Measuring dimuons, quarkonia and heavy flavors

Purpose: Overview some experimental issues which may be crucial to properly understand certain measurements and derive a correct physics interpretation

Disclaimer: I will not attempt to be exhaustive, but rather mention a few concrete examples (if possible from real experiments), to make the points easier to follow

Outline of the presentation:

1. Existing experiments and data
2. Luminosity and trigger
3. Resolutions (dimuon mass, etc)
4. Acceptances, phase space windows and efficiencies
5. Backgrounds and feed downs
6. Reference processes and collision systems
7. Comparing different experiments

Carlos Lourenço – CERN
Hard Probes 2004, Nov. 4-10, 2004

Thanks to Hermine, Andre, Ruben, Hiroaki and Mike for help in preparing these slides

Charmonia: existing experiments

E772/E789/E866 at Fermilab:
800 GeV protons on p, d and nuclear targets
Nuclear dependence of J/ψ and ψ' in the range $-0.1<x_F<0.9$

See talk of Mike Leitch

NA38/NA51/NA50 at the CERN SPS:
450 and 400 GeV protons on p, d and nuclear targets
Nuclear dependence of J/ψ and ψ' in the range $3<y_{lab}<4$
O-Cu, O-U and S-U at 200 and Pb-Pb at 158 GeV/nucleon
As a function of E_T and (Pb only) E_{ZDC} and N_{ch}

See talks of Louis Kluberg & Goncalo Borges

HERA-B at DESY:
920 GeV protons on C and W (wire) targets
Nuclear dependence of J/ψ, ψ' and χ_c in the range $-0.35<x_F<0.15$

See talk of Antonio Zoccoli

PHENIX and STAR at RHIC:
d-Au and Au-Au collisions at $\sqrt{s}$=200 GeV
J/ψ studies, versus centrality, through dimuons (PHENIX)
and di-electrons (PHENIX and STAR)

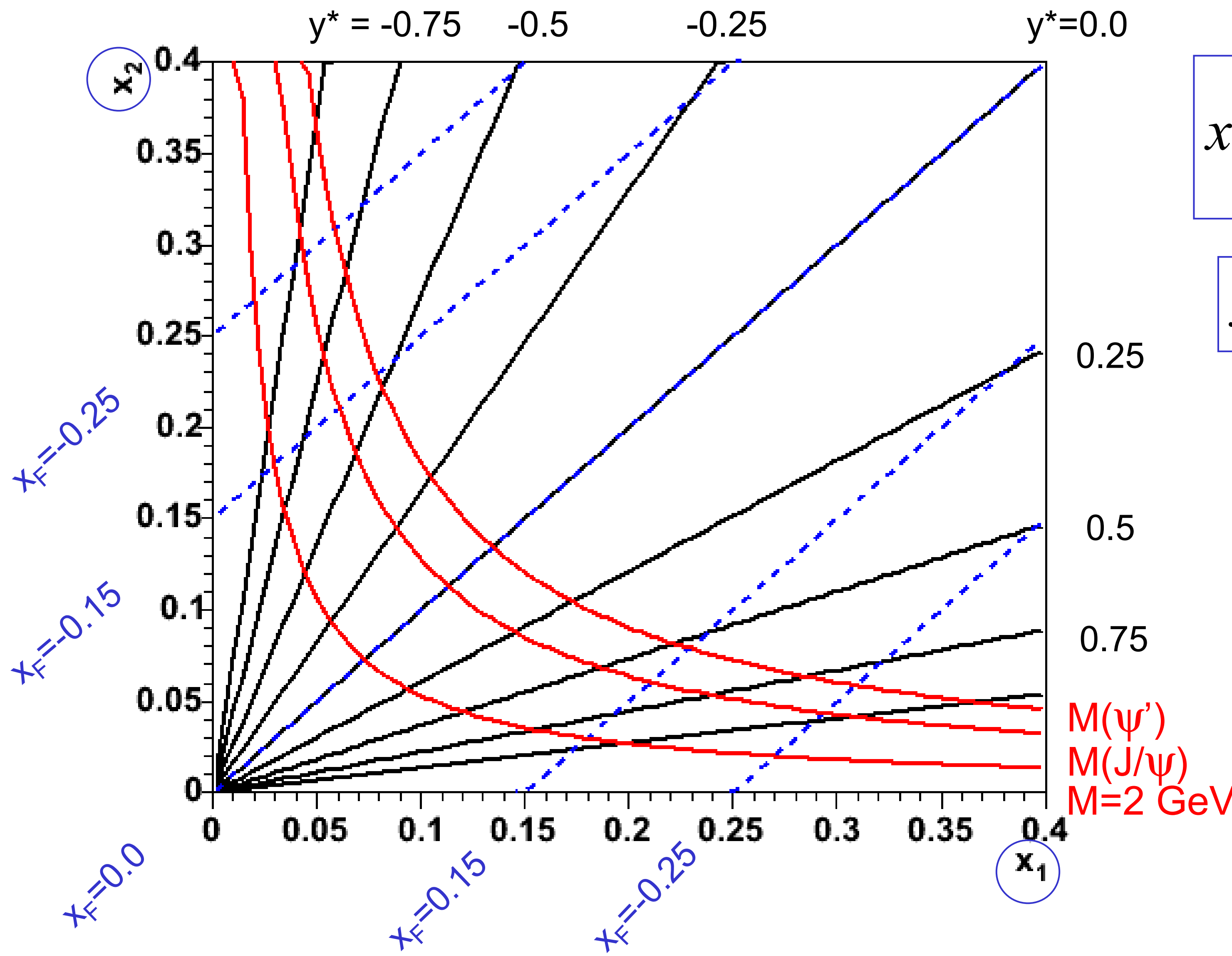
See talks of Marzia Rosati & Alexandre Suaide

NA60 at the CERN SPS:
400 and (J/ψ only) 158 GeV protons on several nuclear targets
Nuclear dependence of J/ψ, ψ' and χ_c in the range $3<y_{lab}<4$
In-In at 158 GeV/nucleon, as a function of E_{ZDC} and N_{ch}

See talk of Roberta Arnaldi

Kinematics: how to go from x_F to y windows

$x_{1,2}$: momentum fraction of partons in beam and target hadrons



$$x_{1,2} = \frac{M}{\sqrt{s}} e^{\pm y^*}$$

$$x_F = x_1 - x_2$$

Integrated luminosity: crucial for the study of rare processes

- To study rare processes with good statistics, we need the highest possible luminosities

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

- High beam intensities imply *primary* beams, directly from the machine. Secondary proton beams are polluted with pions and kaons, and no beam detector can separate them if we run at rates close to 400 MHz (2×10^9 p/burst). NA49 can use secondary beams because they do not need high collision rates (every interaction is a good event). This means that a run with 158 GeV protons at the SPS affects *all* the SPS users. $\Rightarrow$ Very difficult to obtain.

- The target should not 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). Besides, a heavy-ion beam can have a peripheral interaction followed by a second interaction only involving the beam nucleons not participating in the first one. If we cannot distinguish two peripheral collisions from one central collision, in which centrality bin do we place the event?

- The target must be placed in vacuum, at least if we are working with heavy-ion beams. Otherwise, there will be Pb-air collisions, for instance, looking like peripheral Pb-Pb collisions.

See talk of
Louis Kluberg

Luminosity: collider versus fixed target experiments

Example 1: Searching for the $D^0 \rightarrow \mu^+\mu^-$ (forbidden) decay; *NA60 versus CDF*

NA60:

p-U collisions at 400 GeV

2×10^9 p/burst on a 10% λ_{int} U target → 40 MHz interaction rate (being done today)

3 months ~ 300 000 bursts $\Rightarrow$ 6.5 × 10^{13} p-U interactions

σ_{inel}(p-U) = 2 b $\Rightarrow$ **L** ~ 33 × 10^{12} b^{-1} = 33 pb^{-1}

σ(charm) = 20 μb in pp at 400 GeV; A^α with α=1

1.2 D^0 (+D^0bar) per ccbar pair

$\Rightarrow$ 5.6 mb D^0 production cross-section in p-U

$\Rightarrow$ **L** $\times\sigma$ = 1.8 × 10^{11} produced D^0 mesons

leading to around 10^9 $D^0 \rightarrow \mu^+\mu^-$ decay candidates, after acceptance, track reconstruction and matching efficiencies, etc.

CDF:

In 2002 CDF detected 37 000 D^0 in Kπ decays, for p_T>5 GeV/c.

Correcting for the branching fraction (3.8%), and assuming a factor ~ 50 increase in luminosity for FY04 (>3 months), we reach around 5×10^7 D^0 "decay candidates"…

Example 2: Measuring J/ψ and ψ' production in Au-Au collisions; *NA50 vs. PHENIX*

Left as homework exercise …

Trigger: crucial to profit from high collision rates

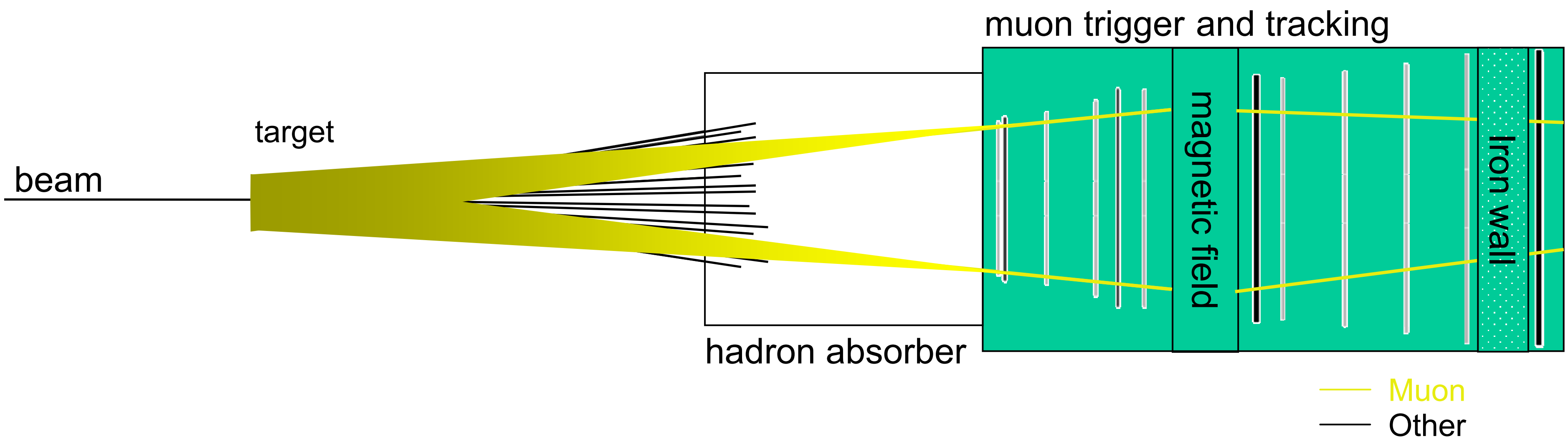
If you have the chance of working in a high luminosity experiment, meaning high interaction rates, then you need a trigger, to select the interesting events among the many (minimum bias) collisions. Otherwise, the data acquisition system will be permanently busy reading out and storing (mostly) non-interesting events.

Remarks concerning the specific example of the NA38/50/60 dimuon trigger system:

- It selects one interesting collision out of around one million inelastic “pp” collisions (the exact number depends on the magnetic field, on the thickness of the hadron absorber, etc).
- Without trigger, the same number of collected J/ψ events, for instance, would require writing on tape a much higher number of events, and do the search for the interesting events at the offline software level.
- In 2003, NA60 was running at 5×10^7 Indium ions per burst, incident on a 18% interaction length target, leading to around 10^7 *probed inelastic collisions* per burst (5 seconds). And every single one is recorded on tape, if it produces a dimuon.
- 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, we take all collisions, from the most peripheral to the most central.

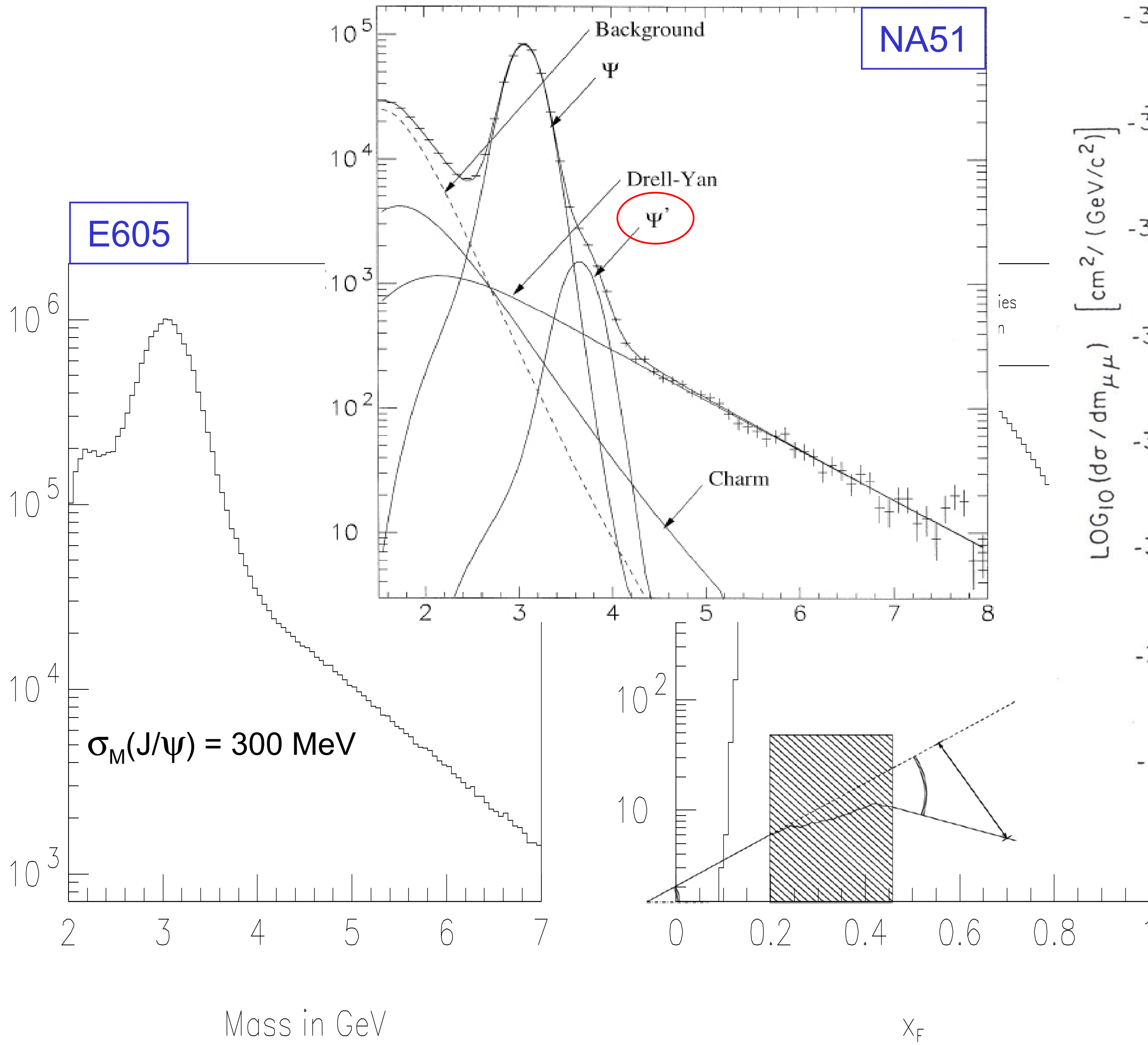
Homework: compare this to the situation of the NA49, NA57 and CERES experiments.

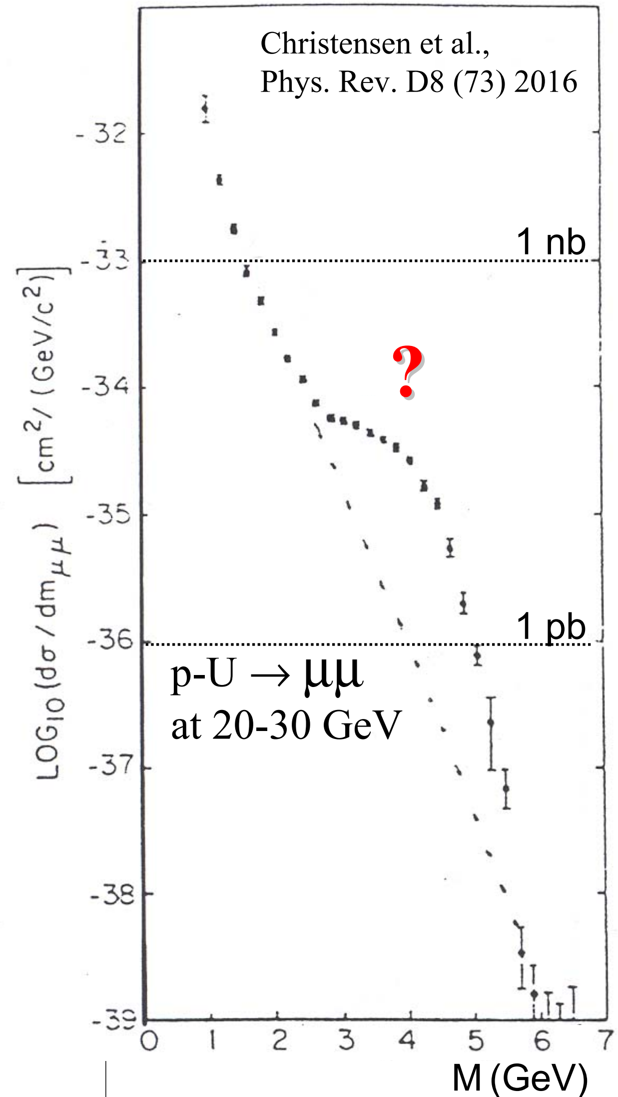
Standard way of measuring dimuons: NA50, PHENIX, ALICE, etc



The dimuon mass resolution is severely affected by multiple scattering

→ difficult to see the ψ' as a shoulder of the J/ψ
→ or the φ as a shoulder of the ρ/ω





How to be less sensitive to the multiple scattering?

1) Radical solution: *eliminate* the hadron absorber

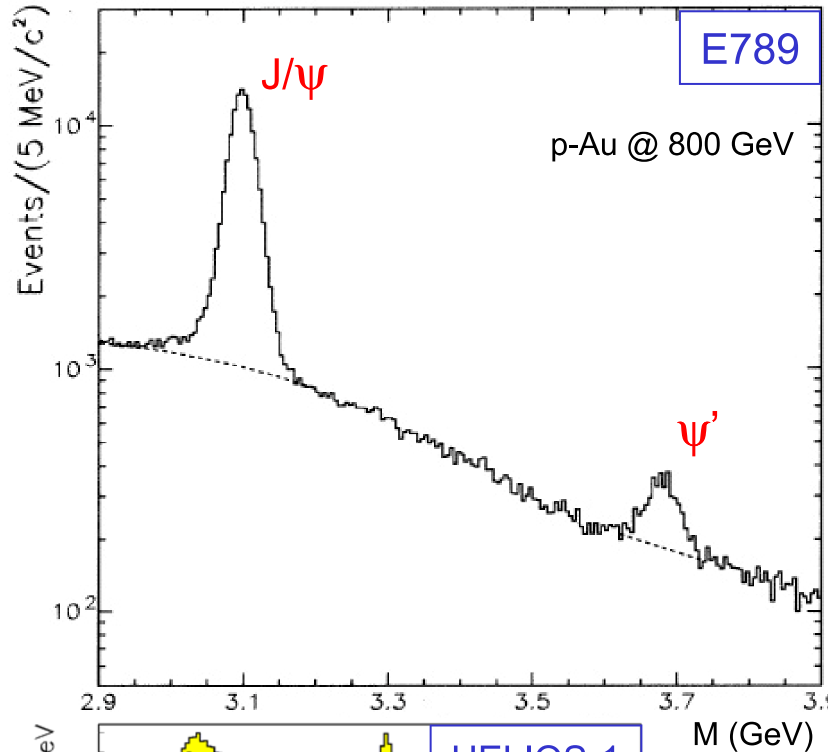
Done by E789 when measuring ψ production in p-Au collisions at 800 GeV
→ 16 MeV dimuon mass resolution at the J/ψ

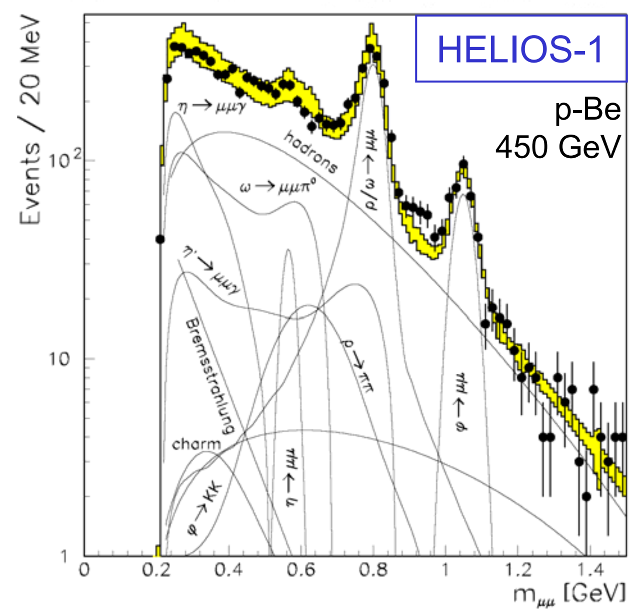
but no dimuon continuum physics…
and not healthy for the tracking chambers, overwhelmed with hadron tracks

2) Add a *vertex detector* and match the muon tracks to tracks in the target region

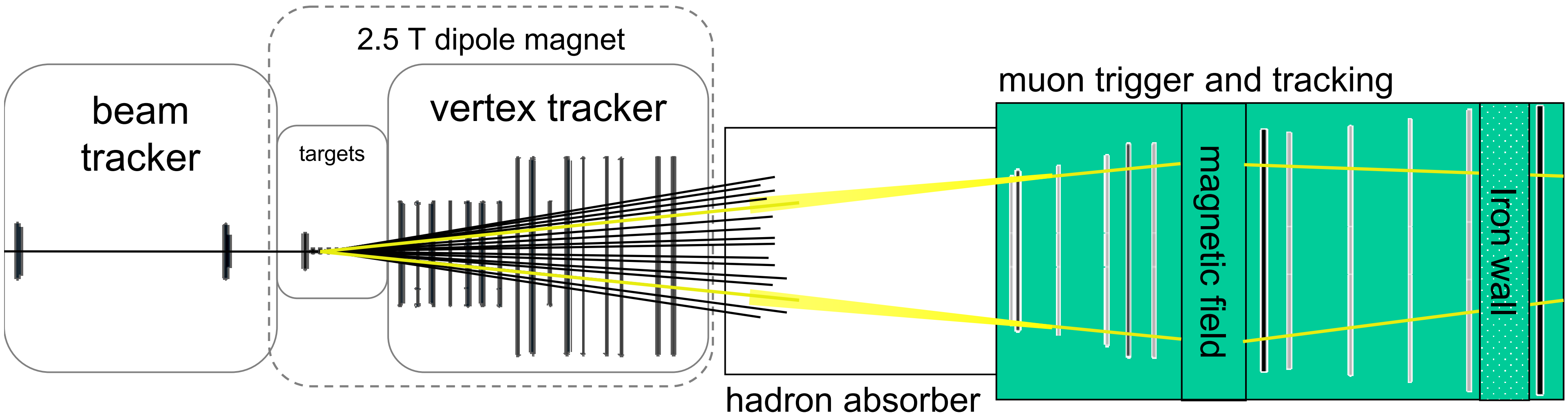
Done by HELIOS-1 in p-Be collisions at 450 GeV (the occupancies in the drift chambers were too high the high rate p-W run)

Presently being done by NA60, with silicon tracking planes, even in the high multiplicity environment of central heavy-ion collisions, thanks to a technological breakthrough: radiation tolerant silicon pixel detectors



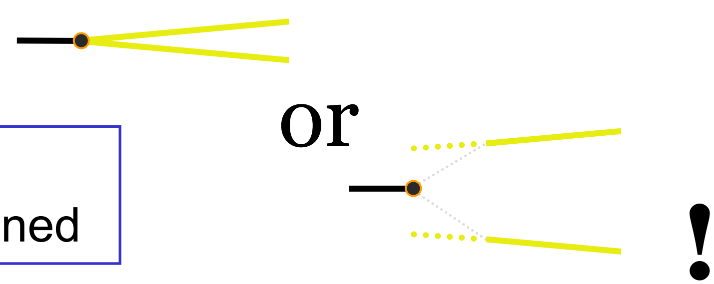


NA60's way of measuring dimuons



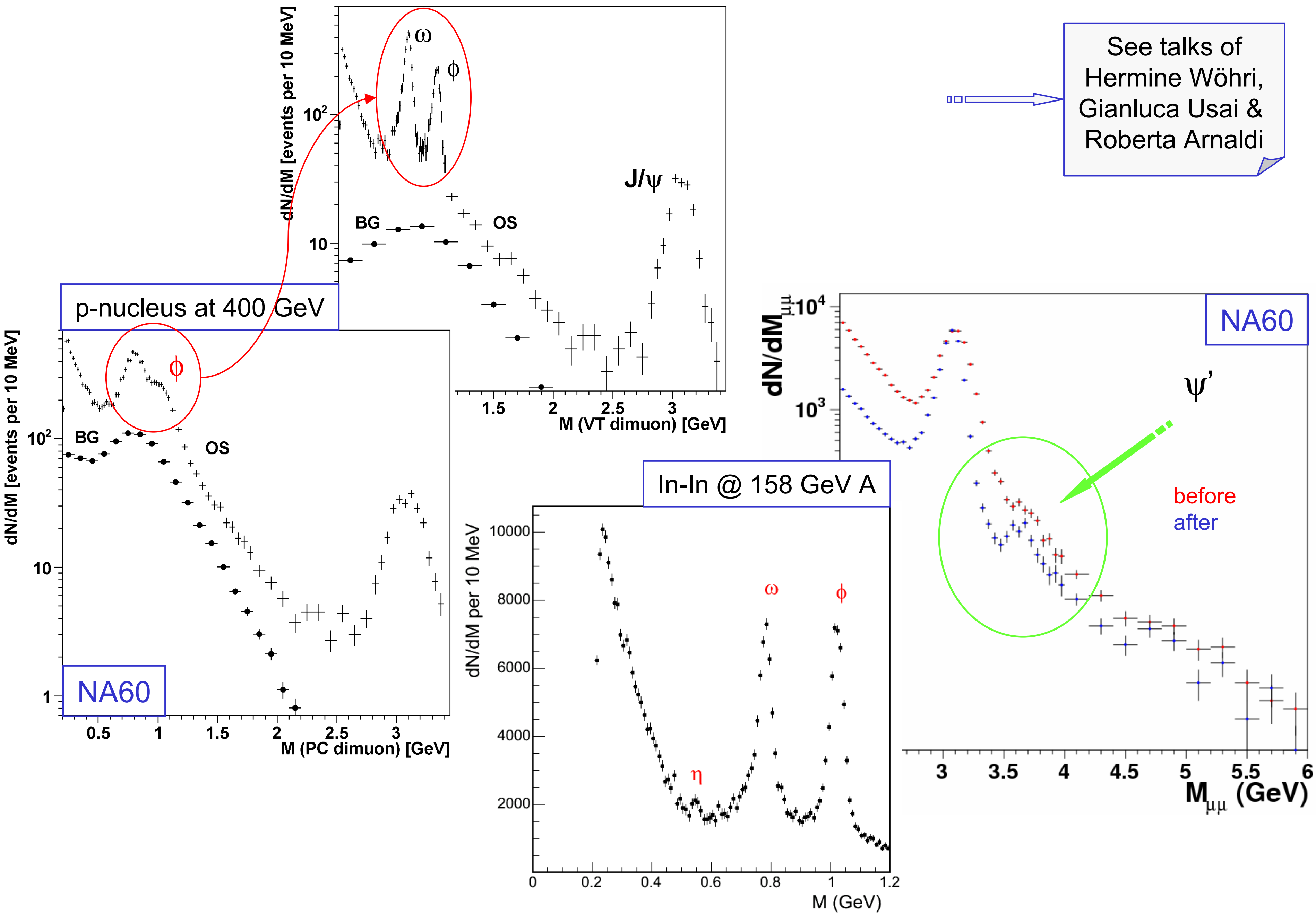
Matching in coordinate and momentum space

- Improved dimuon mass resolution
- Origin of muons can be accurately determined



The dimuon mass resolution is significantly improved by the muon track matching

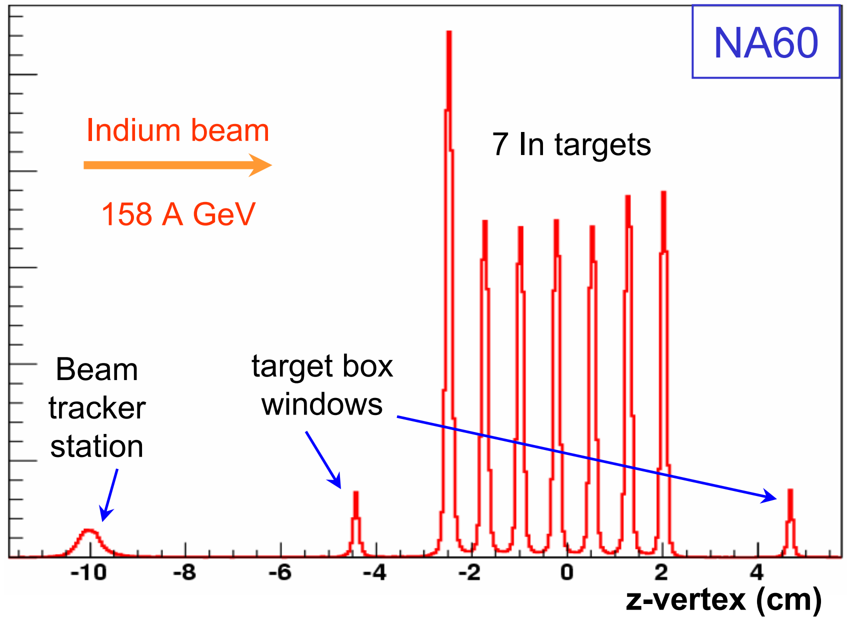
See talks of Hermine Wöhri, Gianluca Usai & Roberta Arnaldi



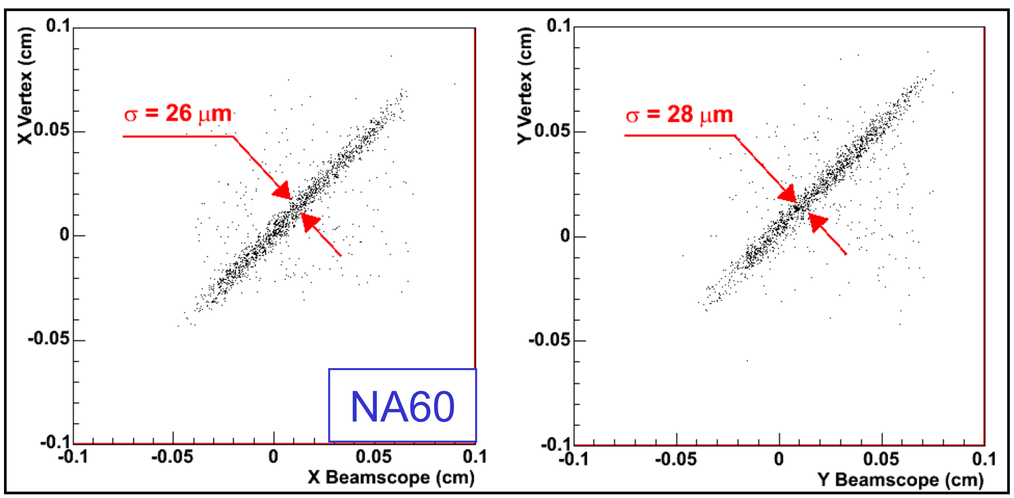
Vertex resolution

See talk of Ruben Shahoyan

The selection of the target where the interaction took place requires a good z-vertex resolution (in NA60: ~ 200 µm)

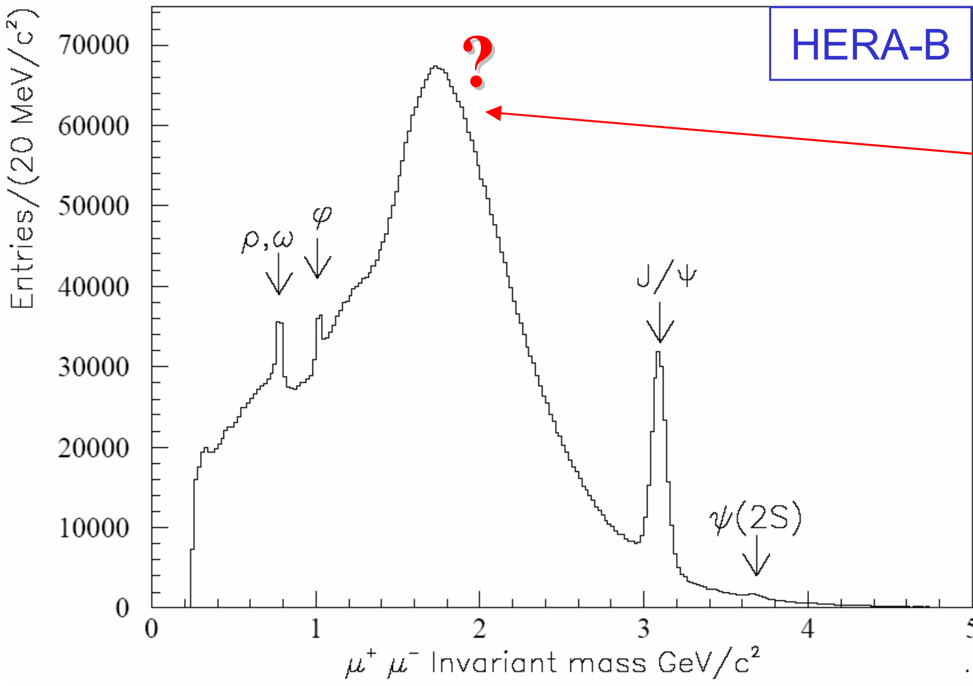


A good accuracy on the determination of the transverse coordinates of the interaction point is needed to separate the prompt dimuons from the charm decays (in NA60: better than 20 µm)



Acceptances

See talk of Antonio Zoccoli

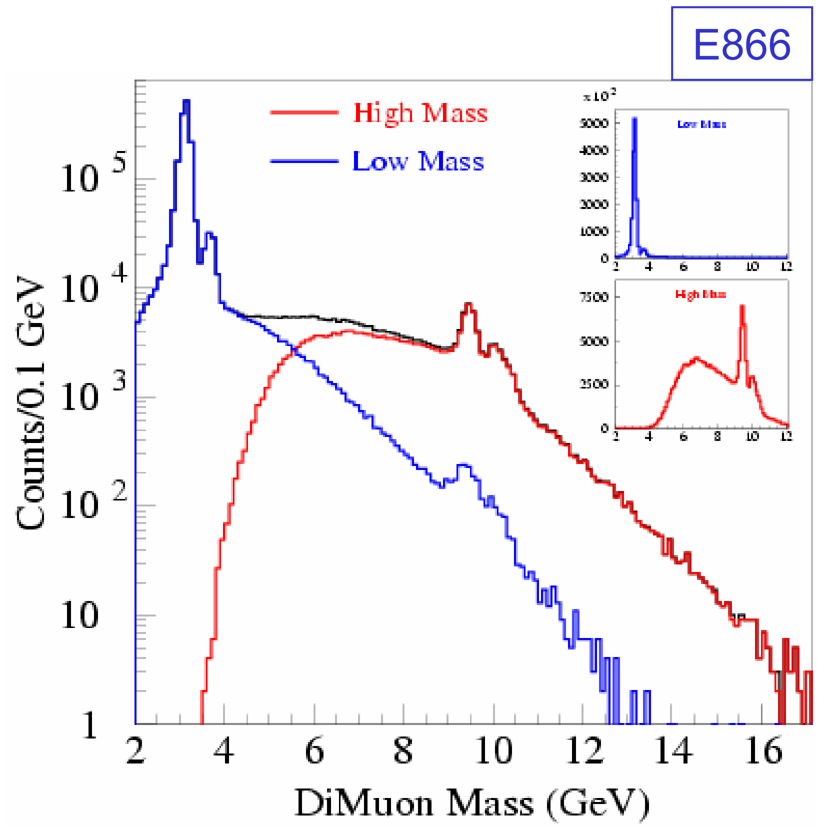


Excellent dimuon mass resolution, but what is the peak at M ~ 1.8 GeV? A signal of $D^0 \rightarrow \mu^+\mu^-$ decays?

No; a signal that the acceptance drops at the lower dimuon masses.

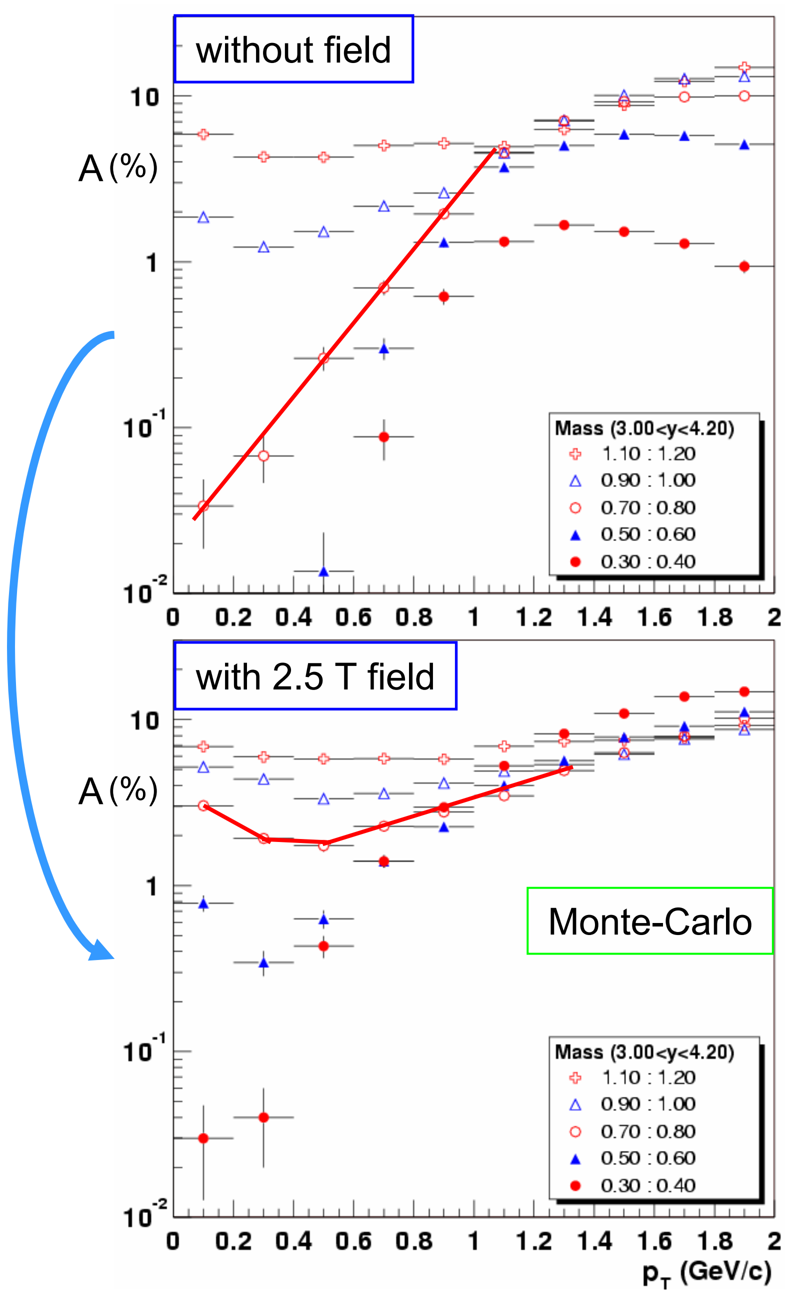
Acceptance is the probability that a dimuon produced with certain kinematical values (mass, rapidity, p_T, $\cos(\theta)$, etc), is detected by the experiment; it is a multidimensional function, not easy to correct for (much trickier than single particle acceptances).

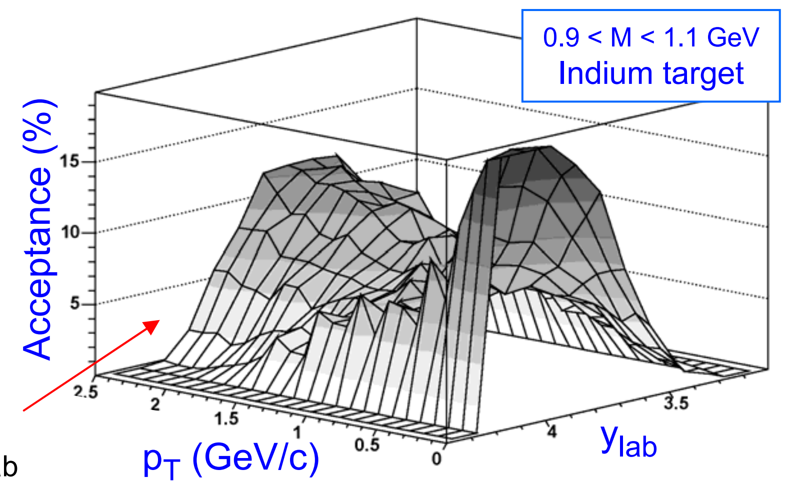
It is better to generate events according to some theoretical model and "filter" them through a Monte Carlo simulation program reproducing the detector limitations and the analysis selection procedures.



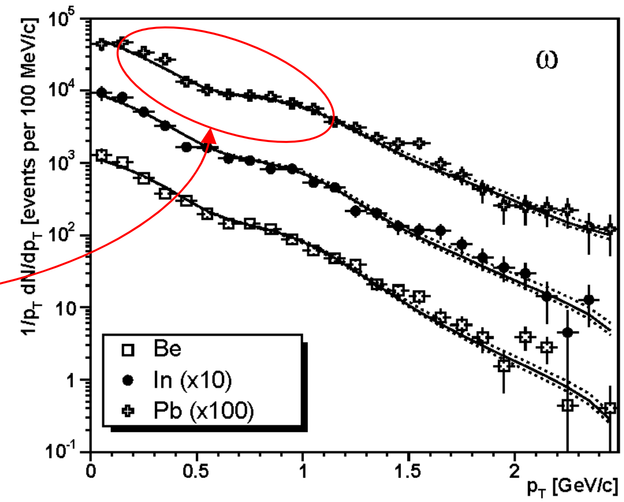
Acceptances in NA60

The acceptances depend on the magnetic fields (in the muon spectrometer and in the vertex telescope), on the “thickness” of the muon filter, on the relative distances between the target, the detecting elements and the magnet, etc. They are evaluated through Monte Carlo simulation.





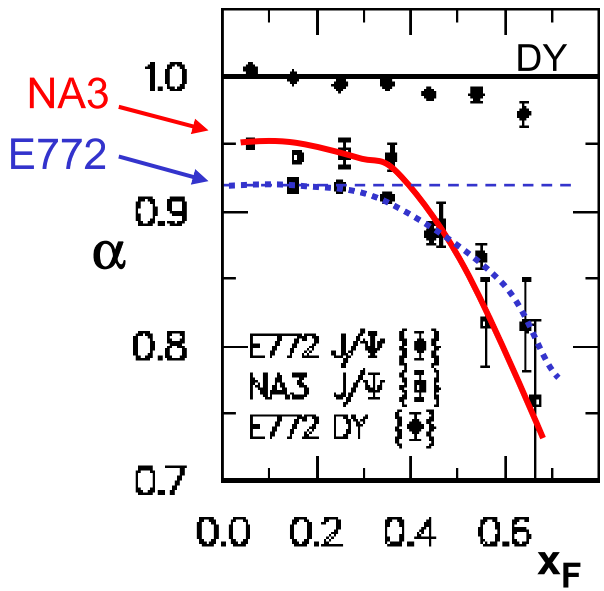
correlation in p_T and y_{lab}

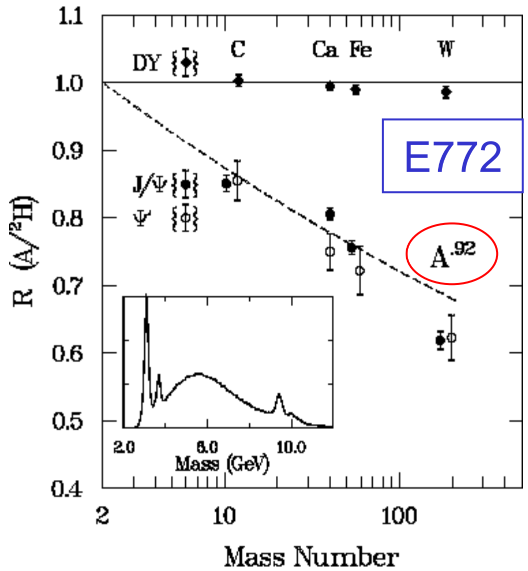


acceptance effect

J/ψ A-dependence in p-nucleus collisions at 800 GeV

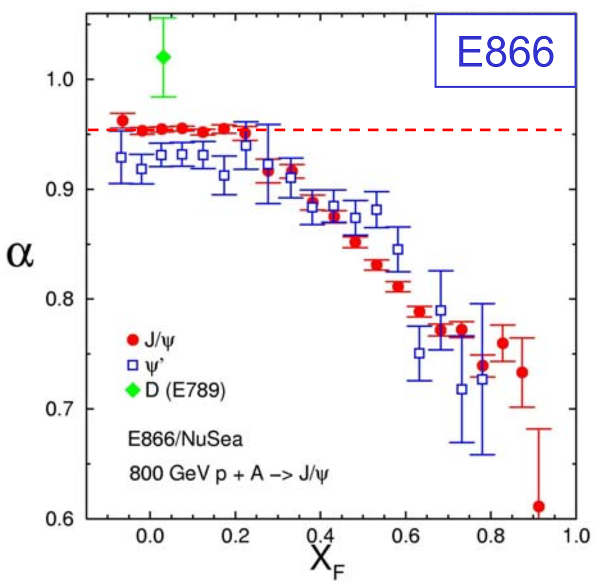
shown in terms of α,
with $\sigma_{p\text{-}A} = \sigma_0 \times A^{\alpha}$
(α=1 $\Rightarrow$ no absorption)





E772 (at x_F~0):

α(J/ψ) ~ 0.92



E866 (at x_F~0) :

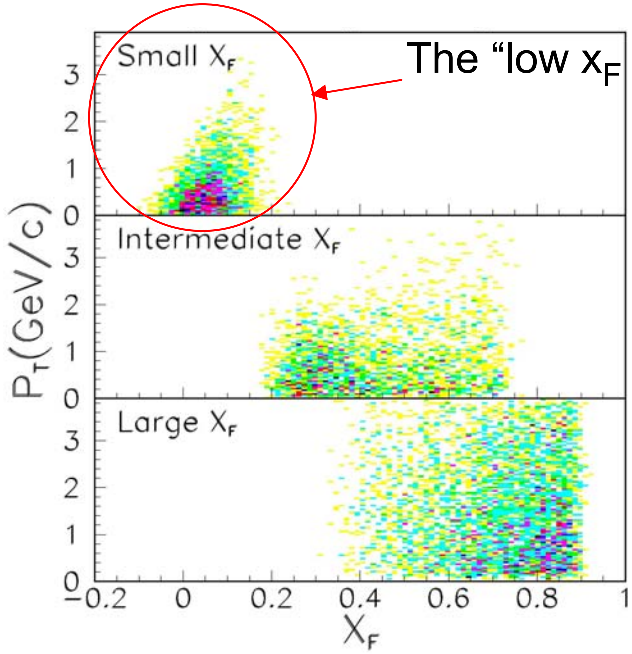
α(J/ψ) ~ 0.95

Why has the value of α changed from E772 to E866 ?

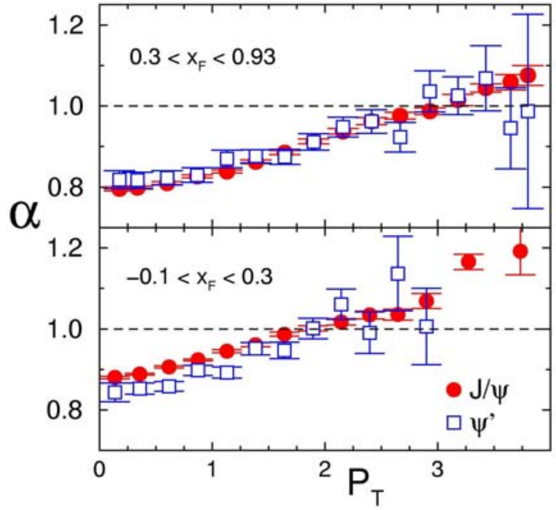
Because of a better understanding of the acceptance effects…

See talk of Mike Leitch

Effect of the acceptance on the measured J/ψ A-dependence

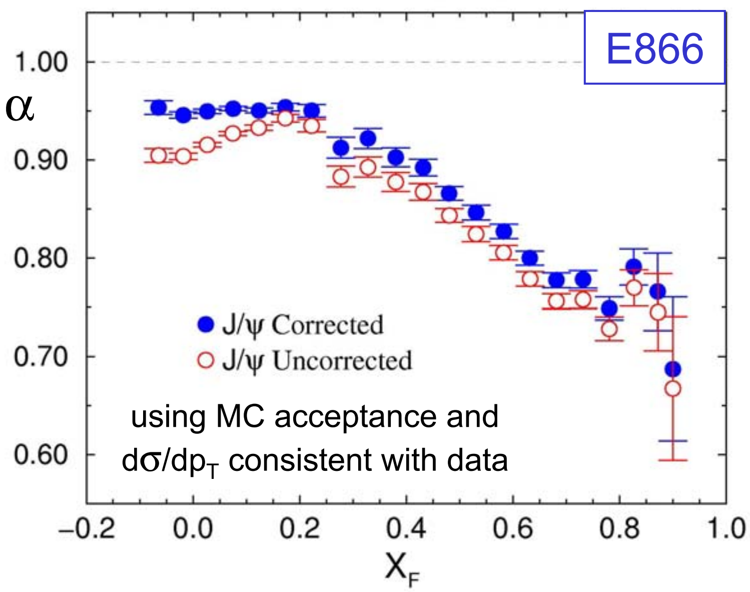


The "low x_F setup" has a very narrow p_T acceptance

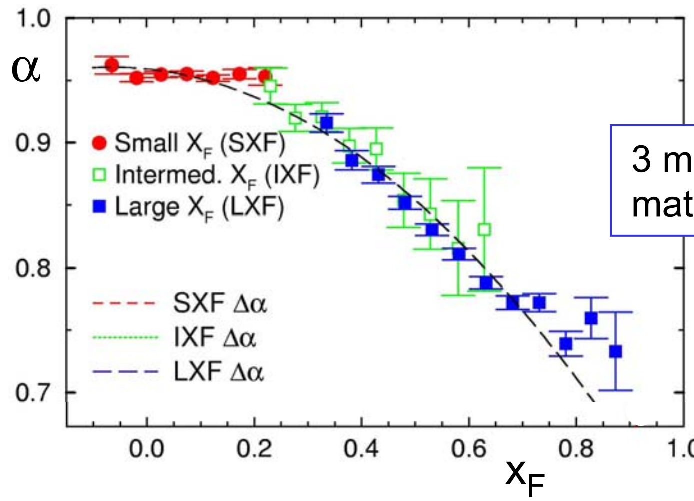


The value of α has a strong dependence on x_F and p_T

the correction of the (correlated) acceptance is crucial, since the incomplete coverage in p_T distorts the J/ψ absorption pattern vs. x_F



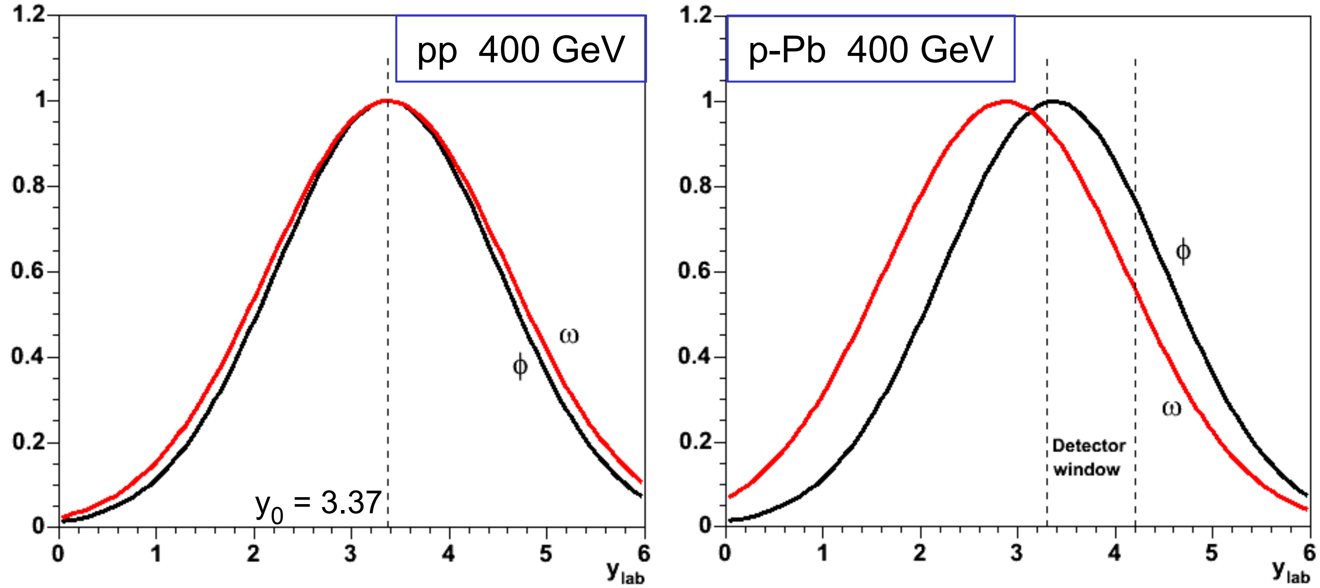
This problem was identified, and solved, because the p_T coverage in E866 is much better than in E772.



3 magnet settings match quite well

Phase space windows

Experiments with narrow phase space coverage should be particularly careful in formulating their results.



Assume that:

→ The ω is "shifted" towards the target hemisphere by 0.5 rapidity units in p-Pb collisions

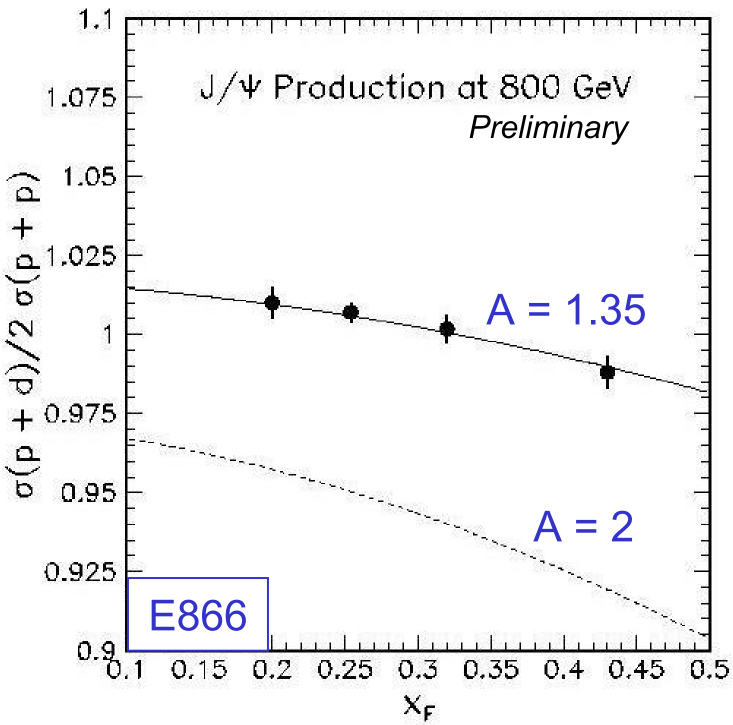
→ The ϕ retains the same y distribution as in pp collisions

Then, a detector measuring dimuons from ω and ϕ decays in the y window $3.3 < y < 4.2$ would see relatively more ϕ than ω events in p-Pb collisions, with respect to pp collisions, in the probed phase space window, $\alpha(\phi) = \alpha(\omega) + 0.04$, even if the (total) production cross-section of the ω and ϕ would have the same nuclear dependence. Another experiment, covering only backward rapidities, would "see" the opposite result: a steeper A-dependence for the ω meson.

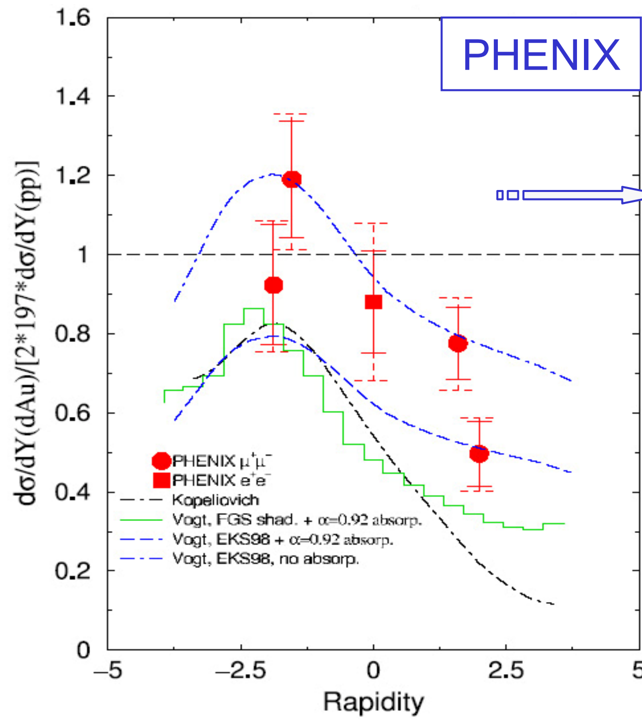
You can correct for acceptances within the phase space window where you have data. But extrapolations to full phase space require assuming kinematical distributions where you cannot check them. Your "measurement" becomes model dependent.

Phase space windows and J/ψ production

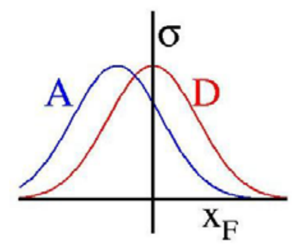
E866: the rapidity distributions of the J/ψ are different from pp to pd collisions



PHENIX: the J/ψ is able to distinguish between the d and the Au hemispheres



See talks of Marzia Rosati & Mike Leitch



The y distributions of the J/ψ change from pp to pd and to d-Au collisions.

⇒ What is the influence of such J/ψ rapidity "shifts" in p-nucleus collisions on the value of the normal nuclear absorption cross-section measured by NA50?

Would it remain σ_{abs} ~ 4.3 mb if measured over a broader coverage in rapidity?

Note: there are no rapidity shifts in symmetric collisions, such as Au-Au or Pb-Pb. The suppression from peripheral to central Pb-Pb collisions, for instance, cannot be due to phase space limitations.

Efficiencies

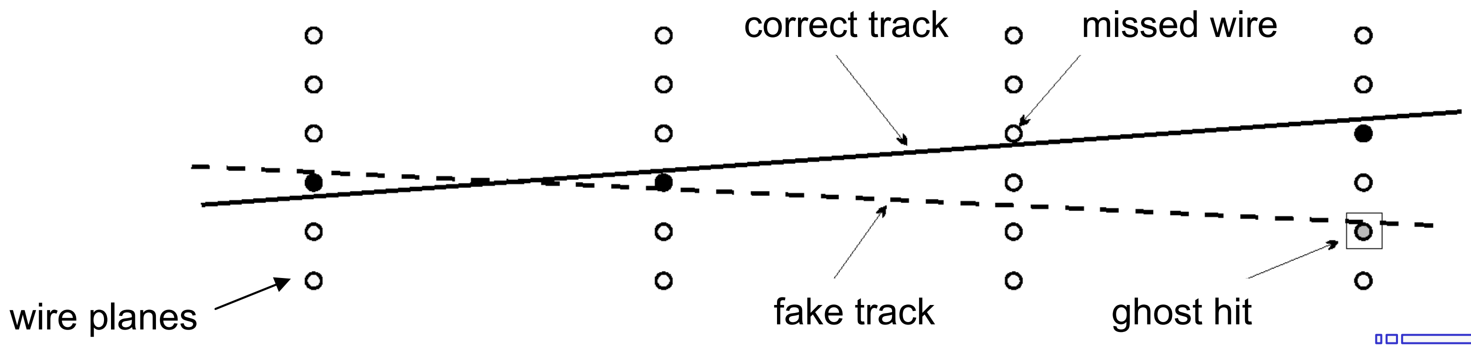
Even within the phase space windows where the detector has a good acceptance, sometimes a J/ψ, for instance, is produced but is not detected. Maybe the trigger system missed it; or the muon tracks were not reconstructed; or the interaction vertex could not be identified; etc.

The convolution of all such inefficiencies, ε, must be taken into account to extract absolute production cross-sections.

$$B\sigma^{J/\psi} = \frac{N^{J/\psi}}{L \cdot A^{J/\psi} \cdot \varepsilon}$$

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

Example of an inefficient tracking algorithm: if a cluster is used to build a track, it is removed from the sample used to look for further tracks. It saves CPU time but, in case of high occupancies, or of noisy detectors, maybe the first track was fake, and you miss the real one. This algorithm was used in NA38 and was inefficient for the reconstruction of a specific data set, collected with a very light hadron absorber (chamber occupancies were higher than usual).



See talk of Gonçalo Borges

Backgrounds

In standard dimuon experiments, the main sources of background are the (uncorrelated) decays of π and K mesons. It can be minimized by having the hadron absorber as close to the collision point as possible. In HELIOS-1 this was not the case and the process $\rho \to \pi^+\pi^- \to \mu^+\mu^-$ could not be neglected, leading to correlated "background" dimuons.

By changing the hadron absorber we change the relative importance of the π and K decays on the measured $\mu^+\mu^-$ sample: good way to control the background, unless its level is too high in both configurations.

"Combinatorial background" sources (π and K decays) also give $\mu^+\mu^+$ and $\mu^-\mu^-$ pairs, which can be used to estimate the corresponding $\mu^+\mu^-$ contribution. This is not that easy (R-factors, image cut, mixed event techniques, etc.) and would require another lecture…

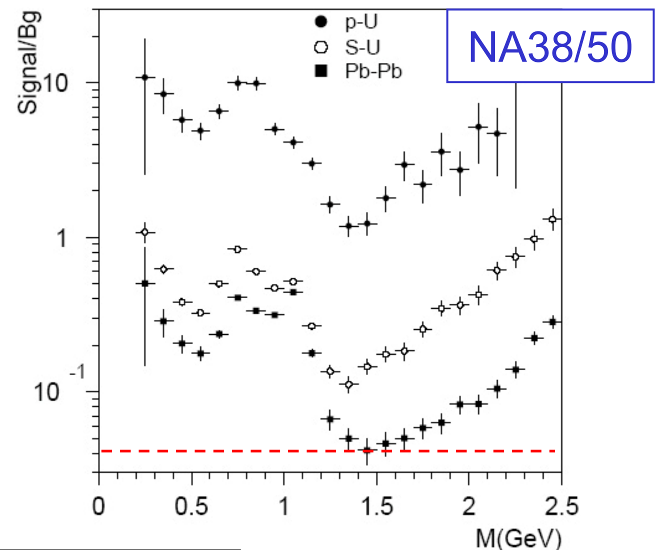
In experiments like NA60, where the muons are matched to tracks in the target region, the combinatorial background is strongly reduced but another source of background comes into play: the fake matches

See talk of
Ruben Shahoyan

→ To properly study a signal, we must understand the backgrounds!

Importance of the signal to background ratio

Suppose the *expected* signal is 4% of the estimated background and you see an "excess" in your data: the number of observed opposite-sign muon pairs is larger than the expected signal plus the estimated background: OS > Signal + Bg

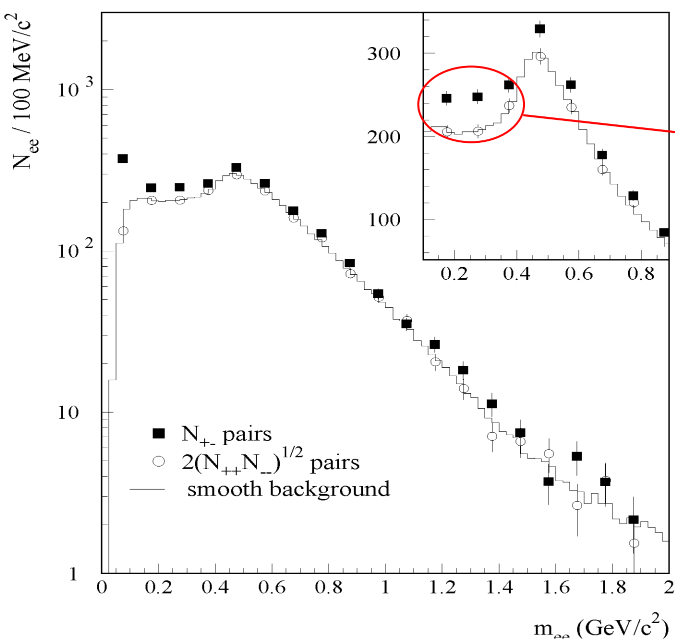


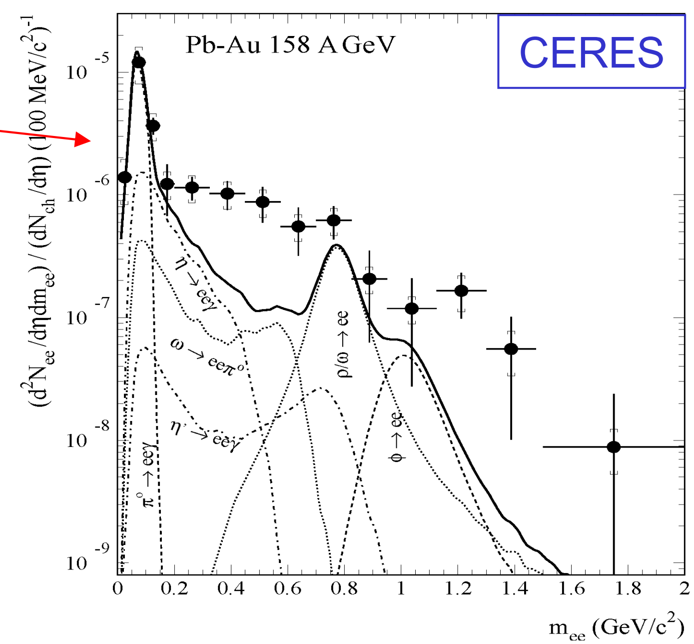
For instance: N^{OS} = 3.7% (expected signal) +
92.6% (expected background) +
3.7% (unexpected source)

What would you say?

☺ the signal is increased by a factor 2 !

☹ the background was underestimated by 4% …





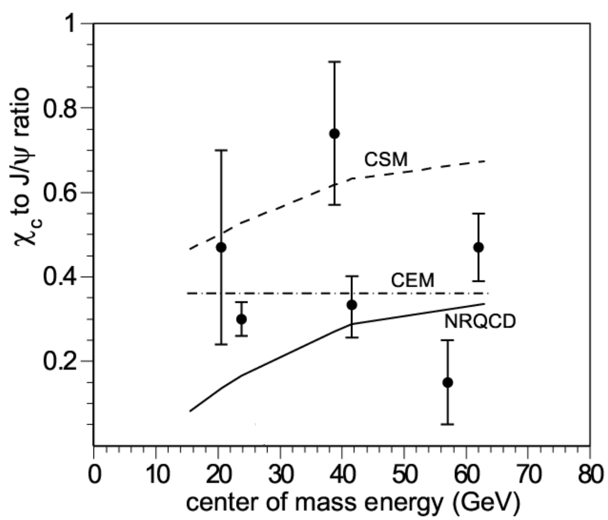
Feed-downs

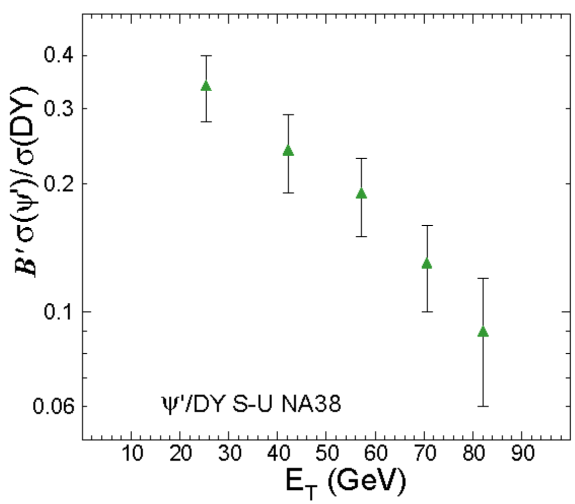
Many of the measured J/ψ mesons are produced by the decay of other particles: χ_c, ψ' and B

See talk of Antonio Zoccoli

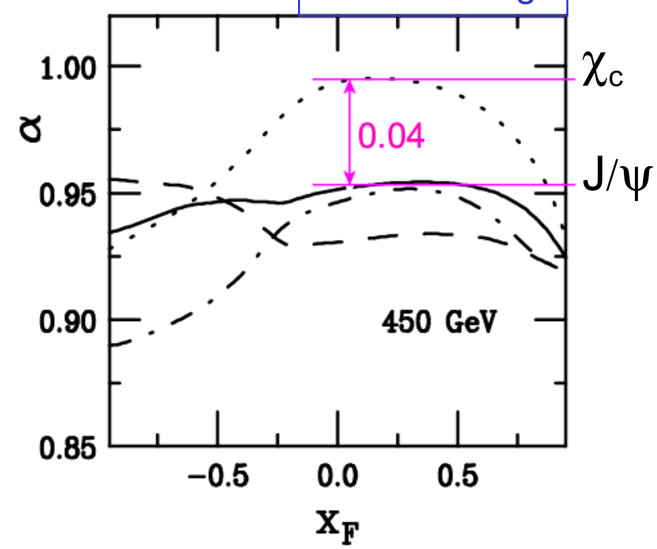
The parent particles have different nuclear dependences:

- the ψ' is more strongly absorbed than the ψ, already in p-A and S-U collisions
- open beauty production should not be absorbed (α~1)
- the χ_c nuclear dependence is not known yet
  - → it is a larger resonance than the ψ ⇒ expect stronger absorption
  - → does not need an extra gluon to be formed ⇒ expect weaker absorption





Ramona Vogt

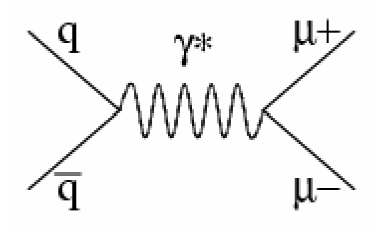


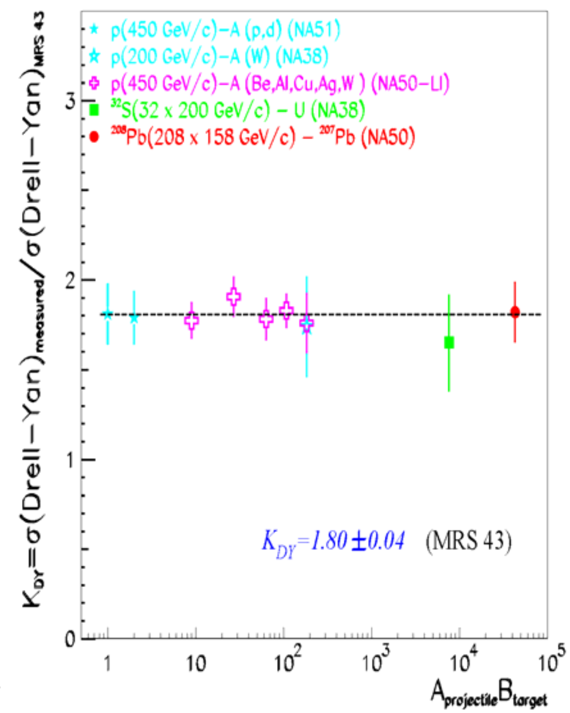
→ Measurements are needed for the χ_c meson (HERA-B, NA60)

→ Vertexing capabilities are needed at RHIC and LHC, to distinguish prompt J/ψ production from beauty decays

See talks of John Harris & Philippe Crochet

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)

See talk of Louis Kluberg

• Charm/beauty decays:
☺ should be ideal reference processes
☹ unless heavy flavor production is also affected by "new physics"?

Reference collision systems

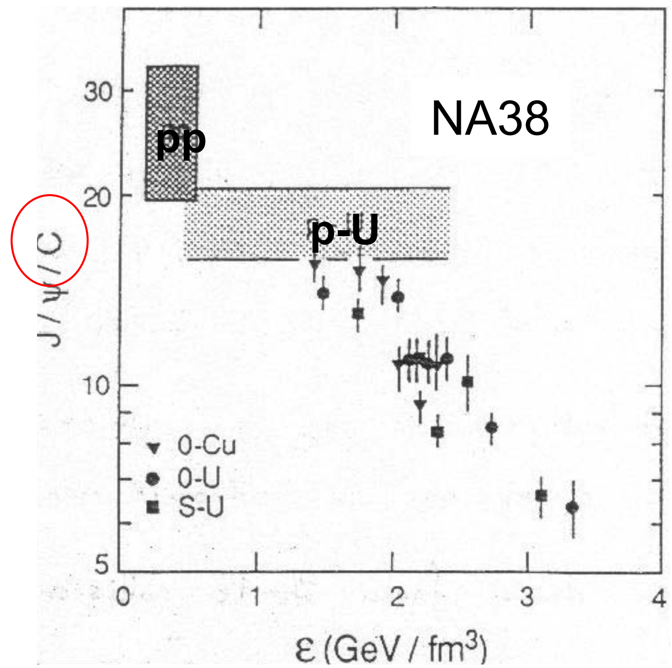
1) pp, p-A, light-ion data; at several energies
2) centrality scan from very peripheral to very central A-A collisions

See talks of Louis Kluberg & Goncalo Borges

→ must be a fundamental component of the heavy-ion physics programme
→ defines the reference baseline relative to which we recognize the HI specific features
→ 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…

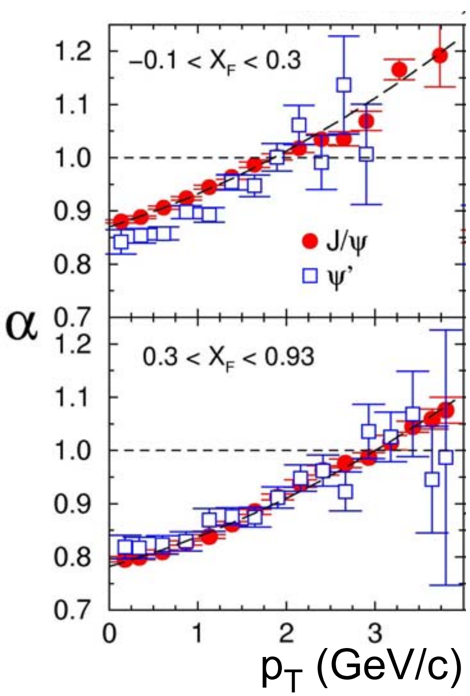
The main difference is the understanding of the references:
→ a lot more p-A data points are available
→ "Continuum" (IMR) was replaced by DY

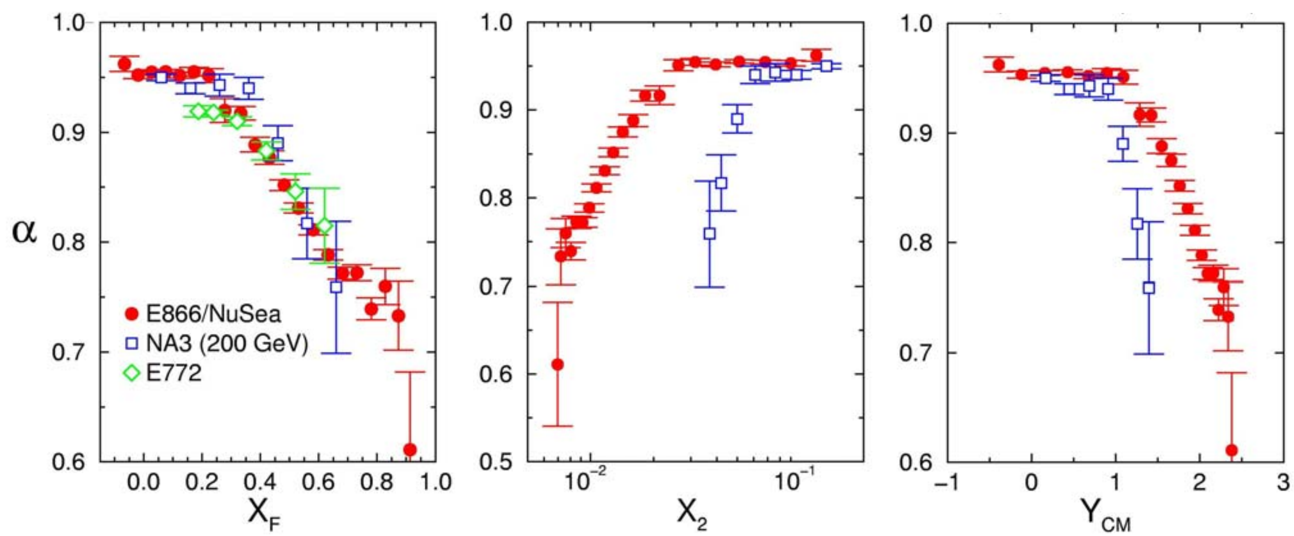
How can we compare the results of different experiments?

It is not easy to compare the results of different experiments, even if all the acceptance and efficiency corrections are well done.
→ different collision systems, energies, phase space domains, feed-downs, etc.

Should the $\alpha(J/\psi)$ measured at Fermilab be the same as the one measured at the SPS? As a function of which "scaling" variable? This is crucial, to learn about production mechanisms, formation times, interactions with nucleons, etc. The NA3 and E866 results seem to overlap best as a function of x_F, rather than x_2, y_{CM} or p_L, for instance.

See talk of Mike Leitch





But NA3 measured α by comparing p-Pt to p-H; and very light targets give biased α values

Three formulations of charmonia nuclear absorption

① A^{α} : widely used but very rough: the lighter is the first target, the higher is the extracted α

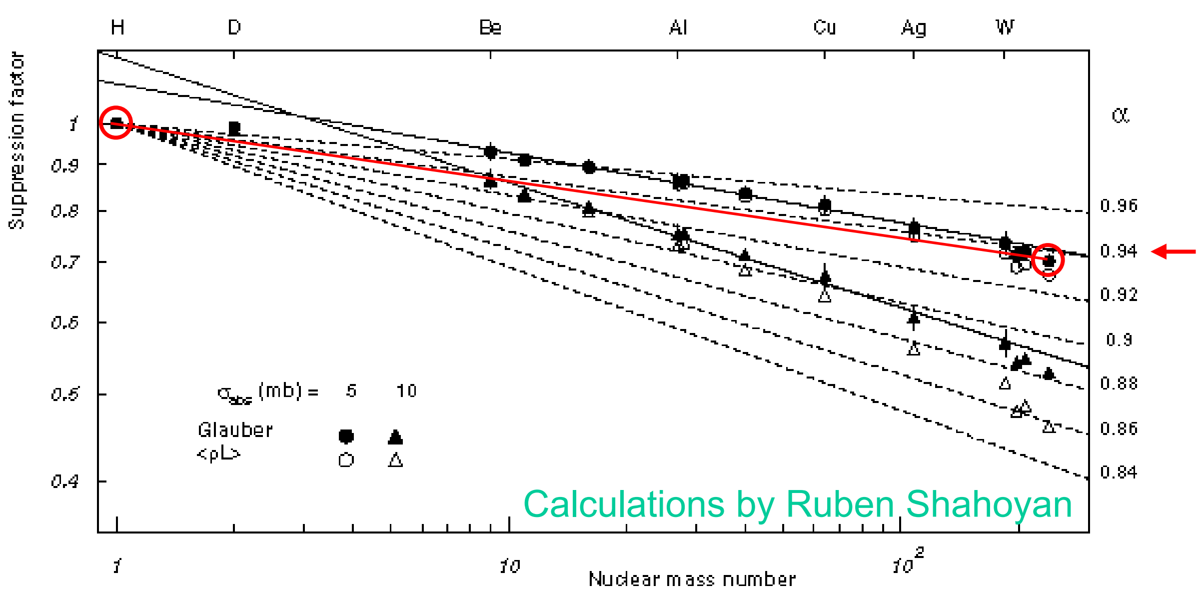
② $\langle \rho L \rangle$: average amount of matter seen by the meson from production until exiting the nucleus

③ Glauber : the meson is produced in a NN interaction, and absorbed in nuclear matter, with a break-up cross section σ_{abs}

→ A^{α} parameterization: $$\sigma_{pA} = \sigma_0 \, A^{\alpha}$$

→ $\langle \rho L \rangle$ parameterization: $$\sigma_{pA} = \sigma_0 A \exp(-\sigma_{abs} < \rho L >)$$

→ full Glauber calculation: $$\sigma_{pA} = \frac{\sigma_0}{\sigma_{abs}} \int d\vec{s} \, [1 - T_A(\vec{s})\sigma_{abs}]^A$$



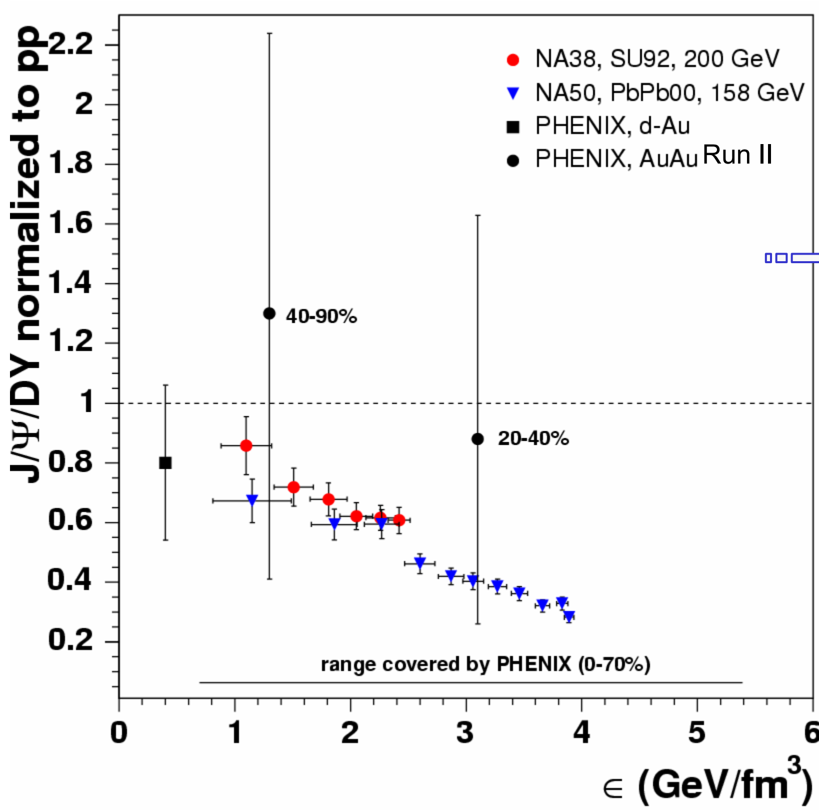
If NA3 had used Glauber, instead of the α fit, they would have derived σ_{abs} ~ 5 mb, like NA50.

If NA3 had p-Be instead of pp, their α would be ~0.92 and not ~0.95

The J/ψ: from the SPS to RHIC

How do we compare the J/ψ suppression pattern measured at the SPS and at RHIC? As a function of L or N_{part}? Surely not! Central Pb-Pb or Au-Au collisions have the same N_{part} ~ 400 at both energies but they must lead to very different energy densities, or gluon densities, for instance.

The SPS ψ data is normalized to the DY yield. At RHIC (or LHC) there is no DY, but the DY yield is proportional to the number of binary nucleon-nucleon collisions, N_{coll}, a variable which can be estimated indirectly.



See talk of Marzia Rosati

Bottom line messages

1) Theorists should read carefully the experimental papers;
   not just the figure captions and the conclusions

2) Experimentalists need time to do a proper job;
   they should resist the temptation of *rushing* into the presentation of “physics results”

3) Important measurements should always be redone, with improved conditions;
   especially those which may indicate significant discoveries