B Physics
@ Belle II & LHCb

Steven Robertson
Institute of Particle Physics
& McGill University

On behalf of the
Belle II and LHCb Collaborations

SUSY2019
Corpus Christi, Texas
May 20 - 24, 2019

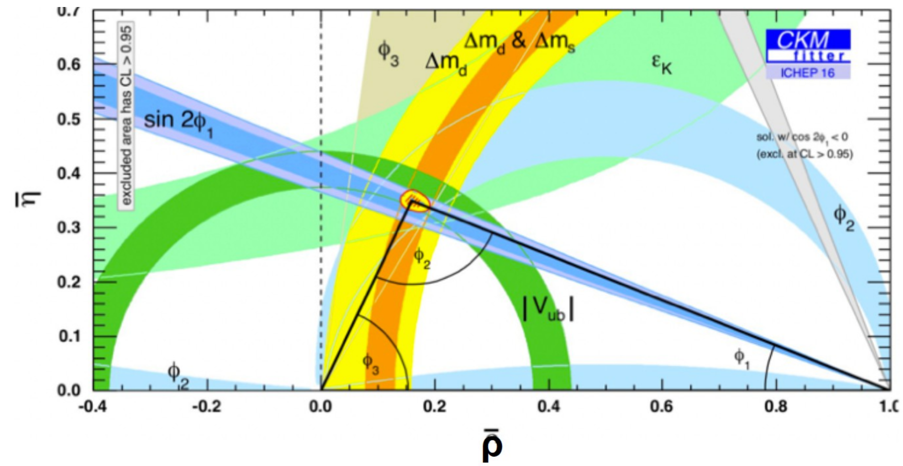
Overview

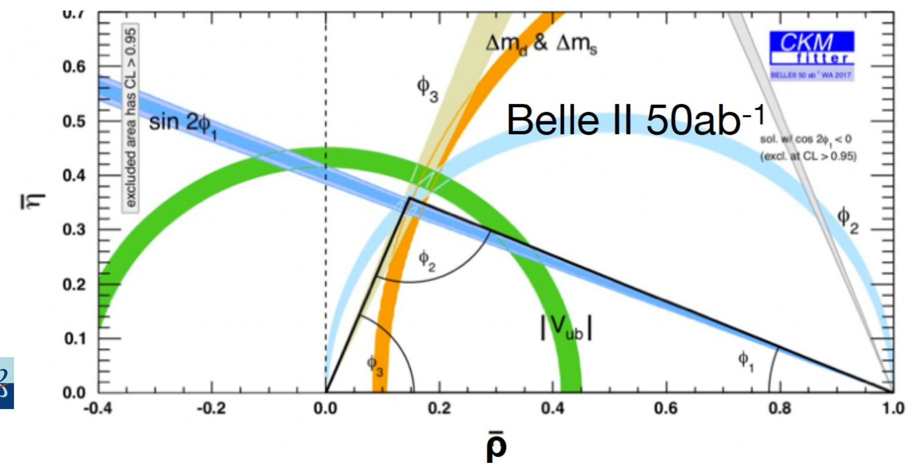
B physics provides very rich sector for precision tests of the Standard Model

- Compare precise measurements with (equally precise) theoretical predictions
- Objective of LHCb and Belle II is to search for evidence of physics beyond SM

Experimentally-oriented presentation on current status and future prospects

- Belle II and LHCb
- $B \to K^{(*)} l^+ l^-$ and $R_{K(*)}$
- Related FCNC modes (including LFV)
- Time dependent $B_s^0 \to \Phi\gamma$
- $\Lambda_b^0 \to \Lambda\gamma$
- Belle II current status and prospects



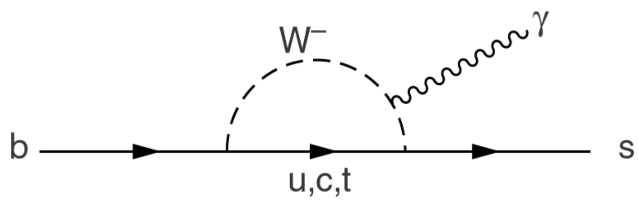


$$V_{CKM} \propto \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|\, e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|\, e^{-i\beta} & -|V_{ts}|\, e^{-i\beta_s} & |V_{tb}| \end{pmatrix}$$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

Electroweak FCNCs

$B \to X_{s/d}\,\gamma$



C_7 (Photon penguin)

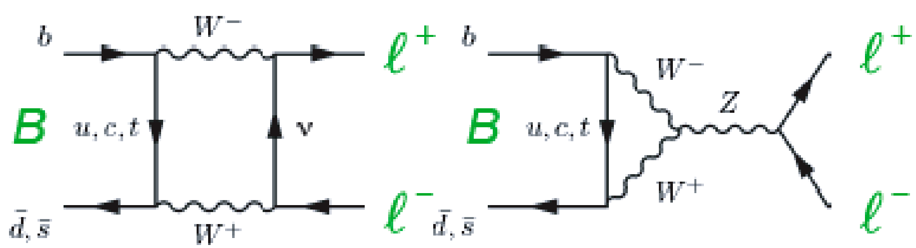
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i(\mu)\, O_i(\mu)$$

Products of field operators (non-perturbative hadronic matrix elements; Heavy quark expansion in inverse powers of m_b)

Wilson coefficients (calculated perturbatively; encode short-distance physics)

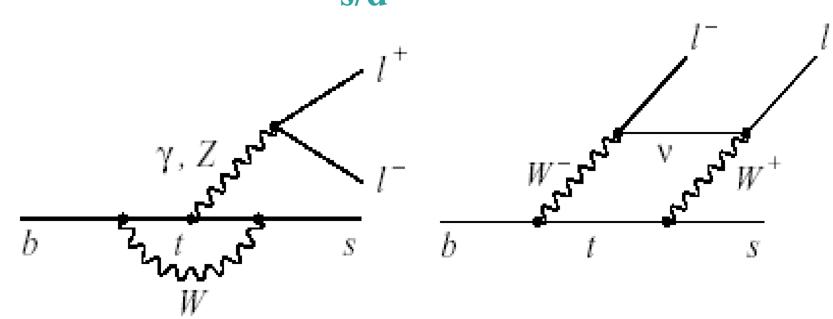
New physics could result in a distinctive pattern of deviations in observables across a variety of related FCNC modes

$B^0_{s/d} \to l^+ l^-$



C_{10} (Axial vector EW)

$B \to X_{s/d}\, l^+ l^-$



C_7, C_9 (Vector EW) and C_{10}

Potentially many observables:

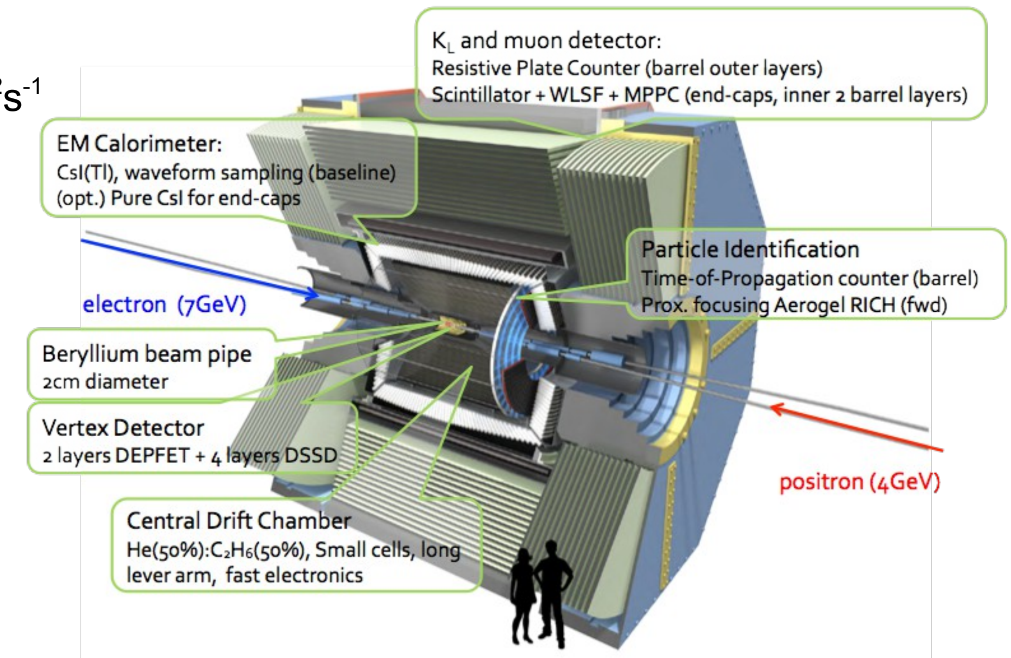
- Branching fractions, CP asymmetries, kinematic distributions, angular distributions and asymmetries

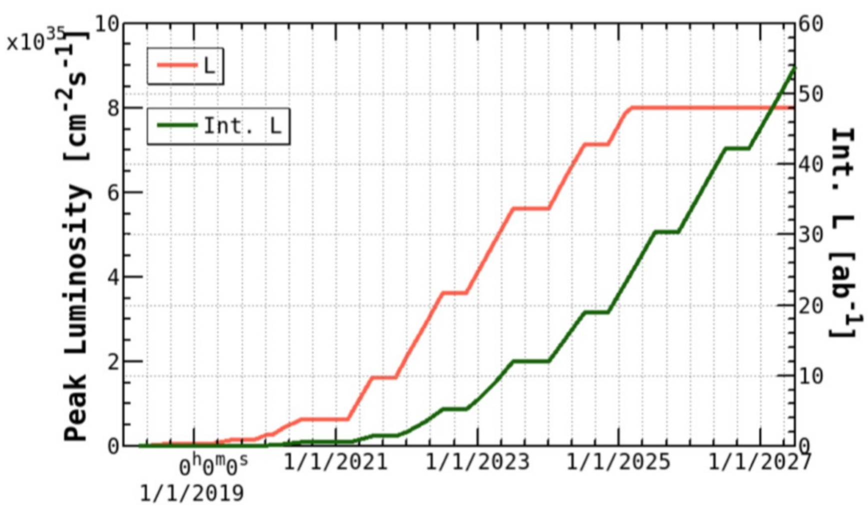
Belle II

Belle II is the successor of the Belle experiment at the KEK laboratory in Tsukuba, Japan

- 4 GeV on 7 GeV e^+e^- collisions at 8 x $10^{35}cm^{-2}s^{-1}$
- Intensity frontier "Super B Factory" flavour physics experiment
- Target data set of 50 ab^{-1}, 30x combined integrated luminosity of *BABAR* + Belle

First collisions achieved in 2018;
Physics run started March 2019





- Smaller beam pipe at IP and redesign of entire inner detector
- New quartz-bar Time-of-Propagation PID in barrel region
- Retain existing CsI(Tl) calorimeter crystals, but entirely new front-end electronics, feature extraction and reconstruction software
- New software framework and distributed computing environment

LHCb

JINST 3, S08005 (2008)

Single-arm forward spectrometer at the LHC optimized for flavour physics

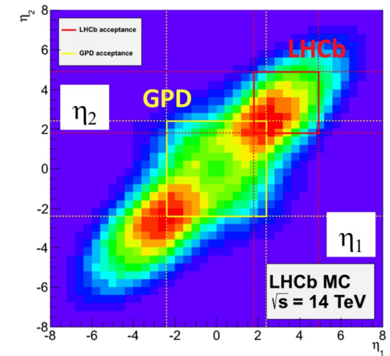
- Exploit forward production of $b\bar{b}$ pairs produced in pp via gluon fusion

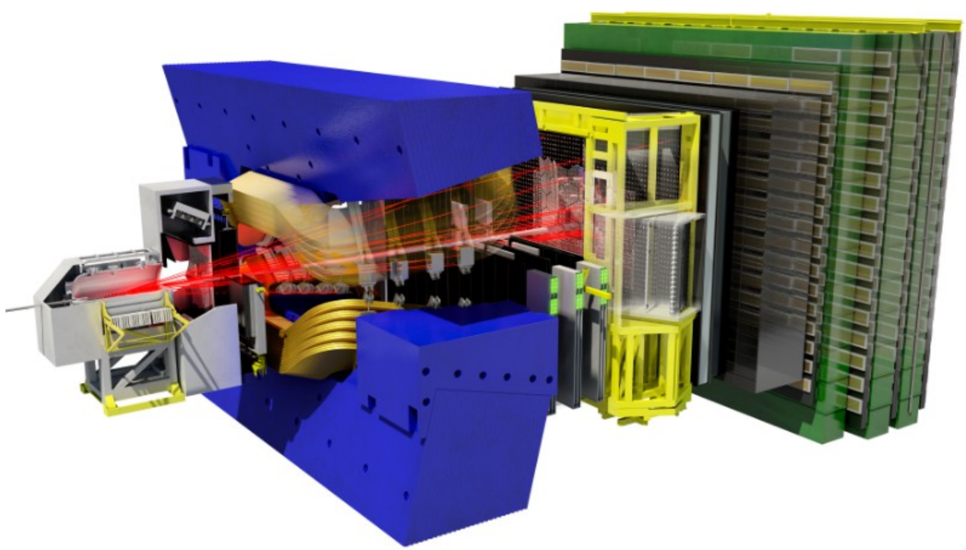
  $2 < \eta < 5$ ~4% of solid angle

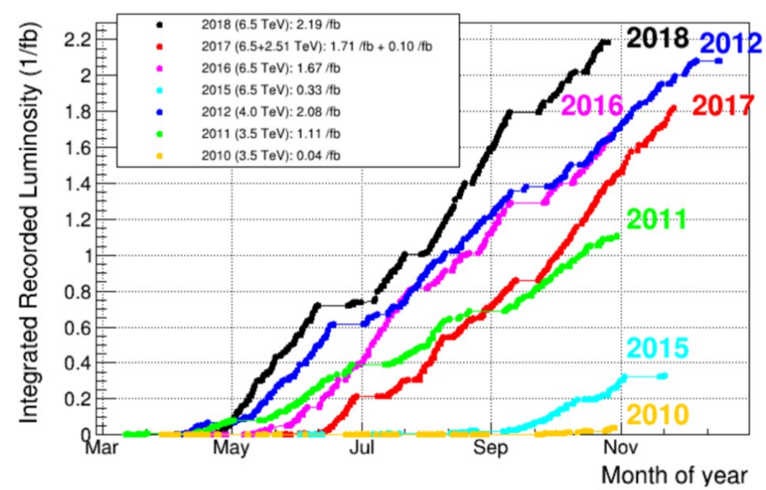
- pp beams displaced to reduce the instantaneous luminosity:

  $L \sim 4 \times 10^{32}\ \mathrm{cm^{-2}s^{-1}}$ twice the design value

  - mean number of interactions per bunch crossing ~1







- Precision vertexing, tracking, PID, EM and hadronic calorimetry, muon ID

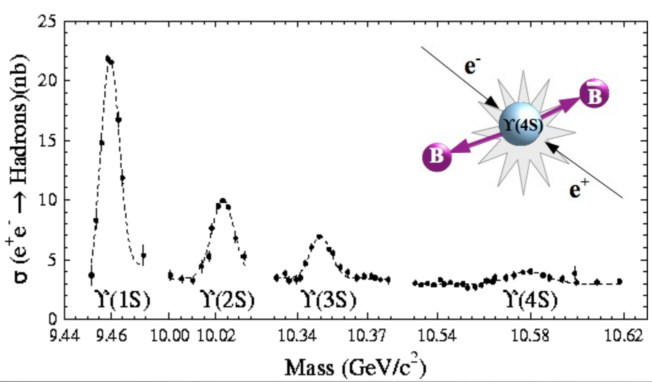
Recorded Luminosity

2011 - 2012 (Run 1)	2015 - 2018 (Run 2)
3.19 fb^{-1} at 7-8 TeV	**5.9 fb^{-1} at 13 TeV**
~ 3 x 10^{11} bb pairs	2 – 6 x 10^{11} bb pairs

What's the difference?

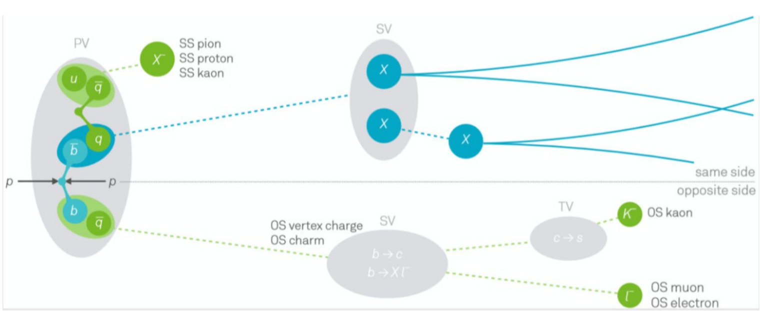
Belle II

- $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B_d\bar{B}_d$
- Exclusive $B_d\bar{B}_d$ production
- σ_{bb}~1.1 nb ~1.1×10^9 $b\bar{b}$ pairs / ab^{-1}
- Hadronic continuum background
  σ_{had}~3.4 nb + QED (ττ, μμ, Bhabha)
- B mesons almost at rest in lab frame; asymmetric beam energies creates boost for decay vertex separation
- Hermetic (>90%) 4π detector and known initial state kinematics
- Photon, K_L and missing energy reconstruction



LHCb

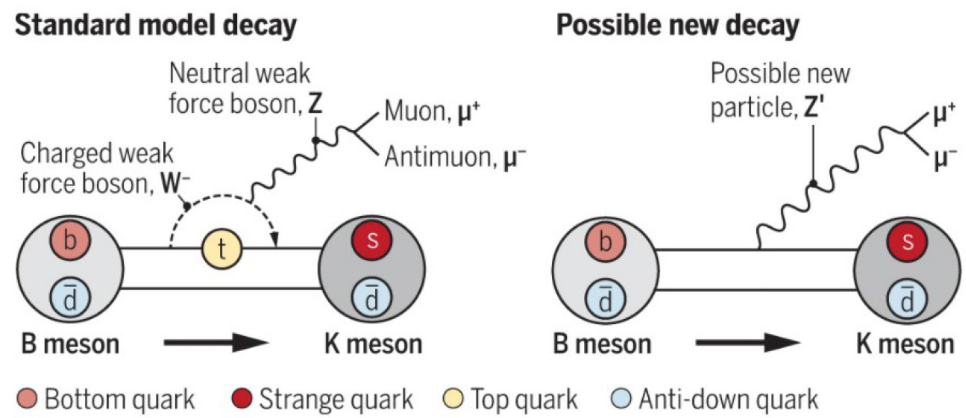
- b quarks produced by gluon fusion in pp collisions
- All b-hadron varieties produced: B_d, B_s, B_c, Λ_b
- σ_{bb}~100 μb ~1.1×10^{11} $b\bar{b}$ pairs / fb^{-1}
- A lot of background...
- Highly boosted topology gives excellent decay vertex separation (background suppression, B reconstruction and time dependent analyses)
- Longitudinally boosted bb pairs
- B longitudinal momentum not known; approximated from event kinematics



$B \rightarrow K^{(*)}\ell^+\ell^-$ and $R_{K(*)}$

$$B \rightarrow K^{(*)}\mu^+\mu^-$$

$$B \rightarrow K^{(*)}e^+e^-$$



Couplings of the gauge bosons leptons independent of lepton flavour

- Not necessarily the case for new physics
- hadronic effects cancel, error is $O(10^{-4})$ [JHEP 07 (2007) 040]
- QED corrections can be $O(10^{-2})$ [EPJC 76 (2016) 440]

$$R_{K^{(*)}}(q^2) = \frac{BF(B \rightarrow K^{(*)}\mu^+\mu^-)}{BF(B \rightarrow K^{(*)}e^+e^-)}$$

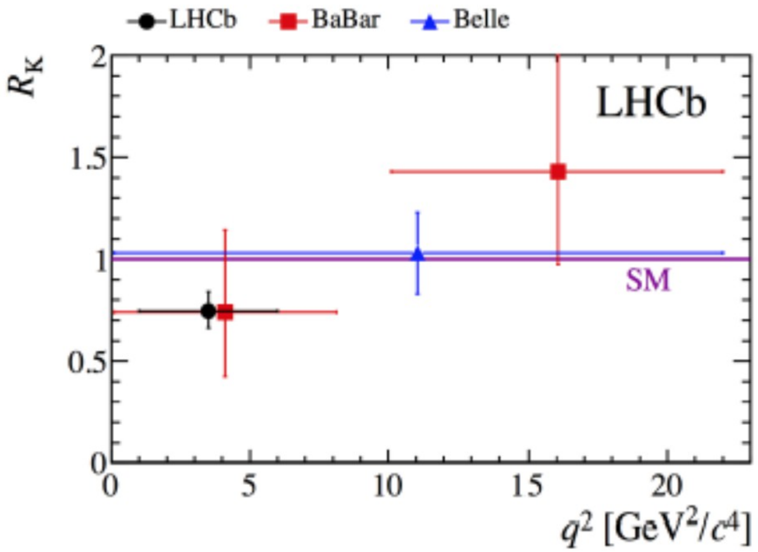
See talks by Alakabha Datta and Xiao-Gang He
(Friday morning plenary session)

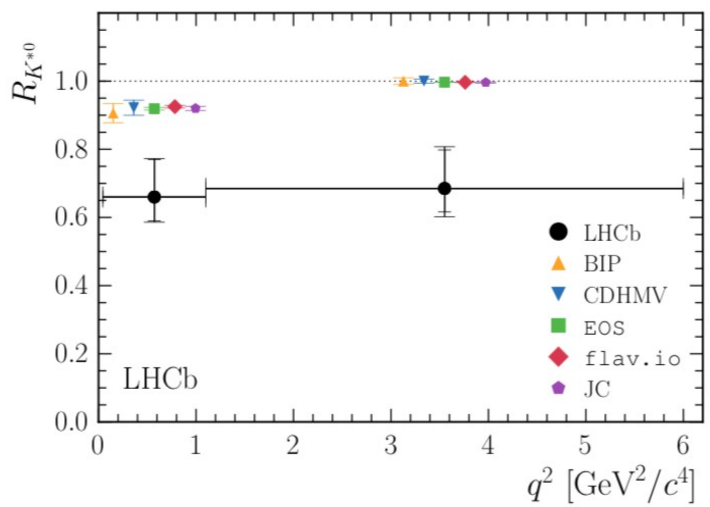
Lepton flavour non-universality would be an indication of New Physics

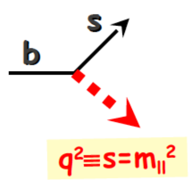
$B \to K^{(*)}\ell^+\ell^-$ and $R_{K^{(*)}}$

Previous LHCb results based on Run 1 data have shown hints of a discrepancy in both R_K and R_{K^*}

PRL. 113 (2014) 151601, arXiv:1406.6482
JHEP 08 (2017) 055, arXiv:1705.05802







Recent LHCb update of R_K measurement in $1.1 < q^2 < 6.0$ GeV^2

- Measurement performed on re-analysed 2011 & 2012 Run 1 data (3 fb^{-1}) plus 2015 and 2016 datasets (2 fb^{-1}) at 13 TeV
  - Larger bb cross-section due to higher √s
  - Improved reconstruction and re-optimised analysis strategy
- Approximately twice as many B's as previous analysis

PRL 122 (2019) 191801
arXiv:1903.09252

R_K method

PRL 122 (2019) 191801
arXiv:1903.09252

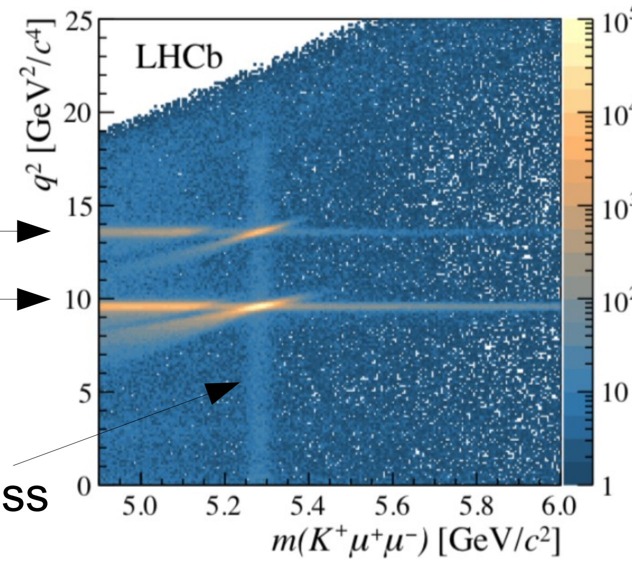
LHCb does not have symmetric performance for electrons and muons

- Larger bremsstrahlung for electrons
- Different trigger strategies for e and μ
- Reduced mass and q^2 resolution, and reconstruction efficiency

Ψ(2S)

J/Ψ

B mass

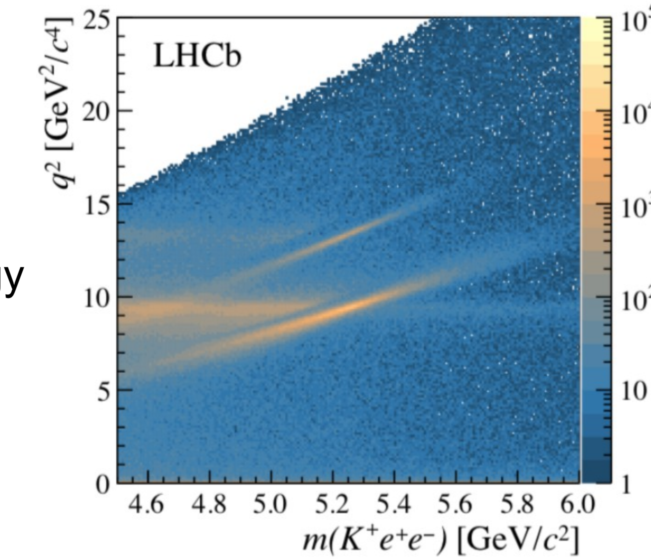


Very challenging for universality test...

- Instead, measure double ratio relative to J/Ψ modes:

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

  - Cancel systematics using modes with similar topology
  - Efficiencies calibrated with control channels and validated via measurements of J/Ψ and Ψ(2S) $B^+\to K^+J/\psi$ and $B^+\to K^+\psi(2S)$ branching fraction ratios in data

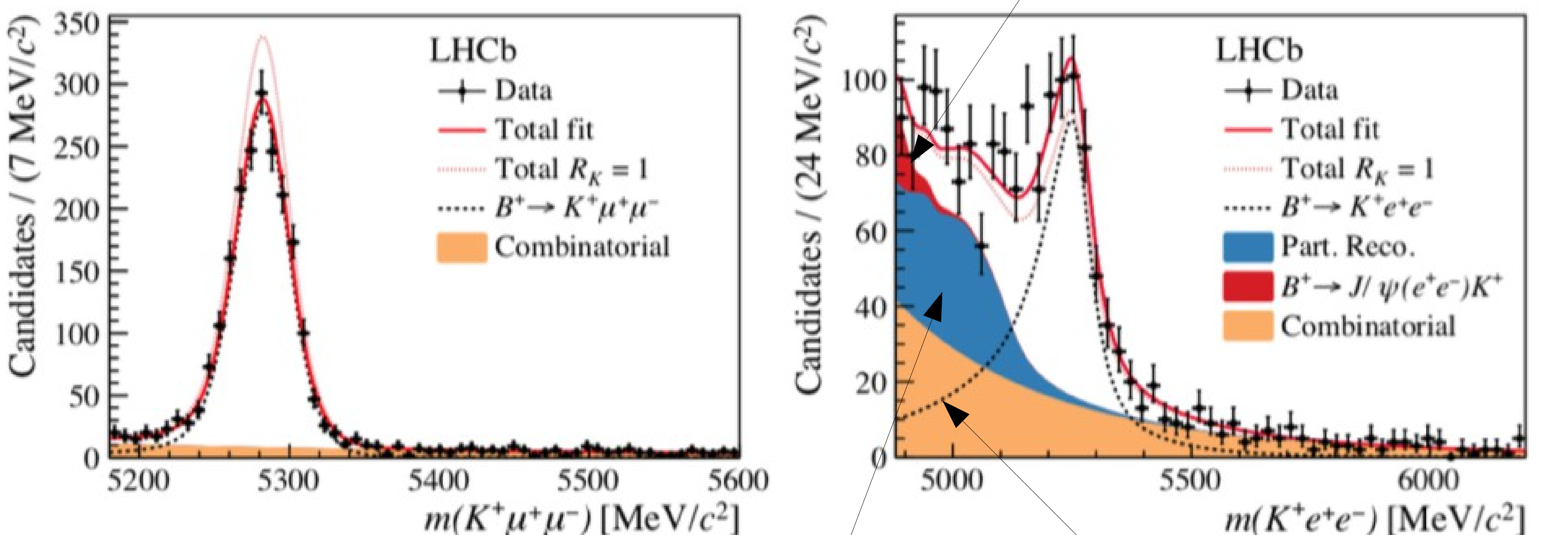


R_K determination

PRL 122 (2019) 191801
arXiv:1903.09252

Signal extracted from a simultaneous fit to $m(K^+\mu^+\mu^-)$ and $m(K^+e^+e^-)$ distributions with R_K as a fit parameter

Leakage from $B \to K^+ J/\psi$ constrained from the fit to the resonant mode



mainly $B^0 \to K^{*0}e^+e^-$

Bremsstrahlung radiative tail

R_K results

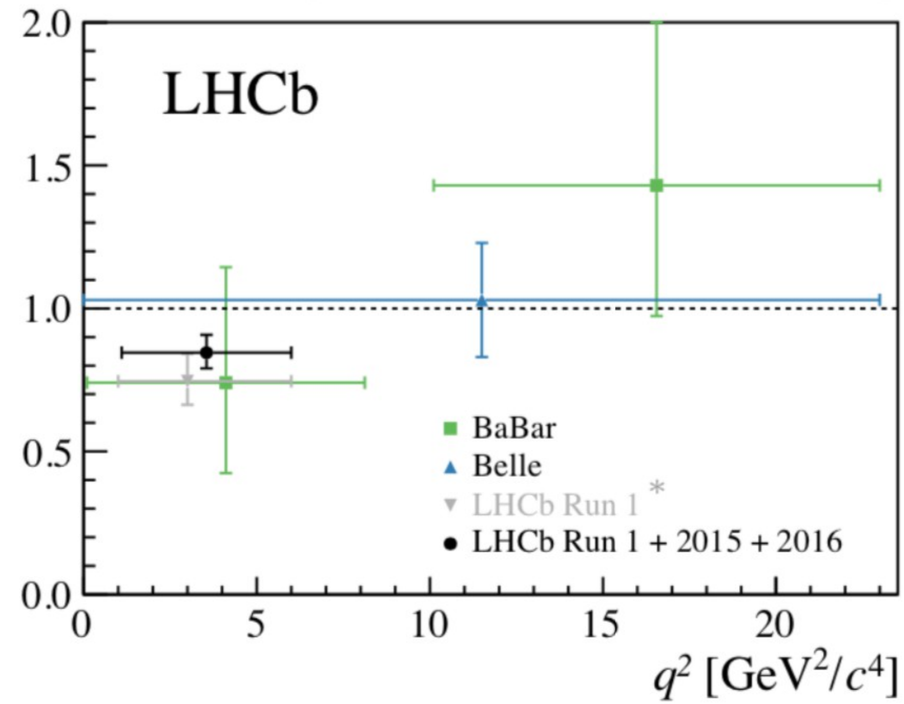
PRL 122 (2019) 191801
arXiv:1903.09252

- Central value moves closer to SM, but smaller uncertainties
  - Similar significance

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

Previous result: $R_K = 0.745 \,^{+0.090}_{-0.074}\,(\text{stat}) \pm 0.036\,(\text{syst})$

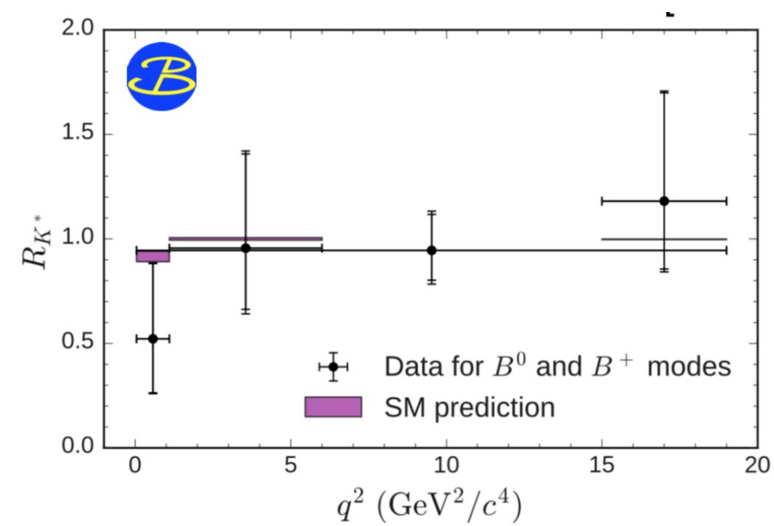
• LHCb data from 2017 & 2018 will effectively double the existing dataset
• Improved and additional LFU analyses
• Updated angular observables



- Recent Belle measurement of R_{K^*} consistent with SM

arXiv:1904.02440

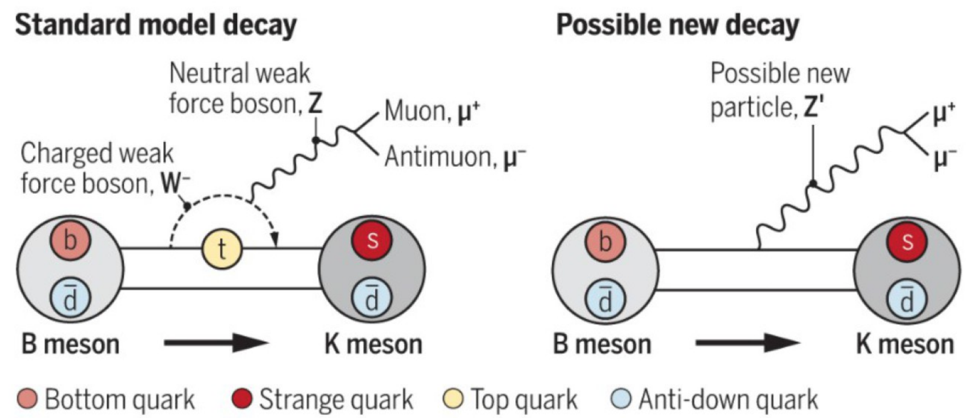
See talk by Youngjoon Kwon
(Weds afternoon parallel session)



$B \to K^{(*)}\ell^+\ell^-$ and $R_{K(*)}$

$B \to K^{(*)}\mu^+\mu^-$

$B \to K^{(*)}e^+e^-$



Independent experimental verification with different techniques and systematics would be needed in order to make a compelling case for new physics

Belle II would have sensitivity comparable to existing LHCb results for both R_K and R_{K^*} with ~5 ab^{-1}

- Belle II has symmetric e/μ PID performance and can measure absolute branching fractions

Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 a
R_K ([1.0, 6.0] GeV^2)	28%	11%	3.6%
R_K (> 14.4 GeV^2)	30%	12%	3.6%
R_{K^*} ([1.0, 6.0] GeV^2)	26%	10%	3.2%
R_{K^*} (> 14.4 GeV^2)	24%	9.2%	2.8%
R_{X_s} ([1.0, 6.0] GeV^2)	32%	12%	4.0%
R_{X_s} (> 14.4 GeV^2)	28%	11%	3.4%

"The Belle II Physics Book"
BELLE2-PAPER-2018-001
arXiv:1808.10567[hep-ex]

- Also precision studies of angular observables

$B \to K^{(*)}l^+l^-$ and $R_{K(*)}$

$B \to K^{(*)}\mu^+\mu^-$

$B \to K^{(*)}e^+e^-$

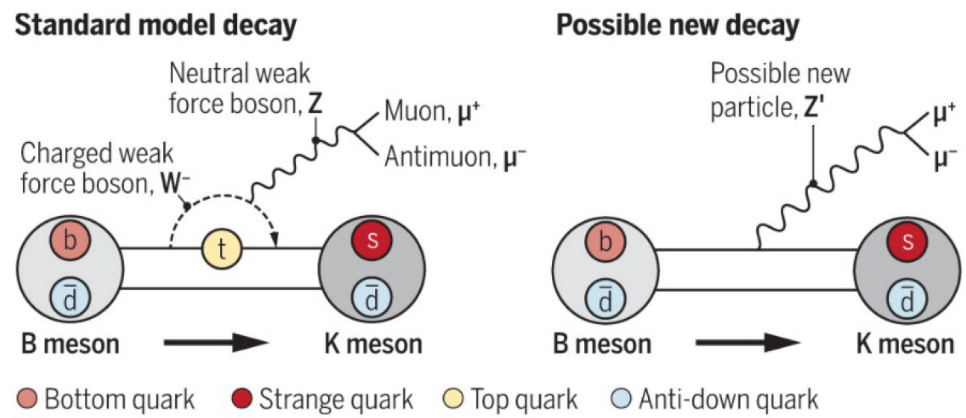
$B^0 \to K^{(*)0}l^+l^-$

$B^+ \to K^{(*)+}l^+l^-$

$B \to \pi l^+l^-$

$B \to X_{s/d}\, l^+l^-$

"Clean" B factory environment is amenable to reconstruction of modes containing neutrals, or inclusive final states



$$R_{K^{(*)}}(q^2) = \frac{BF(B \to K^{(*)}\mu^+\mu^-)}{BF(B \to K^{(*)}e^+e^-)}$$

... but there are also two distinct B charge/flavour states

...and two different final-state quark flavours (s,d)

... and also "inclusive" $X_{s/d}$ hadronic systems (as opposed to exclusive π, K, K* reconstruction)

$B \to X_s^{(*)} l^+ l^-$

arXiv:1808.10567

$B \to K^{(*)} \mu^+ \mu^-$

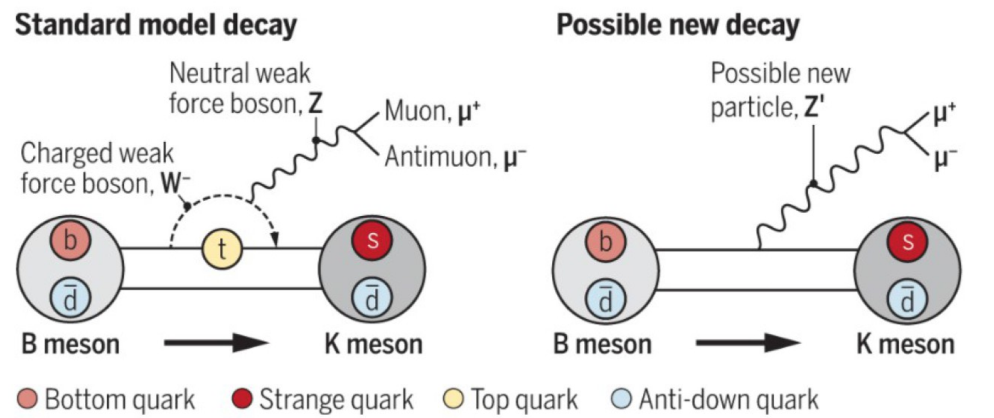
$B \to K^{(*)} e^+ e^-$

$B^0 \to K^{(*)0} l^+ l^-$

$B^+ \to K^{(*)+} l^+ l^-$

$B \to \pi l^+ l^-$

$B \to X_{s/d} l^+ l^-$



Observables	Belle $0.71\,\text{ab}^{-1}$	Belle II $5\,\text{ab}^{-1}$	Belle II $50\,\text{ab}^{-1}$
$\text{Br}(B \to X_s\ell^+\ell^-)$ ($[1.0, 3.5]$ GeV^2)	29%	13%	6.6%
$\text{Br}(B \to X_s\ell^+\ell^-)$ ($[3.5, 6.0]$ GeV^2)	24%	11%	6.4%
$\text{Br}(B \to X_s\ell^+\ell^-)$ (> 14.4 GeV^2)	23%	10%	4.7%
$A_{\text{CP}}(B \to X_s\ell^+\ell^-)$ ($[1.0, 3.5]$ GeV^2)	26%	9.7 %	3.1 %
$A_{\text{CP}}(B \to X_s\ell^+\ell^-)$ ($[3.5, 6.0]$ GeV^2)	21%	7.9 %	2.6 %
$A_{\text{CP}}(B \to X_s\ell^+\ell^-)$ (> 14.4 GeV^2)	21%	8.1 %	2.6 %
$A_{\text{FB}}(B \to X_s\ell^+\ell^-)$ ($[1.0, 3.5]$ GeV^2)	26%	9.7%	3.1%
$A_{\text{FB}}(B \to X_s\ell^+\ell^-)$ ($[3.5, 6.0]$ GeV^2)	21%	7.9%	2.6%
$A_{\text{FB}}(B \to X_s\ell^+\ell^-)$ (> 14.4 GeV^2)	19%	7.3%	2.4%
$\Delta_{\text{CP}}(A_{\text{FB}})$ ($[1.0, 3.5]$ GeV^2)	52%	19%	6.1%
$\Delta_{\text{CP}}(A_{\text{FB}})$ ($[3.5, 6.0]$ GeV^2)	42%	16%	5.2%
$\Delta_{\text{CP}}(A_{\text{FB}})$ (> 14.4 GeV^2)	38%	15%	4.8%

Typically ~5% precision on "inclusive" $B \to X_{s/d} l^+ l^-$ observables with full Belle II data set

Missing energy modes

$B \rightarrow K^{(*)}\mu^+\mu^-$

$B \rightarrow K^{(*)}e^+e^-$

$B^0 \rightarrow K^{(*)0}l^+l^-$

$B^+ \rightarrow K^{(*)+}l^+l^-$

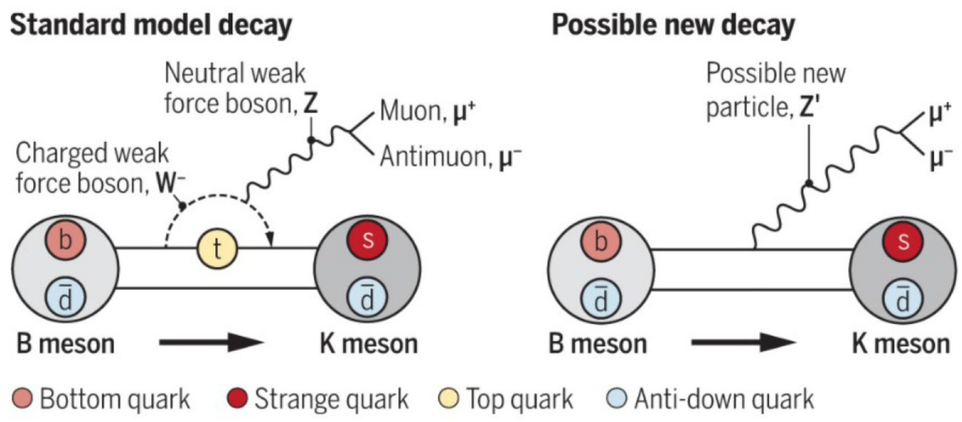
$B \rightarrow \pi\, l^+l^-$

$B \rightarrow X_{s/d}\, l^+l^-$

$B \rightarrow K^{(*)}\tau^+\tau^-$

$B \rightarrow K^{(*)}\nu\bar{\nu}$

$B \rightarrow K^{(*)}\tau^+l^-$



...also two additional lepton types (τ,ν) which can be studied

...as well as lepton flavour violating modes.

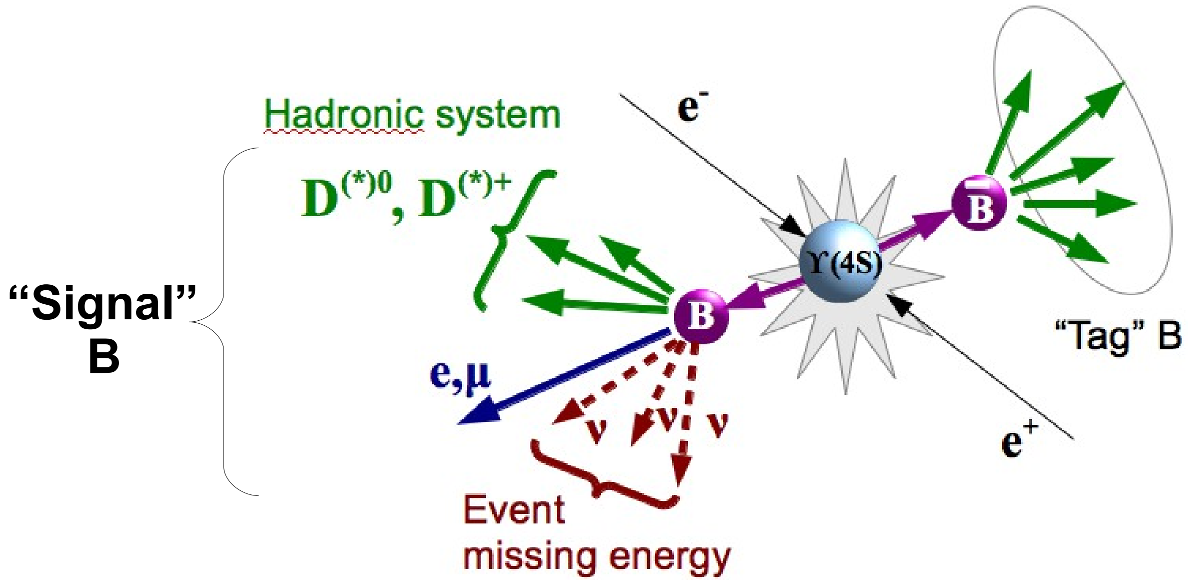
Requires capability to identify signal events in spite of limited kinematic constraints due to multiple undetected particles

Missing energy modes

Unique capability to study B decay modes with missing energy:

- FCNC modes such as $B \rightarrow K^{(*)}\nu\bar{\nu}$, $B^0 \rightarrow \nu\bar{\nu}$, $B \rightarrow K^{(*)}\tau^+\tau^-$ etc.
- Semileptonic B decays such as $B \rightarrow D^{(*)}\tau^+\nu$, $B^+ \rightarrow \mu^+\nu$, and $B^+ \rightarrow \tau^+\nu$

Precisely known CM energy, combined with exclusive hadronic reconstruction of the accompanying B, permit the decay daughters of missing energy decays to be uniquely identified:



$$m_{BC} \equiv \sqrt{E^{*2}_{\text{beam}} - p^{*2}_B}$$
$$\Delta E^* \equiv E^*_B - E^*_{\text{beam}}$$

Similar methodology exists for reconstructing semileptonic B tags

Typically <1% efficiency
- Potential to probe rare decays at 10^{-7} level

Missing energy modes

$B \rightarrow K^{(*)}\mu^+\mu^-$

$B \rightarrow K^{(*)}e^+e^-$

$B^0 \rightarrow K^{(*)0}l^+l^-$

$B^+ \rightarrow K^{(*)+}l^+l^-$

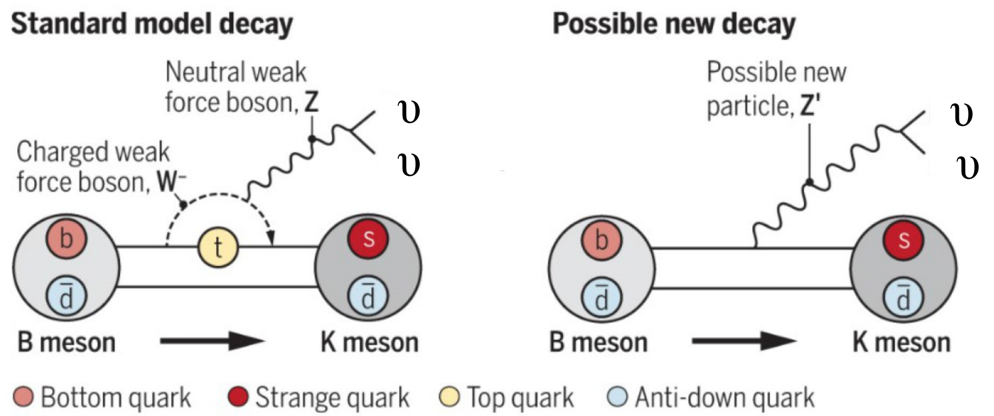
$B \rightarrow \pi l^+l^-$

$B \rightarrow X_{s/d}\, l^+l^-$

$B \rightarrow K^{(*)}\tau^+\tau^-$

$B \rightarrow K^{(*)}\nu\bar{\nu}$

$B \rightarrow K^{(*)}\tau^+l^-$



Observables	Belle $0.71\,\mathrm{ab}^{-1}$ ($0.12\,\mathrm{ab}^{-1}$)	Belle II $5\,\mathrm{ab}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
$\mathrm{Br}(B^+ \to K^+\nu\bar{\nu})$	$< 450\%$	30%	11%
$\mathrm{Br}(B^0 \to K^{*0}\nu\bar{\nu})$	$< 180\%$	26%	9.6%
$\mathrm{Br}(B^+ \to K^{*+}\nu\bar{\nu})$	$< 420\%$	25%	9.3%
$F_L(B^0 \to K^{*0}\nu\bar{\nu})$	–	–	0.079
$F_L(B^+ \to K^{*+}\nu\bar{\nu})$	–	–	0.077
$\mathrm{Br}(B^0 \to \nu\bar{\nu}) \times 10^6$	< 14	< 5.0	< 1.5

~10% measurements in neutral and charged K and K* with full data sample

arXiv:1808.10567

Missing energy modes

$B \to K^{(*)}\mu^+\mu^-$

$B \to K^{(*)}e^+e^-$

$B^0 \to K^{(*)0}l^+l^-$

$B^+ \to K^{(*)+}l^+l^-$

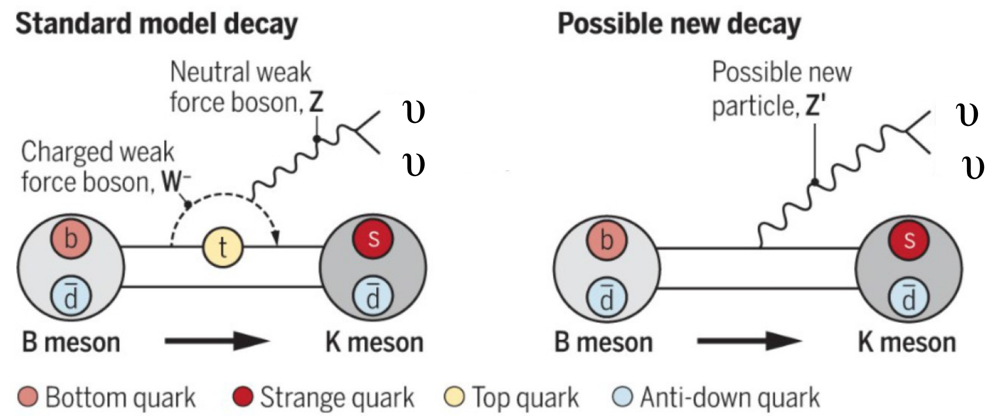
$B \to \pi l^+l^-$

$B \to X_{s/d}\, l^+l^-$

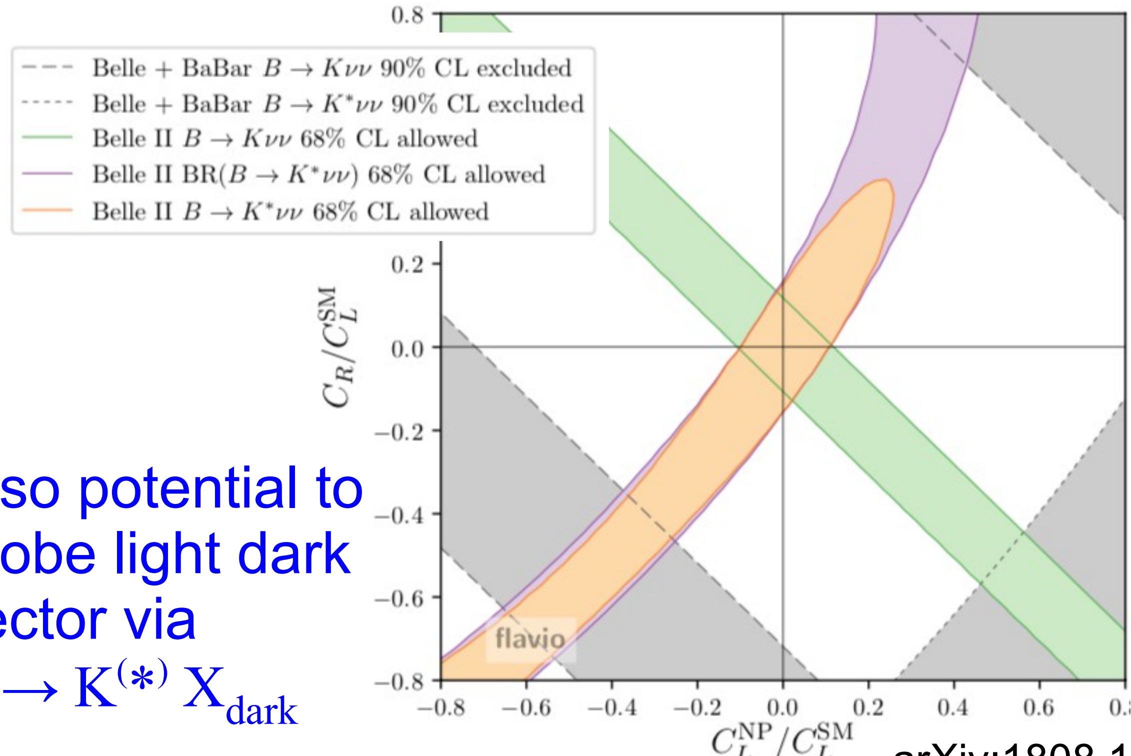
$B \to K^{(*)}\tau^+\tau^-$

$B \to K^{(*)}\nu\bar{\nu}$

$B \to K^{(*)}\tau^+l^-$



Also potential to probe light dark sector via $B \to K^{(*)} X_{dark}$



arXiv:1808.10567

Missing energy modes

$B \rightarrow K^{(*)}\mu^{+}\mu^{-}$

$B \rightarrow K^{(*)}e^{+}e^{-}$

$B^{0} \rightarrow K^{(*)0}l^{+}l^{-}$

$B^{+} \rightarrow K^{(*)+}l^{+}l^{-}$

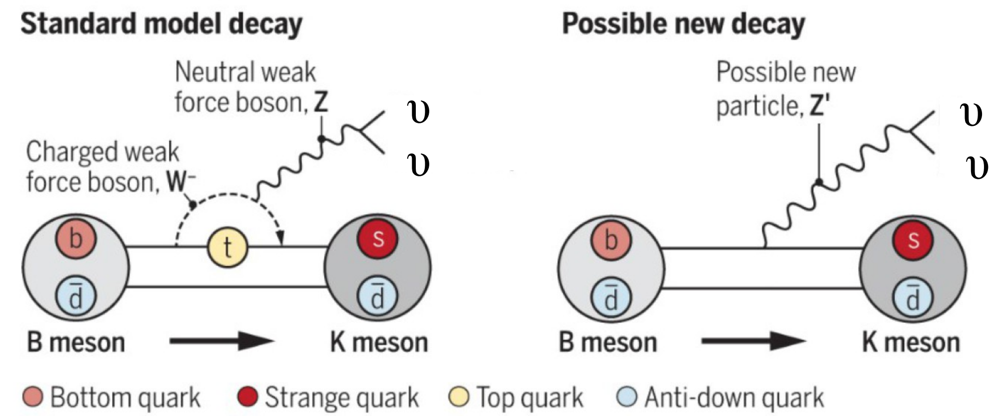
$B \rightarrow \pi l^{+}l^{-}$

$B \rightarrow X_{s/d}\, l^{+}l^{-}$

$B \rightarrow K^{(*)}\tau^{+}\tau^{-}$

$B \rightarrow K^{(*)}\nu\bar{\nu}$

$B \rightarrow K^{(*)}\tau^{+}l^{-}$



$\tau^{+}\tau^{-}$ modes are extremely challenging even for B factories

PRL 118, 031802 (2017)

Observables	Belle $0.71\,\mathrm{ab}^{-1}$ $(0.12\,\mathrm{ab}^{-1})$	Belle II $5\,\mathrm{ab}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
$\mathrm{Br}(B^{+} \to K^{+}\tau^{+}\tau^{-}) \cdot 10^{5}$	< 32	< 6.5	< 2.0
$\mathrm{Br}(B^{0} \to \tau^{+}\tau^{-}) \cdot 10^{5}$	< 140	< 30	< 9.6
$\mathrm{Br}(B_{s}^{0} \to \tau^{+}\tau^{-}) \cdot 10^{4}$	< 70	< 8.1	–
$\mathrm{Br}(B^{+} \to K^{+}\tau^{\pm}e^{\mp}) \cdot 10^{6}$	–	–	< 2.1
$\mathrm{Br}(B^{+} \to K^{+}\tau^{\pm}\mu^{\mp}) \cdot 10^{6}$	–	–	< 3.3
$\mathrm{Br}(B^{0} \to \tau^{\pm}e^{\mp}) \cdot 10^{5}$	–	–	< 1.6
$\mathrm{Br}(B^{0} \to \tau^{\pm}\mu^{\mp}) \cdot 10^{5}$	–	–	< 1.3

Limits on LFV modes with 3rd generation leptons (and quarks)

arXiv:1808.10567

Leptonic and LFV modes

Published searches for $B^0_{(s)} \to \mu^+\mu^-$

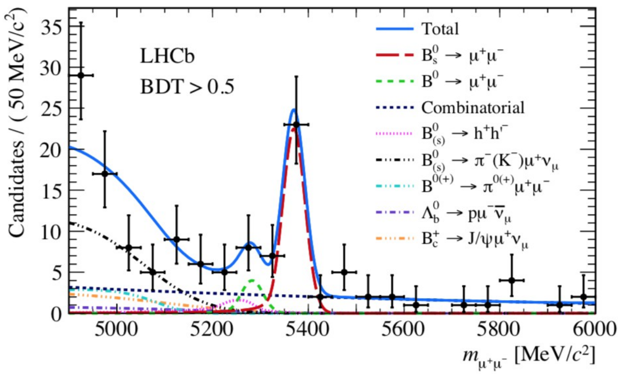
PRL 118(2017)191801

3 fb^{-1} of Run 1 and 1.4 fb^{-1} of Run 2 data (2015 + 2016)

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9} \quad 7.8\sigma$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.5^{+1.2+0.2}_{-1.0-0.1}) \times 10^{-10} \quad 1.6\sigma$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} \text{at 95\% CL}$$



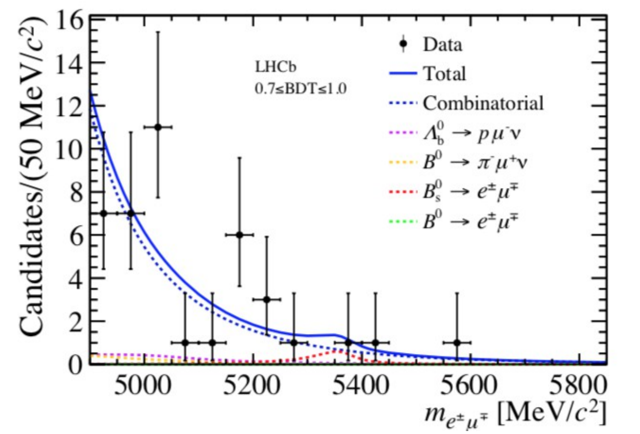
- Also LVF decays $B^0_{(s)} \to e^+\mu^-$

JHEP 1803 (2018) 078

$$\mathcal{B}(B^0 \to e^\pm\mu^\mp) < 1.3(1.0) \times 10^{-9} \text{at 95 (90)\% CL}$$

$$\mathcal{B}(B^0_s \to e^\pm\mu^\mp) < 6.3(5.4) \times 10^{-9} \text{at 95 (90)\% CL}$$

$$\mathcal{B}(B^0_s \to e^\pm\mu^\mp) < 7.2(6.0) \times 10^{-9} \text{at 95 (90)\% CL}$$



- New LHCb limit on LFV $B^0_{(s)} \to \tau^+\mu^-$ based on 3 fb^{-1} 2011 - 2012 data

Based on hadronic $\tau \to 3\pi\nu$ decays

arXiv:1905.06614 [hep-ex]

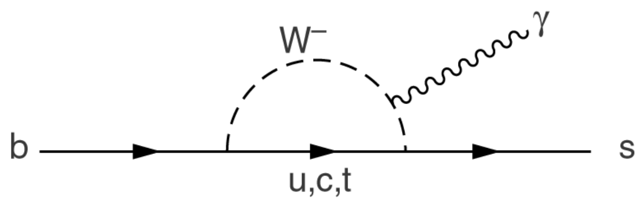
Factor of ~2 improvement in $B^0_d \to \tau^+\mu^-$ over 2008 *BABAR* limit; sensitivity at upper end of prediction range for leptoquark models

$$\mathcal{B}\left(B^0_s \to \tau^\pm\mu^\mp\right) < 4.2 \times 10^{-5}$$

$$\mathcal{B}\left(B^0 \to \tau^\pm\mu^\mp\right) < 1.4 \times 10^{-5}$$

Electroweak FCNCs

$B \rightarrow X_{s/d}\,\gamma$



C_7 (Photon penguin)

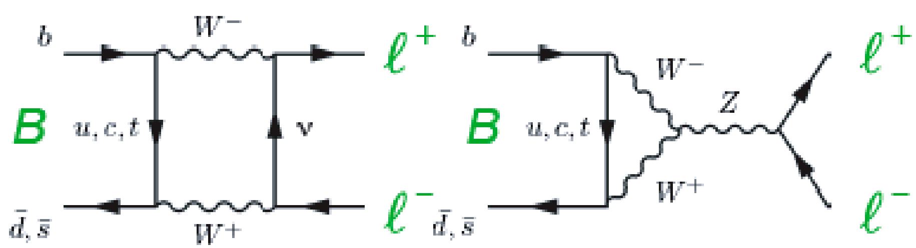
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i(\mu)\, O_i(\mu)$$

Products of field operators (non-perturbative hadronic matrix elements; Heavy quark expansion in inverse powers of m_b)

Wilson coefficients (calculated perturbatively; encode short-distance physics)

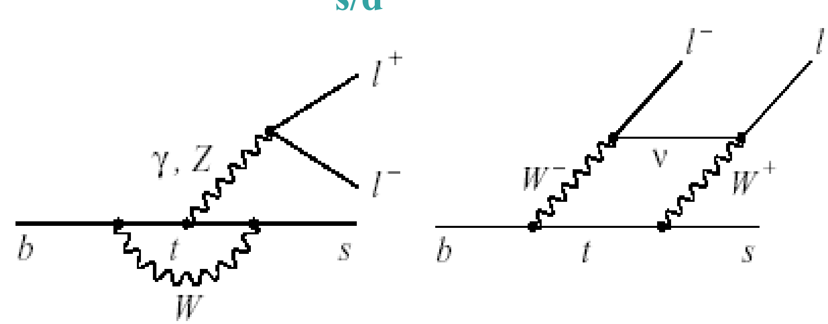
New physics could result in a distinctive pattern of deviations in observables across a variety of related FCNC modes

$B^0_{s/d} \rightarrow l^+l^-$



C_{10} (Axial vector EW)

$B \rightarrow X_{s/d}\, l^+l^-$



C_7 ,C_9 (Vector EW) and C_{10}

Potentially many observables:

- Branching fractions, CP asymmetries, kinematic distributions, angular distributions and asymmetries

$b \to s(d)\gamma$

arXiv:1808.10567

Belle II can access a wide range of $b \to s\gamma$ and $b \to d\gamma$ modes and CP observables in B_d decays:

Observables	Belle 0.71 ab^{-1} (0.12 ab^{-1})	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\Delta_{0+}(B \to K^*\gamma)$	2.0%	0.70%	0.53%
$A_{CP}(B^0 \to K^{*0}\gamma)$	1.7%	0.58%	0.21%
$A_{CP}(B^+ \to K^{*+}\gamma)$	2.4%	0.81%	0.29%
$\Delta A_{CP}(B \to K^*\gamma)$	2.9%	0.98%	0.36%
$S_{K^{*0}\gamma}$	0.29	0.090	0.030
$\mathrm{Br}(B^0 \to \rho^0\gamma)$	24%	7.6%	4.5%
$\mathrm{Br}(B^+ \to \rho^+\gamma)$	30%	9.6%	5.0%
$\mathrm{Br}(B^0 \to \omega\gamma)$	50%	14%	5.8%
$\Delta_{0+}(B \to \rho\gamma)$	18%	5.4%	1.9%
$A_{CP}(B^0 \to \rho^0\gamma)$	44%	12%	3.8%
$A_{CP}(B^+ \to \rho^+\gamma)$	30%		
$A_{CP}(B^0 \to \omega\gamma)$	91%		
$\Delta A_{CP}(B \to \rho\gamma)$	53%		
$S_{\rho^0\gamma}$	0.63		
$\|V_{td}/V_{ts}\|_{\rho/K^*}$	12%		
$\mathrm{Br}(B_s^0 \to \phi\gamma)$	23%		
$\mathrm{Br}(B^0 \to K^{*0}\gamma)/\mathrm{Br}(B_s^0 \to \phi\gamma)$	23%		
$\mathrm{Br}(B_s^0 \to K^{*0}\gamma)$	–		
$A_{CP}(B_s^0 \to K^{*0}\gamma)$	–		
$\mathrm{Br}(B_s^0 \to K^{*0}\gamma)/\mathrm{Br}(B_s^0 \to \phi\gamma)$	–		
$\mathrm{Br}(B^0 \to K^{*0}\gamma)/\mathrm{Br}(B_s^0 \to K^{*0}\gamma)$	–		

- Fully inclusive and "sum of exclusive" measurements of particular theoretical importance:

Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B \to X_s\gamma)_{\text{inc}}^{\text{lep-tag}}$	5.3%	3.9%	3.2%
$\mathrm{Br}(B \to X_s\gamma)_{\text{inc}}^{\text{had-tag}}$	13%	7.0%	4.2%
$\mathrm{Br}(B \to X_s\gamma)_{\text{sum-of-ex}}$	10.5%	7.3%	5.7%
$\Delta_{0+}(B \to X_s\gamma)_{\text{sum-of-ex}}$	2.1%	0.81%	0.63%
$\Delta_{0+}(B \to X_{s+d}\gamma)_{\text{inc}}^{\text{had-tag}}$	9.0%	2.6%	0.85%
$A_{CP}(B \to X_s\gamma)_{\text{sum-of-ex}}$	1.3%	0.52%	0.19%
$A_{CP}(B^0 \to X_s^0\gamma)_{\text{sum-of-ex}}$	1.8%	0.72%	0.26%
$A_{CP}(B^+ \to X_s^+\gamma)_{\text{sum-of-ex}}$	1.8%	0.69%	0.25%
$A_{CP}(B \to X_{s+d}\gamma)_{\text{inc}}^{\text{lep-tag}}$	4.0%	1.5%	0.48%
$A_{CP}(B \to X_{s+d}\gamma)_{\text{inc}}^{\text{had-tag}}$	8.0%	2.2%	0.70%
$\Delta A_{CP}(B \to X_s\gamma)_{\text{sum-of-ex}}$	2.5%	0.98%	0.30%
[illegible] had-tag	[illegible]	[illegible]	[illegible]

$B_s^0 \to \Phi\gamma$

arXiv:1905.06284 (submitted to PRL)

Photons predominately produced with left handed helicity in SM $b \to s\gamma$ processes, but right handed component can be enhanced by new physics

- Potentially observable effects in mixing-induced CP asymmetries and time-dependent decay rates

$B_s^0 \to \Phi\gamma$ is of interest because B_s^0 and $\overline{B}_s^0$ decay to common final state

- Decay time distribution given by

Sensitive to photon helicity amplitudes and weak phases

$$\mathcal{P}(t) \propto e^{-\Gamma_s t}\{\cosh(\Delta\Gamma_s t/2) - \mathcal{A}^{\Delta}\sinh(\Delta\Gamma_s t/2) + \zeta\, C\cos(\Delta m_s t) - \zeta\, S\sin(\Delta m_s t)\}$$

Sensitive to CP violation

where C, S and A^{Δ} coefficients are close to zero in SM

Time-dependent analysis of $B_s^0 \to \Phi\gamma$ decay rate by LHCb

- Flavour-tagging used to determine initial B_s^0 and $\overline{B}_s^0$ flavour
- $B^0 \to K^{*0}\gamma$ $(K^{*0} \to K^+\pi^-)$ used to control decay-time dependence of the efficiency

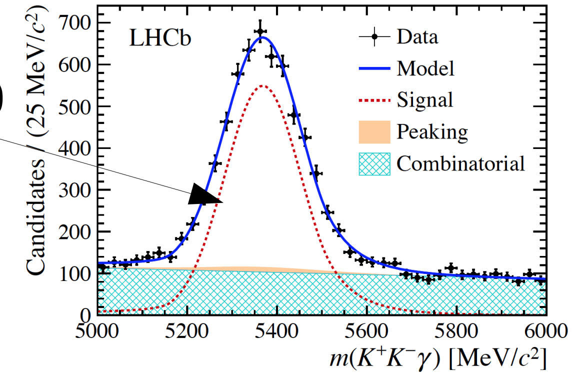
3 fb^{-1} 2011 - 2012 data (7 – 8 TeV)

$B_s^0 \to \Phi\gamma$

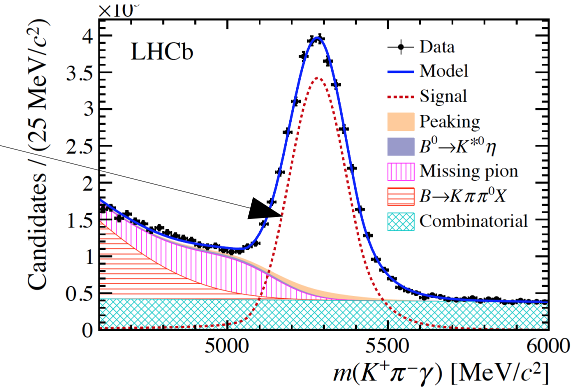
arXiv:1905.06284
(submitted to PRL)

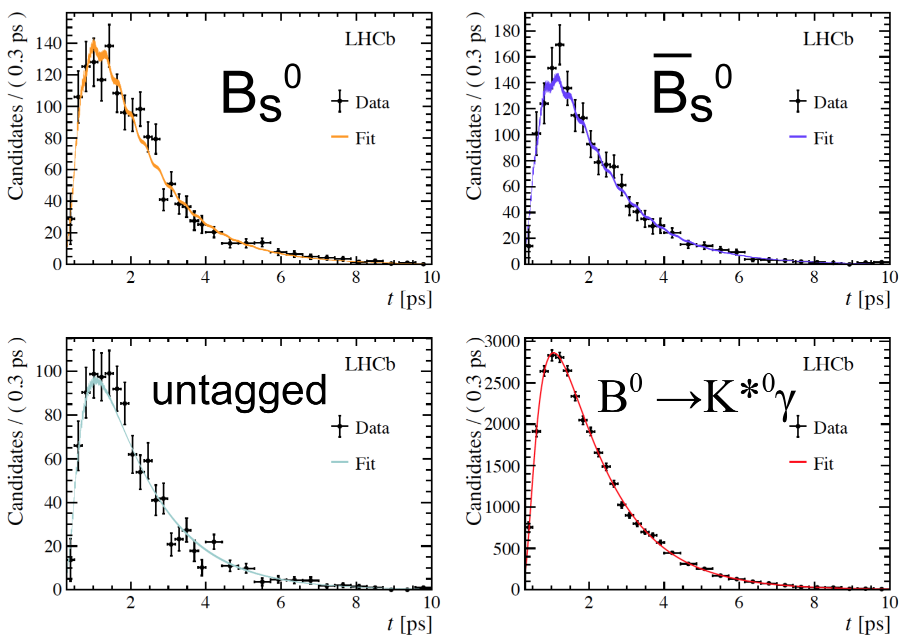
- Reconstruct $\Phi \to K^+K^-$, inconsistent with originating at the primary vertex
- B_s^0 decay times between 0.3 – 10 ps, and consistent with originating from a unique pp interaction vertex
- Flavour tagging based on "same-side" or "opposite side" information
  - Effective tag efficiency of (4.99 ± 0.14)%

5110 ± 90



33860 ± 250





Observables determined from a weighted simultaneous fit to the $B_s^0 \to \Phi\gamma$ and $B^0 \to K^{*0}\gamma$ samples

$$S_{\phi\gamma} = 0.43 \pm 0.30 \pm 0.11$$

$$C_{\phi\gamma} = 0.11 \pm 0.29 \pm 0.11$$

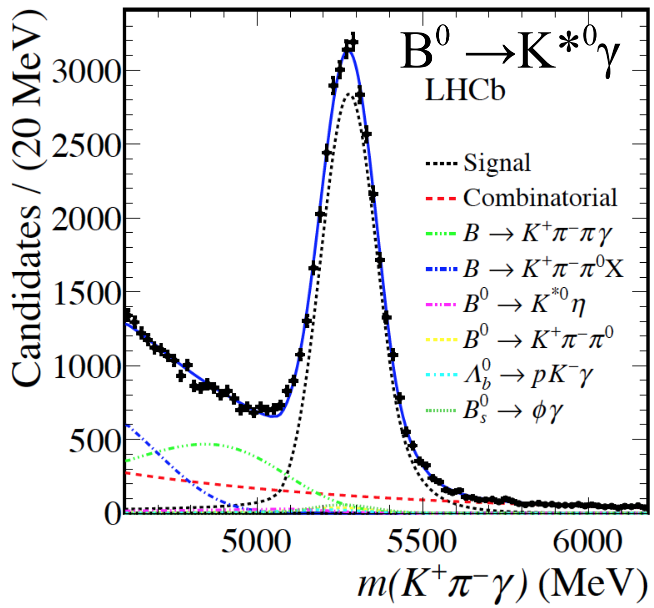
$$\mathcal{A}^{\Delta}_{\phi\gamma} = -0.67\,^{+0.37}_{-0.41} \pm 0.17$$

$\Lambda_b{}^0 \rightarrow \Lambda\gamma$

arXiv:1904.06697
submitted to PRL

First observation of radiative b baryon decay

- Differs from radiative $B_{(s)}$ decays due to non-zero spin of initial and final state baryons
- Probe photon polarization via measurement of Λ helicity, giving access to $b \rightarrow s\gamma$ helicity structure

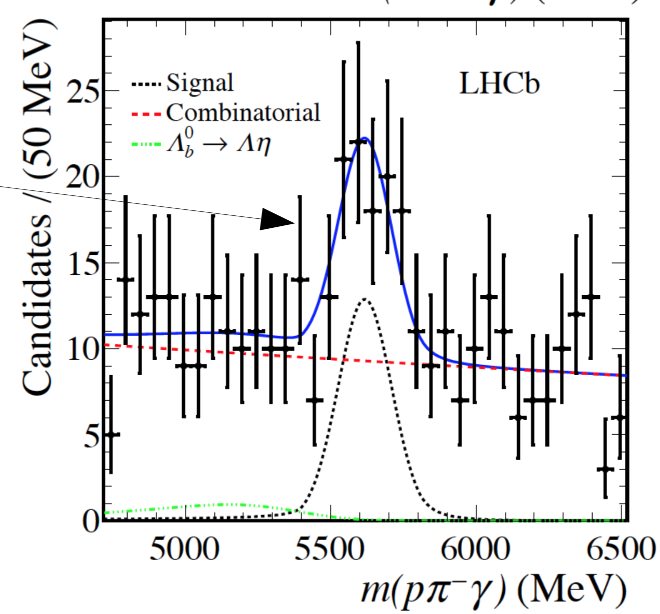


Search for $\Lambda_b{}^0 \rightarrow \Lambda\gamma$ with $\Lambda \rightarrow p\pi^-$

1.7 fb^{-1}
13 TeV (2016)

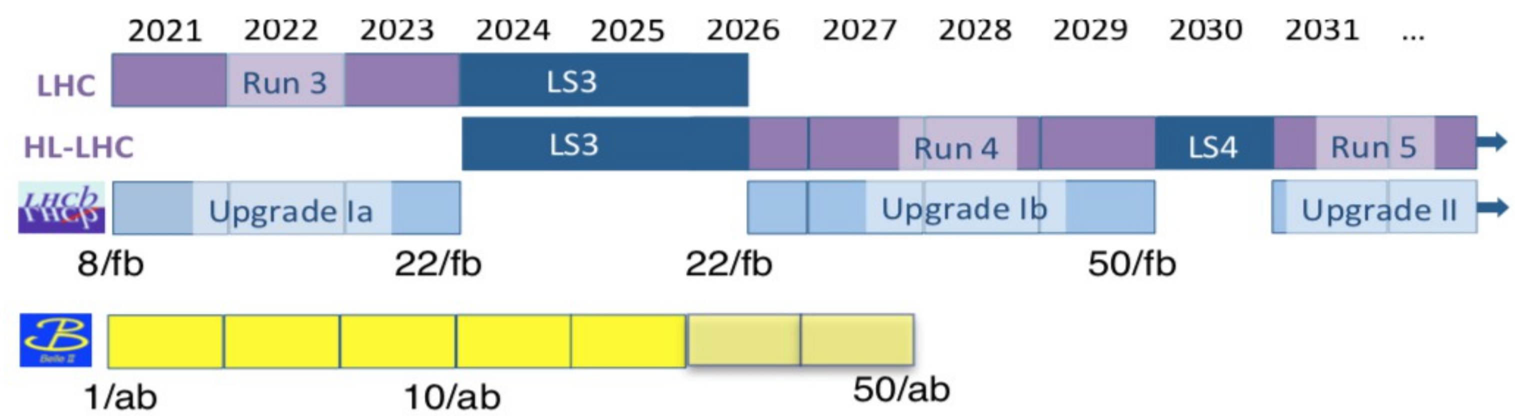
- $\Lambda_b{}^0$ candidate from combination of displaced Λ and calorimeter cluster, pointing back to unique primary vertex
- $B^0 \rightarrow K^{*0}\gamma$ as normalization mode
  - Same selection as signal with exception of K - p particle ID; cancellation of systematics

65 ± 13 events
5.6σ significance

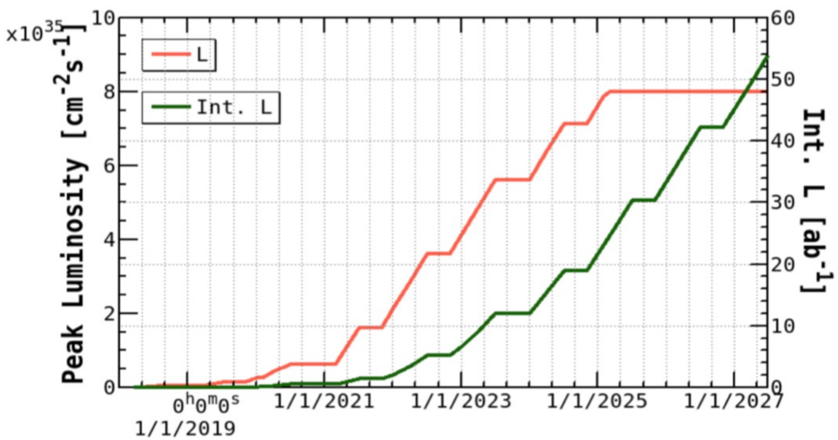


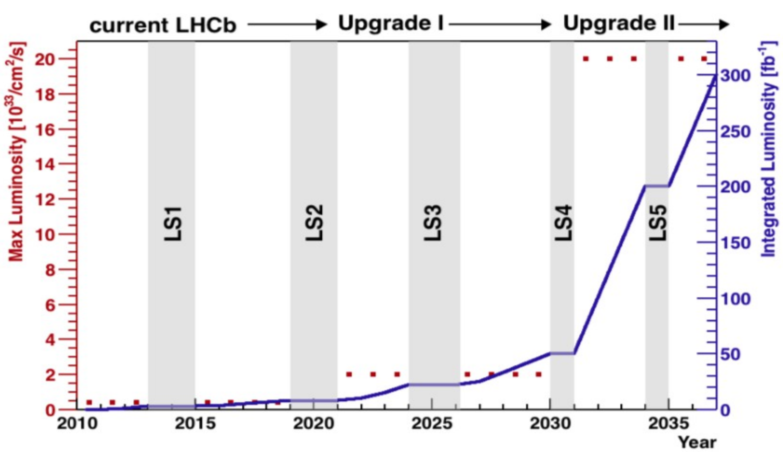
$$\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda\gamma) = (7.1 \pm 1.5 \pm 0.6 \pm 0.7) \times 10^{-6}$$

Timeline



- LHC currently in LS2 as LHCb upgrades for 2 x 10^{33} luminosity
  - ~8 fb^{-1} of additional data recorded in 2015 - 2018
- Belle II began physics data taking program in spring 2019
  - Anticipate O(10) fb^{-1} of data by summer

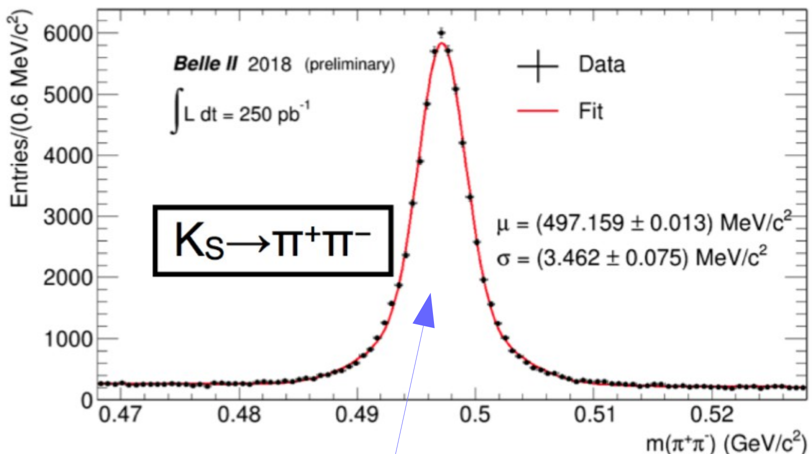


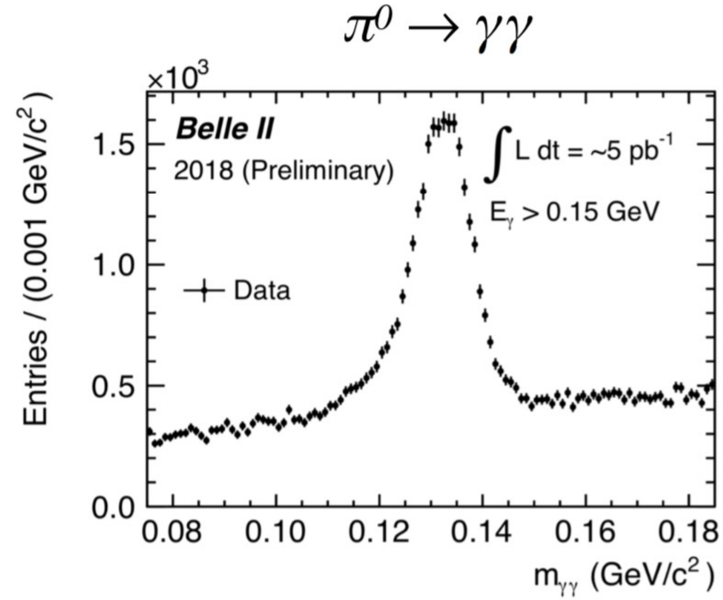


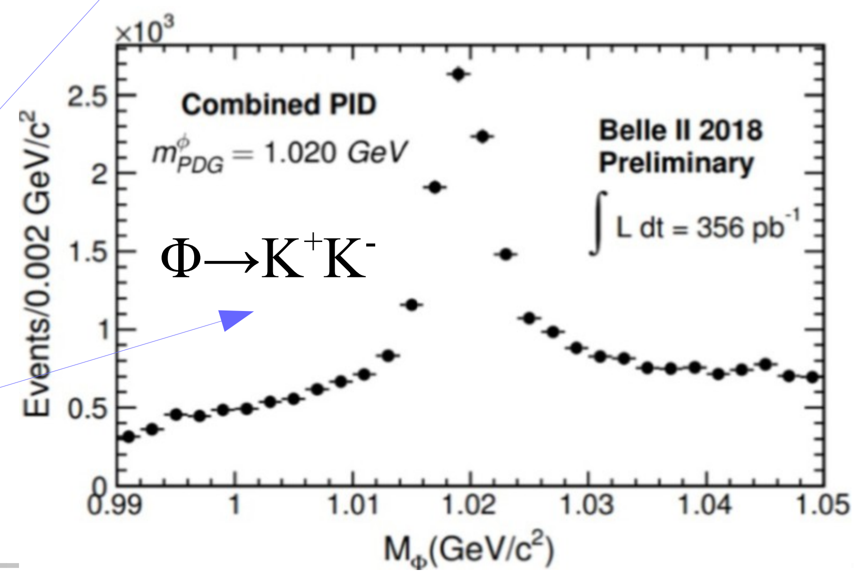
Belle II commissioning

2018 SuperKEKB commissioning run provided opportunity to validate detector performance with colliding beams

- Achieved instantaneous luminosity of 5.5 x 10^{33} cm^{-2} s^{-1}
- Recorded 472 pb^{-1} integrated luminosity (~1 million B mesons)
- Only one sector of vertex detector installed



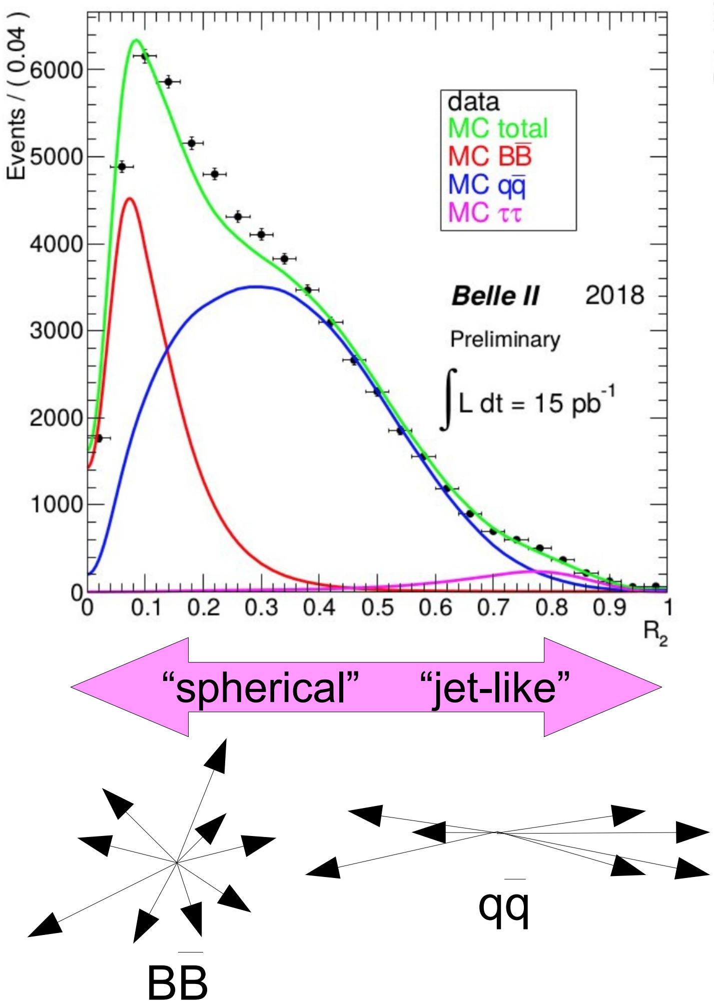


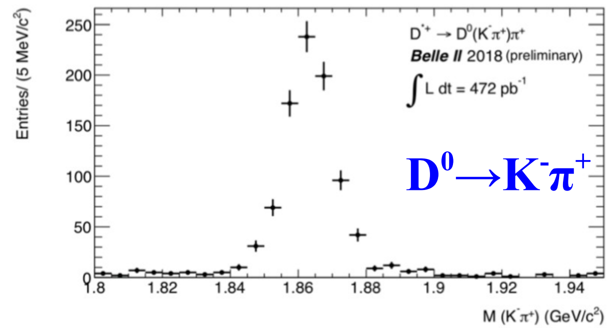


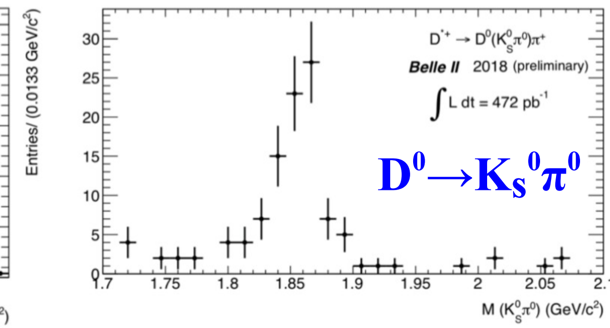
- Track reconstruction (drift chamber and partial vertex detector)
- Photon reconstruction (calorimeter)
- Particle identification (dE/dx and Cherenkov-based systems)

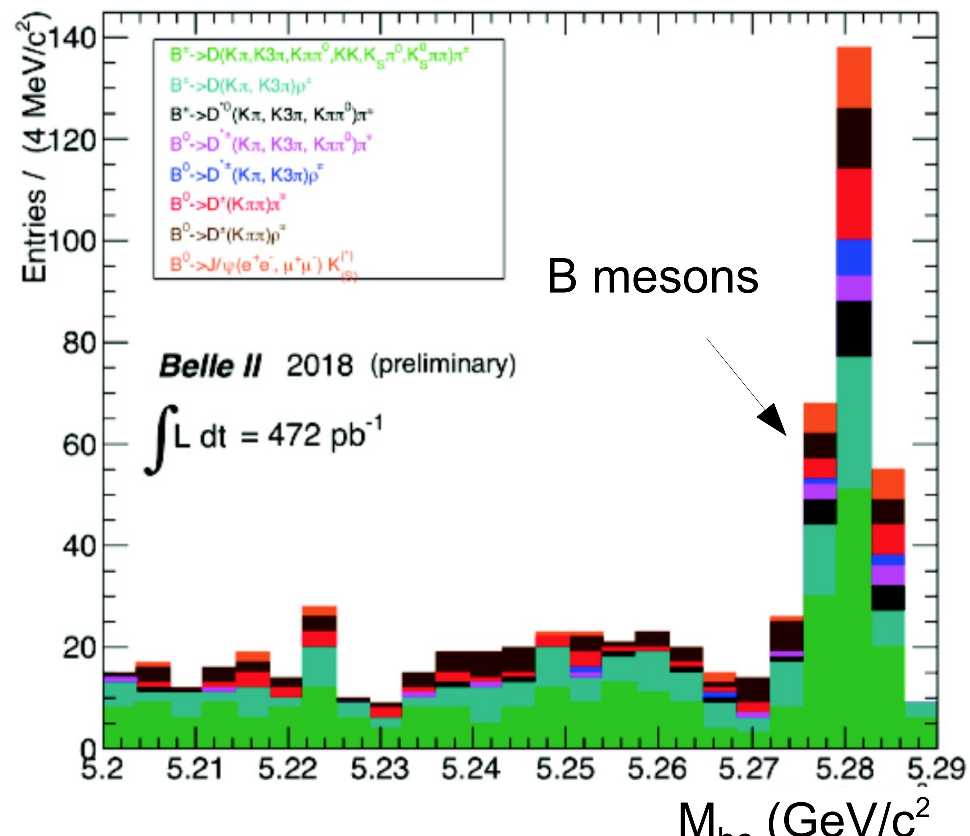
B reconstruction

Topological event shapes:







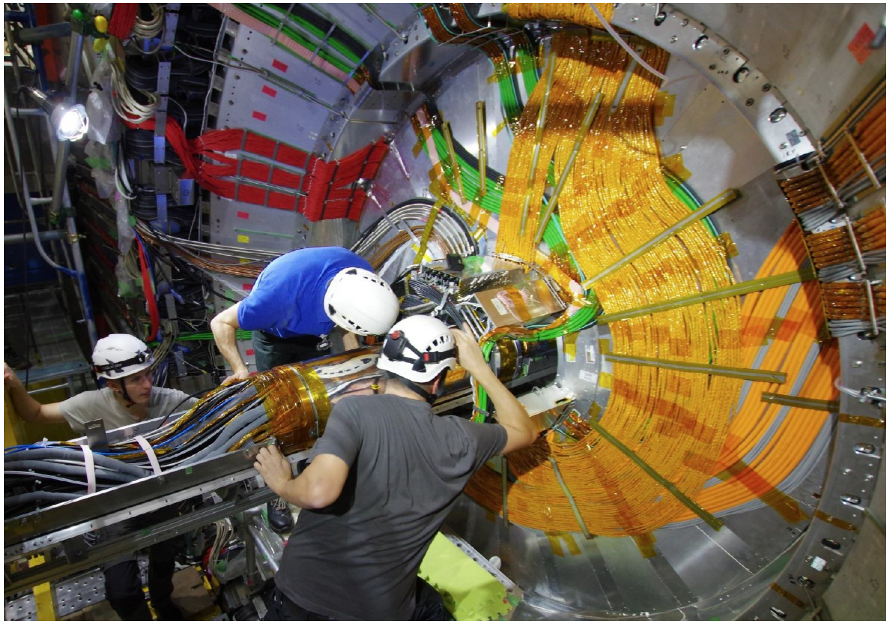


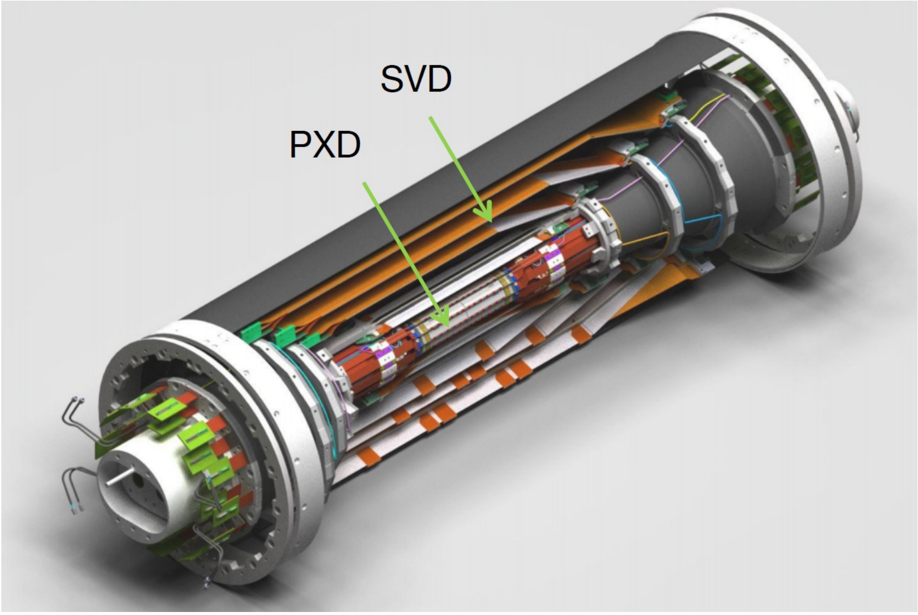
Evidence that SuperKEKB was operating on the $\Upsilon(4S)$ resonance

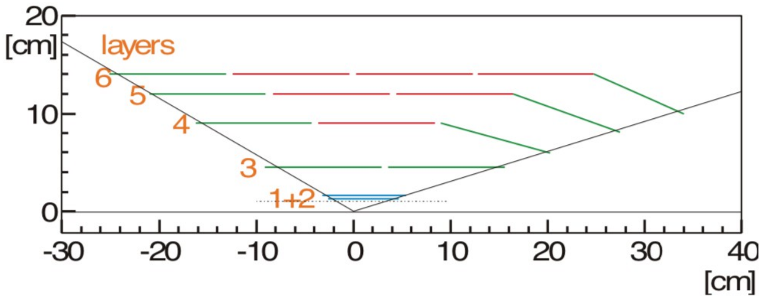
2019 data taking

Collision data taking with full Belle II detector began in March 2019

- Vertex detector has been installed
  - PXD: Full 1st layer and 1/6 of layer 2
  - Remainder of PXD will be added in 2020

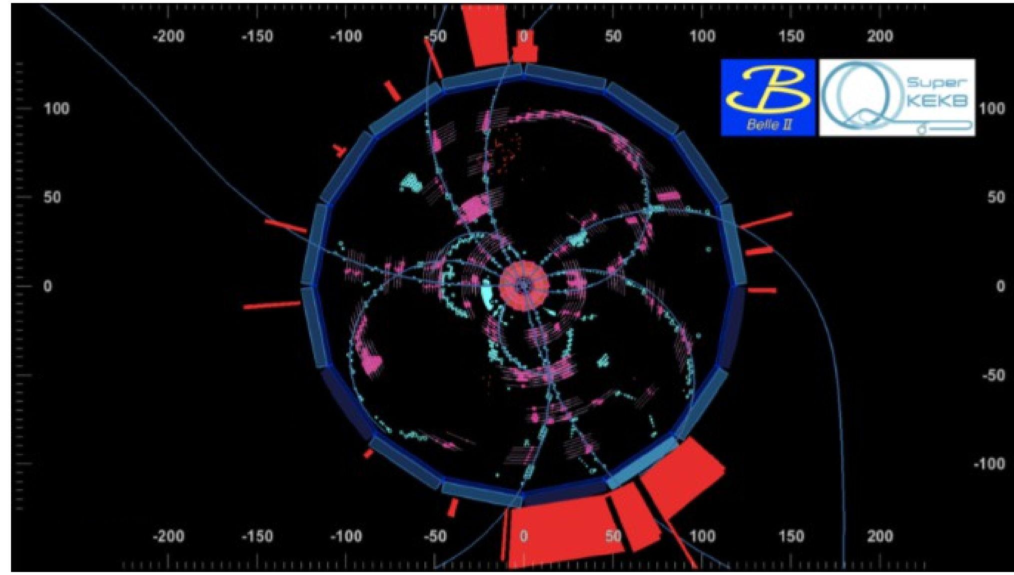






Short term physics goals

Primary focus of Belle II in 2019 will be the continued characterization of the detector and physics environment



However, some "low hanging fruit":

Semileptonic B decays

- $B \to \pi l\nu$ and $\rho l\nu$

Hadronic B Decays

- $B \to K\pi$ (10 fb^{-1})
- $B \to \Phi K$ (10 fb^{-1})
- $B \to J/\psi K$ (2-10 fb^{-1})
- Time dependent B mixing (10 fb^{-1}) B lifetimes (2-10 fb^{-1})

Radiative Electroweak Penguins

- $B \to K^*\gamma$ (2 fb^{-1})
- $B \to X_s\gamma$ (10 fb^{-1})

Non-B physics

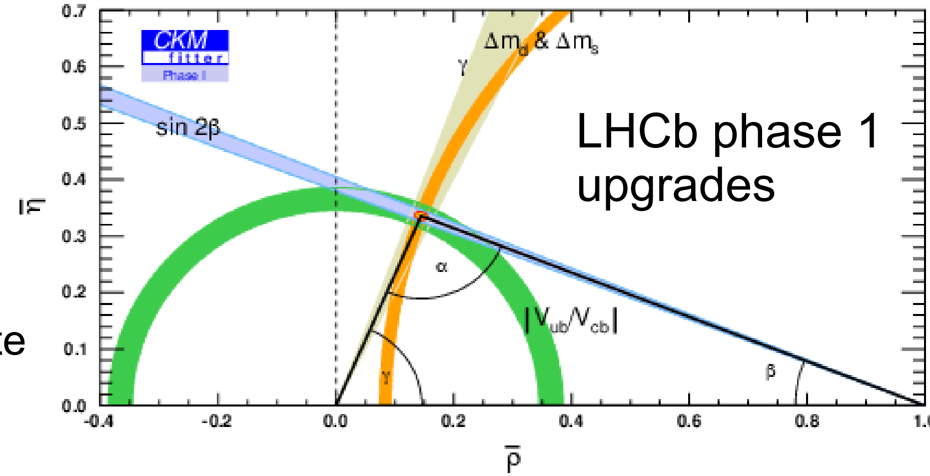
Talk by Luigi Corona (Tues parallel session)

- Dark sector searches (10 fb^{-1})
- D lifetimes (2 fb^{-1}), $D^0 \to K^+\pi^-$, $D^0 \to K^+\pi^-\pi^0$ (10 fb^{-1})

Summary

Very exciting time for B physics!

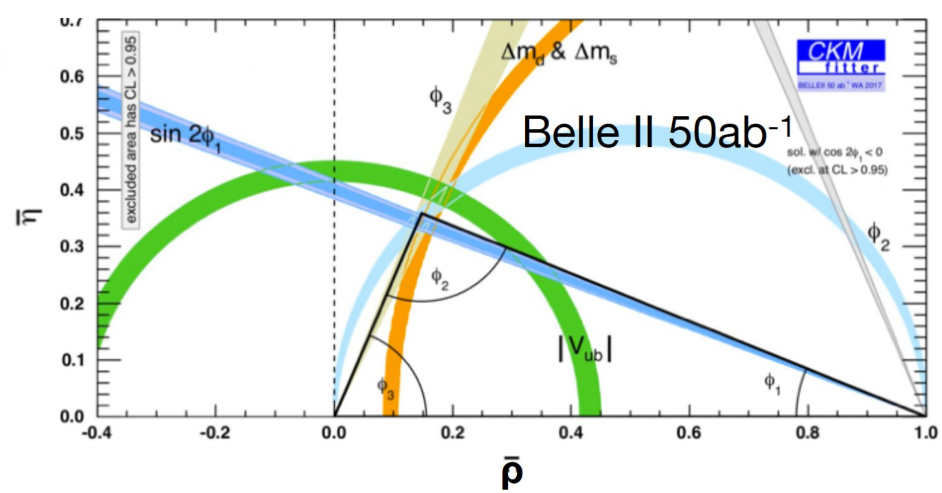
arXiv:1812.07638



New measurements from LHCb:

- Updated R_K in $1.1 < q^2 < 6.0$ GeV^2 region
- New limit on LFV $B^0_{(s)} \rightarrow \tau^+\mu^-$
- Time-dependent analysis of $B_s^0 \rightarrow \Phi\gamma$ decay rate
- Observation of $\Lambda_b^0 \rightarrow \Lambda\gamma$
- Several additional fb^{-1} of Run 2 data still available for analysis, with LHCb currently upgrading for high luminosity running

arXiv:1808.10567



Belle II and SuperKEKB successfully commissioned in 2018, with physics data taking commencing in early 2019

- Detector and physics validation in progress based on initial collisions data
- Physics prospects studied for 50 ab^{-1} target data sample in Belle II Physics Book

Backup Slides

R_K validation

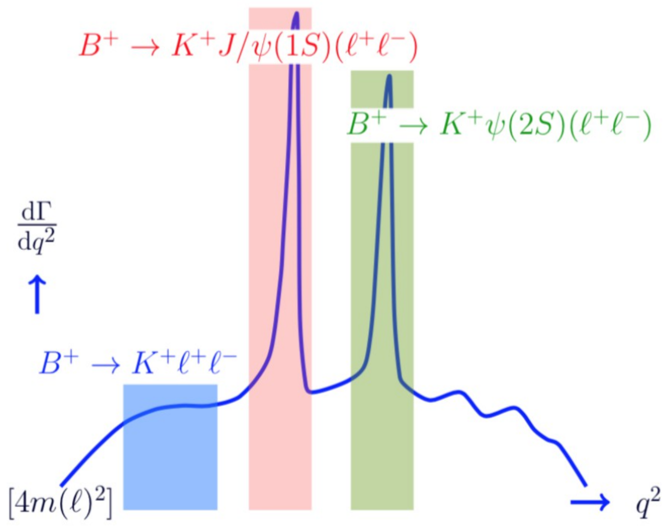
arXiv:1903.09252

Efficiency for $B^+ \to K^+ J/\psi$ for $J/\psi \to e^+e^-$ and $J/\psi \to \mu^+\mu^-$ determined directly from data

- Derive MC corrections and apply to $B^+ \to K^+ J/\psi$ to perform "closure" test:

$$r_{J/\psi} = \frac{\mathcal{B}(B^+ \to K^+ J/\psi(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+ J/\psi(e^+e^-))} = 1$$

$$r_{J/\psi} = 1.014 \pm 0.035$$

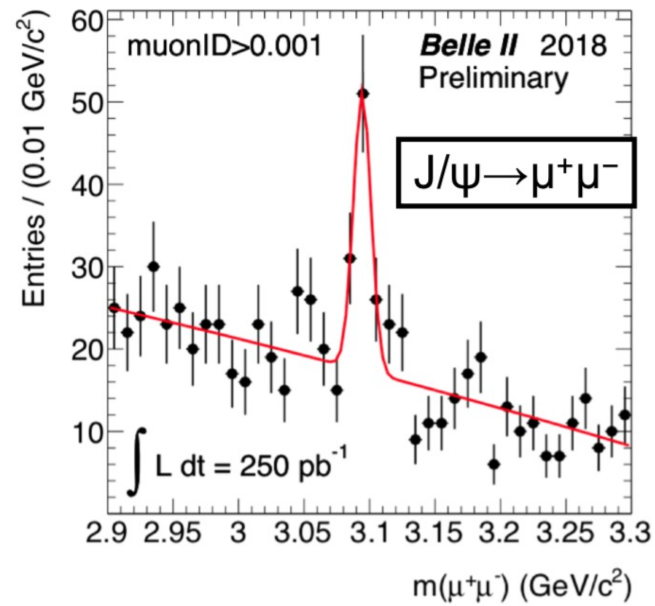


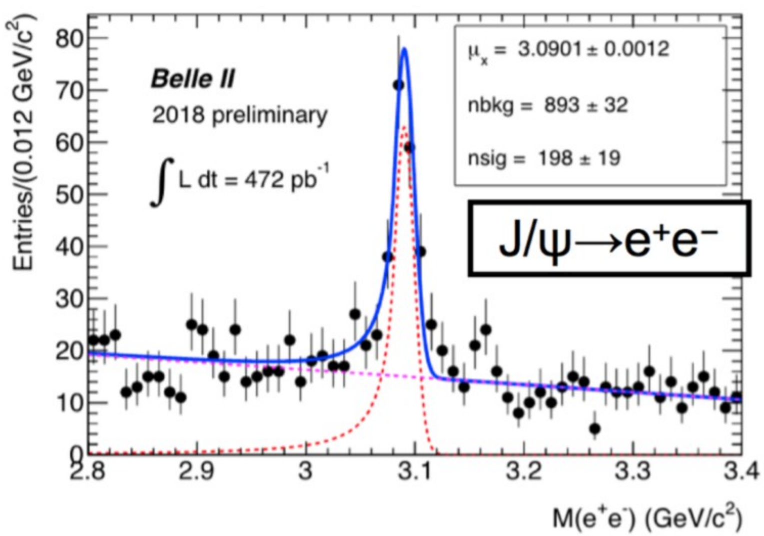
- Does not benefit from cancellation of systematics in double ratio, hence stringent test of efficiency calibration
  - $r_{J/\psi}$ validated as function of various reconstructed variables (e.g. Dilepton opening angle)
  - J/ψ has different q^2 distribution than signal, but detector effects depend on "lab frame" kinematics

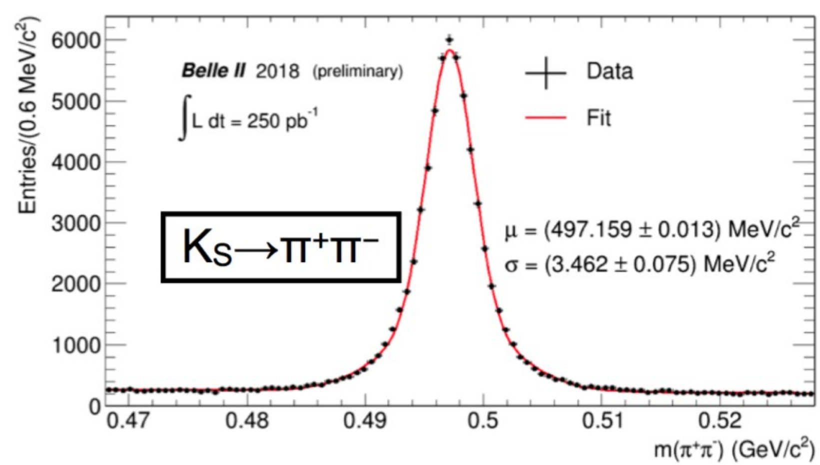
Belle II commissioning

2018 SuperKEKB commissioning run provided opportunity to validate detector performance with colliding beams

- Achieved instantaneous luminosity of 5.5 x 10^{33} cm^{-2} s^{-1}
- Recorded 472 pb^{-1} integrated luminosity (~1 million B mesons)
- Only one sector of vertex detector installed



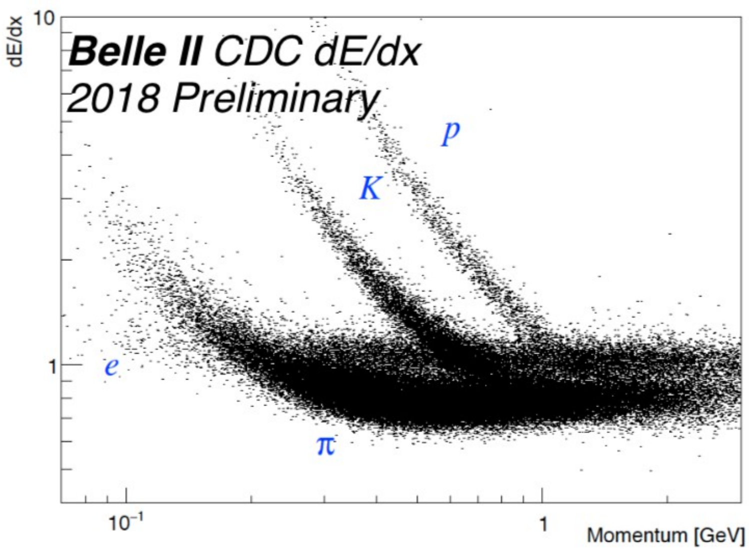




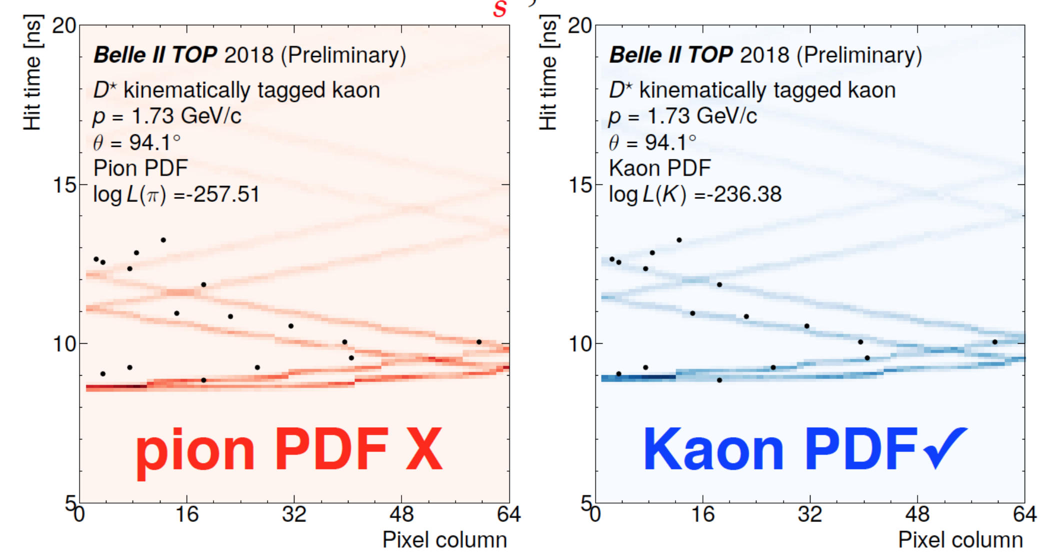
- Track reconstruction (using CDC and partial vertex detector)
- Alignment and solenoid B field are well understood

Particle Identification

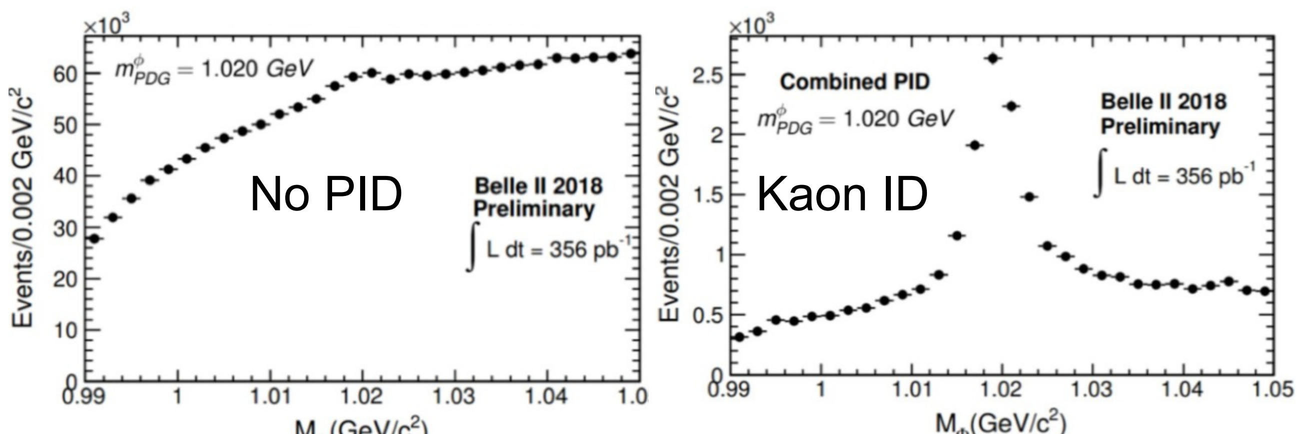
Central Drift Chamber (CDC)

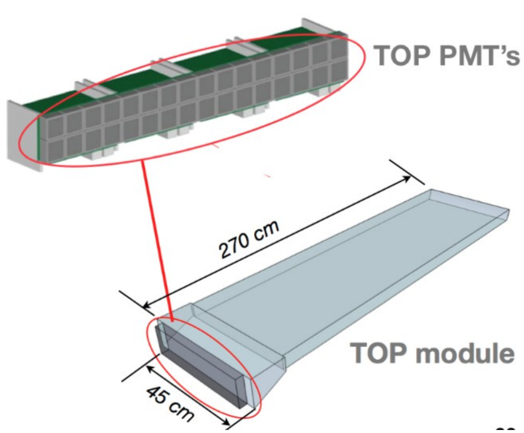


$D^{*+} \to D^0 \pi_s^+ ; D^0 \to K^- \pi^+$



Time of Propagation (TOP) detector



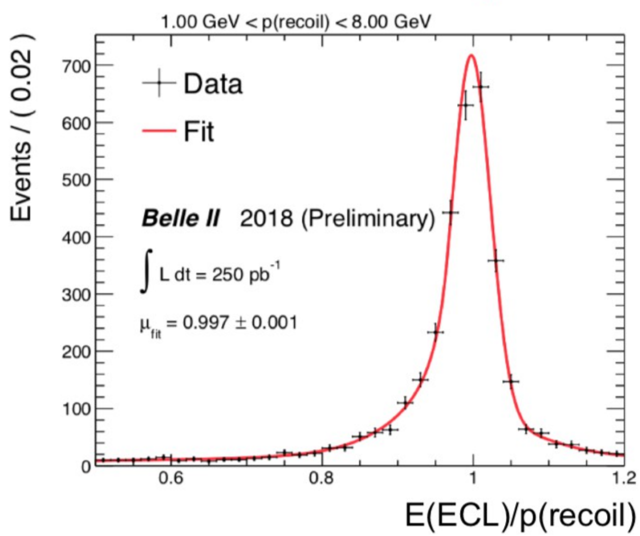


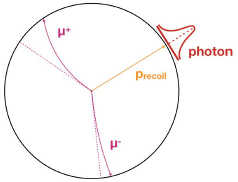
$\Phi \to K^+K^-$ reconstruction

Calorimetry

- Neutrals reconstruction using calorimeter clusters

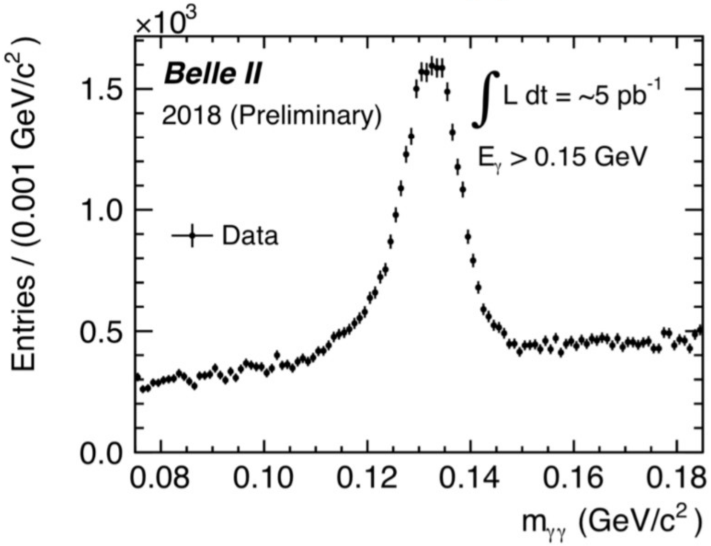
$e^+e^- \rightarrow \mu^+\mu^-\gamma$





Single photon energy resolution based on $\mu^+\mu^-\gamma$ events

$\pi^0 \rightarrow \gamma\gamma$



$\eta \rightarrow \gamma\gamma$