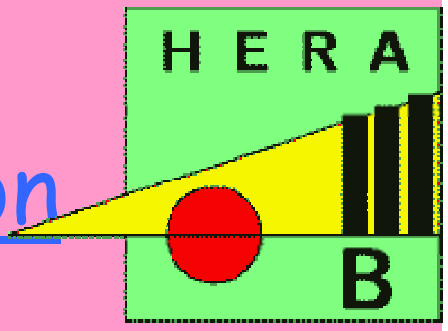
Charm, beauty and charmonium production at HERA-B



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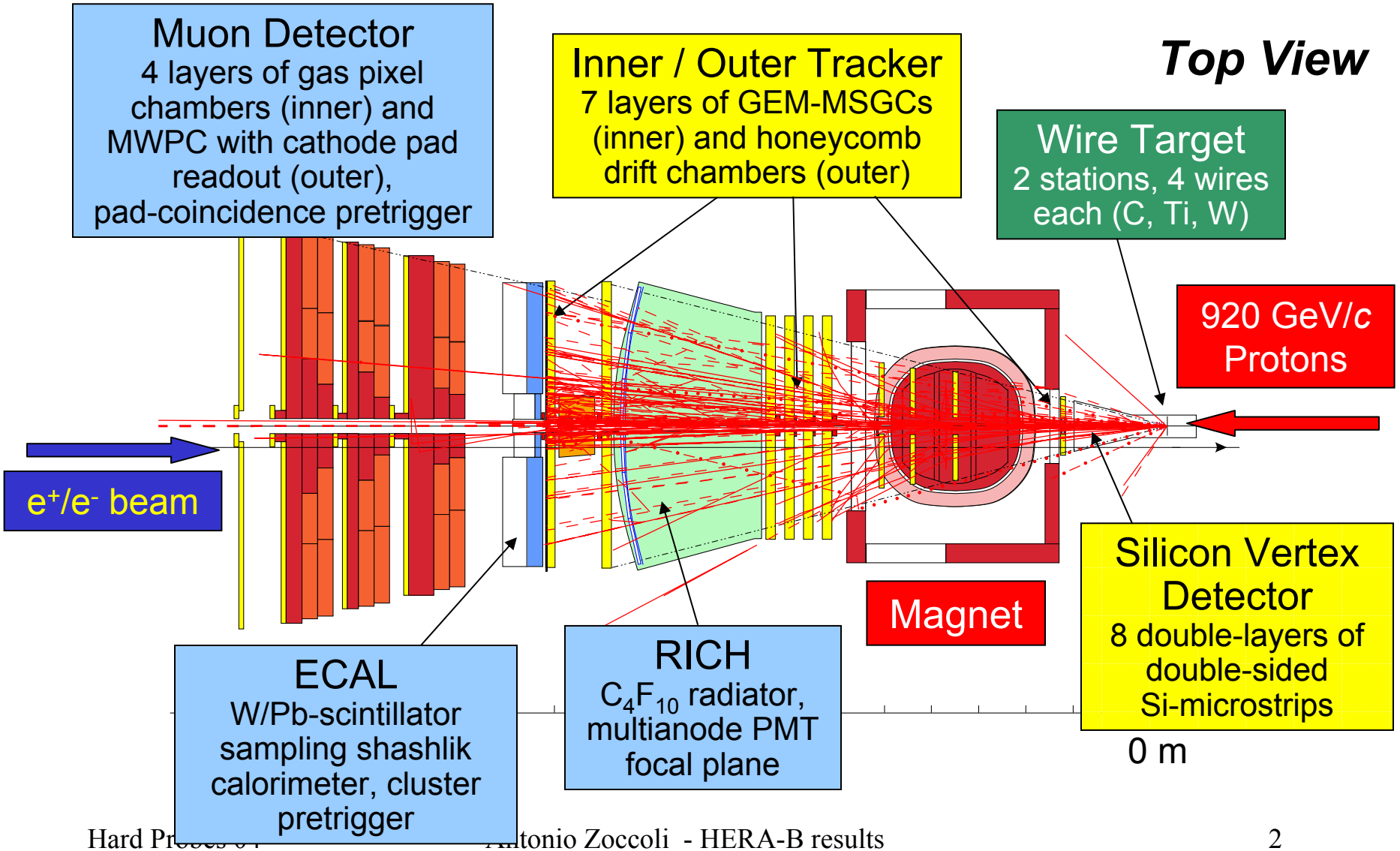
For the HERA-B Collaboration

Outline:

- Detector & trigger
- Data sample
- Results from the 2002/3 run:
  - charmonium production
  - open charm
  - beauty production
- Summary

Hard Probes 2004
Ericeira, Portugal
November 5th, 2004

The HERA-B Detector



The HERA-B detector

- p-Nucleus interactions at 920 GeV → $\sqrt{S}$=41.6 GeV
- BX crossing rate: 10 MHz → Up to $4 \cdot 10^7$ interactions/s (~5ev/bx)

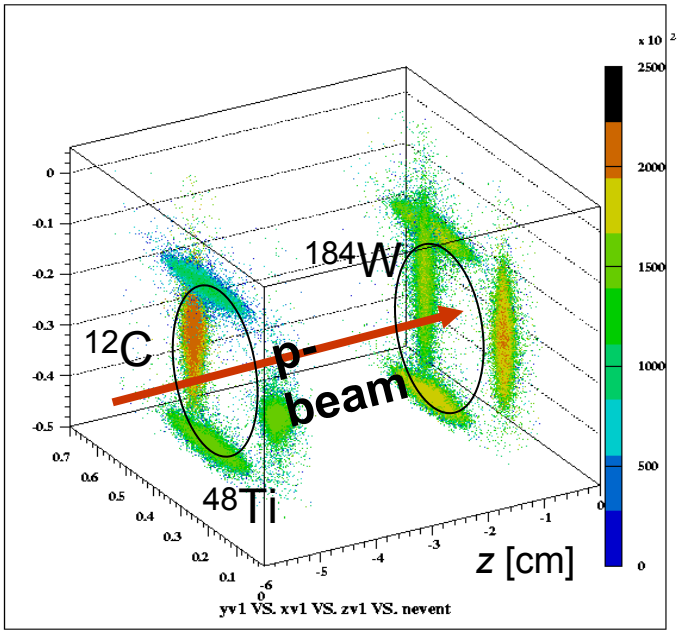
→ Very sophisticated and challenging detector.

- Large central acceptance ($5 > \eta_{lab} > 2$)
- Capability to reconstruct the full event
- Very good particle ID for (e, μ, π, K, p)
- High resolution vertexing
- Target: 8 wires in the p-beam halo
  5 materials: C, Ti, Al, Pd, W

→ Double wire configuration for A-Dependence Measurements: C+W

- Online event reconstruction
- Very selective multilevel trigger

(hardware + software) J/ψ → μμ/ee



→ Suitable for P-Nucleus interaction studies

Trigger & DAQ System

Multilevel trigger scheme based on Kalman filter.

5 (10) MHz
(<12 μs)

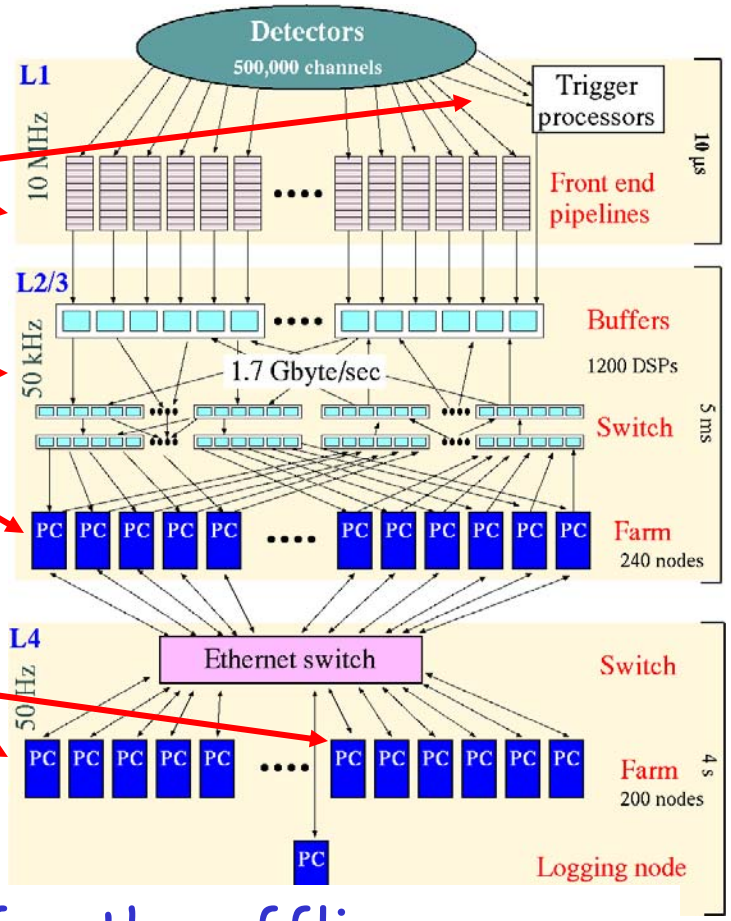
20 KHz
(5-10 ms)

100 Hz
(~1s)

Pretrigger/Level 1
(rejection ~250)

Level 2
(rejection. ~200)

Full online reconstruction
and logging to tape

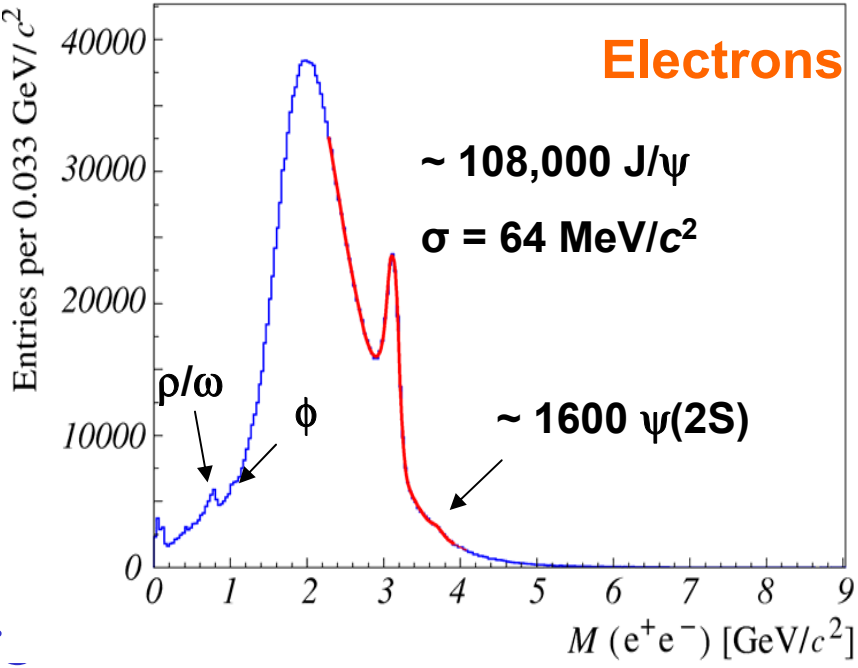


Two PC-Linux farms used in L2 and for the offline reconstruction.

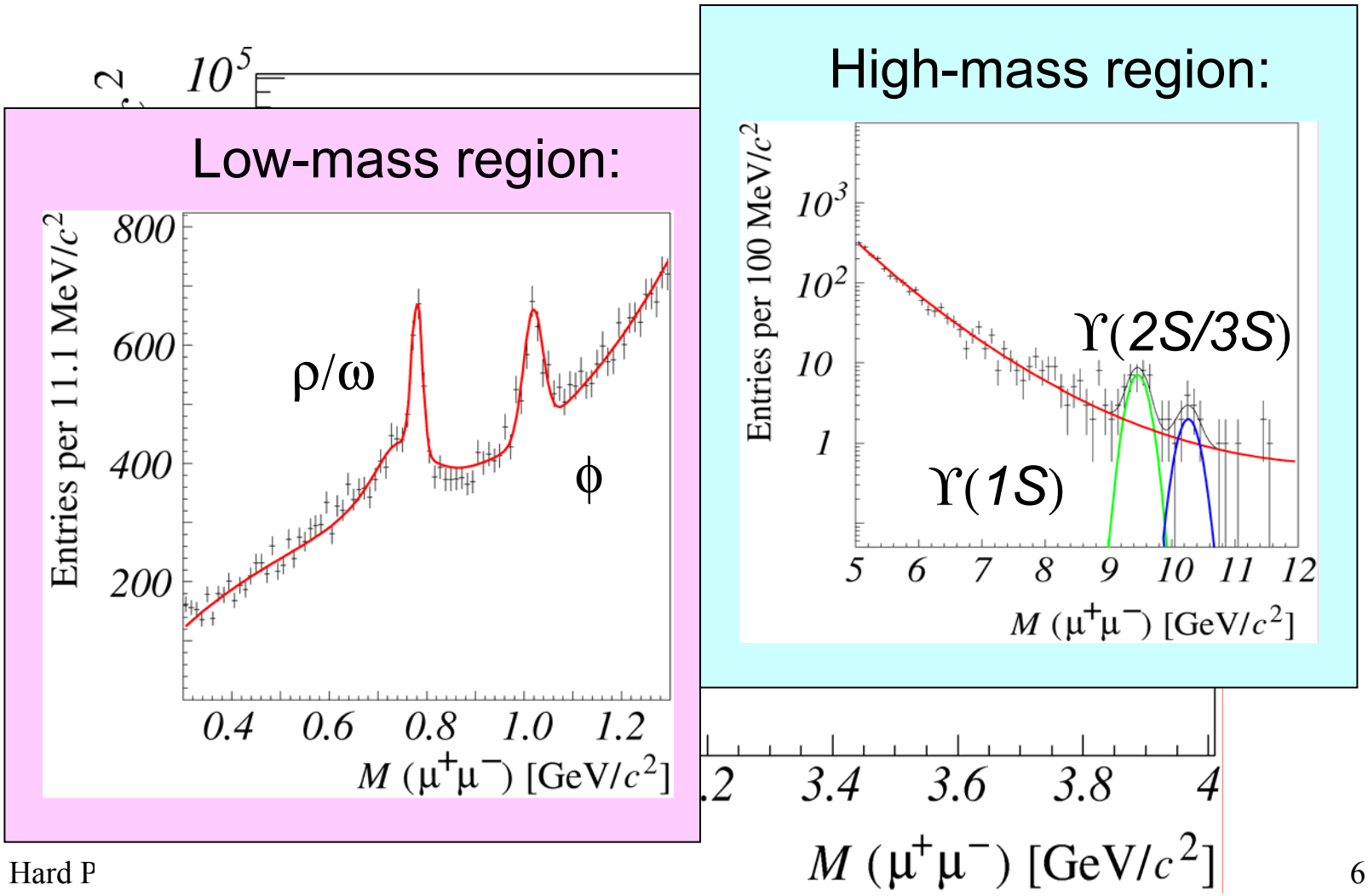
Relevant data samples

Data taking finished in 2003. Analysis in progress

- 150 M di-lepton trigger events ($e^+e^-/\mu^+\mu^-$ triggers)
  - 300 000 J/ψ (>1000 per hour)
  - 15 000 $\chi_{c1}+\chi_{c2}$
  - 5 000 ψ(2S)
- 210 M minimum bias events
  → 1000 ev/s >1TB/day
- 35 M hard photon events
- 60 M "glueball" trigger event



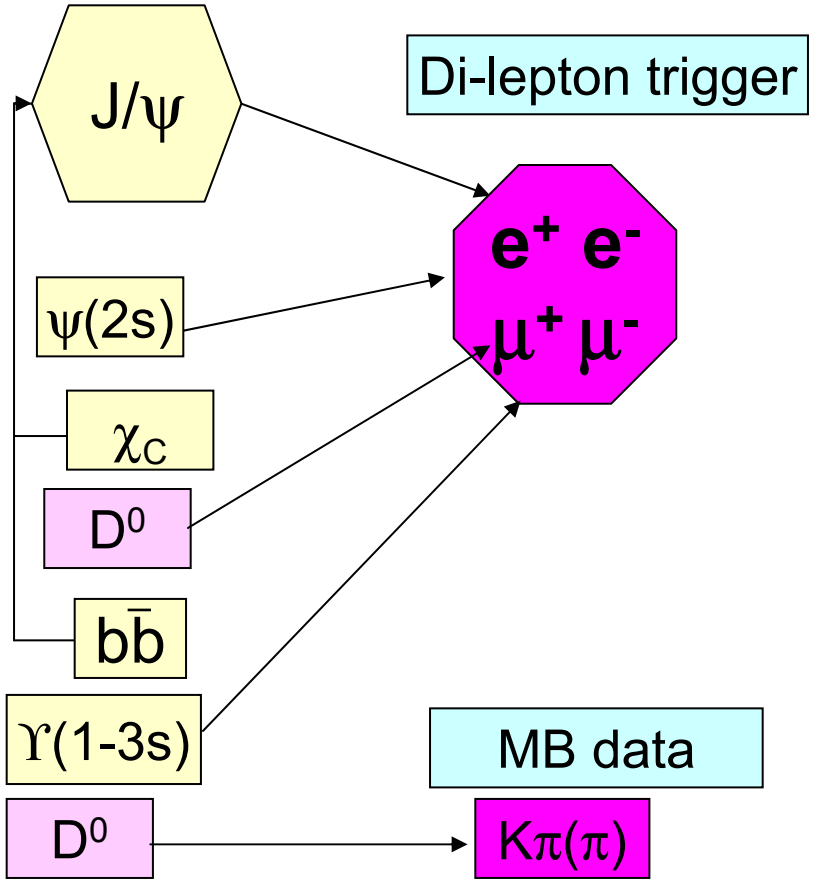
Dilepton spectrum: Muon Channel



Physics topics

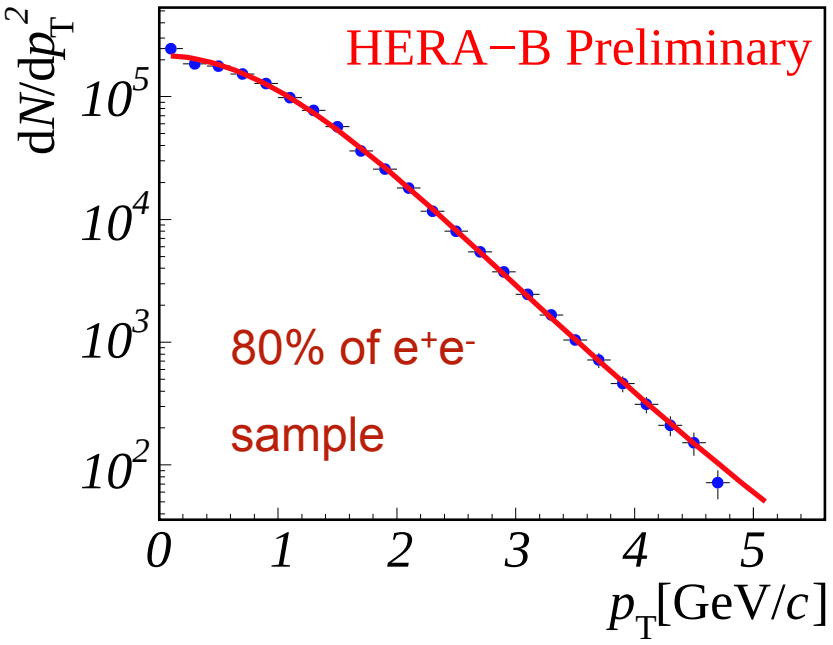
Topics covered in this presentation:

1) J/ψ: p_T distribution
   J/ψ: x_F distribution
   J/ψ: A-dependence
2) ψ(2s) production
3) χ_c/J/ψ production ratio
4) FCNC $D^0 \rightarrow \mu\mu$ Br limit
5) bb cross section
6) ϒ production
7) Open charm production



Disclaimer: All results are preliminary

J/ψ Differential Distribution: p_T



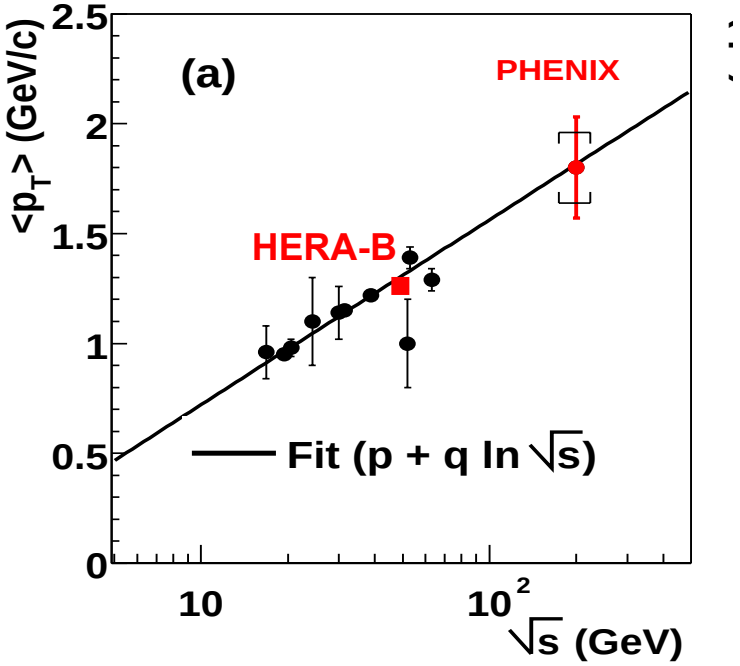
➢Parametrisation:

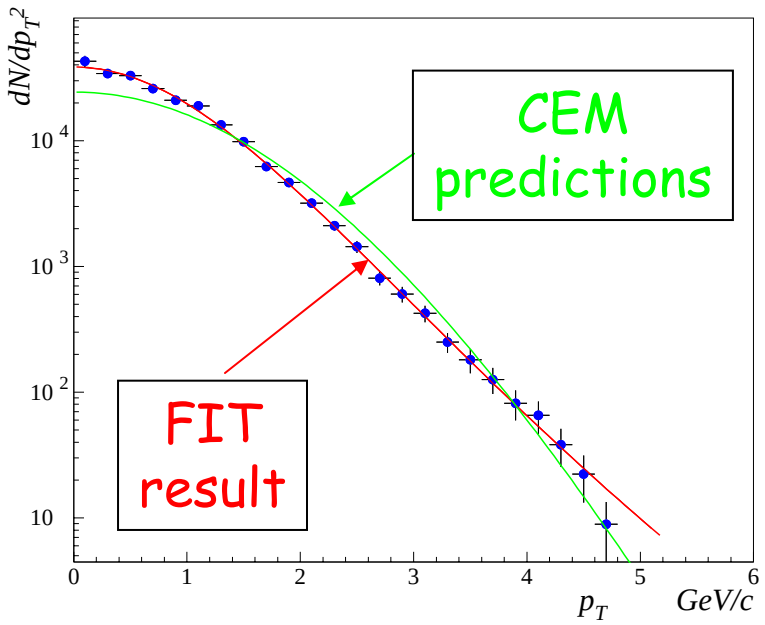
$$\frac{d\sigma}{dp_T^2} = A \cdot \left[1 + \left(\frac{35 \cdot \pi \cdot p_T}{256 \cdot \langle p_T \rangle}\right)^2\right]^{-6}$$

➢Broad p_T coverage, good agreement between electron and muon channels

Target	Experiment	p_T Range [GeV/c]	$\langle p_T \rangle$[GeV/c] e^+e^-	$\langle p_T \rangle$[GeV/c] $\mu^+\mu^-$
C, 920 GeV	HERA-B Preliminary	< 4.8	1.22 ± 0.01	1.22 ± 0.01
W, 920 GeV	HERA-B Preliminary	< 4.8	1.29 ± 0.01	1.30 ± 0.01
Si, 800 GeV	E771	< 3.5		1.20 ± 0.01
Au, 800 GeV	E789	< 2.6		1.290 ± 0.009

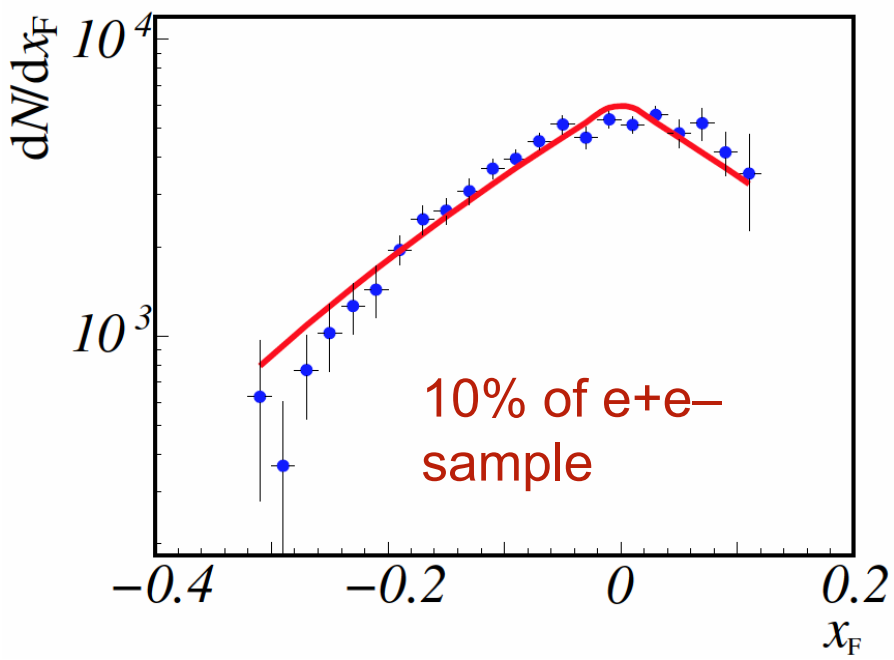
J/ψ Differential Distribution: p_T





- Good agreement with the general energy scaling
- Possible comparison with model predictions (e.g. curve based on CEM by R. Vogt)

J/ψ Differential distribution: x_F



- Large acceptance for negative x_F (fractional longitudinal momentum)
- Usual parametrization:

$$\frac{d\sigma}{dx_F} = A \cdot (1 - |x_F|)^C$$

- Work on systematics and theory function (?)

Target	Experiment	x_F Range	C
C, W, 920 GeV	HERA-B Preliminary	$-0.35 < x_F < 0.15$	$(5-6.5) \pm 0.3$
Si, 800 GeV	E771	$-0.05 < x_F < 0.25$	6.54 ± 0.23
Au, 800 GeV	E789	$-0.03 < x_F < 0.13$	4.91 ± 0.18
Cu, 800 GeV	E789	$0.30 < x_F < 0.95$	5.21 ± 0.04

J/ψ *A*-Dependence

- Test of charmonium production models in nuclear matter (nonrelativistic QCD + initial/final state interactions in nucleus)
- Parametrization: $\sigma_{pA} = \sigma_{pN} \cdot A^{\alpha}; \quad \sigma = N / \varepsilon L$
  - $\alpha < 1$: charmonium suppression by nuclear effects
  - HERA-B: extract α from runs with two target wires simultaneously (carbon: A=12, tungsten: A=184)

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

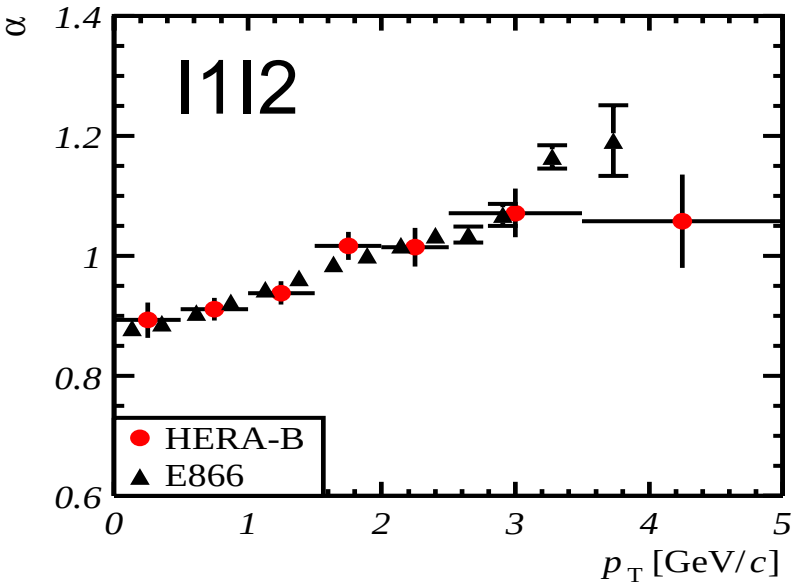
- 3 ingredients of *A*-dependence measurement:

I. Ratio of J/ψ yields: fits to invariant mass spectra

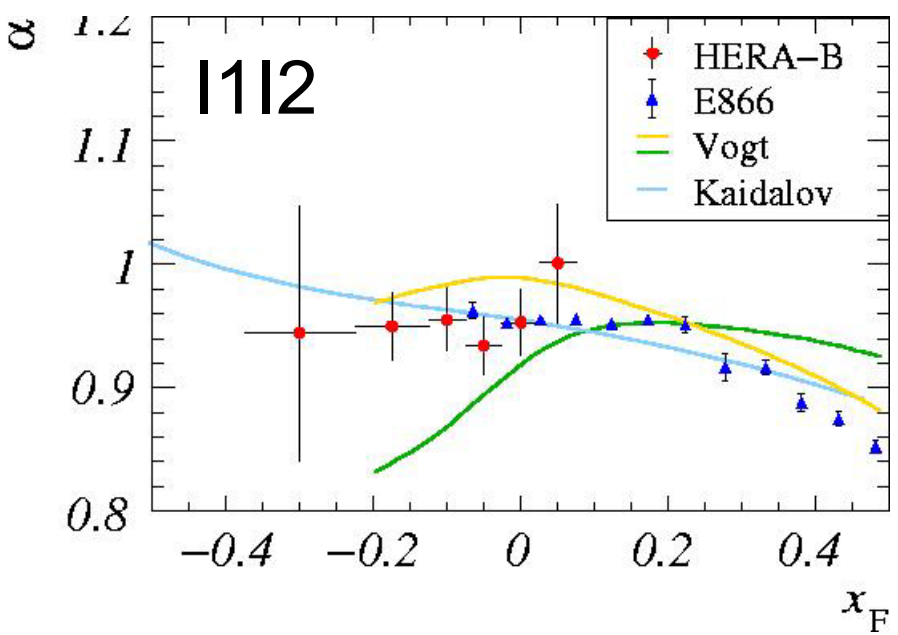
II. Ratio of luminosities: intercalibration of target wires

III. Ratio of efficiencies: detailed detector/trigger simulation

J/ψ A dependence



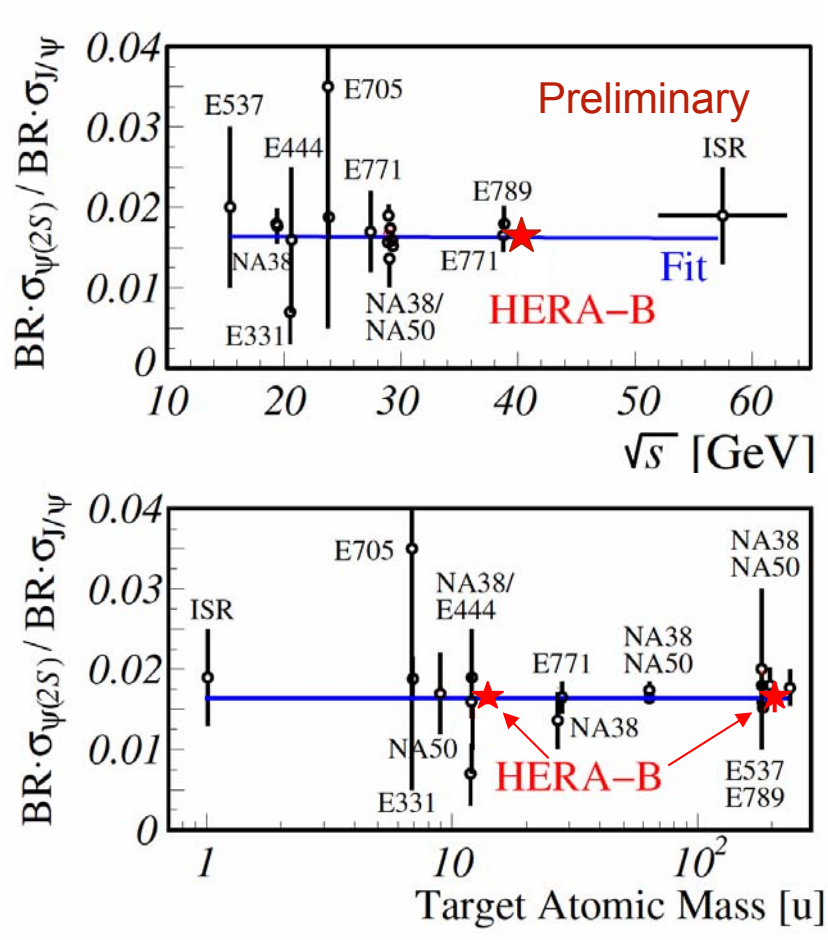
Preliminary



- Previous result of FNAL E866 extended to x_F = -0.35
- Result from 15% of full $\mu^+\mu^-$ sample, statistical uncertainties only, similar results for e^+e^-
- Work on systematics ongoing. Complete the analysis on the full data sample.

ψ(2S) Production

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



- Measure ψ(2S) cross section relative to J/ψ
  →reduce systematic uncertainties

  $\varepsilon_{J/\psi}/\varepsilon_{\psi(2S)}$ ~ 0.7-0.8 (MC)
- Preliminary results for

$$\frac{\mathrm{Br'}\cdot\sigma(\psi')}{\mathrm{Br}\cdot\sigma(J/\psi)}\ [\%]$$

Target	electron	muon
C	1.6 ± 0.2	1.65 ± 0.1
W	1.8 ± 0.4	1.55 ± 0.2

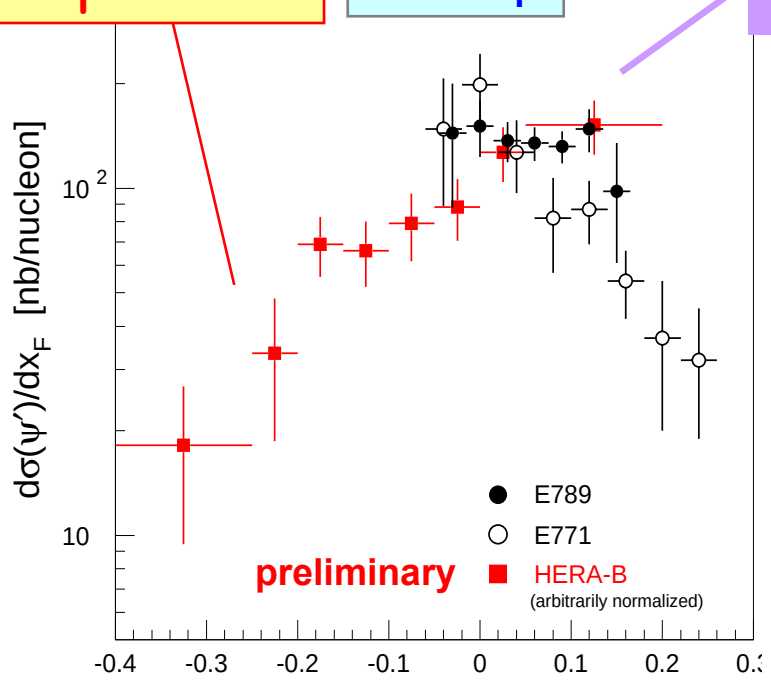
ψ(2S) differential distributions

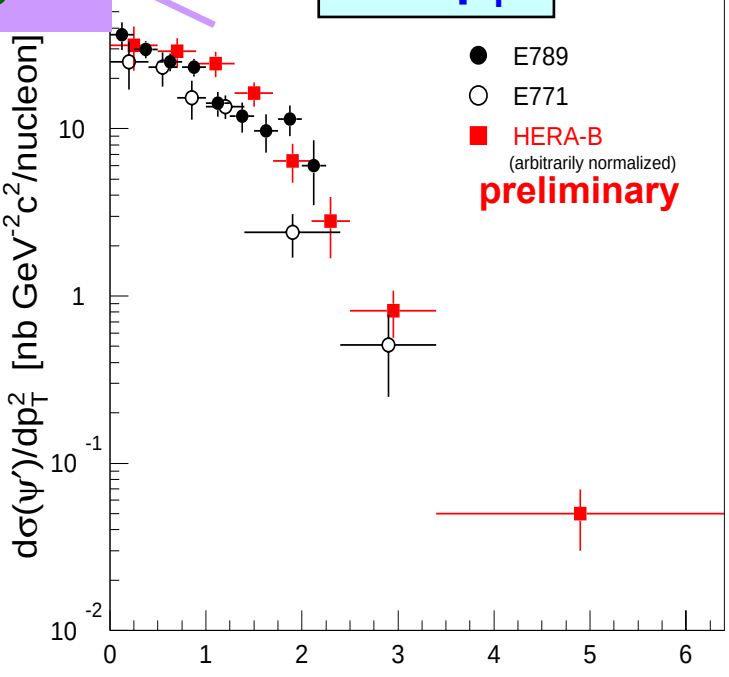
$x_F < 0$

$d\sigma/dx_F$

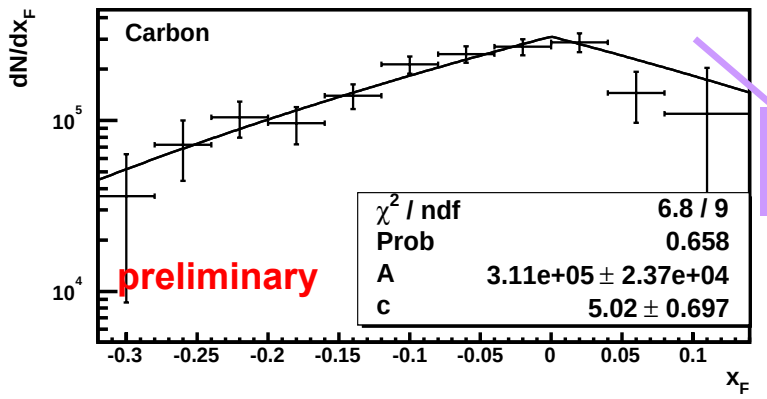
e^+e^-

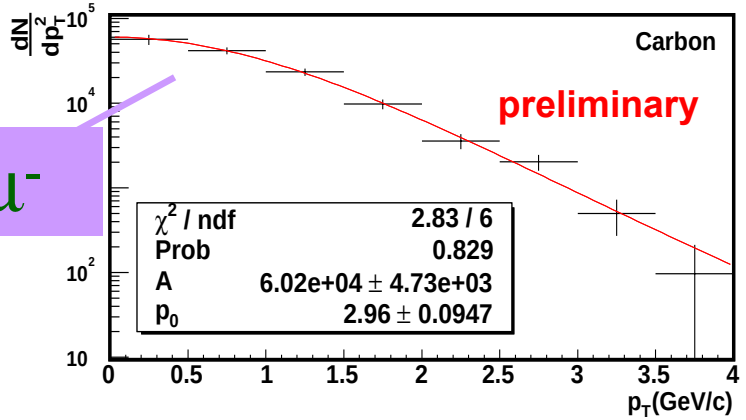
$d\sigma/dp_T^2$





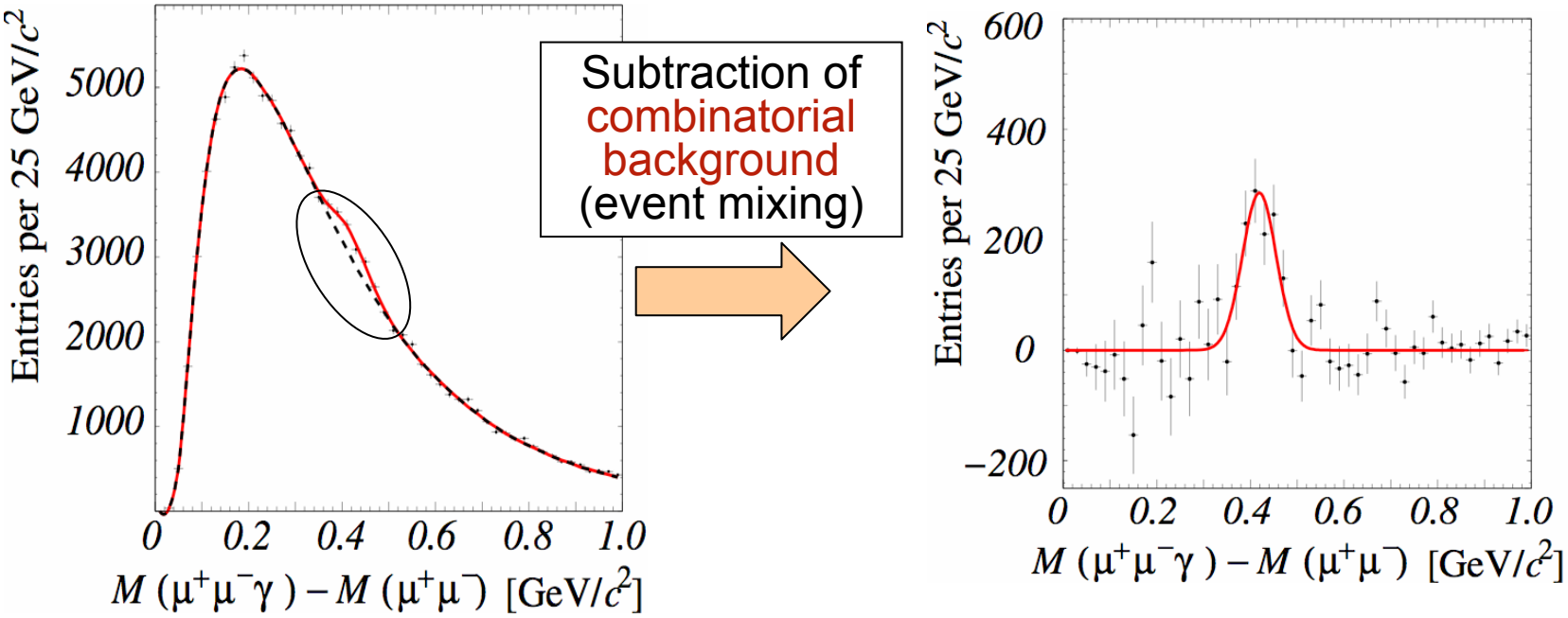
$\mu^+\mu^-$





χ_c Production

- Test of charmonium production models: fraction $R(\chi_c)$ of J/ψ from radiative decays $\chi_c \rightarrow J/\psi\,\gamma \rightarrow \mu^+\,\mu^-\,\gamma$
- Signal found in mass difference $M(J/\psi\,\gamma) - M(J/\psi)$



Where:

$$R(\chi_c) = \frac{\sum_{i=1}^{2} \sigma_{\chi_{c,i}} \cdot \mathrm{BR}(\chi_{c,i} \rightarrow J/\psi\gamma)}{\sigma_{J/\psi}} = \frac{N_{\chi_c}}{N_{J/\psi}} \cdot \frac{\varepsilon_{J/\psi}}{\varepsilon_{\chi_c}\varepsilon_{\gamma}}$$

χ_c Production - II

Preliminary result (15% of $\mu^+\mu^-$ statistics: 1.300 χ_c):

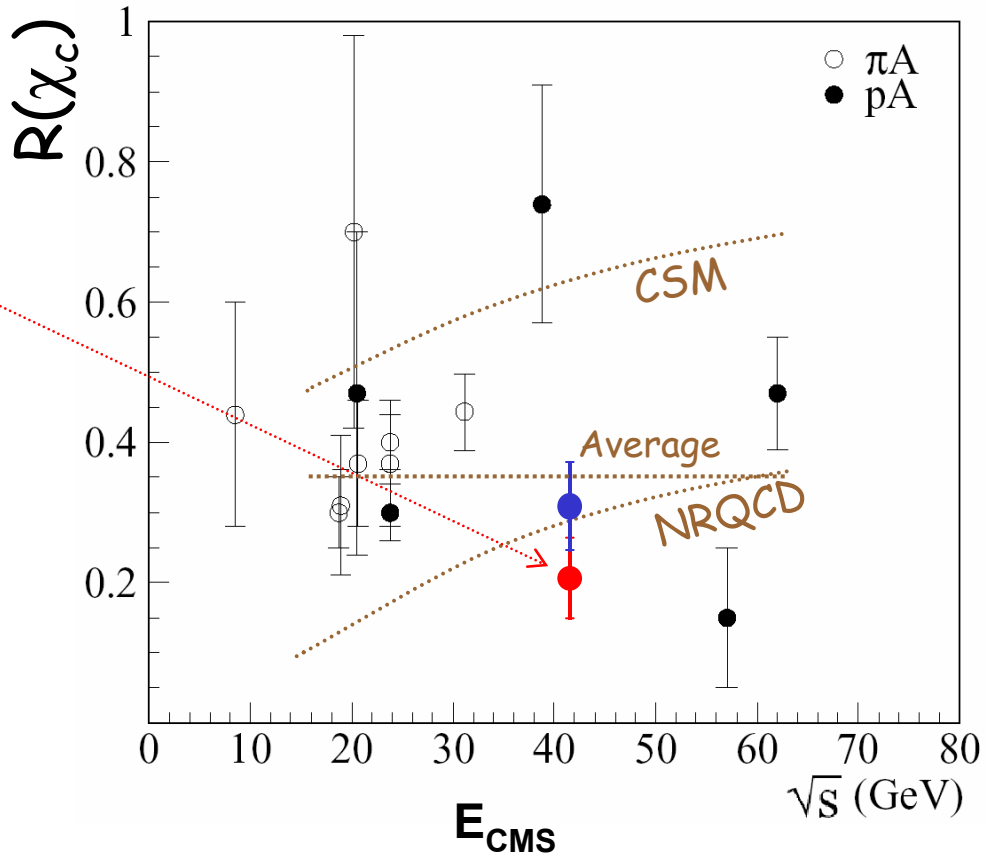
$R(\chi_c)=0.21\pm0.05(stat.)$

Total expected statistics (ee + μμ) ~ 15.000 χ_c .
→ A-Dep. measurement

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

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

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

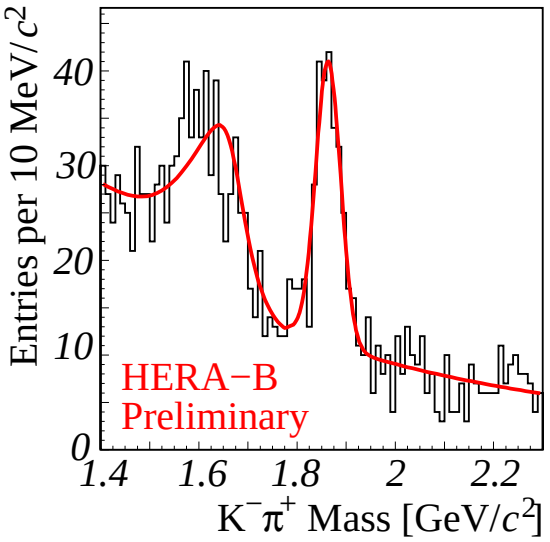


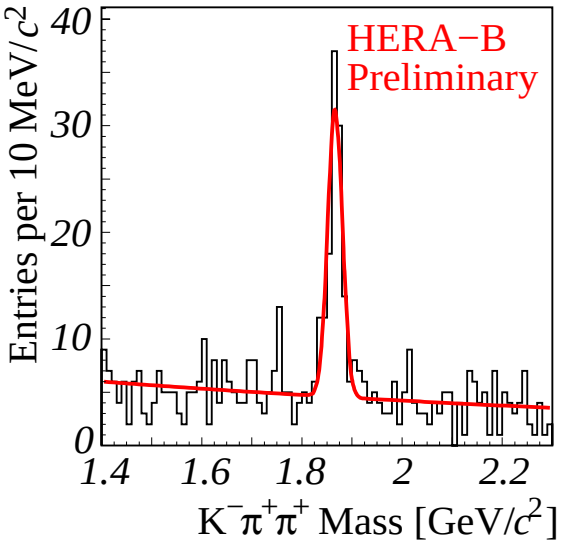
- Results consistent with no E_{CMS} dependency (CEM)
- HERA-B point agrees with NRQCD but NRQCD underestimates R at low Ecms

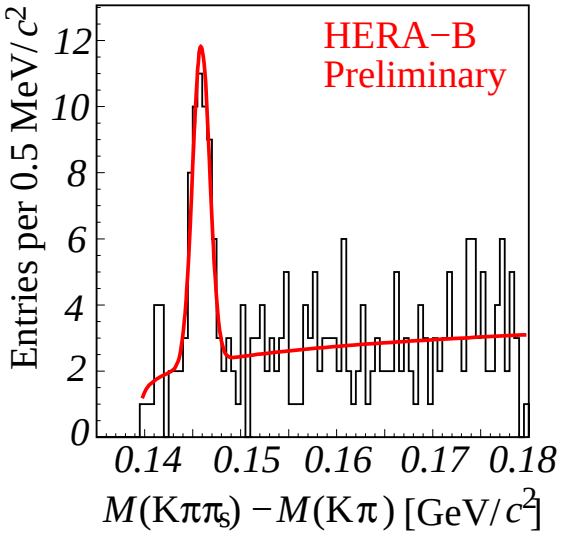
Open charm production

From Minimum Bias data analysis:

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







$N_{D^0} = 189 \pm 20$ $N_{D^+} = 98 \pm 12$ $N_{D^{*+}} = 43 \pm 8$

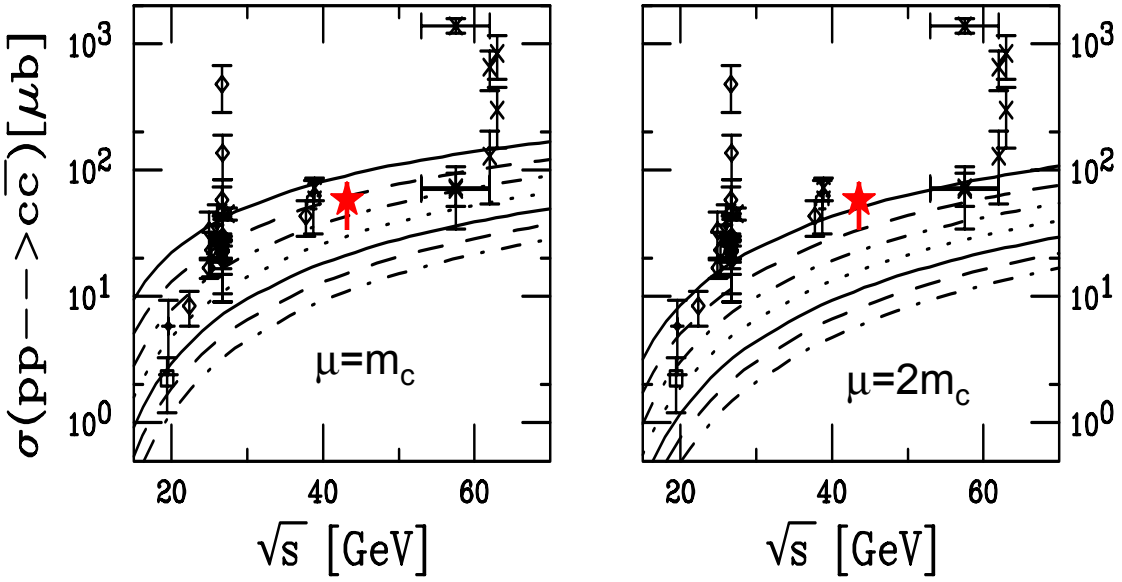
- Production Cross Sections for D^0, D^+, D^{*+}
- Production Ratios D^+/D^0 and D^{*+}/D^0

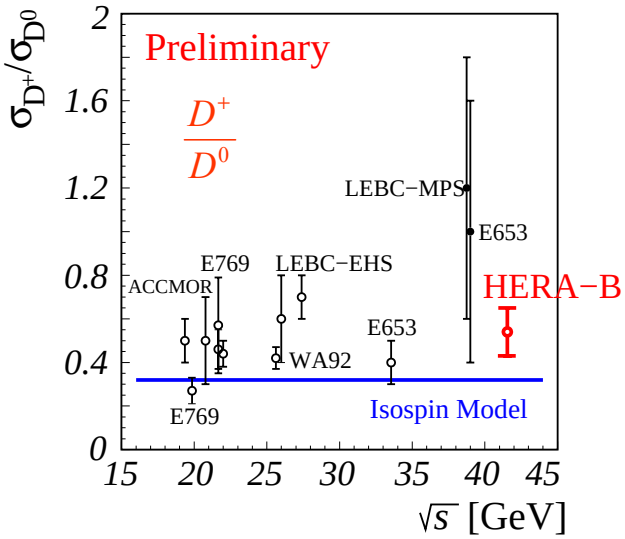
$$\sigma_D = \frac{N_D}{\varepsilon \cdot BR \cdot \sum A_i L_i}$$

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

Open charm production - II

HERA-B: σ Charm = 1.5 σ(D⁰,D⁺)



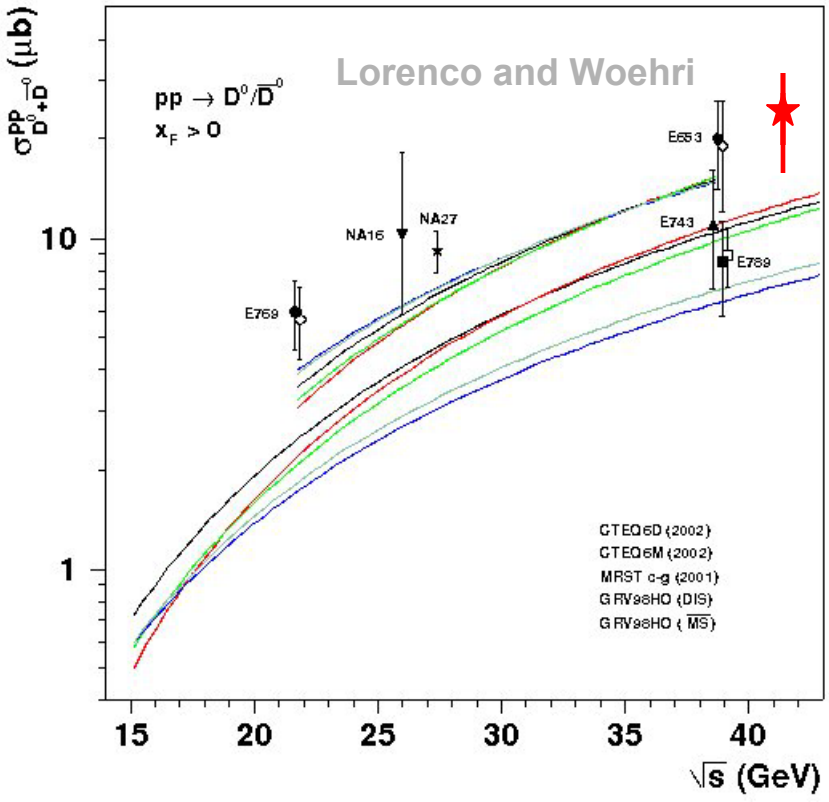


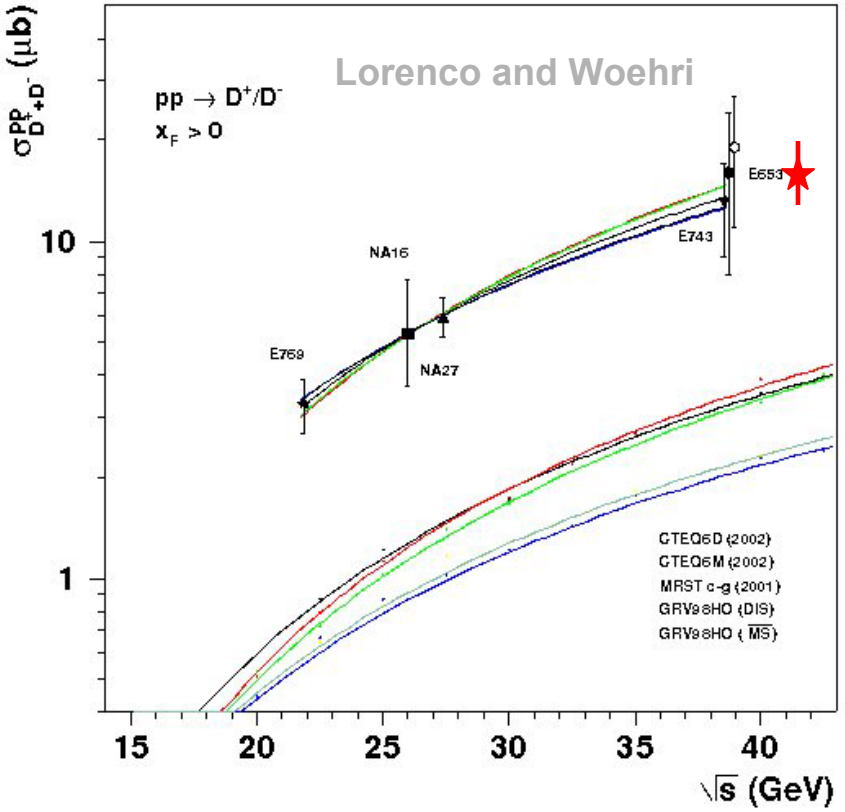
Theoretical curves are NLO from R.Vogt

PYTHIA underestimates D^+/D^0 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 - III

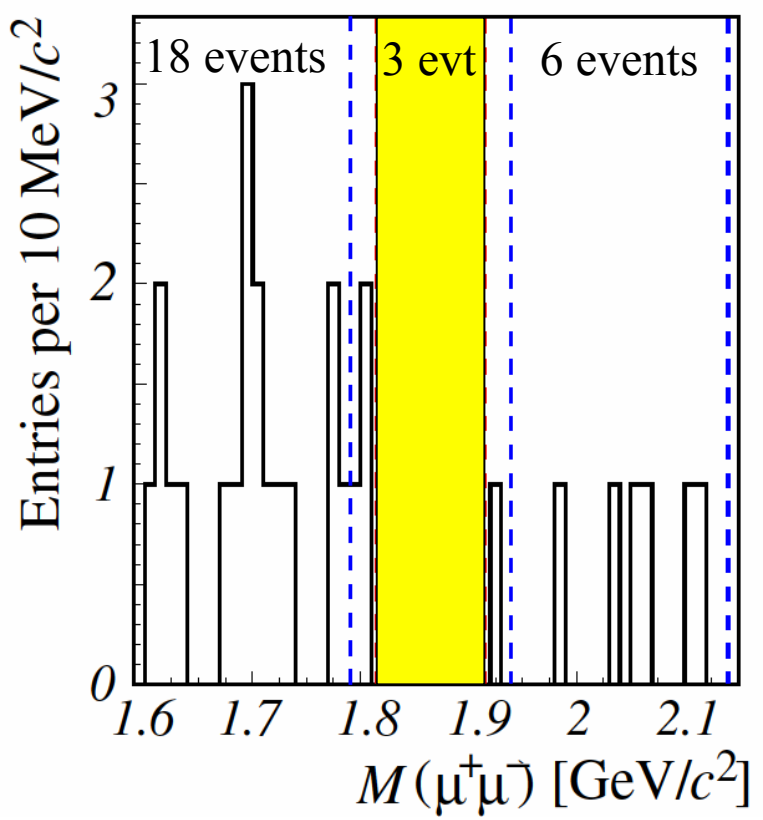


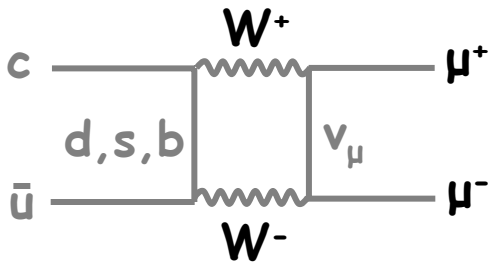


Phythia requires K-factors ~1.5 and ~4.5 to describe D^0 and D^+ data if m_c=1.5 GeV

Smaller m_c require smaller K factors but predict smaller increase of σ at higher E

New Limit on BR($D^0 \to \mu^+\mu^-$)





BR from SM: ~10^{-19}

- Search for flavor-changing neutral current decay $D^0 \to \mu^+\mu^-$ (branching fraction enhanced in some MSSM models ~10^{-7})
- 3 events in signal region:

$BR(D^0 \to \mu^+\mu^-) < 2.0 \times 10^{-6}$ (90% CL)

Phys.Lett.B596:173-183,2004)

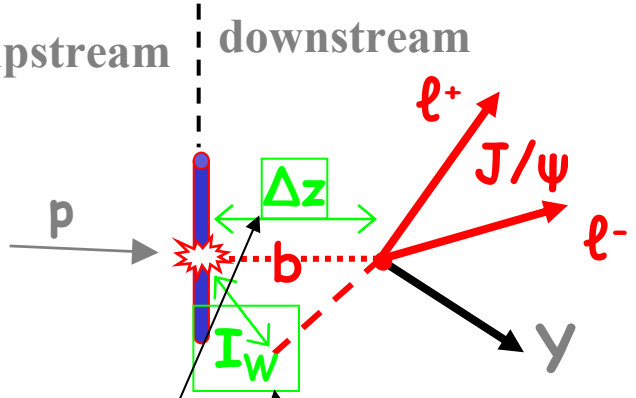
Current limits by :

- CDF: $BR(D^0 \to \mu^+\mu^-) < 2.5 \times 10^{-6}$ (90% CL) Phys. Rev. **D68** (2003) 091101
- BaBar: $BR(D^0 \to \mu^+\mu^-) < 1.3 \times 10^{-6}$ (90% CL) hep-ex/0408023

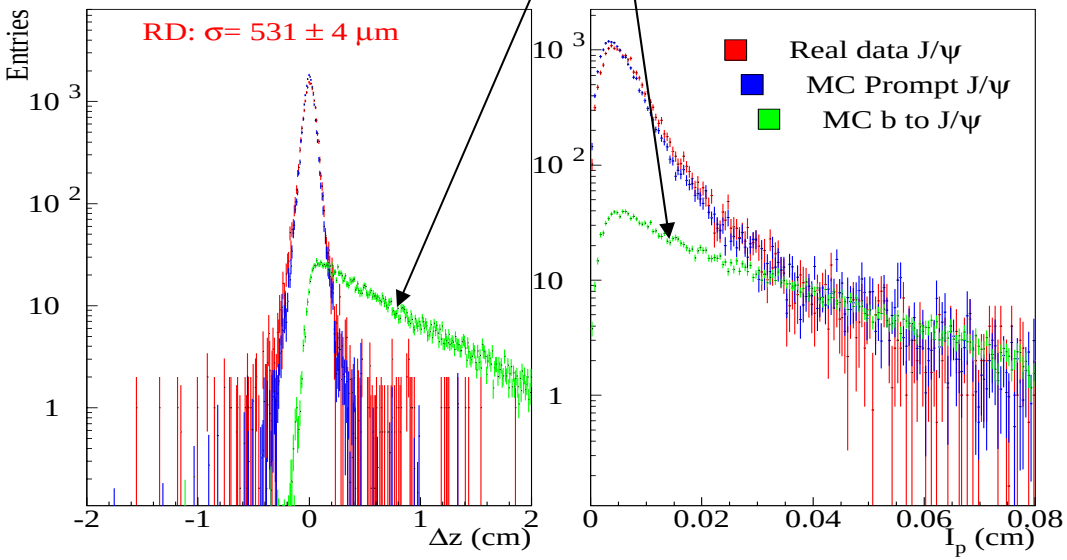
$\sigma(b\bar{b})$: inclusive b production

B Meson has a long life time (~ 9 mm at HERA-B kinematics)
~ 0.5 mm dilepton vertex resolution
J/ψ from a B decay will be detached from primary interaction

$pA \rightarrow b\bar{b}\ X$
$b \rightarrow J/\psi\ Y \rightarrow e^+e^-/\mu^+\mu^-\ Y$



Analysis cuts:
- Decay lenght (Δz)
- Impact parameter



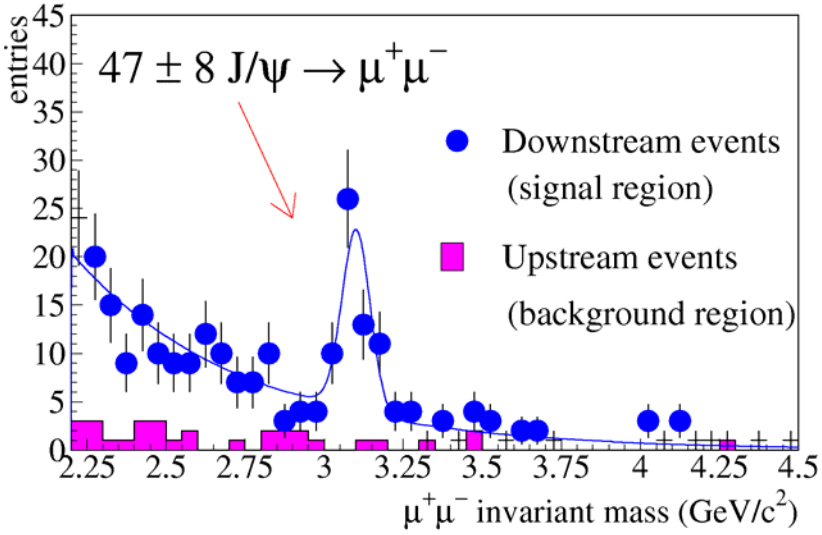
Normalization on the inclusive prompt J/ψ cross section.
→ Systematic error minimization

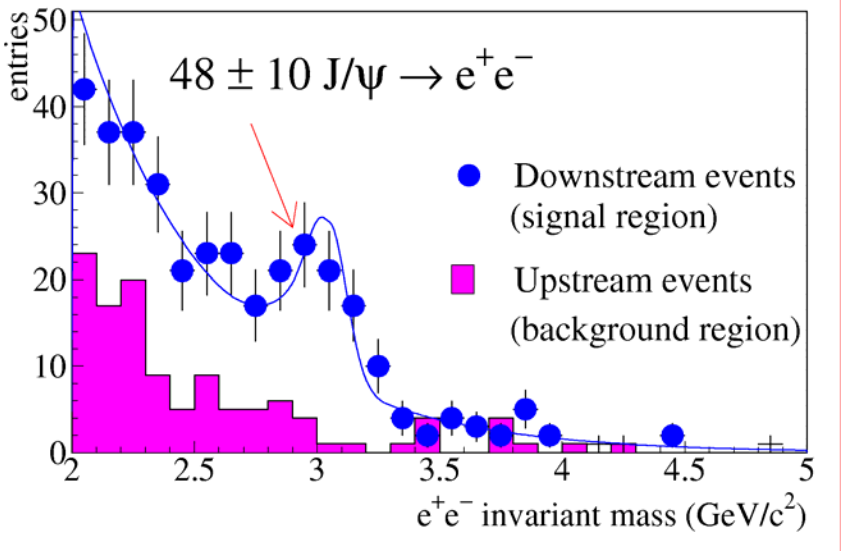
open b production

- C,W,Ti targets
- Full statistics
- Unbinned likelihood fit

$$\frac{\sigma(b\bar{b})}{\sigma(J/\psi)} = 0.027 \pm 0.004 \pm 0.005$$

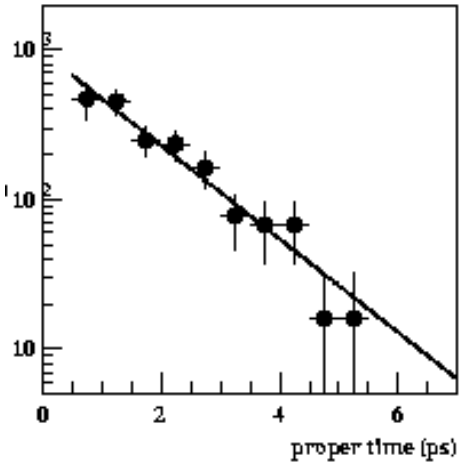
20% sys. error under investigation, main contribution:
Br(bb→J/ψX) = 2.32±0.20%





Lifetime:

τ = (1.41 ± 0.16)ps



Cross section

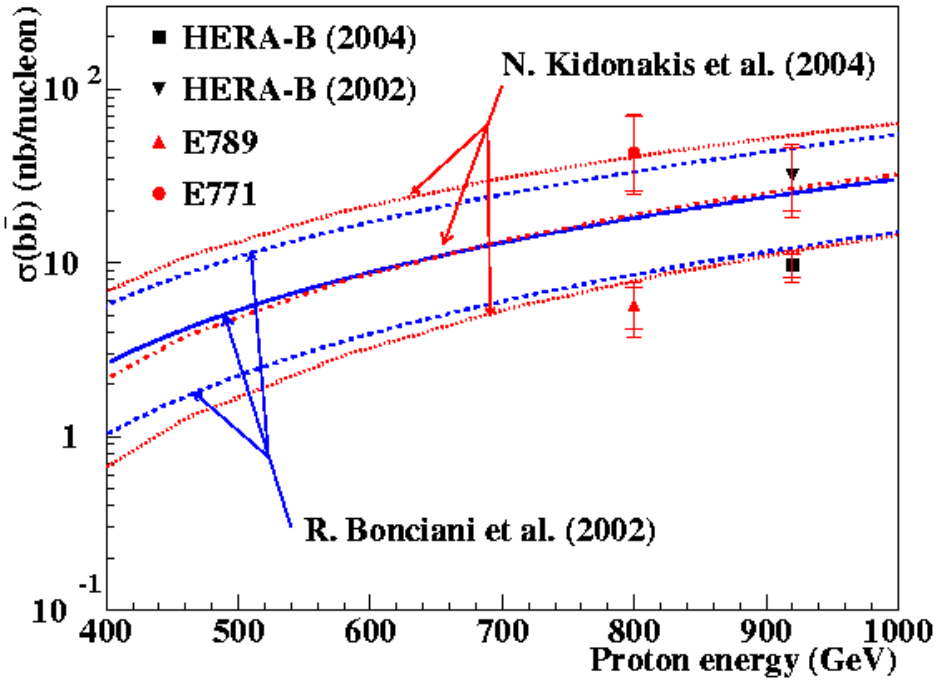
Cross section obtained by using E771/E789 results scaled to 41.6 GeV:
$\sigma(J/\psi)=357 \pm 2 \pm 36$ nb/nucleon

$$\sigma(b\bar{b}) = 9.8 \pm 1.4 \pm 2.0 \text{ nb/nucleon}$$

Previous HERA-B result of year 2000 (~ 10 ev)
[Eur. Phys. J. C26, 345 (2003)]:

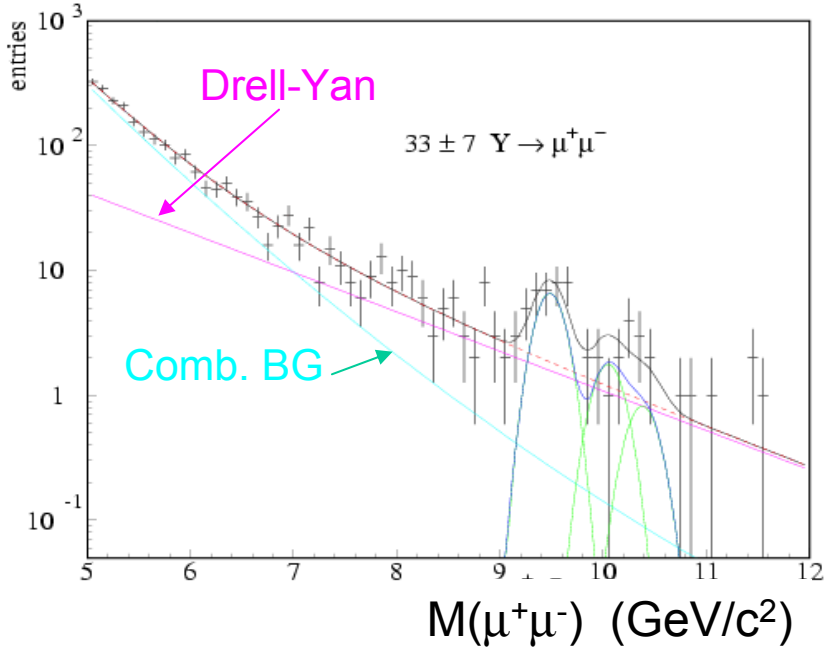
$$s\,(b\bar{b}) = 32^{+14+6}_{-12-7}\ \text{nb/N}$$

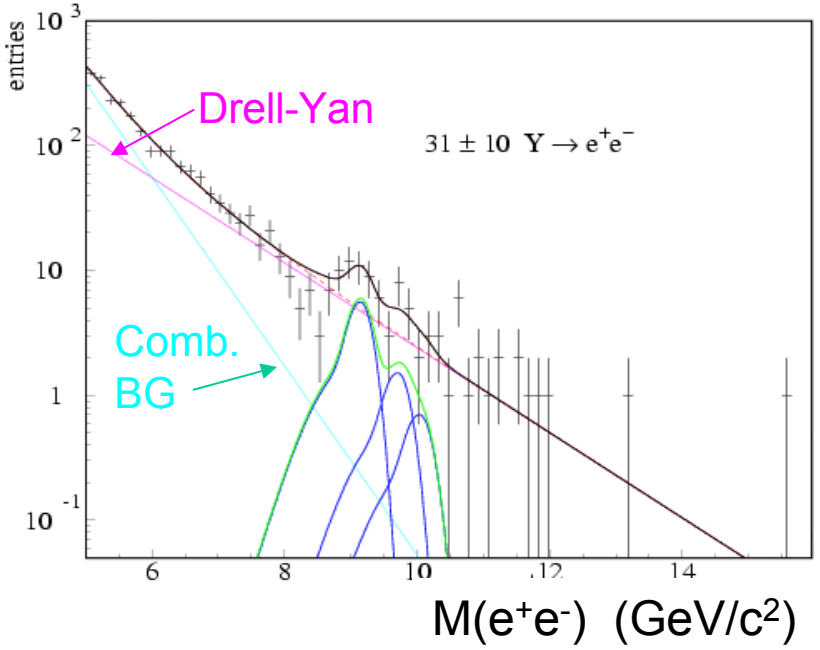
- Theoretical uncertainties:
  - b quark mass 4.5 - 5 GeV
  - At NLO, scale (μ) dependence
- Previous measurements do not agree between each other
- Agreement with the previous HERA-B result (1.5 σ)



Upsilon production

$pN \rightarrow \Upsilon + X,\ \Upsilon \rightarrow \mu^+\mu^-,\ e^+e^-$





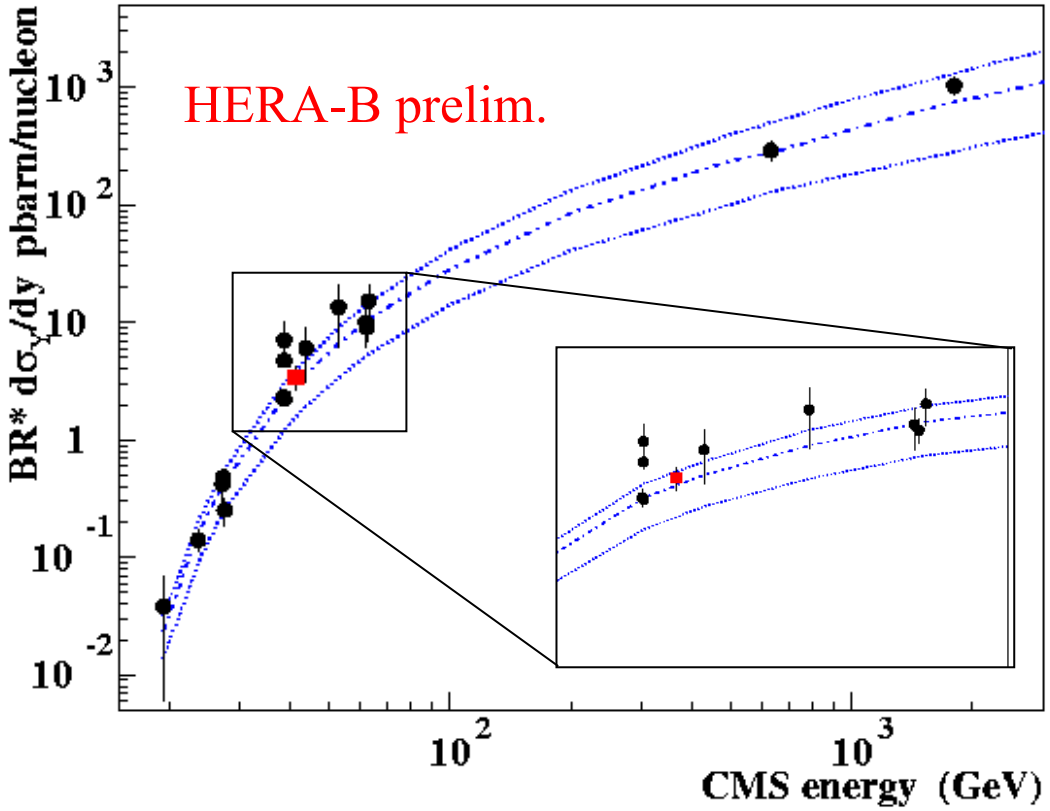
- Relative production of $\Upsilon(1S)/\Upsilon(2S)/\Upsilon(3S)$ fixed on E605 data
- Mass resolution between 140 and 160 MeV/c^2
- Normalization on measured J/ψ or Drell-Yan cross section
- C(75%) + W(25%) targets

Upsilon production - II

Cross section determination:

$$\frac{\sigma(\psi')}{\sigma(J/\psi)} = \frac{N(\psi')}{N(J/\psi)} \times \frac{Br(J/\psi \to l^+l^-)}{Br(\psi' \to l^+l^-)} \times \frac{\varepsilon(J/\psi)}{\varepsilon(\psi')}$$

	$Br \cdot (d\sigma/dy)_{y=0}$
$\mu^+\mu^-$ (33 ± 7)	3.9 ± 1.1 pb/N
e^+e^- (31 ± 10)	2.9 ± 1.2 pb/N
combined	3.4 ± 0.8 pb/N



- Good agreement with CEM predictions (by R. Vogt)
- Results compatible with no nuclear suppression:

$\alpha = 0.99 \pm 0.05$

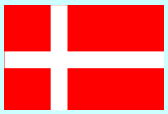
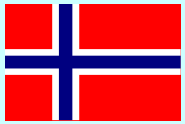
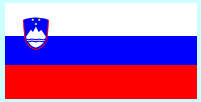
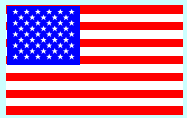
Conclusions

- HERA-B collected 300k J/ψ events on different nuclei
- Preliminary results presented on:
  - J/ ψ cross section, x_F and p_T distributions in a new negative xF range
  - J/ψ A dependence demonstrate a flat behavior in this region
  - Fraction of χ_c and ψ(2S) yields relative to J/ψ
  - D^0, D^+ and D^{*+} cross sections and relative yields
  - Limit on FCNC $D^0 \rightarrow \mu\mu$ decay
  - Open and hidden beauty cross sections
- These results help to constrain theoretical calculations
- Final results on these and other topics are expected in 2005

Backup slides

HERA-B:

13 Nations
30 Institutes
150 physicists

China 	IHEP, Beijing U. Tsinghua
Denmark 	NBI, Copenhagen
Germany 	U. Humboldt, Berlin U. Dortmund DESY MPI Heidelberg U. Heidelberg U. Mannheim MPI Munich U. Rostock U. Siegen DESY Zeuthen
Italy 	INFN, U. Bologna
Netherlands 	U. Utrecht NIKHEF
Norway 	U. Oslo
Portugal 	LIP, U. Coimbra LIP, U. Lisbon
Russia 	ITEP, Moscow JINR, Dubna
Slovenia 	J.F. Inst, Ljubljani
Spain 	U. Barcelona
Switzerland 	U. Zurich
Ukraine 	INR, Kiev
USA 	U. Texas, Austin U. Cincinnati Wayne State U. U. Houston U. Calif, Los Angeles

Why Charmonium Production?

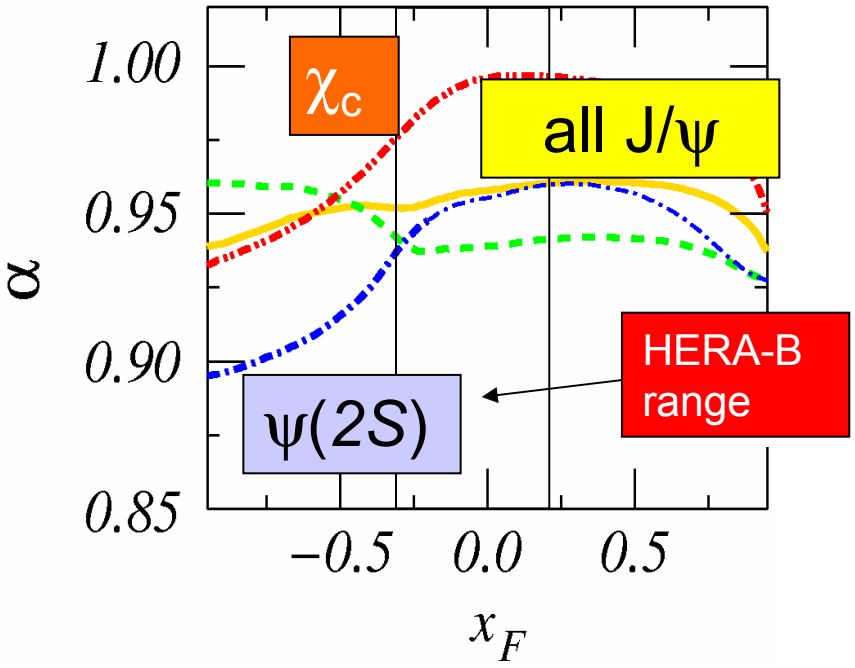
- Test of current framework for charmonium production models: nonrelativistic QCD (perturbative expansion in relative quark velocities)
- Modification of models via nuclear effects
  - Initial state effects, e.g. shadowing, energy loss
  - Final state effects, e.g. absorption in nuclear matter
  - Parametrization: power law with exponent $\alpha = \alpha(x_F, p_T)$

$$\sigma_{pA} = \sigma_{pN} \cdot A^{\alpha}$$

α is measure of A-depencence (A: target atomic mass)
$\alpha < 1$: charmonium suppression by nuclear effects (anomalous suppression: signature for quark-gluon plasma)

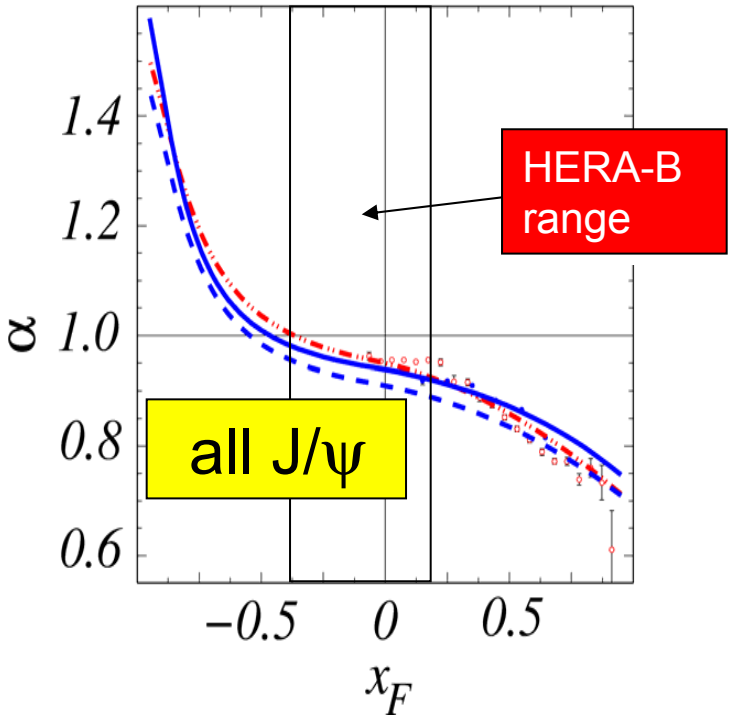
A-Dependence: Theory

- Prediction 1: NRQCD + nuclear absorption



R. Vogt,
Nucl. Phys. **A700** (2002) 539

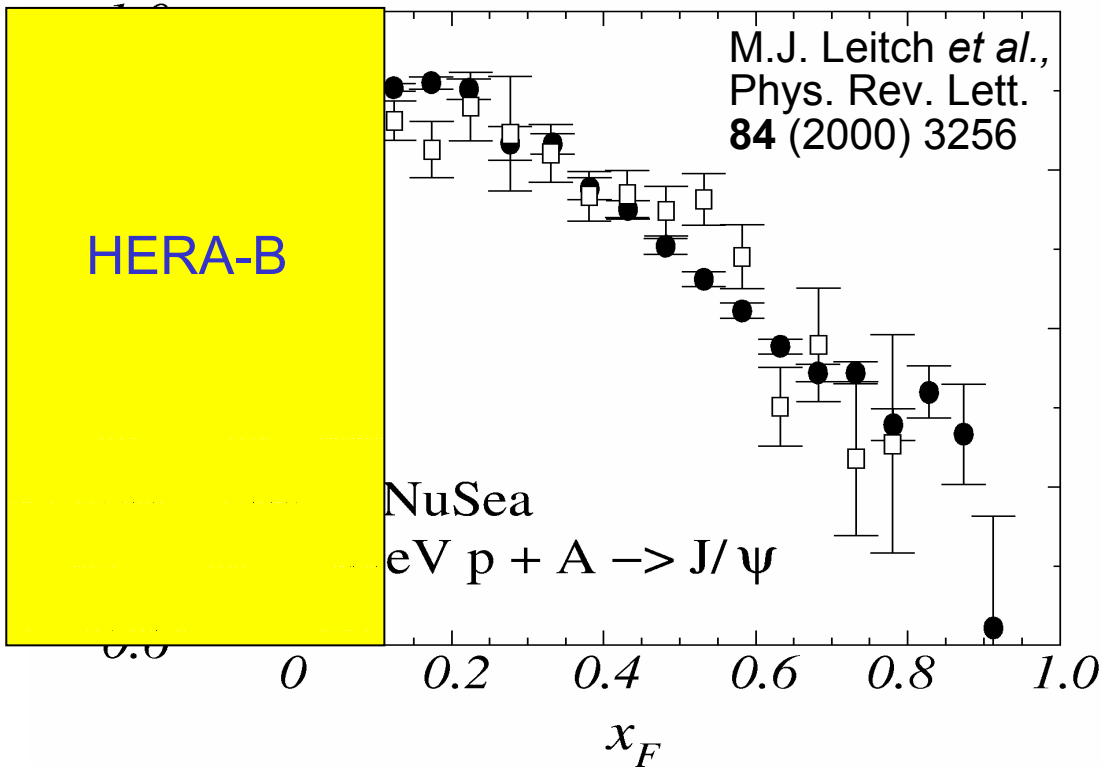
- Prediction 2: BCKT (Reggeon-based)



K.G. Boreskov, A.B. Kaidalov,
JETP Lett. **77** (2003) 599

A-Dependence: HERA-B's Contribution

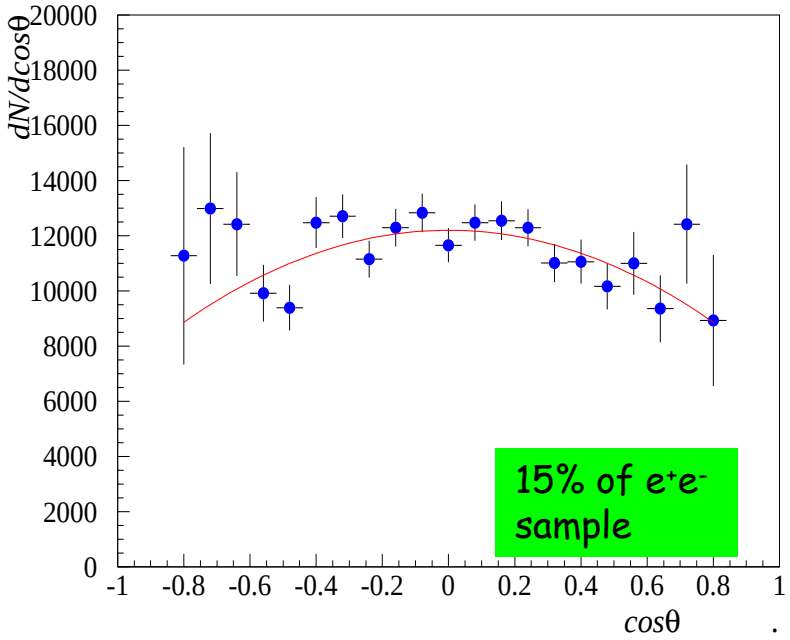
Measurements in proton-nucleus scattering (Fermilab E866/NuSea) as a function of x_F



HERA-B:

- Extend kinematic range to x_F<-0.35
- Triggering 2 channels simultaneously: e, μ
- 2 materials simultaneously (C, W)
  → better control of systematic effects

cosθ differential distribution of J/ψ



θ is the Gottfried-Jackson decay angle

$$\frac{d\Gamma}{d\cos\theta} = \gamma\,(1 + \lambda\cos^2\theta)$$

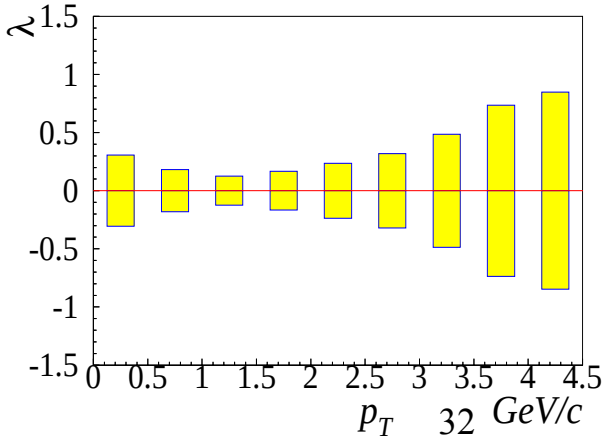
J/ψ polarization described by λ parameter

λ = (0,1,-1) ⟺ (no, trans., long.) polarization

HERA-B variation range ➡ **[-0.5,0.1] ±0.1**

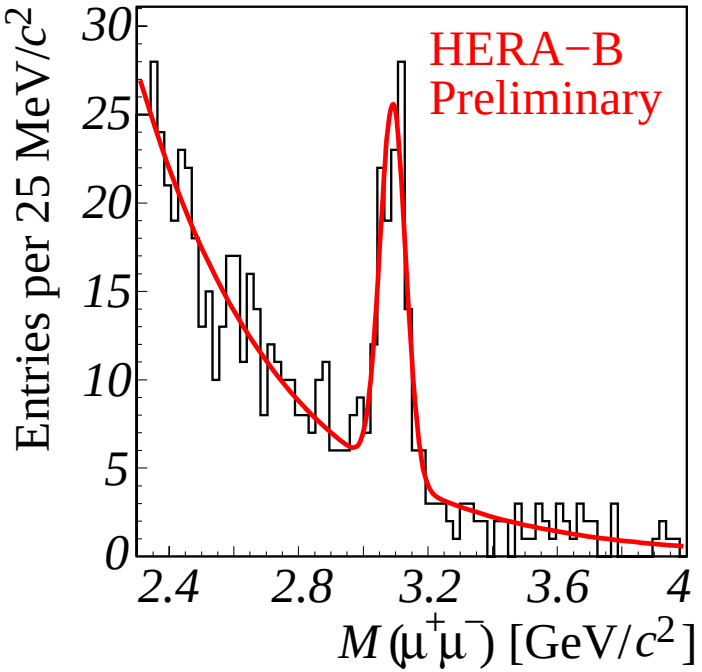
Exp.	Interaction & p-momentum	λ
E379	p-Fe @ 400 GeV	0.16 ± 0.08
E672/E706	p-Be @ 530 GeV	0.01 ± 0.15
E672/E706	p-Be @ 800 GeV	-0.11 ± 0.15
E771	p-Si @ 800 GeV	-0.09 ± 0.12

Important tests for models

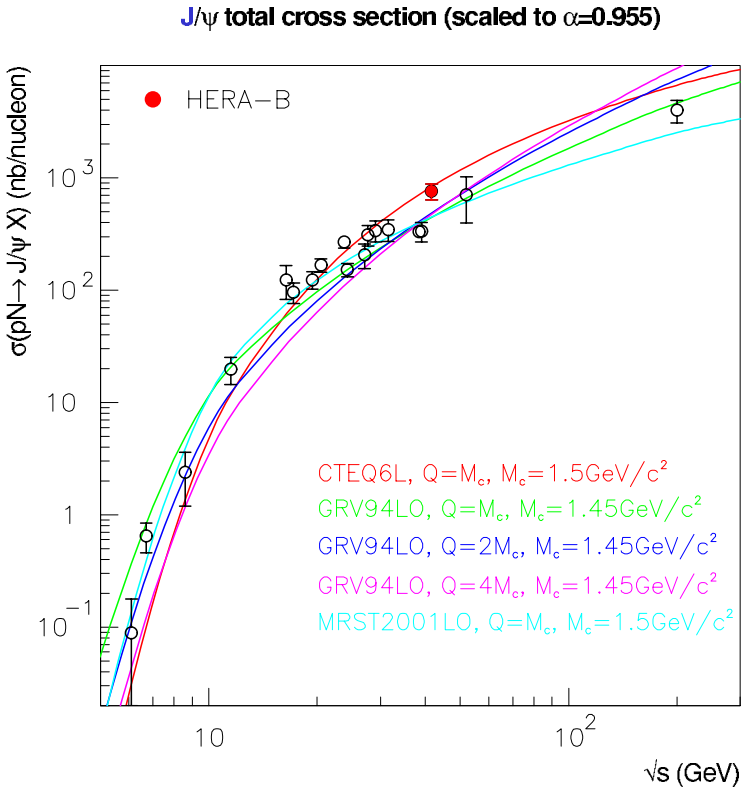


J/ψ Production Cross Section

$J/\psi \to \mu^+\mu^-$ signal in minimum bias data



J/ψ Production cross section as a function of $\sqrt{s}$



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

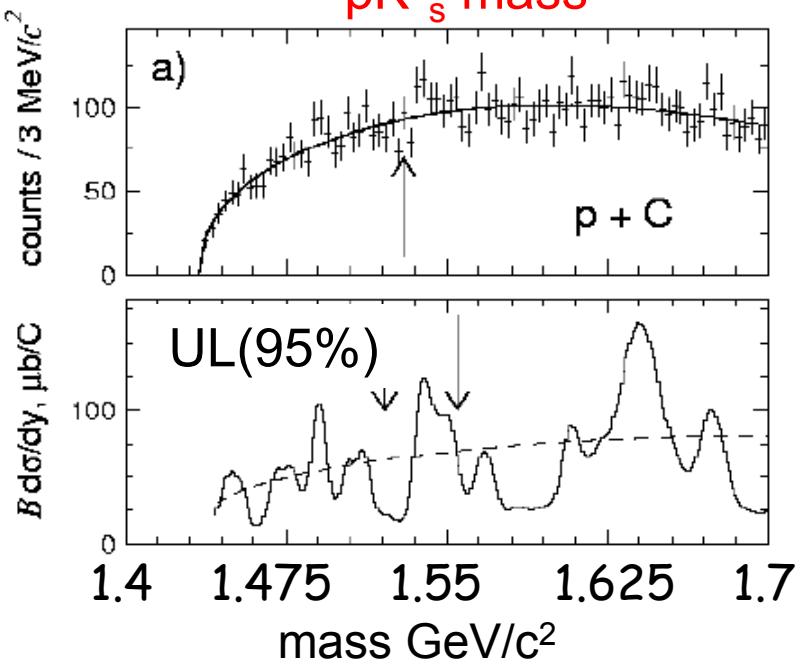
Assuming A^α dependence with α = 0.955

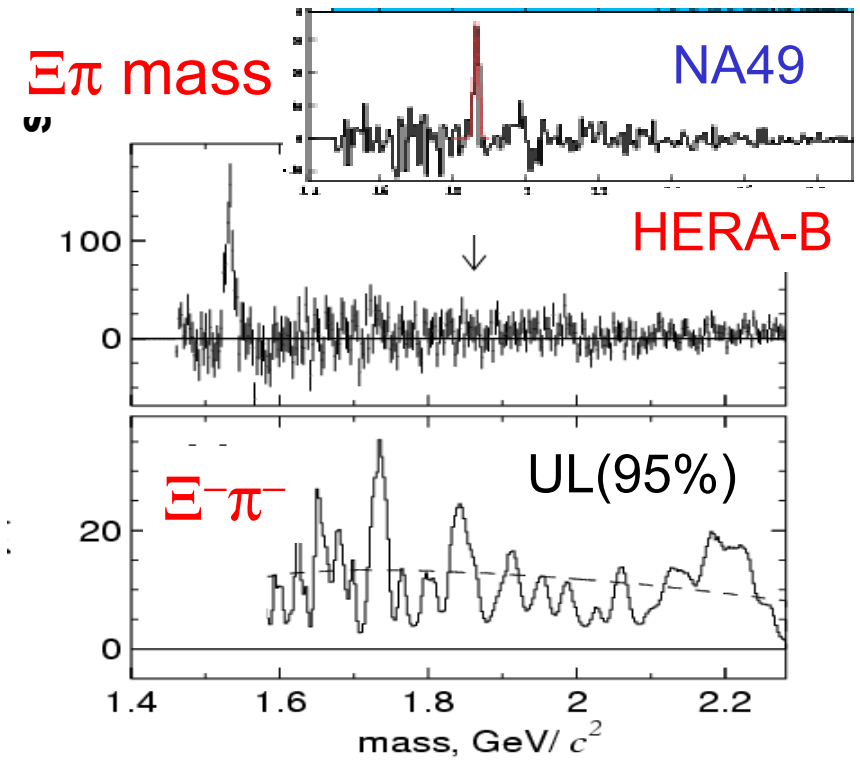
HERA-B result is higher than E771/789

Theoretical description is reasonable but not perfect (fig. is in a log scale)

Θ^+, Ξ^{--} Searches

(hep-ex/0408048) accepted by Phys. Rev. Lett.





UL(95%)$B\cdot d\sigma/dy|_{y=0}$ =
4-16 μb/N
@ 1521-1555 MeV/c^2

Θ+ / $\Lambda(1520)$ < 3 – 12 %

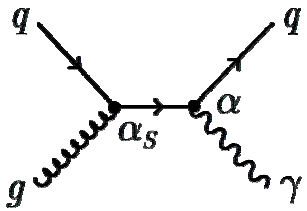
UL(95%)$B\cdot d\sigma/dy|_{y=0}$ =
2.5 μb/N @ 1862 MeV/c^2

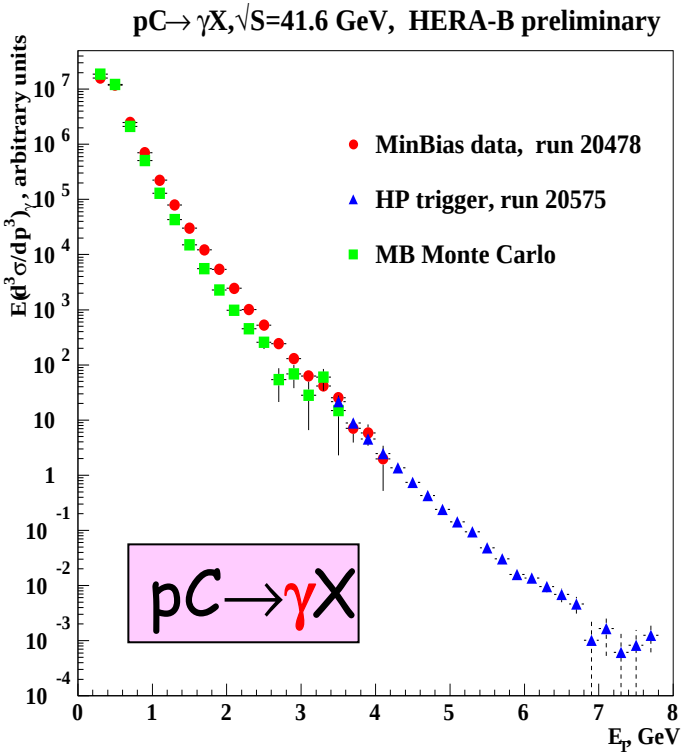
Ξ^{--} / Ξ^- < 3/B %

Ξ^{--} / $\Xi(1530)^0$ < 4/B %

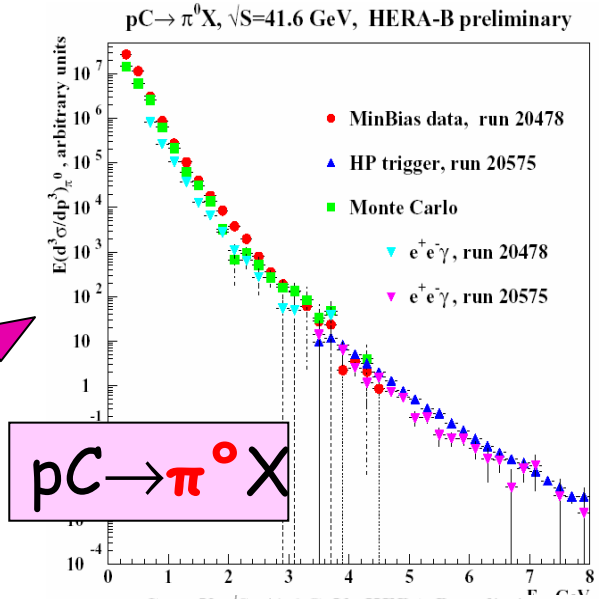
Hard photon analysis

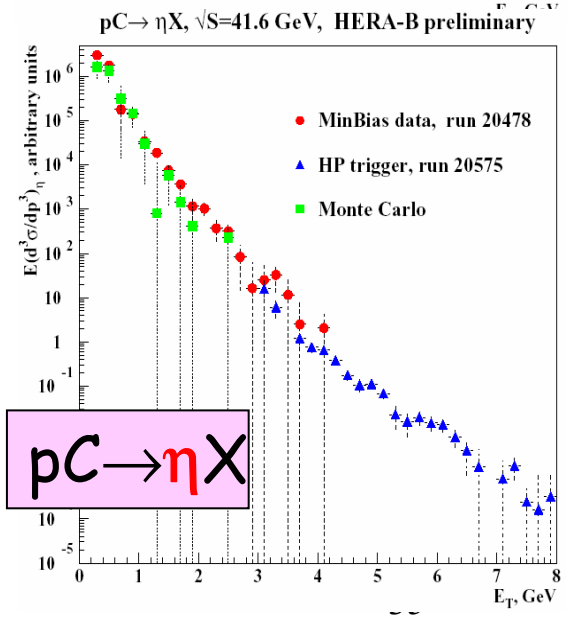
Direct γ production:
dominant process $gq \rightarrow \gamma q$
$\Rightarrow$ Unique sensitivity to gluon density function





Main bkg sources, also important to test QCD





HERA-B:
- Widest rapidity range
- Large p_T range
- Highest energy for pA
- Ongoing analysis on heavier materials

(normalization still arbitrary)