Cold nuclear matter effects in J/ψ production in p-nucleus collisions

- Energy dependence of the J/ψ “absorption cross section”
- J/ψ feed-down fractions from χ_c and ψ’

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Cold nuclear effects in quarkonium production in p-A collisions

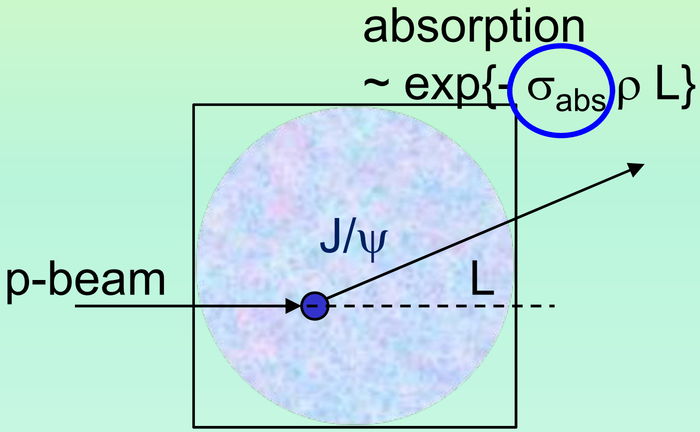
Several “normal nuclear matter effects” can modify the production of quarkonia in p-nucleus collisions with respect to pp collisions. In particular, we can expect:

initial-state effects:

- nuclear modifications to the PDFs
- initial-state energy loss of incident partons

final-state effects:

- formation time effects
- Glauber-like charmonium absorption

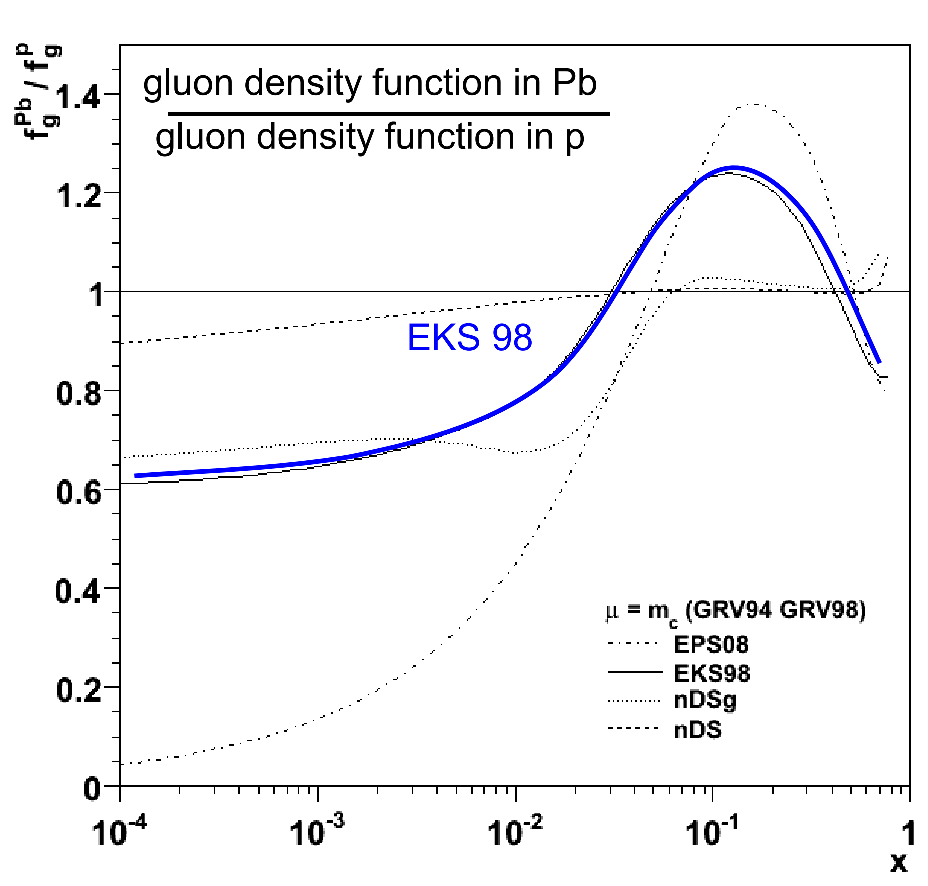


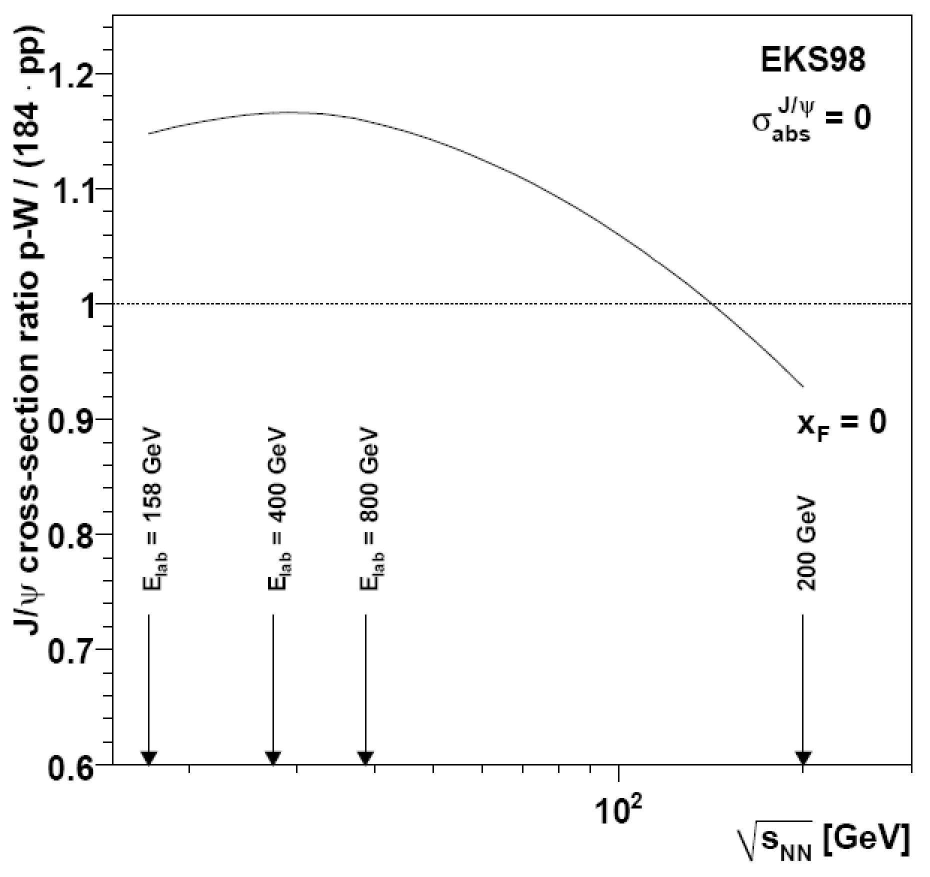
To learn about these mechanisms we need to look at different data sets, collected in different kinematical domains, at different energies, with several nuclear targets, etc.

We also need to analyze in a global way the J/ψ, ψ’ and χ_c data.
What are the feed-down fractions of ψ’ and χ_c to the J/ψ ?

Nuclear effects on the Parton Distribution Functions

The probability of finding a gluon with a momentum fraction *x* is *not* the same in a free proton as in a proton inside a nucleus; this “detail” has significant consequences.



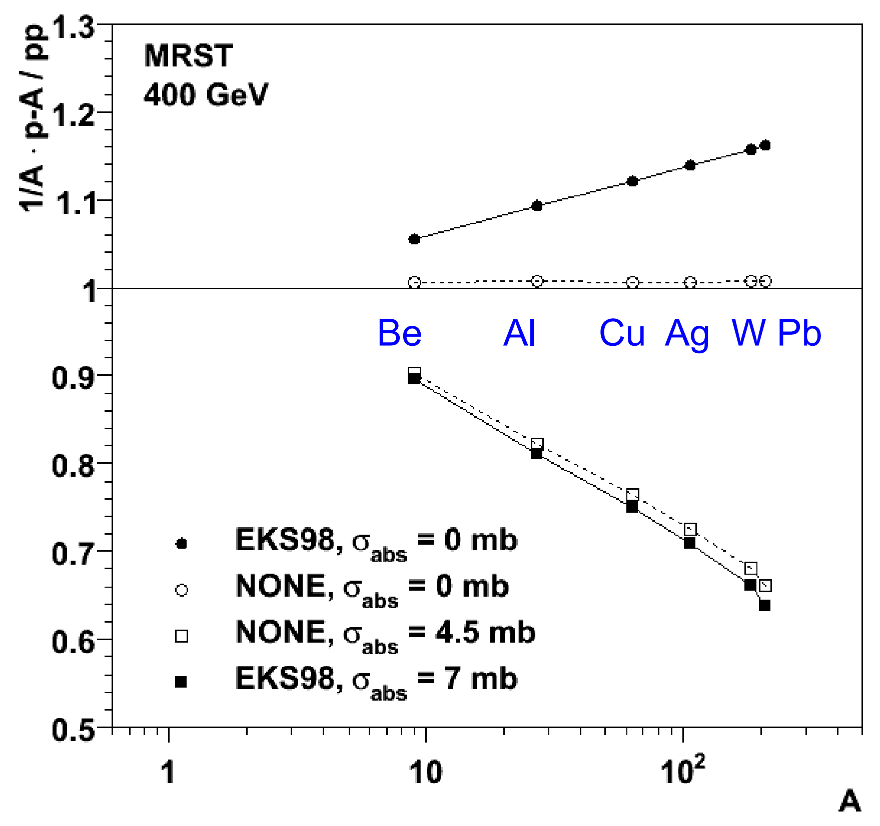


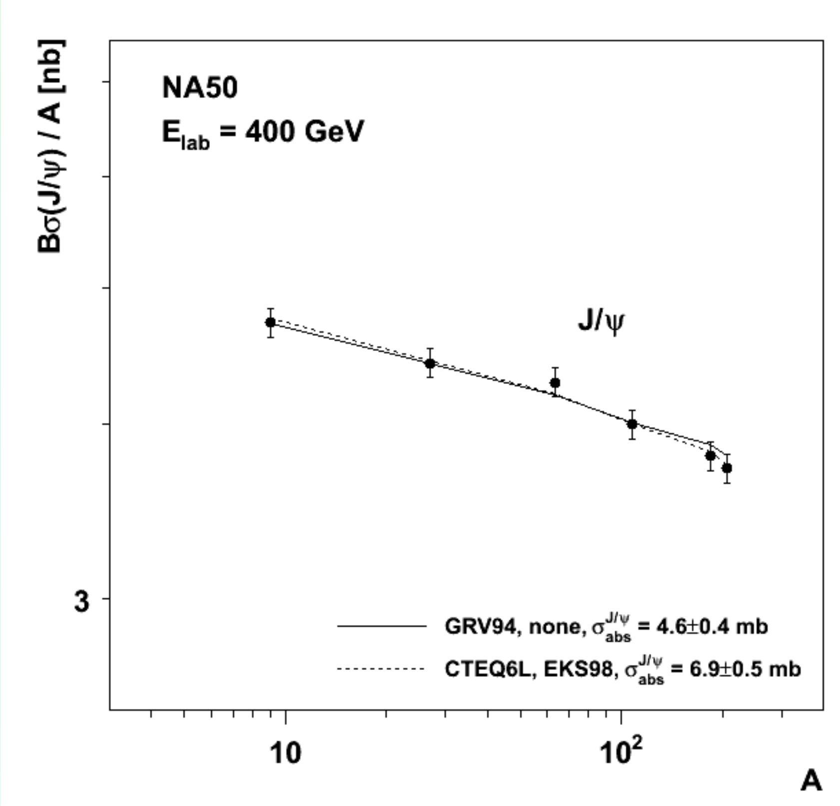
The existence of nuclear effects on the PDFs is well established but their *level* is not accurately known ⇒ calculations done with several models (EKS98, nDS, EPS08, etc).

Nuclear effects on the PDFs vs. final state absorption

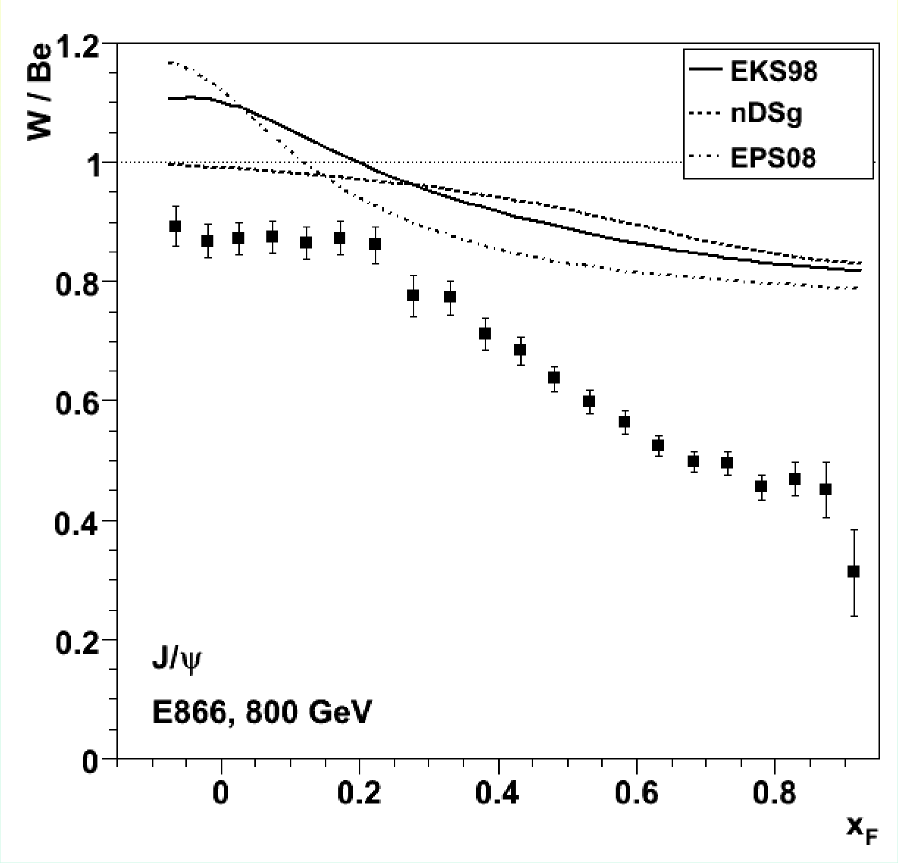
At *x* values ~ 0.1–0.4 (SPS energies), there is gluon *anti-shadowing* (EKS98); the J/ψ prod. cross section per nucleon *increases* from pp to p-Pb (before final state absorption)

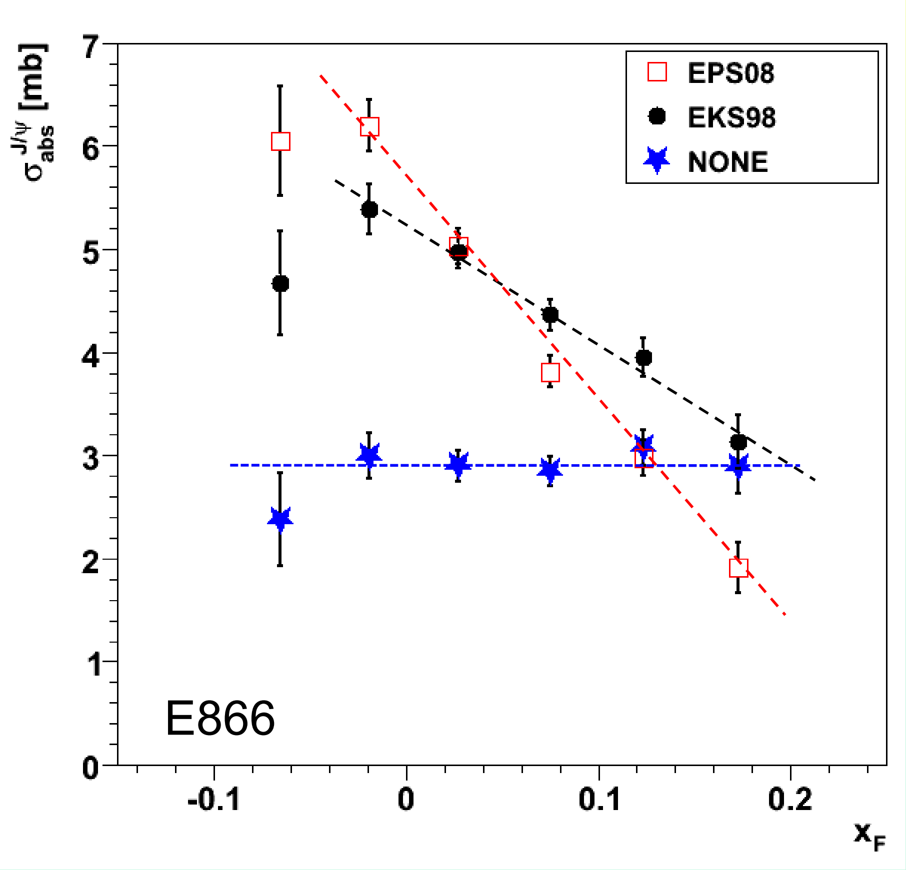
⇒ The NA50 measurements are equally well described using
σ_{abs} = 6.9 mb (with EKS98) or
σ_{abs} = 4.6 mb (with "free protons")





J/ψ σ_{abs} versus x_F : the importance of the N-PDFs

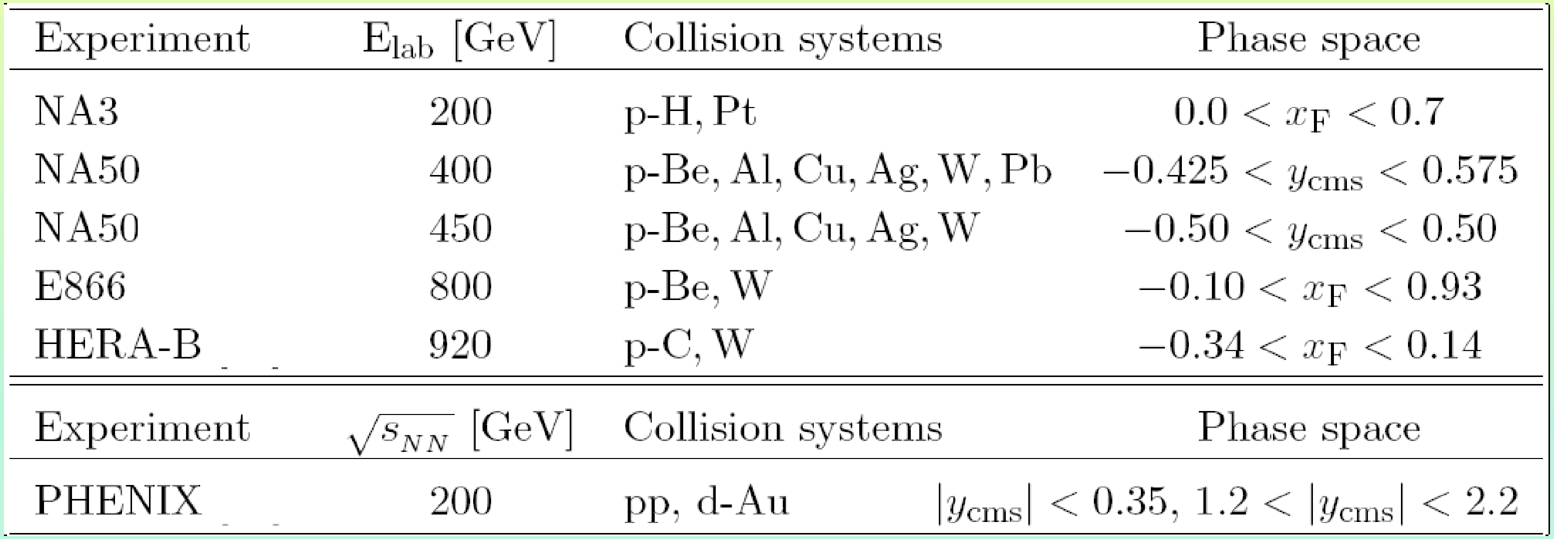




- The nuclear effects on the PDFs are a function of Bjorken-x
  $\Rightarrow$ they are energy *and* x_F (or rapidity) dependent
- At $x_F < 0.2$: strong anti-shadowing in EKS98 and EPS08 :
  $\Rightarrow$ In the absence of other effects, the E866 W/Be ratio should be higher than unity
- The nuclear modifications of the PDFs significantly change the x_F dependence of σ_{abs}

J/ψ nuclear dependence measurements: a global summary

The nuclear dependence of the J/ψ production cross section was studied by several experiments, probing different collision energies and J/ψ kinematics



Experiment	E_{lab} [GeV]	Collision systems	Phase space
NA3	200	p-H, Pt	$0.0 < x_F < 0.7$
NA50	400	p-Be, Al, Cu, Ag, W, Pb	$-0.425 < y_{\mathrm{cms}} < 0.575$
NA50	450	p-Be, Al, Cu, Ag, W	$-0.50 < y_{\mathrm{cms}} < 0.50$
E866	800	p-Be, W	$-0.10 < x_F < 0.93$
HERA-B	920	p-C, W	$-0.34 < x_F < 0.14$

Experiment	$\sqrt{s_{NN}}$ [GeV]	Collision systems	Phase space
PHENIX	200	pp, d-Au	$\lvert y_{\mathrm{cms}}\rvert < 0.35$, $1.2 < \lvert y_{\mathrm{cms}}\rvert < 2.2$

Some J/ψ data we have considered

$B \times \sigma^{J/\psi} / A$ [nb/nucleon]

	NA50-400	NA50-450 "LI"	NA50-450 "HI"
Be	4.717 ± 0.10	5.27 ± 0.23	5.11 ± 0.18
Al	4.417 ± 0.10	5.14 ± 0.21	4.88 ± 0.23
Cu	4.280 ± 0.09	4.97 ± 0.22	4.74 ± 0.18
Ag	3.994 ± 0.09	4.52 ± 0.20	4.45 ± 0.15
W	3.791 ± 0.08	4.17 ± 0.37	4.05 ± 0.15
Pb	3.715 ± 0.08		

NA3

x_F range	H / Pt ratio
0.0 / 0.1	1.27 ± 0.07
0.1 / 0.2	1.40 ± 0.06
0.2 / 0.3	1.34 ± 0.07
0.3 / 0.4	1.36 ± 0.12
0.4 / 0.5	1.75 ± 0.22
0.5 / 0.6	2.62 ± 0.52
0.6 / 0.7	3.58 ± 1.81

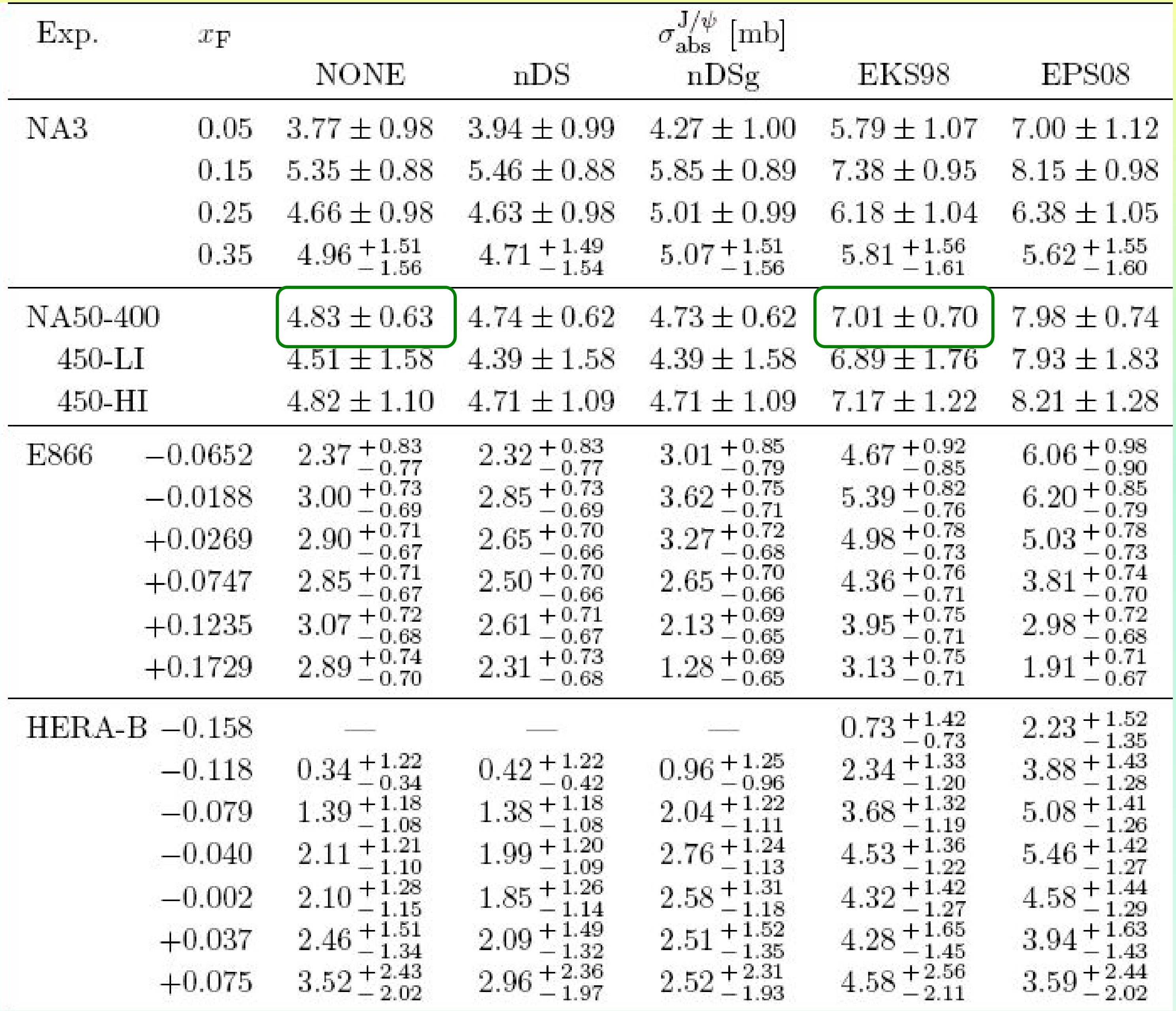
HERA-B

x_F range	$\langle x_F \rangle$	W / C ratio
−0.34 / −0.26	−0.285	1.105 ± 0.158
−0.26 / −0.22	−0.237	1.034 ± 0.096
−0.22 / −0.18	−0.197	1.090 ± 0.063
−0.18 / −0.14	−0.158	1.043 ± 0.042
−0.14 / −0.10	−0.118	0.986 ± 0.030
−0.10 / −0.06	−0.079	0.943 ± 0.022
−0.06 / −0.02	−0.040	0.915 ± 0.021
−0.02 / +0.02	−0.002	0.916 ± 0.025
+0.02 / +0.06	+0.037	0.902 ± 0.036
+0.06 / +0.14	+0.075	0.866 ± 0.063

E866

x_F range	$\langle x_F \rangle$	W / Be ratio
−0.10 / −0.05	−0.0652	0.8929 ± 0.0184
−0.05 / 0.00	−0.0188	0.8682 ± 0.0084
0.00 / +0.05	+0.0269	0.8720 ± 0.0060
+0.05 / +0.10	+0.0747	0.8739 ± 0.0057
+0.10 / +0.15	+0.1235	0.8652 ± 0.0067
+0.15 / +0.20	+0.1729	0.8725 ± 0.0100

J/ψ σ_{abs} for each kinematical window and N-PDF set



Exp.	x_F			$\sigma^{J/\psi}_{abs}$ [mb]		
		NONE	nDS	nDSg	EKS98	EPS08
NA3	0.05	3.77 ± 0.98	3.94 ± 0.99	4.27 ± 1.00	5.79 ± 1.07	7.00 ± 1.12
	0.15	5.35 ± 0.88	5.46 ± 0.88	5.85 ± 0.89	7.38 ± 0.95	8.15 ± 0.98
	0.25	4.66 ± 0.98	4.63 ± 0.98	5.01 ± 0.99	6.18 ± 1.04	6.38 ± 1.05
	0.35	$4.96^{+1.51}_{-1.56}$	$4.71^{+1.49}_{-1.54}$	$5.07^{+1.51}_{-1.56}$	$5.81^{+1.56}_{-1.61}$	$5.62^{+1.55}_{-1.60}$
NA50-400		4.83 ± 0.63	4.74 ± 0.62	4.73 ± 0.62	7.01 ± 0.70	7.98 ± 0.74
450-LI		4.51 ± 1.58	4.39 ± 1.58	4.39 ± 1.58	6.89 ± 1.76	7.93 ± 1.83
450-HI		4.82 ± 1.10	4.71 ± 1.09	4.71 ± 1.09	7.17 ± 1.22	8.21 ± 1.28
E866	−0.0652	$2.37^{+0.83}_{-0.77}$	$2.32^{+0.83}_{-0.77}$	$3.01^{+0.85}_{-0.79}$	$4.67^{+0.92}_{-0.85}$	$6.06^{+0.98}_{-0.90}$
	−0.0188	$3.00^{+0.73}_{-0.69}$	$2.85^{+0.73}_{-0.69}$	$3.62^{+0.75}_{-0.71}$	$5.39^{+0.82}_{-0.76}$	$6.20^{+0.85}_{-0.79}$
	+0.0269	$2.90^{+0.71}_{-0.67}$	$2.65^{+0.70}_{-0.66}$	$3.27^{+0.72}_{-0.68}$	$4.98^{+0.78}_{-0.73}$	$5.03^{+0.78}_{-0.73}$
	+0.0747	$2.85^{+0.71}_{-0.67}$	$2.50^{+0.70}_{-0.66}$	$2.65^{+0.70}_{-0.66}$	$4.36^{+0.76}_{-0.71}$	$3.81^{+0.74}_{-0.70}$
	+0.1235	$3.07^{+0.72}_{-0.68}$	$2.61^{+0.71}_{-0.67}$	$2.13^{+0.69}_{-0.65}$	$3.95^{+0.75}_{-0.71}$	$2.98^{+0.72}_{-0.68}$
	+0.1729	$2.89^{+0.74}_{-0.70}$	$2.31^{+0.73}_{-0.68}$	$1.28^{+0.69}_{-0.65}$	$3.13^{+0.75}_{-0.71}$	$1.91^{+0.71}_{-0.67}$
HERA-B	−0.158	—	—	—	$0.73^{+1.42}_{-0.73}$	$2.23^{+1.52}_{-1.35}$
	−0.118	$0.34^{+1.22}_{-0.34}$	$0.42^{+1.22}_{-0.42}$	$0.96^{+1.25}_{-0.96}$	$2.34^{+1.33}_{-1.20}$	$3.88^{+1.43}_{-1.28}$
	−0.079	$1.39^{+1.18}_{-1.08}$	$1.38^{+1.18}_{-1.08}$	$2.04^{+1.22}_{-1.11}$	$3.68^{+1.32}_{-1.19}$	$5.08^{+1.41}_{-1.26}$
	−0.040	$2.11^{+1.21}_{-1.10}$	$1.99^{+1.20}_{-1.09}$	$2.76^{+1.24}_{-1.13}$	$4.53^{+1.36}_{-1.22}$	$5.46^{+1.42}_{-1.27}$
	−0.002	$2.10^{+1.28}_{-1.15}$	$1.85^{+1.26}_{-1.14}$	$2.58^{+1.31}_{-1.18}$	$4.32^{+1.42}_{-1.27}$	$4.58^{+1.44}_{-1.29}$
	+0.037	$2.46^{+1.51}_{-1.34}$	$2.09^{+1.49}_{-1.32}$	$2.51^{+1.52}_{-1.35}$	$4.28^{+1.65}_{-1.45}$	$3.94^{+1.63}_{-1.43}$
	+0.075	$3.52^{+2.43}_{-2.02}$	$2.96^{+2.36}_{-1.97}$	$2.52^{+2.31}_{-1.93}$	$4.58^{+2.56}_{-2.11}$	$3.59^{+2.44}_{-2.02}$

Errors include the global systematic uncertainties of the ratios:

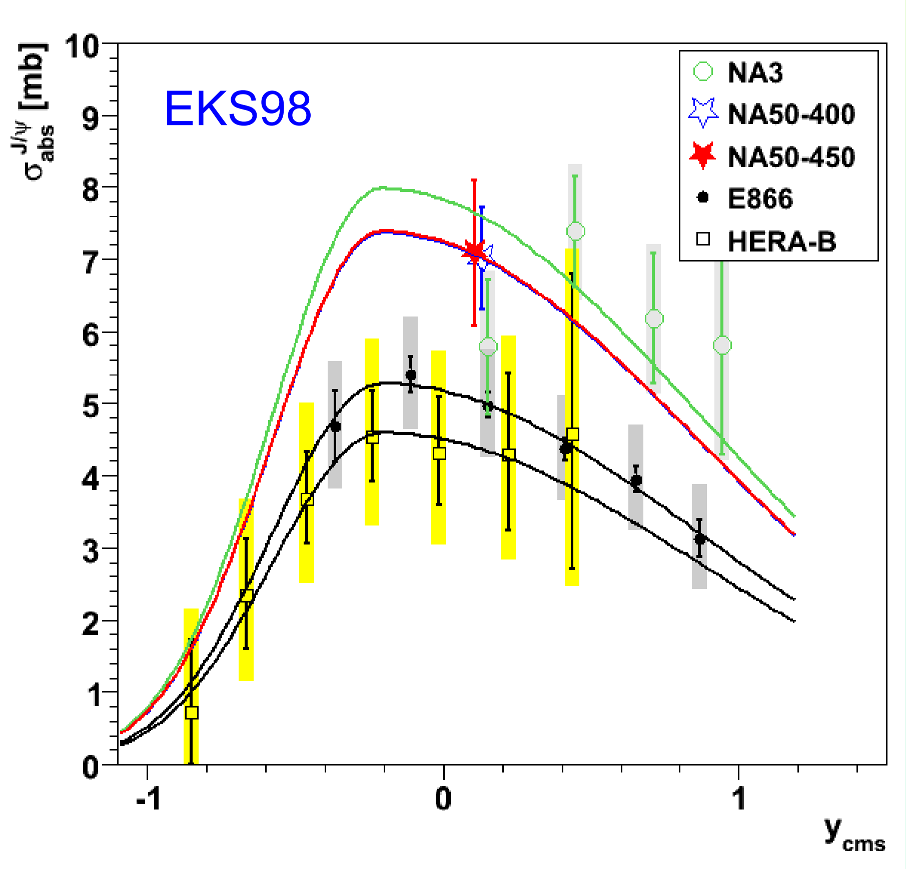
3% in NA3
3% in E866
4% in HERA-B

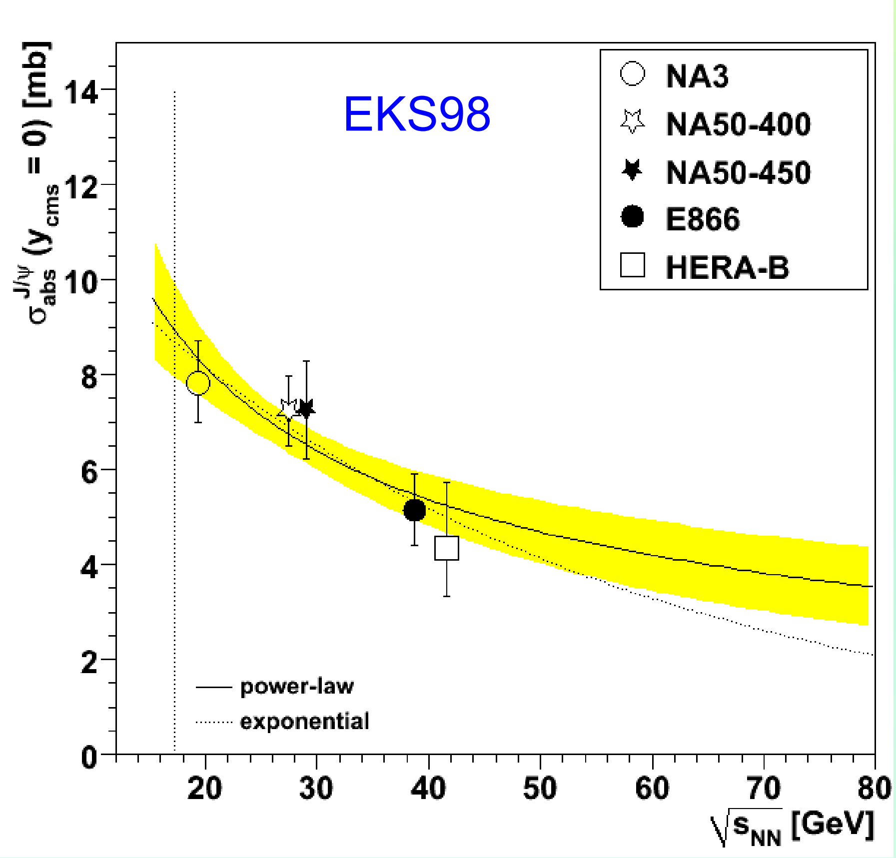
[C. Lourenço et al., JHEP 2 (09) 14]

J/ψ σ_{abs} versus rapidity and collision energy

The E866 and HERA-B patterns define the *shape* of the rapidity dependence of σ_{abs}

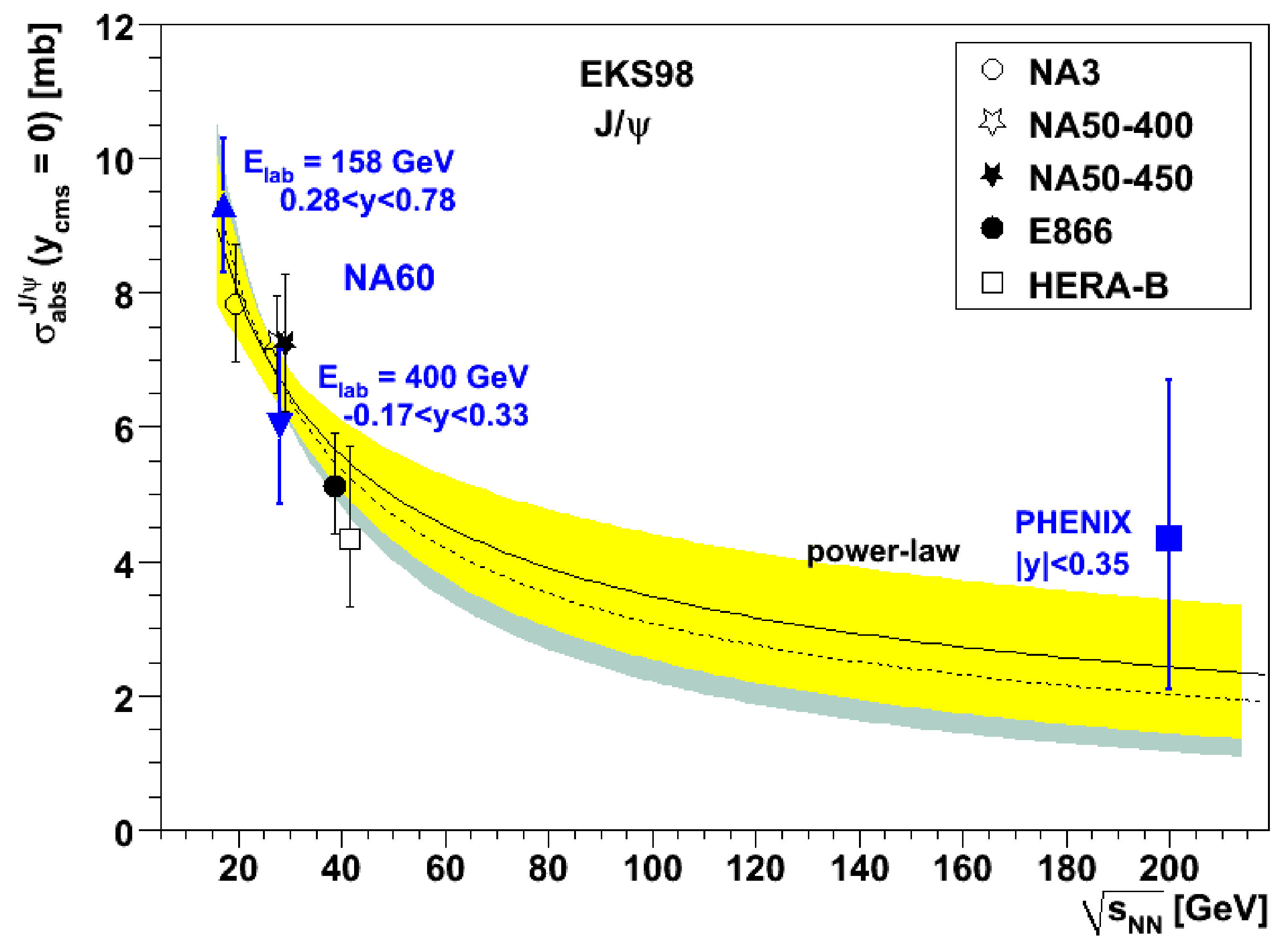
σ_{abs} at y_{cms}=0 decreases with NN collision energy





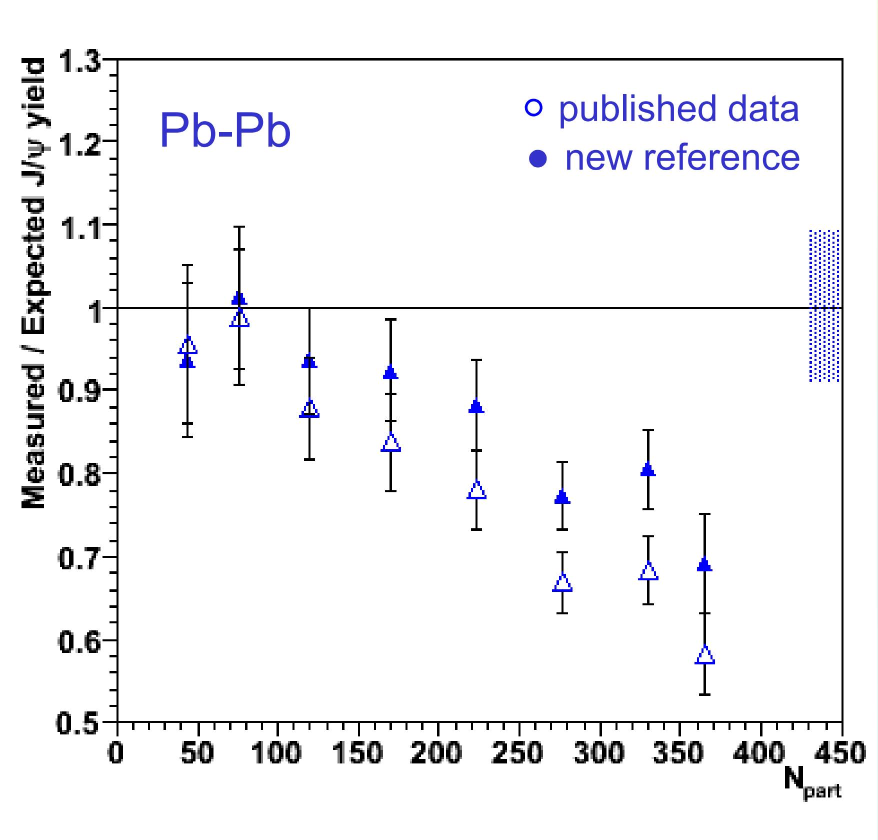
New (preliminary) results from NA60 and PHENIX

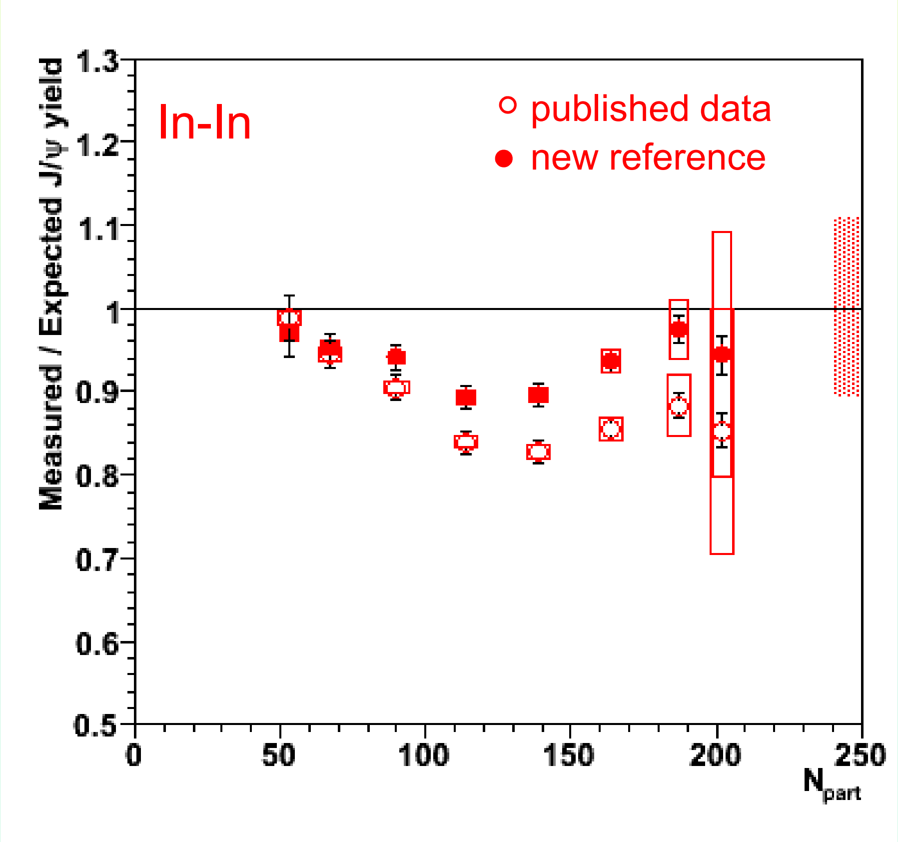
NA60 measured the J/ψ absorption cross section at 400 and 158 GeV, the energy of the SPS heavy-ion data. Both values follow the previously established trend (but are not obtained at exactly y_{cms}=0).



Anomalous J/ψ suppression revisited

The 158 GeV σ_{abs} value is larger than previously assumed and decreases the “anomalous suppression” remaining in the heavy-ion data:





E. Scomparin (NA60), QM09

J/ψ feed-down contributions

So far, only an “effective” absorption cross-section was extracted from the data, being a “weighted” sum of directly produced J/ψ’s and J/ψ’s from ψ’ and χ_c decays

From NA50 we know that $\sigma_{abs}(J/\psi) \neq \sigma_{abs}(\psi')$

To interpret the J/ψ suppression seen in heavy-ion collisions, the J/ψ feed-down fractions from χ_c and ψ’ decays *cannot* be neglected

It is often assumed that 60% of the prompt J/ψ mesons are directly produced, 10% result from ψ’ decays and 30% from χ_c decays, without mentioning uncertainties, measurement conditions, kinematical windows, etc

Let’s have a more detailed look at these values

J/ψ feed-down contributions: from ψ’ decays

The fraction of J/ψ events resulting from ψ’ decays

$$R(\psi') = \frac{J/\psi\text{'s from } \psi'}{ALL\ J/\psi\text{'s}}$$

is obtained from the measurements of

$$\rho(\psi') = \frac{\sigma(\psi')\, B(\psi' \to \ell\ell)}{\sigma_{incl}(J/\psi)\, B(J/\psi \to \ell\ell)}$$

The “pp” value $R^0(\psi')$ is obtained from the p-nucleus data assuming an exponential absorption model:

$$\left(\frac{\sigma^{\psi'}}{\sigma^{J/\psi}}\right)_{p-A} = \left(\frac{\sigma^{\psi'}}{\sigma^{J/\psi}}\right)_{pp} e^{-\Delta\sigma_{abs}\,\rho\, L(A)}$$

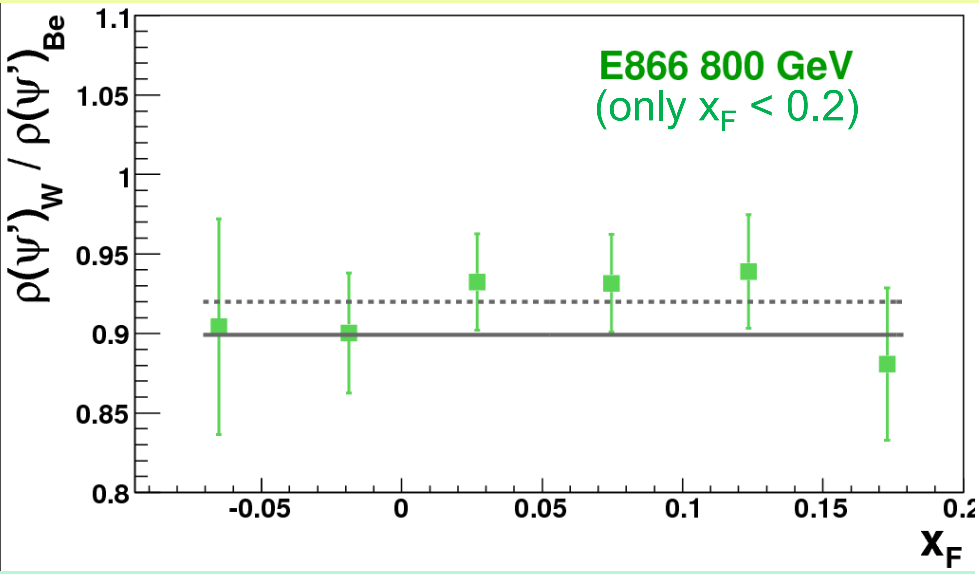
We define the difference of absorptions cross sections as $\Delta\sigma_{abs} = \sigma_{abs}(\psi') - \sigma_{abs}(J/\psi)$ where the J/ψ term does not include the ψ’ contribution

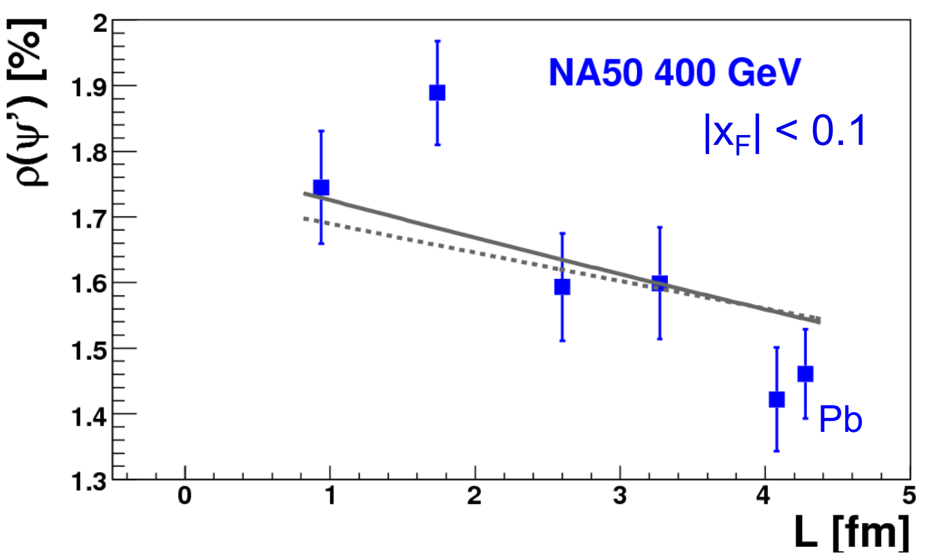
We extract $R^0(\psi')$ and $\Delta\sigma_{abs}$ from a global fit of two data sets:

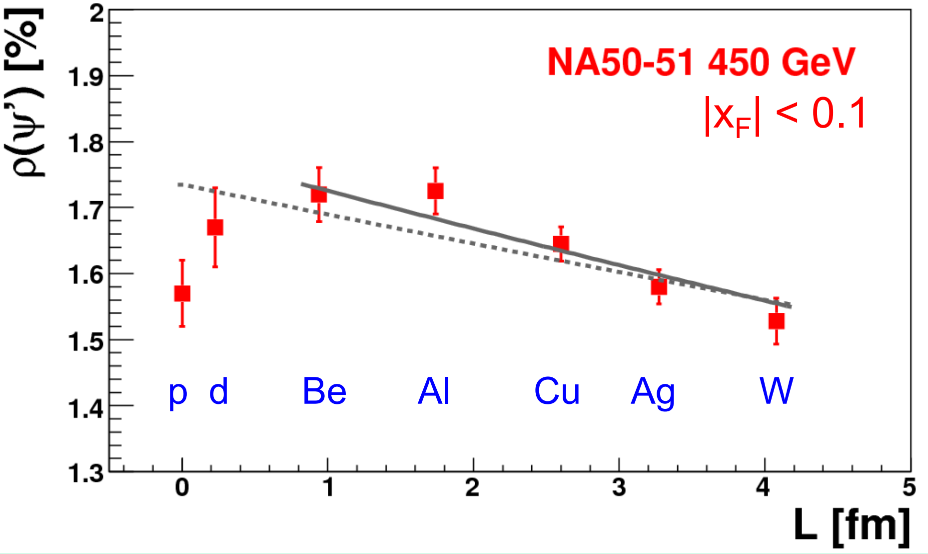
- NA50: production cross sections in 6 target nuclei, at 400 and 450 GeV
- E866: comparing p-W to p-Be, at 800 GeV

[P. Faccioli et al., JHEP 10 (08) 4]

J/ψ feed-down contributions: from ψ' decays



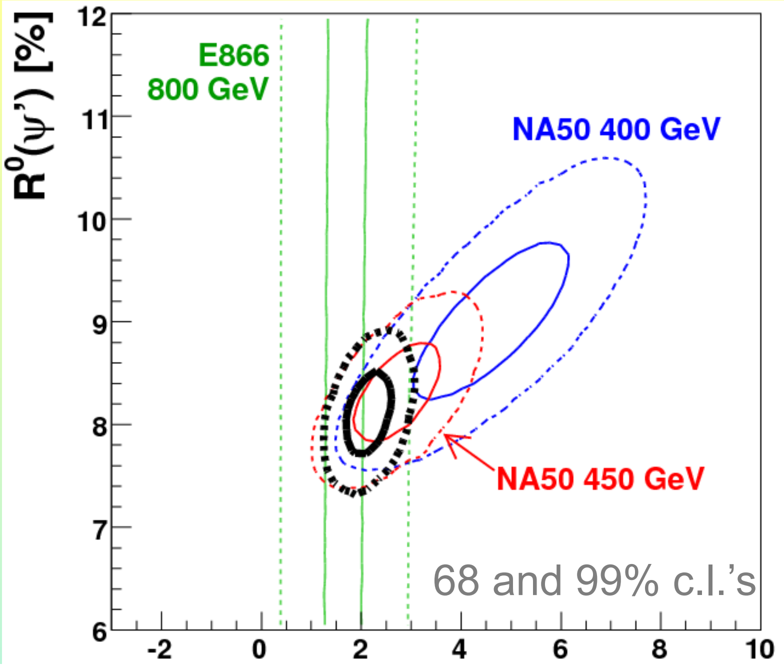


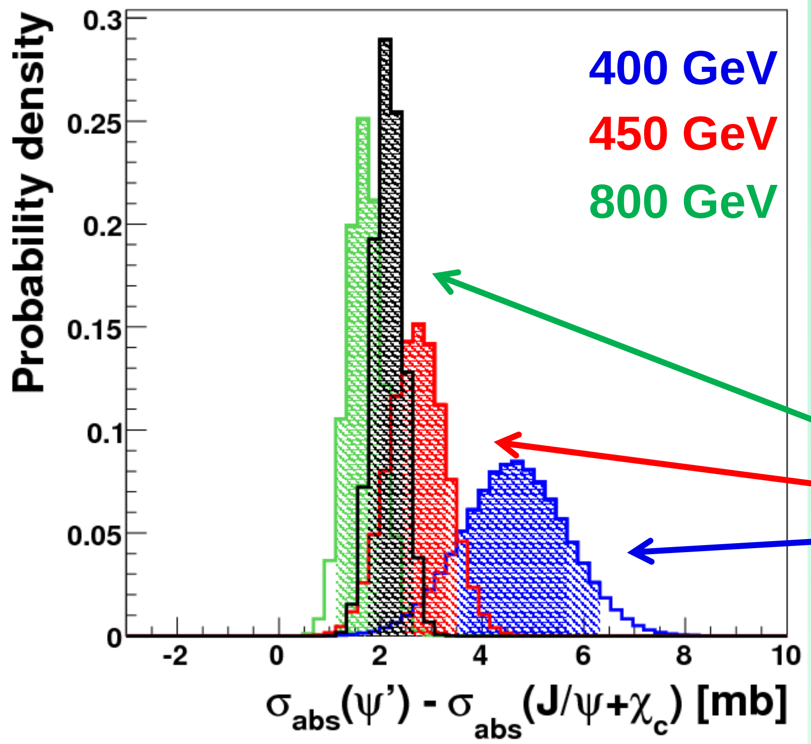


- The simple model used does not account for the H and D data points
- Are H and D nuclei not large enough to be traversed by fully formed states?

All data: P(χ^2) = 1%

Without H and D data: P(χ^2) = 27%





NA50 400 GeV
NA50 450 GeV
E866 800 GeV

black: all combined
(→ global fits shown in
the previous slide)

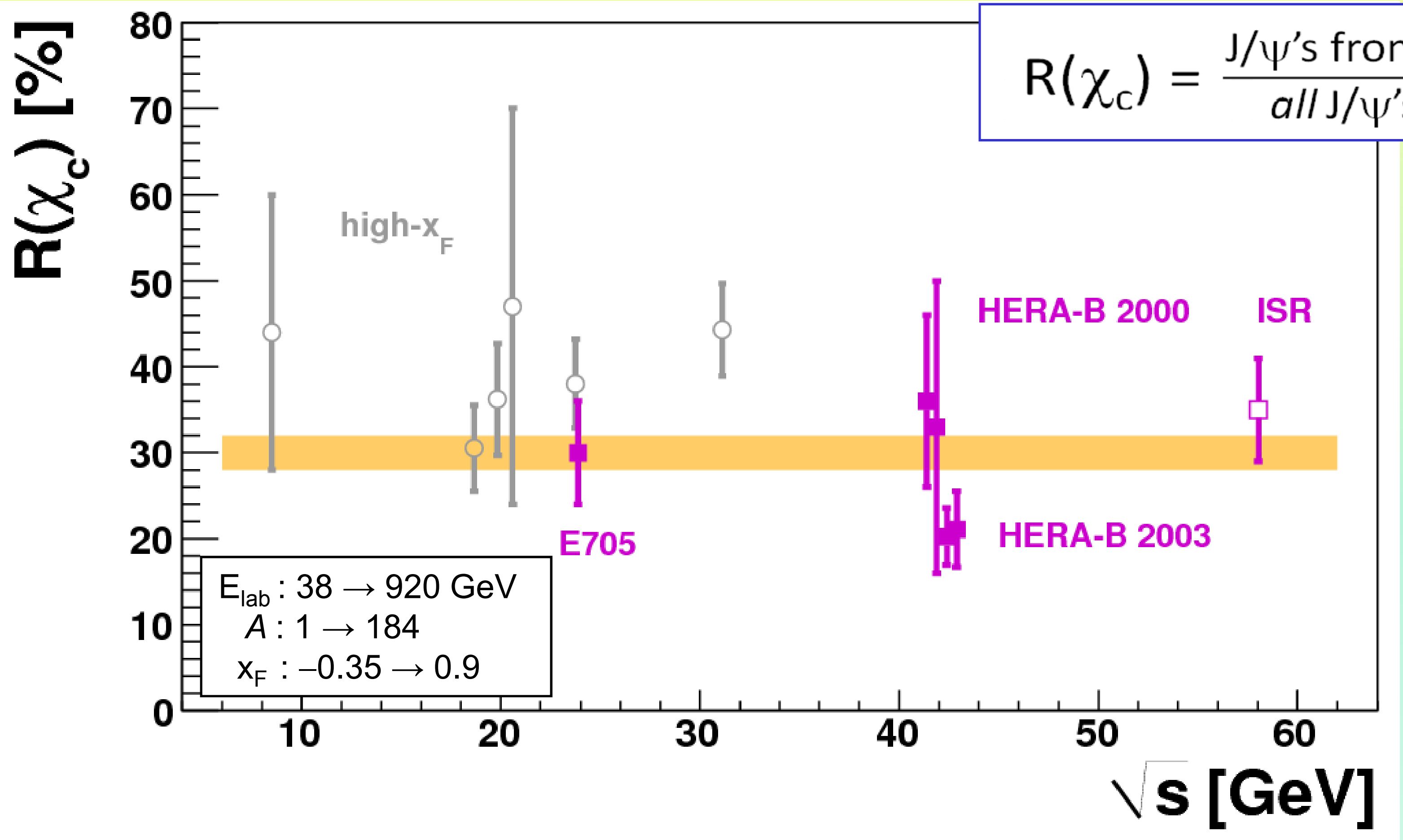
$R^0(\psi') = 8.1 \pm 0.3$ %
$\Delta\sigma_{abs} = 2.2 \pm 0.3$ mb

The error of $R^0(\psi')$ is dominated by uncertainties of branching fractions

Even if the three values are compatible…
it seems that $\Delta\sigma_{abs}$ decreases with energy

J/ψ feed-down contributions: from χ_c decays

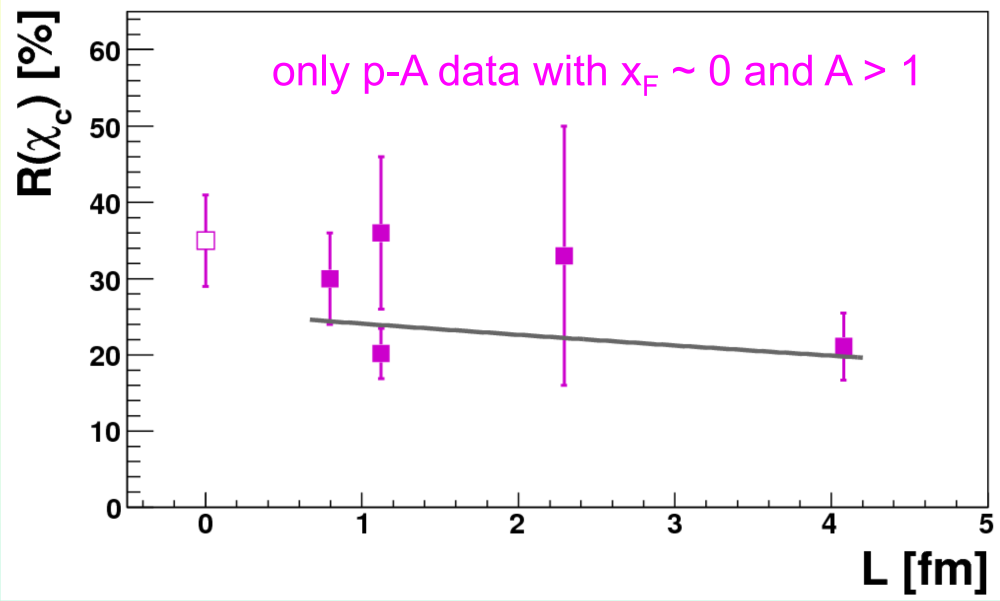
$$R(\chi_c) = \frac{J/\psi\text{'s from } \chi_c}{\textit{all } J/\psi\text{'s}}$$

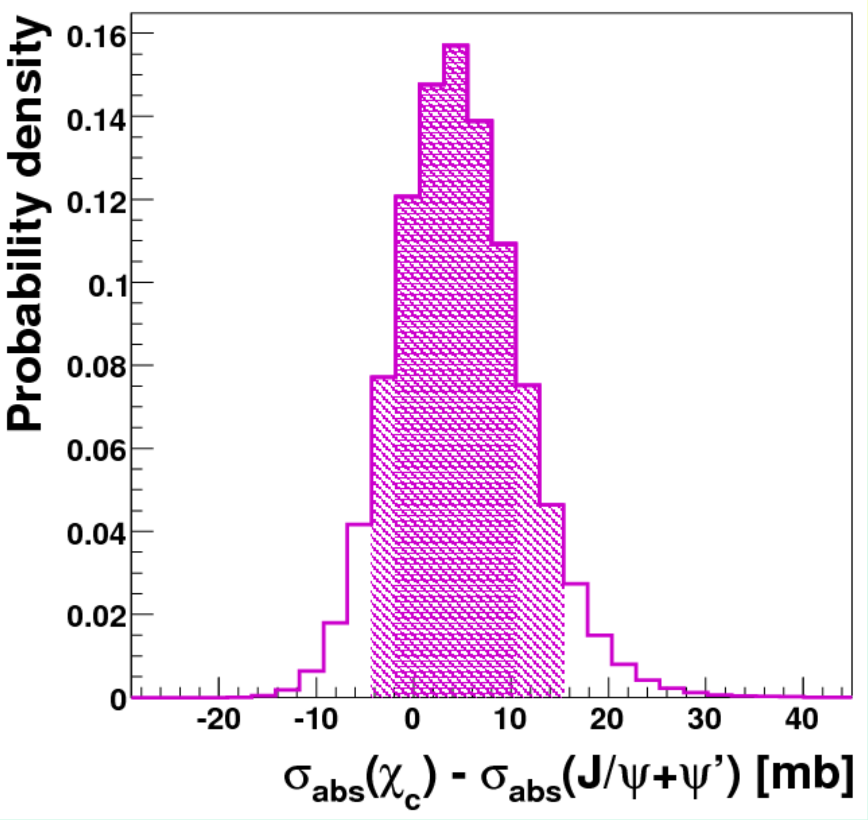


CDF →

A simple global average of all data points gives a very bad fit quality: P(χ^2) < 1%

What if we concentrate on the mid-rapidity region and allow the J/ψ and χ_c to have different absorption cross sections?





The quality of the data description improves very much: $P(\chi^2) = 25\%$

The "pp" feed-down fraction becomes

$R^0(\chi_c) = 25 \pm 5\ \%$

$\Delta\sigma_{abs} > 0$ at 75% c.l.

⇓

nuclear matter breaks the χ_c
more easily than the J/ψ

Summary

- The detailed interpretation of the J/ψ suppression patterns seen in heavy-ion collisions crucially relies on a robust understanding of the nuclear effects already present in proton-nucleus data

- The J/ψ absorption cross section, σ_{abs}, depends on rapidity and collision energy, being larger at 158 GeV than previously assumed

- The J/ψ feed-down fractions from ψ’ and χ_c decays and their different nuclear dependences must be accounted for in the analysis of the heavy-ion results