Recent BelleII results on BSM physics

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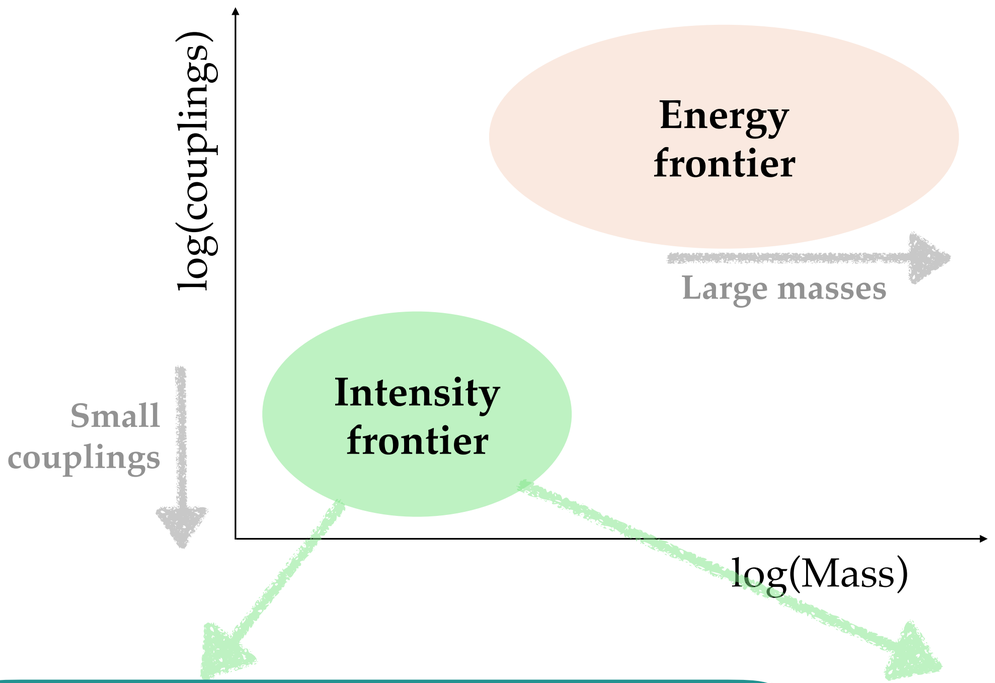
for the Belle2 Collaboration

30 March 2023, DIS2023, Michigan State University

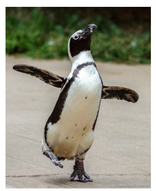
Intensity frontier

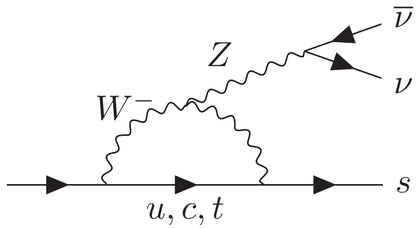


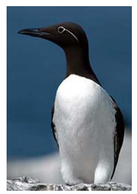
Outline

- SuperKEKB and BelleII
- Tests of light-lepton universality and angular asymmetries
- Search for a long-lived scalar in b → s transitions

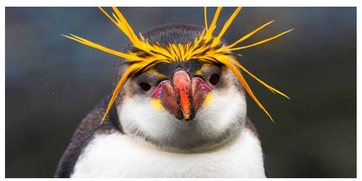
Precision measurements of SM quantities

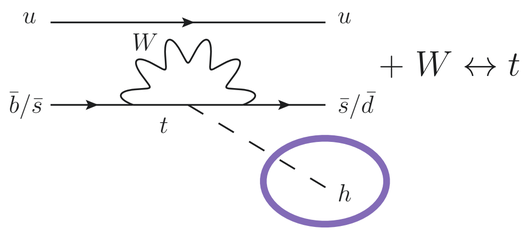






Searches for new feebly interacting particles (for example mediators of the dark sector)

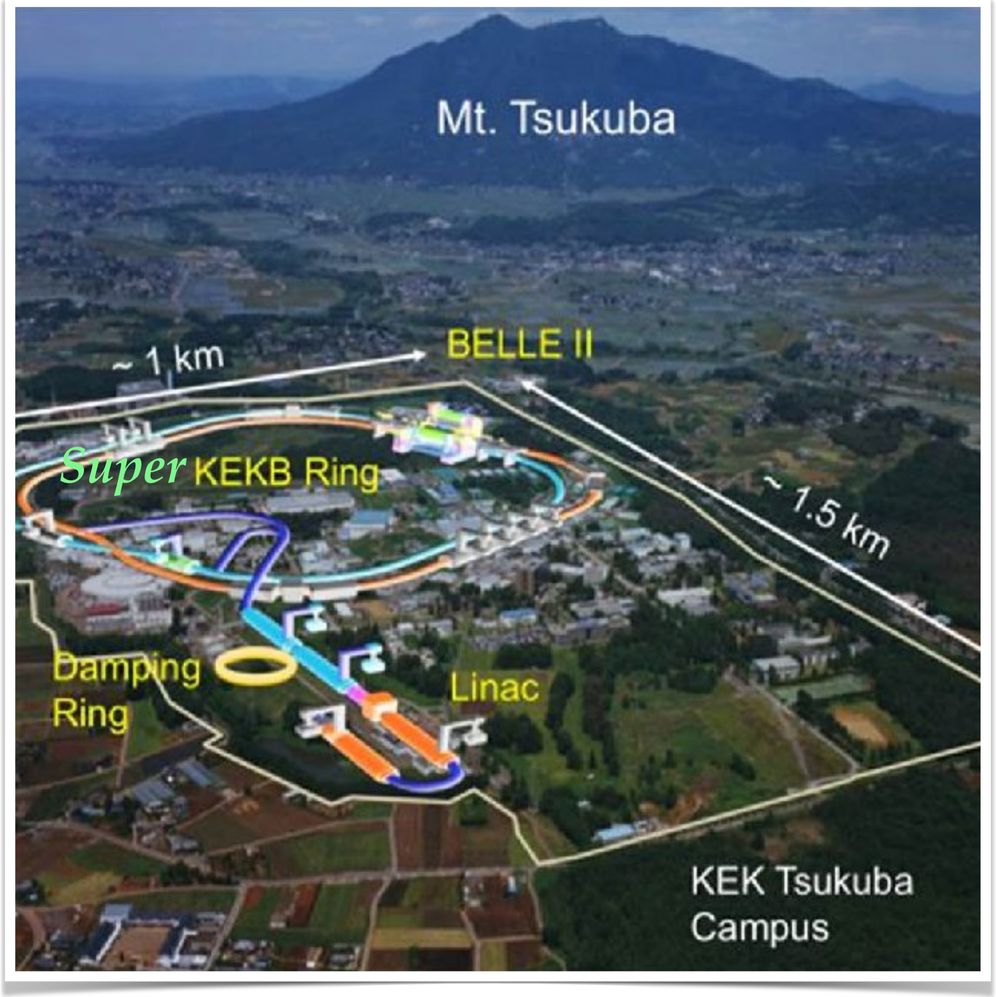




SuperKEKB

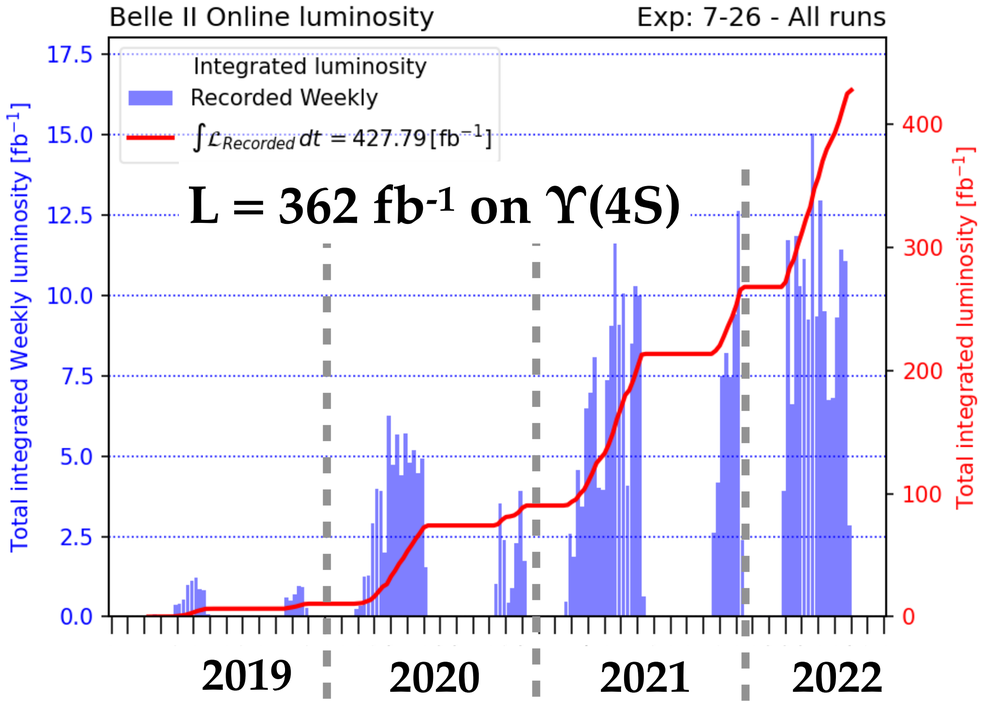
Upgrade of the e^+e^- KEKB collider

e^+e^- with center of mass energy of the $\Upsilon(4S)$ mass



Record of instantaneous luminosity:

$4.7 \cdot 10^{34}\ \mathrm{cm^{-2}s^{-1}}$



2019-2021
L~190 fb^{-1}
Analyses presented in this talk

BelleII detector

Electromagnetic Calorimeter

$\frac{\sigma(E)}{E}$: 2 % - 4 %

[BELLE2-NOTE-PL-2021-008]

Magnet

Silicon Vertex Detector
Pixel Detector

σ(vertex) ~ 15μm

Aerogel RICH Counter
TOP Counter

K-ID efficiency ~ 90%

π mis-ID rate ~ 5%

[BELLE2-CONF-PH-2022-003]

LER e^-
7 GeV

LER e^+
4 GeV

Central Drift Chamber

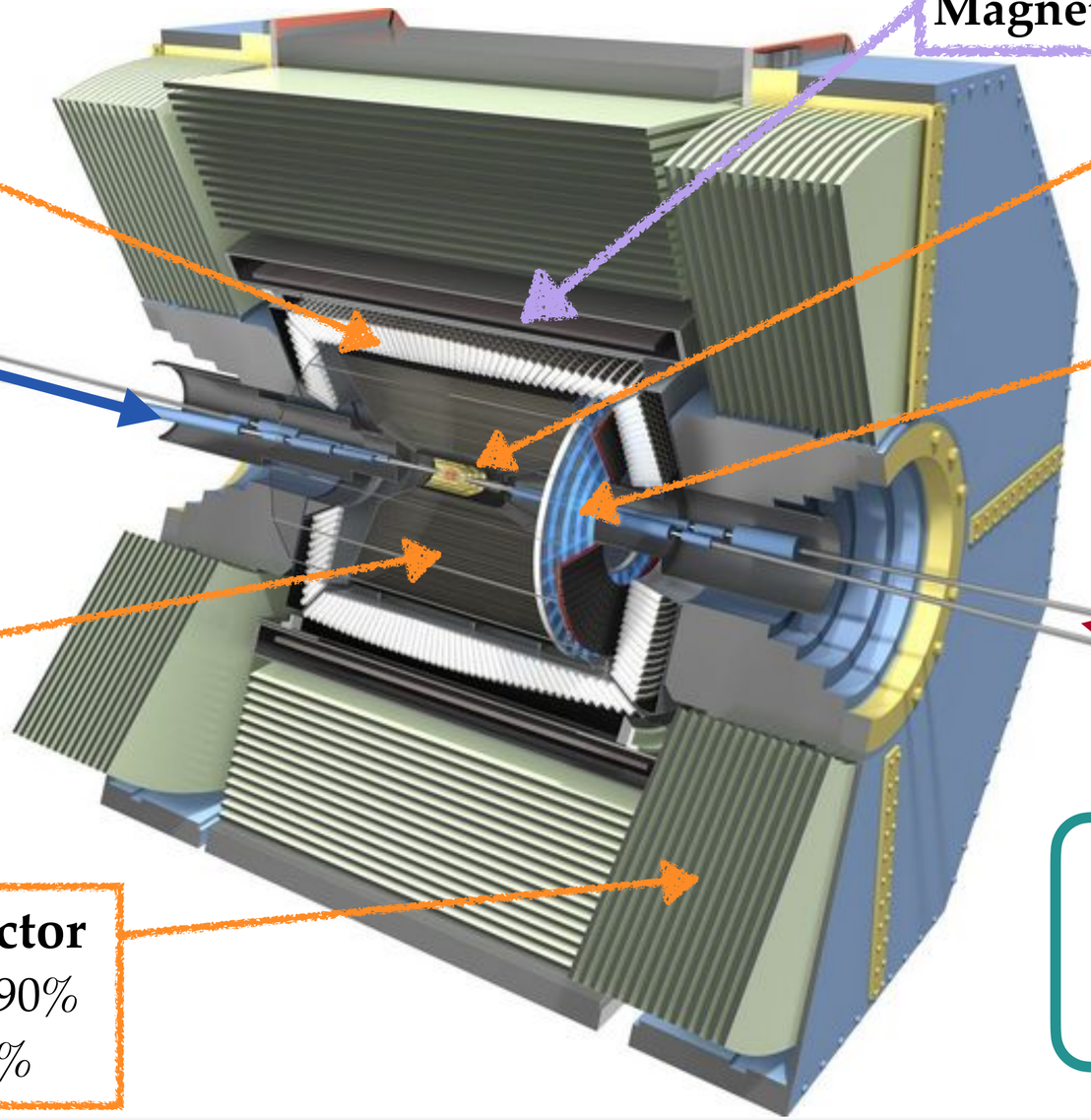
Spacial res. 100 μm

$\sigma\left(\frac{dE}{dx}\right)$: 5 %

KL/Muon Detector

μ ID efficiency ~ 90%

π mis-ID rate ~ 5%



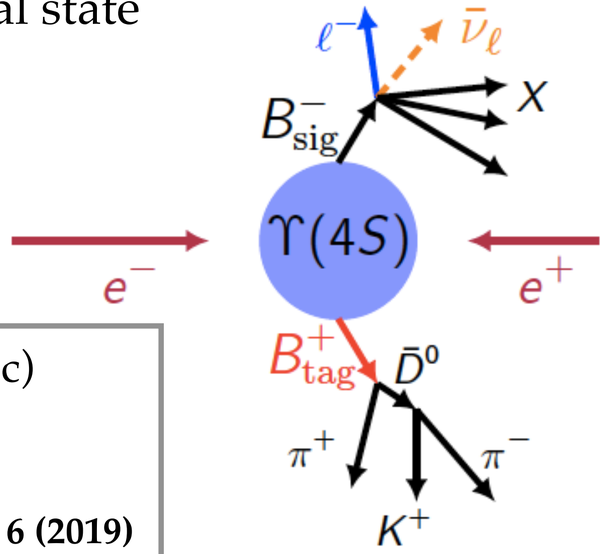
- ☑ Excellent hermeticity
- ☑ Upgraded from the Belle detector

B-tagging

Hadronic B-tagging

kinematical constraints in reconstruction for the signal side with neutrinos in the final state

Not available at hadron colliders



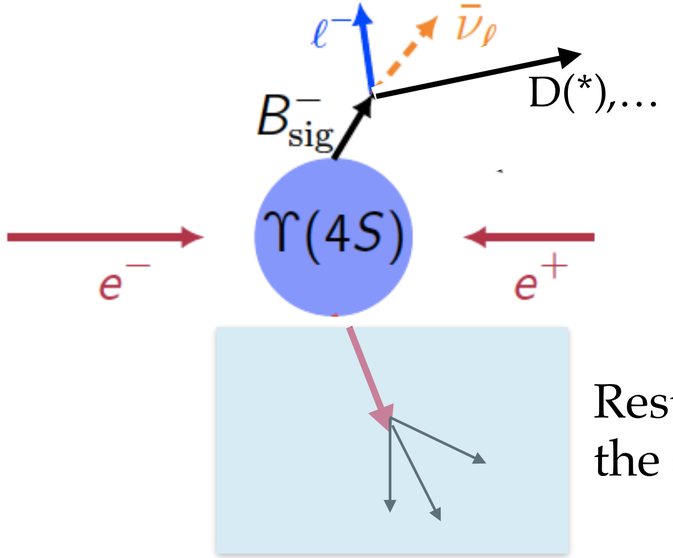
Hadronic (and semi-leptonic) **B-tagging: Full Event Interpretation (FEI)**

Comp. and Soft. For Big Sci. 3, 6 (2019)

arXiv:2008.06096

Inclusive (no B-tagging)

Only reconstruct the signal B final state, no request on the other B



Rest of the event

Less precise reconstruction of final states with neutrinos, but **higher efficiency**

ϵ(**had-tag FEI**) $\sim \mathcal{O}(0.1\% - 0.5\%)$

Efficiency

Purity

Analyses related to Lepton Universality

Tensions in lepton flavor universality

Gauge lagrangian ==> universality of the lepton couplings to the W bosons

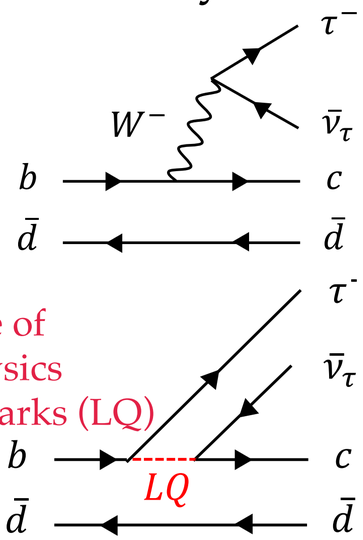
Some hints of lepton flavor universality (LFU) violation:

Flavor changing charged currents in $b \to cl\nu$ decays

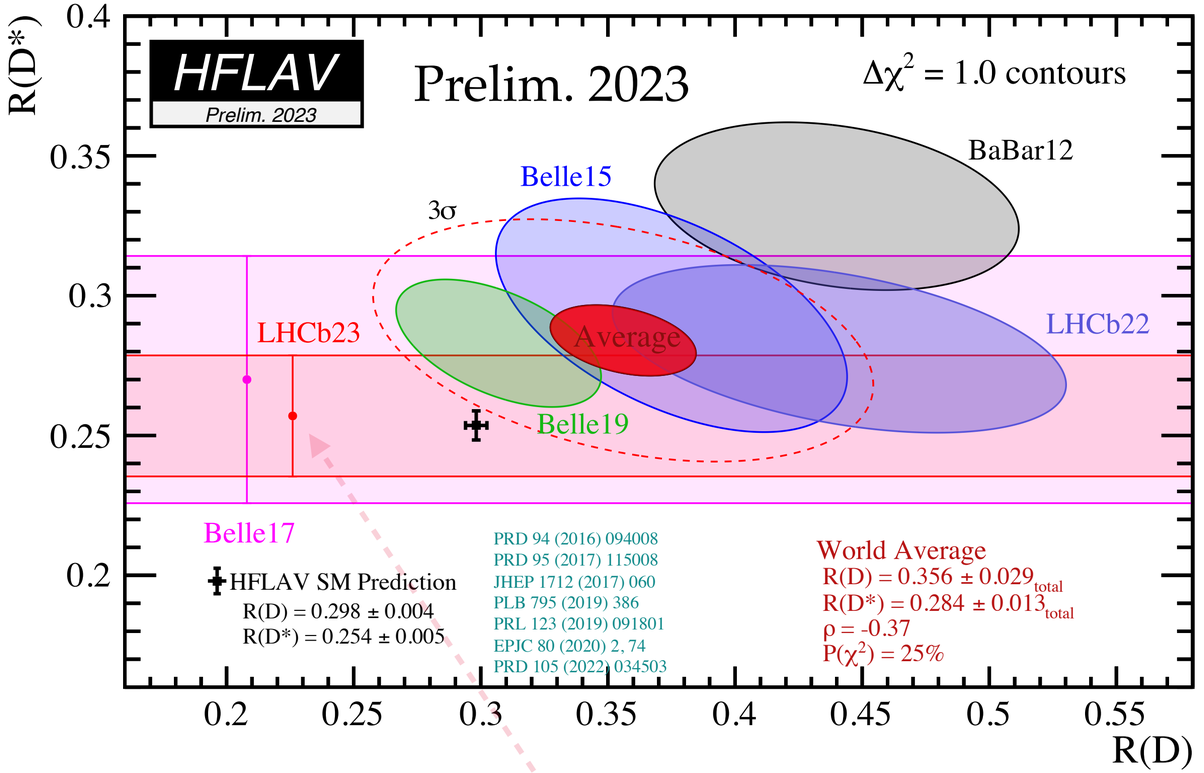
$$R(D^{(*)}) = \frac{B(B \to D^{(*)}\tau\nu)}{B(B \to D^{(*)}l\nu)}$$

$$l = e, \mu$$

If there is a violation, some new physics should be there



Example of new physics Leptoquarks (LQ)



Fresh update from LHCb
https://indico.cern.ch/event/1231797/

Combined R(D) and R(D*) measurements average is **~3.1 σ** away from the SM

$R(X_{e\mu})$ measurement

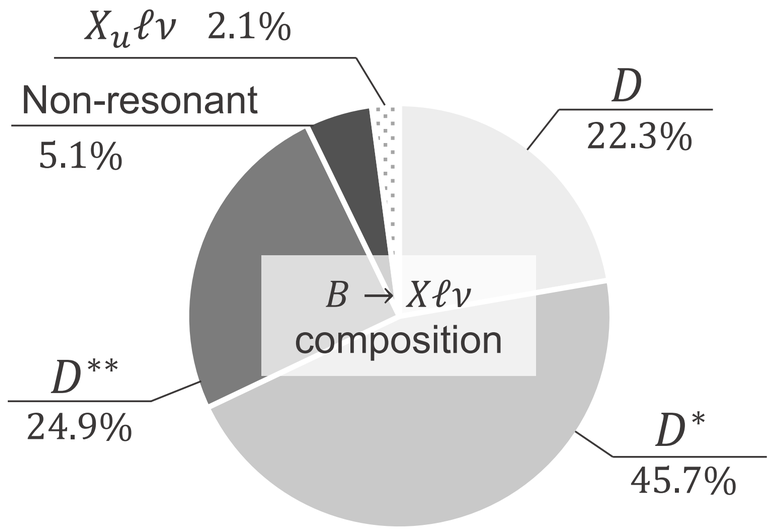
arXiv:2301.08266

$D^{(*)} \to X \qquad R(D^{(*)}) \to R(X)$

X: generic hadronic final state

$$R(X) = \frac{B(B \to X\tau\nu)}{B(B \to Xl\nu)}$$

$$l = e, \mu$$



inclusive measurements possible only at e^+e^- colliders

BelleII performed the $R(X_{e/\mu})$ measurement

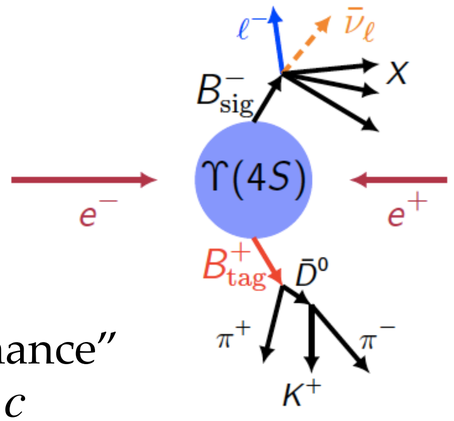
$$R(X_{e/\mu}) = \frac{B(B \to Xe\nu)}{B(B \to X\mu\nu)}$$

Useful also as a preparation for the R(X) measurement

Fully hadronic reconstruction of B-tag with FEI

L = 189 fb^{-1} for on-resonant sample

Additional sample (L = 18 fb^{-1}) of "off-resonance" data to estimate the $e^+e^- \to q\bar{q}, q = u, d, s, c$ background (continuum)

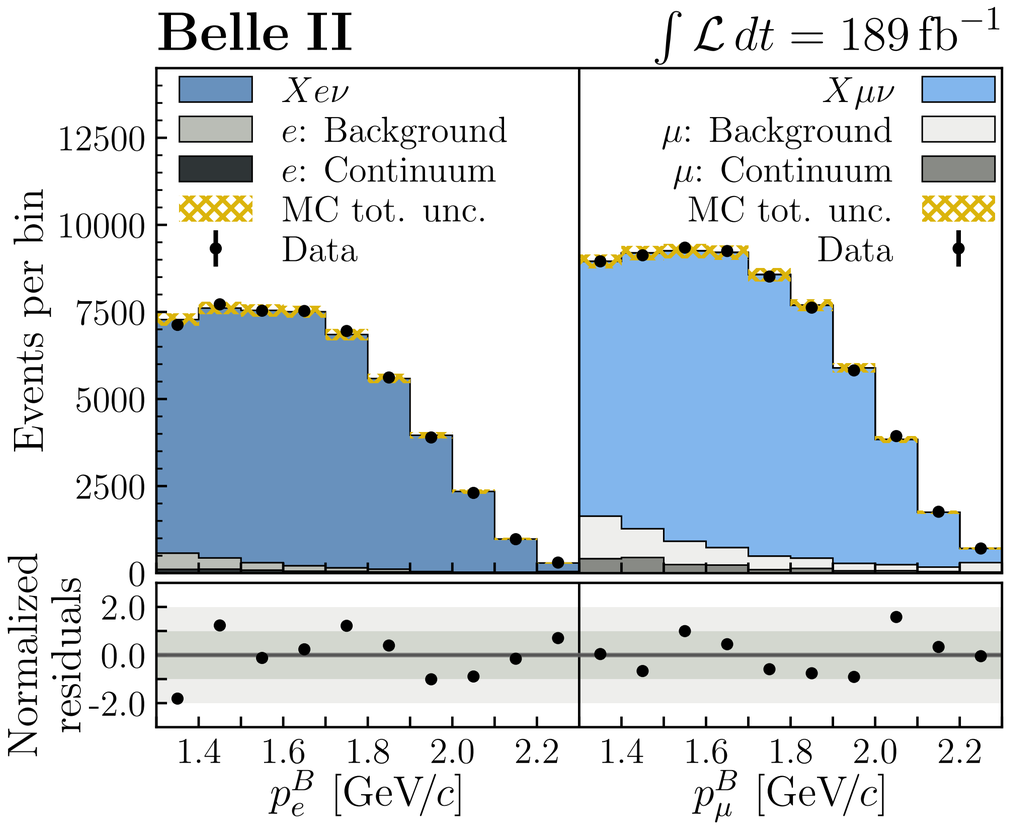


$R(X_{e\mu})$ measurement: Results

arXiv:2301.08266

Control sample with same flavor/charge for tag and signal B to obtain corrections to **normalization**

Simultaneous fit to lepton momentum in the B centre of mass frame for e and μ channels



Background composition :

- BB with hadron mis-id as leptons or real leptons from hadrons
- Continuum: $e^+e^- \to q\bar{q}, q = u, d, s, c$

Main systematic sources:
Lepton-id efficiencies and mis-id probabilities: 1.9%

Result:

$$R(X_{e/\mu}) = 1.033 \pm 0.010\ (\mathrm{stat}) \pm 0.019\ (\mathrm{syst})$$

Compatible with:

- **SM** J. High Energy Phys. 007 (2022),
- **Belle exclusive** $R(D^*_{e/\mu})$: Phys.Rev. D 100, 052007 (2019) and arXiv:2301.07529

Angular asymmetries

Preliminary
To be submitted to PRL

NEW

First dedicated light-LU test using a complete set of angular observables

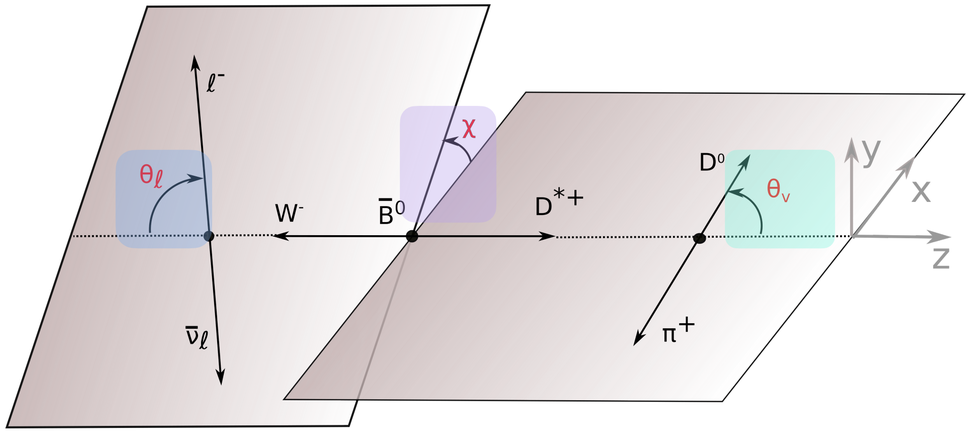
[1-dim: arXiv:2301.07529, Eur. Phys. J. C 81, 984 (2021)]

$$B^0 \to D^{*-} l^+ \nu$$

$$\mathcal{A}_x(w) \equiv \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}w}\right)^{-1} \left[\int_0^1 - \int_{-1}^0\right] \mathrm{d}x \frac{\mathrm{d}^2\Gamma}{\mathrm{d}w \mathrm{d}x}$$

Recoil parameter w

$$w = \frac{m_B^2 + m_{D^*}^2 - q^2 c^2}{2 m_B m_{D^*}}$$



Integrals of differential rates sensitive to LU violations (LUV):

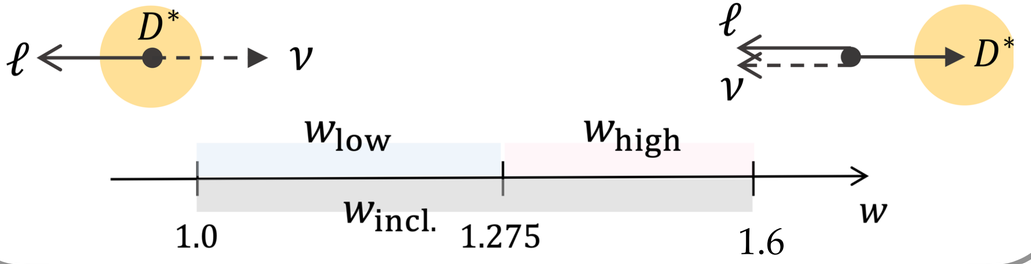
$$A_{\mathrm{FB}} : \mathrm{d}X \to \mathrm{d}(\cos\theta_l)$$
$$S_3 : \mathrm{d}X \to \mathrm{d}(\cos 2\chi)$$
$$S_5 : \mathrm{d}X \to \mathrm{d}(\cos\chi \cos\theta_V)$$

Highly sensitive to LUV

$$S_7 : \mathrm{d}X \to \mathrm{d}(\sin\chi \cos\theta_V)$$
$$S_9 : \mathrm{d}X \to \mathrm{d}(\sin 2\chi)$$

Less sensitive to LUV, used as control of the analysis method

3 ranges in the recoil parameter **w**:
w_{low} :[1,1.275], w_{high}:[1.275,1.6] and w_{inc} :[1,1.6]



Angular asymmetries: analysis strategy

Preliminary
To be submitted to PRL

NEW

Example with $A_{FB} = \left(\frac{d\Gamma}{dw}\right)^{-1}\left[\int_0^1 - \int_{-1}^0\right] dcos\theta_l \frac{d^2\Gamma}{dw\, dcos\theta_l}$

A_{FB} : Propensity for the lepton to travel in the same direction of the W

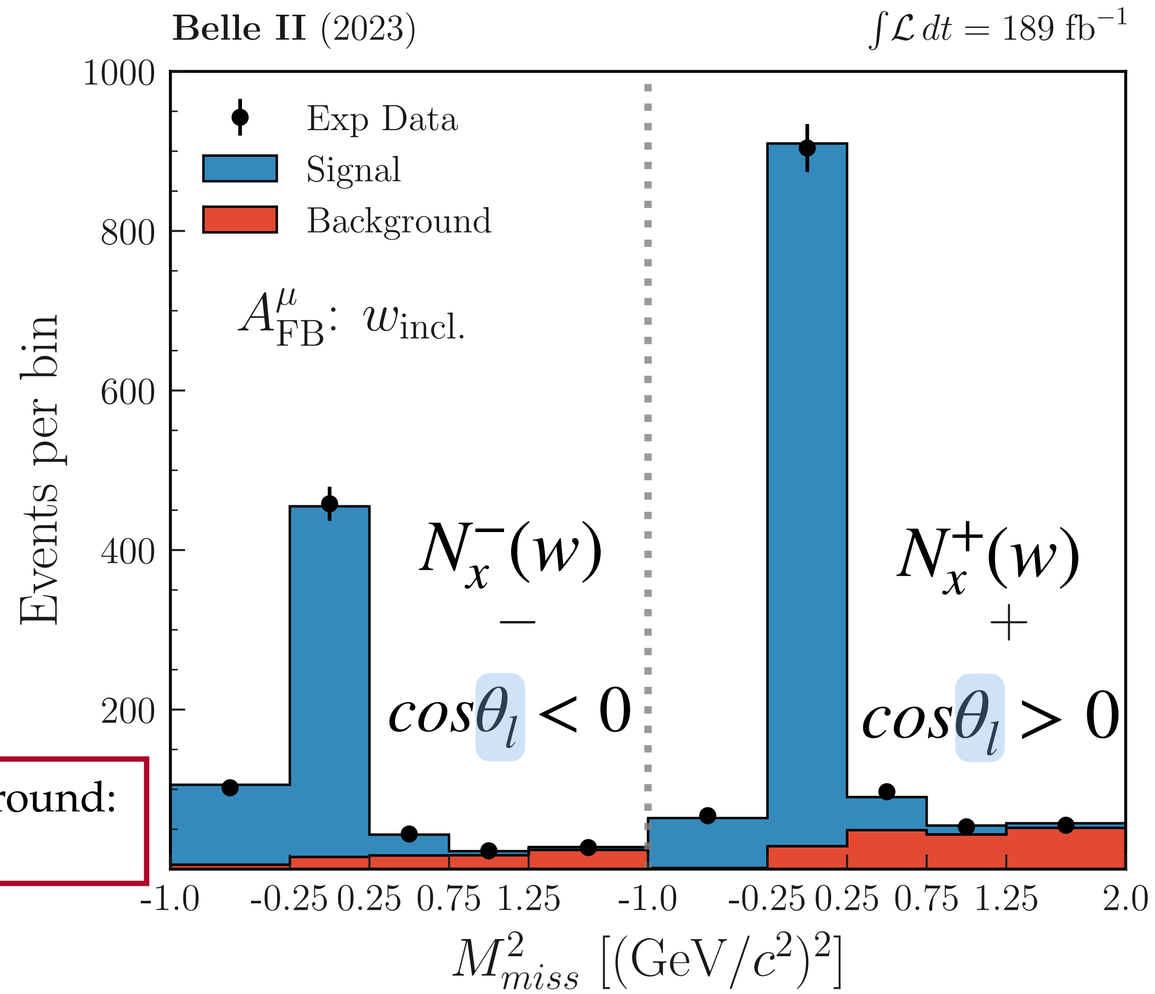
FEI fully hadronic B-tag reconstruction.
After the selection of the signal side we determine the number of events N_x^+ and N_x^- with a fit to M^2_{miss}

$$\mathcal{A}_x(w) = \frac{N_x^+(w) - N_x^-(w)}{N_x^+(w) + N_x^-(w)}$$

$$\Delta\mathcal{A}_x(w) = \mathcal{A}_x^\mu(w) - \mathcal{A}_x^e(w)$$

Clean probes of LUV
Experimental uncertainties and hadronic uncertainties (FF) cancel out

$$M^2_{miss} = (p_{e^+e^-} - p_{B_{tag}} - p_{D^*} - p_l)^2 \sim M^2_\nu$$

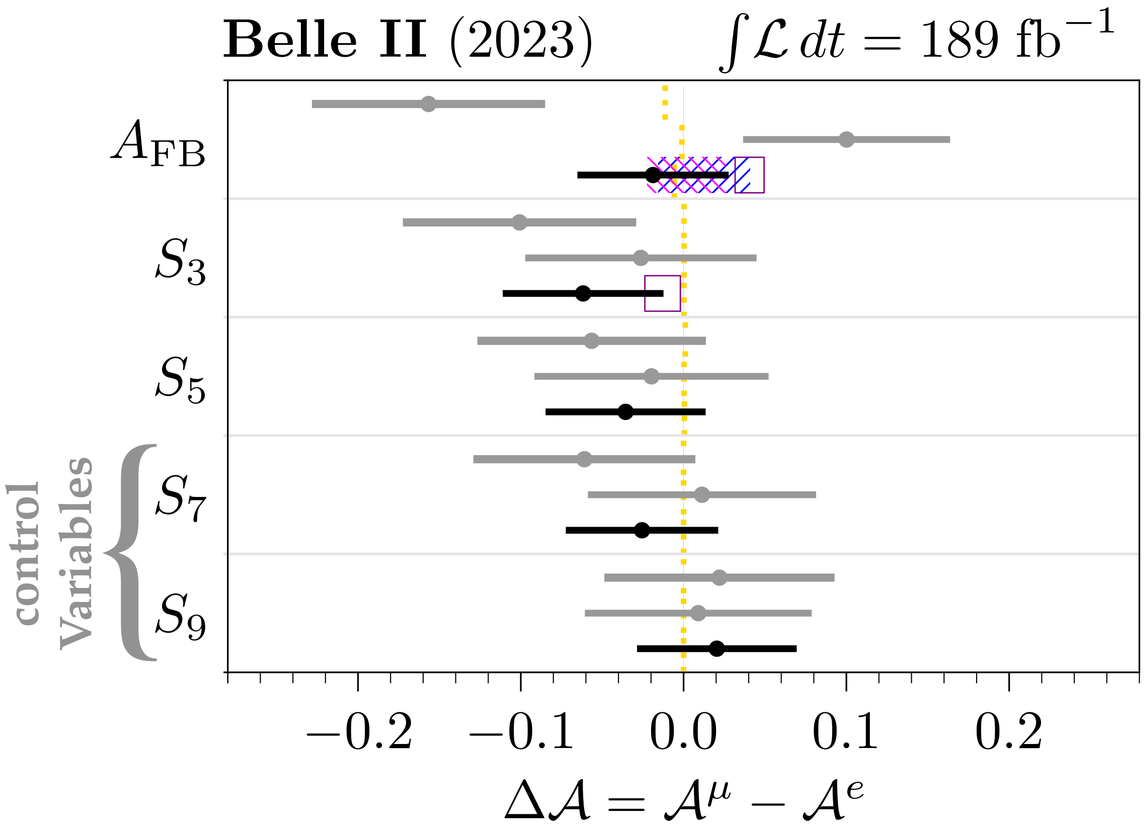


Main background:
$B \to D^{**} l\nu$

Angular asymmetries: results

Preliminary
To be submitted to PRL

NEW



obtained in a slightly reduced w range, (1, 1.5)

Previous measurements only for 1 (out of 5) variable (A_{FB})

Result limited by experimental statistics

- ☑ Agreement with SM, no evidence for LUV
- ☑ First comprehensive tests of LU in the angular distributions of semi-leptonic B decays

Search for a long-lived particle in $b \to s$ transitions

First long lived particle search at BelleII

Search for a Long Lived Particle

NEW

L = 189 fb^{-1} Preliminary

Dark sector mediators can be long-lived particles (**LLP**) due to their small coupling with SM particles

Search for Dark long-lived particle S in b → s transitions

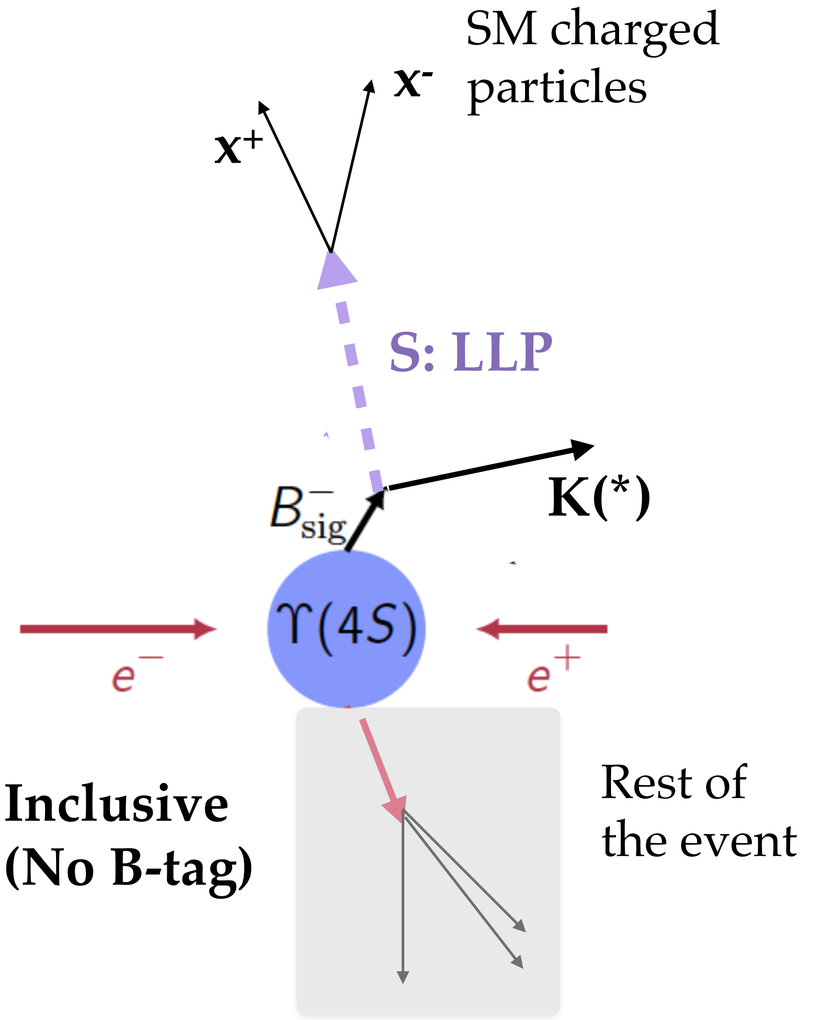
8 exclusive channels:

$B^+ \to K^+ S$

$B^0 \to K^{*0} S$, with $K^{*0} \to K^+\pi^-$

$S \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-, K^+K^-$

- Bump hunting in S mass distribution M_S using unbinned maximum likelihood fits
- Dedicated study of displaced vertex performance, corrections determined with K^0_S control sample



LLP: model independent results

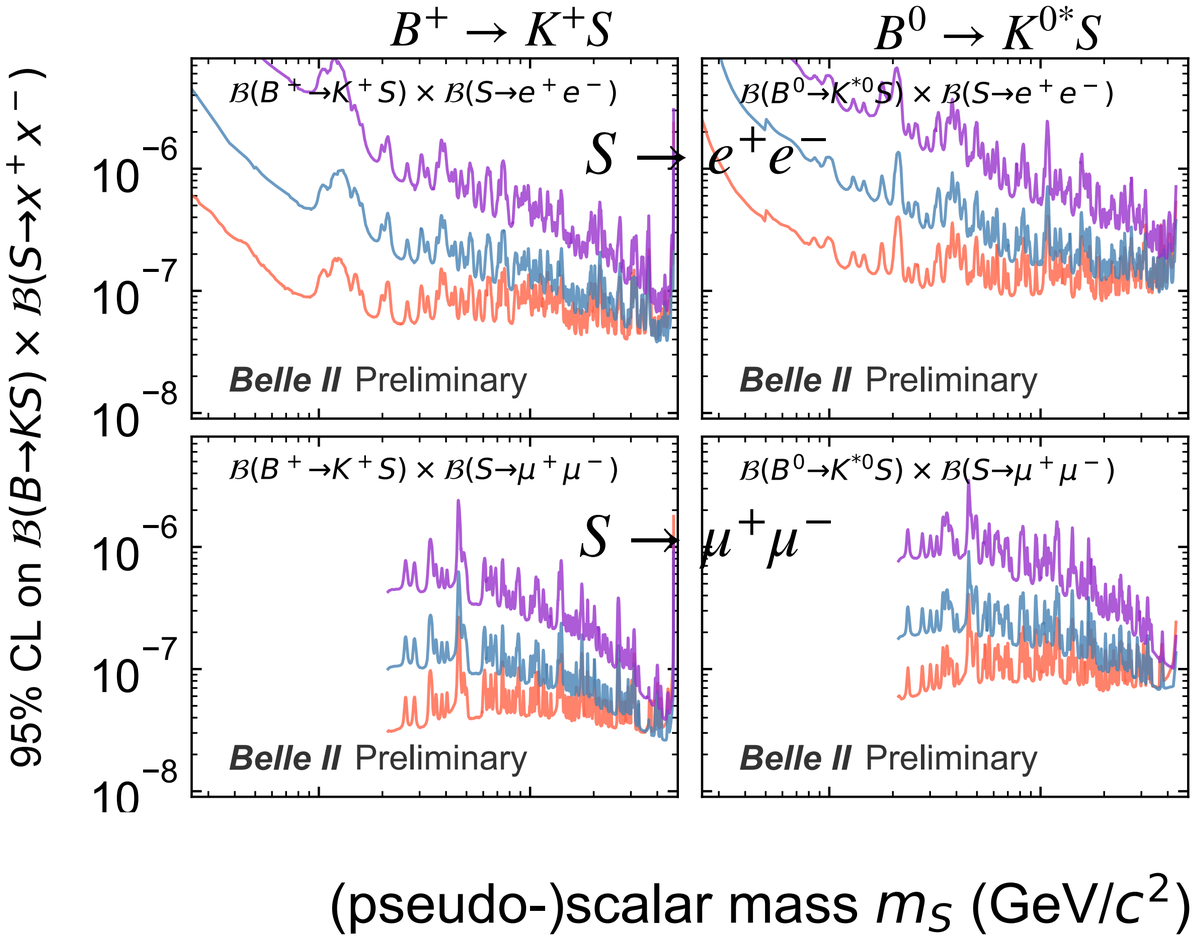
NEW

L = 189 fb^{-1} Preliminary

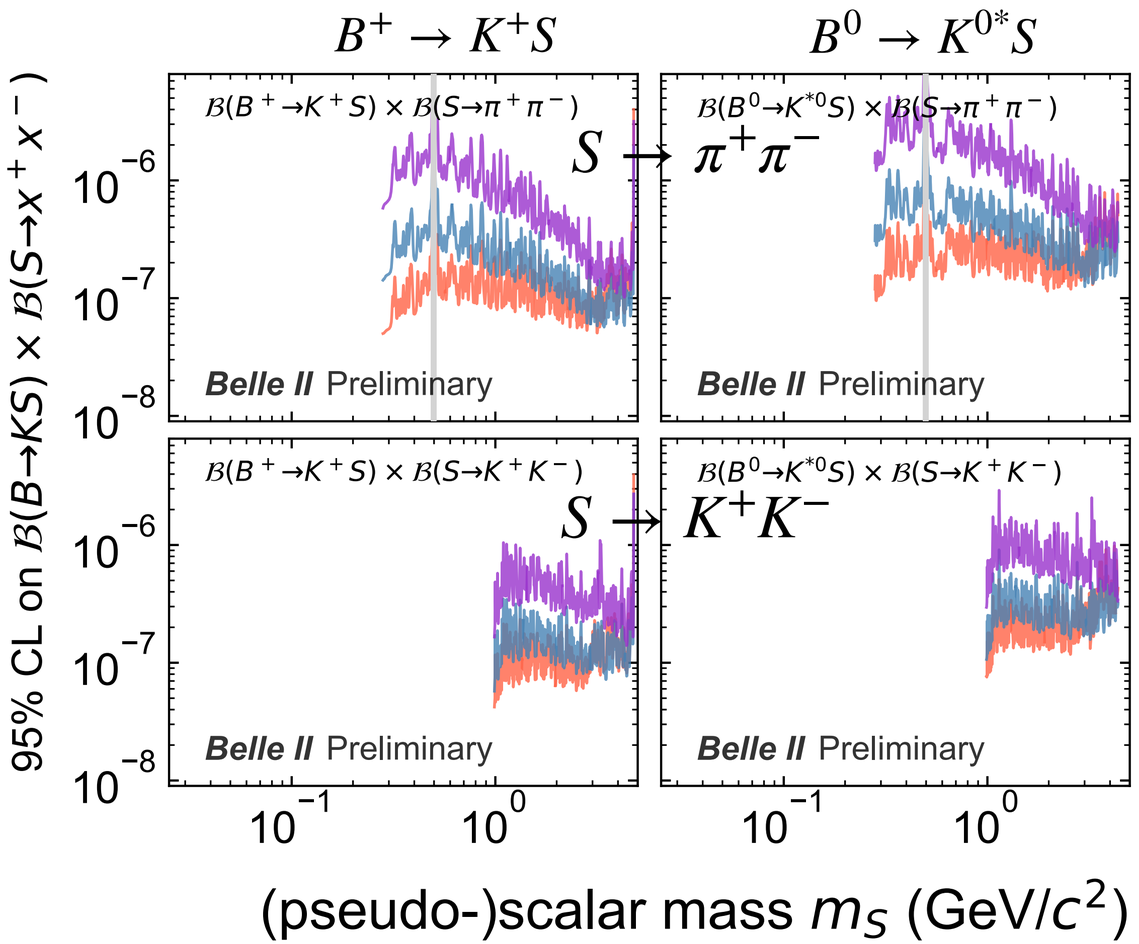
$c\tau_{\mathrm{LLP}} = 1, 10, 50\,\mathrm{cm}$

No deviation from SM observed

Strongest bounds for $S \to e^+e^-$



(pseudo-)scalar mass m_S (GeV/c^2)



(pseudo-)scalar mass m_S (GeV/c^2)

First bounds for hadronic final states

LLP: interpretation in the Higgs-mixing model

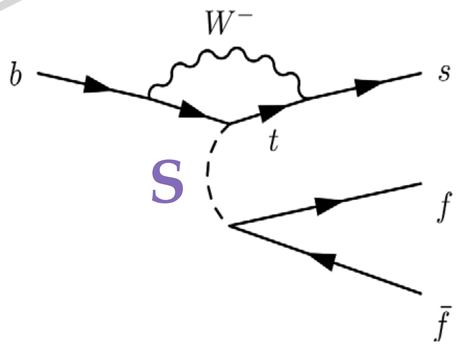
NEW

Preliminary

$$\mathcal{L}_{\text{scalar}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} - (\mu S + \lambda S^2) H^\dagger H$$

With: $\mu = sin\theta$

$\lambda = 0$



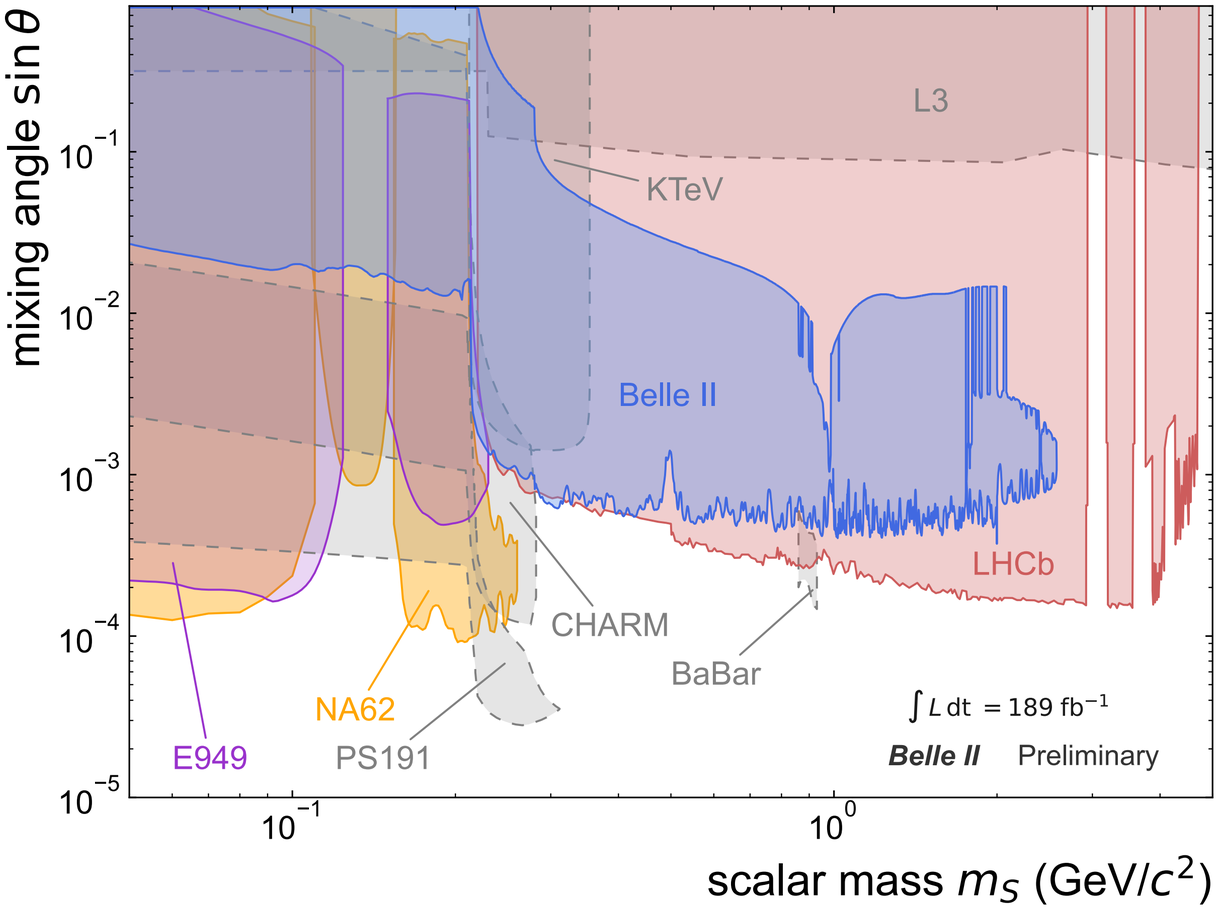
BC4 of PBC [J. Phys. G: Nucl. Part. Phys. 47 010501]

For example Winkler [Phys. Rev. D 101, 095006 (2020)]

$$c\tau_S = f(\theta, m_S)$$

$$c\tau_S \propto \frac{1}{sin^2\theta}\text{nm}$$

Combination of the 8 channels:



Strongest bound for $m_S \sim 0.3$ GeV

Summary

Presented recent results from BelleII

- **Tests of light-lepton universality:**
  - Measurement of $R(X_{e/\mu}) = 1.033 \pm 0.010\ (\text{stat}) \pm 0.019\ (\text{syst})$
  - First dedicated light-LU test using a set of angular observables with the $B^0 \to D^{*-} l^+ \nu$ decay **NEW**
- **Search for a long-lived scalar in b → s transitions** **NEW**

Results compatible with the SM

Analyses using the full dataset (362 fb^{-1}) are ongoing and a **new data taking run will start next winter**

Thank you

Thank you

Back up

Long-shutdown activity and plans

Belle II stopped taking data in Summer 2022 for a long shutdown

- replacement of beam-pipe
- replacement of photomultipliers of the central PID detector (TOP)
- installation of 2-layered pixel vertex detector
- improved data-quality monitoring and alarm system
- complete transition to new DAQ boards (PCIe40)
- replacement of aging components
- additional shielding and increased resilience against beam backgrounds

Currently working on pixel detector installation:

- > shipping to KEK in mid March
- > final test at KEK scheduled in April

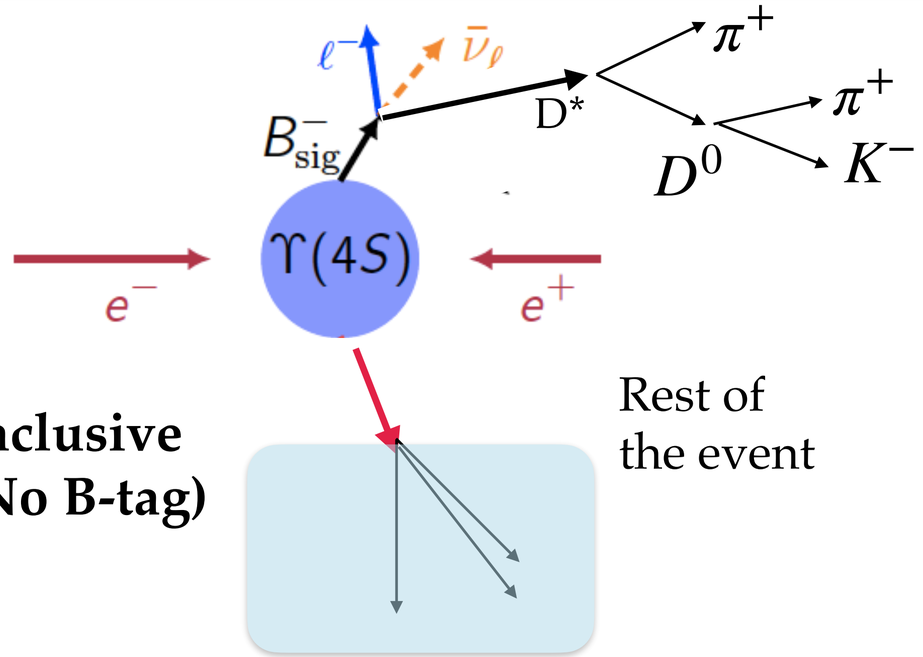
On track to resume data taking next winter with new pixel detector

1

Determination of $|V_{cb}|$ with $\bar{B}^0 \to D^{*+} l^- \bar{\nu}_l$

Preliminary
To be submitted to PRD

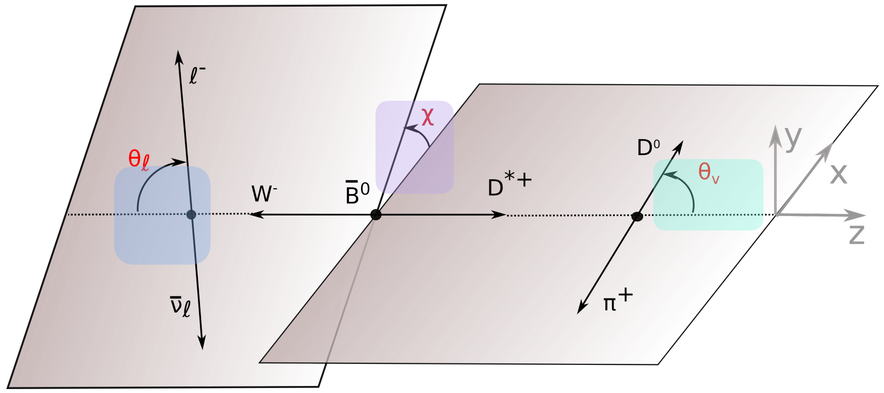
NEW



Inclusive (No B-tag)

Rest of the event

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

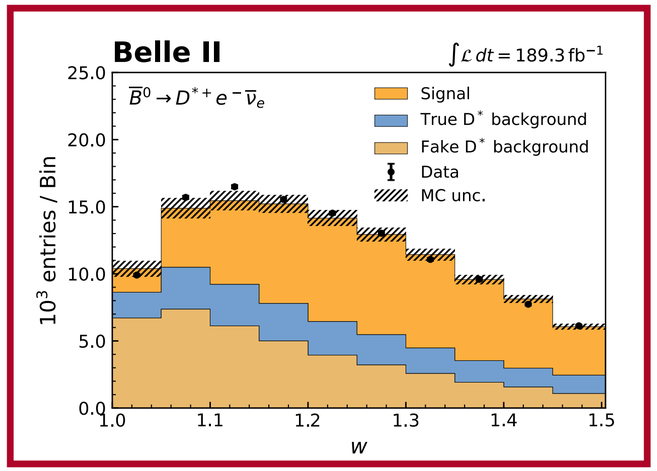


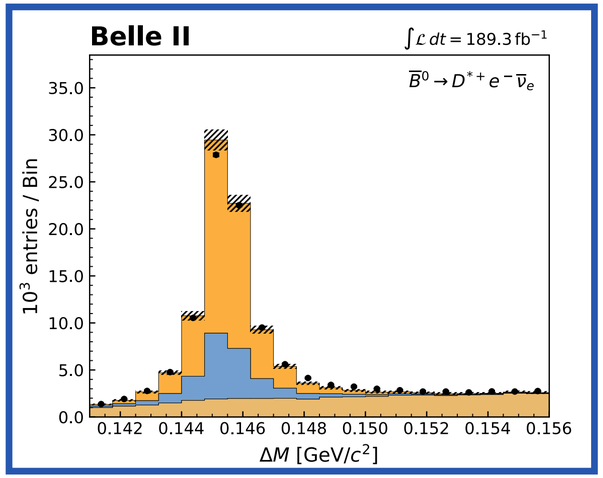
The analysis is performed in bins of $w, cos\theta_l, cos\theta_\nu, \chi$

For each bin fit to the variables $cos\theta_{BY}$ and $\Delta M = M(D^*) - M(D^0)$

The neutrino direction is reconstructed inclusively using θ_{BY} **angle between the B and D*l system**

L = 189 fb^{-1}





Vcb: results

Preliminary
To be submitted to PRD

NEW

Measurement of the branching fractions:

$$\mathcal{B}(\overline{B}^0 \to D^{*+} e^- \bar{\nu}_e) = (4.94 \pm 0.03 \pm 0.22)\%$$
$$\mathcal{B}(\overline{B}^0 \to D^{*+} \mu^- \bar{\nu}_\mu) = (4.94 \pm 0.03 \pm 0.24)\%$$

$$\mathcal{B}(\overline{B}^0 \to D^{*+} \ell^- \bar{\nu}_\ell) = (4.94 \pm 0.02 \pm 0.22)\%$$

Two form factor parametrization:

Boyd, Grinstein, Lebed (**BGL**)
[Phys. Rev. D56, 6895 (1997)]

$$|V_{cb}|_{\mathrm{BGL}} = (40.9 \pm 0.3 \pm 1.0 \pm 0.6) \times 10^{-3}$$

Caprini, Lellouch, Neubert (**CLN**)
[Nucl. Phys. B530, 153 (1998)]

$$|V_{cb}|_{\mathrm{CLN}} = (40.4 \pm 0.3 \pm 1.0 \pm 0.6) \times 10^{-3}$$

$R(X_{e\mu})$ measurement

arXiv:2301.08266

Selection:

FEI had B-tag

Cuts on:

$$M_{\rm bc} = \sqrt{(\sqrt{s}/2)^2 - |\vec{p}^{\,*}_B|^2}$$

$$\Delta E = E^*_B - \sqrt{s}/2$$

FEI probability

Signal B

$p_T(\mu/e) > 0.4/0.3\ GeV/c$

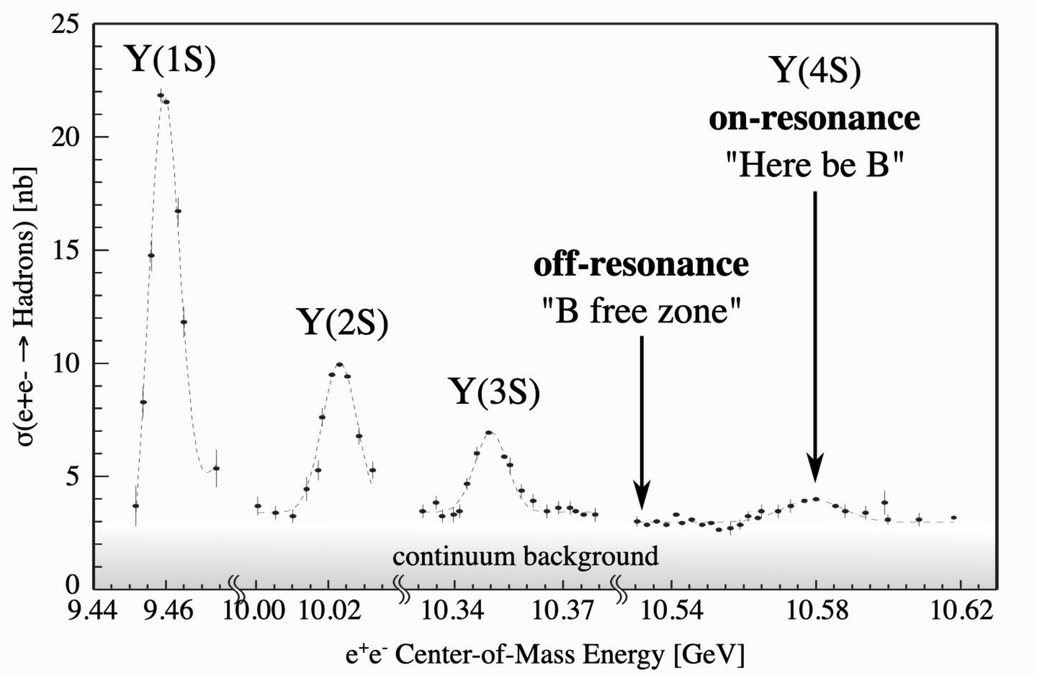
Particle identification

Remaining ECL clusters, tracks,.. —> X system

Boosted decision tree to suppress continuum bkg:
Continuum rejection: 55%
BB efficiency: 97%

Background composition:
- Continuum
- BB with hadron mis-id as leptons or real leptons from hadrons

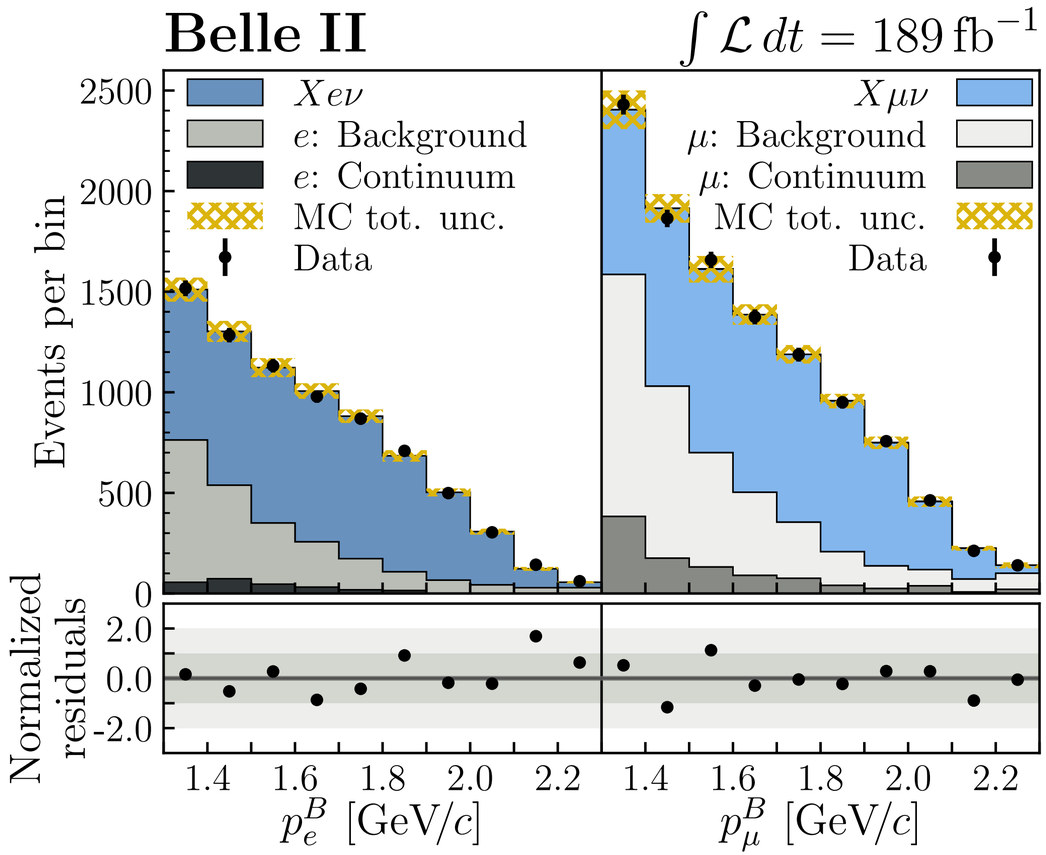
Off-resonance data to estimate the continuum bkg



$R(X_{e\mu})$ measurement

arXiv:2301.08266

Control sample with same flavor/charge for tag and signal B to obtain corrections to **normalization** of the background



Fit to same-sign and opposite-sign samples

$$N_e^{\mathrm{meas}} = 48030 \pm 290$$

$$N_\mu^{\mathrm{meas}} = 58570 \pm 430$$

$$R(X_{e/\mu}) = \frac{N_e^{\mathrm{meas}}}{N_\mu^{\mathrm{meas}}} \cdot \frac{N_\mu^{\mathrm{sel}}}{N_e^{\mathrm{sel}}} \cdot \frac{N_e^{\mathrm{gen}}}{N_\mu^{\mathrm{gen}}}$$

Source	Uncertainty [%]
Sample size	1.0
Lepton identification	1.9
$X_c\,\ell\,\nu$ branching fractions	0.1
$X_c\,\ell\,\nu$ form factors	0.2
Total	2.2

Angular asymmetries

had-Btag FEI requirements

Signal side: $B^0 \to D^{*-}(e^+, \mu^+)\nu$

$B^0 \to D^{*-}(e^+, \mu^+)\nu$

$D^{*-} \to \bar{D}^0\pi^-$

$\bar{D}^0 \to K^+\pi^-, K^+\pi^-\pi^+\pi^-, K^+\pi^-\pi^0, K^+\pi^-\pi^+\pi^-\pi^0$
$K^0_S\pi^+\pi^-, K^0_S\pi^+\pi^-\pi^0, K^0_S\pi^0, K^+K^-$

And charged coniugate

Missing energy > 0.3 GeV

…..

Unfolding of experimental resolution

Results

Obs.	w bin	Measurement	SM$\times 10^5$
$\Delta A_{\rm FB}$	$w_{\rm low}$	0.099 ± 0.064	-104 ± 2
	$w_{\rm high}$	-0.168 ± 0.072	-1133 ± 9
	$w_{\rm incl.}$	-0.024 ± 0.046	-566 ± 7
ΔS_3	$w_{\rm low}$	-0.026 ± 0.071	28 ± 0.2
	$w_{\rm high}$	-0.101 ± 0.072	23 ± 1
	$w_{\rm incl.}$	-0.062 ± 0.049	18 ± 1
ΔS_5	$w_{\rm low}$	-0.019 ± 0.072	27 ± 0.3
	$w_{\rm high}$	-0.055 ± 0.07	107 ± 4
	$w_{\rm incl.}$	-0.035 ± 0.049	49 ± 2
ΔS_7	$w_{\rm low}$	0.011 ± 0.07	0 ± 0
	$w_{\rm high}$	-0.061 ± 0.068	0 ± 0
	$w_{\rm incl.}$	-0.026 ± 0.047	0 ± 0
ΔS_9	$w_{\rm low}$	0.009 ± 0.07	0 ± 0
	$w_{\rm high}$	0.022 ± 0.071	0 ± 0
	$w_{\rm incl.}$	0.02 ± 0.049	0 ± 0

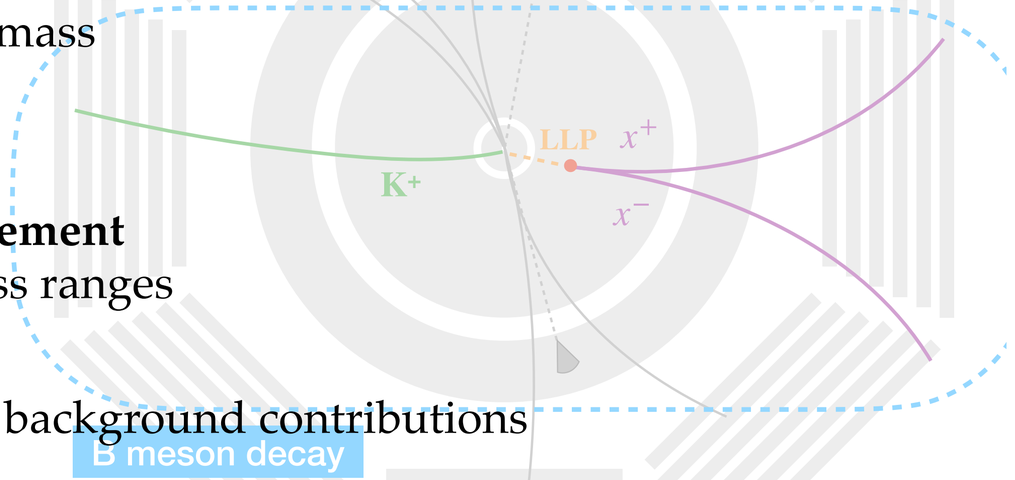
Long Lived scalar

Selection mainly on:

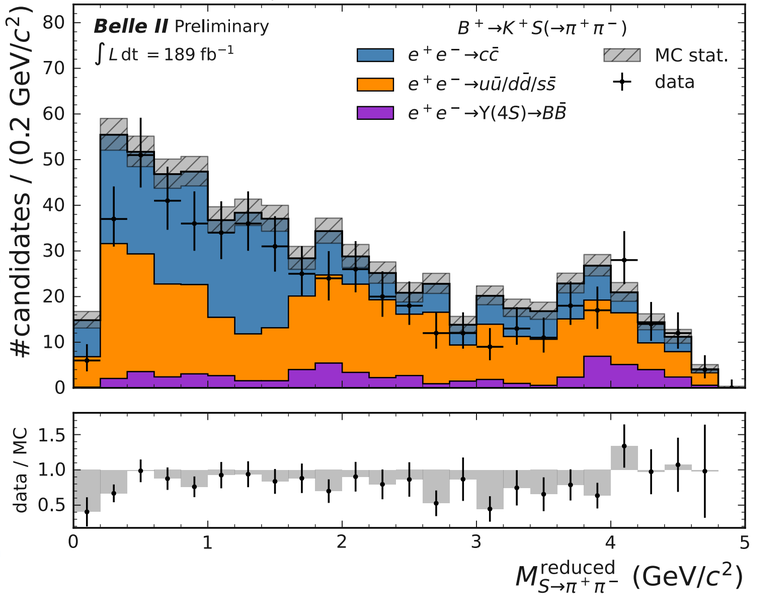
- LLP dr, 2d pointing angle
- Prompt track PID and displaced track PID

peaking backgrounds in LLP mass distributions, examples:
$D^0, J/\psi, \psi(2S) \to \mu\mu$

Reduced by tightening displacement (dr) selection for respective mass ranges



$$M_{\mathrm{LLP}}^{\mathrm{reduced}} = \sqrt{M_{\mathrm{LLP}}^2 - 4m_{\mathrm{final-state}}^2}$$



total 19 lifetime values probed

Several sidebands used to study background contributions

Fitting method:

- Unbinned maximum likelihood fits in steps of $\sigma/2$ in windows around test mass of $\pm 20\ \sigma$
- Limits on the signal BF determined using the modified frequentists CLs method
- combined fit between channels for model dependent limits
- Look-elsewhere effect is taken into account using the Gross-Vittels method
- Systematic uncertainties implemented by nuisance parameters with gaussian priors

adapted from T. Ferber

Largest local significance at

$m_S = 2.619\ \mathrm{GeV}/c^2$

$c\tau = 100$ cm

Local: 3.3σ

Global: 0.3σ