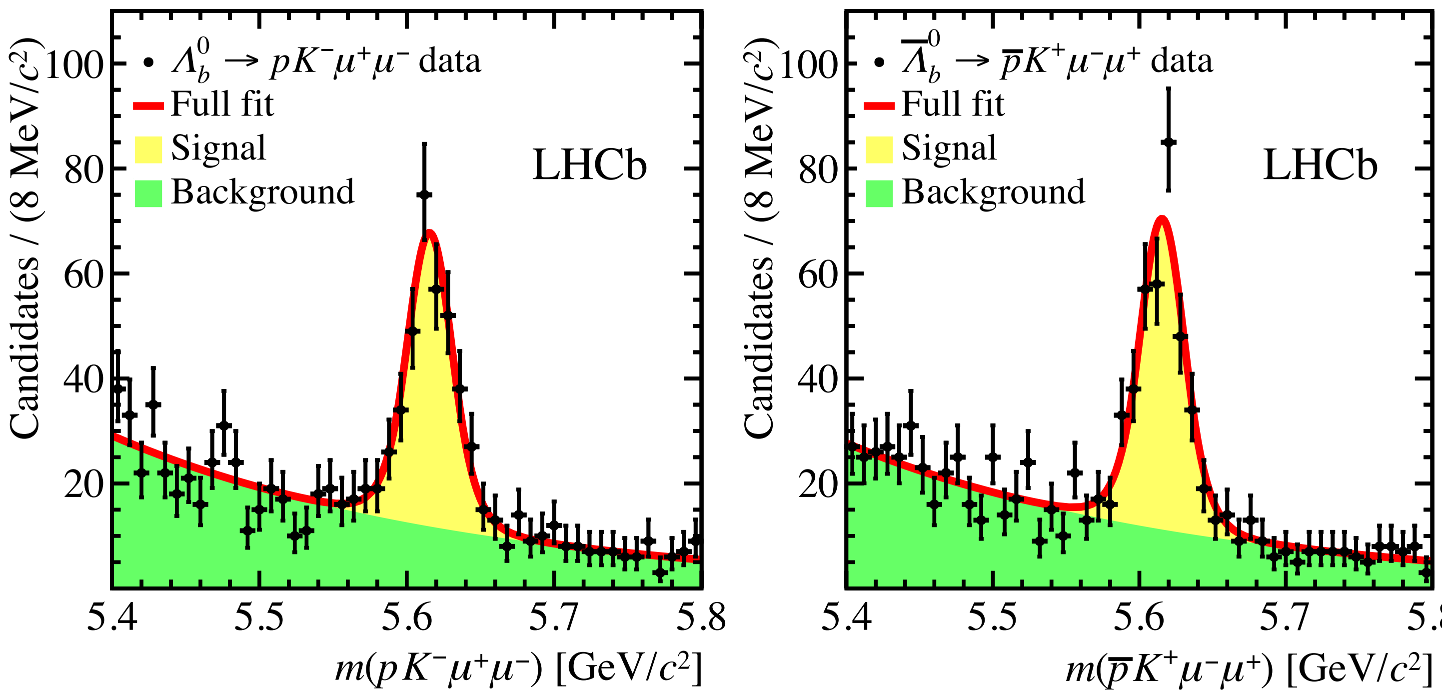
verify whether differential BF disagrees with SM

$\Lambda_b \to \Lambda \mu^+ \mu^-$ gets the most theoretical and experimental attention so far. Can we do more?

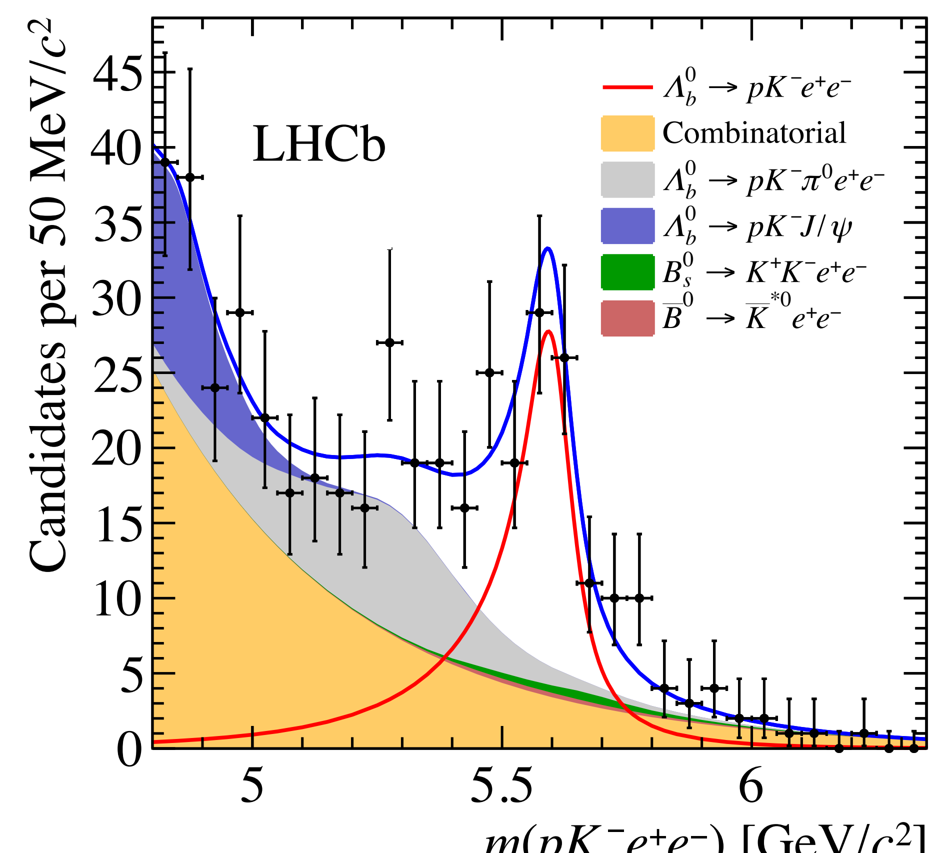
$\Lambda_b \to \Lambda^*(1520)\ell^+\ell^-$

- $\Lambda^*(1520)$ decays strongly to pK, spin 3/2
- Interferes with other resonances
  - For now, studied inclusive m(pK)
- LHCb observed $\Lambda_b \to pK\mu^+\mu^-$ [JHEP 06 (2017) 108]

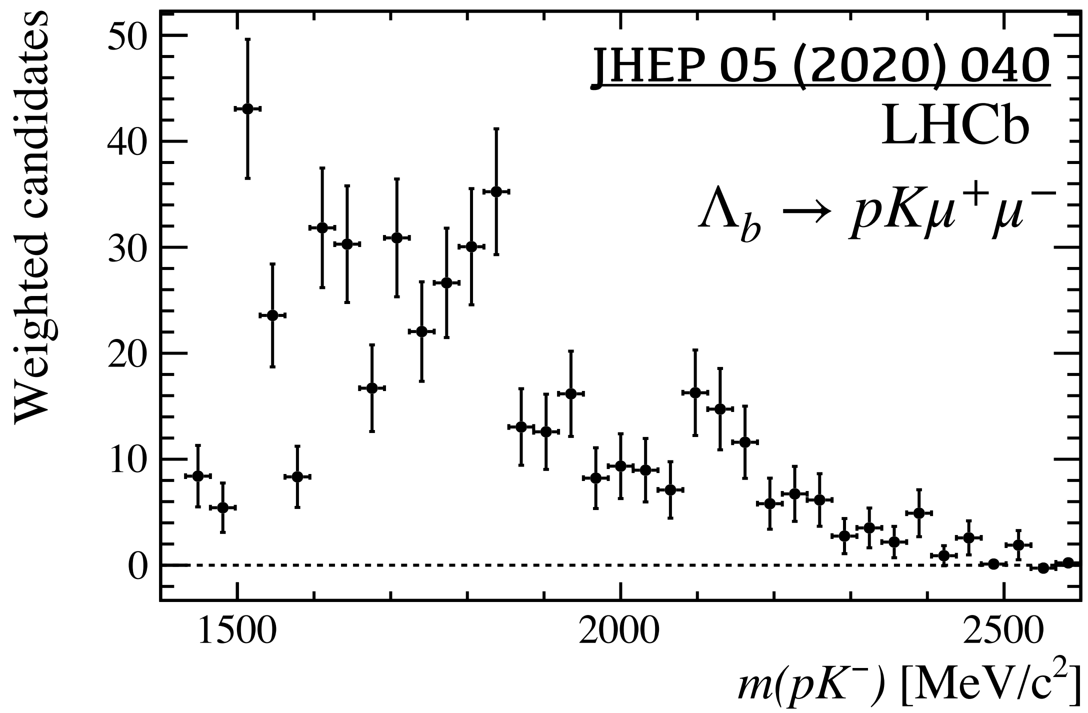




- Also, observed $\Lambda_b \to pKe^+e^-$ [JHEP 05 (2020) 040]
- Test of LFU: $R_{pK} = 0.86^{+0.14}_{-0.11} \pm 0.05$ in $0.1 < q^2 < 6$, $m(pK) < 2.6$ GeV



$\Lambda_b \to \Lambda^*(1520)\ell^+\ell^-$



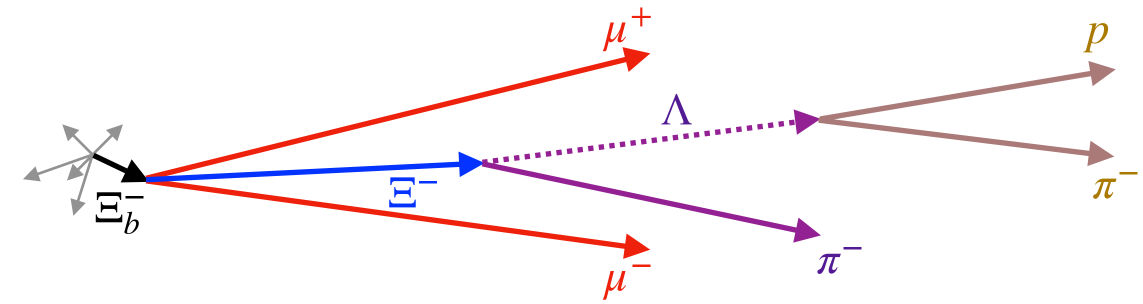
- **Next steps:**
  - differential BF and angular analysis
  - selecting the window around $\Lambda^*(1520)$
  - R_{pK} update with full dataset
- **Theoretical activity:**
  - Form-factors from lattice: 2009.09313
  - diff. rate and angular observables: 2005.09602, *JHEP* 06 (2019) 136, …

- Amplitude analysis of $\Lambda_b \to pK^-\gamma$ (at $q^2 = 0$) to study the composition of all resonances in the pK system
  - Together with the updated $\Lambda_b \to pKJ/\psi$ study, brings valuable input for interpretation of R_{pK} result
  - Theoretical interest in $\Lambda_b \to pK^-\gamma$ [PLB 649 (2007) 152-158]

What about cleaner observables?

$\Xi_b \to \Xi\ell^+\ell^-$

- **Unique cascade topology**
  - **No background from mesons**
  - **Rich angular structure**

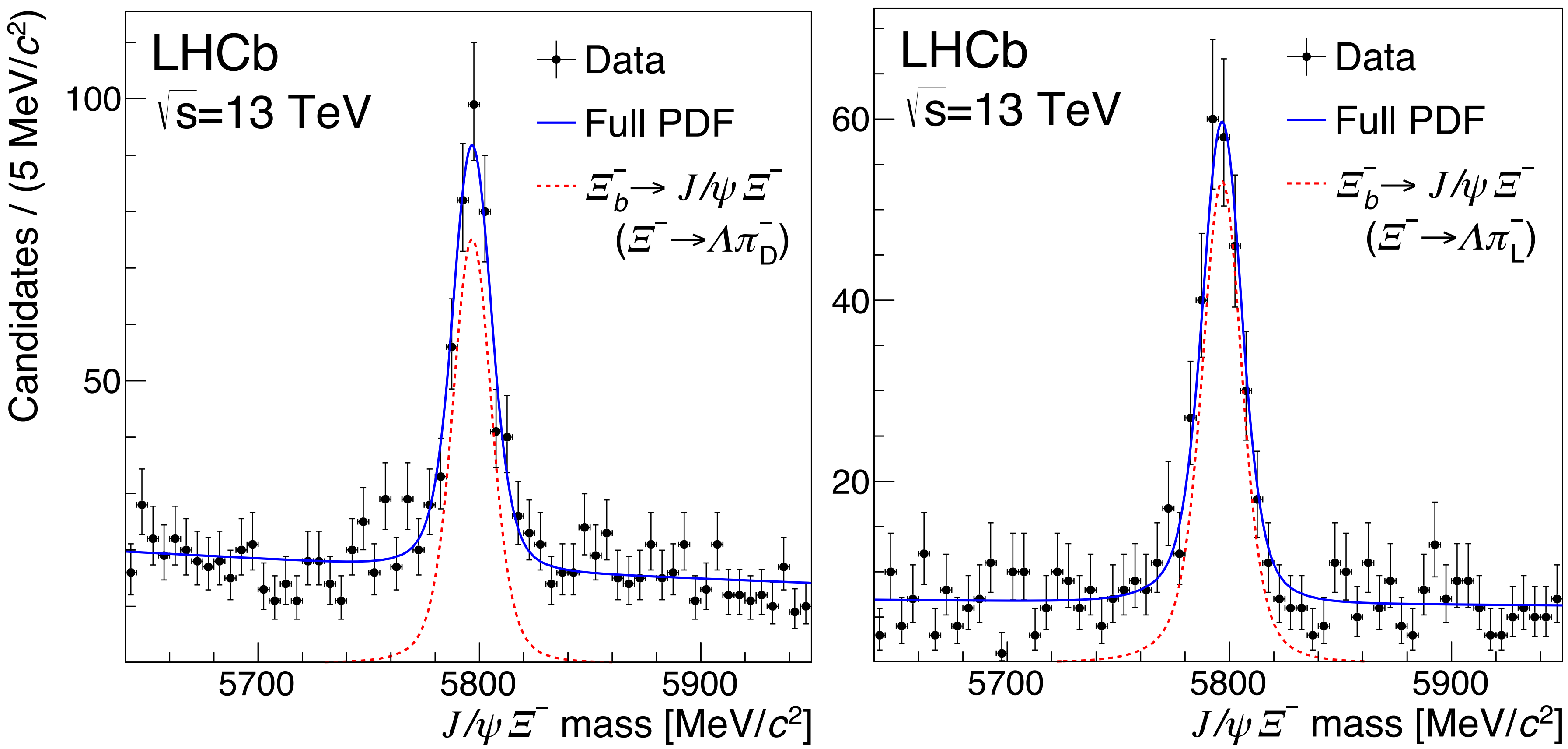


- $\Xi_b \to \Xi\ell^+\ell^-$ is linked via SU(3) symmetry to $\Lambda_b \to \Lambda\ell^+\ell^-$
  - only difference is spectator quark (s vs u/d)
  - expect a similar behavior
  - but: production rate smaller – lower precision

- Th. predictions available: [Int.J.Th.Phys. 59 (2020) 9, 2712-2740] or [1609.09678]
  - Predict BF $\sim 2.3 \times 10^{-6}$ (is it the highest of all $b \to s\ell^+\ell^-$ decays?)
  - enhancement at high q^2 same as in $\Lambda_b \to \Lambda\ell^+\ell^-$

Rare Ξ_b decays never studied before!
Observation of such decays would be a first step.

- LHCb can look for the charged $\Xi_b^- \to \Xi^- \mu^+ \mu^-$



control channel
$\Xi_b^- \to \Xi^- J/\psi$:
2016 data
[PRD99 052006 (2019)]

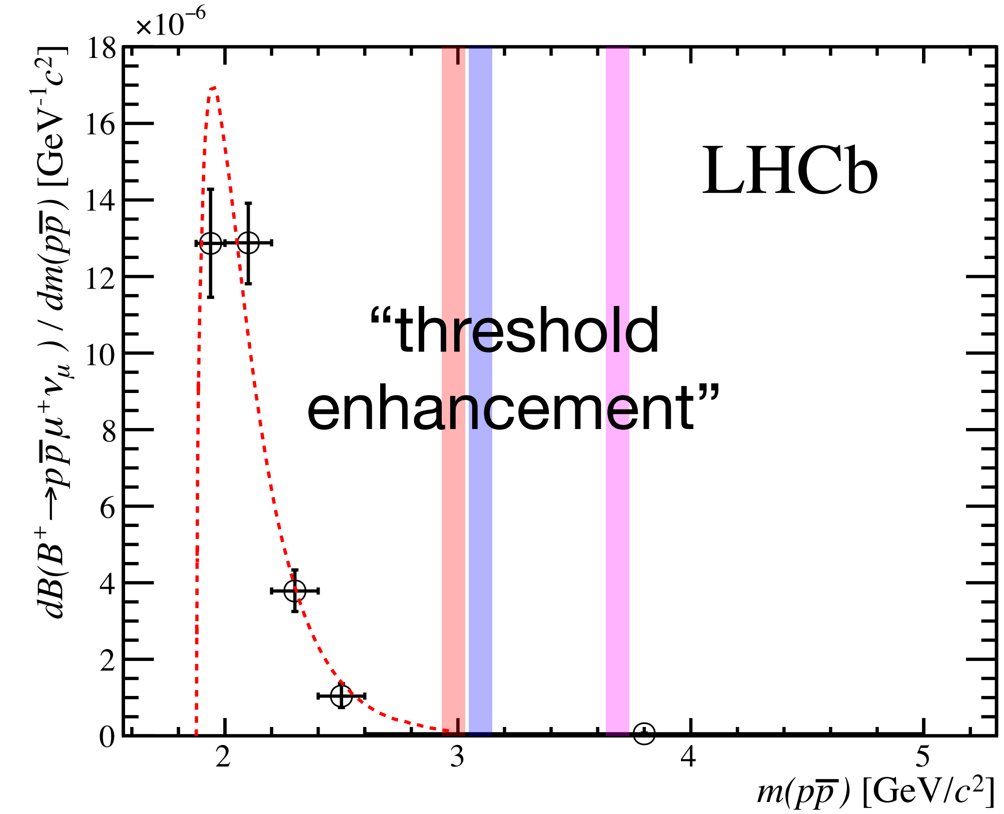
no misidentifications;
low partial-reco from Ξ^*
(see argument in 1007.3632)

- Can also try $\Omega_b^- \to \Omega^- \mu^+ \mu^-$ (same topology)
- Ω is the only known spin-3/2 particle which decays weakly!
  - access to unique observables in angular analyses
  - $\Omega_b^- \to \Omega^- \gamma$: considered as the most attractive radiative baryonic decay
  - "a golden channel to extract the helicity structures of weak effective Hamiltonian" – JHEP12(2011)067 (Siegen group)
- $\Omega_b^- \to \Omega^- \mu^+ \mu^-$ is easier at LHCb than the radiative mode.
- Sensitivity limited by small Ω_b^- production ($f_{\Omega_b} \sim f_{B_c}$)

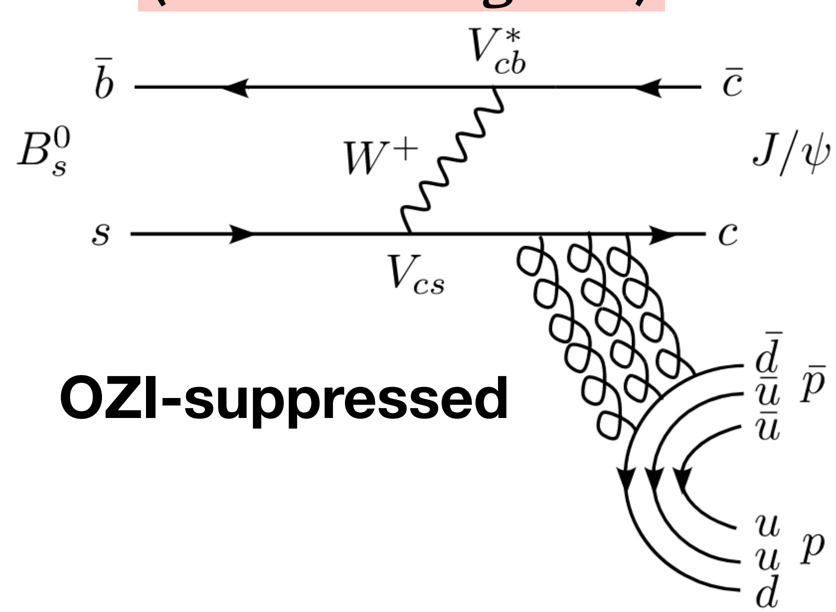
Baryonic B-meson decays

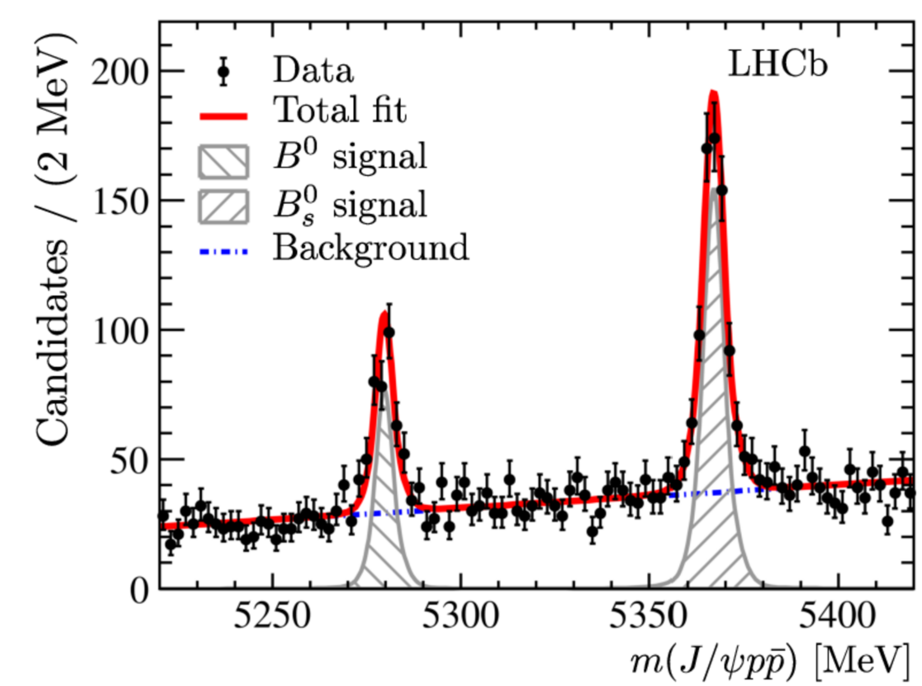
We can also get baryons in decays of B mesons!

- Some curious results from LHCb in tree-level decays:
- $B^+ \to p\bar{p}\mu^+\nu_\mu$ [JHEP 03 (2020) 146]
  - Th: $\mathscr{B} = (1.04 \pm 0.38) \times 10^{-4}$ [PLB704, 495 (2011)]
  - LHCb: $\mathscr{B} = (5.27 \pm 0.35) \times 10^{-6}$
    - factor 20 lower!



- $B_s^0 \to p\bar{p}J/\psi$ [PRL 122 (2019) 191804]
  - Th.expectation: $\mathscr{B} \sim 10^{-9}$ [1412.4900]
  - LHCb: $\mathscr{B} = (3.6 \pm 0.4) \times 10^{-6}$ (2 orders higher!)





Baryonic B-meson decays

- Understanding of decays with $p\bar{p}$ system has to be improved
- What can be happening:
  - Some broad resonance contributing to $p\bar{p}$ system, which has mixing with $s\bar{s}$ component? (enables another diagram)
  - Glueball in $m(p\bar{p})$
  - Pentaquarks in $J/\psi p$ (does not explain the large enhancement?)
  - Predictions do not account for some hadronic dynamics?

Idea: can we study loop-level rare baryonic decays?

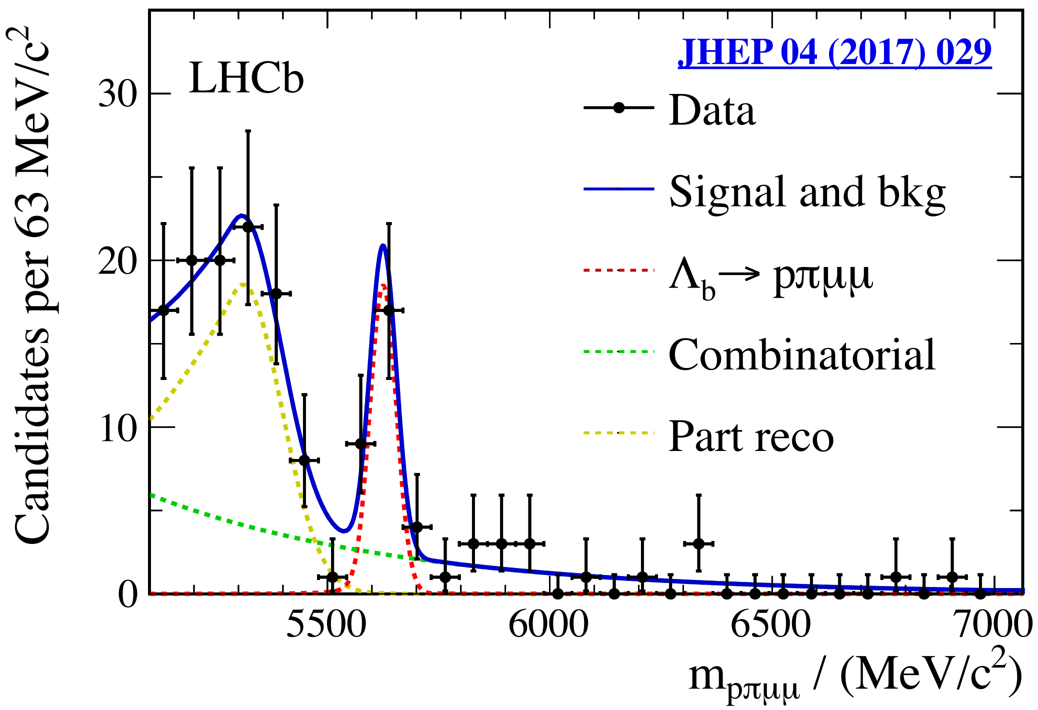
- Search for $B^0_{(s)} \to p\bar{p}\mu^+\mu^-$ is a starting point
  - In case of observation: measured BR can help to understand the $p\bar{p}$ system
  - Combine the "$p\bar{p}$ anomaly" with flavor anomalies?
  - Gathering interest in other similar modes
- Further ideas to be explored in Run 3.

$b \to d\ell^+\ell^-$ with baryons

- Cabibbo-suppressed partner of $b \to s\ell^+\ell^-$, even more rare!

- The simplest baryonic $b \to d\ell^+\ell^-$ transition: $\Lambda_b \to n\ell^+\ell^-$
  - involves a neutron
  - not feasible

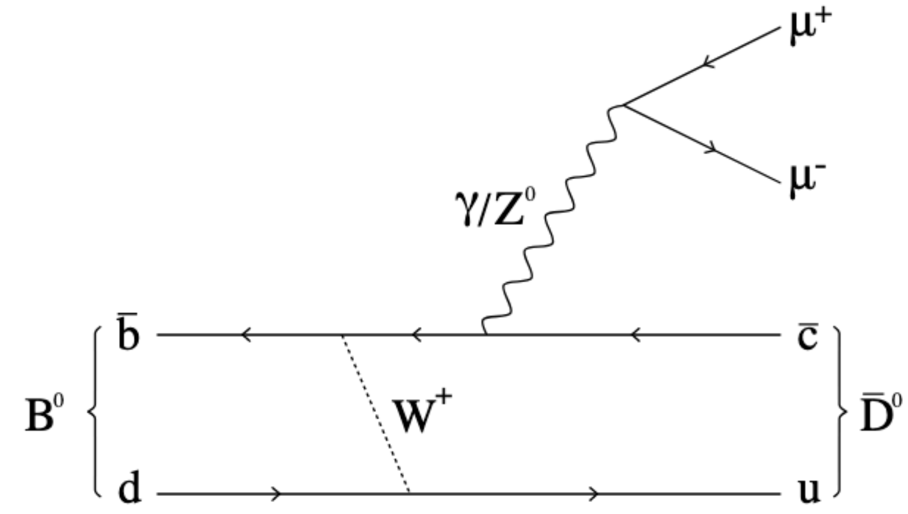
- LHCb has studied $\Lambda_b \to p\pi\mu^+\mu^-$
  - excited N resonances



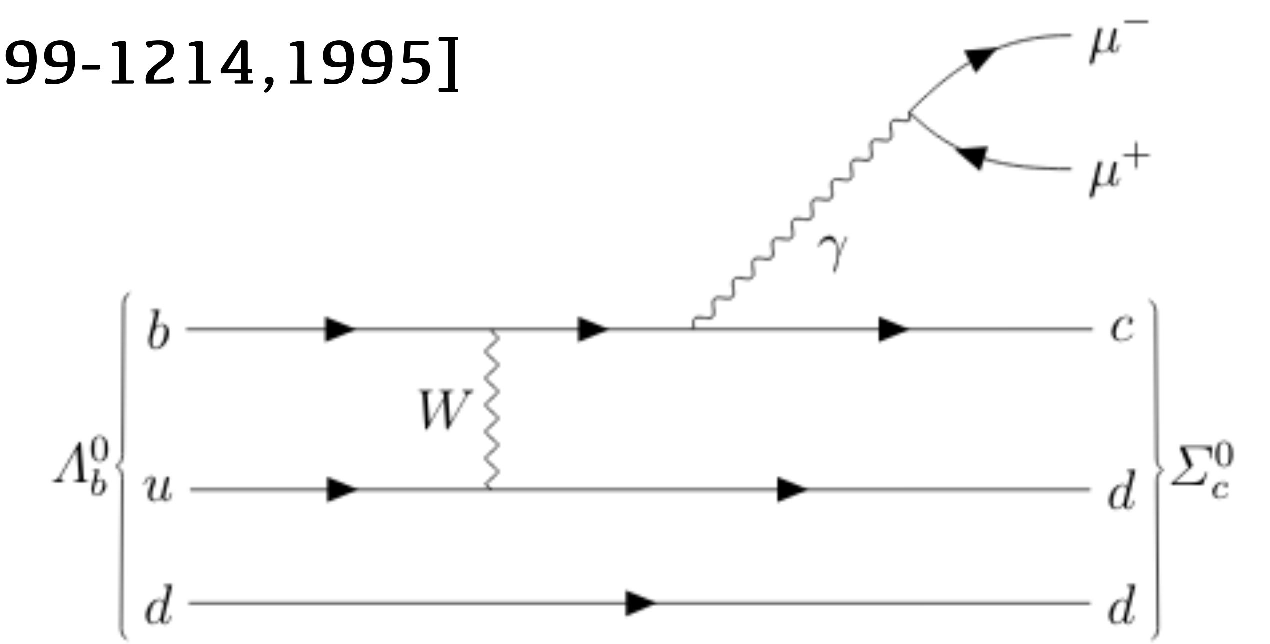
- No much activity beyond that.
- Decays of $\Xi_b \to \Lambda^{(*)}\mu^+\mu^-$ can be accessible in Run 3.

Beyond $b \to s(d)\ell^+\ell^-$

- Mesons: W exchange diagrams
  - example: $B \to D^{(*)}\mu^+\mu^-$



- Same can be done in baryons!
- $\Lambda_b^0 \to \Sigma_c^0\mu^+\mu^-$ or $\Xi_b^0 \to \Xi_c^0\mu^+\mu^-$
- Th: $\mathscr{B}(\Lambda_b^0 \to \Sigma_c^0\gamma) \sim 10^{-6}$ [PRD51:1199-1214,1995]



- Would be interesting to exploit these ideas in Run 3 of LHCb?

Summary

- A plenty of measurements to perform with rare decays of b-baryons
  - Valuable **complementarity** for anomalies seen in **meson sector**
  - **Can only be done at LHC -> we must do it**
    - Some complementarity possible from CMS/ATLAS

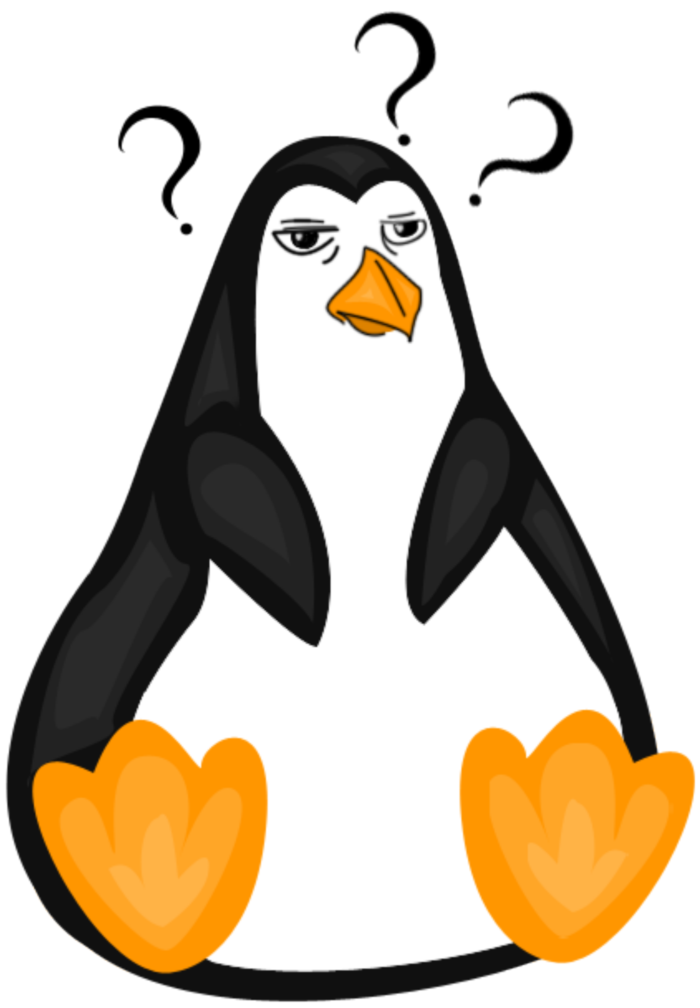
- Many ideas not explored, low hanging fruits
  - Only decays of Λ_b have been studied!

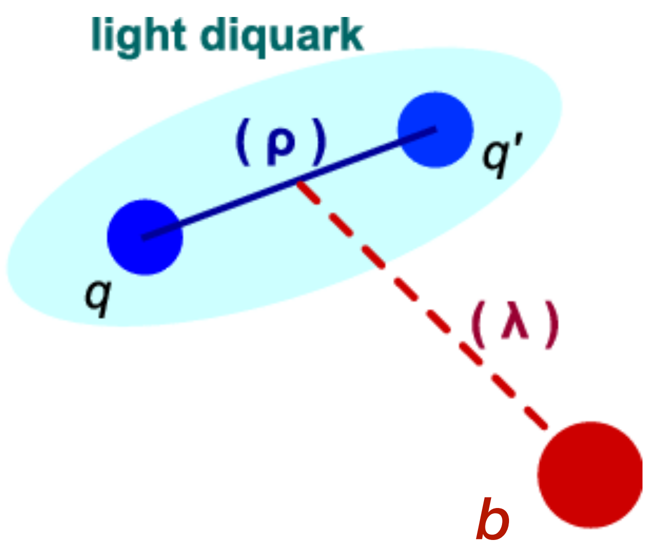
- But: need theoretical and experimental progress on many fronts: form-factors, knowledge of normalisation modes…
  - Absolute BF of Ξ_c and Ω_c (@ Belle II?) – crucial inputs to measure production rates of Ξ_b and Ω_b precisely

- Expertise in Dortmund from both LHCb and theory sides, excellent collaboration opportunities also with other groups

- LHCb Upgrade in progress: potential to improve our triggers
- Interesting opportunities also with charm baryons

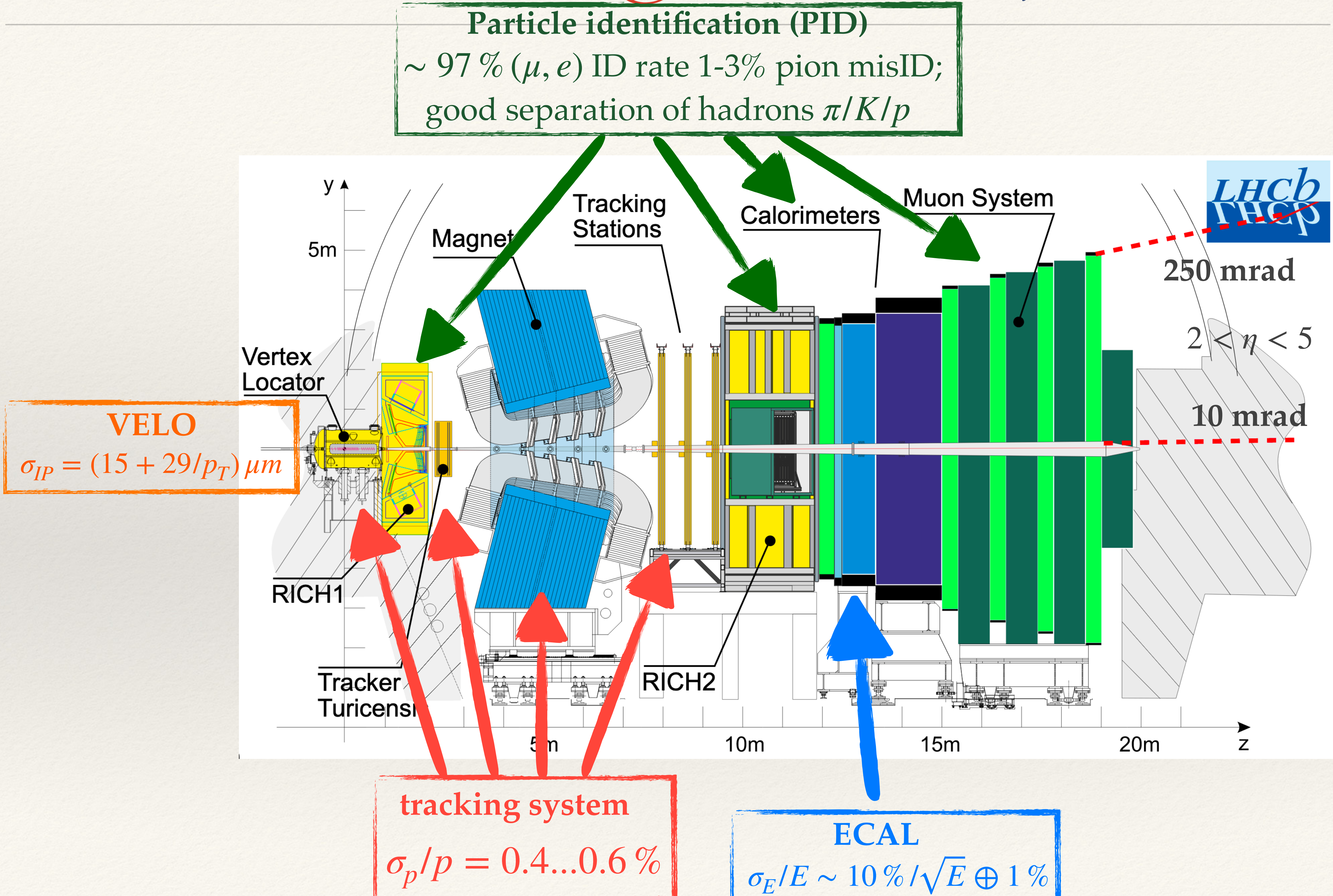
Questions?



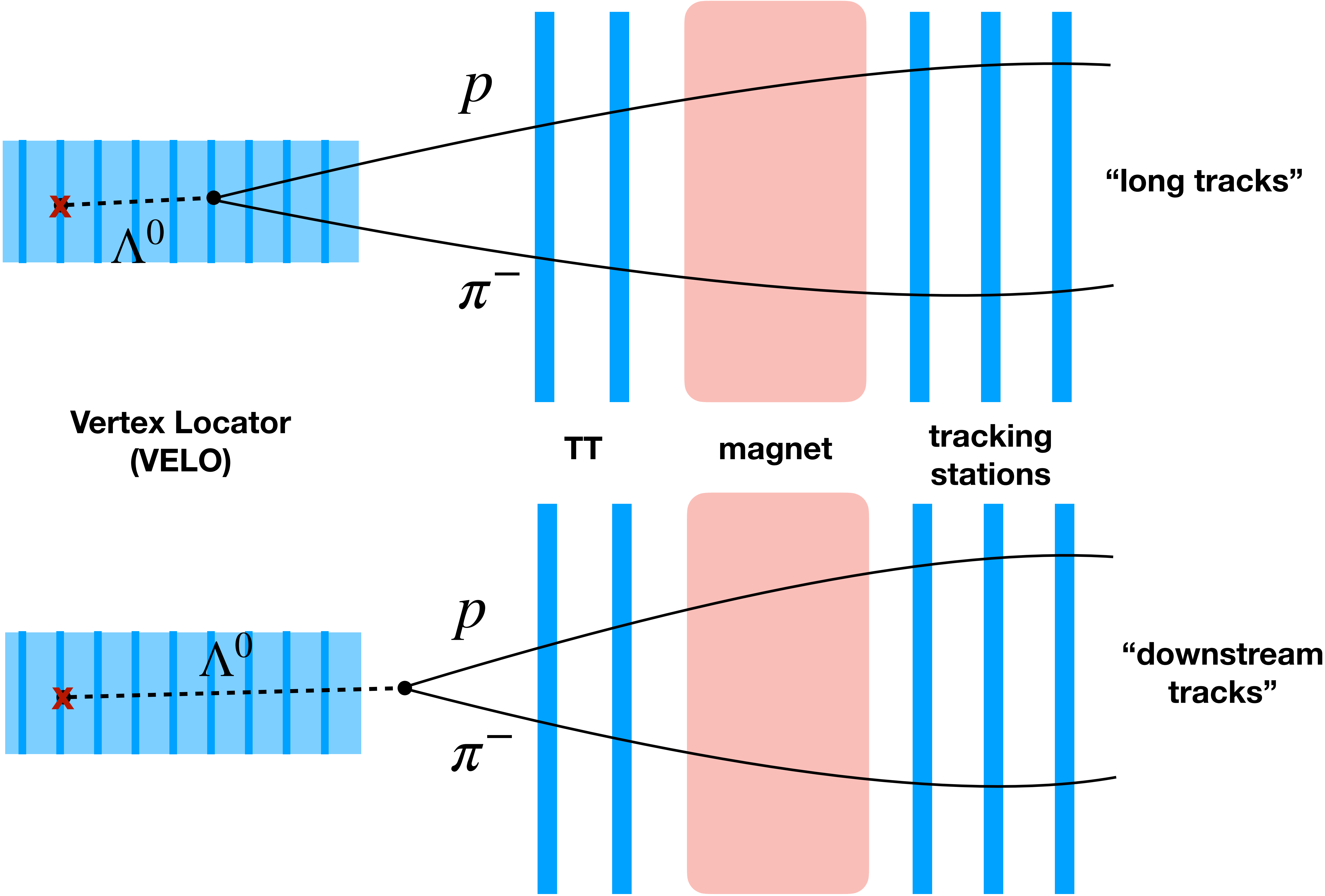


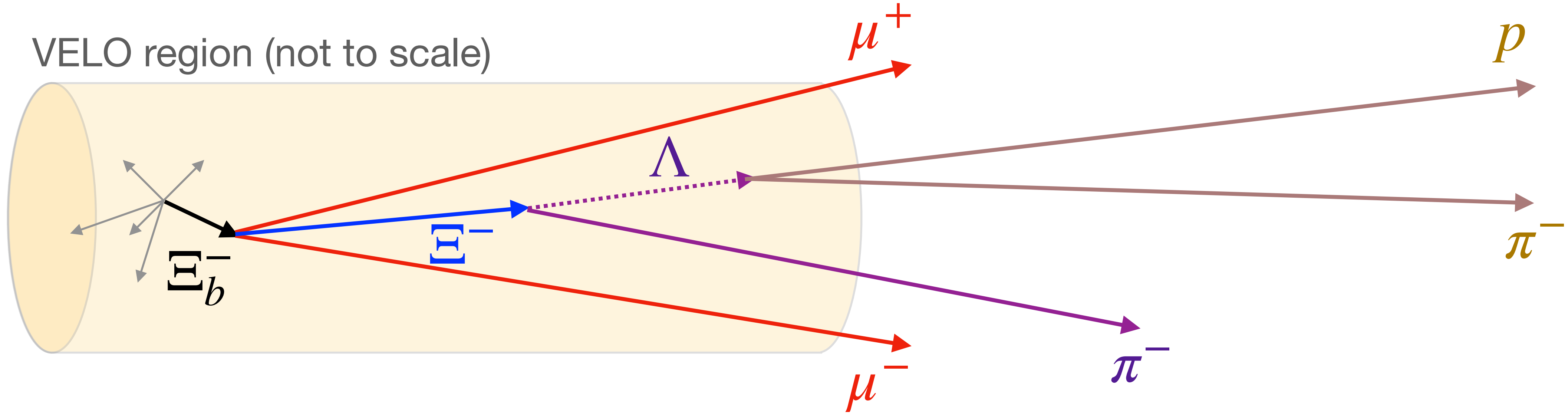
The LHCb detector @ the LHC

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

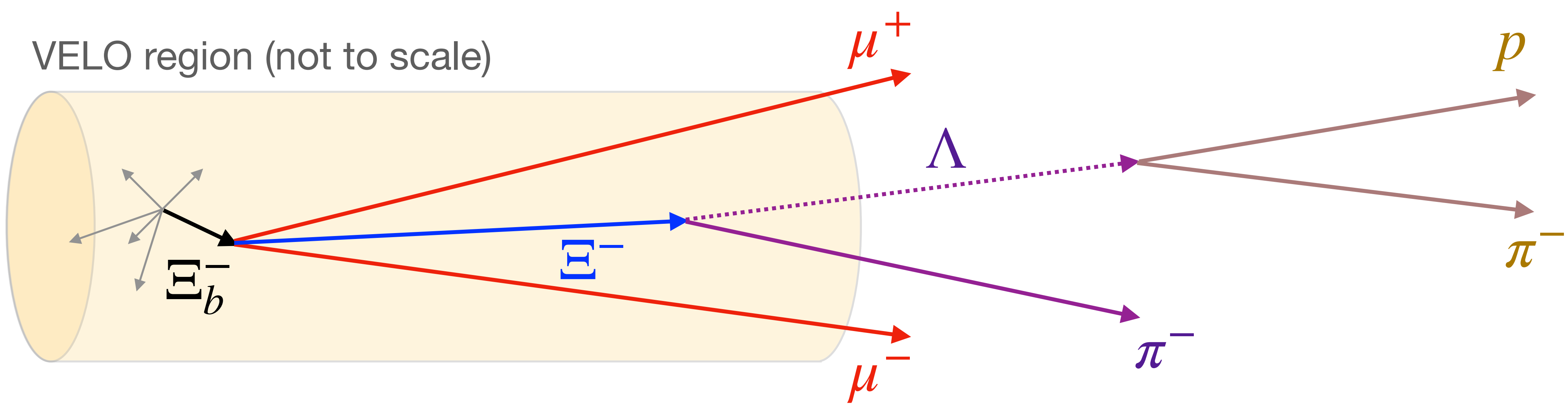


Which configuration is easier?

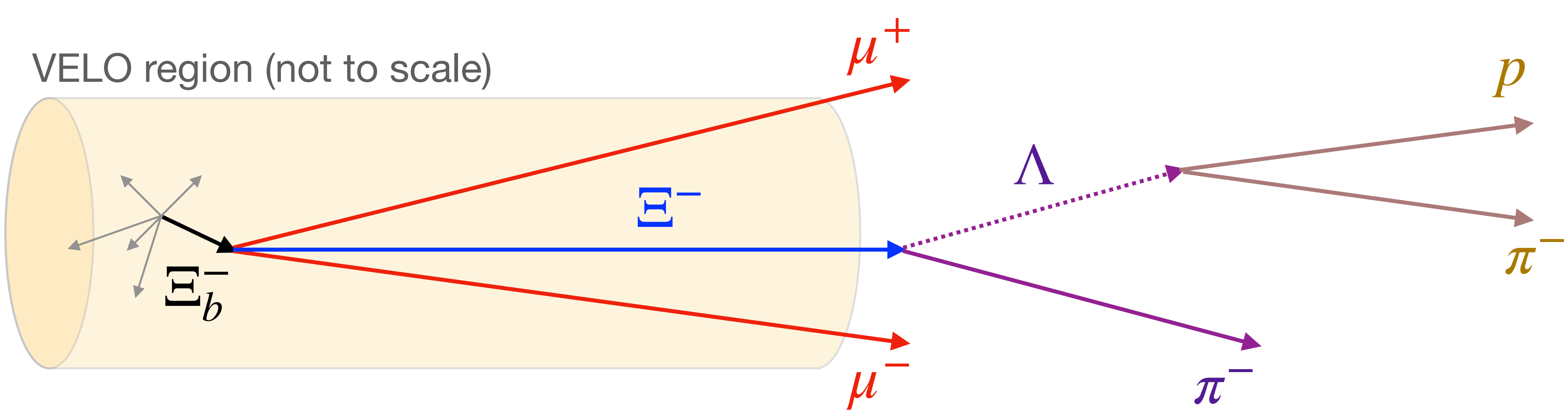



VELO region (not to scale)
μ+
μ−
p
π−
Λ
Ξ−
π−
Ξb−

LLL


VELO region (not to scale)
μ+
μ−
p
π−
Λ
Ξ−
π−
Ξb−

LDD


VELO region (not to scale)
μ+
μ−
p
π−
Λ
Ξ−
π−
Ξb−

DDD

Have rare decays been studied?

Mesons, spin 0

Studied?	Particle	Quarks
yes	B^-	b u
yes	$\overline{B^0}$	b d
yes	$\overline{B^0_s}$	b s
no	B_c^-	b c

Baryons, spin 1/2

Studied?	Particle	Quarks
yes	Λ_b^0	b u d
no	Ξ_b^-	b s d
no	Ξ_b^0	b s u
no	Ω_b^-	b s s
no		b c q

q = u,d,s,c,b

not yet discovered!

Why so?

Production rates

$f(b \to hadron)$

* = large uncertainty
*** = educated guess

Mesons, spin 0

35%	B^-	b $\underline{u}$
35%	$\overline{B^0}$	b $\underline{d}$
8.5%	$\overline{B_s^0}$	b $\underline{s}$
0.3%	B_c^-	b $\underline{c}$

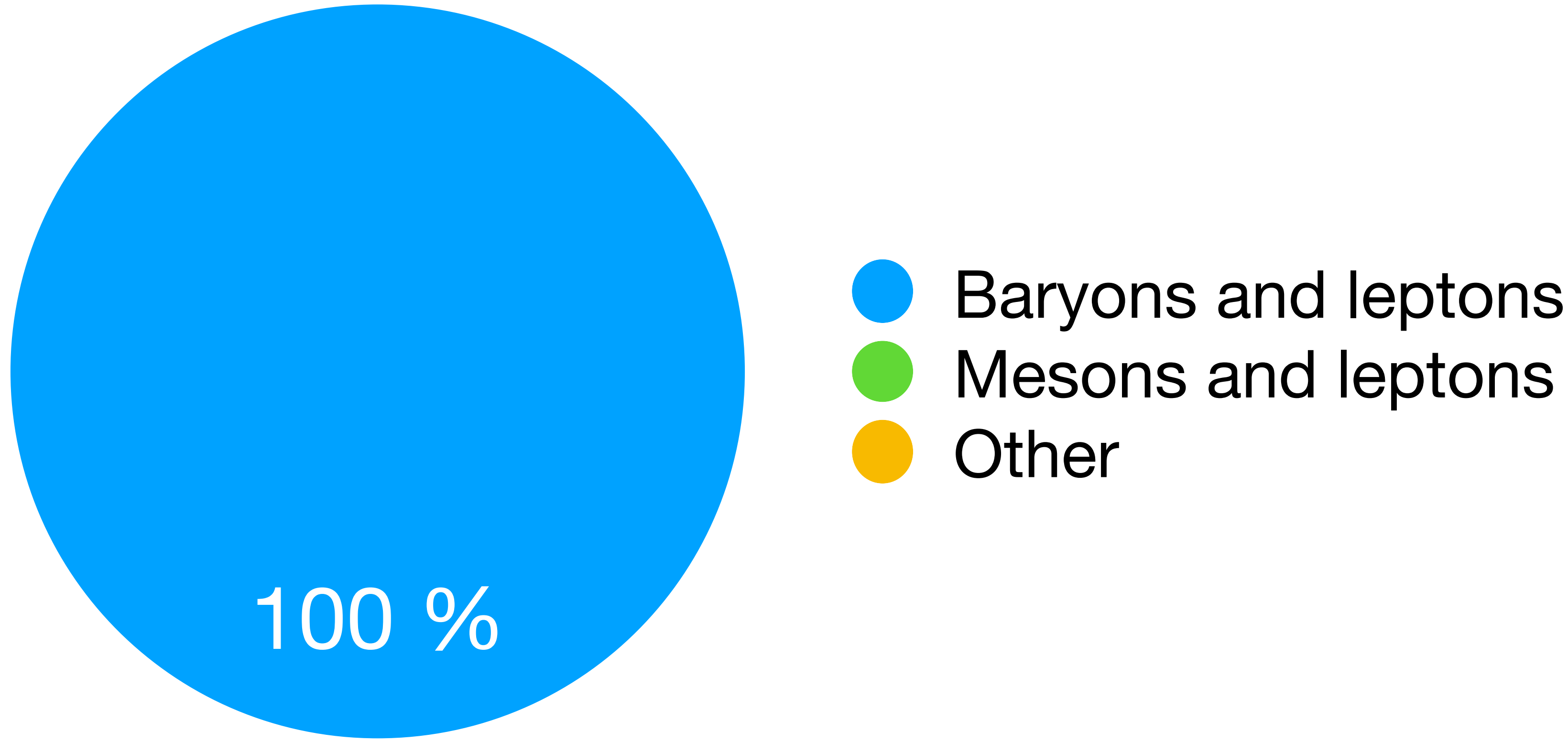
Baryons, spin 1/2

	18%	Λ_b^0	b u d
*	1.5%	Ξ_b^-	b s d
***	1.6%	Ξ_b^0	b s u
***	0.4%	Ω_b^-	b s s
***	< 0.1%		b c q

q = u,d,s,c,b

not yet discovered!

What humans are made of:



What humans of Rare Decays working group of the LHCb experiment published their papers on: