Search for New Physics with invisible particles in Belle II

Jacopo Cerasoli
IPHC Strasbourg

CPPM seminar
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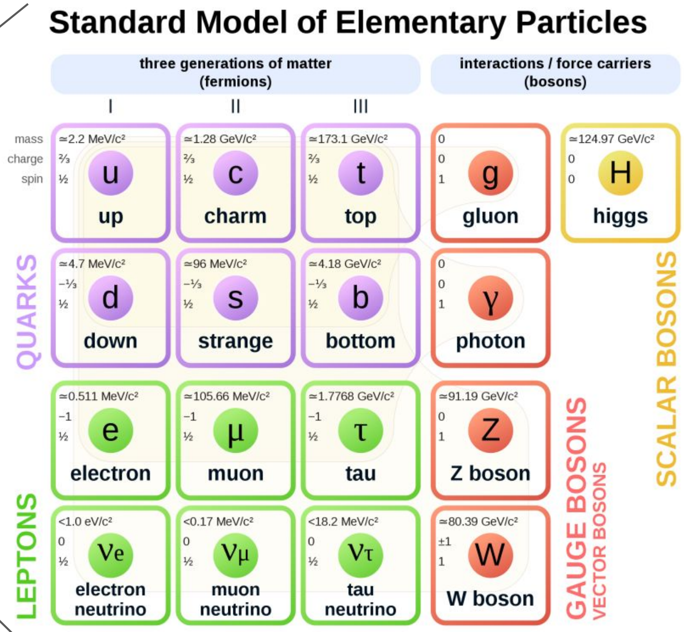
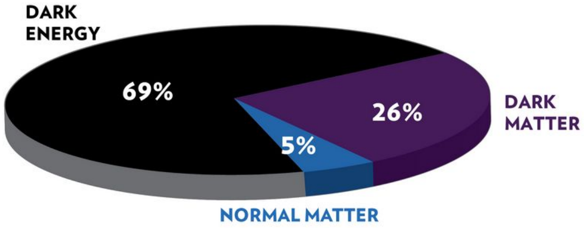
The ultimate question of life, the universe, and everything

- Standard Model is incredibly successful, but presents several shortcomings
  - Dark energy and matter, matter - anti-matter asymmetry, gravity, mass hierarchy, …





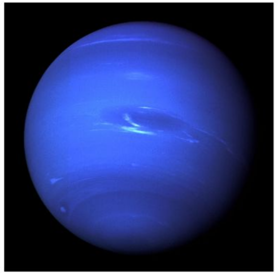
Precision physics

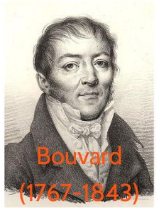
- Two main methods to search for **new physics beyond the SM**:
  - Direct searches of new particles
  - Indirect searches: measurements of SM observables and comparison with theory predictions

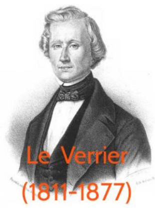
Today!

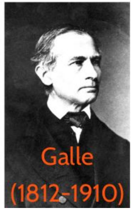
Uranus, discovered 1781

Neptune, discovered 1846 after observing perturbations in Uranus' orbit





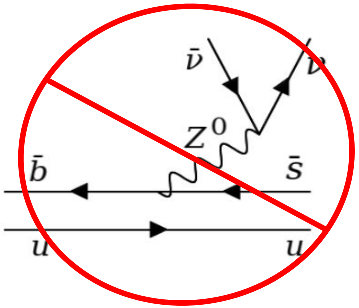


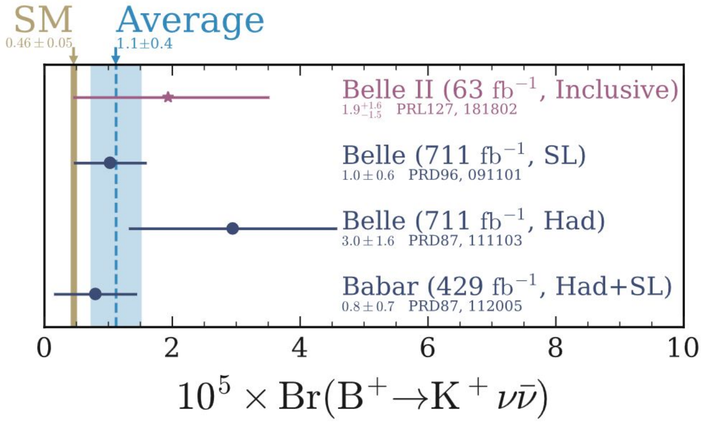


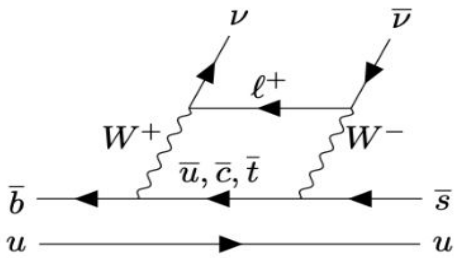
"This could be the greatest discovery of the century. Depending, of course, on how far down it goes..."

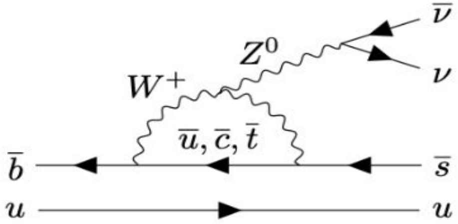
$B^+ \to K^+ \nu\nu$ decay

- b → s transition with missing energy, suppressed in the SM
- $BR_{SM}(B^+ \to K^+\nu\nu) = (5.58 \pm 0.37) \times 10^{-6}$ Phys. Rev. D 107, 119903
- New mediators or new final state particles could affect the branching ratio
  - → **Indirect way to probe multi-TeV scale**





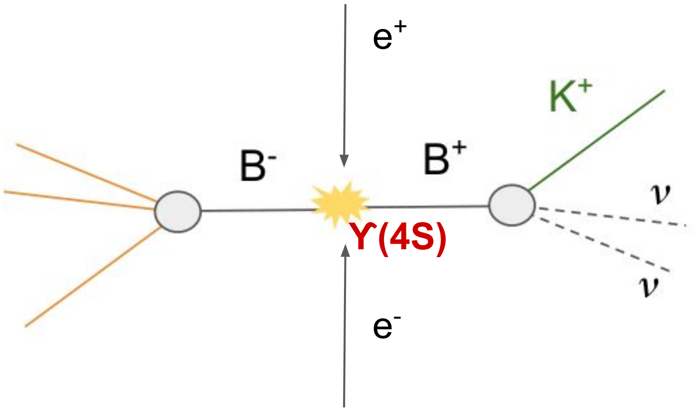


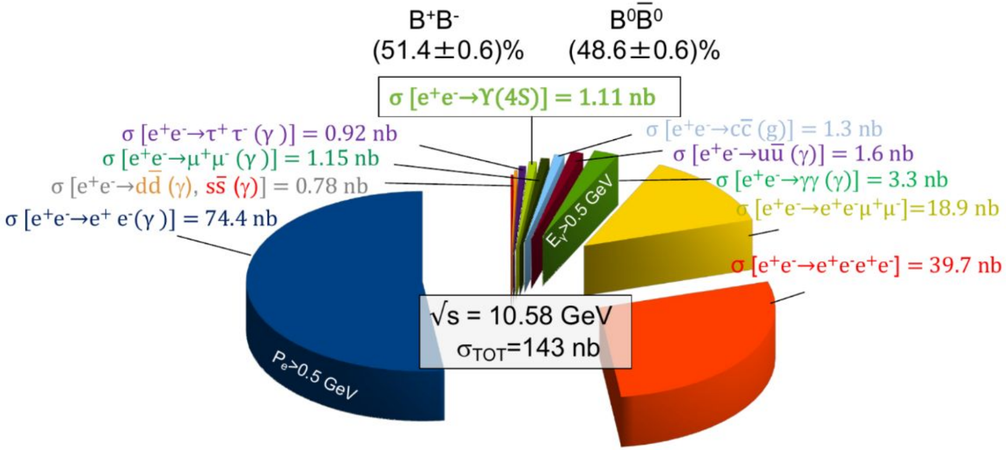


Funny story here

Where to look for *B* mesons?

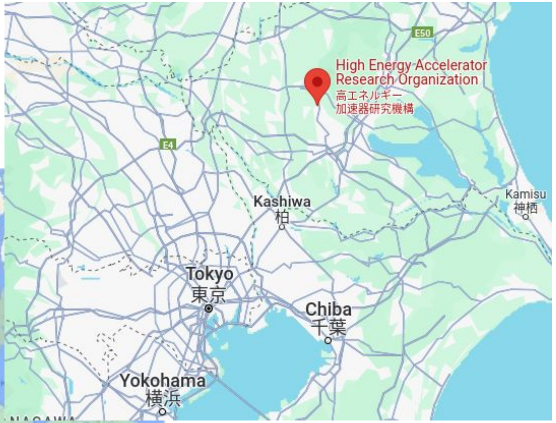
- ***B* factories**: $e^+ e^-$ beams collided asymmetrically at ϒ(4S) energy
  - High amount of *B* mesons produced, but also τ leptons and charm quarks





- First-generation *B* factories: Belle @ KEKB and BaBar @ PEP-II
  - Confirmation of CKM mechanism, b → c τ ν, direct CPV in *B* decay
- Higher luminosity required → Second-generation *B* factory: Belle II @ SuperKEKB

The Belle II collaboration



- ~1000 members from 28 countries, experiment located at KEK lab in Tsukuba, Japan

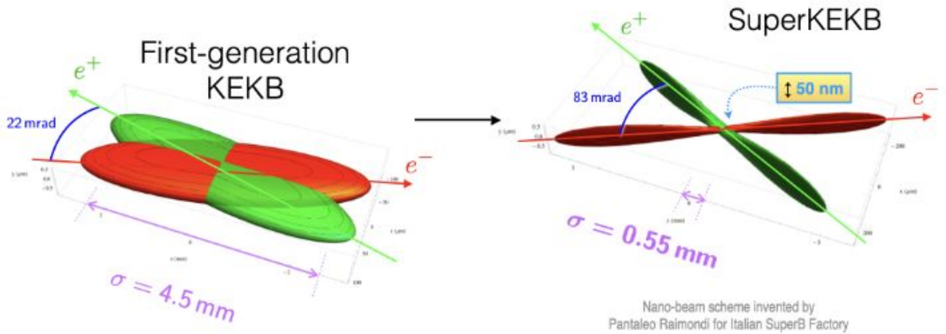
The SuperKEKB accelerator

KEK Report 2010-1

- Upgrade of KEKB to reach 10^{35} cm^{-2} s^{-1} regime…
- … for the moment: **instantaneous luminosity world record @ 4.7 x 10^{34} cm^{-2} s^{-1}**

e^- 7 GeV → ← e^+ 4 GeV

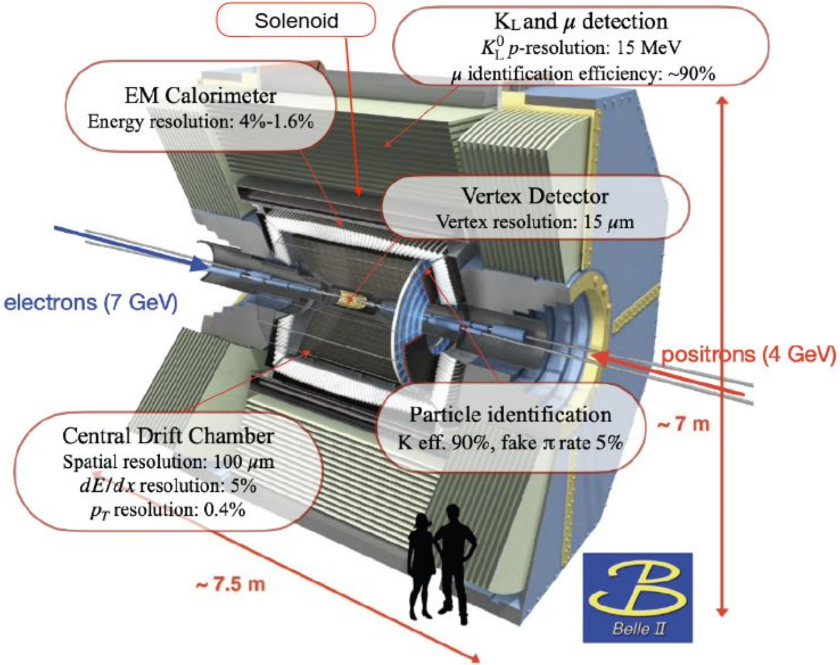
Nano-beam scheme driving the improvement

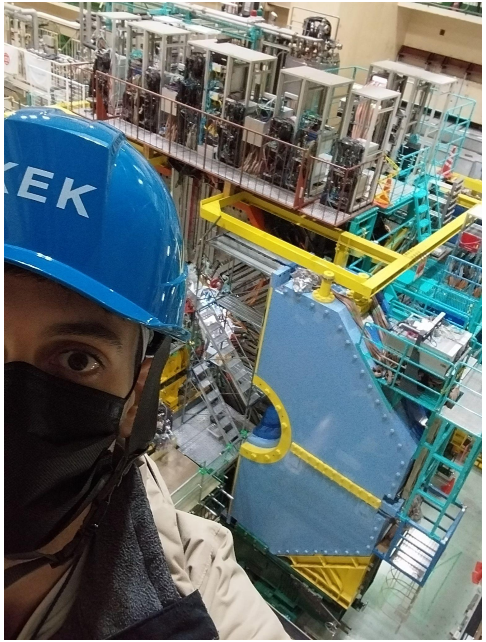


The Belle II detector

KEK Report 2010-1

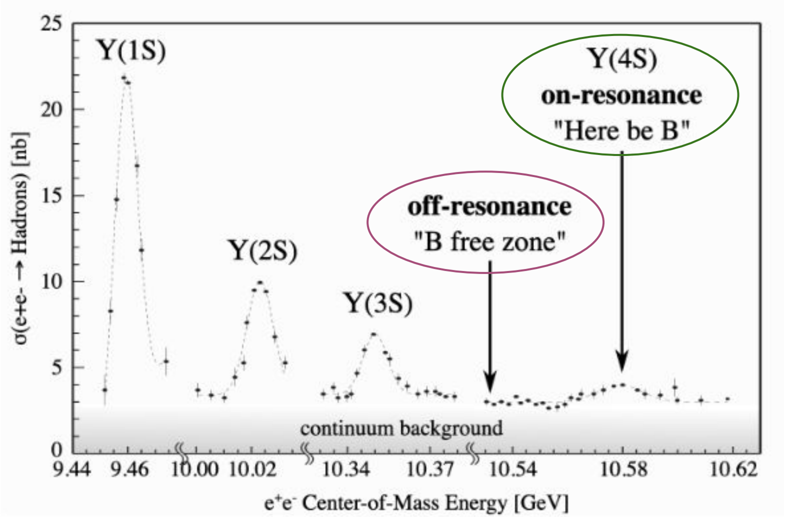
- Suited (among others) for measurements with **neutrals, missing energy and inclusive decays**
- High photon detection efficiency and good energy resolution (π^0 mass resolution ~ 5 MeV)
- Good and similar electrons and muons identification efficiency

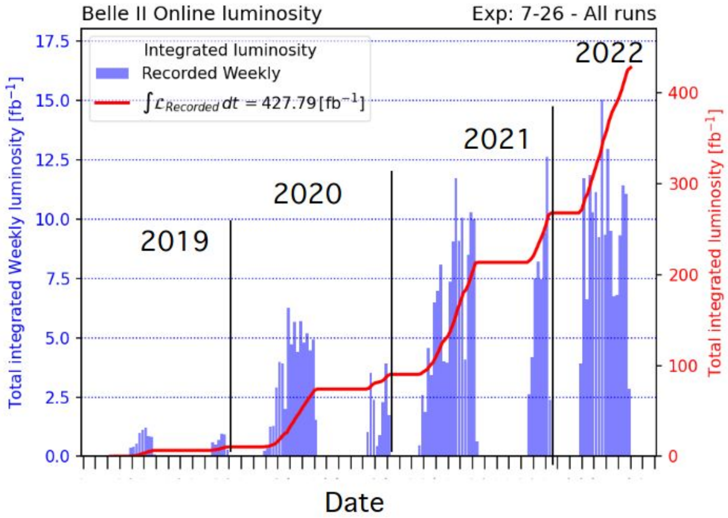




Dataset

- In 2019-2022 collected:
  - 362 fb^{-1} @ Υ(4S) energy → corresponding to ~ 387 · 10^6 BB pairs
  - 42 fb^{-1} off-resonance data → used for characterization of "continuum background"





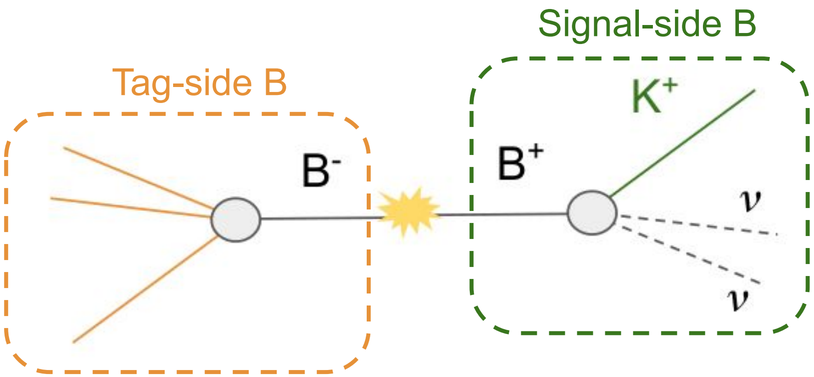
- Detector and accelerator underwent improvement work during Long-Shutdown 1
- **Data-taking restarted on 21/02/2024**, aiming at collecting 50 ab^{-1} at the end of Belle II operation

Search for the $B^+ \to K^+ \nu\nu$ decay

Experimental challenges

- Low branching fraction with large background
- No signal peak, continuum spectrum for signal kaon momentum
- Only **one track in the final state** 😅

- We can exploit some unique features of Belle II:
    - **Initial 4-momentum** is known
    - Detector covers ~ **full solid angle**
    - Υ(4S) decays into **pairs of B mesons**



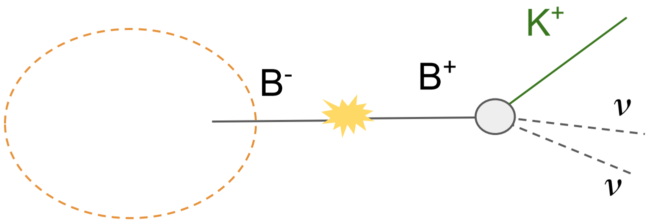
→ reconstruct the *tag-side* B to constrain the kinematics on the signal-side

Two (almost) independent methods

[ArXiv:2311.14647](https://arxiv.org/abs/2311.14647)
Accepted by PRD

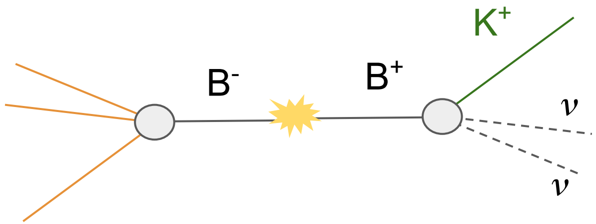
Inclusive tagging analysis (ITA)

Identify signal kaon candidate and assign the *rest-of-event* (ROE) to the B_{tag}



Hadronic tagging analysis (HTA)

Reconstruct B_{tag} hadronically, pair to it a signal kaon candidate



~ 1 % — **Purity** → **~ 7 %**

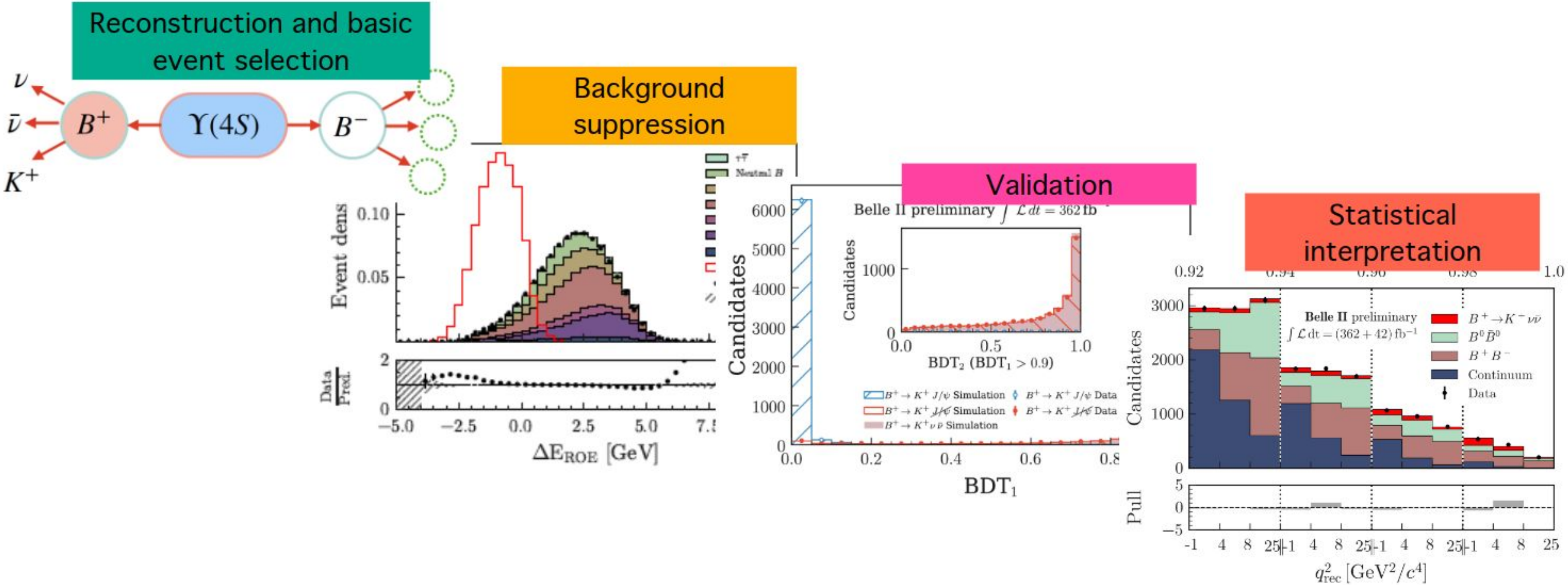
~ 10 % ← **Efficiency** — **~ 0.5 %**

After full selection, ~ 2 % of ITA samples corresponds to 50 % HTA sample

Analysis flow in a nutshell

ArXiv:2311.14647

Accepted by PRD

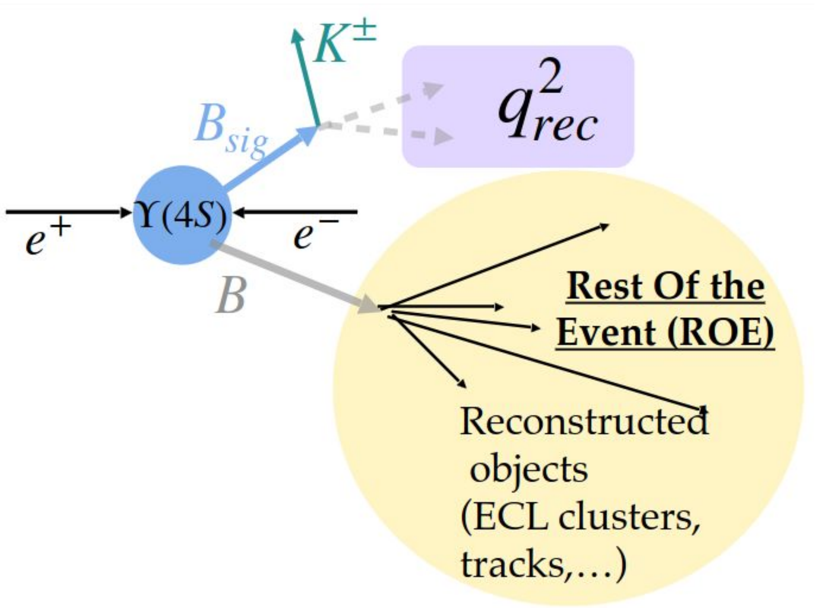


- Except for tagging method, HTA and ITA are kept as similar as possible in all steps

Event reconstruction in ITA

ITA

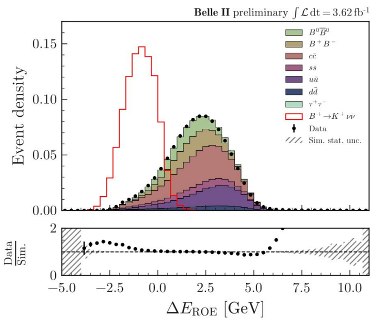
1. K^+ candidate track: at least 1 vertex detector hit and requirement on kaon identification
    - ~68 % kaon efficiency with ~1 % $K \to \pi$ mis ID
2. Identify rest-of-event:
    - Charged particles, photons, K^0_S
3. Compute q^2 of neutrino pair: $q^2_{rec} = \frac{s}{4} + M_K^2 - \sqrt{s} E_K^*$
    - Keep the candidate with lowest q^2 in the event

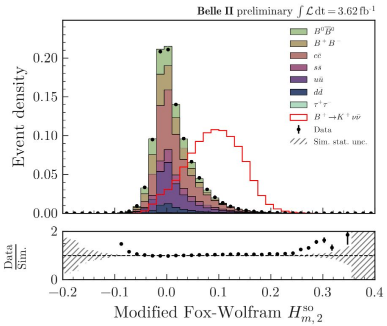


Background suppression

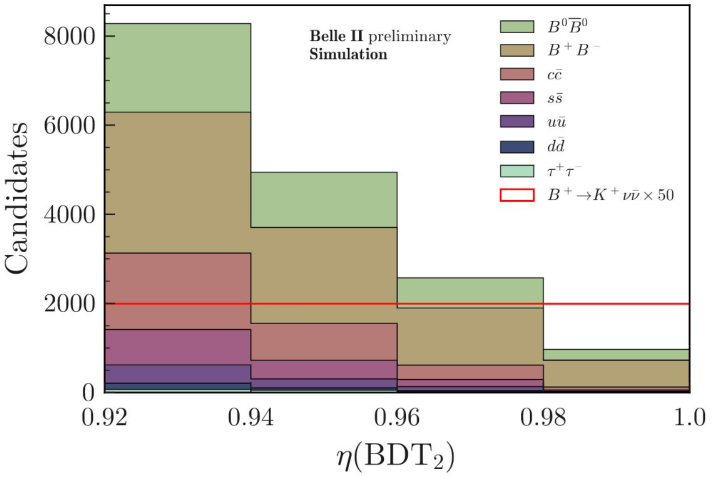
ITA

- Background further suppressed with **two BDTs** in sequence
- BDT1 trained with 12 input variables
  - Most powerful is ROE energy - half c.m. energy
  - Significant discrimination from Fox-Wolfram momenta
- BDT2 trained with 35 variables after cut on BDT1 > 0.9
  - Output flattened on signal sample and called η(BDT2)





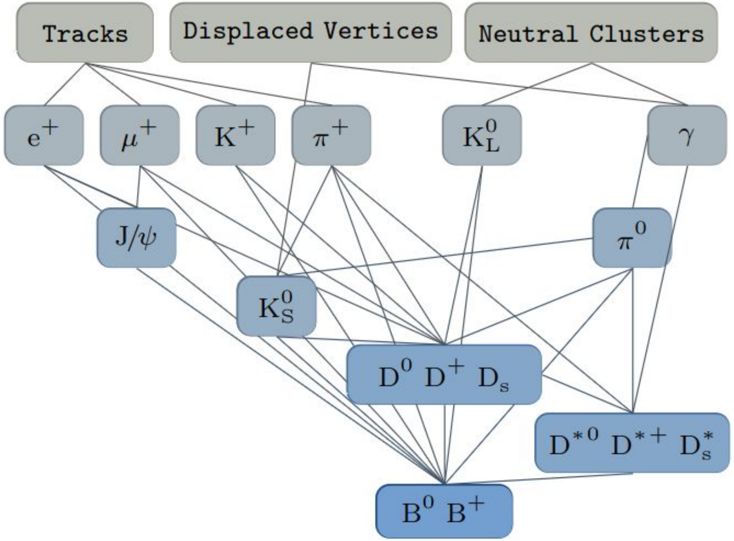
- **Signal region** defined as η(BDT2) > 0.92
  - Total efficiency ~ 8% at ~ 0.8% purity (expected)



Full Event Interpretation [Comput Softw Big Sci 3, 6 (2019)]

HTA

- Tool for ***B*** **reconstruction** in hadronic/semileptonic modes
- Hierarchical approach based on BDTs
  - Reconstruct final state particles
  - Combine final state particles into intermediates
  - Combine intermediates and FSPs into *B* candidates

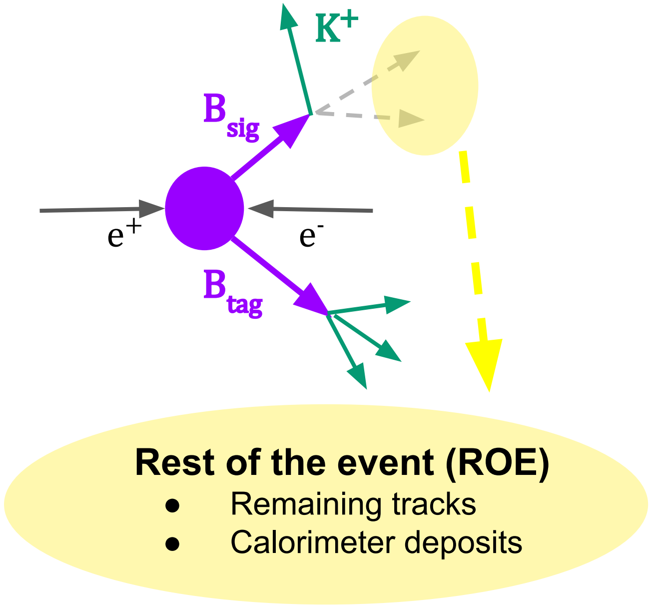


- FEI reconstructs B decays in **~ 10k modes**
- Last BDT interpreted as "*B* probability"
- Overall performances: ~ 1-2 % efficiency at ~ 5-10 % purity

Event reconstruction in HTA

HTA

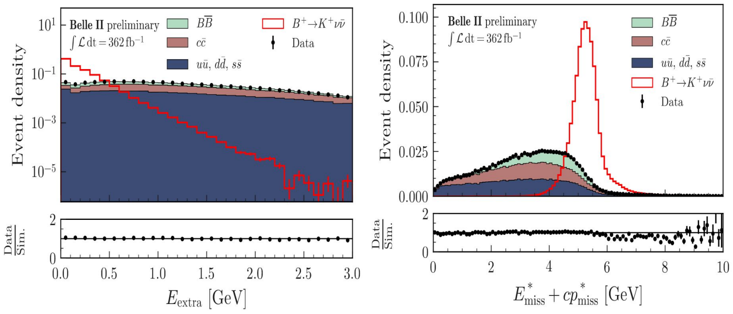
1. Reconstruct B_{tag} using hadronic FEI
2. K^+ candidate track paired to B_{tag}
   - B_{tag} and K^+ must have opposite charge
3. Identify rest-of-event:
   - No “clean” tracks in ROE
   - No K^0_S, π^0 or Λ^0 in ROE



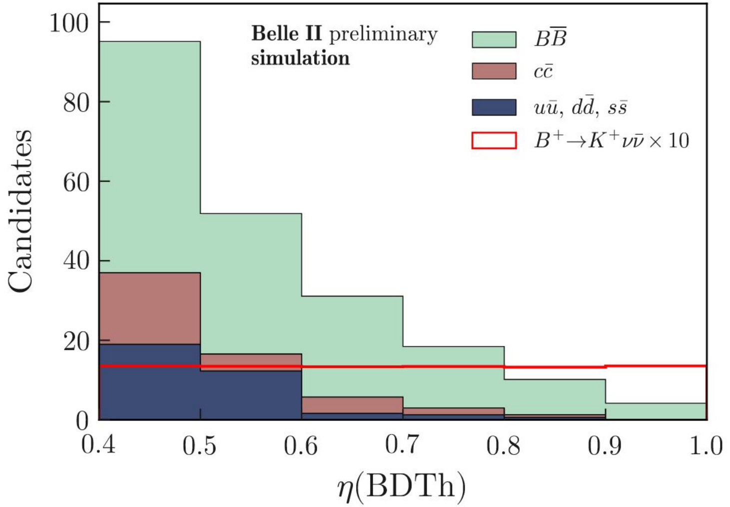
Background suppression

HTA

- Background suppressed with **single BDTh using 12 variables**
  - Most powerful is energy of neutrals in rest-of-event
  - Significant discrimination from sum of missing energy and momentum



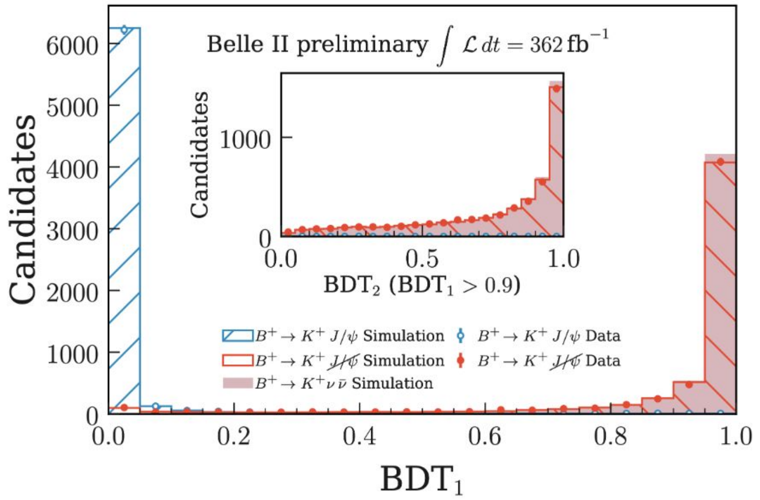
- BDT output flattened on signal events
- **Signal region** defined as η(BDTh) > 0.4
  - Total efficiency ~ 0.4% at ~ 7% purity (expected)



Validation

Signal efficiency validation

- Signal efficiency of BDT selection validated using **embedding procedure**:
  - Select $B^+ \to K^+ J/\Psi (\to \mu^+ \mu^-)$ candidates in data and MC
  - Remove muons and replace K^+ with the ones from signal MC
  - Adjust K^+ kinematics in order to match original B^+ momentum and decay vertex



Data/MC efficiency ratio:

ITA = 1.00 ± 0.03

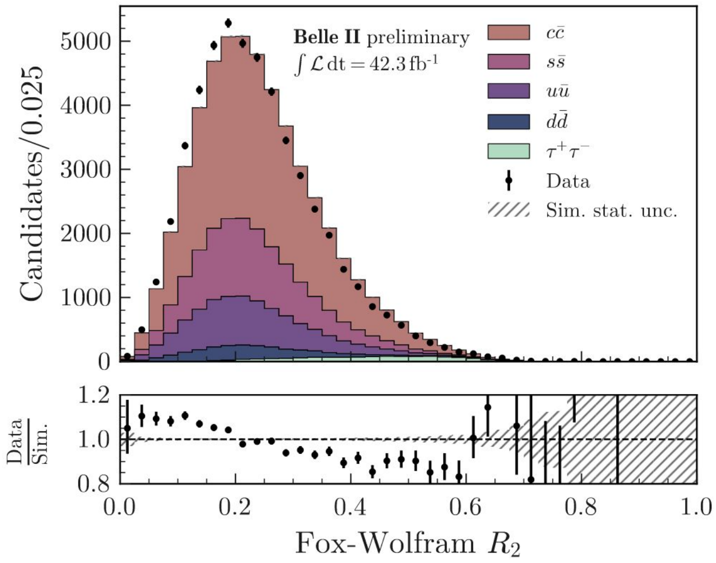
HTA = 0.60 ± 0.10 (in agreement with FEI efficiency calibration)

Uncertainty assigned as systematic

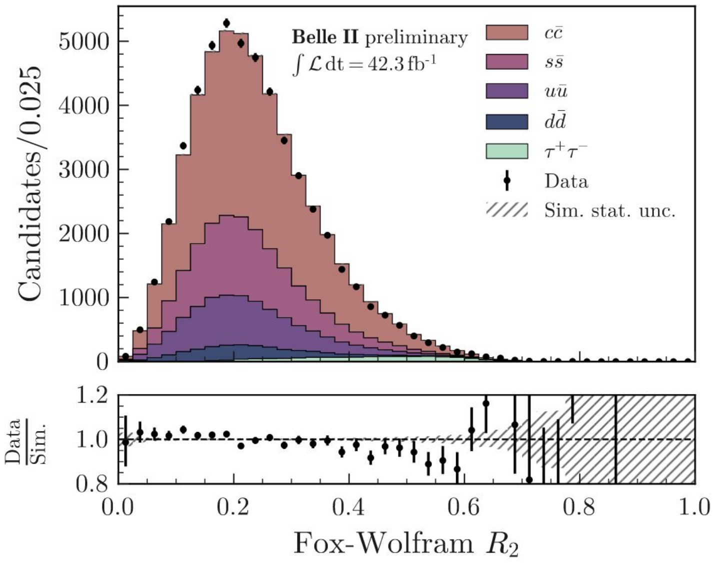
Background validation: continuum

- **Continuum background** ($e^+e^- \to uu, dd, cc, ss$) represents ~30-40% of total background in signal region
- Correction derived from **off-resonance data**
  - Overall normalization correction factor included as systematic uncertainty
  - Shape corrected by applying event-by-event weight J. Phys.: Conf. Ser. 368 012028

Before corrections

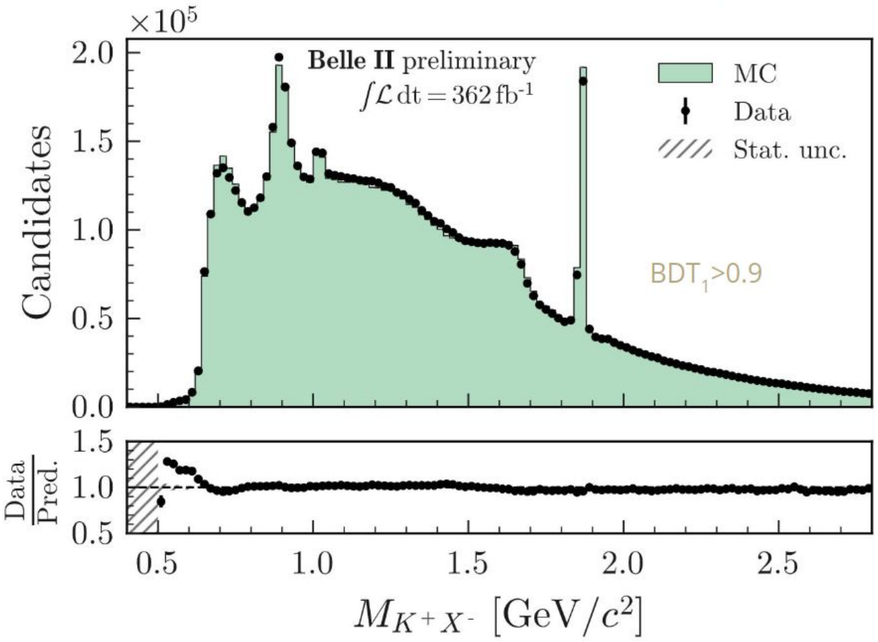


After corrections



Background validation: $B \to D\,(\to K^+ X)\, l\, \nu$

- **Semileptonic *B* decays with K^+ coming from *D* mesons** represent ~50-60% of *B* background
- Distributions checked throughout the analysis → well modeled by the simulation

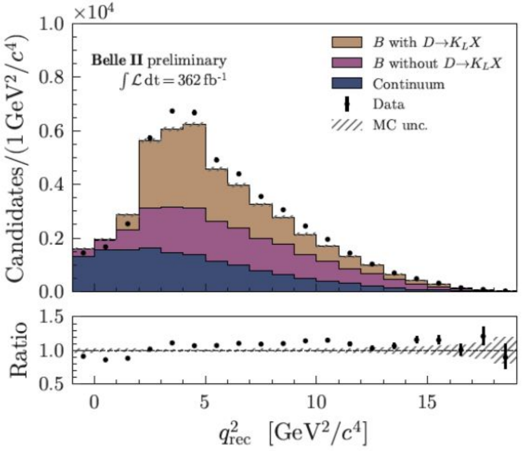


- Example: invariant mass of K^+ and a charged particle from ROE after BDT1>0.9

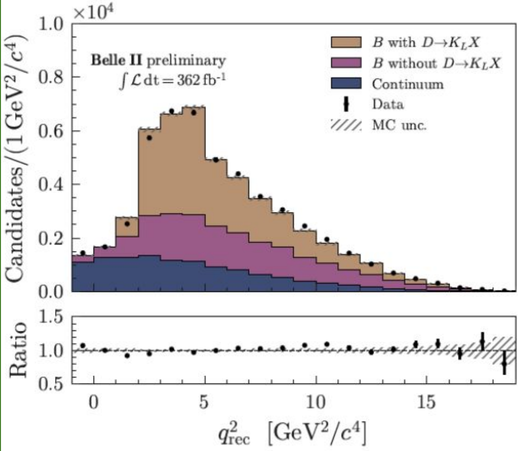
Background validation: $B \to K^+ D^{(*)}$ ($\to K^0_L X$)

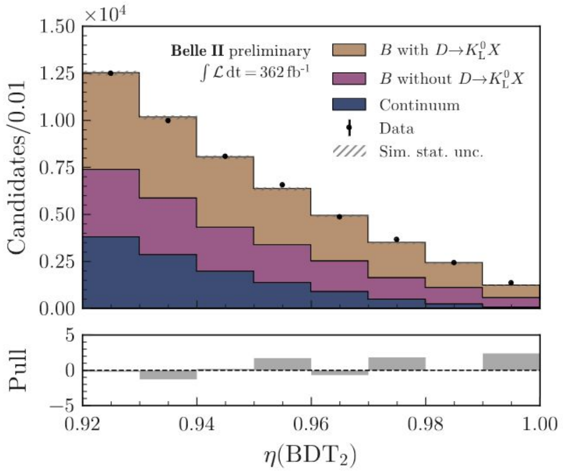
- **Hadronic $B \to K^+ D^{(*)}$** decays represent ~20-40% of B background
  - Sizable and poorly-known branching fractions of $D \to K^0_L X$
- +30% correction on decays with $B \to D \to K^0_L X$ derived from pion-enriched sample
- Muon- and electron-enriched samples used to validate the correction and add 10% systematic

Before scaling



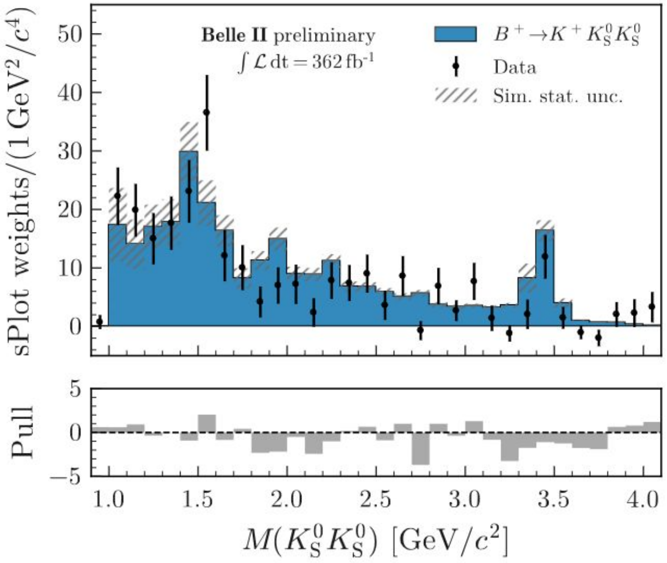
After scaling

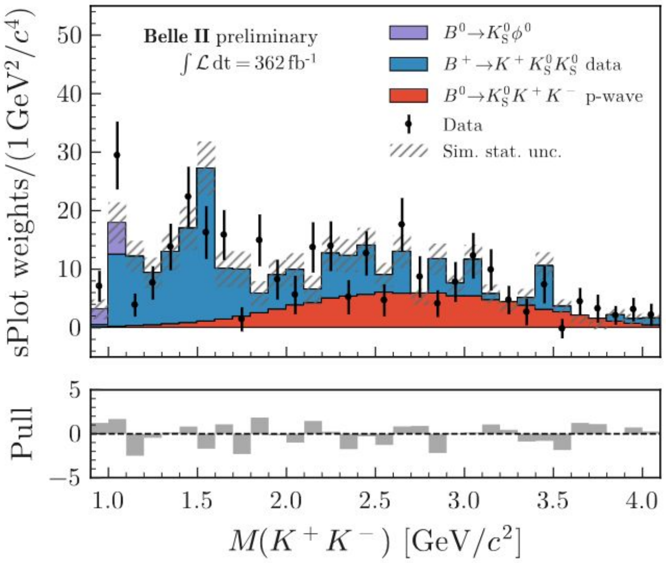




Background validation: $B \rightarrow K^{+} X^{0} X^{0}$

- Remaining background from $B^{+} \rightarrow K^{+} K^{0} K^{0}$ **and** $B^{+} \rightarrow K^{+} nn$
  - Can mimic the signal if neutrals are not reconstructed
- $B^{+} \rightarrow K^{+} K^{0} K^{0}$ validated using $B^{+} \rightarrow K^{+} K^{0}_{S} K^{0}_{S}$ and $B^{0} \rightarrow K^{0}_{S} K^{+} K^{-}$: good agreement observed





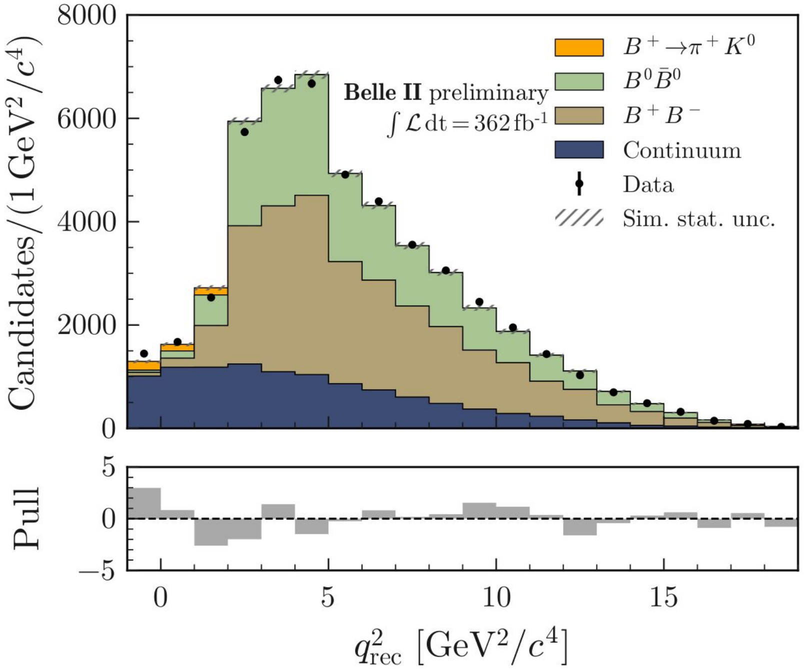
- $B^{+} \rightarrow K^{+}\, n\, n$ modeled using measurements of $B^{+} \rightarrow K^{+}\, p\, p$
- Uncertainties included as systematics

Closure test: measurement of $B^+ \to \pi^+ K^0$ with ITA

- **Measure the known and rare $B^+ \to \pi^+ K^0$ decay** to validate analysis strategy
- Full nominal analysis chain except:
  - Pion ID instead of kaon ID
  - Different q^2 boundaries

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

$BR_{SM}(B^+ \to \pi^+ K^0) = (2.3 \pm 0.08) \times 10^{-5}$

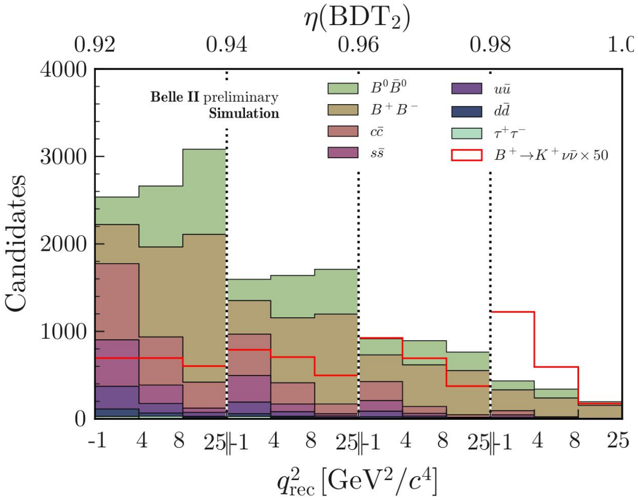


Results

Signal extraction setup

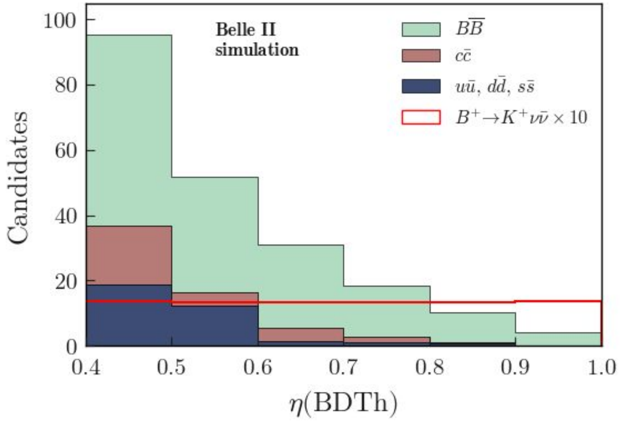
- **ITA performs binned maximum likelihood fit**:
  - η(BDT2) x q^2 x on/off resonance bins

    4 x 3 x 2
- **Similar strategy for HTA**, simpler setup: 6 bins of η(BDT)
- Uncertainties included as gaussian constraints



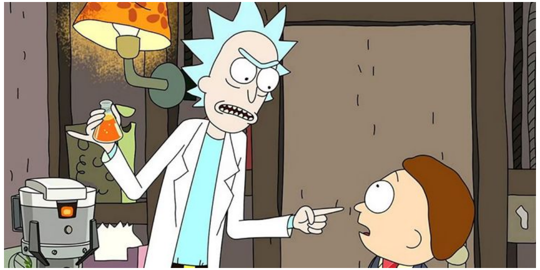
- Fit parameter is signal-strength μ

$$\mu = \frac{\mathrm{BR}(B^+ \to K^+\nu\nu)}{\mathrm{BR_{SM}}(B^+ \to K^+\nu\nu)}$$



Main systematic uncertainties

“Sometimes science is more art than science”



SPOILER

Statistical Δ_μ ITA ~ 1.0

Statistical Δ_μ HTA ~ 1.8

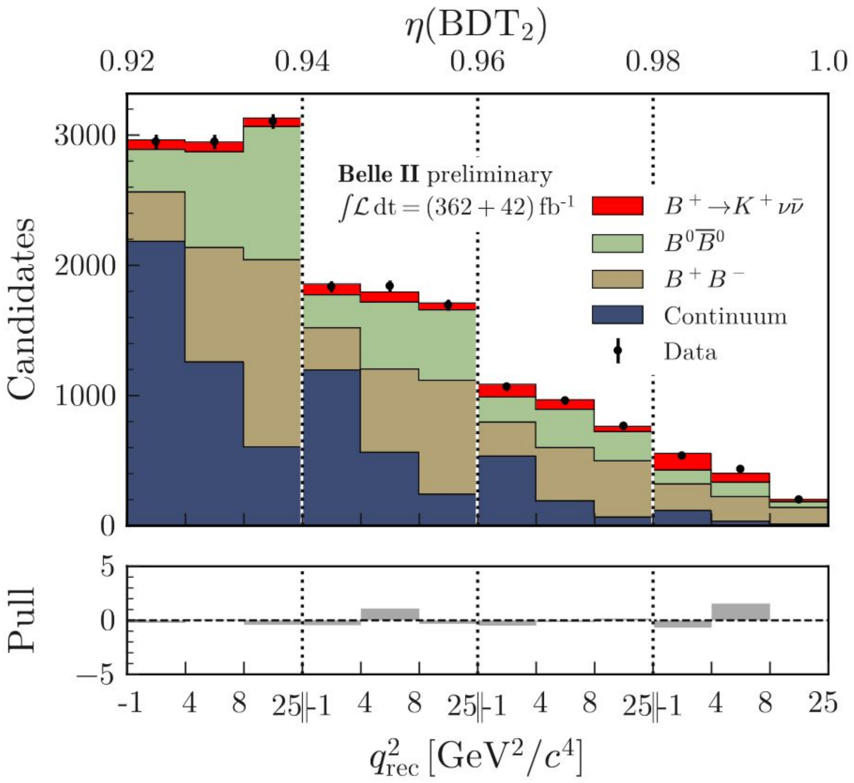
ITA

- **BB normalization**: Δ_μ = 0.90
- **Simulated sample size**: Δ_μ = 0.52
- **BR($B^+ \to K^+ K^0_L K^0_L$)**: Δ_μ = 0.49
- **BR($B \to D^{**} K^+$)**: Δ_μ = 0.42

HTA

- **BB normalization**: Δ_μ = 0.91
- **Extra-photons energy correction:** Δ_μ = 0.61
- **Simulated sample size**: Δ_μ = 0.60
- **Continuum normalization**: Δ_μ = 0.58

ITA results



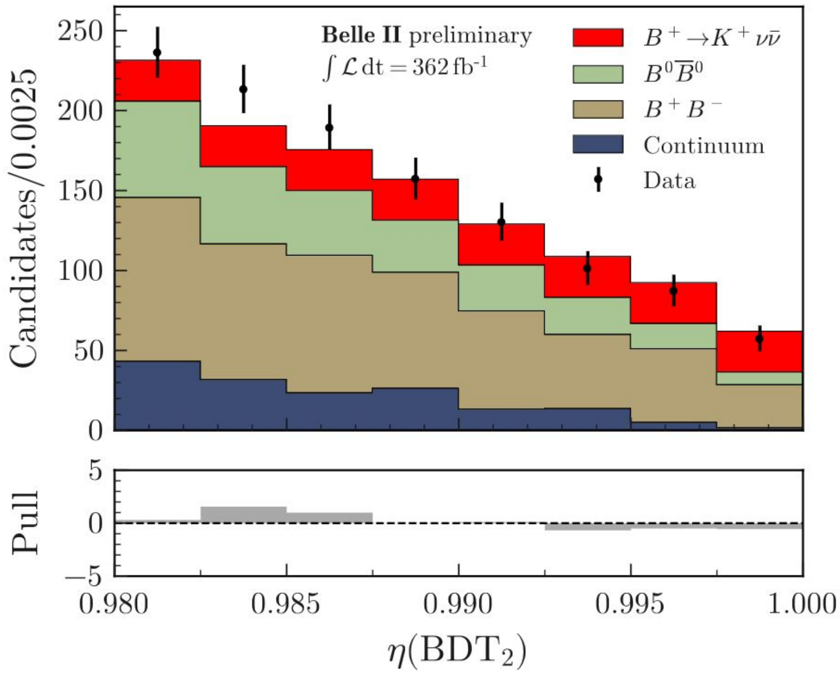
$$\mu = 5.4 \pm 1.0(\mathrm{stat}) \pm 1.1(\mathrm{syst})$$

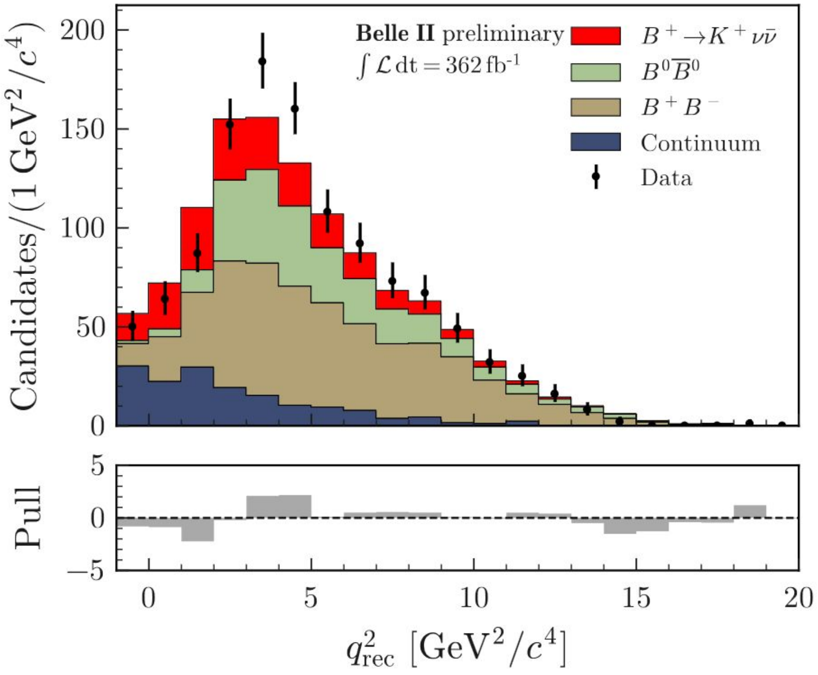
$$\mathrm{BR} = (2.7 \pm 0.5(\mathrm{stat}) \pm 0.5(\mathrm{syst})) \times 10^{-5}$$

- **3.5 σ significance** wrt background-only hypothesis
- **2.9 σ significance** wrt Standard Model prediction

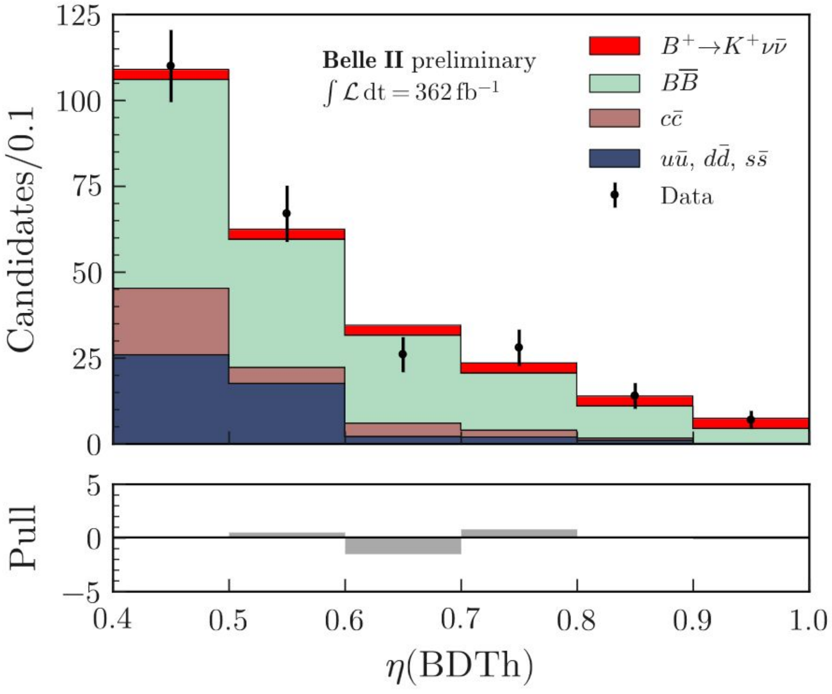
Post-fit distributions in ITA

- $\eta(\mathrm{BDT}_2) > 0.98$
- Good agreement in BDT distribution, some discrepancies in q^2 but not significant





HTA results

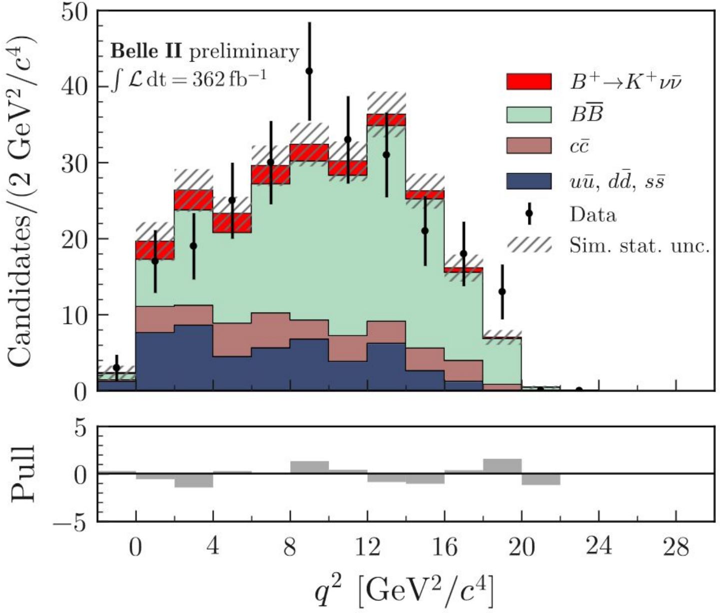


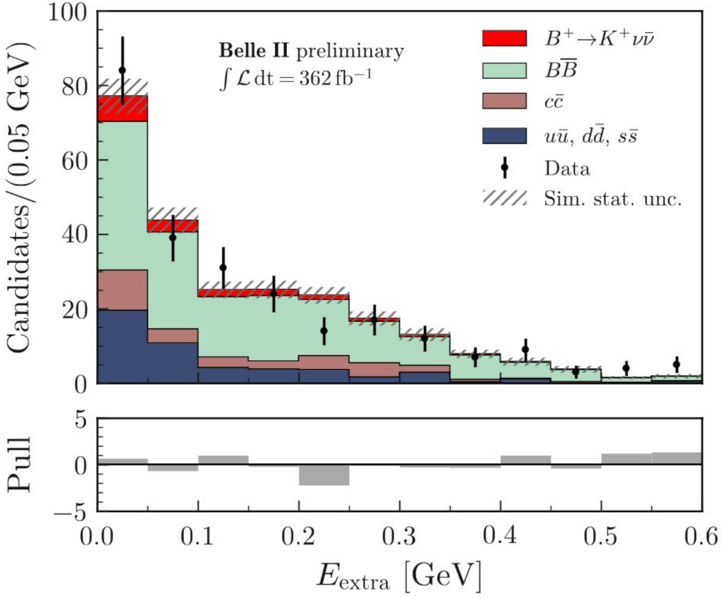
$$\mu = 2.2^{+1.8}_{-1.7}(\mathrm{stat})^{+1.6}_{-1.1}(\mathrm{syst})$$
$$\mathrm{BR} = 1.1^{+0.9}_{-0.8}(\mathrm{stat})^{+0.8}_{-0.5}(\mathrm{syst}) \times 10^{-5}$$

- **1.1 σ significance** wrt background-only hypothesis
- **0.6 σ significance** wrt Standard Model prediction

Post-fit distributions in HTA

- η(BDTh) > 0.6
- Good agreement in BDT and E_{extra}* distributions

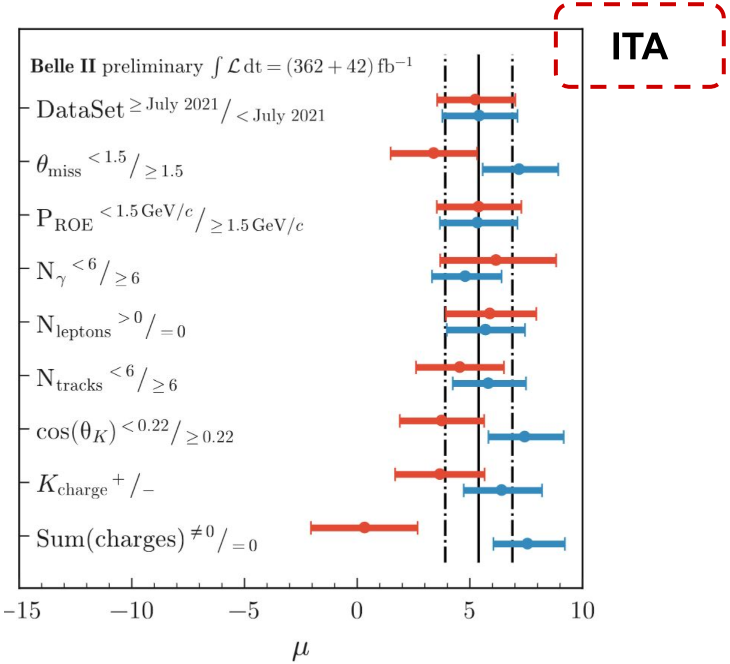


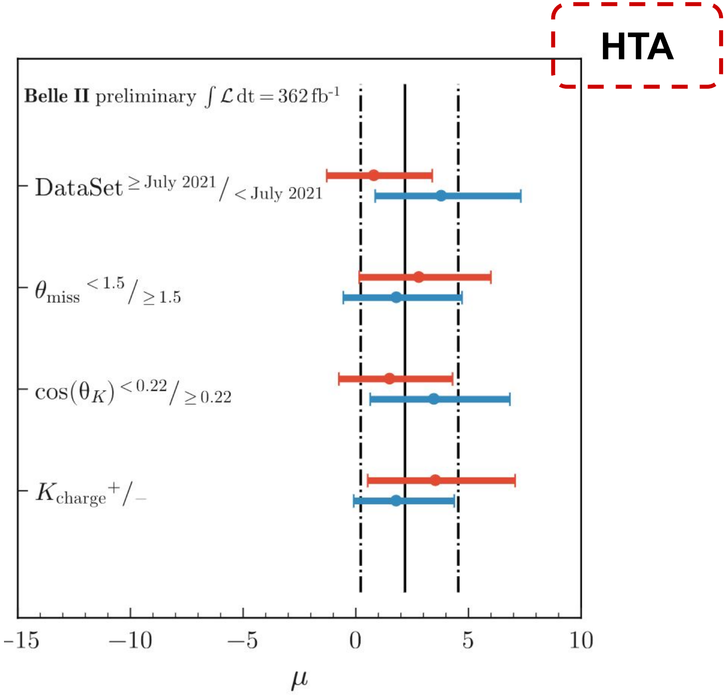


* Most important BDT variable

Consistency checks: split samples

- Split the dataset into statistically independent subsamples

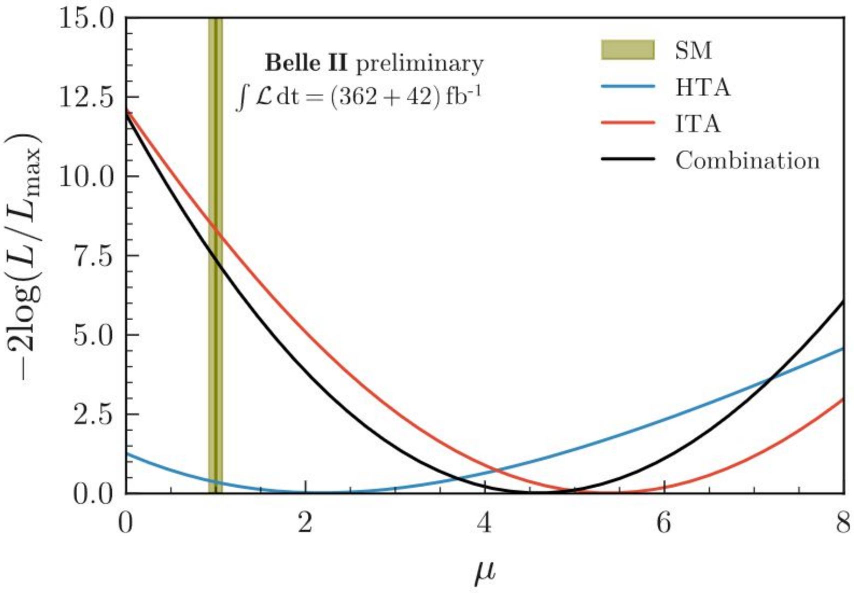




- 2.4 σ discrepancy in Sum(charges) for ITA, no systematic effects found during investigation

Combination of the measurements

- ITA and HTA compatible at 1.2 σ
- Common events removed from ITA (~ 2% of dataset), common systematics taken into account

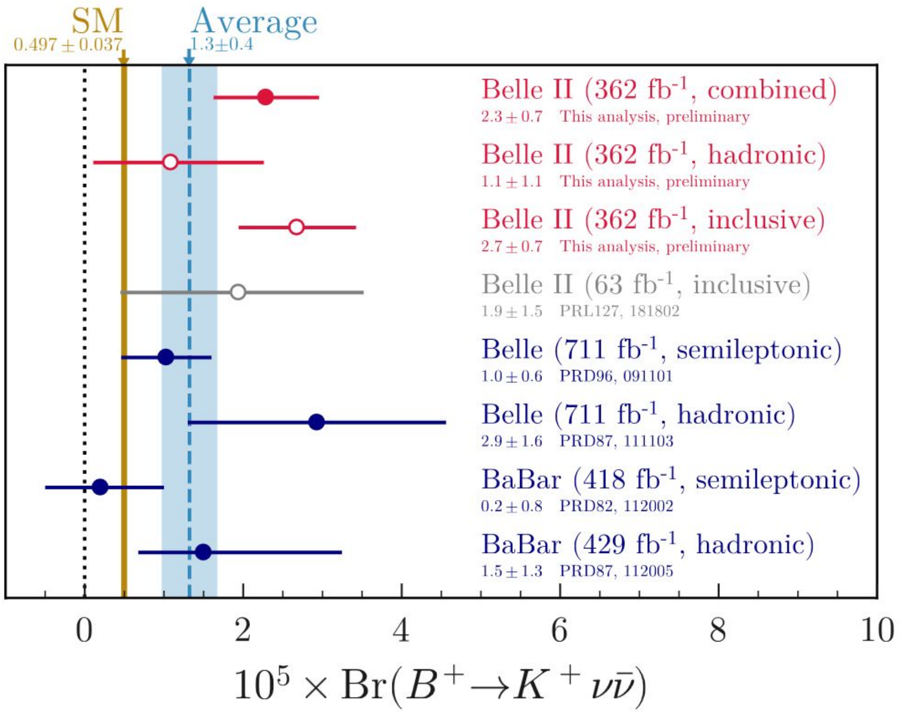


$$\mu = 4.6 \pm 1.0(\text{stat}) \pm 0.9(\text{syst})$$
$$\text{BR} = (2.3 \pm 0.5(\text{stat})^{+0.5}_{-0.4}(\text{syst})) \times 10^{-5}$$

- **3.5 σ significance** wrt background-only hypothesis
- **2.7 σ significance** wrt Standard Model prediction
- 10% improvement on ITA result

Evidence for $B^+ \to K^+ \nu\nu$ decays

New state of the art

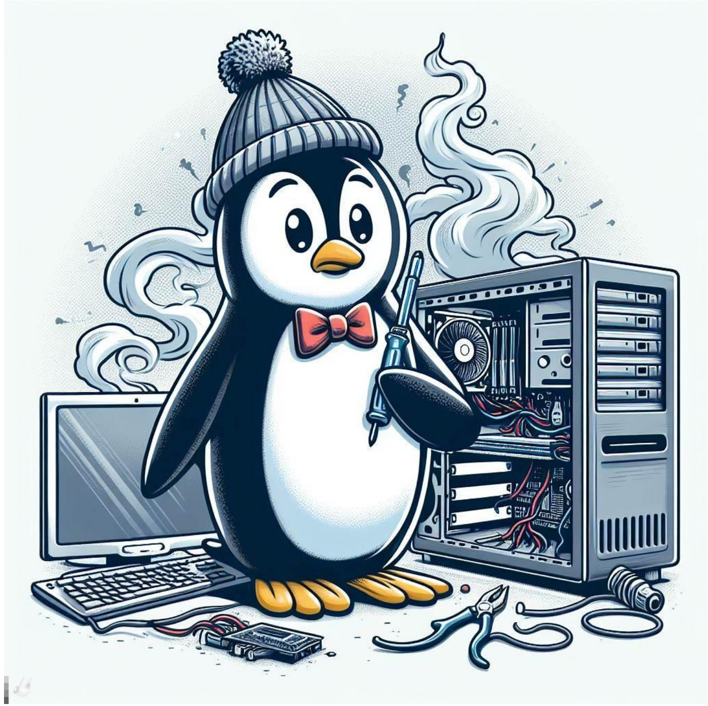


- Combined measurement shows **2.7 σ tension wrt SM**
- ITA precision comparable to previous best results
- HTA best hadronic-tag measurement
- Overall good agreement between measurements
  - χ^2/ndf = 5.6/5 → p = 35 %

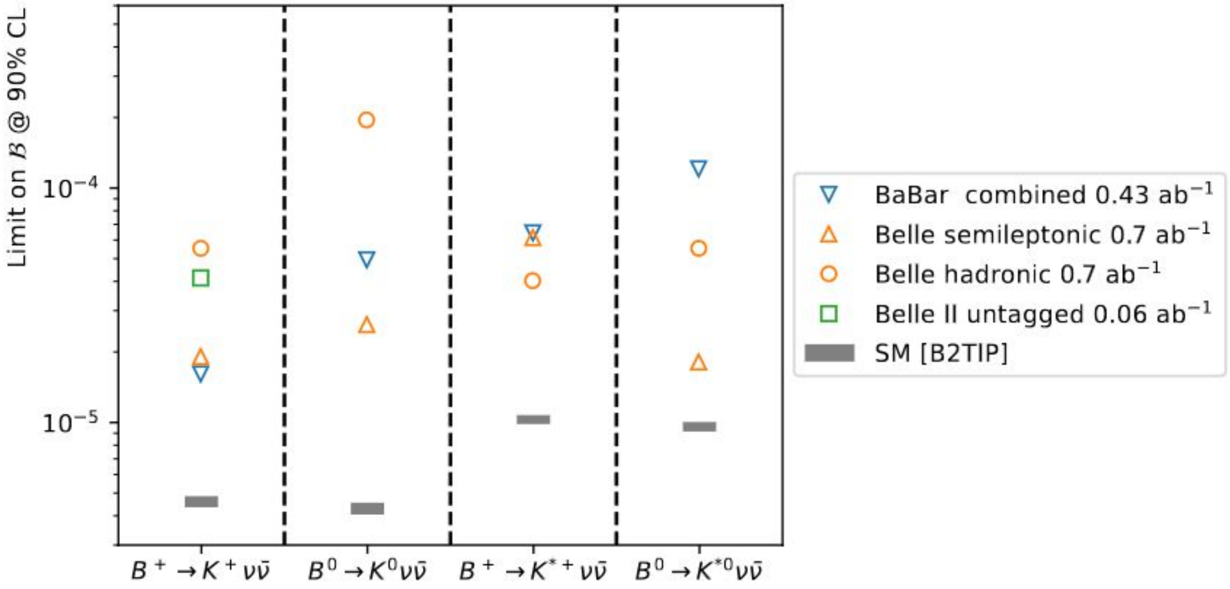
What next?

- **Rich and diversified physics program** at Belle II @ SuperKEKB
- 362 fb^{-1} collected, road to 50 ab^{-1} by the end of Belle II operation
- Intriguing 2.7 σ discrepancy wrt the Standard Model in $B^+ \to K^+ \nu\nu$ decays
  - Inclusive-tag analysis ongoing in K^{*0}, K^{*+} *and* $K^0_{(s)}$ final states
  - Work towards K^+ semileptonic-tag analysis ramping up

Backup



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



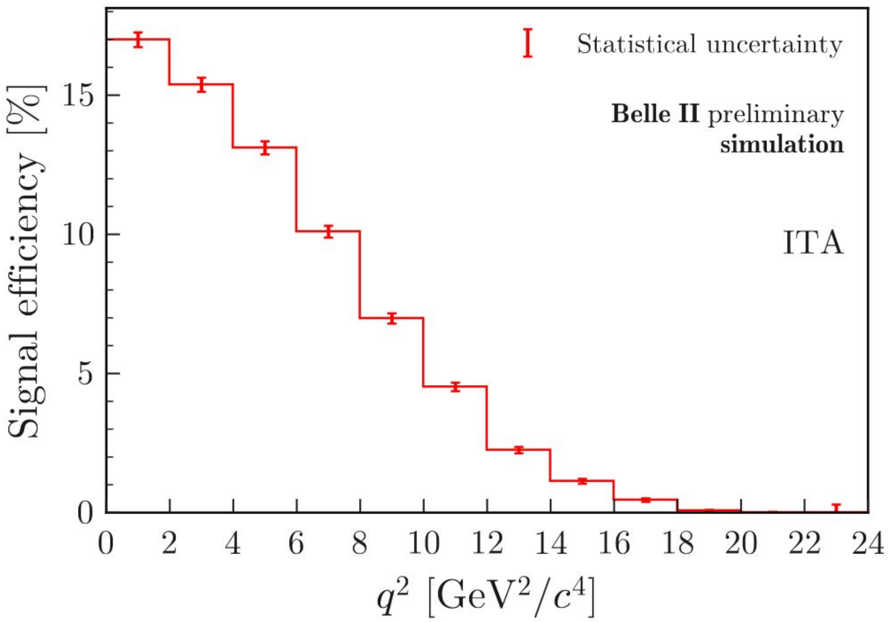
Systematic uncertainties in ITA

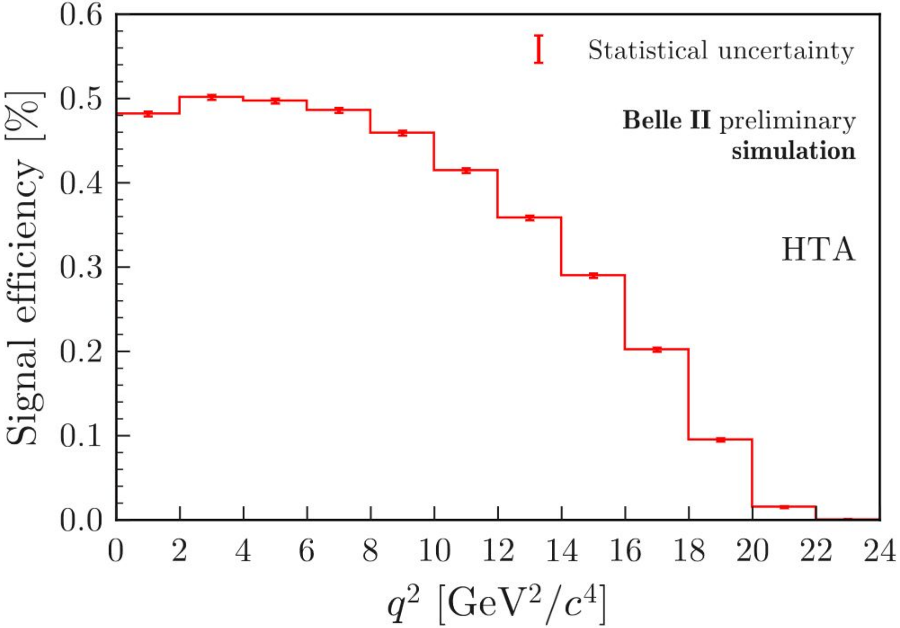
Source	Correction	Uncertainty type, parameters	Uncertainty size	Impact on σ_μ
Normalization of $B\overline{B}$ background	—	Global, 2	50%	0.90
Normalization of continuum background	—	Global, 5	50%	0.10
Leading B-decay branching fractions	—	Shape, 5	$O(1\%)$	0.22
Branching fraction for $B^+ \to K^+ K^0_L K^0_L$	q^2 dependent $O(100\%)$	Shape, 1	20%	0.49
p-wave component for $B^+ \to K^+ K^0_S K^0_L$	q^2 dependent $O(100\%)$	Shape, 1	30%	0.02
Branching fraction for $B \to D^{**}$	—	Shape, 1	50%	0.42
Branching fraction for $B^+ \to K^+ n\bar{n}$	q^2 dependent $O(100\%)$	Shape, 1	100%	0.20
Branching fraction for $D \to K^0_L X$	+30%	Shape, 1	10%	0.14
Continuum-background modeling, BDT$_c$	Multivariate $O(10\%)$	Shape, 1	100% of correction	0.01
Integrated luminosity	—	Global, 1	1%	< 0.01
Number of $B\overline{B}$	—	Global, 1	1.5%	0.02
Off-resonance sample normalization	—	Global, 1	5%	0.05
Track-finding efficiency	—	Shape, 1	0.3%	0.20
Signal-kaon PID	p, θ dependent $O(10-100\%)$	Shape, 7	$O(1\%)$	0.07
Photon energy	—	Shape, 1	0.5%	0.08
Hadronic energy	−10%	Shape, 1	10%	0.37
K^0_L efficiency in ECL	−17%	Shape, 1	8%	0.22
Signal SM form-factors	q^2 dependent $O(1\%)$	Shape, 3	$O(1\%)$	0.02
Global signal efficiency	—	Global, 1	3%	0.03
Simulated-sample size	—	Shape, 156	$O(1\%)$	0.52

Systematic uncertainties in HTA

Source	Correction	Uncertainty type, parameters	Uncertainty size	Impact on σ_μ
Normalization of $B\overline{B}$ background	—	Global, 1	30%	0.91
Normalization of continuum background	—	Global, 2	50%	0.58
Leading B-decay branching fractions	—	Shape, 3	$O(1\%)$	0.10
Branching fraction for $B^+ \to K^+ K^0_L K^0_L$	q^2 dependent $O(100\%)$	Shape, 1	20%	0.20
Branching fraction for $B \to D^{**}$	—	Shape, 1	50%	< 0.01
Branching fraction for $B^+ \to K^+ n\bar{n}$	q^2 dependent $O(100\%)$	Shape, 1	100%	0.05
Branching fraction for $D \to K^0_L X$	+30%	Shape, 1	10%	0.03
Continuum-background modeling, $\mathrm{BDT_c}$	Multivariate $O(10\%)$	Shape, 1	100% of correction	0.29
Number of $B\overline{B}$	—	Global, 1	1.5%	0.07
Track finding efficiency	—	Global, 1	0.3%	0.01
Signal-kaon PID	p, θ dependent $O(10-100\%)$	Shape, 3	$O(1\%)$	< 0.01
Extra-photon multiplicity	$n_{\gamma\mathrm{extra}}$ dependent $O(20\%)$	Shape, 1	$O(20\%)$	0.61
K^0_L efficiency	—	Shape, 1	17%	0.31
Signal SM form-factors	q^2 dependent $O(1\%)$	Shape, 3	$O(1\%)$	0.06
Signal efficiency	—	Shape, 6	16%	0.42
Simulated-sample size	—	Shape, 18	$O(1\%)$	0.60

Efficiency vs q^2





BDT variables in ITA

Variables related to the kaon candidate

- Radial distance between the POCA of the K^+ candidate track and the IP (BDT_2)
- Cosine of the angle between the momentum line of the signal kaon candidate and the z axis (BDT_2)

Variables related to the tracks and energy deposits of the rest of the event (ROE)

- Two variables corresponding to the x, z components of the vector from the average interaction point to the ROE vertex (BDT_2)
- p-value of the ROE vertex fit (BDT_2)
- Variance of the transverse momentum of the ROE tracks (BDT_2)
- Polar angle of the ROE momentum (BDT_1, BDT_2)
- Magnitude of the ROE momentum (BDT_1, BDT_2)
- ROE-ROE (oo) modified Fox-Wolfram moment calculated in the c.m. (BDT_1, BDT_2)
- Difference between the ROE energy in the c.m. and the energy of one beam of c.m. ($\sqrt{s}/2$) (BDT_1, BDT_2)

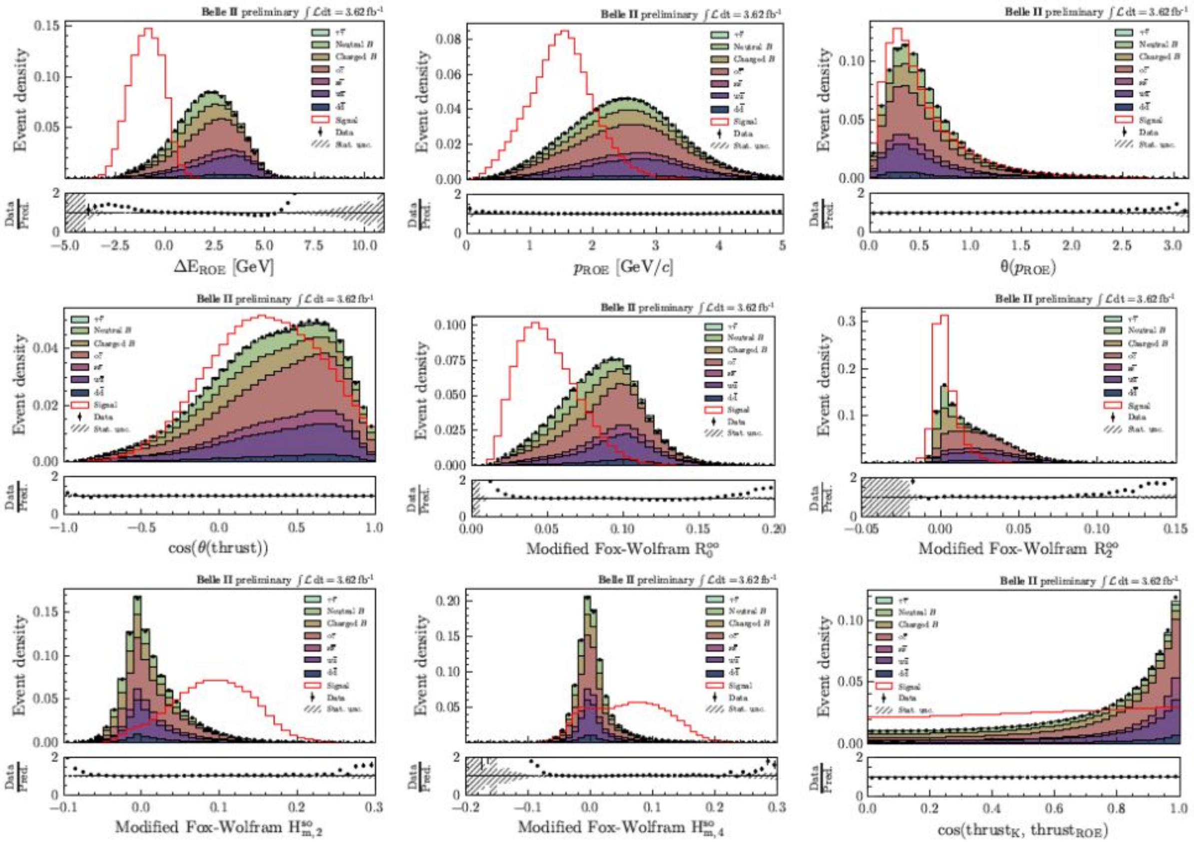
Variables related to the entire event

- Number of charged lepton candidates ($e^\pm$ or $\mu^\pm$) (BDT_2)
- Number of photon candidates, number of charged particle candidates (BDT_2)
- Square of the total charge of tracks in the event (BDT_2)
- Cosine of the polar angle of the thrust axis in the c.m. (BDT_1, BDT_2)
- Harmonic moments with respect to the thrust axis in the c.m. [41] (BDT_1, BDT_2)
- Modified Fox-Wolfram moments calculated in the c.m. [42] (BDT_1, BDT_2)
- Polar angle of the missing three-momentum in the c.m. (BDT_2)
- Square of the missing invariant mass (BDT_2)
- Event sphericity in the c.m. [40] (BDT_2)
- Normalized Fox-Wolfram moments in the c.m. [41] (BDT_1, BDT_2)
- Cosine of the angle between the momentum line of the signal kaon track and the ROE thrust axis in the c.m. (BDT_1, BDT_2)
- Radial and longitudinal distance between the POCA of the K^+ candidate track and the tag vertex (BDT_2)

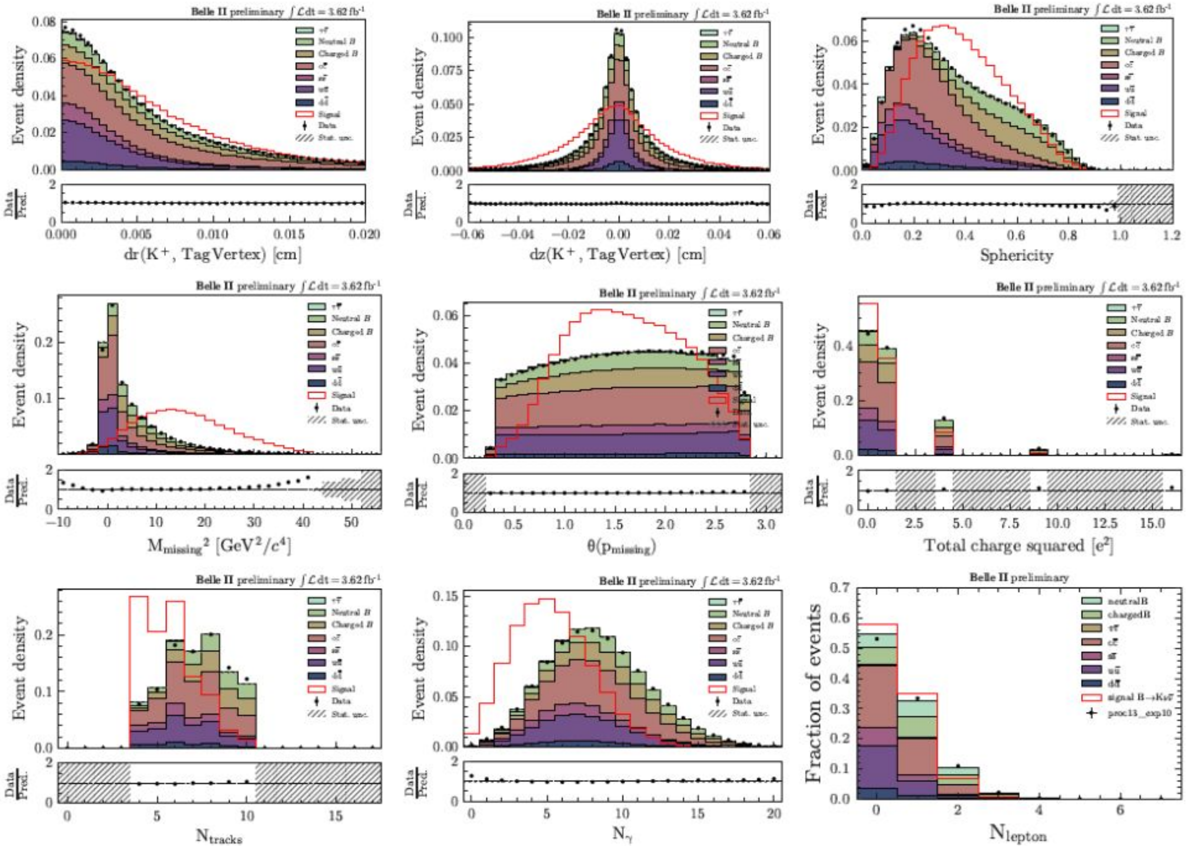
Variables related to the D^0/D^+ suppression

- Radial distance between the best D^+ candidate vertex and the IP (BDT_2)
- χ^2 of the best D^0 candidate vertex fit and the best D^+ candidate vertex fit (BDT_2)
- Mass of the best D^0 candidate (BDT_2)
- Median p-value of the vertex fits of the D^0 candidates (BDT_2)

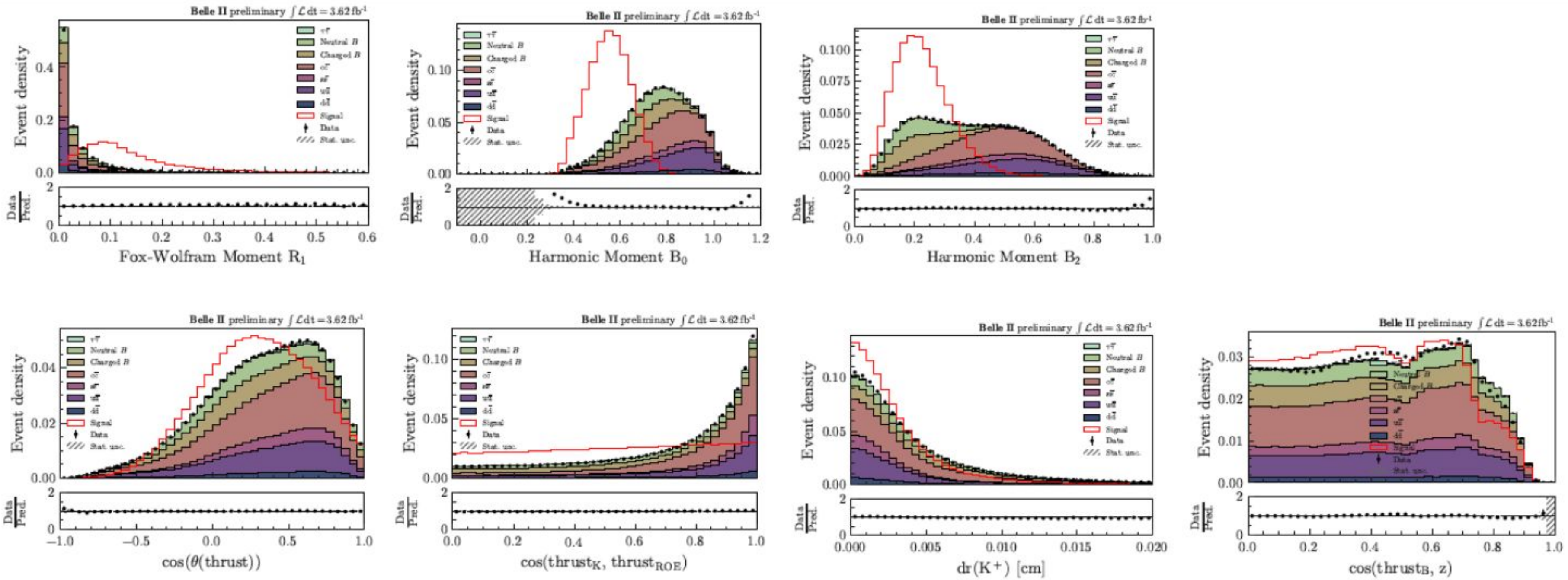
BDT variables in ITA



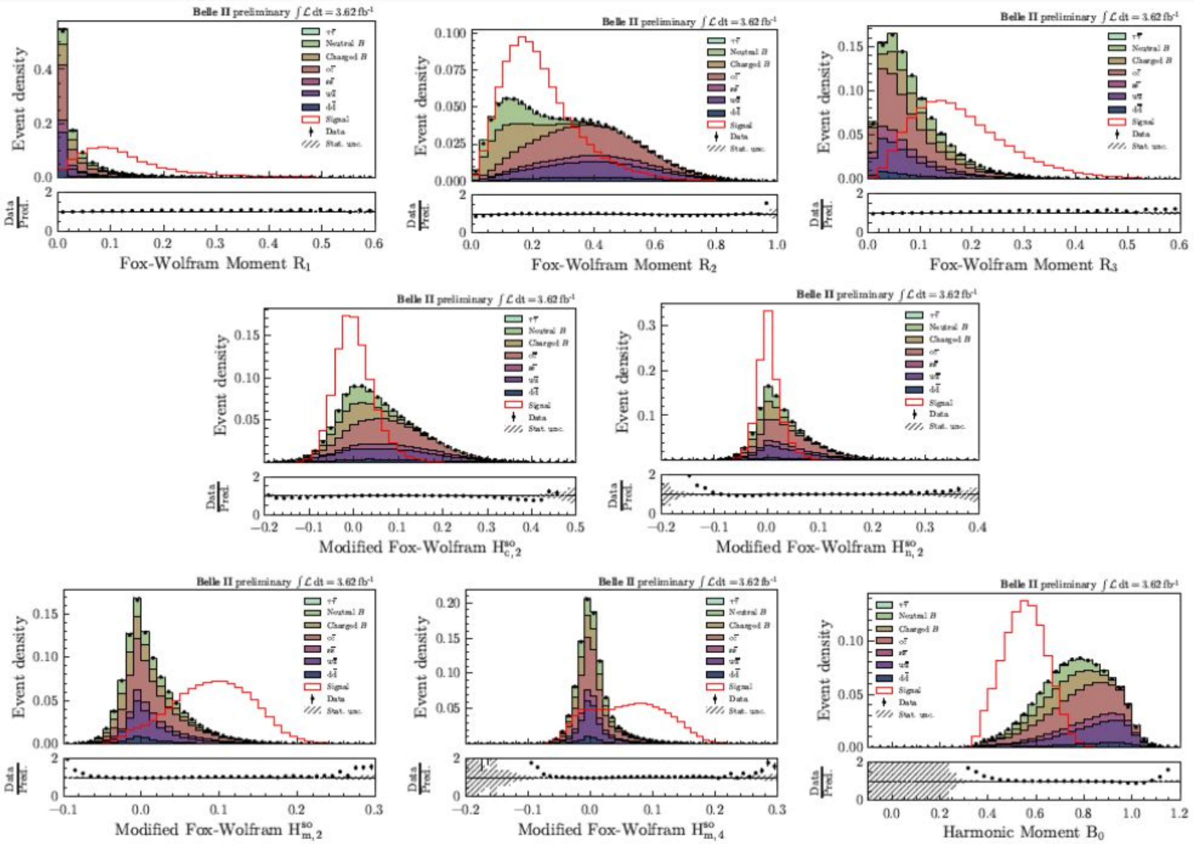
BDT variables in ITA



BDT variables in ITA

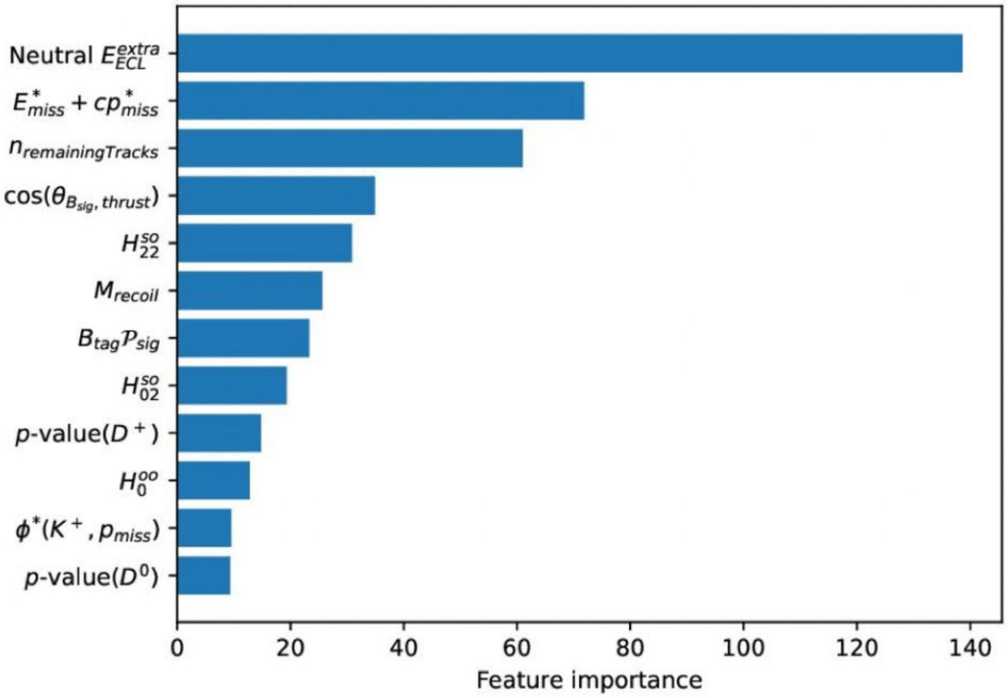


BDT variables in ITA

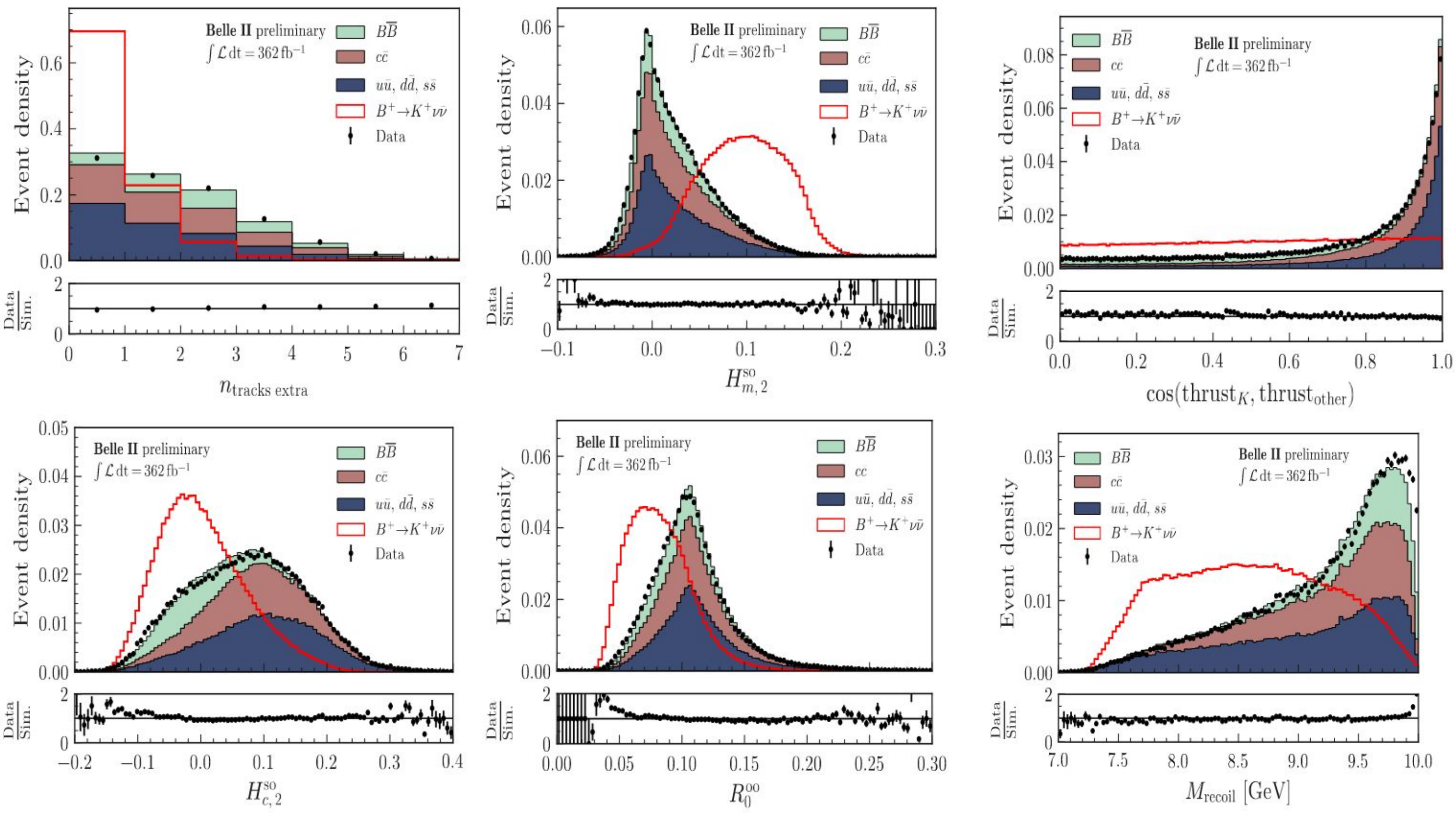


BDT variables in HTA

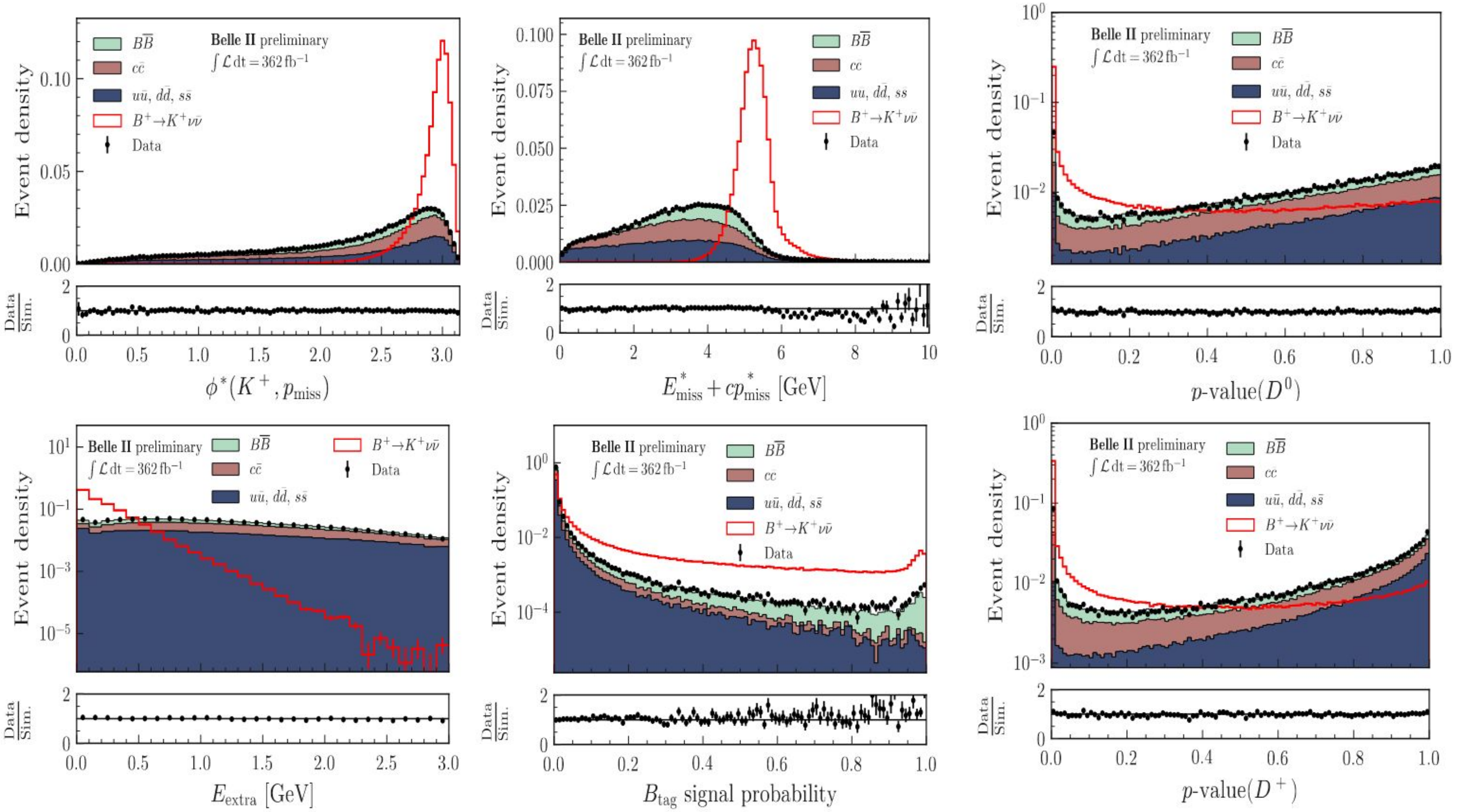
- Sum of photon energy deposits in ECL in ROEh
- Number of tracks in ROEh
- Sum of the missing energy and absolute missing three-momentum vector
- Azimuthal angle between the signal kaon and the missing momentum vector
- Cosine of the angle between the thrust axis of the signal kaon candidate and the 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 variables in HTA



BDT variables in HTA



B background in ITA signal region