Search for Dark Matter in Υ(3*S*) Decays

To appear in PRL

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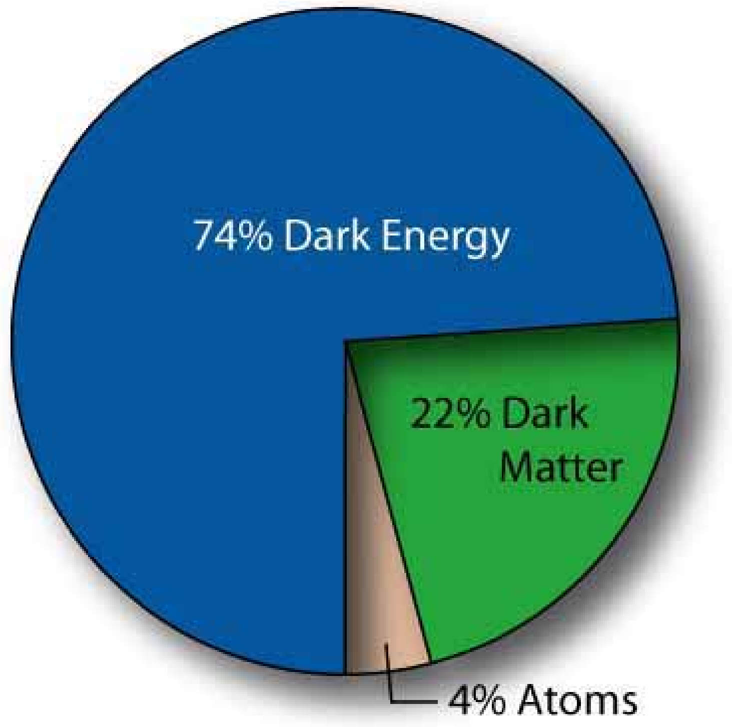
Contents

- Introduction to dark matter
- *Br* of quarkonium decay to the dark matter
- KEKB & Belle – experimental apparatus
- Event reconstruction
- Control sample analysis
- Background
- ***Result***
- Future prospect
- Summary

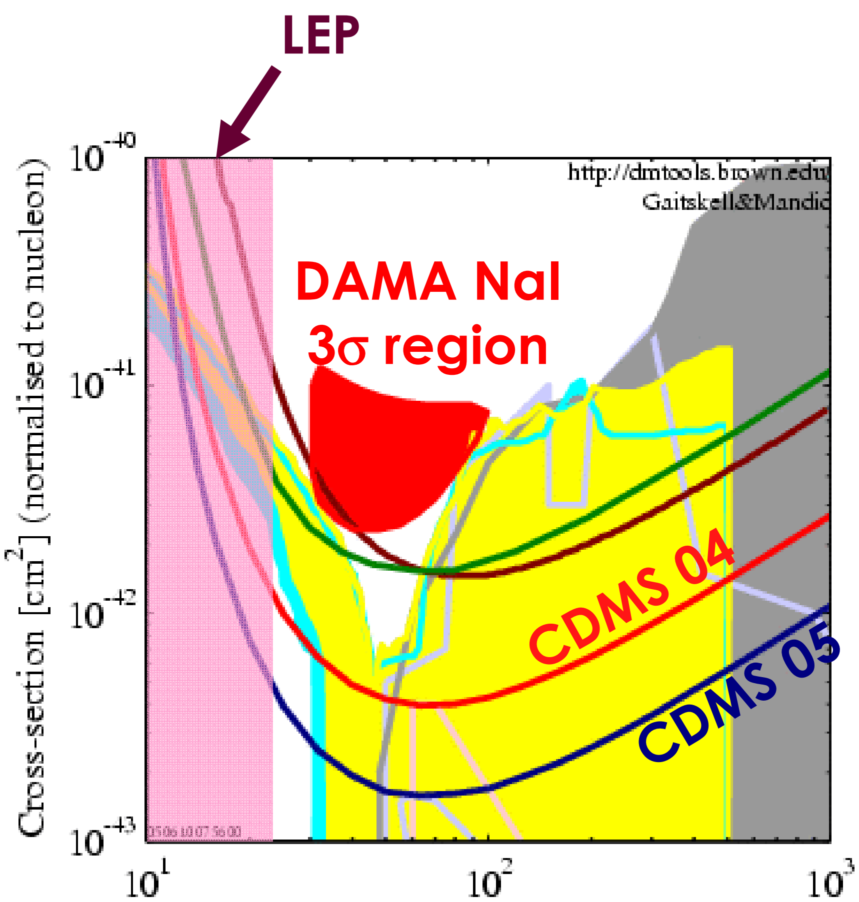
Dark Matter

- **Dark matter (DM) does not absorb light; it has only been measured indirectly by its gravity.**
- **According to the WMAP, 22% of the Universe is comprised of dark matter.**
  - WMAP three year result.



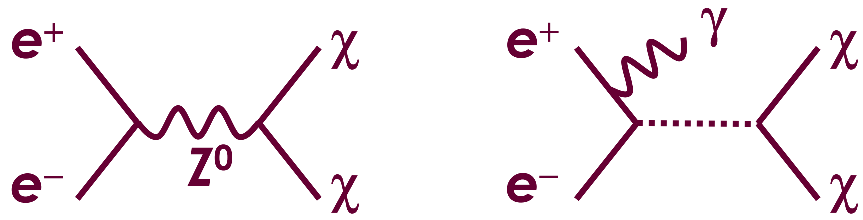
http://map.gsfc.nasa.gov/m_mm.html

DM Search Up To Now

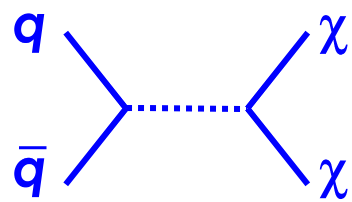


Mass of weakly interacting massive particle [GeV/c^2]

- **LEP limits**
  - DM coupling with Z
  - DM coupling with e^+e^-



- **DM coupling with $q\bar{q}$?**



The Belle contributes to DM searches via quarkonium to DM decay.

Br of Quarkonium to DM Decay

$$\Omega_\chi h^2 = \mathbf{0.113 \pm 0.009} \text{ (WMAP)}$$

$$\simeq \frac{0.1\,\text{pb}\cdot c}{\langle \sigma(\chi\chi \to \text{SM})\cdot v \rangle}$$

Ω_χ: Relic density

h: Hubble constant

v = c/20

$$\sigma(\chi\chi \to \text{SM}) \xrightleftharpoons[\text{reversal}]{\text{time}} \sigma(\text{SM} \to \chi\chi) \sim 18\,\text{pb}$$

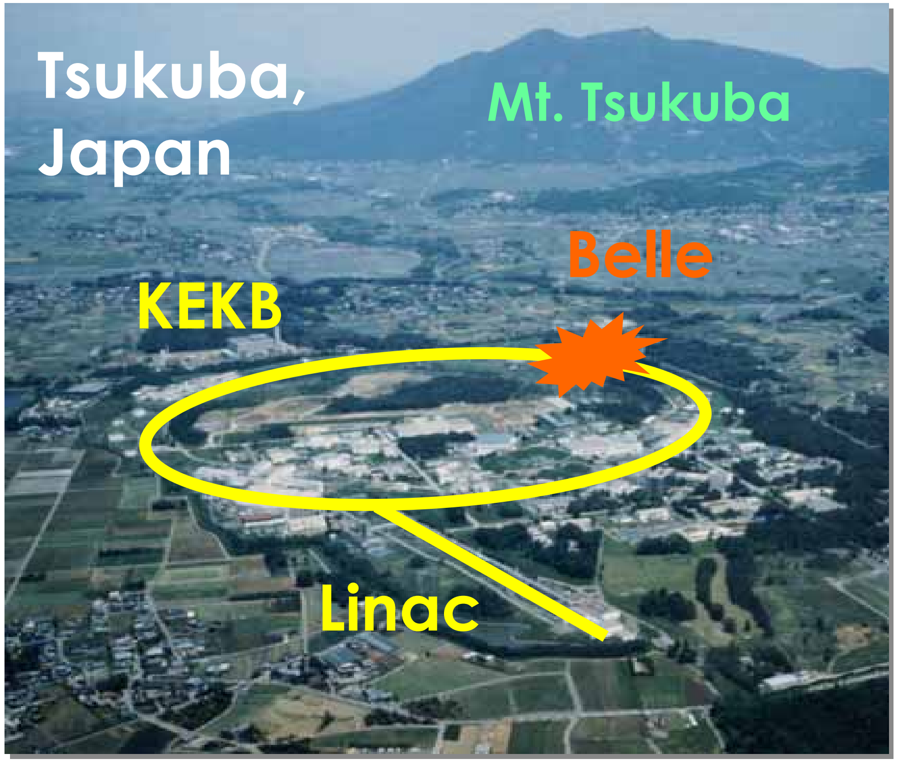
$$Br\left(\Upsilon(1S) \to \chi\chi\right) = f_\Upsilon^2 M_\Upsilon \sigma(b\bar{b} \to \chi\chi)$$

$$= 6\times 10^{-3}$$ (prediction) McElrath, Phys. Rev. D **72**, 103508 (2005)

Previous Limits

- ✓ *Br*(Y(1S)→invisible) < 50 x 10^{-3} CLEO, Phys. Rev. D **30**, 1433 (1984)
- ✓ *Br*(Y(1S)→invisible) < 23 x 10^{-3} ARGUS, Phys. Lett. B **179**, 403 (1986)

The KEKB Accelerator



KEKB is an e^+e^- collider to produce and to deliver $b\bar{b}$ quarkonia to the Belle detector.

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

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

$\int Ldt$ > 700 fb^{-1}

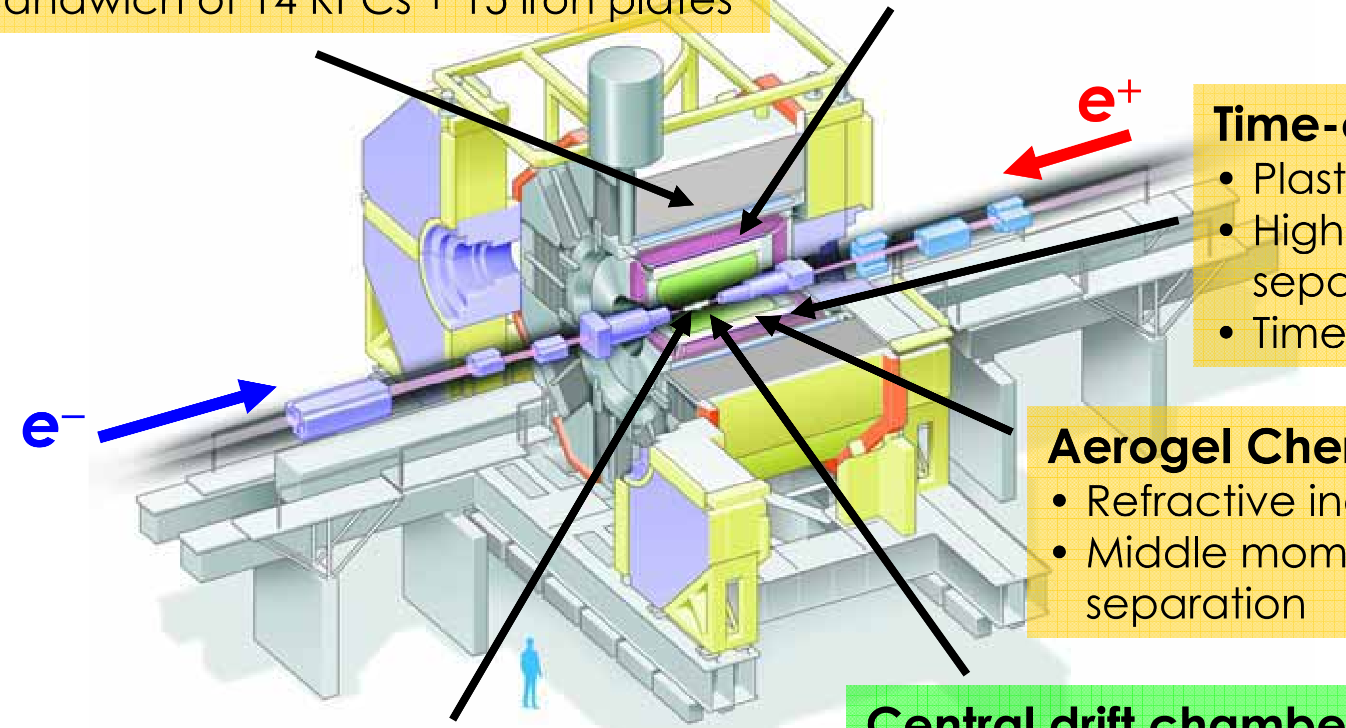
KEKB ring: 3 km in circumference

Linac: 400 m in length

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



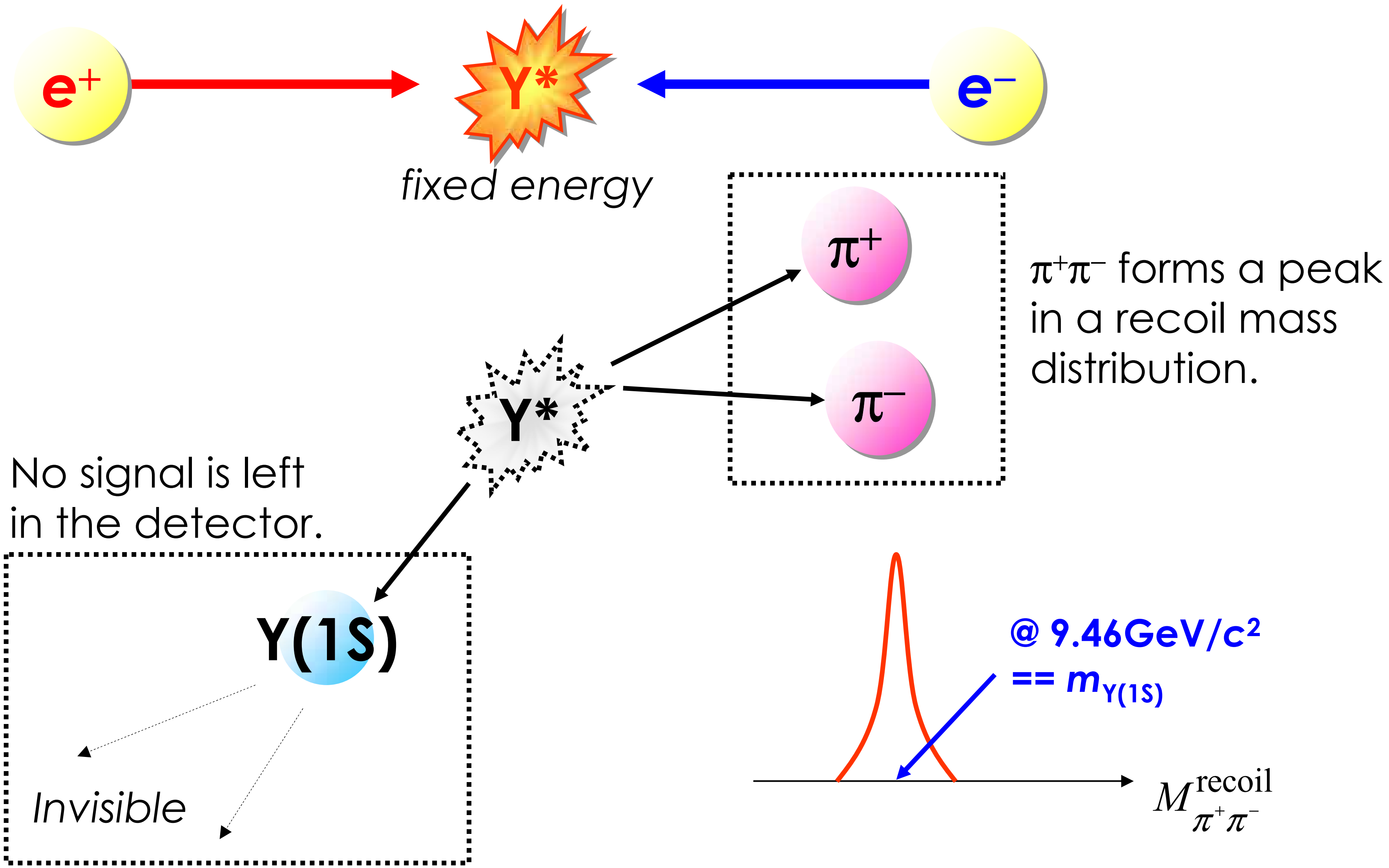
Time-of-Flight counter
- Plastic scintillator
- High momentum K/π separation
- Time resolution ~100 ps

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

Signal for Υ(1S) → invisible



$\Upsilon(1S)$ Production

Our choice

$e^+e^- \rightarrow \Upsilon(3S) \rightarrow \Upsilon(1S)\, \pi^+\pi^-$

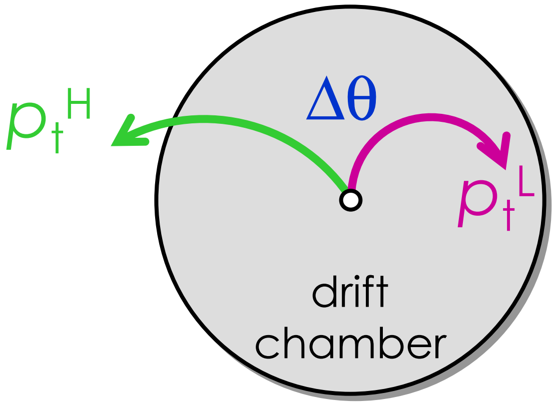
$\sigma \sim 4$ nb

- **$e^+e^- \rightarrow \Upsilon(1S)$**
  - No signal left in the detector at all.
- **$e^+e^- \rightarrow \Upsilon(2S) \rightarrow \Upsilon(1S)\, \pi^+\pi^-$**
  - Cross section is larger than Y(3S) ($\sigma \sim 7$ nb) but momenta of the recoil pions are too low to be triggered by the Belle trigger system.
- **$e^+e^- \rightarrow \Upsilon(4S) \rightarrow \Upsilon(1S)\, \pi^+\pi^-$**
  - Cross section is lower than Y(3S) ($\sigma_{ISR} \sim 0.02$ nb) and S/N is poor (< 1/1000).

Υ(3*S*) → Υ(1*S*) $\pi^+\pi^-$ Special Trigger

- **A looser two track trigger than Υ(4*S*) runs is used.**

  - $p_t^{\mathrm{H}} > 300\,\mathrm{MeV}/c$
  - $p_t^{\mathrm{L}} > 170\,\mathrm{MeV}/c$
  - $\Delta\theta > 30^\circ$



Trigger eff. 89.8±7.8%

Measured L1 rate ~ 850 Hz,
where the typical rate for Υ(4S) runs ~ 450 Hz.

Our DAQ system worked properly even in the doubled trigger-rate condition.

Signal Reconstruction

- **Event selection criteria**
  - 2 charged tracks in the event.
  - Total energy deposit in the calorimeter < 3 GeV.
  - No π^0 candidates in the event; no 2 γ pair with E_γ>20MeV that forms π^0 mass within 16 MeV/c^2.

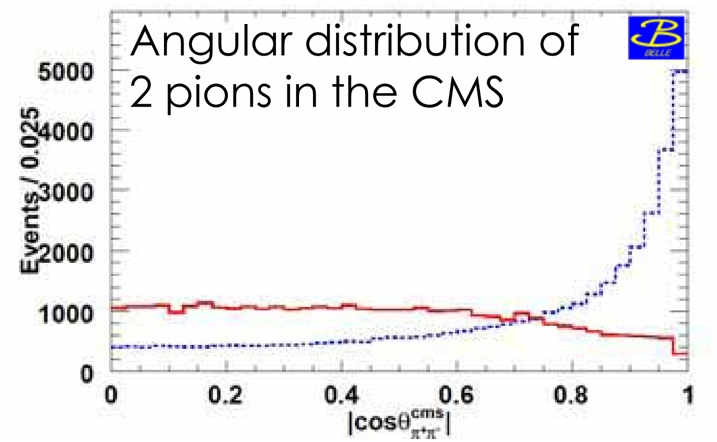
- **Pion selection criteria**
  - Track's polar angle within the detector acceptance.
  - Track is close to interaction point ($|dr|$<1cm, $|dz|$<3cm).
  - Not positively identified as one of $e/\mu/K$.
  - Not forms $K_S{}^0$ mass.

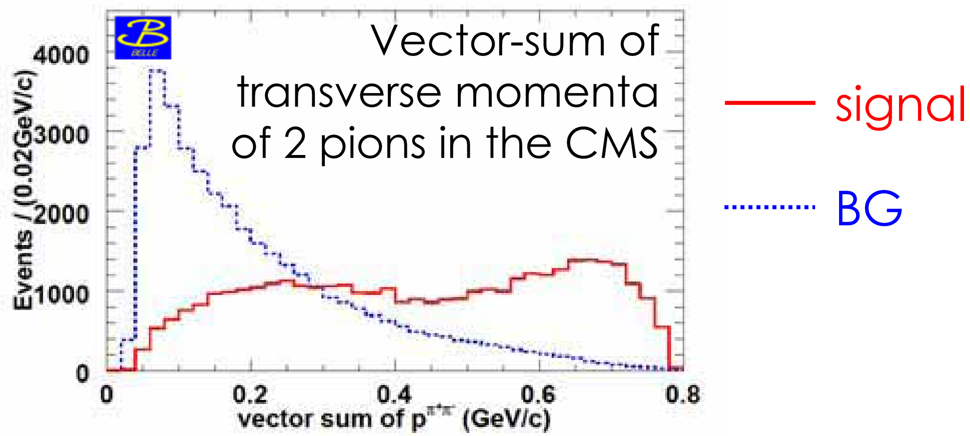
- **Background suppression**
  - See the next slide.

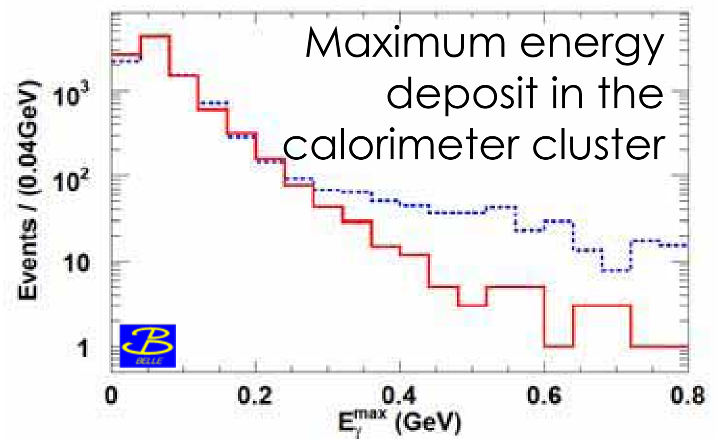
eff^{MC} = 9.16±0.01% w/o trigger efficiency

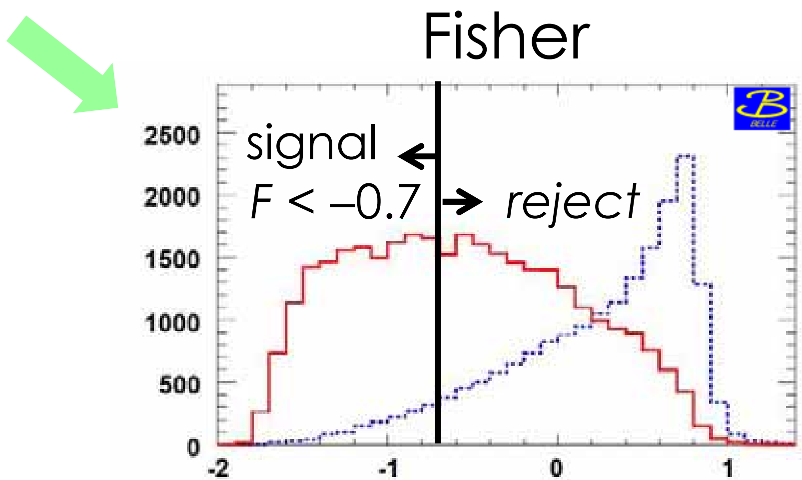
Background Suppression

~ Suppression of 2 photon process ~







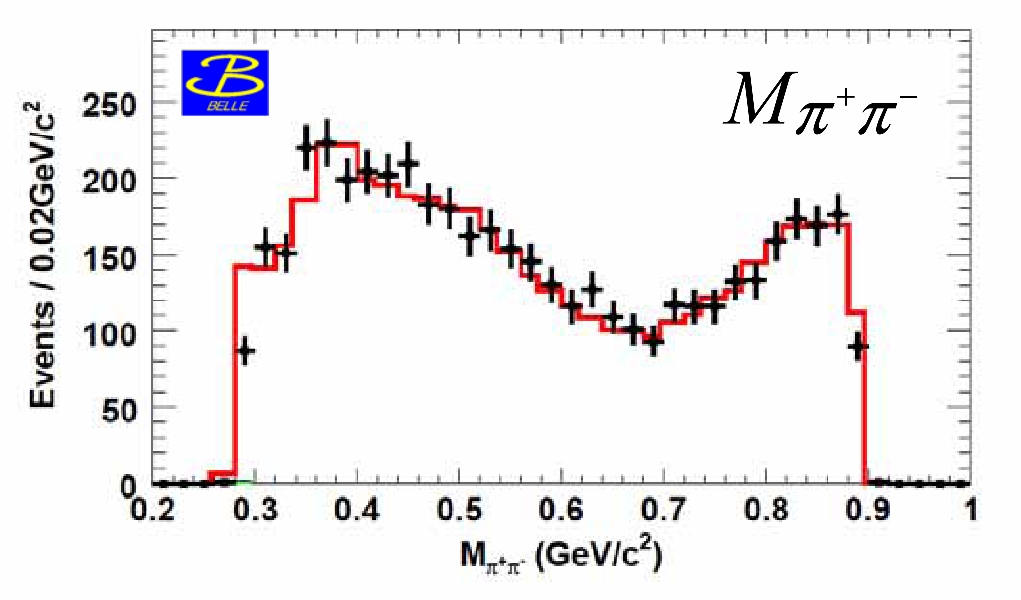


Control Sample Analysis

- **Control sample** **$\Upsilon(3S) \rightarrow \Upsilon(1S)\, \pi^+\pi^-$, $\Upsilon(1S) \rightarrow \mu^+\mu^-$**
- **The control sample is used:**
  - to calibrate MC,
  - to count # of $\Upsilon(3S) \rightarrow \Upsilon(1S)\, \pi^+\pi^-$ in data, and
  - to determine a shape of $M^{\mathrm{recoil}}_{\pi^+\pi^-}$ distribution.

MC Calibration

- **MC is calibrated by the control sample to reproduce the invariant mass distribution of 2 pions.**



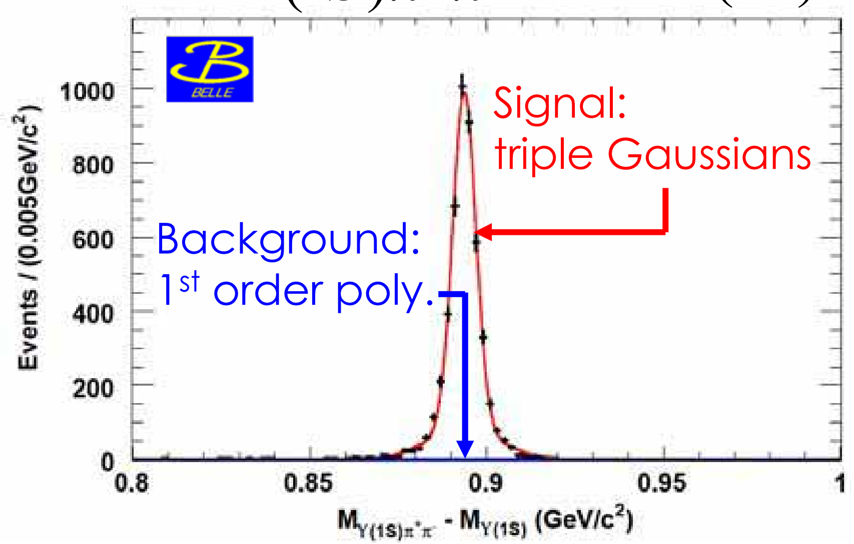
MC

data

MC reproduces the data distribution well.

of Υ(3S) → Υ(1S) $\pi^+\pi^-$ in Data

$$M_{\Upsilon(1S)\pi^+\pi^-} - M_{\Upsilon(1S)}$$



# of control sample events determined by the extended ML fit is

N_{sig} = 4901.9±71

Reconstruction efficiency for the control sample is estimated with MC

eff^{MC} = 39.7%

Br(Υ(1S) → $\mu^+\mu^-$) **= 2.48%**

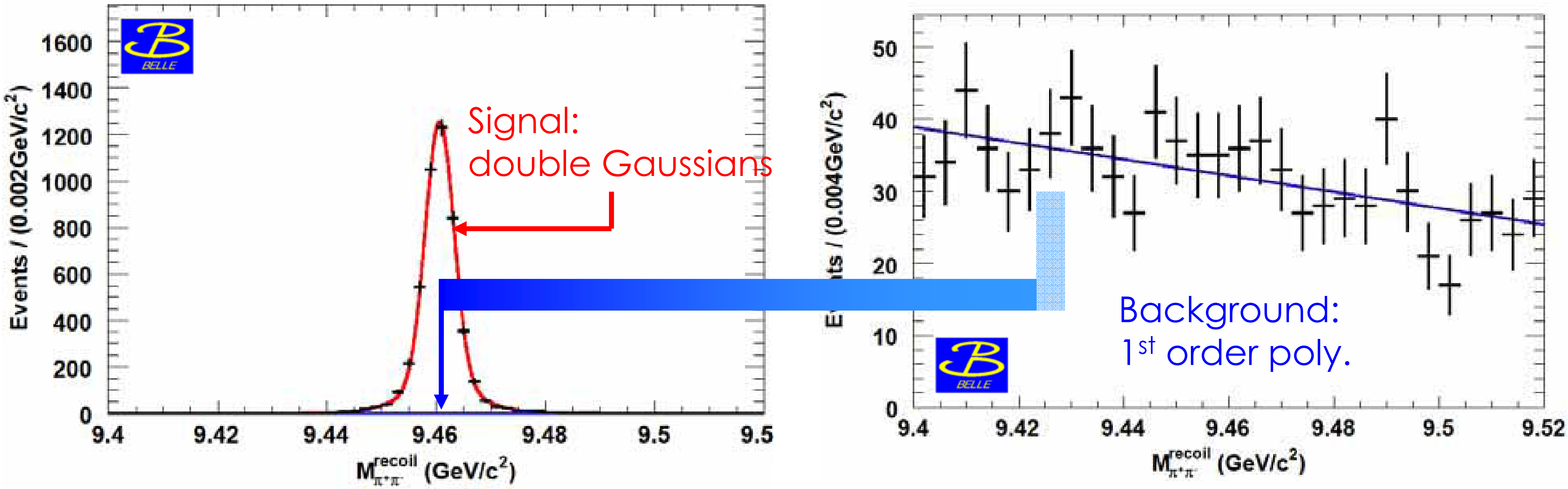
$$N_{\Upsilon(3S)\to\Upsilon(1S)\pi^+\pi^-} = \left(498.3^{+7.2}_{-7.1}(\text{stat}) \pm 34.6(\text{syst})\right) \times 10^3$$

→ expected # of Υ(1S)^{invisible} ~ **244**

Recoil Mass Distribution

$M^{\mathrm{recoil}}_{\pi^+\pi^-}$ for
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-,\ \Upsilon(1S) \to \mu^+\mu^-$

$M^{\mathrm{recoil}}_{\pi^+\pi^-}$ for
Off-resonance data



$$\mu = 9460.6 \pm 0.05\ \mathrm{MeV}/c^2$$

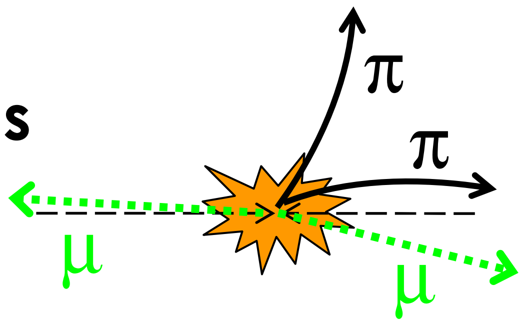
$$\sigma_{\mathrm{main}} = 2.26 \pm 0.06\ \mathrm{MeV}/c^2$$

$$\sigma_{\mathrm{tail}} = 7.01^{+0.32}_{-0.29}\ \mathrm{MeV}/c^2$$

$$f_{\mathrm{tail}} = 0.195^{+0.021}_{-0.020}$$

Parameters determined here are used in the final fit to extract the signal.

Peaking Background



- **$\Upsilon(1S) \rightarrow \tau^+\tau^-, \mu^+\mu^-, e^+e^-$, where leptons go out of acceptance.**
  - One of systematic uncertainty sources.

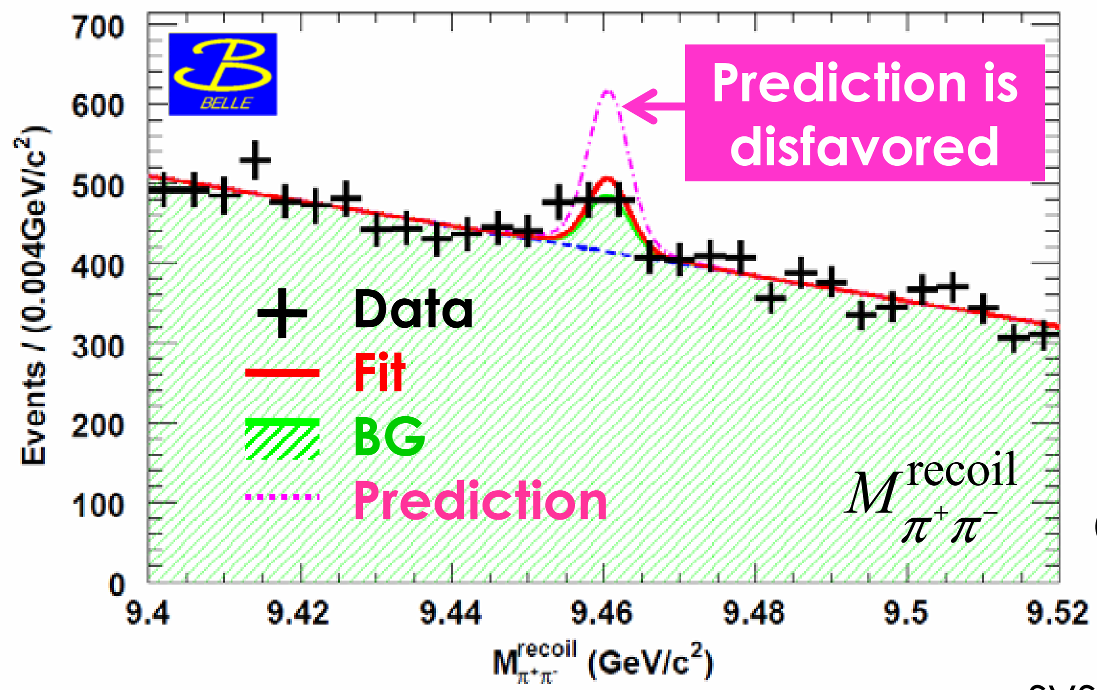
- **Others make very small or negligible contributions to the peaking background.**
  - $\Upsilon(1S) \rightarrow \nu\bar{\nu}$
  - $\Upsilon(1S) \rightarrow$ other modes
  - Others

\# of peaking background estimated by MC

$\Upsilon(1S) \rightarrow \mu^+\mu^-$	77.3	$\pm$12.0
$\Upsilon(1S) \rightarrow e^+e^-$	50.3	$\pm$8.0
$\Upsilon(1S) \rightarrow \tau^+\tau^-$	5.2	$\pm$1.0
$\Upsilon(1S) \rightarrow \nu\bar{\nu}$	0.4	$\pm$0.1
$\Upsilon(1S) \rightarrow$ other modes	0.0	+2.8
Others	0.0	+12.9
Total	**133.2**	$^{+19.7}_{-14.6}$

Result

N_{sig} = 38 ± 39(stat) ⇔ 0 consistent



@ 2.9fb^{-1}

syst. included

***Br*(Y(1S) → invisible) < 2.5 x 10^{-3} (@90%C.L.)**

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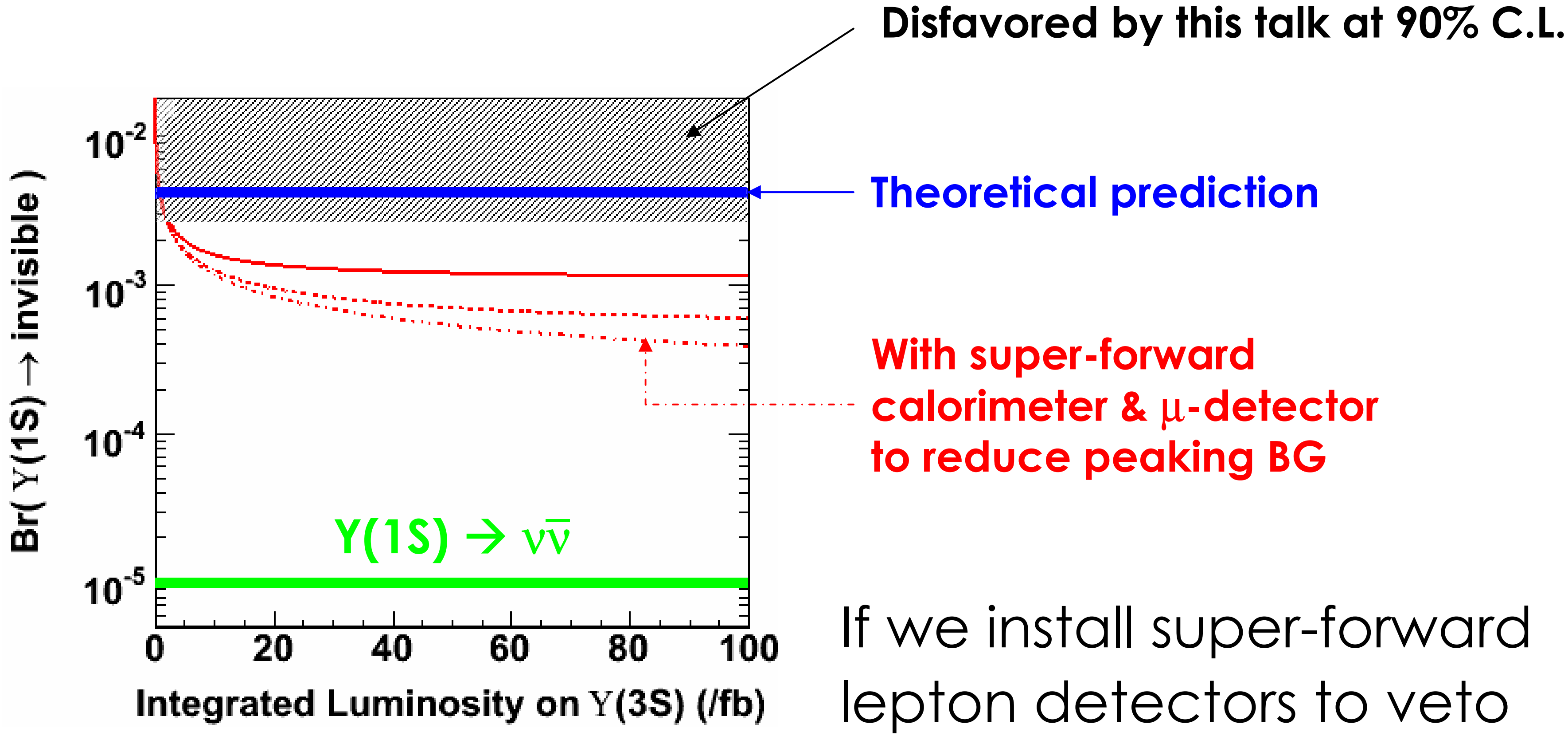
Future Prospect



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

Summary

- We search for dark matter in $\Upsilon(1S) \rightarrow$ invisible decay, where the $\Upsilon(1S)$ is obtained from the $\Upsilon(3S) \rightarrow \Upsilon(1S)\ \pi^+\pi^-$ decay.

- In 2.9 fb^{-1} data, we find 38 ± 39(stat) candidate events for $\Upsilon(1S) \rightarrow$ invisible.

- We obtain the upper limit $Br(\Upsilon(1S) \rightarrow \text{invisible}) < 2.5 \times 10^{-3}$ at 90% C.L. The value inferred from WAMP in the model by McElrath is disfavored.

Backup Slide

Signal Extracting Fit

Extended maximum likelihood fit

$$L = \frac{\exp\left(-\sum_k n_k\right)}{N!} \prod_{i=1}^{N} \left[\frac{\sum_k n_k f_k(M_i^{\text{recoil}})}{\sum_k n_k} \right]$$

k = signal, peaking BG, and combinatorial BG

f_k model

signal: double Gaussians
peaking BG: same as signal
combinatorial BG: 1st order polynomial