Searching for $B^0 \rightarrow p\overline{\Sigma}^0\pi^-$ and $B^+ \rightarrow p\overline{n}\pi^0$ at Belle

- Introduction
- $B^0 \rightarrow p\overline{\Sigma}^0\pi^-$
- $B^+ \rightarrow p\overline{n}\pi^0$
- Prospects

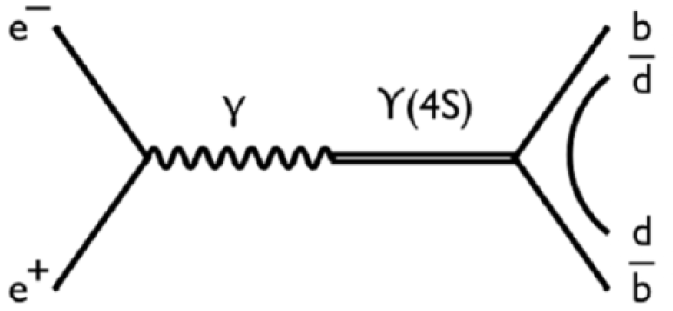
Presenter : Min-Zu Wang

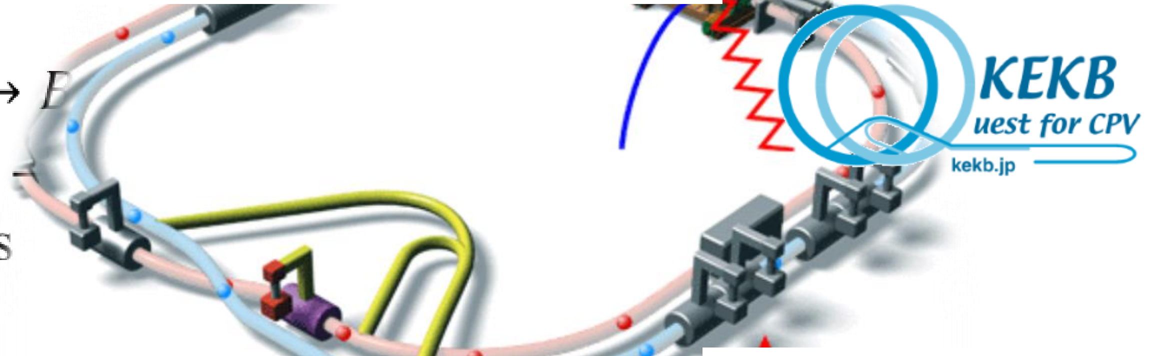
Department of Physics
National Taiwan University

2024/1/12@TQCD Workshop

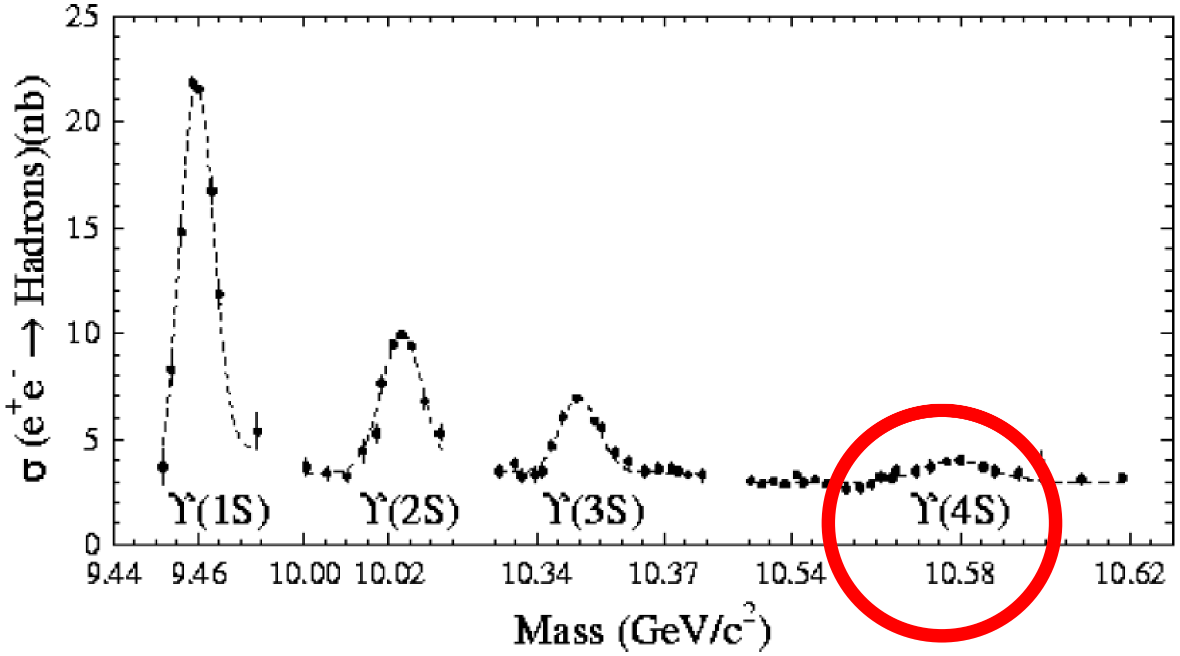
KEKB factory and data sample

- An asymmetric energy e^+e^- collider at KEK.
- LER(e^+): 3.5 GeV
  HER(e^-): 8 GeV
  Crossing angle: ±11 mrad



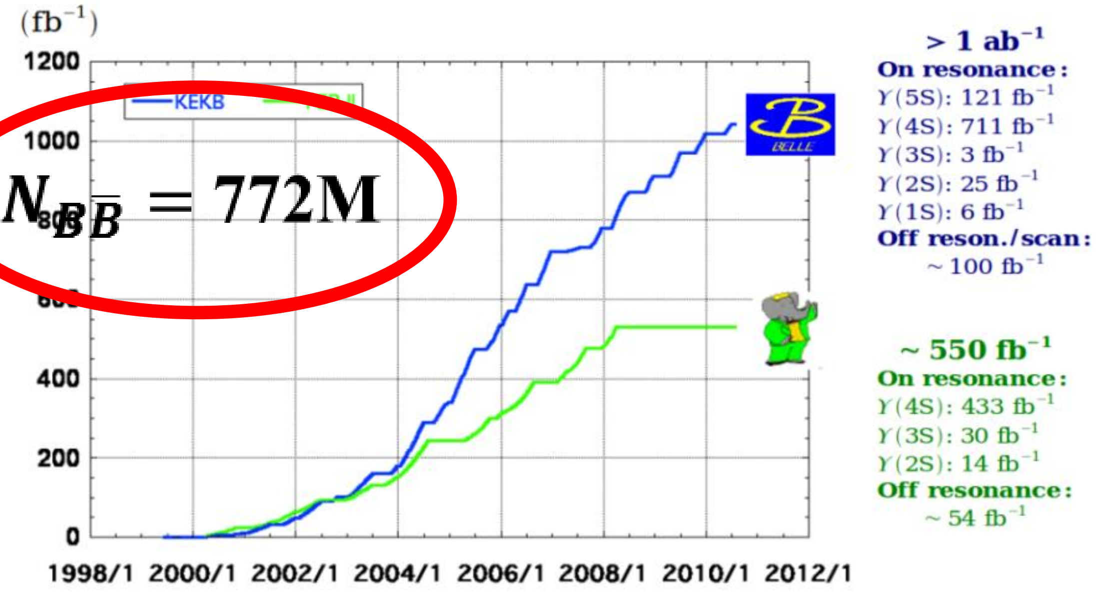


- Target: $e^+e^- \to \Upsilon(4S) \to$
- Main background: e^+e^-
  about 3 times larger cross
- The CM energy of e^+e^-



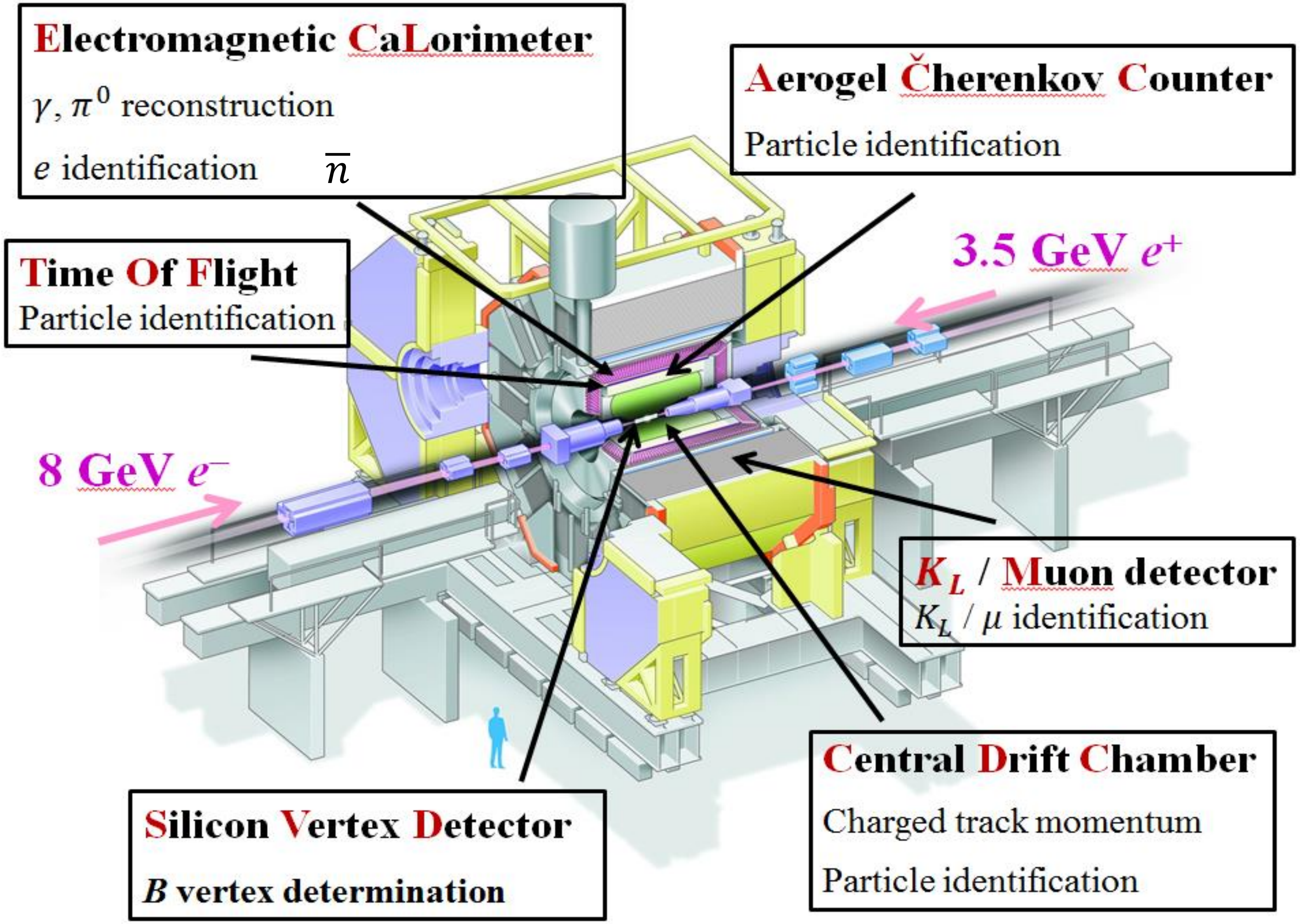
http://www.lns.cornell.edu/public/lab-info/upsilon.html

Integrated luminosity of B factories



$N_{B\bar{B}} = 772\text{M}$

Belle Detector



Electromagnetic CaLorimeter

γ, π^0 reconstruction

e identification $\bar{n}$

Aerogel Čherenkov Counter

Particle identification

Time Of Flight

Particle identification

K_L / Muon detector

K_L / μ identification

Silicon Vertex Detector

***B* vertex determination**

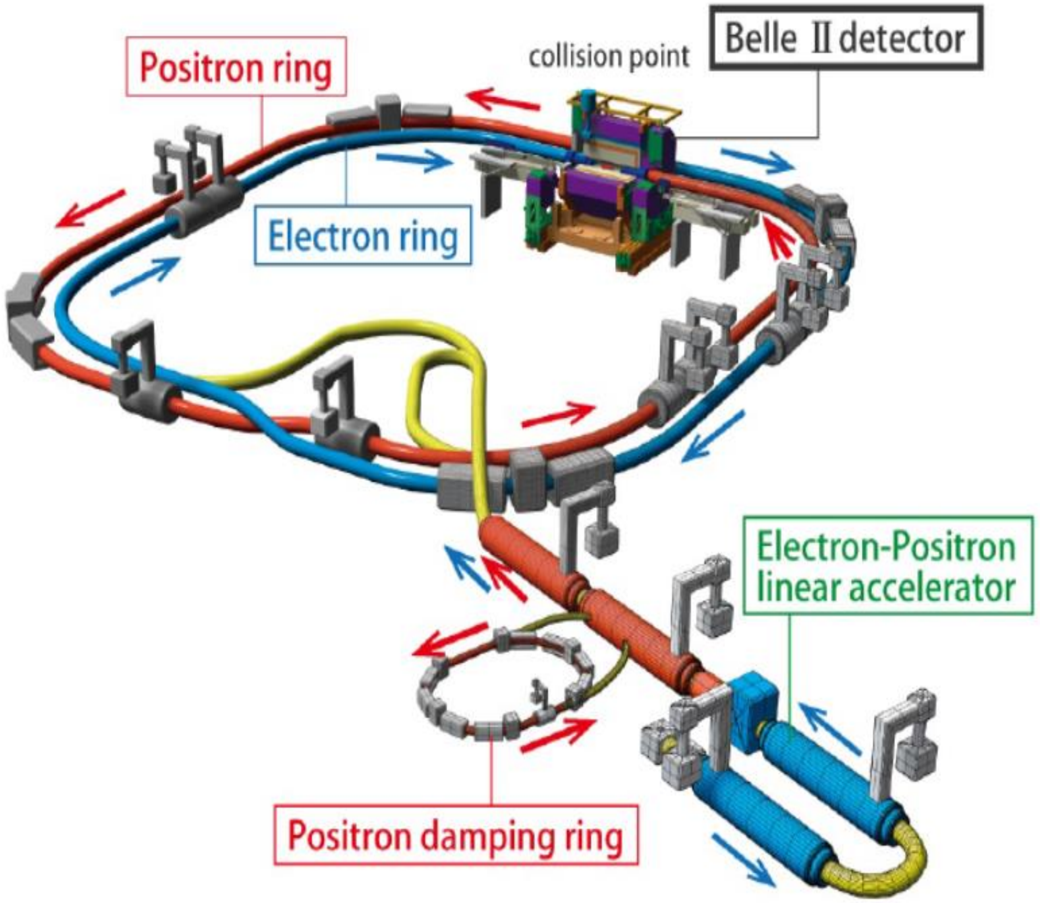
Central Drift Chamber

Charged track momentum

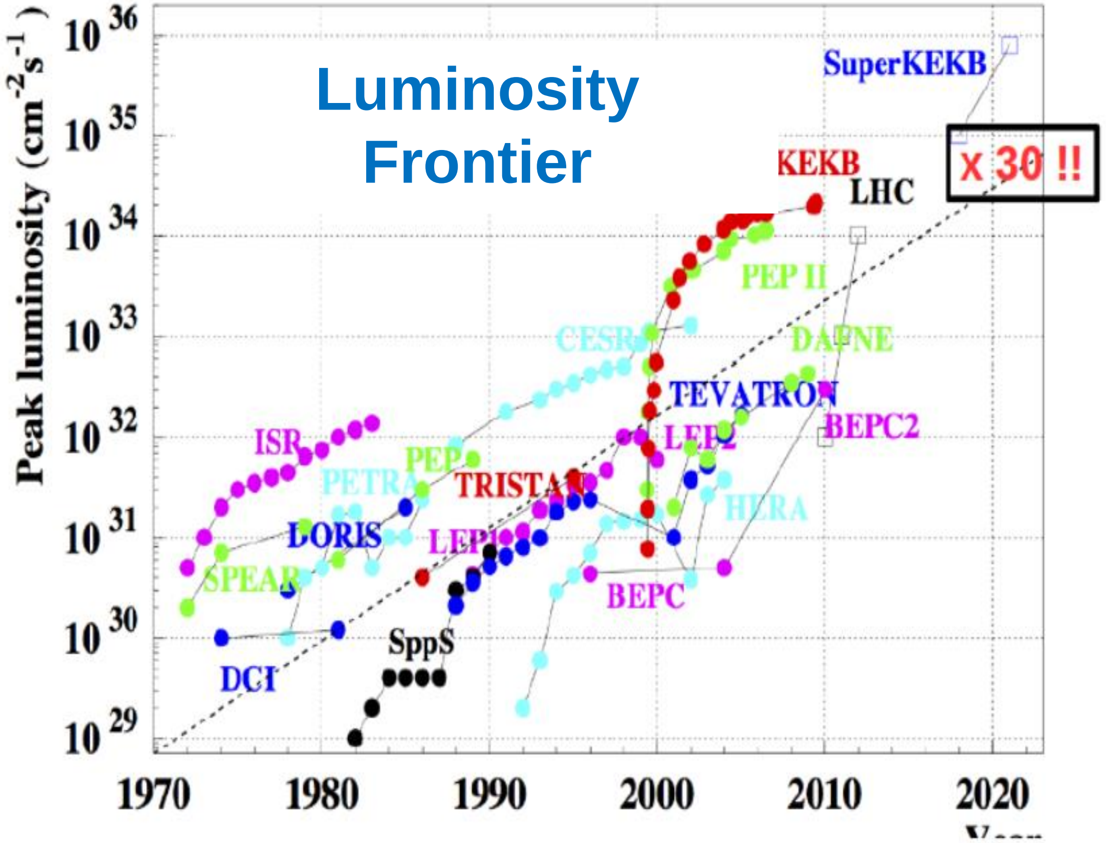
Particle identification

SuperKEKB nano-beam technology

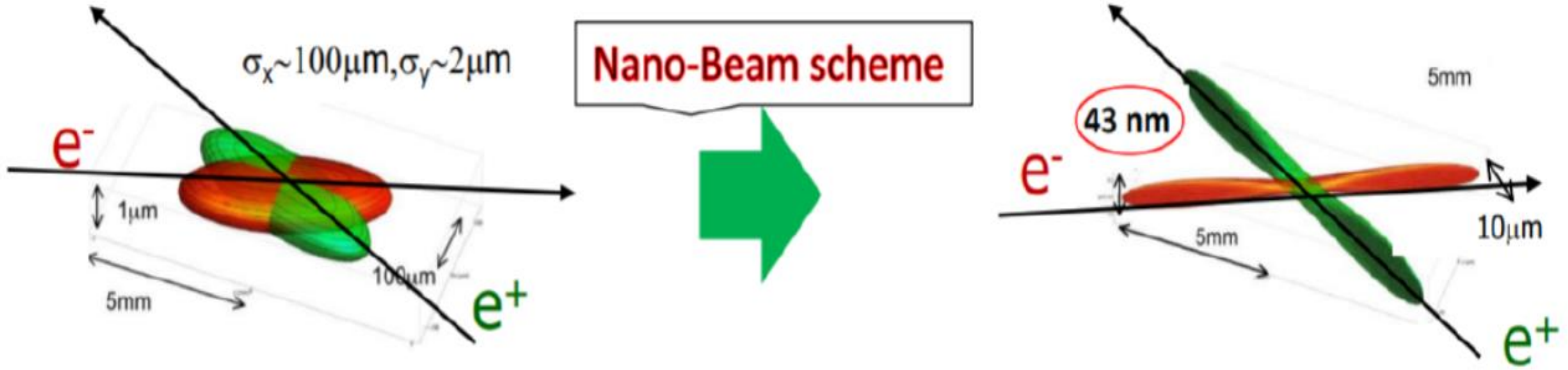
Asymmetric energy e+e- collider at KEK: 7 GeV e- and 4 GeV e+



A 30 fold increase in instantaneous luminosity over Belle, $\mathscr{L} = 6 \times 10^{35} cm^{-2} s^{-1}$



20 times smaller beam spot and 1.5 times increase in beam current ➡ 30 x luminosity

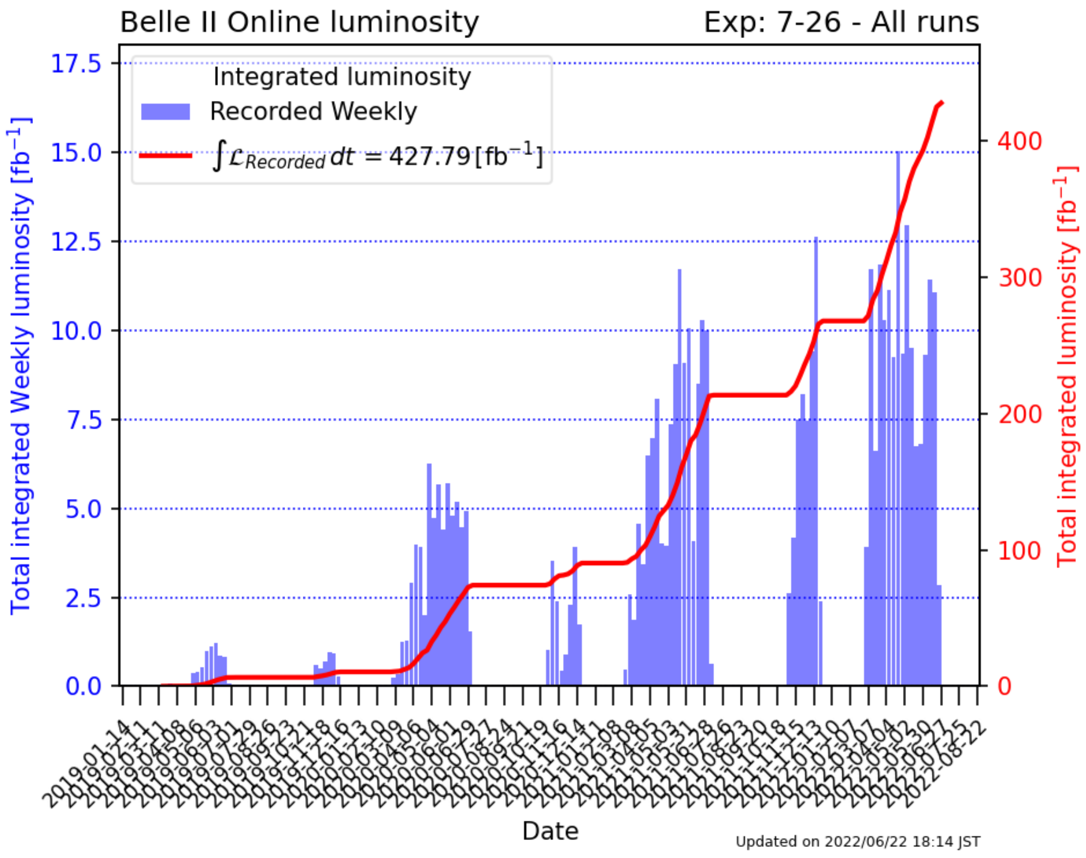


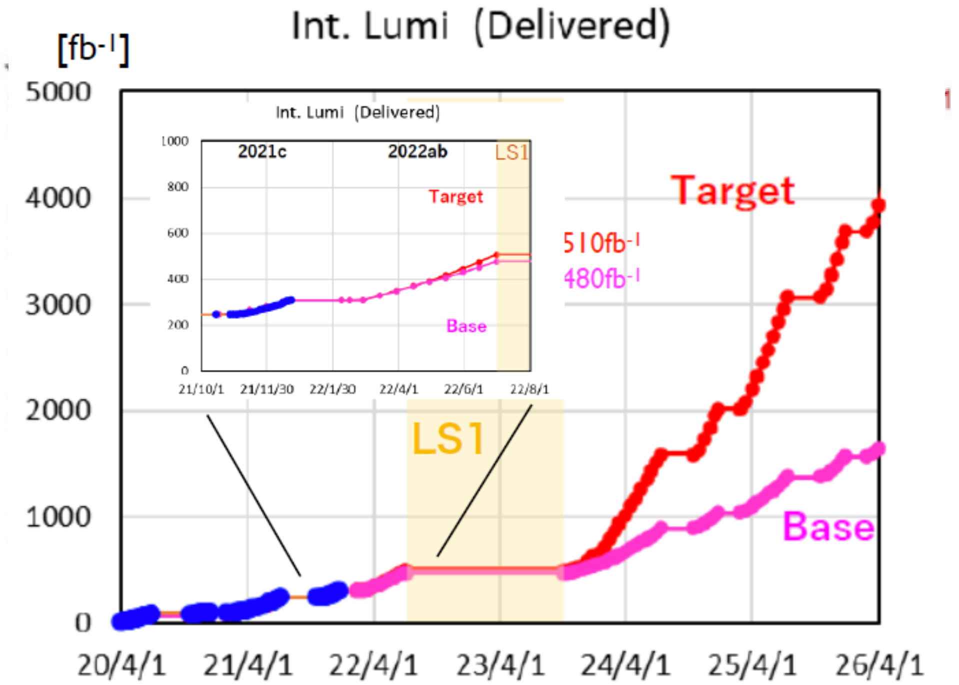
Belle II accumulated data

Luminosity

Status:

- ▷ Collected ~**428** fb^{-1} since April 2019
- ▷ Slower luminosity accumulation than initially planned, but with ~90% data-taking efficiency
- ▷ **Record-breaking instantaneous luminosity: 4.1** $\times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- ▷ **Highest daily integrated luminosity: 2.2 fb^{-1}**



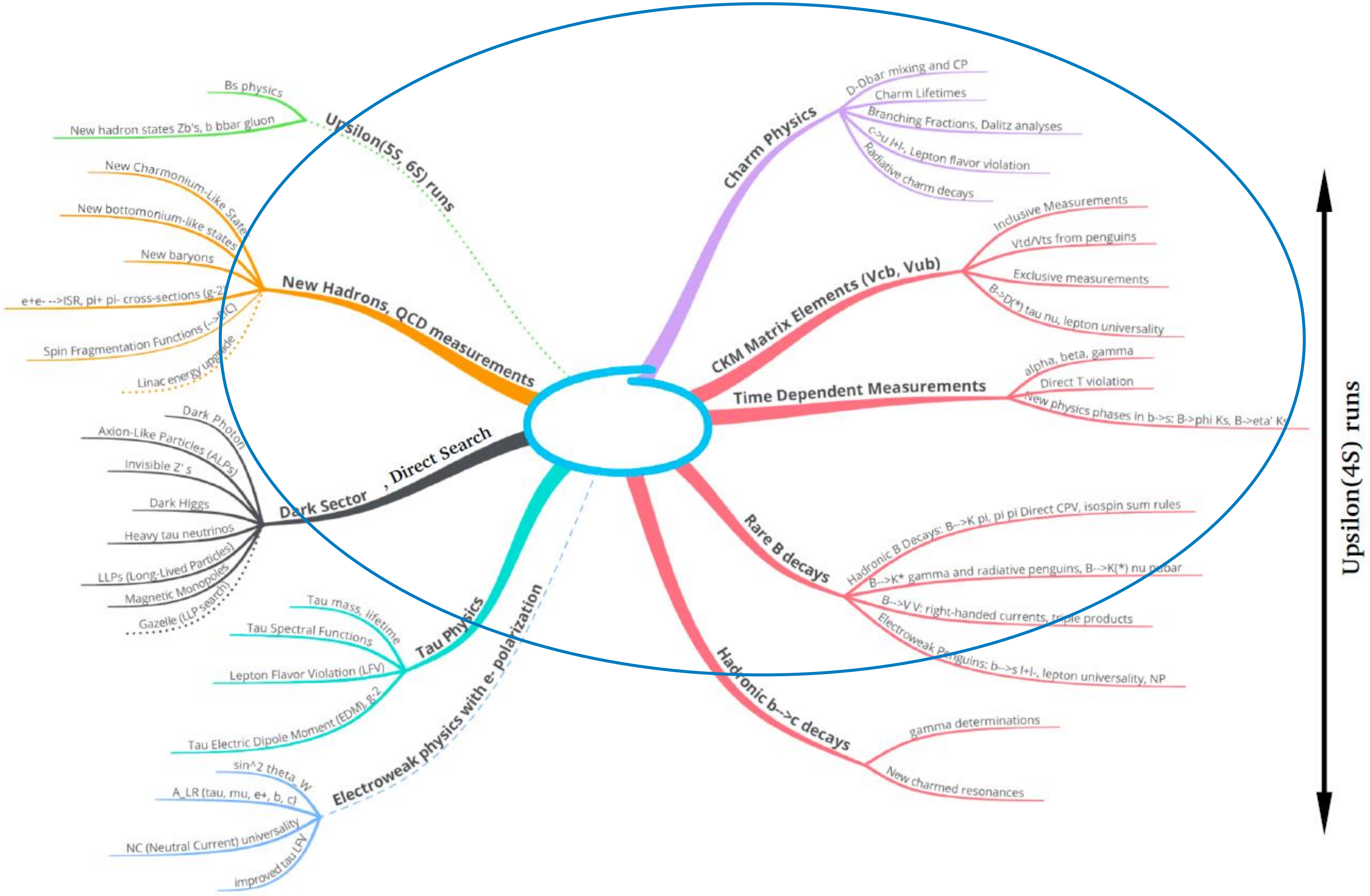


Plans:

- ▷ **Short-term plan**: shutdown in **2022**
  - ▷ full PXD installation → important to maintain good vertex resolution at high luminosity
- ▷ **Goal: 50 ab^{-1}**

One half of Belle data before 2022 LS

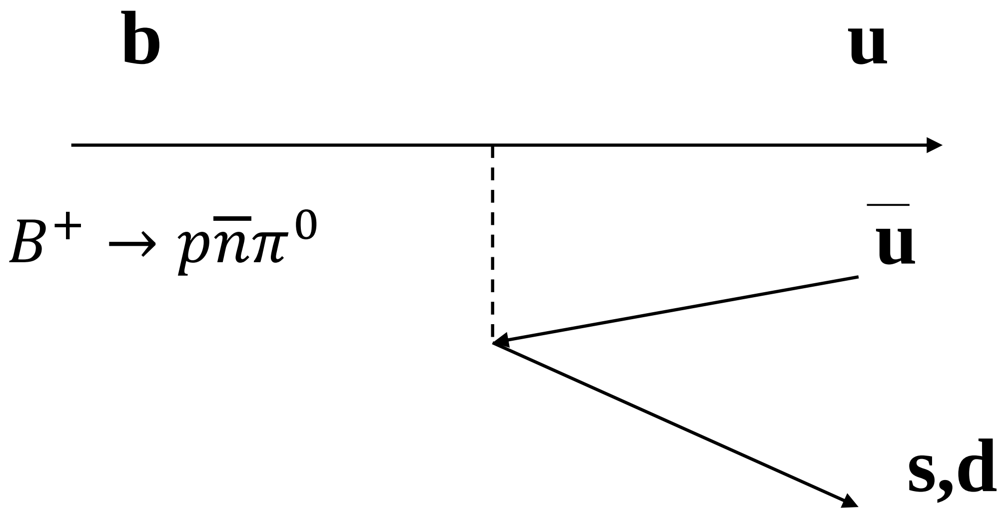
Physics topics at Belle (II)

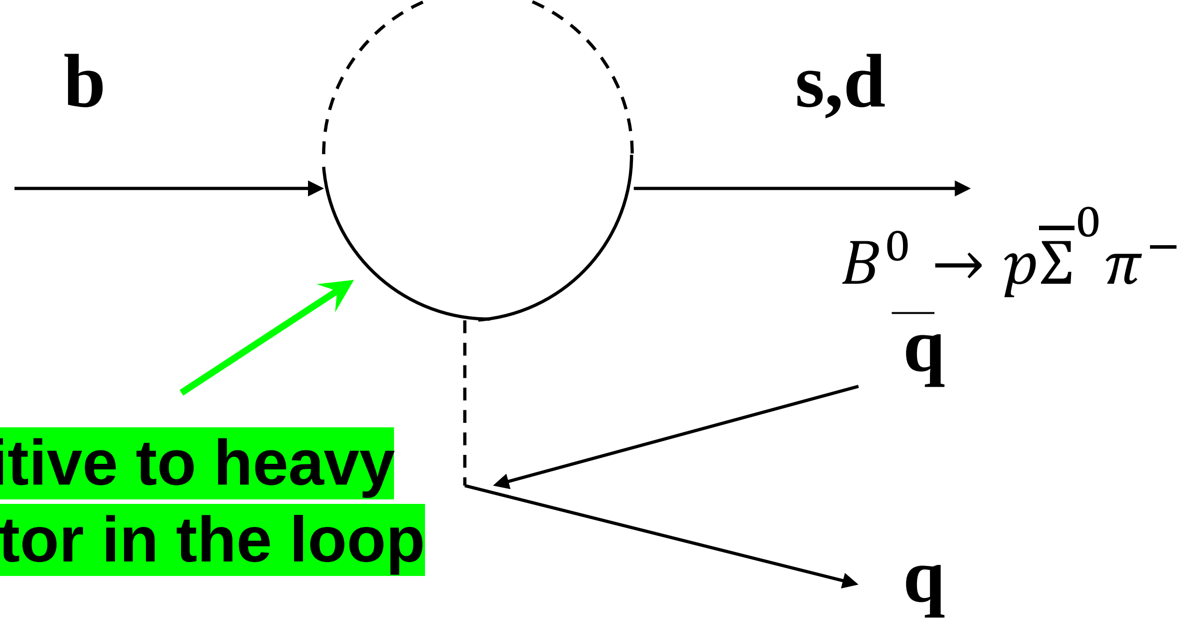


- **Upsilon(5S, 6S) runs**
  - Bs physics
  - New hadron states Zb's, b bbar gluon
- **New Hadrons, QCD measurements**
  - New Charmonium-Like States
  - New bottomonium-like states
  - New baryons
  - e+e- -->ISR, pi+ pi- cross-sections (g-2)
  - Spin Fragmentation Functions (-->EIC)
  - Linac energy upgrade
- **Dark Sector , Direct Search**
  - Dark Photon
  - Axion-Like Particles (ALPs)
  - Invisible Z' s
  - Dark Higgs
  - Heavy tau neutrinos
  - LLPs (Long-Lived Particles)
  - Magnetic Monopoles
  - Gazelle (LLP search)
- **Tau Physics**
  - Tau mass, lifetime
  - Tau Spectral Functions
  - Lepton Flavor Violation (LFV)
  - Tau Electric Dipole Moment (EDM), g-2
- **Electroweak physics with e- polarization**
  - sin^2 theta_W
  - A_LR (tau, mu, e+, b, c)
  - NC (Neutral Current) universality
  - improved tau LFV
- **Charm Physics**
  - D-Dbar mixing and CP
  - Charm Lifetimes
  - Branching Fractions, Dalitz analyses
  - c->u l+l-, Lepton flavor violation
  - Radiative charm decays
- **CKM Matrix Elements (Vcb, Vub)**
  - Inclusive Measurements
  - Vtd/Vts from penguins
  - Exclusive measurements
  - B->D(*) tau nu, lepton universality
- **Time Dependent Measurements**
  - alpha, beta, gamma
  - Direct T violation
  - New physics phases in b->s: B->phi Ks, B->eta' Ks
- **Rare B decays**
  - Hadronic B Decays: B-->K pi, pi pi Direct CPV, isospin sum rules
  - B-->K* gamma and radiative penguins, B-->K(*) nu nubar
  - B-->V V: right-handed currents, triple products
  - Electroweak Penguins: b-->s l+l-, lepton universality, NP
- **Hadronic b-->c decays**
  - gamma determinations
  - New charmed resonances

Basic quark diagrams for charmless B decays

interference between comparable amplitudes causes big cp violation

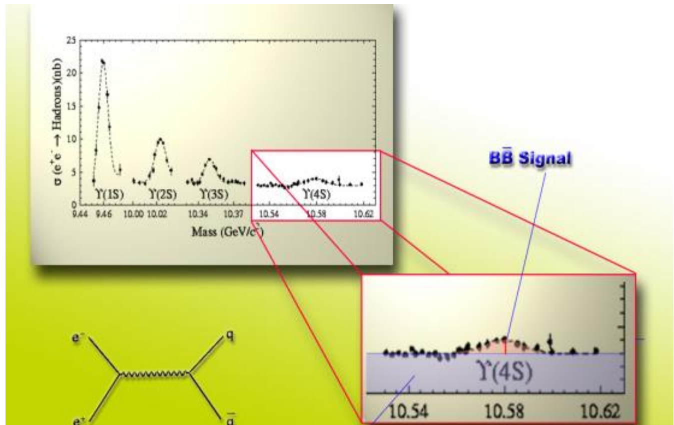




sensitive to heavy mediator in the loop

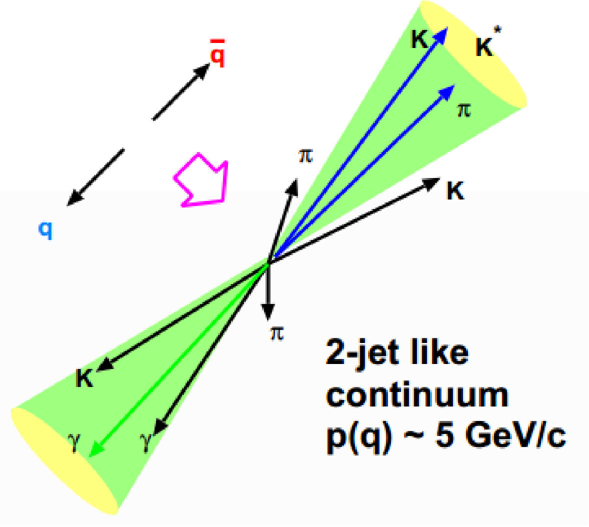
Looking for deviations from the SM predictions of a small BF or Acp

Challenge : continuum background suppression

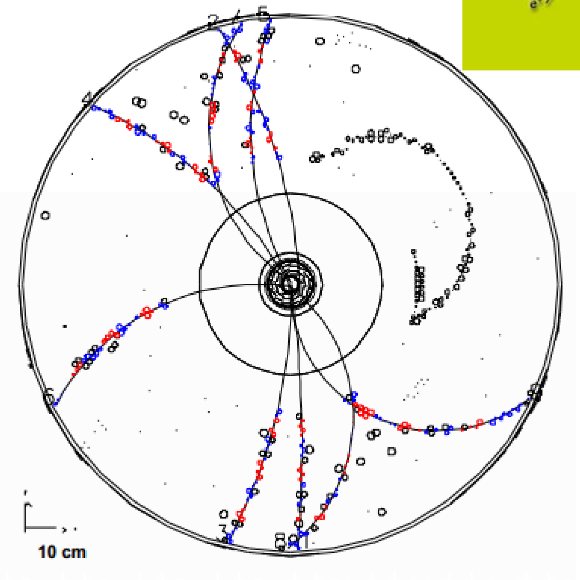


Need to develop good pattern recognition tools (AI) in order to fight against huge continuum background in rare B decays!

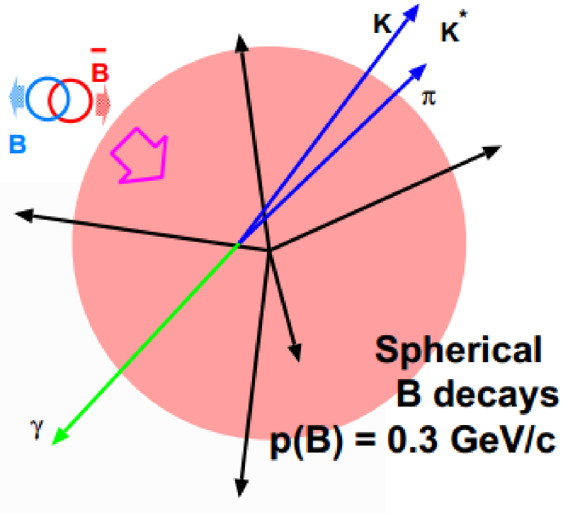
$q\bar{q}$ pair event



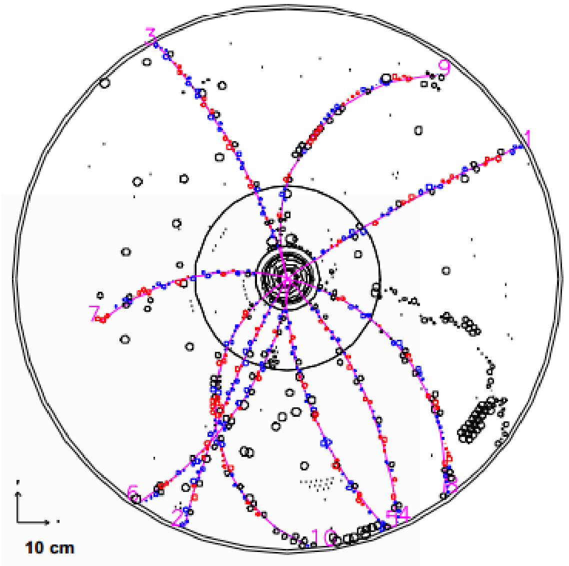
2-jet like
continuum
p(q) ~ 5 GeV/c



***B* decay event**

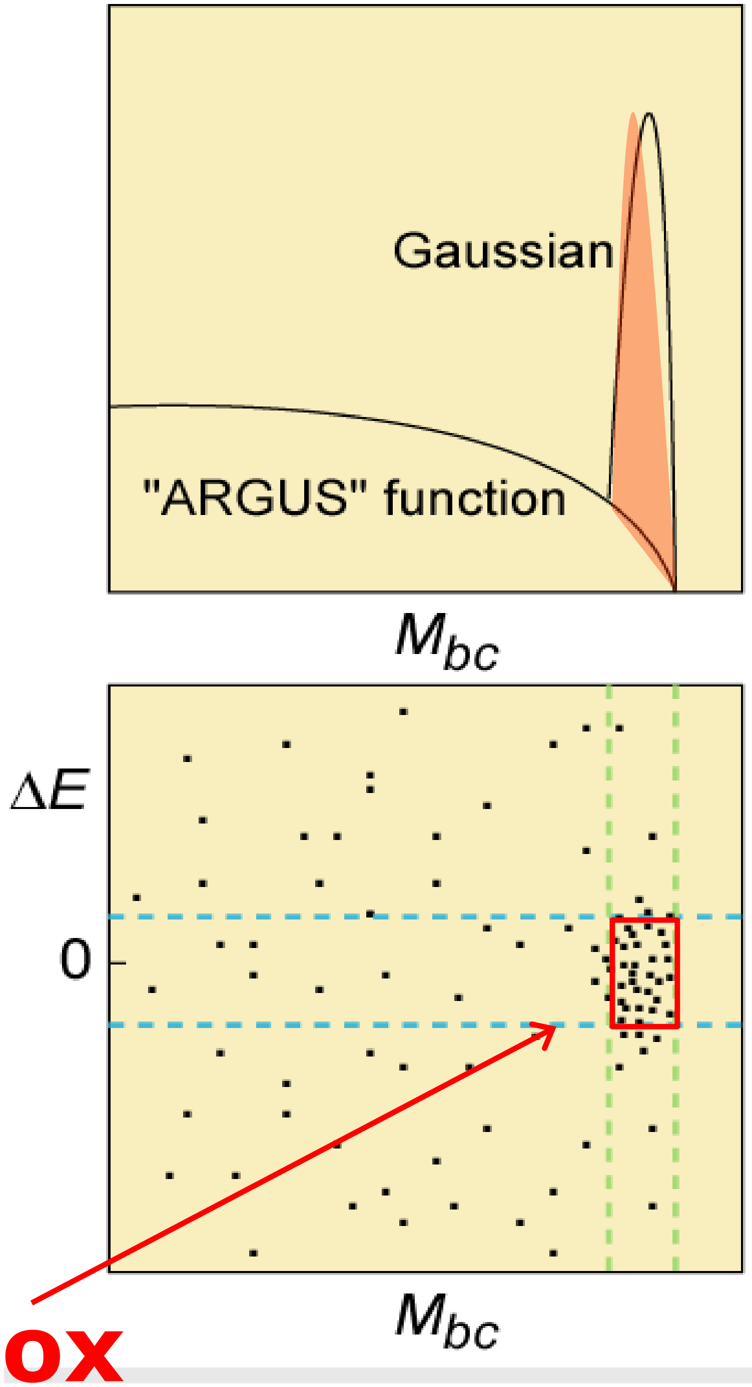


Spherical
B decays
p(B) = 0.3 GeV/c



B signal reconstruction

$BF = Nsig/\varepsilon/N_{BB}$

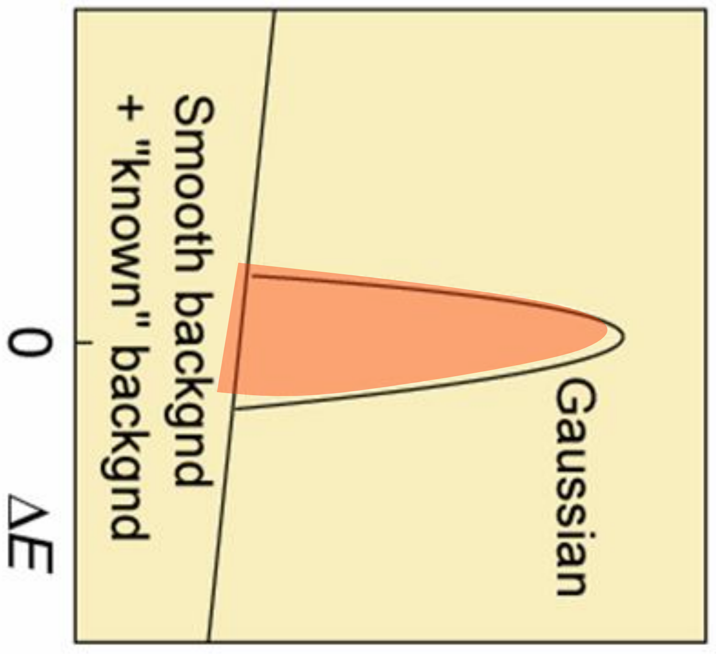


Signal Box

$\Delta E = E(B\ cand.) - E_{beam}$

$M_{bc} = \sqrt{E^2_{beam} - P(B\ cand.)^2}$

(all in CM frame)



Determine Signal and background shapes and use likelihood fit method to extract signal yield

Motivation for studying $B^0 \to p\overline{\Sigma}^0\pi^-$

- Branching Fraction : We observed the deviation between theoretical prediction and experimental measurement

	Theoretical Value	Measurement
$B^0 \to p\overline{\Lambda}\pi^-$	$10^{-7} \sim 3 \times 10^{-6}$	$3.14 \pm 0.29 \times 10^{-6}$
$B^0 \to p\overline{\Sigma}\pi^-$	$\sim 1.6 \times 10^{-6}$	?

With big axial vector and pseudoscalar contribution for $B^0 \to p\bar{\Lambda}\pi^-$

- Threshold Enhancement (TE) :

We observed TE in $B^0 \to p\overline{\Lambda}\pi^-$ channel

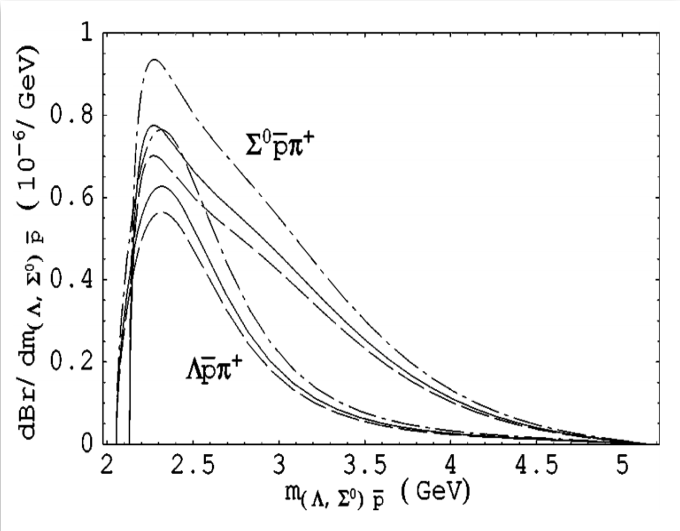
Factorization approaches

QCD counting rules

Cheng & Yang Phys. Rev. D 66 , 014020 (2002)

Chua, Hou & Tsai Phys. Rev. D 66 , 054004 (2002)

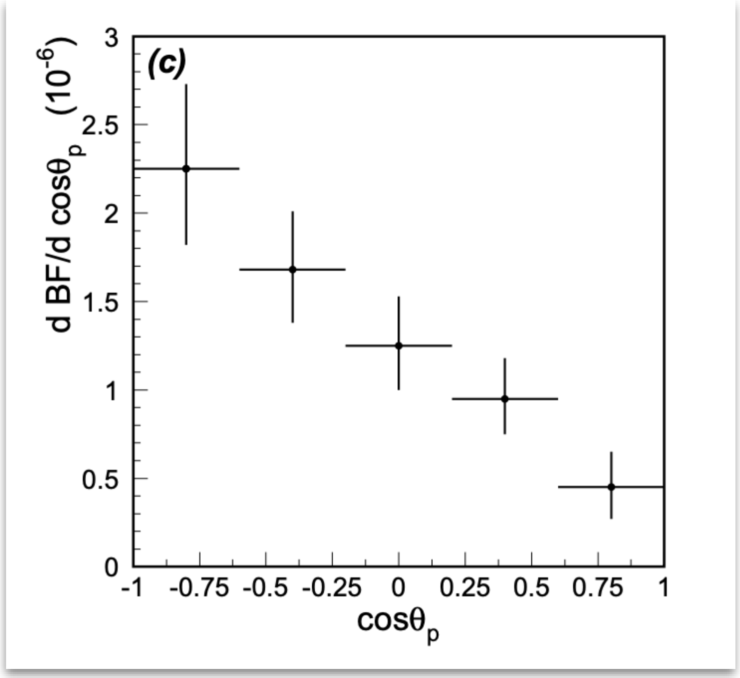
Chua & Hou Eur.Phys.J.C 29, 27-35 (2003)



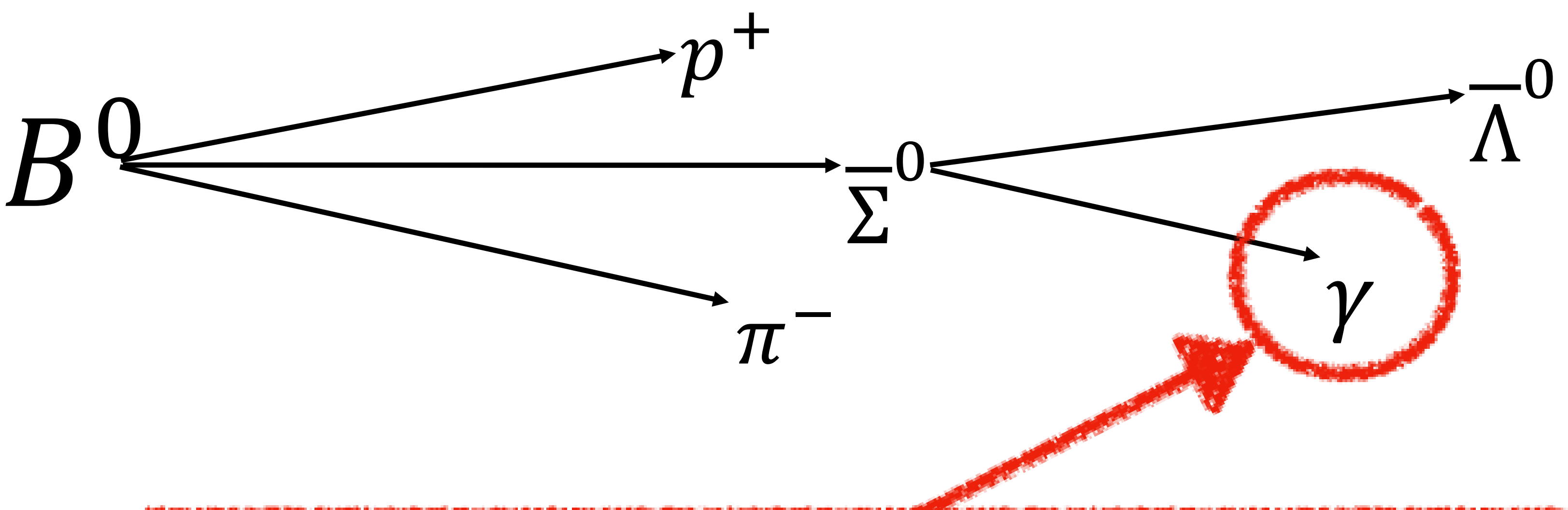
- $cos\theta_p$ Asymmetry : Phys. Rev. D 76 , 052004 (2007)

In $B^0 \to p\overline{\Lambda}\pi^-$ study, we found $cos\theta_p$ asymmetry which cannot be explained by the $b \to sg$ picture

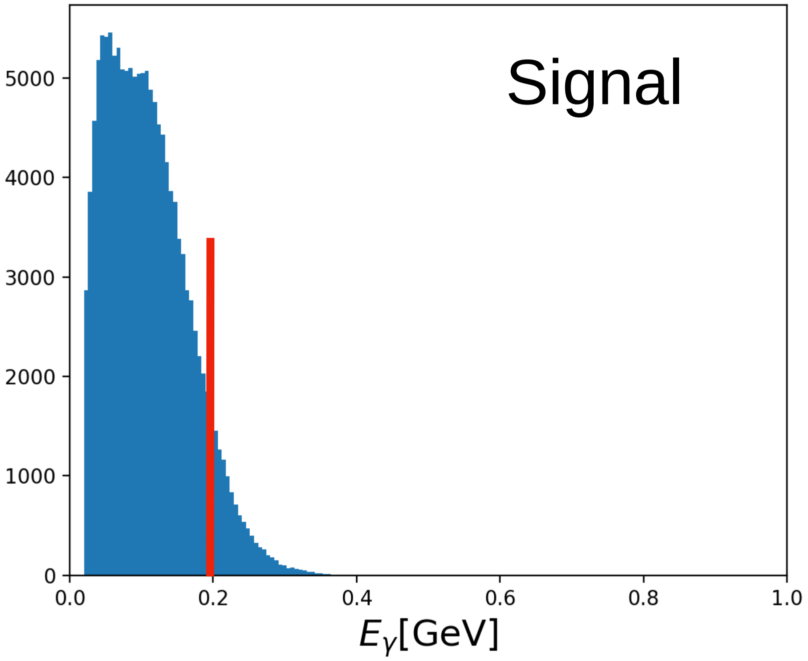
*θ_p is the angular between $p^\pm$ and $h^\pm$ in baryon pair rest frame

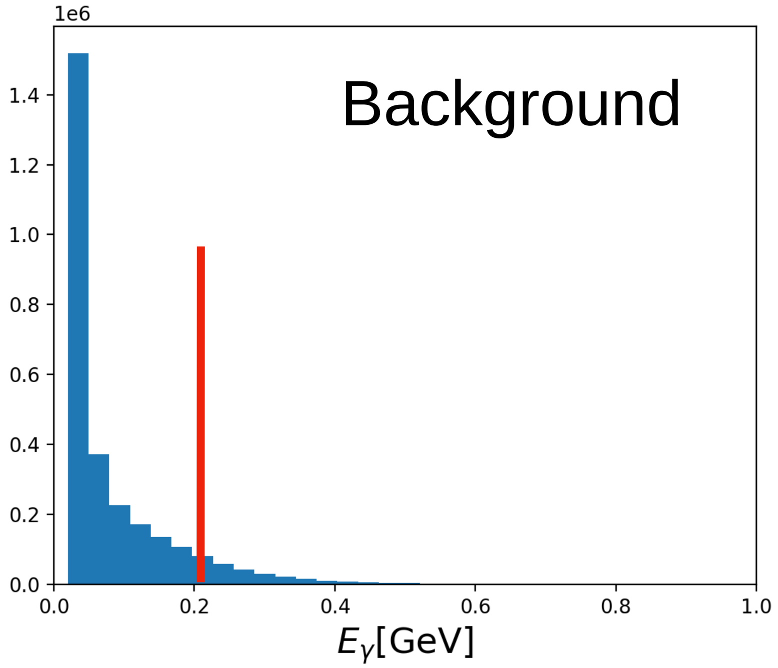


Inclusive $p\bar{\Lambda}\pi^-$ event reconstruction



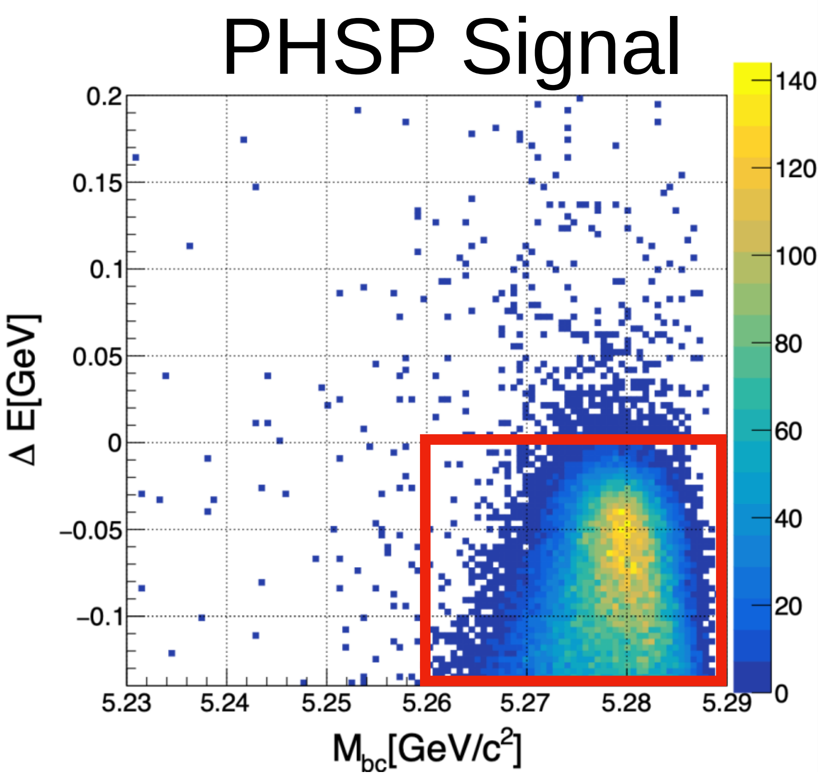
The energy of photon radiated from $\bar{\Sigma}^0$
is about 200 MeV below (as soft as background)

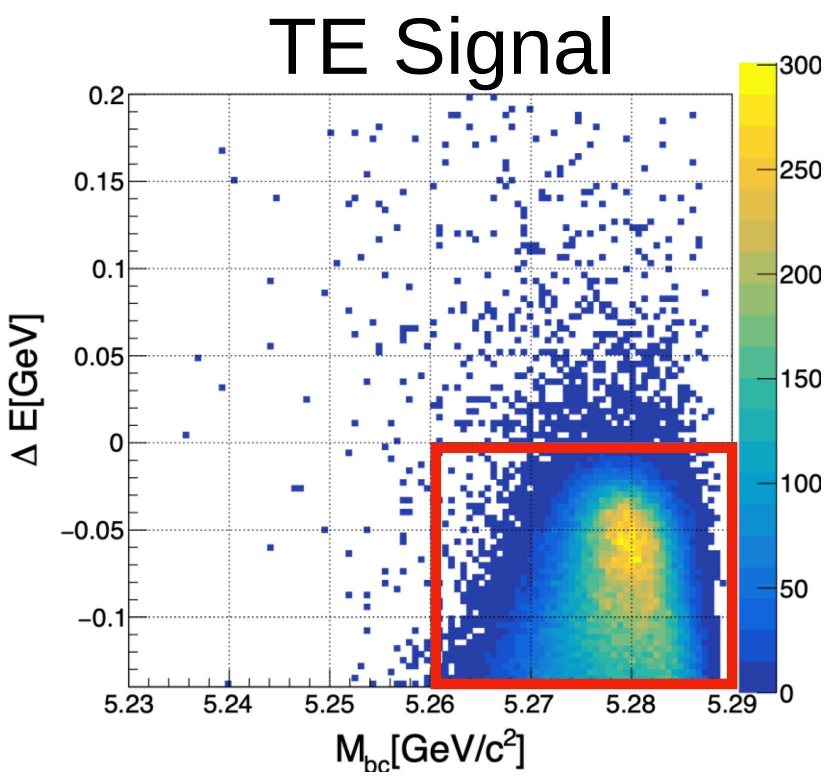




- Reconstruct our candidate with charged particle and measure $B^0 \to p\bar{\Lambda}\pi^-$ simultaneously

Fitting variables





*Red line is signal region

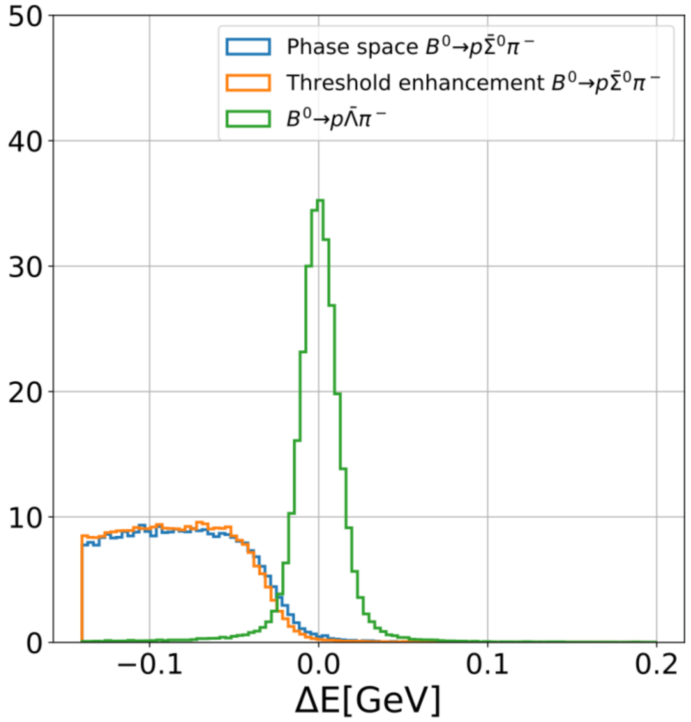
- Energy Difference (ΔE) :

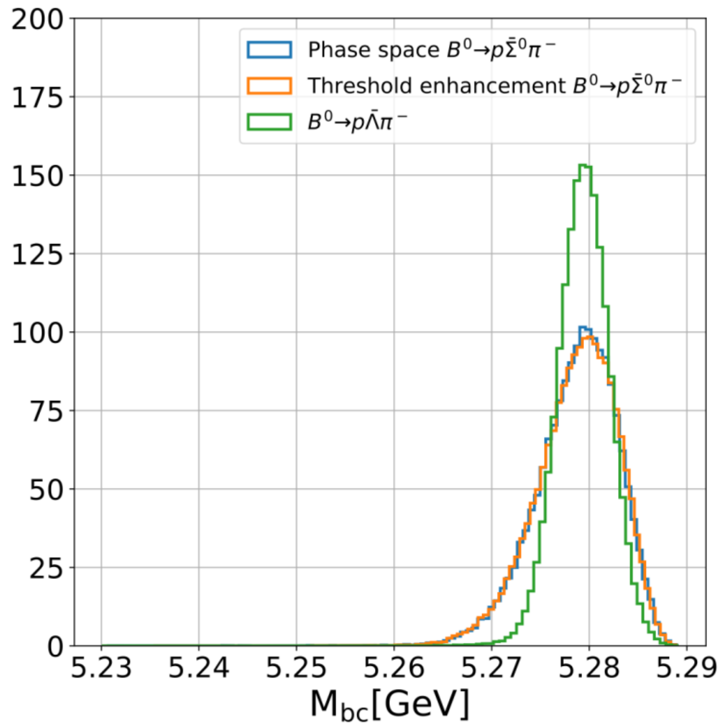
$$\Delta E = E^{*}_{reco} - E_{beam}$$

- E_{beam} Constrained Mass (M_{bc}) :

$$M_{bc} = \sqrt{E^{2}_{beam} - p^{*2}_{B}}$$

* means CM frame





- Fitting region:

$$5.23 < M_{bc} < 5.30\ GeV/c^2$$

$$-0.14 < \Delta E < 0.20\ GeV$$

- Signal region:

$$5.26 < M_{bc} < 5.30\ GeV/c^2$$

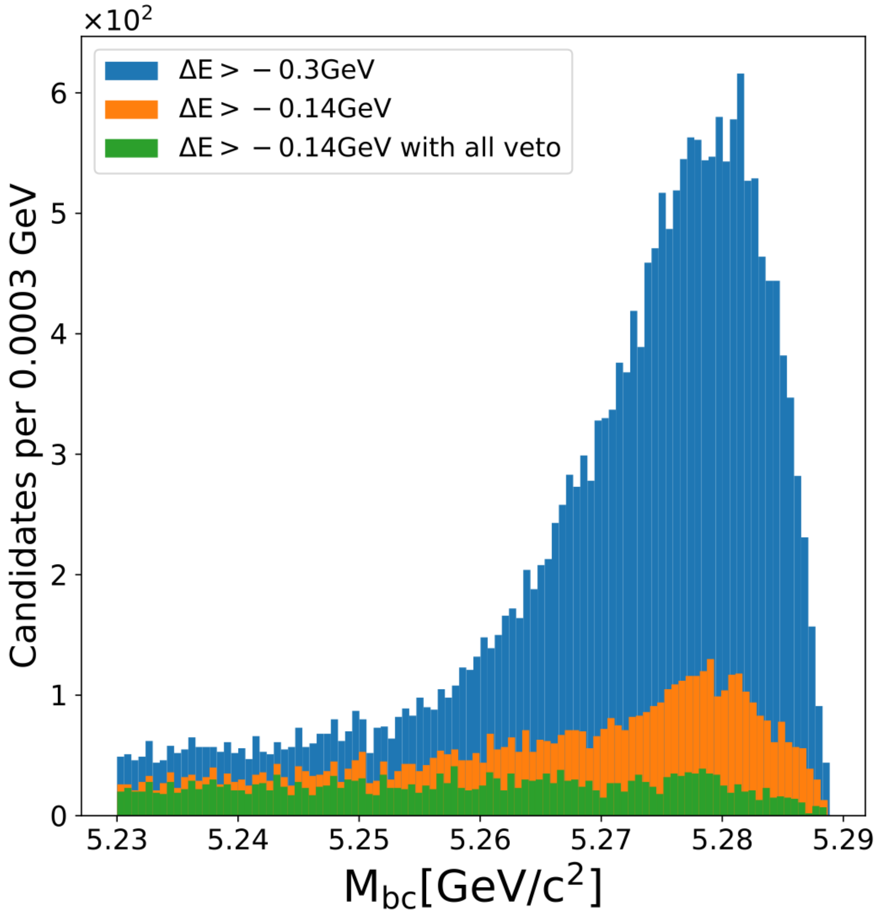
$$-0.14 < \Delta E < 0.00\ GeV$$

- No significant discrepancy of distribution between TE and PHSP

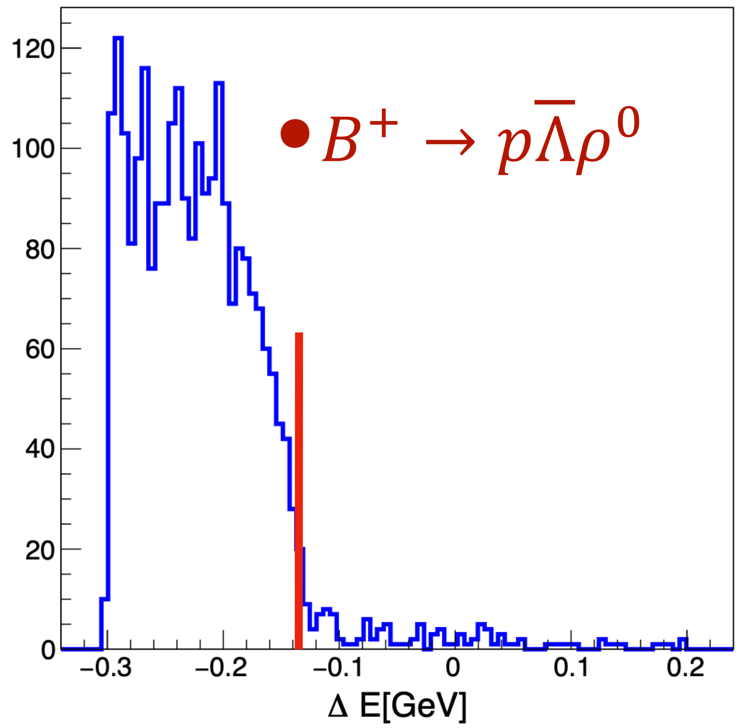
Background study: rare & generic decays

- Main rare decay background list:

Decay channel	$\mathcal{B}(10^{-6})$ in decay table	$\mathcal{B}(10^{-6})$ in PDG
$B^+ \to p\overline{\Lambda}$	0.37	$0.24^{+0.10}_{-0.08} \pm 0.03$
$B^+ \to p\overline{\Sigma}$	1.5	-
$B^+ \to p\overline{\Lambda}\rho^0$	5.7	$4.78^{+0.67}_{-0.64} \pm 0.60$
$B^+ \to \Lambda\overline{\Lambda}\pi^+$	2.8	<0.9
$B^0 \to \Lambda\overline{\Lambda}$	0.3	<0.3
$B^0 \to \Lambda\overline{\Sigma}$	1.0	-
$B^0 \to \Sigma\overline{\Sigma}$	1.0	-



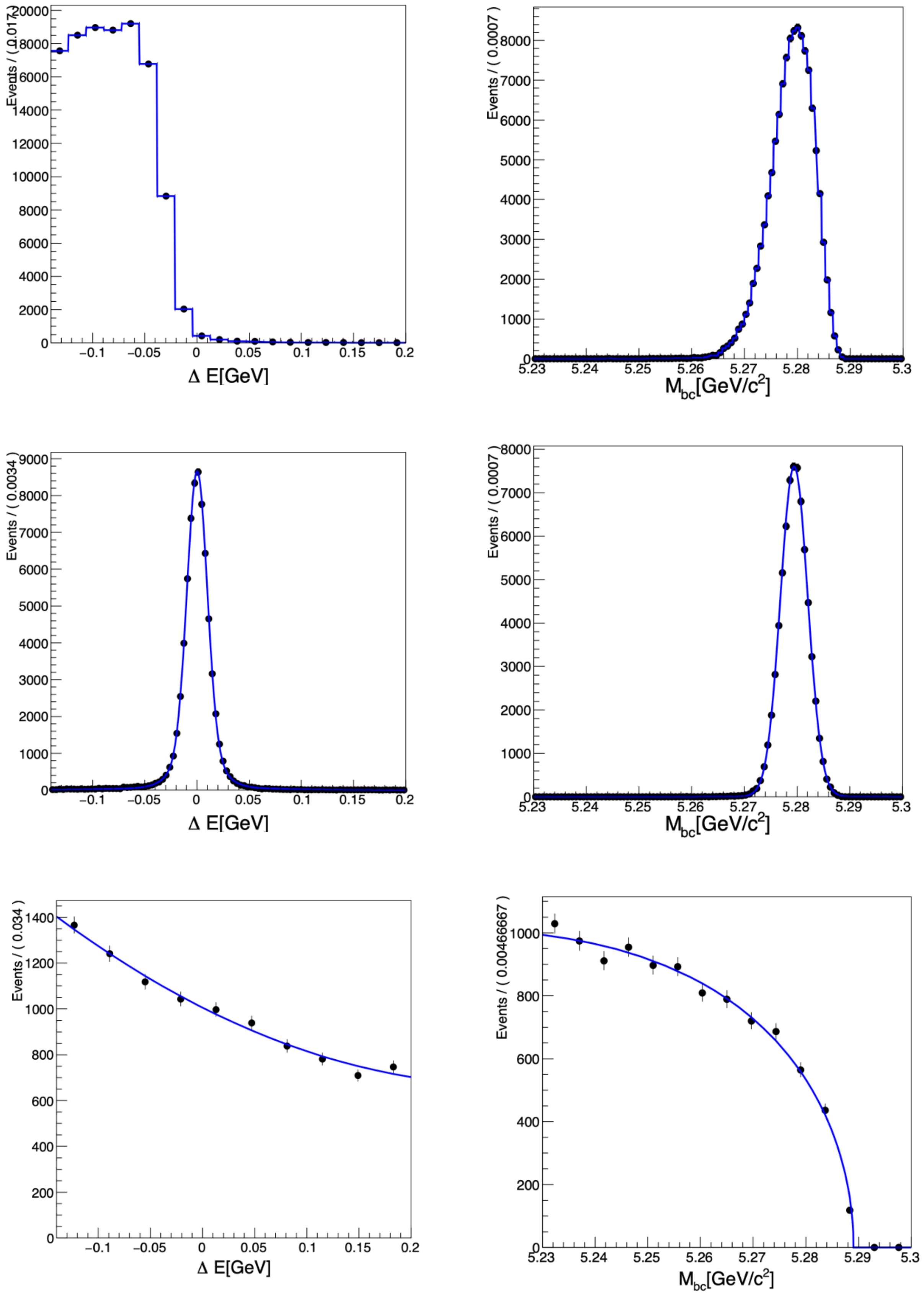
- Narrow down ΔE region can eliminate most rare decay
- Rest of rare decay are too rare and overrated by decay table



- Main generic decay background : $B^0 \to p\Lambda_c^-$

cut off *2.15<$M_{\Lambda\pi}$ <2.30 GeV/c²*

PDF modeling



- Signal :$\mathcal{P}(M_{bc}) \times \mathcal{P}(\Delta E)$

  $\mathcal{P}(M_{bc})$: 1D HistPDF

  $\mathcal{P}(\Delta E)$: 1D HistPDF

- $B^0 \rightarrow p\overline{\Lambda}\pi^-$:$\mathcal{P}(M_{bc}) \times \mathcal{P}(\Delta E)$

  $\mathcal{P}(M_{bc})$: Double Gaussian

  $\mathcal{P}(\Delta E)$: Triple Gaussian

  (Self-cross feed : 2D Kernel)

- Background : $\mathcal{P}(M_{bc}) \times \mathcal{P}(\Delta E)$

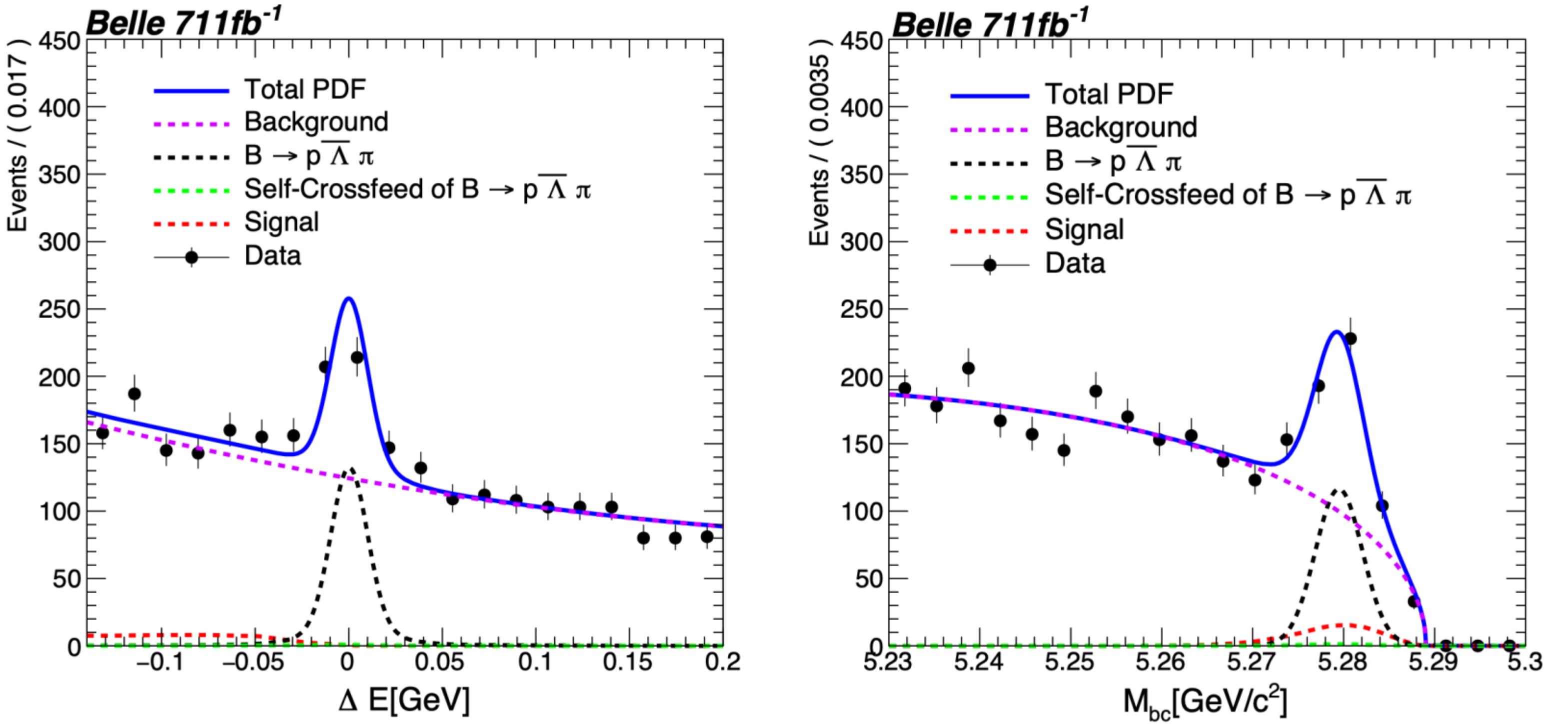
  ($q\overline{q}$+$B\overline{B}$+Rare decay)

  $\mathcal{P}(M_{bc})$: ARGUS Function

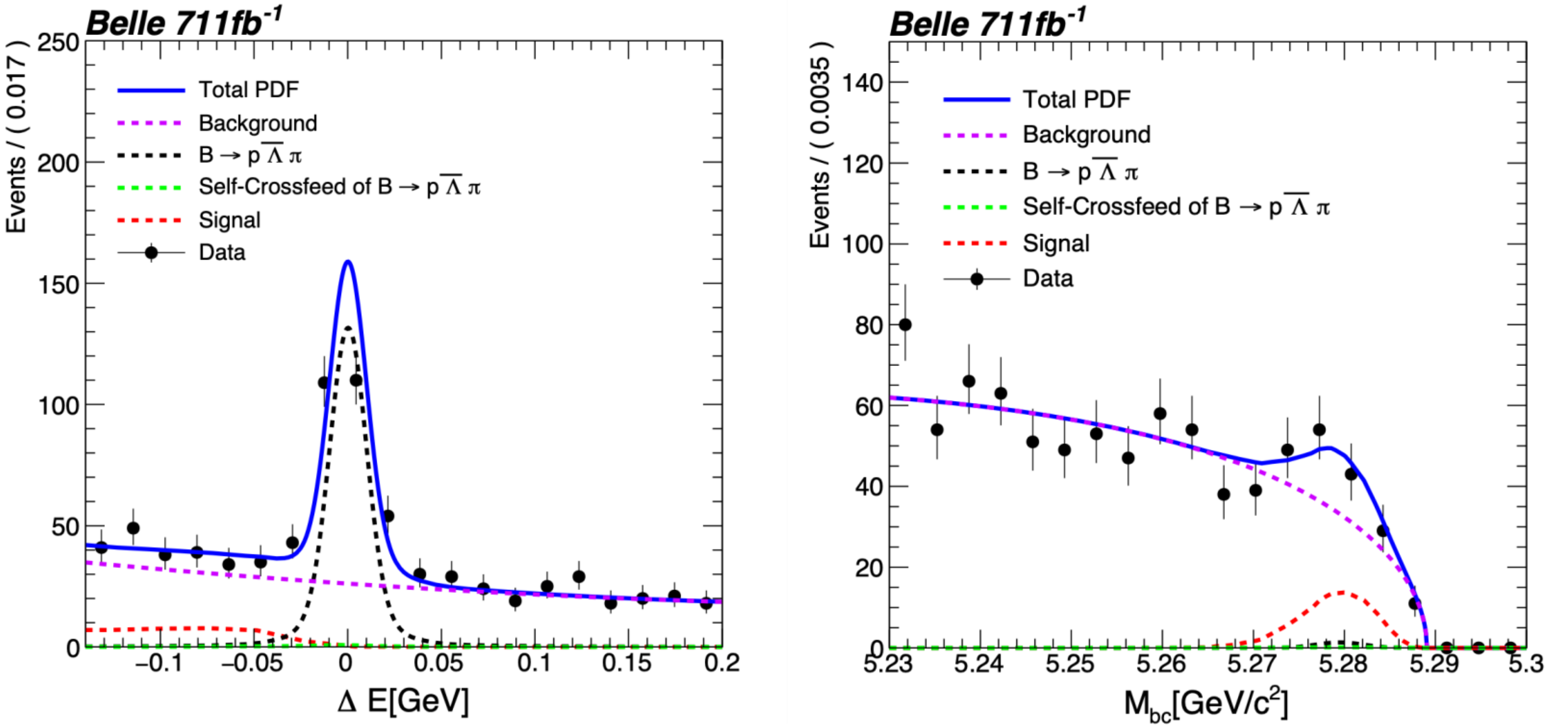
  $\mathcal{P}(\Delta E)$: 2nd Polynomial

Likelihood fit results

- Whole $M_{p\overline{\Lambda}}$ region:



(a) whole fitting region



(b) projected in signal region

$$N_{B^0\to p\overline{\Sigma}\pi^-} = 50.29^{+18.06}_{-17.38}$$

$$N_{B^0\to p\overline{\Lambda}\pi^-} = 215.45^{+17.36}_{-16.62}$$

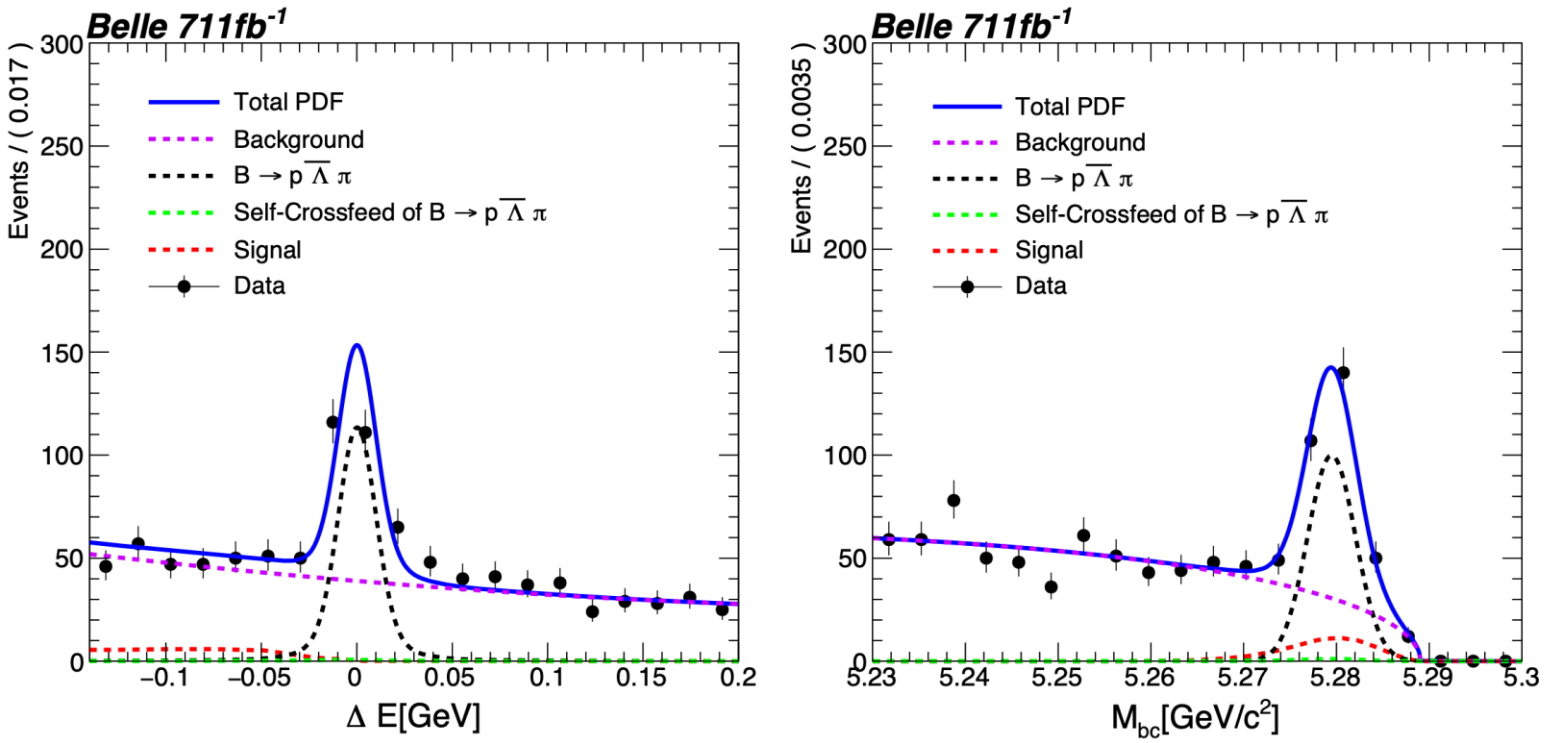
*Projected region :

$$5.26 < M_{bc} < 5.30\ GeV/c^2$$

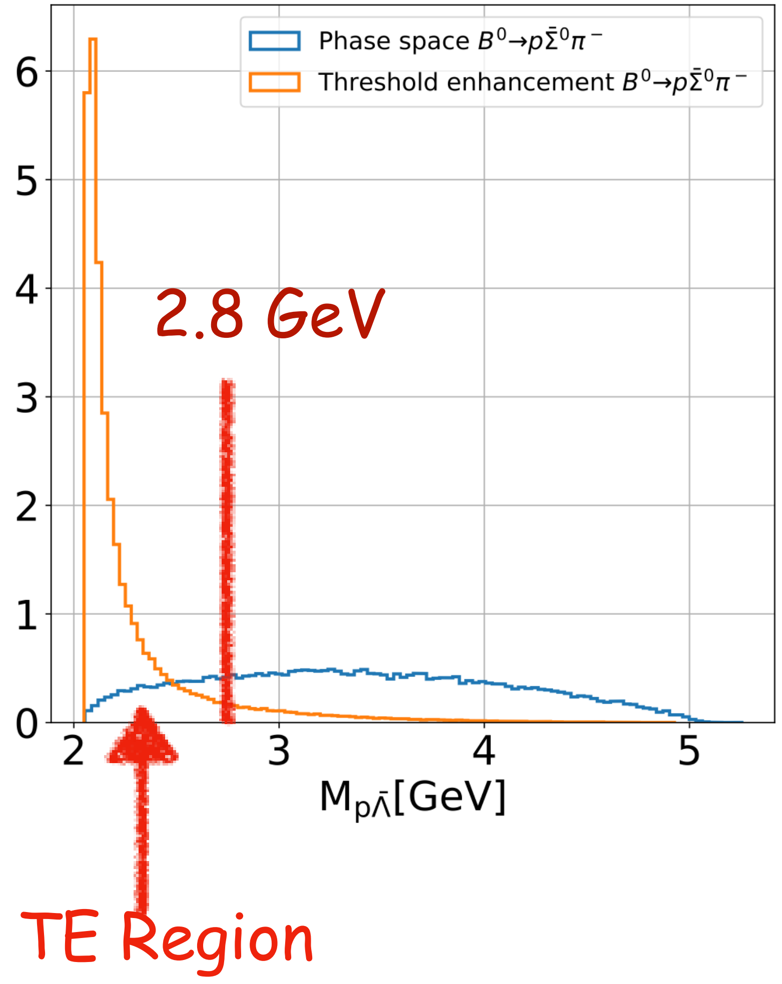
$$-0.14 < \Delta E < -0.05\ GeV$$

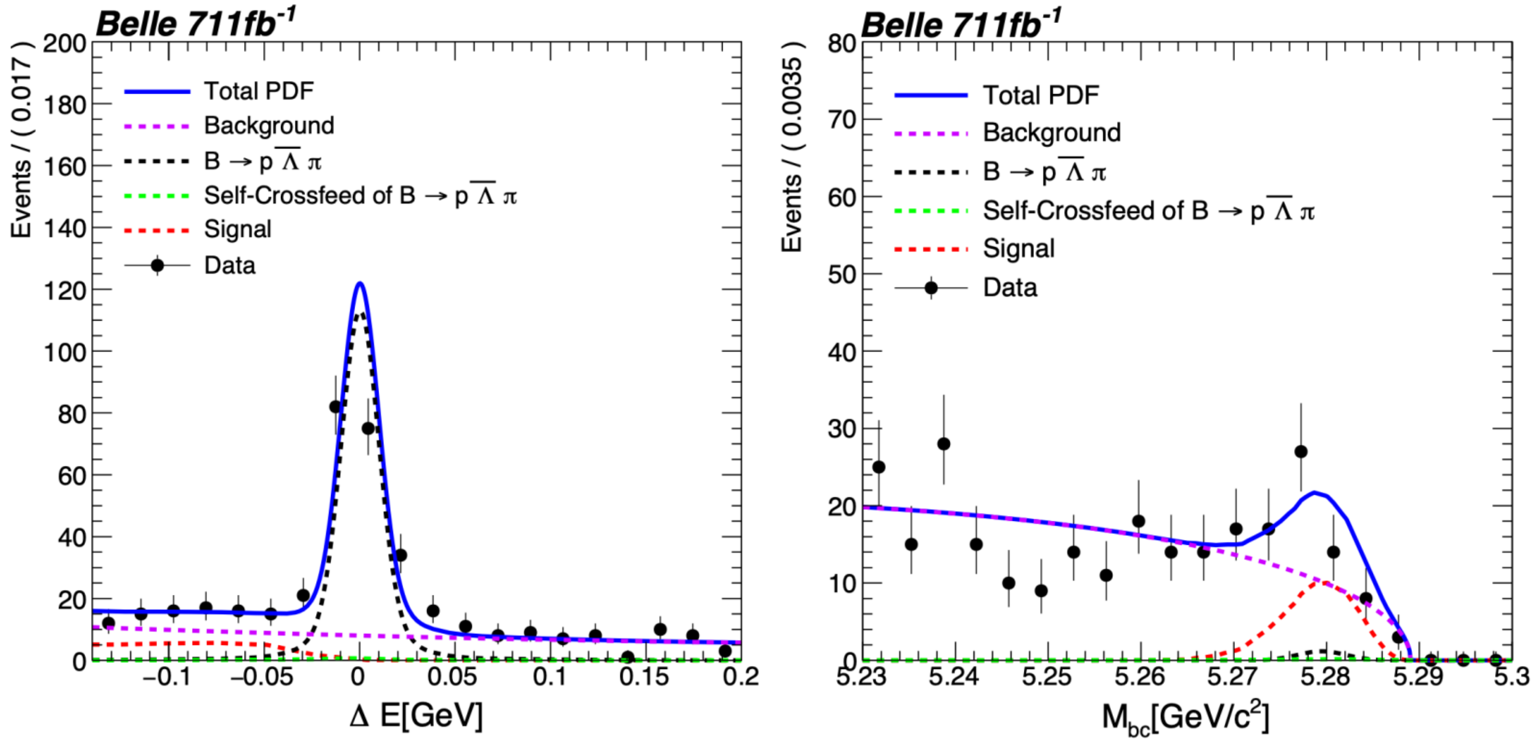
Fit results in TE region

- $M_{p\overline{\Lambda}}$ <2.8 GeV region:



(a) whole fitting region





(b) projected in signal region

$$N_{B^0\to p\bar{\Sigma}\pi^-} = 36.70^{+11.82}_{-11.09}$$

$$N_{B^0\to p\bar{\Lambda}\pi^-} = 184.82^{+15.20}_{-14.52}$$

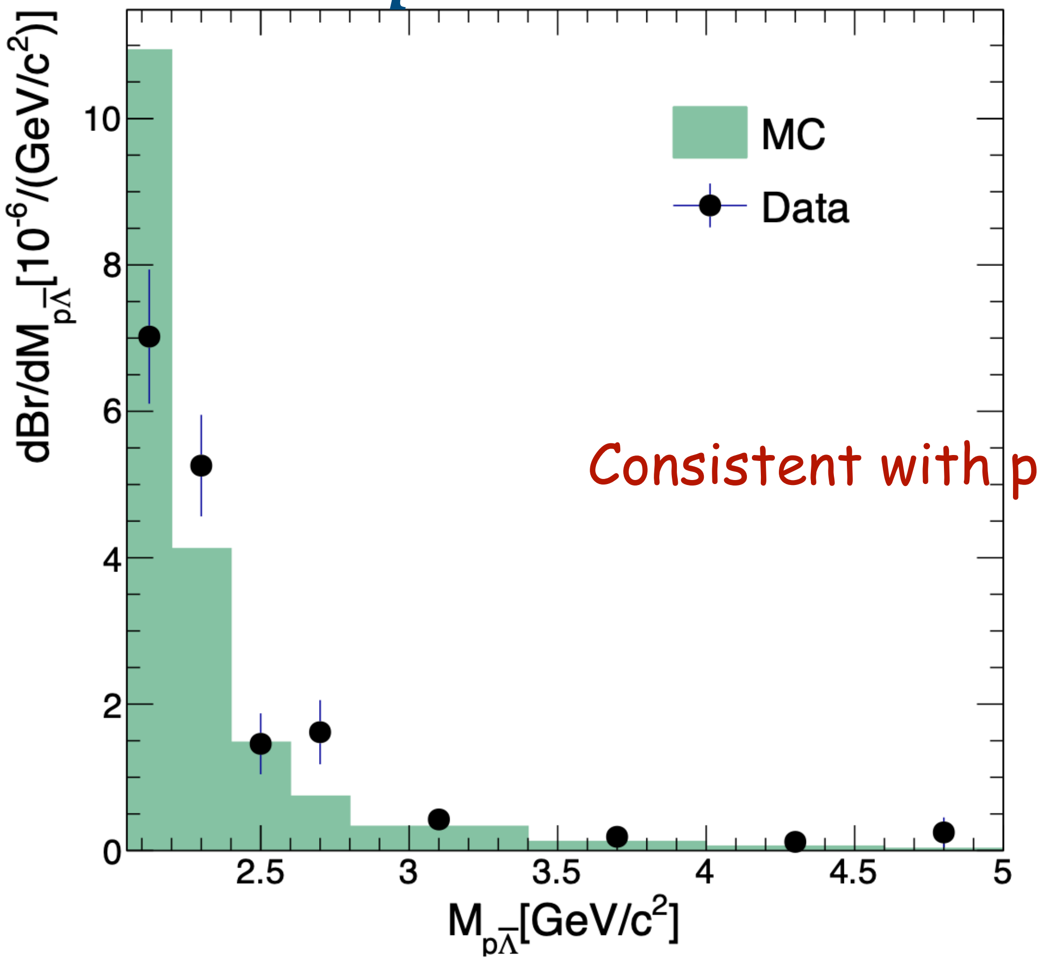
*Projected region :

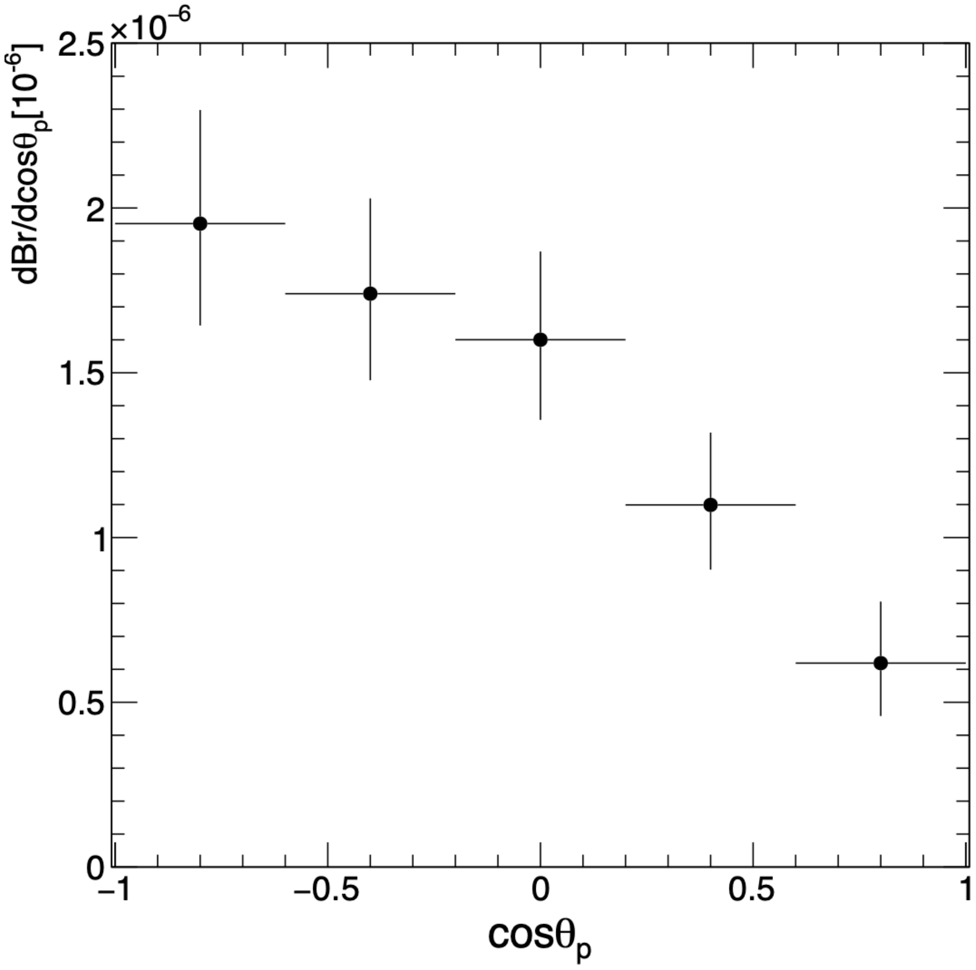
$$5.26 < M_{bc} < 5.30\ GeV/c^2$$

$$-0.14 < \Delta E < -0.05\ GeV$$

Differential branching fractions in $M_{p\overline{\Lambda}}$ & $cos\theta_p$

- $B^0 \to p\overline{\Lambda}\pi^-$ channel:





Consistent with previous study

- $B^0 \to p\overline{\Sigma}\pi^-$ channel:

Region	Signal yield	Significance (Stats)	Significance (Stats+Sys)
Threshold<$M_{p\overline{\Lambda}}$<limit	$50.29^{+18.06}_{-17.38}$	3.00σ	2.98σ
$M_{p\overline{\Lambda}} < 2.8GeV/c^2$	$36.70^{+11.82}_{-10.09}$	3.56σ	3.50σ

Summary for $B^0 \to p\overline{\Sigma}^0 \pi^-$ Phys. Rev. D 108, 052011 (2023)

- The result of $B^0 \to p\overline{\Lambda}\pi^-$ is consistent with previous study
- First measured 3.5 σ $B^0 \to p\overline{\Sigma}\pi^-$ signal with TE
- Agree with the theoretical expectation

$cos\theta_p$ distribution of $B^0 \to p\overline{\Sigma}\pi^-$ needs more data

	$B^0 \to p\overline{\Lambda}\pi^-$	$B^0 \to p\overline{\Sigma}\pi^-$
Threshold Enhancement	✓	✓
$cos\theta_p$ Asymmetry	✓	Not enough statistics

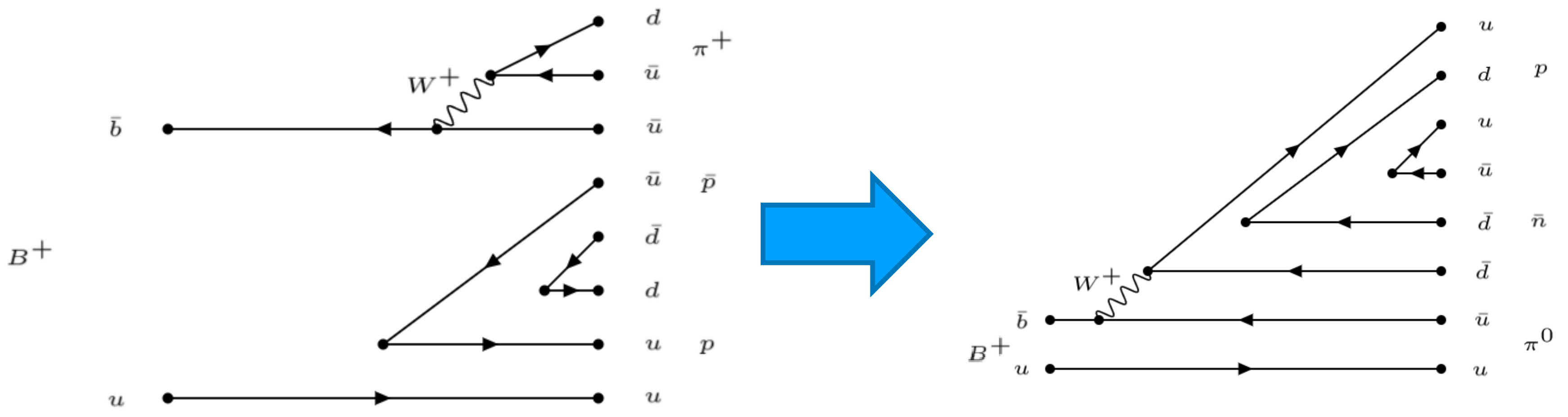
	$B.F(10^{-6})$	Significance
$B^0 \to p\overline{\Sigma}\pi^-$	$1.17^{+0.43}_{-0.40} \pm 0.07$	3.5σ
$B^0 \to p\overline{\Lambda}\pi^-$	$3.21^{+0.28}_{-0.25} \pm 0.16$	18.55σ

Motivation for studying $B^+ \to p\bar{n}\pi^0$

- $\mathcal{B}(B^0 \to p\bar{n}D^{*-}) = (1.4 \pm 0.4) * 10^{-3}$ (CLEO) vs $\mathcal{B}(B^0 \to p\bar{p}D^{*0}) = (9.91.1) * 10^{-5}$ (BABAR), clear deviation from naïve isospin symmetry due to color suppression

- Significant yields for both $\mathcal{B}(B^+ \to p\bar{p}\pi^+) = (1.62 \pm 0.2) * 10^{-6}$ and $\mathcal{B}(B^0 \to p\bar{p}\pi^0) = (5.0 \pm 1.9) * 10^{-7}$

- Determine the contributions from the transition or current produced diagrams for baryon pair


(a)$B^\pm \to p\bar{p}\pi^\pm$

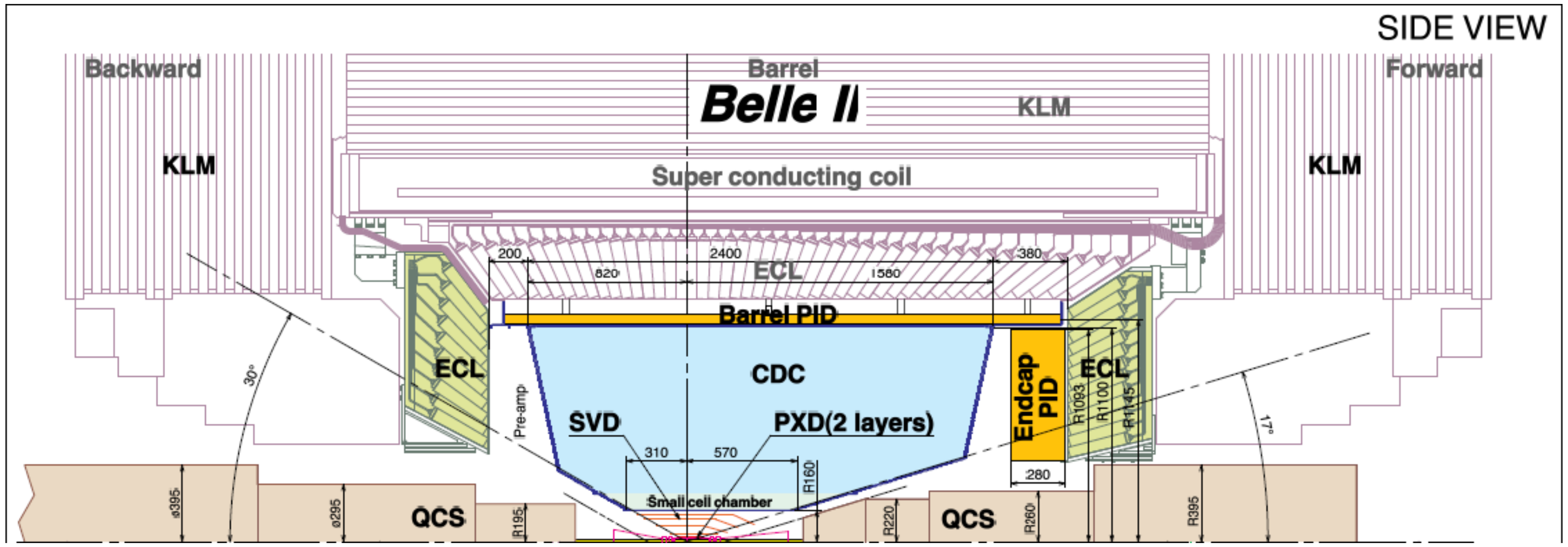
(b)$B^+ \to p\bar{n}\pi^0$

Mechanism for $\overline{n}$ detection and identification

- $\overline{n}$ has high chance to annihilate in Belle2 EM calorimeter, which has crystals with 16.1 X_0 in length. This process makes extra energy deposited at GeV level with distinct shower shape.

- One can use machine learning to develop an $\overline{n}$ tagging tool to separate $\overline{n}$ from γ.

- The cross section 6cm X 6 cm of each crystal also provides good resolution in solid angle. This helps us to determine the direction of $\overline{n}$.



$\bar{n}$ selection and $B^{+}\rightarrow p\bar{n}\pi^{0}$reconstruction

- 1. Get E_p, E_π, $\overrightarrow{P_p}$, $\overrightarrow{P_\pi}$ from CDC and other detectors.

- 2. Set constraints: $M_{\bar{n}}$, M_{B} (from PDG) and

$$E_{\mathrm{B}} = E_p + E_\pi + E_{\bar{n}}\ ,\quad \overrightarrow{P_{\mathrm{B}}} = \overrightarrow{P_p} + \overrightarrow{P_\pi} + \overrightarrow{P_{\bar{n}}}.$$

- 3. Get θ, ϕ from ECL cluster and set:

$$\overbrace{P_{\bar{n}}} = (\sin\theta\cos\phi\,, \sin\theta\sin\phi\,, \cos\theta\,, \sqrt{1 + M_{\bar{n}}^2/P_{\bar{n}}^2}\,)$$

- 4. By applying $M_{\mathrm{B}} = \sqrt{E_{\mathrm{B}}^2 - P_{\mathrm{B}}^2}$ constraint,

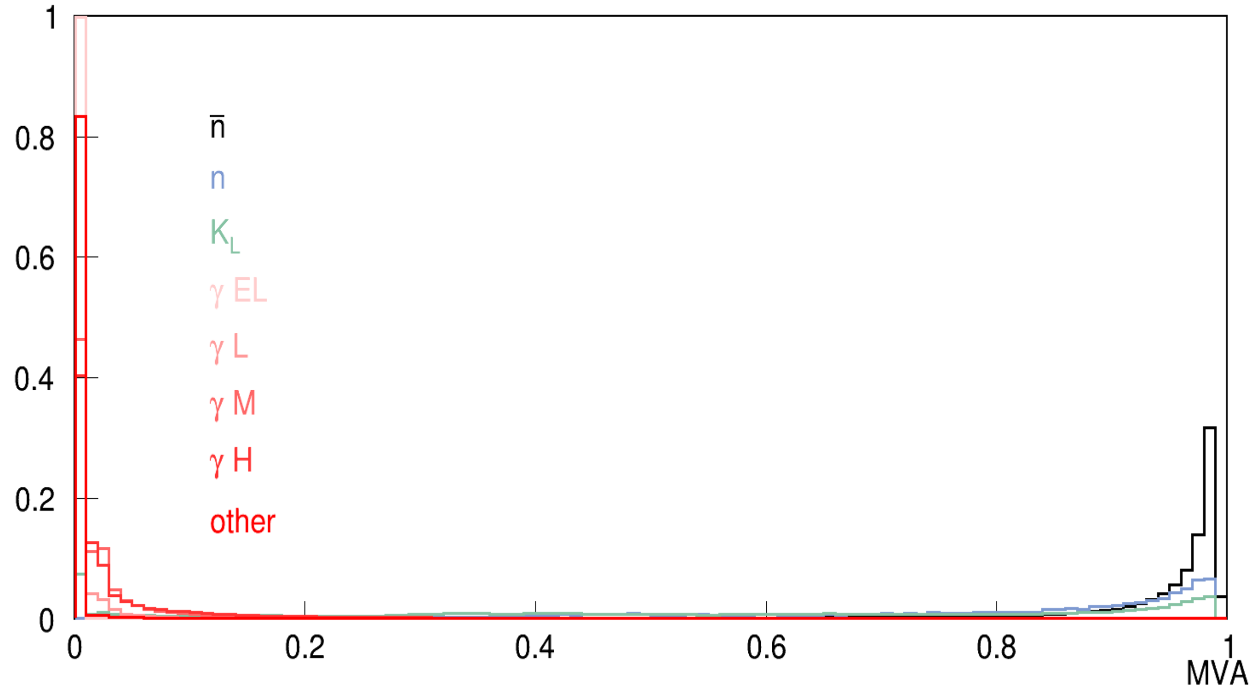
  we can determine $\overrightarrow{P_{\bar{n}}}$ to reconstruct $\overrightarrow{P_{\mathrm{B}}}$, E_{B},

  and obtain $\Delta E = E_{\mathrm{B}} - E_{beam}$

Performance of $\overline{n}$ tagger

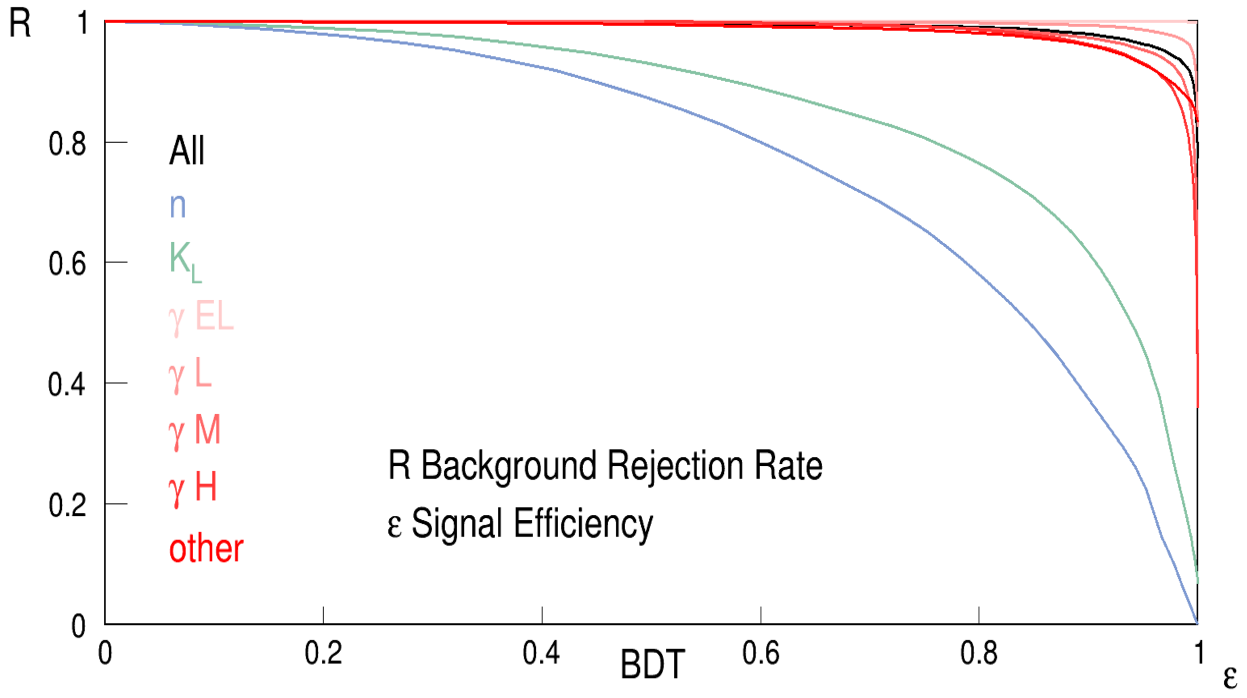
BDT output from MVA

- This model can well separate $\overline{n}$ from other particles, especially for γ.

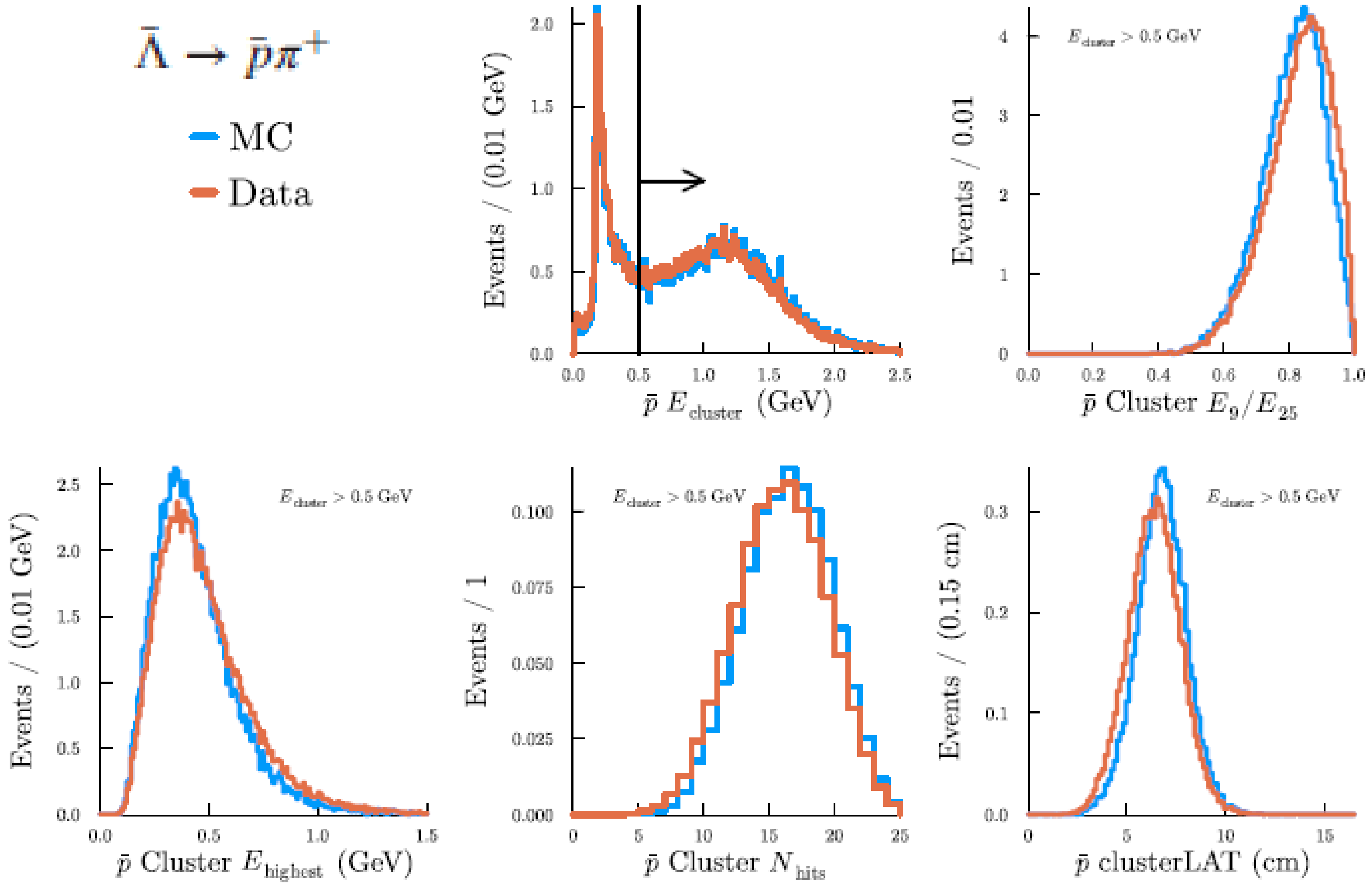


ROC curve

- The ROC curve shows background rejection rate against a fixed signal efficiency. It also shows the model having good performance from the AUC(>98%).



Compare MVA training information for data and MC

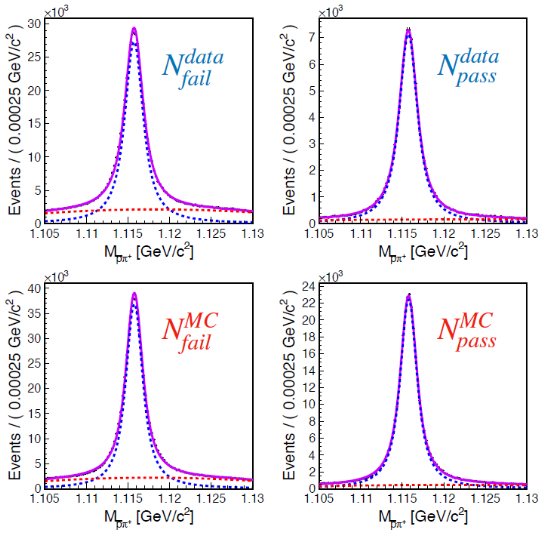


Correction table from $\overline{\Lambda} \to \overline{p}\pi^+$

Calculation of Calibration Factor

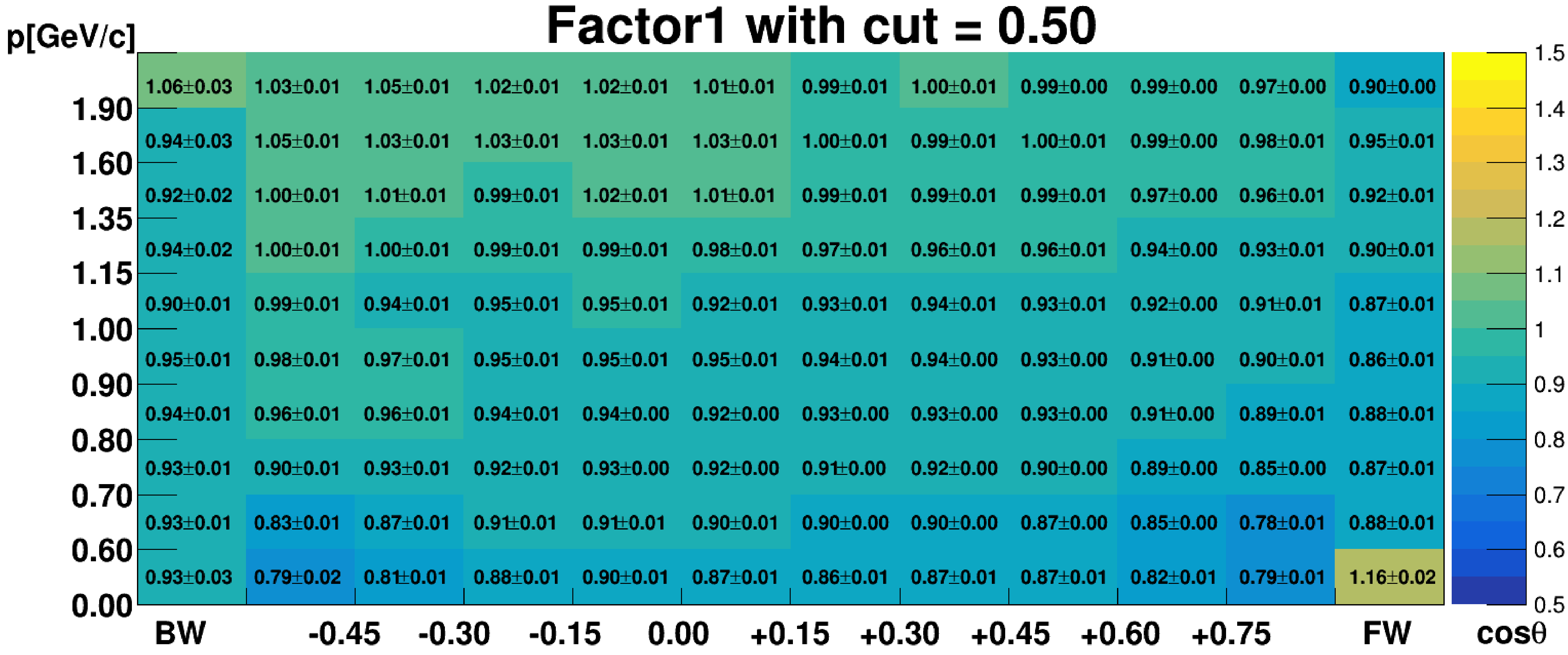
$$C + \delta C = \frac{\epsilon_{data} + \delta\epsilon_{data}}{\epsilon_{MC} + \delta\epsilon_{MC}}$$

$$\frac{\delta C}{C} = \sqrt{\left(\frac{\delta\epsilon_{data}}{\epsilon_{data}}\right)^2 + \left(\frac{\delta\epsilon_{MC}}{\epsilon_{MC}}\right)^2}$$



Apply MVA cut to obtain the eff. ratio in bins of $\overline{p}$ *p* and *cosϑ*

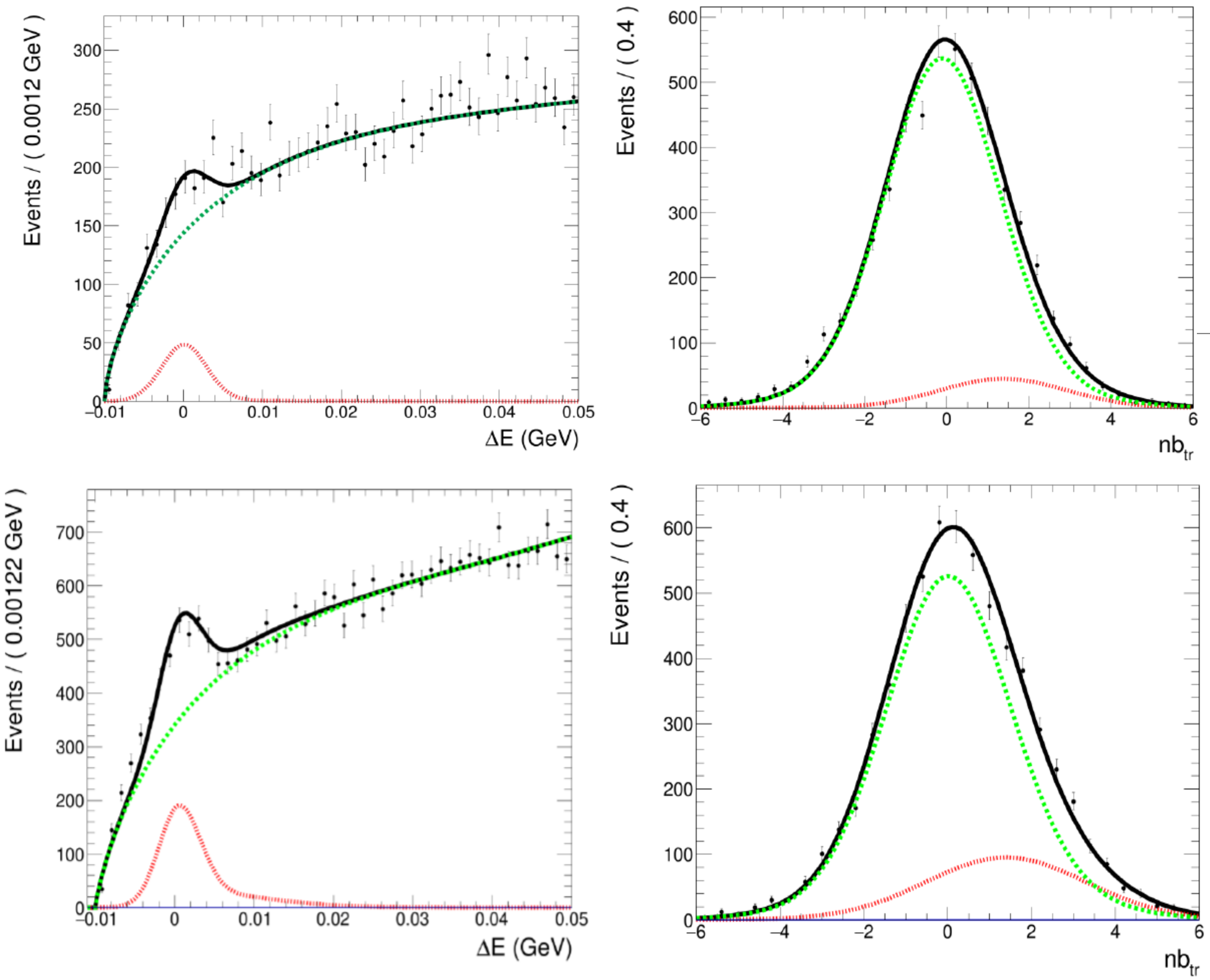
Determine correction table for different cut values



Factor1 with cut = 0.50

1.06±0.03	1.03±0.01	1.05±0.01	1.02±0.01	1.02±0.01	1.01±0.01	0.99±0.01	1.00±0.01	0.99±0.00	0.99±0.00	0.97±0.00	0.90±0.00
0.94±0.03	1.05±0.01	1.03±0.01	1.03±0.01	1.03±0.01	1.03±0.01	1.00±0.01	0.99±0.01	1.00±0.01	0.99±0.00	0.98±0.01	0.95±0.01
0.92±0.02	1.00±0.01	1.01±0.01	0.99±0.01	1.02±0.01	1.01±0.01	0.99±0.01	0.99±0.01	0.99±0.01	0.97±0.00	0.96±0.01	0.92±0.01
0.94±0.02	1.00±0.01	1.00±0.01	0.99±0.01	0.99±0.01	0.98±0.01	0.97±0.01	0.96±0.01	0.96±0.01	0.94±0.00	0.93±0.01	0.90±0.01
0.90±0.01	0.99±0.01	0.94±0.01	0.95±0.01	0.95±0.01	0.92±0.01	0.93±0.01	0.94±0.01	0.93±0.01	0.92±0.00	0.91±0.01	0.87±0.01
0.95±0.01	0.98±0.01	0.97±0.01	0.95±0.01	0.95±0.01	0.95±0.01	0.94±0.01	0.94±0.00	0.93±0.00	0.91±0.00	0.90±0.01	0.86±0.01
0.94±0.01	0.96±0.01	0.96±0.01	0.94±0.01	0.94±0.00	0.92±0.00	0.93±0.00	0.93±0.00	0.93±0.00	0.91±0.00	0.89±0.01	0.88±0.01
0.93±0.01	0.90±0.01	0.93±0.01	0.92±0.01	0.93±0.00	0.92±0.00	0.91±0.00	0.92±0.00	0.90±0.00	0.89±0.00	0.85±0.00	0.87±0.01
0.93±0.01	0.83±0.01	0.87±0.01	0.91±0.01	0.91±0.01	0.90±0.01	0.90±0.00	0.90±0.00	0.87±0.00	0.85±0.00	0.78±0.01	0.88±0.01
0.93±0.03	0.79±0.02	0.81±0.01	0.88±0.01	0.90±0.01	0.87±0.01	0.86±0.01	0.87±0.01	0.87±0.01	0.82±0.01	0.79±0.01	1.16±0.02

Validation using MVA to select $\bar{p}$ for $B^{\pm} \to p\bar{p}h^{\pm}$



$N_s = 450.7 \pm 45$

$N_b = 22425.4 \pm 1570$

$B^{\pm} \to p\bar{p}\pi^{\pm}$

$N_s = 1248.1 \pm 82$

$N_b = 22425.4 \pm 1570$

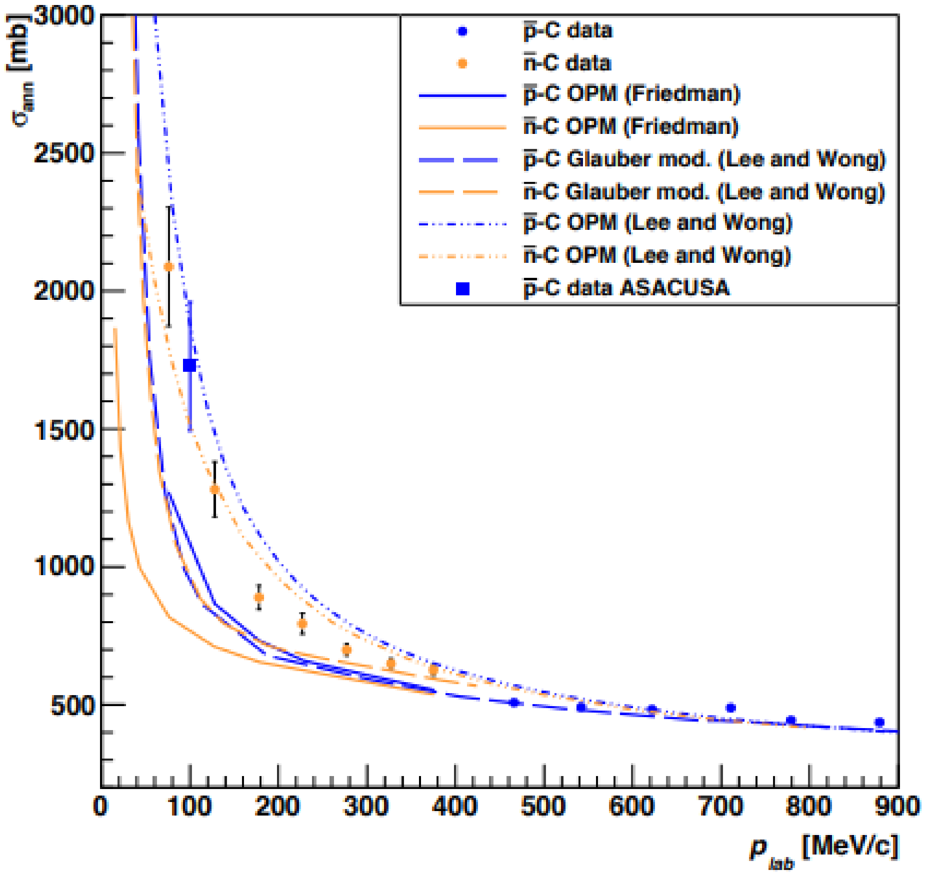
$B^{\pm} \to p\bar{p}K^{\pm}$

Red: Signal, Green: Background

By combining fitting results of $B^{+} \to p\bar{p}\pi^{+}(K^{+})$ and their signal efficiencies in MC respectively, we got $\mathcal{B}(B^{\pm} \to p\bar{p}\pi^{\pm}) = ($ **1.61 ± 0.18** $) * 10^{-6}$ and $\mathcal{B}(B^{\pm} \to p\bar{p}K^{\pm}) = ($ **5.5 ± 0.4** $) * 10^{-6}$.

By previous studies, $\mathcal{B}(B^{\pm} \to p\bar{p}\pi^{\pm}) = (1.62 \pm 0.2) * 10^{-6}$ and $\mathcal{B}(B^{\pm} \to p\bar{p}K^{\pm}) = (5.9 \pm 0.6) * 10^{-6}$.

Systematic uncertainty for $\overline{n}$ tagging



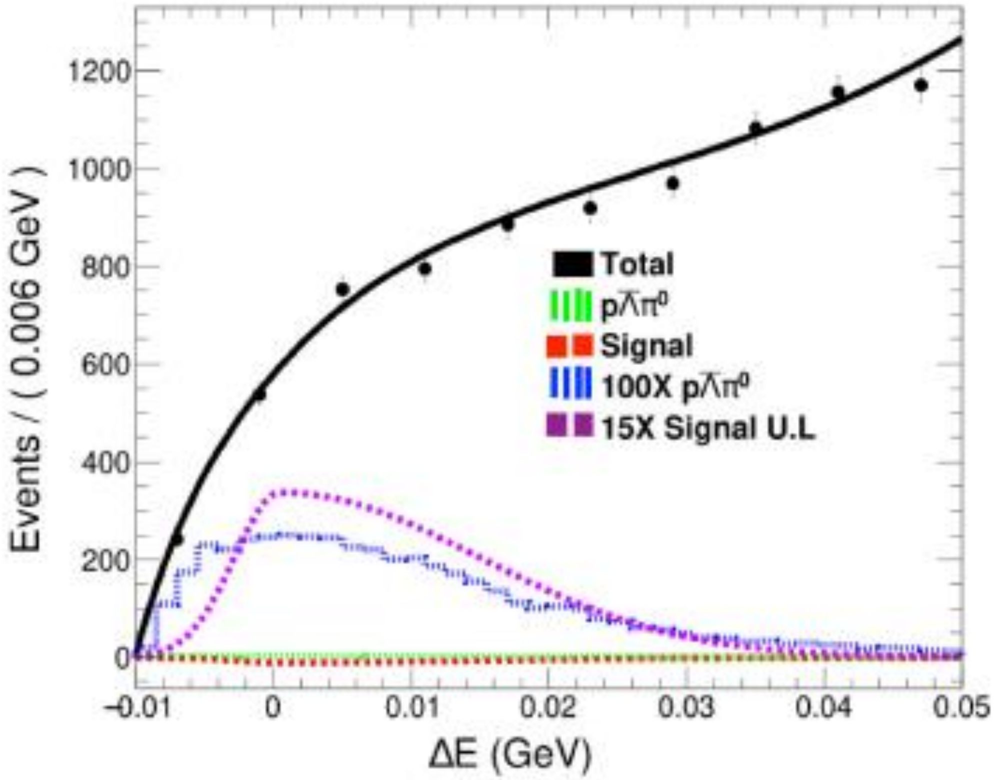
https://doi.org/10.1051/epjconf/201818203013

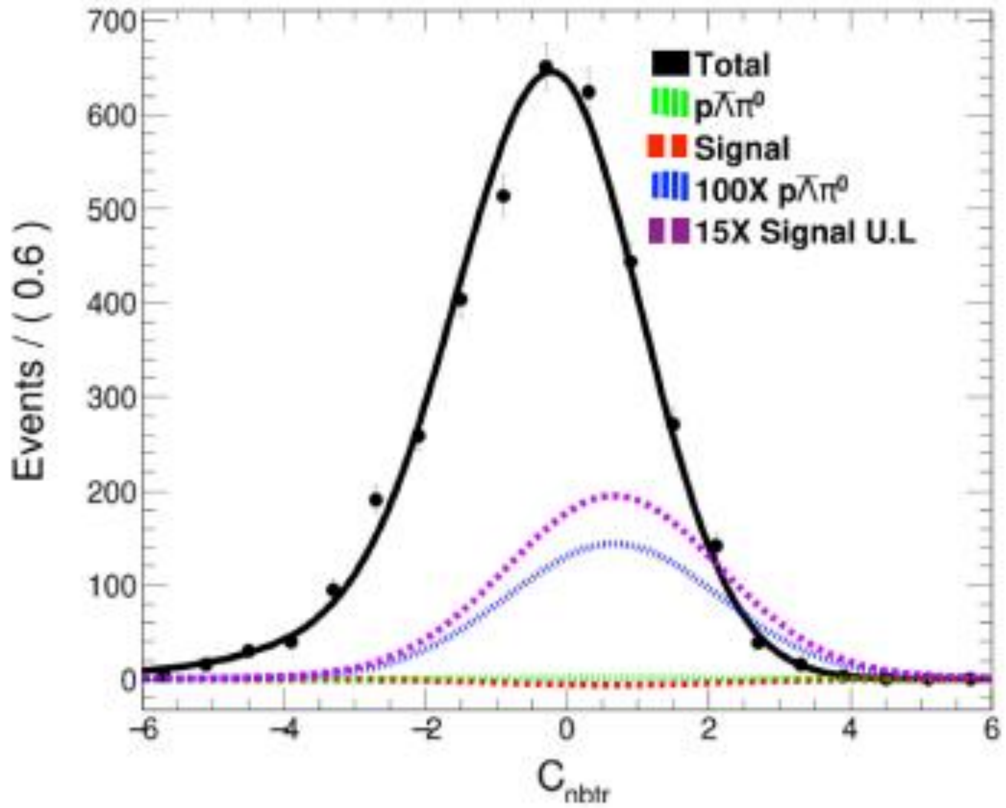
- Dominant source is the different annihilation cross-sections between $\overline{n}$ and $\overline{p}$, especially in the low momentum region

- Correction table related statistical uncertainty and smearing across neighboring bins

- Total is estimated to be 6% for $B^+ \to p\overline{n}\pi^0$

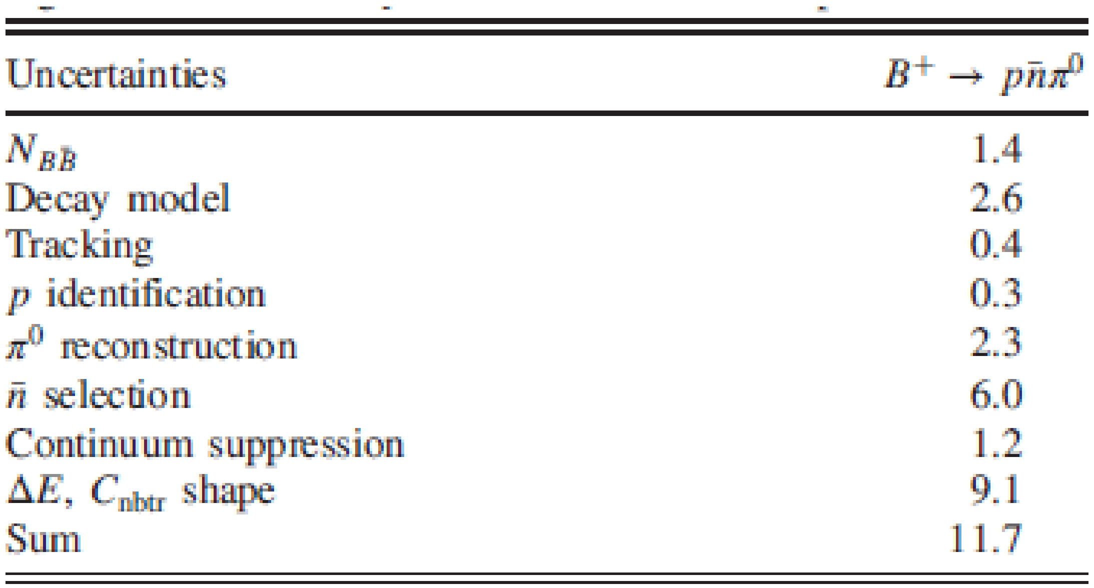
Fit results for $B^+ \to p\bar{n}\pi^0$





Signal yield = −28.7 ± 49.0

$\mathcal{B}(B^+ \to p\bar{n}\pi^0) < 6.3 \times 10^{-6}$



Uncertainties	$B^+ \to p\bar{n}\pi^0$
$N_{B\bar{B}}$	1.4
Decay model	2.6
Tracking	0.4
p identification	0.3
π^0 reconstruction	2.3
$\bar{n}$ selection	6.0
Continuum suppression	1.2
ΔE, $C_{\rm nbtr}$ shape	9.1
Sum	11.7

Summary for $B^+ \to p\bar{n}\pi^0$ Phys. Rev. D 108, 112007 (2023)

- The search result for $B^+ \to p\bar{n}\pi^0$ is negative
  only upper limit is obtained

- Developing an $\bar{n}$ tagging tool is successful
  Efficiency correction table and systematic uncertainty can be applied in future data analysis

- More decay modes such as $B^0 \to p\bar{n}\pi^-$, $\overline{B^0} \to p\bar{n}K^-$
  etc. should be studied

Prospects

- BelleII will collect 1 ab^{-1} data in two years and we will combine Belle and Belle II data for physics search
- Some puzzles from baryonic B decays can still be tackled with Belle data
- More results of anti-neutron in the final state from B decays will be reported in the near future