Searches for $X(214)$ in ISR and in B decays from Belle

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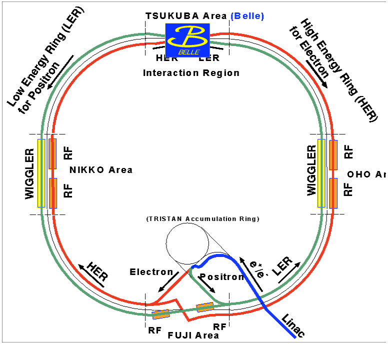
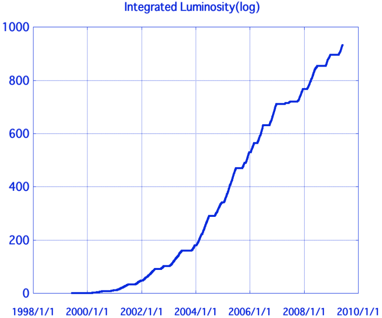
Sep. 24-26, 2009 @ SLAC, "Dark Forces Workshop"

Introduction & Motivation

- Searching for GeV-scale dark sector in e^+e^- collider experiments has been strongly suggested by several theorists
  - *That's what this workshop is for*, 8-)
- Why then $X(214)$?
  - Looking for $X(214)$ signal in ISR shares many features with searching for GeV-scale dark sector
  - with a specific goal of confirming or ruling out someone else's results/hypotheses
- What is $X(214)$?
- Belle's search for $X(214)$ in two ways
  - in ISR, of course
  - and in the B decays, too; *why not?*

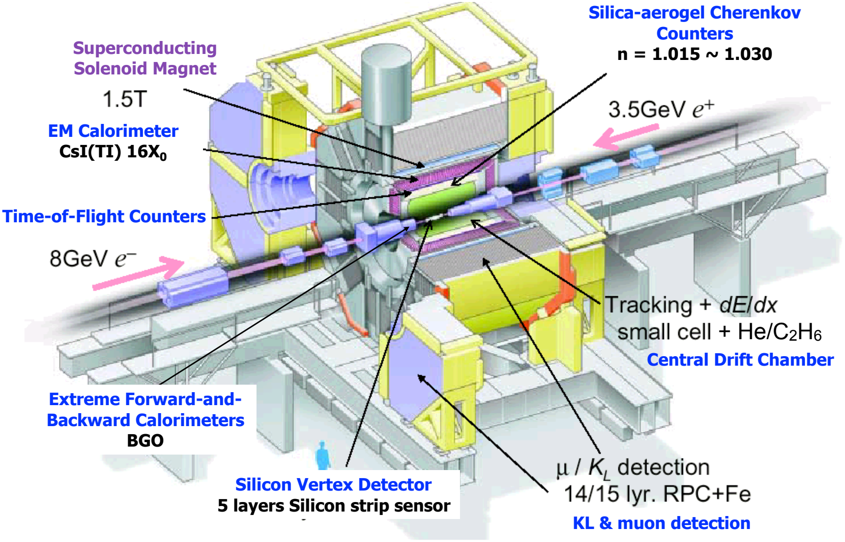
KEKB collider



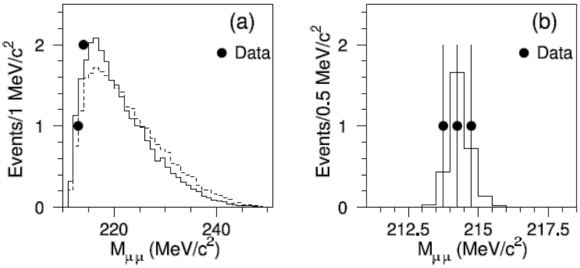


- $\sqrt{s} = 10.58$ GeV on-resonance production of $\Upsilon(4S)$
  - asymmetric energy: e^+ (3.5 GeV) on e^- (8 GeV)
  - ± 11 mrad crossing angle at IP
- Luminosity
  - $\mathcal{L}_{\text{peak}} = 2.11 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$
  - $\int \mathcal{L}\, dt \approx 950\ \text{fb}^{-1}$

Belle detector

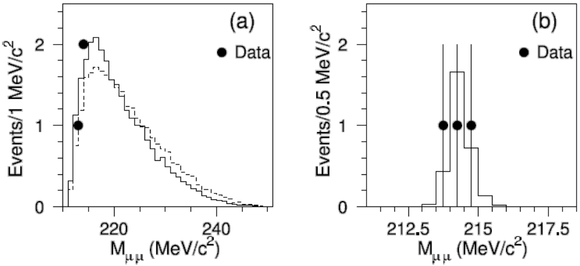


$X(214)$ from HyperCP



- Observed 3 events for $\Sigma^+ \to p\mu^+\mu^-$ — HyperCP Collab., PRL 94, 021801 (2005)
  - All three events near $M_{\mu^+\mu^-} = 214\ \mathrm{MeV}/c^2$
- Some interpretaions
  - sgoldstino ($10^{-15} \lesssim \tau_X \lesssim 10^{-11}$ s) — Gorbunov & Rubakov, PRD 73, 035002 (2006)
  - low-mass Higgs — He, Tandean & Valencia, PRL 98, 081802 (2007)
  - U-boson — Reece & Wang, JHEP 0907, 51 (2008); Pospelov, 0811.1030; Chen, *et al.* PLB 663, 100 (2008)

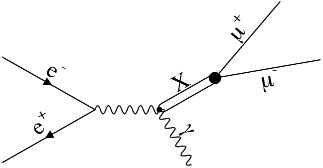
$X(214)$ from HyperCP



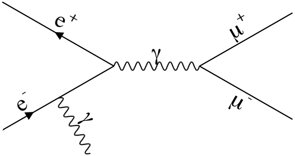
- Observed 3 events for $\Sigma^+ \to p\mu^+\mu^-$ HyperCP Collab., PRL 94, 021801 (2005)
  - All three events near $M_{\mu^+\mu^-} = 214$ MeV/c^2
- $\exists$ limits on $X(214)$ from other experiments
  - $\mathcal{B}(K_L^0 \to \pi^0\pi^0 X) \times \mathcal{B}(X \to \mu^+\mu^-) < 9.41 \times 10^{-11}$ (KTeV)
  - also from KEK-E391a (K_L^0 decays) and BaBar ($\Upsilon(3S) \to \gamma X$ decays)

$X(214)$ in ISR

- Search for $e^+e^- \to \gamma\, X(214) \to \gamma\, \mu^+\mu^-$
- Signal and background (ISR) processes



$e^+e^- \to \gamma X(214) \to \gamma\mu^+\mu^-$

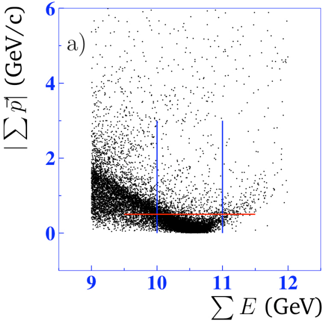


ISR

Event selection

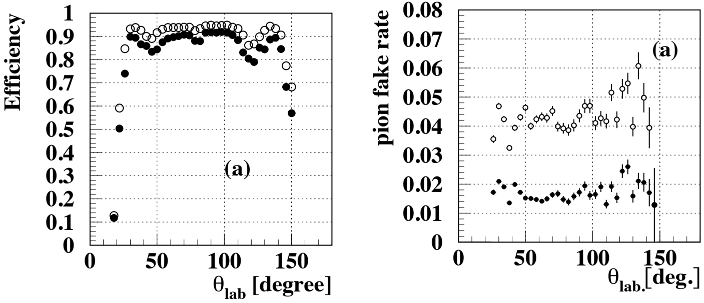
- (Stage 1) Pre-selection using τ-skim algorithm
  - selects events with low-charge-multiplicity ($2 \leq N_{chg} \leq 8$)
  - suppresses $\gamma\, e^+e^-$ and 2γ events

- (Stage 2) *More requirements*
  - $10 < \sum E < 11$ GeV
  - $|\sum \vec{p}| < 0.5$ GeV/c
  - $E_\gamma^{max} > 3$ GeV and $E_\gamma^{other} < 0.2$ GeV
  - $40.1^\circ < \theta_{\gamma_{max}} < 149.0^\circ$
  - $E/p < 0.9$ to suppress $e^+e^- \to \gamma\, e^+e^-$
  - *etc.*



- (Stage 3) μ ID : $\mathcal{L}_\mu > 0.5$ for each μ
- region of interest: $M_{\mu^+\mu^-} < 0.22$ GeV/c^2

Muon identification

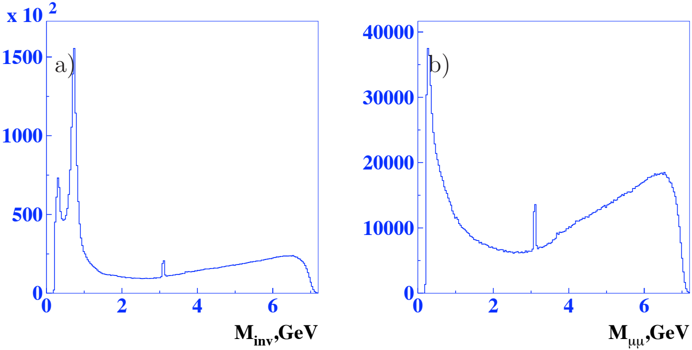


(left) Efficiency measured with $e^+e^- \to e^+e^-\mu^+\mu^-$ events

(right) Fake rate due to pion misidentification (right) measured with $K_S^0 \to \pi^+\pi^-$ events

(both) $1.0 < p < 3.0$ GeV/c; $\mathcal{L}_\mu > 0.9$ (•), $\mathcal{L}_\mu > 0.1$ (∘)

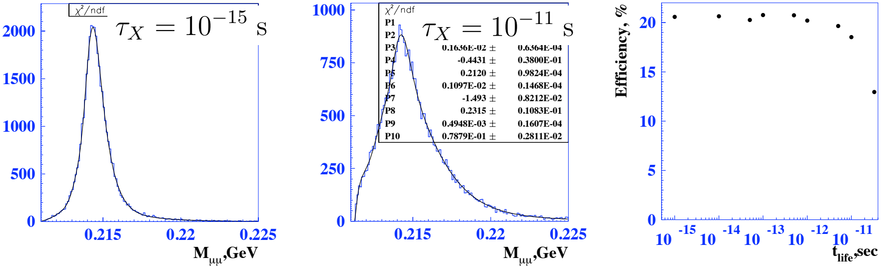
Muon identification



- Invariant mass distribution of oppositely-charged track pairs, before (left) and after (right) applying $\mathcal{L}_\mu > 0.5$ on each track.

$X(214)$ in ISR $M_{\mu^+\mu^-}$ signal MC

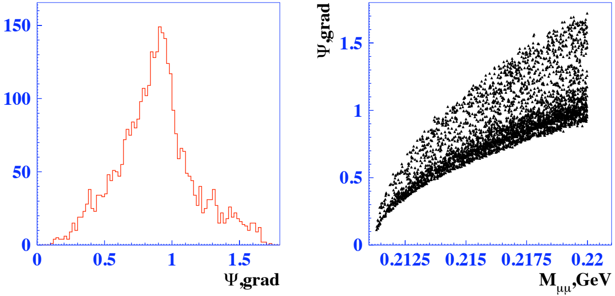
efficiency vs. τ_X



- γ distr. $\propto 1 + \cos^2\theta$
- $M_{\mu^+\mu^-}$ for assumed lifetime τ_X of $X(214)$
  - * $M_{\mu^+\mu^-}$ resolution ~ 0.6 MeV/c^2
    shape is well described by 3 log-gaussians
  - * $\epsilon \sim 20\%$ for $10^{-15} \leq \tau_X \leq 10^{-12}$
  - * $\gamma\beta c\tau \approx 7$ cm ($7\ \mu$m) for $\tau_X = 10^{-11}$ s (10^{-15} s)

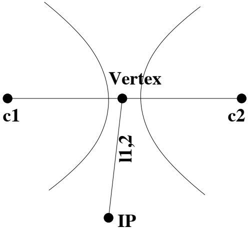
an issue in tracking/vertexing

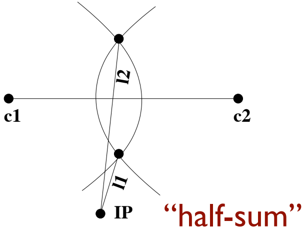
- $M_{X(214)}$ is just above the di-muon threshold but $\gamma_X \approx 24$, which makes the opening angle very small ($\sim 1^\circ$)
  $\Longrightarrow$ *need to be careful in measuring $\vec{p}$, which in turn affects $M_{\mu^+\mu^-}$*



- moreover, $\gamma\beta c\tau \sim \mathcal{O}(0.1\ \mathrm{m})$ for $\tau_X \sim 10^{-11}$ s
- IP-based $M_{\mu^+\mu^-}$ calculation would not work; need to choose *more realistic* vertex position

how to find/define the vertex?

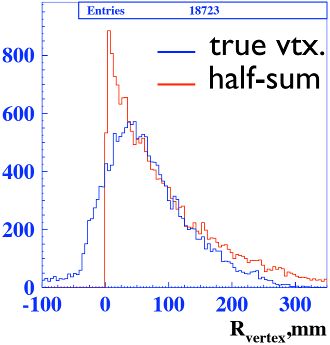


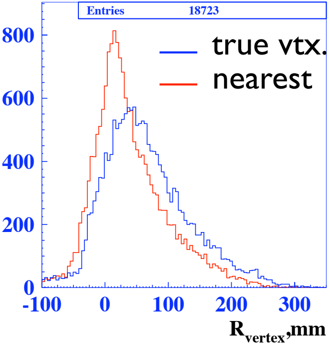


$$\vec{R}_{\text{vtx}} \equiv (\vec{\ell}_1 + \vec{\ell}_2)/2$$

- two helices **non-touching**
  Just take the middle point b/w the 2 helix centers
- two helices **crossing**
  Take the **"half-sum"** defined by $(\vec{\ell}_1 + \vec{\ell}_2)/2$
  Why not simply the nearest $\vec{\ell}$?

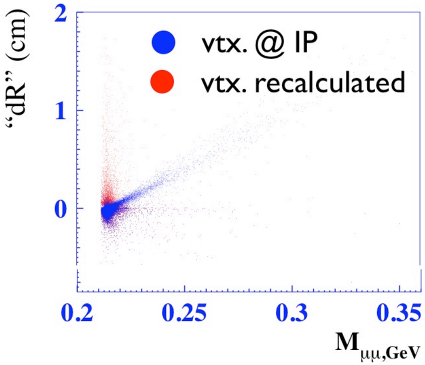
vtx. finding: *half-sum* or *nearest?*





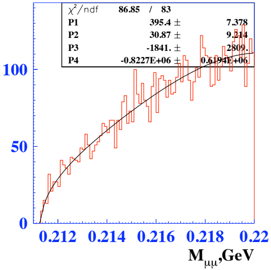
- Take a (extreme) case of $\tau_X = 3.3 \times 10^{-11}$ s
- Half-sum method agrees better with the true vertex distribution for $R < 150$ mm
- Moreover, half-sum method results in better bkgd. suppression

vtx. finding: check of performance



- $M_{\mu^+\mu^-}$ calculation with the new vertexing gives narrower distribution, not much dependent on the vertex distribution

$M_{\mu^+\mu^-}$ bkgd. shape



$M_{\mu^+\mu^-}$ from KKMC

- Background parametrization for $M_{\mu^+\mu^-}$

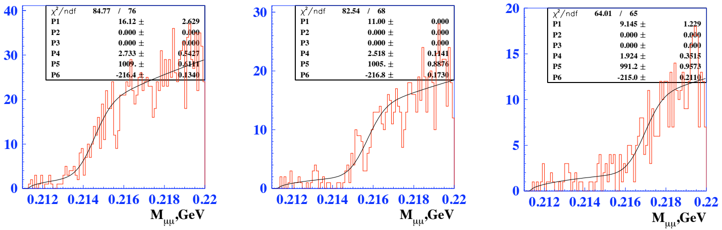
$$f(x) = A\beta(x)(1 + a_1 x + a_2 x^2 + a_3 x^3) \qquad (1)$$

  where $\beta(x) = \sqrt{1 - (2m_\mu/x)^2}$.

- QED cross-section
  $\sigma(e^+e^- \to \gamma^* \to \mu^+\mu^-) \propto \beta\left(1 - \beta^2/3\right)$,
  but including experimental smearing effects, it can be parametrized as Eq. 1.

- for a rough estimate of sensitivity, assuming no signal
  - $\sqrt{N_{\text{bkgd}}} \sim 50$ within $\sim 1\sigma$ region (see Slide 11) for $\int \mathcal{L}\, dt \approx 0.56\ \text{ab}^{-1}$
  - Efficiency $\sim \mathcal{O}(20\%)$ (also Slide 11)
  - Estimated sensitivity: $\sigma_X \lesssim \mathcal{O}(1\ \text{fb})$

$M_{\mu^+\mu^-}$ bkgd. w/ flight dist. cut



$h > 30$ mm **> 42 mm** **> 50 mm**

***h*: half-sum distance**

- Background parametrization for $M_{\mu^+\mu^-}$ with flight-distance cut (by "**half-sum**")

$$f(x) = A\beta(x)(1 + a_1 \mathrm{erf}(a_2 x + a_3)) \tag{2}$$

where $\beta(x) = \sqrt{1 - (2m_\mu/x)^2}$.

Summary and Prospects

- All the machineries are ready for the search of $X(214)$ in ISR at Belle
- Currently, we are checking the systematic issues before opening the data and quantifying the result
- After the $X(214)$ analysis, we will continue the search for general masses and lifetimes, which can be related to the search for GeV-scale Dark Sector

$X(214)$ in B decays

- Why in B decays?
  - B decaying almost at rest
    gives very tight kinematic constraints, *i.e.* $M_{\mathrm{bc}}, \& \Delta E$
  - Hence B decays have been good place to find new particles, *e.g.* $X(3872)$..
  - Ample experiences of B decays to $\ell^+\ell^-$ states, *e.g.* $B \to J/\psi K^*$, $K^*\ell^+\ell^-$, etc.
  - It's good to confirm or disconfirm with two independent processes
- Some predictions for $B \to \mathcal{V}\, X(214)$ where $\mathcal{V} = K^*, \rho$, etc.

Demidov & Gorbunov, JETP Lett, 84, 479 (2006)

$$\mathcal{B}(B \to K^* X(214)) \times \mathcal{B}(X \to \mu^+\mu^-) = 10^{-9} \sim 10^{-6}$$
$$\mathcal{B}(B \to \rho\, X(214)) \times \mathcal{B}(X \to \mu^+\mu^-) = 10^{-9} \sim 10^{-7}$$

$B \to \mathcal{V}\, X(214)$

Modes of study

- Search for $B \to \mathcal{V}\, X(214)$ with $N(B\bar{B}) = 657\text{M}$

  $B^0 \to K^{*0} X(214)$ with $K^{*0} \to K^+\pi^-$ and $X(214) \to \mu^+\mu^-$
  $B^0 \to \rho^0\, X(214)$ with $\rho \to \pi^+\pi^-$ and $X(214) \to \mu^+\mu^-$

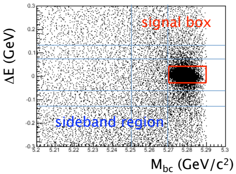
  - both pseudoscalar and axialvector assumptions for $X(214)$ are tried
    - *only pseudoscalar results today*

- Event selection

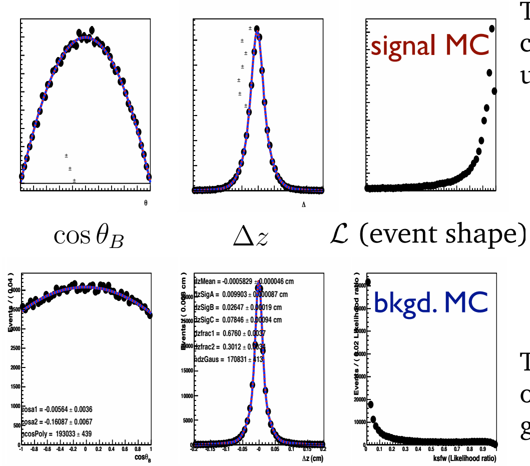
  - good charged track: $dr < 1$ cm, $|dz| < 5$ cm
  - μ ID is tightened compared to ISR study: $\mathcal{L}_\mu > 0.95$
  - Belle standard K/π ID
  - mass windows for K^* and ρ are $\pm 1.5\Gamma$ and $\pm 1\Gamma$, respectively

- usual kinematic variables $M_{\rm bc}$ & ΔE to make sure it came from B decays

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



$B \to \mathcal{V} X(214)$ Background suppression



To suppress dominant bkgd. from continuum, following variables are used

- B flight direction
- vertex distance b/w signal B and the other B
- event shape variables based on modified F-W

To find the cut value, $S/\sqrt{S+B}$ is optimized by MC with judicious guess of signal BF

$B \to \mathcal{V}\, X(214)$ Signal efficiency

Decay mode	Dimuon mass resolution [keV/c^2]	Signal efficiency (ε)
$B \to K^{*0}X^0$	427 ± 14	$(26.3 \pm 0.1)\%$
$B \to \rho^0 X^0$	428 ± 15	$(23.5 \pm 0.1)\%$

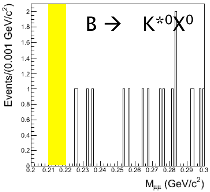
- Signal mass window for $X(214)$ is

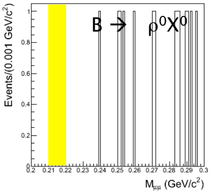
  $$211.5 < M_{\mu^+\mu^-} < 217.1\ \mathrm{MeV}/c^2$$

  $\sim 3\sigma$ range considering HyperCP uncertainty plus Belle resolution
- $X(214)$ is assumed to decay promptly, say $\tau_X \sim 10^{-20}$ s, such that lifetime effect can be neglected w/o noticeable effects on the width
- Other (more realistic) choices for τ_X are also tried: 10^{-15} s, 10^{-12} s,

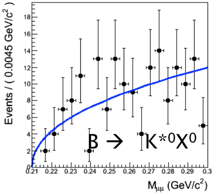
  $\Rightarrow$ *no significant difference!*

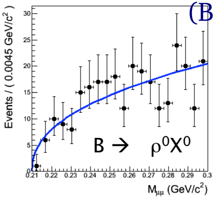
$B \to \mathcal{V}\, X(214)$ Background estimation





(Top) no events in the $M_{\mu^+\mu^-}$ signal region (shaded band) in both modes,
from bkgd. MC samples ($\sim \times 3$ data size)



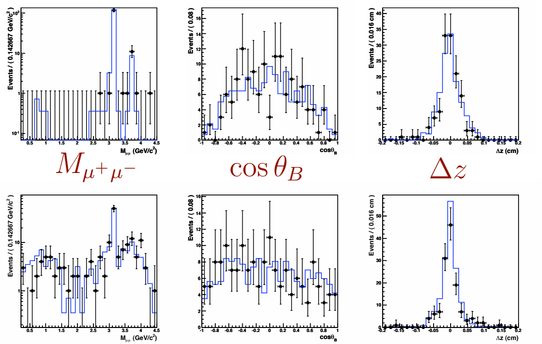


(Bottom) fitting the $M_{\mu^+\mu^-}$ in the $(M_{\rm bc}, \Delta E)$ sideband (for increased stat.) gives

- * 0.13 events for $B \to K^* X(214)$
- * 0.11 events for $B \to \rho\, X(214)$

$B \to \mathcal{V} X(214)$ Data vs. MC comparison

$M_{\rm bc}$, ΔE signal region

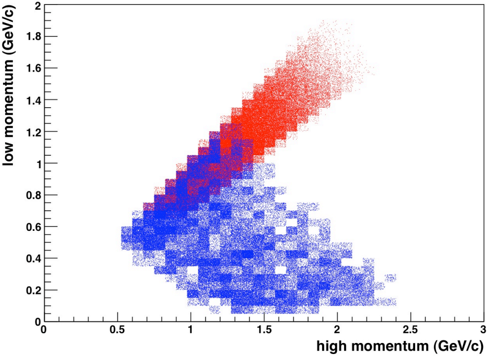


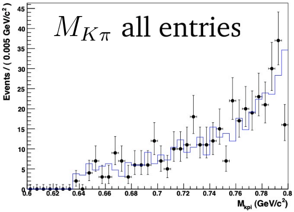
$M_{\rm bc}$, ΔE side-band

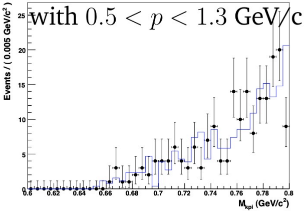
- after all the cuts are determined,
- opening a small data sample $\int \mathcal{L}\, dt \sim 10\ \mathrm{fb}^{-1}$
- to compare distributions of some key variables with those of bkgd. MC samples

$B \to V\,X(214)$ checking small opening angle

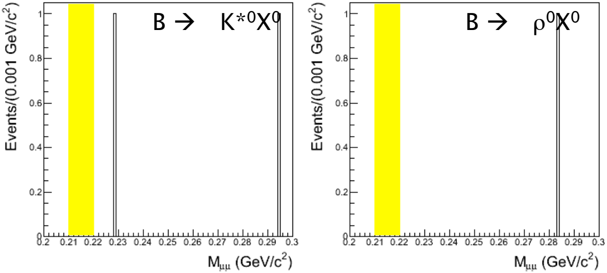
- p_K, p_π in $B \to J/\psi K^+\pi^-$
- p_μ in $B \to K^* X(214)$ signal MC







$B \to \mathcal{V}\, X(214)$ Results



- No events in the signal region in both modes
- Systematic uncertainty
  - mostly efficiency error due to particle ID, tracking
  - 5.2% for $B \to K^* X(214)$, 5.7% for $B \to \rho\, X(214)$
  - 'prompt' decay w/o noticeable effect in the width is assumed
- Upper limits (@ 90% CL.) *preliminary*

$$\mathcal{B}(B \to K^* X(214)) \times \mathcal{B}(X(214) \to \mu^+\mu^-) < 2.01 \times 10^{-8}$$
$$\mathcal{B}(B \to \rho\, X(214)) \times \mathcal{B}(X(214) \to \mu^+\mu^-) < 1.51 \times 10^{-8}$$

$B \to \mathcal{V}\, X(214)$ Theory B.F. as sgoldstino

Branching ratios of decays $P_{B,D} \longrightarrow VP(P \longrightarrow \mu^+\mu^-)$ in the models I, II, and III. Branching ratios of decays $P_{B,D} \longrightarrow VP(P \longrightarrow \gamma\gamma)$ are given by the same numbers multiplied by $\Gamma(P \longrightarrow \gamma\gamma)/\Gamma(P \longrightarrow \mu^+\mu^-)$

Decay	h_{jl}	$A_0^{(P_{B,D},\,V)}$	$\mathrm{Br}_{\text{(model I)}}$	$\mathrm{Br}_{\text{(model II)}}$	$\mathrm{Br}_{\text{(model III)}}$
$B_s \longrightarrow \phi P(P \longrightarrow \mu^+\mu^-)$	$h_{23}^{(D)}$	0.42 [18]	6.5×10^{-9}	8.8×10^{-6}	8.7×10^{-6}
$B_s \longrightarrow K^{*0} P(P \longrightarrow \mu^+\mu^-)$	$h_{13}^{(D)}$	0.37 [18]	5.3×10^{-9}	7.2×10^{-6}	2.3×10^{-7}
$B_c^+ \longrightarrow D^{*+} P(P \longrightarrow \mu^+\mu^-)$	$h_{13}^{(D)}$	0.14 [19]	3.2×10^{-10}	4.4×10^{-7}	1.4×10^{-8}
$B_c^+ \longrightarrow D_s^{*+} P(P \longrightarrow \mu^+\mu^-)$	$h_{23}^{(D)}$	0.14[a]	3.0×10^{-10}	4.0×10^{-7}	4.0×10^{-7}
$B_c^+ \longrightarrow B^{*+} P(P \longrightarrow \mu^+\mu^-)$	$h_{12}^{(U)}$	0.23 [20]	4.1×10^{-10}	4.4×10^{-8}	8.2×10^{-7}
$B^+ \longrightarrow K^{*+} P(P \longrightarrow \mu^+\mu^-)$	$h_{23}^{(D)}$	0.31 [17]	3.8×10^{-9}	5.2×10^{-6}	5.1×10^{-6}
$B^0 \longrightarrow K^{*0} P(P \longrightarrow \mu^+\mu^-)$			3.5×10^{-9}	4.8×10^{-6}	4.7×10^{-6}
$B^0 \longrightarrow \rho P(P \longrightarrow \mu^+\mu^-)$	$h_{13}^{(D)}$	0.28 [17]	3.1×10^{-9}	4.2×10^{-6}	1.4×10^{-7}
$B^+ \longrightarrow \rho^+ P(P \longrightarrow \mu^+\mu^-)$			3.3×10^{-9}	4.6×10^{-6}	1.3×10^{-7}
$D^0 \longrightarrow \rho P(P \longrightarrow \mu^+\mu^-)$	$h_{12}^{(U)}$	0.64 [17]	1.4×10^{-9}	1.5×10^{-7}	2.8×10^{-6}
$D^+ \longrightarrow \rho^+ P(P \longrightarrow \mu^+\mu^-)$			3.5×10^{-9}	3.7×10^{-7}	7.0×10^{-6}

[a] We did not find any estimate of this form factor in literature and use this value as an order-of-magnitude estimate, which is sufficient for our study.

Demidov & Gorbunov, JETP Lett, 84, 479 (2006)

Our upper limits are not consistent with models II and III.

Summary and Prospects

- Belle is searching for $X(214)$ in both ISR and B decays
- ISR
  - basic machineries are ready, including optimized vertexing
  - currently checking systematic issues
- in $B \to K^* X(214)$ and $B \to \rho X(214)$ decays
  - preliminary upper limits for *promptly-decaying* **pseudoscalar** assumption of $X(214)$ is available

    $\mathcal{B}(B \to \mathcal{V} X(214)) \times \mathcal{B}(X(214) \to \mu^+\mu^-) \lesssim \mathcal{O}(10^{-8})$
  - extending the search to be model-independent (*wider ranges of* m_X *and* τ_X) as well as trying **axialvector** assumptions
- After completing the $X(214)$ analysis, we will continue the search for general masses and lifetimes, which can be related to the search for GeV-scale Dark Sector