Explore the unknown: new particles, interactions, and physical principles

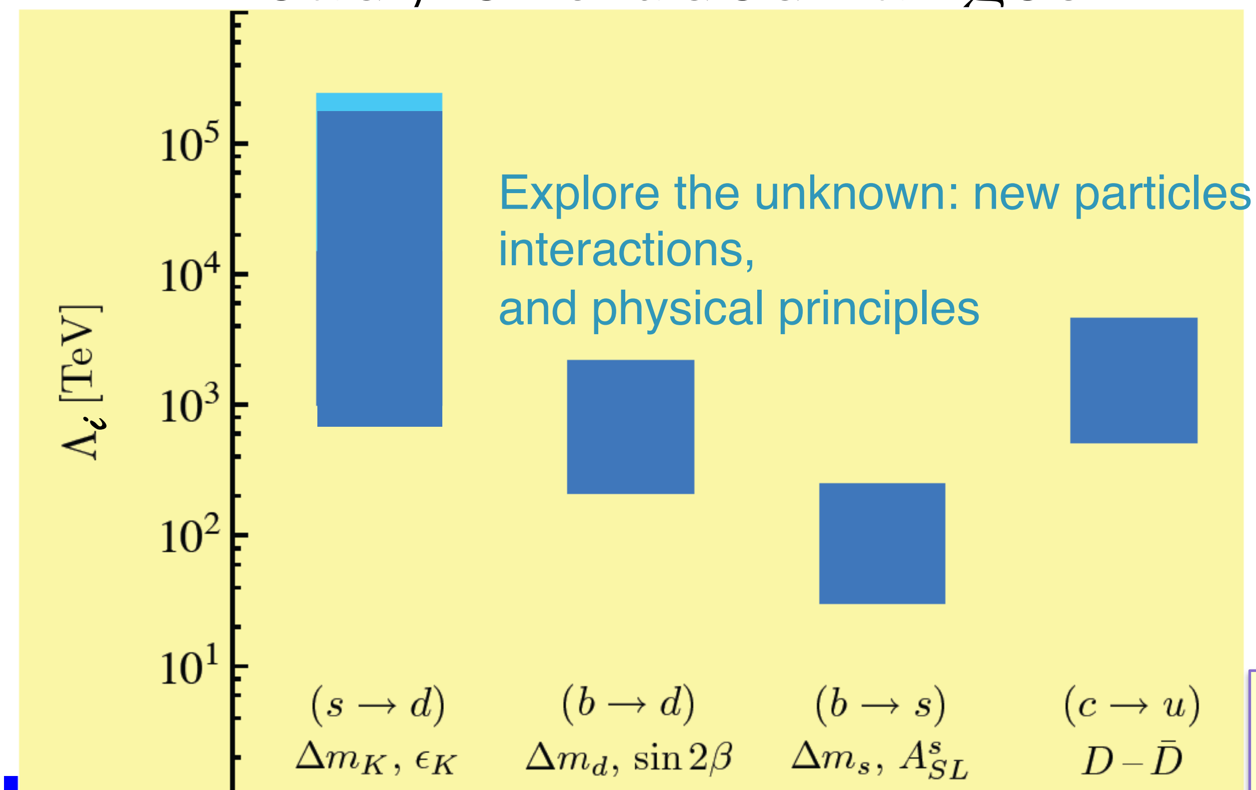
The heavy quark (and τ lepton) path

Marina Artuso

Flavor as a High Mass Probe

$$L_{\mathrm{eff}} = L_{\mathrm{SM}} + \frac{c_i}{\Lambda_i^2} O_i$$

- Already excluded ranges



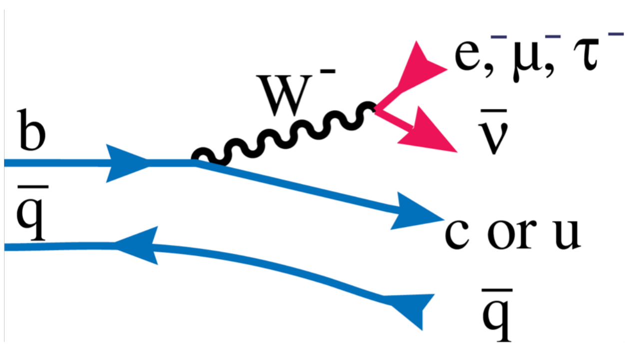
Ways out

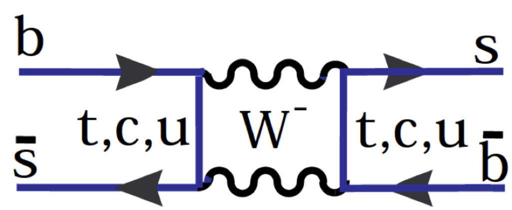
1. New particles have large masses >>1 TeV
2. New particles have degenerate masses
3. Mixing angles in new sector are small, same as in SM (MFV)
4. The above already implies strong constrains on NP

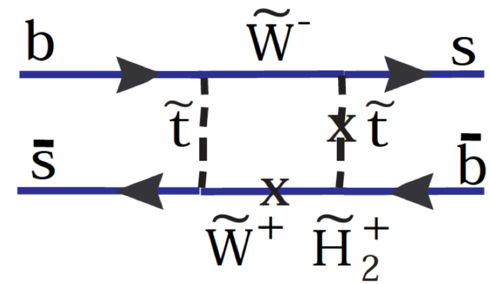
See: Isidori, Nir & Perez arXiv:1002.0900; Neubert EPS 2011 talk

Quantum influences of new particles

- A possible manifestation of new physics in beauty and charm decays



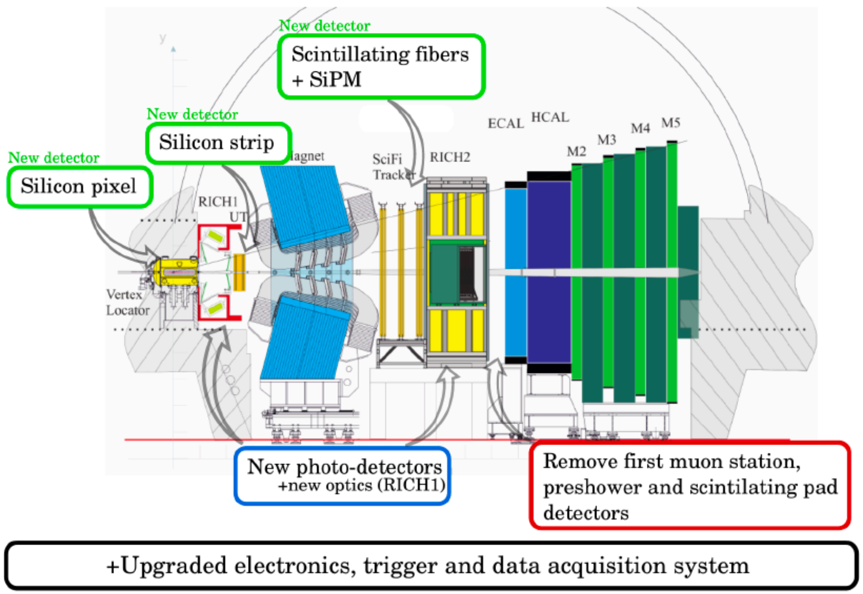




- Caveat: hints of new physics at tree level in semitauonic B decays

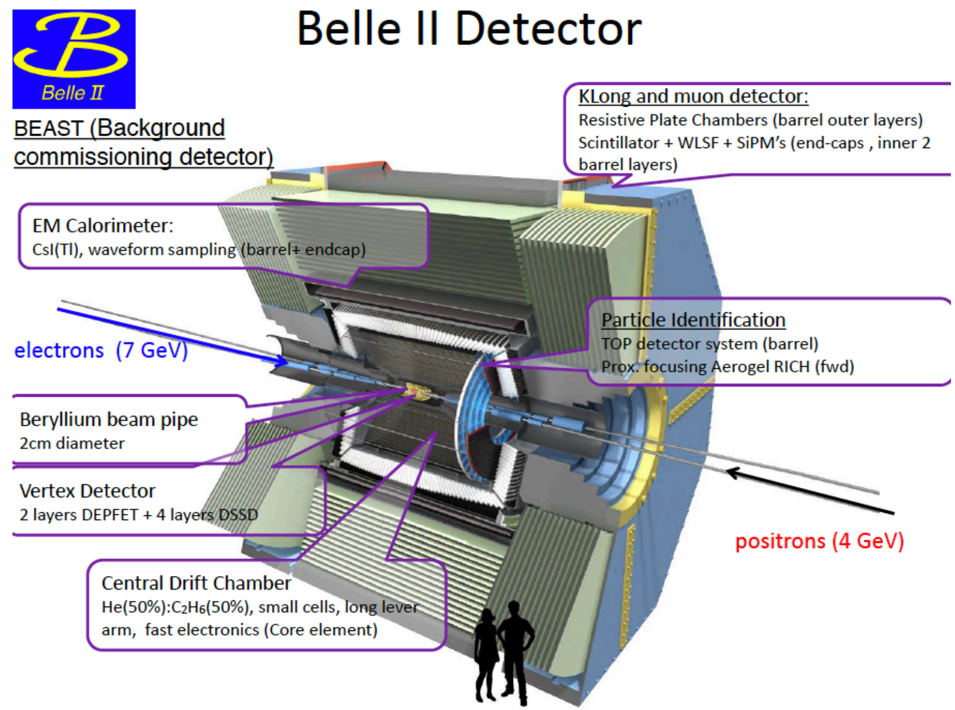
Two experimental approaches

LHCb (& upgrade I)



Forward spectrometer @ LHC, first experiment at hadron collider focused on the study of beauty and charm decays

Belle II



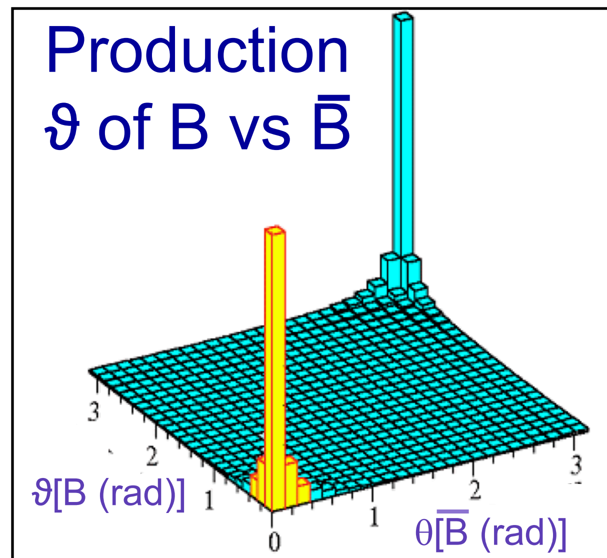
Cylindrical detector at asymmetric e^+e^- b-factory

The Forward Direction at the LHC

- In the forward region at LHC the $b\bar{b}$ production σ is large
- The hadrons containing the b & $\bar{b}$ quarks are both likely to be in the acceptance. Essential for "flavor tagging"
- LHCb uses the forward direction where the B's are moving with considerable momentum ~100 GeV, thus minimizing multiple scattering
- At $\mathcal{L}=4\times10^{32}/\text{cm}^2/\text{s}$, we get ~$10^{12}$ B hadrons ($B^{\pm}$,B^0, but also B_s, b-baryons) in 10^7 sec in the LHCb acceptance.

arXiv:1612.05140

Measured cross section at 13 TeV in LHCb acceptance is (144±7±21) μb



Unique features of the e^+e^- b-factories

The B-anti B meson pairs at the Upsilon(4S) are produced in a <u>coherent</u>, *entangled* **quantum mechanical state**.

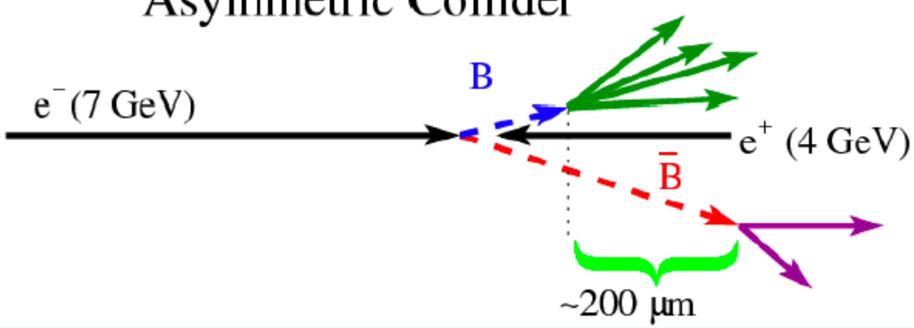
$$|\Upsilon> = |B^0(t_1,f_1)\overline{B^0}(t_2,f_2)> - |B^0(t_2,f_2)\overline{B^0}(t_1,f_1)>$$

(Note the minus sign)

Need to measure decay times to observe CP violation (particle-antiparticle asymmetry).

One B decays →collapses the flavor wavefunction of the other anti-B. (N.B. One B must decay before the other can mix)

Asymmetric Collider



Not to scale

Suited to reconstruct decays with missing particles (constraints from other B)

PHYSICS HIGHLIGHTS

[inspireHEP]

Most Cited hep-ex 2019 preprints

1. **Observation of a narrow pentaquark state, $P_c(4312)^+$, and of two-peak structure of the $P_c(4450)^+$**
(95) LHCb Collaboration (Roel Aaij (NIKHEF, Amsterdam) *et al.*). Apr 8, 2019. 11 pp.
Published in **Phys.Rev.Lett. 122 (2019) no.22, 222001**
LHCb-PAPER-2019-014 CERN-EP-2019-058
DOI: 10.1103/PhysRevLett.122.222001
e-Print: arXiv:1904.03947 **[hep-ex] | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service; Link to SYMMETRY; Link to Fulltext from Publisher; Link to Article from SCOAP3
Data: INSPIRE | HepData
Detailed record - Cited by 95 records 50+

2. **Search for lepton-universality violation in $B^+ \to K^+\ell^+\ell^-$ decays**
(89) LHCb Collaboration (Roel Aaij (NIKHEF, Amsterdam) *et al.*). Mar 21, 2019. 13 pp.
Published in **Phys.Rev.Lett. 122 (2019) no.19, 191801**
LHCb-PAPER-2019-009, CERN-EP-2019-043, LHCb-PAPER-2019-009 CERN-EP-2019-043
DOI: 10.1103/PhysRevLett.122.191801
e-Print: **arXiv:1903.09252 [hep-ex] | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service; Link to Fulltext from Publisher; Link to Article from SCOAP3
Detailed record - Cited by 89 records 50+

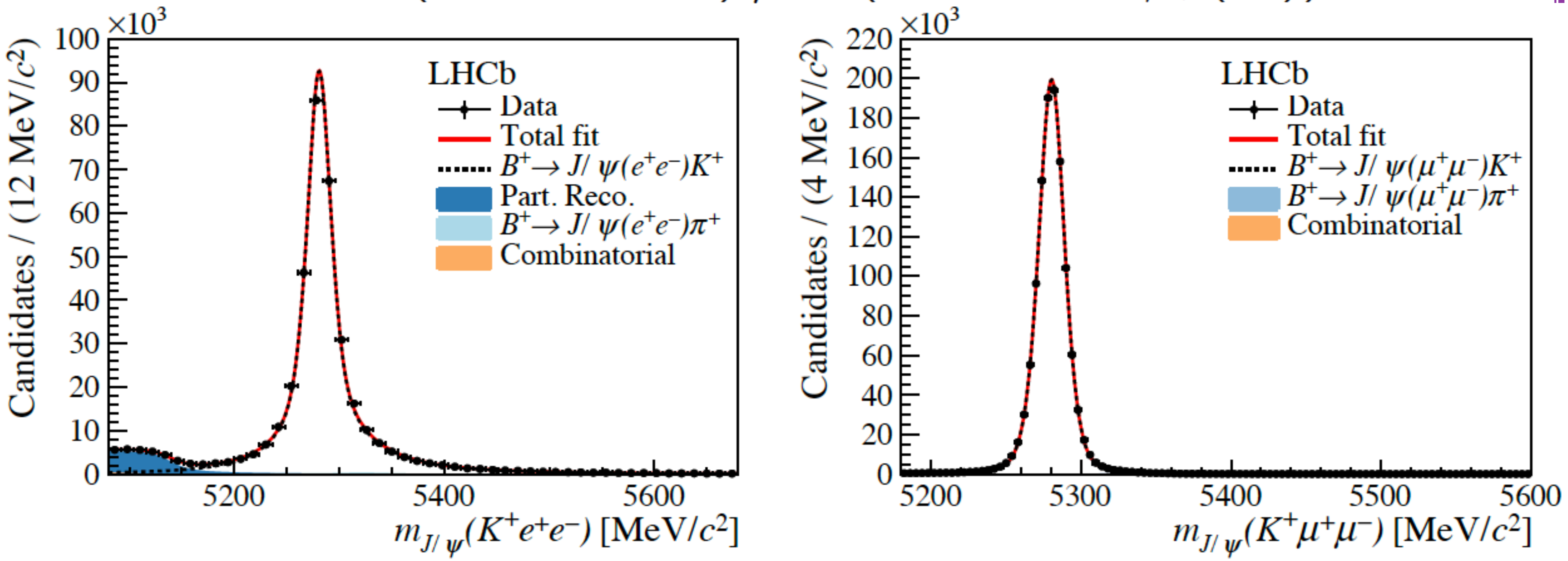
3. **Measurement of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ with a semileptonic tagging method**
(58) Belle Collaboration (A. Abdesselam (Tabuk, Coll. Technol.) *et al.*). Apr 18, 2019. 12 pp.
e-Print: **arXiv:1904.08794 [hep-ex] | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record - Cited by 58 records 50+

4. **Physics Beyond Colliders at CERN: Beyond the Standard Model Working Group Report**
(47) J. Beacham (Ohio State U., Columbus (main)) *et al.*. Jan 20, 2019. 150 pp.
CERN-PBC-REPORT-2018-007
e-Print: **arXiv:1901.09966 [hep-ex] | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service
Detailed record - Cited by 47 records

5. **Test of lepton flavor universality in $B \to K^*\ell^+\ell^-$ decays at Belle**
(46) Belle Collaboration (A. Abdesselam (Tabuk, Coll. Technol.) *et al.*). Apr 4, 2019. 8 pp.
BELLE-CONF-1901
e-Print: **arXiv:1904.02440 [hep-ex] | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record - Cited by 46 records

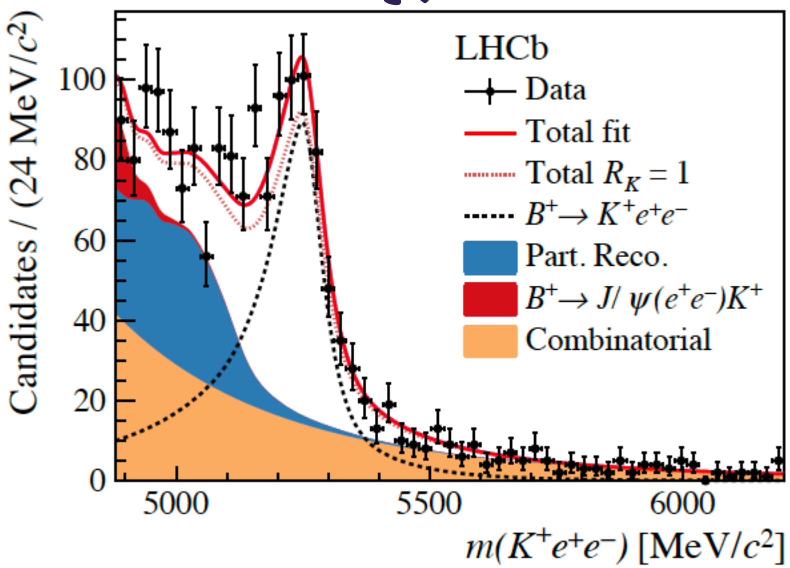
Lepton Universality Violation?

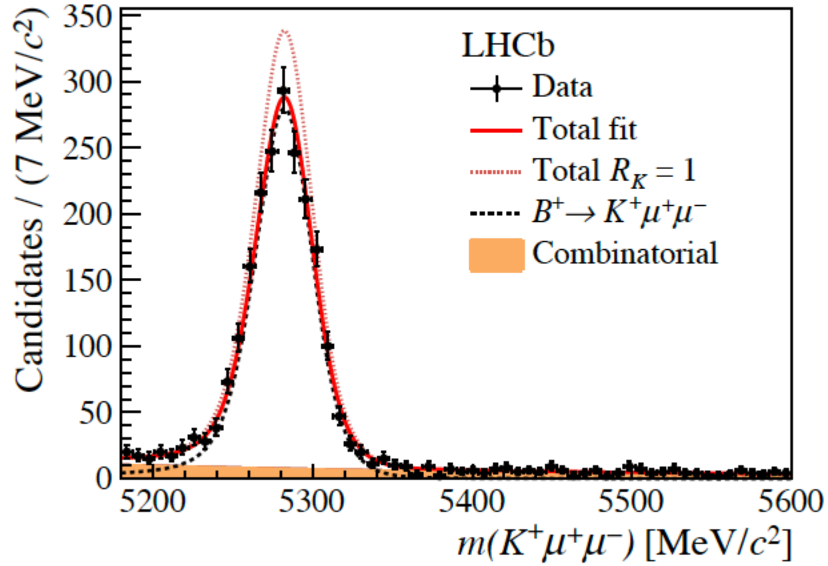
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu\mu)}{\mathcal{B}(B^+ \to K^+ee)} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+J/\psi(\mu\mu))}{\mathcal{B}(B^+ \to K^+J/\psi(ee))}$$



- J/ψ modes, $R_{J/\psi} = 1.014 \pm 0.035$, only a check

R_K results: $1<q^2<6\text{GeV}^2$

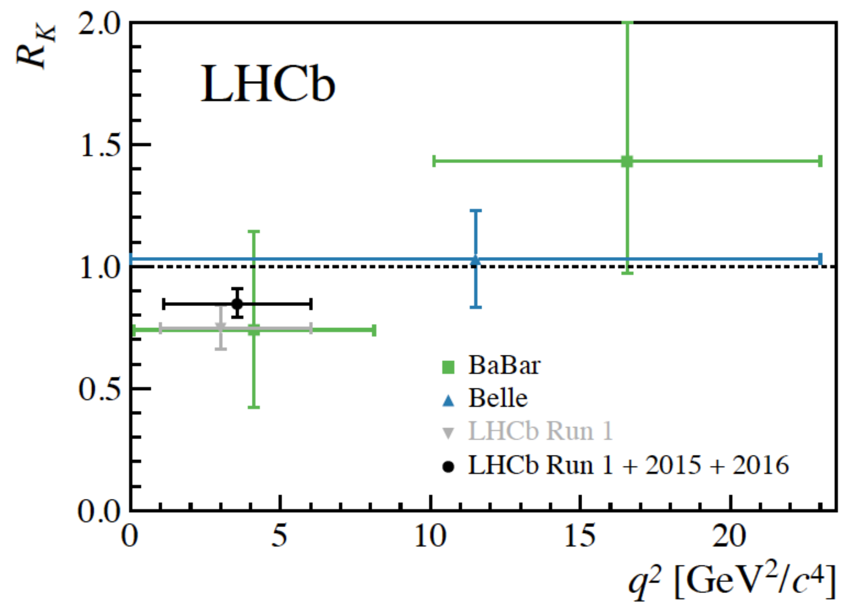




$$R_K = 0.846^{+0.060+0.016}_{-0.054-0.014}$$

- ~2.5σ from SM
- 3/fb Run I + 1.7/fb

  Run II



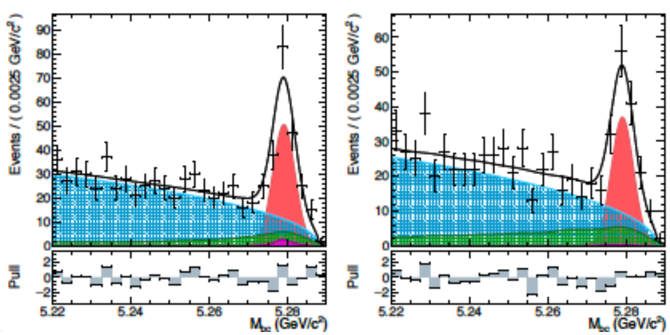
R_{K*} Belle

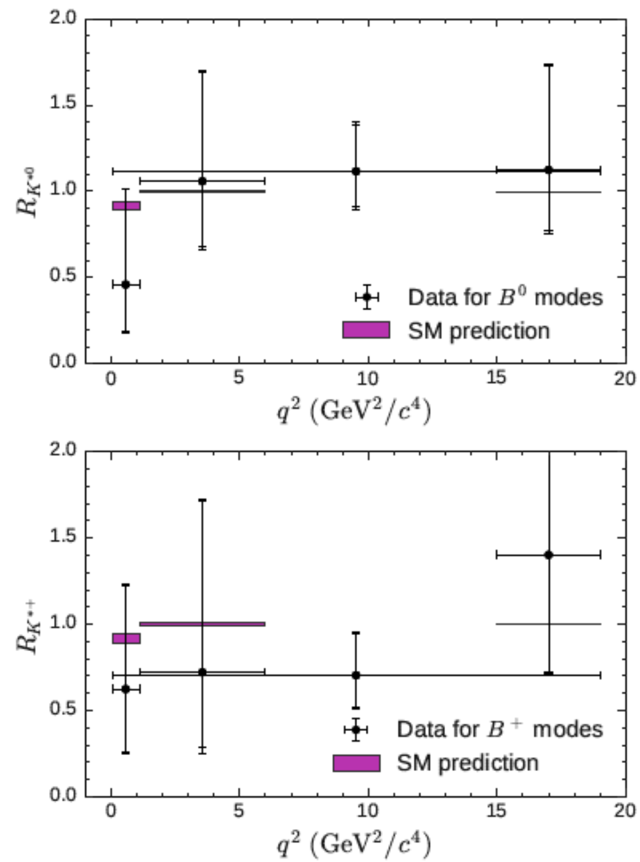
[Belle, arXiv:1904.02440]

R_{K^*} at Belle

Using 711fb^{-1} data, Belle measure R_{K^*}

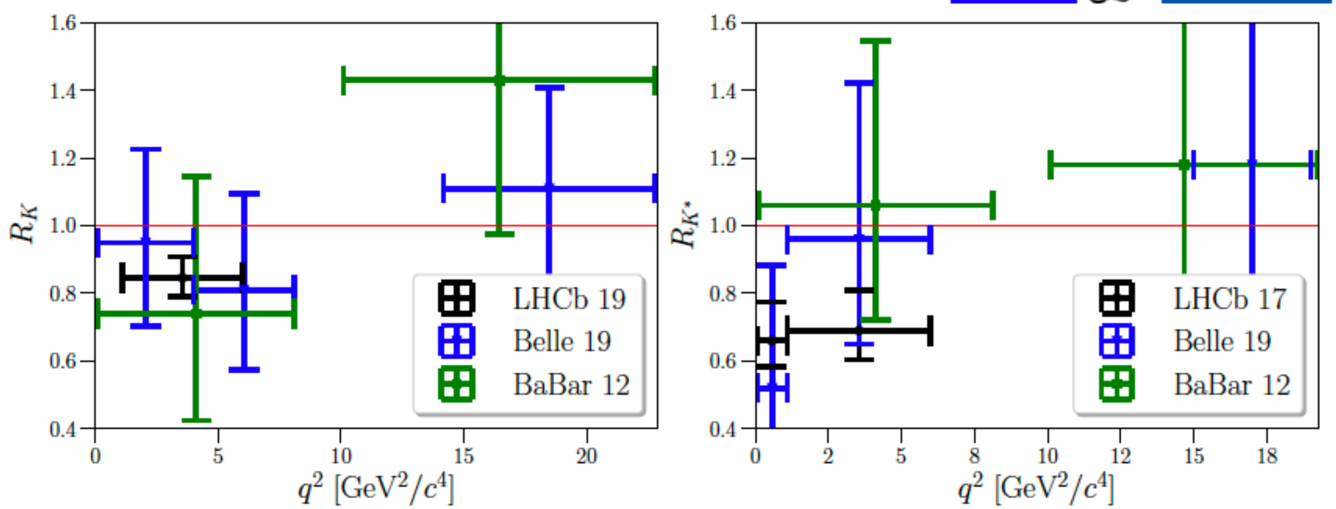
- Find 103 ± 13 $B \to K^* e^+ e^-$ and 140 ± 16 $B \to K^* \mu^+ \mu^-$ decays, adding B^0 and B^+
- Cross-check $r_{J/\psi} = 1.015 \pm 0.025 \pm 0.038$
- Results, split by B^0 and B^+ →





Summary on R_K/R_{K*} in B decays

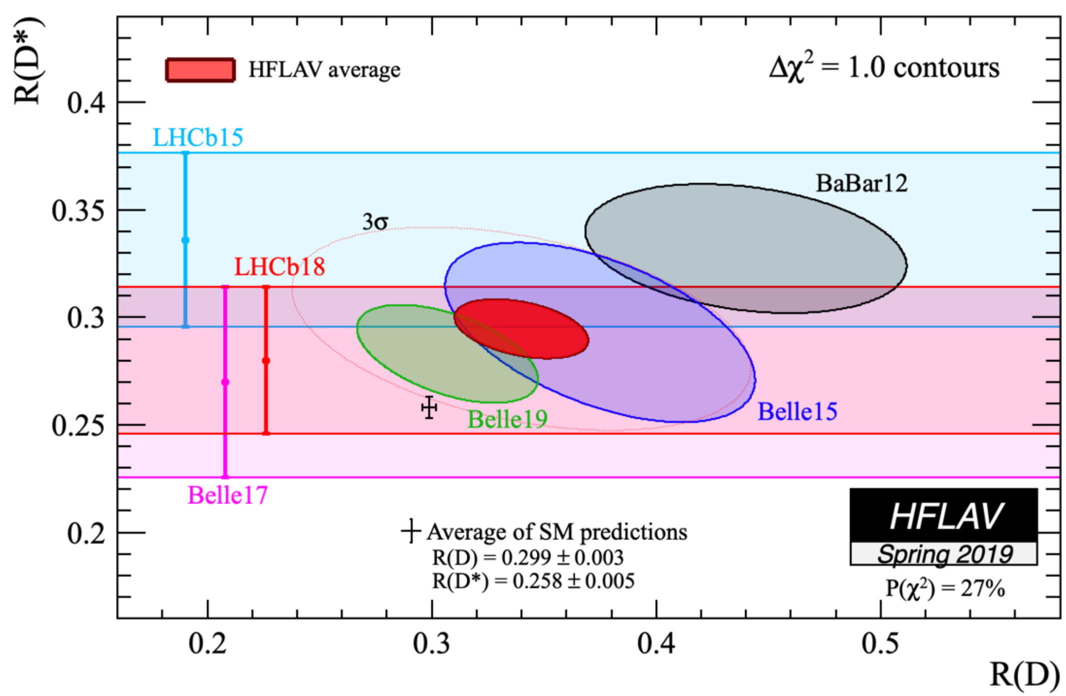
R_K AND R_{K*}



LHCb [JHEP 08 (2017) 055] [PRL 122 (2019) 191801]. Belle [arXiv:1904.02440] [arXiv:1908.01848].
BaBar [PRD 86 (2012) 032012].

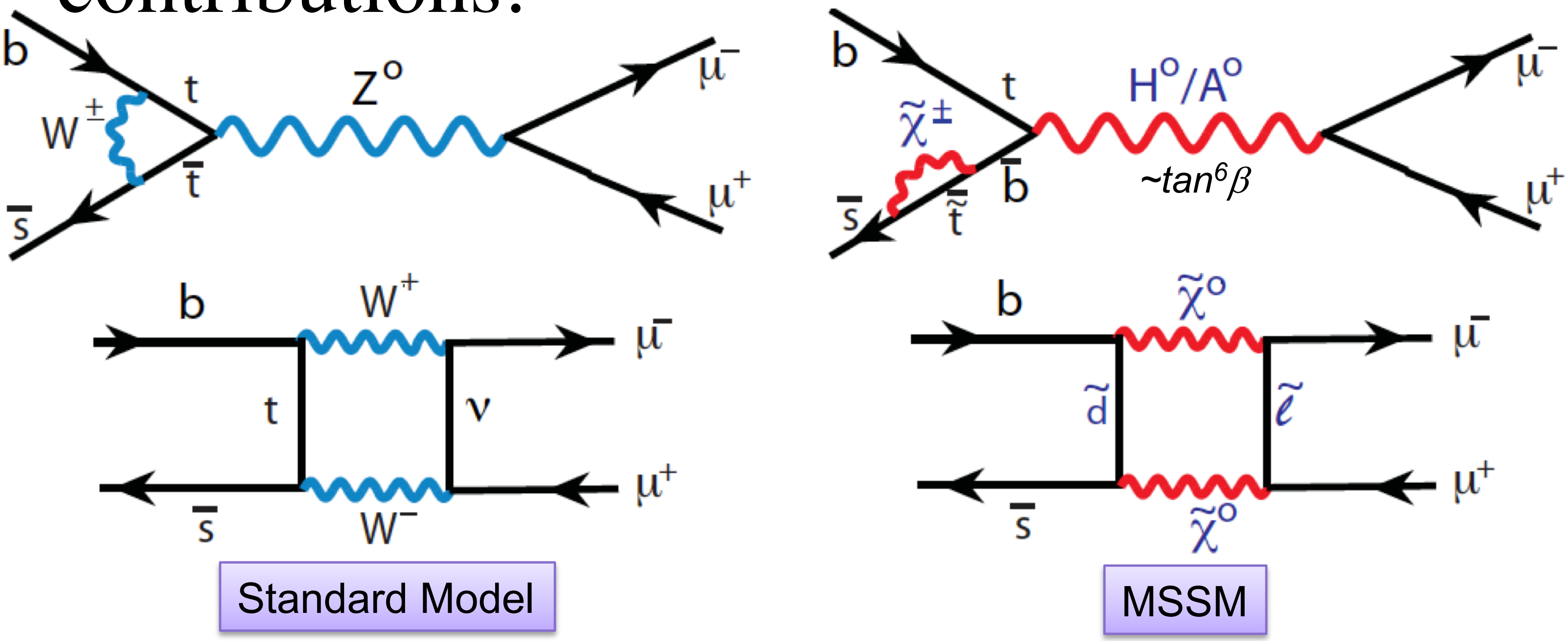
NP at tree level?

- $$R_{D^{(*)}} = \frac{\bar{B} \to D^{(*)} \tau^- \bar{\nu}}{\bar{B} \to D^{(*)} \mu^- \bar{\nu}}$$
- A very difficult measurement in e^+e^- & hadron colliders
- Belle average is now 1.6σ of SM
- World average diff with SM decreases from 3.8σ to ß3.1σ



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

- SM branching ratio is $(3.65\pm0.23)\times10^{-9}$ [Bobeth et al., arXiv:1311.0903], NP can make large contributions.



$B \to \mu^+\mu^-$ results

- 1st evidence LHCb
- 1st observation at 6.3σ
- 1st in a single exp., 7.8σ

$\mathcal{B}(B_s \to \mu^+\mu^-) = \left(3.0 \pm 0.6^{+0.3}_{-0.2}\right) x10^{-9}$

$\mathcal{B}(B^0 \to \mu^+\mu^-) < 0.34x10^{-9}$ at 95% CL (Run I + some II)

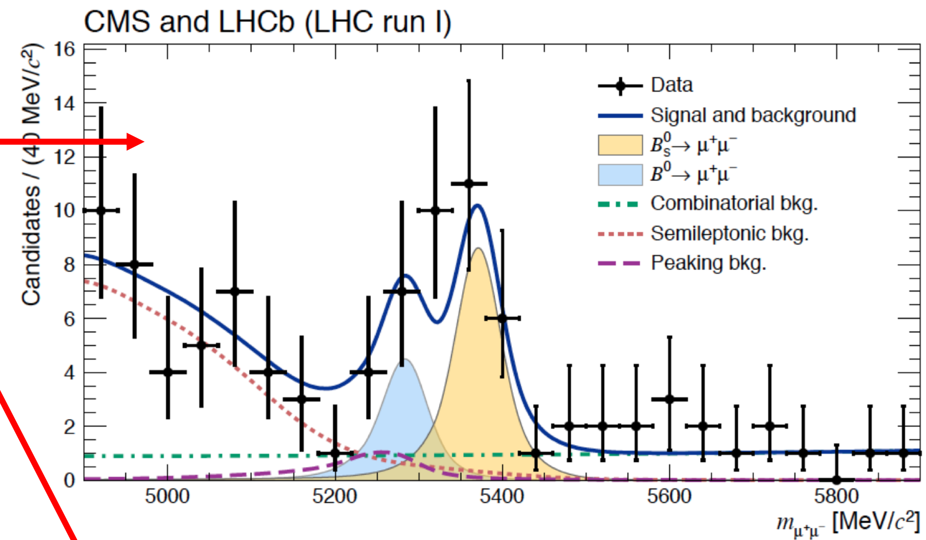
- New ATLAS results

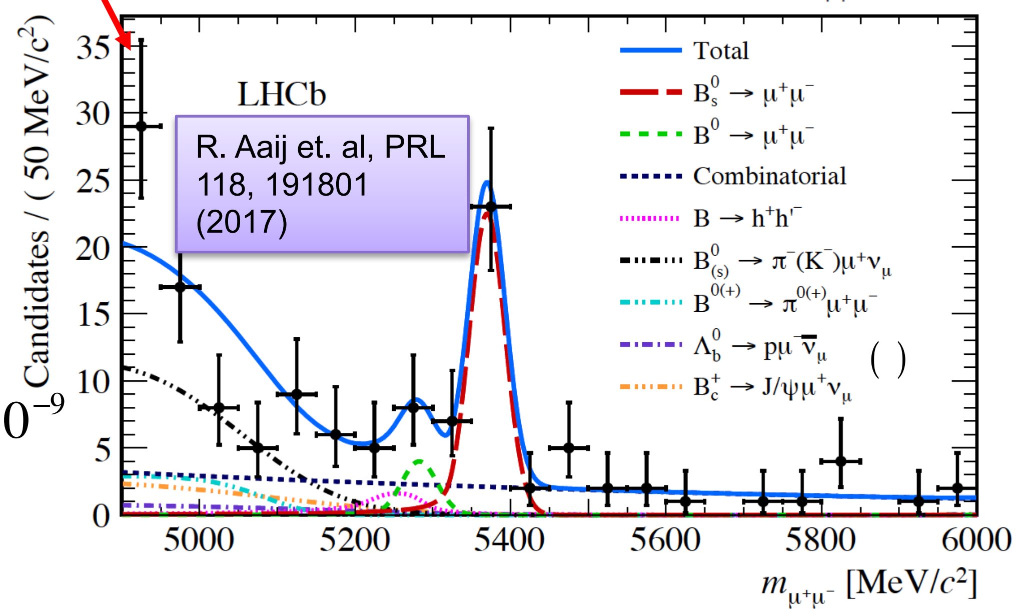
$\mathcal{B}(B_s \to \mu^+\mu^-) = (2.8 \pm 0.8)x10^{-9}$

$\mathcal{B}(B^0 \to \mu^+\mu^-) < 0.21x10^{-9}$

- CMS: $\mathcal{B}(B_s \to \mu^+\mu^-) = \left(3.0^{+1.0}_{-0.9}\right) x10^{-9}$

Avg $B_s = (2.9 \pm 0.4)x10^{-9}$





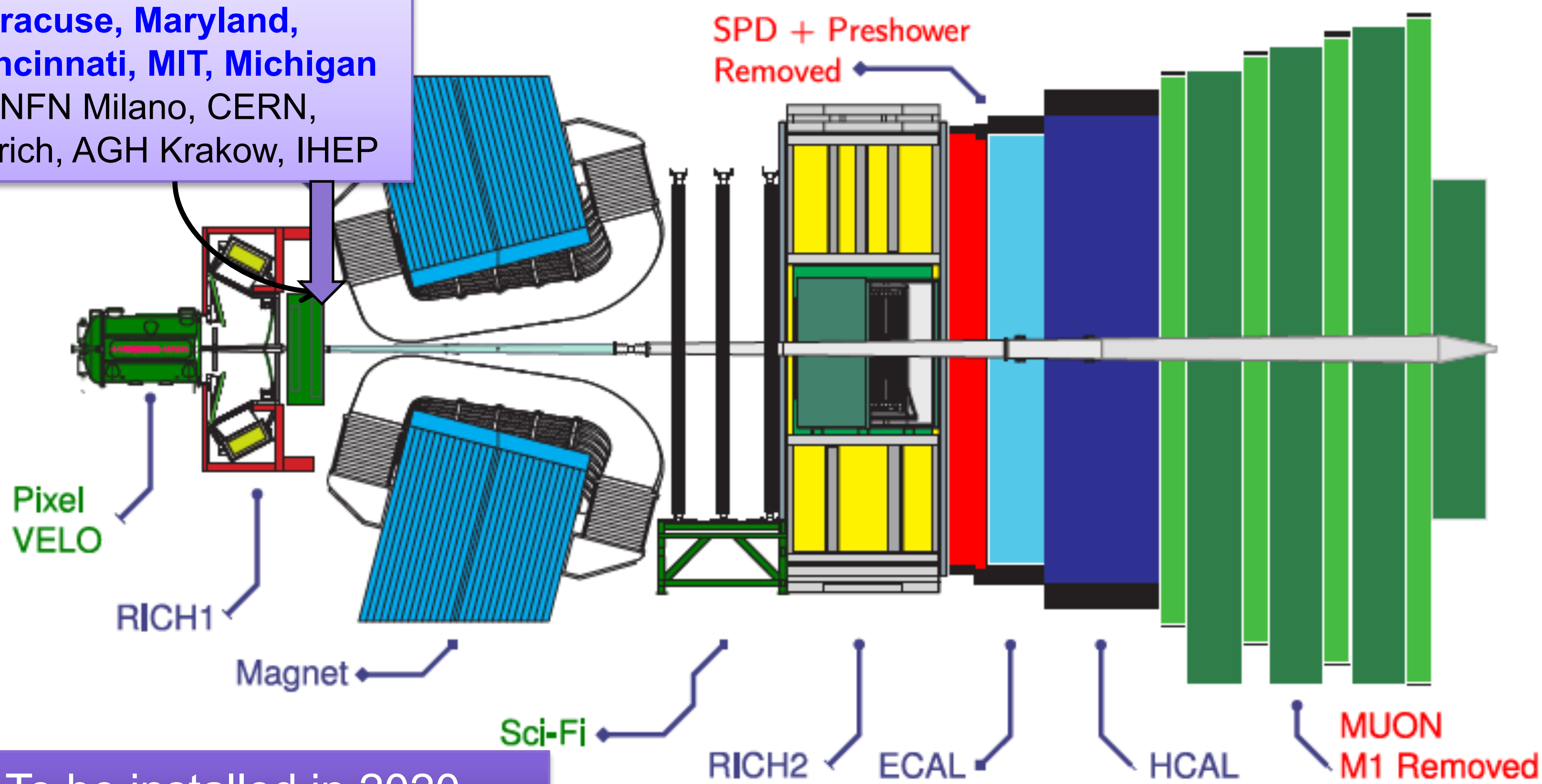
Taking strides towards the future

THE LHCb PHASE 1 UPGRADE

The LHCb PHASE 1 upgrade

Luminosity to increase by 5x, and we will move to a triggerless-readout system. Many detector elements being redesigned to make this possible.

US lead (NSF supported):
Syracuse, Maryland, Cincinnati, MIT, Michigan
& INFN Milano, CERN, Zurich, AGH Krakow, IHEP

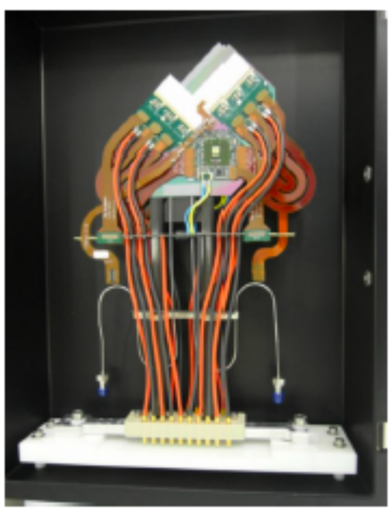


To be installed in 2020

A new tracking system

UT

Lead by US
NSF funded

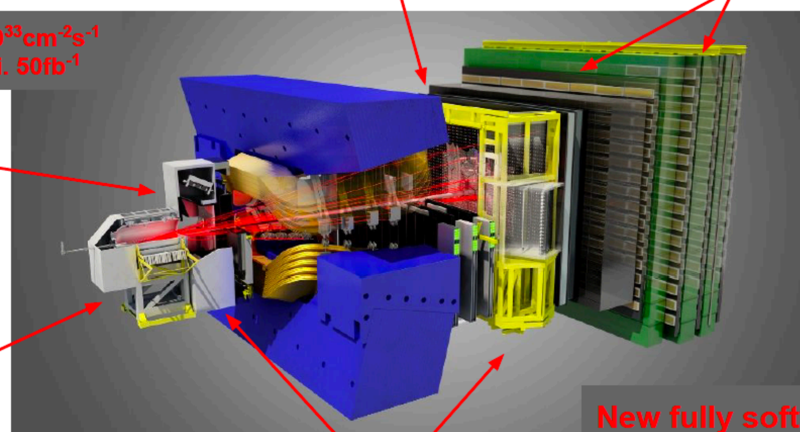


Prototype CF1 CF2 CF3

Sci-Fi assembly hall

Upgrade I

Inst. Lumi. $2x10^{33}cm^{-2}s^{-1}$
Target Int. Lumi. $50fb^{-1}$



New scintillating fibre tracker (SciFi)

New electronics (CALO, MUON)

New silicon upstream tracker (UT)

New pixel vertex detector (VELO)

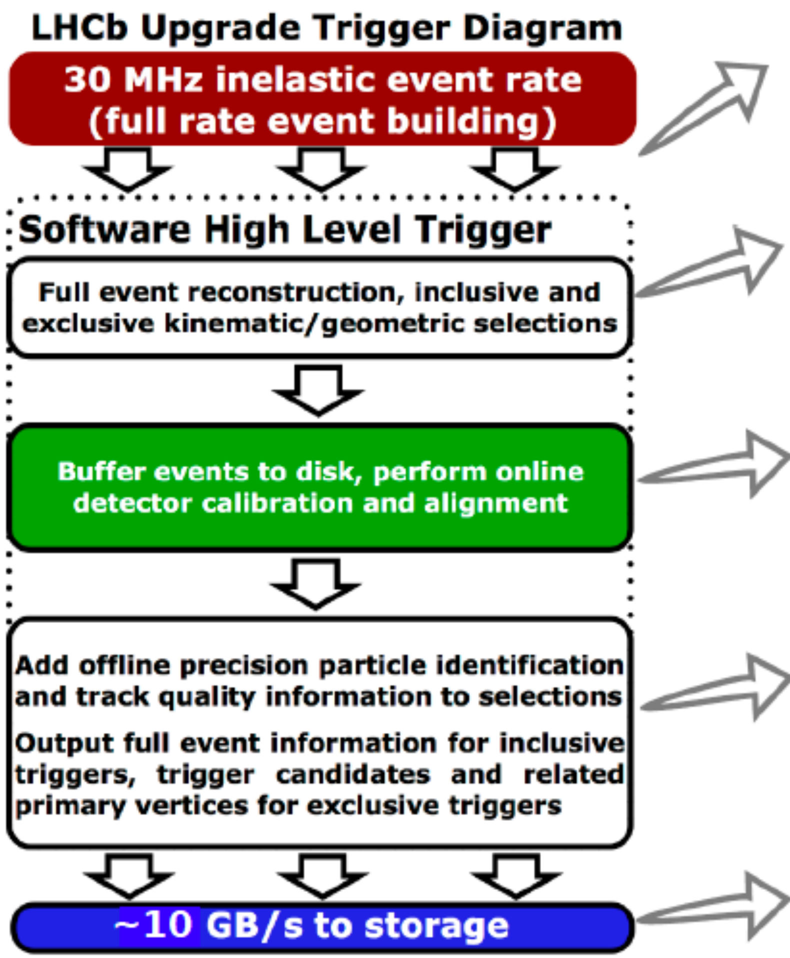
New optics and photodetectors (RICH)

New fully software trigger - all sub-detectors must read out at 40MHz

LHCB-TDR-12
LHCB-TDR-13
LHCB-TDR-14
LHCB-TDR-15
LHCB-TDR-16
LHCB-TDR-17
LHCB-TDR-18

The LHCb Upgrade trigger concept

THE TRIGGER: THE UPGRADE WORKHORSE



40 MHz readout. Aggregate 40 Tbit/s.

Tracking, followed by high efficiency 1-, 2-displaced tracks inclusive selections

→ reduce to 1 Tbit/s

Disk buffering and online calibration/alignement mechanisms demonstrated in Run 2.

Full reconstruction including particle identification + pure and efficient exclusive selections

[arXiv:1604.05596]

Turbo stream for high rate signals

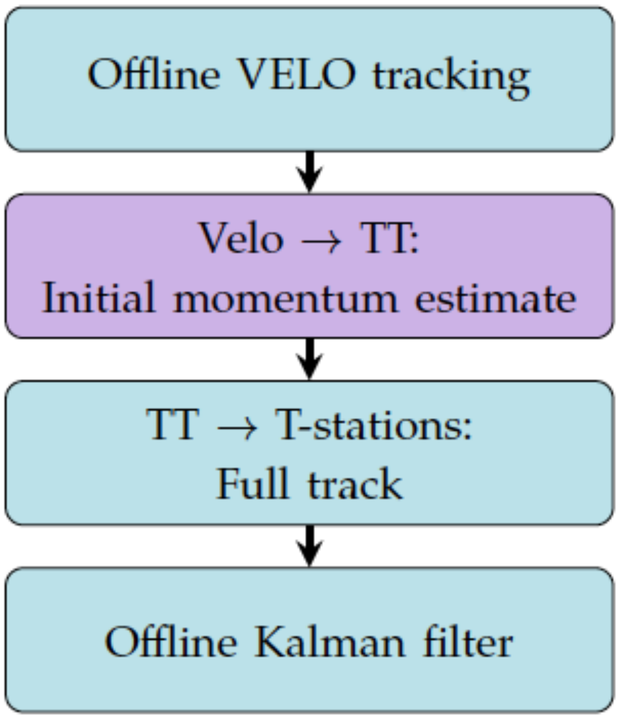
→ Analysis on trigger object, only save what is necessary from the event

- Challenging project using modern computing methods.

→ Upgrade Software and Computing TDR [CERN-LHCC-2018-007]

Tracking in HLT1

Tracking in HLT1 for Run II

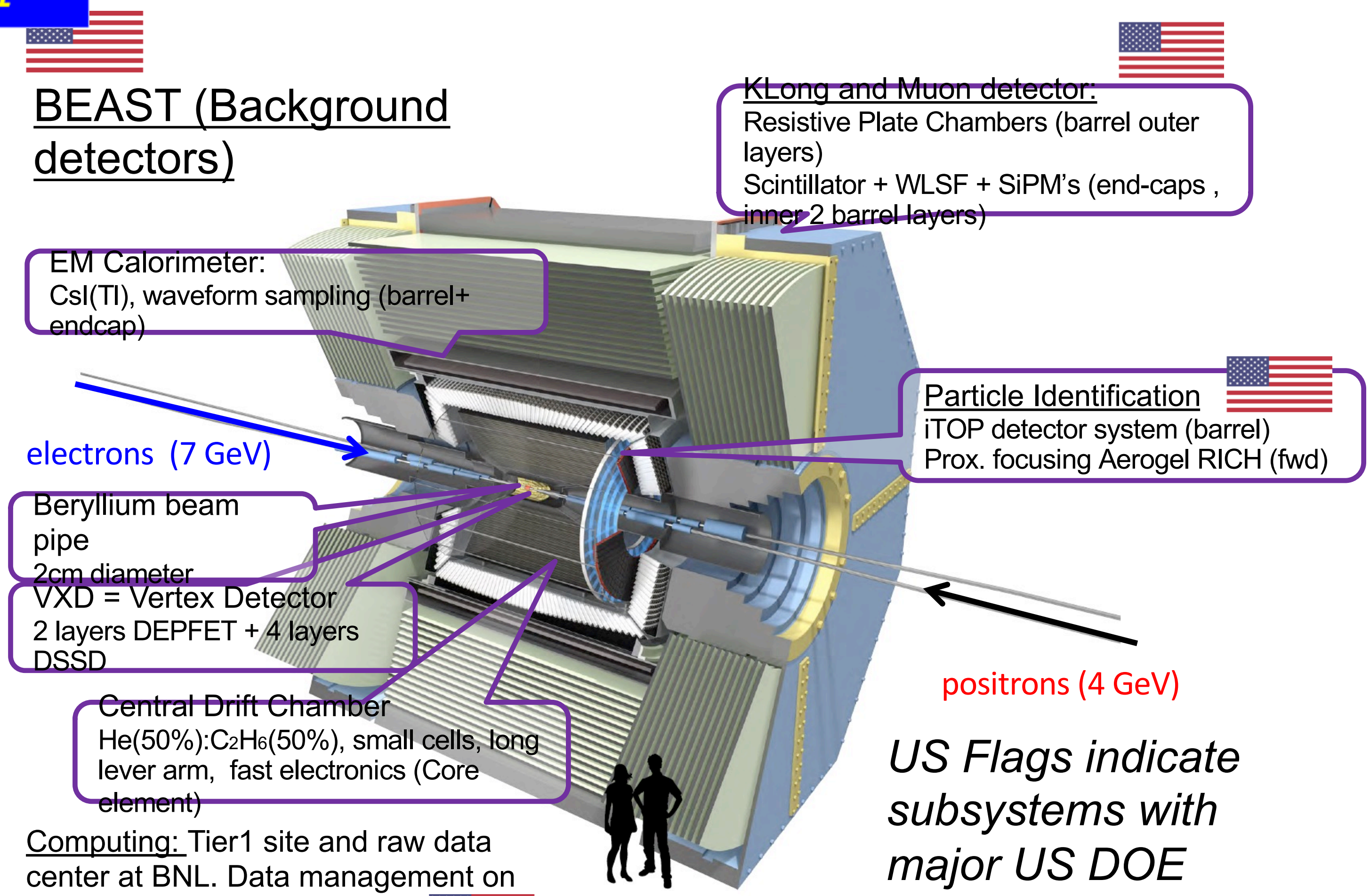


- Improved sequence forming Velo-TT tracks as an intermediate stage
- Momentum estimate allows a preselection on the p_T of tracks
- Charge estimate allows greatly reduced search windows downstream of the magnet
  - Vast reduction in both ghost rate (factor 4) and execution time (factor 3)

To be improved in the PHASE 1 upgrade with replacement of TT→UT with optimized acceptance and granularity, construction project lead by US institutions with NSF support

THE BELLE II UPGRADE

Belle II Detector



<u>Computing:</u> Tier1 site and raw data center at BNL. Data management on the worldwide computing grid.

US Flags indicate subsystems with major US DOE operations and construction contributions.

Highlight of detector innovations

Advanced & Innovative Technologies used in Belle II

<u>Pixelated photo-sensors play a central role</u>

MCP-PMTs in the iTOP
HAPDs in the ARICH
SiPMs in the KLM

Collaboration with Industry

DEPFET pixel sensors

<u>Waveform sampling with precise timing is "saving us".</u>

Front-end custom ASICs (Application Specific Integrated Circuits) for most subsystems

→ DAQ with high performance network switches, large HLT software trigger farm

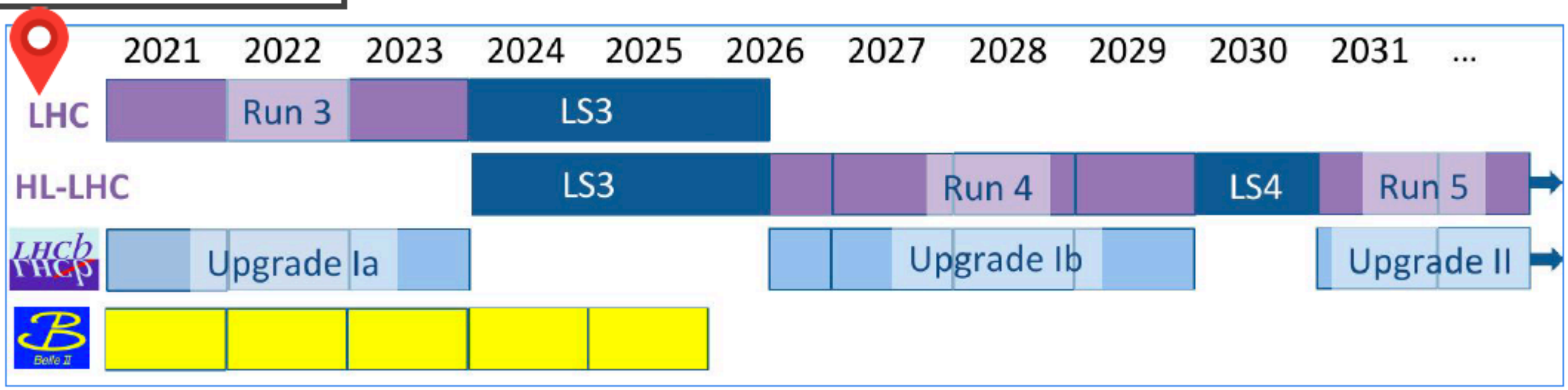
→ <u>a 21st century HEP experiment.</u>

KLM (*TARGETX* ASIC)
ECL (New waveform sampling backend with good timing)
TOP (*IRSX* ASIC)
ARICH (KEK custom ASIC)
CDC (KEK custom ASIC)
SVD (APV2.5 readout chip adapted from CMS)

New methods of neutron detection with TPC's for the background. Directions !

Beyond Phase I upgrade

Upgrade II

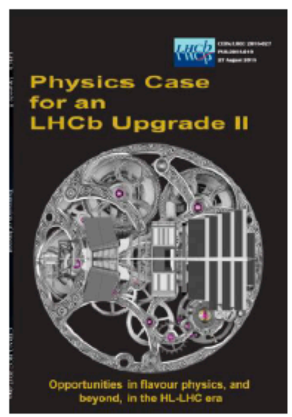


-Fully exploit HL-LHC for flavour and other forward physics

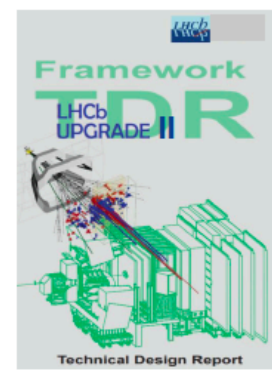
-Aim for >300fb^{-1} with Inst. Lumi. - 2x10^{34}

- Expression of interest
- Feasibility study by LHC
- Physics case

-Support in Briefing book for European particle physics strategy update



Proceed with framework TDR...



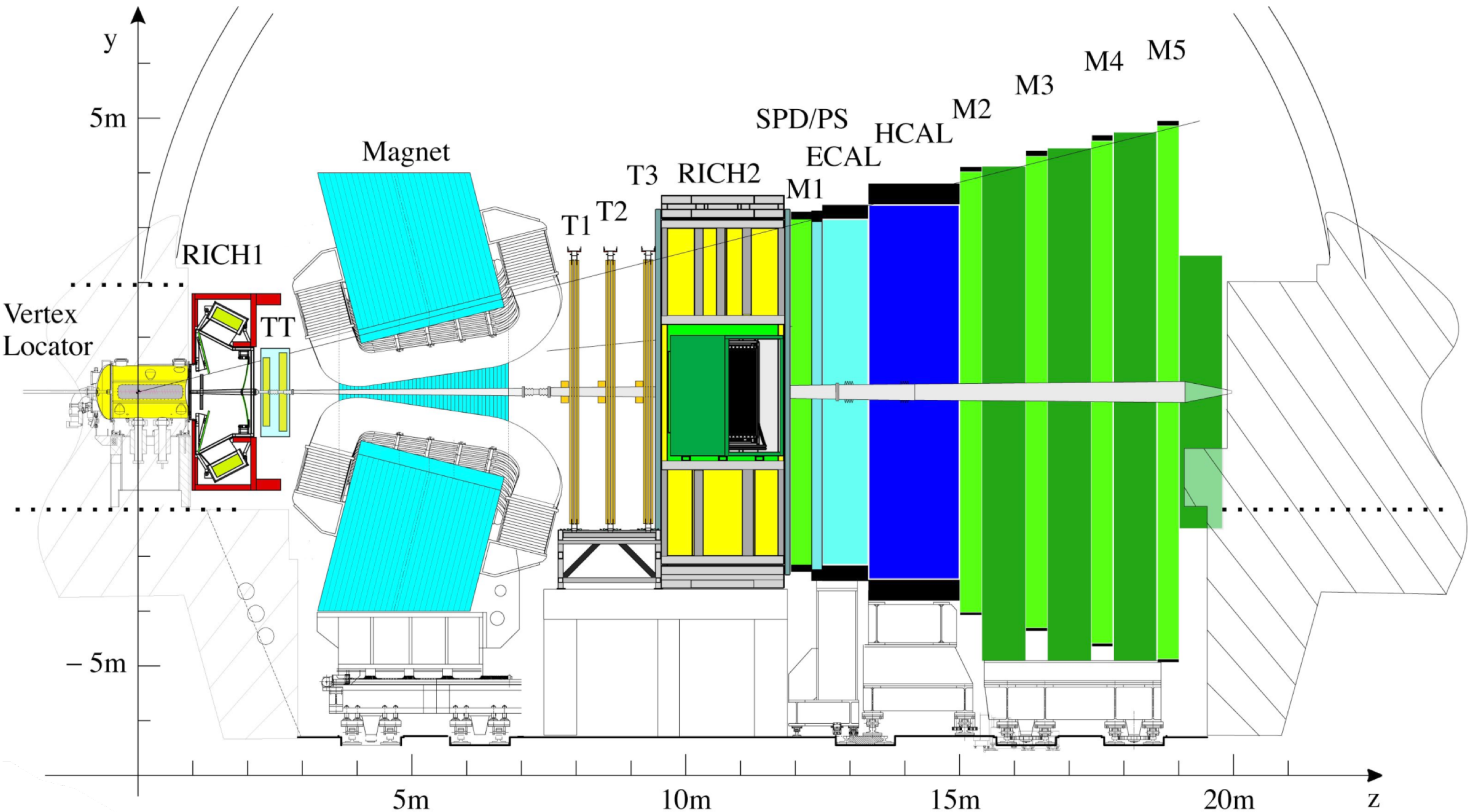
*Artists impression

Conclusions

- The physics case for a long and vibrant program studying beauty, charm and τ lepton decays is very strong
- A very interesting data taking phase has started for Belle II and is imminent for LHCb, with a wealth of findings that will probe **new physics signatures** and much else
- Effective theories and lattice QCD calculations are key to relate experimental data to fundamental parameters

THE END

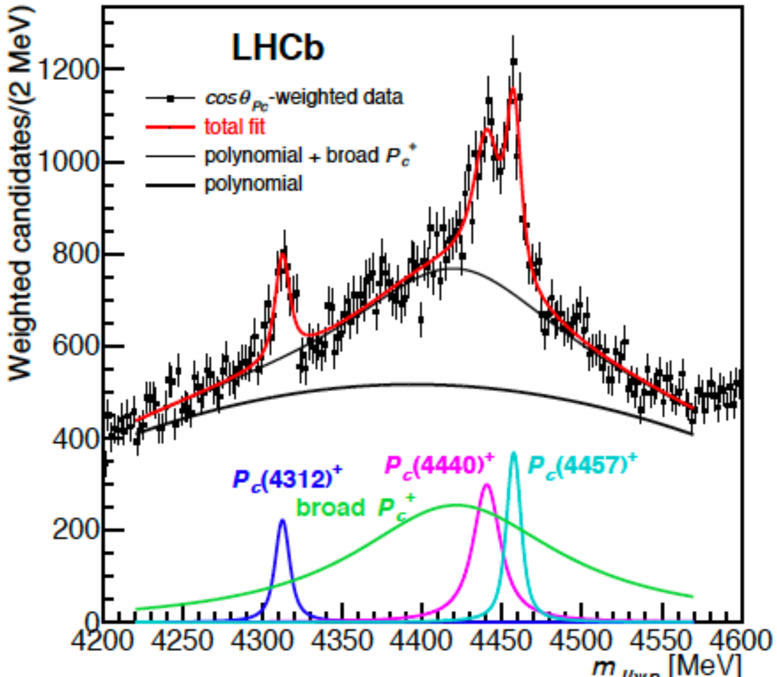
The LHCb detector



Observation of narrow pentaquarks

Three states are observed:

- $P_c(4312)^+$ $\Gamma \sim 10$ MeV (7σ), which we could not see with $3\,\text{fb}^{-1}$
- $P_c(4440)^+$ $\Gamma \sim 20$ MeV and
- $P_c(4457)^+$ $\Gamma \sim 6$ MeV. The significance of the 2-peak structure is 5.4σ
- ✗ No sensitivity to the wide $P_c(4380)^+$



State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7\,^{+6.8}_{-0.6}$	$9.8 \pm 2.7\,^{+3.7}_{-4.5}$	(< 27)	$0.30 \pm 0.07\,^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3\,^{+4.1}_{-4.7}$	$20.6 \pm 4.9\,^{+8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33\,^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6\,^{+4.1}_{-1.7}$	$6.4 \pm 2.0\,^{+5.7}_{-1.9}$	(< 20)	$0.53 \pm 0.16\,^{+0.15}_{-0.13}$

US Institutes and Roles

The US Belle II construction project went through the full DOE CD process and cost about 16 million dollars. It was managed by PNNL and completed in 2016. *Host lab transitioned from PNNL to BNL in FY18.*
Following construction, about $7.5M/year in DOE support.

18 Belle II institutes, 127 US collaborators (33 faculty, 25 postdocs, 21 technical staff, 24 PhD students, 3 Master students, 20 undergraduates, 1 visitor) [~$4.5 million/year in DOE programmatic funding]

Brookhaven National Laboratory	University of Cincinnati
Carnegie Mellon University	University of Florida
Duke University	University of Hawaii
Indiana University	University of Mississippi
Kennesaw State University	University of Pittsburgh
Luther College	University of South Alabama
Pacific Northwest National Laboratory	University of South Carolina
Virginia Tech	University of Louisville
Wayne State University	Iowa State University

We are now in the operations stage, managed by BNL and focused on detector operations and GRID computing (~$3 million/year).

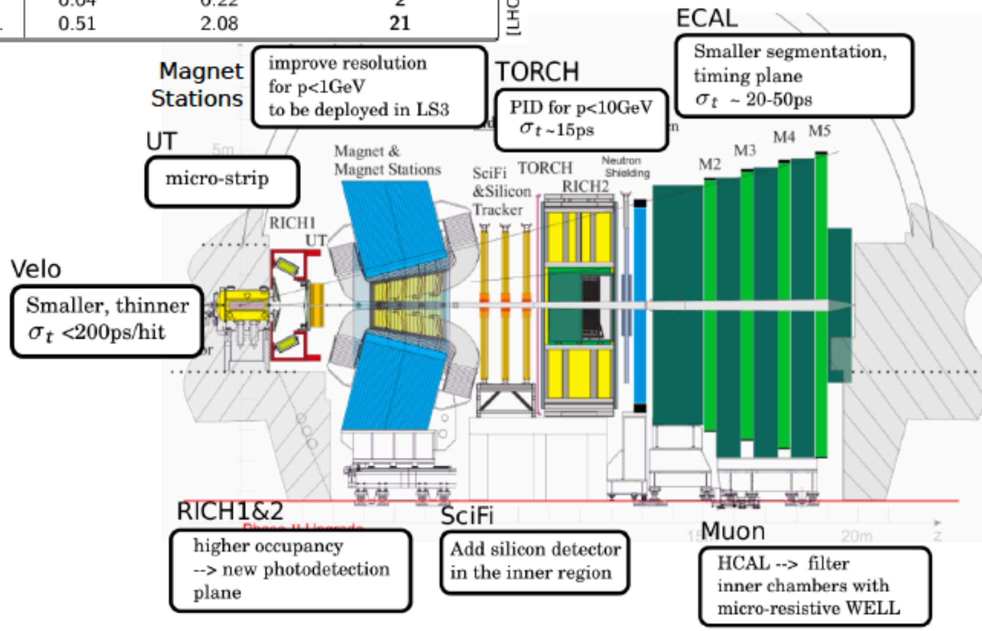
LHCb Upgrade II

LHCb Upgrade 2

EOI [CERN-LHCC-2017-003] and Physics case [CERN-LHCC-2018-027]

	LHCb	LHCb Upgrade I	LHCb Upgrade II
$\mathcal{L}_{instantaneous}$ ($cm^{-2}s^{-1}$)	4×10^{32}	2×10^{33}	$\mathbf{2 \times 10^{34}}$
Pile-up	1	6	**60**
b-hadron per evt.	0.003	0.02	**0.2**
c-hadron per evt.	0.04	0.22	**2**
light,long-lived per evt.	0.51	2.08	**21**

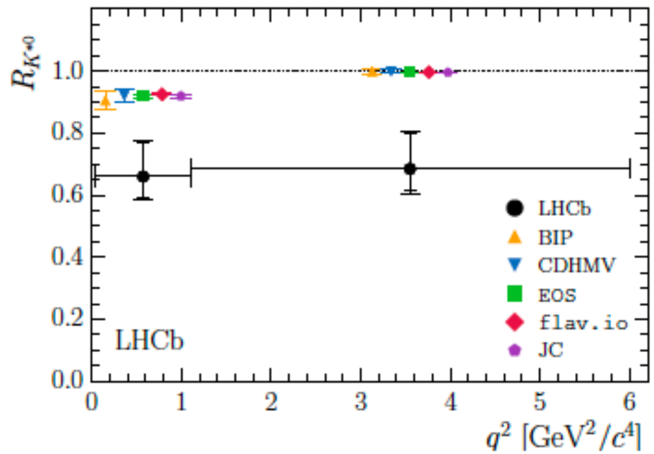
[LHCb-PUB-2014-027]

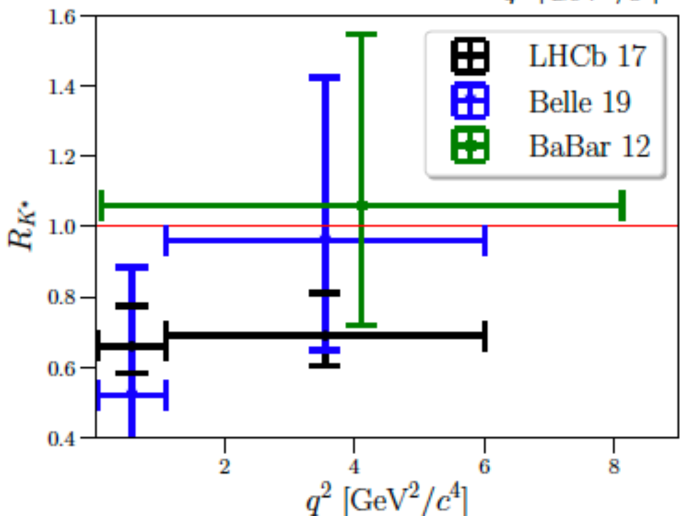


- Trigger have to select between signal and interesting signal.
- Probably need dedicated hardware for tracking.
- Timing will be crucial to minimize combinatorics and PV mis-association

R_{K^*} LHCb

$B \rightarrow K^* \ell^+ \ell^-$





Measure ratio R_{K^*} of $B^0 \rightarrow K^{*0}\mu^+\mu^-$ to $B^0 \rightarrow K^{*0}e^+e^-$ in $0.045 < q^2 < 1.1$ and $1.1 < q^2 < 6$ GeV^2

- ✔ Signal clearly visible in $K^{*0}\mu^+\mu^-$
- Yields entering the double ratio:

	$B^0 \rightarrow K^{*0}\ell^+\ell^-$ low- q^2	$B^0 \rightarrow K^{*0}\ell^+\ell^-$ central- q^2	$B^0 \rightarrow J/\psi\, K^{*0}$
$\mu^+\mu^-$	285 ± 18	353 ± 21	$274416\,^{+602}_{-654}$
e^+e^-	$89\,^{+11}_{-10}$	$111\,^{+14}_{-13}$	43468 ± 222

Build a double ratio $R_K =$

$$\left(\frac{\mathcal{N}_{K^{*0}\mu^+\mu^-}}{\mathcal{N}_{K^{*0}e^+e^-}}\right)\left(\frac{\mathcal{N}_{J/\psi(e^+e^-)K^{*0}}}{\mathcal{N}_{J/\psi(\mu^+\mu^-)K^{*0}}}\right)$$

$$= \begin{cases} 0.66\,^{+0.11}_{-0.07} \pm 0.03 & 0.045 < q^2 < 1.1 \\ 0.69\,^{+0.11}_{-0.07} \pm 0.05 & 1.1 < q^2 < 6.0 \end{cases}$$

This about 2 to 2.5σ from the SM, depending on predictions. [BIP, EPJC 76 440] [CDHMV, JHEP04(2017)016] [EOS, PRD 95 035029] [flav.io, EPJC 77 377] [JC, PRD93 014028]