The dark side of Belle

(searches for the light dark matter)

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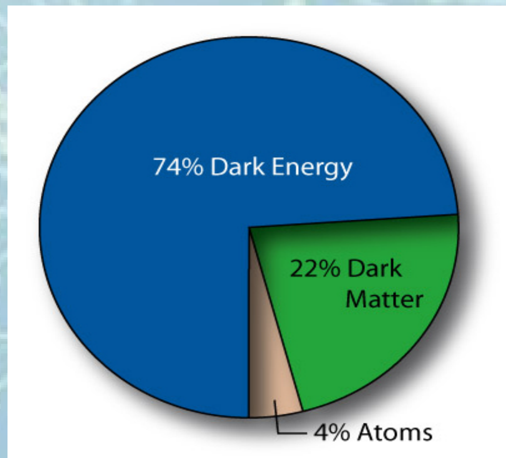
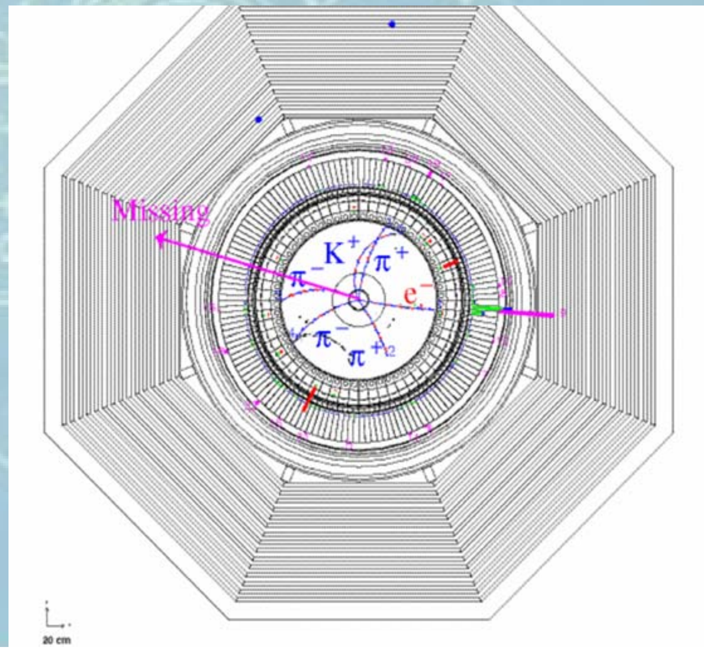
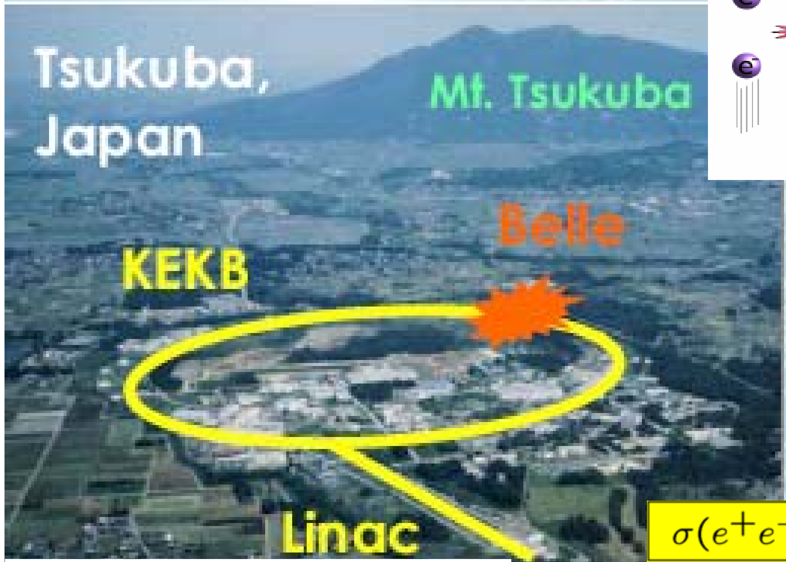




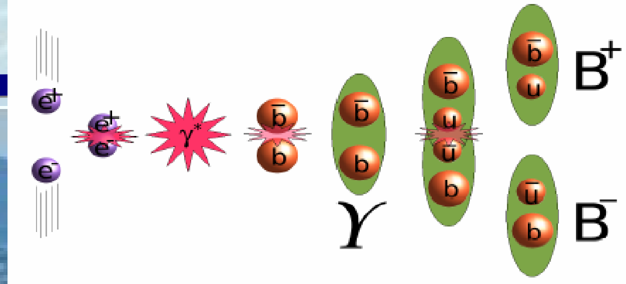
Outline

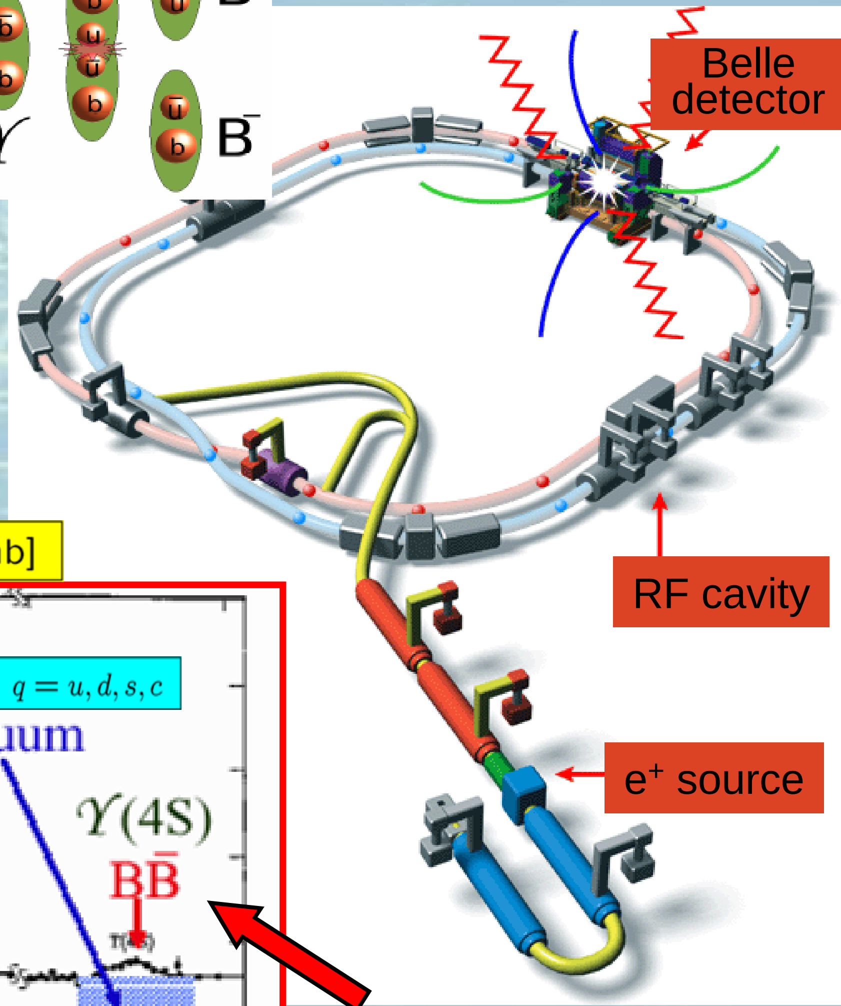
- The KEKB accelerator and Belle detector
- **Search for invisible decays of the Υ(1S)**
- Search for $B \rightarrow h^{(*)}\nu\underline{\nu}$ **decays**
- **Future prospects of B-factories**

The KEKB accelerator



KEKB ring: 3 km in circumference





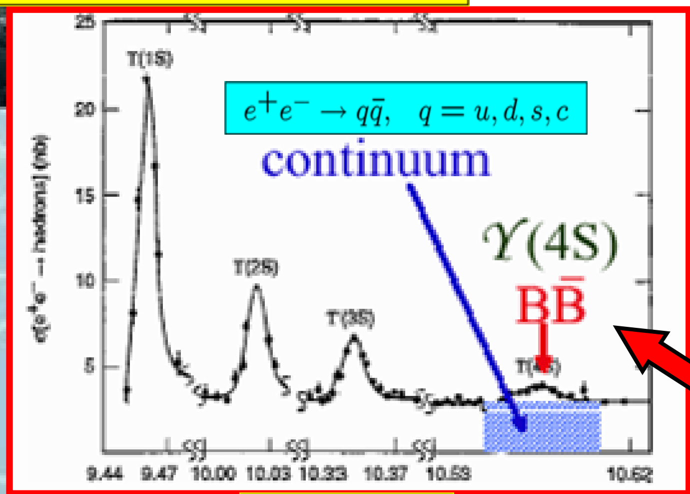
asymmetry in beam energies
8 GeV (e^-) $\times$ 3.5 GeV (e^+)

World records at $\sqrt{s} = 11.5$ GeV

L_{peak} = 1.7118 x 10^{34} cm^2/s

$\int L dt$ > 700 fb^{-1}

$\sigma(e^+e^- \to hadrons)$ [nb]



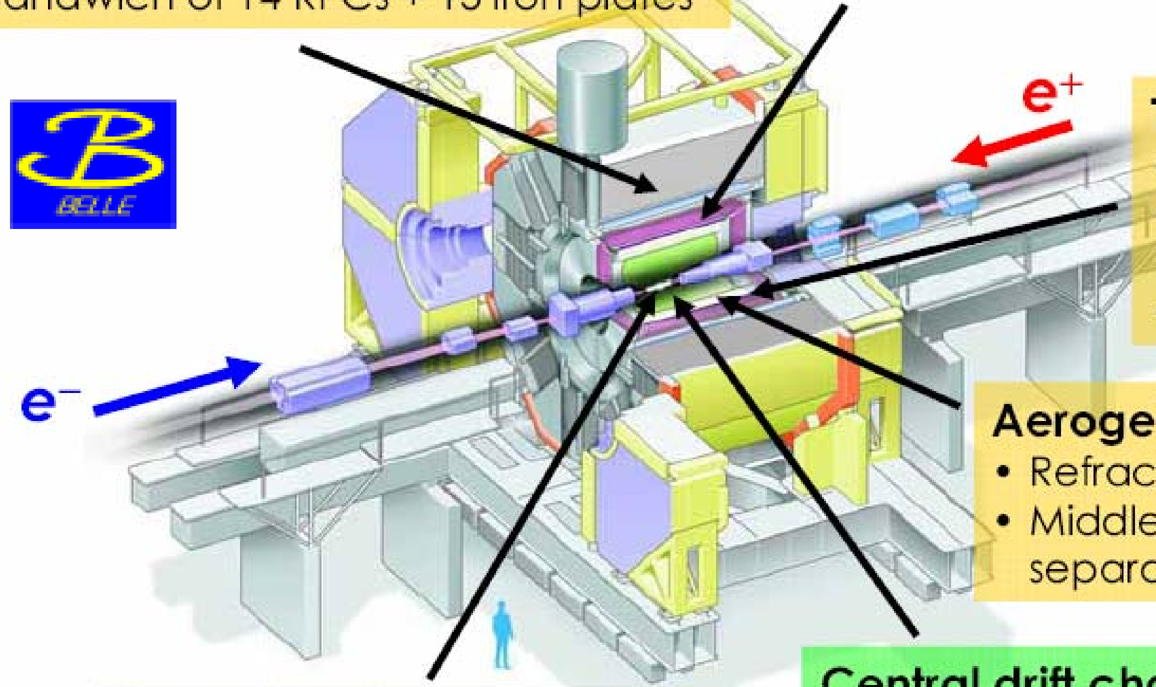
$\sqrt{s}$ [GeV]

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


The Belle detector

Electromagnetic calorimeter
- CsI (Tl) crystal
- $\sigma_E/E \sim 1.6\%$ @ 1 GeV

$K_L\mu$ detector
- Sandwich of 14 RPCs + 15 iron plates



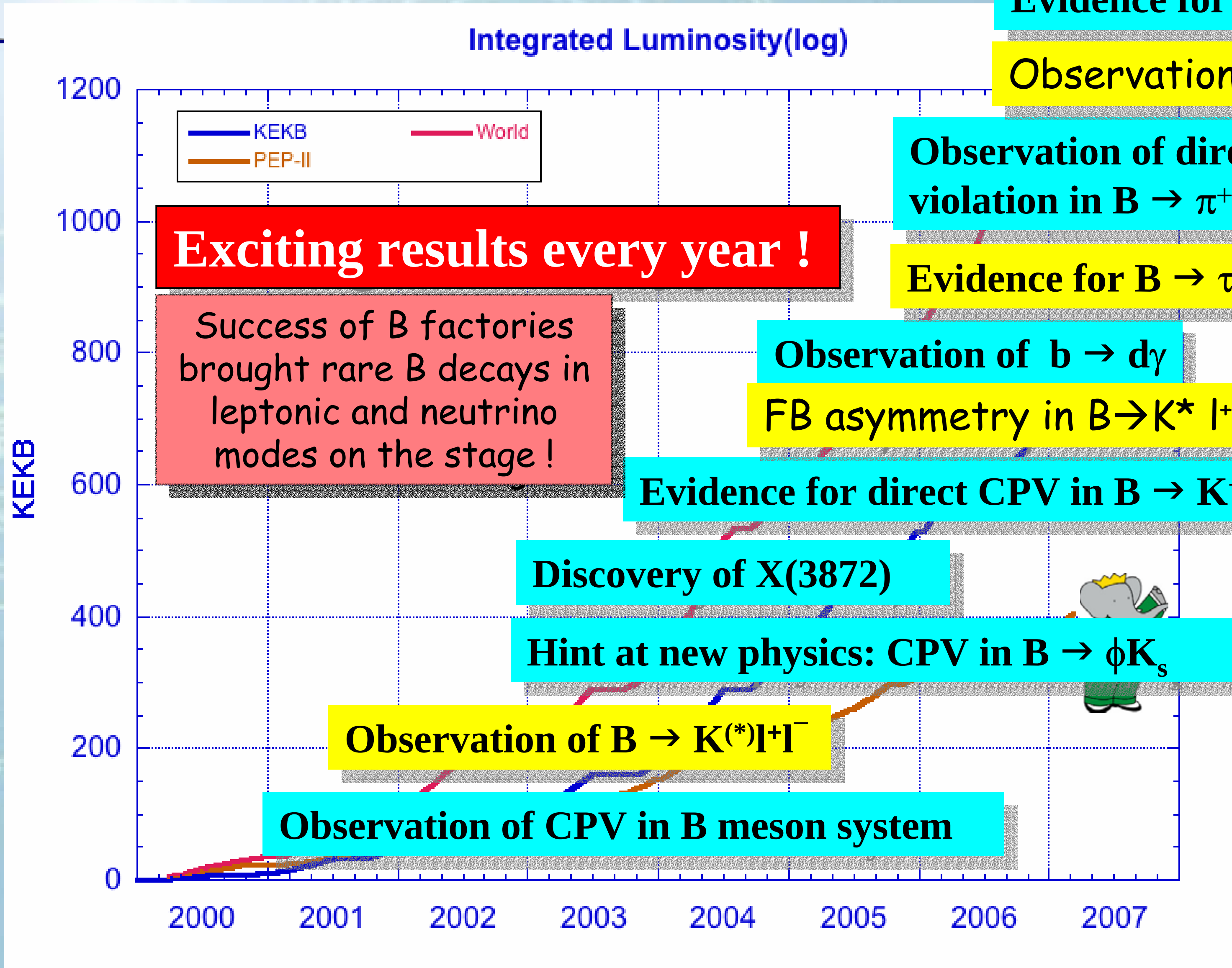
Time-of-Flight counter
- Plastic scintillator
- High momentum K/π separation
- Time resolution ~100 ps

Aerogel Cherenkov counter
- Refractive index: n=1.01-1.03
- Middle momentum K/π separation

Silicon vertex detector
- 4 layers of DSSD
- Vertex resolution ~ 100 μm

Central drift chamber
- 8400 sense wires
- $\sigma_{p_t}/p_t \sim 0.28 p_t(\mathrm{GeV}) \oplus 0.3\%$
- B = 1.5 T

Achievements at B factories



Exciting results every year !

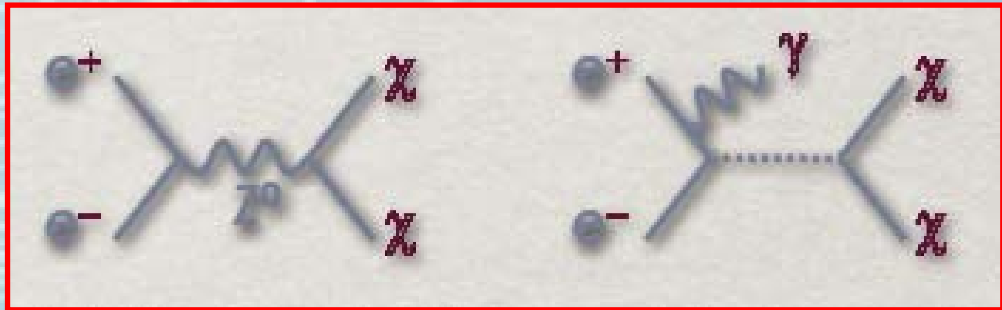
Success of B factories brought rare B decays in leptonic and neutrino modes on the stage !

- **Evidence for D^0 mixing**
- Observation of $B \to D^* \tau\nu$
- **Observation of direct CP violation in $B \to \pi^+\pi^-$**
- **Evidence for $B \to \tau\nu$**
- **Observation of $b \to d\gamma$**
- FB asymmetry in $B \to K^* l^+ l^-$
- **Evidence for direct CPV in $B \to K^+\pi^-$**
- **Discovery of X(3872)**
- **Hint at new physics: CPV in $B \to \phi K_s$**
- **Observation of $B \to K^{(*)} l^+ l^-$**
- **Observation of CPV in B meson system**

Search for invisible decays of the $\Upsilon(1S)$

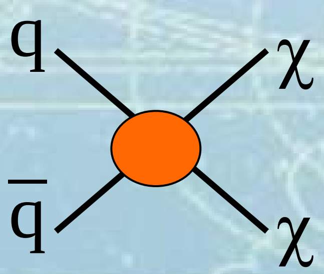
Motivation

- The previous accelerator searches for dark matter (DM) in e^+e^- annihilation
  ➔ based on the DM coupling to the Z (see LEP):

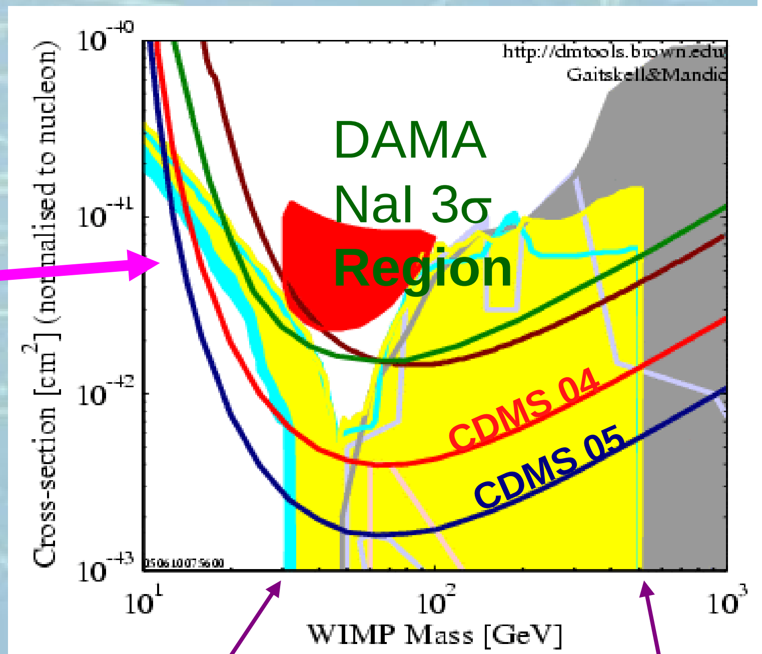


- Belle: search for the DM coupled to a quarkonium

PRL 98, 132001 (2007)



χ – an overall dark matter particle that is lighter than the beauty quark



Lee-Weinberg window

- The basic idea is <u>to look for decays of the Υ(1S) to the 'invisible' particles in the final state</u>

Expectations for B(Υ(3S) → invisible)

- The upper limits from previous searches (ARGUS and CLEO):

$$Br(\Upsilon(1S) \to invisible) < 50 \times 10^{-3} \quad (90\%C.L.)$$ CLEO, Phys. Rev. D 30, 1433 (1984)

$$Br(\Upsilon(1S) \to invisible) < 23 \times 10^{-3} \quad (90\%C.L.)$$ ARGUS, Phys. Lett. B 179, 403 (1986)

- The only invisible decay in the Standard Model:

$$\mathcal{B}(\Upsilon(1S) \to \nu\bar{\nu}) = (9.9 \pm 0.5) \times 10^{-6}$$

L.N. Chang et al., PLB 441, 419 (1998)

- The theoretical expectation for the invisible decay to the pair of overall dark matter particles that are lighter than the beauty quark

$$\mathcal{B}(\Upsilon(1S) \to \chi\bar{\chi}) \approx 6 \times 10^{-3}$$

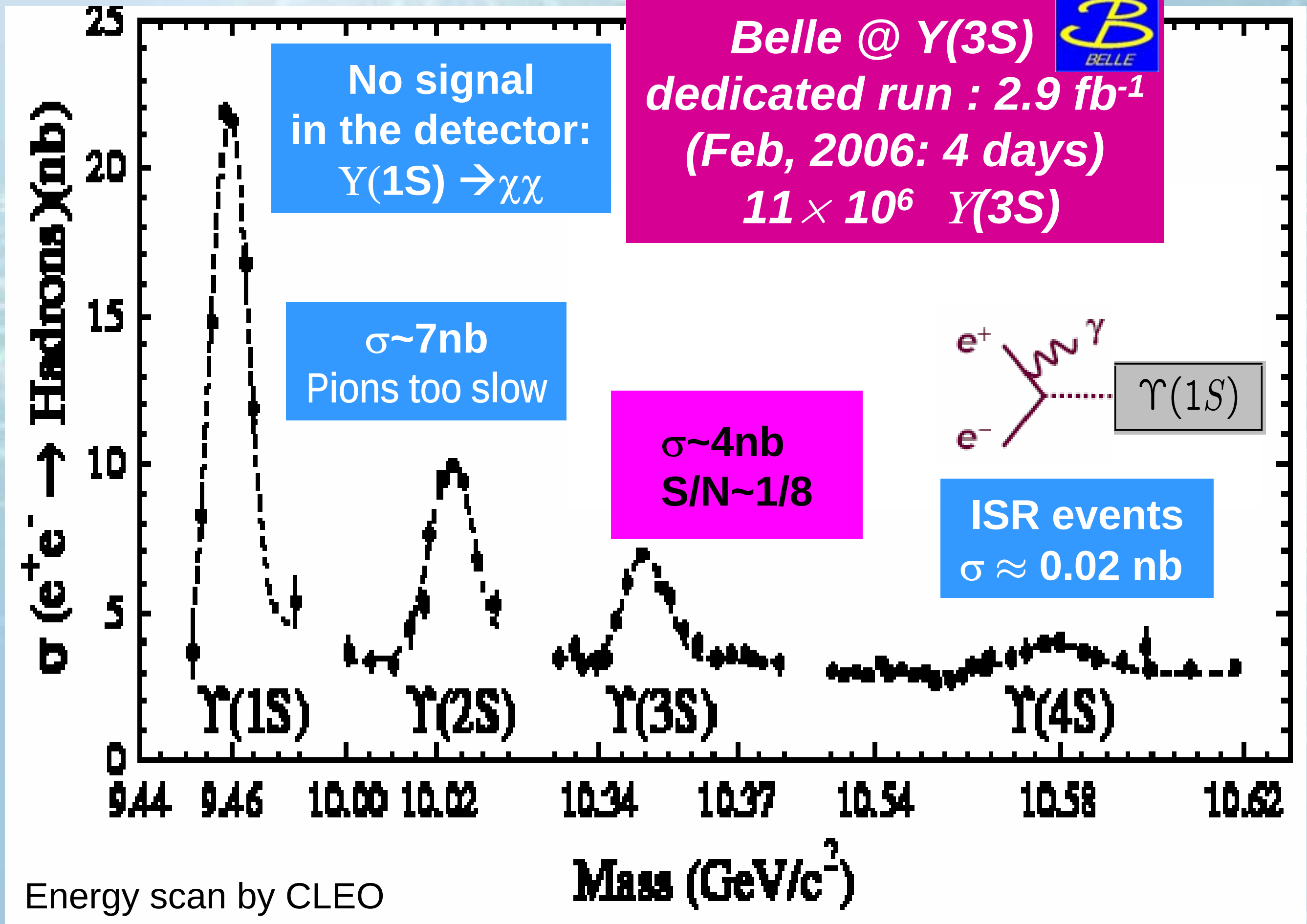
B. McElrath PRD 72, 103508 (2005)

From:

$$\Omega_\chi h^2 \approx 0.11 \approx \frac{0.1\text{pb}\cdot c}{<\sigma v>}$$

Υ(3S) – the best working point

➢ The decay $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$ provides the cleanest sample of Υ(1S) decays with sensitivity better than from 7 year Υ(4S) data

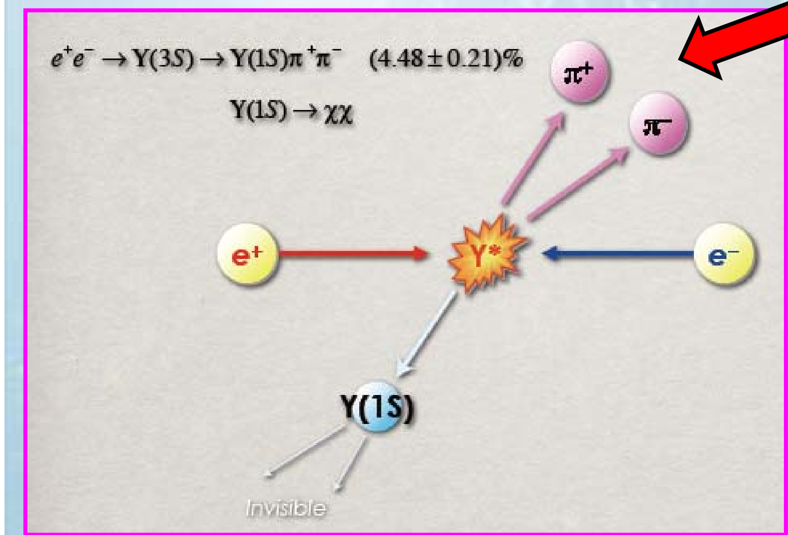


✓ **Υ(1S):** no signal in the detector

✓ **Υ(2S):** pions are too slow; very low trigger efficiency

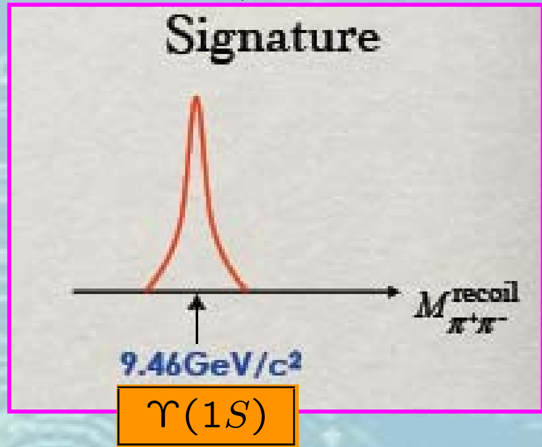
✓ **Υ(4S):** very small cross section and poor S/N (~ 0.001)

The signal and the control sample

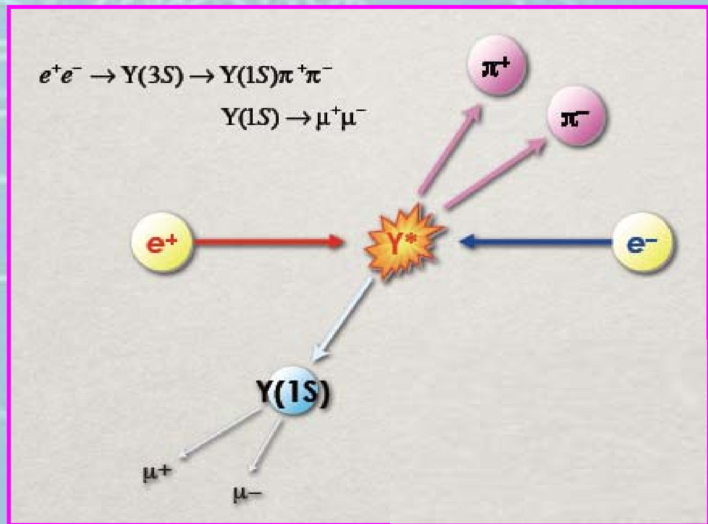


- The SIGNAL: Only two (slow) pions in the final state

- Look at the mass recoiling against the $\pi^+\pi^-$ pair

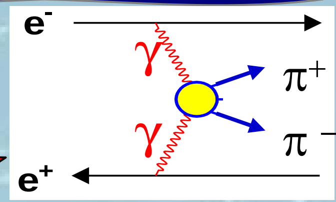


- In addition: a control sample:
  - to check if our Monte Carlo simulation reproduces the overall properties of the $\Upsilon(3S) \to \pi\pi\Upsilon(1S)$:
  - to estimate the number of $\Upsilon(3S)$ in the data sample
  - optimisation of selection criteria
  - determination of a shape of the recoil mass distribution



A dedicated trigger

- Selection of the $\Upsilon(3S) \to \pi^+\pi^-$ ($\Upsilon(1S) \to$ invisible)



- **Signature:** just two oposite-charge tracks in the events
- **Main background:** two-photon processes: $e^+e^- \to e^+e^-X$ (no-tag, $X \to \pi^+\pi^-(\pi^0)$, $\mu^+\mu^-$)
- A **dedicated two-track trigger** applied (looser than at the $\Upsilon(4S)$):

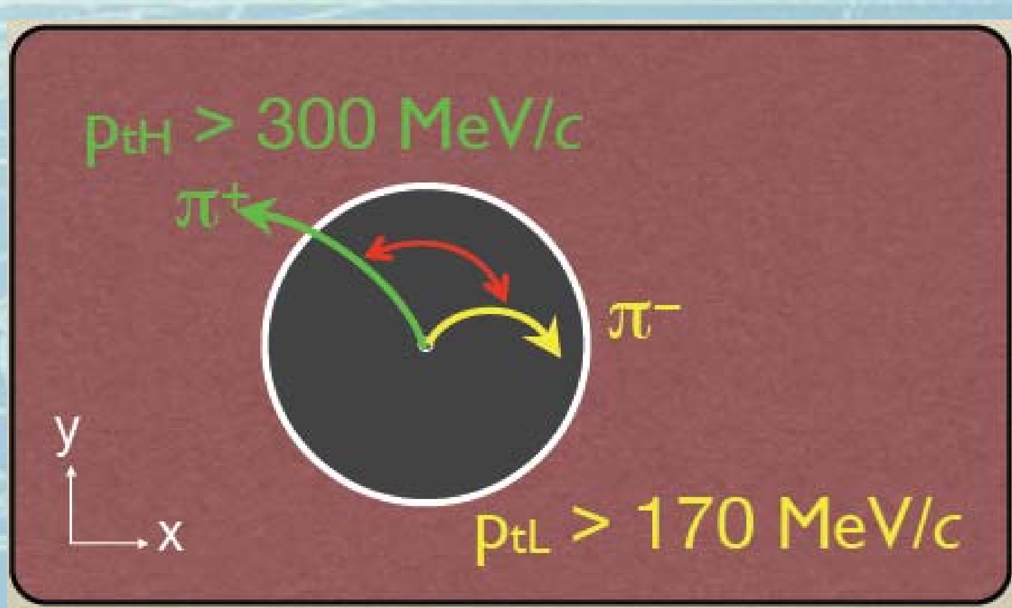
$$p_{tH} > 300 \text{ MeV/c}$$

$$p_{tL} > 170 \text{ MeV/c}$$

$$\phi(\pi\pi) > 30^0$$

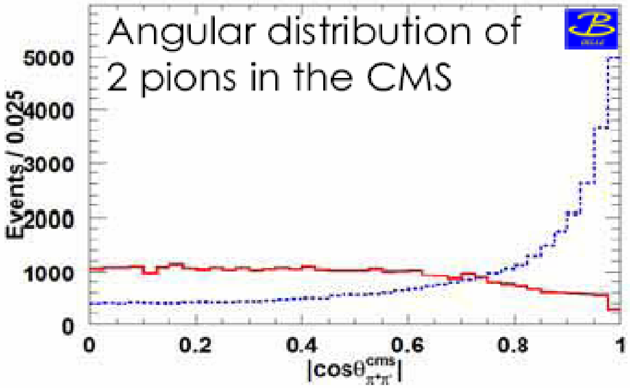
Trigger eff. 89.8%

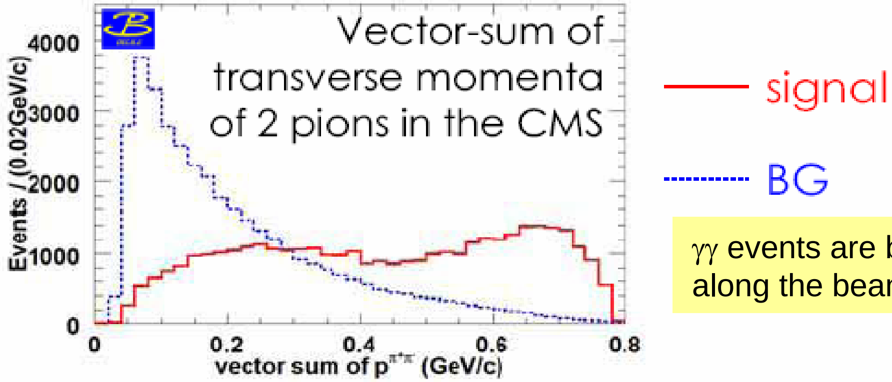
Trigger rate 850 Hz
(450 at the $\Upsilon(4S)$)



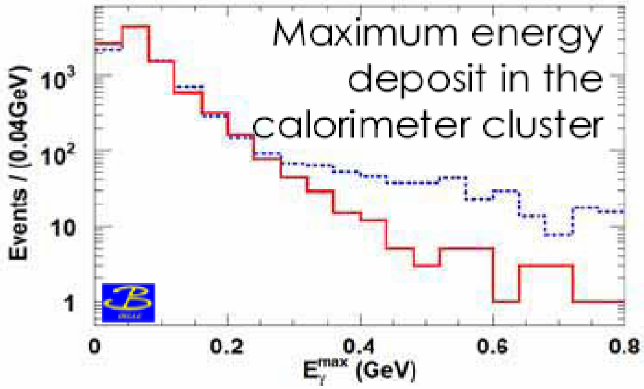
- **The total visible energy in the electromagnetic calorimeter less than 3 GeV (rejection of $\Upsilon(1S) \to$ neutral particles)**
- **Rejection of tracks identified as electrons, muons or kaons**

Suppression of two photon processes

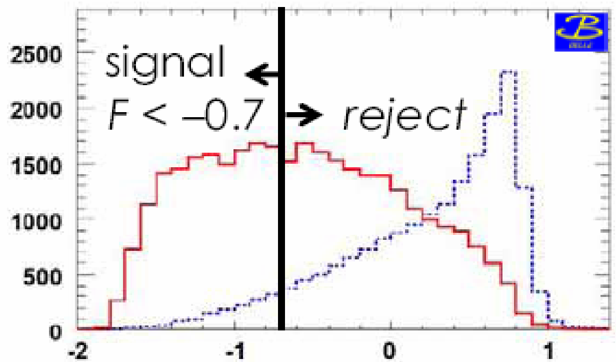




$\gamma\gamma$ events are boosted along the beam direction



Fisher discriminant



$$F = 0.87 \times |\cos\theta_{\pi\pi}| - 2.4 \times p_t^{\pi\pi} + 1.43 \times E_\gamma^{max}$$

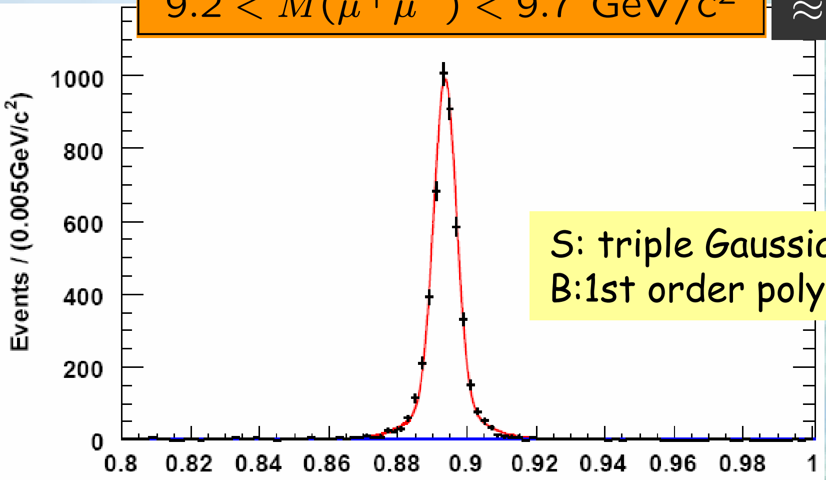
Event reconstruction eff. 9.1%

Overall eff: 9.1 × 89.8 = 8.2 %

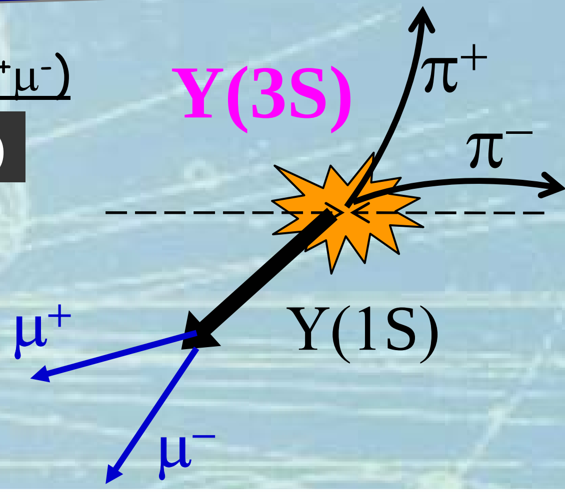
Studies of the control sample

- The control sample $\Upsilon(3S) \to \pi^+\pi^-$ ($\Upsilon(1S) \to \mu^+\mu^-$)

$9.2 < M(\mu^+\mu^-) < 9.7$ GeV/c^2 $\approx$ M(Υ(1S))

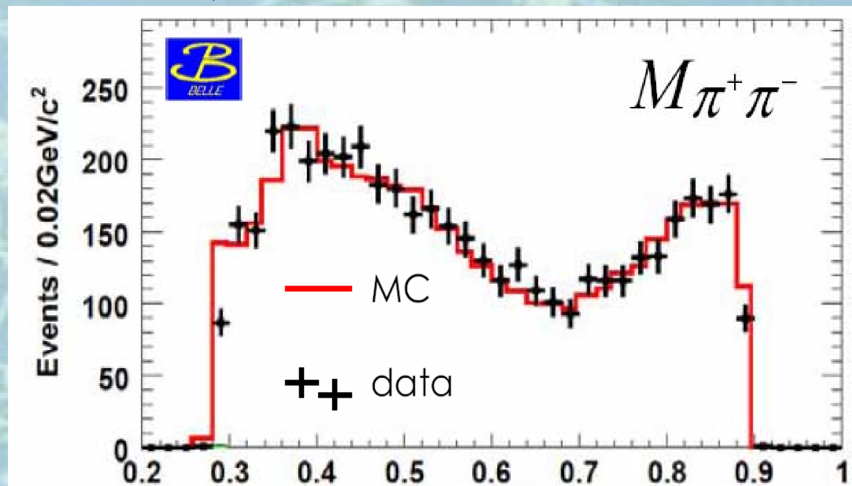


$\Delta M = M(\mu^+\mu^-\pi^+\pi^-) - M(\mu^+\mu^-)$ GeV/c^2



Signal:	4902+-71 events
Background:	87+-15 events
Detection efficiency:	39.7 %

Br(Υ(1S) → $\mu^+\mu^-$) = **2.48%**

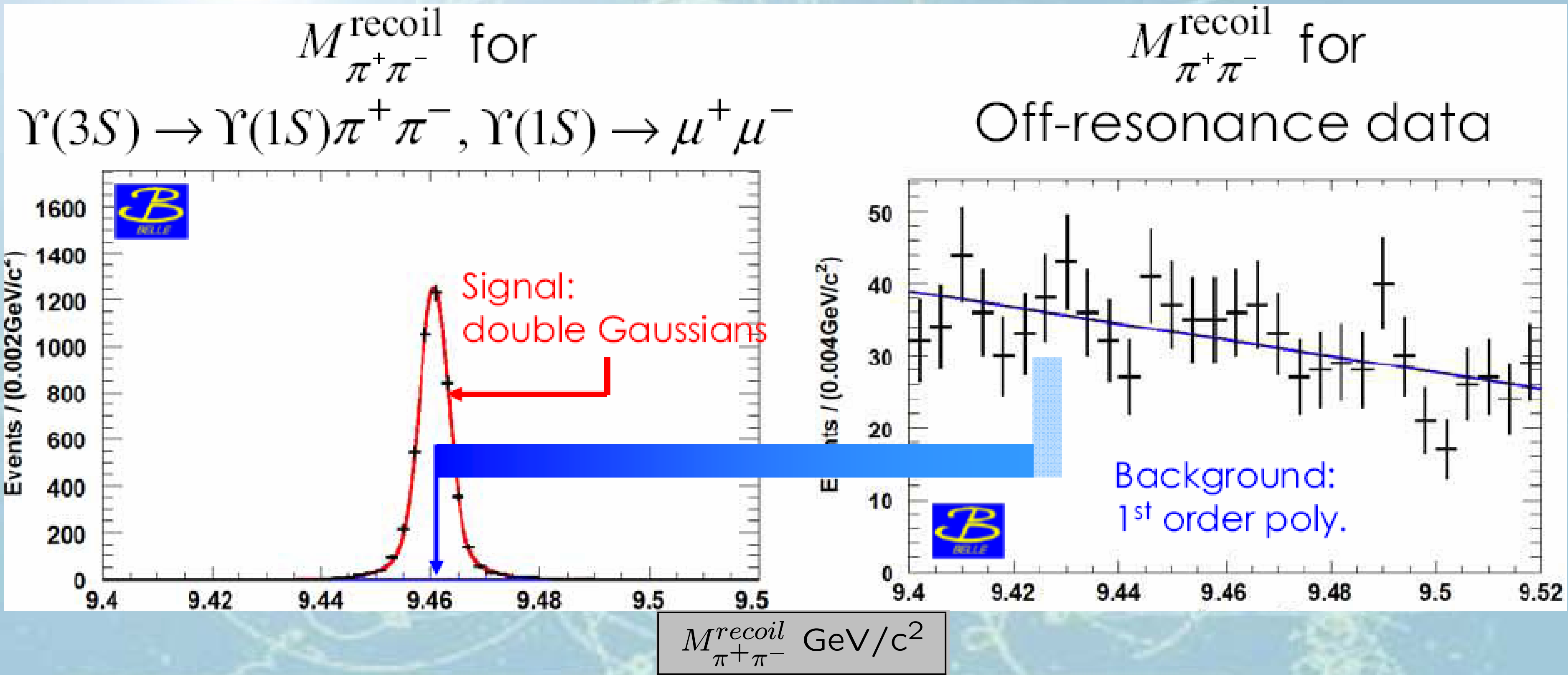


$M(\pi^+\pi^-)$ GeV/c^2

$$N_{\Upsilon(3S)\to\Upsilon(1S)\pi^+\pi^-} = \left(498.3^{+7.2}_{-7.1}(\text{stat}) \pm 34.6(\text{syst})\right)\times 10^3$$

Other control variables also agree data vs MC

The control sample as the peaking background to the signal itself



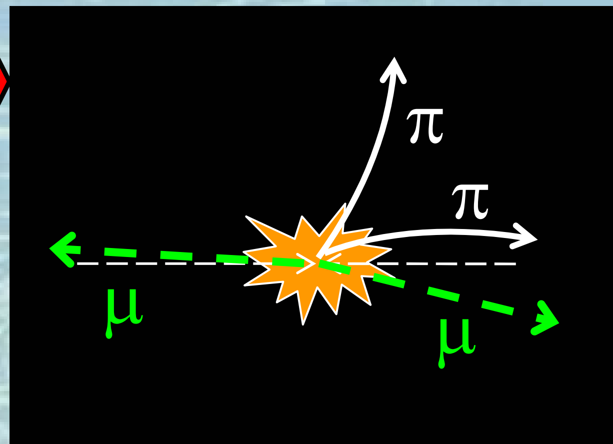
The recoil mass against the ($\pi^+\pi^-$) subsystem peaks at the mass of Υ(1S) for those cases where all of the Υ(1S) decay products go outside of the detector acceptance

➔ The control sample provides a peaking background

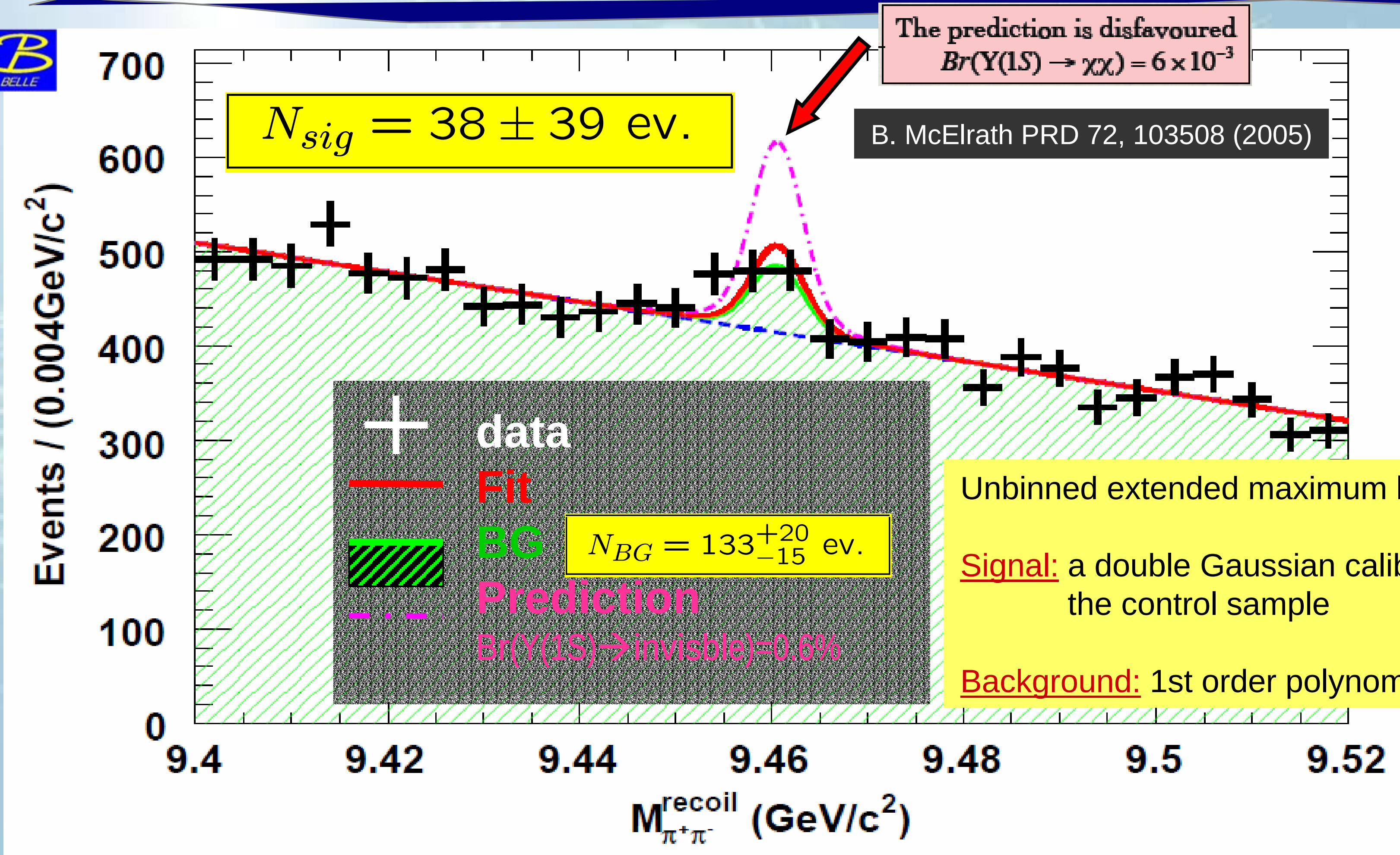
The peaking background

The source	# of events
$\Upsilon(1S) \to \mu^+\mu^-$	77.3 ± 12.0
$\Upsilon(1S) \to e^+e^-$	50.3 ± 8.0
$\Upsilon(1S) \to \tau^+\tau^-$	5.2 ± 1.0
$\Upsilon(1S) \to \nu\bar{\nu}$	0.4 ± 0.1
$\Upsilon(1S) \to$ other modes	$0.0 \quad +2.8$
Others	$0.0 \quad +12.9$
Total	**$133.2^{+19.7}_{-14.6}$**

The dominant contribution:



Search for light dark matter on Υ(3S)



Unbinned extended maximum likelihood fit

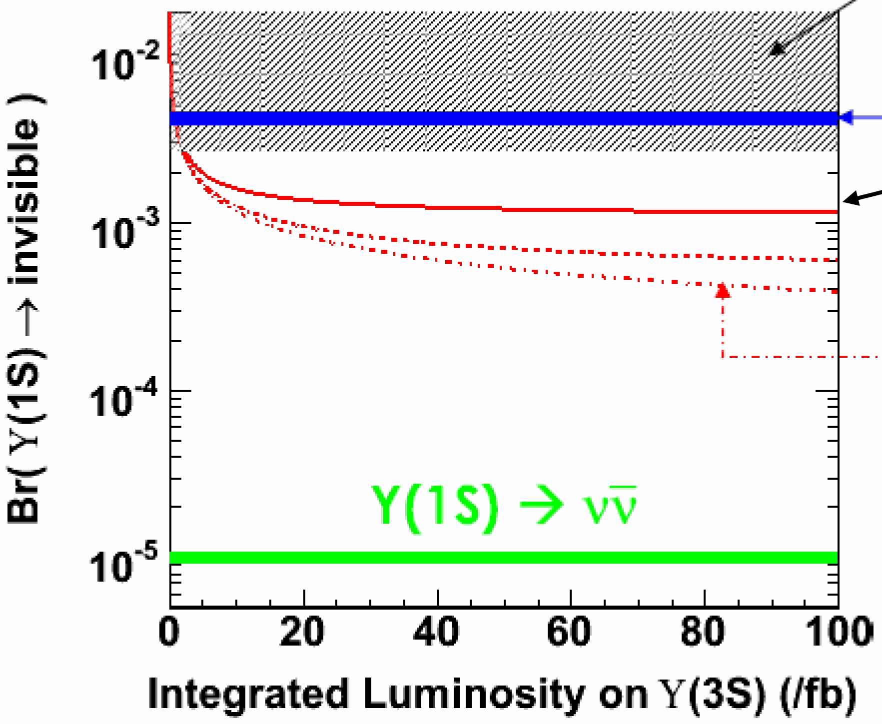
Signal: a double Gaussian calibrated using the control sample

Background: 1st order polynomial

$\mathcal{B}(\Upsilon(1S) \to \text{invisible}) < 2.5 \times 10^{-3}$ (90 % C.L.)

[PRL 98, 132001 (2007)]

Future prospects



More data → ~ 1 × 10^{-3} can be reached; then saturation

With super-forward calorimeter & μ-detector to reduce peaking BG

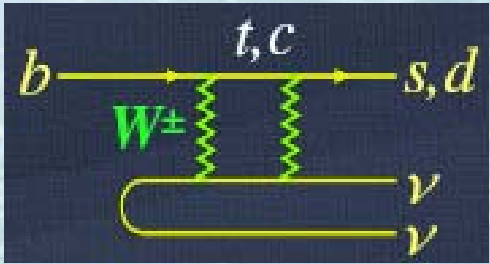
better veto (hermeticity) on Υ(1S) → l^+l^- (l=e,μ)

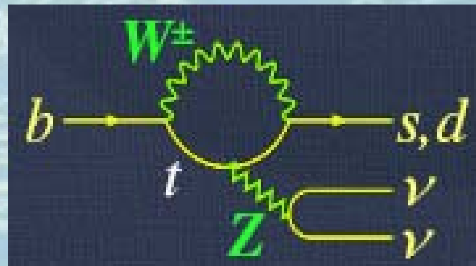
If we install super-forward lepton detectors to veto Υ(1S) → $\ell^+\ell^-$, sensitivity of the branching fraction improves to ~ 4×10^{-4} with L = 100 fb^{-1}.

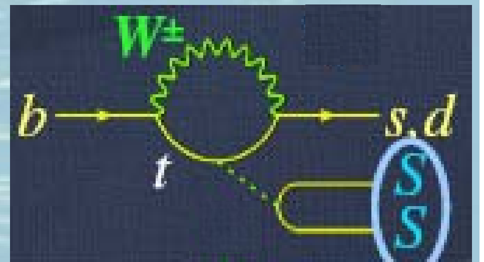
Search for B → $h^{(*)}\nu\underline{\nu}$ decays

Motivation for the search for B → h(*)νν

- h(*) stands for the light mesons: π^{+-}, π^0, ρ^{+-}, ρ^0, K^{+-}, K^0_s, K^{*+-}, K^{*0} and ϕ
- Proceed through loop diagrams & electroweak penguins



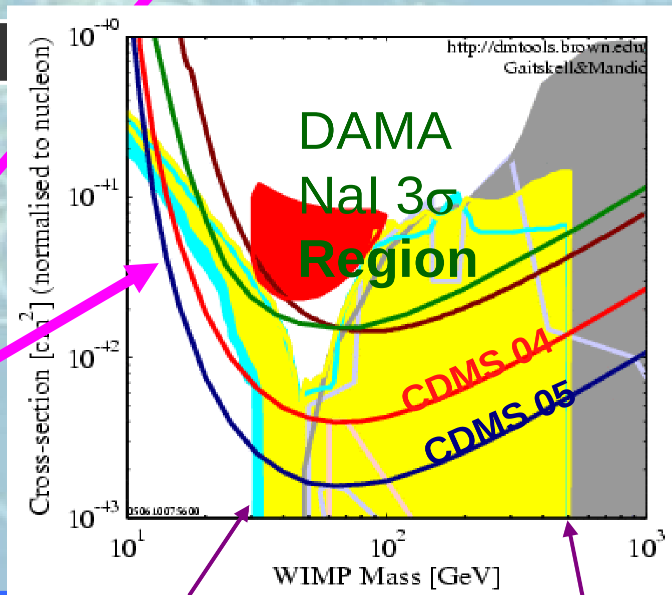




- Advantages:
  - ✓ **Theoretically clean:**
    no long-distance contributions (present in B→ $K^{(*)}l^+l^-$)
    SM (NLO) expectations: G. Buchalla et al., PRD 63, 014015 (2001)

    $\mathcal{B}(B \to K\nu\bar{\nu}) = 4 \times 10^{-6}$ $\mathcal{B}(B \to K^*\nu\bar{\nu}) = 1.3 \times 10^{-5}$

  - ✓ Sensitive to the New Physics (in both diagrams; branching fraction enhancement e.g. SUSY)
  - ✓ Sensitivity to the light dark matter (M_S < 2 GeV)
    C. Bird, PRL 93, 201803 (2004)
  - ✓ M < 10 GeV essentially out of reach for direct searches

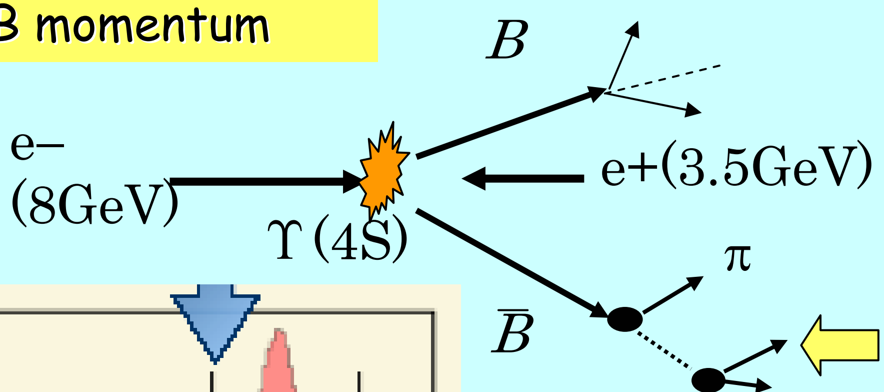


Lee-Weinberg window

B meson beam: full reconstruction method

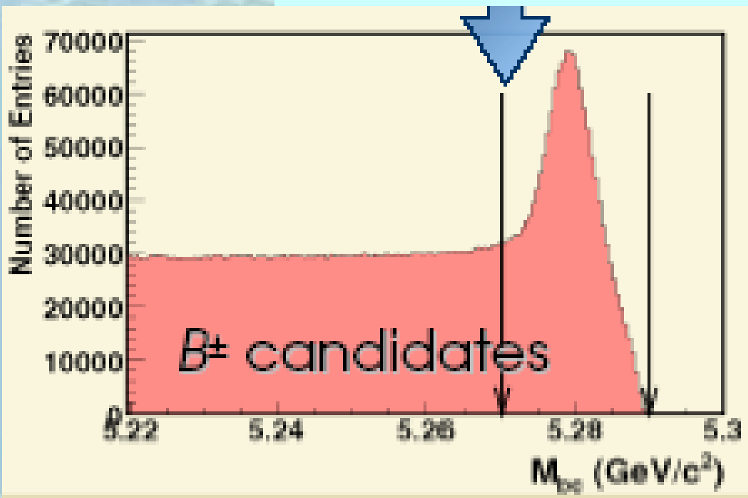
- **One of the two B's from the decay $\Upsilon(4S) \rightarrow B\,\underline{B}$ is fully reconstructed in order to tag:**

  - B production
  - B flavor/charge
  - B momentum



Decays of interests
$B \rightarrow X_u\, l\, \nu$,
$B \rightarrow K\, \nu\, \nu$
$B \rightarrow D\tau\nu$, $\tau\nu$

Full reconstruction
(tagging rate of 0.1~0.3%)
$D^{(*)}\pi$, $D^{(*)}\rho$, $D^{(*)}a_1$, or $D^{(*)}D_s^{(*)}$



Offline single B meson beam !

A powerful tool in particular for B decays with neutrinos

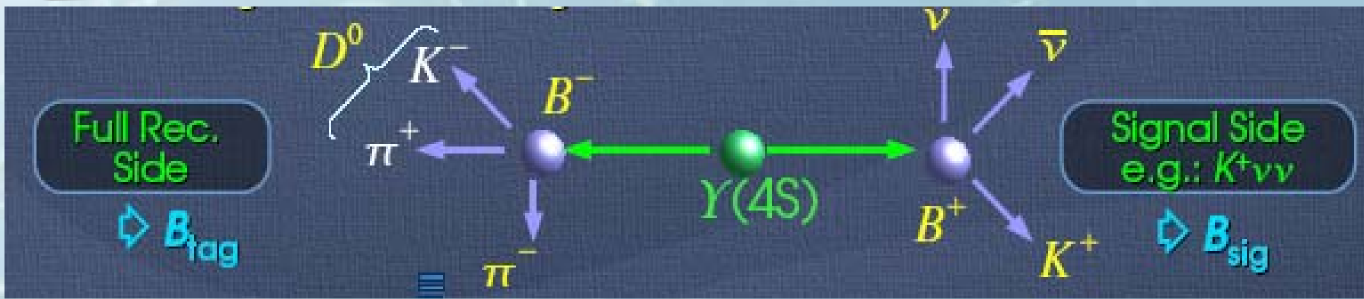
$B \to h^{(*)}\nu\bar{\nu}$: reconstruction

Presented at FPCP7, Bled, Slovenia May.2007; to be submitted to PRL

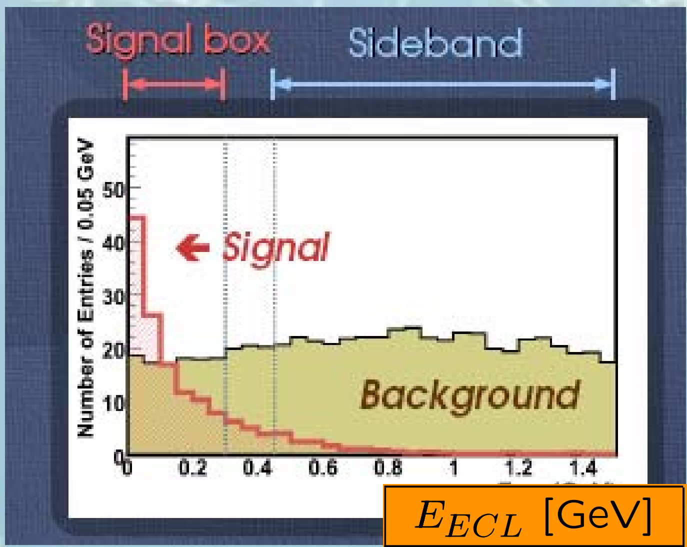
492 fb^{-1}

535× 10^6 B-meson pairs

- Exploit the offline beam of B mesons:



- The particles which were not attributed to B_{tag} are used to reconstruct $B_{sig} \to h^{(*)}\nu\bar{\nu}$
- <u>The key variable:</u> amount of extra energy in the calorimeter ECL (summation over neutral clusters that are not associated neither with B_{tag} nor the $h^{(*)}$):



$$E_{ECL} = E_{total} - E_{rec.}$$

E_{total} –total visible energy measured by the calorimeter ECL

E_{rec} – measured energy of reconstructed objects including the B_{tag} and the signal side $h^{(*)}$ candidate

$E_{ECL} < 0.3$ GeV — The signal region

$E_{ECL} \geq 0.3$ GeV — The presence of additional neutral clusters

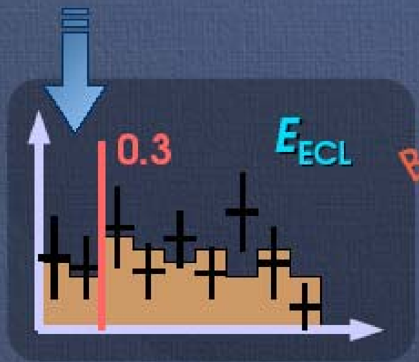
$B \to D^* l\nu$ used as a control sample: data and MC agree

B → K*νν̄ results

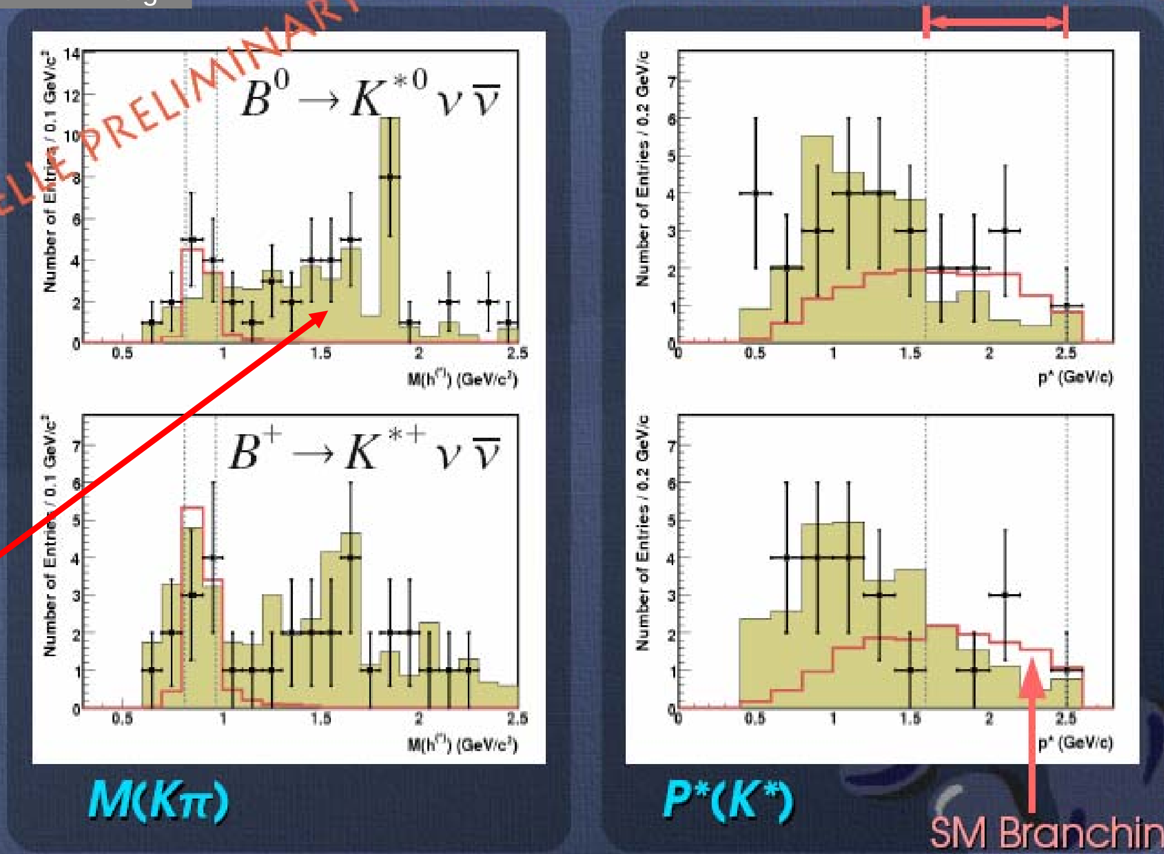
The dominant background: generic $B^0\bar{B}^0$ decays

The $P^*(K^*)$ is defined in the rest frame of the B_{sig}

Momentum requirement (1.6-2.5 GeV/c)
lower bound: suppresses $b \to c$
upper bound: rejects 2-body (e.g. $K^*\gamma$)



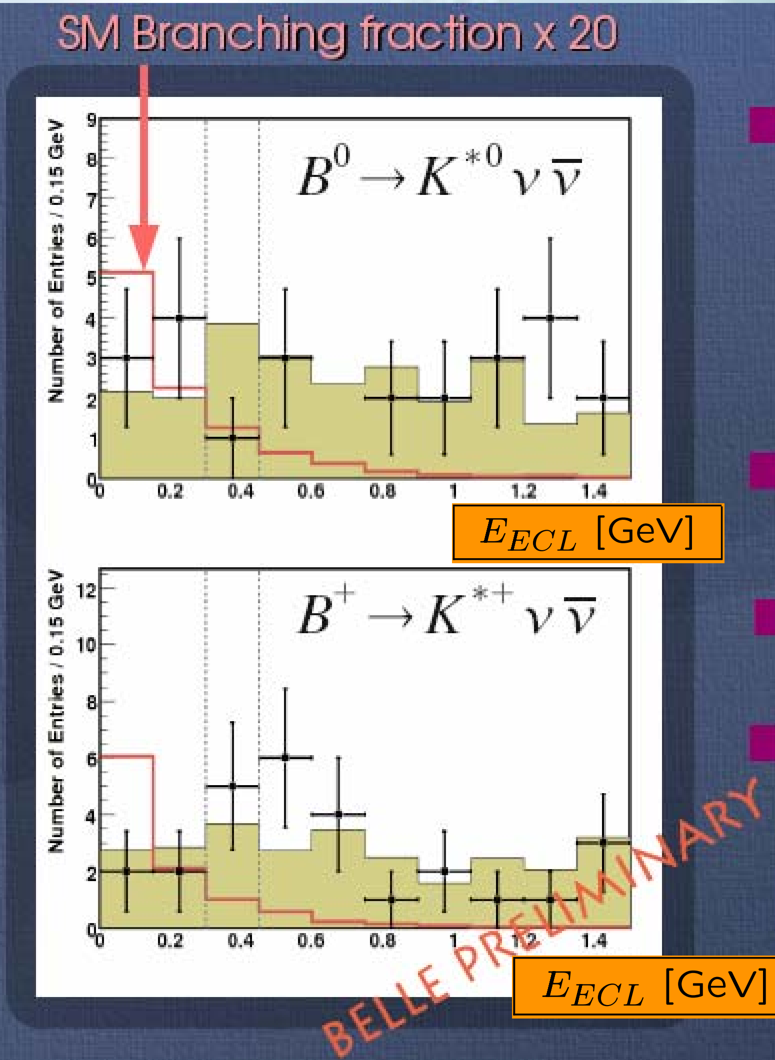
Pickup the events in the signal box (E_{ECL}<0.3) and examine other variables:



SM Branching fraction x 20

(Shaded) distributions of backgrounds are estimated with MC simulations

B → K*νν results



- SM Predictions:

$$Bf(B \to K^* \nu \bar{\nu}) \sim 1.3 \times 10^{-5}$$
$$Bf(B \to K \nu \bar{\nu}) \sim 4 \times 10^{-6}$$

Ref. Buchalla et al. PRD 63, 014015 (2001)

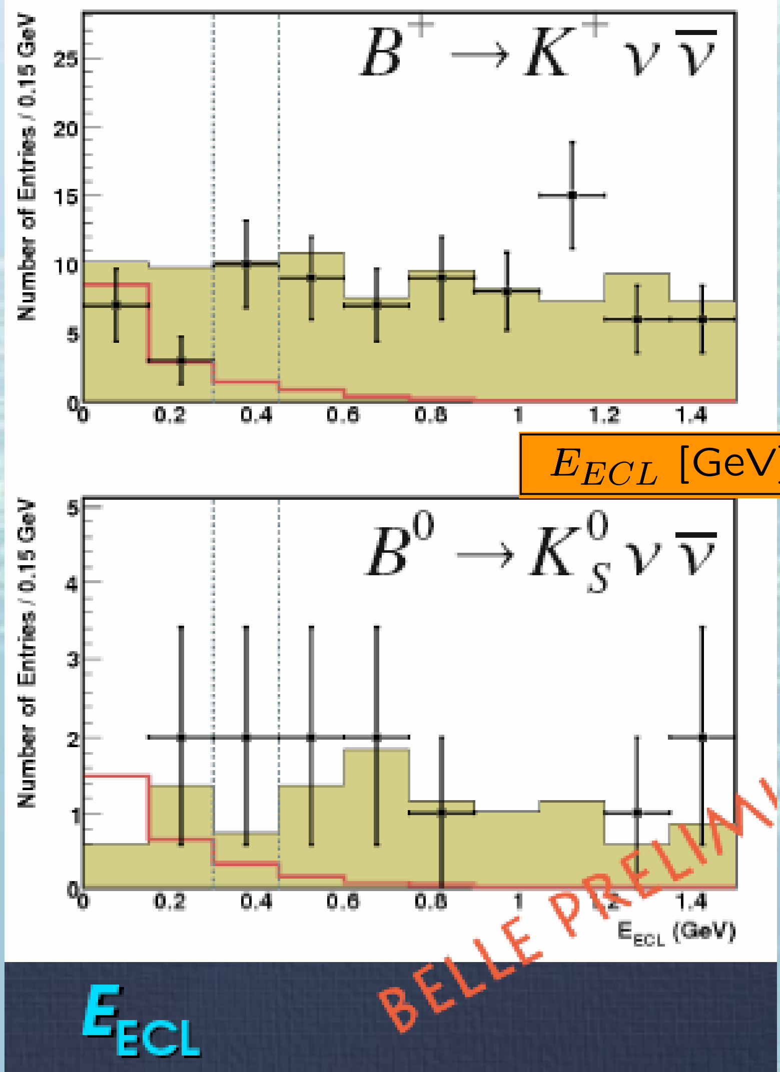
- Reconstructed modes:

$$K^{*0} \to K^+ \pi^-, K^{*+} \to K_S^0 \pi^+ \,\&\, K^+ \pi^0$$

- Supersedes summer 2006 result, with improvements on MC statistics.
- New results (U.L. @ 90% C.L.):

	N_{obs}	N_b	U.L.
$K^{*0} \nu \bar{\nu}$	7	4.2±1.4	< 3.4x10^{-4}
$K^{*+} \nu \bar{\nu}$	4	5.6±1.8	< 1.4x10^{-4}

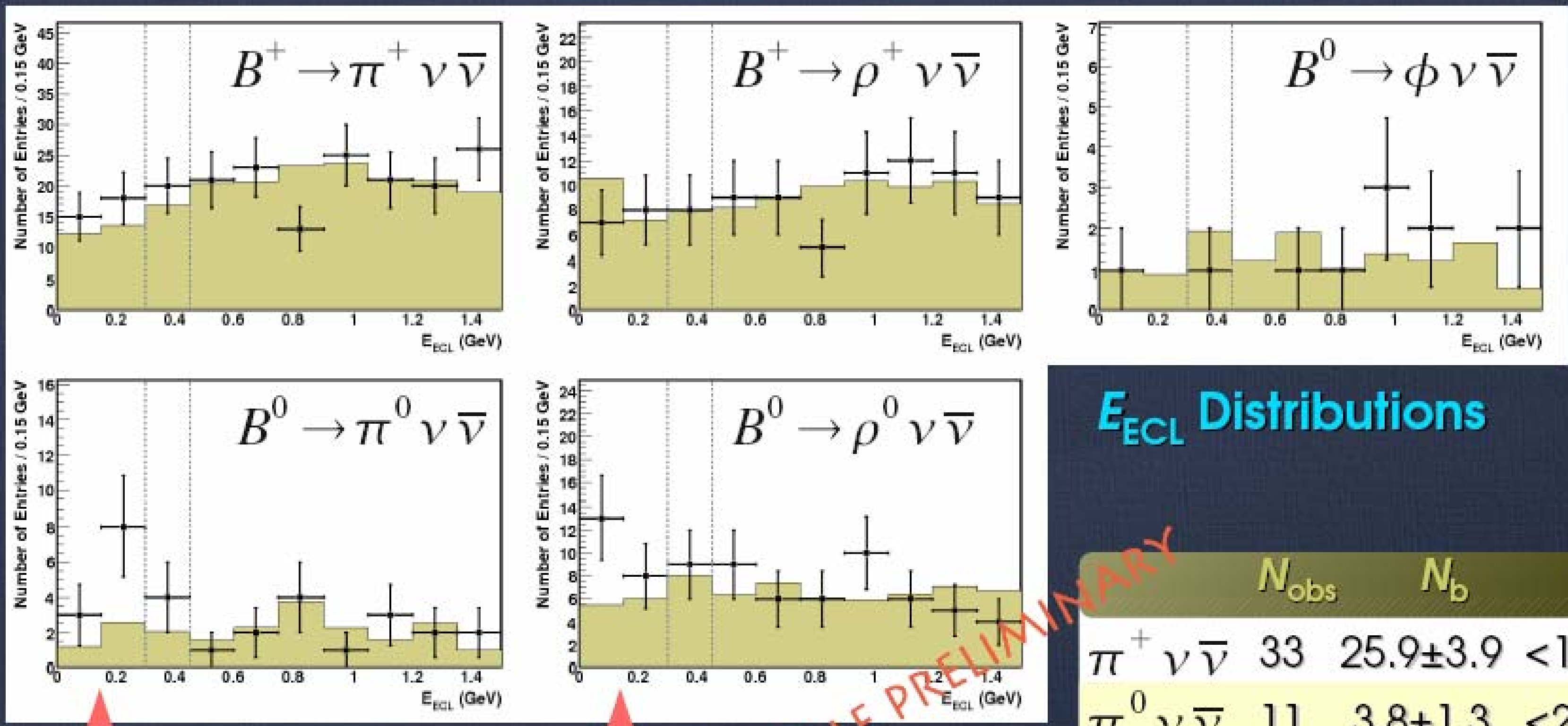
B → Kνν̄ results



Most stringent limit, but still 3x larger then the SM branching fraction (4×10^{-6})

	N_{obs}	N_b	U.L.
$K^+ \nu \bar{\nu}$	10	20.0±4.0	$< 1.4 \times 10^{-5}$
$K^0 \nu \bar{\nu}$	2	2.0±0.9	$< 1.6 \times 10^{-4}$

B → (π,ρ,φ)νν̄ results



E_{ECL} Distributions

Small excess (<2σ) found, need more data to verify.

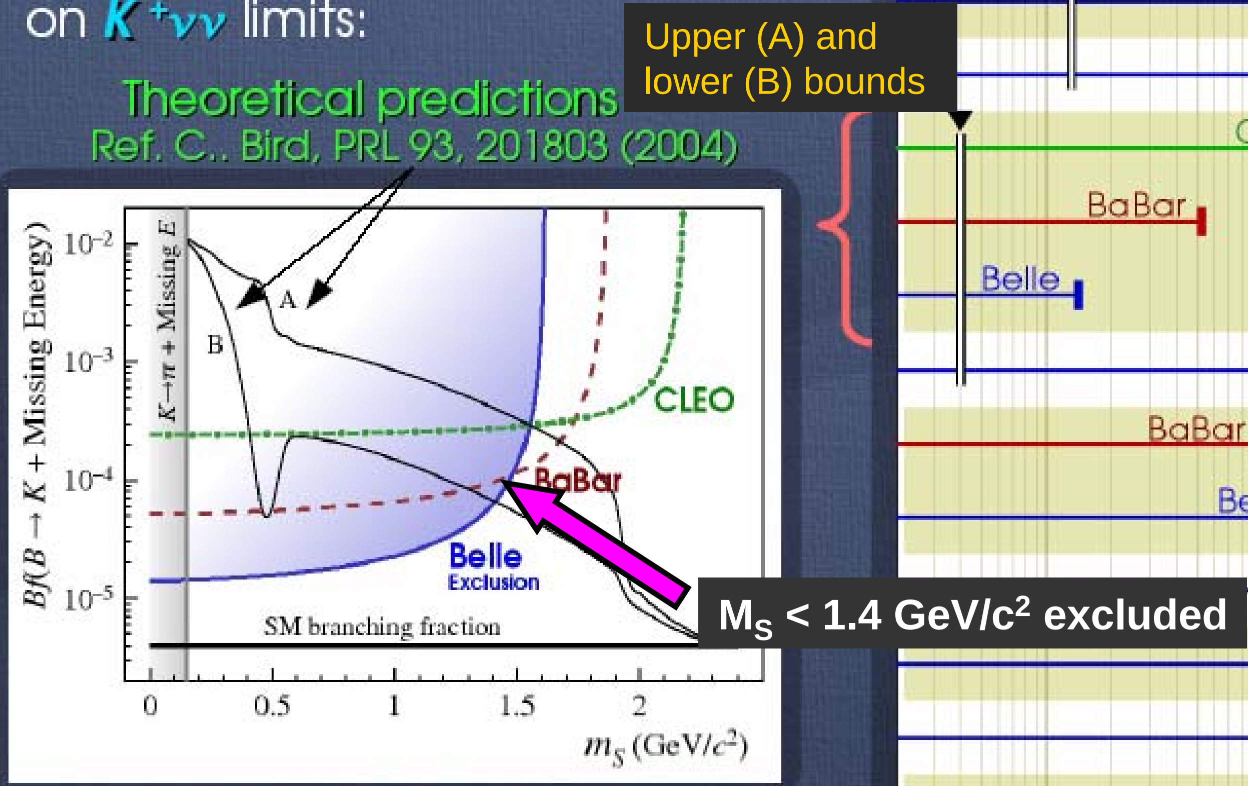
BELLE PRELIMINARY

	N_{obs}	N_b	U.L.
$\pi^+ \nu \bar{\nu}$	33	25.9±3.9	<1.7x10^{-4}
$\pi^0 \nu \bar{\nu}$	11	3.8±1.3	<2.2x10^{-4}
$\rho^+ \nu \bar{\nu}$	15	17.8±3.2	<1.5x10^{-4}
$\rho^0 \nu \bar{\nu}$	21	11.5±2.3	<4.4x10^{-4}
$\phi \nu \bar{\nu}$	1	1.9±0.9	<5.8x10^{-5}

$B \to h^{(*)}\nu\bar{\nu}$: summary

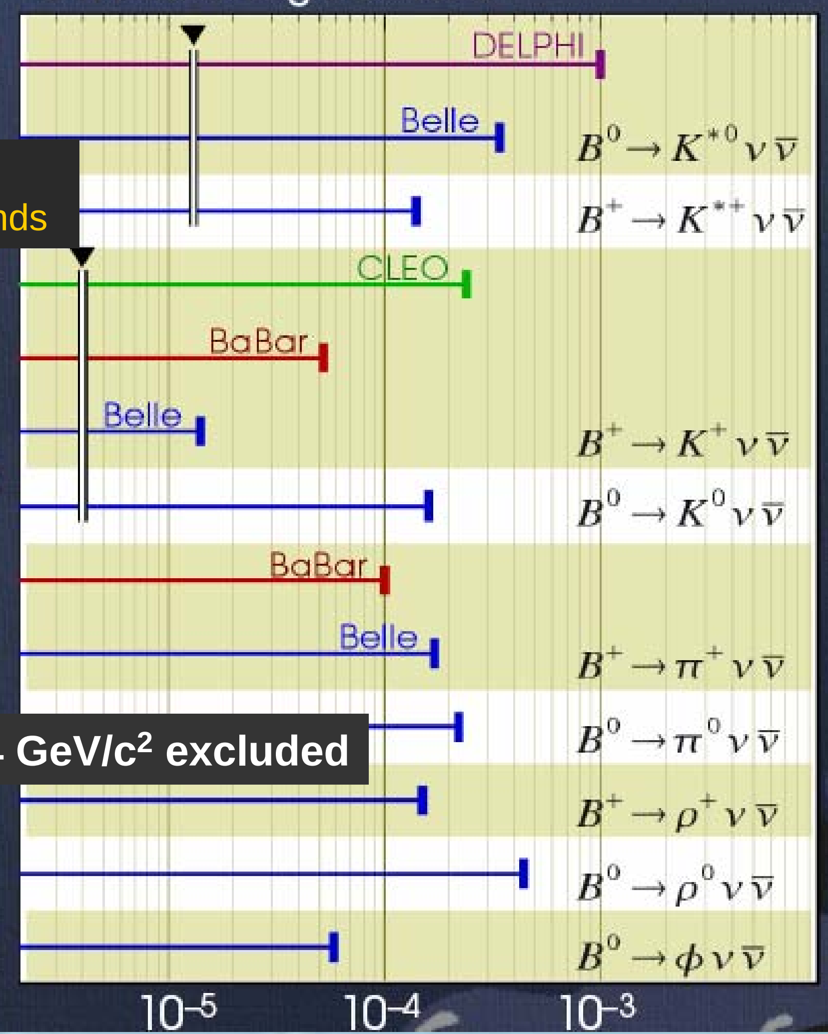
- Summary of experimental limits:
- Limit on light dark matter based on $K^+\nu\nu$ limits:

Theoretical predictions
Ref. C.. Bird, PRL 93, 201803 (2004)



The curvature is due to the lower bound on $P^*(K)$

SM branching fractions

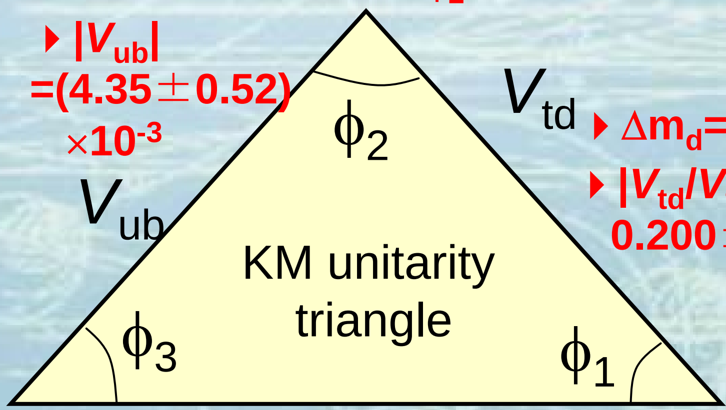


Future prospects of B-factories

Achievements of B-factories

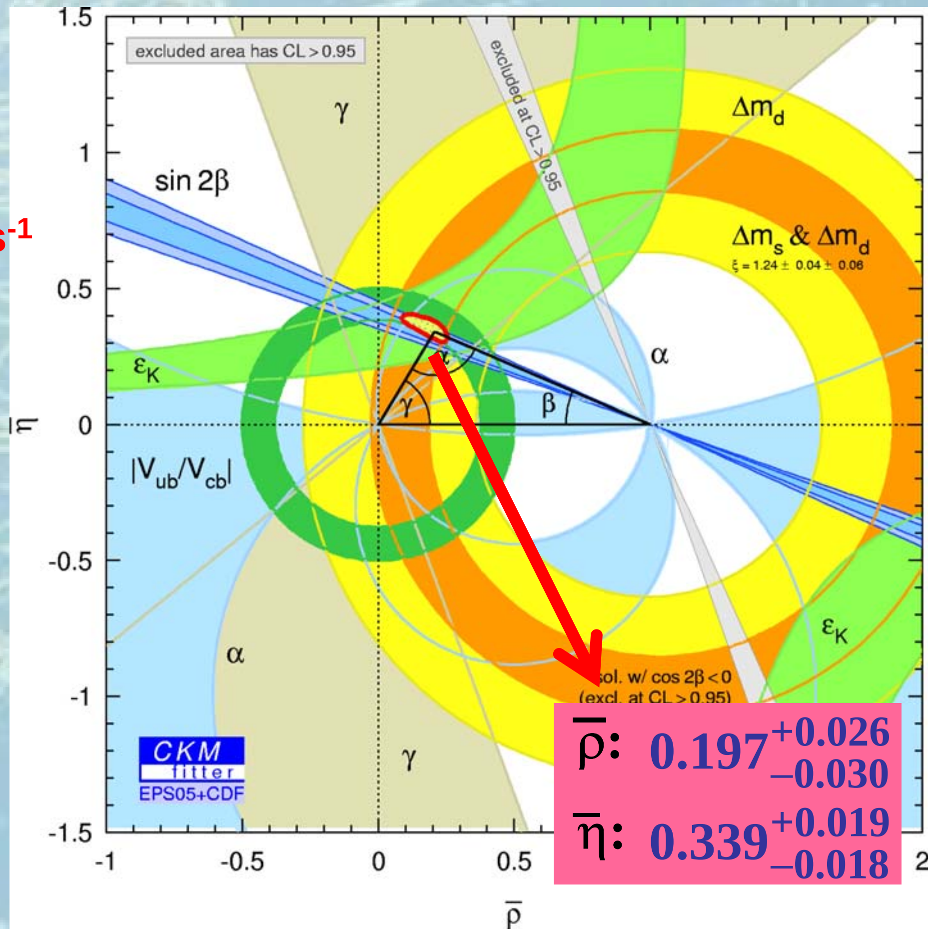
Quantitative confirmation of the CKM model

- $75^\circ < \phi_2 < 113^\circ$
- $|V_{ub}| = (4.35 \pm 0.52) \times 10^{-3}$
- $\Delta m_d = 0.511 \text{ps}^{-1}$
- $|V_{td}/V_{ts}| = 0.200 \pm 0.046$



- $22^\circ < \phi_3 < 113^\circ$
- $\sin 2\phi_1 = 0.728 \pm 0.061$
- $|V_{cb}| = (4.08 \pm 0.27) \times 10^{-2}$

(Belle, 2005)



Future prospects of B-factories

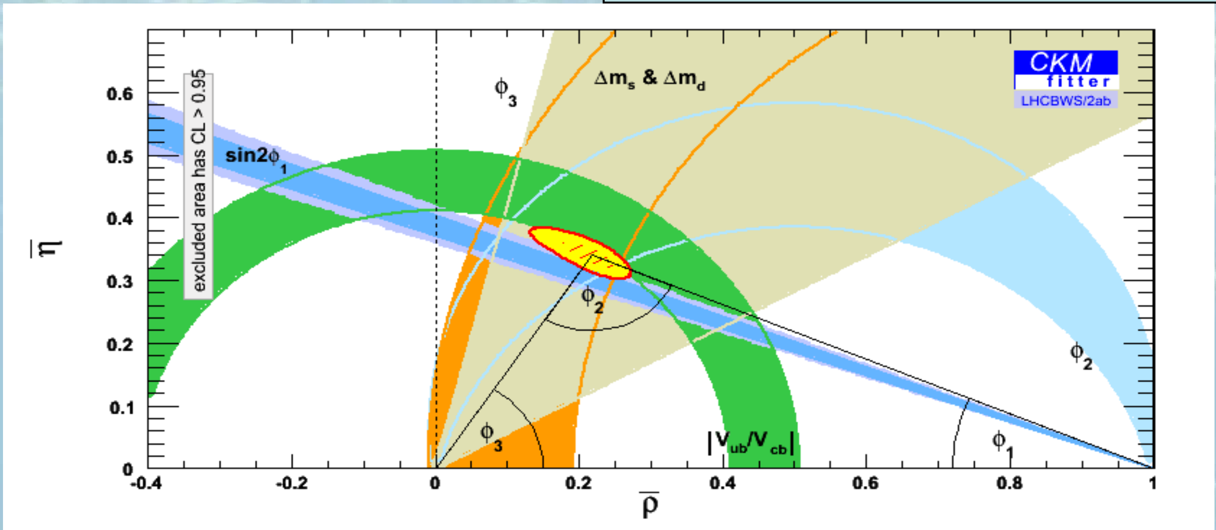
- ~2/ab from BaBar+Belle by the end of 2008
- BaBar will end in 2008
- Belle proposing a major upgrade
  - part of the "Japanese HEP master plan"
  - luminosity goal : 8 x $10^{35}/cm^2/s$ (peak), 50/ab (integrated)

Important topics with $2ab^{-1}$

- $b \rightarrow s$ tCPV: $2.6\sigma \rightarrow \sim 4\sigma$ (for the same central values)
- Improved study of D^0 mixing
- Follow-up studies of $B \rightarrow \tau\nu$
- Evidence for $B \rightarrow \mu\nu$
- More precise angle measurements, in particular ϕ_3 with significant observation in $B \rightarrow D^{(*)}K^{(*)}$

Physics reach at 2ab^{-1}

	Today	2ab^{-1}
$\sin 2\phi_1/\beta(b \to c)$	0.026	0.020
$\sin 2\phi_1/\beta(b \to s)$	0.05	0.035
ϕ_2	11°	6°
ϕ_3	19°	12°
V_{ub}(inclusive)	6.3%	4.9%
Δm_d	0.8%	0.8%
$B(B \to (\rho,\omega)\gamma)$	20.4%	10.3%
$B(B \to \tau\nu)$	36%	27%
$A_{FB}(K^* l^+ l^-)$	23%	10%



$\delta(\bar{\rho},\bar{\eta})$ = (10.0%,4.4%)

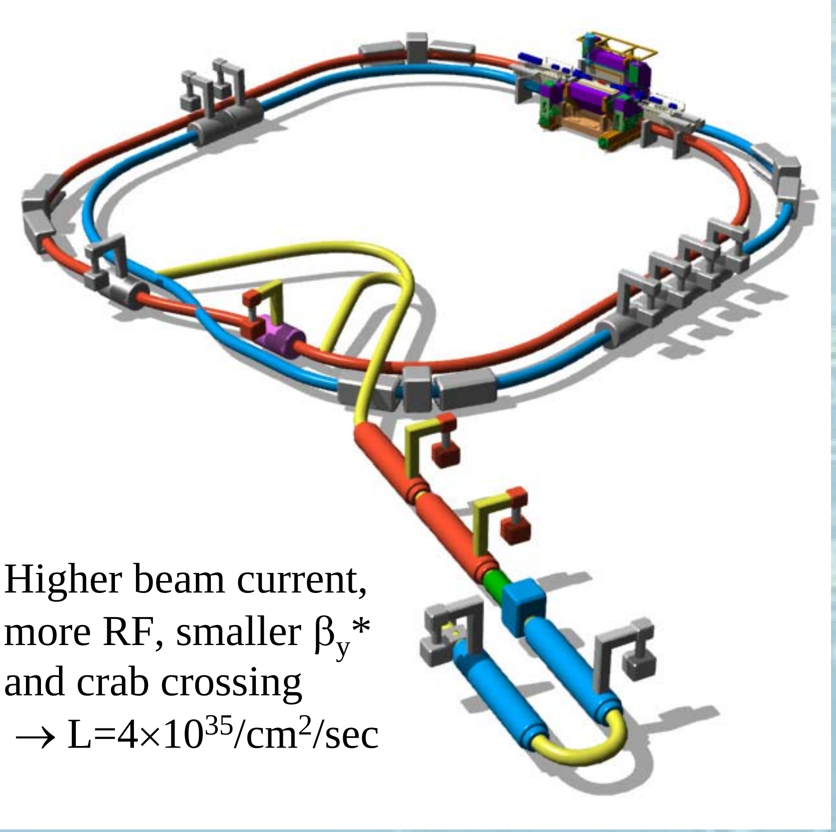
R. Itoh, @LHC upgrade WS, Jan. 2007

SuperKEKB

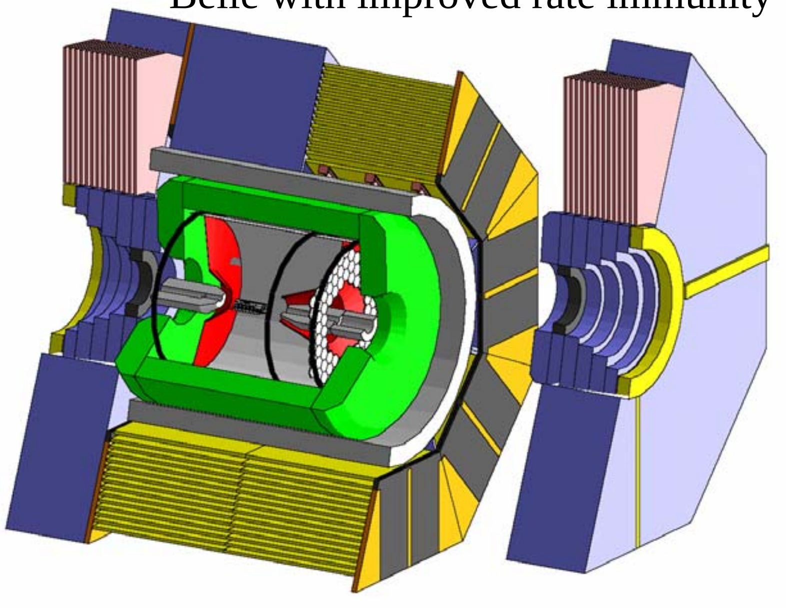
- *Asymmetric energy e^+e^- collider at E_{CM}=m(ϒ(4S)) to be realized by upgrading the existing KEKB collider.*
- *Super-high luminosity ≅ 8×10^35/cm²/sec → 1×10^10 BB per yr.*

→ 9×10^9 $\tau^+\tau^-$ per yr.

http://belle.kek.jp/superb/loi



Higher beam current, more RF, smaller β_y* and crab crossing
→ L=4×10^35/cm²/sec

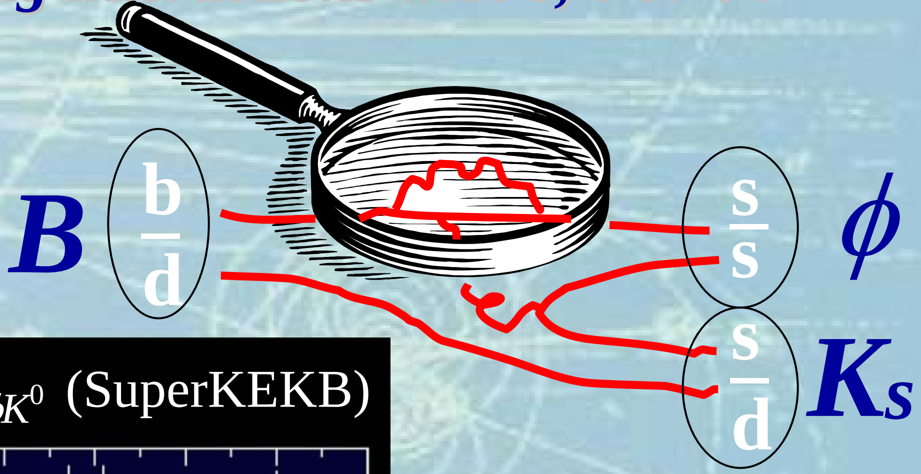


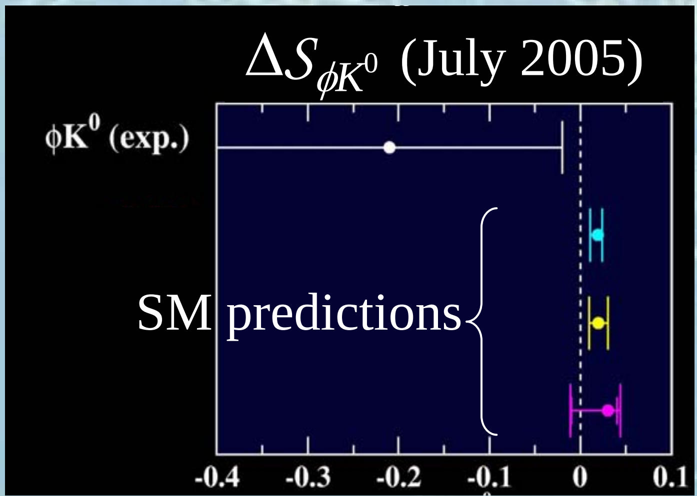
Belle with improved rate immunity

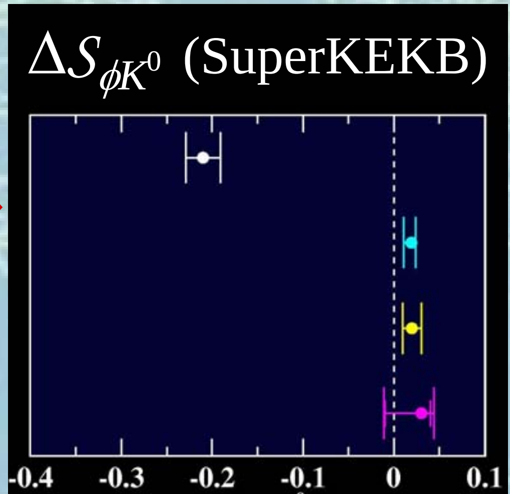
Flavour physics at SuperKEKB

1. *Are there new CP-violating phases ?*
2. *Are there new right-handed currents ?*
3. *Are there new flavor-changing interactions with b, c or τ ?*

SuperKEKB will answer these questions by scrutinizing loop diagrams.



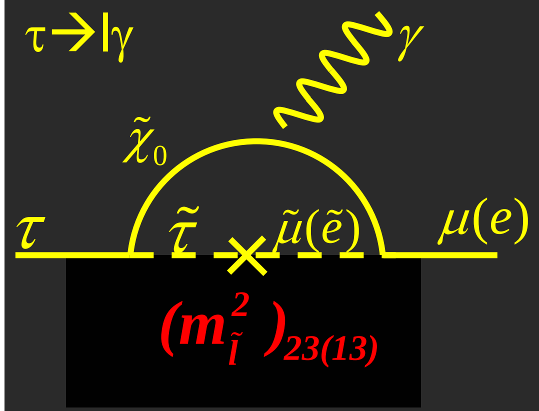


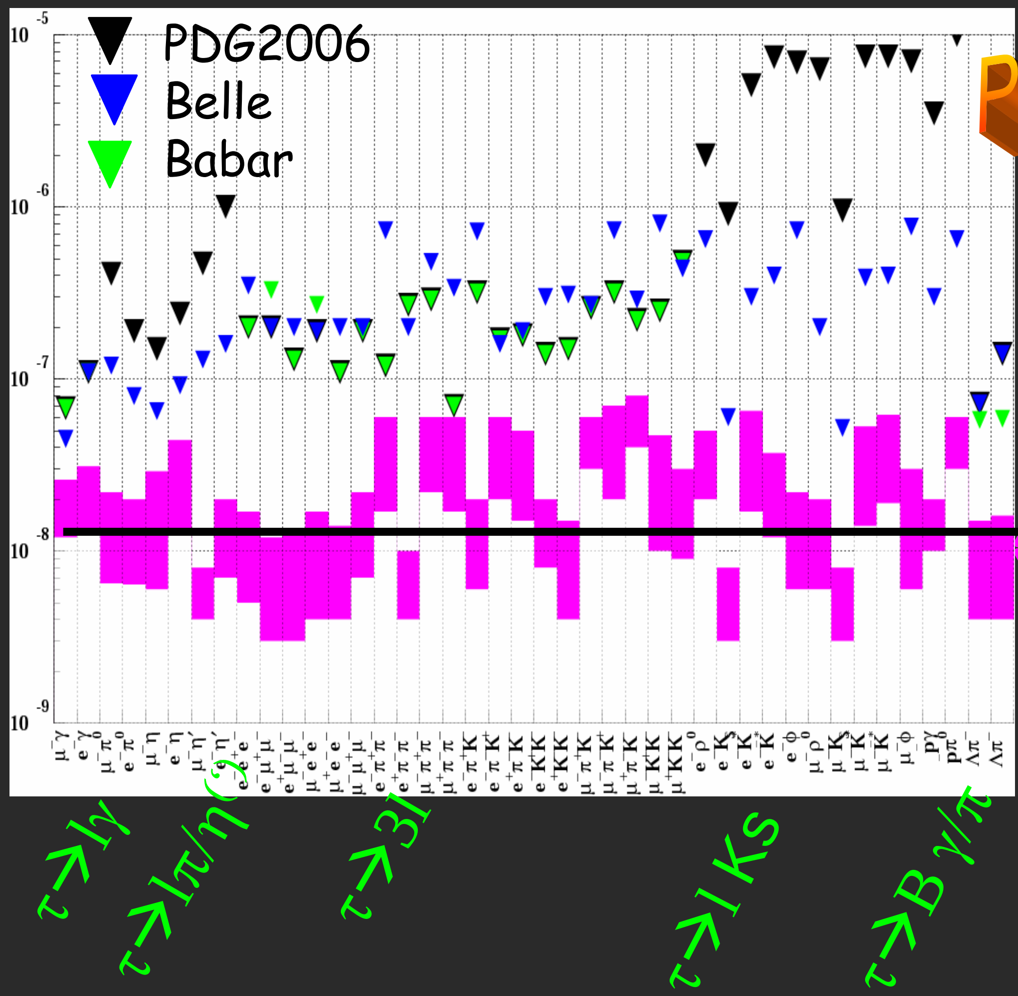


LFV search at the SuperKEKB

cf) Hayasaka at BNM2006

τ→lγ



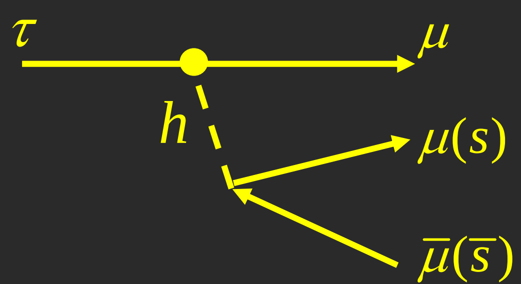


Preliminary

based on eff. and N_{BG} of most sensitive analysis

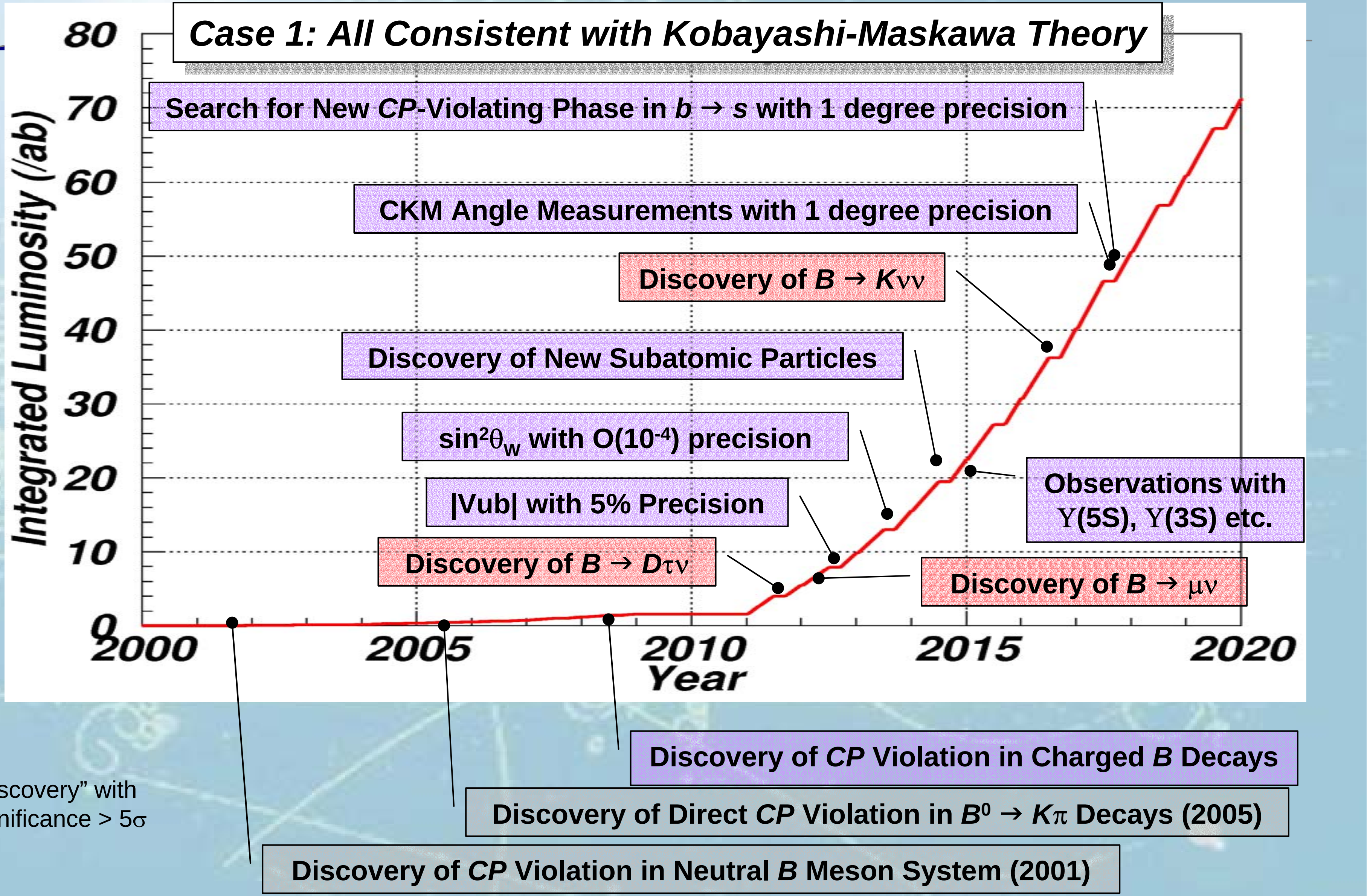
Estimated upper limit range of Br

τ→3l, lη



Search region enters into O(10^{-8}→10^{-9})

Expected highlights at SuperKEKB



"Discovery" with significance > 5σ

Summary

Invisible decays of the Υ(3S)

- No observation of light dark matter (LDM)

  $\mathcal{B}(\Upsilon(1S) \to \text{invisible}) < 2.5 \times 10^{-3}$ (90 % C.L.)

- The experimental limit disfavours theoretical expectations for LDM
- Possibility of a substantial improvement in the sensitivity

B→ $h^{(*)}\nu\bar{\nu}$

- Usage of the offline B meson beam
- The search for six exclusive decays → negative results
- → a restriction on the existence of light dark matter (provided by the $K\nu\bar{\nu}$ limit) $m_S > 1.4$ GeV/c^2

Prospects for a rich harvest of interesting results at the SUPER KEKB