Inclusive B decays with η mesons and other flavor puzzles at Belle and Belle II

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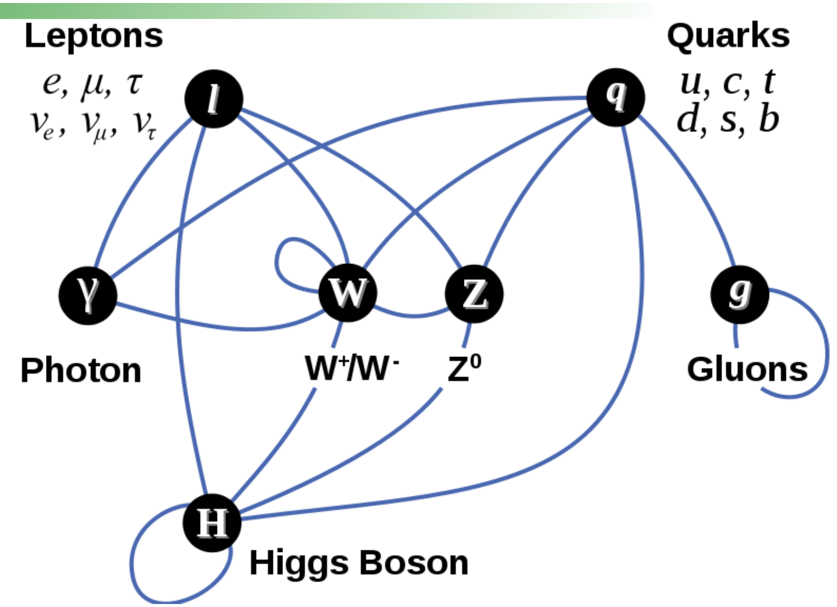
SLAC Experimental Particle Physics Seminar
August 28, 2012

The Standard Model

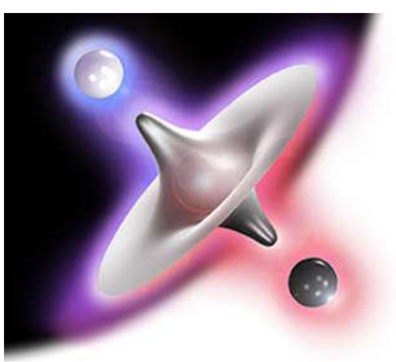
- The Standard Model of particle physics:
  - Describes the known fundamental matter particles:
    - Quarks
    - Leptons
  - And interactions between them (mediated by gauge bosons):
    - Electromagnetic
      - Photon (γ) – couples to electrically charged particles.
    - Strong
      - Gluons – couple to quarks (and other gluons).
    - Weak
      - W, Z – couple to quarks and leptons

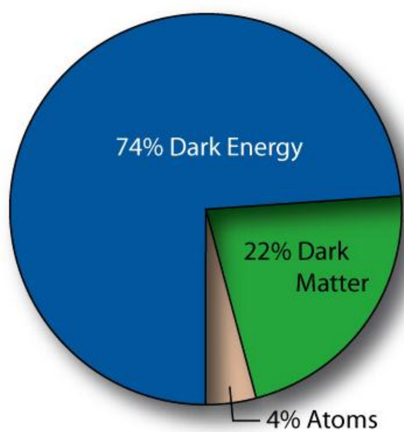


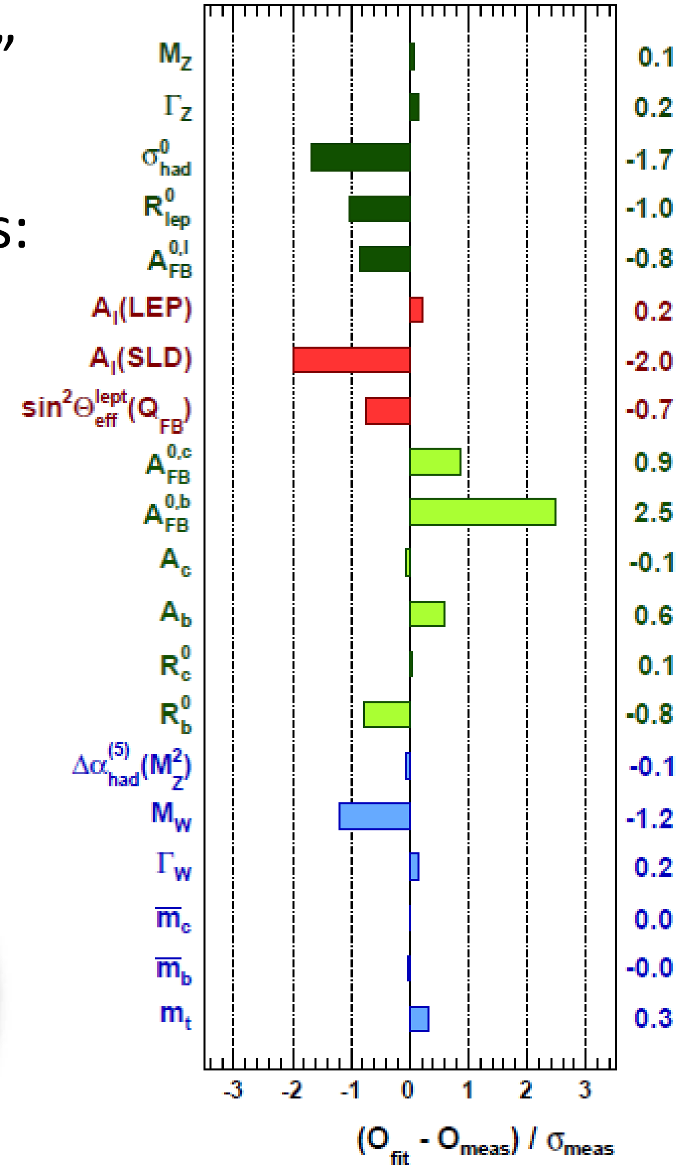
Particle name	Symbol	Electric charge ($e = 1.60 \times 10^{-19}$ C)	Mass (GeV/c^2)
quarks			
up	u	+2/3	2.49×10^{-3}
down	d	-1/3	5.05×10^{-3}
strange	s	-1/3	1.01×10^{-1}
charm	c	+2/3	1.27
bottom	b	-1/3	4.19
top	t	+2/3	1.72×10^{2}
leptons			
electron	e	-1	5.11×10^{-6}
muon	μ	-1	1.06×10^{-3}
tau	τ	-1	1.78
electron neutrino	ν_e	0	$< 2 \times 10^{-9}$
muon neutrino	ν_μ	0	$< 2 \times 10^{-9}$
tau neutrino	ν_τ	0	$< 2 \times 10^{-9}$
gauge bosons			
gluon	g	0	0
photon	γ	0	0
W boson	W	+1	8.04×10^{1}
Z boson	Z^0	0	9.12×10^{1}
Higgs boson	H	0	$> 1.14 \times 10^{2}$

Beyond the Standard Model?

- Standard Model is "frustratingly successful."
  - Have we found the last missing piece?
- But it has distinct flaws, just a few examples:
  - Our universe displays a wildly asymmetric ratio of matter to antimatter:
    - "The degree of asymmetry predicted … is ten orders of magnitude too small."
      - M. Peskin, Nature **452**, 293 (2008).
  - Standard model has no dark matter candidate.
- So we expect something must lie beyond.



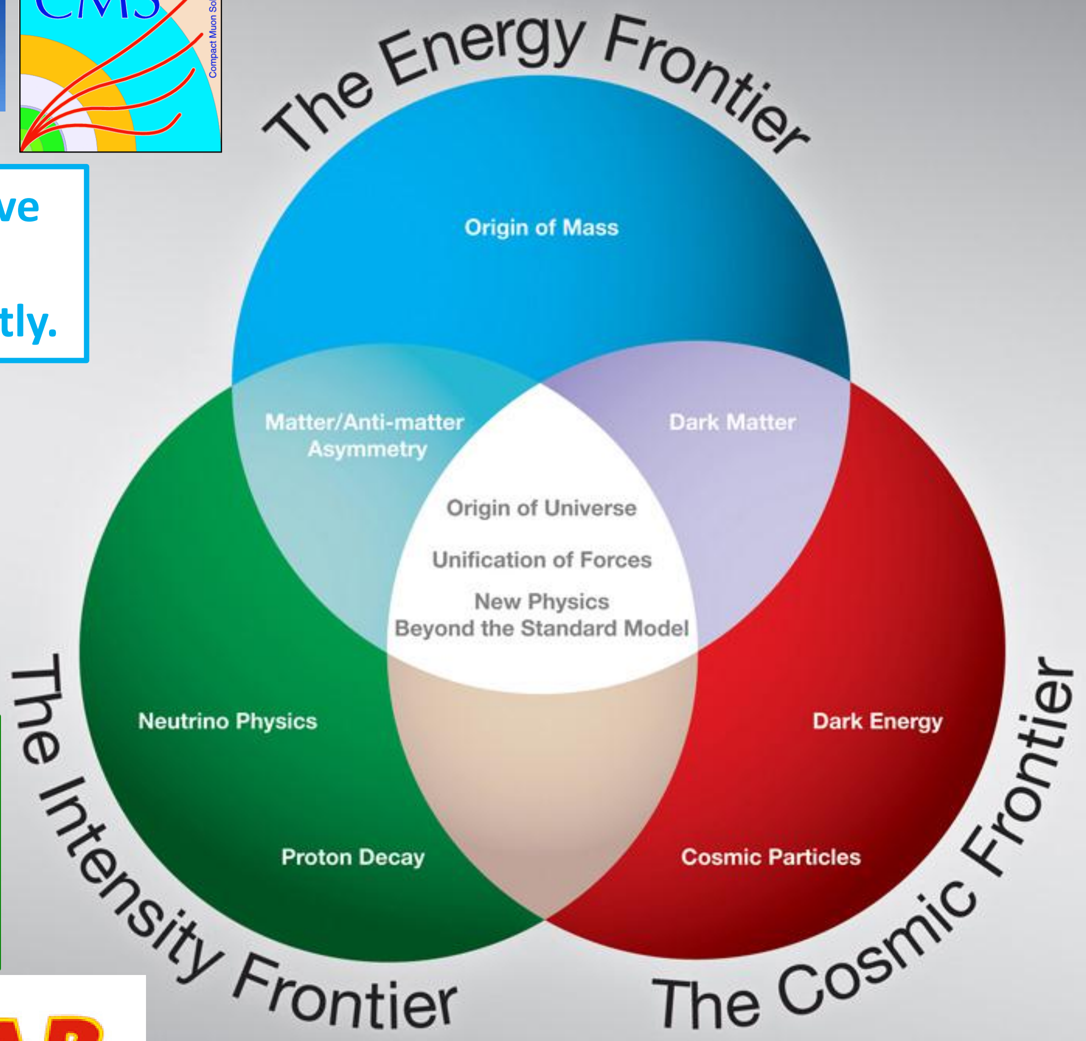




Gfitter group, [arXiv: 1107.0975]

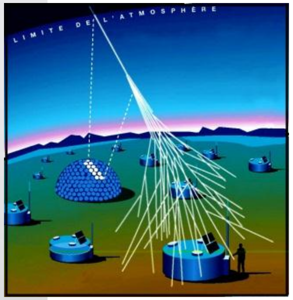
Searches for New Physics

Produce and observe new particles or phenomenon directly.



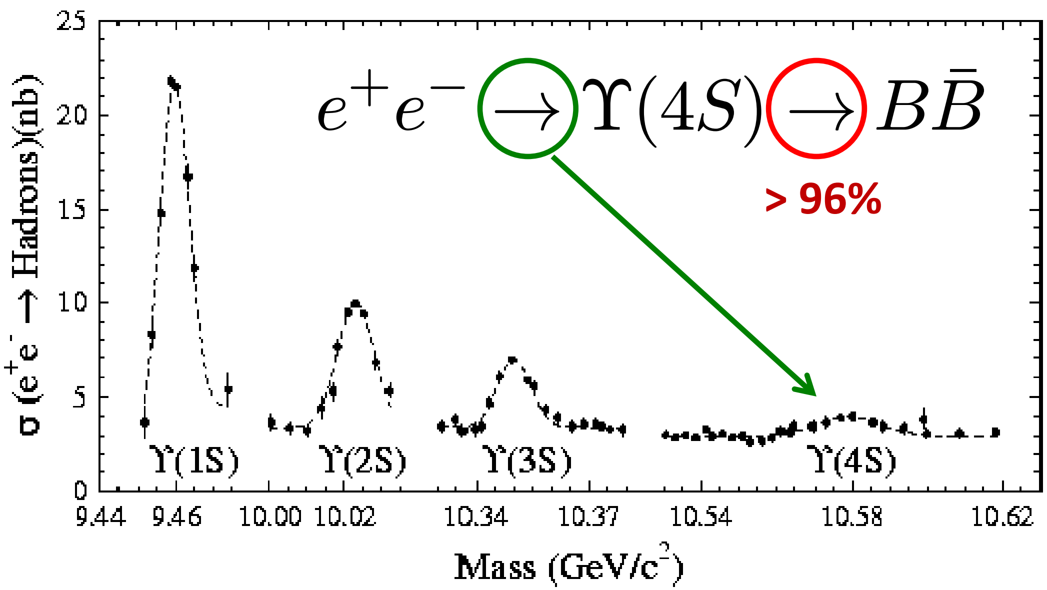
Observe processes that are extremely rare or forbidden in Standard Model.

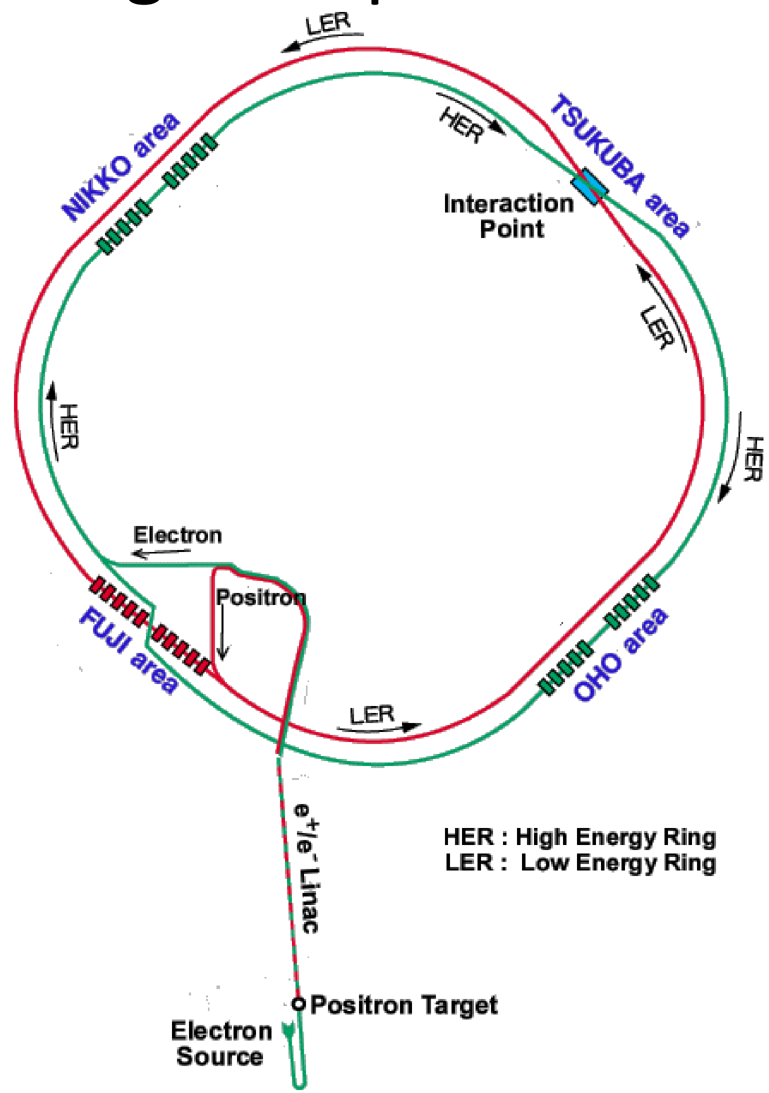
Use cosmic rays to search for new particles or probe energies beyond those available at colliders.



B Factories

- *B* mesons can be produced through the process:





- *B* factories are colliders tuned to operate at the energy of the $\Upsilon(4S)$:
  - CESR accelerator / CLEO detector
    - Cornell – New York
  - PEP-II accelerator / BaBar detector
    - SLAC - California
  - **KEKB accelerator / Belle detector**
    - **KEK – Tsukuba, Japan**

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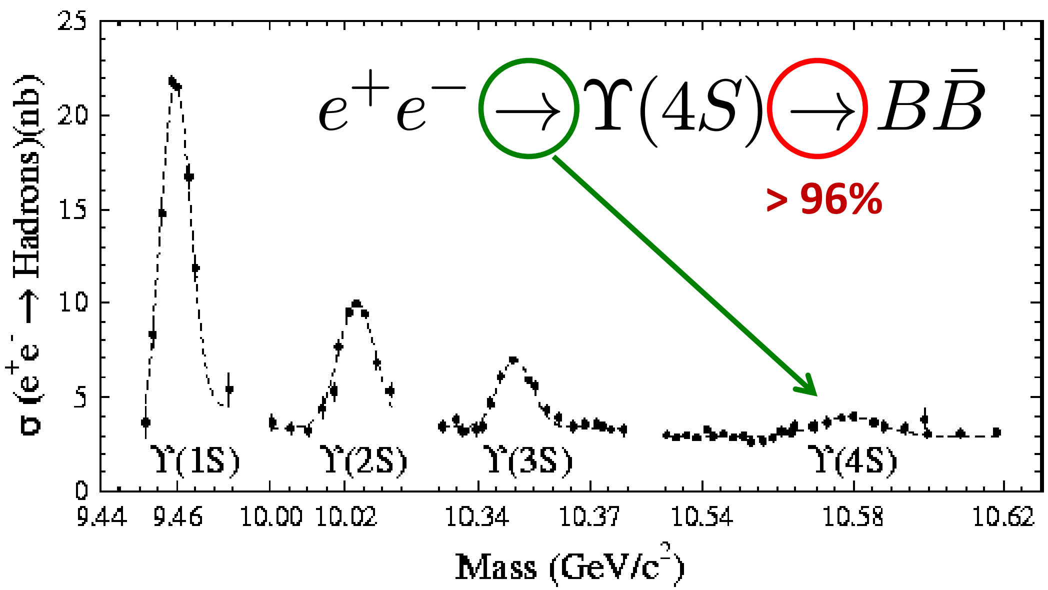

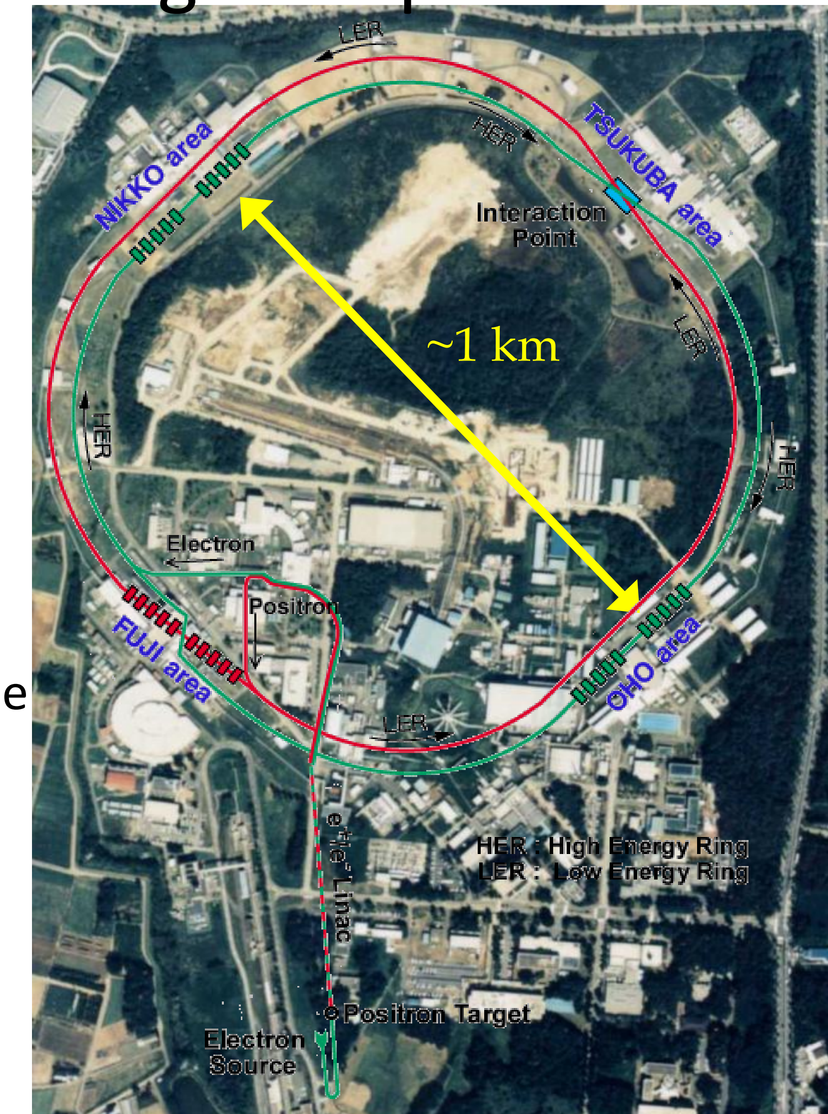

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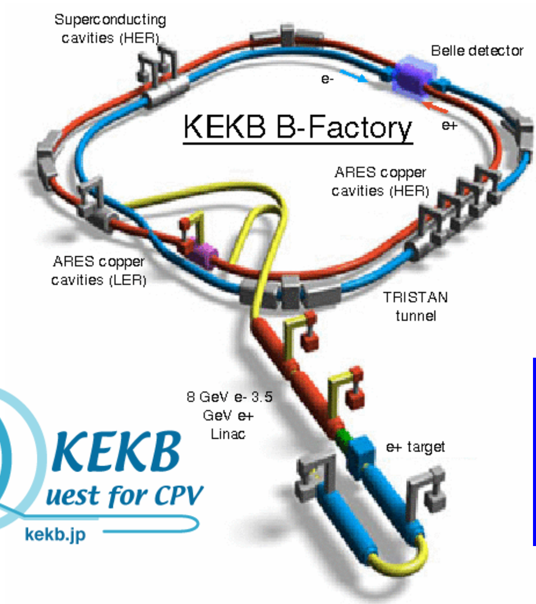
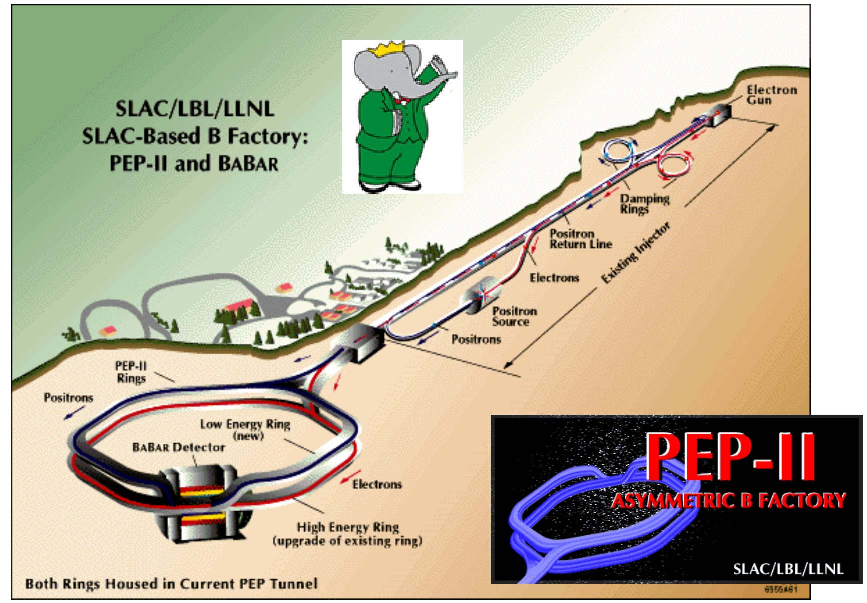
Measuring CPV at Asymmetric *B* Factories

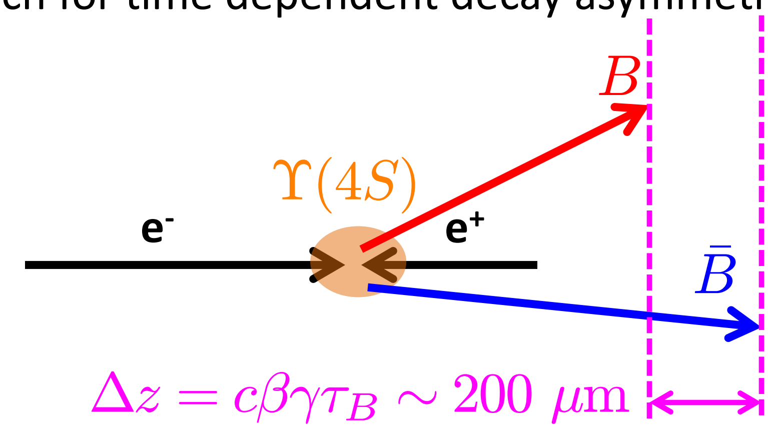
Primary physics goal of the *B* factories:

- **Measure CP violation in *B* meson system, confirm the KM mechanism of CP violation...**





Search for time dependent decay asymmetries:



Belle

8.0 GeV e^- , 3.5 GeV e^+

$\beta\gamma = 0.42$

BaBar

9.0 GeV e^- , 3.1 GeV e^+

$\beta\gamma = 0.56$

Success in Time Dependent CPV

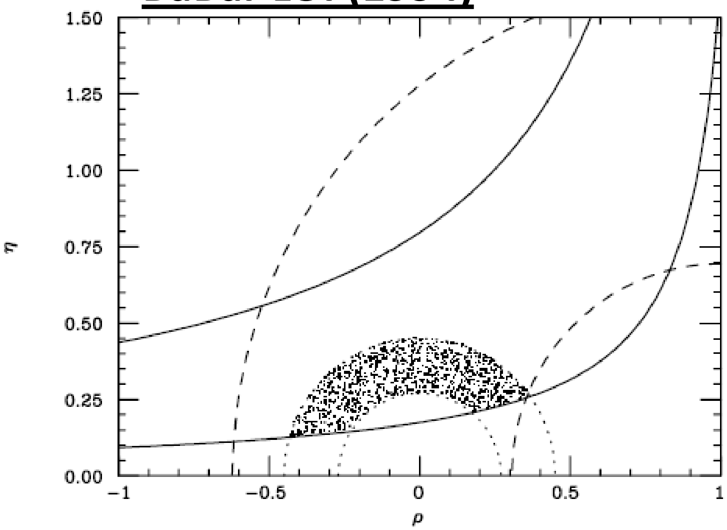
VOLUME 87, NUMBER 9 PHYSICAL REVIEW LETTERS 27 AUGUST 2001

Observation of Large *CP* Violation in the Neutral *B* Meson System

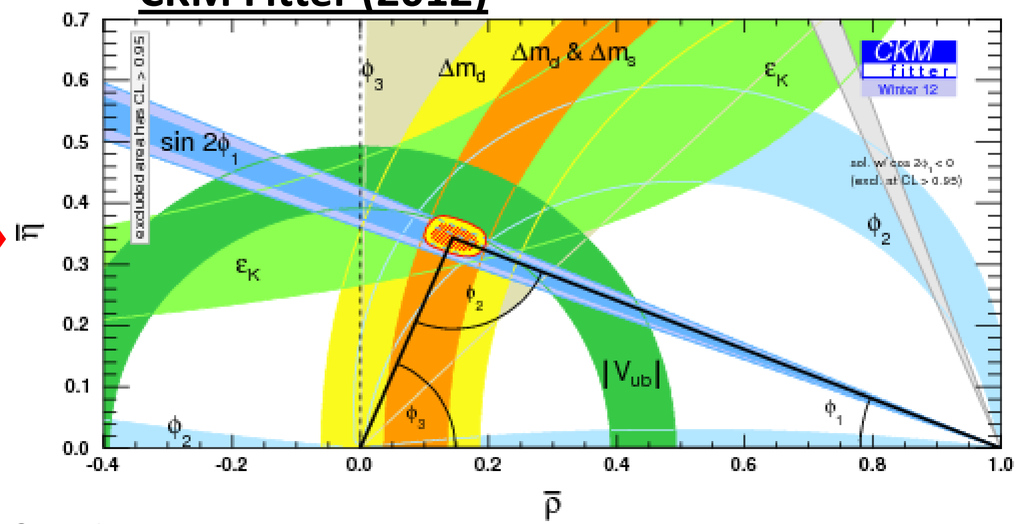
VOLUME 87, NUMBER 9 PHYSICAL REVIEW LETTERS 27 AUGUST 2001

Observation of *CP* Violation in the B^0 Meson System

BaBar LOI (1994)



CKM Fitter (2012)

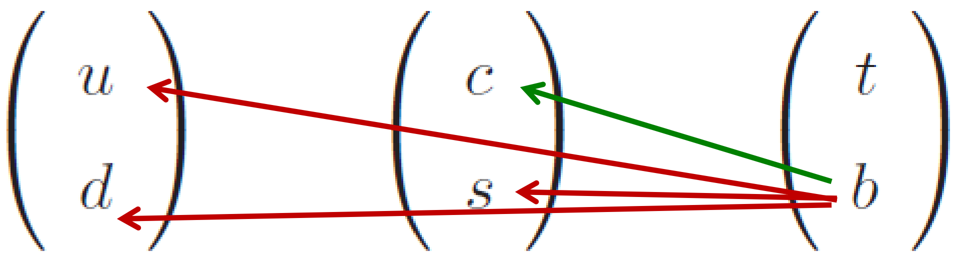


➔ CKM verified to ~10%!

A great success, but *B* factories have much broader physics program.

Charmless Decays of the *b* Quark

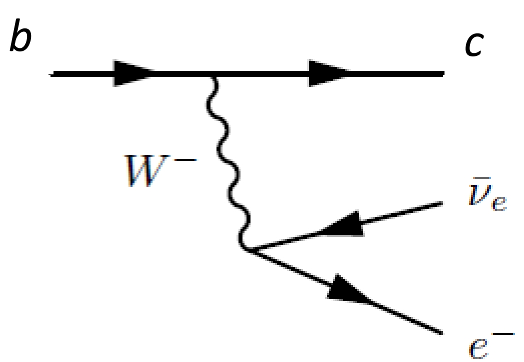
- Bottom quark is second most massive.
  - Many decay channels, many potential measurements.



Most common decays

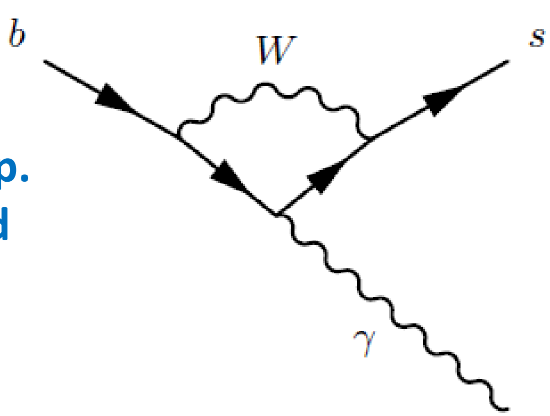
Suppressed

- Decays to charm can happen at tree level:



- Decays to strange include loops:

Virtual particles contribute in loop.
➔ Both Standard Model and new physics particles.

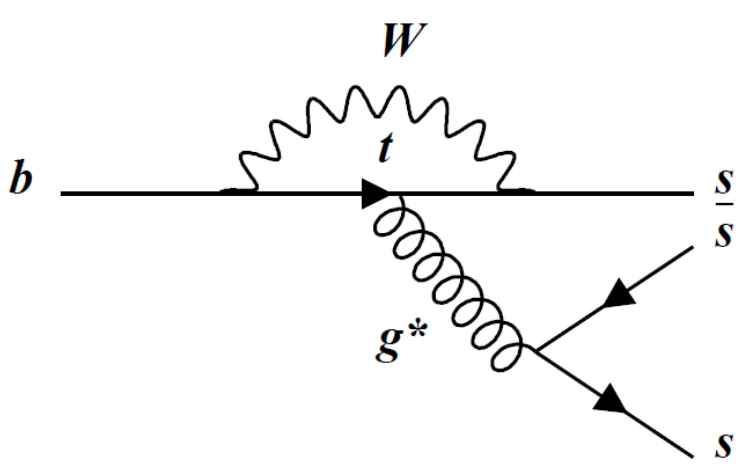


Hadrons, Exclusive/Inclusive Decays

- Standard Model Lagrangian describes interactions at quark level, but we only observe quarks bound into hadrons.
  - Baryons (three quarks)
    - e.g., neutron (udd), proton (uud)
  - Mesons (quark-antiquark)
    - e.g., B mesons: $B^+ = u\overline{b},\ B^0 = d\overline{b},\ \overline{B}^0 = \overline{d}\,b,\ B^- = \overline{u}\,b,$

      D mesons: $D^+ = c\overline{d},\ D^0 = c\overline{u},\ \overline{D}^0 = \overline{c}\,u,\ D^- = \overline{c}\,d,$

      Kaons: $K^+ = u\overline{s},\ K^0 = d\overline{s},\ \overline{K}^0 = \overline{d}\,s,\ K^- = \overline{u}\,s,$



<u>Quark level process</u>…
➔ "Straightforward" theoretical treatment.

Hadrons, Exclusive/Inclusive Decays

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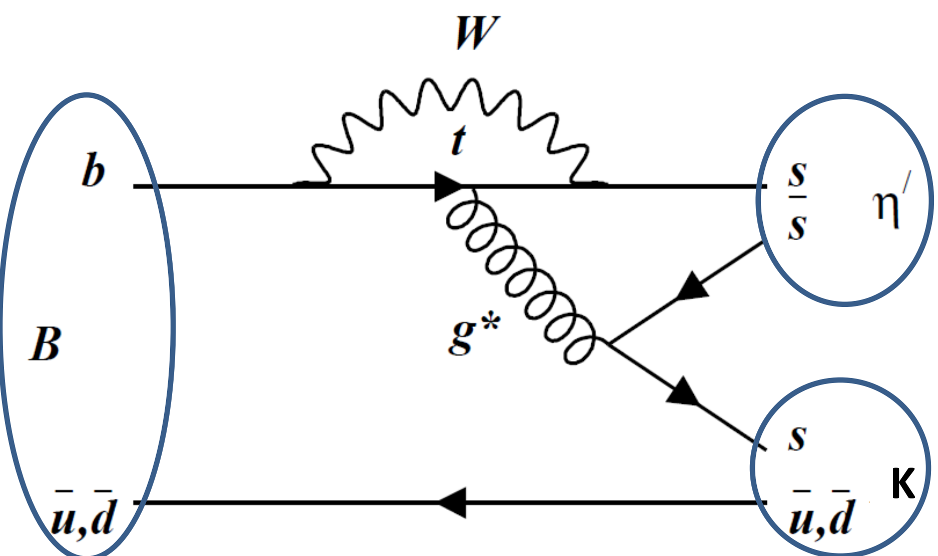

<u>Exclusive process</u> – all hadrons identified explicitly.
➔Experimentally accessible.
➔Hadronization process introduces significant theoretical uncertainties.

Hadrons, Exclusive/Inclusive Decays

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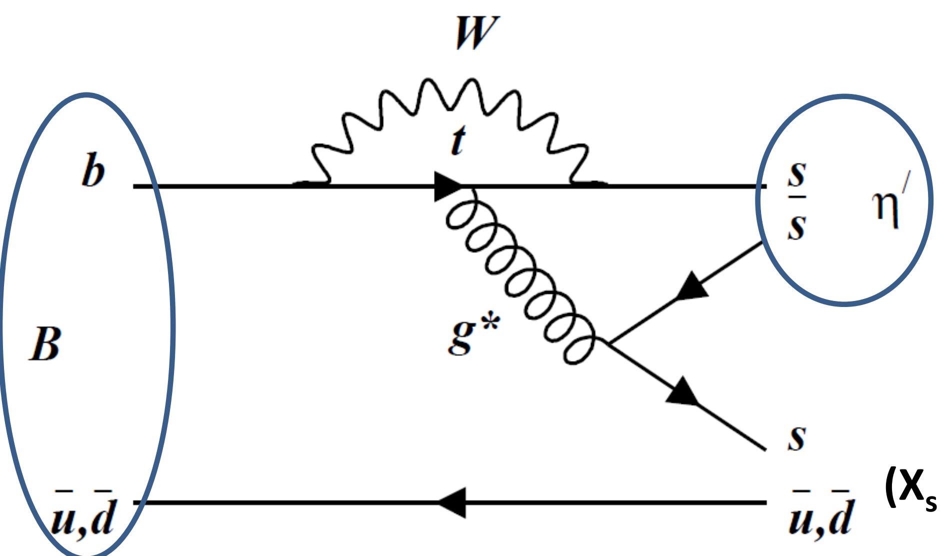


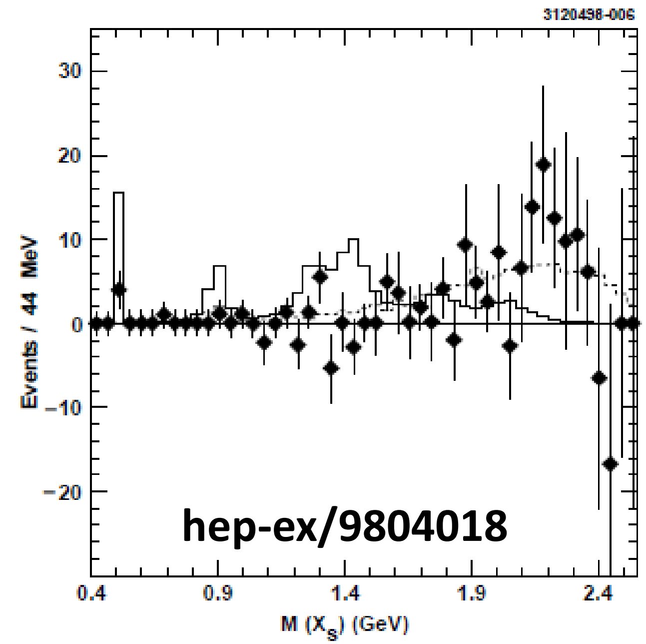
(X$_s$ = K, K*, etc.)

<u>Inclusive or semi-inclusive process</u>

➔Experimentally: effectively measure over many final states.

➔ Potentially reduced theoretical errors.

$B \to X_s\,\eta'$ and $B \to X_s\,\eta$

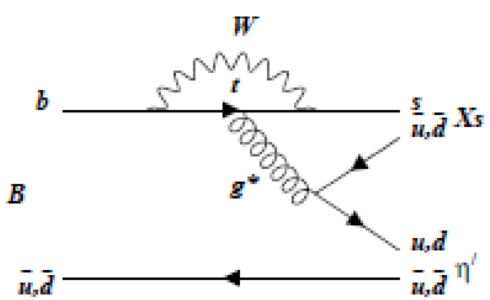


- 1998: The CLEO collaboration measures the inclusive proccess $B \to X_s\,\eta'$
  - Mass spectrum and branching faction were both considered surprising:
    - Peaking at high X_s mass.
    - Anomalously high (in a relative sense…):

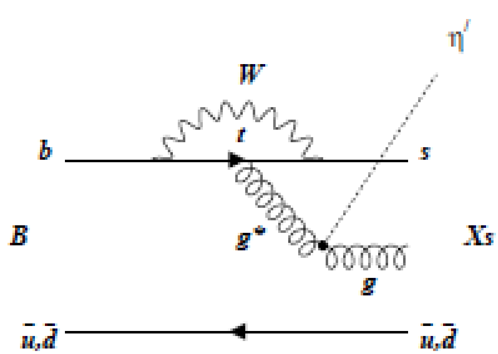
$$\mathcal{B}(B \to X_s\eta') = (6.2 \pm 1.6^{+1.3}_{-2.0}) \times 10^{-4}$$

  - Confirmed in 2003 by CLEO, 2004 BaBar: $\mathcal{B} = (4.2 \pm 0.9) \times 10^{-4}$ (world average)

"2-body" decay



QCD anomaly decay

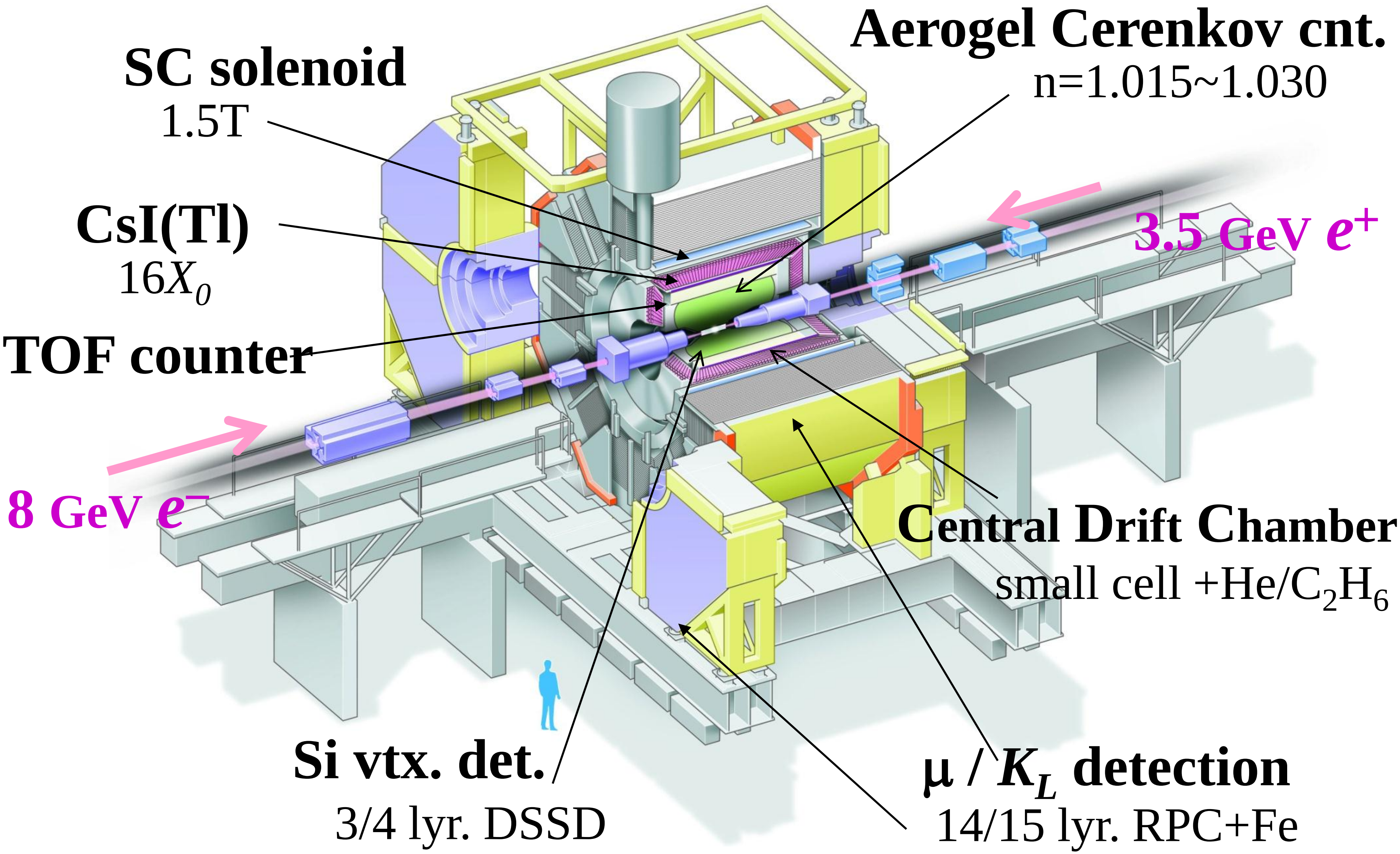


- There was significant debate over whether new physics was required to explain this result.
  - Attributed to a special property of the η' meson, "QCD anomaly."

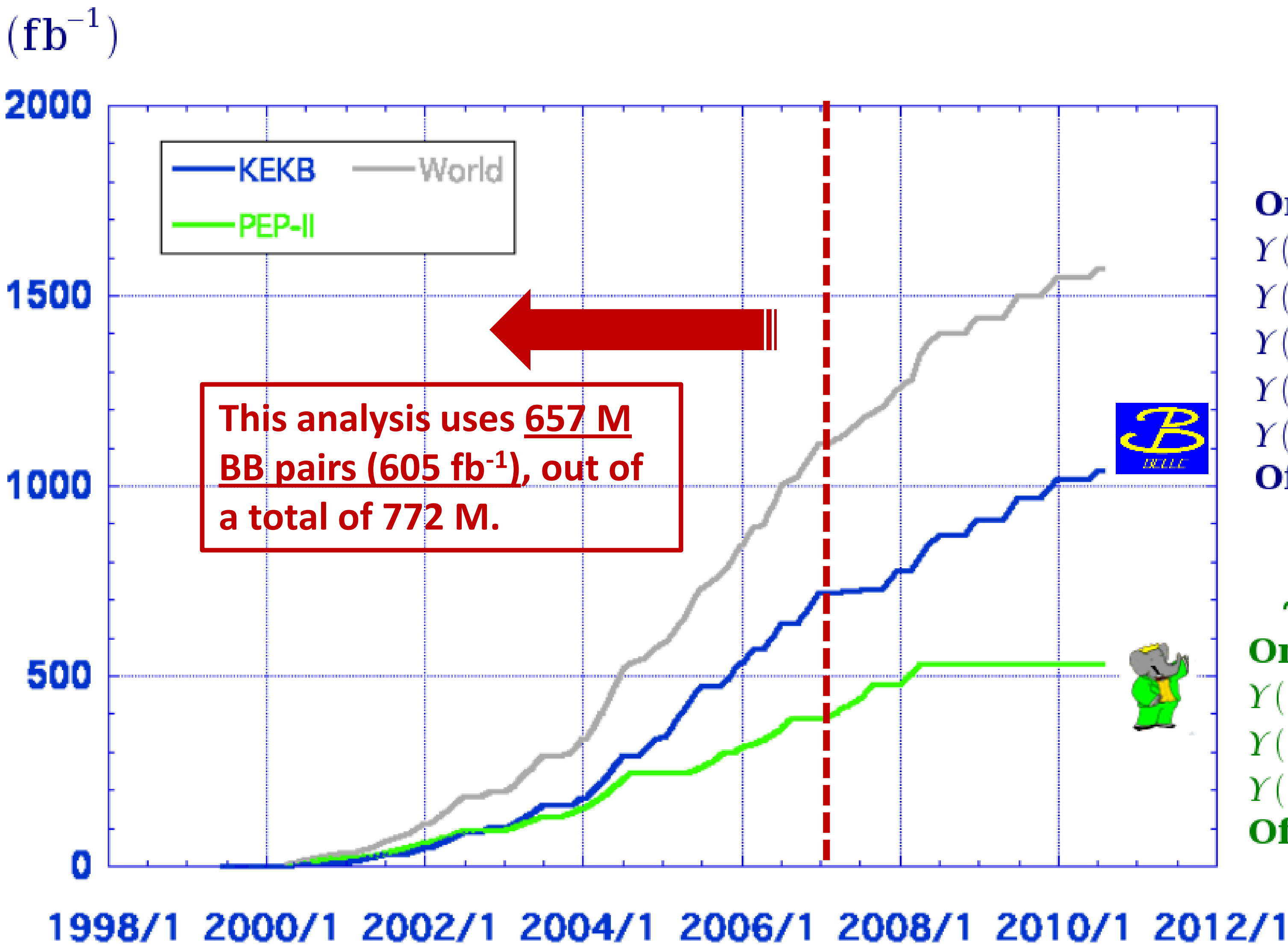
    [Atwood, Soni: hep-ph/9704357]
    - Despite name, this is actually Standard Model physics.
  - To date, no conclusive explanation.
  - η and η' mesons mix!

➔ Measure this at Belle, but exchange for η' for η to help favor or rule out explanations.

Belle Experiment



Belle Data Sample



> 1 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 24 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

~ 100 fb^{-1}

~ 550 fb^{-1}

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

$\Upsilon(3S)$: 30 fb^{-1}

$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

~ 54 fb^{-1}

Measuring B $\rightarrow$ X_s η at Belle

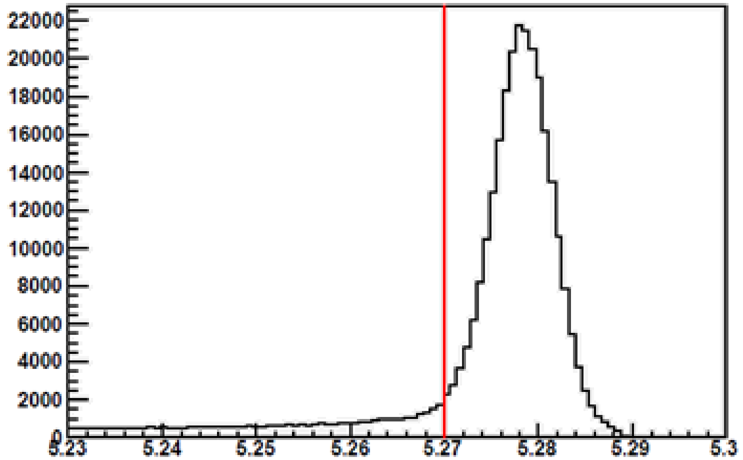
- η is reconstructed through $\eta \rightarrow \gamma\gamma$
  - We look for pairs of photons that have energies consistent with coming from an η.
- The X_s state is anything with a net strangeness of 1.
  - We only look for the following decays (pseudo-inclusive):

$$
\begin{array}{ll}
B^+ \rightarrow K^+(\pi^0)\eta & B^0 \rightarrow K^0_S(\pi^0)\eta \\
B^+ \rightarrow K^0_S\pi^+(\pi^0)\eta & B^0 \rightarrow K^+\pi^-(\pi^0)\eta \\
B^+ \rightarrow K^+\pi^+\pi^-(\pi^0)\eta & B^0 \rightarrow K^0_S\pi^+\pi^-(\pi^0)\eta \\
B^+ \rightarrow K^0_S\pi^+\pi^-\pi^+(\pi^0)\eta & B^0 \rightarrow K^+\pi^-\pi^+\pi^-(\pi^0)\eta \\
B^+ \rightarrow K^+\pi^+\pi^-\pi^+\pi^-\eta & B^0 \rightarrow K^0_S\pi^+\pi^-\pi^+\pi^-\eta
\end{array}
$$

  - Efficiency becomes too low to make others worth measuring.
  - Because we don't measure all possible modes, we have to make an efficiency correction to account for these "missing" modes.

B Meson Reconstruction: M_{bc} & ΔE

- Beam-constrained mass:



$$M_{\rm bc} = \sqrt{(E^*_{\rm beam})^2 - |\mathbf{p}^*_B|^2}$$

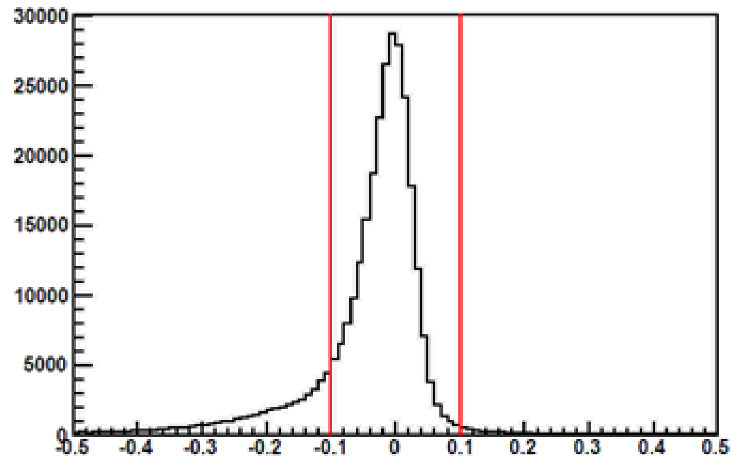
(or M_{ES})

  – Peaks at *B* mass for correctly reconstructed B mesons.
  – Using known beam energy gives improved resolution relative to measuring invariant mass of B candidate directly.

- Energy Difference:

$$\Delta E = E^*_B - E^*_{\rm beam}$$

  – Peaks at 0 for correct B candidates.

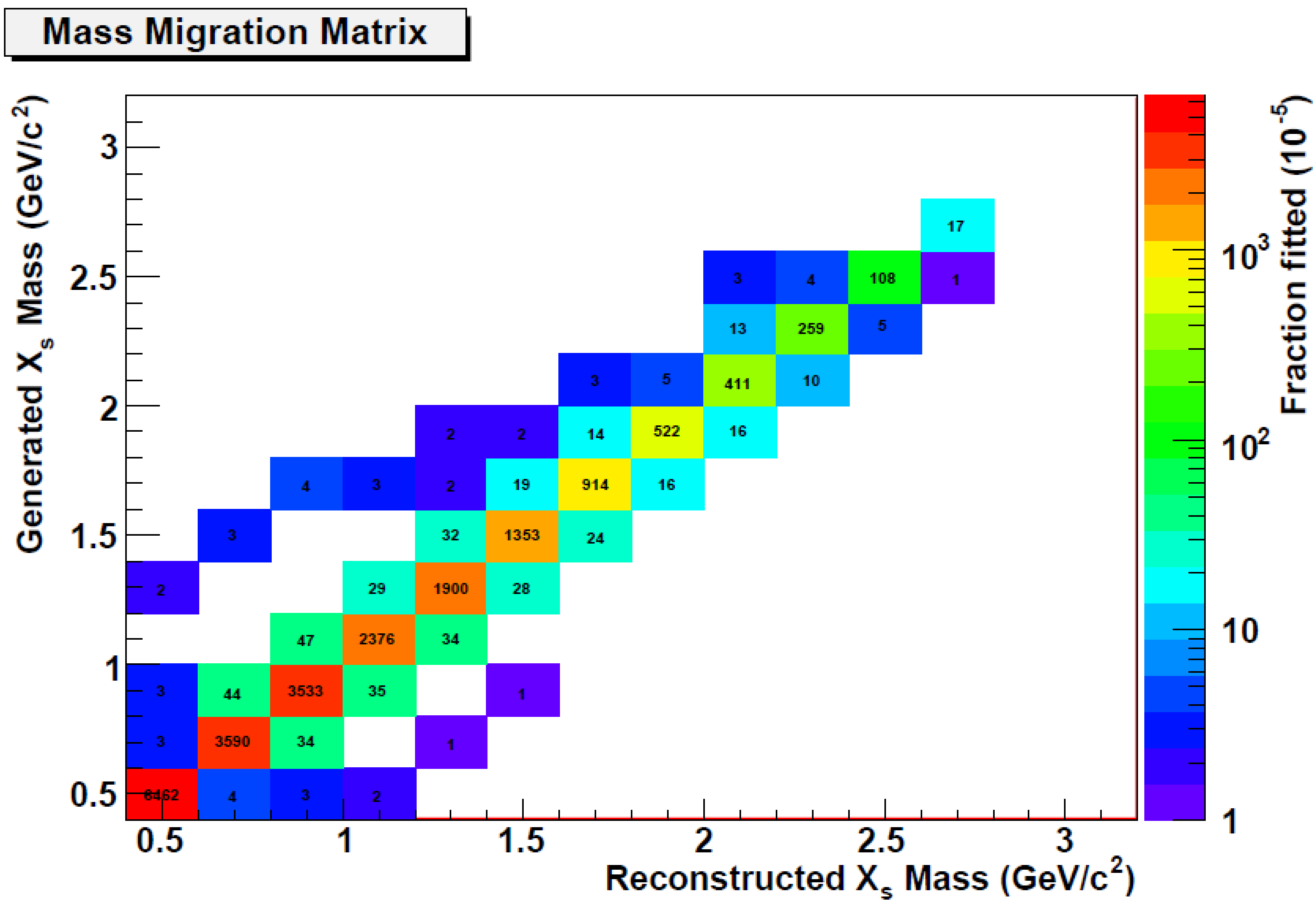


Candidate Selection

- With so many modes reconstructed, there are many combinations of particles that can make a *B* candidate.
  - We choose the best candidate as the one with the lowest $\chi^2 = \chi^2_{vtx} + \chi^2_{\Delta E}$
    - Vertex fit of charged tracks – tracks should come from interaction point.
    - True *B* candidates should have ΔE ~ 0

  ➔This biases the ΔE distribution, so we do not use it for fitting later.
- We can check the effectiveness of candidate selection by looking at "migration" between modes (or between masses)…

Candidate Selection



Backgrounds to $B \to X_s\,\eta$

- We have many competing processes that can fake our signal:

$$e^+e^- \to \Upsilon(4S) \to B\bar{B}$$

$q\bar{q}$ continuum

Strategy:

- **Suppress/veto backgrounds as much as is practical.**
- **Estimate what remains and model it into a fitting procedure.**

Biggest challenges:

- **The largest charm and rare backgrounds are not well measured, so we must estimate them from data.**
- **Efficiency relies on assumptions about the X_s and "missing" modes that we must validate in data.**

$X_c\eta$

$X_c \to X_s\eta$

"generic" charm backgrounds

$X_s\eta$

Signal

X_s in a mode we measure

X_s in a "missing" mode

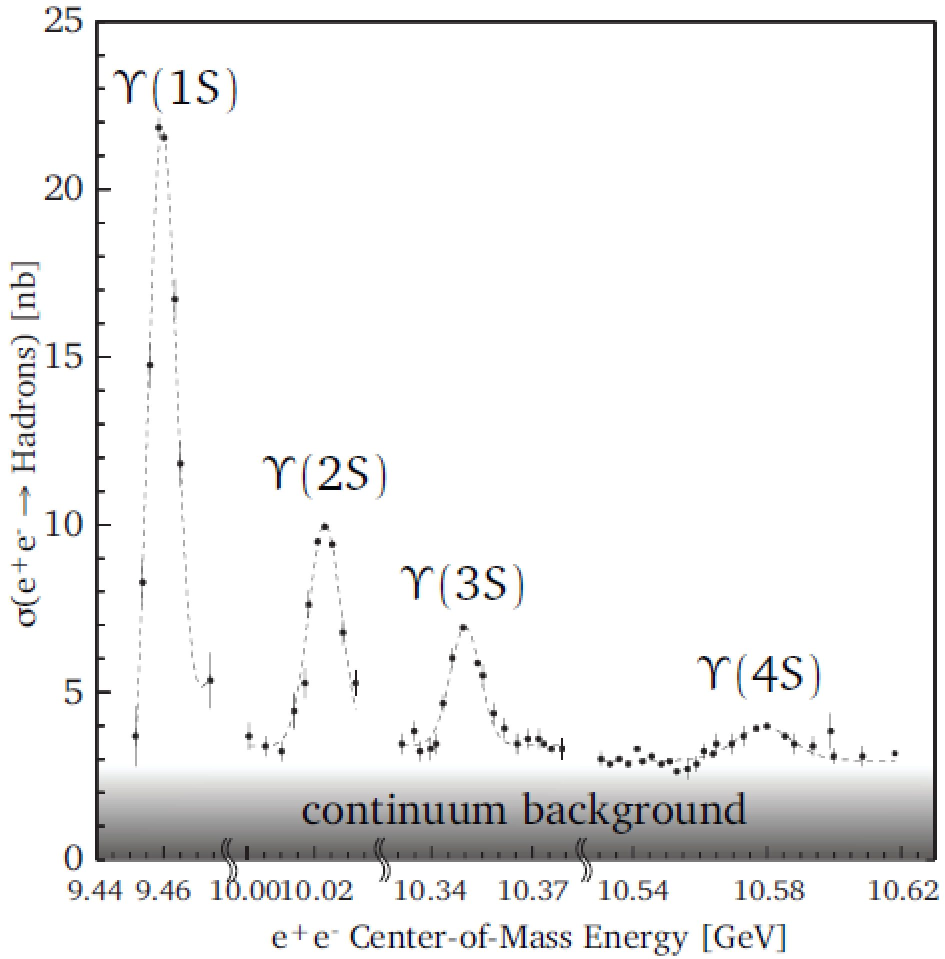
$X_s\eta' \to X_s\eta$

$X_{(u,d)}\eta$

…

rare backgrounds

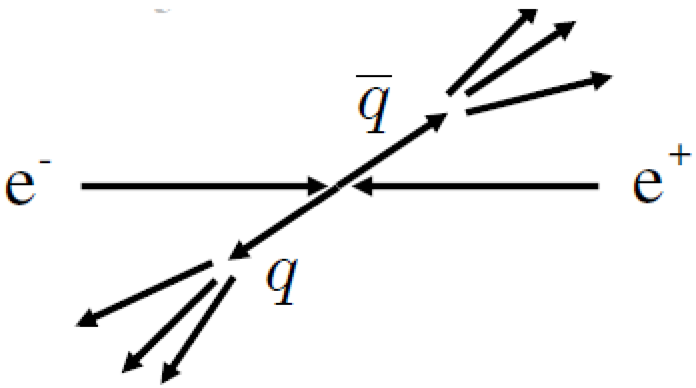
Continuum Suppression



- Cross section to produce $q\bar{q}$ is about 3 times as large as that to produce $\Upsilon(4S)$.

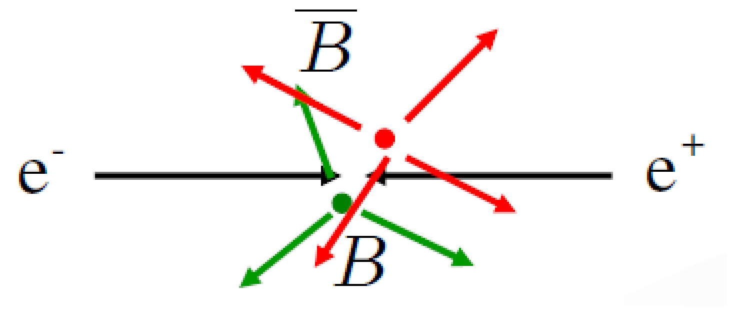
Continuum Suppression

- Continuum events:



  - Light quarks produced back-to-back.
  - Jets of hadrons along quark momentum vectors.

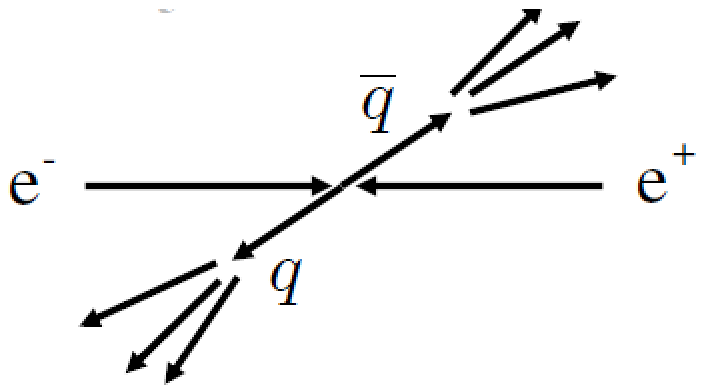
- BB events:



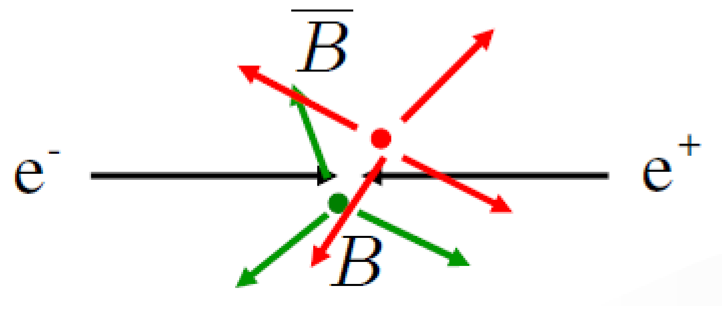
  - B pair produced at threshold, each B is nearly at rest.
  - Decay products isotropic.

Continuum Suppression

- Continuum events:



- BB events:



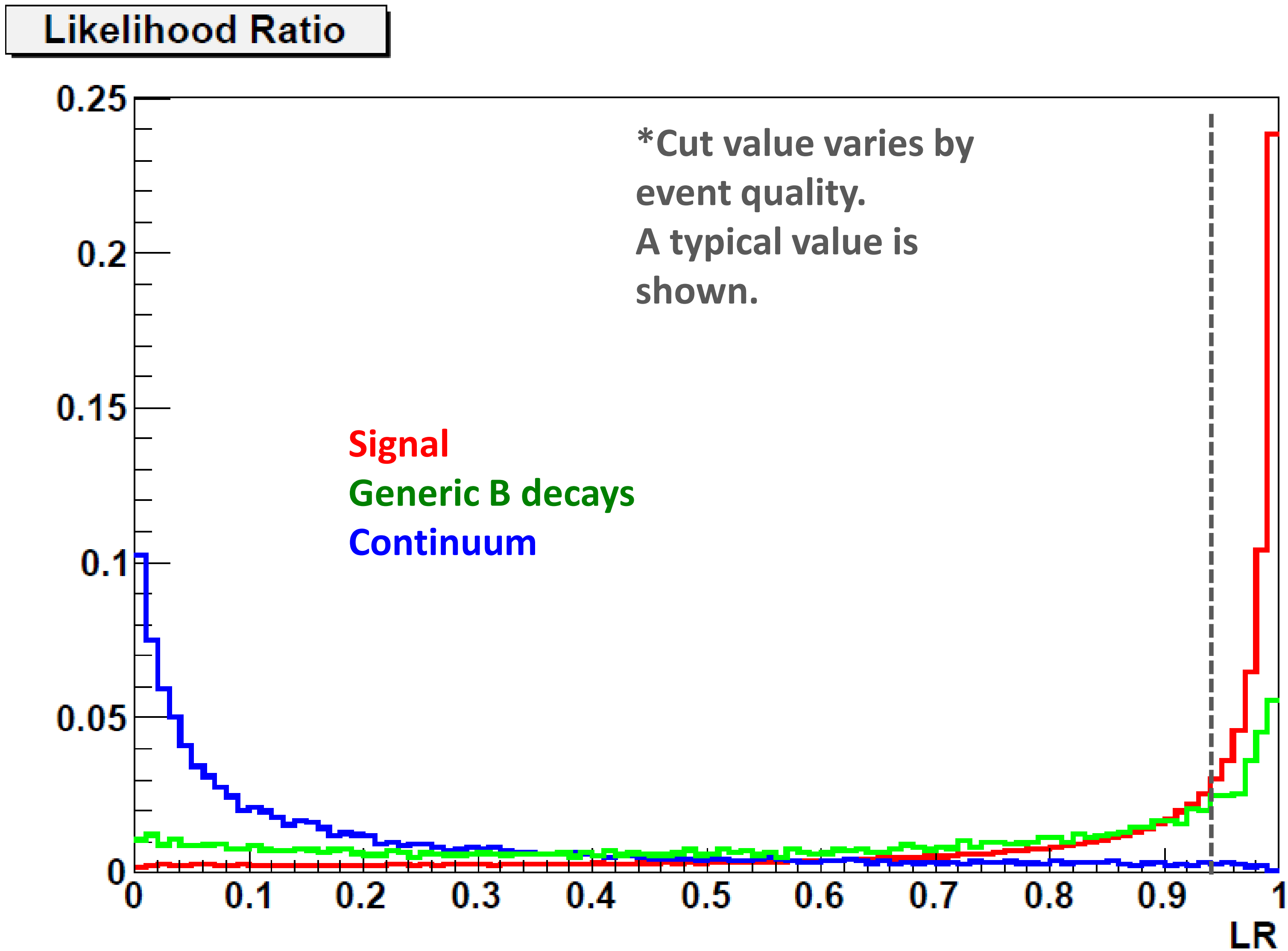
Suppress continuum based on:

- Linear discriminant formed from Fox-Wolfram moments:

$$H_l = \sum_{i,j} \frac{|\vec{p_i}||\vec{p_j}|}{s} P_l(\cos\phi_{ij})$$

- Distance between reconstructed B pairs, Δz
- Cosine of B flight direction: cos θ_B
- Combine all into a likelihood ratio.

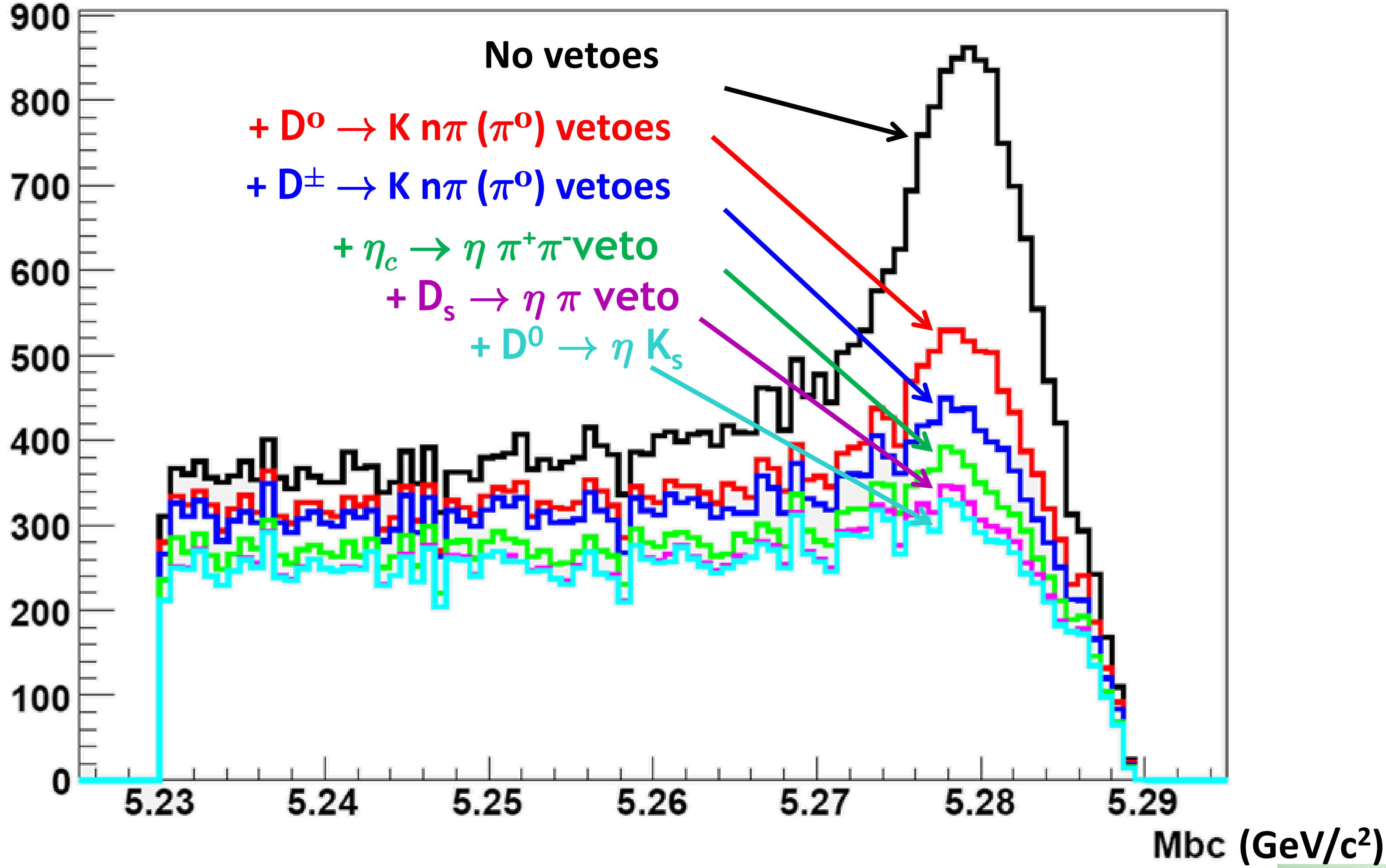
Continuum Suppression



Suppresses 99.5% of continuum, retains 34% signal.

Generic (b → c) Peaking Backgrounds

Identify common b → c backgrounds from MC. Look for them explicitly in our signal events and "veto" the event if we see something consistent with them:



Fitting Procedure

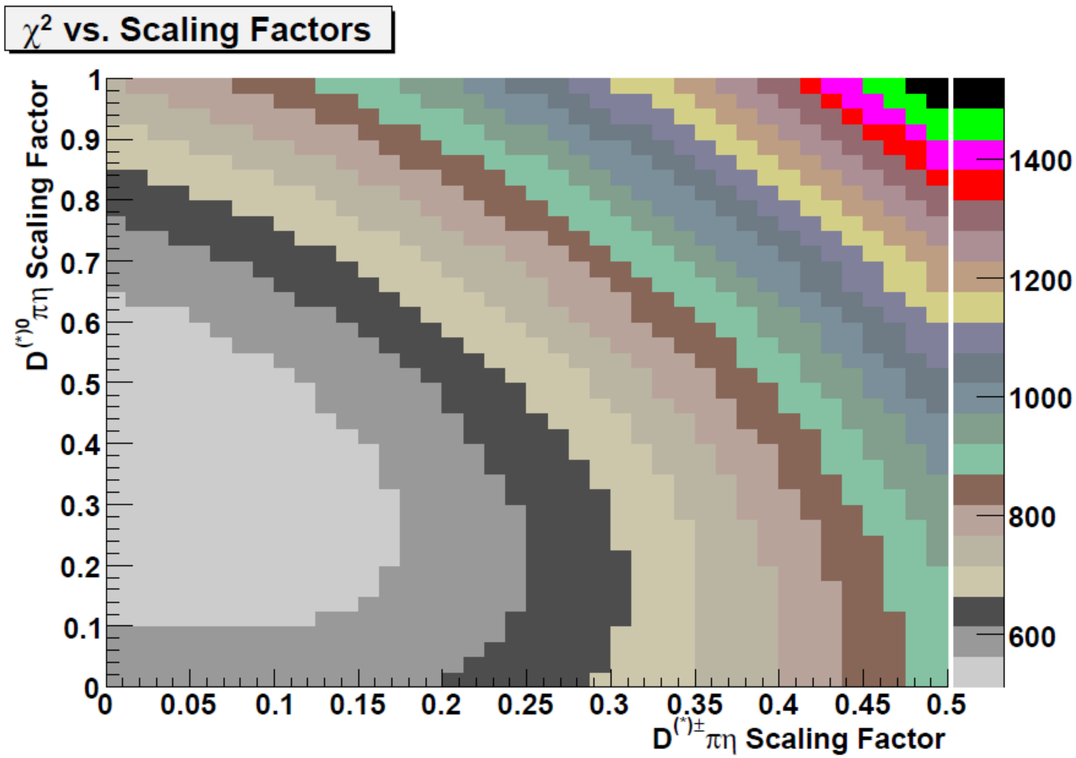
- The number of signal events is determined with 1-dimensional fits to M_{bc} distributions in bins of X_s mass. Fit components:
  - Signal – Gaussian
  - Continuum – ARGUS function ($t\sqrt{1-t^2}e^{\alpha(1-t^2)}$)
  - BB backgrounds – divided into 5 components:

$$B^0 \to \bar{D}^0\eta$$
$$B^0 \to \bar{D}^{*0}\eta$$
$$B^+ \to D^{(*)-}\pi^+\eta$$
$$B^0 \to \bar{D}^{(*)0}\pi^+\eta$$
$$\text{All other } B\bar{B} \text{ backgrounds}$$

  - Rare backgrounds are small. Expected contributions are checked against sidebands, subtracted after fit.

Veto Window Calibration

- MC normalizations need adjustment.
  - Most challenging for poorly measured $D^{(*)}$ (π) η decays.
  - We use previous Belle measurements for D η, D^* η.
  - $D^{(*)}$ π η is not measured. Calibrated from data with χ^2

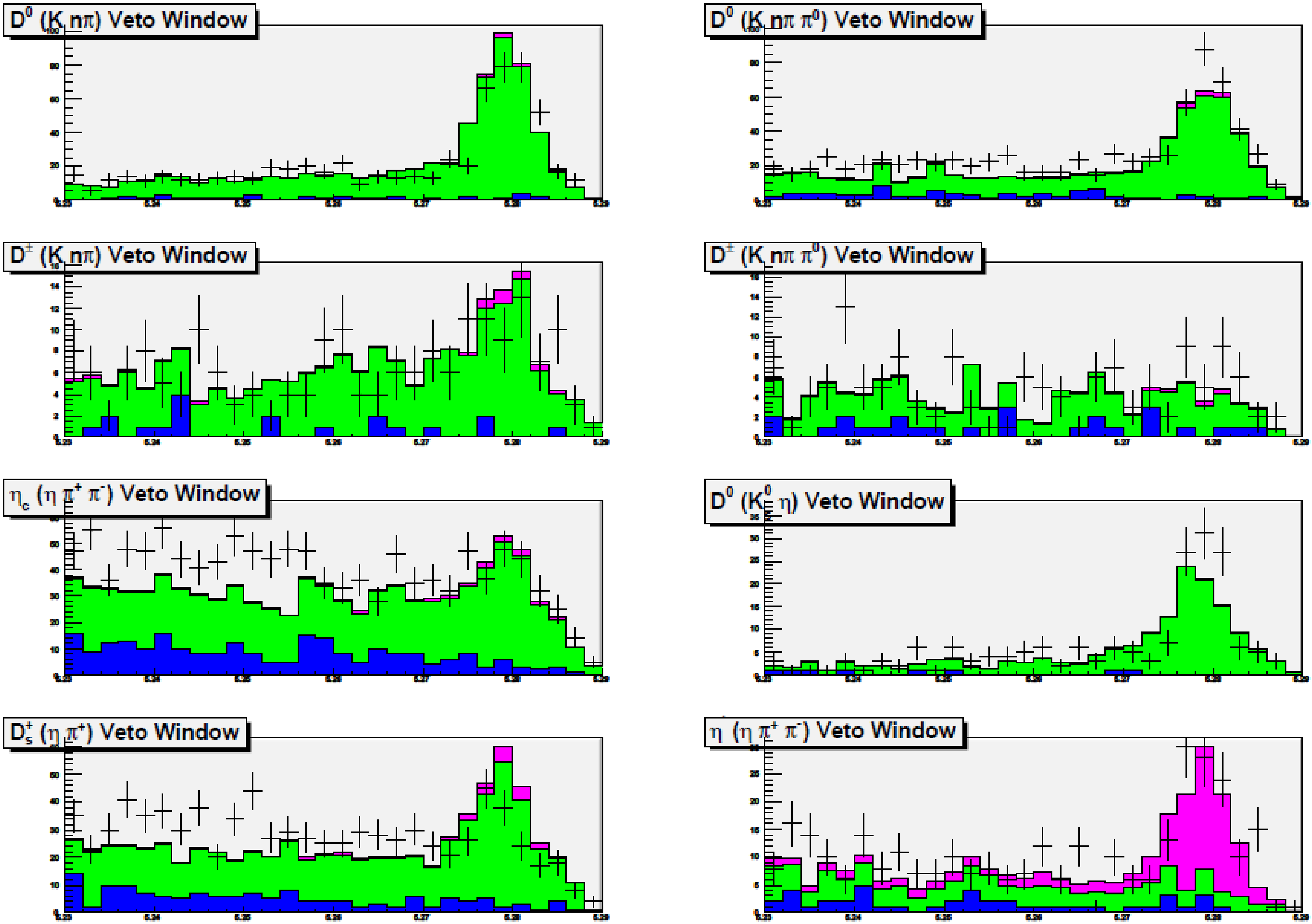


$$\chi_n^2 = \sum_i \left(\frac{N_{\rm MC}^i - N_{\rm data}^i}{\sqrt{N_{\rm data}}} \right)^2$$

Background mode	Scaling factor
$B^0 \to \overline{D^0}\eta$	1.07
$B^0 \to \overline{D^{*0}}\eta$	0.79
$B^0 \to D^-\pi^+\eta$	0.00
$B^0 \to D^{*-}\pi^+\eta$	0.00
$B^+ \to \overline{D^0}\pi^+\eta$	0.39
$B^+ \to \overline{D^{*0}}\pi^+\eta$	0.39
Other $b \to c$ decays	1.00

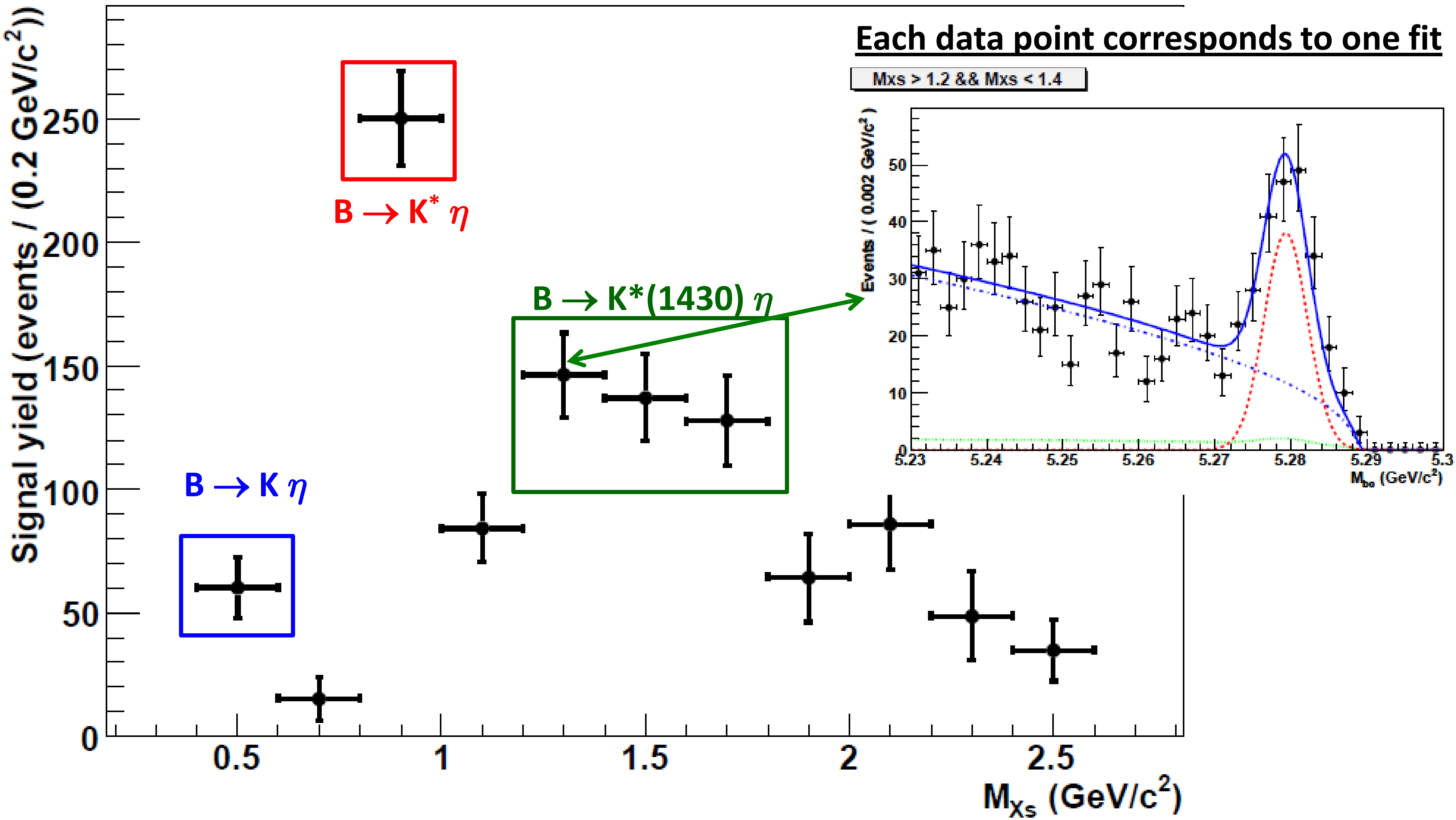
Veto Window M_{bc} Distributions

(Post-Calibration)



Fits to Data

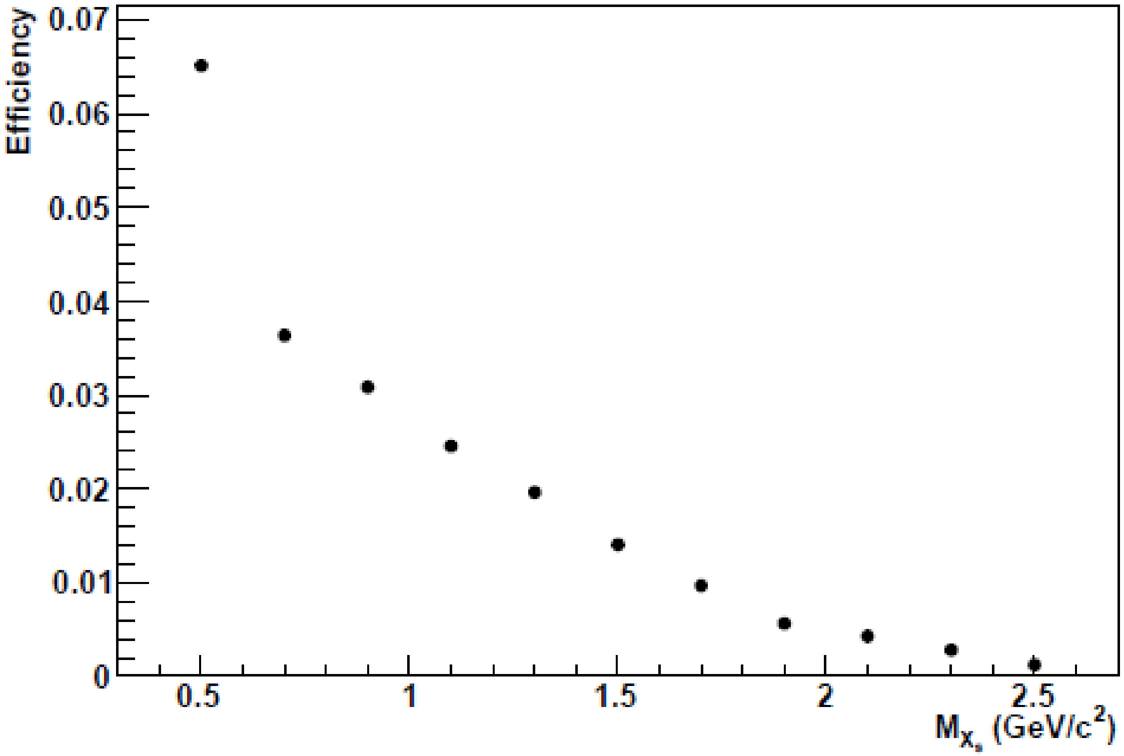
- Perform fitting procedure on full data sample…



Branching Fraction Calculation

- Branching fraction in each X_s mass bin defined as:

$$\mathcal{B}(B \to X_s\eta)_i = \frac{N^i_{\text{sig}} - N^i_{X_s\gamma} - N^i_{X_d\eta} - N^i_{X_s\eta'}}{2N_{B\overline{B}}\epsilon_i r_i \mathcal{B}(\eta \to \gamma\gamma)}$$



- **Correct by subtracting small number of expected rare backgrounds.**
- **N_{BB} is the total number of BB pairs.**
- **ϵ is the reconstruction efficiency (left)**
- **r represents correction factors between data/MC**
- **Correct for only reconstructing η in the $\gamma\gamma$ mode.**

Systematic Uncertainties on Signal Yields

X_s Mass range (GeV/c^2)	Fit yield			$\mathcal{S}$
0.4 - 0.6	60.2	$\pm$ 12.4	$^{+1.8}_{-1.9}$	5.7
0.6 - 0.8	15.3	$\pm$ 8.8	$^{+0.8}_{-2.1}$	1.9
0.8 - 1.0	250.0	$\pm$ 19.2	$^{+3.6}_{-4.4}$	14.0
1.0 - 1.2	84.2	$\pm$ 13.8	$^{+2.4}_{-3.1}$	6.6
1.2 - 1.4	146.2	$\pm$ 17.2	$^{+3.4}_{-4.4}$	9.2
1.4 - 1.6	137.0	$\pm$ 17.6	$^{+3.8}_{-4.6}$	8.1
1.6 - 1.8	127.7	$\pm$ 18.4	$^{+5.5}_{-5.6}$	7.2
1.8 - 2.0	64.2	$\pm$ 17.8	$^{+8.6}_{-8.1}$	3.5
2.0 - 2.2	85.7	$\pm$ 18.4	$^{+5.8}_{-7.0}$	4.6
2.2 - 2.4	48.6	$\pm$ 17.9	$^{+7.1}_{-7.4}$	2.7
2.4 - 2.6	34.8	$\pm$ 12.5	$^{+4.6}_{-6.5}$	2.7
0.4 - 2.6	1054	$\pm$ 54	$^{+16}_{-18}$	23
1.8 - 2.6	233	$\pm$ 34	$^{+13}_{-15}$	7

- Contributions from PDF shapes / normalizations – any value that was fixed in the fit is varied to study how yields change.
- Rare background subtractions are varied and effect on yield is tabulated.

→All significantly smaller than the statistical uncertainties.

Other Systematic Uncertainties

$$\mathcal{B}(B \to X_s\eta)_i = \frac{N^i_{\rm sig} - N^i_{X_s\gamma} - N^i_{X_d\eta} - N^i_{X_s\eta'}}{2N_{B\overline{B}}\epsilon_i r_i \mathcal{B}(\eta \to \gamma\gamma)}$$

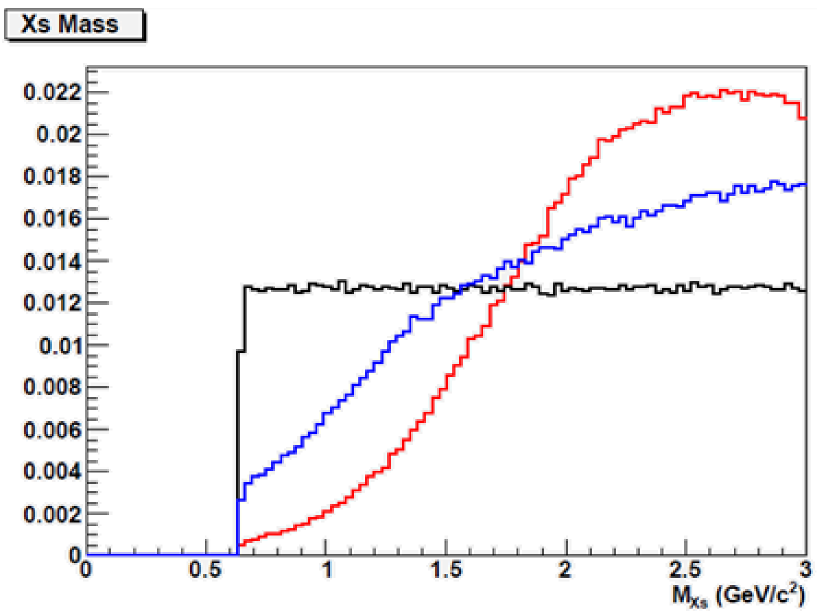
- Include uncertainties from:
  - N_{BB} : 1.4%
  - B($\eta \to \gamma\gamma$) : < 1%
  - r_i:
    - η recon. : 2.7%
    - qq suppression: 3.7%
    - Candidate selection: <1%
    - Other reconstructions, particle ID, & tracking (see table)

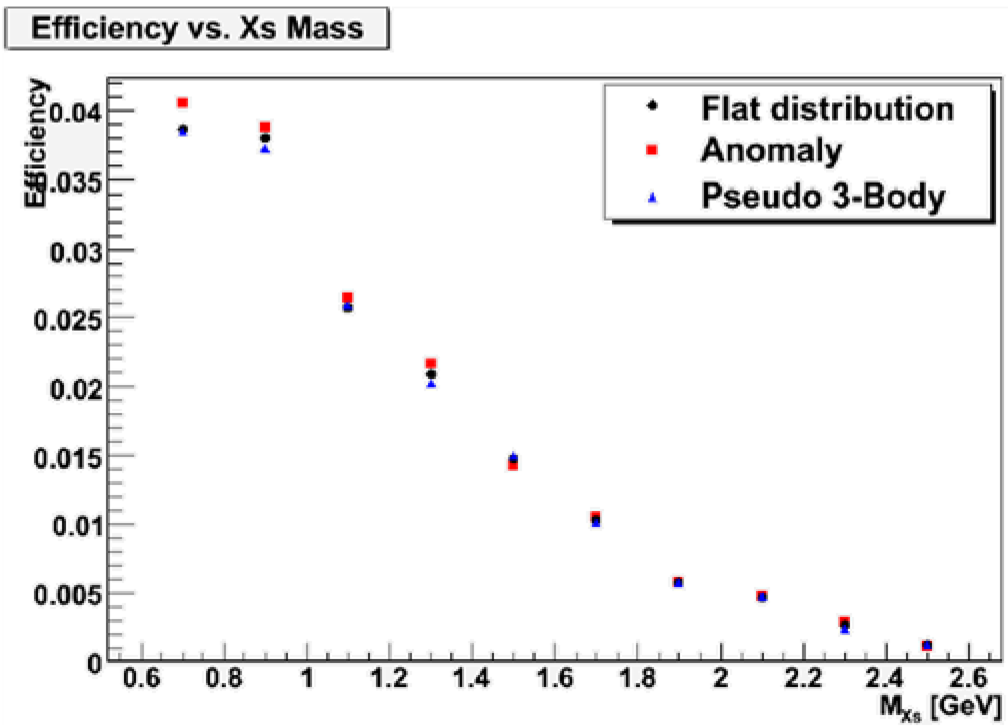
M_{X_s} (GeV/c^2)	K^0_S ($\pm$%)	π^0 ($\pm$%)	$\pi^\pm$ ($\pm$%)	$K^\pm$ ($\pm$%)	Tracking ($\pm$%)	Total ($\pm$%)
0.4–0.6	1.08	0.00	0.00	0.74	0.77	5.07
0.6–0.8	1.07	0.40	0.37	0.70	1.60	5.29
0.8–1.0	1.08	0.38	0.38	0.72	1.81	5.36
1.0–1.2	1.06	0.57	0.49	0.76	2.04	5.47
1.2–1.4	1.03	0.65	0.59	0.80	2.35	5.61
1.4–1.6	1.02	0.70	0.68	0.84	2.62	5.74
1.6–1.8	1.01	0.74	0.78	0.87	2.92	5.91
1.8–2.0	0.92	0.62	0.92	0.88	3.25	6.07
2.0–2.2	0.96	0.72	0.93	0.92	3.20	6.07
2.2–2.4	0.95	0.75	0.97	0.95	3.31	6.14
2.4–2.6	0.89	0.76	0.98	0.97	3.40	6.19

- Most are studied using independent control samples.
- Again, these are all smaller than statistical errors.

Modeling Systematics

- Dominant for this measurement!
- Studied three models:
  - **Flat X_s mass, QCD anomaly-like, three body $b \to (u,d)\ s\ \eta$**

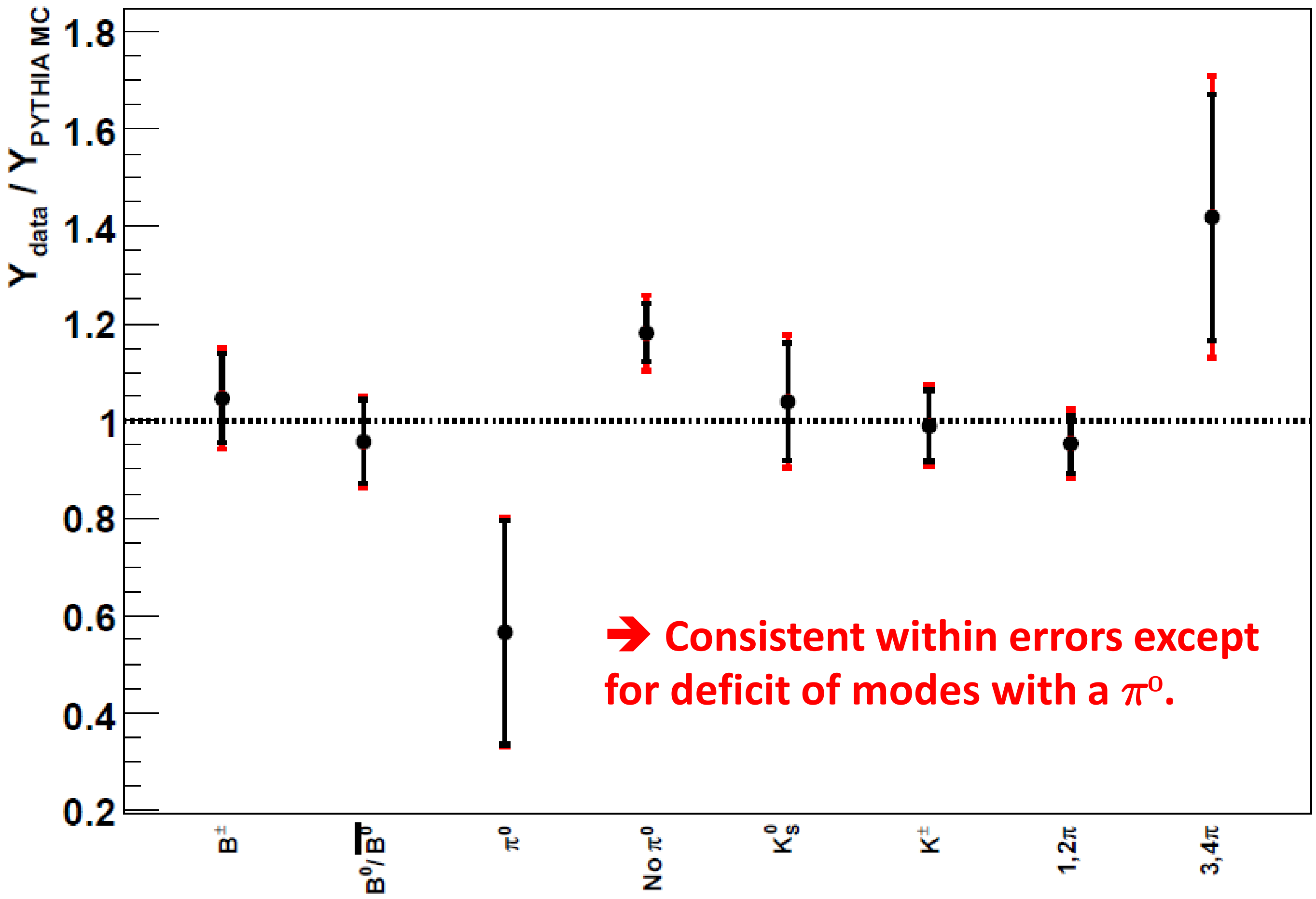




- Efficiency does not change dramatically!
- …but all models use PYTHIA for fragmentation of X_s into hadrons.

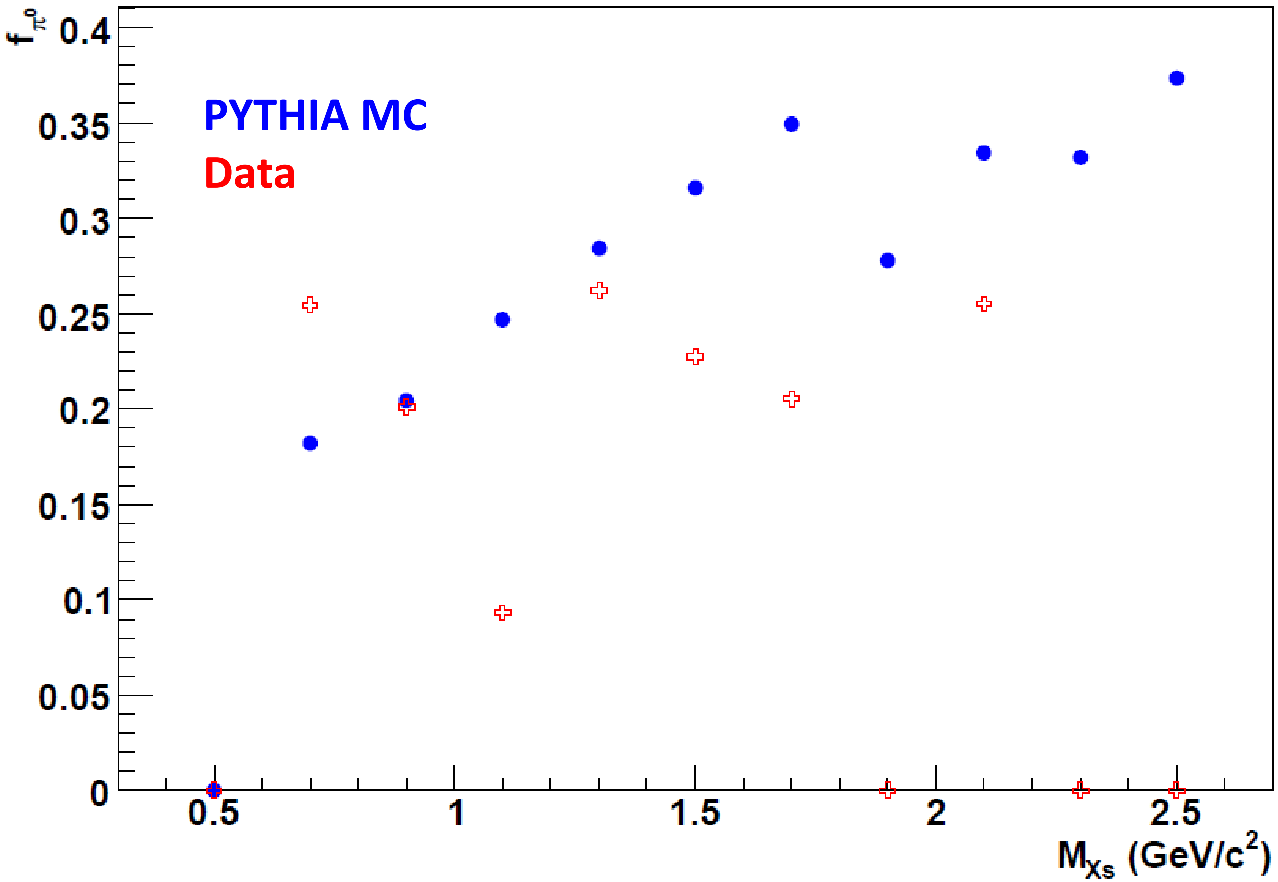
X_s Fragmentation (PYTHIA)

- Repeat fits in sub-categories & compare expected mode distributions in PYTHIA MC to data:



X_s Fragmentation, π^o Deficit

- Fraction of modes with a π^o is studied in data and MC.
- Can calculate a reweighted efficiency and compare with that calculated from MC → assign a systematic error.



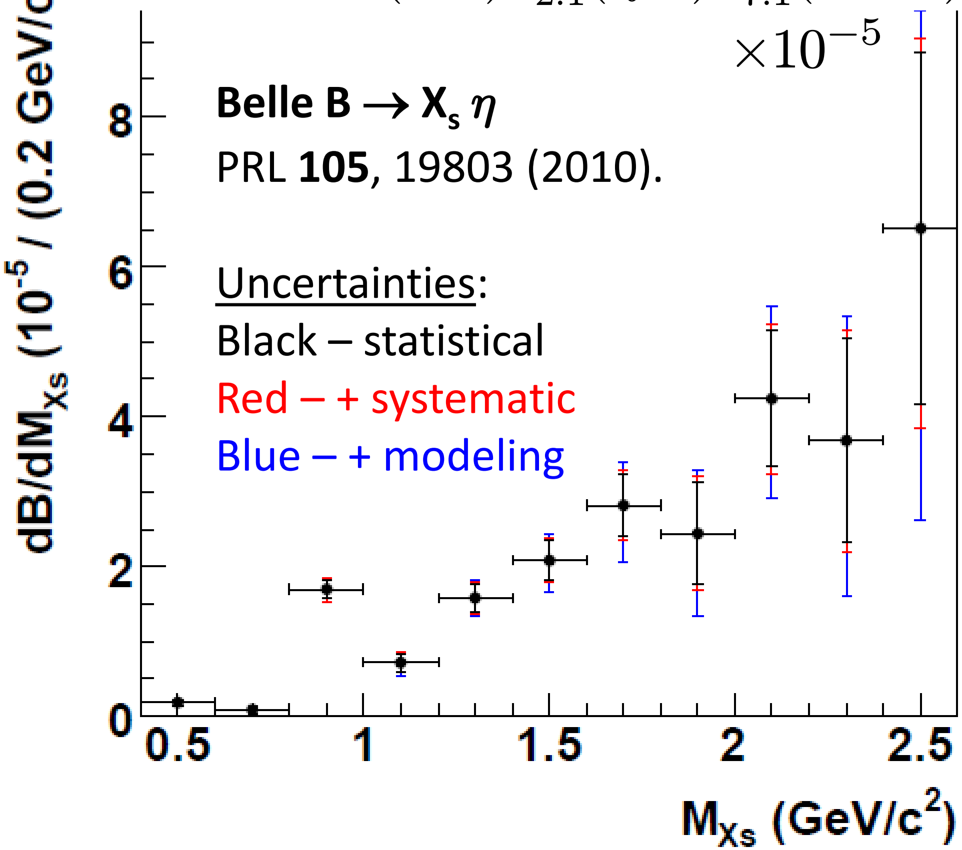
X_s Fragmentation, π^o Deficit

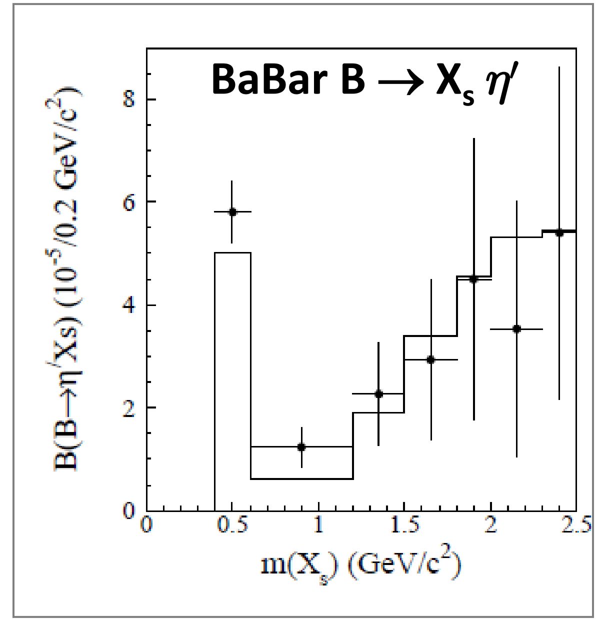
- Fraction of modes with a π^o is studied in data and MC.
- Can calculate a reweighted efficiency and compare with that calculated from MC → assign a systematic error.
- Total from modeling errors:

M_{X_s} (GeV/c^2)	Mass migration ($\pm$%)	Missing modes ($\pm$%)	PYTHIA (+%)	PYTHIA (-%)	Total (%)
0.4–0.6	0.70	0.00	0.00	0.00	±0.70
0.6–0.8	2.20	0.07	9.62	0.00	$^{+9.87}_{-2.20}$
0.8–1.0	2.82	0.00	0.00	0.00	±2.85
1.0–1.2	3.06	3.63	0.00	18.26	$^{+4.75}_{-18.87}$
1.2–1.4	4.54	4.47	0.00	2.64	$^{+6.37}_{-6.90}$
1.4–1.6	5.68	7.25	0.00	9.56	$^{+9.21}_{-13.28}$
1.6–1.8	5.30	10.24	0.00	18.39	$^{+11.53}_{-21.70}$
1.8–2.0	7.01	13.21	0.00	27.99	$^{+14.95}_{-31.74}$
2.0–2.2	5.76	16.33	0.00	10.85	$^{+17.32}_{-20.43}$
2.2–2.4	8.46	18.89	0.00	33.40	$^{+20.69}_{-39.29}$
2.4–2.6	7.35	21.06	0.00	37.37	$^{+22.31}_{-43.52}$

Final Results and Implications

$$\mathcal{B} = 26.1 \pm 3.0(\text{stat})^{+1.9}_{-2.1}(\text{syst})^{+4.0}_{-7.1}(\text{model}) \times 10^{-5}$$



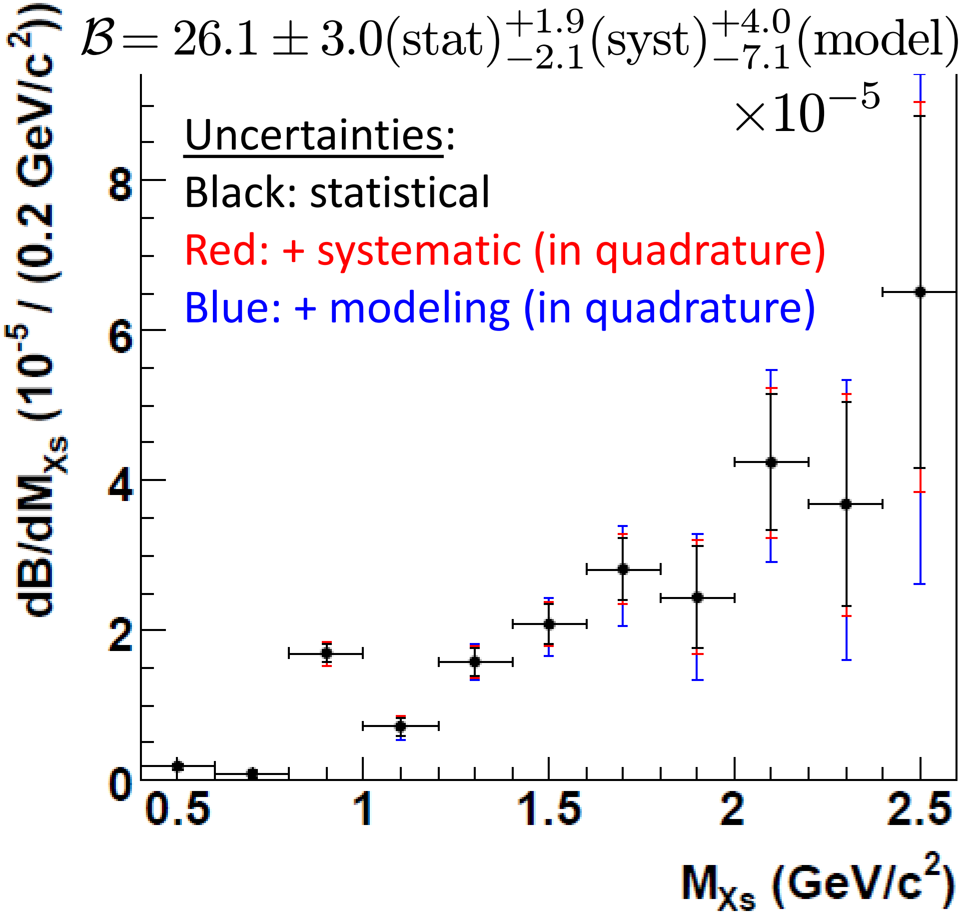


$\mathcal{B} = (4.2 \pm 0.9) \times 10^{-4}$ (world average)

- Similar shape between $X_s\eta$ and $X_s\eta'$ disfavors previous explanations based on special features of the η'.

- Unfortunately, there still is no definitive conclusion.
  - Theoretical side: not much work has been done on this topic recently.
    - A study by Chay, Kim, Leibovich, Zupan [arXiv:0708.2466] suggested this measurement would be useful to pin down contributions to both modes, but no follow-ups yet.
  - Experimental side: uncertainties are still large.

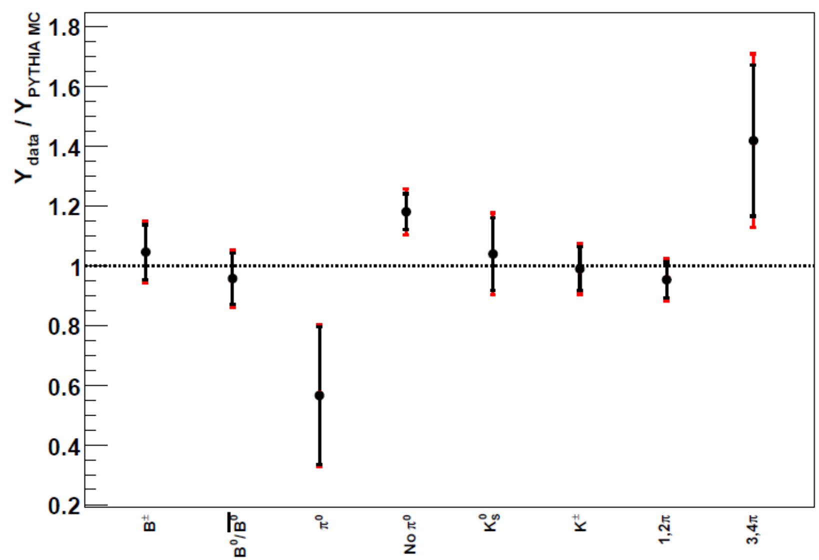
Future Measurements?



- Especially at large X_s mass, the statistical uncertainties are very high.

➔ Increase statistics significantly (√N)

- Modeling uncertainties rely on measuring what was in the X_s.



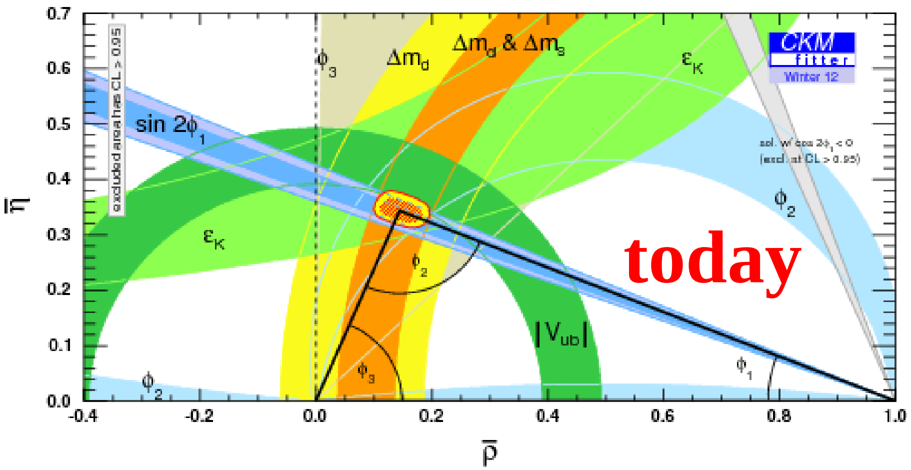
➔ Again, higher statistics would allow more detailed comparisons, lead to more reliable models.

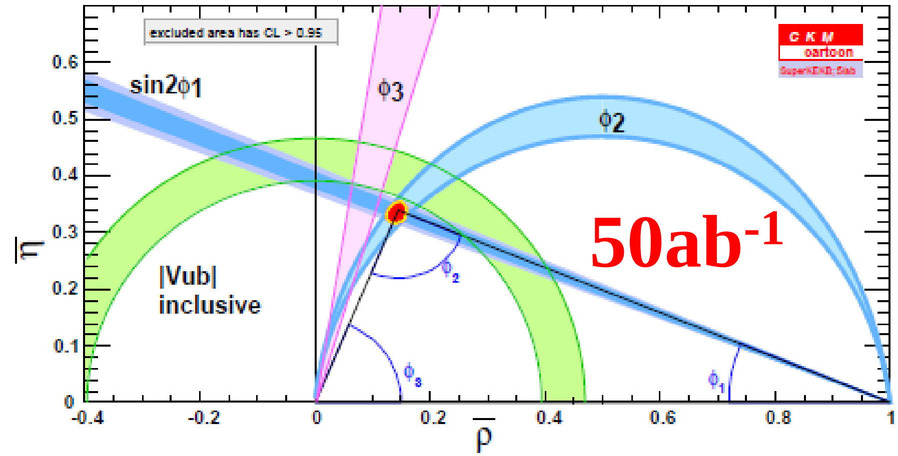
- Some backgrounds were from bad particle identification.
  $\pi^+\pi^-\eta$ can look very similar to $K^+\pi^-\eta$ if the π^+ is misidentified.

➔ Improve the detector performance.

Other Future Measurements

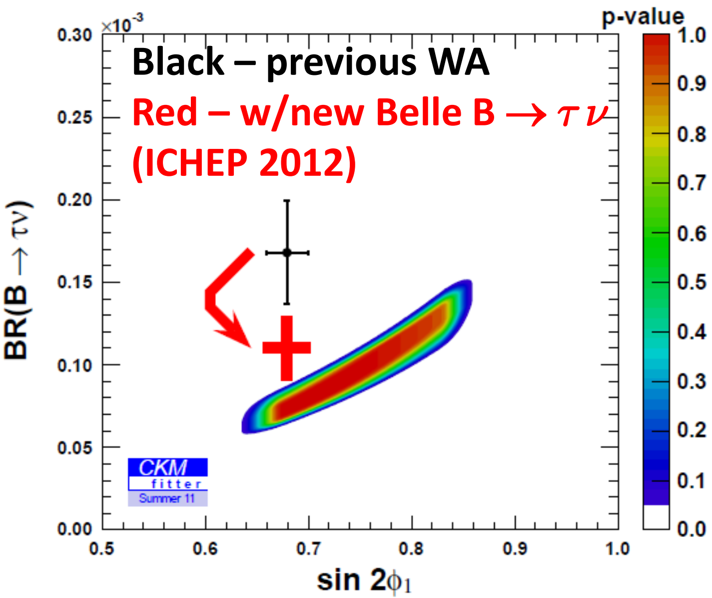
- Improving precision on CKM picture, search for deviations:



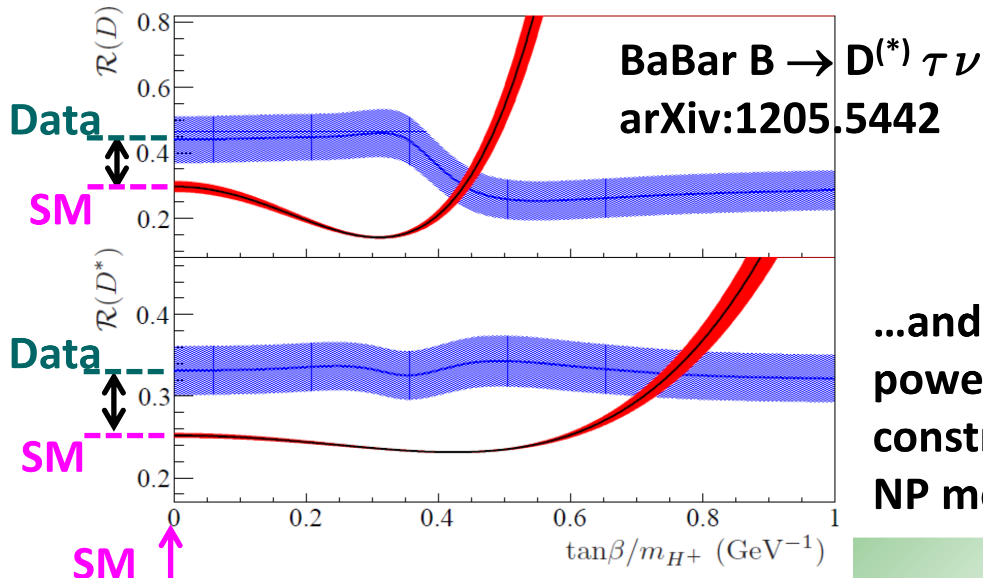


- Continue a varied flavor physics program; explore existing tensions…

As some tensions ease…



Others emerge…

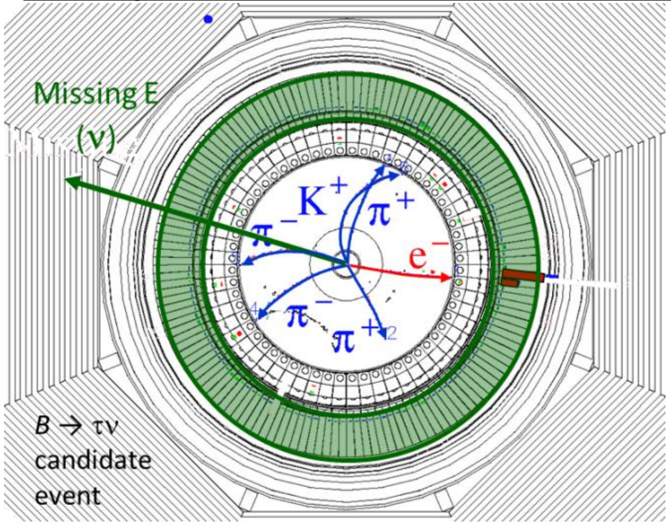


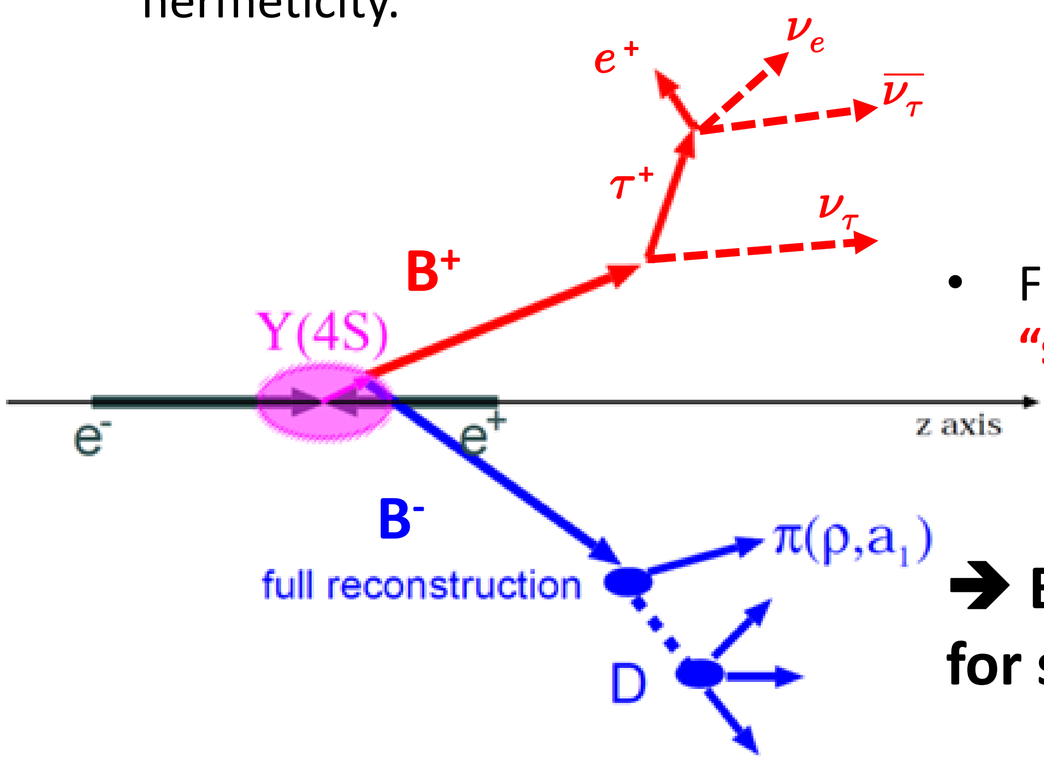
…and provide powerful constraints on NP models.

Complementary to LHC Searches

- Previous examples include modes with missing energy.
- $B \to \tau\,\nu$; $B \to D^{(*)}\,\tau\,\nu$
  - Multiple neutrinos! Significant missing energy.
- These are very challenging experimentally…
  - Rely on clean e^+e^- environment and detector hermeticity.

Example Belle $B \to \tau\,\nu$ candidate

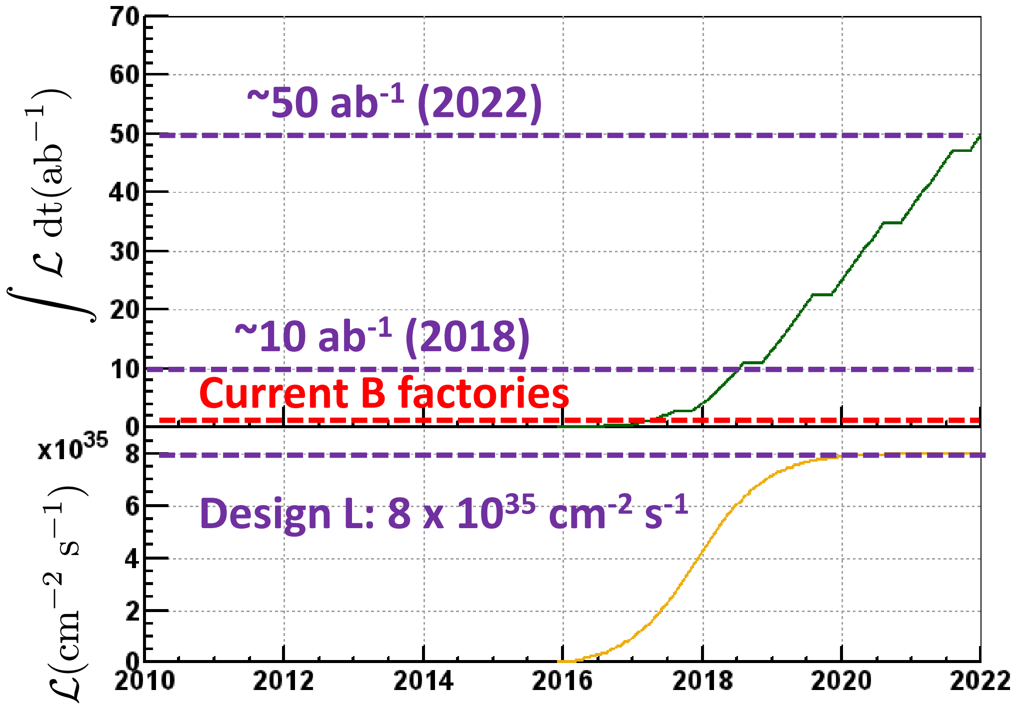


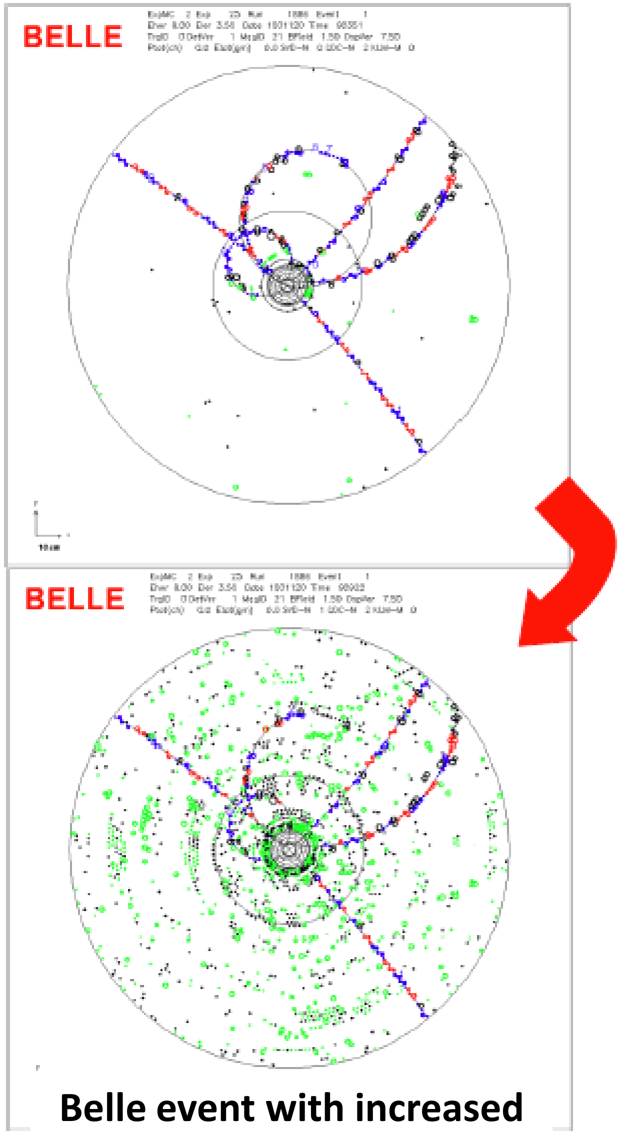


- Fully reconstruct **"tag"** ***B*** to determine **"signal"** ***B*** flavor, charge, momentum.

➔ B factories are uniquely suited for such measurements!

Upgrading KEKB and Belle





Belle event with increased background overlaid.

- Increased luminosity:
  - ~10-20x higher backgrounds, rad. damage
  - Increased trigger rates (0.5 → 200 kHz).
- Need to maintain or improve on existing performance.

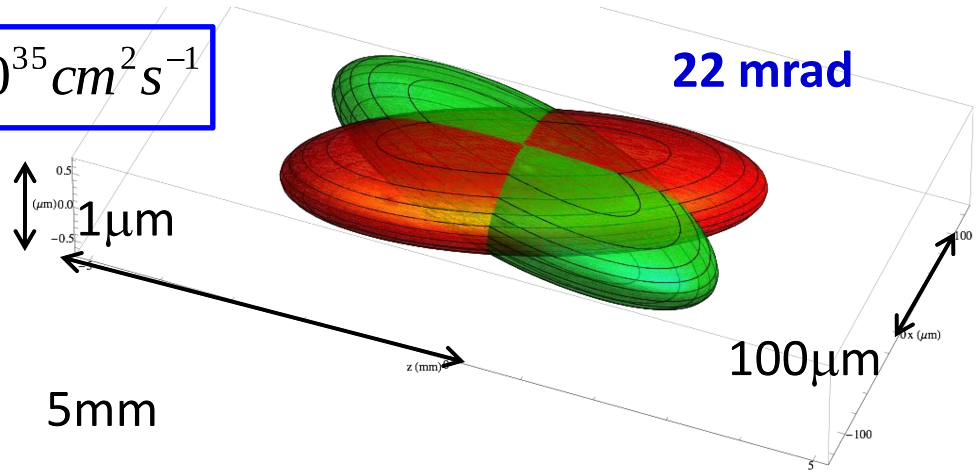
→Significant detector upgrades!

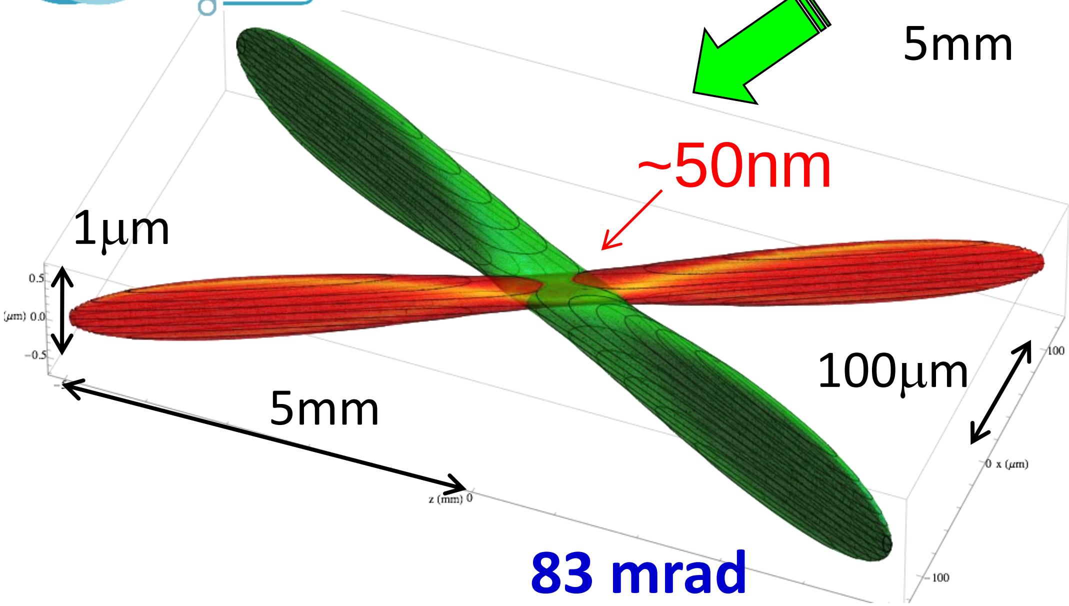
Nano-beams at Super KEKB

Use nano-beam scheme developed by P. Raimondi for SuperB

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right) = 8\times10^{35}\, cm^2 s^{-1}$$

(w/o crab)





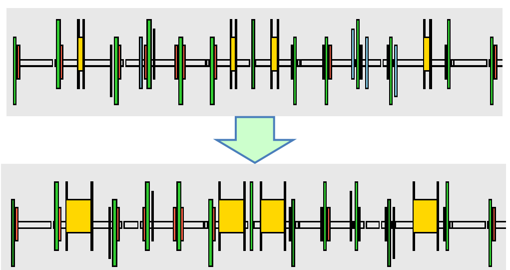
Vertical beta function reduction
β_y^* 5.9 mm → 0.3 mm

Beam current increase.

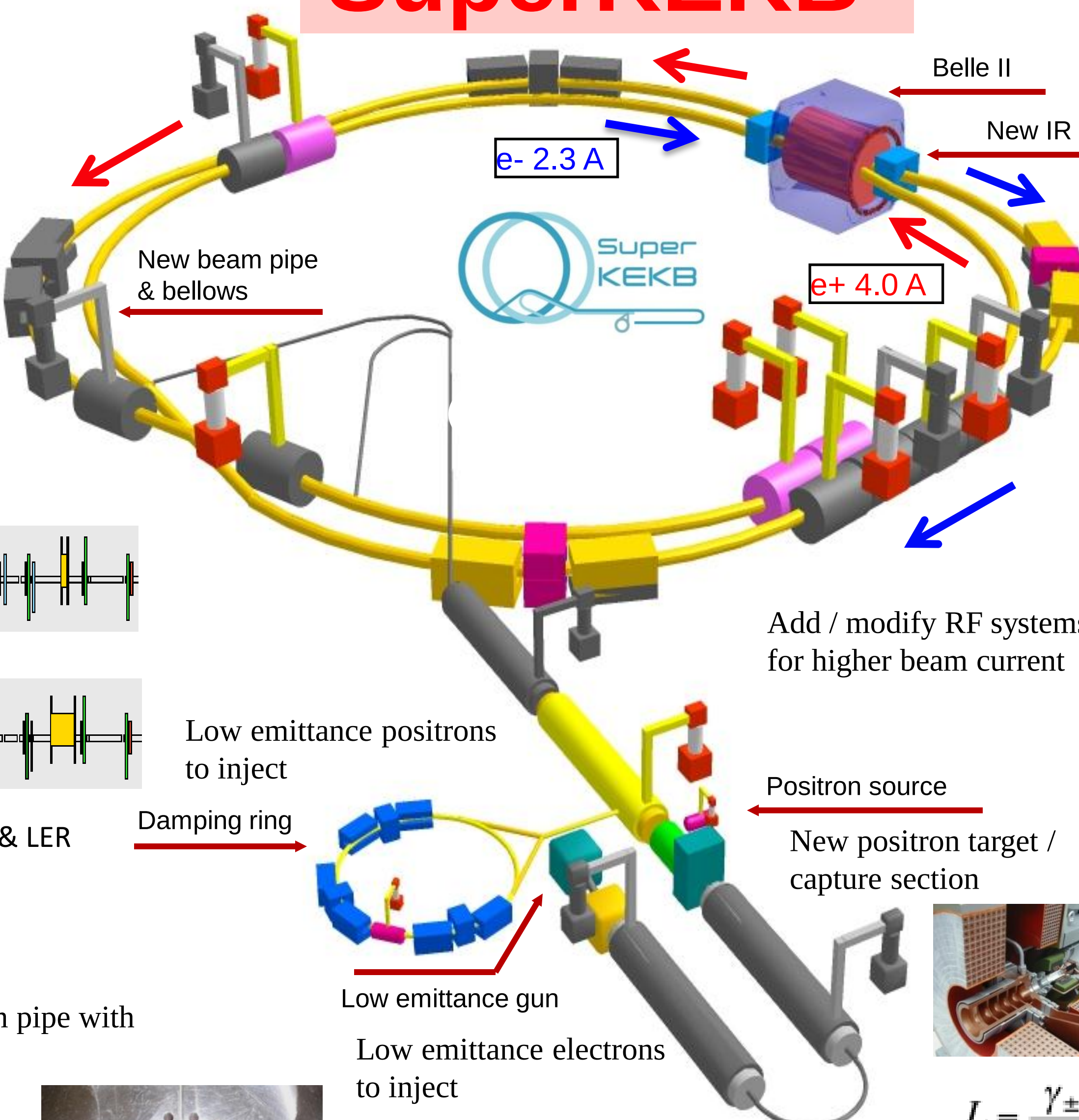
Overall 40x higher luminosity!

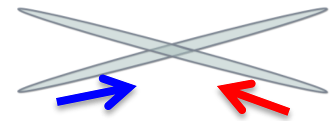
SuperKEKB

Replace short dipoles with longer ones (LER)



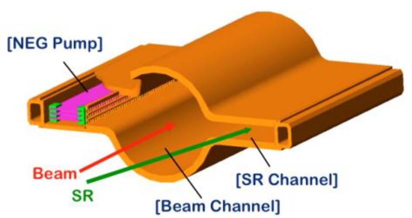
Redesign the lattices of HER & LER to squeeze the emittance

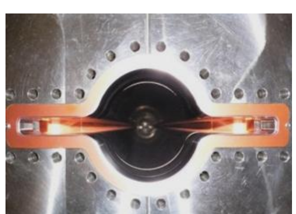




New superconducting /permanent final focusing quads near the IP

TiN-coated beam pipe with antechambers





$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

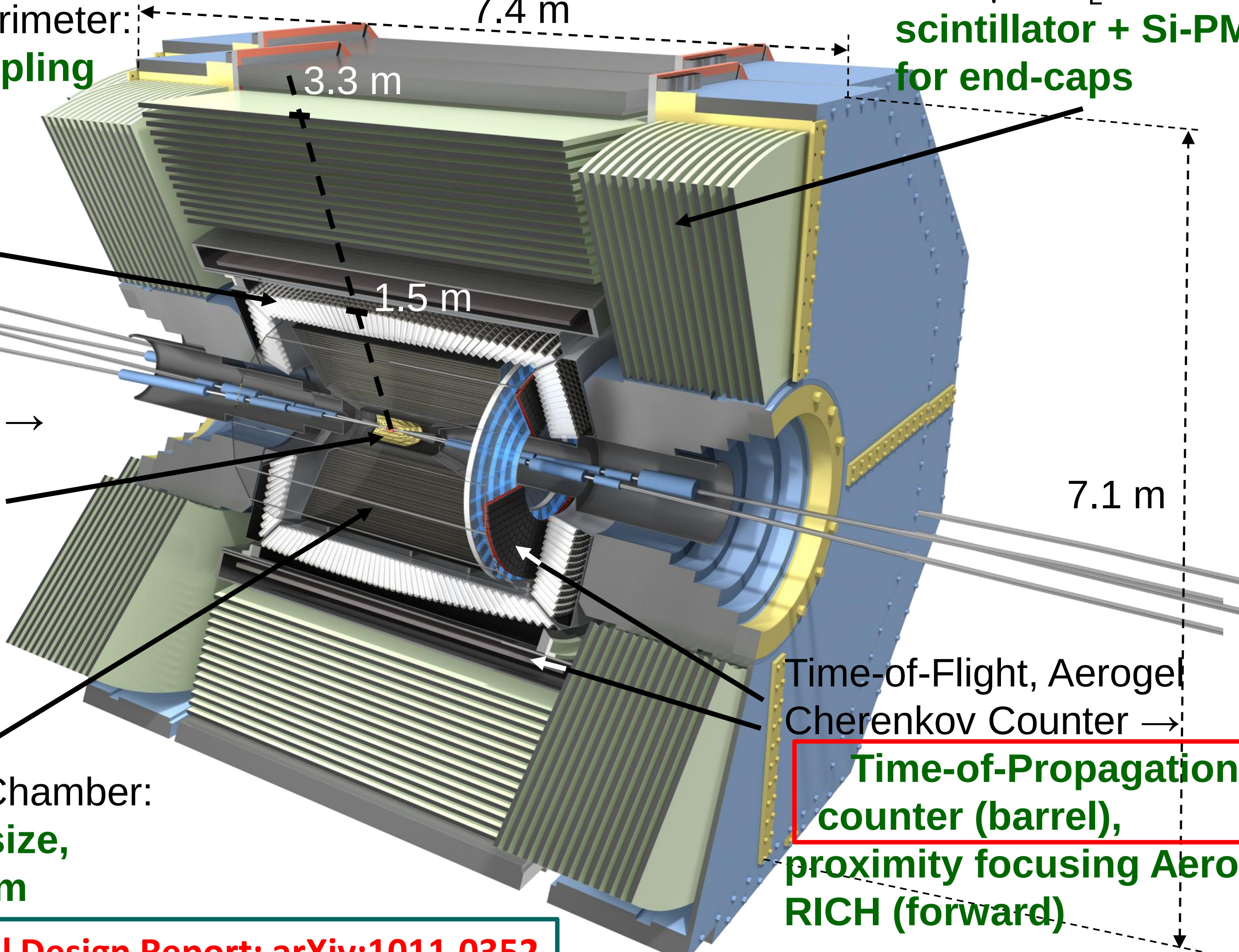
$L=8\cdot10^{35}\ s^{-1}cm^{-2}$

x 40 Gain in Luminosity

The Belle II Detector

CsI(Tl) EM calorimeter:
waveform sampling electronics, pure CsI for end-caps

RPC μ & K_L counter:
scintillator + Si-PM for end-caps



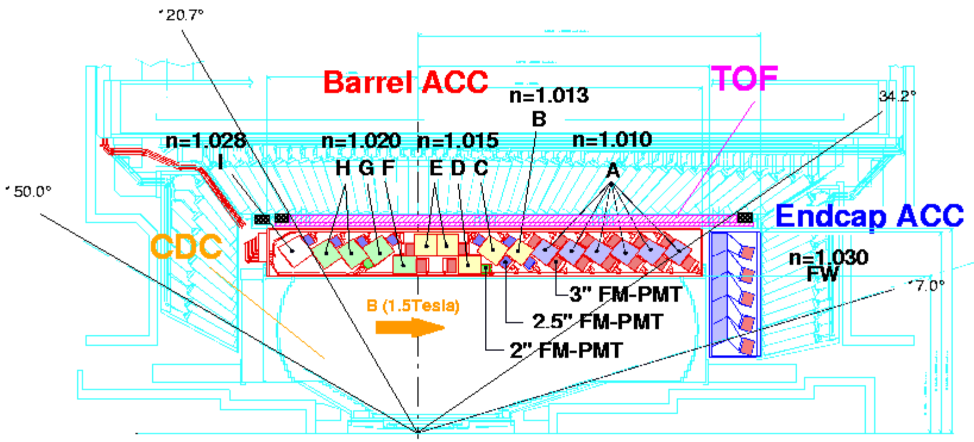
4 layers DSSD →
2 layers PXD (DEPFET) + 4 layers DSSD

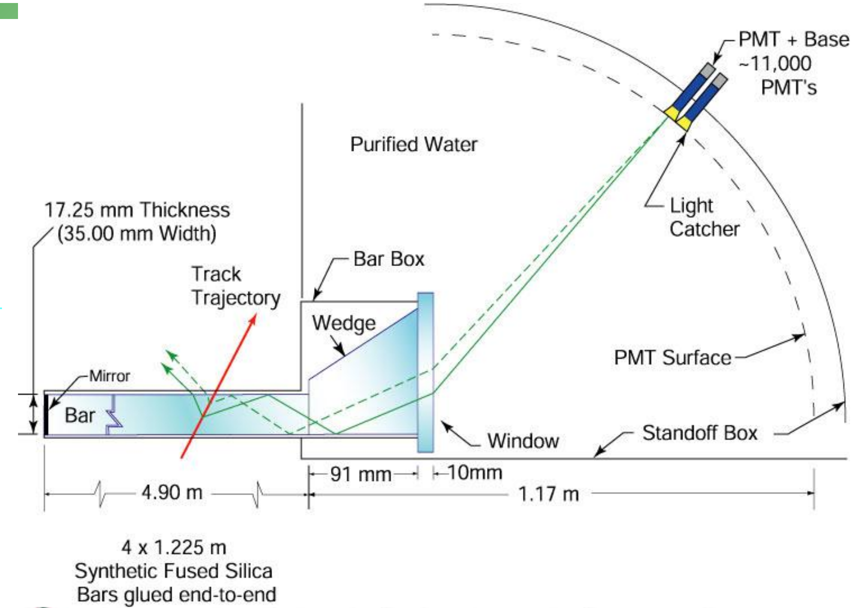
Time-of-Flight, Aerogel Cherenkov Counter →
Time-of-Propagation counter (barrel), proximity focusing Aerogel RICH (forward)

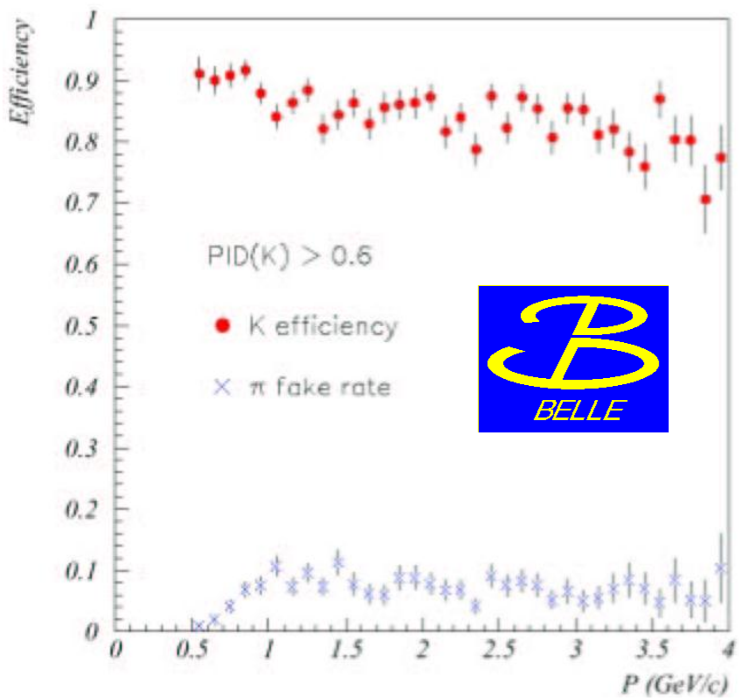
Central Drift Chamber:
smaller cell size, long lever arm

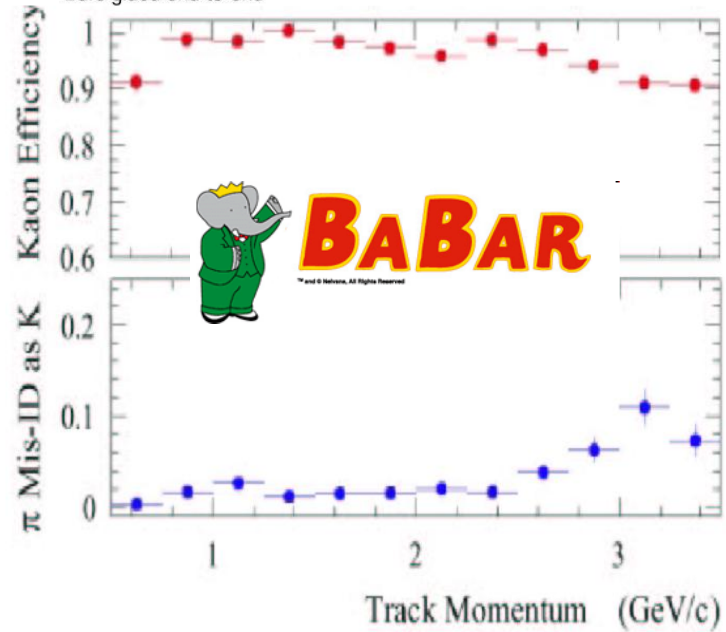
Belle II Technical Design Report: arXiv:1011.0352

K/π Identification at Belle & BaBar





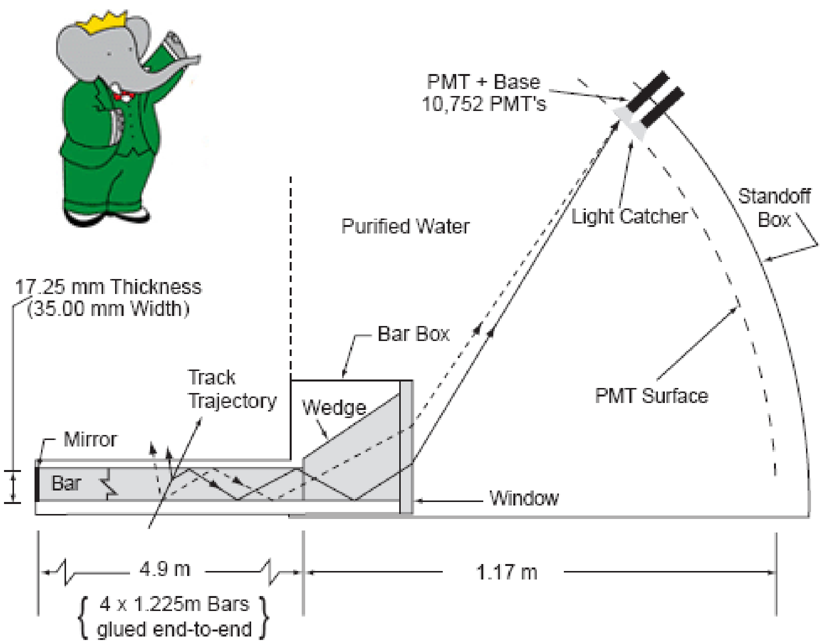




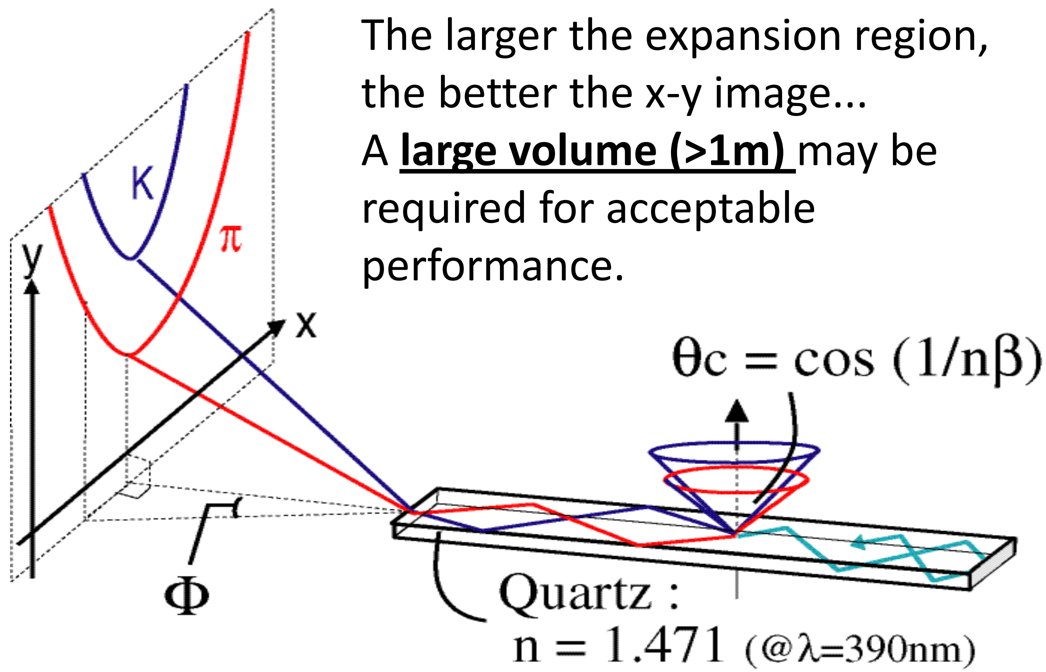
45

Detection of Internally Reflected Cherenkov Light

- Charged particles of same momentum but different mass (e.g., $K^{\pm}$ and $\pi^{\pm}$) emit Cherenkov light at different angles.
  - Momentum measured by curvature of the particle through tracking.
- Detect the emitted photons in 2+ dimensions (x,y,t)
- BaBar DIRC as a model:



The larger the expansion region, the better the x-y image...
A **<u>large volume (>1m)</u>** may be required for acceptable performance.



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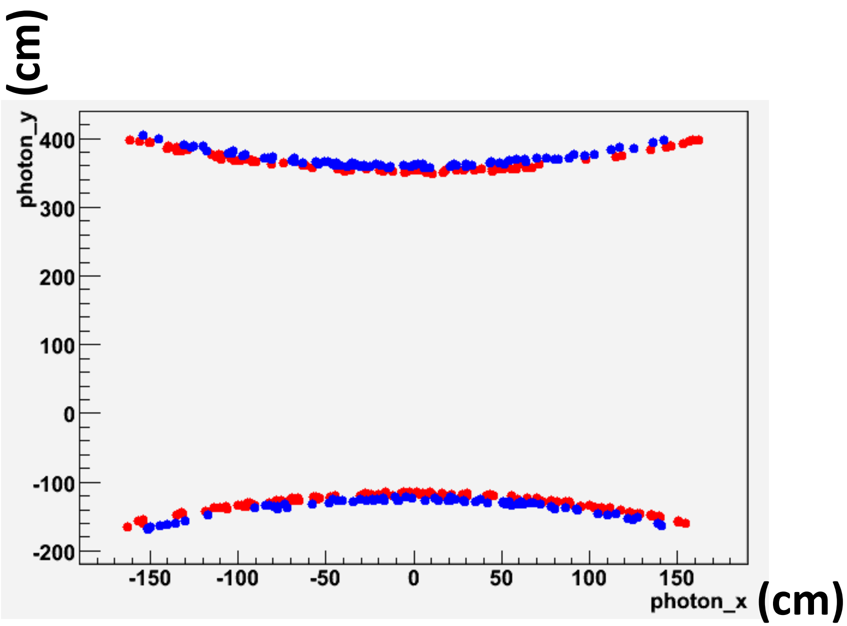

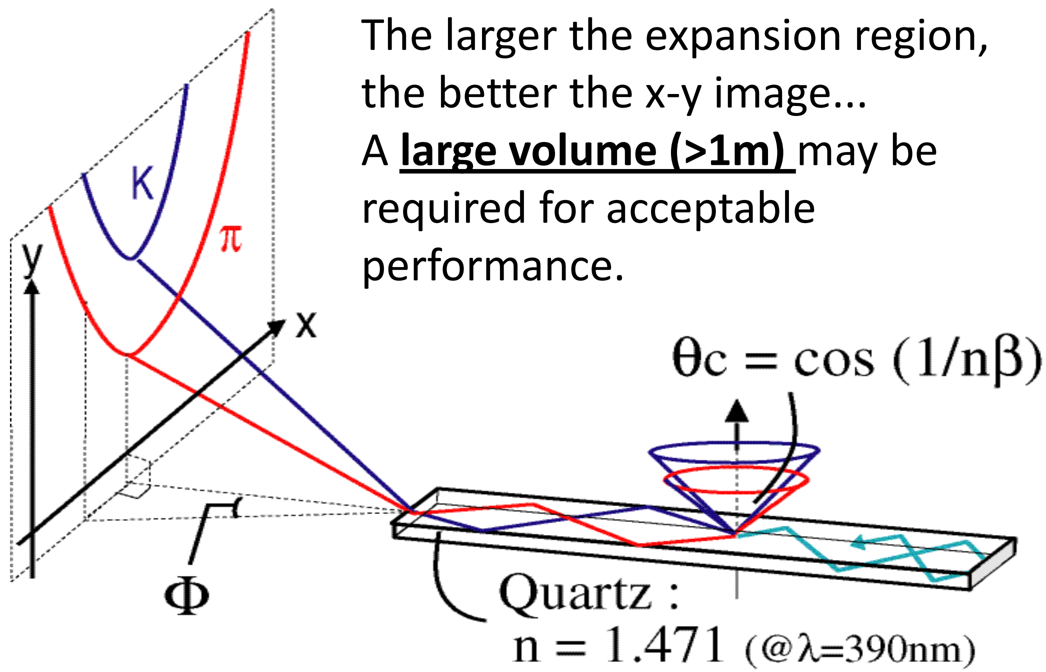

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Left: Simulation w/ 2 m expansion volume, 2 GeV K/π

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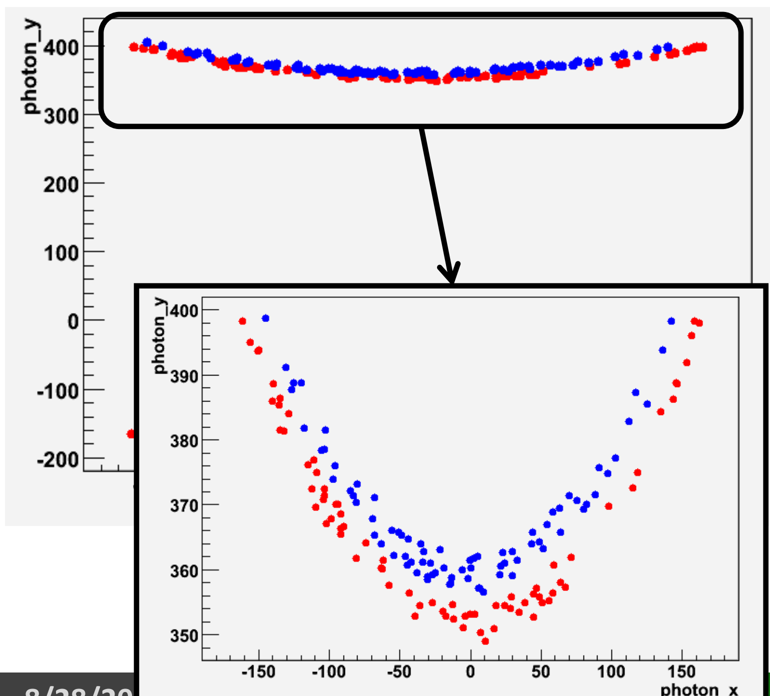

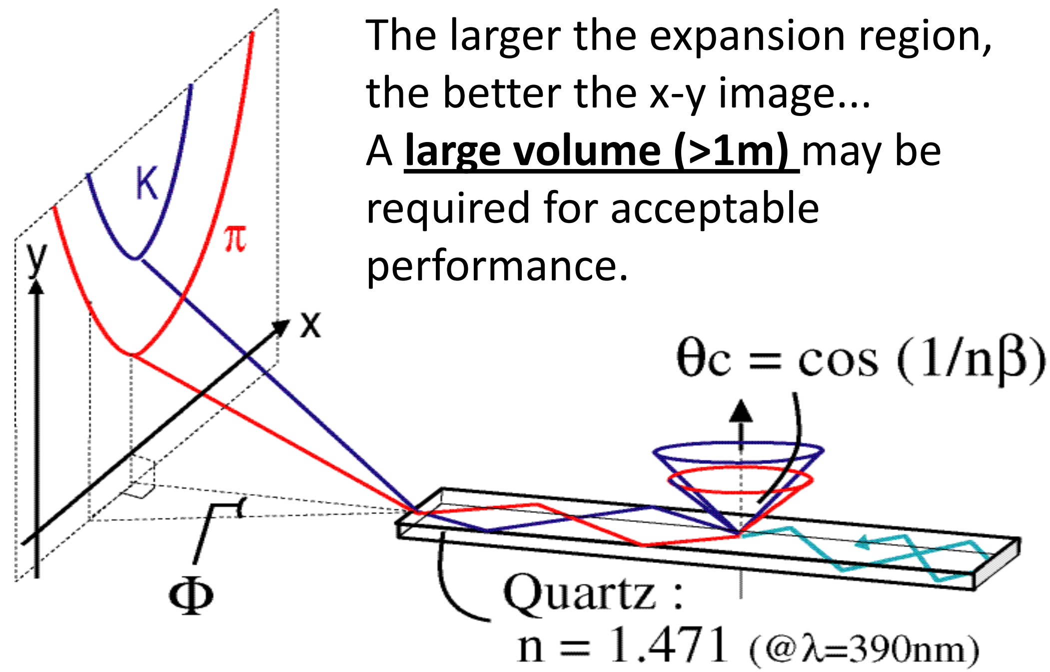

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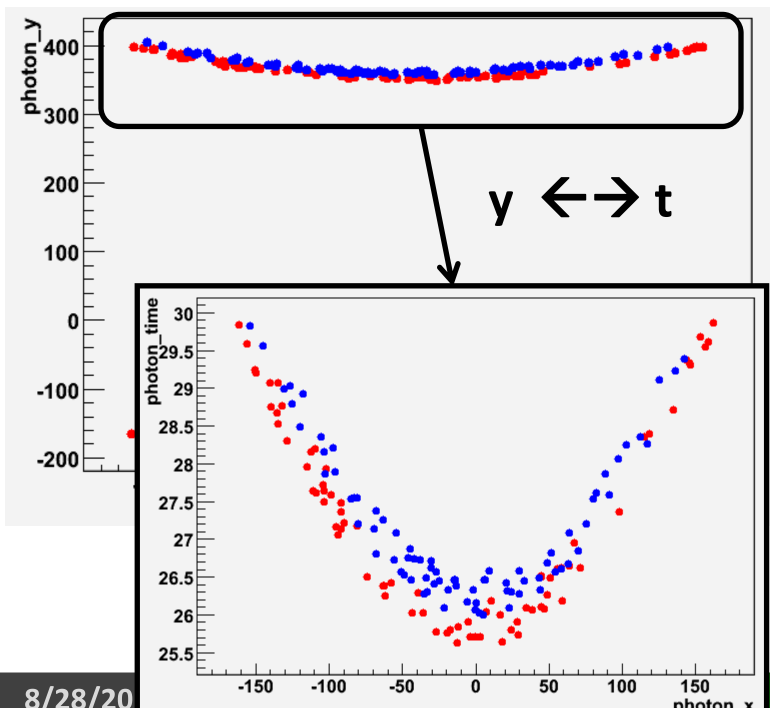

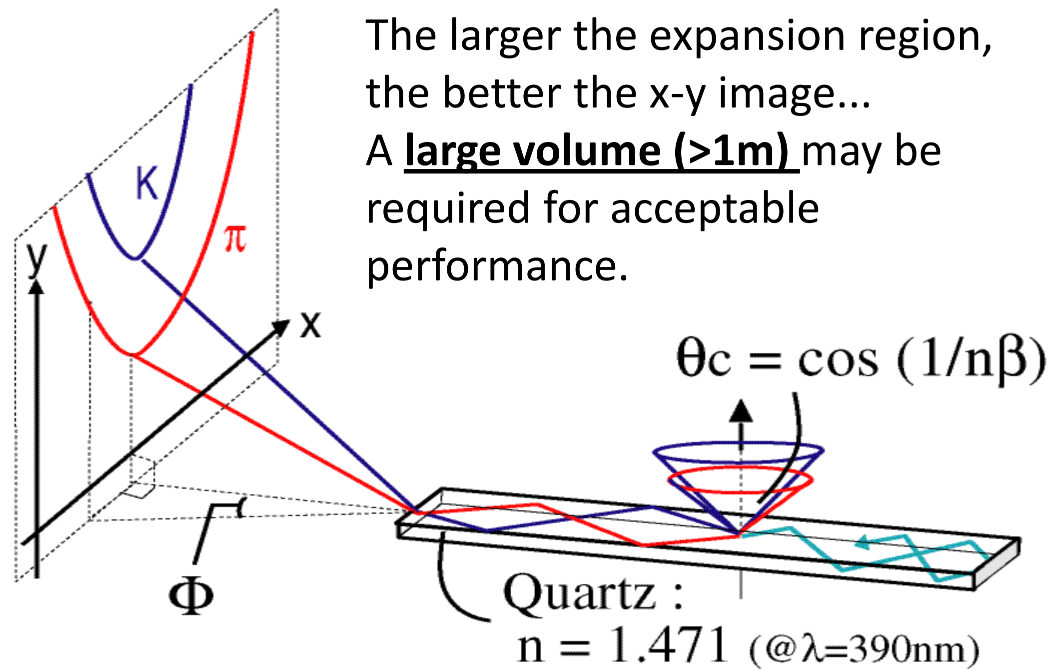

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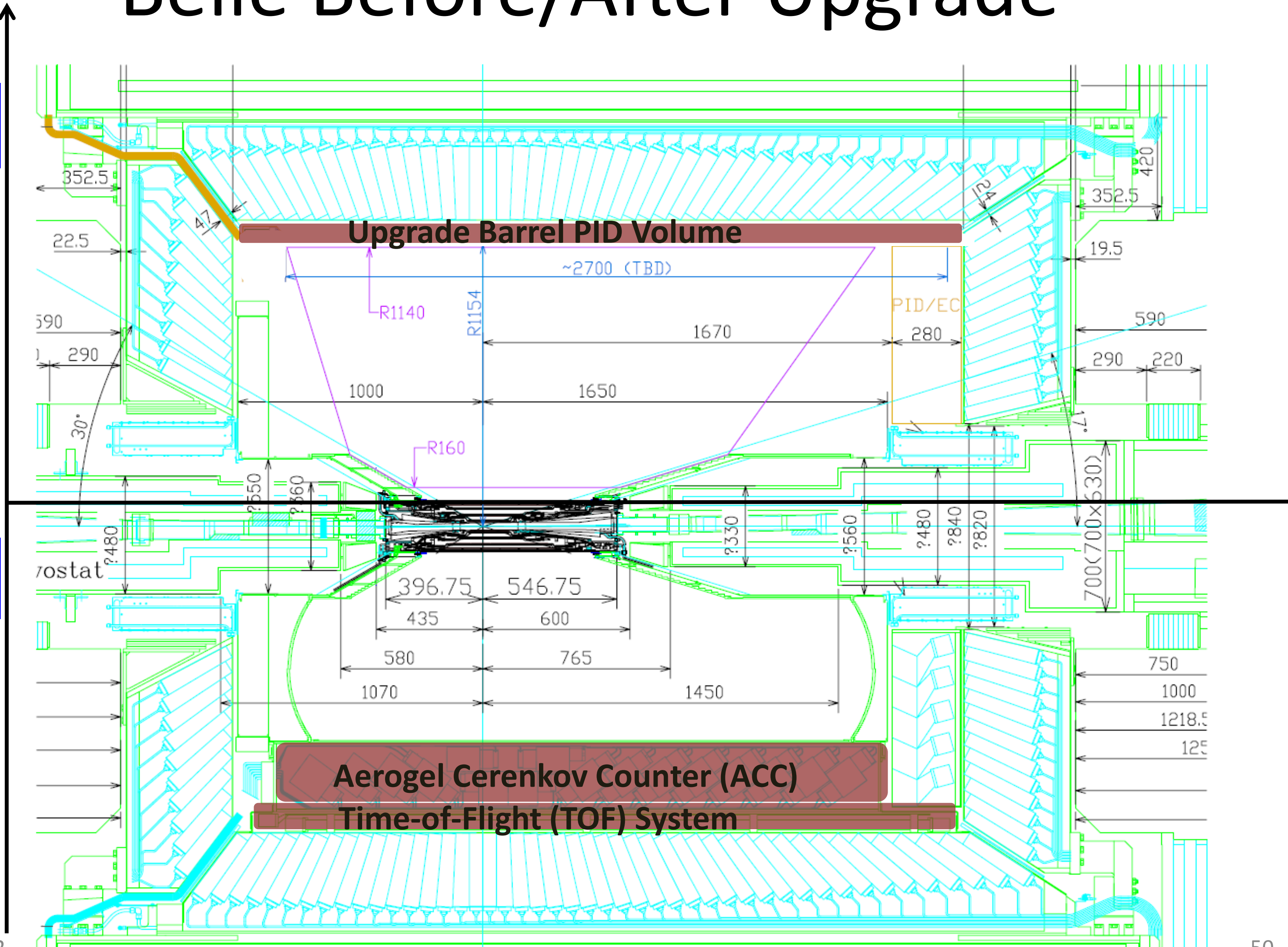
Belle Before/After Upgrade

Belle-II Upgrade

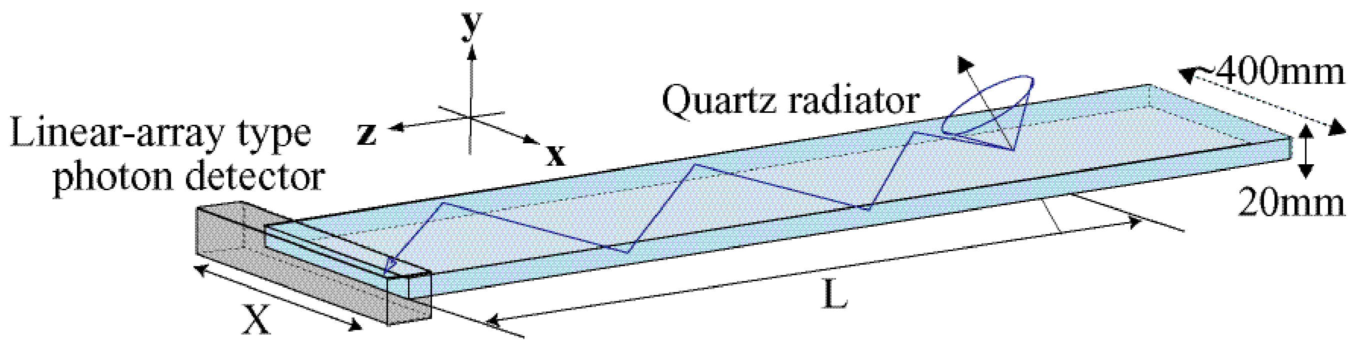


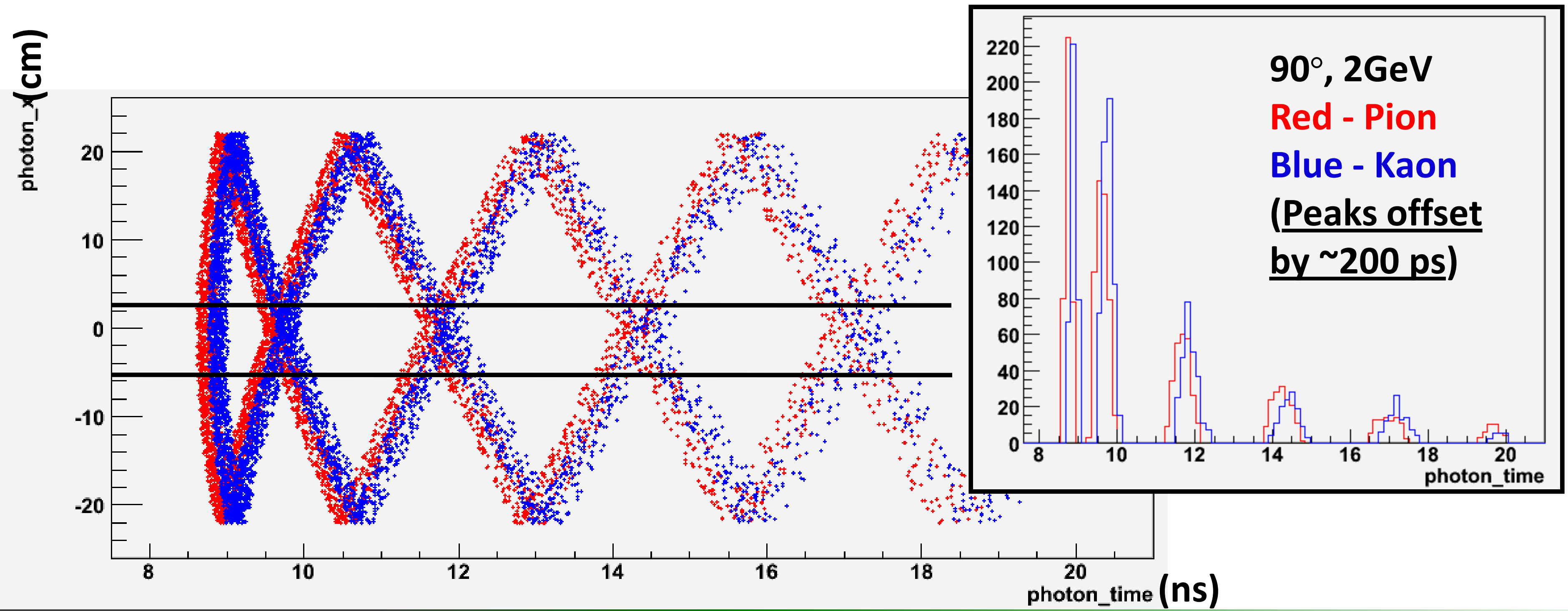
Original Belle

Time-of-Propagation (TOP) Counter

- Work at bar end, measure x,t, not y ➔ compact!

e.g., NIM A, 494, 430-435 (2002)

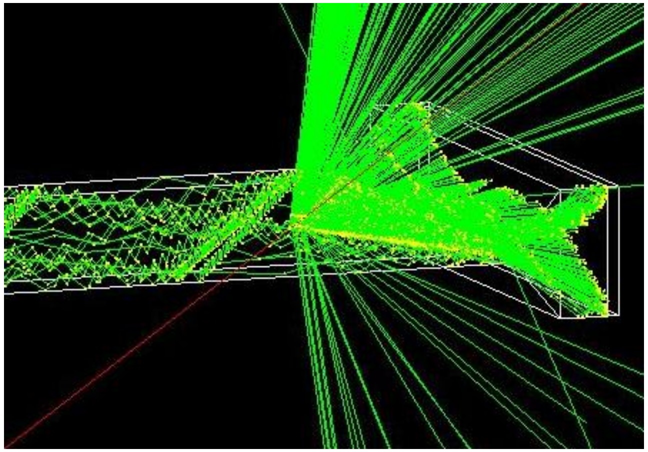


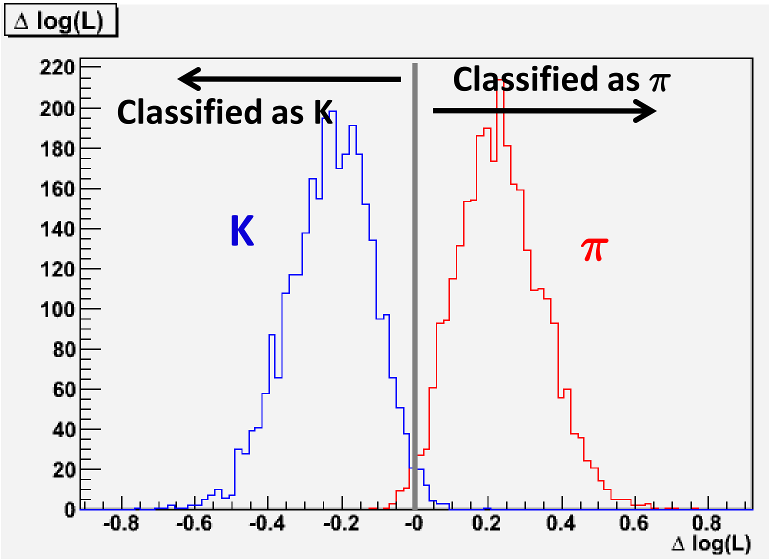


Simulation Studies

- Independent simulations:
  - Belle Geant3 + standalone code (Nagoya)
  - Standalone Geant4 (Hawaii)
  - Standalone code (Ljubljana)
  - Recently, full Belle II Geant4 simulation.
- All utilize a Δlog(Likelihood) approach to determine particle classification.
  - PDFs are defined in x,y, and t
  - Geant-based versions take probability distribution functions from simulated events.

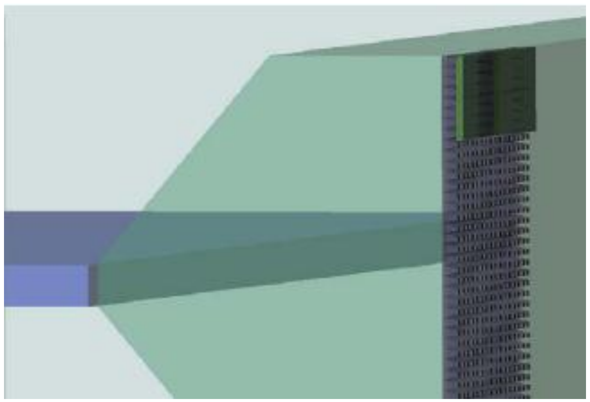
    ➔Extremely time consuming to generate the PDFs, but can include all the effects (scattering, ionization, delta-rays, etc.) that Geant can provide.
  - Δlog(Likelihood) in Ljubljana code utilizes analytical expressions for the likelihood functions.

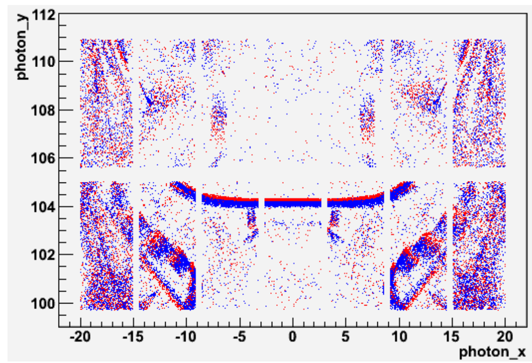


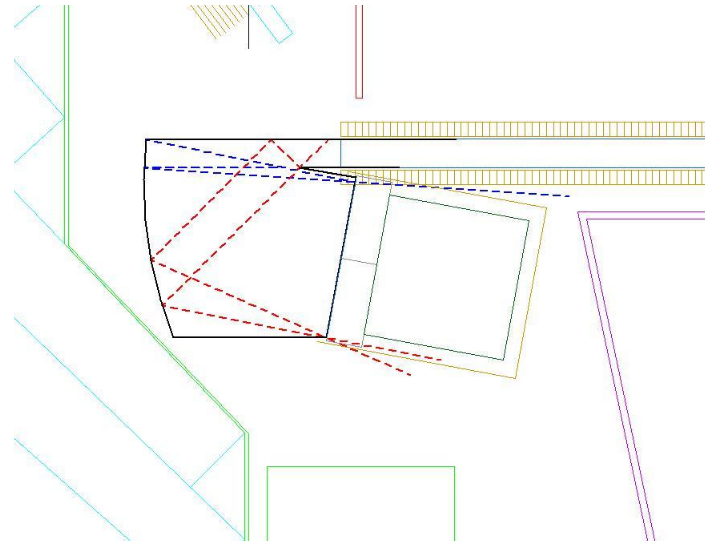


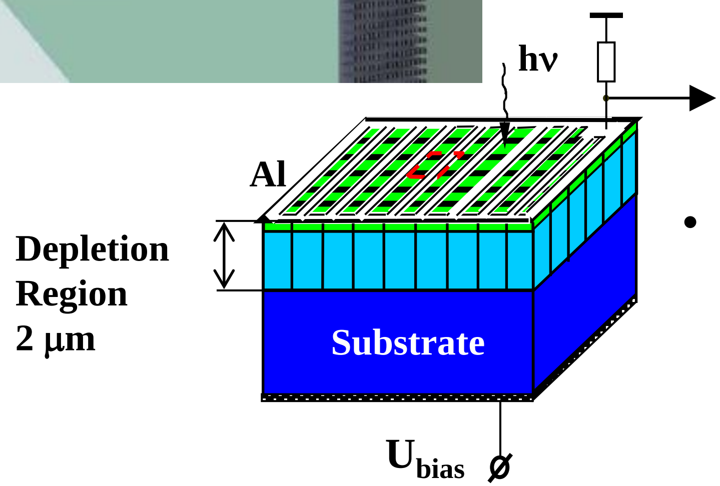
Adding Imaging to the TOP?

- To improve the performance (and ease burden on precision timing):
  - Explored a few geometries and photodetectors.
  - Fine pixelization with Geiger-mode APDs.
  - Adding optics elements to backward end of detector.



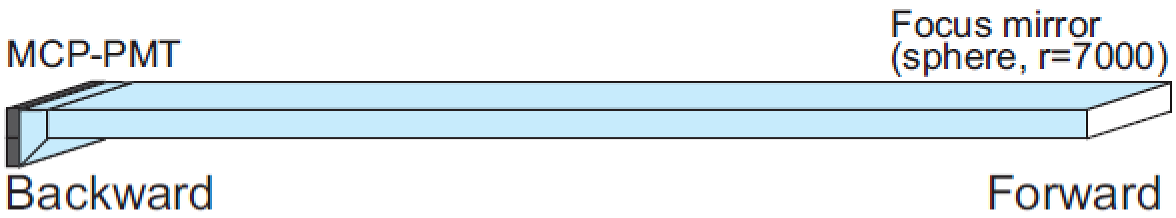






- Many studies were killed before they could be fully explored:
  - MPPCs are too susceptible to neutron damage.
  - Extra optics required modifications to the calorimeter.

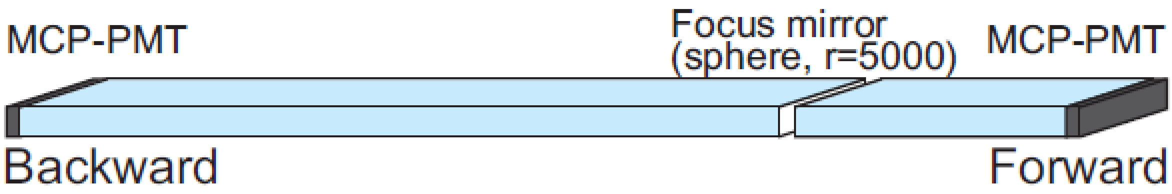
Nominal Belle II iTOP Design



Single bar option (iTOP)

L_{bar} ~ 2600mm

$L_{expansion}$ ~ 100 mm



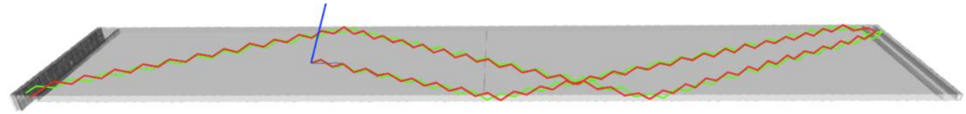
Two bar option

$L_{backward}$ ~ 1850mm

$L_{forward}$ ~ 750 mm

- Relatively small expansion volume.
- Advantages of the iTOP option, relative to two-bar TOP:
  - Less dependent on how well we can synchronize our timing with the collision time for each event (nominally we would like ~25 ps).
  - Less sensitive to timing resolution of single detected photons.
  - Readout was easier to implement (single location for readout modules).
  - No alignment issues between forward and backward blocks.

Detector and Electronics Requirements



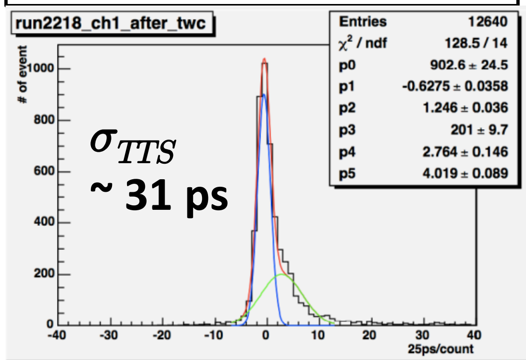
- Photodetectors:
  - Excellent single γ timing resolution (< 100 ps).
  - Must work in magnetic field.

  ➔ Hamamatsu SL-10 micro-channel plate photomultiplier tubes (MCP-PMTs)

2x16 SL-10 per bar

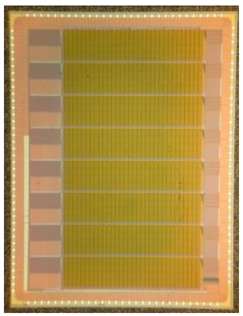
- Electronics:
  - Fit in the very compact space.
  - Utilize excellent timing resolution of the MCP-PMTs.
  - Accommodate ~5 μs Belle II trigger latency.
  - Provide information on all photons to Belle II trigger system.
  - No dead time at single pixel hit rates of ~100 kHz.

*K. Inami, et al.,
NIM A 592 (2008) 247-253

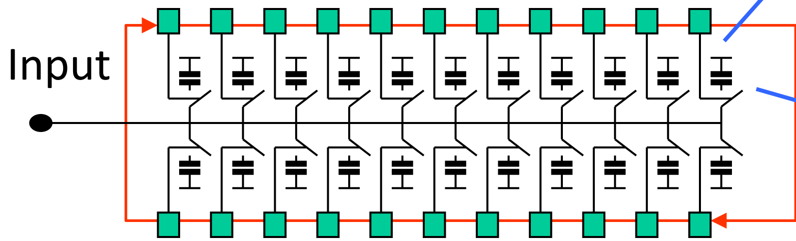


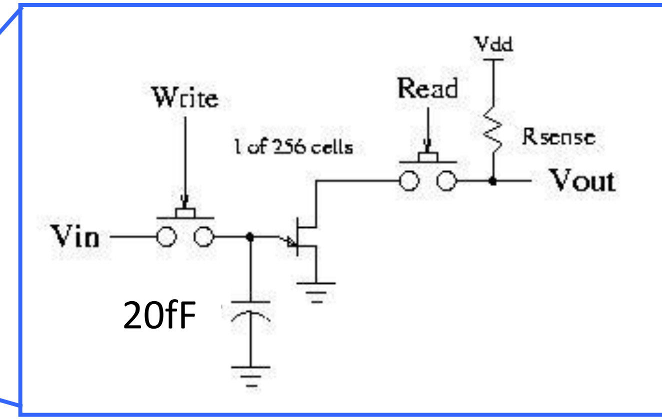
Waveform Sampling

e.g., 8-channel IRS2, designed by Gary Varner (UH)



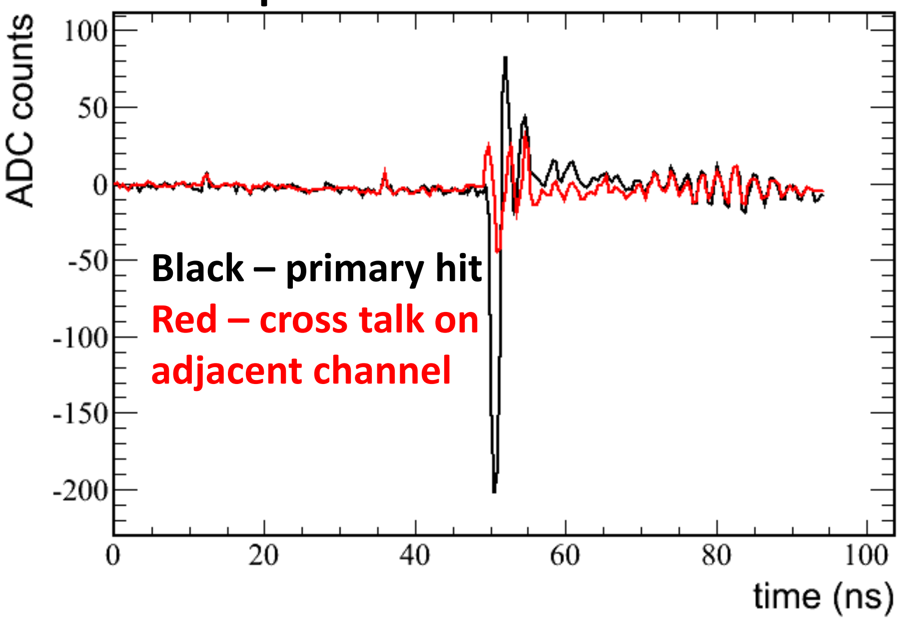
Switched capacitor array sampling





Tiny stored charge: 1mV ~ $100e^-$

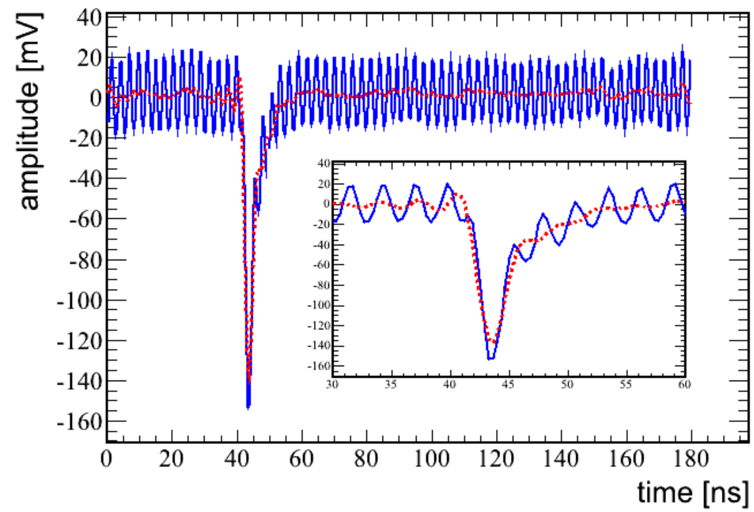
Example MCP-PMT waveform:



- Multi-gigasample per second waveform digitization.
  - Voltages are stored in analog form, using a switched capacitor array.
  - Analog storage memory is 32k samples deep to accommodate trigger latency.
  - Digitization of analog memory occurs when a L1 trigger is received.
  - Allows for full record of the event, and many signal processing possibilities.

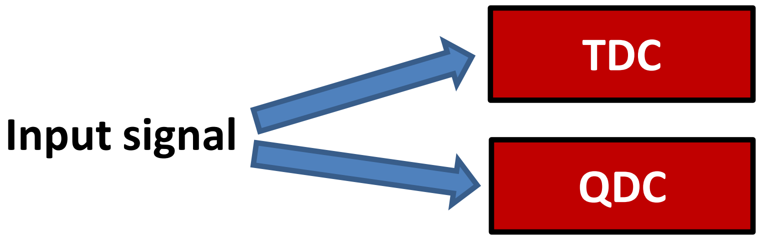
Caveats of Waveform Sampling

- More data than you might often want!
  - It's nice to have waveforms as a diagnostic tool…
    - Example where waveform sampling allowed us to see and filter out a sinusoidal noise source:



512 samples * 12 bits = 768 bytes / γ

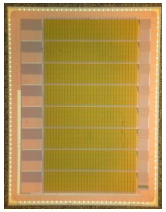
    - But in the end, we are usually interested in just a couple features (e.g., time and charge).



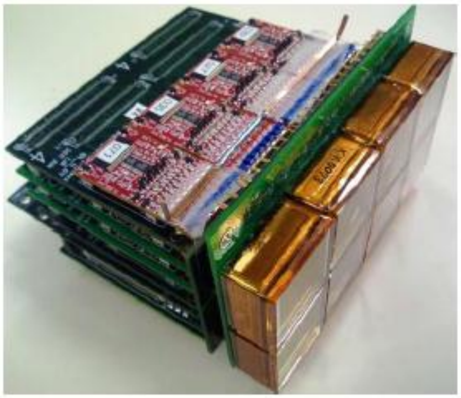
32 bits + 32 bits = 8 bytes / γ

    - Using waveform sampling <u>requires</u> that we take on the burden of the feature extraction.
      - Either in hardware or offline analysis.

Elements of iTOP Electronics



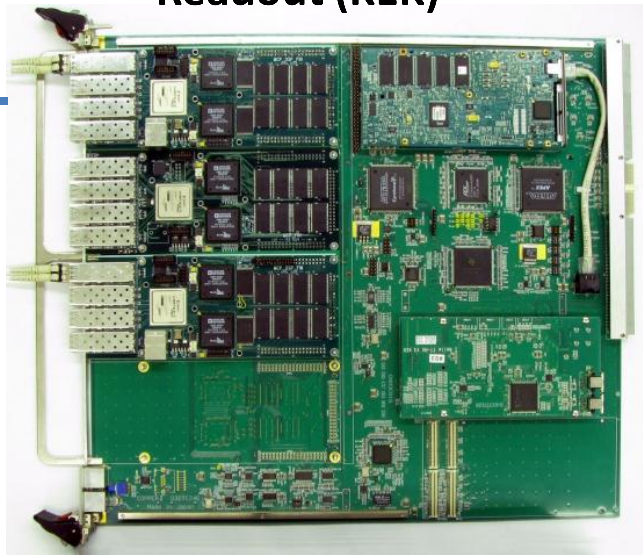
Waveform sampling ASICs (Hawaii)



SCROD-based board stack, ASICs + Spartan-6 FPGA (Hawaii)

Waveform data by fiberoptic

COPPER Based Readout (KEK)



DSP_FIN (Hawaii)

Trigger data by fiberoptic

Timing/trigger distribution (CAT-7)

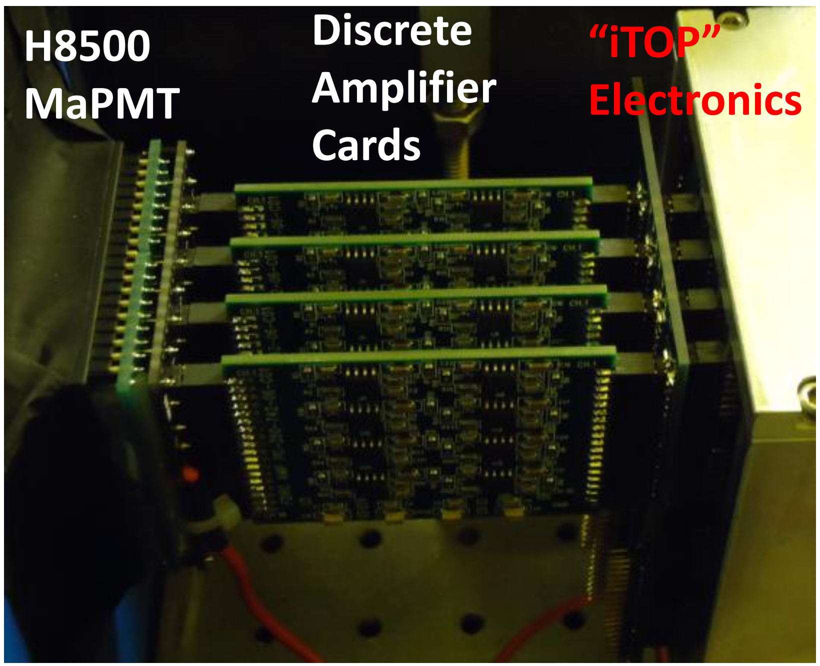
Remote programming link (CAT-7)

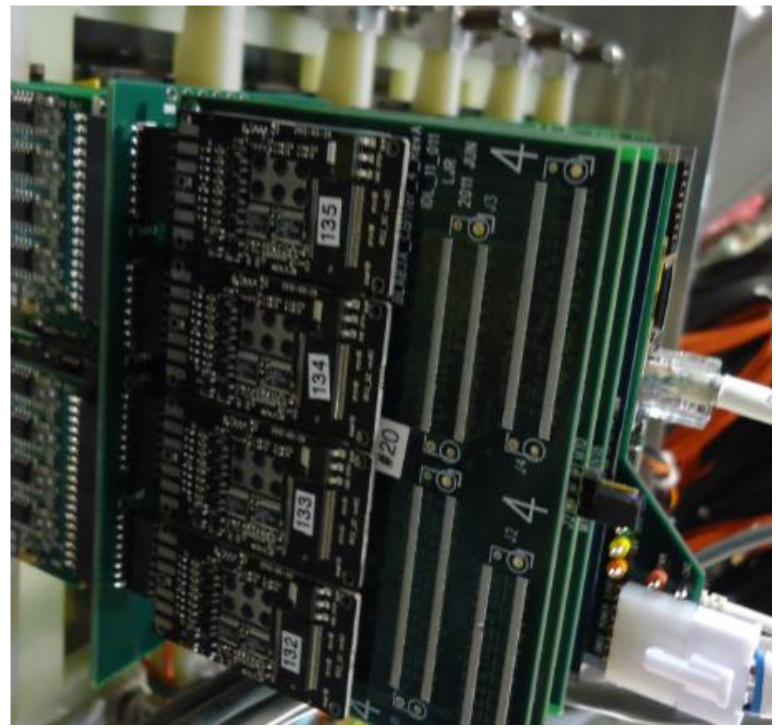
FTSW

TRG_FIN (Hawaii)

Aside: Flexible Front-end Electronics

- Same electronics can be used for multiple readouts (by changing “front” board).
- For example, same packages are being used to instrument the FDIRC prototype with Jerry Va’vra here at SLAC in a cosmic ray test stand (total 768 channels).





“iTOP” Electronics

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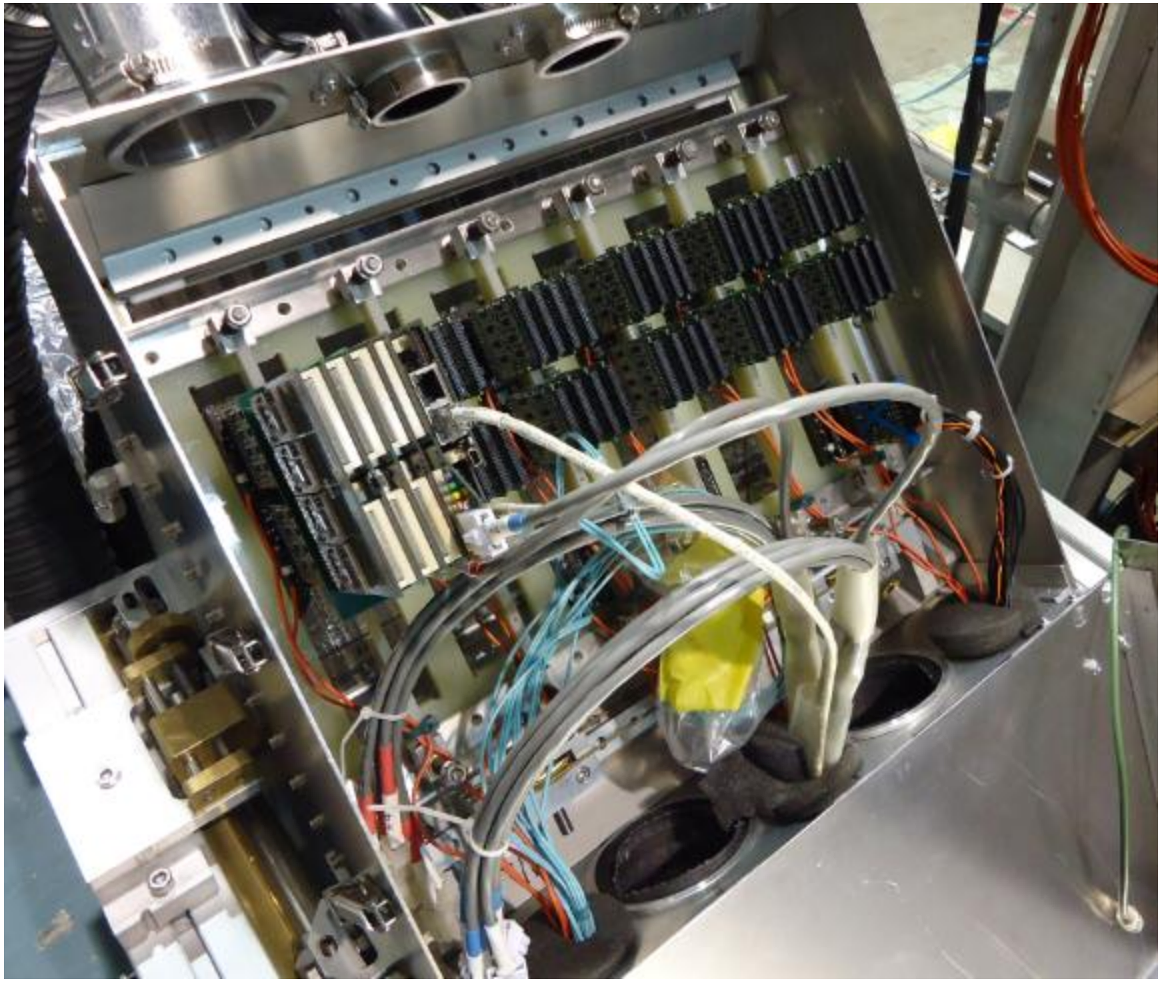
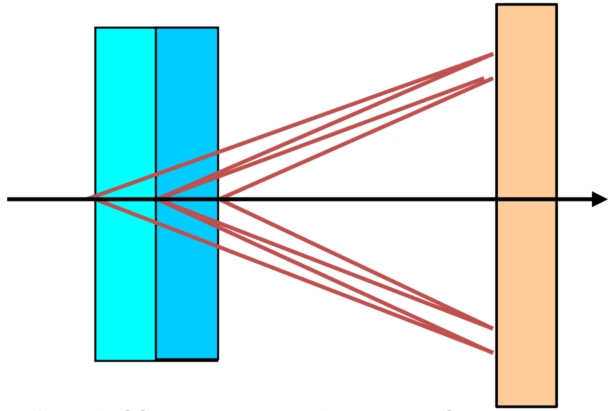
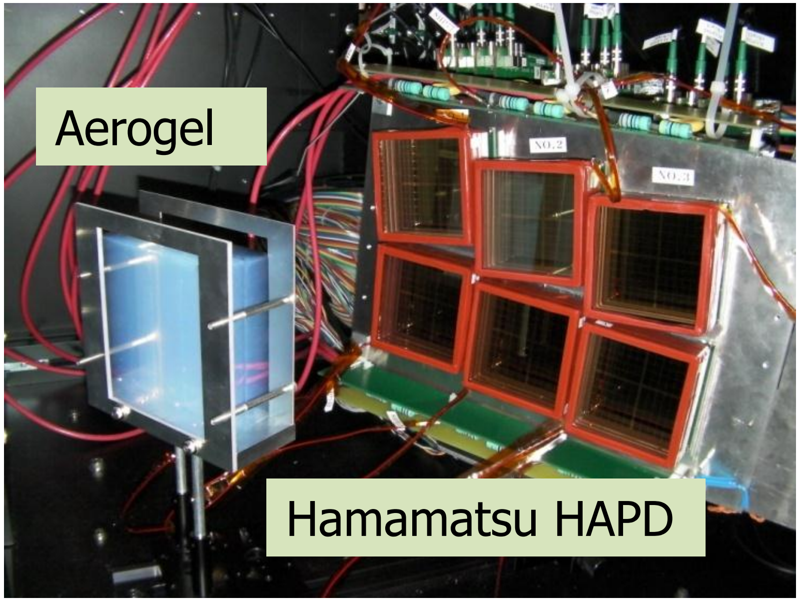


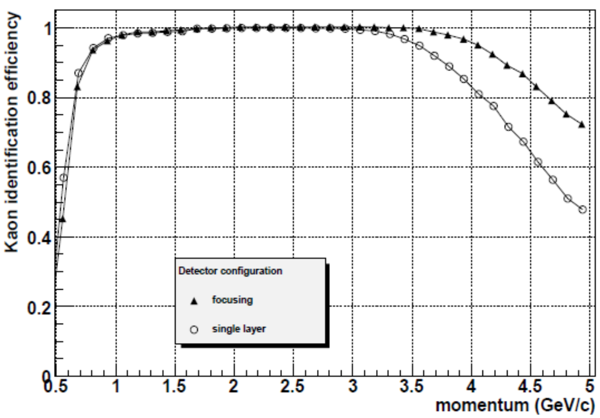
Other Belle II Upgrades – Endcap PID

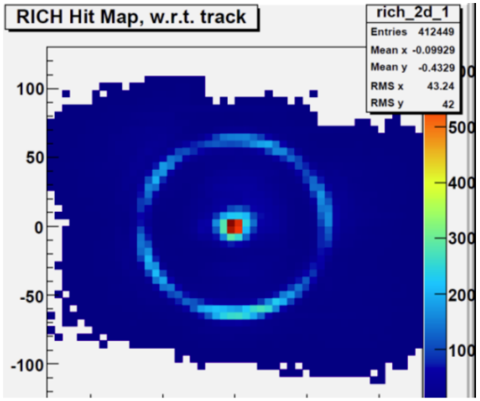
Proximity focusing scheme:

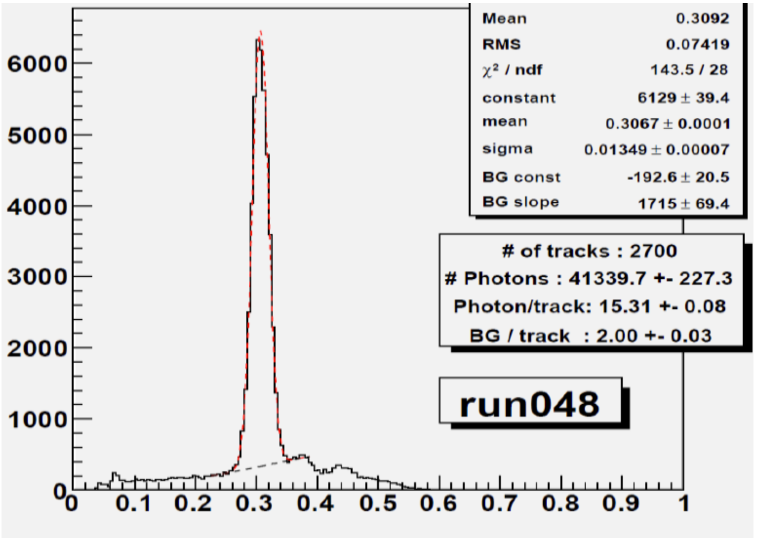


Slightly different indices of aerogel stacked ➔ improve Cherenkov angle resolution.





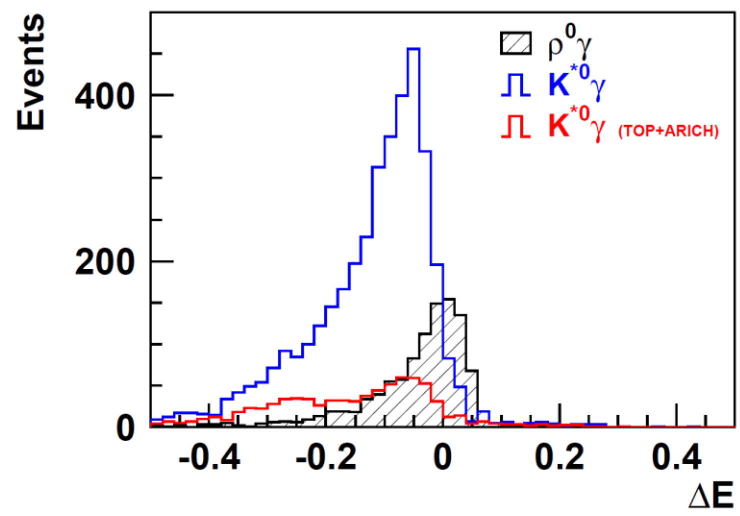




➔ Excellent PID efficiency over wide momentum range.

Improved PID Performance at Belle II

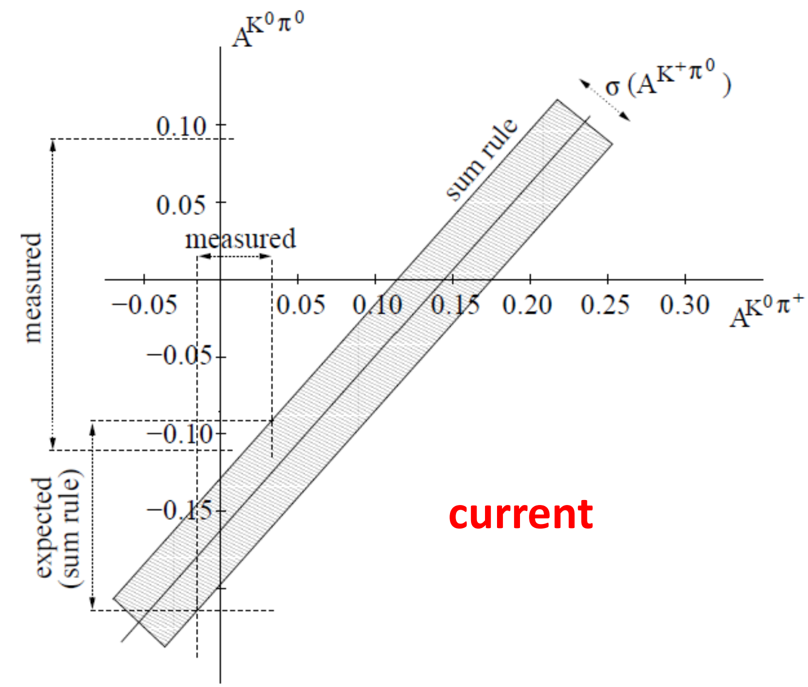
- Significant improvement in K/π discrimination:
  - Rare radiative processes:
    - B $\rightarrow \rho^o (\rightarrow \pi^+\pi^-) \gamma$
    - B $\rightarrow$ K* $(\rightarrow K^+\pi^-) \gamma$



- Other physics impact: Kπ CPV puzzle.
  - Naively, for $K^+\pi^o$, $K^+\pi^-$ we expect: $\Delta\mathcal{A} = 0$.
  - Current Belle value (EPS 2011): $\Delta\mathcal{A} = +0.112 \pm 0.028$ @ 4σ
  - …but theoretical uncertainty can be large.
- Model independent sum rule:

$$A_{CP}(K^+\pi^-) + A_{CP}(K^0\pi^+)\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} = A_{CP}(K^+\pi^0)\frac{2\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} + A_{CP}(K^0\pi^0)\frac{2\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

Gronau, PL**B627**, 82 (2005)



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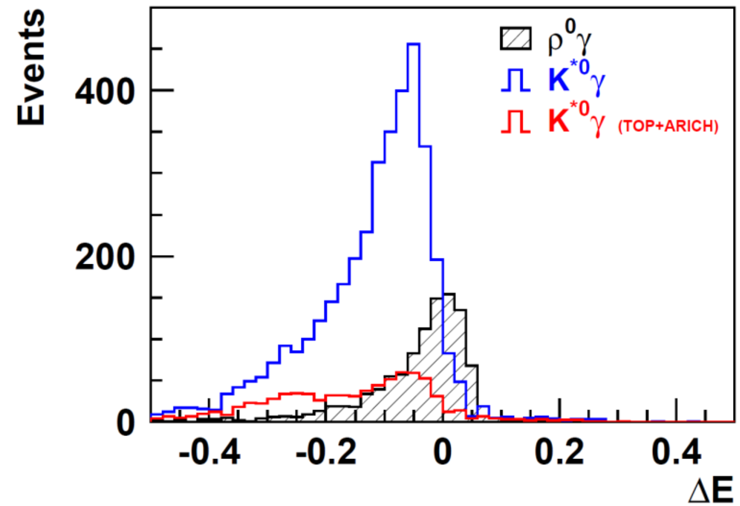

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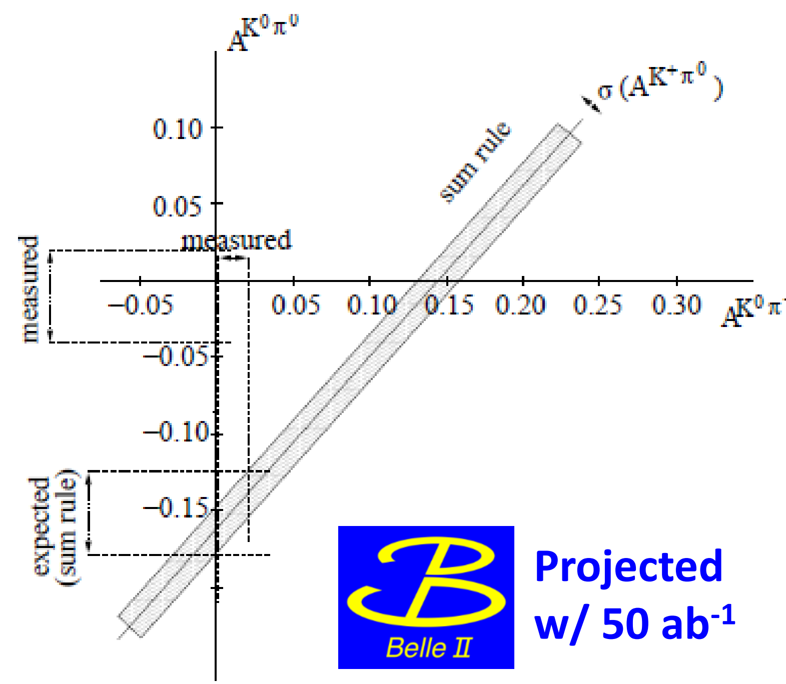

Projected w/ 50 ab^{-1}

Other Belle II Physics…

Observable	Belle 2006	SuperKEKB		†LHCb	
	(~0.5 ab^{-1})	(5 ab^{-1})	(50 ab^{-1})	(2 fb^{-1})	(10 fb^{-1})
Hadronic $b \to s$ transitions					
$\Delta\mathcal{S}_{\phi K^0}$	0.22	0.073	0.029		0.14
$\Delta\mathcal{S}_{\eta' K^0}$	0.11	0.038	0.020		
$\Delta\mathcal{S}_{K_S^0 K_S^0 K_S^0}$	0.33	0.105	0.037	-	-
$\Delta\mathcal{A}_{\pi^0 K_S^0}$	0.15	0.072	0.042	-	-
$\mathcal{A}_{\phi\phi K^+}$	0.17	0.05	0.014		
$\phi_1^{eff}(\phi K_S)$ Dalitz		3.3°	1.5°		
Radiative/electroweak $b \to s$ transitions					
$\mathcal{S}_{K_S^0 \pi^0 \gamma}$	0.32	0.10	0.03	-	-
$\mathcal{B}(B \to X_s\gamma)$	13%	7%	6%	-	-
$A_{CP}(B \to X_s\gamma)$	0.058	0.01	0.005	-	-
C_9 from $\overline{A}_{\rm FB}(B \to K^*\ell^+\ell^-)$	-	11%	4%		
C_{10} from $\overline{A}_{\rm FB}(B \to K^*\ell^+\ell^-)$	-	13%	4%		
C_7/C_9 from $\overline{A}_{\rm FB}(B \to K^*\ell^+\ell^-)$	-		5%		7%
R_K		0.07	0.02		0.043
$\mathcal{B}(B^+ \to K^+\nu\nu)$	†† $< 3\,\mathcal{B}_{\rm SM}$		30%	-	-
$\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu})$	†† $< 40\,\mathcal{B}_{\rm SM}$		35%	-	-
Radiative/electroweak $b \to d$ transitions					
$\mathcal{S}_{\rho\gamma}$	-	0.3	0.15		
$\mathcal{B}(B \to X_d\gamma)$	-	24% (syst.)		-	-
Leptonic/semileptonic B decays					
$\mathcal{B}(B^+ \to \tau^+\nu)$	3.5σ	10%	3%	-	-
$\mathcal{B}(B^+ \to \mu^+\nu)$	†† $< 2.4\mathcal{B}_{\rm SM}$	4.3 ab^{-1} for 5σ discovery		-	-
$\mathcal{B}(B^+ \to D\tau\nu)$	-	8%	3%	-	-
$\mathcal{B}(B^0 \to D\tau\nu)$	-	30%	10%	-	-
LFV in τ decays (U.L. at 90% C.L.)					
$\mathcal{B}(\tau \to \mu\gamma)$ [10^{-9}]	45	10	5	-	-
$\mathcal{B}(\tau \to \mu\eta)$ [10^{-9}]	65	5	2	-	-
$\mathcal{B}(\tau \to \mu\mu\mu)$ [10^{-9}]	21	3	1	-	-
Unitarity triangle parameters					
$\sin 2\phi_1$	0.026	0.016	0.012	~0.02	~0.01
ϕ_2 ($\pi\pi$)	11°	10°	3°	-	-
ϕ_2 ($\rho\pi$)	$68° < \phi_2 < 95°$	3°	1.5°	10°	4.5°
ϕ_2 ($\rho\rho$)	$62° < \phi_2 < 107°$	3°	1.5°	-	-
ϕ_2 (combined)		2°	$\lesssim 1°$	10°	4.5°
ϕ_3 ($D^{(*)}K^{(*)}$) (Dalitz mod. ind.)	20°	7°	2°	8°	
ϕ_3 ($DK^{(*)}$) (ADS+GLW)	-	16°	5°	5-15°	
ϕ_3 ($D^{(*)}\pi$)	-	18°	6°		
ϕ_3 (combined)		6°	1.5°	4.2°	2.4°
$\lvert V_{ub}\rvert$ (inclusive)	6%	5%	3%	-	-
$\lvert V_{ub}\rvert$ (exclusive)	15%	12% (LQCD)	5% (LQCD)	-	-
††† $\bar{\rho}$	20.0%		3.4%		
††† $\bar{\eta}$	15.7%		1.7%		

Observable	Belle	Belle/SuperKEKB		LHCb†	
				(2 fb^{-1})	(10 fb^{-1})
B_s physics	(25 fb^{-1})	(5 ab^{-1})			
$\mathcal{B}(B_s \to \gamma\gamma)$	$< 8.7 \times 10^{-6}$	0.25×10^{-6}		-	-
$\Delta\Gamma_s^{CP}/\Gamma_s$ ($Br(B_s \to D_s^{(*)}D_s^{(*)})$)	3%	1% (model dependency)		-	-
$\Delta\Gamma_s/\Gamma_s$ ($B_s \to f_{CP}$ t-dependent)	-	1.2%		-	-
ϕ_s (with $B_s \to J/\psi\phi$ etc.)	-	-	-	0.02	0.01
$\mathcal{B}(B_s \to \mu^+\mu^-)$	-			6 fb^{-1} for 5σ discovery	
ϕ_3 ($B_s \to KK$)	-			7-10°	
ϕ_3 ($B_s \to D_sK$)	-			13°	
Υ decays	(3 fb^{-1})	(500 fb^{-1})			
$\mathcal{B}(\Upsilon(1S) \to$ invisible)	$< 2.5 \times 10^{-3}$	$< 2 \times 10^{-4}$			
	(~0.5 ab^{-1})‡	(5 ab^{-1})	(50 ab^{-1})		
Charm physics					
D mixing parameters					
x	0.25%	0.12%	0.09%		0.25%††
y	0.16%	0.10%	0.05%		0.05%††
$\delta_{K\pi}$	10°	6°	4°		
$\lvert q/p\rvert$	0.16	0.1	0.05		
ϕ	0.13 rad	0.08 rad	0.05 rad		
A_D	2.4%	1%	0.3%		
New particles$^{\aleph}$					
$\gamma\gamma \to Z(3930) \to D\bar{D}^*$		$> 3\sigma$			
$B \to KX(3872)(\to D^0\bar{D}^{*0})$		400 events			
$B \to KX(3872)(\to J/\psi\pi^+\pi^-)$		1250 events			
$B \to KZ^+(4430)(\to \psi'\pi^+)$		1000 events			
$e^+e^- \to \gamma_{\rm ISR}Y(4260)(\to J/\psi\pi^+\pi^-)$		3000 events			
Electroweak parameters		(~10 ab^{-1})			
$\sin^2\Theta_W$	-	3×10^{-4}			

Very broad physics program within Belle II!

For many more specific examples, see arXiv:1002.5012: "Physics at Super *B* Factory"

Closing Remarks

- Super B factories will allow many sensitive searches for new physics.
  - Existing tensions can be fully explored. Others may arise.
- Super KEKB & Belle II are approved by Japanese government.
  - ~400 members from over 60 institutes in 19 countries.
  - Accelerator and detector upgrades are occurring now.
  - Belle II Technical Design Report: arXiv:1011.0352
- Planning to collect 50 ab^{-1} by 2022.
  - <u>Broad</u> physics program, complementary to LHC.
  - More details: arXiv:1002.5012