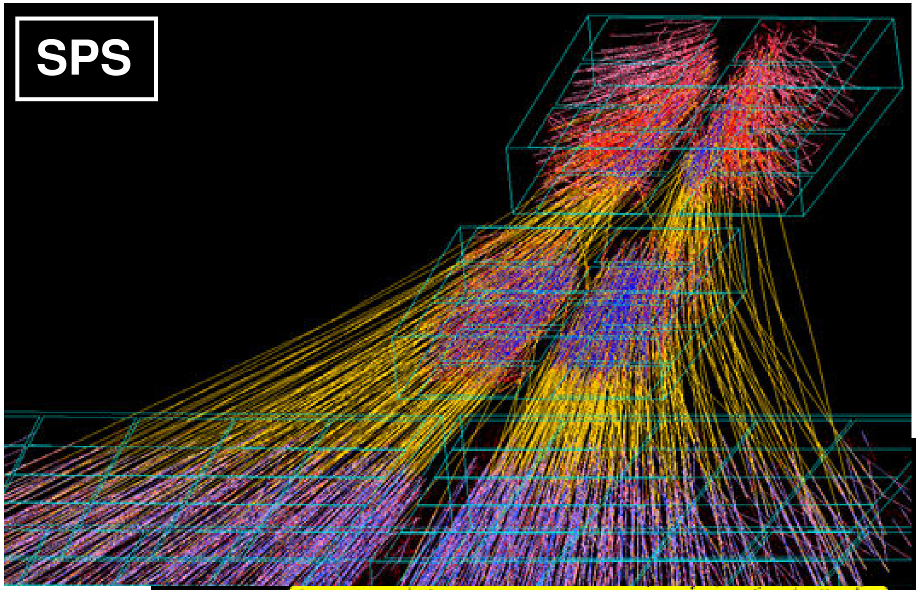
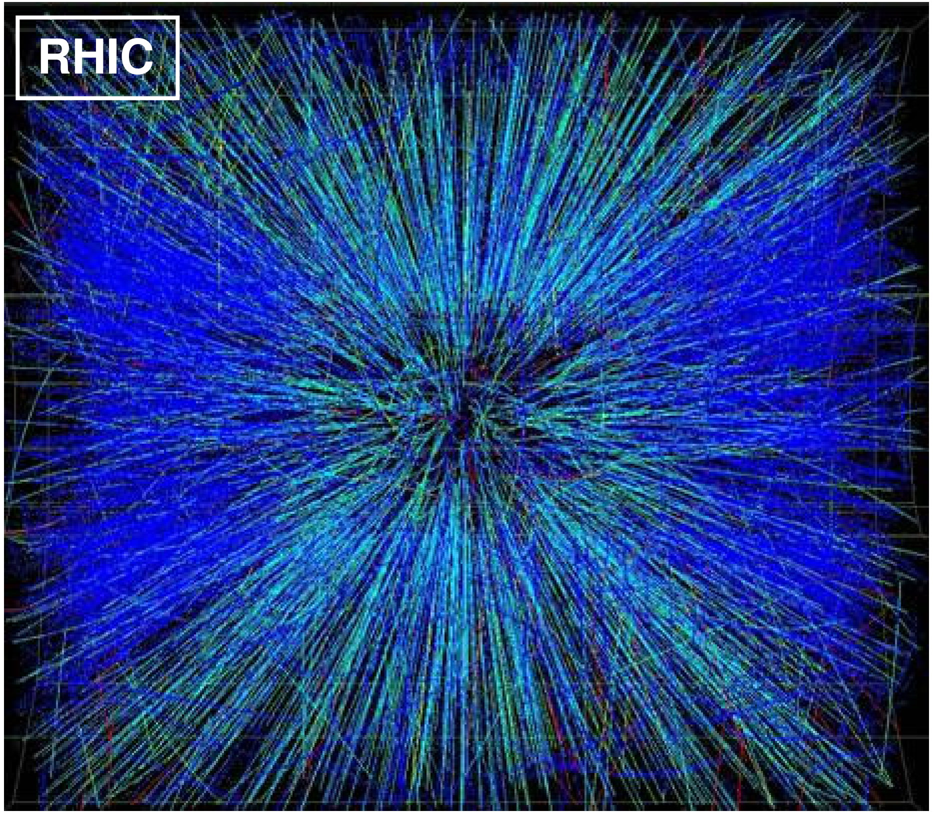
From High-Energy Heavy-Ion Collisions to Quark Matter

Episode II : The art of experimental (high-energy) physics

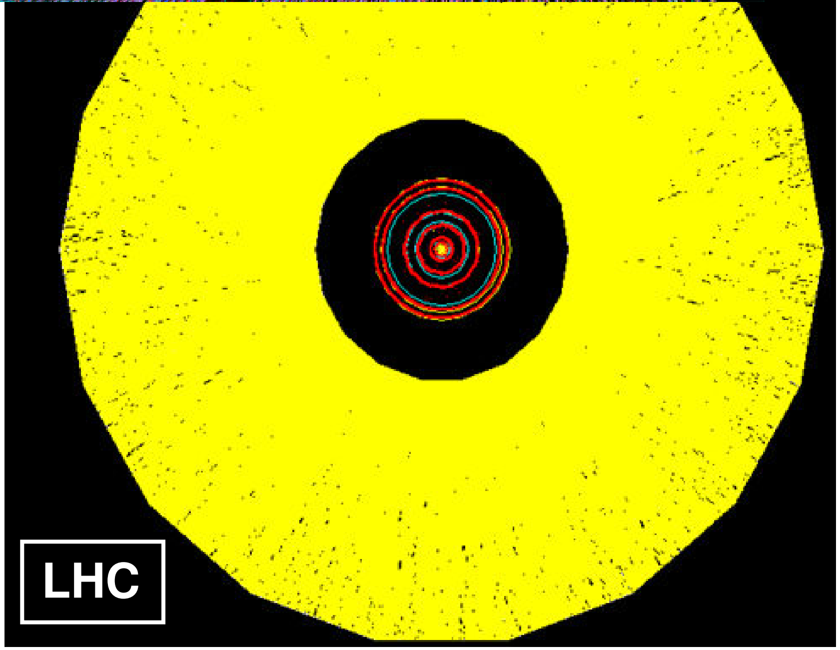
What you see is not what you get…



SPS



RHIC



LHC

Reminder: the question and the path towards the answer

Goal: to study QCD in the extreme conditions of the early Universe

Method:

1) Collide high-energy heavy nuclei to create hot and dense strongly interacting matter, over extended volumes

2) 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

Problem:
It is not easy to read Mother Nature’s book; what you see is *not* what you get…

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

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

- 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

If we misunderstand these issues we can miss an important discovery…
or we can “discover” non-existent “new physics”

My name is ψ, James ψ (a charming Bond)

The J/ψ is a bound state of a charm quark and a charm antiquark (the 1S state)
It has a mass of 3.1 GeV and decays, e.g., into a pair of muons, $\mu^+\mu^-$

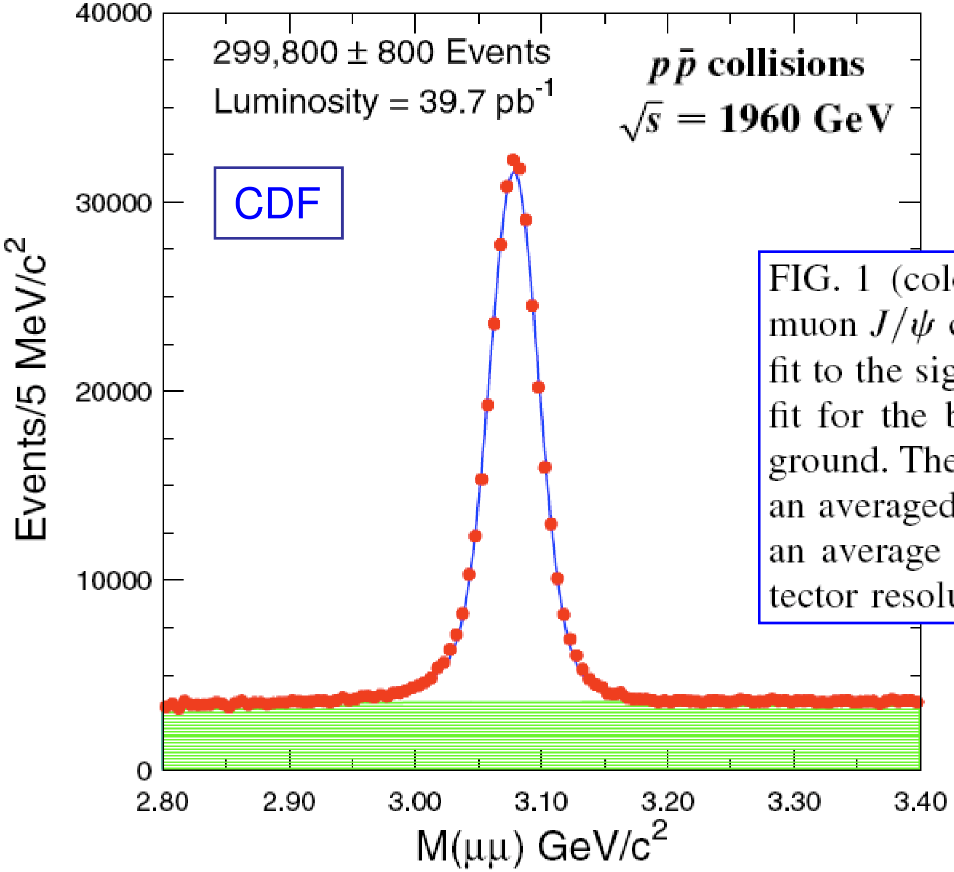


FIG. 1 (color online). Mass distribution of reconstructed dimuon J/ψ candidates. The points are data. The solid line is the fit to the signal approximated as a double Gaussian and a linear fit for the background. The hatched region is the fitted background. The fit gives a signal of 299 800 ± 800 J/ψ events with an averaged mass of $3.093\,91 \pm 0.000\,08$ GeV$/c^2$ obtained and an average width of 0.020 ± 0.001 GeV$/c^2$ mainly due to detector resolution. The uncertainties here are statistical only.

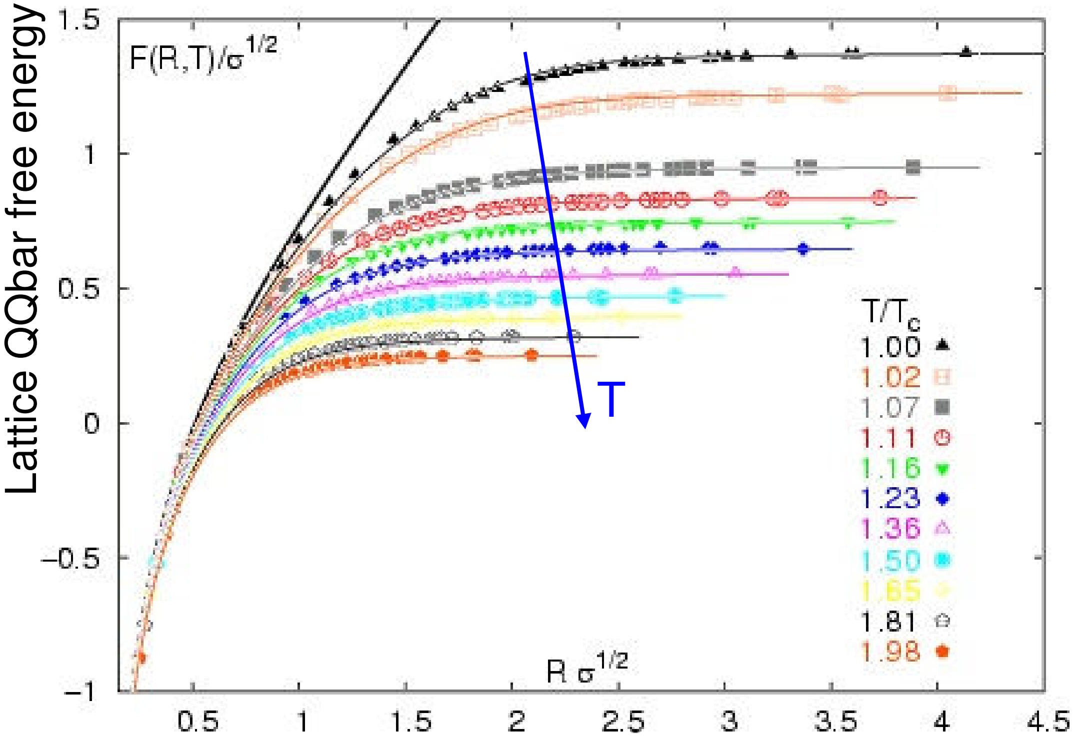
Phys. Rev. D 71, 032001 (2005)

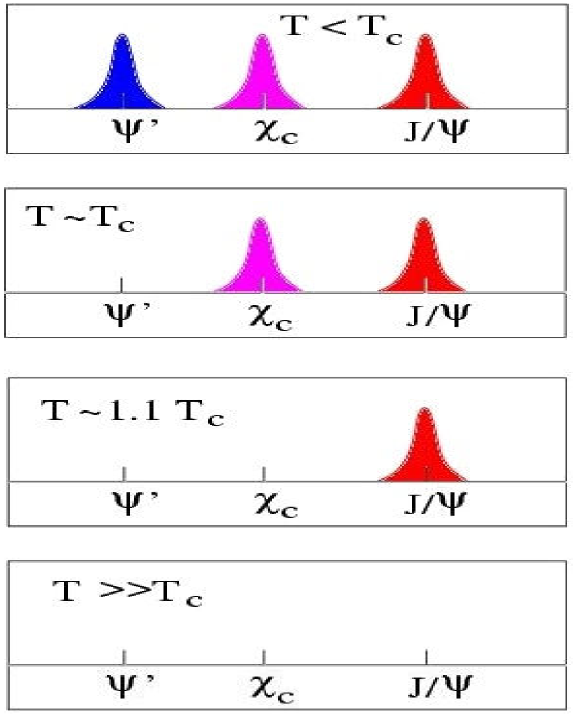
The CDF experiment sees a beautiful “resonance”, on the top of a flat continuum, away from acceptance edges, with a very good dimuon mass resolution and an excellent “signal over background” ratio… An ideal (recent) measurement…

J/ψ suppression in nuclear collisions: a QGP signal

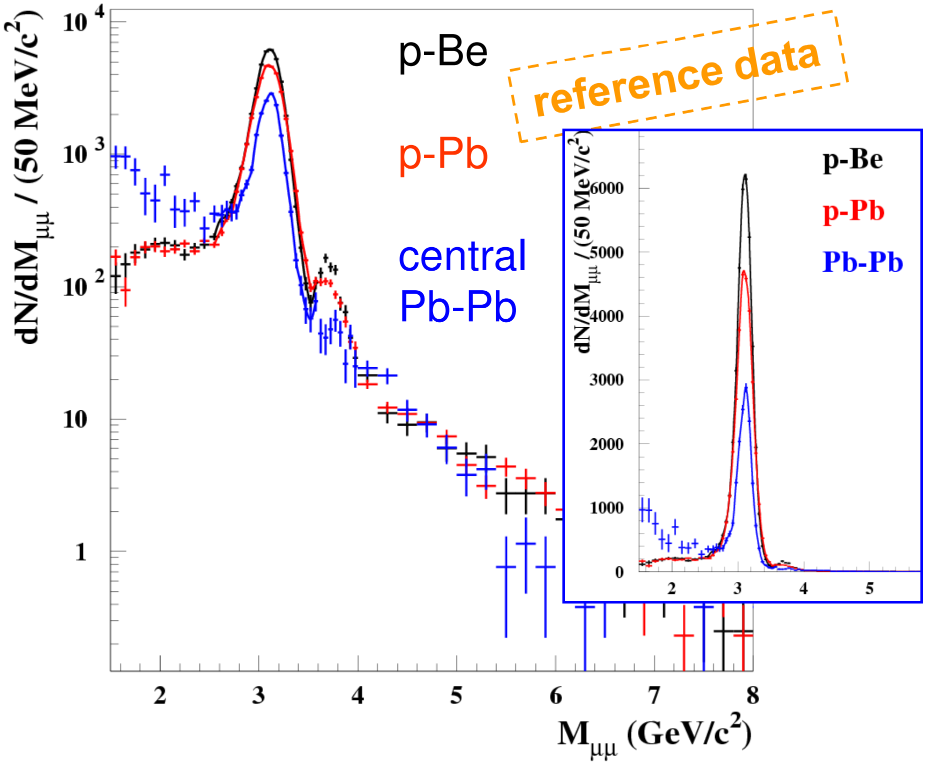
In a medium with deconfined quarks and gluons, the QCD potential is screened and the heavy quarkonium states are “dissolved” into open charm or beauty mesons

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

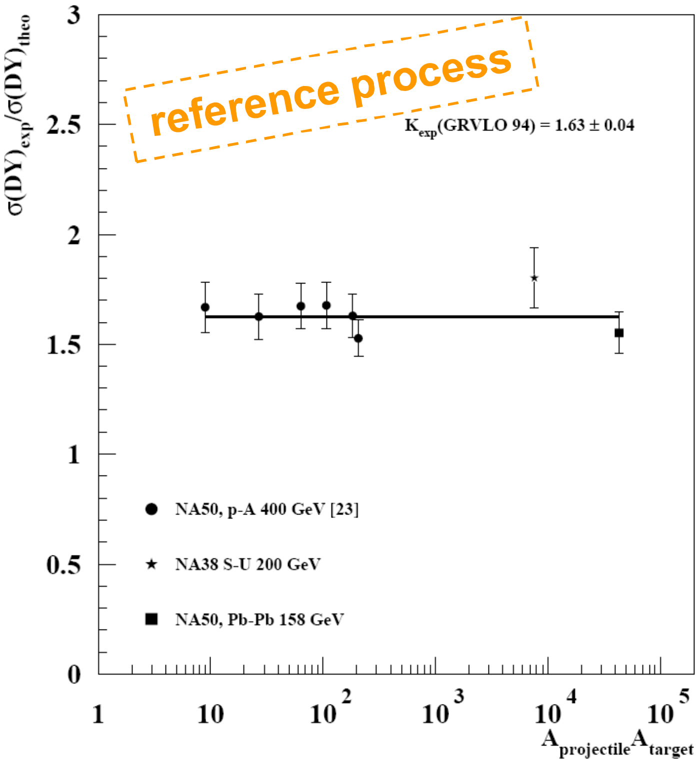




J/ψ suppression in Pb-Pb collisions at the SPS



reference data



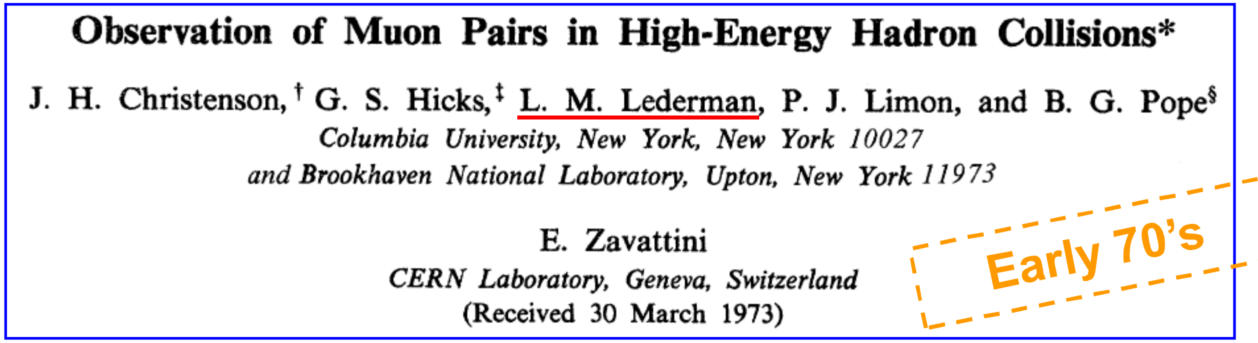
reference process

The J/ψ yield (per Drell-Yan 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

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

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

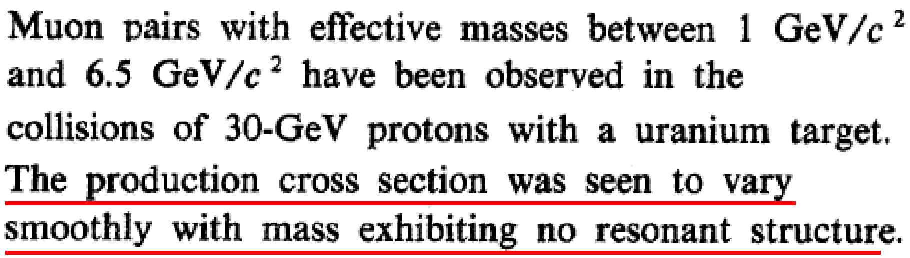


Observation of Muon Pairs in High-Energy Hadron Collisions*

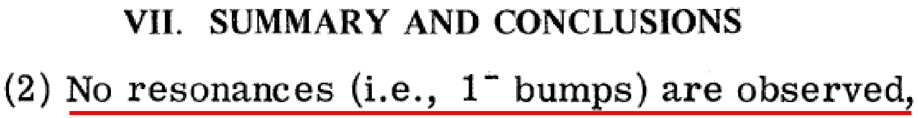
J. H. Christenson,[†] G. S. Hicks,[‡] L. M. Lederman, P. J. Limon, and B. G. Pope[§]
Columbia University, New York, New York 10027
and Brookhaven National Laboratory, Upton, New York 11973

E. Zavattini
CERN Laboratory, Geneva, Switzerland
(Received 30 March 1973)

Early 70's



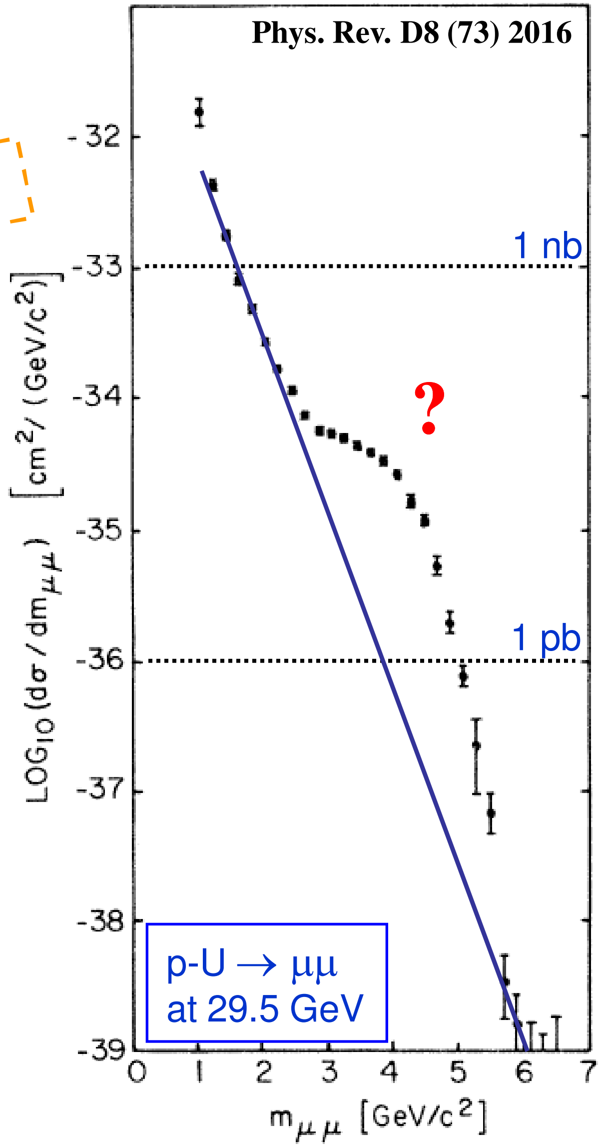
Muon pairs with effective masses between 1 GeV/c^2 and 6.5 GeV/c^2 have been observed in the collisions of 30-GeV protons with a uranium target. The production cross section was seen to vary smoothly with mass exhibiting no resonant structure.



VII. SUMMARY AND CONCLUSIONS

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

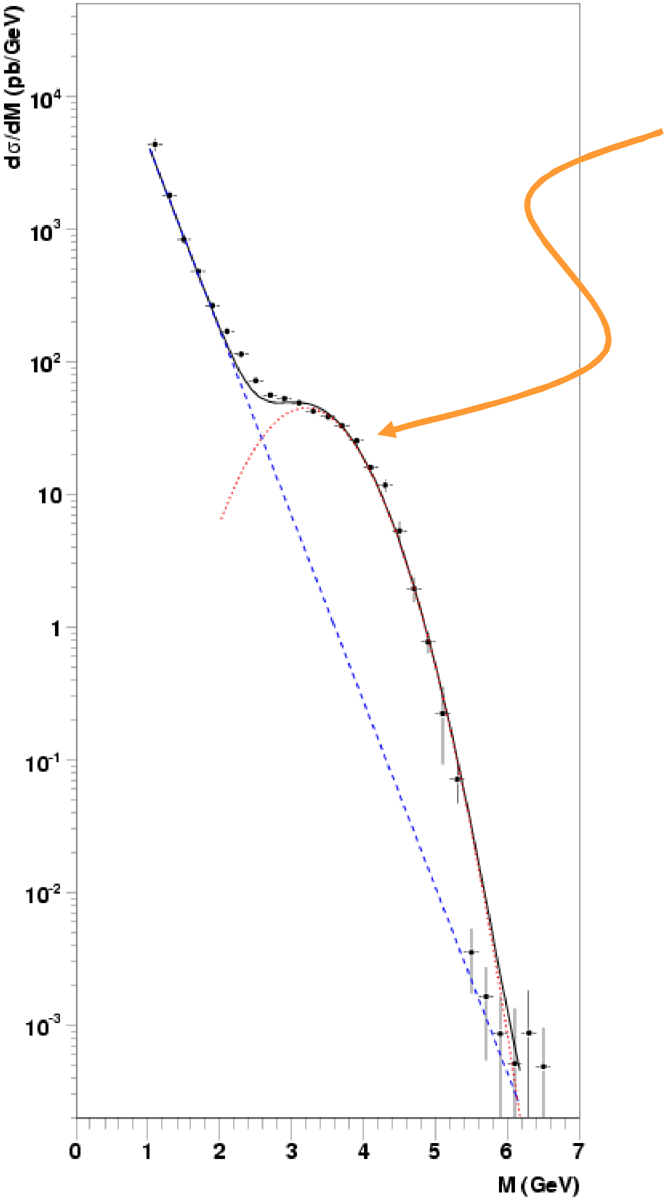
Lederman was a careful person...
and ***not*** in a hurry to get the Nobel prize ☺



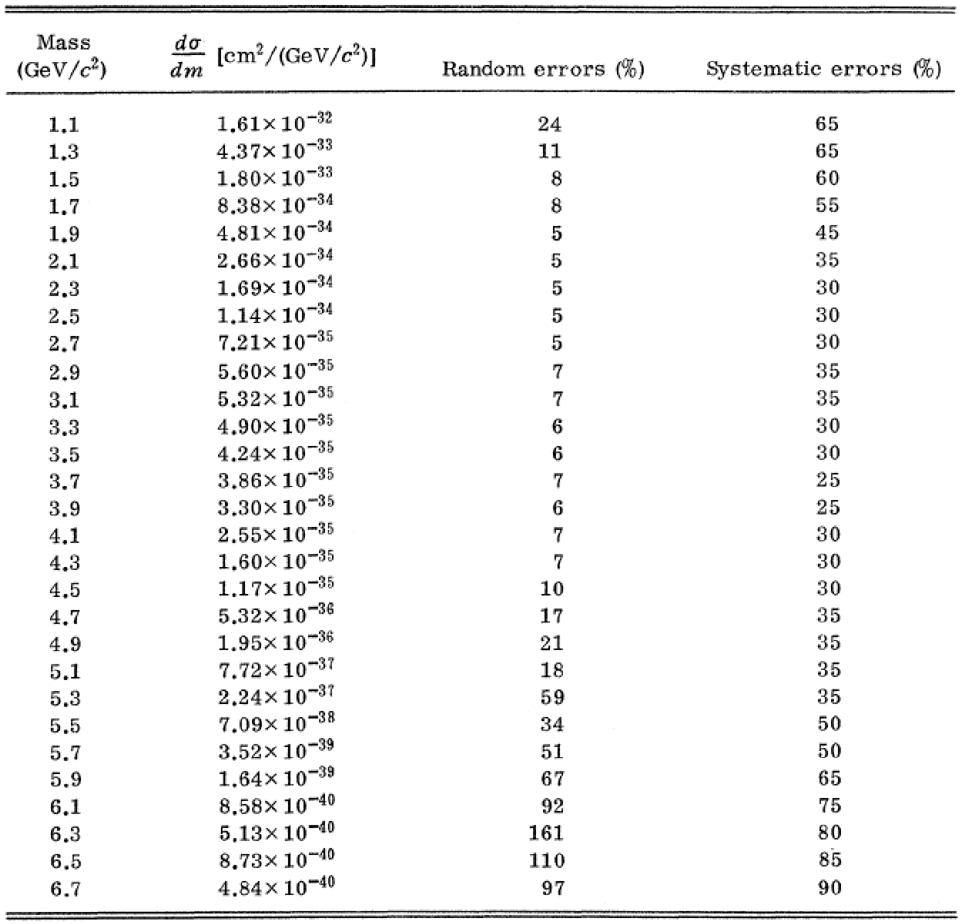
Phys. Rev. D8 (73) 2016

p-U → μμ
at 29.5 GeV

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"

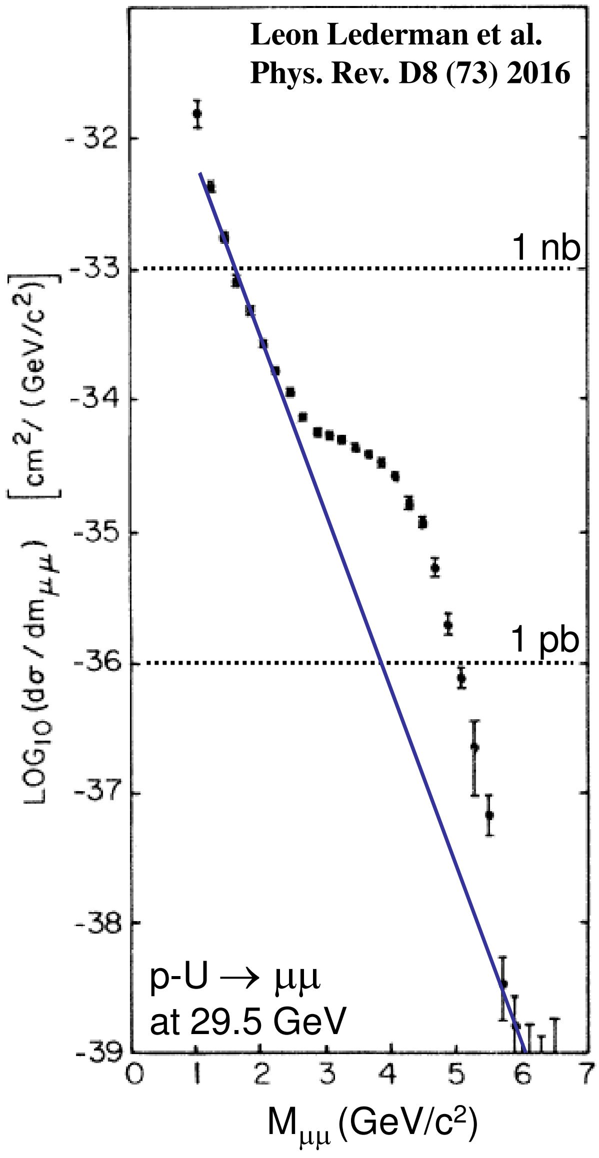


It works quite well, with a "resonance" centered at ~3.2 GeV with ~600 MeV dimuon mass resolution



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

Resolutions and acceptances distort the reality



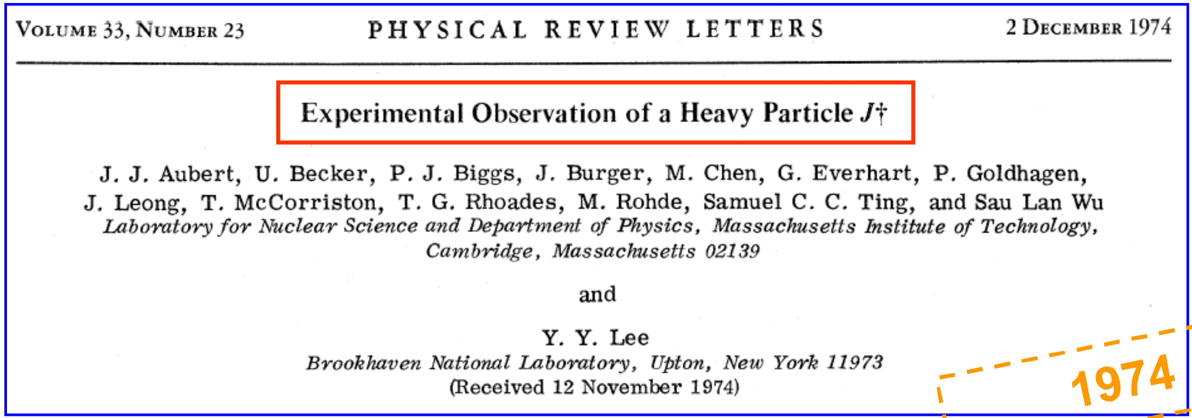
They were convinced that the experiment had a better dimuon mass resolution: a “resonant structure” should show up as a narrower peak…

And they thought that “the bump” could be an artifact caused by the acceptance edge…

In the early 1970’s it was not very easy to simulate the acceptance and resolution of a detector

And if you misunderstand such “details”, you miss the ticket to Stockholm

Double J/□ 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
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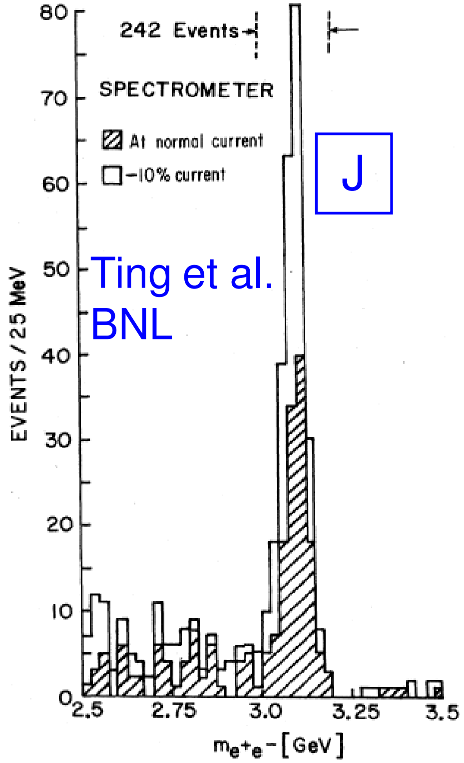
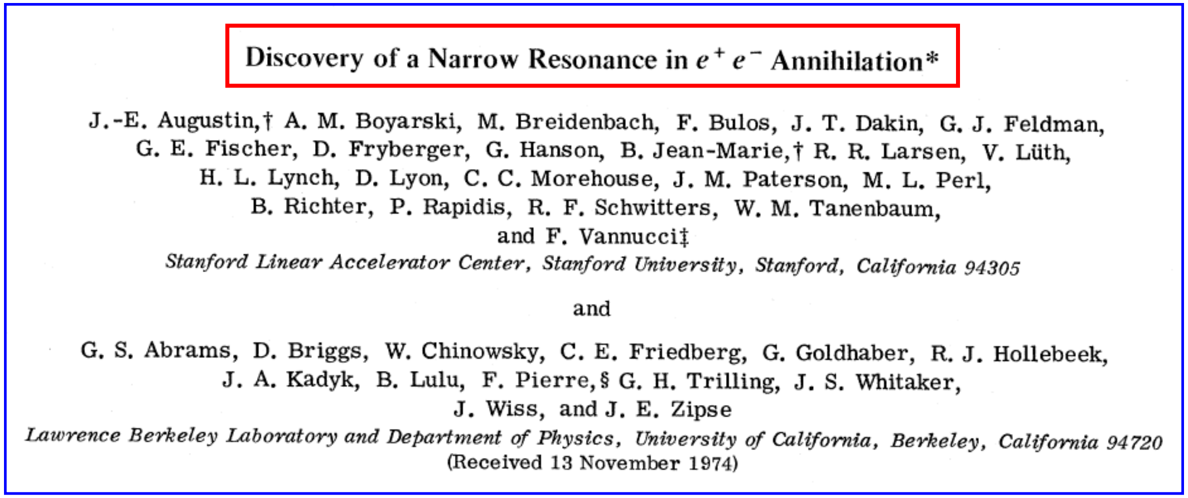
(Received 12 November 1974)

1974



J

Ting et al.
BNL

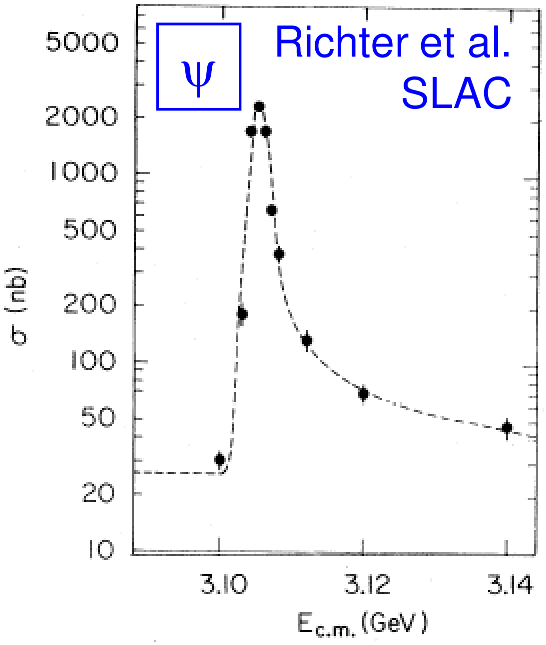


Discovery of a Narrow Resonance in e^+e^- Annihilation*

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)

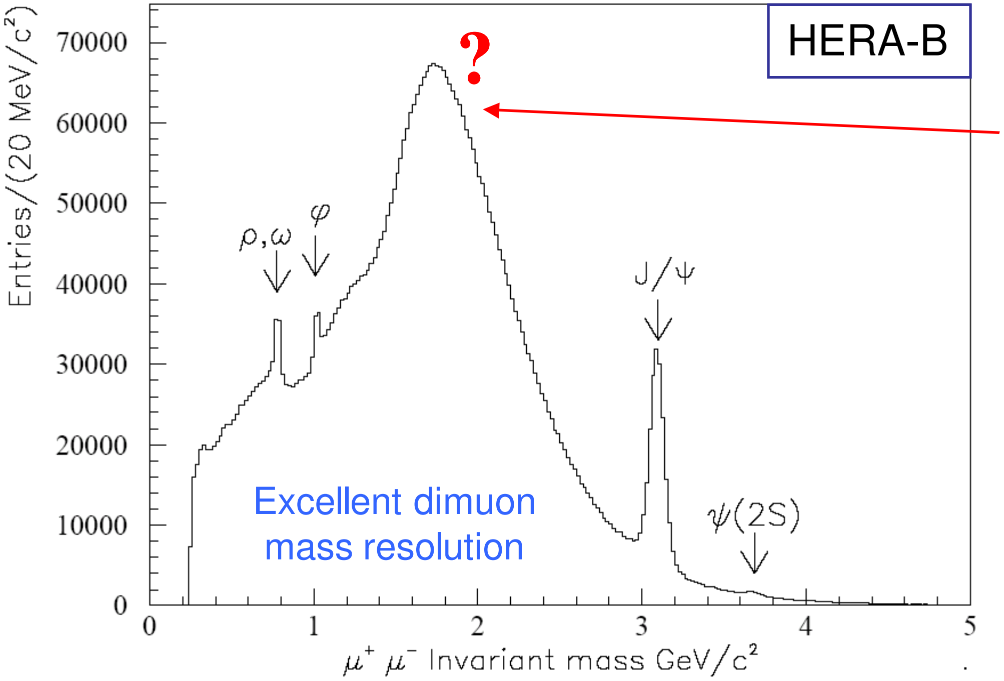


ψ

Richter et al.
SLAC

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

Acceptances

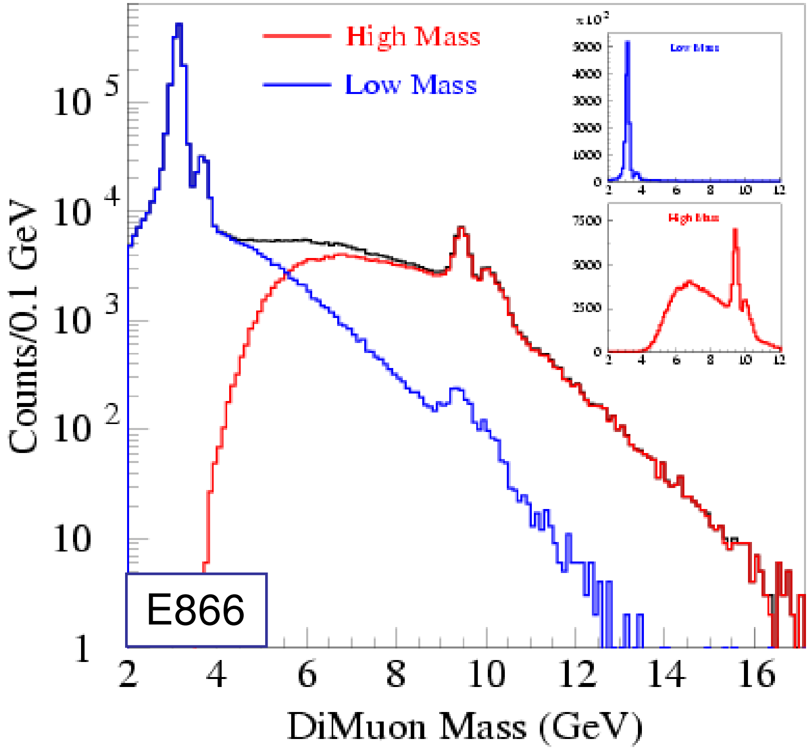


What is the peak at M ~ 1.8 GeV ?
A signal of $D^0 \rightarrow \mu^+\mu^-$ decays ?

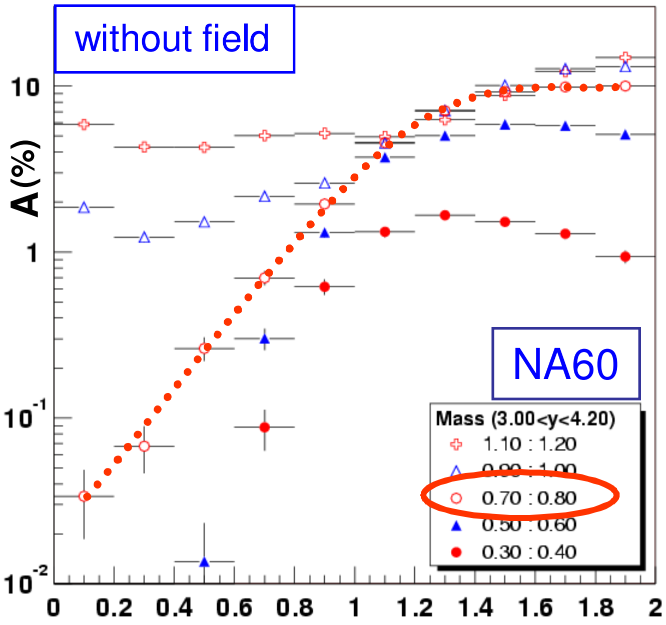
Not really…
Just a signal that the acceptance changes significantly in this region

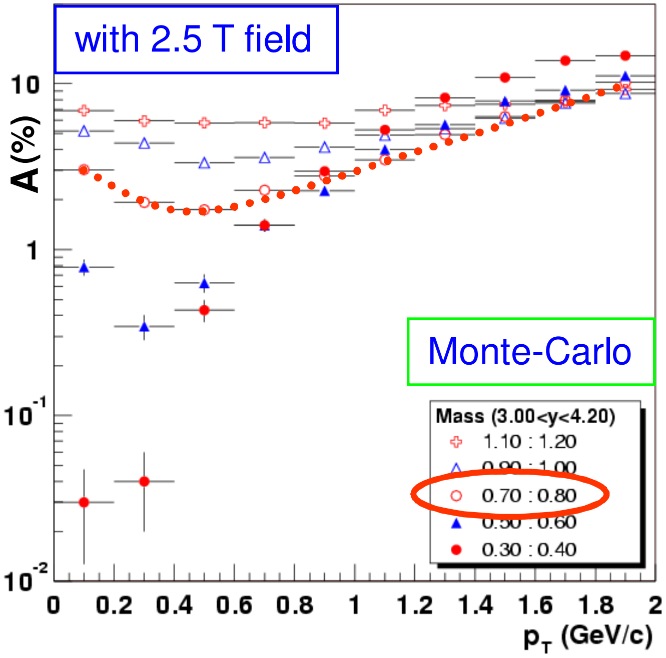
Acceptance is the probability that a particle is detected by the experiment

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

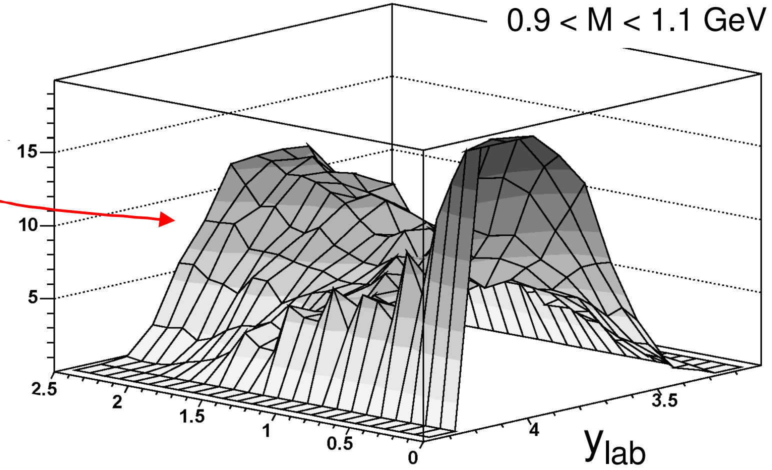


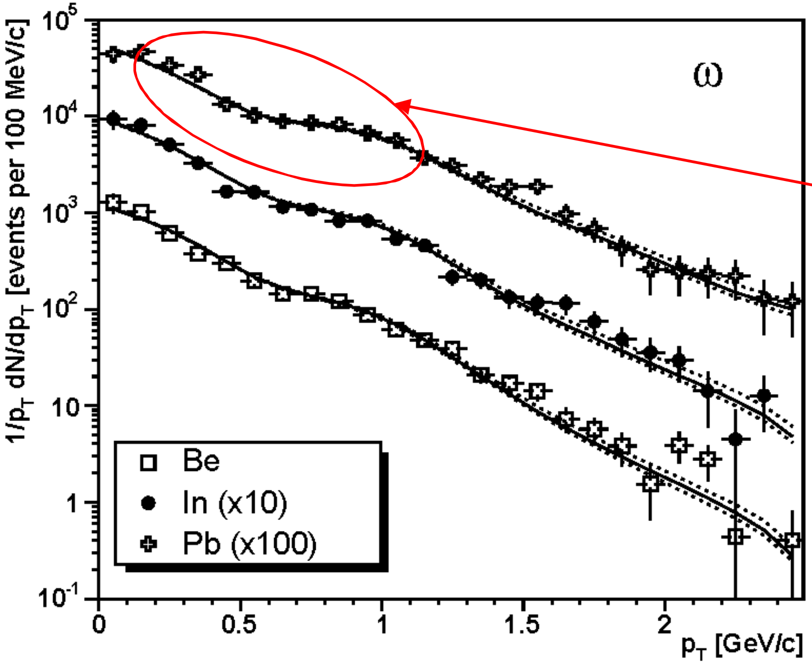
The dimuon acceptances depend on the magnetic fields, on the thickness of the muon filter, on the distance between the target and the detectors, etc





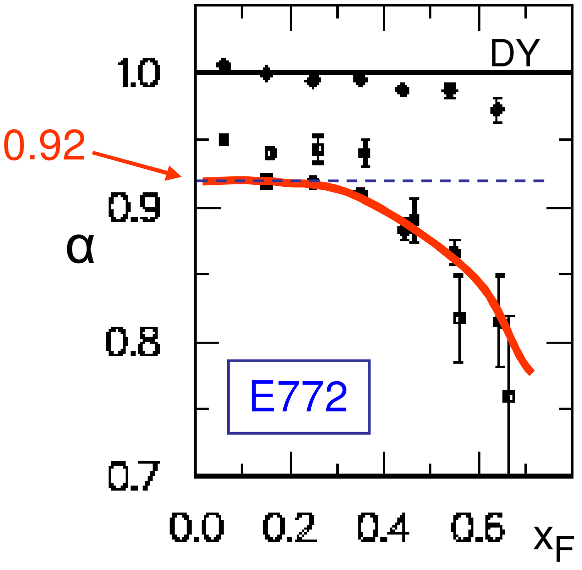
correlation in p_T and y_{lab}





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)

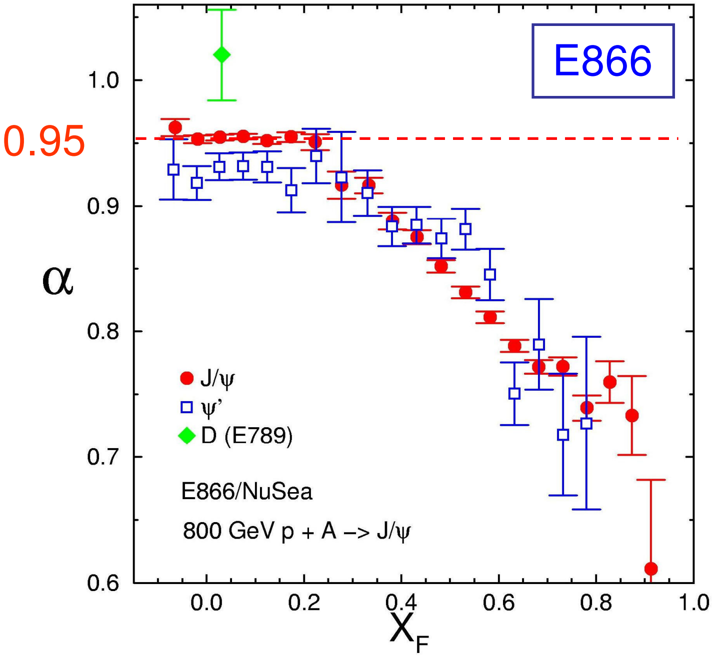
E772 (at x_F~0) 1992

$\alpha(J/\psi)$ ~ 0.92

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

E866 (at x_F~0) 1997

$\alpha(J/\psi)$ ~ 0.95

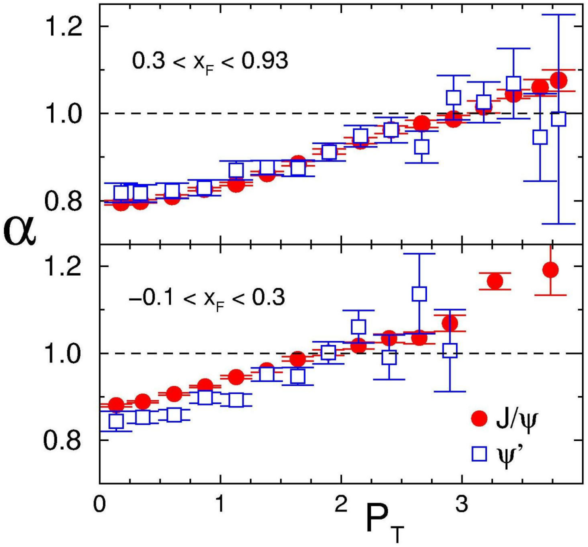


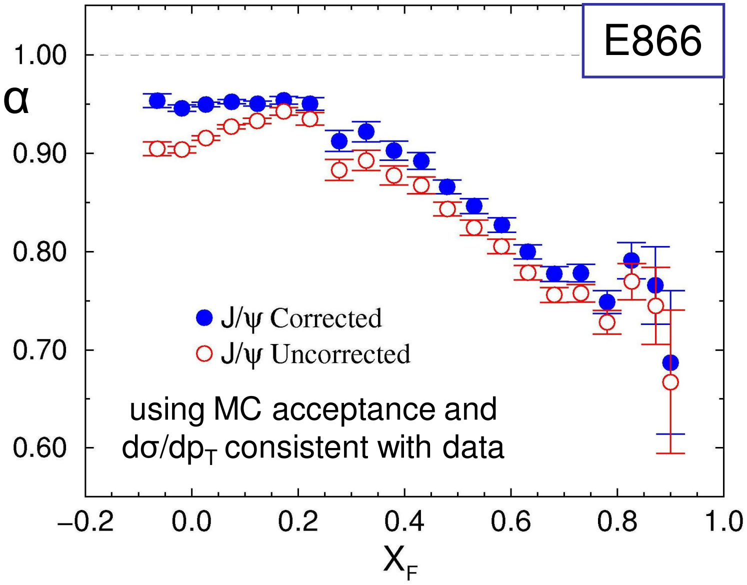
Because the understanding of acceptances improved…

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

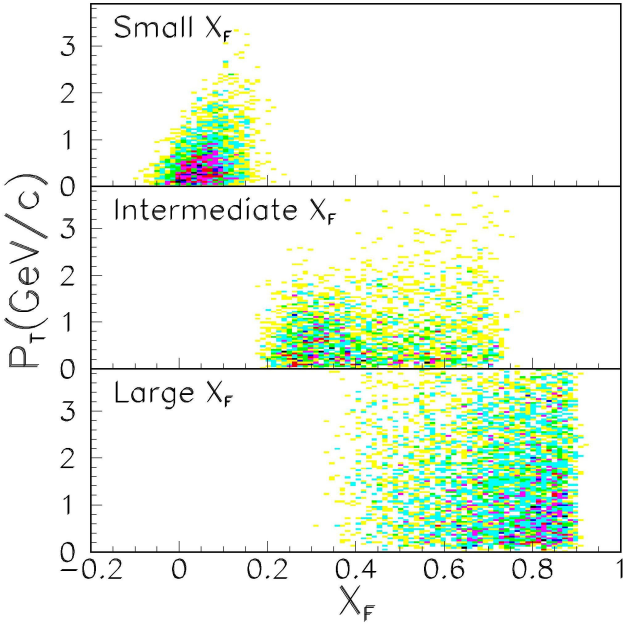
The correction of the (correlated) acceptance is crucial





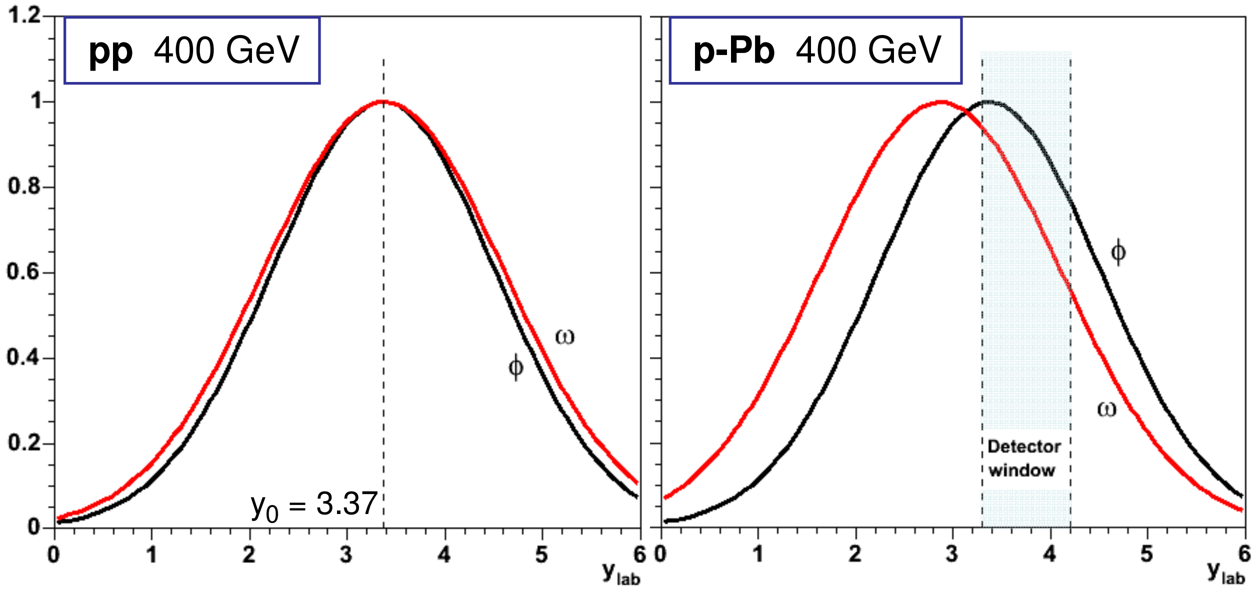
The problem was identified because the p_T coverage in E866 was better than in E772

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



Phase space windows

Assume that the ϕ has the same rapidity 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* rapidity, would "see" the opposite result: a *decrease* of the ϕ / ω ratio from pp to p-Pb collisions… Both would be wrong !
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 !

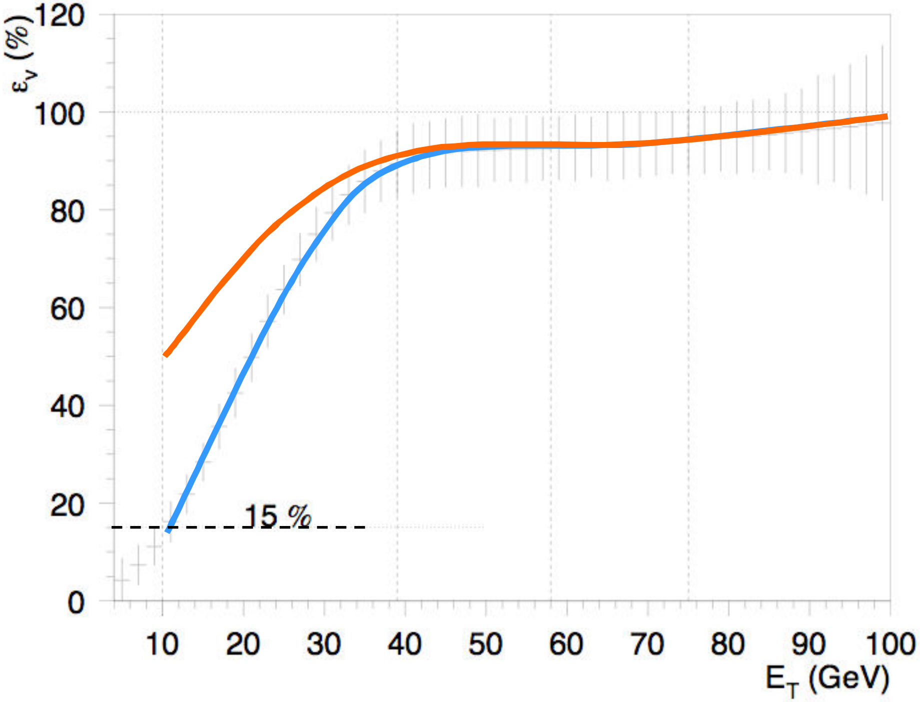
Efficiencies

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.

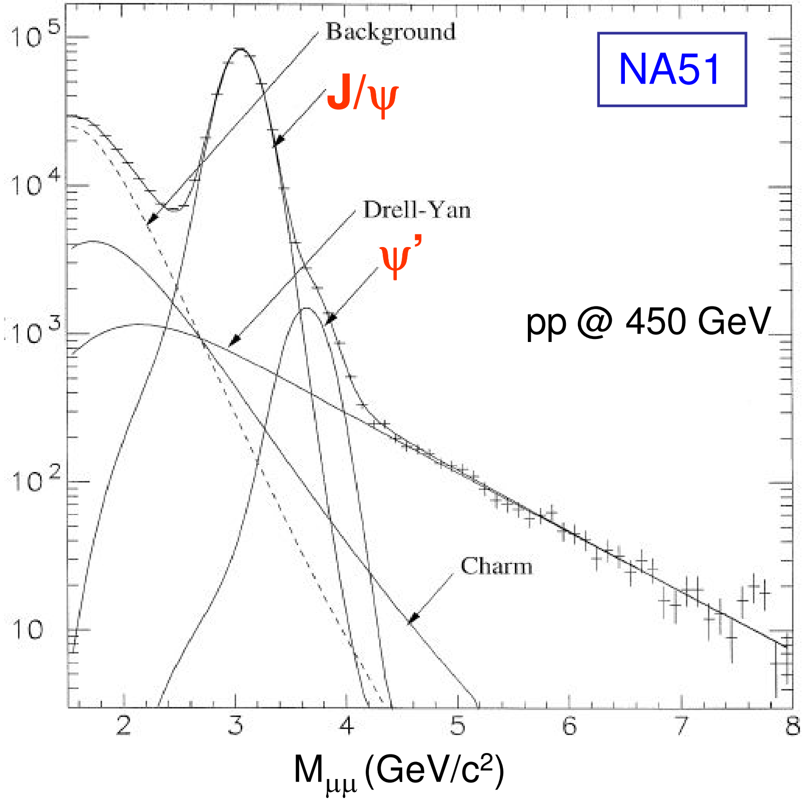
The measurements must be corrected for these detection *inefficiencies*

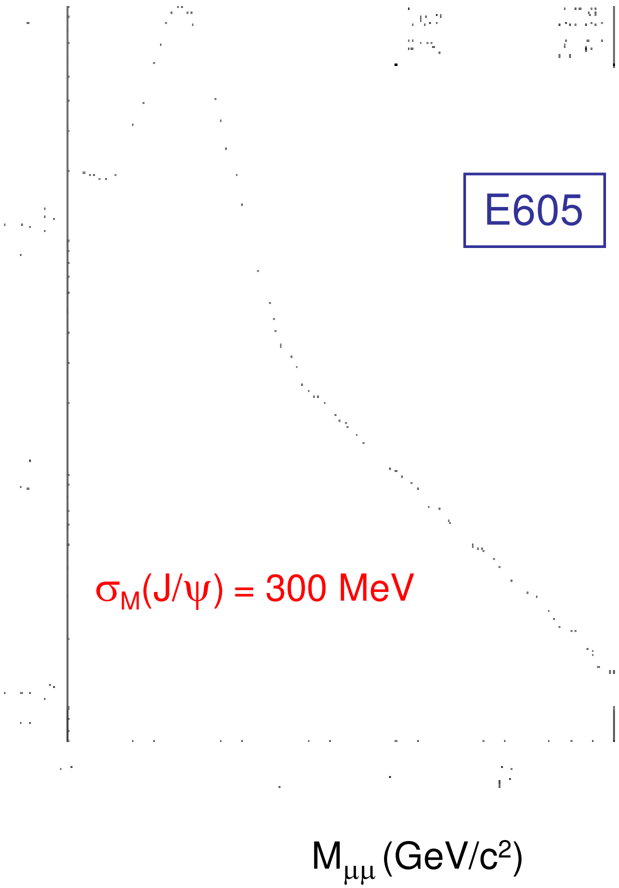
They might be measured in “special data samples”, or estimated by MC simulation using the same algorithms as used for the reconstruction and analysis of the data

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



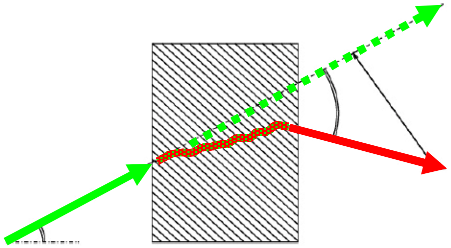
Multiple scattering and dimuon mass resolution



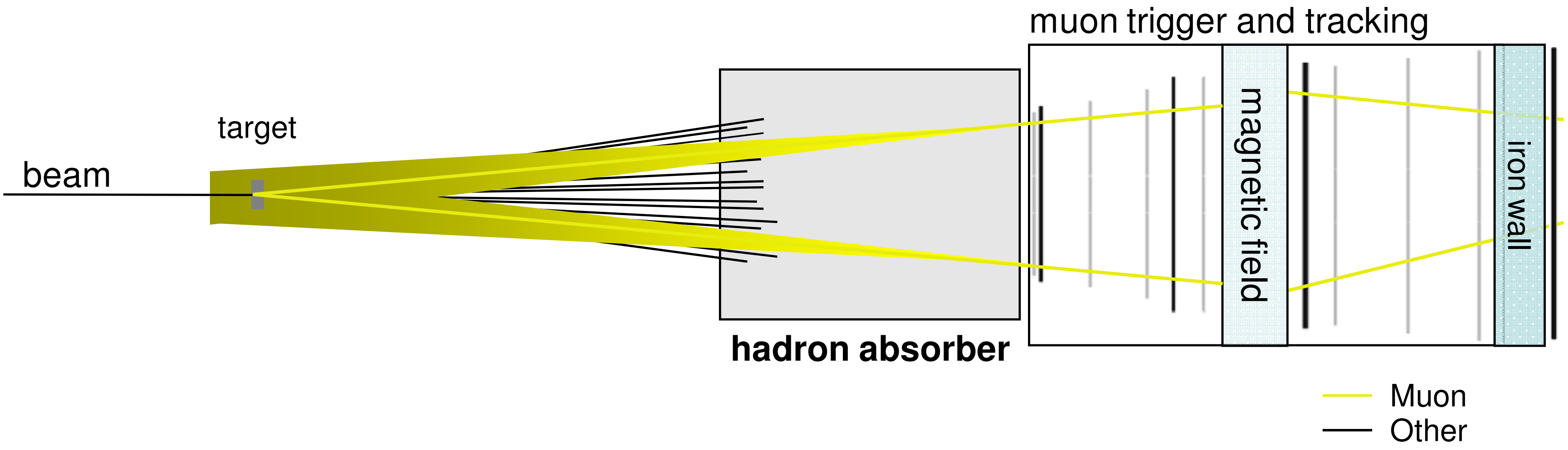


Muons are “identified” by absorbing all other charged particles in a “hadron absorber”...

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

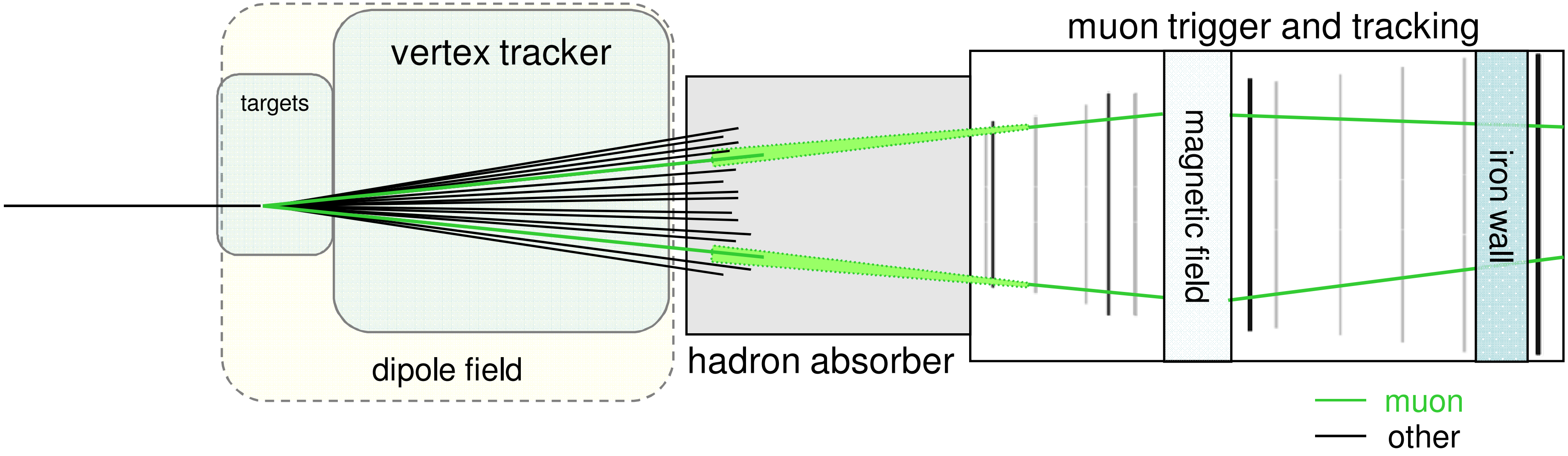


Standard way of measuring dimuons (NA50, PHENIX, ALICE, etc)



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

Overcoming multiple scattering with vertex tracking

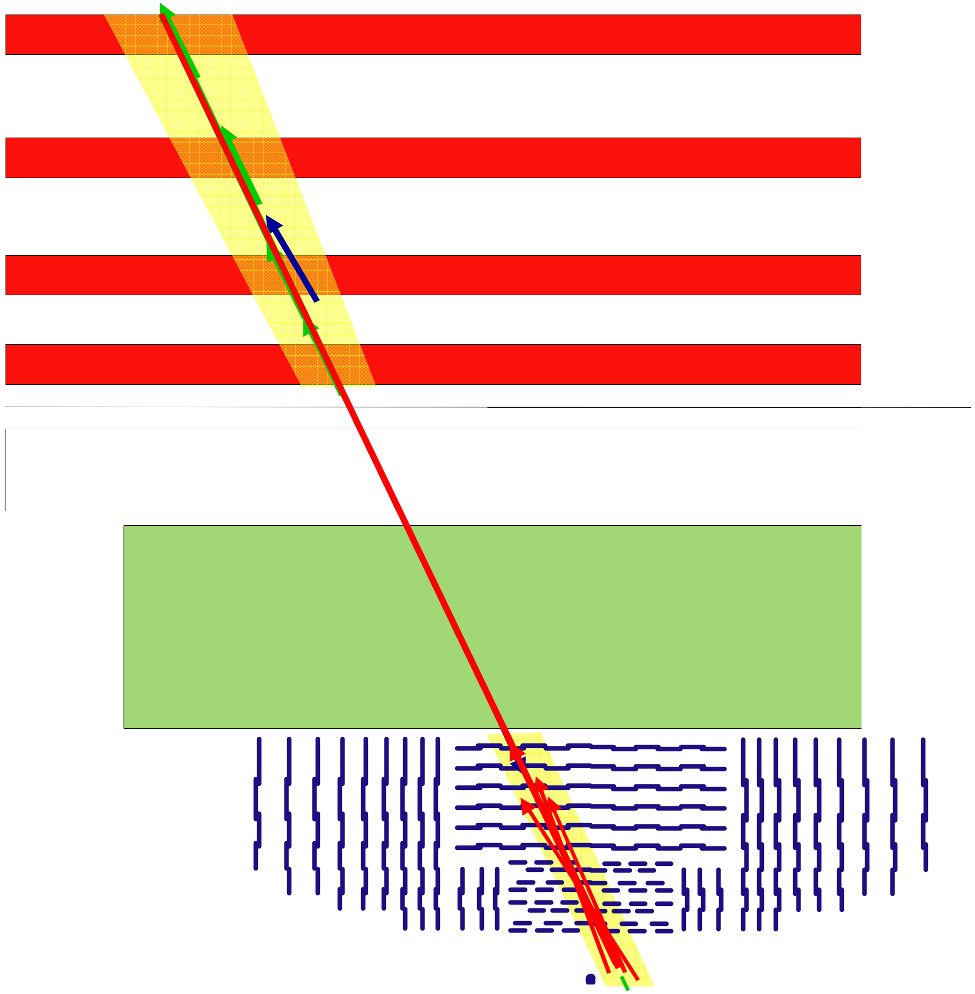


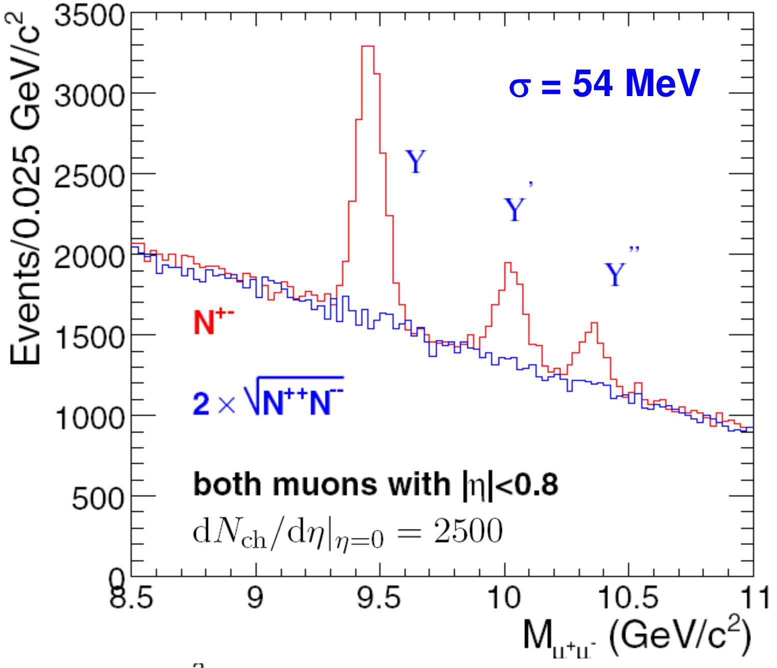
Concept used in NA60 and CMS :

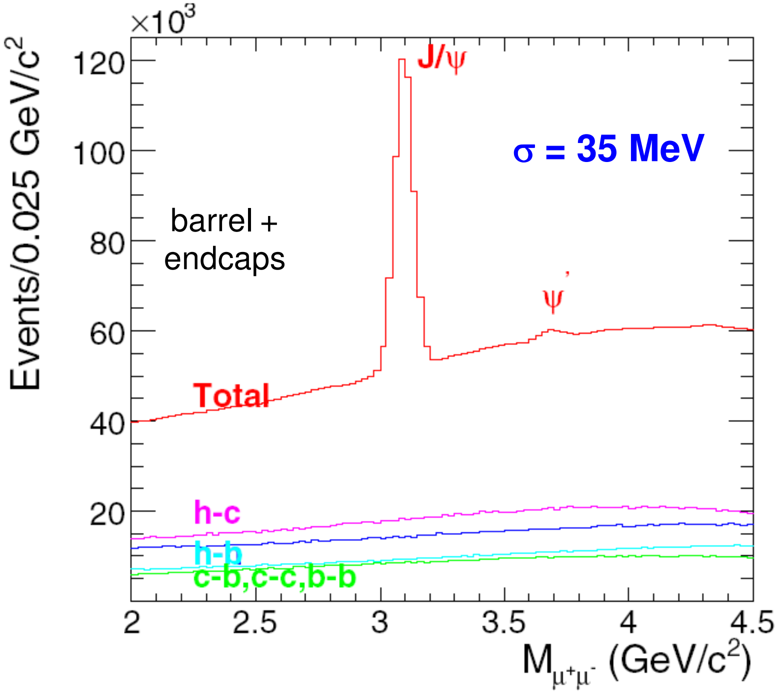
- The hadron absorber allows us to trigger on collisions that produce dimuons
- The muons are tracked in the vertex tracker, *before* they suffer multiple scattering in the hadron absorber, and matched to the tracks of the muon chambers
- We can also see if the muons come from the collision vertex or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

Muon track matching in CMS

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

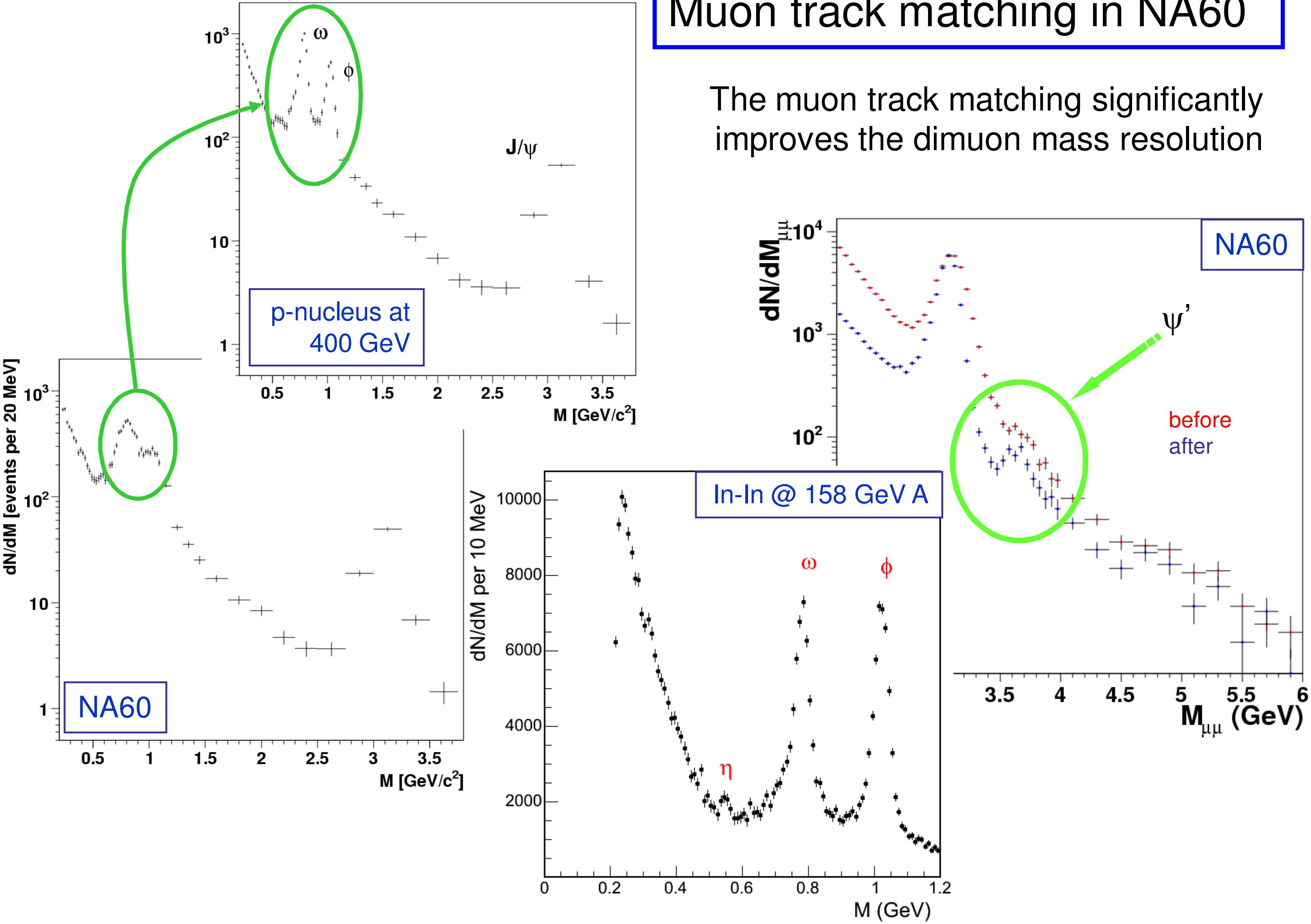






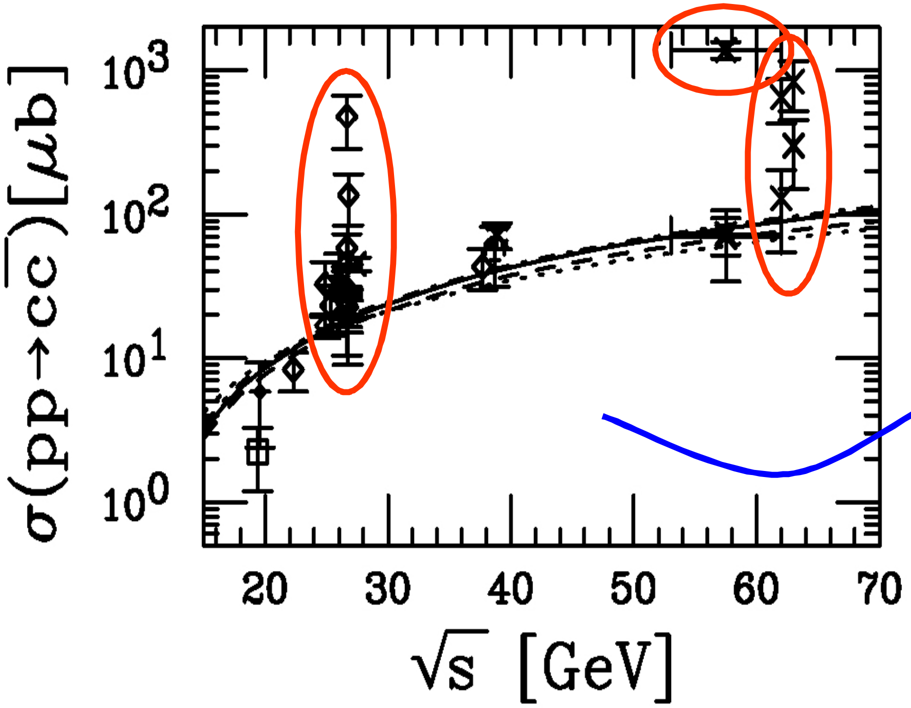
Muon track matching in NA60

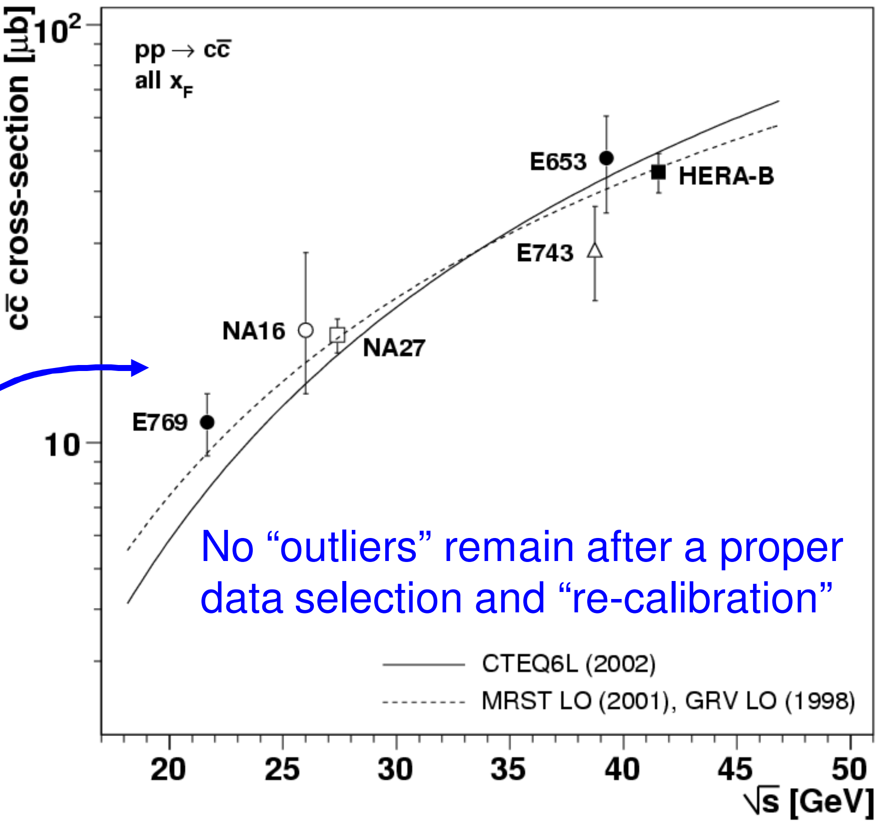
The muon track matching significantly improves the dimuon mass resolution



Data selection

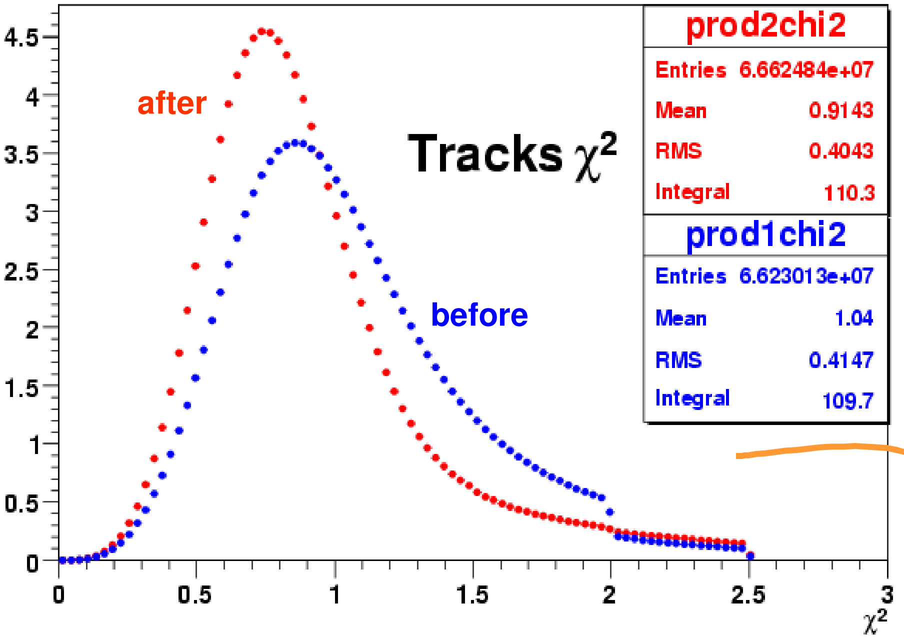
A small but clean event sample is better than a large but “dirty” one.
And statistical errors are much easier to deal with than systematic uncertainties.

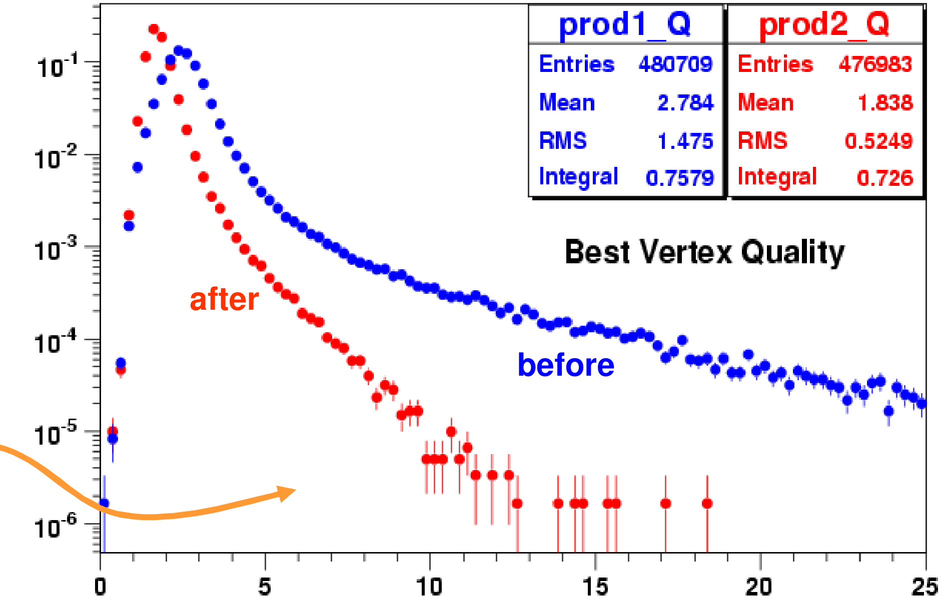




No “outliers” remain after a proper data selection and “re-calibration”

Good alignment ⇒ good muon offset resolution

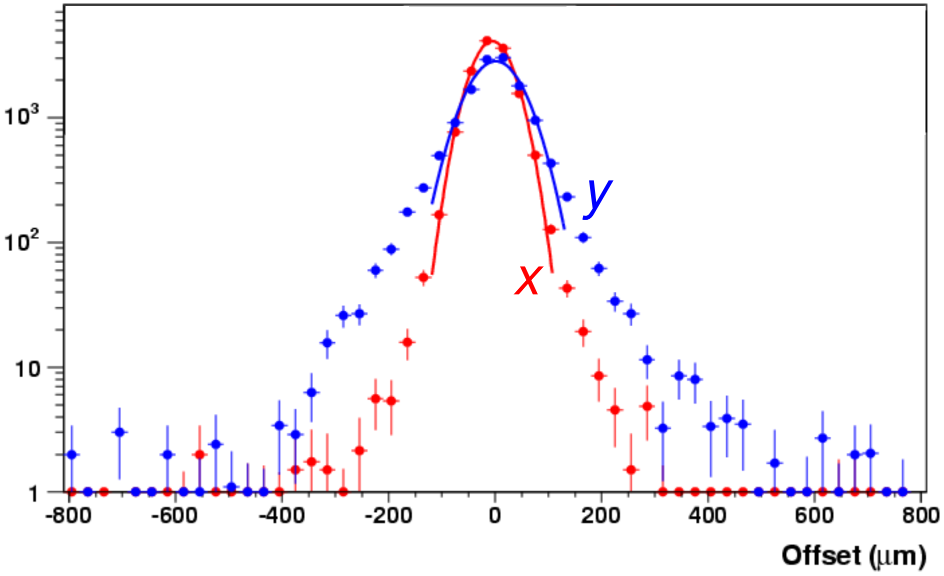




Reconstructing the data after aligning the silicon pixel planes significantly improves the tracking and vertexing

⇒ better resolution of the muon offset

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



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

But the trigger systems are not 100% efficient…

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)

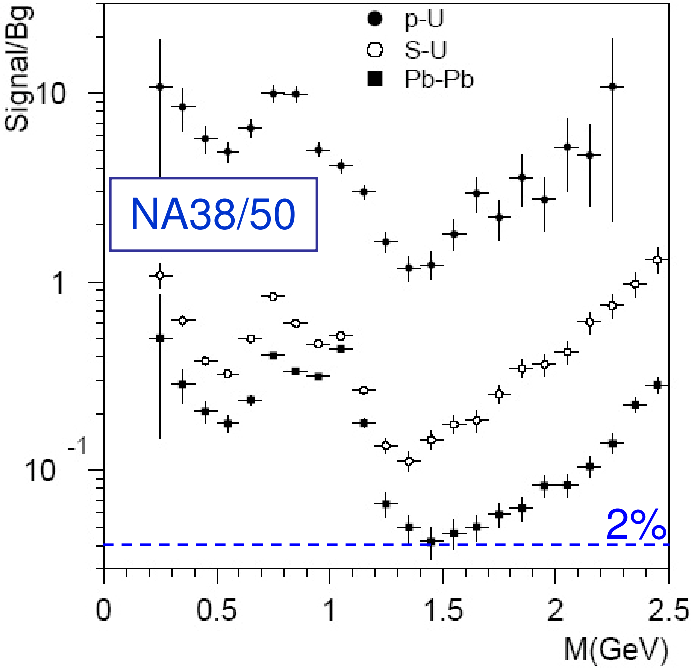
Great !

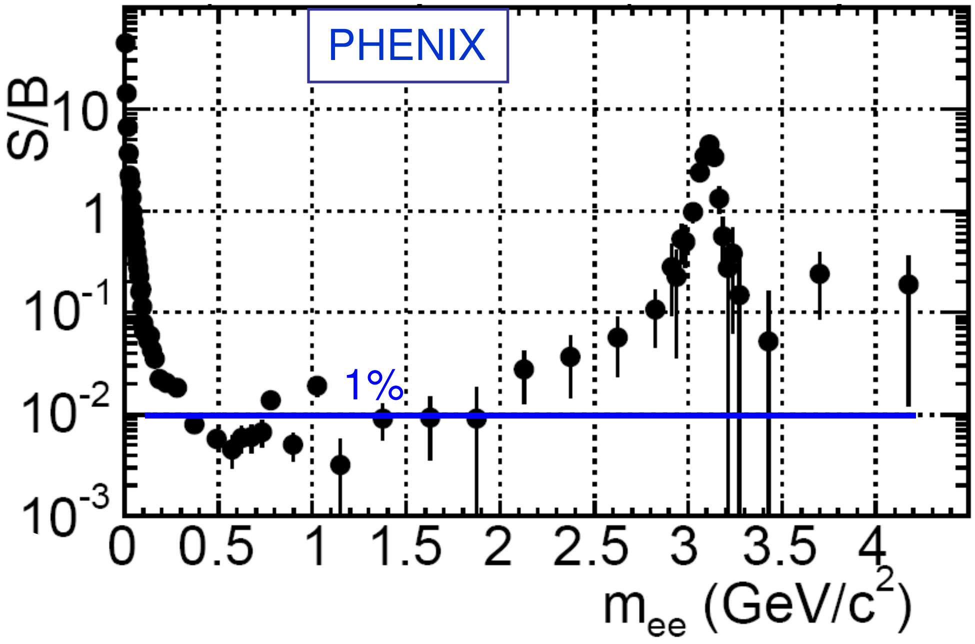
What would you say?

⇒ 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 !



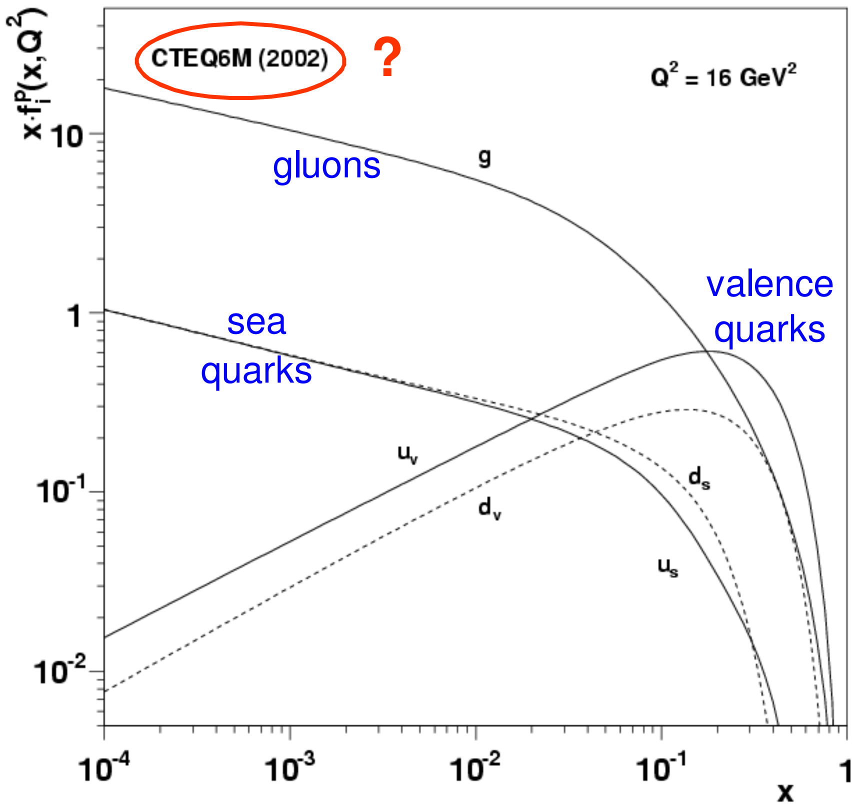


Know your reference !

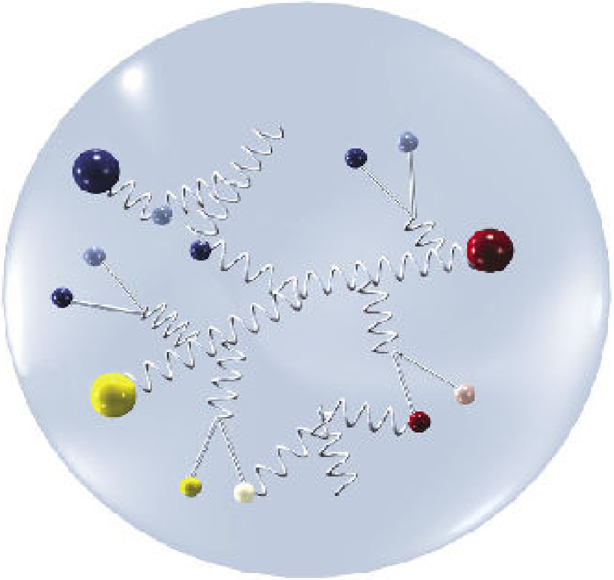
pQCD calculates *partonic processes*, like qq → qq, qg → qg, gg → gg

But our beams (and targets) are made of protons, neutrons, antiprotons...
not of quarks and gluons !

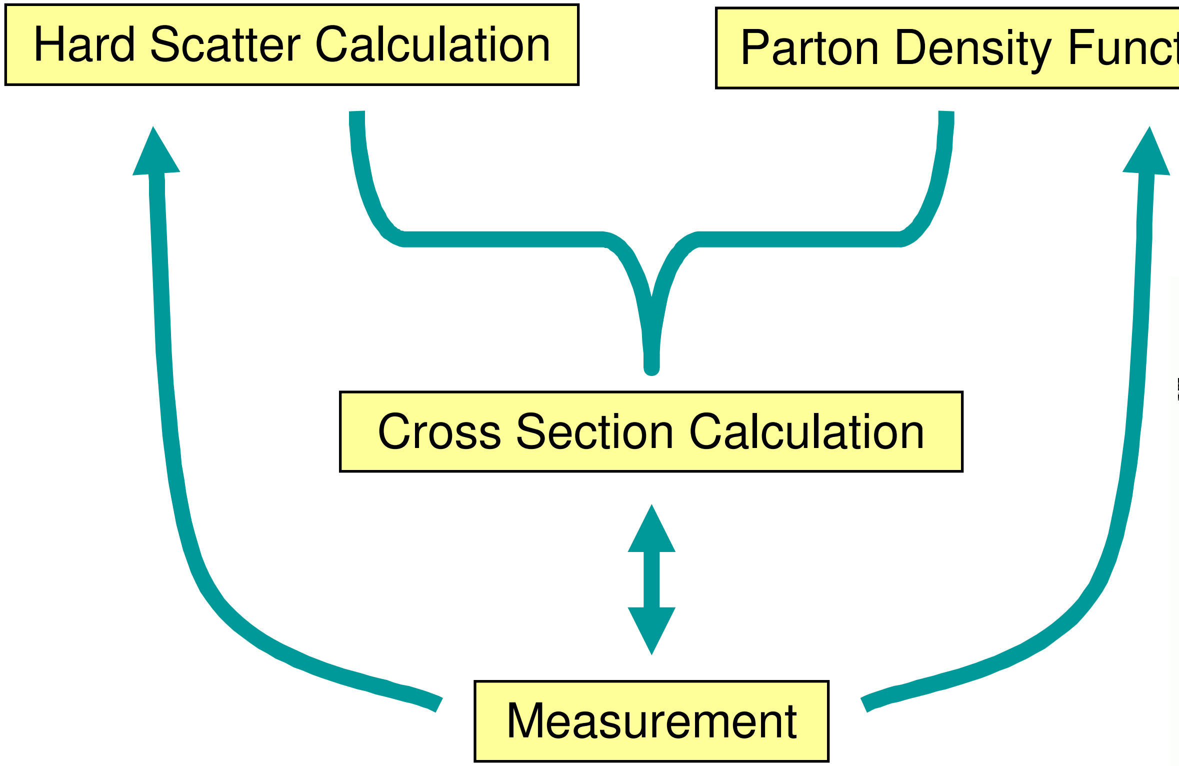
The probability that we find quarks, anti-quarks or gluons inside a proton depends on their fractional momenta and on the “resolution” of our probe: $f(x,Q^2)$



parton distribution functions, PDFs



How do we know what the parton densities are ?

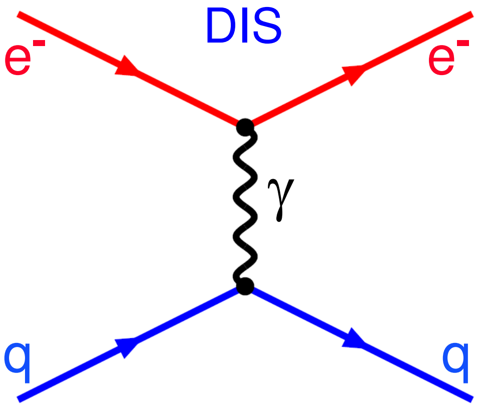


Hard Scatter Calculation

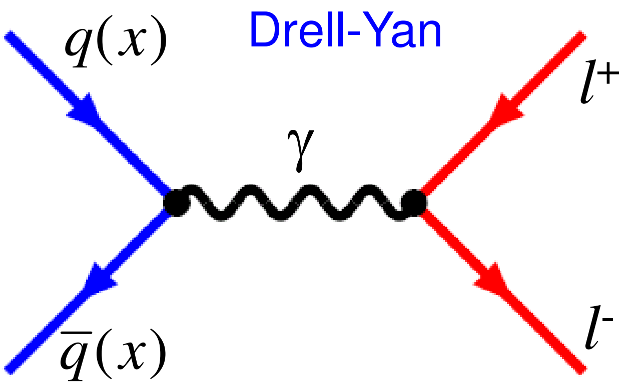
Parton Density Functions

Cross Section Calculation

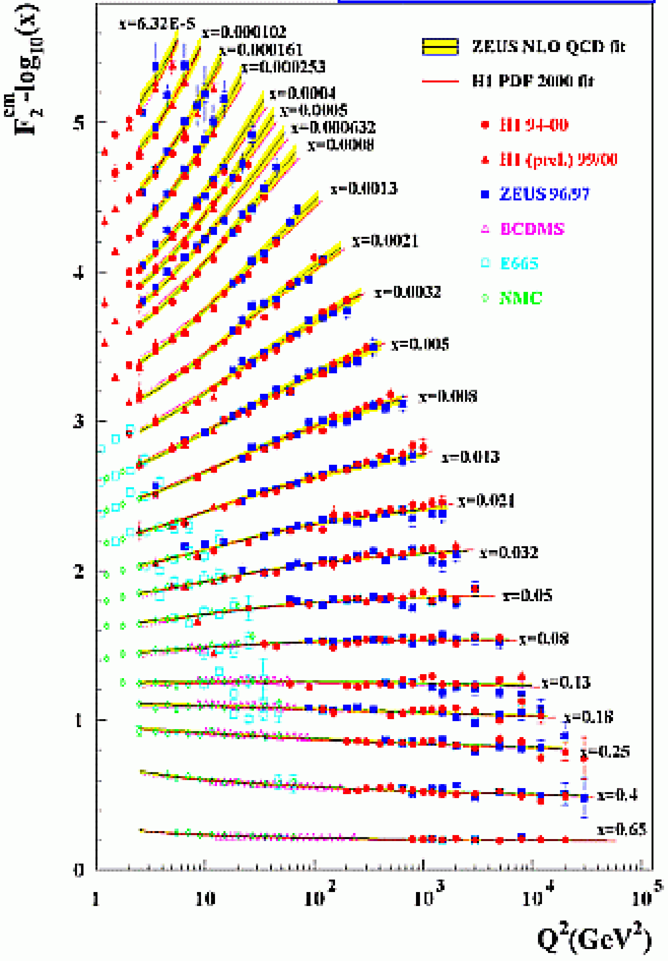
Measurement



DIS



Drell-Yan



5 experiments

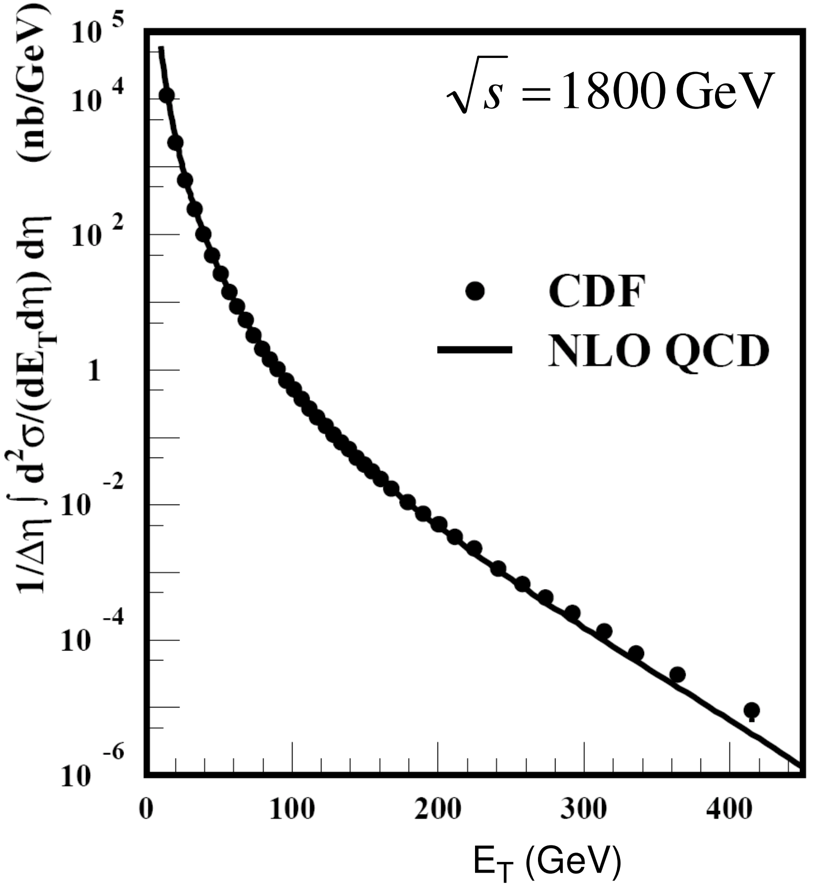
What means MRST, CTEQ6M, etc ?

- Each class of experiments (DIS, Drell-Yan, etc) gets part of the story
  No single experiment measures the full picture of the proton

- The results from each experiment go into a *global fit*
  Not all experiments agree – there is an *art* to “average” them together

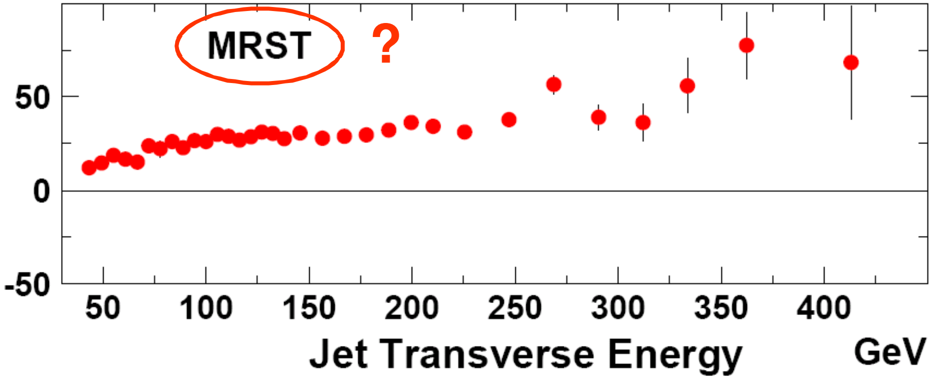
- Two main groups are experts in this art :
  → Martin, Roberts, Stirling and Thorne ⇒ **MRST**
  → Coordinated Theoretical-Experimental project on QCD ⇒ **CTEQ**

Jet production: data versus perturbative QCD calculations



The data points seem to agree with the pQCD calculation, over 11 orders of magnitude…

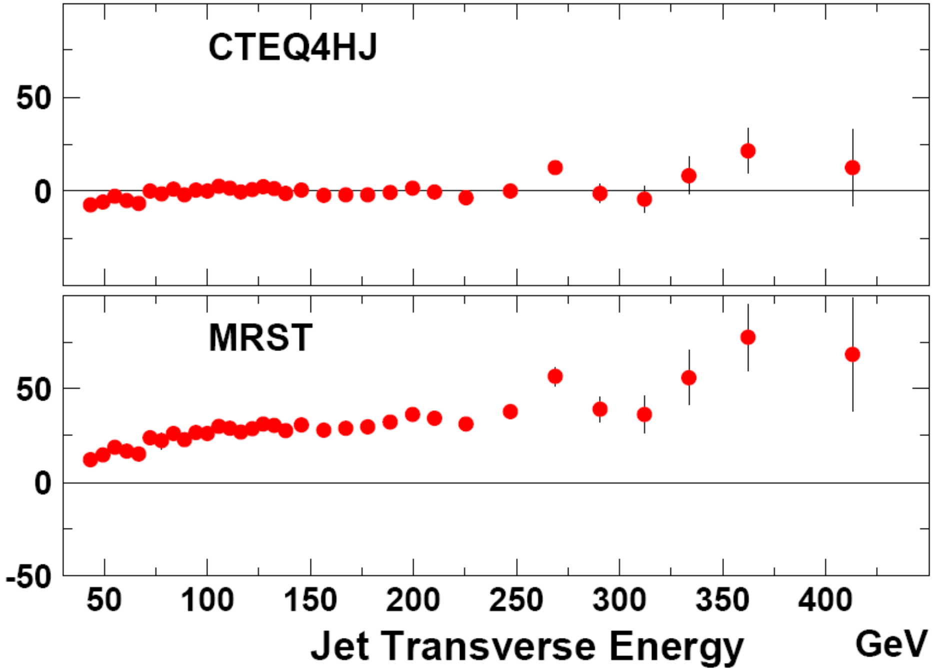
Except if you look at the high E_T tail... on a linear scale, as (data-theory) / theory



⇒ A clear indication of quark substructure (compositeness) ! Really ???

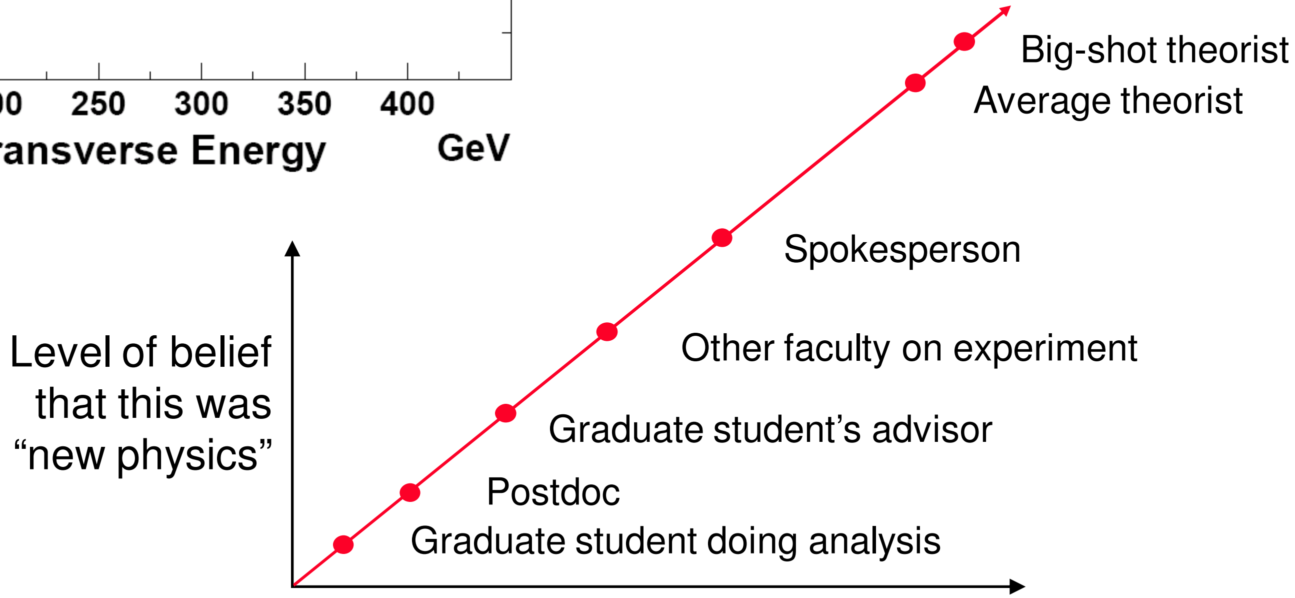
The high-E_T jet excess got renormalized into a new reference

New sets of Parton Distribution Functions were calculated, *including the CDF data*



The excess is gone!

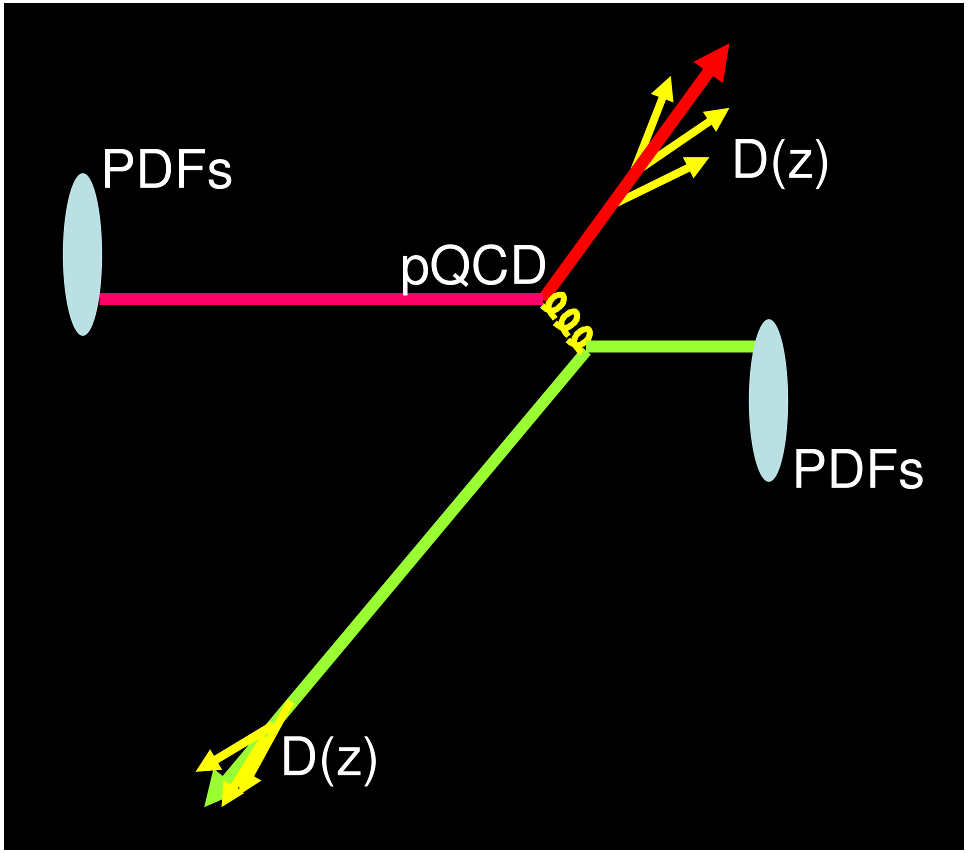
The quarks do not have substructure after all...



Fragmentation into the final state hadrons

We need to convolute the pQCD hard interaction with (initial state) parton densities and (final state) fragmentation functions, which define how the quarks and gluons hadronise. We operate *particle* detectors, not parton detectors...

The PDFs and the fragmentation functions should be universal: the same for all processes.



$$\underset{\text{hadrons}}{\boxed{\frac{d\sigma^{h}_{pp}}{dy\,d^{2}p_{T}}}} = K\sum_{abcd}\int dx_a\,dx_b\,\enclose{circle}{f_a(x_a,Q^2)\,f_b(x_b,Q^2)}\,\underset{\text{partons}}{\boxed{\frac{d\sigma}{d\hat{t}}(ab\to cd)}}\,\enclose{circle}{\frac{D^{0}_{h/c}}{\pi z_c}}$$

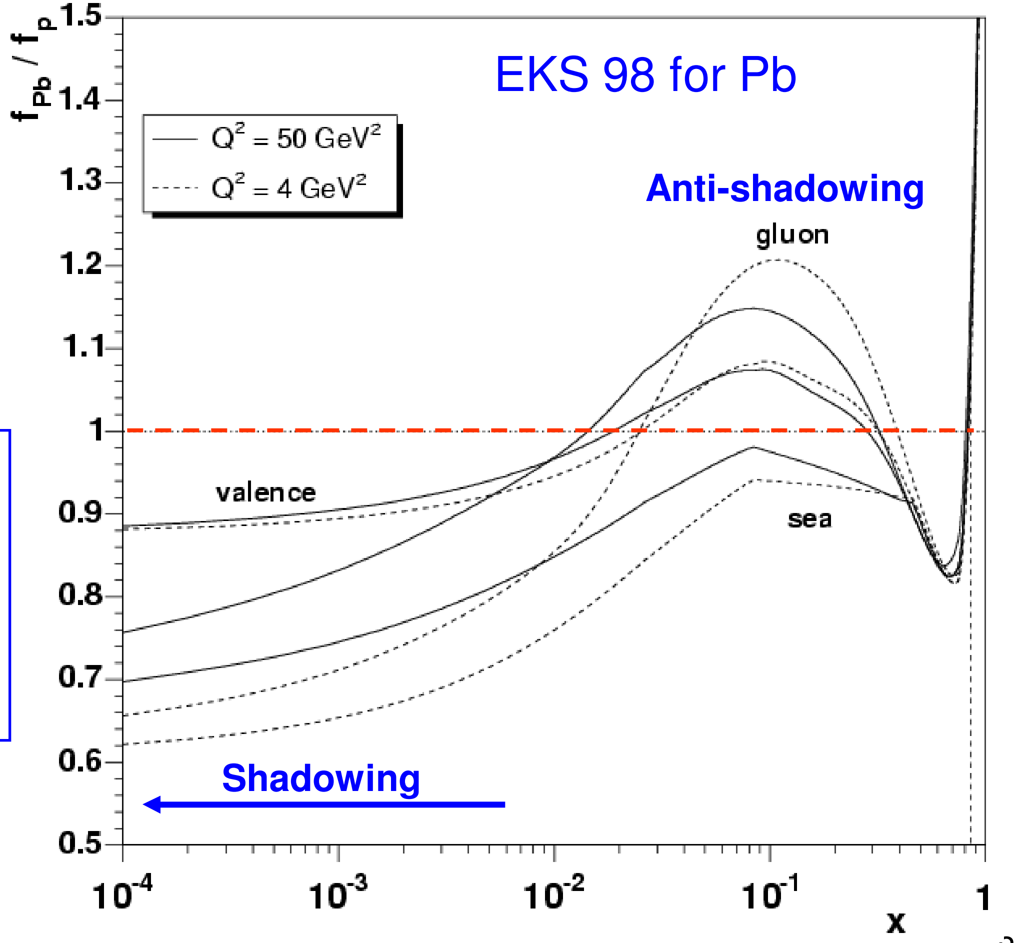
Back to the Parton Distribution Functions

Is a free proton the same as a proton inside a nucleus?
No! There are “nuclear effects” modifying the parton distribution functions.
The probabilities of finding partons of given *x* change when the proton is inside a nucleus. The “EKS 98 model” provides the ratio between the PDFs in a proton of a nucleus of mass number A and in a free proton:

$$\boxed{R_i^A(x,Q^2) = \frac{f_i^A(x,Q^2)}{f_i^p(x,Q^2)}}$$

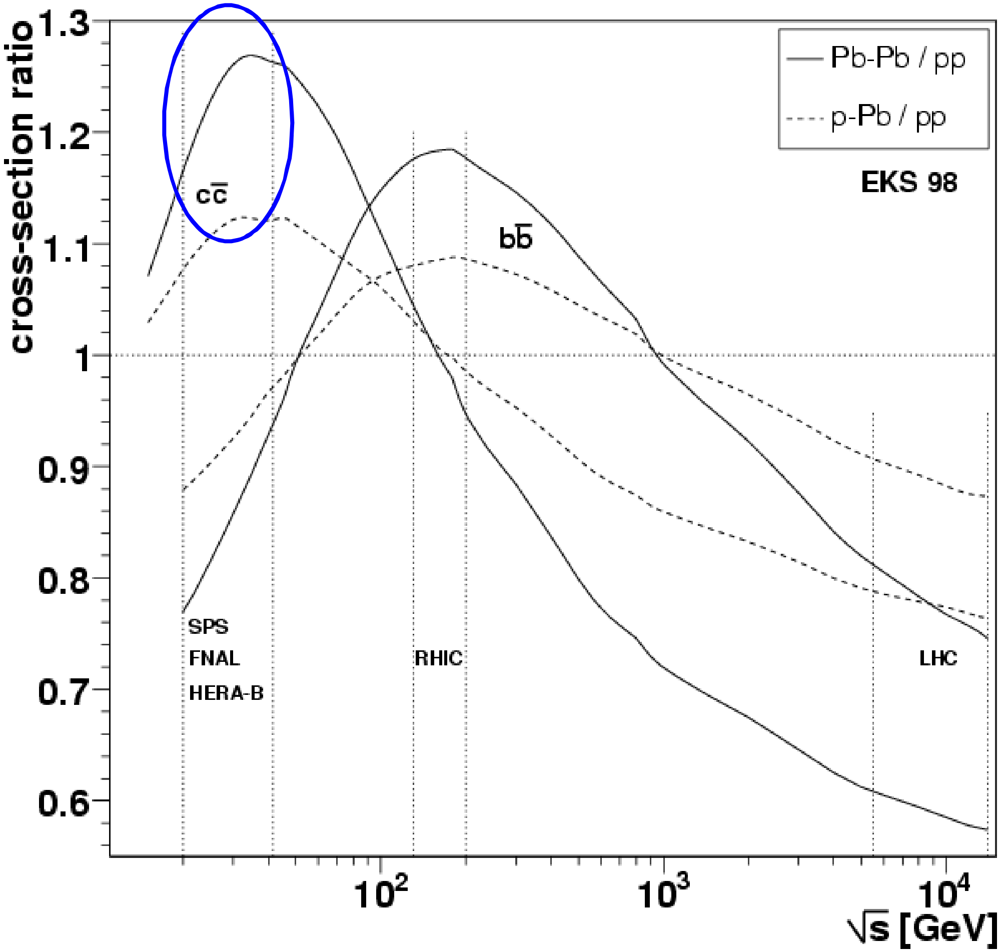
<u>“Shadowing” or “anti-shadowing”:</u>

decrease or increase of the parton’s density in the nucleus, in a certain kinematic range



Is this an important effect ?

This implies a ~20% *higher* charm production cross section in Pb-Pb collisions at the SPS and a ~40% *lower* value at the LHC, as compared to a linear extrapolation from pp collisions.



Remarks:

For a given collision energy and a given mass produced, the values of *x* depend on the rapidity range where the measurement is made.

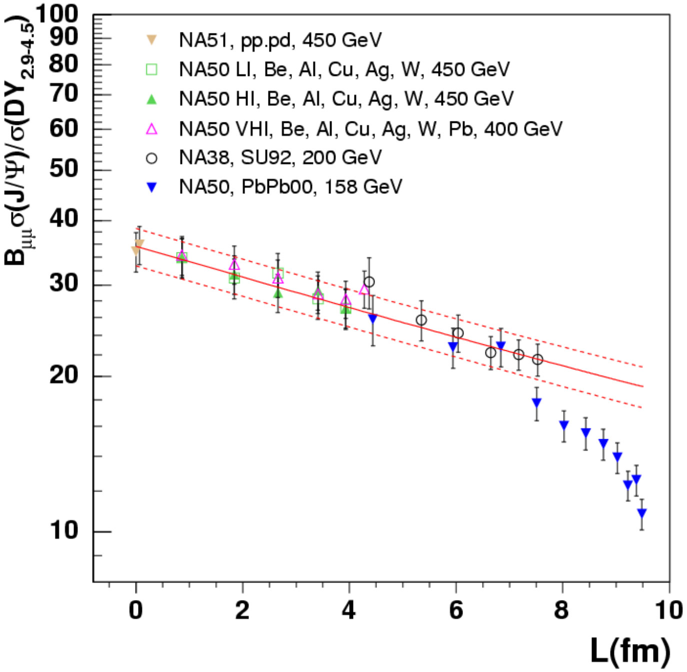
If the pp and Pb-Pb collisions are collected at different energies, the corrections for the nuclear effects are particularly tricky. We cannot *directly* compare heavy-ion and pp data.

Important in the analysis of the SPS J/ψ suppression data.

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

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.

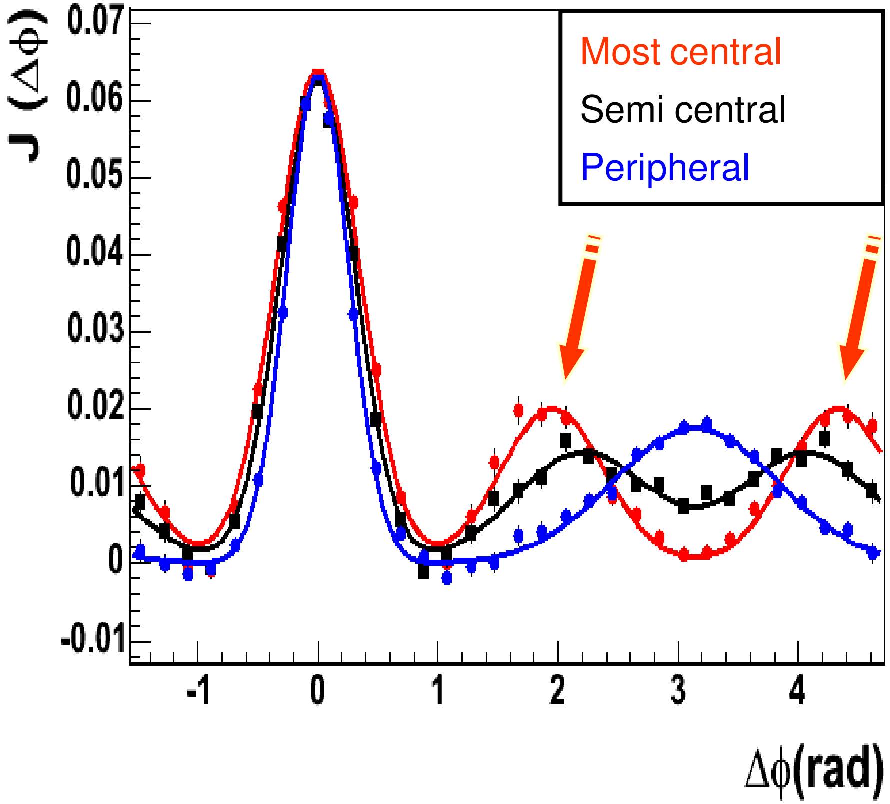
The acceptances, efficiencies, signal/background ratio, resolutions, etc., will change; but the physics results, obtained after all the corrections are made, must remain the same (within *statistical* errors)

Important analyses should always be *independently* made by at least two different groups and with different choices of model dependent assumptions.

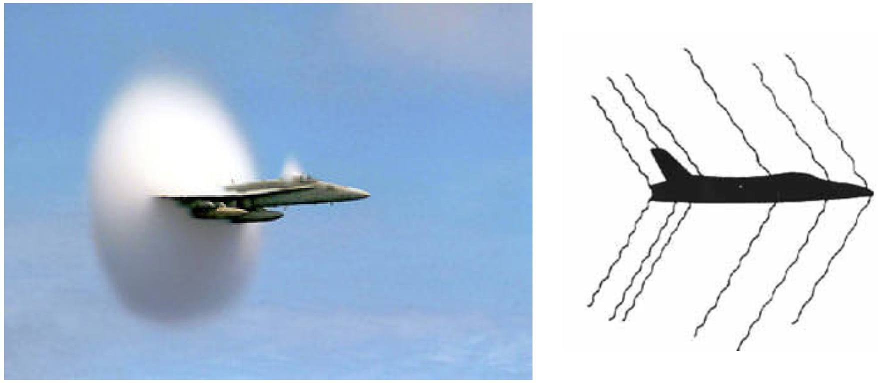
If after all checks you still have doubts about your exciting “new physics” results
— you should *always* doubt everything, especially *exciting results* —
make a better experiment, or at least a vastly improved measurement

Latest news on the “away-side double-peak” structure

The di-hadron azimuthal distribution in central Au-Au collisions at RHIC reveals a curious double-peak structure, instead of the (peripheral) away-side peak



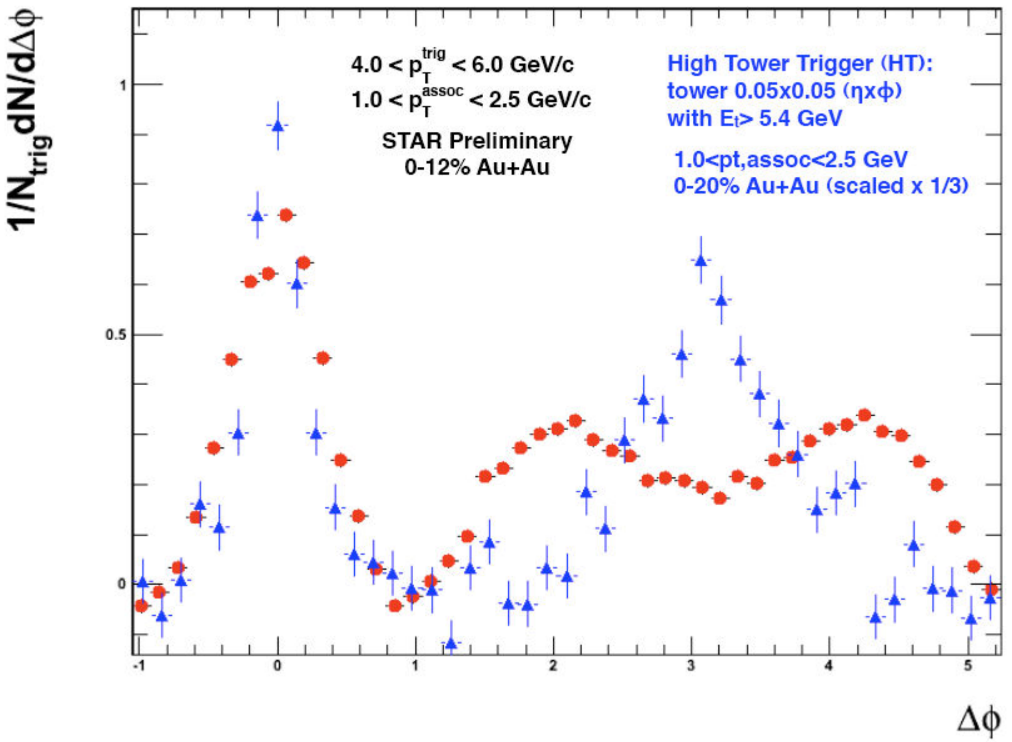
A Mach-cone effect ?
Are the particles moving faster than the speed of sound in the medium ?

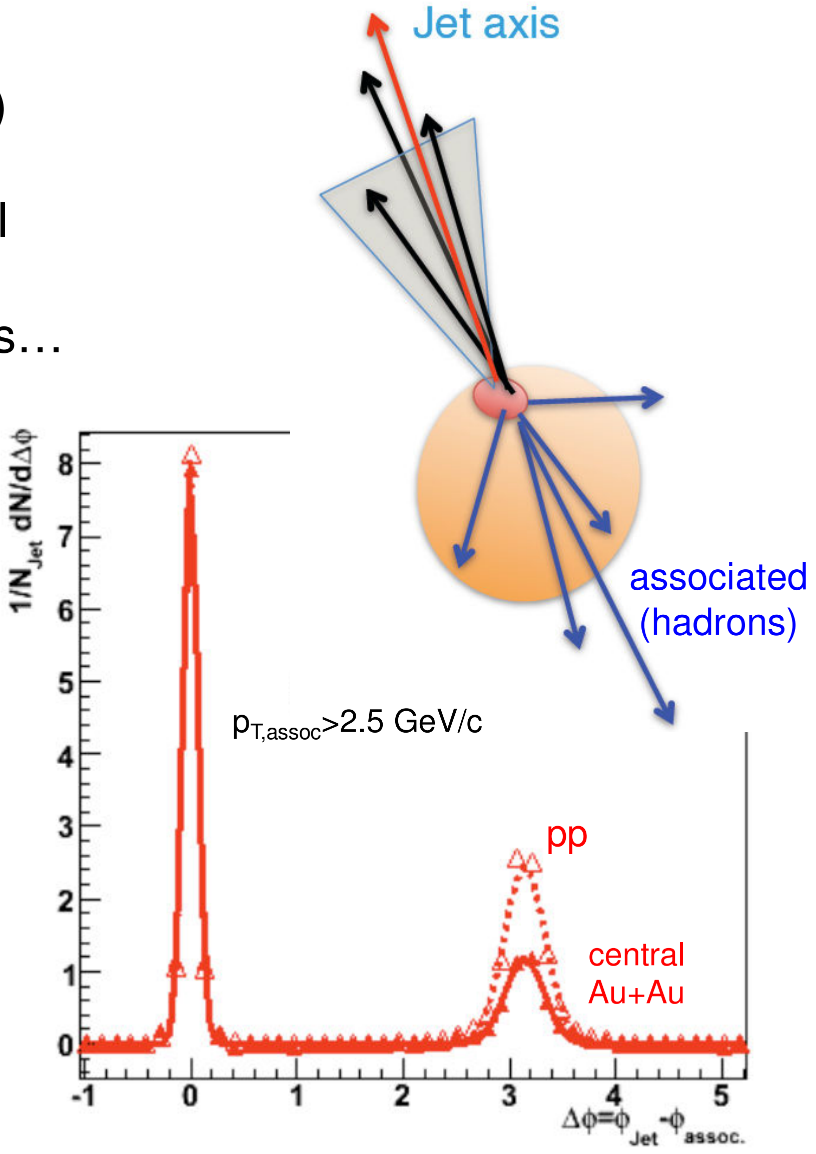


News from June 2009:
Maybe an artifact of over-subtracting the underlying v2 modulation (elliptical flow)

Jet-hadron versus hadron-hadron azimuthal correlations

Recent progress: jets were fully reconstructed in heavy-ion collisions, replacing the (“jet-like”) high-pT leading hadrons.
The jet-hadron azimuthal distribution in central collisions shows a narrower peak than the di-hadron distribution; no double-peak appears…





The signal is only as good as our understanding of the backgrounds, references…

Today’s take-home messages

Experimental studies of high-energy heavy-ion collisions are very difficult and often must be redone after significant improvements (resolutions, acceptances, signal to background ratios, efficiencies, etc)

It is *dangerous* to derive a small signal by subtracting many “negligible” backgrounds

Between “what you see” and “what you get”, you need some “common sense”…
and the common sense changes with time and “reference frame”

“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...