20 years of J/ψ suppression at the CERN SPS

Results from experiments NA38, NA51 and NA50

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Acknowledgements

Thanks to the work of the 150 members of the
NA38, NA51 and NA50 Collaborations
and, in particular,
to the enthusiasm and endless efforts of
the students and colleagues
who have been struggling for years
to discover the mysteries, understand the problems
and overcome the countless traps
hidden in our data
...

The questions

A critical review of past results

- Is there still any *anomalous* J/ψ suppression ?

  1. What is *normal* suppression ?
  2. What is *abnormal* suppression ?
  3. Was there ever an *anomaly* ?
  4. Is the *anomaly* still there ?

- The *anomaly* (if any): updated features

The proposal and original experimental goal

Experiment NA38 was proposed in March 1985:

- to study thermal dimuon production in O-induced reactions
- using the NA10 muon spectrometer
- without even mentioning J/ψ production

From the abstract of the proposal :

Shuryak (1980), Kajantie and Miettinen (1982), Hwa and Kajantie (1985), McLerran and Toimela (1985)

....Thermal dimuons are expected to be emitted from a quark-gluon plasma at a reasonable rate in the 1-3 GeV/c^2 transverse mass range, and to differ from ordinary dimuons by their p_t and rapidity distributions....

And then...came Matsui and Satz (1986)

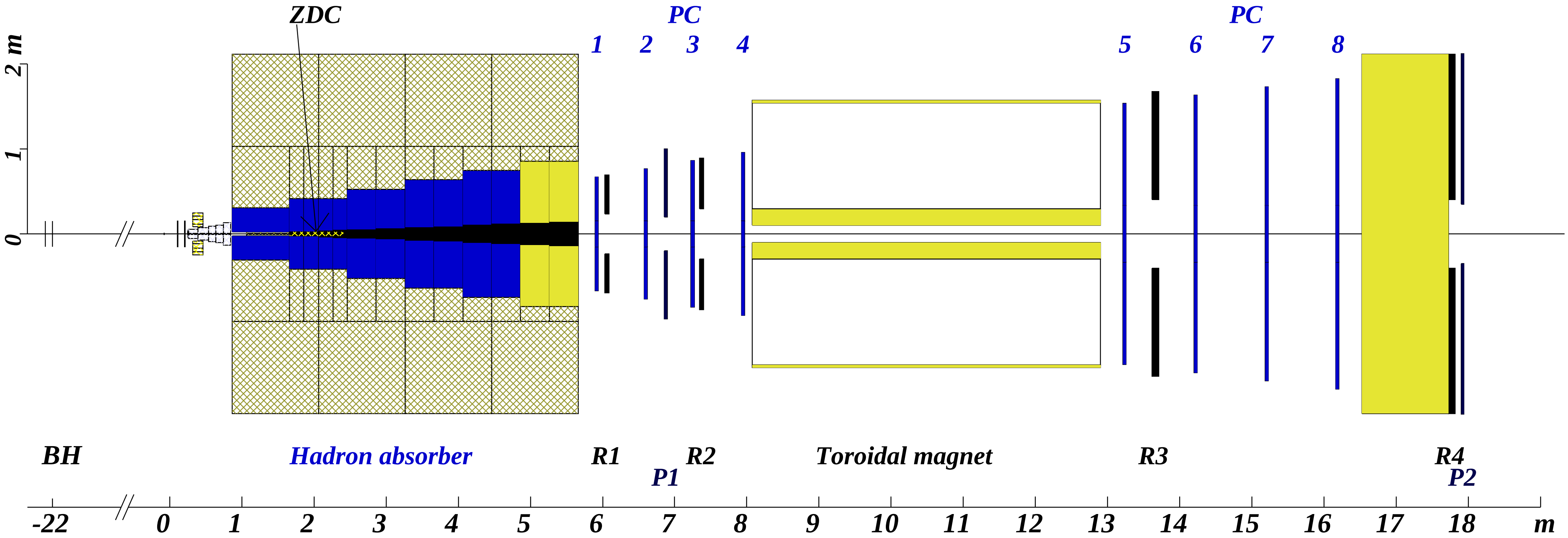
From their abstract (Phys. Lett. B 178 (1986) 416.):

If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region.../... It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation.

Had this prediction (not postdiction) not existed:

- NA38/50 might have found....thermal dimuons (??????)
- "comovers" would probably still be unknown particles
- PHENIX (RHIC) and ALICE would look quite different and...
- Many theoreticians might have 50% less (or quite different) publications

The NA10/38/51/50...60 muon spectrometer



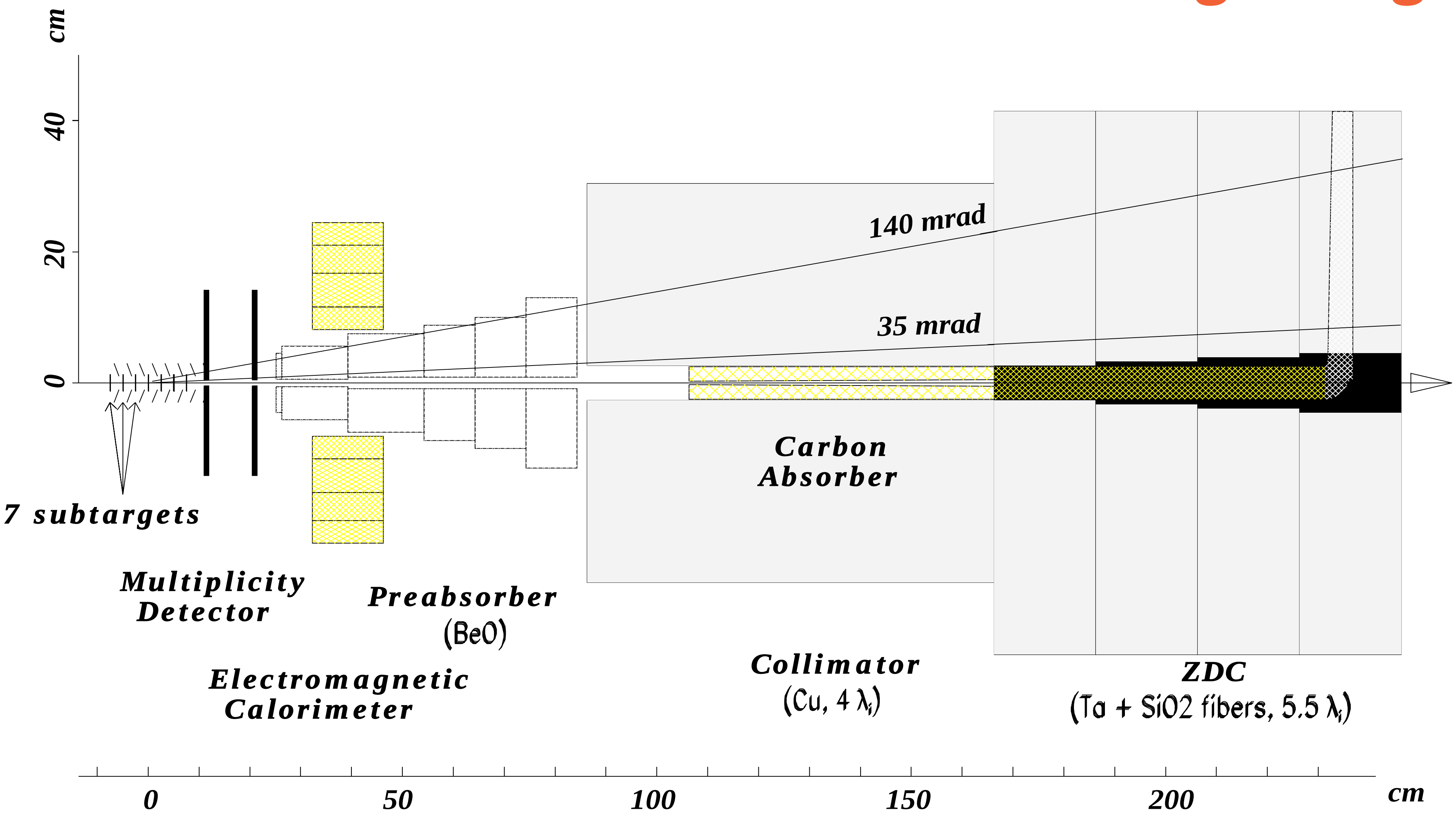
Kinematical coverage: • $0 \leq y_{cm} \leq 1 \quad (2.92 \leq y_{lab} \leq 3.92)$

• $|\cos\theta_{CS}| < 0.5$

Acceptances: • $Acc(J/\psi) = 12.5\%$

• $Acc(DY) = 13.8\%$ (for $2.9 < M_{\mu\mu} < 4.5\ GeV/c^2$)

The NA50 target region



Acceptance: $1.9 \leq \eta_{lab} \leq 4.2$ *for the Multiplicity detector*

$1.1 \leq \eta_{lab} \leq 2.3$ *for the EM Calorimeter*

$\eta_{lab} \geq 6.3$ *for the Zero Degree Calorimeter*

The muon pair mass spectrum

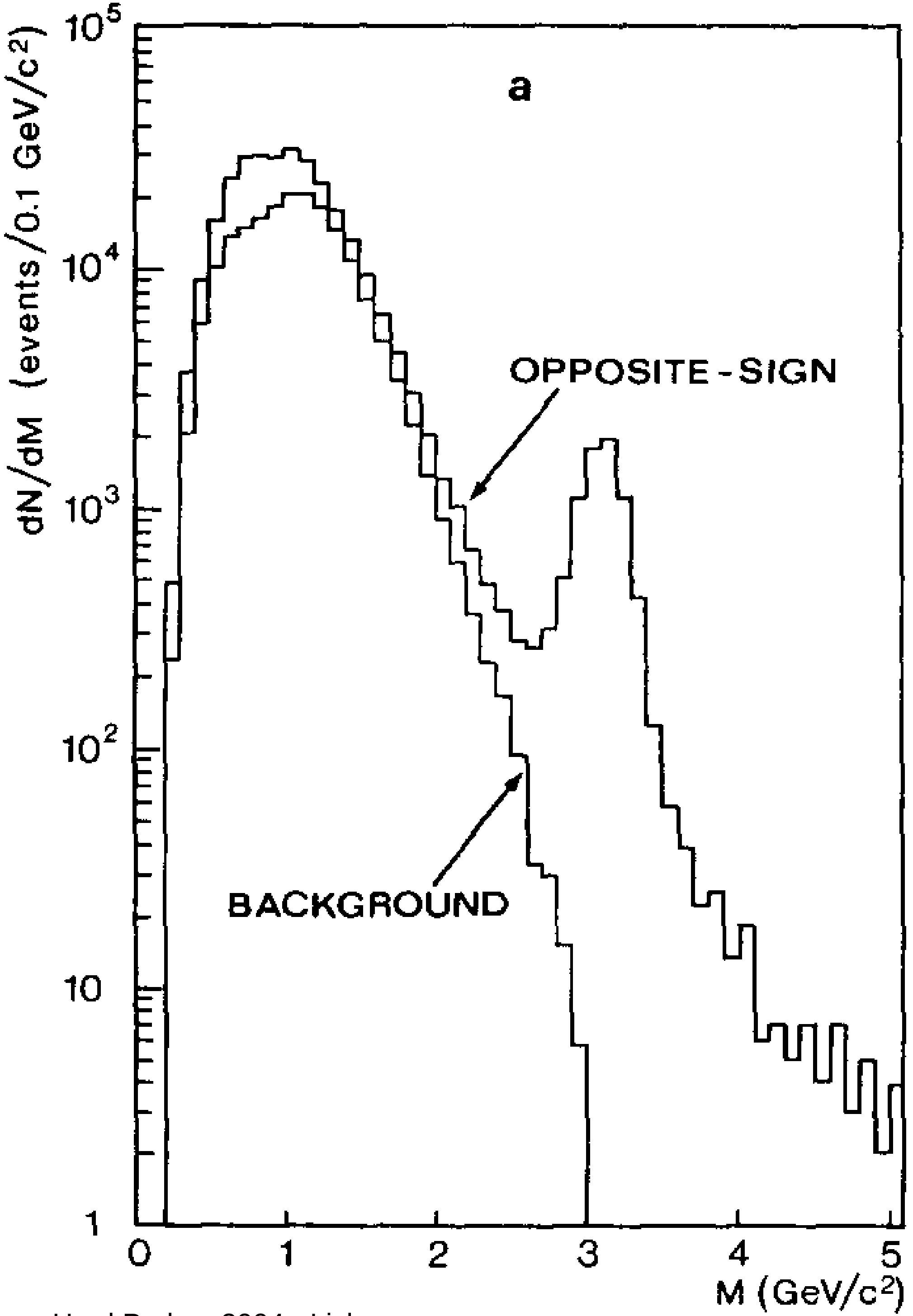
In the beginning...there was no Drell-Yan.

and there was no anticipated normal behaviour either

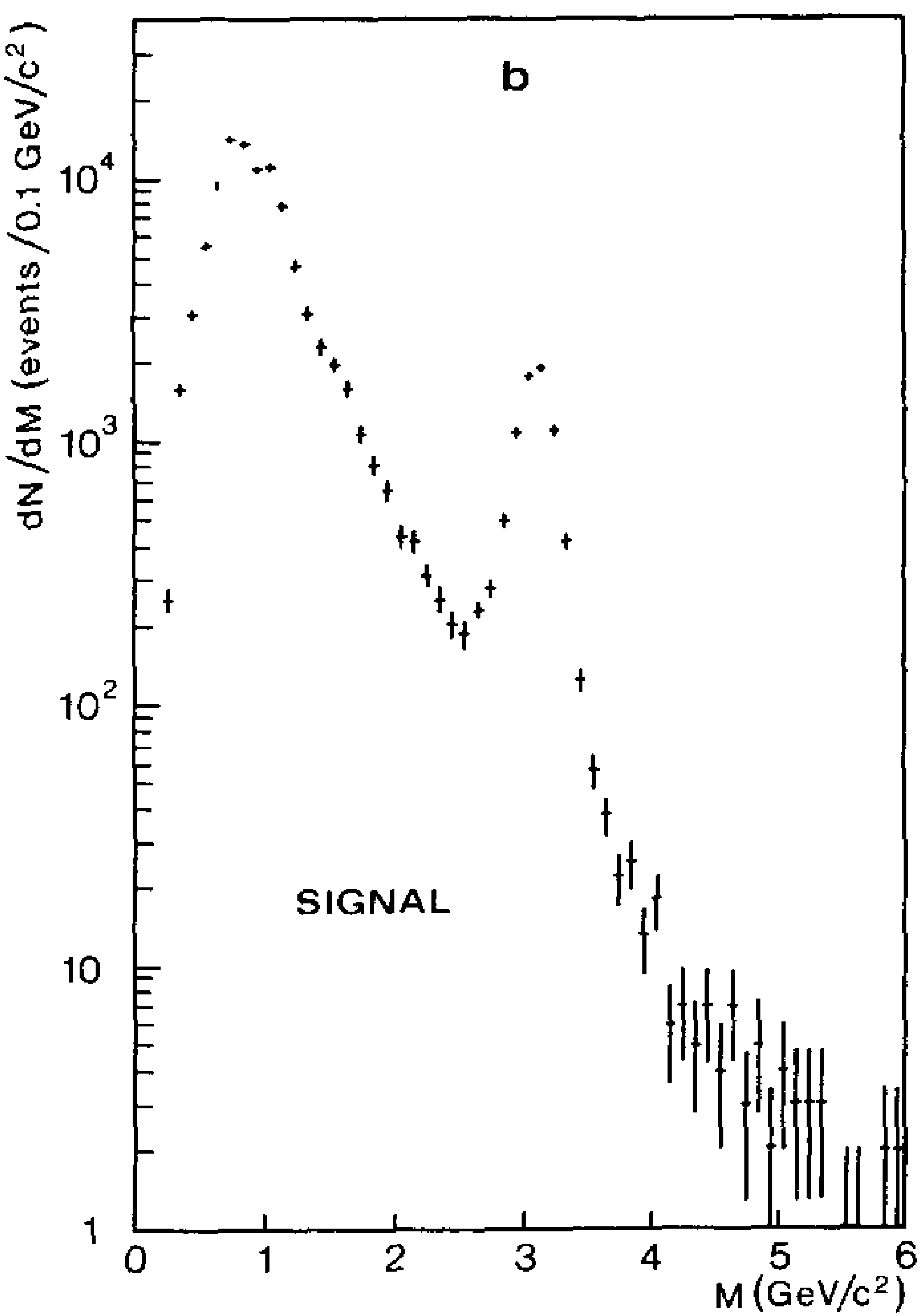
And we had to live without....

as shown in the next slides
for our first muon pair mass spectrum
in 200 GeV O-U reactions

Was O-U at 200 GeV abnormal ???



a
OPPOSITE - SIGN
BACKGROUND
dN/dM (events/0.1 GeV/c²)
M (GeV/c²)



b
SIGNAL
dN/dM (events/0.1 GeV/c²)
M (GeV/c²)

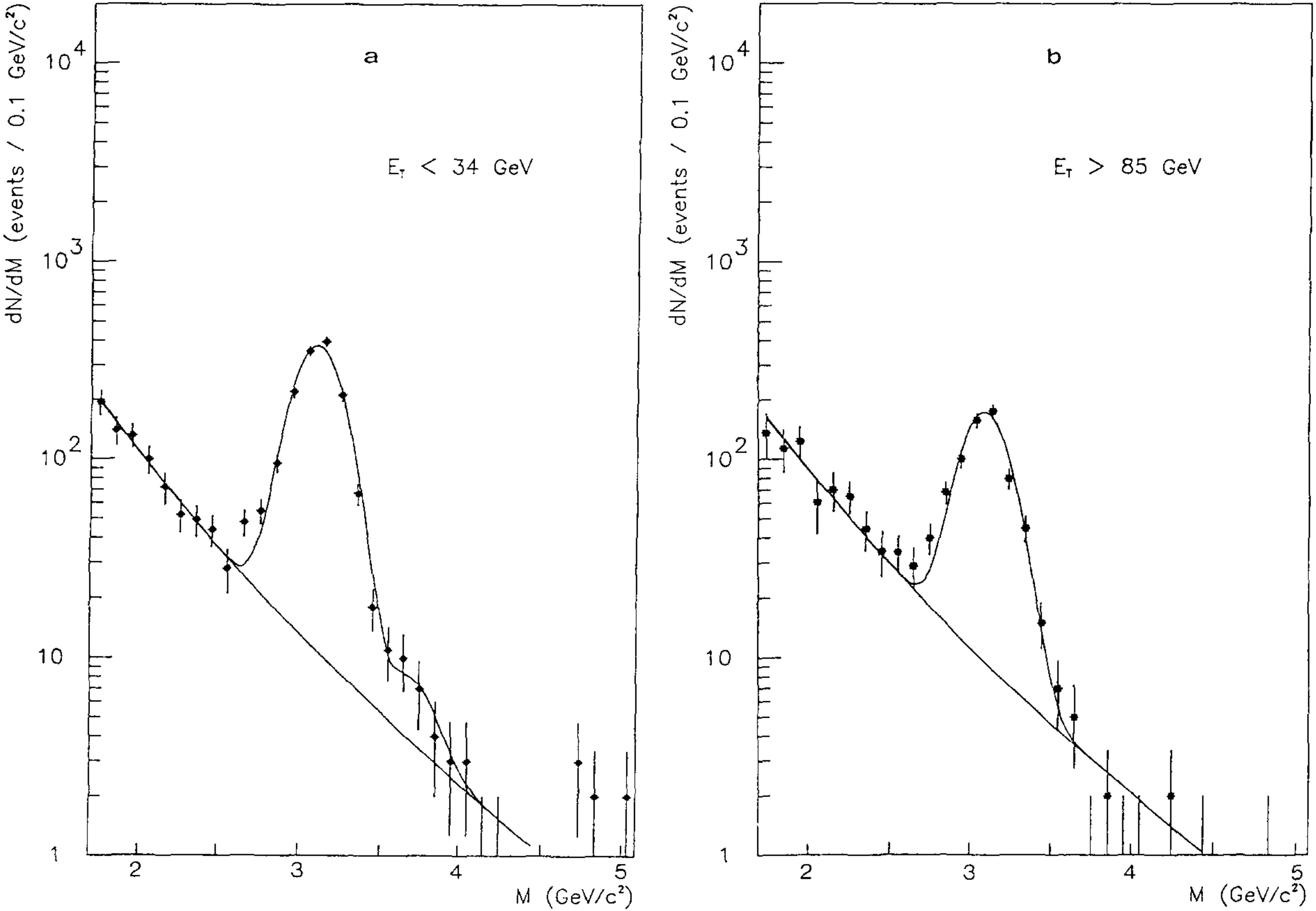


Fig. 5. Mass spectrum and fit of the signal muon pairs in two different E_T bins: $E_T < 34$ GeV (a) and $E_T > 85$ GeV (b).

NA38 first results:

O-U at 200 GeV/c:

$$S = \frac{J/\psi}{continuum \quad (2.7\text{--}3.5)}$$

Factor 2 suppression....
....explained with...
...comovers

but...including:
- "normal" nucl. absorption
- IMR charm-like excess

(fit starts from 1.7 (or 2.1) GeV/c^2 !)

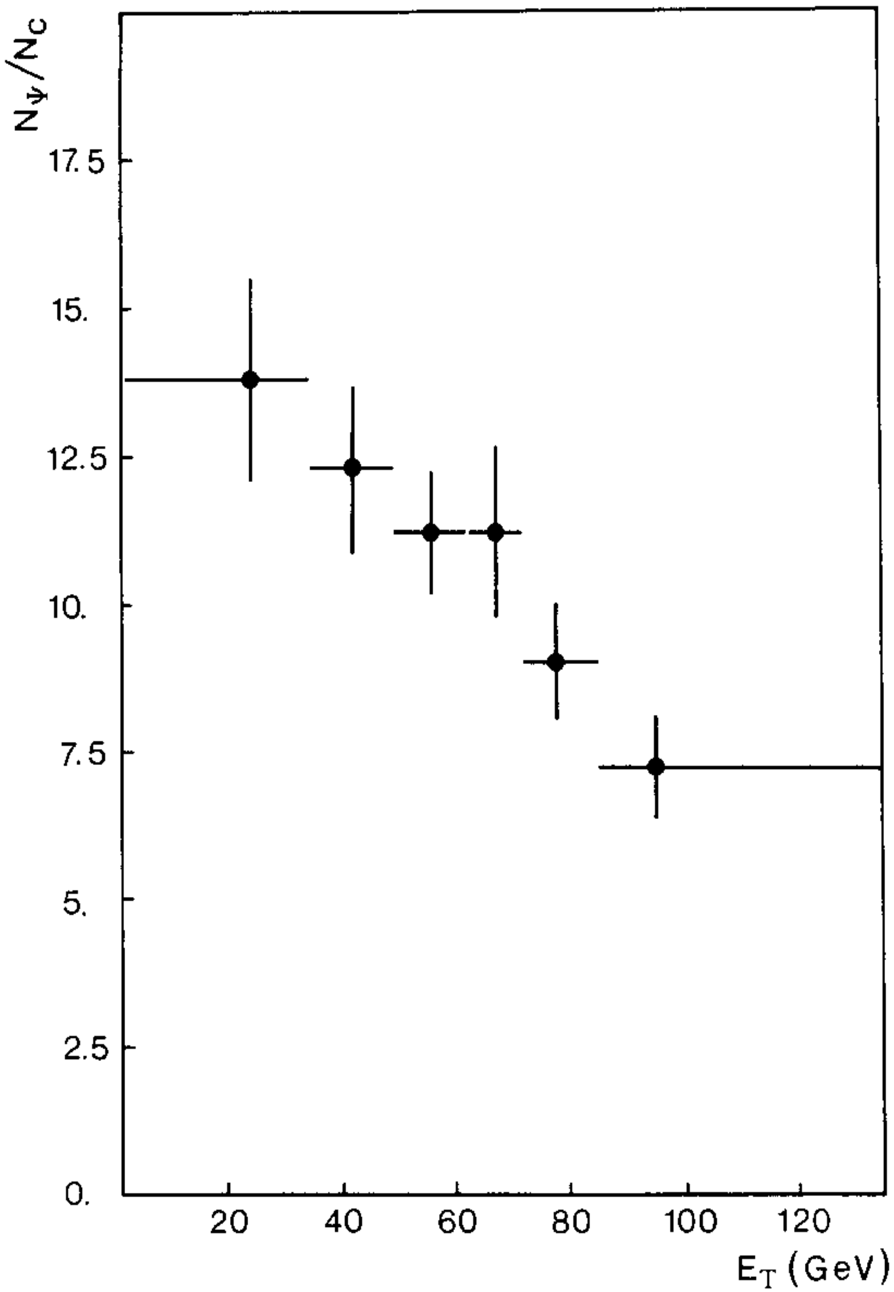
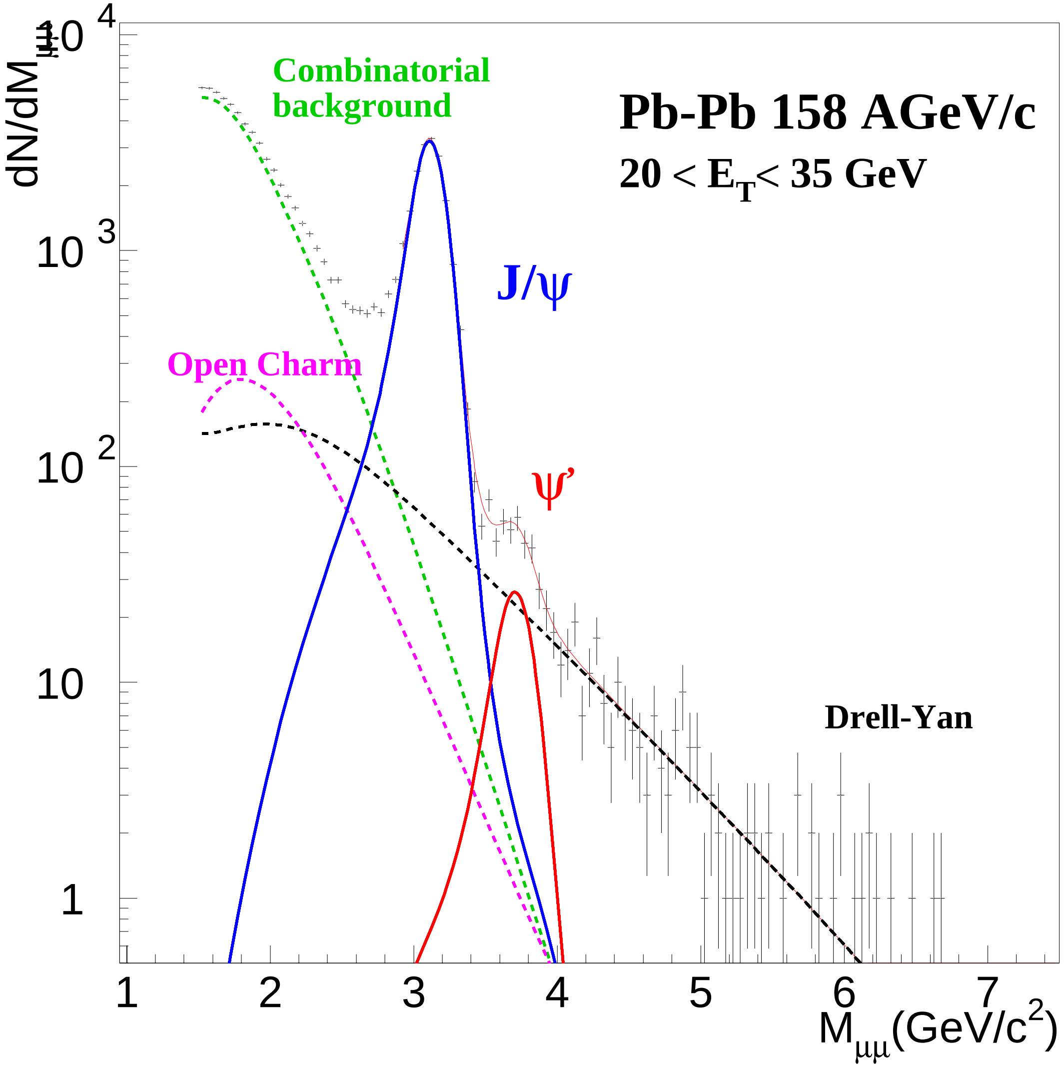


Fig. 6. The evolution of $S = N_\Psi/N_c$ as a function of E_T.

The muon pair mass spectrum...15 years later

$$\frac{dN^{+-}}{dM} = A_{J/\psi}\frac{dN_{J/\psi}}{dM} + A_{\psi'}\frac{dN_{\psi'}}{dM} + A_{DY}\frac{dN_{DY}}{dM} + A_{D\bar{D}}\frac{dN_{D\bar{D}}}{dM} + \frac{dN_{BG}}{dM}$$



- J/ψ, ψ', DY and $D\bar{D}$ shapes are generated by Monte Carlo and reconstructed as real data
- J/ψ and ψ' mass resolutions are ~100 MeV
- Combinatorial background, mostly from pion and kaon decays, is extracted from measured like-sign pairs
- Final fit performed for M $>$ 2.9 GeV/c^2

Why do we use Drell-Yan ?

Drell-Yan (muon pairs) is now a well known computable process, proportional to the nr. of elementary nucleon-nucleon collisions, with the following priceless advantages:

- identical experimental biases
- identical inefficiencies
- identical selection criteria
- identical cuts

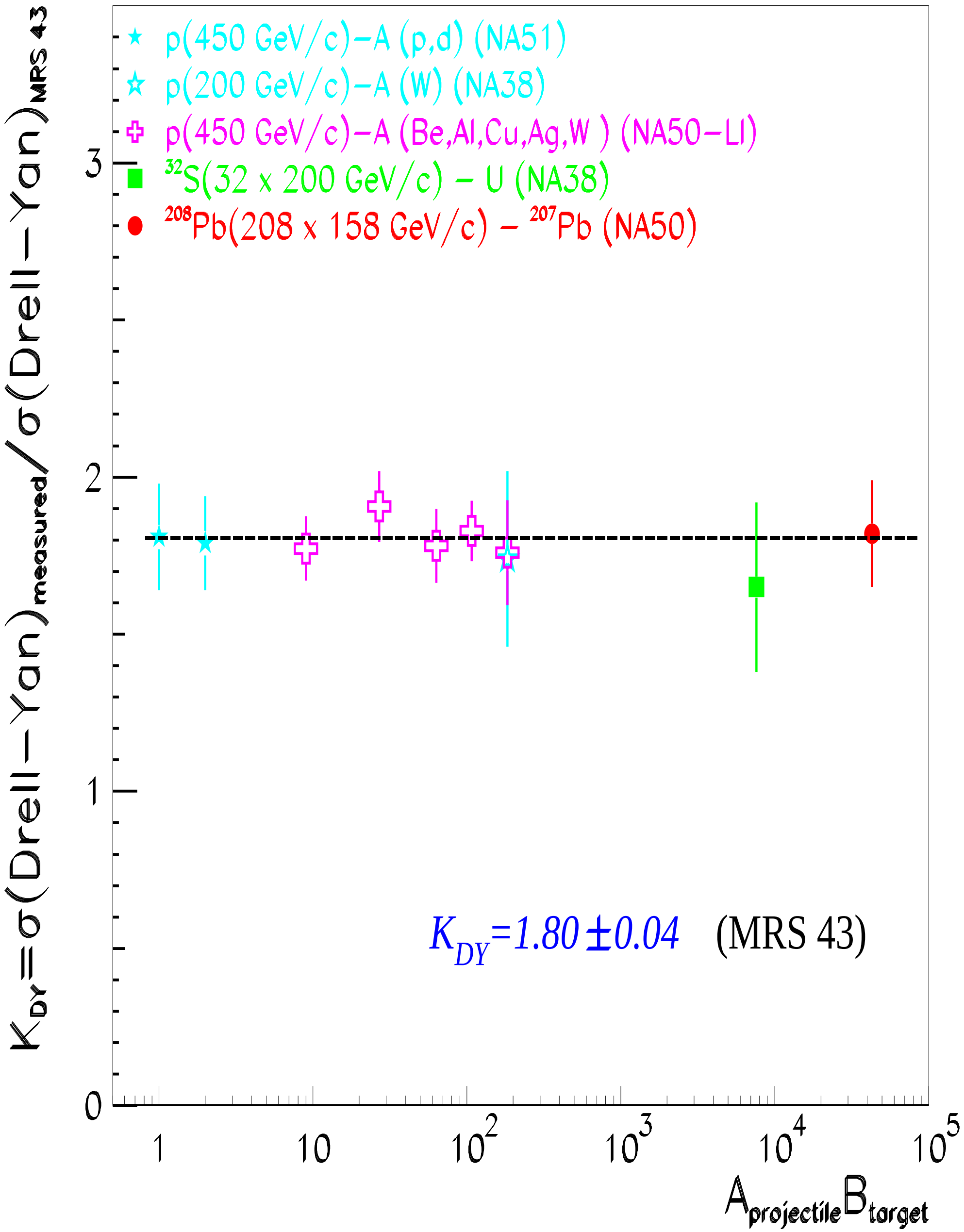
} as J/ψ

Therefore, the corrections cancel out in the ratio

$$\boxed{\frac{\sigma(J/\psi)}{\sigma(DY)}}$$

which is, moreover, insensitive to normalization factors/uncertainties.

Advantages and drawbacks of Drell-Yan



- Under control
- σ(DY) is proportional to the number of nucleon-nucleon collisions from pp up to Pb–Pb (in our phase space domain, at least)
- Ideal to compare different reactions
- Needs "isospin" correction
- DY Statistics always small and $<<< J/\psi$ statistics

Why do we use a reference curve ?

The question:

- Is J/ψ abnormally suppressed in nucleus-nucleus collisions and, in particular, in Pb-Pb collisions at 158 GeV/nucl. ?

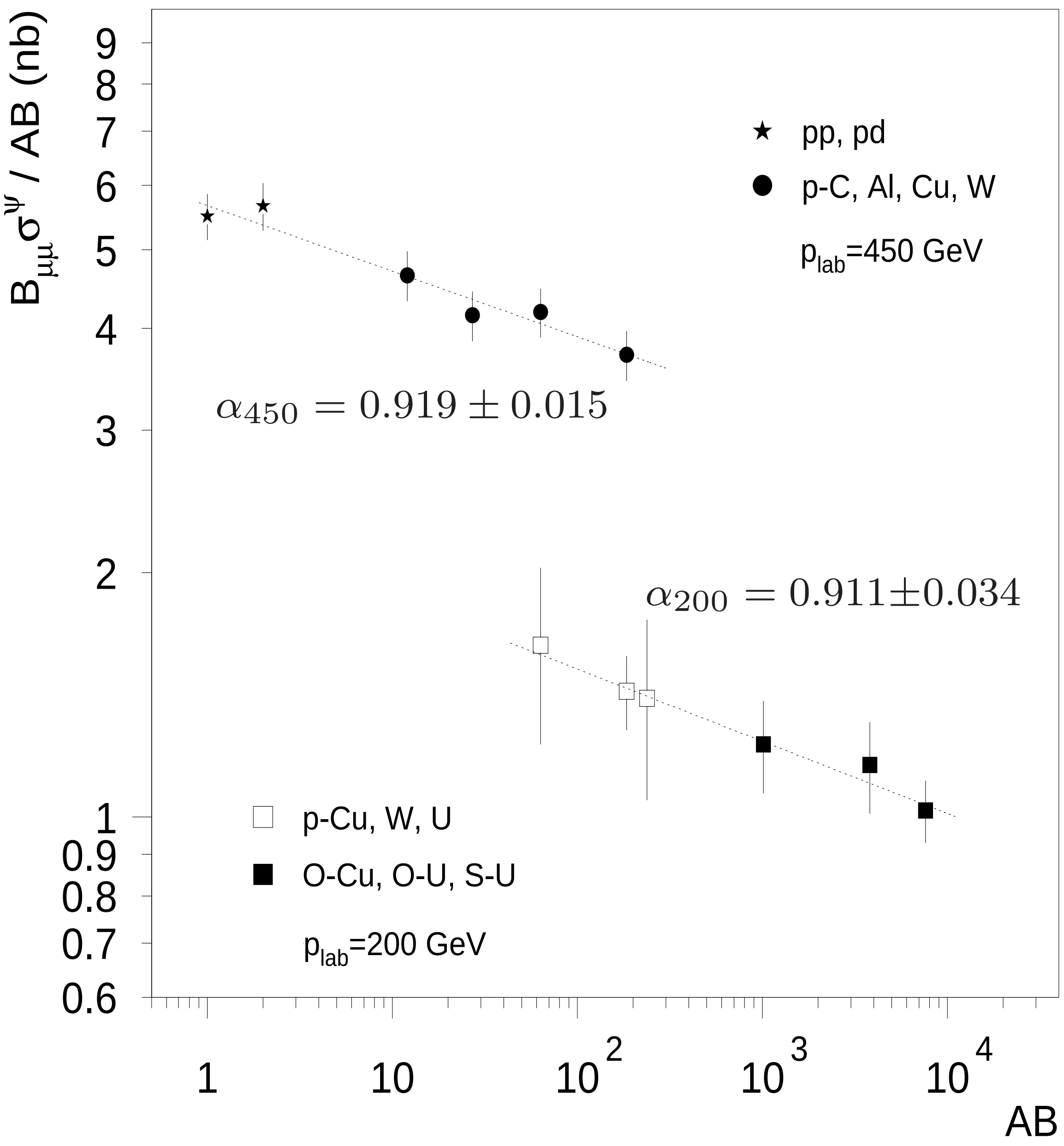
The standard:

- How is it suppressed in
p-A collisions at 158 GeV/nucl. (normally, by definition) ?

Our only "available tool"
(while waiting for NA60 direct measurement at 158 GeV)

- A set of: p-A measurements at 450/400 GeV
  p-A and A-B measurements at 200 GeV

J/ψ normal nuclear absorption: published (I)

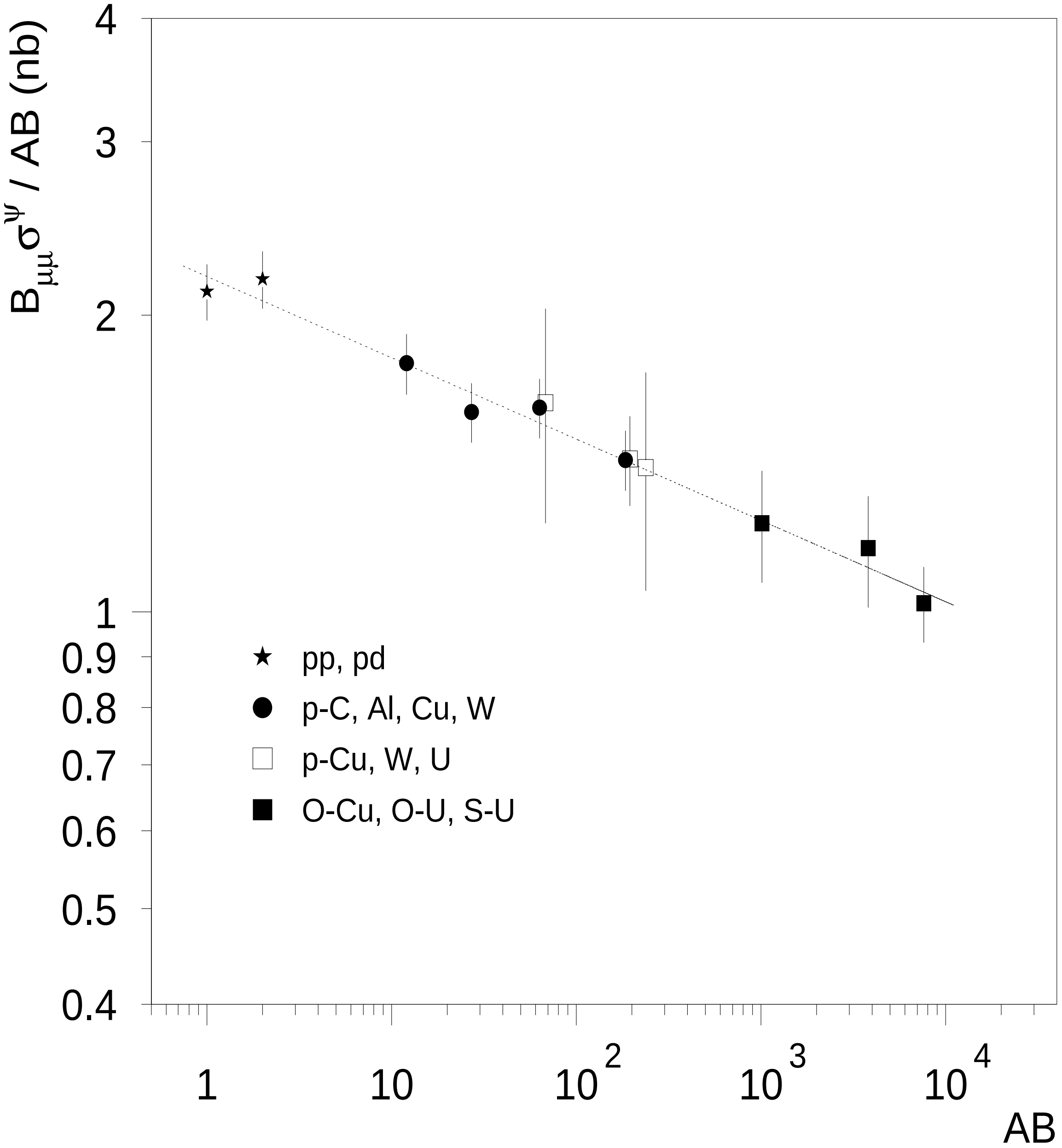


- *p-A 450 GeV from NA38: 1st p-A sample (1987)*
- *pp, p-d 450 GeV from NA51: collected in 1992*
- *p-A 200 GeV secondary beam collected in 1987/88 and*
- *A-B 200 GeV (1986/1990)*
- *Separate fit of* $B_{\mu\mu}\sigma_0(A \times B)^{\alpha-1}$. α_{450} *and* α_{200} *compatible*
- *"Simultaneous" fit (same* α*)* $\rightarrow$ *rescaling 450* $\searrow$ *200 GeV*

BUT samples collected under significantly different experimental conditions.

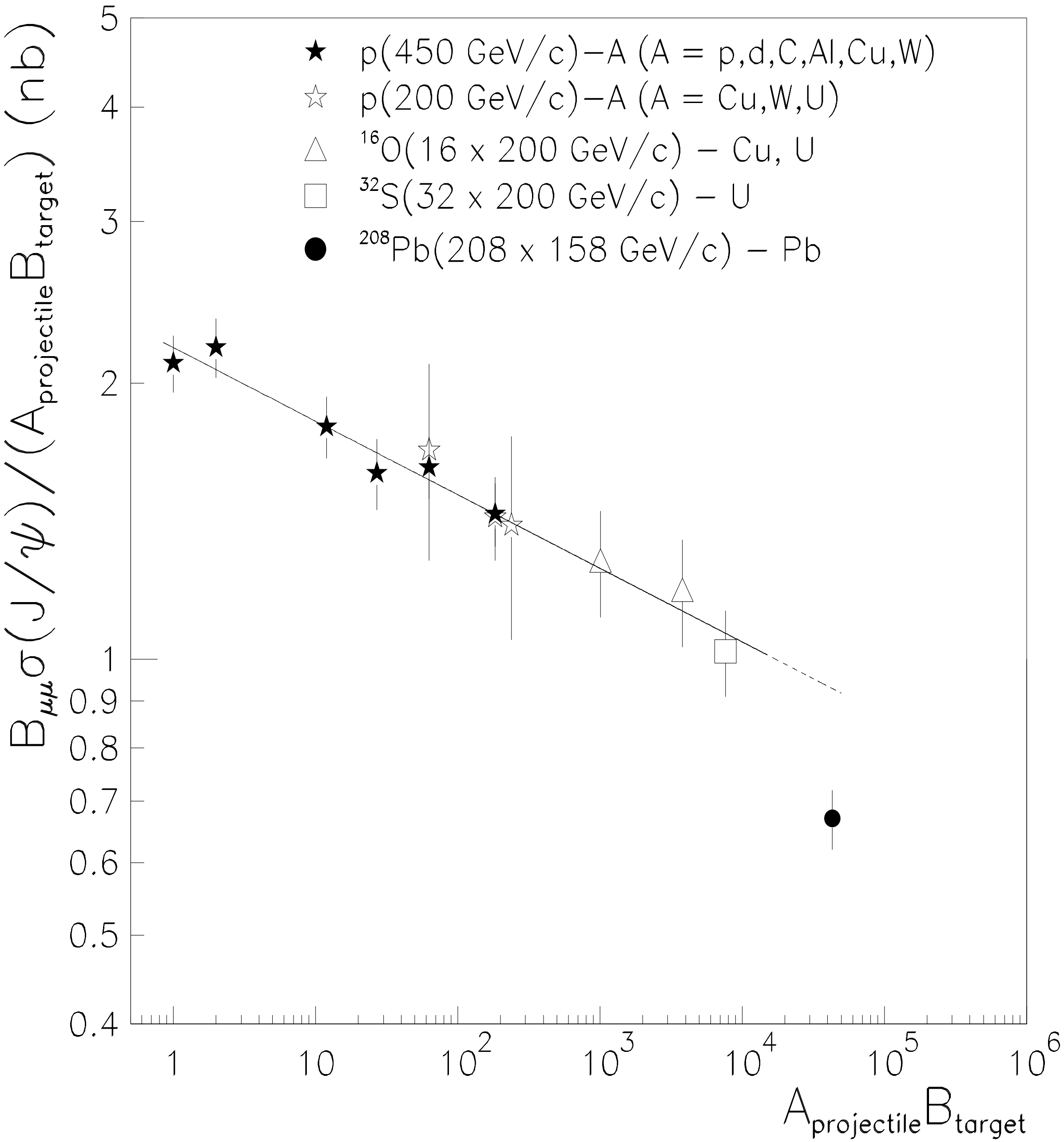
Beware when combining !!!

J/ψ *normal nuclear absorption: published(II)*



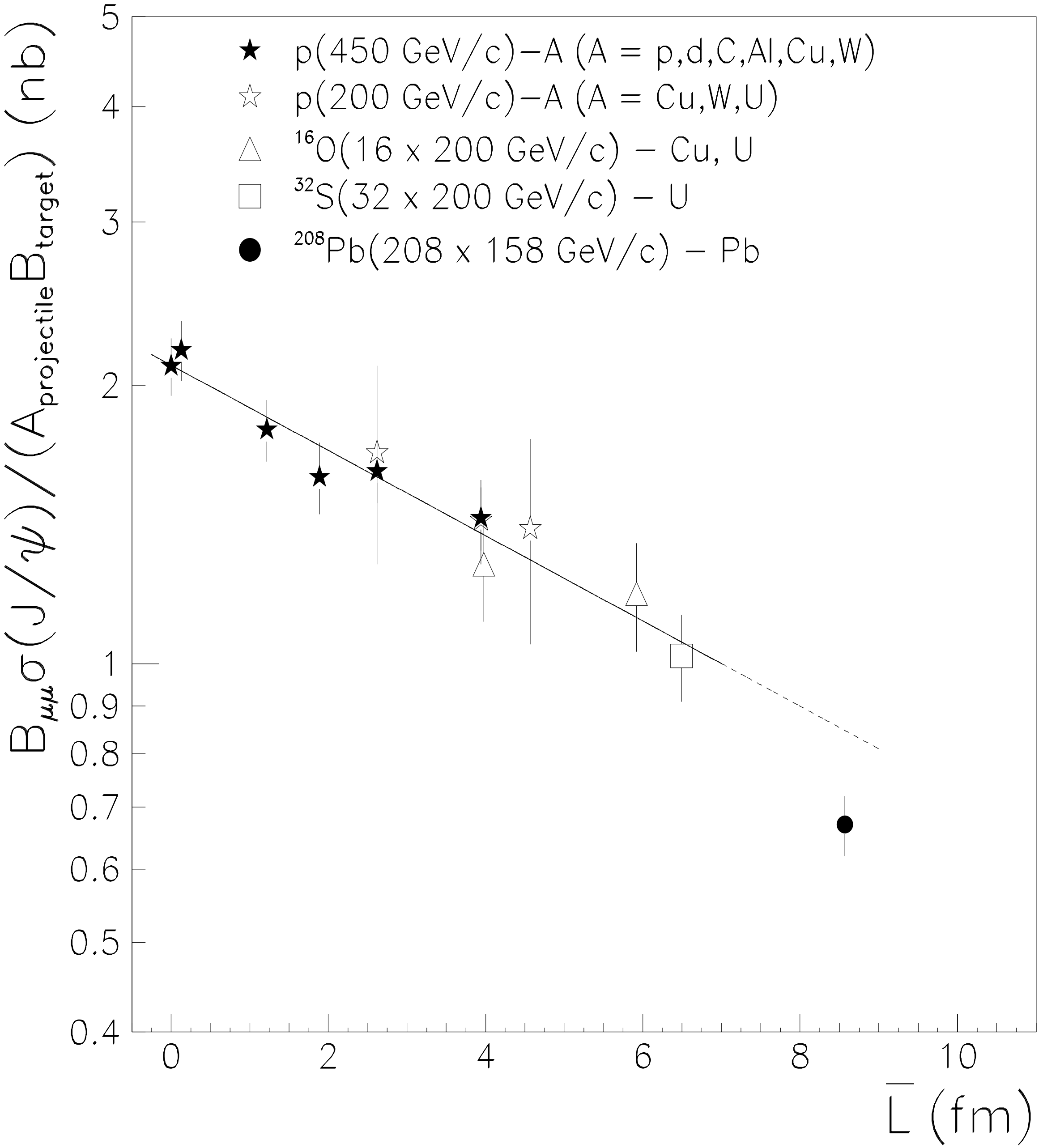
- *Simultaneous fit leads to* $\alpha_{sim} = 0.918 \pm 0.015$ *and to the rescaling factor 450 GeV ↘ 200 GeV*
- *After rescaling to 200 GeV*
- *Apparently normal behaviour : from pp up to S-U*

J/ψ absorption in Pb-Pb: published (I)



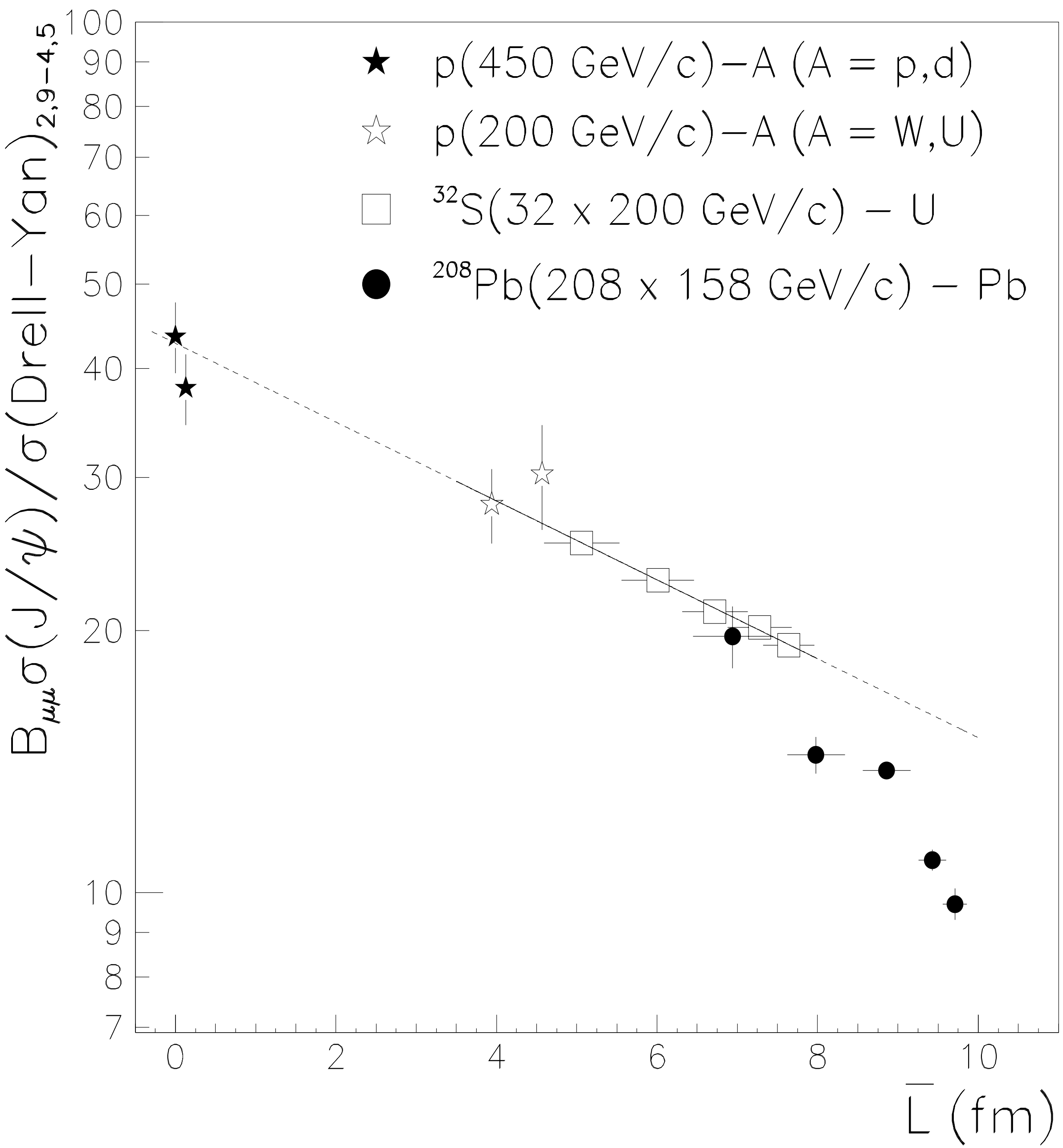
- All data including
  450 GeV reference data
  rescaled to 200 GeV
- Shows:
  difference between
  "normal" absorption
  and Pb-Pb behaviour
- leads to:
  Anomalous J/ψ suppression
  in Pb-Pb interactions
  (PLB (1997))

J/ψ absorption in Pb-Pb: published (II)



- Same as previous plot
- Data plotted vs. $\bar{\mathrm{L}}$
- leads,
  by simple exponential fit
  $\sigma_\psi(AB) \propto (AB)exp(-\rho_0\sigma_{abs}\bar{L})$
  to: $\sigma_{abs} = 6.2 \pm 1.1$ mb or
  $\simeq 6.9 \pm 1.2$ mb (Glauber)
- allows centrality study
  of J/ψ suppression

J/ψ absorption in Pb-Pb: published (III)



- J/ψ / Drell-Yan ratio
- Pb-Pb data rescaled to 200 GeV
- Reference only from available 200 GeV samples with Drell-Yan events
- $\sigma_{abs} = 7.1 \pm 3.0$ mb (in Pb96 paper, unpublished S-U had significantly underestimated errors)
- first pattern of centrality dependence of J/ψ suppression

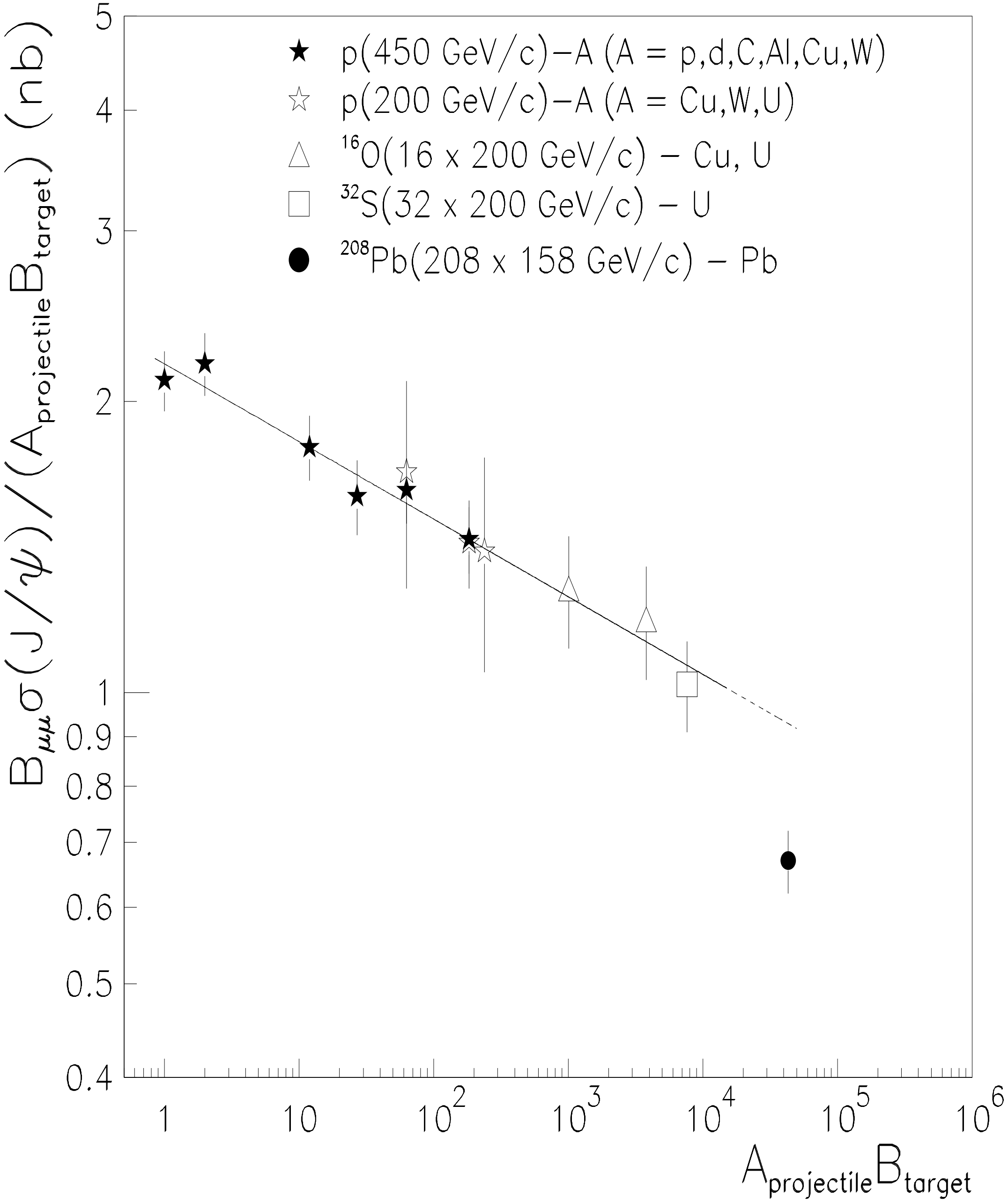
The J/ψ suppression pattern in Pb-Pb

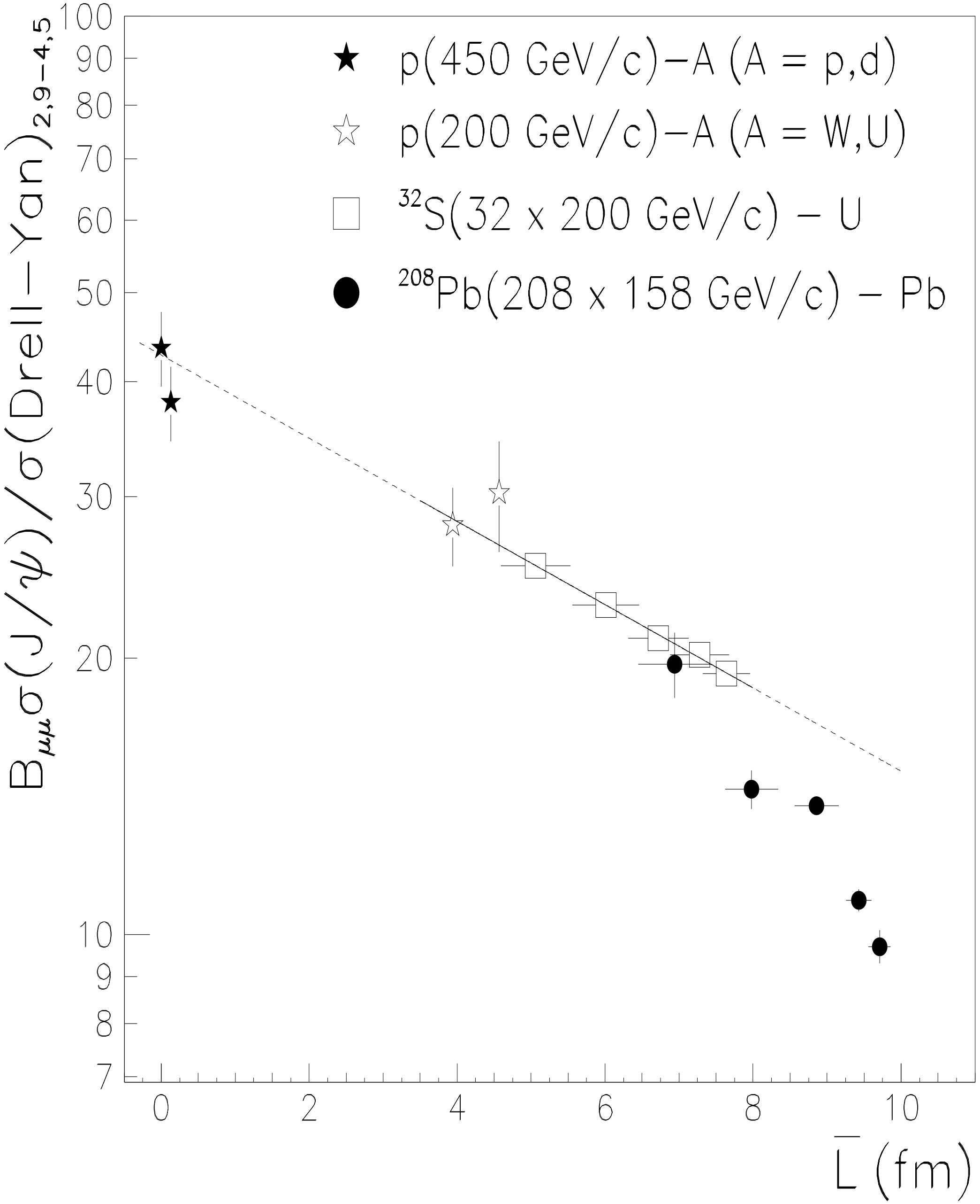
The data samples

Data samples in Pb–Pb collisions

data sample	Interaction length (L_T/λ_I)	number of sub-targets	beam intensity (ions/burst)	number of J/ψ	number of ψ'	Published
1995	17% λ_I	7 (in air)	3×10^7	50 000	–	Yes
1996	30% λ_I	7 (in air)	5×10^7	190 000	–	Yes
1998	7% λ_I	1 (in air)	5.5×10^7	49 000	380	Partially
2000	9.5% λ_I	1 (in vacuum)	7×10^7	129 000	905	No

Looking backwards to 1995... (I)





Looking backwards to 1995...(I bis)

We want (much) more data !

incident intensity limited by pileup

$\Longrightarrow$ naive (most clever ?) solution:

- increase total target length

which led to...

Looking backwards to 1996...(I)

1996 data sample was the largest one (190 000 J/ψ)
thanks to 7 (2 $\times$ 1mm + 5 $\times$ 2mm thick) targets
but:

- Pb-air interactions difficult to identify:

  $\Longrightarrow$ potential Pb-air contamination, centrality & mass smearing $\}$ peripheral reactions

- For peripheral Pb-Pb, sub-target inefficiently identified:

  $\Longrightarrow$ centrality & mass smearing $\}$ peripheral reactions

- Target of 12 mm total length induces reinteractions

  $\Longrightarrow$ centrality smearing $\}$ central reactions

The standard and "minimum bias" methods

- In the "standard method", for each centrality bin, the fit of the dimuon mass spectrum $\Longrightarrow$

$$\boxed{\frac{B_{\mu\mu}\sigma_{J/\psi}}{\sigma_{DY}}}$$

- In the "minimum bias" method, for each centrality bin,
the dimuon mass spectrum $\Longrightarrow$ the number of J/ψ
the "minimum bias" spectrum $\Longrightarrow$ the number of MB events
the number of DY events is then *computed* from:

$$\boxed{(dN/dE_T)_{DY^*} = (dN/dE_T)^{exp}_{MB} \times \frac{(dN/dE_T)^{th}_{DY}}{(dN/dE_T)^{th}_{MB}}}$$

and allows to compute:

$$\boxed{\frac{B_{\mu\mu}\sigma_{J/\psi}}{(\sigma_{DY})^*}}$$

The "MB" method: drawbacks and advantages

Advantage: Huge sample of "minimum bias" events

$\Longrightarrow$ tiny statistical errors

BUT:

unnormalized sample and:

- NON identical experimental biases
- NON identical inefficiencies
- NON identical selection criteria
- NON identical cuts

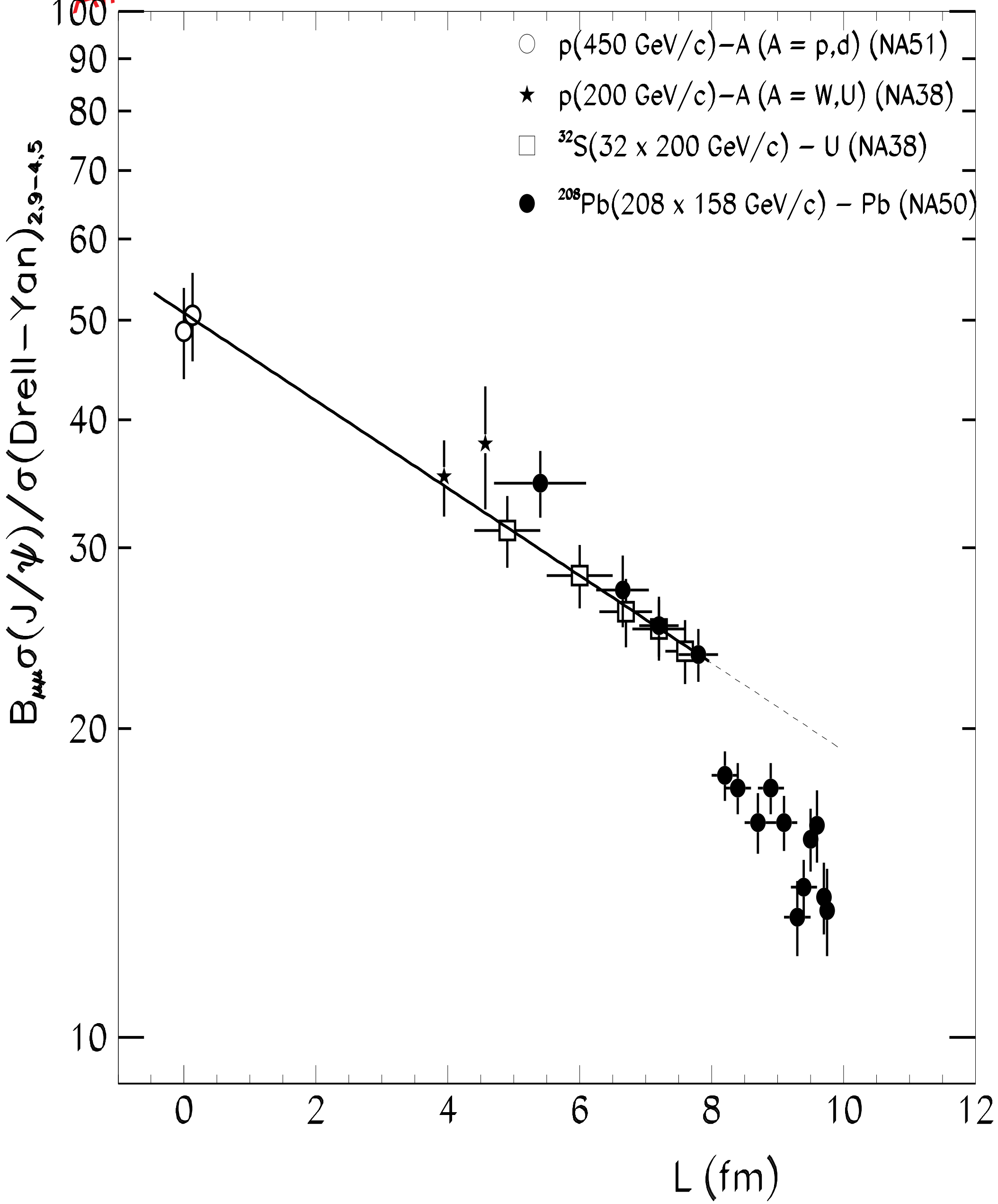
} as J/ψ

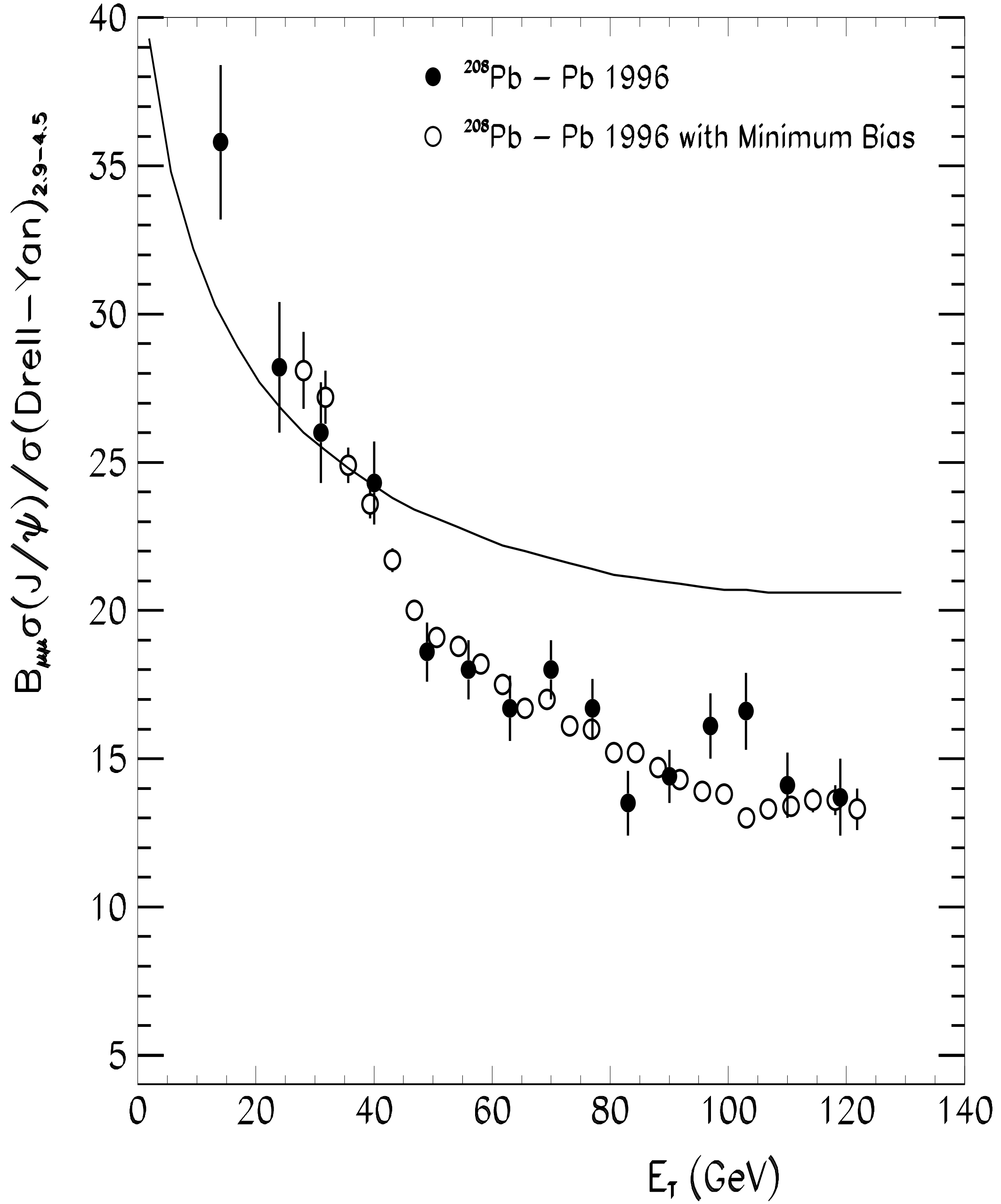
Therefore, the corrections DO NOT cancel out in the ratio

$$\boxed{\frac{\sigma(J/\psi)}{\sigma(DY)^*}}$$

Looking backwards to 1996... (II)

All data rescaled at 158 GeV !





Looking backwards to 1998...(I)

1998 data sample intended to clarify doubts from 1996 thanks to 1 single (3mm thick) target (still not in vacuum) but:

- Pb-air interactions poorly identified:

  $\Longrightarrow$ contamination by Pb-air } peripheral reactions

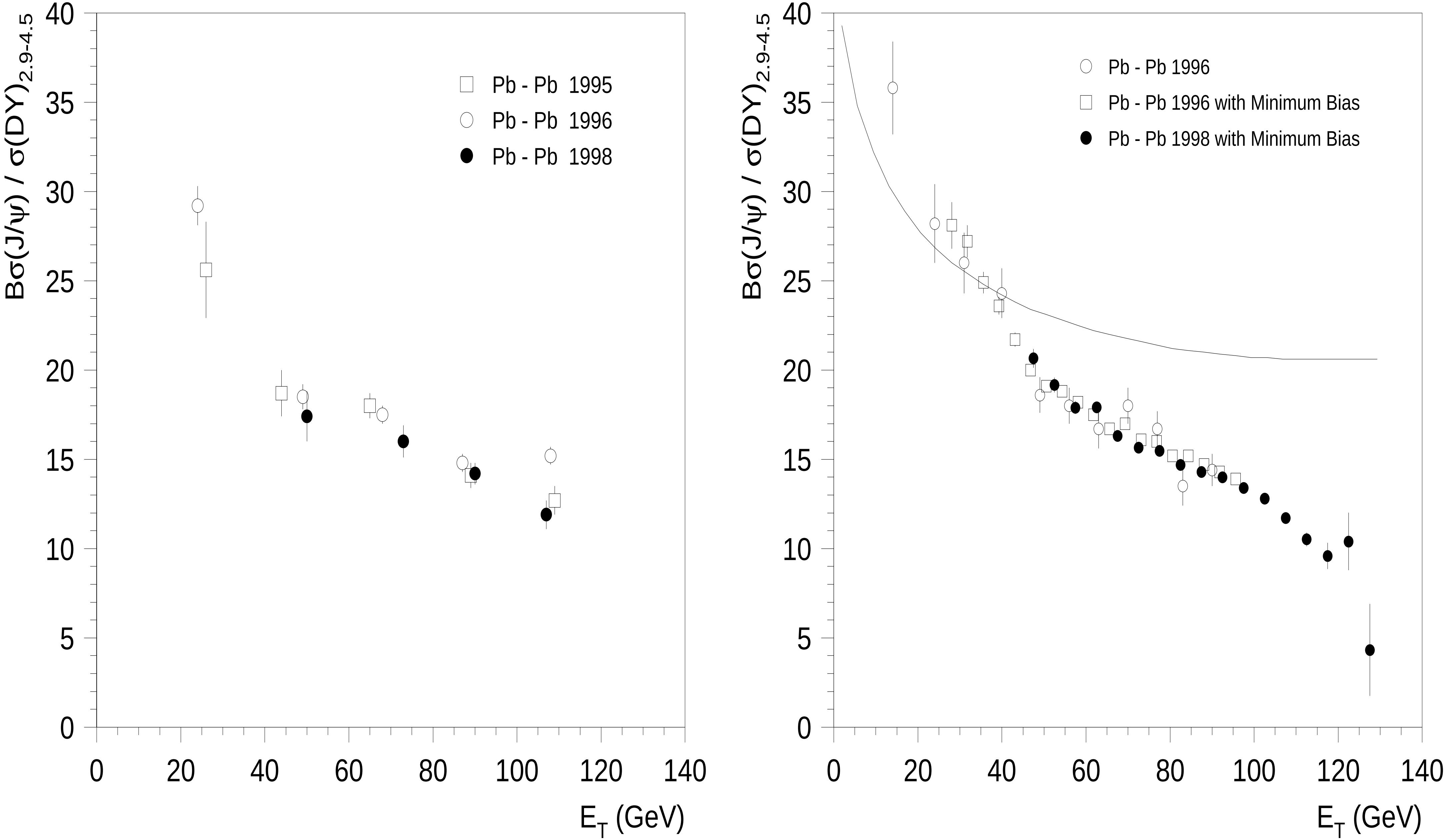
- Only 3mm thick target:

  $\Longrightarrow$ Pb-Air/Pb-Pb up wrt 1996 } peripheral reactions

- Only 3mm thick target

  $\Longrightarrow$ "almost" no reinteractions } central reactions

Looking backwards to 1998... (II)



The year 2000 data

In 2000, and from the lessons from the previous samples:

1 *single (4mm thick)* target *in vacuum*

Use of tracking in MD to identify primary interaction vertex:

- ***No Pb-air contamination in peripheral interactions***
- ***Efficient primary vertex ”on target” identification***
- ***No reinteractions in central collisions***

$\Longrightarrow$ The cleanest of all our samples !!!

MD tracking technique, later extended to 1998

$\Longrightarrow$ 1998 and, in particular, peripheral of 1998 reanalyzed with only small Pb-Air contamination

The year 2000 analysis

Standard analysis with:

- adapted minimal cuts (allowed by clean sample)
- use of GRVLO94 (practically same result with GRVLO98)
- improved J/ψ line shape

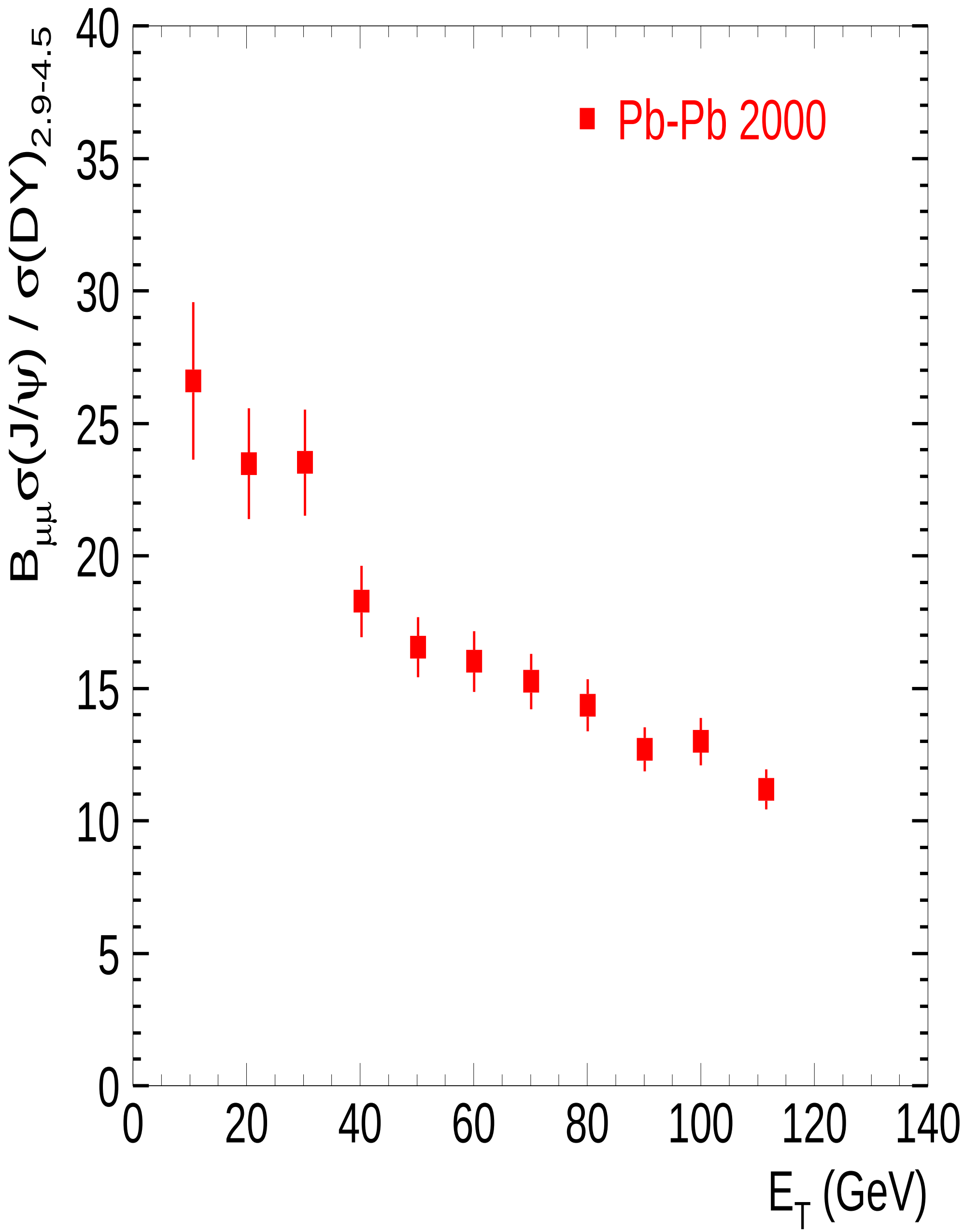
Affect only absolute normalization, not pattern shape itself

Special effort on the reference curve: Normal Nuclear Absorption

- Based on all our recent p-A data at 450 and 400 GeV and using at 200 GeV
  - either, as in the past, both p-A and S-U data
  - or, newest development:
    ONLY p-A data

NEW !

The year 2000 results (I)



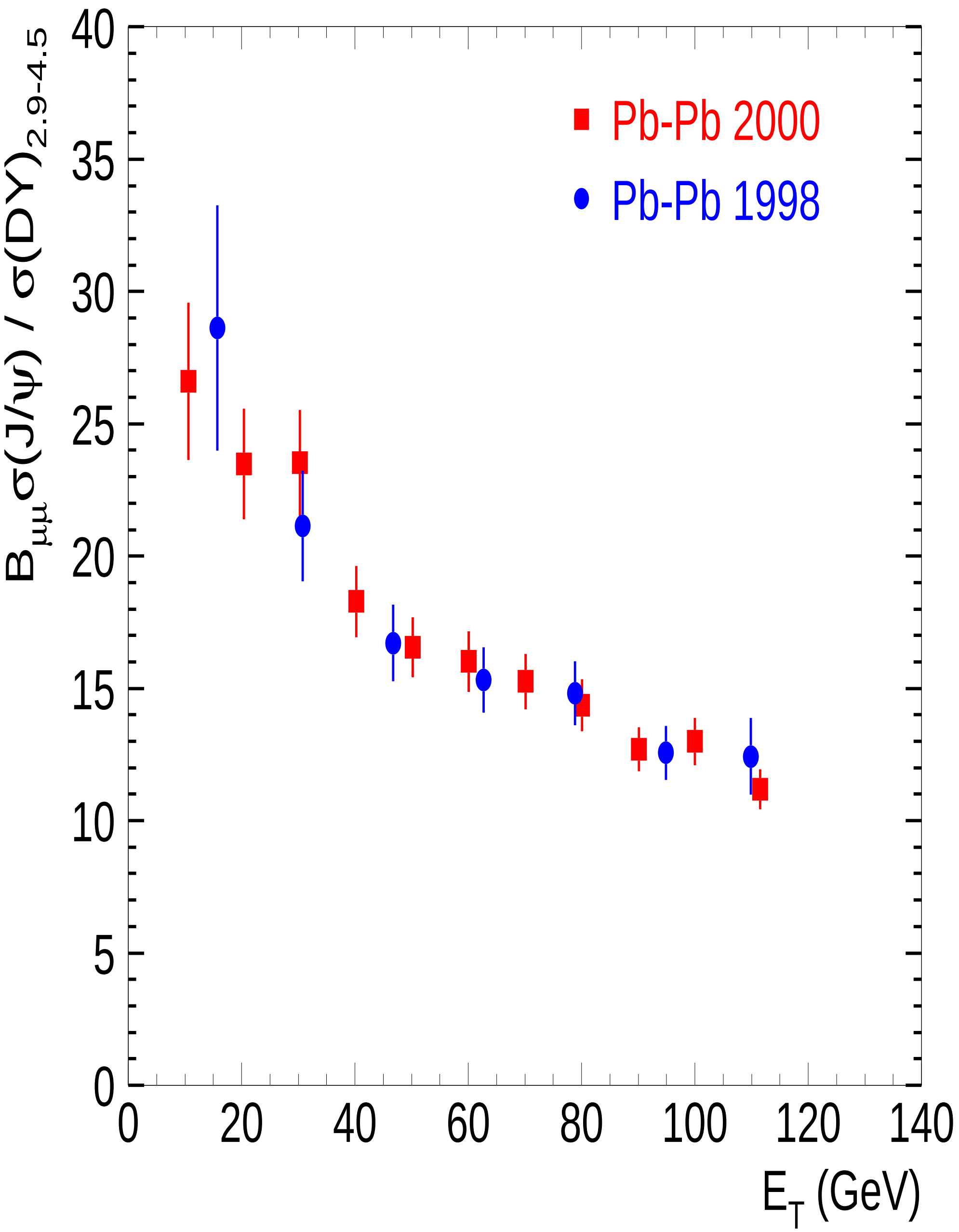
As a function of E_T used here as a centrality estimator:

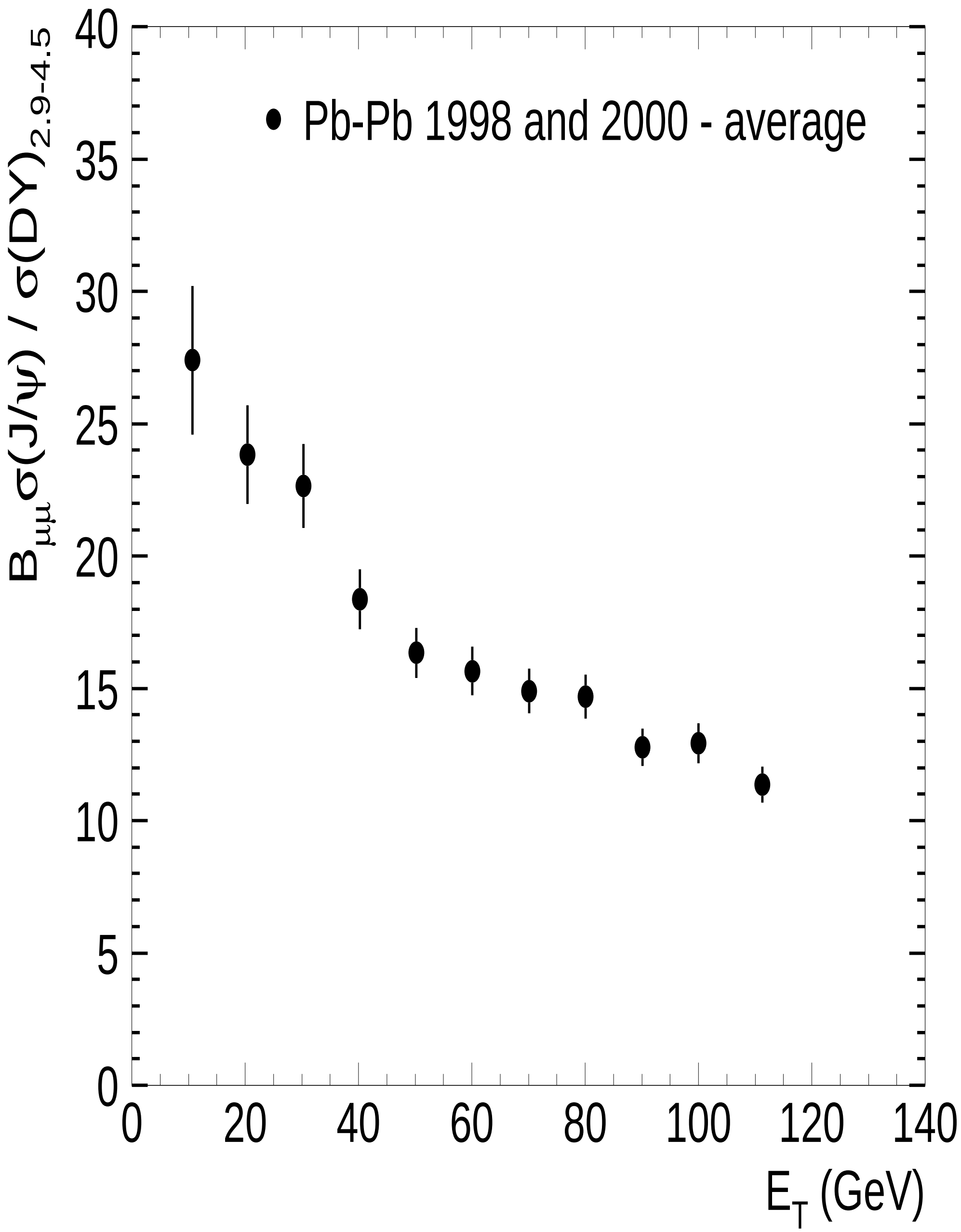
- the ratio of cross-sections

$$\boxed{\frac{\sigma(J/\psi)}{\sigma(DY)}}$$

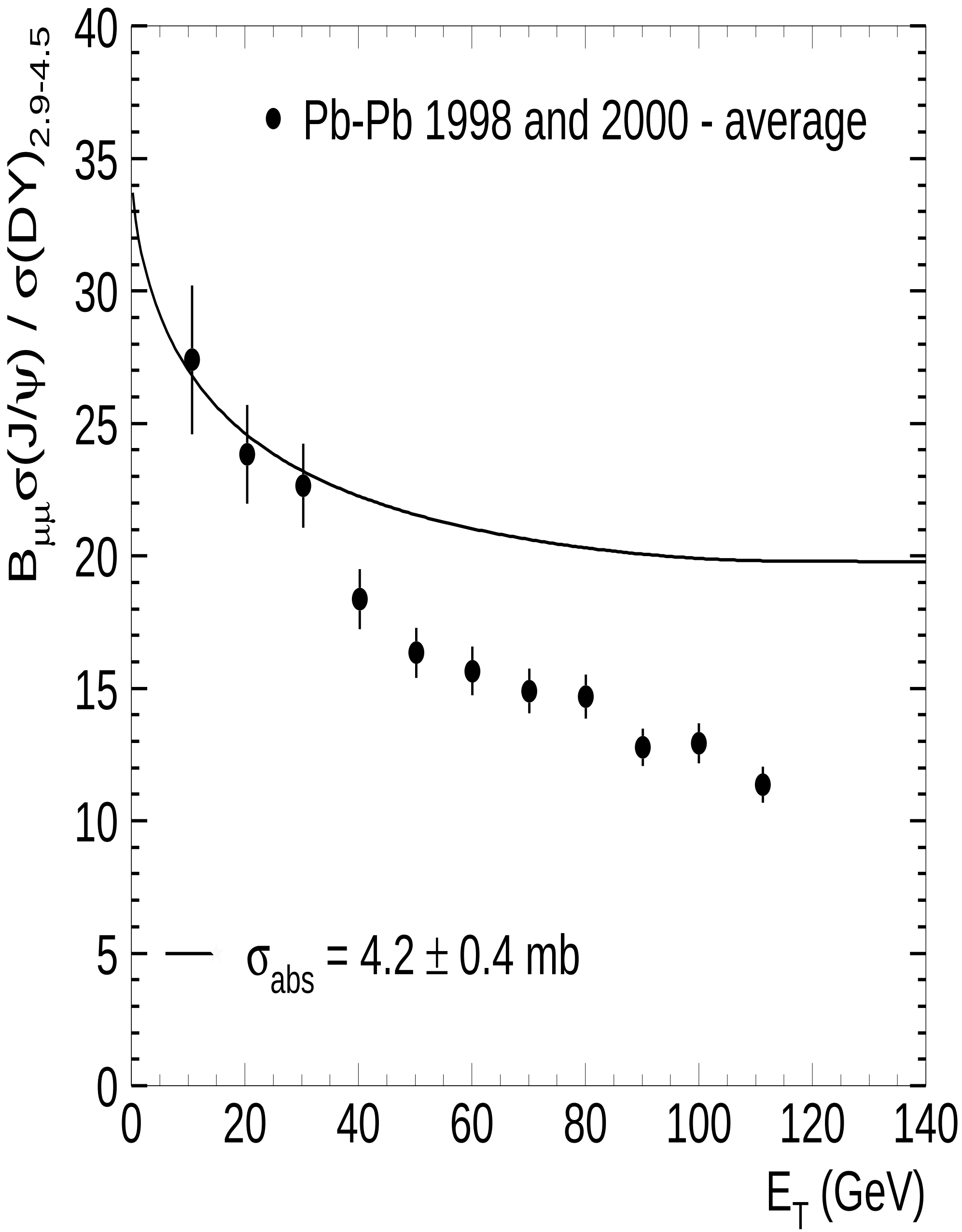
  steadily decreases, from peripheral to central collisions by a factor $\simeq$ 2.5
- No saturation is seen for the most central collisions
- Statistical errors are in the range [9% - 7%]

The Y2K results (II)





The Y2K results (III)



Normal nuclear absorption determined from:

- new p-A data at 450 and 400 GeV
- S-U (200 GeV)

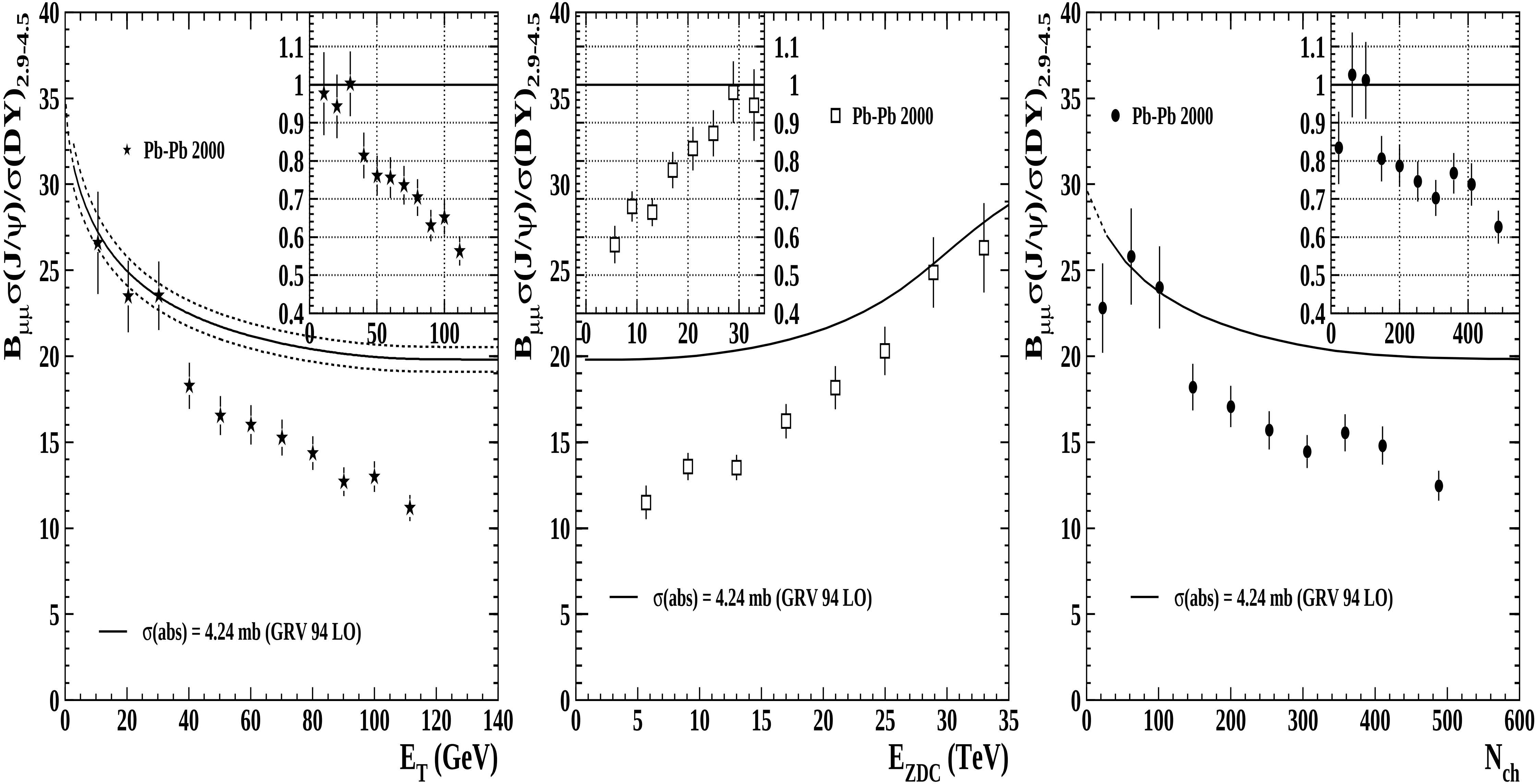
leading to σ_{abs} = 4.2 $\pm$ 0.4 mb
and providing the rescaling factor
450/400 $\rightarrow$ 200 GeV
by "simultaneous" (same σ_{abs}) fit.

The ratio $\dfrac{\sigma(J/\psi)}{\sigma(DY)}$

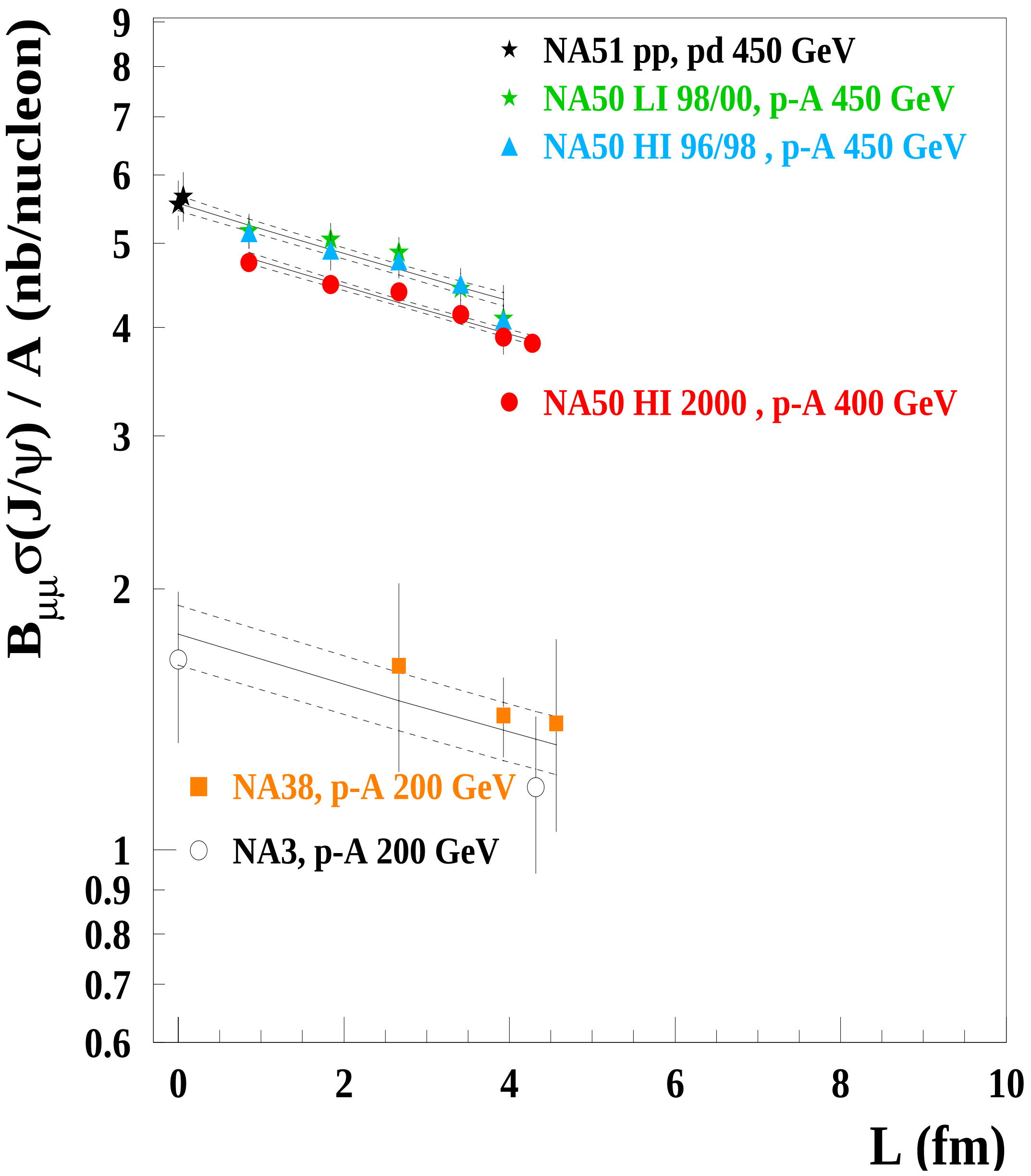
behaves:

- "normally" for peripheral collisions
- more and more "abnormally" for more and more central collisions

The Y2K results (IV)



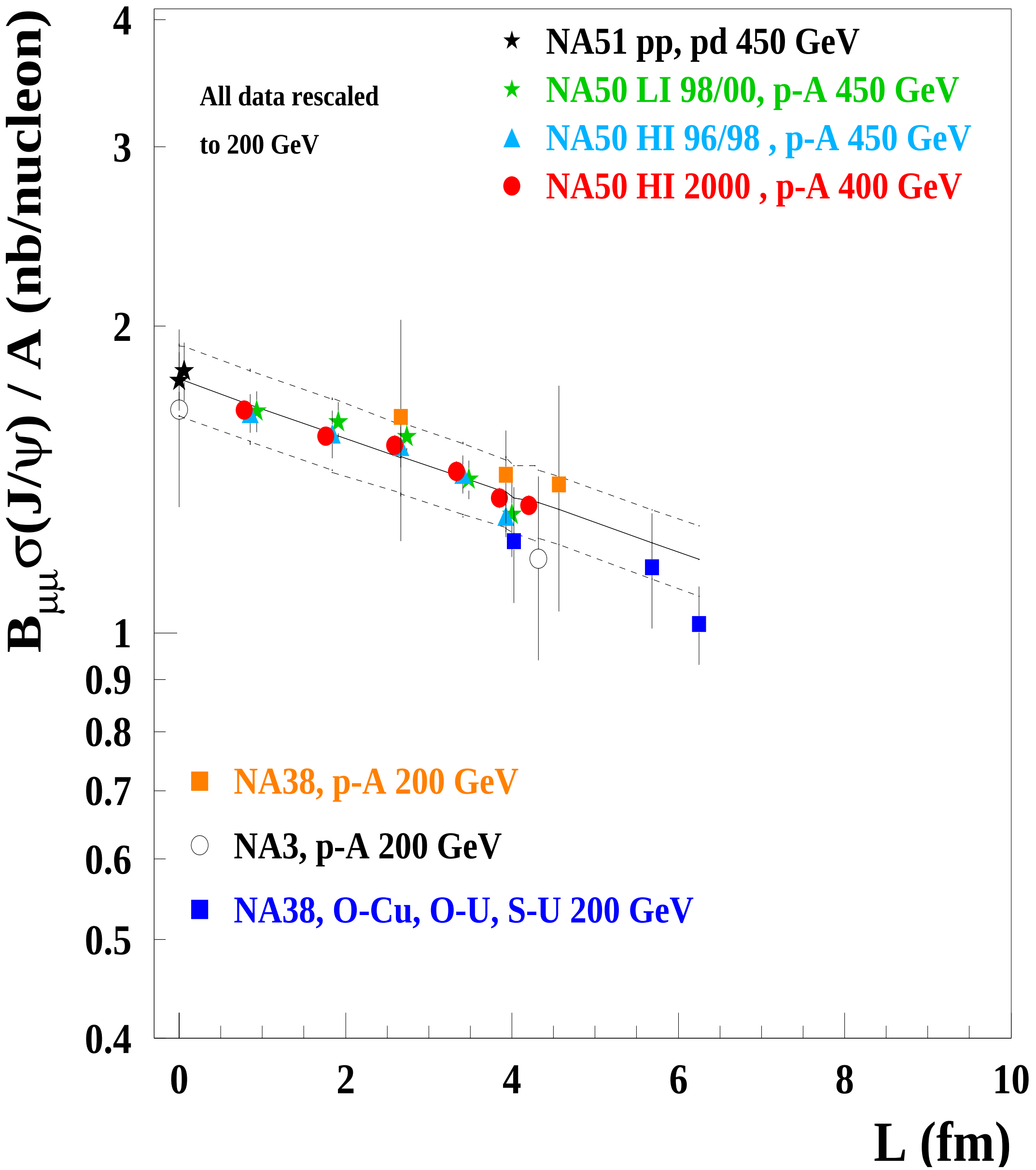
"New" pure p-A reference (I)



Determine absorption reference at 158 GeV from p-A data only as S-U could be already abnormal, i.e. maybe affected by comovers...

- Only use most precise data
- All available 200 GeV data (NA38) plus pp and p-Pt (NA3)
- No Drell Yan at 200 GeV $\Longrightarrow$ absolute J/ψ cross-sections
- Separate fits show: excellent compatibility
- "Simultaneous" fit leads to σ_{abs} and rescaling factor 450/200

"New" pure p-A reference (II)



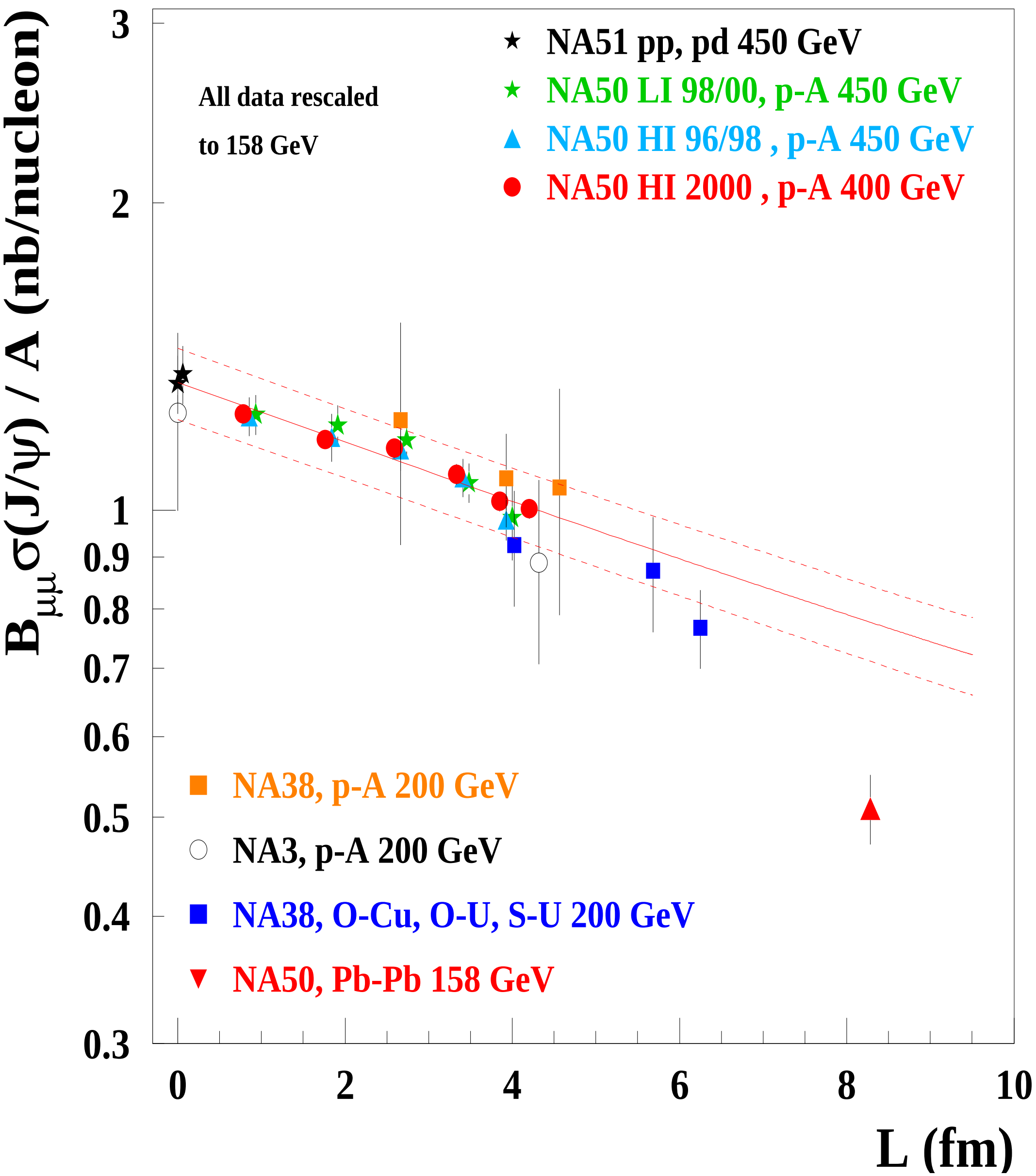
- Glauber fit
  on p-A data only leads to:

$\sigma_{abs} = 4.1 \pm 0.4$ mb from xsection
$\sigma_{abs} = 4.2 \pm 0.4$ mb from $J/\psi/DY$

- Absolute cross-sections "experimentally" rescaled to 200 GeV, from p-A only

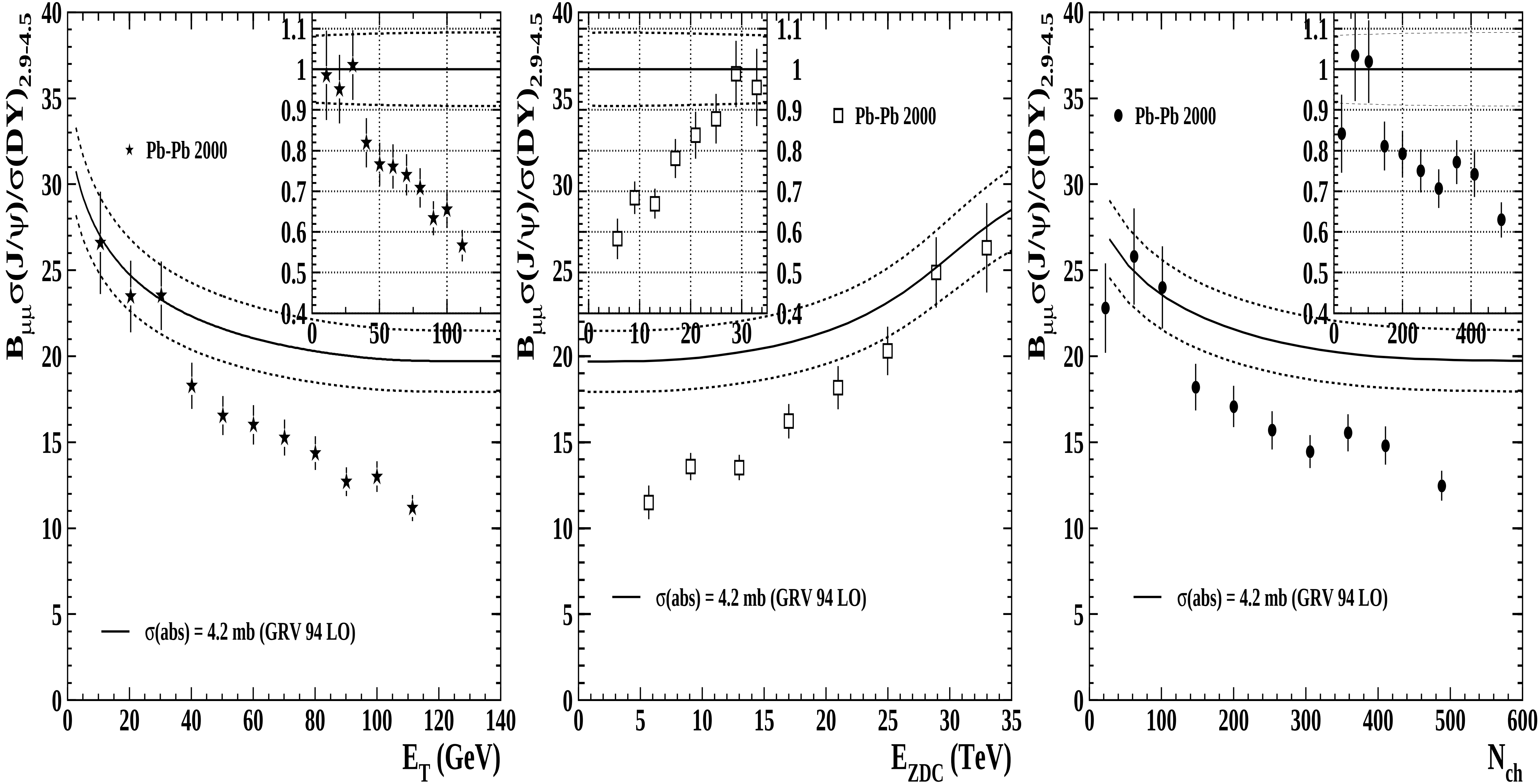
- O-Cu, O-U and even S-U are just plotted BUT NOT INCLUDED in the fit
  They show, within errors, a p-A - like behaviour

1995 J/ψ suppression in Pb-Pb (updated)

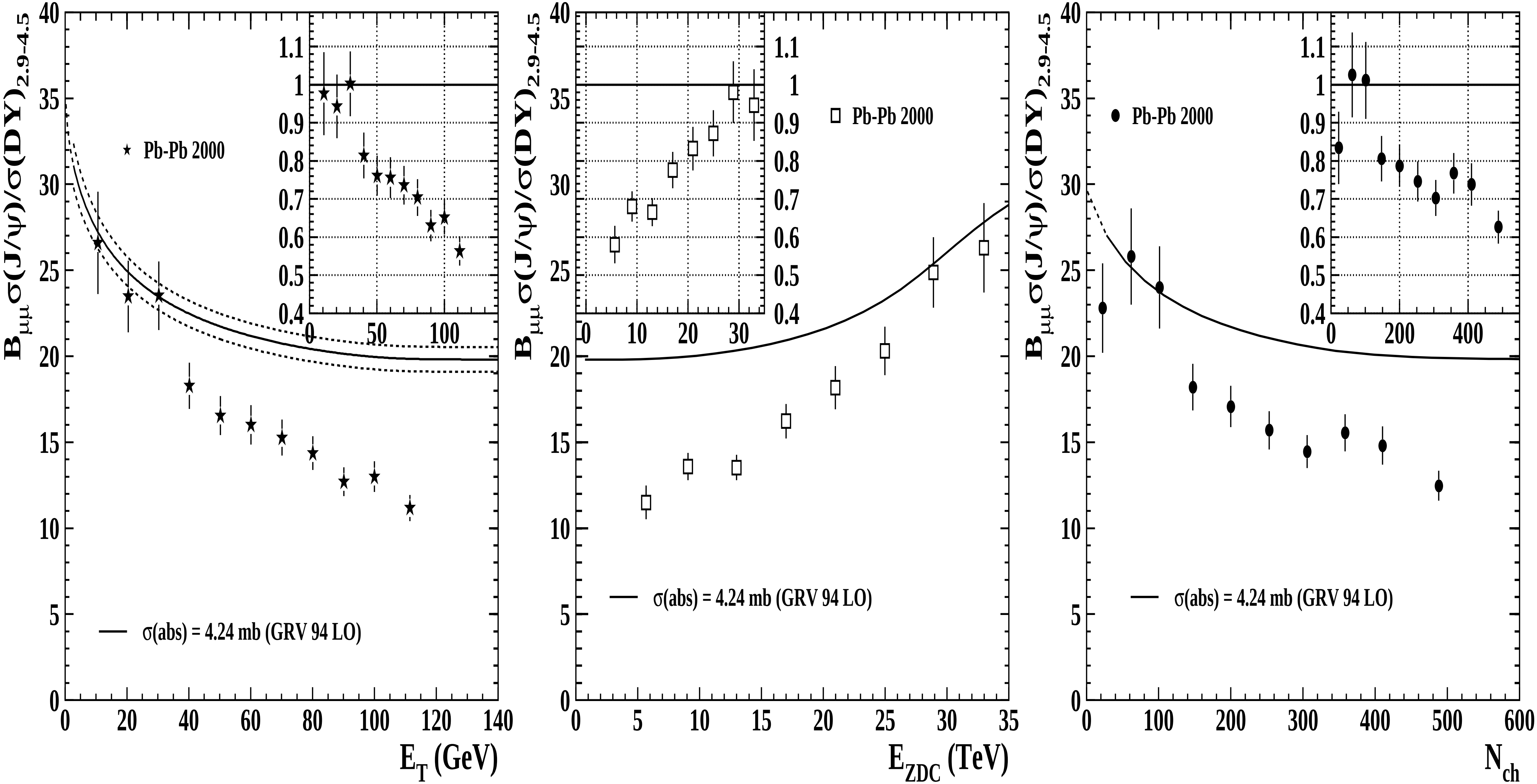


- Same as previous plot with all data rescaled at 158 GeV
- Confirm: In Pb-Pb, with pure p-A reference, J/ψ is still "anomalously" suppressed
- for $J/\psi/DY$ "normal" absorption reference: the normalization ↘ by 0.6% !! its uncertainty ↗ by a factor 2 !!
- For Pb-Pb, the ratio "Measured/Expected" amounts to 0.65 ± 0.08

The Y2K results with updated p-A reference



and... with traditional (p-A and S-U) reference



J/ψ suppression: p_T dependence (I)

An attempt to study p_T dependent features of J/ψ suppression.

We consider 11 bins in p_T, the transverse momentum of the J/ψ
We study the ratios:

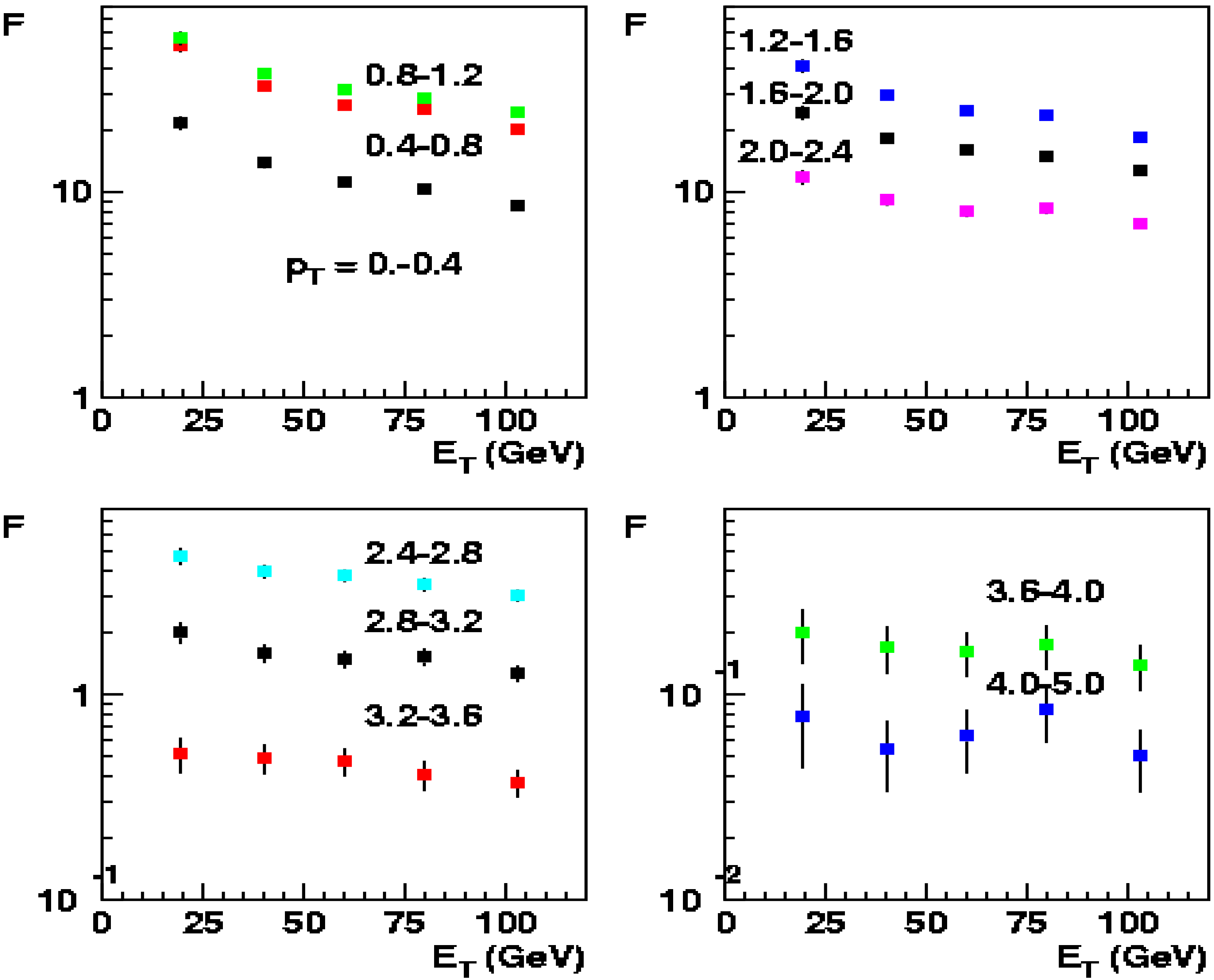
$$F_i = \frac{dN_{J/\psi}/dp_T}{N_{DY\,(M>4.2GeV/c^2)}} \qquad \text{and} \qquad R_i = \frac{F_i}{F_1}$$

where i is the i^{th} centrality bin and

$$\begin{cases} dN_{J/\psi}/dp_T \text{ is the nb. of } J/\psi \text{ of a given } p_T, \\ N_{DY\,(M>4.2GeV/c^2)} \text{ is the \textit{total} nb. of } DY \text{ evts. of } M > 4.2GeV/c^2 \end{cases}$$

as a function of the centrality of the collision

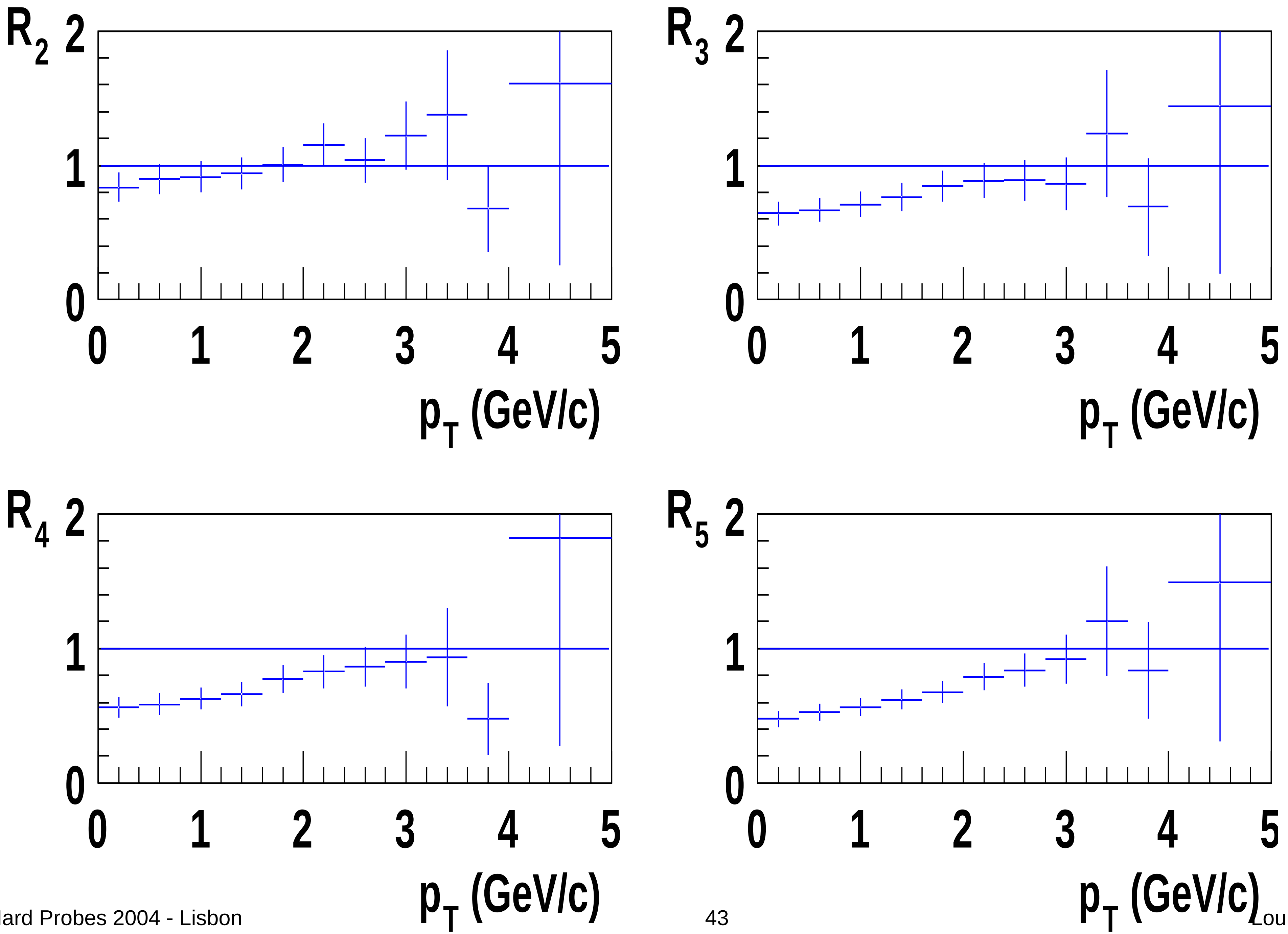
J/ψ suppression: p_T dependence (II)



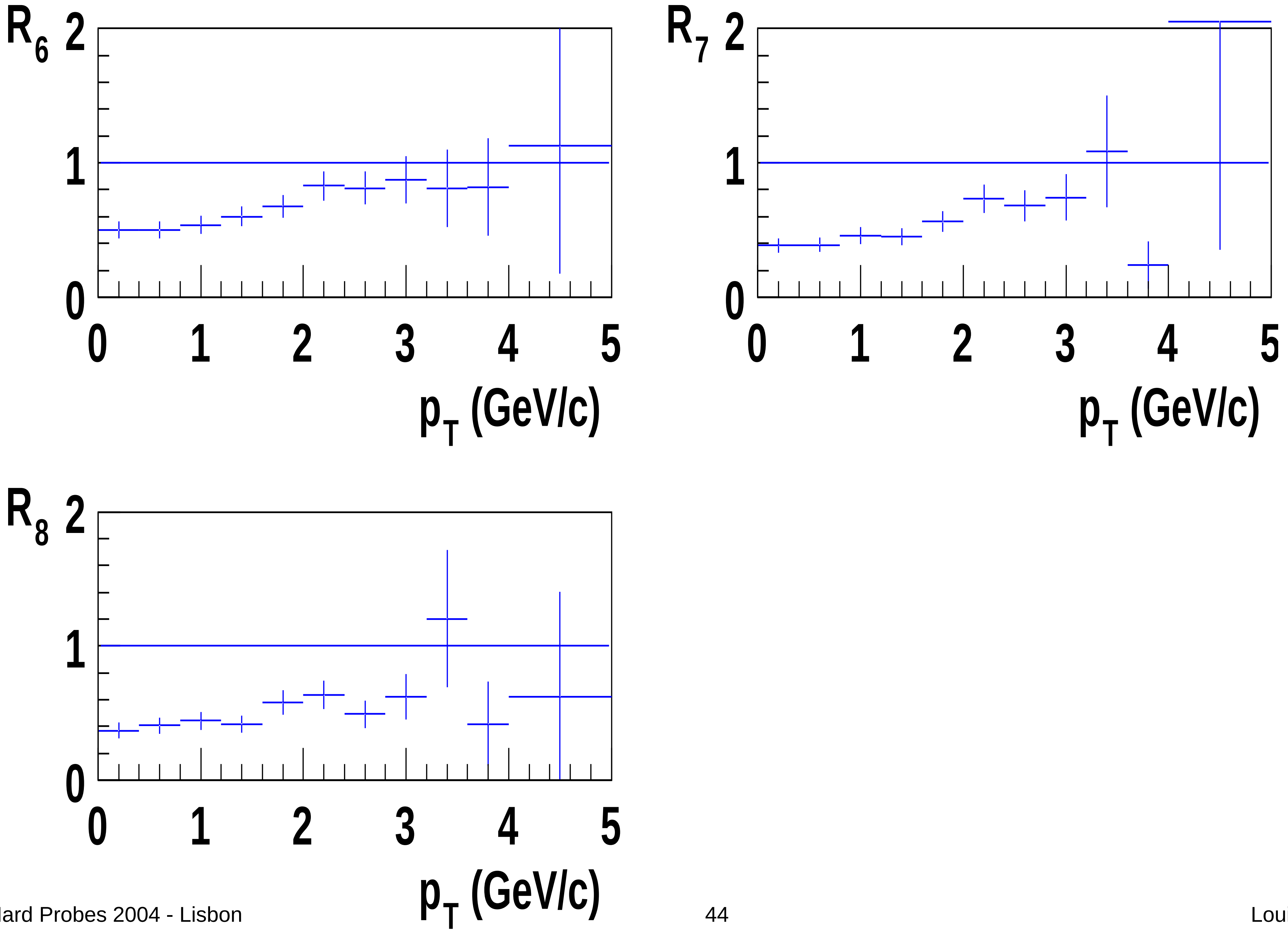
As a function of centrality:

- clear suppression for low p_T
- much weaker suppression for high p_T

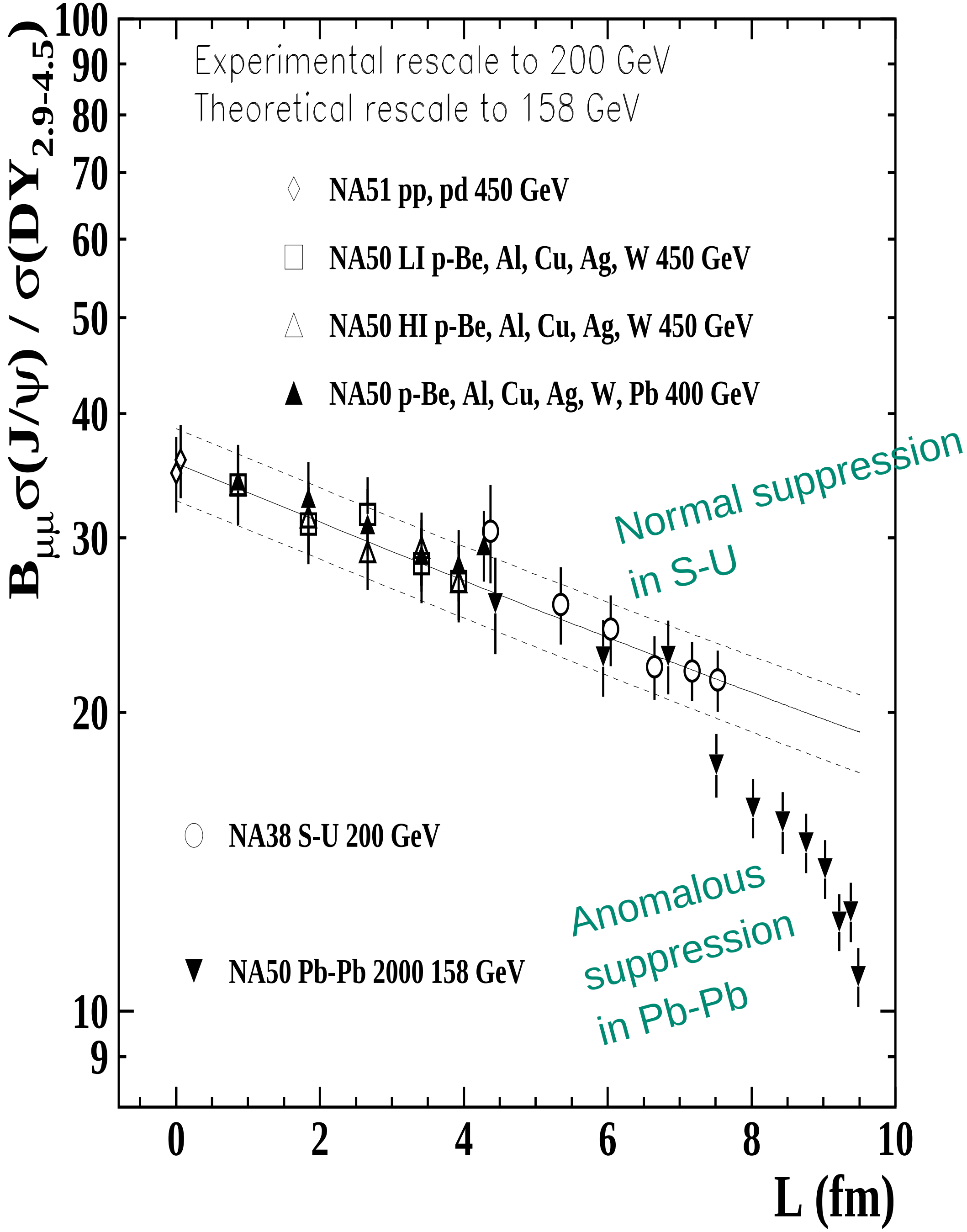
J/ψ suppression: p_T dependence (III)

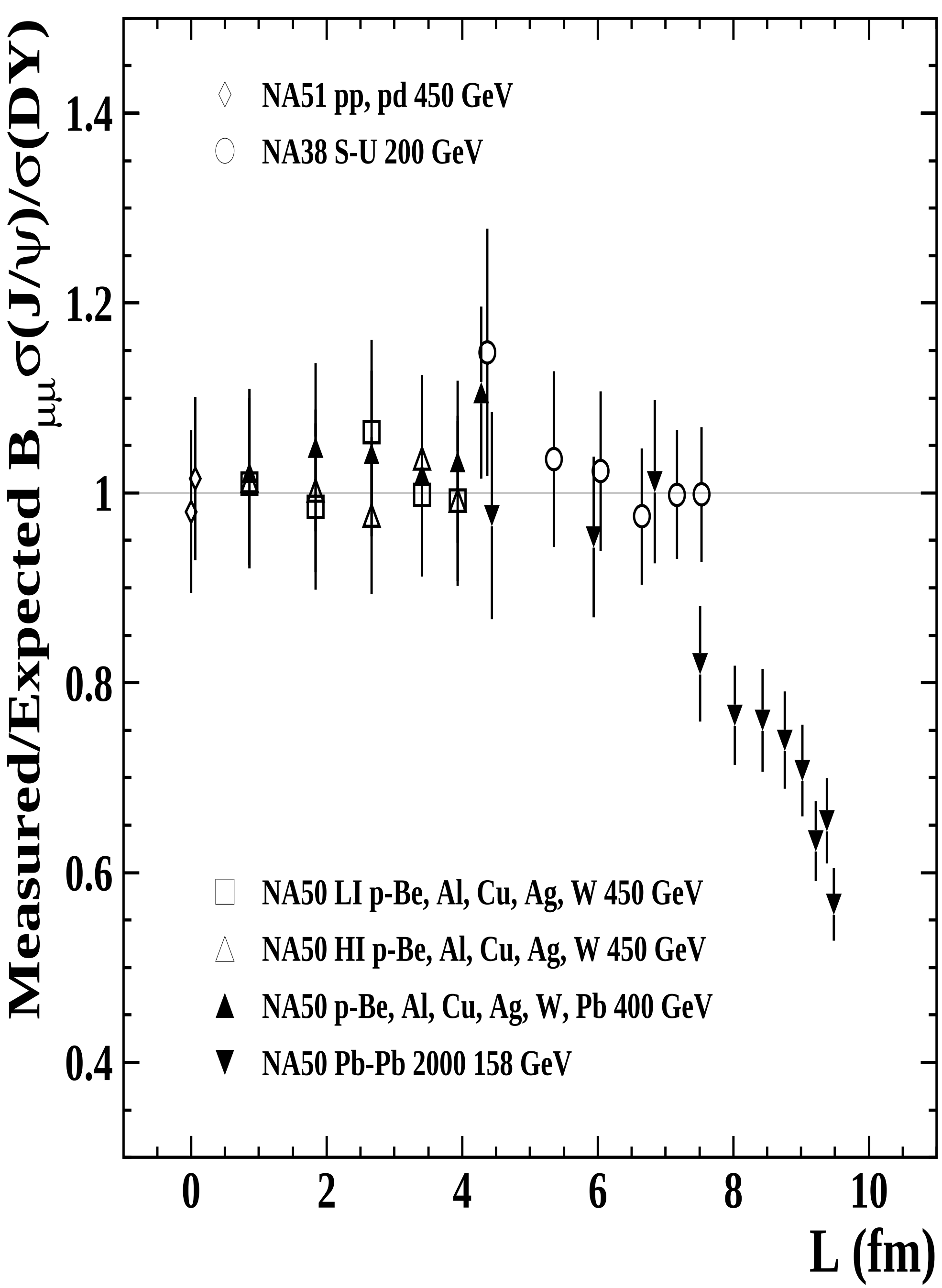


J/ψ suppression: p_T dependence (IV)

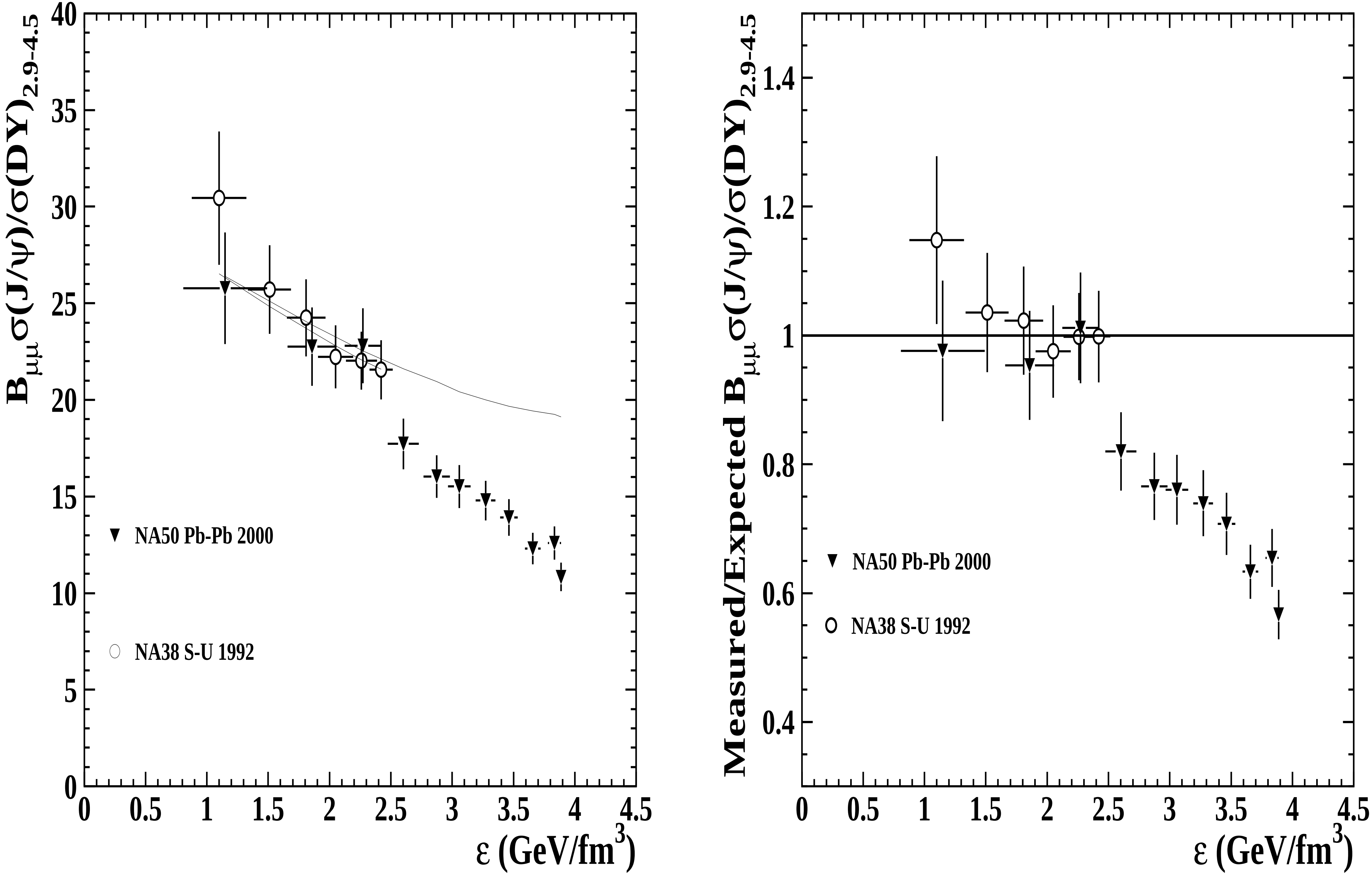


From pp...to Pb-Pb





The Y2K results vs. energy density



Conclusions(I)

1. Drell-Yan (muon pair) production exhibits a "normal" behaviour, i.e.,

   $\sigma_{DY} \propto$ number of nucleon-nucleon collisions

   from pp up to Pb-Pb interactions. (1995/1996-2000)

2. From measured J/ψ production in p-A collisions at 450, 400 and 200 GeV/c we have now (2004) a

   robust experimental determination of $(\sigma_{abs}^{J/\psi})_{200}$

   and a

   reliable calculation of $(\sigma_{abs}^{J/\psi})_{158}$

   based on p-A interactions *exclusively* (fall 2004 !)
   (attend G. Borges talk for details)

Conclusions(II)

3. With respect to the expected values, as extrapolated from p-A exclusively (1995/2004):

   $\sigma_{J/\psi}{}^{Pb-Pb}$ is significantly suppressed

4. Pb-Pb 2000 data, free from past problems, show and confirm (2004) that:

   For *peripheral* Pb-Pb reactions, the ratio $\sigma_{J/\psi}{}^{Pb-Pb}/\sigma_{DY}^{Pb-Pb}$ follows the "normal" nuclear absorption (like p-A).

   and

   For more *central* collisions, i.e., $b \leq 9$ fm, J/ψ production departs from this "normal" behaviour. It exhibits an "abnormal" suppression which increases with increasing centrality.

Conclusions(III)

What I learned from experiment:

1/ *The only 100% right paper is, usually, the NEXT one to be published.*

and also:

2/ *Never build models with adjustable free parameters to try and reproduce still UNPUBLISHED, and therefore preliminary results.*

For PUBLISHED results...beware of 1/