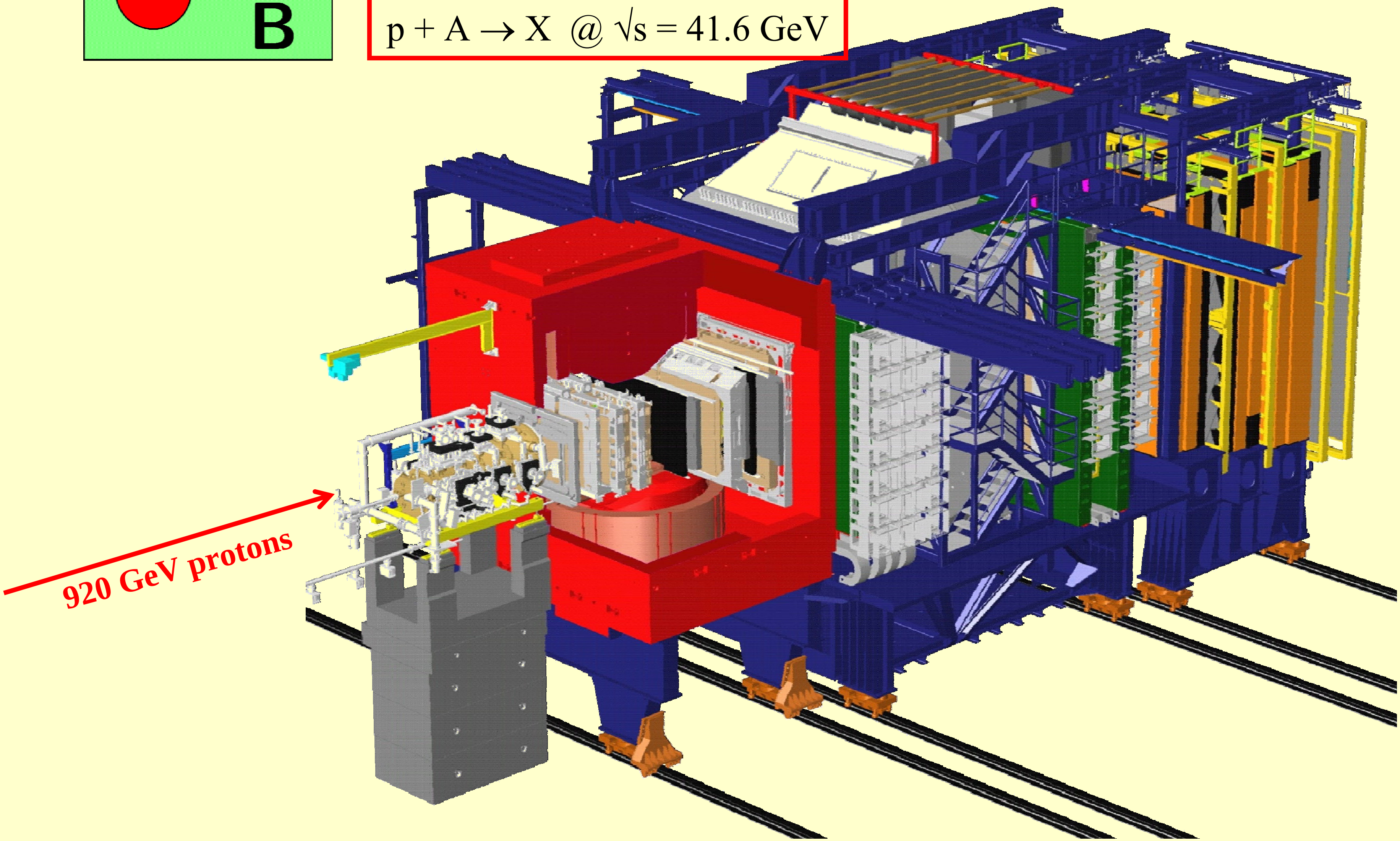
HERA-B Results on Heavy Flavor Production
in 920 GeV Proton-Nucleus Interactions

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

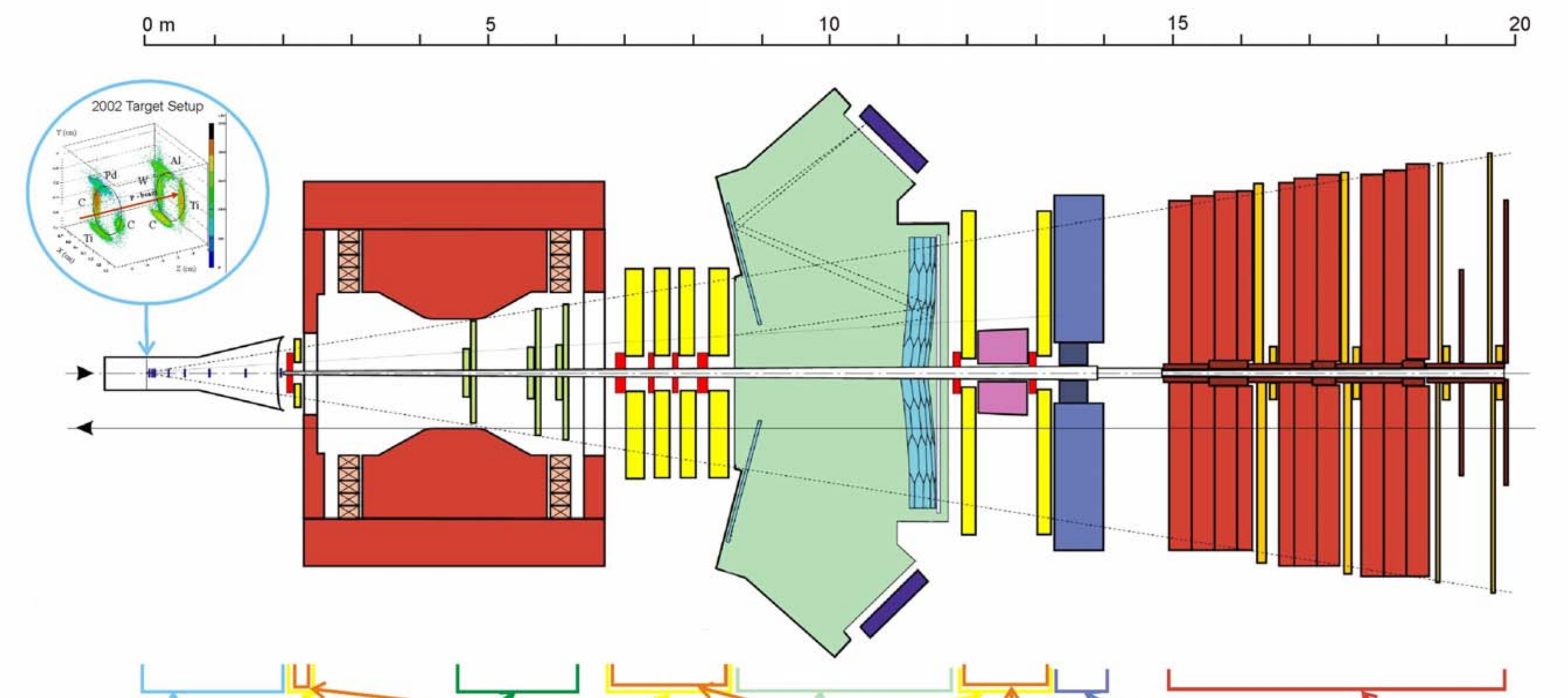
- **Charmonium production: J/ψ, ψ', χ_c**
- **Open charm production: D^0, $D^{\pm}$, D^***
- **Hidden and open beauty production: $\sigma(b\bar{b})$, $\Upsilon(ns)$**

The HERA-B Experiment

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



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 hit coincidence in muon detector as trigger seed (custom hardware)

3 MHz

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

20 kHz

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

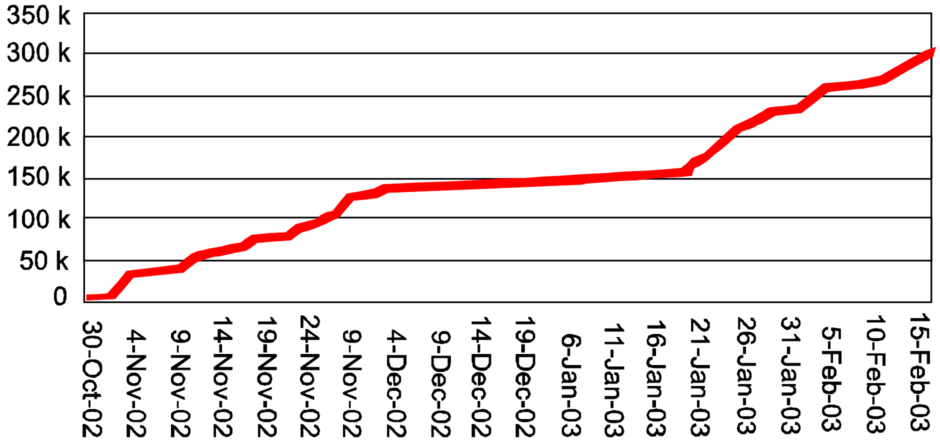
100 Hz

Data samples

Data taking is finished in 2003; analysis is in progress

- 150 M di-lepton trigger events
- 210 M minimum bias events
- 35 M hard photon trigger events
- 60 M “glueball” trigger events

(300 000 J/ψ: $e^+e^- + \mu^+\mu^-$)



Topics of di-lepton trigger analysis

1) p_t distribution
   x_F distribution
   A-dependence
   polarisation

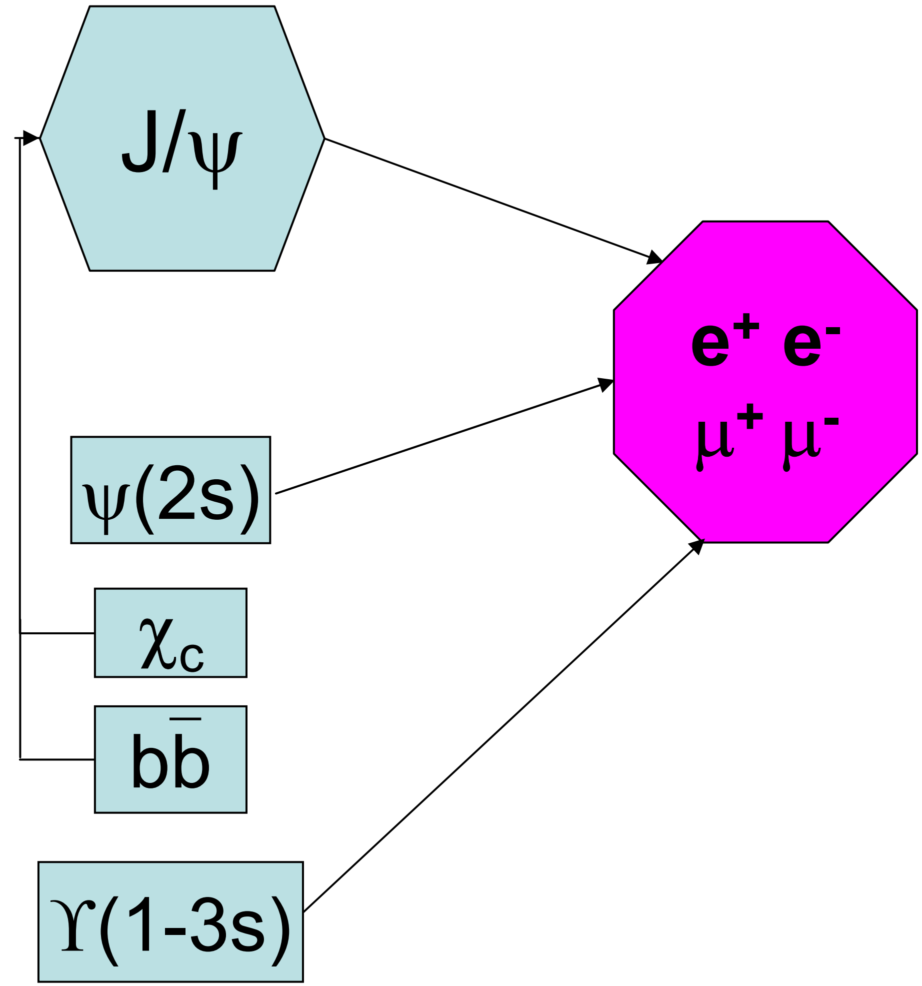
2) $\psi(2s)/J/\psi$ production ratio

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

4) bb cross section

5) Υ production

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



Most results are preliminary

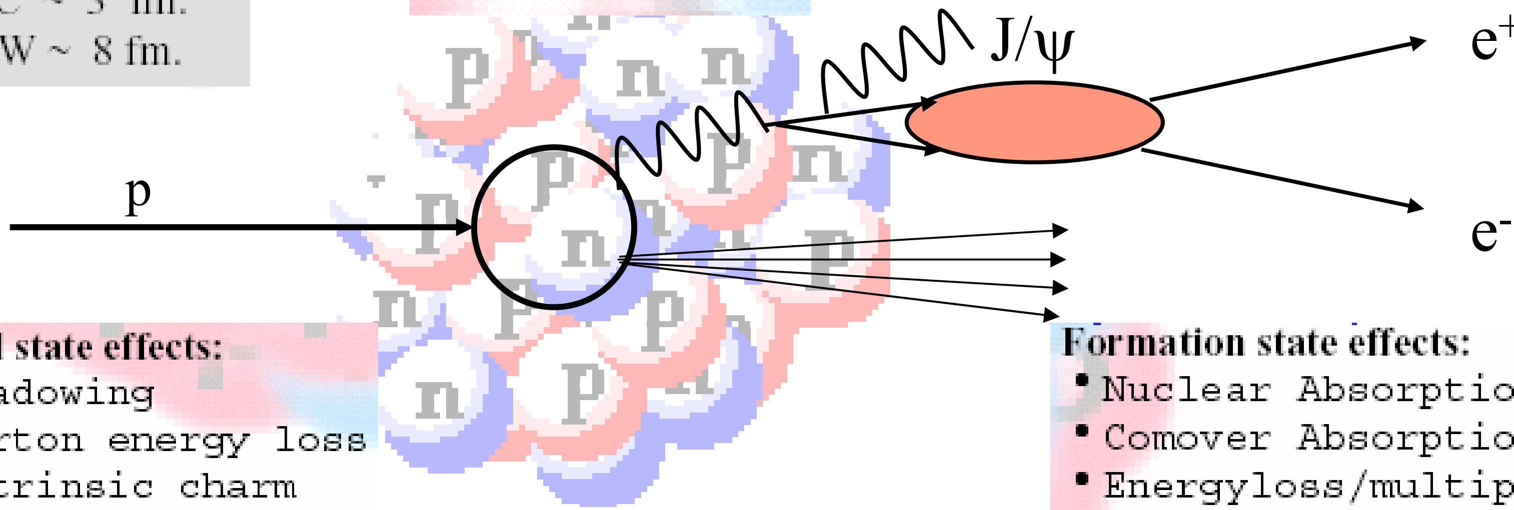
Study of Charmonium Suppression

x_f measures the distance the ccg state travels before charmonium formation.

X_f	Dist.
0.2	15fm
0.0	5fm
-0.2	1.5fm

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

$$\Delta t = 0.5\ fm \times \gamma$$



Initial state effects:

- Shadowing
- Parton energy loss
- Intrinsic charm

Formation state effects:

- Nuclear Absorption
- Comover Absorption
- Energyloss/multiple soft scattering

•Positive x_f → ccg abandons the nucleus before it forms a bound state.

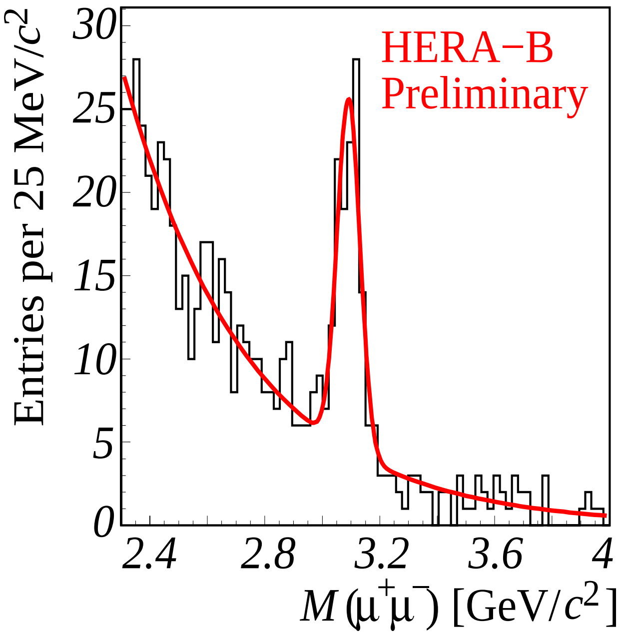
•Negative x_f → charmonium is formed before leaving the nucleus.

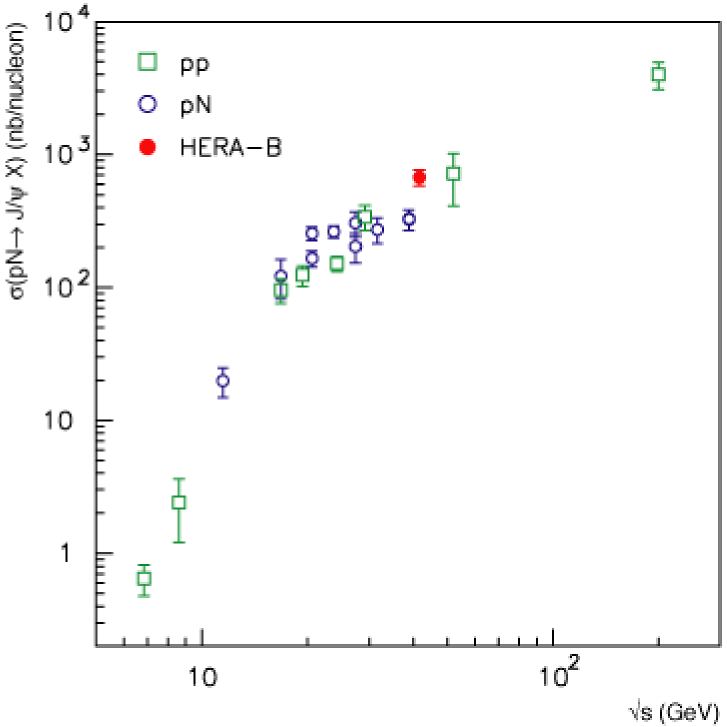
$$\sigma_{c\bar{c}} = \sigma_0 \bullet N^{\alpha}$$

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

J/ψ from Minimum Bias data

Important for cross section normalisation of di-lepton triggered data





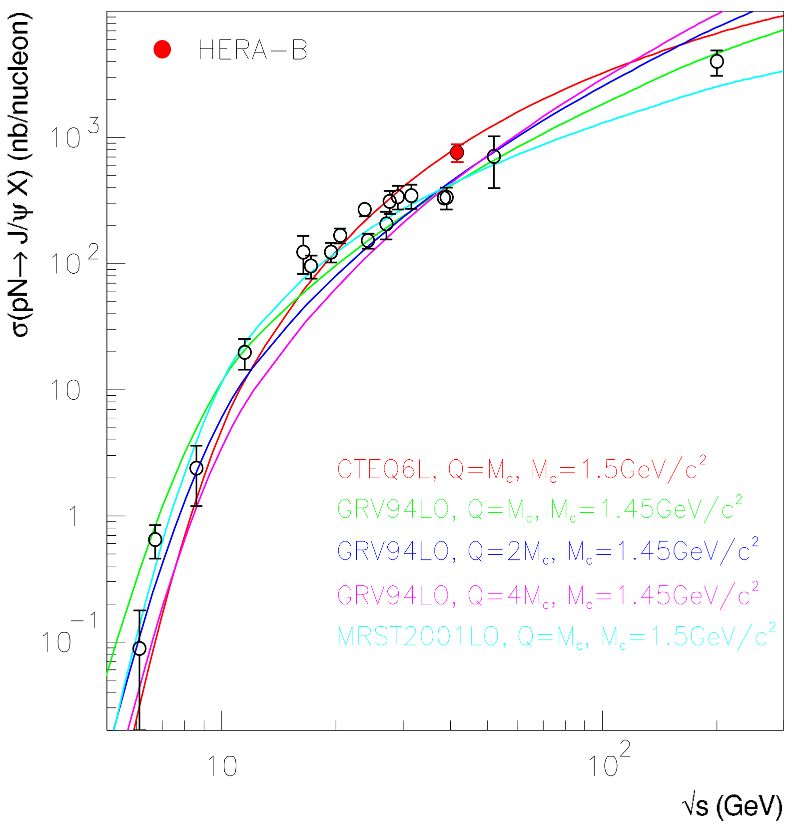
$$\sigma_{J/\psi} = \frac{N_{J/\psi}}{\varepsilon_{J/\psi} \cdot BR(J/\psi \to \mu^+\mu^-) \cdot \sum_i A_i^{\alpha} L_i}$$

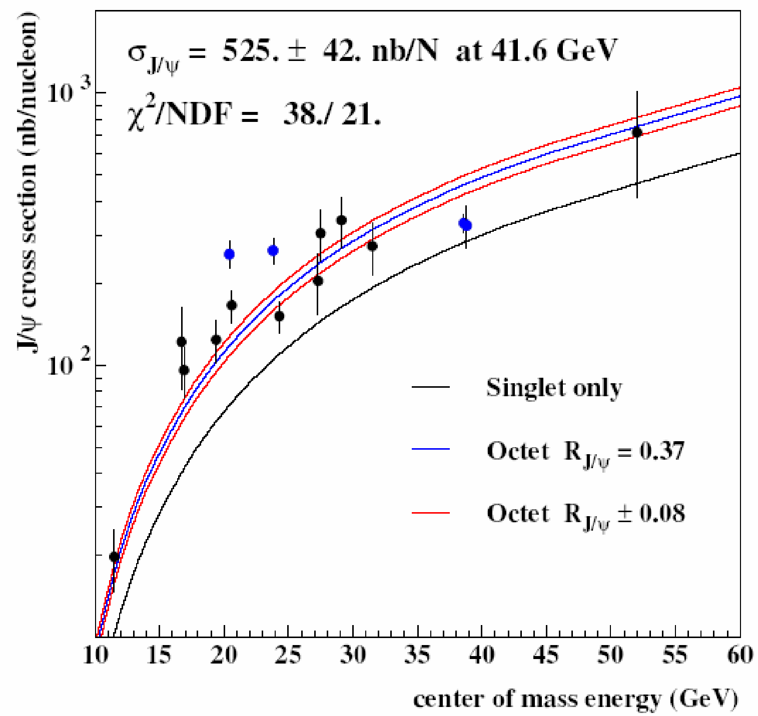
$\alpha = 0.96$

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

Study of J/ψ Cross Section Parametrisations

J/ψ total cross section (scaled to α=0.955)





Fit of cross section data currently studied with F.Maltoni

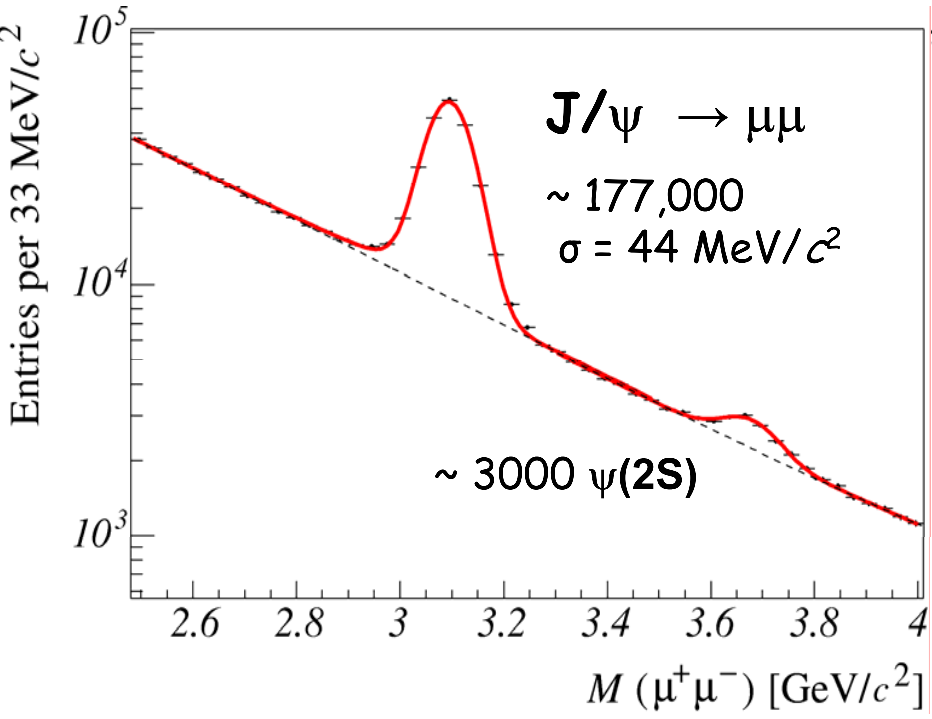
Biggest problem: inconsistent exp.data

Implemented matrix elements

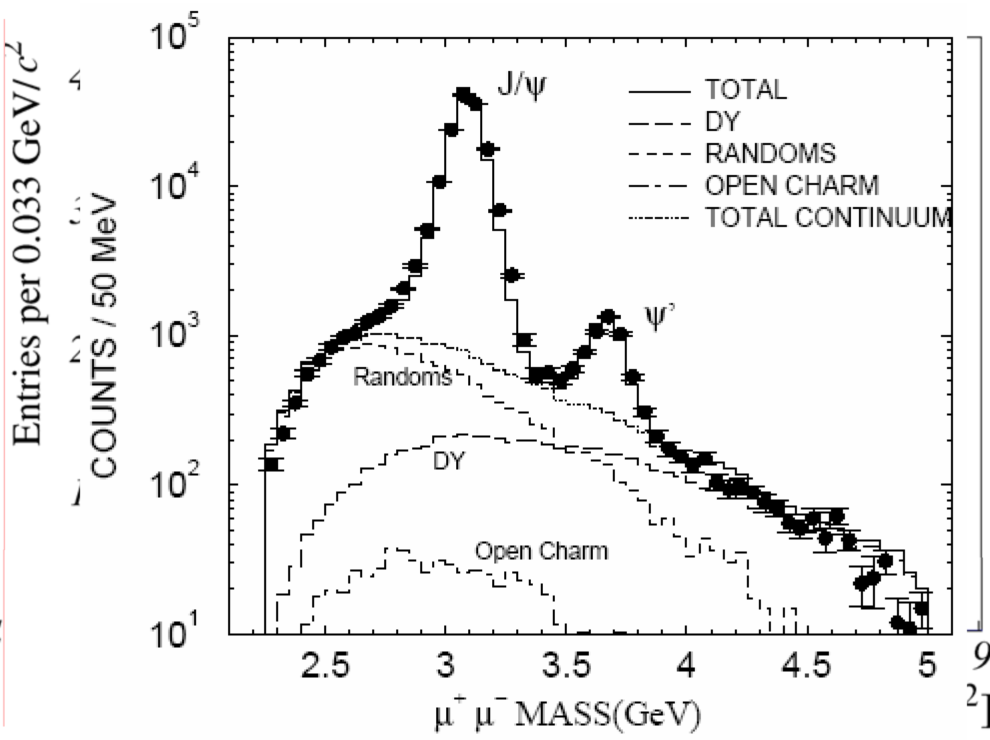
ME (GeV^3)	J/ψ	ψ'	χ_{c0}
$<\bar{\mathcal{O}}_1^H(^3S_1)>$	1.16/6	0.76/6	-
$<\bar{\mathcal{O}}_8^H(^1S_0)>$	fit	fit	-
$<\bar{\mathcal{O}}_1^H(^3P_0)>/m_c^2\cdot 10^2$	-	-	4.0/6
$<\bar{\mathcal{O}}_8^H(^3S_1)>\cdot 10^2$	1.06	0.46	0.32

J/ψ Production: di-lepton triggered

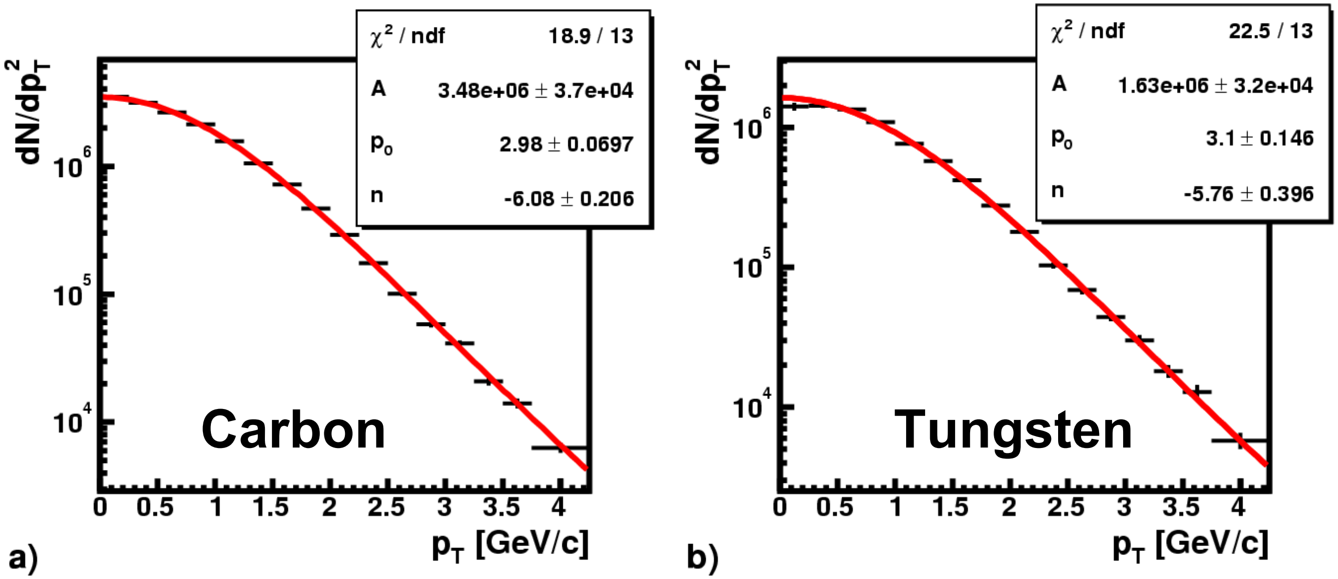
Mass Resolution HERA-B vs. E866



E866 (Phys.Rev.Lett.84:3256-3260,2000)



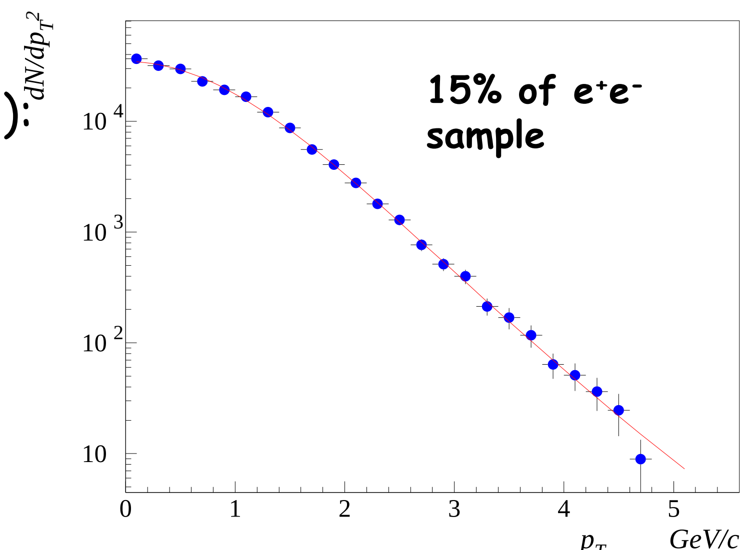
J/ψ production: p_T distribution



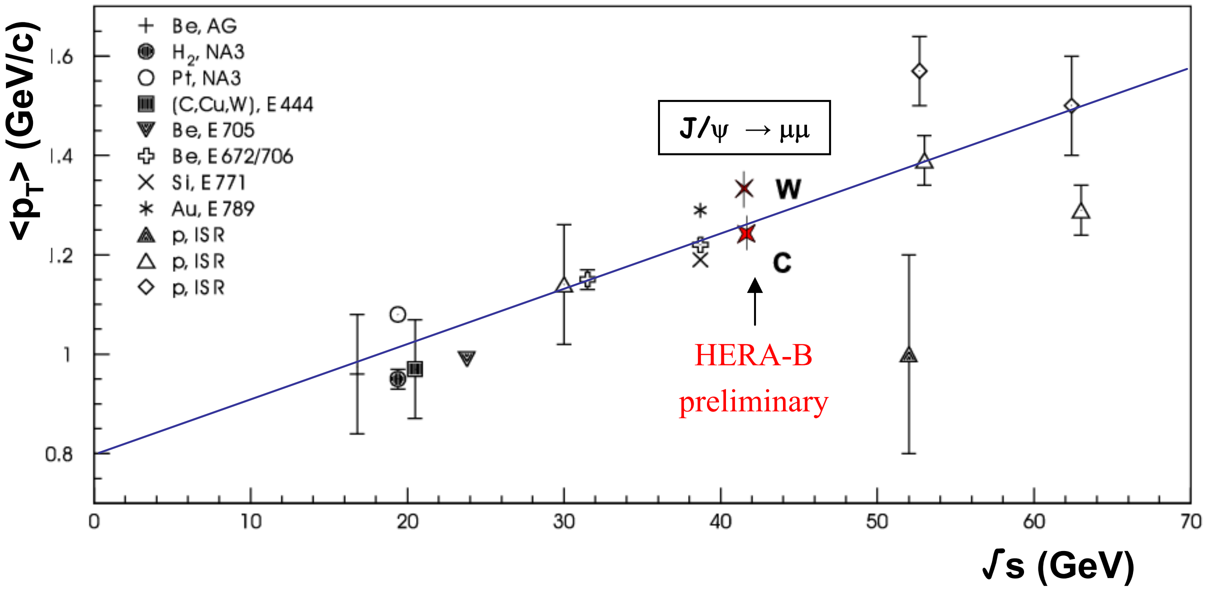
$$\frac{d\sigma}{dp_T^2} = A\left[1+\left(\frac{p_T}{p_0}\right)^2\right]^{-n}$$

Preliminary results for ⟨p_T⟩ (GeV/c) (n=6 fixed):

Target	electron	Muon
C	**1.24 ± 0.01**	**1.24 ± 0.03**
W	**1.29 ± 0.01**	**1.30 ± 0.04**



Energy dependence of $\langle p_T \rangle$



Phenomenological fit

$$\langle p_T \rangle = A + B\sqrt{s}$$

$A = 0.813 \pm 0.014$ GeV/c
$B = 0.0105 \pm 0.0004$ c^{-1}

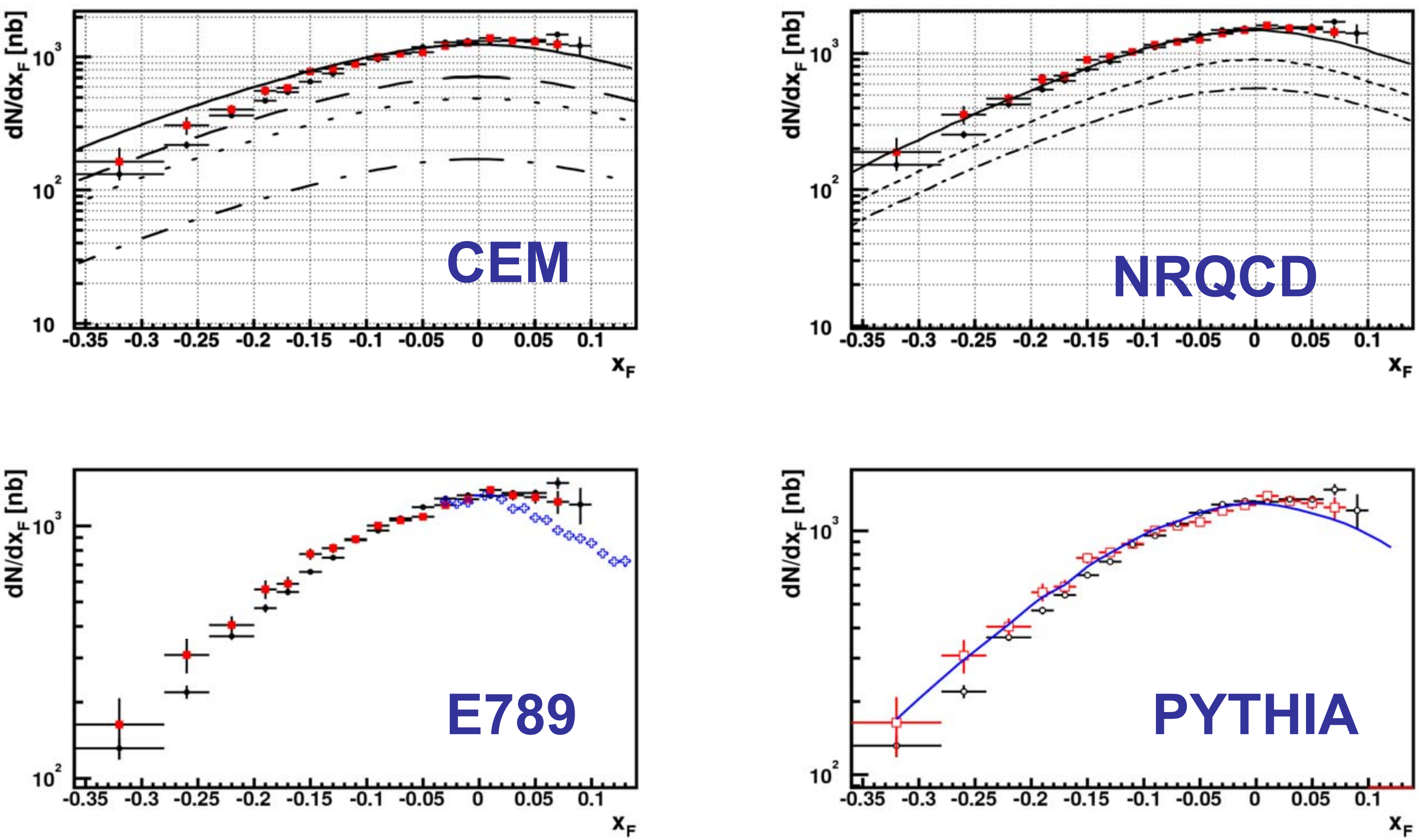
A dependence:
W wider than C

Comparing X_F distributions

▪ C
• W

$J/\psi \rightarrow \mu\mu$

CEM, NRQCD: calculated by R.Vogt for HERA-B energy (pp)



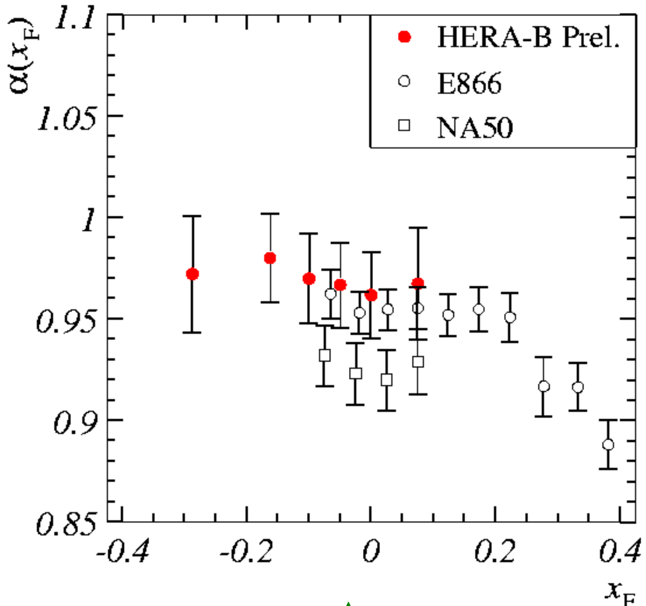
A dependence: $\alpha(x_F)$

$$\sigma_{pA} = \sigma_{pN} \cdot A^{\alpha}; \quad \sigma = N/(\varepsilon \cdot L)$$

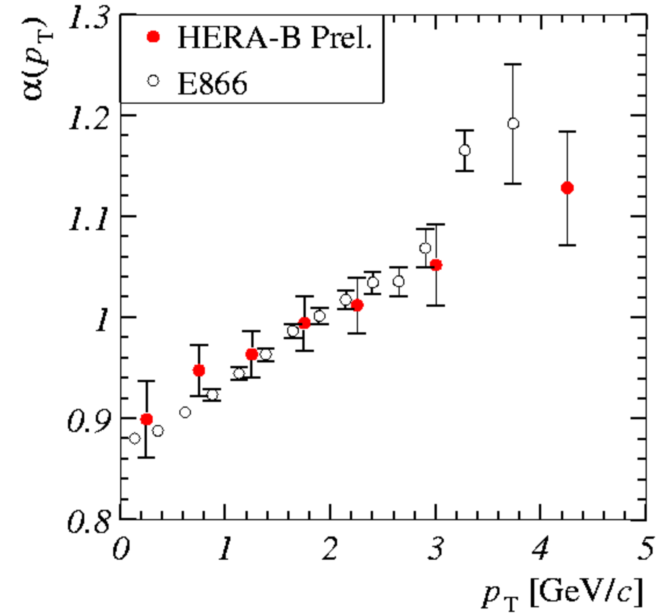
$$\alpha = \frac{1}{\ln(A_W/A_C)} \cdot \ln\left(\frac{N_W}{N_C}\frac{L_C}{L_W}\frac{\varepsilon_C}{\varepsilon_W}\right)$$

main syst.: "wire sharing

2-wire runs (C, W), μμ data:



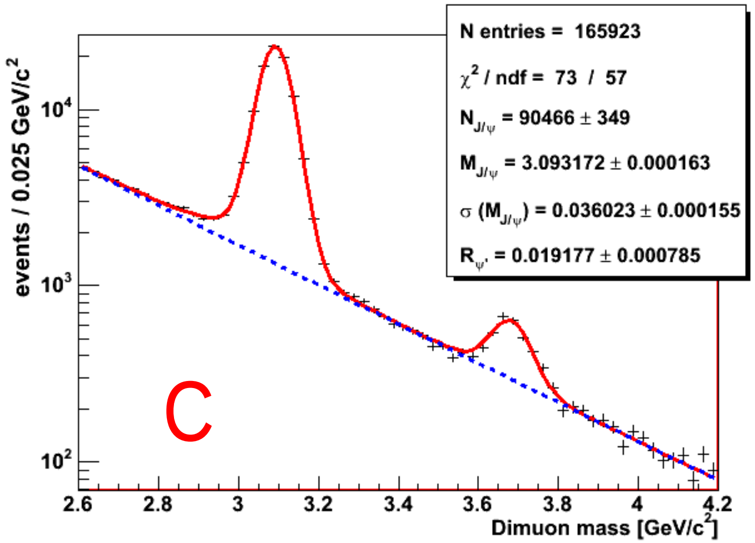
HERA-B now absolutely normalized

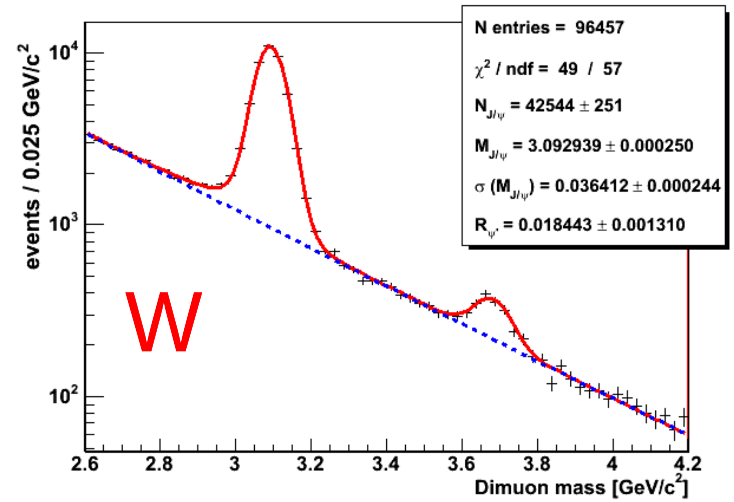


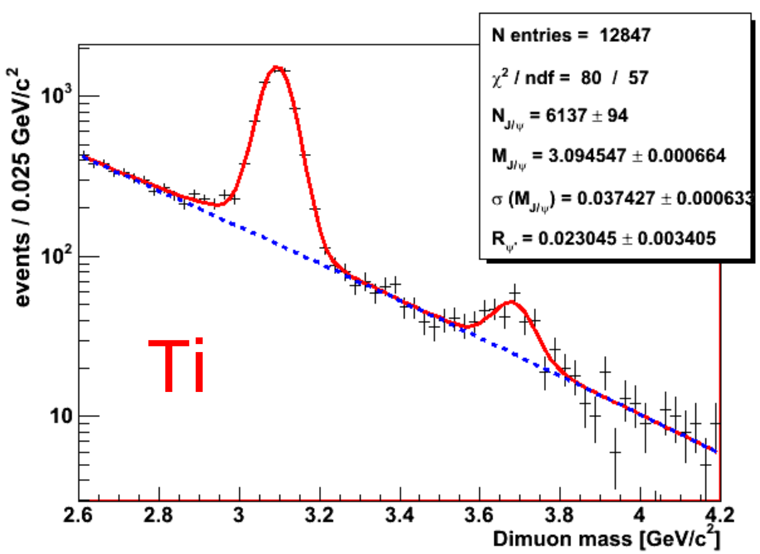
FNAL E866
extended to $x_F = -0.3$

- Samples have different wire configurations
  ⇒ consistency check of acceptances
- Systematic studies ongoing

ψ’ production: σ(ψ’) / σ(ψ)



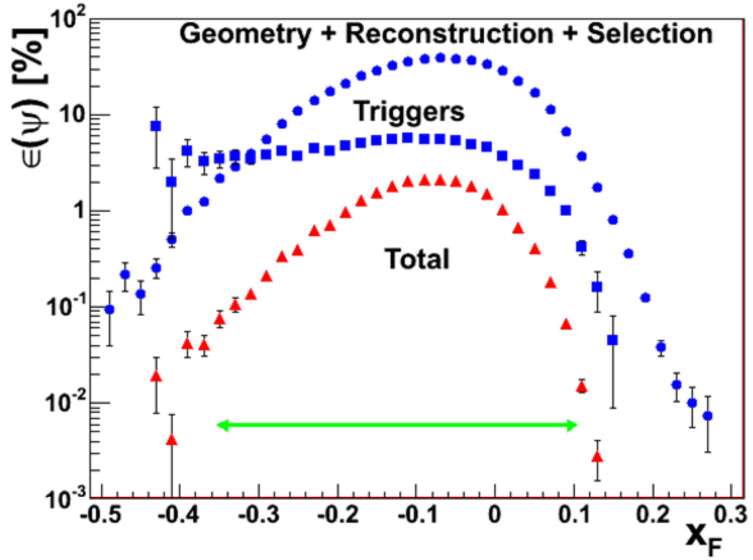


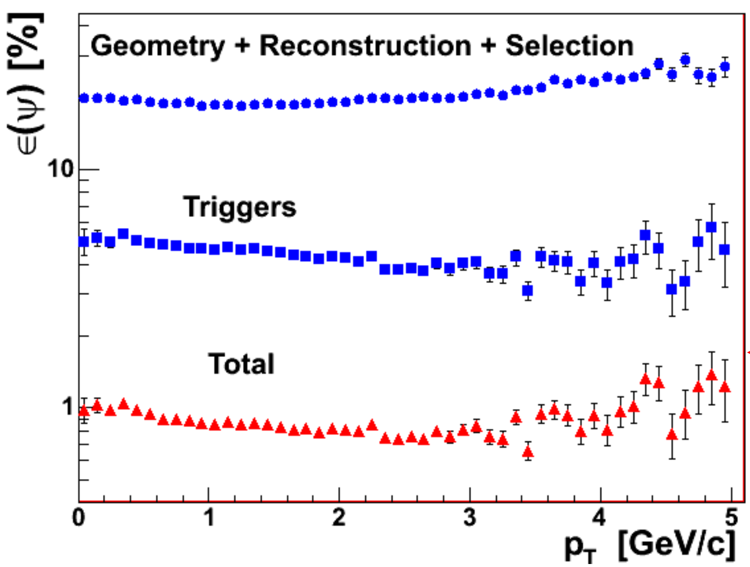


Target	N(J/y)
C	90466 ± 349
W	42544 ± 251
Ti	6137 ± 94

$$\frac{BR(\psi(2S) \to l^+l^-)\cdot\sigma_{\psi(2S)}}{BR(J/\psi \to l^+l^-)\cdot\sigma_{J/\psi}} = \frac{N_{\psi(2S)}}{N_{J/\psi}}\,\frac{\varepsilon_{J/\psi}}{\varepsilon_{\psi(2S)}}$$

Acceptance of the J/ψ vs x_F, p_T

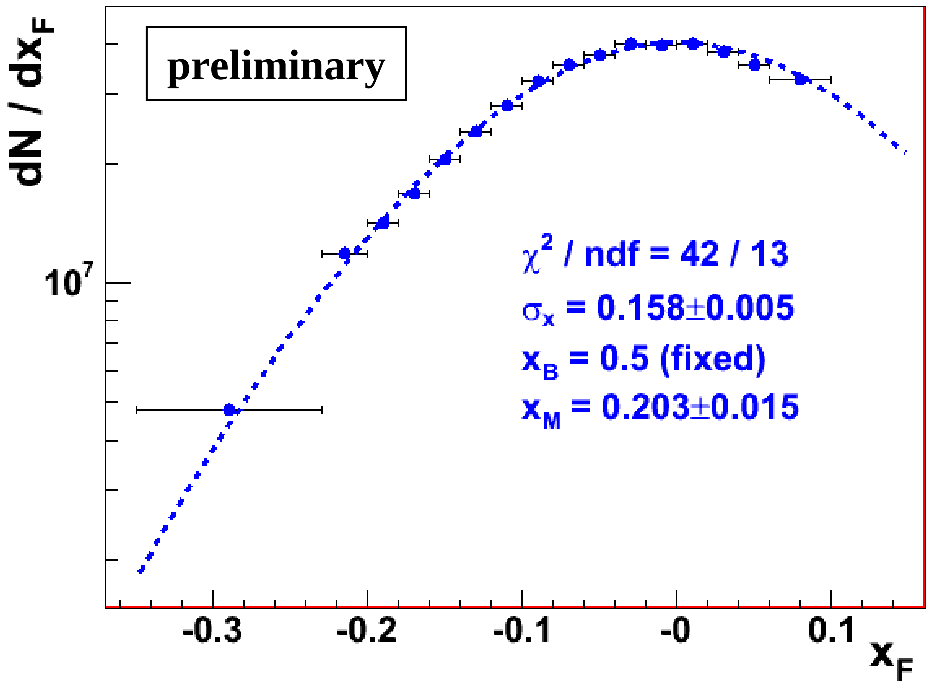




⟸ **flat in p_T**

- Total acceptance is ~1%
- cancellation in the ψ'/ψ ratio
- $\varepsilon(\psi) / \varepsilon(\psi')$ is ~86%

Fitting of x_F distribution for J/ψ



Fitting function:

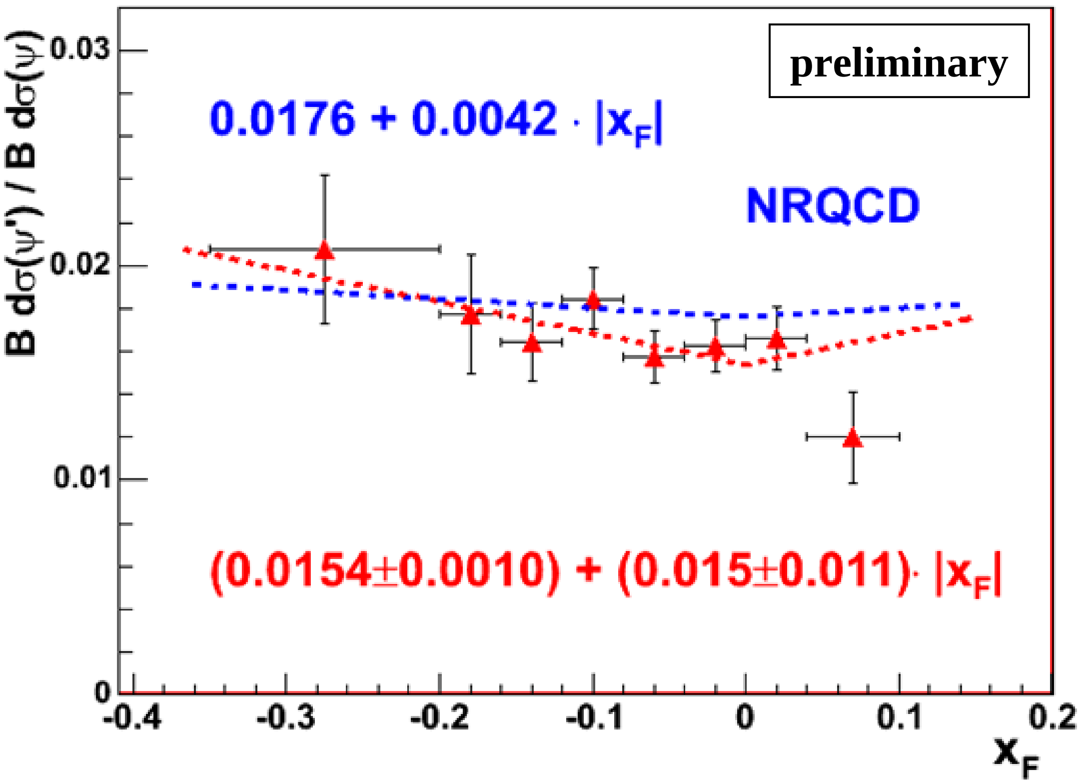
(fits well NRQCD, PHYTHIA)

$$g(x_F) = \frac{f(x_F \mid x_{B,} \sigma_x)}{\sqrt{x_M^2 + x_F^2}}$$

$$x_F < x_B : \quad f \sim \exp\left(-\frac{x_F^2}{2\sigma_x^2}\right)$$

$$x_F > x_B : \quad f \sim \left(1 - |x_F|\right)^C$$

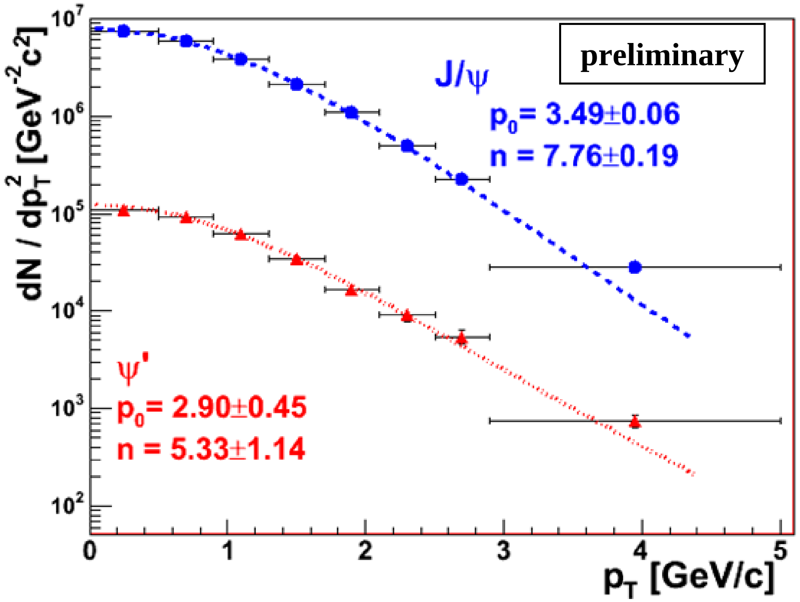
ψ'/ψ vs x_F for all data

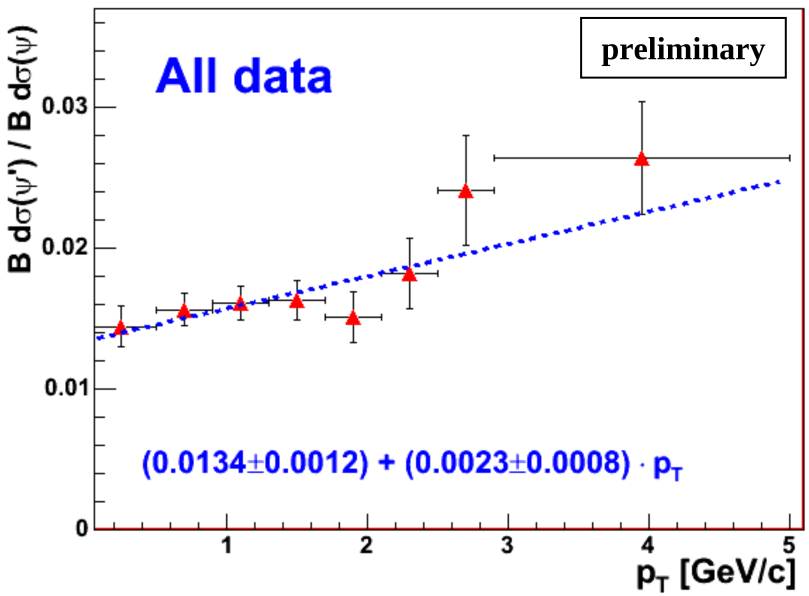


Fitted by $a + b \cdot |x_F|$

- In agreement with NRQCD
- almost constant vs x_F

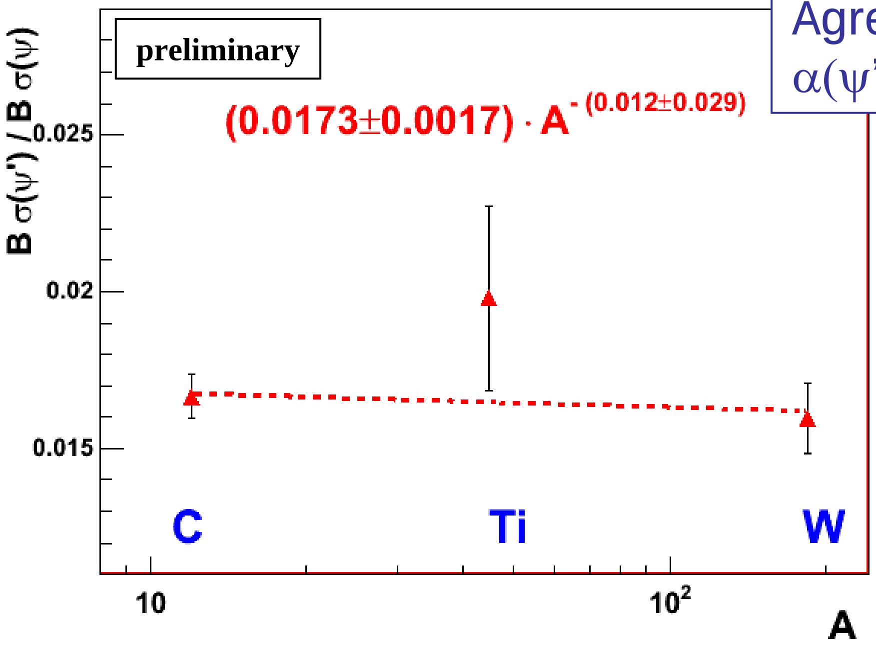
Dependence on p_T





- Power-low is suitable for the fitting
- Indication of p_T dependence
- How to treat different materials ?

A-Dependence of $\sigma(\psi') / \sigma(\psi)$



Agrees with E866 value:
$\alpha(\psi') - \alpha(\psi) = -0.026 \pm 0.005$

prelim.

$R = B\,\sigma(\psi') / B\,\sigma(\psi)$	
C :	(1.667 +/- 0.069) %
W:	(1.596 +/- 0.114) %
Ti:	(1.979 +/- 0.293) %
All:	(1.659 +/- 0.058) % , (as one sample)

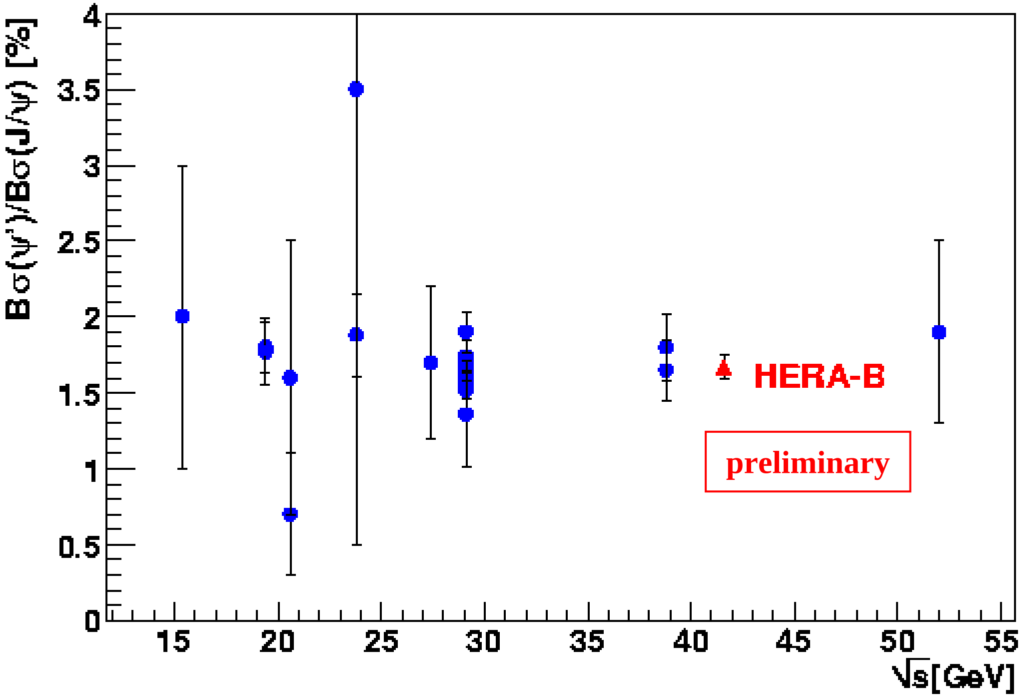
A-dependence should be taken into account:

Define R separately for C, W and Ti targets and fit:

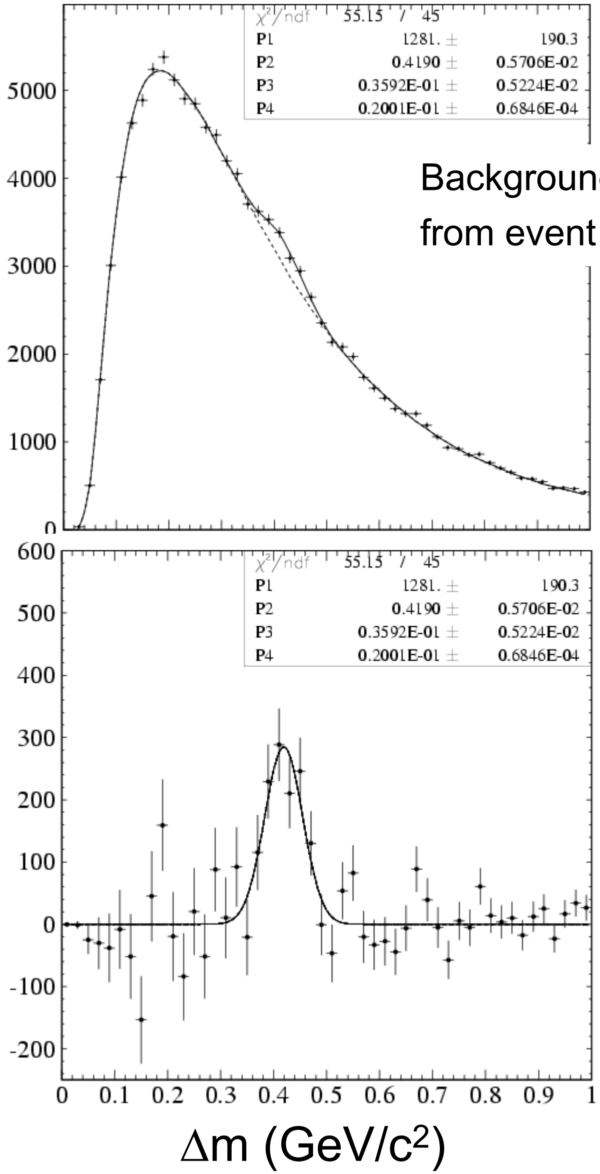
$$R(A) = R_1 \cdot A^{-(0.026 \pm 0.005)}$$

(R_1 will be the final result)

Energy Dependence of $\sigma(\psi') / \sigma(\psi)$



χ_c / J/ψ production ratio



Background shape from event mixing

observed in radiative decay

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

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

<u>Analysis of 2002/03 data:</u>

- Comb. background by event mixing
- Carbon target
- In ~10% of $\mu^+\mu^-$ statistics about 1300 χ_c
- Expect N(χ_c) ~ 15k for full sample

χ_c production: results

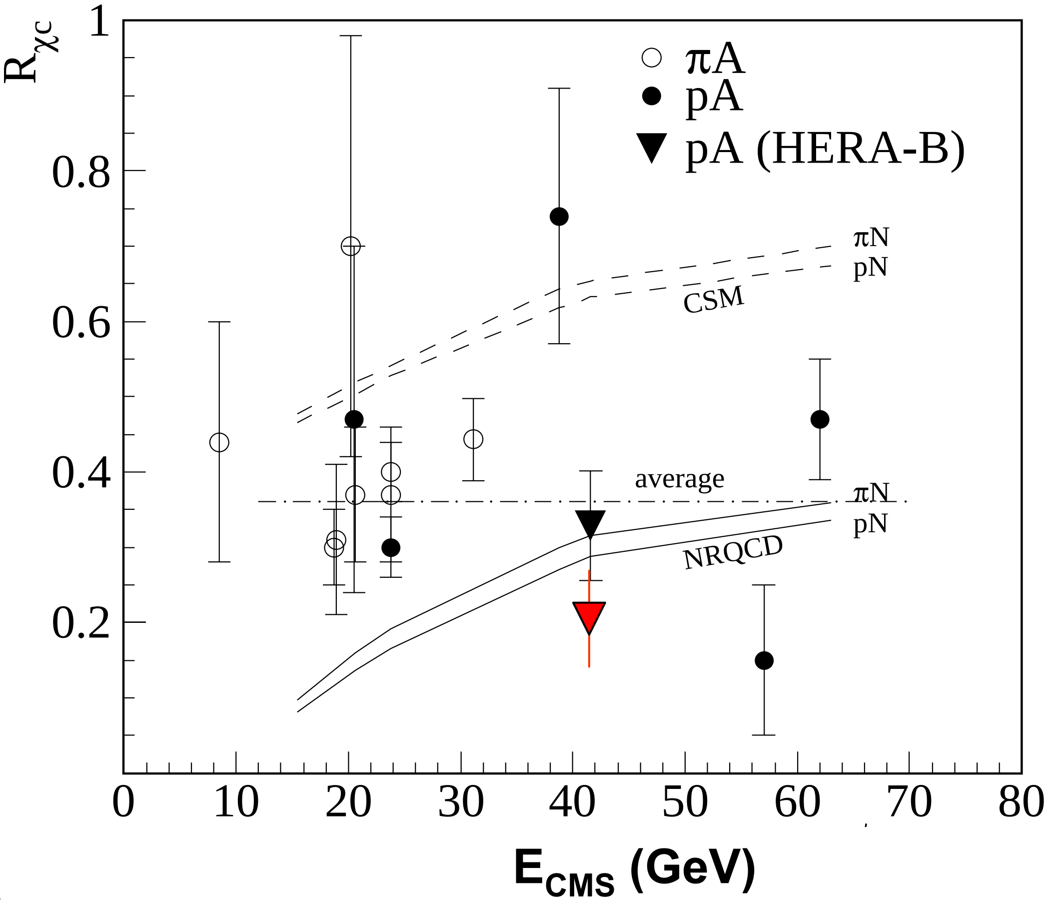
Published result of 2000
(Phys. Lett. B561(2003) 61)

$$N(\chi_c) = 370 \pm 74$$

$$R_{\chi_c} = 0.32 \pm 0.06(stat) \pm 0.04(sys)$$

10% of 2002/03 data

$R(\chi_c) = 0.21 \pm 0.05$



Systematic studies ongoing

(e.g. **efficiency dep. on polarisation**)

Electron channel gives compatible result

HERA-B point agrees with NRQCD but NRQCD underestimates R at low E_{cms}

Open Charm

- Search for FCNC in the decay BR($D^0 \rightarrow \mu^+ \mu^-$)

  see: Phys Lett B 569 (2004) 173 (hep-ex/0405059)

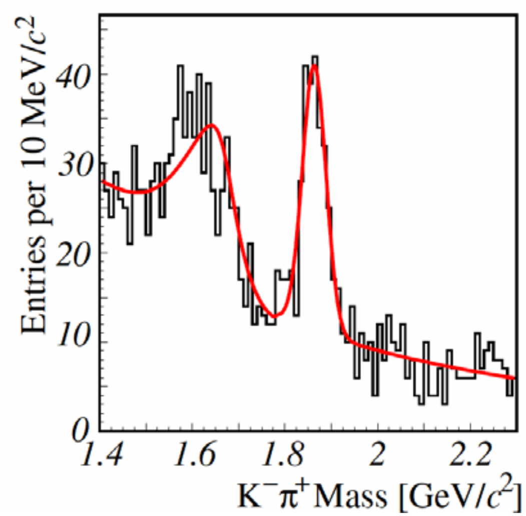
- Open charm signals in minimum bias data

  - Production Cross Sections for D^0, D^+, D^{*+}

  - Production Ratios D^+/D^0 and D^{*+}/D^0

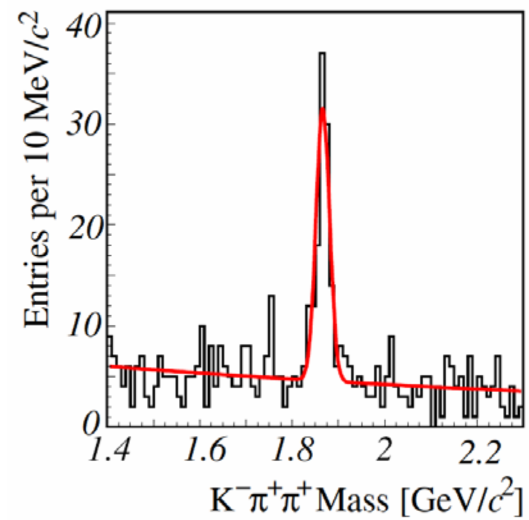
Open charm signals in minimum bias data

$D^0 \rightarrow K^- \pi^+$



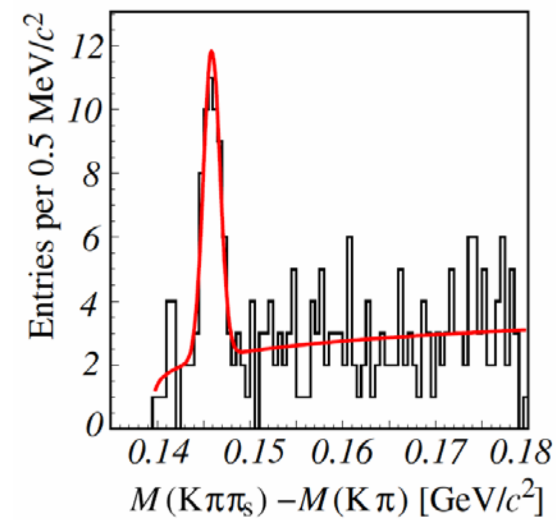
Events:	189 ± 20
M [MeV/c^2]:	1863 ± 3
σ [MeV/c^2]:	25 ± 3

$D^+ \rightarrow K^- \pi^+ \pi^+$



Events:	98 ±12
M [MeV/c^2]:	1866 ± 2
σ [MeV/c^2]:	15 ± 2

$D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^+$



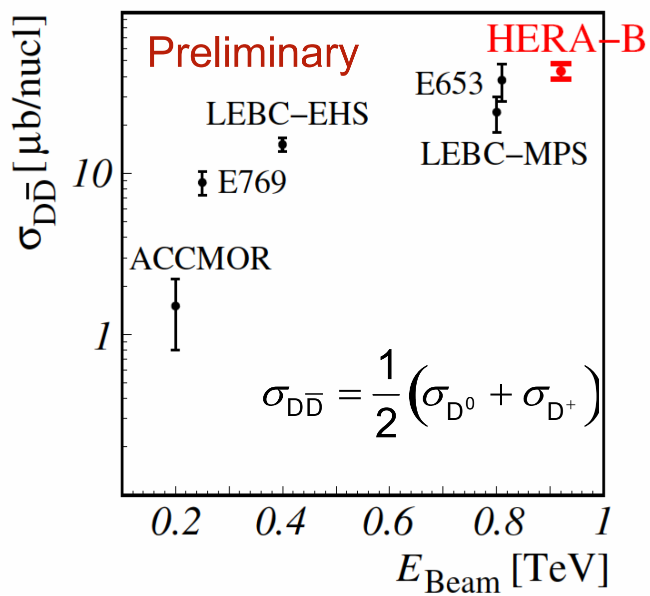
Events:	43 ± 8
Δ*M* [MeV/c^2]:	145.9 ± 0.2
σ [MeV/c^2]:	0.89 ± 0.15

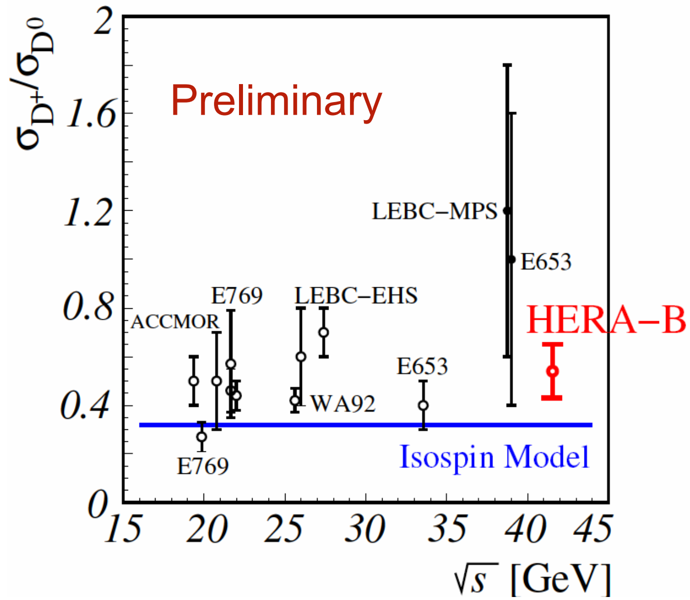
- **Production Cross Sections for D^0, D^+, D^{*+}**
- **Production Ratios D^+/D^0 and D^{*+}/D^0**

$$\sigma_D = \frac{N_D}{\varepsilon \cdot BR \cdot \sum A_i L_i}$$

Assuming A^α dependence with $\alpha = 1$

Open Charm Production



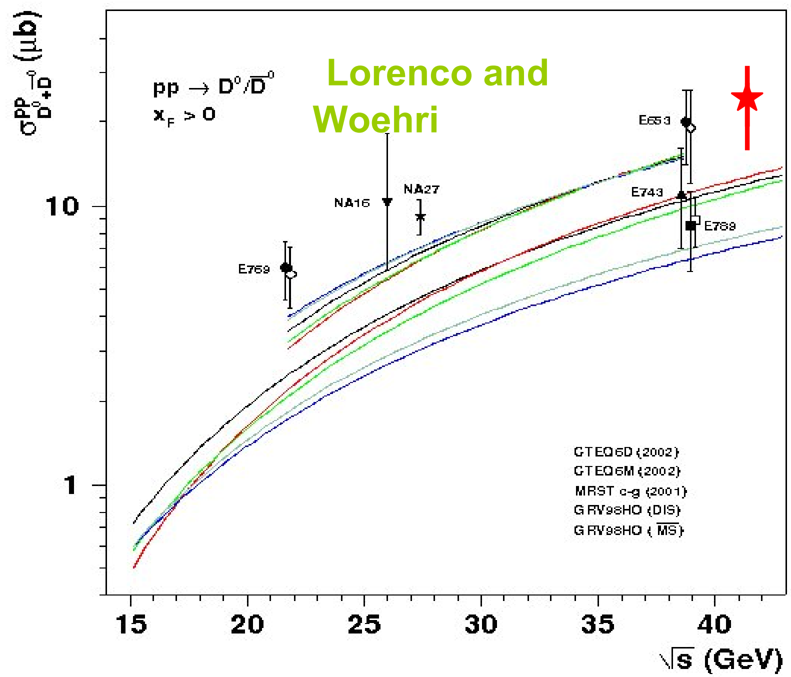


PYTHIA underestimates D+/D0 ratio

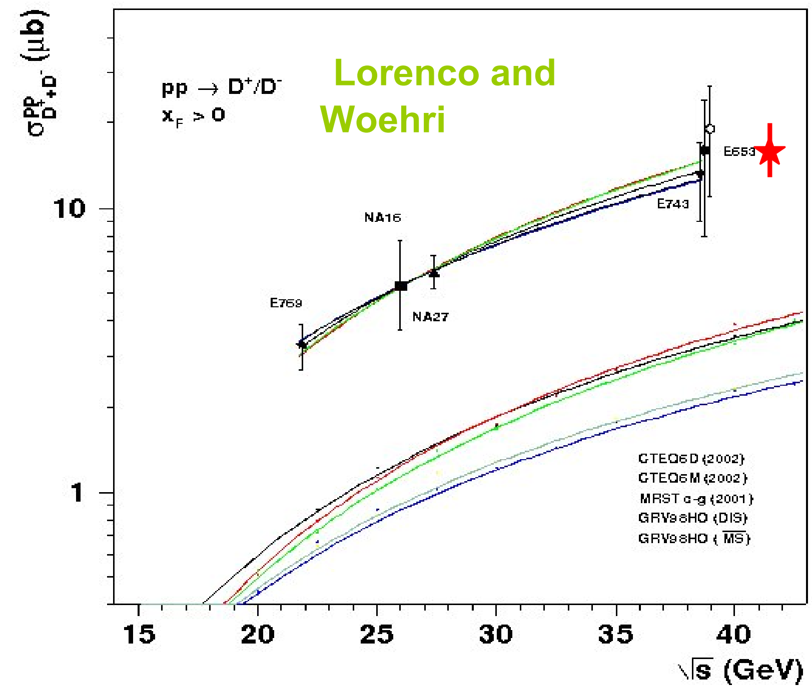
Preliminary	$-0.1 < x_F < 0.05$	full x_F range
σ_{D^0} [μb/nucl]	$21.4 \pm 3.2 \pm 3.6$	$56.3 \pm 8.5 \pm 9.5$
σ_{D^+} [μb/nucl]	$11.5 \pm 1.7 \pm 2.2$	$30.2 \pm 4.5 \pm 5.8$
$\sigma_{D^{*+}}$ [μb/nucl]	$10.0 \pm 1.9 \pm 1.4$	$27.8 \pm 5.2 \pm 3.9$
Ratio $\sigma_{D^+}/\sigma_{D^0}$		$0.54 \pm 0.11 \pm 0.14$
Ratio $\sigma_{D^{*+}}/\sigma_{D^0}$		$0.49 \pm 0.12 \pm 0.10$

Open charm production: models

D^0



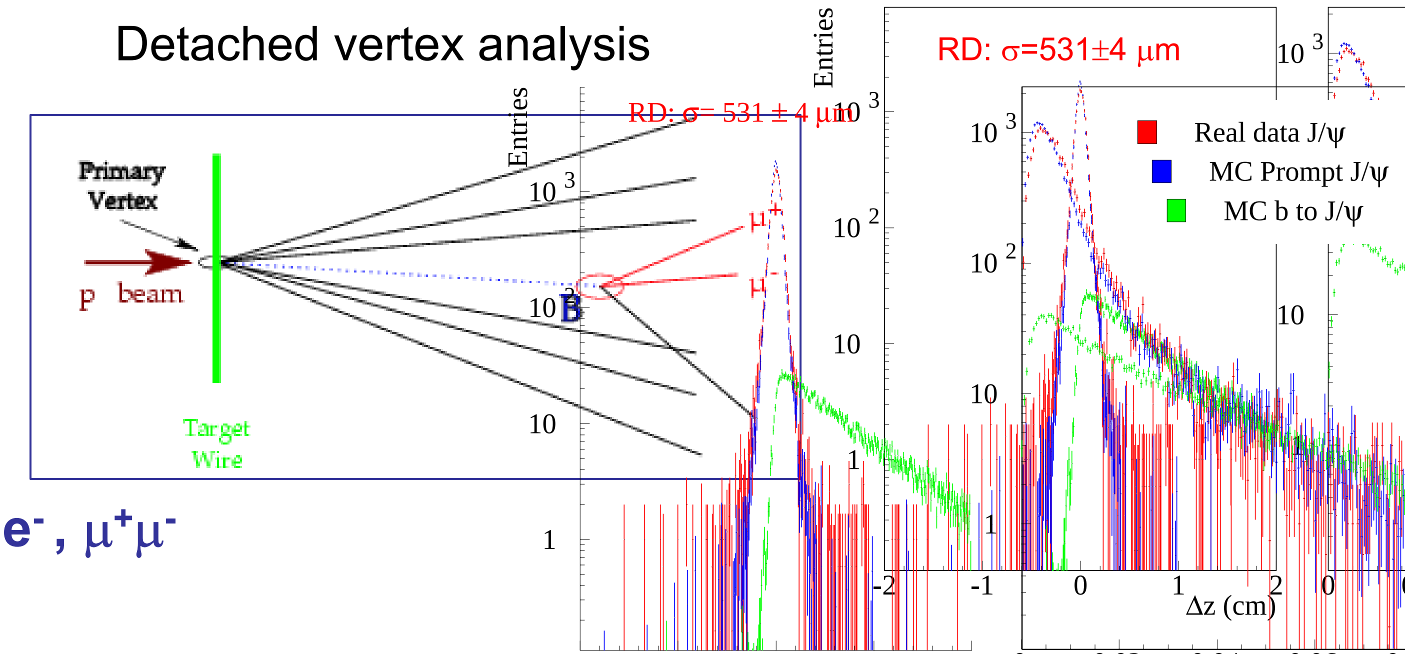
$D^\pm$



Pythia requires K-factors ~1.5 and ~ 4.5 to describe D^0 and D^+ data if m_c=1.5 GeV
Smaller m_c require smaller K factors but predict smaller increase of σ at higher E

Beauty Production

Detached vertex analysis



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

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

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

$pA \rightarrow Y(ns) + X$

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

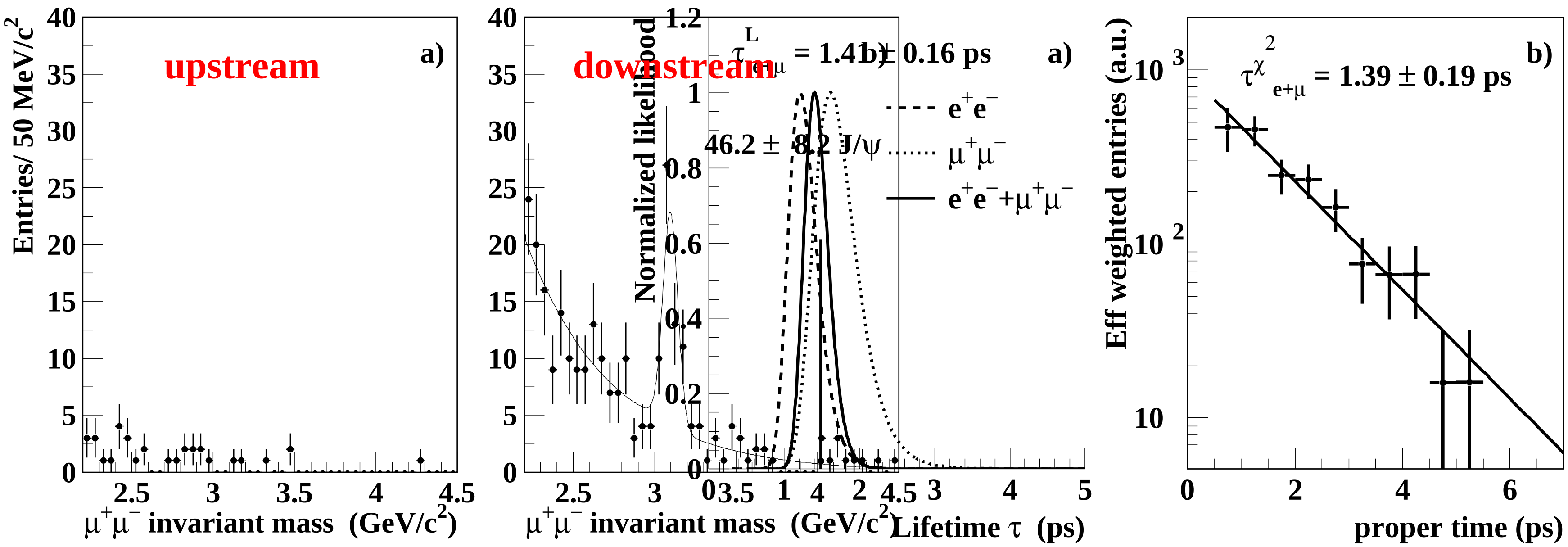
Cross sections normalised to prompt J/ψ

HERA-B used E771/E789 data:

$\sigma(pN \rightarrow J/\psi\ X) = (357 \pm 8 \pm 27)$ nb/nucleon

(with $\alpha = 0.955 \pm 0.005$ and energy rescaling)

Open beauty production



Analysis of 2002/03 data:

- Full e^+e^- and $\mu+\mu-$ statistics
- Carbon + Tungsten targets
- J/ψ acceptance: $-0.35 < x_F < 0.15$
  (90% of bb cross section)

Open beauty production

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

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

Preliminary results with full statistics

$\sigma_{bb}/\sigma_{J/\psi}$ = 0.033 ± 0.005 ± 0.004

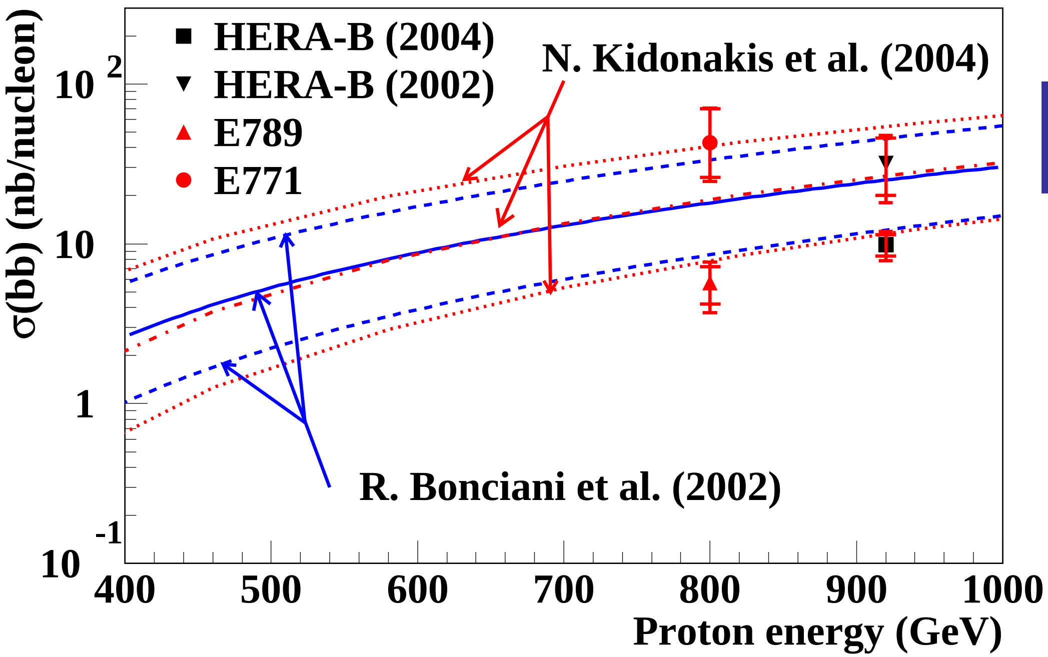
Syst. error mainly from B(b→J/ψ)

■

Beauty Production Cross Section

Normalizing to $\sigma_{J/\psi}$ from E771 and E789

$\sigma(pN \rightarrow J/\psi\ X) = (357 \pm 8 \pm 27)$ nb/nucleon



$\sigma_{bb} = 9.9 \pm 1.5 \pm 1.4$ nb/nucleon

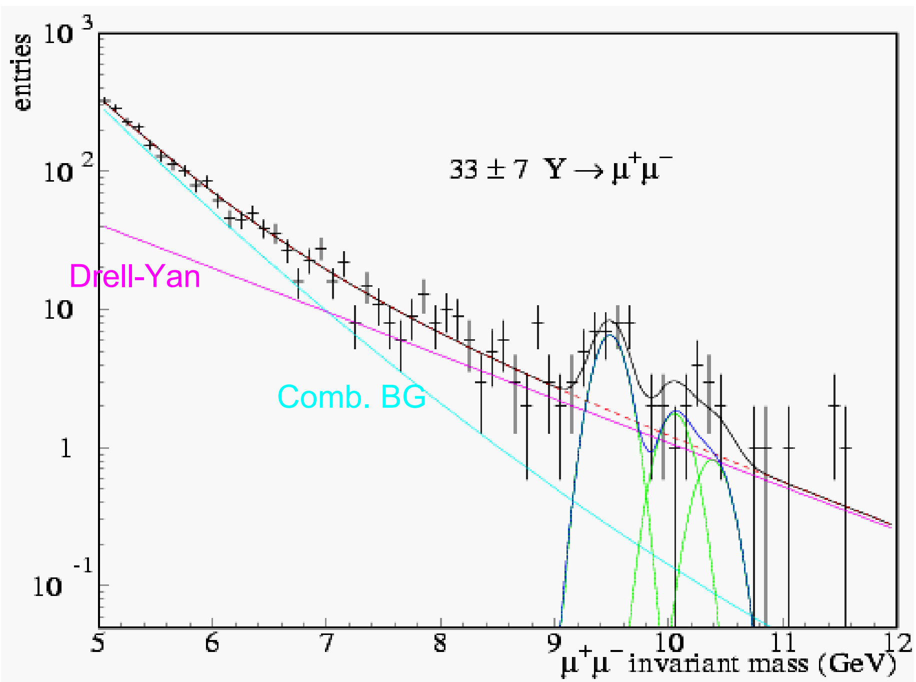
(preliminary, normalized to FNAL data)

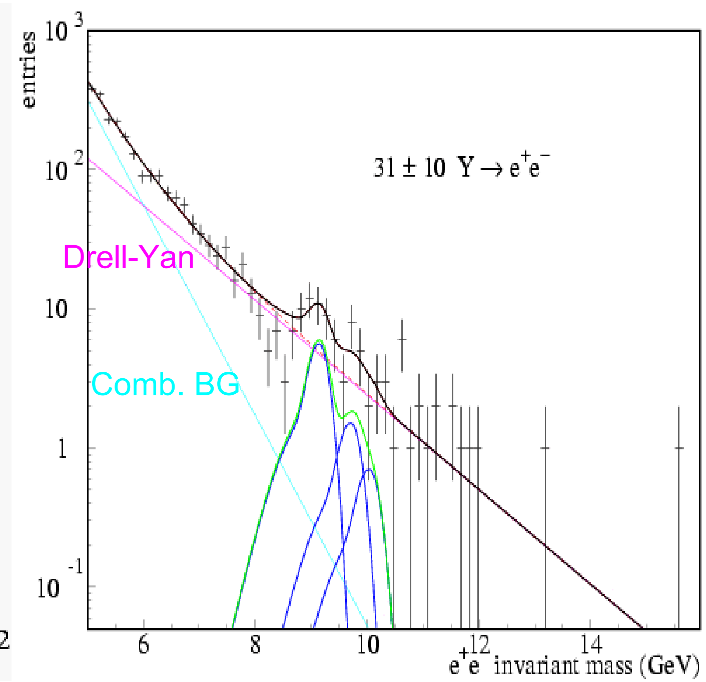
will change with HERA-B minbias data

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

Hidden beauty production

$$\sigma_{\Upsilon} = \sigma_{J/\psi} \cdot \frac{n_{\Upsilon}}{n_{J/\psi}} \cdot \frac{Br(J/\Psi \to l^+l^-)}{Br(\Upsilon \to l^+l^-)} \cdot \frac{\varepsilon^{J/\psi}}{\varepsilon^{\Upsilon}}$$





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

M(e^+e^-) (GeV/c^2)

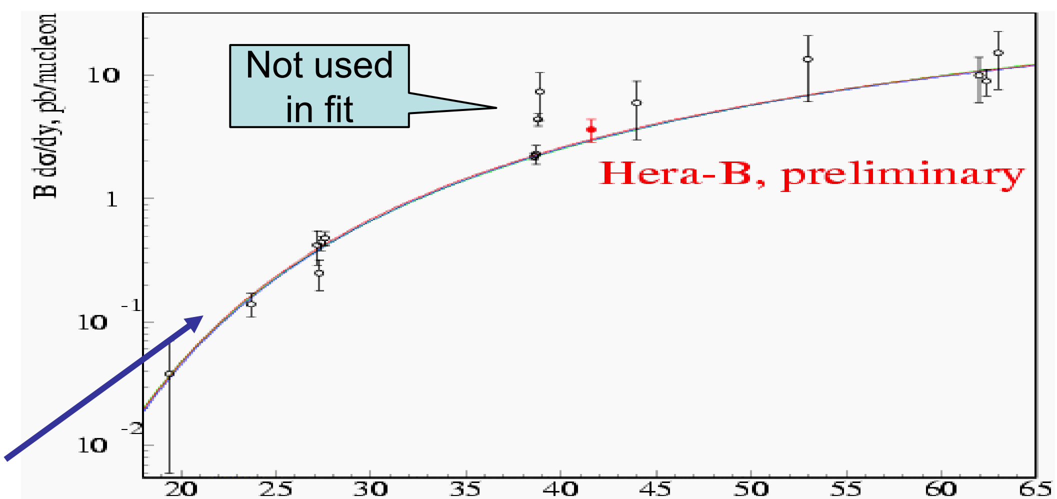
Hidden beauty production

	Events	Br• dσ/dy $\vert_{y=0}$
$\mu^+\mu^-$	33±7	3.9±1.1 pb/N
e^+e^-	31±10	2.9±1.2 pb/N
both		3.4±0.8 pb/N

Normalized to FNAL prompt J/ψ

- All C and W data used (150 M evts)
- Modified Craigie applied to allow for nuclear suppression: α=0.99±0.05

$$Br \times \frac{d\sigma_{\Upsilon}}{dy}\bigg|_{y=0} (\sqrt{s}) = \sigma_o \exp\left(-\frac{m_o}{\sqrt{s}}\right) \cdot A^{\alpha-1}$$



√s (GeV)

Summary

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

Preliminary results are presented on:

- J/ψ cross section, x_F and p_T distributions in a new negative x_F range
  J/ψ A dependence shows a flat behavior in this region
- Fraction of χ_c and $\psi(2S)$ yields relative to J/ψ
- D0, D+ and D*+ cross sections and relative yields
- Open and hidden beauty cross sections

Final results on these and other topics are expected until the end of 2005

Main problem: systematic errors must have been underestimated by some or all experiments