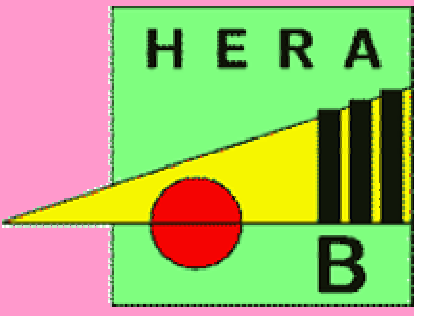
HERA-B results



Antonio Zoccoli
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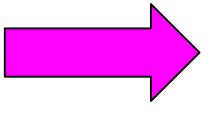
For the HERA-B Collaboration

HERA-B history

The history of the experiment:
- 1994 proposal
- 1995 experiment approved
- 1995-1999 R&D, production and installation
- 2000 first detector commissioning
- 2001-2002 detector upgrade (HERA shut down) and update of the physics program
- 2002 Nov.–2003 Feb. data taking

Only 4 months for the physics data taking !

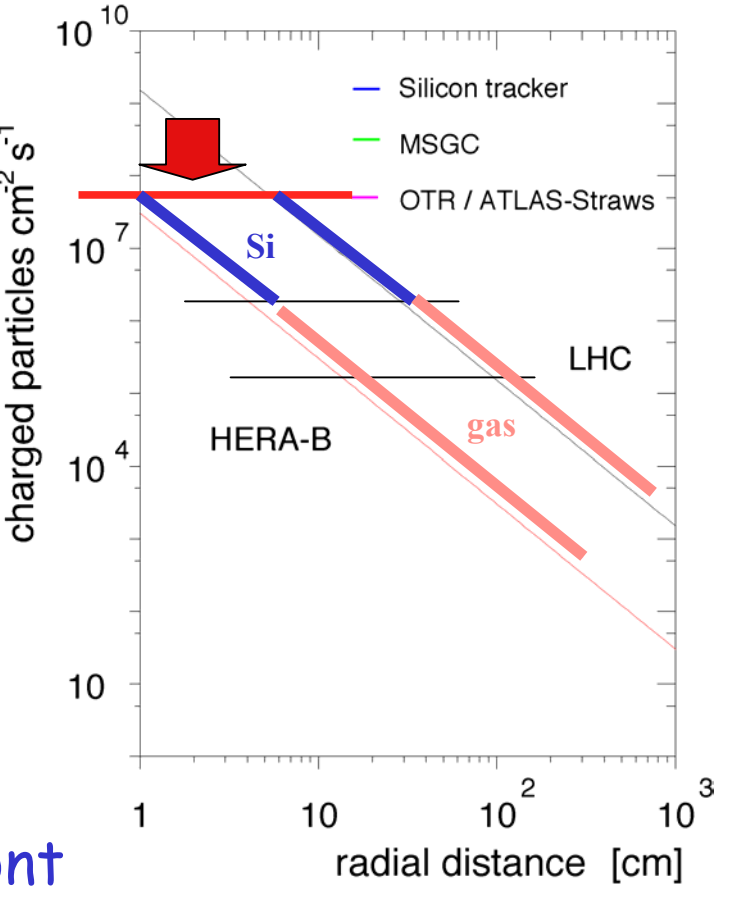
The original schedule was very tight.
An unforeseen R&D phase was necessary due to aging problems → Delays on the schedule



= high rates

had to face LHC equivalent particle flux 10 years in advance.

→ exploring a new regime of radiation load, particle flux, event rates...



detectors
trigger system
DAQ

} At forefront of technology

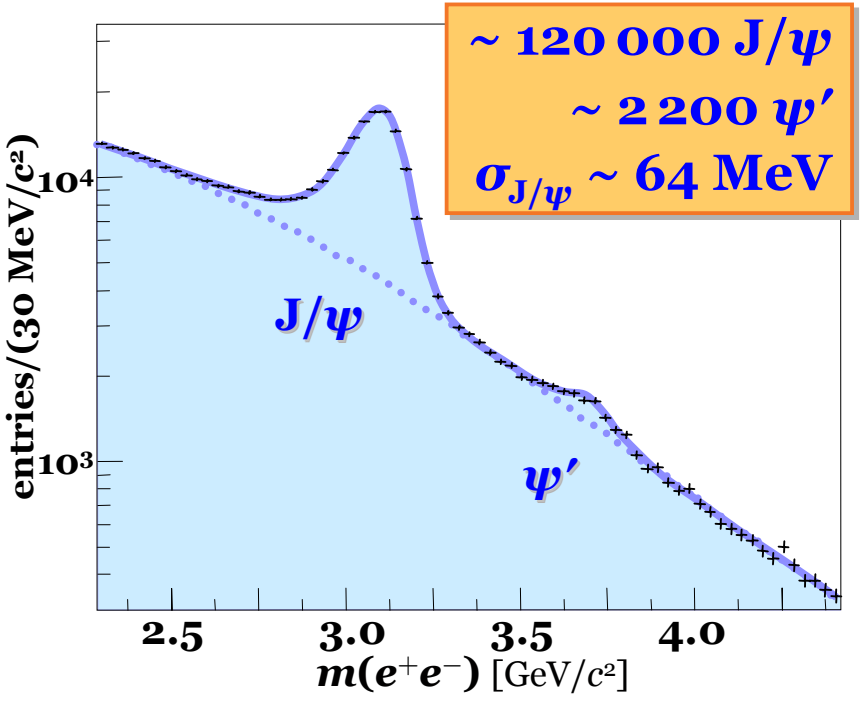
Main data samples

- 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

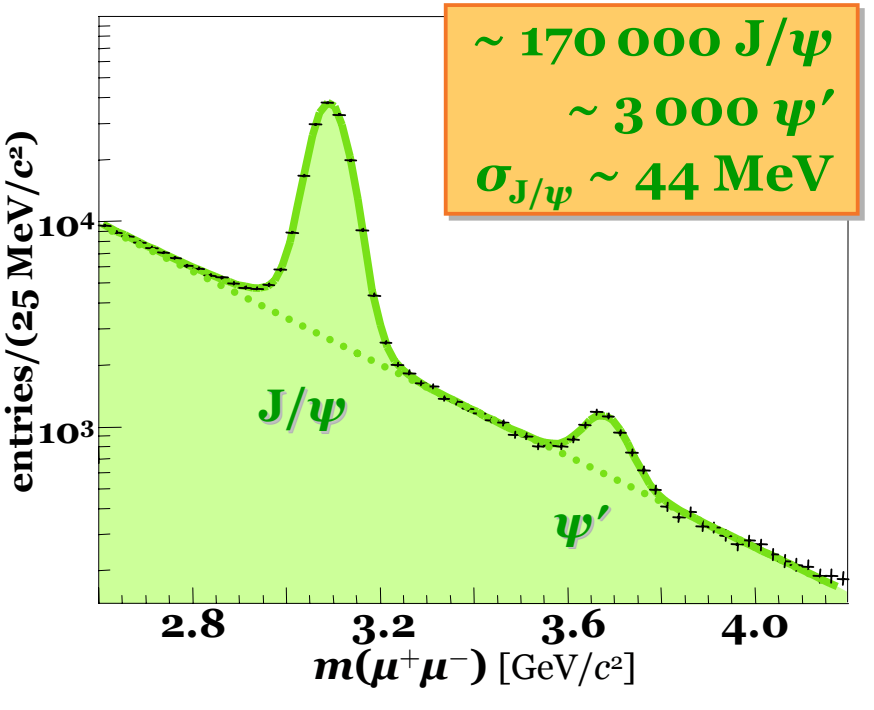
→ 1000 ev/s >1TB/day

Three target materials: pC,pW and pTi collisions

e^+e^-



$\mu^+\mu^-$



Physics topics

FCNC $D^0 \rightarrow \mu\mu$ Br limit	Phys. Lett. B596 (2004) 173.
Beauty production:	
bb cross section (J/ψ det.)	Phys. Rev. D73 (2006) 052005.
bb cross section (semilept.)	Paper ready
Υ production	Phys. Lett. B638 (2006) 13.
Charmonium studies:	
J/ψ production	Phys. Lett. B638 (2006) 407.
J/ψ diff. distributions	Note stage
J/ψ A-dependence	Analysis ongoing
$\psi(2s)$ production	In press on Eur. Phys. J C.
$\chi_c/J/\psi$ production ratio	Note stage
Pentaquark production	Phys. Rev. Lett. 93 (2004) 212003.
Λ polarization	Phys. Lett. B638 (2006) 415.
K^*/Φ production	In press on Eur. Phys. J C.
Open charm production	Note stage
Deuteron production	Analysis ongoing
Hyperon production	Note stage
Luminosity determination	Paper Draft

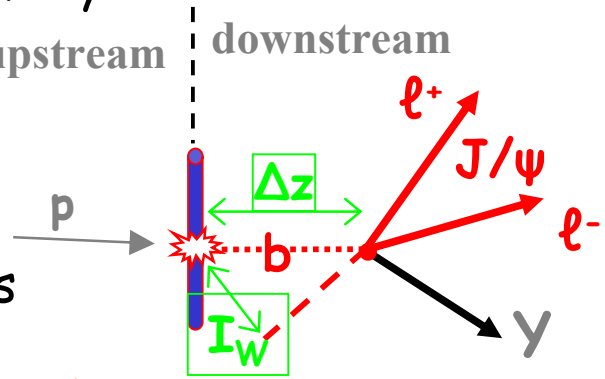
Beauty production

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

B Meson has a long life time (~ 9 mm at HERA-B kinematics)
~ 0.5 mm dilepton vertex resolution. Two methods:

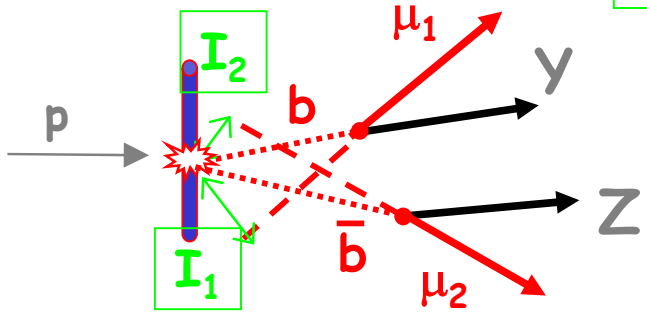
1) J/ψ from a B decay detached from primary interaction

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



2) two leptons from B semileptonic decays

$pA \rightarrow b\bar{b}\ X$
$b \rightarrow \mu_1\ Y$
$\bar{b} \rightarrow \mu_2\ Z$



Analysis cuts:
- Impact parameter
- [Decay length (Δz)]

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

Open b production

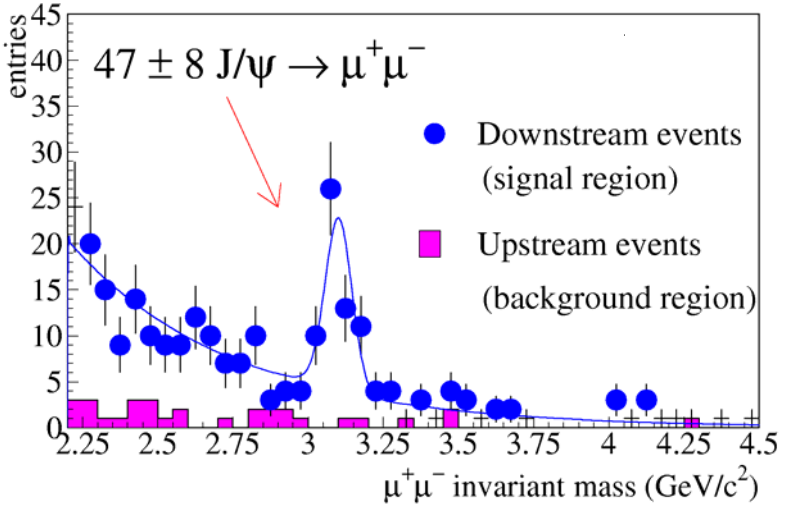
1) Detached J/ψ method

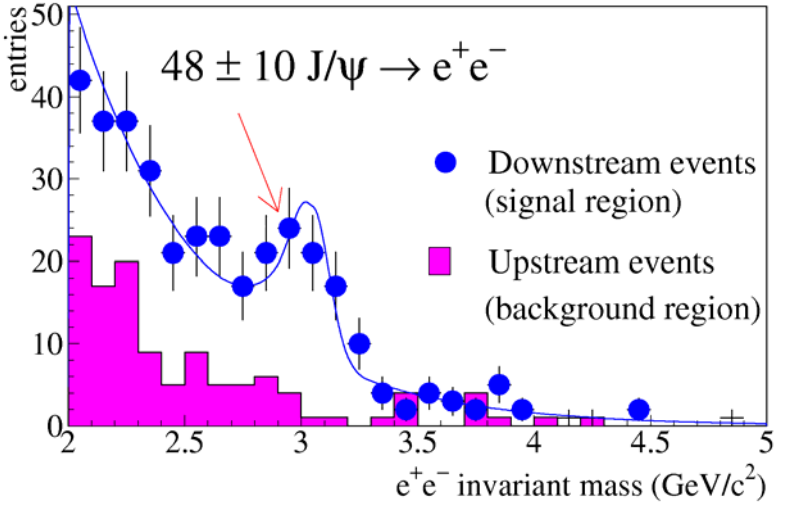
- C,W,Ti targets
- Full statistics
- Unbinned likelihood fit

$$\frac{\sigma(b\bar{b})}{\sigma(J/\psi)} = 0.032 \pm 0.005 \pm 0.004$$

20% sys., main contribution:

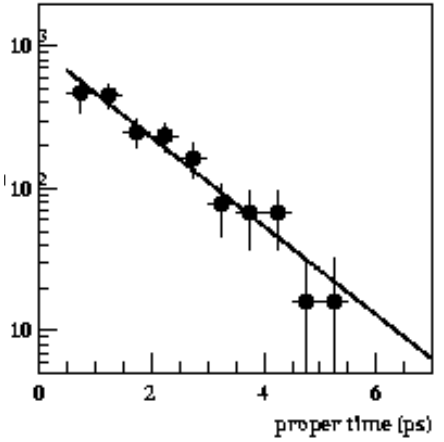
Br(bb→J/ψX) = 2.32±0.20%





Lifetime:

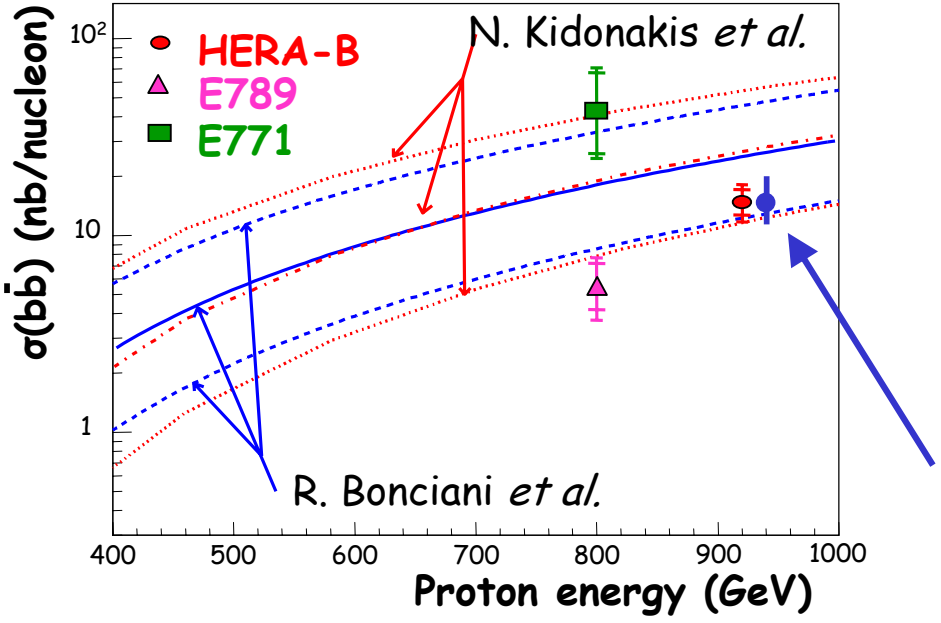
τ = (1.39 ± 0.19)ps



Open b cross section

$$\sigma\left(b\bar{b}\right) = 14.9 \pm 2.2 \pm 2.4 \text{ nb/nucleon}$$

Phys. Rev. **D73** (2006) 052005



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

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

- Theoretical uncertainties:
  - b quark mass 4.5 - 5 GeV
  - At NLO, scale (μ) dependence
- E789/E771 measurements do not agree with each other

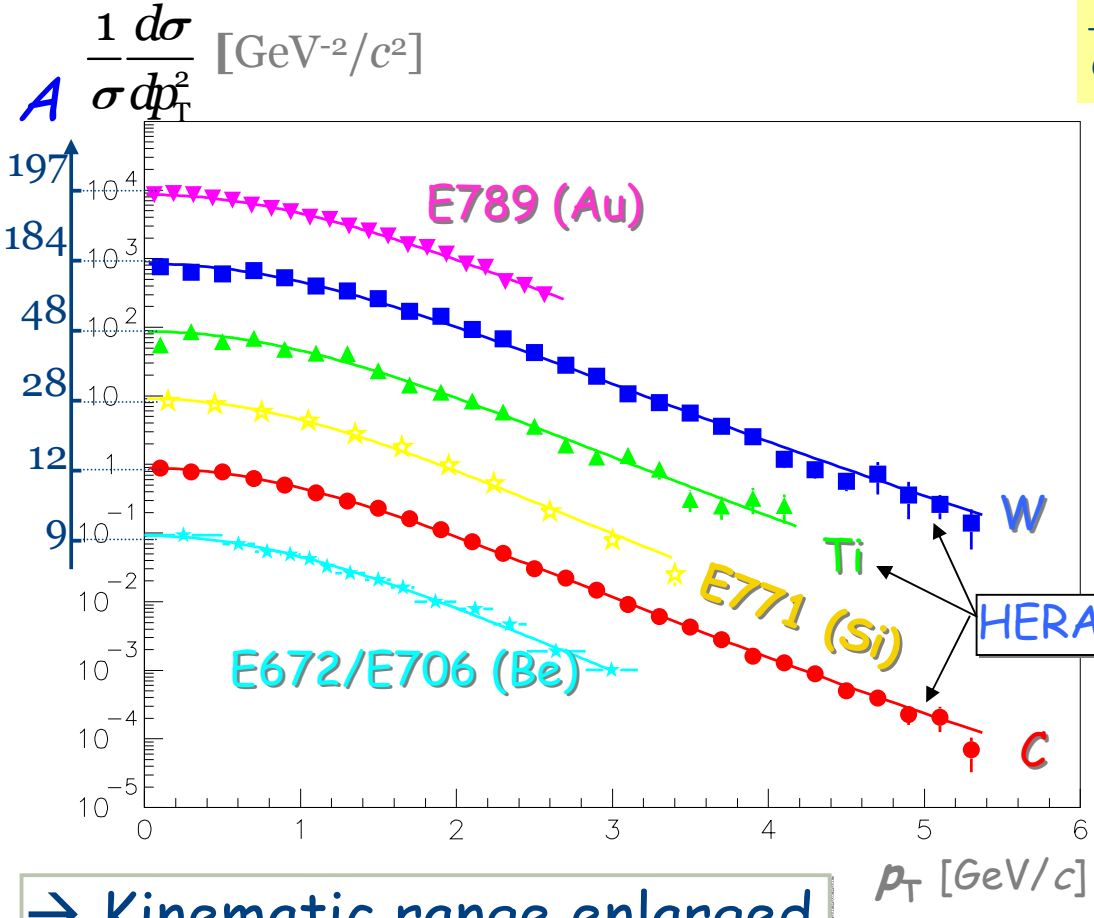
2) Semileptonic B decay method: preliminary result.

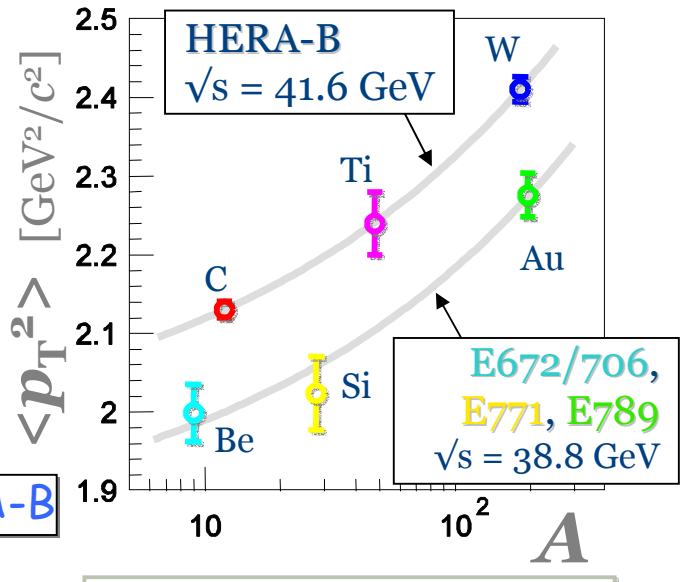
Charmonium studies

J/ψ differential distribution: p_T

Electron channel: compared with p-A results ($\sqrt{s}$=38.8 GeV) agreement with muon channel in all distributions.

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



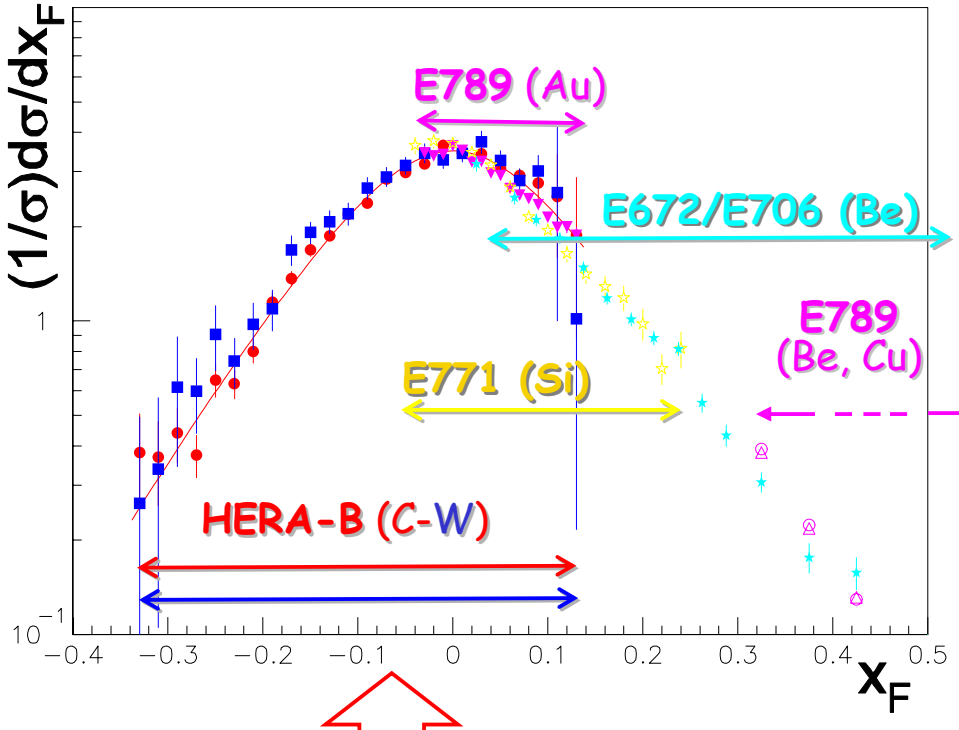


→ Kinematic range enlarged

Increase of $\langle p_T^2\rangle$ with cms energy and with A.
→ Consistent with a linear dependence on the nuclear path length.

J/ψ differential distribution: x_F

Electron channel: compared with p-A results ($\sqrt{s}$=38.8 GeV) agreement with muon channel in all distributions.

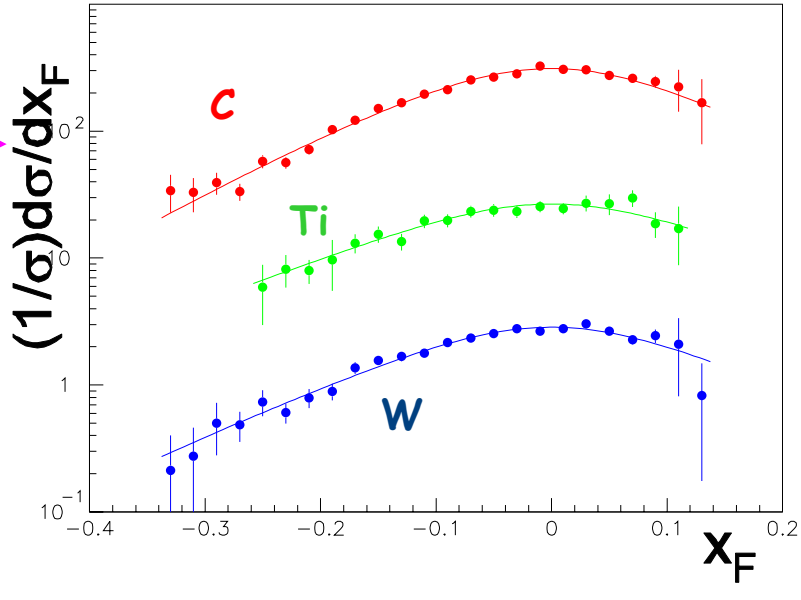


first data produced at negative x_F

Fitting curves:

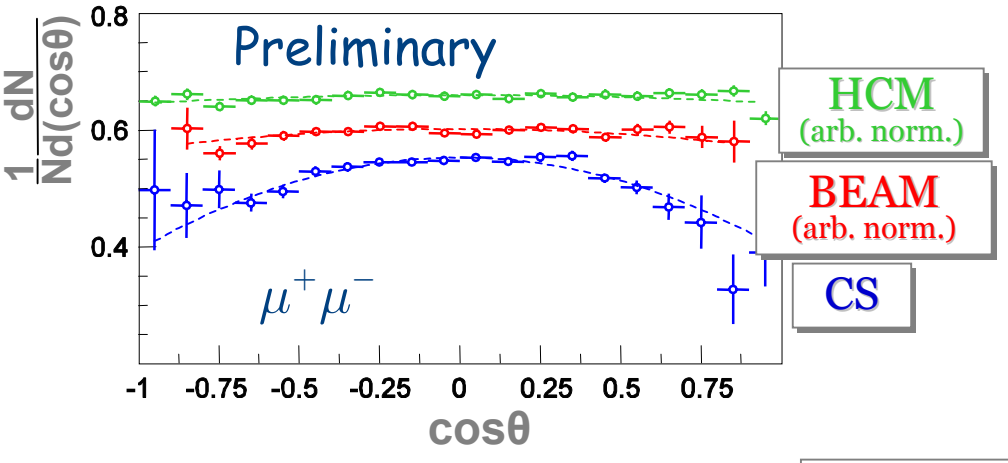
$$d\sigma/dx_F \propto [(1-x_1)(1-x_2)]^{\kappa}/(x_1+x_2)$$

with $$x_{1,2}=\frac{1}{2}\left(\sqrt{x_F^2+4m_{J/\psi}^2/s}\pm x_F\right)$$



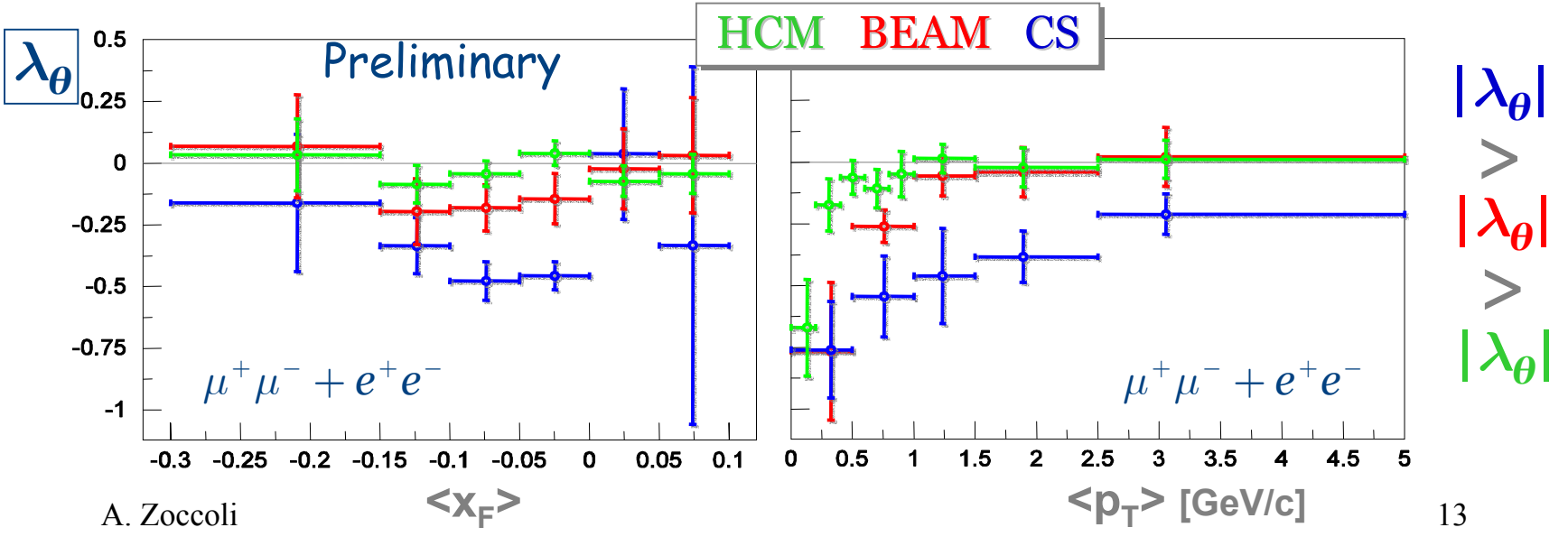
J/ψ polarization

Measured in different reference systems (CS, GJ, HCM) and wrt p_T and x_F



$$dN/d(\cos\theta) \propto 1 + \lambda_\theta \cos^2\theta$$

-CS frame shows the largest longitudinal polarization.
-Kinematical dependence on p_T.
-Not in conflict with other experiments.



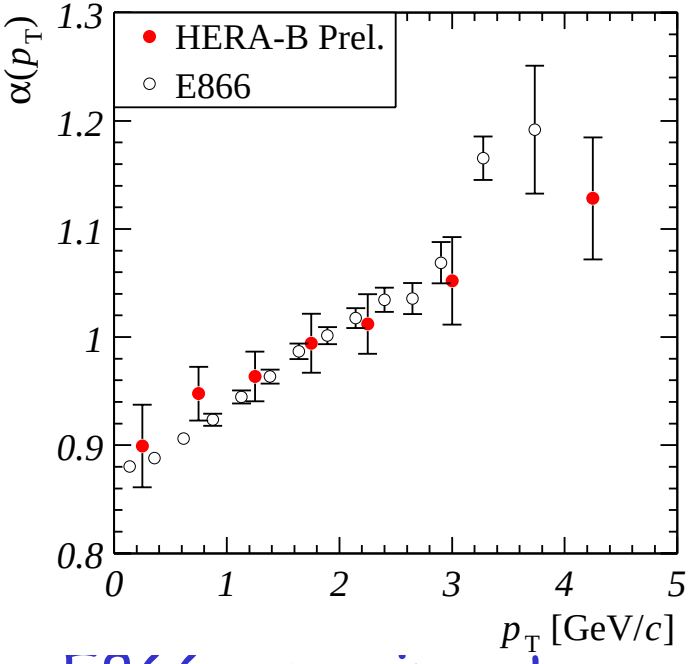
$|\lambda_\theta|$ > $|\lambda_\theta|$ > $|\lambda_\theta|$

J/ψ A-Dependence

Test of charmonium production models in nuclear matter (NRQCD + initial/final state interactions in nucleus)

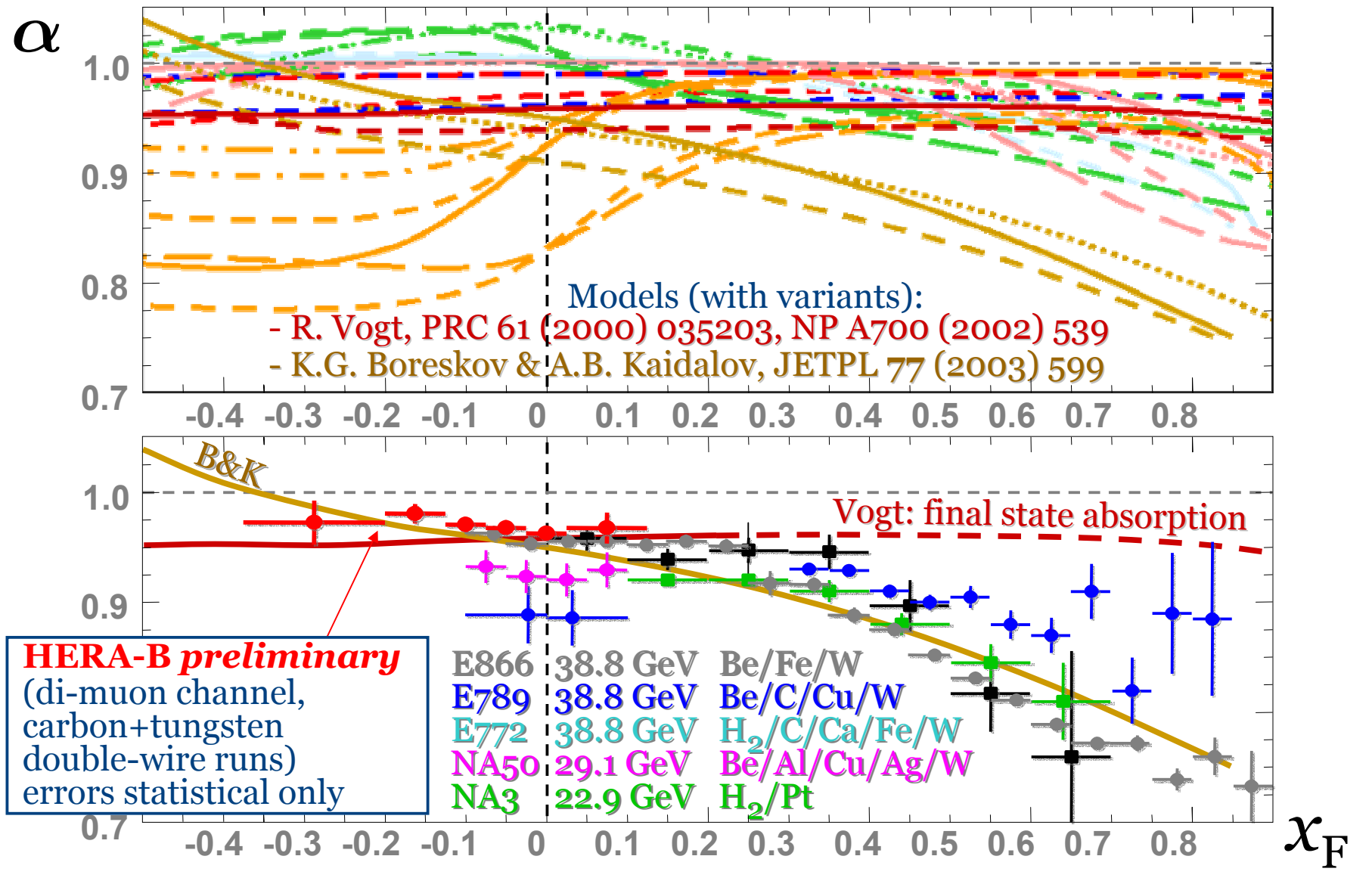
$$\sigma_{pA} = \sigma_{pN} \cdot A^{\alpha}; \quad \sigma = N / \varepsilon L$$

- α < 1: charmonium suppression by nuclear effects
- HERA-B: extract α from runs with two target wires simultaneously (carbon: A=12, tungsten: A=184)
- Results from full $\mu^+\mu^-$ sample. Only statistical uncertainties. Similar results from the e^+e^- sample.



- P_T broadening effect as seen by E866 experiment
- Previous result of FNAL E866 extended to x_F = -0.35

J/ψ A-Dependence

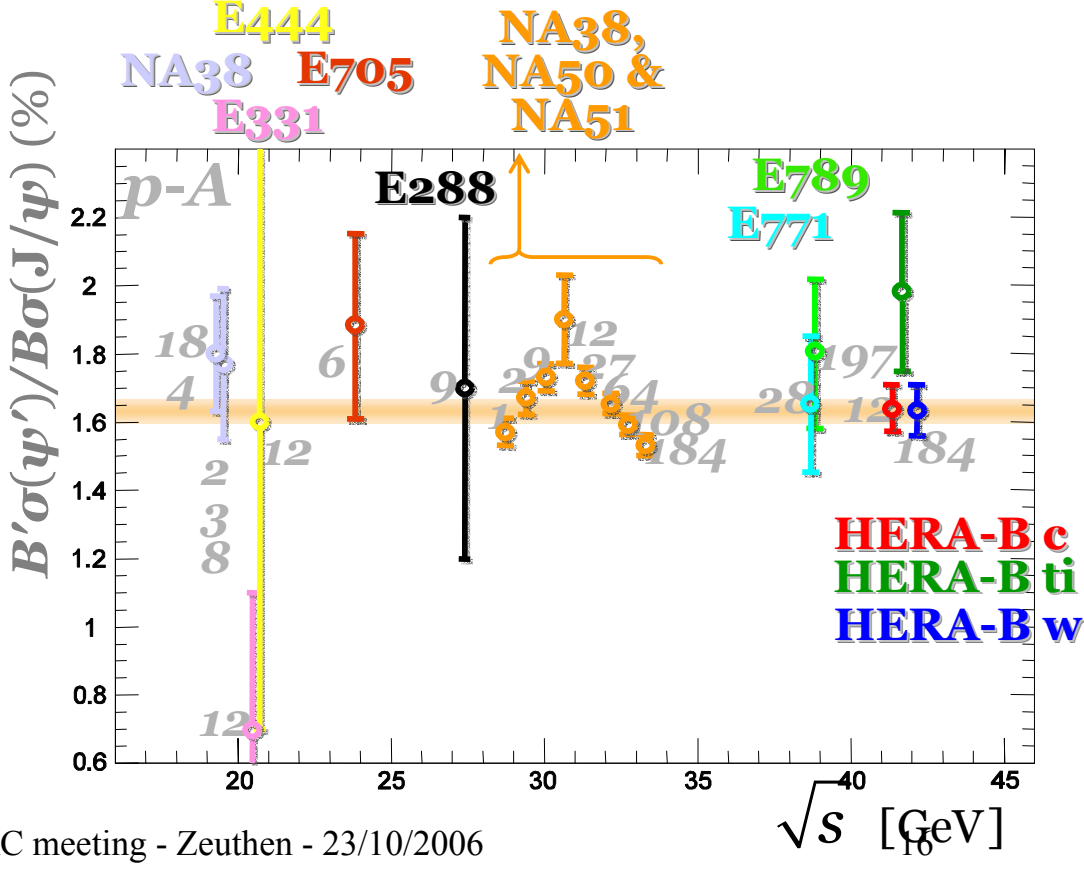


ψ(2S) Production

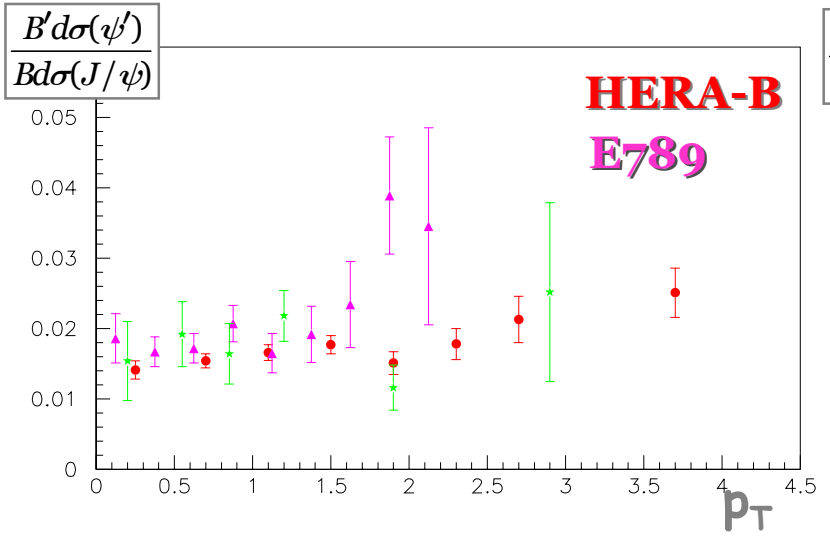
Combined results (e^+e^- + $\mu^+\mu^-$):

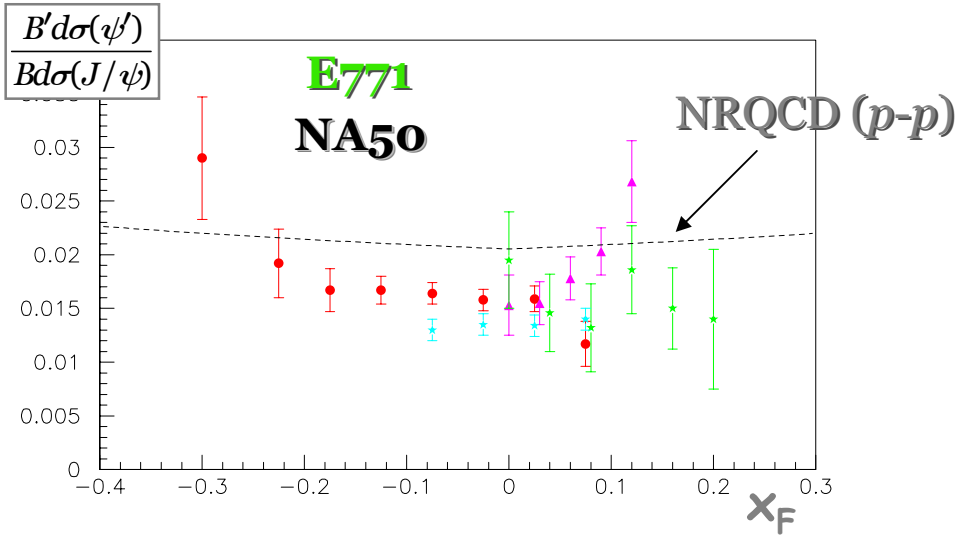
$$\rho_{\psi'}^{e^+e^-} = \frac{B_{\psi'\to\ell^+\ell^-}\,\sigma_{\psi'}}{B_{J/\psi\to\ell^+\ell^-}\,\sigma_{J/\psi}} = \begin{cases} 1.63\pm0.08\,\%\,(\mathrm{C}) \\ 1.99\pm0.26\,\%\,(\mathrm{Ti}) \\ 1.62\pm0.11\,\%\,(\mathrm{W}) \end{cases}$$

- ψ(2S) cross section measurement relative to J/ψ
→ reduction of systematic uncertainties
- No dependence on cms energy and kinematics except for Na38/50/51. All results consistent within 4%.



ψ(2S) differential distributions





→ ψ(2S) and J/ψ states have very similar kinematics

Fraction of J/ψ from ψ(2S) :

$$R_{\psi'} = \rho_{\psi'} \times \frac{B_{J/\psi\to\ell^+\ell^-}}{B_{\psi'\to\ell^+\ell^-}} \cdot B_{\psi'\to \begin{cases} J/\psi\pi^+\pi^- \\ J/\psi\pi^0\pi^0 \\ J/\psi\eta \\ J/\psi\pi^0 \end{cases}} = (7.0 \pm 0.2 \pm 0.4_{BRs})\%$$

Constraint on the double ratio (test of lepton universality):

$$\rho_{\psi'}^{e^+e^-} \Big/ \rho_{\psi'}^{\mu^+\mu^-} = \frac{B_{\psi'\to e^+e^-}}{B_{J/\psi\to e^+e^-}} \Bigg/ \frac{B_{\psi'\to \mu^+\mu^-}}{B_{J/\psi\to \mu^+\mu^-}} = 1.00 \pm 0.08 \pm 0.04$$

current PDG avg.: 1.03 ± 0.12

χ_c Production

Selection:

$$\chi_c \longrightarrow J/\psi \ \gamma$$
$$J/\psi \rightarrow \begin{cases} e^+e^- \\ \mu^+\mu^- \end{cases}$$

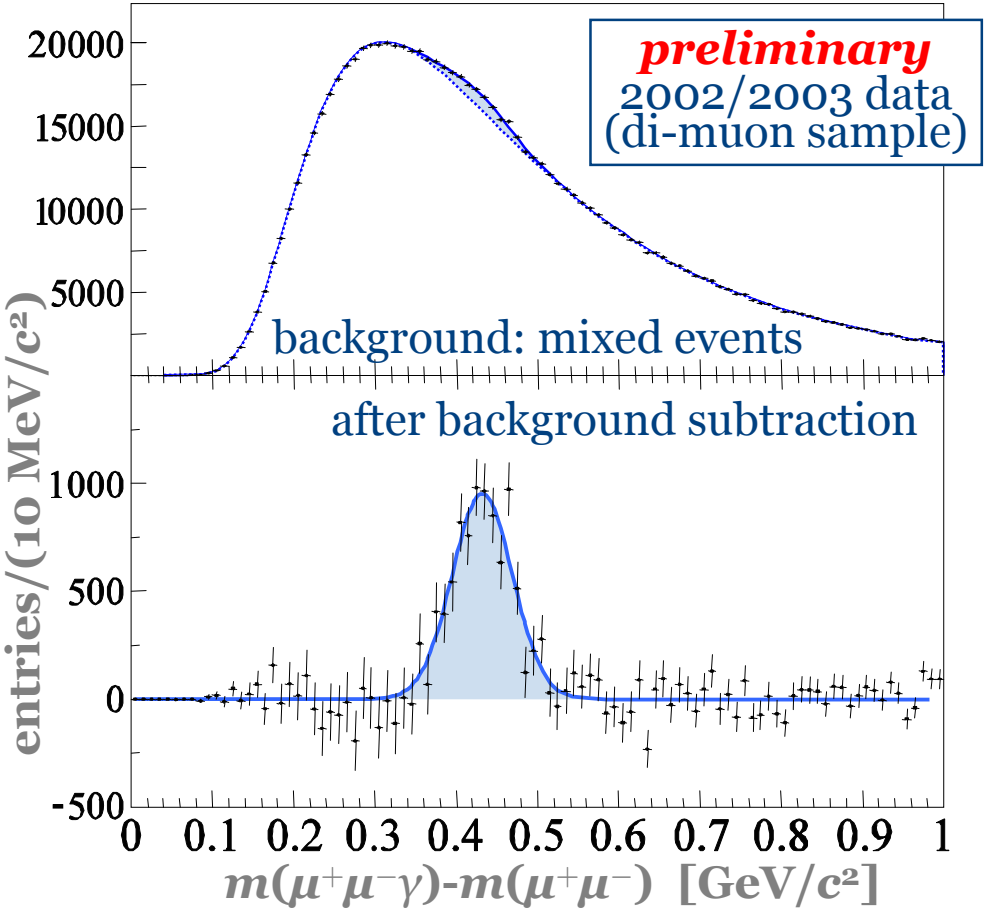
The measurement:

- fraction of J/ψs from χ_c:

$$R_{\chi_c} = \frac{\sum \sigma(\chi_{c(i)} \rightarrow J/\psi\gamma)}{\sigma_{\mathrm{INCL}}(J/\psi)}$$

- kinematic distributions
- A-dependence

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)]



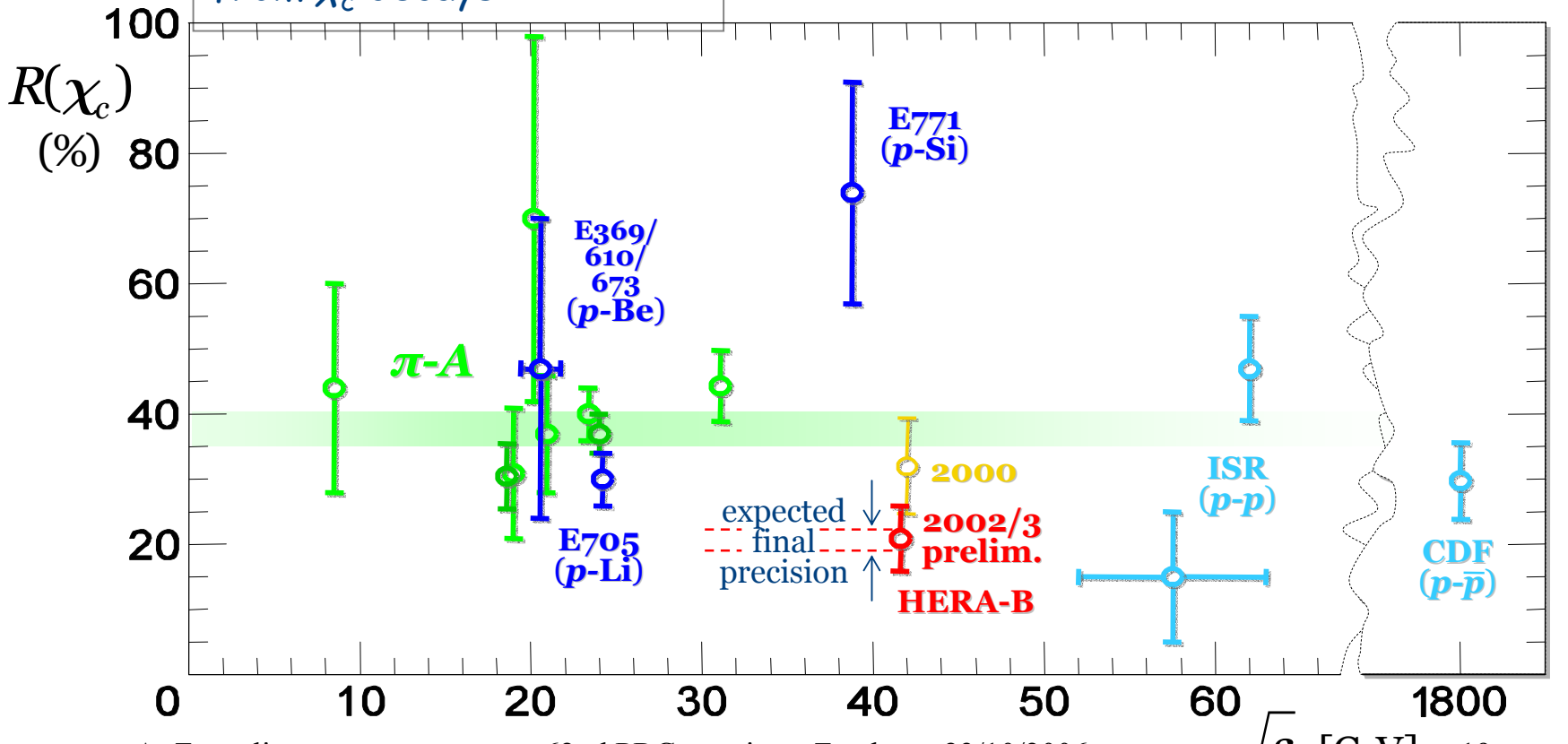
new data: 40× bigger χ_c statistics
(the largest analyzed in a hadronic experiment)

$R(\chi_c)$

Preliminary evaluation (2002/2003 data):

(21 ± 5)% of the produced J/ψs come from χ_c decays

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



Indirect and direct J/ψ production

Using partial/preliminary HERA-B results:

(to be improved!)

$(21 \pm 5)\%$ $(7.0 \pm 0.4)\%$ $(0.065 \pm 0.011)\%$

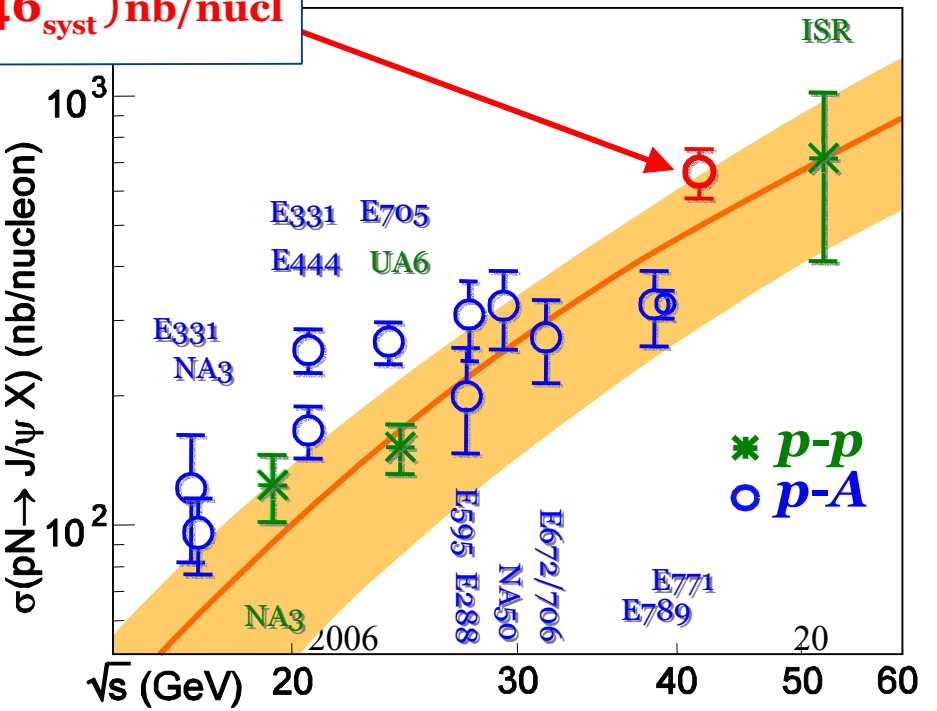
$$\sigma_{\mathrm{DIR}}^{J/\psi} = \sigma_{\mathrm{INCL}}^{J/\psi} \left[1 - R\left(\chi_c \to J/\psi\right) - R\left(\psi' \to J/\psi\right) - R\left(b \to J/\psi\right) - \cdots \right]$$

$$\sigma_{pN}^{J/\psi}[41.6\ \mathrm{GeV}] = (663 \pm 74_{\mathrm{stat}} \pm 46_{\mathrm{syst}})\ \mathrm{nb/nucl}$$

extracted from MB data

(72 ± 5)% of the J/ψs are produced directly

Curve: NLO NRQCD fit of all data (Maltoni *et al.*, hep-ph/0601203)



Other topics

Pentaquark Searches

Phys. Rev. Lett.93:212003,2004

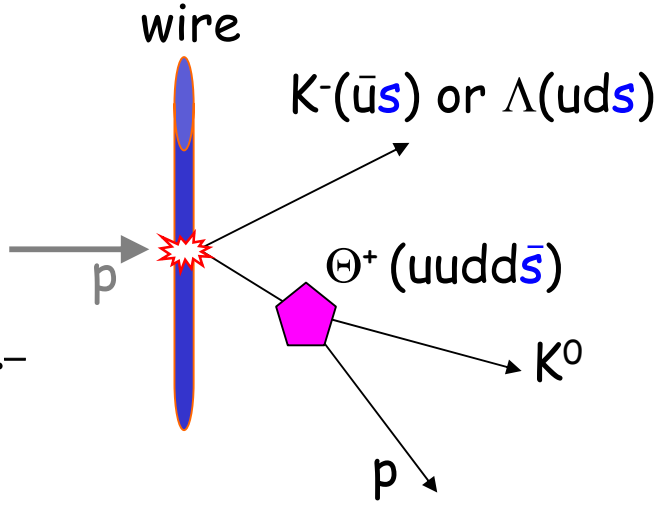
First reported negative result based on high statistics.

Searched pentaquark states:

$\Theta^+(1530,\ uudd\bar{s}) \rightarrow pK^0$ (or nK^+)

$\Xi^{--}(ddss\bar{u}) \rightarrow \Xi^- \pi^-$ (or $\Sigma^- K^-$) $\rightarrow \Lambda\pi^-\pi^-$

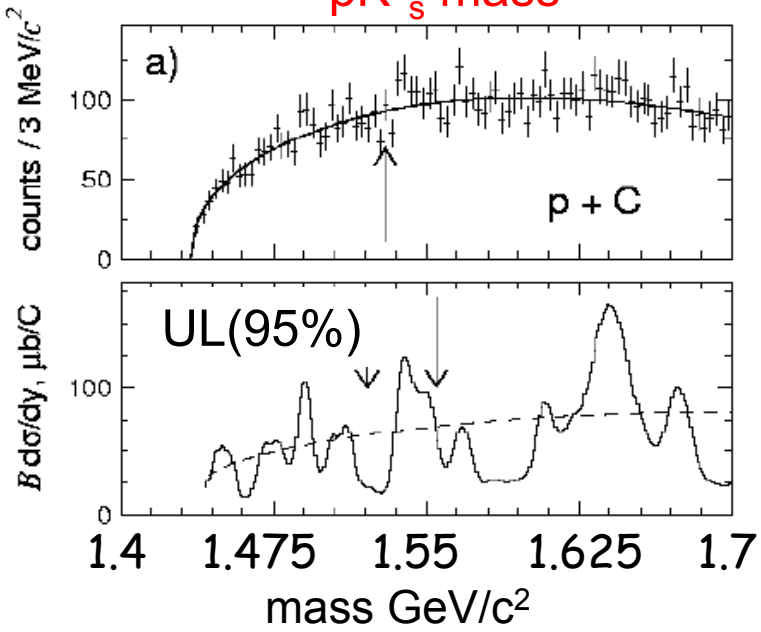
and charge c.



MB data sample (~210M evts, 3 nuclear targets C, Ti, W) used to:

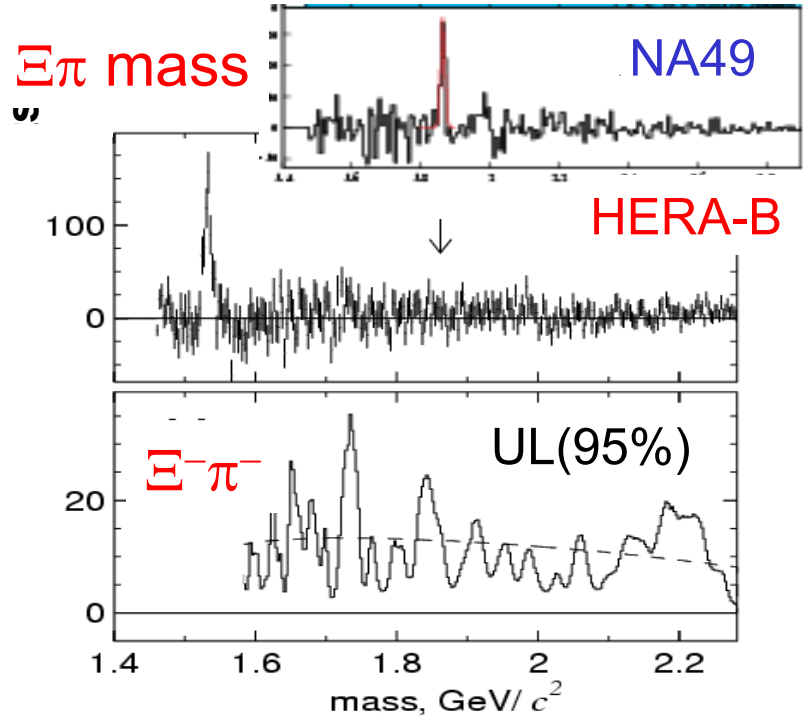
- search for the reported pentaquark signals
- provide upper limits on particle yield ratios (vs $\Lambda(1520)$ and $\Xi^0(1530)$)
- possibly determine physical quantities (width, spin, parity, charge) of pentaquarks for different final states (p-K^0, Ξ-π)

Θ^+, Ξ^{--} signals



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

Θ+ / Λ(1520) < 3 – 12 %



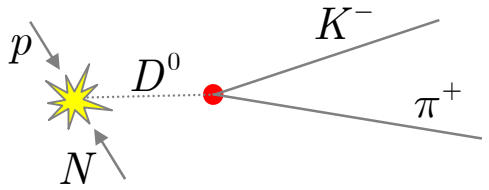
UL(95%)$B\cdot d\sigma/dy|_{y=0}$ =
2.5 μb/N @ 1862 MeV/c^2

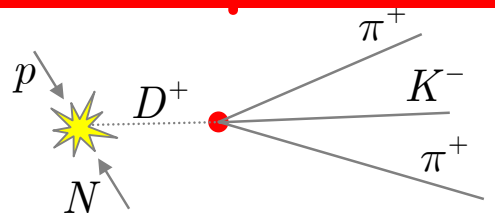
Ξ^{--} / Ξ^- < 3/B %

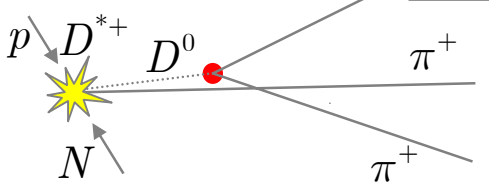
Ξ^{--} / $\Xi(1530)^0$ < 4/B %

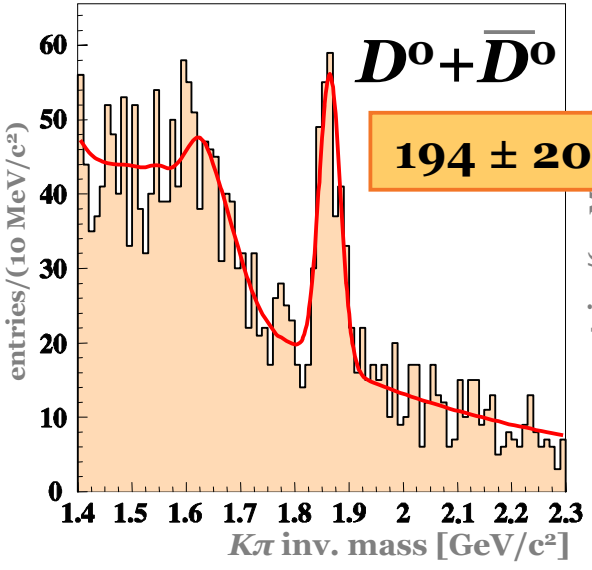
Phys. Rev. Lett. **93** (2004) 212003

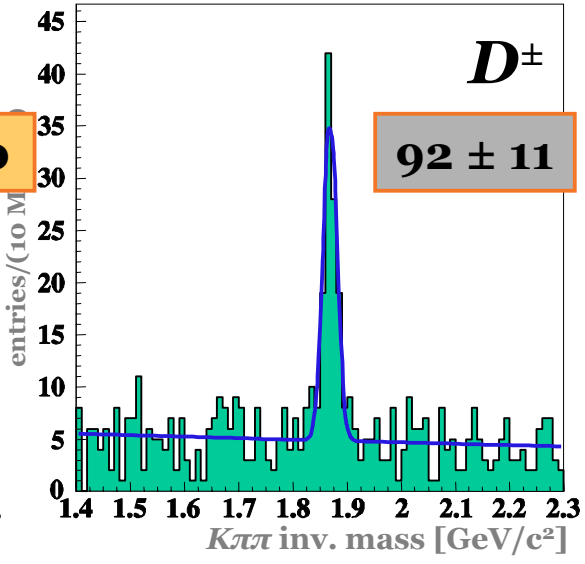
Open charm production

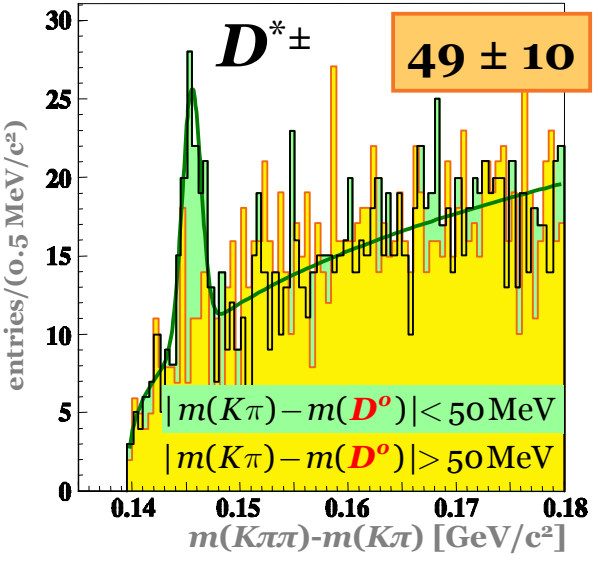








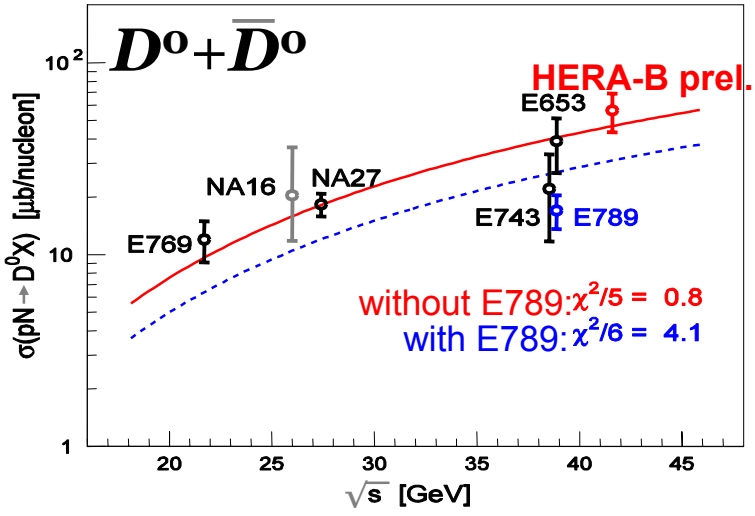


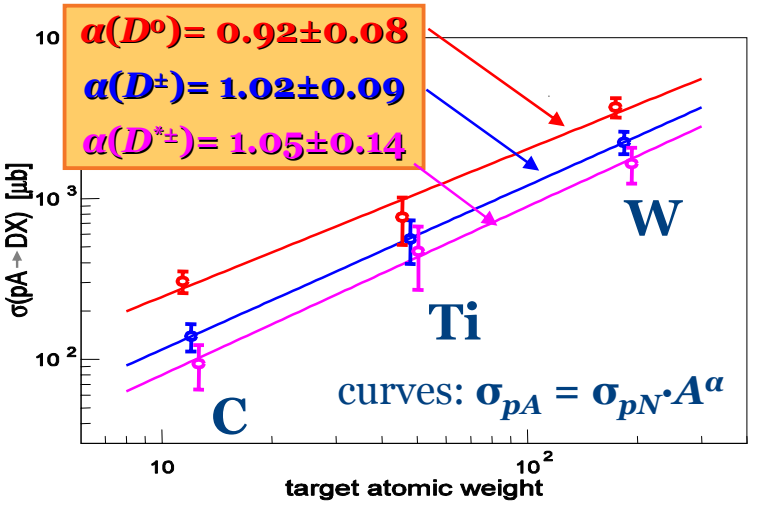


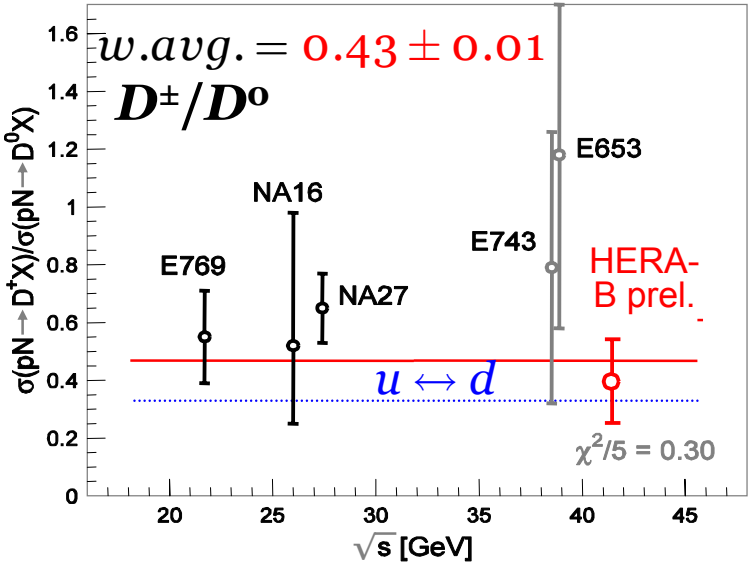
Cross section measurements:

Preliminary	$\Delta\sigma$ ($-0.1 < x_F < 0.05$)
$\Delta\sigma(D^0)$ [μb/nucl]	26.3 ± 2.4 ± 2.6
$\Delta\sigma(D^+)$ [μb/nucl]	10.7 ± 1.2 ± 1.4
$\Delta\sigma(D^{*+})$ [μb/nucl]	11.5 ± 2.0 ± 1.3
$\sigma(D^+)/\sigma(D^0)$	0.40 ± 0.06 ± 0.04
$\sigma(D^{*+})/\sigma(D^0)$	0.44 ± 0.09 ± 0.02

Open charm production: results







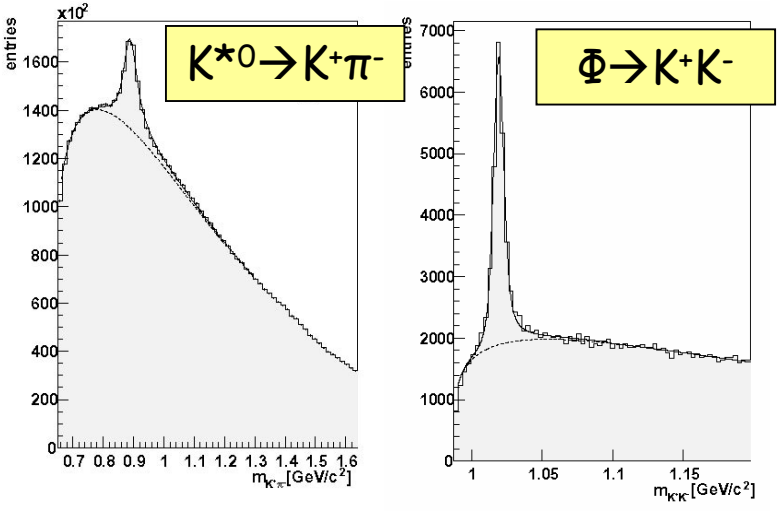
- D0: unclear situation at high √s
E789 result clearly disfavored
- energy dependence well described in each case by the function

$$\sigma_D \propto [1 - 1.2/(\sqrt{s})^{0.35}]^{12}$$

- a consistent with NO suppression
- from isospin symmetry and feeddown BRs

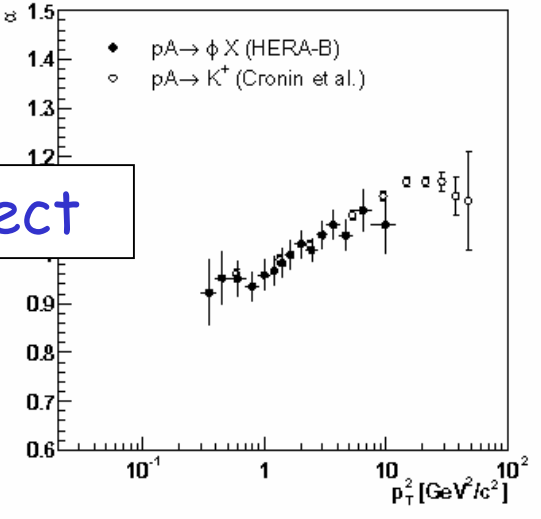
$\sigma(D^+)/\sigma(D^0) = 0.326 \pm 0.003$

K*/Φ + (anti)deuteron production

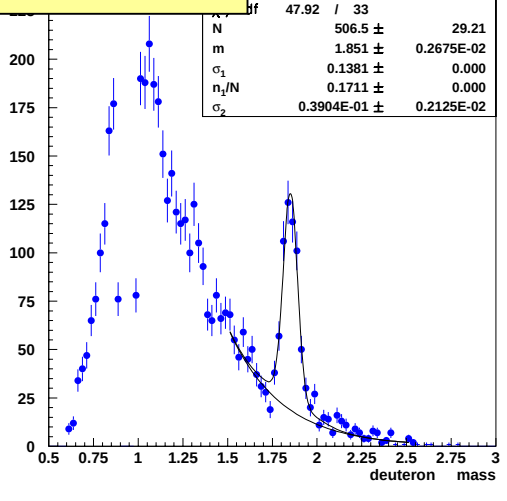


Exploited the very good PiD (RICH).

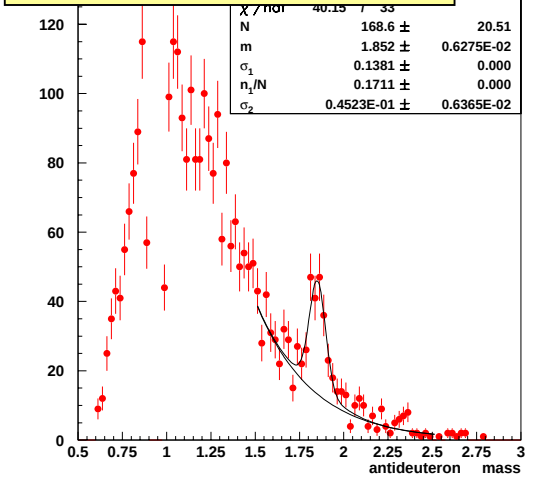
Cronin effect



Deuteron



Anti-Deuteron



Preliminary results

Cross section measurements.

Summary

- HERA-B was installed in 2000. Designed to face LHC equivalent particle flux and data rates 10 years in advance.
- Very important experience for the people involved, but also for many other experiments
- About 100 PhD theses finalized
- The physics data taking was in 2002-2003 (4 months)
- The physics program was limited by the statistics, but provided interesting results (e.g. QGP community)
- About 20 physics papers are foreseen:
  - 11 paper published,
  - 6 in advanced stage,
  - few analyses still ongoing

Conclusions

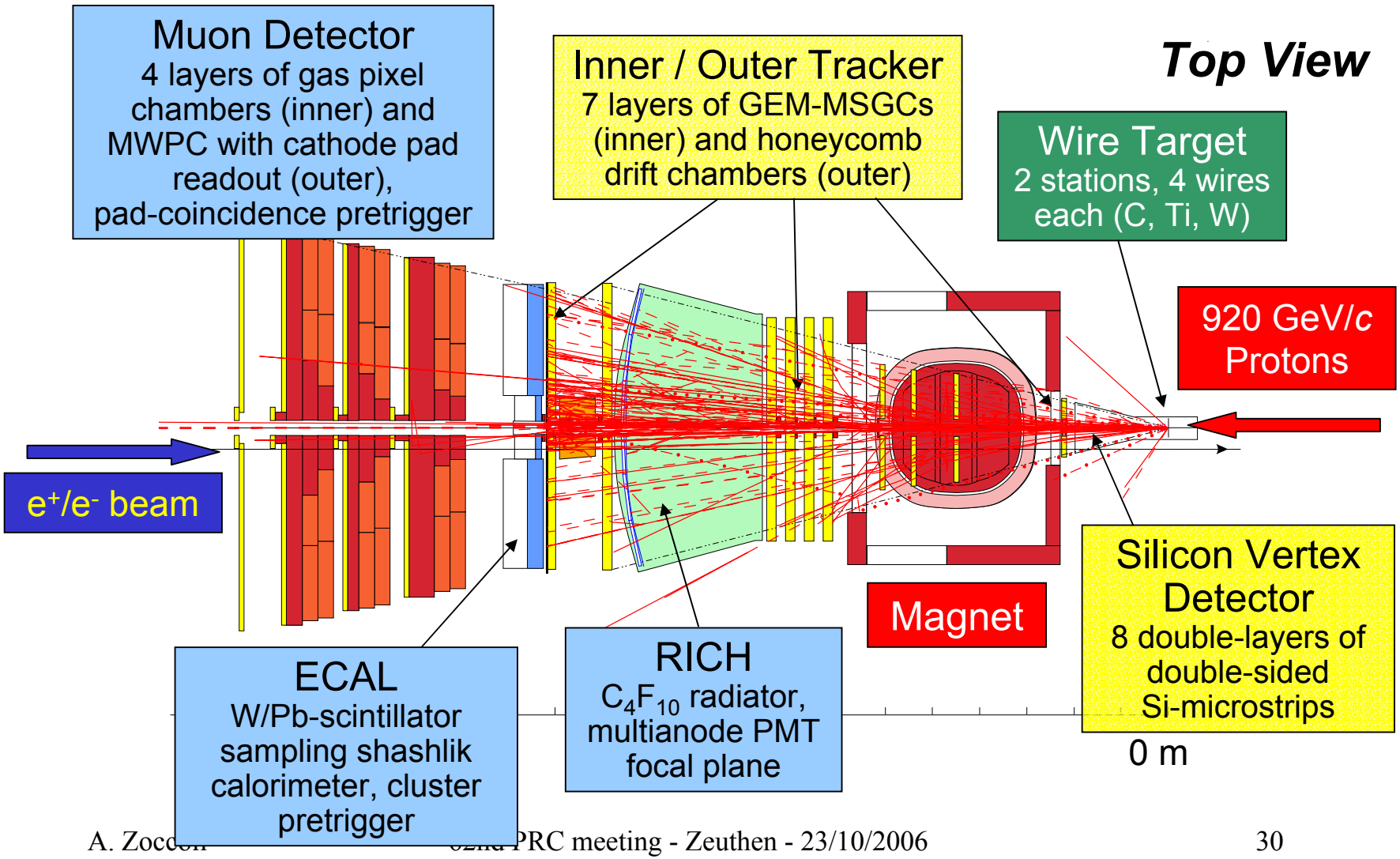
- HERA-B has been partly disappointing since our original ambitious goal could not be fulfilled. Nonetheless, valuable results have been achieved: detector and triggering/DAQ innovations, several published physics results, many successful former HERA-B students.

- HERA-B analysis activities are drawing to an end. The last results are being prepared for publication. At that point we will have produced results on all topics (and more) outlined in our May 2001 report to the PRC. (the basis for the PRC's approval for running after the HERA upgrade shutdown)

- We would like to thank the Directorate, the Laboratory, the PRC, the Referee's for their strong support and their guidance over the last decade. THANK YOU!

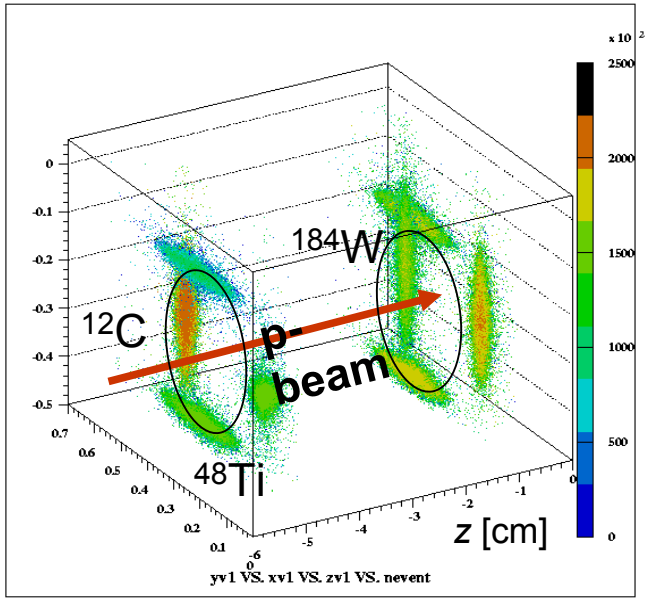
Backup Slides

The HERA-B Detector



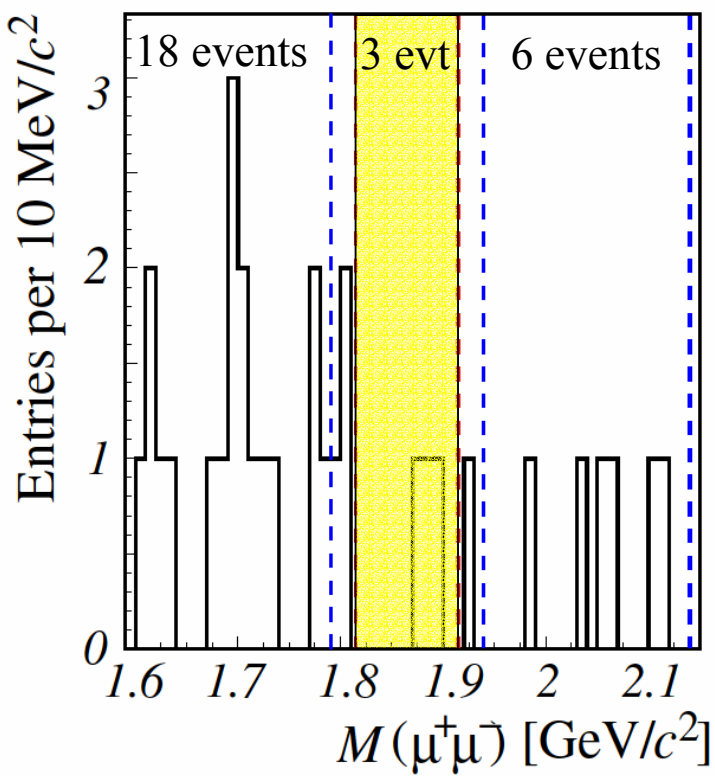
The HERA-B detector

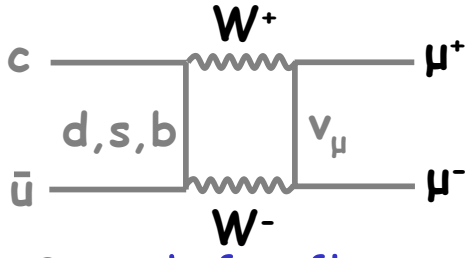
- p-Nucleus interactions at 920 GeV → $\sqrt{S}$=41.6 GeV
- BX crossing rate: 10 MHz → Up to $4 \cdot 10^7$ interactions/s (~5ev/bx)
- → Very sophisticated and challenging detector.
- Large central acceptance ($5 > \eta_{lab} > 2$)
- Capability to reconstruct the full event
- Very good particle ID for (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

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:

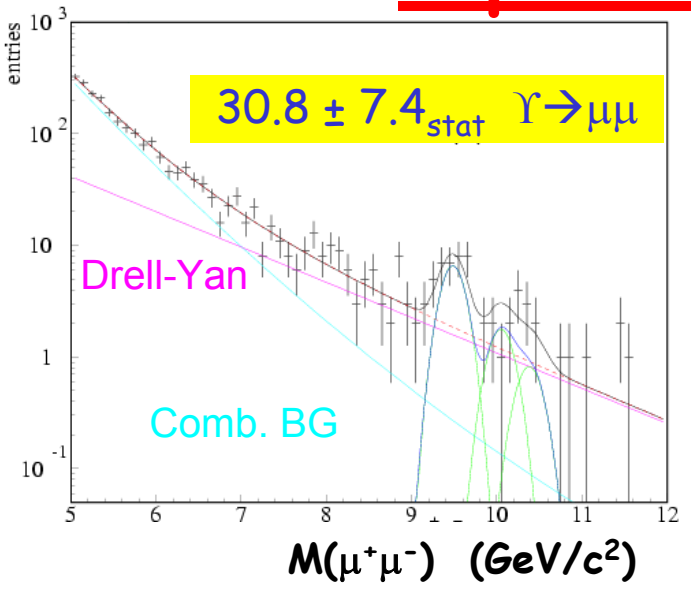
$BR(D^0 \to \mu^+\mu^-) < 2.0 \times 10^{-6}$ (90% CL)

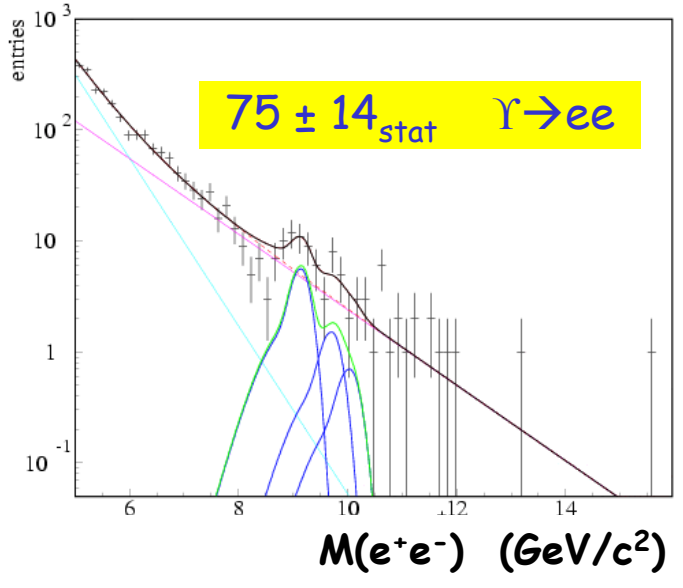
Phys.Lett.B596:173-183,2004

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) Phys. Rev. Lett. **93** (2004) 191801

Upsilon production

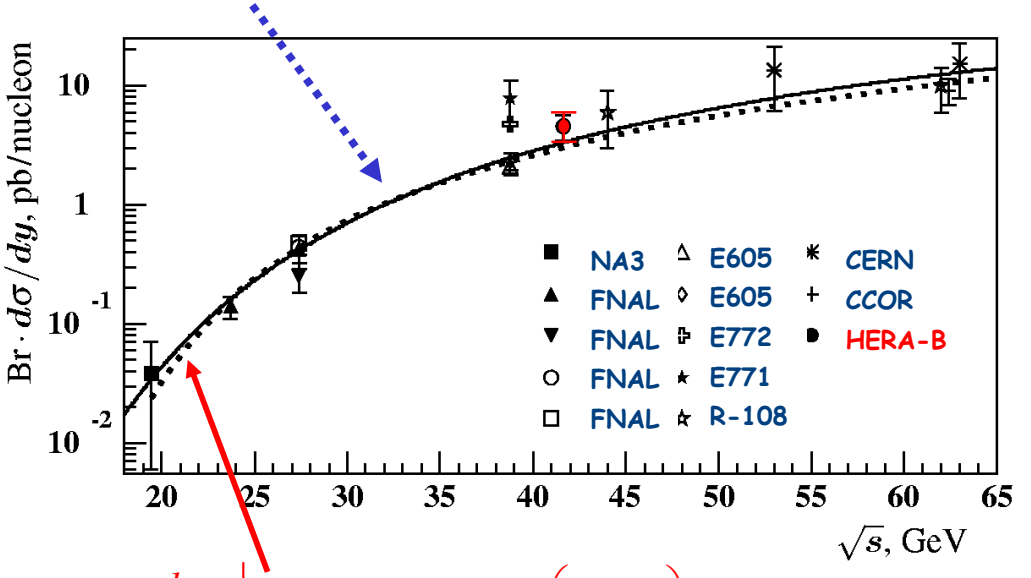




$pN \to \Upsilon + X, \quad \Upsilon \to \mu^+\mu^-, e^+e^-$

$$\frac{Br(\Upsilon \to l^+l^-)\cdot \frac{d\sigma}{dy}(\Upsilon)\big|_{y=0}}{Br(J/\Psi \to l^+l^-)\cdot \sigma_{J/\psi}} = \frac{n_\Upsilon}{n_{J/\psi}}\cdot\frac{\varepsilon^{J/\psi}}{\varepsilon^{\Upsilon}}\cdot\frac{1}{\Delta y_{eff}}$$

NLO/CEM calculations (hep-ph/0311048)



$$Br \times \left.\frac{d\sigma_\Upsilon}{dy}\right|_{y=0}(\sqrt{s}) = \sigma_o \exp\left(-\frac{m_o}{\sqrt{s}}\right)$$

Craigie parametrization

Decay angular distribution: polarization frames

Il Nuovo Cimento Vol. XXXIII, N. 2 (1964)

Gottfried-Jackson ("GJ")

target direction in the J/ψ rest frame = (-)J/ψ direction in the lab frame

reformulated as

2) "**BEAM**"

beam direction in the J/ψ rest frame

E615, E672-706, E771, E537, etc.

Phys. Rev. D16, 2219 (1977)

1) Collins-Soper ("**CS**")

bisector between **beam and (–)target directions** in the J/ψ rest frame

E866, NA3, etc.

3) helicity "**HCM**"

J/ψ direction in the hadron (p-n) **CM frame**

CDF, NA60, etc.

experimental situation: CS frame

J/ψ significantly polarized at low momentum (low p_T *and* $|x_F|$)