Charmonium, open charm and beauty production at HERA-B

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Hard Probes 2006 Asilomar

June 14, 2006

Asilomar Conference Grounds, Pacific Grove, California

outline

- HERA-B detector and physics topics
- results and comparison with previous experiments

*first data at **negative x_F***

- ***J/ψ production***
  - p_T and x_F distributions, A-dependence
  - ***new: decay angular distributions***

*observation of **low-p_T/$|x_F|$ effects***

- ***heavier states and feeddown to J/ψ***
  - ***ψ′/ψ*** and kinematics
  - fraction of **J/ψ**'s from χ_c
  - fraction of **J/ψ**'s from ***b*** decays

largest χ_c statistics *analyzed in hadron collisions*

- ***charm***
  - inclusive D^0, D^+, D^{*+} and ratios
  - A-dependence

highest energy among fixed-target experiments

often unclear experimental picture, especially for p-A collisions

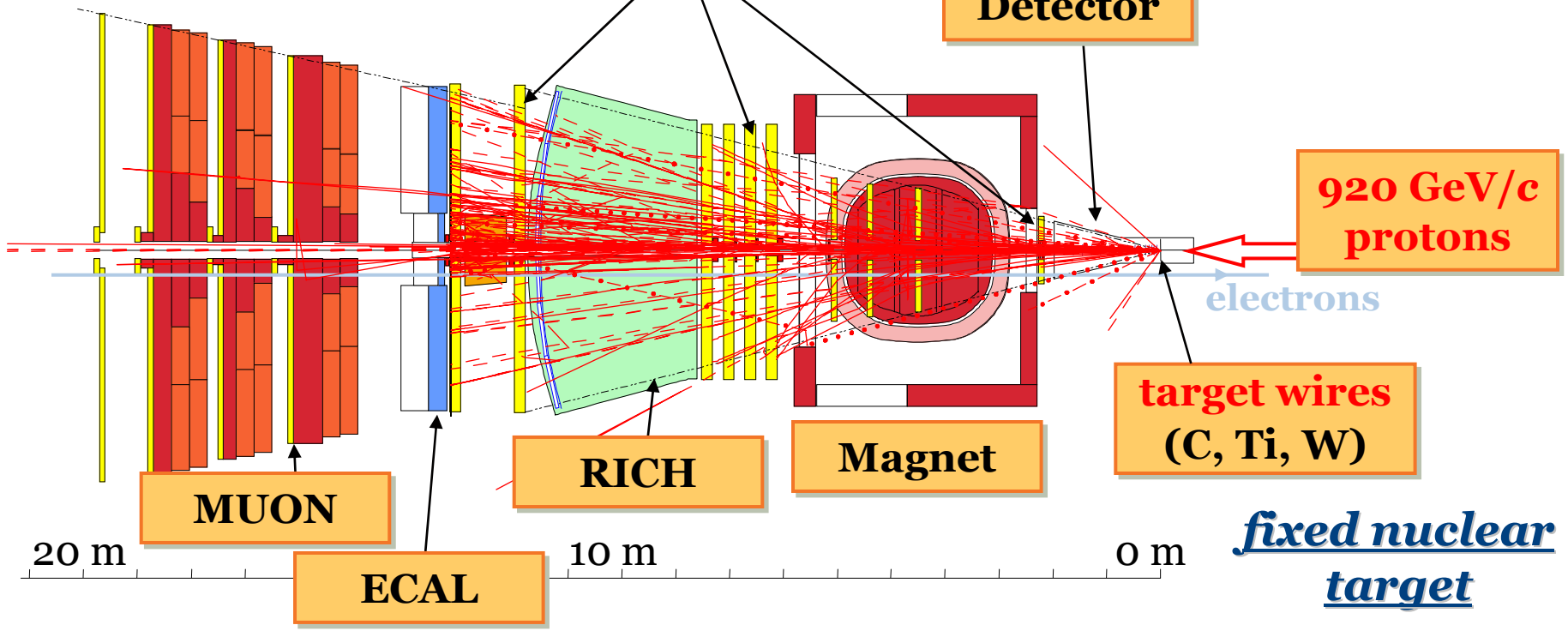
test production models (pQCD + initial/final state interactions in nuclei)

the HERA-B detector

(top view)

high resolution

large acceptance
(15-220 mrad)



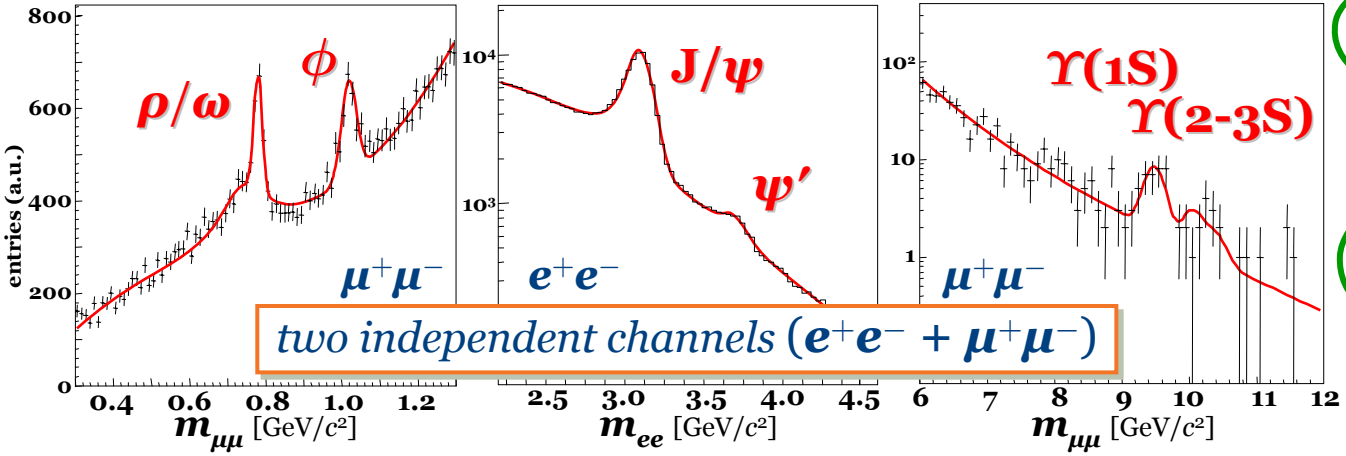
fixed nuclear target

$\sqrt{s}$ = 41.6 GeV
A = 12 ÷ 184

good PID
($e^{\pm}$, $\mu^{\pm}$, π, K, p)
+ photon reconstruction

physics at HERA-B

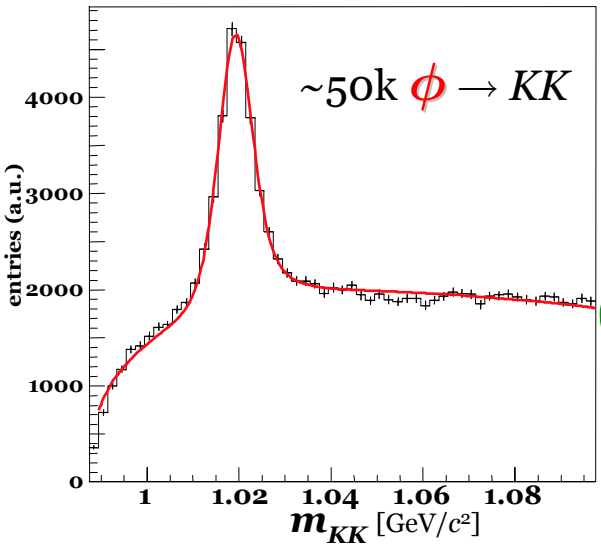
dilepton trigger: ~ 150·10⁶ events



two independent channels ($e^+e^- + \mu^+\mu^-$)

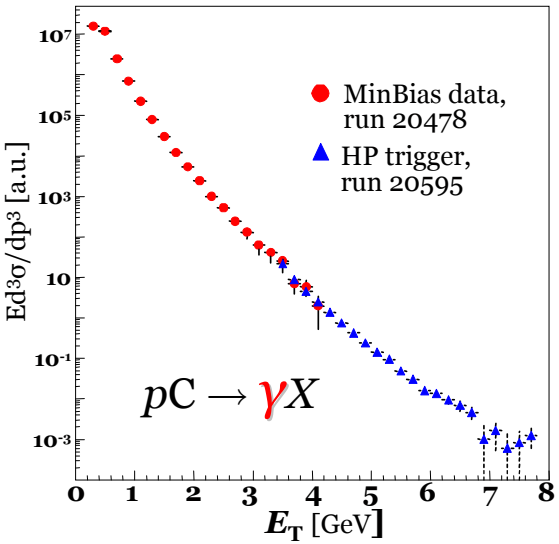
- J/ψ, χ_c, ψ', with A-dependence
- $D^0 \to \mu^+\mu^-$ (FCNC)
- **inclusive b** production
- Υ, ϕ, ρ/ω

~ 210·10⁶ minimum bias events



- K_s, K^*, Λ, ϕ, Ξ^{+-}
- pentaquarks
- D^0, D^+, D^{*+}, D_s
- J/ψ

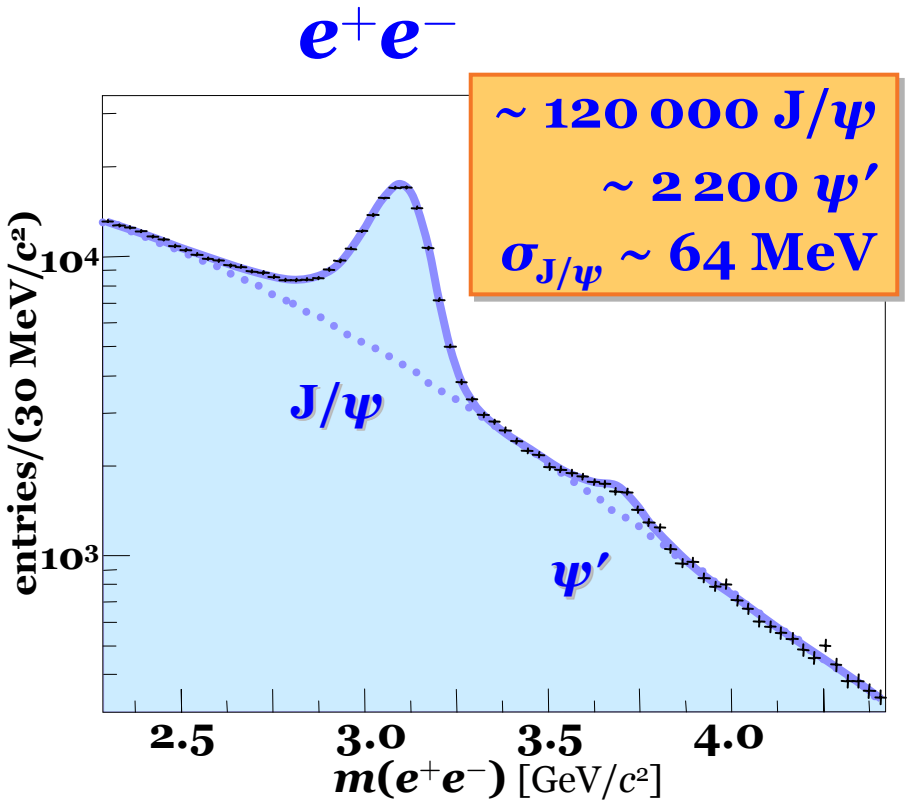
'hard photon' trigger: ~ 35·10⁶ events

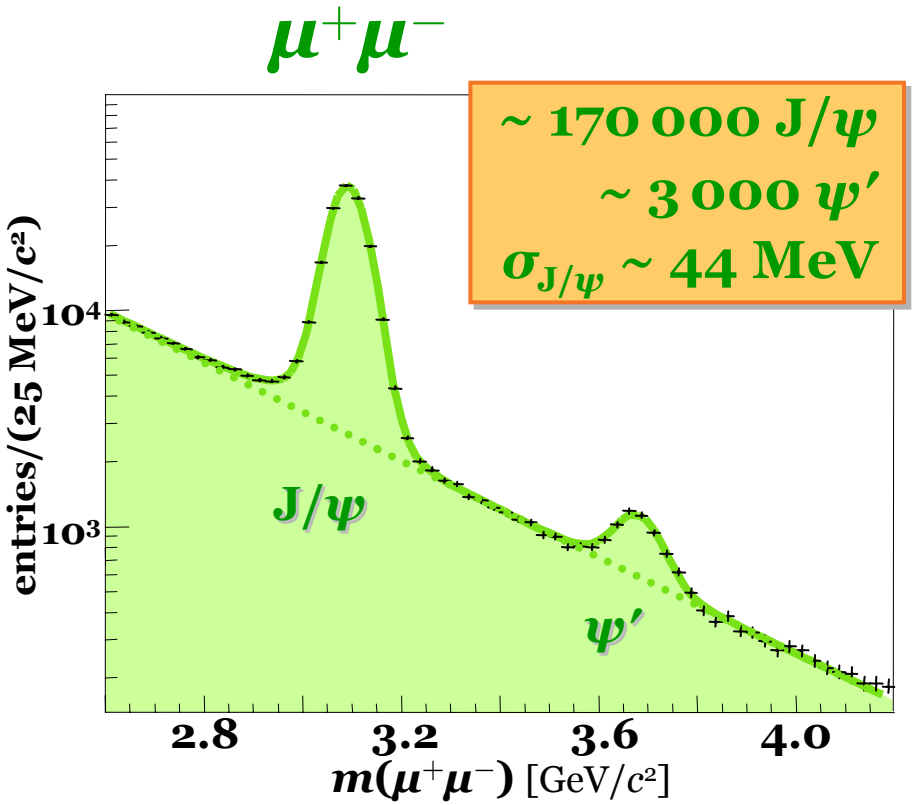


direct γ, π^0, η production with four different nuclei

J/ψ and ψ' signals

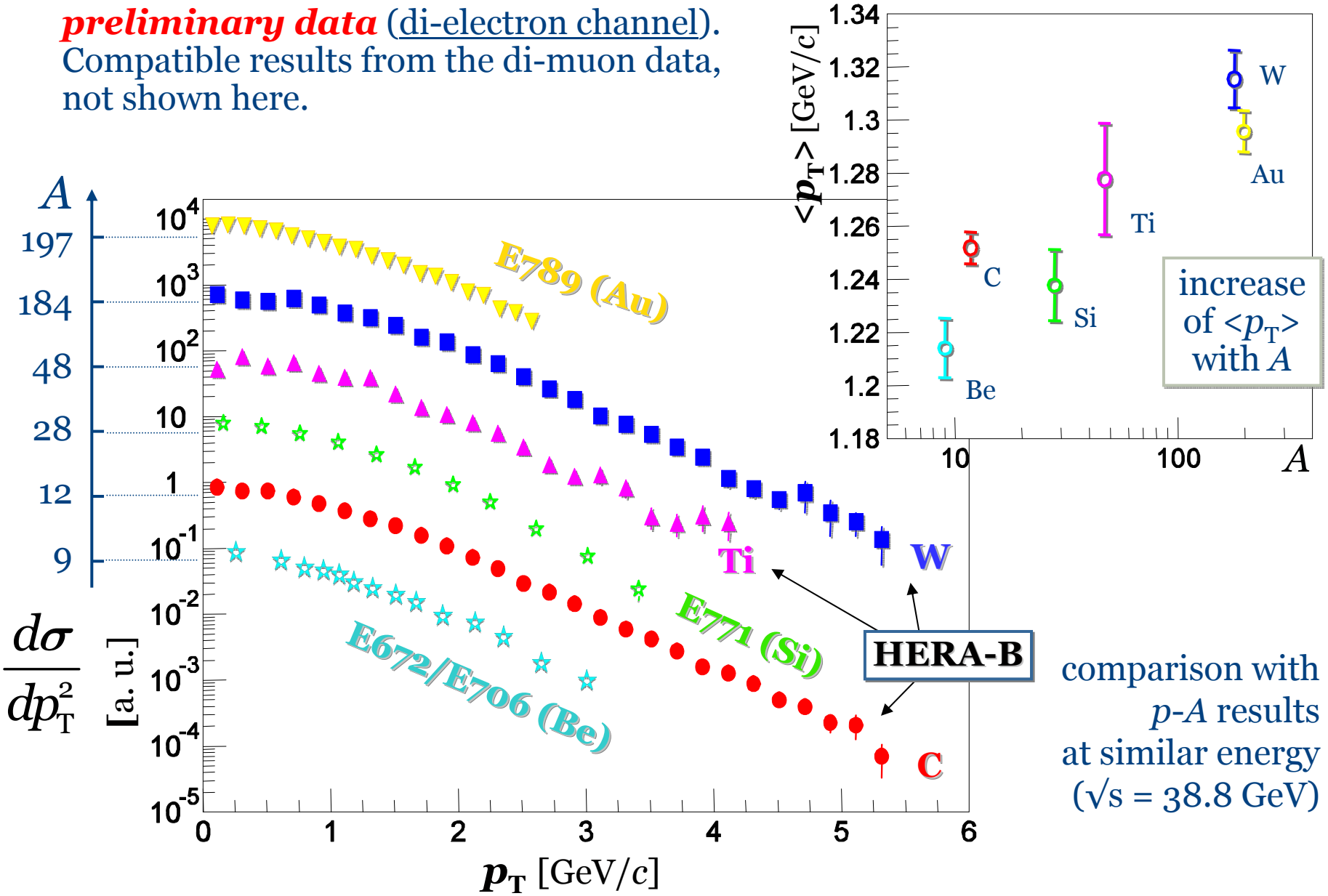
***full dilepton data sample* (3 target materials)**





J/ψ production kinematics: p_T distribution

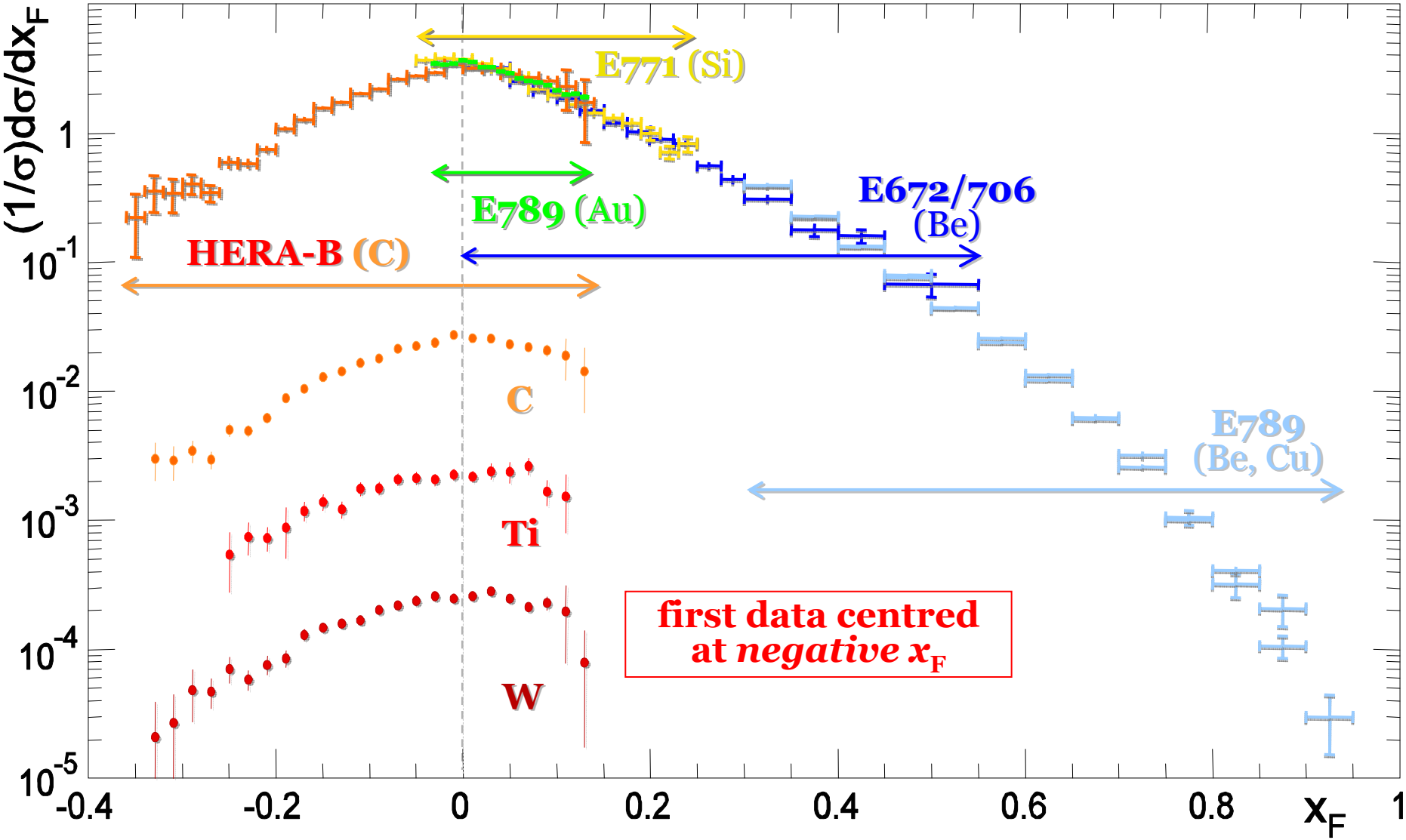
preliminary data (di-electron channel). Compatible results from the di-muon data, not shown here.



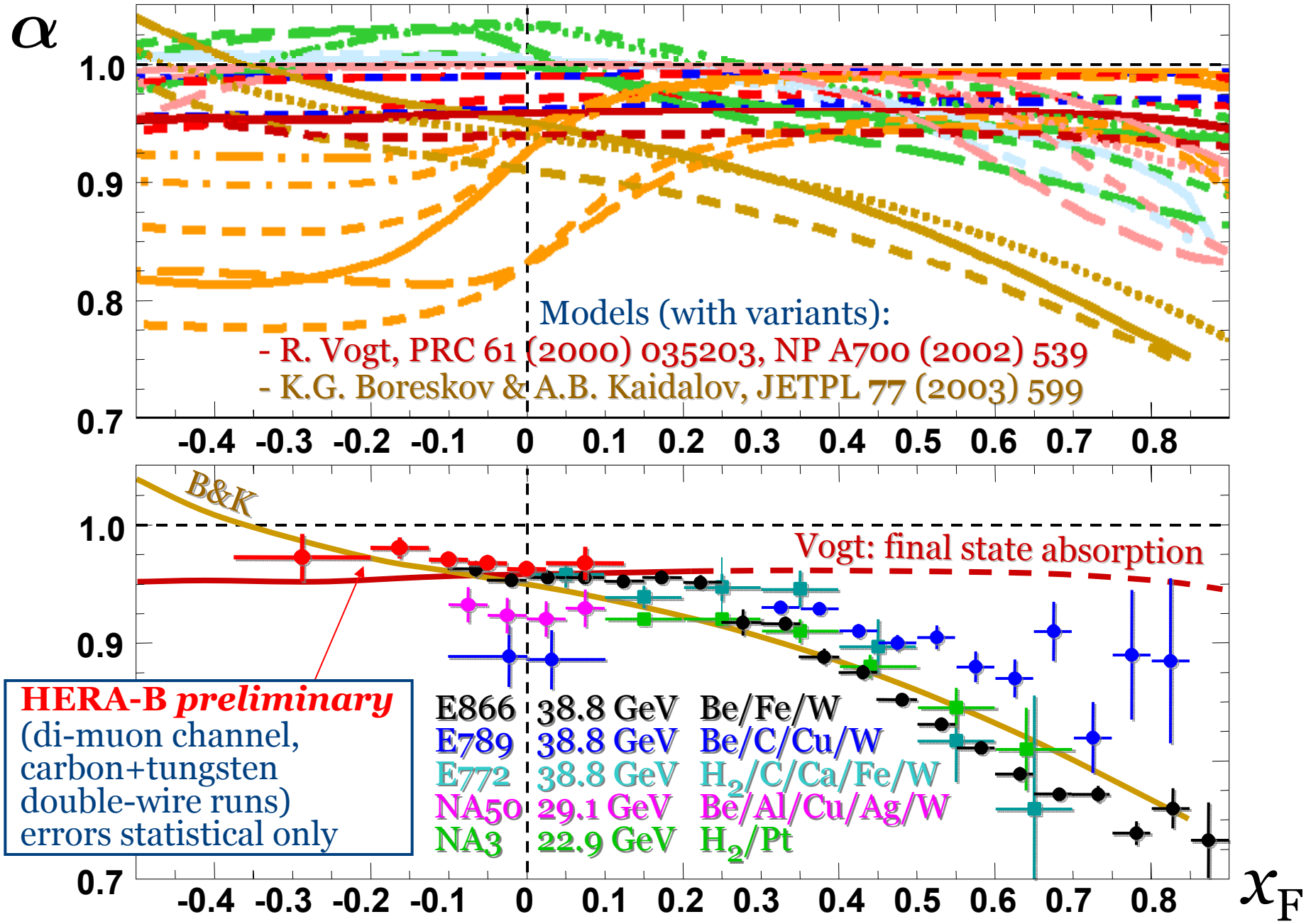
comparison with *p-A* results at similar energy ($\sqrt{s}$ = 38.8 GeV)

x_F distribution

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



A-dependence



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.

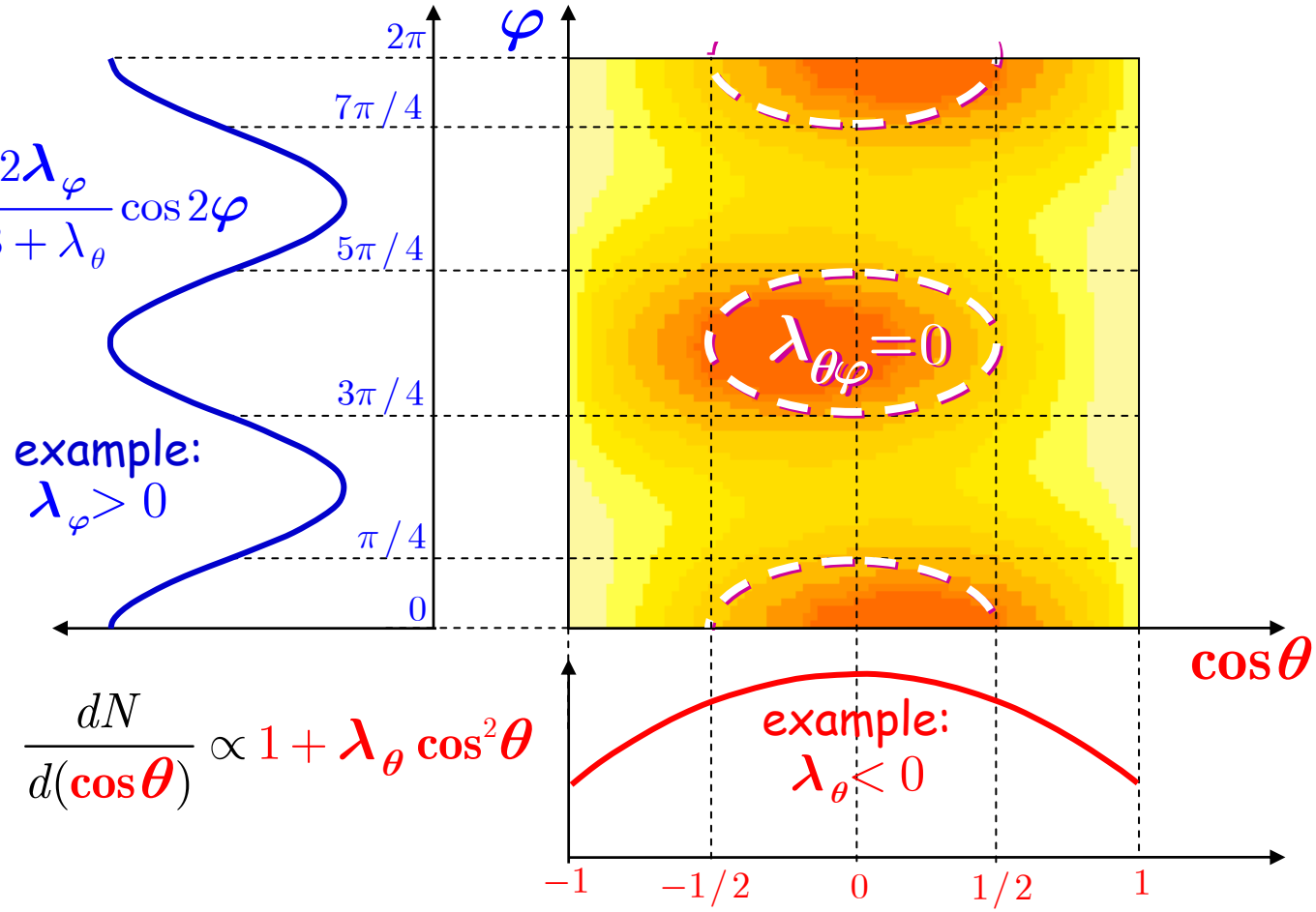
3) helicity "**HCM**"

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

CDF, NA60, etc.

parametrization

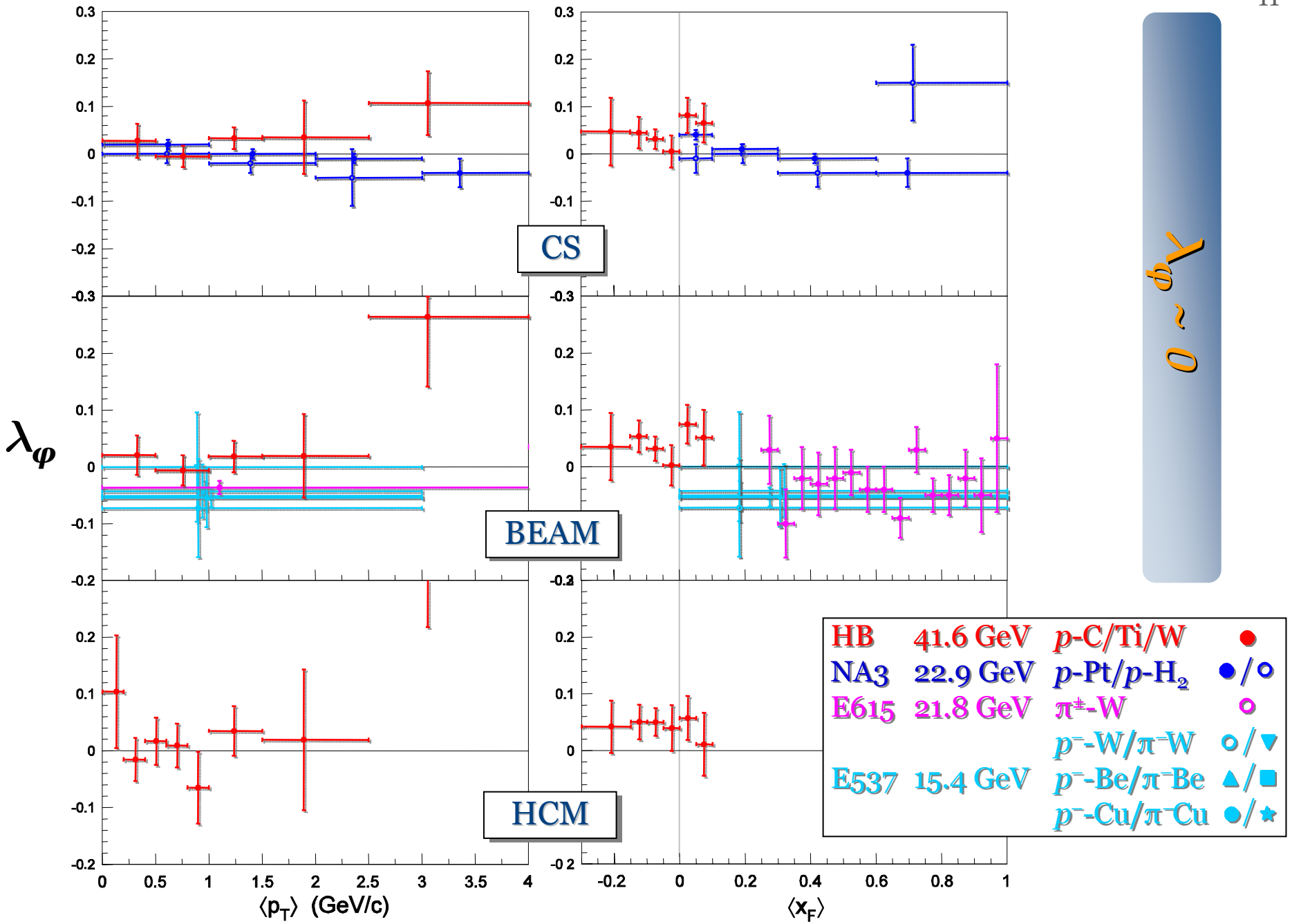
$$\frac{dN}{d\varphi} \propto 1 + \frac{2\lambda_\varphi}{3+\lambda_\theta}\cos 2\varphi$$



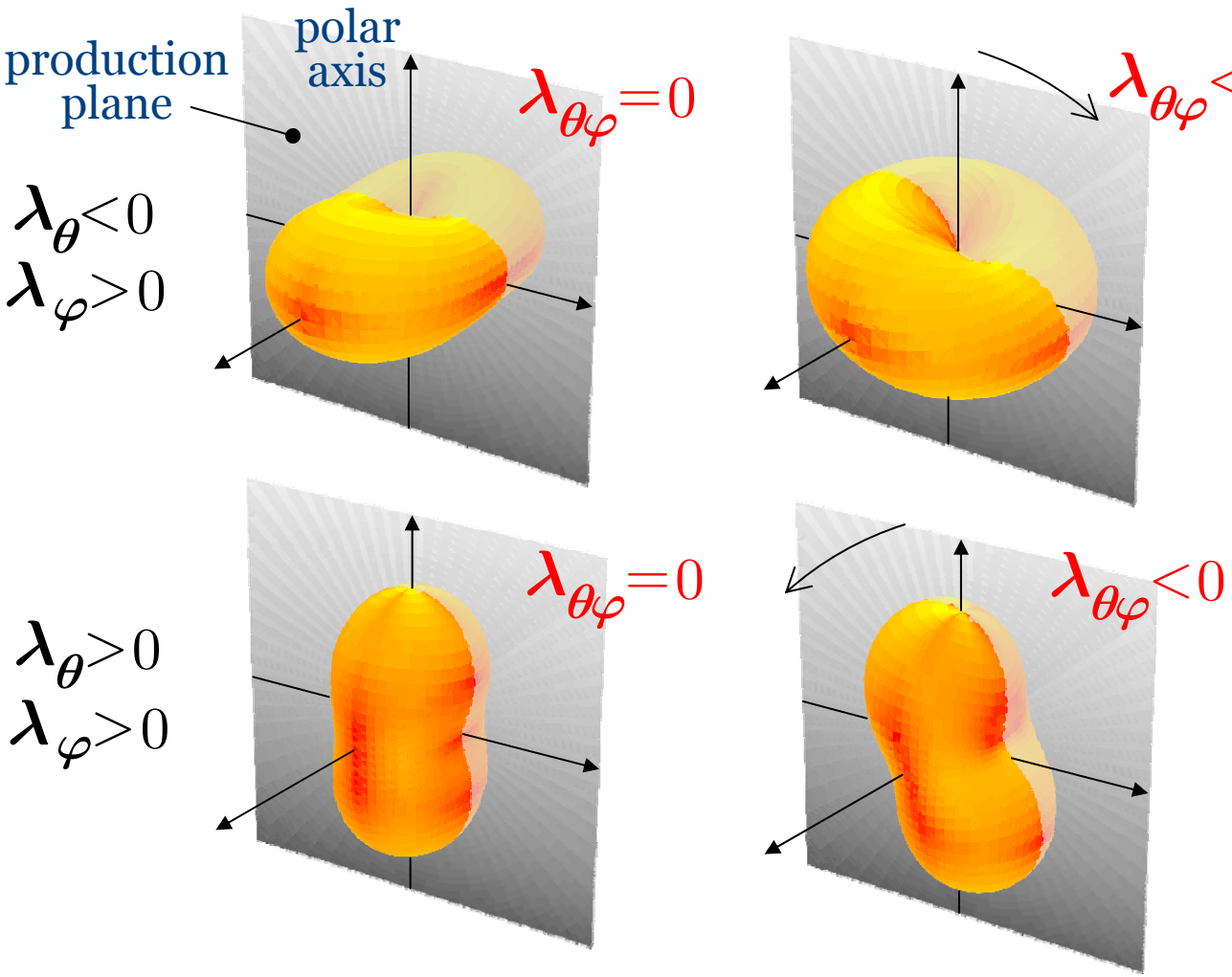
$$\frac{dN}{d(\cos\theta)} \propto 1 + \lambda_\theta \cos^2\theta$$

$$\frac{dN}{d(\cos\theta)d\varphi} \propto 1 + \boxed{\lambda_\theta}\cos^2\theta + \boxed{\lambda_{\theta\varphi}}\sin 2\theta \sin\varphi + \boxed{\lambda_\varphi}\sin^2\theta \cos 2\varphi$$

(x axis $\perp$ reaction plane)


λ_φ
CS
BEAM
HCM
$\langle p_T \rangle$ (GeV/c)
$\langle x_F \rangle$
HB 41.6 GeV p-C/Ti/W
NA3 22.9 GeV p-Pt/p-H2
E615 21.8 GeV π±-W
p⁻-W/π⁻W
E537 15.4 GeV p⁻-Be/π⁻Be
p⁻-Cu/π⁻Cu
$\lambda_\varphi \sim 0$

meaning of $\lambda_{\theta\varphi}$

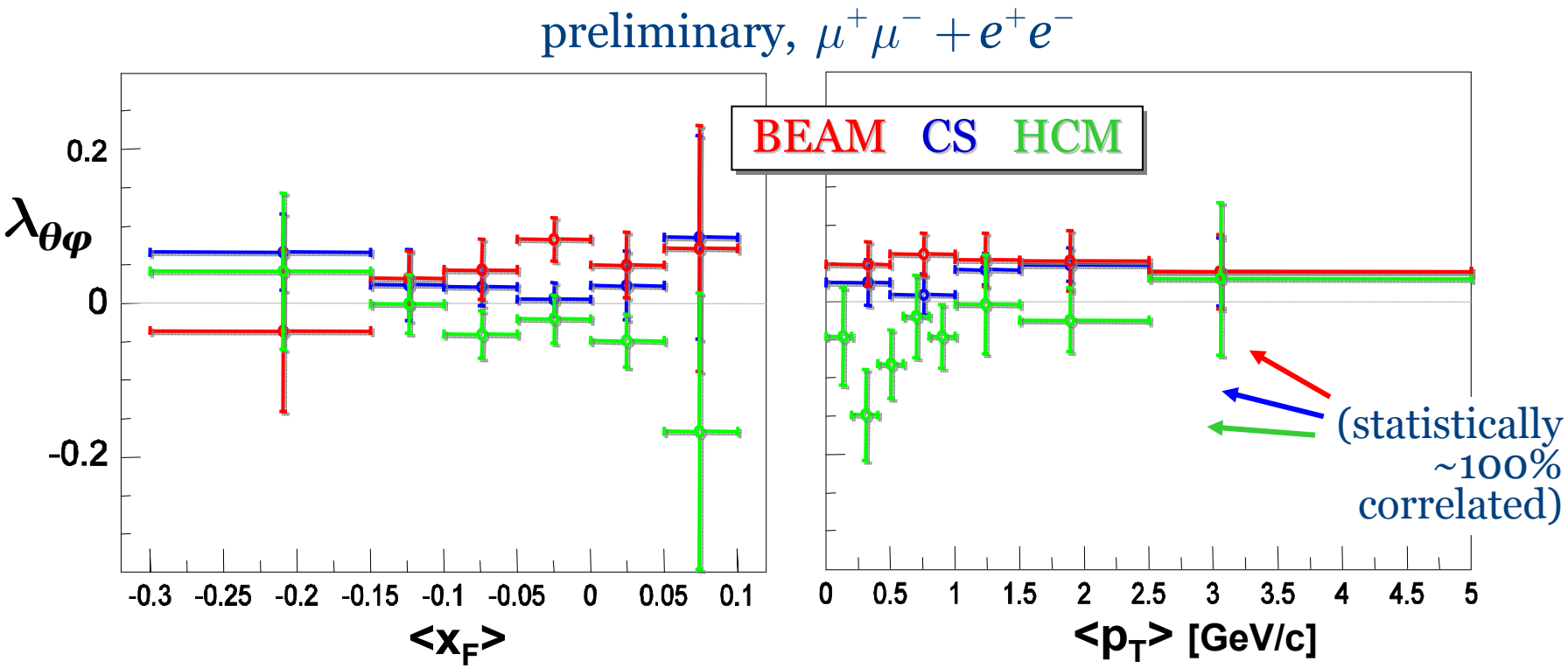


$\lambda_{\theta\varphi} \neq 0$ means that the axes of the current frame are not principal axes of symmetry for the angular distribution.

But it is always possible to define a reference frame with this property: the angular distribution can always be diagonalized to a form with $\lambda_{\theta\varphi} = 0$

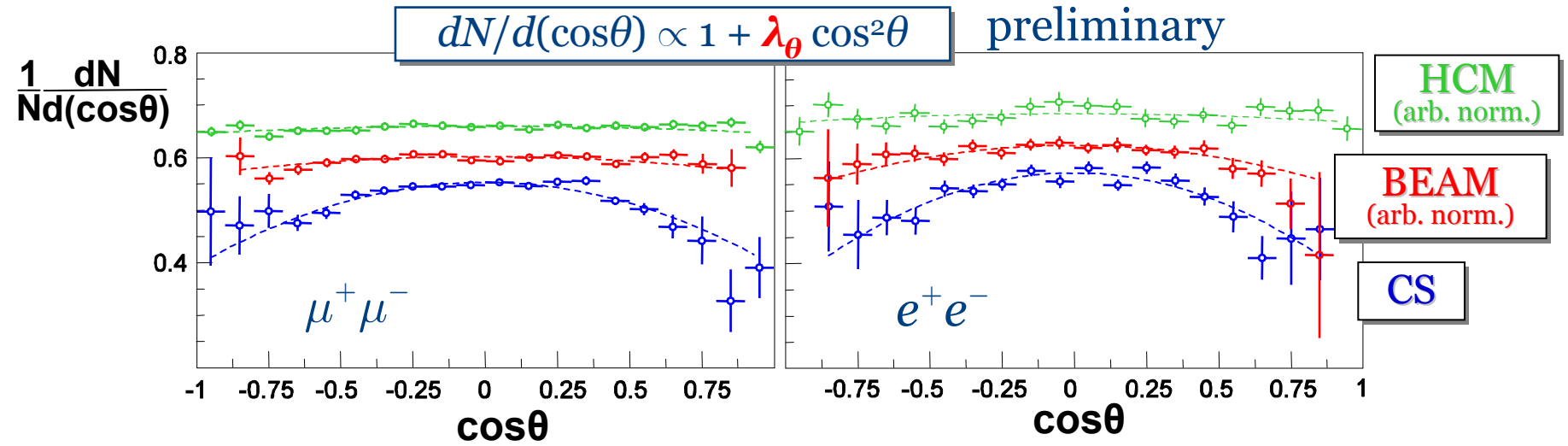
The "natural" polarization frame has $\lambda_{\theta\varphi}$ equal to zero: in such frame the decay distribution is symmetric and is described by only two parameters.

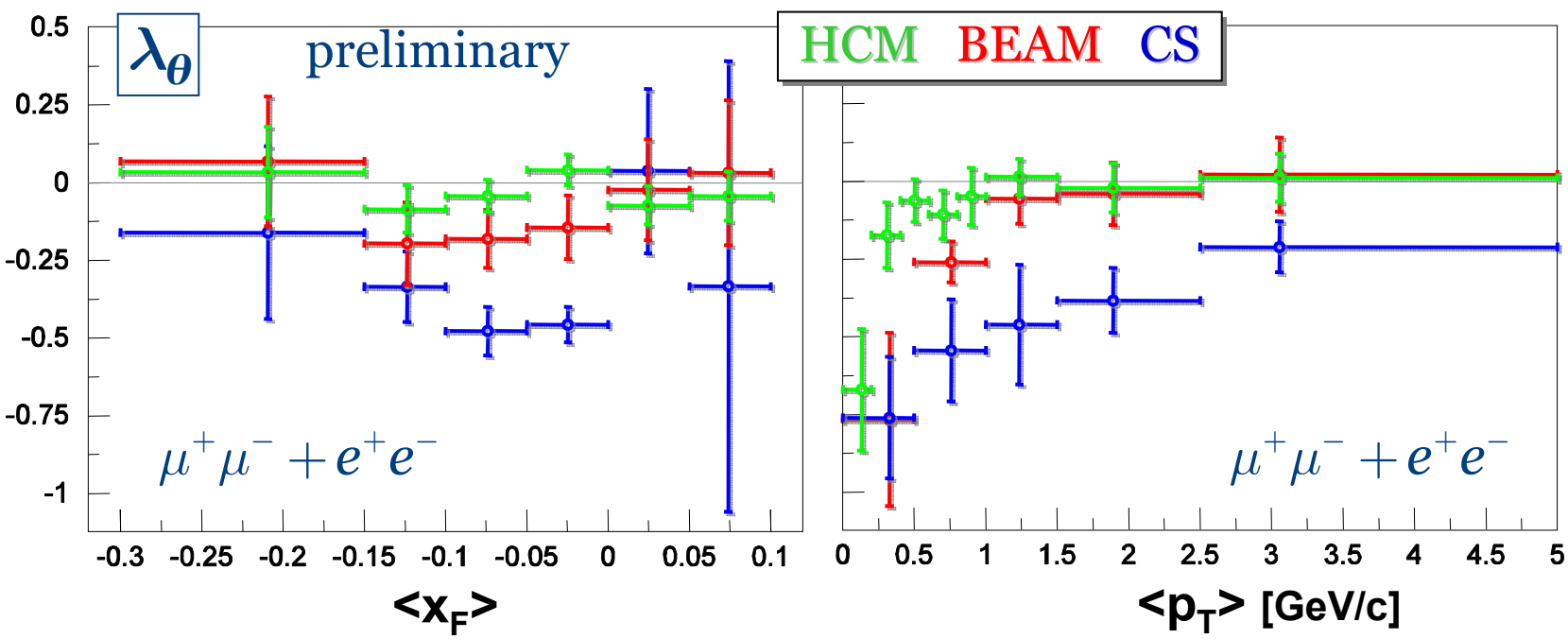
$\lambda_{\theta\varphi}$ in the three frames



- The three frames actually see the decay kinematics from different perspectives
- $|\lambda_{\theta\varphi}| \lesssim |\lambda_{\theta\varphi}|, |\lambda_{\theta\varphi}|$ $\Rightarrow$ CS the best frame?

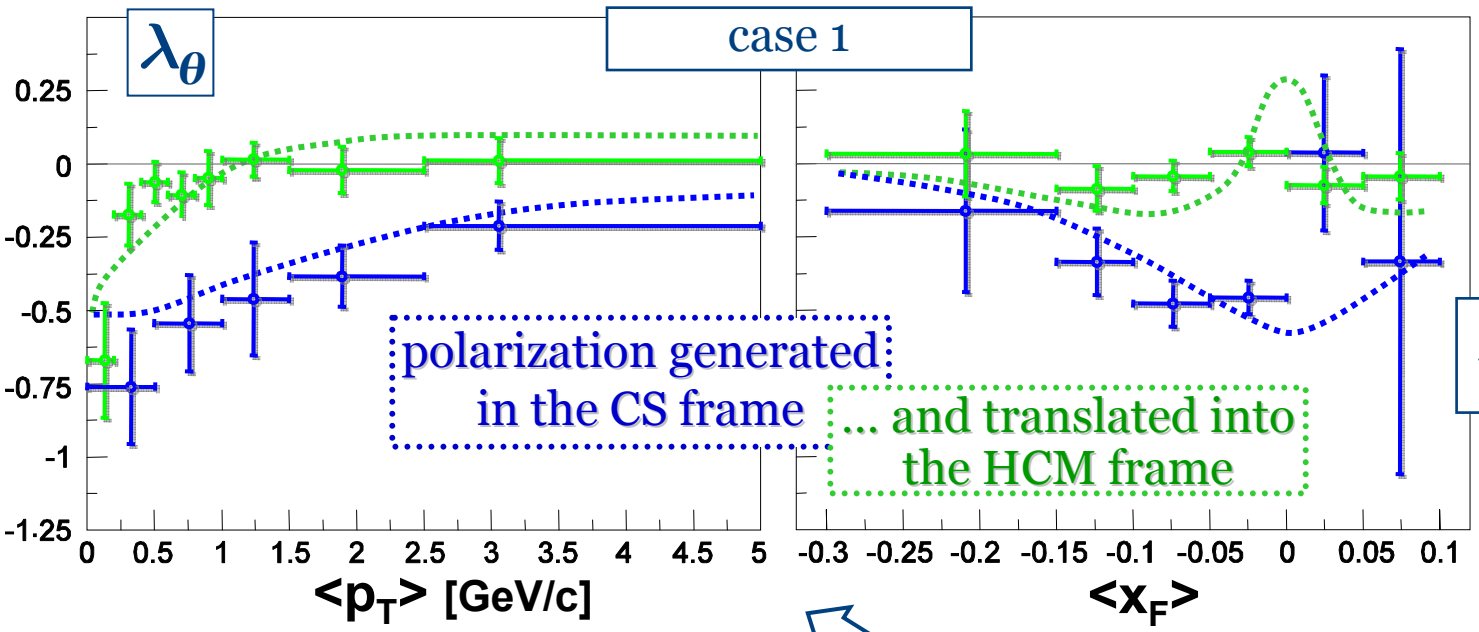
λ_θ and the hierarchy of frames





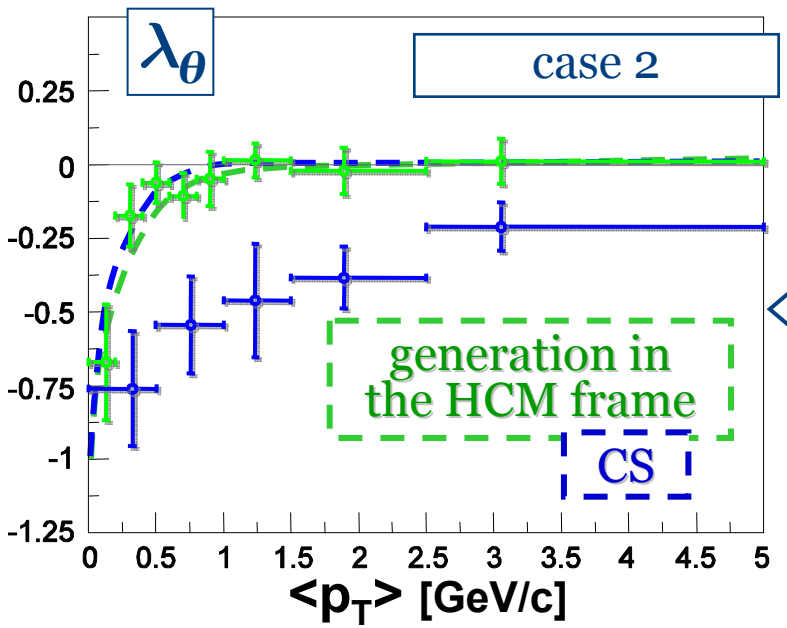
$|\lambda_\theta| > |\lambda_\theta| > |\lambda_\theta|$

interpretation



HCM
CS

points = data,
lines = Toy MC



The data are consistent (for example) with a polarization

$$\lambda_\theta = -1 \cdot \exp\left[-p^{\mathrm{CM}}_{J/\psi}/(2\mathrm{GeV}/c)\right]$$

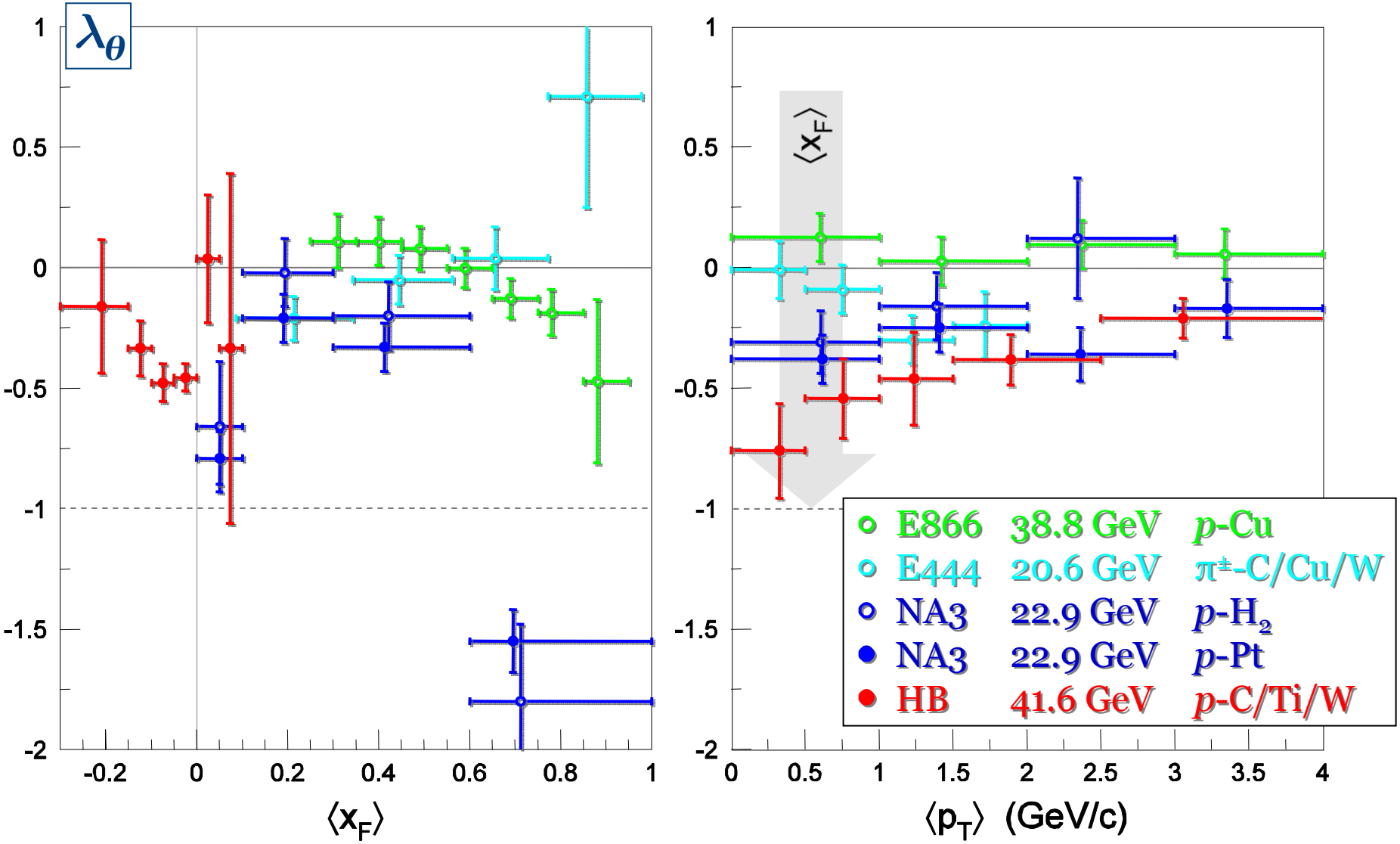
generated **in the CS frame**

No hypothesis of generation in the HCM fr. can reproduce the data in the CS fr.

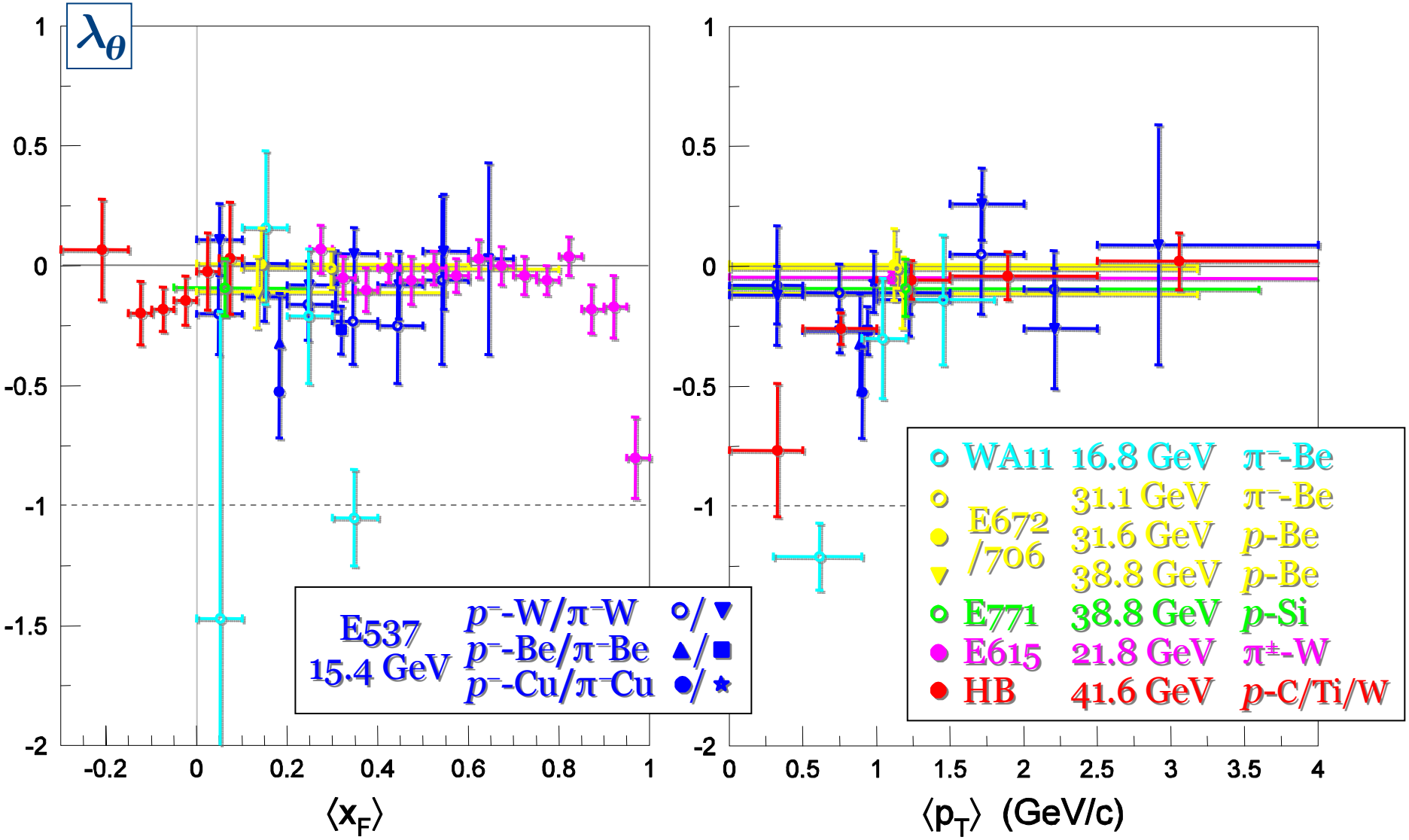
The CS frame is the best approximation of the "natural" polarization frame
→ physics: origin of J/ψ polarization

experimental situation: CS frame

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

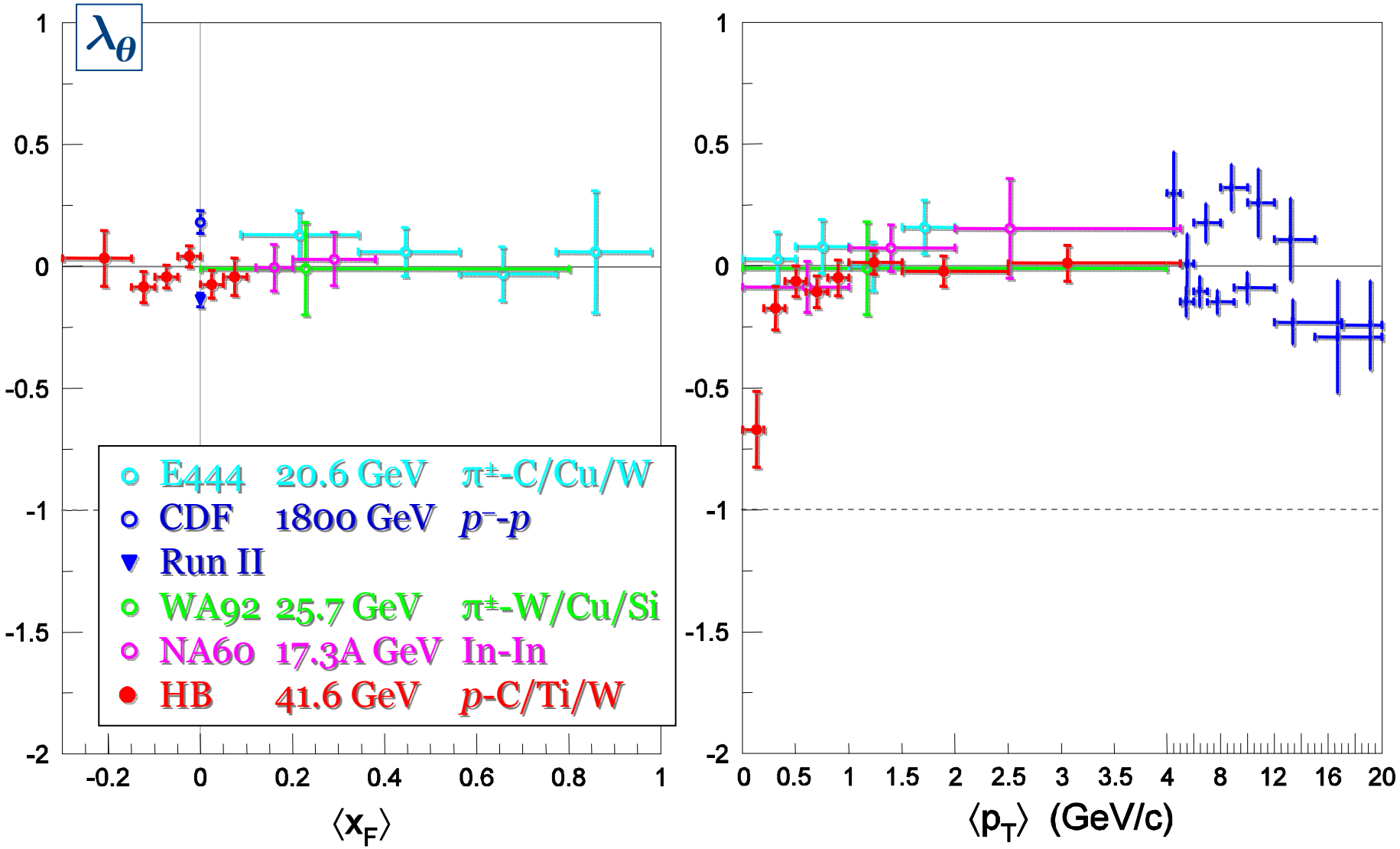


BEAM frame


λ_θ
1
0.5
0
-0.5
-1
-1.5
-2
-0.2
0
0.2
0.4
0.6
0.8
1
$\langle x_F \rangle$
E537
15.4 GeV
p^--W/π^-W ○/▼
p^--Be/π^-Be ▲/■
p^--Cu/π^-Cu ●/★
0
0.5
1
1.5
2
2.5
3
3.5
4
$\langle p_T \rangle$ (GeV/c)
WA11 16.8 GeV π^--Be
E672 /706
31.1 GeV π^--Be
31.6 GeV p-Be
38.8 GeV p-Be
E771 38.8 GeV p-Si
E615 21.8 GeV $\pi^\pm$-W
HB 41.6 GeV p-C/Ti/W

HCM frame

polarization almost completely smeared out, except for p_T very close to zero

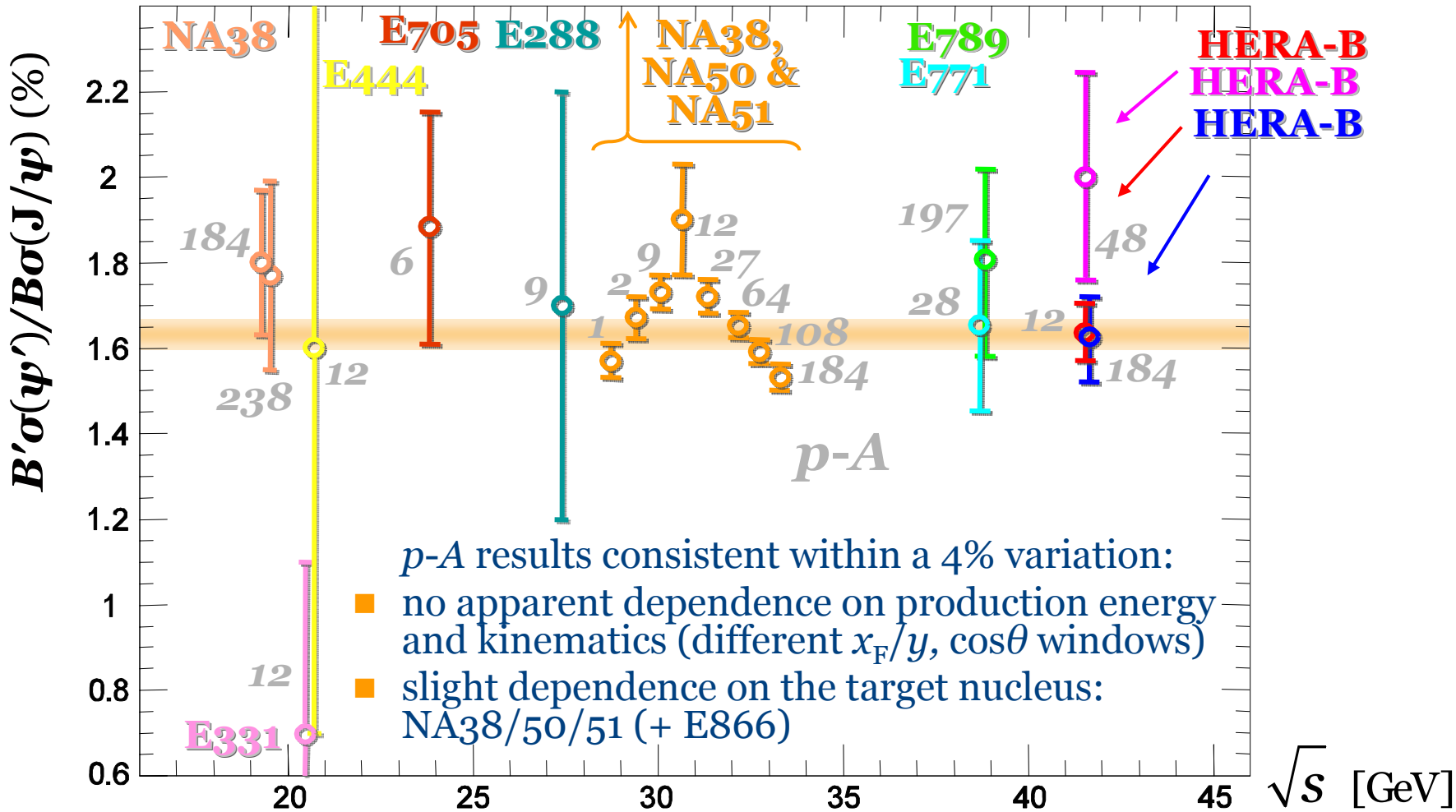


ψ′-to-J/ψ production ratio

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

$$\rho_{\psi'}^{e^+e^-} = \frac{B_{\psi'\to\ell^+\ell^-}\,\sigma_{\psi'}}{B_{J/\psi\to\ell^+\ell^-}\,\sigma_{J/\psi}} = \begin{cases} 1.63 \pm 0.08\,\%\,(\mathrm{C}) \\ 1.99 \pm 0.26\,\%\,(\mathrm{Ti}) \\ 1.62 \pm 0.11\,\%\,(\mathrm{W}) \end{cases}$$

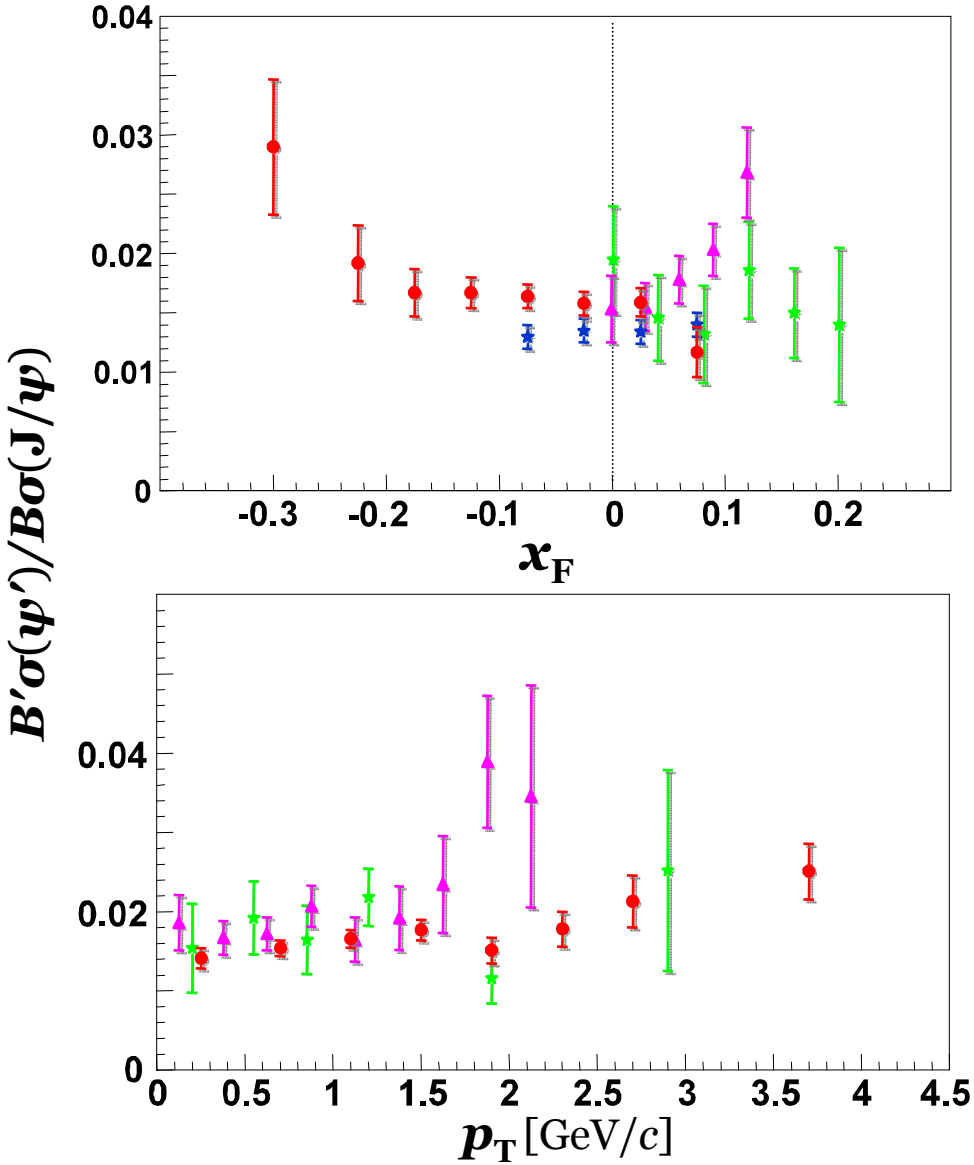
$$R_{\psi'} = \rho_{\psi'} \times \frac{B_{J/\psi\to\ell^+\ell^-}}{B_{\psi'\to\ell^+\ell^-}} \cdot B_{\psi'\to \begin{cases} J/\psi\pi^+\pi^- \\ J/\psi\pi^0\pi^0 \\ J/\psi\eta \\ J/\psi\pi^0 \end{cases}} = (7.0 \pm 0.2 \pm 0.4_{BRs})\%$$



p-A results consistent within a 4% variation:

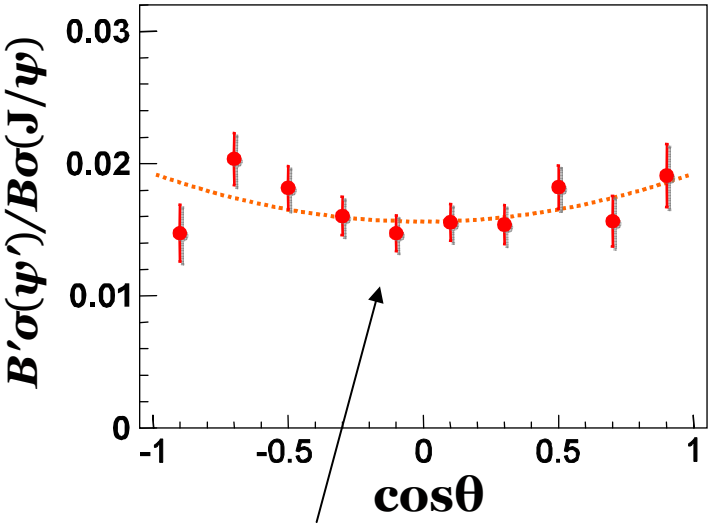
- no apparent dependence on production energy and kinematics (different x_F/y, $\cos\theta$ windows)
- slight dependence on the target nucleus: NA38/50/51 (+ E866)

ψ′ kinematics



measured relative to the J/ψ distributions: $B'\sigma(\psi')/B\sigma(J/\psi)$ as a function of x_F. p_T , $\cos\theta$

HERA-B (full stat, $e^+e^-/\mu^+\mu^-$ avg.)
E789 (38.8 GeV)
E771 (38.8 GeV)
NA50 (29.1 GeV)



$\lambda_\theta(\psi') - \lambda_\theta(J/\psi) = 0.23 \pm 0.17$

χ_c production

selection:

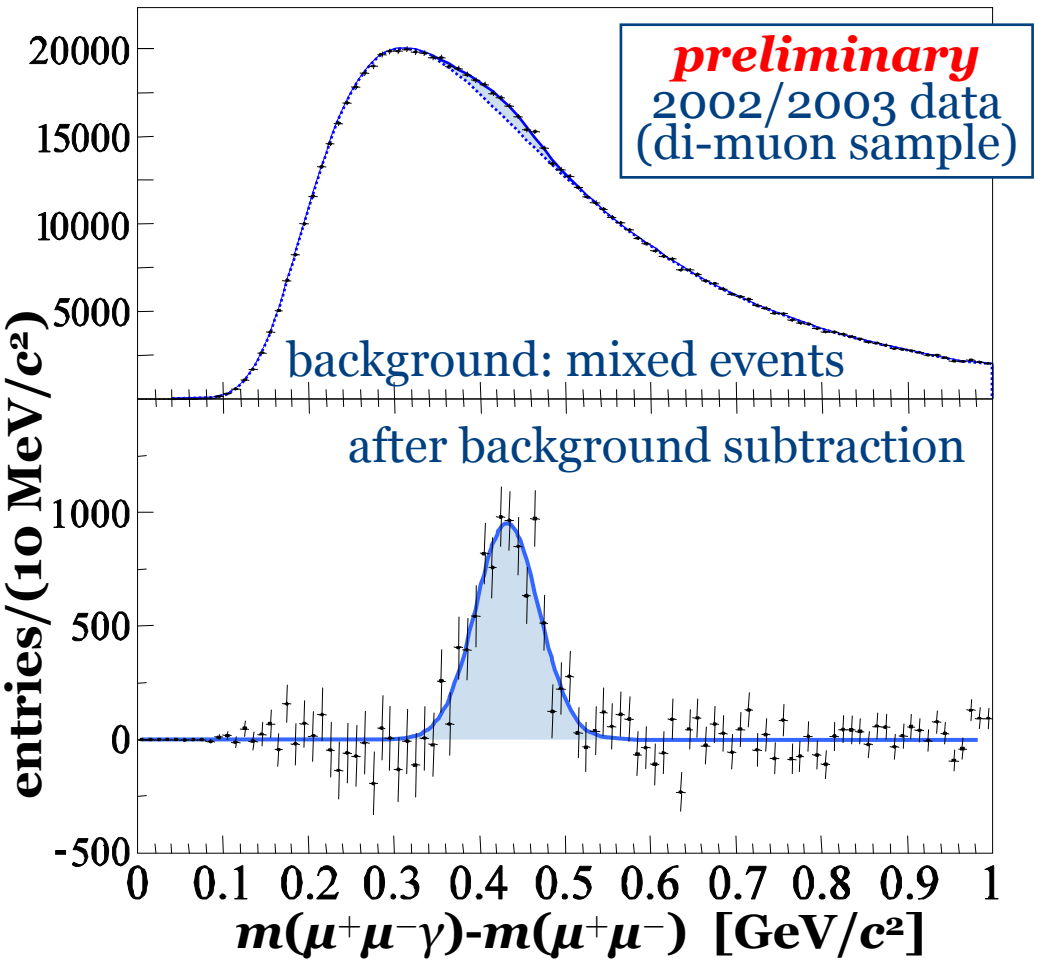
$$\chi_c \longrightarrow J/\psi \;\; \gamma$$
$$J/\psi \rightarrow \begin{cases} e^+e^- \\ \mu^+\mu^- \end{cases}$$

measurement:

- **fraction of J/ψ's from χ_c:**

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

- **kinematical 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)]

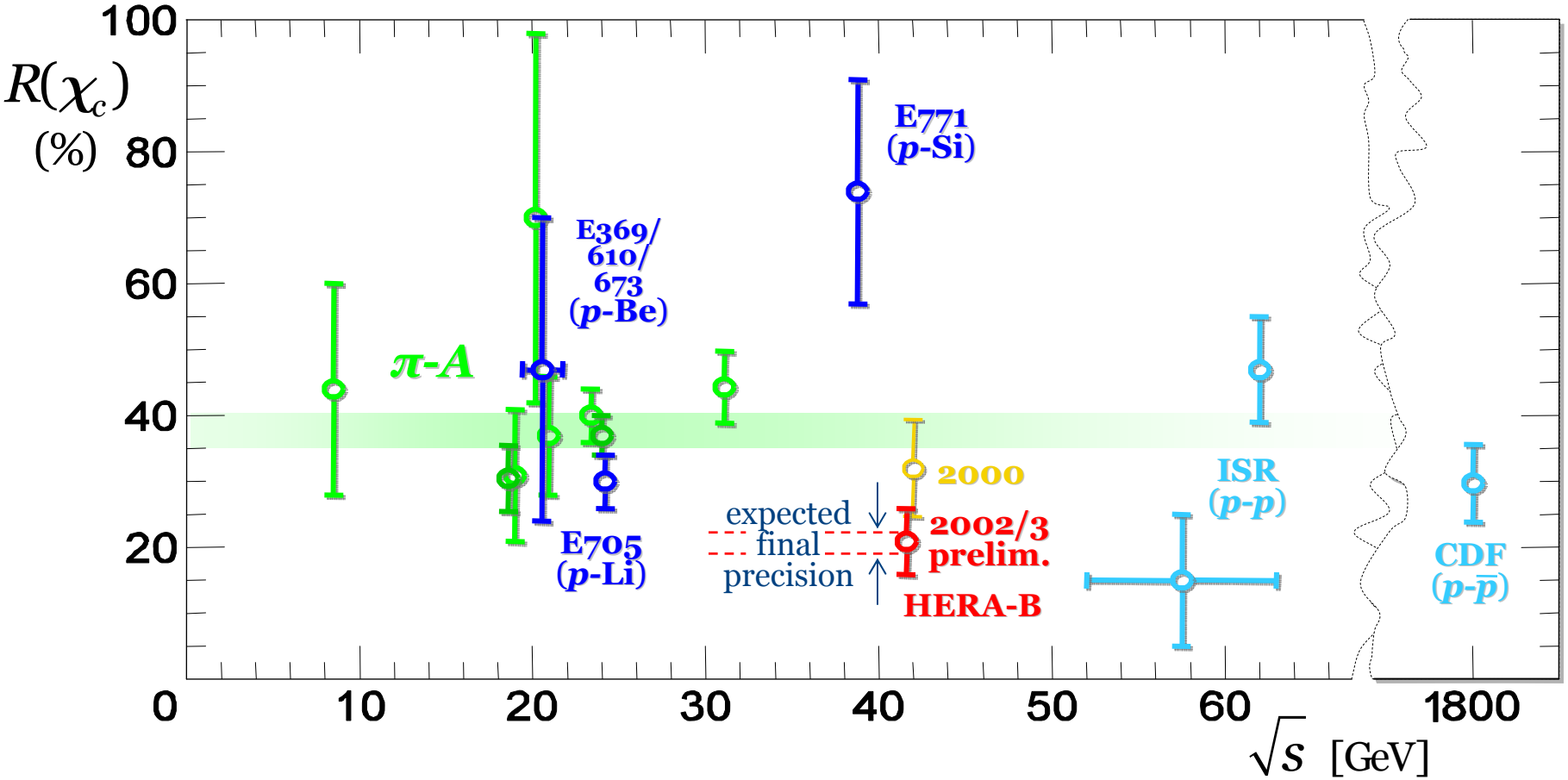
new data: 40× bigger χ_c statistics
(the largest analyzed in a hadronic experiment)

$R(\chi_c)$

preliminary evaluation (2002/2003 data):

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

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

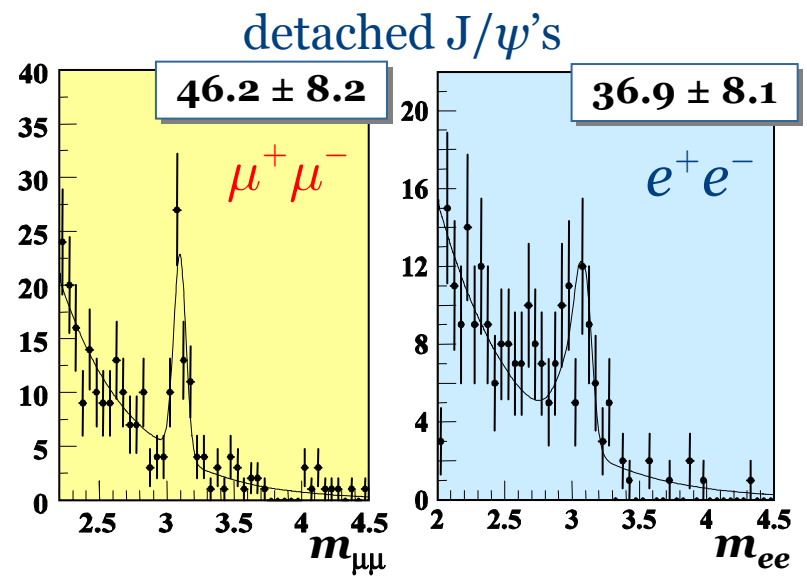


J/ψ's from b decays

$pA \to b\bar{b}\,X$

$b \to J/\psi\,Y \to e^+e^-/\mu^+\mu^-\,Y$

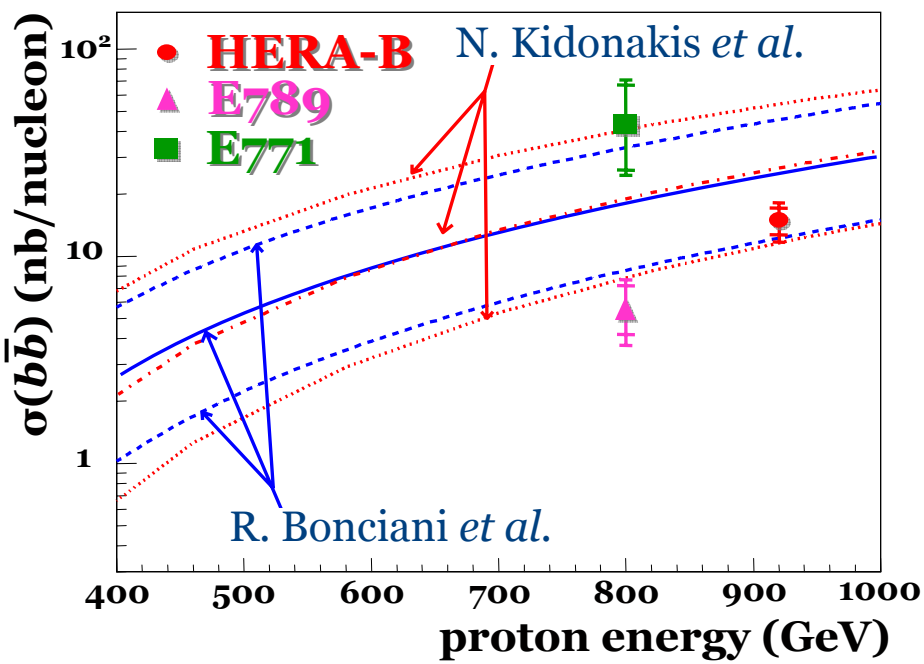
$$R_b = \frac{N(J/\psi \leftarrow b)}{N_{TOT}(J/\psi)} = (0.065 \pm 0.011)\%$$



- extrapolation to full x_F range
- normalization by total J/ψ cross sect.
- correction by BR of $b \to J/\psi$

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

[Phys. Rev. D 73, 052005]



indirect and direct J/ψ production

Using partial/preliminary HERA-B results:

(to be improved!)

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

(21 ± 5)%

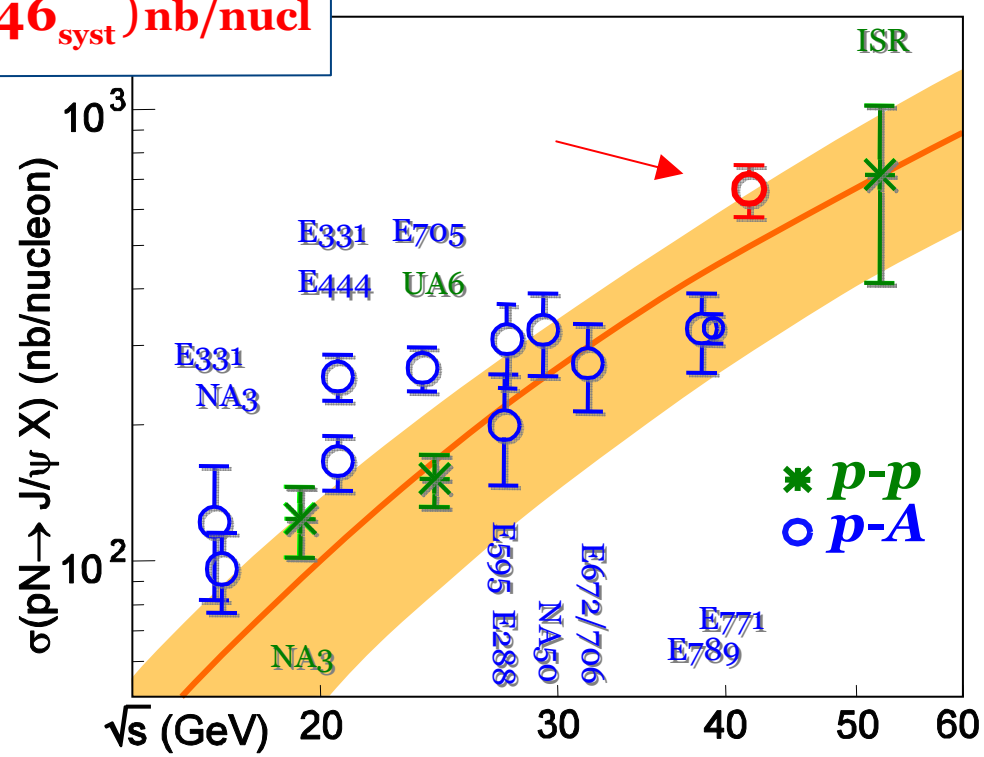
(7.0±0.4)%

(0.065±0.011)%

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

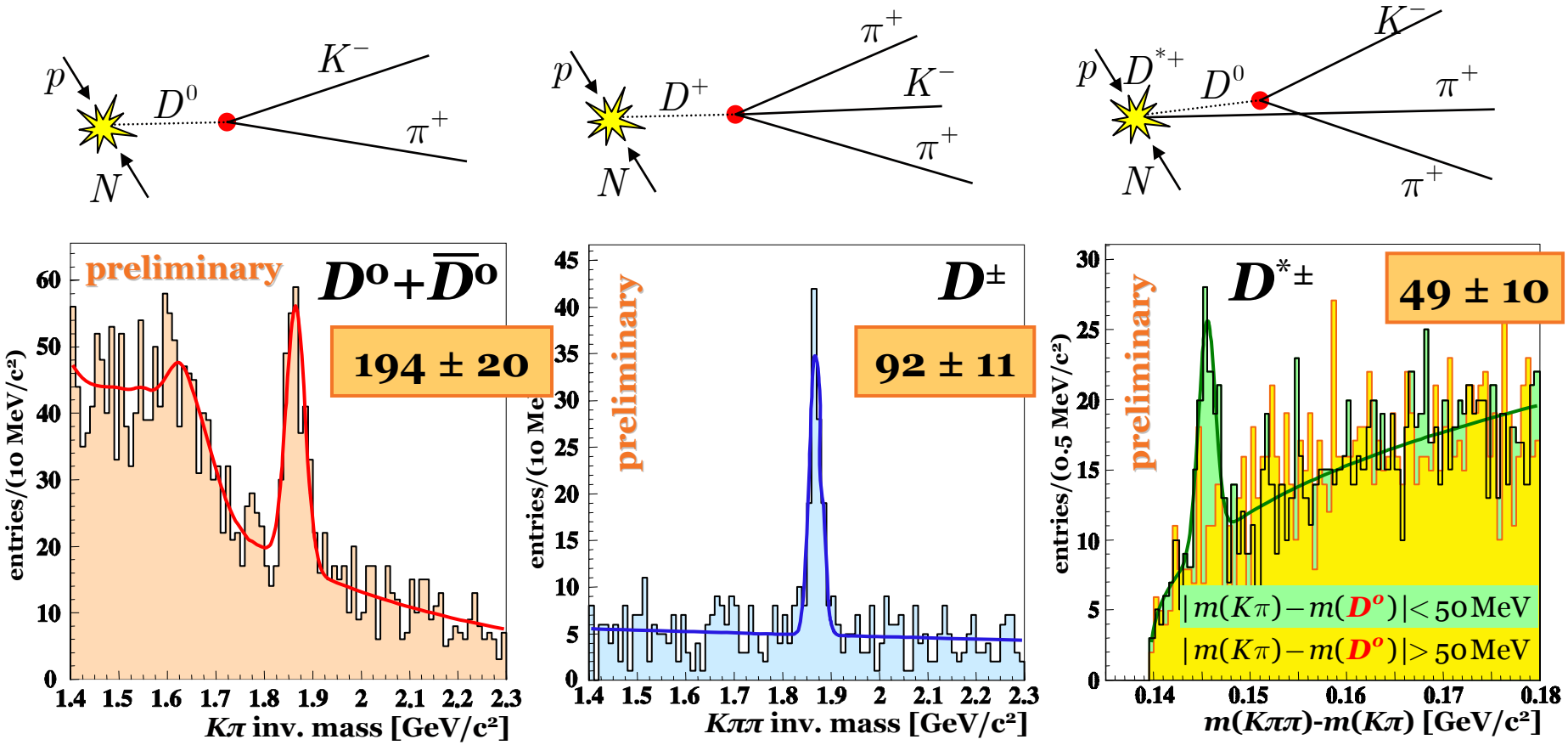
extracted from MB data

(72 ± 5)% of the J/ψ's are produced directly



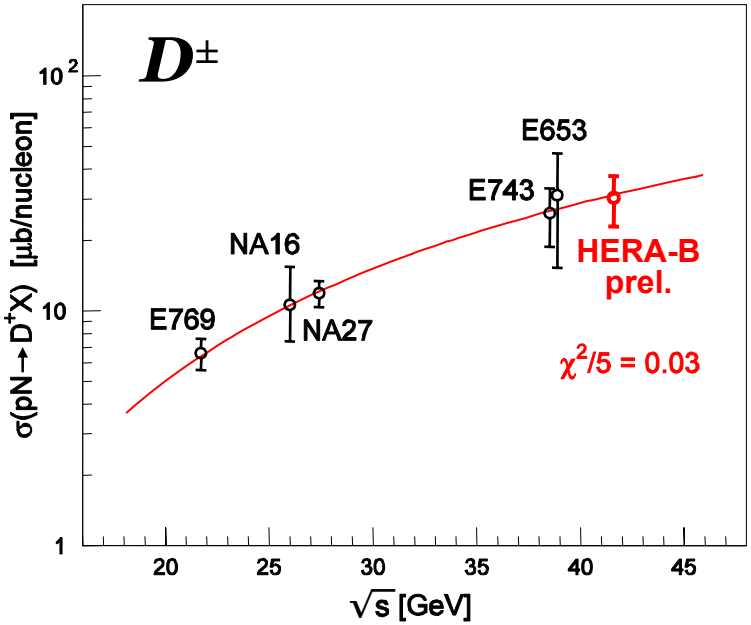
curve: NLO NRQCD fit of all data (Maltoni *et al.*, hep-ph/0601203)

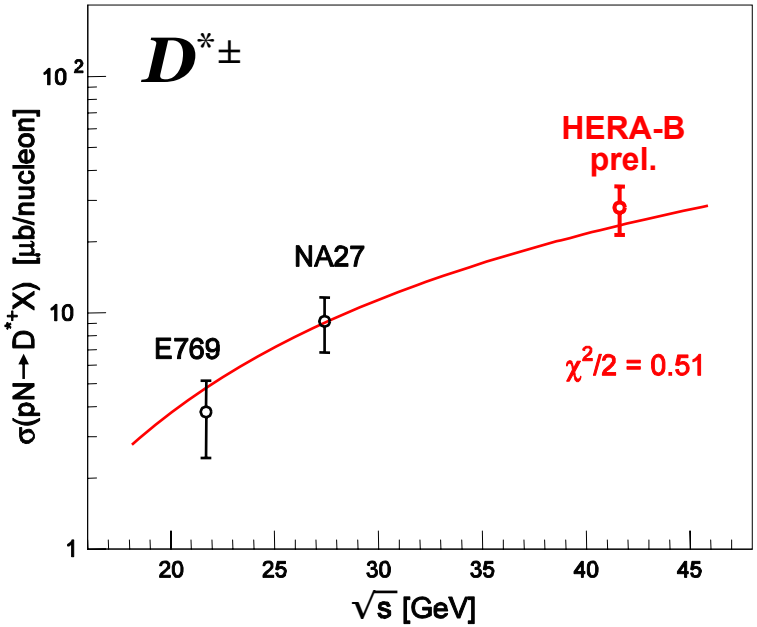
open charm: reconstructed signals

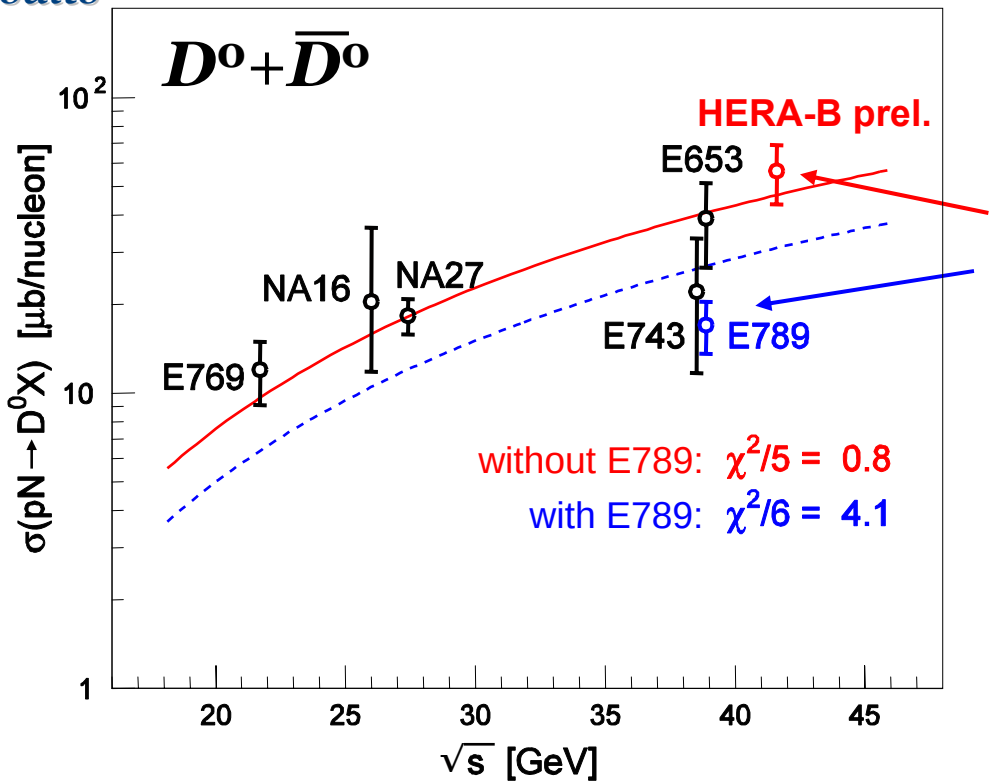


D cross sections

comparison with p-p/p-A results







- D^0: unclear situation at **high √s**
  - E789 result clearly disfavoured
- **energy dependence** well described in each case by the function

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

reflecting the behaviour of **proton PDFs** (Lourenço & Wöhri)

cross section ratios: experiments vs. isospin symmetry

isospin symmetry

$u \leftrightarrow d$ — 3 polar. states

$$\sigma_{\mathrm{DIR}}(D^0) = \sigma_{\mathrm{DIR}}(D^+) = \frac{1}{3}\sigma(D^*)$$

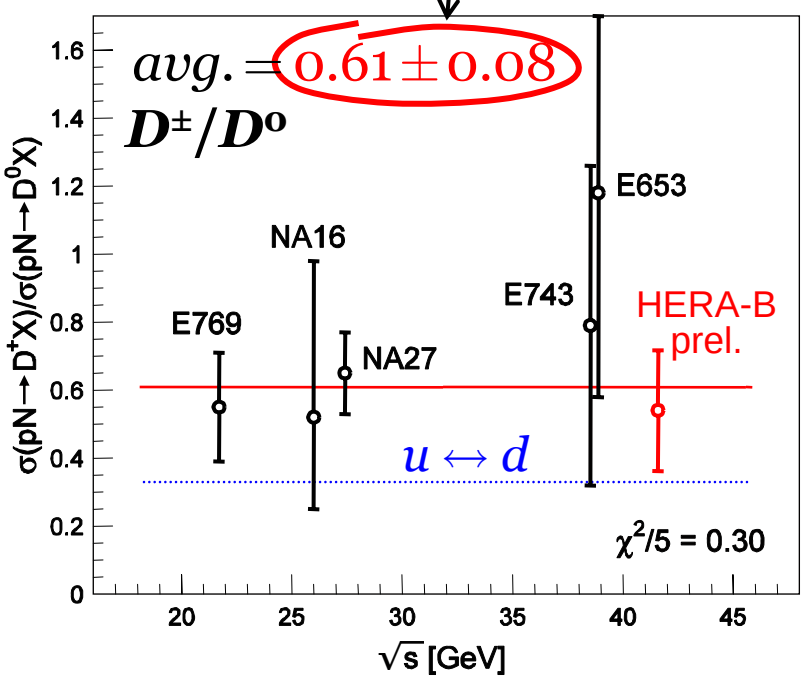
+ PDG averages for $D^{*0}, D^{*\pm} \to D^0, D^\pm$ feeddown BRs

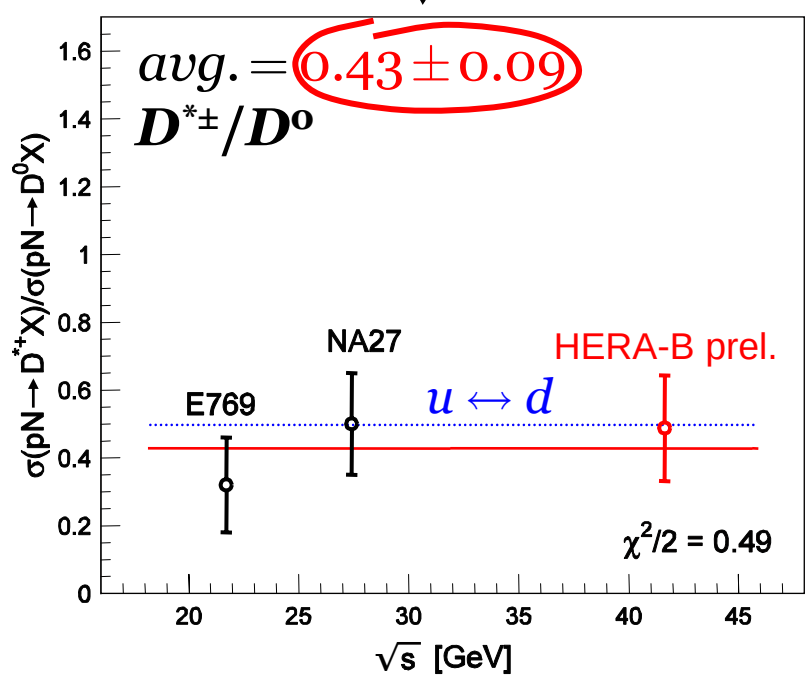
$$\sigma_{\mathrm{INCL}}(D^\pm)/\sigma_{\mathrm{INCL}}(D^0) = 0.326 \pm 0.003$$

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

violated *by a factor of* **1.87 ± 0.25**

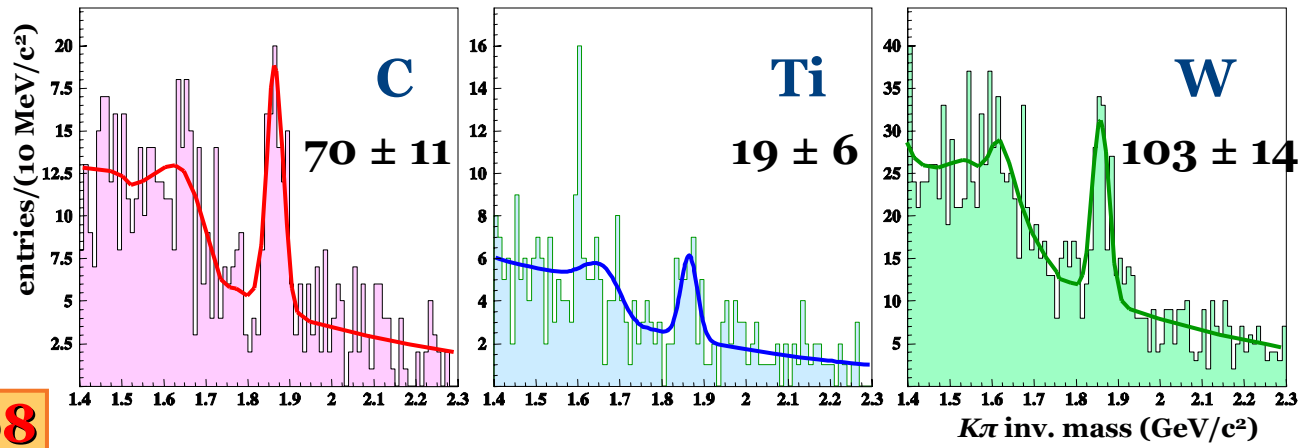
experiments





A-dependence

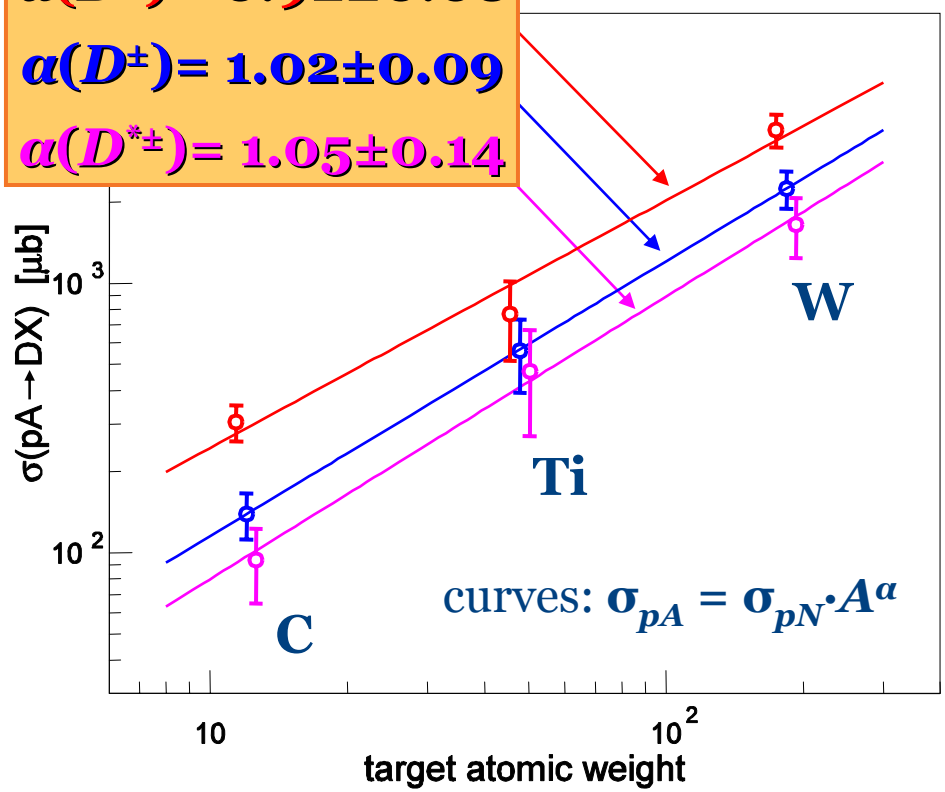
mass spectra
by target material
(e.g. for D^0):



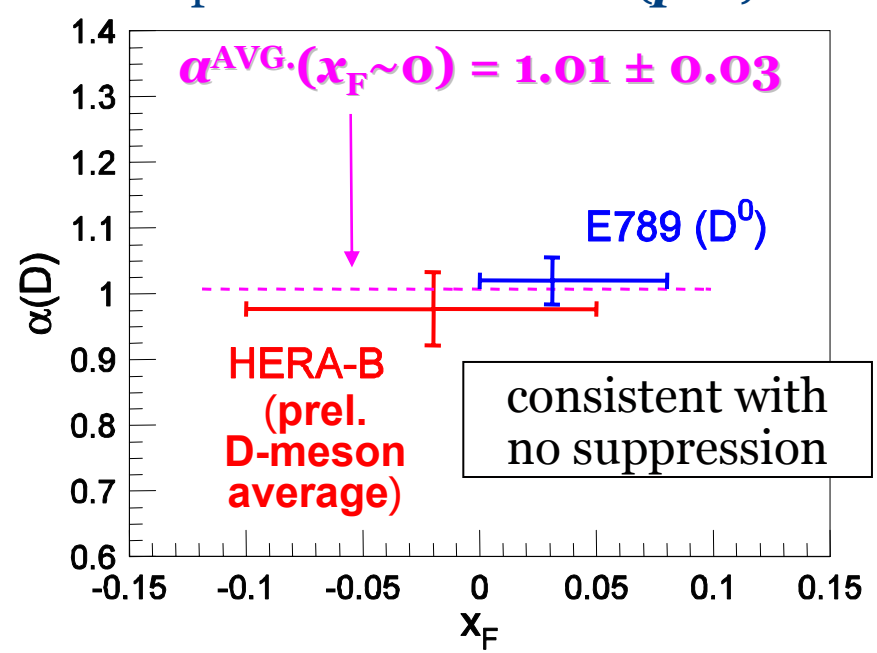
$\alpha(D^0) = 0.92 \pm 0.08$

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

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



experimental situation (p-A):



summary

J/ψ production in p-A collisions at $\sqrt{s}$ = 41.6 GeV ...

- high statistics, clean signals, two decay channels — 300000 J/ψ's
- wide kinematical coverage
  - p_T up to 5.5 GeV/c
  - negative x_F
- A-dependence:
  - flat suppression down to $x_F \sim -0.35$

... and its components:

- ψ'-to-J/ψ ratio — 5000 ψ''s
- fraction of J/ψ's from χ_c — 15000 χ_c's
- fraction of J/ψ's from b — 80 J/ψ's from b

J/ψ decay angular distributions

- longitudinal polarization rapidly increasing in magnitude with decreasing p_T and $|x_F|$
- strong hierarchy of frames: the direction of the original interaction (CS frame) is better than the J/ψ "flight" direction (HCM) as a reference for the observation of the "true" decay distribution

open charm

- D^0, $D^\pm$, $D^{*\pm}$ inclusive production cross sections and ratios
- A-dependence consistent with $\alpha = 1$