Cold nuclear matter effects in J/ψ production

- Impact of the nuclear modifications of the parton densities
- Energy and rapidity dependence of $\sigma_{abs}(J/\psi)$
- Initial state parton energy loss
- Recent progress using EPS09

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Quarkonium in Hot Medium – from QCD to Experiment
Seattle, June 2009

With Carlos Lourenço, Ramona Vogt,
Pietro Faccioli and João Seixas

Nuclear effects in quarkonium production in p-A collisions

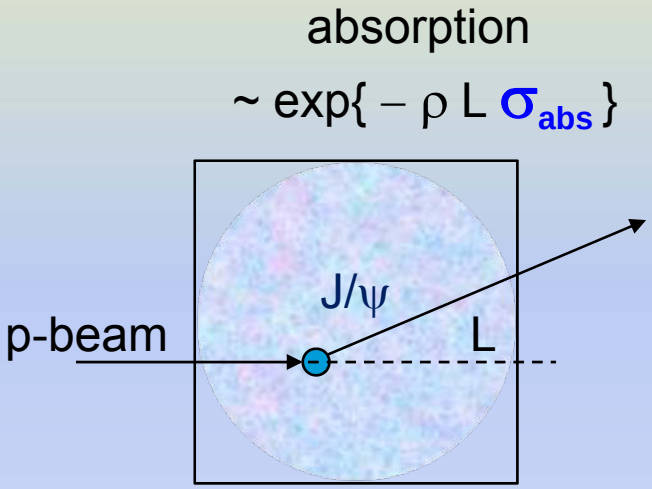
Several “cold nuclear matter effects” can modify the production of quarkonia in p-nucleus collisions with respect to pp collisions; in particular, we expect:

initial-state effects:

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

final-state effects:

- break-up of formed or pre-resonant charmonia (different for each charmonium state)

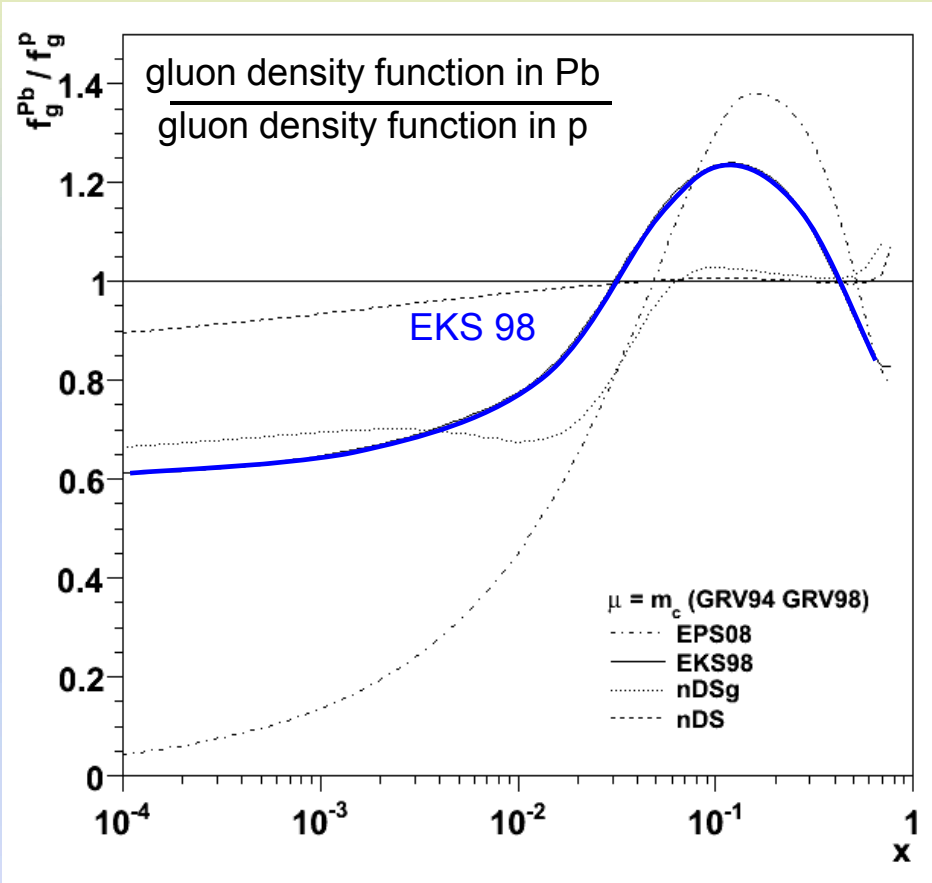


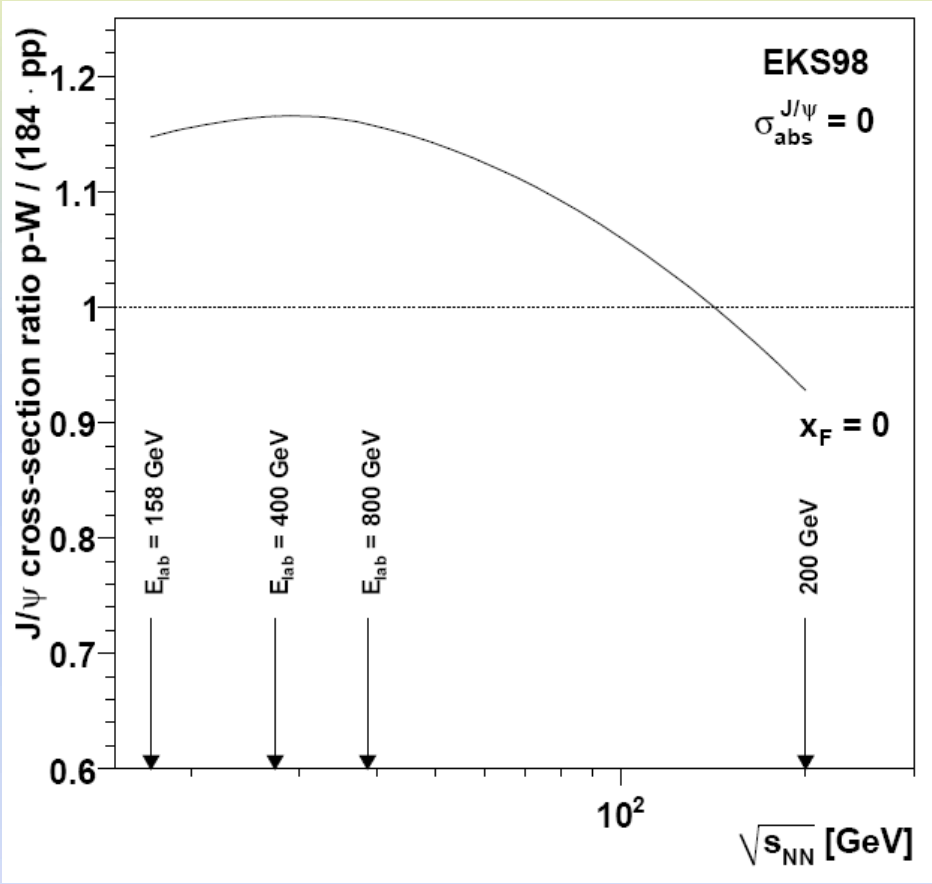
To understand these effects we need to study several data sets, collected in different kinematical domains, at different energies, with several nuclear targets, etc

And we need to consider the ψ' and χ_c measurements, together with the J/ψ results; around 1/3 of the J/ψ yield is due to decays of ψ' and χ_c mesons

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



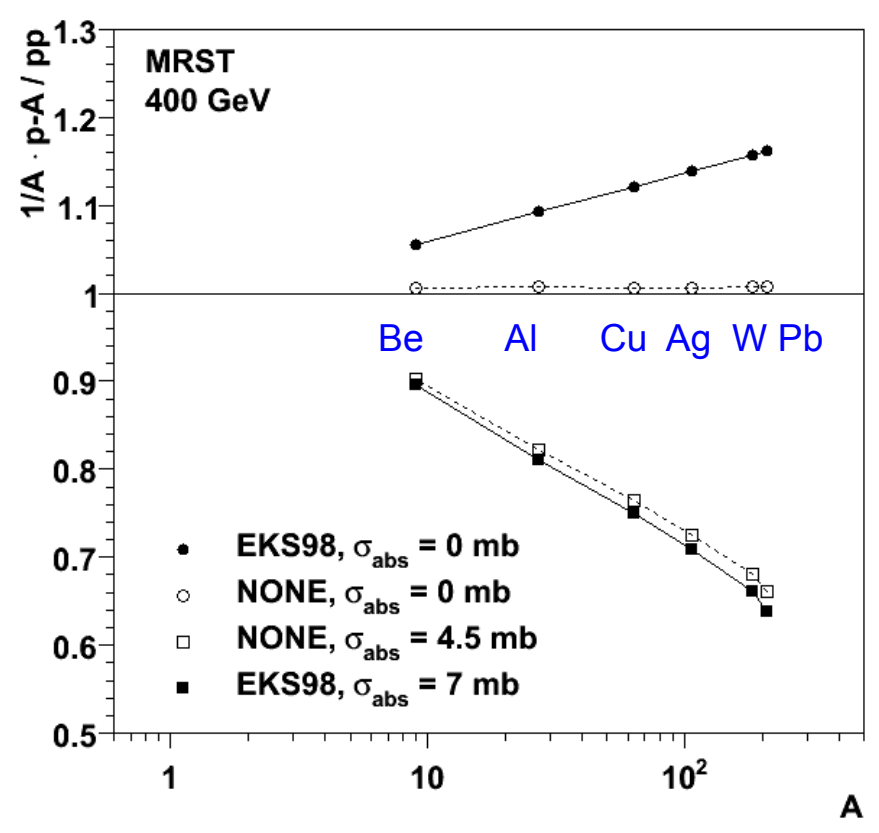


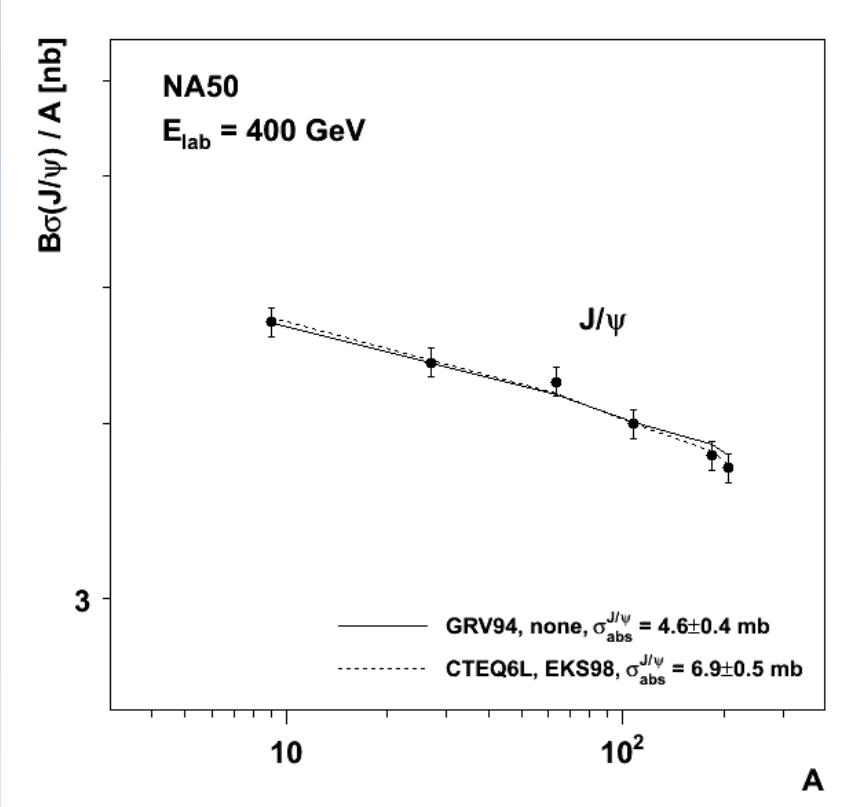
The existence of nuclear effects on the PDFs is well established but their *level* is not accurately known ⇒ calculations done with several models (EKS98, nDS, EPS09, etc)

Nuclear effects on the PDFs vs. final state absorption

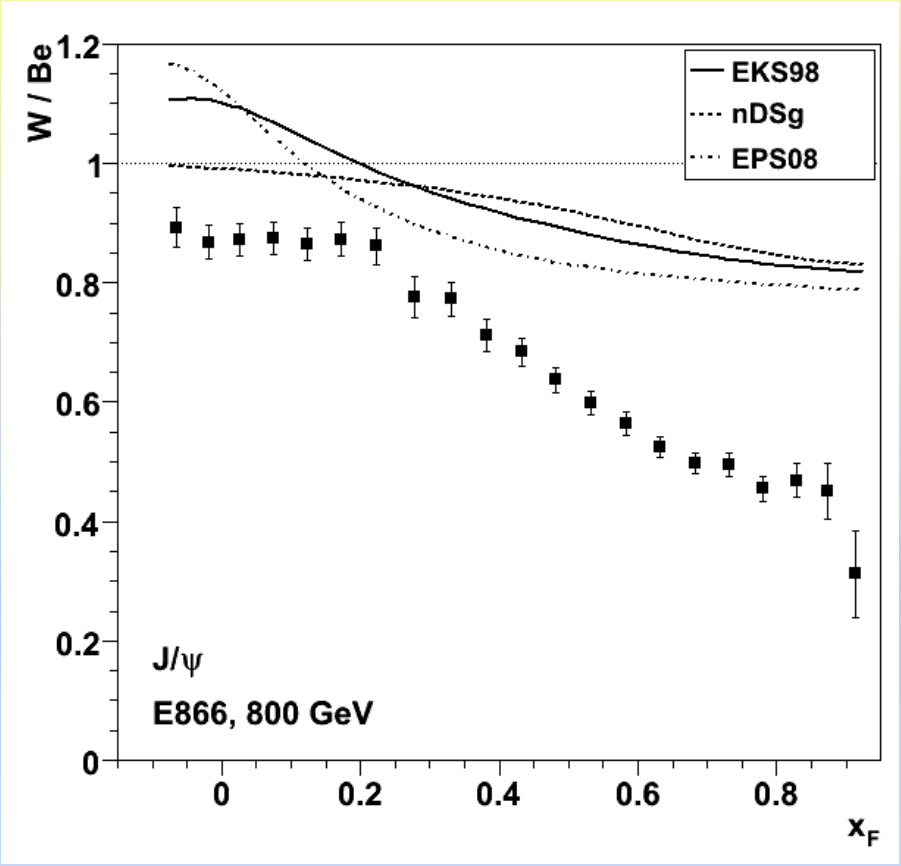
At *x* values ~ 0.1–0.4 (SPS energies), there is gluon *anti-shadowing* (EKS98); the J/ψ prod. cross section per nucleon *increases* from pp to p-Pb (before final state absorption)

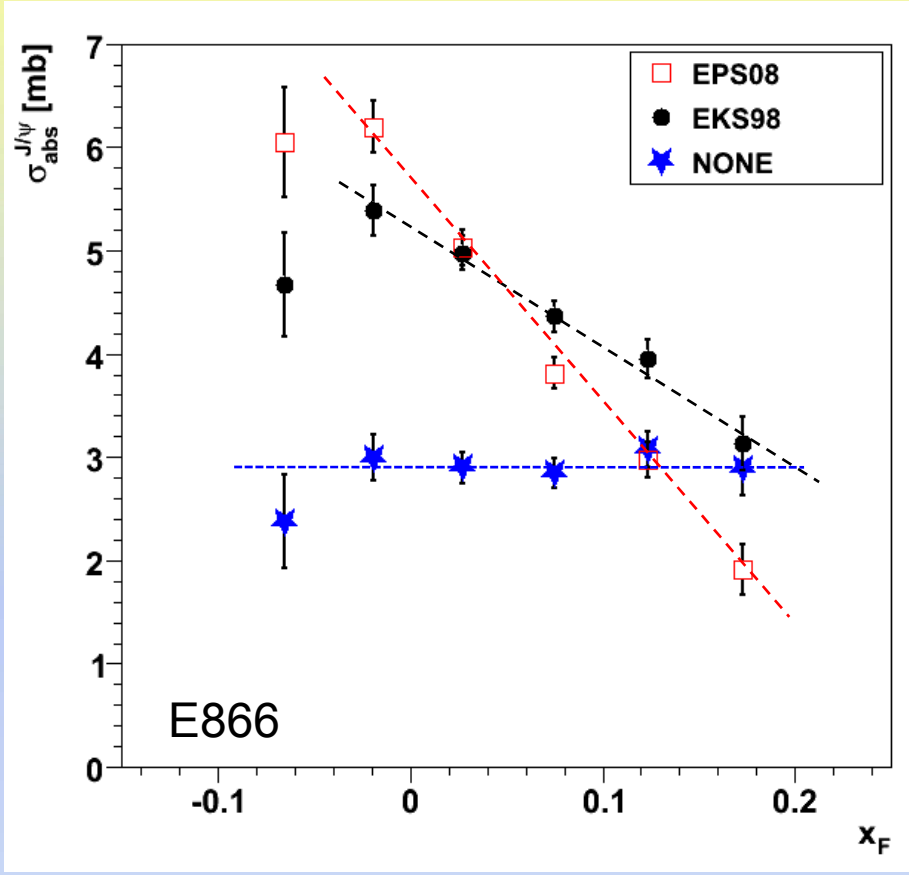
⇒ The NA50 measurements are equally well described using
σ_{abs} = 6.9 mb (with EKS98) or
σ_{abs} = 4.6 mb (with "free protons")





J/ψ σ_{abs} versus x_F : the importance of the nPDFs





- The nuclear effects on the PDFs are a function of Bjorken-x
  $\Rightarrow$ 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	$-0.425 < y_{cms} < 0.575$
NA50	450	p-Be, Al, Cu, Ag, W	$-0.50 < y_{cms} < 0.50$
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	$\lvert y_{cms}\rvert < 0.35,\ 1.2 < \lvert y_{cms}\rvert < 2.2$

NA60 measured the J/ψ at 400 and 158 GeV (energy of the heavy-ion data) with a proton beam incident on 7 nuclear targets: Be, Al, Cu, In, W, Pb and U

$0.28 < y_{cms} < 0.78$ (158 GeV) and

$-0.17 < y_{cms} < 0.33$ (400 GeV)

Results shown at QM09

J/ψ σ_{abs} for each kinematical window and nPDF set

Exp.	x_F	$\sigma_{abs}^{J/\psi}$ [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:

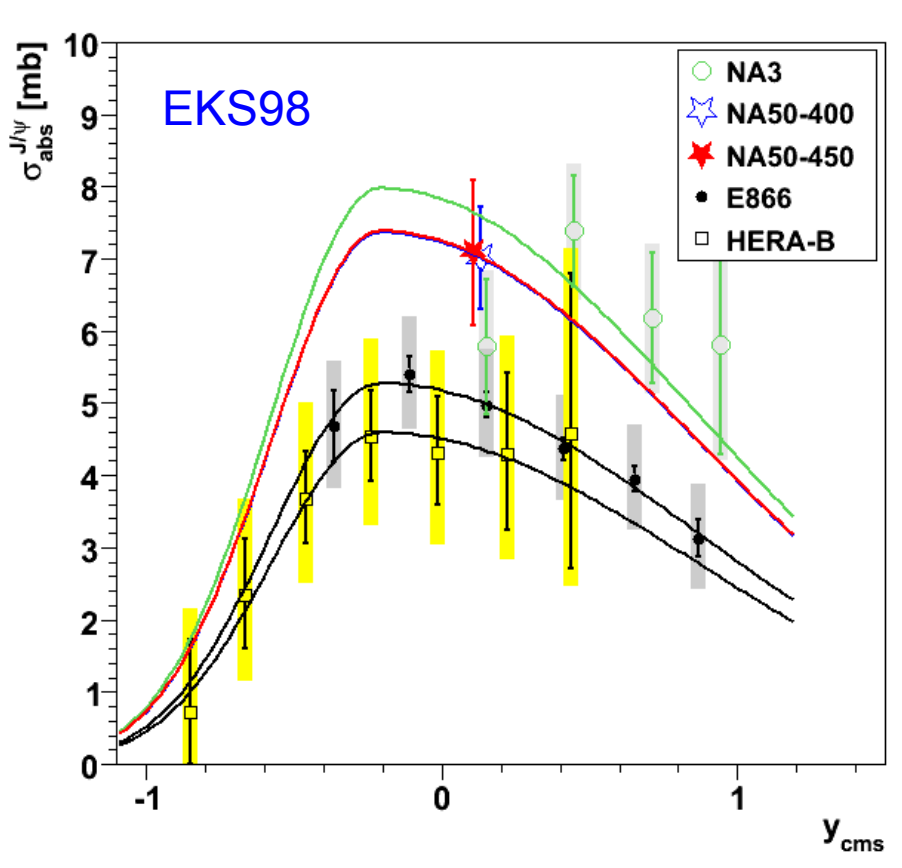
3% in NA3
3% in E866
4% in HERA-B

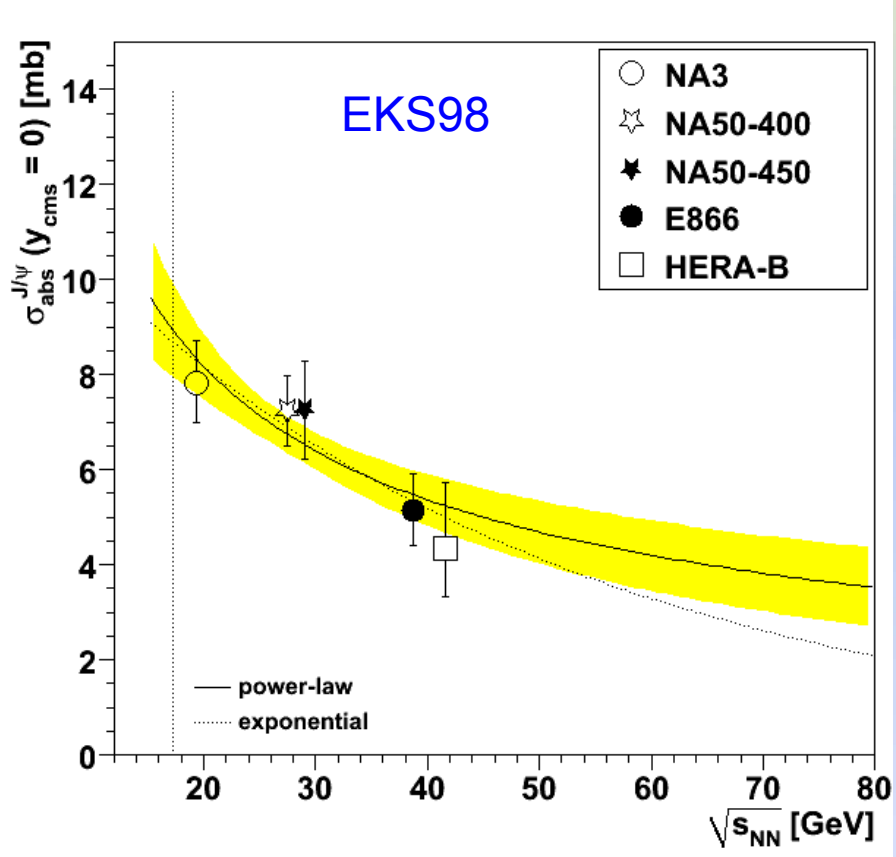
C. Lourenço, R. Vogt and H.K. Wöhri, JHEP 2 (09) 14

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

The E866 and HERA-B patterns have enough (accurate) points to define the *shape* of the rapidity dependence of σ_{abs}

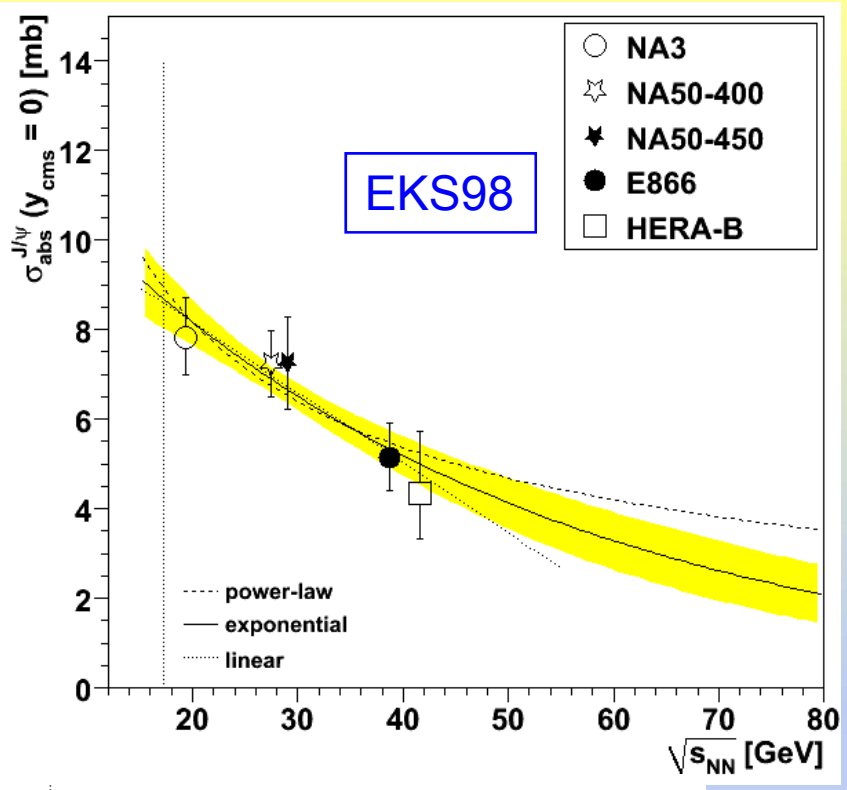
σ_{abs} at y_{cms}=0 decreases with NN collision energy

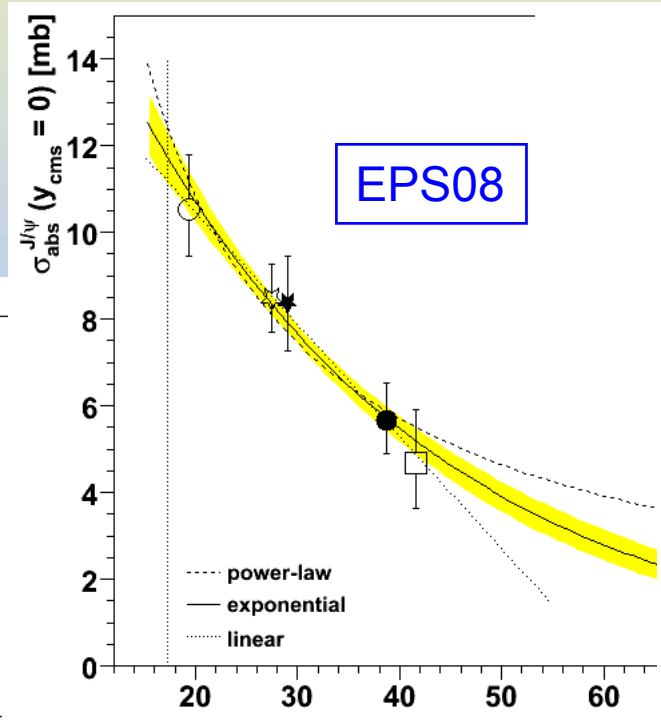


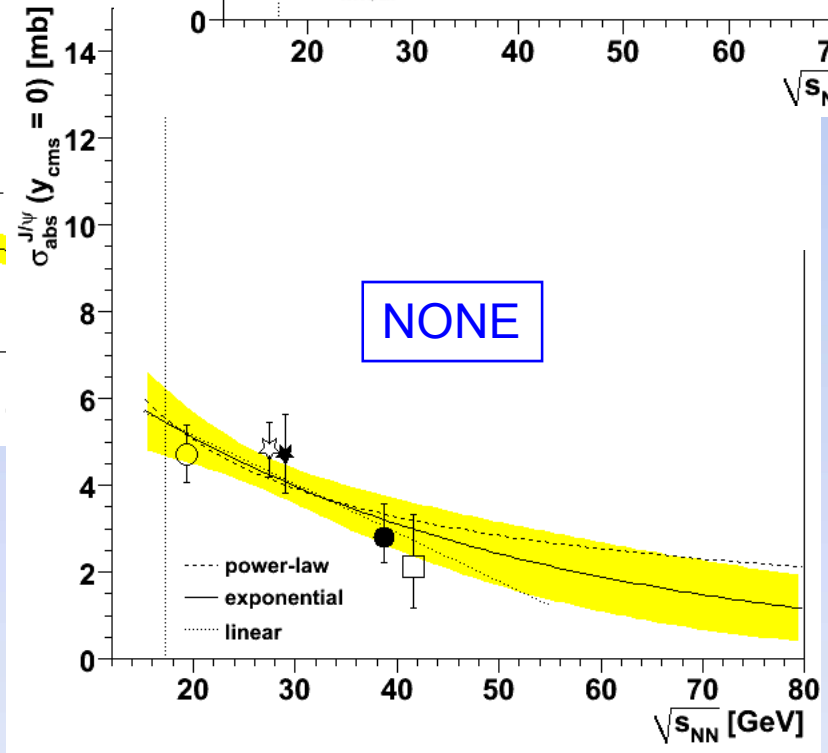


J/ψ σ_{abs} at y_{cms}=0 vs. $\sqrt{s_{NN}}$

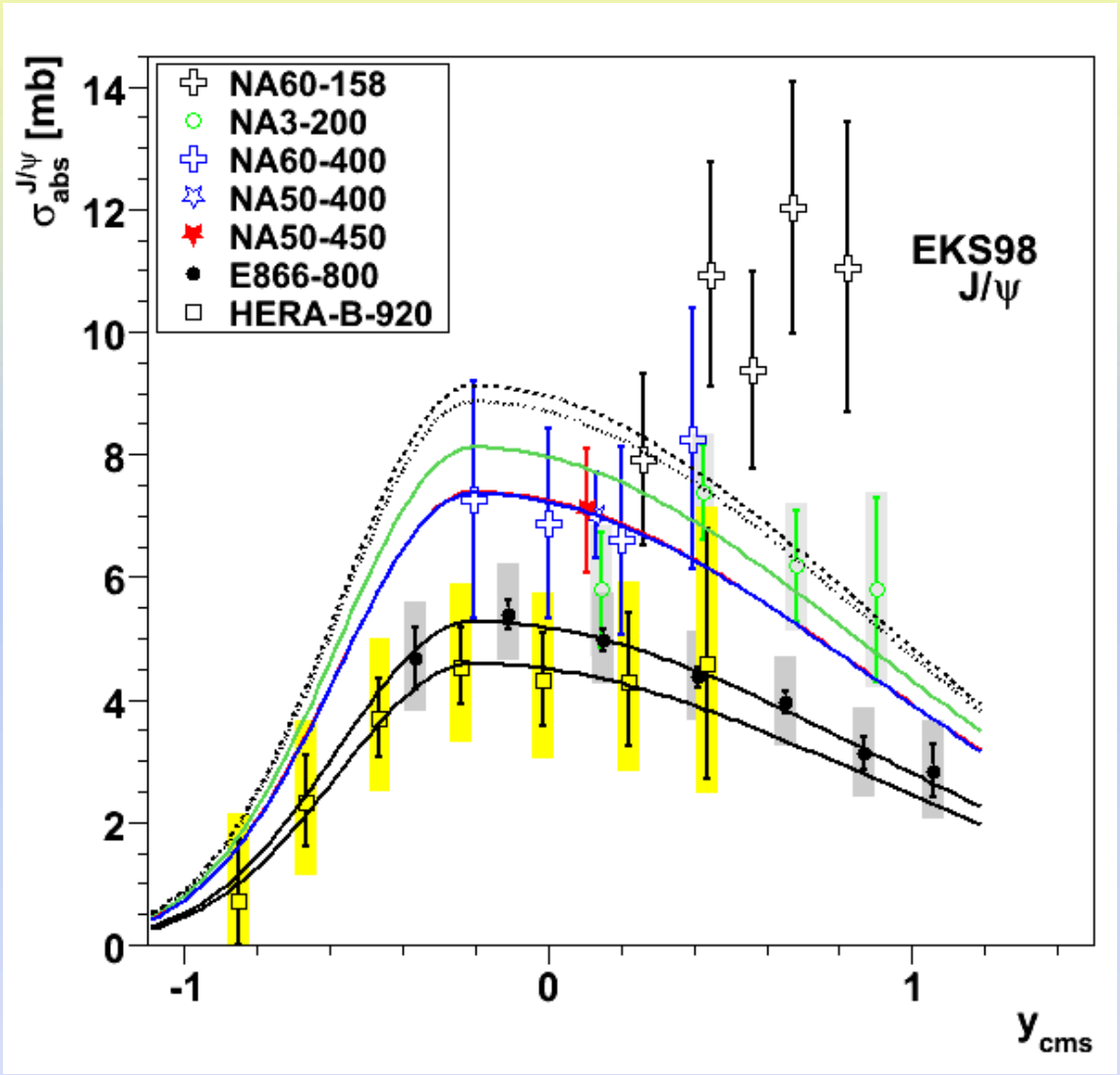
Whatever nPDF model we use, σ_{abs} at y_{cms}=0 decreases with NN collision energy







What can we learn from the new NA60 data?



Extrapolation to y_{CMS}=0 at 158 GeV gives a σ_{abs} of:
9.0±0.9 mb with power-law
8.7±0.6 mb with exponential

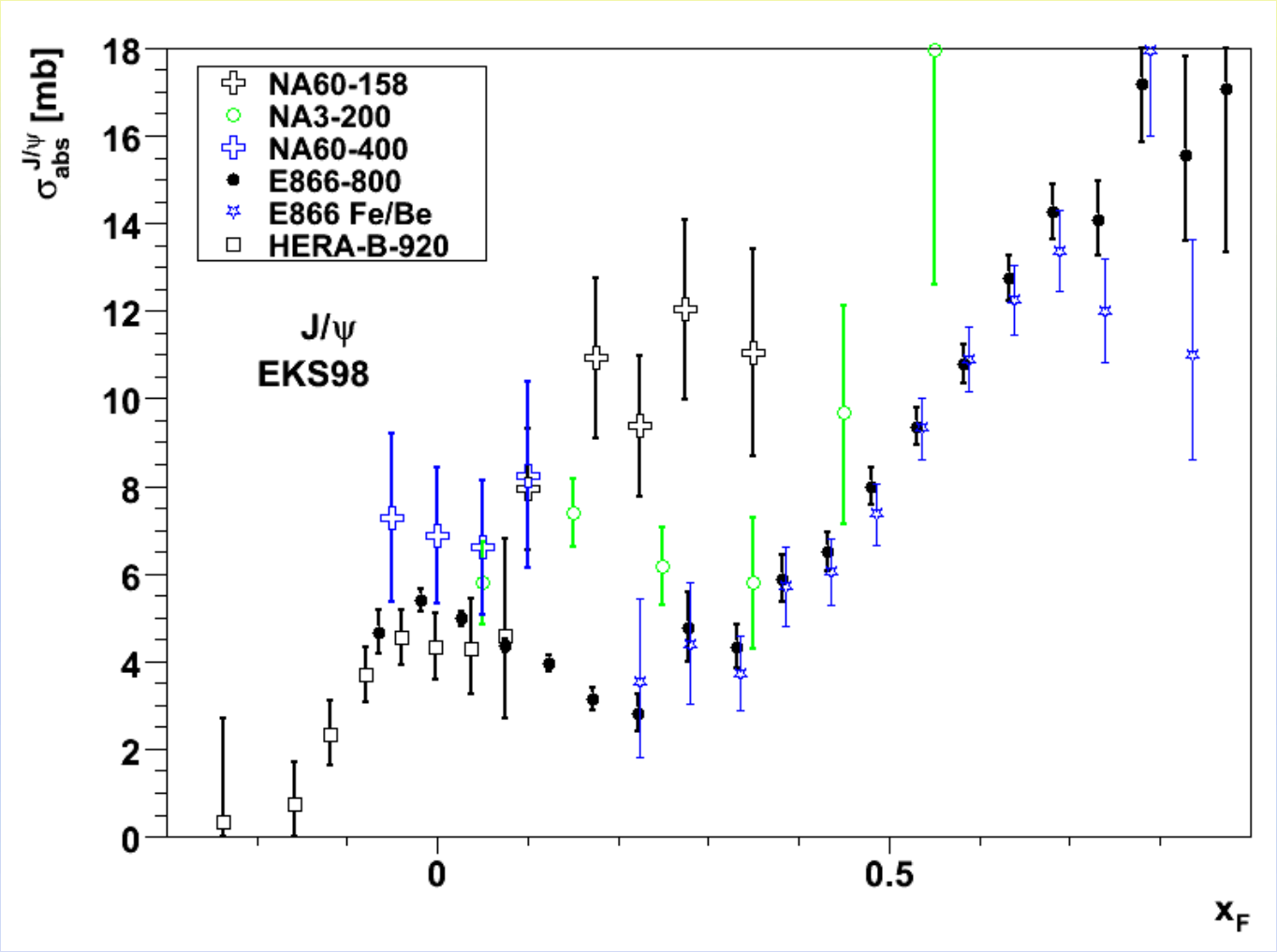
Let's compare to the new NA60 data, shown at QM09

The 400 GeV data points are perfectly compatible with the previously established trend

The first 158 GeV point sits on the expected curve but the others are much higher

Do we see a departure from the absorption pattern? What about other nuclear matter effects?

The forward x_F region is visibly different



E866 shows that at forward x_F other effects play a role

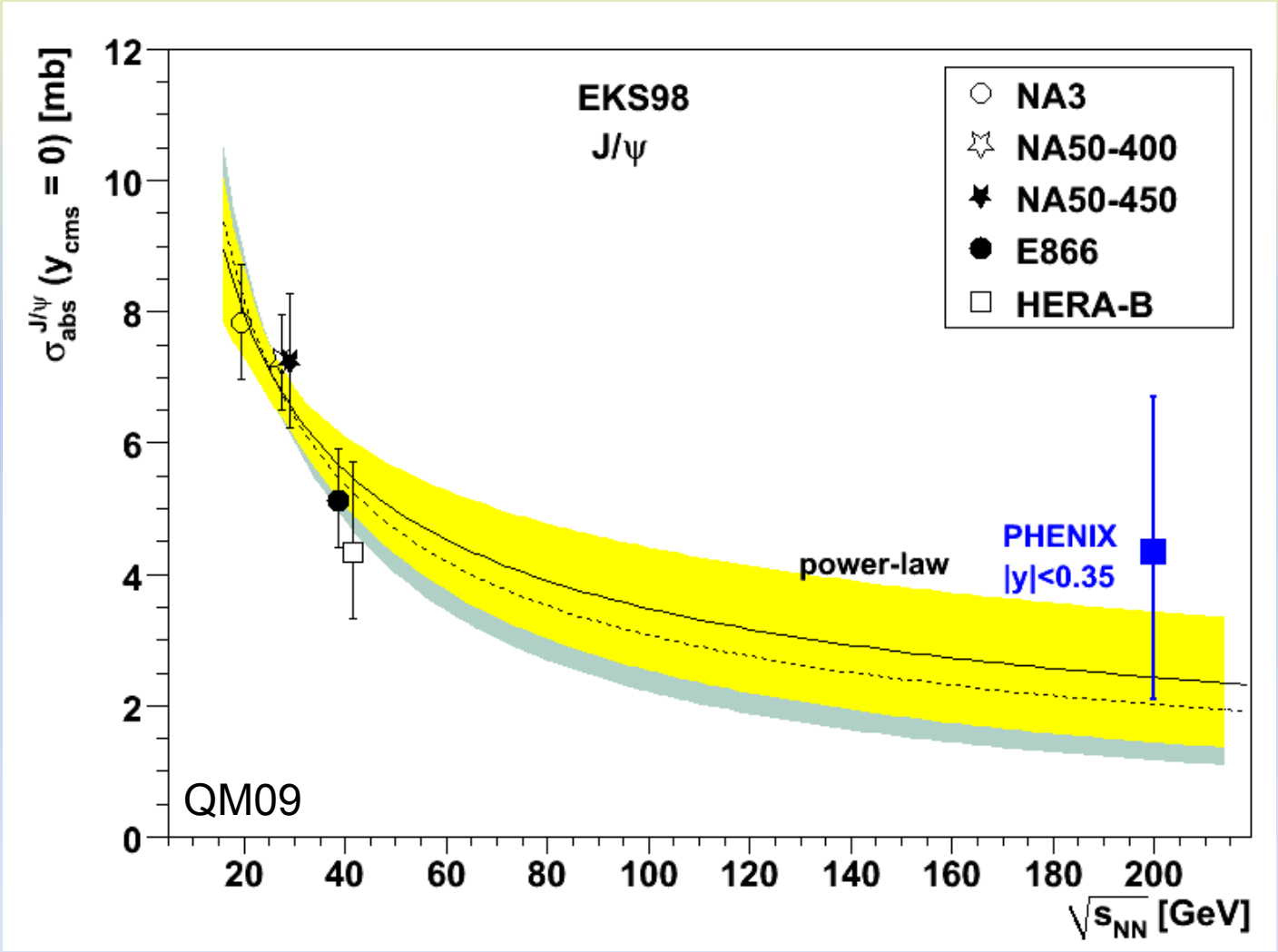
NA3 also shows much larger σ_{abs} at forward x_F

NA60-400 (at x_F~0) is compatible with absorption only…

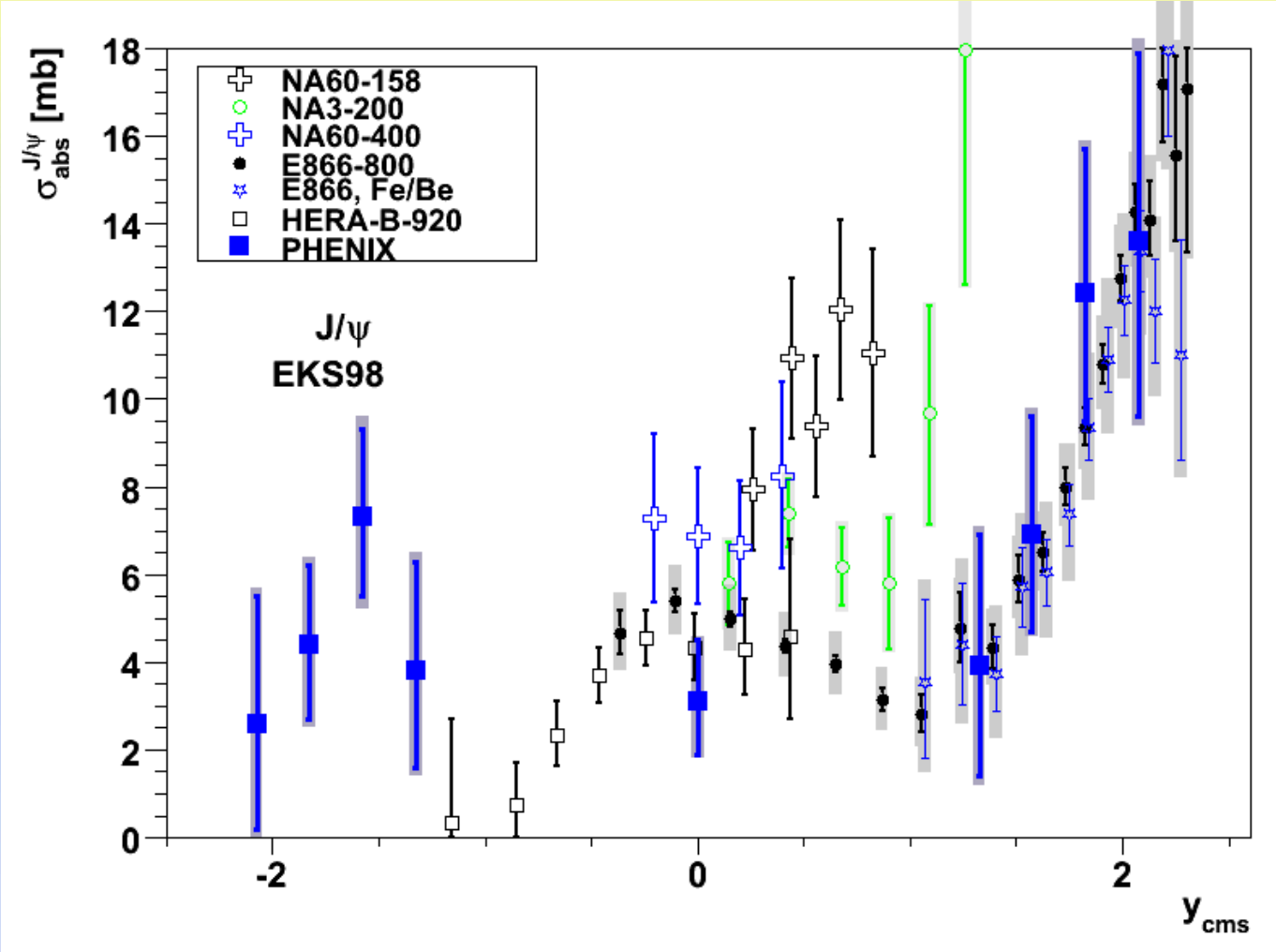
while the (forward) 158 GeV data seem to follow the E866 trend

How does PHENIX fit into the game?

The mid-rapidity PHENIX value is perfectly compatible with the power-law trend suggested by the fixed-target data

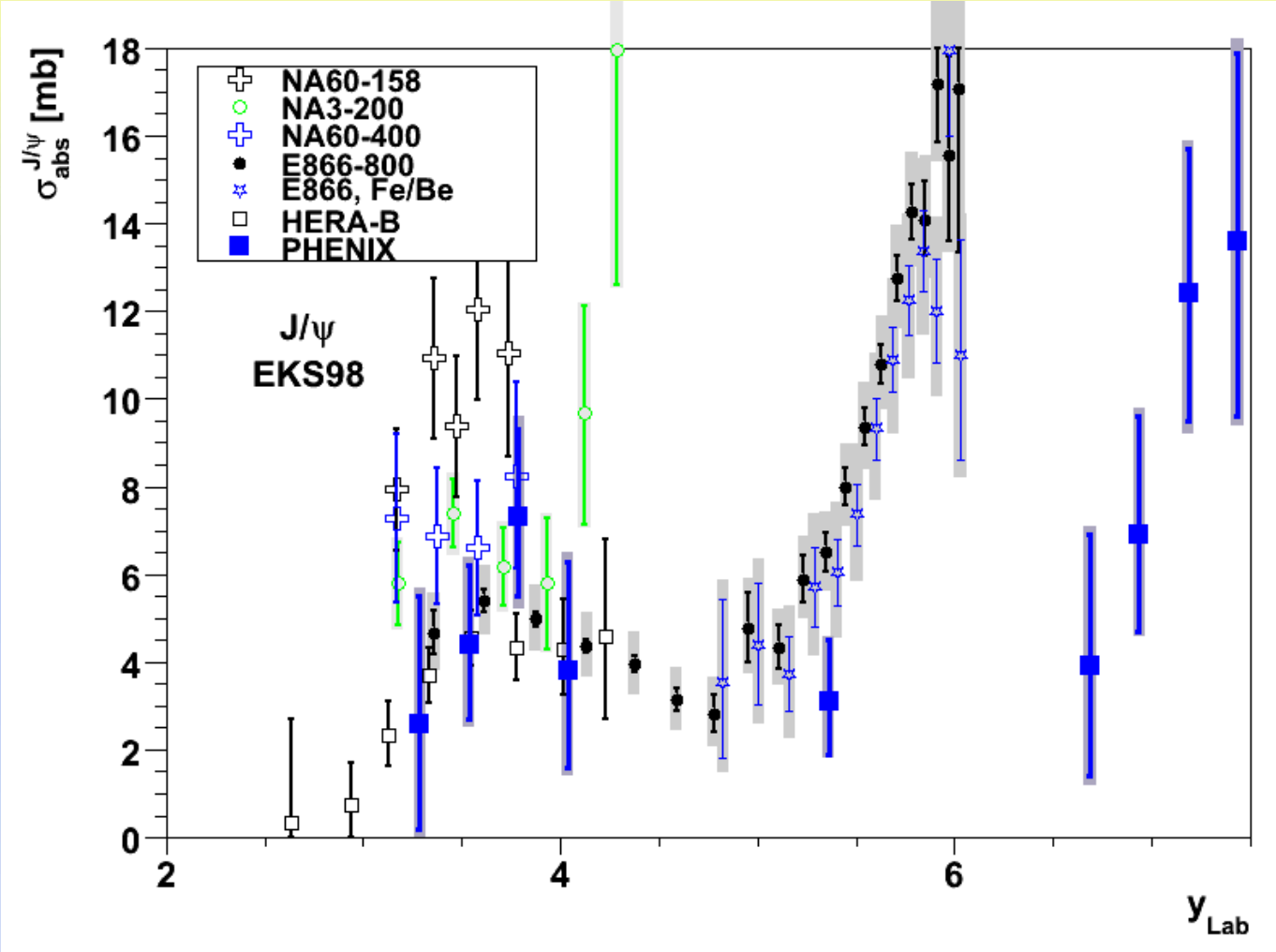


What can we learn from the PHENIX data?



The broad rapidity coverage of the PHENIX data should considerably help in discriminating the different cold nuclear effects, by comparing data sets as a function of several kinematical variables

What can we learn from the PHENIX data?



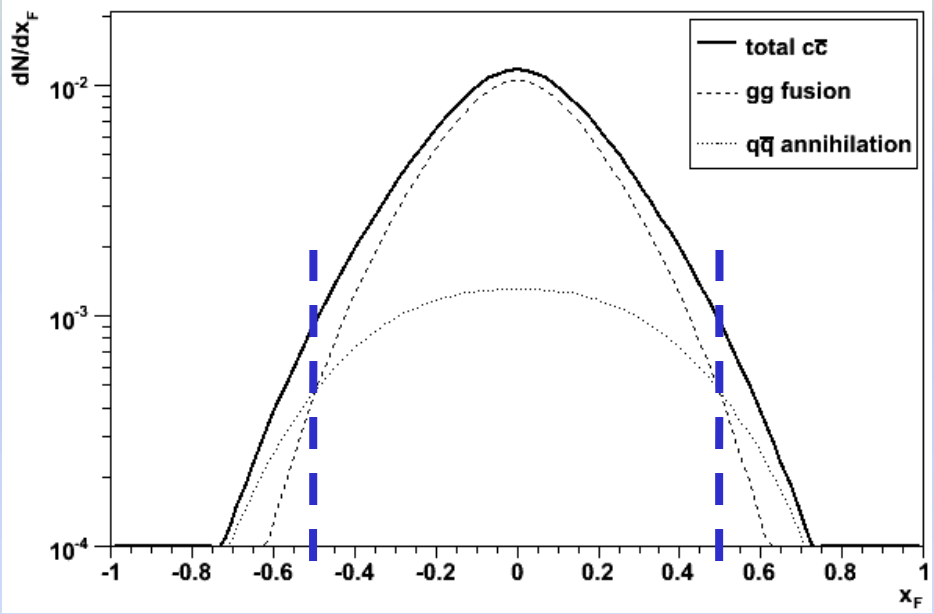
Unfortunately, the error bars are still very large

A first and simple look at parton energy loss

The beam partons may lose energy by traversing the nucleus, before J/ψ creation. We model this effect in a very simple way, assuming a constant fractional loss of energy per "collision", $x_1' = x_1 (1 - \varepsilon_g)^{(N_{coll} - 1)}$, with the average N_{coll} from Glauber

The gluon and quark energy loss parameters are related by $\varepsilon_g = 9/4\ \varepsilon_q$

Note: qqbar annihilation dominates quarkonium production for $x_F > 0.5$, according to the CEM and using CTEQ6L PDFs

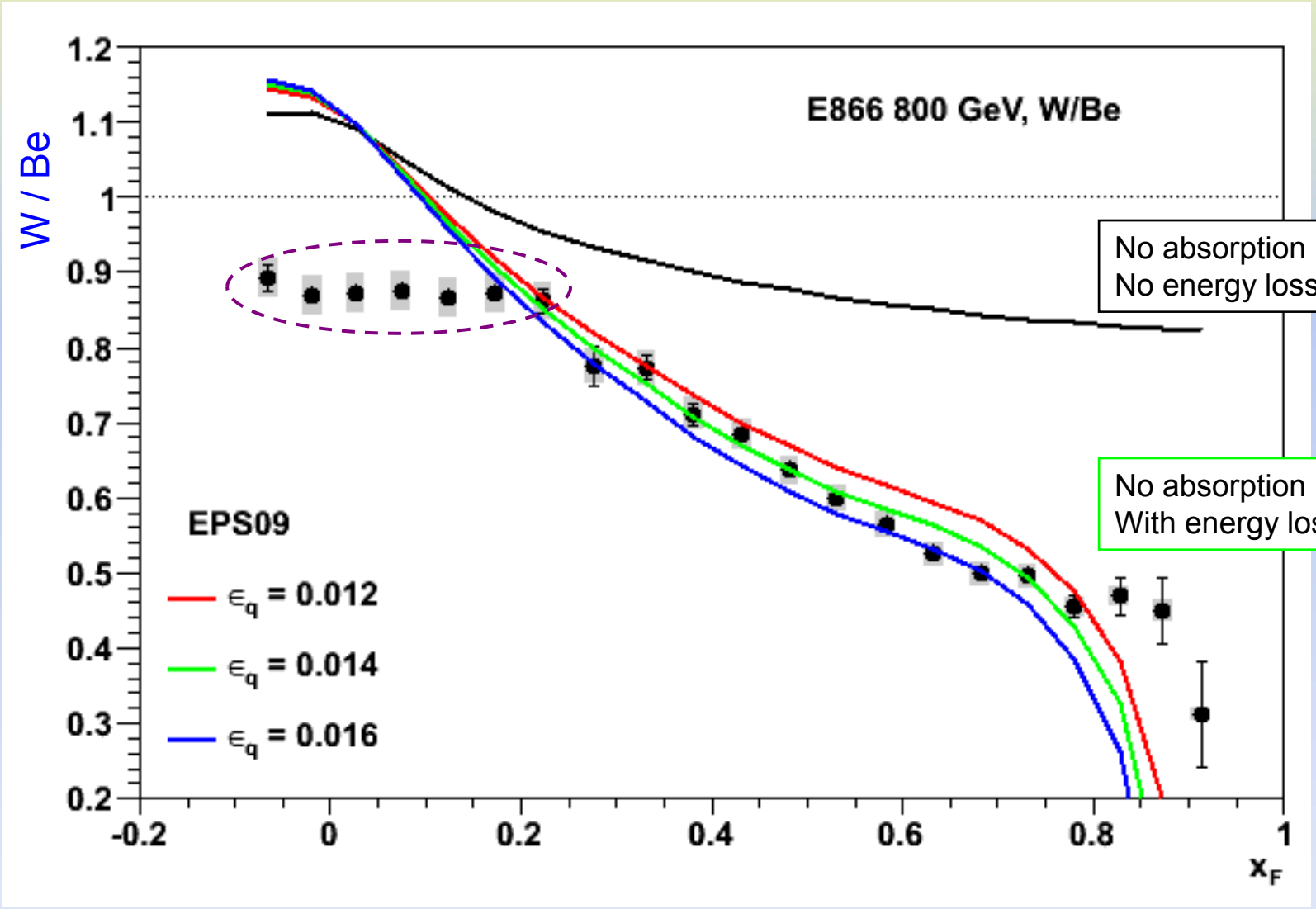


The decreased energy ($x_1' < x_1$) leads to a "backward shift" of the J/ψ's x_F distribution ($\rightarrow x_F' < x_F$)

E866, 800 GeV, p-W / p-Be ratio

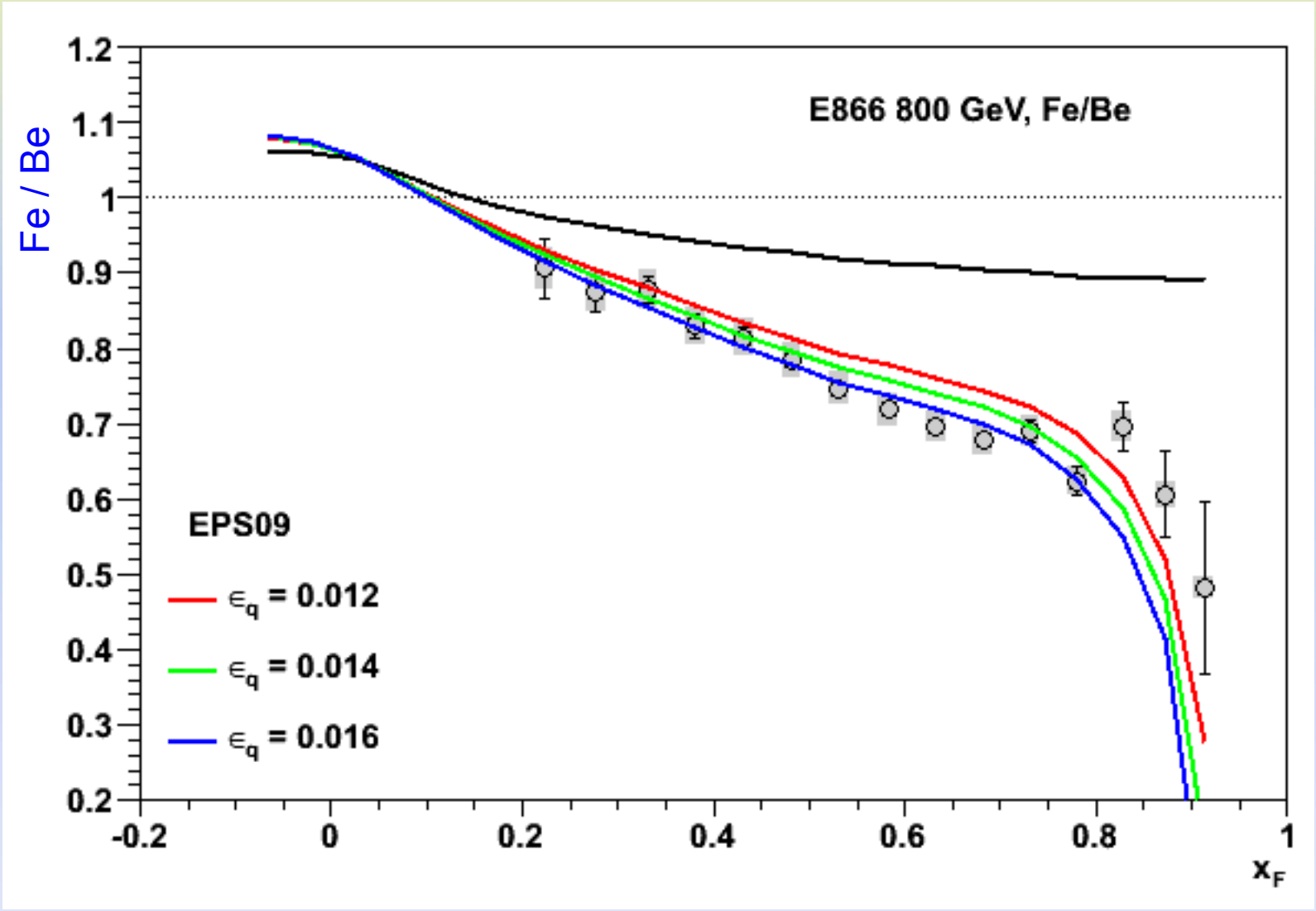
The $x_F < 0.2$ region is affected by final state absorption, not included in these curves

The $0.2 < x_F < 0.75$ window is well described by $\varepsilon_q \sim 1.5\%$ and $\varepsilon_g = 9/4\ \varepsilon_q \sim 3.3\%$



E866, 800 GeV, p-Fe / p-Be ratio

The p-Fe data of E866 is equally well reproduced with the same ε_q and ε_g values

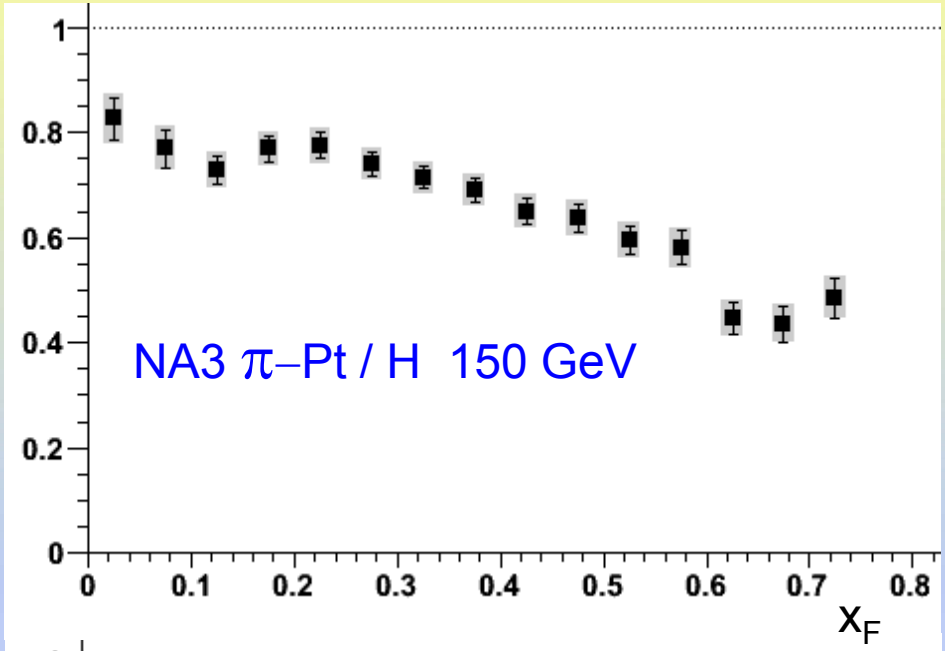


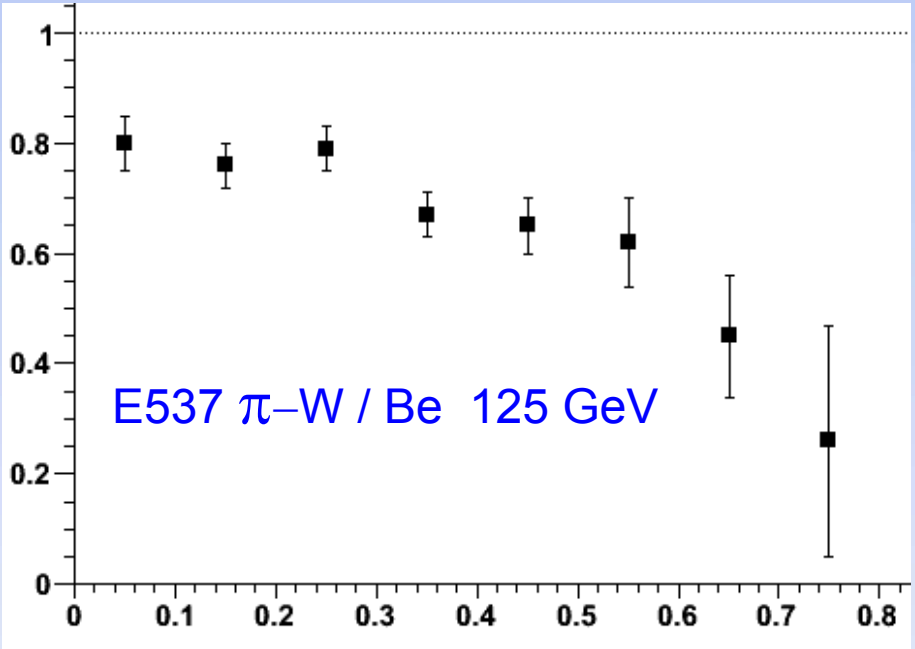
Future “ingredients” to settle the energy loss process

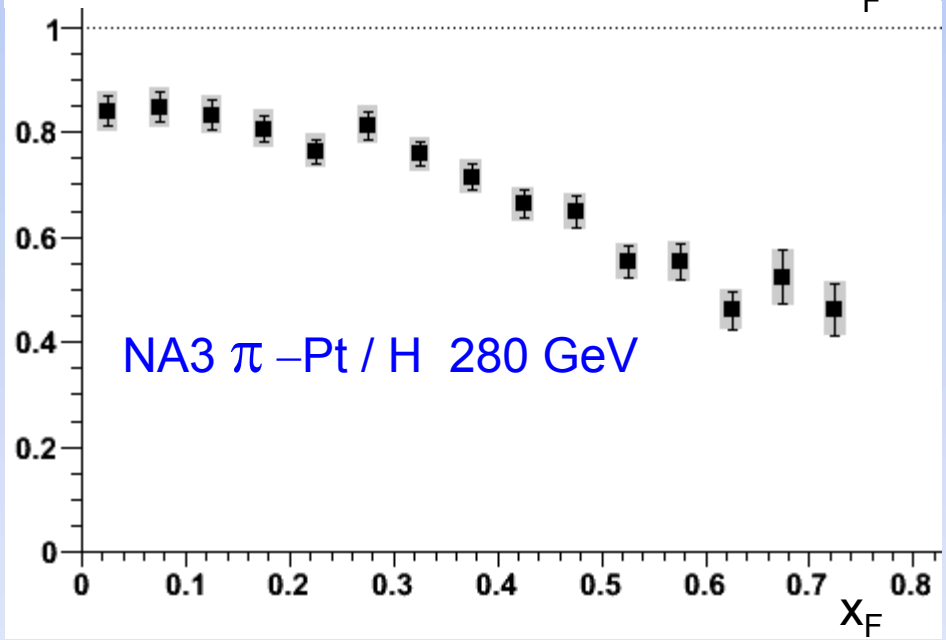
There are forward x_F J/ψ data from E866 (p-Fe,W), NA3 (p-Pt) and PHENIX (d-Au)

Plus the new open charm data of E866

And Drell-Yan and π-A data which might help studying the quark energy loss

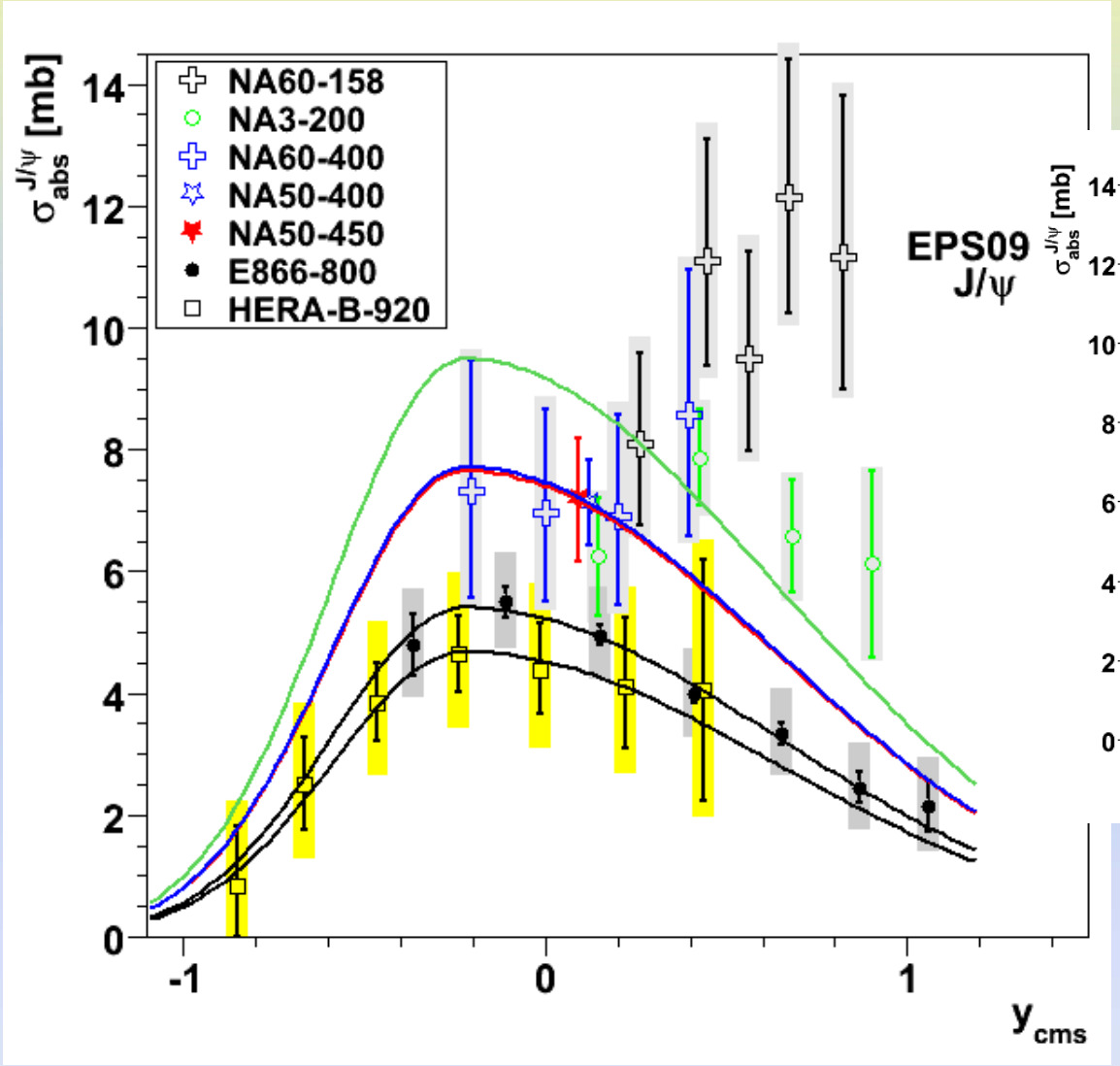


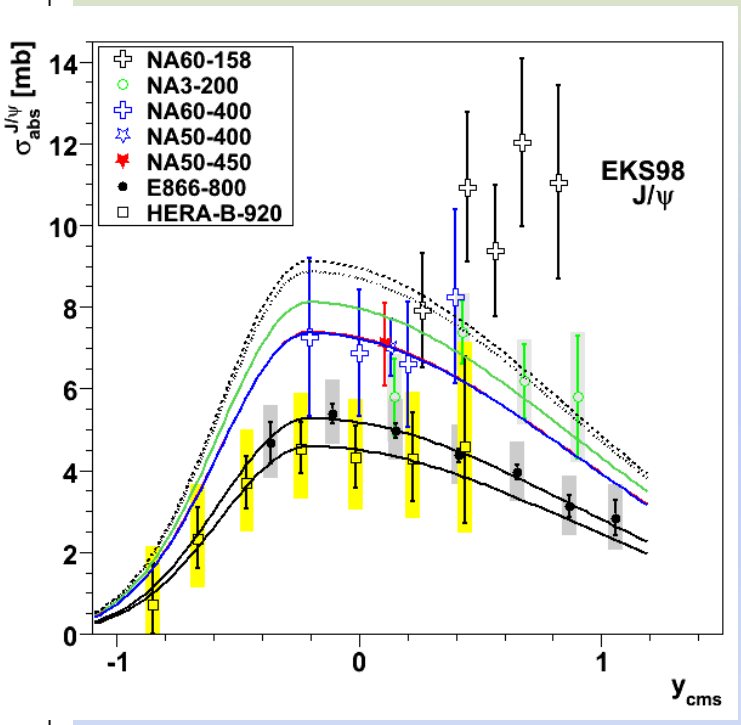


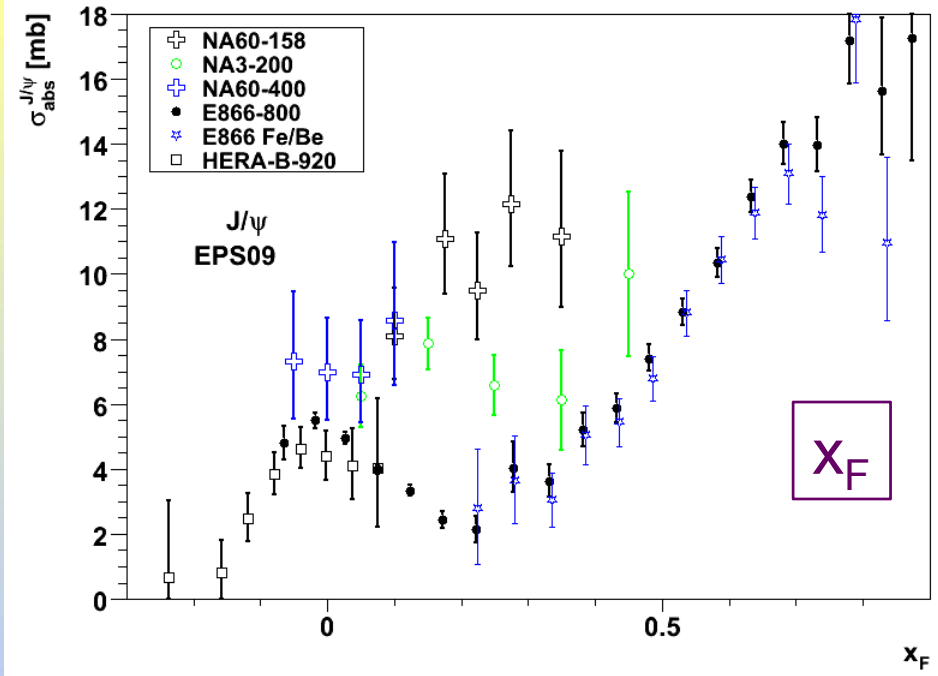


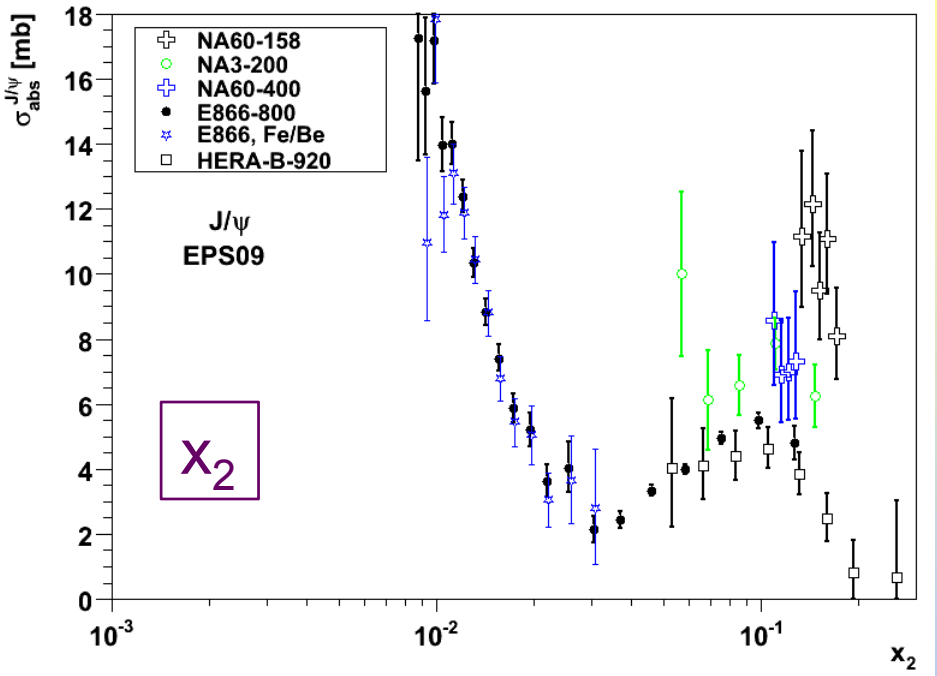
Recent progress using the EPS09 nPDFs

Here in Seattle, we have redone several figures using the EPS09 nPDFs






NA60-158
NA3-200
NA60-400
E866-800
E866 Fe/Be
HERA-B-920
J/ψ
EPS09
x_F
$\sigma^{J/\psi}_{abs}$ [mb]
x_F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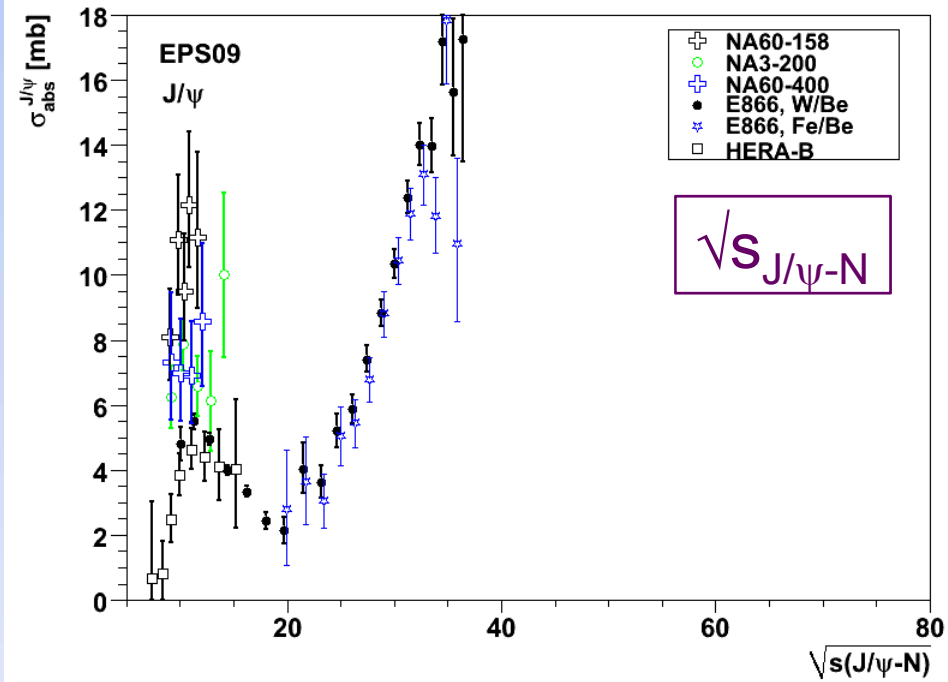
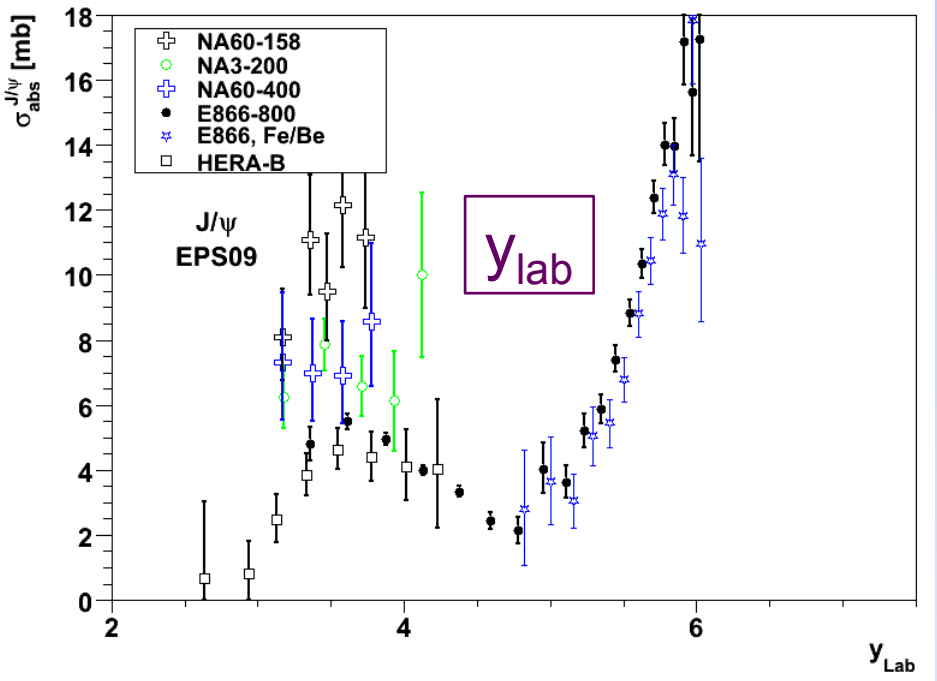
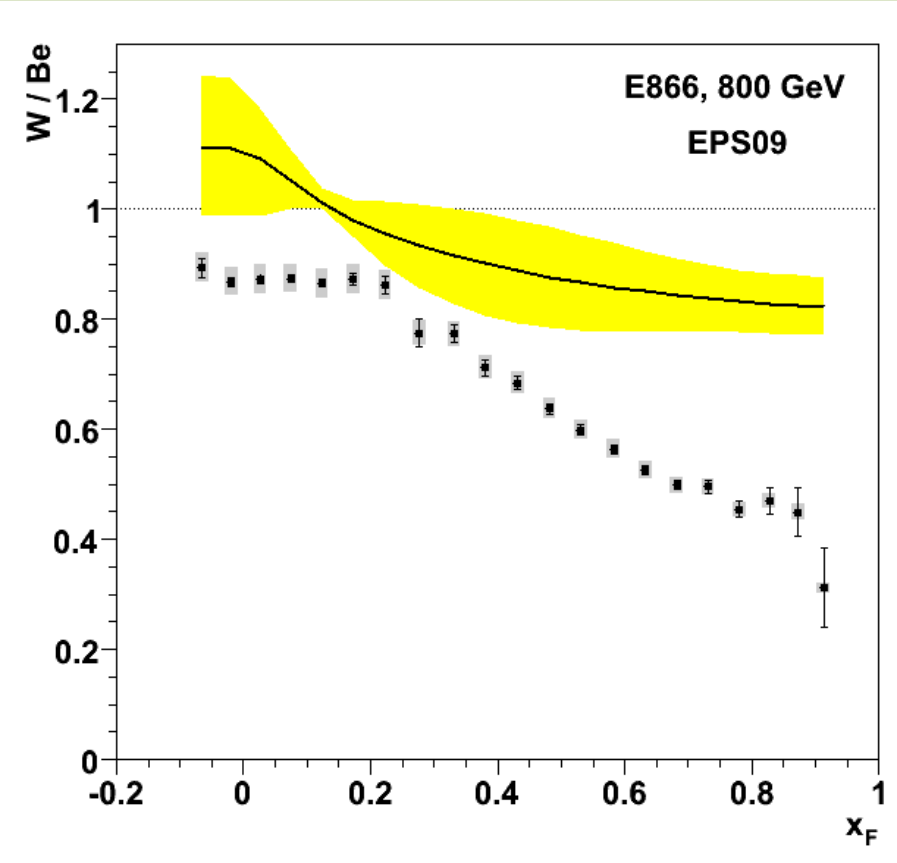
NA3-200
NA60-400
E866-800
E866, Fe/Be
HERA-B-920
J/ψ
EPS09
x_2
$\sigma^{J/\psi}_{abs}$ [mb]
x_2

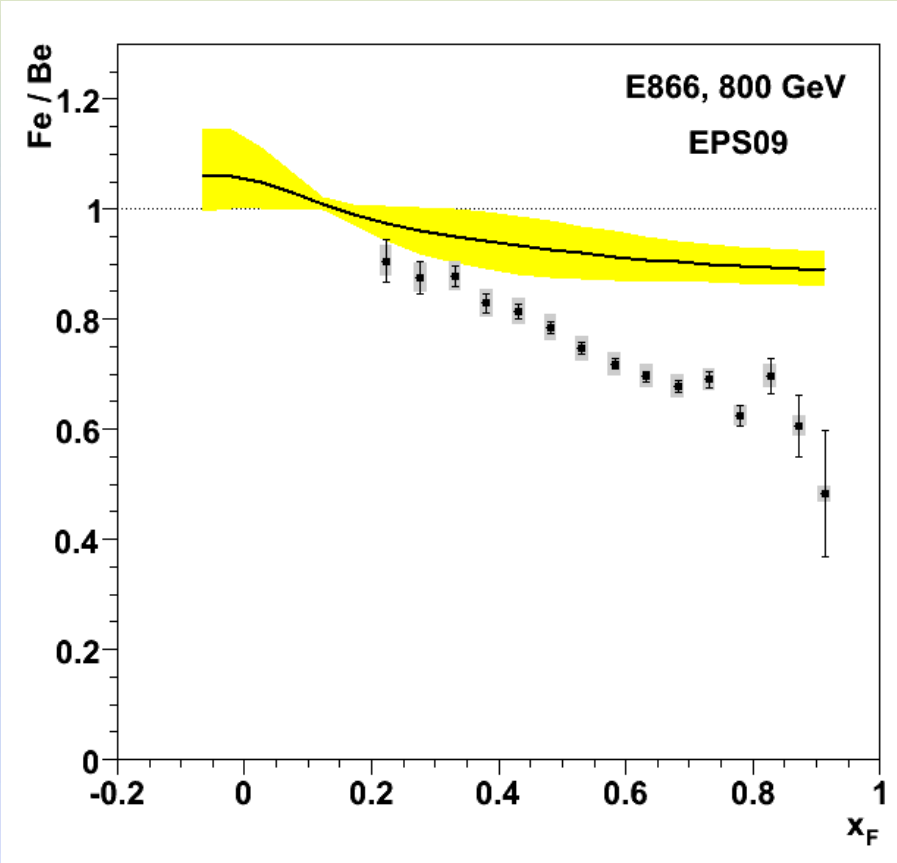

EPS09
J/ψ
NA60-158
NA3-200
NA60-400
E866, W/Be
E866, Fe/Be
HERA-B
$\sqrt{s}_{J/\psi-N}$
$\sigma^{J/\psi}_{abs}$ [mb]
$\sqrt{s(J/\psi-N)}$


NA60-158
NA3-200
NA60-400
E866-800
E866, Fe/Be
HERA-B
J/ψ
EPS09
y_{lab}
$\sigma^{J/\psi}_{abs}$ [mb]
y_{Lab}

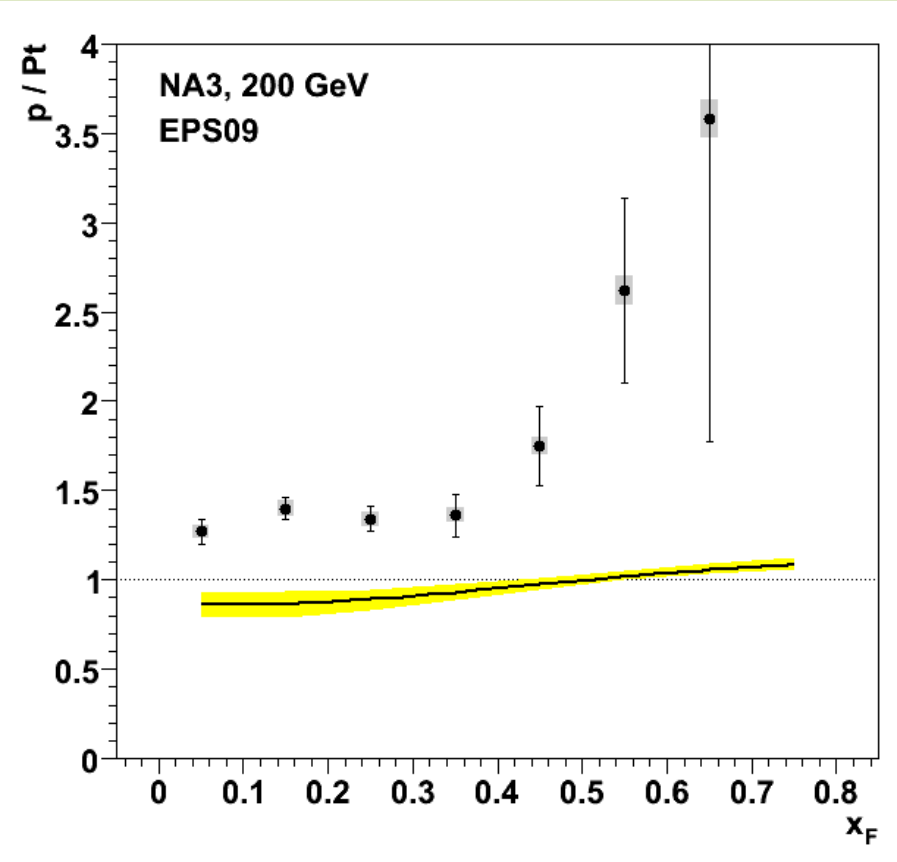
EPS09 uncertainty: E866 cases

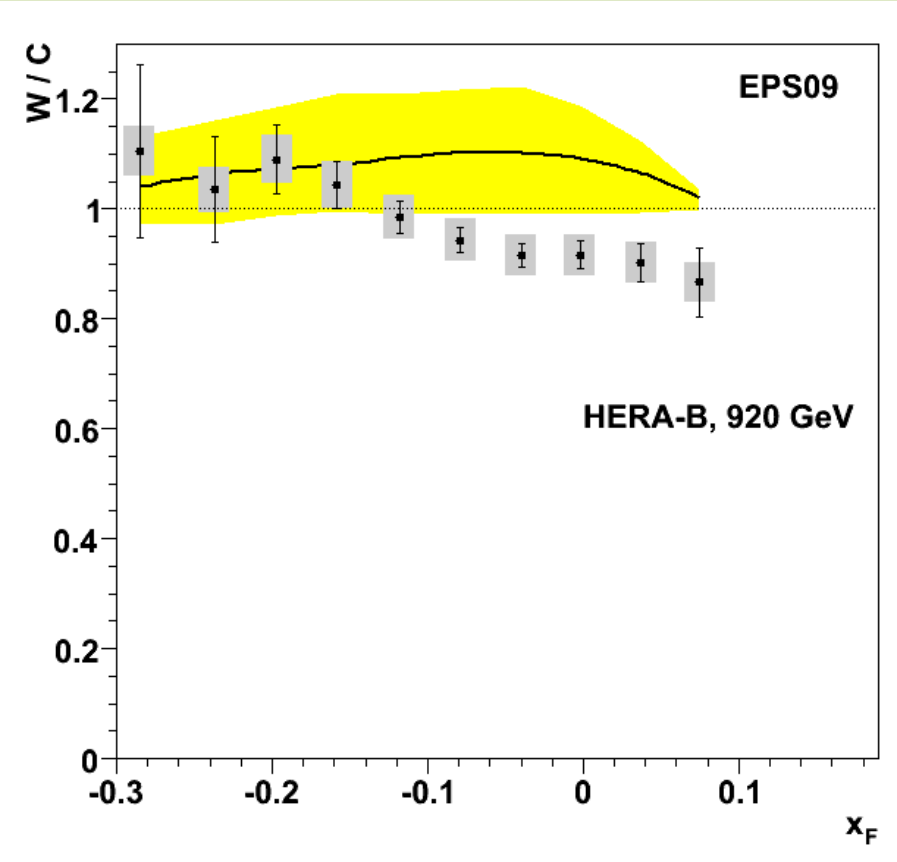
- Uncertainty band calculated following the procedure outlined in the EPS09 paper [JHEP04(2009)065]
- It represents the sum in quadrature of 15 parameters changed by ±1σ





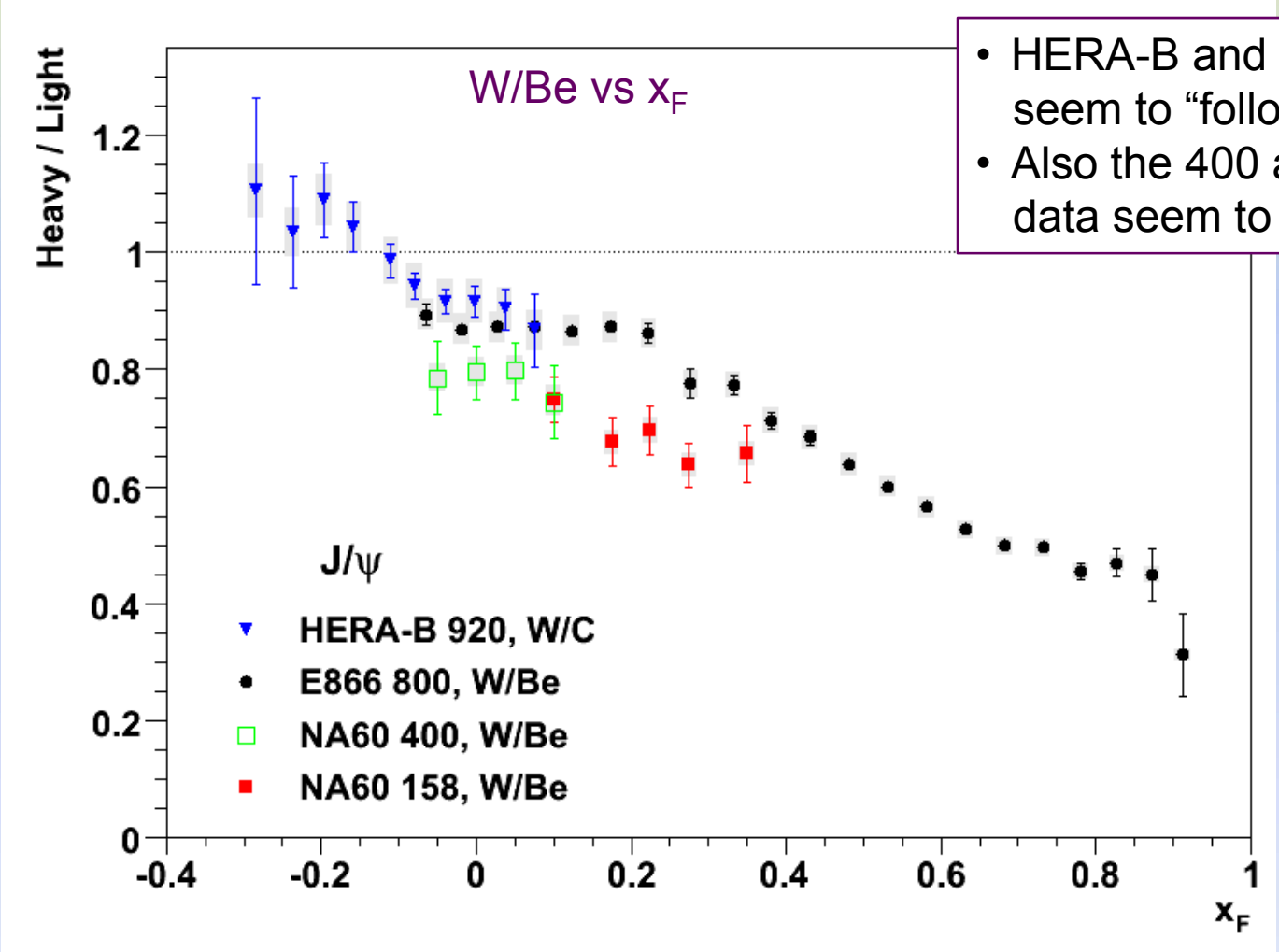
EPS09 uncertainty: NA3 and HERA-B cases





Another look at the measurements

Since there are several different mechanisms affecting J/ψ production in p-nucleus collisions and it is unreasonable to convolute them all in a single “effective variable”, let’s go back to the data, to search for scaling features and inspiration…



- HERA-B and E866 patterns seem to “follow each other”
- Also the 400 and 158 GeV data seem to be well “aligned”

Another look at the measurements

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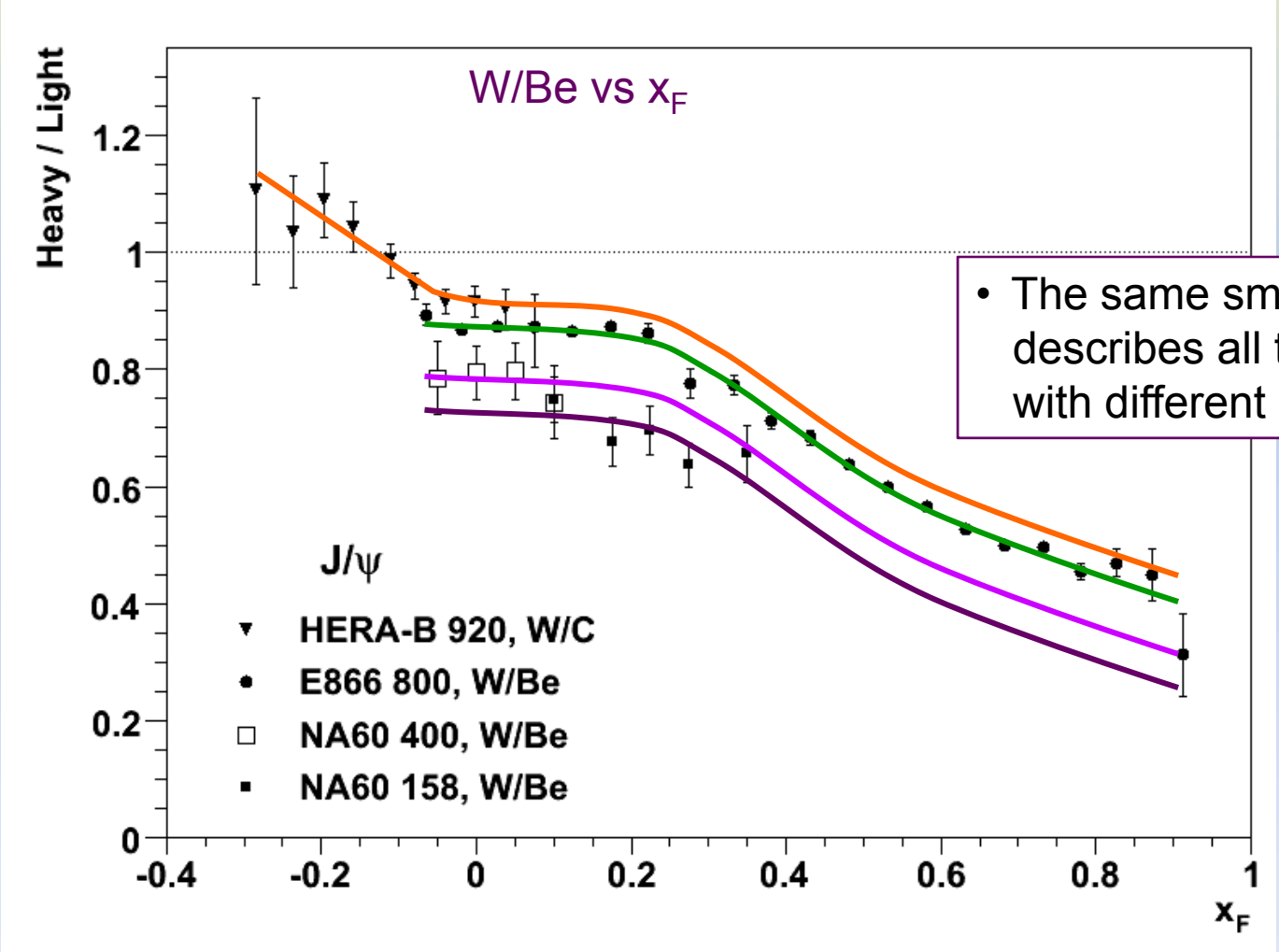

- The same smooth pattern describes all the four data sets with different normalisations

Another look at the measurements

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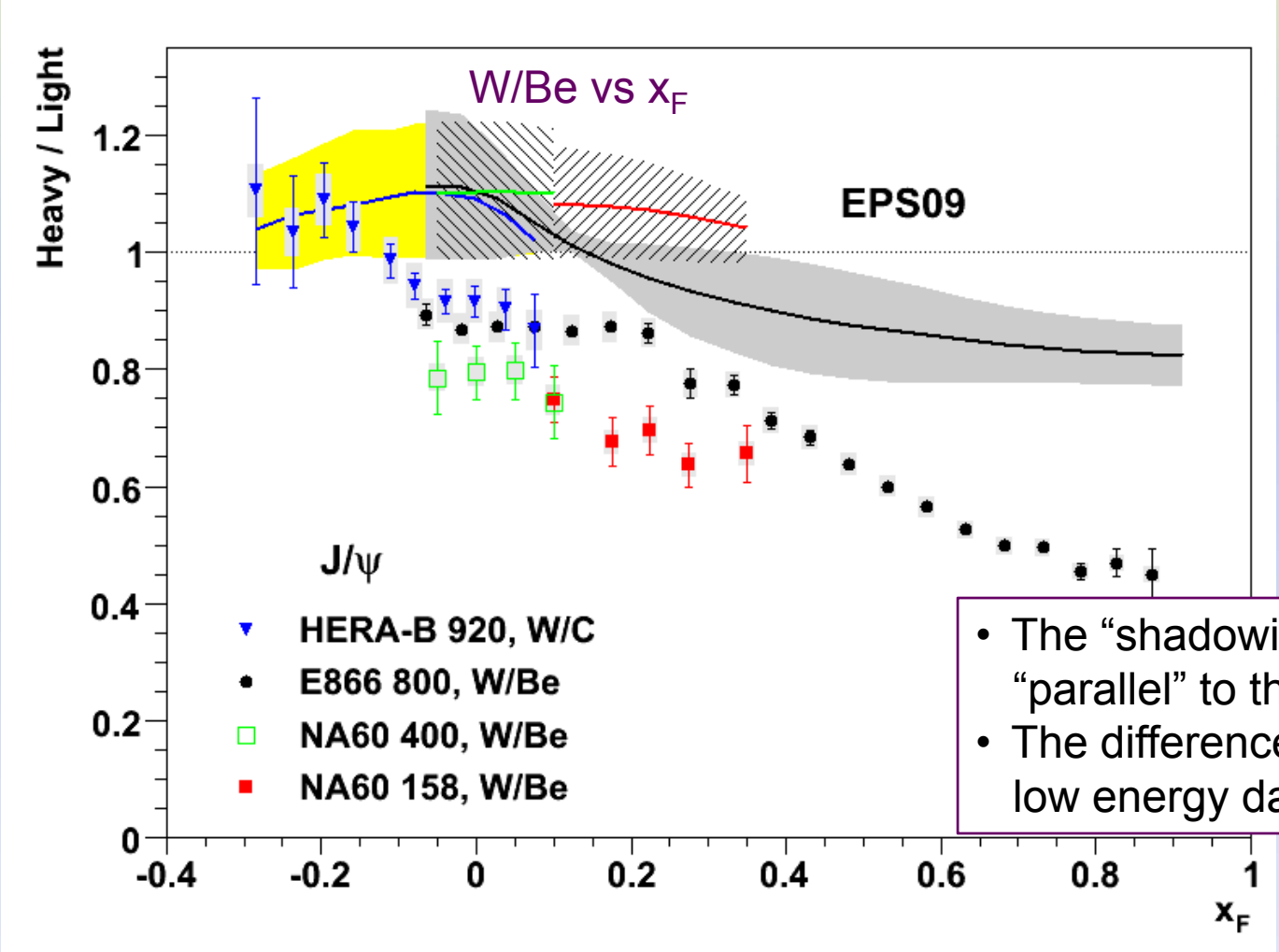
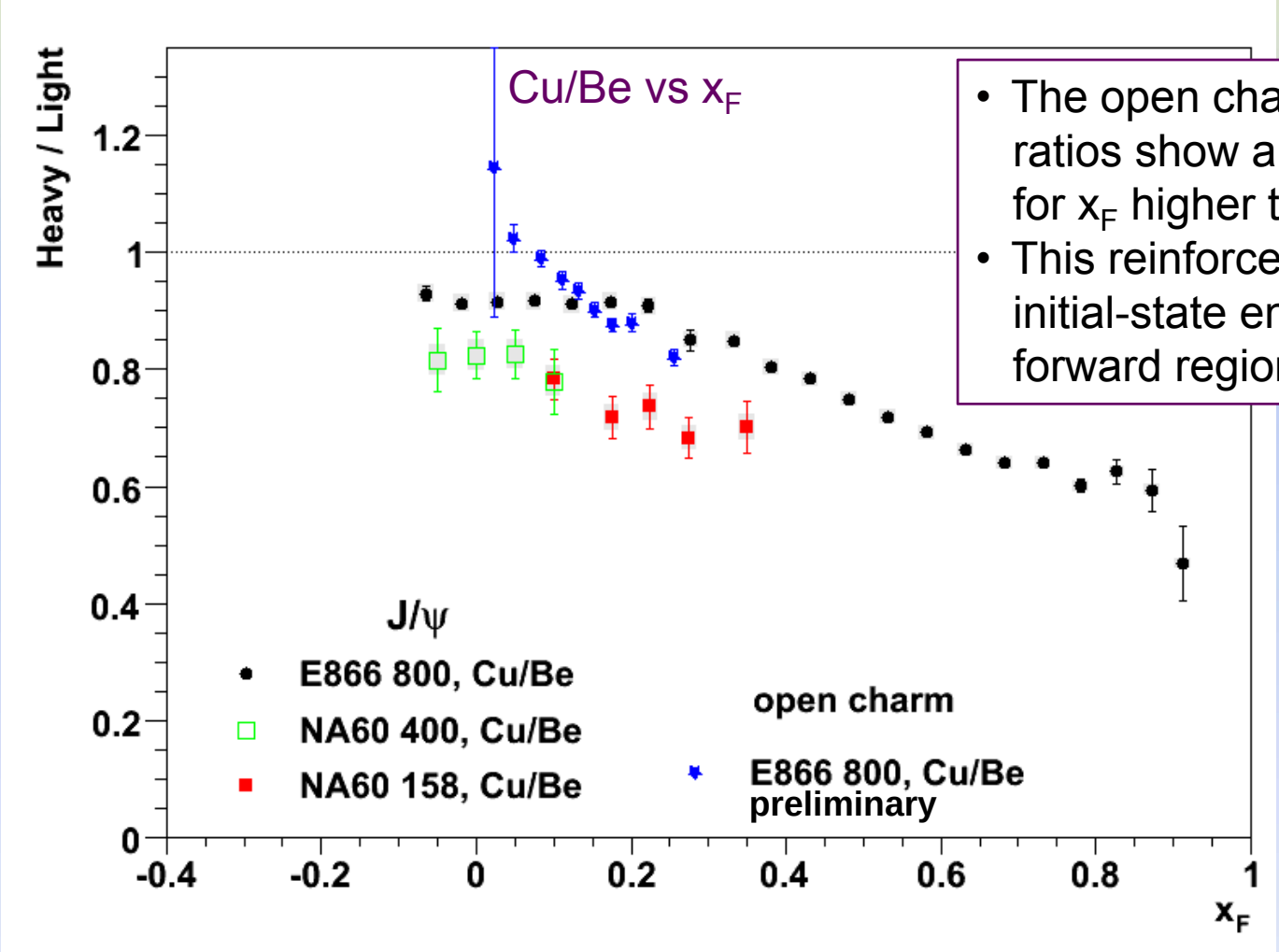


- The “shadowing” curves are not “parallel” to the measured patterns
- The difference is larger for the low energy data sets

Another look at the measurements

Since there are several different mechanisms affecting J/ψ production in p-nucleus collisions and it is unreasonable to convolute them all in a single “effective variable”, let’s go back to the data, to search for scaling features and inspiration…



- The open charm and J/ψ Cu / Be ratios show a similar decrease for x_F higher than ~ 0.15
- This reinforces the idea that initial-state energy loss drives the forward region

Summary

• There are several different “cold nuclear matter effects” affecting quarkonium production in proton-nucleus collisions

• Our best chance to disentangle them is to perform a global study of many sets of nuclear dependent measurements, including J/ψ, ψ’ and χ_c mesons, but also open charm and Drell-Yan, as a function of kinematics, collision energy, etc

• What can we learn from the p_T dependence, not addressed so far?

• Only once we have a model incorporating initial state parton energy loss, shadowing, formation time effects, final state break-up, … we will have a proper understanding of J/ψ production in nuclear targets.
This could help disentangling colour singlet vs. colour octet production

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

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

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