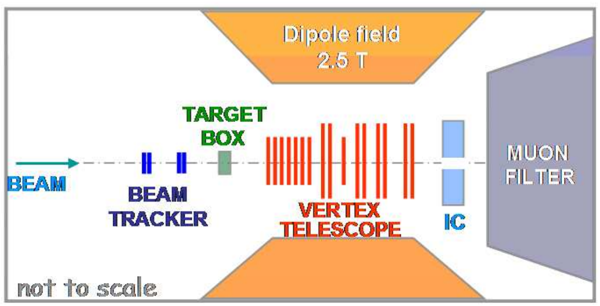
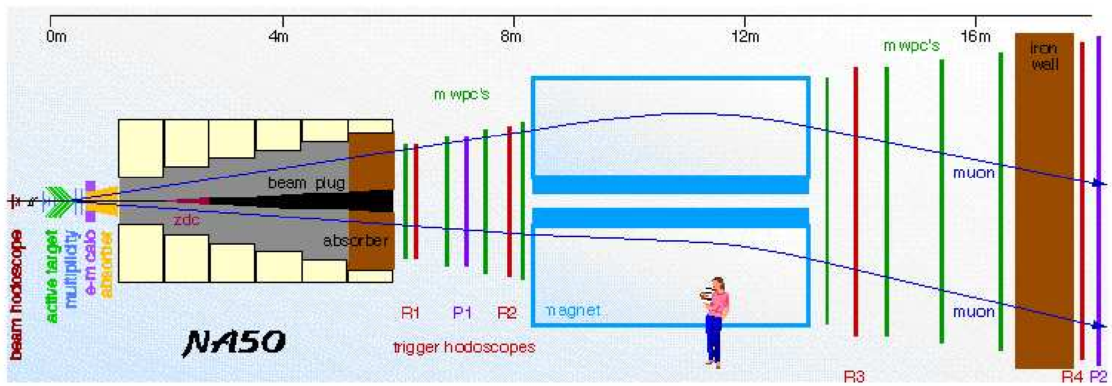
Quarkonium production and suppression in proton-nucleus and ion-ion collisions at SPS energies

NA60 vertex region





NA50 dimuon spectrometer

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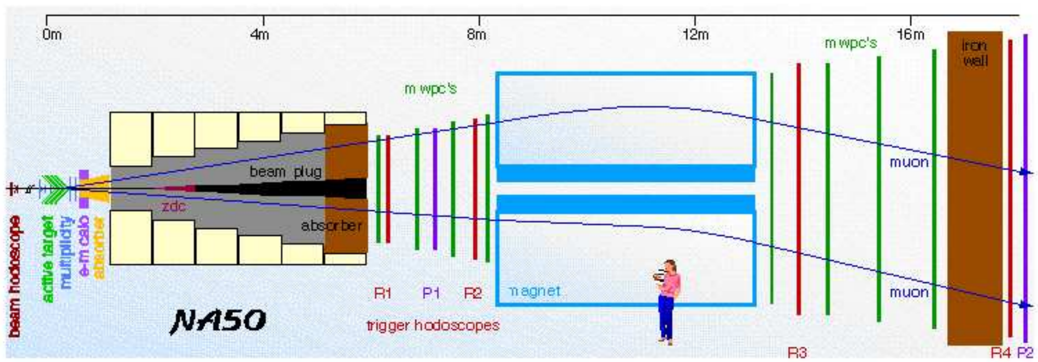
WHEPP 9: IX Workshop on High Energy Physics Phenomenology

Bhubaneswar, Orissa, INDIA, Jan. 3-14, 2006

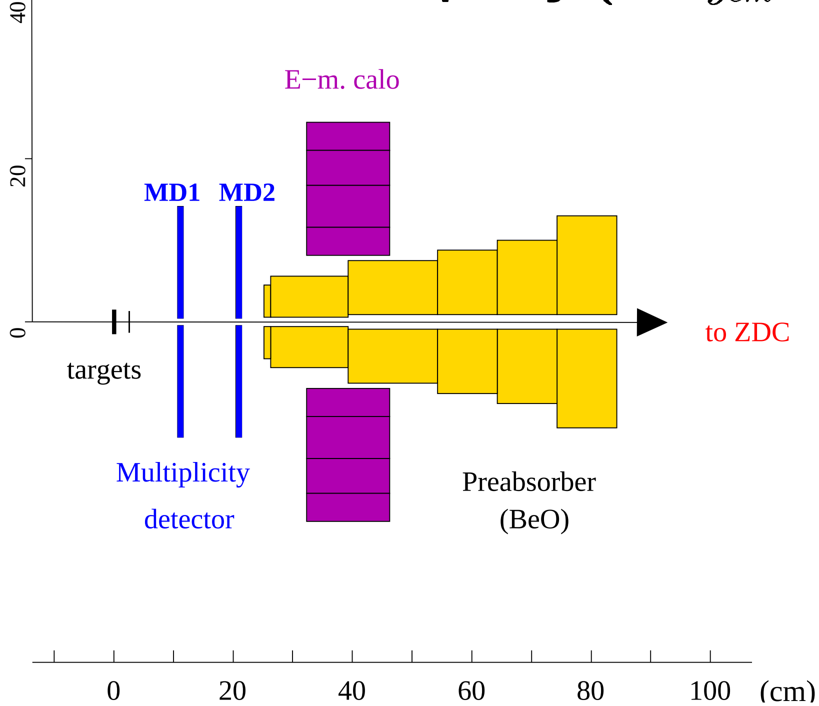
Outline of the talk

- The **NA50** experiment: goals and methods
- A **new reference** for J/ψ normal nuclear absorption using only high statistics **p-A** data at 450, 400 and 200 GeV
- J/ψ **anomalous suppression** in **Pb-Pb** collisions at 158 GeV/nucleon
- ψ' **absorption** from p-A to Pb-Pb
- The **NA60** experiment: goals and methods
- J/ψ **anomalous suppression** in **In-In** collisions at 158 GeV/nucleon
- Conclusions

The NA50 experiment



dimuon rapidity ($0 < y_{cm} < 1$), polar angle ($-0.5 < \cos\theta_{CS} < 0.5$)



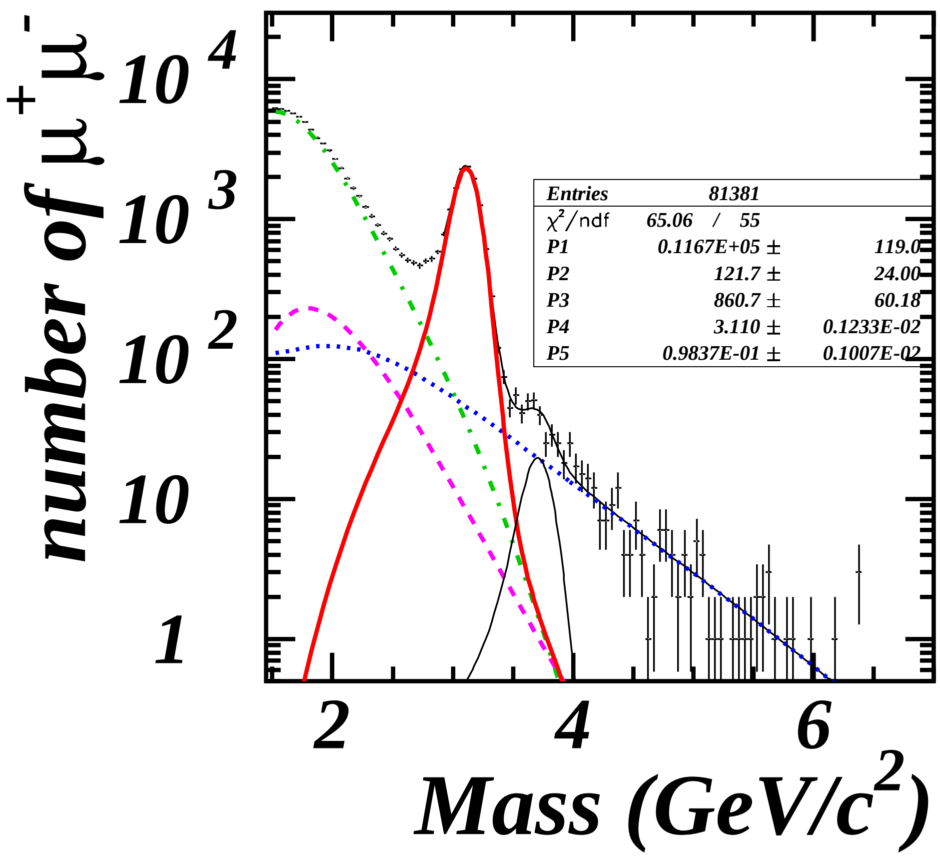
dimuon mass resolution:
$\sigma \simeq 105$ MeV/c^2 at the J/ψ

Three centrality detectors:
E.M. Calo. ($1.1 < \eta < 2.3$)
Multiplicity Det. ($1.9 < \eta < 4.2$)
Zero Degree Calo. ($\eta > 6.3$)

Beam Hodoscope
Beam Interaction / Halo detectors

The fit to $\mu^+\mu^-$ mass spectra

J/ψ/DY: ratio of events collected with same trigger; Drell-Yan cross-section is $\propto$ number of collisions



- Combinatorial background (π, K decays) estimated from measured like-sign pairs

- Signal mass shapes from Monte Carlo: PYTHIA and GRV 94 LO parton densities, GEANT 3.21 for detector simulation

- Multi-step fit to obtain J/ψ, ψ', Drell-Yan (DY) and Charm yields

- Acceptance correction to obtain the **J/ψ/DY cross-section ratio**

- The normalization to a hard process (DY) allows the **centrality-dependent** study of J/ψ suppression

Charmonium physics in NA50

- **Charmonium suppression** by QGP color screening: Matsui+Satz 1986

- Measurements by NA38 with **p-A**, **O-U** and **S-U** collisions (1986-1992):
  - observed suppression of J/ψ finally understood as due to absorption in ordinary nuclear matter

- New measurements by **NA50** with **p-A** and **Pb-Pb** collisions:
  - Discovery of **anomalous J/ψ suppression** in central Pb-Pb collisions (1995-1996 data)
  - Last two Pb-Pb data samples collected under improved conditions $\Rightarrow$ **final results**:
    * **single thin target** (1998) $\Rightarrow$ no reinteractions in targets
    * **vacuum** around target (2000) $\Rightarrow$ no Pb-air interactions

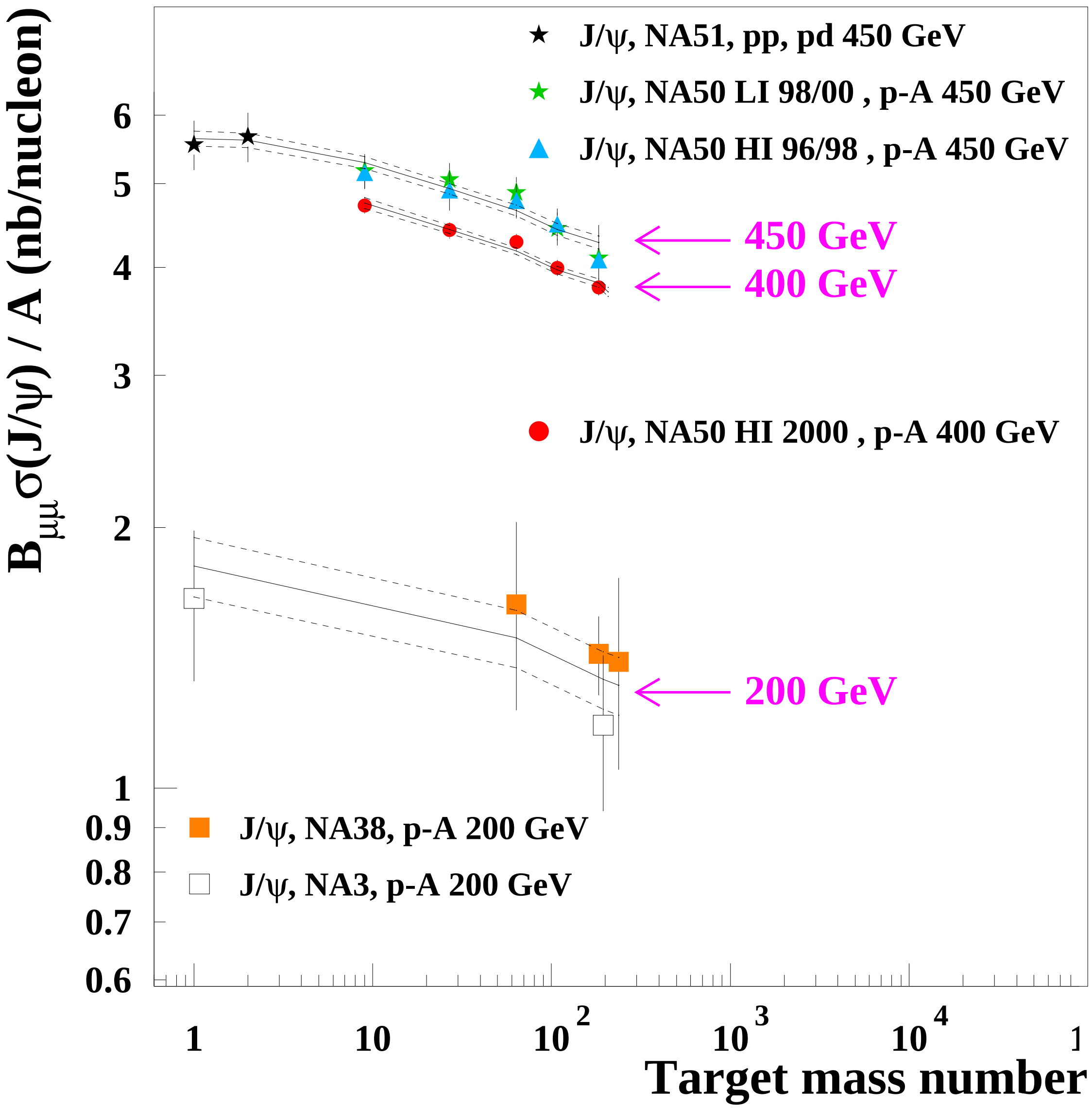
Recent developments in NA50 analysis

- Charmonium analysis (ratios of J/ψ and ψ' to Drell-Yan) in Pb-Pb:
  - **Same PDF's** (GRV 94 LO) used for Drell-Yan **in all analyses**

- Reference curve for normal nuclear absorption:
  no available 158 GeV p-A data $\Rightarrow$ use higher energy p-A & rescale:
  - Determine $\sigma_{abs}^{J/\psi}$ from a coherently analyzed set of $(J/\psi)/DY$ **p-A** data at **450** and **400** GeV $\Rightarrow$ shape of absorption curve
  - Determine level of $(J/\psi)/DY$ at **158** GeV without using S-U data but only J/ψ cross-sections from 450, 400 and 200 GeV p-A data, plus calculation for Drell-Yan $\Rightarrow$ normalization of absorption curve
  - Take into account the **neutron halo** (different spatial distributions of neutrons and protons in nuclei) $\Rightarrow$ affects centrality dependence of absorption curve

Reference for neutron halo: Phys. Rev. Lett. 87 (2001) 082501.

J/ψ cross-sections in p-A at 450, 400 and 200 GeV



- Glauber fit to $B_{\mu\mu}\sigma(J/\psi)$
  $\Rightarrow \quad \sigma_{abs}^{J/\psi} = 4.48 \pm 0.42$ **mb**
  $N_{200}/N_{450} = 0.320 \pm 0.025$
  $N_{200}/N_{400} = 0.357 \pm 0.027$

  normalizations N_{450}, N_{400} *and* N_{200} **include both energy and kinematical domain changes**

- $(J/\psi)/DY$ ratios (available only at 450, 400 GeV)
  $\Rightarrow \quad \sigma_{abs}^{J/\psi} = 4.18 \pm 0.35$ **mb**

  Fair agreement between both determinations

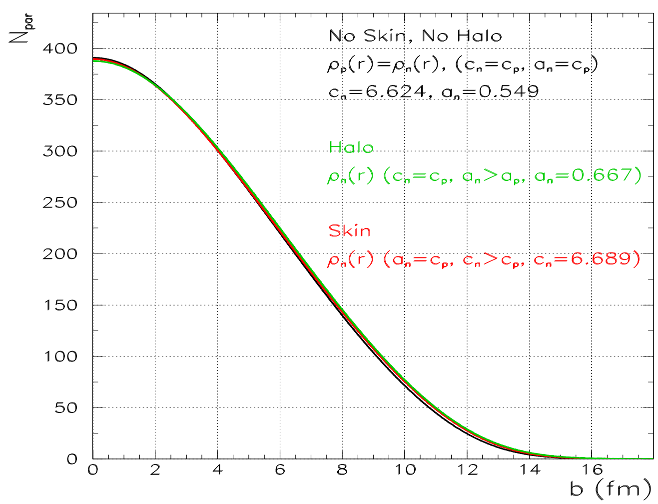
The absorption curve for $(J/\psi)/DY$ in Pb-Pb

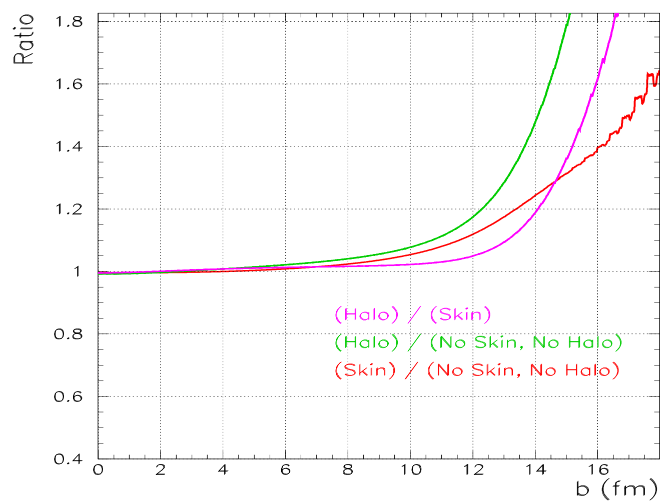
- Start from $(J/\psi)/DY$ **normalization at 450 GeV** (**1.4%** error)
- **Rescale to 200 GeV** using:
  ◇ *measured* absolute J/ψ cross-sections (**7.8%** error, incl. syst.)
  ◇ LO *calculation* for Drell-Yan (**2.5%** error)
- **Rescale to 158 GeV** using:
  ◇ *fit "à la Schuler"* to measured J/ψ cross-sections (**1.5%** error)
  ◇ LO *calculation* for Drell-Yan (negligible error)
- **Glauber calculation** (incl. neutron halo) plus experimental smearing to obtain absorption curve vs. observables E_T, E_{ZDC}, N_{ch}
- **Remarks**:
  1. **Main assumption is:**
     J/ψ **normal nuclear absorption cross-section is the same** at 158 GeV and in 450, 400 and 200 GeV p-A collisions
  2. Absorption curve **determination independent of S-U** (used previously to fix normalization of normal nuclear absorption curve at 200 GeV and reduce its error)

Number of participants vs. impact parameter

^{208}*Pb* - ^{208}*Pb Glauber calculations - Npar(b)*

	No effect		Neutron Skin			Neutron Halo		
E_T (GeV)	$< N_{par} >$	RMS	$< N_{par} >$	RMS	$\frac{\Delta <N>}{<N>}(\%)$	$< N_{par} >$	RMS	$\frac{\Delta <N>}{<N>}(\%)$
3 - 15	34.63090	13.15030	34.59240	13.12730	-0.1	34.42650	13.22610	-0.6
15 - 25	70.60890	13.22340	70.39300	13.14620	-0.3	70.46070	13.25230	-0.2
25 - 35	104.32200	14.38110	104.11200	14.54420	-0.2	104.45300	14.42960	0.1
35 - 45	138.12500	15.75760	138.09700	15.65450	0.0	138.13600	15.62360	0.0
45 - 55	172.23199	16.72130	171.81000	16.58630	-0.2	171.97501	16.72760	-0.1
55 - 65	205.88699	17.66050	205.59900	17.85420	-0.1	205.82500	17.71700	0.0
65 - 75	239.79500	18.81230	239.85300	18.88530	0.0	239.87900	18.90940	0.0
75 - 85	273.80399	19.65190	273.67200	19.48680	0.0	273.79599	19.50840	0.0
85 - 95	307.61200	20.44670	307.35599	20.44140	-0.1	307.55099	20.51250	0.0
95 - 105	340.69699	20.42970	340.29999	20.33750	-0.1	340.56201	20.28300	0.0
105 - 150	369.06000	15.66590	367.96500	15.43910	-0.3	367.29001	15.05720	-0.5





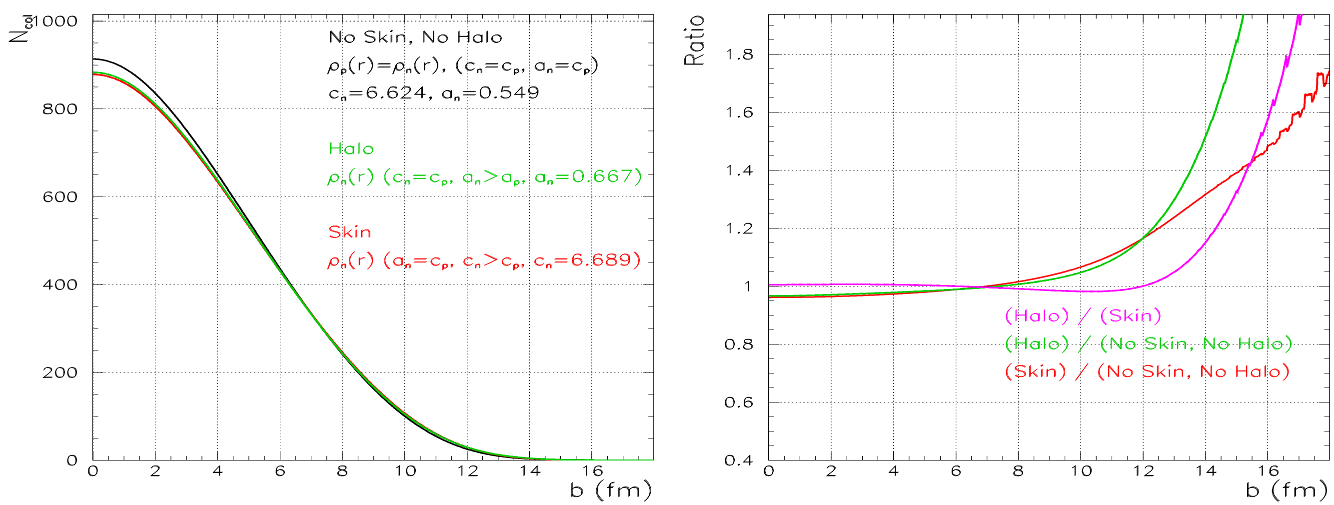
– p.12

Ratio between protons and neutrons depends on centrality

Number of collisions vs. impact parameter

^{208}Pb - ^{208}Pb Glauber calculations - Ncol(b)

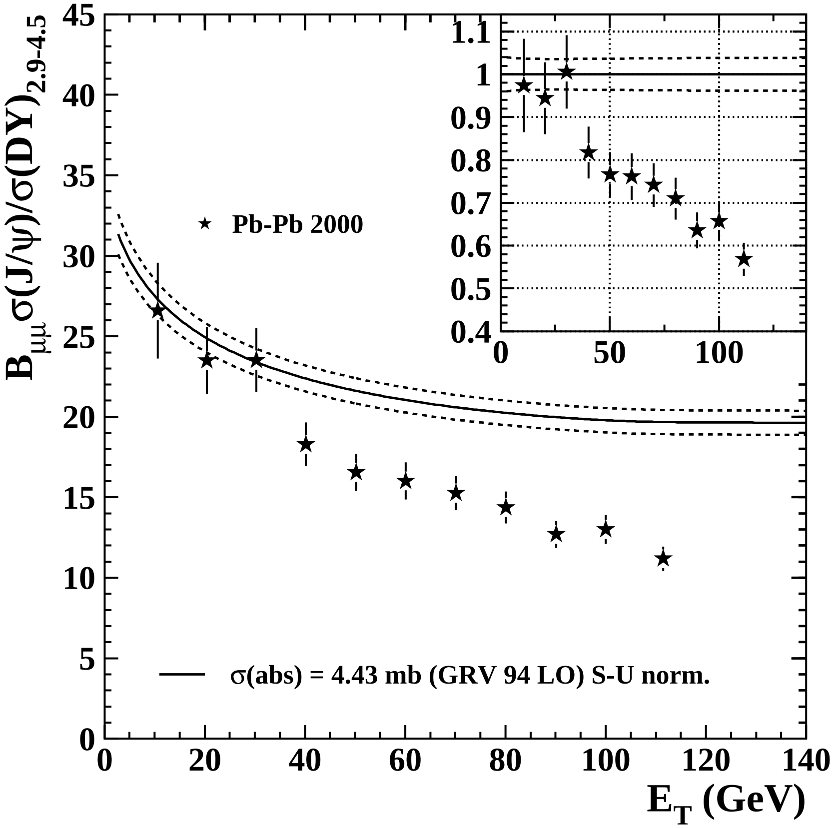
	No effect		Neutron Skin			Neutron Halo		
E_T (GeV)	$< N_{col} >$	RMS	$< N_{col} >$	RMS	$\frac{\Delta<N>}{<N>}(\%)$	$< N_{col} >$	RMS	$\frac{\Delta<N>}{<N>}(\%)$
3 - 15	40.35780	19.09640	40.40580	18.96210	0.1	37.91750	18.03550	-6.0
15 - 25	99.30790	24.26370	98.65390	23.74500	-0.7	94.06280	23.14990	-5.3
25 - 35	165.20599	30.10680	163.27600	29.32950	-1.2	157.28101	28.86970	-4.8
35 - 45	238.51500	35.19390	234.62100	34.43840	-1.6	227.74300	33.96780	-4.5
45 - 55	317.09399	40.01630	311.47601	39.00520	-1.8	303.95200	38.91850	-4.1
55 - 65	400.33801	44.77920	392.03101	43.07140	-2.1	384.89301	43.54780	-3.9
65 - 75	487.52899	49.01050	475.92300	47.31100	-2.4	469.88599	48.04820	-3.6
75 - 85	577.62799	53.04300	562.94598	51.06370	-2.5	558.36401	52.00140	-3.3
85 - 95	670.58698	57.16800	652.07098	54.67620	-2.8	649.88800	56.81410	-3.1
95 - 105	764.47400	58.87980	741.29602	55.68220	-3.0	743.13397	58.27540	-2.8
105 - 150	847.55103	46.49600	817.80103	43.05110	-3.5	821.07703	44.50240	-3.1



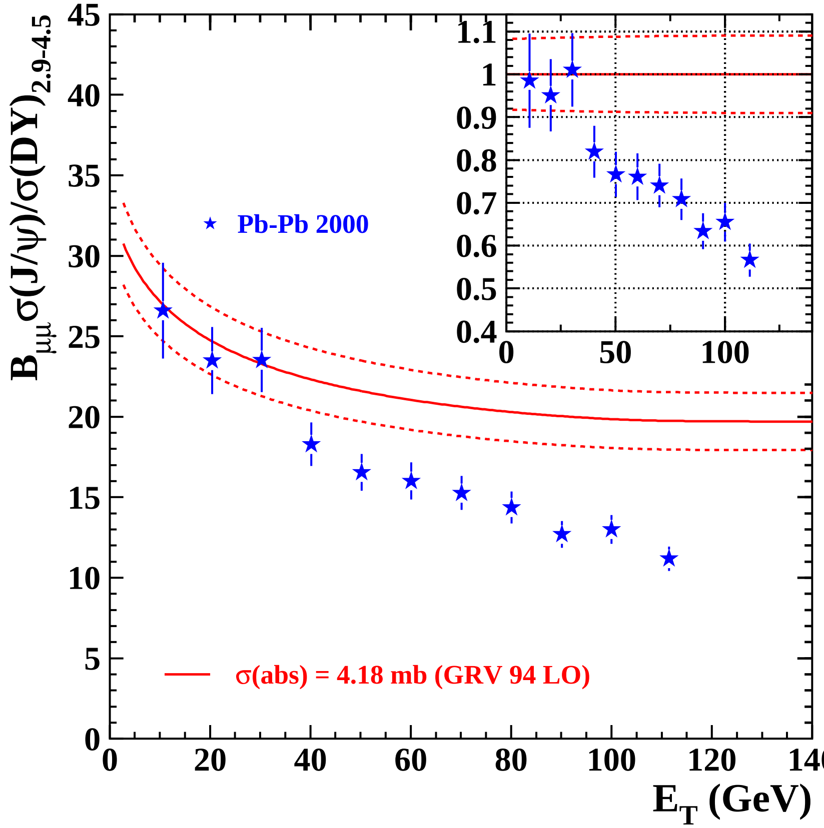
– p.13

Also the DY cross-section becomes a fn. of centrality (effect < 1% for b < 12 fm)

$(J/\psi)/DY$ vs. E_T in Pb-Pb (2000 data)



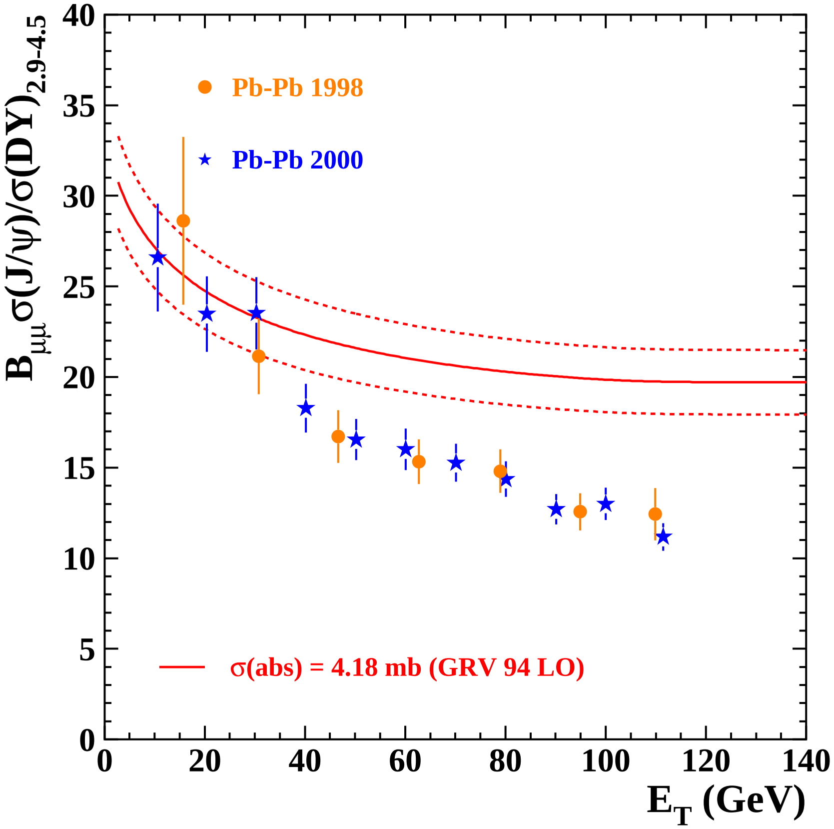
Previous procedure using also S-U data for absorption curve normalization: small error BUT assumes S-U is normal



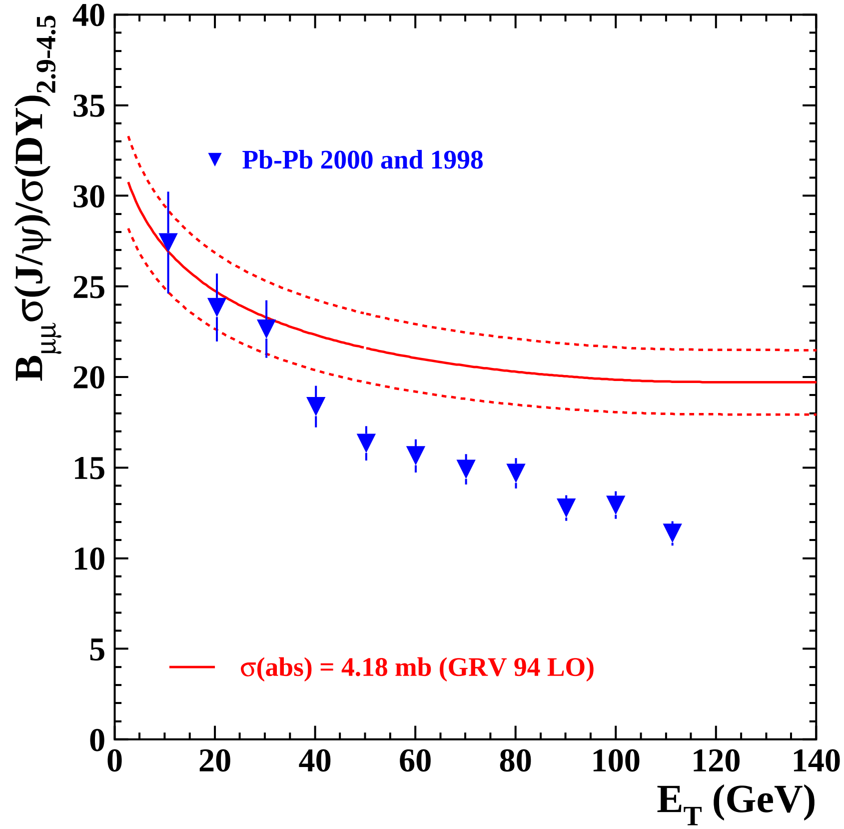
New procedure with absorption curve from p-A data only: larger error BUT free from assumptions on S-U

The absorption curve itself is almost the same with both procedures

Anomalous J/ψ suppression vs. E_T in Pb-Pb



Pb-Pb 1998 and 2000 data . . .



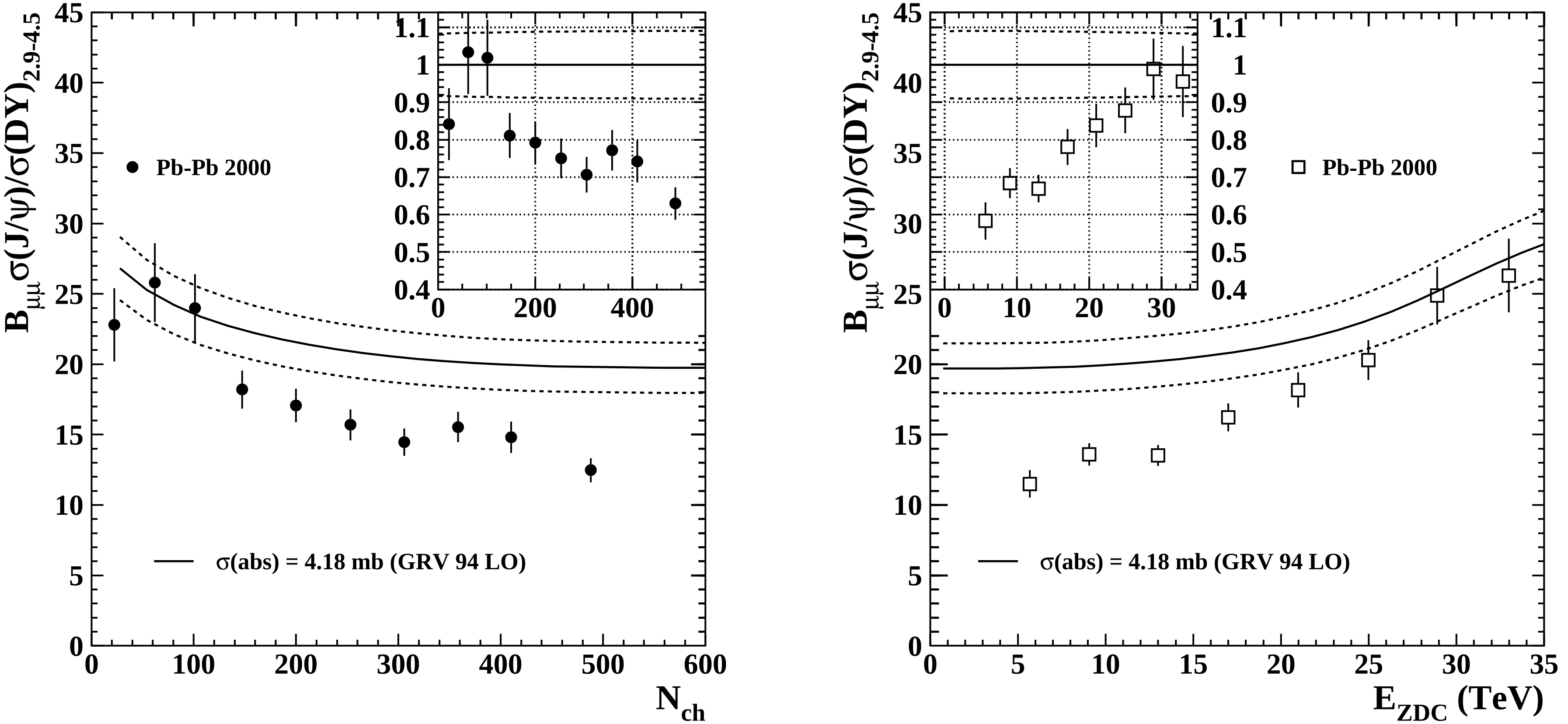
. . . and averaged result

Pb-Pb (1998 + 2000 data):

⇒ **departure from normal nuclear absorption at mid-centrality**

⇒ **suppression increases with centrality**

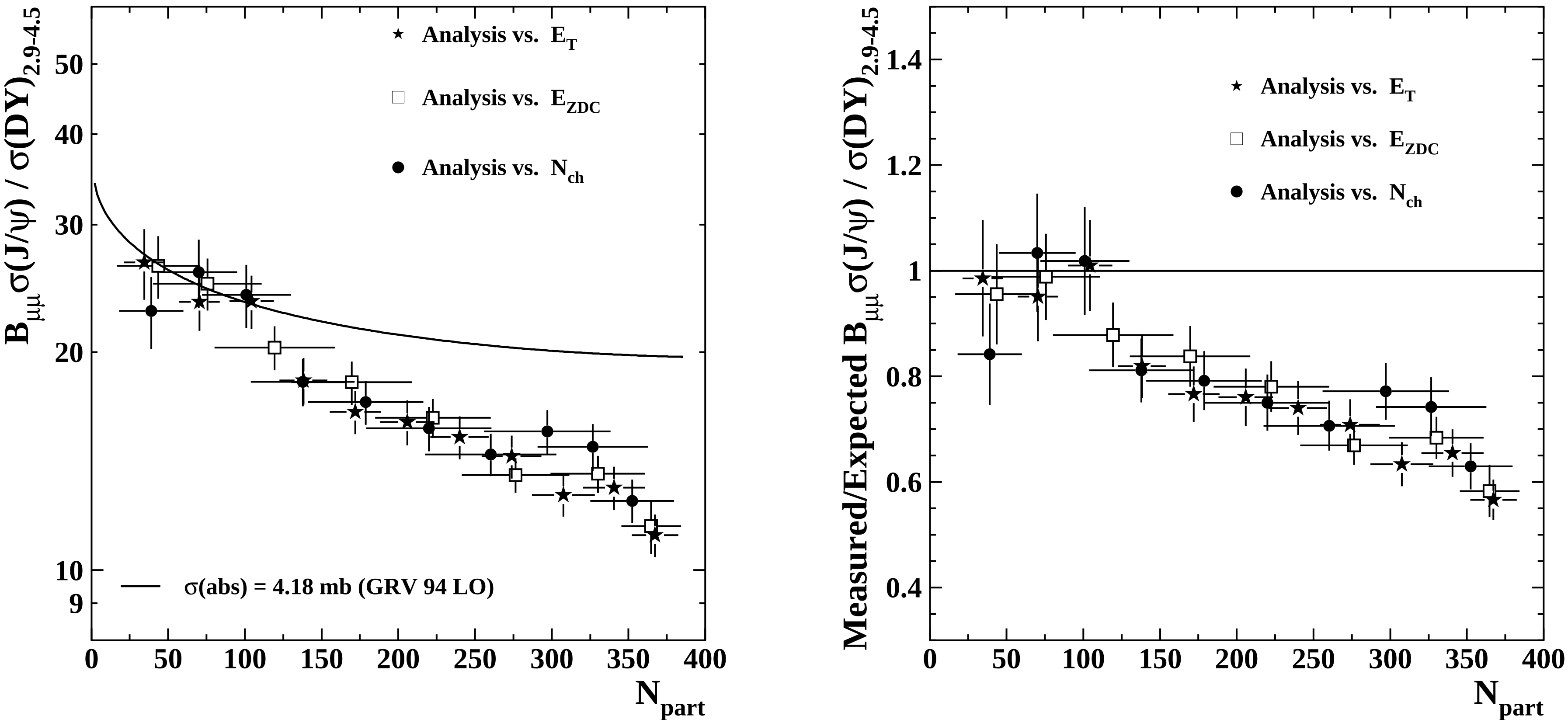
Anomalous J/ψ suppression vs. N_{ch}, E_{ZDC}



Independent analysis vs. N_{ch} . . . . . . and vs. forward energy E_{ZDC}

$\Rightarrow$ similar suppression pattern as previously shown vs. E_T

J/ψ suppression with 3 centrality variables

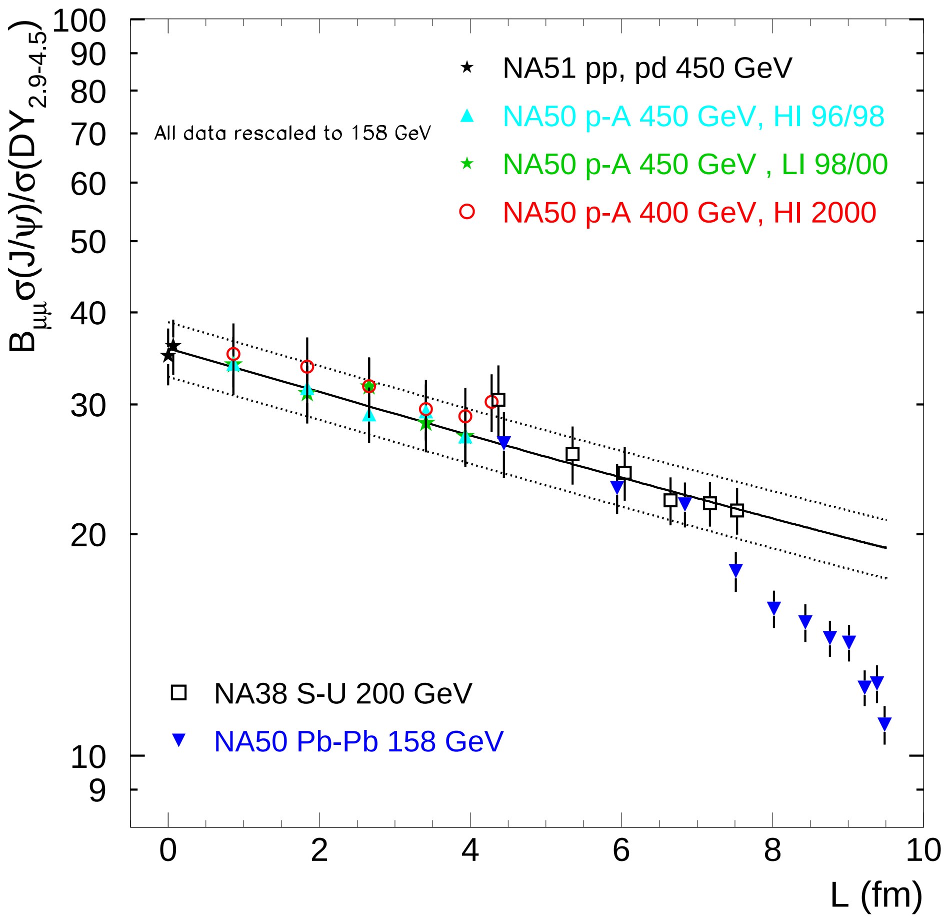


J/ψ/DY ratio

measured/(normal nuclear absorption)

⇒ consistency among three independent analyses

$(J/\psi)/DY$: p-A, S-U and Pb-Pb collisions



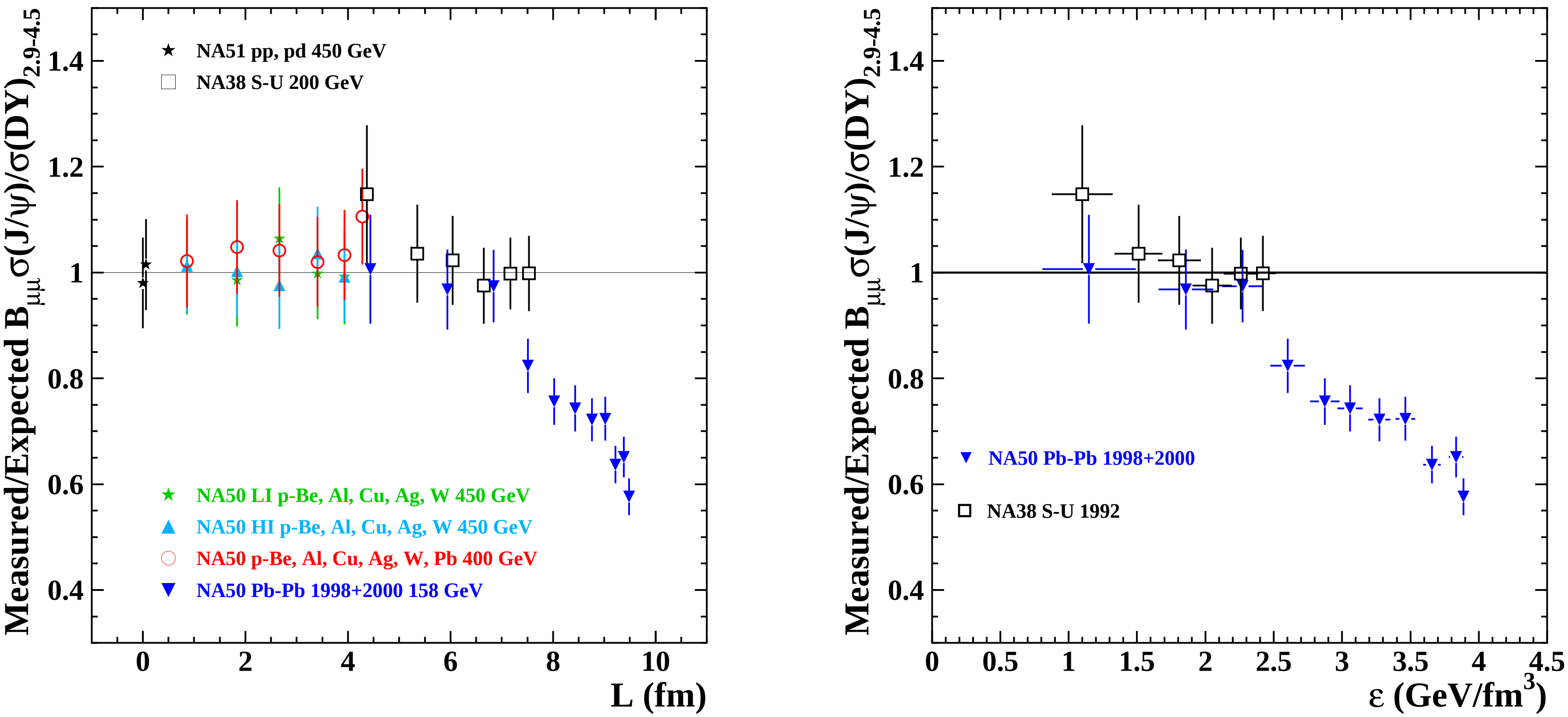
- **Average path L in nuclear matter**: appropriate to visualize nuclear absorption in different systems

- **Absorption curve from p-A data only**

  $\Rightarrow$ allows new conclusion

- **Peripheral Pb-Pb data points but ALSO all of S-U data points compatible with normal nuclear absorption**

$(J/\psi)/DY$: Measured/Expected in A-B collisions



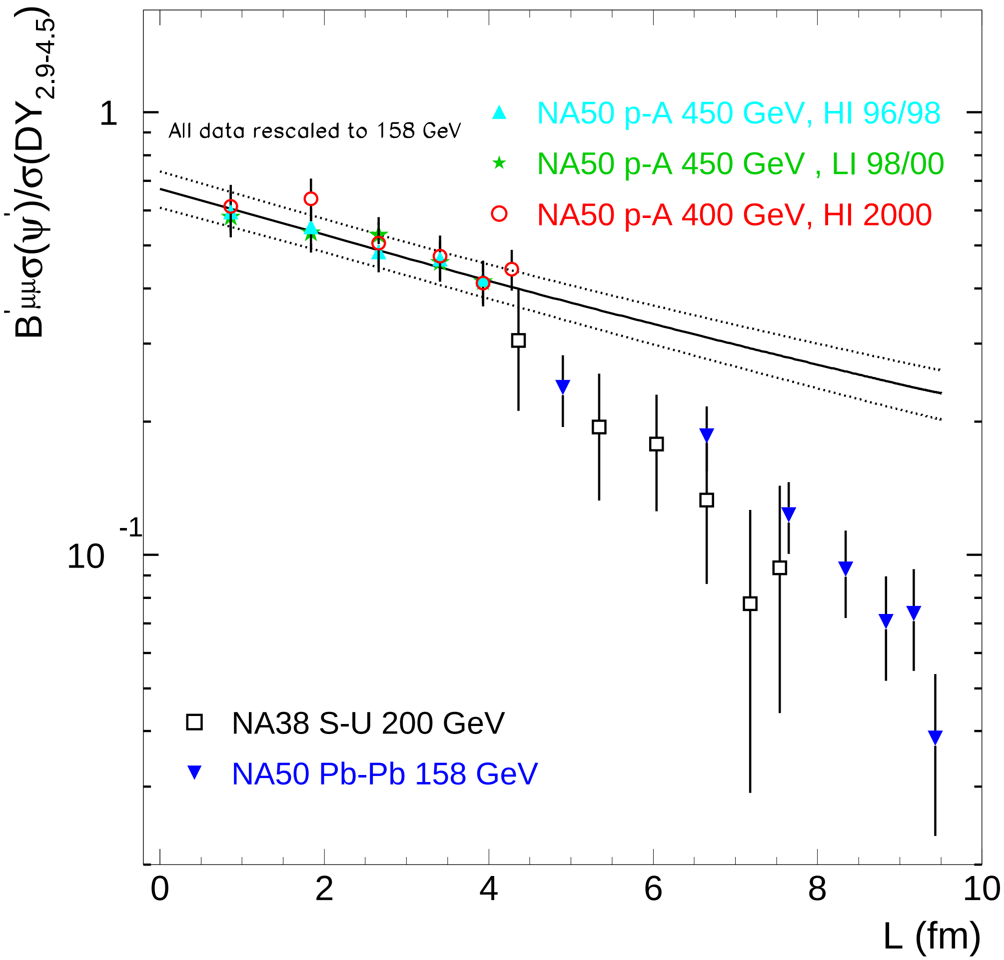
From results of previous slide but here in terms of

"measured/normally expected"

as a function of:

average path L and **energy density** ϵ

ψ'/DY: p-A, S-U and Pb-Pb collisions

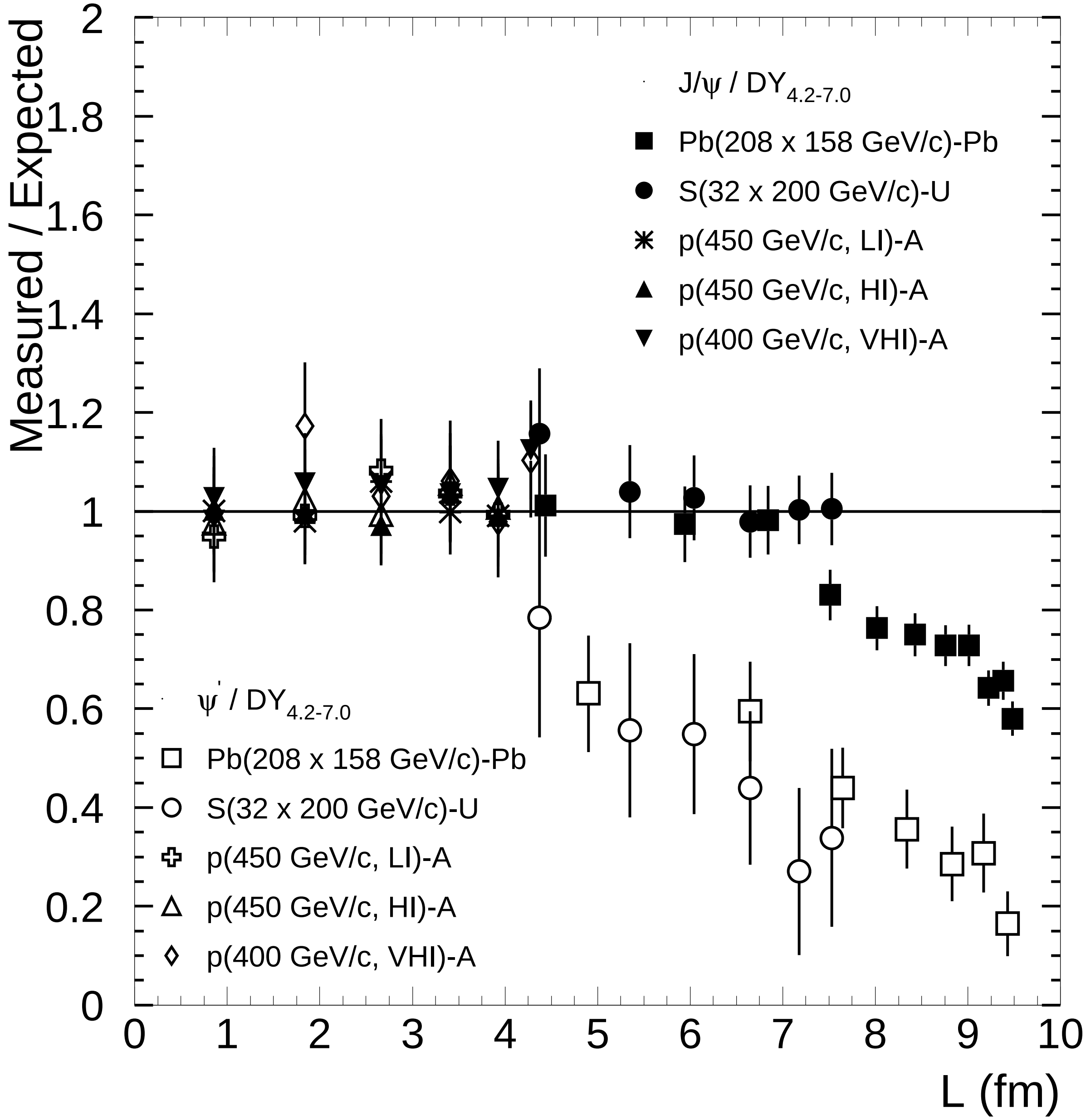


- Glauber fit to p-A ψ'/DY
  $\Rightarrow \sigma^{\psi'}_{abs,pA} = 7.6 \pm 1.1$ **mb**

- **Already in S-U**
  ψ'/DY deviates from p-A behaviour, showing
  larger absorption

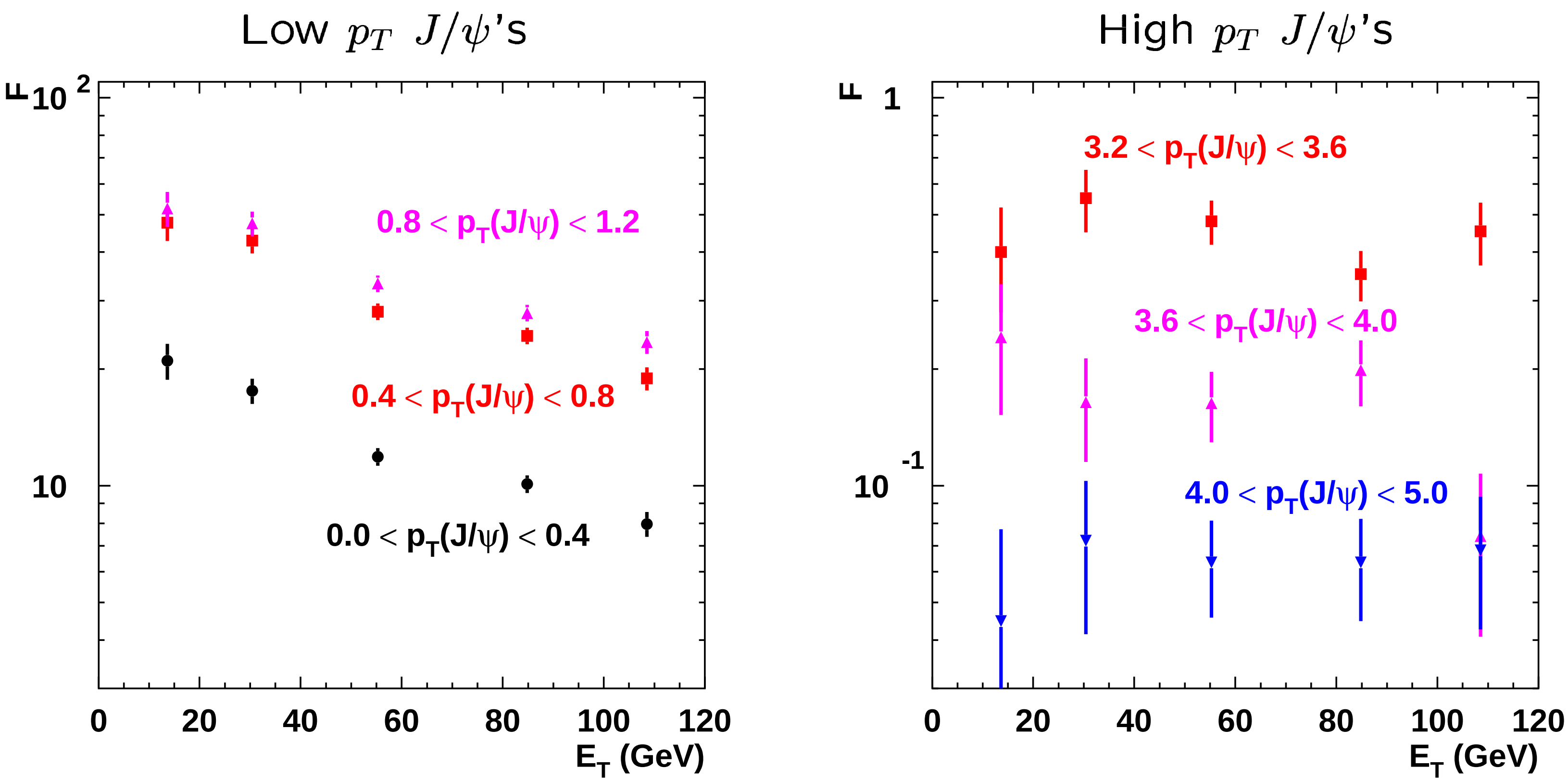
- **Pb-Pb and S-U show very similar ψ' absorption larger than observed in p-A**

NA50: J/ψ and ψ' absorption



J/ψ suppression vs. centrality in p_T bins

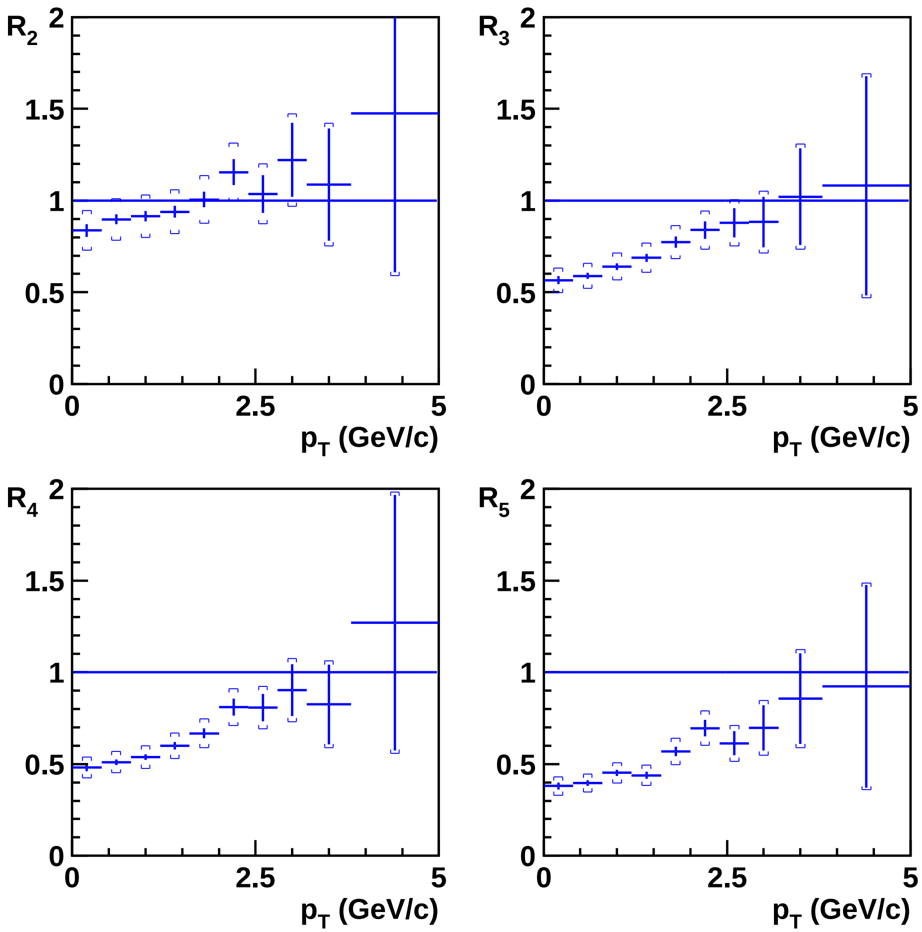
$$F(E_T; p_{Ti}) = N_\psi(E_T; p_{Ti})/N_{DY}(E_T)$$



$F(E_T; p_{Ti})$ is the ratio $(J/\psi)/DY$ limited to J/ψ's in a given p_T bin

⇒ **Anomalous J/ψ suppression is concentrated at low p_T**

J/ψ central to peripheral ratio "R_{CP}" vs. p_T



Ratios $R^i_{CP}(p_T)$ defined as:

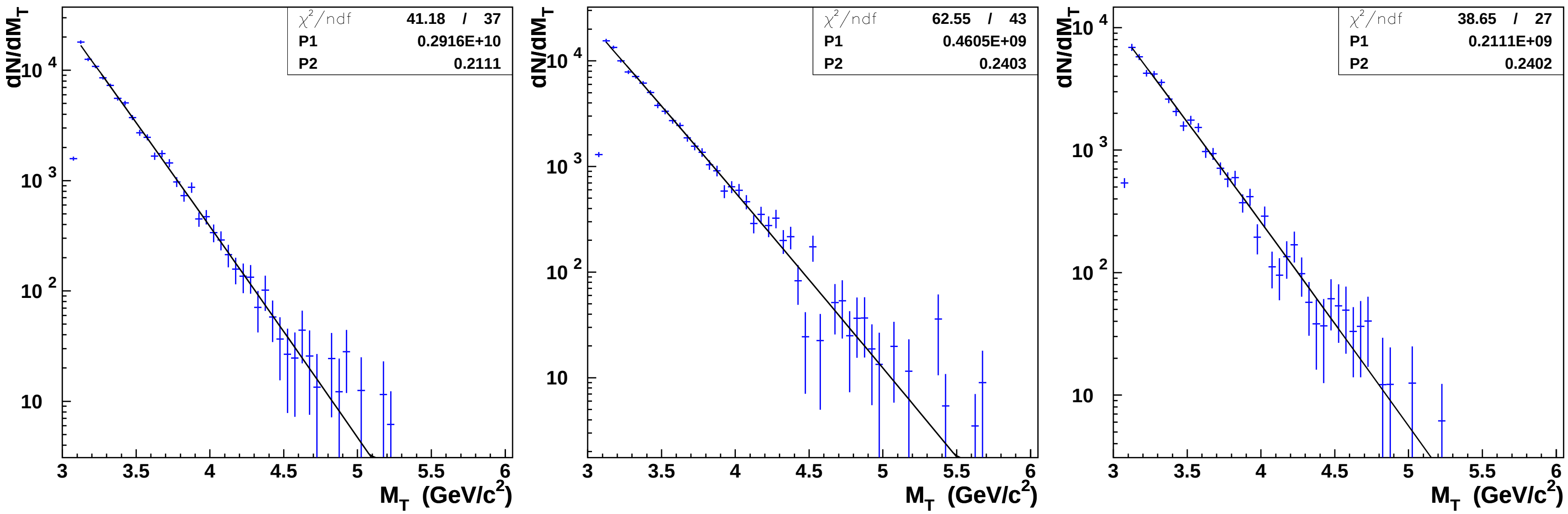
$$\frac{N_{\psi,i}(p_T)}{N_{DY,i}} \Big/ \frac{N_{\psi,1}(p_T)}{N_{DY,1}}$$

with $N_{DY,i}$ prop. to N^i_{coll}

- Central to peripheral ratio R^i_{CP} for centrality bins $i = 2, 5$ where $i = 1$ is the most peripheral bin
- **J/ψ suppression is mainly at low p_T**
- **For $p_T > 3.5$ GeV/c centrality dependence of J/ψ suppression is weak**

J/ψ transverse mass distributions in Pb-Pb

Peripheral | Semi-central | Central



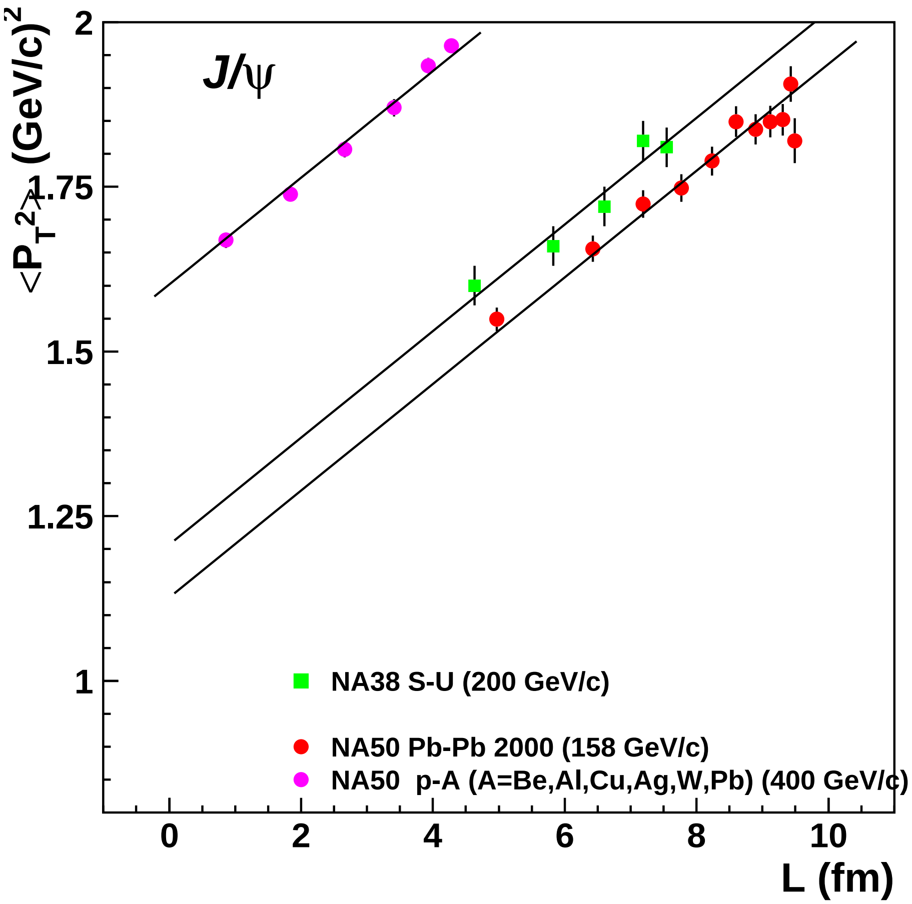
	Peripheral	Semi-central	Central
$T =$	211 ± 2 MeV	240 ± 3 MeV	240 ± 5 MeV
$< p_T^2 > =$	1.55 ± 0.02 GeV^2	1.84 ± 0.02 GeV^2	1.82 ± 0.03 GeV^2

Fit transverse mass distributions dN/dM_T in each centrality bin with thermal model: $M_T^2 K_1(M_T/T)$

Extract effective **temperature** T from fit

note that T and $< p_T^2 >$ are linearly correlated

J/ψ's $< p_T^2 >$ from p-A to Pb-Pb

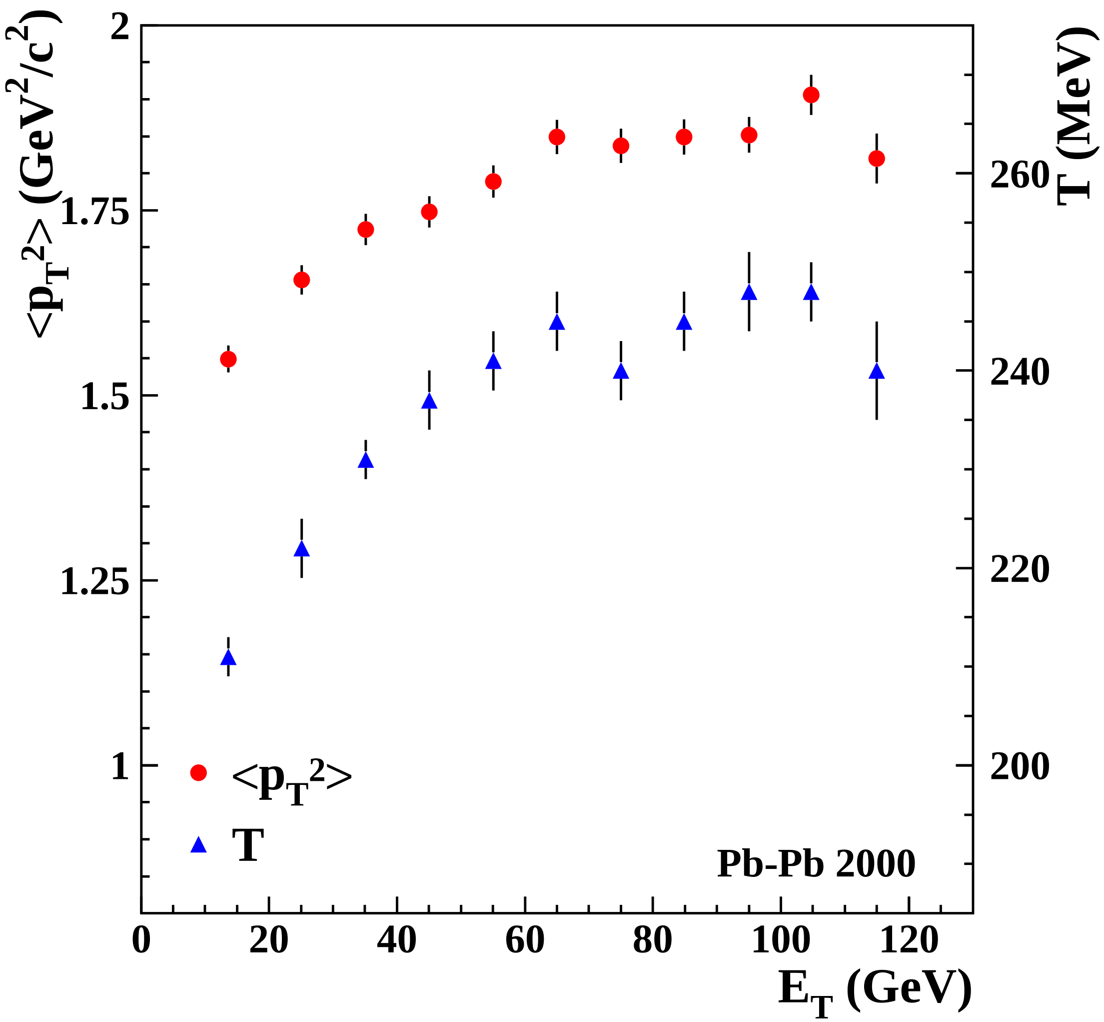


- All systems show that both $< p_T^2 >$ **and** T are **linearly increasing** with average path L

- Attributed to multiple scattering of initial partons (gluons)

- Phenomenological description with the expression:
  $< p_T^2 > (L) =< p_T^2 >_{pp} + \alpha_{gN} L$
  with an energy dependent $< p_T^2 >_{pp}$ and a common slope:
  $\alpha_{gN} = 0.081 \pm 0.002$ GeV^2/c^2/fm

$< p_T^2 >$ and T of surviving J/ψ's vs. centrality



- More detailed examination of $< p_T^2 >$ and T in Pb-Pb vs. centrality (here vs. measured E_T)

$$\Downarrow$$

- **Saturation of:**

  $< p_T^2 >$ **vs.** E_T

  is observed for central Pb-Pb collisions

- **Same behaviour for:**

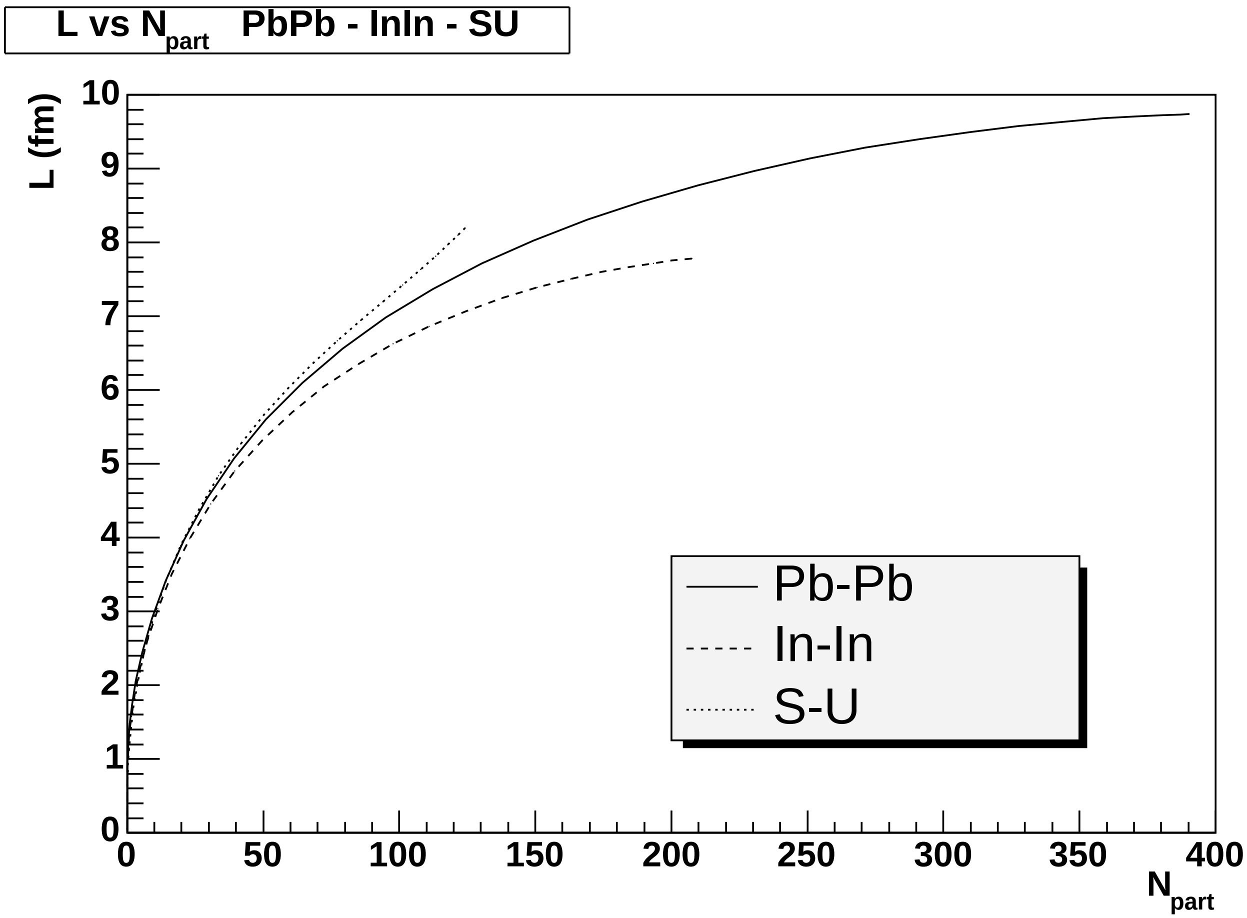
  T **vs.** E_T

Charmonium: open questions after NA50

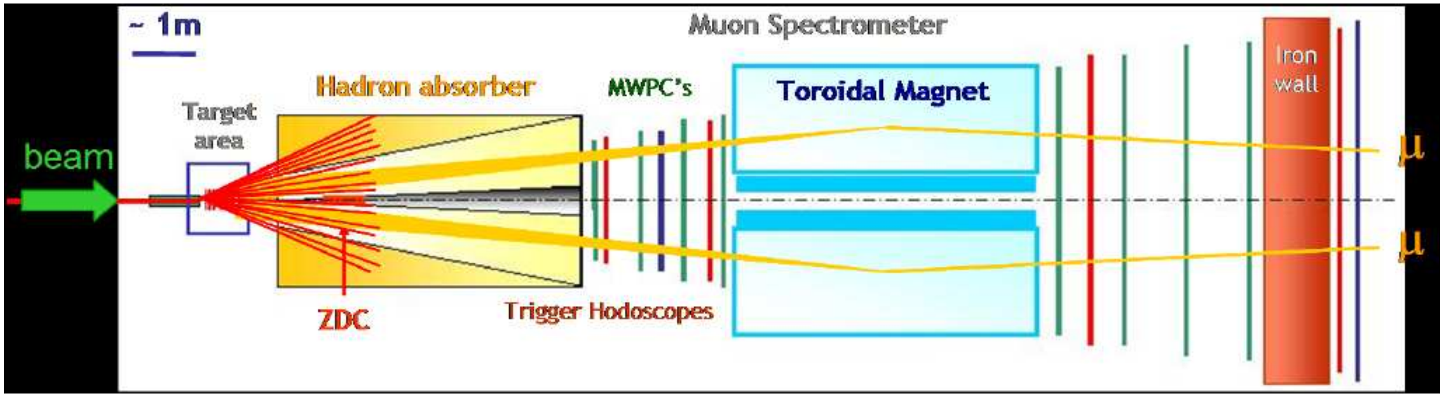
- Is **anomalous suppression** also present in lighter nuclear systems ?
- Which is the variable driving the suppression ?
  - among different **centrality variables**: length of path in nuclear matter L, number of participants N_{part}, energy density ϵ, ... any of them could be the relevant one
  - studying different centrality variables and comparing **different systems** will help disentangle the issue
- Which is the value of $\sigma_{\mathrm{abs}}^{J/\psi}$ at the heavy ion energy of SPS ?
- What contribution of χ_c **feed-down** on the observed J/ψ suppression pattern ?

NA60 experiment designed to answer these questions by collecting new and accurate data on **In-In** collisions and **p-A** collisions at **158** GeV

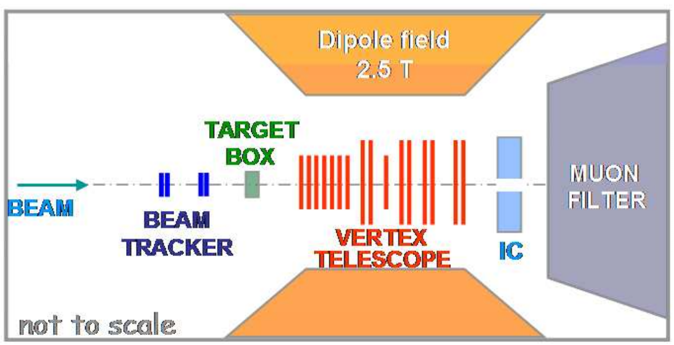
L vs. N_{part} in three systems



The NA60 experiment



NA50 dimuon spectrometer + NEW vertex spectrometer



radiation hard vertex telescope: measure muons before they suffer multiple scattering and energy loss

matching in coordinate and momentum space: $\sigma \simeq 70$ MeV/c^2 at the J/ψ

origin of muons precisely determined

Main centrality detector:
Zero Degree Calorimeter

NA60 $(J/\psi)/DY$ analysis

- NA60 **In-In** data collected in 2003 with two samples:
  - 4000 A in magnet: higher acceptance for J/ψ and DY
  - 6500 A in magnet: better mass resolution, lower comb. background

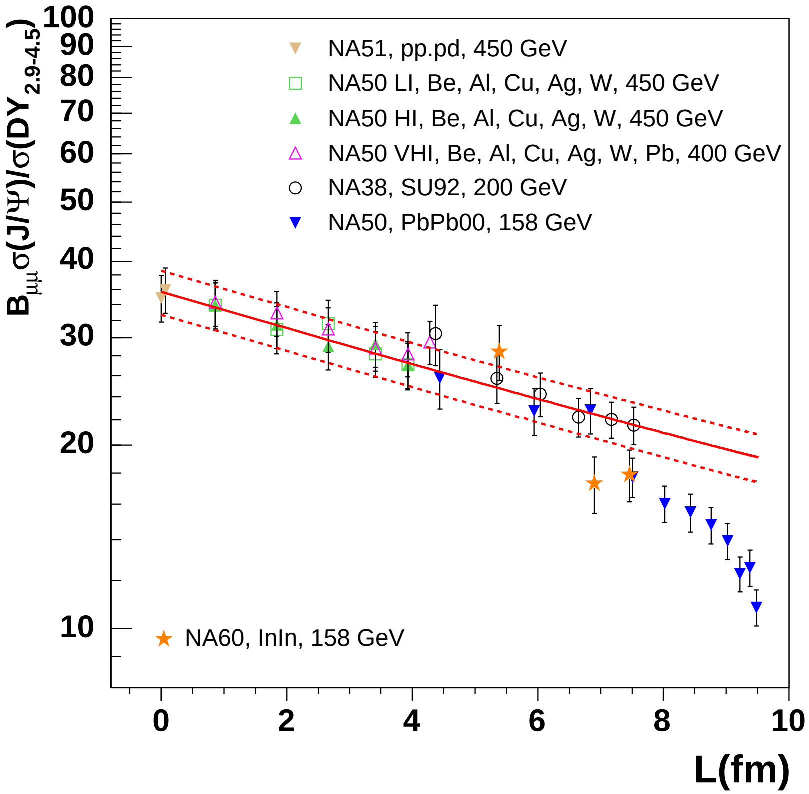
- $J/\psi/DY$ ratio of two processes collected with same trigger, inefficiencies and biases **cancel out** (no requirement on matching, same result with larger stat. errors when matching is required)

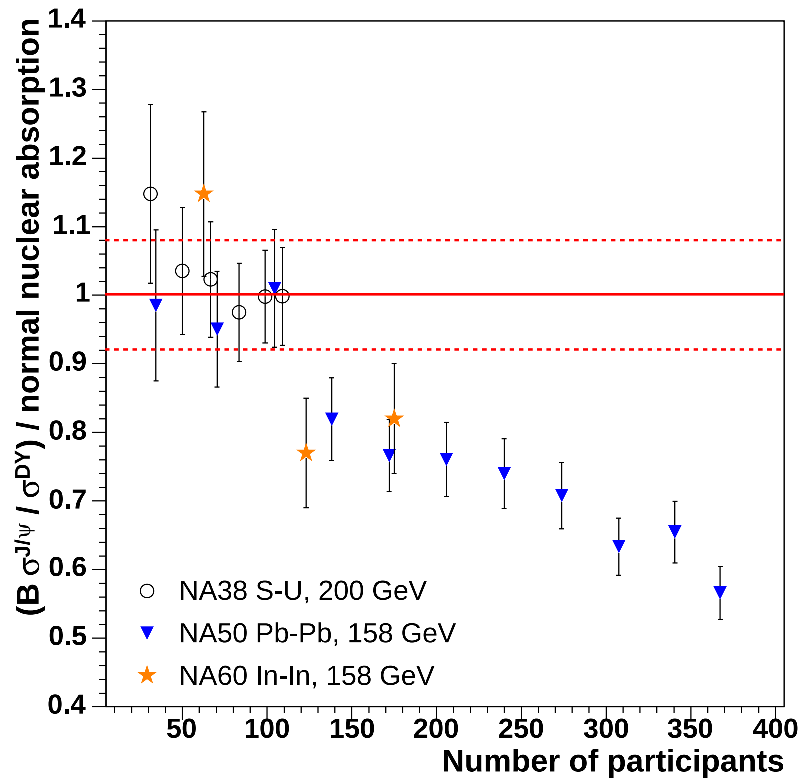
- Drell-Yan is a **hard process** whose cross-section scales with the number of collisions and does not suffer final state effects

- easy comparison with NA50 (Pb-Pb, p-A) and NA38 (S-U) results

- **statistical errors** are imposed by the $\approx$ 100 times smaller DY process
  - only 3 centrality bins for In-In

NA60 $(J/\psi)/DY$ result





Anomalous suppression is present already in **Indium-Indium** collisions

Uncertainty on absolute value of absorption curve ($\approx 8\%$) dominated by extrapolation of p-A data from 450, 400 GeV: **new p-A data** collected at 158 GeV in 2004, analysis under way

NA60 direct J/ψ analysis

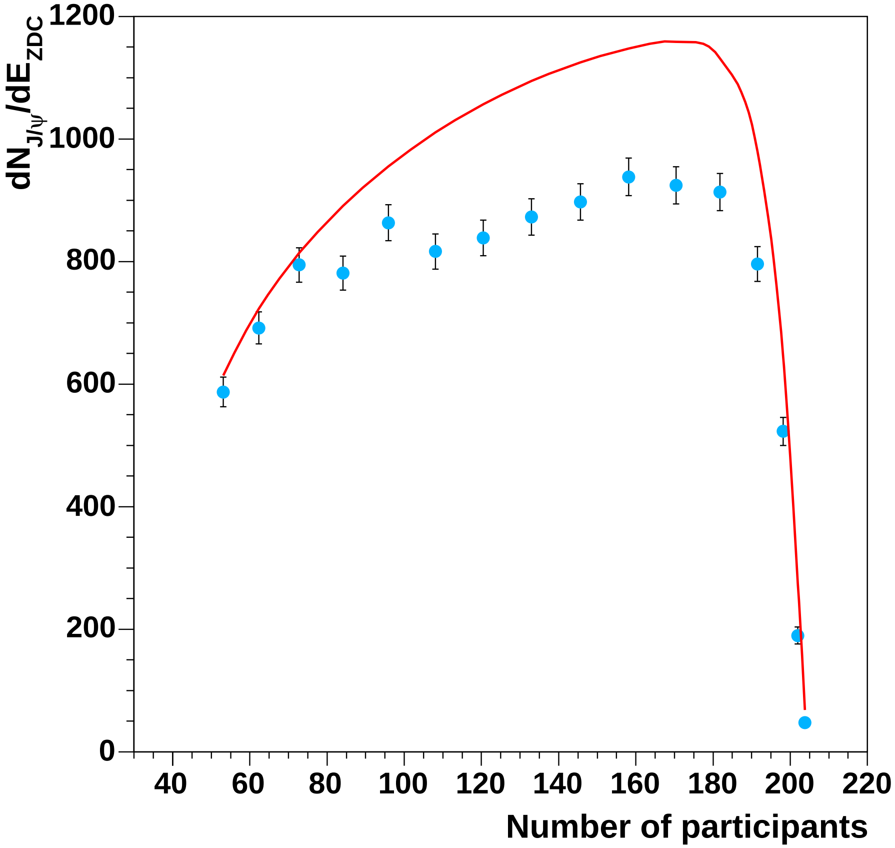
- Compare measured J/ψ **sample** (vs. centrality) with theoretical distribution expected in case of pure nuclear absorption, computed using Glauber model and measured $\sigma_{\text{abs}}^{J/\psi}$

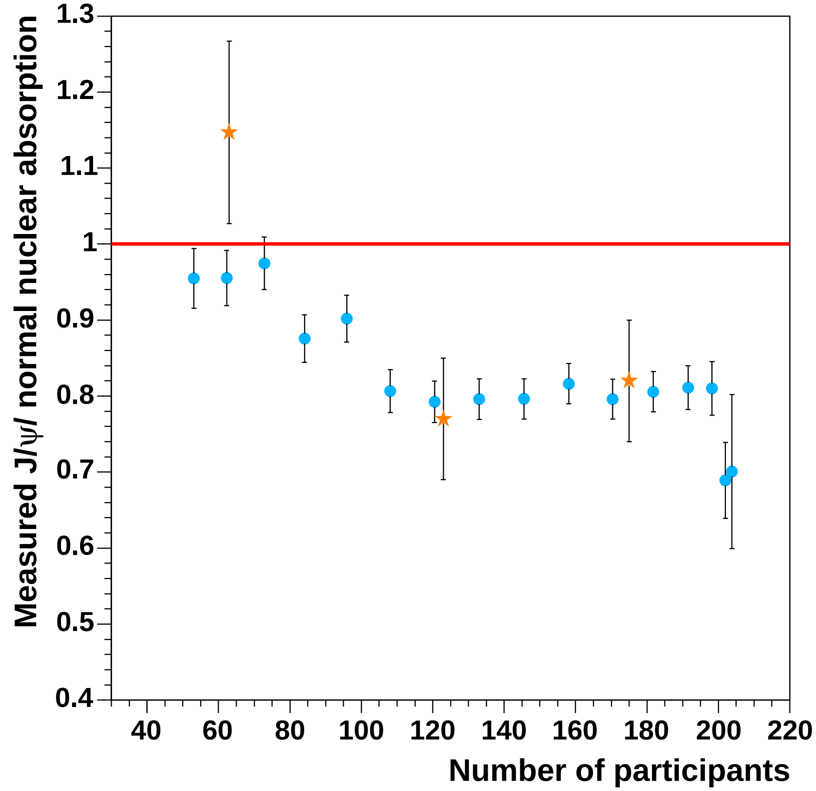
- Use only **matched** J/ψ's (cleaner spectrum), subtract combinatorial background

- Advantages of the direct J/ψ analysis:
  - small stat. errors, **detailed pattern** vs. centrality
  - only dimuon trigger involved
  - event selection and vertexing efficiencies do not depend practically on centrality

- Drawback: **no intrinsic normalization**
  - normalize to the standard $(J/\psi)/DY$ analysis for $E_{\text{ZDC}} < 11$ TeV

NA60 direct J/ψ result (1)

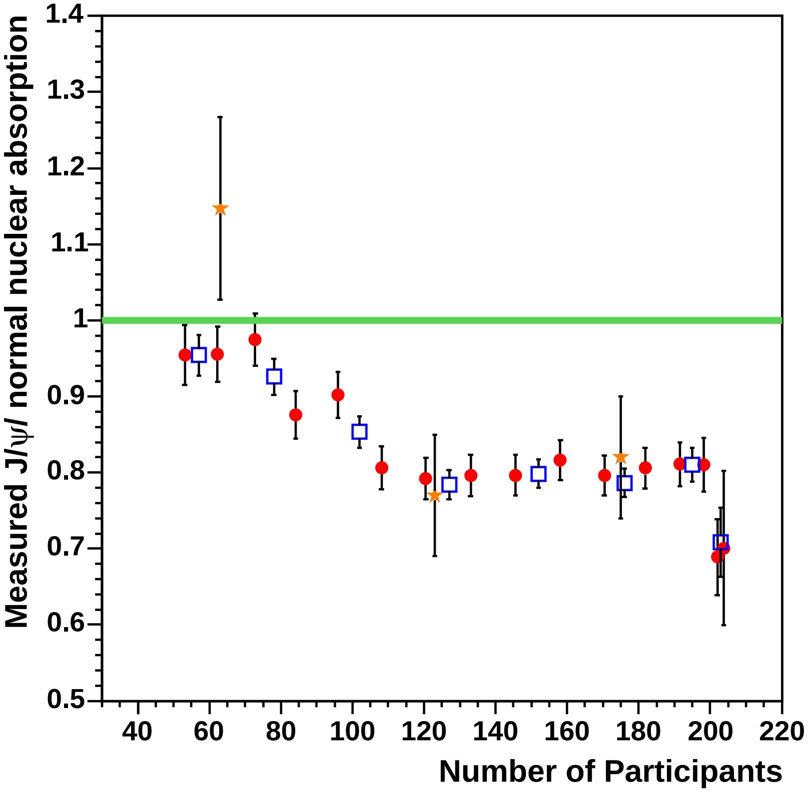


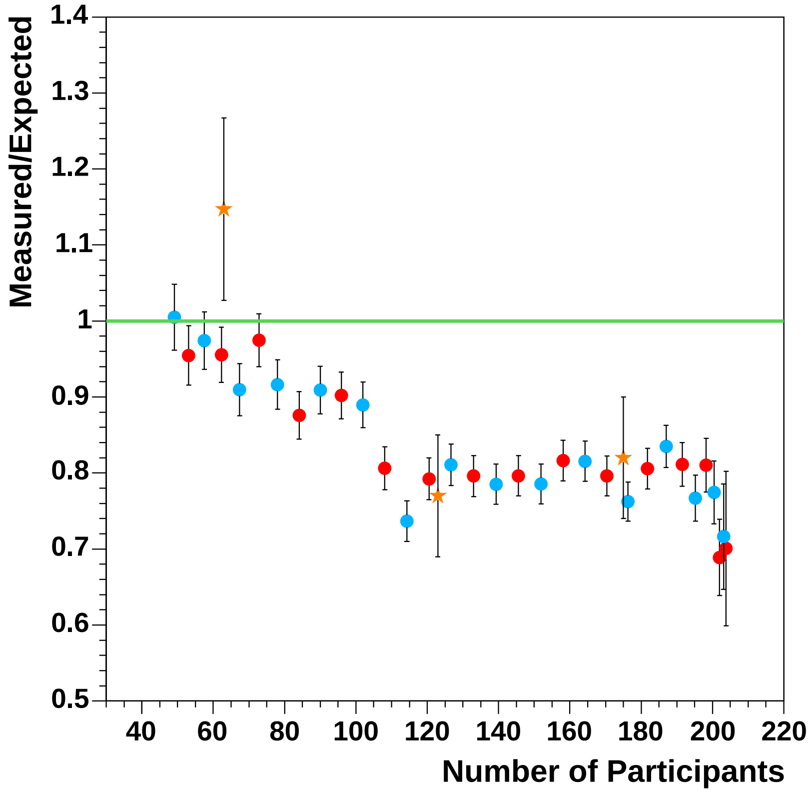


Onset of anomalous suppression in the range $80 < N_{\text{part}} < 100$

Saturation at large N_{part}

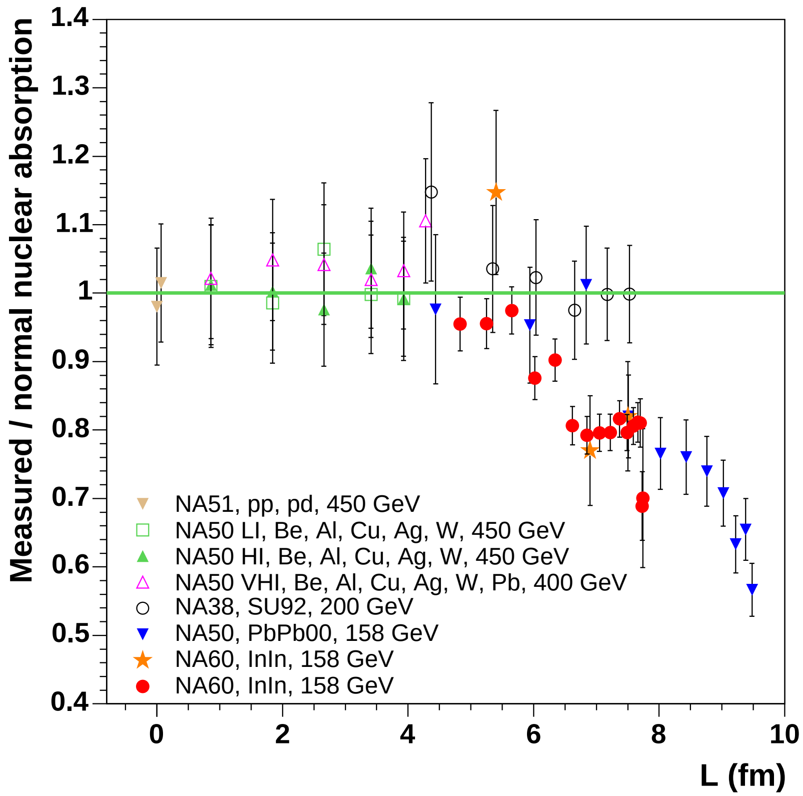
NA60 direct J/ψ result (2)

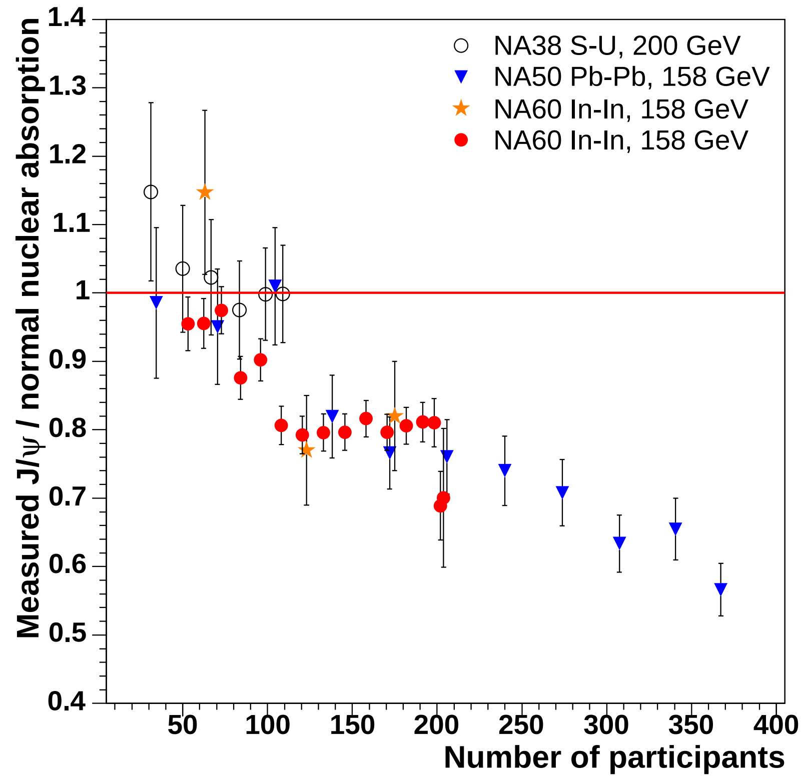




Observed pattern confirmed by similar analyses with a reduced number of bins (width: 2 TeV instead of 1 TeV) or with 16 bins shifted by half bin width

Direct J/ψ result and previous results (1)

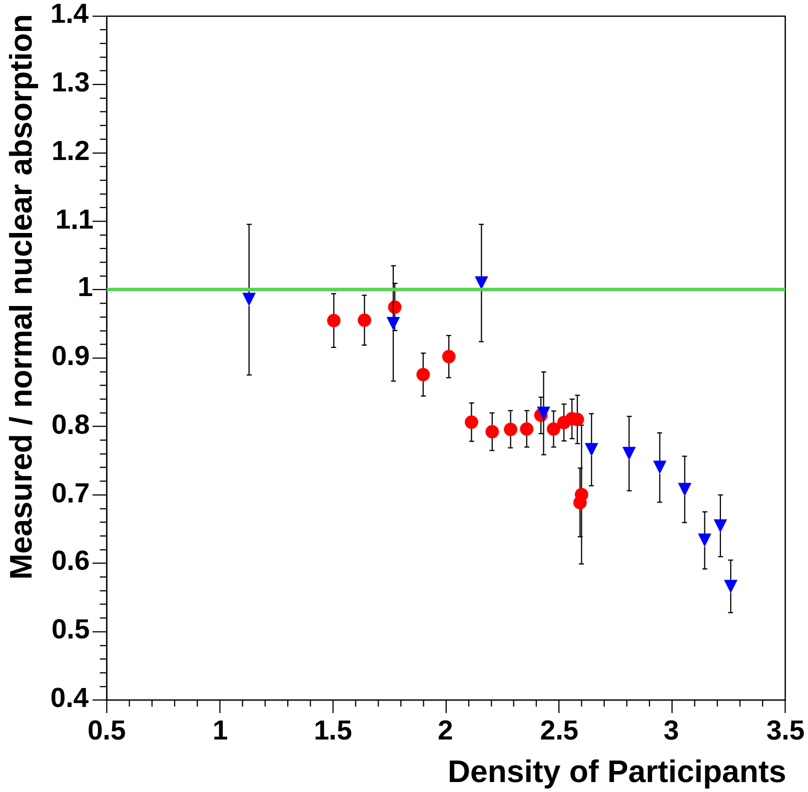


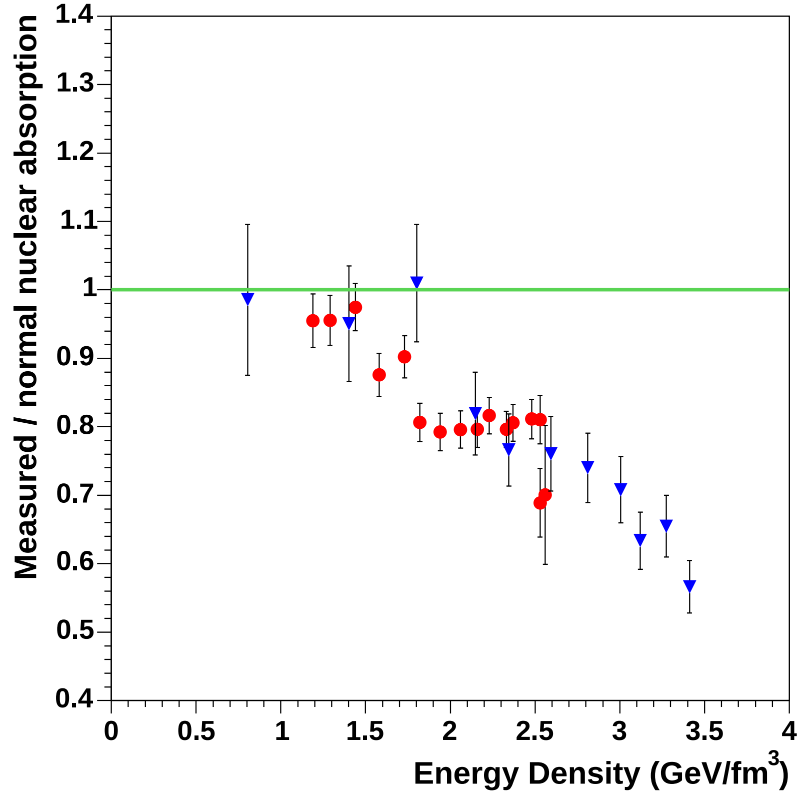


The S-U, In-In and Pb-Pb data points do not overlap in the L variable

The J/ψ suppression patterns are in fair agreement in the N_{part} variable

Direct J/ψ result and previous results (2)

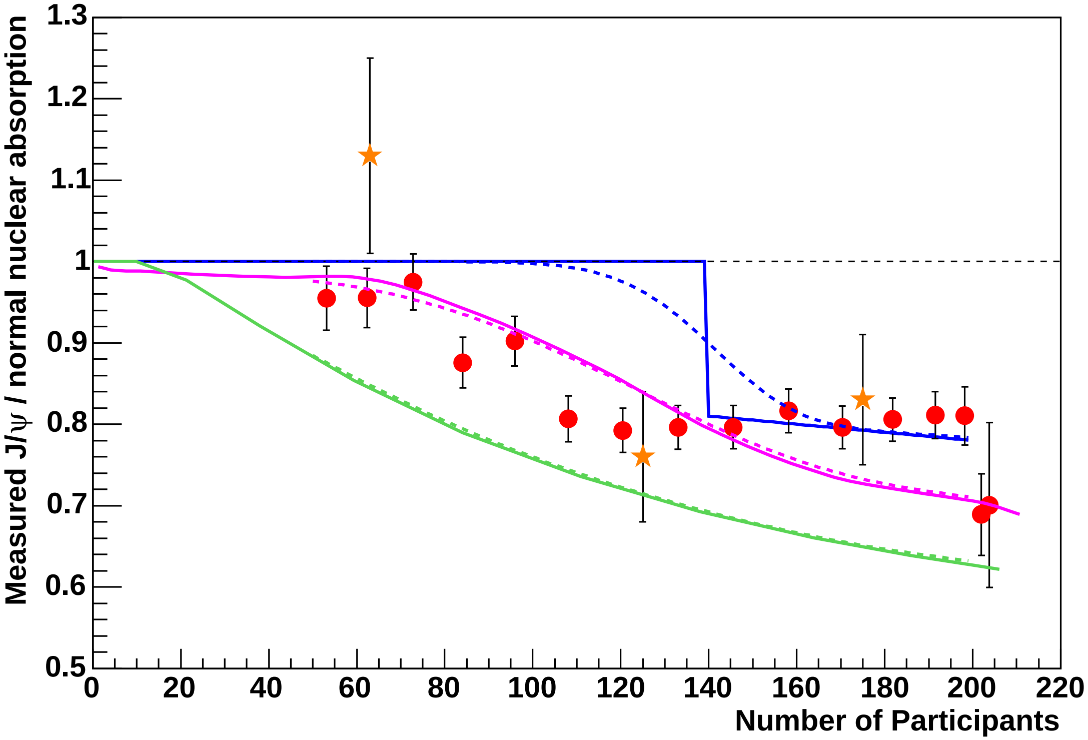




Density of participants (see hep-ph/0408050) is preliminary and does not include smearing due to experimental resolutions

Bjorken energy density has been estimated with VENUS

NA60 Direct J/ψ: comparison with models



- Models **previously tuned** to p-A, S-U and Pb-Pb suppression patterns obtained by NA38 and NA50
- Predictions specifically made for **In-In** collisions:
  1. **Satz et al.** [Eur. Phys. J. C32 (2004) 547]: χ_c suppression in percolation model, predicts onset at $N_{\text{part}} \approx 140$, In-In data alone favour onset at 90
  2. **Rapp et al.** [Nucl. Phys. A715 (2003) 545; PRL 92 (2004) 212301; hep-ph/0403204]: suppression in QGP and hadronic phases + thermal regeneration
  3. **Capella et al.** [hep-ph/0505032]: nuclear + comover absorption

Energy density: NA50 evaluation

$$\epsilon = \frac{dE_T/d\eta_{max}}{c\tau \cdot A_T} = \frac{a \cdot b \cdot E_{T,cal}}{c\tau \cdot A_T \cdot \Delta\eta} \qquad \text{(Bjorken, 1983)}$$

- $E_{T,cal}$ is the measured transverse energy in the e.m. calorimeter, in GeV
- b is the conversion factor from measured to total transverse energy
- a is the conversion factor from $\langle dE_T/d\eta \rangle$ in the calorimeter coverage to $dE_T/d\eta_{max}$, depending on centrality
- $c\tau$ is taken as 1 fm (at least for SPS energies)
- A_T is the transverse area of overlap between colliding nuclei in fm^2, evaluated within the Glauber model
- $\Delta\eta$ is the calorimeter η coverage (different in NA38 and NA50)

Adopting the wounded nucleon model for E_T production, $E_{T,cal} = qN_w$:

$$\epsilon = \frac{a \cdot b \cdot q \cdot N_w}{c\tau \cdot A_T \cdot \Delta\eta} = \mathrm{C} \cdot \frac{N_w}{A_T}$$

with factor C depending on colliding system (b, q, $\Delta\eta$) and centrality (a)

Energy density: NA60 evaluation

- Bjorken's formula with $c\tau = 1$ fm

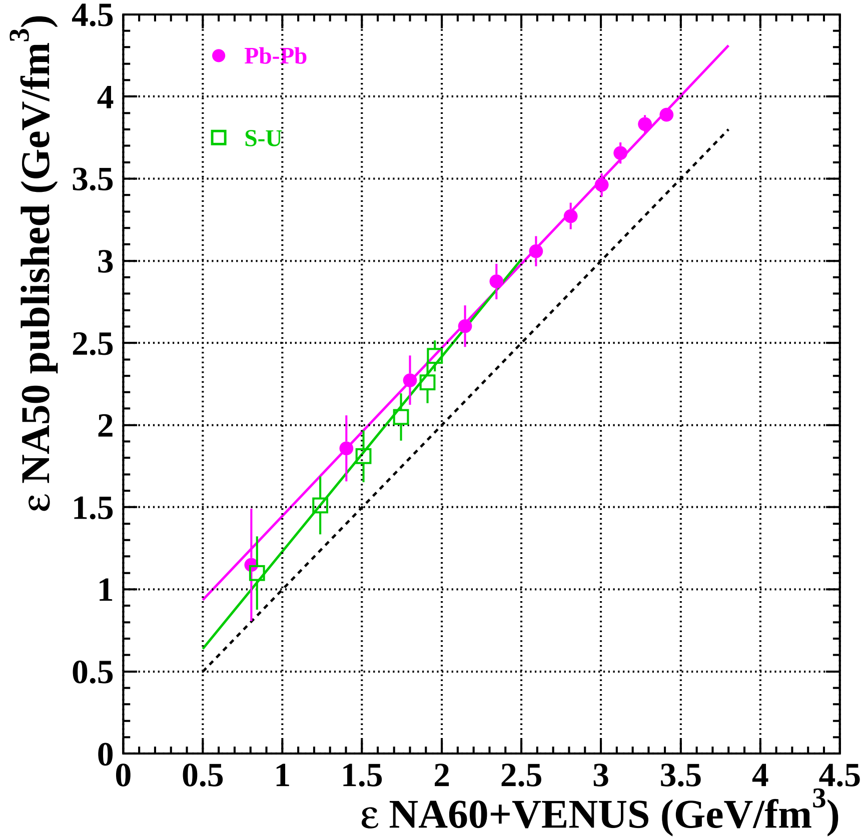
- transverse area of overlap from Glauber calculation

- total E_T (π's, K's, p's) at midrapidity obtained using **VENUS 4.12** for the three systems: S-U, Pb-Pb and In-In, and correlated to the number of participants N_{part} (it has been verified that VENUS gives a reasonable description of measured E_T distributions on the Pb-Pb measurement of NA49)

- correlation ϵ vs. N_{part} using Bjorken's formula

- for each centrality bin, assigned from **measured E_T (S-U, Pb-Pb)** or from **measured E_{ZDC} (In-In)**, the average N_{part} and therefore ϵ is obtained

Energy density: NA50 vs. NA60



- Considering the 3rd and 4th Pb-Pb points and the 6th S-U point we see that published NA50 energy densities are about 25% higher than the NA60-VENUS evaluation

- The pattern of J/ψ suppression vs. ϵ and the relative position of S-U and Pb-Pb data points are practically unchanged between the two evaluations

The NA60-VENUS method gives lower energy densities for both S-U and Pb-Pb,

but the **comparison between the S-U and Pb-Pb** J/ψ **absorption patterns** in the two cases is **robust**
The NA60-VENUS method is so far the only one allowing a comparison between NA60 (centrality given by $E_{\rm ZDC}$) and other experiments (centrality given by $E_{\rm T}$)

Conclusions on charmonium at SPS (1)

- **Charmonium production and suppression:**
  with **normal** nuclear absorption **derived from p-A collisions only**
  NA50 finds in Pb-Pb collisions at 158 GeV/nucleon:
  - $(J/\psi)/DY$:

    ♢ **Anomalous suppression** in semicentral and **central** collisions

    ♢ **Peripheral Pb-Pb BUT ALSO ALL OF S-U** production in **agreement with normal** nuclear absorption

    ♢ **Anomalous suppression** of J/ψ mostly **at low** J/ψ p_T

  - ψ'/DY:

    ♢ **same suppression pattern in S-U and in Pb-Pb**, **very different from** normal absorption in **p-A collisions**

- J/ψ **transverse momentum distributions:**

  ♢ **saturation of** $< p_T^2 >$ **and temperature** T **for central Pb-Pb collisions**

Conclusions on charmonium at SPS (2)

- **Charmonium suppression** in **In-In** collisions:

  NA60 finds in collisions at 158 GeV/nucleon:

  – $(J/\psi)/DY$ standard analysis:

  ♢ **Anomalous suppression** is already present in In-In

  – direct J/ψ analysis:

  ♢ suppression in In-In is **centrality dependent** and sets in at a number of **participants** $\approx$ **90**

  – **none** of the available models (tuned to p-A, S-U and Pb-Pb collisions) properly describes the observed suppression pattern

References for Charmonium results at SPS

- Historical overview of J/ψ suppression at CERN SPS
  - L. Kluberg, Eur. Phys. J C43 (2005) 145

- NA50 proton-nucleus results, normal absorption curve
  - M.C. Abreu et al. (NA50 Collab.), Phys. Lett. B553 (2003) 167
  - B. Alessandro et al. (NA50 Collab.), Eur. Phys. J C33 (2004) 31
  - G. Borges at al. (NA50 Collab.), Eur. Phys. J C43 (2005) 161
    and NA50 Collab., Charmonium production and nuclear absorption in p-A interactions at 400 GeV, *in prep.*

- NA50 Pb-Pb results (recently analyzed 1998, 2000 data)
  - B. Alessandro et al. (NA50 Collab.), Eur. Phys. J C39 (2005) 335
  - L. Ramello for the NA50 Collab., Proc. QM 2005 [http://qm2005.kfki.hu/]

- NA60 In-In results (preliminary analysis)
  - E. Scomparin for the NA60 Collab., Proc. QM 2005 [http://qm2005.kfki.hu/]
  - R. Arnaldi for the NA60 Collab., Proc. QM 2005 [http://qm2005.kfki.hu/]