Belle II

Université de Strasbourg

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cnrs

Search for the $B^+ \to K^+ \nu\bar{\nu}$ decay in the Belle II experiment

PhD thesis 2020 - 2023

Lucas Martel

Under the supervision of Isabelle Ripp and Giulio Dujany

I. Motivations

II. Improvement of the Belle II Silicon Vertex Detector

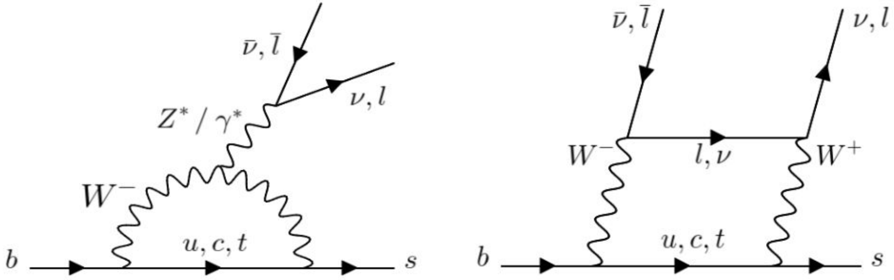
III. Search for the $B^+ \rightarrow K^+ \nu\bar{\nu}$ decay

The $B \to K^{(*)} \nu\bar{\nu}$ decays in the Standard Model (SM)

- Occur through a $b \to s\nu\bar{\nu}$ Flavour Changing Neutral Current (FCNC) transition **not allowed at tree level**
- FCNC = **good tests** of the SM
- SM branching ratio:

$$\mathbf{BR(B^+ \to K^+ \nu\bar{\nu}) = (4.43 \pm 0.42) \times 10^{-6}}$$

[Bečirević et. al. '23]



Rare:
Suppressed in the SM by the GIM mechanism

Challenging identification:
Neutrinos do not interact with our detectors →final state mostly invisible

Decays not observed to this day

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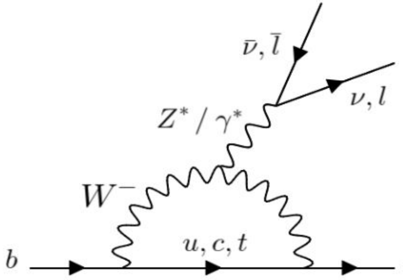
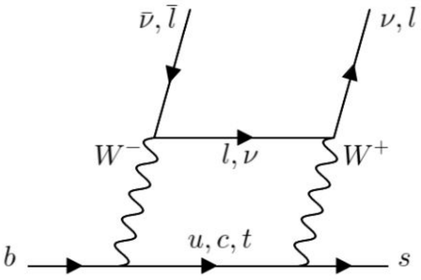
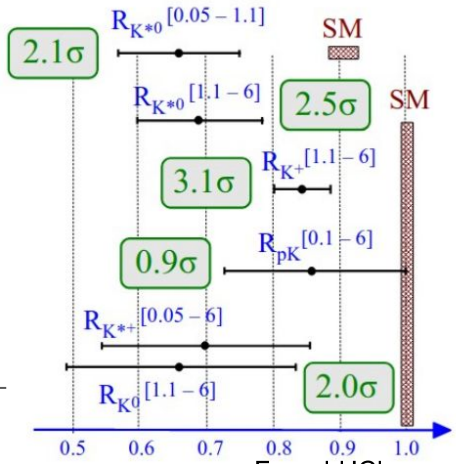
[Bečirević et. al. '23]

- $b \to s$ FCNC searches motivated by previous $b \to s \ell^+ \ell^-$ measurements showing tensions with SM expectations

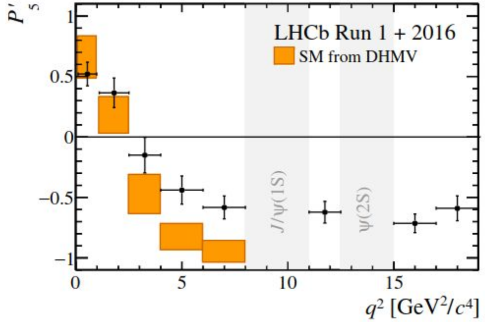




$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)} \mu^+ \mu^-)}{BR(B \to K^{(*)} e^+ e^-)}$$



From LHCb



[PRL 125, 011802]

The $B \to K^{(*)} \nu\bar{\nu}$ decays in the Standard Model (SM)

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[Bečirević et. al. '23]

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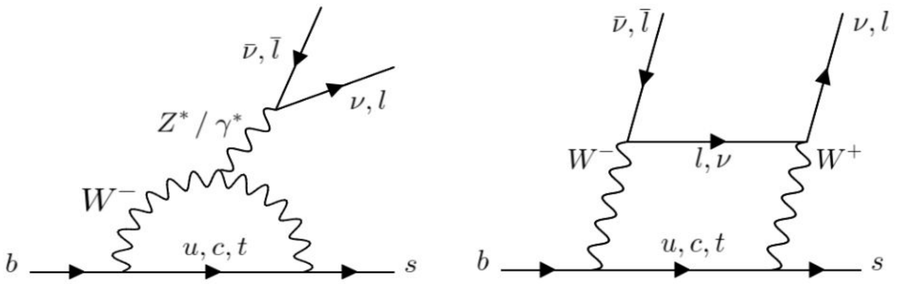
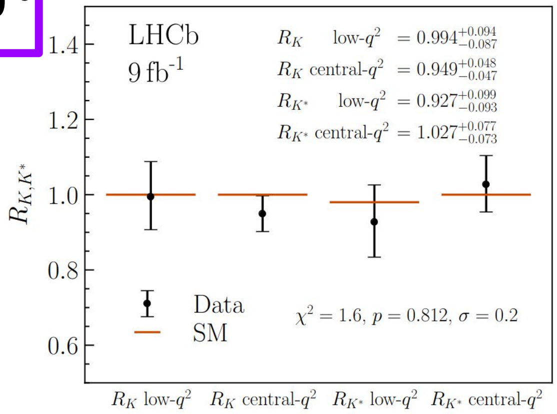
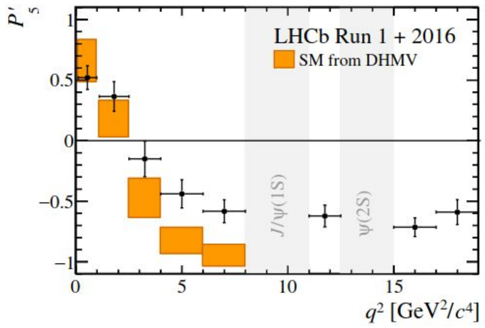
Recent updates see these tensions vanish





[PRD 108, 032002]

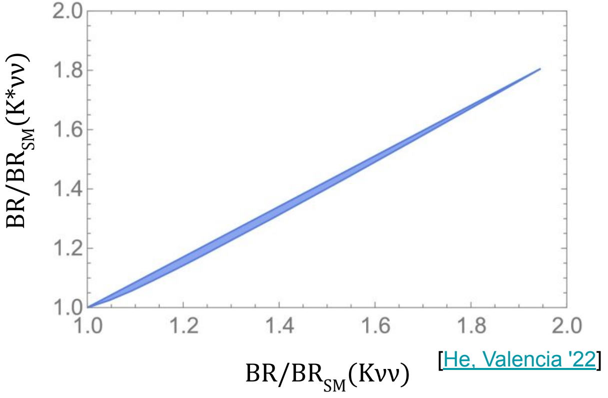


[PRL 125, 011802]

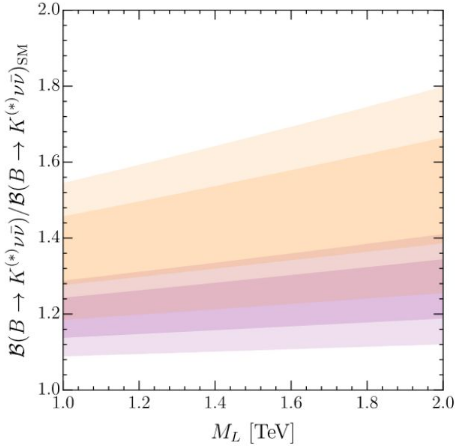
- Several models of Beyond Standard Model (BSM) physics predict significant changes to BR(B→K$^{(*)}$ν$\bar{\nu}$)
- Modifications may be caused by:
  - Z' boson
  - Leptoquarks
  - Axion-Like Particles

- **Added value w.r.t.** b→sℓ$^+$ℓ$^-$:
  - Theoretically "cleaner"
  - Probe 3rd generation lepton couplings
  - Actually study B→K$^{(*)}$+ invisible
  - Allows to constrain the C_L and C_R Wilson coefficients

→ **Overall "cast a wider net"**



[He, Valencia '22]



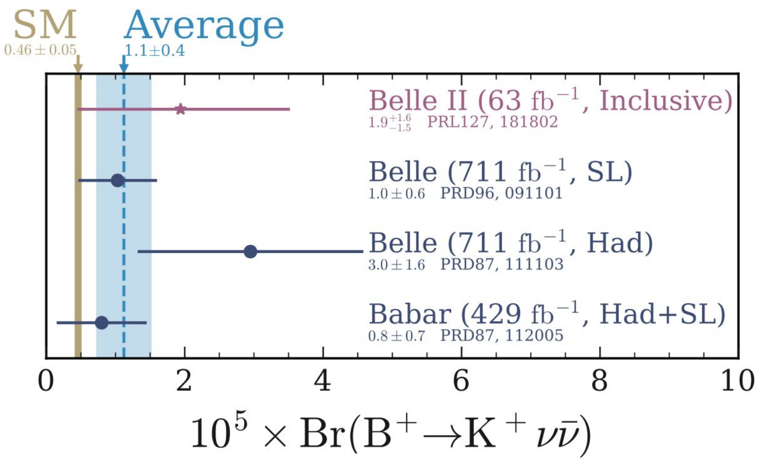
[Cornella et. al. '21]

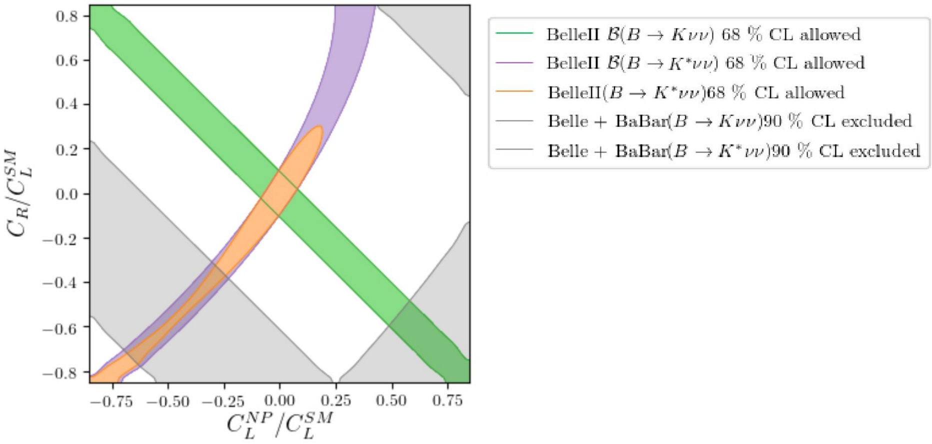
- No observation as of yet, several searches by Belle, BaBar and Belle II
- World leading limit by BaBar [PRD87, 112005]:

$$BR(B^+ \to K^+ \nu\bar{\nu}) < 1.6 \times 10^{-5} \text{ @90\% CL}$$

- First analysis by Belle II using a new inclusive tagging method [PRL127, 181802]
- No significant signal observed

Belle II is the only current experiment that can hope to measure these decays !

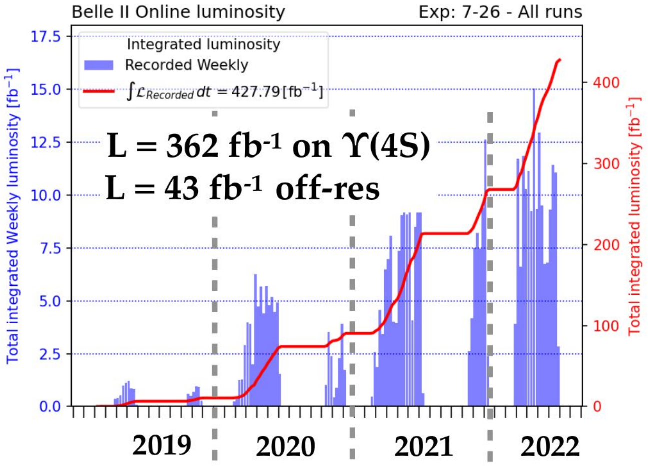


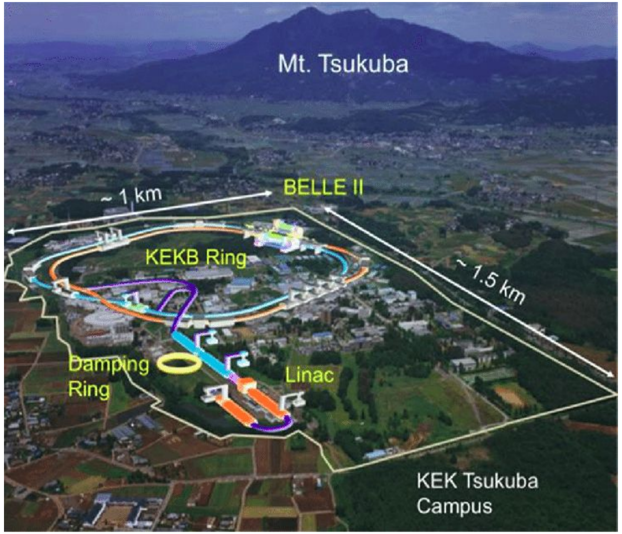


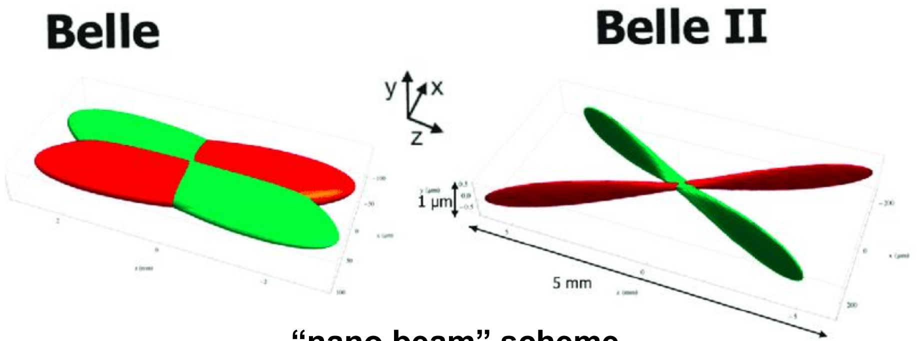
The Belle II experiment at SuperKEKB

- Asymmetric e^+e^- collisions at $\sqrt{s}$ ~ 10.58 GeV = mass of ϒ(4S)
- World record instantaneous luminosity (4.7 x 10^{34} $cm^{-2}s^{-1}$)
- Goal to reach **50 ab^{-1}** of int. luminosity (This work based on **362 fb^{-1}**)

Main target = discovery of BSM physics
Especially in rare and/or partially invisible decays





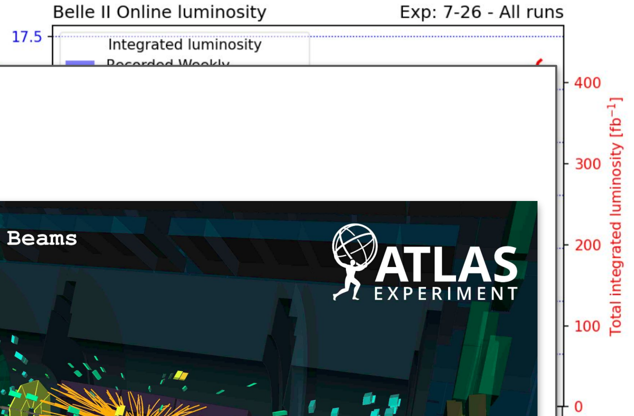


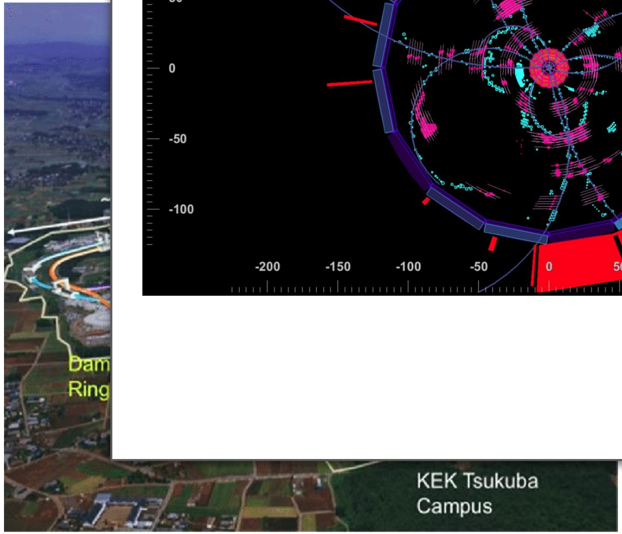
"nano beam" scheme

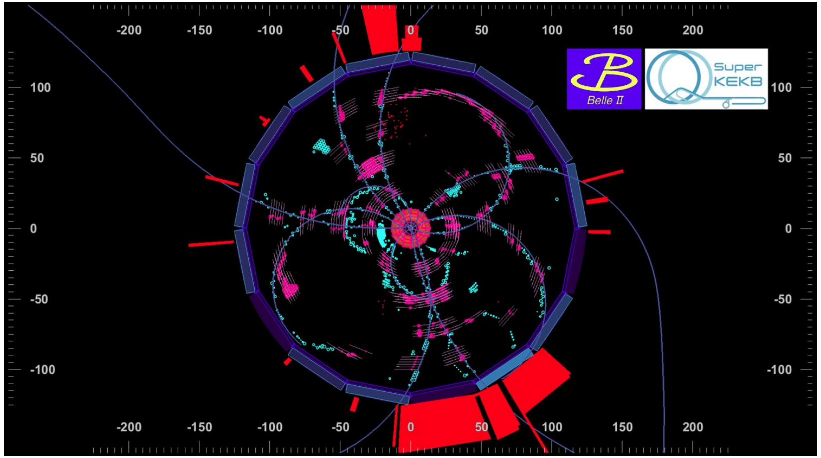
- Asymmetric e^+e^- collisions at $\sqrt{s} \sim 10.58$ GeV = mass of $\Upsilon(4S)$

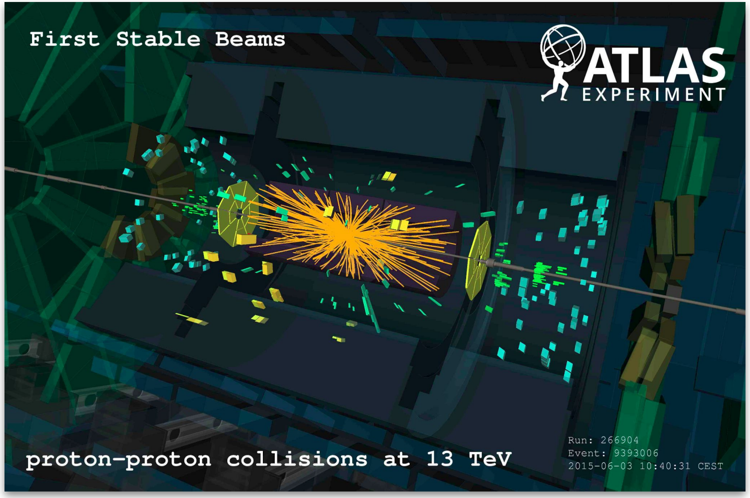
Ma

Es



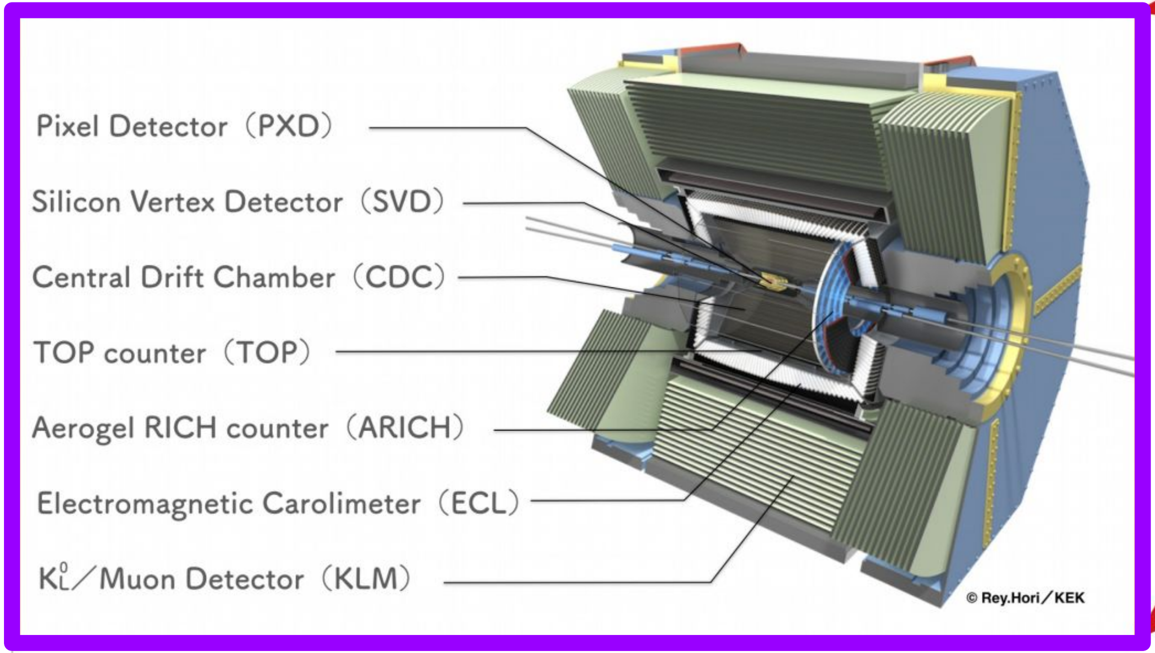


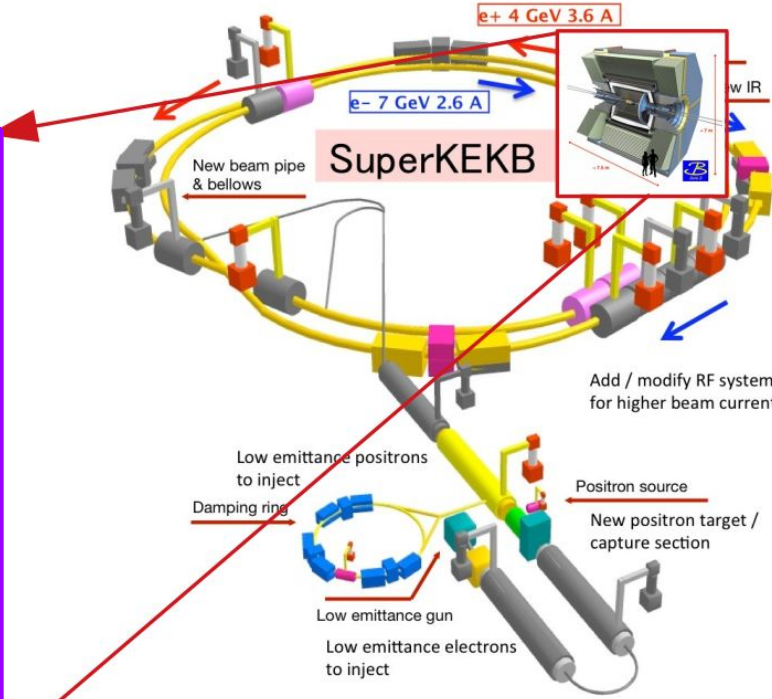


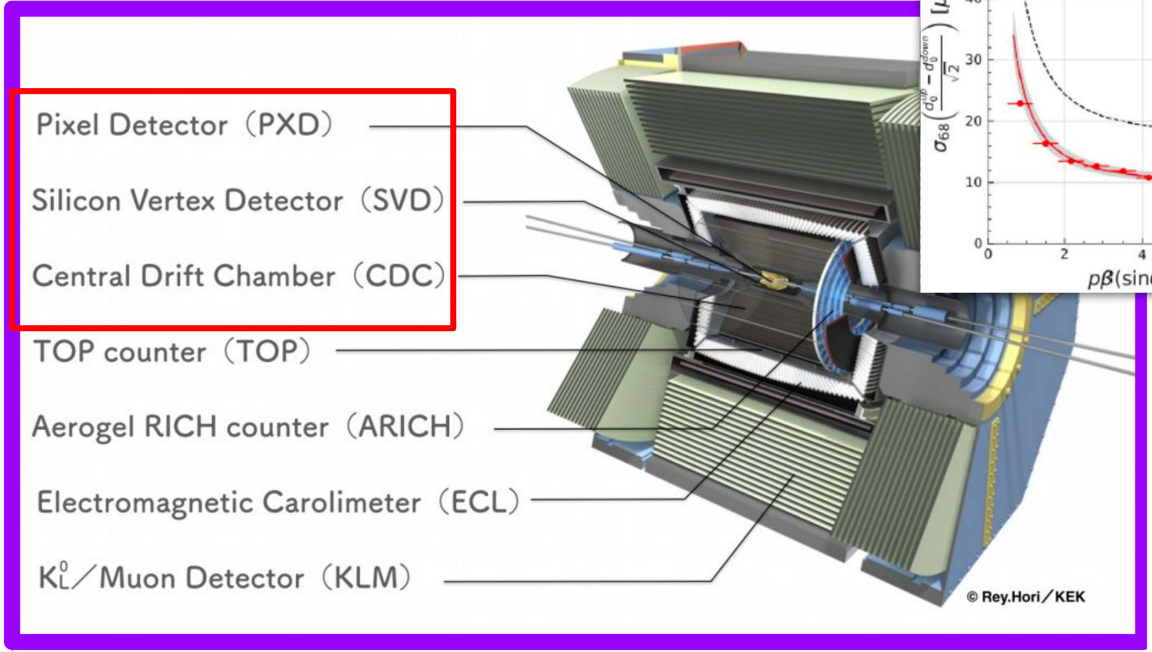


e^+e^- → clean collisions

“nano beam” scheme


Pixel Detector（PXD）
Silicon Vertex Detector（SVD）
Central Drift Chamber（CDC）
TOP counter（TOP）
Aerogel RICH counter（ARICH）
Electromagnetic Carolimeter（ECL）
K_L^0／Muon Detector（KLM）
© Rey.Hori／KEK


e+ 4 GeV 3.6 A
e- 7 GeV 2.6 A
SuperKEKB
New beam pipe
& bellows
Add / modify RF system
for higher beam current
Low emittance positrons
to inject
Damping ring
Positron source
New positron target /
capture section
Low emittance gun
Low emittance electrons
to inject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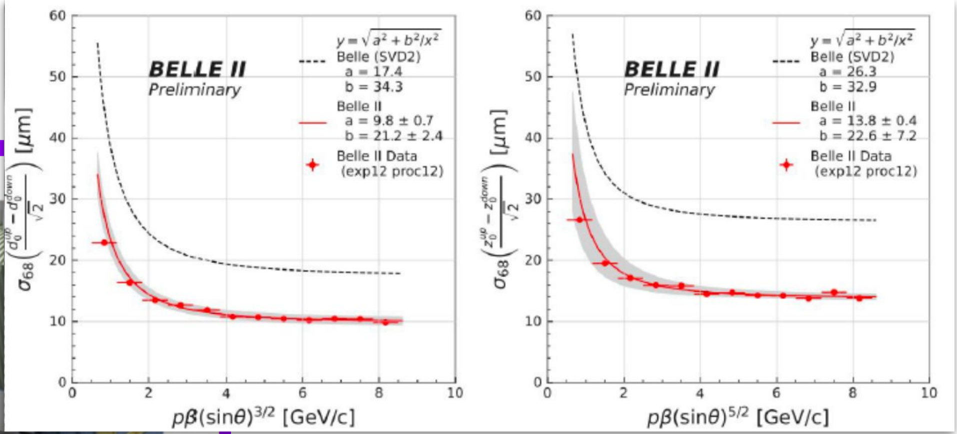
BELLE II
Preliminary
$y = \sqrt{a^2 + b^2/x^2}$
Belle (SVD2)
a = 17.4
b = 34.3
Belle II
a = 9.8 ± 0.7
b = 21.2 ± 2.4
Belle II Data
(exp12 proc12)
$\sigma_{68}\left(\frac{d_0^{up} - d_0^{down}}{\sqrt{2}}\right)$ [μm]
$p\beta(\sin\theta)^{3/2}$ [GeV/c]
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$y = \sqrt{a^2 + b^2/x^2}$
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a = 26.3
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a = 13.8 ± 0.4
b = 22.6 ± 7.2
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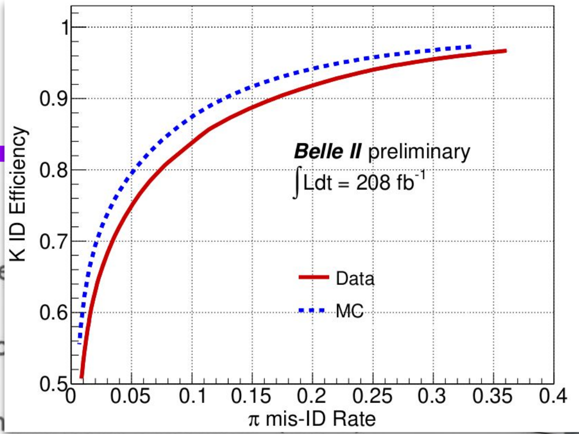
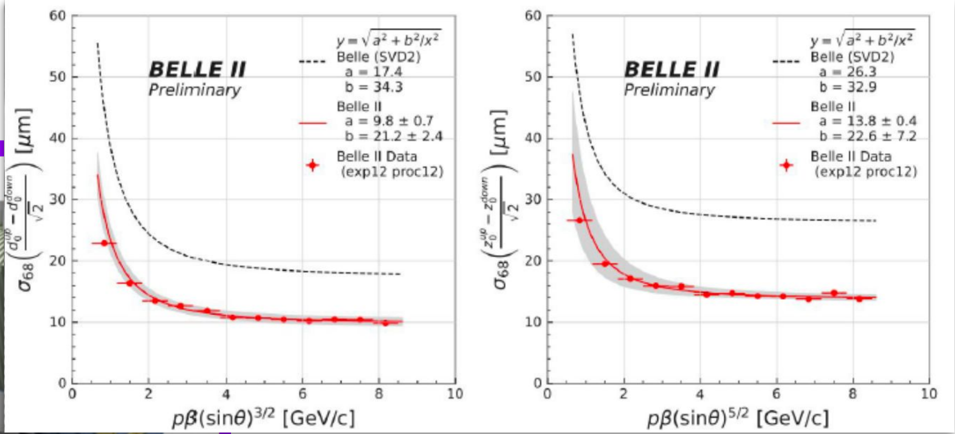
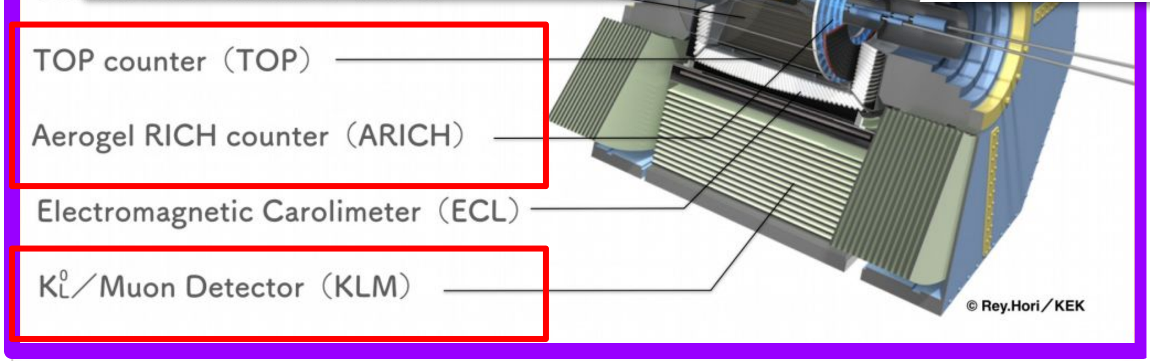
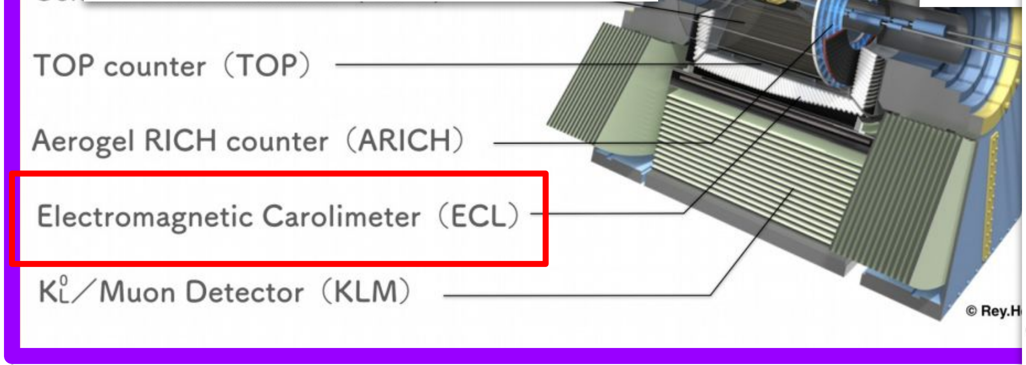
$p\beta(\sin\theta)^{5/2}$ [GeV/c]

The Belle II detector - Particle Identification








Pixe
Silic
Cen
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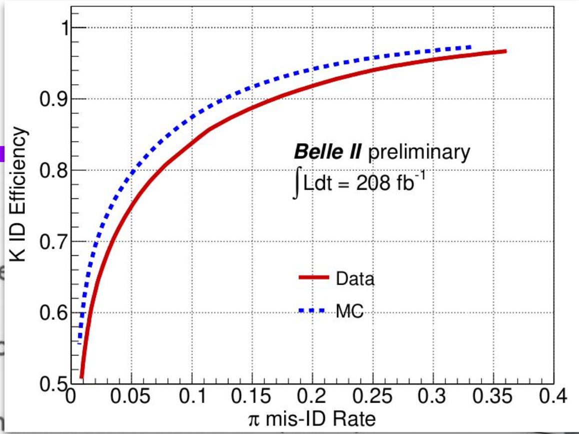
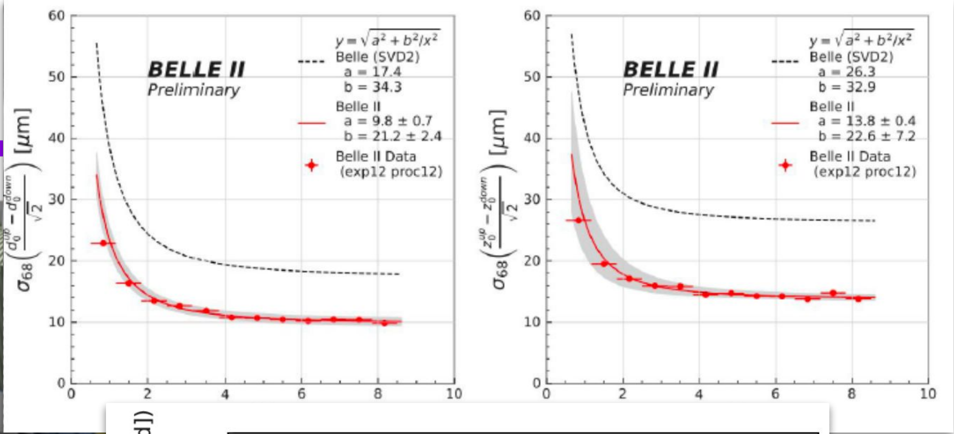
© Rey.H


K ID Efficiency
π mis-ID Rate
Belle II preliminary
∫Ldt = 208 fb⁻¹
Data
MC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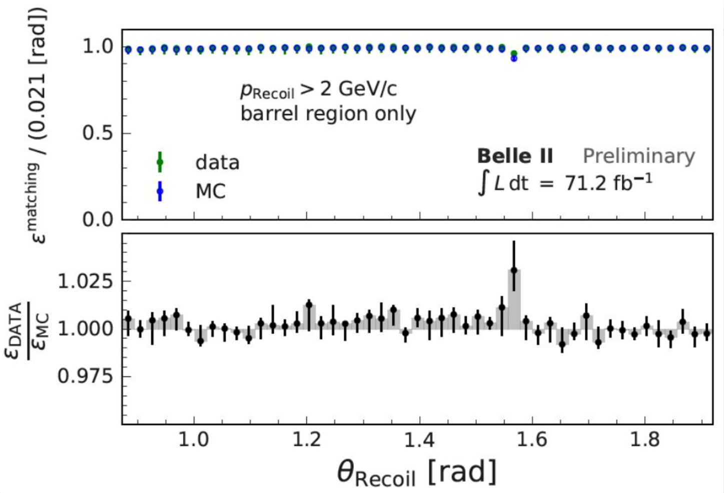
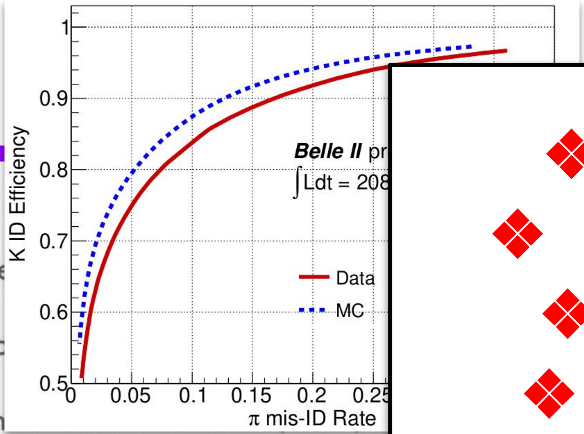
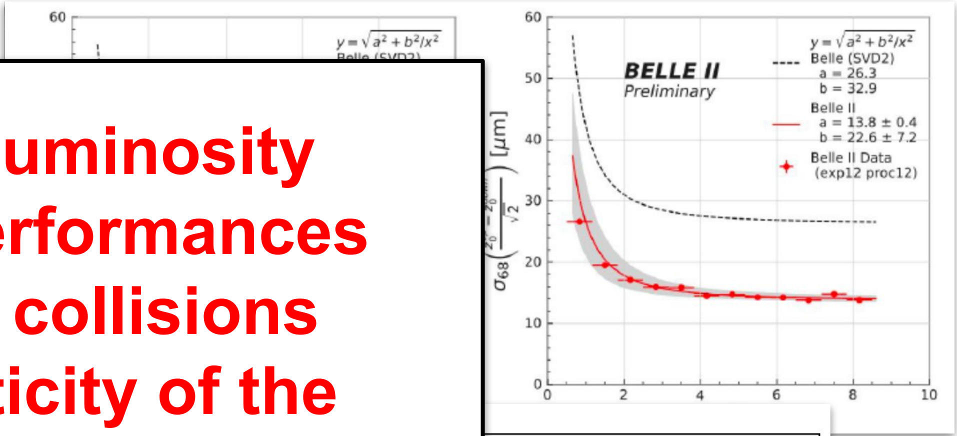
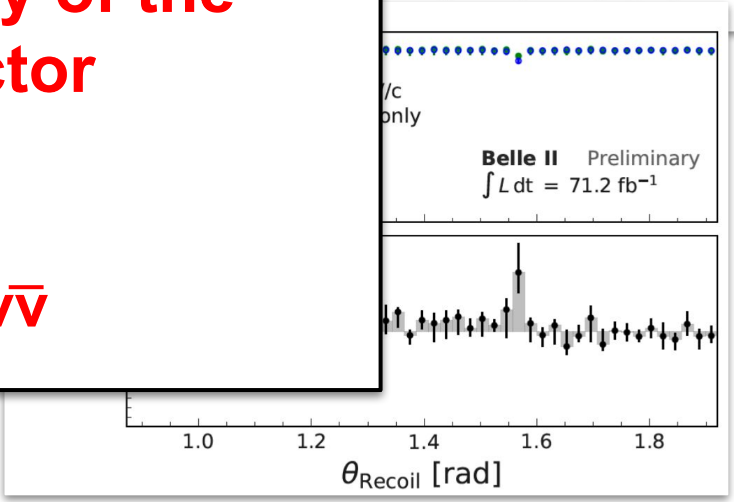

$\varepsilon^{matching}$ / (0.021 [rad])
p_{Recoil} > 2 GeV/c
barrel region only
data
MC
Belle II Preliminary
∫L dt = 71.2 fb⁻¹
$\frac{\varepsilon_{DATA}}{\varepsilon_{MC}}$
θ_{Recoil} [rad]







Pixe
Silic
Cen
TOP counter (TOP)
Aerogel RICH counter (ARICH)
Electromagnetic Carolimeter (E
K_L^0/Muon Detector (KLM)

- **High luminosity**
- **High performances**
- **Clean collisions**
- **Hermiticity of the detector**

↓

$B^+ \to K^+ \nu\bar{\nu}$

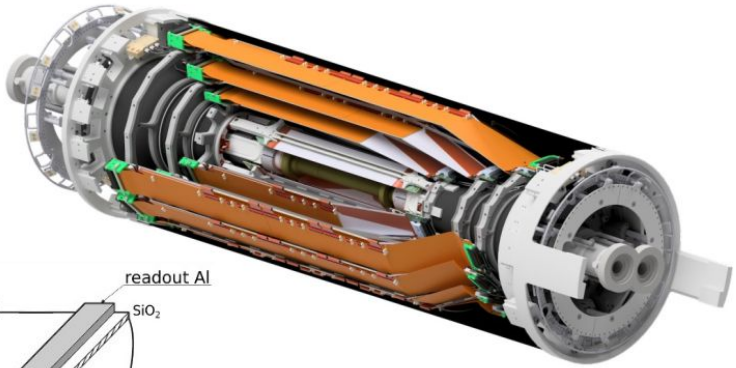
I. Motivations

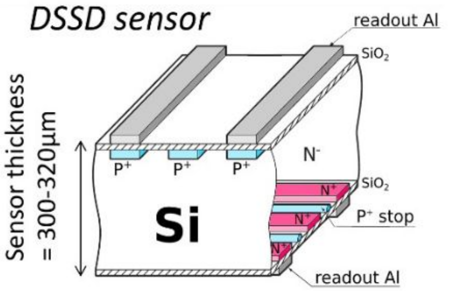
II. Improvement of the Belle II Silicon Vertex Detector

III. Search for the $B^+ \rightarrow K^+ \nu\bar{\nu}$ decay

The Silicon Vertex Detector (SVD)

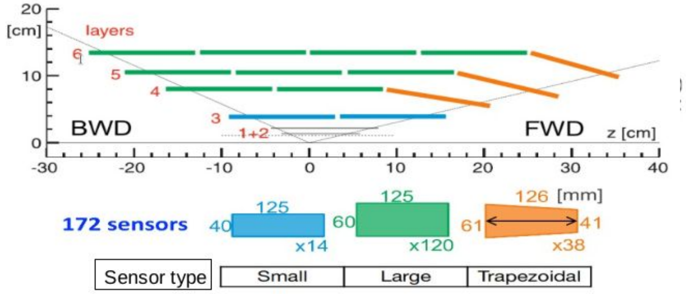
- 4 concentric layers of detectors
- Double Sided Silicon strip Detectors (DSSD) → two sides (u/P and v/N)
- Readout with APV25 chips
- Goal: give 3D position, hit time and deposited charge from **charged** particles (for tracking, PID, etc..)





Distance between strips : 50 – 240 µm

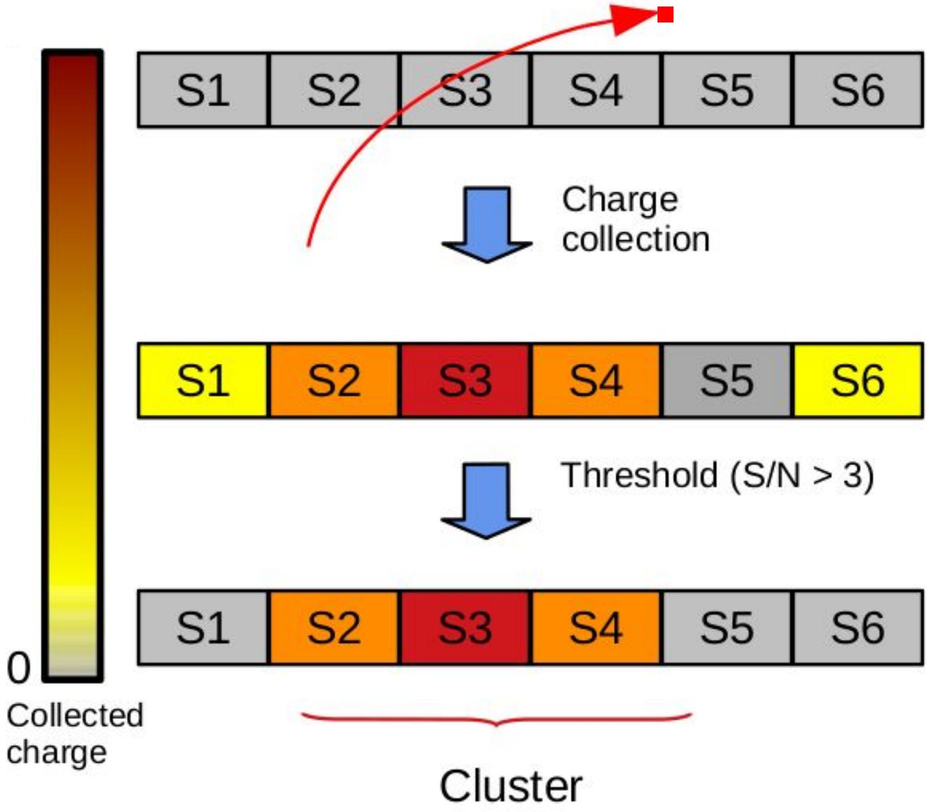
	Small	Large	Trapezoidal
pitch p (digital res.)	50(7) µm	75(11) µm	50-75(11) µm
pitch n (digital res.)	160(23) µm	240(35) µm	240(35) µm



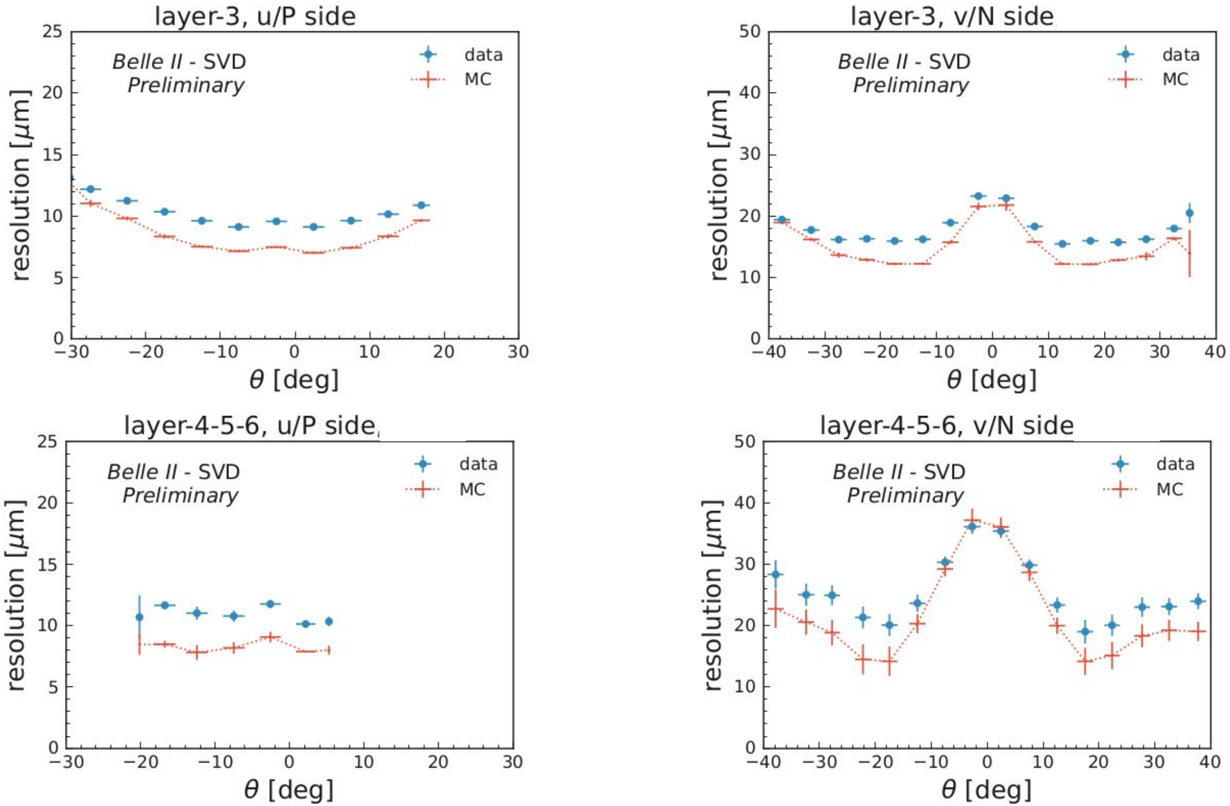
- **Cluster** = **estimator** of crossing **position** of a particle
- For each strip, access to:
  - Collected charge
  - Noise
  - Gain
- Selection to discard noisy strips
- Set of retained strips = **cluster**
- For each cluster compute the charge $\mathbf{S_{cl}}$ and position $\mathbf{x_{cl}}$:

$$S_{cl} = \sum S_i$$

$$x_{cl} = \frac{\sum x_i \times S_i}{\sum S_i}$$



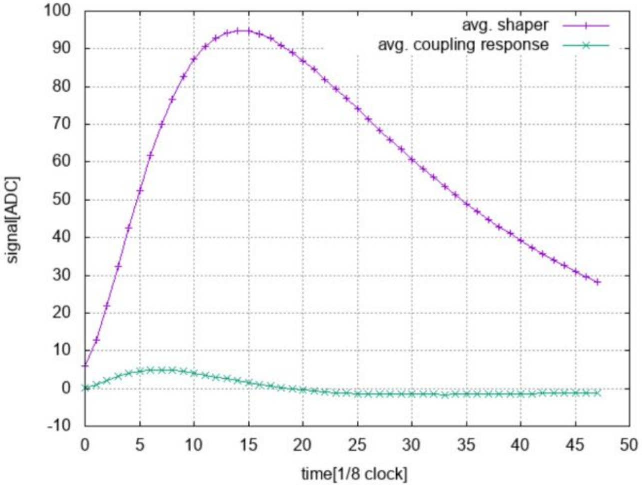
- Resolution of the detector estimated both in data and Monte Carlo (MC) simulation
- Satisfactory data/MC agreement
- But discrepancies observed
- Need to understand smaller effects
- Studies performed to identify the root of the discrepancies (timing, charge collection…)

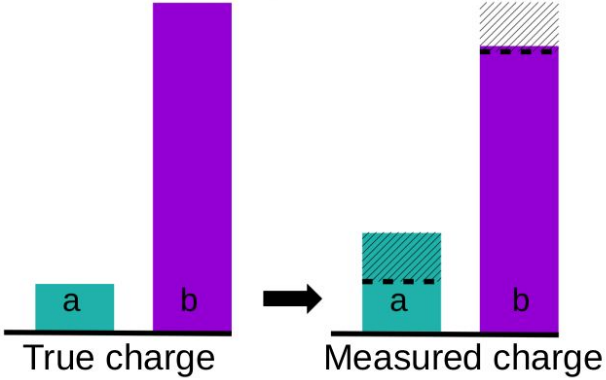


Electronic channel couplings

- Tests performed: a signal is injected on a given strip while checking the response of the adjacent APV channel
- Small signal observed in the adjacent APV channel with a ~30 ns shift in time
- Expected effect on measured strip charge:

$$\text{charge}_{\text{meas}}(\mathbf{a}) = \text{charge}_{\text{real}}(\mathbf{a}) + 0.06 \times \text{charge}(\mathbf{b})$$





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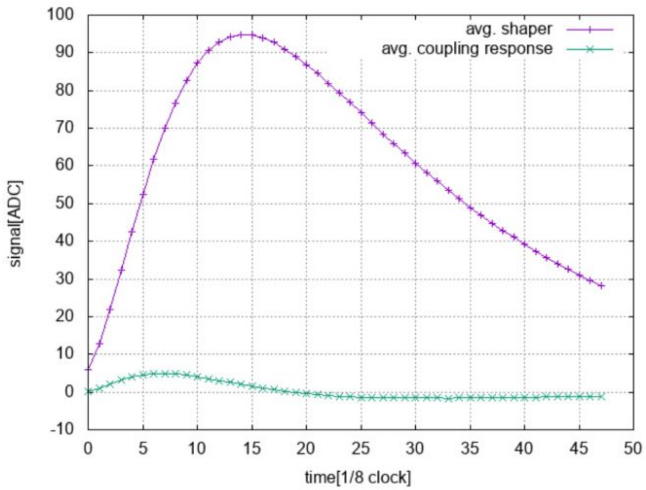
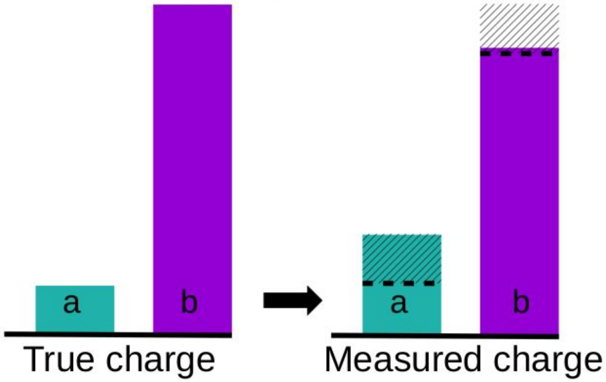
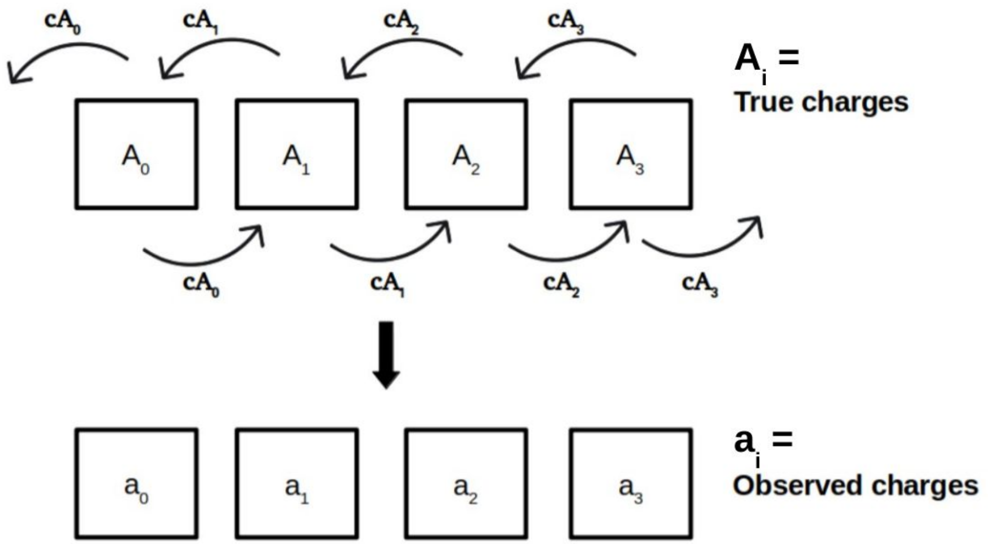


$$\text{charge}_{meas}(\mathbf{a}) = \text{charge}_{real}(\mathbf{a}) + 0.06 \times \text{charge}(\mathbf{b})$$

Charge used to compute x_{cl}

→ **Bias in charge = bias in position**

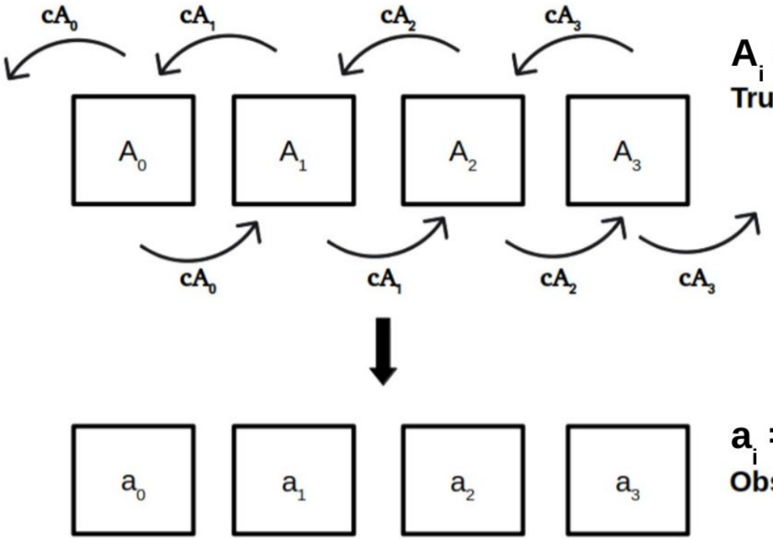




The observed charge (biased) follows:

$$a_i = (1-2\mathbf{c})A_i + \mathbf{c}(A_{i-1} + A_{i+1})$$

From the checks on electronics we expect **c** ~ 0.06



A_i =
True charges

a_i =
Observed charges

The observed charge (biased) follows:

$$a_i = (1-2\textcolor{red}{c})A_i + \textcolor{red}{c}(A_{i-1} + A_{i+1})$$

From the checks on electronics we expect **c** ~ 0.06

To correct this effect, we propose to "unfold" the cluster charges :

M

$$\begin{pmatrix} 1-2c & c & 0 & 0 \\ c & 1-2c & c & 0 \\ 0 & c & 1-2c & c \\ 0 & 0 & c & 1-2c \end{pmatrix} \begin{pmatrix} A_1 \\ A_2 \\ A_3 \\ A_3 \end{pmatrix} = \begin{pmatrix} a_1 \\ a_2 \\ a_3 \\ a_3 \end{pmatrix}$$

True Obs

Unfold by inversion :

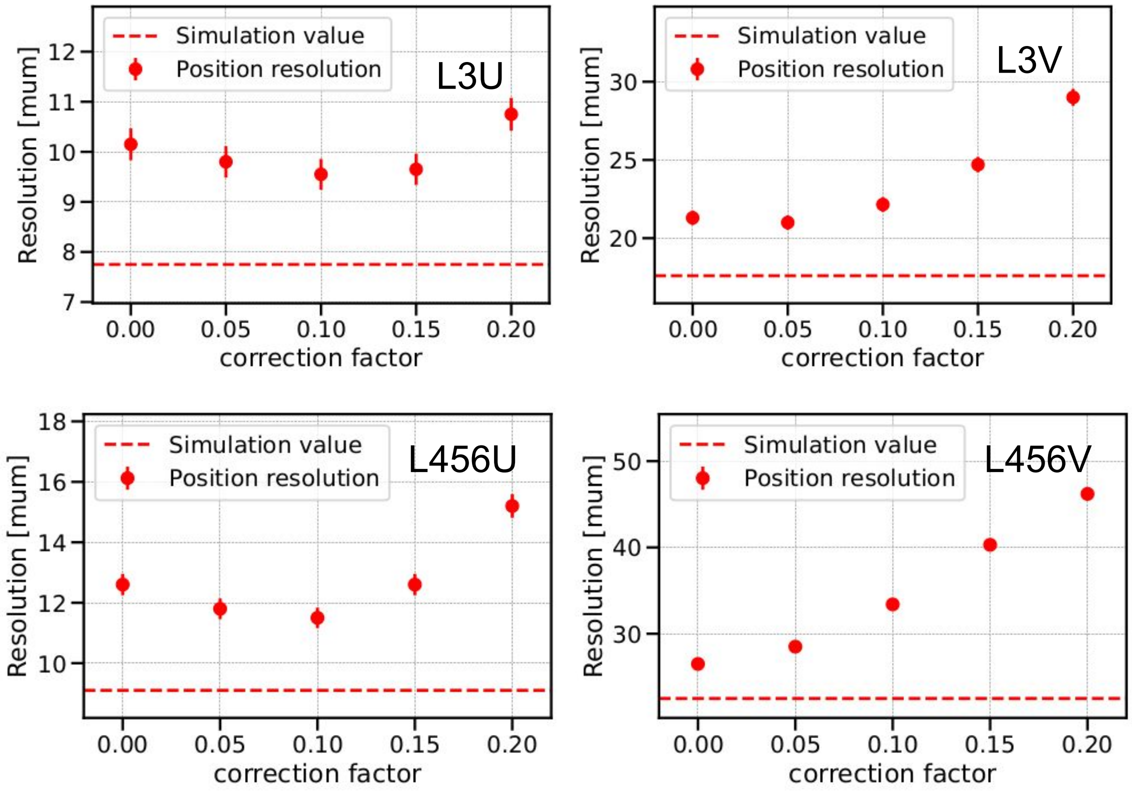
$$\begin{pmatrix} A_1 \\ A_2 \\ A_3 \\ A_3 \end{pmatrix} = M^{-1} \begin{pmatrix} a_1 \\ a_2 \\ a_3 \\ a_3 \end{pmatrix}$$

True Obs

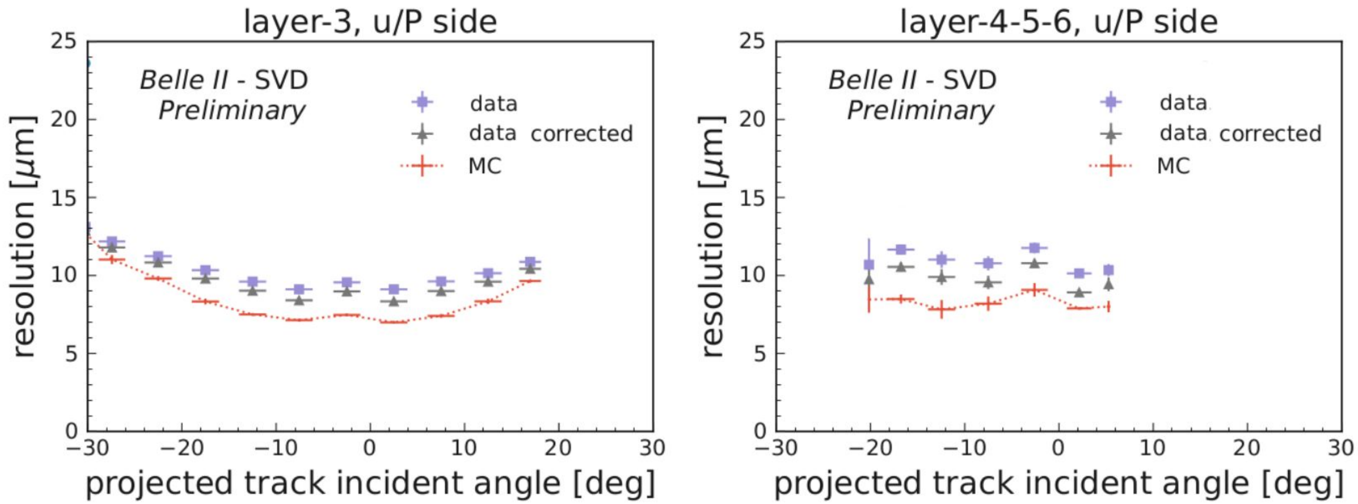
M is an n x n matrix, with n the size of the cluster of interest

The Cluster Unfolding - estimation of the correction factor

- Resolution is computed for each type of sensor for different **c** values
- No improvement seen on V-side sensors
- **U-side** sensors benefit from the method, optimal gain for **c = 0.1** across the board



The Cluster Unfolding - implementation



- We see an improvement on U-side sensors with the method, which allows to gain ~5 - 15% on the position resolution
- This in turn allows to bridge part of the gap between data and MC
- The method has thus been implemented in the Belle II analysis software

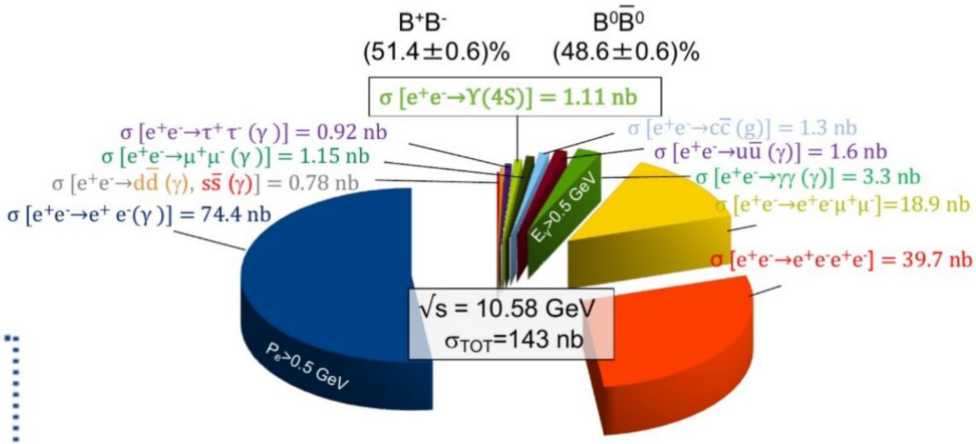
I. Motivations

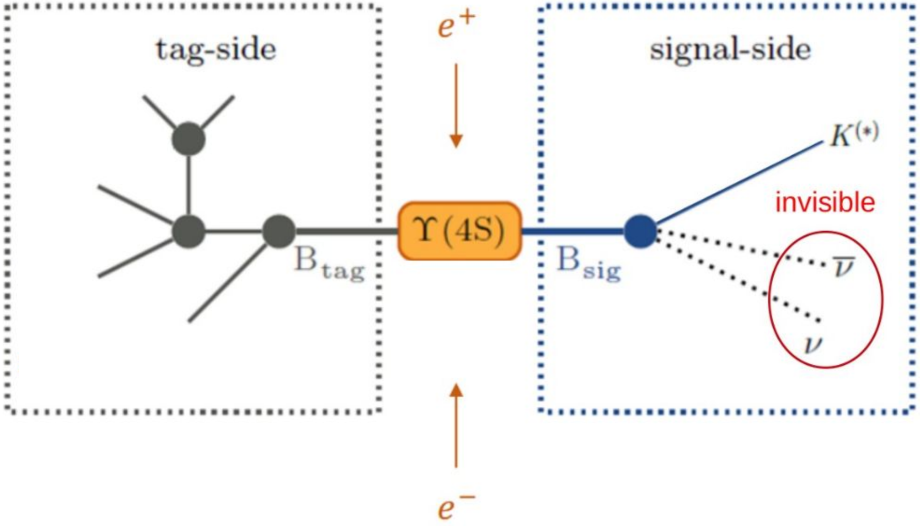
II. Improvement of the Belle II Silicon Vertex Detector

III. Search for the $B^+ \rightarrow K^+ \nu\bar{\nu}$ decay

A Belle II event at 10.58 GeV

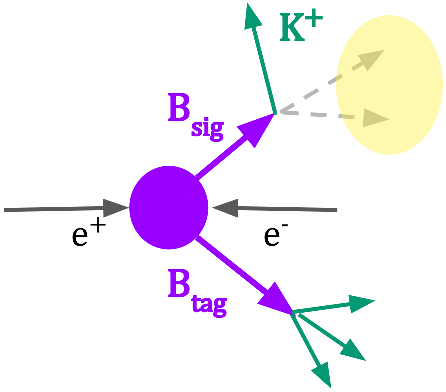
- e^+e^- collisions at 10.58 GeV
- Signal events: $e^+e^- \to \Upsilon(4S)$
- $\Upsilon(4S)$ decays as B^+B^- or $B^0\bar{B}^0$



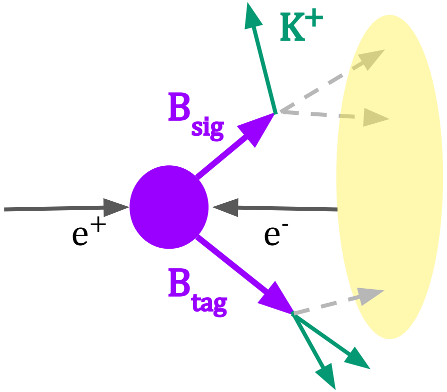


- Well known event kinematics
- Signal info from the **other** B (**B tag**)
  ➡ **tagging**

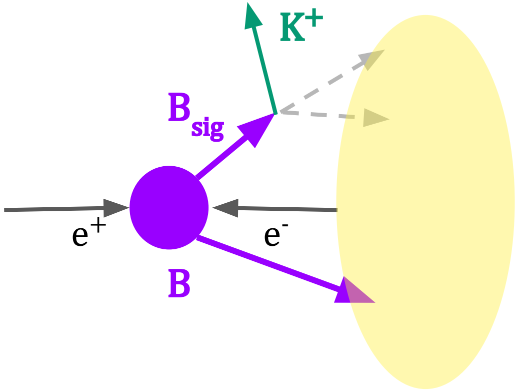
Hadronic B-tagging
Strong kinematic **constraints**
Low fraction of B decays



Semileptonic B-tagging
Less kinematic **constraints** (neutrinos on both sides)
High fraction of B decays



Inclusive B-tagging
Only reconstruct signal B
No constraints on other B
Less pure but **higher efficiency**



ε~ 0.1% - 0.5 % — **Efficiency** → **ε~ 10 %**

80% - 20 % ← **Purity** — **O(1%)**

Hadronic B-tagging
Strong kinematic **constraints**
Low fraction of B decays

Semileptonic B-tagging
Less kinematic **constraints** (neutrinos on both sides)
High fraction of B decays

Inclusive B-tagging
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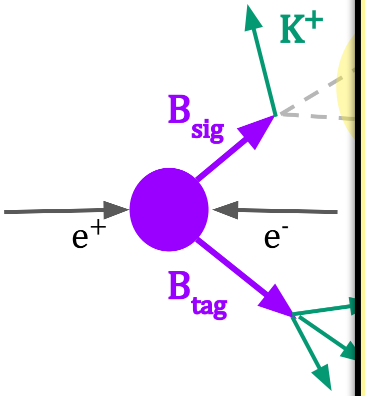
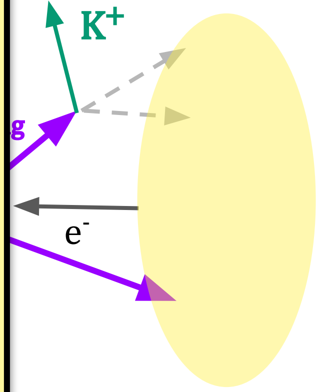


HERE

Hadronic-tag analysis
(HTA)

my thesis

Inclusive-tag analysis
(ITA)



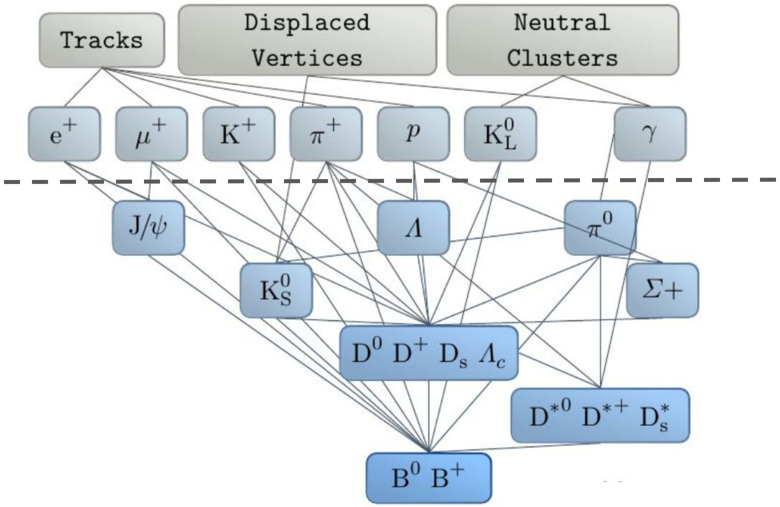
d approach

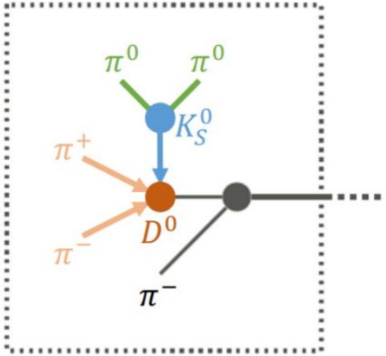
ε~ 0.1% - 0.5 % **Efficiency** ε~ 10 %

Purity

The Full Event Interpretation algorithm

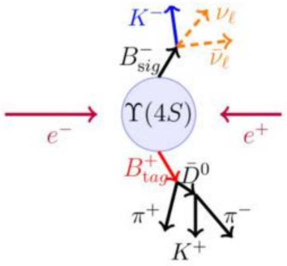
- Here, use **hadronic** tagging
  → Full Event Interpretation (**FEI**) algorithm
- Use final state particles to hierarchically reconstruct the **most probable** Btag
- Reconstruction done within a list of **O(10^4)** hadronic decay chains



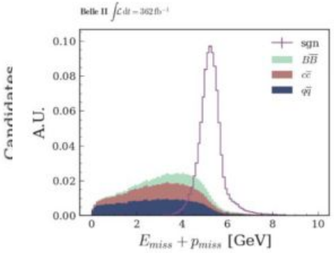


Analysis strategy

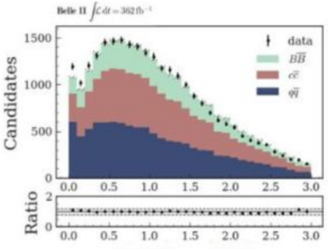
Basic selection and reconstruction



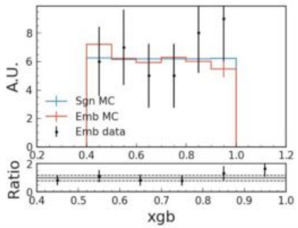
Background suppression



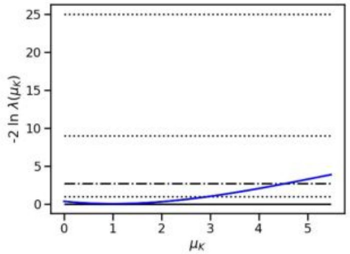
Data-MC corrections



Validation



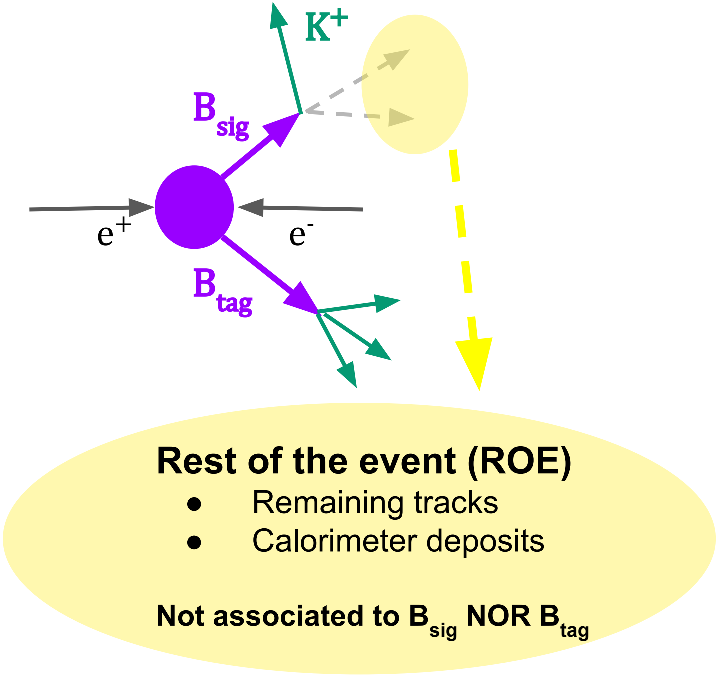
Statistical interpretation



Basic selection and reconstruction

- The B_{tag} is reconstructed in one of the hadronic decays known to the FEI [arXiv:1807.08680]
- Signal K^+ selection:
  - At least one PXD hit
  - High probability to be a kaon (kaonID > 0.9)
- Event selection:
  - B_{tag} and K^+ opposite charge
  - Number of good quality tracks < 12
  - No clean tracks in ROE
  - No K^0_S, π^0 or Λ^0 in ROE

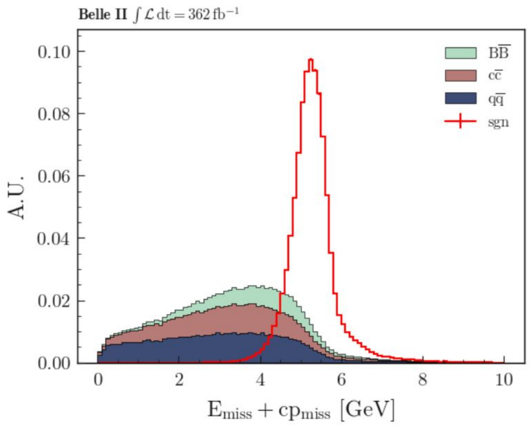
- kaonID discards ~ 32% of real kaons
- π -> K misID ~ 1.2%

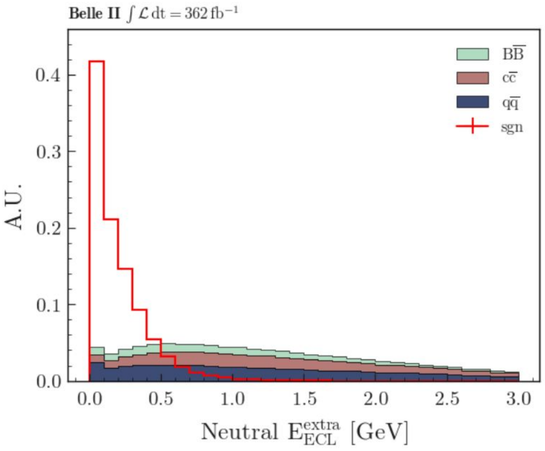


Boosted Decision Tree based selection

Background suppression

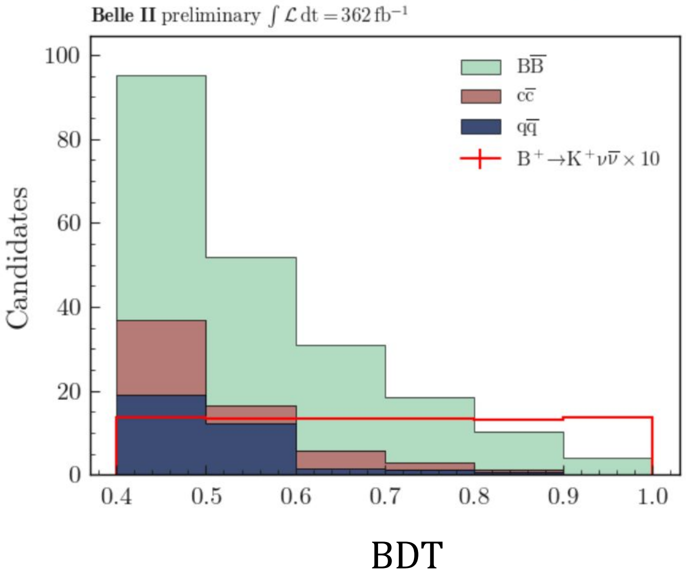
- Build a BDT based on XGBoost to distinguish between signal and background
- 12 features used in the training:
  - Extra calorimeter energy
  - Event topology
  - Signal K^+ kinematics
  - D meson suppression variables
  - Missing quantities (E,p) in the event
- 3 background contributions: $e^+e^- \to$ light-$q\bar{q}$, $c\bar{c}$ and $B\bar{B}$
- Signal search region based on BDT output

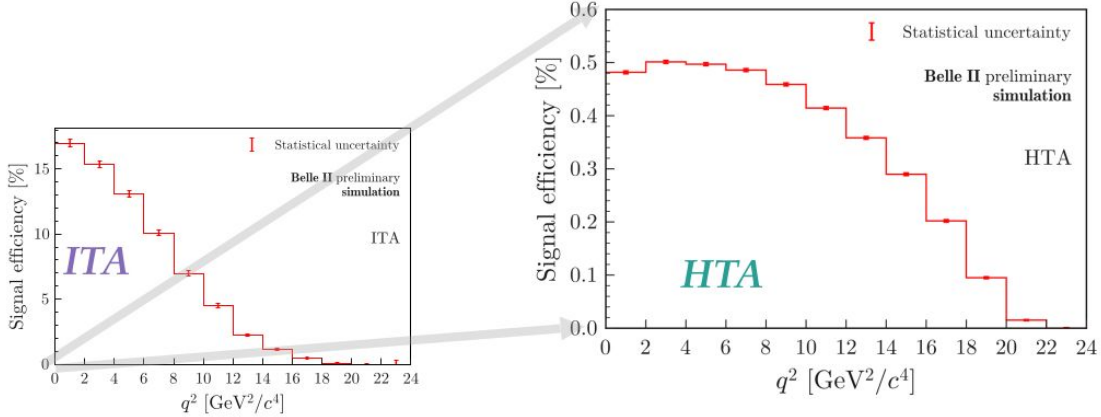




Background suppression

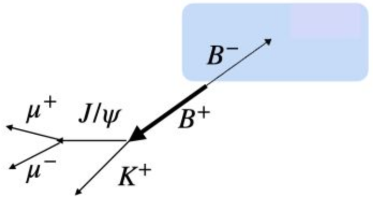
- Signal Region (SR) defined as BDT output ∈ [0.4, 1]
- SR divided into 6 bins
- Signal efficiency = 0.4%
- Low efficiency but high sample purity
- Higher q^2 resolution w.r.t. other tagging methods

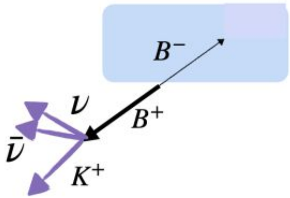


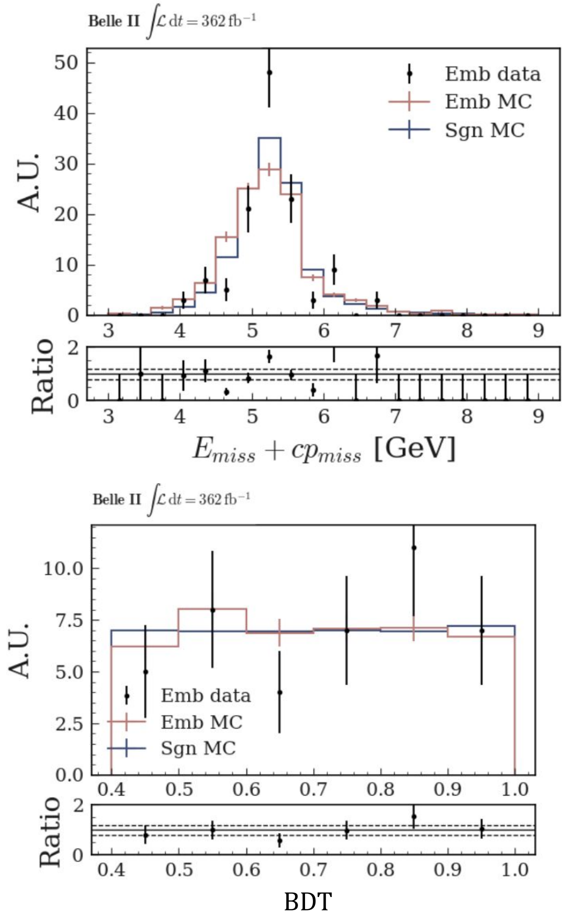


- Validate signal behavior by **embedding** signal MC into data events
- Use $B^+ \to K^+ J/\psi(\mu\mu)$ events, replace B decays by simulated signal and match kinematics
- Done for both data and simulation
- Data/MC efficiency ratio = 0.67 ± 0.06

→ Use as calibration factor and propagate uncertainty







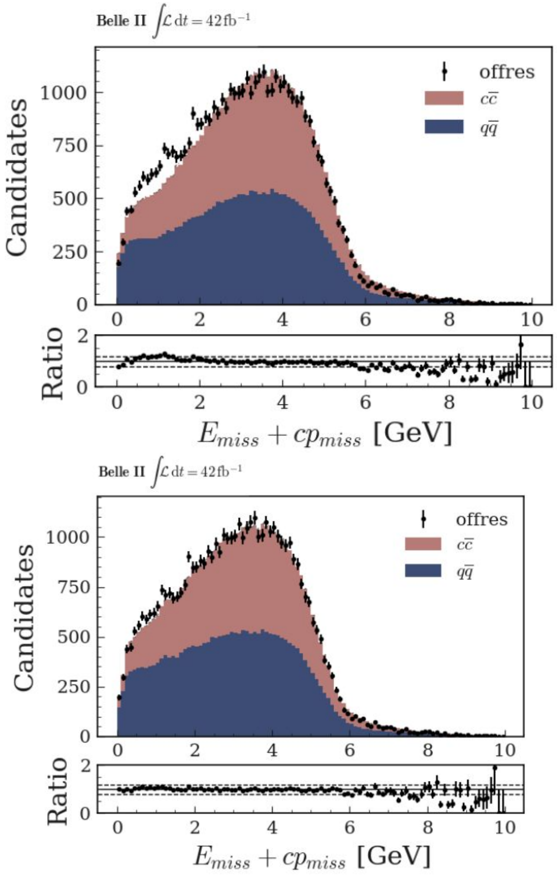
Validation

Data-MC corrections

Validation

Data-MC corrections

- $c\bar{c}$ and light-$q\bar{q}$ background simulation studied in off-resonant data (collected 60 MeV below Υ(4S) mass)
- Overall acceptable agreement, but some discrepancies are seen
- In normalization: data/MC ratio = 0.82 ± 0.01 → reweighting of the simulation
- In shape: devise a correction using an additional BDT to correct simulation and derive a systematic uncertainty
- After corrections, data/MC agreement greatly improves



Validation of $B\bar{B}$ background using signal sidebands

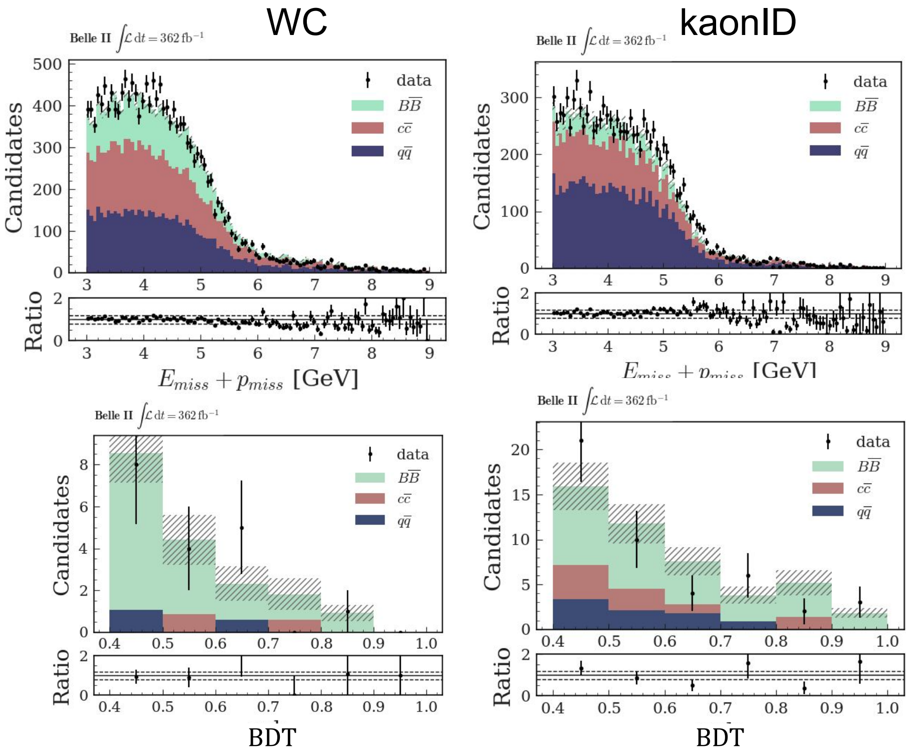
Validation

Data-MC corrections

- On-resonance data: need to limit signal contamination
- Same selection as signal
- Some cuts inverted to avoid looking at the SR:
  - "**Wrong charge**": the B_{tag} and B_{sig} are required to be of same electrical charge
  - "**kaonID**" the reconstructed signal kaon is required to be compatible with the pion hypothesis
- Overall acceptable data-MC agreement
- data/MC ratios are computed:

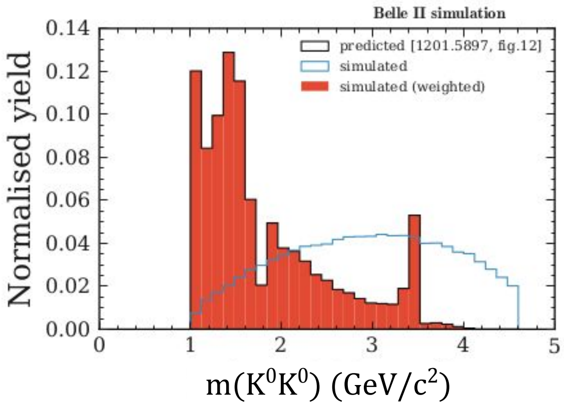
1.6 ± 0.6	**1.24 ± 0.27**
wrong charge	kaonID

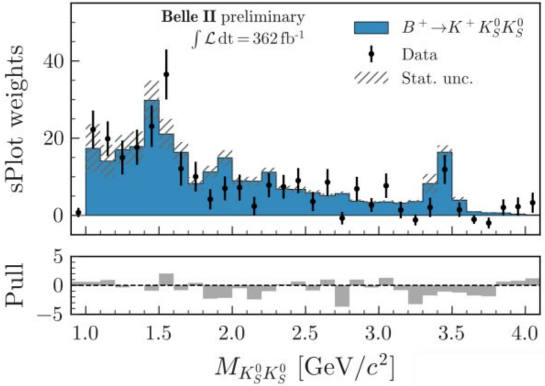
- Compatible with 1 but large stat uncertainty → treated as systematic uncertainty

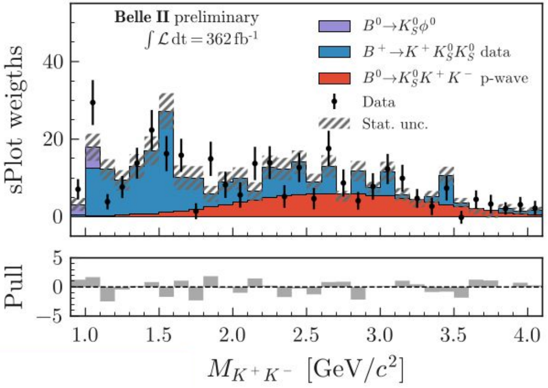


Data-MC corrections

- Several decays show intrinsic signal likeness
- For example: $B^+ \to K^+ K^0 \overline{K}^0$
- BaBar study shows complex structure of the $B^+ \to K^+ K^0_S K^0_S$ decay [PhysRevD.85.112010]
- Use this study to correct Belle II phasespace simulation
- In addition, use $B^+ \to K^+ K^0_S K^0_S$ and $B^0 \to K^0_S K^+ K^-$ data to model $B^+ \to K^+ K^0_S K^0_L$
- Do the same for $B^+ \to K^+ n \bar{n}$

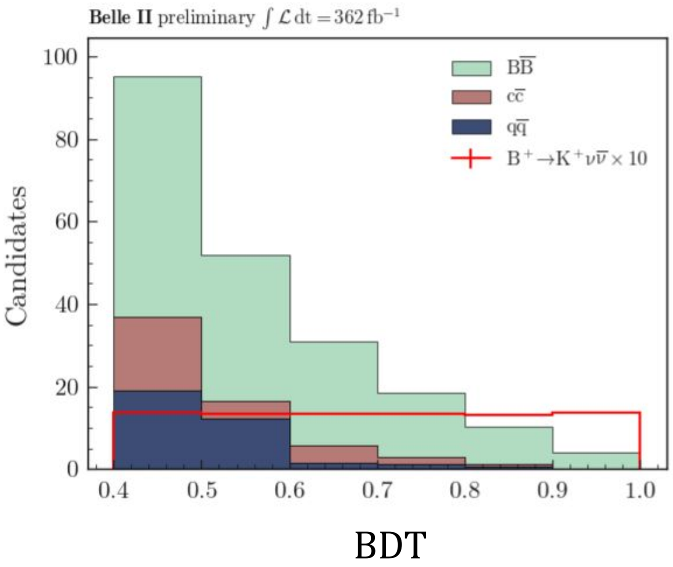






Statistical interpretation

- Estimate BR($B^+ \to K^+ \nu\bar{\nu}$) from a 1-dimensional likelihood fit to the SR distributions
- 4 contributions taken into account:
  - $B\bar{B}$, $c\bar{c}$, light-$q\bar{q}$ backgrounds
  - signal
- The fit takes into account 45 nuisance parameters, as well as the parameter of interest: the signal strength **μ = BR/BR$_{SM}$**



Systematics

Statistical interpretation

Source	Uncertainty size	Impact on σ_μ
Normalization $B\bar{B}$ background	30%	0.91
Normalization continuum background	50%	0.58
Leading B-decays branching fractions	$O(1\%)$	0.10
Branching fraction for $B^+ \to K^+ K^0_L K^0_L$	20%	0.20
Branching fraction for $B \to D^{(**)}$	50%	< 0.01
Branching fraction for $B^+ \to K^+ n\bar{n}$	100%	0.05
Branching fraction for $D \to K_L X$	10%	0.03
Continuum background modeling, $\mathrm{BDT_c}$	100% of correction	0.29
Number of $B\bar{B}$	1.5%	0.07
Track finding efficiency	0.3%	0.01
Signal kaon PID	$O(1\%)$	< 0.01
Extra photon multiplicity	$O(20\%)$	0.61
K^0_L efficiency	17%	0.31
Signal SM form factors	$O(1\%)$	0.06
Signal efficiency	16%	0.42
Simulated sample size	$O(1\%)$	0.60

Stat. unc. = 2.3

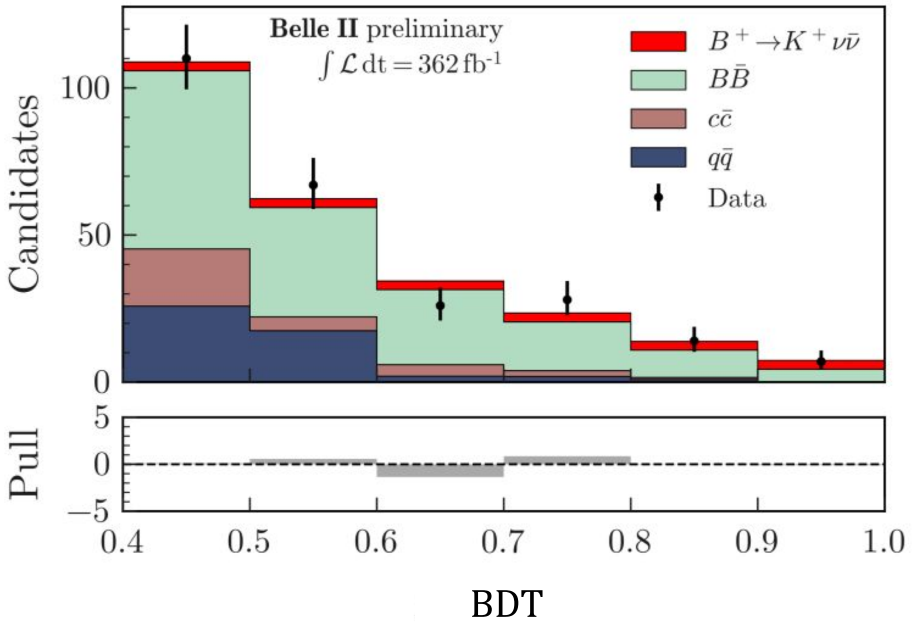
- Finally, we measure in data:

$$\mu = 2.2 \pm 2.3(\text{stat})^{+1.6}_{-0.7}(\text{syst})$$

- Giving:

$$BR(B^+ \rightarrow K^+\nu\bar{\nu}) = [1.1^{+0.9}_{-0.8}(\text{stat})^{+0.8}_{-0.5}(\text{sys})] \times 10^{-5}$$

- Significance with respect to background only hypothesis ($\mu = 0$): **1.1σ**
- With SM signal: **0.6σ**



This **improves** on previous **hadronic tag** results:

- **30% improvement** in uncertainty w.r.t **Belle** hadronic tag measurement with a **2x smaller** dataset
- **15% improvement** in uncertainty w.r.t **BaBar** hadronic tag measurement with a **20% smaller** dataset

However still statistically limited

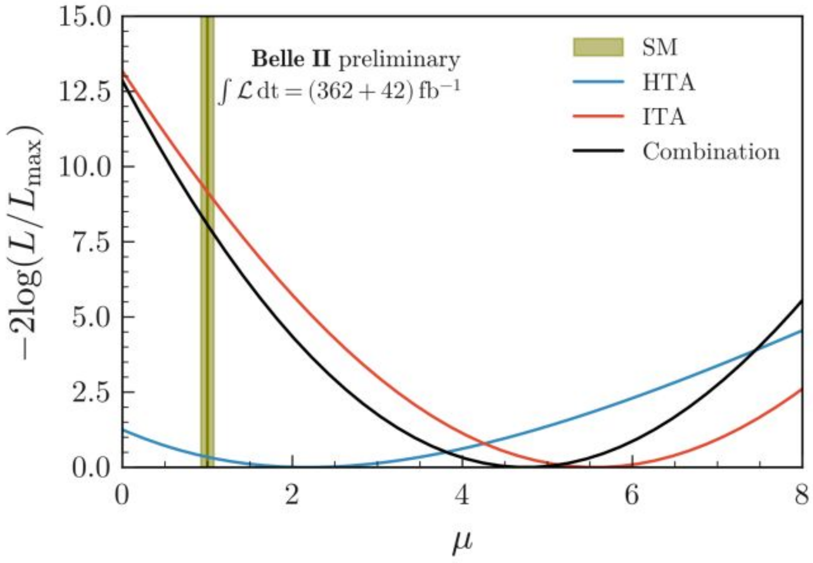
- Analysis performed in tandem with another analysis using **inclusive tagging**
- Using this method we find:

$$\mu = 5.6 \pm 1.1(\text{stat})^{+1.0}_{-0.9}(\text{syst})$$ **or** $$BR(B^+ \to K^+ \nu\bar{\nu}) = [2.8 \pm 0.5(\text{stat}) \pm 0.5(\text{sys})] \times 10^{-5}$$

- Significance with respect to background only hypothesis (μ = 0): **3.6σ**
- With SM signal: **3.0σ**

New at EPS-HEP 2023

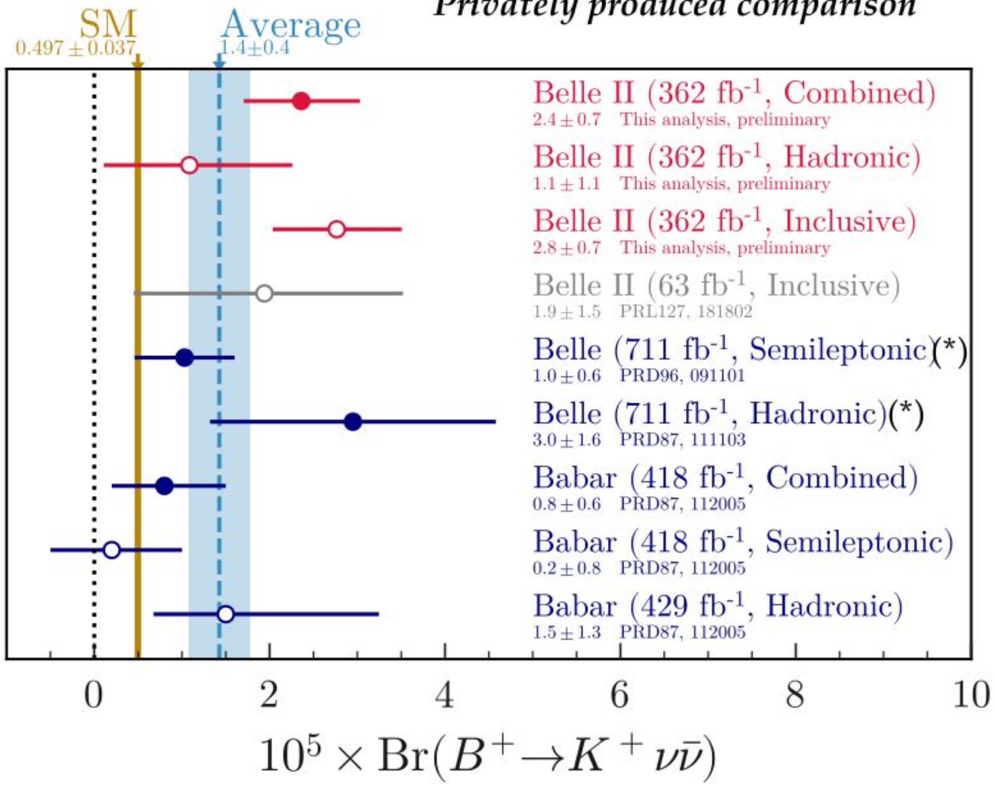
- A combination of both results is performed
- Correlations among common systematic uncertainties are taken into account
- The combination **improves the precision** of the inclusive tag-only measurement by **10%**



$\mu = 4.7 \pm 1.0(\text{stat}) \pm 0.9(\text{syst})$
$BR(B^+ \to K^+ \nu\bar{\nu}) = [2.4 \pm 0.5(\text{stat})^{+0.5}_{-0.4}(\text{syst})] \times 10^{-5}$

3.6σ significance w.r.t background-only hyp. (2.8σ w.r.t SM) → **First evidence of the $B^+ \to K^+$ + inv. decay !** (and $b \to s$ + inv.)

Privately produced comparison

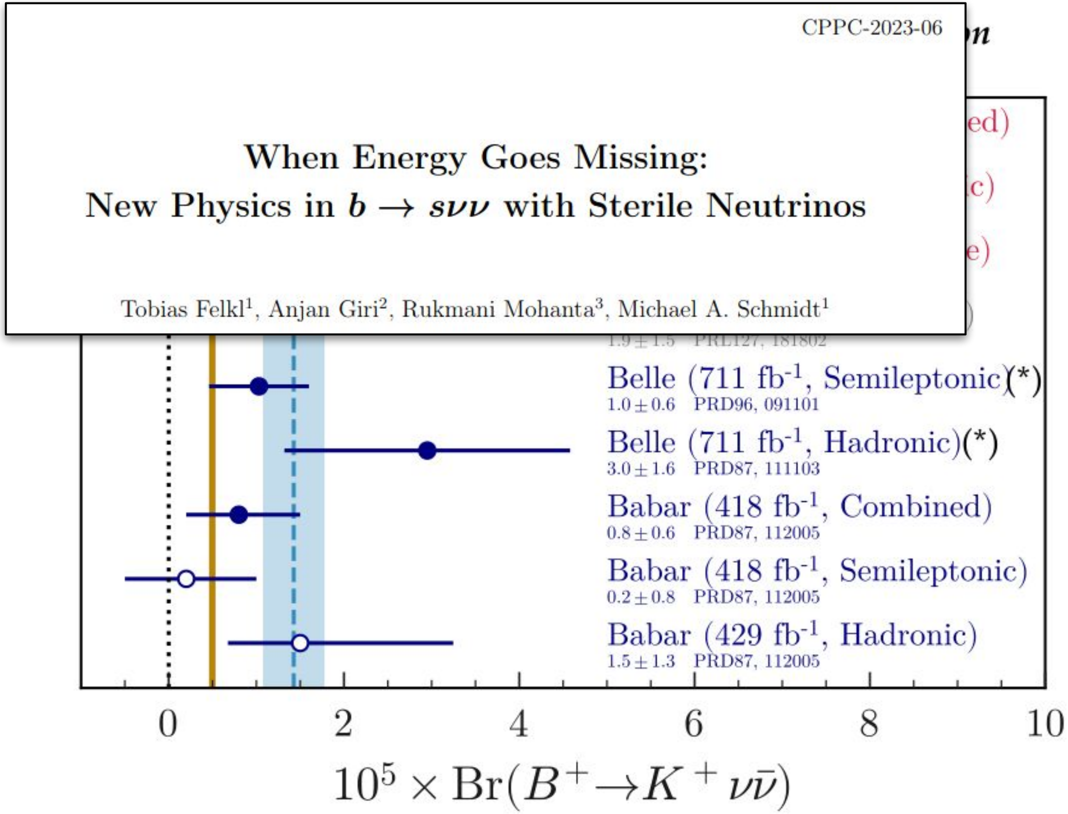


ITA result has some tension with previous semi-leptonic tag measurements
a 2.4σ tension with BaBar
a 1.9σ tension with Belle

HTA result in agreement with all the previous measurements

Overall compatibility is good: $\chi^2/ndf = 4.3/4$

(*) Belle reports upper limits only; branching fractions are estimated using published number of events and efficiency



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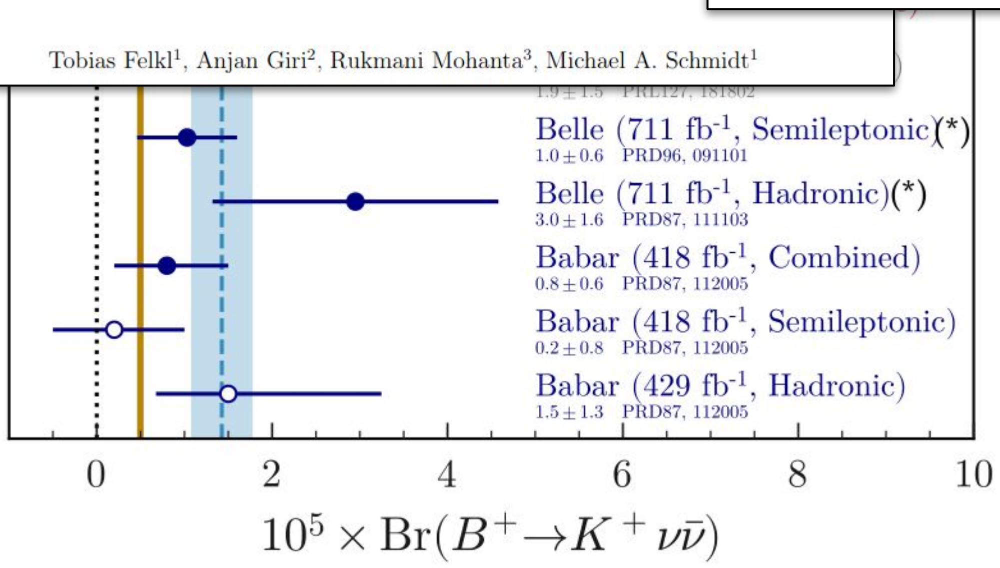
New experimental state of the art

When Energy Goes Missing:
New Physics in $b \to s\nu\nu$ with Sterile Neut

Tobias Felkl[1], Anjan Giri[2], Rukmani Mohanta[3], Michael A. Schmidt[1]

Understanding the first measurement of $\mathcal{B}(B \to K\nu\bar{\nu})$

L. Allwicher,[1,*] D. Bečirević,[2,†] G. Piazza,[2,‡] S. Rosauro-Alcaraz,[2,§] and O. Sumensari[2,¶]
[1] *Physik-Institut, Universität Zürich, CH-8057 Zürich, Switzerland*
[2] *IJCLab, Pôle Théorie (Bat. 210), CNRS/IN2P3 et Université, Paris-Saclay, 91405 Orsay, France*



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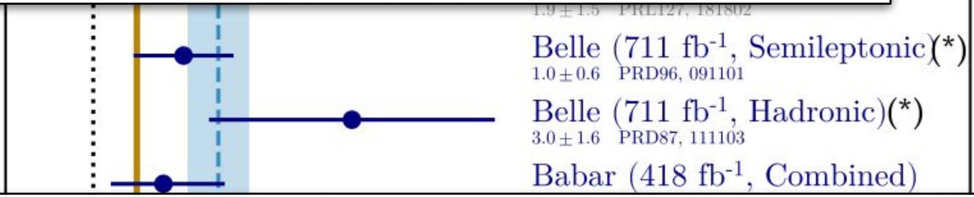

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Implications of an enhanced $B \to K\nu\bar{\nu}$ branching ratio

Rigo Bause,[1,*] Hector Gisbert,[2,3,†] and Gudrun Hiller[1,4,‡]
[1] TU Dortmund University, Department of Physics, Otto-Hahn-Str.4, D-44221 Dortmund, Germany
[2] Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Padova,,Via F. Marzolo 8, 35131 Padova, Italy
[3] Dipartimento di Fisica e Astronomia "Galileo Galilei", Universita di Padova,Via F. Marzolo 8, 35131 Padova, Italy
[4] Department of Physics and Astronomy, University of Sussex, Brighton, BN1 9QH, U.K.

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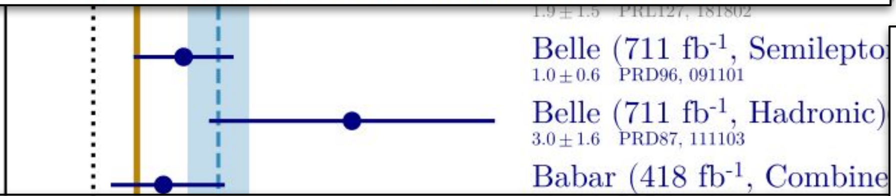

B meson anomalies and large $B^+ \to K^+\nu\bar{\nu}$ in non-universal $U(1)'$ models

Peter Athron,[a] R. Martinez,[b] Cristian Sierra[a]
[a] *Department of Physics and Institute of Theoretical Physics, Nanjing Normal University, Wenyuan Road, Nanjing, Jiangsu, 210023, China*
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New experimental state of the art

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The Decay $B \to K\nu\bar{\nu}$ at Belle II and a Massless Bino in R-parity-violating Supersymmetry

Herbert K. Dreiner,[1,*] Julian Y. Günther,[1,†] and Zeren Simon Wang[2,3,‡]
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aBar

$K^+\nu\bar{\nu}$ in

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Implic

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(*) Belle reports upper limits only; branching fractions are estimated using published number of events and efficiency

New experimental state of the art

When Energy Goes Missing:
New Physics in $b \to s\nu\nu$ with Sterile Neu

Tobias Felkl[1], A

Understanding the first measurement of $\mathcal{B}(B \to K\nu\bar{\nu})$

L. Allwicher,[1,*] D. Bečirević,[2,†] G. Piazza,[2,‡] S. Rosauro-Alcaraz,[2,§] and O. Sumensari[2,¶]
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aBar

$K^+\nu\bar{\nu}$ in

Exciting result !

Implic

Rigo Bause,[1,*] Hector Gisbert,[2,3,†] and Gudrun Hiller[1,4,]
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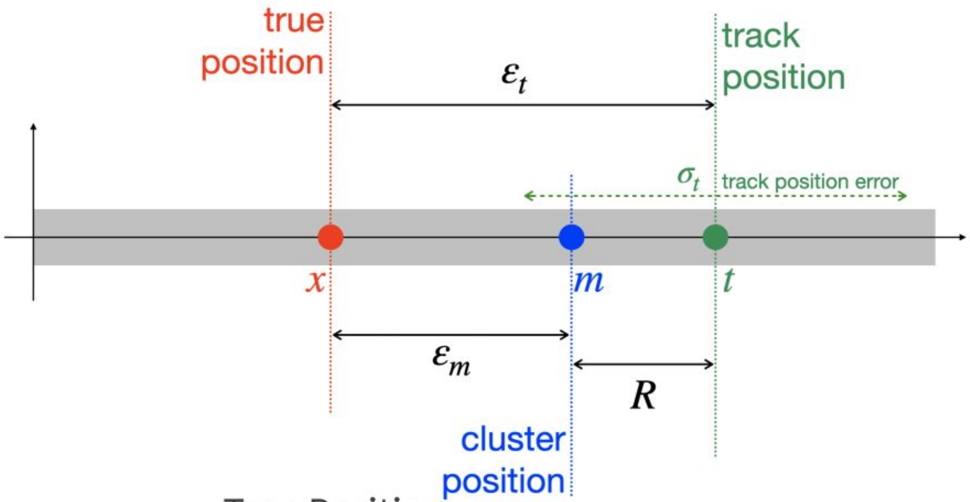
Summary

- **First evidence** of the **$B^+ \to K^+$ + inv.** decay and **improvement** of Belle II **Silicon Vertex Detector**
- Development of a calibration method allowing to gain **~5 - 15%** in SVD **spatial resolution**
- Two analyses aimed at observing $B^+ \to K^+$ + inv. : **hadronically** and **inclusively** tagged
- Combination of the result allows for a first evidence of the decay (**3.6σ** away from null hypothesis) and shows a **2.8σ** tension with SM expectations
- Really exciting result ! Additional work needed to get a clearer picture:
  - Complementary semileptonic tag analysis
  - other $b \to s$ + inv. modes

Thank you !

Backup



True Position	x		
Cluster Position	m	$\rightarrow$	Center of Gravity
Unbiased Track Position	t	$\rightarrow$	Track fitting
Track position error	σ_t		

Residuals

Residual	$R = m - t$
Track Residual	$\varepsilon_t = t - x$
True Residual	$\varepsilon_m = m - x$

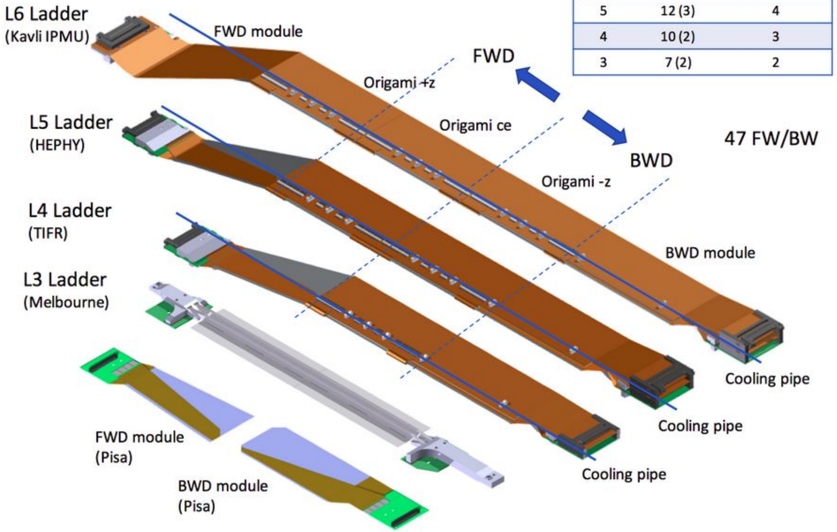
Spatial Resolution σ_{cl}

$$\sigma_{cl}^2 = Var[\varepsilon_m] = E[(m - x)^2] - E[(m - x)]^2$$

Note: the true position x is only available in simulation !

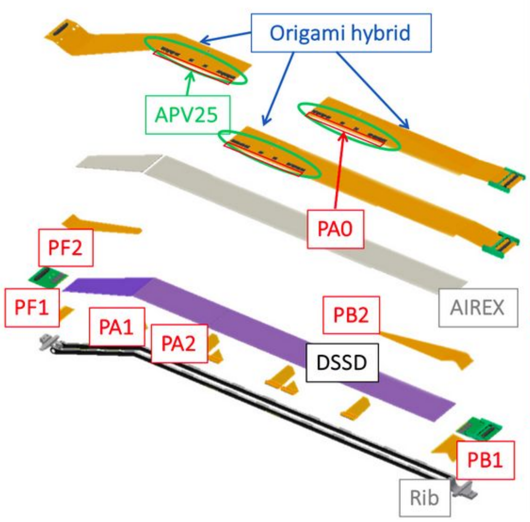
SVD ladders

Layer	Ladders (spares)	DSSDs / ladder
6	16 (4)	5
5	12 (3)	4
4	10 (2)	3
3	7 (2)	2



G. Rizzo - SVD Ladder Production - BPAC - Feb 13th 2017 3

Ladder Anatomy (L6 ladder)



DSSDs
- 2 small rectangular (L3)
- 2-4 large rectangular (L4-6)
- 1 trapezoidal (L4-6)

Origami hybrid
Flexible circuit to transmit detector signals to the ladder ends

APV25
Readout ASIC of the strips

FlexPA (PA/PF/PB)
Flexible circuit to transmit detector signals to the APV25

PA0
Flexible circuit glued on the Origami hybrid to transmit *n*-side detector signals to the APV25

AIREX
Thermal insulator between the DSSD and APV25

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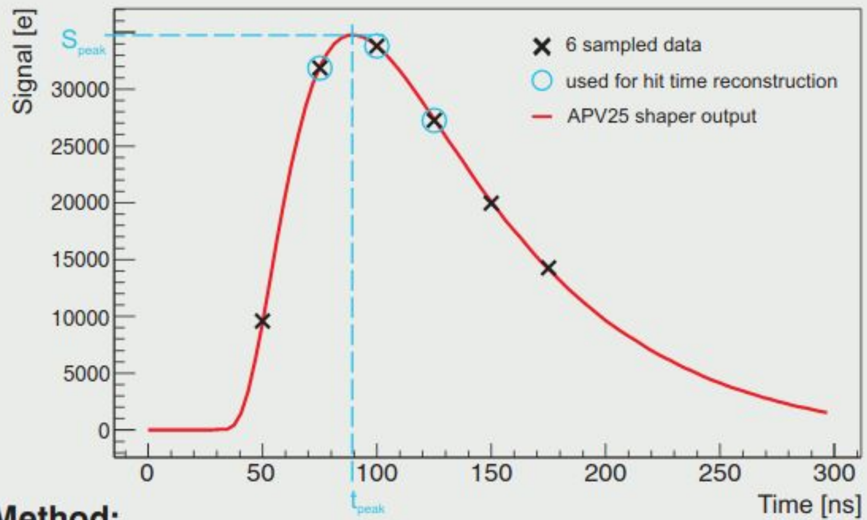
	Small	Large	Trapezoidal
Readout strips (p/R-φ/U)	768	768	768
Readout strips (n/Z/V)	768	512	512
Readout pitch (p/R-φ/U)	50 μm	75 μm	75-50 μm
Readout pitch (n/Z/V)	160 μm	240 μm	240 μm
Chip size (mm^2)	124.88x40.43 = 5048.90	124.88x 59.60 = 7442.85	125.58x(60.63-41.02) = 6382.60
Active area (mm^2)	122.90x38.55 = 4737.80	122.90x57.72 = 7029.88	122.76x(57.59-38.42) = 5890.00
Wafer Thickness	320 μm	320 μm	280 μm * to be checked *



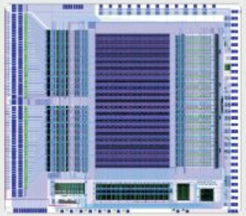
Method:

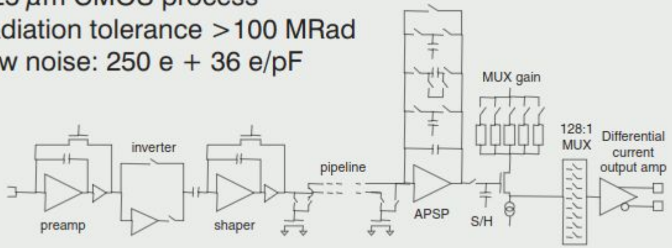
The multi-peak mode of the APV25 allows to take 3, 6, 9, ... consecutive samples of the shaper output signal. Three points around the maximum of the curve can be used to determine timing and amplitude of the peak with lookup tables, which are generated from the calibration pulse of the APV25.
Thanks to using only three out of six samples, a trigger jitter of up to +/- 2 clocks can be tolerated.

APV25

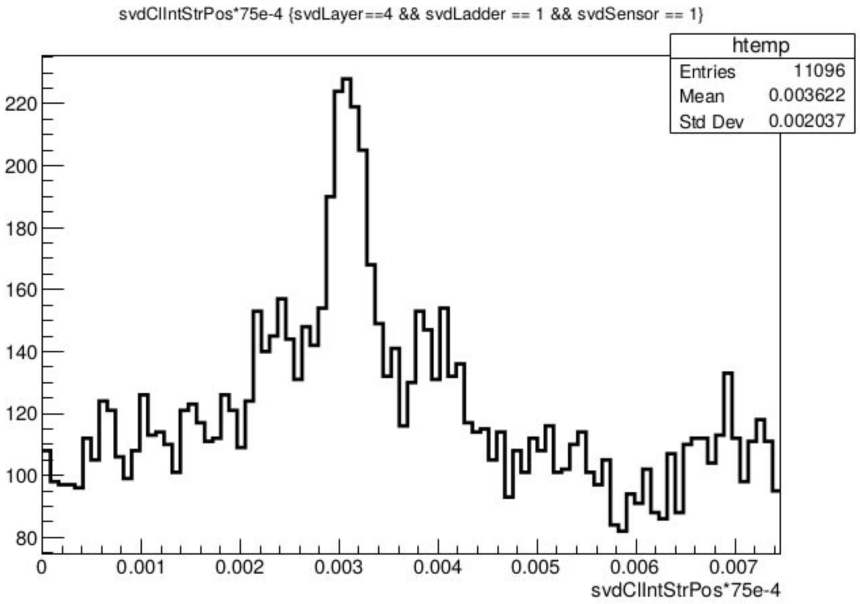
APV25 Front-End Chip Features

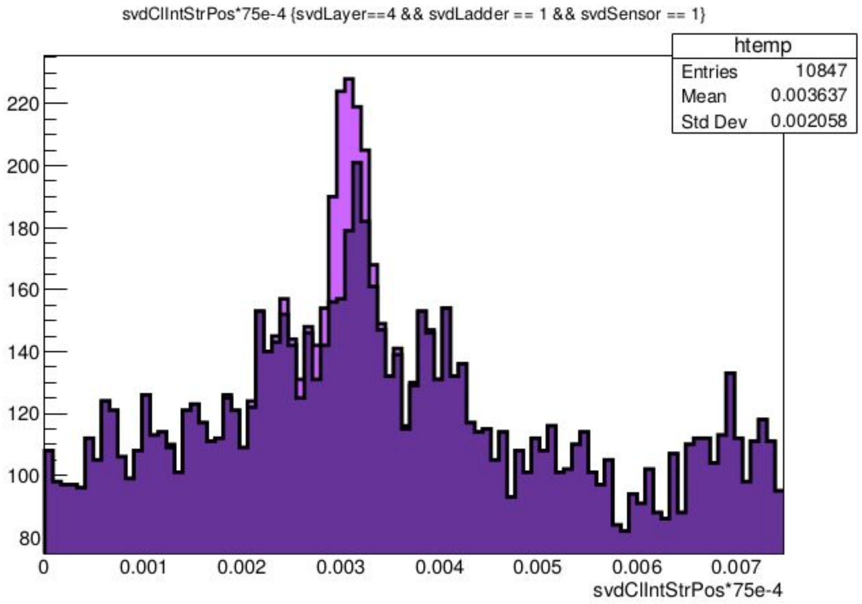
40 MHz operation
128 channels
192 cell deep analog pipeline
50 ns shaping time (adjustable)
Modes: Peak / Deconvolution / Multi-peak
0.25 μm CMOS process
Radiation tolerance >100 MRad
Low noise: 250 e + 36 e/pF





Eta correction





Eta correction

$$x_{IS} = x_{COG} mod(p)$$

p = pitch

$$\zeta_{IS} = \frac{x_{IS}}{p}$$

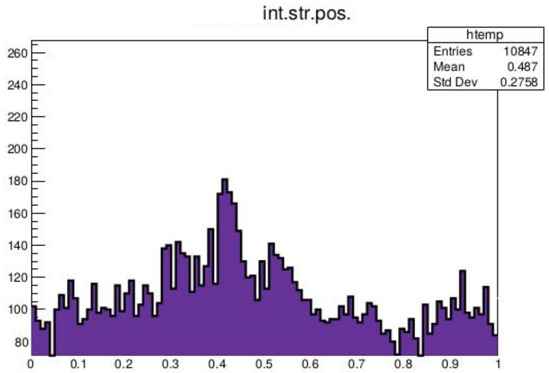
Correction:

$$F(\zeta_{IS} = \zeta) = \int_0^{\zeta} P(\zeta_{IS}) d\zeta_{IS}$$

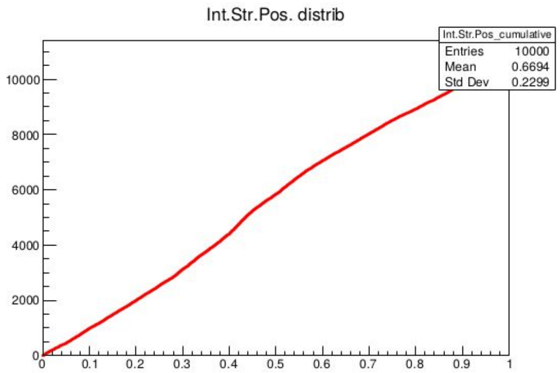
$$x_{\eta} = x_{S0} + p * F(\zeta_{IS})$$

xS0 = position of the central strip in the cluster

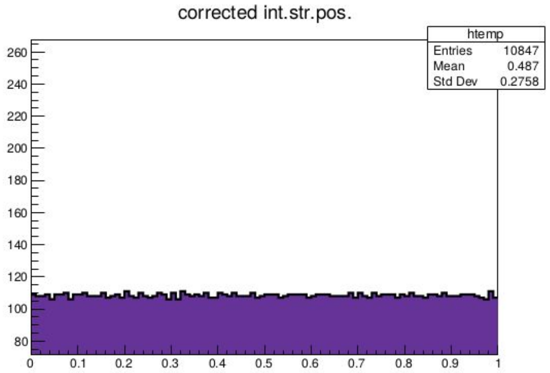
Eta correction



(a)

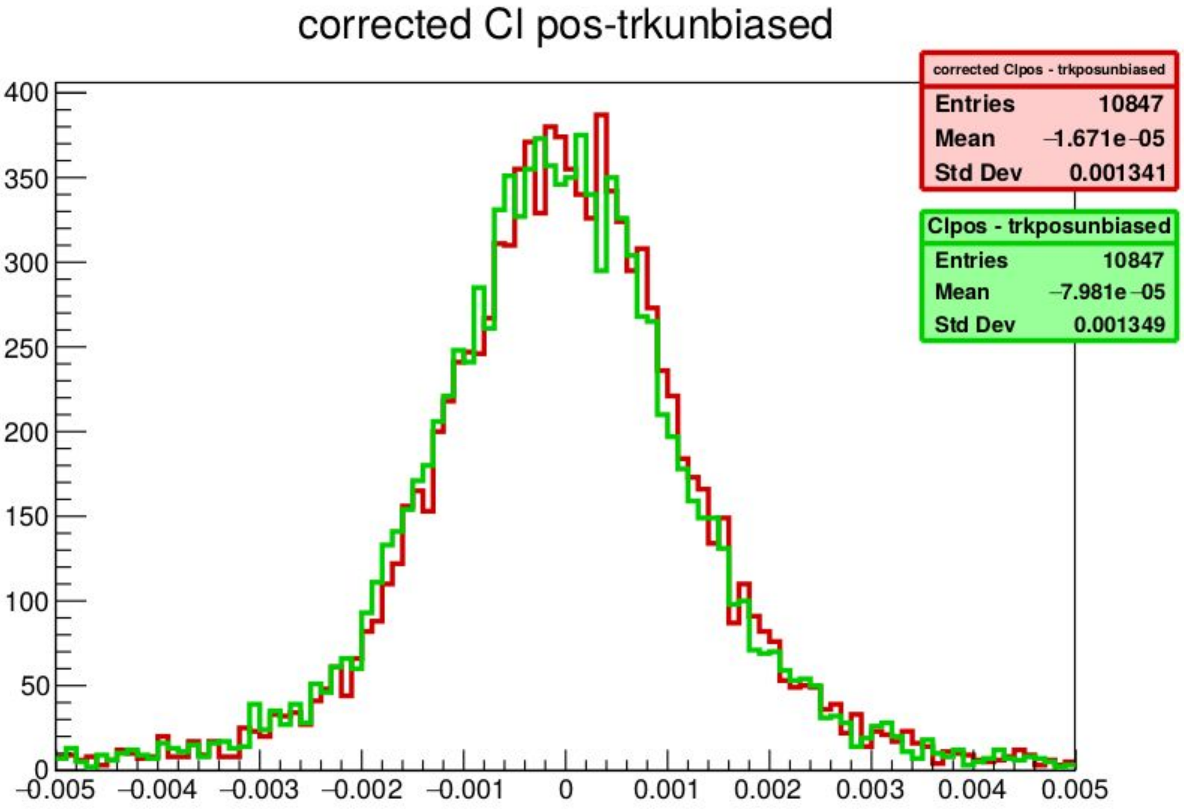


(b)



(c)

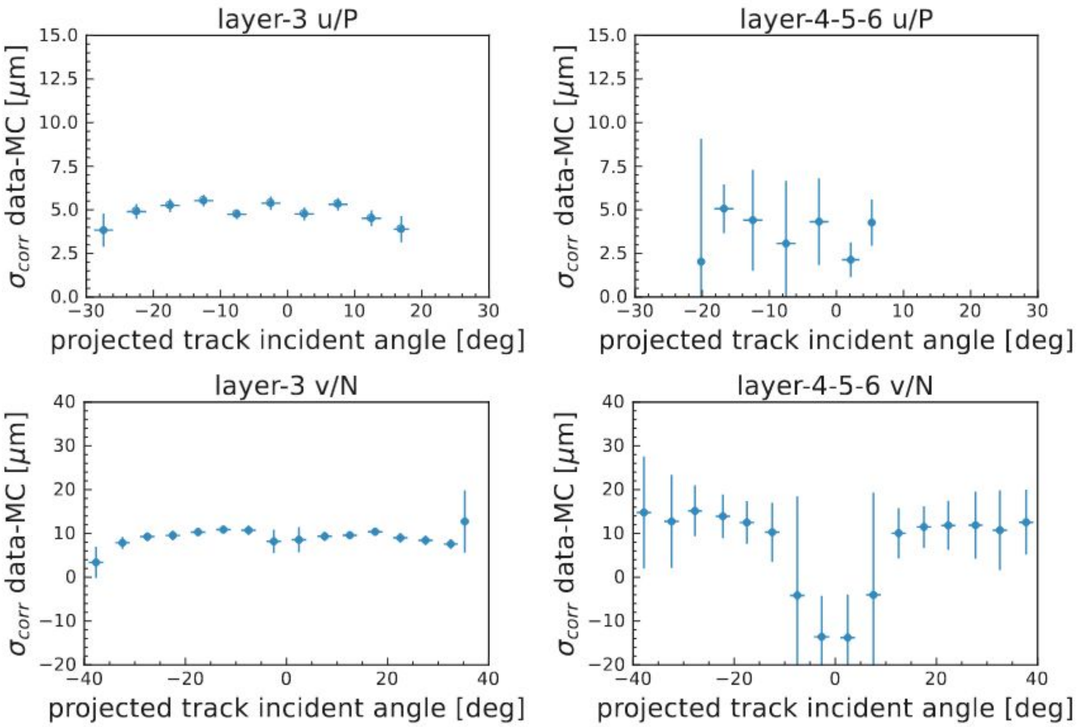
Eta correction



Fudge factors

MC res. altered by a random amount taken from a gaussian of mean 0 and sigma:

$$\sigma_{\text{corr}} = \text{sign}(\sigma^2_{\text{data}} - \sigma^2_{\text{MC}}) \cdot \sqrt{|\sigma^2_{\text{data}} - \sigma^2_{\text{MC}}|},$$



MC res. altered by a random amount taken from a gaussian of mean 0 and sigma:

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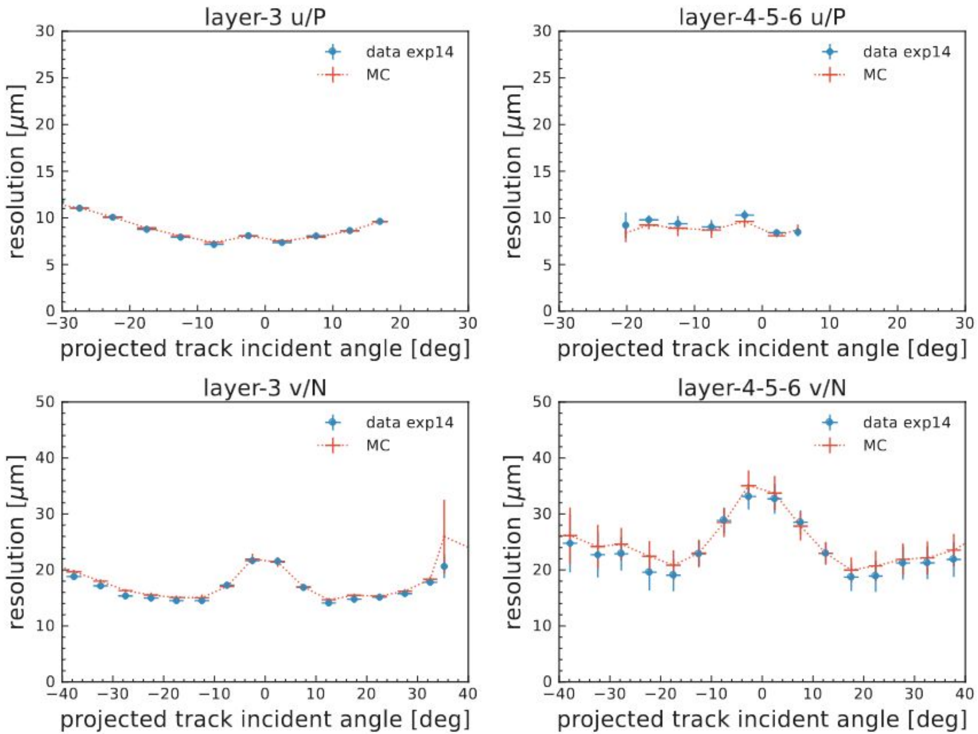
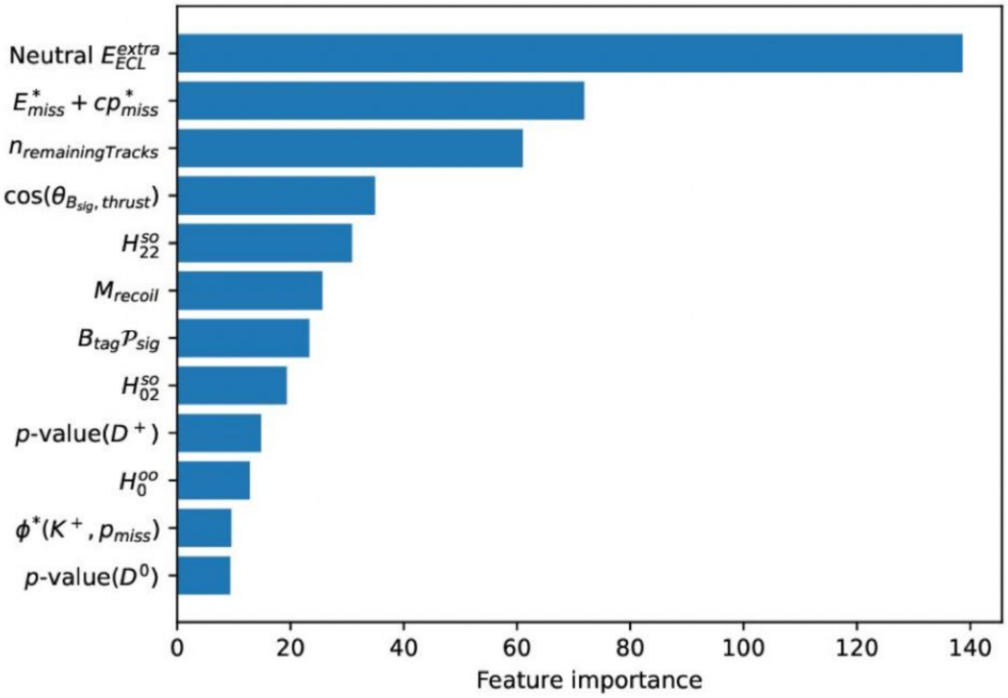


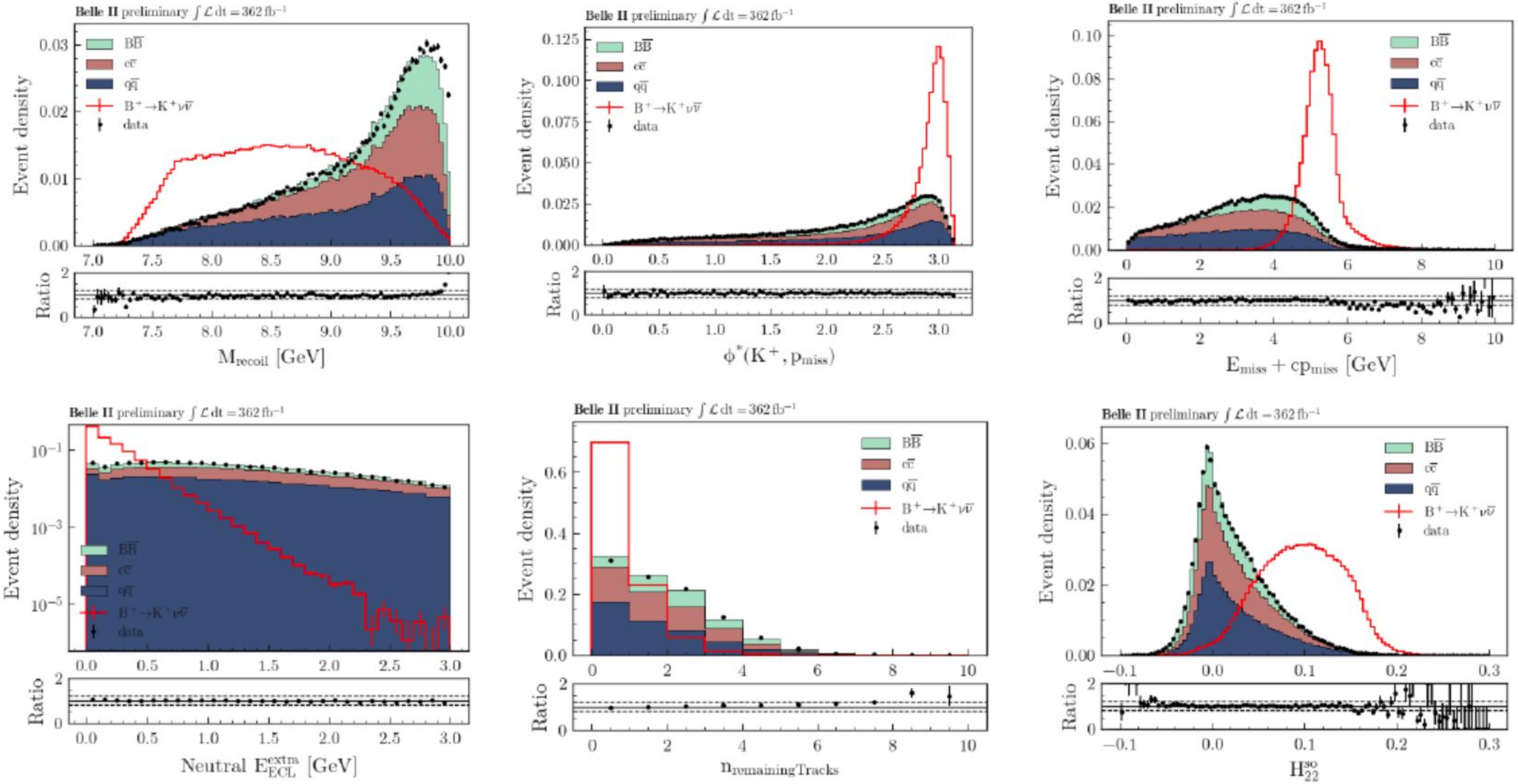
Observables	Belle $0.71\,\mathrm{ab}^{-1}$ $(0.12\,\mathrm{ab}^{-1})$	Belle II $5\,\mathrm{ab}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
$\mathrm{Br}(B^+ \to K^+ \nu\bar{\nu})$	$< 450\%$	30%	11%
$\mathrm{Br}(B^0 \to K^{*0} \nu\bar{\nu})$	$< 180\%$	26%	9.6%
$\mathrm{Br}(B^+ \to K^{*+} \nu\bar{\nu})$	$< 420\%$	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
$\mathrm{Br}(B_s \to \nu\bar{\nu}) \times 10^5$	< 9.7	< 1.1	–

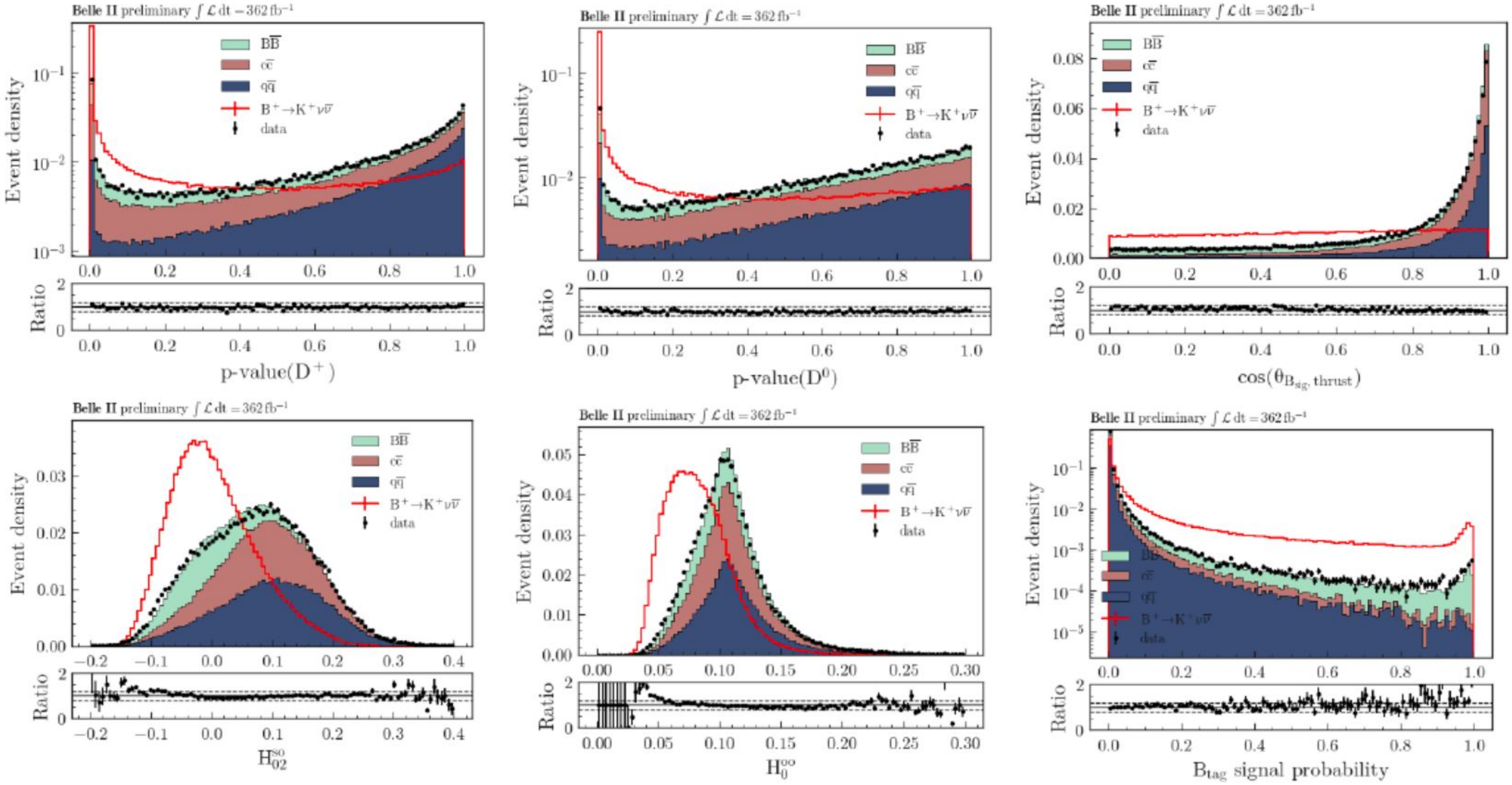
Expected sensitivities

- Sum of photon energy deposits in ECL in ROEh
- Number of tracks in ROEh
- Sum of the missing energy and absolute missing three-momentum vector
- Azimuthal angle between the signal kaon and the missing momentum vector
- Cosine of the angle between the thrust axis of the signal kaon candidate and the thrust axis of the ROEh
- Kakuno-Super-Fox-Wolfram moments H_{22}^{so}, H_{02}^{so}, H_0^{oo}
- Invariant mass of the tracks and energy deposits in ECL in the recoil of the signal kaon
- p-value of B_{tag}
- p-value of the vertex fit of the signal kaon and one or two tracks in the event to reject fake kaons coming from D^0 or D^+ decays



BDT features




Belle II preliminary $\int \mathcal{L}\,dt = 362\,fb^{-1}$
$B\overline{B}$
$c\overline{c}$
$q\overline{q}$
$B^+ \to K^+ \nu \overline{\nu}$
data
Event density
Ratio
p-value(D^+)
p-value(D^0)
$\cos(\theta_{B_{sig}, thrust})$
H_{02}^{so}
H_0^{oo}
B_{tag} signal probability

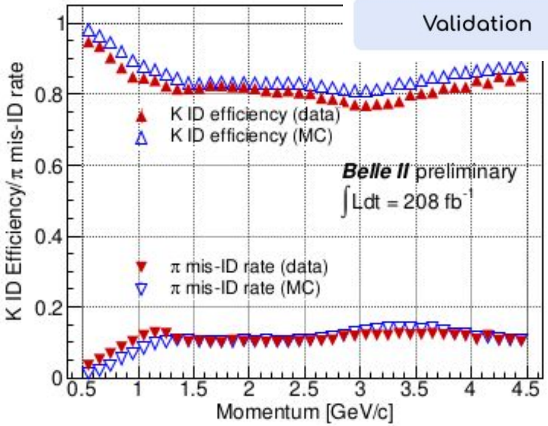
Most fake kaons are **misidentified pions**

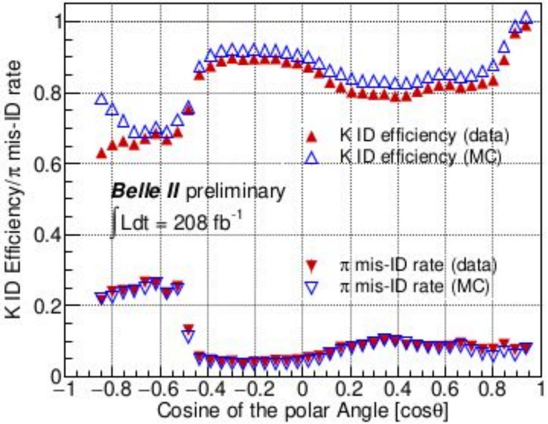
Sample selected as $D^{*+} \to \pi^+ D^0(\to K^- \pi^+)$ provides abundant and low background K^- and π^+ samples

Use to determine kaon ID efficiency and pion-to-kaon fake rates as functions of relevant variables.

Data/MC comparison shows that
simulation underestimates the pion-to-kaon fake rate

Validation





Validation

Use $B^+ \to \overline{D}^0(\to K^+\pi^-)h^+$ with $h = K, \pi$

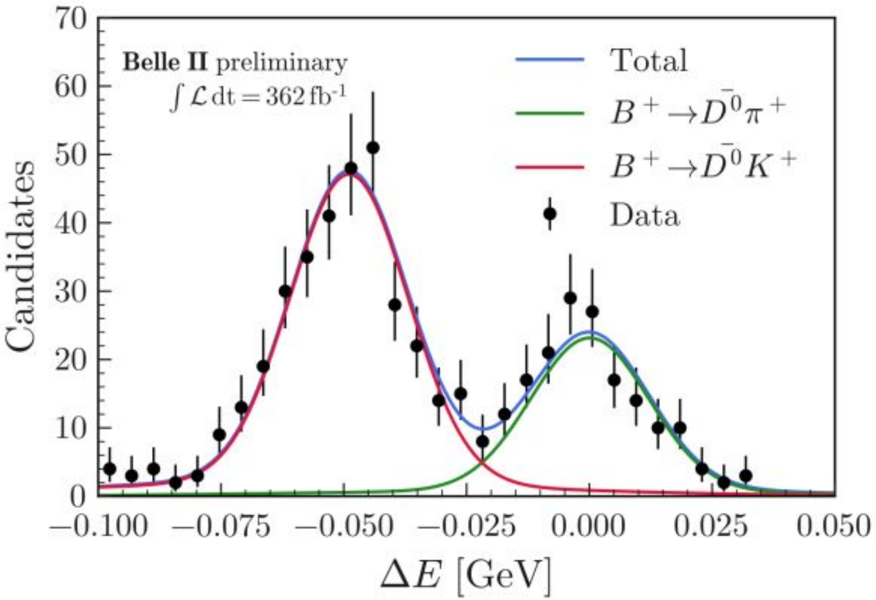
Use D-decay tracks to select the event and then remove to mimic signal topology

- Use the full $B^+ \to K^+\nu\bar{\nu}$ selection
- Compute ΔE with π mass hypothesis and select h with nominal K-id

estimate the number of $B^+ \to \overline{D}^0 K^+$ and $B^+ \to \overline{D}^0\pi^+$ by fitting ΔE both for MC and **data**

Obtain fake rate $F = N_\pi/(N_\pi + N_K)$.
Data consistent with MC within 9%
No further corrections applied

$B^+ \to K^+\nu\bar{\nu}$ signal region



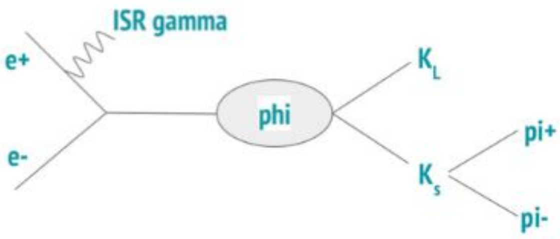
Observed minus expected B energy: $\Delta E = E_B^* - \sqrt{s}/2$

Validation

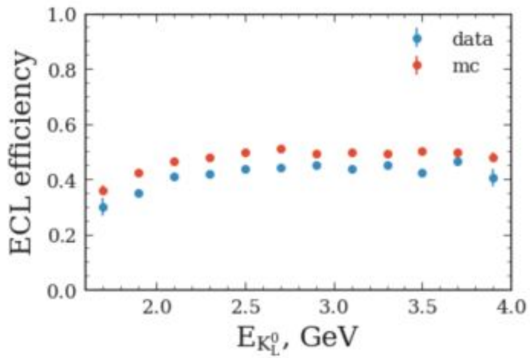
1) Partially reconstruct $e^+e^- \to \gamma_{\rm ISR}\phi(\to K_L^0 K_S^0)$

2) Infer K_L^0 information by using known ϕ mass and collision energy

3) Match K_L^0 candidates to ECL clusters within 15 cm of the inferred direction of K_L^0.
(ECL cluster list follows $B^+ \to K^+\nu\bar{\nu}$ selection)



$$\varepsilon(K_L^0) = \frac{N(K_L^0 \text{ distance to ECL cluster} < 15\text{cm})}{N(\text{total})}$$



Caveat: probes only high-energetic K_L^0 (more on this later)

Globally suggested correction is 17±8%

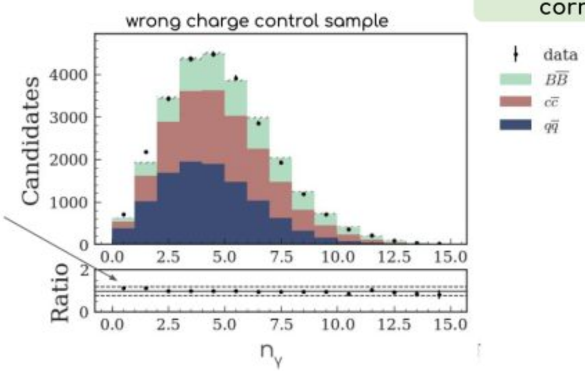
Background suppression

Data-MC corrections

Correct simulation to account for residual data-simulation discrepancy by using extra photon multiplicity.

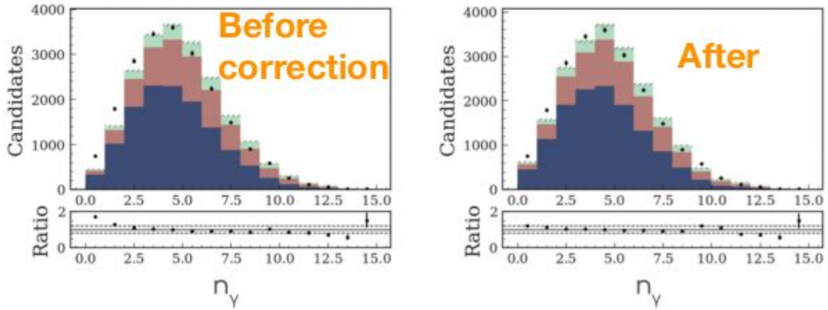
- Use wrong-charge sideband to derive the correction
- Use pion-ID sideband to validate it and estimate systematic uncertainty.

$$w_{n_\gamma} = \frac{n_{data}(n_\gamma)}{n_{MC}(n_\gamma)}$$



Apply the weight $w_{n\gamma}$ in the signal region based on the associated n_γ.

pion-ID sideband



Data-simulation agreement is improved but residual discrepancy persists.

Assign 100% of residual discrepancy as systematic uncertainty

$B \to X_c(\to K^0_L + X)$ + ANYTHING

Study **pion ID** sideband (do the analysis with **pion ID > 0.9**)

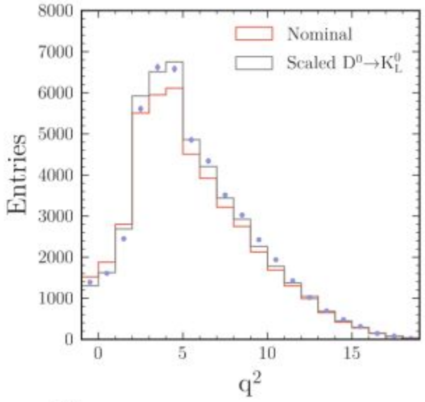
Binned fit of q^2_{rec} in signal search region ($\mu(\text{BDT}_2) > 0.92$) to determine scaling of simulated $B\bar{B}$ events containing a charm decay involving a K^0_L on signal side, $X_c(\to K^0_L + X)$.

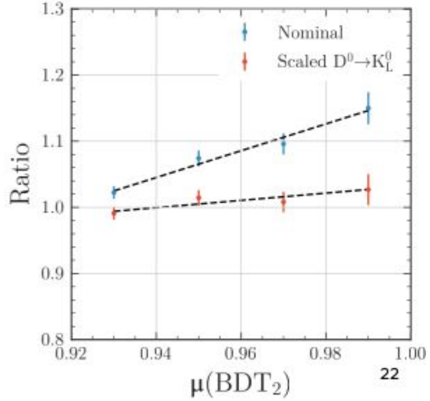
3 fit components: $X_c(\to K^0_L + X)$, $B\bar{B}$ background, continuum background.

$B\bar{B}$ and continuum normalisation uncertainties set to 1% and 10%, respectively.

	pion ID sideband	electron ID sideband	muon ID sideband
Scaling of $X_c \to K_L + X$	1.30±0.02	1.38±0.01	1.35±0.01

Scale up $B \to X_c(\to K^0_L + X)$ by 1.3 in the MC and assign systematic of 0.1





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Diving deeper in BB backgrounds

Several decays show high signal-likeness, and need to be studied

- Low multiplicity decays:
  - $B^+ \to K^+ n\bar{n}$
  - $B^+ \to K^+ K^0 \bar{K}^0$
- Charm decays:
  - $D \to K_L$
  - D^{**} decays

Different corrections and/or systematics applied

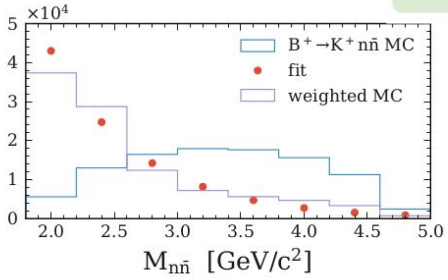
$B^+ \to K^+ n\bar{n}$:

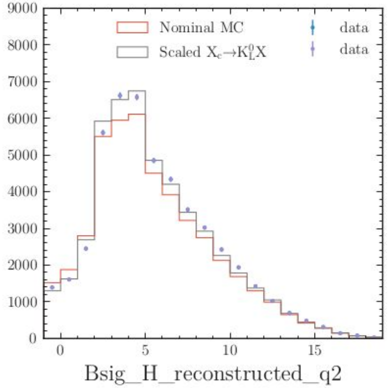
- Never been observed, but $B^0 \to K^0_S p\bar{p}$ studied by BaBar [Phys. Rev. D 76, 092004]
- $B^0 \to K^0_S p\bar{p}$ sees an enhancement at the $p\bar{p}$ production threshold
- Assuming isospin symmetry, reweight $B^+ \to K^+ n\bar{n}$ events in the simulation

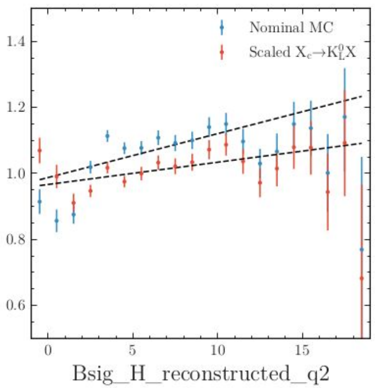
$D \to K_L$:

- Contribution from prompt K^+ prodcution in $B^+ \to D^{*0,+} K^+$ is important in the signal region
- Mainly due to sizeable, less-known X_c decays involving K_L
- We study these decays in the sidebands data samples
- We determine a (1.30 ± 0.1) $X_c \to K_L$ scaling from a fit to the signal region in the sidebands

Data-MC corrections







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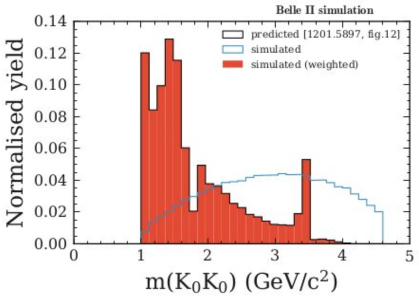
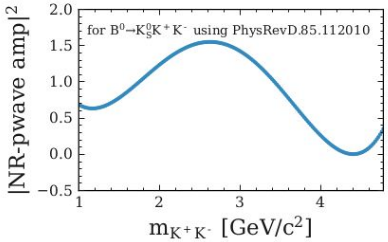
- Low multiplicity decays:
  - $B^+ \to K^+ n\bar{n}$
  - $B^+ \to K^+ K^0 \bar{K}^0$
- Charm decays:
  - $D \to K_L$
  - D^{**} decays

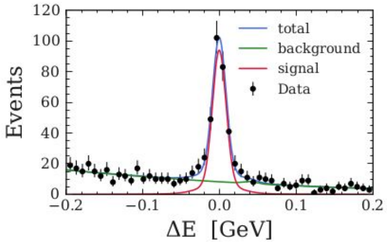
$B^+ \to K^+ K^0 \bar{K}^0$, several cases:

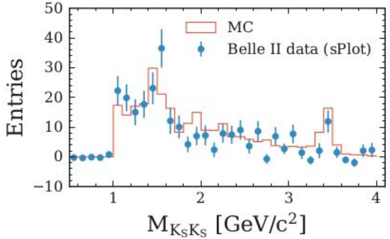
- Modeled in Belle II as a sum of phase space contribution and resonances
- BaBar paper finds complex Dalitz structure for $B^+ \to K^+ K^0_S K^0_S$ **[Phys Rev D 85, 112010]**
- $B^+ \to K^+ K^0_S K^0_S$ and $B^+ \to K^+ K^0_L K^0_L$ phase space reweighted from BaBar paper
- $B^+ \to K^+ K^0_S K^0_L$ is trickier, likely dominated by ϕ plus P-wave contribution
- Keep $B^+ \to \phi K^+$ as is, reweight phase space to P-wave contribution
- Check correction in data using $B^+ \to K^+ K^0_S K^0_S$ and $B^0 \to K^0_S K^+ K^-$

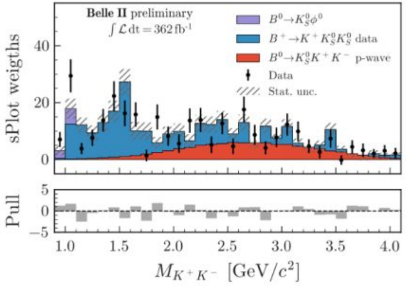
Data-MC corrections











Background composition

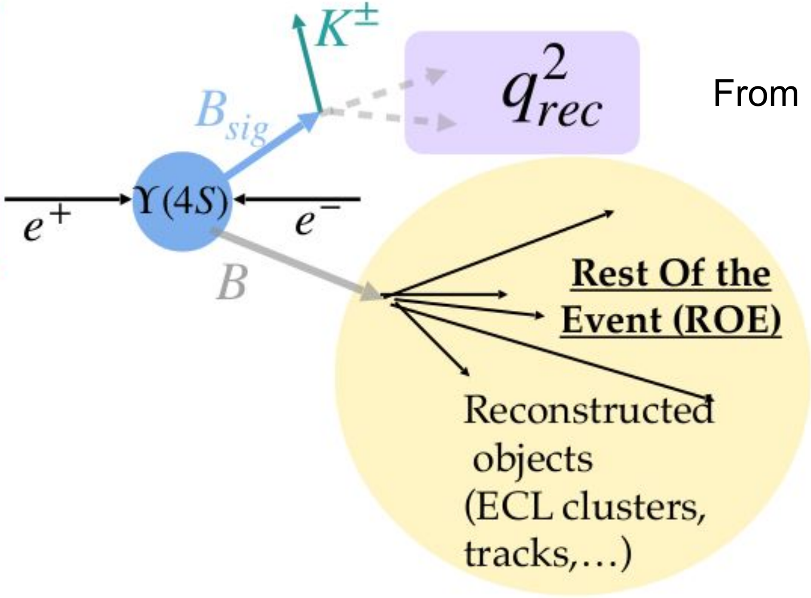
B^+B^- event type	occurence (%)
misidentified K_{sig}	3.42%
$D n\pi + D\ell\nu$	50.34%
$D n\pi + Hadrons$	4.97%
$D n\pi + c\bar{c}$	3.84%
$D\ell\nu + D\ell\nu$	3.77%
$D n\pi + K^+K^0K^0$	3.69%
$D\ell\nu + DHadrons$	3.54%
$D\ell\nu + DD$	2.94%
$D n\pi + D\tau\nu$	2.86%
$D n\pi + DHadrons$	2.86%
$D\ell\nu + c\bar{c}$	2.64%
$D n\pi + D n\pi$	2.03%
$D n\pi + DD$	0.98%
$D\ell\nu + D\tau\nu$	0.90%
$D\ell\nu + Hadrons$	0.60%
$c\bar{c} + DD$	0.45%
$c\bar{c} + Hadrons$	0.45%
$DHadrons + DHadrons$	0.45%
$DHadrons + Hadrons$	0.45%
$D\tau\nu + c\bar{c}$	0.30%
$K^+K^0K^0 + c\bar{c}$	0.23%
$DD + DHadrons$	0.23%
$D\tau\nu + DHadrons$	0.15%
$K^+K^0K^0 + DD$	0.15%
$DD + Hadrons$	0.15%
$D\ell\nu + K^+K^0K^0$	0.08%
$n\pi\ell\nu + c\bar{c}$	0.08%
$D\tau\nu + DD$	0.08%
$K^+K^0K^0 + DHadrons$	0.08%
$c\bar{c} + c\bar{c}$	0.08%
$c\bar{c} + DHadrons$	0.08%
$Hadrons + Hadrons$	0.08%
other	10.12%

$B^0\bar{B}^0$ event type	occurence (%)
misidentified K_{sig}	10.14%
$D n\pi + D\ell\nu$	41.13%
$D n\pi + DHadrons$	10.48%
$D\ell\nu + D\ell\nu$	6.45%
$D\ell\nu + cc$	4.03%
$D\ell\nu + DD$	4.03%
$D\ell\nu + Hadrons$	3.23%
$D n\pi + Hadrons$	2.42%
$D\ell\nu + DHadrons$	2.42%
$DHadrons + DHadrons$	2.42%
$D n\pi + D n\pi$	1.61%
$D n\pi + D\tau\nu$	1.61%
$D n\pi + cc$	1.61%
$D n\pi + DD$	1.61%
$DHadrons + Hadrons$	1.61%
$D\ell\nu + D\tau\nu$	0.81%
$D\tau\nu + DHadrons$	0.81%
$D\tau\nu + Hadrons$	0.81%
$cc + Hadrons$	0.81%
$DD + Hadrons$	0.81%
other	10.14%

K^+ selection
Reconstruct a track with at least one pixel hit in and use PID to identify it askaon

- $\epsilon(\text{KaonID}) \sim 68\,\%$
- mis-tag rate $(\pi \to K) \sim 1.2\,\%$

Rest of the Event (ROE)
- Charged particles
- Neutrals
- K_S



From R. Volpe

q^2_{rec} : mass squared of the neutrino pair

$$q^2_{rec} = \frac{s}{4} + M_K^2 - \sqrt{s}E_K^*$$

If multiple signal candidates are reco'd, pick lowest q^2_{rec} one

Missing momentum: complement to total momentum from all particles

θ^*_{miss} is the polar angle of the missing momentum in the center of mass frame

Event cleaning:
$4 \leq N_{tracks} \leq 10$
$17° \leq \theta^*_{miss} \leq 160°$

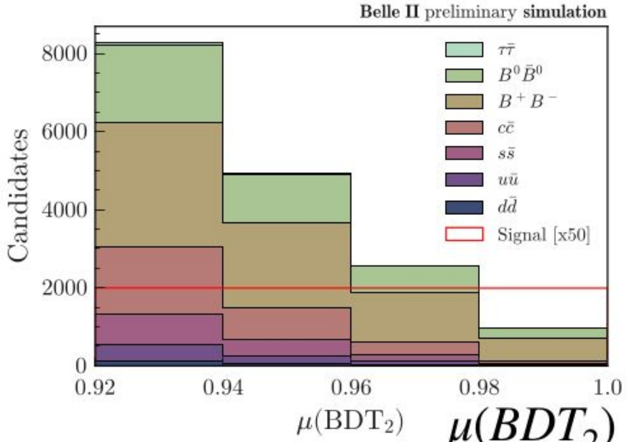
From R. Volpe

Two multivariate binary classifiers based on boosted decision trees (BDT)

A first filter uses 12 input variables to reduce data obtaining 34% efficiency (BDT1>0.9)

Key discrimination achieved by 35 inputs fed to BDT_2

(Output mapped in a new variable $\mu(BDT_2)$ defined to make signal efficiency is flat)



$\mu(BDT_2)$

Signal region defined by:

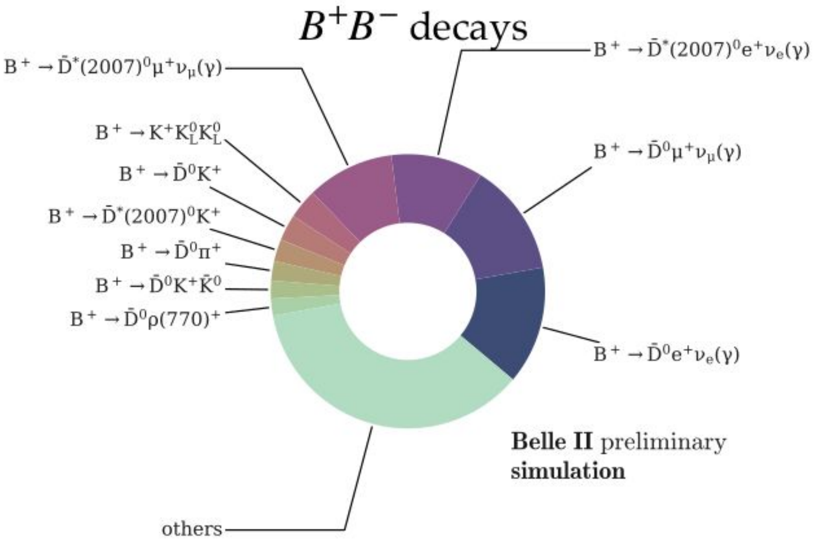
$BDT_1 > 0.9$
$\mu(BDT_2) > 0.92$

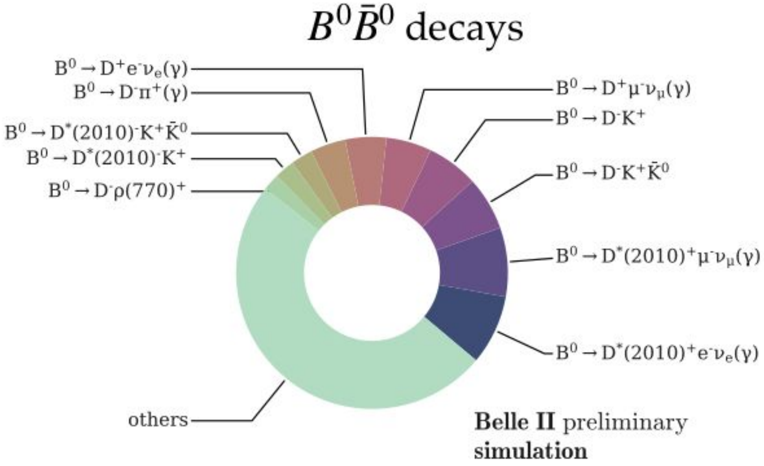
The analysis is developed using simulated samples.

Data are used to derive corrections and validate them

From R. Volpe

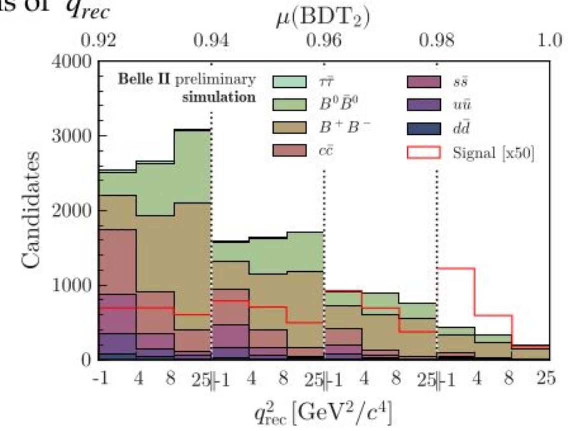
- Continuum ($q\bar{q}$) is 40%
- B-meson decays 60% — 47% from **semileptonic with $D \rightarrow KX$**, 52% from hadronic decays involving D and K





From R. Volpe

Signal region divided into 4 bins of $\mu(BDT_2)$ and 3 bins of q^2_{rec}



Off-resonance data used as well to better constraint background

$\mu(BDT_2) \times q^2_{rec} \times$ [on/off res]

4 bins 3 bins 2 bins

24 bins total

Binned likelihood fit to signal and 7 background categories

- Poisson uncertainties for data counts
- Systematic uncertainties included in the fit as predicted rate modifiers with Gaussian likelihoods
- MC statistical uncertainties are included as nuisance parameters, per each bin and each fit category

From R. Volpe

Source	Uncertainty size	Impact on σ_μ
Normalization of $B\bar{B}$ background	50%	0.88
Normalization of continuum background	50%	0.10
Leading B-decays branching fractions	$O(1\%)$	0.22
Branching fraction for $B^+ \to K^+ K^0_L K^0_L$	20%	0.48
p-wave component for $B^+ \to K^+ K^0_S K^0_L$	30%	0.02
Branching fraction for $B \to D^{(**)}$	50%	0.42
Branching fraction for $B^+ \to n\bar{n}K^+$	100%	0.20
Branching fraction for $D \to K_L X$	10%	0.14
Continuum background modeling, $\mathrm{BDT_c}$	100% of correction	0.01
Integrated luminosity	1%	< 0.01
Number of $B\bar{B}$	1.5%	0.02
Off-resonance sample normalization	5%	< 0.01
Track finding efficiency	0.3%	0.20
Signal kaon PID	$O(1\%)$	0.07
Photon energy scale	0.5%	0.07
Hadronic energy scale	10%	0.36
K^0_L efficiency in ECL	8%	0.21
Signal SM form factors	$O(1\%)$	0.02
Global signal efficiency	3%	0.03
Simulated sample size	$O(1\%)$	0.52

statistical uncertainty on $\mu = 1.1$

From R. Volpe

Measure a known decay mode to validate the background estimation

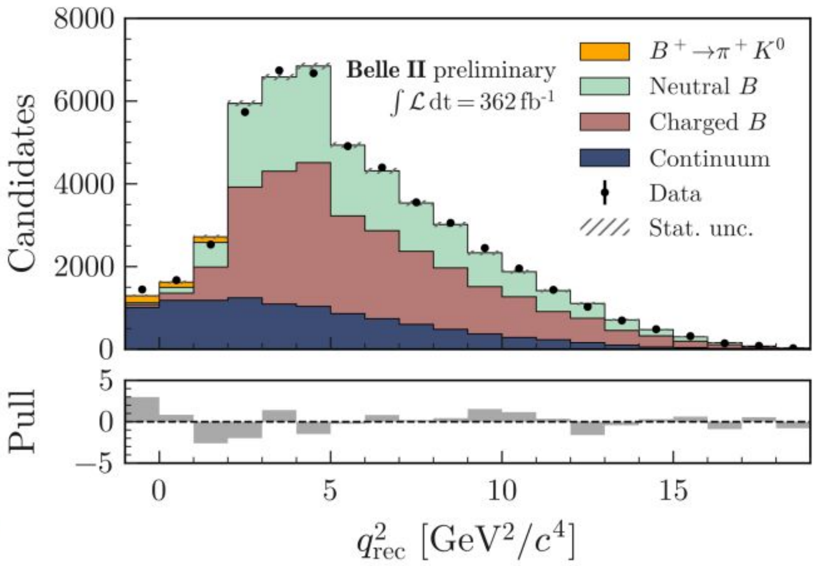
to measure $B^+ \to \pi^+ K^0$ with the full nominal analysis applied

But:

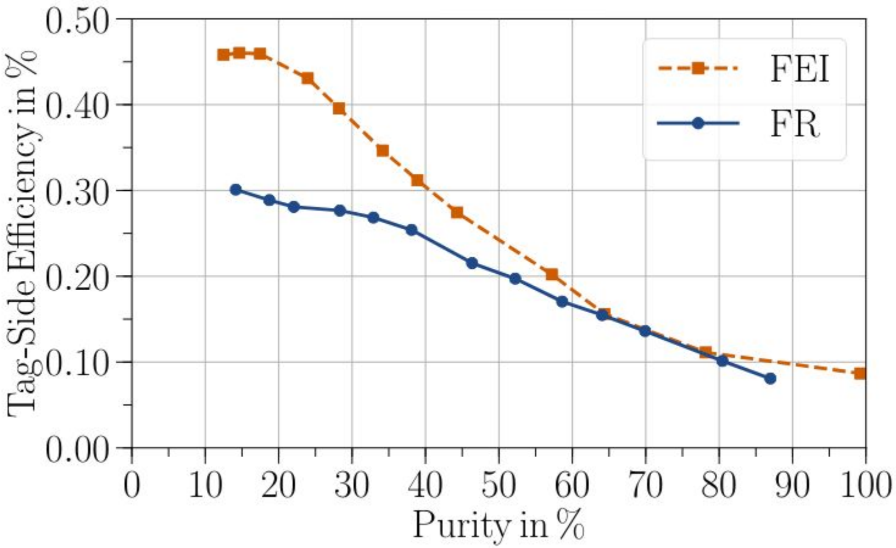
- Pion ID instead of Kaon ID
- Different q^2 bin boundaries
- only on-res data used
- only normalization syst included

$$BR(B^+ \to \pi^+ K^0) = (2.5 \pm 0.5) \times 10^{-5}$$

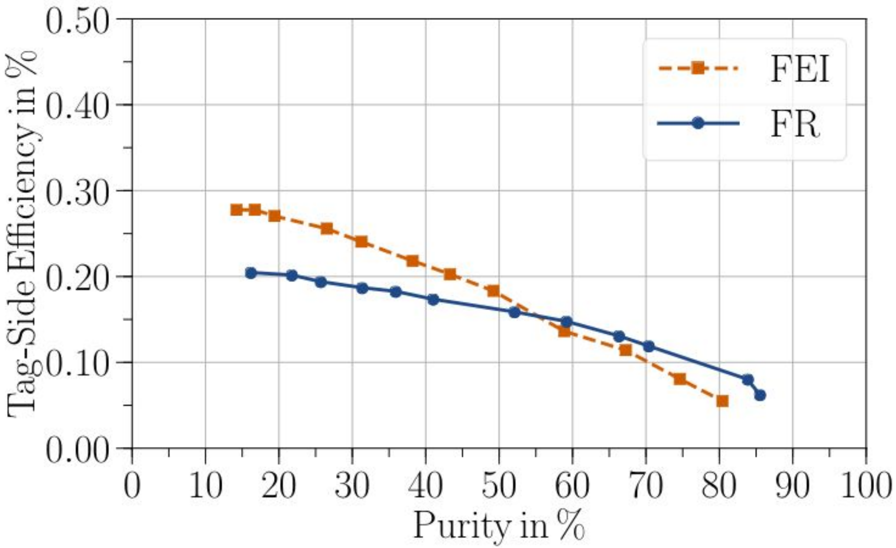
Consistent with PDG:
$BR(B^+ \to \pi^+ K^0) = (2.3 \pm 0.08) \times 10^{-5}$



B+


Tag-Side Efficiency in %
Purity in %
FEI
FR
0.00
0.10
0.20
0.30
0.40
0.50
0
10
20
30
40
50
60
70
80
90
100

B0


Tag-Side Efficiency in %
Purity in %
FEI
FR
0.00
0.10
0.20
0.30
0.40
0.50
0
10
20
30
40
50
60
70
80
90
100

Graph-based Full Event Interpretation (graFEI) model based on *graph network* blocks [5] and **trained on** $\Upsilon(4S) \to B^0(\to \nu\bar{\nu})\bar{B}^0(\to X)$ **simulated signal events**. Performances evaluated on simulated signal events and background from random combinations of tracks from B^0 decays.

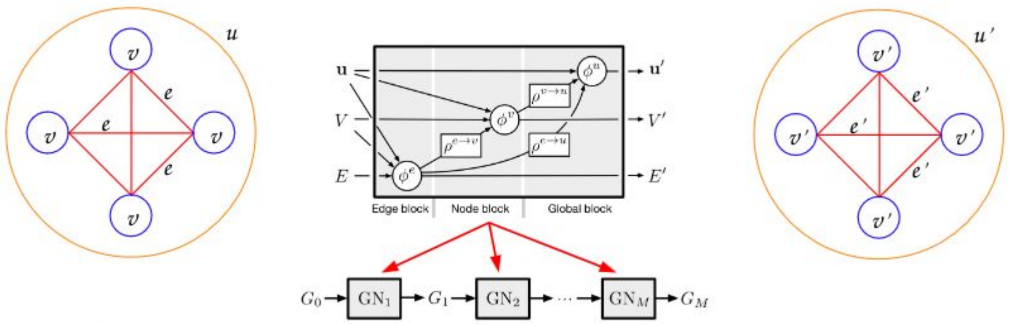


Figure 5: Schematic view of the graFEI model. The graph keeps the same structure while its features are updated.

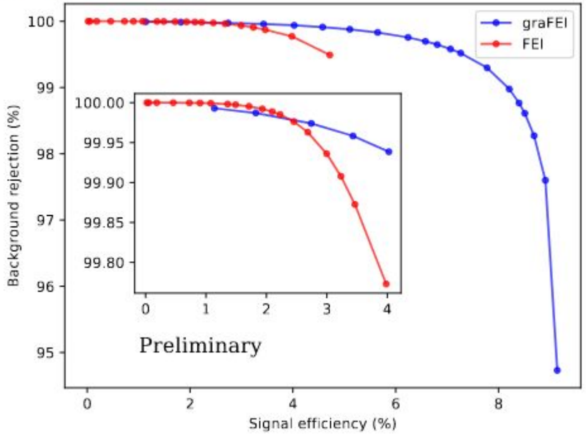
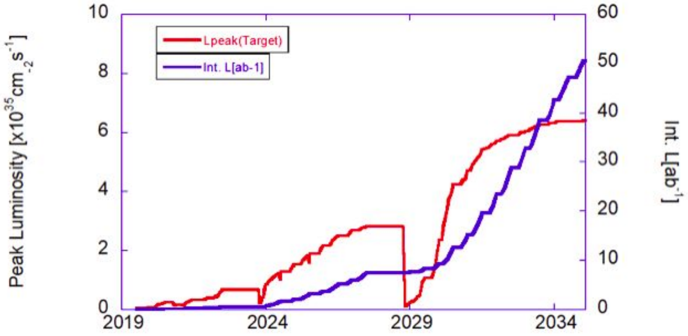


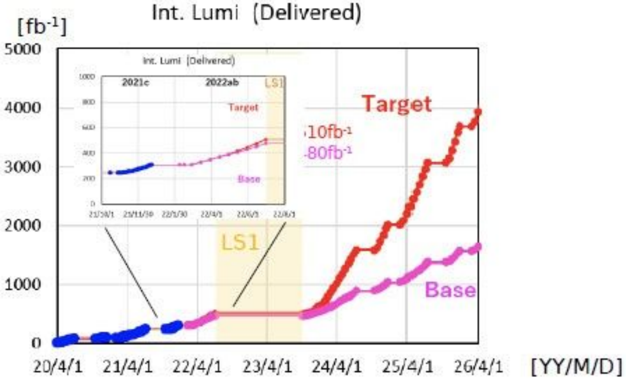
Figure 6: Signal efficiency and background rejection for FEI and graFEI.



Projection of integrated luminosity delivered by SuperKEKB to Belle II

Target scenario: extrapolation from 2021 run including expected improvements.

Base scenario: conservative extrapolation of SuperKEKB parameters from 2021 run



- We start long shutdown 1 (LS1) from summer 2022 for 15 months to replace VXD. There will be other maintenance/improvement works of machine and detector.
- We resume physics running from Fall 2023.
- A SuperKEKB International Taskforce (aiming to conclude in summer 2022) is discussing additional improvements.
- An LS2 for machine improvements could happen on the time frame of 2027-2028

SM tension

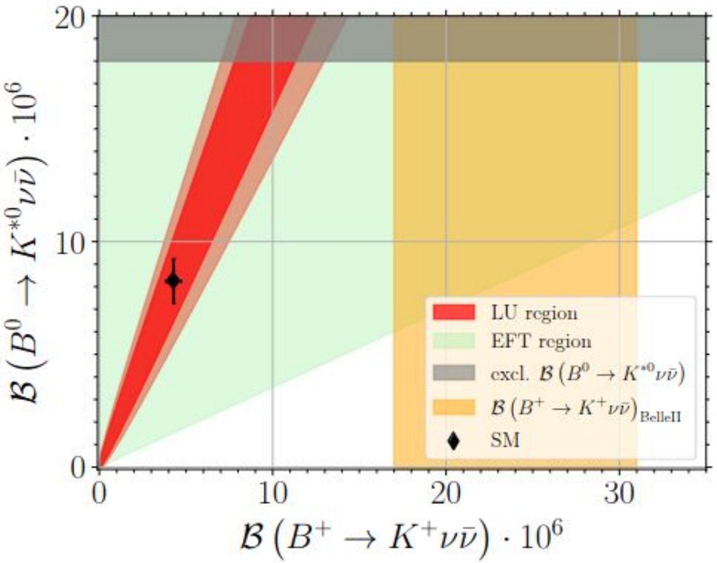
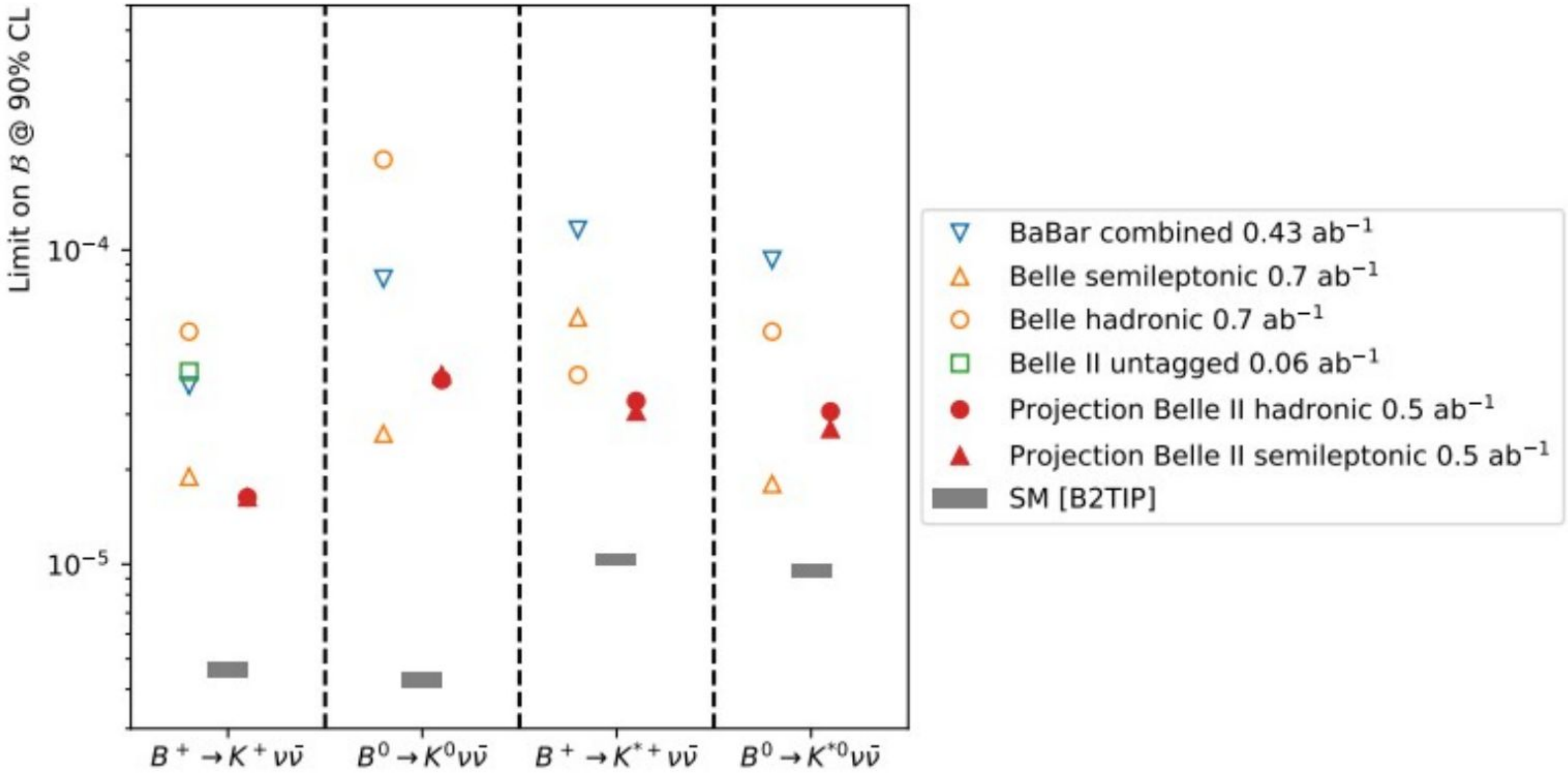


Figure 2: Branching ratios of $B \to K^{0*}\nu\bar{\nu}$ and $B^+ \to K^+\nu\bar{\nu}$ in the SM (black cross), where for graphical reasons the uncertainty in $\mathcal{B}\left(B^+ \to K^+\nu\bar{\nu}\right)$ has been inflated to 10% to the value in (3). In addition, the Belle II data (1) (vertical orange band) and the 90 % CL excluded region (10) (horizontal gray area) are shown. The red (dark red) area (15) denotes the 1σ (2σ) region that is consistent with lepton flavor universality. The green area is the one consistent with (6) and (19).

Prospects

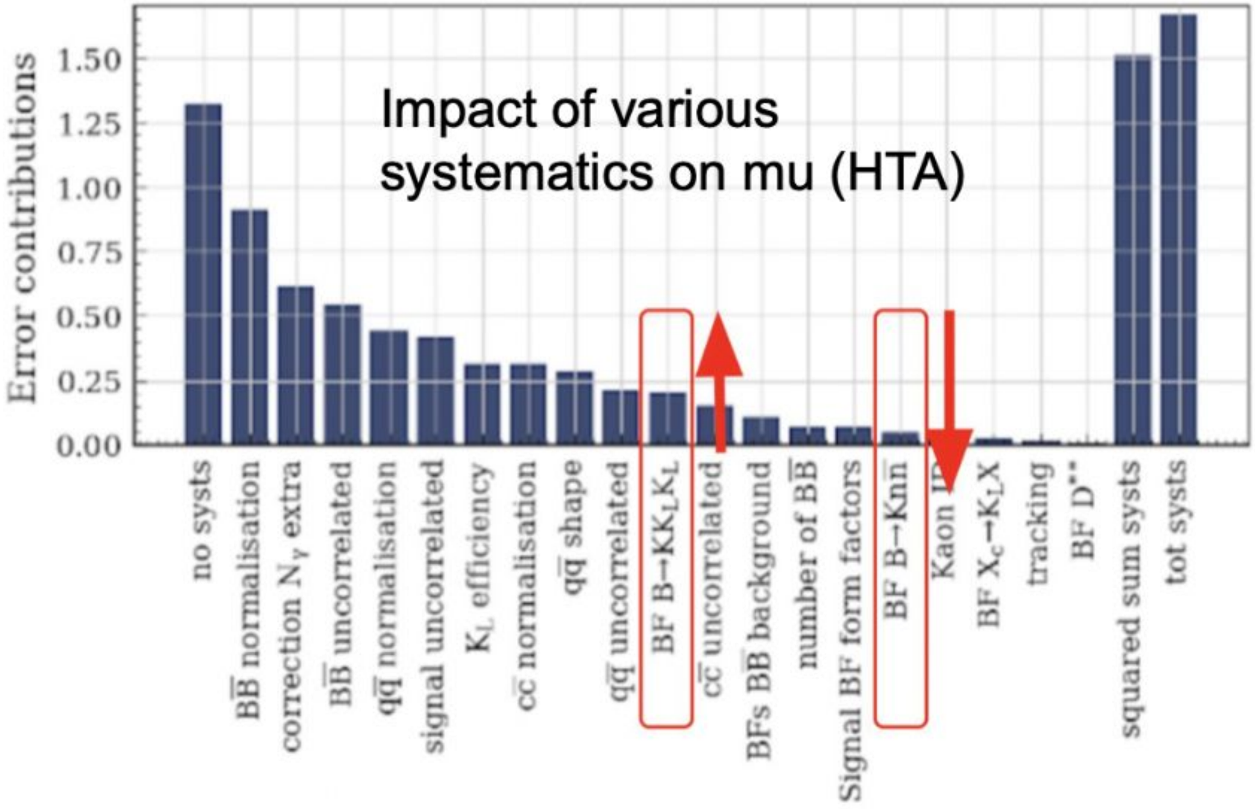


Limit on $\mathcal{B}$ @ 90% CL
10^{-4}
10^{-5}
$B^+ \to K^+ \nu\bar{\nu}$
$B^0 \to K^0 \nu\bar{\nu}$
$B^+ \to K^{*+} \nu\bar{\nu}$
$B^0 \to K^{*0} \nu\bar{\nu}$
BaBar combined 0.43 ab^{-1}
Belle semileptonic 0.7 ab^{-1}
Belle hadronic 0.7 ab^{-1}
Belle II untagged 0.06 ab^{-1}
Projection Belle II hadronic 0.5 ab^{-1}
Projection Belle II semileptonic 0.5 ab^{-1}
SM [B2TIP]

“no systs”: all errors fixed to zero, fit is performed. We take the best fit. What is left is not exactly the stat. unc.

stat unc.: Take all the yields from the data hist, make every yield vary according to a Poisson and then perform the fit (with cysts.) for each toy.

Correlation b/w stat and cyst.



in B centre of mass of mass

$$p_{K*}^2 = (p_B - p_{\nu\overline{\nu}})^2$$

becomes

$$(m_B - E_{\nu\overline{\nu}})^2 - p_{\nu\overline{\nu}}^2 = m_{K*}^2$$

that is an hyperbola and has as asymptote

$$E_{\nu\overline{\nu}} + p_{\nu\overline{\nu}} = m_B$$