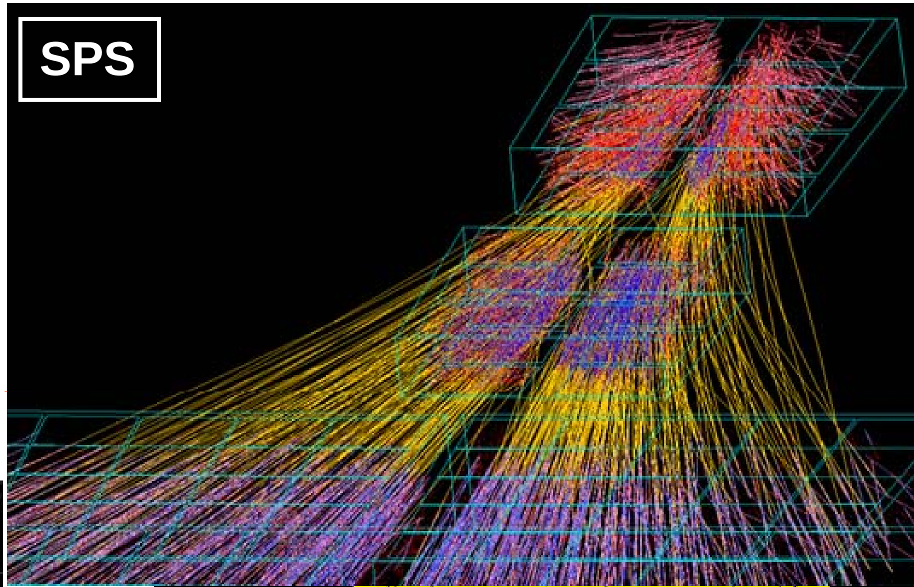
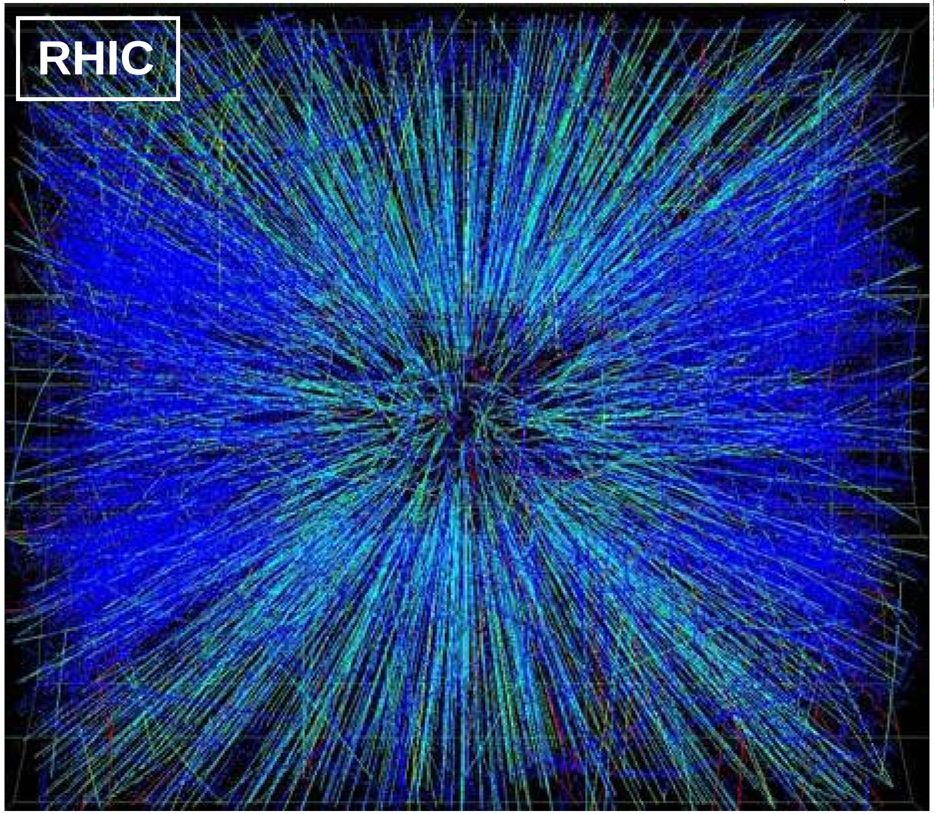
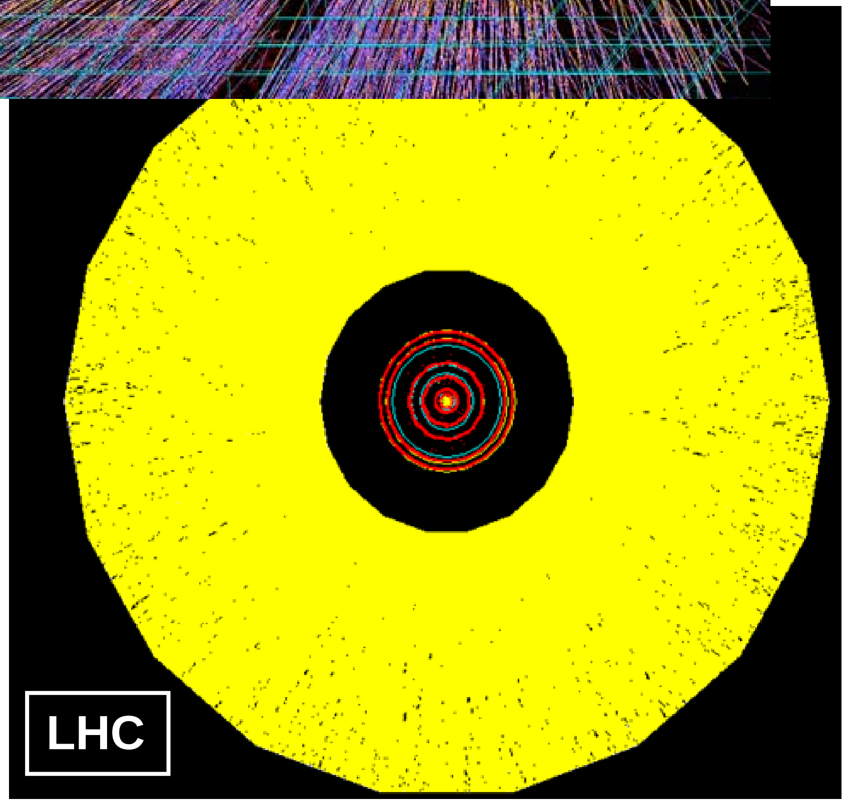
From High-Energy Heavy-Ion Collisions to Quark Matter

Lecture 2:

The art of *experimental*
high-energy (heavy-ion) physics







Reminder: what is the question?

We want to study the nature of Quantum Chromo-Dynamics under the extreme conditions which occurred in the earliest stages of the evolution of the Universe

We do experiments in the laboratory, colliding high-energy heavy nuclei, to produce hot and dense strongly interacting matter, over extended volumes

We use certain “signals” to “probe” the properties of the created matter and see how the quarks and gluons interact in a medium where colour is deconfined

However, there is a problem:
It is not easy to read Mother Nature’s book; what you see is *not* what you get…

The art of experimental (heavy-ion) physics…

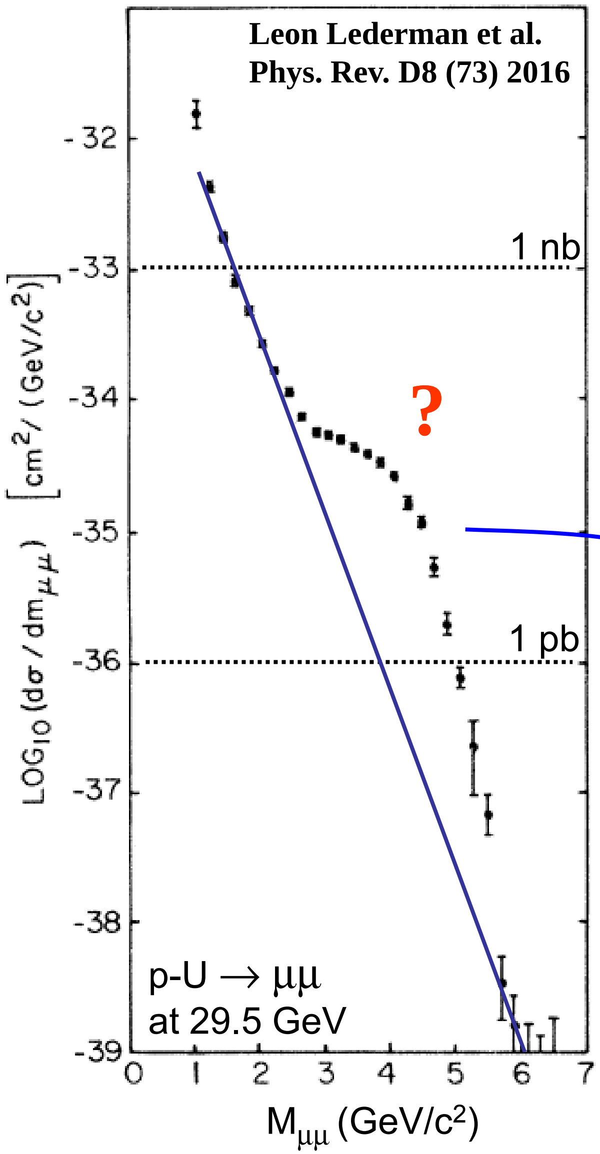
1) Many experimental issues are crucial to properly understand the measurements and derive a correct physics interpretation, such as:

- Acceptances and phase space windows
- Efficiencies (of track reconstruction, vertexing, track matching, trigger, etc)
- Resolutions (of mass, momenta, energies, etc)
- Backgrounds, feed-downs and “expected sources”
- Data selection
- Monte Carlo adjustments, calibrations and smearing
- Luminosity and trigger conditions
- Evaluation of *systematic* uncertainties
- and several others...

2) “New physics” often appears as *excesses* or *suppressions* with respect to “normal baselines”, which must be very carefully established, on the basis of “reference” physics processes and collision systems

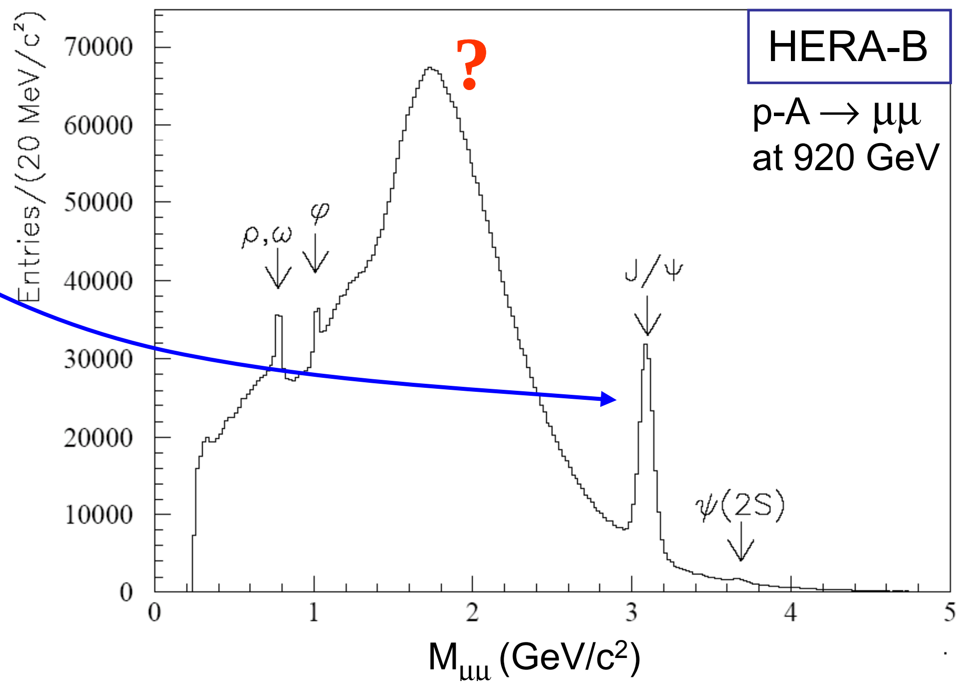
The next slides illustrate some of these issues, with examples from measurements made by NA60 and many other experiments

Resolutions and acceptances distort the reality



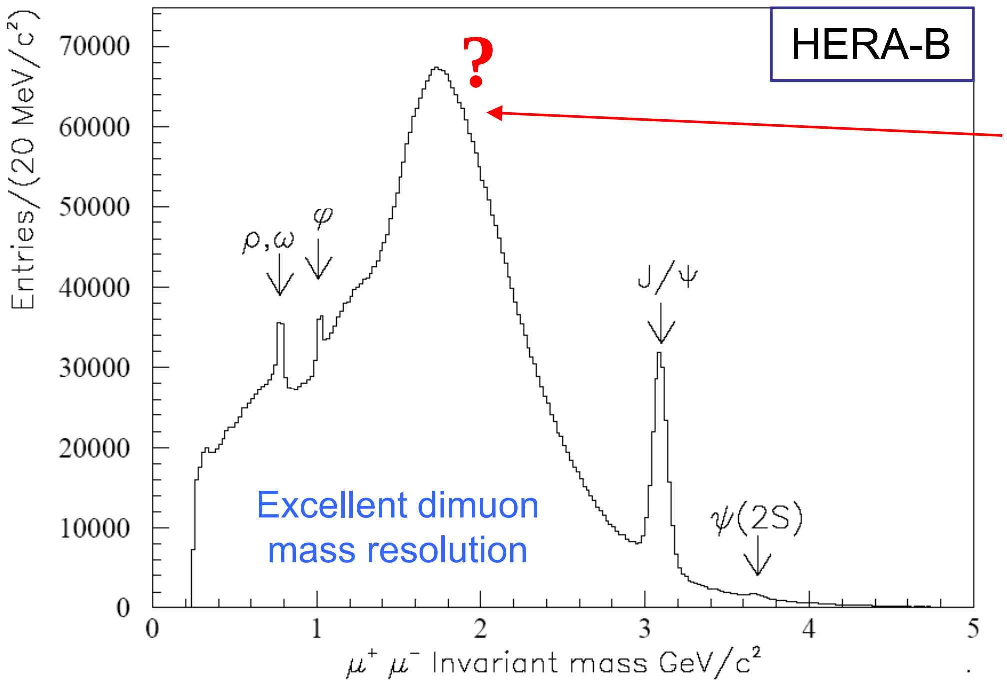
How do you turn a resonance (peak) into a continuum?
Use a lousy resolution...

How do you turn a continuum into a peak?
Use a fancy acceptance curve!



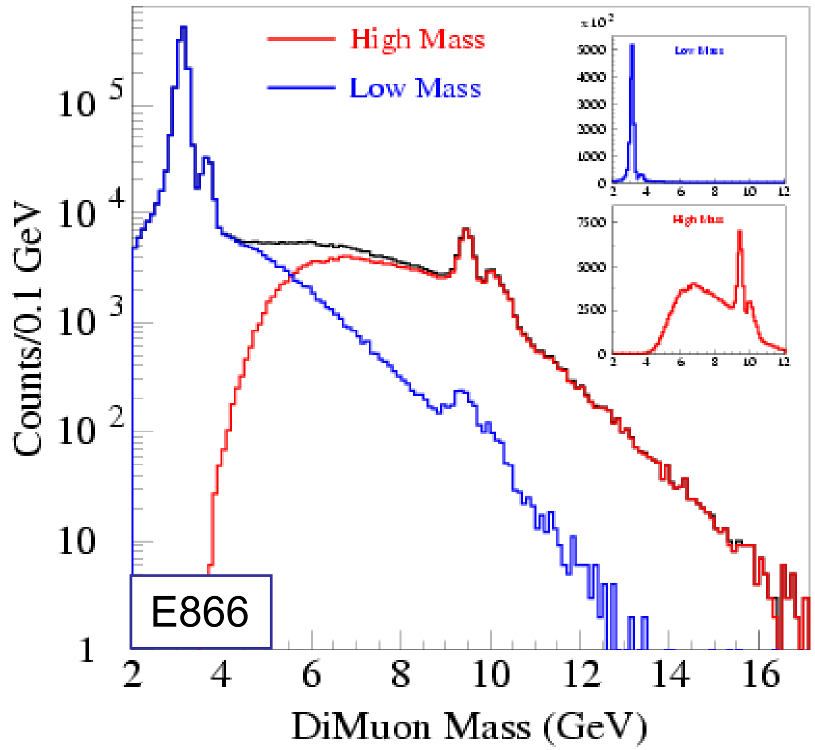
resonances: ρ, ω, ϕ, J/ψ, ψ' → $\mu^+\mu^-$

Acceptances



What is the peak at M ~ 1.8 GeV ?
A signal of $D^0 \rightarrow \mu^+\mu^-$ decays ?

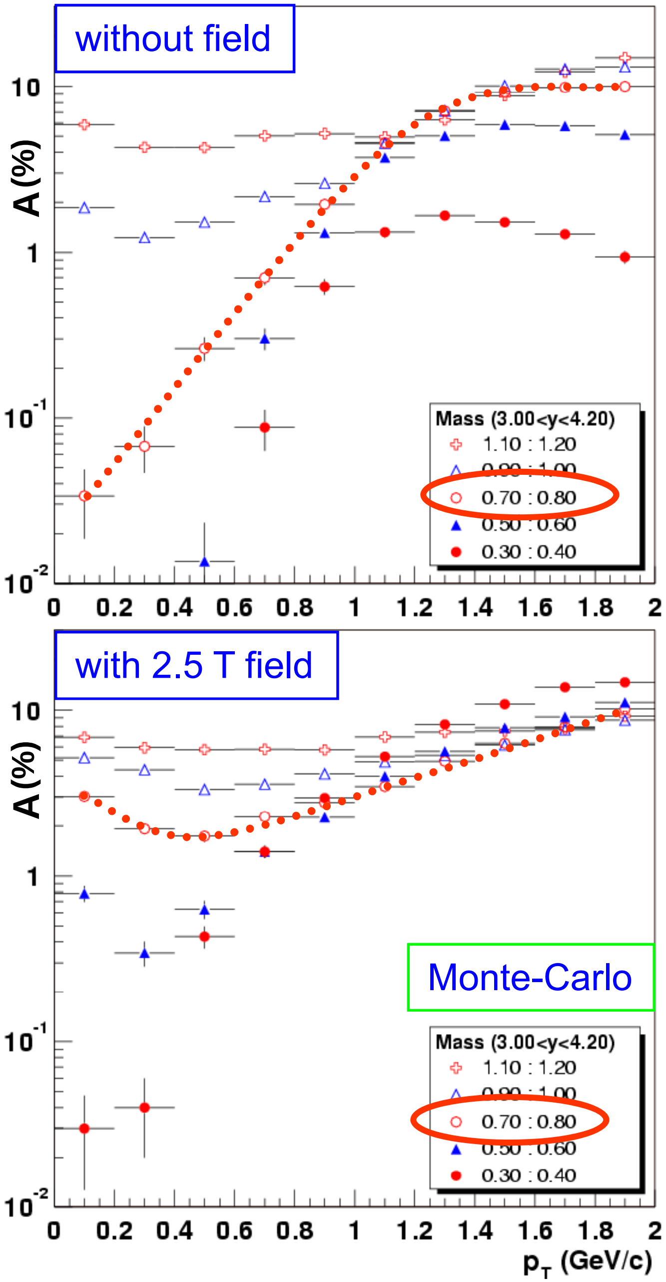
Not really…
Just a signal that the acceptance changes significantly in this region



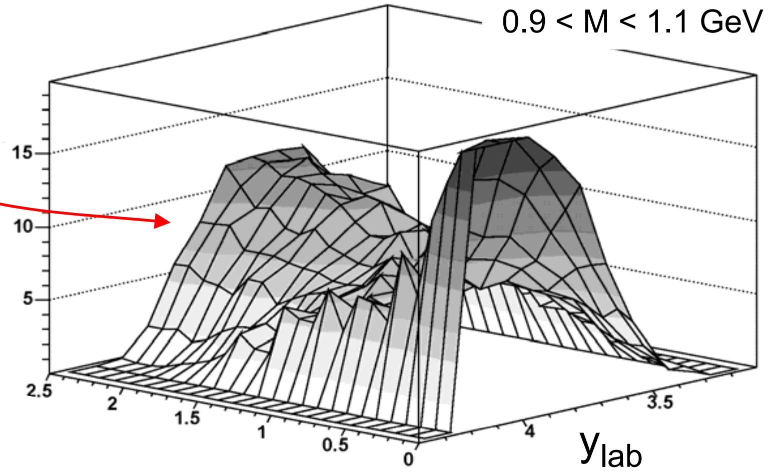
Acceptance is the probability that a particle is detected by the experiment

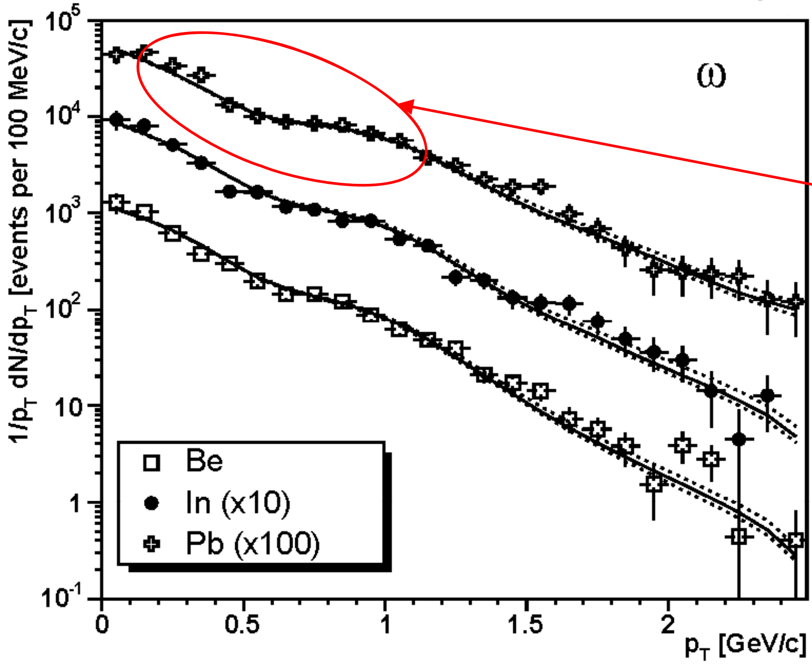
It depends on the kinematical values (rapidity, p_T, etc) and can be calculated by Monte Carlo simulation, reproducing the detector limitations and the analysis selection procedures

The dimuon acceptances depend on the magnetic fields, on the thickness of the muon filter, on the distance between the target and the detectors, etc



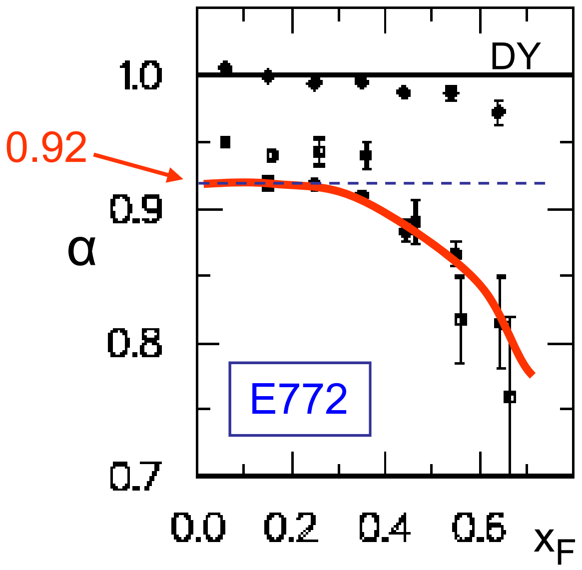
correlation in p_T and y_{lab}

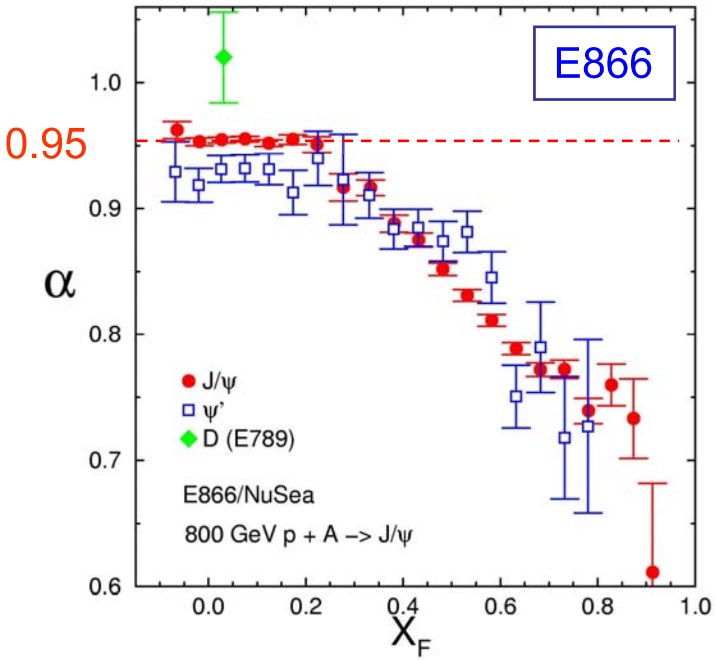




acceptance effect

Acceptance effects on the J/ψ nuclear dependence





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

E772 (at $x_F \sim 0$) 1992
$\alpha(J/\psi) \sim 0.92$

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

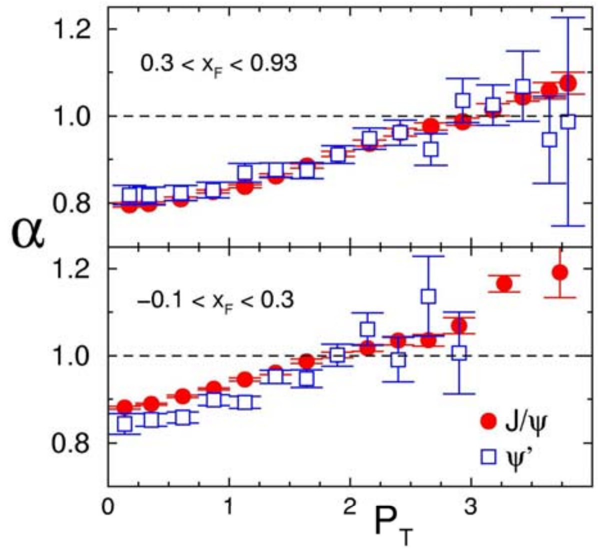
E866 (at $x_F \sim 0$) 1997
$\alpha(J/\psi) \sim 0.95$

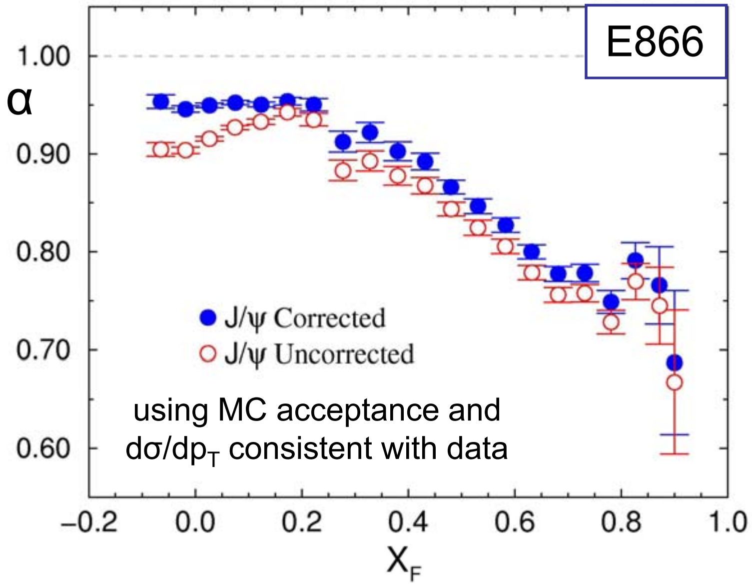
Because the understanding of acceptances improved…

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

$\Rightarrow$ The incomplete p_T coverage distorts the pattern vs. x_F

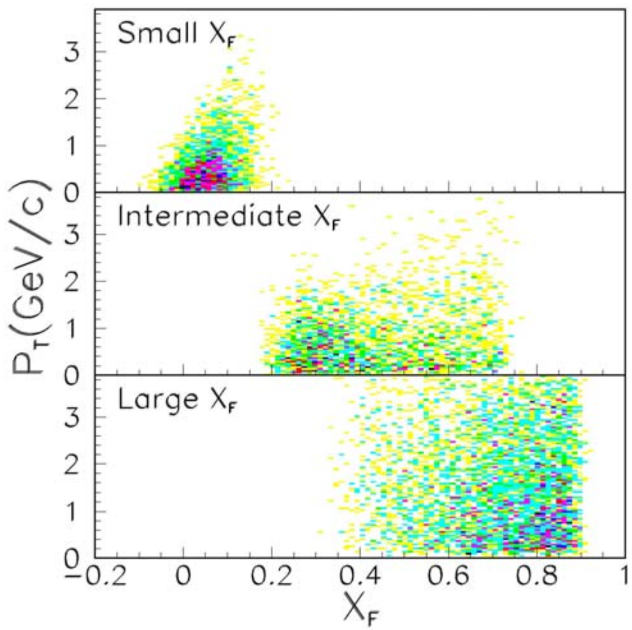
The correction of the (correlated) acceptance is crucial





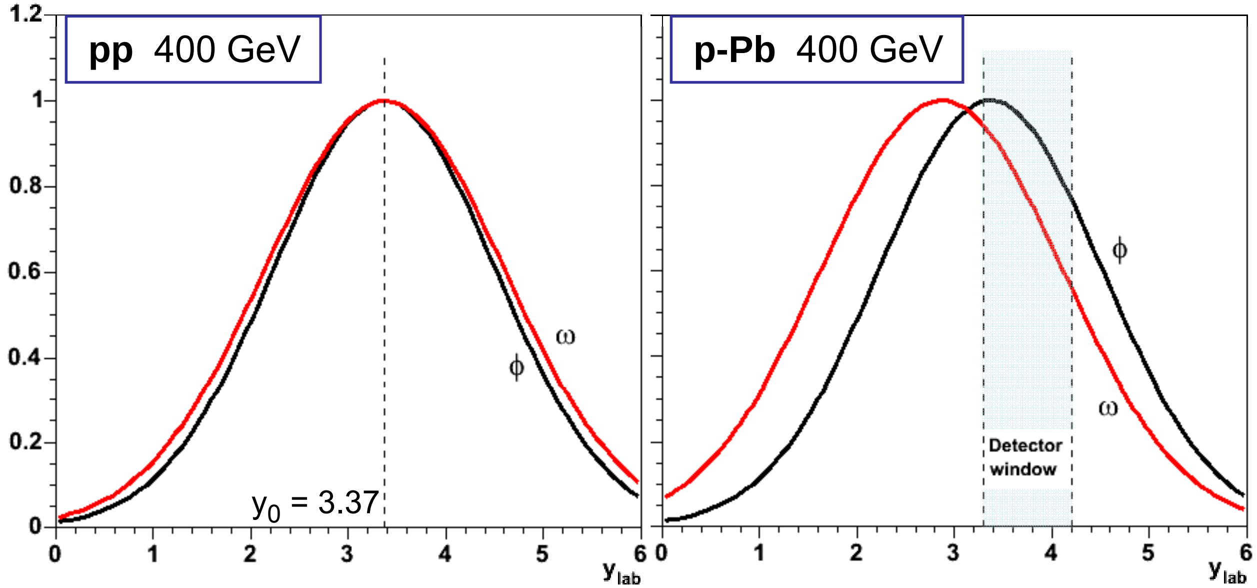
The problem was identified because the p_T coverage in E866 was better than in E772

E866 collected data with three magnet settings, each covering a different phase space window



Phase space windows

Assume that the ϕ has the same y distribution in pp and p-Pb collisions while the ω is "shifted"



A detector measuring dimuons in the window 3.3 < y < 4.2 sees the ϕ / ω ratio *increase* from pp to p-Pb, concluding that $\alpha(\phi) = \alpha(\omega) + 0.04$

Another detector, covering only *backward* rapidities, would "see" the opposite result: a *decrease* of the ϕ / ω ratio from pp to p-Pb collisions…

The result depends on the probed phase space window !

We can only correct for acceptances within the phase space window where we have data. Extrapolations to *full* phase space require assuming kinematical distributions that we cannot check: *the "measurement" becomes model dependent*.

Experiments with a narrow phase space coverage should be extremely careful in formulating their results !

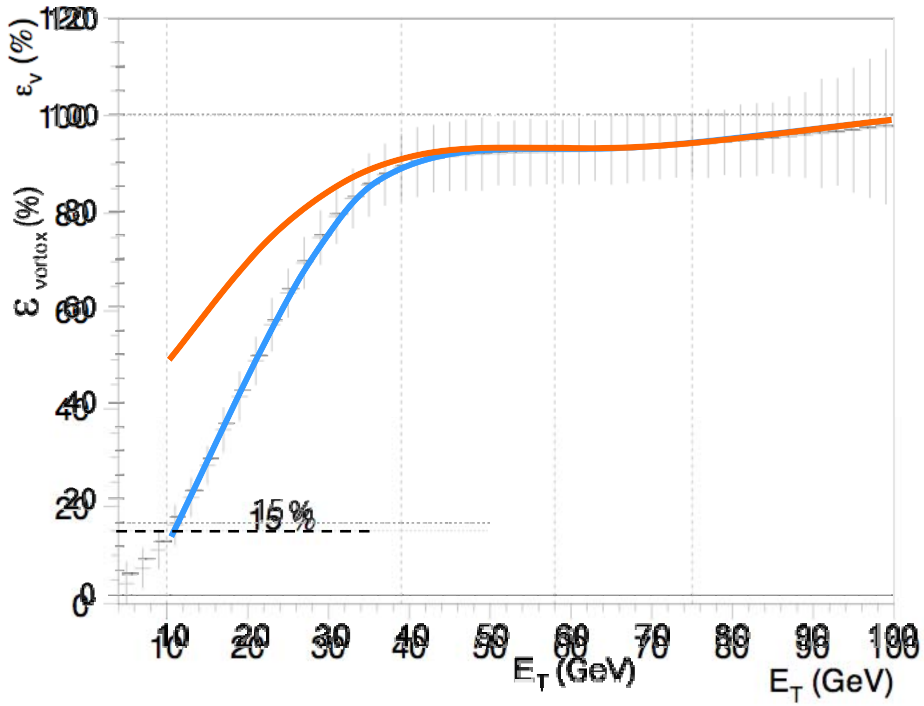
Efficiencies

Even in the phase space window well covered by the detector, sometimes a particle is produced but is not detected: maybe the trigger system missed it; or the tracks were not reconstructed; or the interaction vertex could not be identified; etc.

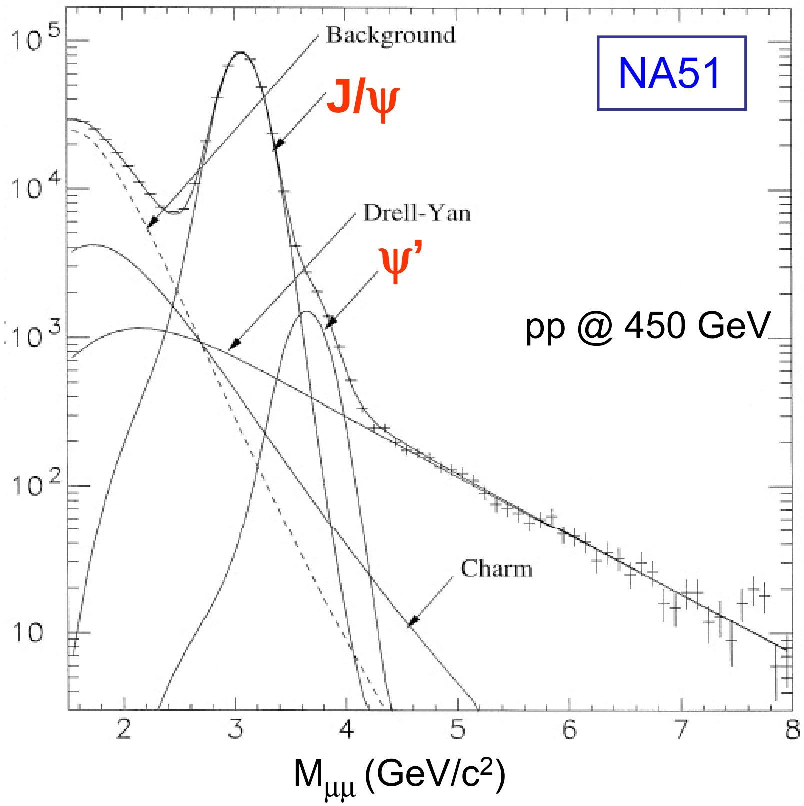
The measurements must be corrected for these detection inefficiencies

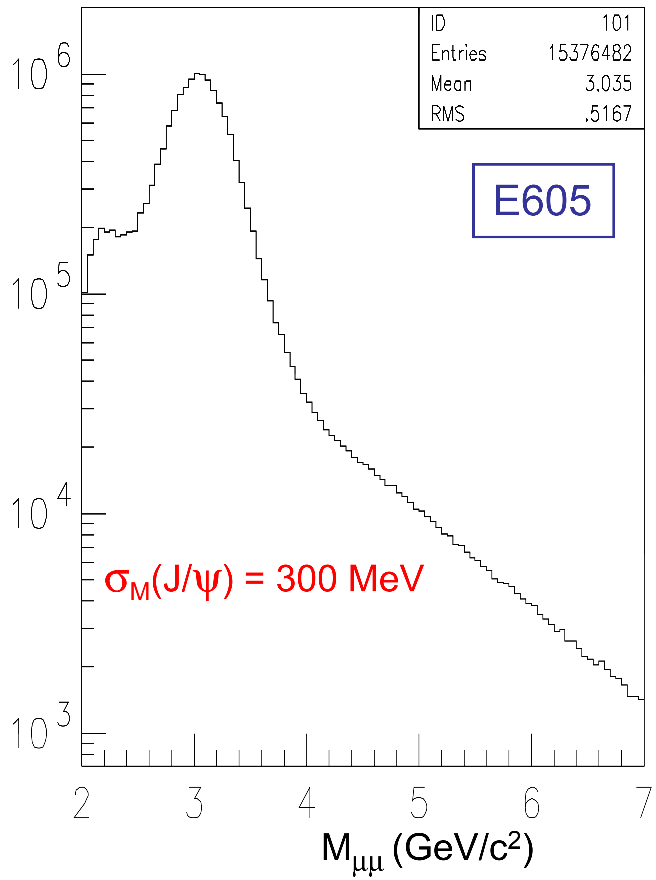
They might be measured in “special runs”, or estimated by Monte Carlo simulation, using the same algorithms as used for the reconstruction and analysis of the data

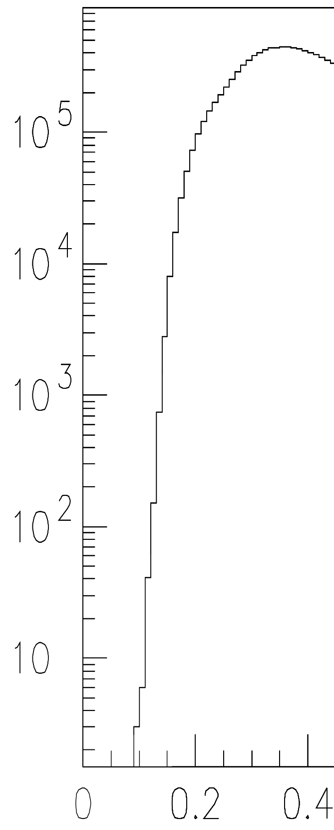
Efficiencies which depend on the centrality of the heavy-ion collisions are particularly dangerous: if not accurately corrected they may look like anomalies and taken for “new physics”



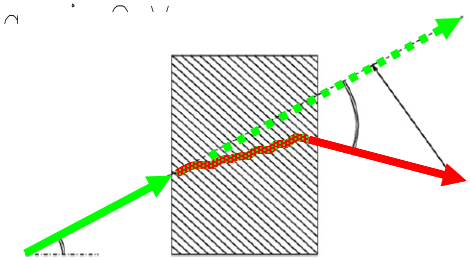
Multiple scattering and dimuon mass resolution





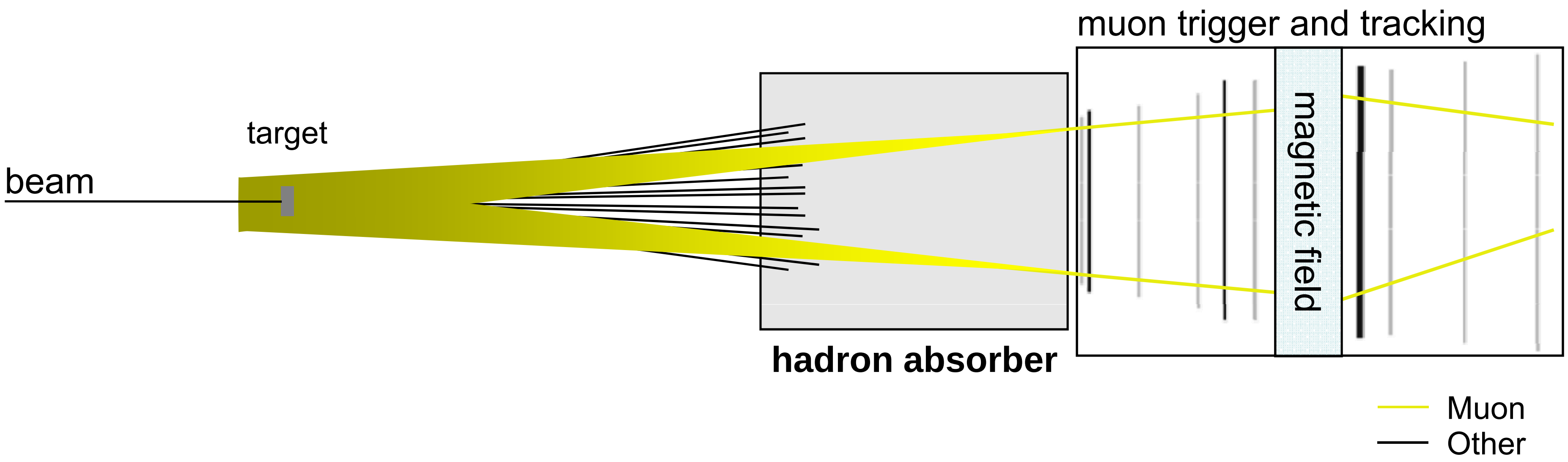


Muons are “identified” by absorbing all other charged particles in a “hadron absorber”...



But the muons suffer multiple scattering and energy loss while traversing this “muon filter”

Standard way of measuring dimuons (NA50, PHENIX, ALICE, etc)

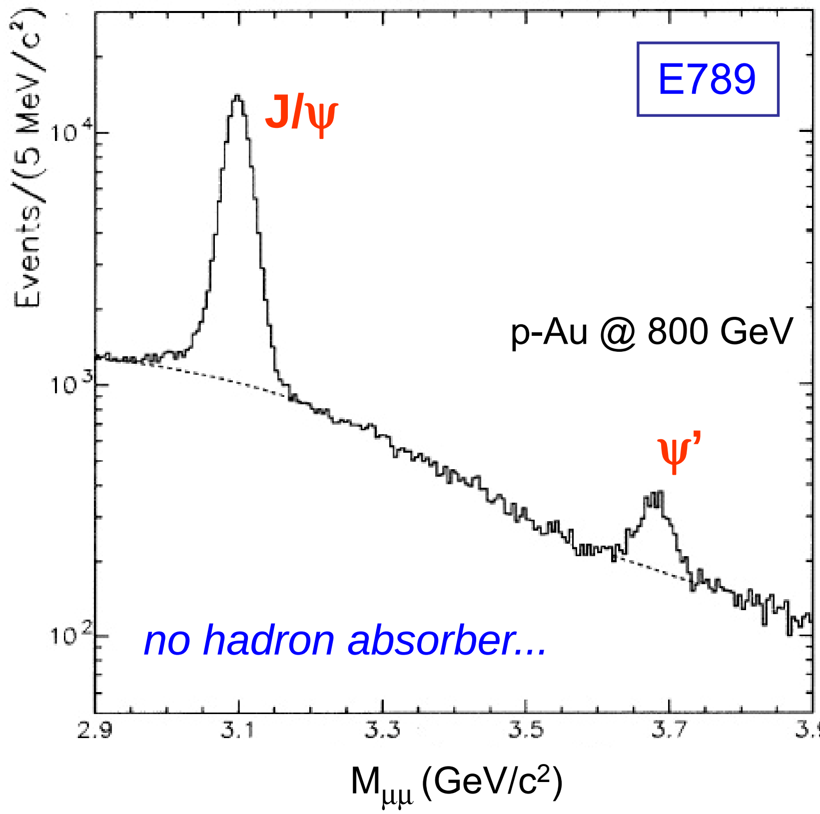


The muons suffer multiple scattering
and energy loss in the hadron absorber

Overcoming multiple scattering: no hadron absorber

E789 removed the hadron absorber to measure J/ψ and ψ' production in p-Au collisions at 800 GeV

⇒ 16 MeV dimuon mass resolution at the J/ψ peak !

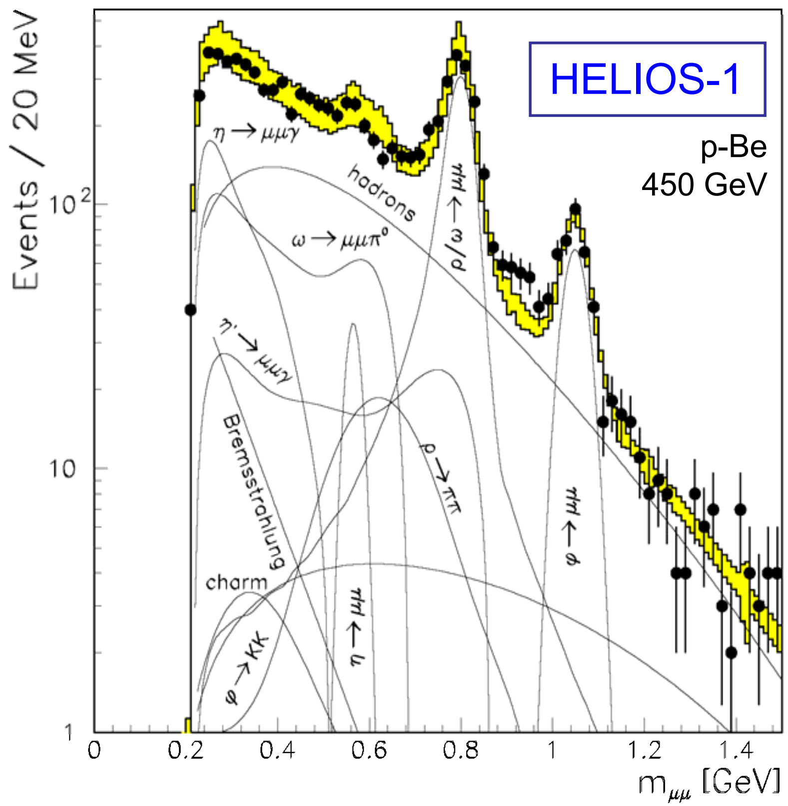


Overcoming multiple scattering: adding vertex tracking

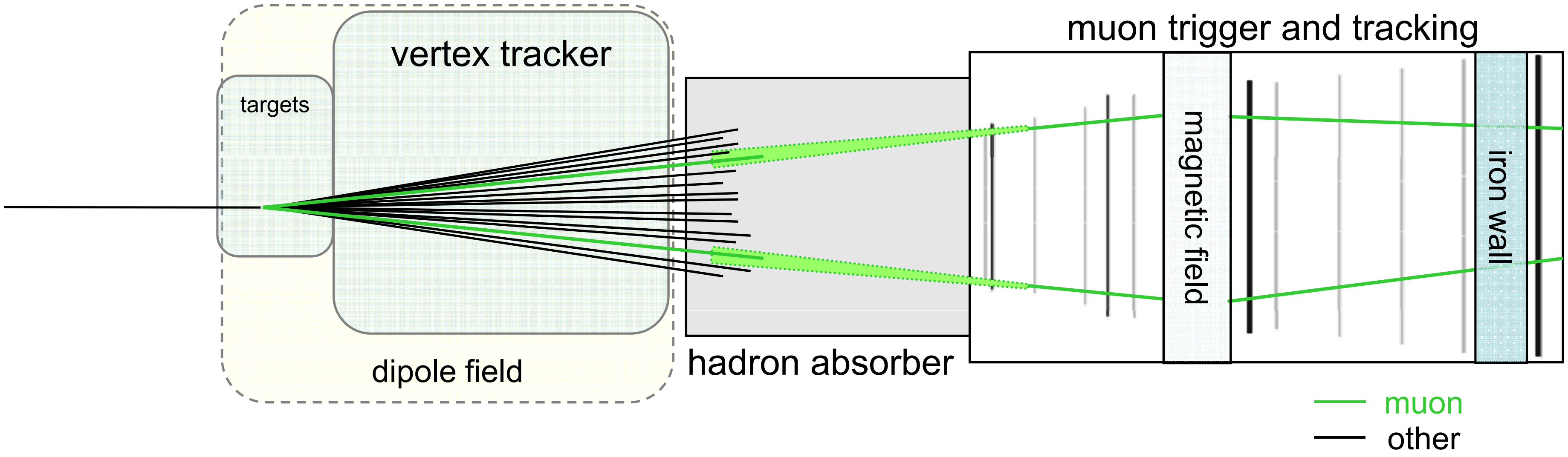
HELIOS-1 added a vertex detector (drift chambers) to match the muon tracks to tracks in the target region

⇒ 20 MeV dimuon mass resolution at the ω peak

But the drift chambers only worked in p-Be runs at low beam intensity...



Technological breakthrough: rad-hard silicon vertex trackers

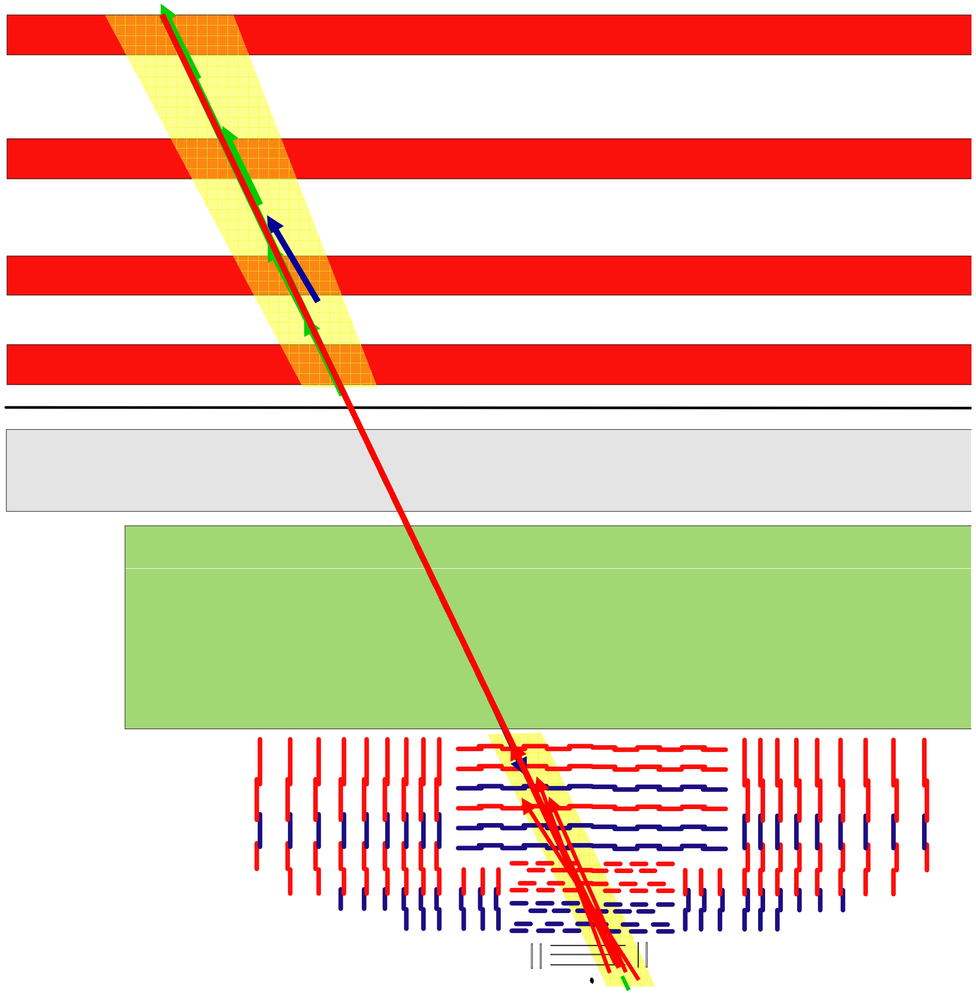


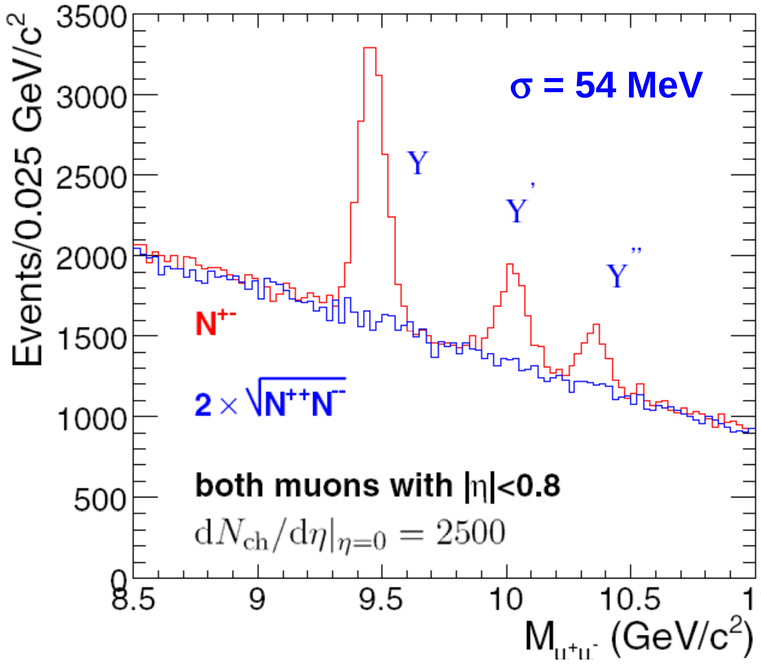
Concept used in NA60 and CMS :

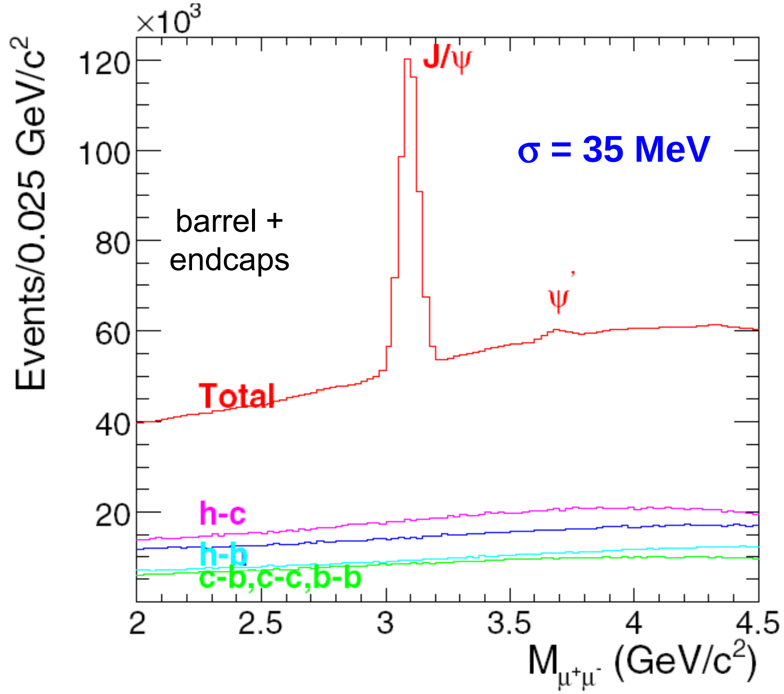
- The hadron absorber allows us to trigger on collisions that produce dimuons
- The muons are tracked in the vertex tracker, *before* they suffer multiple scattering in the hadron absorber, and matched to the tracks of the muon chambers
- We can also see if the muons come from the collision vertex or not...

Muon track matching in CMS

Very good dimuon mass resolution from the matching of the muons to the silicon tracks

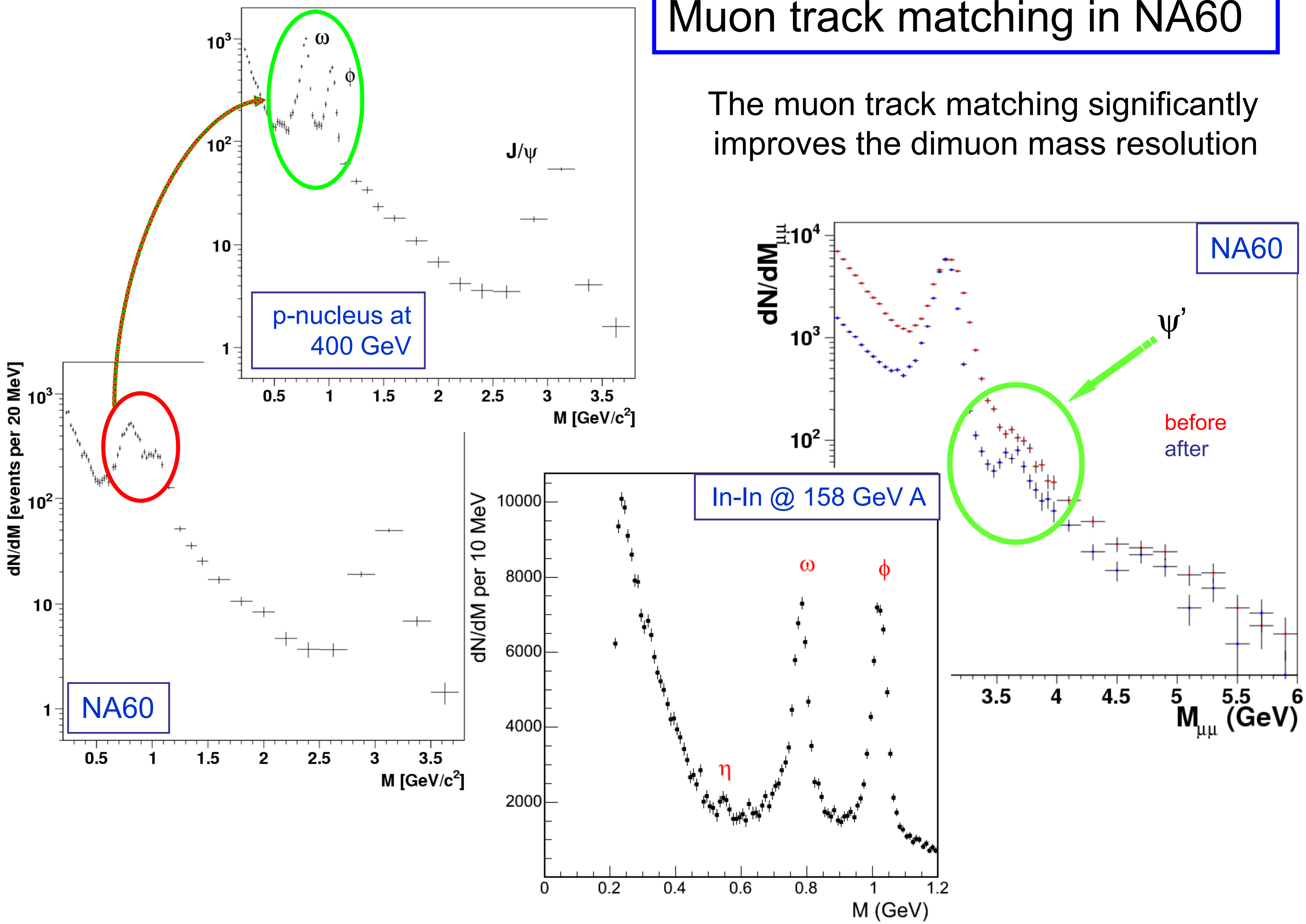




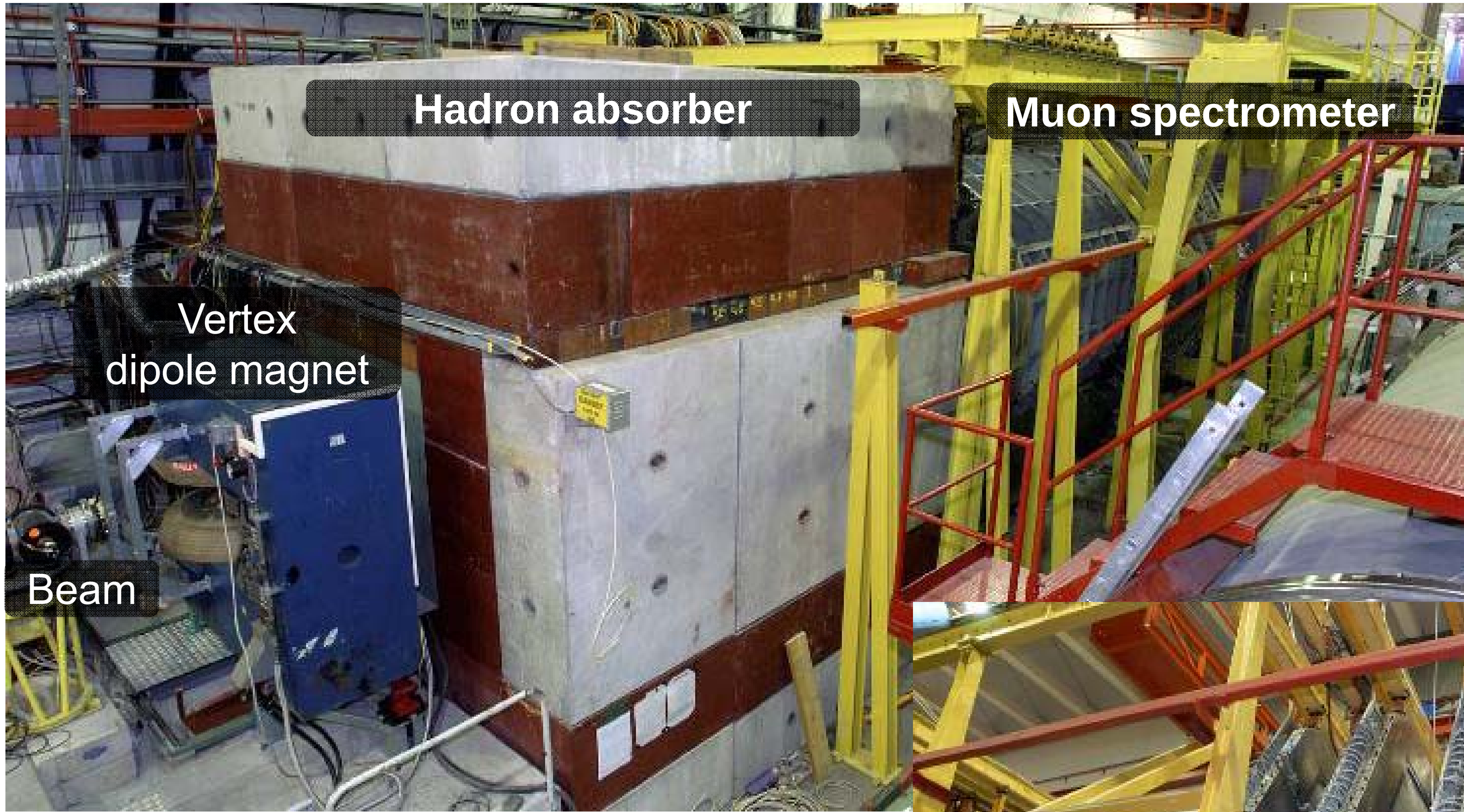


Muon track matching in NA60

The muon track matching significantly improves the dimuon mass resolution

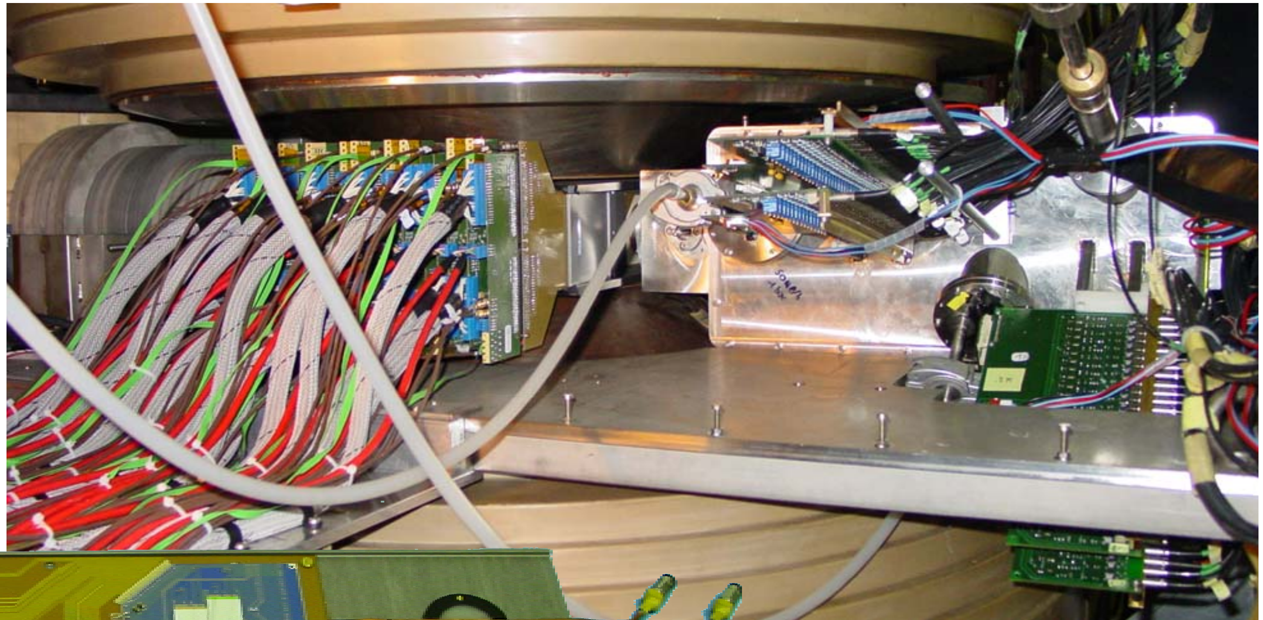


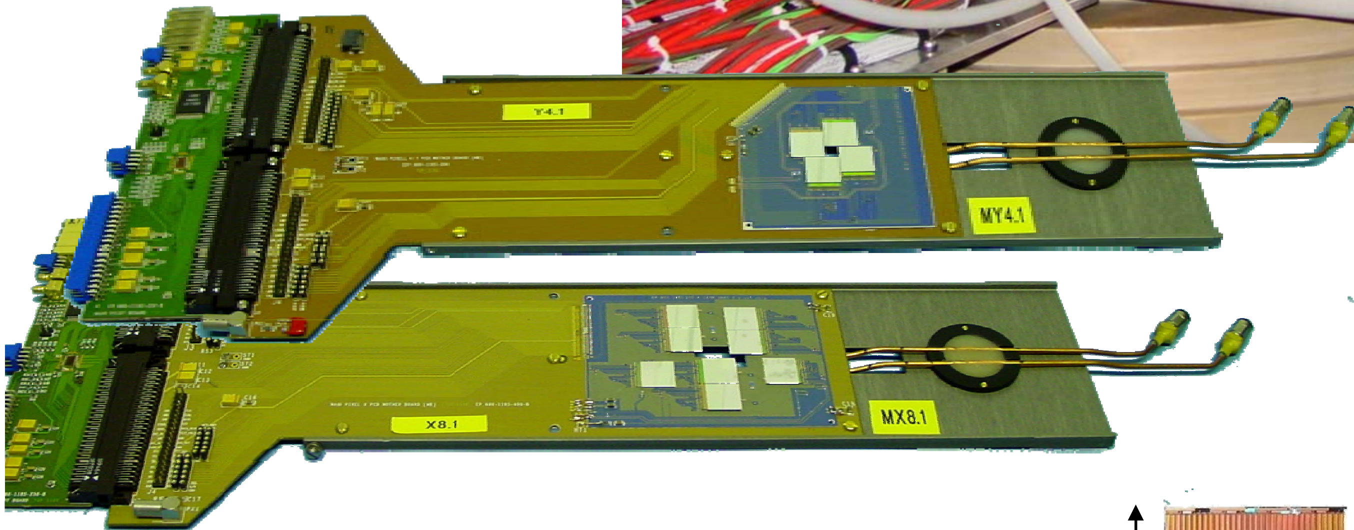
A closer look to the NA60 case

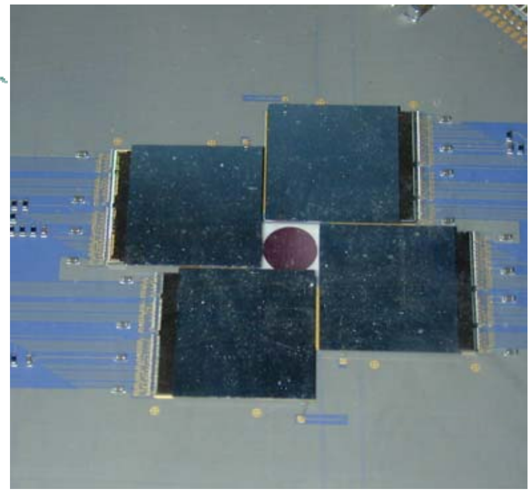


The NA60 silicon pixel vertex tracker

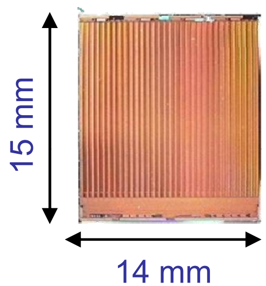
- 8 “small” 4-chip planes
- 8 “large” 8-chip planes
- ~ 800’000 channels



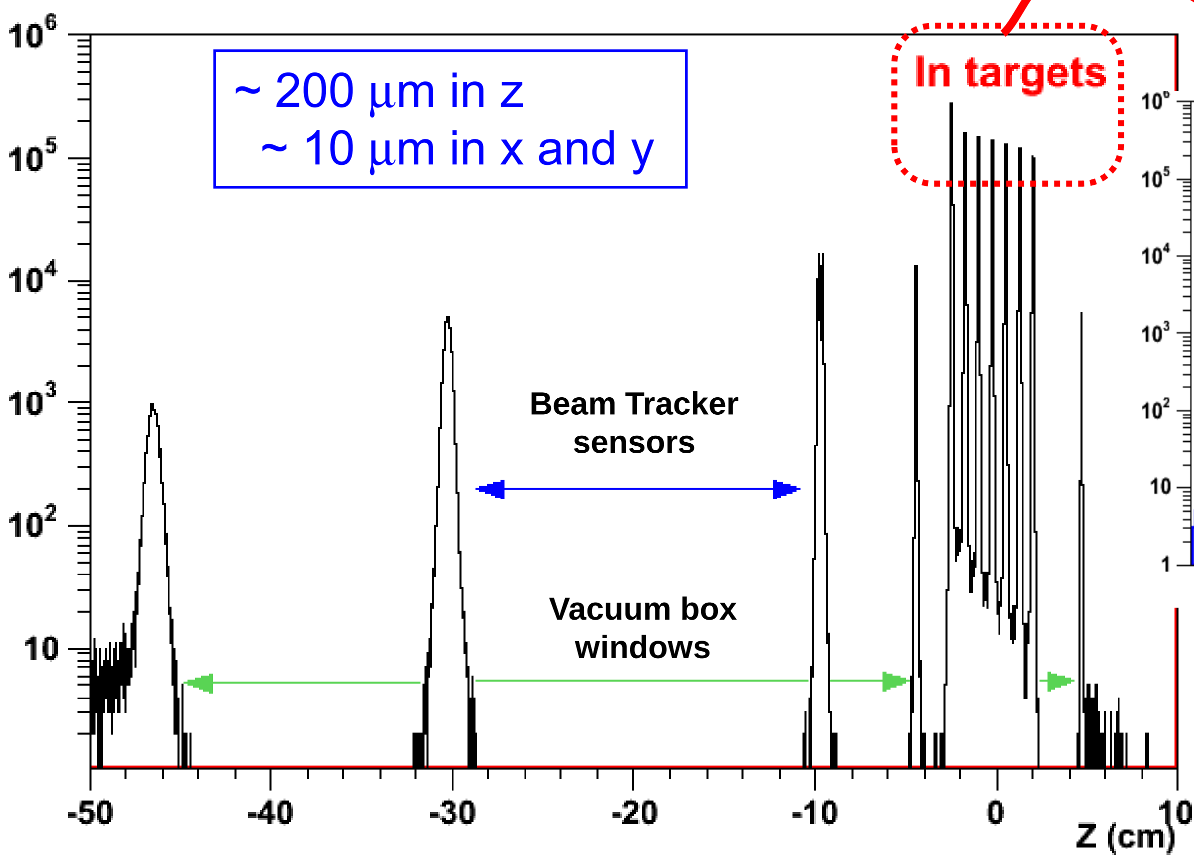




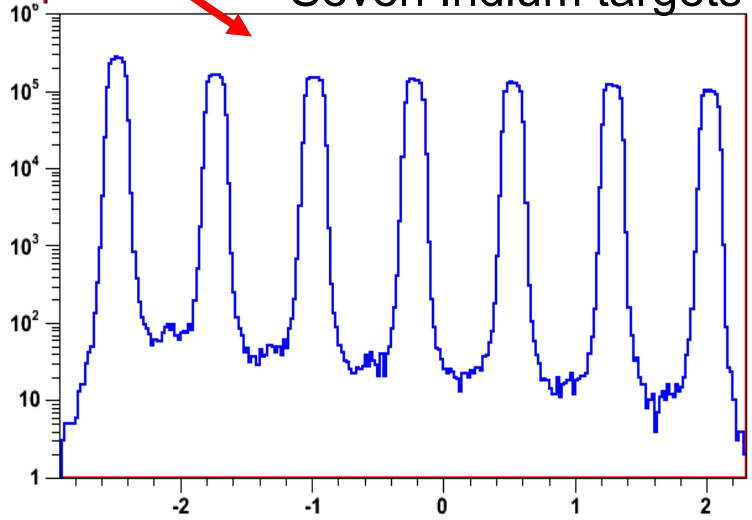
32 × 256 pixels of
425 μm × 50 μm



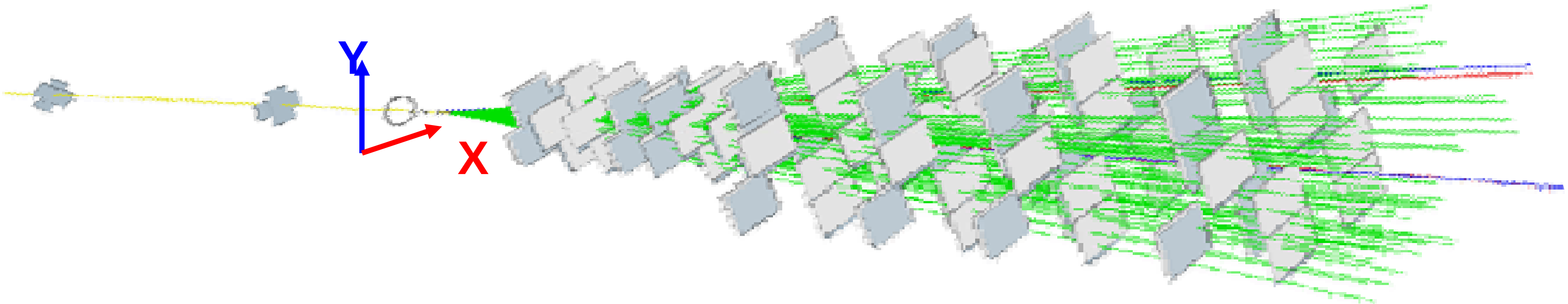
Vertexing resolution



Seven Indium targets



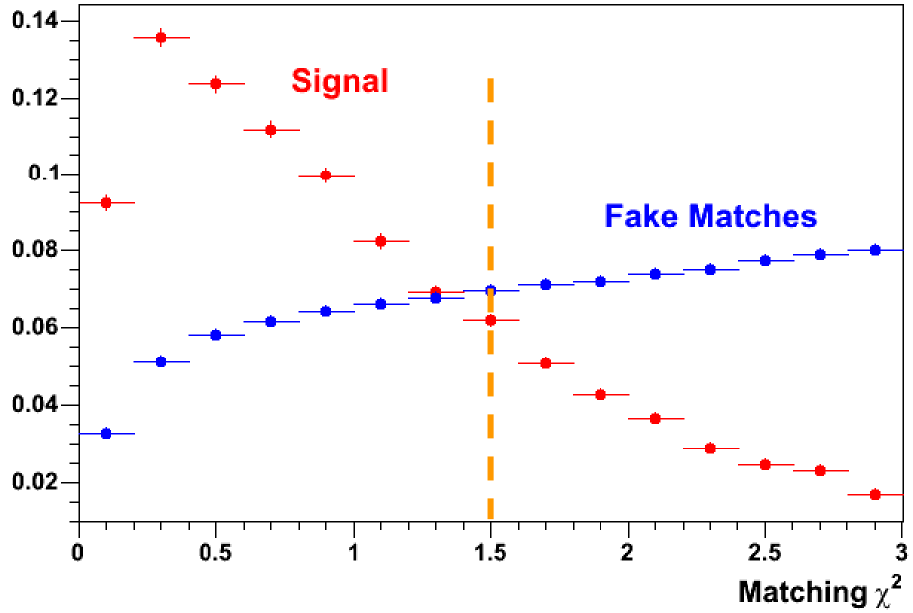
Good target identification even for very peripheral collisions



Back to the muon track matching…

Muons from the Muon Spectrometer are matched to tracks of the Vertex Tracker by comparing the angles and momenta

Candidates passing a matching χ^2 cut are refitted using the track *and* the muon measurements, to improve kinematics



Muons from π and K decays, usually the main source of background dimuons, are rejected in the matching step…
but a muon may be matched to a wrong track $\Rightarrow$ "fake matches" background

The "like-sign pairs", $\mu^+\mu^+$ and $\mu^-\mu^-$, can be used to estimate the "uncorrelated backgrounds", using "mixed event techniques"

Background subtraction in NA60

Four sources contribute to the opposite-sign dimuon distributions:

Correct signal: muons matched to their tracks in the vertex telescope

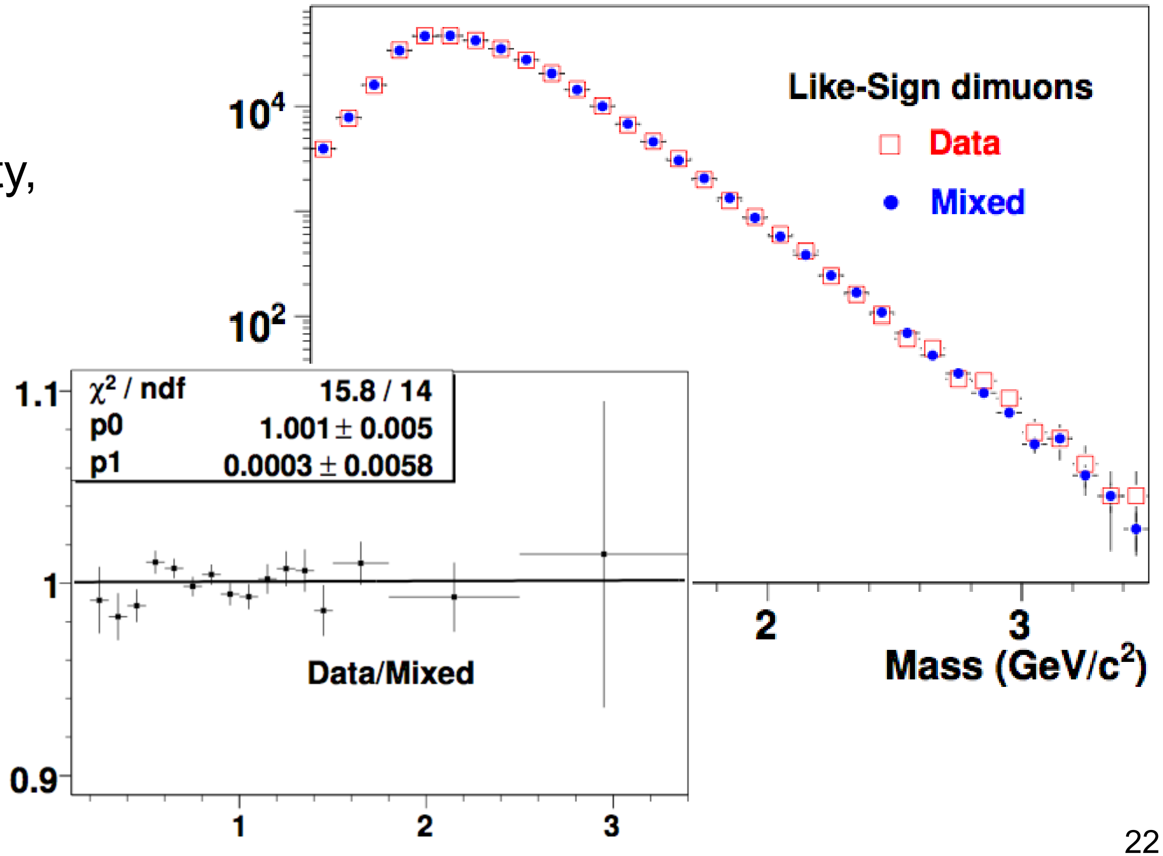
Fake signal: at least one of the muons is matched to a wrong vertex track

Correct decay muons: decay muons matched to their tracks or their parents' tracks

Fake decay muons: association between a decay muon and a wrong vertex track

All background sources are evaluated through event mixing, in narrow bins of track multiplicity, for each target and combination of magnetic field polarities

The quality of the background subtraction procedure is evaluated by comparing the measured Like-Sign with the mixed event Like-Sign spectra



Signals, backgrounds and “excesses”

Suppose the *expected* signal is a small fraction (1%) of the *estimated* background and the number of *measured* opposite-sign muon pairs is larger than their sum:

OS = Bg + ExpectedSignal + Excess

For instance: 1000 = 10 (expected signal) +
970 (estimated background) +
20 (unexpected source)

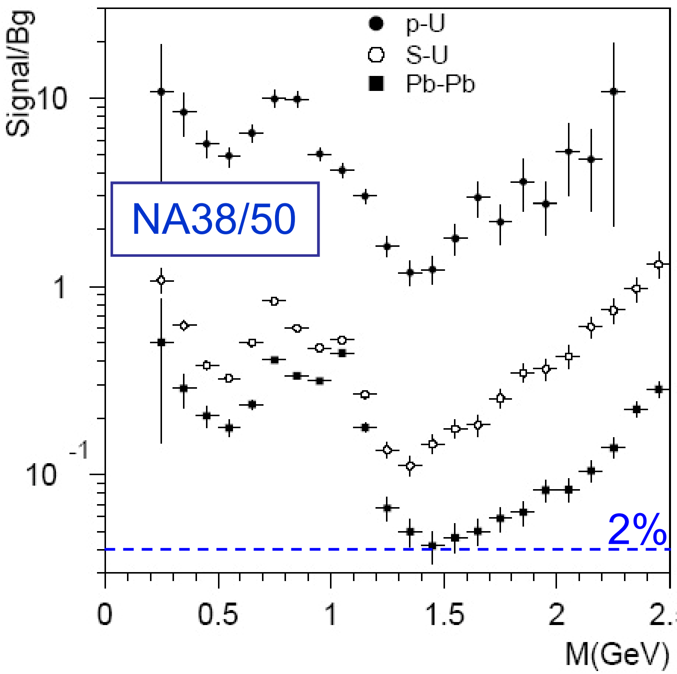
Great !

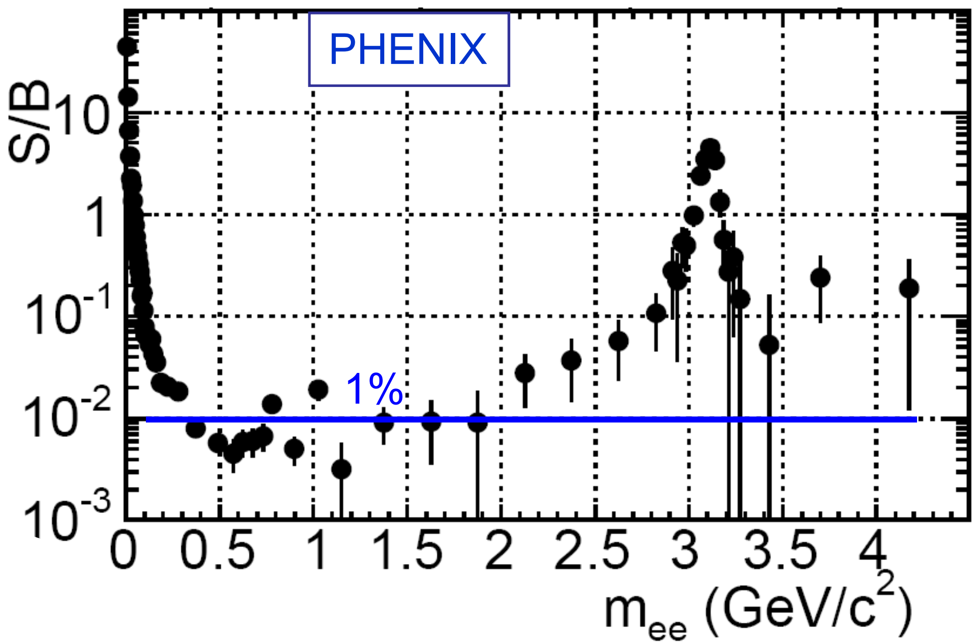
What would you say?

⇒ the signal is increased by a factor 3 → Big “excess” → New physics !

⇒ or the background was underestimated by 2% ?

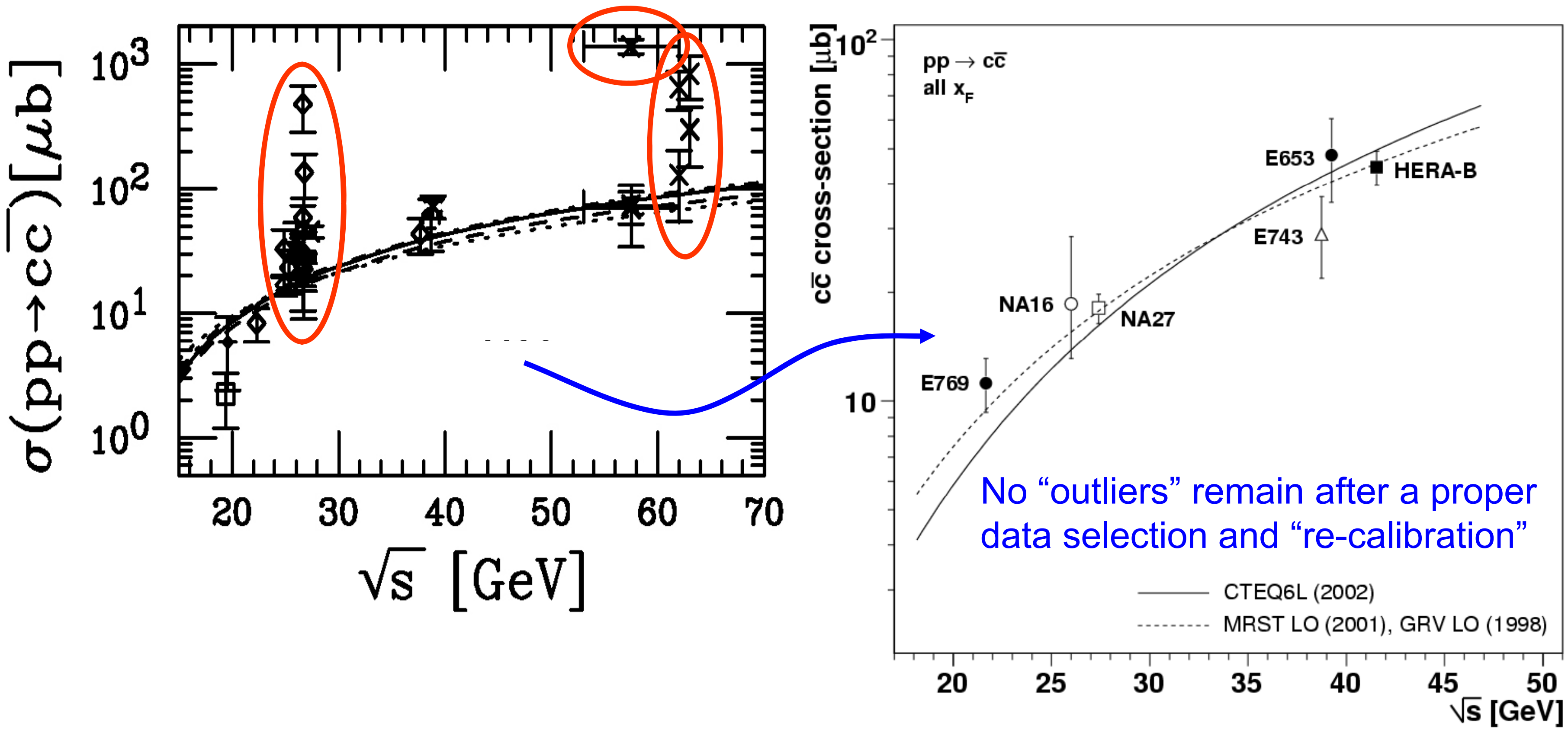
⇒ To properly study a signal, we must understand its backgrounds !



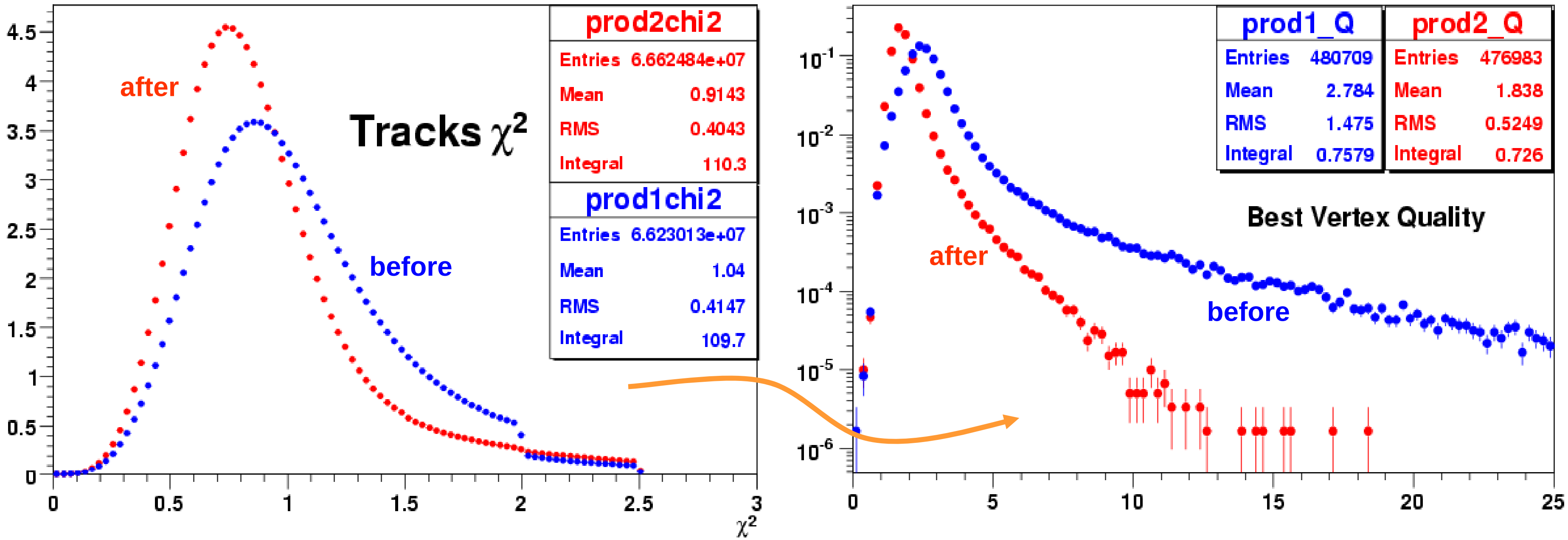


Data selection

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



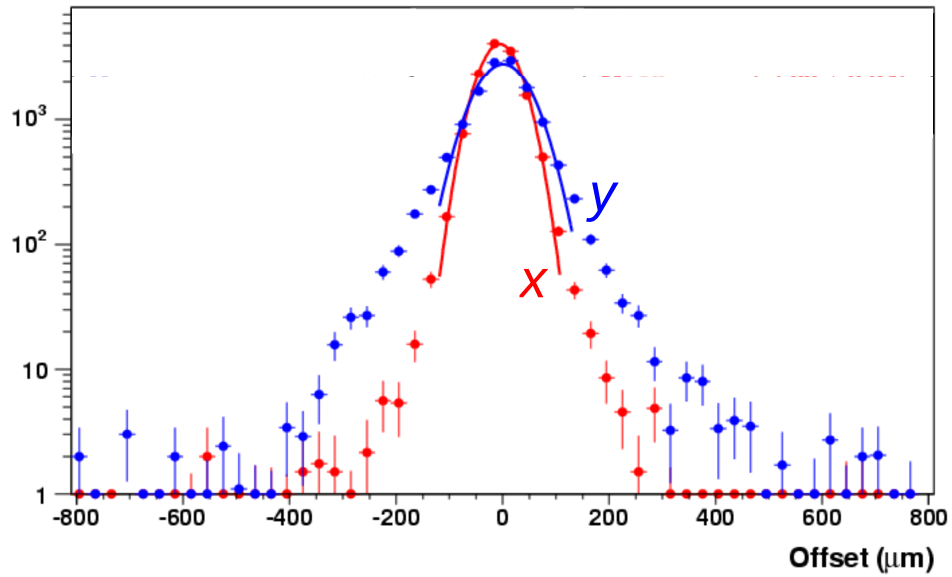
Good alignment ⇒ good muon offset resolution



Reconstructing the data after aligning the silicon pixel planes significantly improves the tracking and vertexing

⇒ better resolution of the muon offset
37 μm in *x* and 45 μm in *y*

⇒ less background on the displaced muons (open charm) signal



Calibration of Monte Carlo distributions

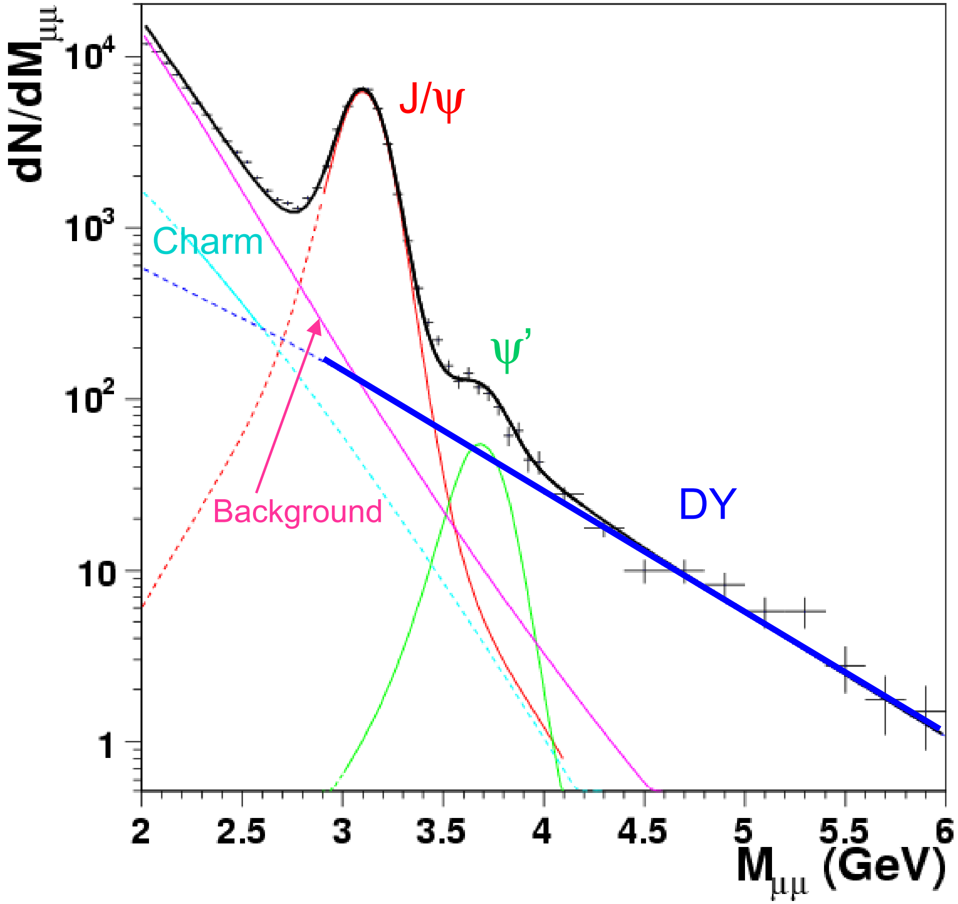
Monte Carlo simulations cannot *perfectly* describe the experiment's details: geometry, material densities, multiple scattering, energy loss, noisy / dead channels, alignment, efficiencies, etc. They change with time, beam intensity, accumulated radiation dose, temperature, etc., and we cannot make a new simulation each time a silicon pixel chip stops working or the beam position changes by 100 μm.

So, the MC distributions are "better" than the measured ones and need to be "smeared" to describe the data. This must be done with extreme care…

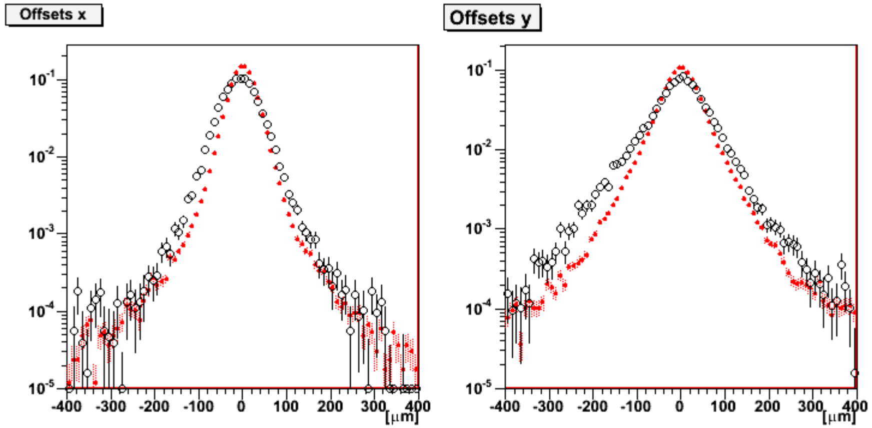
Example:

What happens if we fit the dimuon mass distribution with a J/ψ shape purely determined by the MC simulation ?

Since the J/ψ drives the fit, a wrong J/ψ shape will bias the Drell-Yan yield.

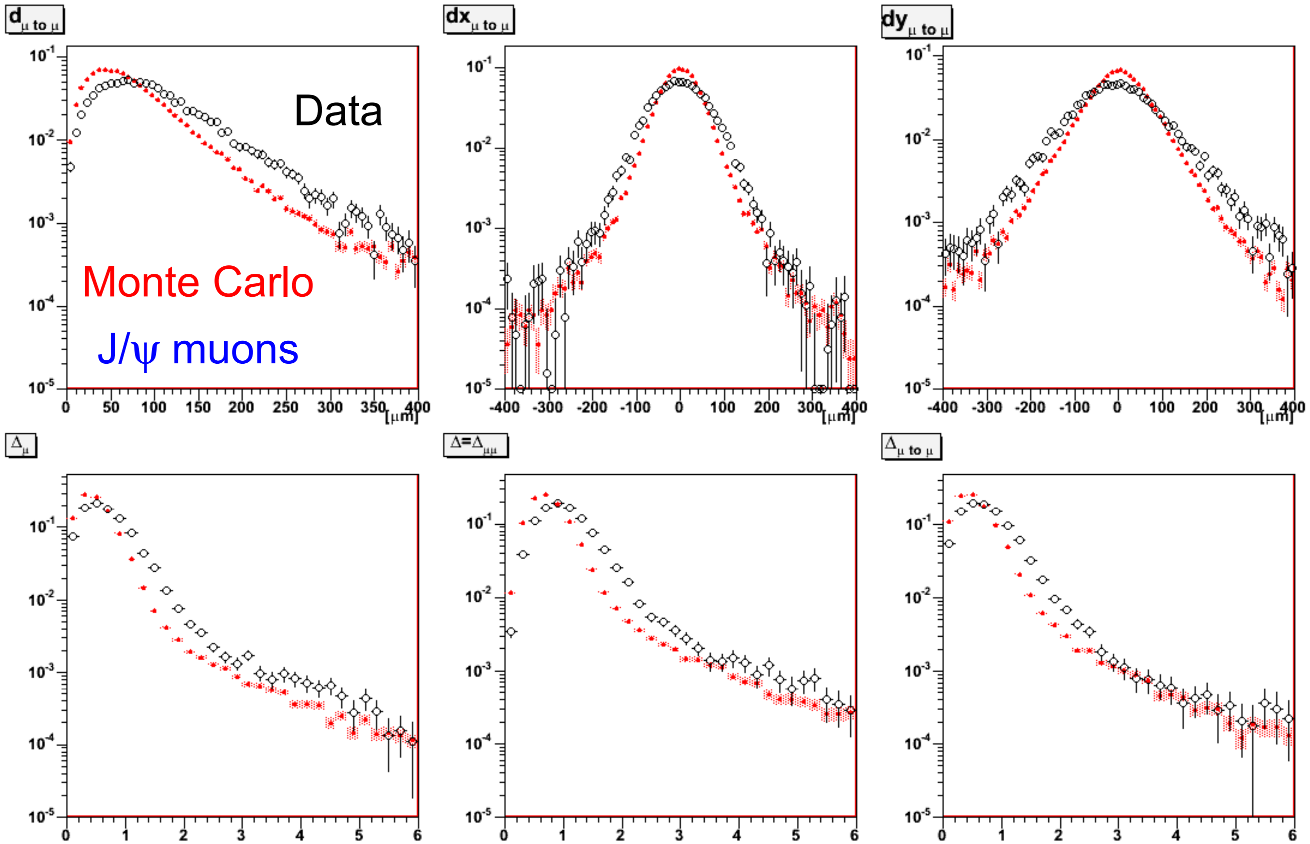


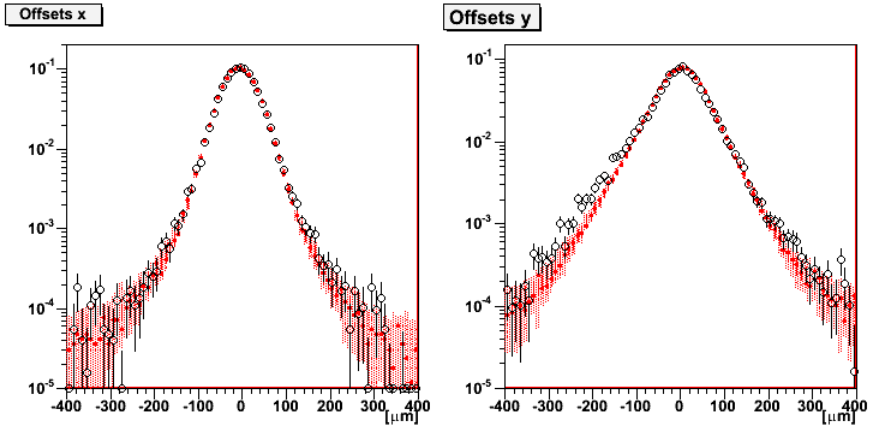
Calibration of simulated muon offset distributions



<u>Before adjustments:</u>

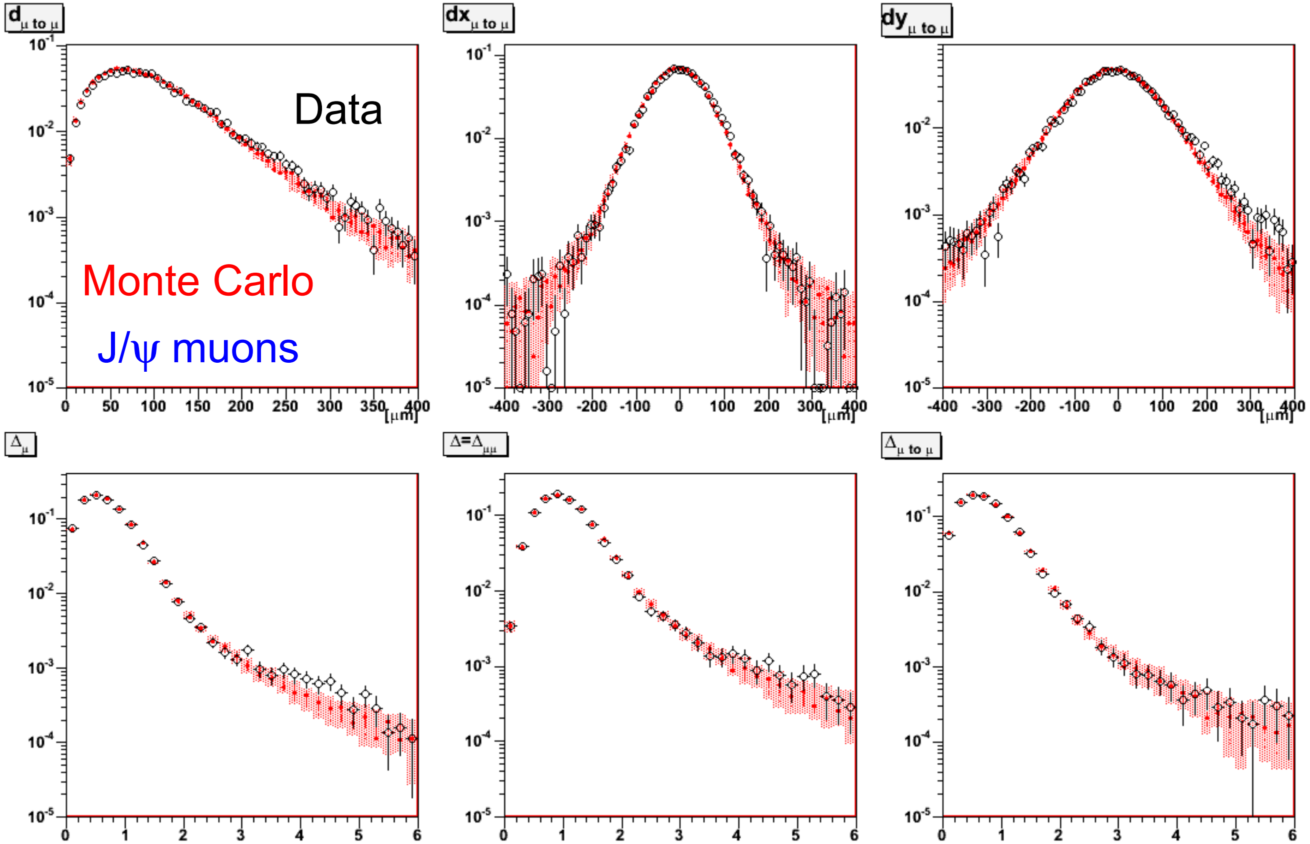
Monte Carlo spectra are “too good”





<u>After smearing:</u>

Monte Carlo spectra reproduce the data



Calibration of dimuon mass

The absolute calibration of the dimuon mass changes when measurements are made with different hadron absorber materials, different magnetic fields, etc.

The J/ψ "pole mass" changed from 3.086 GeV/c^2 in NA38 to 3.110 GeV/c^2 in NA50 and 3.078 GeV/c^2 in NA60…

A "shift" in the absolute dimuon mass calibration is crucial for the determination of the Drell-Yan yield in a fixed mass window, such as 2.9–4.5 GeV/c^2

The DY mass window much be adapted to match the J/ψ pole:

NA38 : 2.876–4.476 GeV/c^2
NA50 : 2.9–4.5 GeV/c^2 $\rightarrow$ taken as reference
NA60 : 2.87–4.45 GeV/c^2

Given the exponential shape of the DY dimuon mass spectrum, its yield changes by 4% if the mass calibration changes by 1%

Luminosity: crucial for studies of rare processes

Collecting many *rare* events requires the highest possible “integrated luminosities”. Since time is always short, this means high intensity beams (and thick targets).

But… high interaction rates lead to “interaction pile-up”: more than one collision occurs within the “read-out gate” of the detectors…

In fixed target experiments, a beam ion can have a peripheral interaction followed by a second interaction, only involving the nucleons not participating in the first one (“spectators”); if two peripheral collisions look like a central one, the event will be tagged as central while the J/ψ, say, was produced in a peripheral collision.

Trigger: crucial to handle high collision rates

High interaction rates require a trigger, to select the interesting events among the many collisions; otherwise, the data acquisition system would be permanently busy reading out and storing (mostly) non-interesting events

For instance, thanks to its dimuon trigger system, NA60 probed 10^7 In-In collisions per burst (5 seconds), with a beam of 5×10^7 ions per burst, writing a few thousand of them to permanent storage

Systematic effects are difficult to control

To verify the understanding of systematic effects, it is important to redo the measurements in different configurations, in terms of magnetic field polarity and magnitude, hadron absorber thickness, beam intensity and energy, etc.

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

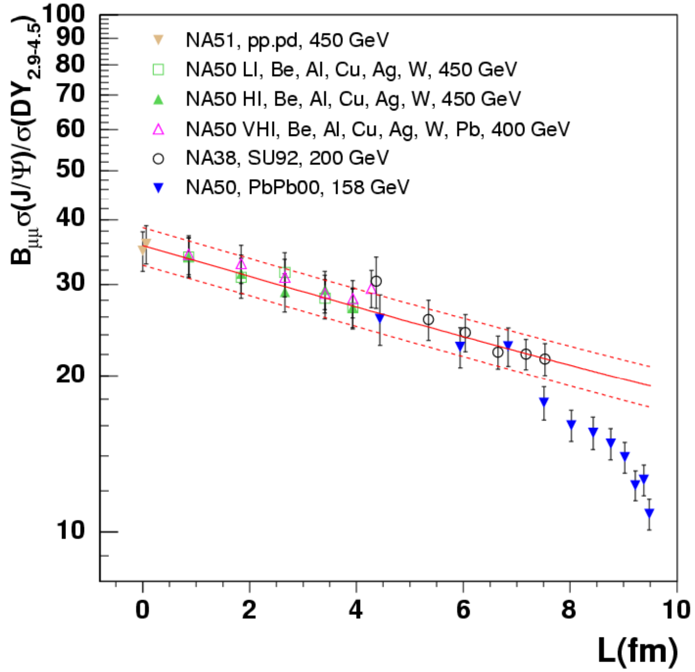
Important analyses should always be *independently* made by at least two different groups and with different choices of model dependent assumptions. Will the results change if you replace PYTHIA by HERWIG or ISAJET ? or CTEQ6L by MRST LO?

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

Reference collision systems

In 1987, when p-U was the only p-nucleus data, NA38 saw that the J/ψ was suppressed from p-U to S-U collisions

Once several p-A data points became available we saw that J/ψ production is already suppressed from pp to p-U and that the S-U pattern follows that trend



Collecting pp, p-A and light-ion data is crucial to define the reference baseline relative to which we can look for "heavy-ion specific features", and to constrain the interpretations of the results

"Centrality scans" from peripheral to very central HI collisions are equally crucial

J/ψ production from feed-down decays

Many of the detected J/ψ mesons are produced through the decay of other particles, mostly χ_c, ψ' and B mesons, which have different nuclear dependences:

- the ψ' is more strongly absorbed than the J/ψ, already in p-nucleus collisions
- open beauty production should not be absorbed
- **the χ_c nuclear dependence has not yet been measured**

The take-home message of today

Experimental studies of high-energy heavy-ion collisions are done in very difficult conditions (occupancies, data rates, radiation damage, etc) and often must be redone after significant improvements (resolutions, acceptances, signal/background ratios, efficiencies, etc)

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

"Playing" with acceptances, efficiencies, backgrounds and "well-known" references, you can easily find "anomalies" in your data...

The more "explosive" is your "discovery", the more carefully you must handle the breaks...