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# B and Upsilon cross sections (HERA-B)

On behalf of the HERA-B collaboration

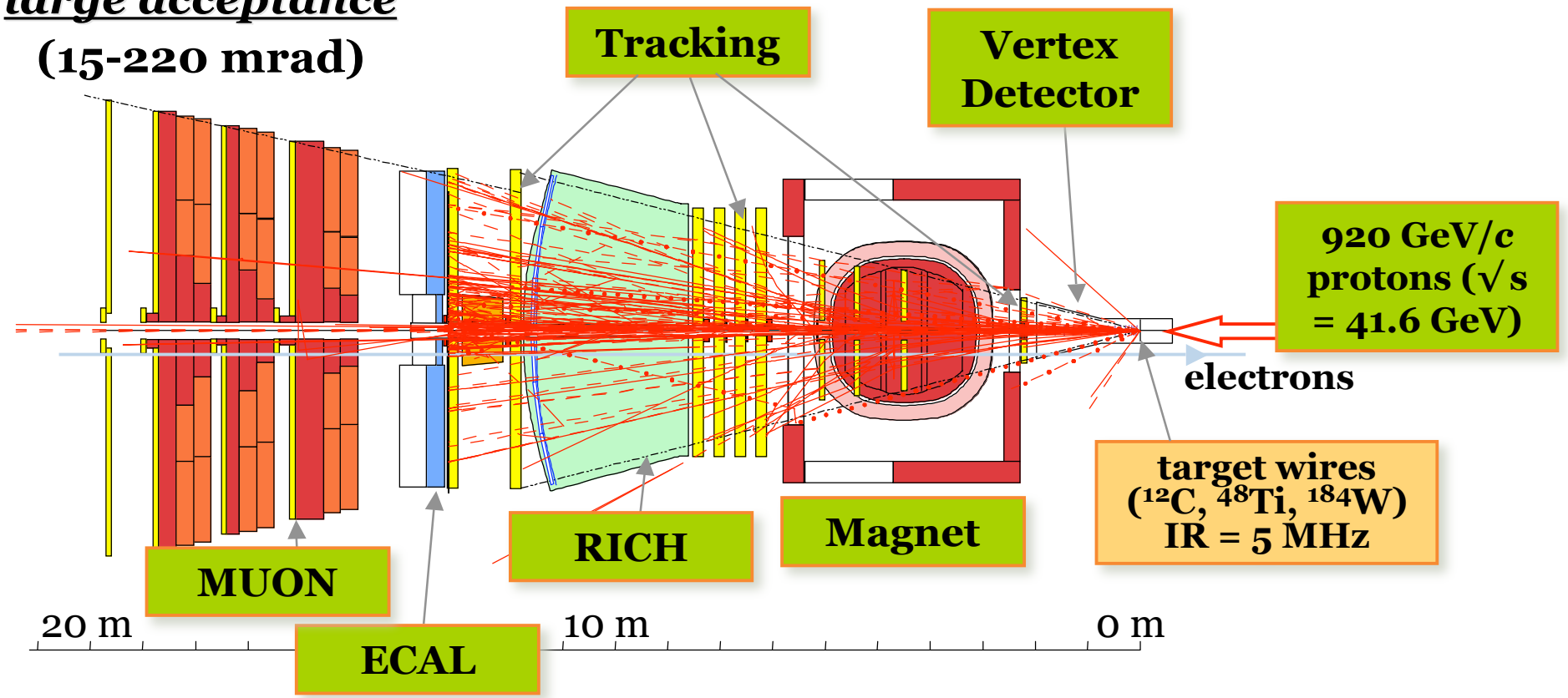
# Outline

- HERA-B detector
- Dilepton triggered data sample
- Open $b\bar{b}$ production cross section
  - inclusive J/$\psi$ decays
  - double semileptonic $b$ decays
- $\Upsilon$ production cross section

# HERA-B (top view)

***high vertex resolution***
**(500 μm along beam)**

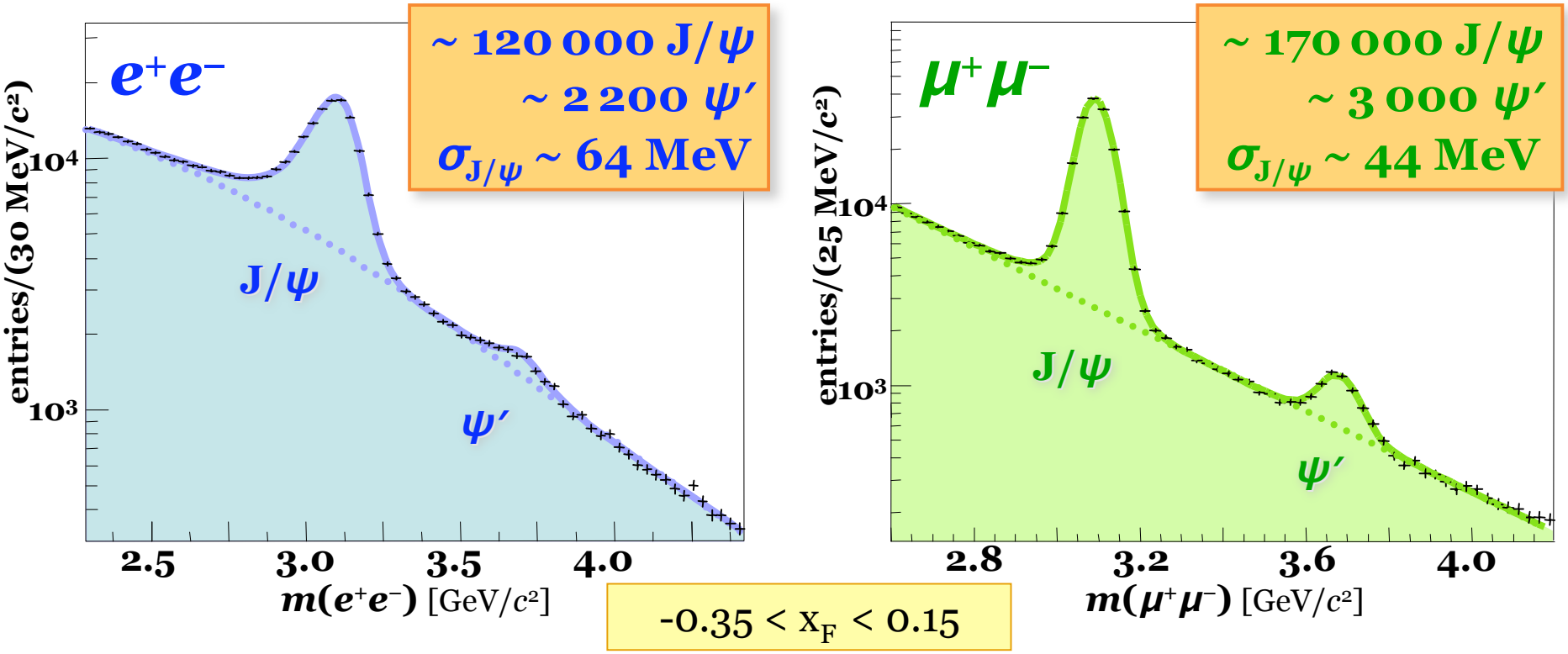
***large acceptance***
**(15-220 mrad)**




***good PID*** **($e^{\pm}$, $\mu^{\pm}$, $\pi$, $K$, $p$) + $\gamma$ *reconstruction***

# Dilepton triggered data sample

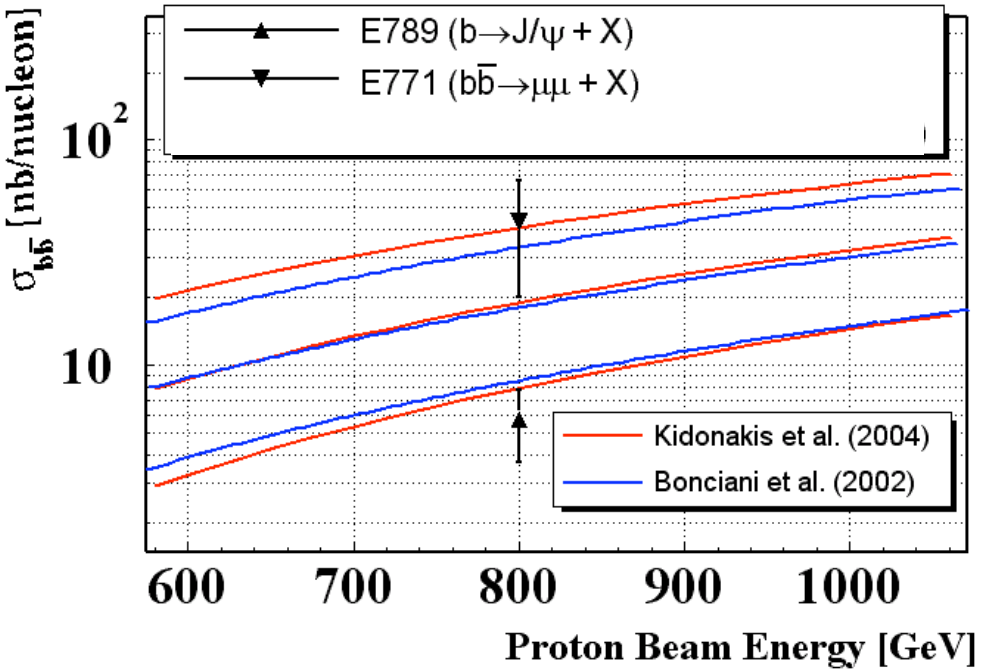
Hardware track finding behind magnet, seeded by ECAL or MUON hits.
Independent software track finding + vertex fit.
Performance: ~150·10$^6$ events @ 100 Hz (~1000 J/ψ per hour).
Statistics per wire: $^{12}$C (64%), $^{48}$Ti (9% ), $^{184}$W (27% ).




Study of charmonium (J/ψ, $\chi_c$, ψ′, with A-dependence) → see talk of M. Zur Nedden.

# Open beauty: Motivation

Experiments: poor statistics, incompatible results.




Theory: test of pQCD in the near threshold energy regime (41.6 GeV).

At first order, bb quark pairs are produced by gluon-gluon fusion. Higher order processes, such as soft gluon emission, are calculated.

Theoretical uncertainty includes variations of *b* mass (4.5-5.0 GeV), factorization and renormalization scales (0.5-2.0 *b* mass).

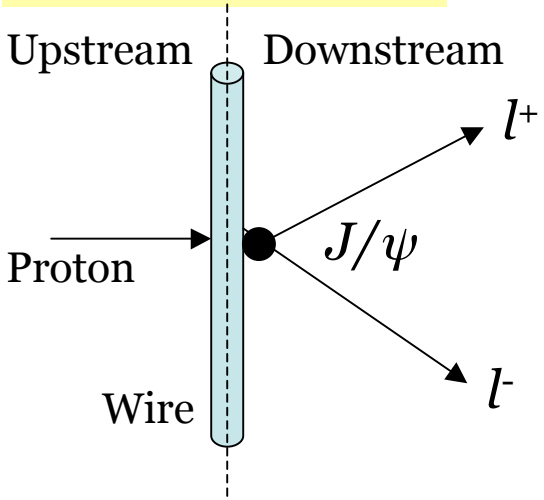
| **Theory** | **Order** | $\sigma_{b\bar{b}}$[nb/nucleon] |
|---|---|---|
| Kidonakis *etal.*, Eur. Phys. J. **C36** (2004), 201 | NLO + NNL | 30 ± 18 |
| Bonciani *etal.*, Nucl. Phys. **B529** (1998), 424 | NLO + NNLL | 25 ± 17 |

# Open beauty: Measurement methods

Exploit the *b*-hadron (B) long lifetime (≅ 9 mm = 18 $\sigma_Z$ @ HERA-B).

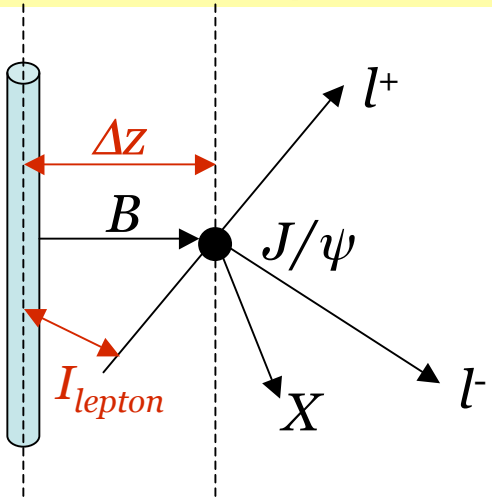
Normalisation

$pA \rightarrow J/\psi \rightarrow l^+ l^- X$



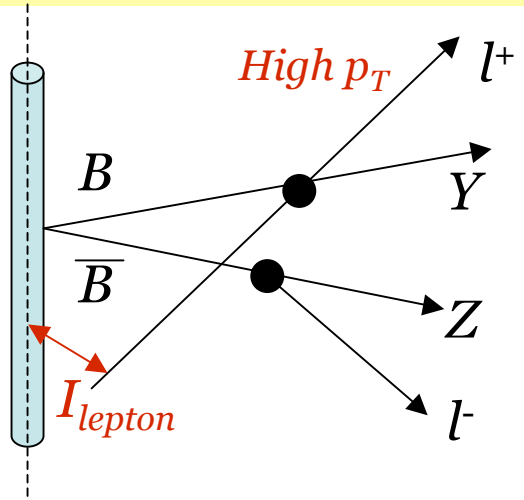

Signal: detached J/ψ

$pA \rightarrow b\bar{b} \rightarrow J/\psi \rightarrow l^+ l^- X$




Signal: double semileptonic

$pA \rightarrow b\bar{b} \rightarrow J/\psi \rightarrow l^+ l^- X$




J/ψ method: count events with a J/ψ detached from the primary vertex.

Double semileptonic method: count events with at least two heavy quarks $\left(b,\bar{b},c \text{ or } \bar{c}\right)$ decaying semimuonically (high $p_T$ and high impact to the wire).

# Open beauty: Measurement methods

The rate of *b*-hadrons is normalized to prompt J/ψ → systematic effects are reduced.

J/ψ method

$$R_{\Delta\sigma} = \frac{\sigma(b\bar{b})}{\sigma(J/\psi)} = \frac{n_B}{n_{J/\psi}} \cdot \frac{1}{\varepsilon_R \cdot \varepsilon_B^{\Delta z} \cdot \mathrm{Br}(b\bar{b} \to J/\psi + X)}$$

$\varepsilon_R$: ratio of trigger efficiency of prompt and detached J/ψ
$\varepsilon_B$: efficiency of Δz cut
$\sigma_{J/\psi}$: 502 ± 44 nb/nucleon [hep-ex/0003003]

$\sigma_{J/\psi}$ from a NRQCD fit to world data (incl. HERA-B) → M. Zur Nedden's talk.

semileptonic

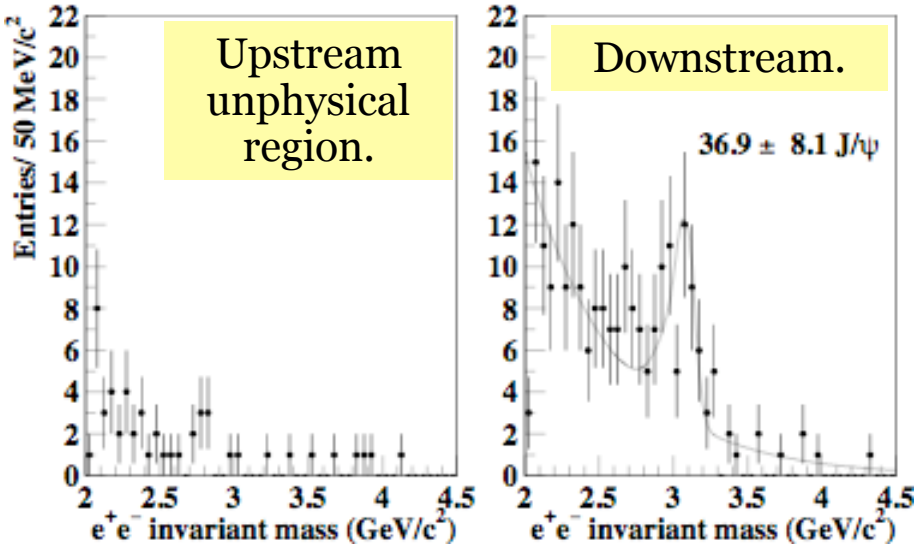
$$R_{\Delta\sigma} = \frac{\sigma(b\bar{b})}{\sigma(J/\psi)} = \frac{n_B \cdot \mathrm{Br}(J/\psi \to \mu^+\mu^-) \cdot \varepsilon_{J/\psi}}{n_{J/\psi} \sum_j \mathrm{Br}_j(b\bar{b} \to \mu^+\mu^-) \cdot (1 - \vartheta_j) \cdot \varepsilon_{j,B}}$$

All possibile decays leading to dimuon final state are included (via $c \to \mu$ decays).
The θ factor accounts for the effect of neutral B meson mixing.

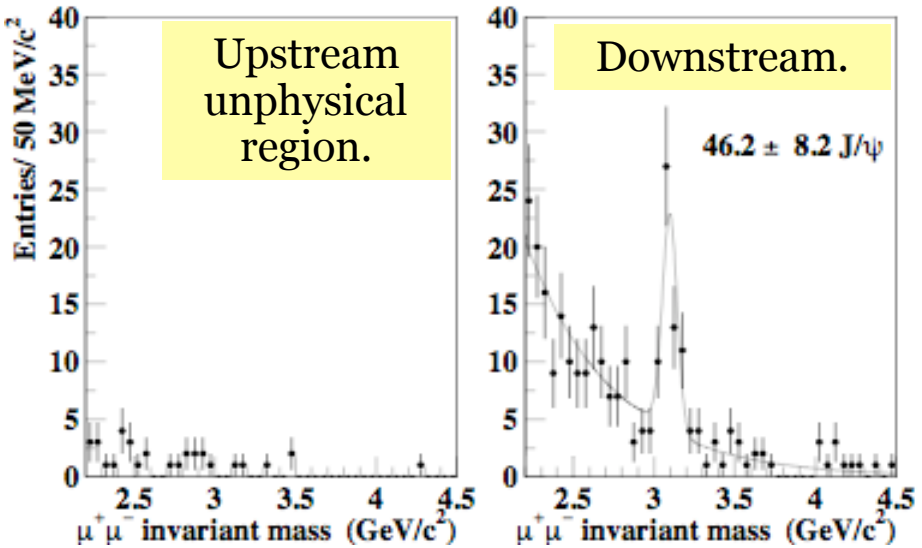
# Detached J/ψ signal

Blind and simultaneous cut optimization, based on the signal significance.

$\Delta z>10\ \sigma$, $I_{lepton}>3.0\ \sigma$, $I_{J/\psi}<12\ \sigma$




$\Delta z>9\ \sigma$, $I_{lepton}>2.6\ \sigma$, $I_{J/\psi}<9\ \sigma$

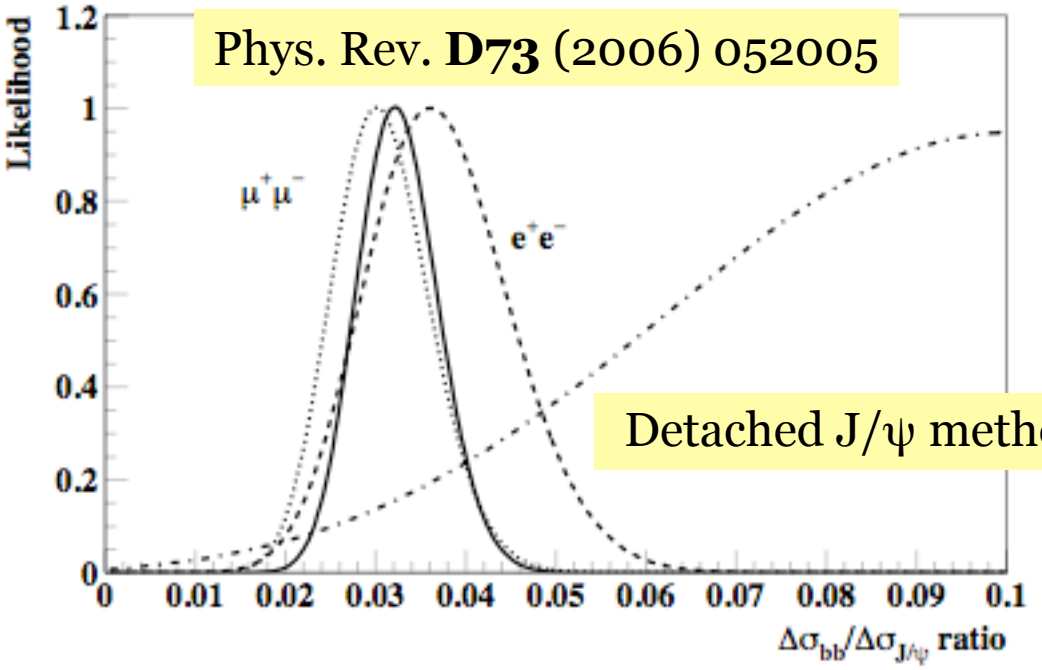



<u>Background</u>

Combinatorial (44%) and double semileptonic *b* (43%) and *c* (13%) decays.
Prompt J/ψ are negligible.

# Beauty cross section from detached J/ψ

Unbinned likelihood fits, within HERA-B kinematical range (83 ± 1%).

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Detached J/ψ method

| $R_{\Delta\sigma}$ [$10^{-2}$] | |
|---|---|
| Electrons | $2.95 \pm 0.55_{stat}$ |
| Muons | $3.53 \pm 0.78_{stat}$ |
| Combined | $3.2 \pm 0.5_{stat} \pm 0.4_{sys}$ |

Electron and muon channels results are independent (to a large extent) and consistent.

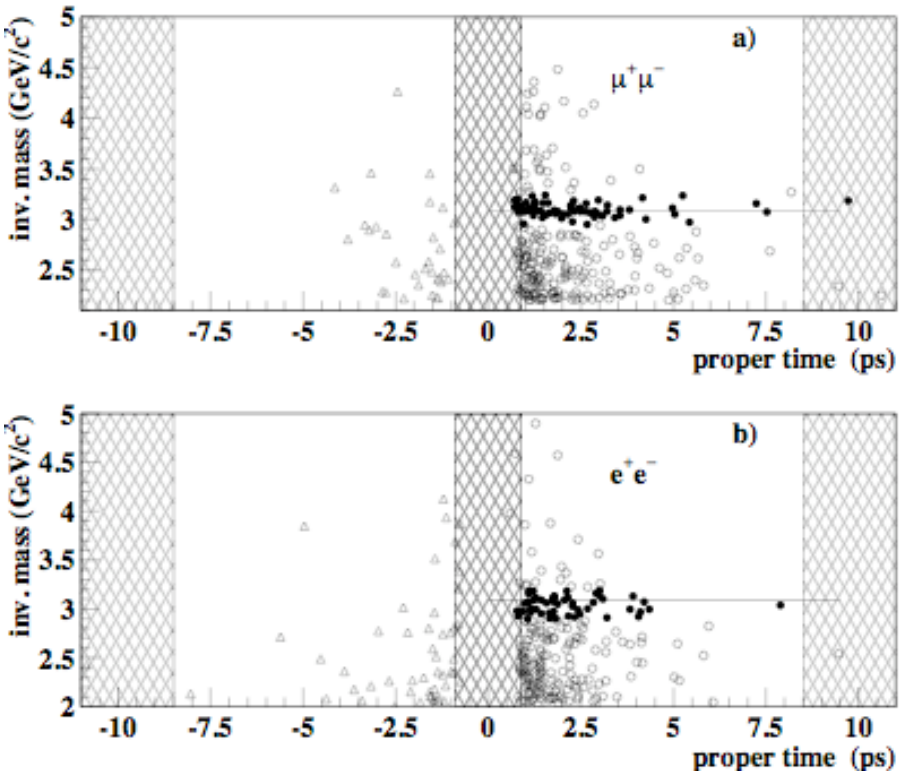
Main systematic uncertainty:
$\sigma(BR_{J/\psi}) = 8.6\ \%$

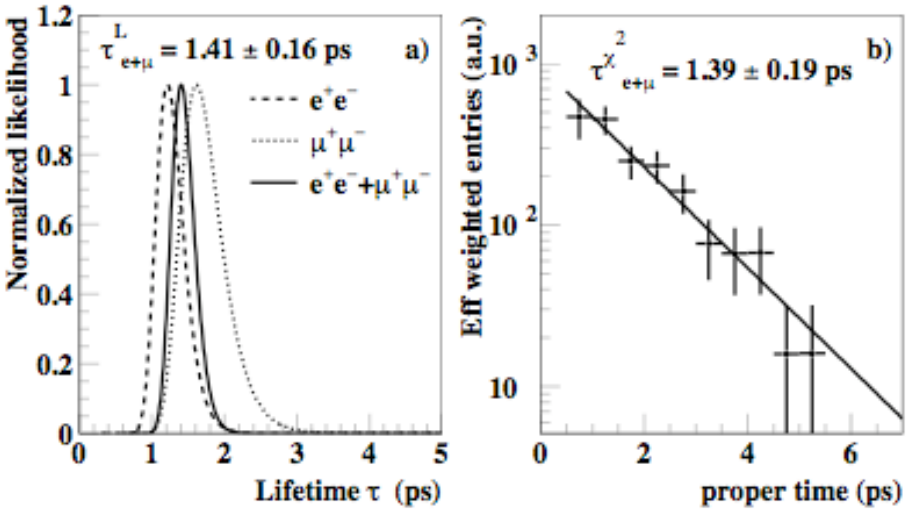
Extrapolation to full range + $\sigma_{J/\psi} = 502 \pm 44$ nb/nucleon

$$\sigma_{b\bar{b}} = 14.9 \pm 2.2_{stat} \pm 2.4_{sys}\ \text{nb/nucleon}$$

# B lifetime

The lifetime is exploited to confirm the *b*-flavour of the detached candidates.



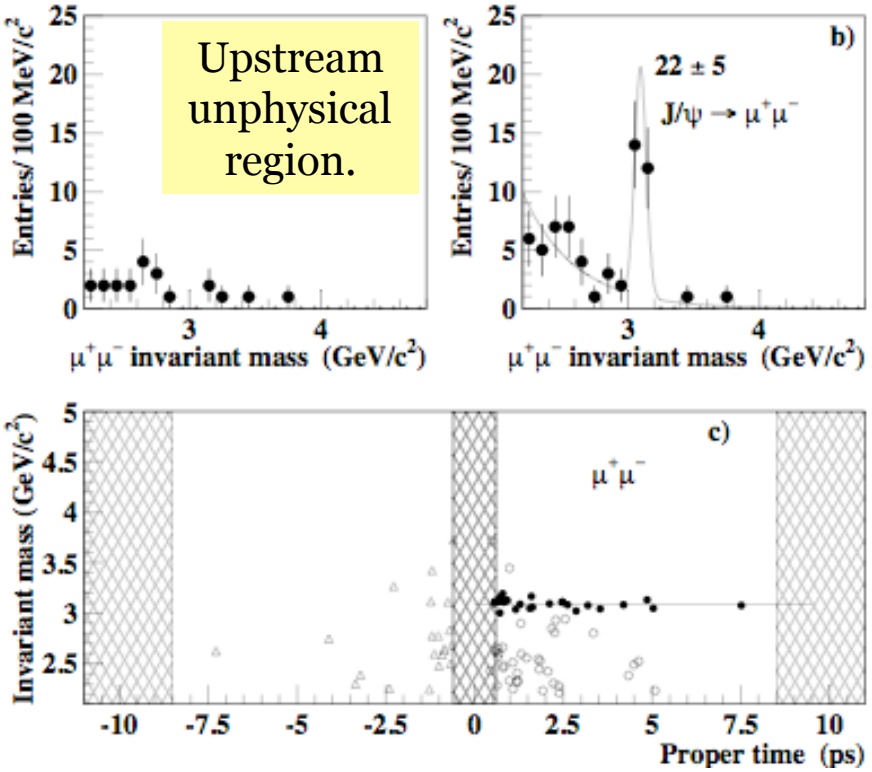




Long lived candidates are concentrated around the J/ψ mass.

The lifetime is consistent with the PDG value (τ = 1.54 ps).

# Other B confirmation

Search for additional tracks consistent with a common vertex ($B \rightarrow J/\psi + h^{\pm}$)




Selection criteria released

New vertex fit with a 3$^{th}$ charged track, having low momentum, pointing far away from the primary vertex.

Fully reconstructed events are partially overlapped with the previous sample (50% overlap).

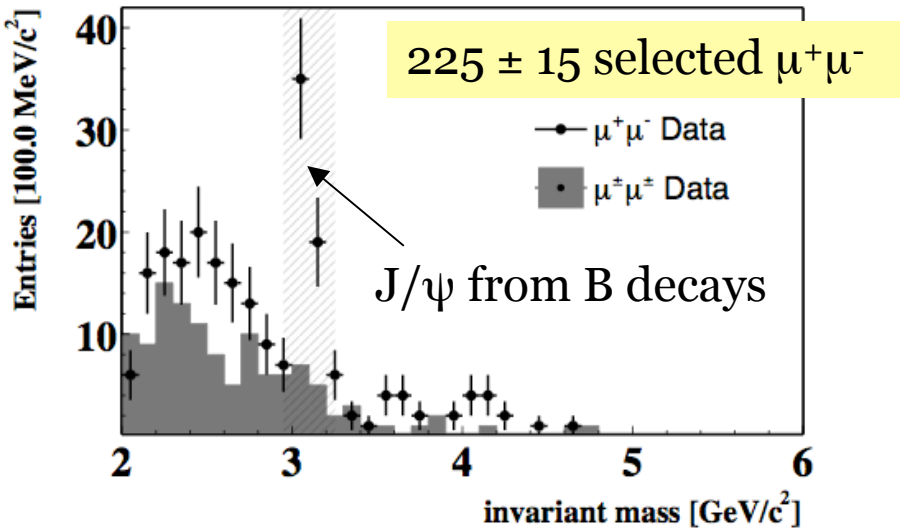
The cross section ratio ($R_{\Delta\sigma} = 4.3 \times 10^{-2}$) is consistent with the previous result.

Cross-check confirmation (not a new measurement).

# Selection of double semileptonic *b* decays

Blind and simultaneous cut optimization, based on the signal significance.

$I_{lepton} > 4.0\ \sigma$, $p_T > 1$ GeV, $\Delta z > 0.2$ cm,




$x_F$ of accepted muons: [-0.3, 0.15]

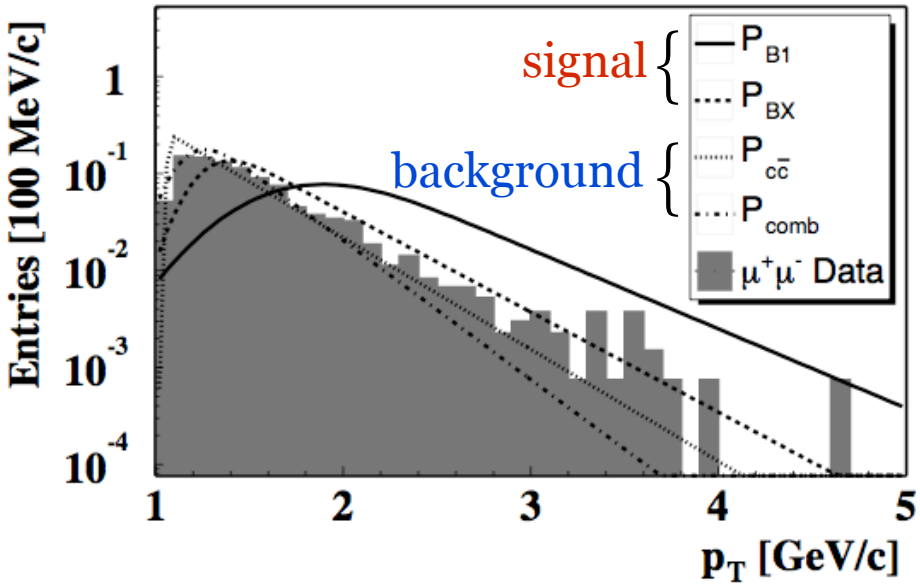
A soft $\Delta z$ cut (0.2 cm) on the fictious dimuon vertex rejects unphysical muon pairs, keeping an high signal efficiency.

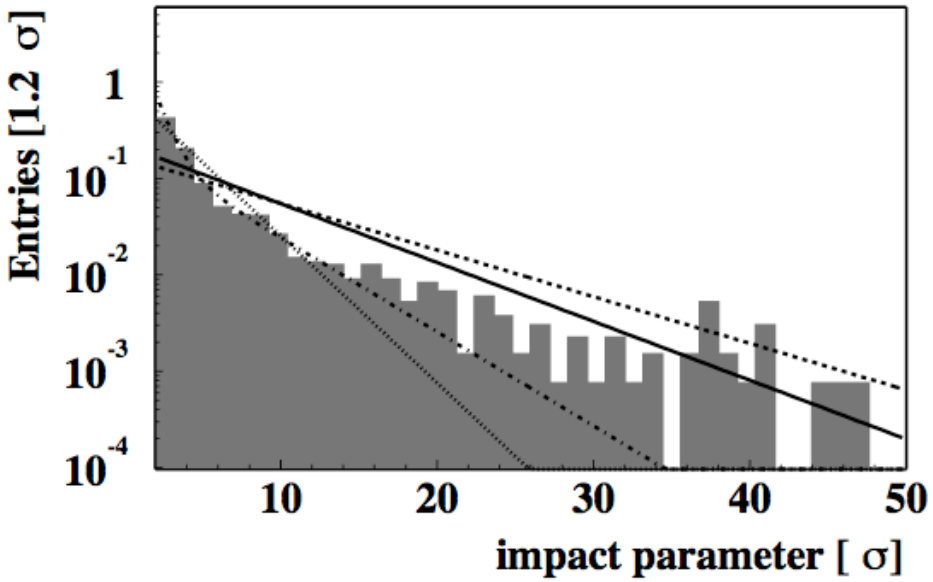
The J/ψ invariant mass region is excluded in order to be statistically independent from the detached J/ψ method.

<u>Background</u>

Combinatorial, including decays in flight of kaons and pions (from like-sign muon data).
Double semileptonic decays of charmed hadrons (from MC).

# Beauty cross section




The likelihood function is based on the shape of the simulated distributions of the muon impact parameter and $p_T$.

$$L(n_S, n_B) = \frac{(n_S + n_B)^n e^{-(n_S + n_B)}}{n!} \prod_1^n \left( \frac{n_S P_S + n_B P_B}{n_S + n_B} \right)$$

**Free parameters**

$n_S$: number of $b\bar{b} \rightarrow \mu^+\mu^-$ events

$n_B$: number of background events

The relative strength of the different signal and background contributions are obtained from MC simulations.

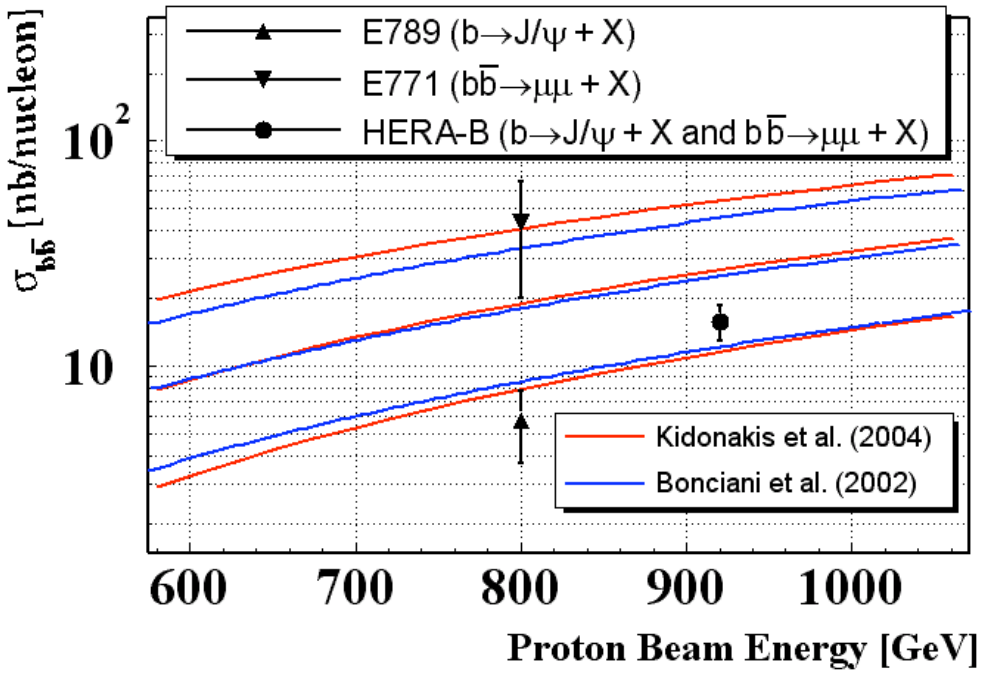
**Fit result**

$n_S = 83 \pm 12$, $n_B = 142 \pm 15$

$$\sigma_{b\bar{b}} = 17.5 \pm 2.6_{\text{stat}} \text{ nb/nucleon}$$

# Comparison with theoretical predictions

Accepted for publication by Phys. Lett. **B**




| $\sigma_{bb}$ [nb/nucleon] | |
|---|---|
| J/ψ method | $14.9 \pm 2.2_{stat} \pm 2.4_{sys}$ |
| Semileptonic | $17.5 \pm 2.6_{stat} \pm 3.3_{sys}$ |

The results of the two methods are consistent.

The combined result is consistent with the latest QCD predictions based on NLO calculations and resummation of soft gluons.

| Exp. | Year | Target | $E_p$[GeV] | Events | Method | $\sigma_{b\bar{b}}$[nb/nucleon] |
|---|---|---|---|---|---|---|
| E789 | 1995 | Au | 800 | 19 | J/ψ | $5.7 \pm 1.5 \pm 1.3$ |
| E771 | 1999 | Si | 800 | 15 | Semi | $43^{+27}_{-17} \pm 7$ |
| HERA-B | 2006 | C/Ti/W | 920 | 176 | J/ψ + Semi | $15.8 \pm 1.7_{stat} \pm 1.3^{uncorr.}_{sys} \pm 2.0^{corr.}_{sys}$ |

# Υ: Measurement method

Measure the number of Υ mesons relative to prompt J/ψ mesons
→ systematic effects are reduced.

$$pA \rightarrow \Upsilon \rightarrow l^+ l^- X$$

$$\mathrm{Br}(\Upsilon \rightarrow l^+ l^-) \times \left.\frac{d\sigma_\Upsilon}{dy}\right|_{y=0} = \mathrm{Br}(J/\psi \rightarrow l^+ l^-) \cdot \sigma_{J/\psi} \cdot \frac{N_\Upsilon}{N_{J/\psi}} \cdot \frac{\varepsilon_{J/\psi}}{\varepsilon_\Upsilon} \cdot \frac{1}{\Delta y_{eff}}$$

$\Delta y_{eff}$: ratio between mid-rapidity ($y$=0) and full Υ cross section
$\varepsilon_{J/\psi}$ and $\varepsilon_\Upsilon$ : detection efficiency of J/ψ and Υ
$\sigma_{J/\psi}$: 502 ± 44 nb/nucleon

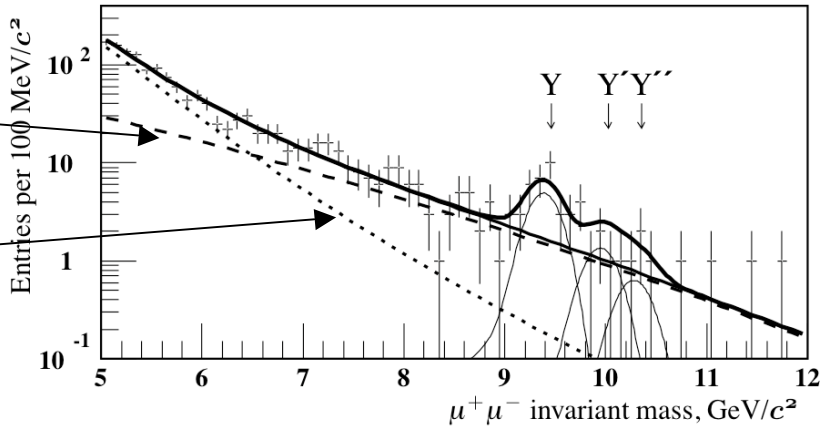
The same nuclear suppression is assumed for J/ψ and Υ.

# Υ: Signal

The analysis is performed simultaneously on the electron and muon channel.

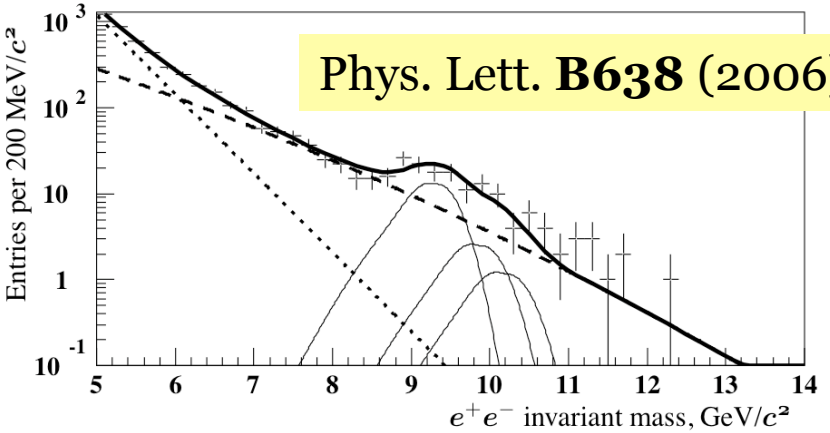
Drell-Yan background: the shape is fixed to the MC.

Combinatorial background, as estimated from like-sign muon pairs.




Combinatorial background, as estimated from event mixing.

For masses larger than 6 GeV, Drell-Yan background is dominating.

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The strength of the relative signals Υ/Υ′/Υ″ is fixed according to the E605 results.

# $\Upsilon$: Results

Using $\sigma_{J/\psi} = 502 \pm 44$ nb/nucleon.

| Exp. | Events | $Br \times d\sigma/dy\,\big|_{y=0}$[pb/n] |
|---|---|---|
| $\mu^+\mu^-$ | $30.8 \pm 7.4$ | $4.0 \pm 1.0_{stat} \pm 0.8_{sys}$ |
| $e^+e^-$ | $75 \pm 14$ | $5.5 \pm 1.0_{stat} \pm 1.4_{sys}$ |
| Combined | | $4.5 \pm 1.1$ |

The results in the muon and electron channel are compatible.

The HERAB result is extrapolated to $\sqrt{s} = 38.8$ GeV , to be compared with the Fermilab experiments E605 and E771:

$$Br \times d\sigma/dy\,\big|_{y=0} = 3.4 \pm 0.8 \text{ pb/n}$$

The HERA-B result is half-way, and does not favour one experiments over the other.

The Drell-Yan background is compatible with the value found in literature.

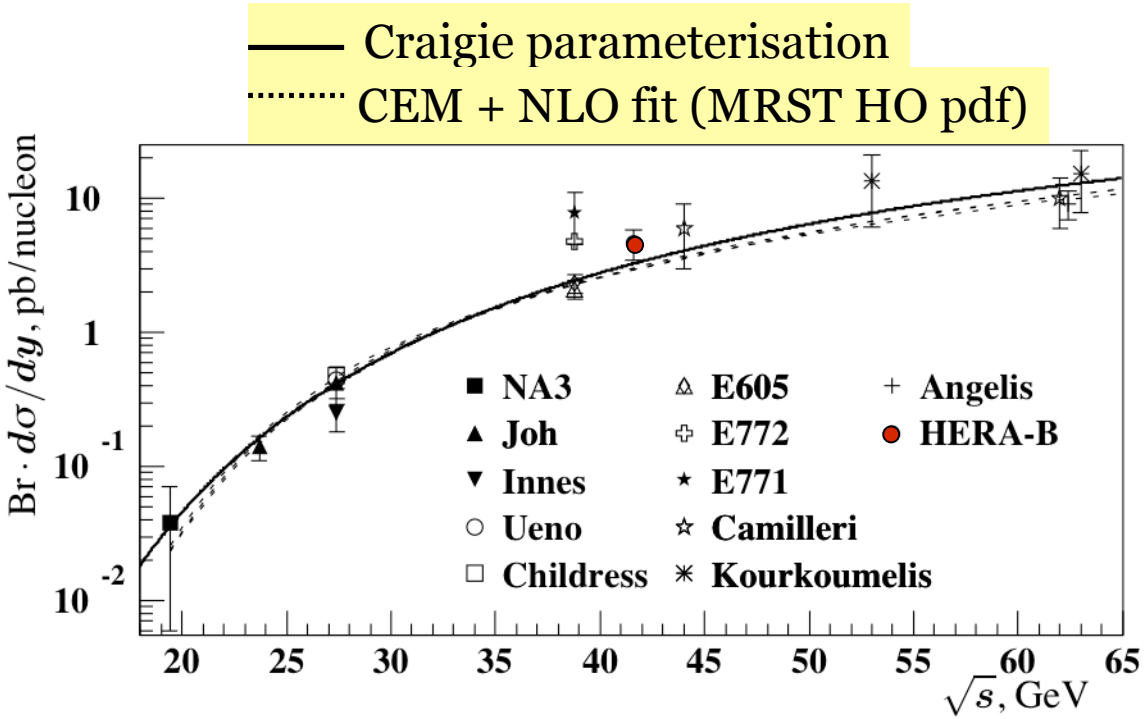
# ϒ: Theory and experiments

The study of ϒ production provides a test of quarkonium production models.

Craigie parameterisation

$$f\left(\sqrt{s}\right) = \sigma_0 \cdot e^{-\frac{m_0}{\sqrt{s}}}$$

Most of the other measurements have large uncertainties, apart from Fermilab experiments, which are in poor agreement among each other.




Theoretical uncertainty includes variations of *b* mass (4.5-5.0 GeV), factorization and renormalization scales (0.5-2.0 *b* mass).

The HERA-B result agrees within 1.4σ with CEM NLO.

# Conclusions

The HERA-B data of *p*A collisions (√s=41.6 GeV) were used to measure:

- The B cross section from 176 $b \rightarrow J/\psi \rightarrow \mu^+\mu^- + X$ and $bb \rightarrow \mu^+\mu^- + X$ decay events:

$$\sigma_{b\bar{b}} = 15.8 \pm 1.7_{\text{stat}} \pm 1.3^{\text{uncorr.}}_{\text{sys}} \pm 2.0^{\text{corr.}}_{\text{sys}} \text{ nb/nucleon}$$

The result is consistent with the latest QCD predictions.

- The $\Upsilon$ cross section at mid-rapidity from 106 $\Upsilon \rightarrow \mu^+\mu^-$ and $\Upsilon \rightarrow e^+e^-$ decay events:

$$\text{Br} \times d\sigma_\Upsilon/dy\,\big|_{y=0} = 4.5 \pm 1.1 \text{ pb/nucleon}$$

The extrapolation to √s=38.8 GeV is consistent with existing (less precise) experimental data and with theoretical predictions.

Both results are obtained assuming $\sigma_{J/\psi} = 502 \pm 44$ nb/nucleon.