Charmonium production and suppression as a signal of QGP formation in heavy-ion collisions

Illustrated edition

Outline:

- The (pre-)history of J/ψ suppression…

  … and of the QCD phase diagram

- Looking for quark-gluon deconfinement with quarkonium probes
- Is the J/ψ suppression pattern "smoothy" or "steppy"?
- From expectations to achievements: what have we learned?

The strange ups and downs of charmonia souppression

Carlos Lourenço, CERN
Third International Workshop on Charm Physics, Charm 2009, Leimen, May 2009

The first time the J/ψ was suppressed...

Observation of Muon Pairs in High-Energy Hadron Collisions*

J. H. Christenson,[†] G. S. Hicks,[‡] L. M. Lederman, P. J. Limon, and B. G. Pope[§]
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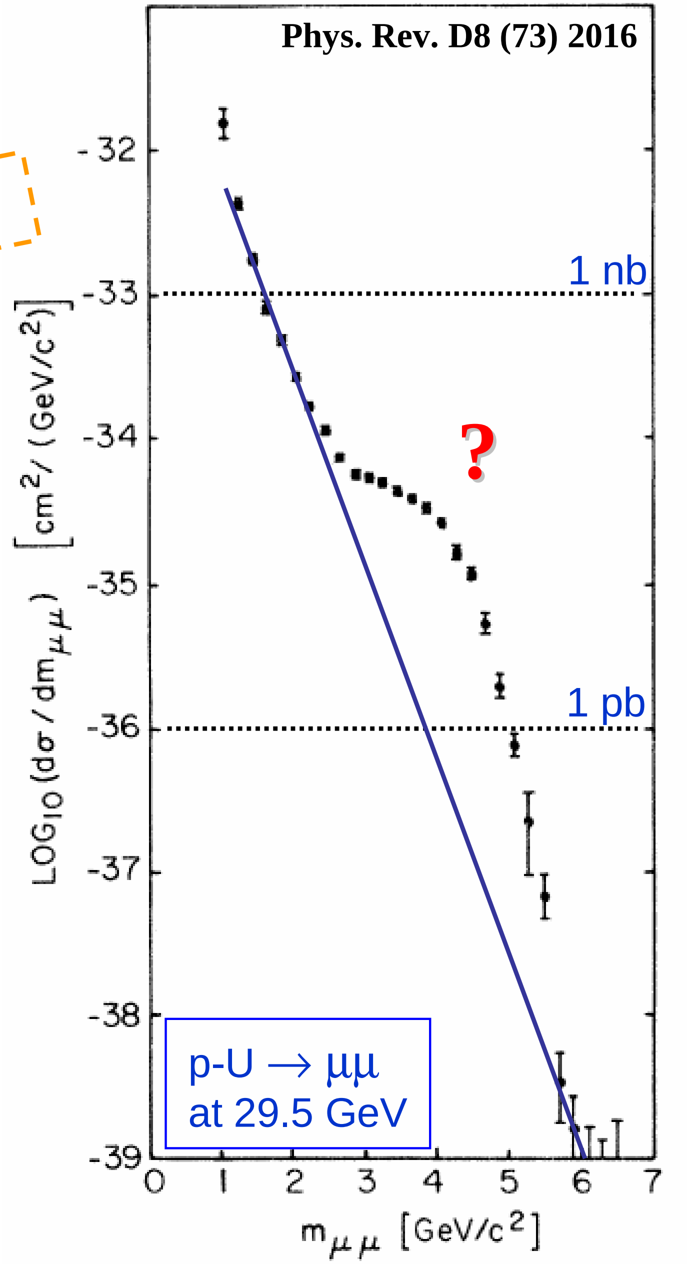
E. Zavattini
CERN Laboratory, Geneva, Switzerland
(Received 30 March 1973)

Early 70's

Muon pairs with effective masses between 1 GeV/c^2 and 6.5 GeV/c^2 have been observed in the collisions of 30-GeV protons with a uranium target. The production cross section was seen to vary smoothly with mass exhibiting no resonant structure.

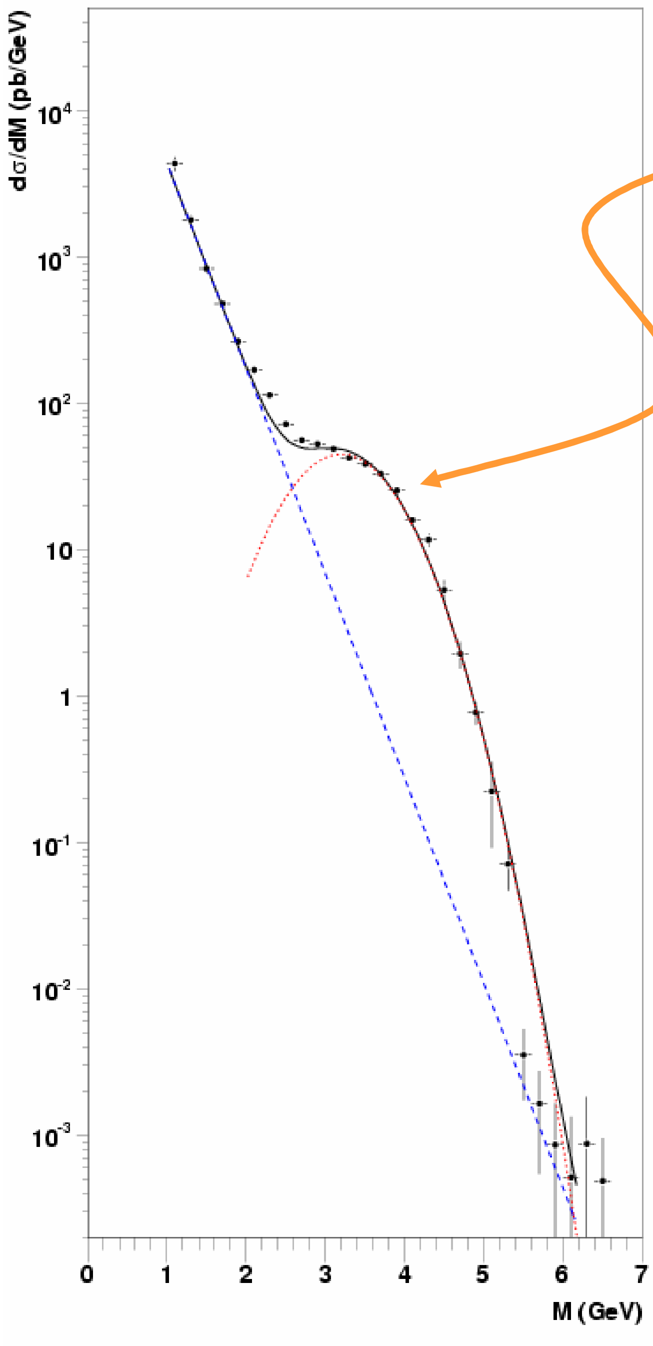
VII. SUMMARY AND CONCLUSIONS

(2) No resonances (i.e., 1^- bumps) are observed,



Lederman was a careful person...
and ***not*** in a hurry to get the Nobel prize

The paper gives plenty of detailed information, including all the numerical values…
We can fit the data to the sum of an exponential continuum and a Gaussian “peak”



It works quite well, with a “resonance” centered at ~3.2 GeV with ~600 MeV dimuon mass resolution

Mass (GeV/c^2)	$\frac{d\sigma}{dm}$ [$cm^2/(GeV/c^2)$]	Random errors (%)	Systematic errors (%)
1.1	1.61×10^{-32}	24	65
1.3	4.37×10^{-33}	11	65
1.5	1.80×10^{-33}	8	60
1.7	8.38×10^{-34}	8	55
1.9	4.81×10^{-34}	5	45
2.1	2.66×10^{-34}	5	35
2.3	1.69×10^{-34}	5	30
2.5	1.14×10^{-34}	5	30
2.7	7.21×10^{-35}	5	30
2.9	5.60×10^{-35}	7	35
3.1	5.32×10^{-35}	7	35
3.3	4.90×10^{-35}	6	30
3.5	4.24×10^{-35}	6	30
3.7	3.86×10^{-35}	7	25
3.9	3.30×10^{-35}	6	25
4.1	2.55×10^{-35}	7	30
4.3	1.60×10^{-35}	7	30
4.5	1.17×10^{-35}	10	30
4.7	5.32×10^{-36}	17	35
4.9	1.95×10^{-36}	21	35
5.1	7.72×10^{-37}	18	35
5.3	2.24×10^{-37}	59	35
5.5	7.09×10^{-38}	34	50
5.7	3.52×10^{-39}	51	50
5.9	1.64×10^{-39}	67	65
6.1	8.58×10^{-40}	92	75
6.3	5.13×10^{-40}	161	80
6.5	8.73×10^{-40}	110	85
6.7	4.84×10^{-40}	97	90

Observation of Muon Pairs in High-Energy Hadron Collisions*

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E. Zavattini

I see a resonance; you see a resonance; how can they have missed it?

Maybe they also saw it !
And they did not claim the discovery of a new particle because...
…they did not know how to name it ☺

The Christ particle? The Hicks boson? The Limon? The Pope particle?

Not an easy choice... Imagine me arriving at Rome’s airport:
Customs’ officer: Purpose of your visit to Italy?
Answer: Giving a lecture on “Pope suppression with nuclear collisions”

Double J/ψ production, and the Nobel

VOLUME 33, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 1974

Experimental Observation of a Heavy Particle J†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

Y. Y. Lee
Brookhaven National Laboratory, Upton, New York 11973
(Received 12 November 1974)

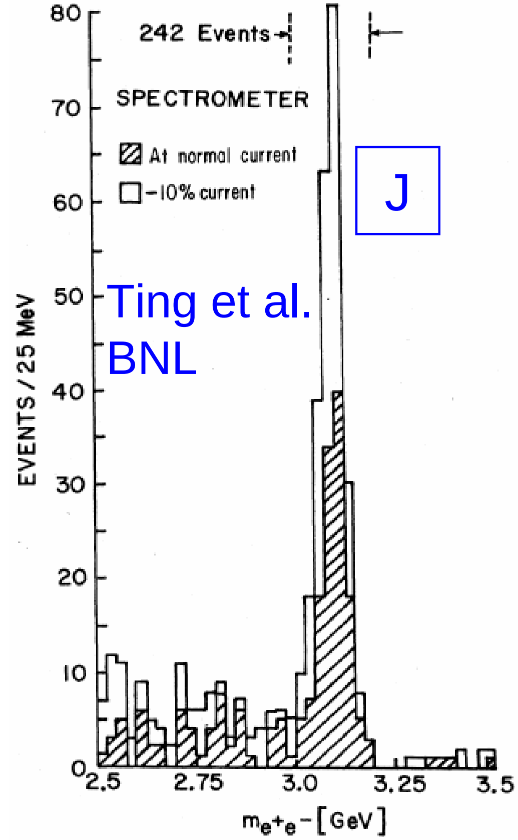
1974

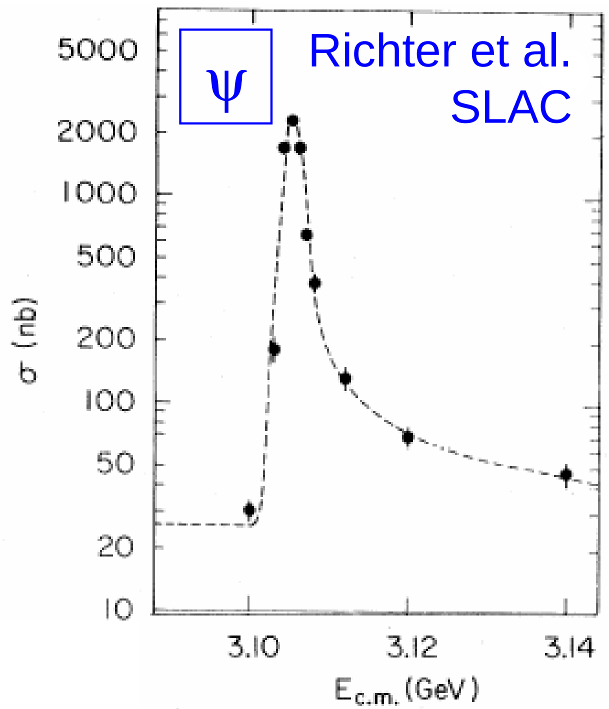
Discovery of a Narrow Resonance in e^+e^- Annihilation*

J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

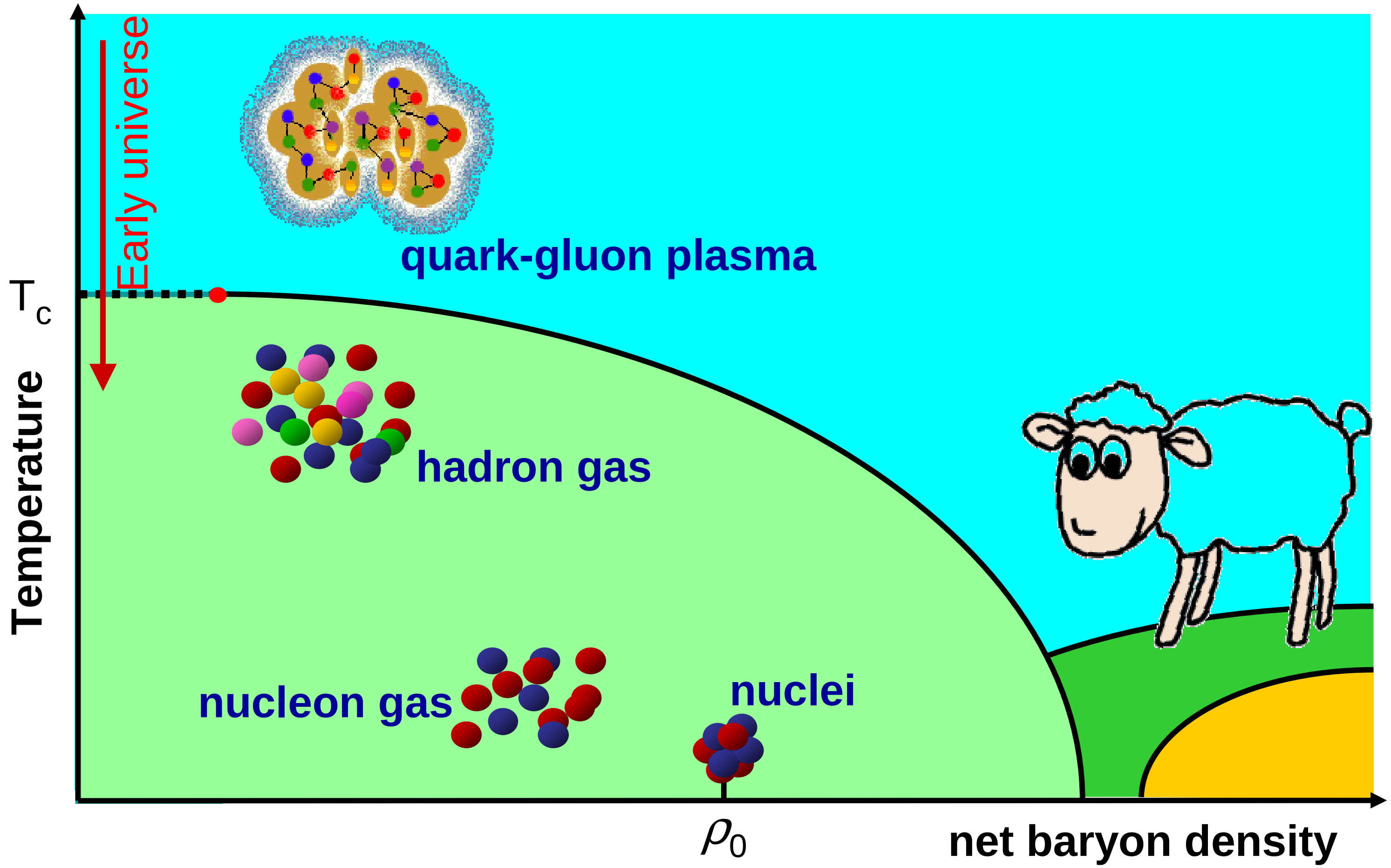
G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720
(Received 13 November 1974)





The new particle got a "re-combined" name: **J / ψ**
(in France it is known as "le Gypsy")

The QCD phase diagram (latest version)



(it looks sheep because of budget cuts)

The QCD phase diagram (earlier version)

EXPONENTIAL HADRONIC SPECTRUM AND QUARK LIBERATION

N. Cabibbo and G. Parisi, Phys. Lett. B59 (1975) 67

The exponentially increasing spectrum proposed by Hagedorn is not necessarily connected with a limiting temperature, but it is present in any system which undergoes a second order phase transition. We suggest that the "observed" exponential spectrum is connected to the existence of a different phase of the vacuum in which quarks are not confined.

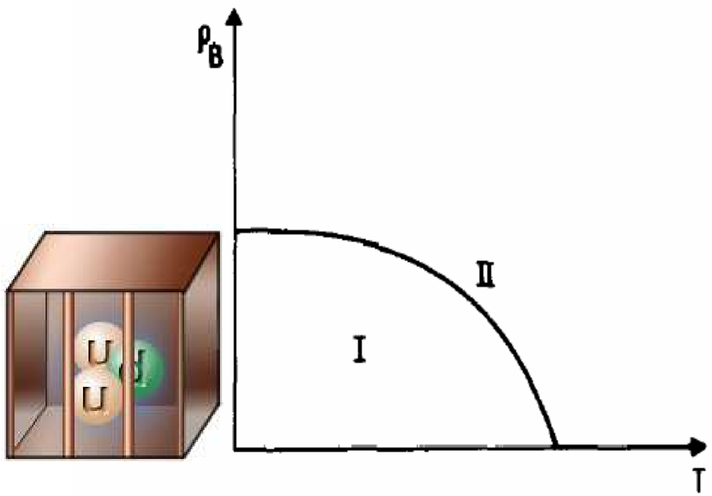
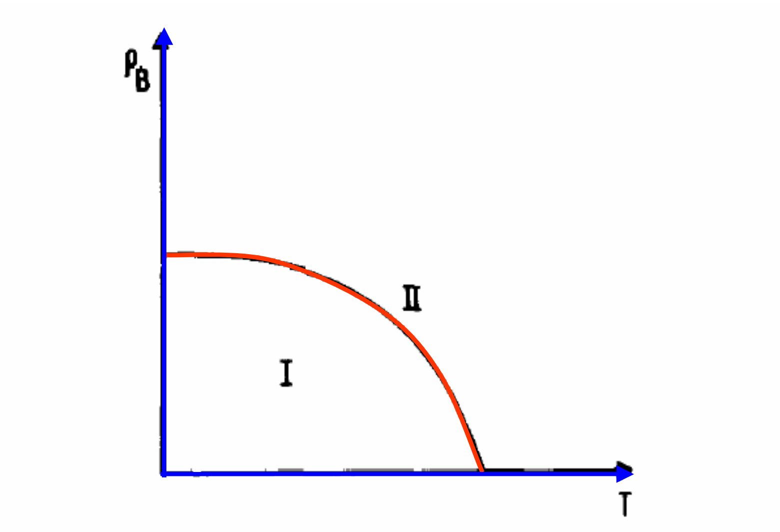


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

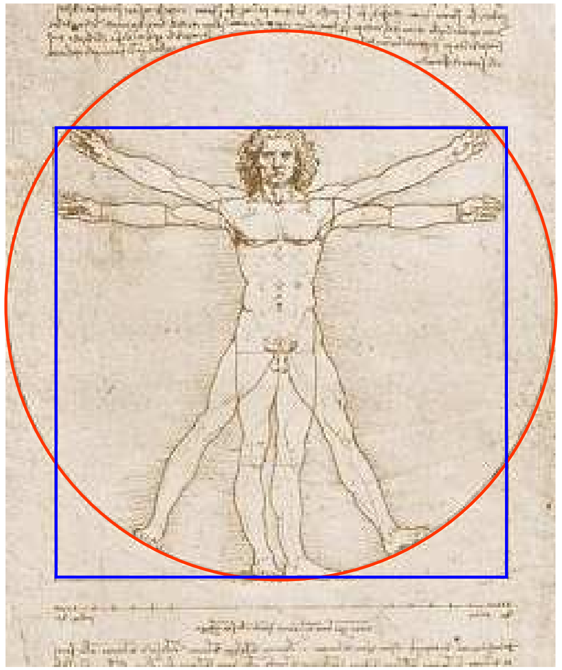
The *really* first QCD phase diagram…

…was found by Leonardo da Vinci,
a long time ago



Not easy to see...
unless you know what you are looking for

So Dark the Con*finement* of Man

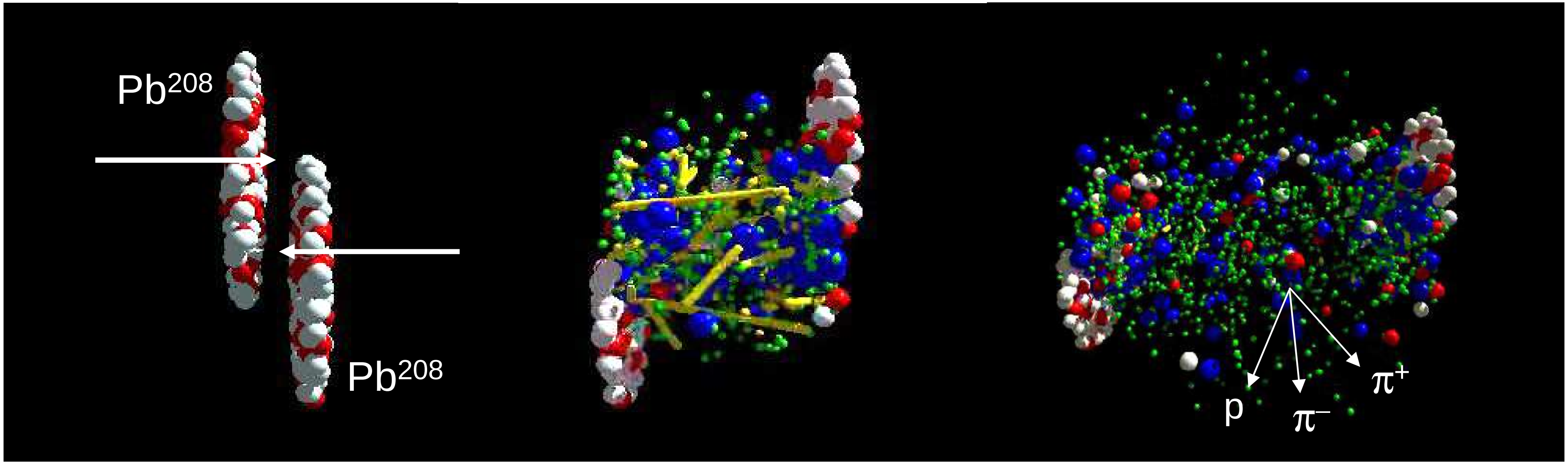


For details, see:

"The Da Vinci colour Code"

How do we study “free” quarks ?

Instead of removing the quarks out of the hadrons…
“remove the hadrons out of the quarks”…

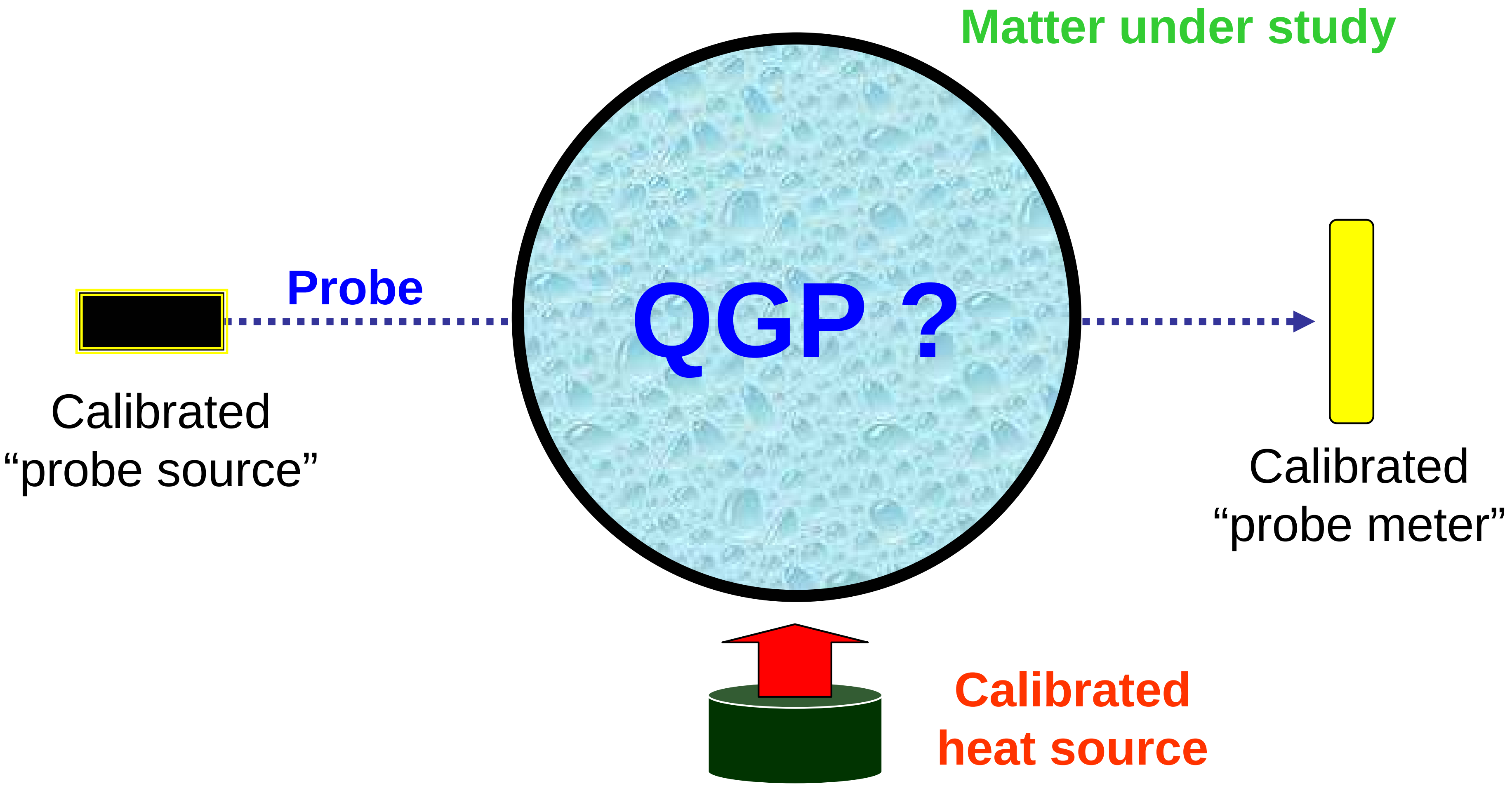


We heat and compress a large number of hadrons
by colliding heavy nuclei at very high energies

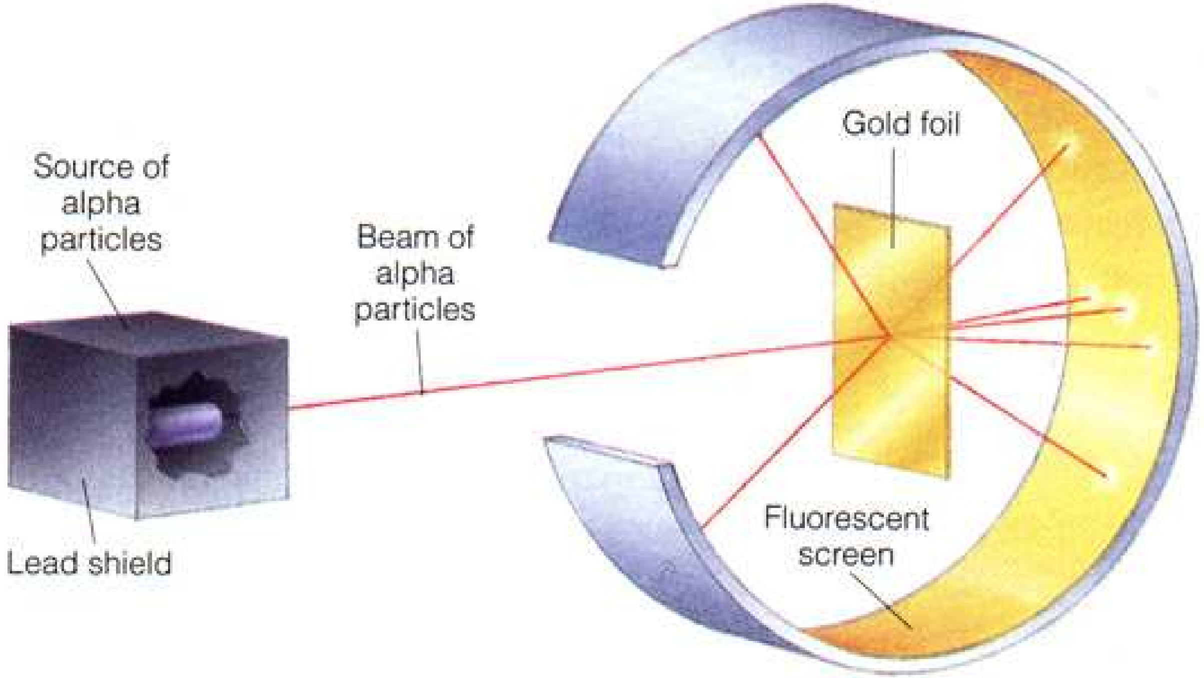
A very large volume of **C**ompressed **B**aryonic **M**atter…
but the experimentalist remained confined (very un**FAIR**)…

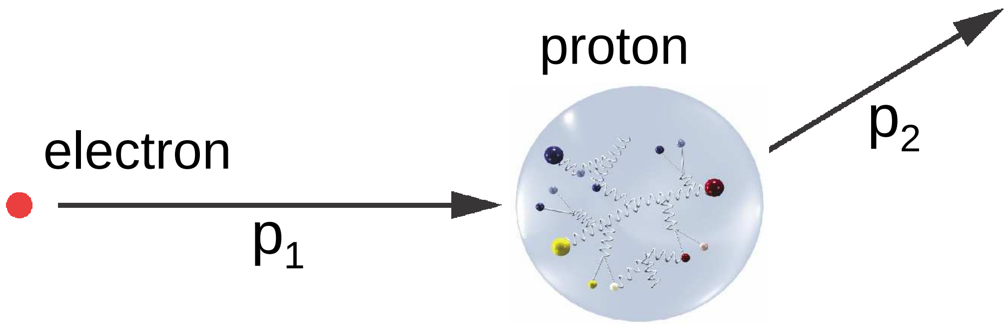
How can we “see” the QGP ?

We study the bulk QCD matter produced in HI collisions by seeing how it affects
well understood probes
as a function of the temperature of the system (centrality of the collisions)

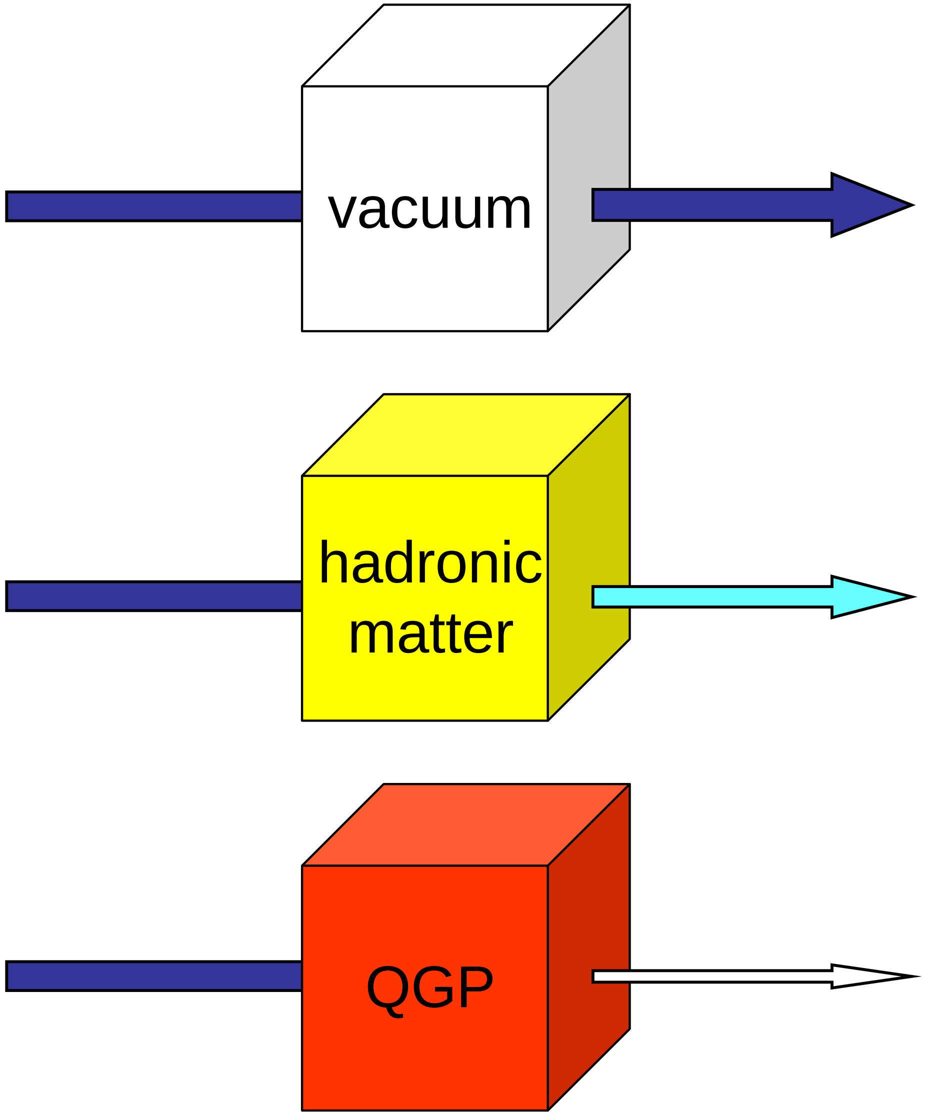


Similar, in spirit, to Rutherford scattering experiments…





Challenge: finding the good QGP probes



The good QCD matter probes should be:

Well understood in “pp collisions”

Only slightly affected by the hadronic matter, in a well understood way, which can be “accounted for”

Strongly affected by the deconfined QCD medium...

And the probes must be produced *very early*, to be there *before* the QGP…

Heavy quarkonia (J/ψ, ψ’, Υ, Υ’, etc) are very good QCD matter probes !

The Matsui an'Satz paper...

By 1985, Matsui had worked on "Matsui's *Theolem*" and on "Matsui's *Conjectule*"... but he always got something *wlong*. He then tried "Matsui's Ansatz"...

The result was the well-known "Matsui An'Satz paper", where J/ψ suppression is proposed as a signal of the QCD phase transition from confined hadronic matter to a deconfined partonic plasma

J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

I have a dream...

T. MATSUI
Center for Theoretical Physics, Laboratory
Cambridge, MA 02139, USA

and

H. SATZ
Fakultät für Physik, Universität Bielefeld,
and Physics Department, Brookhaven Nati

"we thus conclude that:

- there appears to be no mechanism for J/ψ suppression in a nuclear collision except the formation of a plasma
- and if such a plasma is produced, there seems to be no way to avoid J/ψ suppression"

Received 17 July 1986

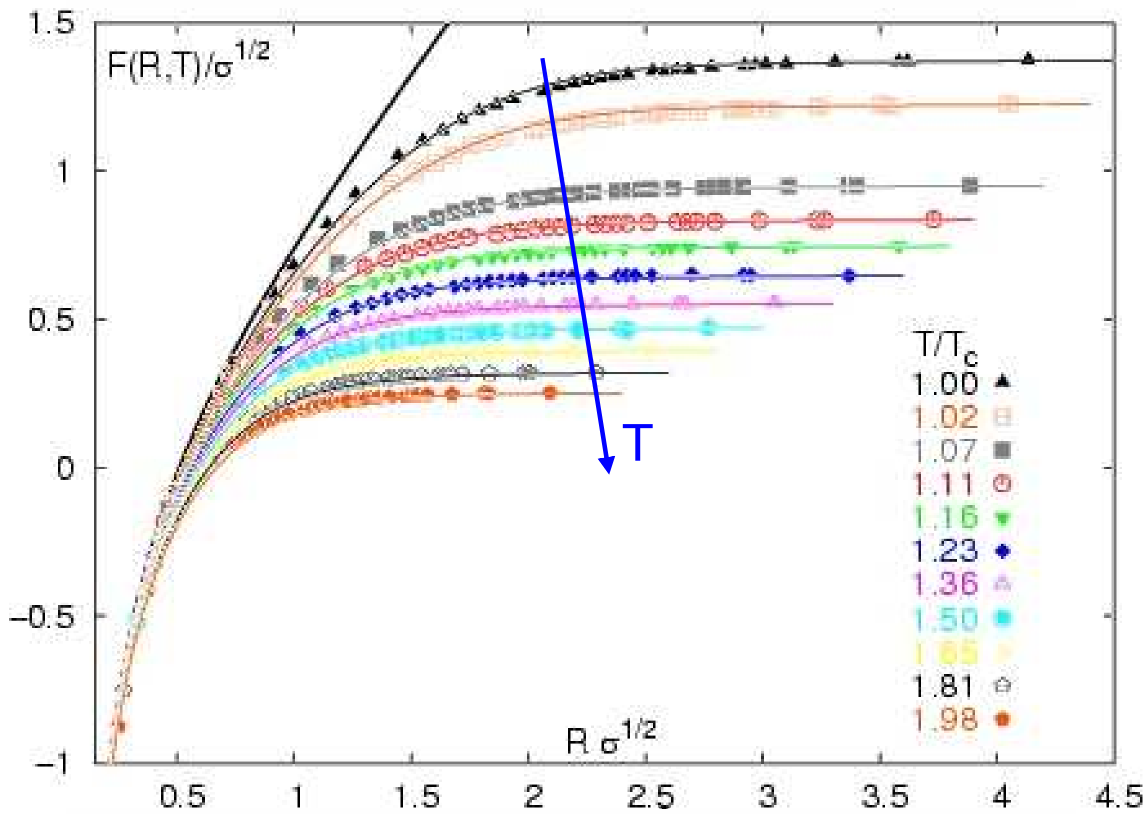
Cited 1236 times!

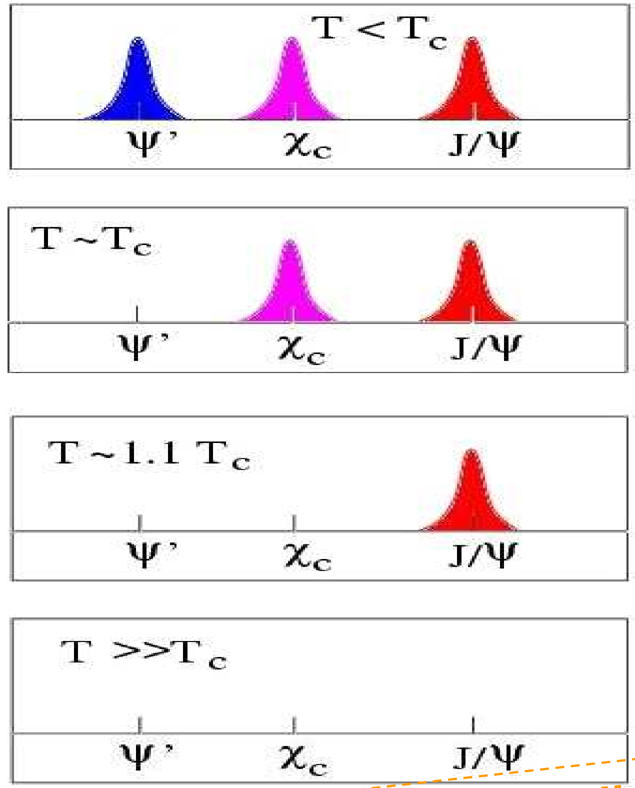
If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, as obtained from lattice QCD, is compared with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark–gluon plasma formation.

Probing the temperature of the QGP

In the deconfined phase the QCD potential is screened and the heavy quarkonium 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.

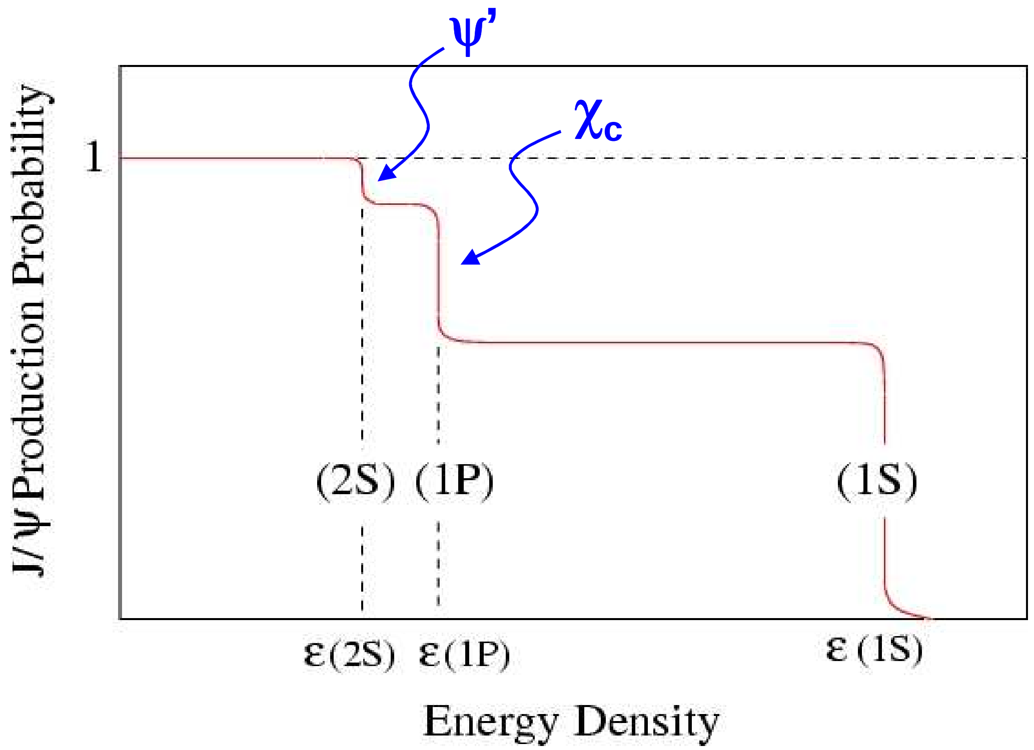




More details in Peter's talk

A QGP "smoking gun" signature: steps

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



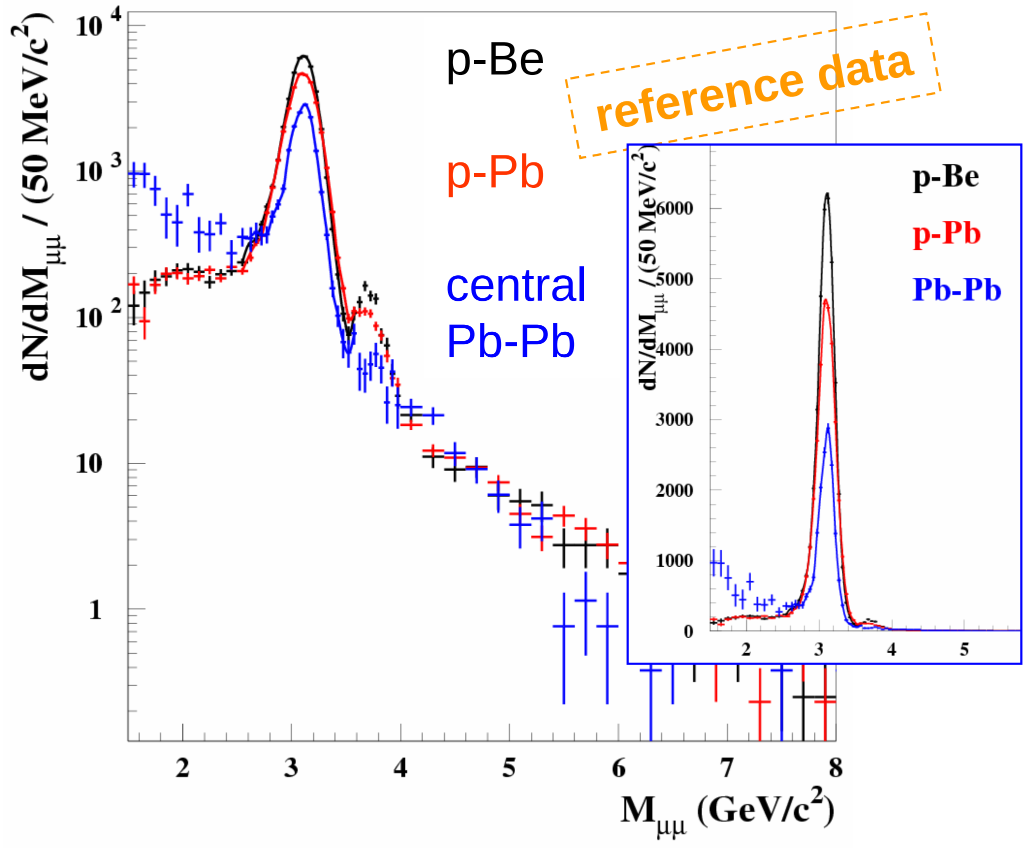
J/ψ cocktail:

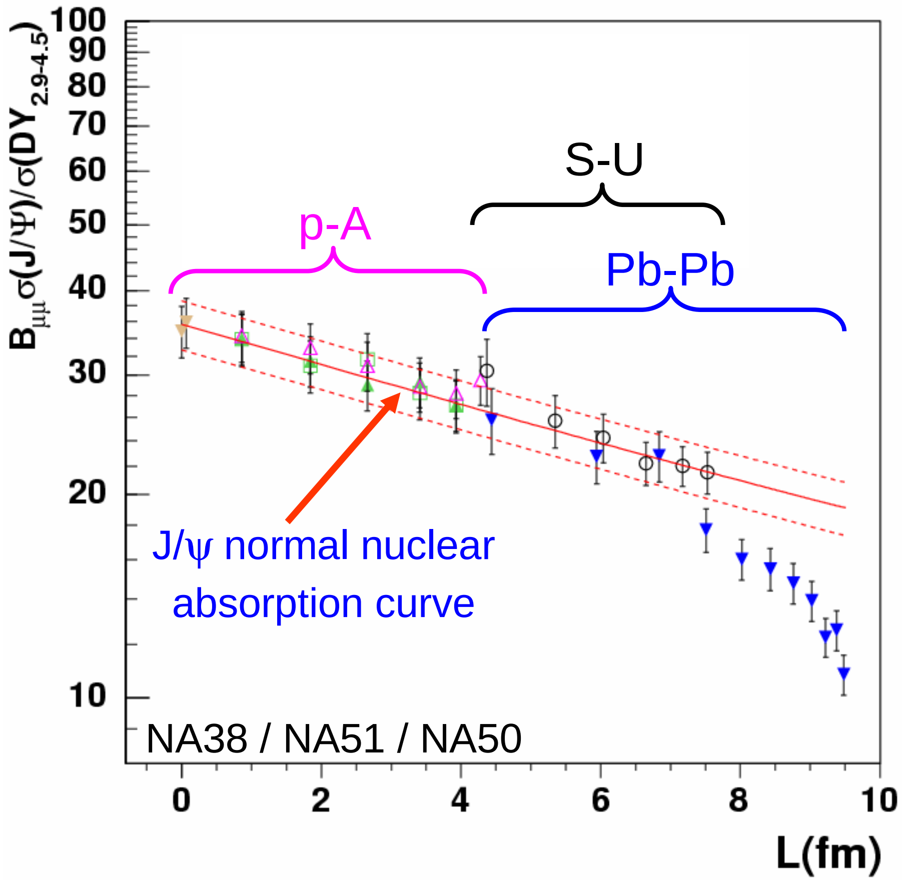
~ 10% from ψ' decays

~ 25% from χ_c decays

~ 65% direct J/ψ

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



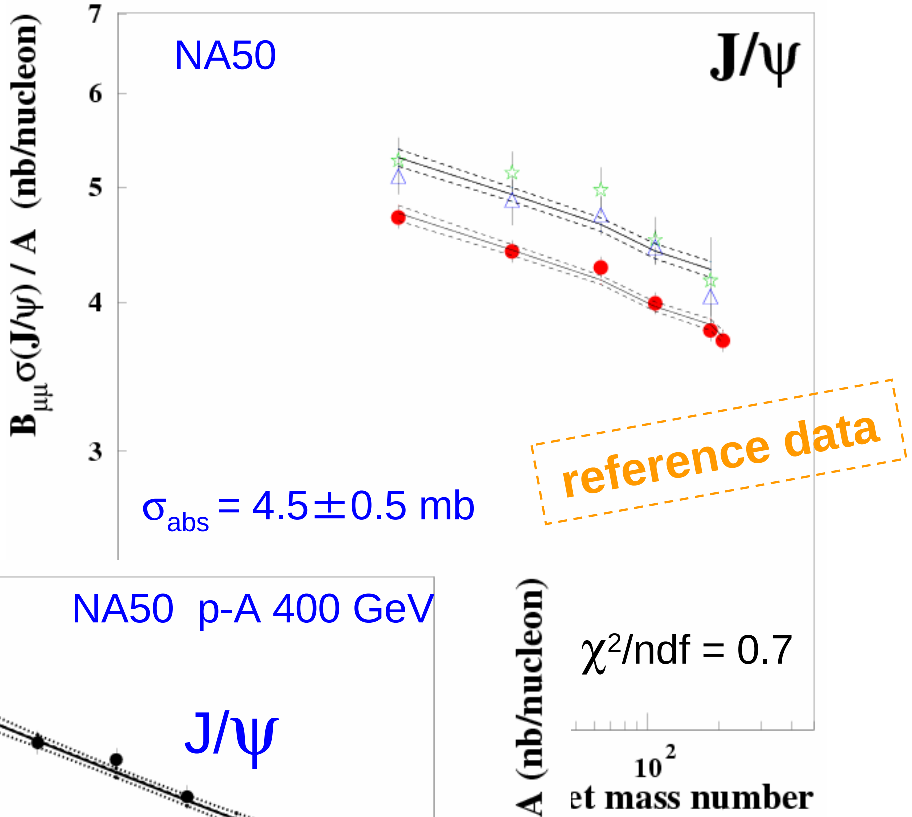


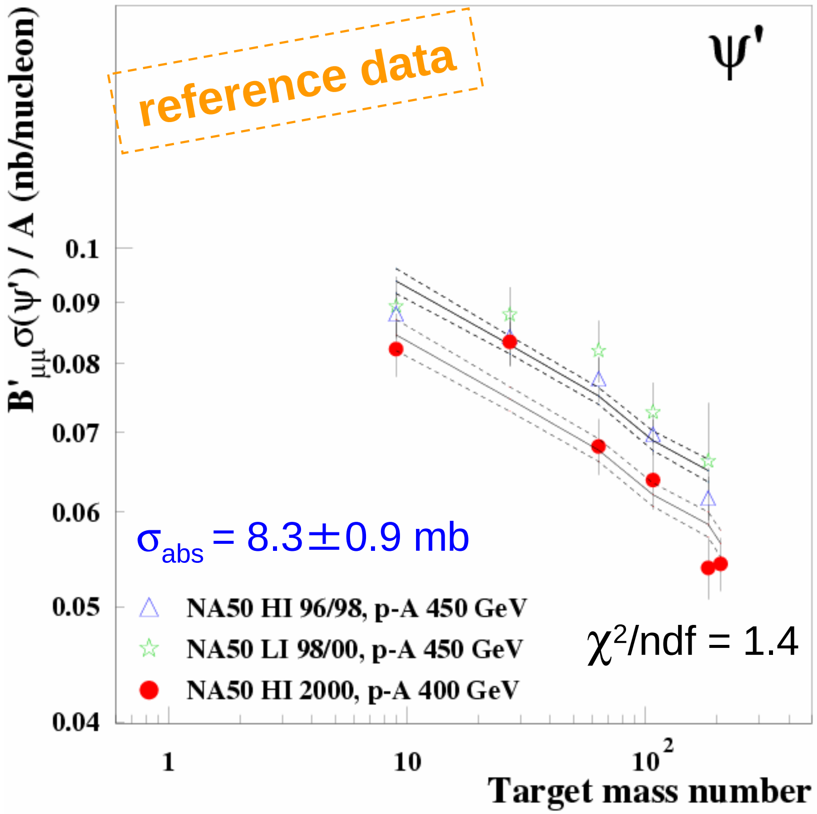
The yield of J/ψ mesons (per DY dimuon) is "slightly smaller" in p-Pb collisions than in p-Be collisions; and is ***strongly*** suppressed in central Pb-Pb collisions

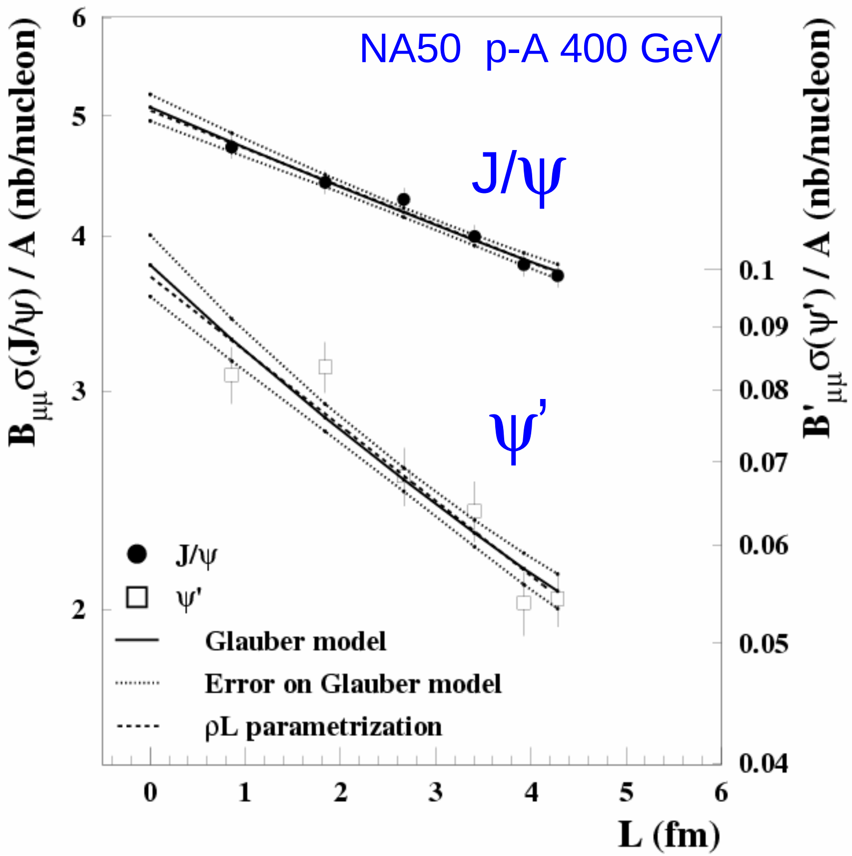
Drell-Yan dimuons are not affected by the dense medium they cross

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

The J/ψ and ψ' "normal nuclear absorption"



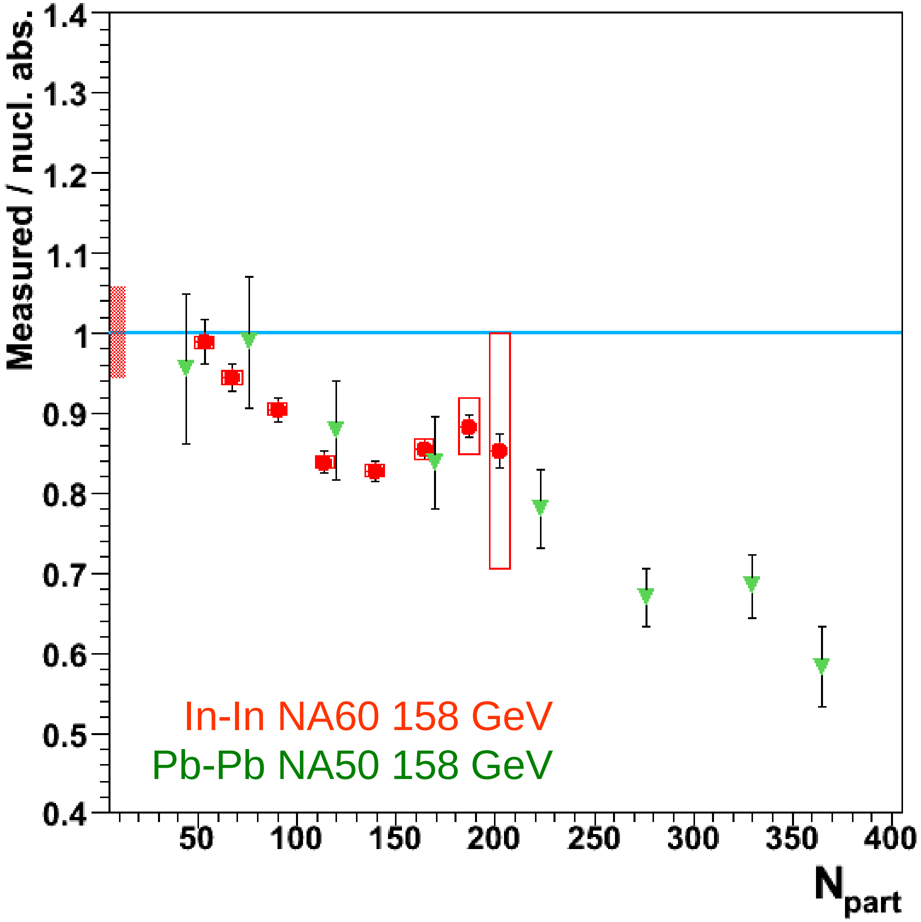


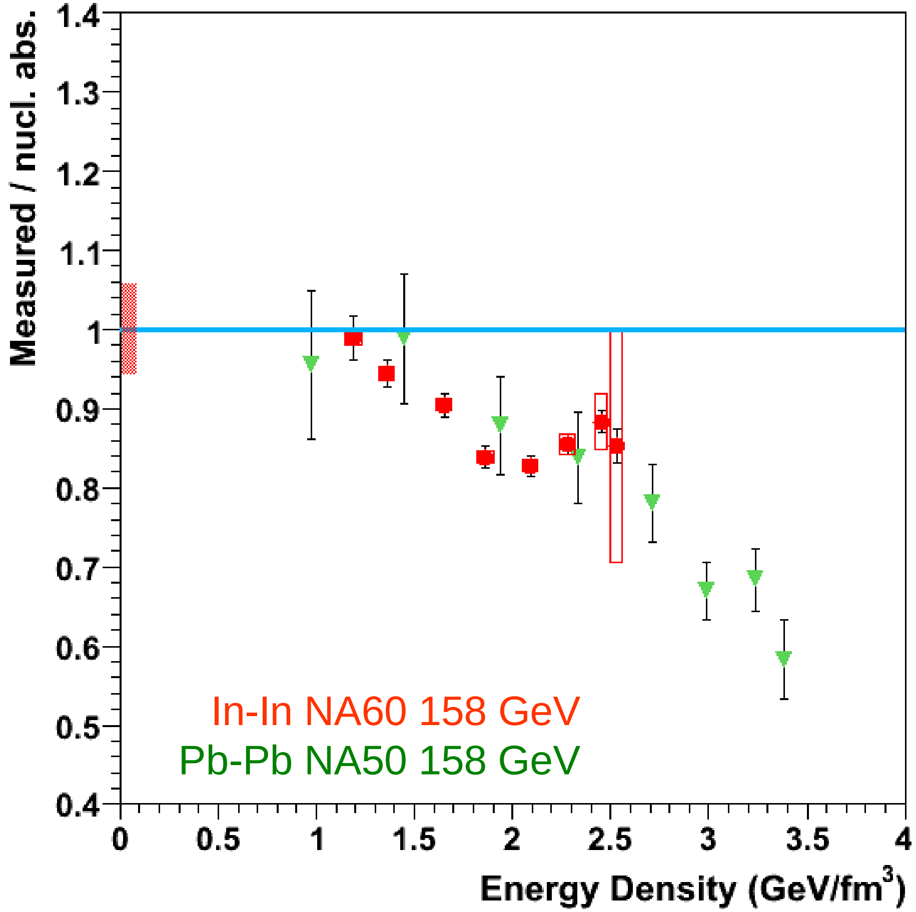


The Glauber model describes the J/ψ and ψ' "normal nuclear absorption", in p-A collisions, in terms of final state absorption, with a single parameter, the absorption cross section

More details in Hermine's talk

In-In vs. Pb-Pb J/ψ suppression patterns

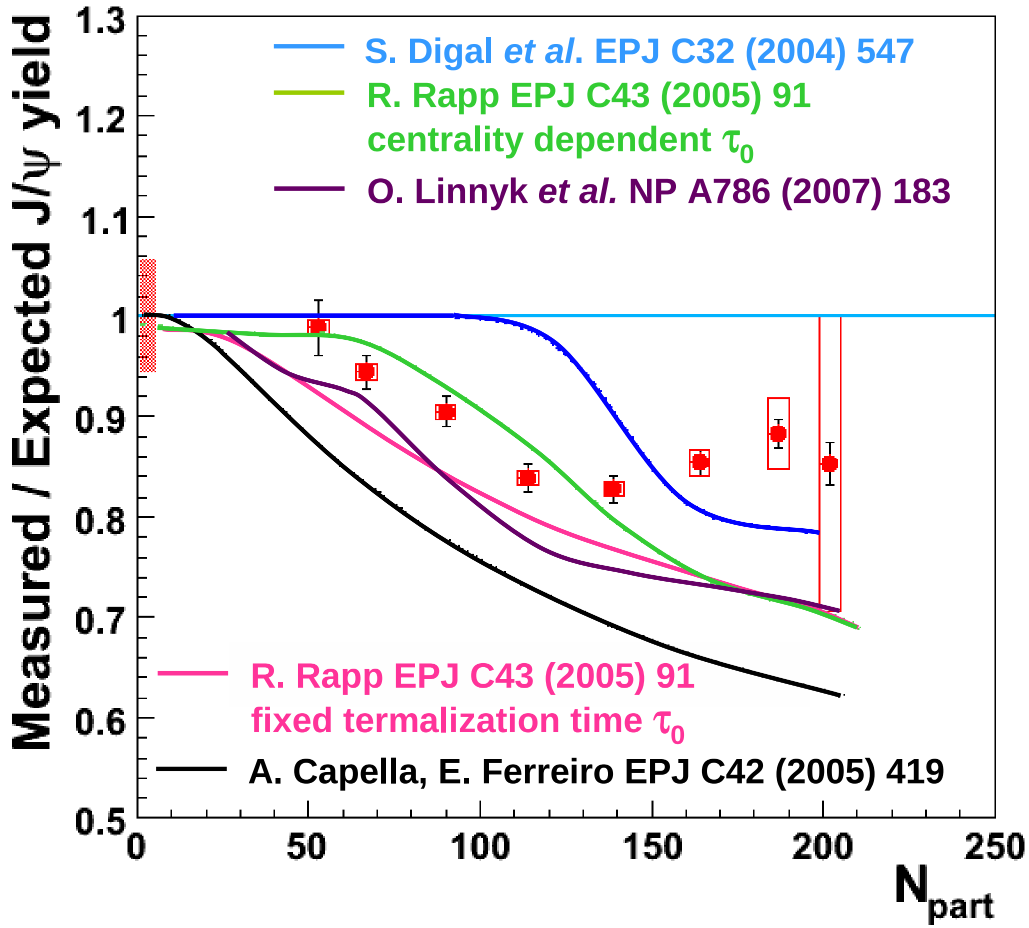




The Pb-Pb and In-In suppression patterns overlap when plotted as a function of the number of participant nucleons or as a function of the estimated energy density

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

In-In data vs. theory *predictions* tuned on the Pb-Pb data



None of the calculations describes the measured suppression pattern...

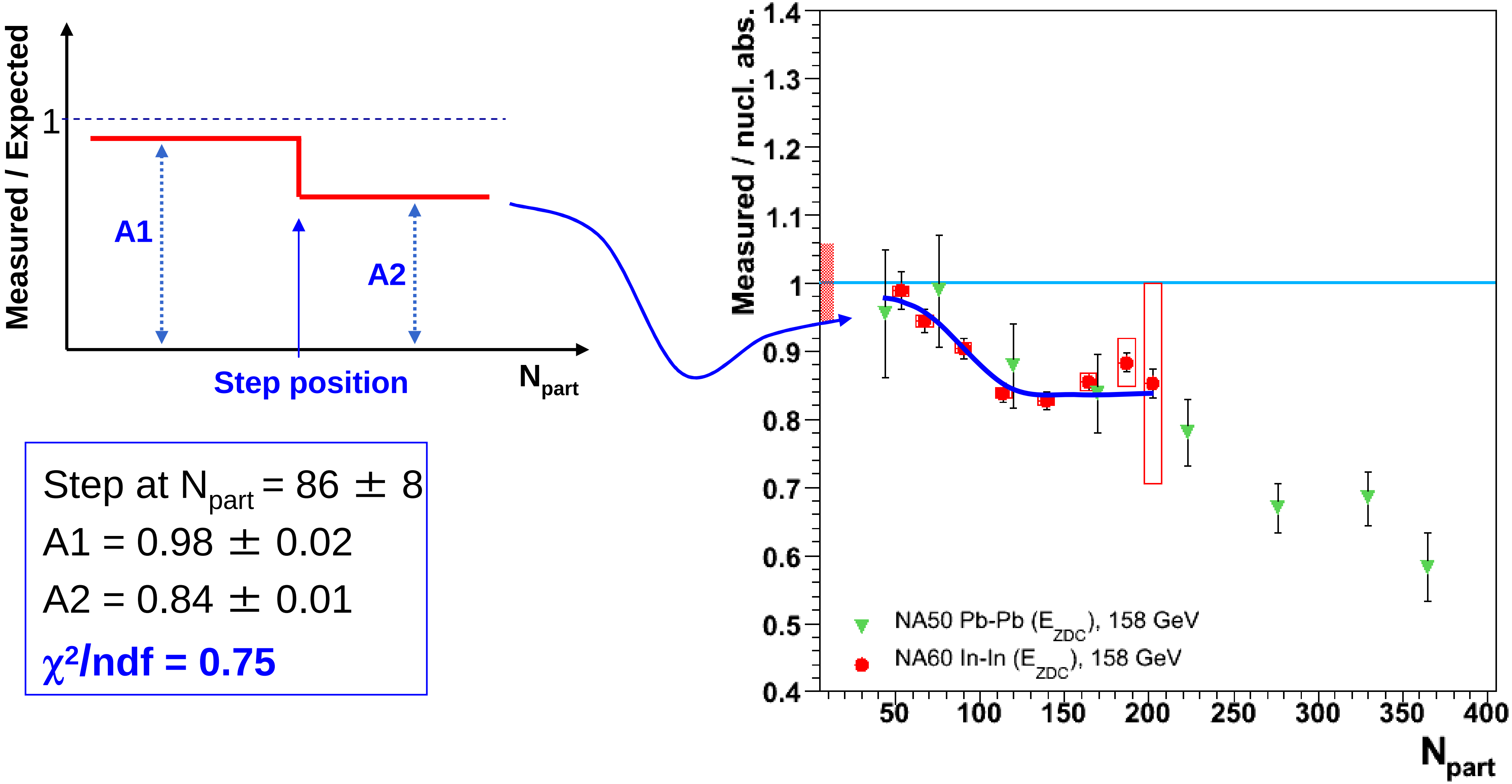
χ^2/ndf for each of these curves:

- Digal et al. = 21
- Rapp (variable τ_0) = 9
- Rapp (fixed τ_0) = 14
- Capella & Ferreiro = 49
- Linnyk et al. = 16 (post-diction)

The In-In data sample was taken at the same energy (158 GeV) as the Pb-Pb data… to minimise the “freedom” of the theoretical calculations ☺

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

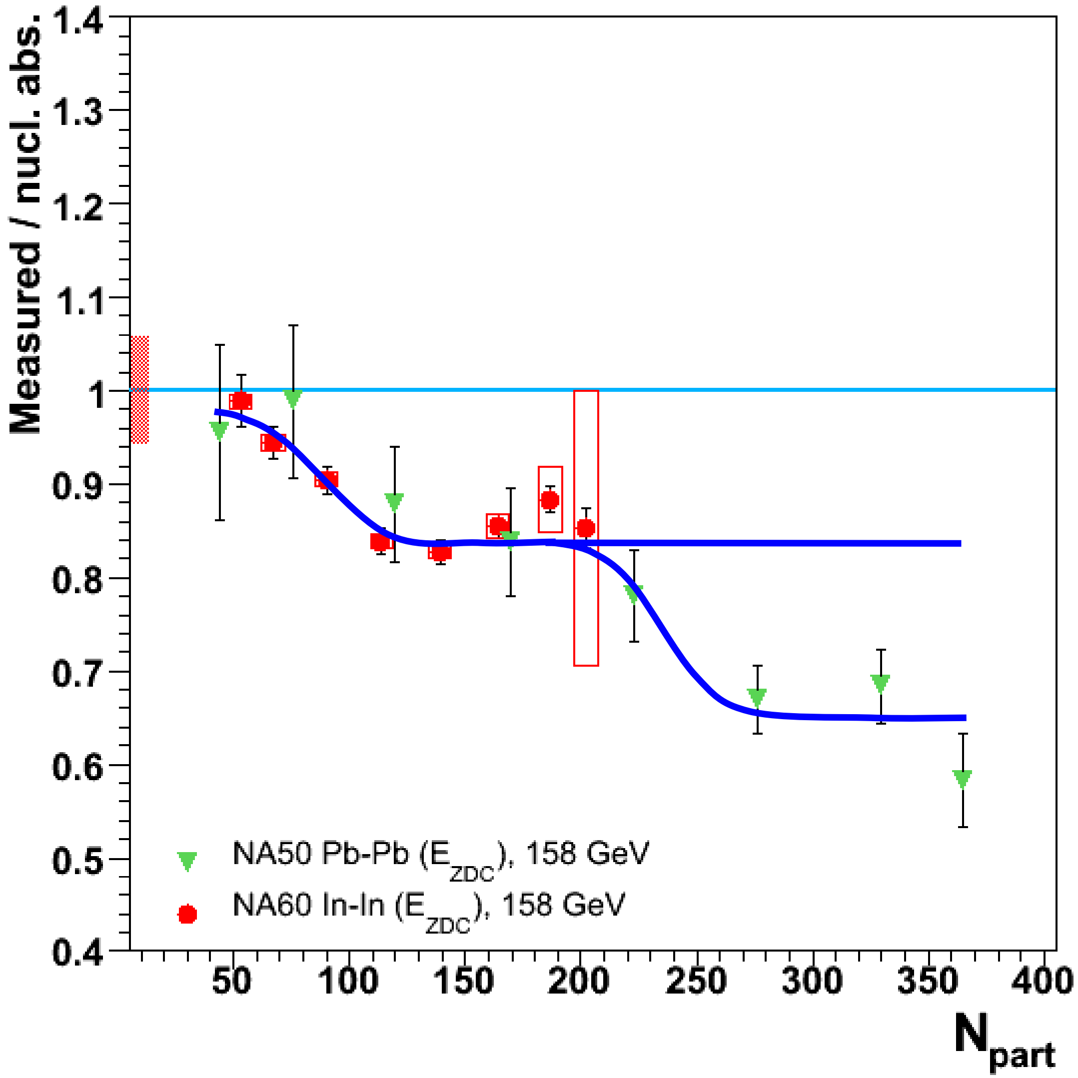
The In-In data vs. a simple step function

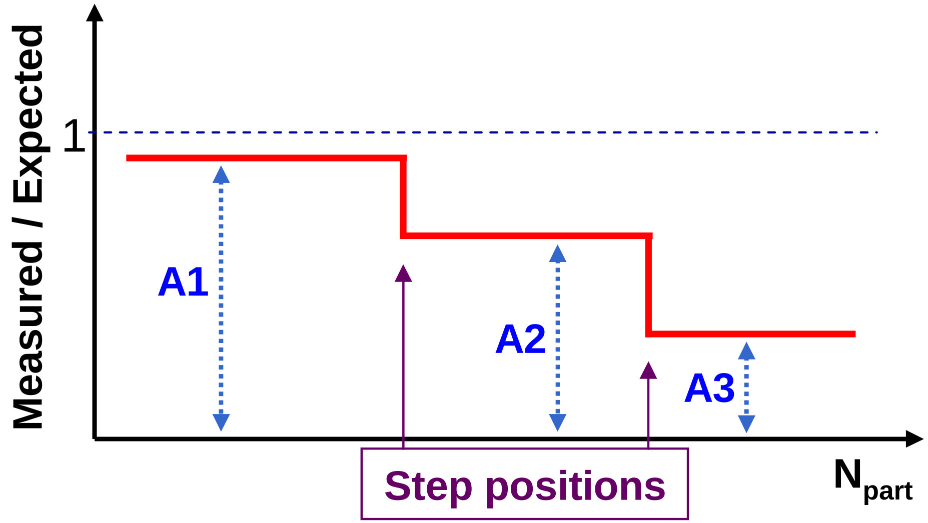


Step at N_{part} = 86 ± 8
A1 = 0.98 ± 0.02
A2 = 0.84 ± 0.01
χ^2/ndf = 0.75

Taking into account the E_{ZDC} resolution,
the measured pattern is *perfectly* compatible with a step function in 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

ψ'

χ_c

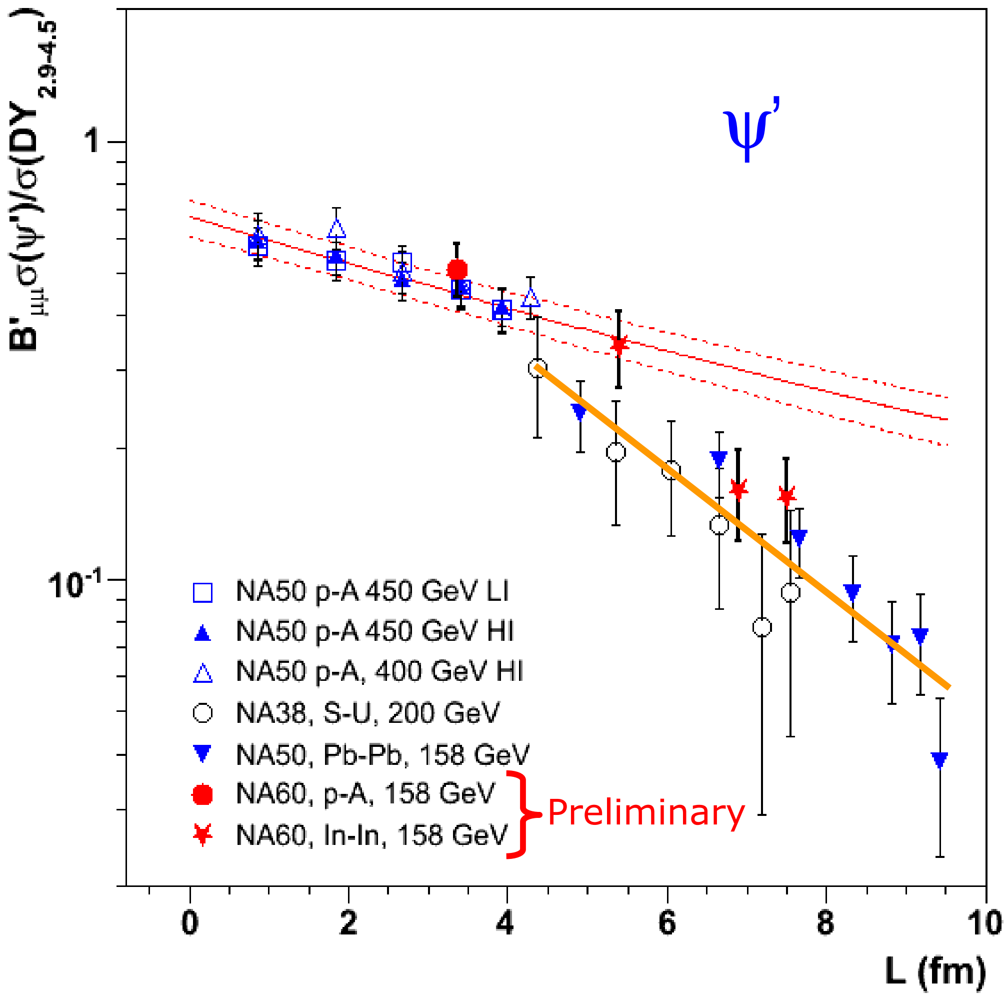
χ^2/ndf = 0.72

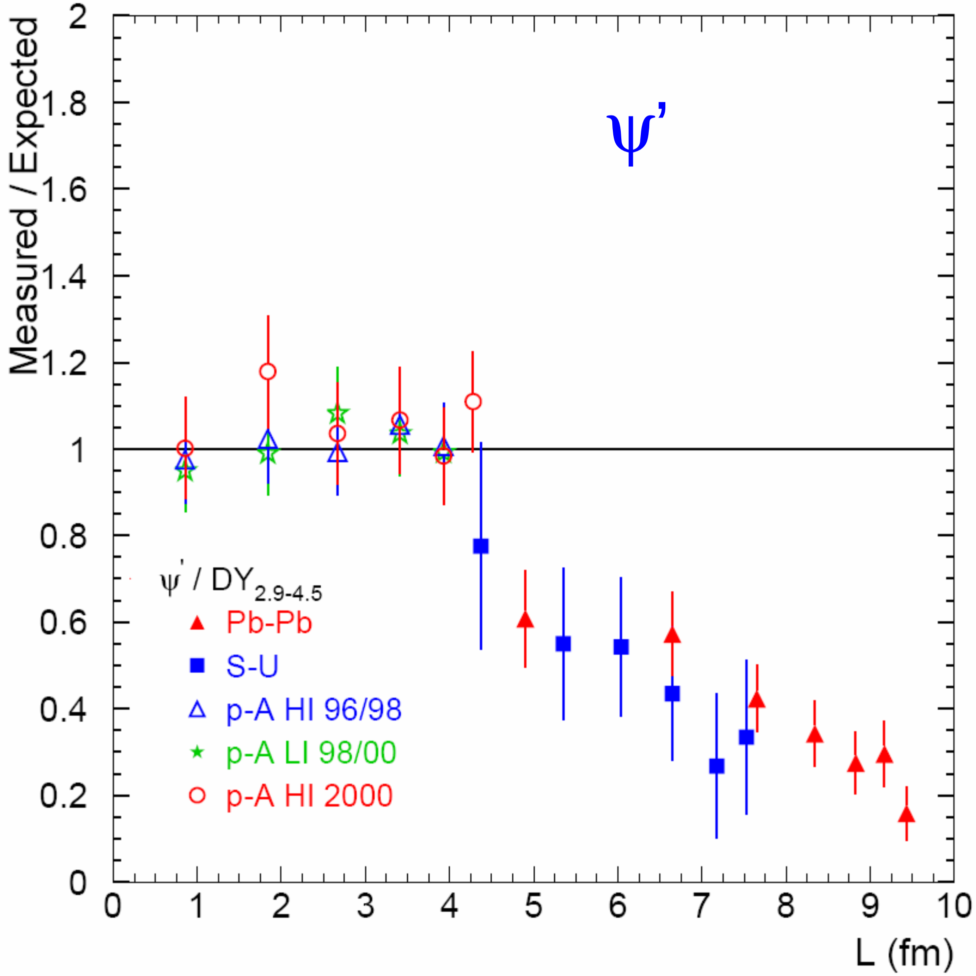
Fitting the In-In and Pb-Pb data with one single step leads to χ^2/ndf = 5 !

In summary, the Pb-Pb pattern 1) rules out the single-step function and
2) indicates the existence of a second step...

What about the ψ' suppression pattern?

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

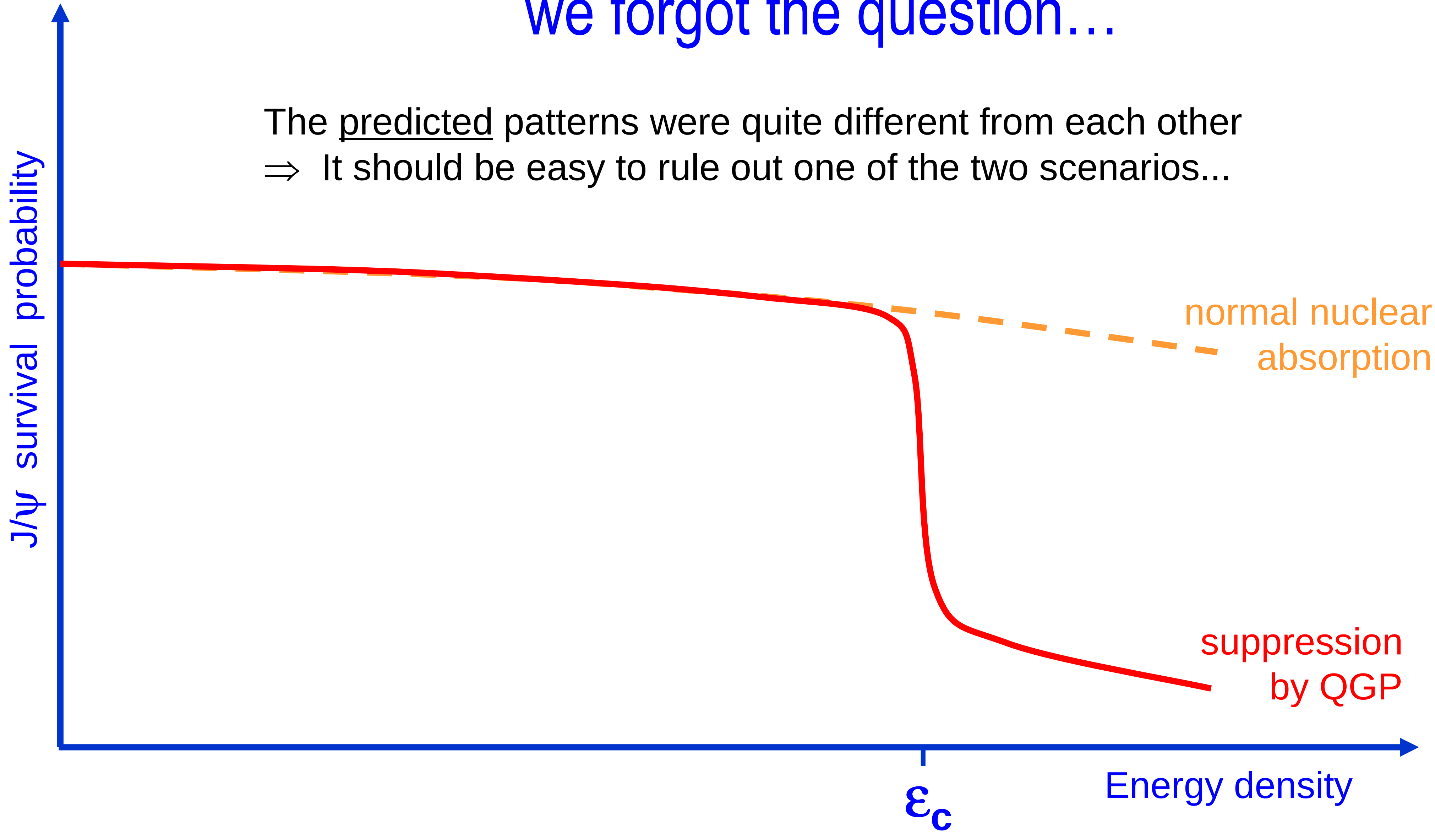




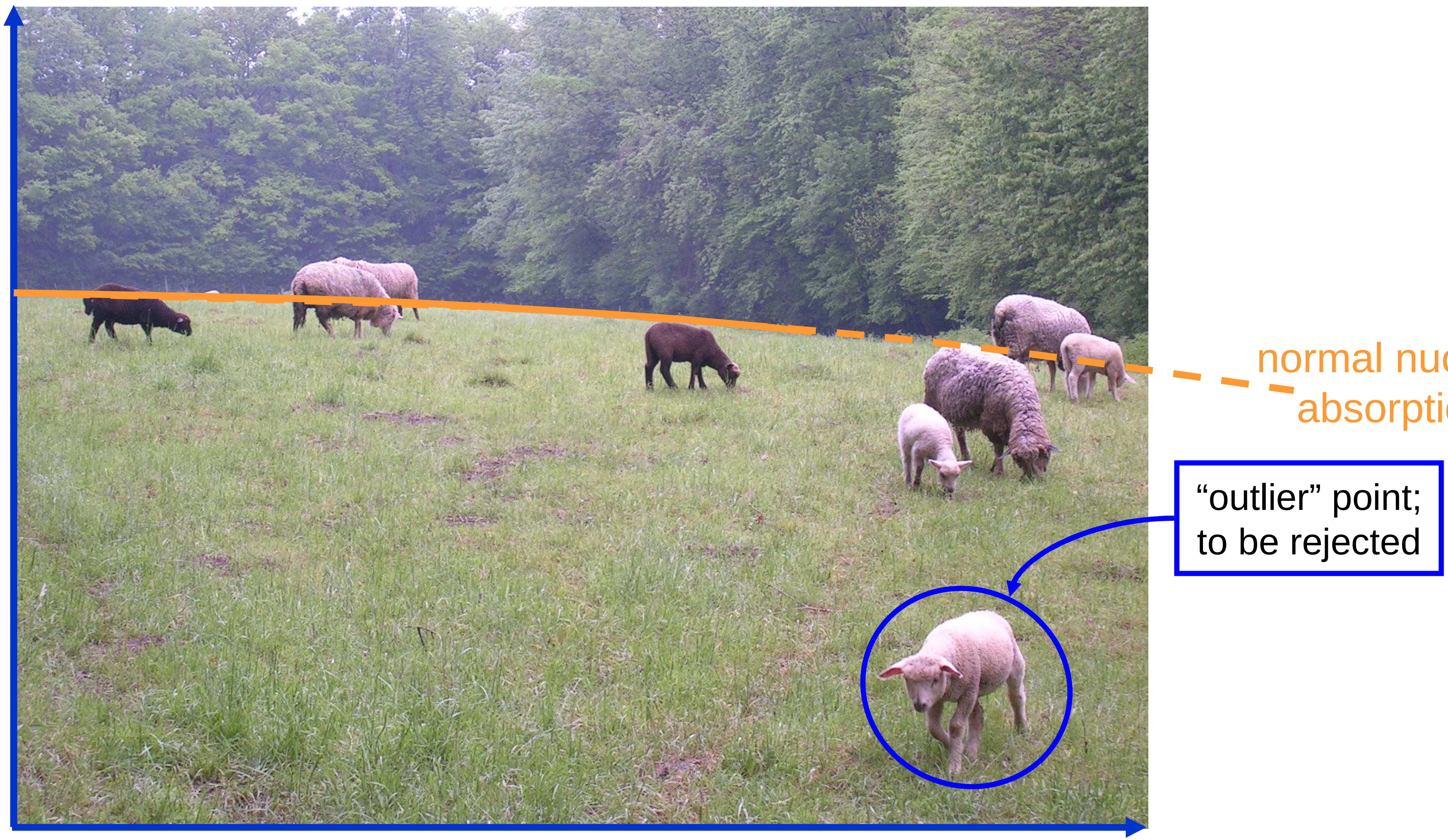
The third step ! Starts to look like a "stairway to heaven"...

Just when we were about to find the answer…
we forgot the question…

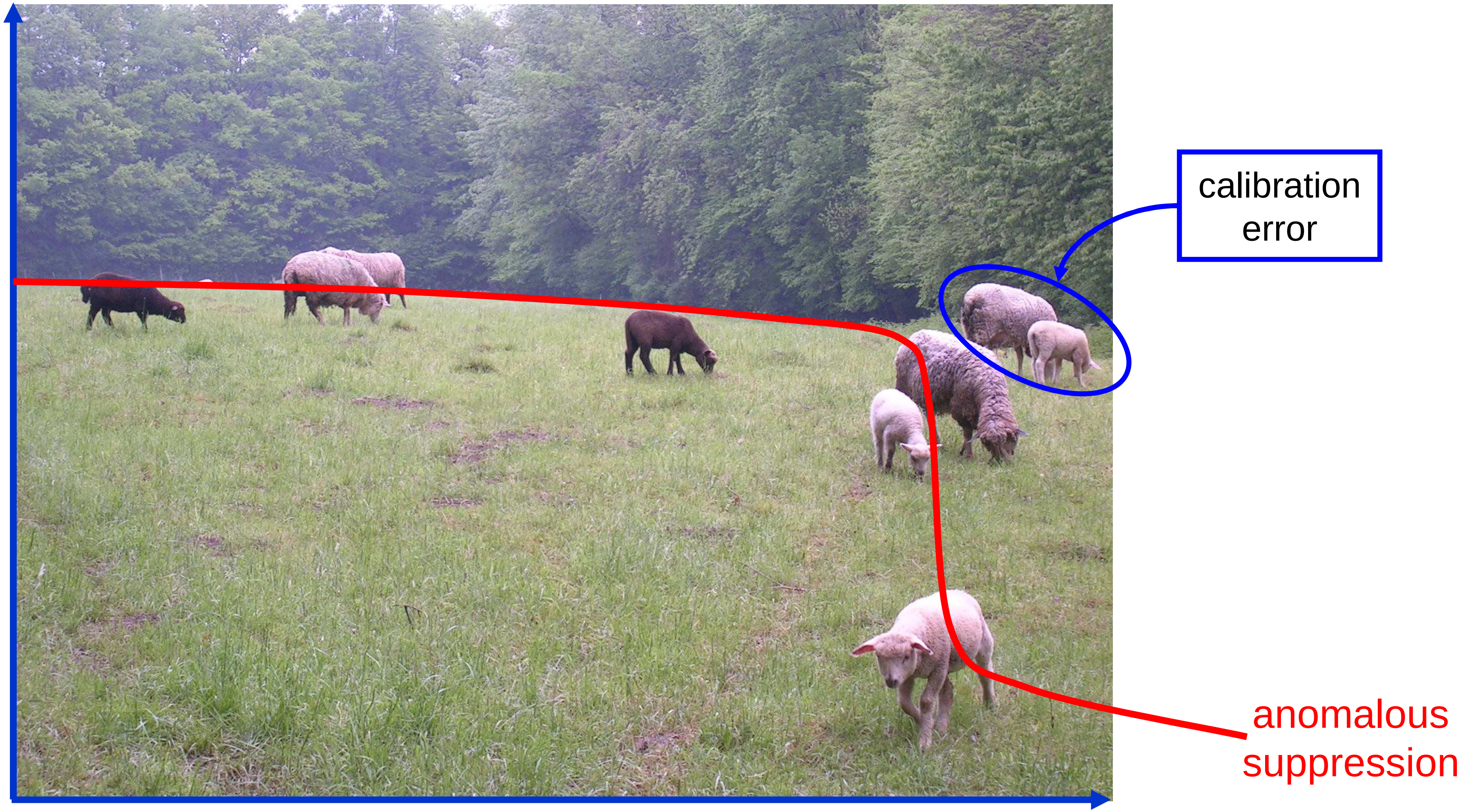
The <u>predicted</u> patterns were quite different from each other
⇒ It should be easy to rule out one of the two scenarios...



Can any of the models describe the data points seen at CERN ?

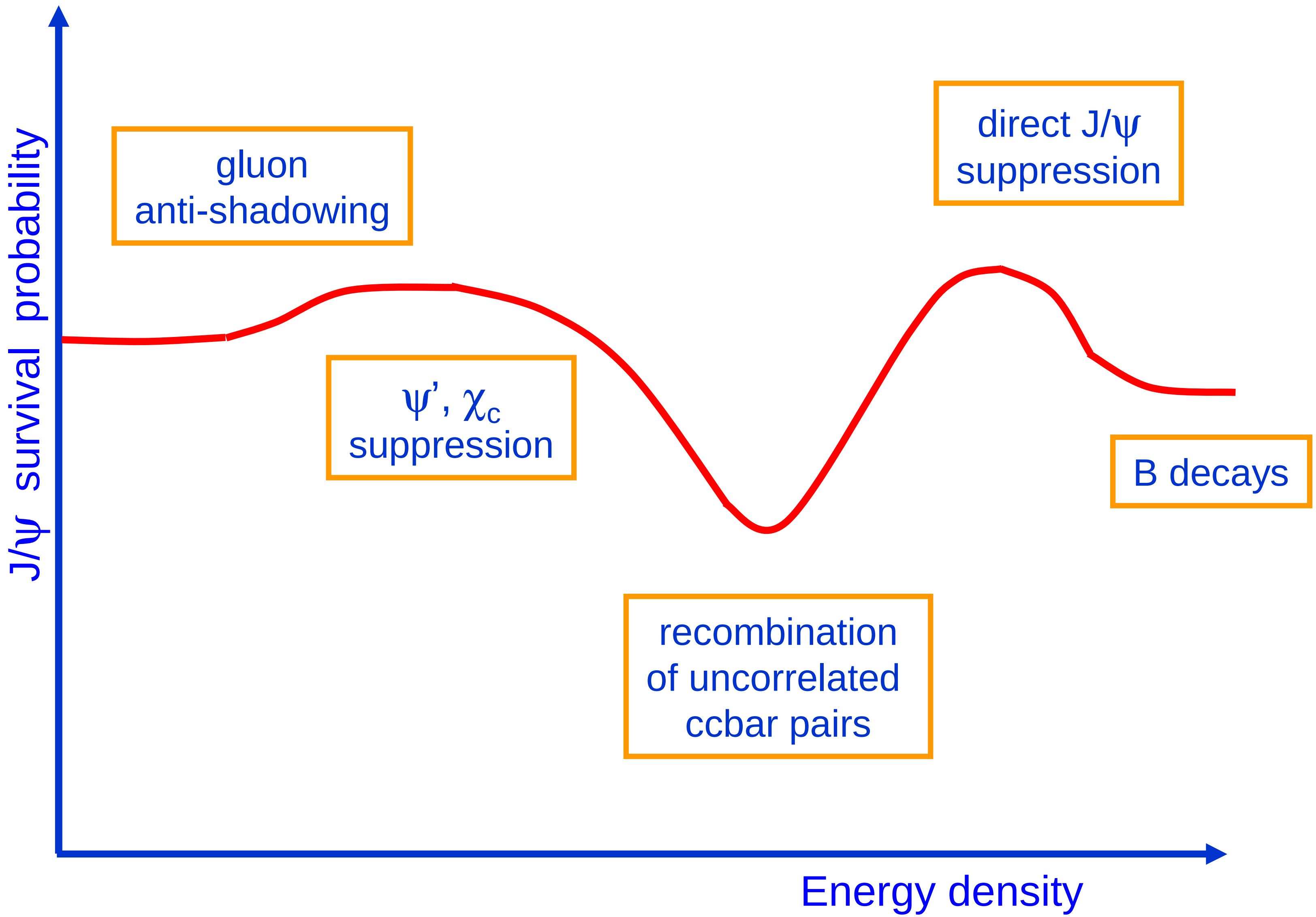


⇒ All *kept* data points agree with the expected *normal nuclear absorption* pattern!

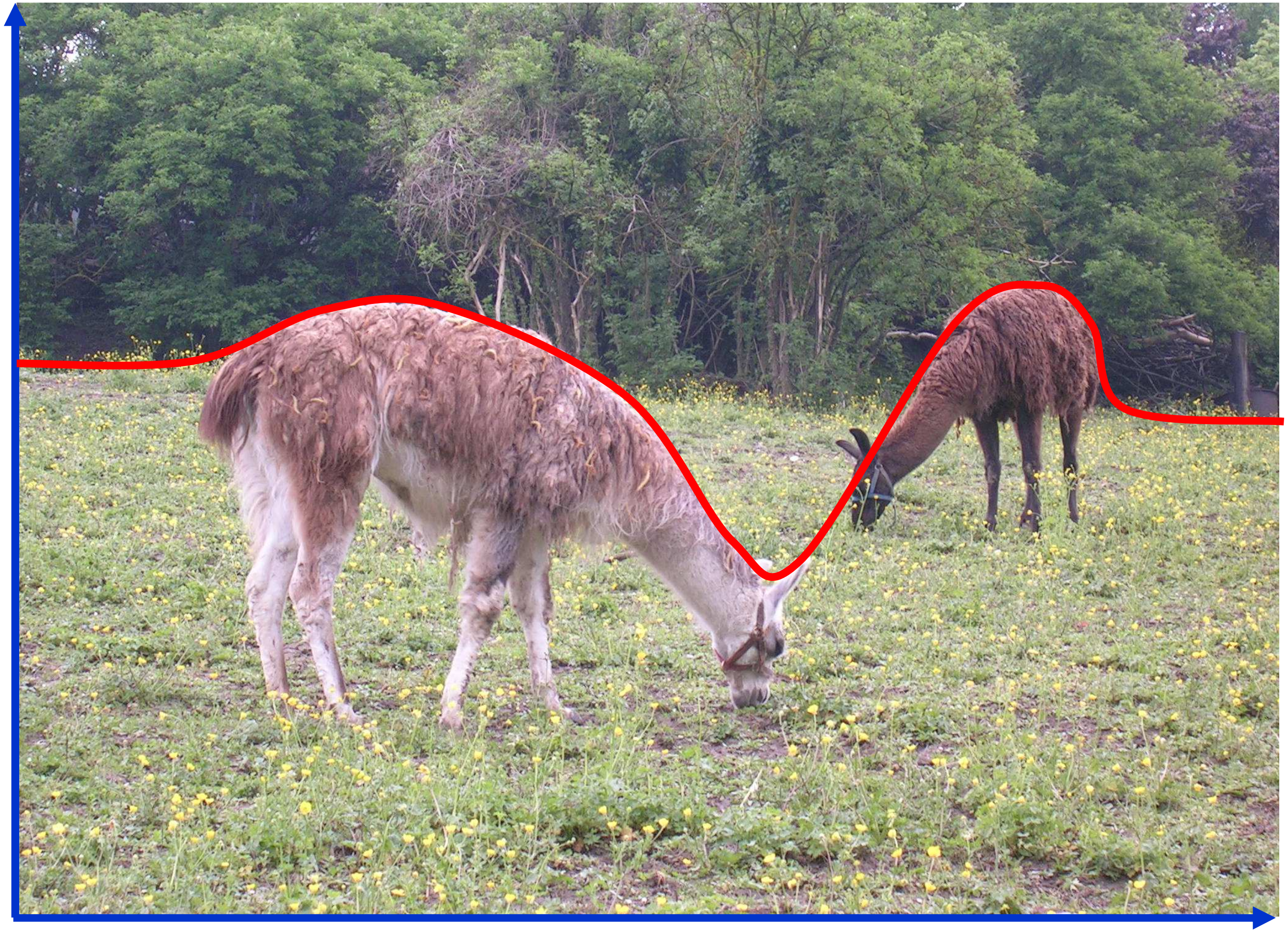


⇒ All *kept* data points agree with the expected QGP suppression pattern!

The theorists develop a considerably improved model…



A second generation experiment is conceived at CERN



Once again, the model *prediction* agrees with the observations...

Take home messages…

1) No fancy theory can reproduce the measured J/ψ suppression patterns

2) A simple step function gives a *perfect* description of the In-In pattern;
a second step is needed to describe the Pb-Pb pattern as well
$\Rightarrow$ **We found what we were told to look for, as a "smoking gun QGP signal"**

3) However, there is a **BIG** difference between
"the measurements are *compatible with the model expectations*..." and
"the measurements *show beyond reasonable doubt* that the model is correct"

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

See next talks for improved looks