Heavy Flavor Production at HERA-B

in 920 GeV Proton-Nucleus Interactions

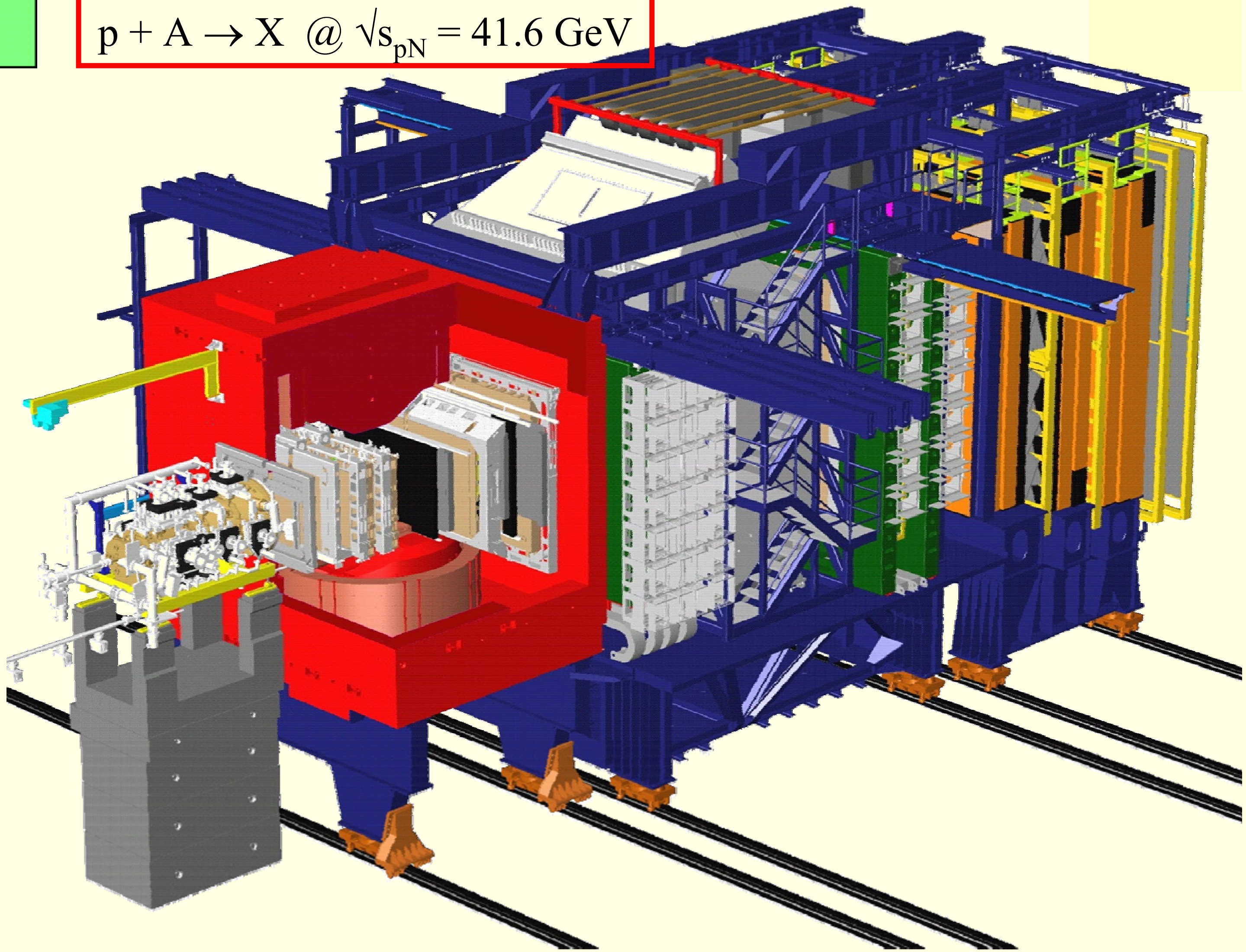
Hermann Kolanoski
Humboldt Universität zu Berlin and DESY Zeuthen
for the HERA-B Collaboration

Brookhaven, 4.April 2006

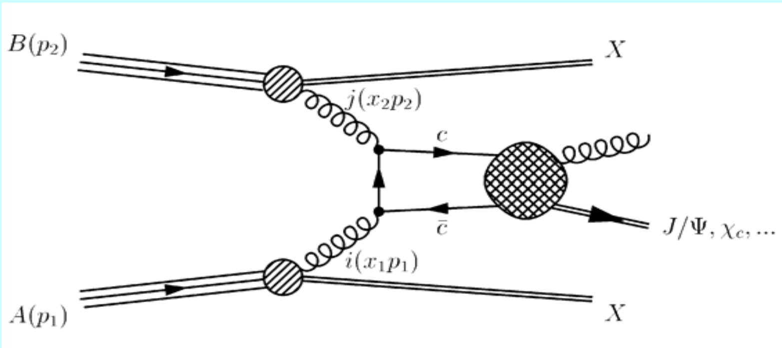
- **Charmonium production: J/ψ, ψ', χ_c**
  - **J/ψ production cross section**
  - **Differential distributions, polarisation**
  - **Nuclear dependence**
  - **Production ratios ψ'/ J/ψ, χ_c/ J/ψ**
- **Hidden and open beauty production: $\sigma(b\bar{b})$, Υ(ns)**
  - **$b\bar{b}$ production cross section**
  - **Υ production cross section**

The HERA-B Experiment

$p + A \rightarrow X \; @ \; \sqrt{s_{pN}} = 41.6 \text{ GeV}$



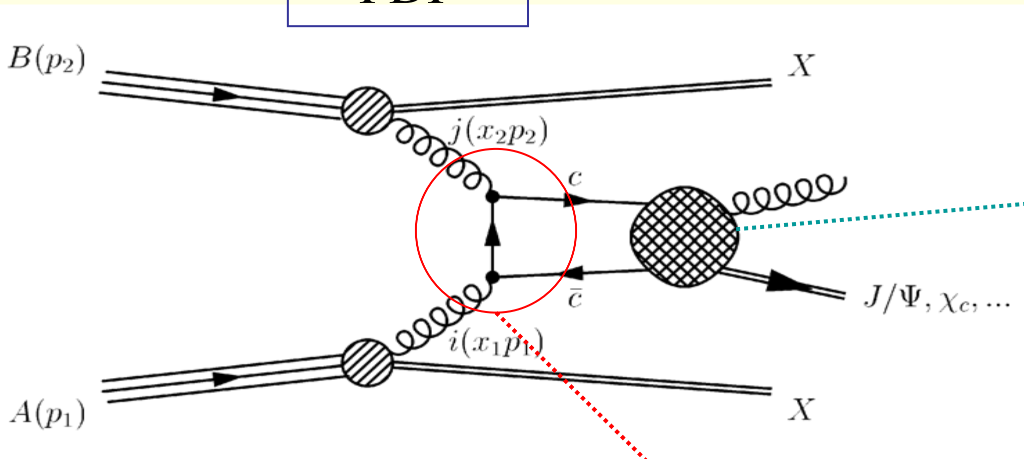
Models of Heavy Flavour Production in Hadronic Interactions



Factorisation

$$\sigma_{\mathcal{CH}} = \sum_{i,j}\int \underbrace{dx_1 dx_2 f_{i/A} f_{j/B}}_{\Lambda_{QCD}} \times \underbrace{\hat{\sigma}[ij \to (c\bar{c}[n] + X')]}_{m_c} \times \underbrace{O[c\bar{c} \to \mathcal{CH}]}_{m_c v} + \mathcal{O}\left(\frac{\Lambda_{QCD}}{m_c^2}\right)$$

PDF



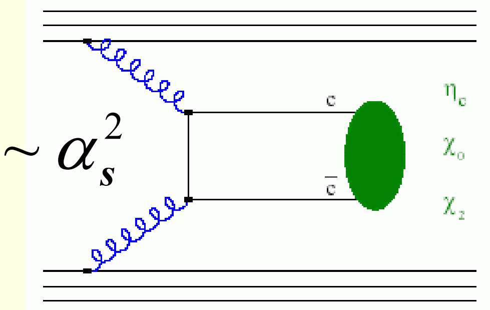
hadronization

Long distance ($\sim 1/(m_c v)$) process
→ non-perturbative calculations + input from experiments

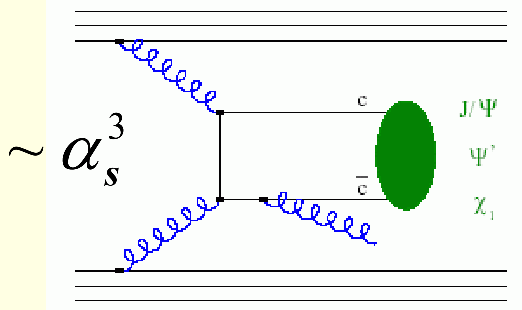
$q\bar{q}$ formation

short distance ($\sim 1/m_c$) / high momentum process
→ perturbative calculations

Perturbative $c\bar{c}$ Generation:
Color Singlet or Octet?



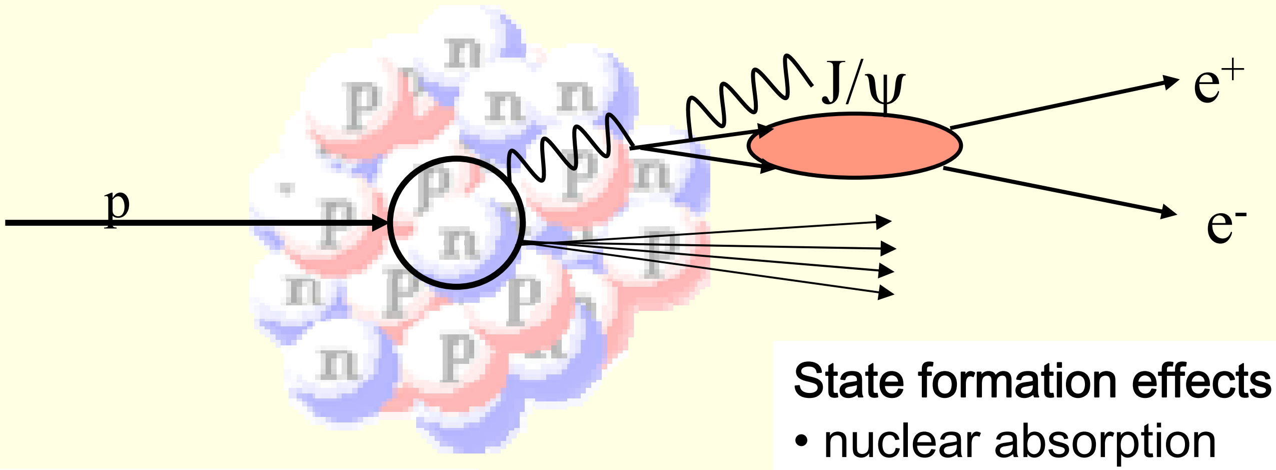
J^{PC}
0^{-+}
0^{++}
2^{++}



J^{PC}
1^{--}
1^{--}
1^{++}

- **Color Singlet Model (CSM):** $c\bar{c}$ pair is produced as a color singlet with quantum numbers of the final charmonium state.
  ⇒ absolute predictions, but: not supported by experiment
- **Color Evaporation Model (CEM):** $c\bar{c}$ pair production is the same for all charmonium states; quantum numbers arranged by "evaporation" of soft gluons.
  ⇒ predicts the same production dynamics of all states; cross section differences only from phase space and wave functions.
- **Non-Relativistic QCD Model (NRQCD):** more rigorous (?) QCD treatment (singlet + octet + non-perturbative ME)
  ⇒ free parameters adjusted to data, predictions tested in different models, energies, final states, …

Study of Charmonium Suppression



State formation effects:
- nuclear absorption
- comover absorption
- multiple scattering + energy loss

Initial state effects:
- shadowing (nuclear PDFs)
- parton energy loss
- intrinsic charm

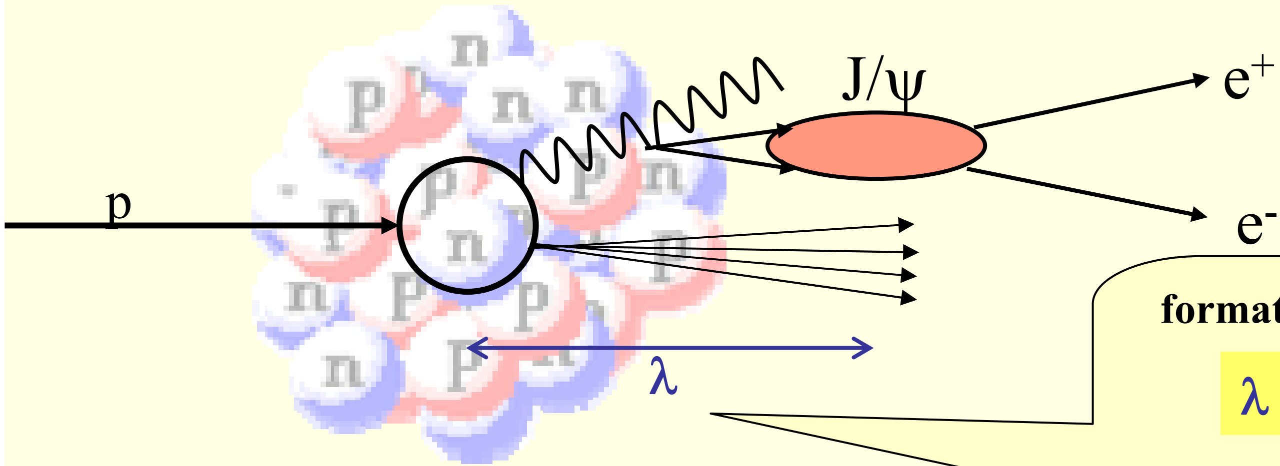
$$\sigma_{cc} = \sigma_0 \cdot A^{\alpha}$$

$\alpha \neq 1 \;\Rightarrow$ "suppression"

Measurement of α for 2 wire materials:

$$\alpha = \frac{\log\left(\frac{\sigma_2}{\sigma_1}\right)}{\log\left(\frac{A_2}{A_1}\right)} = \frac{\log\left(\frac{N_2}{N_1}\frac{L_1}{L_2}\frac{\varepsilon_1}{\varepsilon_2}\right)}{\log\left(\frac{A_2}{A_1}\right)}$$

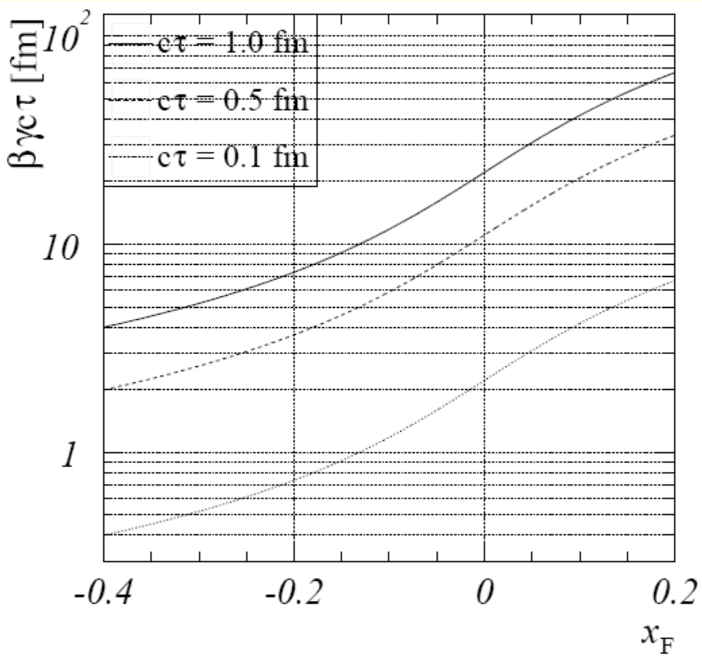
x_F-Dependence of Nuclear Suppression



formation time and length:

$$\lambda\,(x_F) = \beta\,\gamma\,c\,\tau$$

$\gamma = \gamma(x_F)$ **boost of J/ψ w.r.t. nucleus**

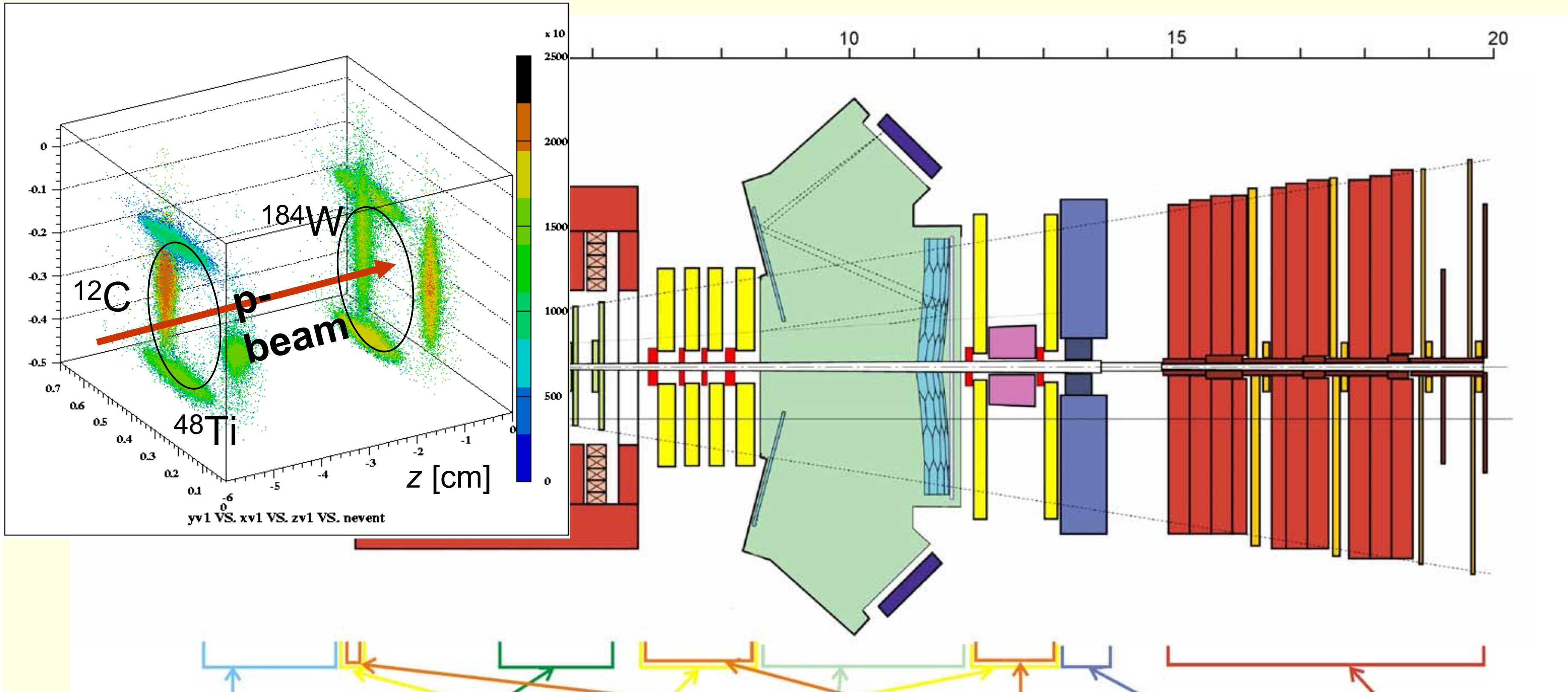


for $c\tau$ = **0.5 fm**	
$x_F = p_L / p_L^{max}$	λ [fm]
0.2	30
0	10
-0.2	4

Nuclear radius:
C ~ 3 fm.
W ~ 8 fm.

The HERA-B Detector, Trigger and Data Samples

The HERA-B Detector



Target & Vertex
8 layers of double-sided Si-microstrips, movable on Roman-Pots; 8 wire-target (see above)

High p_T
3 superlayers gas, pixel and pad chambers; pre-trigger for high p_T tracks

Outer Tracker
7 superlayers of honeycomb drift chambers, 5 and 10mm cells

RICH
Spherical mirror inside C_4F_{10} radiator, Lens-enhanced multianode PMT focal plane.

Inner Tracker
7 superlayers of Micro Strip Gas Chambers with GEM-foil

Electromagnetic Calorimeter
W/Pb scintillator sandwich, shashlik WLS readout with PMTs; energy-cluster pre-trigger

Muon System
4 superlayers of gas-pixel, tube & pad chambers; pad-coincidence pre-trigger

The Dilepton Trigger

HERA-B detector: data is read out and buffered for 12 μs (proton bunches cross every 96 ns, 0.5 interactions/BX)

5 MHz

Pretriggers: ECAL cluster or muon hit coincidence as **trigger seed** (custom hardware)

3 MHz

First Level Trigger (FLT): **Track trigger** in hardware using tracking detectors, seeding by pretriggers

20 kHz

Second Level Trigger (SLT): FLT tracking confirmed, extrapolation to vertex detector, vertex fit (PC farm)

100 Hz

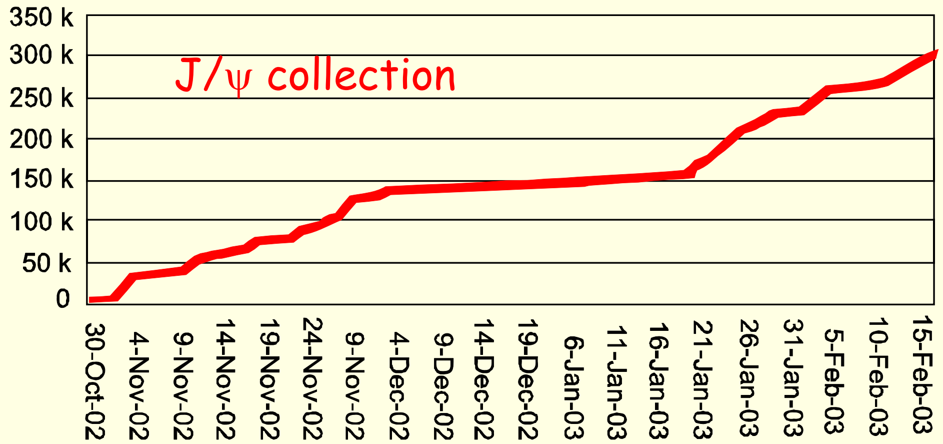
Fourth Level Trigger (4LT): online reconstruction (and filtering) on PC farm

100 Hz

Data samples

Data taking has finished in 2003;

analysis is close to be finalized



Data samples:

- **150 M di-lepton trigger events** (300 000 J/ψ)
- **210 M minimum bias events**
- **35 M hard photon trigger events**

10× more was planned!

Topics of di-lepton trigger analysis

1) p_t distribution

x_F distribution

A-dependence

polarisation

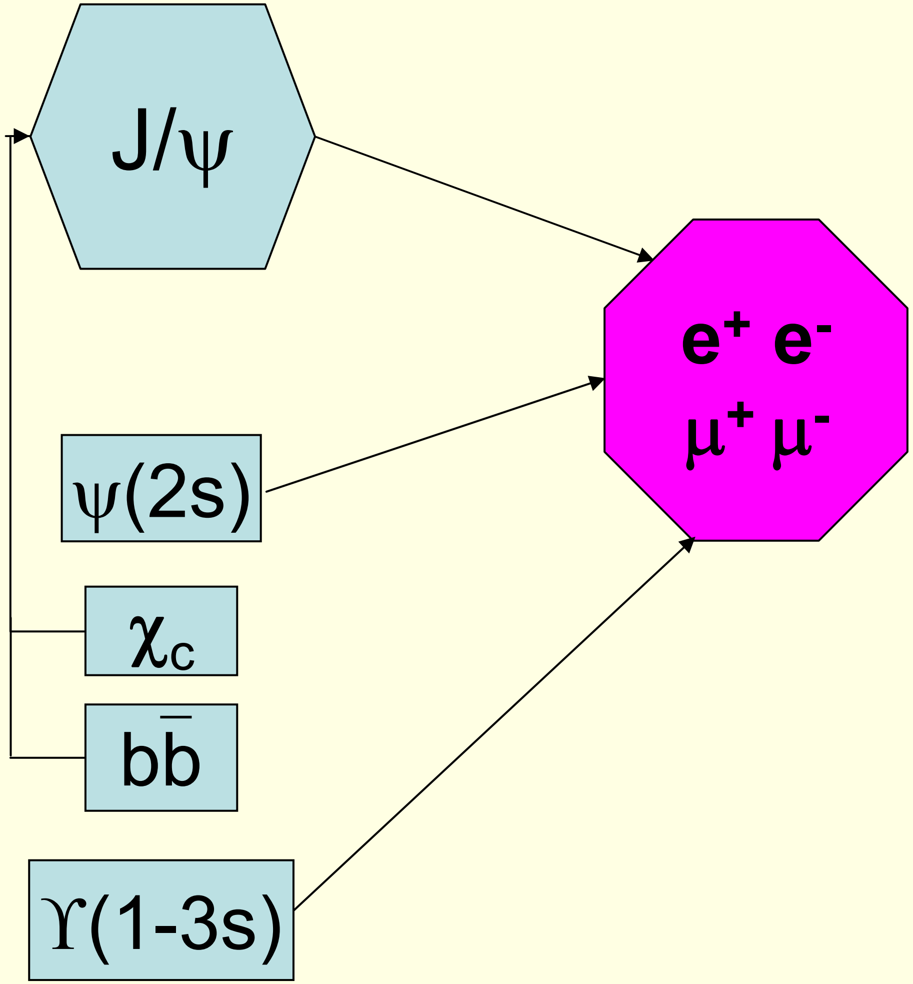
2) $\psi(2s)$ production ratio

3) $\chi_c/J/\psi$ production ratio

4) bb cross section

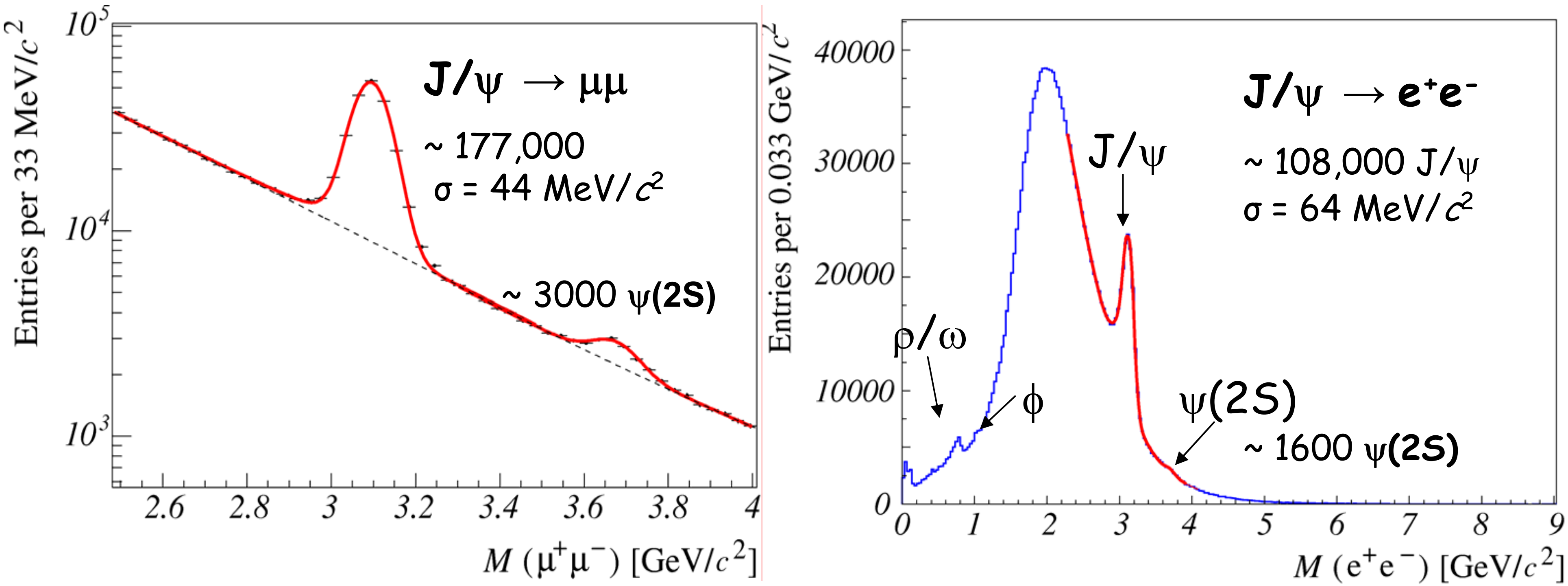
5) Υ production

6) ($D^0 \rightarrow \mu\mu$)



Most results are final or close to final

J/ψ Production: di-lepton triggered



absolute cross sections from di-lepton triggered data

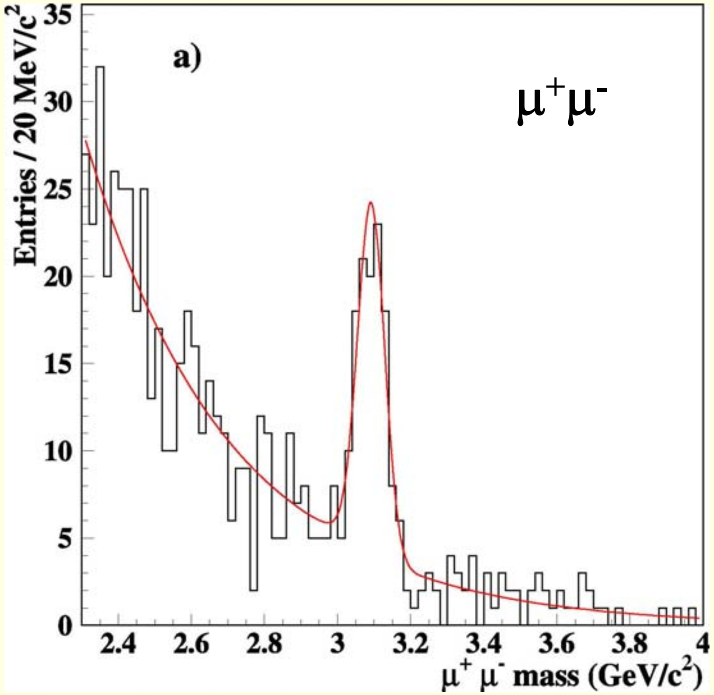
need **reference cross section**

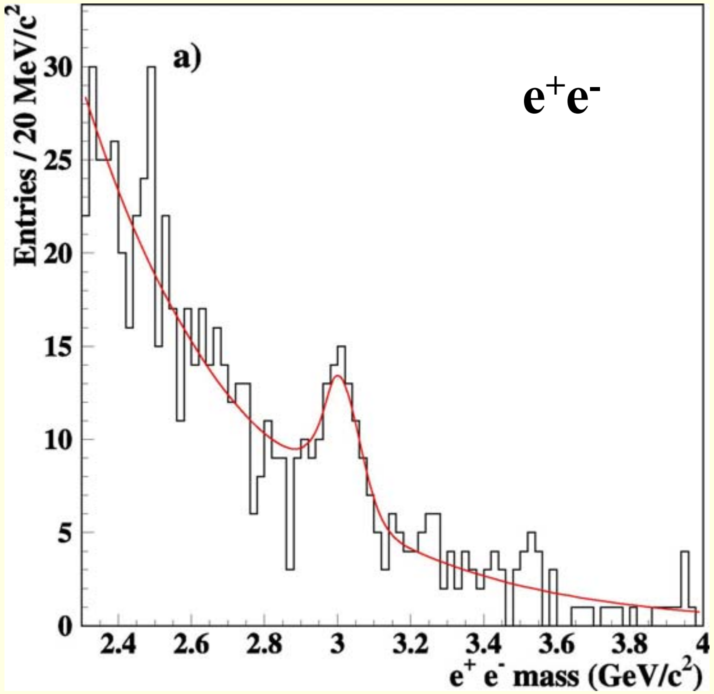
Interlude:

J/ψ cross section from Minimum Bias data

J/ψ cross section from Minimum Bias data

Important for **cross section normalisation** of di-lepton triggered data

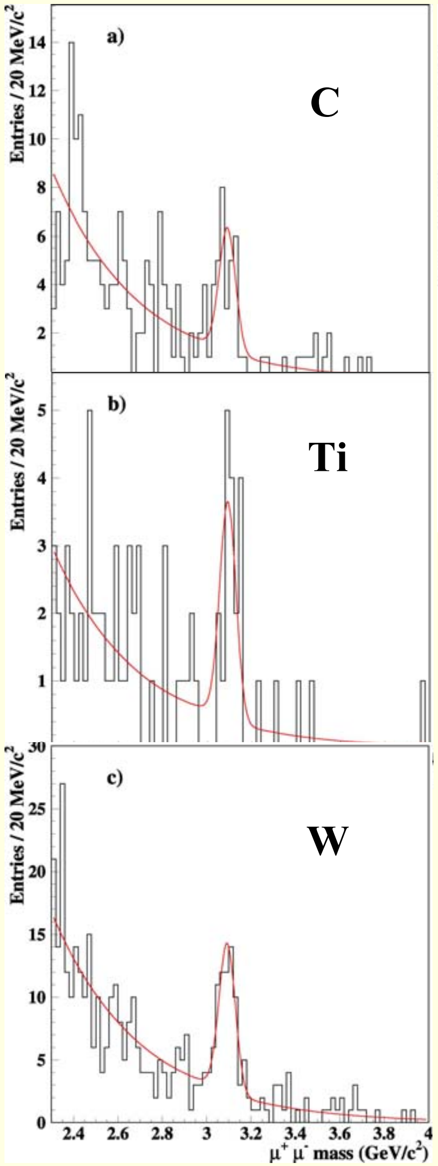


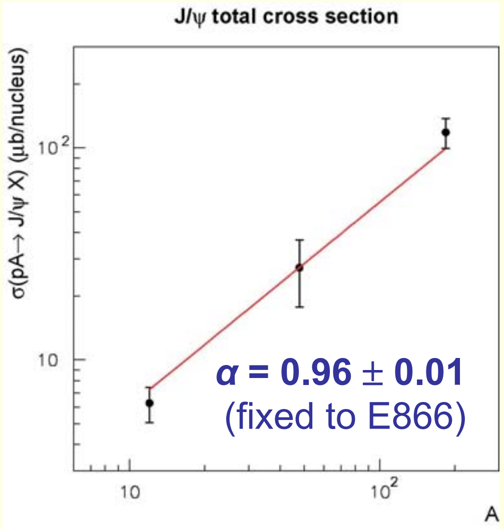


- low statistics
- but: efficiency and luminosity well understood

⇒ systematic uncertainties small (usually dominant)

J/ψ (MinB): A-Dependence and Results





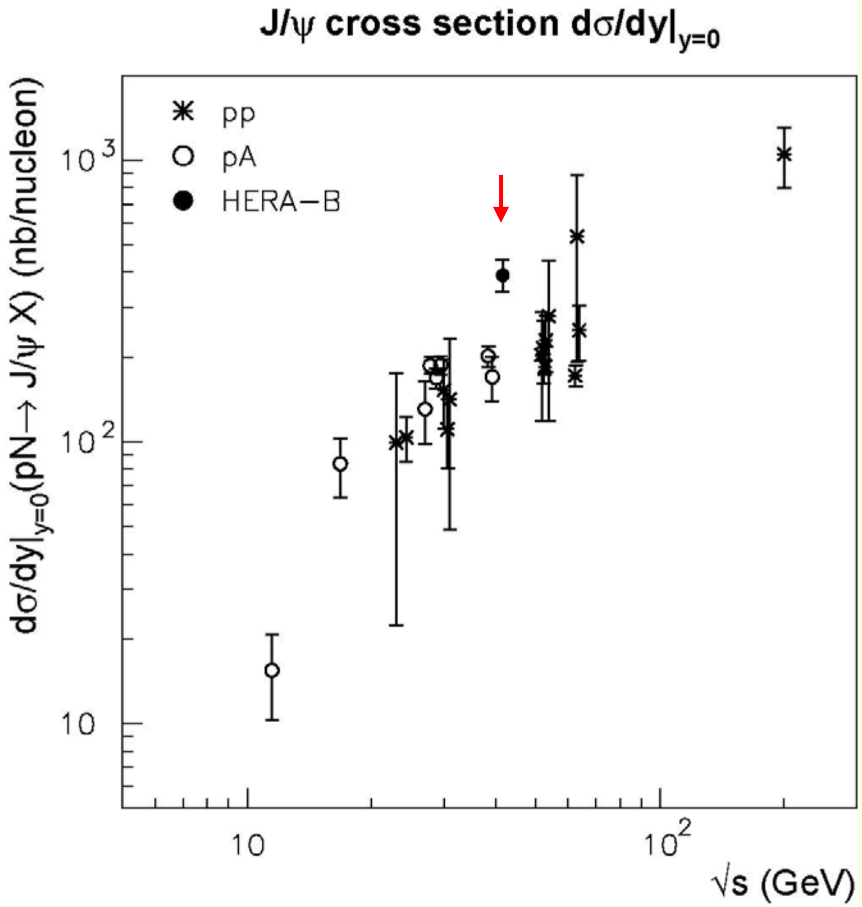
$$\sigma_{J/\psi} = \frac{N_{J/\psi}}{\varepsilon_{J/\psi} \cdot BR(J/\psi \to \mu^+\mu^-) \cdot \sum_i A_i^\alpha L_i}$$

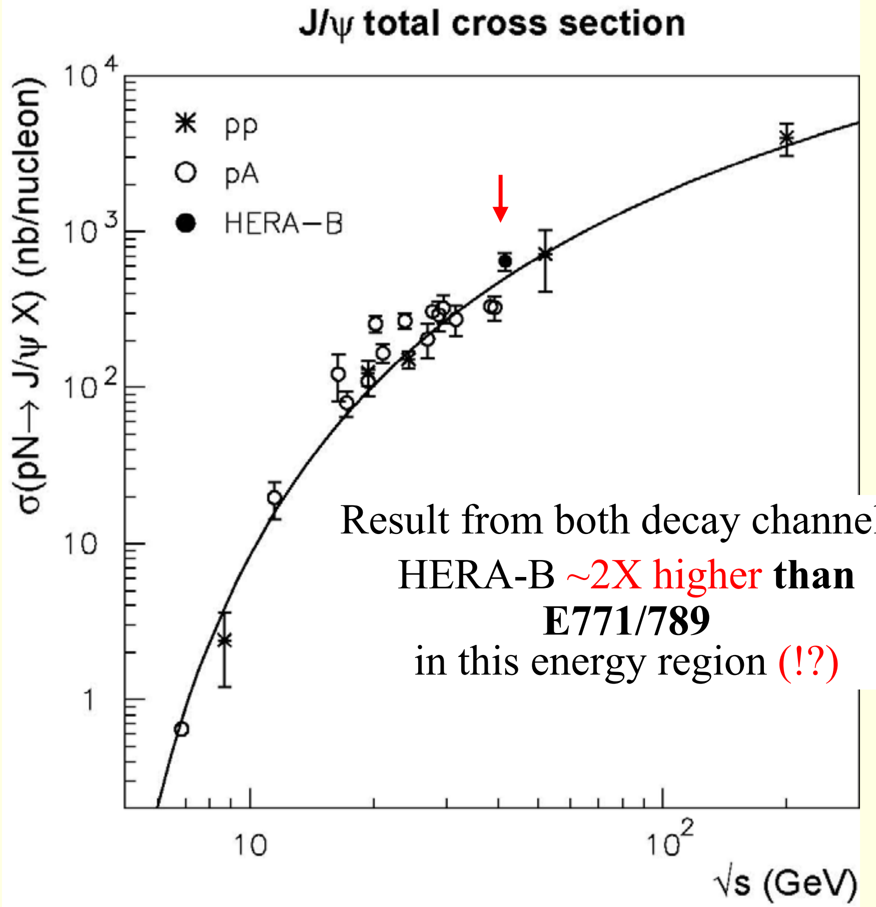
Results:

$$\sigma_{pN}^{J/\psi} = 663 \pm 74 \pm 46 \text{ nb/nucleon.}$$

$$\left. \frac{d\sigma_{pN}^{J/\psi}}{dy} \right|_{y=0} = 392 \pm 44 \pm 27 \text{ nb/nucleon.}$$

J/ψ (MinB): Comparison with other Results





Result from both decay channels:
HERA-B ~2X higher **than E771/789**
in this energy region (!?)

Mesurements are in general
not very consistent
with each other

How to get a reference cross section ???

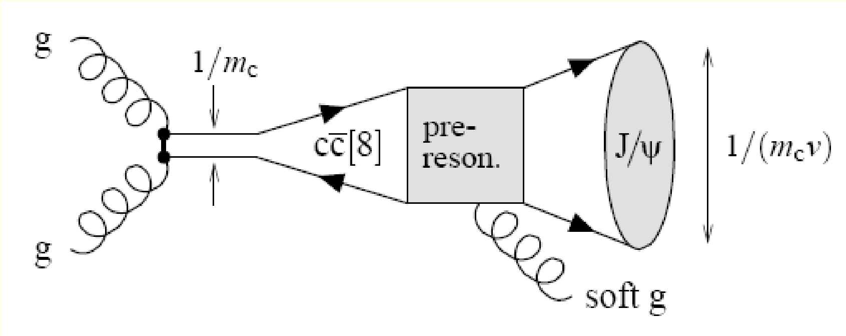
NRQCD Based Evaluation of J/ψ and ψ' Cross Sections

Towards a ‚reference cross section‘:

- **include all measurements (J/ψ, ψ′ , χ_c)**
- **combine by ‚QCD-inspired‘ fit**

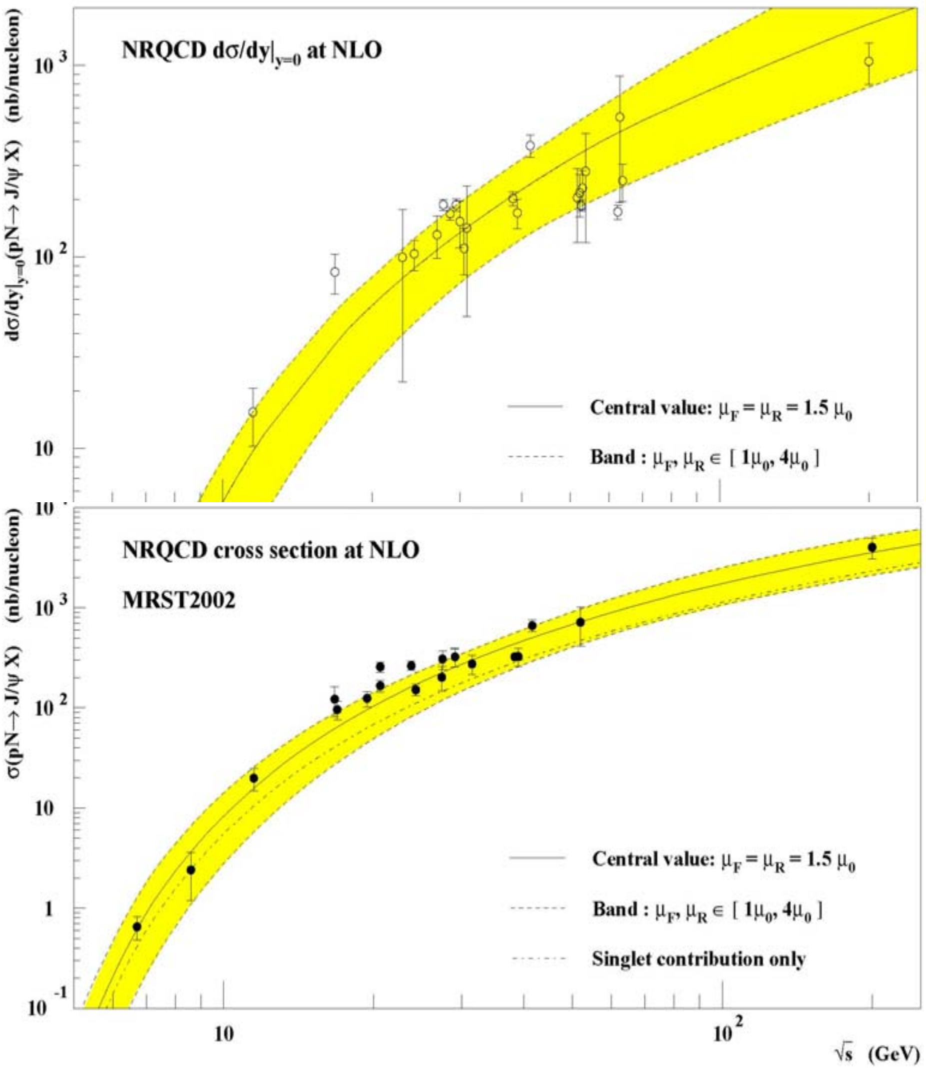
F. Maltoni et al. (= HERA-B Collaborators),
‚Analysis of charmonium production
at fixed-target experiments in the NRQCD approach‘,
hep-ph/0601203

$$\sigma(pp \to H + X) = \sum_{i,j} \int dx_1 dx_2 f_{i/p} f_{j/p} \sum_n \hat{\sigma}(ij \to Q\overline{Q}\,[n] + x)\,\langle \mathcal{O}^H\,[n] \rangle$$



$$\begin{aligned}
\langle \mathcal{O}_8^{\psi}(^3P_J) \rangle &= (2J+1)\,\langle \mathcal{O}_8^{\psi}(^3P_0) \rangle\,, \\
\langle \mathcal{O}_8^{\chi_{cJ}}(^3S_1) \rangle &= (2J+1)\,\langle \mathcal{O}_8^{\chi_{c0}}(^3S_1) \rangle \\
\langle \mathcal{O}_1^{\chi_{cJ}}(^3P_J) \rangle &= (2J+1)\,\langle \mathcal{O}_1^{\chi_{c0}}(^3P_0) \rangle
\end{aligned}$$

QCD Based Evaluation of J/ψ and ψ’ Cross Sections:
Fit Results



$$\sigma_{\psi(2S)} = \sigma^{\mathrm{D}}_{\psi(2S)},$$

$$\sigma_{J/\psi} = \sigma^{\mathrm{D}}_{J/\psi} + \sum_{J=0}^{2} \mathrm{Br}(\chi_{cJ} \to J/\psi\gamma)\, \sigma^{\mathrm{D}}_{\chi_{cJ}} + \mathrm{Br}(\psi(2S) \to J/\psi X)\, \sigma_{\psi(2S)},$$

$$R_\psi = \frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi}},$$

Fit results at HERA-B energy
√s = 41.6 GeV:

$$\sigma_{J/\psi} = (502 \pm 44)\ \mathrm{nb/nucleon}\ ,$$

$$\sigma_{\psi(2S)} = (65 \pm 11)\ \mathrm{nb/nucleon}\ ,$$

$$R_\psi = (0.130 \pm 0.019)\ ,$$

F. Maltoni et al., ‚Analysis of charmonium production at fixed-target experiments in the NRQCD approach‘, hep-ph/0601203

… back to two-lepton triggered data:

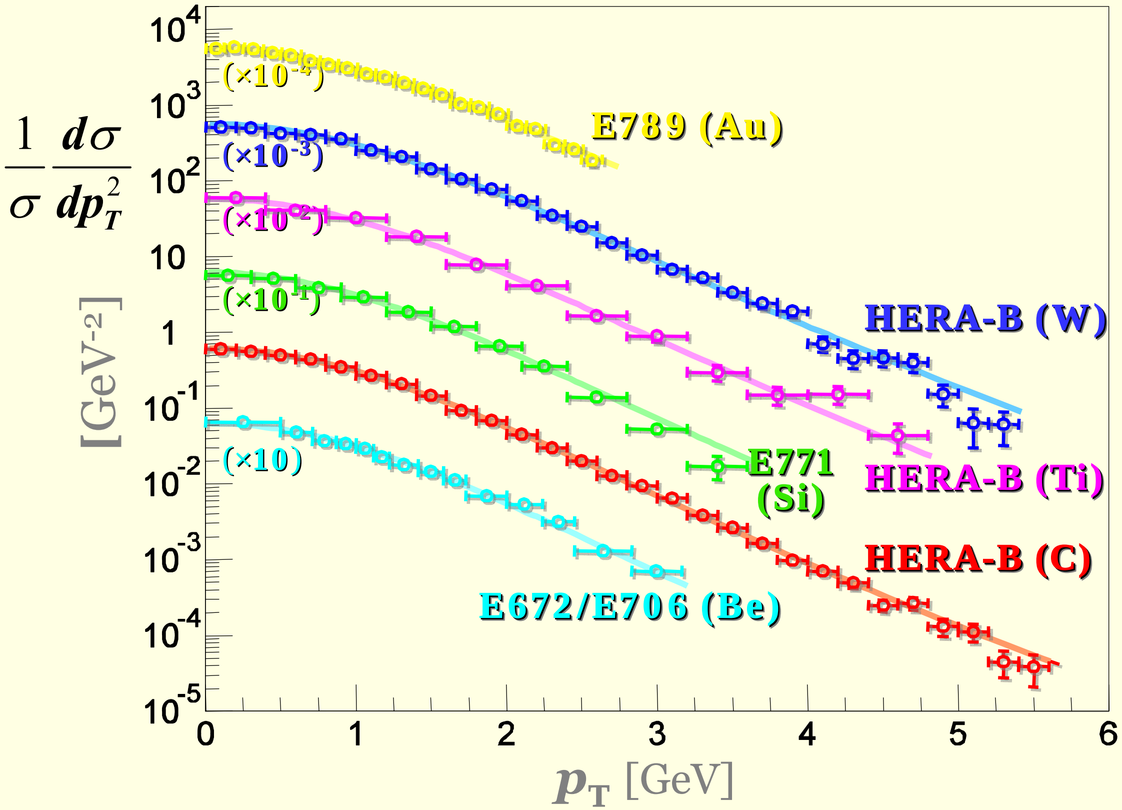
Charmonium Production

J/ψ differential cross sections

(preliminary)

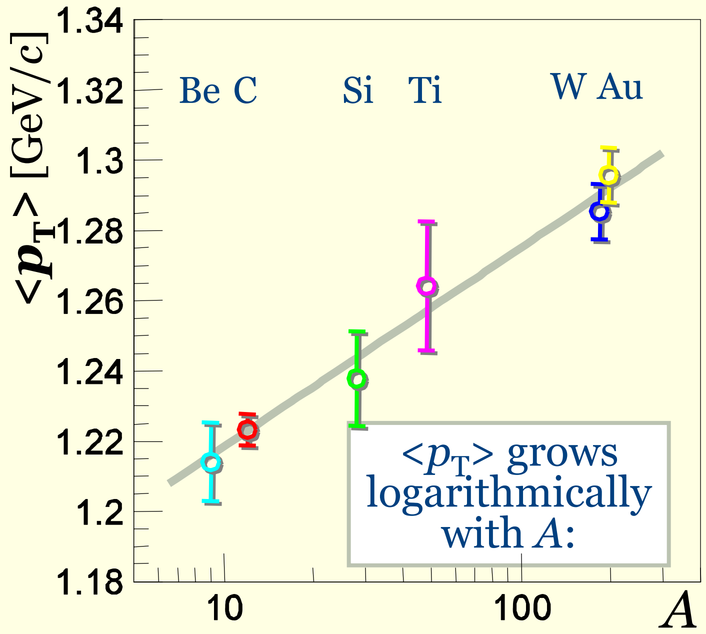
J/ψ p_T distributions (nucl.dep.)

preliminary data (di-electron only), compared with *p-A* results at similar energy ($\sqrt{s}$ = 38.8 GeV)



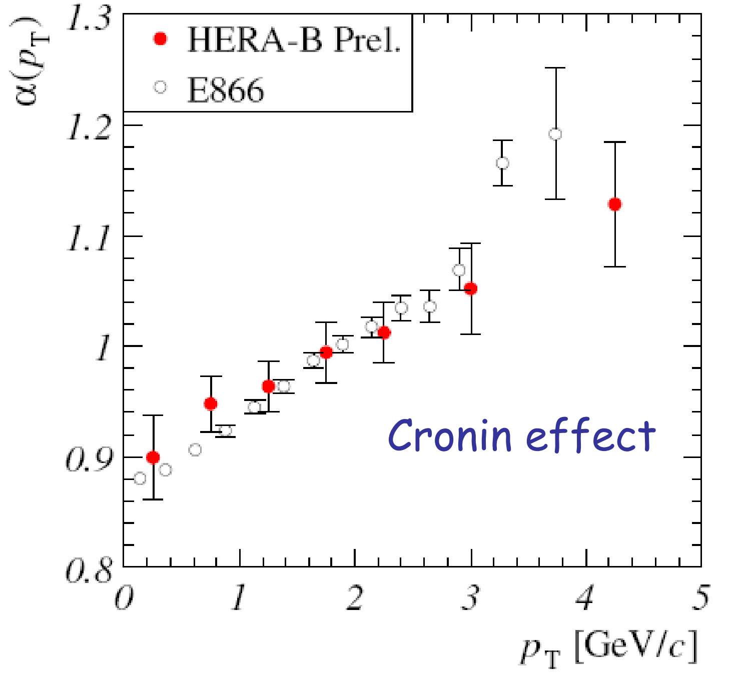
standard fit:

$$\frac{d\sigma}{dp_T^2} = A\left[1+\left(\frac{35\pi}{256}\frac{p_T}{\langle p_T\rangle}\right)^2\right]^{-6}$$



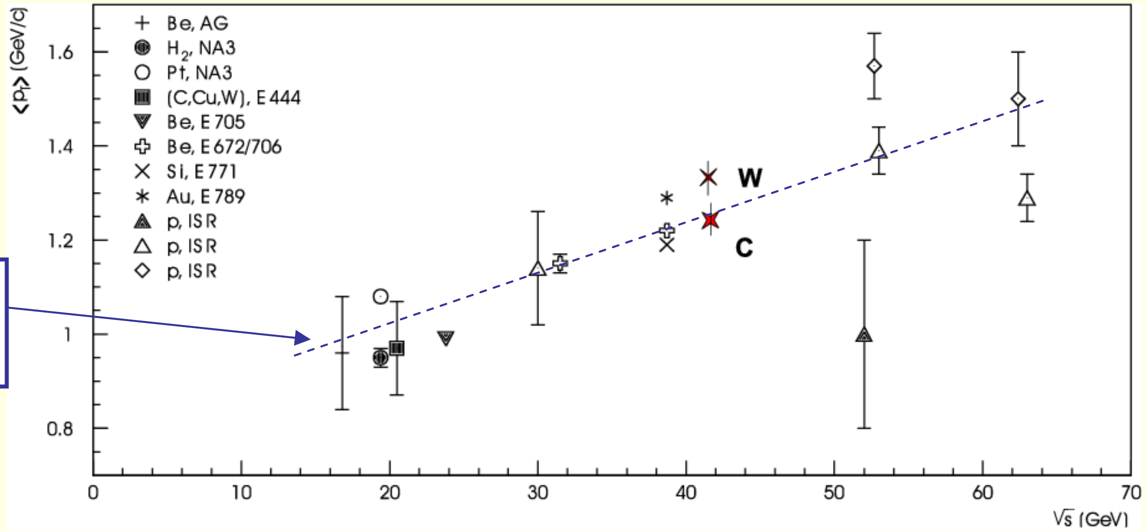
$$\frac{d\langle p_T\rangle}{d\ln A} = 0.0246 \pm 0.0026$$

J/ψ p_T distributions (nucl.dep.)



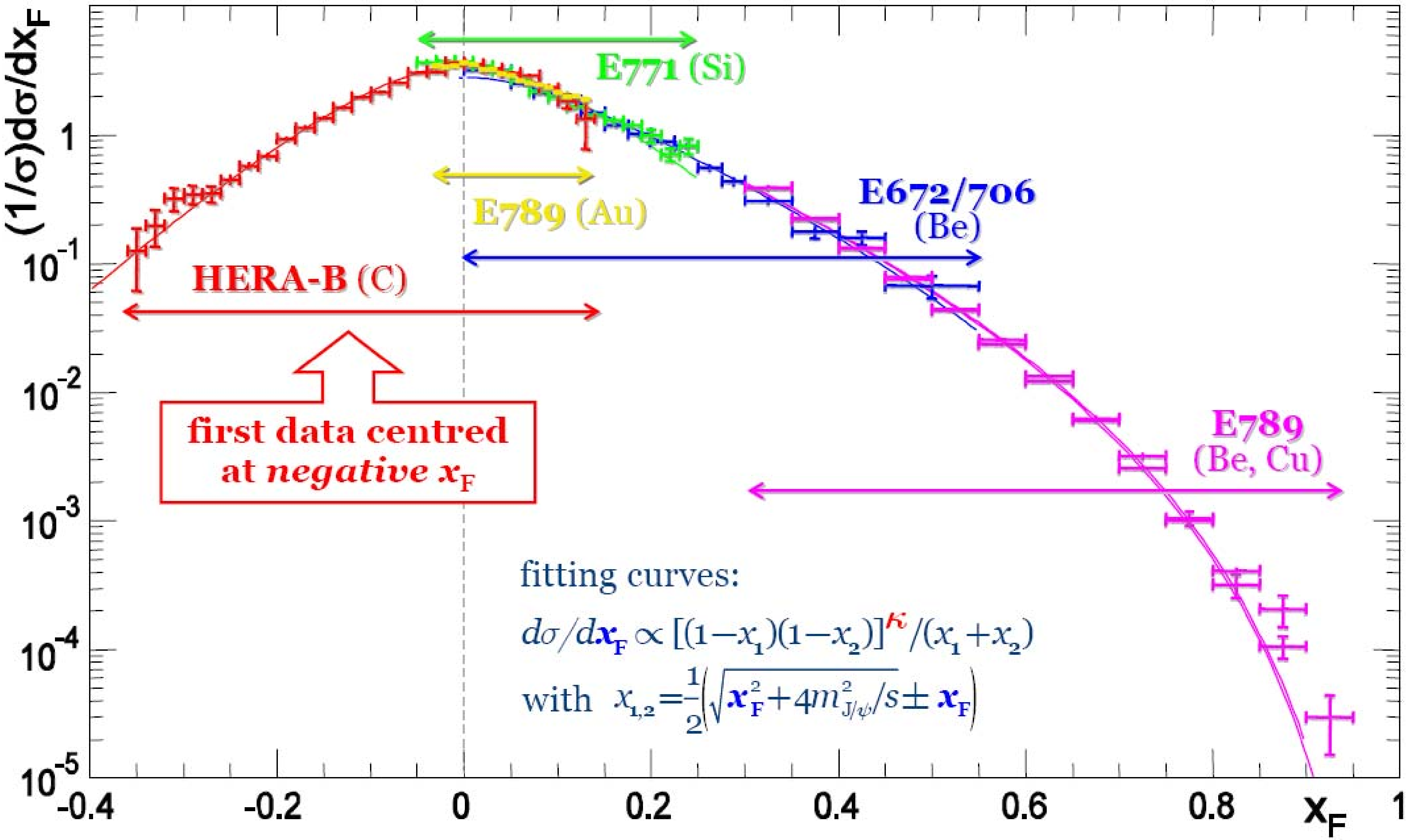
$<p_T>$ grows with s:

$<p_T> \approx 0.8 + 0.01\cdot\sqrt{s}$

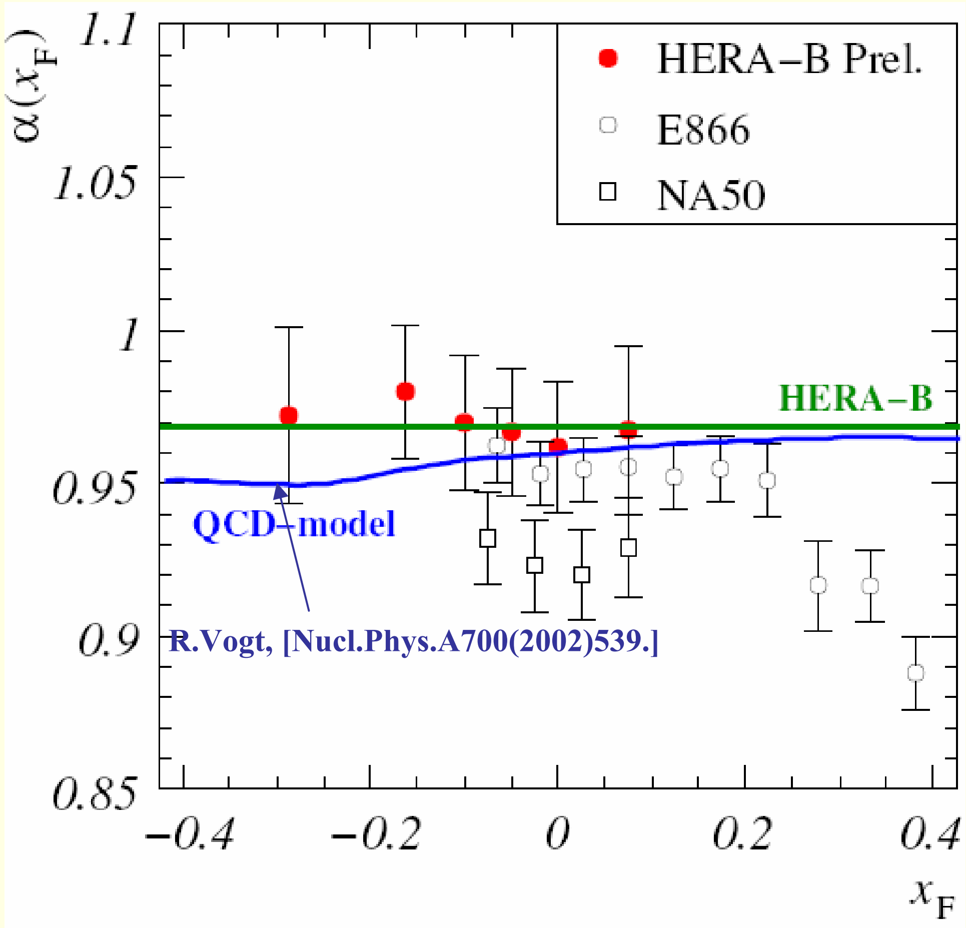


J/ψ x_F distribution

Preliminary data (e^+e^-– C sample), compared with *p-A* results at 38.8 GeV



J/ψ: A-dependence (x_F)



First measurement at x_F < -0.1:
constant small suppression

preliminary result:

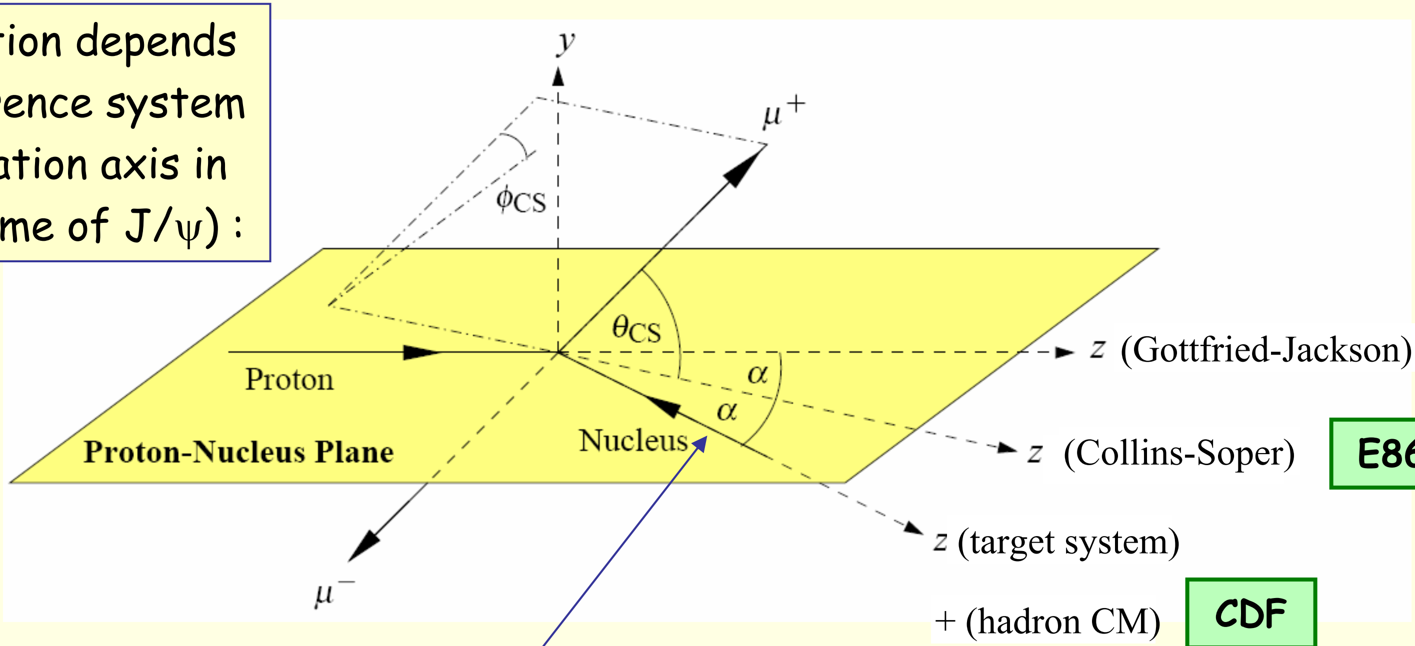
$\alpha = 0.969 \pm 0.003_{stat} \pm 0.021_{sys}$

J/ψ Polarisation

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} = \frac{3}{4\pi(3+\lambda_\vartheta)}\left\{1 + \lambda_\vartheta \cos^2\vartheta + \lambda_{\vartheta\varphi}\sin 2\vartheta \sin\varphi + \lambda_\varphi \sin^2\vartheta \cos 2\varphi\right\}$$

usually only $\lambda = \lambda_\vartheta$ is given;

polarisation depends on reference system (polarisation axis in rest frame of J/ψ) :



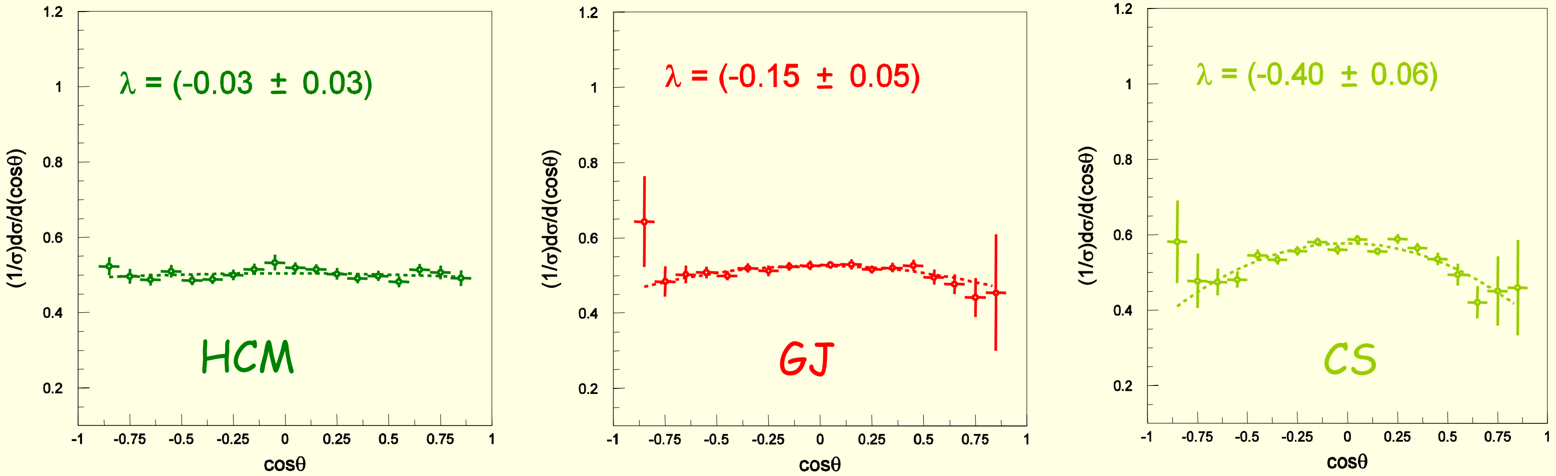
E771, E672/E706

E866

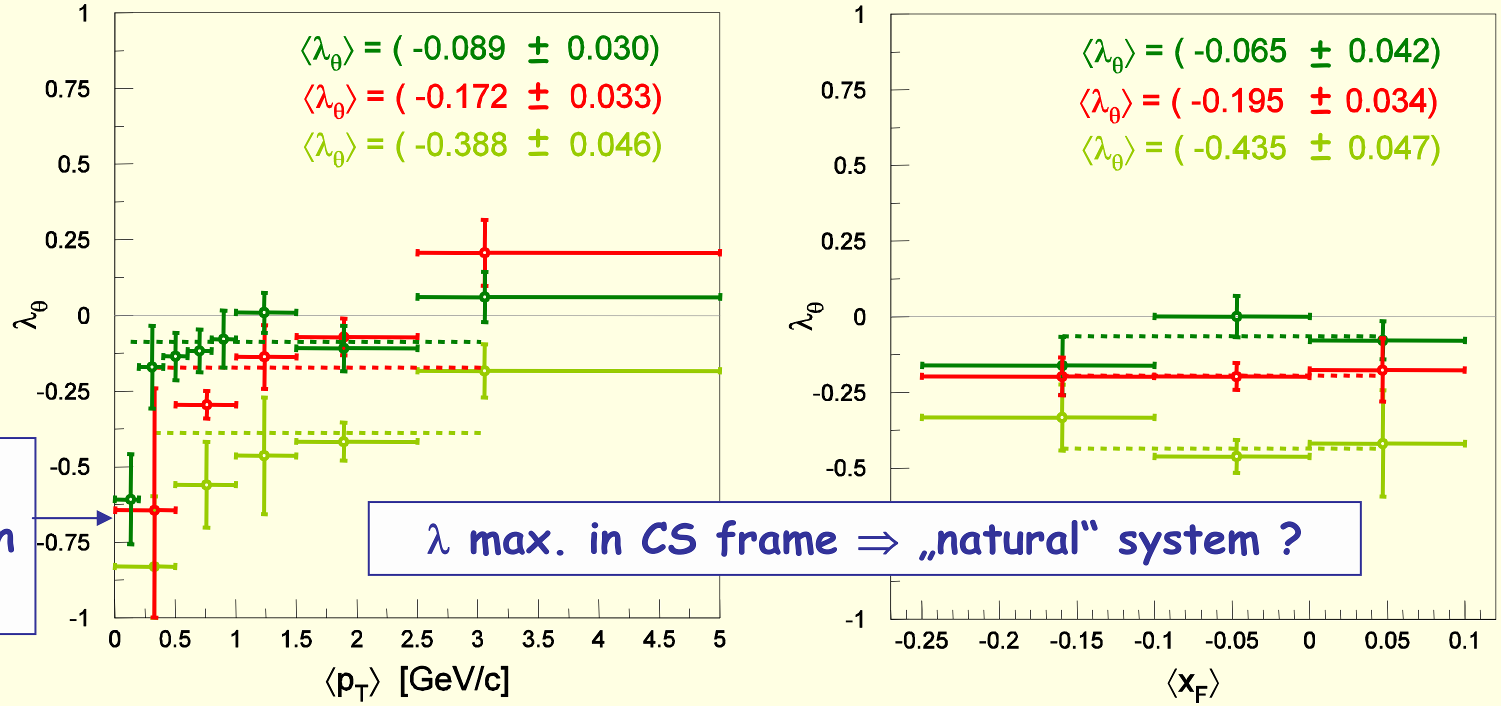
CDF

$\tan\alpha = p_T/M_{J/\psi}$ ⇒ only for $p_T \neq 0$ are the systems different

Preliminary Polarisation Results



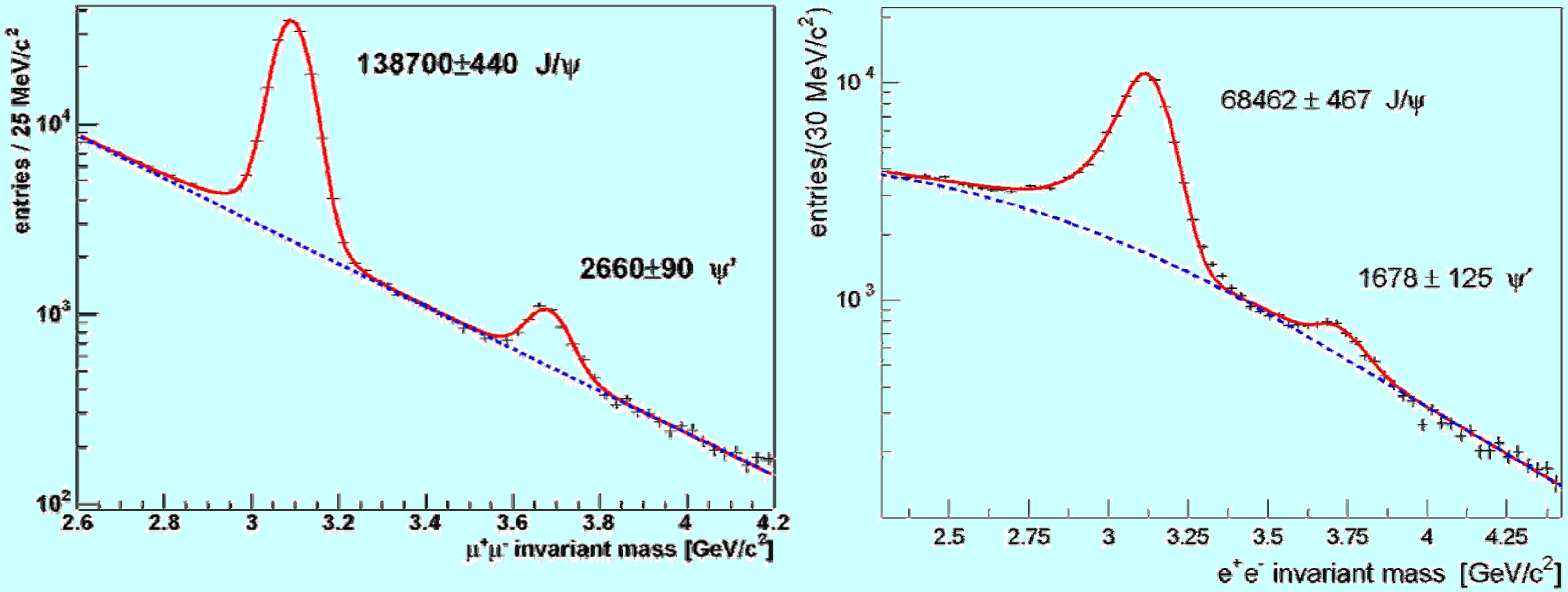
HCM
GJ
CS



large polarisation at p_T=0

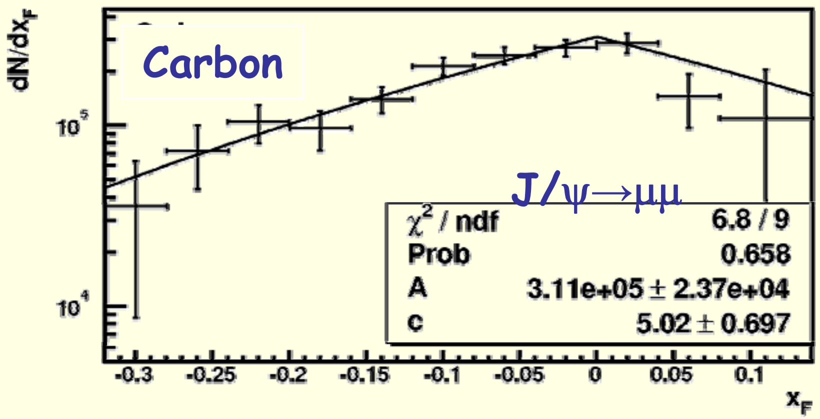
λ max. in CS frame ⇒ „natural" system ?

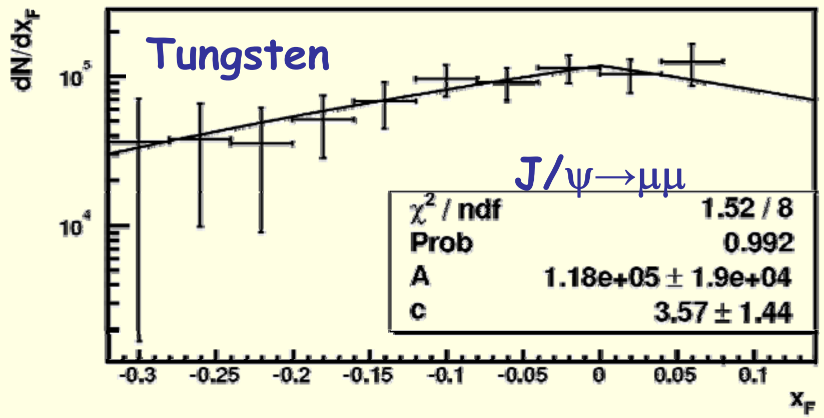
ψ'/ J/ψ production ratio

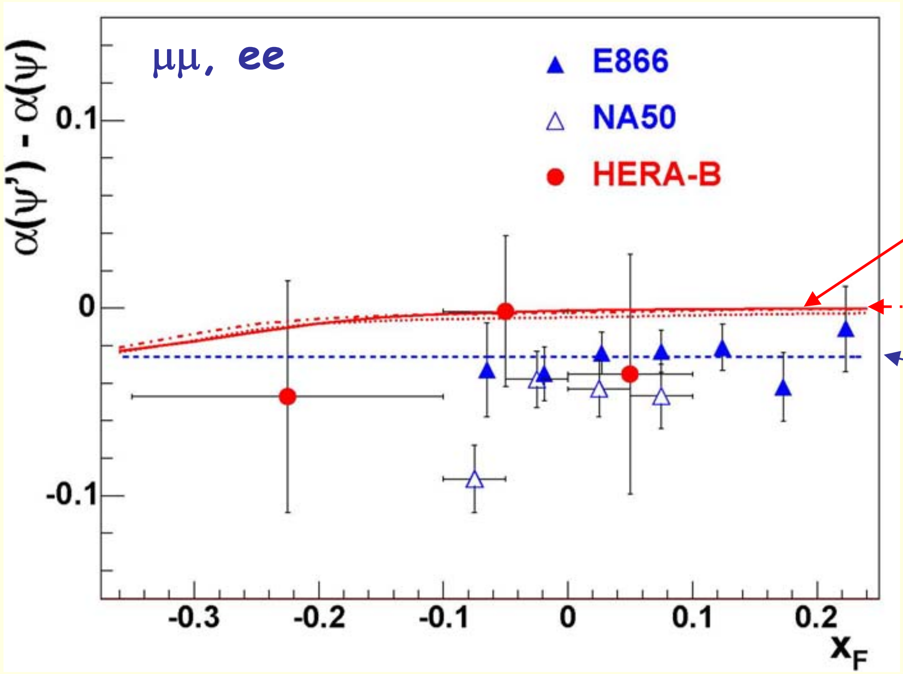


$$\frac{BR(\psi' \to l^+l^-)\cdot\sigma_{\psi'}}{BR(J/\psi \to l^+l^-)\cdot\sigma_{J/\psi}} = \frac{N_{\psi'}}{N_{J/\psi}}\frac{\varepsilon_{J/\psi}}{\varepsilon_{\psi'}}$$

ψ' production: x_F distributions







A-dependence: $\Delta\alpha(x_F) = \alpha' - \alpha$

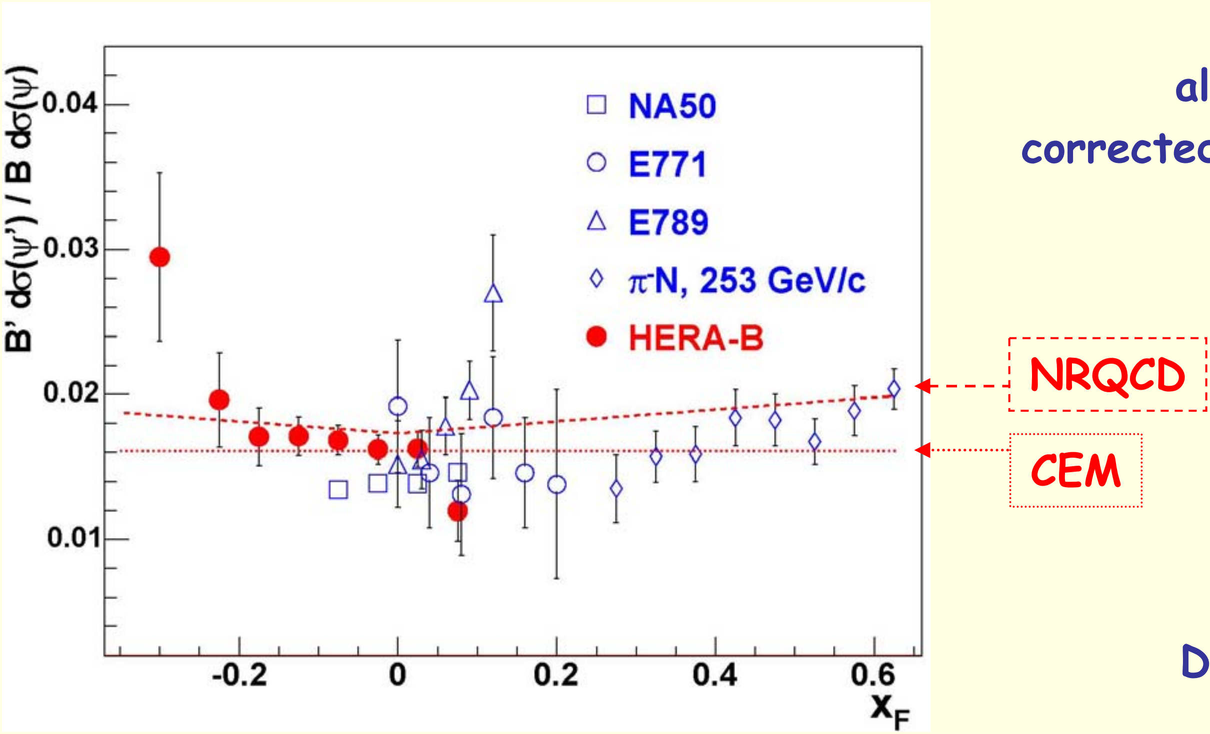
CEM for color-1 nuclear absorption

NRQCD for color-1 & -8 nuclear absorption

fit with const: $\Delta\alpha(E866) = -0.026 \pm 0.005$

All consistent with no x_F dependence.
We use average of E866 and NA50:
$\Delta\alpha(E866, NA50) = -0.030 \pm 0.004$

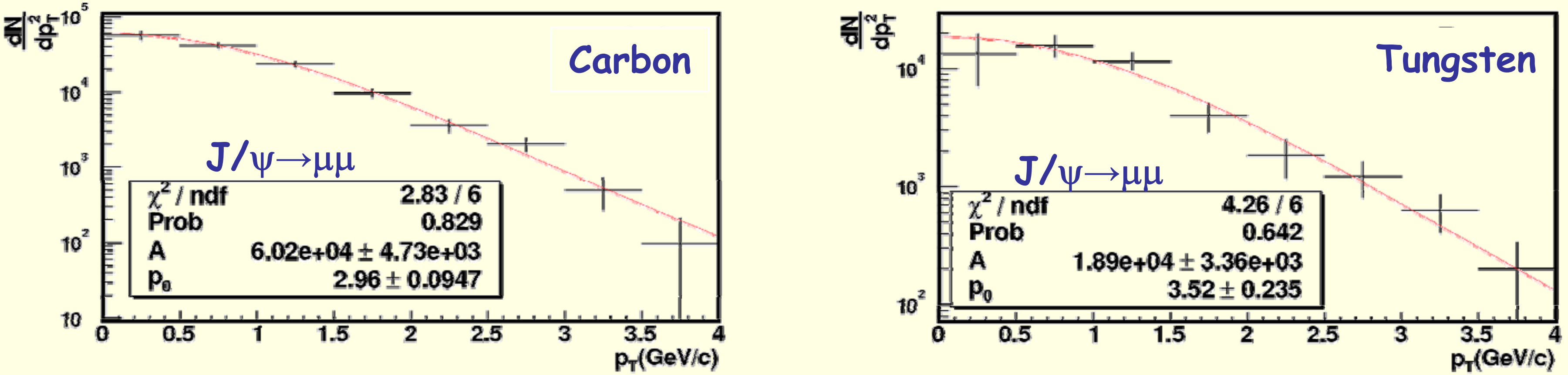
ψ' production: x_F distributions

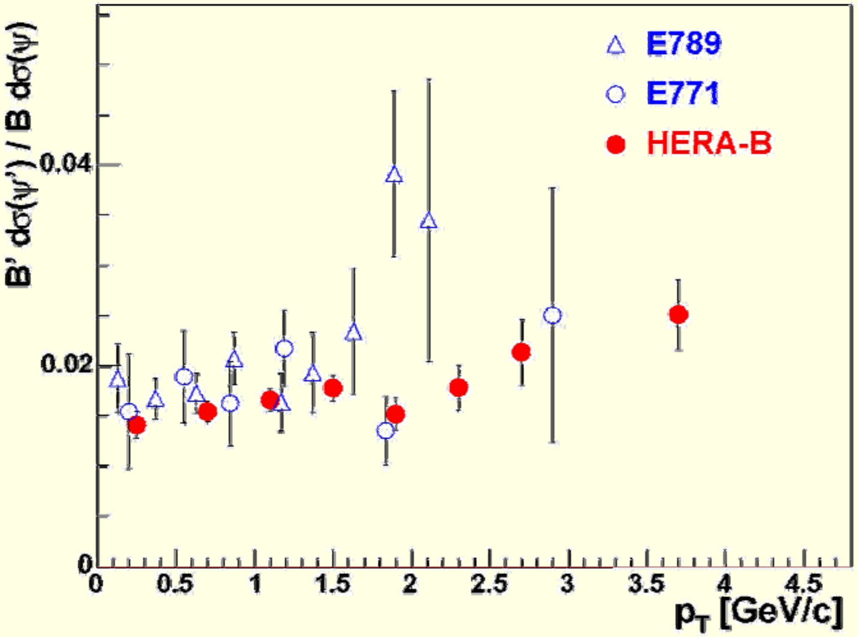


all targets included,
corrected for nuclear effects with
$\Delta\alpha$(E866, NA50)

Data are consistent
with both models
(and with no x_F dependence)

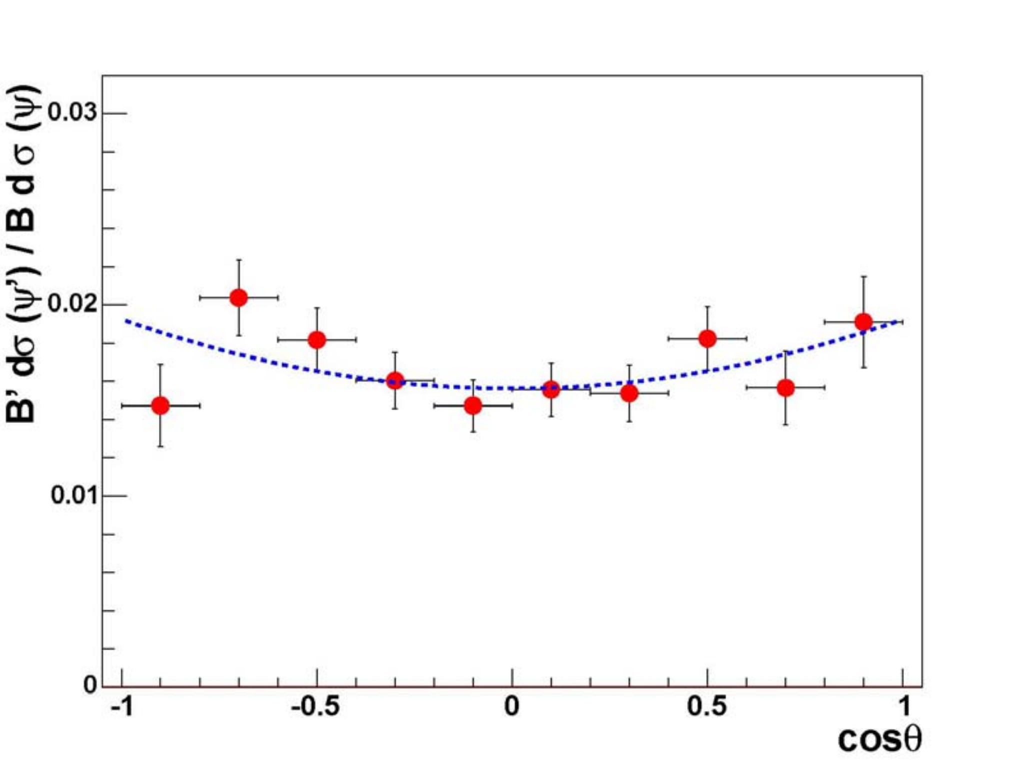
ψ' production: p_T distributions





⇒ **tendency for a wider p_T distribution of ψ′**
(increasing with A?)

ψ' production: polarisation



$$\frac{d\sigma}{d\cos\theta} \propto (1 + \lambda \cos^2\theta)$$

$$\frac{B' \, d\sigma'/d\cos\theta}{B \, d\sigma/d\cos\theta} \propto \frac{1 + \lambda' \cos^2\theta}{1 + \lambda \cos^2\theta}$$

Result:

$$\Delta\lambda = \lambda' - \lambda = 0.23 \pm 0.17$$

compatible with no polarisation difference

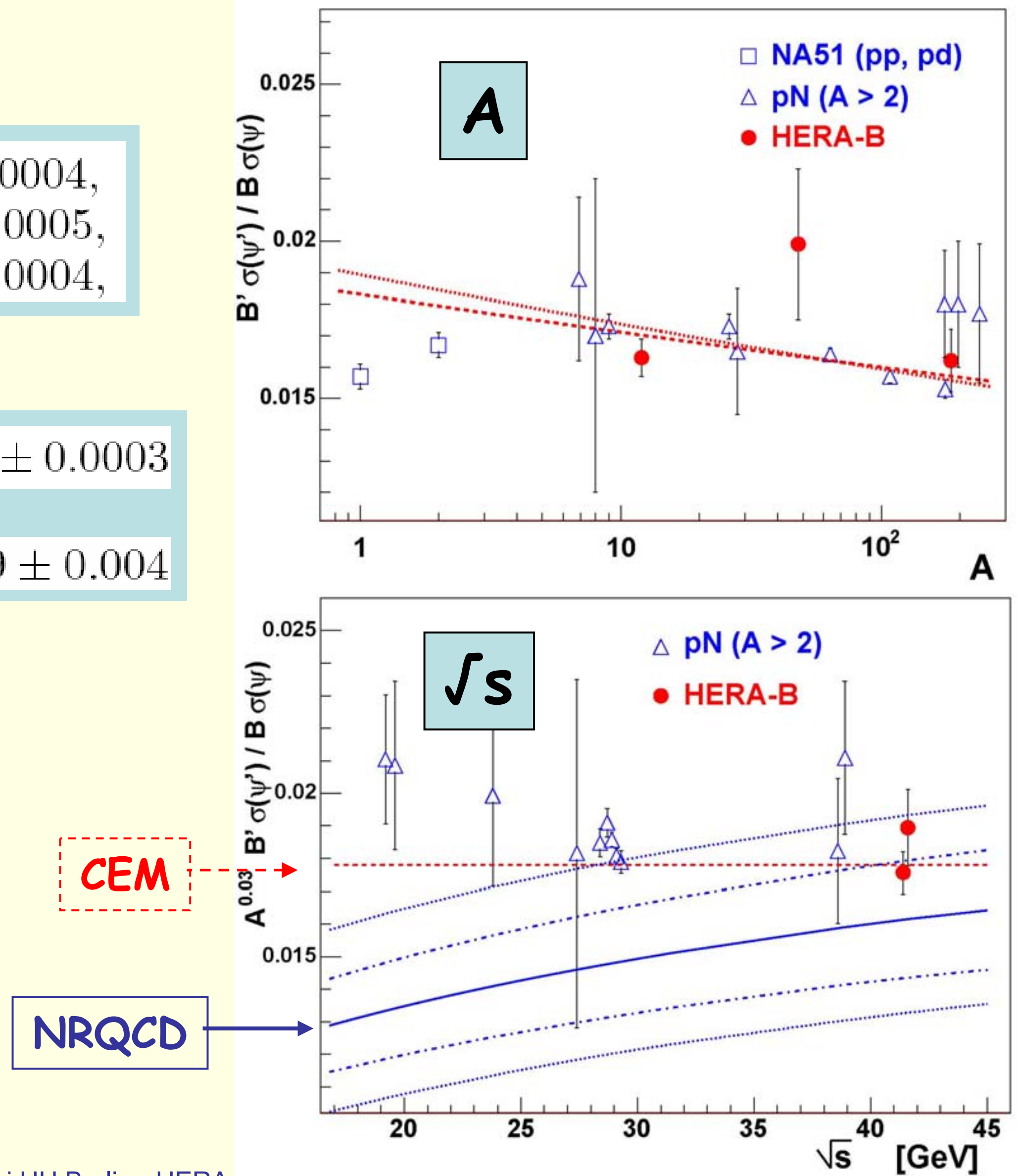
Production ratio ψ' / J/ψ

$$B'\,\sigma'\,/\,B\,\sigma\ (\mathrm{C}) = 0.0163 \pm 0.0006 \pm 0.0004,$$
$$B'\,\sigma'\,/\,B\,\sigma\ (\mathrm{Ti}) = 0.0199 \pm 0.0024 \pm 0.0005,$$
$$B'\,\sigma'\,/\,B\,\sigma\ (\mathrm{W}) = 0.0162 \pm 0.0010 \pm 0.0004,$$

$$\frac{B'\,\sigma_A(\psi')}{B\,\sigma_A(\psi)} = R_{1\psi'} \cdot \mathrm{A}^{\Delta\,\alpha}$$

$$R_{1\psi'} = 0.0183 \pm 0.0003$$

$$\Delta\alpha = -0.029 \pm 0.004$$



χ_c / J/ψ production ratio

χ_c production

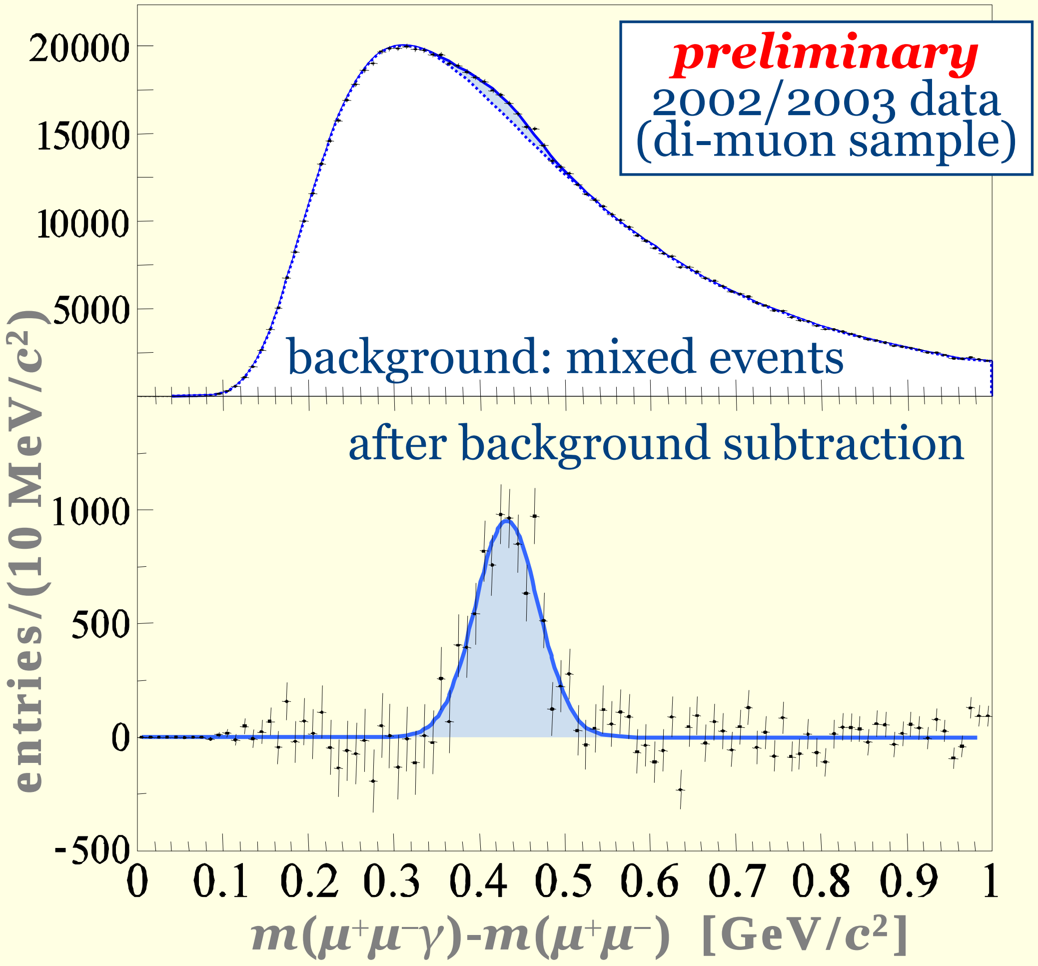
selection: $\chi_c \to J/\psi\, \gamma$, $J/\psi \to l^+ l^-$

measurement:

- **fraction of J/ψ's from χ_c:**

$$R_{\chi_c} = \frac{\sum_{i=1}^{2} \sigma_{\chi_{ci}} \cdot BR(\chi_{ci} \to J/\psi\gamma)}{\sigma_{J/\psi}} = \frac{N_{\chi_c}}{N_{J/\psi}} \cdot \frac{\varepsilon_{J/\psi}}{\varepsilon_{\chi_c} \varepsilon_\gamma}$$

- **kinematical distributions**



from the 2000 data, with
370 ± 74 χ_c's ($\mu^+\mu^- + e^+e^-$):
$R(\chi_c)$ = **0.32 ± 0.06 ± 0.04**
[Phys. Lett. B 561, 61 (2003)]

new data: 40× bigger χ_c statistics
(the largest ever analyzed)

χ_{c1} - χ_{c2} separation

further step (?):

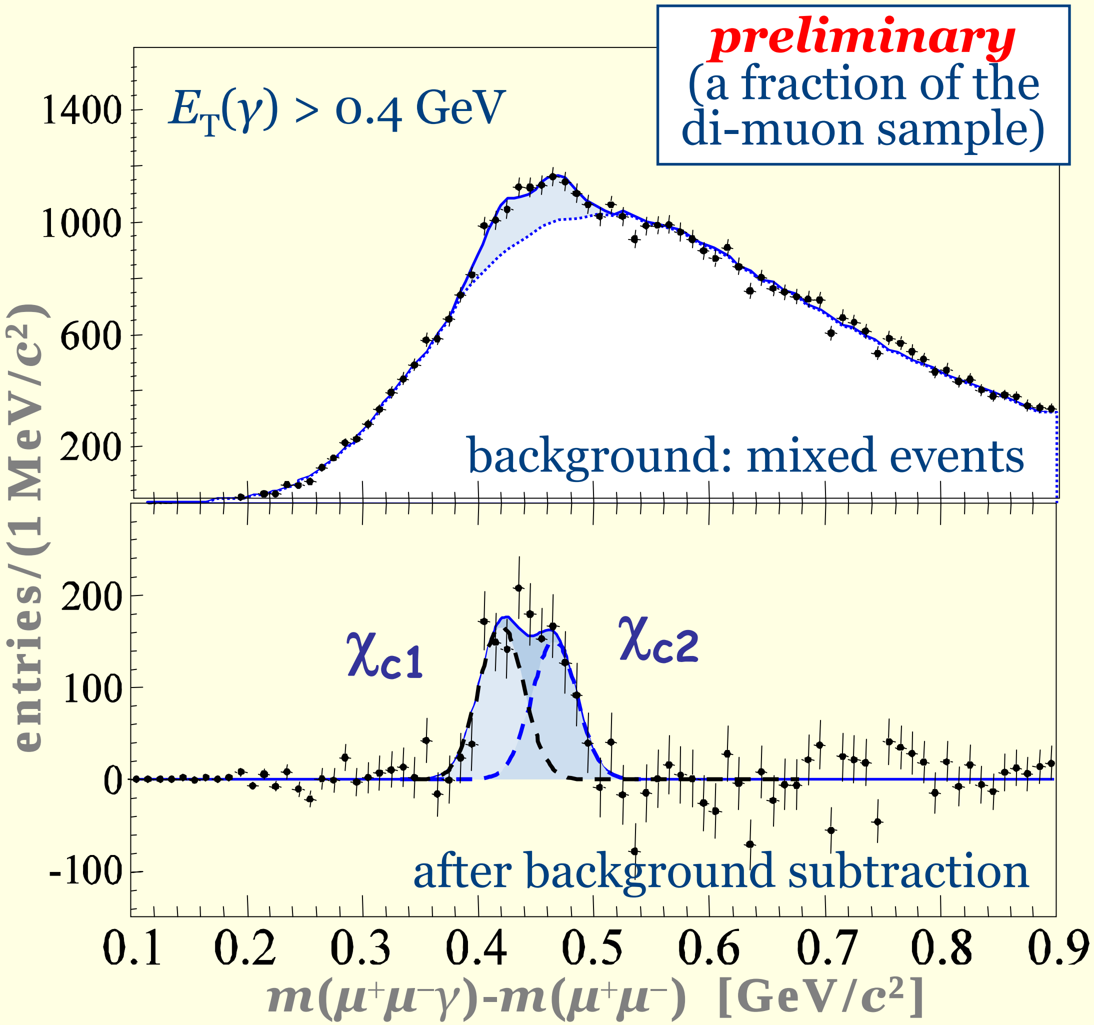
separate different states by varying the selection cuts

measure the

χ_{c2}/χ_{c1} **production ratio**

↓

interesting constraints on the QCD models

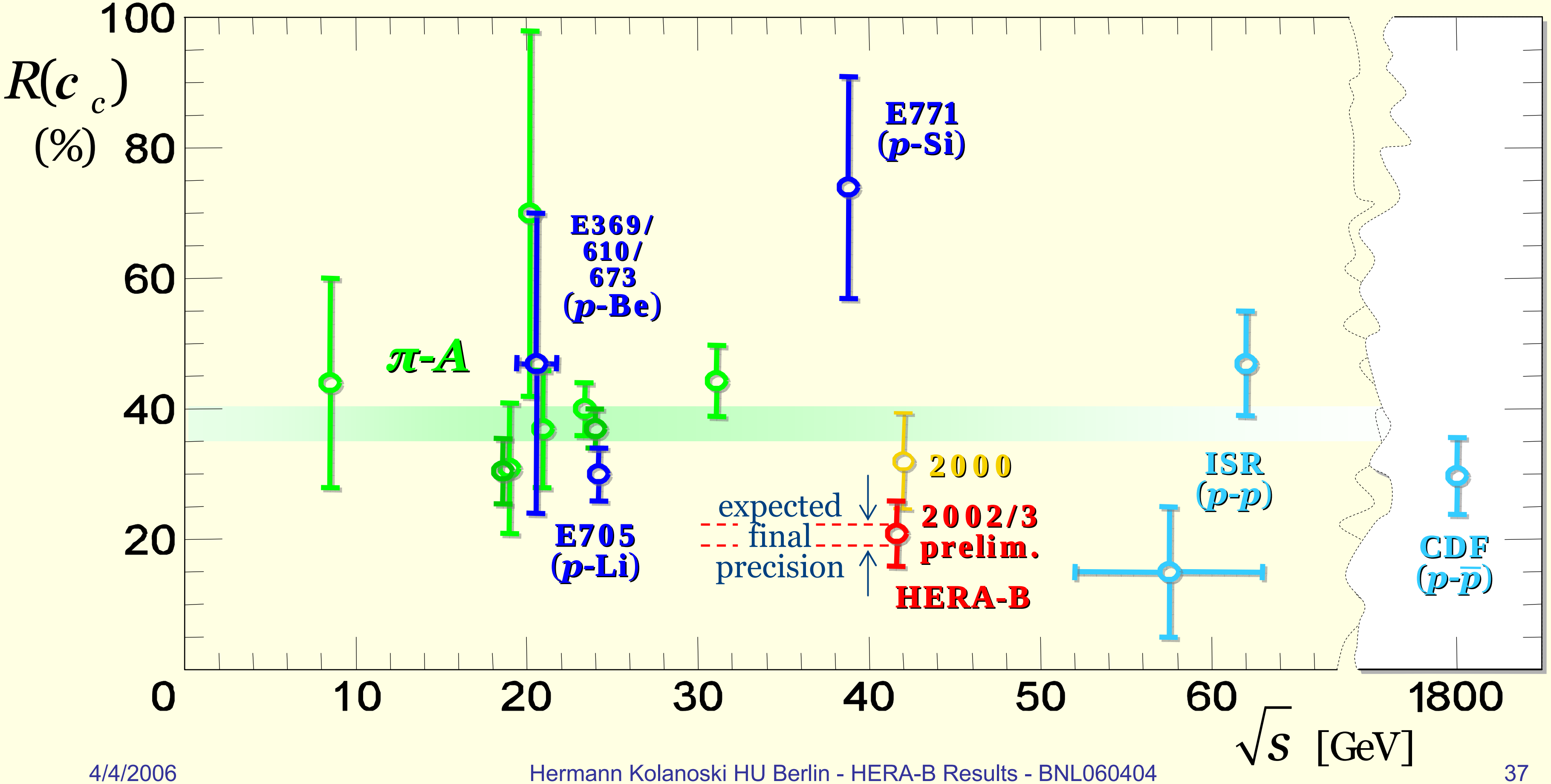


R(χ_c)

preliminary evaluation (2002/2003 data):

(21 ± 5)% of the produced J/ψ's come from χ_c decays

based on 1300 χ_c's reconstructed in the di-muon channel (less than 10% of the total statistics)



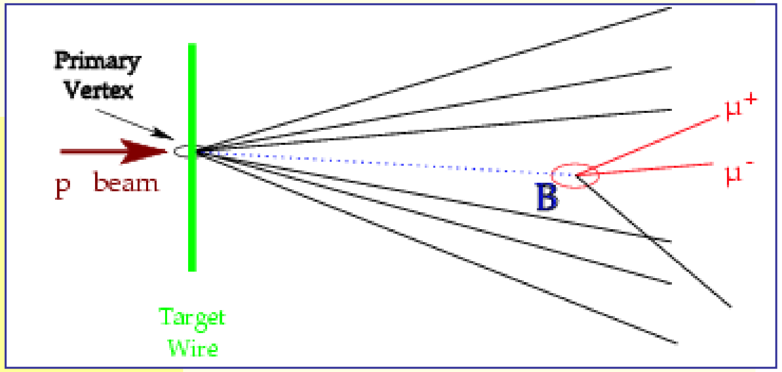
Beauty production:

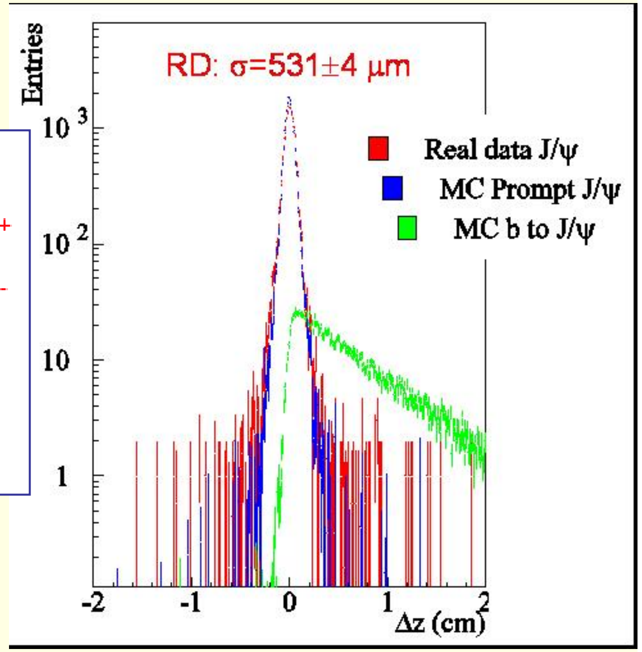
open & hidden

beauty

Open and Hidden Beauty Production

Detached vertex analysis





open

$pA \rightarrow b\ \bar{b} + X$

$\quad\quad \hookrightarrow J/\psi + X'$

$\quad\quad\quad\quad \hookrightarrow e^+ e^-, \mu^+\mu^-$

hidden

$pA \rightarrow \Upsilon(ns) + X$

$\quad\quad \hookrightarrow e^+ e^-, \mu^+\mu^-$

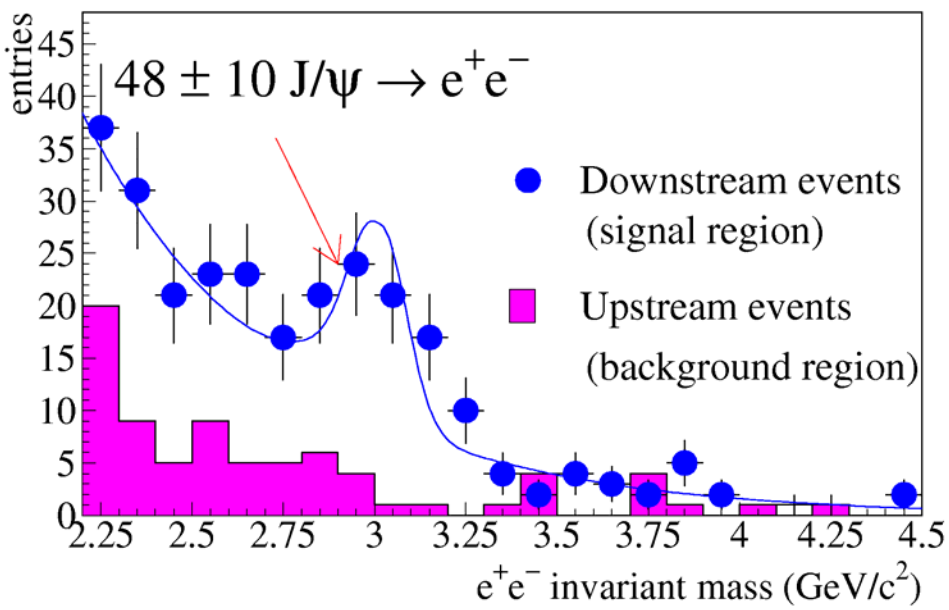
Cross sections normalised to prompt J/ψ

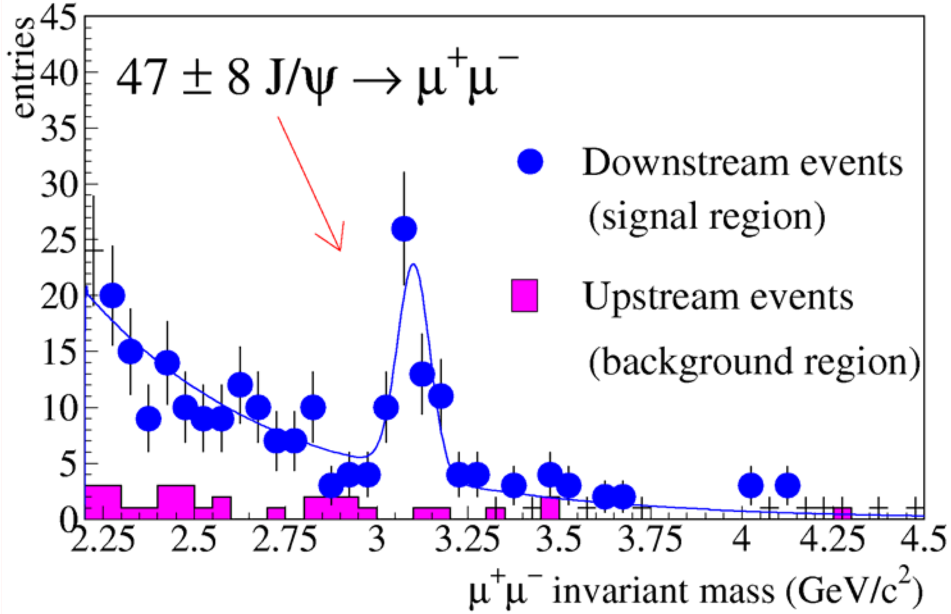
using the 'NRQCD supported' evaluation:

σ(pN → J/ψ X) = (502 ± 44) nb/nucleon

(with $\alpha = 0.96 \pm 0.01$)

Open beauty production





Analysis of 2002/03 data:

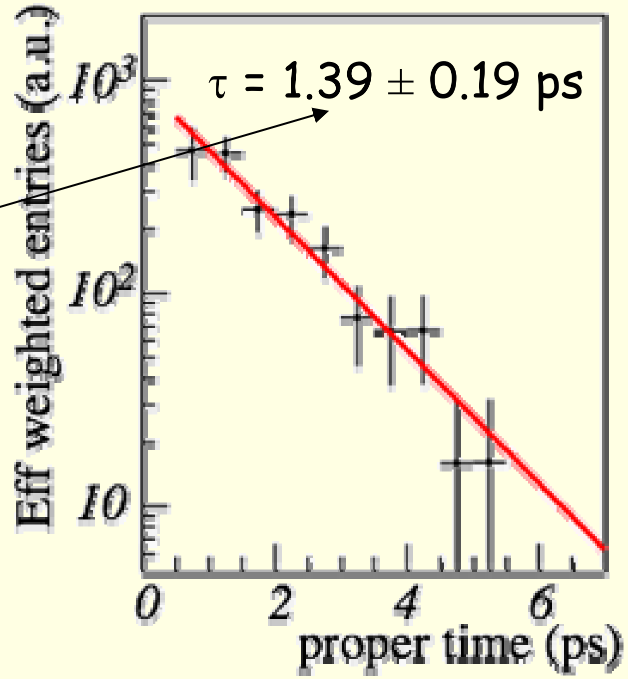
- e^+e^- and $\mu^+\mu^-$ triggered data
- C, W, Ti targets ($\alpha \approx 1$ for $b\bar{b}$)
- J/ψ acceptance: $-0.35 < x_F < 0.15$

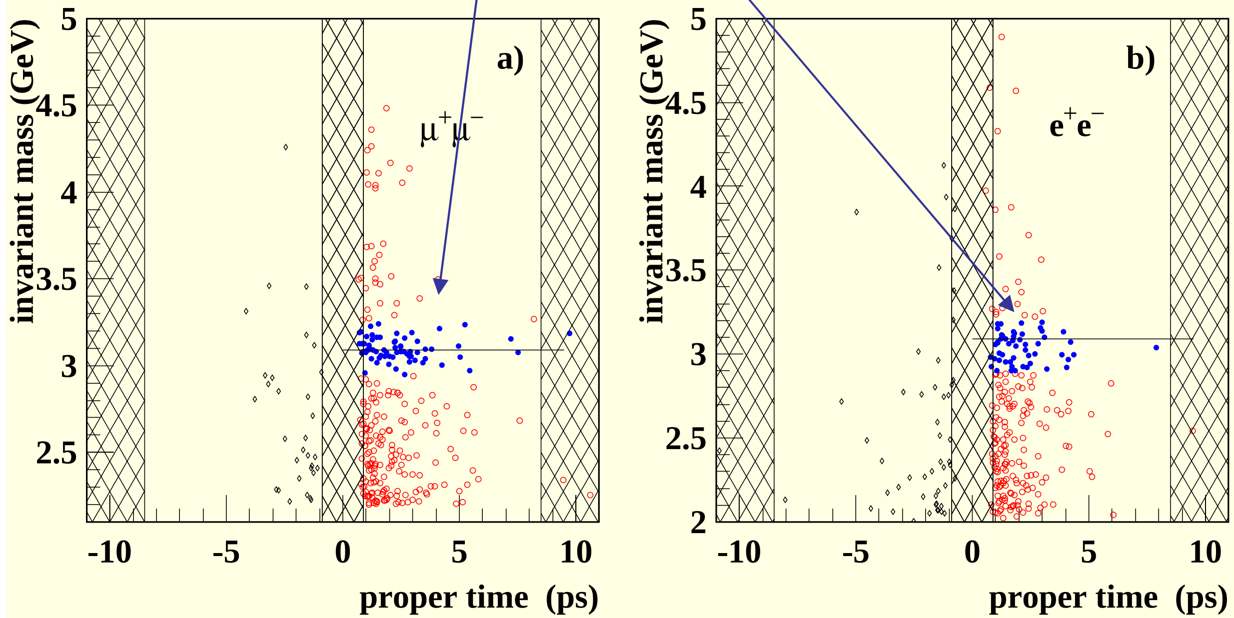
  (90% of bb cross section)

B Flavour Confirmation

Long lived candidates around J/ψ mass

B lifetime compatible with expected 1.54 ps (PDG)





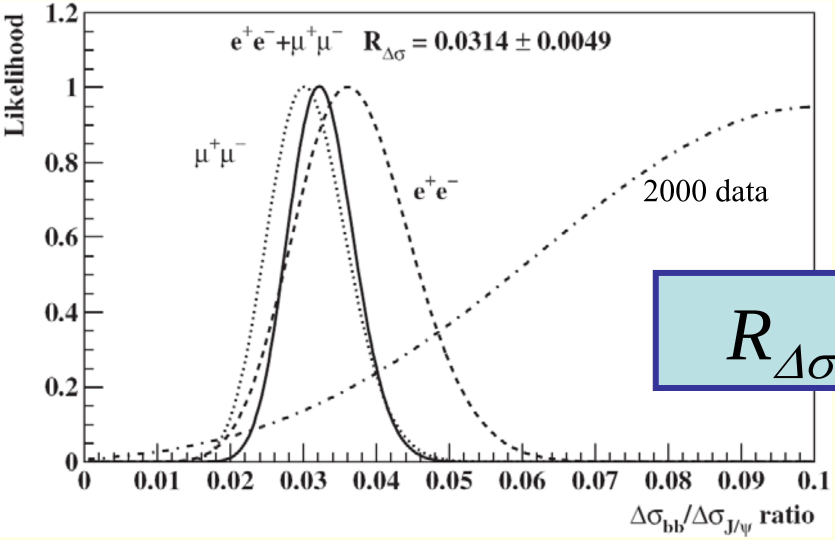
Open beauty production: $R_{\Delta\sigma}$

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

Relative to prompt J/ψ
to minimize uncertainties
from efficiencies, luminosity …

$\Delta\sigma$ for $-0.35 < x_F < 0.1$, $0 < p_T < 6$ GeV

$$\Delta\sigma_{b\bar{b}} = (0.906 \pm 0.005) \cdot \sigma_{b\bar{b}}$$
$$\Delta\sigma_{J/\Psi} = (0.83 \pm 0.01) \cdot \sigma_{J/\Psi}$$



Combined result of 2000 and 2002/3 data:

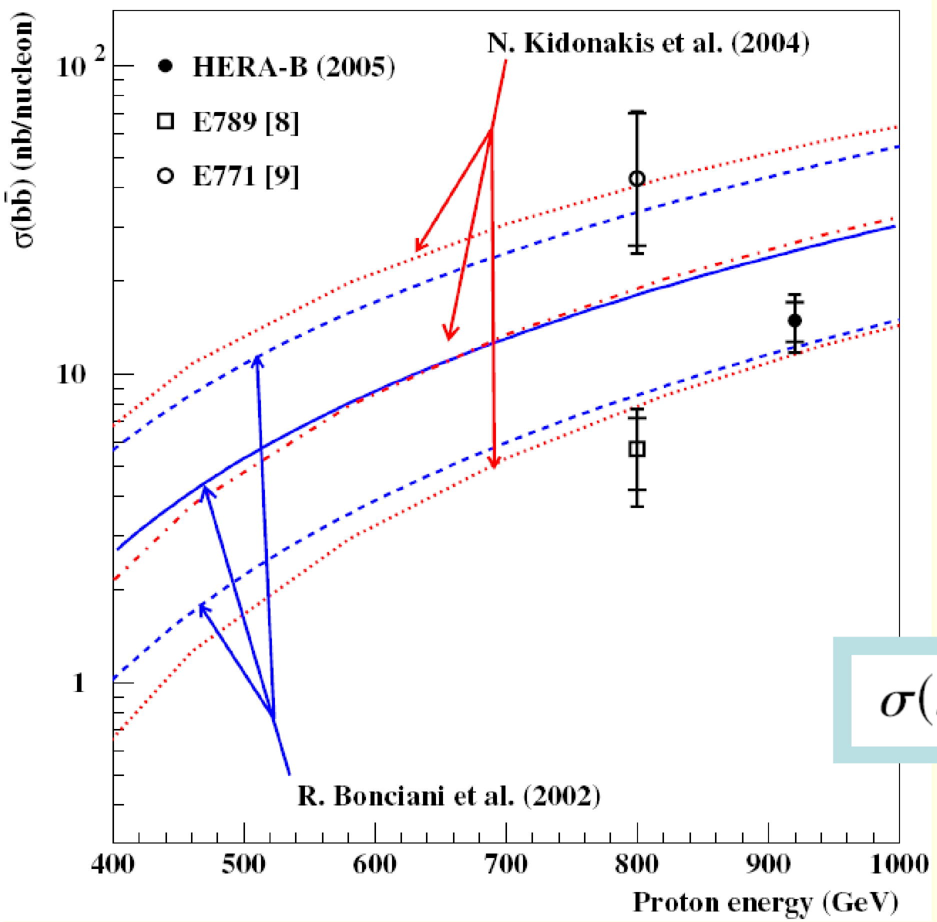
$$R_{\Delta\sigma} = 0.032 \pm 0.005_{stat} \pm 0.004_{sys}$$

(syst. error mainly from B(b→J/ψ))

PHYSICAL REVIEW D **73,** 052005 (2006)

2000 data: Eur. Phys.J. C26 (2003) 345

$b\bar{b}$ Production Cross section



$$\sigma_{b\bar{b}} = R_{\Delta\sigma} \cdot \sigma_{J/\Psi} \cdot \frac{f_{J/\Psi}}{f_{b\bar{b}}}$$

$$\frac{f_{J/\Psi}}{f_{b\bar{b}}} = \frac{0.83 \pm 0.01}{0.906 \pm 0.005}$$

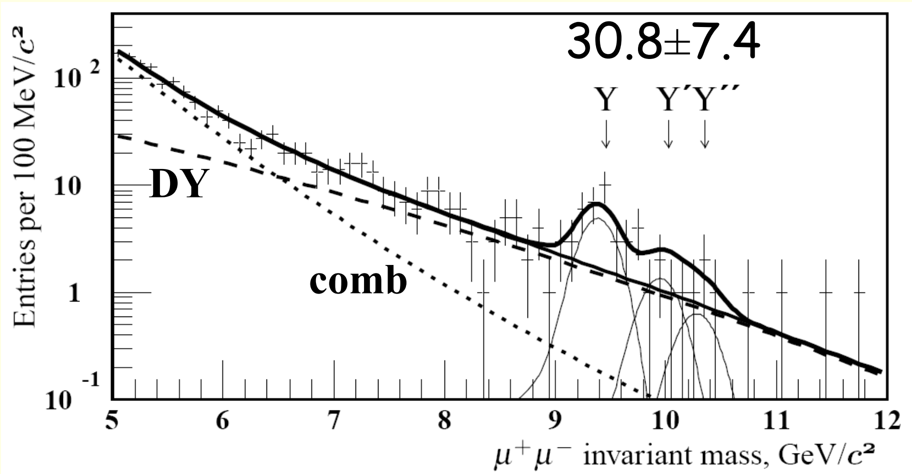
Normalizing to $\sigma_{J/\psi}$ from Maltoni et al.:
$\sigma(pN \rightarrow J/\psi\ X) = (502 \pm 44)$ nb/N

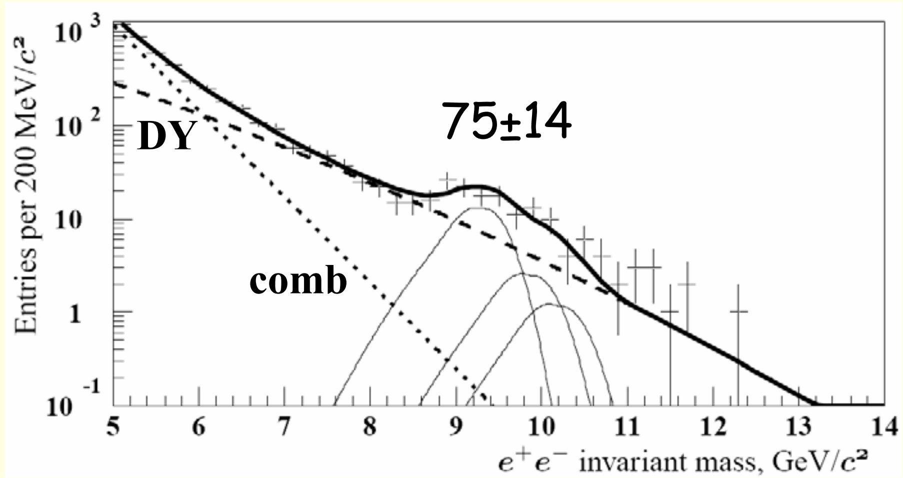
$$\sigma(b\bar{b}) = 14.9 \pm 2.2_{\text{stat}} \pm 2.4_{\text{sys}} \text{ nb/nucleon.}$$

Hidden beauty production

$\Upsilon(1S) + \Upsilon(2S) + \Upsilon(3S)$

Hidden beauty: Υ(1S) + Υ(2S) + Υ(3S)





Fit: A· (Υ(1S) + Υ(2S) + Υ(3S)) + B · Drell-Yan + Combinatorial

Υ(1S) : Υ(2S) : Υ(3S)
ratio fixed to E605 results

shape from MC

from like-sign pairs

$$\mathrm{Br}(\Upsilon \rightarrow l^+l^-) \cdot \frac{d\sigma}{dy}(\Upsilon)\Big|_{y=0} = \mathrm{Br}(J/\psi \rightarrow l^+l^-) \cdot \sigma(J/\psi) \cdot \frac{N(\Upsilon)}{N(J/\psi)} \frac{\varepsilon(J/\psi)}{\varepsilon(\Upsilon)} \frac{1}{\Delta y_{\mathrm{eff}}}$$

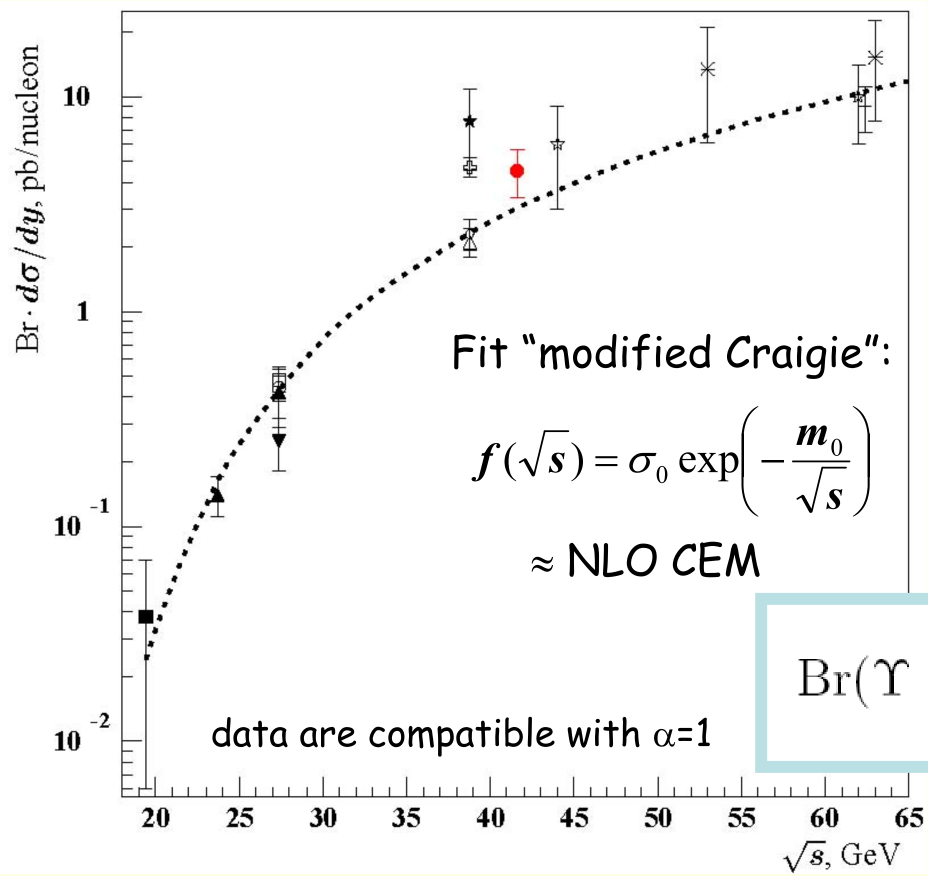
$$R_{J/\psi} \equiv \frac{\mathrm{Br}(\Upsilon \rightarrow l^+l^-) \cdot d\sigma(\Upsilon)/dy|_{y=0}}{\sigma(J/\psi)}$$

Hidden beauty production: Results

$$R_{J/\psi} = (9.0 \pm 2.1) \cdot 10^{-6}$$

Normalized to J/ψ

$$\sigma_{pN}(J/\psi) = 502 \pm 44 \, \frac{\text{nb}}{\text{nucleon}}$$



Fit "modified Craigie":

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

≈ NLO CEM

data are compatible with α=1

$$\text{Br}(\Upsilon \to l^+ l^-) \cdot \frac{d\sigma}{dy}(\Upsilon)\Big|_{y=0} = 4.5 \pm 1.1 \, \frac{\text{pb}}{\text{nucleon}}$$

Summary

HERA-B collected 300k J/ψ and 200M min.bias events on various nuclei

Results on charmonium production (partly preliminary):

- **J/ ψ cross section (and QCD evaluation)**
- **J/ ψ: x_F and p_T distributions in a new negative x_F range**
  J/ψ A dependence demonstrate a flat behavior in this region
- **Fraction of χ_c and ψ(2S) yields relative to J/ψ**
- **Open and hidden beauty cross sections**

Final results on J/ ψ, χ_c and ψ(2S) in 2006

The end of HERA-B is close