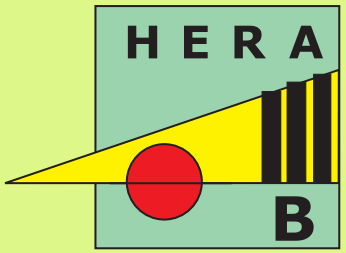


Heavy flavor production at HERA-B

Roberto Spighi, INFN Bologna Italy
For the HERA-B Collaboration

XIV INTERNATIONAL WORKSHOP ON DEEP INELASTIC SCATTERING 20-24 APRIL 2006, TSUKUBA

Outline and physics motivation

Heavy Flavor production at HERA-B

- *J/ψ inclusive production*
  - kinematical distributions, polarization
  - A-dependence
- *heavier charmonium states*
  - ψ' / J/ψ production ratios
  - fraction of J/ψ's from χ_c and b decays
- *Hidden beauty production ϒ(1-3 S)*
- *Open charm*
  - production ratios and A-dependence

Conclusions

Test of QCD predictions

results in the negative x_F range

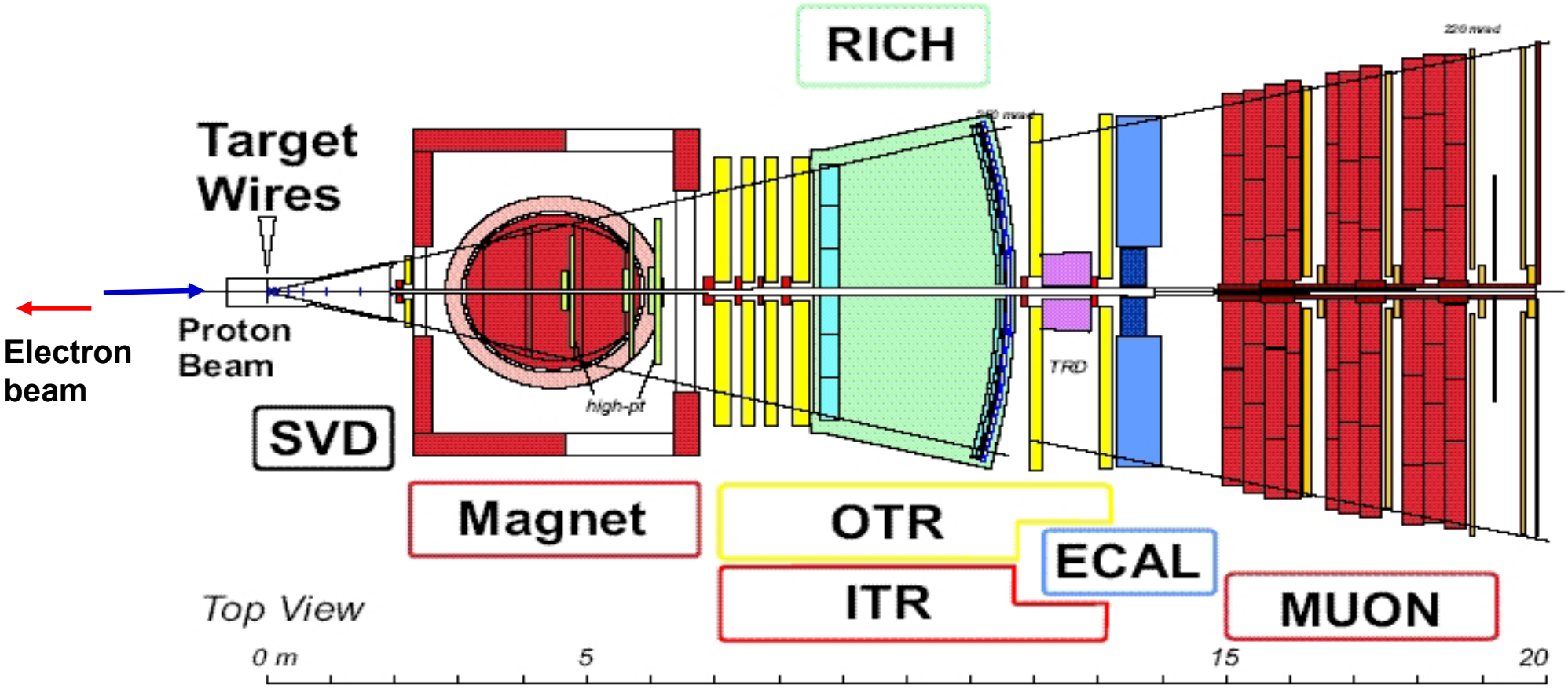
few results for J/ψ-ψ(2S) polarization

Investigation of nuclear effects

$\sigma(b\bar{b})$ and $R(\chi_c/J/\psi)$ few results with poor compatibility

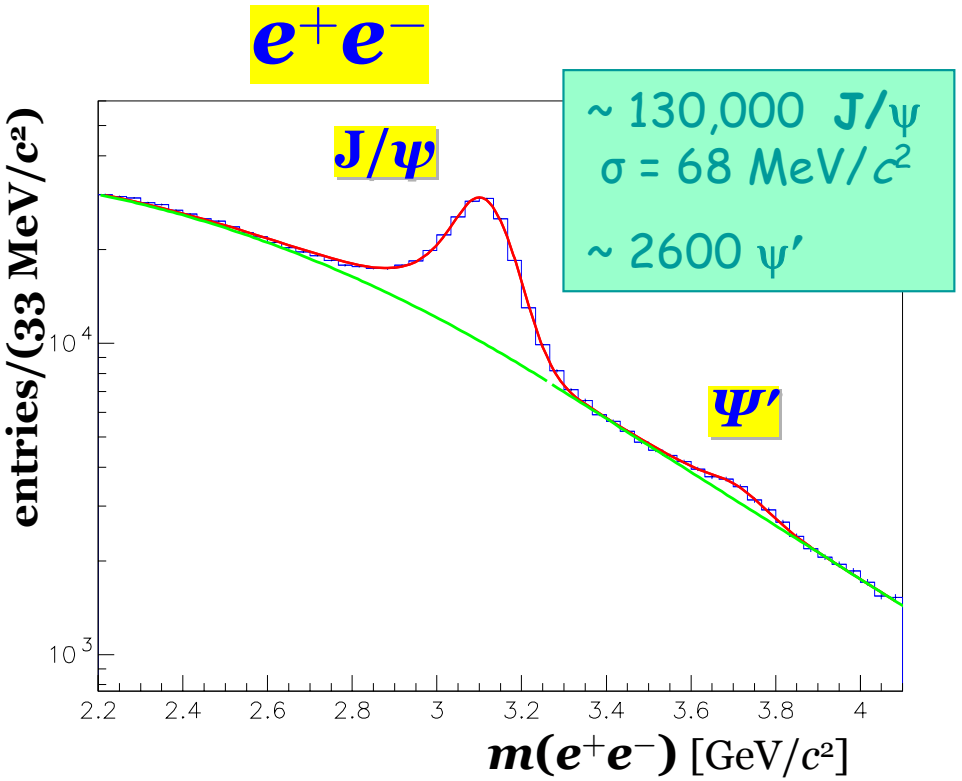
$\sigma(\Upsilon)$: testing ground for theoretical models

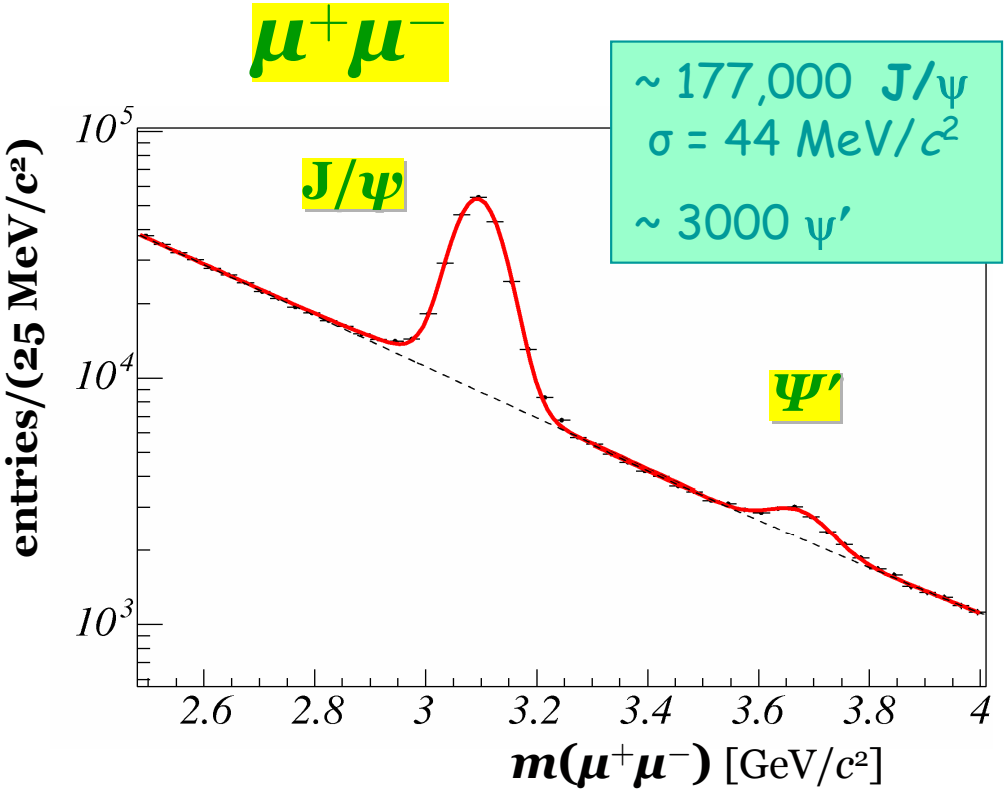
The HERA-B detector

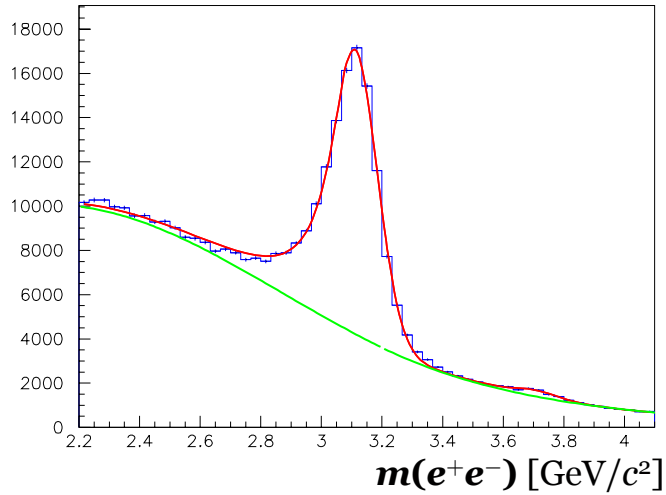


- **Fixed target** detector at HERA (DESY) — IR ~5 MHz
- **920 GeV/c** proton beam ($\sqrt{s}$ = 41.6 GeV)
- Di-lepton trigger (e^+e^- and $\mu^+\mu^-$)
- High angular coverage (15-220 mrad in bending plane)
- High resolution spectrometer — very good **particle ID** for (e, μ, π, K, p)

J/ψ and ψ' signals







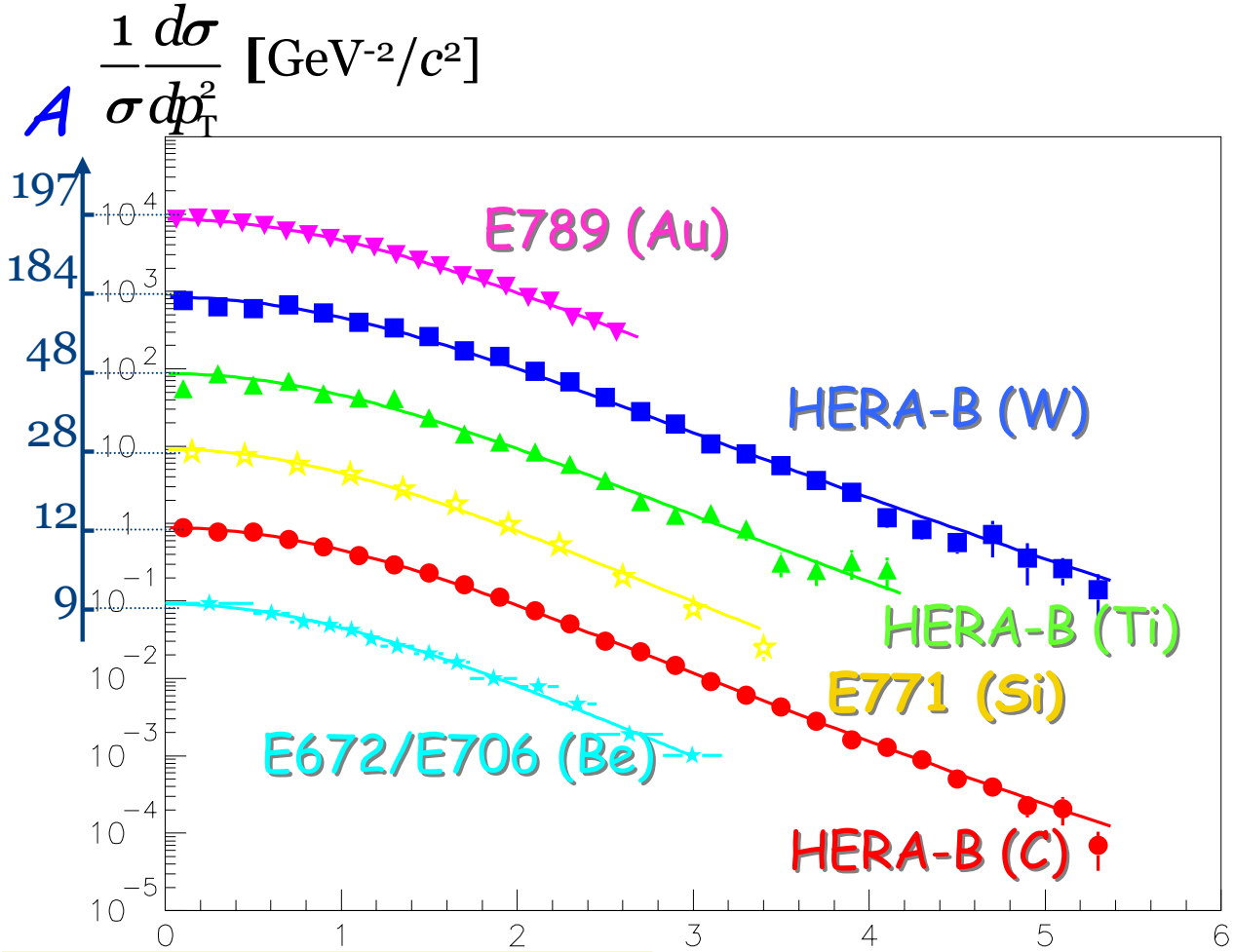
Al charmonium analyses performed in both di-lepton decay channels

For most analyses in electron channel selected sample with a strong PID (at least 1BR cluster) → 90 K J/ψ

J/ψ production: p_T distribution

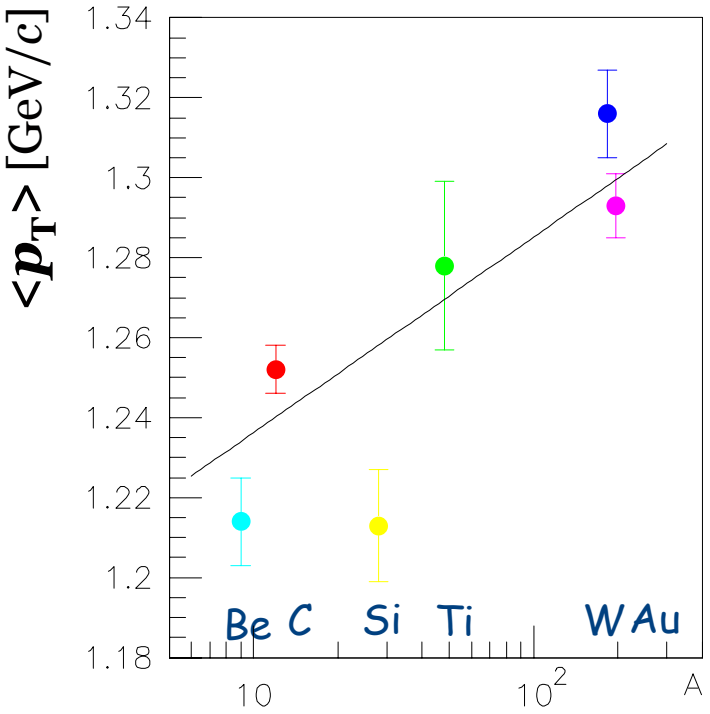
preliminary data (electron channel), compared with p-A results ($\sqrt{s}$=38.8 GeV)

agreement with muon channel in all distributions



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

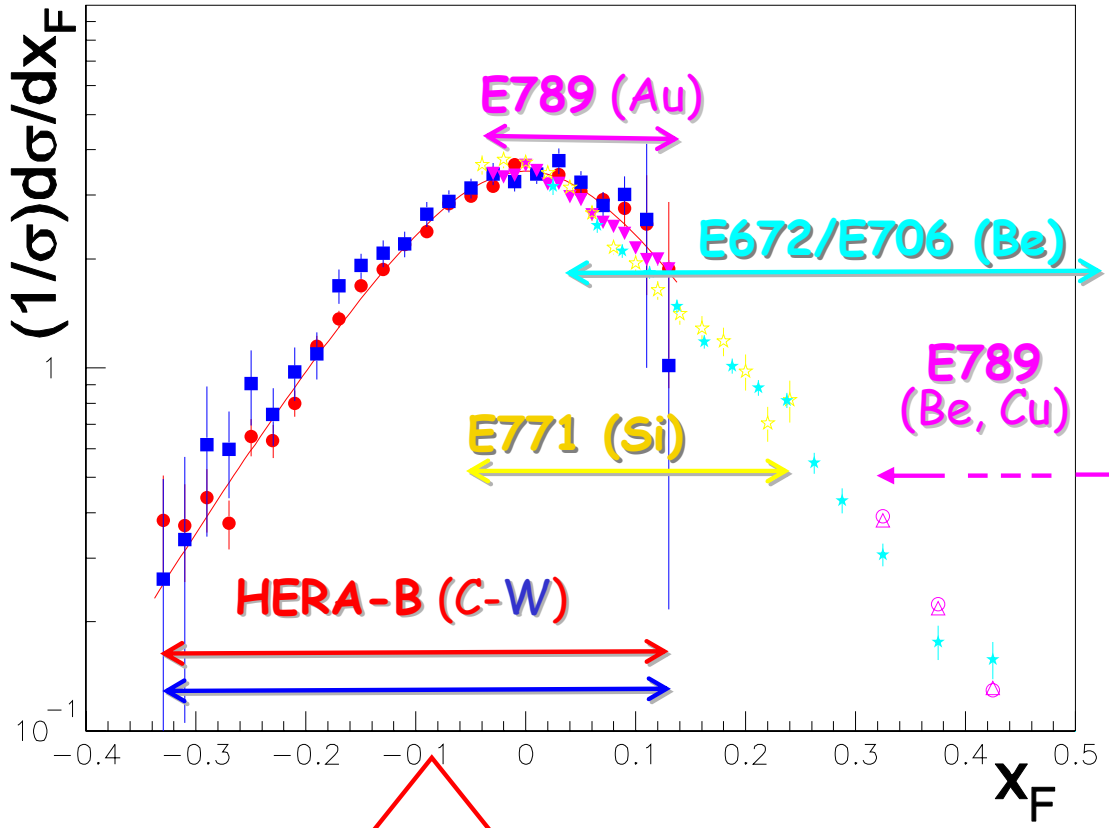
$\langle p_T\rangle$ grows logarithmically with A:



$$\frac{d\langle p_T\rangle}{d\ln A} = 0.021 \pm 0.003$$

J/ψ production: x_F distribution

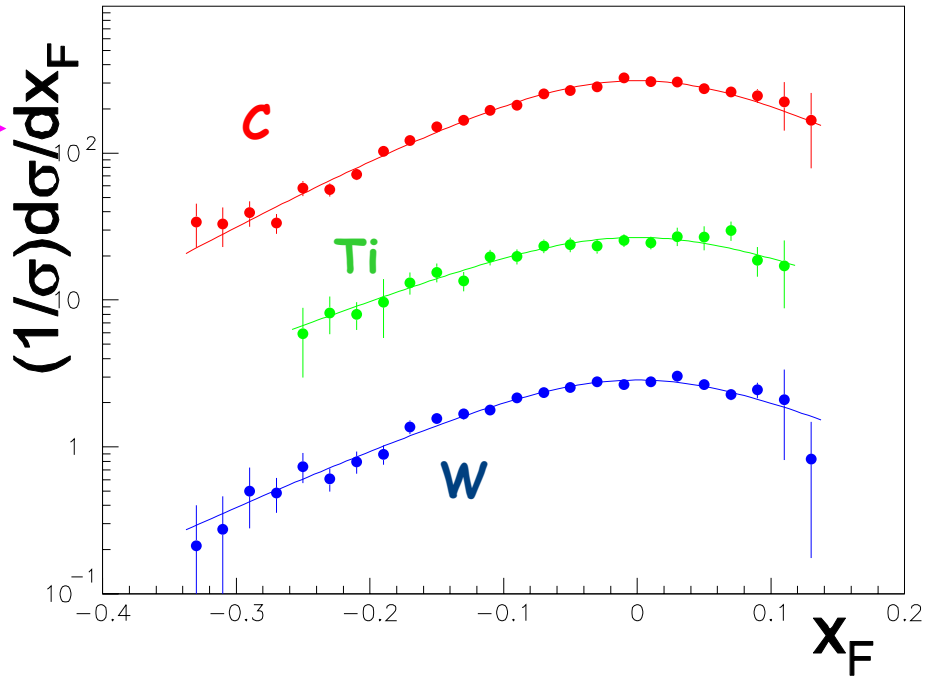
Preliminary data (e^+e^- sample), compared with p-A results at 38.8 GeV



fitting curves:

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

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



first data produced at negative x_F

$K \in [5:6]$

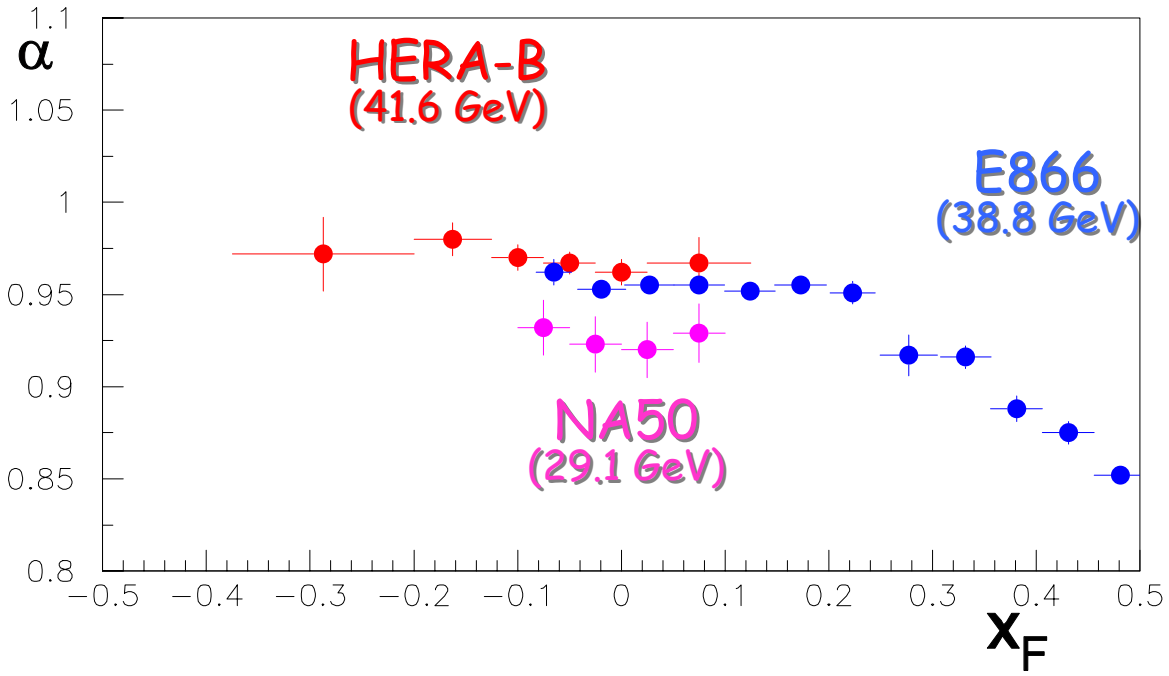
A dependence of J/ψ production

Parameterization of cross section: $\sigma_{pA} = \sigma_{pN} \cdot A^{\alpha}; \quad \sigma = \mathrm{N}/(\varepsilon \cdot L)$

$$\frac{d\sigma_{pA}/dx_F}{d\sigma_{pN}/dx_F} = A^{\alpha(x_F)}$$

Determine α from two different targets: C (A=12) and W (A=183.8)

$$\alpha = \frac{1}{\ln(A_W / A_C)} \cdot \ln\left(\frac{\mathrm{N}_W}{\mathrm{N}_C}\frac{L_C}{L_W}\frac{\varepsilon_C}{\varepsilon_W}\right)$$



x_F < 0: charmonium state formed **inside the target nucleus**

Study of initial and final state effects

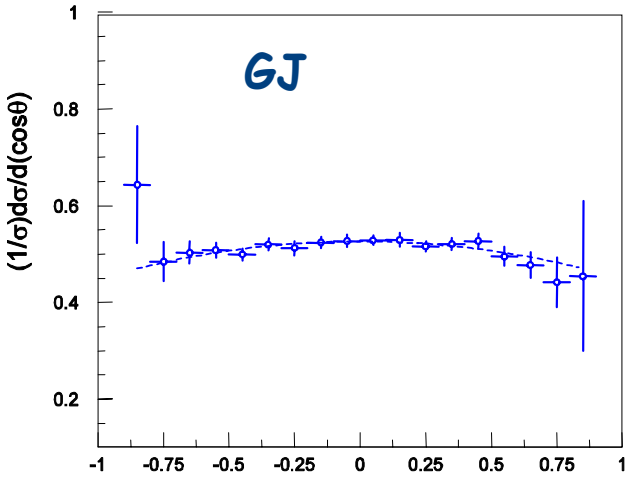
→ distinguish between different models

better agreement with E866 than with NA50 (energy dependence?)

x_F ~ constant, small suppression

J/ψ polarization

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



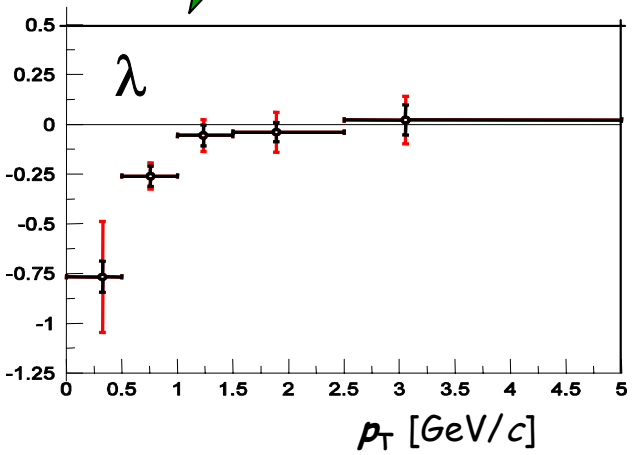
$d\sigma/d\cos\theta \propto 1 + \lambda\cos^2\theta$

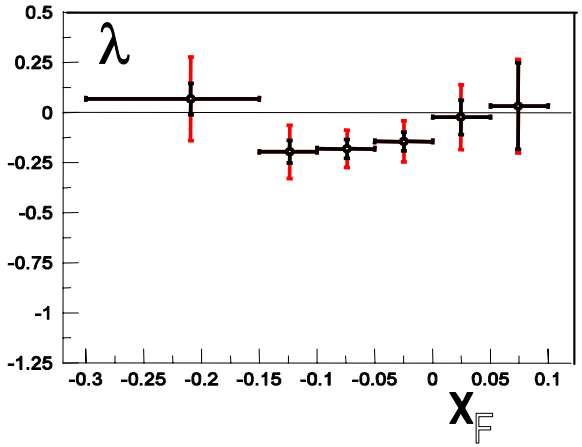
Preliminary for λ:
[-0.2,0.0] ±0.1

Same range as previous experiments →

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
E866	p-Cu @ 800 GeV	[+0.1 : -0.5] xf [0.3:0.9]

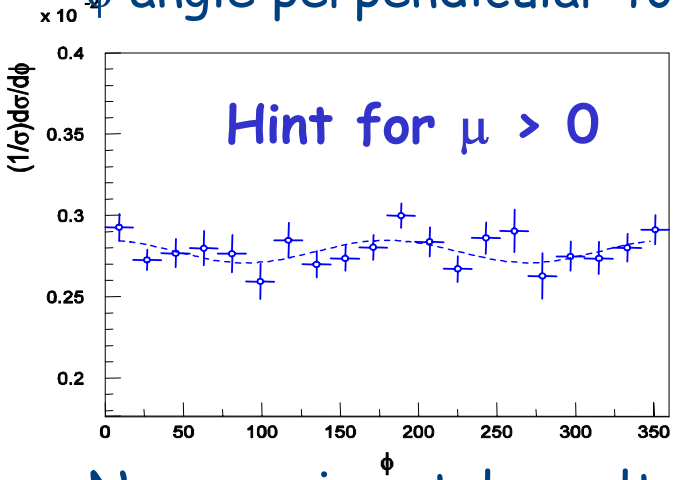
p_T ↘ x_F ↘





$d\sigma/d\phi \propto 1 + \mu\cos 2\phi$

φ angle perpendicular to θ



No experimental results
→important to study also φ

Also studied by CDF but at larger p_T

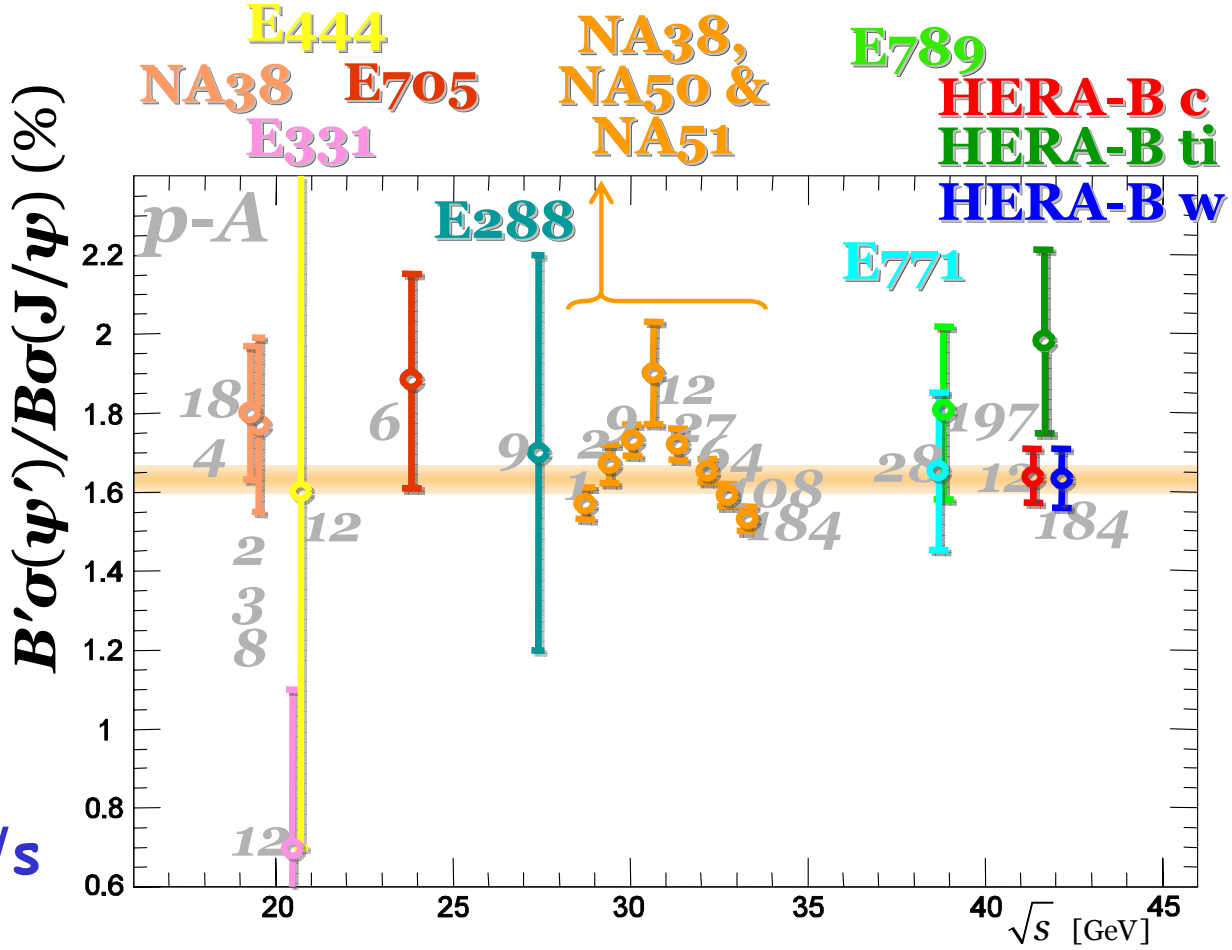
ψ' / J/ψ production ratio

ε → efficiency

Br →branch ratio

Measurement of $$\rho(\psi') = \frac{Br(\psi' \to \ell^+\ell^-)\cdot\sigma(\psi')}{Br(J/\psi \to \ell^+\ell^-)\cdot\sigma(J/\psi)} = \frac{N_{\psi'}}{N_{J/\psi}} \cdot \frac{\varepsilon_{J/\psi}}{\varepsilon_{\psi'}} =$$

$$= \begin{cases} (1.63 \pm 0.07)\% & C \\ (1.99 \pm 0.24)\% & Ti \\ (1.62 \pm 0.10)\% & W \end{cases}$$



Competitive measurements

No dependence wrt A and √s

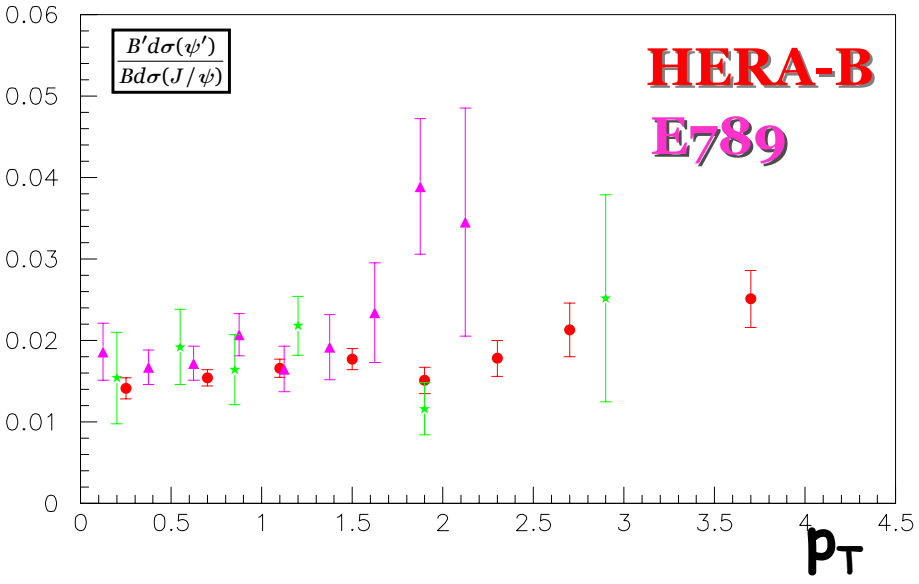
Ψ' production ratio: p_T and x_F distributions

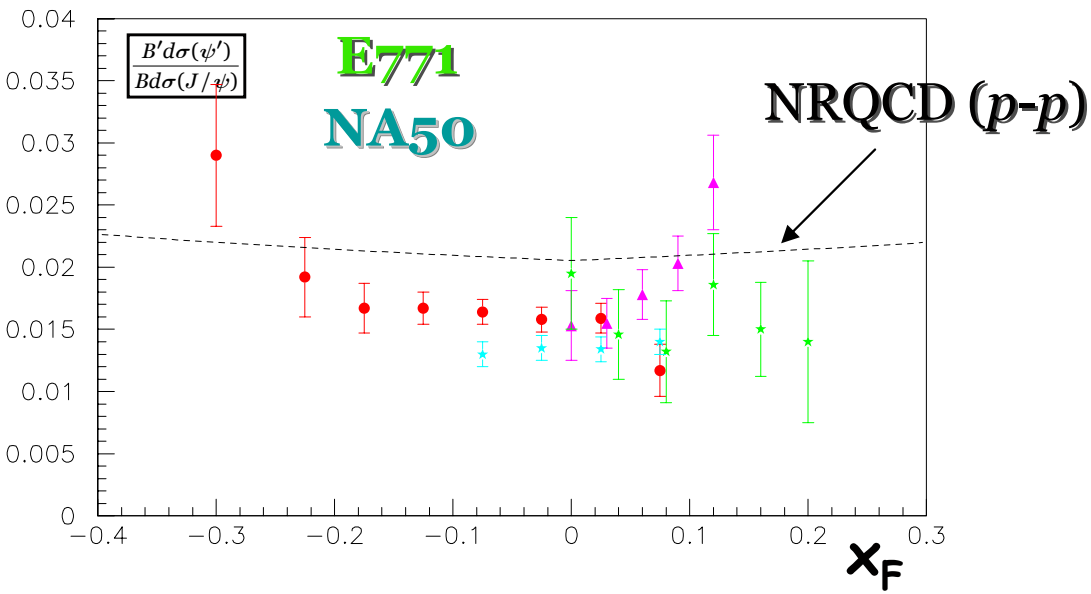
fraction of J/ψ from ψ': $R_{\psi'} = \rho_{\psi'} \times \frac{B_{J/\psi \to \ell^+\ell^-}}{B_{\psi' \to \ell^+\ell^-}} \cdot B_{\psi' \to \begin{cases} J/\psi\pi^+\pi^- \\ J/\psi\pi^0\pi^0 \\ J/\psi\eta \\ J/\psi\pi^0 \end{cases}} = (7.0 \pm 0.2 \pm 0.4_{BRs})\%$

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





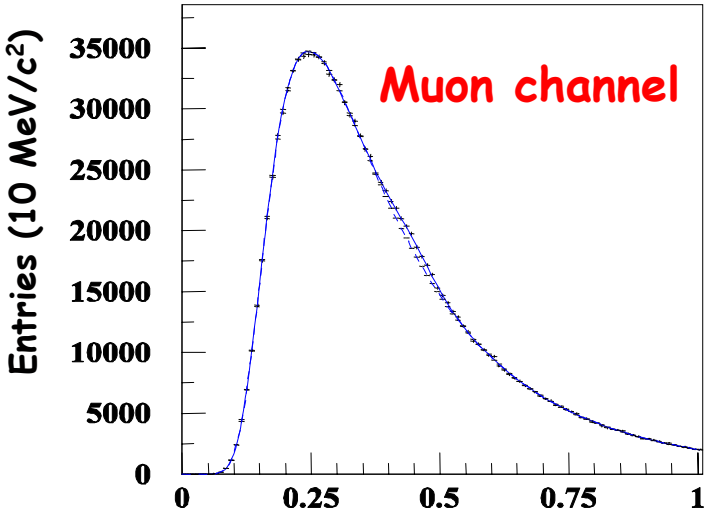
HERA-B measurements extend the range of the previous results with comparable or better precision

χ_c to J/ψ production ratio

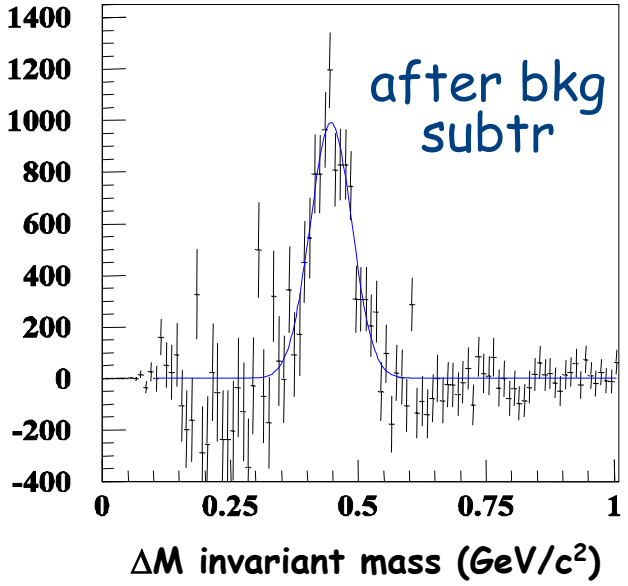
$$\chi_c \longrightarrow J/\psi\ \gamma \qquad \begin{cases} e^+e^- \\ \mu^+\mu^- \end{cases}$$

$$R_{\chi c} = \frac{\sum \sigma(\chi_{c(i)} \to J/\psi\gamma)}{\sigma_{\mathrm{INCL}}(J/\psi)} = \frac{N(\chi_c)}{N(J/\psi)} \cdot \frac{\varepsilon_{J/\psi}}{\varepsilon_{\chi\to J/\psi}\cdot\varepsilon_\gamma}$$

background: mixed events



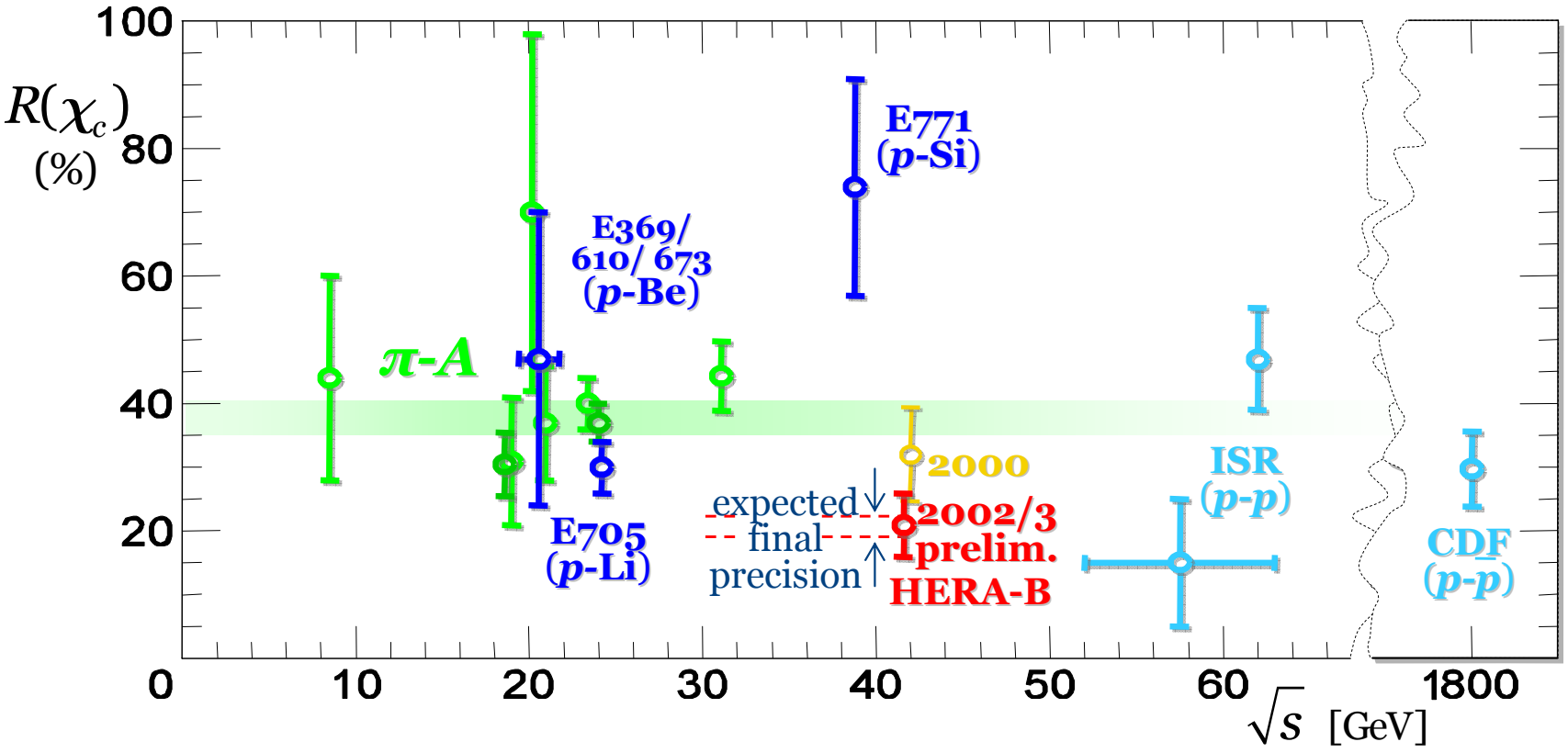
Result already published from the 2000 data
370 ± 74 χ_c's ($\mu^+\mu^-$ + e^+e^-):
$R(\chi_c)$ = 0.32 ± 0.06 ± 0.04
[Phys. Lett. B 561, 61 (2003)]



Preliminary: 2002/3 data
10080 ± 740 χ_c's ($\mu^+\mu^-$) 5870 ± 660 χc's (e^+e^-)
(the largest ever analyzed)

Fraction of J/ψ from χc → **$R(\chi c)$ = 0.21 ± 0.05**

$R_{\chi c}$ experimental situation



Not clear experimental panorama

Open beauty production

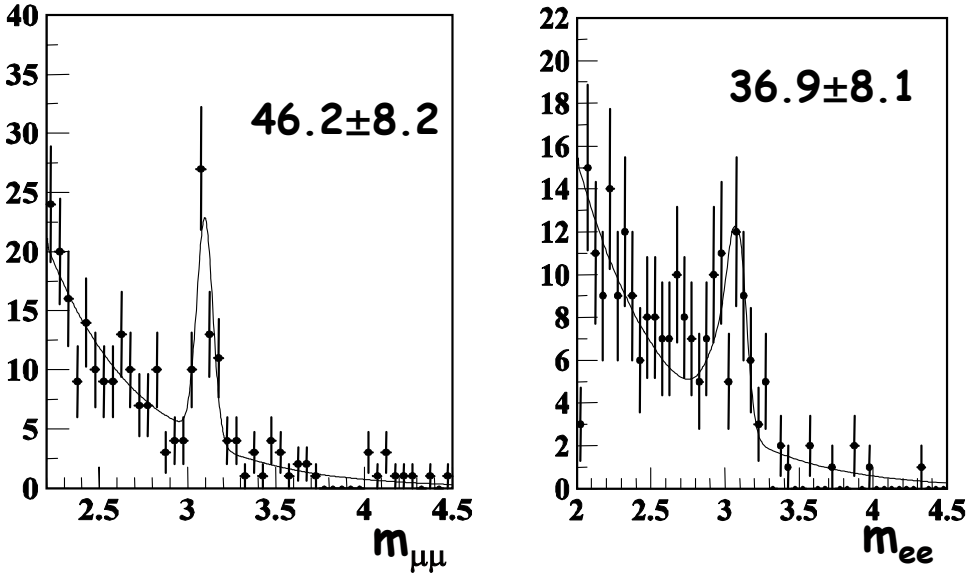
Phys.Rev.D73:052005

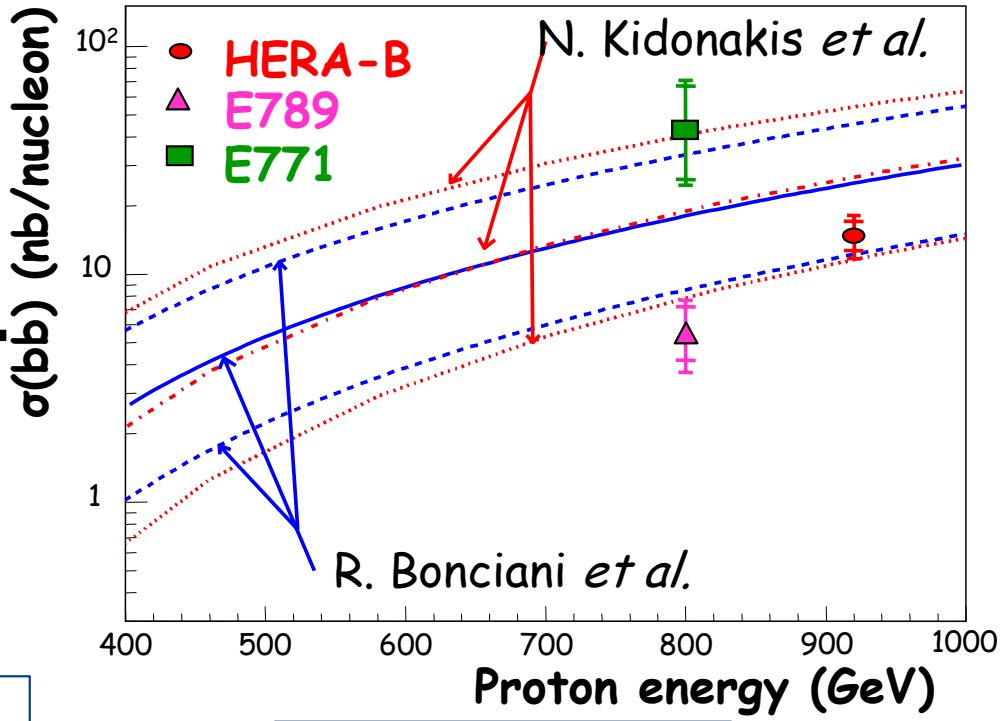
$R\Delta\sigma = 0.032 \pm 0.005_{stat} \pm 0.004_{syst}$

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

$pA \rightarrow b\bar{b} + X \qquad b \rightarrow J/\psi + Y$

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





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

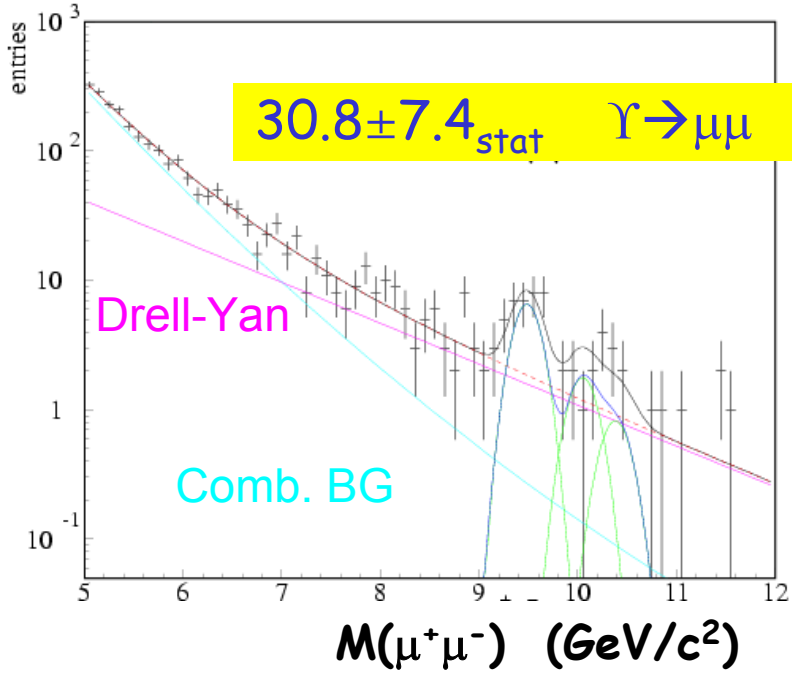
$$\sigma^{J/\psi}_{DIR} = \sigma^{J/\psi}_{TOT}\left[1 - R\left(\chi_c \rightarrow J/\psi\right) - R\left(\psi' \rightarrow J/\psi\right) - R\left(b \rightarrow J/\psi\right) - \cdots\right]$$

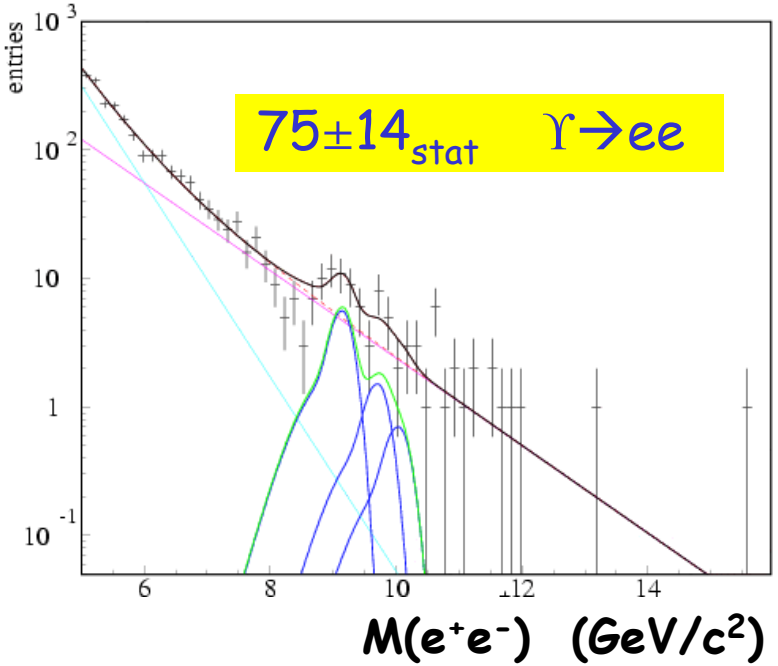
$\sigma^{J/\psi}_{pN}[41.6\ GeV] = (663 \pm 74_{stat} \pm 46_{syst})$ nb/nucl

extracted from MB

Hidden beauty production

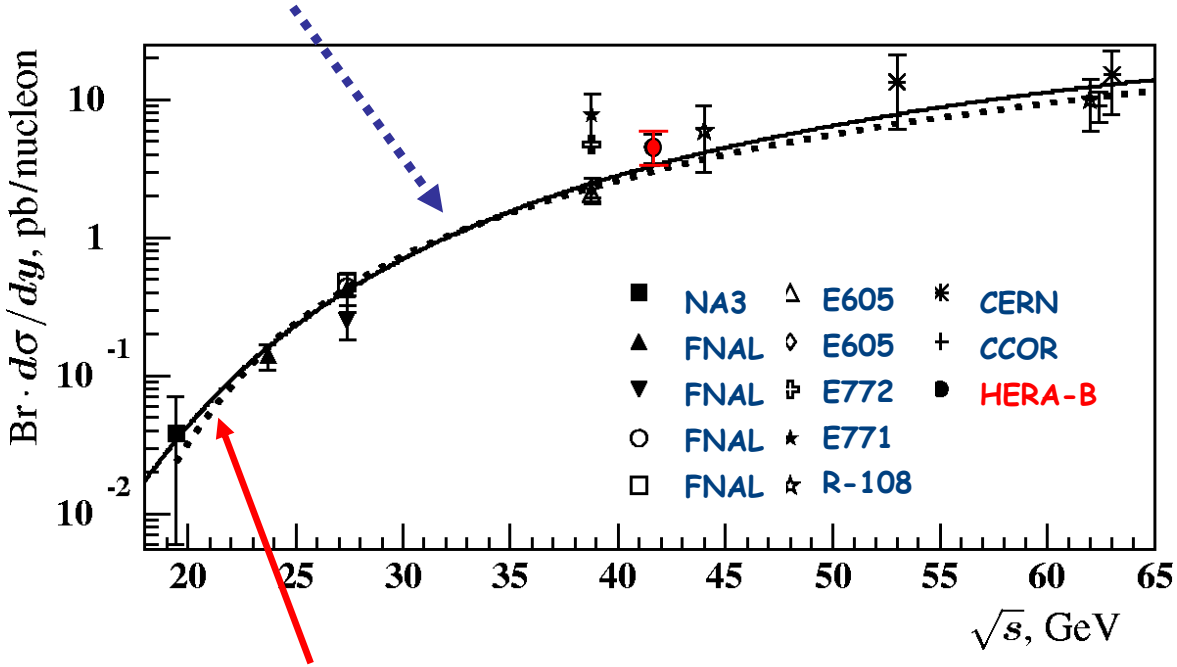
$pN \to \Upsilon + X, \quad \Upsilon \to \mu^+\mu^-,\ e^+e^-$





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

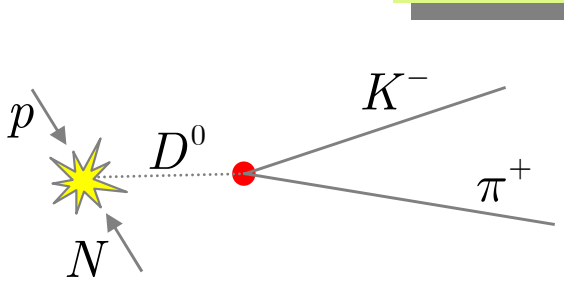
NLO calculation inside CEM (hep-ph/0311048)

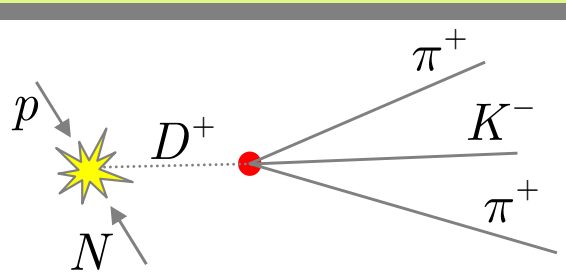


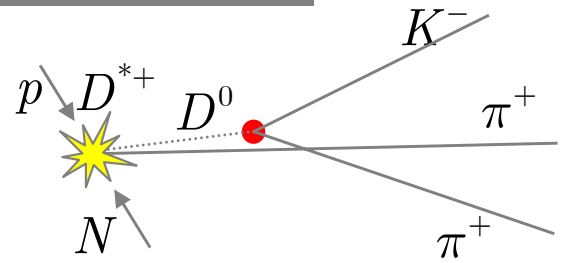
$$Br \times \left.\frac{d\sigma_\Upsilon}{dy}\right|_{y=0}(\sqrt{s}) = \sigma_o \exp\left(-\frac{m_o}{\sqrt{s}}\right)$$

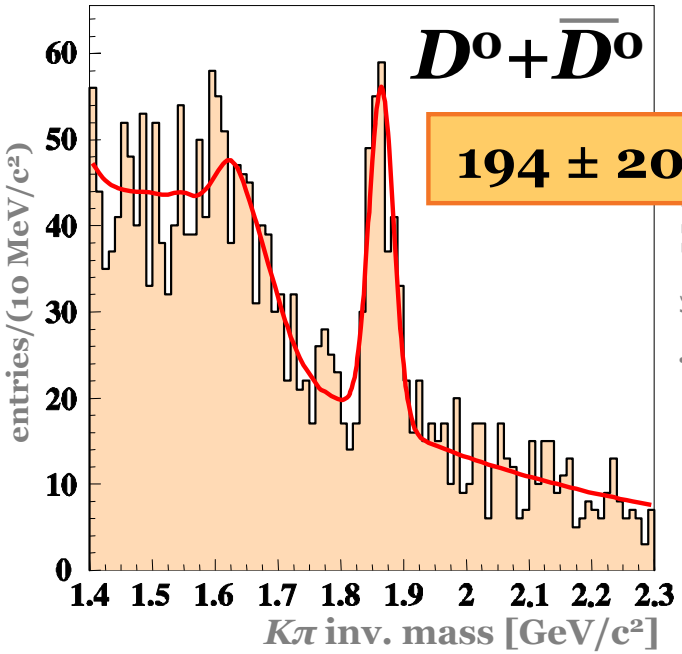
Craigie parametrization

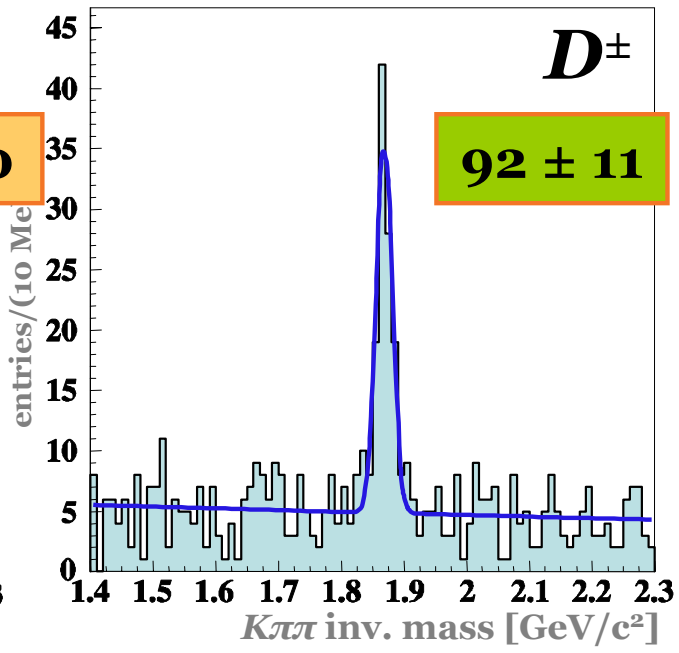
Open charm production: signals

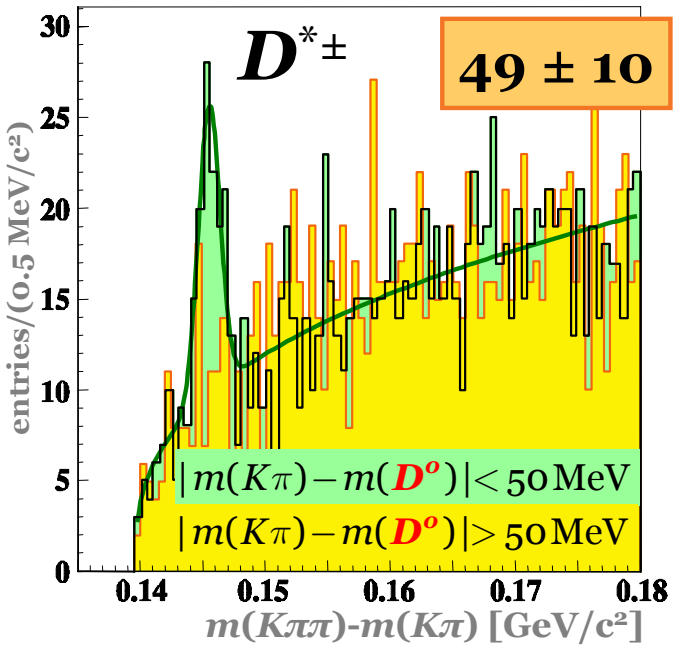




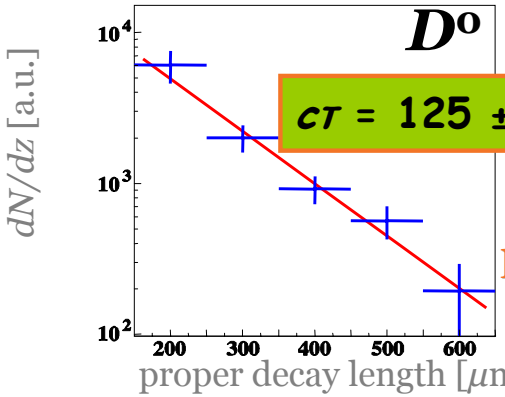




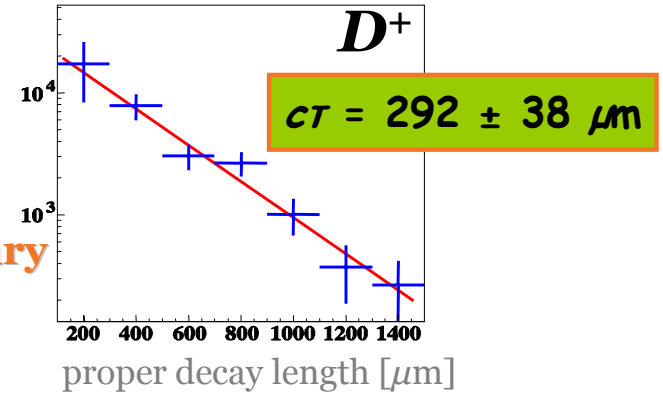




agreement with PDG values



preliminary



Open charm production: cross sections

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

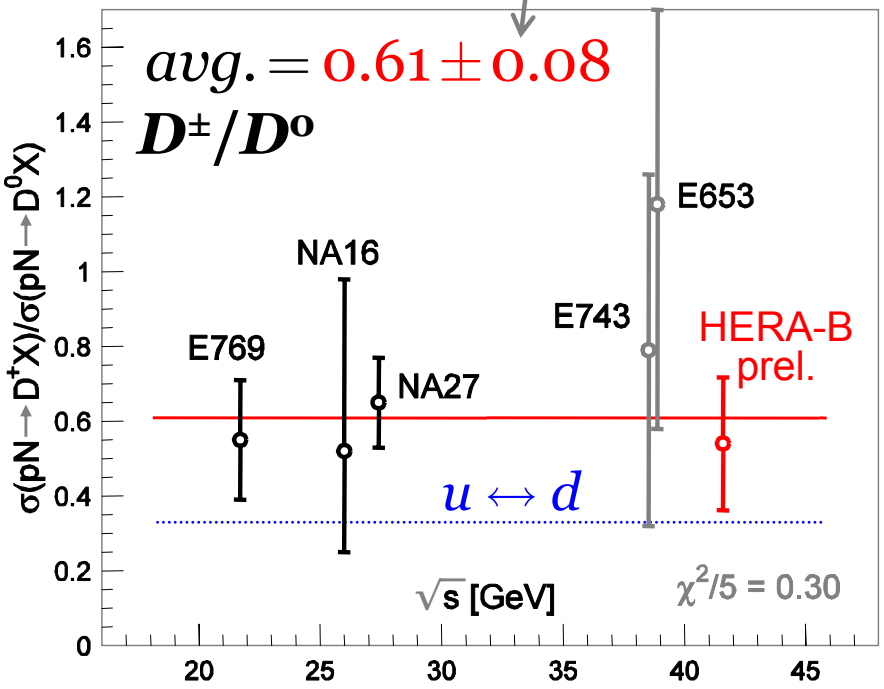
For Isospin symmetry and feeddown BRs, expected

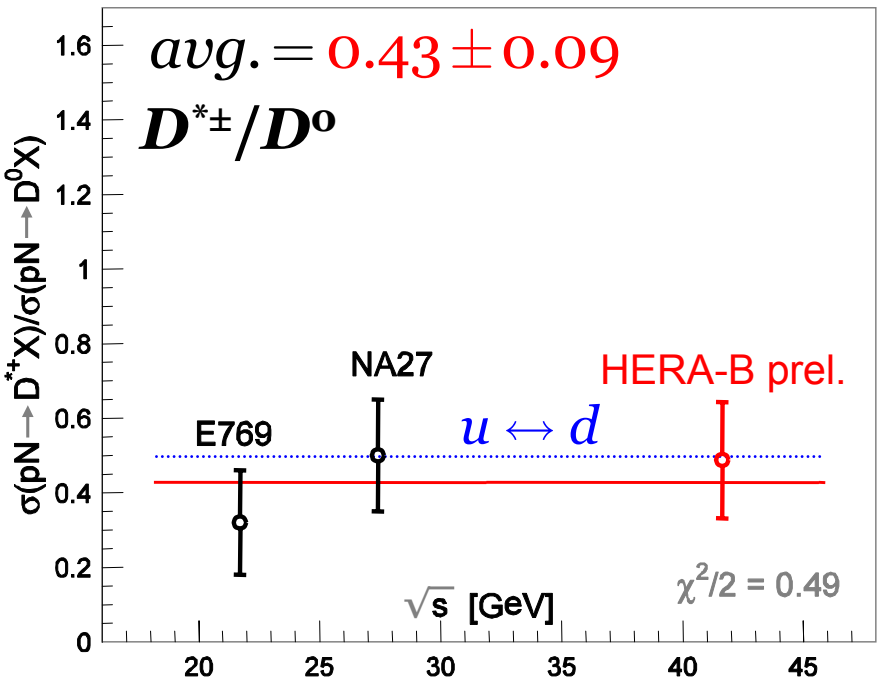
$$\sigma_{\mathrm{INCL}}(D^{\pm})/\sigma_{\mathrm{INCL}}(D^{0}) = 0.326 \pm 0.003$$

violated by 1.87±.25

$$\sigma_{\mathrm{INCL}}(D^{*\pm})/\sigma_{\mathrm{INCL}}(D^{0}) = 0.497 \pm 0.001$$

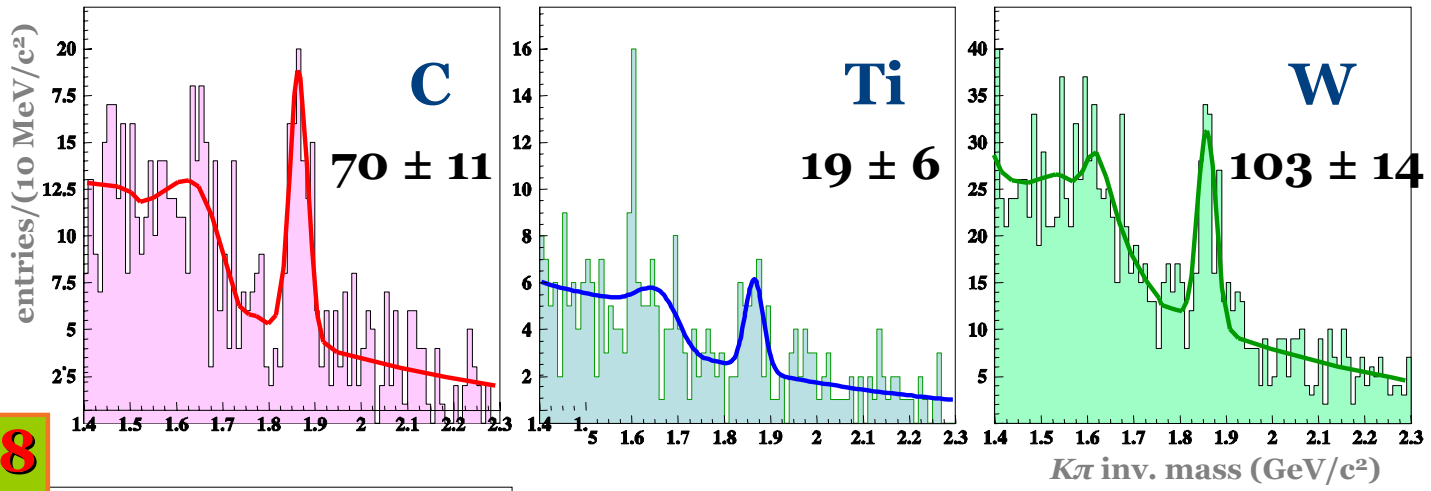
Important test for QCD





Open charm production: A dependence

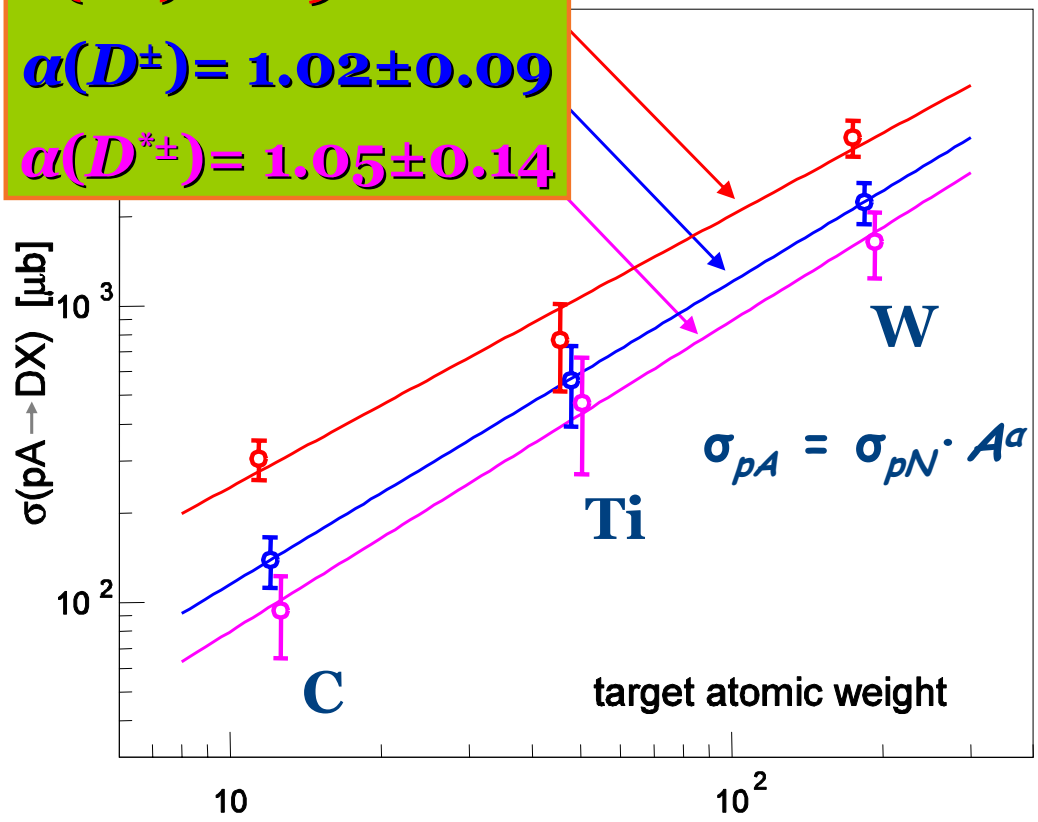
mass spectra
by target material
(e.g. for D^0):



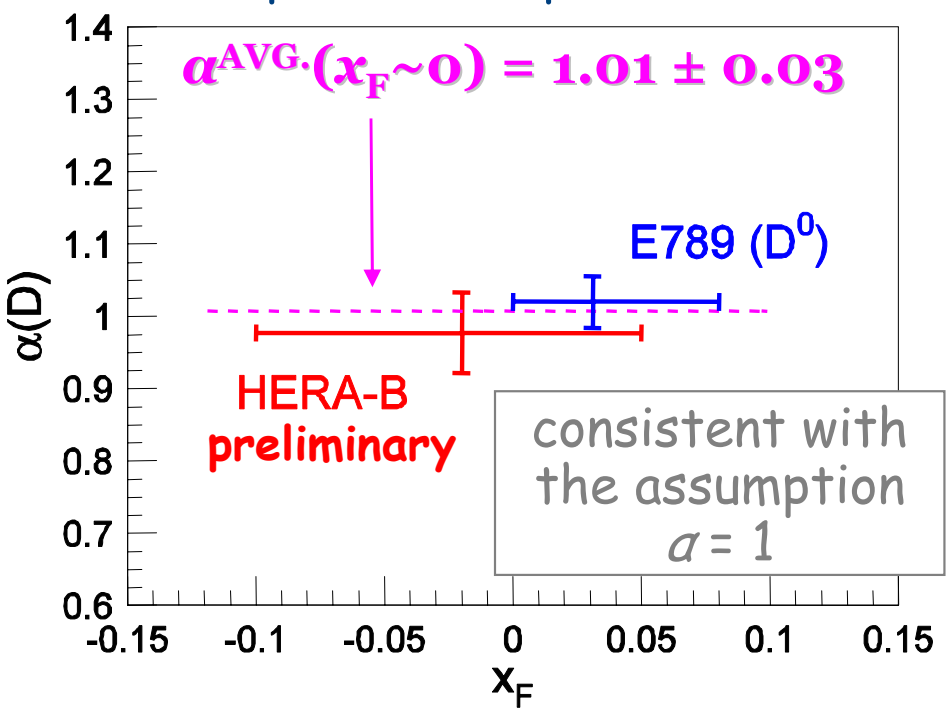
$\alpha(D^0) = 0.92 \pm 0.08$

$\alpha(D^\pm) = 1.02 \pm 0.09$

$\alpha(D^{*\pm}) = 1.05 \pm 0.14$



experimental panorama

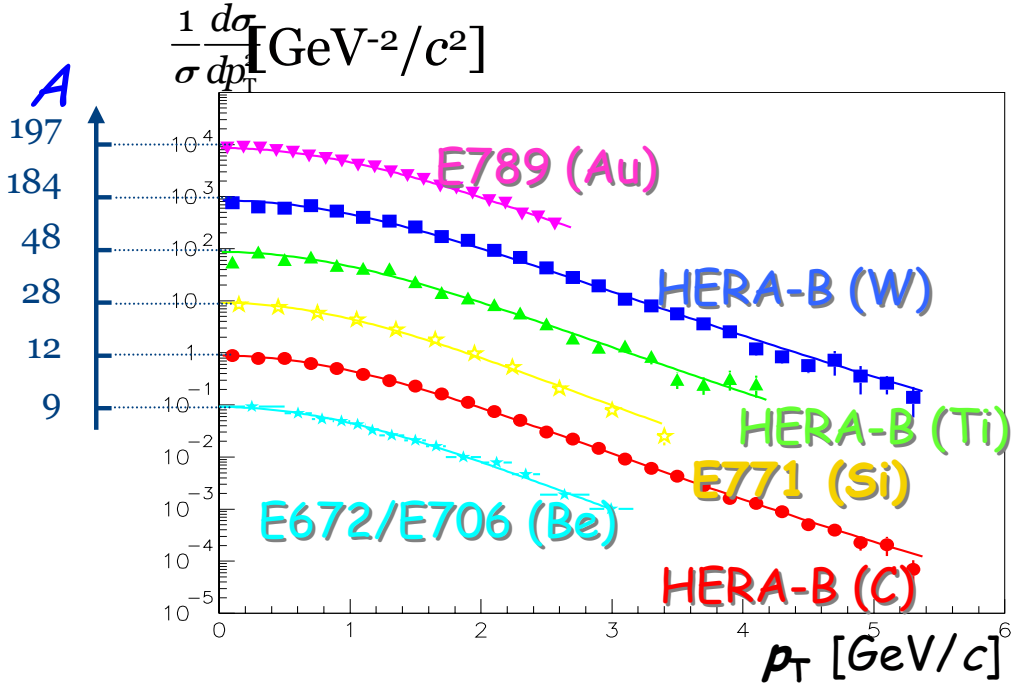


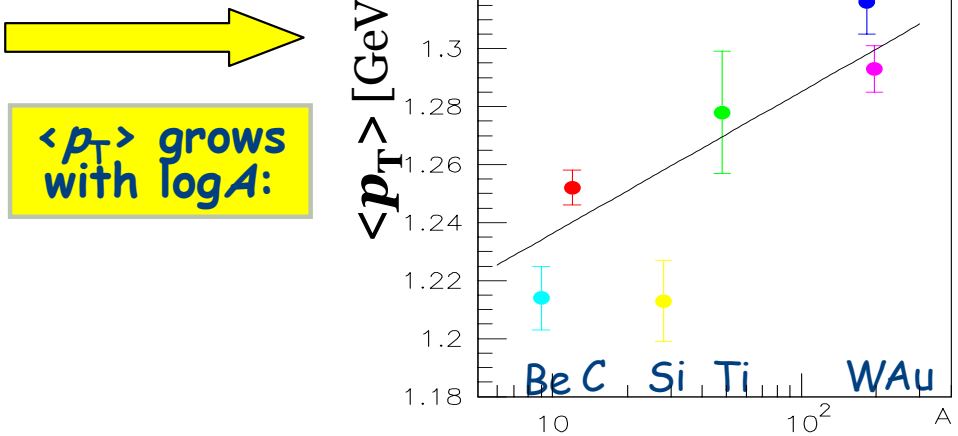
Conclusion

- Many physics topics addressed by HERA-B
- Detector
  - Large acceptance and good PID
- High statistics, clean signals
- Study on heavy flavor production
  - Detailed charmonium studies
    - wide kinematical coverage (p_T, x_F)
    - Two decay channels
    - Feeddown to J/ψ
    - Nuclear effects
  - Open charm cross sections
  - Open and hidden beauty production
- Extension of the previous experimental panorama

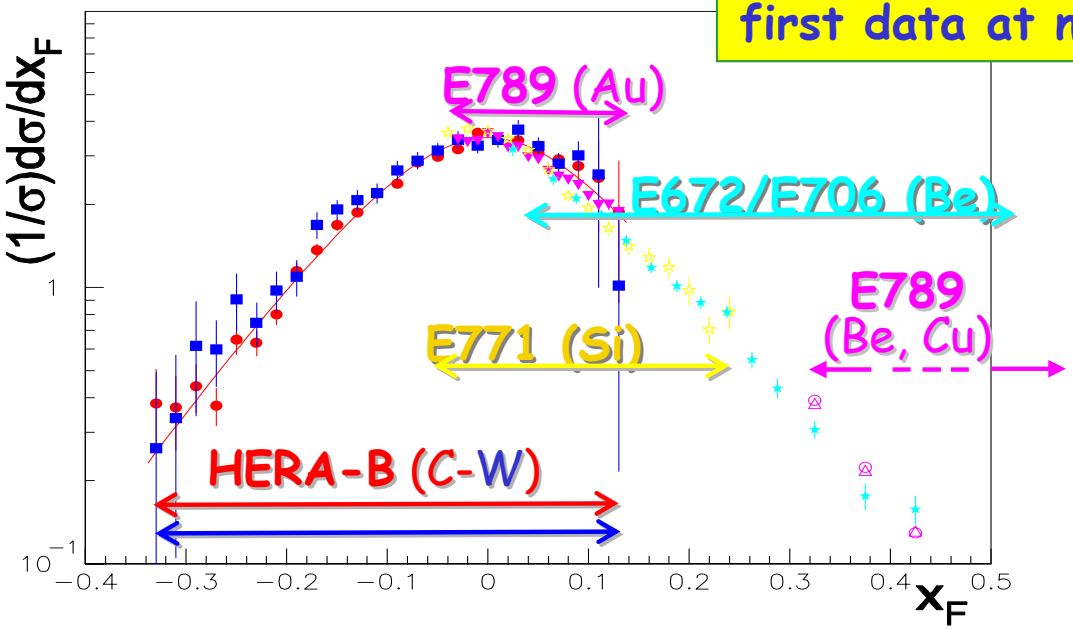
Summary slides

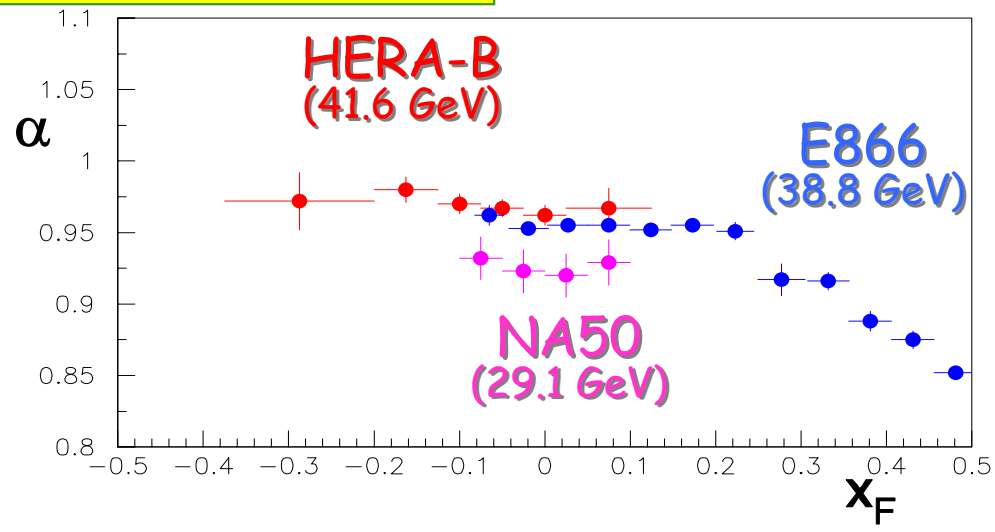
J/ψ production distributions and nuclear effects





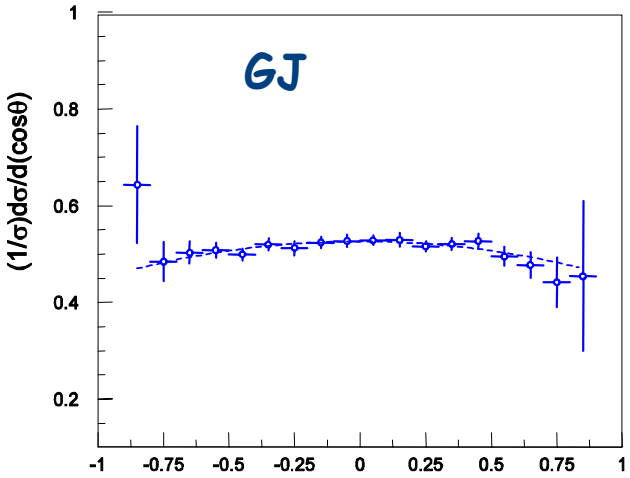
first data at negative x_F $K \in [5:6]$





J/ψ polarization

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



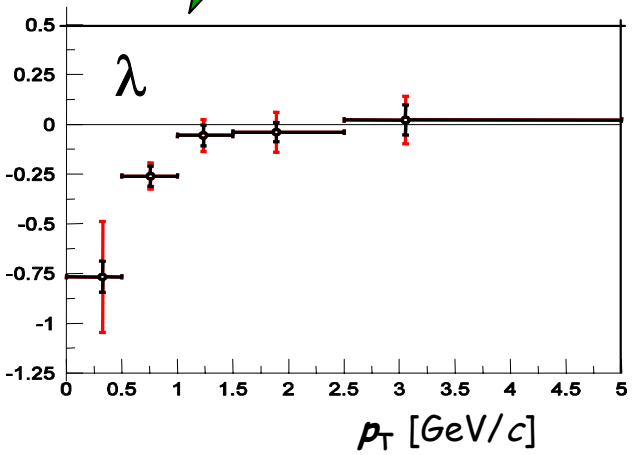
$d\sigma/d\cos\theta \propto 1 + \lambda\cos^2\theta$

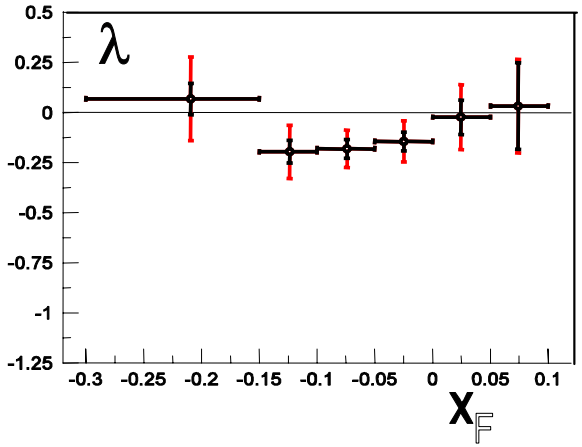
Preliminary for λ:
[-0.2,0.0] ±0.1

Same range as previous experiments →

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
E866	p-Cu @ 800 GeV	[+0.1 : -0.5] xf [0.3:0.9]

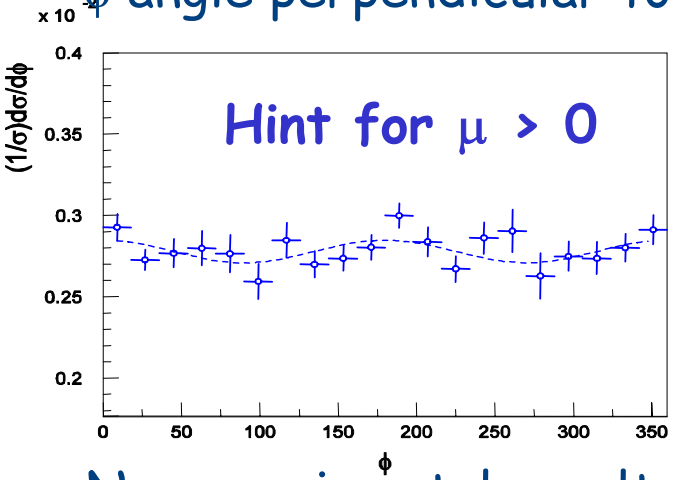
p_T ↘ x_F ↙





$d\sigma/d\phi \propto 1 + \mu\cos 2\phi$

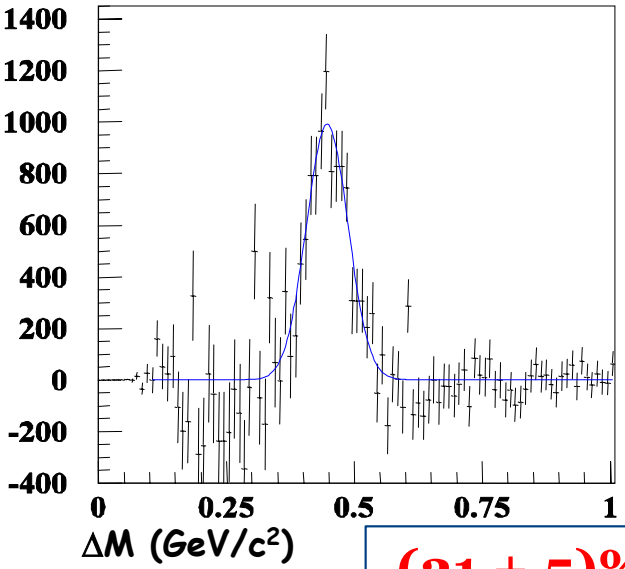
φ angle perpendicular to θ



No experimental results
→important to study also φ

Also studied by CDF but at larger p_T

Feeddown to J/ψ



15K χ_c's → J/ψ γ
(with J/ψ→ μ+μ- , e+e-)

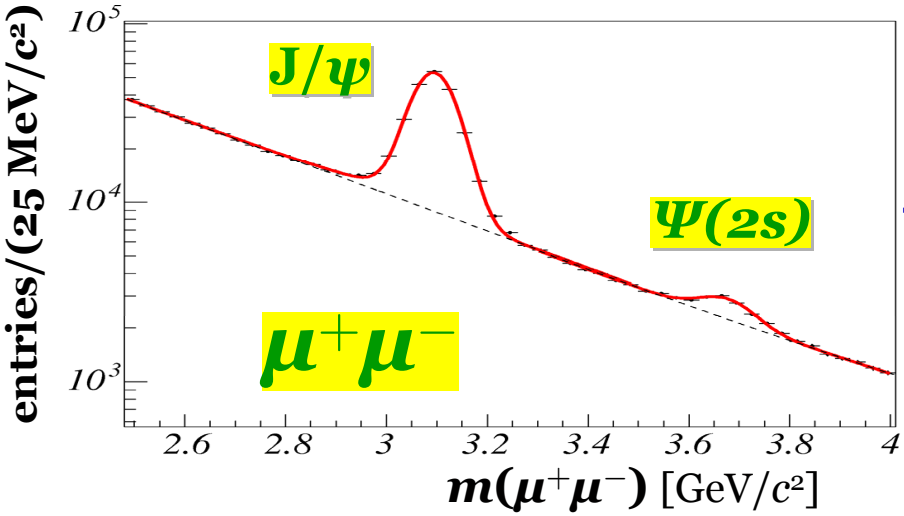
(21 ± 5)%

(7.0±0.4)%

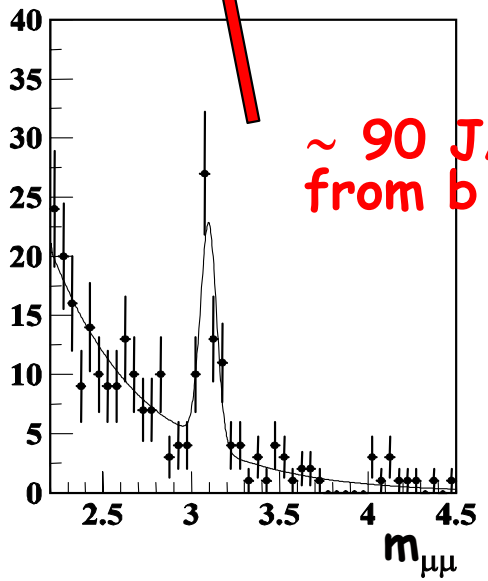
(0.065±0.011)%

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

$\sigma^{J/\psi}_{pN}[41.6\ \mathrm{GeV}] = (663 \pm 87)\ \mathrm{nb/nucl}$



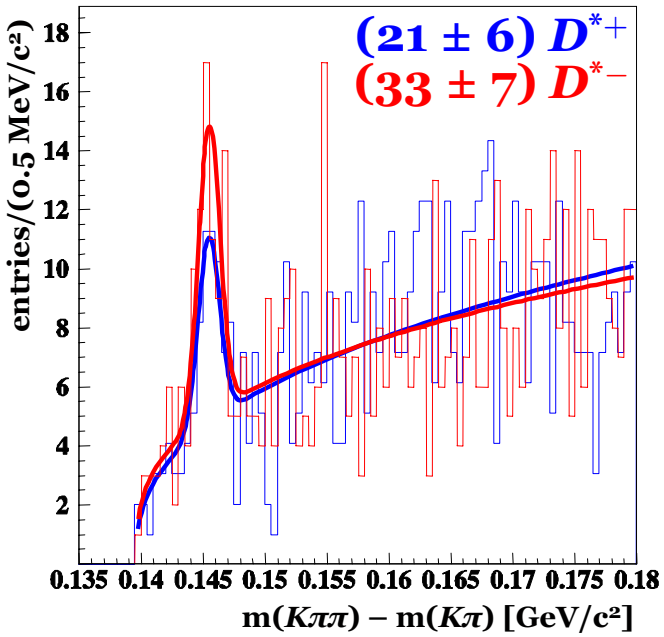
5.5K ψ(2S)
→ μ+μ- , e+e-



~ 90 J/ψ
from b decay

Spare slides

Preliminary results on particle-antiparticle asymmetry



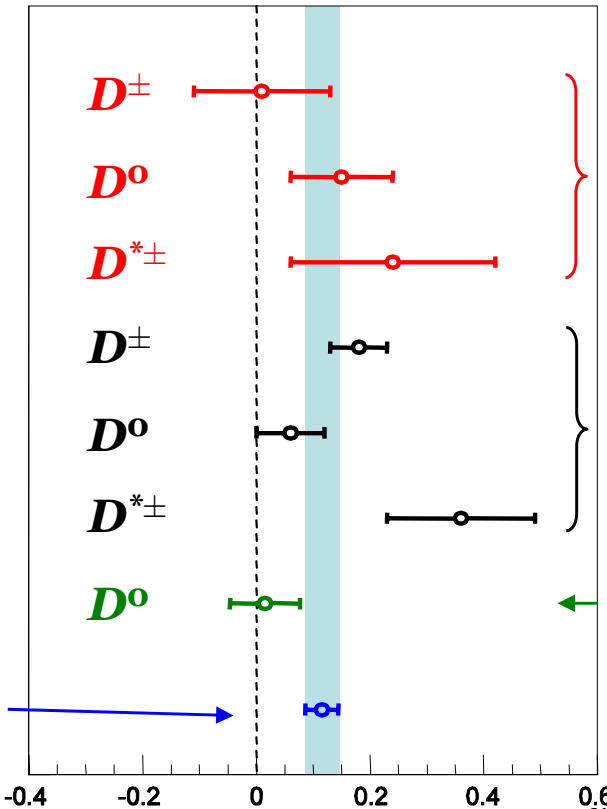
"Leading-Particle" asymmetries:

$$a_{LP} = \frac{\sigma_{LP} - \sigma_{nonLP}}{\sigma_{LP} + \sigma_{nonLP}}$$

LP: has a light quark in common with the beam particle

***p* beam: LP=antiparticle**

	Asymm.
$D^{\pm}$	0.01 ± 0.12
D^0	0.15 ± 0.09
$D^{*\pm}$	0.24 ± 0.18



HERA-B prel. (-0.1 < x_F < 0.05)

E769 (0 < x_F < 0.08)

E789 (x_F >0)

p-A "average" **0.12 ± 0.03**

pQCD: a_{LP} = 0 at LO and << 1 at NLO

J/ψ cross section: signals

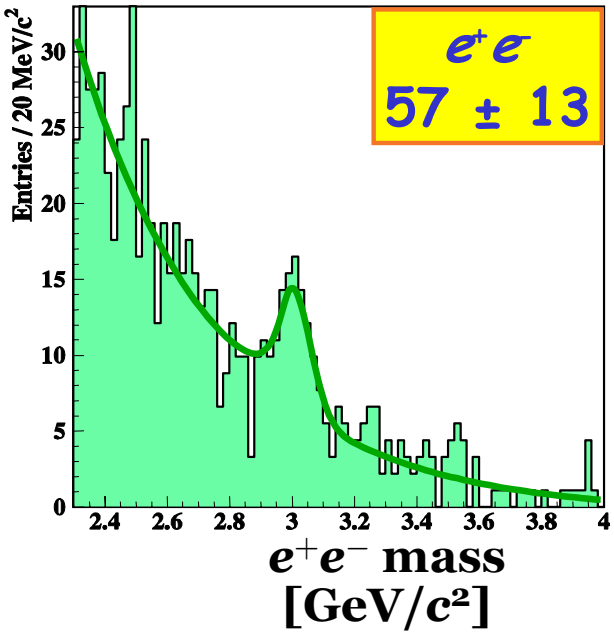
$$\sigma^{(A)}_{J/\psi} = \frac{N^{(A)}_{J/\psi \to e^+e^- / \mu^+\mu^-}}{Br(J/\psi \to e^+e^- / \mu^+\mu^-) \cdot \mathcal{L}^{(A)} \cdot \varepsilon^{(A)}}$$

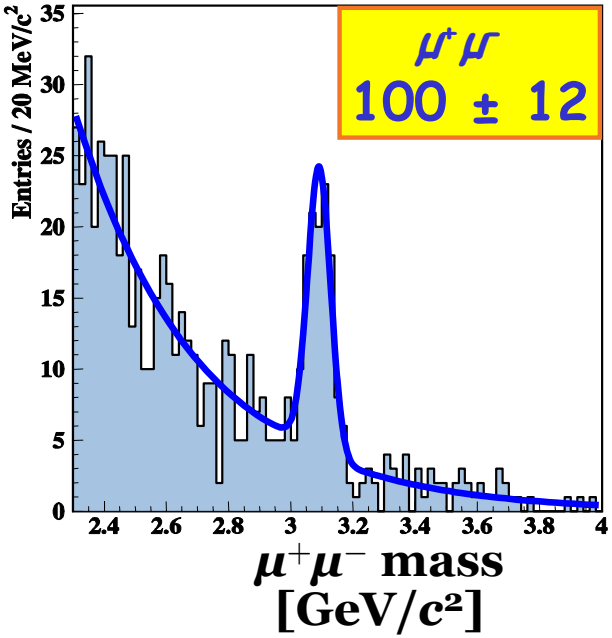
for each target material
(A = 12 [C], 48 [Ti], 184 [W])

N→ number of J/ψ ε → efficiency

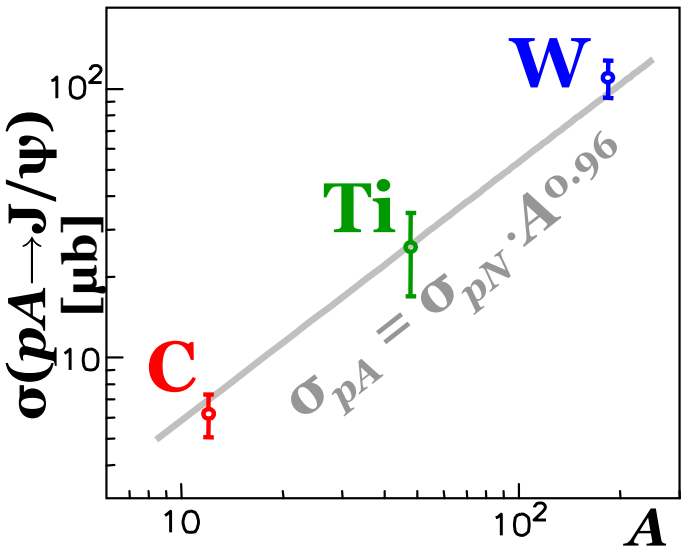
£ → Luminosity BR → branching ratio

inclusive **measurement**





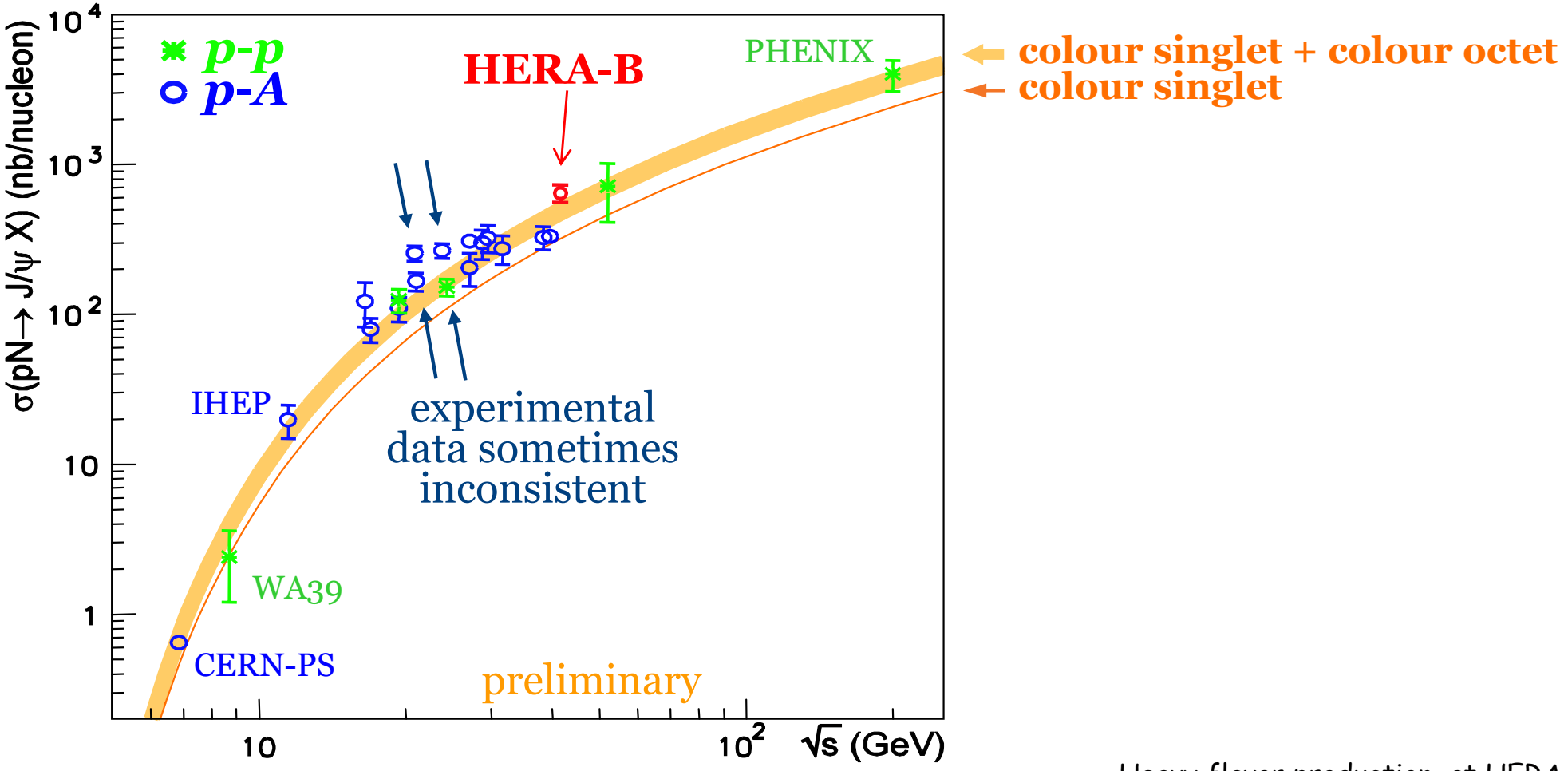
used **MB data** to minimize trigger systematics



$$\sigma_{pN}(J/\psi) = (663 \pm 74_{stat} \pm 46_{syst})\,nb/nucl$$

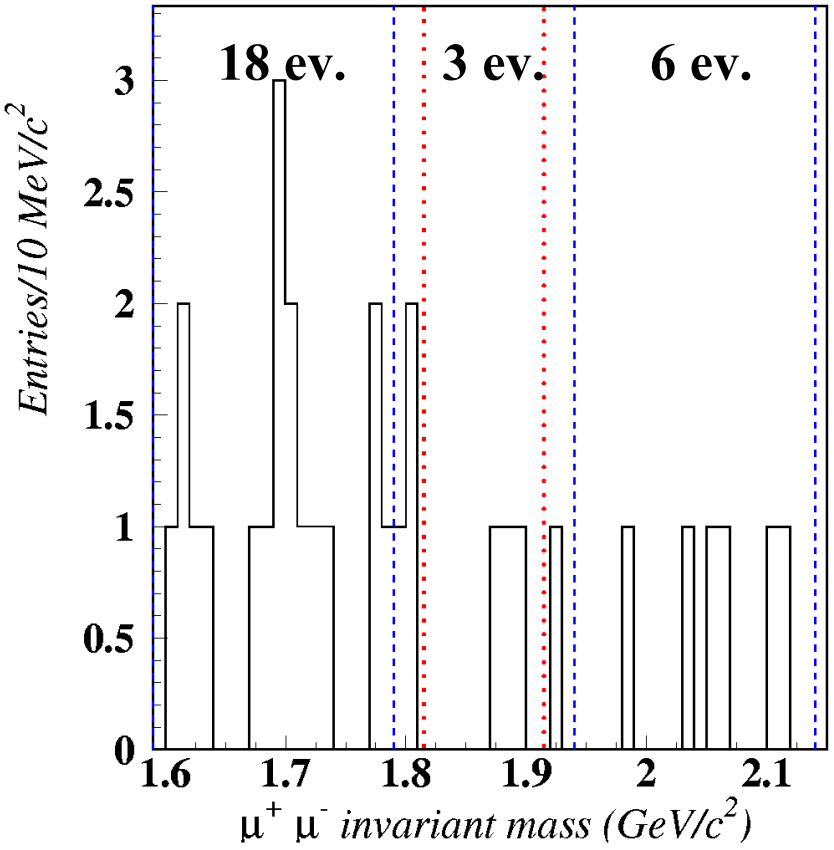
J/ψ cross section: experiments and theory

- σ_{pN} and σ_{pp} results with $\sqrt{s}$ from **6.8 to 200 GeV**
- all measurements corrected for the same **updated** BRs and *A*-dep. parameter
- theoretical curve: **fit** to **J/ψ** measurements + **ψ'** cross sections and **ψ'/ψ** production ratios (29 results in all) in the context of **NLO NRQCD** (F. Maltoni)



$D^0 \rightarrow \mu^+\mu^-$

expected BR for Standard Model ~ 10^{-19}
supersimmetric model enhances to ~ 10^{-7}



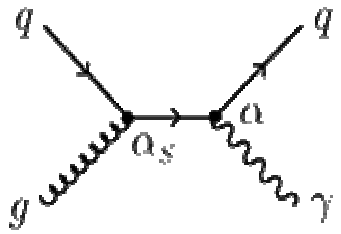
Upper limit on the branching ratio:

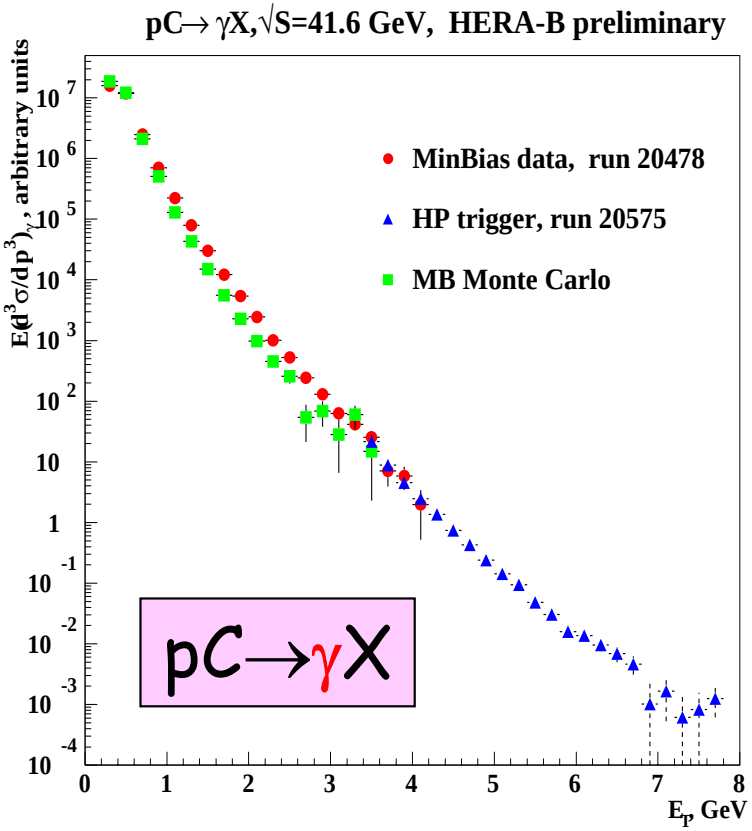
$BR(D^0 \rightarrow \mu^+\mu^-) < 2.0 \times 10^{-6}$ (90% cl)
hep-ex/0405059
Phys Lett B 596 (2004) 173

Previous limit:
CDF: $BR(D^0 \rightarrow \mu^+\mu^-) < 2.5 \times 10^{-6}$
Phys.Rev. D 68 (2003) 091101

Hard photon analysis

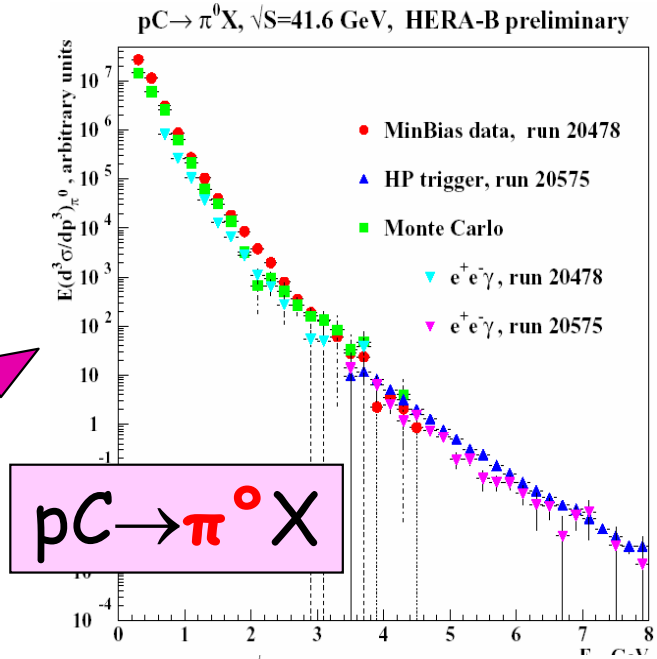
Direct γ production: dominant process $gq \rightarrow \gamma q$ ⇒ Unique sensitivity to gluon density function

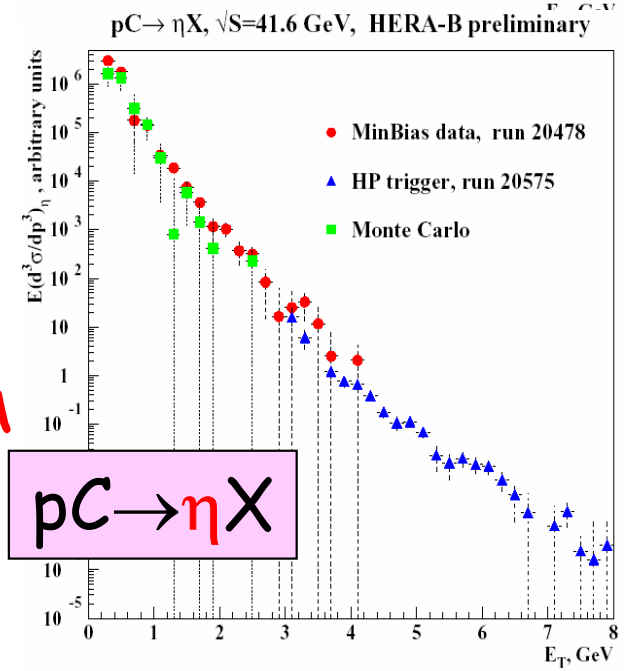




(normalization still arbitrary)

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**

Pentaquark search

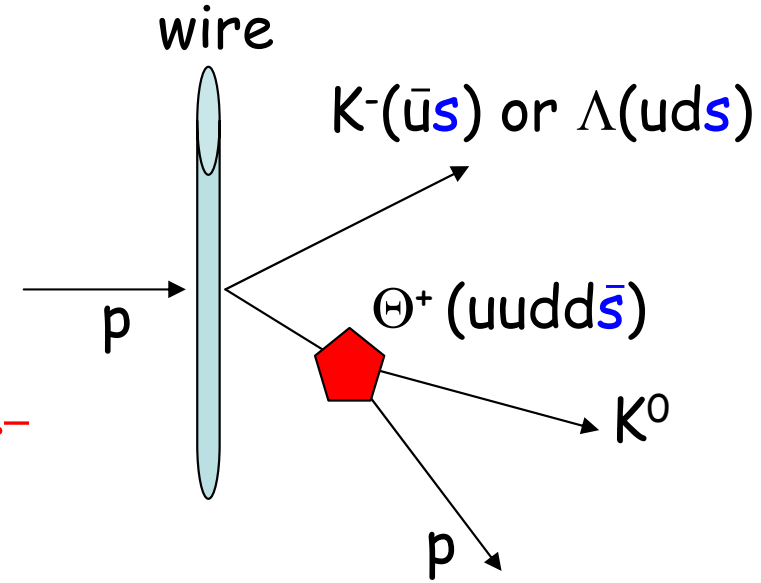
Phys. Rev. Lett.93:212003,2004

Possible 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.



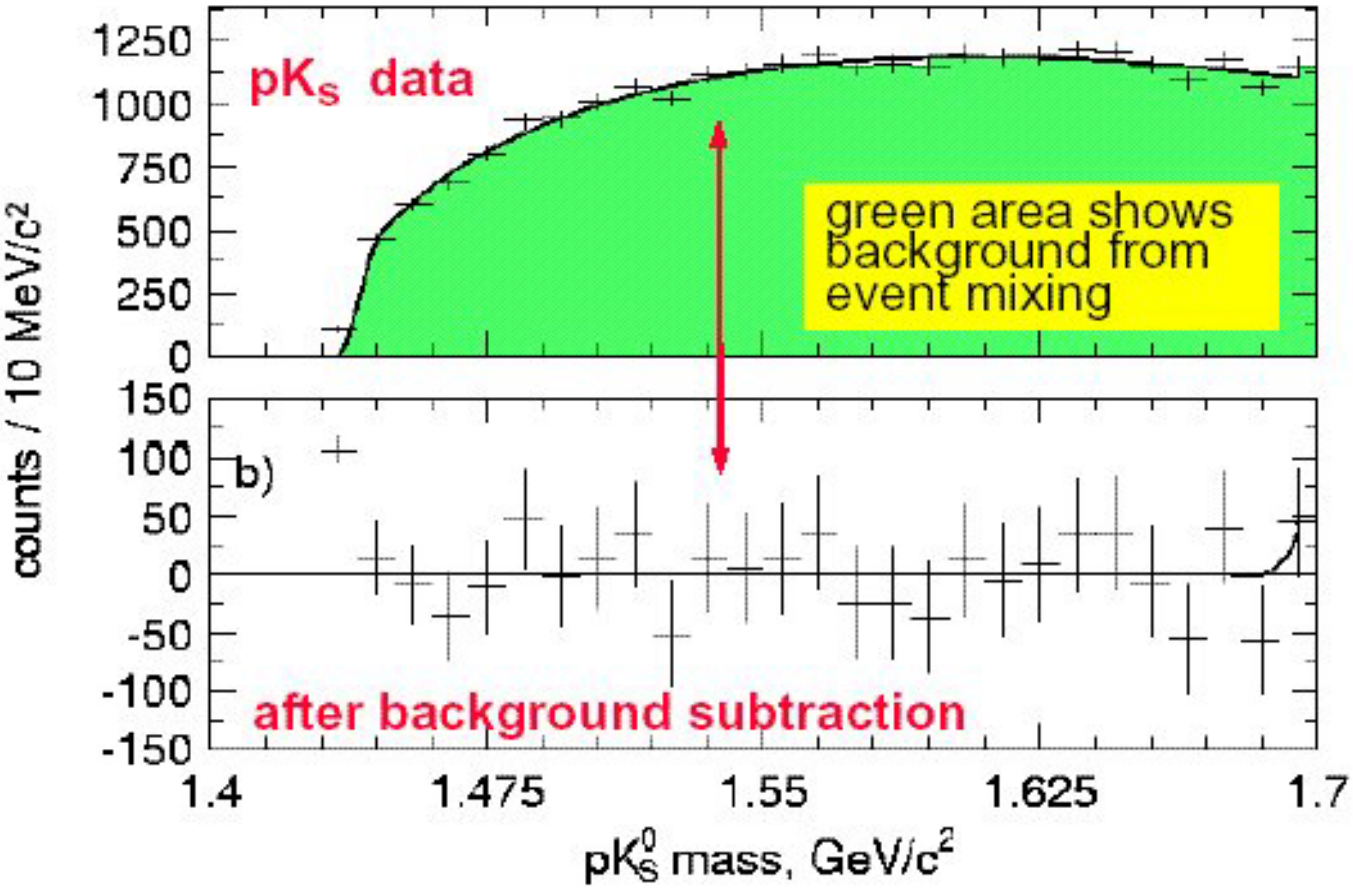
Use the full MB data sample (~210M evts, 3 nuclear targets C, Ti, W) to:

- 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)

Pentaquark search $\Theta^+ \rightarrow pK^0$

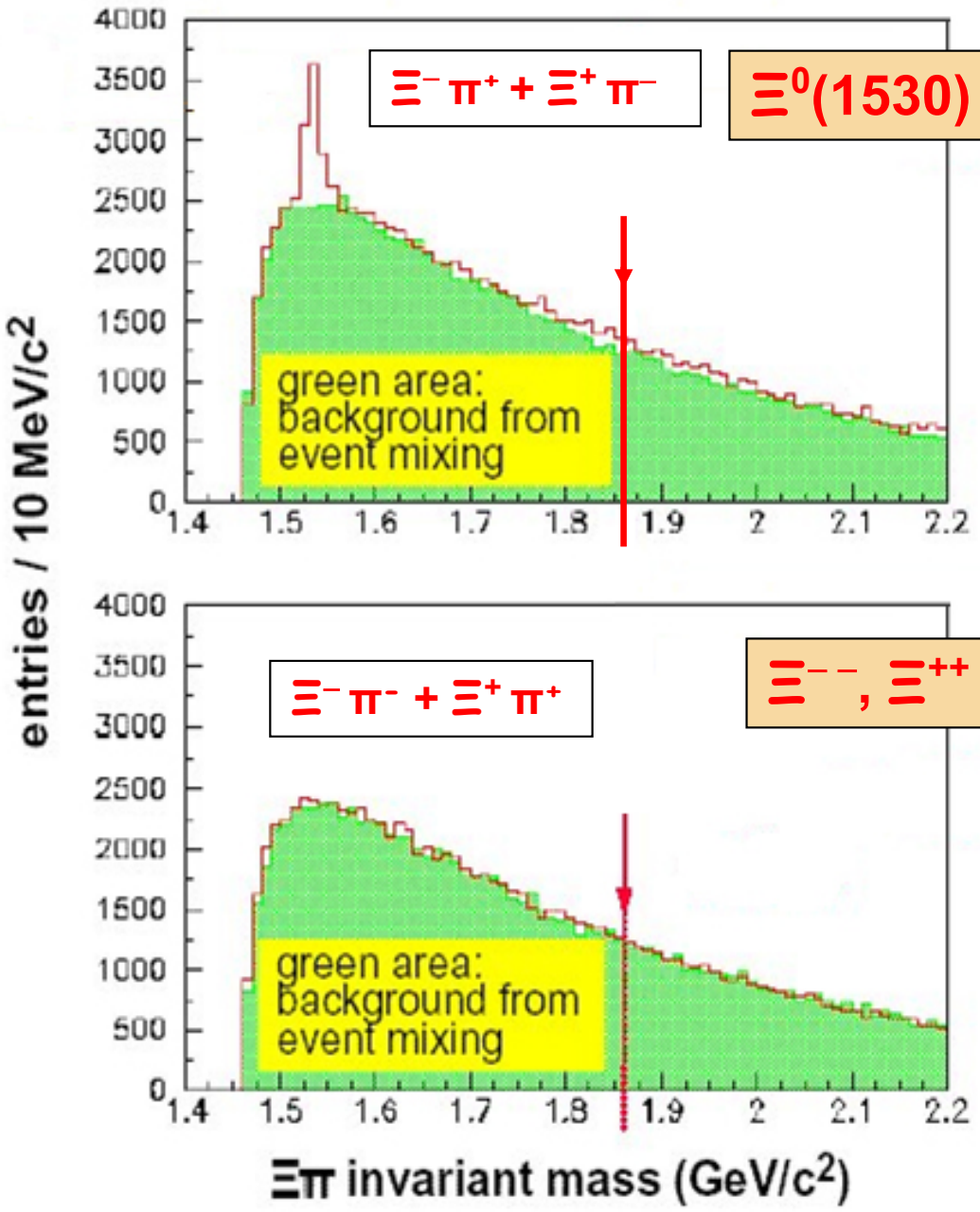
sensitivity in $BR \cdot (d\sigma/dx_f)$

~ 5μb/nucleon



- No evidence of signals where expected (~ 1530 MeV/c^2)
- Upper limit on particle yield ratio:
  $\Theta^+/\Lambda_{1520} < 0.02$ at 95% C.L.
  (Hermes: ~ 1.6 ÷ 3.5)
  } **assuming BR($\Theta^+ \rightarrow pK_S$) = 0.25**
- Upper Limit on $\left.\frac{Bd\sigma}{dy}\right|_{y\sim 0}$ is 3.7 (2.5) μb/nucl for Θ^+ (Ξ^{--})

Pentaquark search $\Xi^{--}(\Xi^{++}) \rightarrow \Xi^{-}\pi^{-}(\Xi^{+}\pi^{+})$



Good $\Xi^{0}(1530)$ reconstruction

- No evidence of Ξ^{--}, Ξ^{++} around 1862 MeV/c^2
- Upper limits (95% cl):
  $\Xi^{--}(1862) / \Xi^{0}(1530) < 0.077$
  $\Xi^{++}(1862) / \Xi^{0}(1530) < 0.058$