Measurement of the $b\bar{b}$ Cross Section at HERA–B

BEAUTY 2003 – Pittsburgh

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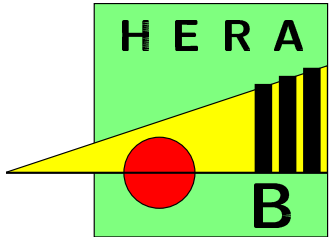


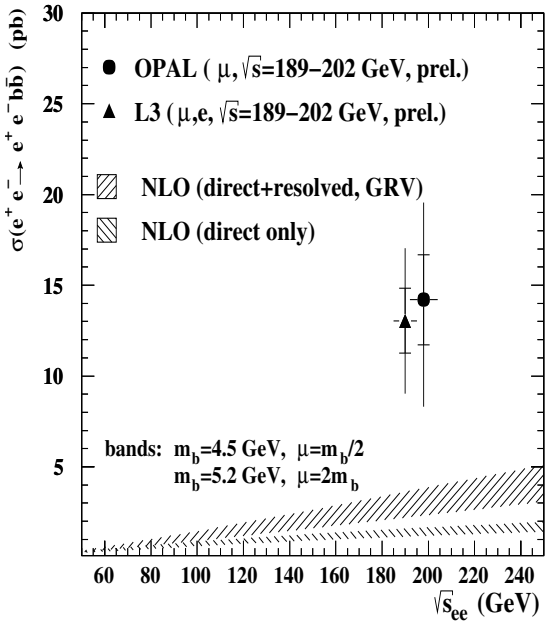
bmb+f - Förderschwerpunkt
HERA - B
Großgeräte der physikalischen Grundlagenforschung

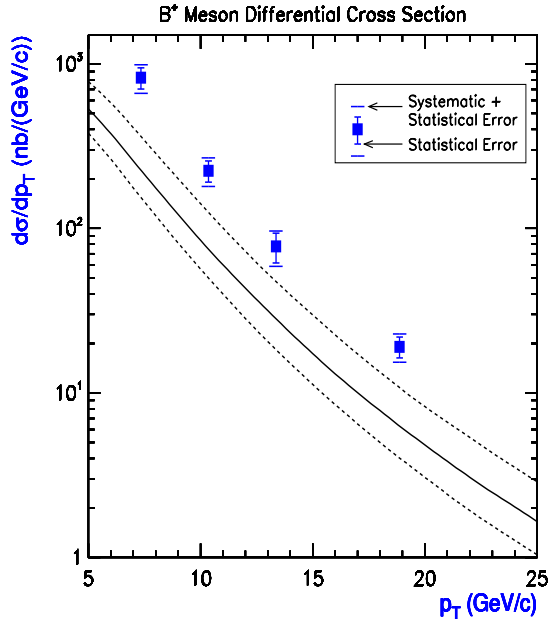
Contents

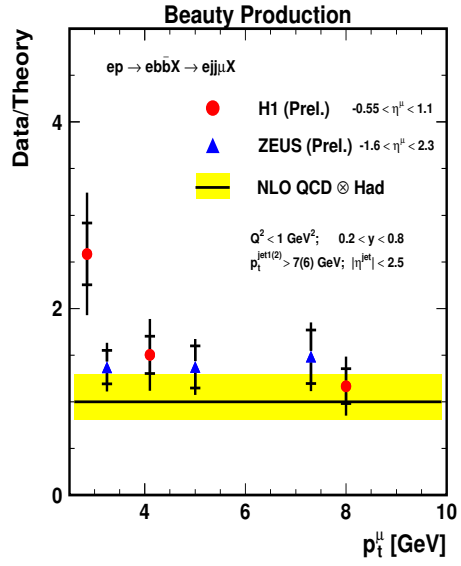
- Beauty production at HERA–B
  – a short overview –
- The HERA–B detector and trigger
- The measurement
- Results
- Comparisons with QCD predictions
- Outlook

Impact of the $\sigma(b\bar{b})$ Measurement

Theoretical predictions contain large uncertainties:







$\gamma\gamma$ reactions at LEP $\quad$ $p\bar{p}$ interactions at CDF $\quad$ ep scattering at HERA

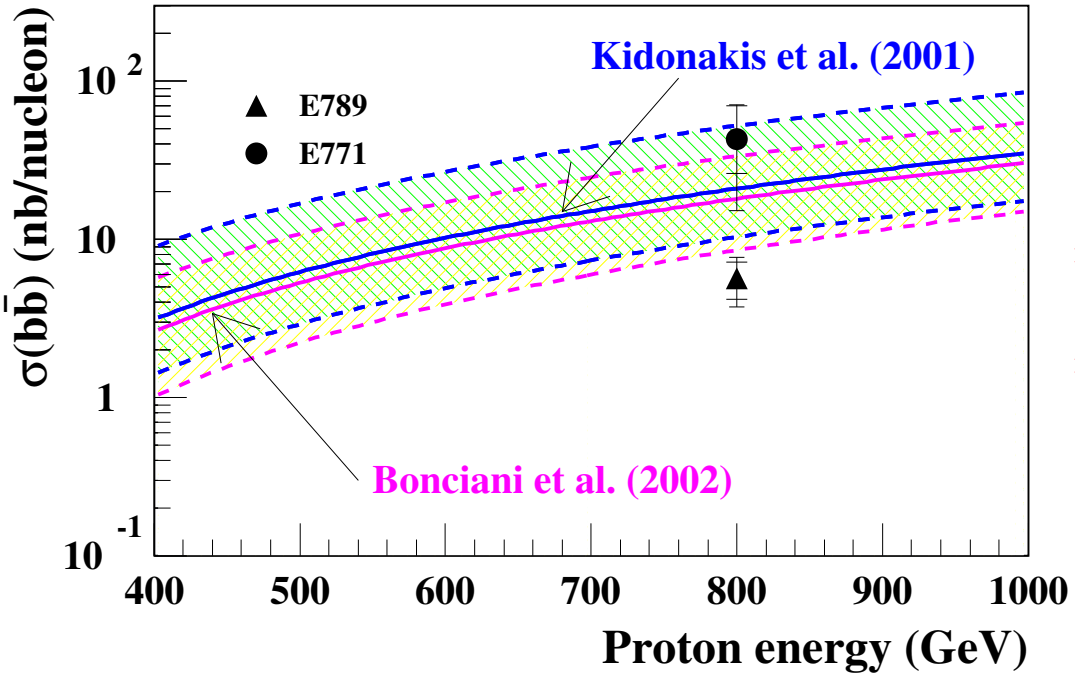
Cross sections and QCD NLO expectations not yet in good agreement

$\Rightarrow$ precise measurement of the $b\bar{b}$ cross sections is an important input to perturbative QCD calculations

Other $\sigma(b\bar{b})$ measurements

sensitive test for QCD predictions

Exp.	Target	E_p–Beam	$\sigma(b\bar{b})$	channel
E789	Au	800 GeV	$5.7 \pm 1.5 \pm 1.3$ nb/nuc.	$b \to J/\psi(\mu^+\mu^-)X$
E771	Si	800 GeV	$43\ ^{+27}_{-17} \pm 7$ nb/nuc.	μ(s.l.) / $b(\bar{b})$ dec.
Theory prediction: $9 \leq \sigma(b\bar{b}) \leq 55$ nb/nucleon				



$\Rightarrow$ large uncertainties

$\Rightarrow$ poor compatibility of measurements

HERA–B Physics Program

The HERA–B **ABC**

A. A**-dependence** of charmonia production

B. $b\bar{b}$ production cross section

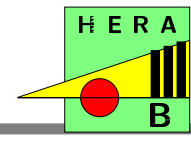
C. **Charmonium** production: $J/\psi,\ \psi',\ \chi_c$

In addition

220 million **minimum bias** events:

strangeness production, open charm, ...

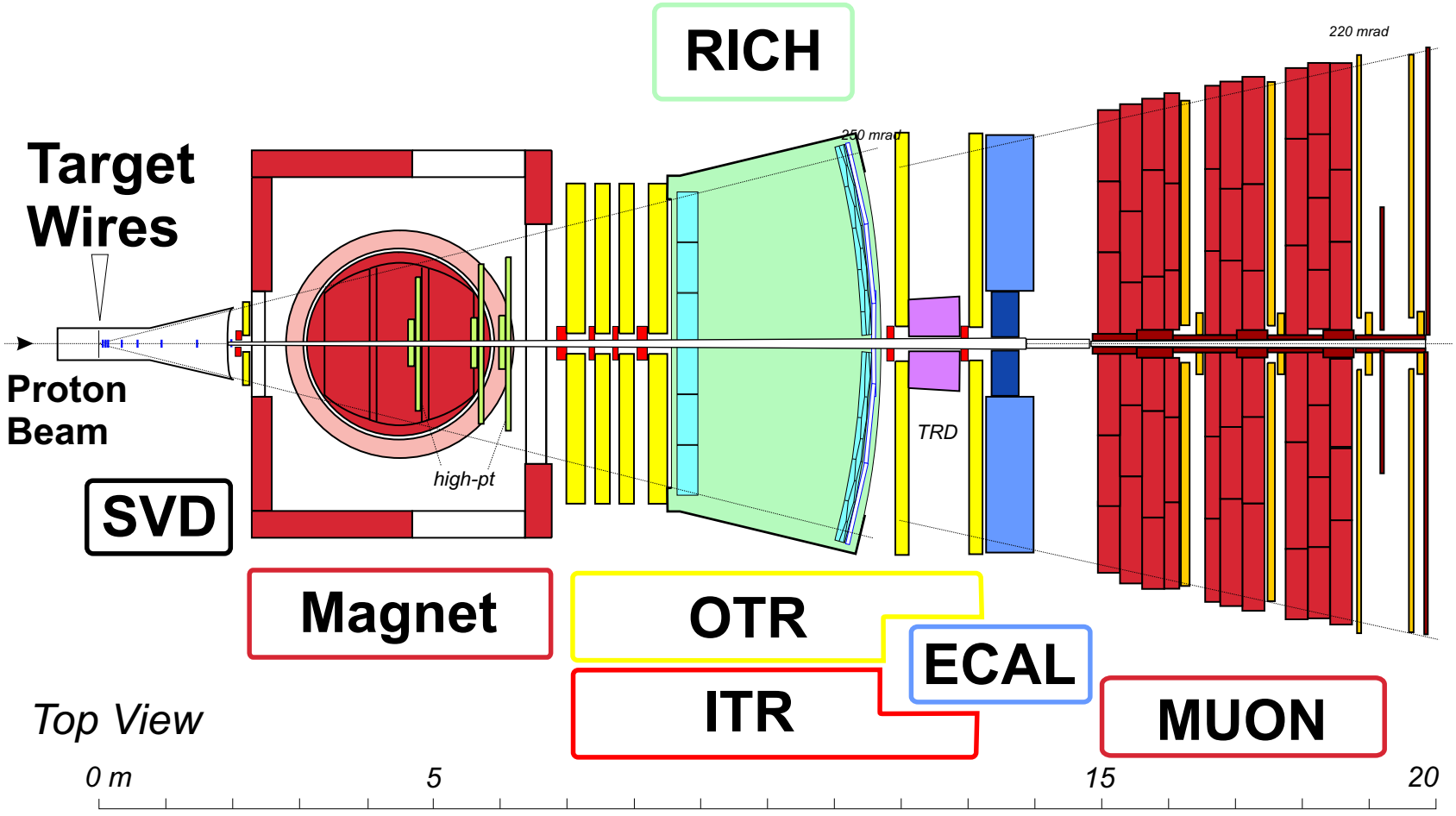
J/ψ production cross section



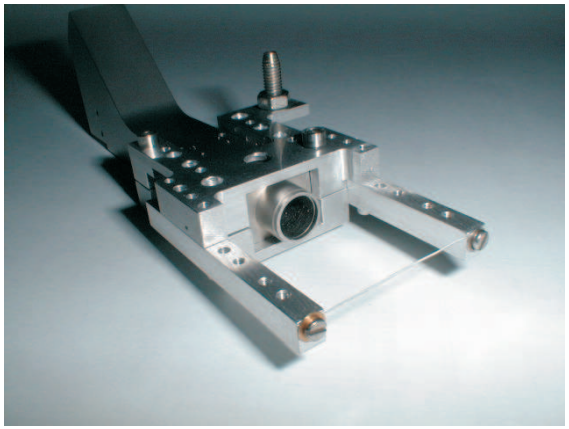
The HERA–B Detector

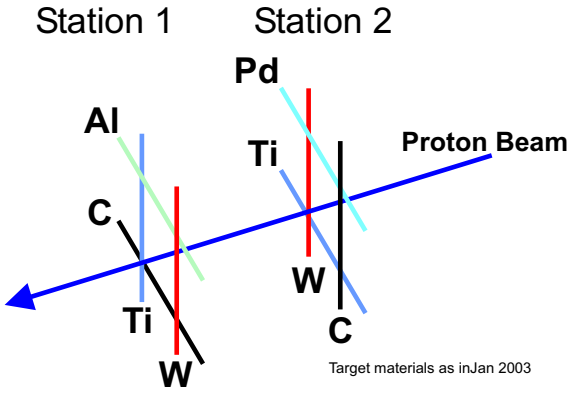
A fixed target spectrometer at the HERA proton beam

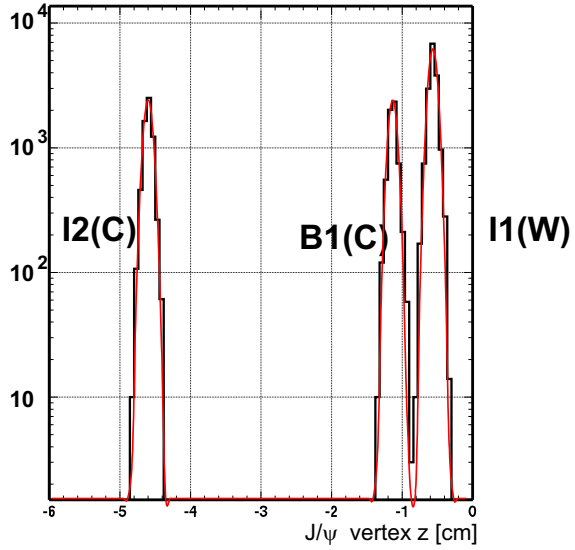
$\sqrt{s} = 41.6$ GeV



Target

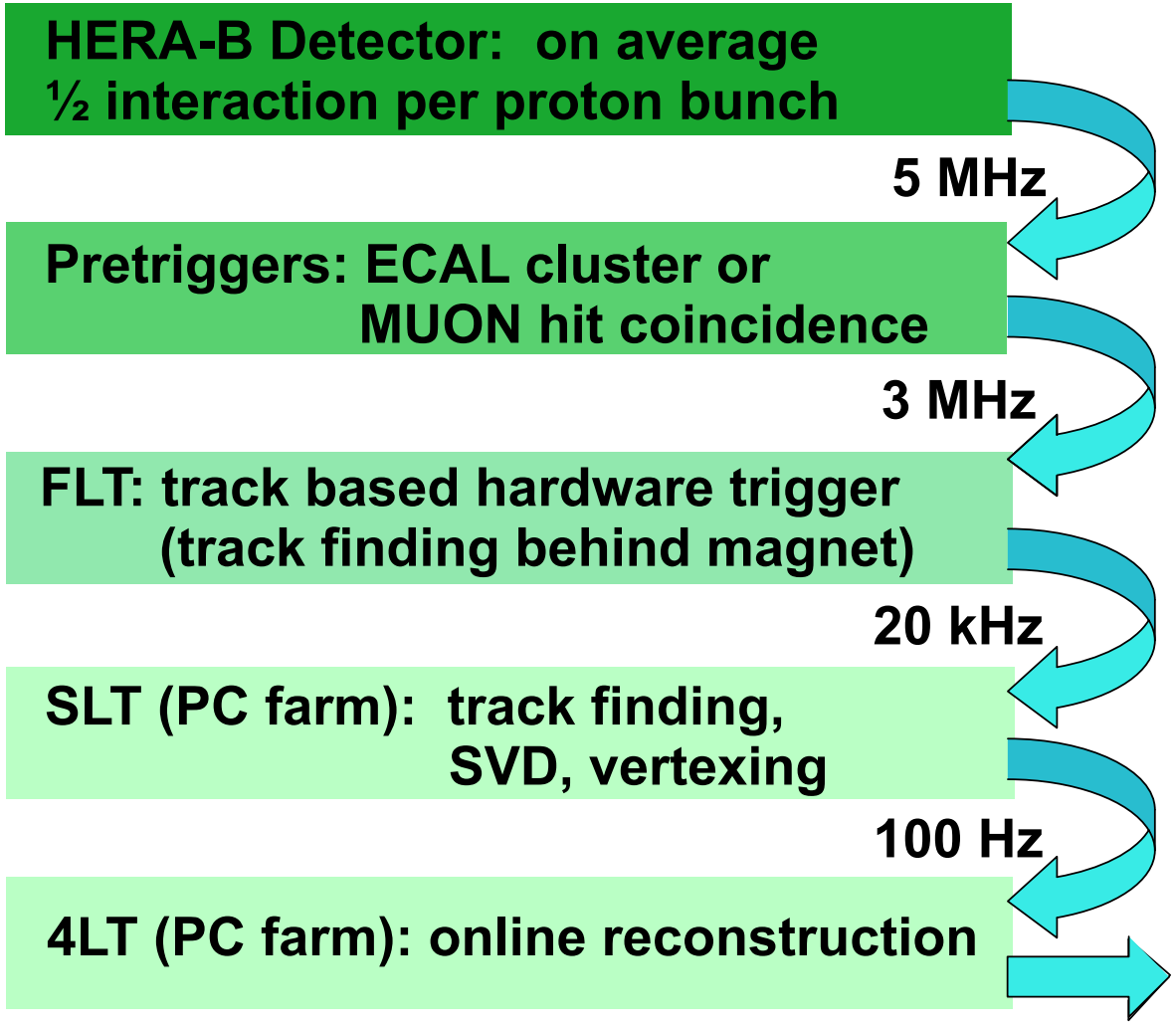






- Different targets can be used simultaneously.
  A–dependence measurements $\Rightarrow$ control of systematic errors.
- Events from different wires can be separated easily.

J/ψ–Trigger



Main trigger setup in 2002/3:

$(1\ FLT$ track) + ($2\ SLT$ tracks with PreTrigger seeds)

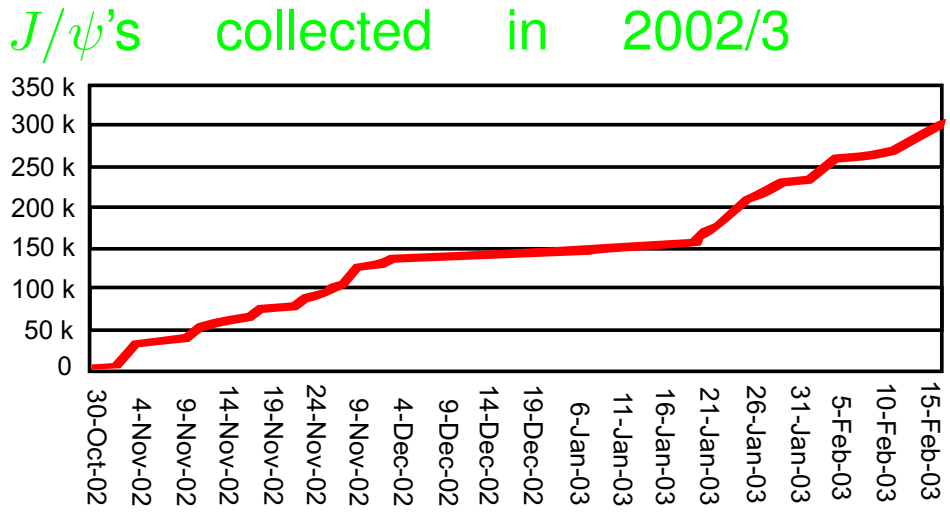
so-called $1FLT/2SLT^*$ mode

Year	$J/\psi\ h^{-1}$
2000	25-30
2002/3	1000-1500

Data Sets with Di-Lepton Triggers

2000: short physics run during HERA-B commissioning: runs with 1 and 2 target wires,
mainly carbon and titanium,
≈ 8600 J/ψ's

2002/3: 3 months of data taking:
runs with 1 and 2 target wires,
mainly carbon and tungsten,
≈ 300000 $J/\psi \rightarrow l^+l^-$

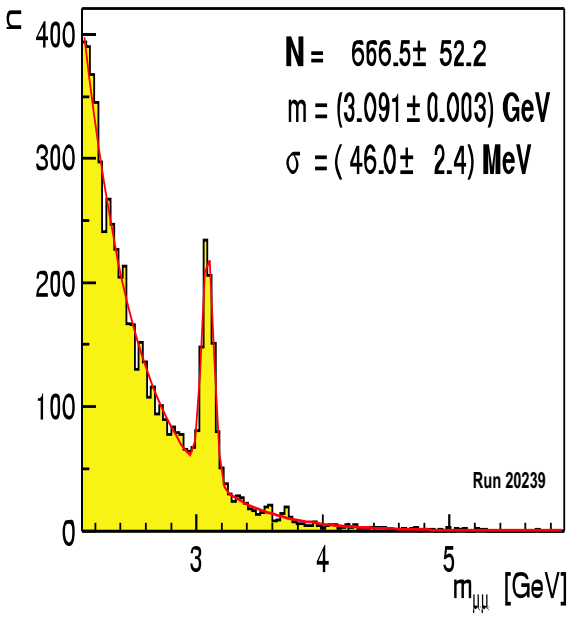


Many improvements for 2002/3

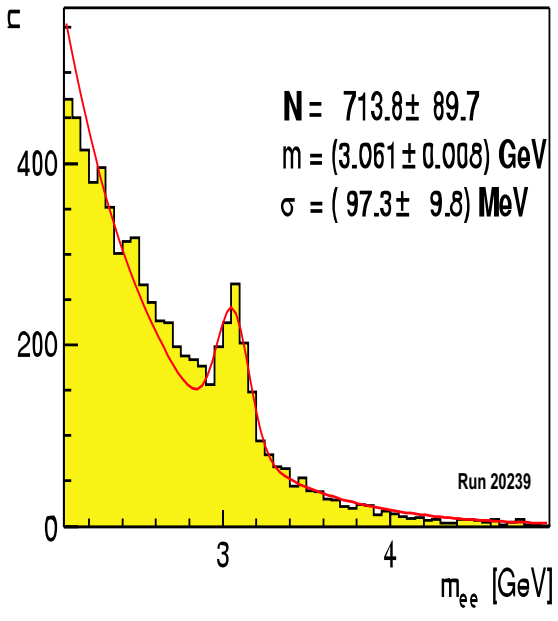
- Less material in magnet area
- ECAL: less noise, improved calibration
- Improved tracking efficiency, trigger, ...

Detector performance in 2002/3

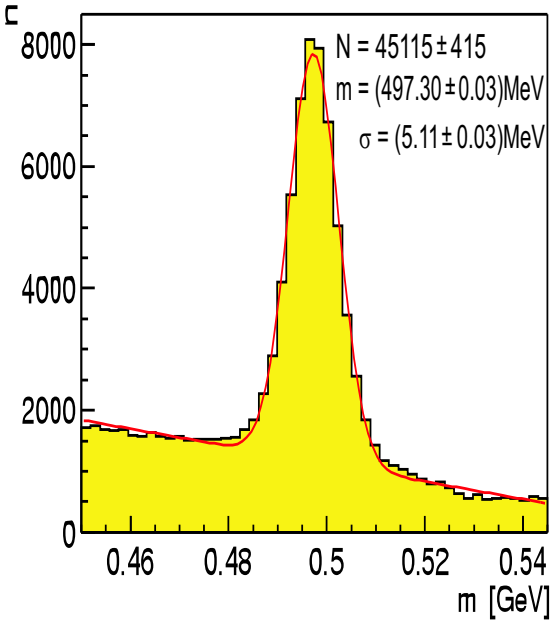
Online data quality, e.g :



$J/\psi \to \mu^+\mu^-$



$J/\psi \to e^+e^-$

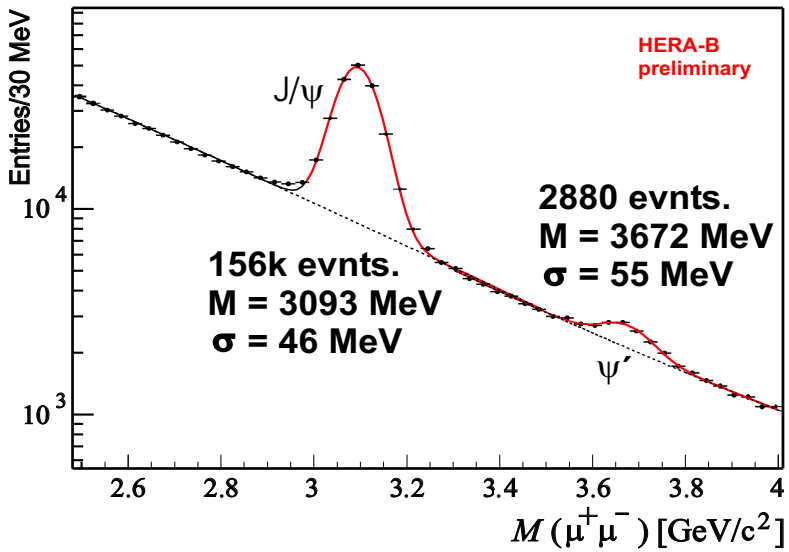


K^0_s width as expected from Monte Carlo

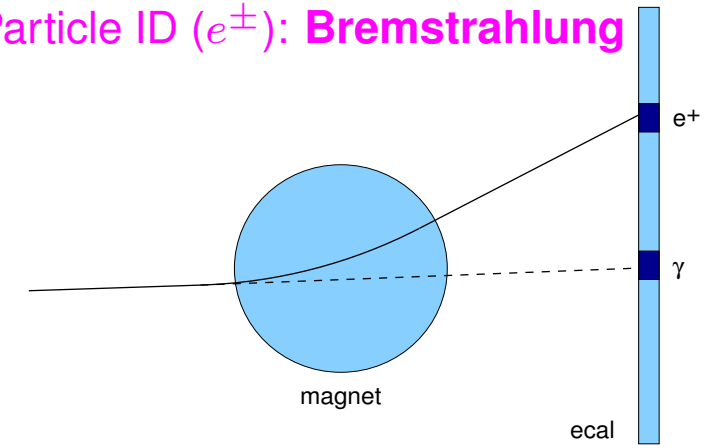
Signals as seen during data taking

Invariant Mass of Lepton Pairs in 2002/3

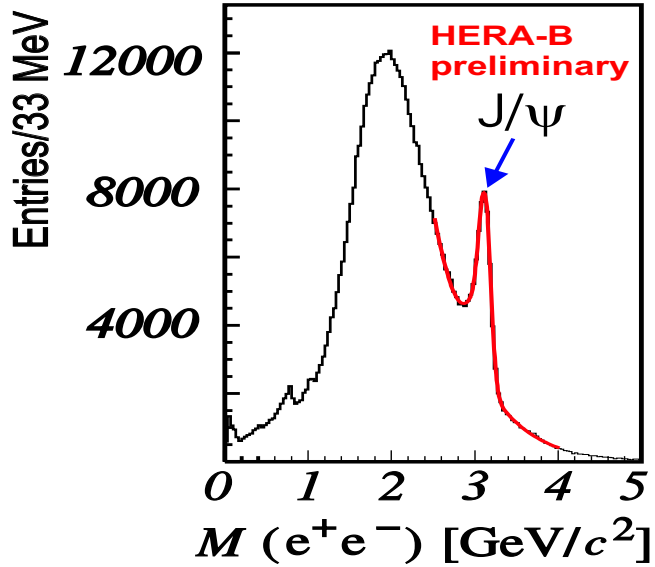
Muon



Particle ID ($e^{\pm}$): **Bremstrahlung**

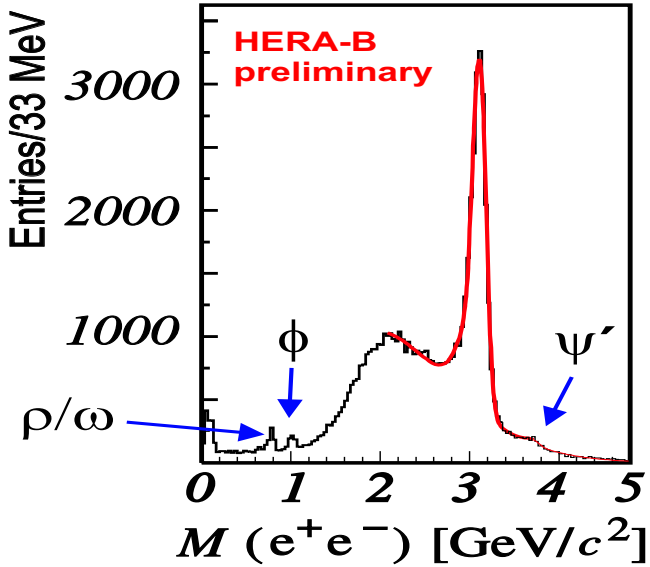


Electrons



1 brems-
strahlung γ

$\Longrightarrow$



The HERA–B $\sigma(b\bar{b})$ Measurement

HERA–B can measure the $b\bar{b}$ cross section simultaneously in

$$b \to J/\psi X \to \mu^+\mu^- X \text{ and } b \to J/\psi X \to e^+e^- X$$

common approach to e and μ:

- increase statistics
- cross check the result

First measurement of $\sigma(b\bar{b})$ in a fixed–target experiment and in negative x_F region:

J/ψ acceptance region for HERA–B: $x_F \in [-0.35, 0.15]$

$$x_F = \frac{p_L^{cms}}{(p_L^{cms})_{max}}$$

Cross Section Formula

$\Rightarrow$ to minimize systematic errors and to remove luminosity measurement dependence:

$\sigma(b\bar{b})$ measured relative to prompt J/ψ cross section (n_P):

$$\Delta\sigma_{b\bar{b}} = \Delta\sigma_r \cdot \frac{n_B}{n_P} \cdot \frac{1}{\epsilon_R \cdot \epsilon_B^{\Delta z} \cdot BR(b\bar{b} \to J/\psi x)}$$

- n_B/n_P: observed b and prompt J/ψ events
- ϵ_R: relative efficiency ($\epsilon_R = \epsilon_B^{J/\psi}/\epsilon_P^{tot}$, $\epsilon_B^{tot} = \epsilon_B^{J/\psi} \cdot \epsilon_B^{\Delta z}$)
  B– to prompt J/ψ–efficiency ratio (trigger + reco + selection)
- $BR(b\bar{b} \to J/\psi) = (2.32 \pm 0.20)\ \%$: branching ratio (LEP)
- $\Delta\sigma_r$: reference (prompt J/ψ) cross section in HERA–B acceptance
- $\Delta\sigma_{b\bar{b}}$: measured cross section in HERA–B acceptance

Reference cross section (prompt J/ψ)

Exp.	Target	E_p–Beam	$\sigma(J/\psi)$	α
E789	Au	800 GeV	$442 \pm 2 \pm 88$ nb/nuc.	0.9 ± 0.02
E771	Si	800 GeV	$375 \pm 4 \pm 30$ nb/nuc.	0.92 ± 0.008

using $\alpha = 0.955 \pm 0.005$ (**E866**) and scaling to HERA–B energies:

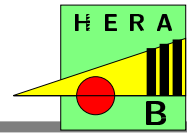
$$\sigma(pN \to J/\psi) = (357 \pm 8 \pm 27) \text{ nb/nuc.}$$

in our acceptance we see $f_P = (77 \pm 1)\ \%$ of the prompt J/ψ and $f_B = (90.6 \pm 0.5)\ \%$ of the $b\bar{b}$ events

Nuclear dependence A_P^α: $\alpha = 0.955 \pm 0.005$ for prompt J/ψ

Reference prompt J/ψ cross section(E789 + E771):

$$\Delta\sigma_r = f_P \cdot \sigma(pN \to J/\psi) \cdot A_P^\alpha$$



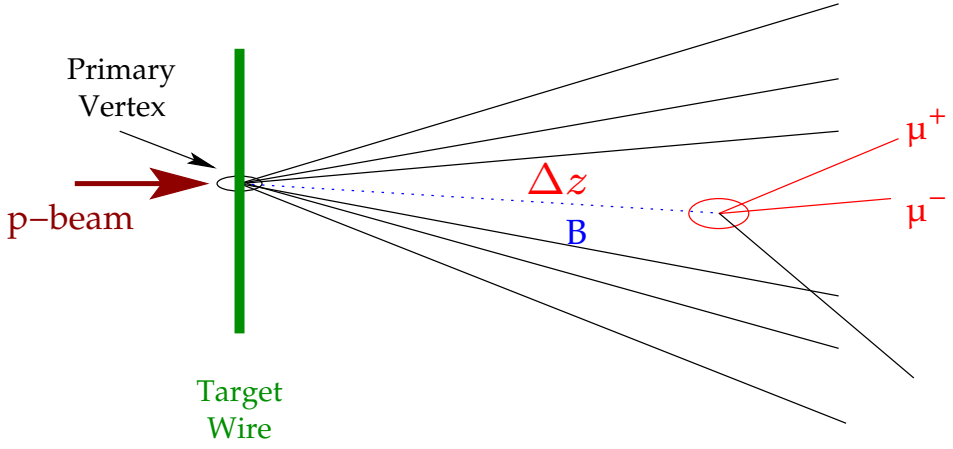
MC Models

- $b\bar{b}$ production model:
  - PYTHIA for heavy flavor quark production in $pA \rightarrow Q\bar{Q}X$ interactions and heavy quark hadronization in nuclear environment
  - FRITIOF for the remaining process (X): light quark production, secondary interactions and pA inelastic interactions
  - generated b–quark kinematics (x_F, p_T) using **NNLL MRST** PDF's ($\mu_R = \sqrt{m_b^2 + p_T^2}$, $m_b = 4.75$ GeV$/c^2$)
  - intrinsic k_T of partons smeared: $\langle k_T^2 \rangle = 0.5$ GeV$^2/c^2$
  - b–quark fragmentation to hadrons using $\epsilon_{peterson} = 0.006$
- prompt J/ψ model:
  1. reweighting of events to match E789 x_f–range ($x_f > -0.05$)
  2. extrapolate to negative x_F

Detached Vertex Selection

Identify b–hadrons by their decay length using the decay chain

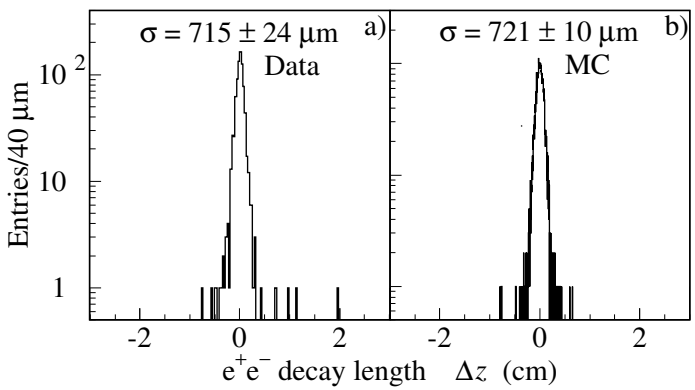
$$pN \rightarrow b\bar{b}X \rightarrow J/\psi XY \rightarrow l^+l^- XY$$



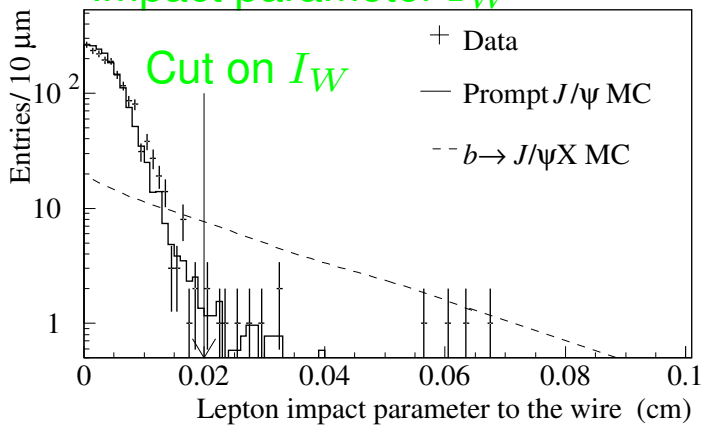
average decay length (DL)
of B–mesons at HERA–B:

$DL \approx 8$ mm $\gg \sigma_{\Delta z}$

Real Data Δz Monte Carlo



Impact parameter I_W



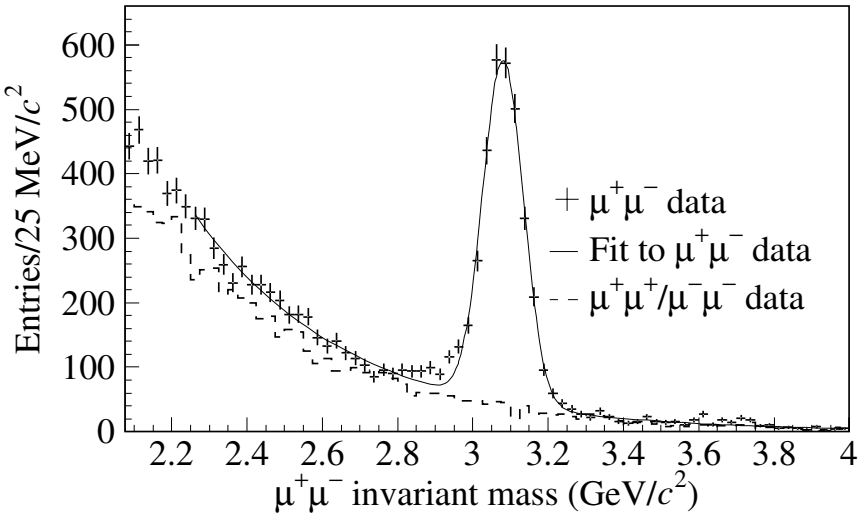
Prompt J/ψ: e and μ data 2000

Reco tracks confirmed by trigger

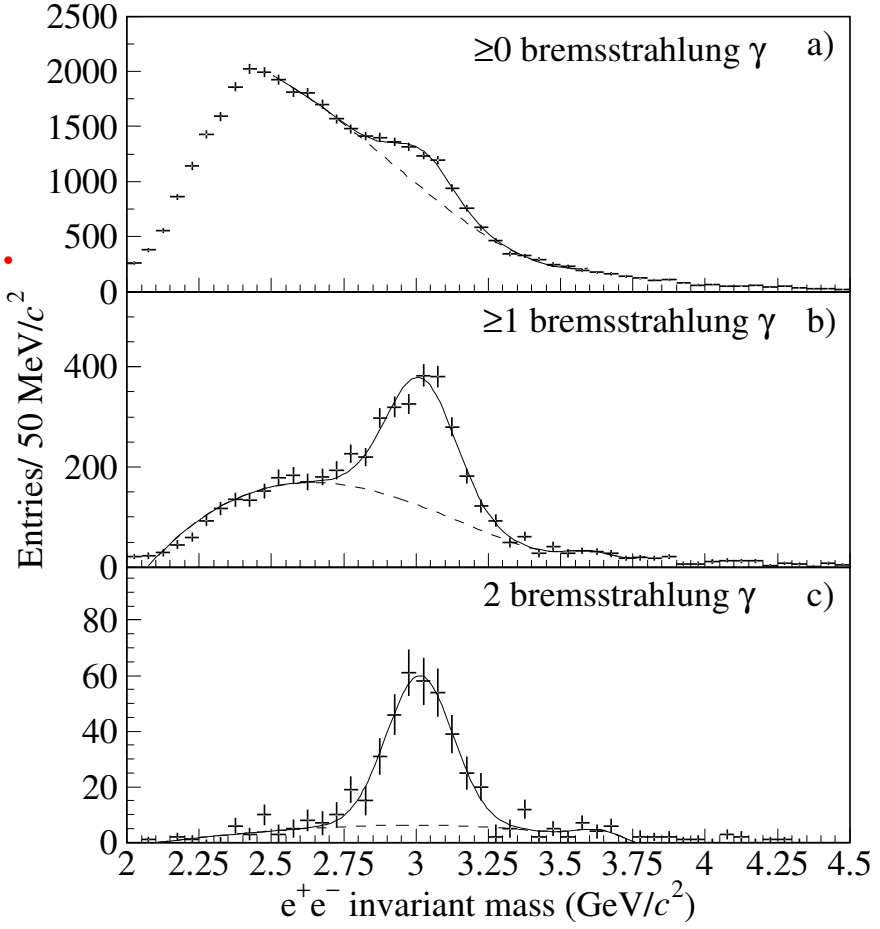
$$n_P^{\mu} = 2880 \pm 60$$

$$n_P^{e} = 5719 \pm 380_{stat.} \pm 280_{sys.}$$

PID: μ likelihood from Muon detector and RICH

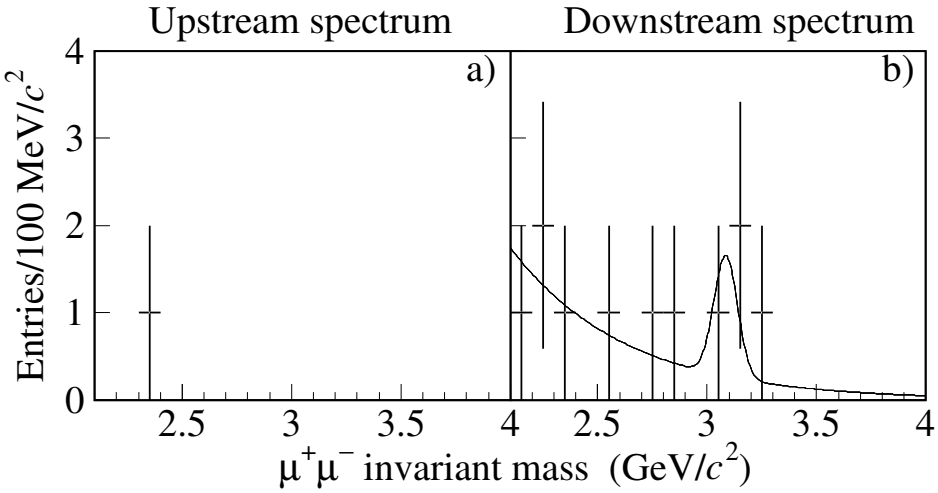


PID: E/p and bremsstrahlung



$$\epsilon_{brem} = 0.34 \pm 0.02_{stat.} \pm 0.02_{sys.}$$

Muon Data 2000: b–Cuts



$$\epsilon_R \cdot \epsilon_B^{\Delta z} = 0.41 \pm 0.01$$

$$\boldsymbol{n_B = 1.9^{+2.2}_{-1.5}}$$

Low statistics $\Longleftrightarrow$ unbinned likelihood fit

Mass spectrum: Prompt J/ψ shape + exponential BG

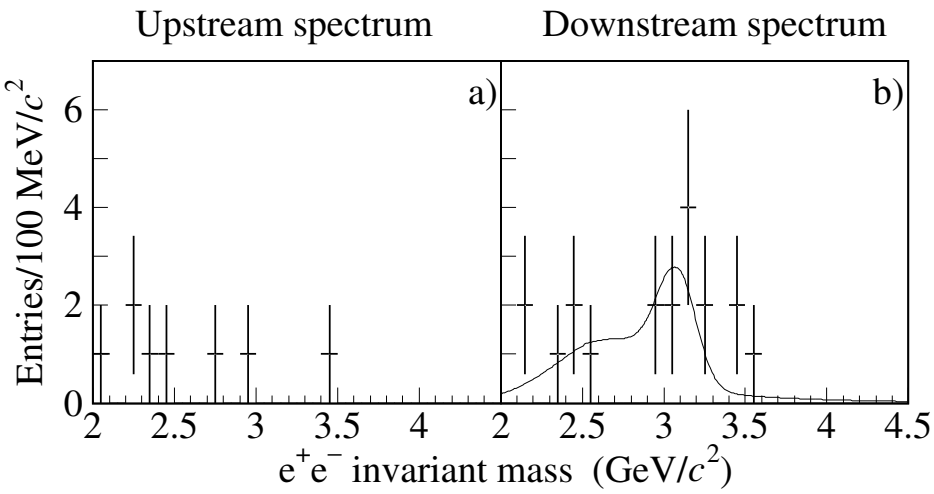
$\Longrightarrow n_B$ + BG level and slope

$\mu^\pm$ Impact parameter to wire $I_W > 35$ μm (b1 wire) / $I_W > 45\mu$m (i1 wire)

$\mu^\pm$ Impact parameter to primary vertex $I_P > 160$ μm

Decay length $\Delta z > 7.5 \cdot \sigma_z$

Electron Data 2000: b–Cuts



$$\epsilon_R \cdot \epsilon_B^{\Delta z} = 0.44 \pm 0.02$$

$$n_B = 8.6^{+3.9}_{-3.2}$$

Low statistics $\Longleftrightarrow$ unbinned likelihood fit

Mass spectrum: Prompt J/ψ shape + exponential BG

$\Longrightarrow n_B$ + BG level and slope

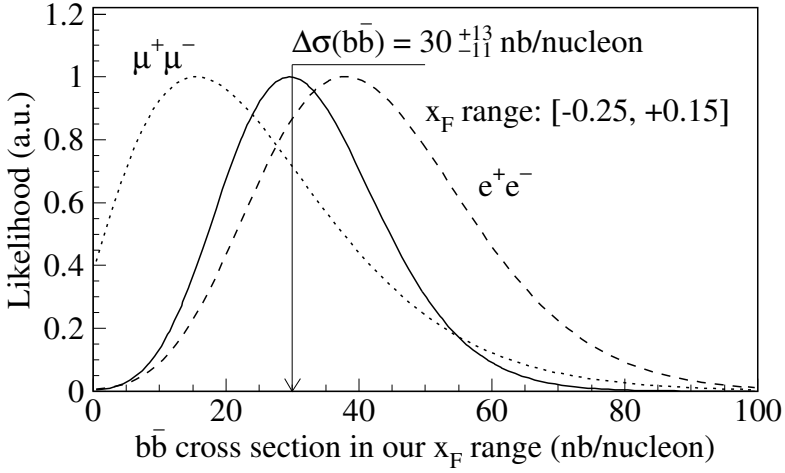
$e^{\pm}$ Impact parameter to wire $I_W > 200$ μm OR

min. dist. at Z_W to any other track > 250 μm

Decay length $\Delta z > 0.5$cm

The 2000 $\sigma(b\bar{b})$ Measurement

simultaneous fit to e^+e^- and $\mu^+\mu^-$ Data samples



e–channel:

$n_B = 8.6^{+3.9}_{-3.2}$, $n_P = 5710 \pm 380$

μ–channel:

$n_B = 1.9^{+2.2}_{-1.5}$, $n_P = 2880 \pm 60$

Target: 77 % C ($A = 12$) and 23 % Ti ($A = 48$) **Reference**: $\sigma_r = 357 \pm 28$ nb/nuc.

Results in the x_F acceptance region of HERA–B

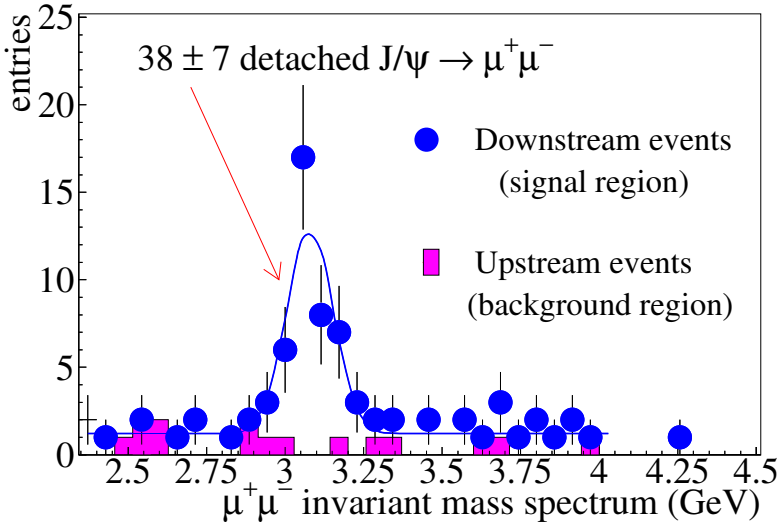
e–channel: $\Delta\sigma(b\bar{b}) = 38^{+18}_{-15}$ nb/nuc. μ–channel: $\Delta\sigma(b\bar{b}) = 16^{+18}_{-12}$ nb/nuc.

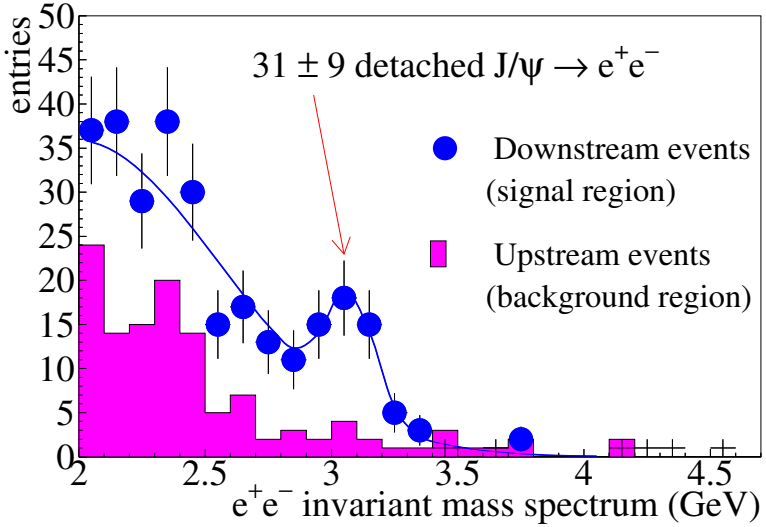
$$\Delta\sigma(b\bar{b}) = 30^{+13}_{-11} \text{ nb/nucleon}$$

$$\boldsymbol{\sigma(b\bar{b}) = 32^{+15}_{-12} \pm 8_{sys}} \text{ nb/nucleon}$$ [**Eur.Phys.J.C26(2003)345**]

Actual detached Signals of 2002/3 data

Detached J/ψ search on $40\ \%$ of the full statistics:





$n_B^\mu = 38 \pm 7 \quad \Longrightarrow$ expected 2002/3: $n_B^\mu \approx 95 \pm 11$

$n_B^\mu(2000) = 1.9^{+2.2}_{-1.5}$

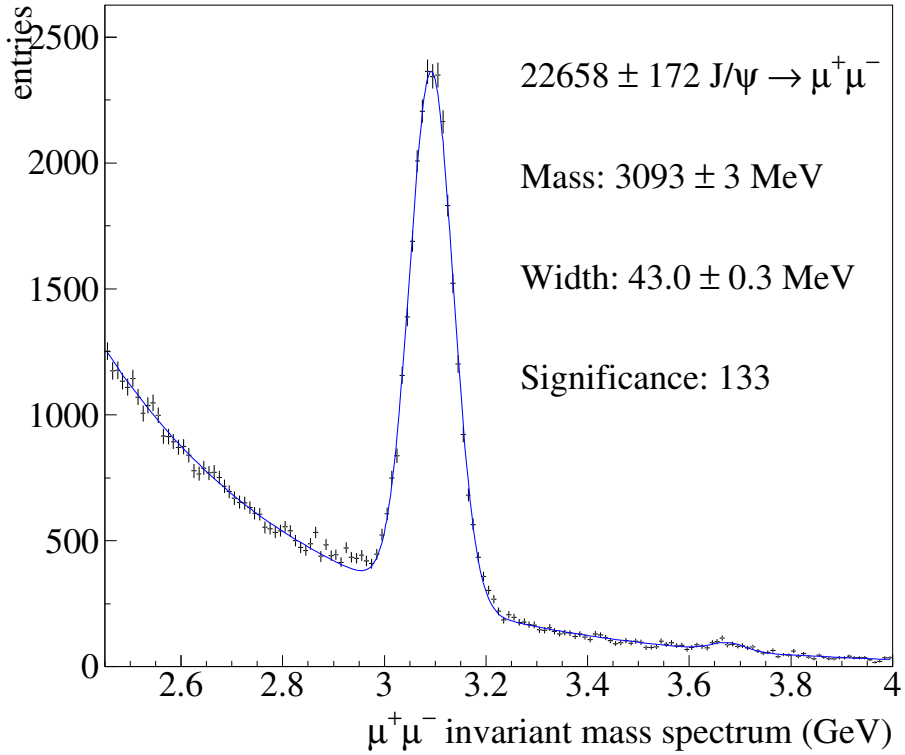
$n_B^e = 31 \pm 9 \quad \Longrightarrow$ expected 2002/3: $n_B^e \approx 80 \pm 13$

$n_B^e(2000) = 8.6^{+3.9}_{-3.2}$

Improvement of stat. error from $\approx 40\ \%$ (2000) to $\approx 10\ \%$ (2002/3)

Status of analysis of 2002/3 data

Optimize cuts on small part of the 2002/3 data sample ($\approx 16\ \%$)



μ–channel:

$$n_P^{\mu} = 22658 \pm 172$$

$$n_P^{\mu}(2000) = 2880 \pm 60$$

use the optimized cuts on **full sample** (blind analysis)

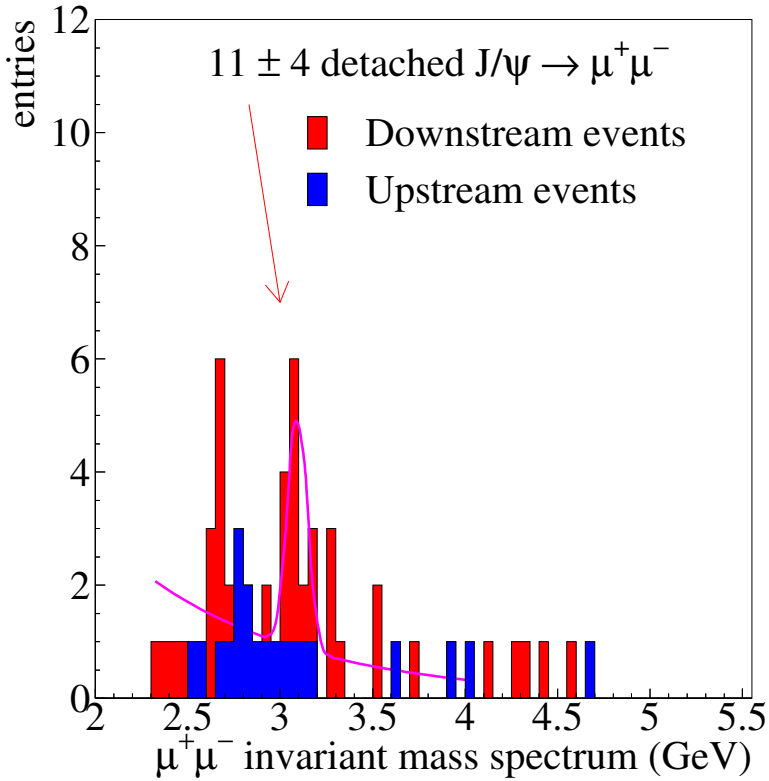
PID: μ likelihood from Muon detector and RICH

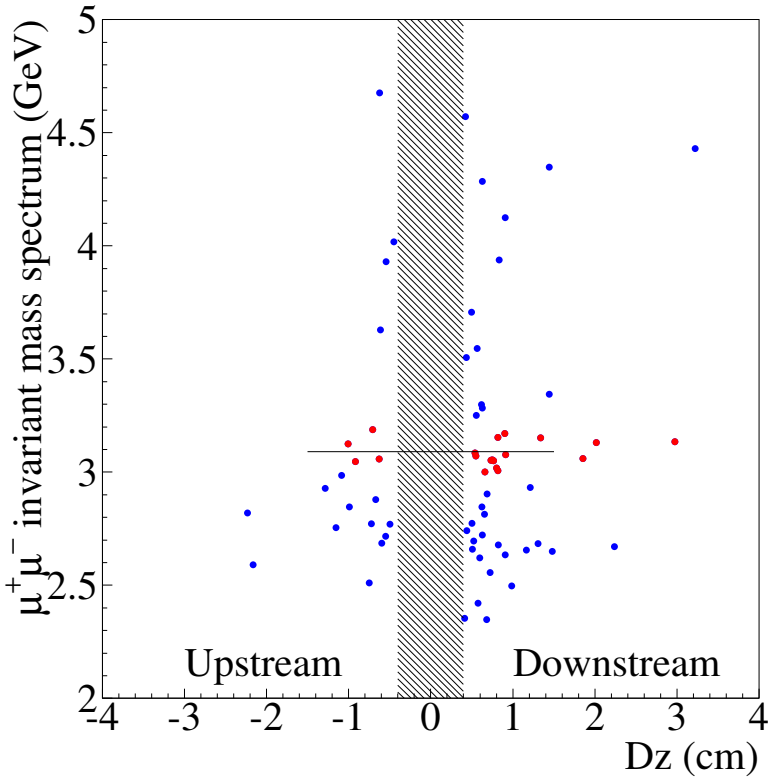
$$-0.35 < x_F < 0.15$$

$\longrightarrow$ **Analysis is still going on** $\longleftarrow$

Detached J/ψ Signal in 2002 (μ–channel)

small part of the 2002/3 data sample ($\approx 16\ \%$)





Decay length $|\Delta z| > 0.4$ cm

Decay length $|\Delta z| > 12 \cdot \sigma_Z$

Impact parameter to primary vertex $I_P > 160\ \mu$m

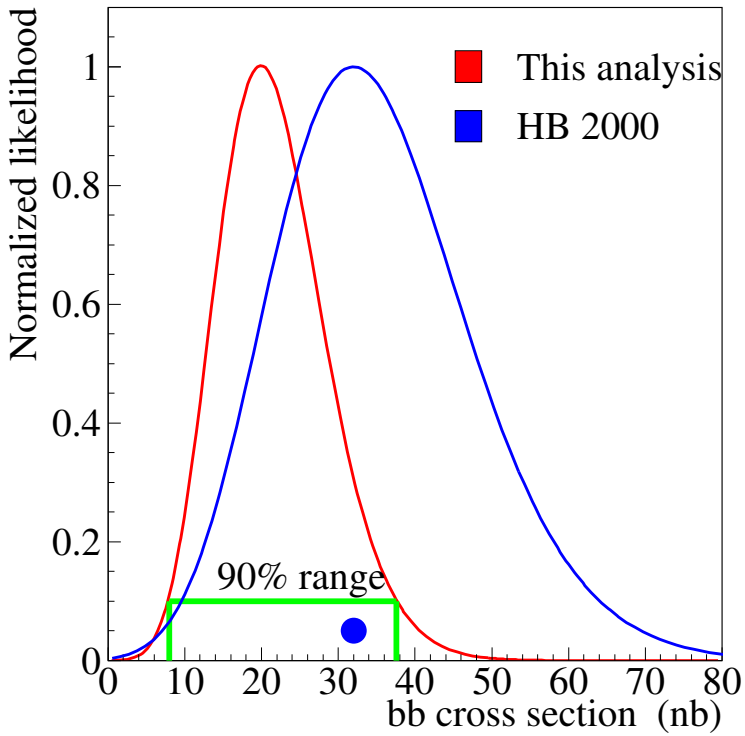
unbinned maximum likelihood fit:

$$n_B^{\mu} = 11.0^{+4.4}_{-3.7}$$

$$n_B^{\mu}(2000) = 1.9^{+2.2}_{-1.5}$$

Preliminary Result $\sigma(b\bar{b})$ 2002 (μ only)

$$\Delta\sigma_{b\bar{b}} = \Delta\sigma_r \cdot \frac{n_B}{n_P} \cdot \frac{1}{\epsilon_R \cdot \epsilon_B^{\Delta z} \cdot BR(b\bar{b} \to J/\psi x)} \qquad \sigma_{b\bar{b}} = \Delta\sigma_{b\bar{b}} / f_B$$



$BR(b\bar{b} \to J/\psi X) = (2.32 \pm 0.02)\ \%$

$\Delta\sigma_r^C = (245 \pm 6 \pm 19)$ nb/nuc.

$f_B = (90.6 \pm 0.5)\ \%$

$n_B = 11^{+4.4}_{-3.7}$ **(16 % of full data sample)**

$n_P = 22658 \pm 172$ **(16 % of full data sample)**

$\epsilon_R = 1.01 \pm 0.02$

$\epsilon_B^{\Delta z} = (28.1 \pm 0.9)\ \%$

$7 < \Delta\sigma_{b\bar{b}} < 34$ and $8 < \sigma_{b\bar{b}} < 38$ nb/nucl. at 90 % CL

analysis on reduced sample (16 %): μ channel, single wire runs 2002 (I2, C)

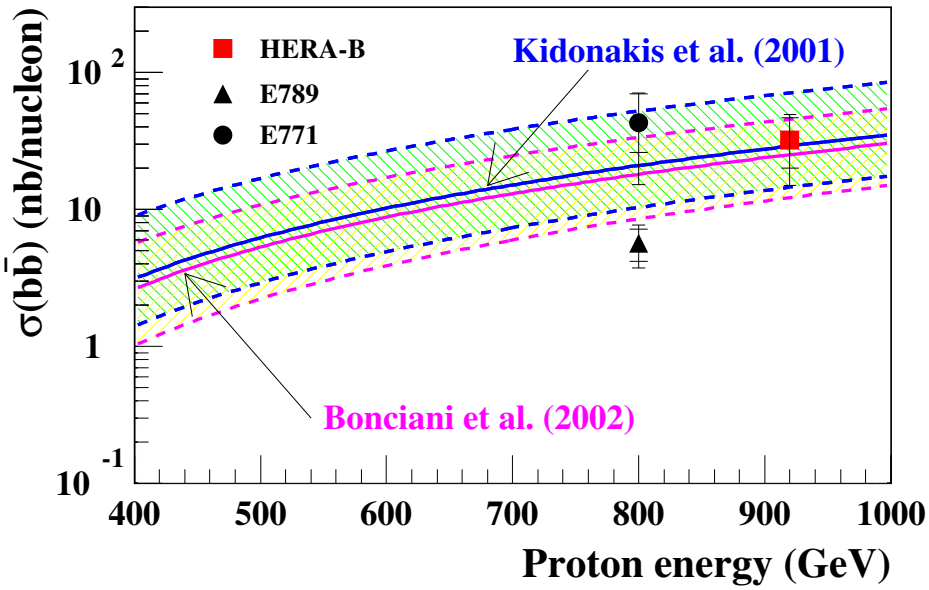
Systematic Uncertainties

for the analysis using the data of 2000

expectations for the data of 2002/3

source	channel	err.2000 [%]	err.2002/3 [%]
reference J/ψ cross section (σ_r)	e, μ	11 %	11 %
prompt J/ψ MC production model ($\epsilon_P^{J/\psi}$)	e, μ	2.5 %	2.5 %
b production and decay model (ϵ_B^{tot})	e, μ	8 %	8 %
trigger simulation (ϵ_R)	e, μ	5 %	5 %
A dependence ignored in $\epsilon_R \cdot \epsilon_B^{\Delta z}$	e, μ	1.7 %	1.7 %
b lifetime error ($\epsilon_B^{\Delta z}$)	e, μ	< 1 %	< 1 %
prompt J/ψ counting (n_P)	e	5 %	1 %
$J/\psi \to e^+e^-\gamma$ channel	e	1 %	1 %
background shape	e / μ	14 % / 20 %	5 % / 7 %
background fluctuations	e / μ	11 % / 23 %	4 % / 8 %
total contribution	e / μ	**24 % / 33 %**	**16 % / 18 %**

Comparison to QCD Models



measurement with data of 2000 shows good agreement with QCD calculation beyond NLO

measurement with new data (2002/3) can be used to reduce the theoretical uncertainties (mainly mass of b–Quark, $m_b \in [4.5, 5.0]$ GeV) ($\sim 30\times$ more statistics)

- N. Kidonakis et al, Phys.Rev.D64(2001)114001.
  NLO + NNLL: $15 < \sigma(b\bar{b}) < 70$ nb/nucl.

- R. Bonciani et al, Nucl.Phys.B529(1998)24.
  NLO+NLL: $12 < \sigma(b\bar{b}) < 45$ nb/nucl.
  corrected for the last MRST pdf: A.D. Martin et al., Phys.Lett.B531(2002)216.

Outlook

- cut optimisation done on $16\ \%$ of data,
  fix cuts to be used for blind analysis on full sample
- we expect ~ 95 detached J/ψ's in μ–channel and ~ 80 in e–channel in data taken in 2002/3

  $\Longrightarrow$ measurement improved in statistical and systematic errors
- input on b-Quark mass and on QCD calculations
- clear improvement in signal over noise in e–channel
- exclusive b–decay search: $B^{\pm} \to J/\psi K^{\pm}$,
  $B^0 \to J/\psi K^{\pm}\pi^{\mp}$ and $B^0 \to J/\psi K_s$ in progress
- search for double semileptonic decays $b\bar{b} \to \mu\mu X$,
  $B \to \mu\nu X$: analysis in progress, first $\sigma_{b\bar{b}}$ measurement expected soon

Summary

- new measurement of cross sections with reduced statistics fully compatible with measurement of 2000
- clear improvement of the measurement in statistical errors and systematic uncertainties for full statistics expected
- additional measurement of $\sigma_{b\bar{b}}$ using exclusive and double semileptonic b decays
- analysis is still going on