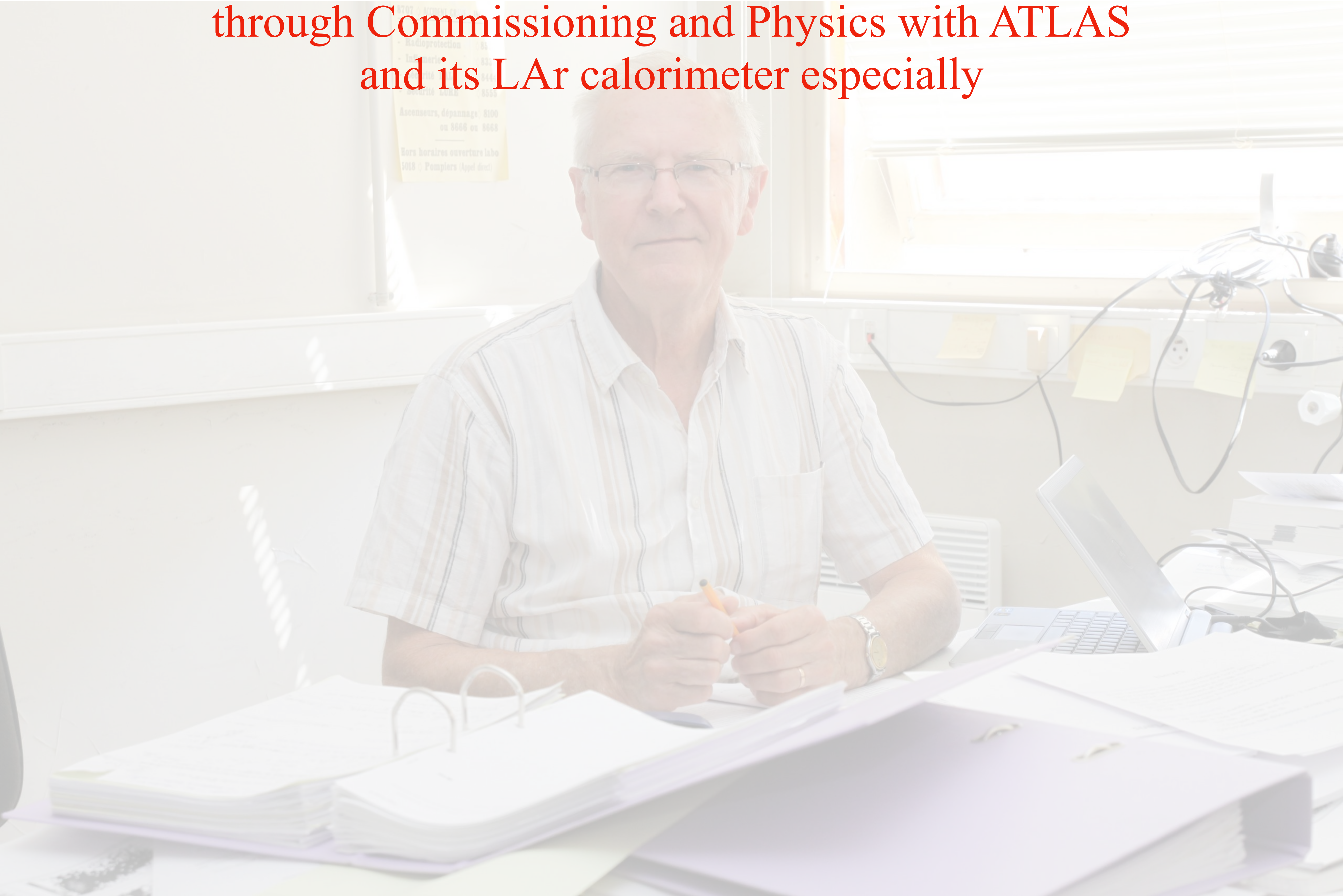
A journey with Daniel
through Commissioning and Physics with ATLAS
and its LAr calorimeter especially

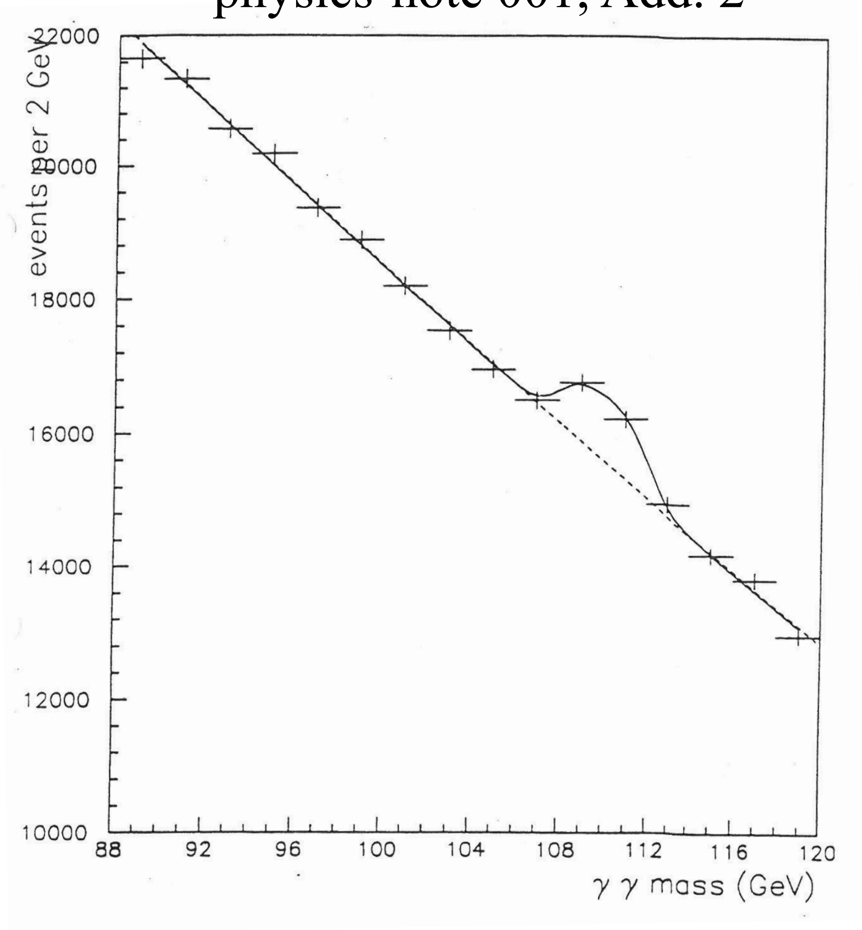


The no-loose theorem, a long time ago

After LEP, if the Higgs boson is still missing, a hadron collider with $\sqrt{s} \gtrsim 10$ TeV should discover it whatever its mass ($\lesssim$ TeV) or observe new (strong) interactions at E ~ TeV $\Rightarrow$ **LHC**

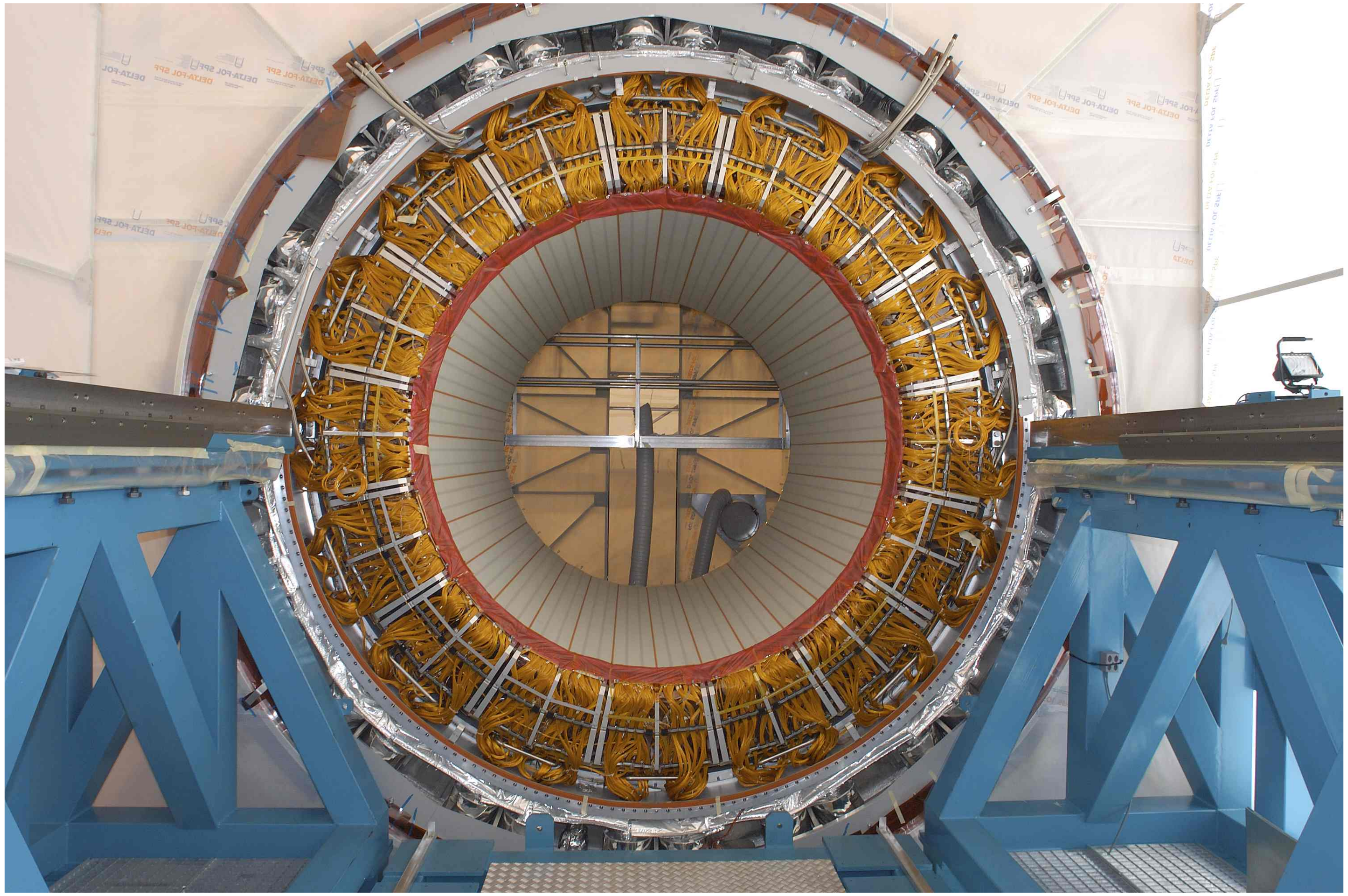
At low mass, the di-photon decay $H \to \gamma\gamma$ is one of the most promising channels.
People wanted to see something like this (1991) :

Ascot/Eagle,
physics-note 001, Add. 2



Sets the requirements for the EM calorimeter :
- a good energy resolution (10%/$\sqrt{E}$ sampling term and < 1% constant term)
- with fine granularity for background rejection (lateral segmentation) and pointing (longitudinal segmentation)

Since 2005, the LAr calorimeter is in place in the ATLAS pit and collecting data…

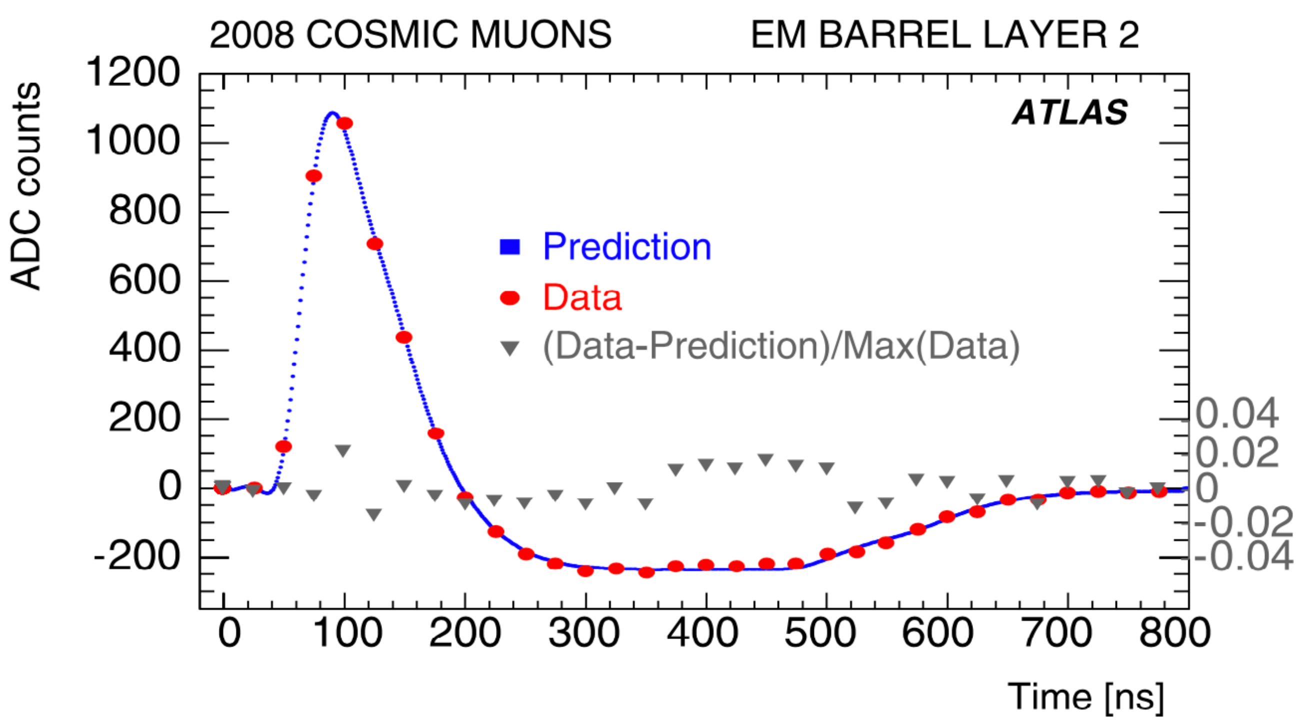


⇒ Can we reach the initial goal with this object ?

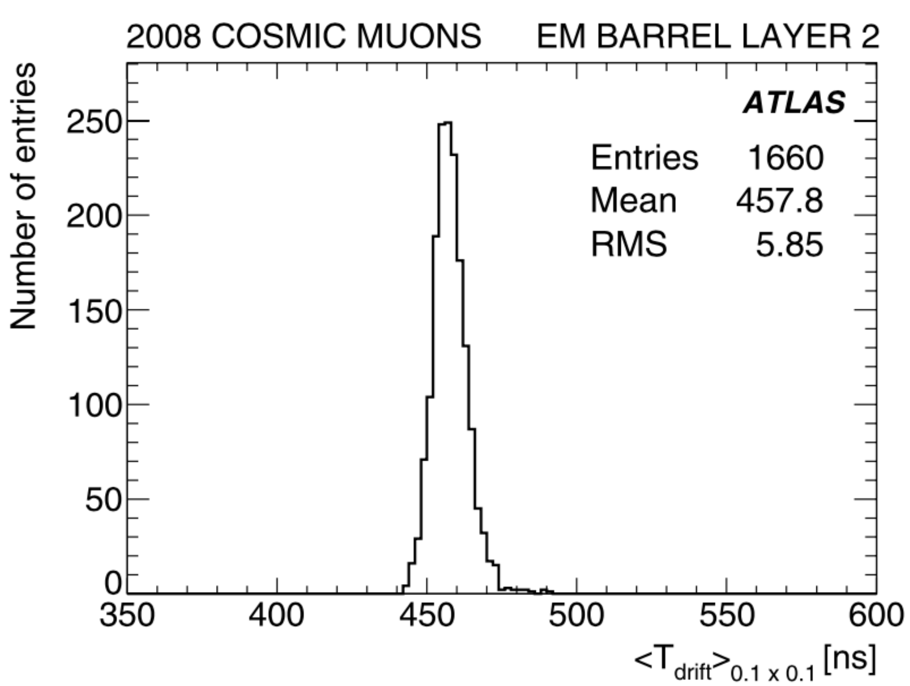
Uniformity from drift time measurements with cosmic muons

With Sophie, Caroline, Pauline, Marumi, Guillaume, among others

A typical pulse recorded in the barrel calorimeter



Using « first principle method » FPM prediction
(pulse shape description using electronics characteristics measured properties of detector cells)
to extract drift time (→ gap width)



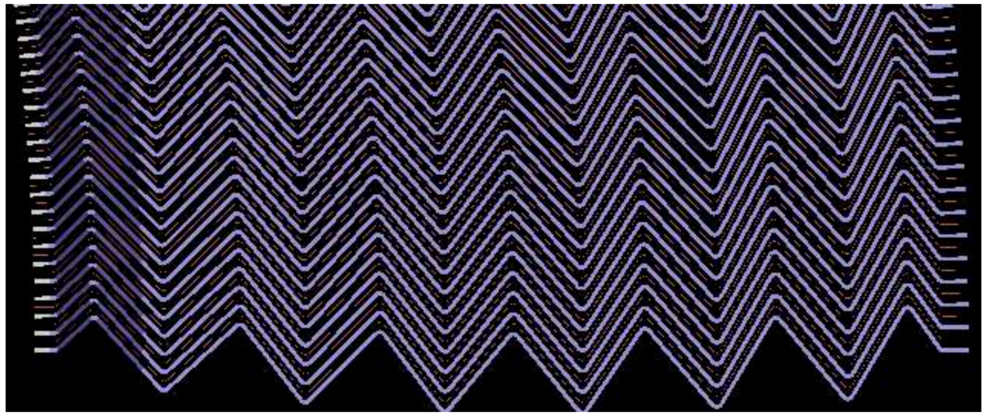
⇒ drift time uniformity ~ 1.28%,
translated into a contribution to the energy response uniformity of ~ 0.29%

Daniel pushed a lot the FPM method with many young contributors,
that allowed to discover / measure very subtil effects (electrode displacements, etc…)

Measuring sagging using drift time !

With Xifeng, Zhiqing

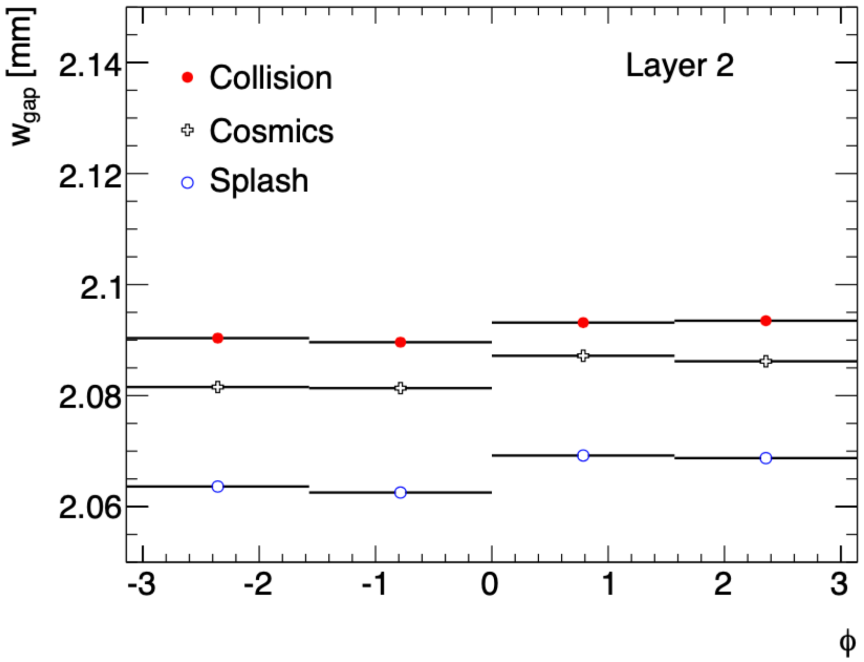
The LAr sandwich is not very rigid…
Due to gravity, more compressed at $\varphi < 0$



$\Rightarrow$ impact on response uniformity ?

Repeat previous analysis with collisions / splashes

Link Drift time ↔ gap
$T_D \sim (w_{gap})^{1+\alpha}$



Larger gap at $\varphi > 0$ as naively expected !

But seems to depend on data type 🤔 ?
Well, reasons can be invented to justify this…

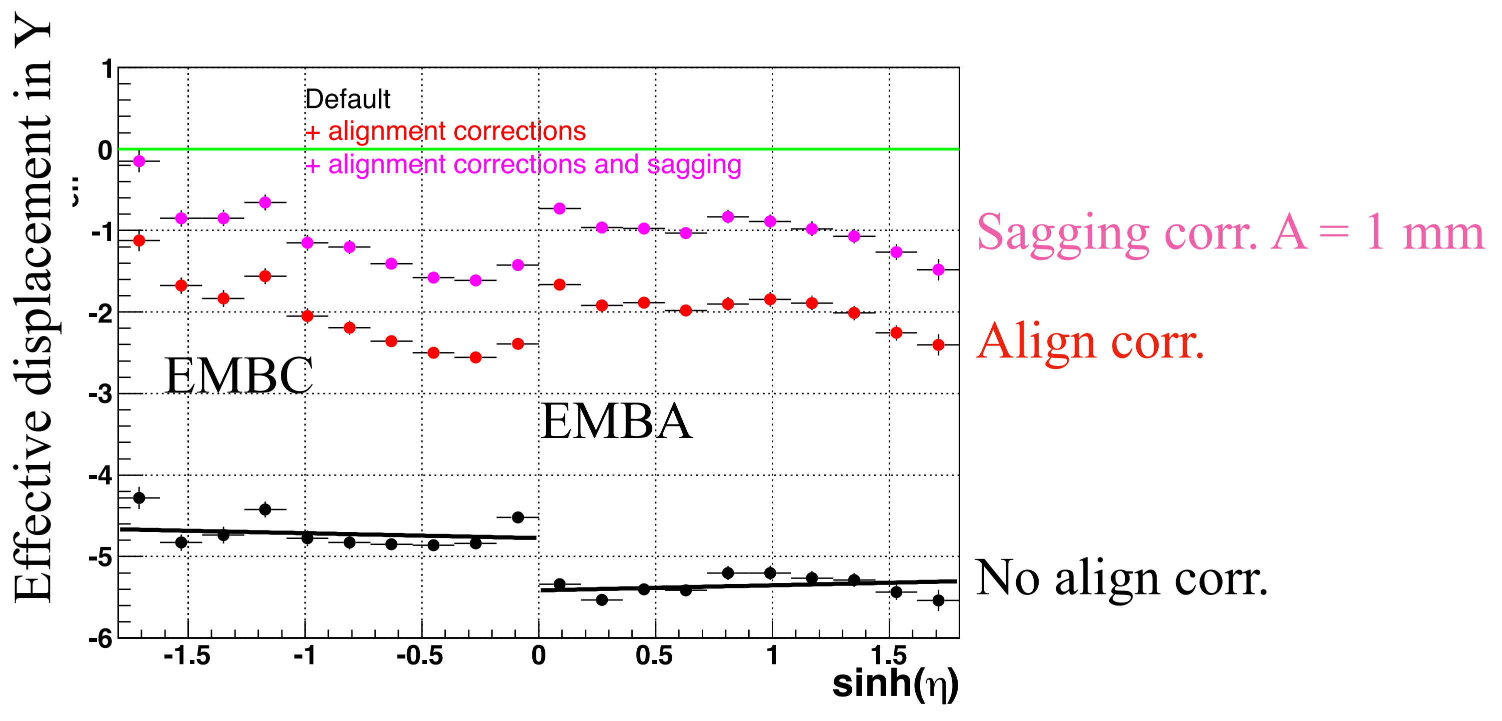
The amplitude of the sagging can be determined from this measurement
A ~ 1.2 - 2.1 mm,
compatible with mechanical computations

The LAr - ID inter-alignment saga

With Yu, Sandrine, Rémi, Guillaume, Martin, JB and others

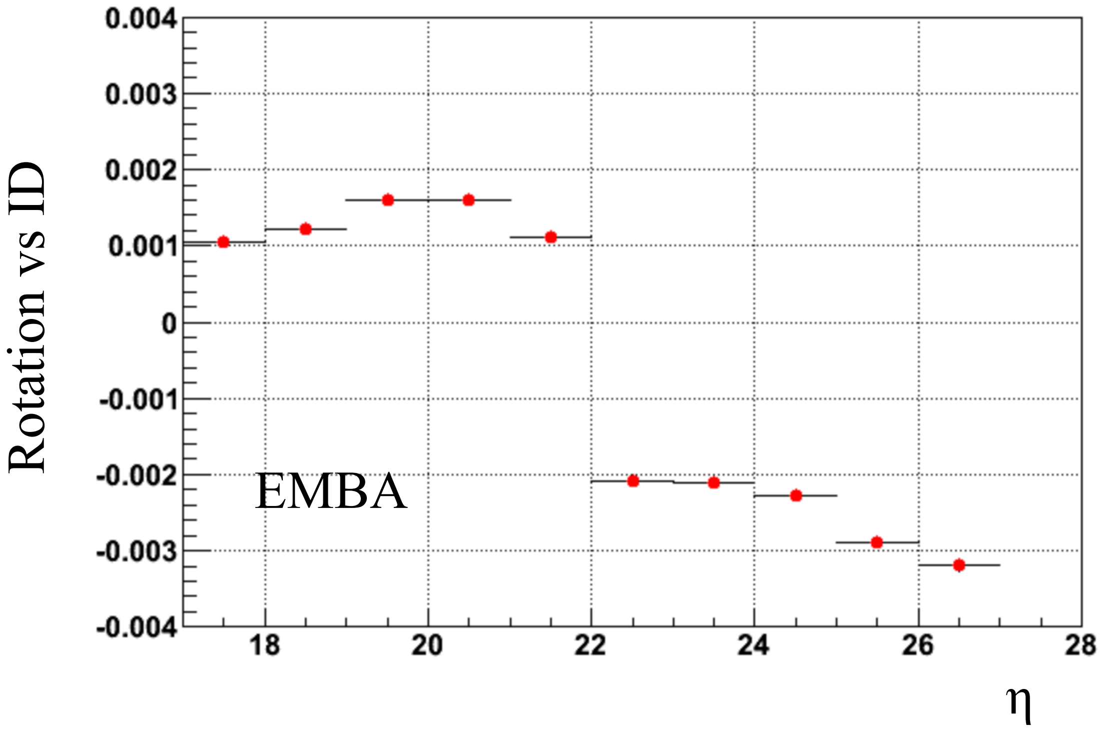
For a good electron identification (cluster-track match, bremsstrahlung recovery) the position of the LAr w.r.t. ID needs to be known with some accuracy…

⇒ compare impact of track extrapolation in calo and cluster position, correct for differences



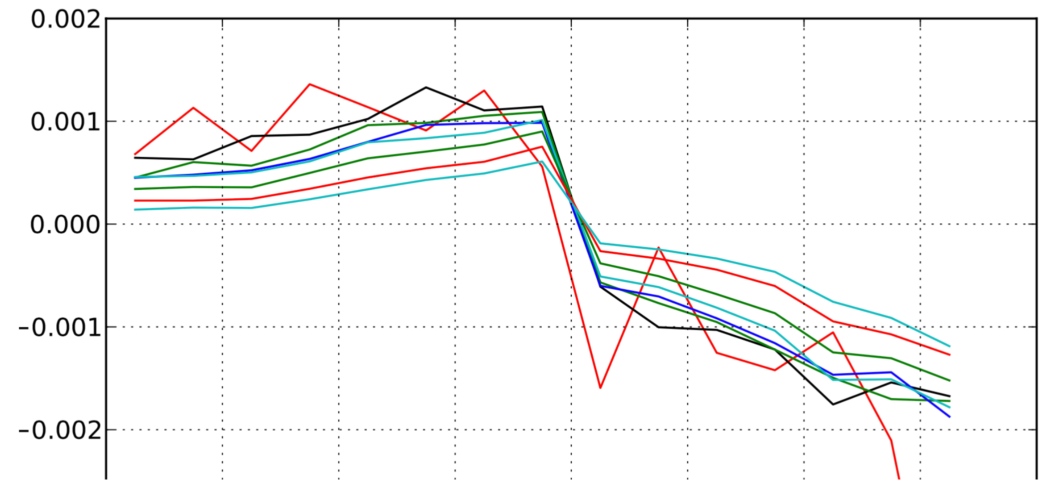
⇒ suggest A ~ 2 mm, compatible with extraction from drift time !

The LAr rotation and debugging the simulation…



Supposed to be flat : cannot twist the calo that much !

On the other hand, weirdly similar in shape to the phi-offset correction :



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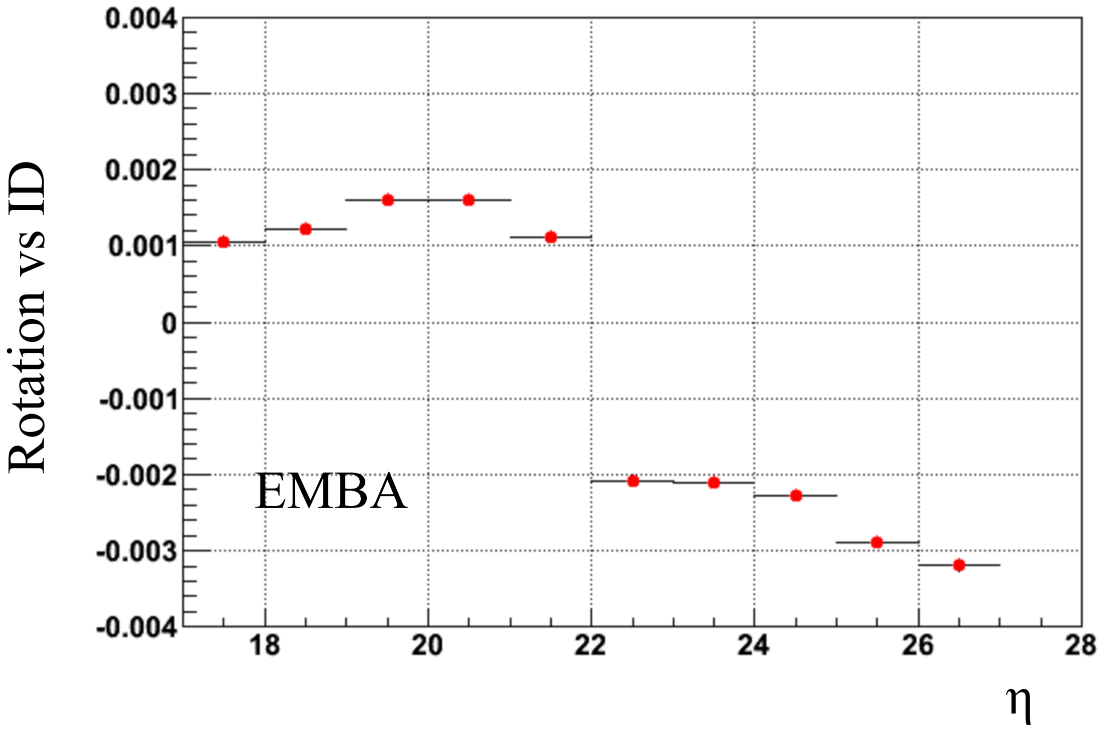

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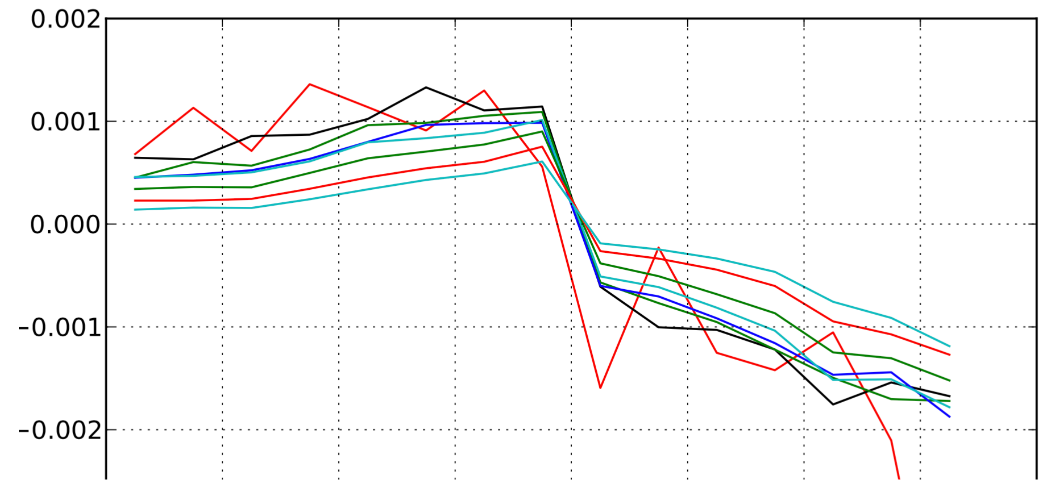


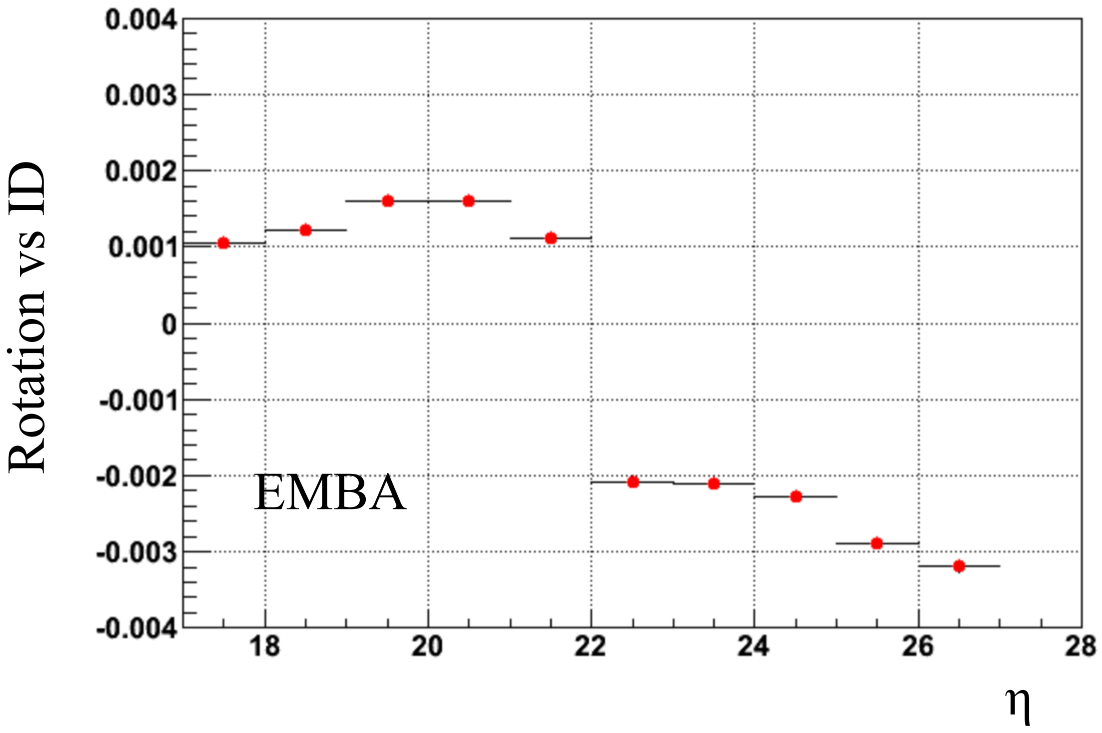
From Guillaume :

J'ai mis Daniel en copie pour la question sur le signe du premier zig-zag des accordéons.

Si je suis un peu audacieux, peut on en conclure qu'il faudrait appliquer aux données la correction avec le signe opposé ? (les données après correction ont un effet presque deux fois la taille de la correction)

Est-il possible qu'on se soit trompé sur la direction du premier zig-zag et donc qu'on génère dans le MC des corrections avec des signes opposés par rapport aux data ?

The LAr rotation and debugging the simulation…



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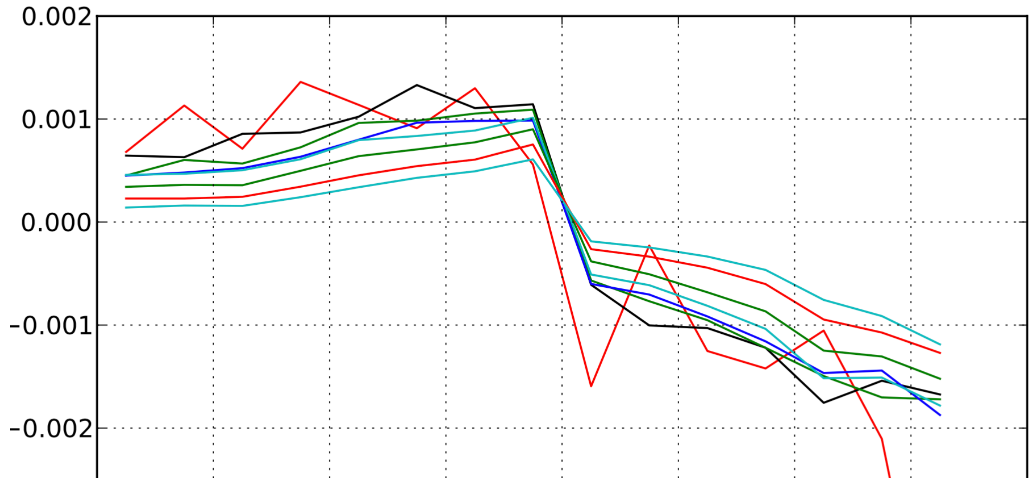
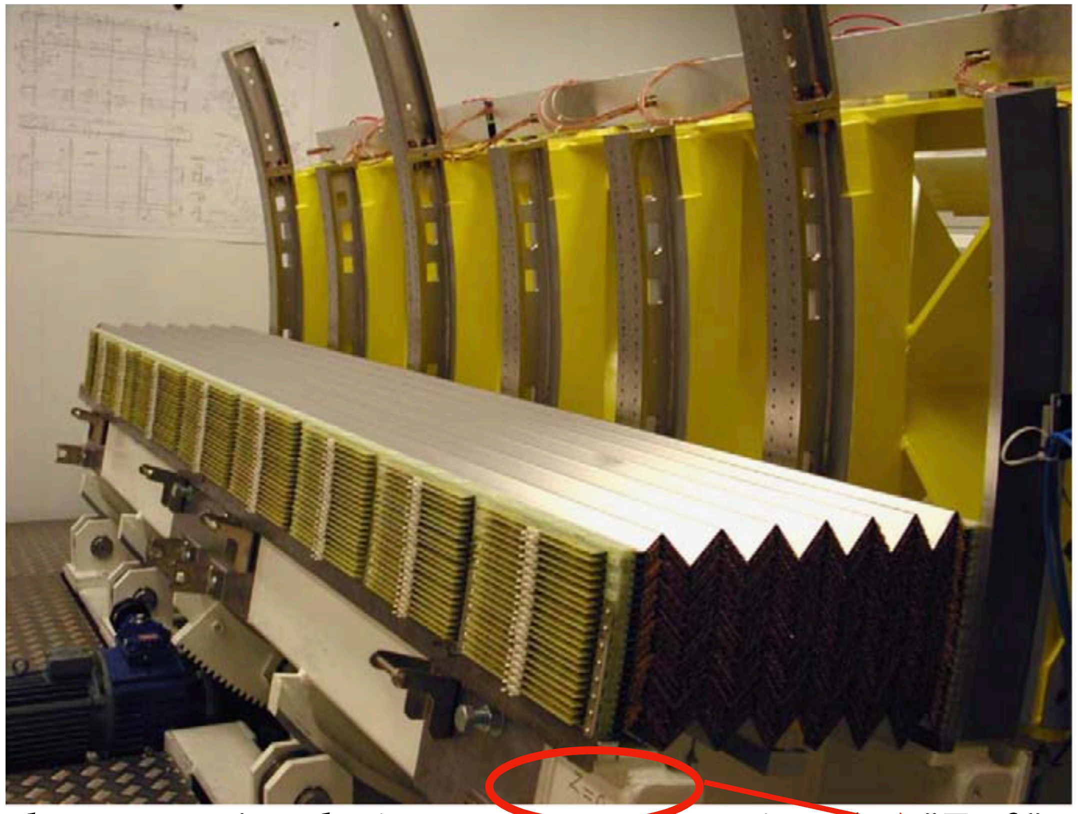
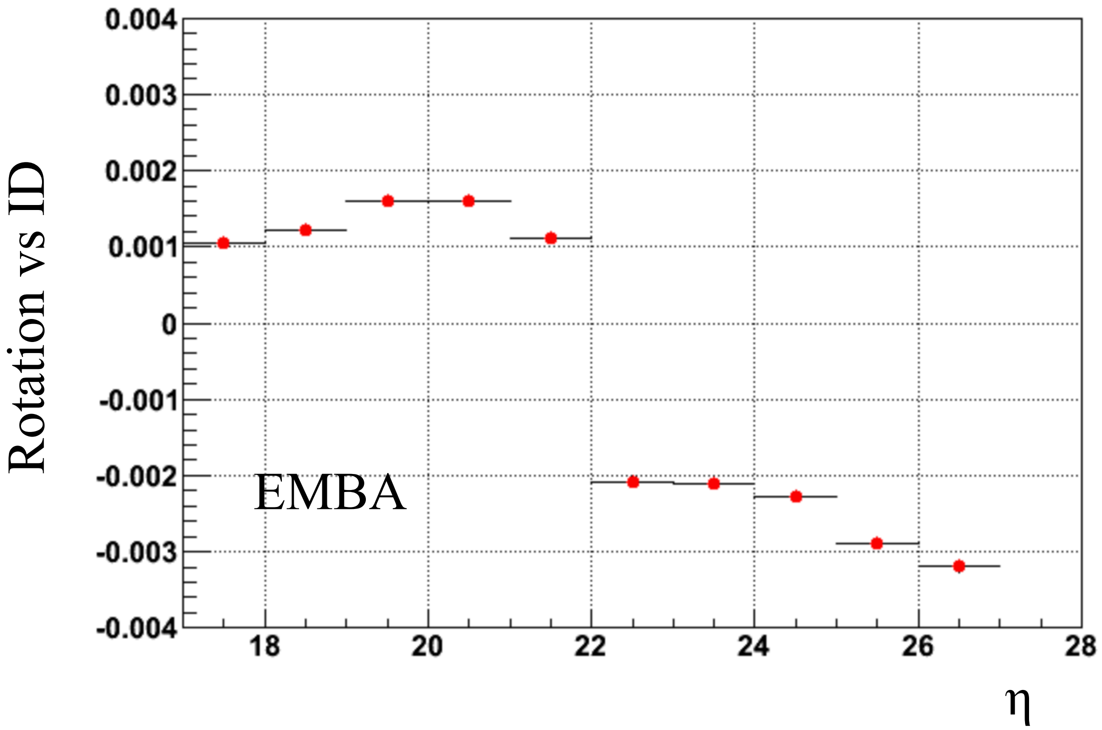


J'ai passé un certain temps à regarder la photo figure 2 du papier barrel construction



et SI sur cette photo, ce qu'on devine marqué au premier plan "Z=0" correspond bien à la position Z=0 dans Atlas, alors il me semble bien que les zig-zag dans Atlas ont la parité opposée à ce qui est dans la simulation...

The LAr rotation and debugging the reconstruction…



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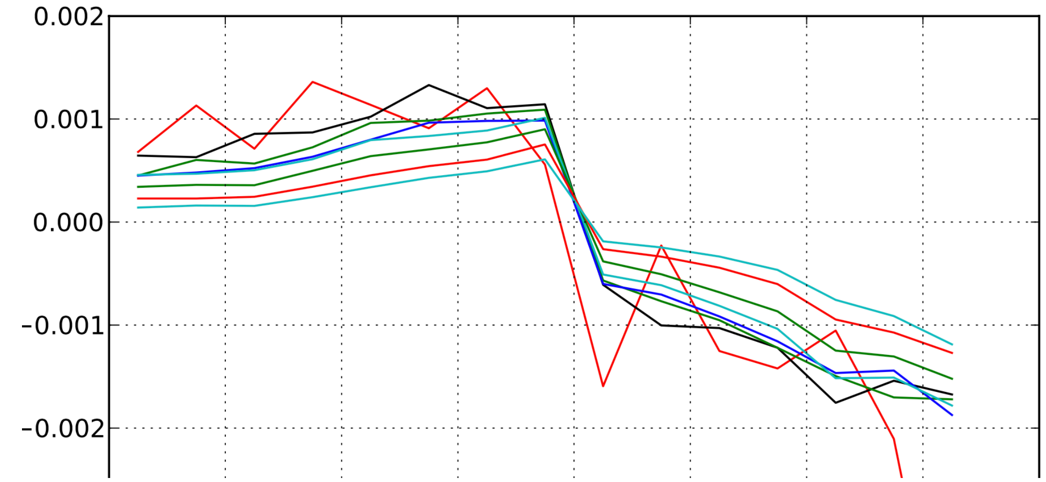
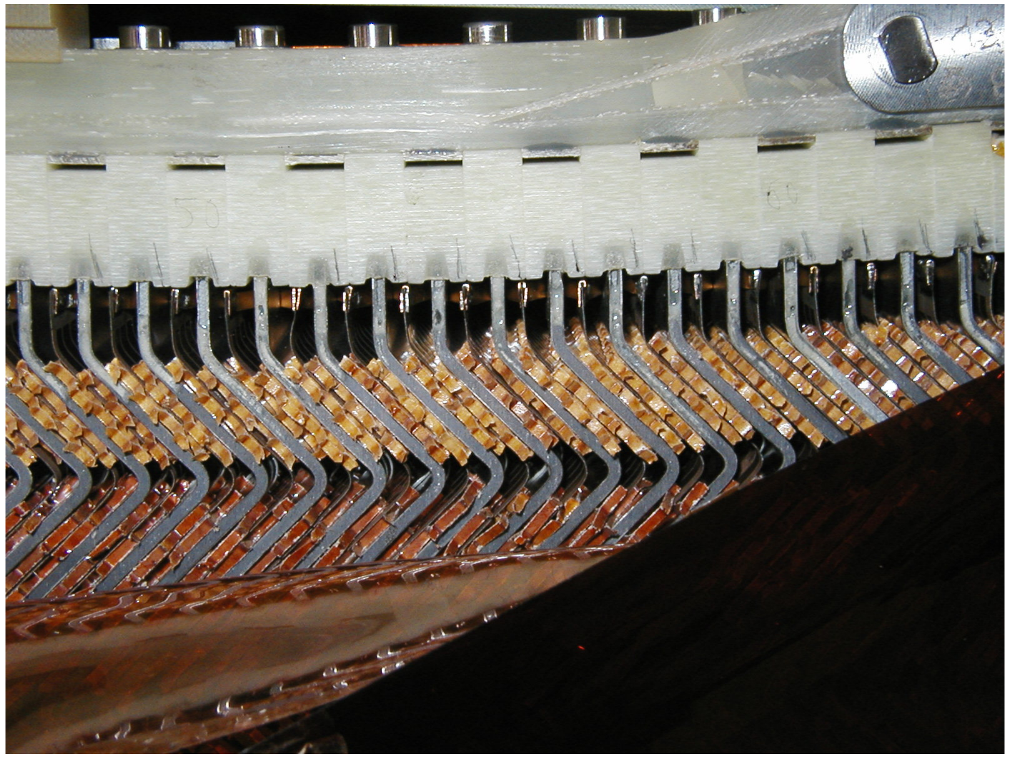


From Daniel :

Bonjour Guillaume,

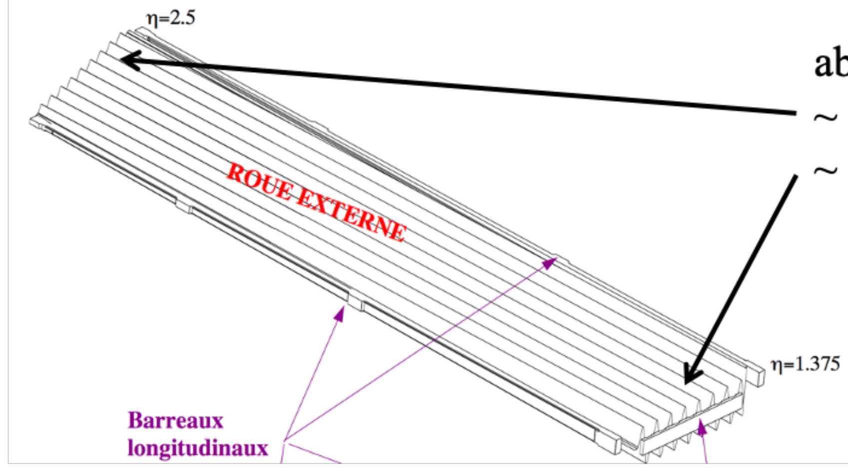
Compliments pour ton coup d'oeil: effectivement c'est bien Z=0 qui est écrit sur le bâti d'assemblage. ...
Maintenant, pour être sur de l'orientation en position "montée" j'ai recherché parmi les photos qui restent dans mon PC ...
La deuxième est éventuellement plus intéressante. C'est une vue de la roue M ... en place, prise depuis Z=0 ... Je dirais que le demi-pli part vers le haut dans le plan horizontal et une orientation sortant du LHC, et vers le bas dans la direction qui va vers le centre.



⇒ The Δφ mystery is solved !

With Guillaume, JB, L. March, J. del Peso, J. Toth

Sagging in the endcaps

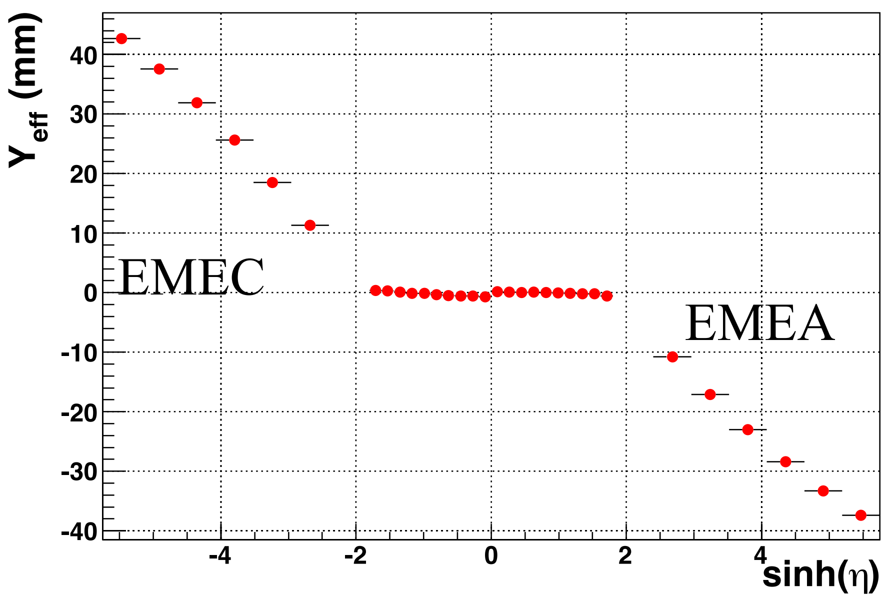


Lateral bar at large R

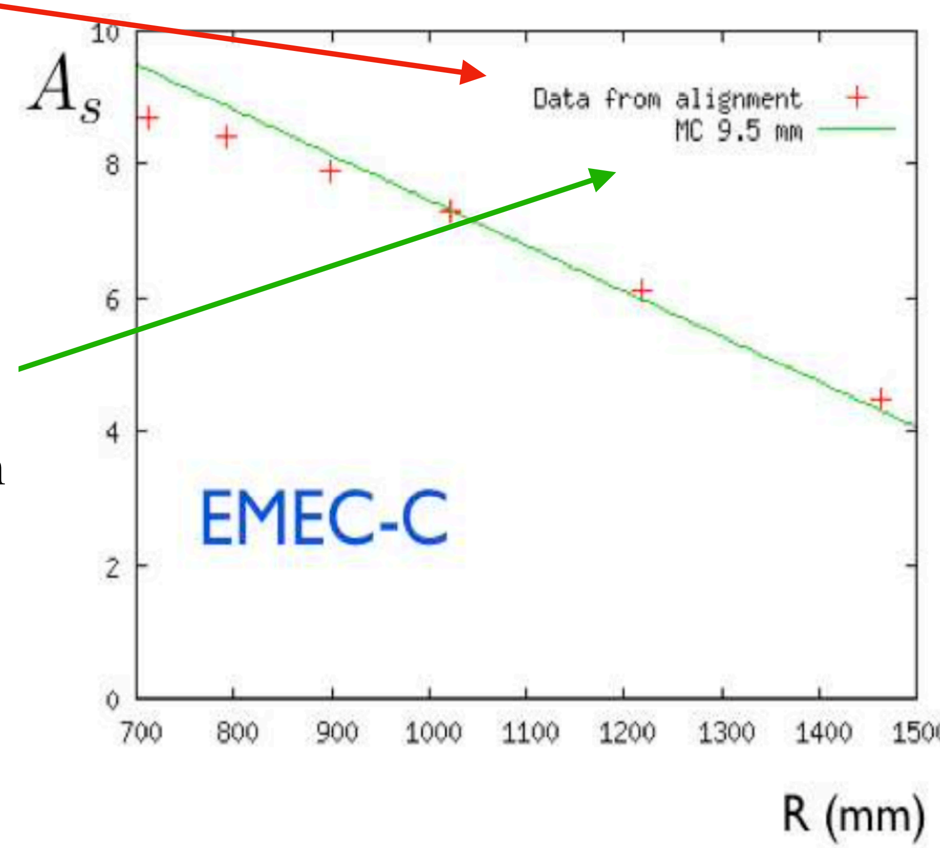
absorbers :
~ "floating" at small radius R (large |η|)
~ fixed at large radius R (small |η|)

⇒ Expect higher amplitude at large |η|

Huge effective displacement seen in inter-alignment…

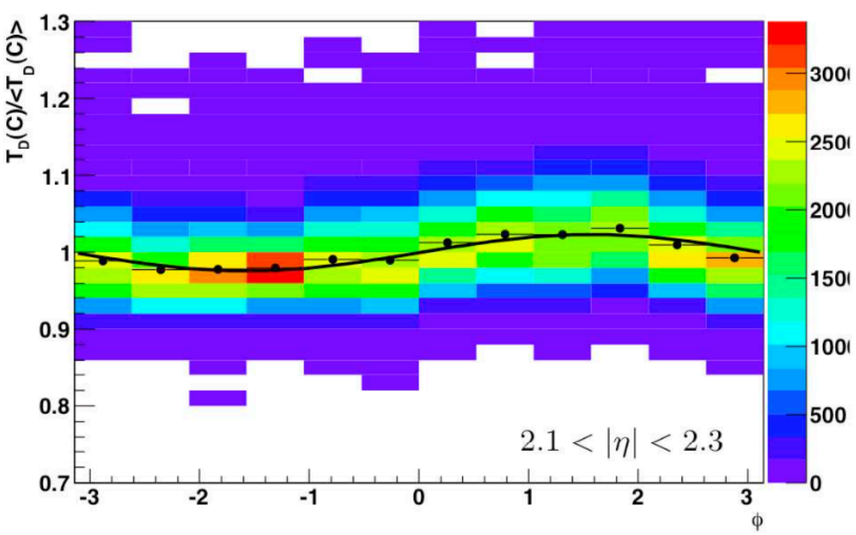


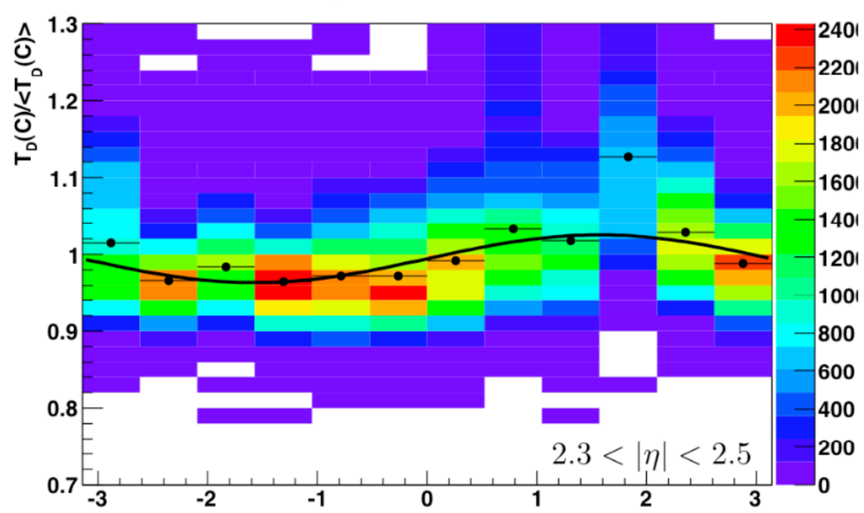
Pointing to consistent (large) sagging amplitude



MC from best fit to drift time extraction

… and also sinusoidal variation for drift time vs η





Corrected for in track-cluster matching

Could be also used to improve the energy response uniformity…

The electron and photon energy calibration

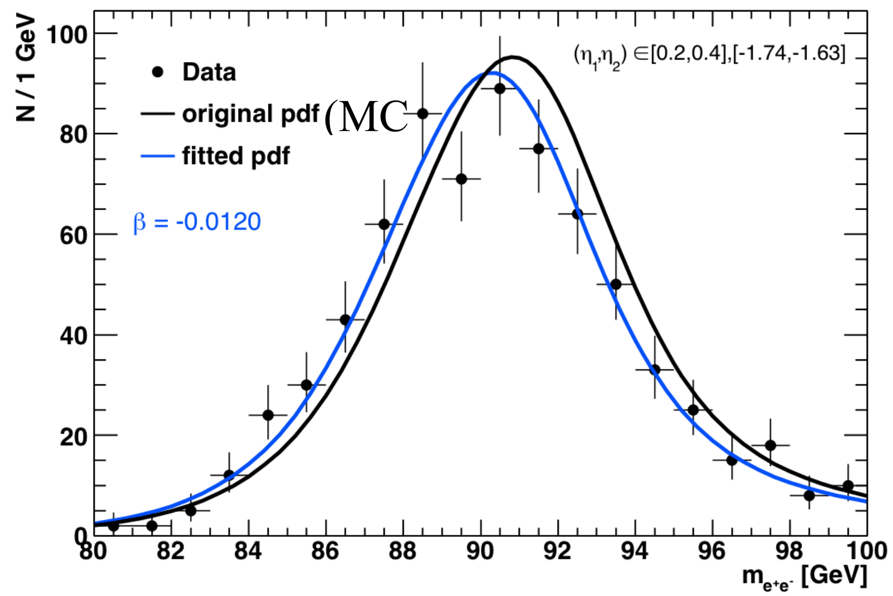
With LaurentS, Nikola, Narei, Marumi,
Nansi, Christophe, David, Linghua, Marc, Louis, RD, Lydia, JB,
Nathalie, JBB, Maarten, Guillaume and others

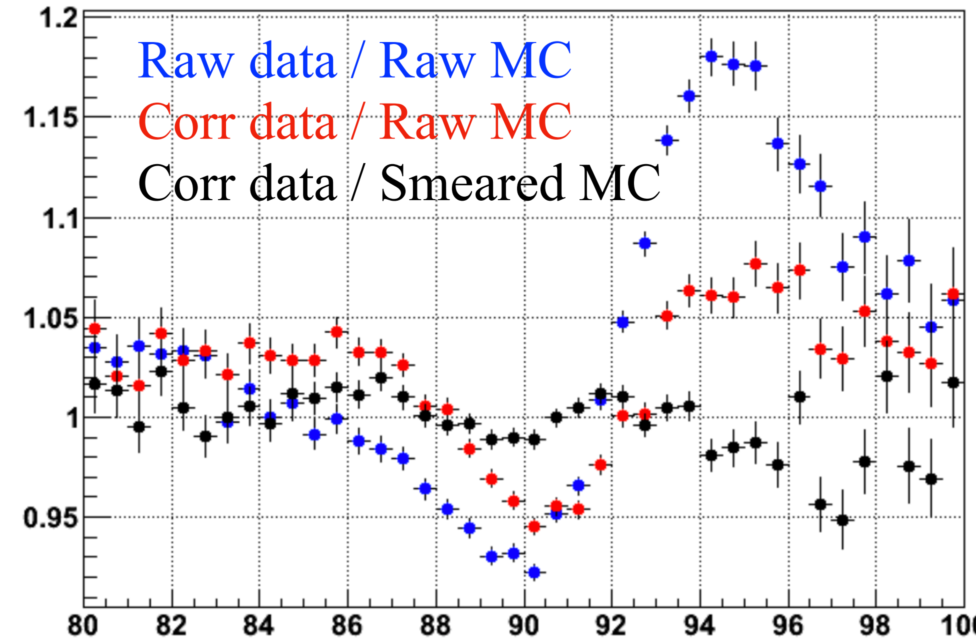
The final step : data / MC scale equalization

use Z → ee to set the absolute (vs MC) scale in data $\alpha(\eta)$ and an additional smearing term for MC $c(\eta)$

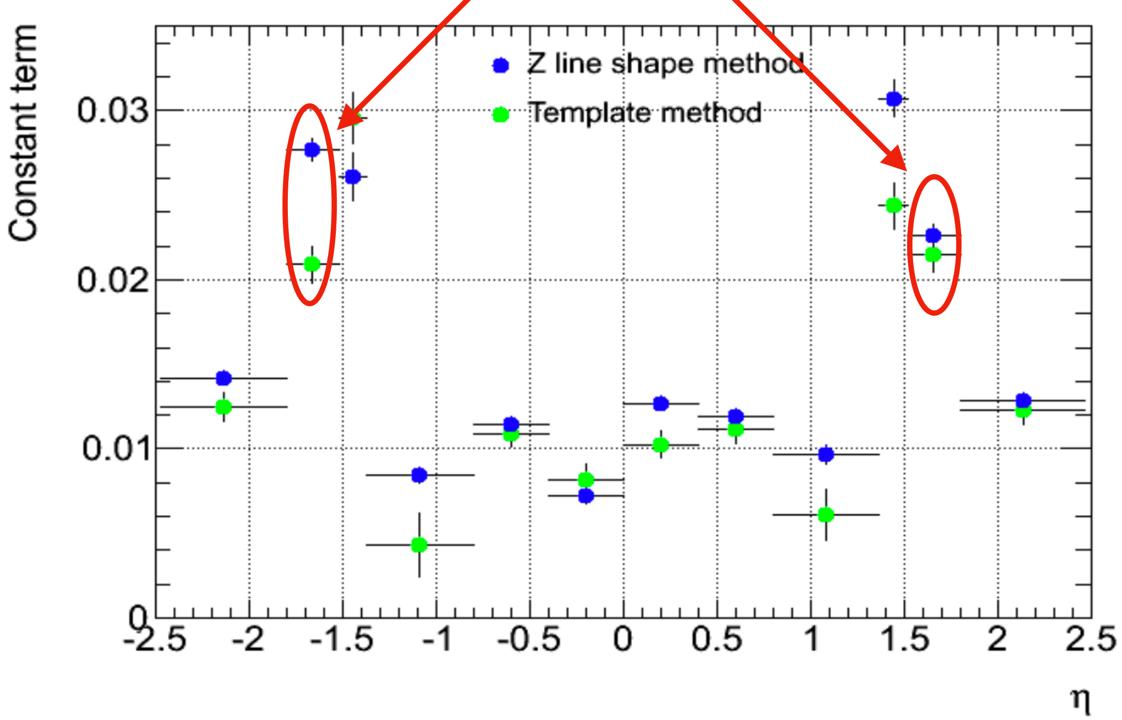
$E_{corr} = E_{raw} / (1+\alpha(\eta))$

- fit $\beta(\eta_1,\eta_2) = [\alpha(\eta_1)+\alpha(\eta_2)] / 2$
- extract $\alpha(\eta)$





Smearing larger than « design » value (~ 0.7%) but not so far away
except in the ***bad bin* |η| in [1.5,1.8]** ([1.4,1.5] « bad » but crack)

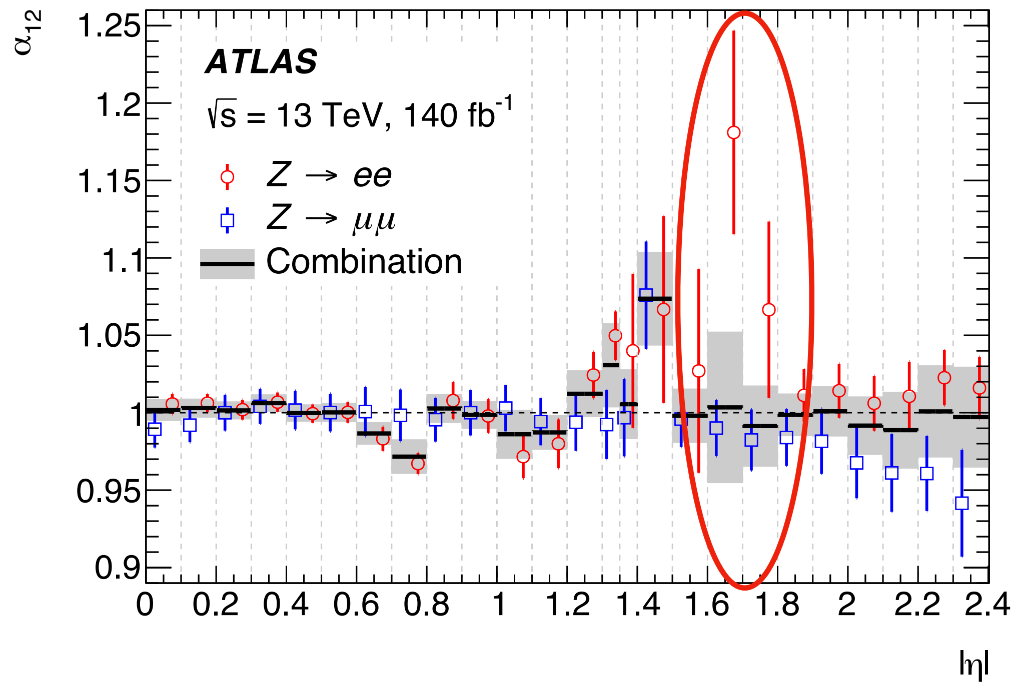


⇒ New beginning of very detailed investigations to better understand the calibration and improve it !

Many directions followed to understand, using various probes

- layer inter-calibration (LArEM has 3 samplings in depth + one pre-sampler)
- Material description : services, cryostats, etc…
- Use E/p as variable of interest (instead of m_{ee}, recently revisited in the linearity context)
- Use W → eν Jacobian pic

⇒ The ***bad bin*** is still bad in 2018 (more work is needed !)
e.g. hard to measure the relative energy scale between layer 1 and layer 2



But a bit less bad :-)

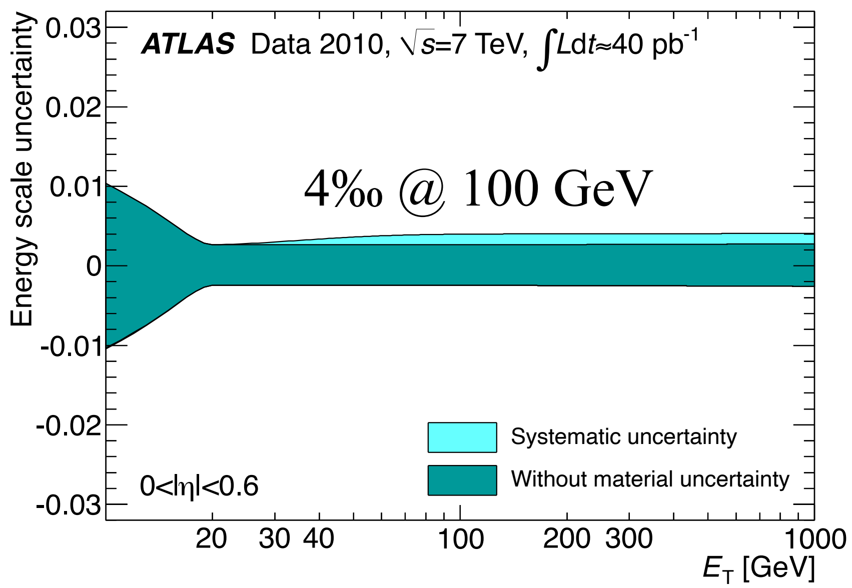
And all the methods / checks developed to understand it were invaluable for the global calibration analysis

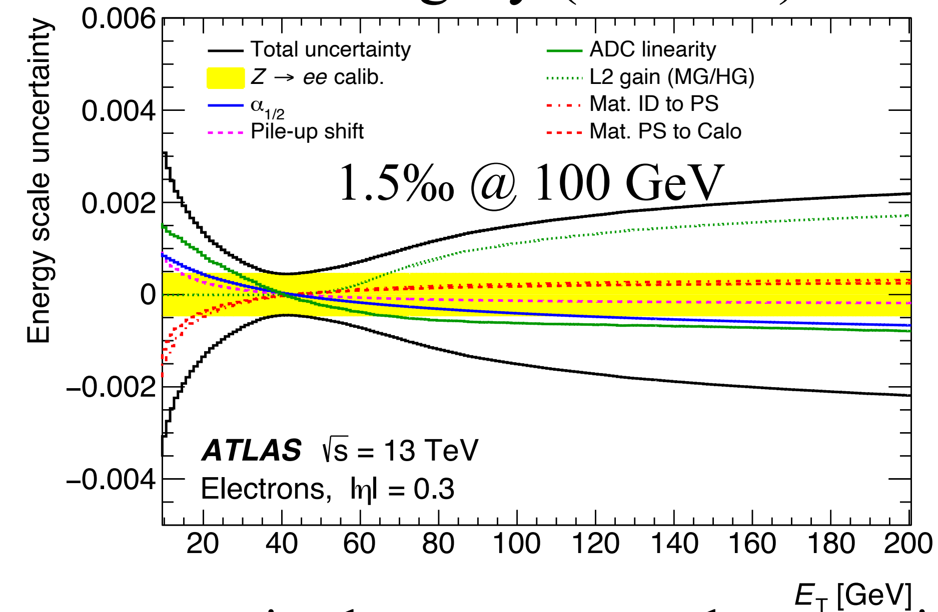
The state-of-the-art

e.g. Energy scale uncertainty vs E_T

From early data (2010, 40 pb^{-1}) to Run 2 legacy (140 fb^{-1})

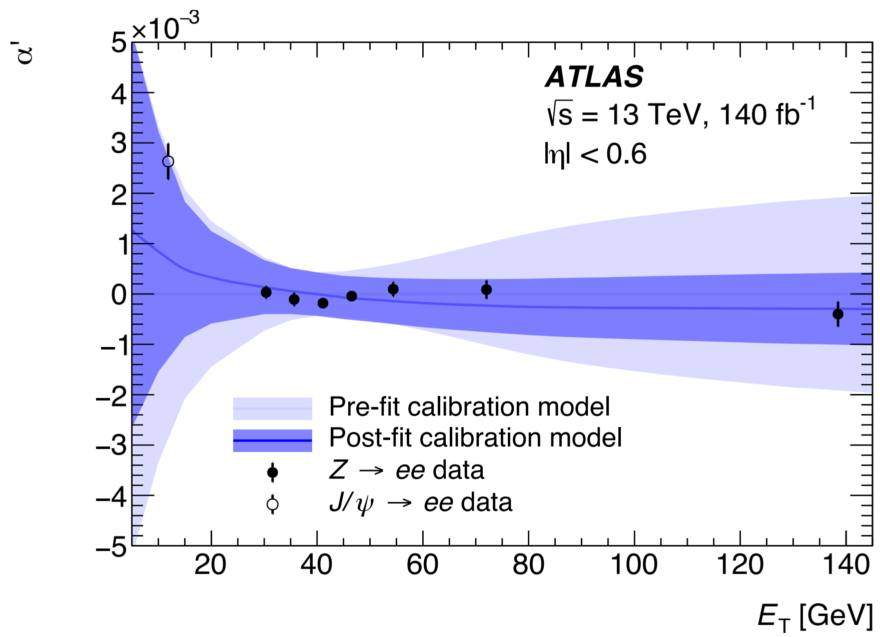
(y range divided by 5)

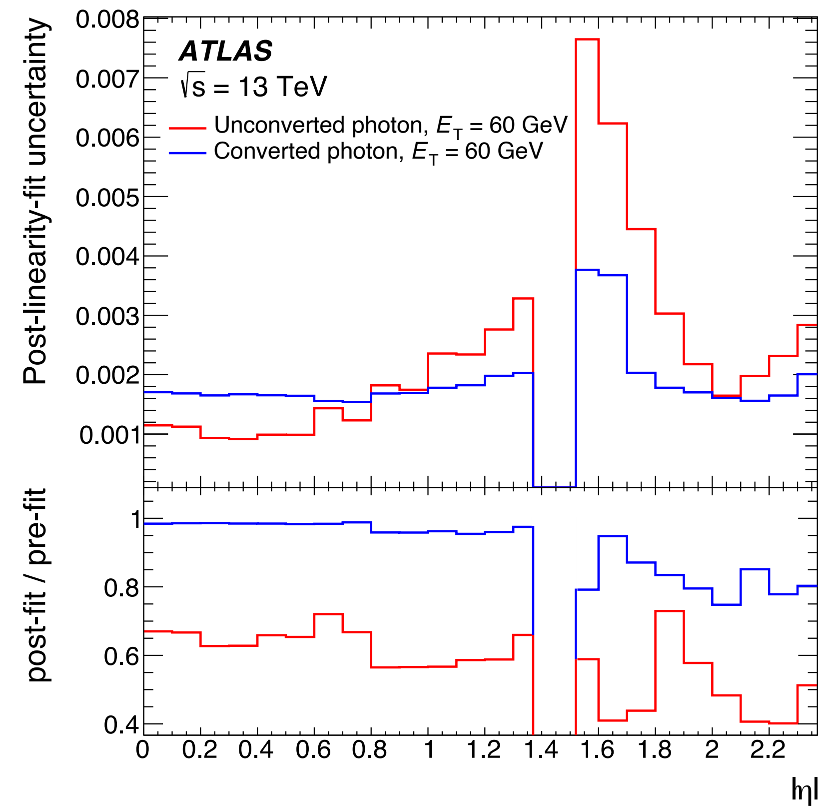




⇒ Big improvements in photon energy scale uncertainty paving the way to a very precise measurement of the Higgs boson mass with $H \rightarrow \gamma\gamma$

+ huge $Z \rightarrow ee$ sample to constrain the uncertainties from linearity measurements





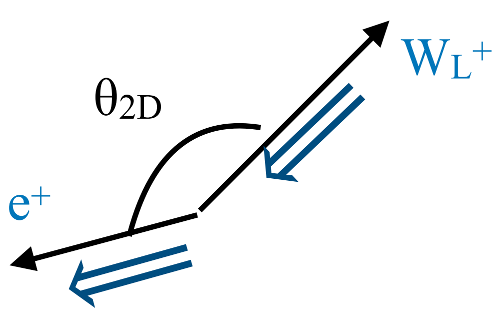
⇒ And also, obviously, on the electron side, to future precise measurements of W mass in $W \rightarrow e\nu$…

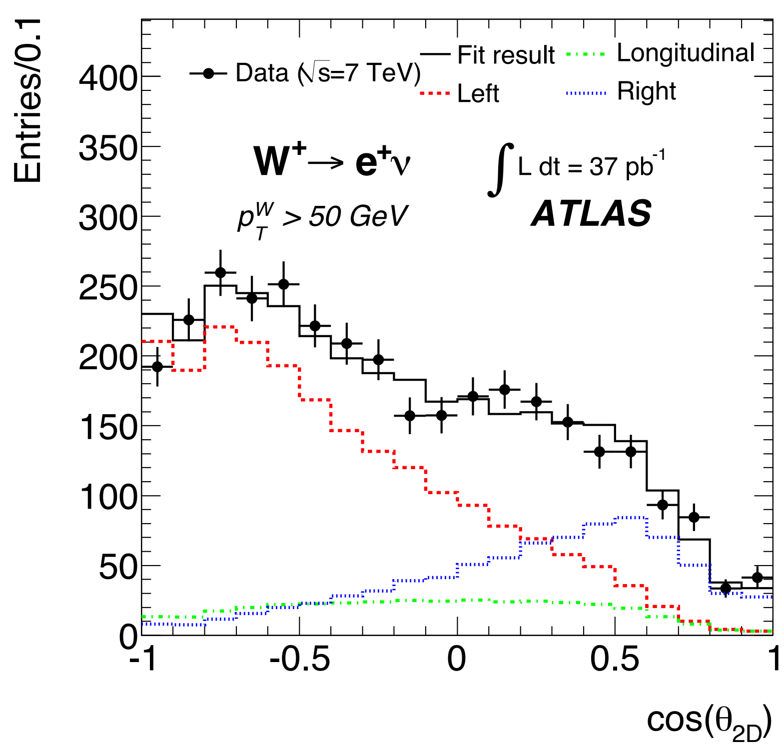
With JBB, LaurentS, Nikola

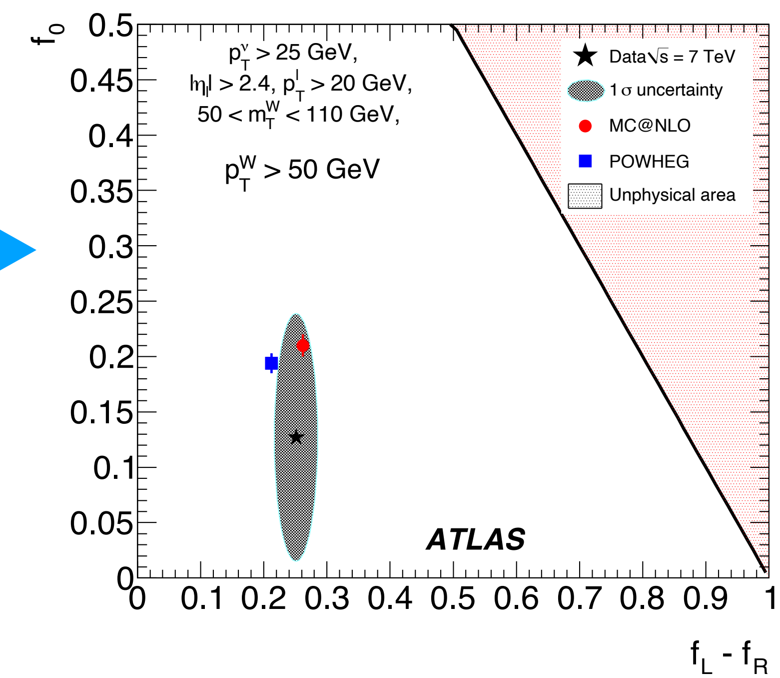
Given the « huge » W cross-section, even at 7 TeV, very relevant fondamental measurements can be performed with good precision at low luminosity

The most famous one : the W mass ! But this is a very long term endeavor, not easy on a phD time-scale…
⇒ Study W polarization first

Template fit to lepton angle to extract fraction of longitudinal and transverse polarizations

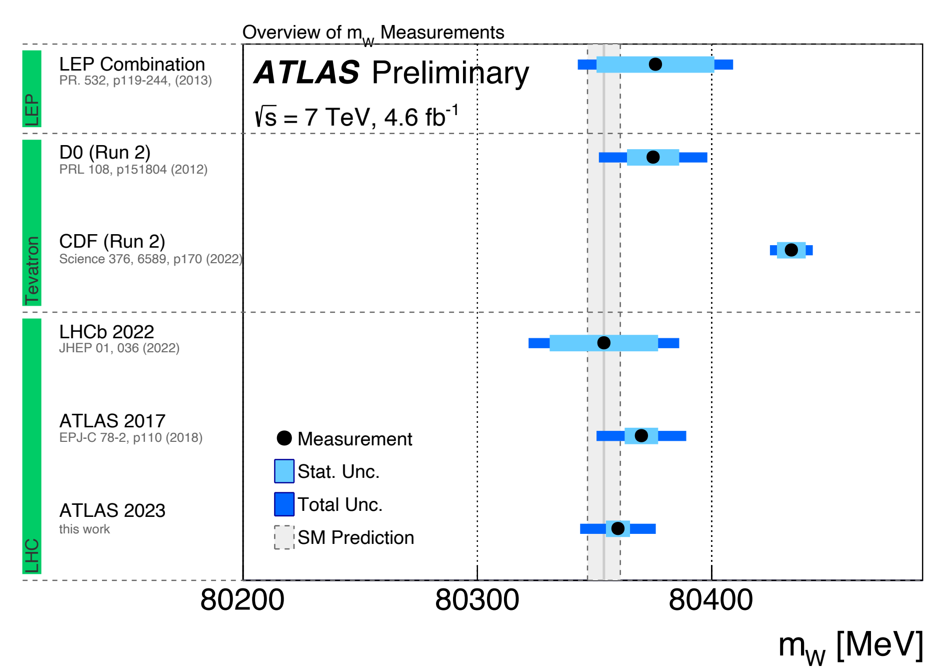






⇒ Better understand W production
Tests of Monte Carlo generators

One of the many measurements seminal
for the precise determination of W mass !
(In addition to the precise lepton energy scale determination…)

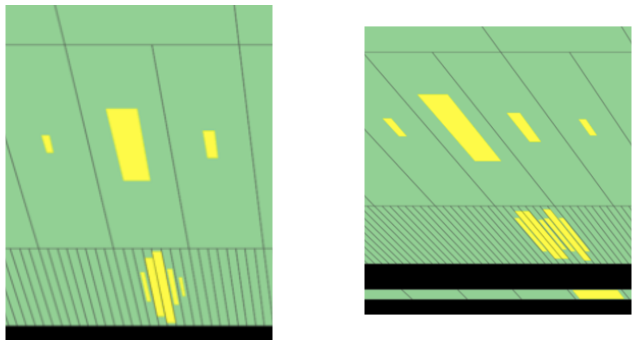


The Higgs boson discovery

Using the $H \to \gamma\gamma$ channel

Everybody is now convinced that LArEM is very good at :

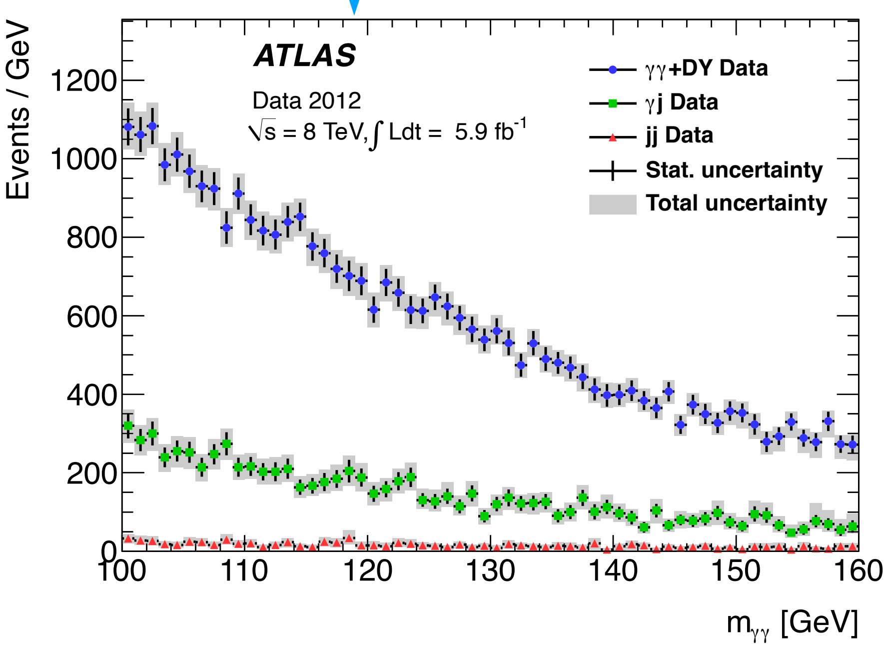
- seeing photons and rejecting π^0



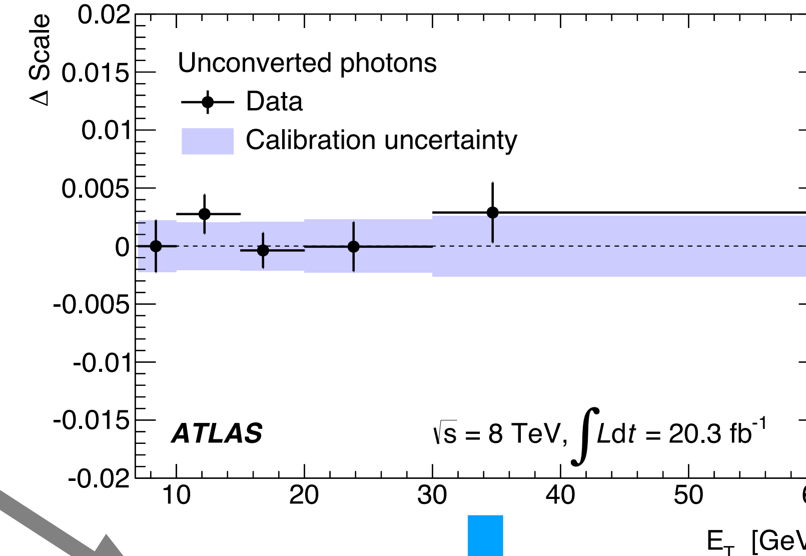
2 samplings (+ fine S_1 granularity) also used to measure photon direction

Hence, $\gamma\gamma$ mass resolution « only » limited by energy resolution

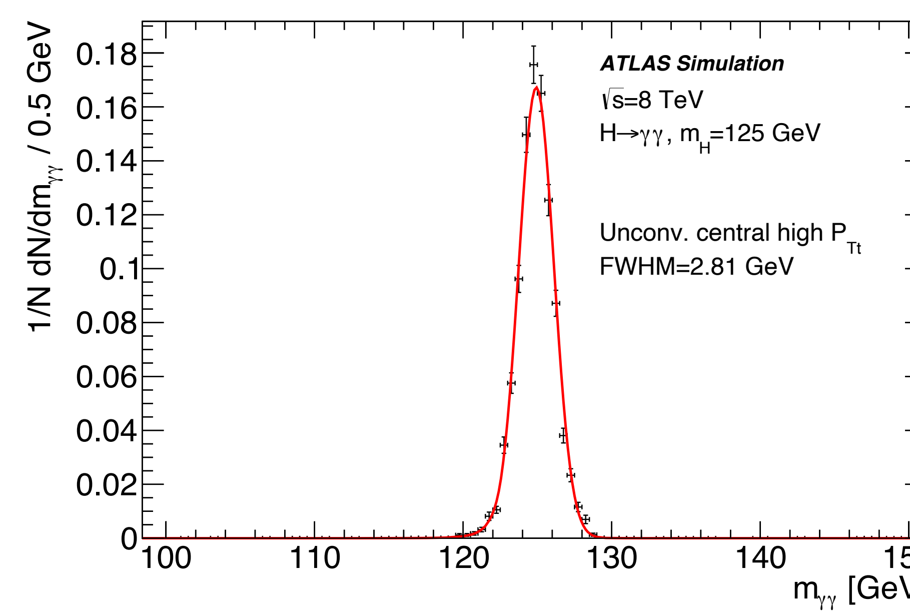
Rather pure di-photon sample



- measuring photon energy with very good accuracy

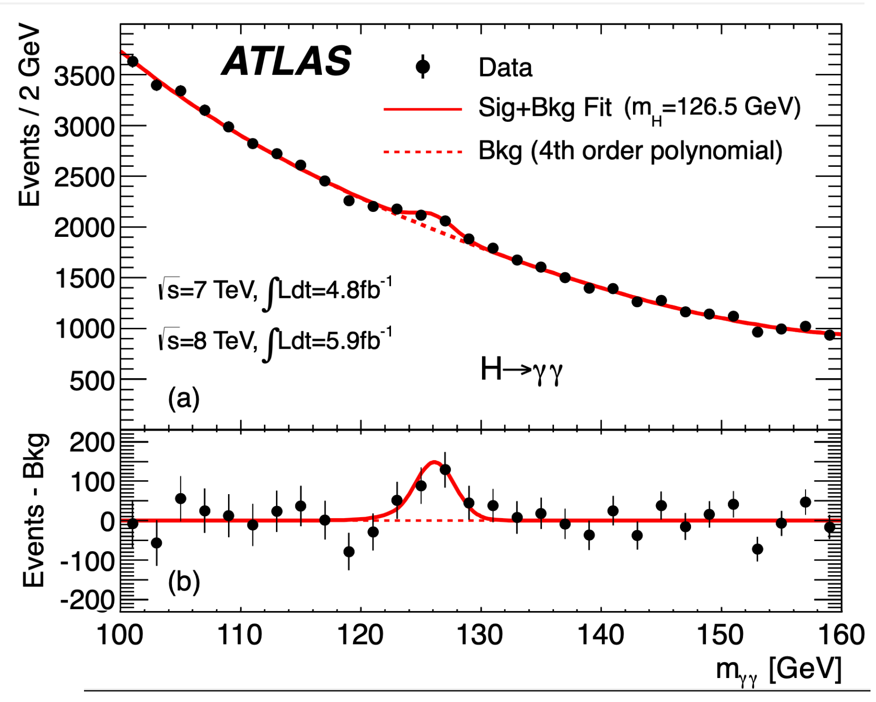


Good di-photon mass resolution

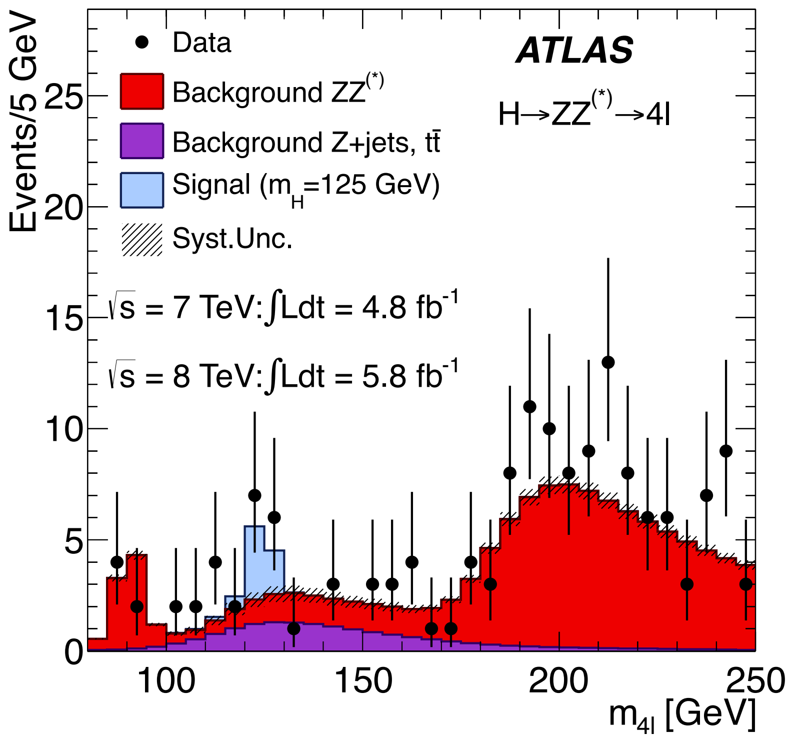


$\Rightarrow$ Everything in place to search for a bump in the di-photon mass spectrum…

Combining 4.8 fb^{-1} at 7 TeV and 5.9 fb^{-1} at 8 TeV :
4.5σ local significance with $H \to \gamma\gamma$ alone…



And combining with $H \to 4\ell$, $\ell\nu\ell\nu$



⇒ 6σ significance + similar in CMS : Discovery of a new particle X !

+ first mass measurement (prior to all the improvements in the calibration) in the region favored by EWPT :

$m_X = 126.0 \pm 0.4_{stat} \pm 0.4_{syst}$ GeV , already quite precise at 5‰

+ di-photon decay : very likely a scalar

(Remember « Is it spin 0 or spin 2 ? » : this question carries a similar potential for surprise as a football game between Brazil and Tonga)

+ measured yield close to those predicted for the SM Higgs boson

⇒ X is likely ***a* Higgs boson**…

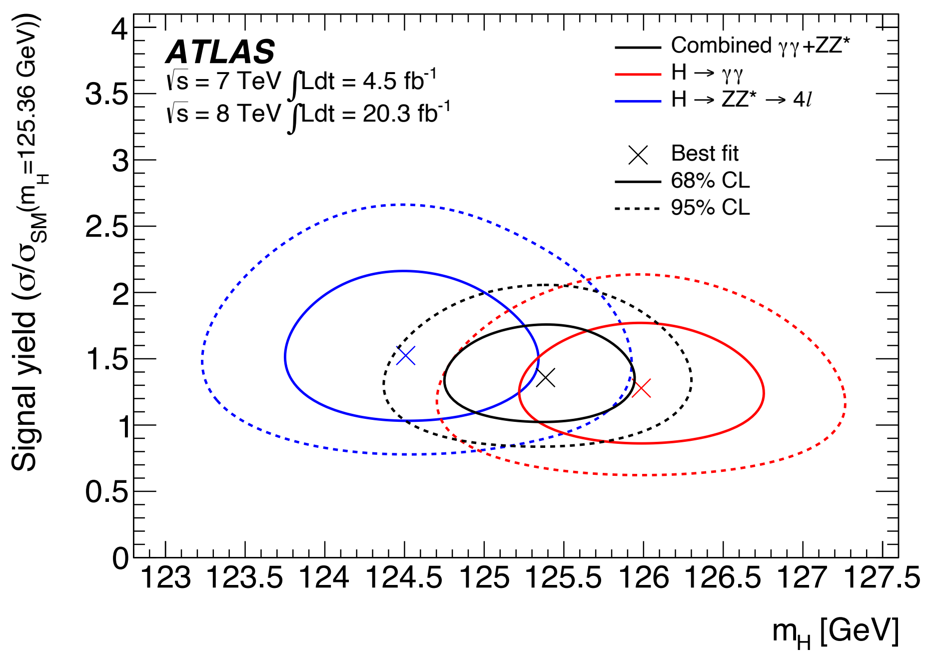
… Would be nice if it is not exactly ***the SM Higgs boson*** but rather a ***portal to BSM Higgs boson***

A (the ?) major achievement in Particle Physics in the 21st century !

The beginning of a new program of ~ 30 years of measurements in the Higgs sector at (HL-)LHC…

… And beyond, at future Higgs factories and energy frontier colliders

Mass measurement : from Run I



Intriguing mass difference in $H \to \gamma\gamma$ vs $H \to 4\ell$

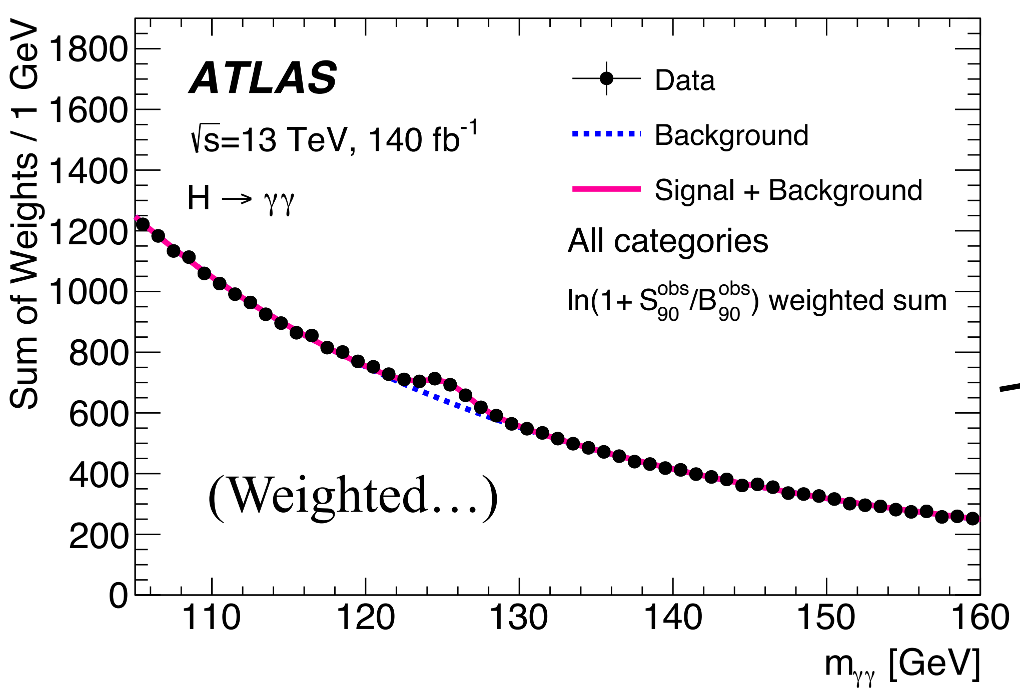
(But still compatible at ~ 2σ : $\Delta = 1.47 \pm 0.72$ GeV)

First observed at discovery time…

That triggered endless discussions and fights even at LAL 🙂…

But has been also in part at the origin of the complete and thorough re-appraisal of the energy calibration procedure

… to Run 2 legacy

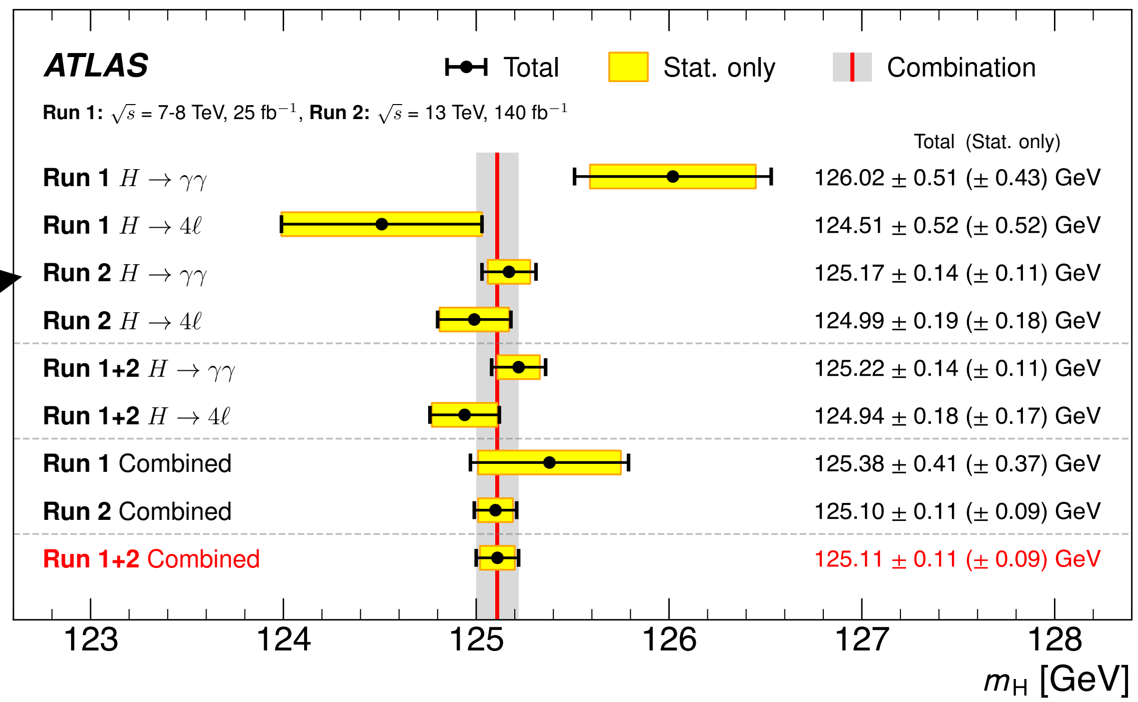


⇒ Great precision !

0.11% precision from $H \to \gamma\gamma$

0.09% when combined with $H \to 4\ell$

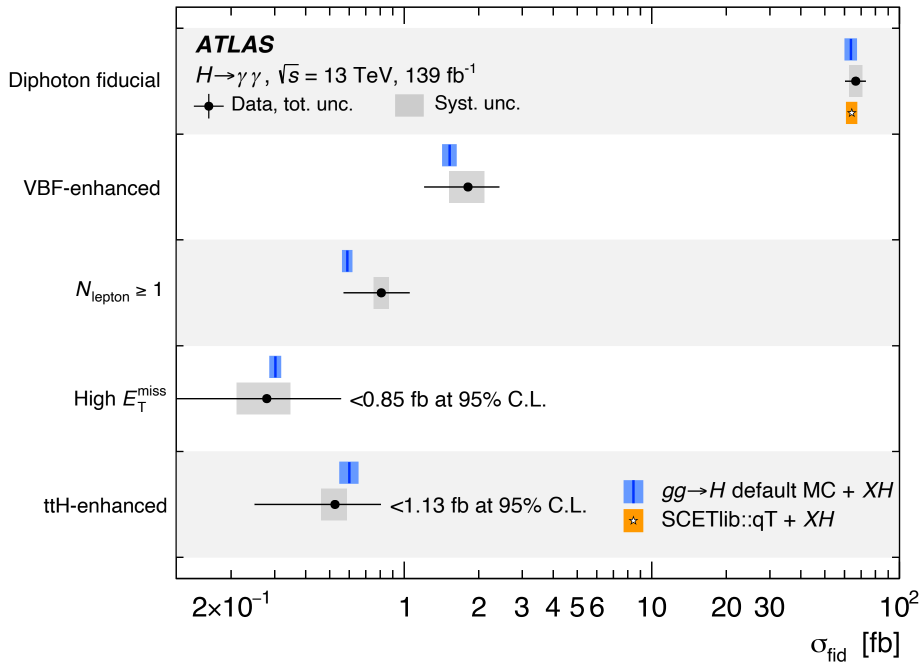
(With ATLAS only)



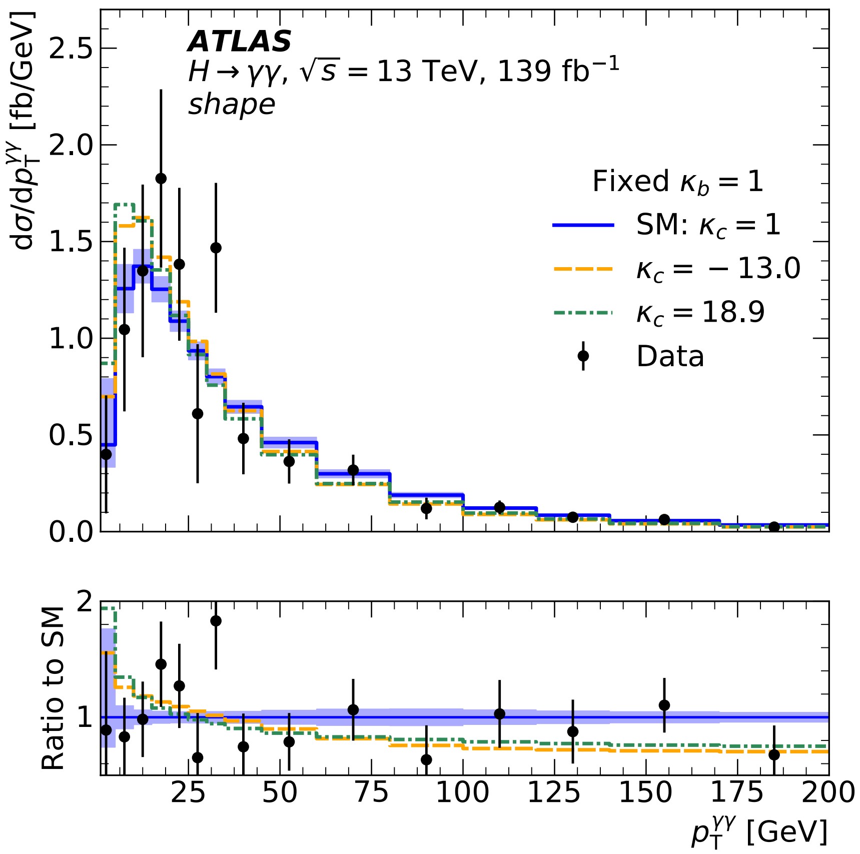
H → γγ instrumental to Higgs boson characterization

➤ Higgs boson production modes (QCD studies, BSM)

Total fiducial cross-section measured with precision below 10%
Not so far from the theoretical precision (~ 5%)



➤ Differential cross-sections , e.g. $1/\sigma \times d\sigma/dp_T(H)$,
with precision that can allow decent constraints on couplings
very difficult to measure, such as charm-Yukawa coupling :



Almost model-independent
$-12.6 < \lambda_c / \lambda_c^{SM} < 18.3$

Not so bad compared to
the direct search for H → cc
in W/Z+H production
$|\lambda_c / \lambda_c^{SM}| < 8.5$

All these rather precise measurements,
with only 1/20 of the luminosity expected to be collected at LHC,
were made possible thanks to the excellent performance of ATLAS,
and its LAr calorimeter in particular !

(Di-)Photon as a portal to new physics

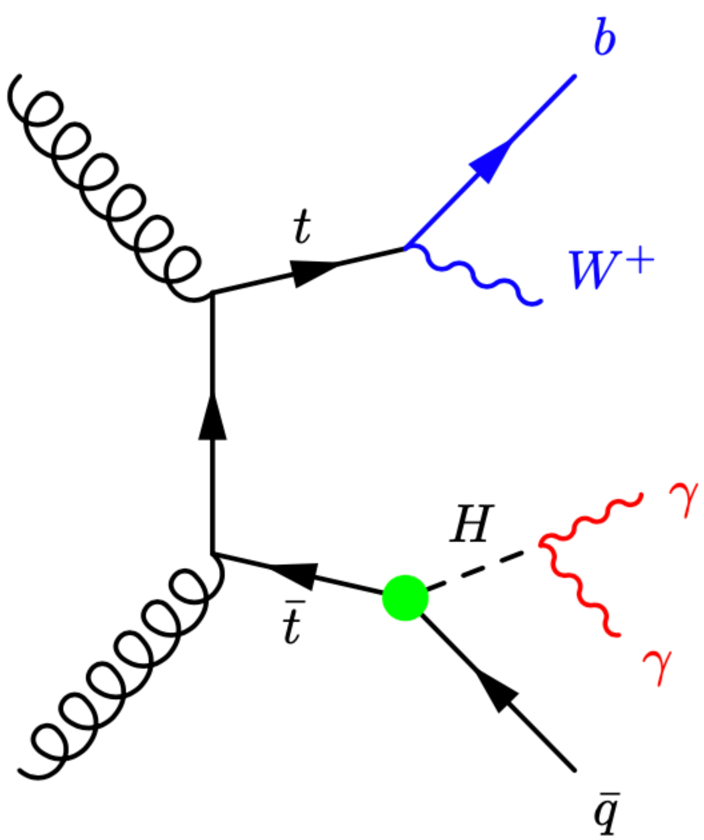
With Charles, JB and others

The Higgs boson is (one of) the strangest beast of the standard model :
a fundamental scalar, with no underlying principle to dictate its dynamic
Yet : the corner stone of the model

⇒ Need to measure its properties as precisely as possible
very likely a good portal to go Beyond the SM

The top quark is in a way the most natural fermion, coupling to H with Yukawa ~ 1
⇒ the two particles seem to like each other

With this in mind, given $m_{top} > m_H$ and the LHC is a top factory,
why not search for top quark decays into a Higgs boson and a lighter quark $t \to qH$?



Flavor Changing Neutral interactions, highly suppressed in SM

$B(t \to qH) \sim 4\times10^{-15}$

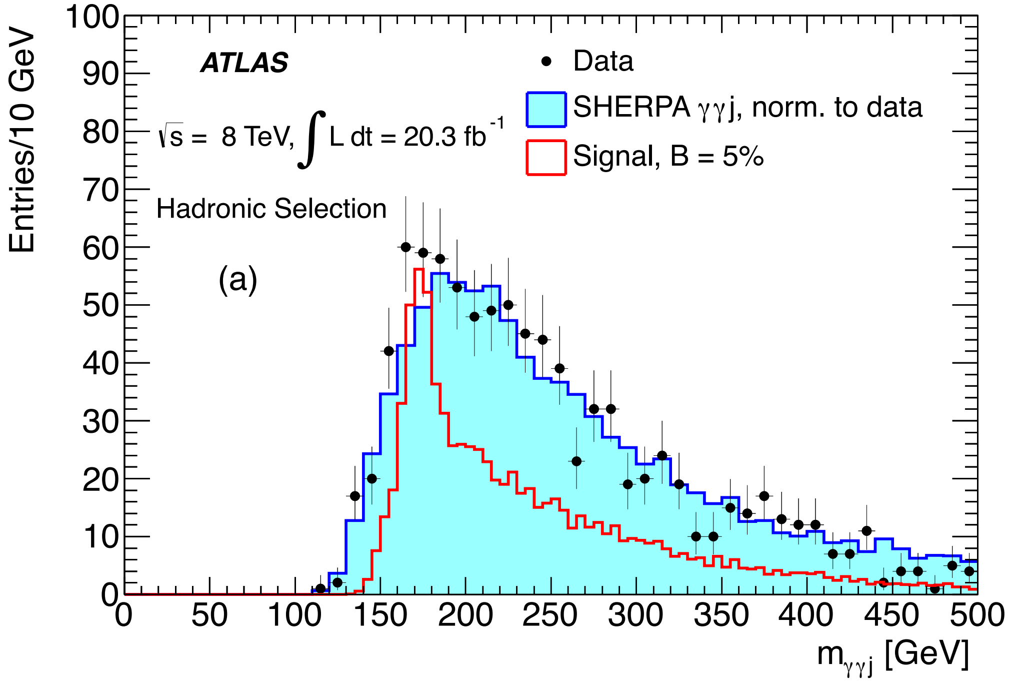
Could be highly enhanced in BSM, up to ~ 0.1%

Daniel proposed to undertake this search, with $H \to \gamma\gamma$, in 2012 soon after the Higgs boson discovery announcement

Run I and the first round

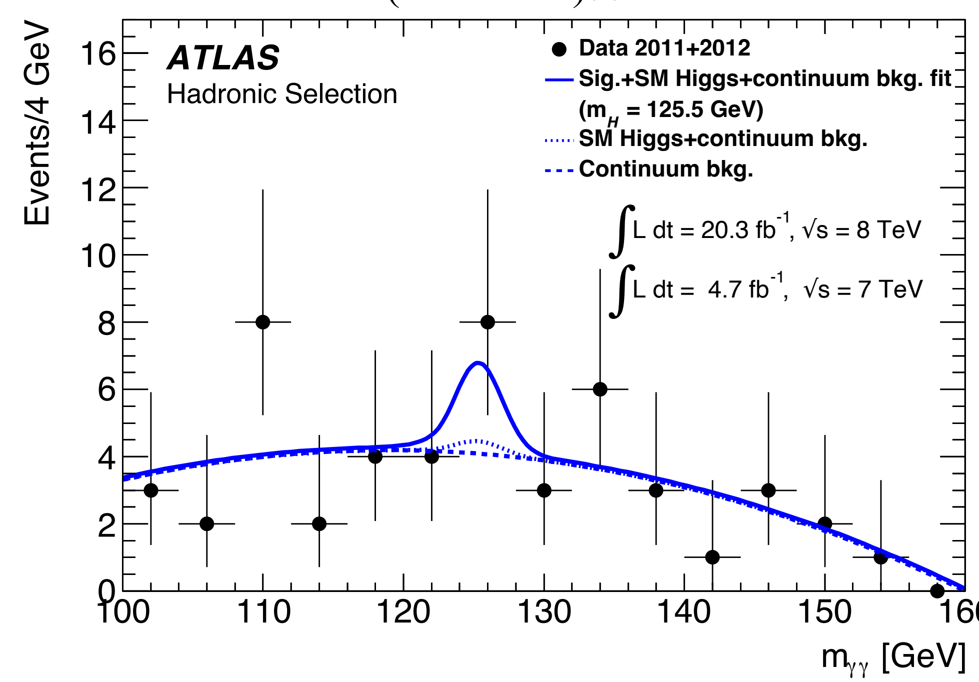
A rather simple cut-and-fit analysis, benefitting from all the knowledge learnt during the SM $H \to \gamma\gamma$ analysis developments

Very good S/B thanks to $t \to$ jet-$\gamma\gamma$ clean reconstruction



And unfortunately no signal…

B ~ (0.22±0.29)%



Run I and the first round

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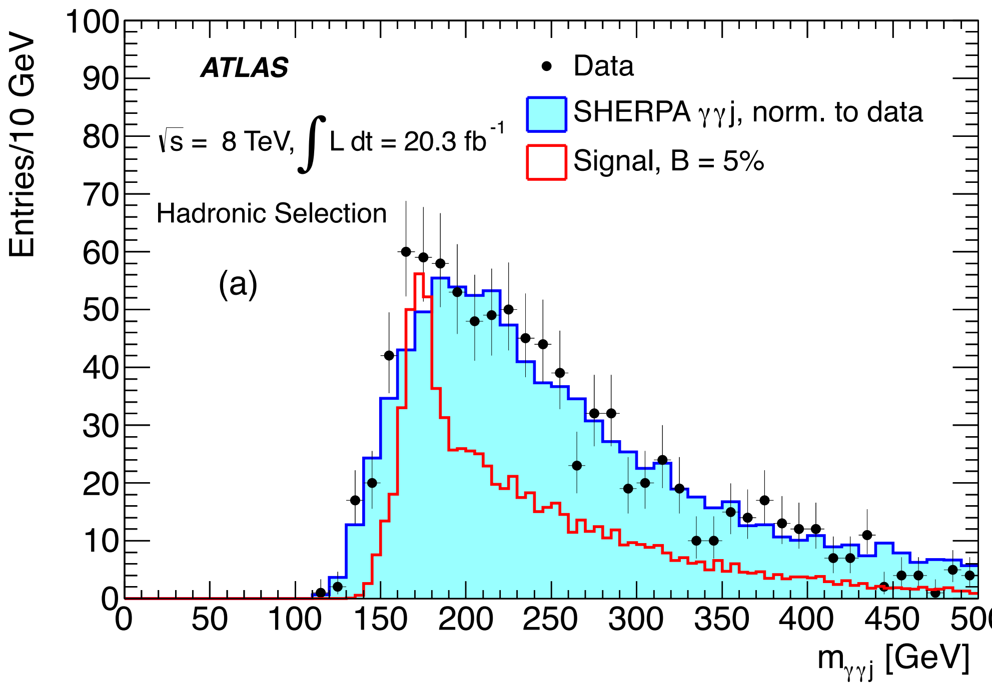

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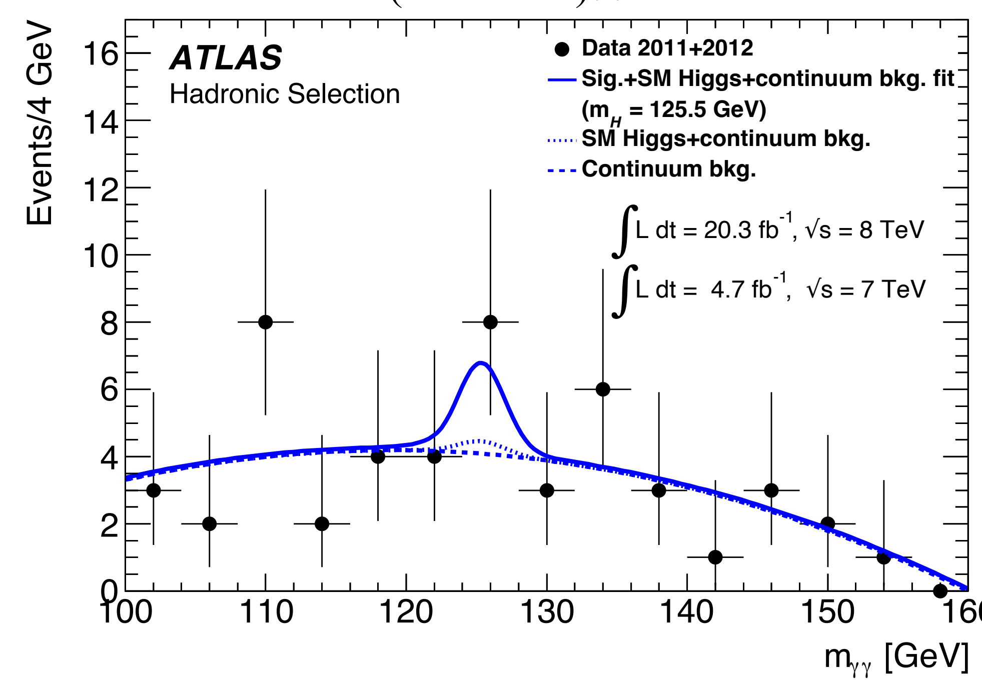


This caught the eyes of some theoreticians,
in particular W.-S. Hou who proposed to
search for this, 20 years earlier (before top discovery) !

Dear Jean-Baptiste and Daniel,

(…) the day after EPS, at Higgs Hunting, this result was announced by ATLAS. It is a good result, and I congratulate you for the pioneering thought. (…)
Now, what is the story that ATLAS withheld from EPS, and choosing to announce in Higgs Hunting instead? Paris, of course.

I guess this may be also the reason why you did not come up to me for a chat after my talk. You guys already had this bombshell under your sleeves. Now CMS would have to scramble! (…)

Best wishes!
George

Always going forward, soon after,
Daniel also performed a sensitivity study for HL-LHC

And other colleagues studied other H decays
(bb, WW, ZZ, $\tau\tau$) to improve the sensitivity

Run II and the second and third rounds

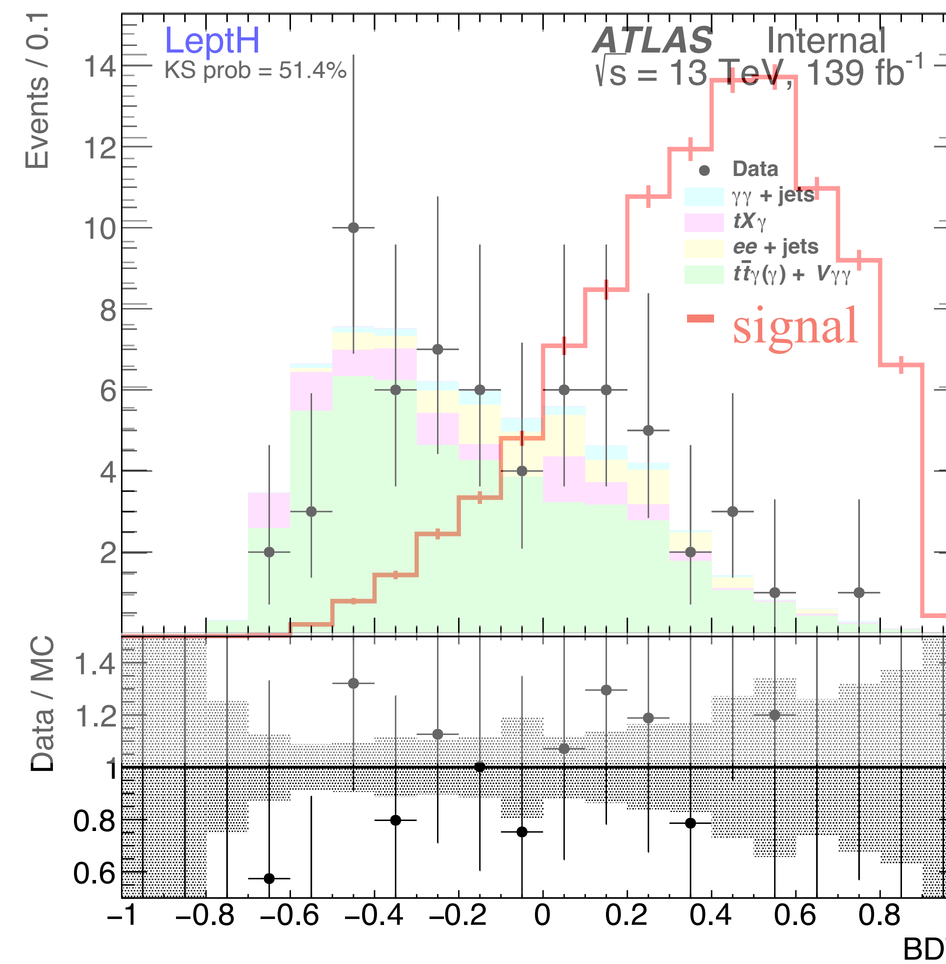
Run II : 8 →13 TeV : should allow a big step in sensitivity
thanks to the large cross-section increase
+ > 5× more luminosity

Improving the sensitivity : trying to catch the ATLAS standards
→ Design more categories
→ Use up-to-date tools : e.g. c-tagging
→ Go for multi-variate analyses

Quite good performance…

Daniel, working with TMVA to train a boosted decision tree
Under the watch of his two students / supervisors

⇒



Result recently submitted to JHEP, thanks to Daniel's determination and perseverance !
(And resilience to his collaborator's despair 😁)

Still, no signal observed, but got beyond the *Naturalness* limit

Run II and the second and third rounds

Run II : 8 →13 TeV : should allow a big step in sensitivity
thanks to the large cross-section increase

Impro

—

—

—

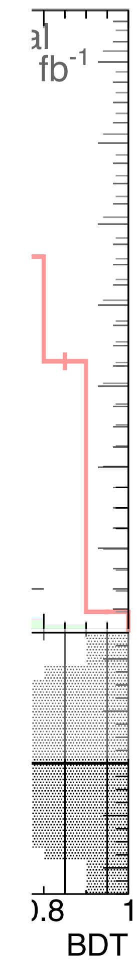
And making sure the analysis is useful outside of ATLAS,
and properly referenced !

Daniel
U

Dear Colleagues,

*Working in ATLAS, in the field of top to Higgs FCNCs,
we have looked with interest to your draft [2002.05311].
In this paper you make reference to ATLAS results, in particular
in your table 1.* ***In this table you quote bb-bar and tautau-bar as the most sensitive channels. This is not quite the case, as the multi lepton and diphoton are the most sensitive channels,*** *followed by tautau-bar and bb-bar, the latter being much less sensitive than any of the other three
(Table 3 of your reference 23 -JHEP 1905 (2019) 123-, expected limits).*

This may be of interest for your article, which is based on the diphoton final state.



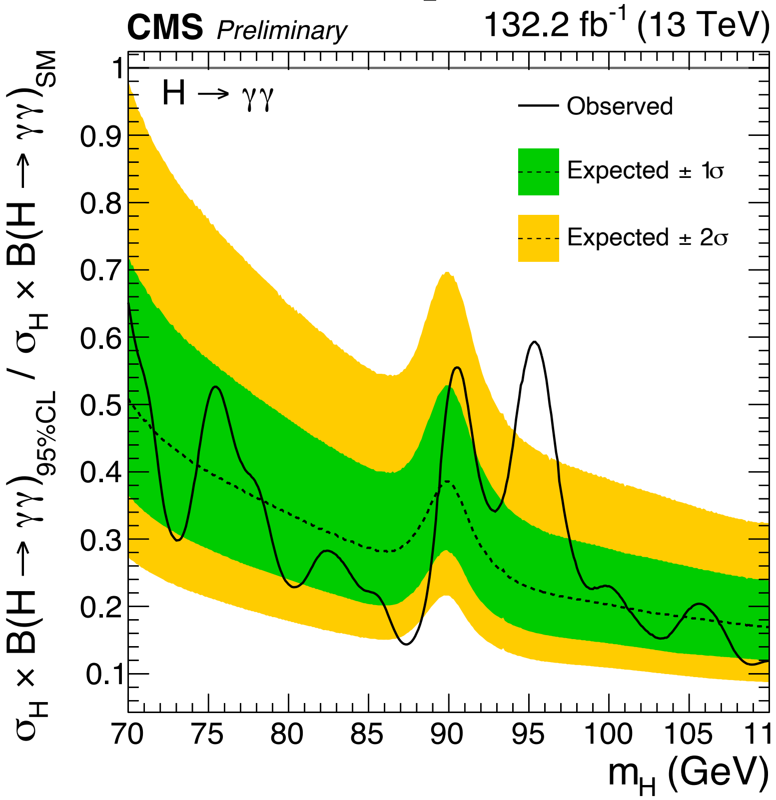
The final published paper indeed updated its table 1 😃

What if Daniel had more collaborators, recently …

An open mind with limitless curiosity !

Among many other things…

★ The CMS low mass di-photon excess

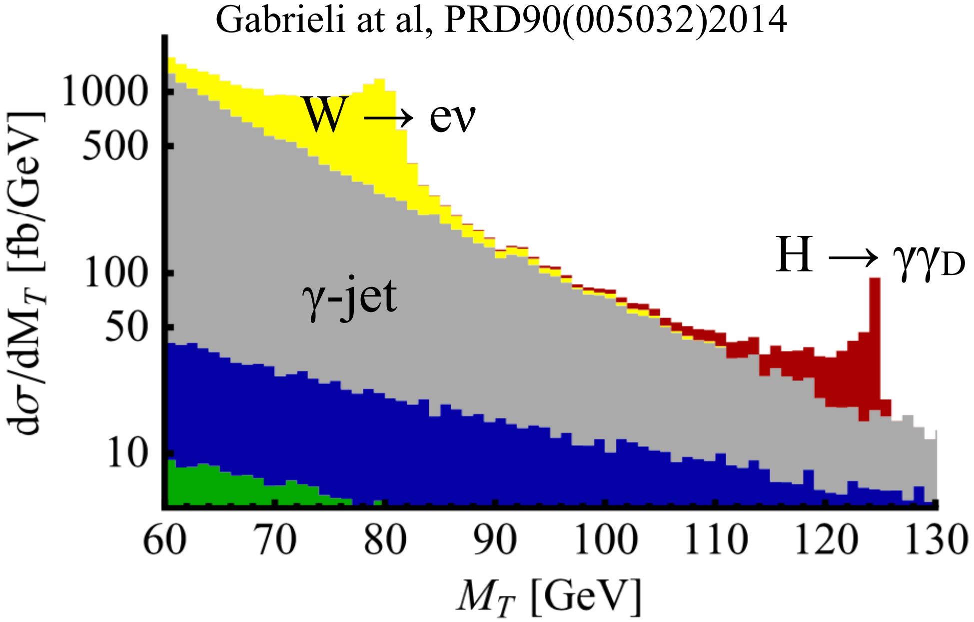


- scrutinizing the « inclusive » analysis…
- and in addition : could this be a scalar S with FCNC interactions ?
  Search for t → qS, with m_S in [20,160] GeV/c²
  Currently ongoing with m_S = 95 GeV 😁

(The tqS search was in the pipeline regardless of this excess of course !)

★ Higgs boson as a portal to the dark sector :
gg → H, H → $\gamma\gamma_D$ with γ_D the (invisible) dark photon

Gabrieli at al, PRD90(005032)2014



Promising sensitivity (from pheno !) with Run I

Daniel's contributions :

- Tigger studies (isolated tightID photon + MET)
- sensitivity studies @ 13 TeV
  → unfortunately not so promising !
  → Daniel could not push the study further due to lack of time (competition with FCNC analysis)

Some people took over…
but had to revert to pp → ZH production mode for trigger and background rejection
⇒ obviously far less sensitive than phenomenological study

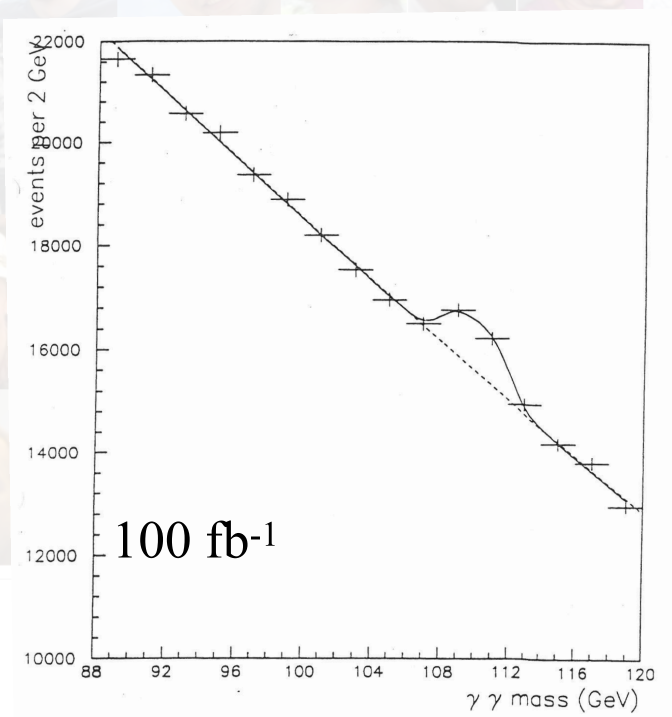
Some conclusions

From the early design of the ATLAS experiment to the huge harvest of physics results, Daniel has been a great leader, coordinator, and inspirer for many collaborators

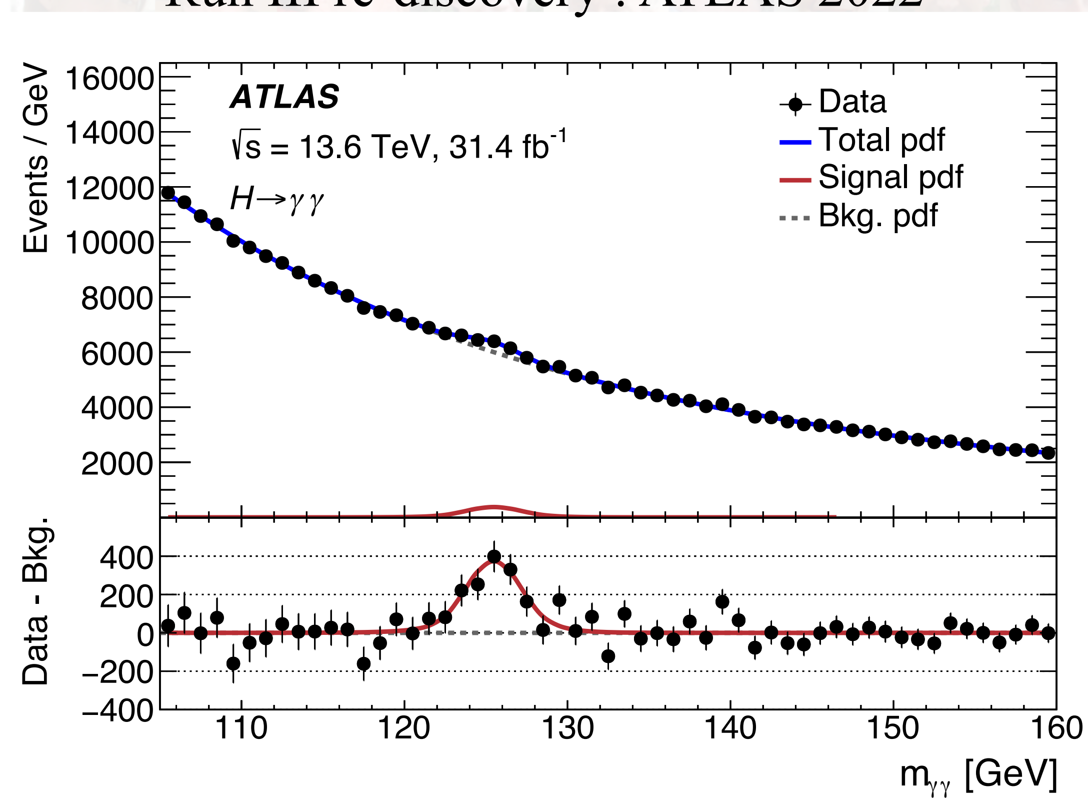
Of which some are rather famous 😀

After ~ 40 years of hard work, ***mission (more than) accomplished !***

Eagle, 1991



Run III re-discovery : ATLAS 2022



Perhaps less spectacular but surely more realistic !

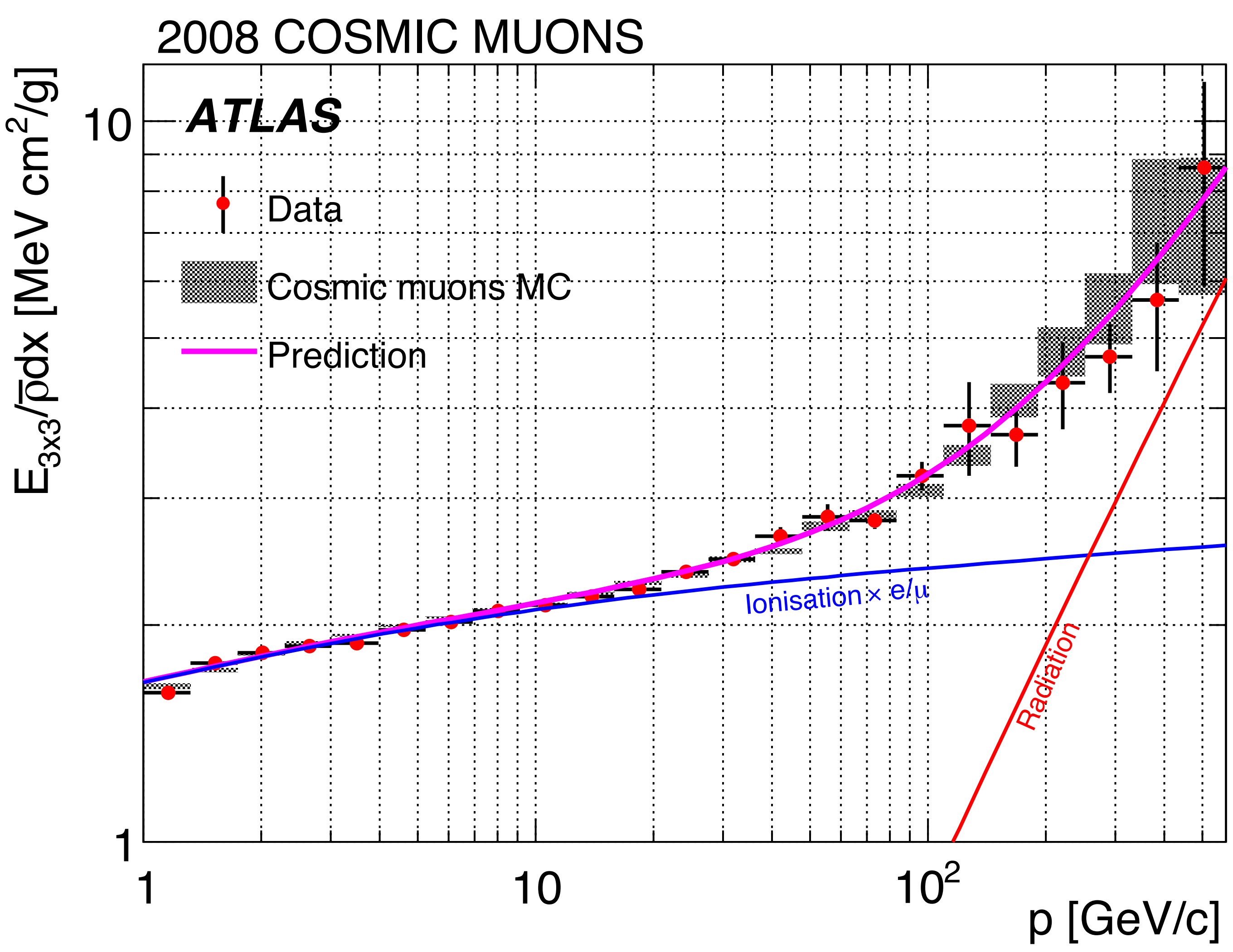
And the exploration goes on !

Playing with cosmics

Try to measure energy loss as a function of momentum in EM calo.
Can we get a prediction for that, without MC ?

Daniel: « In the central part, the equivalent LAr molecule is $Pb_{30}Ar_{56}Fe_{24}C_{21}H_{41}$ » 🙂

+ Bragg additivity for dE/dx



Not so bad !

(OK, we cheated a bit,
the prediction curve has been
rescaled by 0.89)

And excellent stability with time and pileup