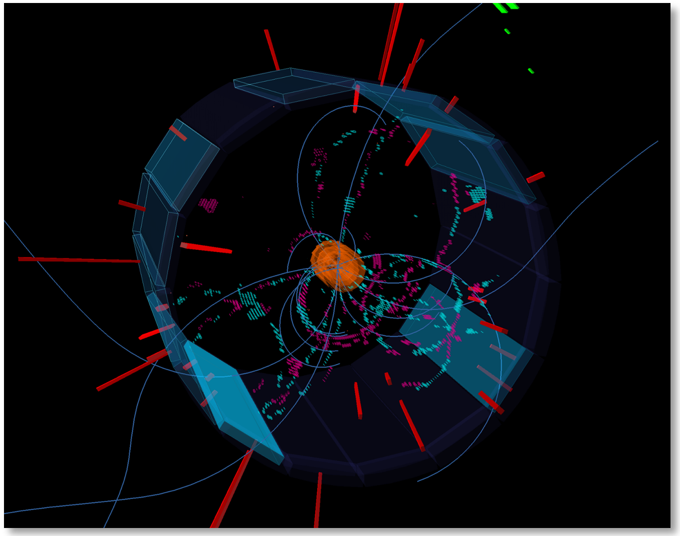
Leptonic and Semileptonic *B* Decays at Belle II

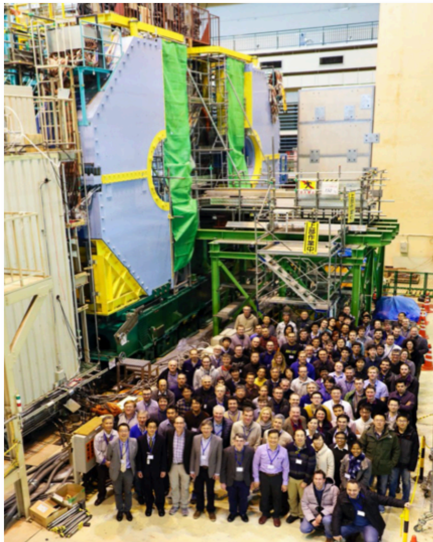
Andreas Warburton
McGill University

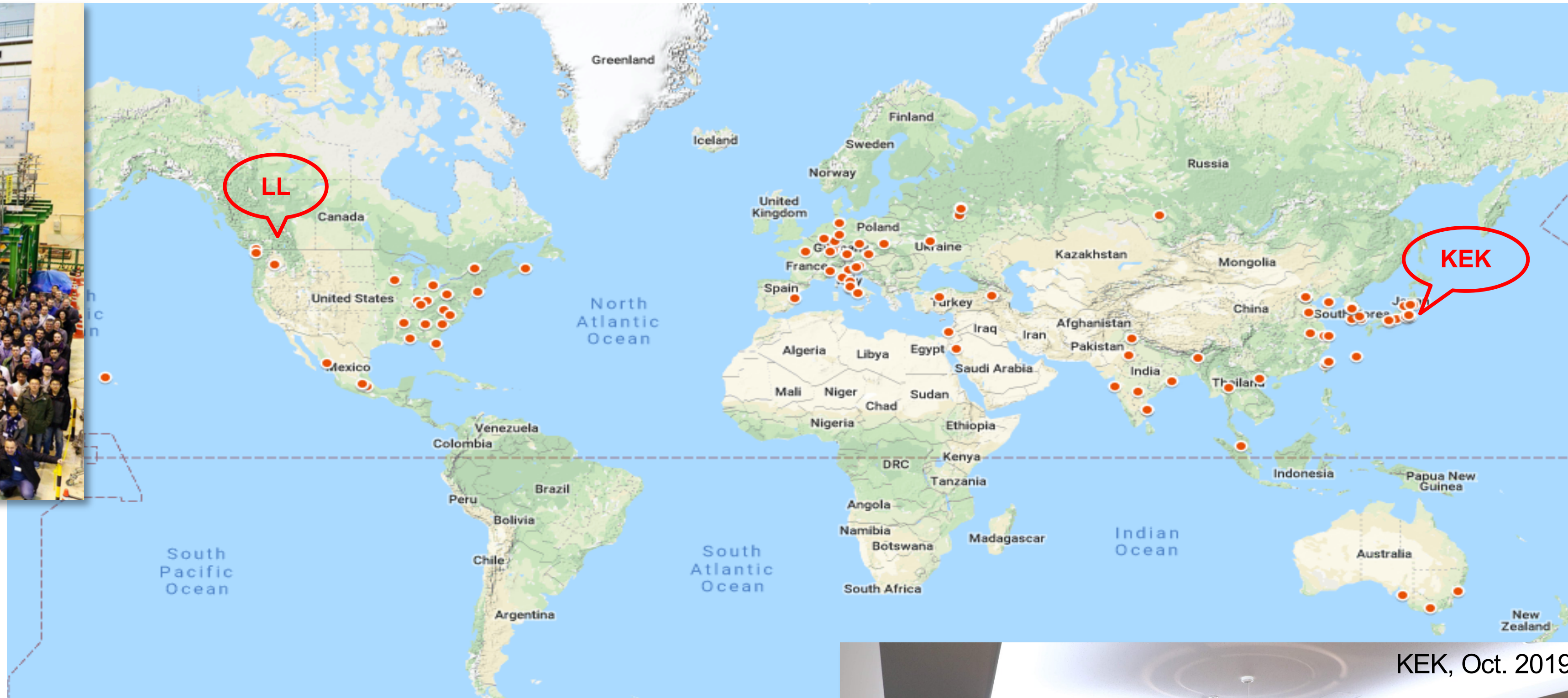


Lake Louise Winter Institute
Fundamental Interactions in Particle Physics
LLWI 2020
February 9 – 15, 2020

https://belle2.jp

Belle II Collaboration





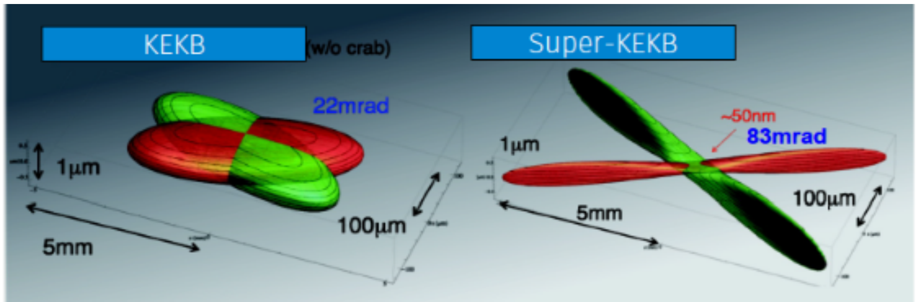
113 Institutes in 26 Countries

~1000 Collaborators (including ~300 Students)

Canadian Belle II Group: 18 members
(including 8 students, 3 postdocs)

SuperKEKB & Belle II

Asymmetric electron-positron collisions



	E (GeV) LER/HER	β^*_y (mm) LER/HER	β^*_x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L (cm^{-2}s^{-1})
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1 x 10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80 x 10^{34}

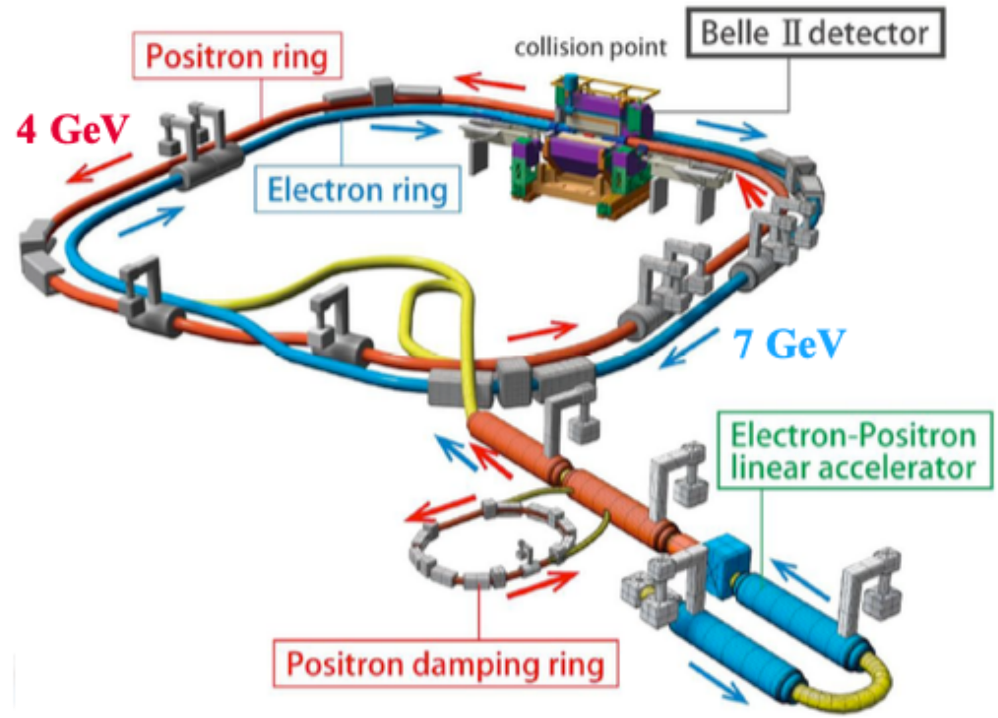
beam current

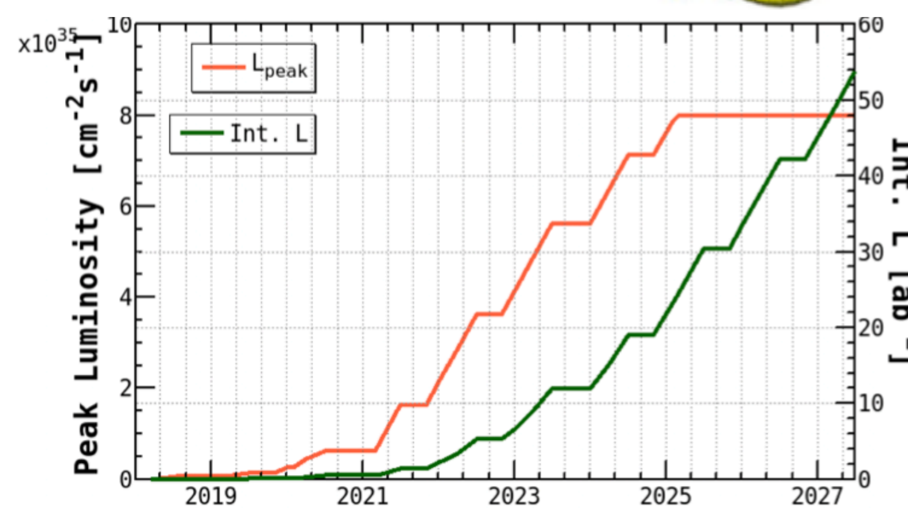
$$L = \frac{\gamma_\pm}{2 e r_e}\left(1 + \frac{\sigma^*_y}{\sigma^*_x}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}}\frac{R_L}{R_{\xi_y}}$$

vertical beta function at IP

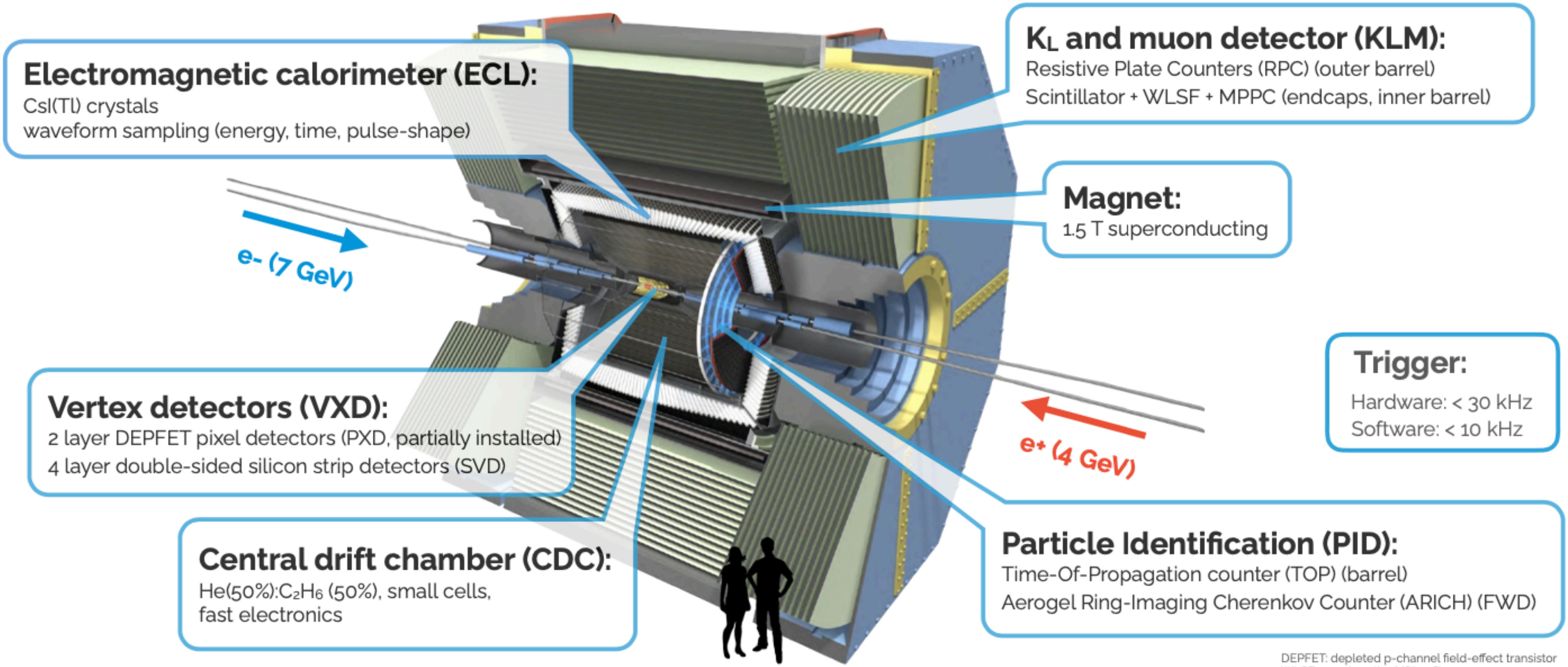
New upgraded facility to search for BSM physics:
B, τ, charm branching fractions to $O(10^{-9})$

SuperKEKB accelerator upgrade targets:
Luminosity 8 x 10^{35} cm^{-2}s^{-1} [KEKB x 40]
Integrating to 50 ab^{-1} of collision data
[BaBar + Belle] x 30





Belle II Detector



DEPFET: depleted p-channel field-effect transistor
WLSF: wavelength-shifting fiber
MPPC: multi-pixel photon counter

Solid angle 90% covered; substantially upgraded:

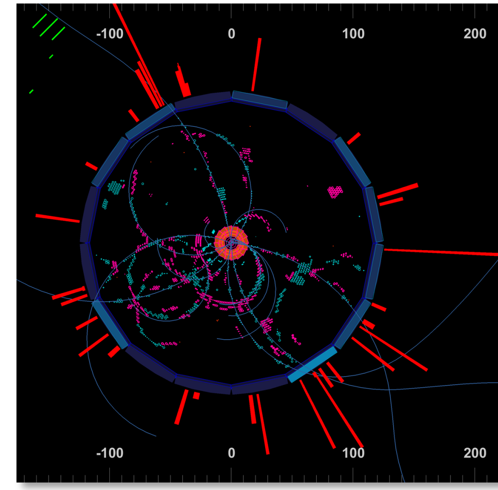
- **Preparing for higher rates, especially backgrounds!**
- **All new inner-tracking systems, front-end electronics, software, distributed computing**
- **New PID functionality**

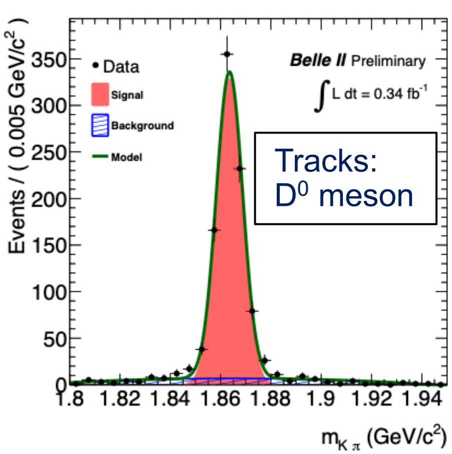
Belle II TDR: arXiv:1011.0352

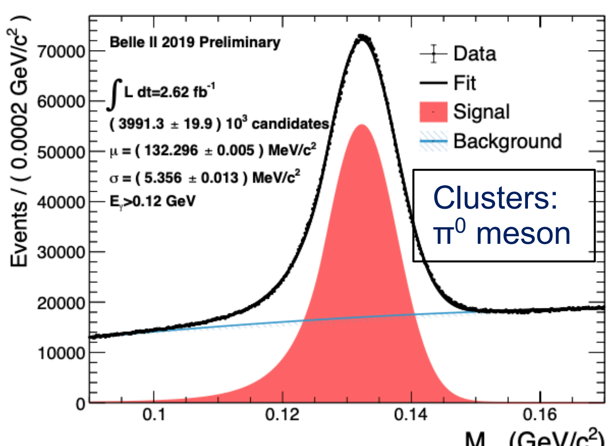
Belle II Program

Experiment commissioning in three phases:

- First colliding beam data recorded Spring 2018: “Phase 2”, without full vertex detectors; 0.5 fb^{-1} data recorded
- Phase 3 commenced 2019, with vertex detectors installed: physics run; >10 fb^{-1} of data recorded so far
- Run continuing to Summer 2020: anticipate ~100 – 150 fb^{-1}
- **Focus is on commissioning of SuperKEKB accelerator and Belle II detector**
- First physics analyses: accessible with modest integrated luminosity, “rediscovery”







Publications [updates in the last 2 months]:

The Belle II Physics Book, arXiv:1808.10567
Prog. Theor. Exp. Phys. **2019**, 123C01 (2019)

Measurement of the Integrated Luminosity of the Phase 2 Data of the Belle II Experiment, arXiv:1910.05365
Chinese Physics C **44**, 021001 (2020)

Search for an Invisibly Decaying Z’ Boson at Belle II in $e^+e^- \to \mu^+\mu^-(e^\pm\mu^\mp)$ Plus Missing Energy Final States
arXiv:1912.11276 [submitted to Phys. Rev. Lett.]

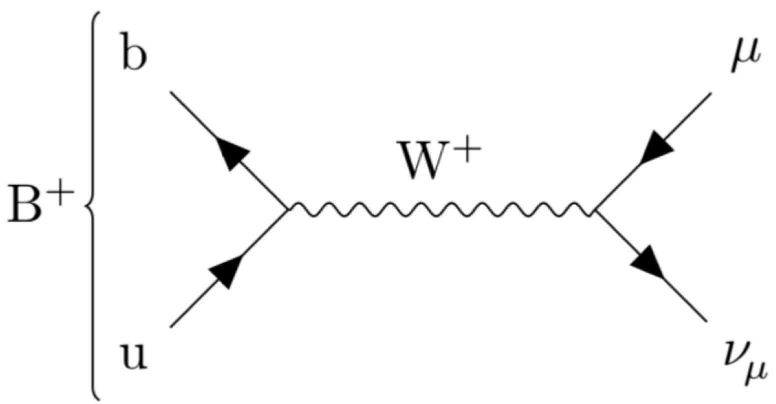
Three other **Belle II** talks later this week!

- DM Searches (M. De Nuccio, Thursday)
- Status & Prospects (T. Bilka, Friday)
- Rare *B* Decays (M.-C. Chang, Friday)

(Semi)Leptonic Decays

- Instrumental for determining Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix elements
- Improved theoretical tractability over fully hadronic decays, due to reduced influence of QCD
- Sensitive probes for New Physics and tests of Lepton Flavour Universality

Leptonic Example



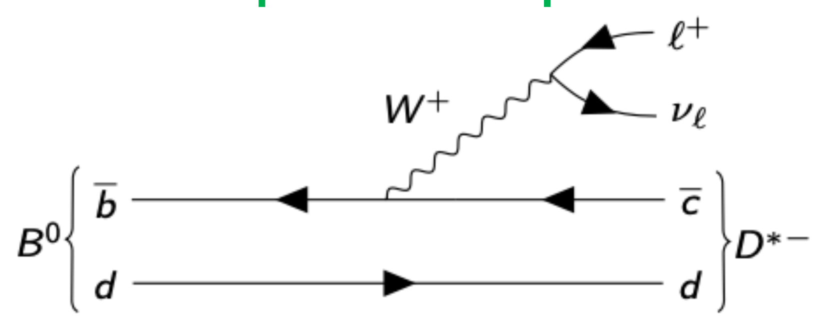
$$\mathcal{B}(B^+ \to \ell^+\nu_\ell) = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1-\frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

Prediction: $\mathcal{B}(B \to \mu\nu_\mu)_{SM} = (3.46 \pm 0.28) \times 10^{-7}$

Evidence:

Belle (2.4σ): PRL **121**, 031801 (2018)
Belle (2.8σ): arXiv:1911.03186 [hep-ex]

Semileptonic Example



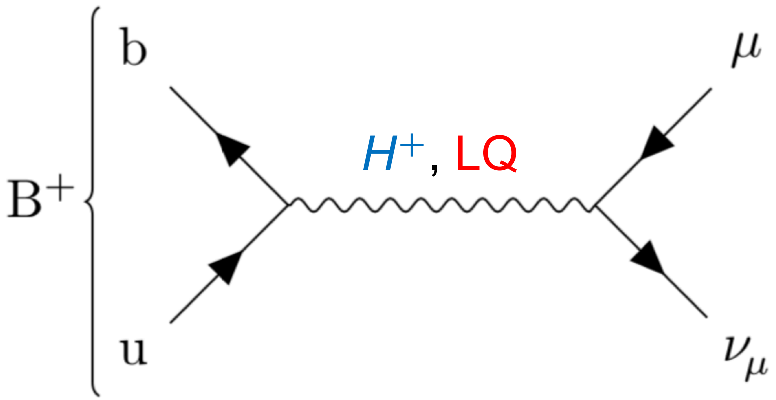
Standard Model $B^0 \to D^{*-}\ell^+\nu_\ell$

Abundant: 5% branching fraction (the above decay)
10% branching fraction ($B^0 \to X\ell\nu$)

(Semi)Leptonic Decays

New Physics (NP) Possibilities

Leptonic Example

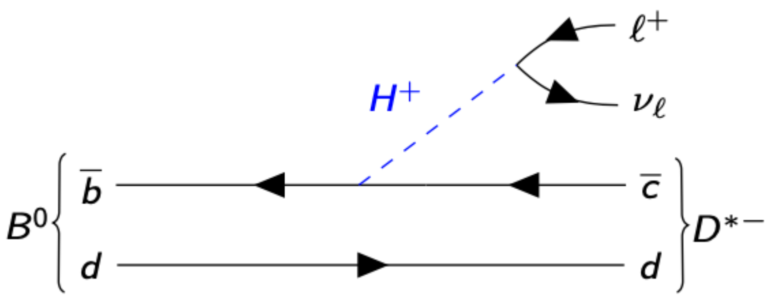


Modification of cross section due to NP process:

$$\mathcal{B}(B \to \mu\nu_\mu)_{NP} = \mathcal{B}(B \to \mu\nu_\mu)_{SM} \times \left|1 + r^{\mu}_{NP}\right|^2$$

The Belle II Physics Book, arXiv:1808.10567
Prog. Theor. Exp. Phys. **2019**, 123C01 (2019)

Semileptonic Example



Same decay via a BSM charged Higgs

NP Examples:

Two-Higgs doublet models: H^+

Leptoquarks: LQ

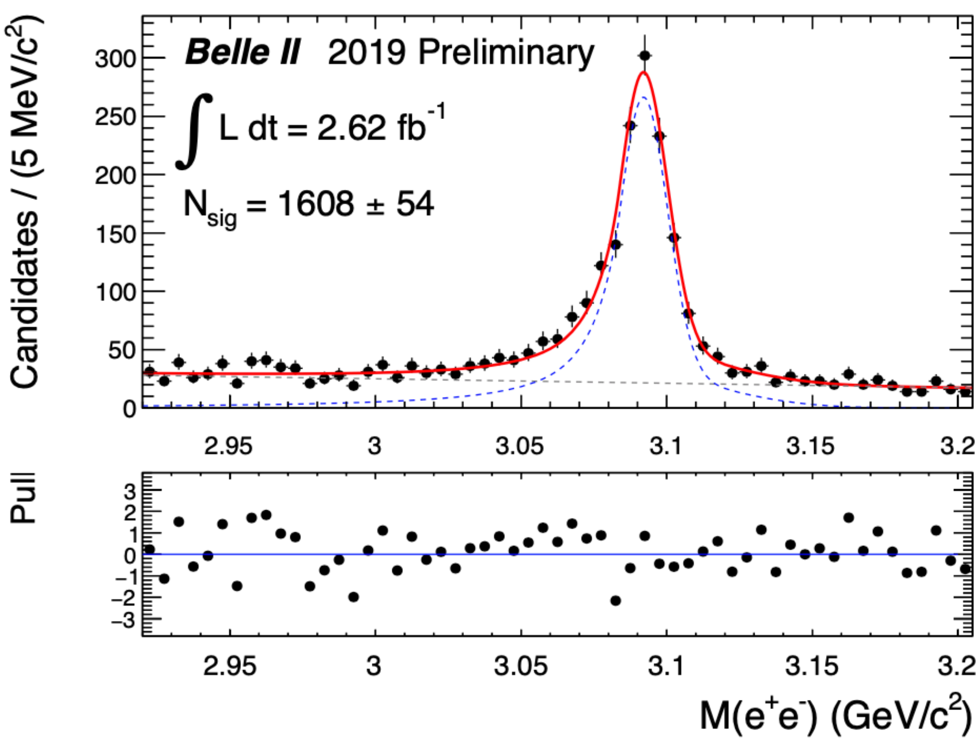
Lepton-Flavour Universality Violations (LFUV): $R(\ell\ell') = \Gamma(\ell) / \Gamma(\ell')$

Lepton Identification

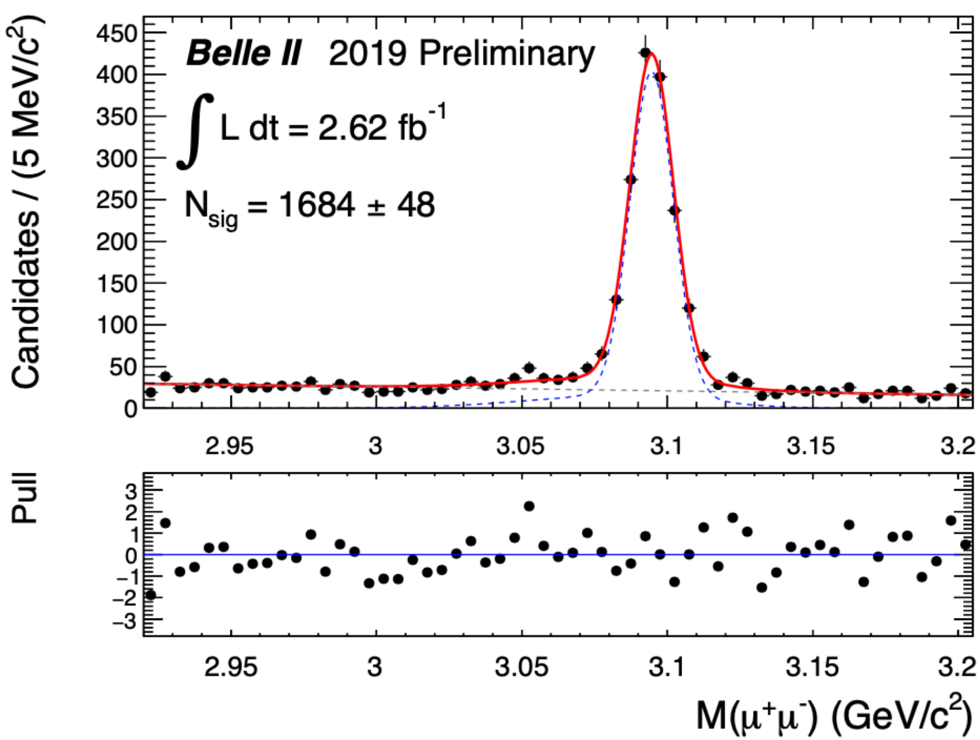
$$R_e = \frac{L_e}{L_e + L_\mu + L_\pi + \ldots}$$

- **e ID**: electromagnetic calorimeter (ECL) & inner tracking detectors → E/p + other PID criteria
- **μ ID**: K_L and muon detector (KLM) & inner tracking detectors

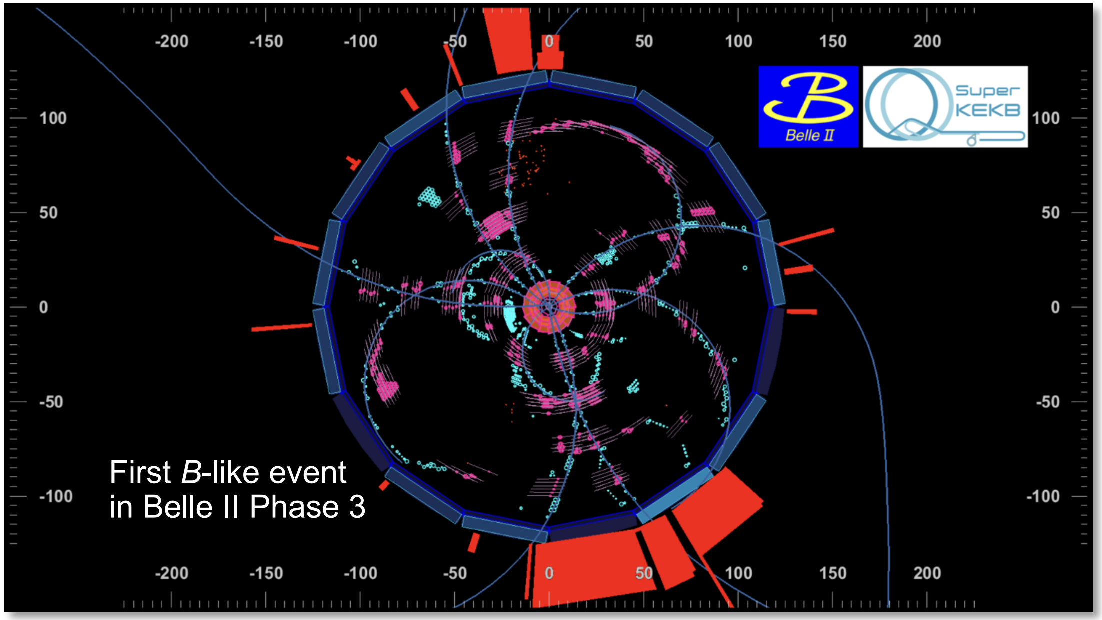
$J/\psi \to e^+e^-$



$J/\psi \to \mu^+\mu^-$



B-Meson Selection



Fox-Wolfram moments

$$H_l = \sum_{ij} |p_i| |p_j| P_l(\cos\theta_{ij})$$

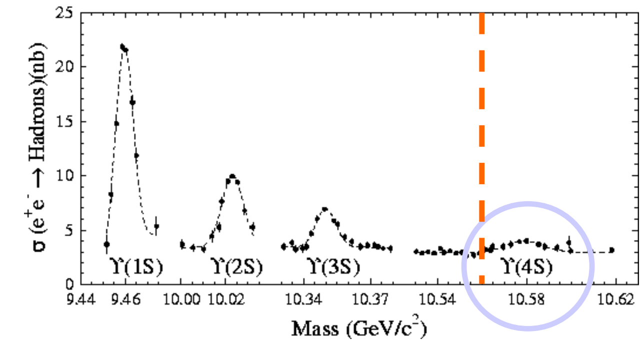
i, j = charged & γ

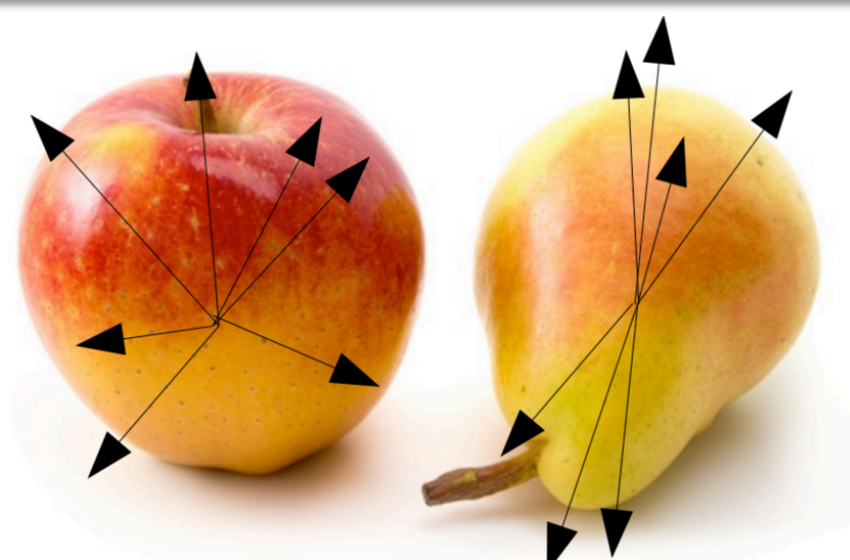
Momentum of particle i and j

Legendre polynomial

Angle between particle i and j

$R_2 = H_2/H_0$



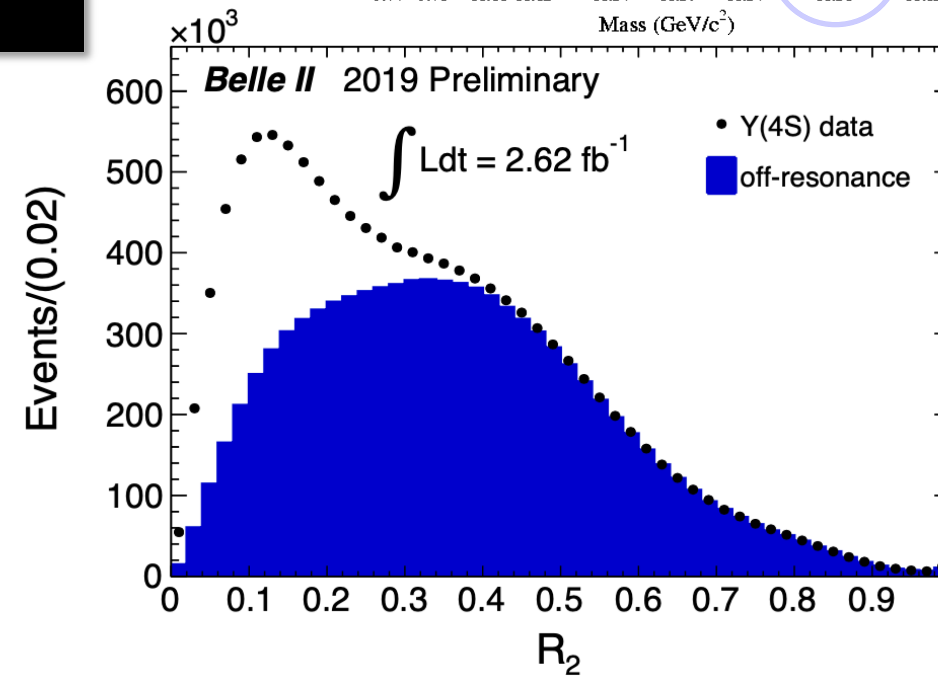


$\Upsilon(4S) \to B\bar{B}$

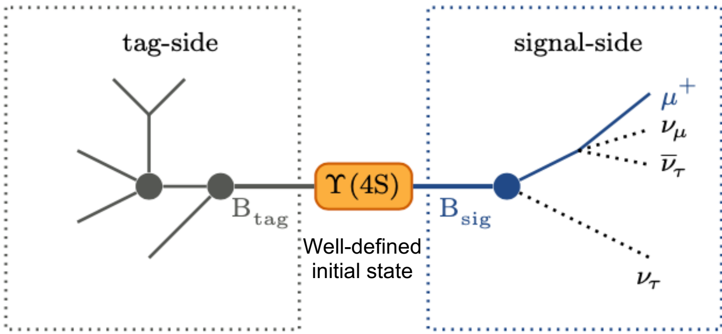
$R_2 \to 0$

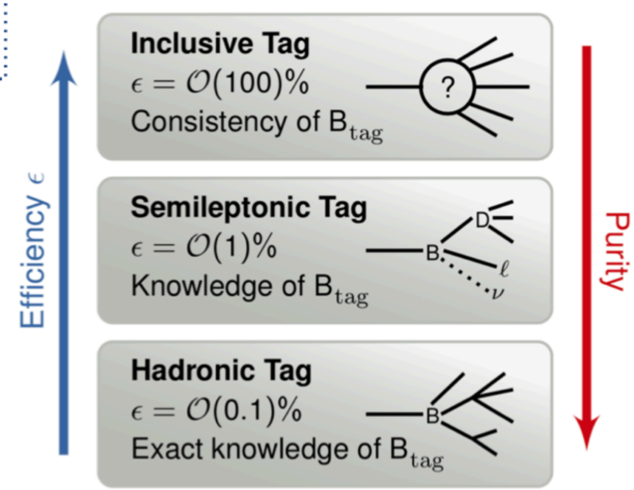
$e^+e^- \to$ light quarks

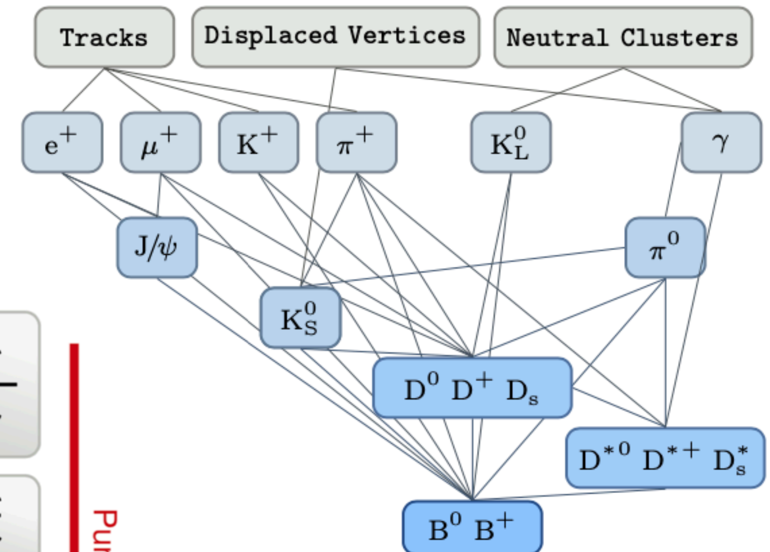
$R_2 \to 1$

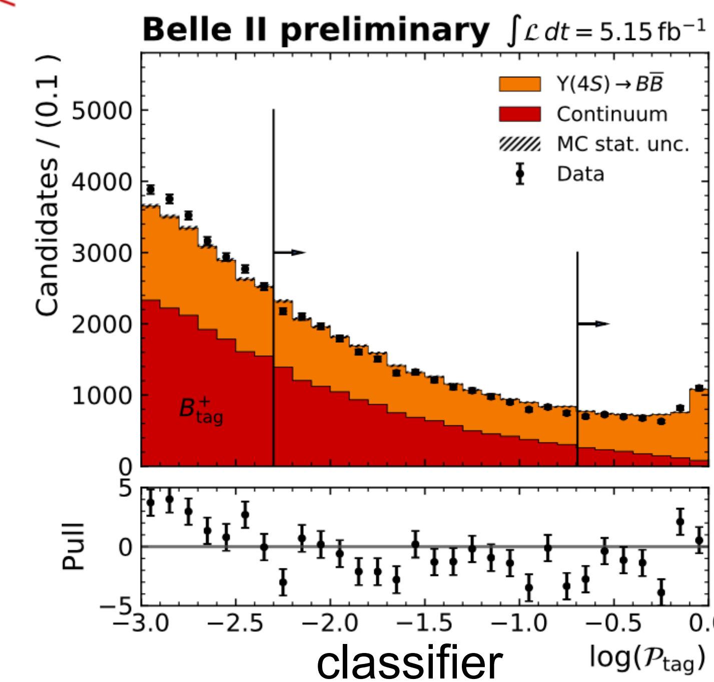


Full Event Interpretation (FEI)









Second B meson (tag-side) Reconstruction:

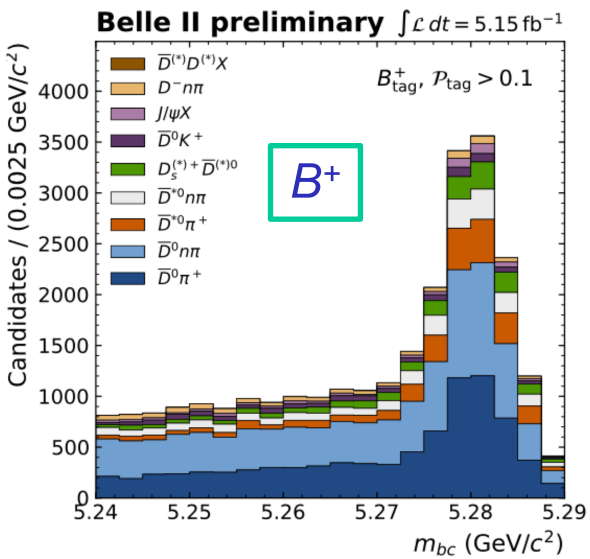
- Key to studying decays with missing energy
- Exclusive reconstruction, multi-stage classifier (fast BDT)
- >100 explicit tag-side channels configured [$O(10^4)$ decay chains]
  - Semileptonic tagging: efficiency ↑
  - Hadronic tagging: purity ↑

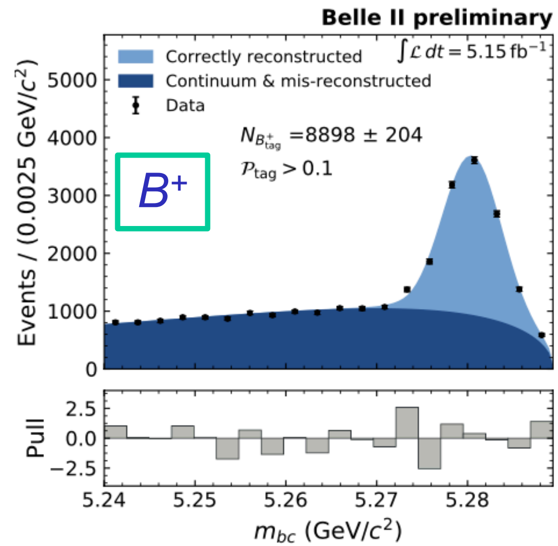
arXiv:1807.08680; Comput. Softw. Big Sci. (2019) 3:6

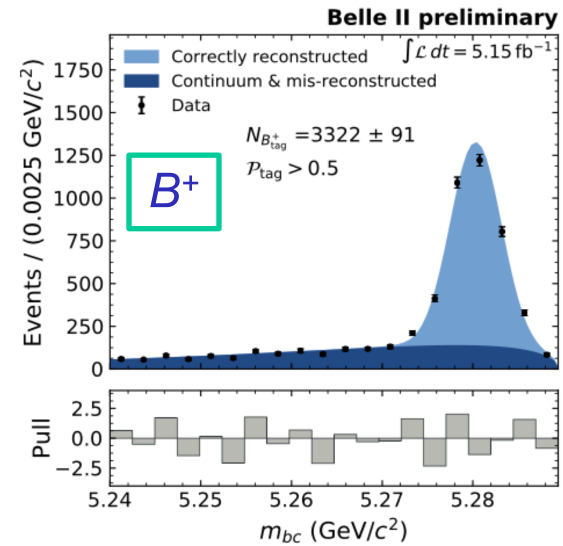
FEI 2019 Performance

A measure of reconstruction quality: Beam-Constrained Mass

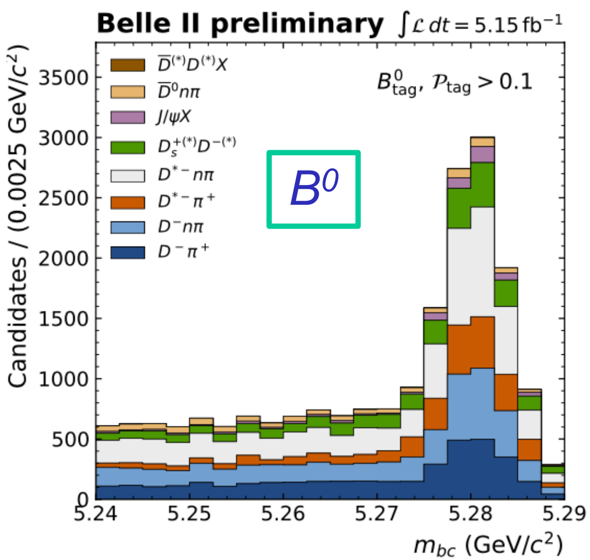
$$m_{bc} = \sqrt{s/4 - |\vec{p}^{\,*}_{B_{\rm tag}}|^2}$$

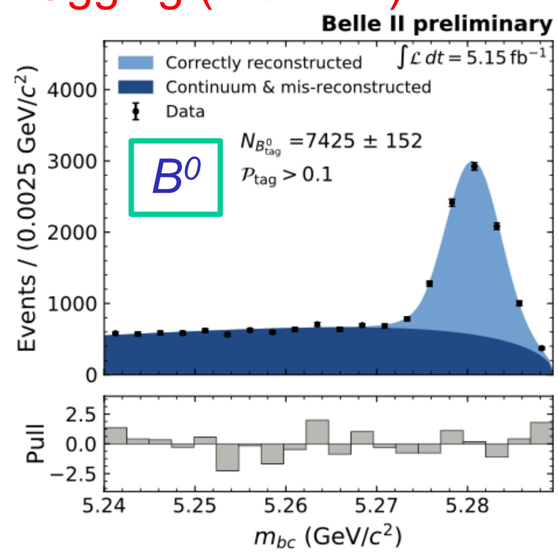


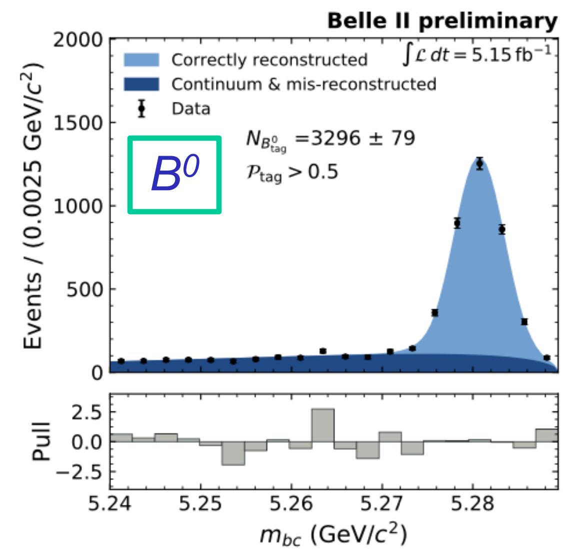




Hadronic Tagging (with FEI)







$B \to Xe\nu$ with hadronic FEI

Reconstruction of a physics signal mode:

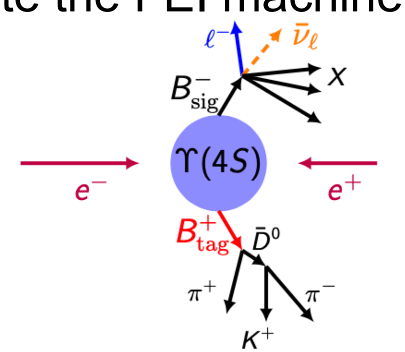
Tight classifier: $P_{tag} > 0.01$

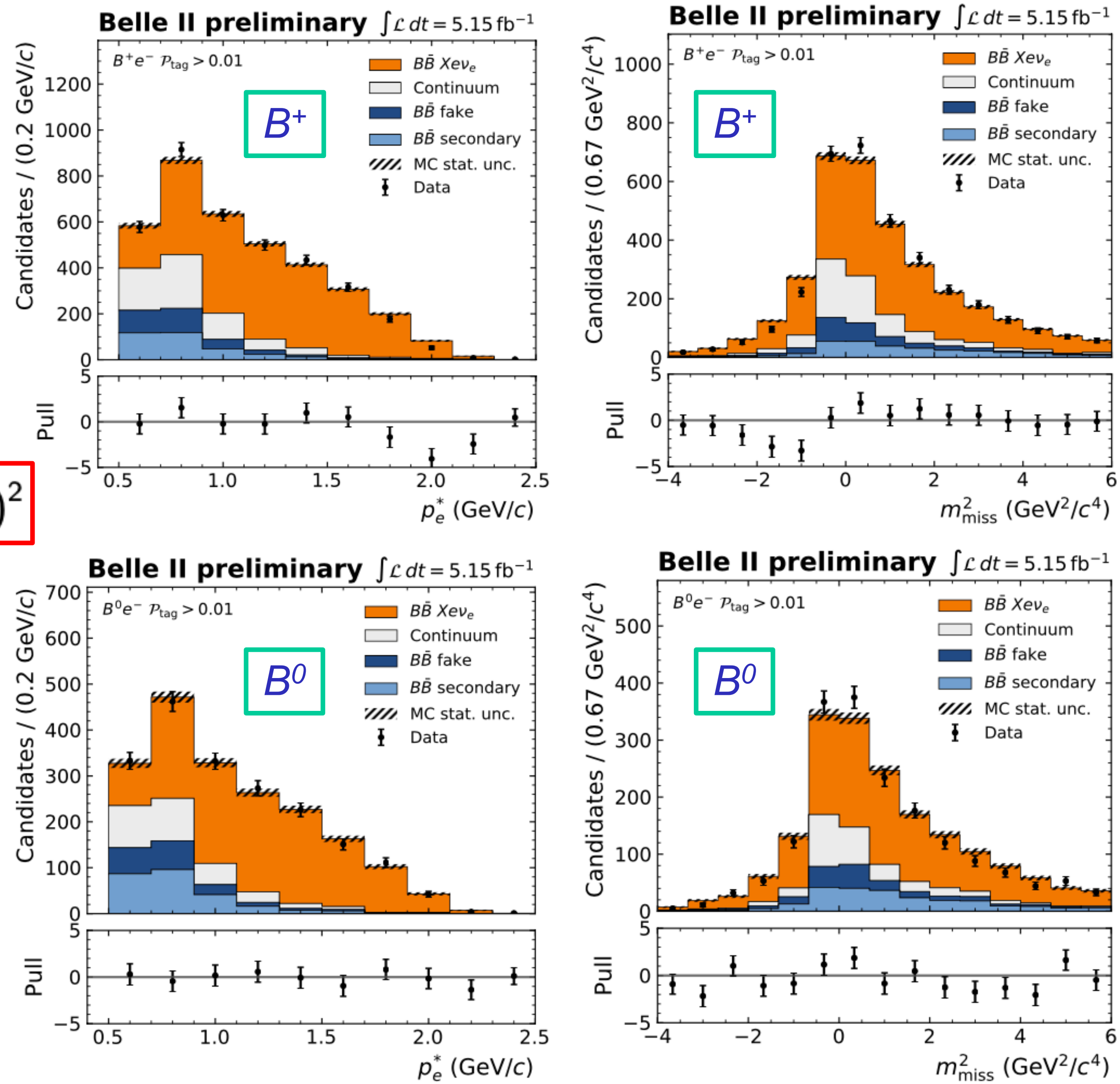
Select a lepton and sum the remaining particles' kinematics

$$m^2_{\text{miss}} = (p^*_{e^+e^-} - p^*_{B_{\text{tag}}} - p^*_{\ell} - p^*_{X})^2$$

Seek consistency with well-known $B \to Xe\nu$ mode

Calibrate the FEI machinery





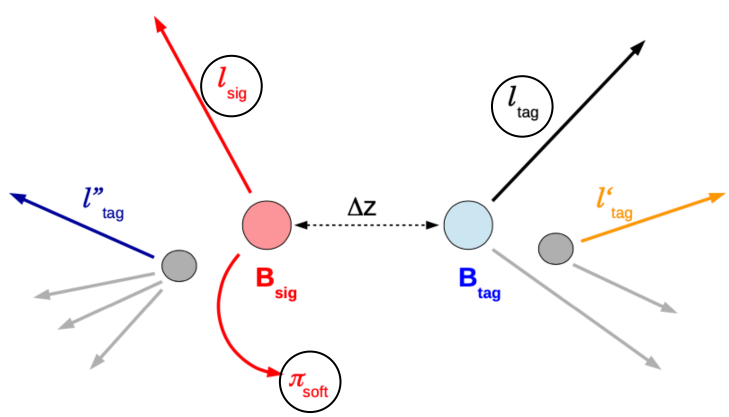
Mixing, Partial Reconstruction

An early look for evidence of the finite B^0 lifetime and $B^0\overline{B}^0$ mixing

Three charged tracks:

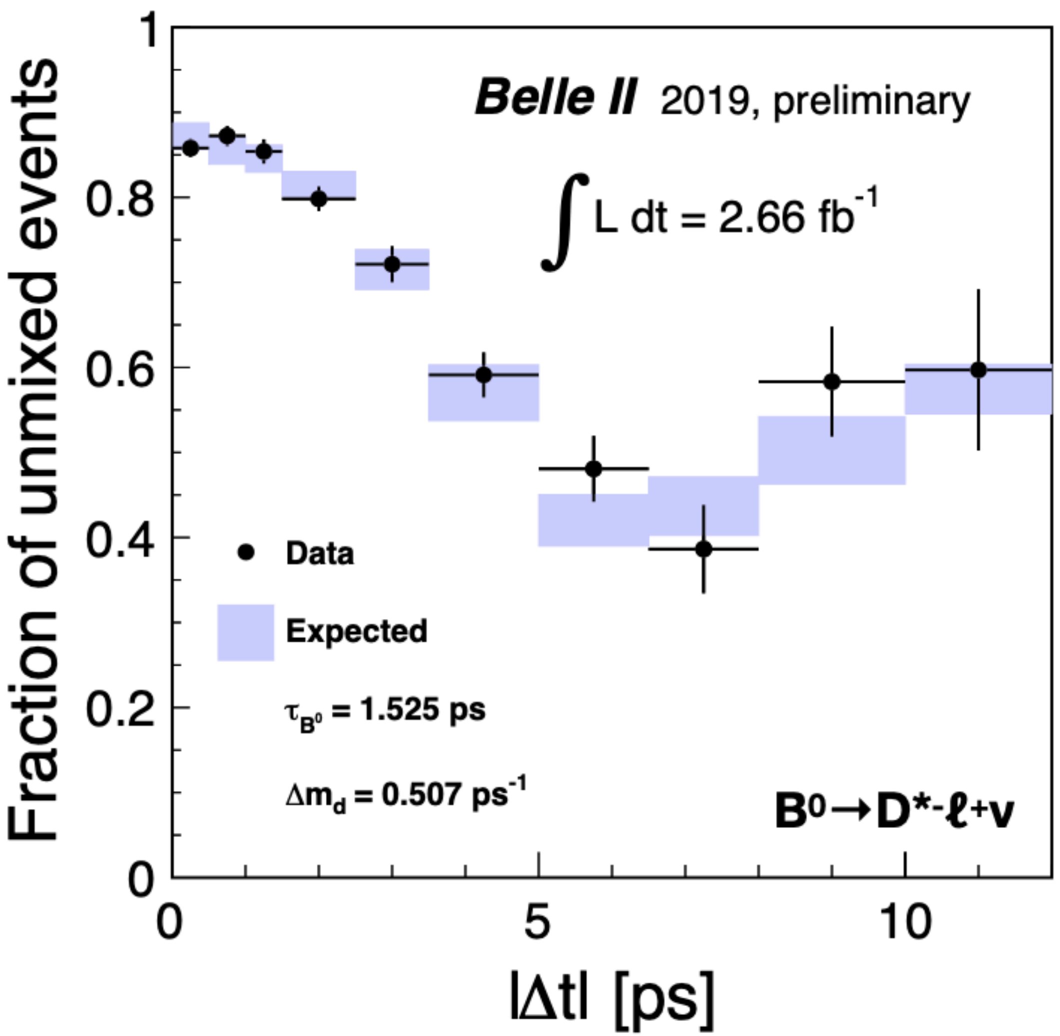
- Signal side:
  - soft pion
  - charged lepton
- Tag side:
  - charged lepton

Partial $D^*\ell\nu$ Reconstruction



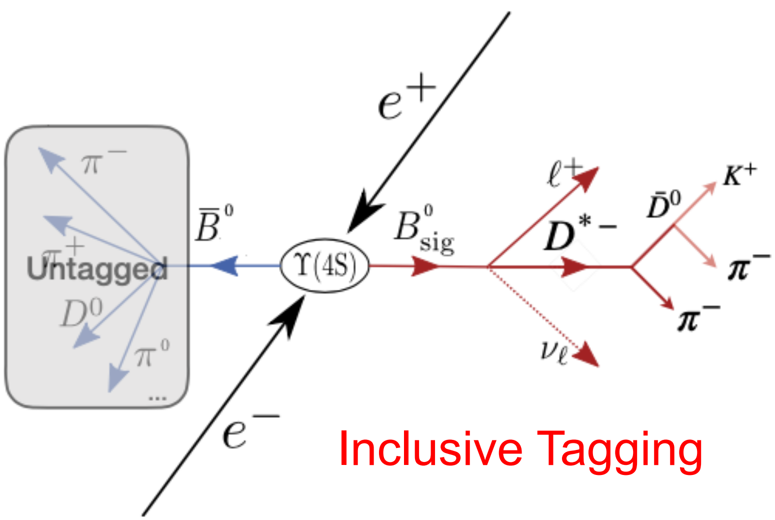
Test of vertex reconstruction of both primary B-meson vertices, in preparation for time-dependent measurements

Semileptonic Tagging (non-FEI)

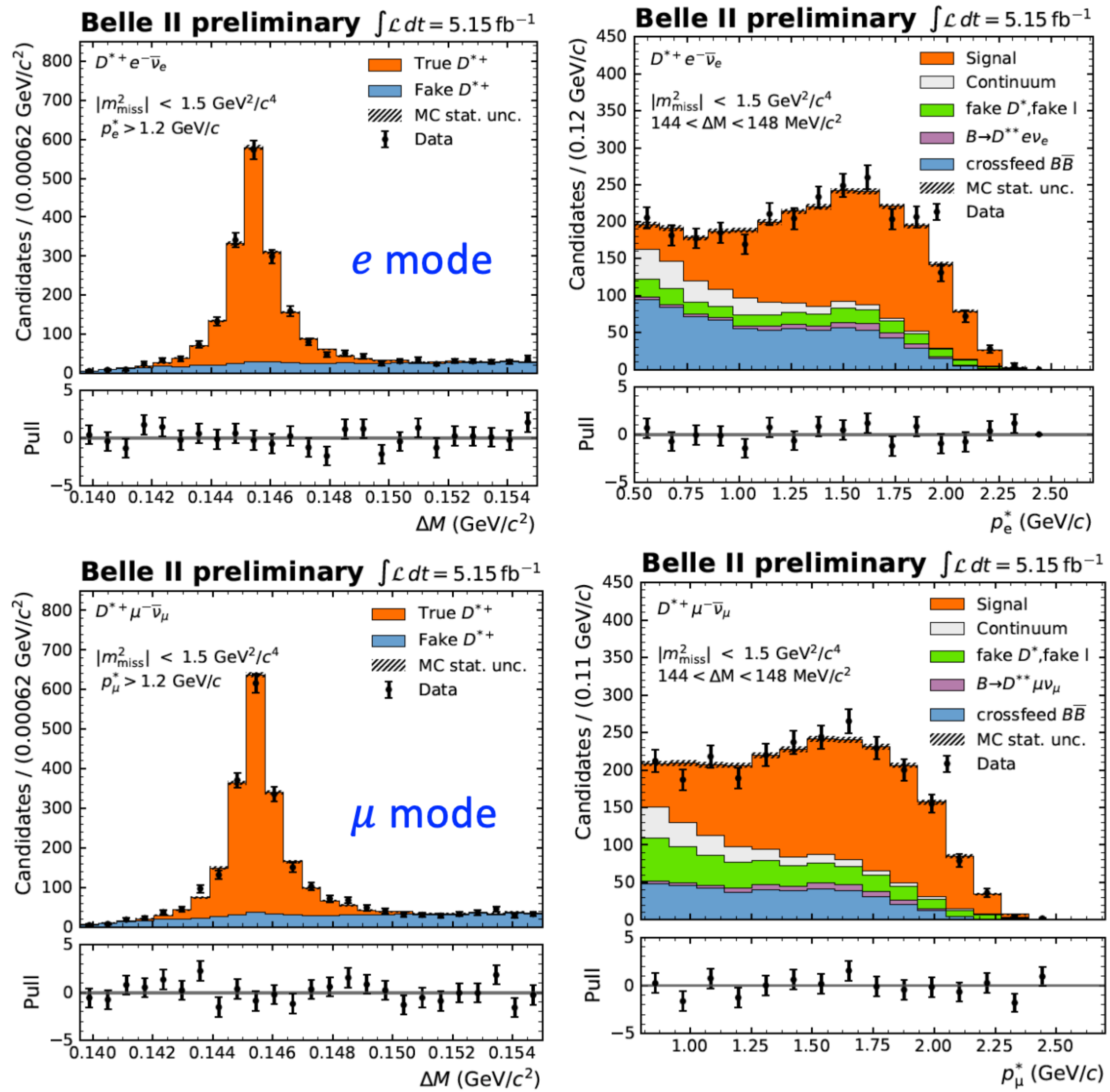


Untagged $B^0 \to D^*\ell\nu$

- Reconstruct $D^*\ell\nu$ candidates in the early Phase 3 data
- Mode will be used in $|V_{cb}|$ and $R(D^*)$ measurements (see later)
- Important test for lepton PID and tracking performance

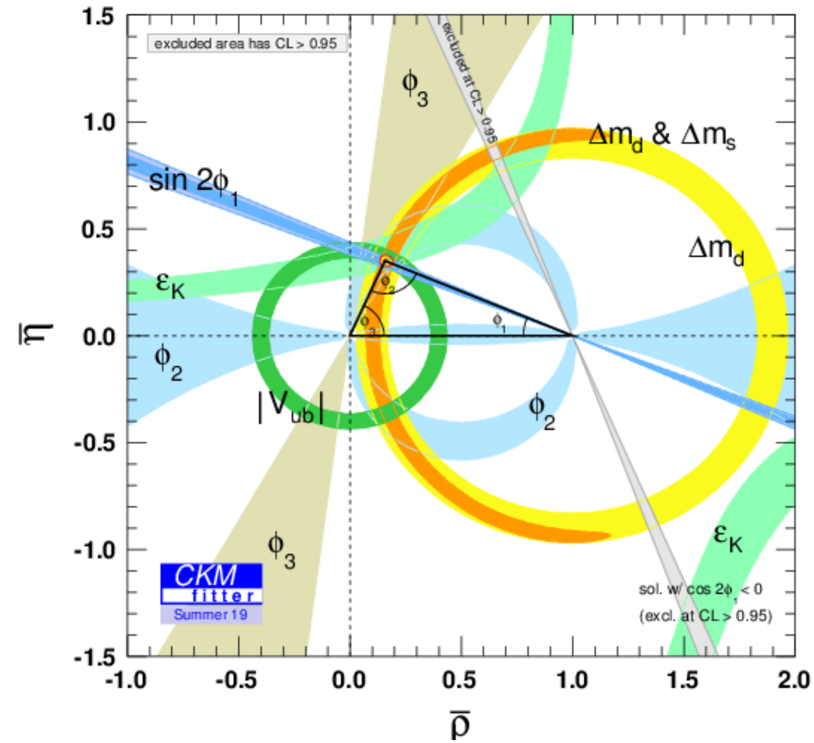


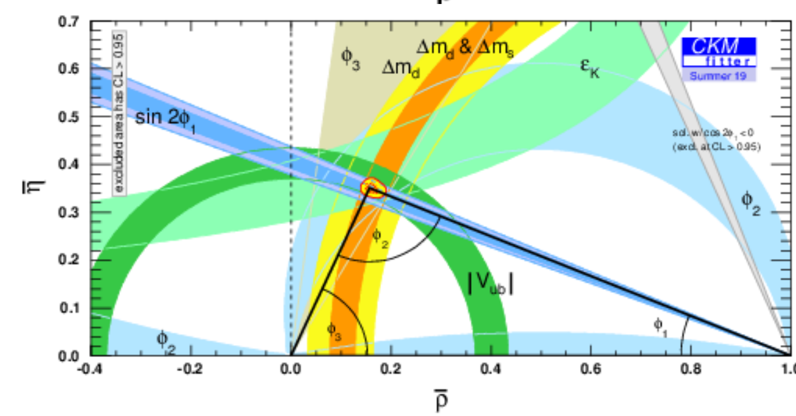
$\boxed{\Delta M = M(D^*) - M(D)}$



Physics Outlook 2020+

Current World Constraints on CKM Unitarity Triangle





CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005) [hep-ph/0406184], updated results and plots available at: http://ckmfitter.in2p3.fr

Physics with $O(10\ \text{fb}^{-1})$:

$B \to X\ell\nu$, $B \to D^*\ell\nu$, using semileptonic FEI

Demonstration of nonzero V_{ub} in inclusive $B \to X\ell\nu$ decays

Physics with $O(100\ \text{fb}^{-1})$:

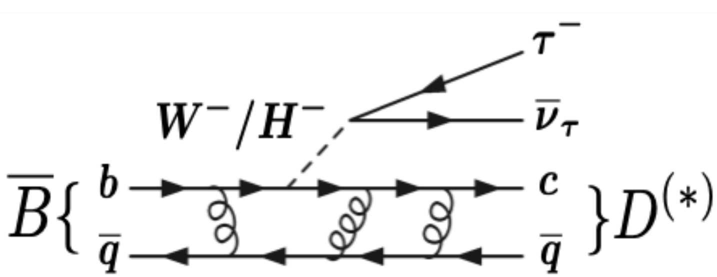
Exclusive V_{ub} via $B \to \pi\ell\nu$; V_{cb} via $B \to D^*\ell\nu$

$(\ell = e, \mu)$

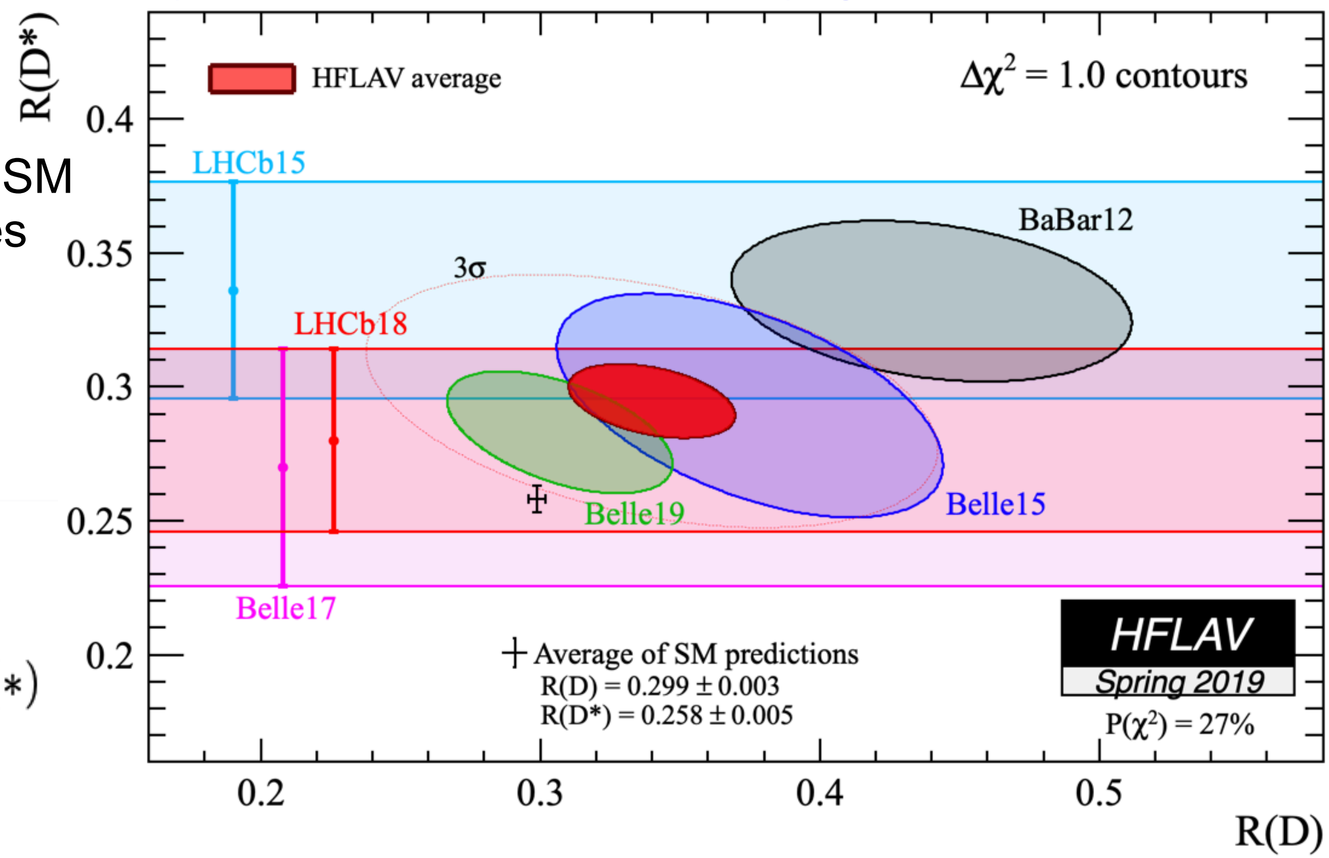
Semitauonic Decays

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^- \bar{\nu}_\ell)} \quad (\ell = e, \mu)$$

- $|V_{cb}|^2$ cancels and form-factor uncertainties are less impactful → well predicted theoretically
- Experimentally: tagging efficiencies cancel
- Tension exists (3.1σ) between SM predictions and world averages
- Sensitivity to lepton-flavour dependent NP in the quark flavour-changing propagator



https://hflav-eos.web.cern.ch/hflav-eos/semi/spring19/html/RDsDsstar/RDRDs.html



R(D), R(D^*) Projections

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)} \quad (\ell = e, \mu)$$

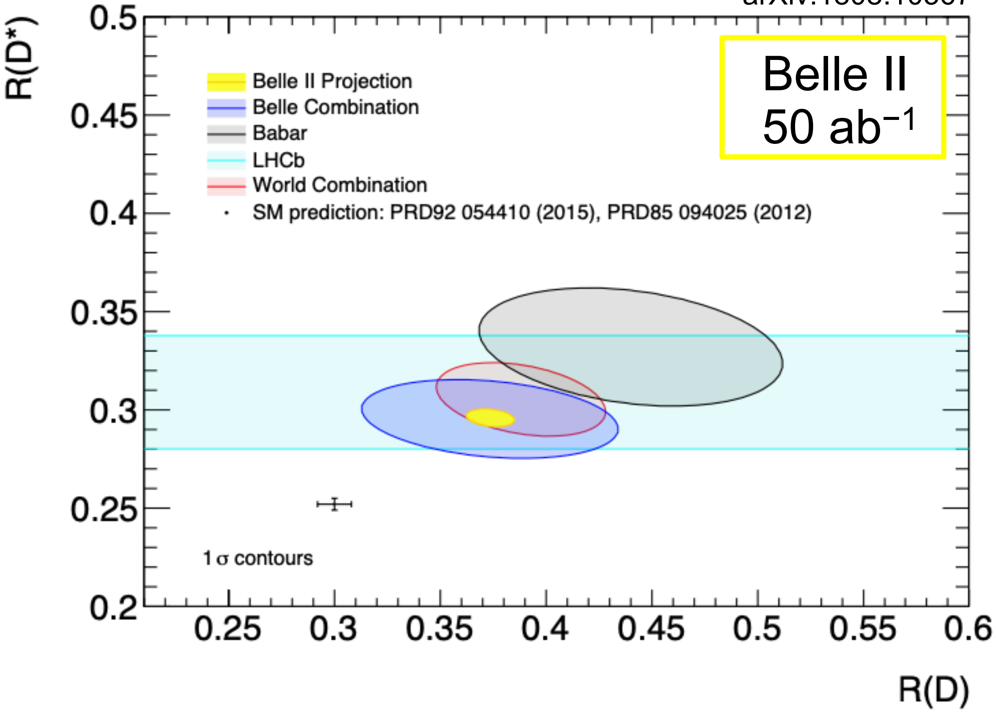
Belle II will initially require ~1.5 ab^{-1}

Projected Belle II stat. ⊕ syst. precision:

	5 ab^{-1}	50 ab^{-1}
R_D	$(\pm 6.0 \pm 3.9)\%$	$(\pm 2.0 \pm 2.5)\%$
R_{D^*}	$(\pm 3.0 \pm 2.5)\%$	$(\pm 1.0 \pm 2.0)\%$
$P_\tau(D^*)$	$\pm 0.18 \pm 0.08$	$\pm 0.06 \pm 0.04$

The Belle II Physics Book, arXiv:1808.10567
Prog. Theor. Exp. Phys. **2019**, 123C01 (2019)

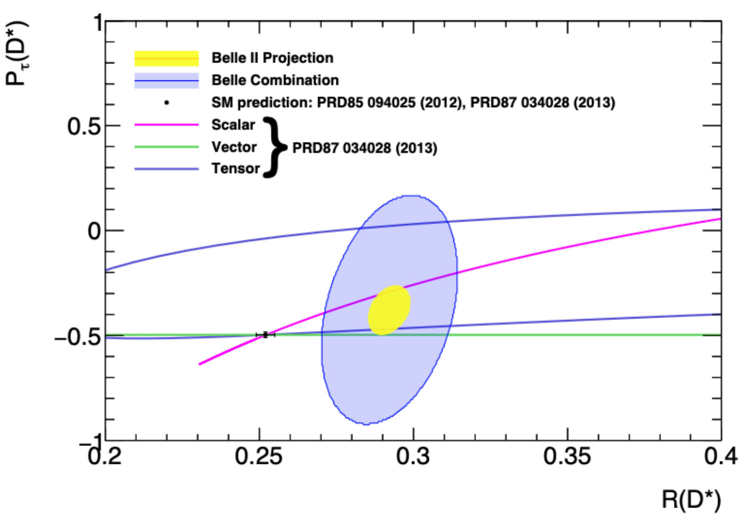
arXiv:1808.10567



Polarisation measurements can also reveal or rule out New Physics

$$P_\tau(D^{(*)}) = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$$

$$P_{D^*} = \frac{\Gamma_L}{\Gamma_L + \Gamma_T}$$



Concluding Remarks

- The Belle II detector and the SuperKEKB collider provide a unique environment to search for physics Beyond the Standard Model via rare B, τ, and charm decay processes
- Leptonic and Semileptonic decays are promising sensitive probes into potential New Physics phenomena, manifested as modified decay rates
- Semileptonic decays are proving to be excellent systems for the commissioning of the Belle II detector and its reconstruction performance
- Full Event Interpretation, a powerful new tool for *B*-meson tagging in the uniquely coherent initial state of an e^+e^- machine, is undergoing calibration
- Stay tuned for physics results to come!

Three other **Belle II** talks later this week!
- DM Searches (M. De Nuccio, Thursday)
- Status & Prospects (T. Bilka, Friday)
- Rare *B* Decays (M.-C. Chang, Friday)

Backup Slides

Projections

Observables

Observables	Belle (2017)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\lvert V_{cb}\rvert$ incl.	$42.2 \cdot 10^{-3} \cdot (1 \pm 1.8\%)$	1.2%	–
$\lvert V_{cb}\rvert$ excl.	$39.0 \cdot 10^{-3} \cdot (1 \pm 3.0\%_{\text{ex.}} \pm 1.4\%_{\text{th.}})$	1.8%	1.4%
$\lvert V_{ub}\rvert$ incl.	$4.47 \cdot 10^{-3} \cdot (1 \pm 6.0\%_{\text{ex.}} \pm 2.5\%_{\text{th.}})$	3.4%	3.0%
$\lvert V_{ub}\rvert$ excl. (WA)	$3.65 \cdot 10^{-3} \cdot (1 \pm 2.5\%_{\text{ex.}} \pm 3.0\%_{\text{th.}})$	2.4%	1.2%
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	$91 \cdot (1 \pm 24\%)$	9%	4%
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	< 1.7	20%	7%
$R(B \to D\tau\nu)$ (Had. tag)	$0.374 \cdot (1 \pm 16.5\%)$	6%	3%
$R(B \to D^*\tau\nu)$ (Had. tag)	$0.296 \cdot (1 \pm 7.4\%)$	3%	2%

Golden & Silver Modes

Process	Observable	Theory	Sys. dom. (Discovery) [ab^{-1}]	vs LHCb	vs Belle	Anomaly	NP
$B \to \pi\ell\nu_\ell$	$\lvert V_{ub}\rvert$	★★★	10-20	★★★	★★★	★★	★
$B \to X_u\ell\nu_\ell$	$\lvert V_{ub}\rvert$	★★	2-10	★★★	★★	★★★	★
$B \to \tau\nu$	$Br.$	★★★	>50 (2)	★★★	★★★	★	★★★
$B \to \mu\nu$	$Br.$	★★★	>50 (5)	★★★	★★★	★	★★★
$B \to D^{(*)}\ell\nu_\ell$	$\lvert V_{cb}\rvert$	★★★	1-10	★★★	★★	★★	★
$B \to X_c\ell\nu_\ell$	$\lvert V_{cb}\rvert$	★★★	1-5	★★★	★★	★★	★★
$B \to D^{(*)}\tau\nu_\tau$	$R(D^{(*)})$	★★★	5-10	★★	★★★	★★★	★★★
$B \to D^{(*)}\tau\nu_\tau$	P_τ	★★★	15-20	★★★	★★★	★★	★★★
$B \to D^{**}\ell\nu_\ell$	$Br.$	★	-	★★	★★★	★★	-

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Ir(reducible) Systematics

Examples of Reducible (Irreducible) Systematics from Belle

$B^0 \to \pi^- \ell^+ \nu_\ell$	711 fb^{-1}	605 fb^{-1}
Source	Error (Limit) [%]	
	Tagged [%]	Untagged
Tracking efficiency	0.4	2.0
Pion identification	–	1.3
Lepton identification	1.0	2.4
Kaon veto	0.9	–
Continuum description	1.0	1.8
Tag calibration and $N_{B\bar{B}}$	4.5 (2.0)	2.0 (1.0)
$X_u \ell \nu$ cross-feed	0.9	0.5 (0.5)
$X_c \ell \nu$ background	–	0.2 (0.2)
Form factor shapes	1.1	1.0 (1.0)
Form factor background	–	0.4 (0.4)
Total	5.0	4.5
(reducible, irreducible)	(4.6, 2.0)	(4.2, 1.6)

$B \to X_u \ell \nu$	605 fb^{-1}
Source	Error on $\mathcal{B}$ (irreducible limit)
$\mathcal{B}(D^{(*)}\ell\nu)$	1.2 (0.6)
Form factors $(D^{(*)}\ell\nu)$	1.2 (0.6)
Form factors & $\mathcal{B}(D^{(**)}\ell\nu)$	0.2
$B \to X_u \ell \nu$(SF)	3.6 (1.8)
$B \to X_u \ell \nu (g \to s\bar{s})$	1.5
$\mathcal{B}(B \to \pi/\rho/\omega\ell\nu)$	2.3
$\mathcal{B}(B \to \eta^{(\prime)}\ell\nu)$	3.2
$\mathcal{B}(B \to X_u \ell\nu)$ unmeasured/fragmentation	2.9 (1.5)
Continuum & Combinatorial	1.8
Secondaries, Fakes & Fit	1.0
PID& Reconstruction	3.1
BDT/Normalisation	3.1 (2.0)
Total	8.1
(Total reducible)	7.4
(Total irreducible)	3.2

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