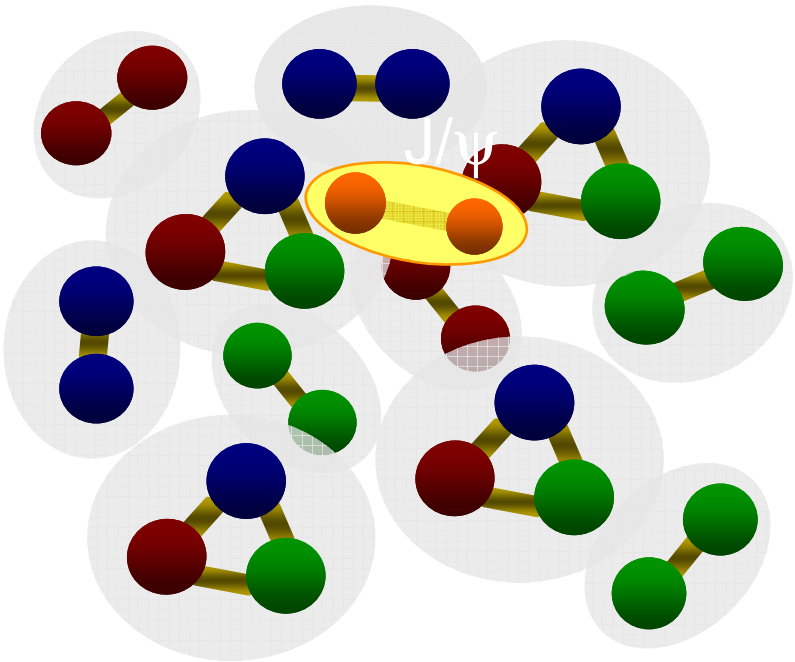
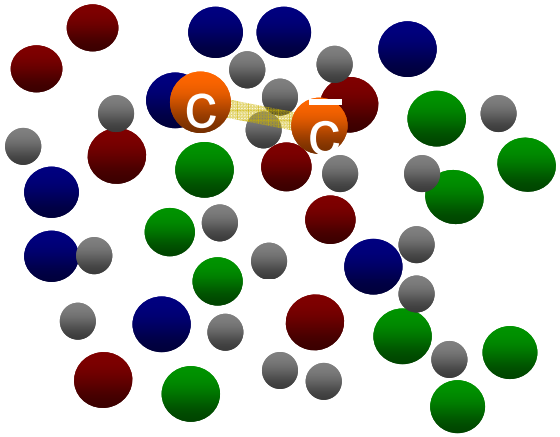
From High-Energy Heavy-Ion Collisions to Quark Matter

Lecture 3:

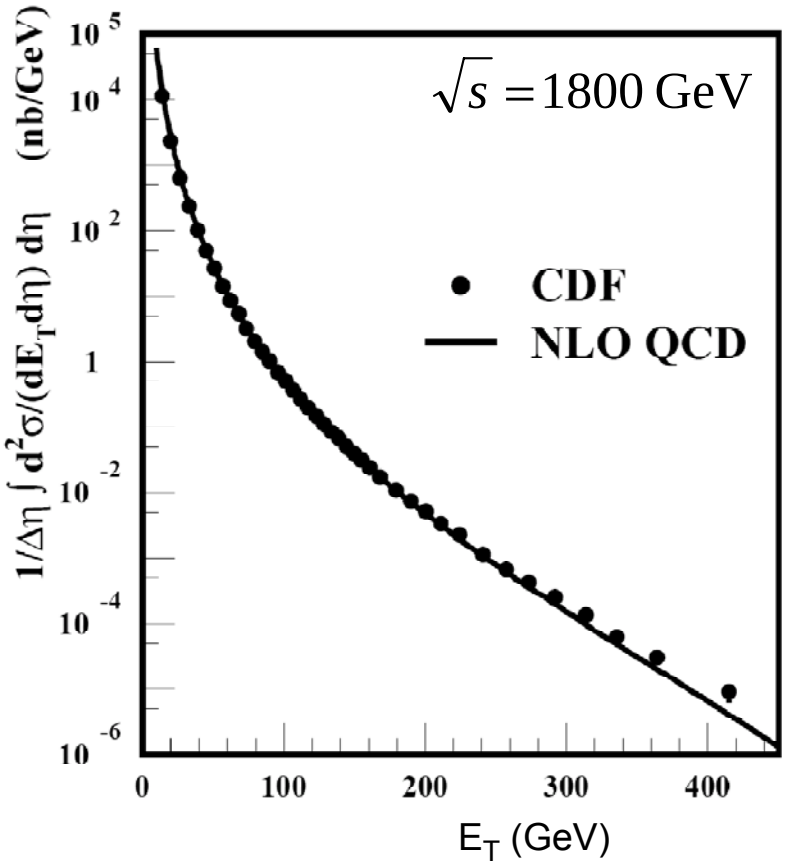
Past anomalies, today's work, future hopes



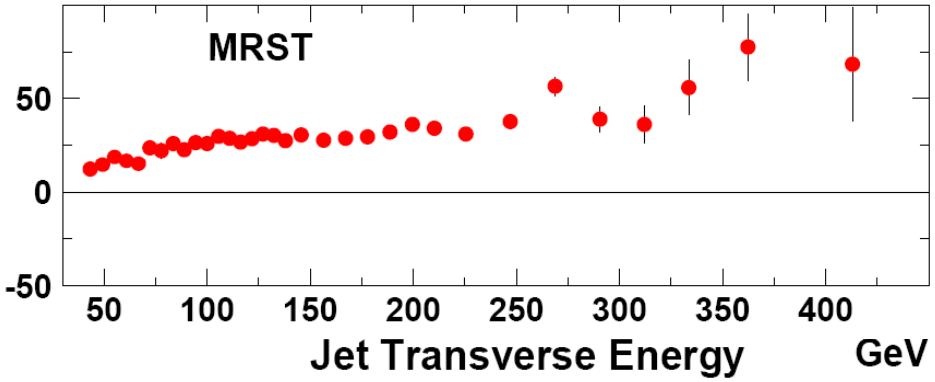


A “new physics” signal or a “not yet good enough” reference?

Some years ago CDF measured jet production in proton-antiproton collisions and compared the data to perturbative QCD calculations.
The data points seem to agree very well with the calculation…



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



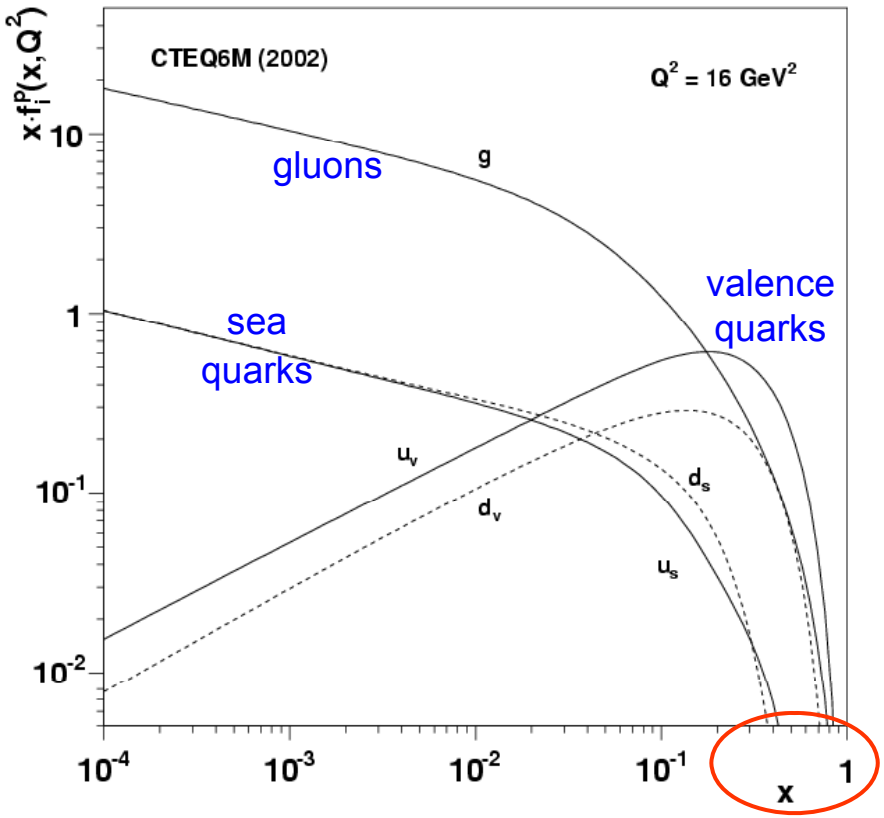
Is this “high E_T excess” a signal of *quark compositeness* ?

Reminder: what are the protons made of ?

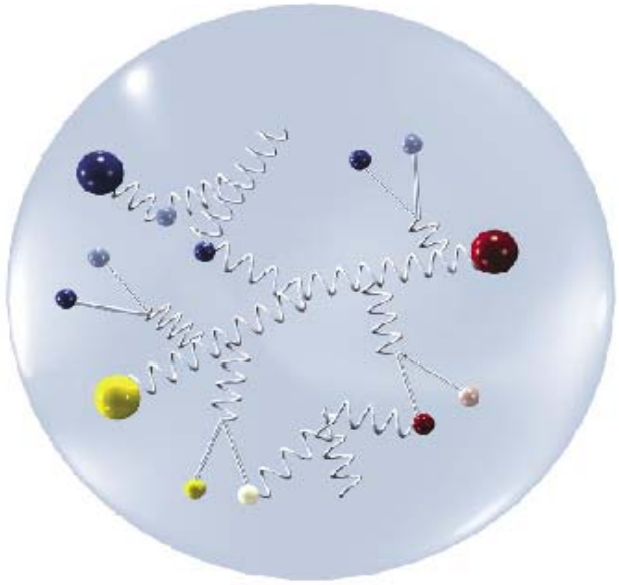
pQCD calculates *partonic processes*, like qq → qq, qg → qg, gg → gg

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)**



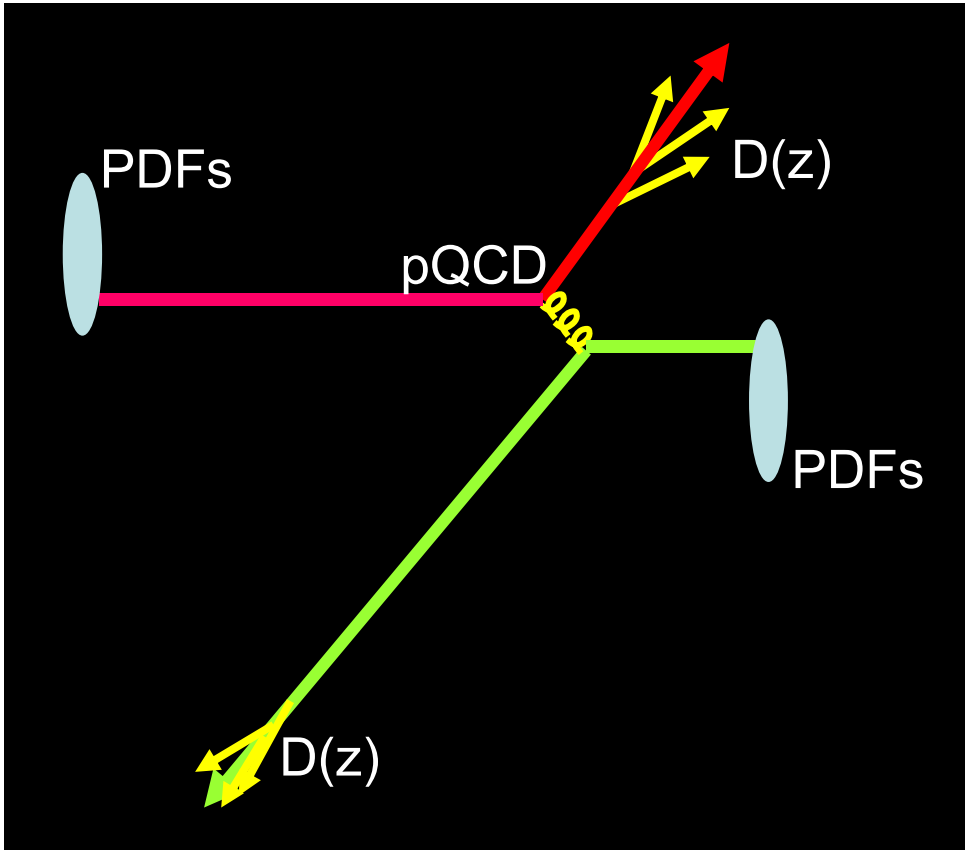
parton distribution functions, PDFs



From hadrons to partons… and back

People operate *particle* detectors, not parton detectors...
To get hadron spectra, we need to convolute the hard interaction with (initial state) parton densities and (final state) fragmentation functions, which define how the quarks and gluons hadronise.

The PDFs and the fragmentation functions are (supposed to be) the same for all processes.



$$\frac{d\sigma_{pp}^{h}}{dyd^{2}p_{T}} = K\sum_{abcd}\int dx_{a}dx_{b}\, f_{a}(x_{a},Q^{2})\, f_{b}(x_{b},Q^{2})\,\frac{d\sigma}{d\hat{t}}(ab\rightarrow cd)\,\frac{D_{h/c}^{0}}{\pi z_{c}}$$

hadrons (measurement)

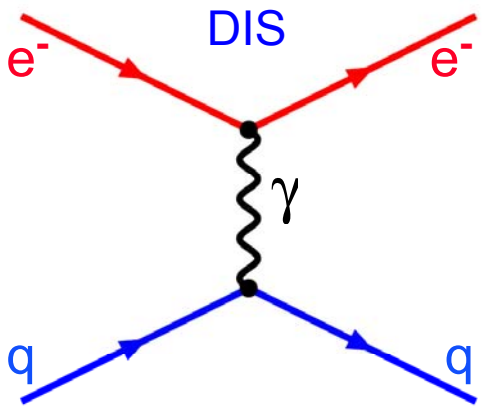
partons (calculation)

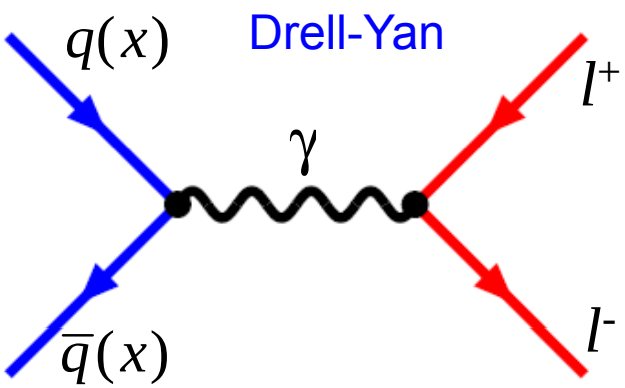
Hard Scatter Calculation

Parton Density Functions

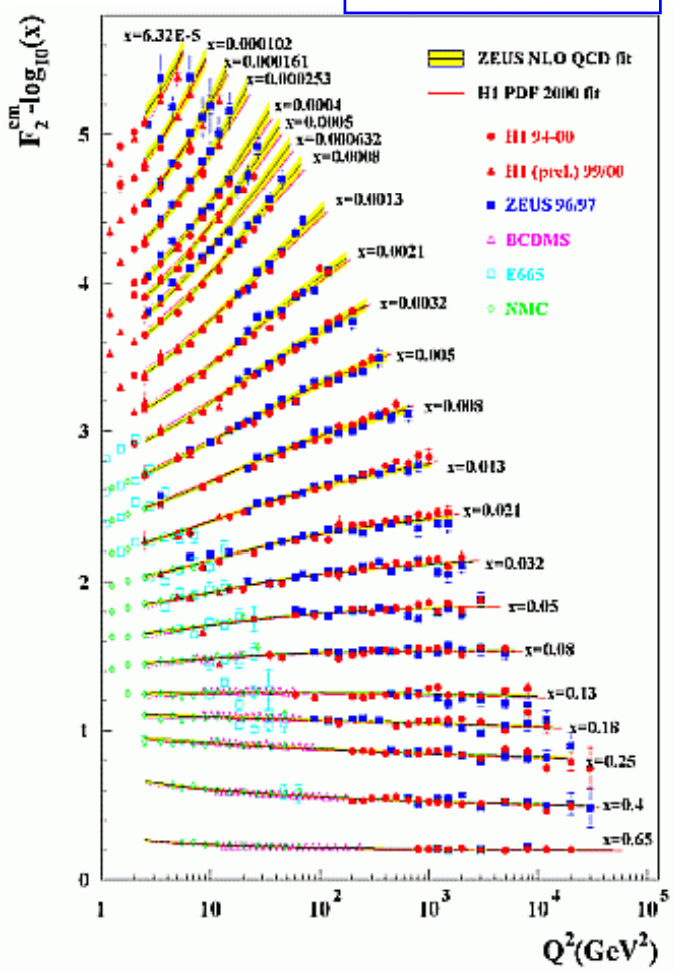
Cross Section Calculation

Measurement





5 experiments



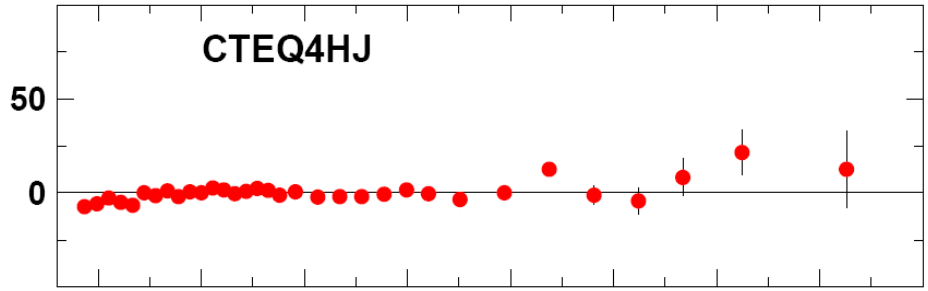
New data ⇒ new PDFs ⇒ improved reference

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

The results from each experiment go into a *global fit*
Not all measurements 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**

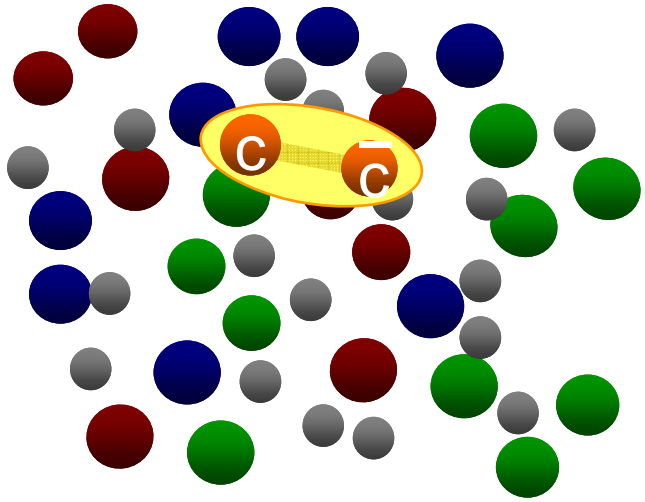
New Parton Distribution Functions were fitted, *including the CDF data*

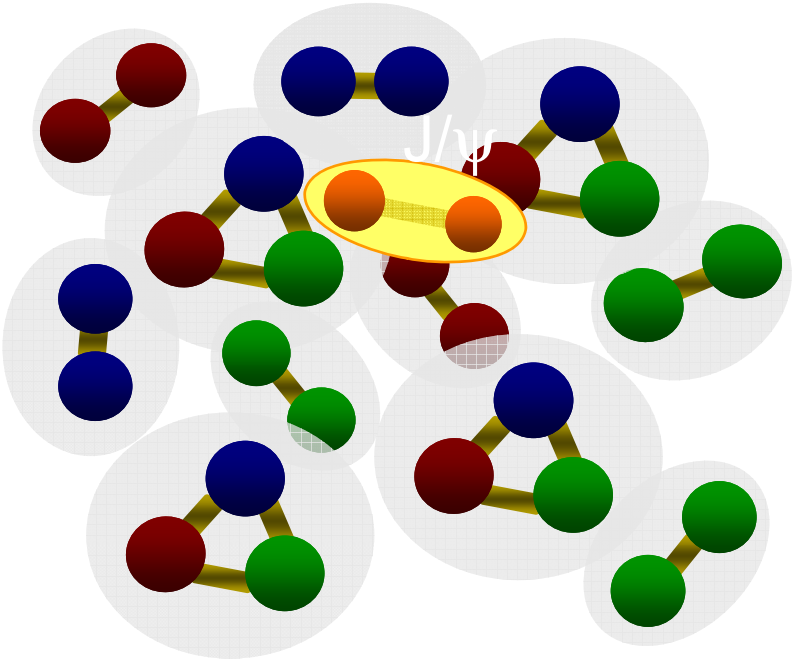


The measurement is the same but the "excess" is gone, using the new reference
Important lesson: the "new physics signal" was due to a wrong reference

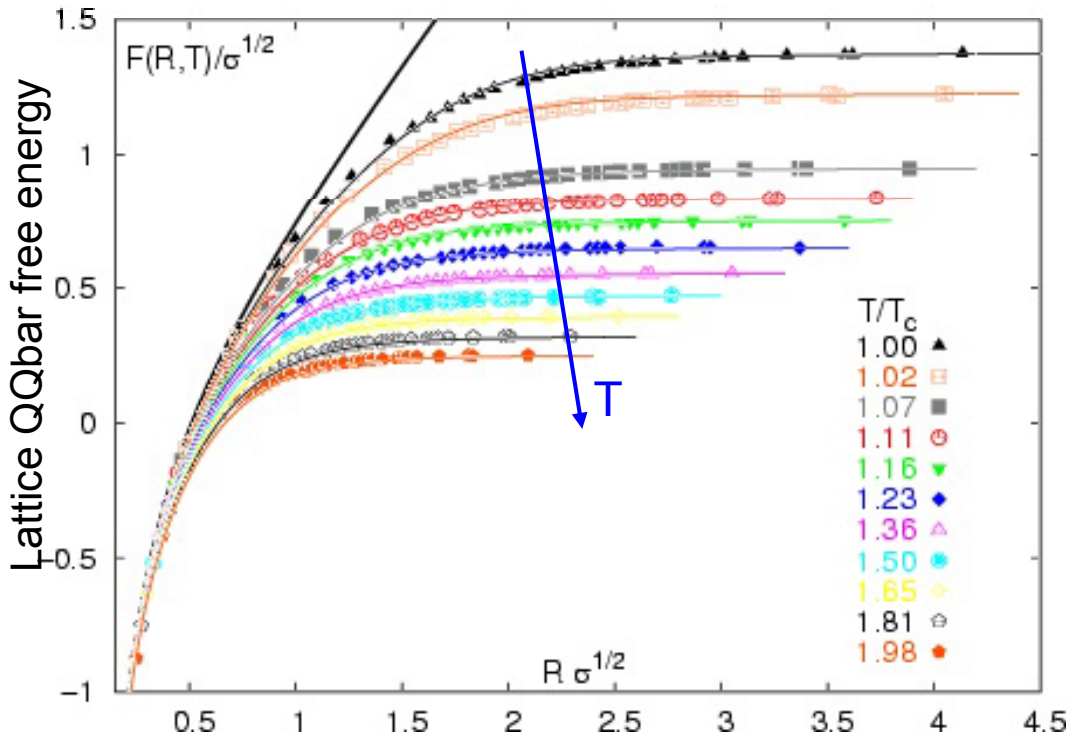
Quarkonia melting: a clean signal of QGP formation

In a deconfined medium, the QCD potential is screened and the heavy quarkonium states are "dissolved" into open charm or beauty mesons



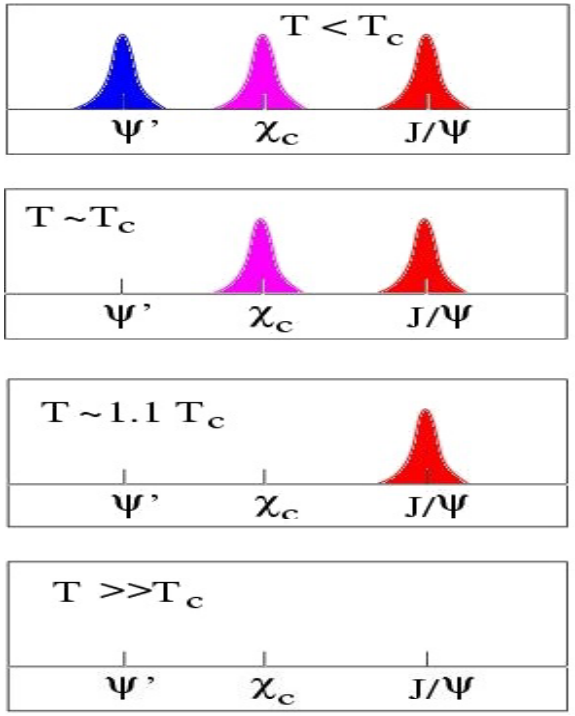


Charmonium melting should be easy to see experimentally, as a strong suppression of the J/ψ and ψ' production yields

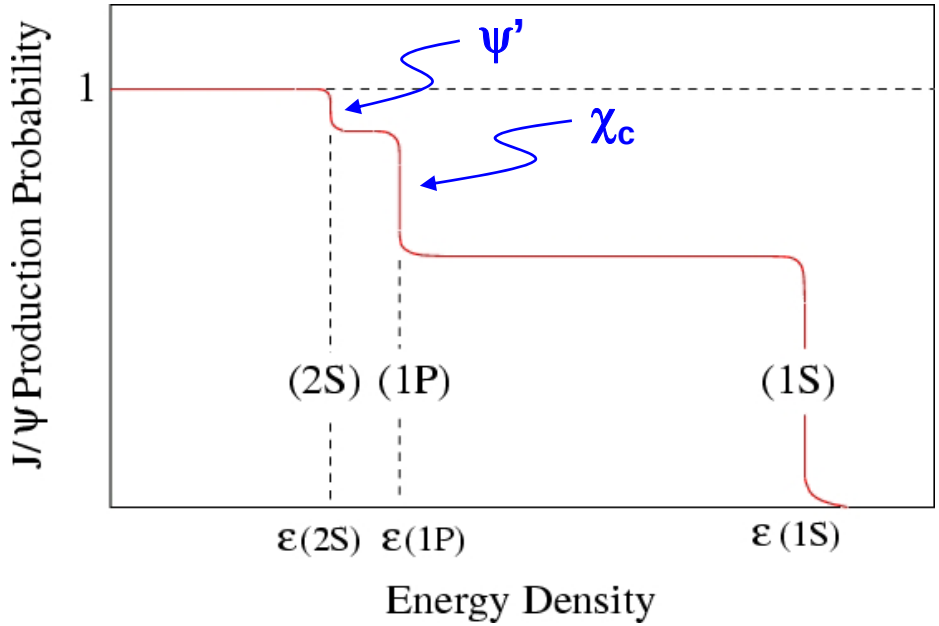


Quarkonia melting probes the QGP temperature

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



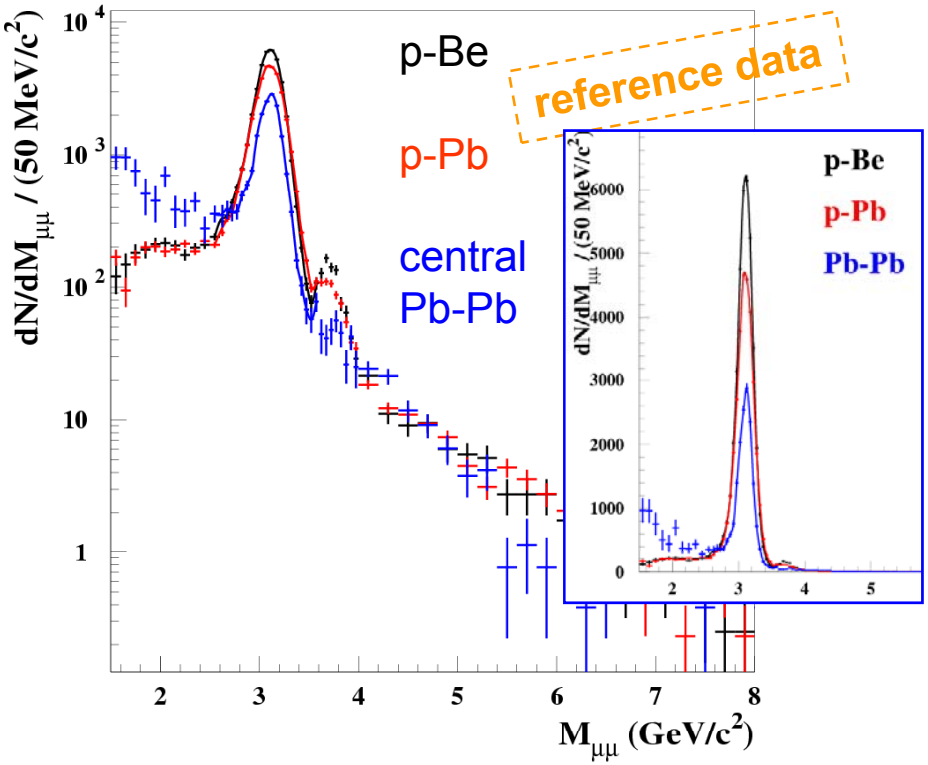
The feed-down from higher states leads to a *"step-wise"* J/ψ suppression pattern

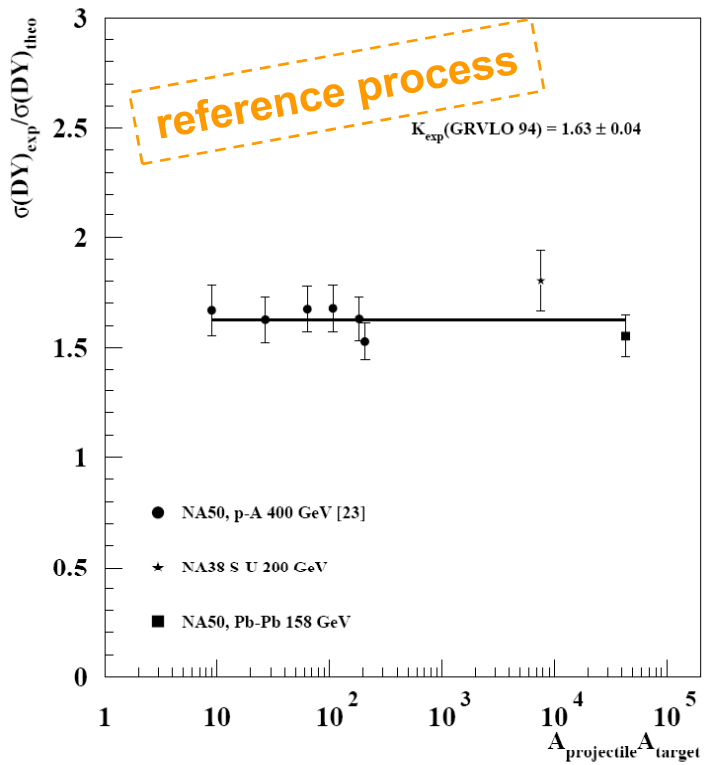


<u>J/ψ cocktail:</u> ~ 65% direct J/ψ ; ~ 25% from χ_c decays ; ~ 10% from ψ' decays

Bottom line : thresholds → steps → a QGP "smoking gun signature"

J/ψ suppression in S-U and Pb-Pb collisions (NA38+NA50)



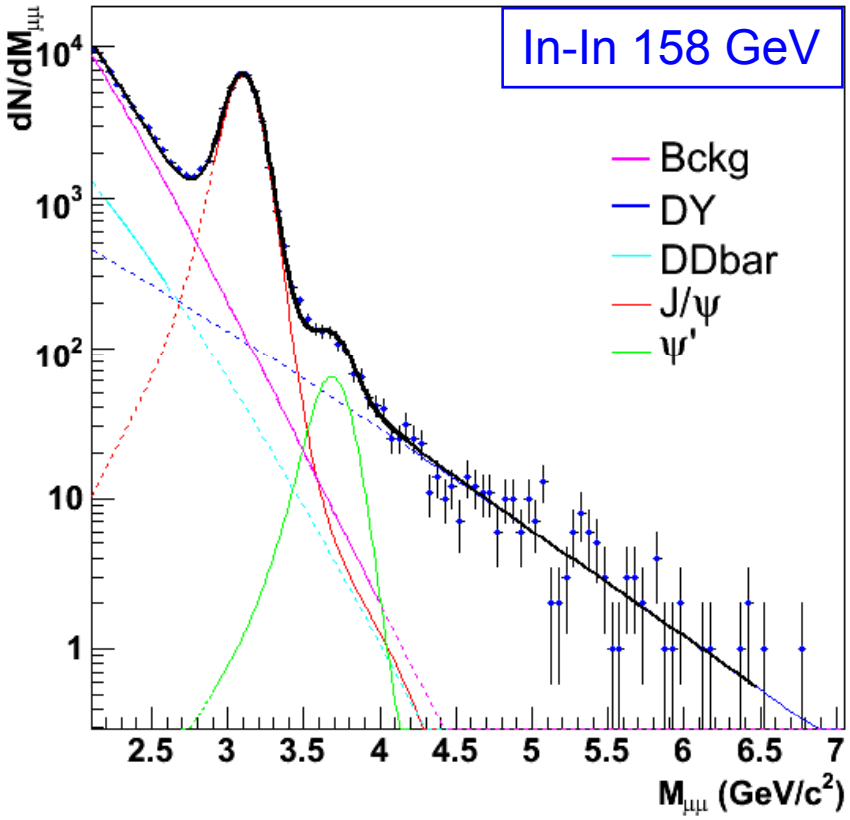


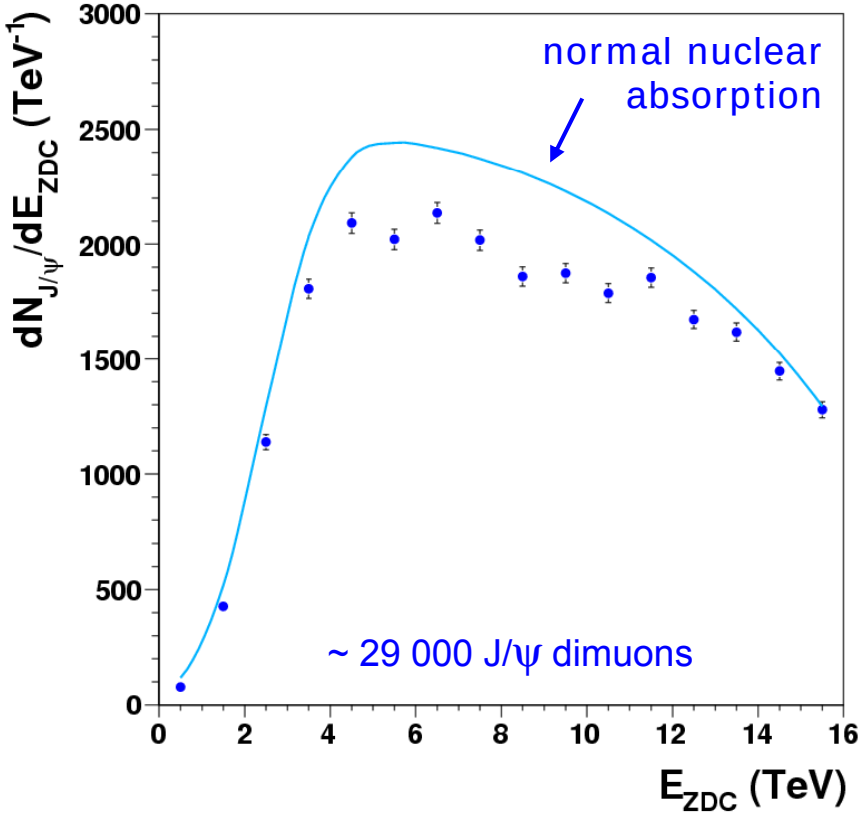
The yield of J/ψ mesons (per DY dimuon) is "slightly smaller" in p-Pb collisions than in p-Be collisions; and is ***strongly*** suppressed in central Pb-Pb collisions

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

<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

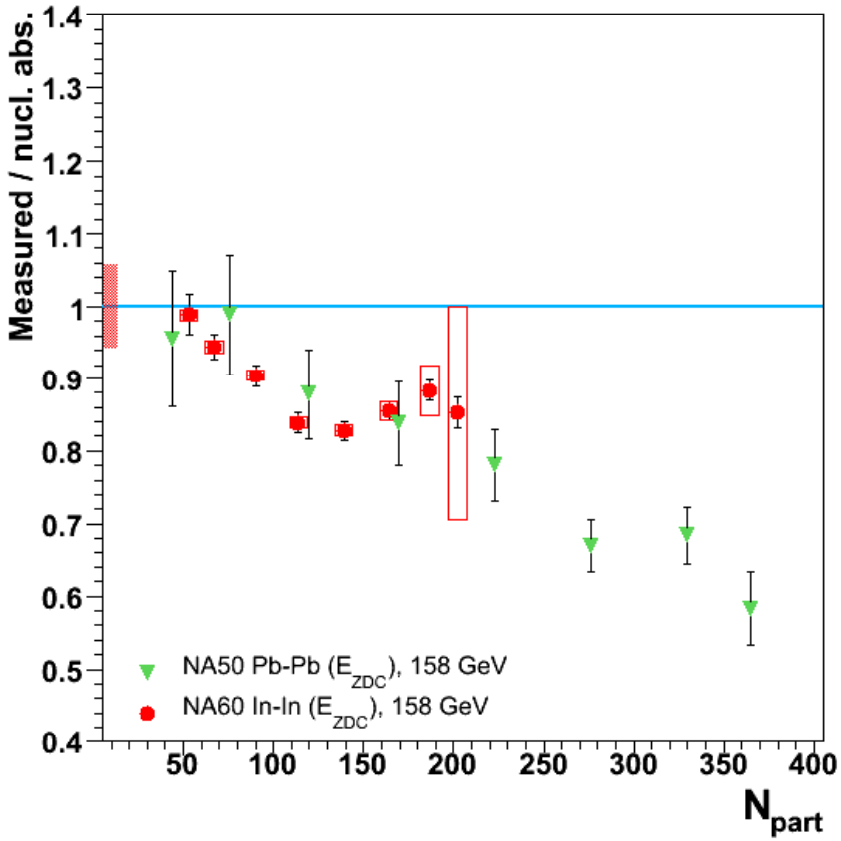
J/ψ suppression in In-In collisions (NA60)

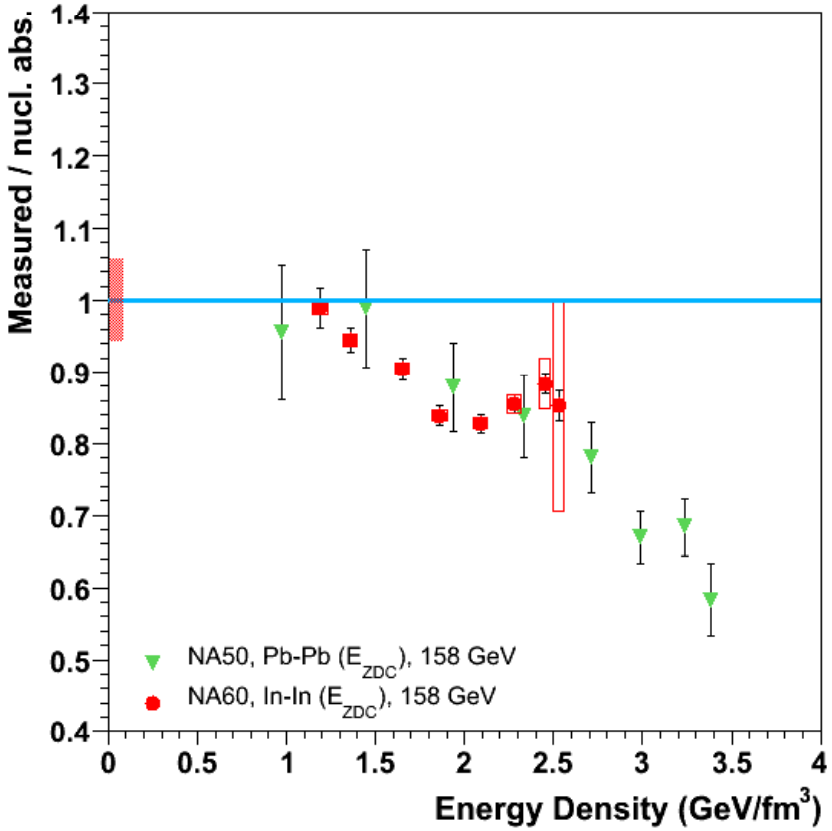




NA60 collected less J/ψ events in In-In than NA50 in Pb-Pb but the accuracy of the pixel vertex tracker allows us to directly compare the measured yields to the *normal nuclear absorption* curve, derived from the p-nucleus data with the "Glauber model", without using the Drell-Yan reference (very limited in statistics)

J/ψ suppression: In-In versus Pb-Pb patterns

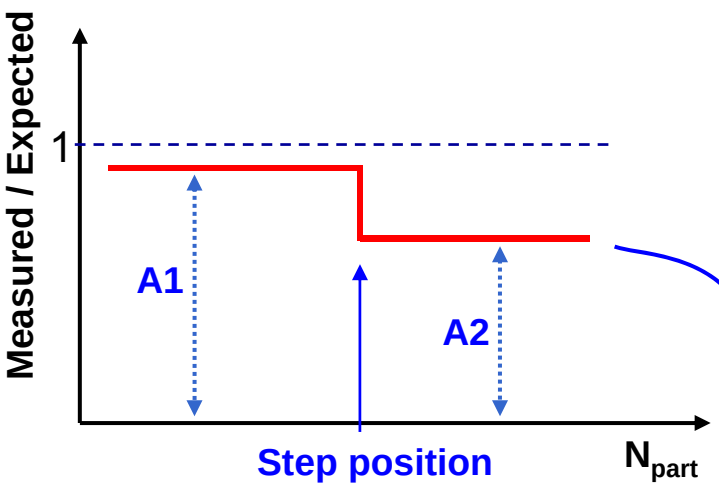


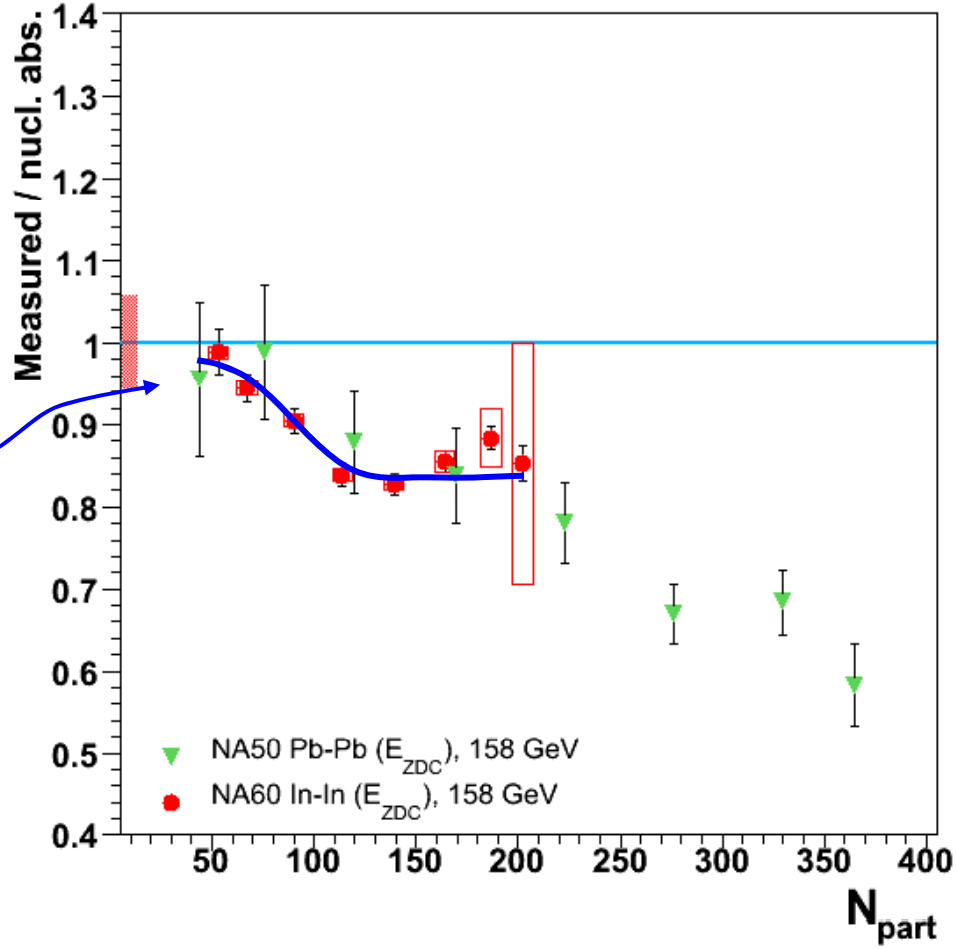


The Pb-Pb and In-In suppression patterns overlap in N_{part} or energy density; the statistical accuracy of the In-In points is very good

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

The In-In J/ψ suppression pattern versus a step function





Step at N_{part} = 86 ± 8

A1 = 0.98 ± 0.02

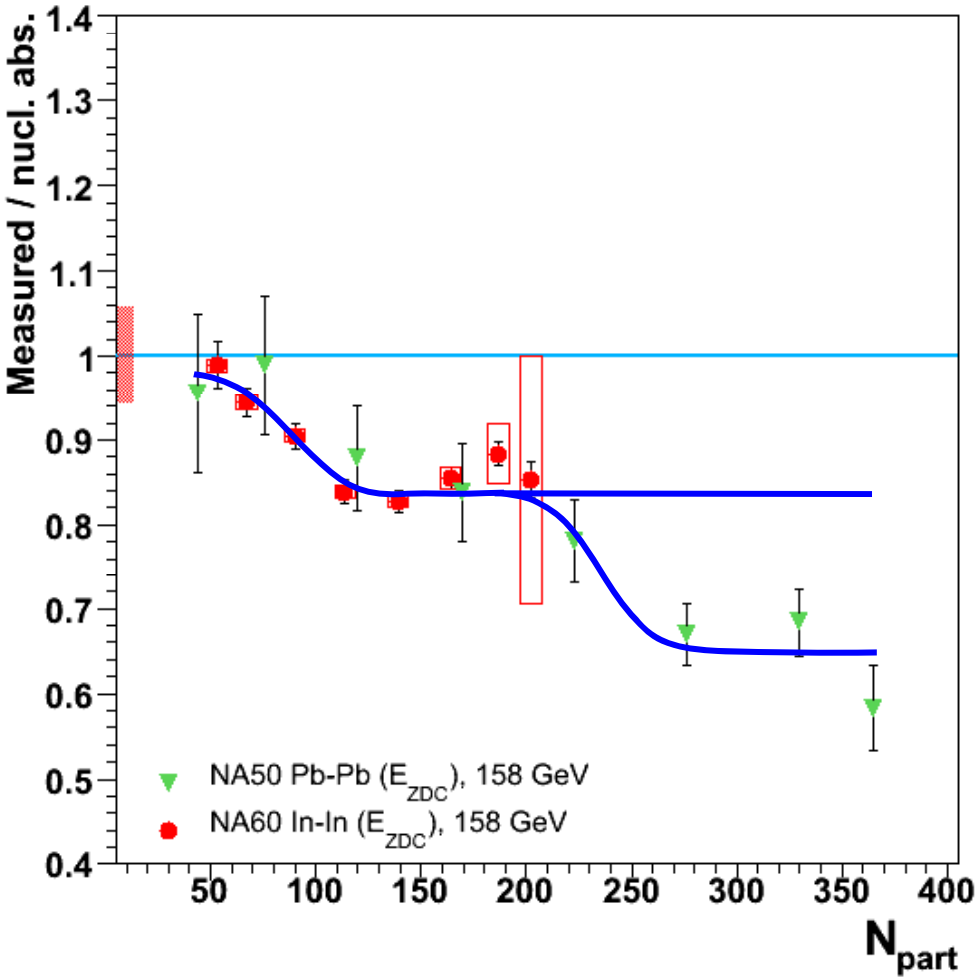
A2 = 0.84 ± 0.01

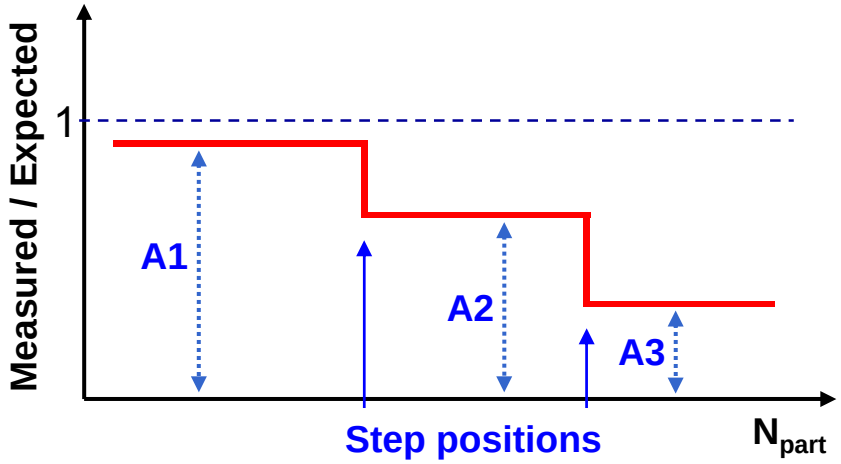
χ^2/ndf = 0.75 (ndf = 8–3 = 5)

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

12% : ψ' !

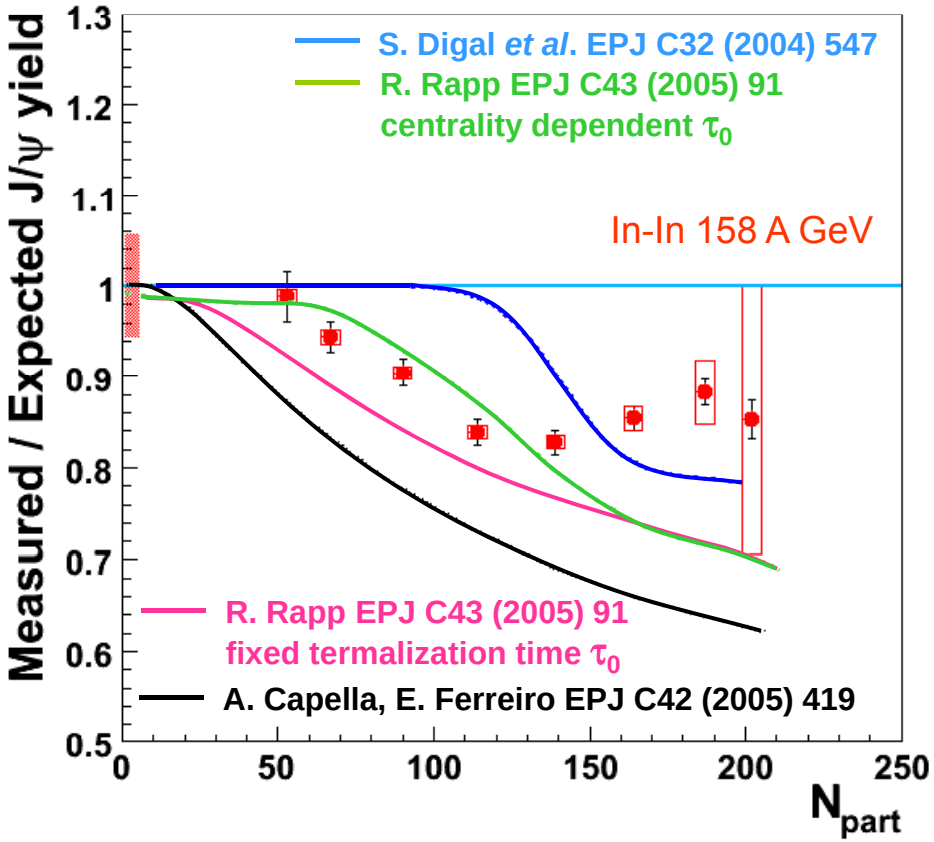
21% : χ_c !

χ^2/ndf = 0.72 (ndf = 16–5 = 11)

If we try fitting the In-In and Pb-Pb data with one single step we get χ^2/ndf = 5 !

⇒ the Pb-Pb pattern rules out the single-step function and indicates a second step

The In-In J/ψ suppression pattern versus non-QGP models



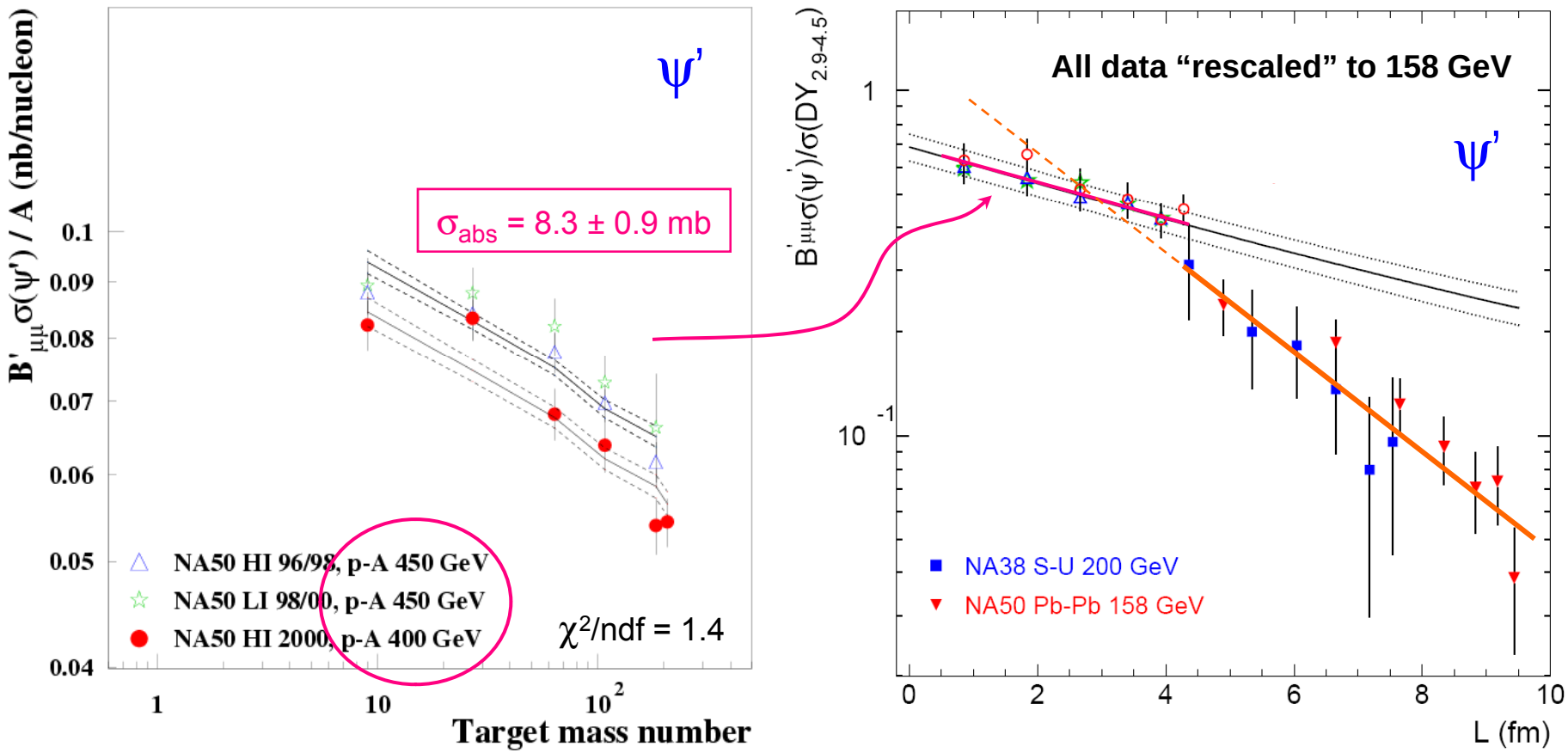
These models were "tuned" on the Pb-Pb pattern… but fail to describe the In-In suppression pattern...

<u>Exercise:</u>
calculate the χ^2/ndf for each of these curves (ndf = 8)

The In-In data sample was taken at the same energy as the Pb-Pb data... to minimise the "freedom" of the theoretical calculations ☺

What about the ψ' suppression pattern?

The ψ' suppression in Pb-Pb collisions (at 158 GeV) is <u>significantly stronger</u> than expected on the basis of the absorption observed in p-A data (at 400–450 GeV)



Is the abrupt "change of slope" due to the formation of the QGP state ? ☺
or due to an increase of σ_{abs} between 450 and 158 GeV ? ☹

“Anomalous suppression” vs. “normal nuclear absorption”

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
→ we have a “signature”

Above certain *consecutive thresholds*, the ψ', the χ_c and the J/ψ resonances (and the Upsilon states) will “dissolve” in the formed medium
→ we have a “smoking gun”...

However, already in *p-nucleus* collisions the charmonium states are *absorbed* by “cold nuclear matter effects”
⇒ This “normal absorption” must be well understood before *convincing evidence* of colour deconfinement can be derived from the J/ψ and ψ' *nucleus-nucleus* data

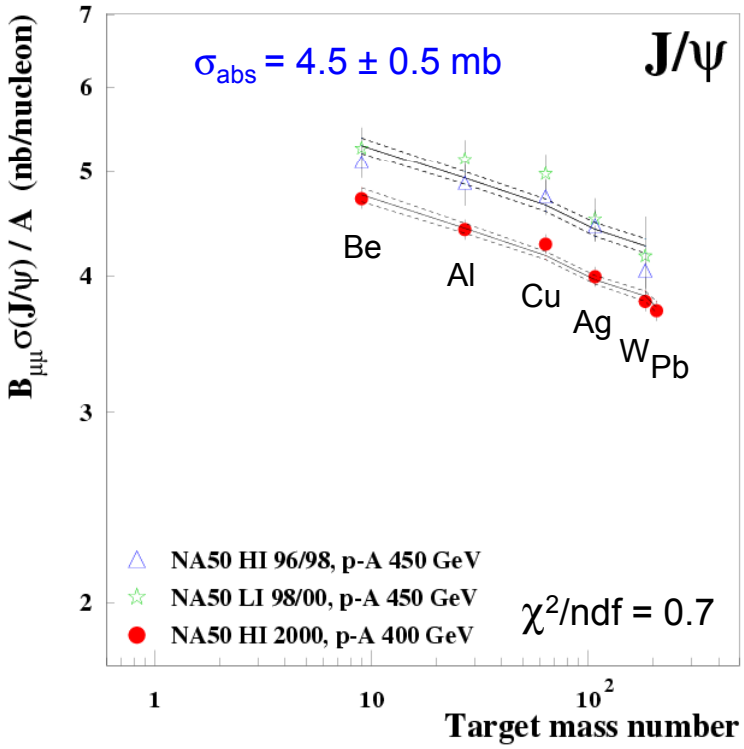
Could the charmonium suppression be due to a wrongly determined reference?
Recall the high E_T “excess” seen by CDF…

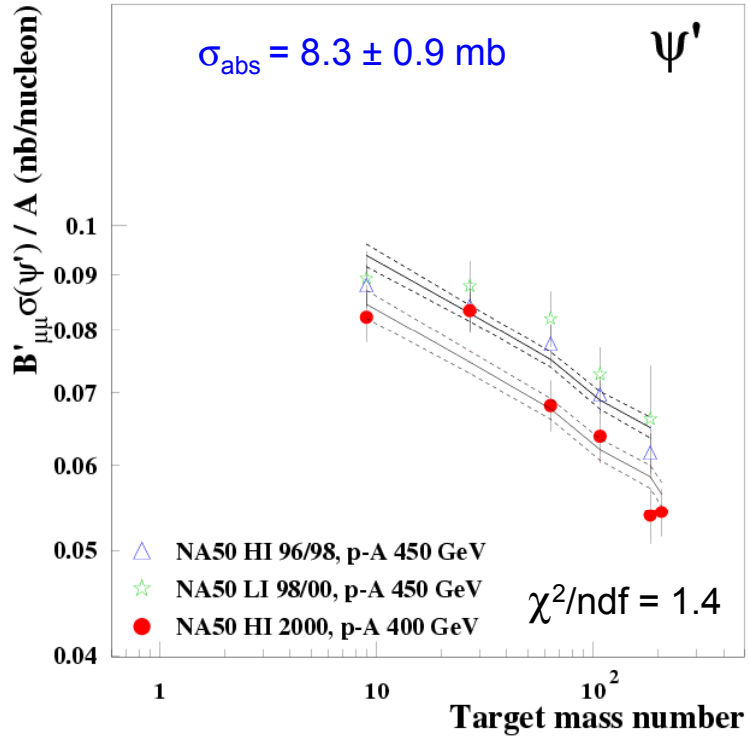
We must carefully review the determination of the “normal nuclear absorption” and look for possible problems…

“What gets you into trouble is not what you don’t know…
but what *you think* you know” Mark Twain

The “normal nuclear absorption” revisited

The J/ψ and ψ’ production cross sections scale less than linearly with the number of target nucleons. The “Glauber model” describes the “normal nuclear absorption” with a single parameter, the absorption cross section: σ_{abs}

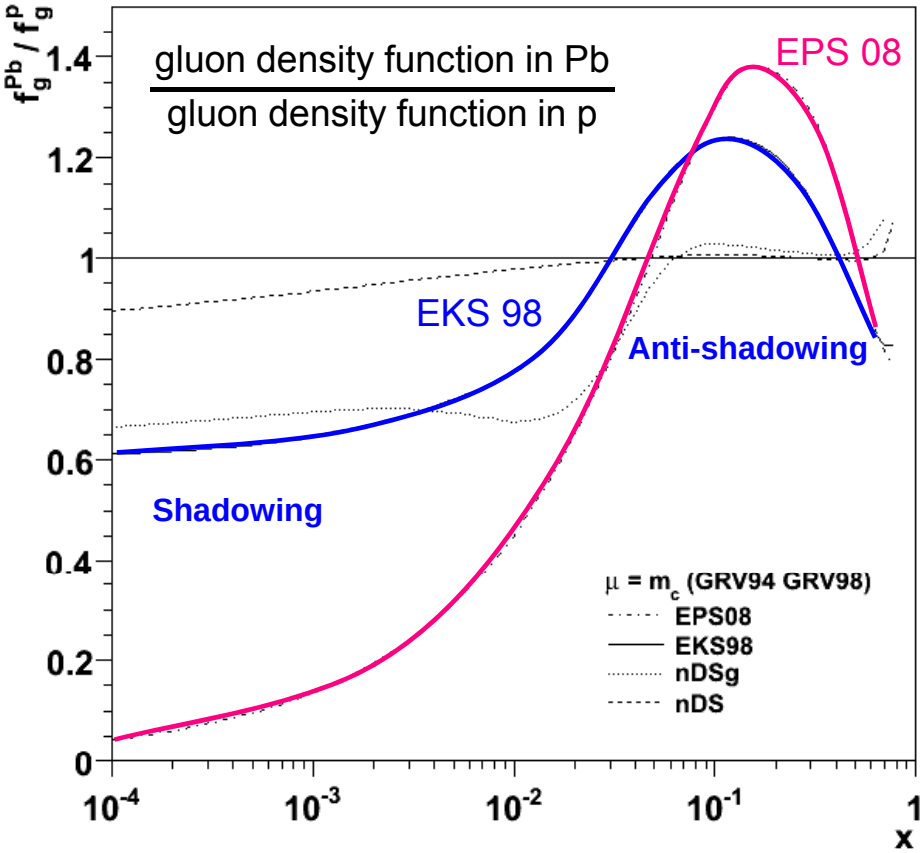


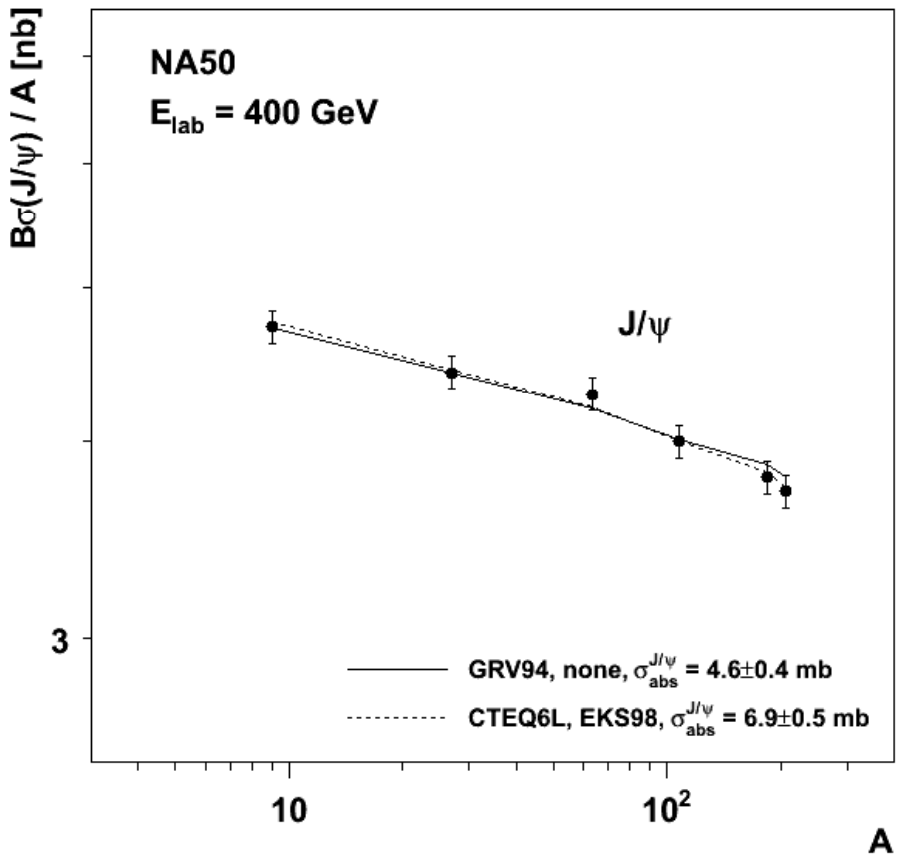


The NA50 calculations neglect the nuclear effects on the PDFs and the feed-down sources of J/ψ’s from χ_c and ψ’ decays; and assume that σ_{abs} does not change with collision energy or kinematics, besides a few other assumptions…

Nuclear PDFs versus charmonium nuclear absorption

The probability of finding a gluon in a proton changes when the proton is inside a nucleus; these nuclear effects can be calculated, by "EKS98" and other models

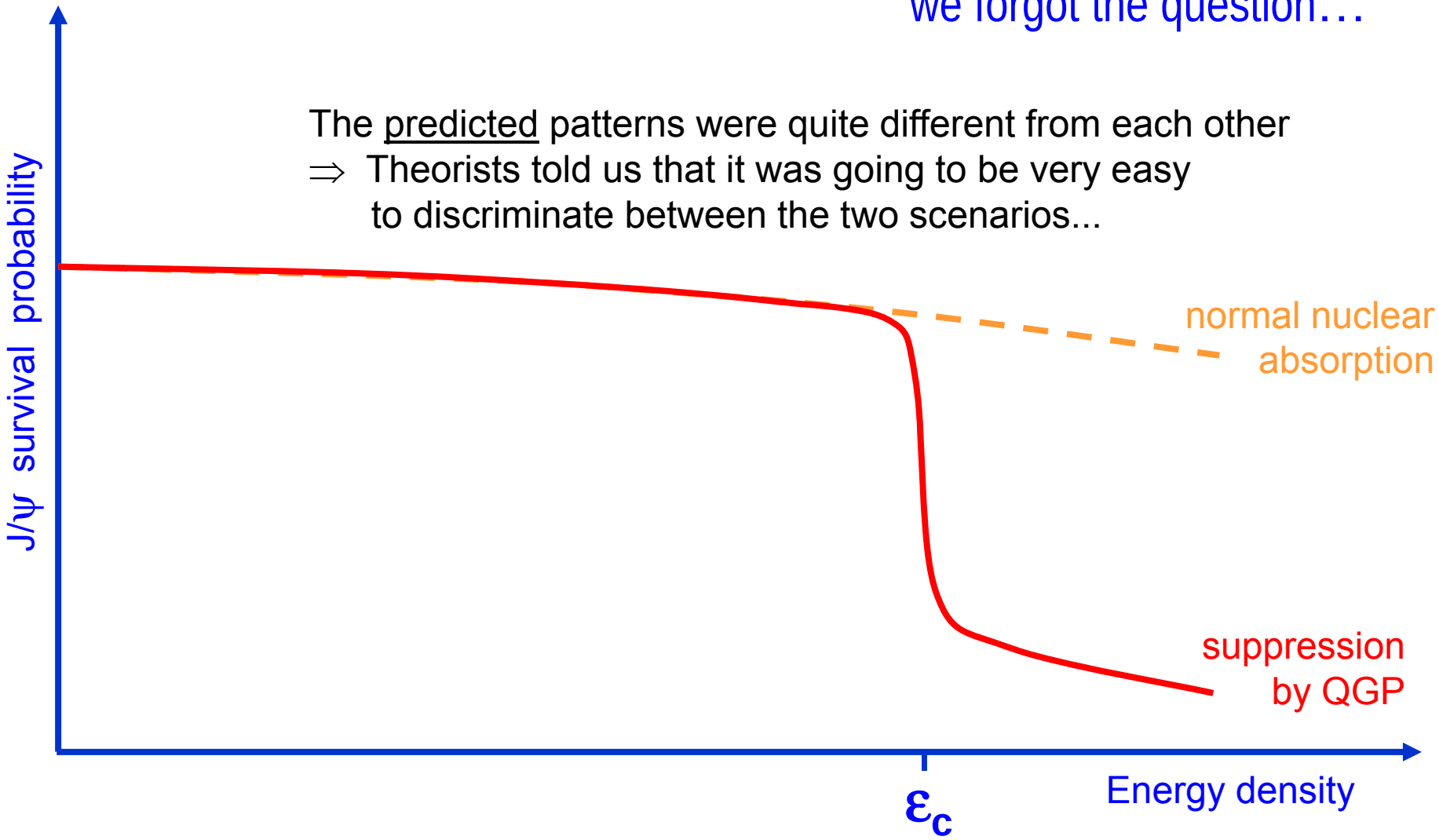




When we consider EKS98 N-PDFs, σ_{abs} changes from 4.6±0.5 mb to 6.9±0.5 mb
There is also significant evidence that σ_{abs} changes with energy, p_T and rapidity…

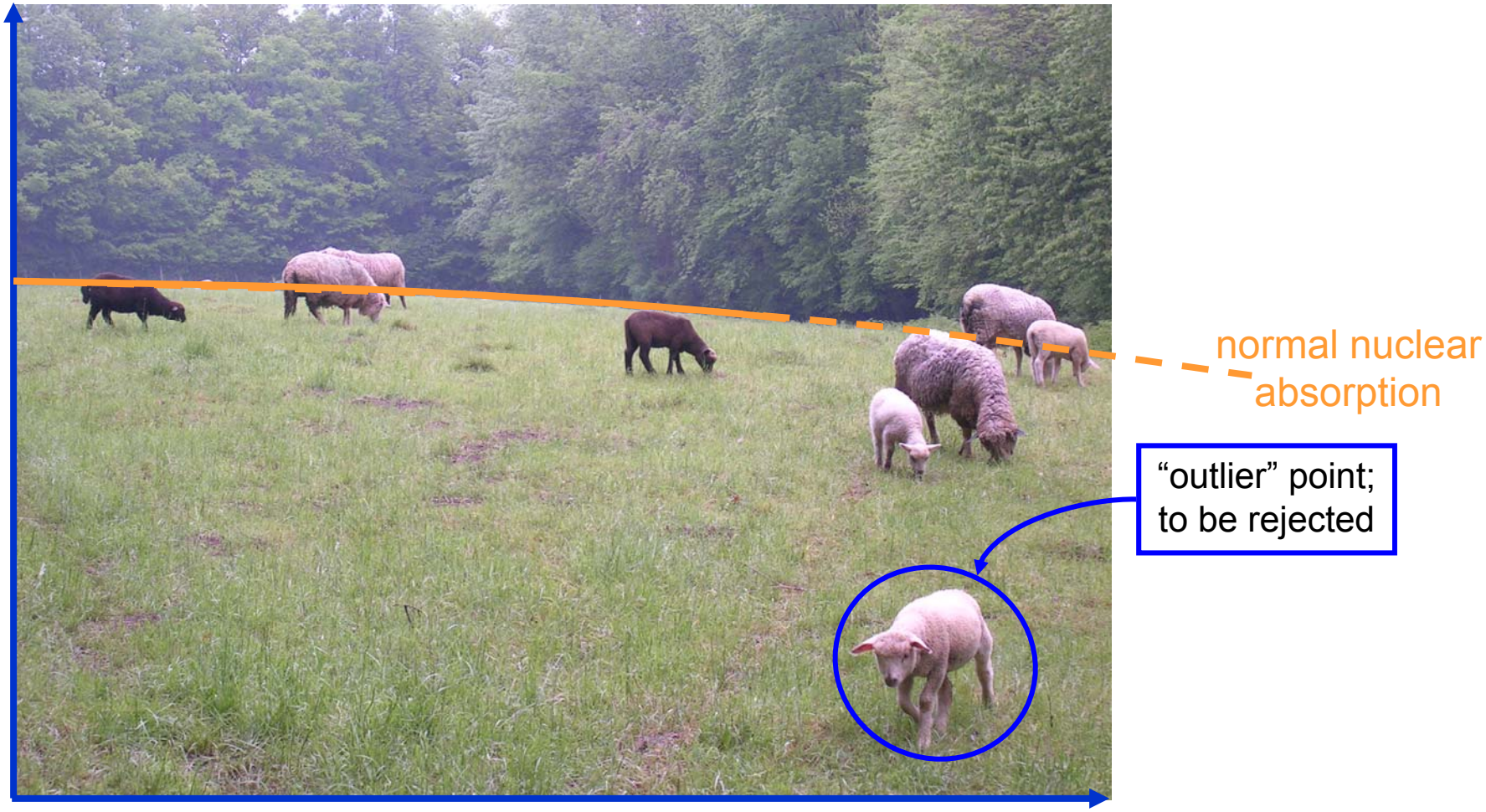
Just when we were about to find the answer…
we forgot the question…

The predicted patterns were quite different from each other
⇒ Theorists told us that it was going to be very easy
to discriminate between the two scenarios...

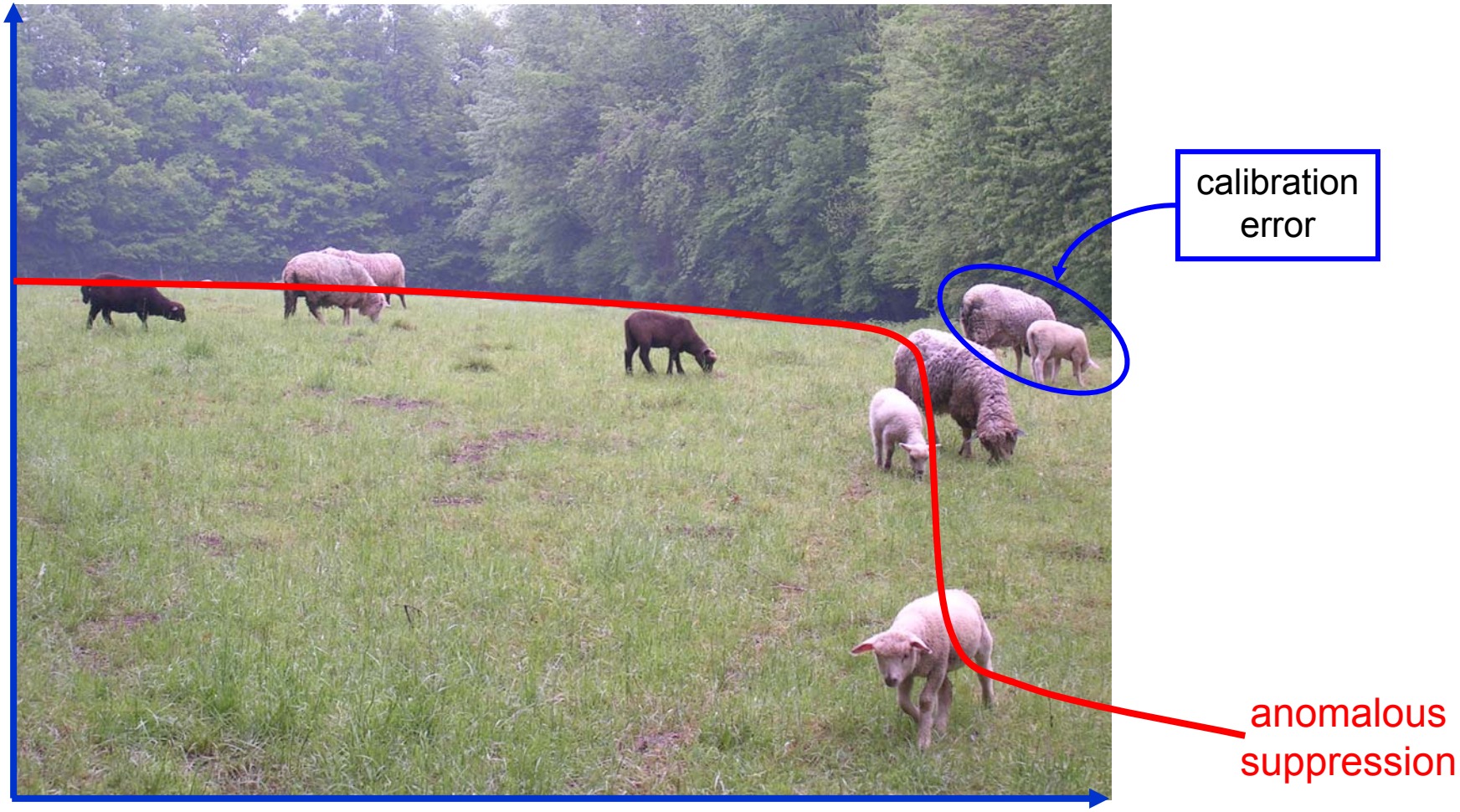


We made measurements, to rule out one of these two scenarios (or both)

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 lessons of the day…

1) 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 good"

2) "Nature never tells you when you are right, only when you are wrong"
Hence, you only learn something when the theory *fails* to describe the data...
[Bacon, Popper, Bo Andersson]

3) *Before the measurements are made*, theorists often say that
the interpretation of the data will be easy
→ Theorists are often wrong...
especially before the measurements are made...

The LHC: the next chapter in the QGP saga…

- AGS : 1986 – 1998 : up to Au-Au at $\sqrt{s}$ = 5 GeV

  ⇒ properties of the hadronic phase

- SPS : 1986 – 2003 : O, S, Pb and In beams ; $\sqrt{s}$ = 20 GeV

  J/ψ and ψ' (and χ_c ?) suppression ⇒ deconfinement

  ⇒ *compelling evidence* for a "new state of matter" with "QGP-like properties"

- RHIC : 2000 – ?? : Cu-Cu, Au-Au at $\sqrt{s}$ = 200 GeV

  parton energy loss (jet quenching)

  parton flow

  ⇒ *compelling evidence* for a strongly-coupled QGP ("the perfect fluid")

- LHC : 2009 – ?? : Pb-Pb at $\sqrt{s}$ = 5500 GeV

  jets, upsilons, charm, beauty, thermal photons

  precision spectroscopy

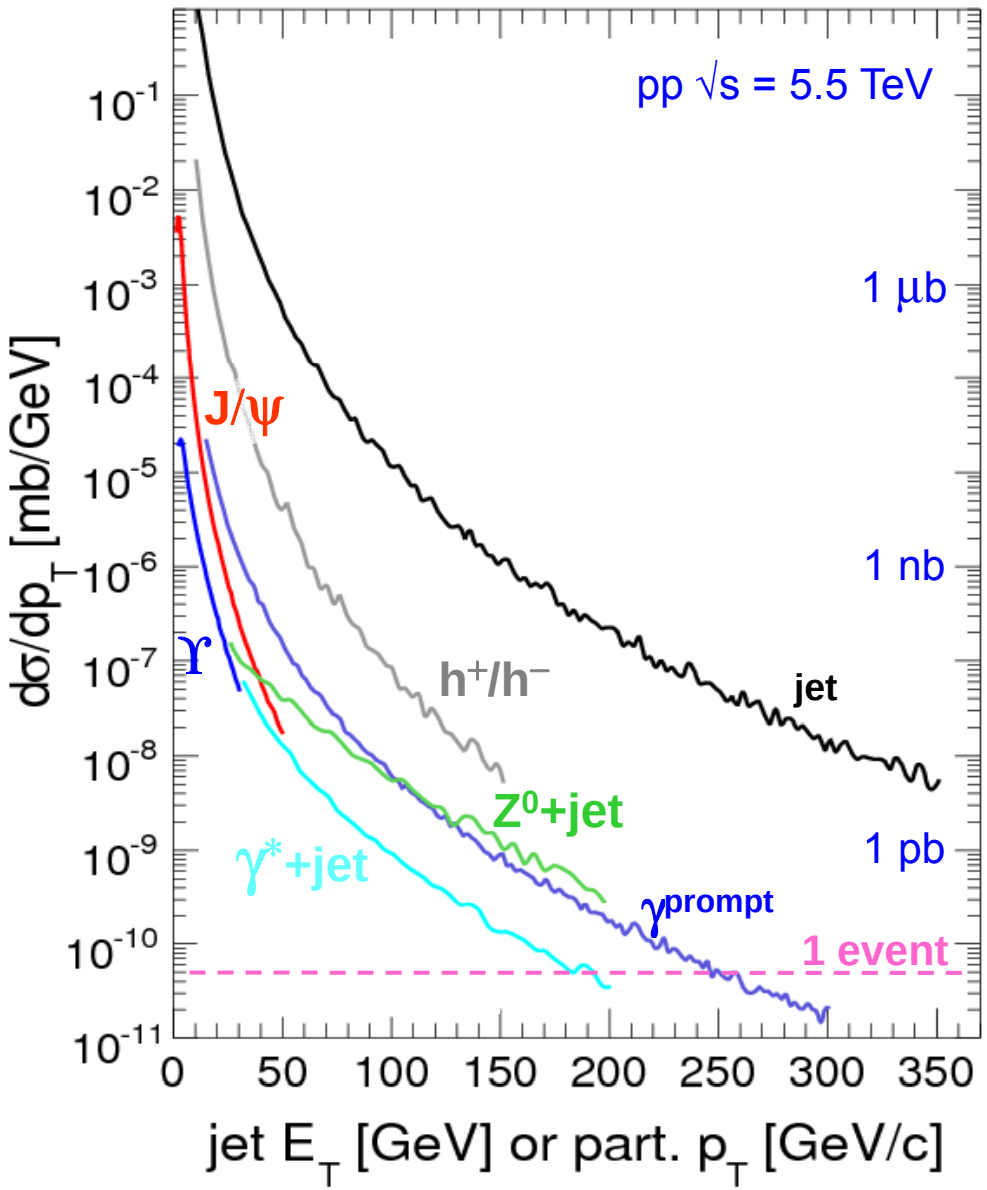
  ⇒ continue exploration of high-density QCD properties

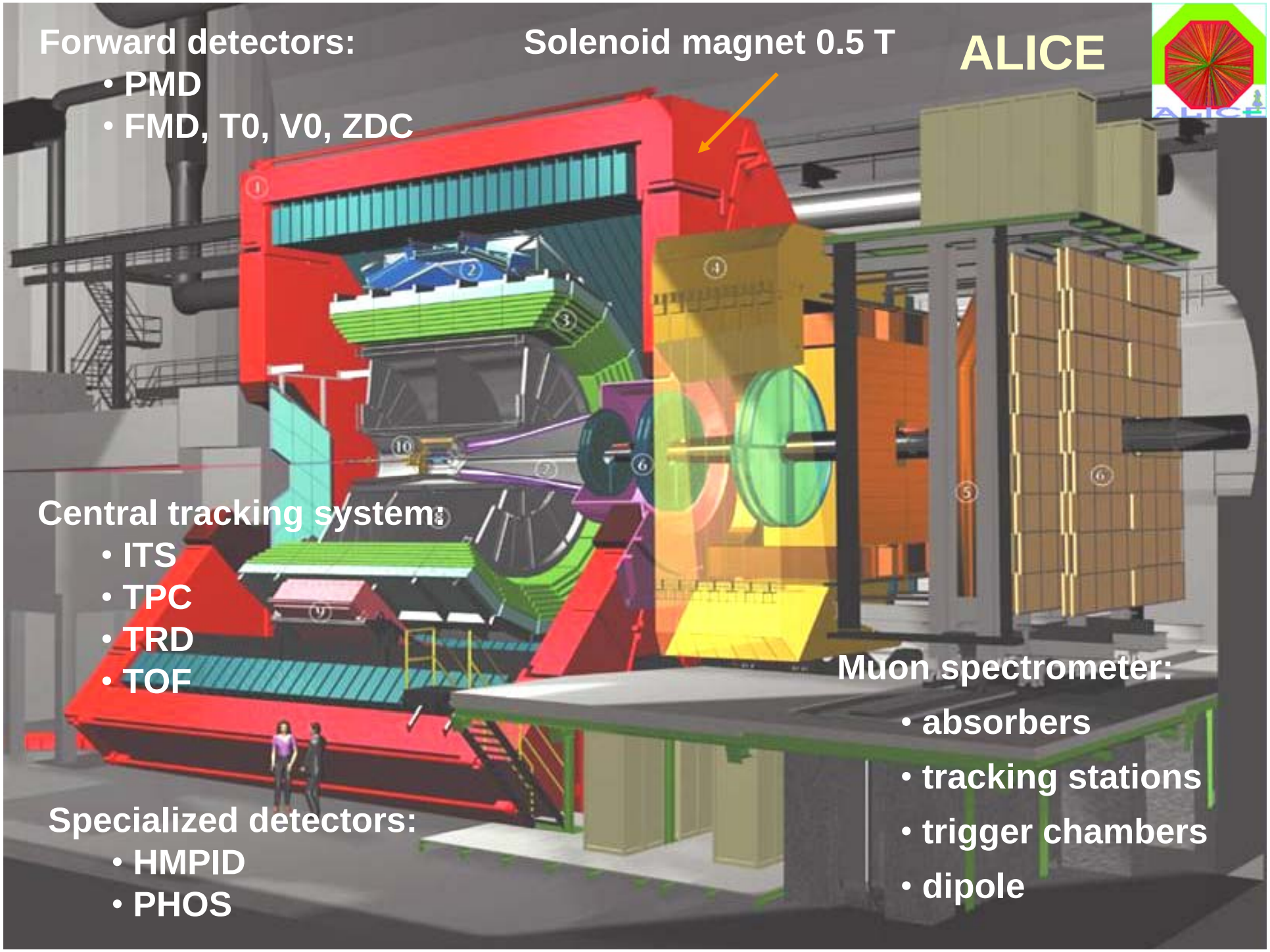
Hard Probes of QCD matter at LHC energies

- Very large cross sections at the LHC
- Pb-Pb instant. luminosity: 10^{27} $cm^{-2}s^{-1}$
- $\int L\,dt = 0.5\ nb^{-1}$ (1 month, 50% run eff.)
- Hard cross sections: Pb-Pb = A^2 x pp

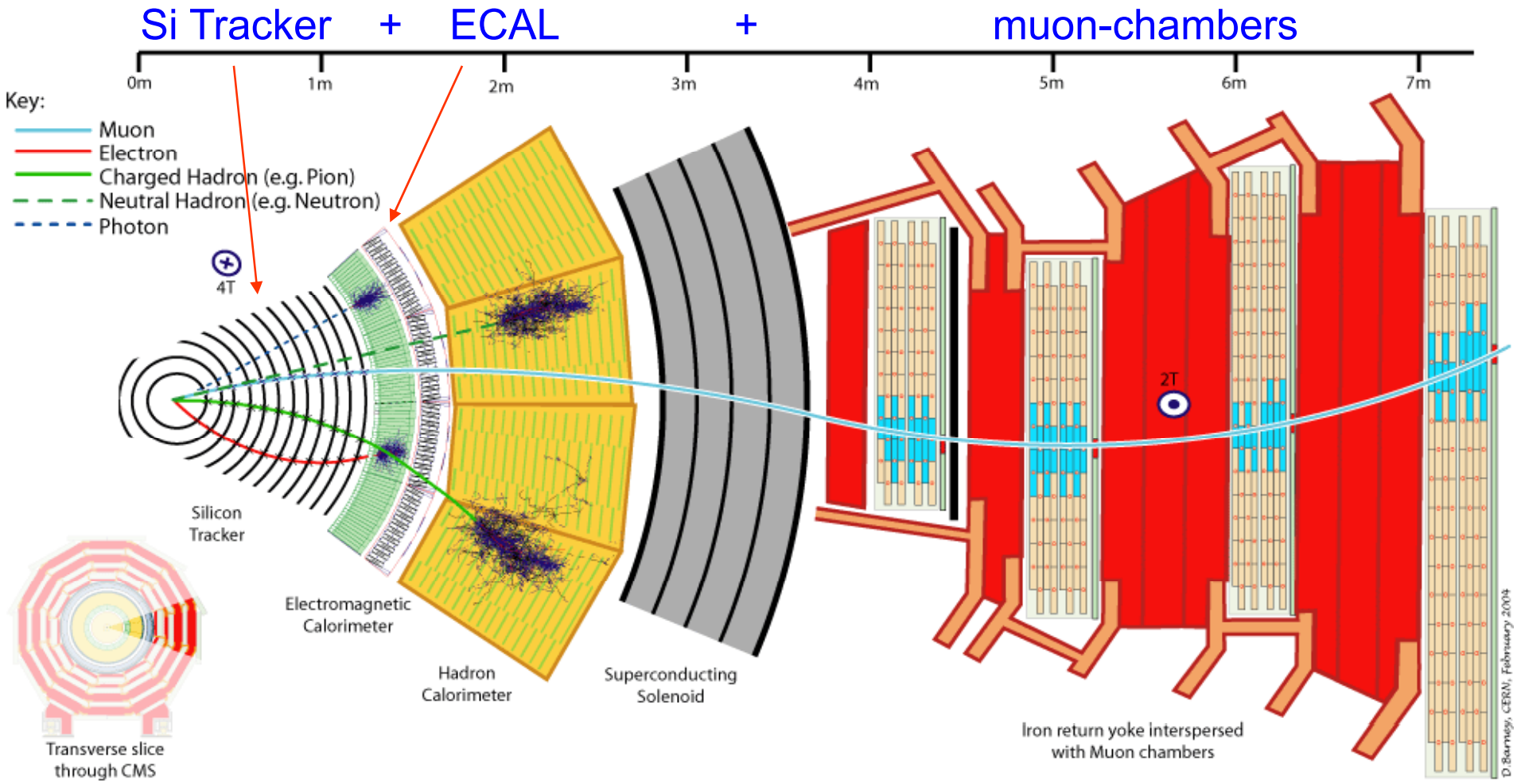
  ⇒ pp-equivalent $\int L\,dt = 20\ pb^{-1}$

  ⇒ 1 event limit at 0.05 pb (pp equiv.)




Forward detectors:
• PMD
• FMD, T0, V0, ZDC
Solenoid magnet 0.5 T
ALICE
Central tracking system:
• ITS
• TPC
• TRD
• TOF
Muon spectrometer:
• absorbers
• tracking stations
• trigger chambers
• dipole
Specialized detectors:
• HMPID
• PHOS

$h^{\pm}$, $e^{\pm}$, γ, $\mu^{\pm}$ measurement in the CMS barrel ($|\eta| < 2.5$)



Si Tracker

Silicon micro-strips and pixels

Calorimeters

ECAL $PbWO_4$

HCAL Plastic Sci/Steel sandwich

Muon Barrel

Drift Tube Chambers (**DT**)

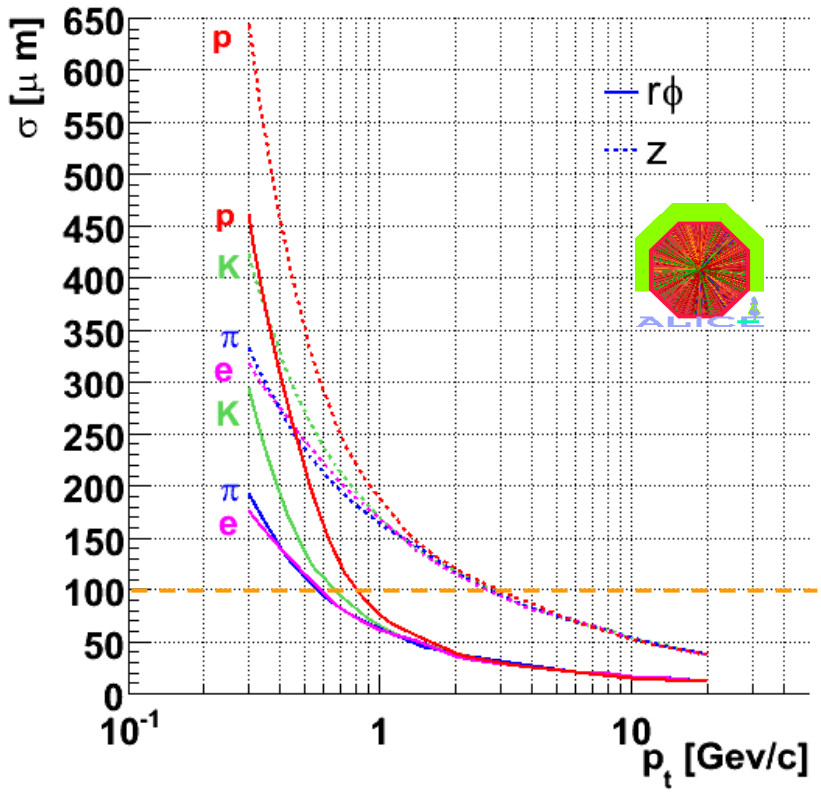
Resistive Plate Chambers (**RPC**)

Charm and beauty production

- The charm production cross section at $\sqrt{s}$ = 5.5 TeV is ~10 times higher than at RHIC and ~100 times higher than at the SPS
- Central Pb-Pb collisions will produce ~100 c-cbar pairs and ~5 b-bbar pairs!
- Several physics topics can be studied for the first time (heavy quark energy loss in the medium, charm thermalisation, etc)

The detection of D and B mesons requires an accurate determination of the collision vertex and of the distance between the extrapolated charged tracks and the vertex, in the transverse plane and in the beam axis

Typical impact parameters: a few 100 μm for D decays and ~500 μm for B mesons

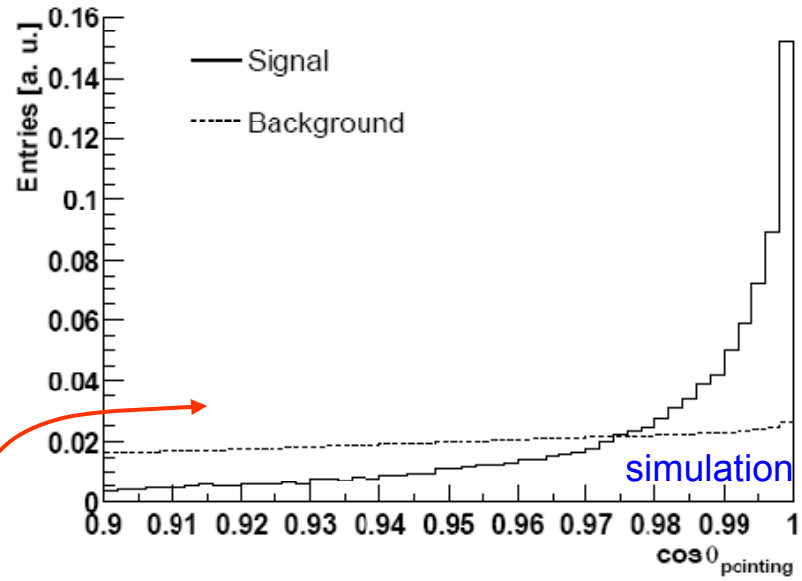


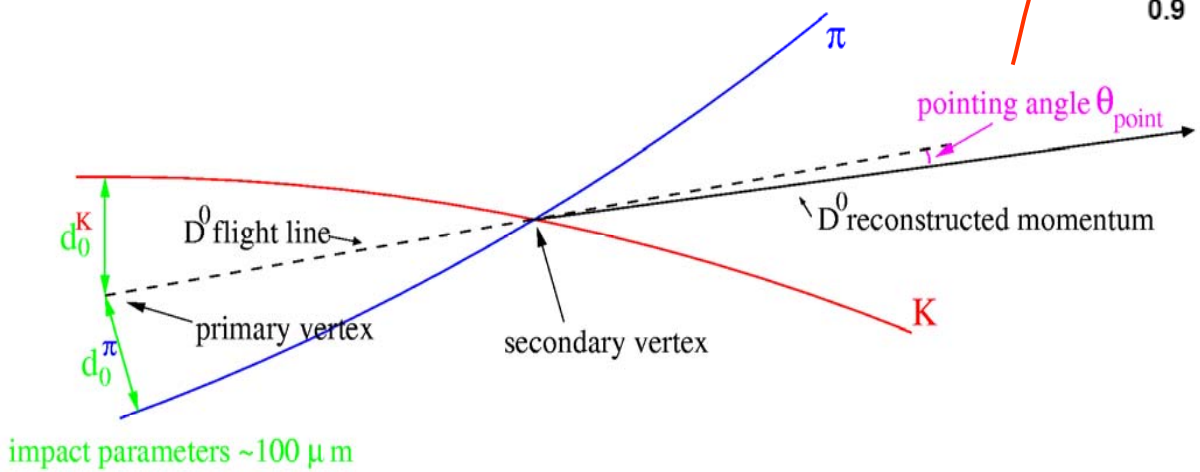
Reconstruction of $D^0 \rightarrow K^- \pi^+$ decays in ALICE

Large combinatorial background

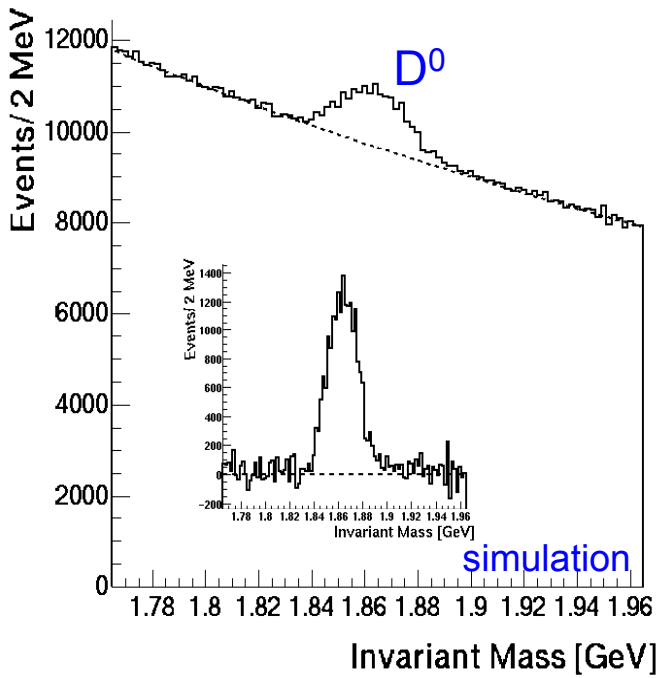
Main selection cuts:

- pair of opposite-charge tracks with large impact parameters
- good pointing of the reconstructed D^0 momentum to the primary vertex

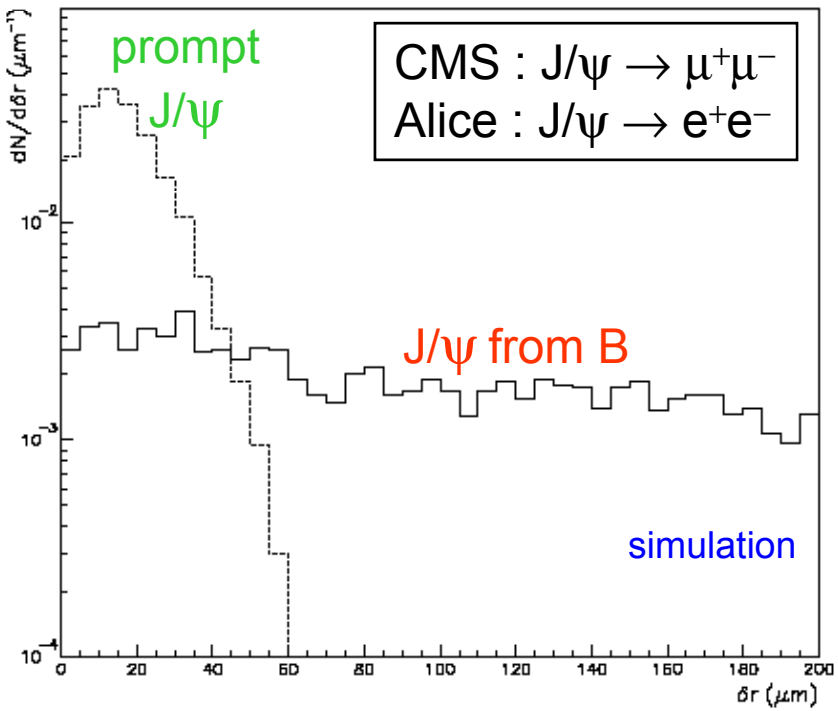


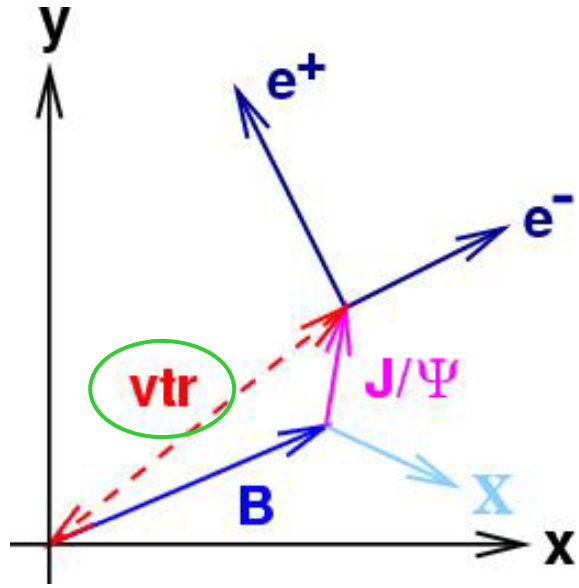


Invariant mass analysis



Measuring beauty yields from displaced J/ψ production

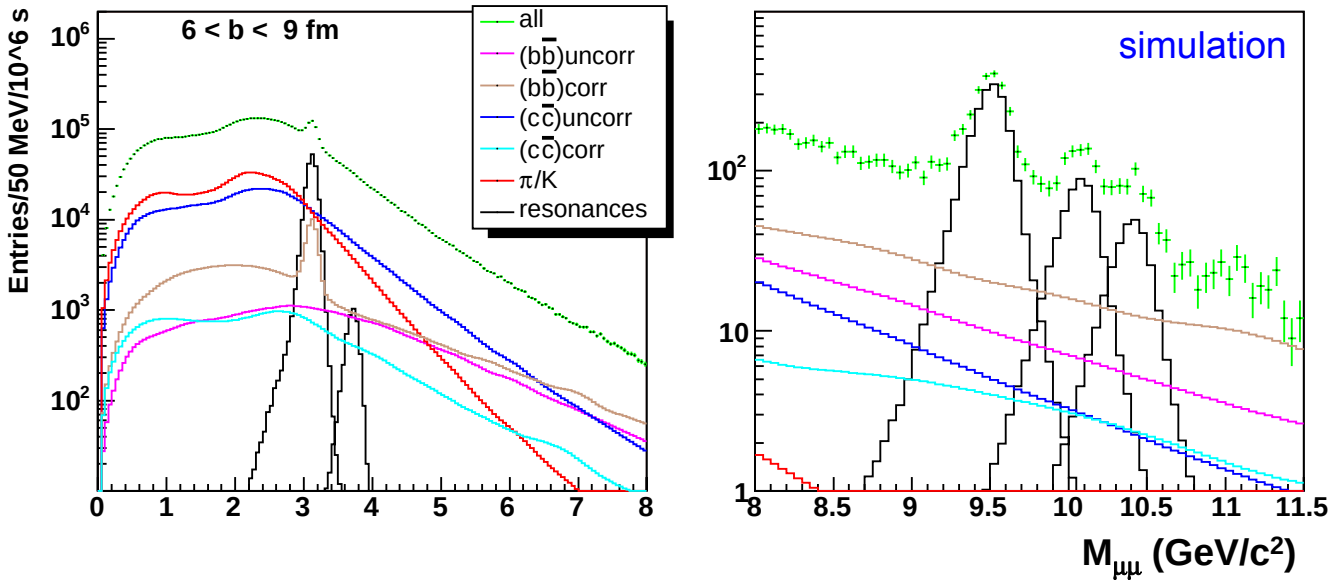




A large fraction of the J/ψ mesons observed at the LHC will come from decays of B mesons

They can be separated from the “prompt” J/ψ mesons because they are produced away from the collision vertex

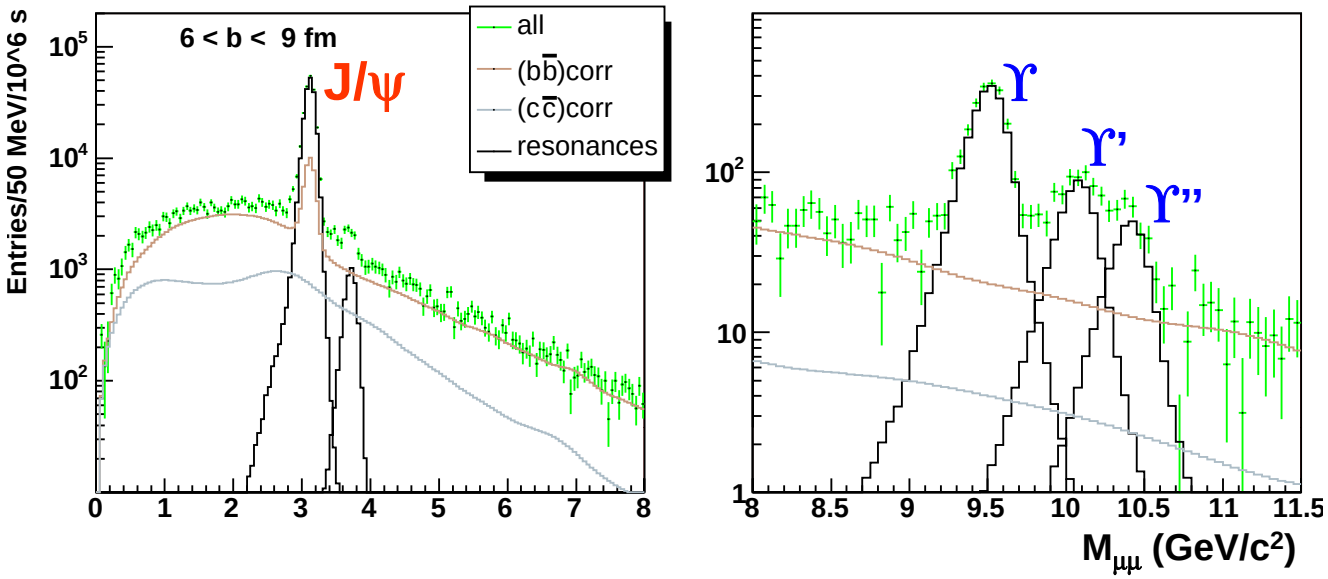
Quarkonia studies in ALICE



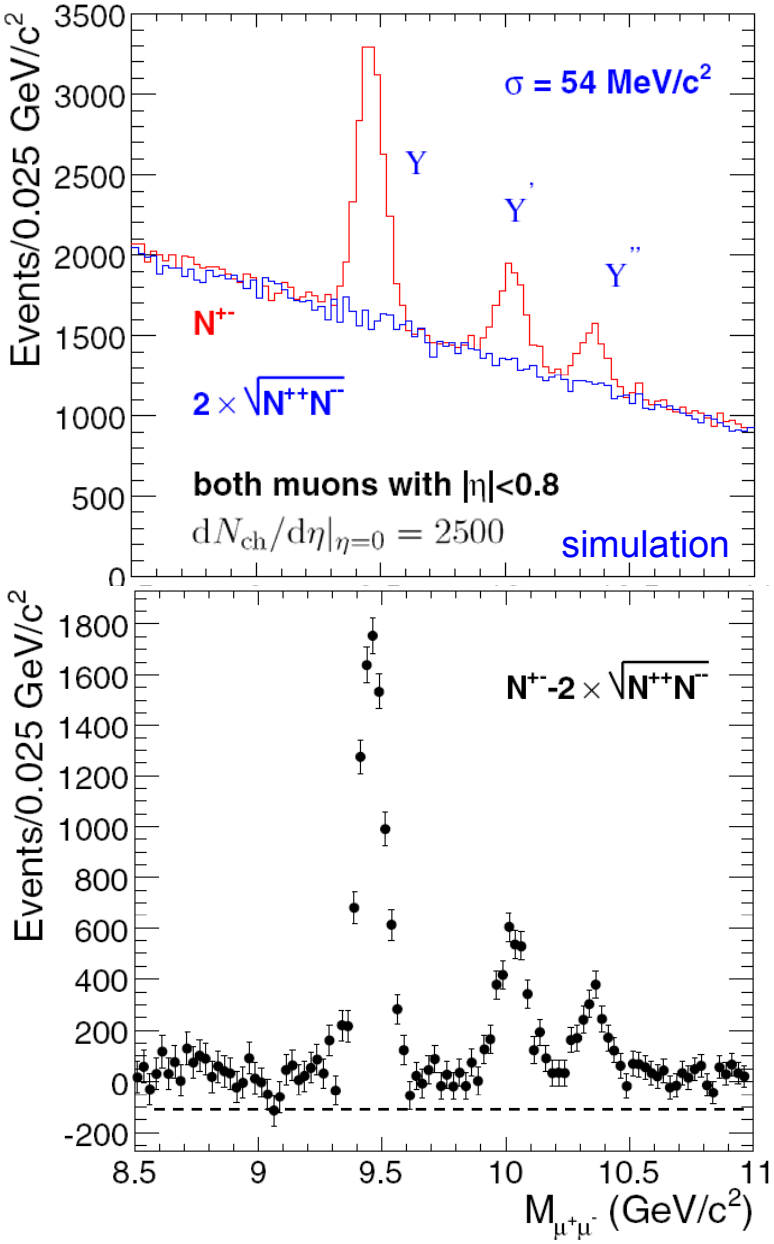
Rapidity window:
2.4–4.0

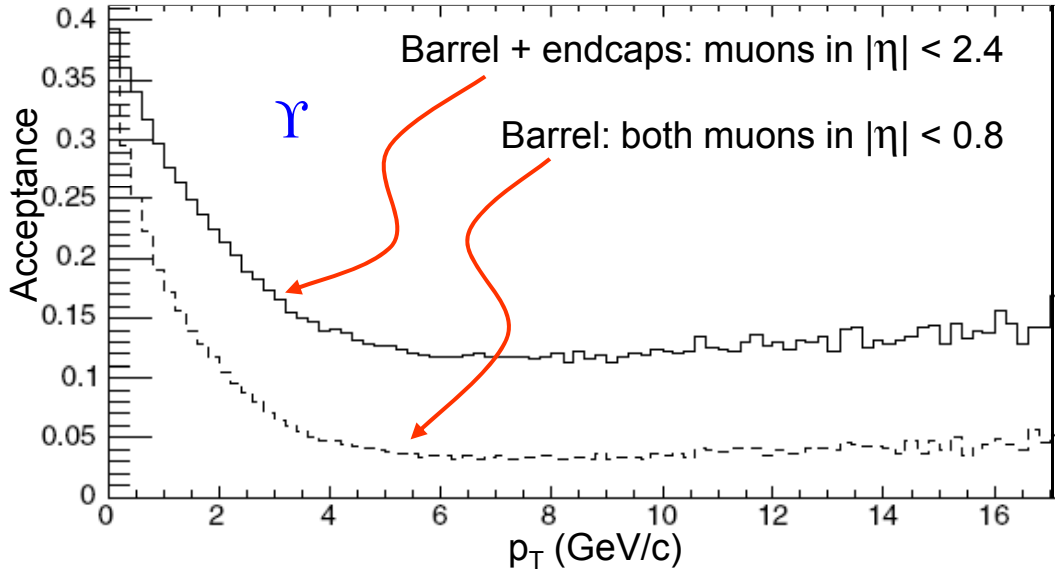
Resolution:
70 MeV at the J/ψ
100 MeV at the Υ

After combinatorial background subtraction :



$\Upsilon \rightarrow \mu^+\mu^-$ in CMS



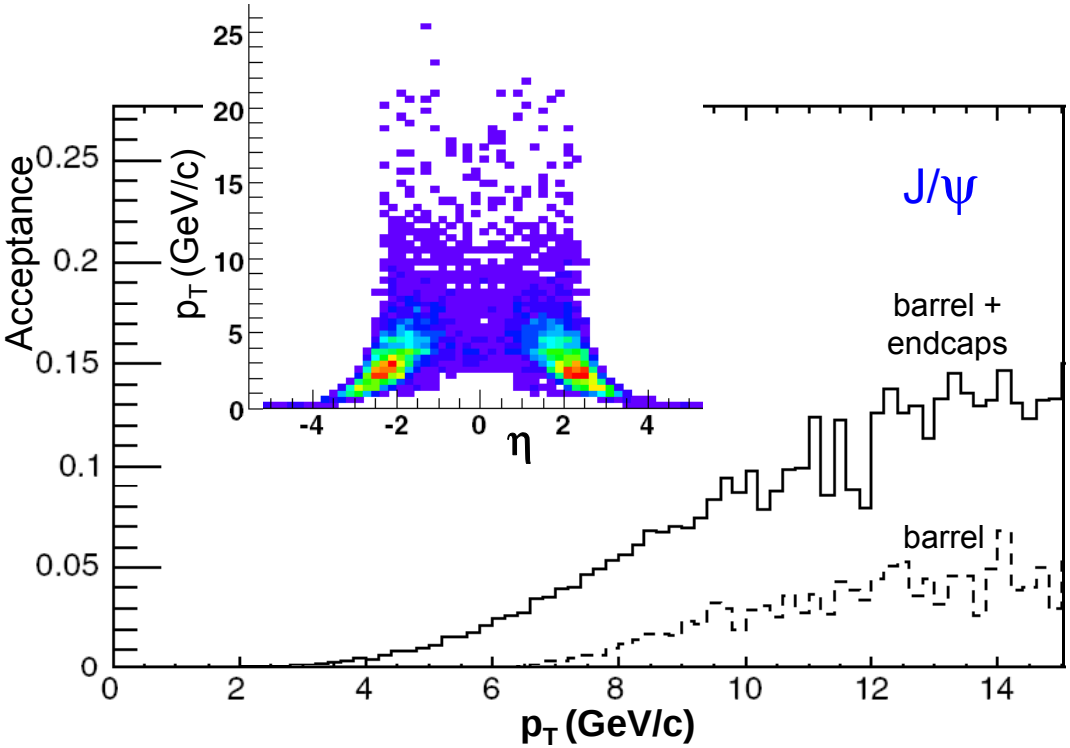


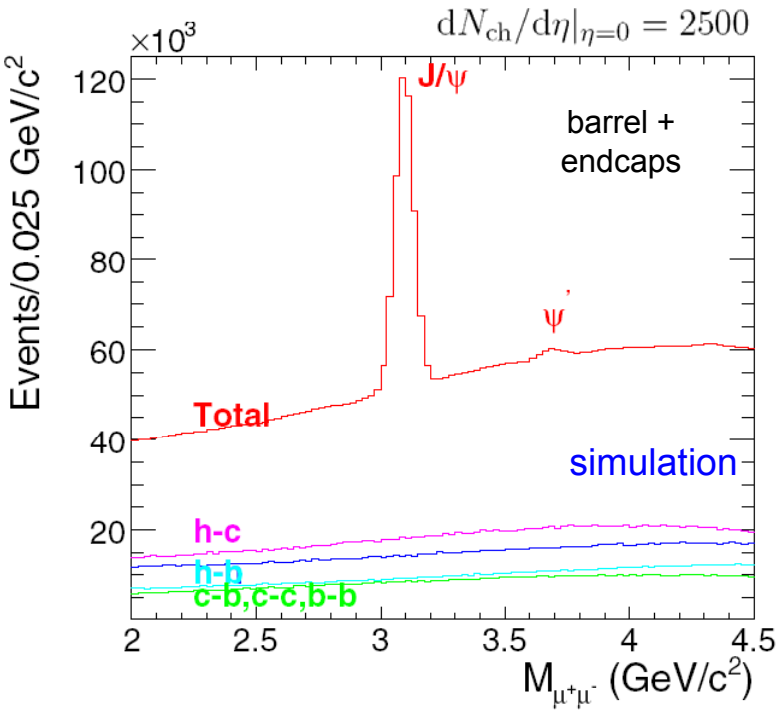
CMS has a very good acceptance for dimuons in the Upsilon mass region (21% total acceptance, barrel + endcaps)

The dimuon mass resolution enables the separation of the three Upsilon states:
~ 54 MeV within the barrel and
~ 86 MeV when including the endcaps

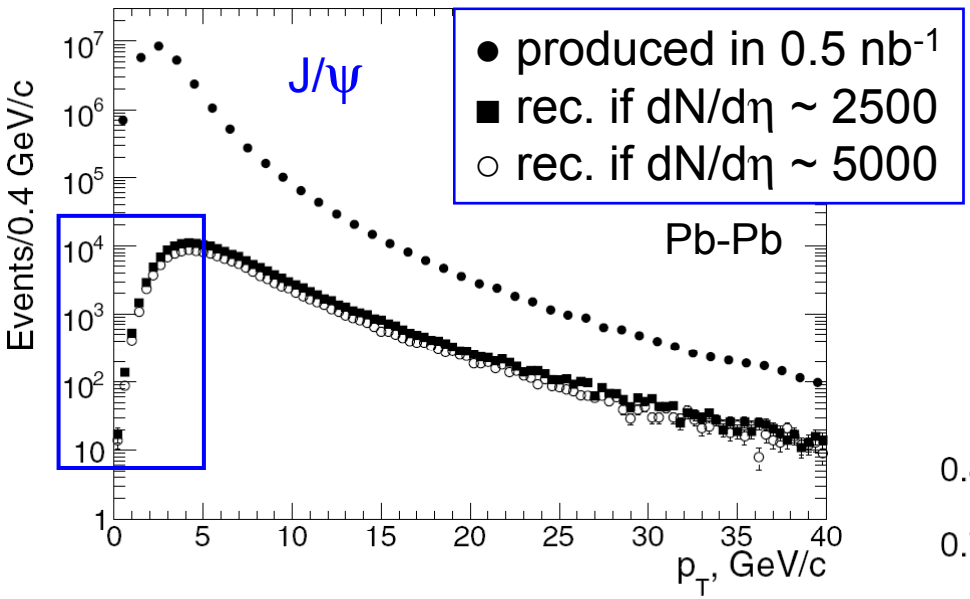
$J/\psi \rightarrow \mu^+\mu^-$ in CMS

- The material between the silicon tracker and the muon chambers (ECAL, HCAL, magnet's iron) prevents hadrons from giving a muon tag but impose a minimum muon momentum of 3.5–4.0 GeV/c. This is no problem for the Upsilons, given their high mass, but sets a relatively high threshold on the p_T of the detected J/ψ's.
- The dimuon mass resolution is 35 MeV, in the full η region.





p_T reach of CMS quarkonia measurements (for 0.5 nb^{-1})

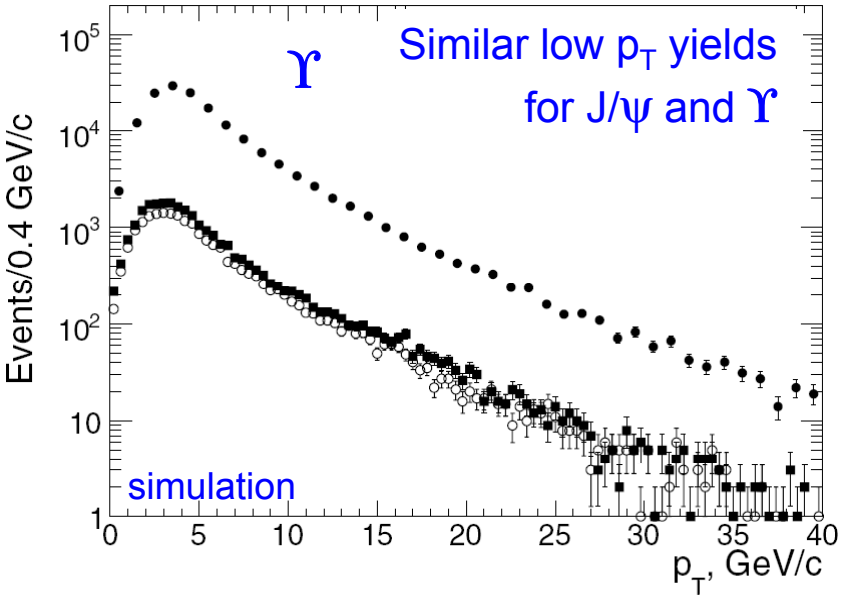


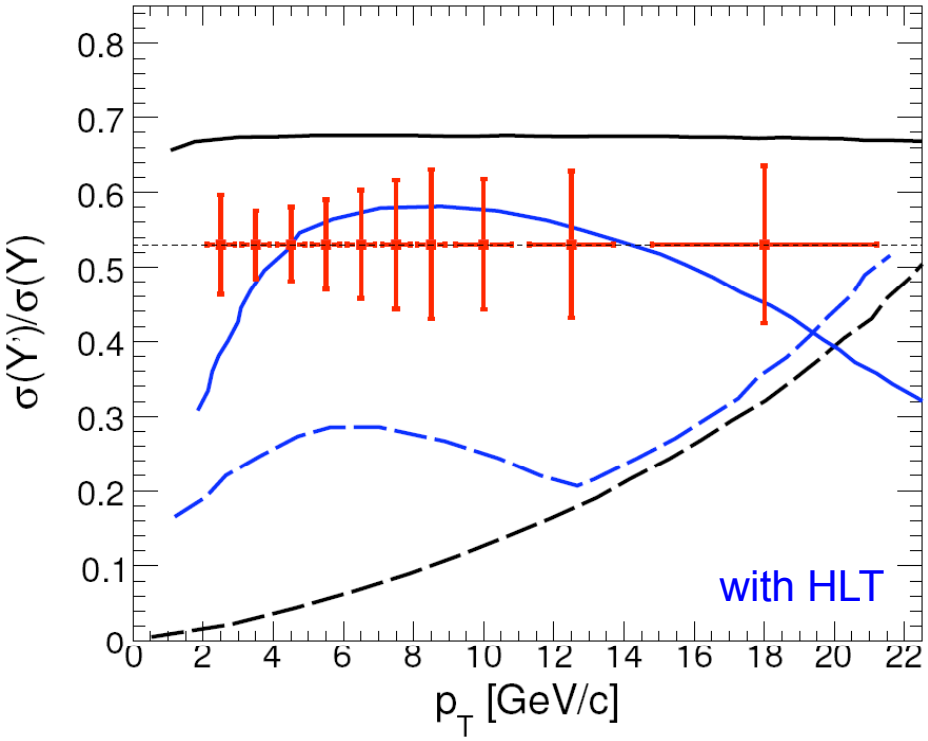
Expected rec. quarkonia yields:

J/ψ : ~ 180'000

Υ : ~ 26'000

Υ' : ~ 7'300; Υ'' : ~ 4'400





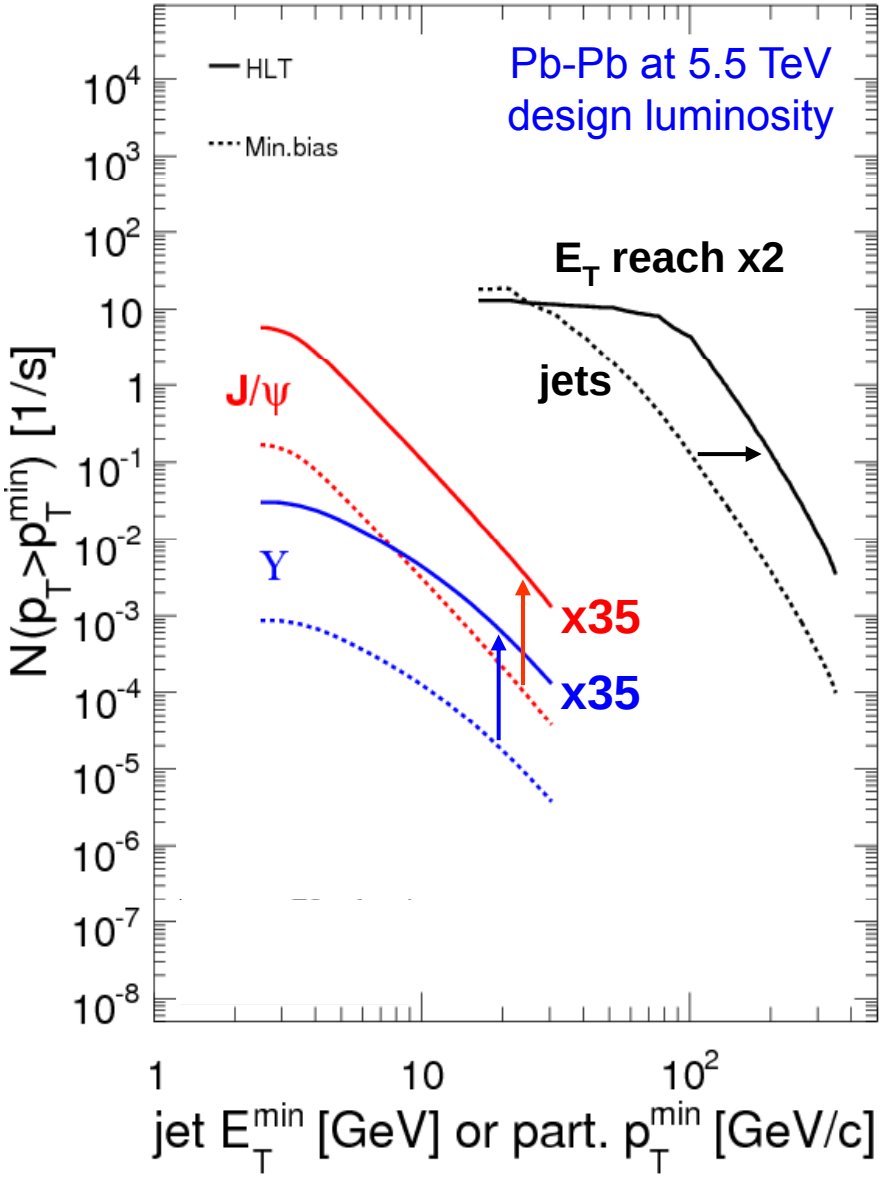
The CMS High Level Trigger

- CMS High Level Trigger:
  12 000 CPUs of 1.8 GHz ~ 50 Tflops !
- Processes *full events* with fast versions of the offline algorithms

- pp L1 maximum *trigger* rate : 100 kHz
- Pb-Pb *collision* rate : less than 8 kHz
  ⇒ pp L1 trigger rate > Pb-Pb collision rate
  ⇒ the HLT can process *all* Pb-Pb events

- Average HLT time budget per event: ~10 s

- The samples of rare events are enhanced by very large factors



Take home messages

Nature's secrets are never easy to uncover and much detective work is needed to understand how the Universe's most fundamental building blocks (the quarks and gluons) interact in the extreme densities and temperatures which existed just after the Big Bang, before protons and neutrons were formed.

The SPS data revealed some "exquisite anomalies", surprisingly similar to what was predicted in case of QGP formation; has a *"new state of matter"* really been formed?

RHIC was built to study the QGP, thought as a gas of quarks and gluons. Instead, it served a nearly perfect liquid, an *even more remarkable state of matter*, where the particles flow as one entity.

The LHC (Large Heavy-ion Collider) will surely also provide intriguing revelations… if we don't get lost on the way…

Good luck !