# Evidenza del decadimento $B^+ \to K^+ \nu\bar{\nu}$

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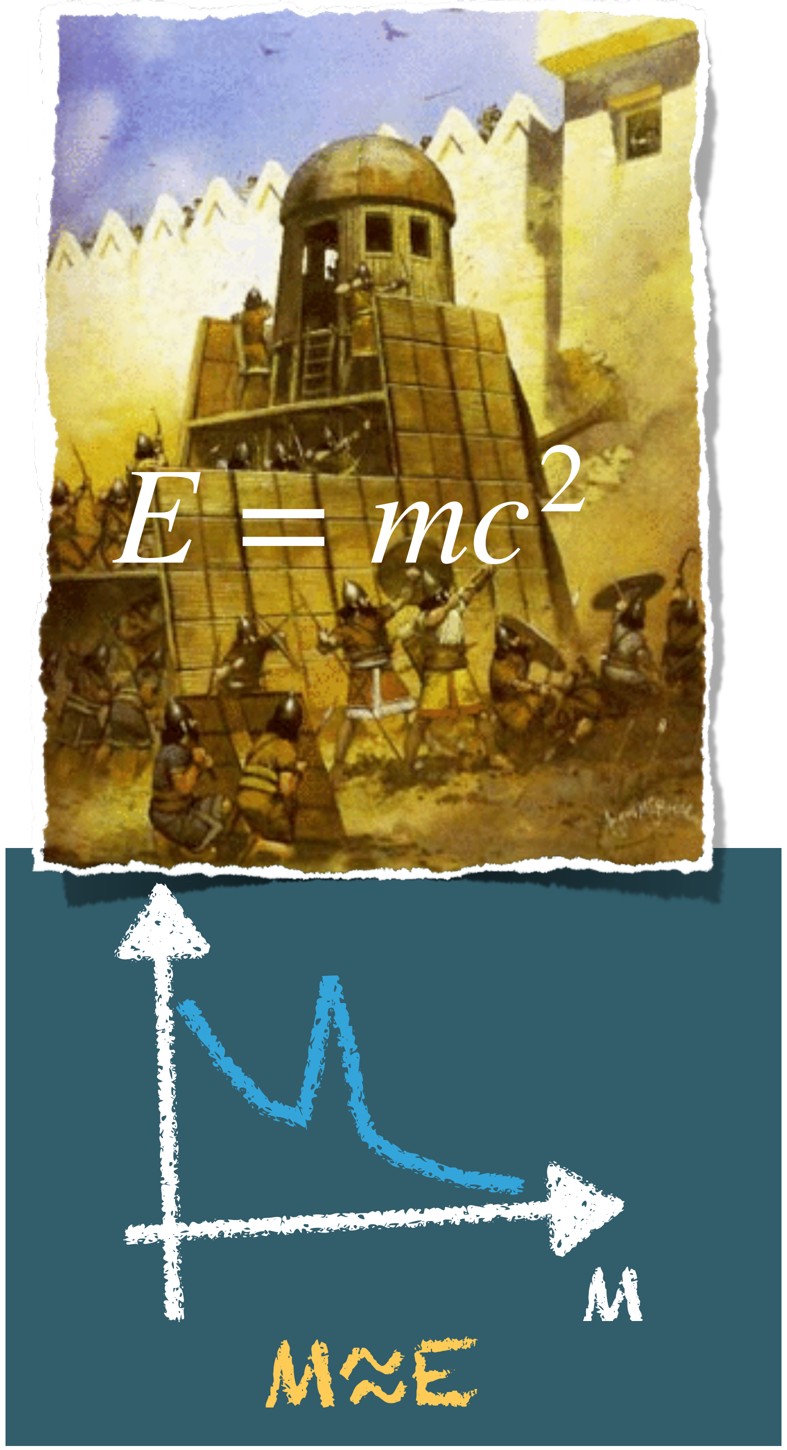
CDS INFN Apr 7,2024
Trieste

# Il successo del modello standard


Domande aperte indicano la necessità di un’estensione con particelle di massa >10 TeV

# Forza bruta o astuzia?




Produco e osservo direttamente

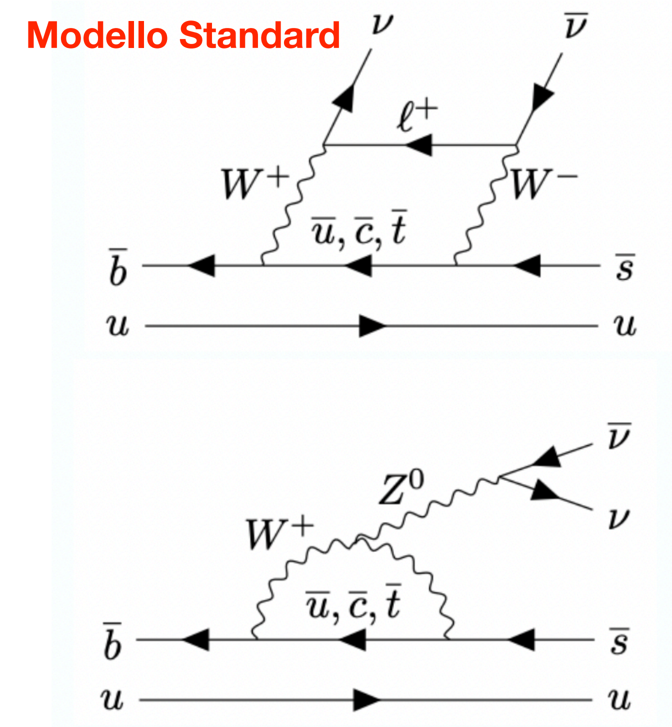

Discrepanza teoria/misure ad alta precisione

# $B^+ \to K^+\nu\bar{\nu}$ — rilevante, ma *difficile*

La probabilita di decadimento nel Modello Standard è nota con precisione

$B(B \to K^+ \nu\nu) = (5.6 \pm 0.4) \times 10^{-6}$ (arXiv:2207.13371)

Ed è sensibile a un'ampia varietà di nuove particelle, che la aumenterebbero, anche significativamente.



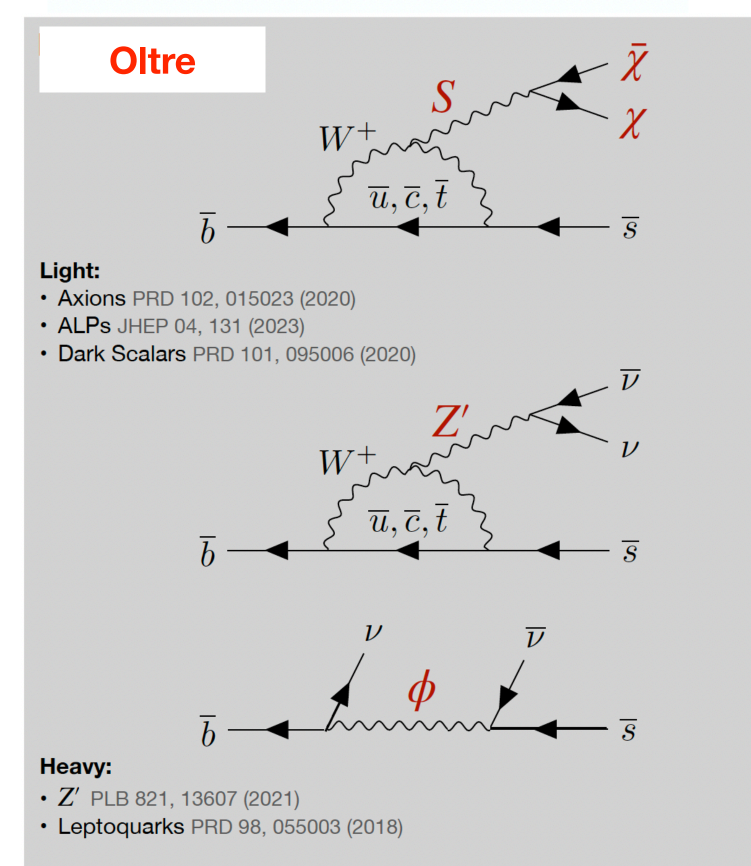

Il decadimento è raro: 6 eventi ogni milione di $B^+$.

I processi di fondo sono 10 000 000 maggiori

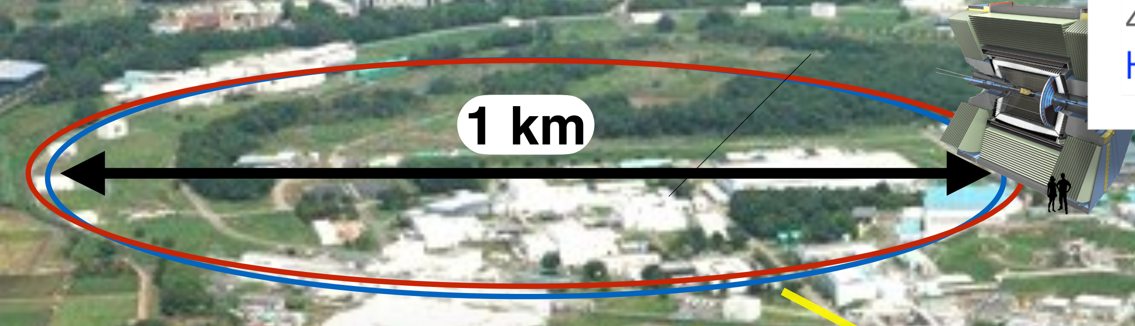
Identificare il segnale è un incubo: solo un *K* carico. i neutrini non sono rivelati: nessuna distribuzione ha "picco" di segnale

Lo si cerca da 20 anni.

Solo Belle II oggi può cercarlo realisticamente



# Chi siamo




## SuperKEKB

Goal: 30x luminosity wrt KEKB thanks to nanobeams: squeeze beta fcn in the luminous region and minimize longitudinal beam overlap.

Modest (1.5x-2x) increase in currents. Large (20x) increase in beam cross section. Increase x-ing angle to 83 mrad

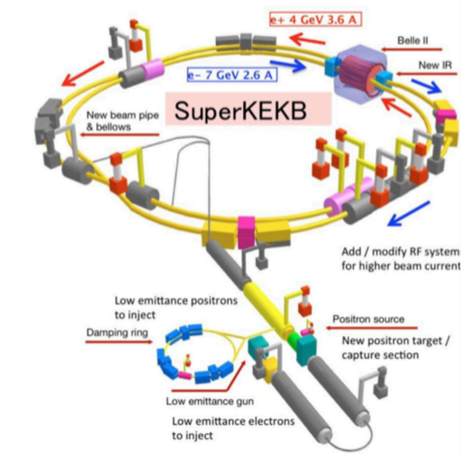
Achieving 50 nm vertical size requires low emittance and powerful and sophisticate final focus

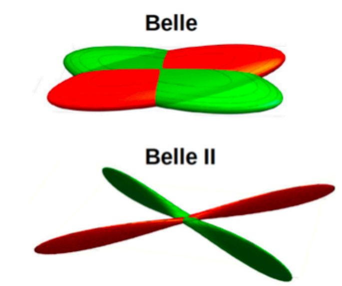
So far 10x below design, improving steadily

$4.7 \times 10^{34}$ cm$^{-2}$ Hz record
(w/ currents 2-3x lower than at PEPII)

90% data taking efficiency 1–2 fb$^{-1}$/day, 8–12 fb$^{-1}$/week, 20–40 fb$^{-1}$/month.

430 fb$^{-1}$ collected (>50% of Belle, ~Babar).
Half of Babar's sample in just one year.







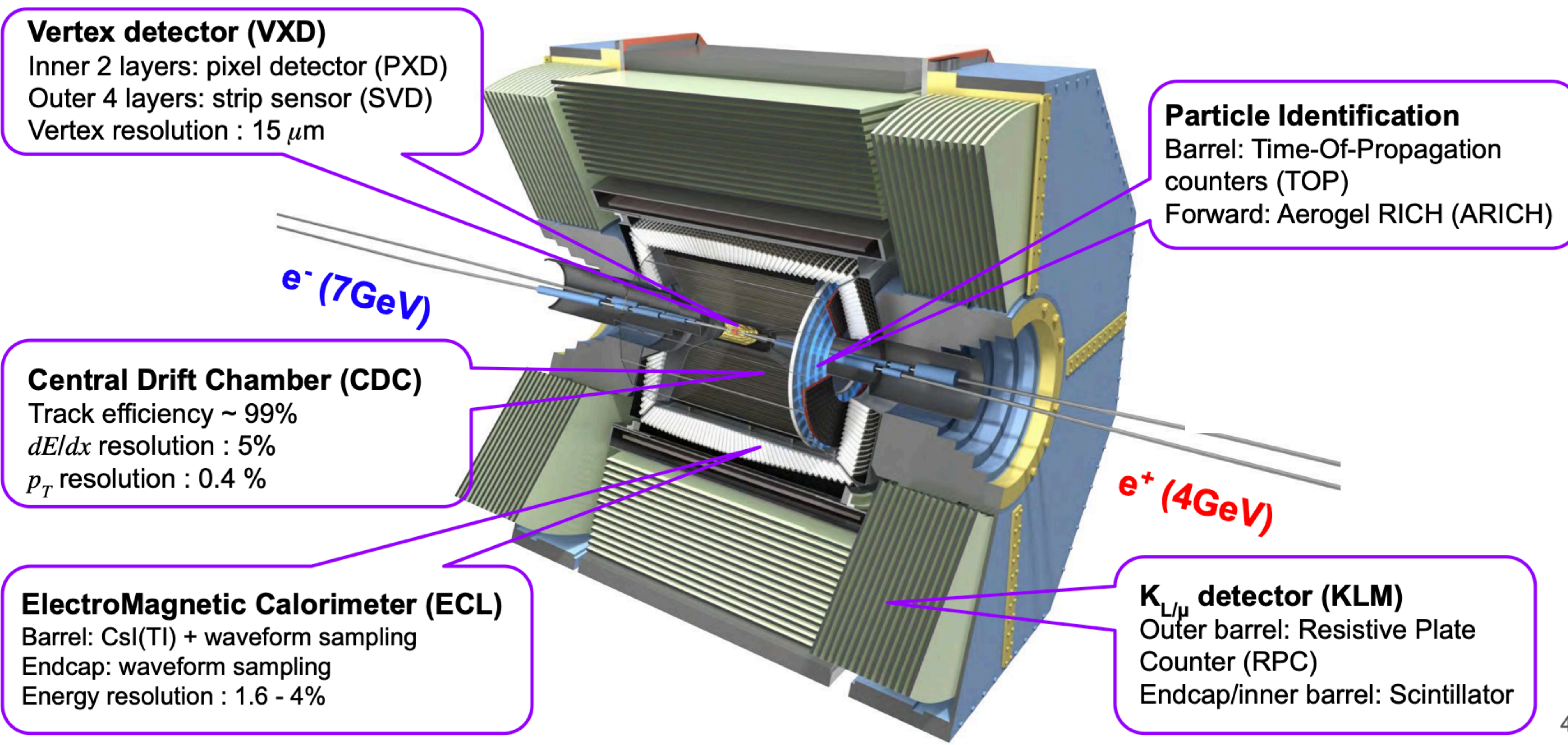
700 fisici da 125 instituti in 28 paesi (250 studenti 150 postdocs)

Elettroni da 7 GeV contro positroni da 4 GeV all'energia della Y(4S). Da 30 (now) a 600 (design) $B\bar{B}$ *al secondo* (con fondi tre volte maggiori da quark leggeri)

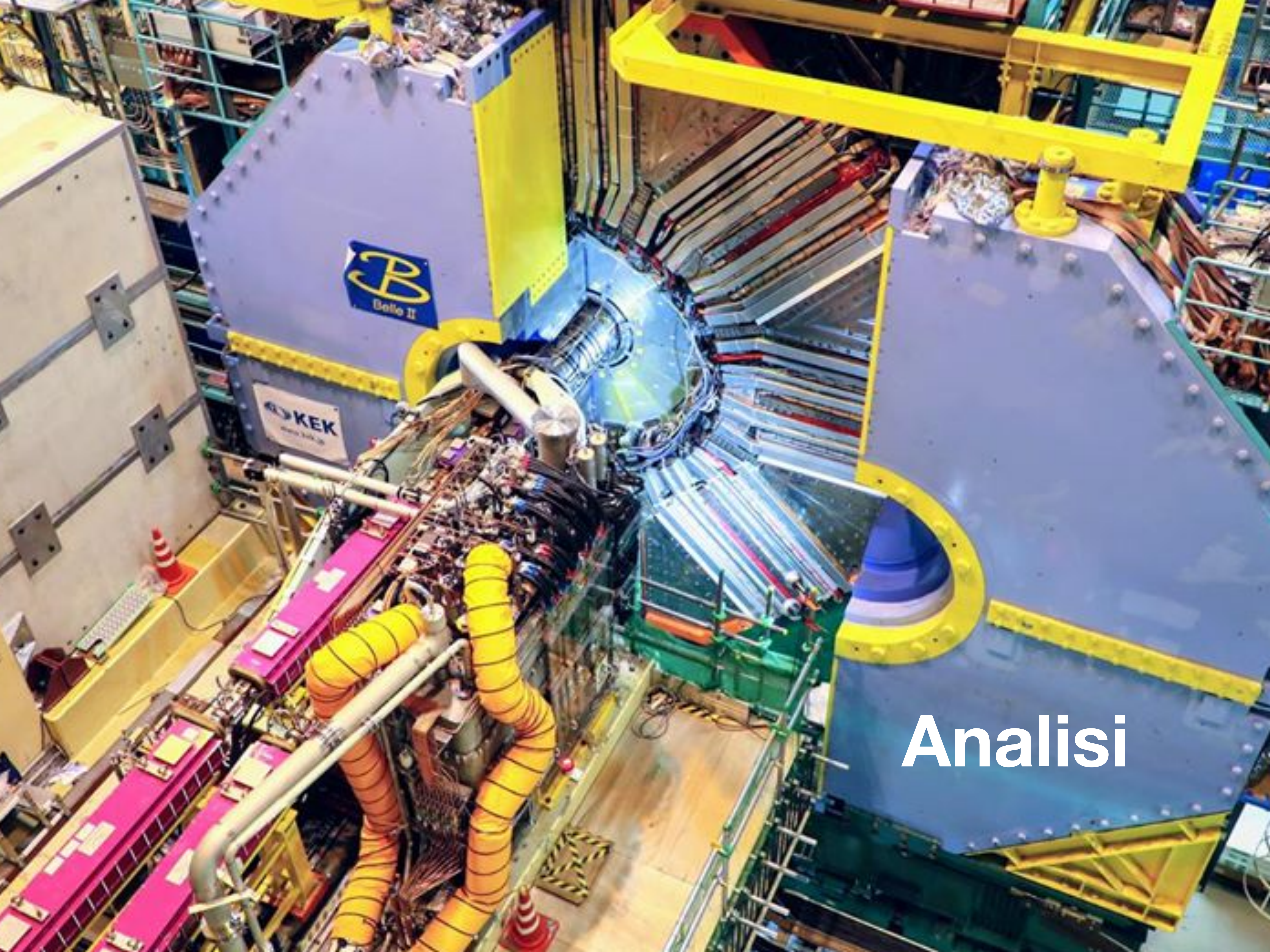
# Lo strumento

Assomiglia a Belle. Di fatto è quasi tutto nuovo.

Only structure, magnet and calorimeter crystals are re-used

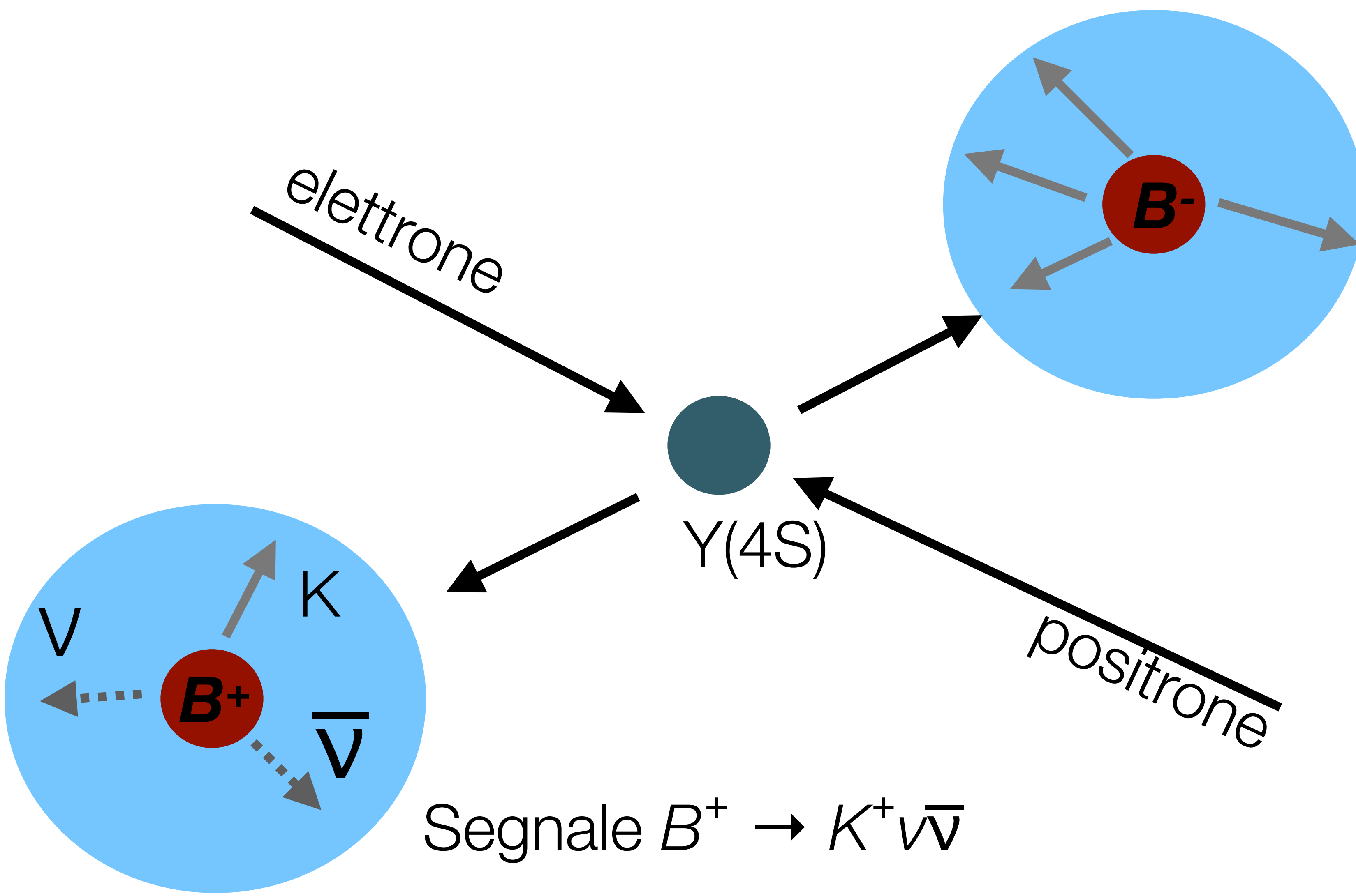


# Analisi



# Mappa concettuale

*B* prodotti in coppie ed in soglia. Riconoscere la presenza del partner *B* sopprime molto fondo da quark leggeri.




Segnale $B^+ \rightarrow K^+\nu\bar{\nu}$

### Partner *B*

- elettrone o muone: efficiente ma sporco
- ricostruisco $B \rightarrow D\pi$: inefficiente (<1%} ma pulito: analisi di controllo
- inclusivo, molto efficiente (8%), molto sporco: analisi principale

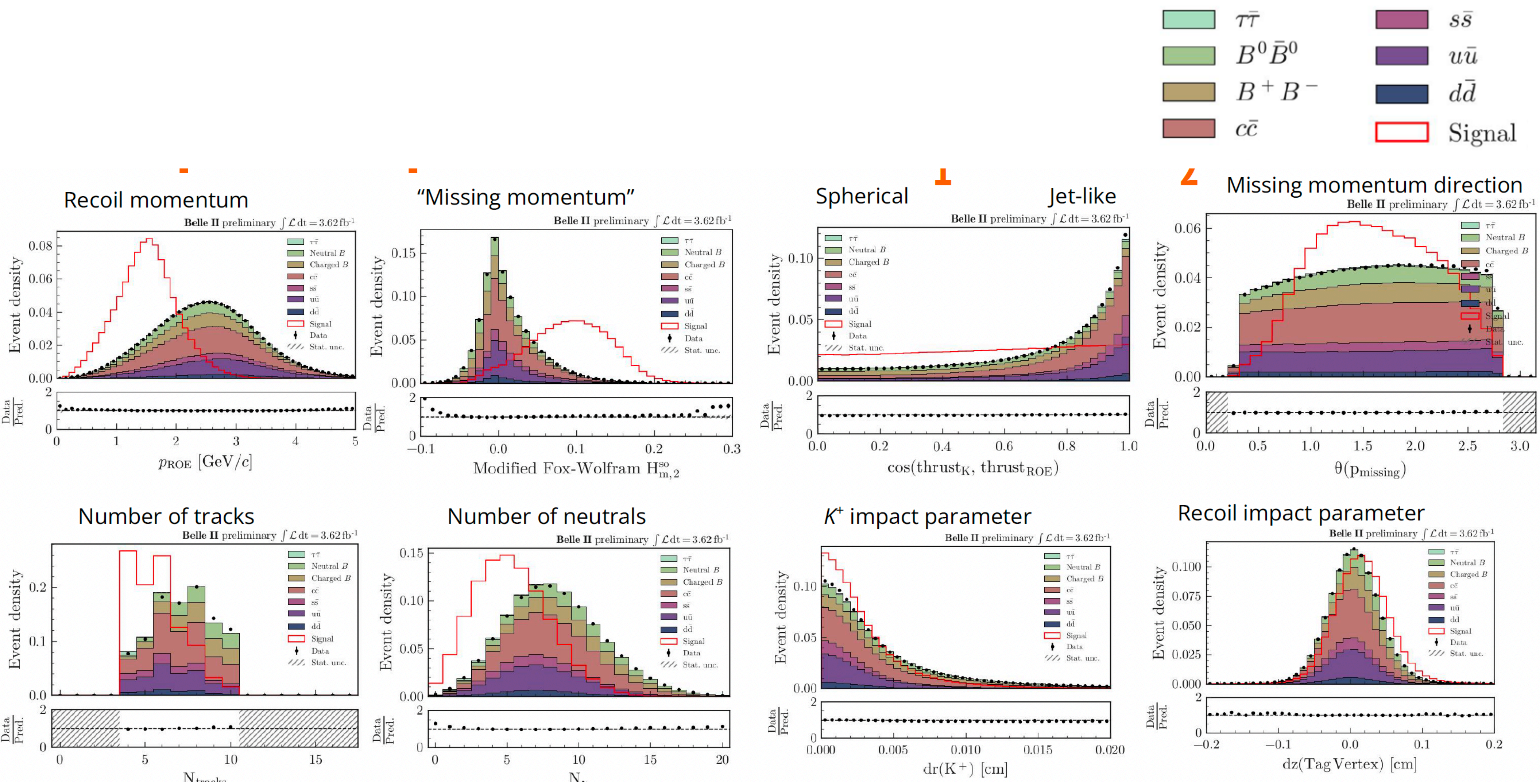
### Fondi

- Decadimenti di *B* in *K* e particelle attribuite al partner *B* o invisibili (neutroni, $K_L$, ecc)
- $e^+e^-$ in quark leggeri

Una traccia carica identificata K

- Selezione iniziale: efficienza alta e nota (particelle >100 MeV da zona di interazione rivelate centralmente)
- Filtro intermedio: 12 variabili cinematiche sulla "forma" dell'evento combinate da intelligenza artificiale
- Discriminante finale: 35 variabili di segnale ed evento combinate da intelligenza artificiale
- Estrazione segnale: fit del discriminante finale

# Selezione degli eventi

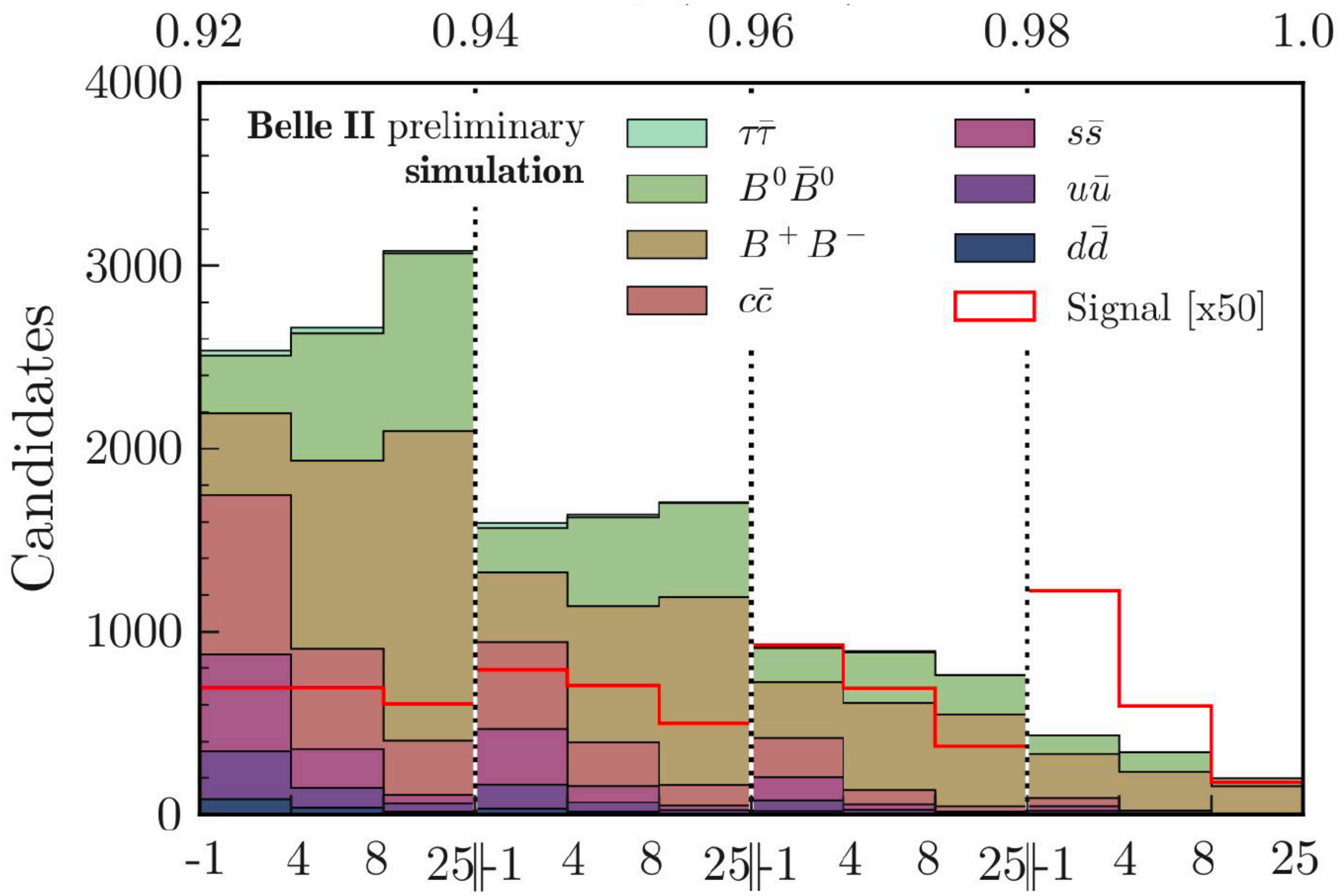



Combinazione di decine di variabili discriminanti (e ben descritte da simulazione)

# Estrazione del segnale

Fit alla coda signal-like della distribuzione del discriminante finale in tre bin di massa invariante della coppia di neutrini (sensibilità dipende anche da quella)

Valori del discriminante




Massa quadra $\nu\bar{\nu}$ Massa quadra $\nu\bar{\nu}$ Massa quadra $\nu\bar{\nu}$ Massa quadra $\nu\bar{\nu}$ (GeV[2])

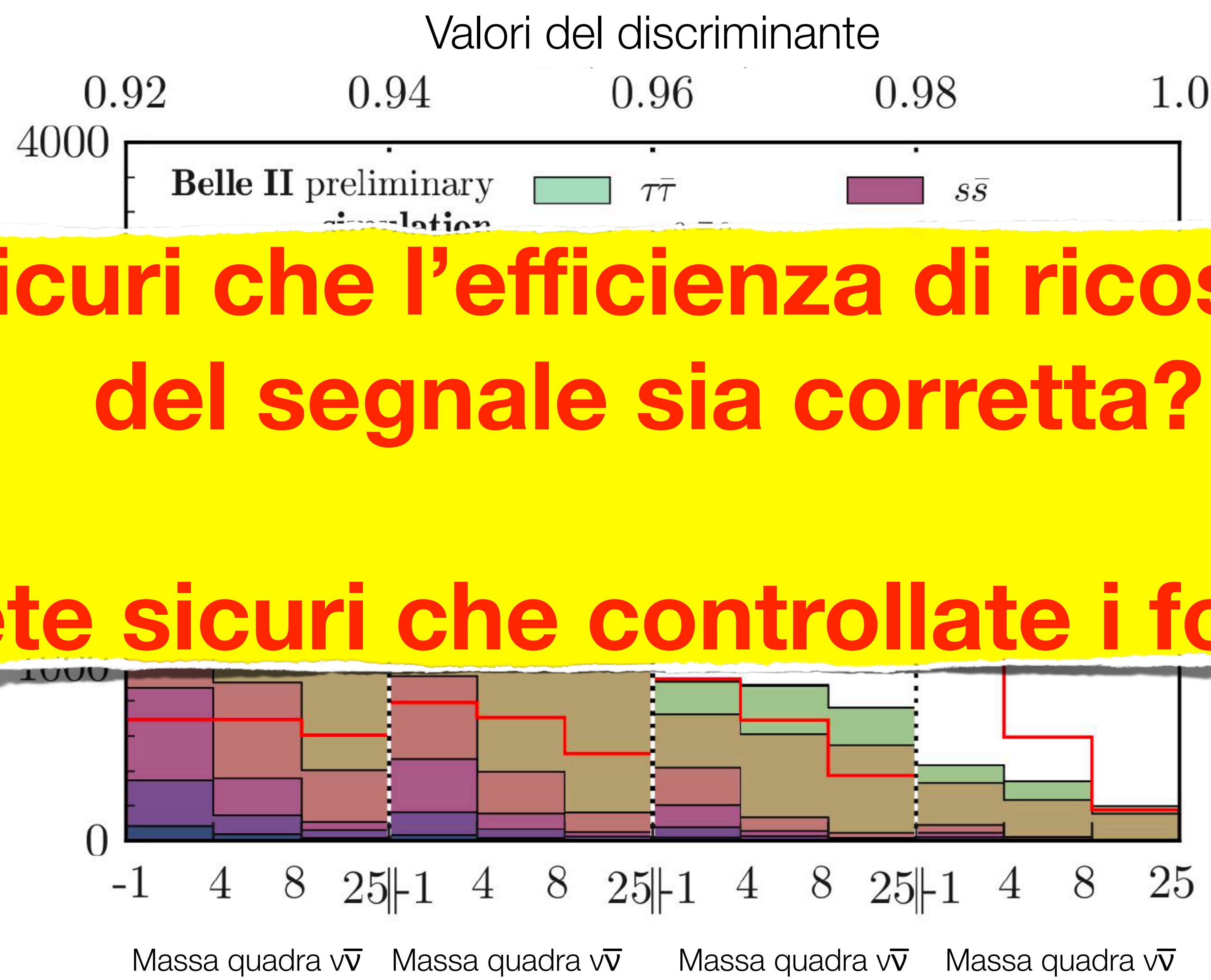
Modello di segnale e dei 7 fondi da simulazione e validata su campioni di controllo.

Size del continuo vincolata da dati presi fuori dalla Y(4S)

Generose incertezze sistematiche incluse nel fit.

# Estrazione del segnale — due domande

Fit alla coda signal-like della distribuzione del discriminante finale in tre bin di massa invariante quadra dei due neutrini (sensibilità dipende anche da quella)

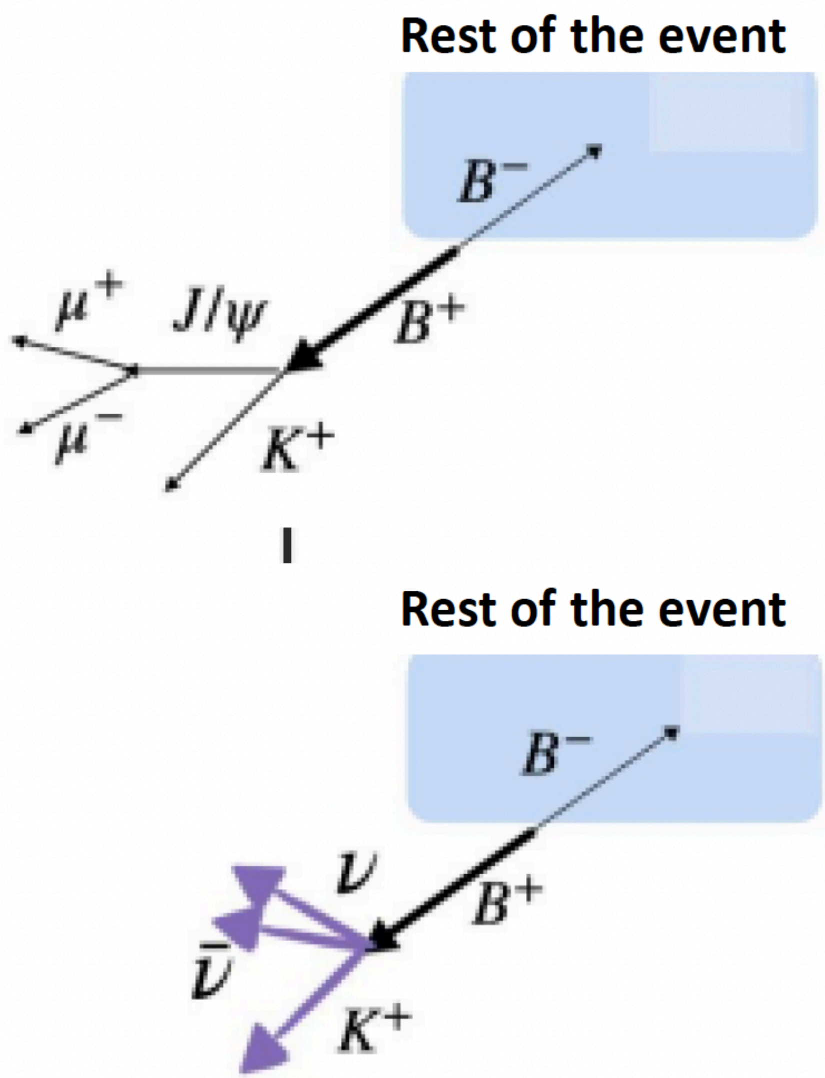


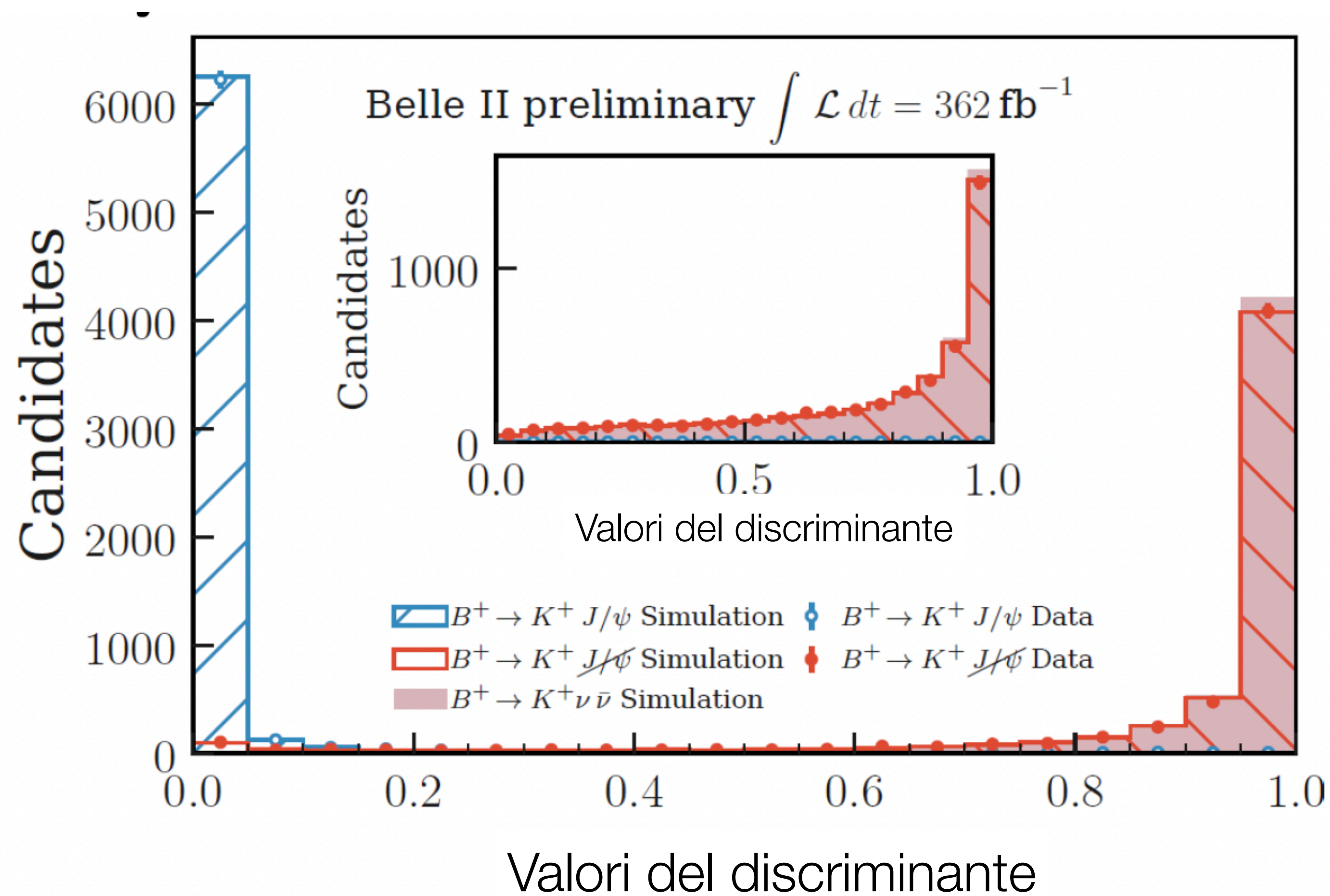

**Siete sicuri che l'efficienza di ricostruzione del segnale sia corretta?**

**Siete sicuri che controllate i fondi?**

# Efficienza sul segnale

Verifico “trapiantando” eventi di segnale simulati su dati di controllo



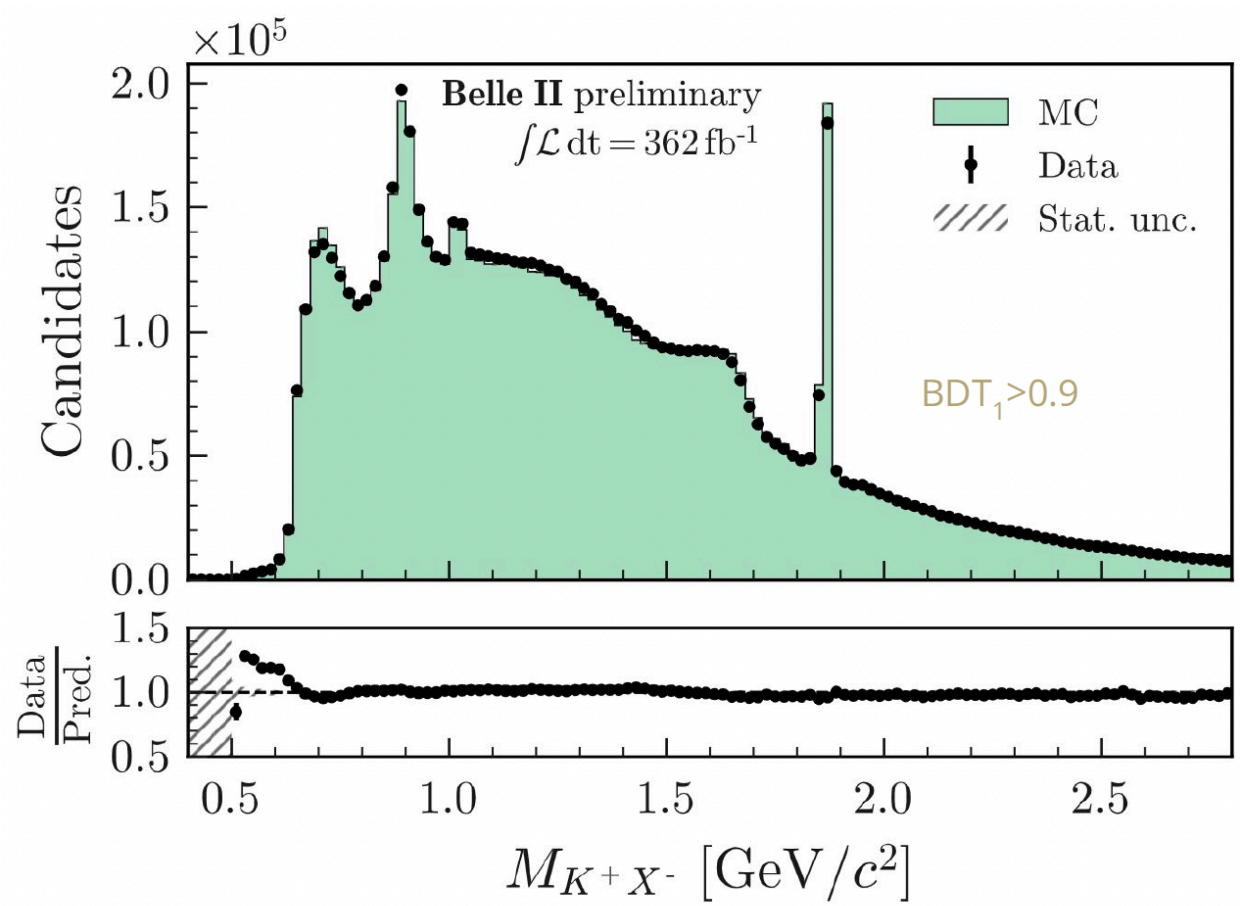

Efficienza sui dati uguale a quella sulla simulazione entro il 3%

# Controllo fondi - fondi dominanti

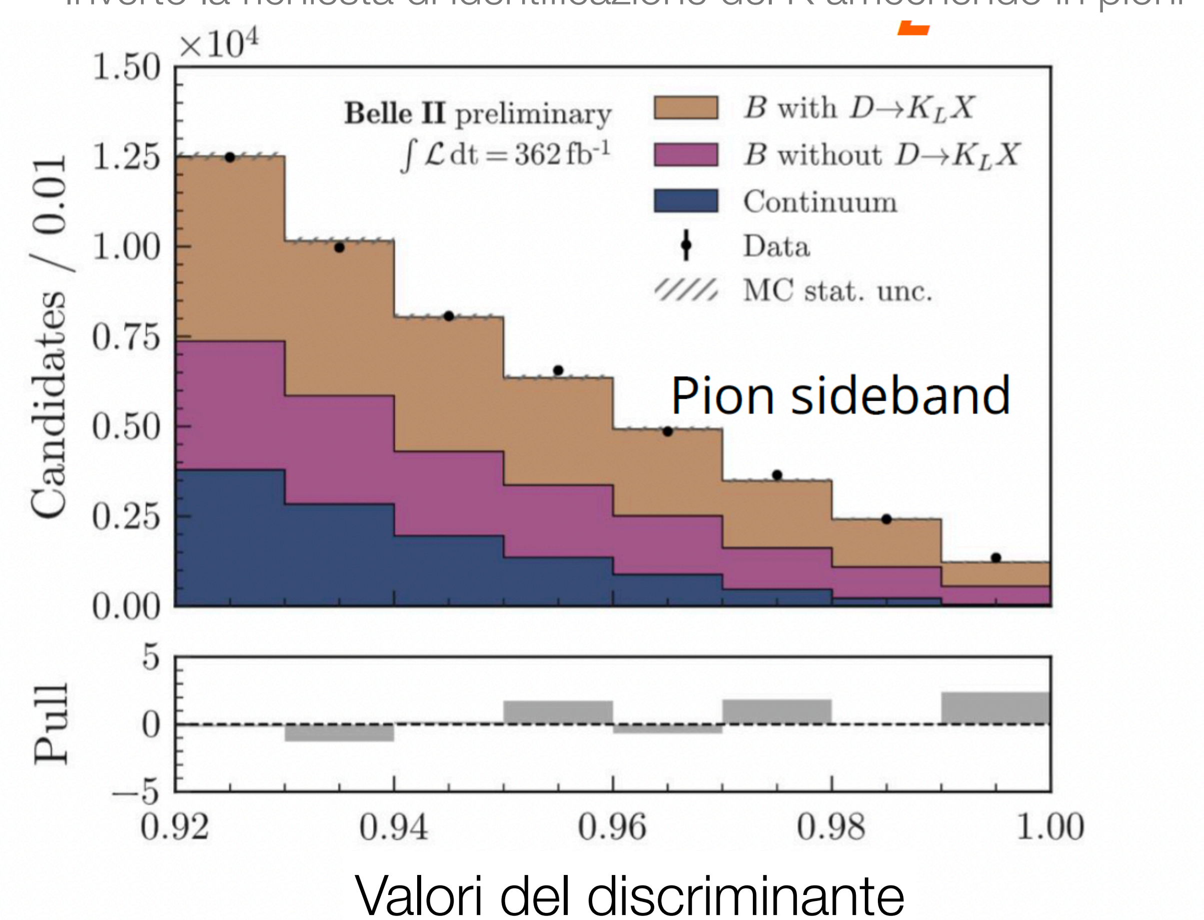
90% dei fondi da

- $B \to D\,(\to K\,X)\,\ell\,\nu$ soppressi dai discriminatori
- $B \to K\,X$ validato usando $B \to \pi\,X$

Generose incertezze sistematiche su decadimenti (poco noti) come $D\,(\to K_L\,X)$ o $B \to D^{**}\,X$




Inverto la richiesta di identificazione del K arricchendo in pioni

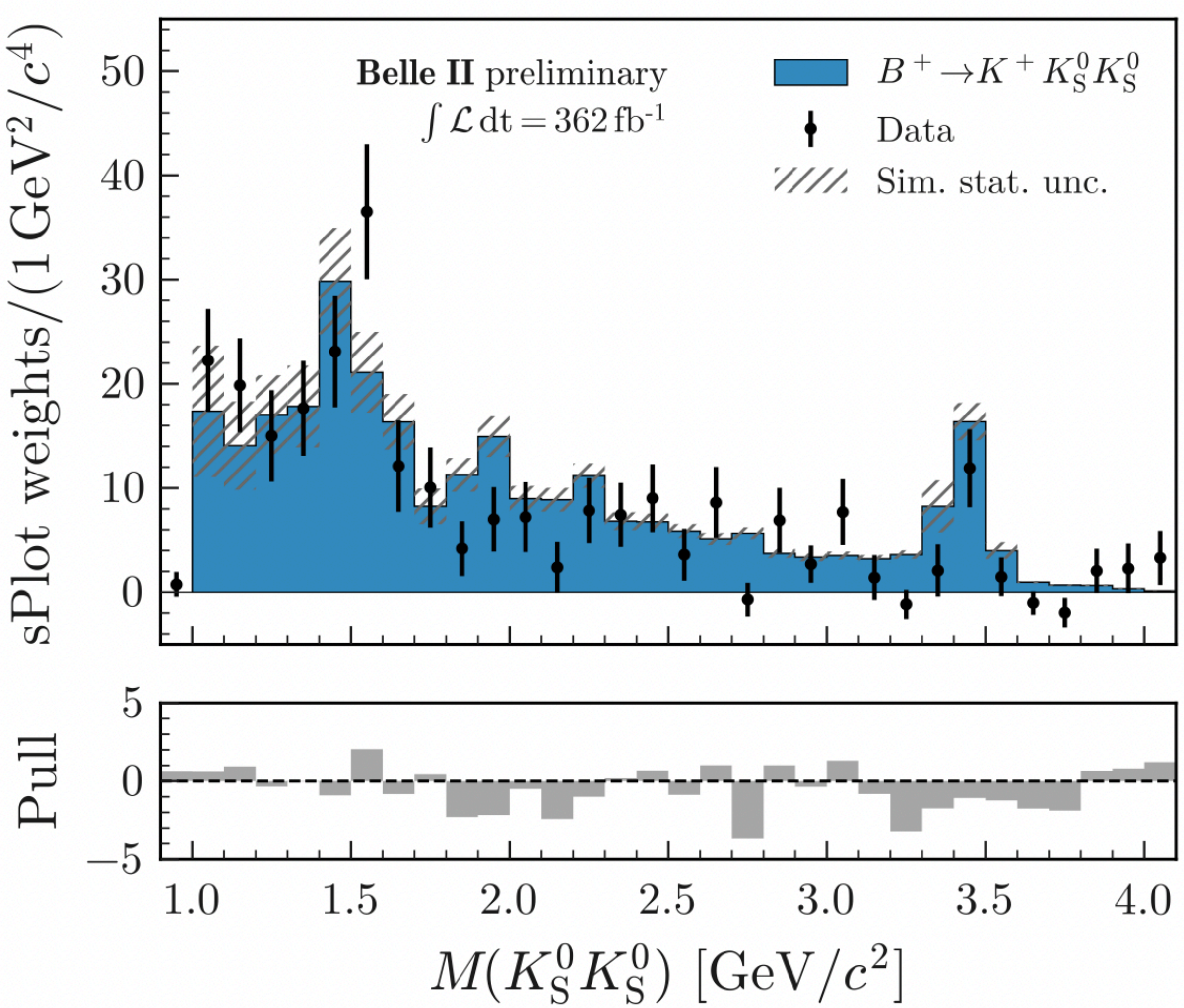


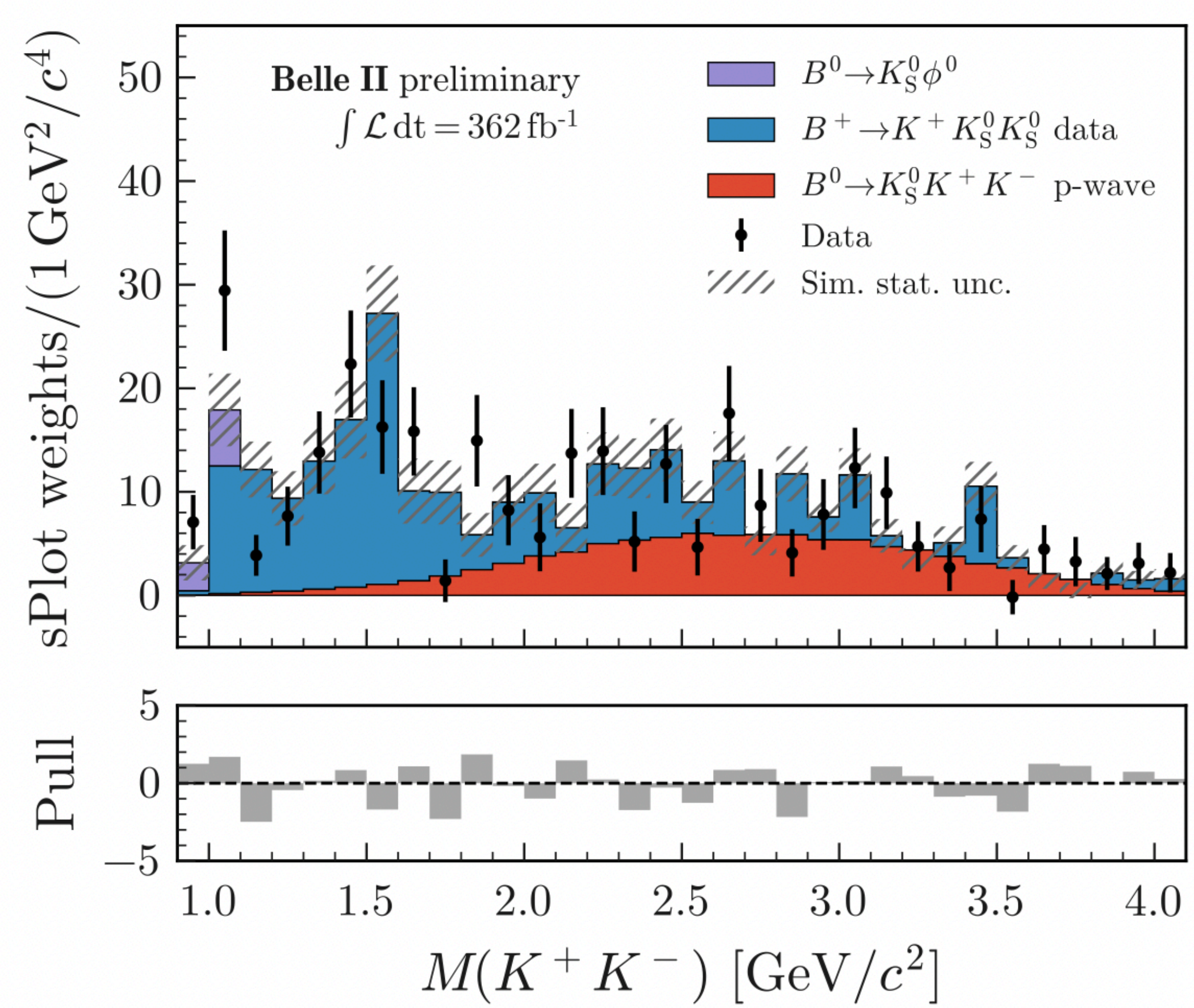
# Controllo fondi - fondi irriducibili

$B^+ \rightarrow K^+ n\bar{n}$ e $B^+ \rightarrow K^+ K^0\bar{K}^0$ hanno rate 10 volte maggiori del segnale e gli assomigliano quando neutroni e $K_L$ scappano dal calorimetro

Verifica efficienza di ricostruzione $K_L$ usando $e^+e^- \rightarrow \phi(\rightarrow K_L K_S)\gamma$

Accordo dati/MC su canali di controllo $B^+ \rightarrow K^+ K_S K_S$ e $B^0 \rightarrow K^+ K^- K_S$ (ed assegno sistematiche generose)



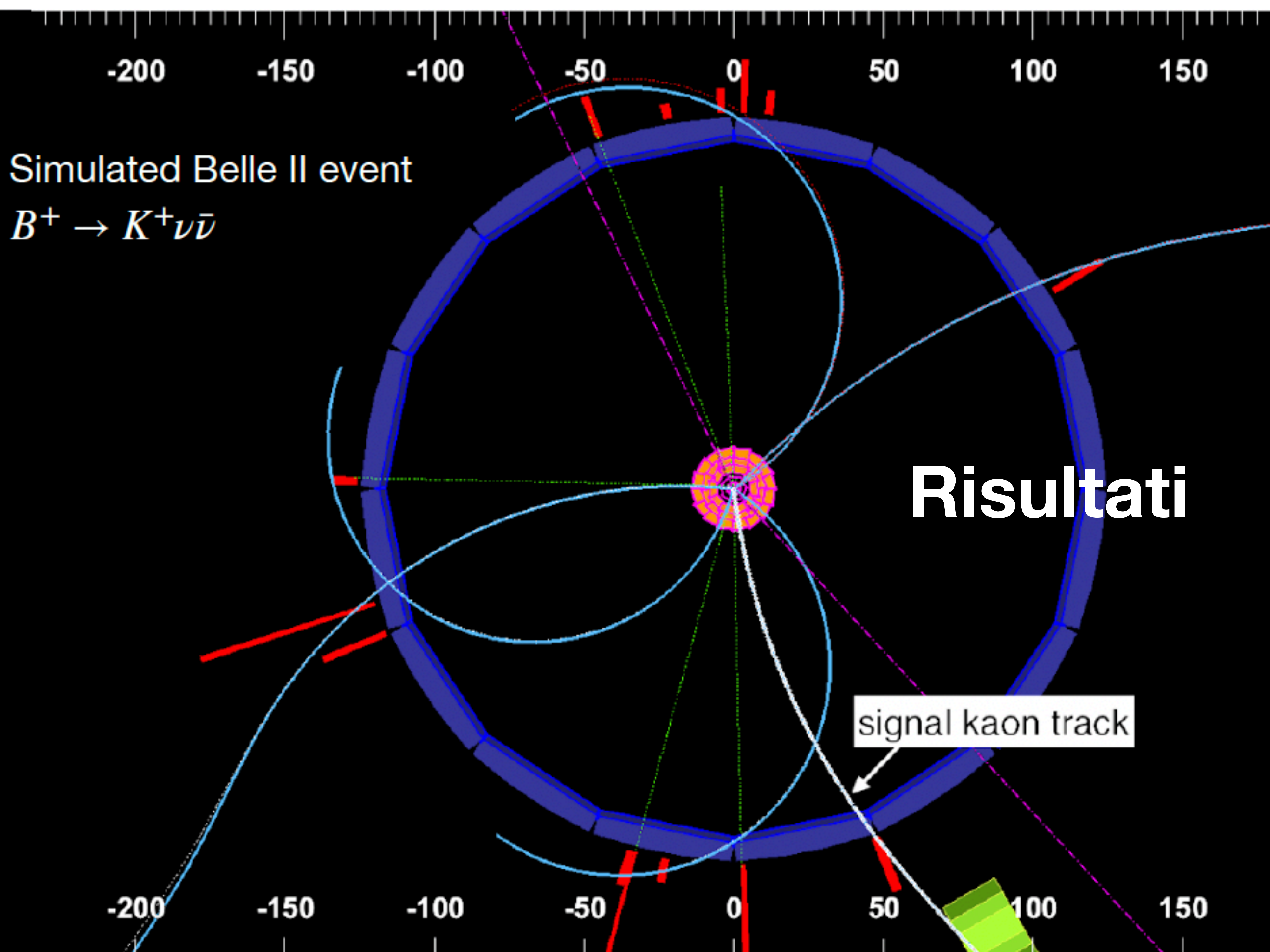



# Incertezze sistematiche

TABLE I. Sources of systematic uncertainty in the ITA, corresponding correction factors (if any), their treatment in the fit, their size, and their impact on the uncertainty of the signal strength $\mu$. The uncertainty type can be "Global", corresponding to a global normalization factor common to all SR bins, or "Shape", corresponding to a bin-dependent uncertainty. Each source is described by one or more nuisance parameters (see the text for more details). The impact on the signal strength uncertainty $\sigma_\mu$ is estimated by excluding the source from the minimization and subtracting in quadrature the resulting uncertainty from the uncertainty of the nominal fit.

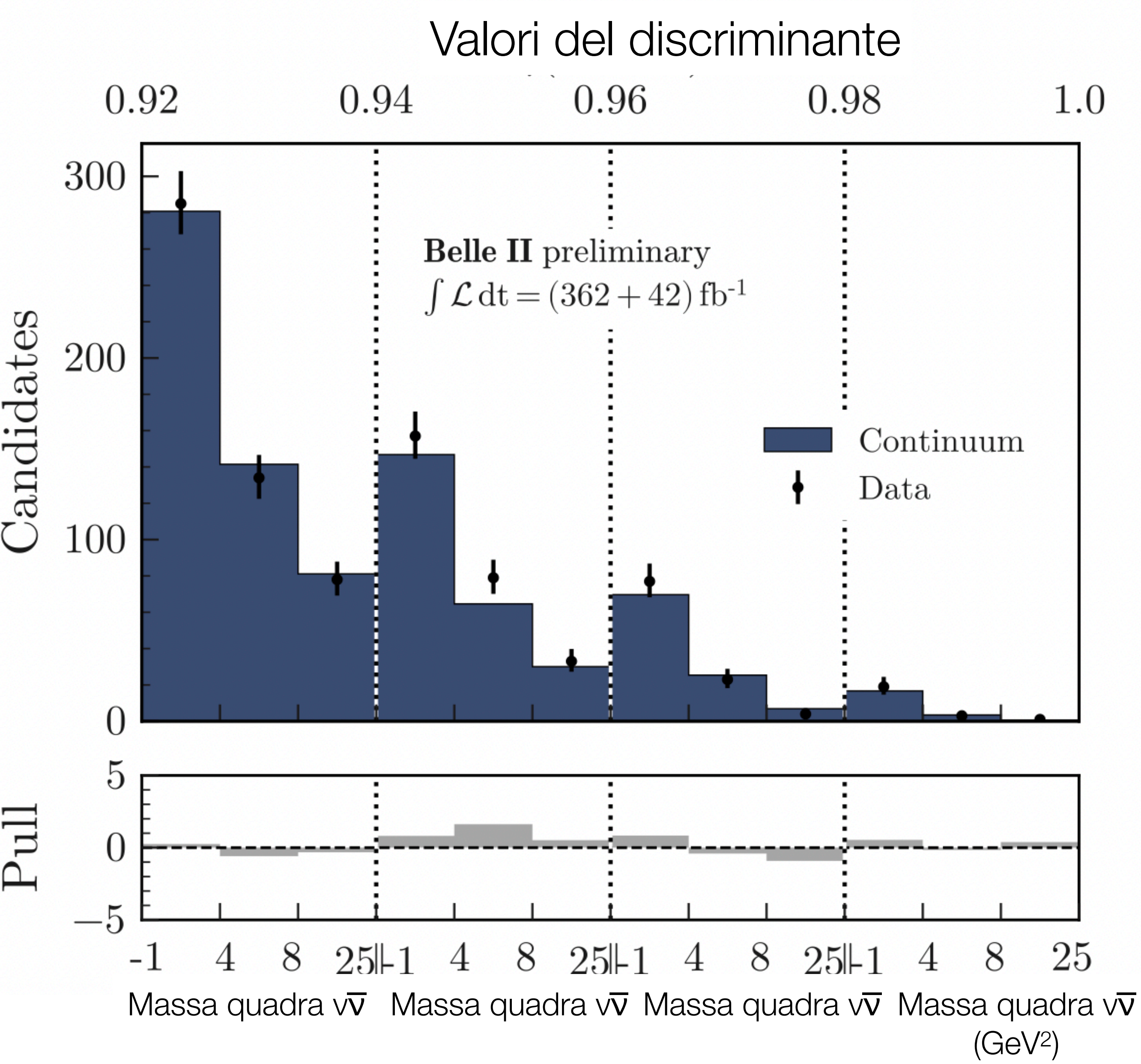
| Source | Correction | Uncertainty type, parameters | Uncertainty size | Impact on $\sigma_\mu$ |
|---|---|---|---|---|
| Normalization of $B\bar{B}$ background | — | Global, 2 | 50% | 0.90 |
| Normalization of continuum background | — | Global, 5 | 50% | 0.10 |
| Leading $B$-decay branching fractions | — | 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 $B\bar{B}$ | — | 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 | $p, \theta$ 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 |

# Risultati

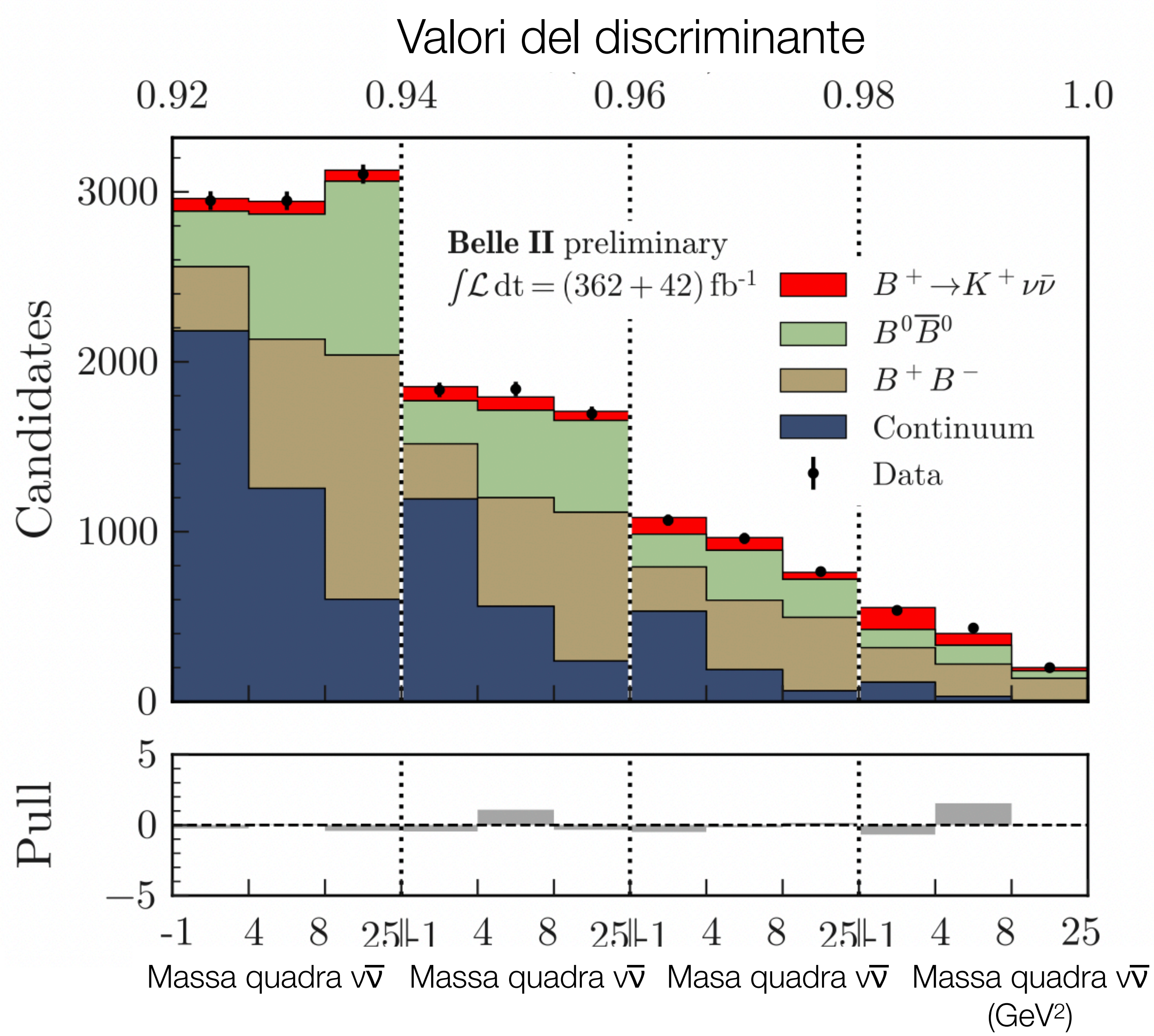

Simulated Belle II event
$B^+ \to K^+\nu\bar{\nu}$
signal kaon track
-200 -150 -100 -50 0 50 100 150
-200 -150 -100 -50 0 50 100 150

# Il fit ai dati

Fuori dalla Y(4S) (solo quark leggeri)




Alla Y(4S) (quark leggeri più *BB*)

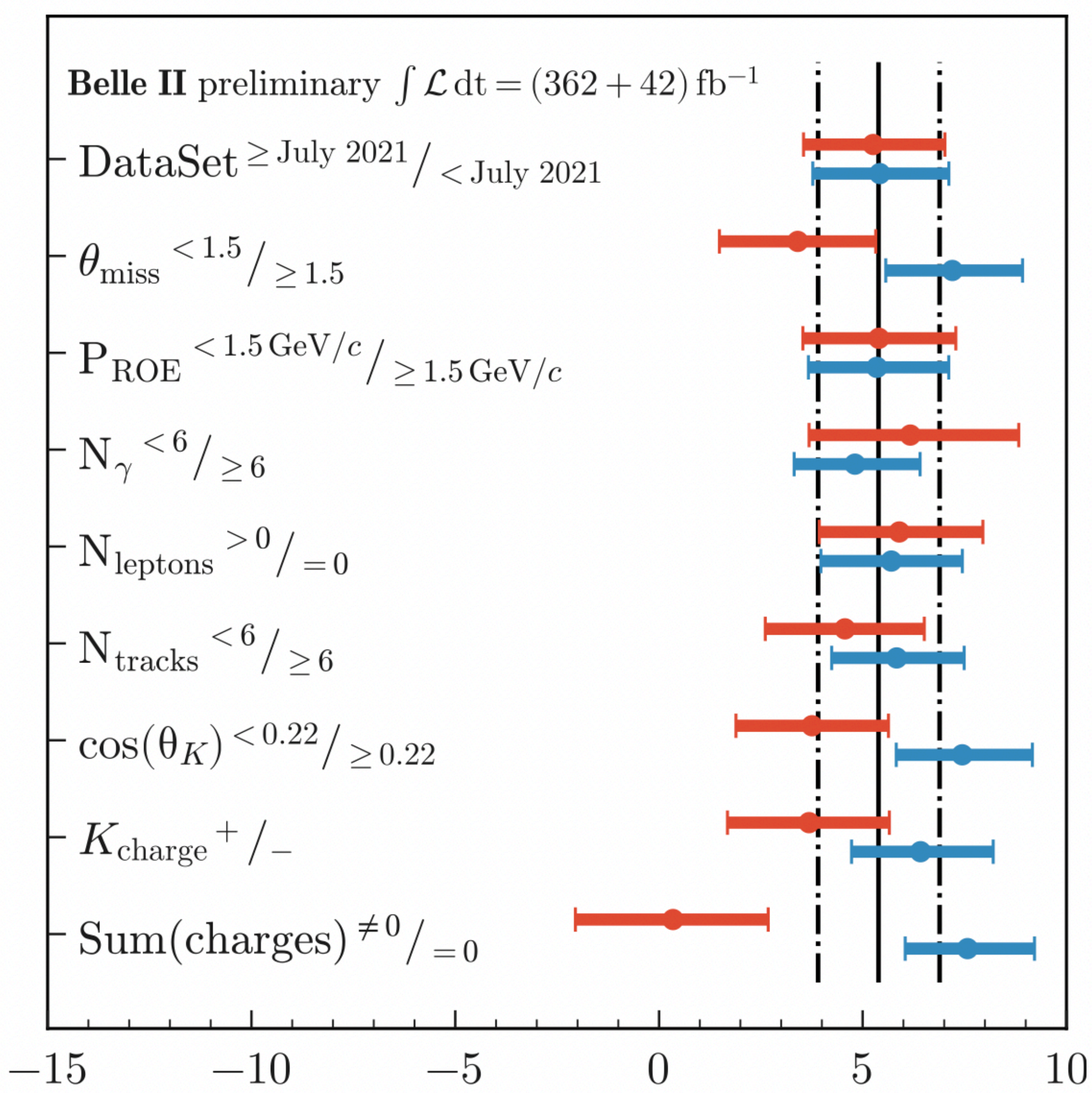



B($B^+ \to K^+ \nu\bar{\nu}$) = (2.7 ± 0.5 ± 0.5)× $10^{-5}$ (3.5σ da 0.0)

5.4 ±1.5 volte lo SM (2.9σ da SM)

# Controlli di consistenza

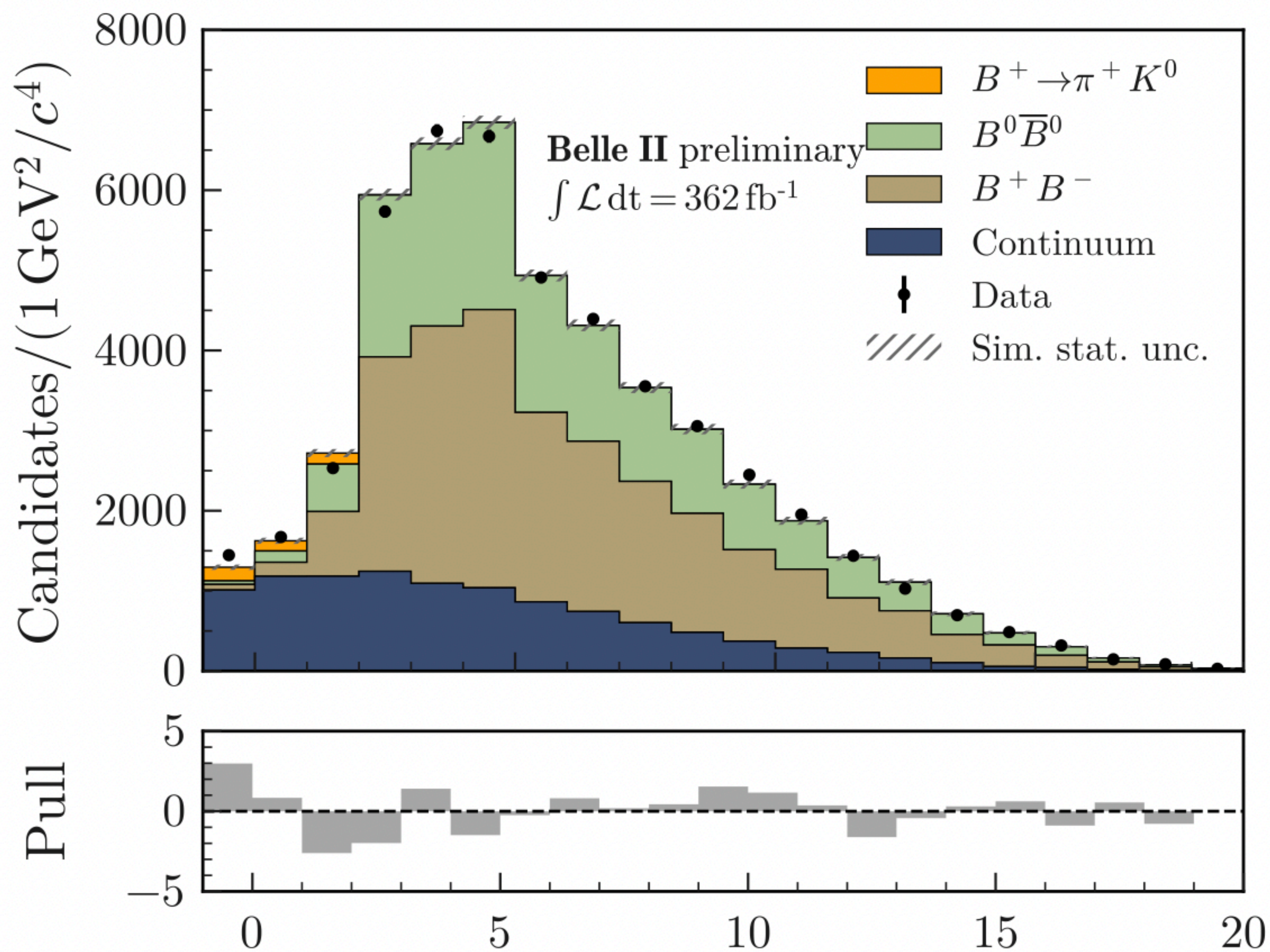
## Risultati osservati in sottocampioni




Probabilità di decadimento rispetto allo SM

Consistenza in (quasi) tutti i sottocampioni

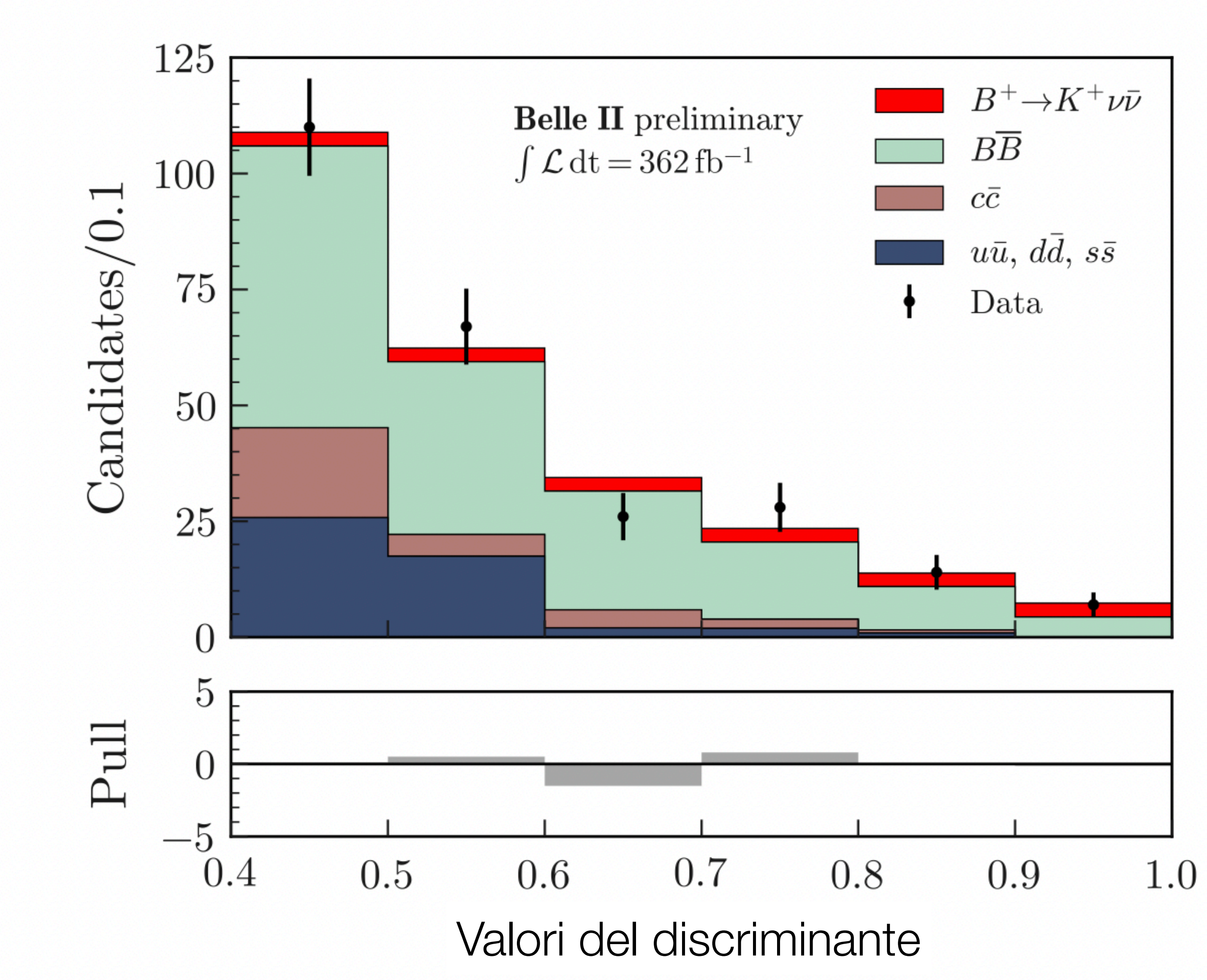
## Misuro B($B^+ \to K^0\pi^+$) ignorando il $K^0$




Massa quadra del K0

B($B^+ \to K^0\pi^+$) = (2.3 ± 0.5)× $10^{-5}$
(consistente con valore noto 2.38±0.08)

# Analisi alternativa (e conservativa) di controllo



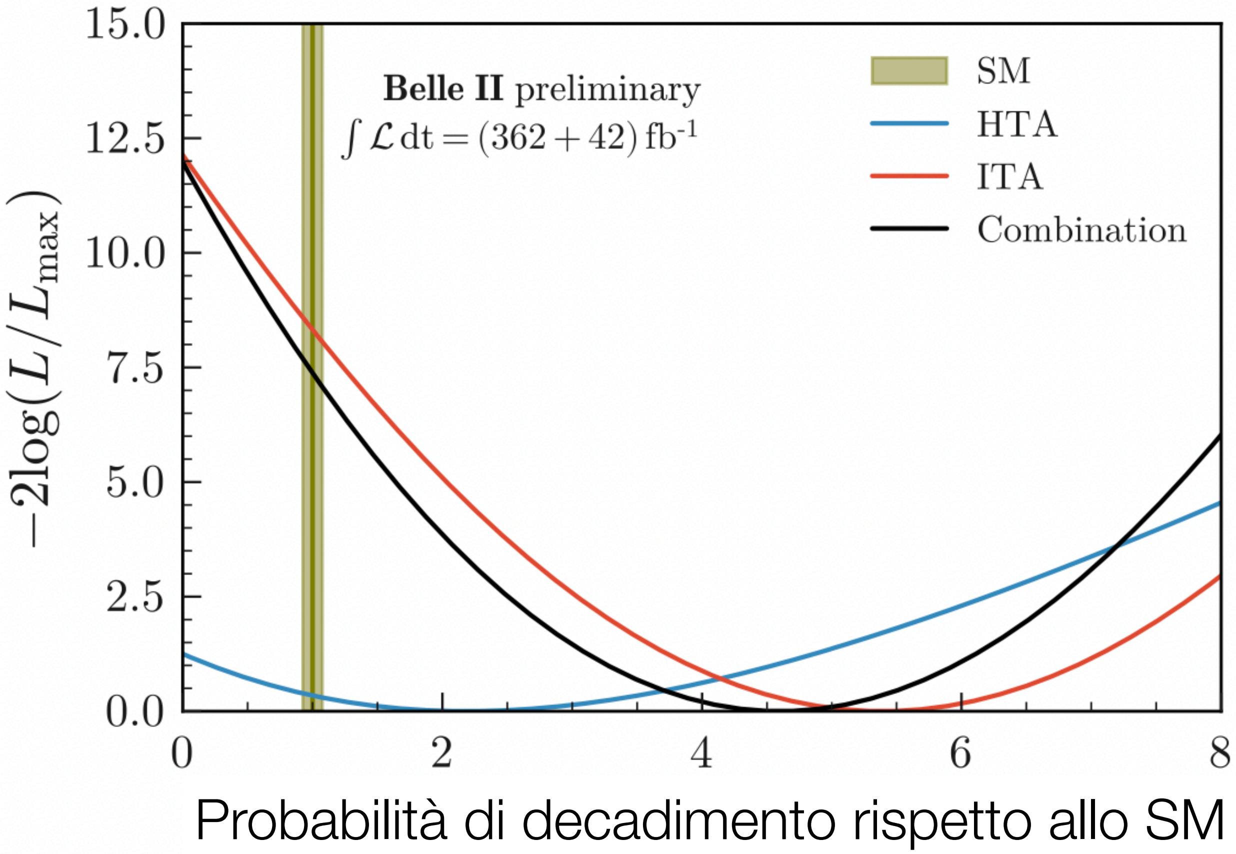

$$B(B^+ \to K^+ \nu\bar{\nu}) = (1.1\ ^{+0.9}_{-0.8}\ ^{+0.8}_{-0.5}) \times 10^{-5}\ (1.1\sigma)$$

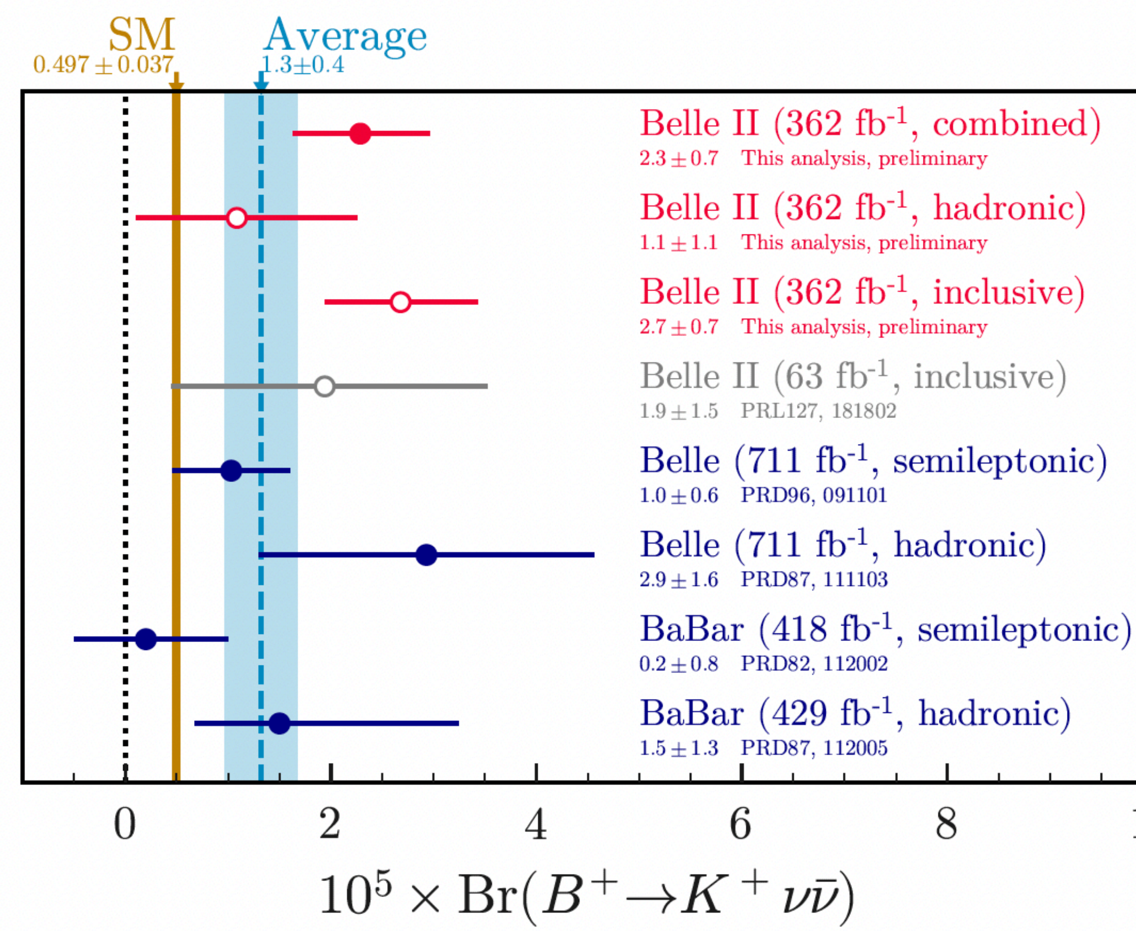
$2.2\ ^{+2.4}_{-2.0}$ volte lo SM (0.6σ da SM)

Risultati consistenti con analisi principale (1.2σ)

# Combinazione

L'overlap minimale dei campioni permette combinazione: +10% sensibilità



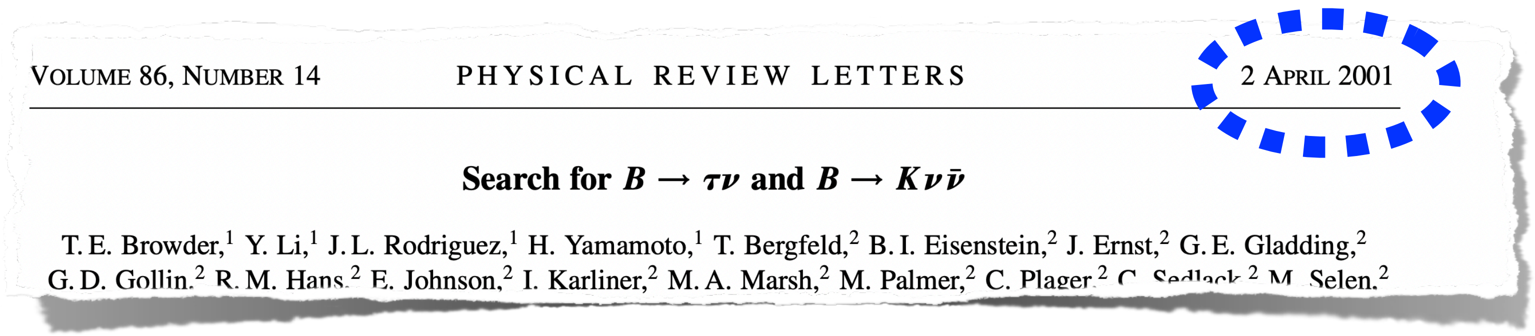

$B(B^+ \to K^+ \nu\bar{\nu}) = (2.3 \pm 0.5\ ^{+0.5}_{-0.4}) \times 10^{-5}$ (3.5σ da 0.0)

4.6 ±1.3 volte lo SM (2.7σ da SM)

Fluttuazione statistica? Improbabile. Errore nella misura? Possibile. Eccesso reale? Improbabile, non impossibile.

# In prospettiva

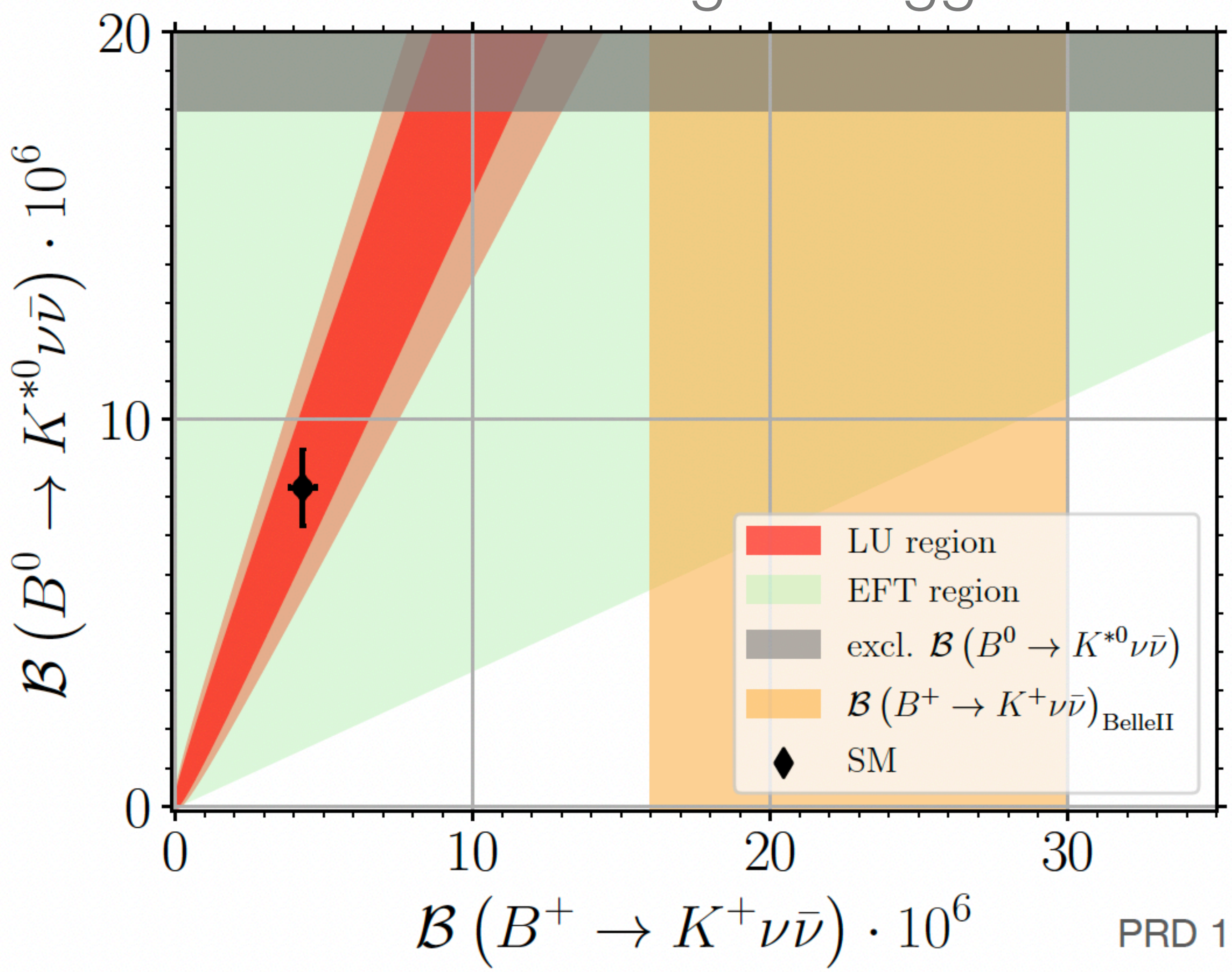
Dalla prima ricerca, più di 20 anni fa


VOLUME 86, NUMBER 14 PHYSICAL REVIEW LETTERS 2 APRIL 2001

**Search for $B \to \tau\nu$ and $B \to K\nu\bar{\nu}$**

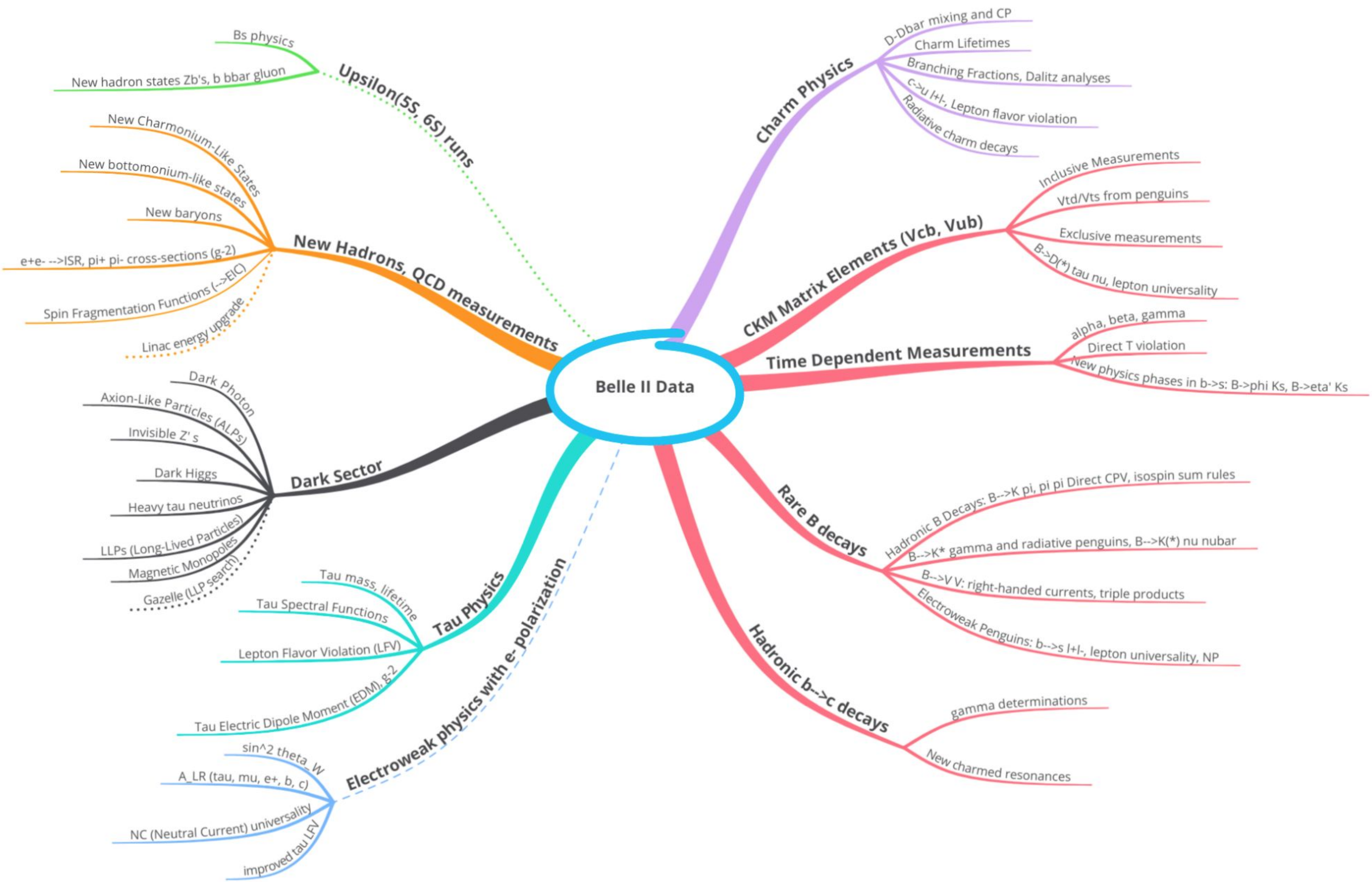
T. E. Browder,[1] Y. Li,[1] J. L. Rodriguez,[1] H. Yamamoto,[1] T. Bergfeld,[2] B. I. Eisenstein,[2] J. Ernst,[2] G. E. Gladding,[2]
G. D. Gollin,[2] R. M. Hans,[2] E. Johnson,[2] I. Karliner,[2] M. A. Marsh,[2] M. Palmer,[2] C. Plager,[2] C. Sedlack,[2] M. Selen,[2]

Alle implicazioni sulla fenomenologia di oggi



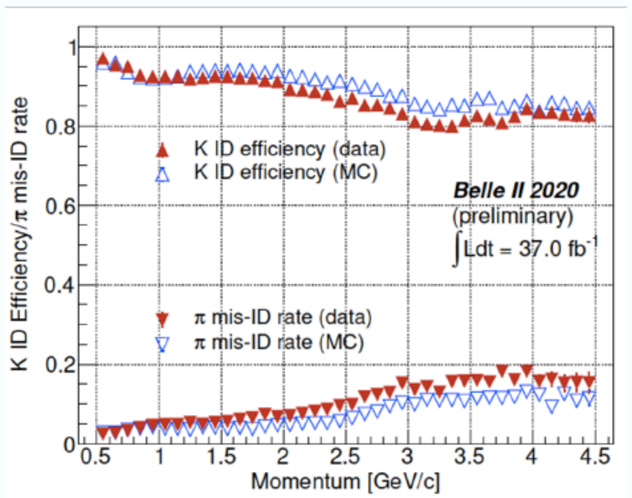

PRD 109, 015006 (2024)

# La fisica di Belle II è molta di più

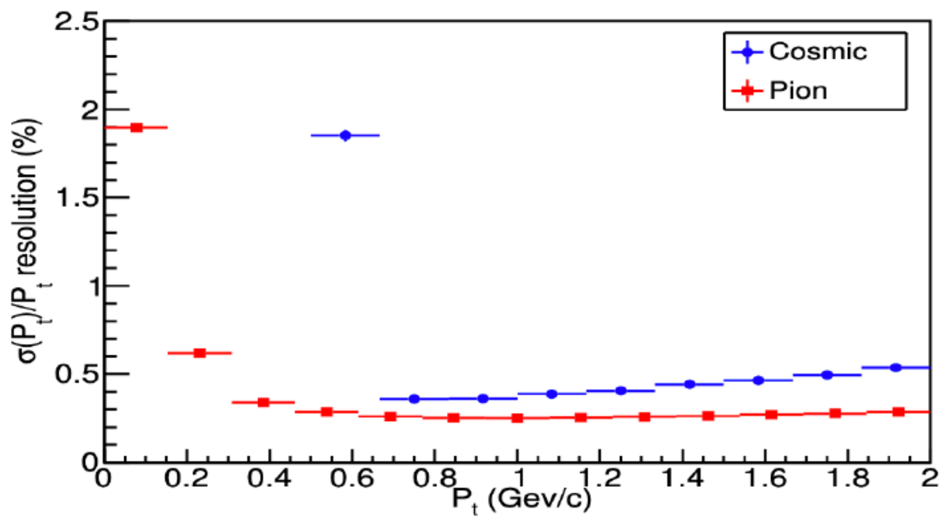



Fine

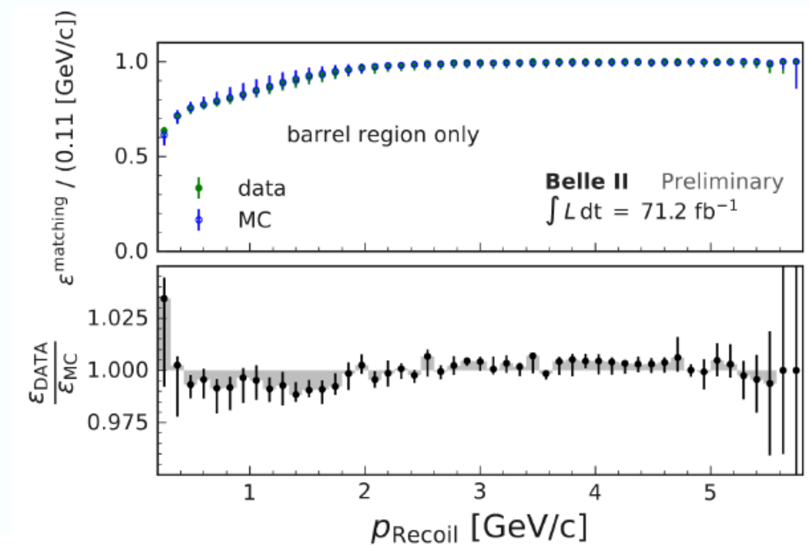
# Performance



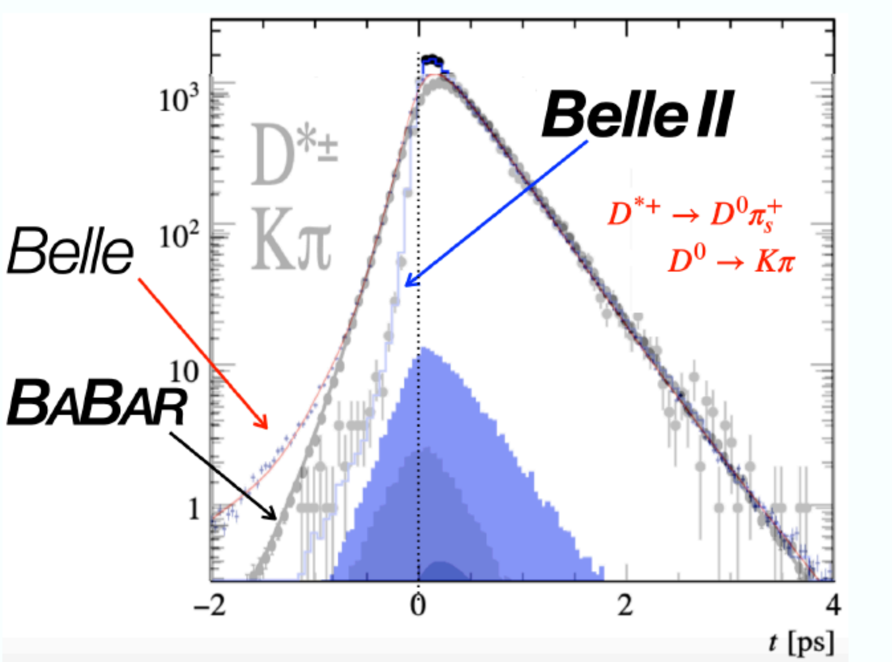

PID similar to Belle



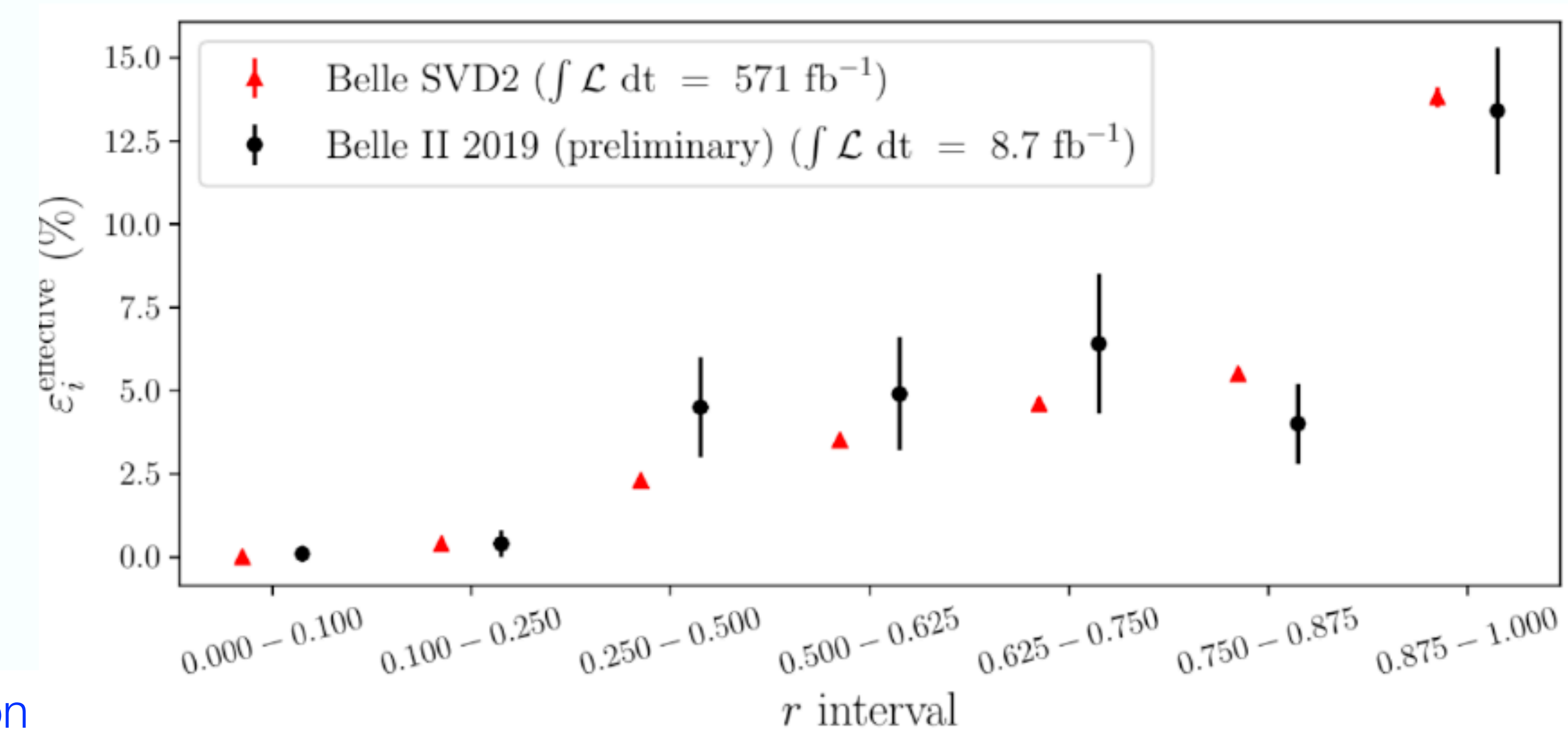

Momentum resolution 20% better than Belle




High photon efficiency,




Nearly 2x better decay-time resolution than Belle




Tagging performance similar to Belle and improving

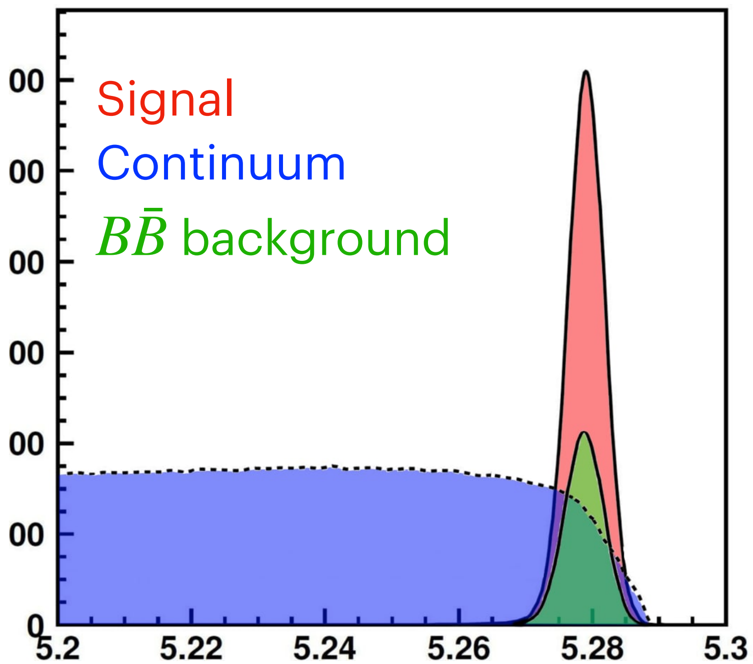
# *B* factory analysis 101

Point-like particles colliding at *BBbar* threshold:

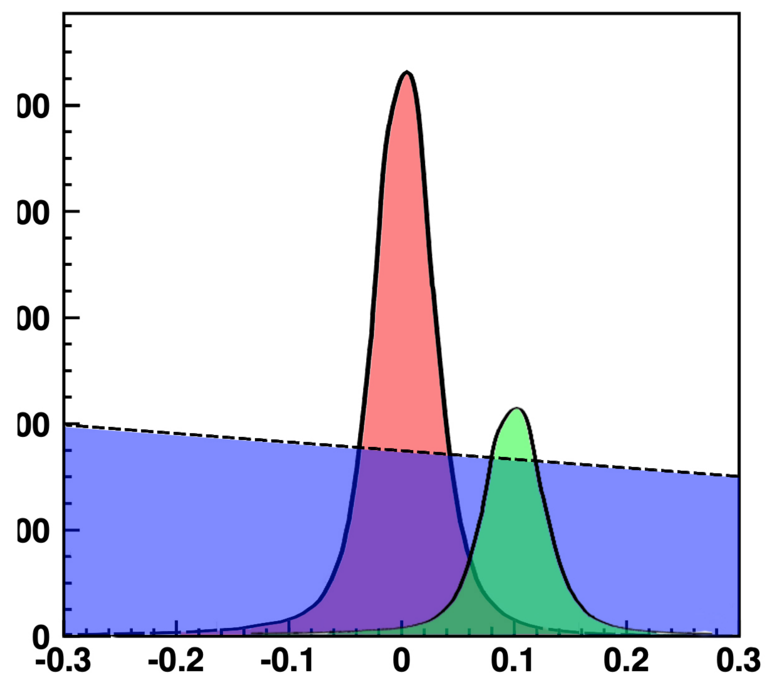
Low background and knowledge of initial state: stringent kinematic constraints.

Extract signal using kinematics

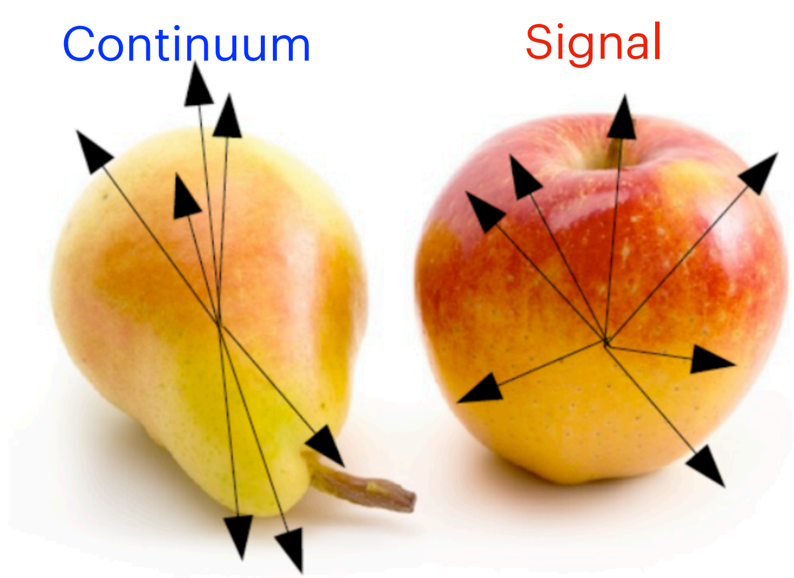
..and event shape

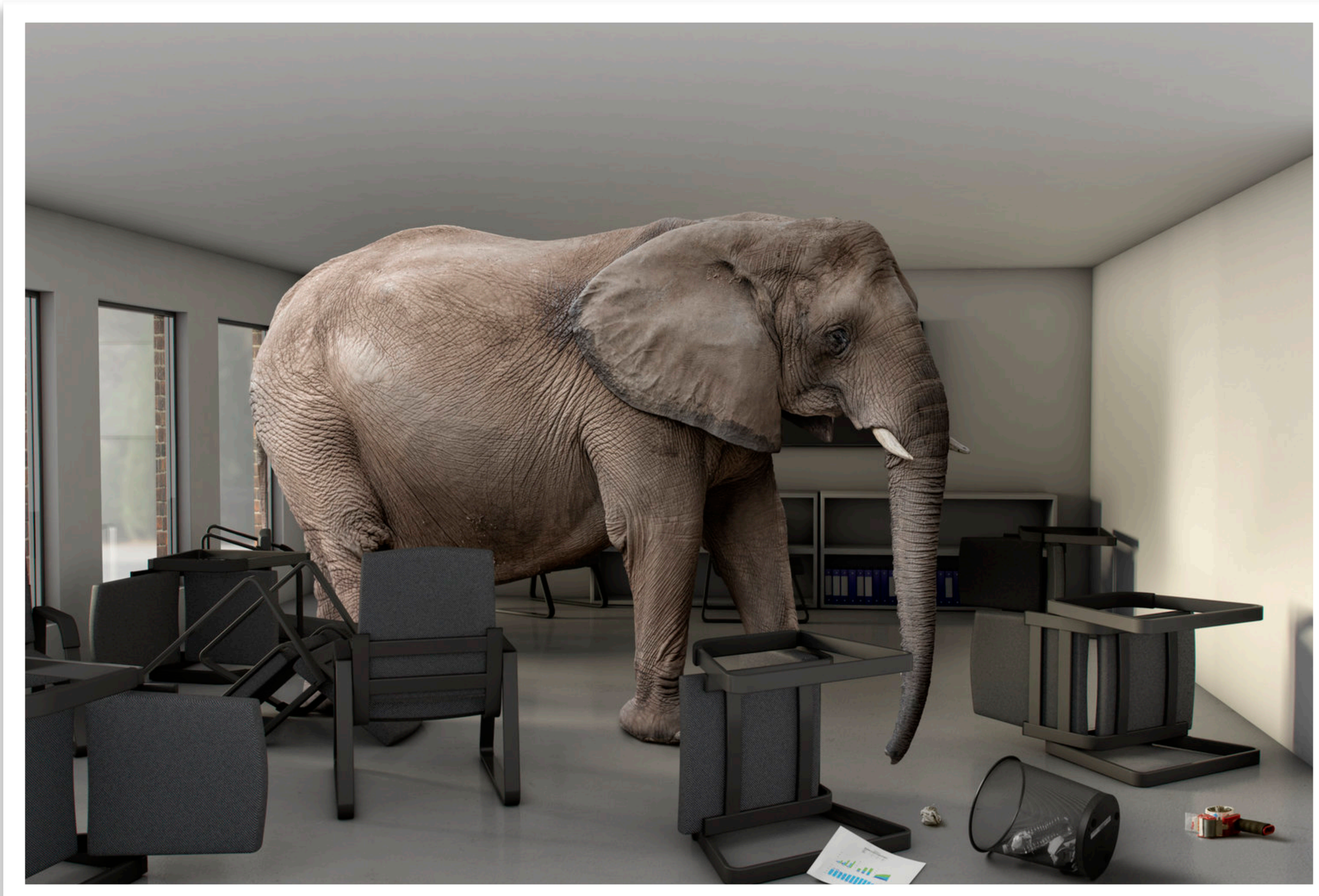



Invariant $B$ mass with $B$ energy replaced by half of the collision energy.




Difference between expected and observed B energy





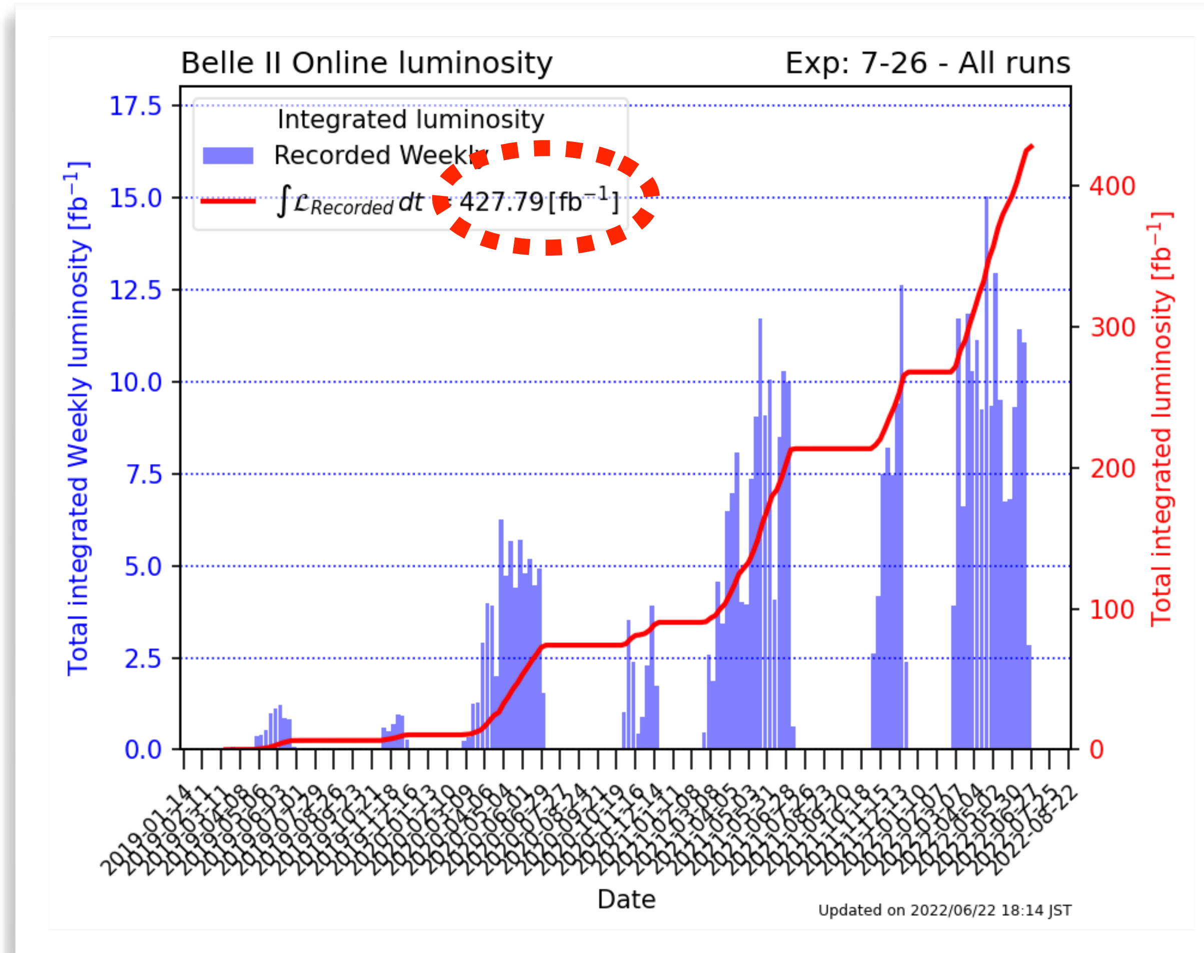
# 428 $fb^{-1}$ after 4 years

Shortcomings in injection, collimation, beam stability, control of beam-backgrounds etc

SuperKEKB integrated luminosity ~10x off with respect to plans (Tip: SuperKEKB is exploring uncharted territory)

Issues getting addressed as we speak

Still, we only got a sample equivalent to Babar's and to 50% of Belle's so far




We have a newer and better detector than our predecessors

We have a larger and stronger collaboration than our predecessors

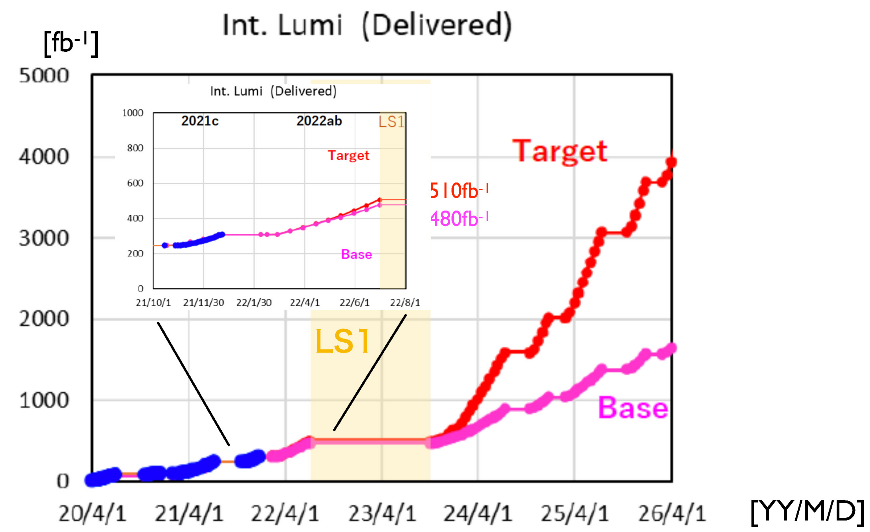
We benefit from 20+ years of progress in analysis and tools.

# Future

## 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 2026-2027

Submitted to the Proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021)

### Snowmass White Paper: Belle II physics reach and plans for the next decade and beyond

Belle II Collaboration


**Abstract**

We describe the physics potential of the Belle II experiment with electron-positron data corresponding to integrated luminosities of 1 $\mathrm{ab}^{-1}$ to 50 $\mathrm{ab}^{-1}$. We discuss Belle II's unique capabilities in reconstructing neutral particles, neutrinos and other "invisible" particles, and inclusive final states to probe non-standard-model physics. We project sensitivities for compelling measurements that are of primary relevance and where Belle II reach is unique or world leading.


arxiv:2207.06307

- Executive summary of Belle II/SuperKEKB White Papers, https://arxiv.org/abs/2203.10203
- Opportunities for Precision QCD at Belle II, https://arxiv.org/abs/2204.02280
- Charged Lepton Flavor Violation in the Tau Sector (joint paper of Belle II and other future experiments), https://arxiv.org/abs/2203.14919
- Dark Sector (joint paper of Belle II and other intensity frontier experiments), https://arxiv.org/abs/2207.00597
- Belle II Detector Upgrades White Paper, https://arxiv.org/abs/2203.11349
- Belle II User-based GRID analysis, https://arxiv.org/abs/2203.07564
- Beam Background Expectations for Belle II at SuperKEKB, http://arxiv.org/abs/2203.05731
- SuperKEKB Electron Polarization Upgrade White Paper, https://arxiv.org/abs/2205.12847
- Future HEP Computing Challenges (Belle II/DUNE joint paper), https://arxiv.org/abs/2203.07237
- Physics reach of a long-lived particle detector at Belle II, https://arxiv.org/abs/2105.12962

# Auxiliary plots

## Validazione di K identification

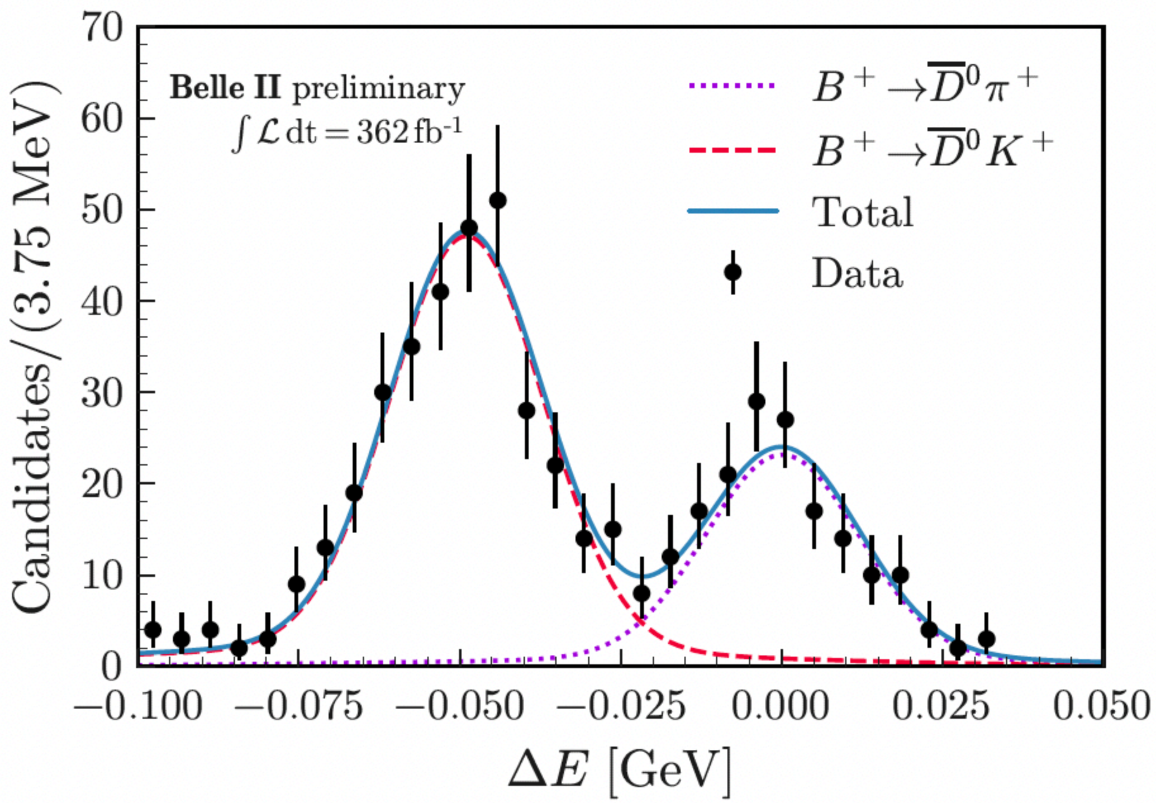



FIG. 2. Distribution of $\Delta E$ in data (dots with error bars) obtained for $B^+ \to h^+ \overline{D}^0$ decays, where $h^+ = \pi^+$ or $K^+$, computed assuming a pion mass hypothesis for $h^+$. The blue solid line represents the fit result to the data, modeled as a sum of two Gaussian shapes corresponding to $B^+ \to K^+ \overline{D}^0$ (dashed red line) and $B^+ \to \pi^+ \overline{D}^0$ (dotted magenta line) decays. Events selected for the figure are reconstructed as $B^+ \to K^+ \nu \bar{\nu}$ events, with the daughters from the $\overline{D}^0$ decays removed, and chosen to be in the signal region of the ITA.

## Validazione dell'energia dei fotoni

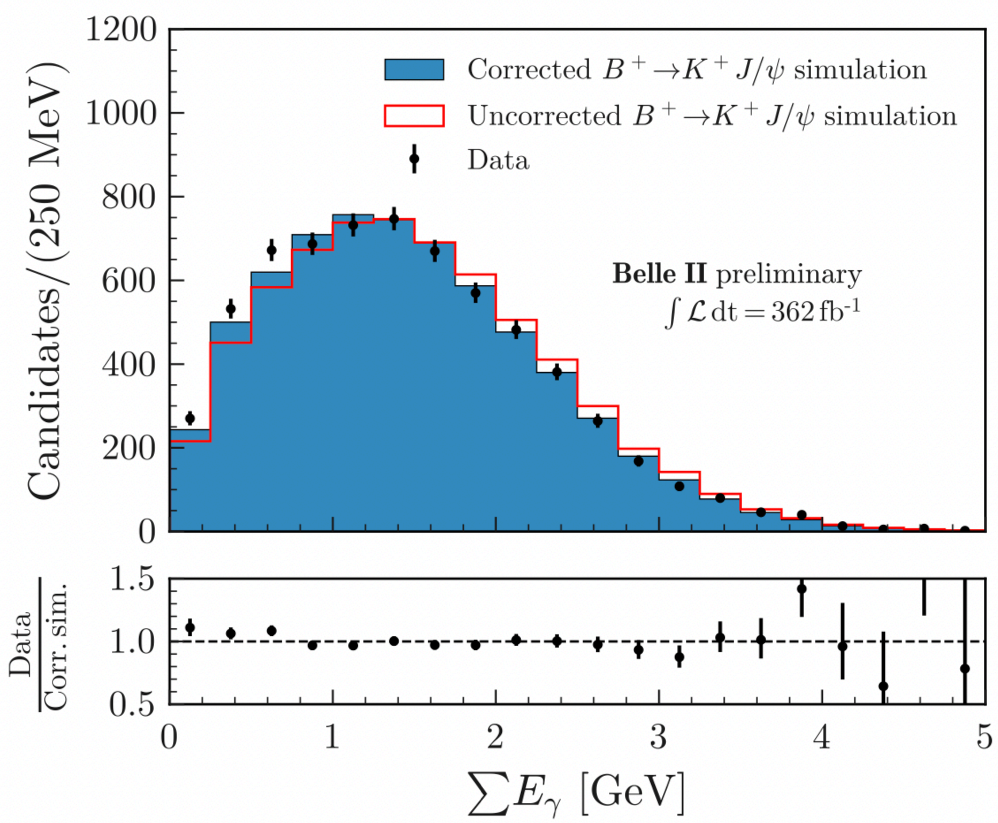



FIG. 3. Distribution of the summed energy of the photon candidates obtained in collision data (points with error bars), uncorrected simulated data (open histogram), and corrected simulated data (filled histogram), for events in which a $B^+ \to K^+ J/\psi$ decay is reconstructed. The correction corresponds to a variation of the hadronic energy by $-10\%$. The simulation is normalized to the number of events in data. The ratio shown in the lower panel refers to data over corrected simulation.

# Auxiliary plots

Efficienza di ricostruzione KL

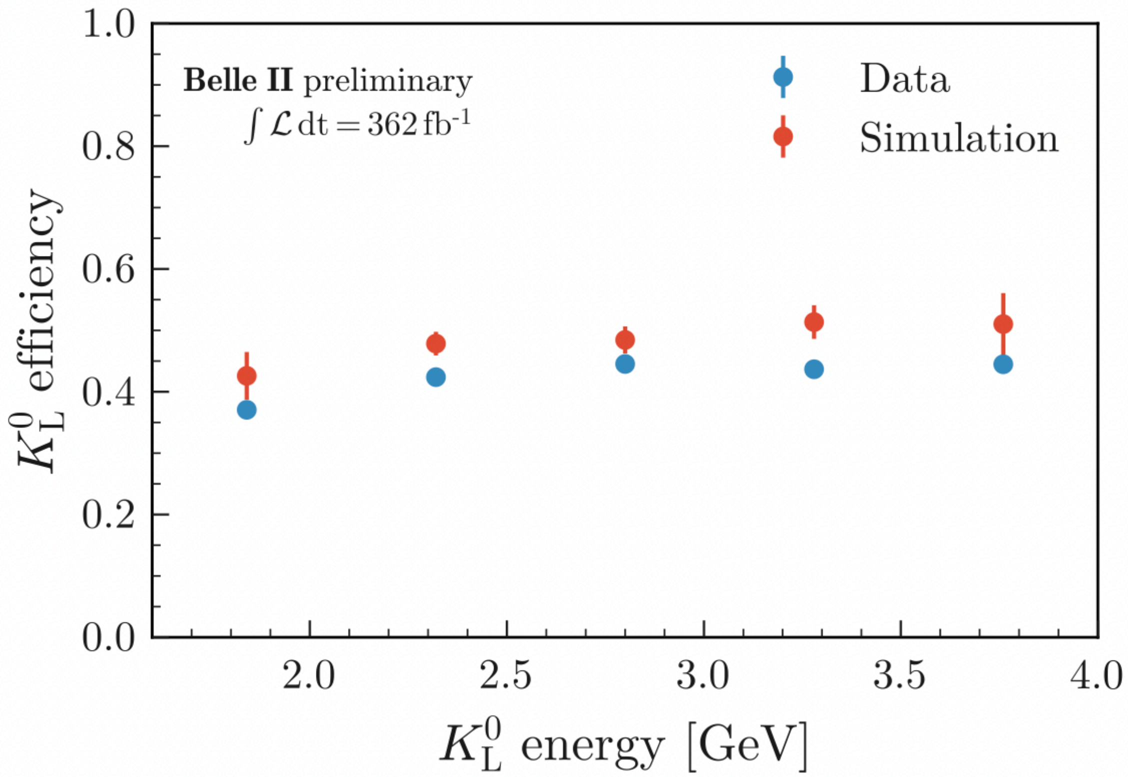



FIG. 5. Efficiency of reconstructing an energy deposit in the ECL matched to the $K^0_L$ direction, as a function of the $K^0_L$ energy, for $e^+e^- \to \gamma\phi$ data and simulation. The energy deposits are selected following the ITA criteria.

Differenza del 17% - corretta ed aggiunto un 9% (assoluto) di sistematica

Validazione del continuo

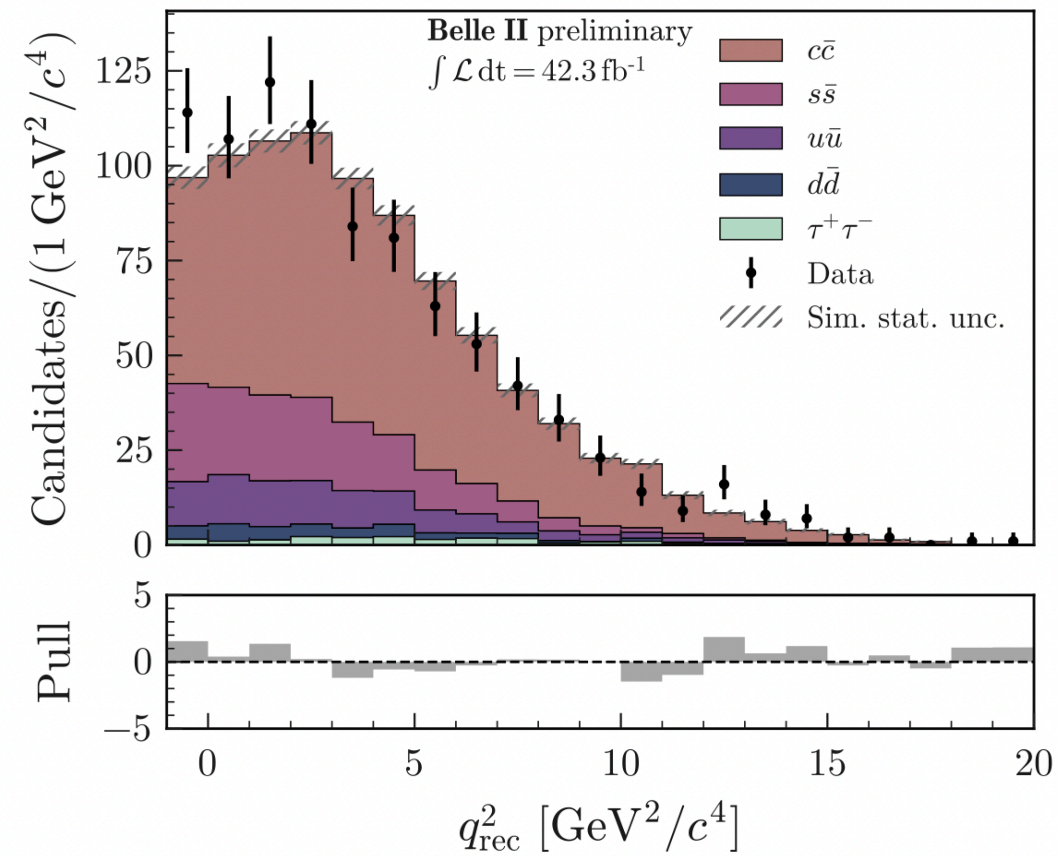



FIG. 8. Distribution of $q^2_{rec}$ for the off-resonance data (points with error bars) and continuum background simulation (filled histograms) in the SR for the ITA. The simulation is normalized to the number of events in the data. The distribution of the difference between data and simulation divided by the combined uncertainty (pull) is shown in the bottom panel.

Shape OK, ma 40% di discrepanza in size

# Auxiliary plots

Efficienza di ricostruzione in funzione del quadrato della dineutrino mass

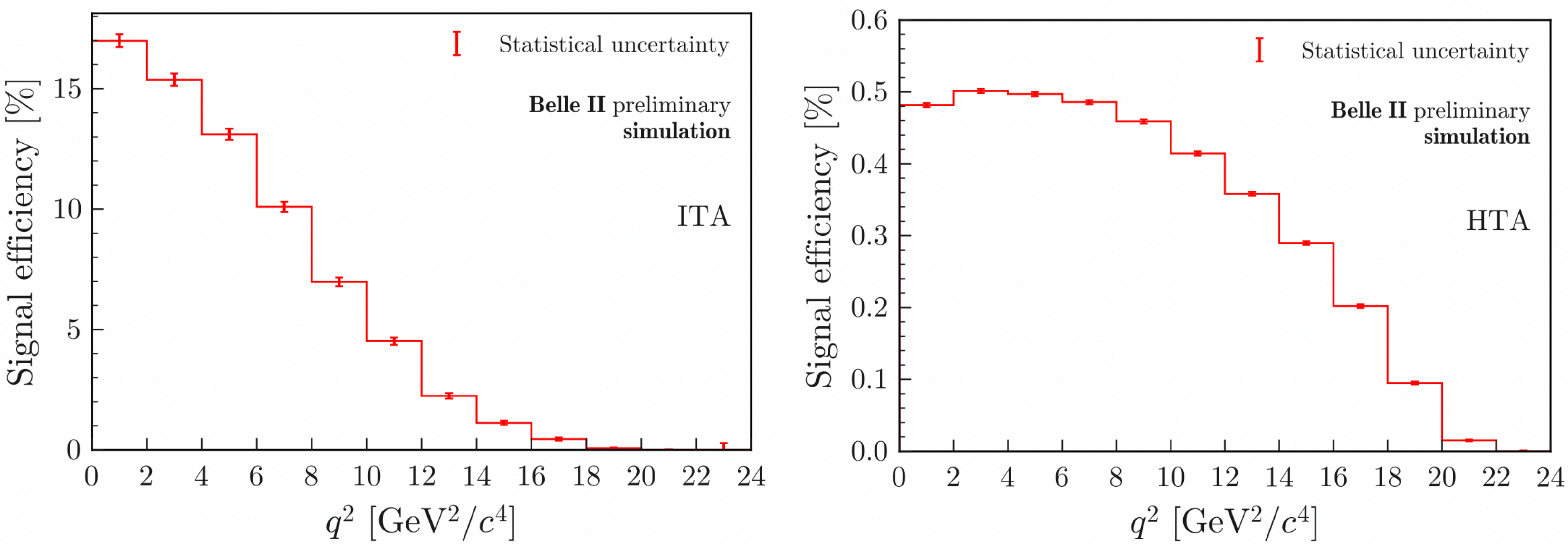



FIG. 6. Signal-selection efficiency as a function of the dineutrino invariant mass squared $q^2$ for simulated events in the SR for the ITA (left) and HTA (right). The error bars indicate the statistical uncertainty.

# Auxiliary plots

## Correzione dei BF (D -> KL)

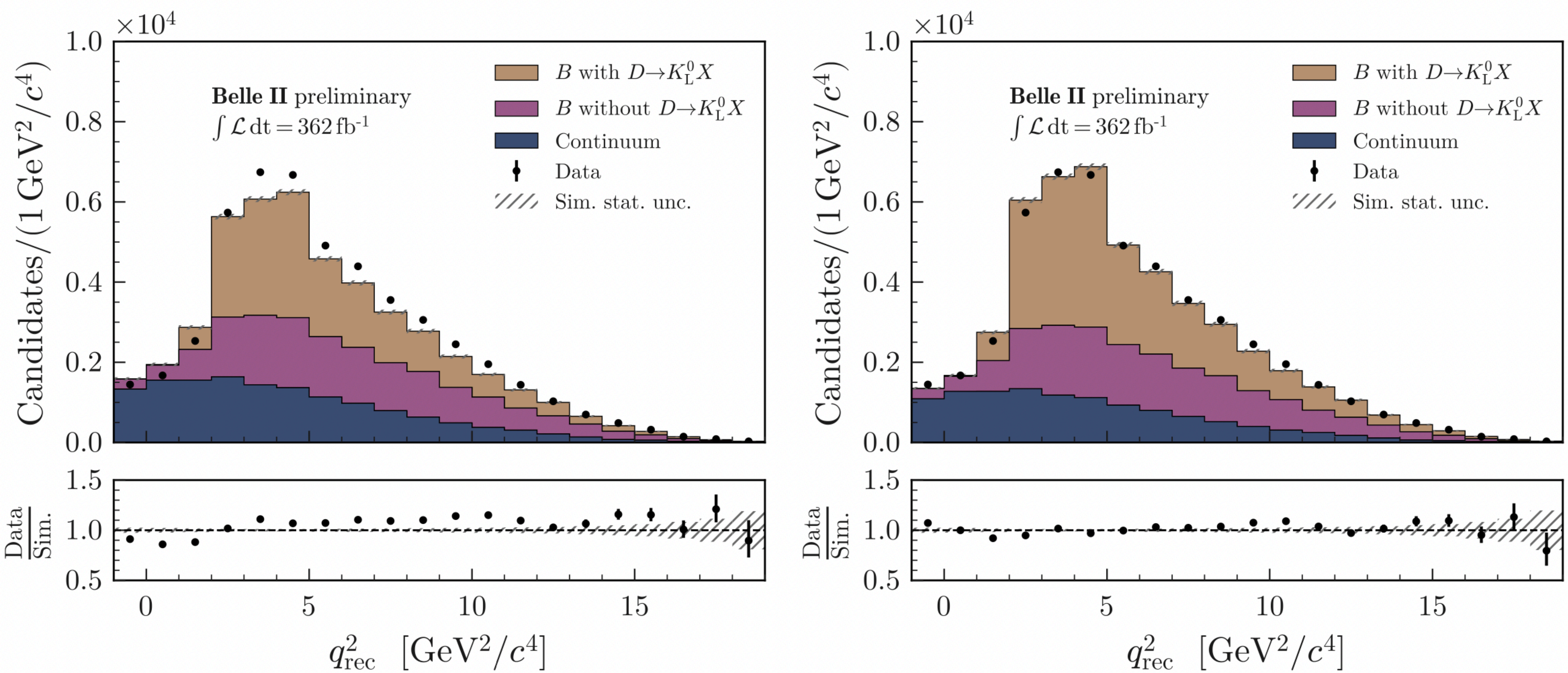



FIG. 10. Distribution of $q^2_{\mathrm{rec}}$ in data (points with error bars) and simulation (filled histograms) divided into three groups ($B$-meson decays with and without subsequent $D \to K_L^0 X$ decays, and the sum of the five continuum categories) for the pion-enriched sample in the ITA. The left (right) panel shows pre-(post-)fit distributions. The data-to-simulation ratios are shown in the bottom panels.

# Look back plots

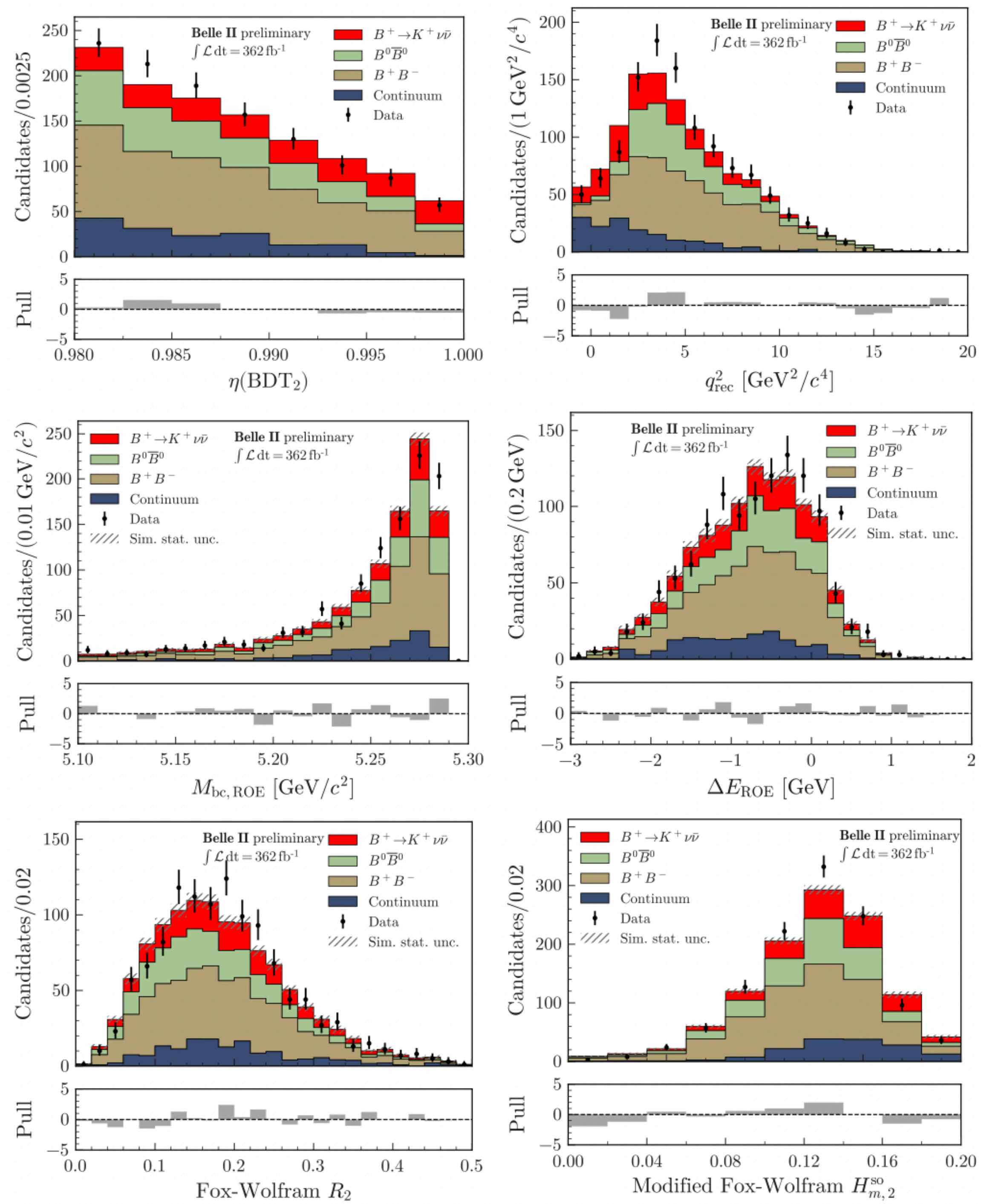



FIG. 18. Distributions of $\eta(\mathrm{BDT}_2)$, $q^2_{\mathrm{rec}}$, beam-constrained mass of the ROE $M_{\mathrm{bc,ROE}}$, $\Delta E_{\mathrm{ROE}}$, Fox-Wolfram $R_2$, and modified Fox-Wolfram $H^{\mathrm{so}}_{m,2}$ in data (points with error bars) and simulation (filled histograms) shown individually for the $B^+ \to K^+\nu\bar{\nu}$ signal, neutral and charged $B$-meson decays, and the sum of the five continuum categories in the ITA. Events in the most signal-rich region, with $\eta(\mathrm{BDT}_2) > 0.98$, are shown. Data and simulation are normalized to an integrated luminosity of 362 $\mathrm{fb}^{-1}$. The pull distributions are shown in the bottom panels.