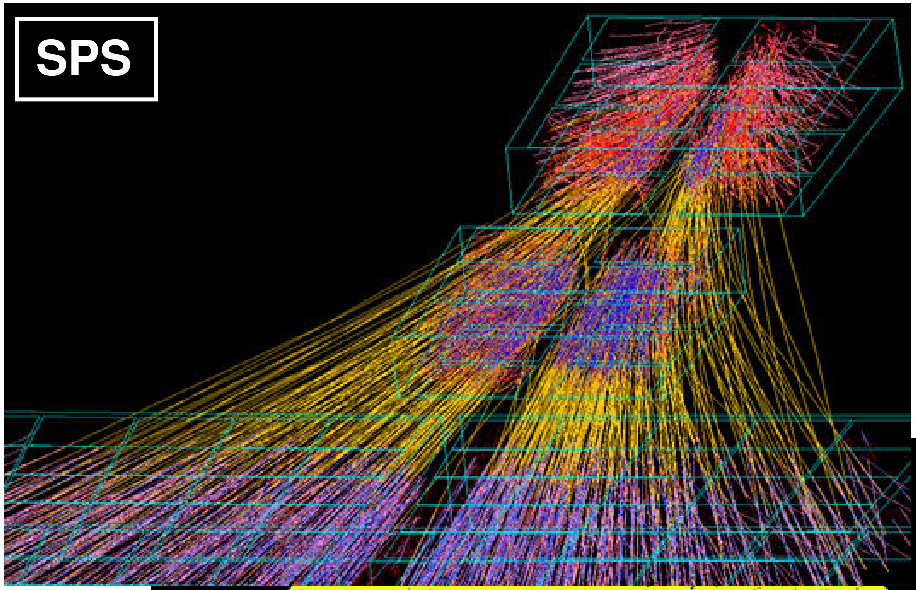
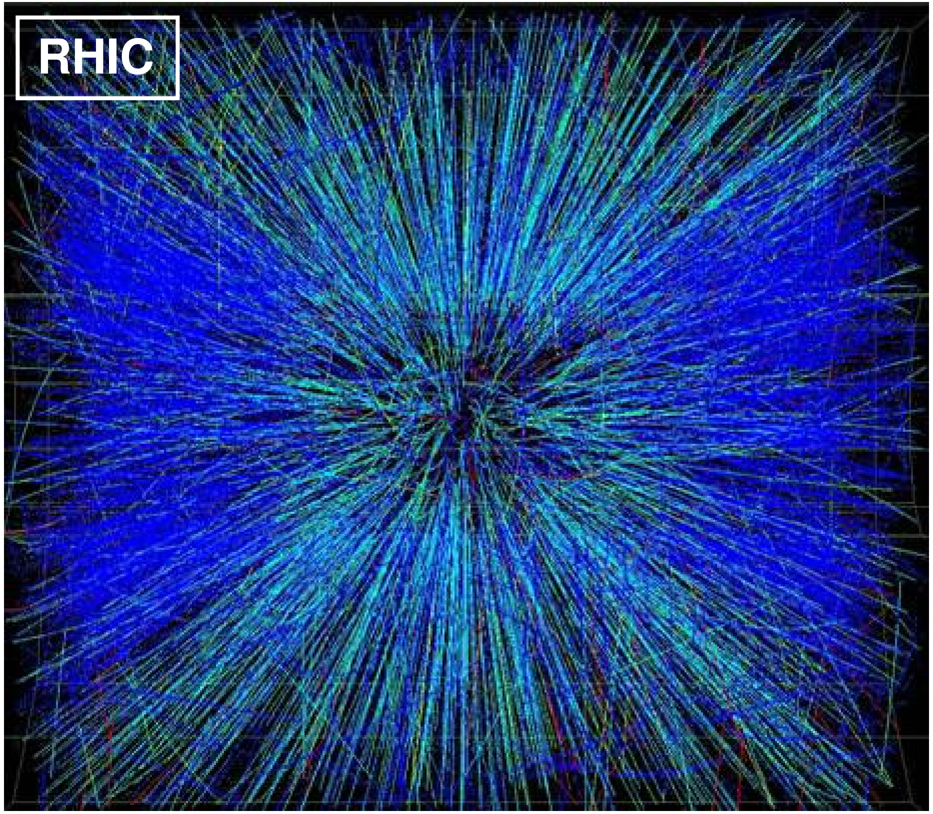
From High-Energy Heavy-Ion Collisions to Quark Matter

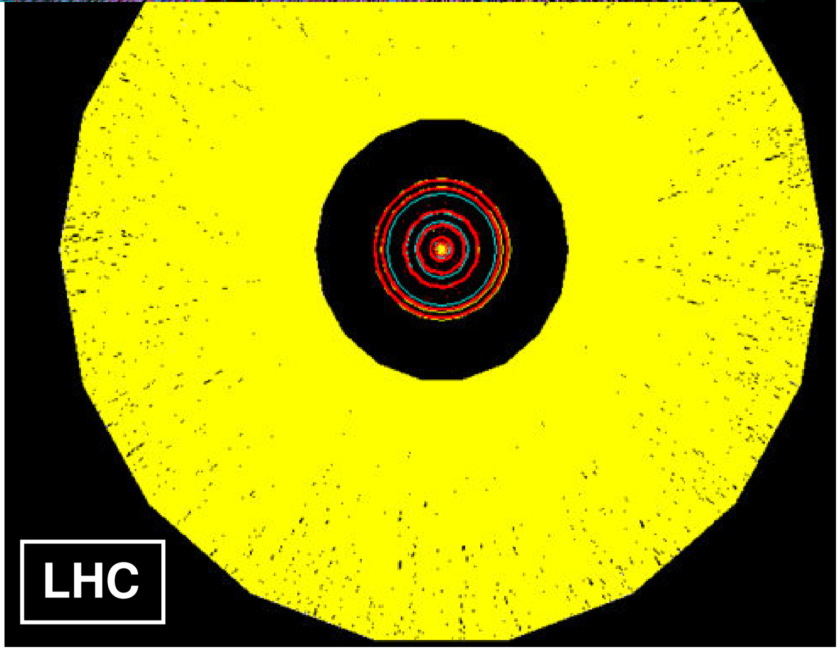
Episode III : Back to the future

From the SPS and RHIC to the LHC

as soon as possible… but not sooner


SPS


RHIC


LHC

One small step for a man, a giant leap for mankind…

	SPS	RHIC	LHC	
$\sqrt{s_{NN}}$ (GeV)	17	200	5500	
dN_{ch}/dy	500	850	1500-4000	
τ^0_{QGP} (fm/c)	1	0.2	0.1	
T/T_c	1.1	1.9	3-4	Hotter
ε (GeV/fm^3)	3	5	15-60	Denser
τ_{QGP} (fm/c)	≤ 2	2-4	≥ 10	Longer
τ_f (fm/c)	~10	20-30	30-40	
V_f (fm^3)	few 10^3	few 10^4	few 10^5	Bigger

The LHC is a big jump forward in QGP physics, well beyond existing facilities

Heavy-ion / QGP physics from SPS to RHIC

- SPS : 1986 – 2003 : Pb-Pb and In-In at $\sqrt{s}$ = 20 GeV

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

  thermal dimuon production ⇒ thermal QCD medium

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

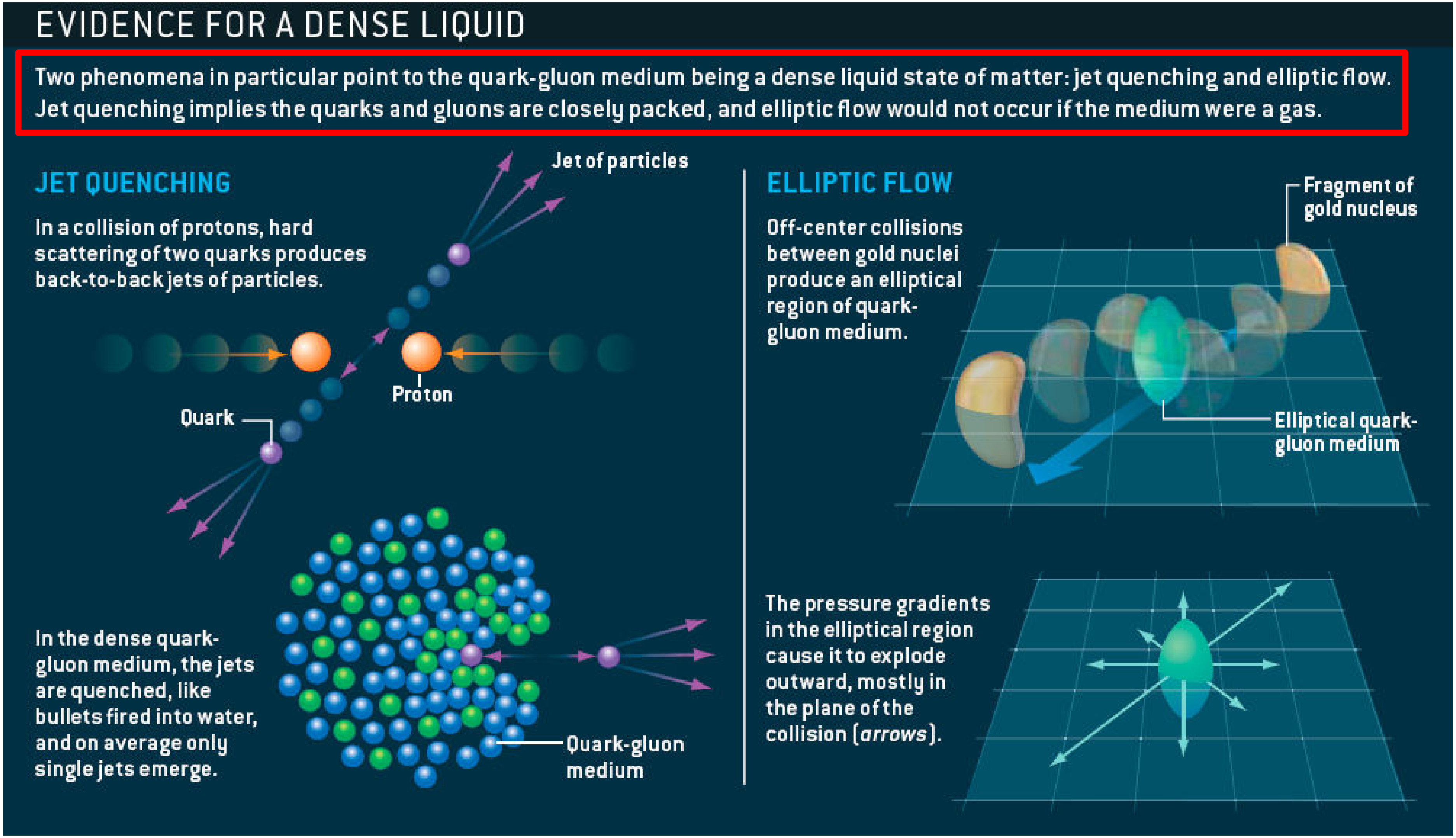
- RHIC : 2000 – ?? : Au-Au at $\sqrt{s}$ = 200 GeV

  jet quenching: parton energy loss ⇒ very dense QCD medium

  baryon/meson elliptical flow scaling ⇒ partonic degrees of freedom

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

The “perfect fluid” found at RHIC, in the Scientific American



EVIDENCE FOR A DENSE LIQUID

Two phenomena in particular point to the quark-gluon medium being a dense liquid state of matter: jet quenching and elliptic flow. Jet quenching implies the quarks and gluons are closely packed, and elliptic flow would not occur if the medium were a gas.

JET QUENCHING

In a collision of protons, hard scattering of two quarks produces back-to-back jets of particles.

In the dense quark-gluon medium, the jets are quenched, like bullets fired into water, and on average only single jets emerge.

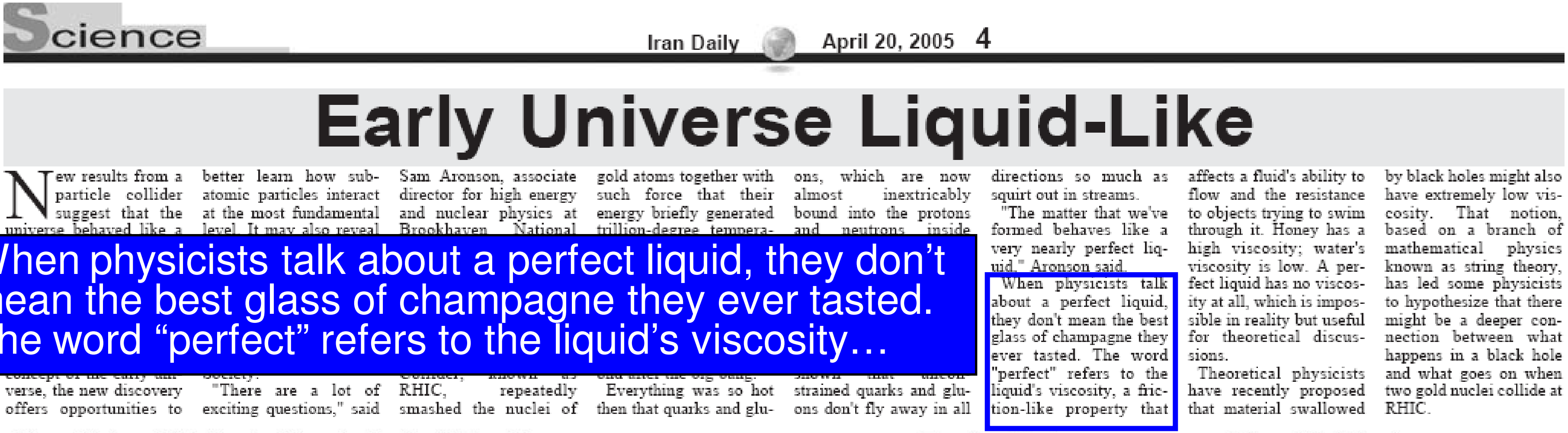
ELLIPTIC FLOW

Off-center collisions between gold nuclei produce an elliptical region of quark-gluon medium.

The pressure gradients in the elliptical region cause it to explode outward, mostly in the plane of the collision (*arrows*).

M. Roirdan and W. Zajc, Scientific American, May 2006

The “perfect fluid” found at RHIC, in other press



Science Iran Daily April 20, 2005 4

Early Universe Liquid-Like

New results from a particle collider suggest that the universe behaved like a

verse, the new discovery offers opportunities to better learn how subatomic particles interact at the most fundamental level. It may also reveal

"There are a lot of exciting questions," said Sam Aronson, associate director for high energy and nuclear physics at Brookhaven National

RHIC, repeatedly smashed the nuclei of gold atoms together with such force that their energy briefly generated trillion-degree tempera-

Everything was so hot then that quarks and gluons, which are now almost inextricably bound into the protons and neutrons inside

strained quarks and gluons don't fly away in all directions so much as squirt out in streams.

"The matter that we've formed behaves like a very nearly perfect liquid," Aronson said.

When physicists talk about a perfect liquid, they don't mean the best glass of champagne they ever tasted. The word "perfect" refers to the liquid's viscosity, a friction-like property that affects a fluid's ability to flow and the resistance to objects trying to swim through it. Honey has a high viscosity; water's viscosity is low. A perfect liquid has no viscosity at all, which is impossible in reality but useful for theoretical discussions.

Theoretical physicists have recently proposed that material swallowed by black holes might also have extremely low viscosity. That notion, based on a branch of mathematical physics known as string theory, has led some physicists to hypothesize that there might be a deeper connection between what happens in a black hole and what goes on when two gold nuclei collide at RHIC.

When physicists talk about a perfect liquid, they don’t mean the best glass of champagne they ever tasted. The word “perfect” refers to the liquid’s viscosity…

New State of Matter Is 'Nearly Perfect' Liquid

Physicists working at Brookhaven National Laboratory announced today that they have created what appears to be a new state of matter out of the building blocks of atomic nuclei, quarks and gluons. The researchers unveiled their findings--which could provide new insight into the composition of the universe just moments after the big bang--today in Florida at a meeting of the American Physical Society.

SCIENTIFIC AMERICAN

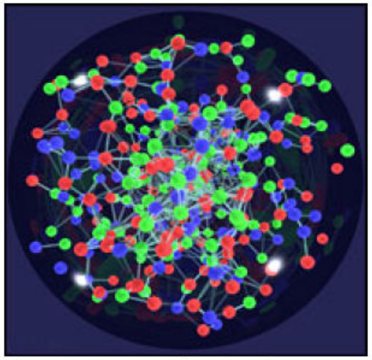
Image: BNL

There are four collaborations, dubbed BRAHMS, PHENIX, PHOBOS and STAR, working at Brookhaven's Relativistic Heavy Ion Collider (RHIC). All of them study what happens when two interacting beams of gold ions smash into one another at great velocities, resulting in thousands of subatomic collisions every second. When the researchers analyzed the patterns of the atoms' trajectories after these collisions, they found that the particles produced in the collisions tended to move collectively, much like a school of fish does. Brookhaven's associate laboratory director for high energy and nuclear physics, Sam Aronson, remarks that "the degree of collective interaction, rapid thermalization and extremely low viscosity of the matter being formed at RHIC make this the most nearly perfect liquid ever observed."

Early Universe was 'liquid-like'

Physicists say they have created a new state of hot, dense matter by crashing together the nuclei of gold atoms.

BBC NEWS



The impression is of matter that is more strongly interacting than predicted

The high-energy collisions prised open the nuclei to reveal their most basic particles, known as quarks and gluons.

The researchers, at the US Brookhaven National Laboratory, say these particles were seen to behave as an almost perfect "liquid".

The work is expected to help scientists explain the conditions that existed just milliseconds after the Big Bang.

Heavy-ion / QGP physics from SPS / RHIC to the LHC

- LHC : 2009 – ?? : Pb-Pb at √s = 5500 GeV

⇒ confirm interpretation of SPS & RHIC results by testing predictions

⇒ explore & understand high-density QCD properties with original measurements

heavy quarks (charm, beauty), jets, upsilons

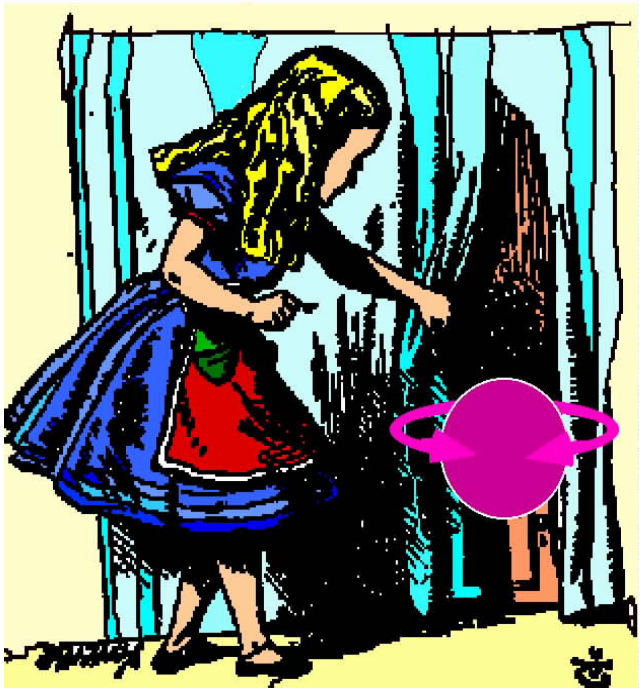
⇒ is the initial state at the LHC yet another state of matter ?

colour glass condensate ? (QCD in the classical field theory limit)

⇒ transition from a strongly coupled QGP to an ideal QGP ?

⇒ surprises ? more puzzles ?

what will we find behind the curtain ?



LHC “nominal” running parameters

Collision system	$\sqrt{s_{NN}}$ (TeV)	$\mathcal{L}_0$ (cm^{-2}s^{-1})	$<\mathcal{L}>/\mathcal{L}_0$ (%)	Run time (s/year)
pp	14.0	10^{34}		10^{7}
Pb-Pb	5.5	10^{27}	50	10^{6}
p-Pb	8.8	10^{29}		10^{6}
Ar-Ar	6.3	10^{29}	65	10^{6}

Expected integrated luminosity in a typical Pb-Pb run : $\mathcal{L}_{int}$(Pb-Pb) ~ 0.5 nb^{-1}/year

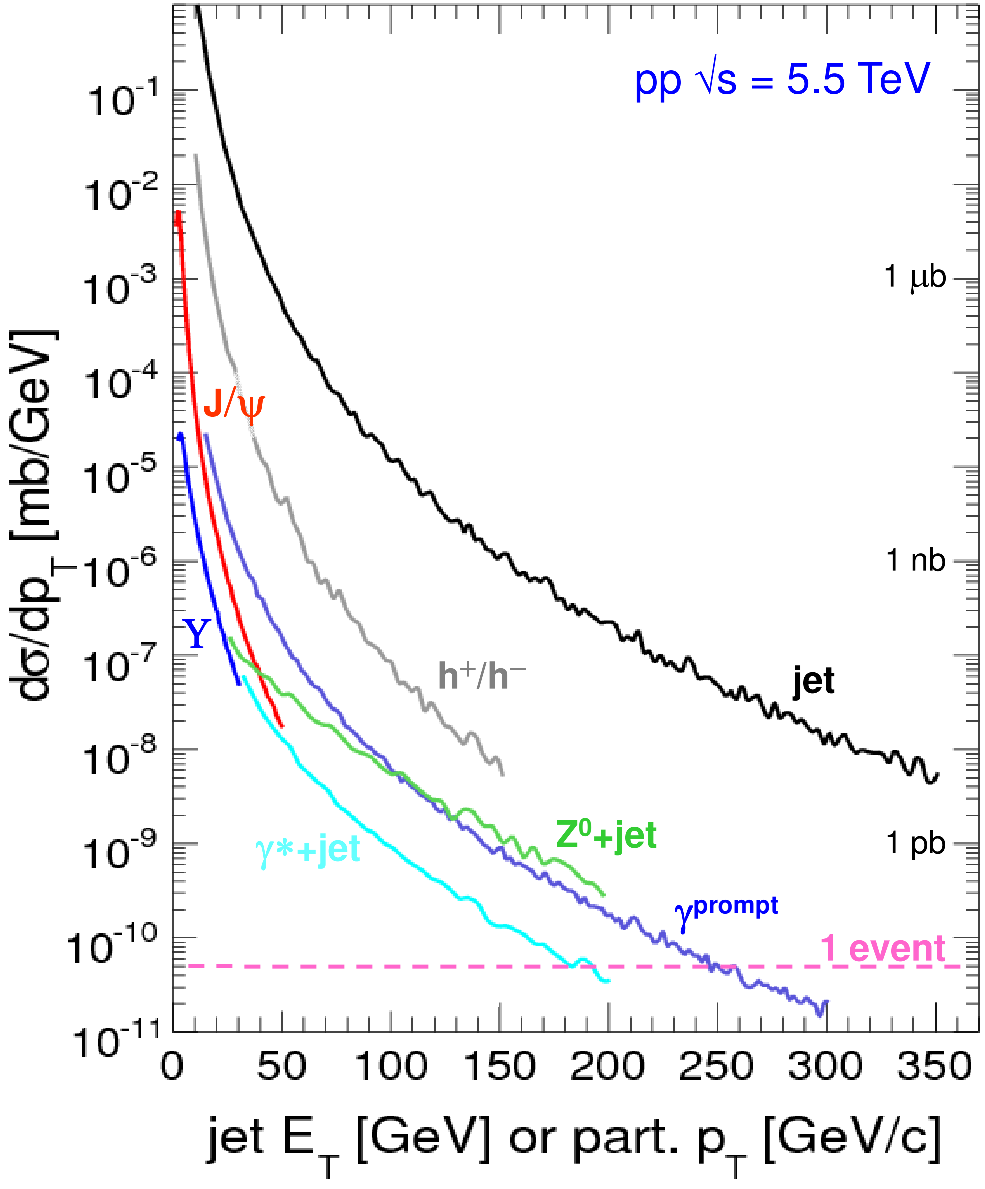
The LHC is expected to run “heavy-ions” for around 1 month each year

Hard Probes of QCD matter at LHC energies

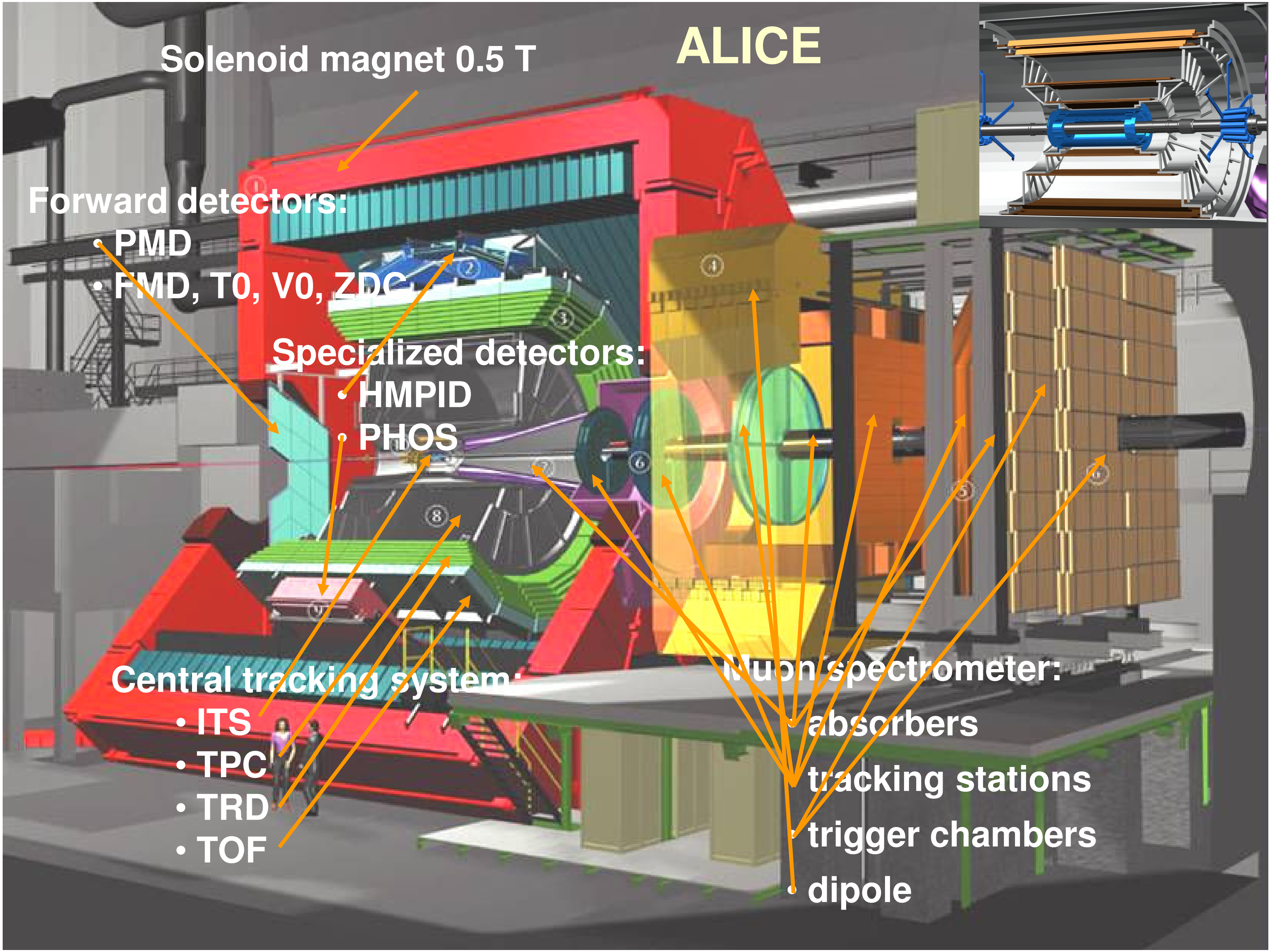
- Very large cross sections at the LHC
- Pb-Pb instant. luminosity: 10^{27} cm^{-2}s^{-1}
- $\int$L dt = 0.5 nb^{-1} (1 month, 50% run eff.)
- Hard cross sections: Pb-Pb = A^2 x pp

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

$\Rightarrow$ 1 event limit at 0.05 pb (pp equiv.)



ALICE



Solenoid magnet 0.5 T

Forward detectors:
- PMD
- FMD, T0, V0, ZDC

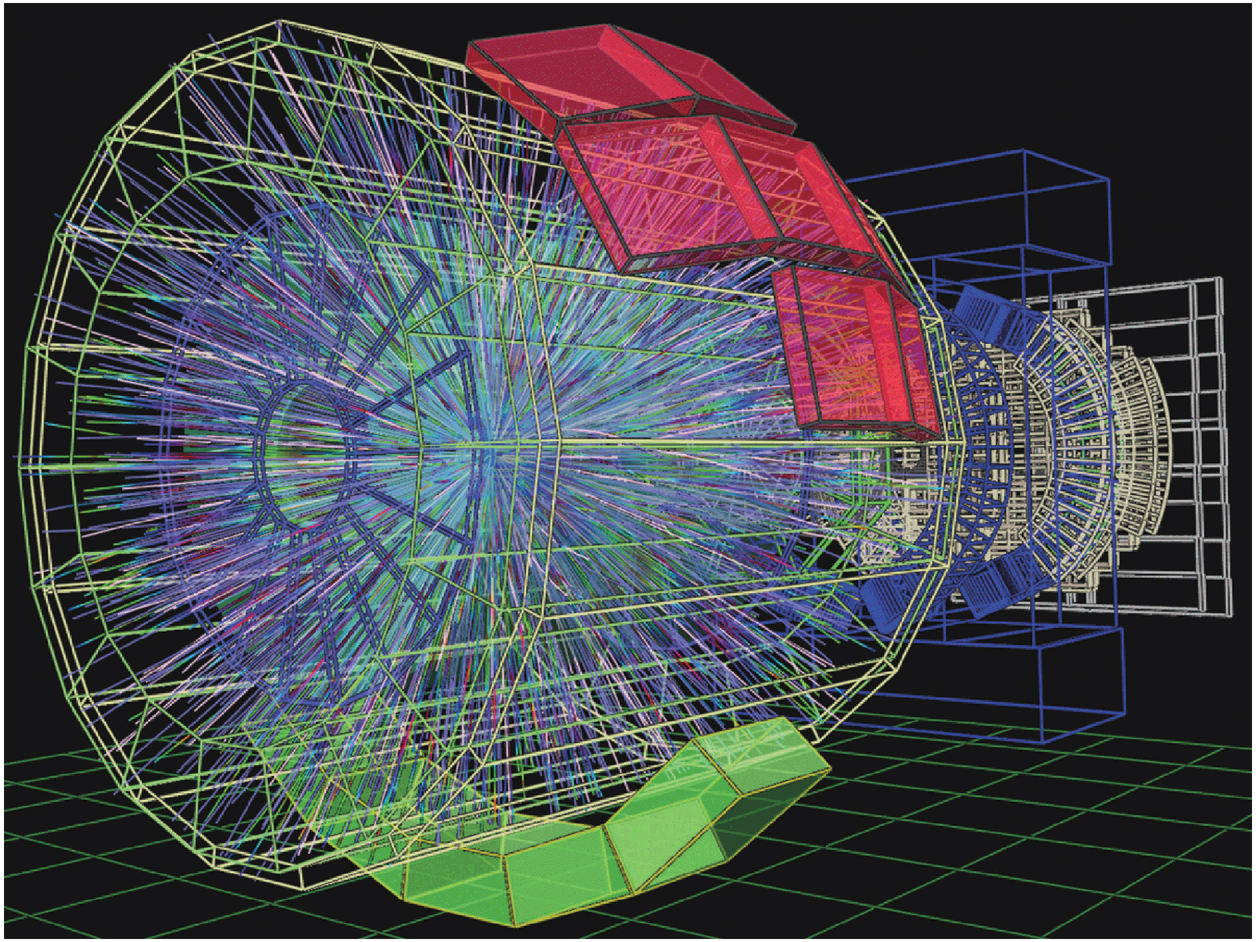
Specialized detectors:
- HMPID
- PHOS

Central tracking system:
- ITS
- TPC
- TRD
- TOF

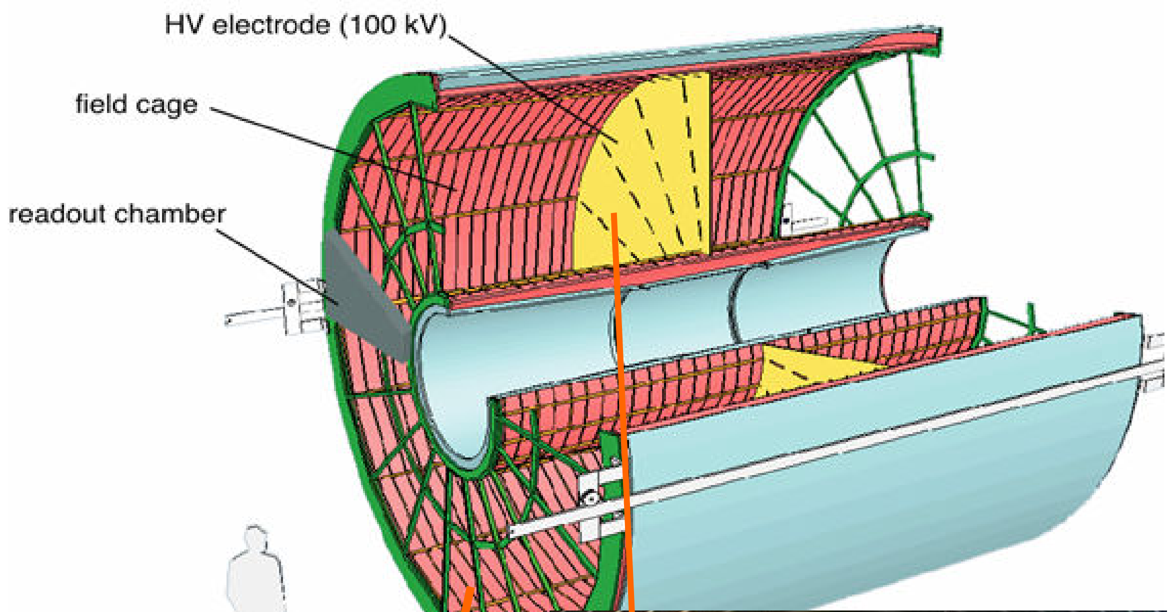
Muon spectrometer:
- absorbers
- tracking stations
- trigger chambers
- dipole

A global view of the ALICE experiment

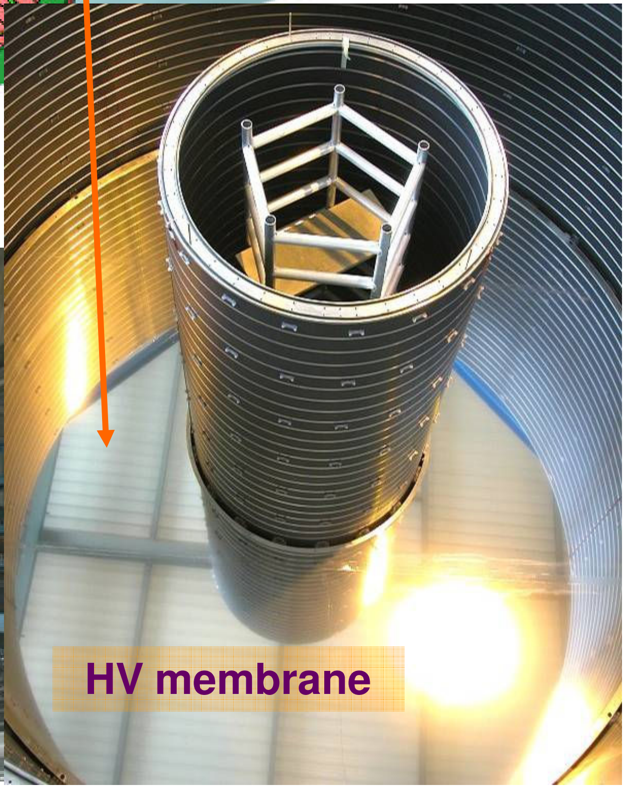
- Covers very low-p_T (~ 100 MeV/c) and high-p_T (> 100 GeV/c)
- Has particle identification over a large momentum range
- Is able to handle large charged particle multiplicities
- Will measure open charm, beauty, direct photons, J/ψ, etc



The ALICE TPC

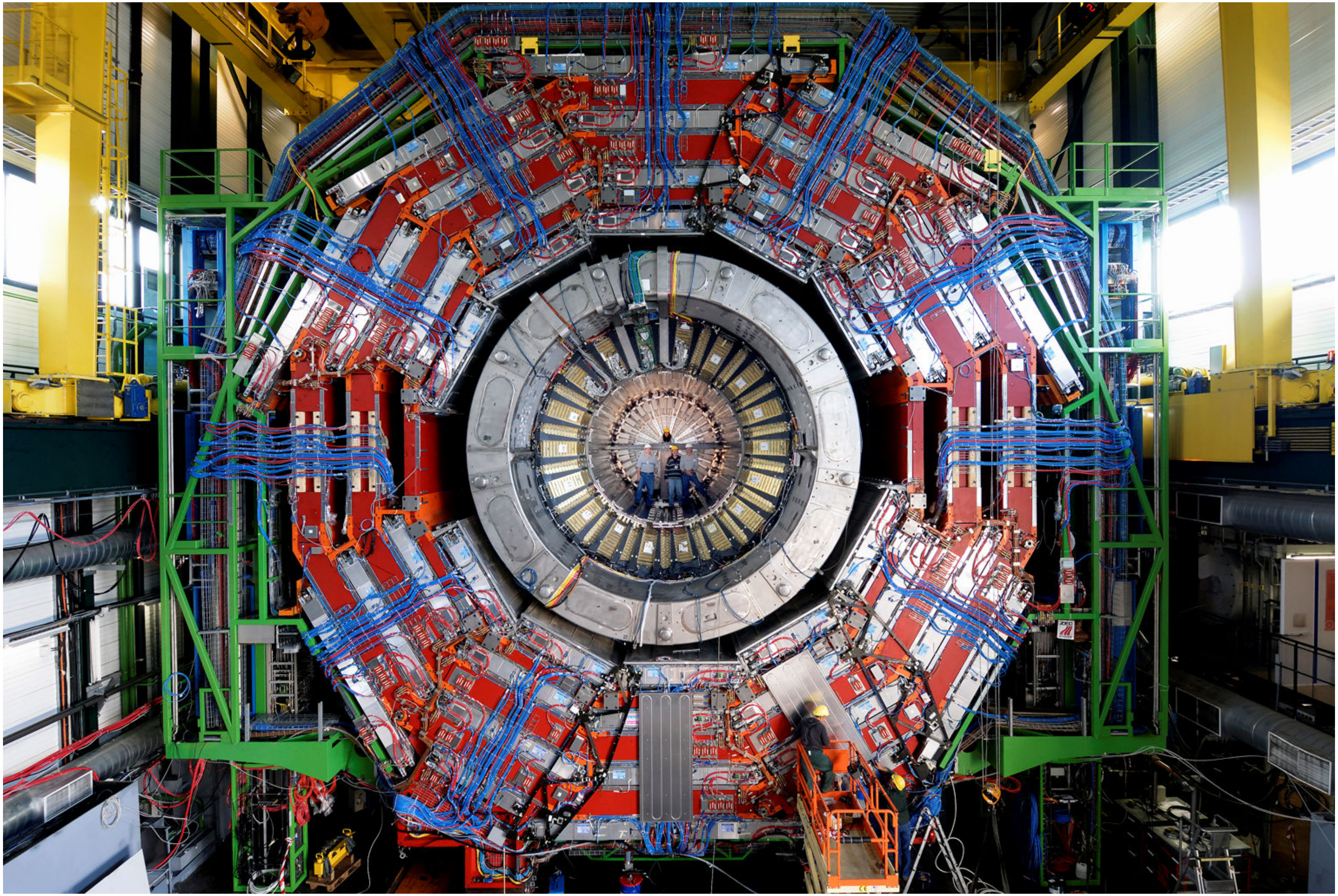


Largest TPC ever
88 m^3, 570k channels
90% Ne – 10% CO_2



Other ALICE detectors

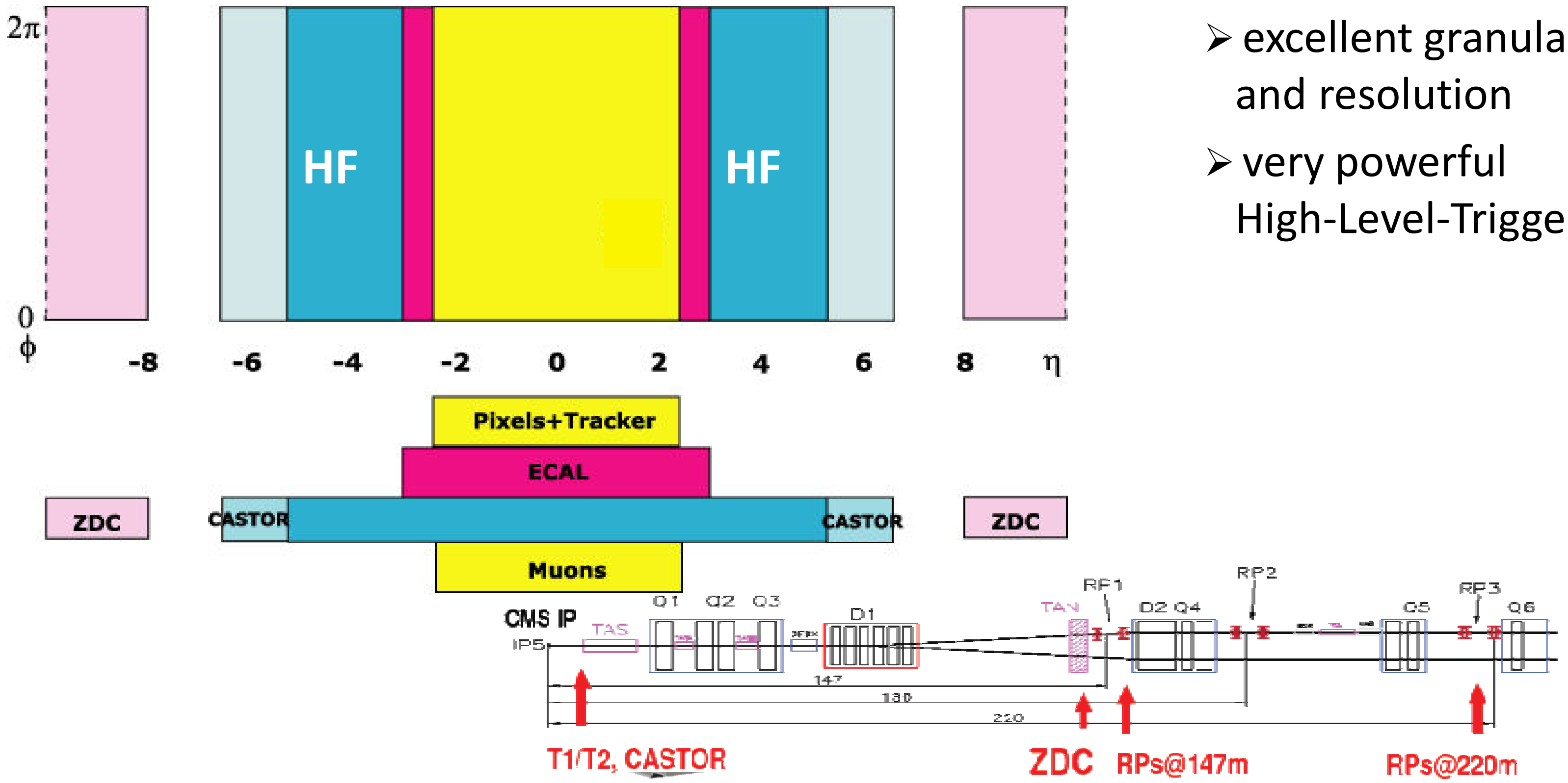
A global view of the CMS experiment



Phase space coverage of the CMS detector

CMS + TOTEM: full φ and almost full η acceptance at the LHC

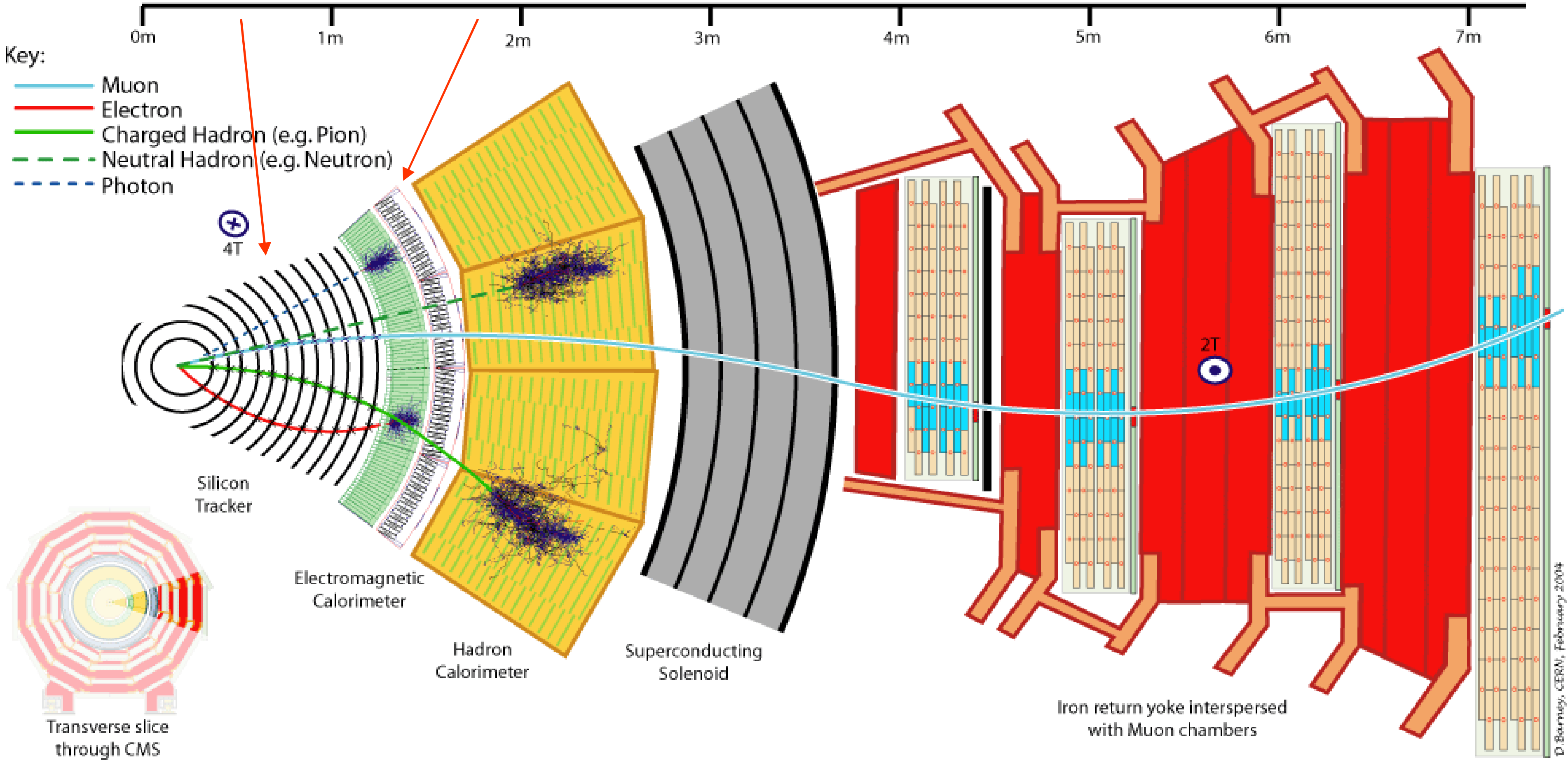
- charged tracks and muons: |η| < 2.5
- electrons and photons: |η| < 3
- jets, energy flow: |η| < 6.7 (plus η > 8.3 for neutrals, with the ZDC)



- excellent granularity and resolution
- very powerful High-Level-Trigger

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

Si Tracker + ECAL + muon-chambers



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 yields vs. energy and collision system

Charm cross section at the LHC is higher by a factor ~ 10 w.r.t. RHIC energies and by a factor ~ 1000 w.r.t. SPS energies:

- $\sqrt{s} = 20$ GeV $\Rightarrow \sigma_{cc}^{pp} \sim 5\ \mu b$
- $\sqrt{s} = 200$ GeV $\Rightarrow \sigma_{cc}^{pp} \sim 600\ \mu b$
- $\sqrt{s} = 5.5$ TeV $\Rightarrow \sigma_{cc}^{pp} \sim 6600\ \mu b$

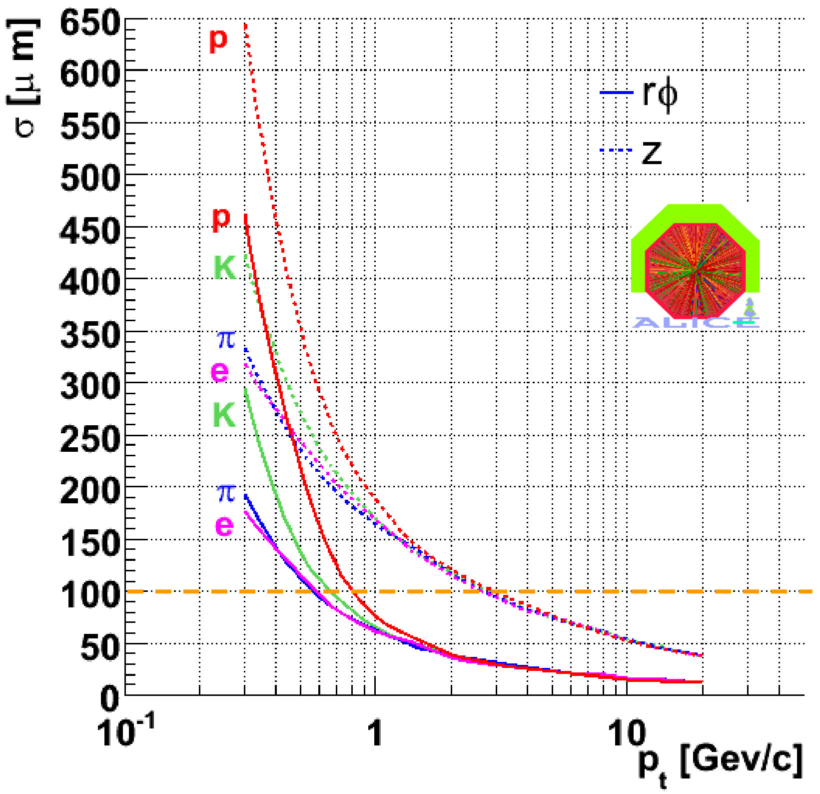
Including EKS98 shadowing

	SPS central Pb-Pb	RHIC central Au-Au	LHC pp	LHC p-Pb	LHC central Pb-Pb
N(cc)/event	0.2	10	0.16	0.8	115
N(bb)/event	--	0.05	0.006	0.03	4.6

Abundance of charm production at the LHC will enable detailed studies of several topics, including charm thermalisation (through elliptic flow measurements)

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

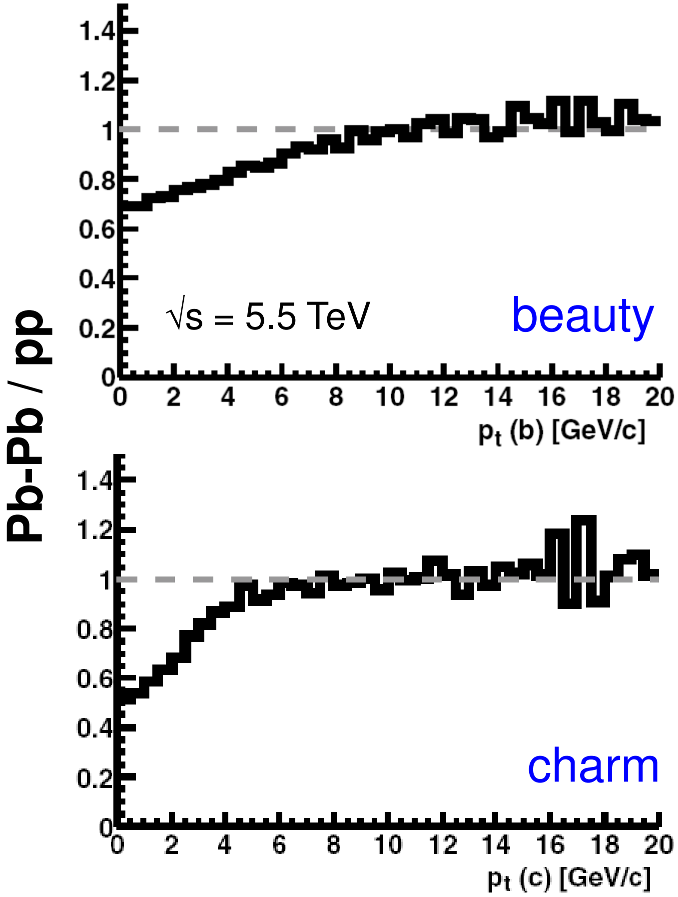
Typical impact parameters: a few 100 μm for D decays and ~500 μm for B mesons



Heavy flavour production at LHC energies

Initial state effects:

Nuclear shadowing suppresses low-p_T heavy flavoured particles in p-A and A-A collisions:
~ 35% reduction of charm production and
~ 15% reduction of beauty (EKS98 dixit)
⇒ It *must* be studied in p-A collisions



Heavy Quark energy loss:

Parton energy loss is expected to occur by:
- medium-induced gluon radiation
- collisions in the medium

It depends on the properties of the medium: length, energy density, etc.

$$\Delta E\ (L,\ \varepsilon_{QGP})$$

It is also expected to depend on the colour factor and on the quark mass:

$$\Delta E_g > \Delta E_{c\sim q} > \Delta E_b \;\Rightarrow\; R_{AA}^{\pi} < R_{AA}^{D} < R_{AA}^{B}$$

We will probe heavy quark energy loss through ratios of p_T distributions, between Pb-Pb and pp, between B and D mesons, etc

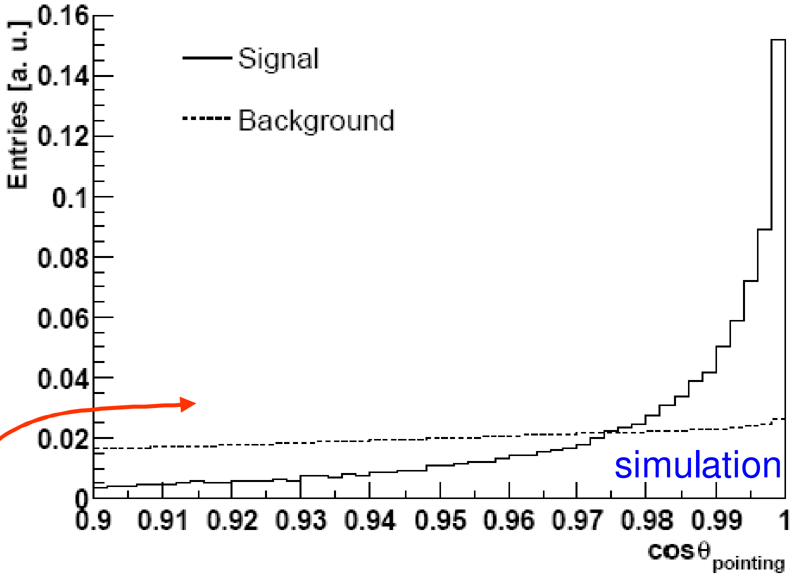
We will also do these studies using jets tagged by the presence of D or B mesons

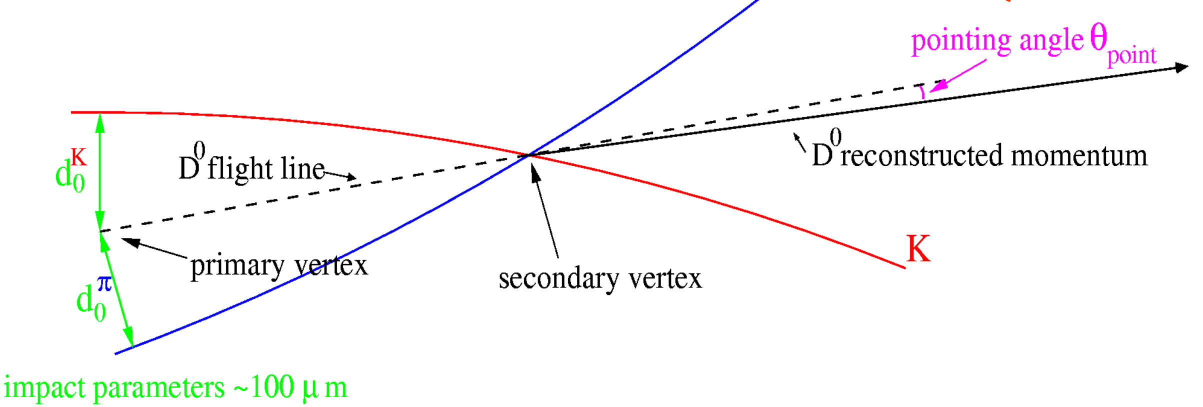
Reconstruction of $D^0 \rightarrow K^- \pi^+$ decays in ALICE

Large combinatorial background

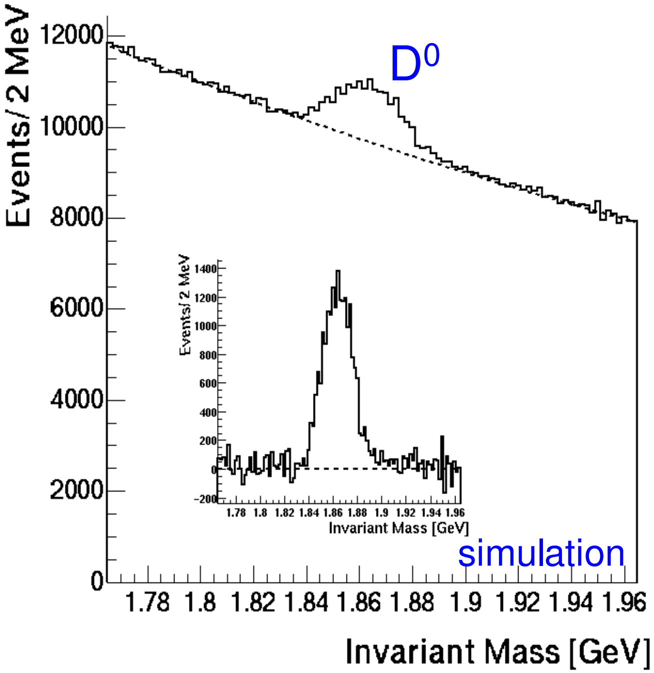
Main selection cuts:

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

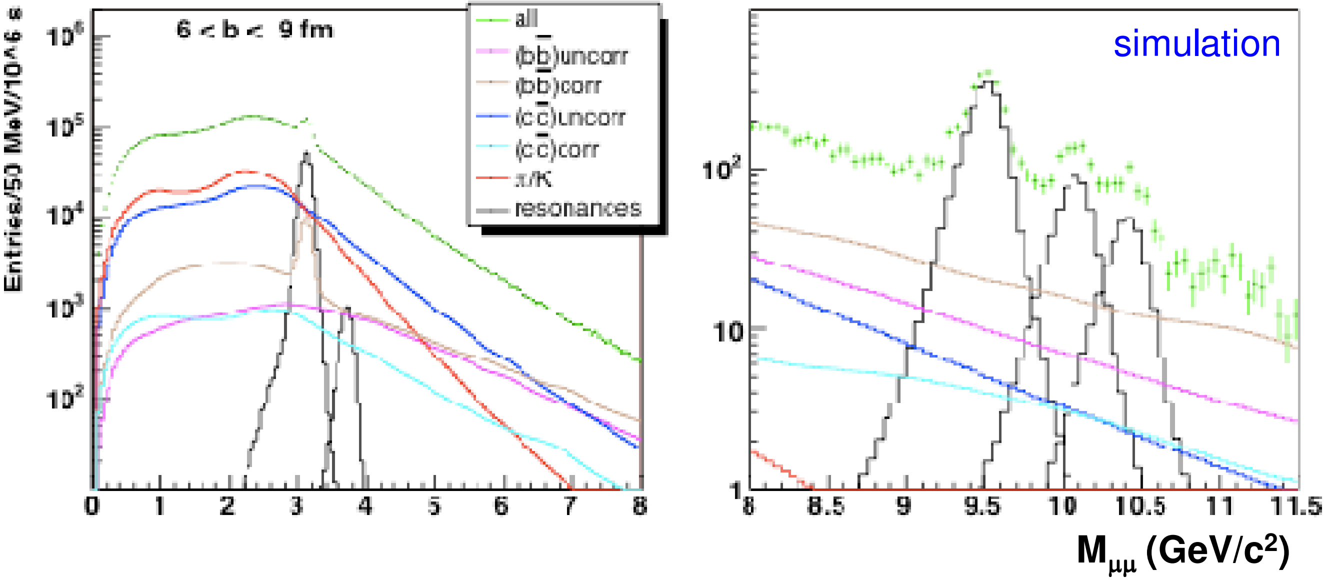




→ Invariant mass analysis



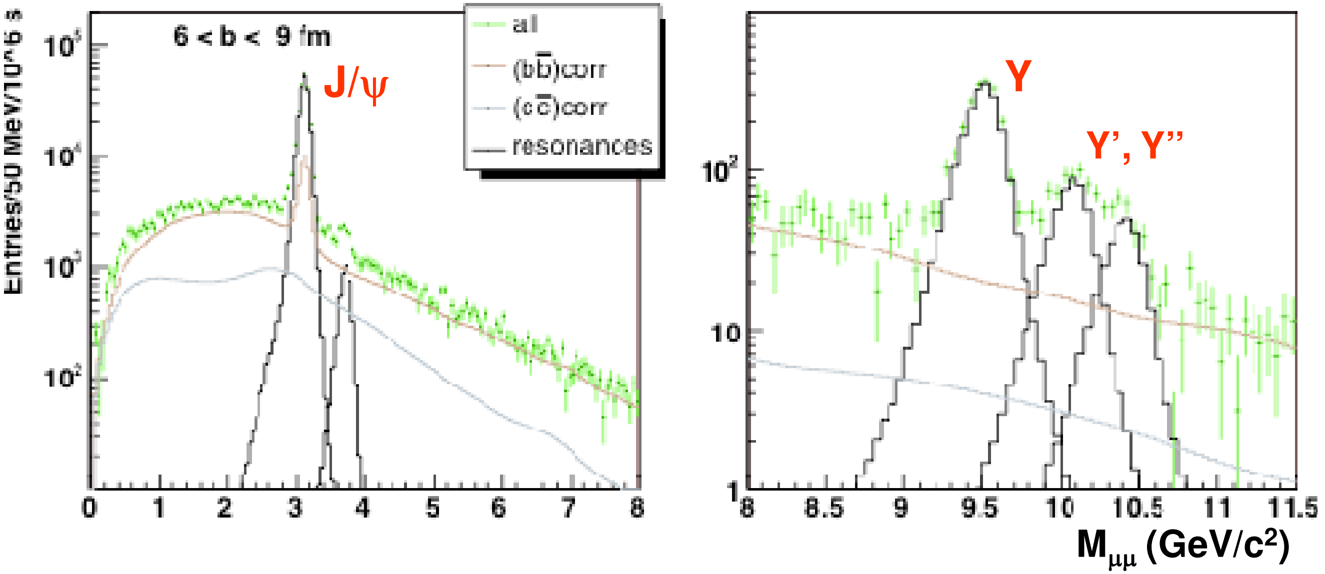
Quarkonia studies in ALICE with dimuons



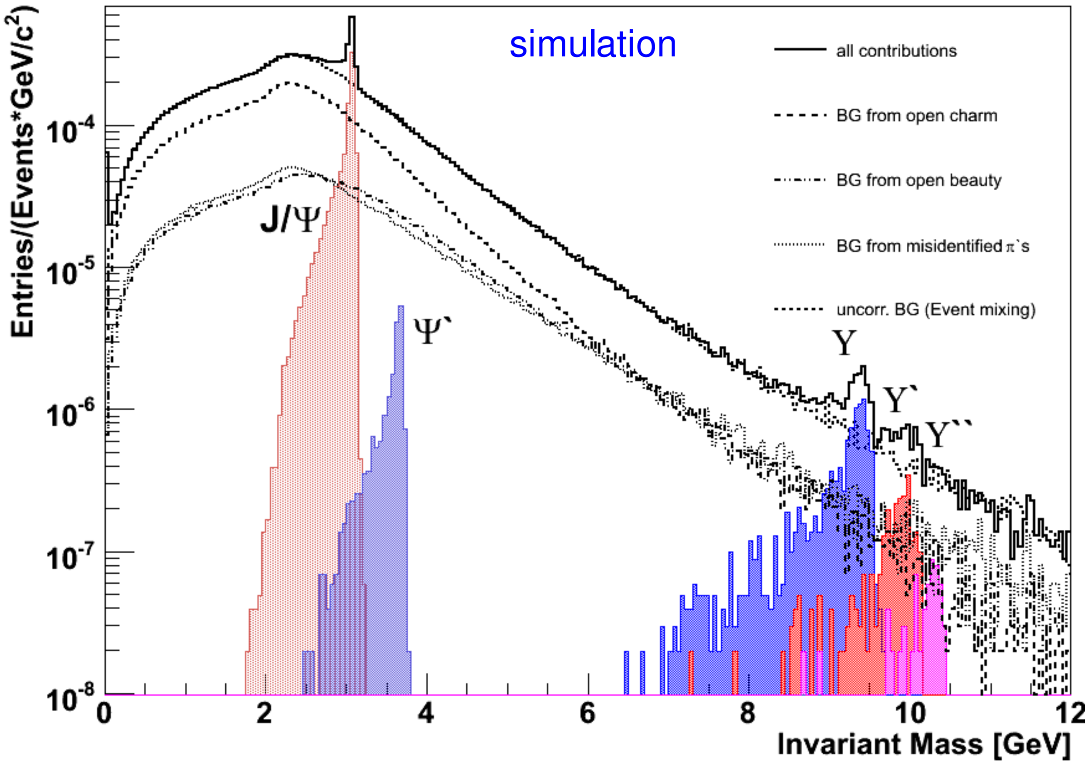
Rapidity window:
2.4–4.0

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

After combinatorial background subtraction :

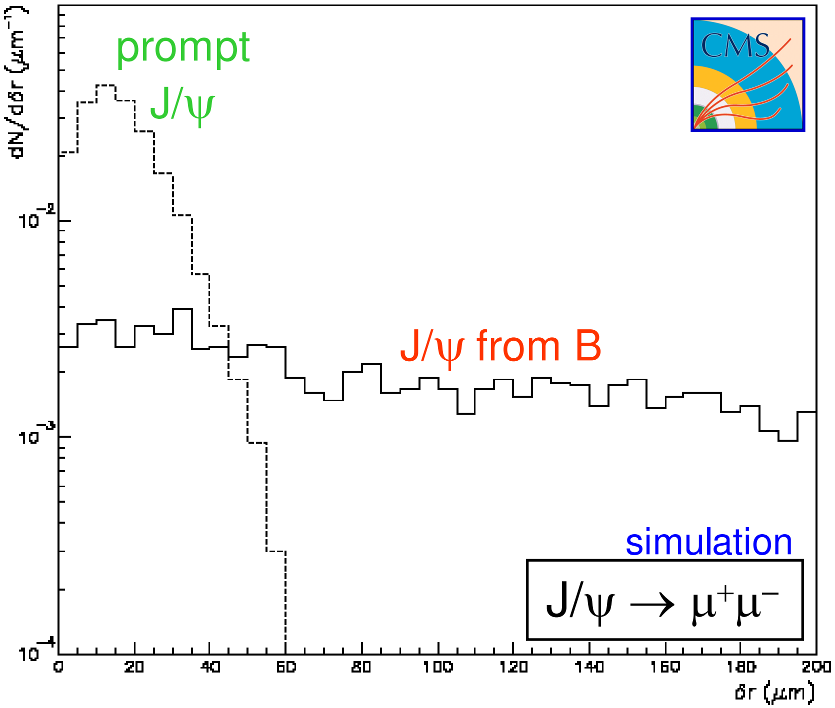


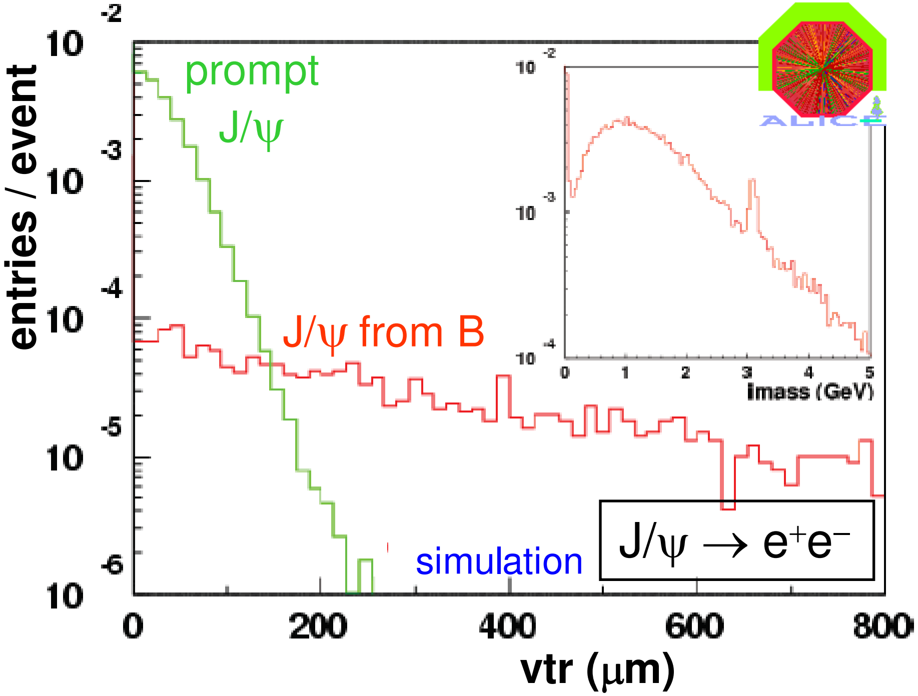
Quarkonia studies in ALICE with electron-positron pairs



Combining the ITS, TPC and TRD data, available for $|\eta| < 0.9$,
ALICE will have access to vertexing information for the electrons
(but not for the muons, contrary to CMS)

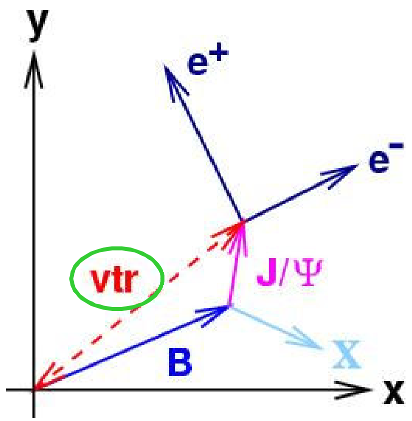
Measuring beauty yields from displaced J/ψ production





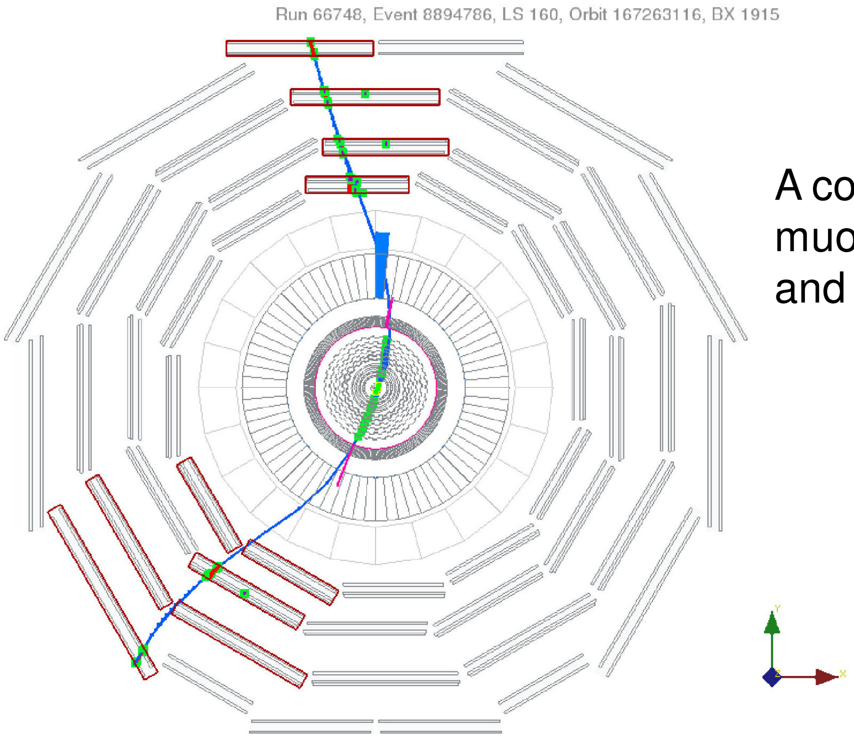
Many of the J/ψ mesons observed at the LHC come from decays of B mesons

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



Quarkonia studies in CMS

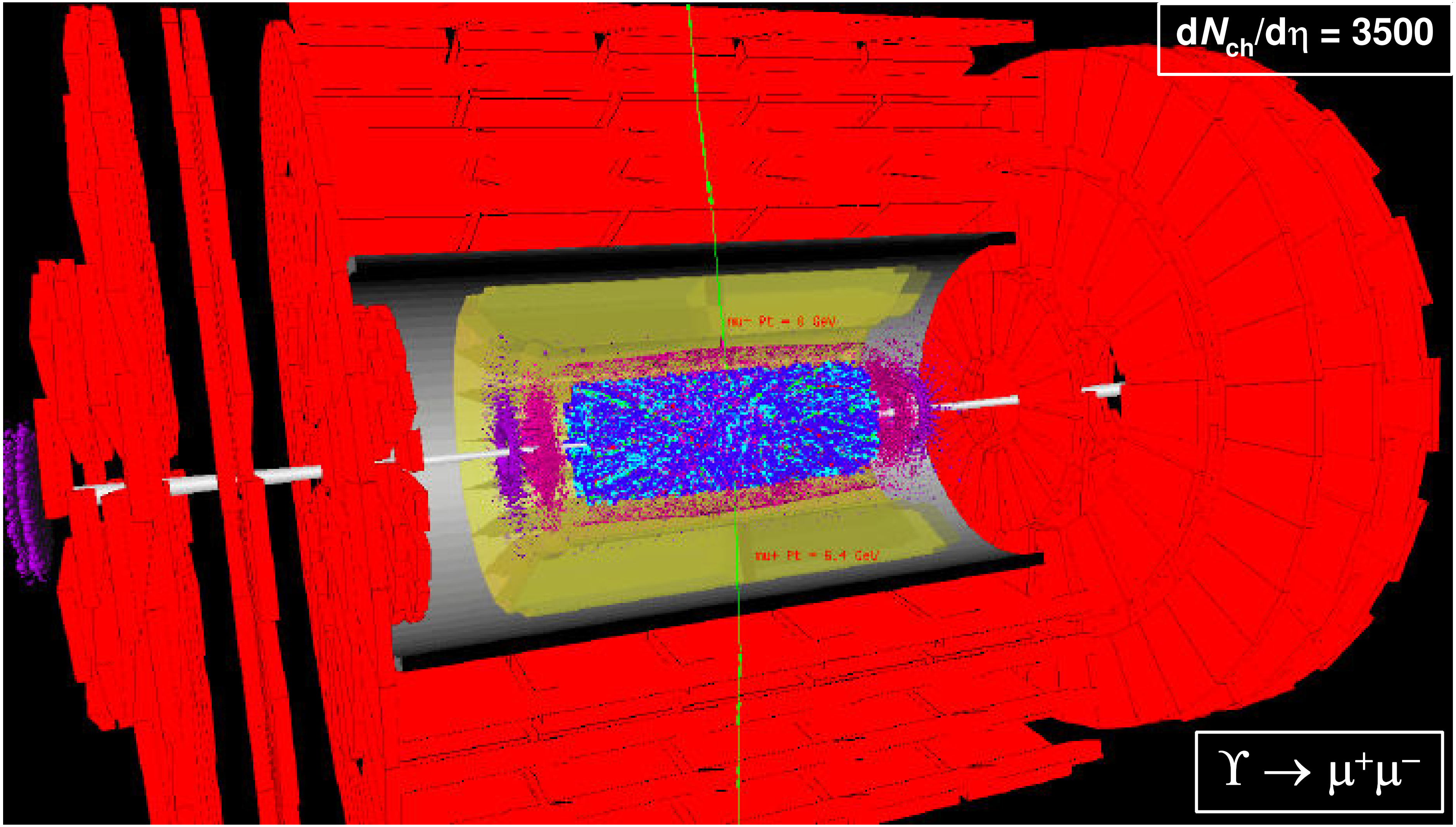
The physics performance has been evaluated with the 4 T field (2 T in return yoke) and requiring a good track in the muon chambers. The good momentum resolution results from the matching of the muon tracks to the tracks in the silicon tracker.



A cosmic muon that traversed the barrel muon systems, the barrel calorimeters, and the silicon strip and pixel layers

In 2008, CMS recorded almost 300 million cosmic muons in one month of 24 / 7 running, at full magnetic field and with all detectors operational

Pb-Pb → Υ + X event

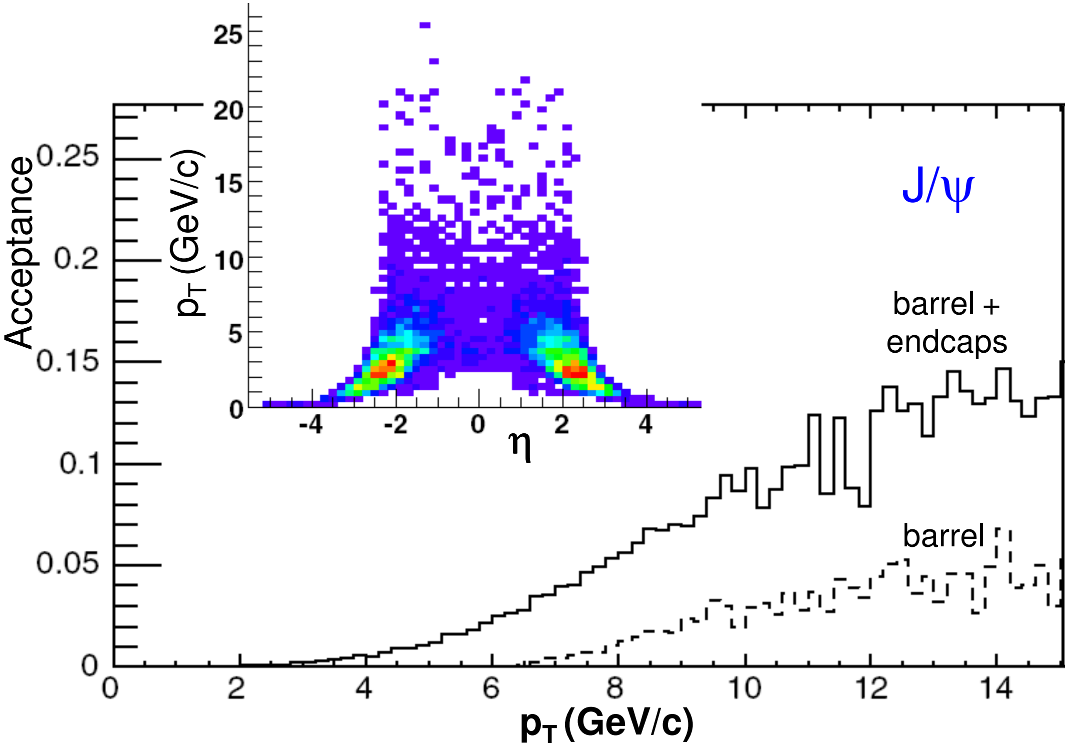


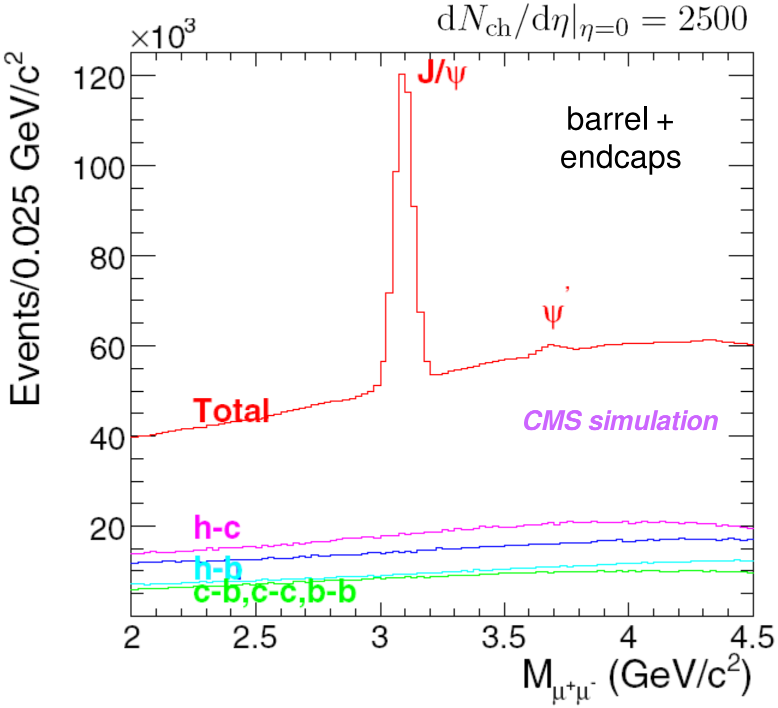
dN_{ch}/dη = 3500

Υ → $\mu^+\mu^-$

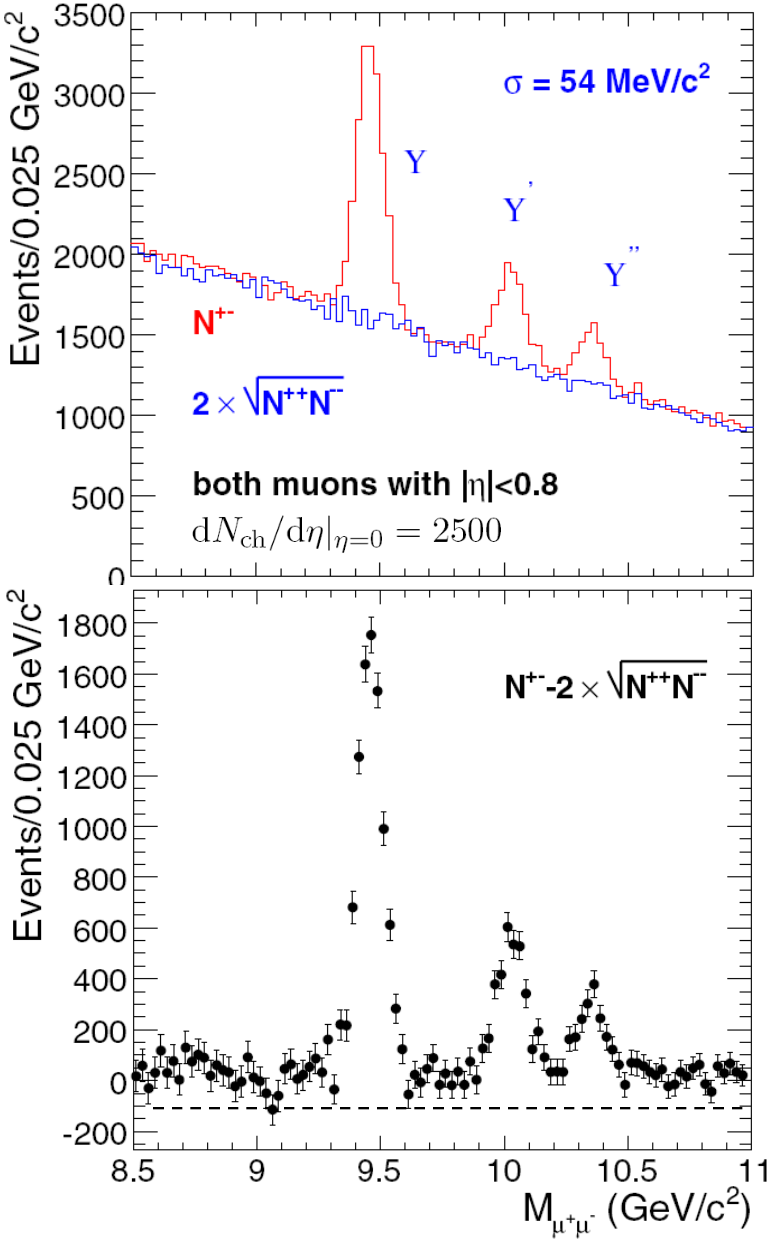
J/ψ → $\mu^+\mu^-$: acceptances and mass resolutions

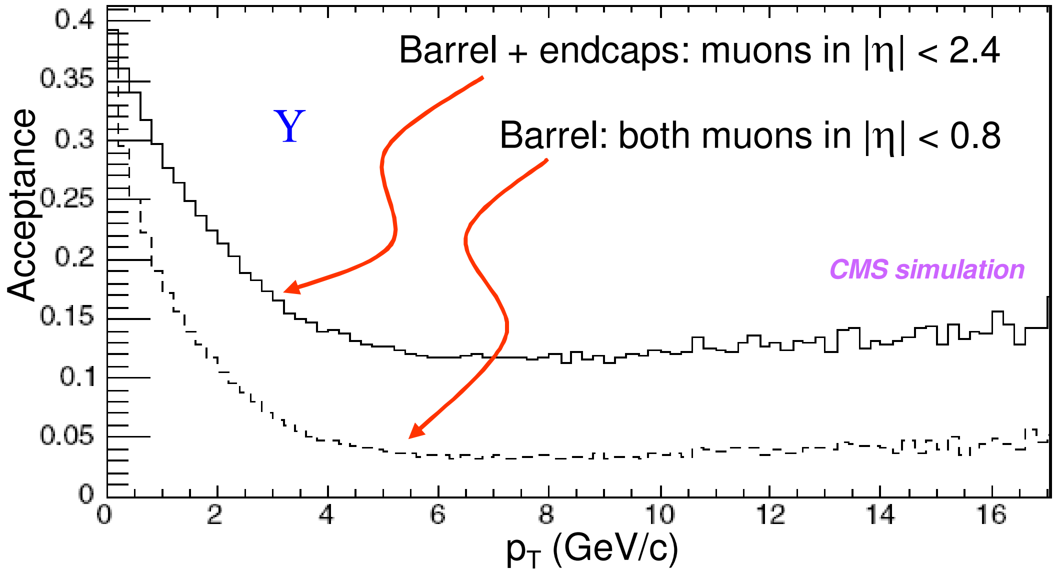
- The material between the silicon tracker and the muon chambers (ECAL, HCAL, magnet's iron) prevents hadrons from giving a muon tag but impose a minimum muon momentum of 3.5–4.0 GeV/c. This is no problem for the Upsilons, given their high mass, but sets a relatively high threshold on the p_T of the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





$\Upsilon \to \mu^+\mu^-$: acceptances and mass resolutions

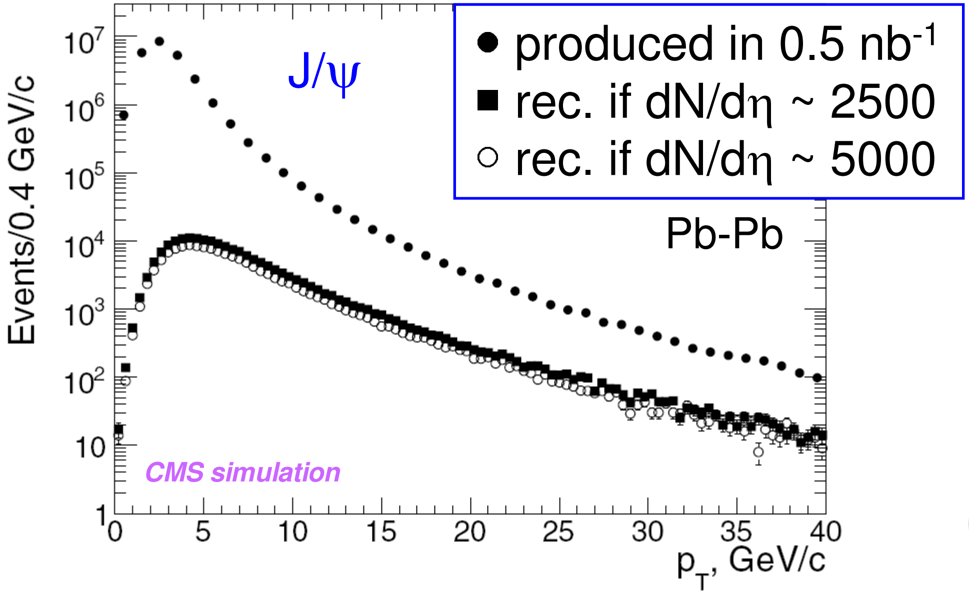




CMS has a very good acceptance for dimuons in the Upsilon mass region (21% total acceptance, barrel + endcaps)

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

p_T reach of quarkonia measurements

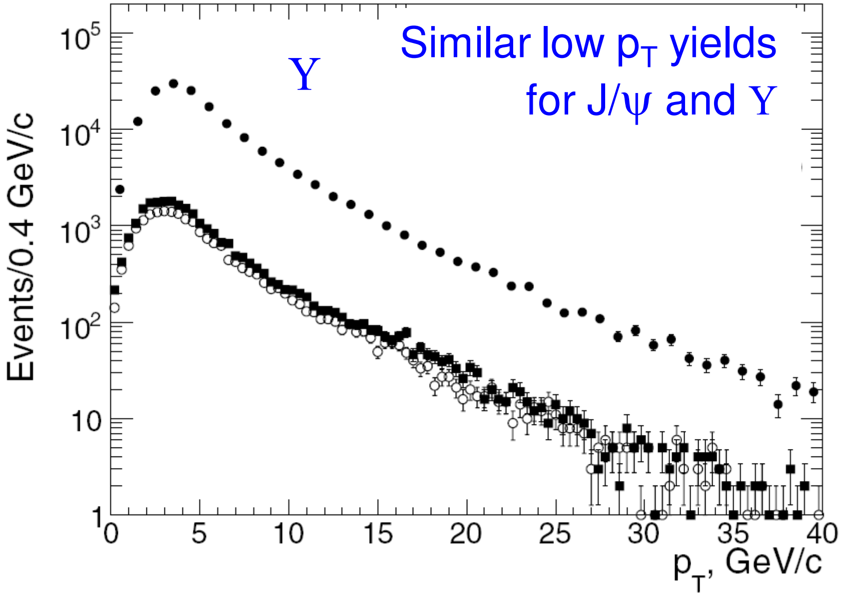


0.5 nb^{-1} : 1 month at 4x10^{26} cm^{2}s^{-1}

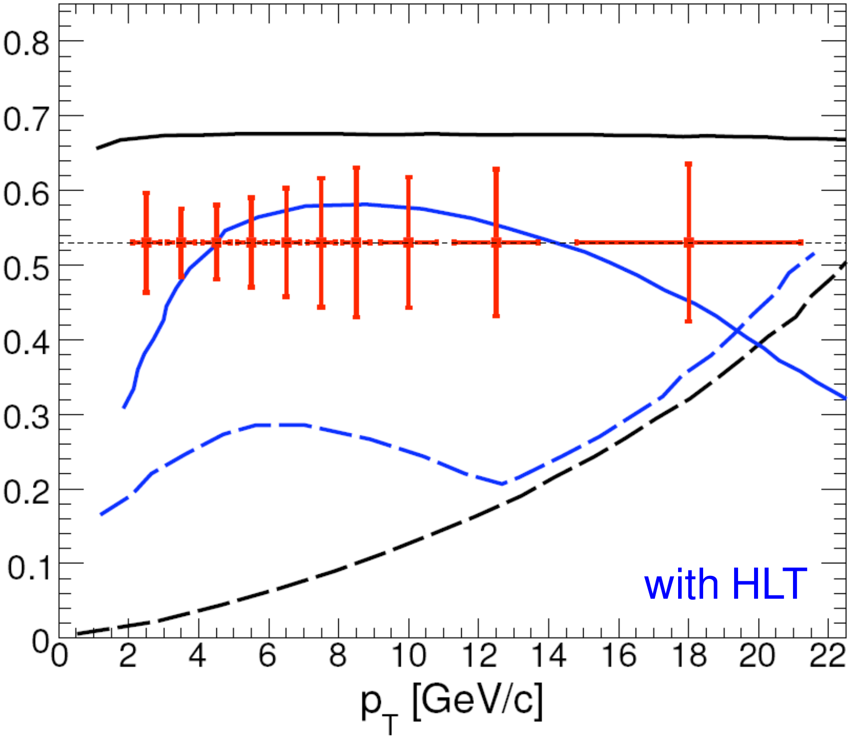
Expected rec. quarkonia yields:

J/ψ : ~ 180 000 Υ : ~ 26 000

Statistical accuracy (with HLT) of Υ' / Υ ratio vs. p_T should be good enough to rule out some models



Similar low p_T yields for J/ψ and Υ



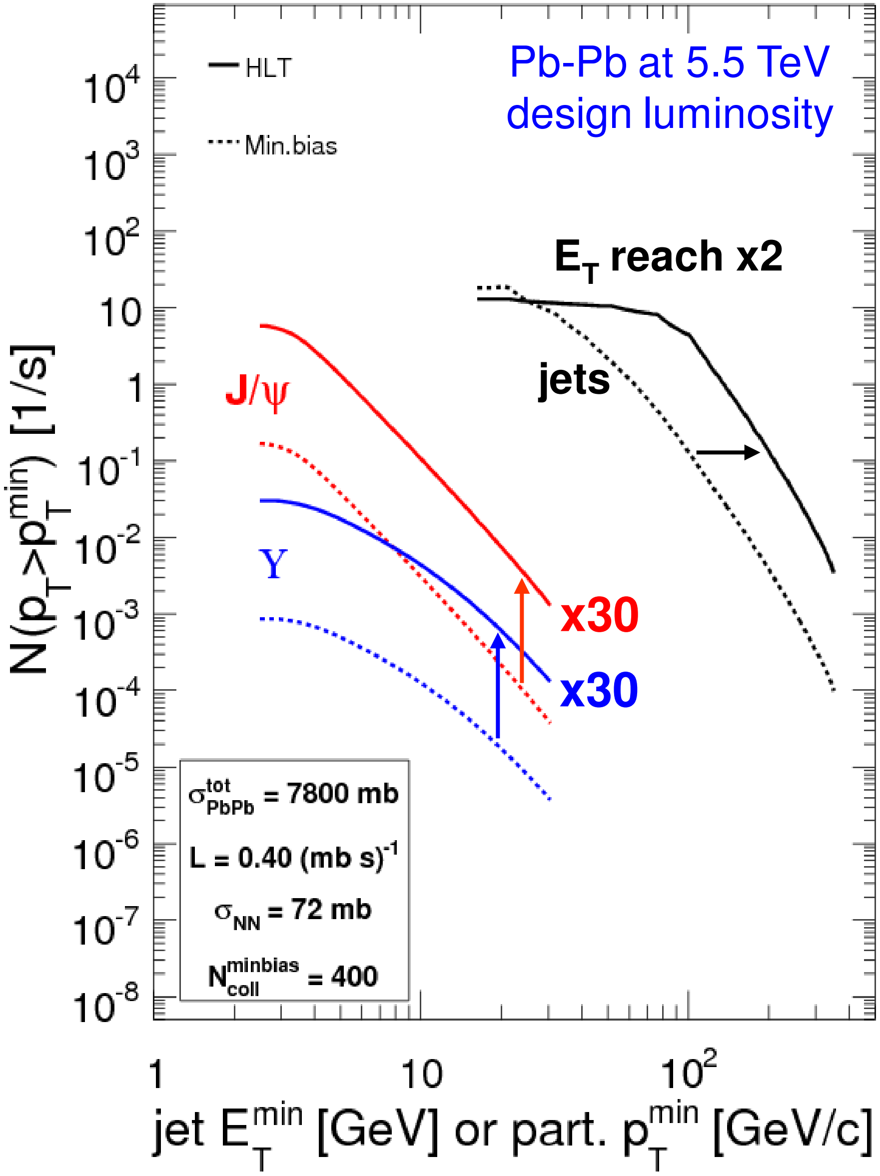
The CMS High Level Trigger

- CMS High Level Trigger:
  12 000 CPUs of 1.8 GHz ~ 50 Tflops !
- Executes "offline-like" algorithms

- pp design luminosity L1 trigger rate: 100 kHz
- Pb-Pb collision rate: 3 kHz (peak = 8 kHz)
  $\Rightarrow$ pp L1 trigger rate $>$ Pb-Pb *collision* rate
  $\Rightarrow$ run HLT codes on *all* Pb-Pb events

- Pb-Pb event size: ~2.5 MB (up to ~9 MB)
- Data storage bandwidth: 225 MB/s
  $\Rightarrow$ 10–100 Pb-Pb events / second
- HLT reduction factor: 3000 Hz → 100 Hz
- Average HLT time budget per event: ~4 s

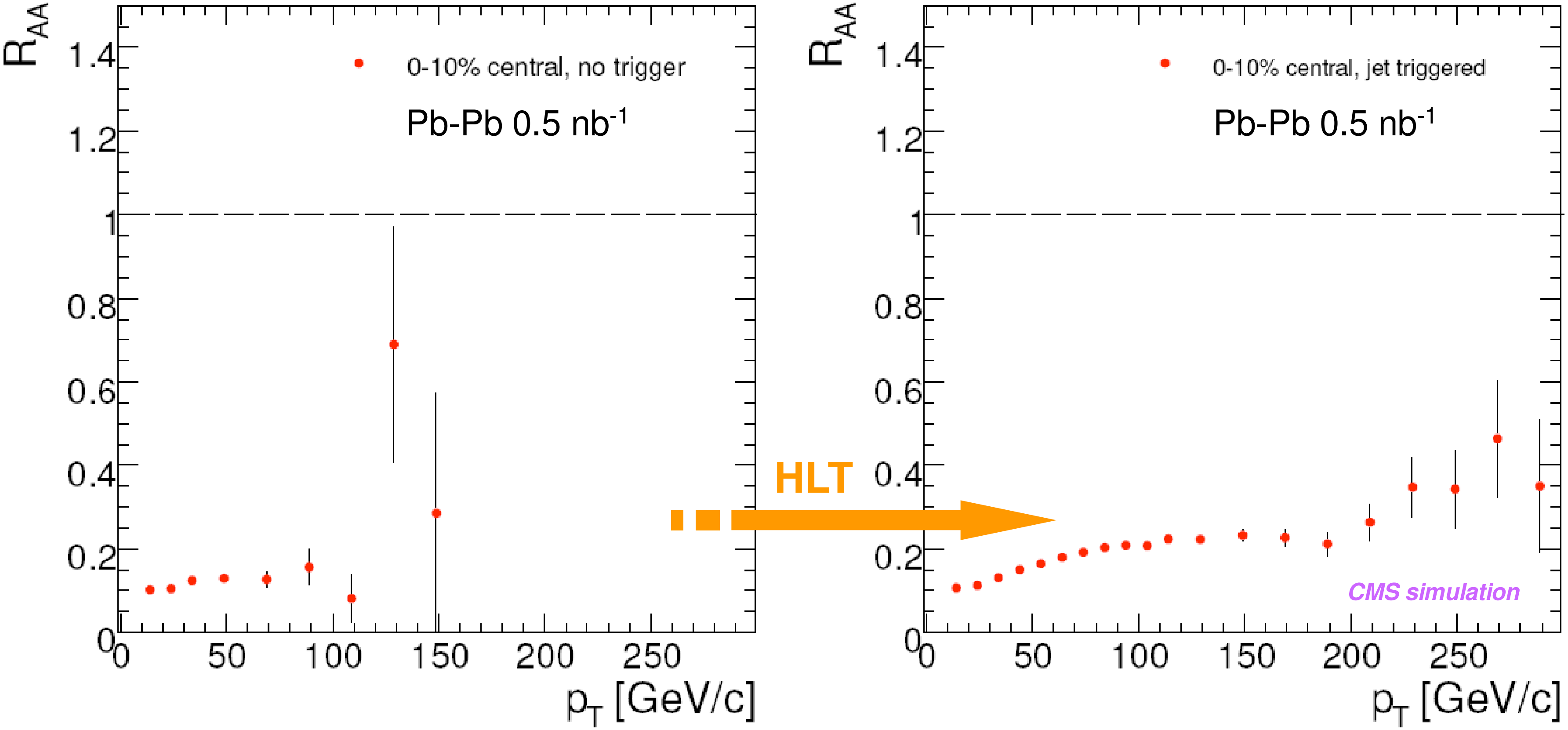
- Using the HLT, the event samples of hard processes are statistically enhanced by considerable factors



Impact of the HLT on the p_T reach of R_{AA}

Nuclear modification factor =
“QCD medium” / “QCD vacuum”

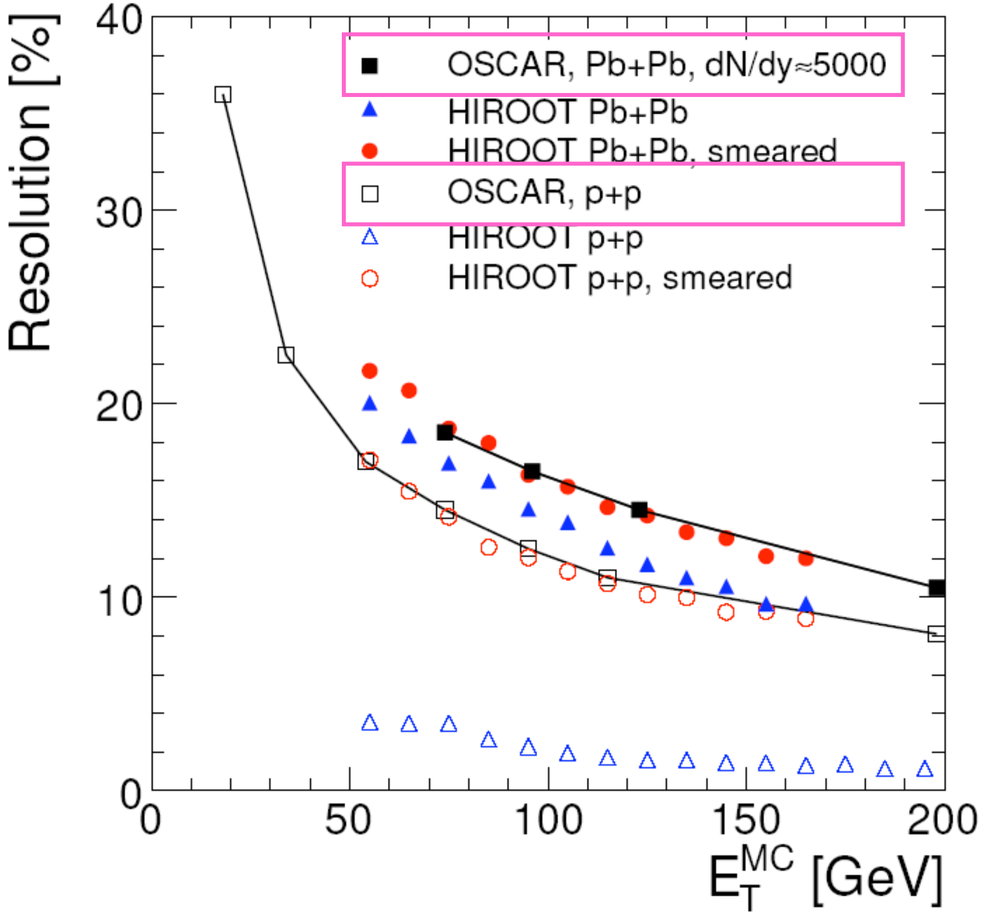
$$R_{AA}(p_T) = \frac{d^2N_{AA}/dydp_T}{\langle T_{AB}(b)\rangle \cdot d^2\sigma_{pp}/dydp_T}$$

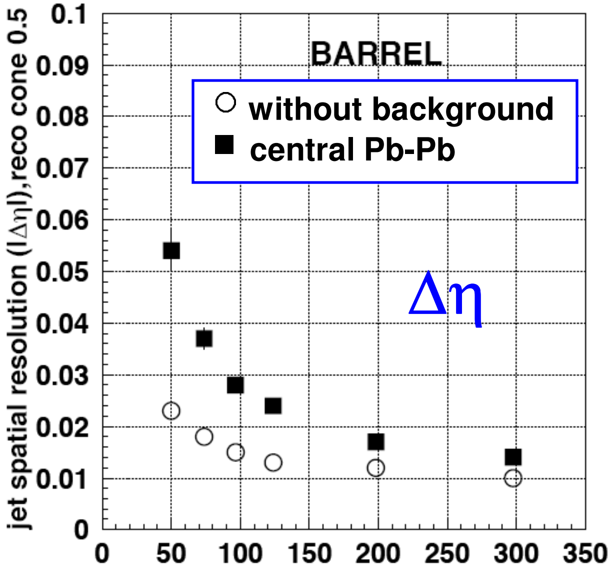


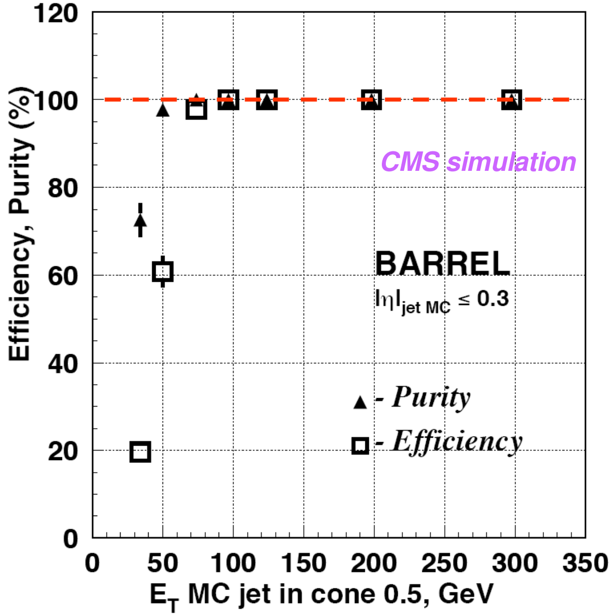
Important measurement to compare with parton energy loss models and derive the initial parton density, dN_g/dy, and the medium “transport coefficient”

Jet reconstruction, efficiency, resolution

- Iterative cone method plus background subtraction
- Jet spatial resolution in pseudo-rapidity and azimuth: better than 3% for $E_T > 100$ GeV
- The E_T resolution is ~10% in pp and ~15% for Pb-Pb

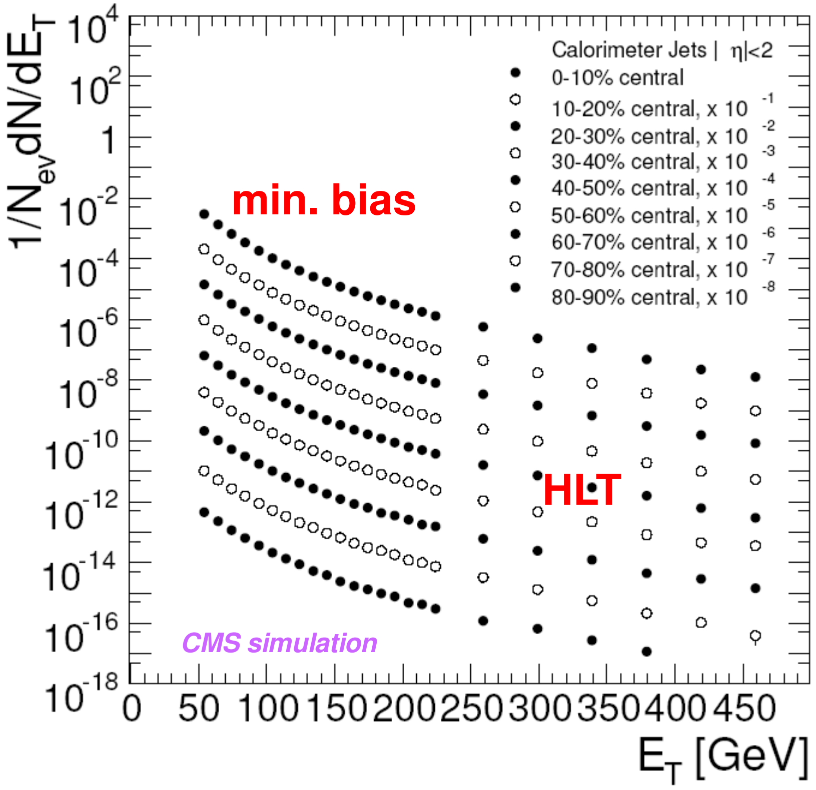






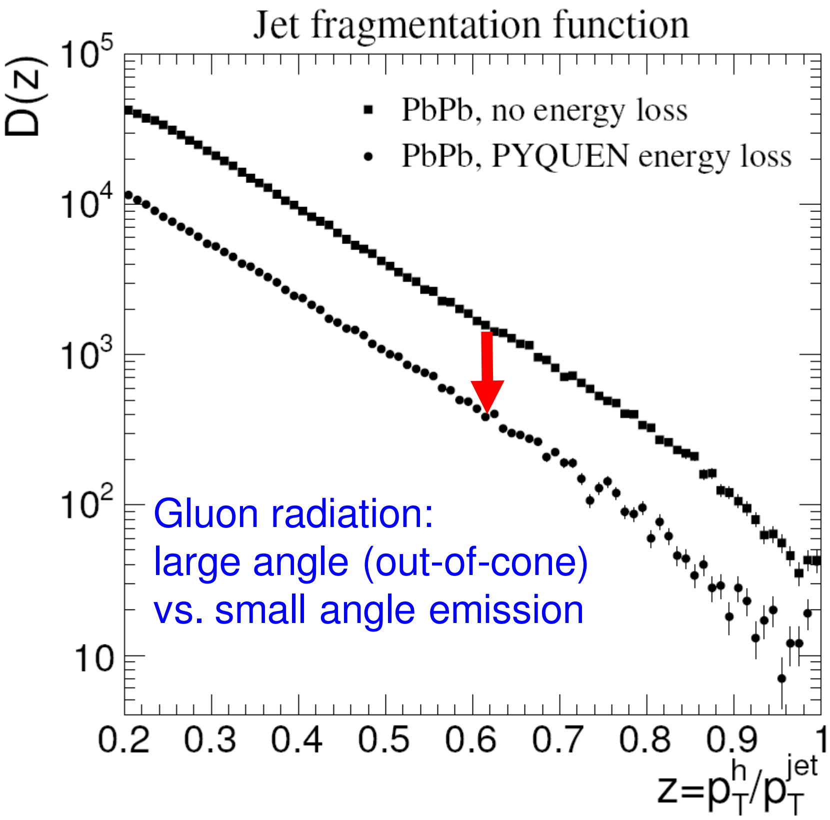
Jet E_T reach and fragmentation functions

Jet spectra up to E_T ~ 500 GeV (Pb-Pb, 0.5 nb^{-1}, HLT-triggered)
⇒ Detailed studies of medium-modified (quenched) jet fragmentation functions



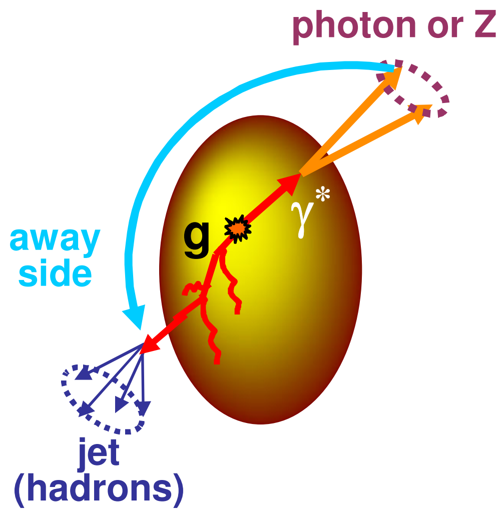
min. bias

HLT


Jet fragmentation function

Gluon radiation:
large angle (out-of-cone)
vs. small angle emission

γ, γ^* and Z tagging of jet production



The dense QCD medium redistributes the *initial* parton energy, E_{jet}, in the hadron jet

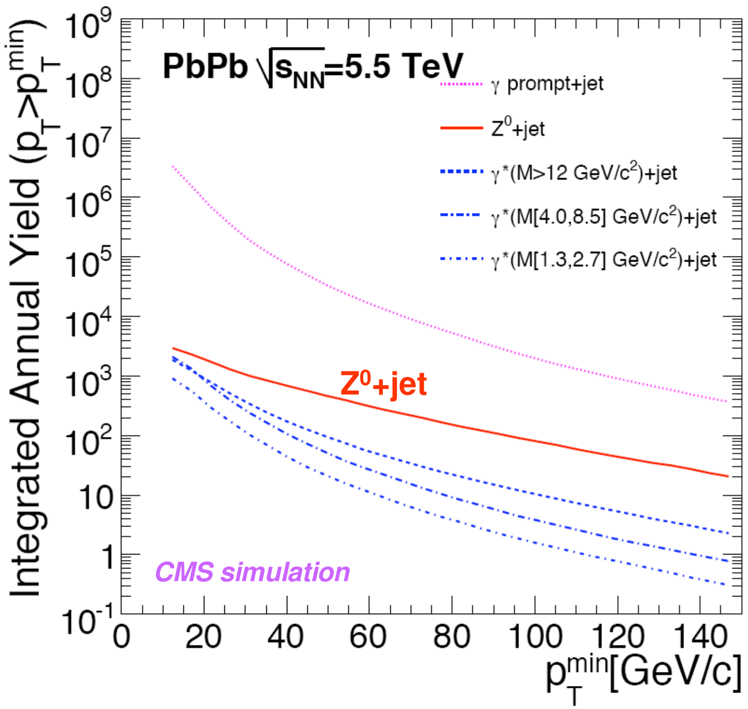
This redistribution is measured in the Fragmentation Function… if we know E_{jet}

But it is very difficult to access E_{jet} in HI collisions, because of the medium modifications…

Sometimes, the parton that fragments to a jet is produced back-to-back with a photon: $E_\gamma = E_{jet}$

Measuring the photon, unaffected by the medium, gives an ideal way to calibrate the jet energy loss

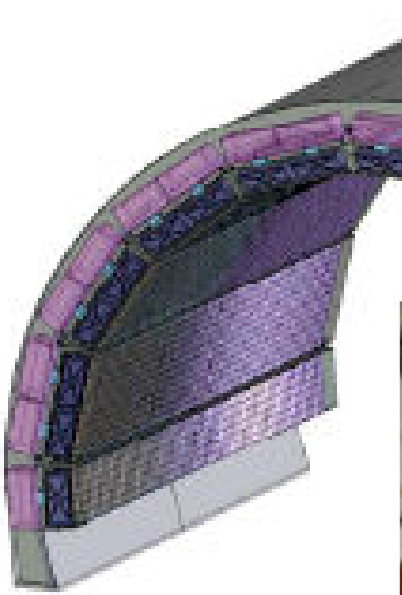
The Z^0 can also be used: large production cross sections at LHC energies and easy to detect



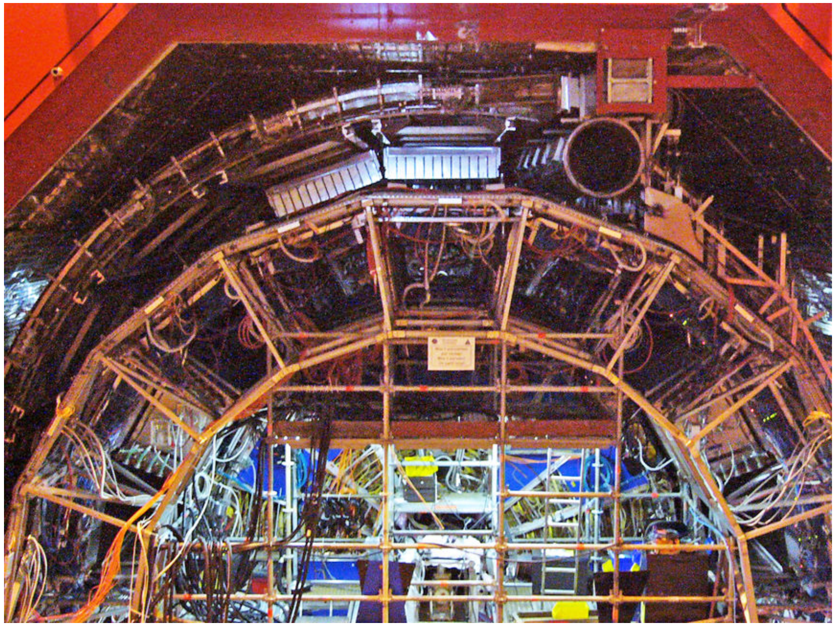
ALICE already had its first detector upgrade

Lead-scintillator sampling calorimeter
Shashlik fiber geometry
Avalanche photodiode readout

Coverage: |□|<0.7, □□ = 110°
~13k towers (□□x□□ ~ 0.014x0.014)
Design resolution: $□_E$/E ~ 1% + 0.08/√E

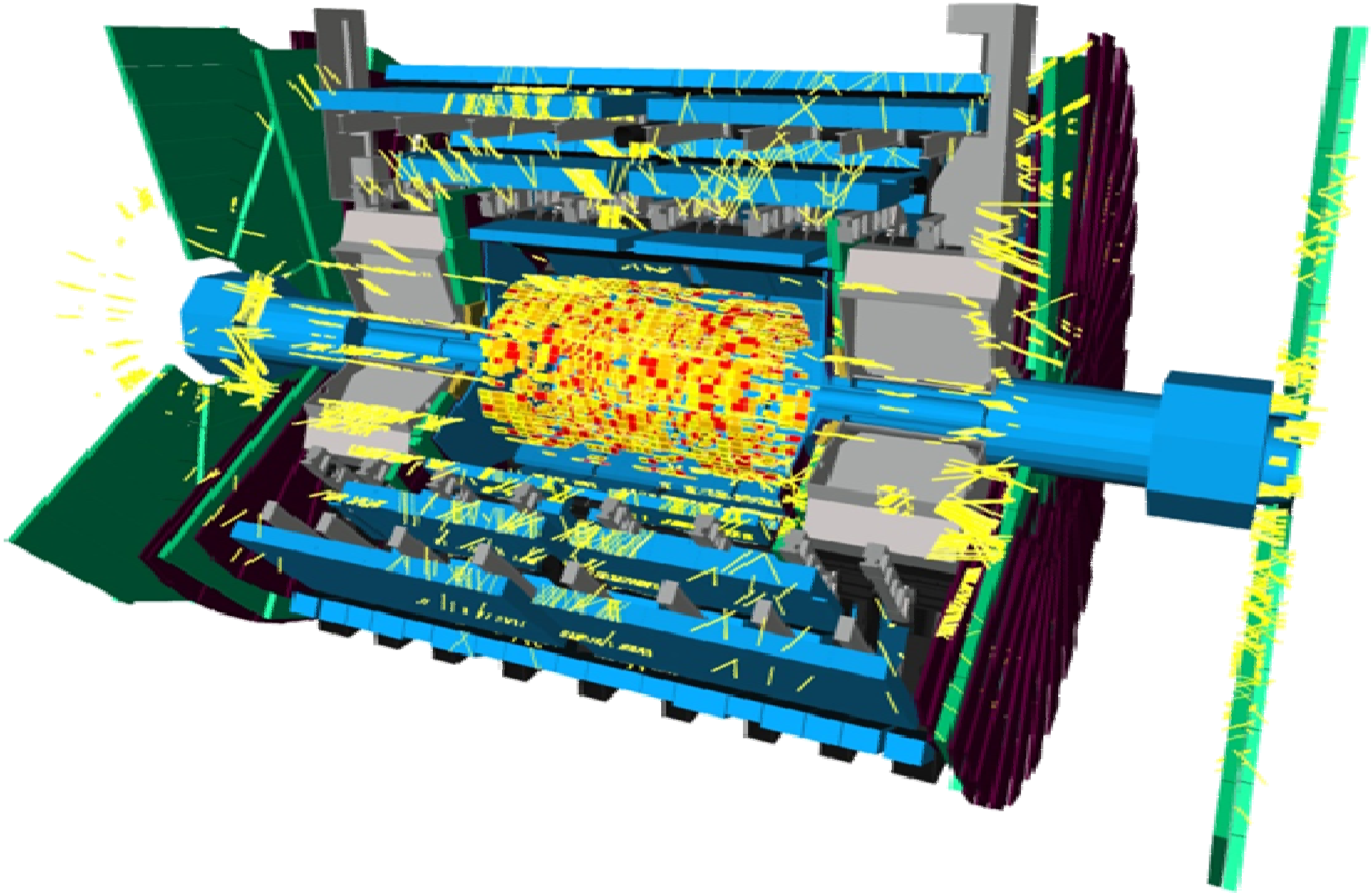


EMCal Module = 4 towers



The first two EMCal modules (out of 12) were installed in March 2009 between the magnet and the “space frame” that holds the TPC and other central detectors

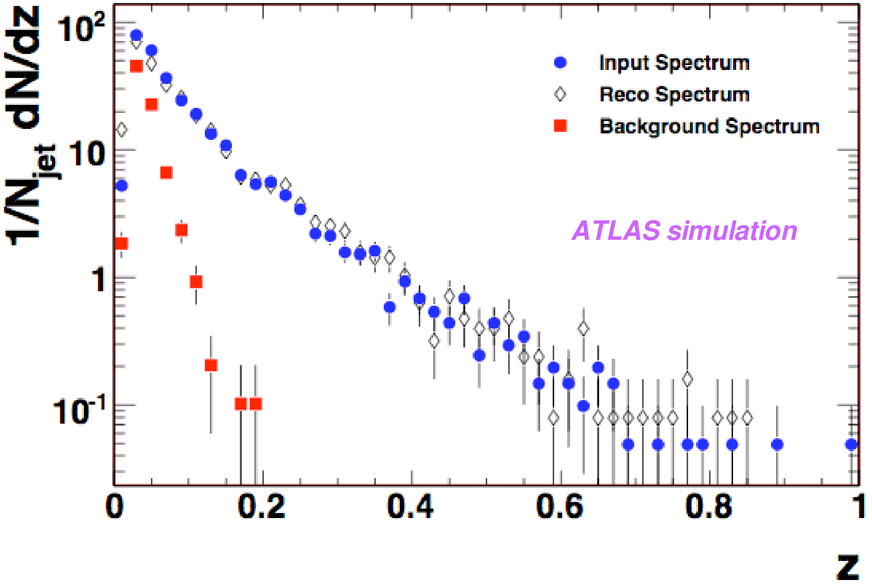
ATLAS will also study QGP physics with Pb-Pb collisions

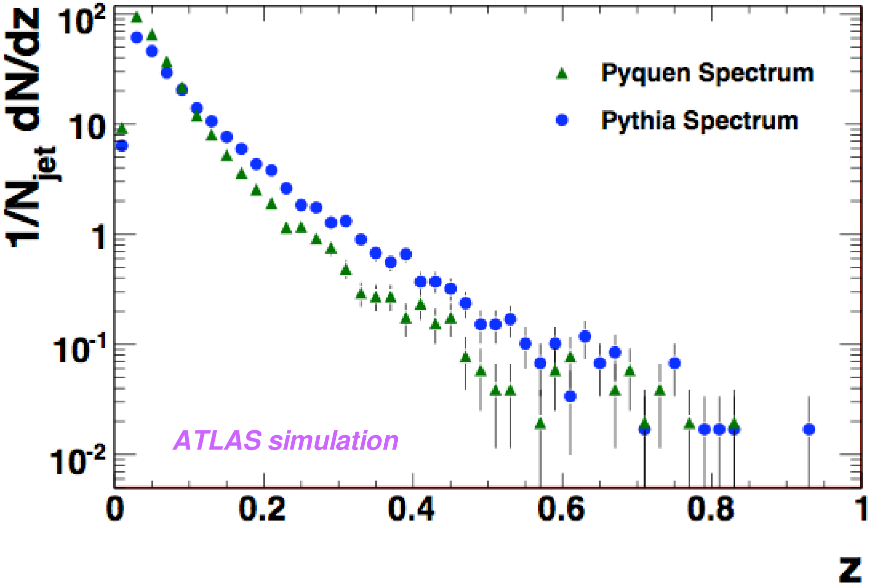


- ATLAS is fully operational and recorded several hundred million cosmic events
- Extensive preparations for the Pb-Pb program show a promising performance

ATLAS will measure jets in Pb-Pb collisions

Fragmentation function: D(z)





Reliable reconstruction of *D(z)*:
Reconstructed tracks with $p_T > 2$ GeV matching calorimeter jets

Comparing PYTHIA to PYQUEN gives the scale of possible modifications of the fragmentation function in Pb-Pb

ATLAS can measure jet quenching of the size simulated by PYQUEN

Lessons from the SPS and RHIC to the LHC

Before the measurements are made,
theorists often think that the interpretation
of the data will be easy
However, theorists are often wrong…
especially before the measurements are made

This is a data-driven field; based on the SPS and RHIC “learning curves”, we now have clear directions concerning the path to follow at the LHC...

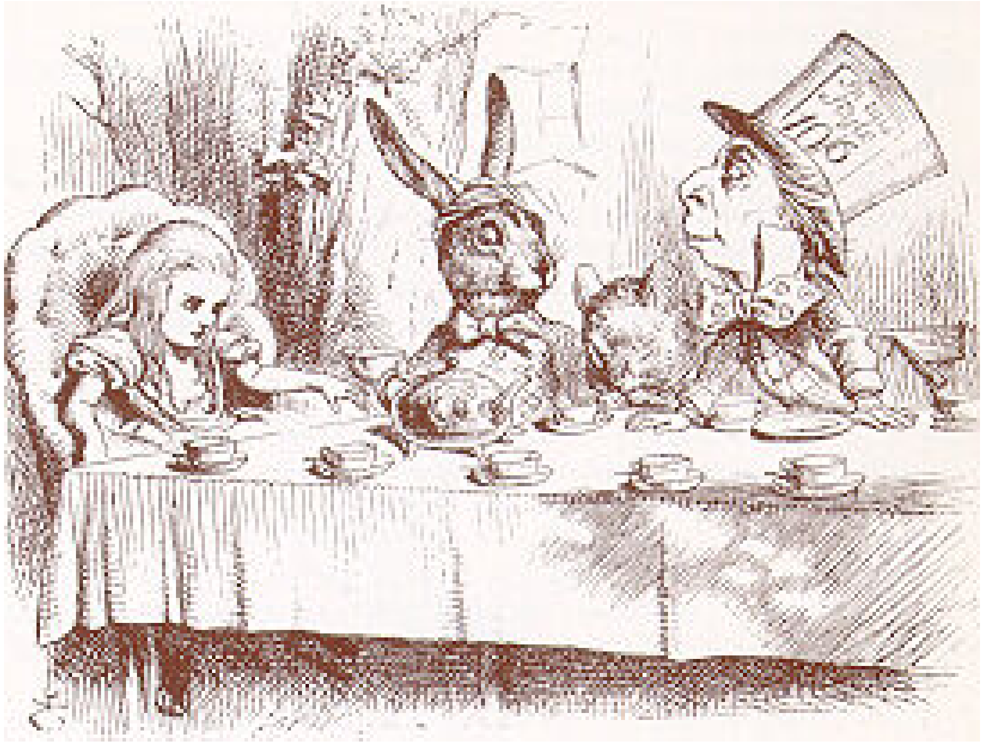
We *will* find the way out...

We are looking forward to
“take some more” LHC collisions…

“Take some more tea”, the March Hare said to Alice, very earnestly.

“I've had nothing yet”, Alice replied in an offended tone, “so I can't take more”.

“You mean you can't take LESS”, said the Hatter:
“it's very easy to take MORE than nothing”.



Lewis Carroll, Alice in Wonderland

We are looking forward to
“take some more” LHC collisions…