Measuring *dimuon* and *quarkonium* production in high-energy heavy-ion collisions

<u>Issues addressed in these lectures:</u>

- Using dileptons and quarkonia to study heavy-ion collisions;
  a brief introduction to some basic concepts

- Measuring dimuons and charmonia

- Some issues that must be carefully studied before interpreting the measurements

- Bonus slides: energy dependence of charmonium absorption cross section

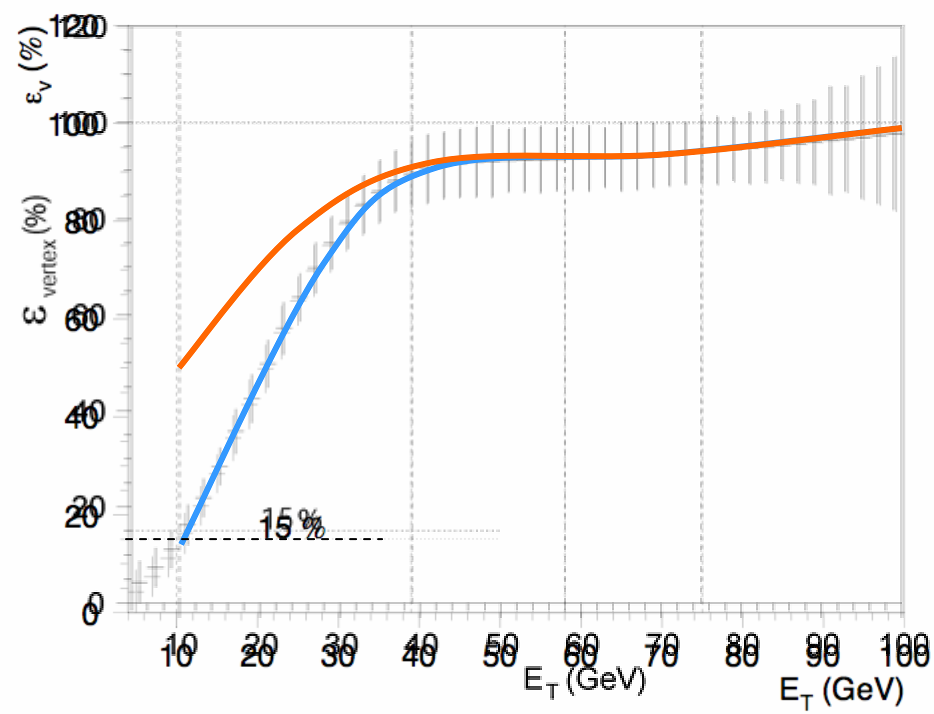
Lecture 2

Efficiencies

Even within the phase space window where the detector has a good acceptance, sometimes a J/ψ, for instance, is produced but is not detected. Maybe the trigger system missed it; or the muon tracks were not reconstructed; or the interaction vertex could not be identified; etc.

The measurements must be corrected for these inefficiencies.

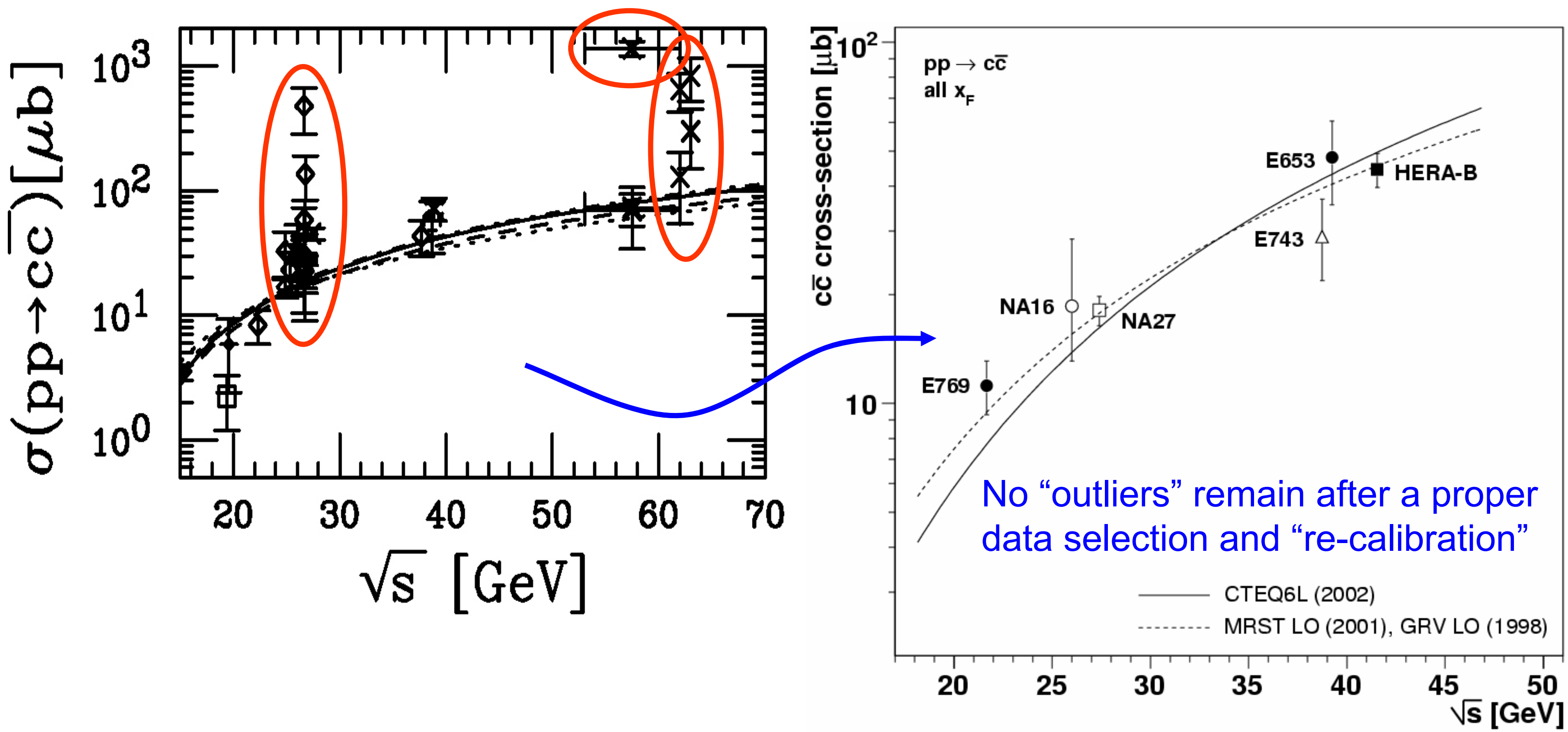
Some of them can be measured in "special runs", others must be estimated by a detailed Monte Carlo simulation of the detector, using the same algorithms as used for the reconstruction and analysis of the collected data.



Efficiencies which depend on the centrality of the heavy-ion collision are particularly dangerous. If not carefully understood, they may look like "very interesting" anomalies, which may be taken for "new physics" (like the suppression or enhancement of particle production).

Data selection

"The choice of procedure is less significant than the initial choice of data.
We place a great emphasis on the choice of data to include or exclude."
Particle Data Group



A small but clean event sample is better than a large but "dirty" one.
And statistical errors are much easier to deal with than systematic uncertainties.

Systematic effects must be controlled

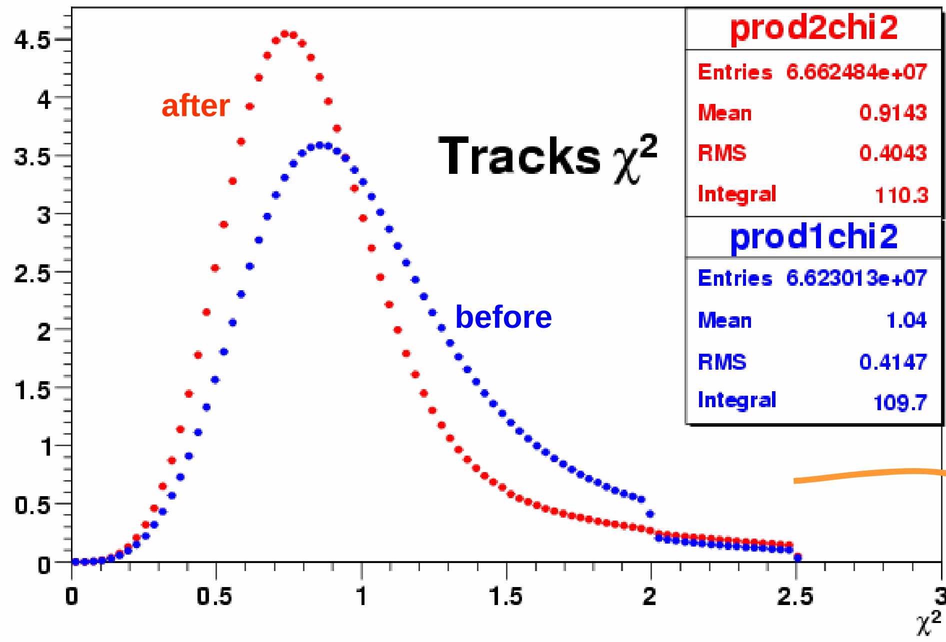
To verify the understanding of systematic effects, redo the measurements in different configurations. For instance, change the magnetic field polarity regularly, take data with two different field currents, change the hadron absorber thickness, change the beam intensity, and the beam energy, etc.

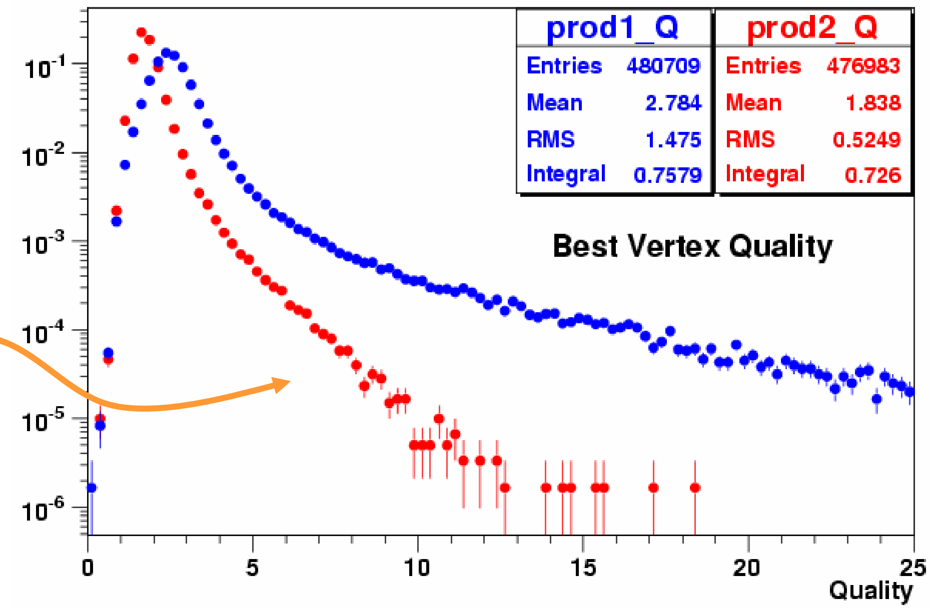
The acceptances, efficiencies, signal/background ratio, resolutions, etc., will certainly change; but the physics results, obtained after all the corrections are made, must remain the same (within *statistical* errors).

Important physics topics should always be *independently* analysed by at least two different people/groups, with different choices of the model dependent assumptions. Will the results change if you replace PYTHIA by HERWIG or ISAJET ? or CTEQ6L by MRST LO?

If after all checks you still have doubts about your exciting “new physics” results
—you should *always* doubt everything, especially *exciting results*—
make a new experiment, with vastly improved capabilities...

Importance of a good alignment





Redoing the data reconstruction after realigning the silicon pixel planes significantly improves the tracking and vertexing quality

$\Rightarrow$ better resolution of the impact parameter of the muon track
$\Rightarrow$ less background on the open charm signal

Calibration of Monte Carlo distributions

No Monte Carlo simulation *perfectly* describes all the details affecting the measurements: geometry, material densities, multiple scattering, energy loss, digitization, noisy channels, dead channels, alignment, detection efficiencies, etc.

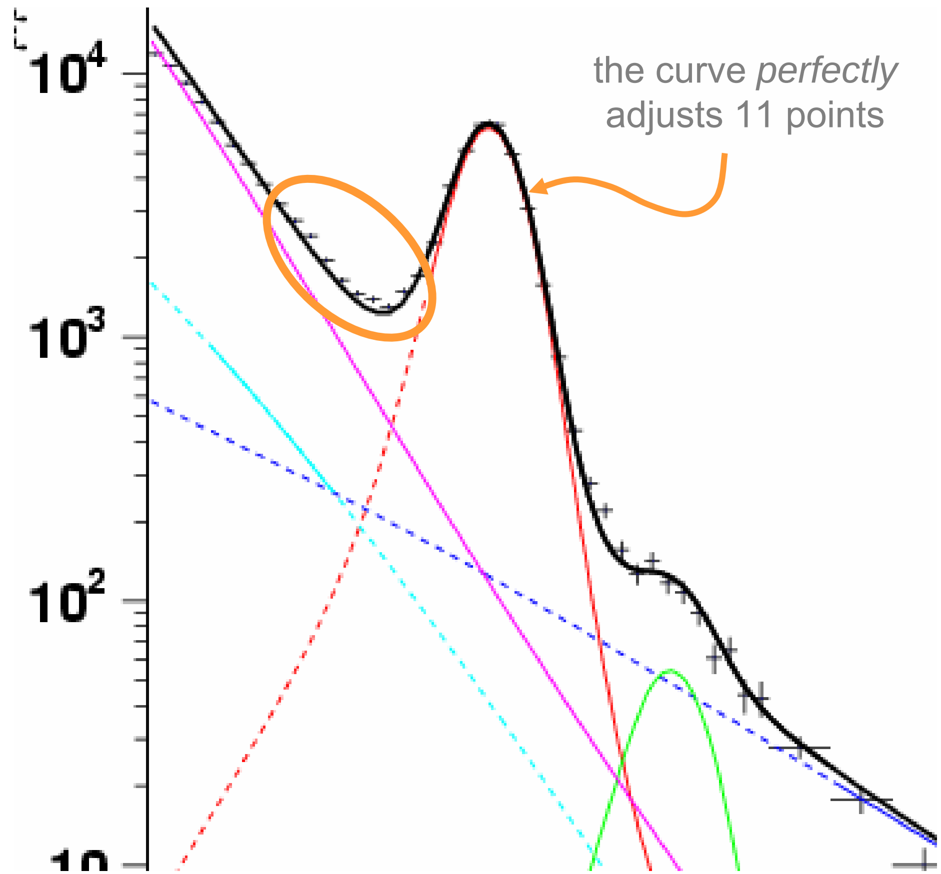
Some of these things change with time, with beam intensity, with accumulated radiation dose, with temperature, etc. And we cannot make a new Monte Carlo simulation each time a silicon pixel chip stops working or the beam position changes by 100 μm or so.

So, we have to live with the fact that the MC distributions will, in general, be "too good" with respect to the measured ones.

What happens when you fit the dimuon mass distribution with a J/ψ shape purely determined by the MC simulation, without any adjustment?

Since the J/ψ is a peak, it determines the fit; wrong "pole mass", resolution and tails will directly bias the less robust Drell-Yan yield.

But we must be careful... Too much "tuning" might distort the real physics; better to leave some imperfections than to "over correct".



Calibration of dimuon mass

In different years, with different hadron absorber configurations (more carbon or more iron), different currents in the toroidal magnet (4000 A or 7000 A), etc., the absolute calibration of the dimuon mass may change slightly

The J/ψ "pole mass" in the NA50 Pb-Pb data is 3.110 GeV/c^2, while in the NA38 S-U data is 3.086 GeV/c^2 and in the In-In data of NA60 is 3.078 GeV/c^2 (in one of the data sets)

A "shift" in the absolute dimuon mass calibration is not important for the J/ψ itself, because its yield is integrated over the full peak range, but is crucial for the determination of the Drell-Yan yield, obtained as the integral (of an exponential spectrum) in the mass window 2.9–4.5...

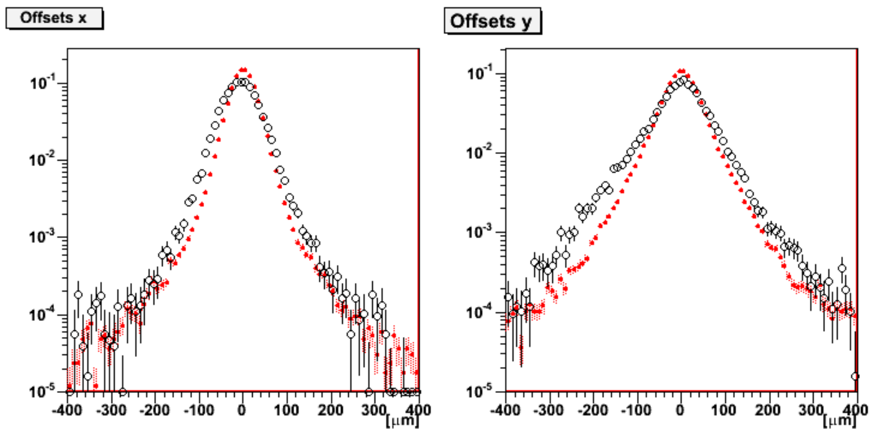
We must adapt the DY mass window to match the J/ψ pole:

in Pb-Pb (NA50) : 2.9–4.5 GeV/c^2
in S-U (NA38) : 2.876–4.476 GeV/c^2
in In-In (NA60) : 2.87–4.45 GeV/c^2

Note that a change of the mass calibration by 1% changes the DY yield by 4%

Question: how do you know that the ϕ mass does not change from p-A to In-In collisions?
If you calibrate the data to the PDG value in each data set... you may miss interesting signals

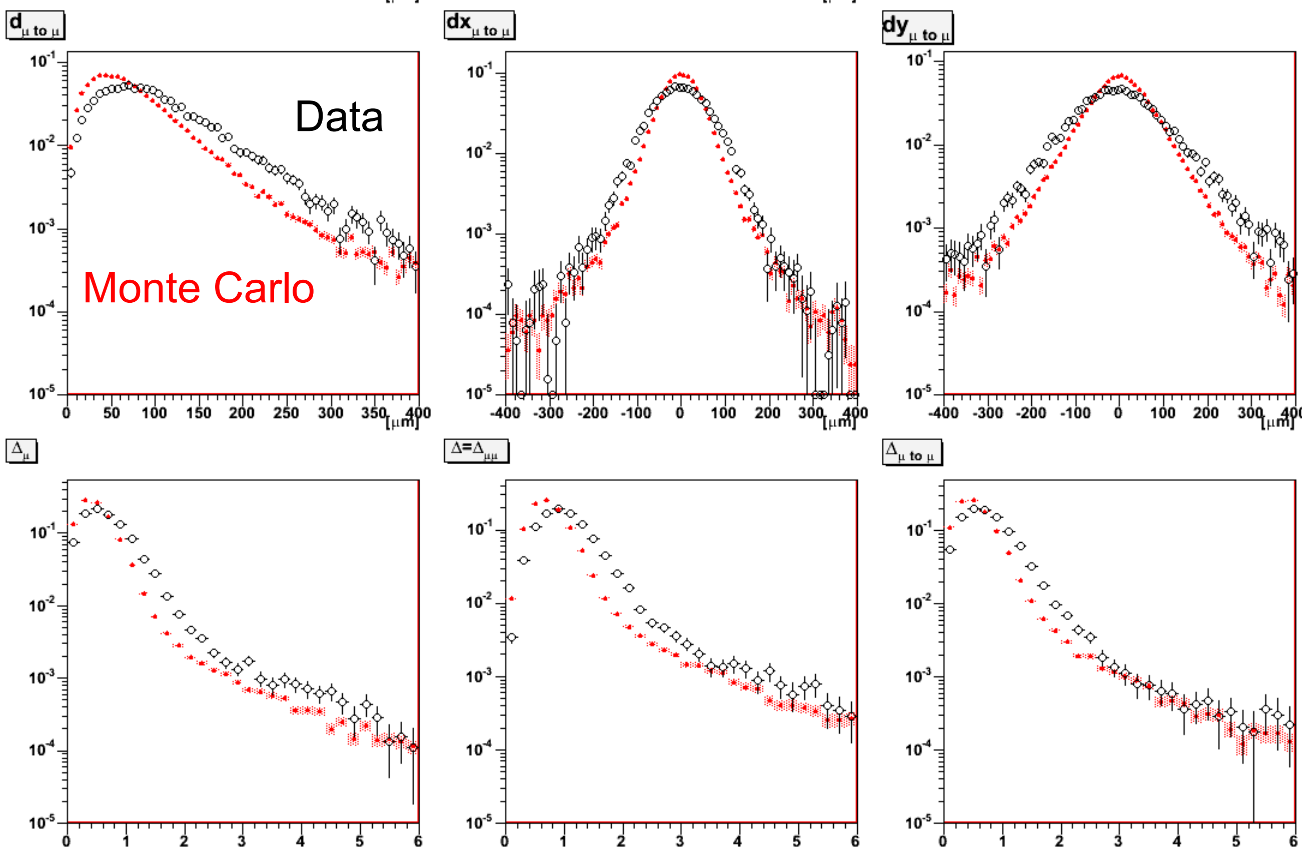
Calibration of muon offset distributions

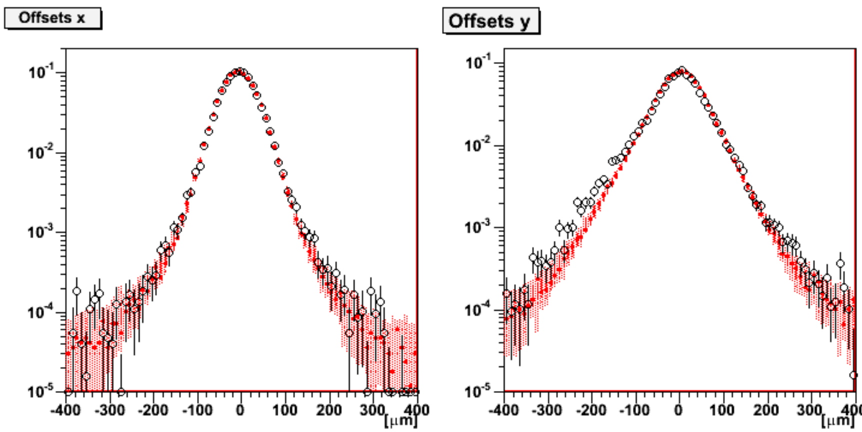


Before adjustments:

Monte Carlo spectra are “too good”

muons from the J/ψ peak

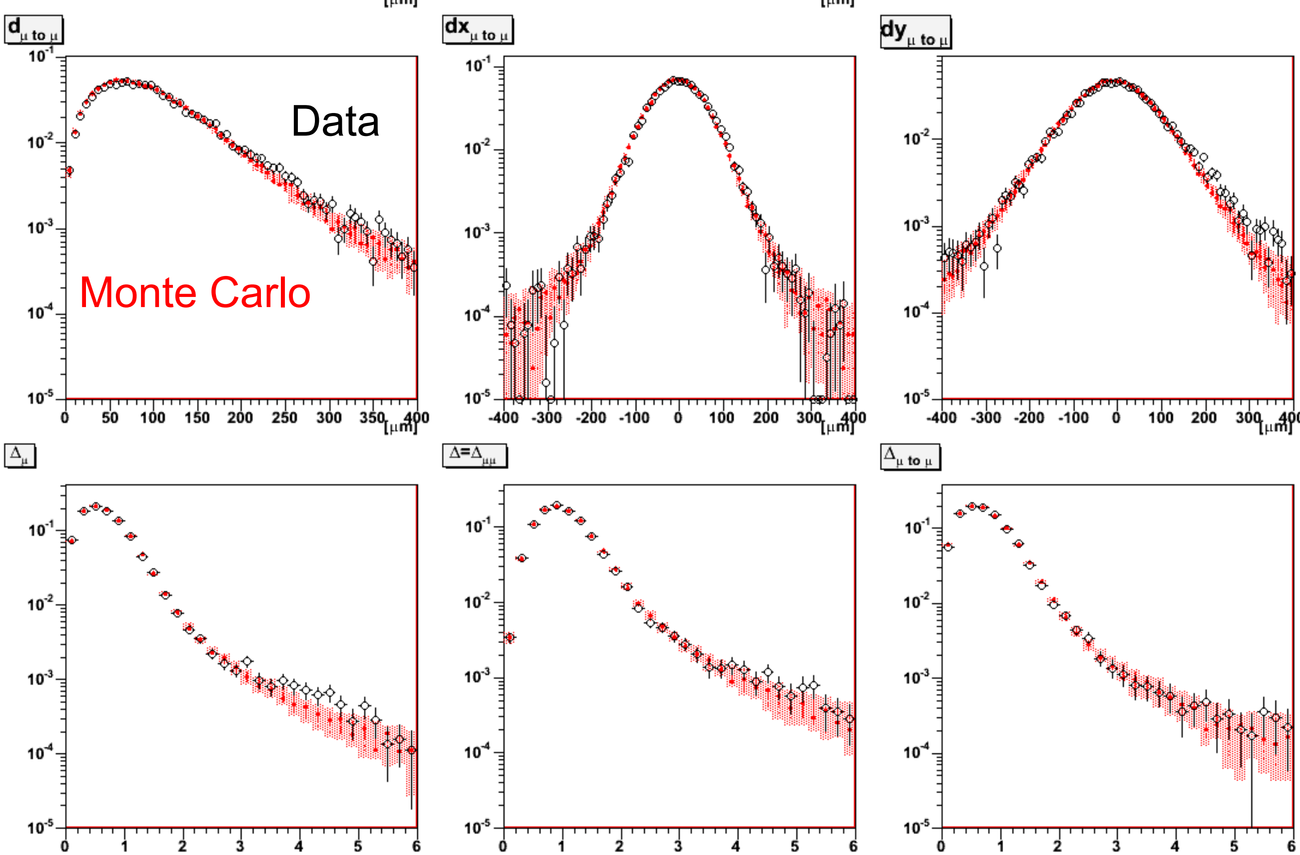




After smearing:

Monte Carlo spectra reproduce the data

muons from the J/ψ peak



Luminosity: crucial for studies of rare processes

Achieving good statistics in the study of rare processes requires the highest possible luminosities

In a fixed target mode, this means high beam intensities incident on thick targets

Primary beams, directly from the machine are mandatory for high beam intensities; secondary proton beams are polluted with pions and kaons, and no beam detector can separate them if we run at collision rates close to 40 MHz (2×10^9 p/burst)

A run with 158 GeV primary protons at the SPS affects all SPS users...
$\Rightarrow$ Almost impossible to obtain

Targets cannot be too thick, or we will have too much “interaction pile-up”: more than one beam particle interacts in the target, within the “read-out gate” of the detectors

A beam ion can have a peripheral interaction followed by a second interaction only involving the nucleons not participating in the first one (“spectators”). If we cannot distinguish two peripheral collisions from a central one, the event’s centrality will be incorrectly tagged

Targets must be placed in vacuum, at least if we are working with heavy-ion beams; otherwise, there will be Pb-air collisions looking like peripheral Pb-Pb collisions

Trigger: crucial to handle high collision rates

If you work in a high luminosity experiment, meaning high interaction rates, then you need a trigger, to select the interesting events among the many (minimum bias) collisions

Otherwise, the data acquisition system will be permanently busy reading out and storing (mostly) non-interesting events

In particular, the NA38 / NA50 / NA60 dimuon trigger system:

Selects one interesting collision out of around one million inelastic "pp" collisions (the exact number depends on the magnetic field, thickness of the hadron absorber, etc) without trigger, the same number of studied J/ψ events, say, would require writing on tape a much higher number of events, and search for the interesting ones at the *offline* level

NA60 probed 10^7 inelastic collisions per burst (5 seconds) in 2003, when running at 5×10^7 Indium ions per burst, incident on a 18% interaction length target.
And every single one is recorded on tape, if it produces a dimuon (in the acceptance window).
Since we are only interested in looking at dimuon events, a dimuon trigger is a minimum bias trigger: it only rejects collisions which would anyway not be looked at in the offline analysis.
In particular, NA60 has no centrality bias: it takes all collisions, from the most peripheral to the most central.

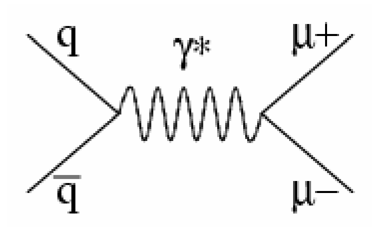
Feed-downs

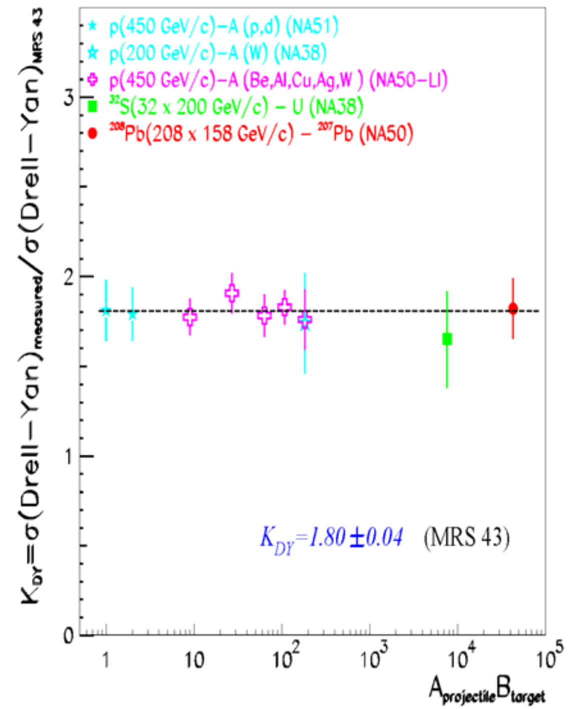
Many detected J/ψ mesons are produced through the decay of other particles, mostly χ_c, ψ' and B mesons

Parent particles have different nuclear dependences:

- the ψ' is more strongly absorbed than the J/ψ, already in p-A and S-U collisions
- open beauty production should not be absorbed (α ~ 1.0)
  → Vertexing capabilities are needed at RHIC and LHC,
  to distinguish prompt J/ψ production from beauty decays
- **the χ_c nuclear dependence has not yet been measured**
  → it is a larger object than the ψ $\Rightarrow$ expect ***stronger*** absorption
  → doesn't need an extra gluon to be formed $\Rightarrow$ expect ***weaker*** absorption
  → robust measurements are needed for the χ_c meson

Reference physics processes





$\alpha(J/\psi) \sim 0.92 \Rightarrow$ the J/ψ is suppressed …

$\alpha(\phi) \sim 0.92 \Rightarrow$ the ϕ is enhanced …

Suppressions, enhancements… *with respect to what ?*
We need a physics process which provides a solid reference

Drell-Yan

⇒ proportional to the number of binary nucleon-nucleon collisions
⇒ very robust on theory grounds
⇒ lacks statistics at the SPS and is buried under charm/beauty decays at RHIC/LHC energies
⇒ probes the quark/anti-quark distributions, not the gluons which produce charmonium states

Minimum bias events

⇒ huge statistics
⇒ but tricky systematics (very different from the dimuon triggers)

Charm / beauty decays

⇒ should be ideal reference processes
⇒ unless heavy flavor production is also affected by "new physics"

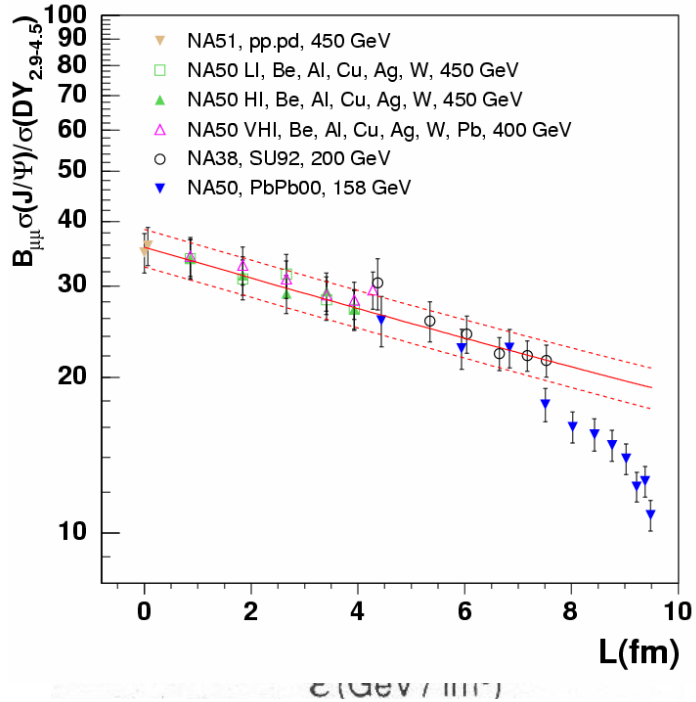
Reference collision systems

1. pp, p-A, light-ion data; at several energies
2. Centrality scan from very peripheral to very central A-A collisions

→ must be a fundamental component of any heavy-ion physics programme
→ defines the reference baseline relative to which we recognize HI specific phenomena
→ gives strict constraints on the interpretations of the results
→ requires a serious effort in terms of beam time and data analysis resources

Example: in 1987/88, when p-U was the only p-A data, and high mass Drell-Yan had *very* poor statistics, NA38 found that the J/ψ was suppressed with respect to the (IMR) *dimuon continuum*

- from p-U to O-U and S-U
- in S-U, from peripheral to central collisions



Now we know that there is nothing new in the J/ψ production yields from pp to S-U…

The main difference is the understanding of the references:
→ several p-A data points became available
→ “Continuum” (IMR) was replaced by DY
isospin correction added to compare p-A and HI data

The art of experimental heavy-ion physics

Experimental studies of high-energy heavy-ion collisions are very difficult; much more than the studies of e^+e^- or pp interactions

Add up many “negligible” backgrounds and the sum will no longer be negligible; it is *difficult* to measure a small signal by subtracting a big background from a big total

The measurements are done in very difficult conditions (occupancies, data rates, radiation damage, etc) and often must be redone after significant improvements

Extraordinary claims require extraordinary evidence; or at least a second ***good*** look

There is no QGP “Standard Model”... This is a data-driven field

Before the measurements are made, theorists often say that the data will be easy to interpret...
but theorists are often wrong...
especially before the measurements are made...

Quarkonium studies in proton-nucleus collisions: why?

Theoretical prediction: in the presence of *new physics* (formation of a QCD medium with deconfined quarks and gluons) the centrality dependence of quarkonium production yields will be very significantly affected
→ we have a "signature"

Above certain *consecutive thresholds*, the ψ', the χ_c and the J/ψ resonances (besides the Upsilon states) will "dissolve" in the formed medium
→ we have more than a simple signature; we have a "smoking gun"...

However, ...
What happens to the charmonium states in the presence of "*old physics*"?
What are the basic properties of J/ψ and ψ' production in pp and p-A collisions?
Do we have a *robust* and well understood baseline, in A-A collisions, with respect to which we can clearly and unambiguously identify patterns specific to the high density medium produced in high-energy nuclear collisions?
What should we *really* expect in the *absence* of a deconfined QCD medium but accounting for all the other "standard" aspects of nuclear collisions?

→ We need accurate p-A data and a robust model to turn the p-A patterns into reliable A-A expectations...

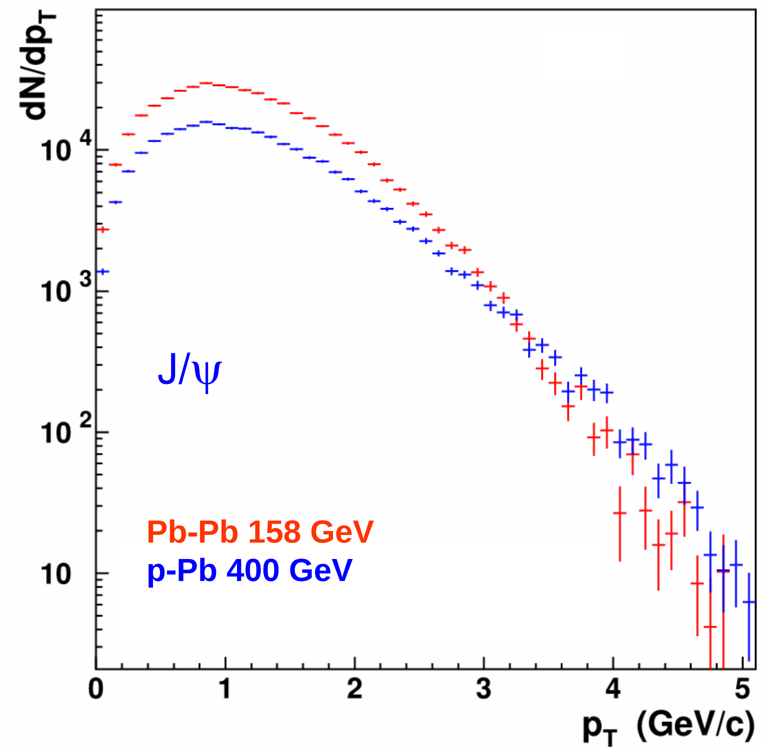
Charmonium studies made by NA50

Measurements of J/ψ and ψ' production were made in the last few years at the SPS by the NA50 collaboration, in p-A and Pb-Pb collisions.

Charmonium production yields have been presented either in relative terms, with respect to the yield of high-mass Drell-Yan dimuons, or as absolute production cross-sections per target nucleon.

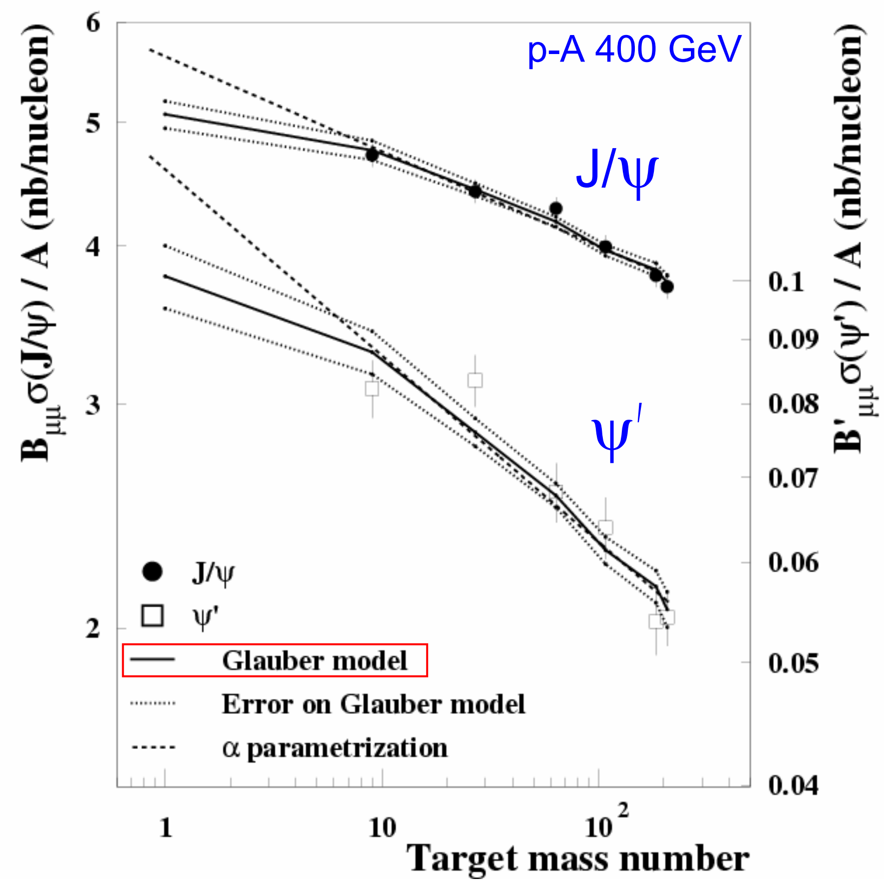
Results have also been obtained in what concerns p_T distributions, centrality dependence of production yields, etc.

NA50 collected p-A data at 400 and 450 GeV, with 5 or 6 different target nuclei.
More than 3 000 000 J/ψ events have been analyzed, in total, from these p-A data sets.

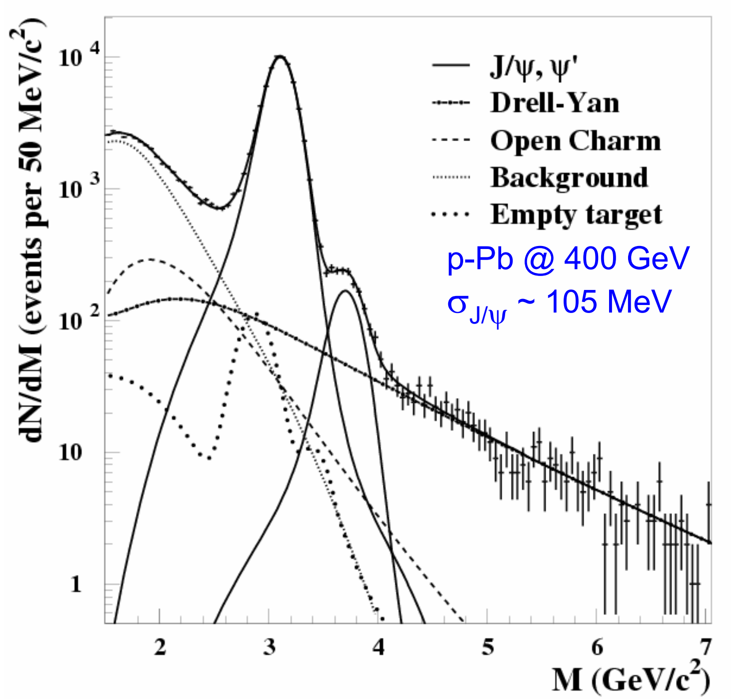


The J/ψ and ψ’ are *absorbed* in p-nucleus collisions

The J/ψ and ψ’ production cross sections scale less than linearly with the number of target nucleons (contrary to what happens with high-mass Drell-Yan dimuons)



NA50 collected p-A data in year 2000, with Be, Al, Cu, Ag, W and Pb targets

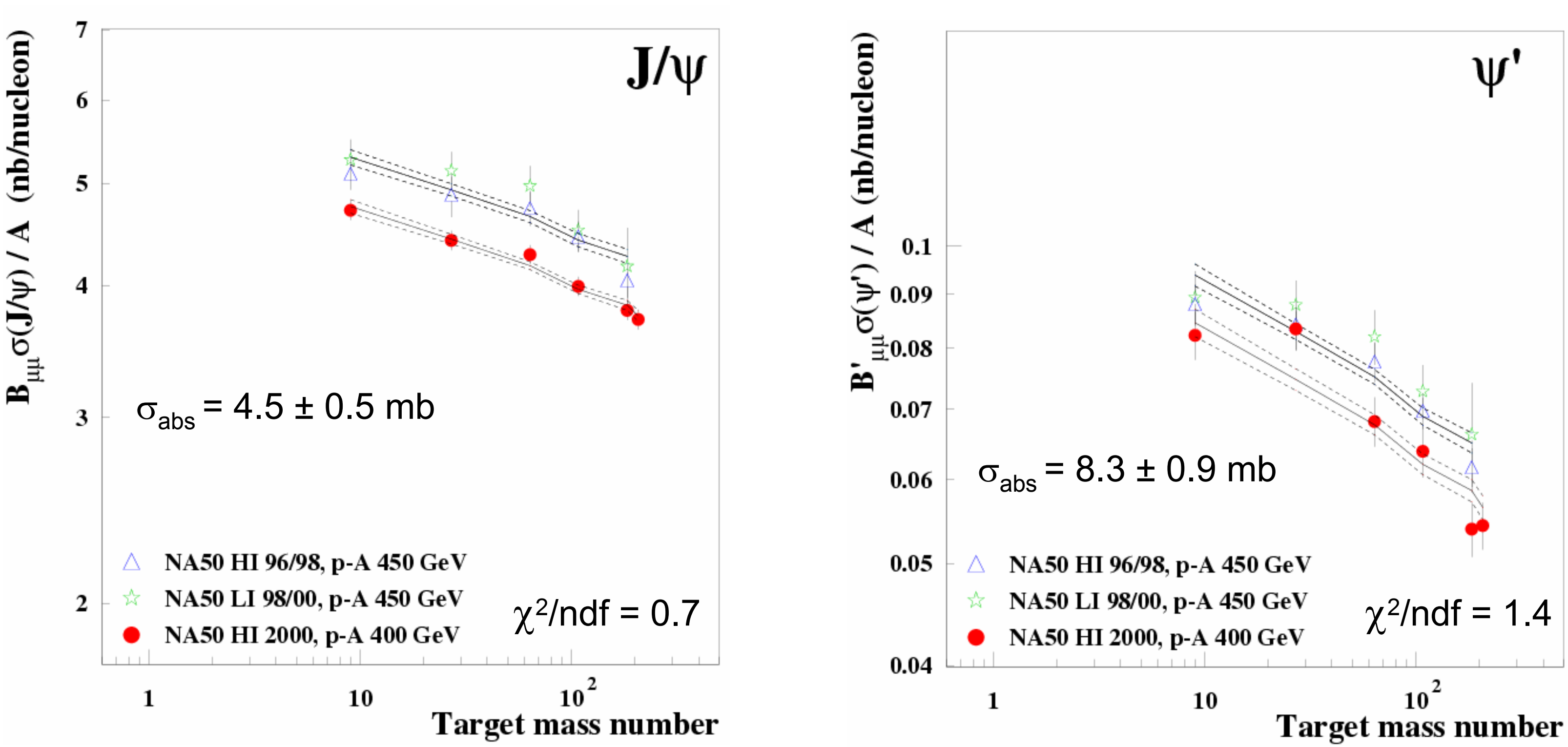


The Glauber model describes the J/ψ and ψ’ “normal nuclear absorption” with a single parameter, the absorption cross section

From a global fit to the 400 and 450 GeV p-A data (16 independent measurements), NA50 determined the following absorption cross-sections (with GRV94LO PDFs):

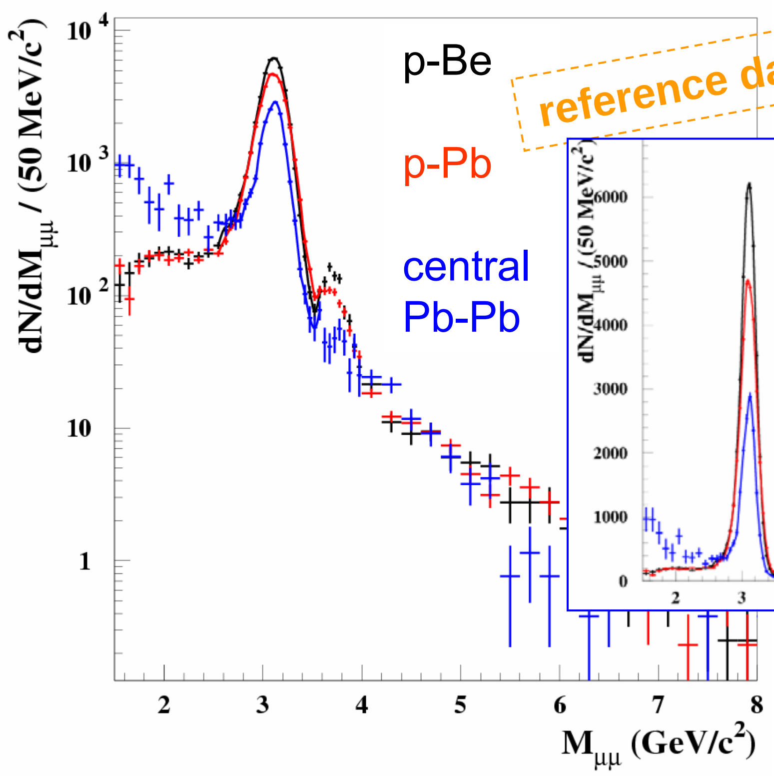
$\sigma_{abs}(J/\psi) = 4.5 \pm 0.5$ mb ; $\sigma_{abs}(\psi') = 8.3 \pm 0.9$ mb from production cross-sections

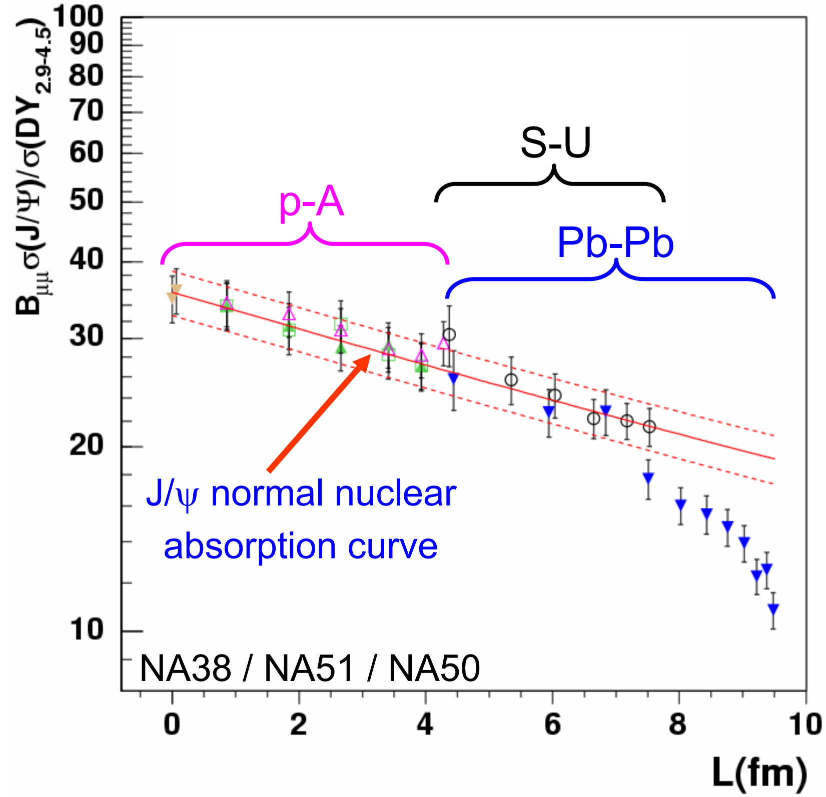
$\sigma_{abs}(J/\psi) = 4.2 \pm 0.5$ mb ; $\sigma_{abs}(\psi') = 7.7 \pm 0.9$ mb from cross-section ratios (ψ/DY)



These calculations assume that the reduction of the production cross-section per target nucleon is exclusively due to *final state absorption* of the charmonium states in the traversed cold nuclear matter

J/ψ suppression in the NA38, NA50 and NA51 data





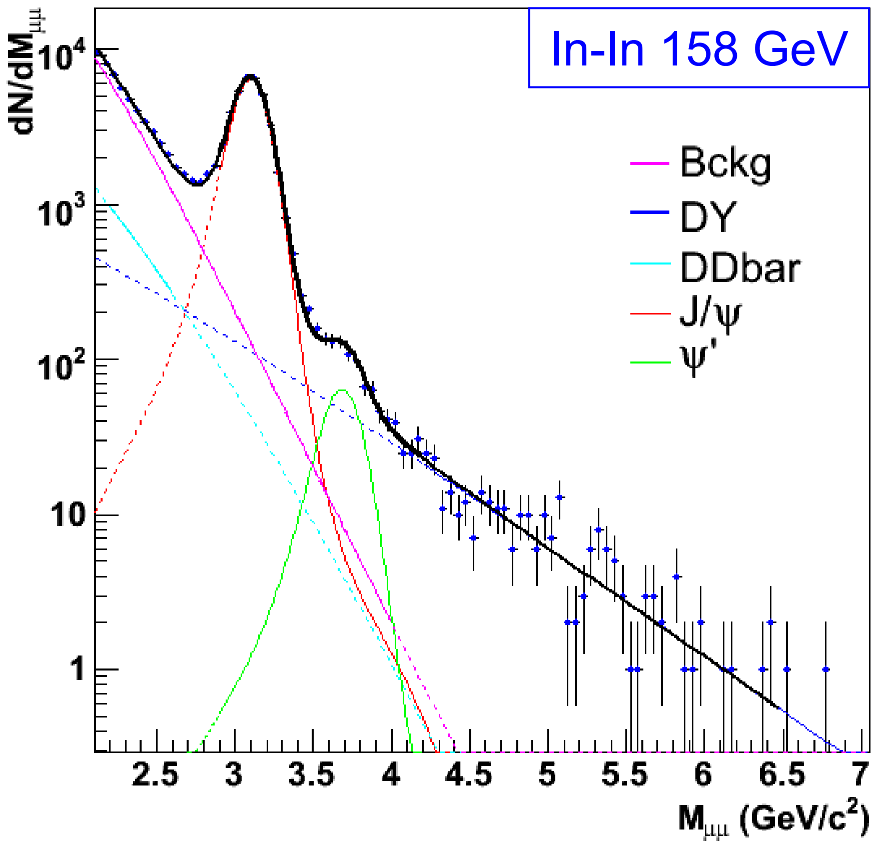
The yield of J/ψ mesons (per DY dimuon) is "slightly smaller" in p-Pb collisions than in p-Be collisions; and is ***strongly*** suppressed in central Pb-Pb collisions

Drell-Yan dimuons are not affected by the dense medium they cross

Interpretation: strongly bound c-cbar pairs (our probe) are "anomalously dissolved" by the QCD medium created in central Pb-Pb collisions at SPS energies

NA60: an improved look at the J/ψ suppression pattern

NA38 and NA50 determined the J/ψ suppression pattern through the *ratio* of the J/ψ and Drell-Yan production cross-sections, to cancel out the vertex identification inefficiencies and other potential experimental biases (pile-up, efficiencies of event selection cuts, centrality scale, etc)

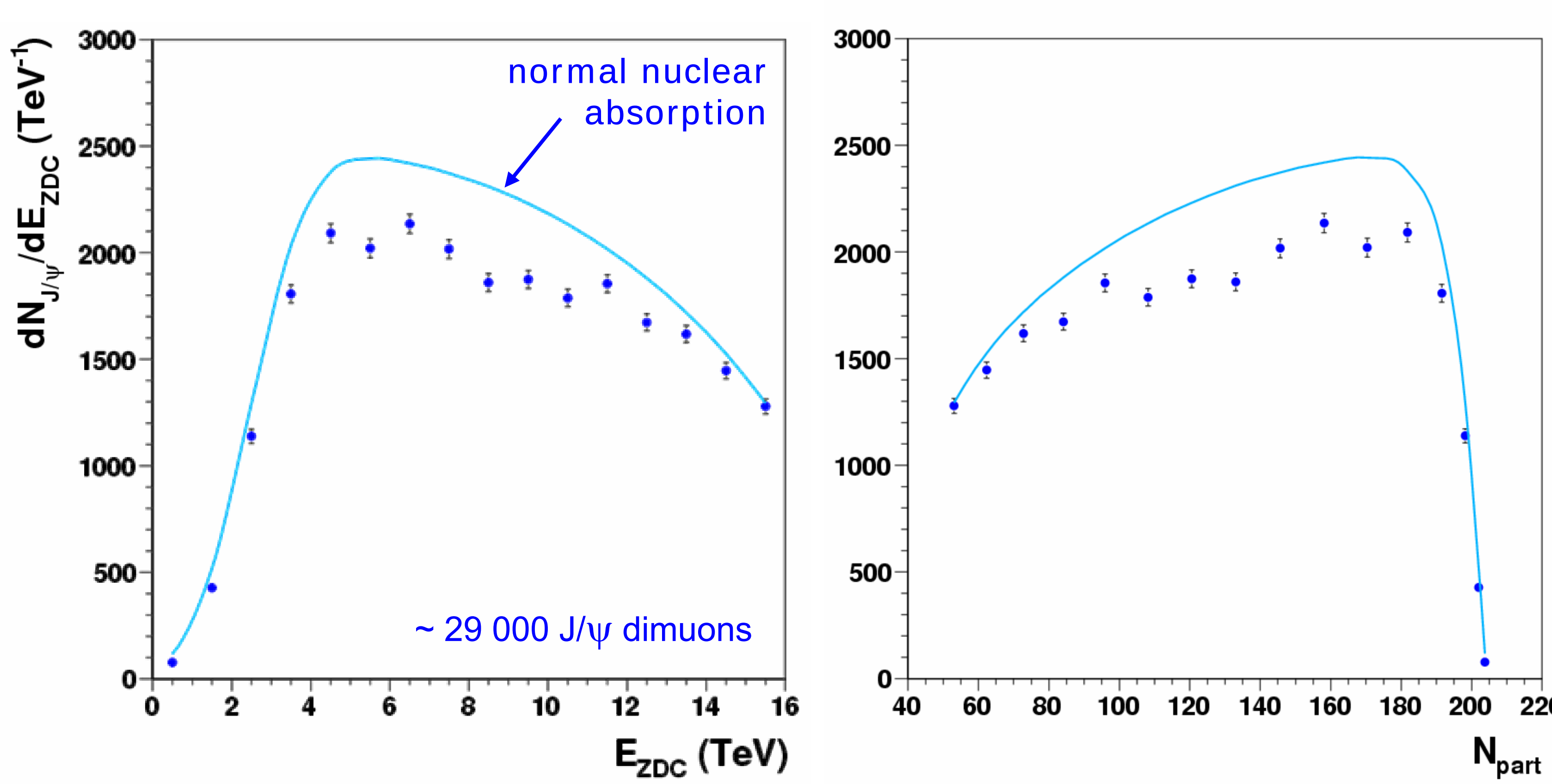


This "ψ/DY analysis" is not sensitive to many systematic effects but is limited by the poor statistics of high mass dimuons

The error bars of the J/ψ suppression pattern are determined by the reference (DY) and not by the signal (J/ψ)

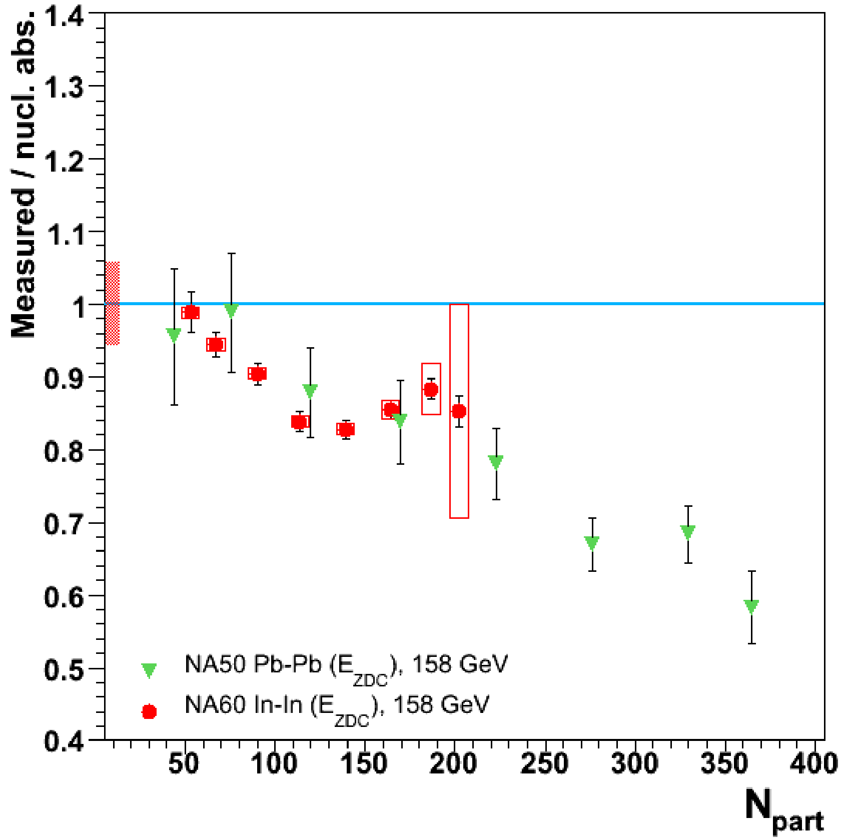
NA60 collected less J/ψ events in In-In than NA50 in Pb-Pb but they are directly compared to the *normal nuclear absorption* curve, calculated with the Glauber model, without using the "statistically challenged" Drell-Yan yield

Thanks to the accuracy provided by the silicon pixel vertex tracker, NA60 has no vertexing efficiencies (or others) depending on the collision centrality



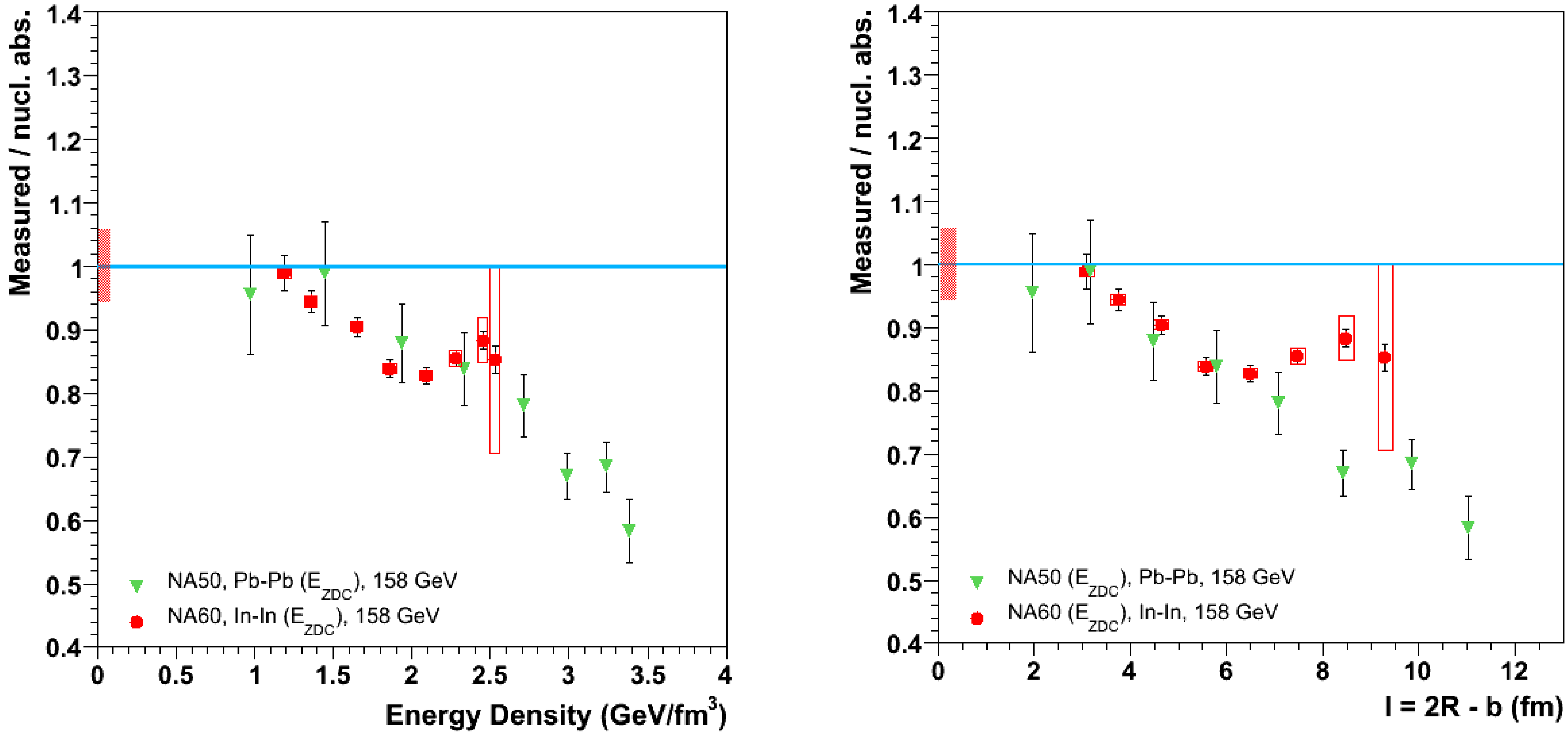
The calculation of N_{part} for each E_{ZDC} bin uses the Glauber model, which reproduces distributions collected with minimum bias triggers (no dimuons)

The J/ψ suppression pattern: In-In versus Pb-Pb



There is a good agreement between the Pb-Pb and In-In suppression patterns when plotted as a function of the N_{part} variable, determined from the (same) ZDC detector; the statistical accuracy of the In-In points is, however, much better...

The pink box represents the ±6% global systematic uncertainty in the *relative* normalization between the In-In and the Pb-Pb data points

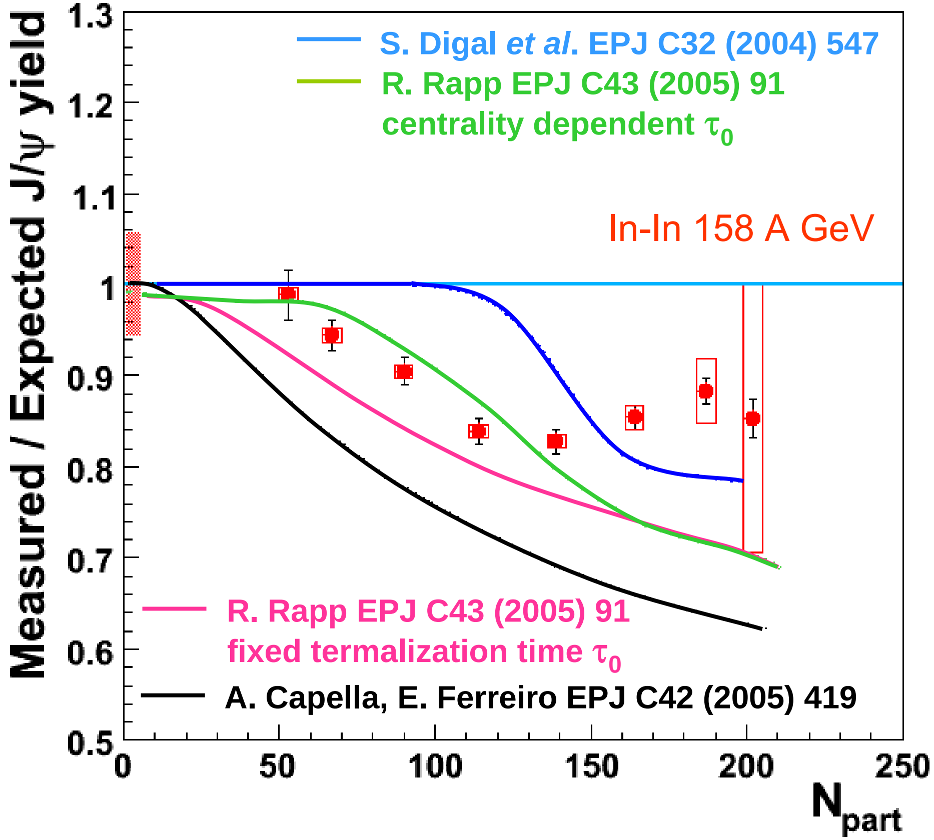


The agreement between the Pb-Pb and In-In suppression patterns remains good when plotted as a function of the energy density

The two patterns do not overlap as a function of the “fireball’s transverse size”

A better understanding of what is “the” scaling variable requires improved Pb data

The In-In J/ψ suppression pattern versus theory

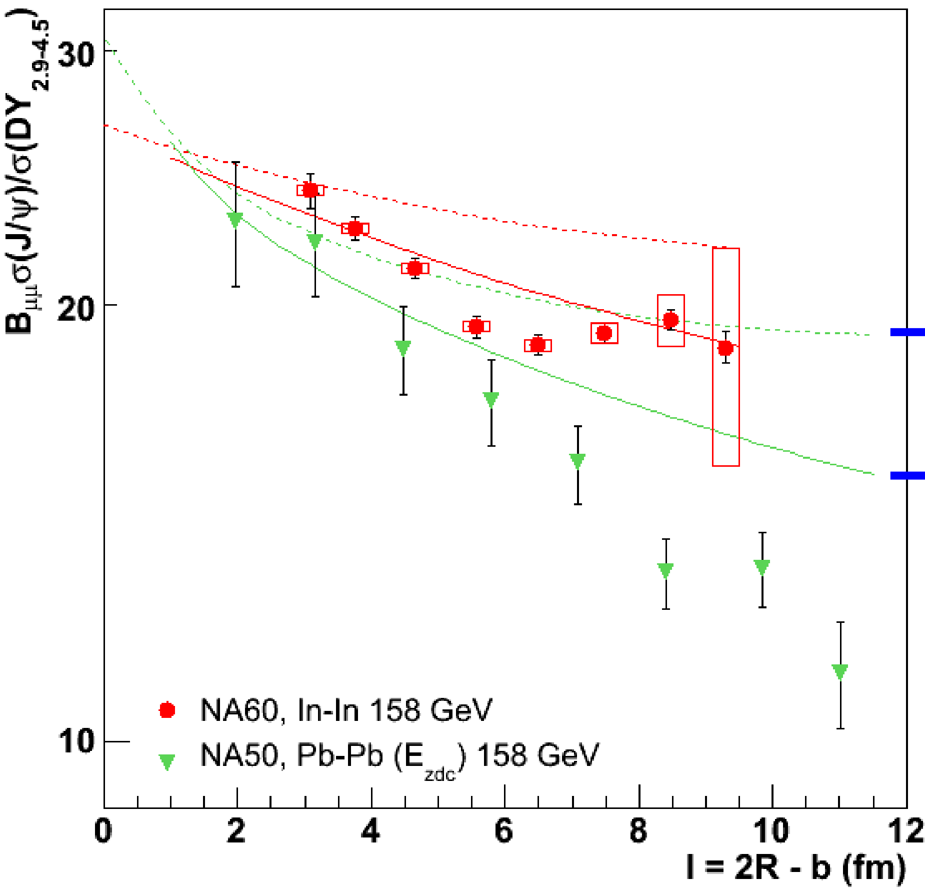


None of these *predictions* describes the measured suppression pattern...

<u>Homework exercise:</u>
calculate the χ^2/ndf for each of these curves (ndf = 8)

The In-In data sample was taken at the same energy as the Pb-Pb data...
to minimise the "freedom" of the theoretical calculations ☺

Moving up or down *all* the data points, we can decrease the χ^2/ndf, but it always remains too high...



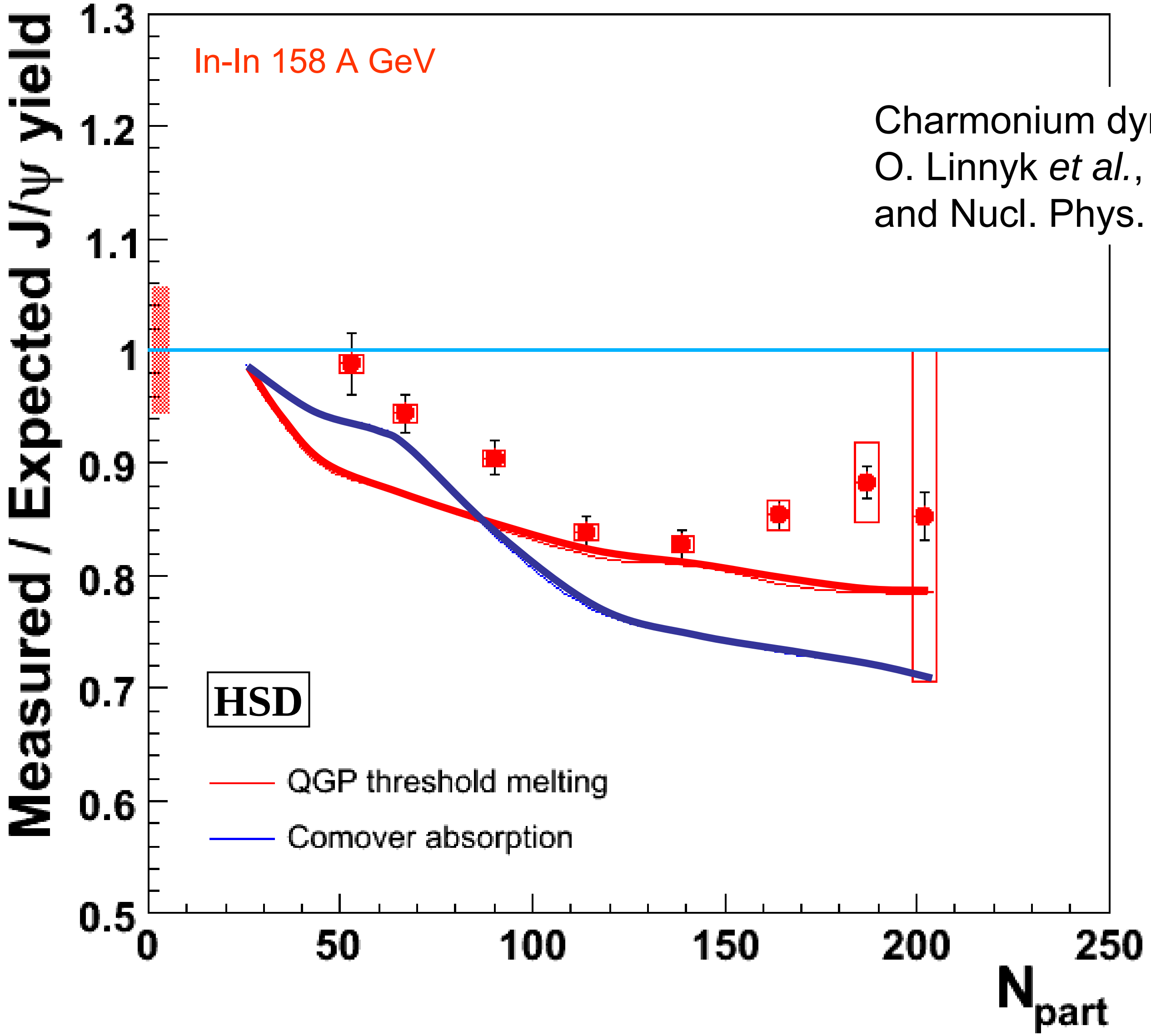
Nuclear plus hadron gas absorption
L. Maiani *et al.*, NP A748 (2005) 209
F. Becattini *et al.*, PL B632 (2006) 233

Nuclear absorption only...

plus largest possible absorption
in a hadron gas
(T = 180 MeV)

This figure gives convincing evidence that neither nuclear nor hadronic absorption can explain the drop in J/ψ production

These results suggest that a different mechanism is responsible for the J/ψ suppression at large centralities, which could very well be the formation of quark–gluon plasma.



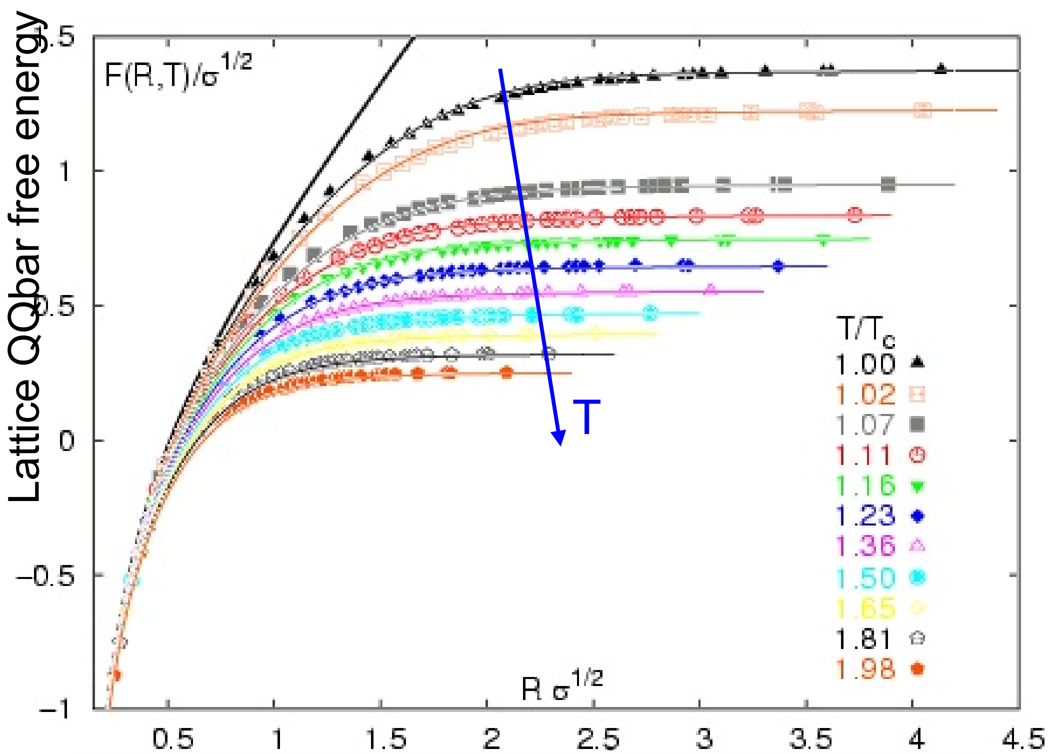
Charmonium dynamics in heavy ion collisions
O. Linnyk *et al.*, SQM 2007, June 28, 2007
and Nucl. Phys. A 786 (2007) 183.

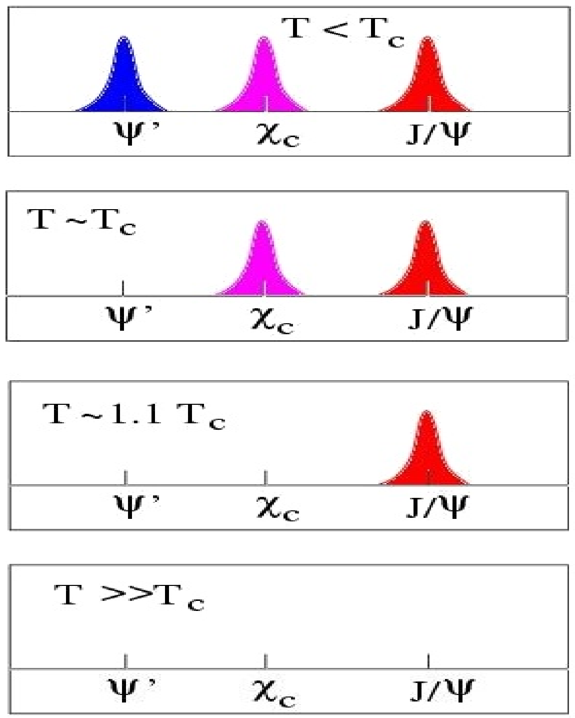
The probability that the measurements *should really be* on any of these two curves and "statistically fluctuated" to where they were observed is... zero

Reminder: quarkonia melting probes the QGP temperature

In the deconfined phase, the QCD potential is screened and the heavy quarkonia states are “dissolved” into open charm or beauty mesons

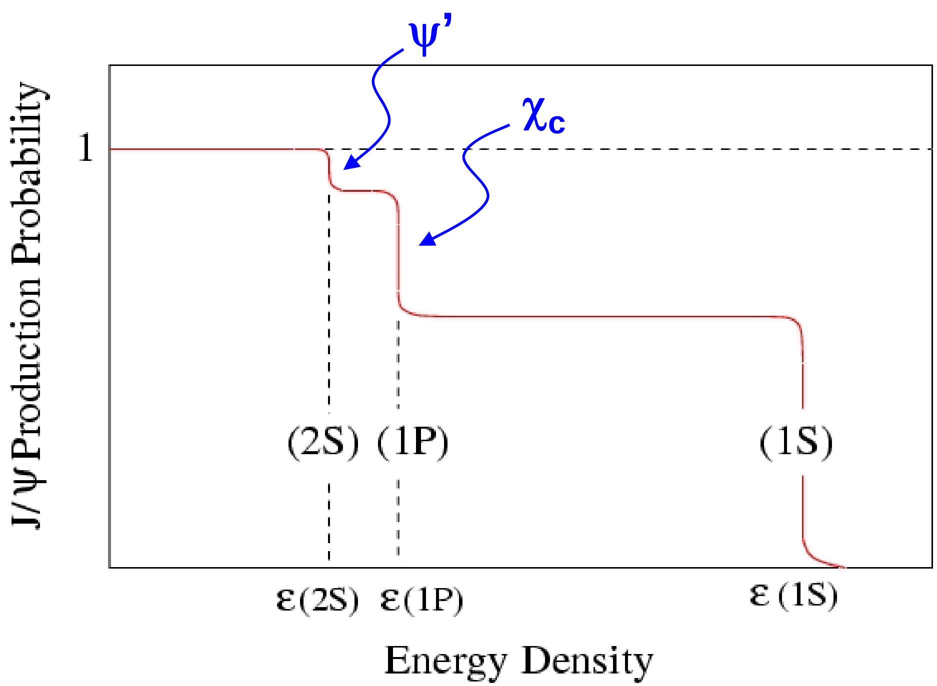
Different heavy quarkonium states have different binding energies and, hence, are dissolved at successive thresholds in energy density or temperature of the medium; their suppression pattern works as a “thermometer” of the produced QCD matter





A QGP "smoking gun" signature: thresholds ⇒ steps

The feed-down from higher states leads to a "step-wise" J/ψ suppression pattern



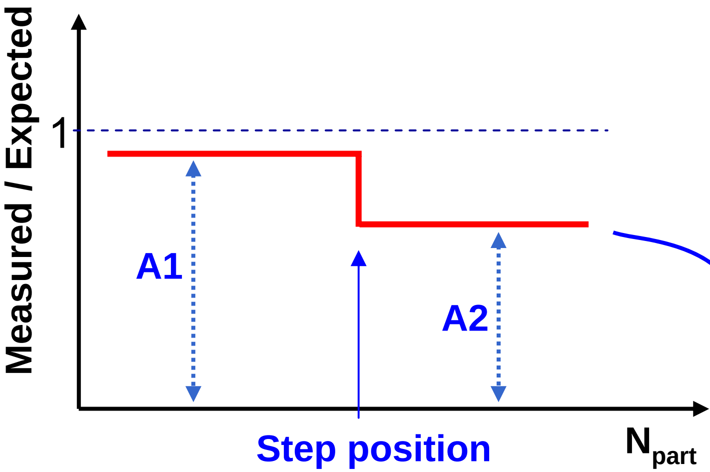
<u>J/ψ cocktail:</u>

~ 65% direct J/ψ

~ 25% from χ_c decays

~ 10% from ψ' decays

The In-In J/ψ suppression pattern versus a step function

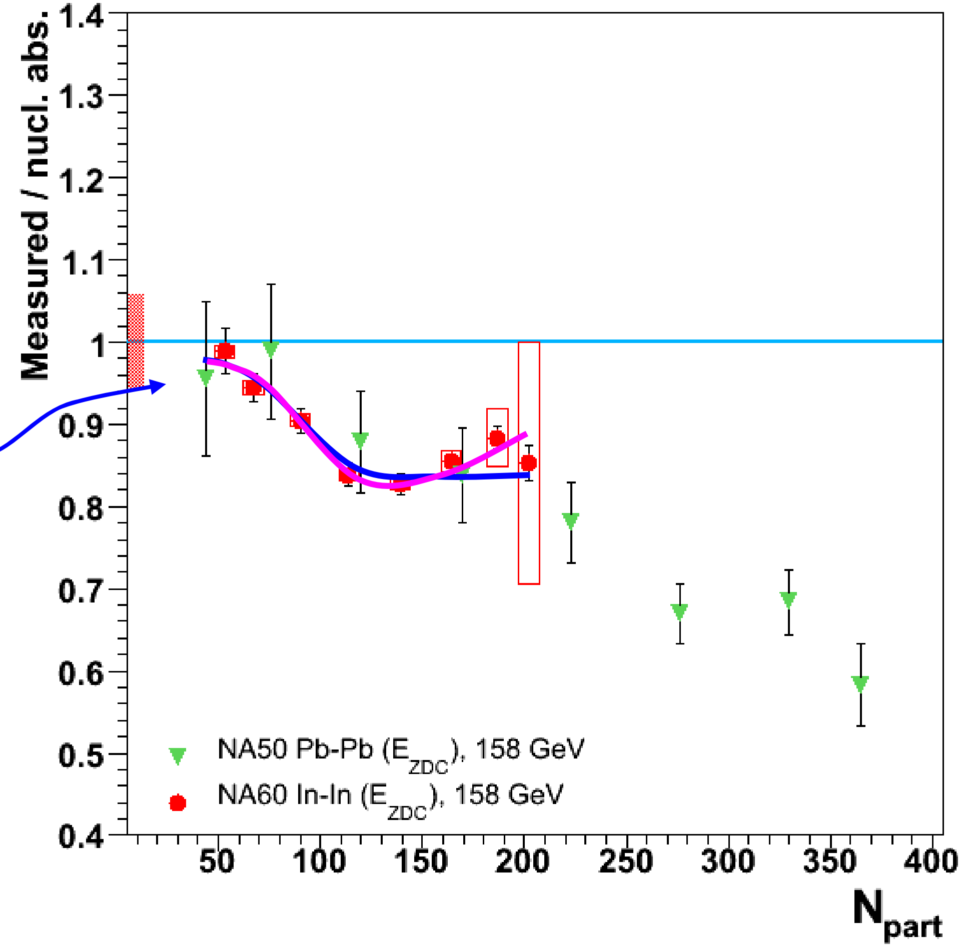


Step at N_{part} = 86 ± 8

A1 = 0.98 ± 0.02

A2 = 0.84 ± 0.01

χ^2/ndf = 0.75 (ndf = 8–3 = 5)



Taking into account the E_{ZDC} resolution,

the measured pattern is *perfectly* compatible with a step function in N_{part}

Maybe there is even a hint of charm “coalescence” in the most central collisions ☺

Is the step in Npart or in another variable?

N_{part} is convenient to compare the measured In-In and Pb-Pb data, because it is derived from the same E_{ZDC} variable (measured by the same detector) using the same Glauber formalism (except for different nuclear density functions)

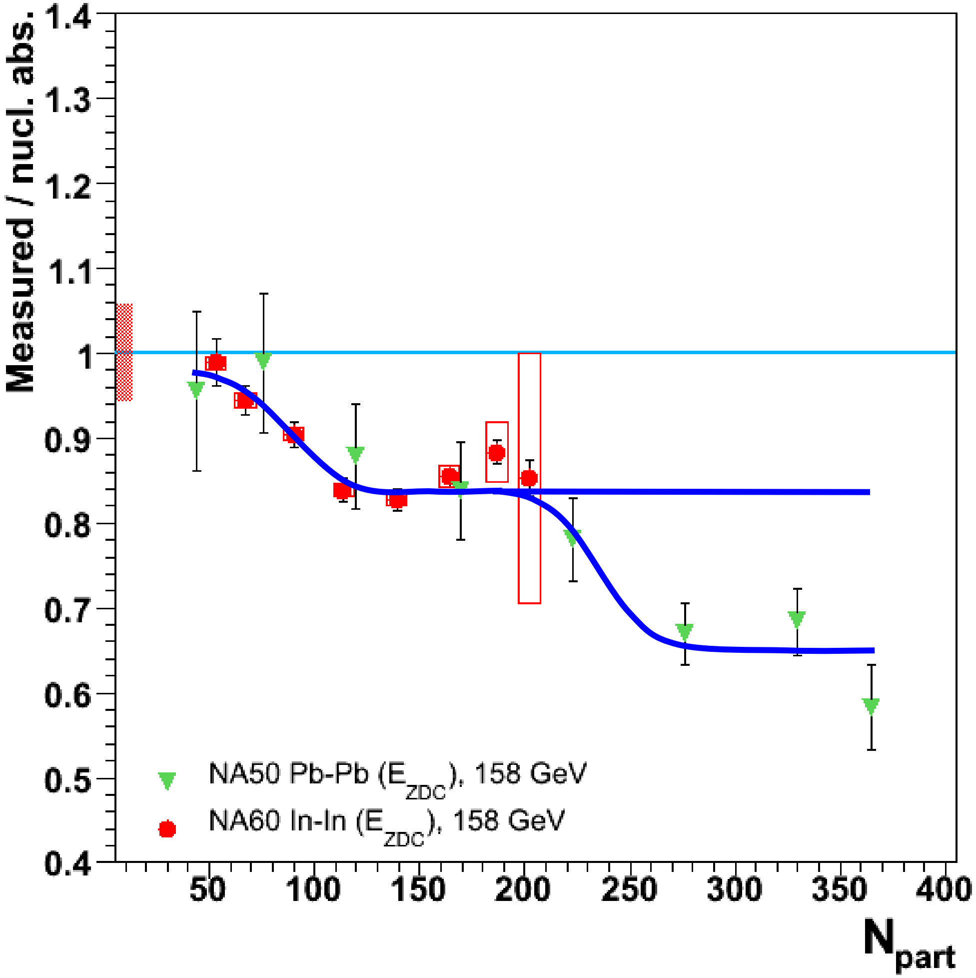
Also, the derivation of N_{part} from E_{ZDC} is trivial and essentially model independent

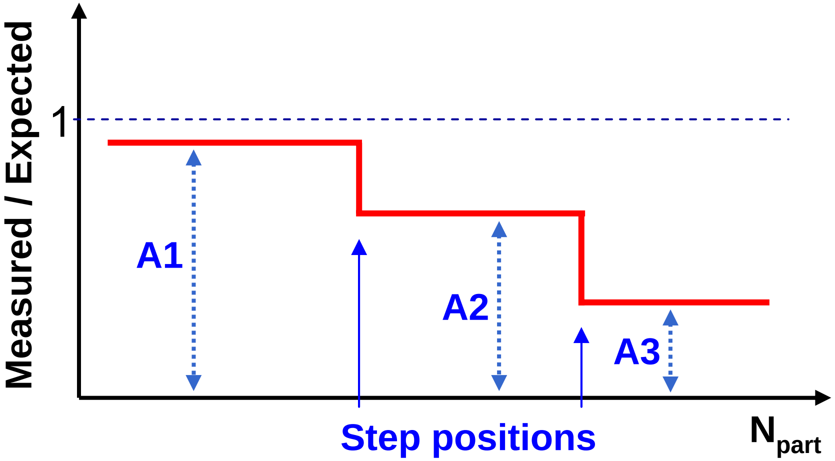
But maybe the "*real variable*" driving charmonium suppression is *not* N_{part}. Then, the *measured* smearing is the *convolution* of the detector resolution with the "physics smearing", due to the conversion from the "real variable" to N_{part}

But the N_{part} "detector resolution" is 20 (from the measured E_{ZDC} resolution) and that is the value we get if we fit it from the measured pattern, indicating that the "physics smearing" is negligible with respect to the ZDC resolution...

In summary, the In-In data provides "circumstantial evidence" indicating a step in the J/ψ suppression pattern and suggests that the "physics variable" is N_{part} or a variable very strongly correlated to N_{part}

What about the Pb-Pb suppression pattern?





Steps: N_{part} = 90 ± 5 and 247 ± 19

A1 = 0.96 ± 0.02

A2 = 0.84 ± 0.01

A3 = 0.63 ± 0.03

-12% : ψ' ?

-21% : χ_c ?

χ^2/ndf = 0.72 (ndf = 16–5 = 11)

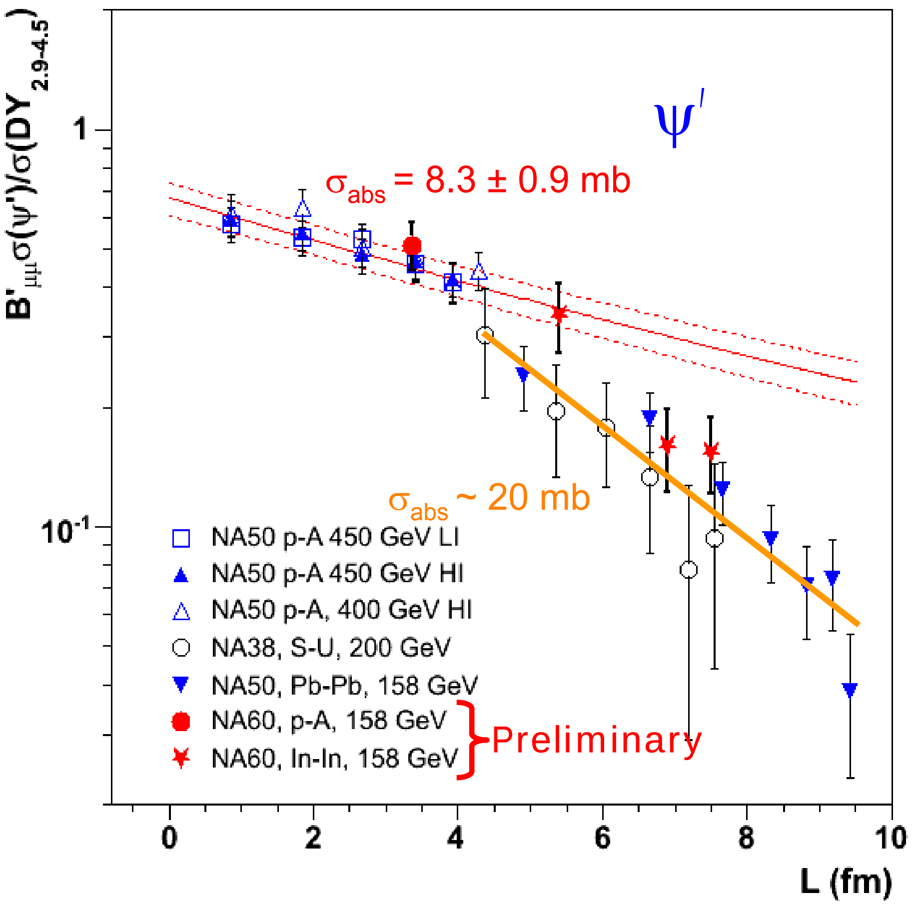
If we try fitting the In-In and Pb-Pb data with one single step we get χ^2/ndf = 5 !

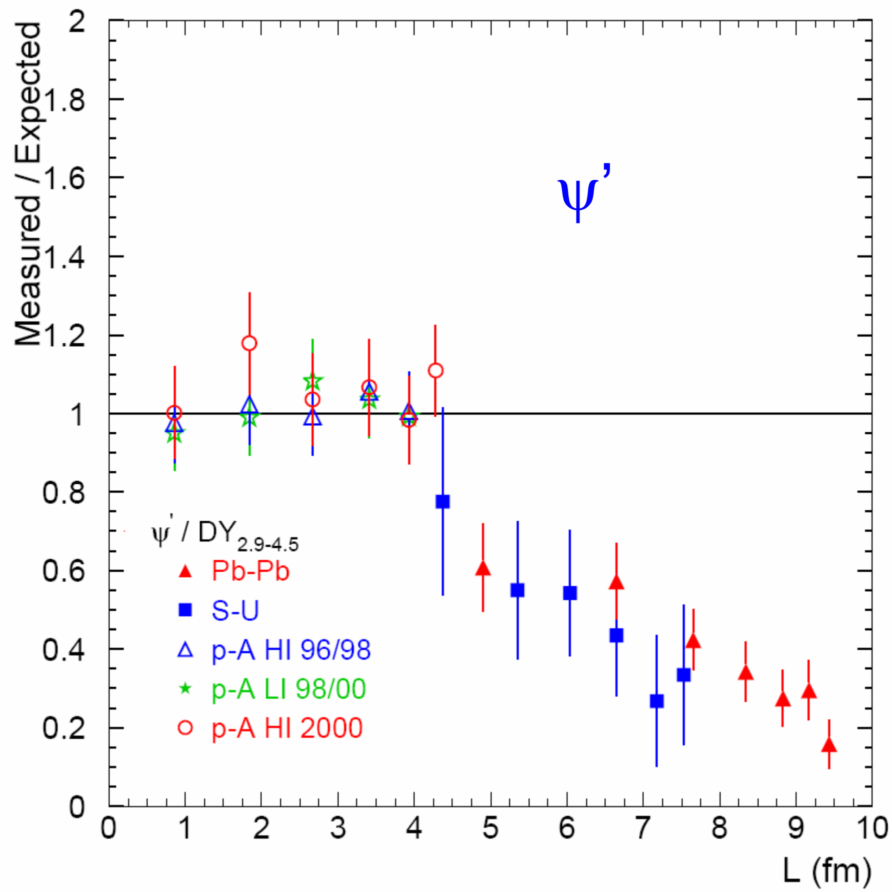
⇒ the Pb-Pb pattern rules out the single-step function and indicates a second step

Can we have a Pb-Pb J/ψ suppression pattern with much smaller errors?

What about the ψ' suppression pattern?

The ψ' suppression pattern also shows a *significant and abrupt drop* between the "normal extrapolation" of the p-A data and the S-U and Pb-Pb patterns





But this "step" happens between 400-450 GeV data and 158-200 GeV data… and would disappear if the ψ' σ_{abs} changes from 8 to 20 mb, between these energies !

Are we really sure that σ_{abs} does not depend on the collision energy?

Pertinent questions… first answers… and two remarks

Q1: Can we have a Pb-Pb J/ψ suppression pattern with much smaller errors?

Homework for HP08

A1: Yes, we can, but it requires some time and effort to go back to the NA50 data and redo the analysis… and the NA50 experts are no longer available to do it

Q2: Are we really sure that σ_{abs} does not depend on the collision energy?

Homework for HP08

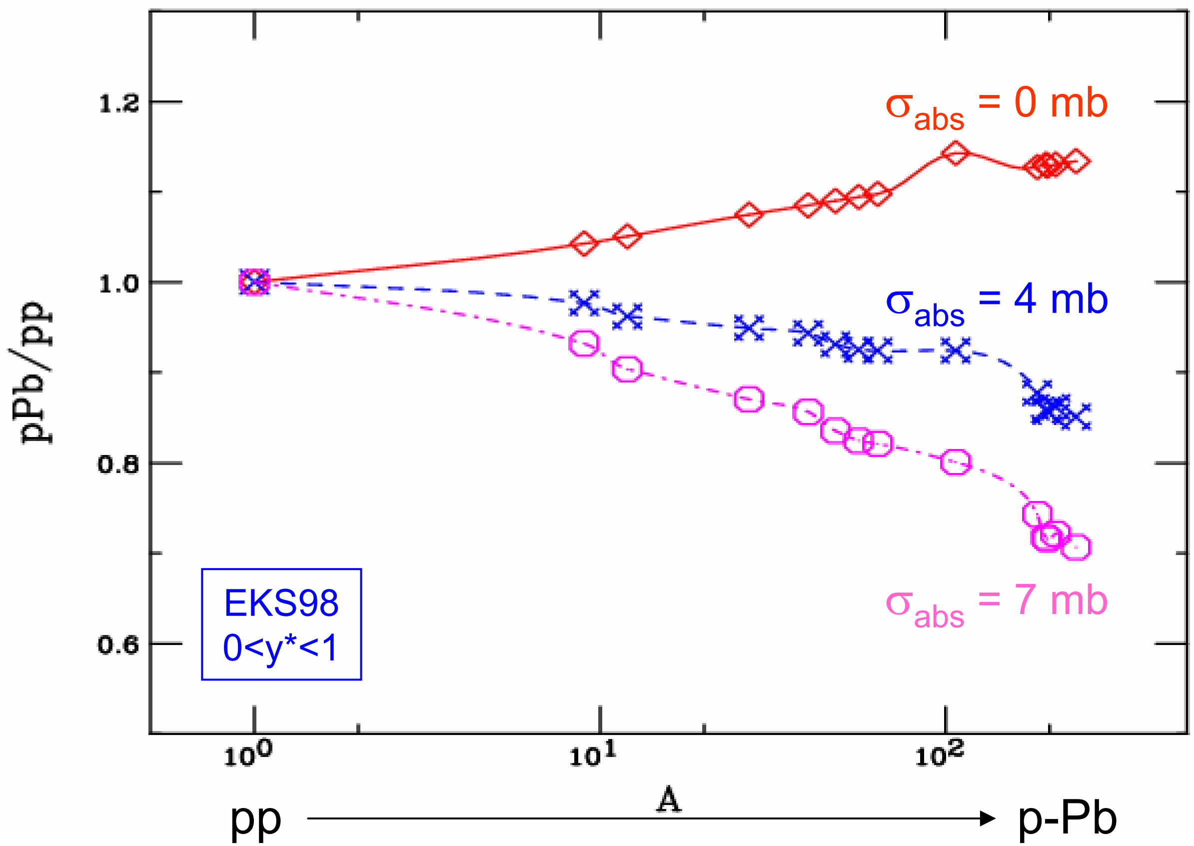
A2: In fact, I am sure that *it depends on energy*: it drops as the energy increases… This is shown in work I did last Summer with Ramona Vogt and Hermine Wöhri, not yet written up…

Remark 1:
The fitted value of σ_{abs} changes when we consider nuclear effects on the PDFs; the final state absorption *increases* to compensate the initial state gluon *anti*-shadowing with respect to the fits ignoring nuclear effects

Remark 2:
The absorption of the J/ψ must be a convolution of the absorptions of three physical states: the directly produced J/ψ and the feed-down sources ψ' and χ_c

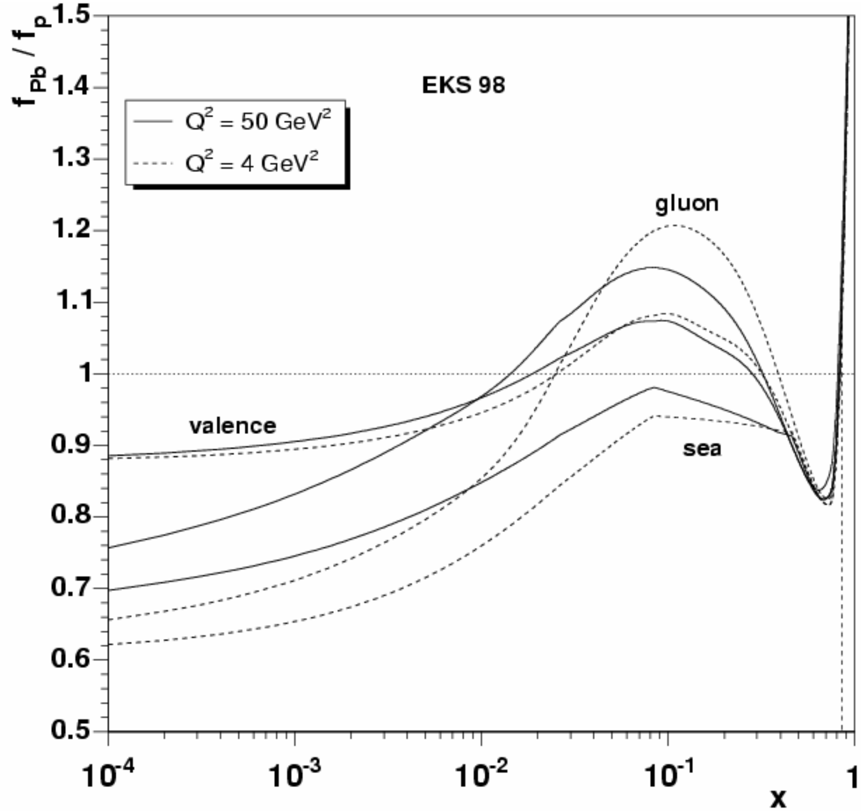
Initial state nuclear effects vs. final state absorption

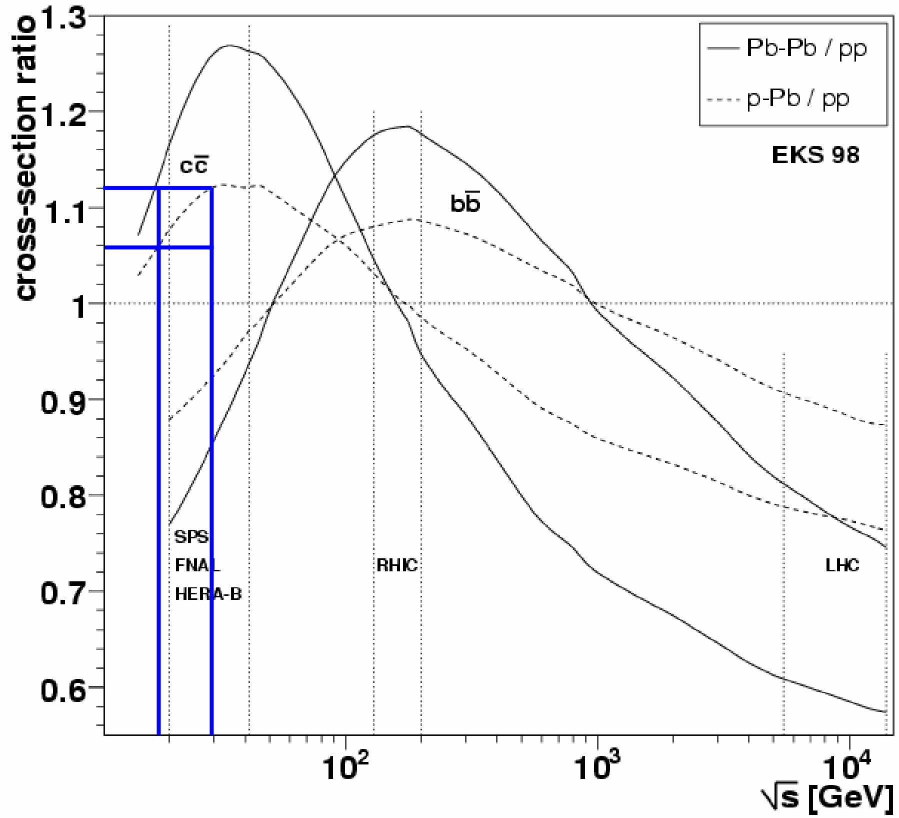
At SPS energies, the gluon anti-shadowing makes the J/ψ production cross section per nucleon *increase* from pp to p-Pb, if we ignore final state absorption



Calculations made by Ramona Vogt

Nuclear effects on the PDFs from p-A to Pb-Pb

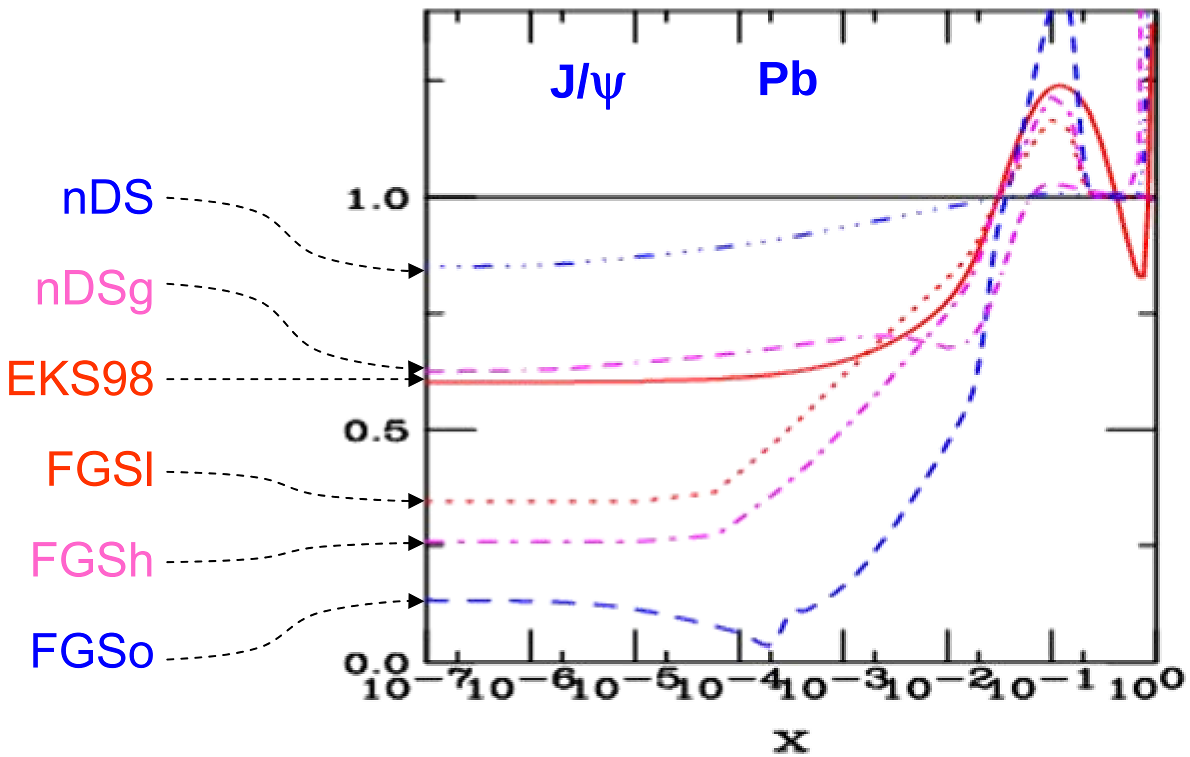




The EKS 98 model gives the same anti-shadowing effect for charm production in p-Pb collisions at 450 GeV as in Pb-Pb collisions at 158 GeV; by chance, no need to change σ_{abs} between p-A and Pb-Pb when nuclear PDFs are considered…
But if we would start from p-A data collected at 158 GeV, we would have to take into account that ~6% more J/ψ mesons are produced, per nucleon, in Pb-Pb than in p-Pb, in the initial state, before any nuclear absorption or QGP suppression

More parameterizations of Nuclear PDFs (too many…)

EKS98 is not the only available model of nuclear effects on the parton densities



DeFlorian and Sassot

Eskola, Kolhinen and Salgado

Frankfurt, Guzey and Strikman

The model of DeFlorian and Sassot does not “predict” *any* anti-shadowing for J/ψ production at SPS energies (!) while the FGSo parameterization predicts even more anti-shadowing than the EKS98 model does

Absorption of ψ' and χ_c states (feed-down sources of J/ψ)

Approximate radii of the J/ψ, ψ' and χ_c states:

r(J/ψ) = 0.25 fm;   r(ψ') = 2 × r(J/ψ);   r(χ_c) = 1.5 × r(J/ψ)

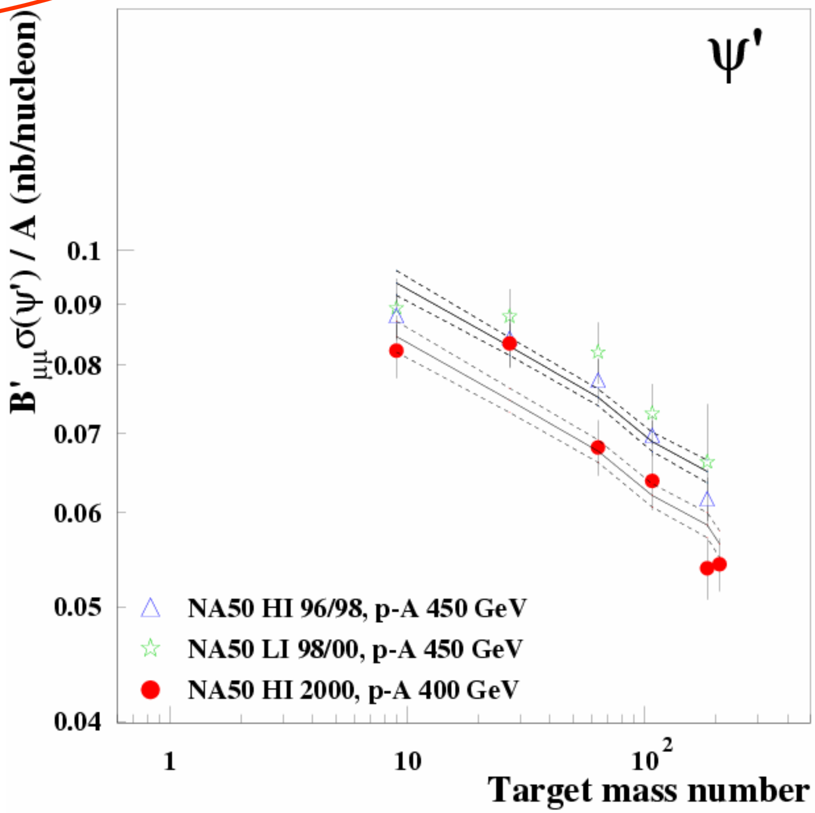
coincidence?

Geometrical cross-sections of the J/ψ, ψ' and χ_c states:

σ_{geom}(J/ψ) = 1.96 mb; σ_{geom}(ψ') = 7.85 mb; σ_{geom}(χ_c) = 4.42 mb

NA50 data: σ_{abs}(ψ') = 7.7 ± 0.9 mb

or σ_{abs}(ψ'/DY) = 8.3 ± 0.9 mb



(no nuclear effects considered here)

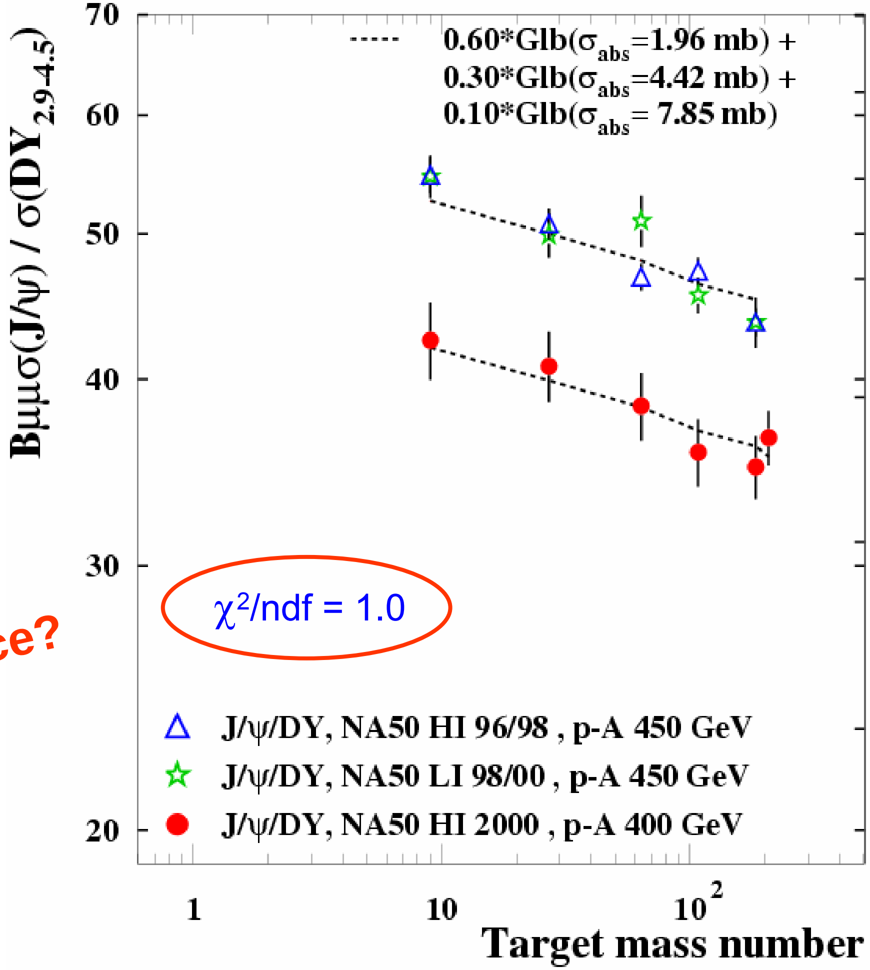
Influence on J/ψ absorption of feed-down from higher states

We can redo the Glauber calculations assuming 60% / 30% / 10% as the fractions of direct J/ψ production and feed-downs from χ_c and ψ' decays...

And *fixing* the σ_{abs} of each of these three states to their geometrical values

The result is perfectly equivalent to the calculation made with an *effective* σ_{abs}(J/ψ) left as a free parameter

coincidence?



(no nuclear effects considered here)

From qualitative hints to more detailed calculations

Let's express the σ_{abs} values of the three charmonium states in terms of the value of the directly produced 1S state, called "J" to distinguish it from the observed "J/ψ" (affected by feed-down), assuming that they scale with the square of their radii:

$$\sigma_{\rm abs}^{C} = \sigma_{\rm abs}^{J} \left(\frac{r_C}{r_J} \right)^2$$ with $r(\chi_c) / r(J) = 1.44$; $r(\psi') / r(J) = 1.8$

This is a guess… but it is better to assume an answer based on an educated guess than to ignore the existence of the question…

The generic survival probability for the state J (or ψ', or χ_c) is then given by:

$$S_{A,J}^{\rm abs}(\vec{b}, z') = \exp\left\{ -\int_{z'}^{\infty} dz \rho_A(\vec{b}, z) \sigma_{\rm abs}^{J}(z' - z) \right\}$$

And assuming 60% J (direct J/ψ), 30% χ_c feed-down and 10% ψ' feed down, the survival probability to be compared to the J/ψ data is calculated as:

$$S_{A}^{\rm abs}(\vec{b}, z') = 0.6 S_{A,J}^{\rm abs}(\vec{b}, z') + 0.3 S_{A,\chi_{cJ}}^{\rm abs}(\vec{b}, z') + 0.1 S_{A,\psi'}^{\rm abs}(\vec{b}, z')$$

Now we can fit the existing J/ψ *and* ψ' data with a single free parameter: $\sigma_{\rm abs}^{J}$

The J/ψ production cross section in p-A collisions

$$\frac{d\sigma_{pA}^{J}}{dy d^2b} = 2F_J K_{\rm th} \int dz' \int_{2m_c}^{2m_D} dm\, m \boxed{S_A^{\rm abs}(\vec{b}, z')} \Big\{ f_g^p(x_1, Q^2) F_g^A(x_2, Q^2, \vec{b}, z') \frac{\hat{\sigma_{gg}}(m^2)}{m^2}$$
$$+ \sum_{q=u,d,s} \Big[f_q^p(x_1, Q^2) F_{\bar{q}}^A(x_2, Q^2, \vec{b}, z') + f_{\bar{q}}^p(x_1, Q^2) F_q^A(x_2, Q^2, \vec{b}, z') \Big] \frac{\hat{\sigma_{q\bar{q}}}(m^2)}{m^2} \Big\}$$

F_J	fraction of charm-anticharm cross section below $2m_D$
K_{th}	K factor to match the magnitude of the LO and NLO cross sections
S_A^{abs}	survival probability for nuclear absorption
$f_j^p(x_1,Q^2)$	parton density in the proton; j = g, q, qbar
$F_j^A(x_2,Q^2,b,z')$	parton density in the nucleus

$$F_j^A(x_2, Q^2, \vec{b}, z') = \rho_A(\vec{b}, z') R_j(A, x_2, Q^2) f_j^p(x_2, Q^2)$$

$\rho_A(b,z')$	nucleon density in the nucleus
$R_j(A,x_2,Q^2)$	modification of the parton densities in the nucleus
x_1, x_2	parton momentum fractions

The calculations were done for four PDF sets (GRV LO 94, GRV LO 98, CTEQ6L and MRST2001LO), without and with nuclear effects, modeled by three different parameterizations (EKS98, nDS and nDSg)

J/ψ and ψ' cross sections in p-A collisions

From the measurements of **NA3**, **E866** and **HERA-B**, respectively at 200, 800 and 920 GeV, we calculated the mid-rapidity ratios between the heavy and light targets of J/ψ (and ψ') "per nucleon cross sections"

200 GeV : p-Pt / pp = 0.737 $\pm$ 0.026 for the J/ψ → 1 data point

800 GeV : p-W / p-Be = 0.8713 $\pm$ 0.0263 for the J/ψ
and 0.8032 $\pm$ 0.0274 for the ψ' } 2 data points

920 GeV : p-W / p-C = 0.903 $\pm$ 0.031 for the J/ψ → 1 data point

From the **NA50** measurements, at 400 and 450 GeV, we calculated the J/ψ and ψ' cross section ratios, between the heavy targets (Al, Cu, Ag, W, Pb) and Be

10 data points

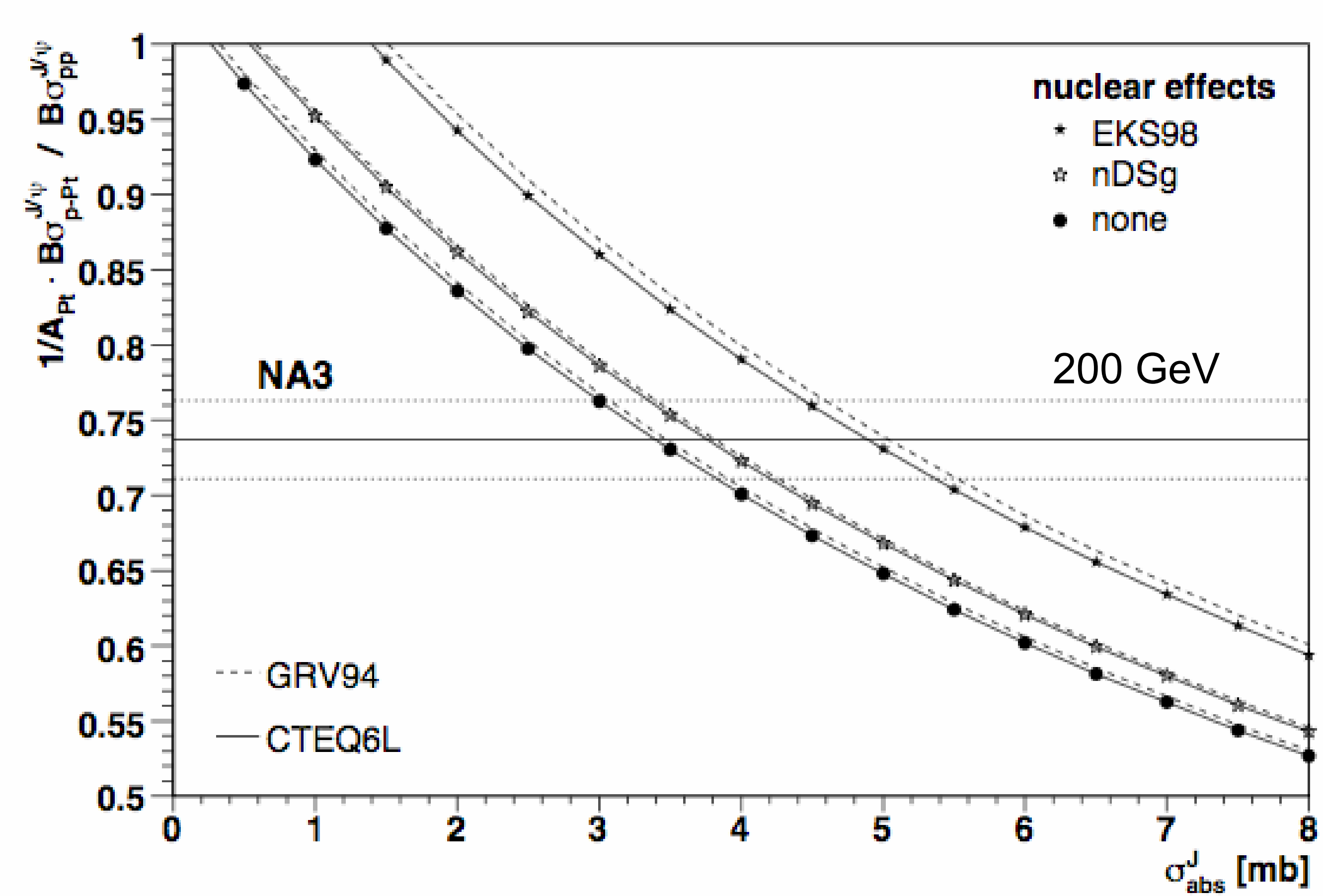
400	**J/ψ**	**ψ'**
Al/Be	0.936±0.029	1.015±0.071
Cu/Be	0.907±0.028	0.829±0.063
Ag/Be	0.847±0.026	0.776±0.060
W/Be	0.804±0.025	0.655±0.052
Pb/Be	0.788±0.024	0.660±0.049

8 data points

450	**J/ψ**	**ψ'**
Al/Be	0.965±0.041	0.967±0.051
Cu/Be	0.934±0.037	0.893±0.044
Ag/Be	0.866±0.034	0.799±0.038
W/Be	0.792±0.036	0.706±0.039

Data versus calculations

For each energy and target, the calculations were made with several N-PDFs and for σ_{abs} values between 0.0 and 8.0 mb, in steps of 0.5 mb
Comparing these calculated curves with the measured data points we derive the "best" σ_{abs} value, and its uncertainty

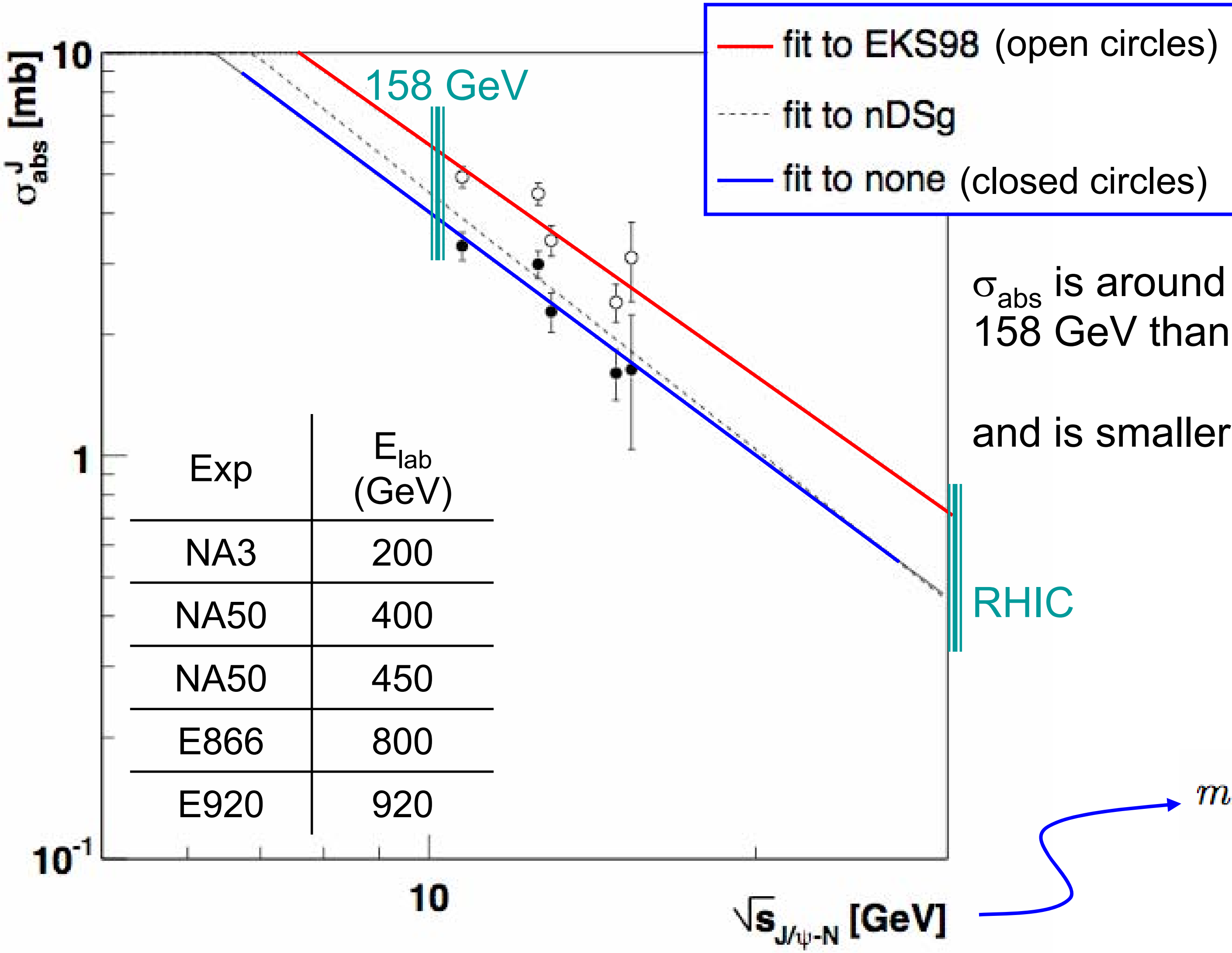


σ_{abs} (mb)	
4.88±0.29	EKS98
3.75±0.27	nDSg
3.39±0.26	none

Almost no dependence on the PDF set used but results change very much with the nuclear effects model assumed

Significant drop of σ_{abs} with collision energy

The J/ψ and ψ’ absorption, at mid-rapidity, becomes weaker with increasing collision energy, at least among the fixed-target measurements



Exp	E_{lab} (GeV)
NA3	200
NA50	400
NA50	450
E866	800
E920	920

σ_{abs} is around 50% higher at 158 GeV than at 400-450 GeV

and is smaller than 1 mb at RHIC

$$m_\psi \cdot \sqrt{1 + \left(\sqrt{s} \,/\, \sqrt{m_\psi}\,\right)}$$

Summary and outlook (homework assignments…)

The J/ψ and ψ' final state "normal nuclear absorption", determined by p-A data, shows a negligible sensitivity to the PDF set used but is significantly affected by the nuclear effects model assumed: none, EKS98, nDSg

The latest PDF sets are mature, constrained by a wealth of data (DIS, DY, etc), while the nuclear effects on the gluon densities have not yet been measured…

$\Rightarrow$ Crucial to measure open charm nuclear dependence, in p-A, versus p_T and y

All existing J/ψ and ψ' p-A data can be very well described by Glauber calculations using one single σ_{abs} parameter, that of the directly produced 1S ccbar state, with the χ_c and ψ' values fixed by geometrical scaling and the "observed J/ψ" value fixed from the feed-down fractions

The fitted σ_{abs} values show a significant energy dependence from NA3 to HERA-B energies: the value extrapolated to 158 GeV is larger than currently assumed !

$\Rightarrow$ Crucial to re-evaluate the Pb-Pb and In-In suppression patterns, for the J/ψ and for the ψ', with increased σ_{abs} and with N-PDFs : how much of the "anomalous suppression" will survive?