Measurement of $\Upsilon(nS)$ production at 7 TeV with the CMS experiment and Using G-APDs in HEP calorimeters

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On behalf of the CMS collaboration

Outline (2 parts)

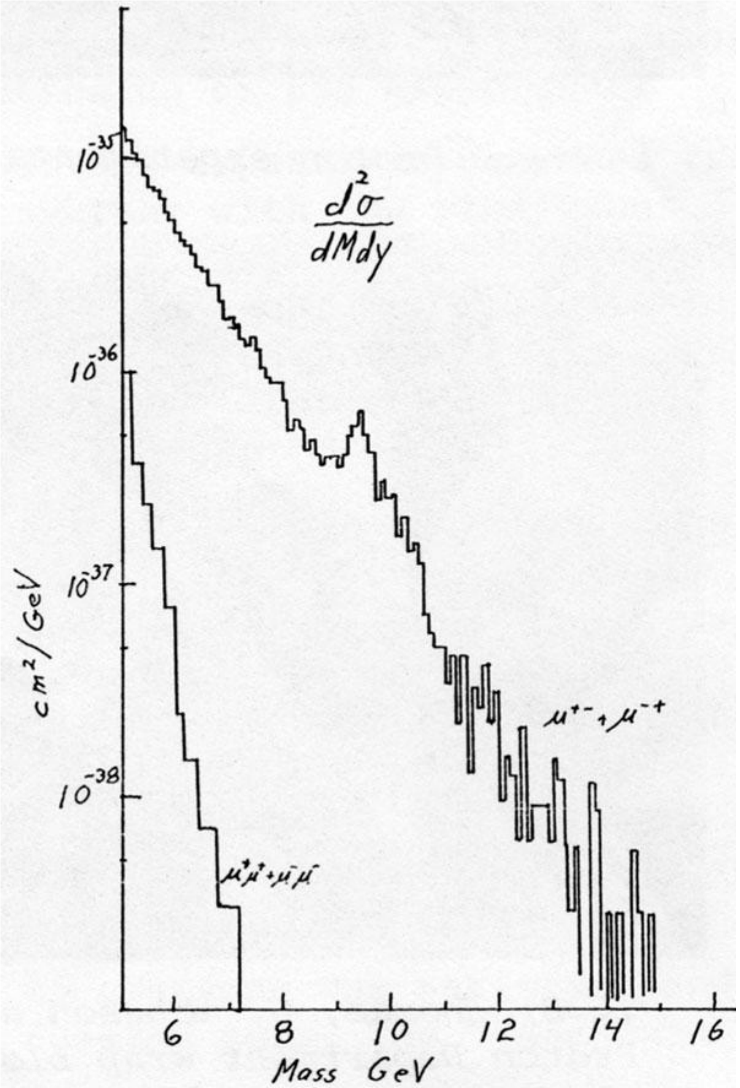
$\Upsilon(nS)$ production cross-section

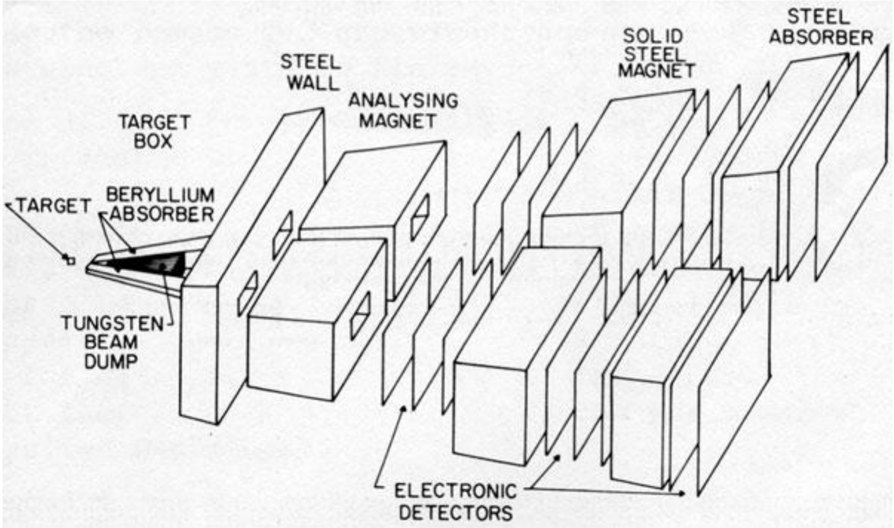
- Historical context
- Theoretical considerations
- The CMS detector
- The Υ cross-section
  - Signal selection
  - Analysis technique
  - Results and systematic uncertainties
- Comparisons with other experiments and theory
- Future considerations

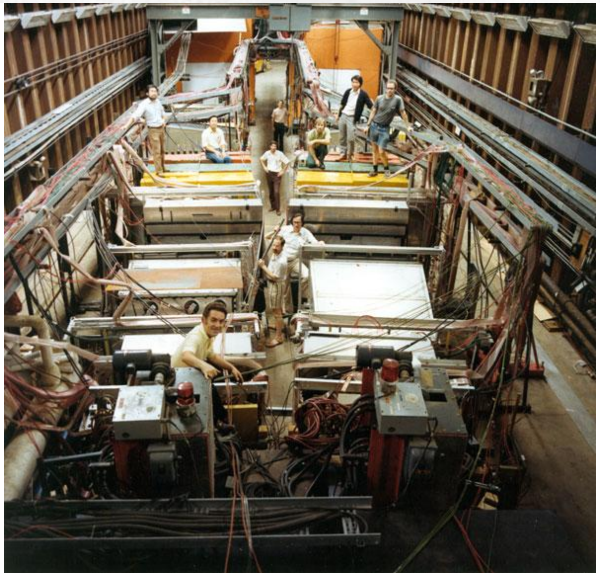
G-APD's in HEP

- What is a G-APD?
  - Basic properties
  - Pros and cons
  - Properties important to HEP detectors
- Using SiPM sensors in CMS Hcal
  - Studies
  - HO photo-sensors
  - HB/HE upgrades
- The future of G-APD's in HEP

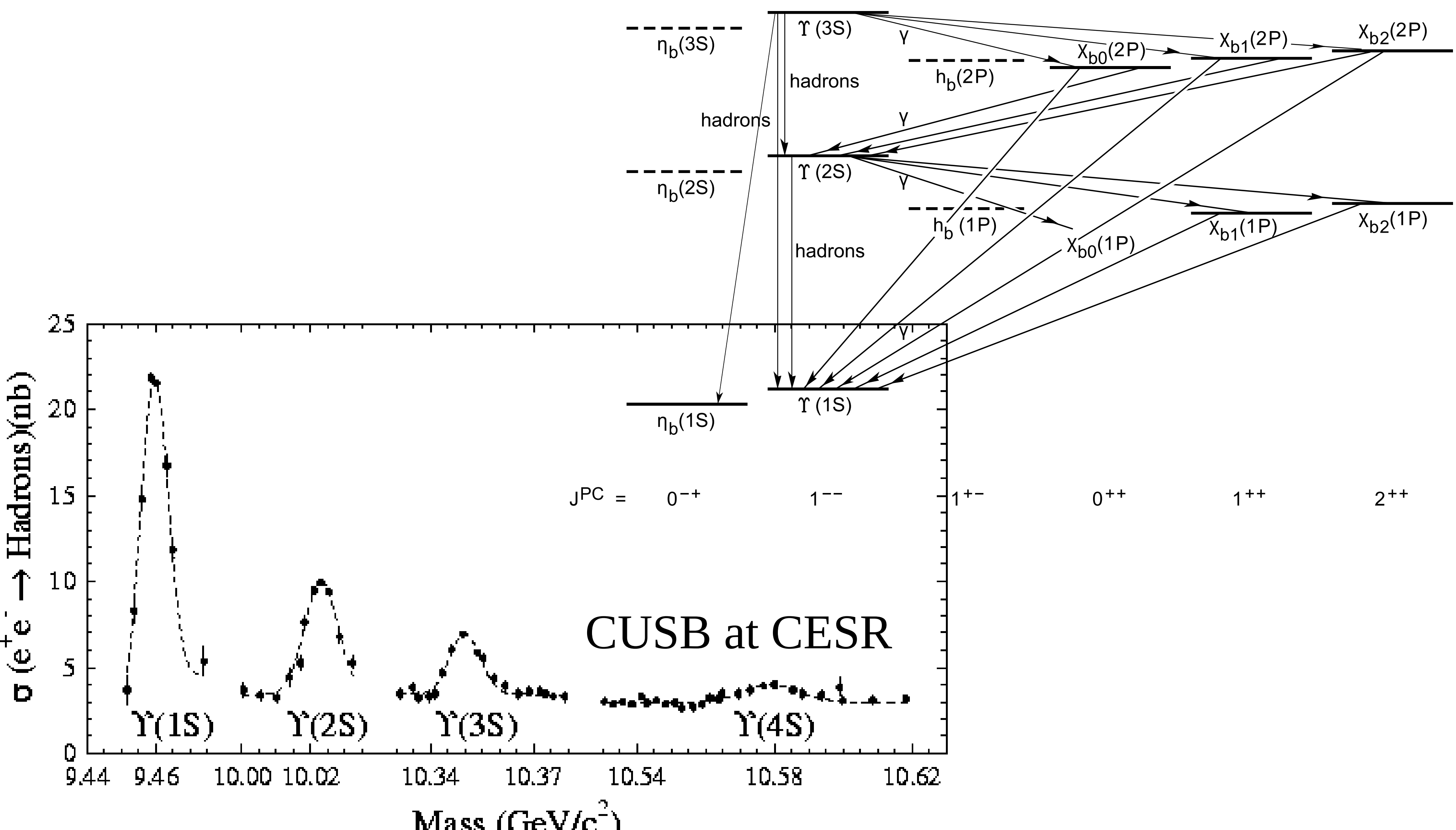
Υ history (1977)



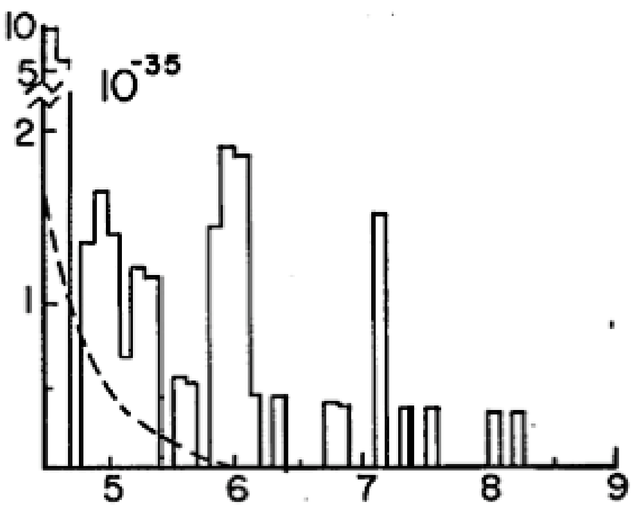




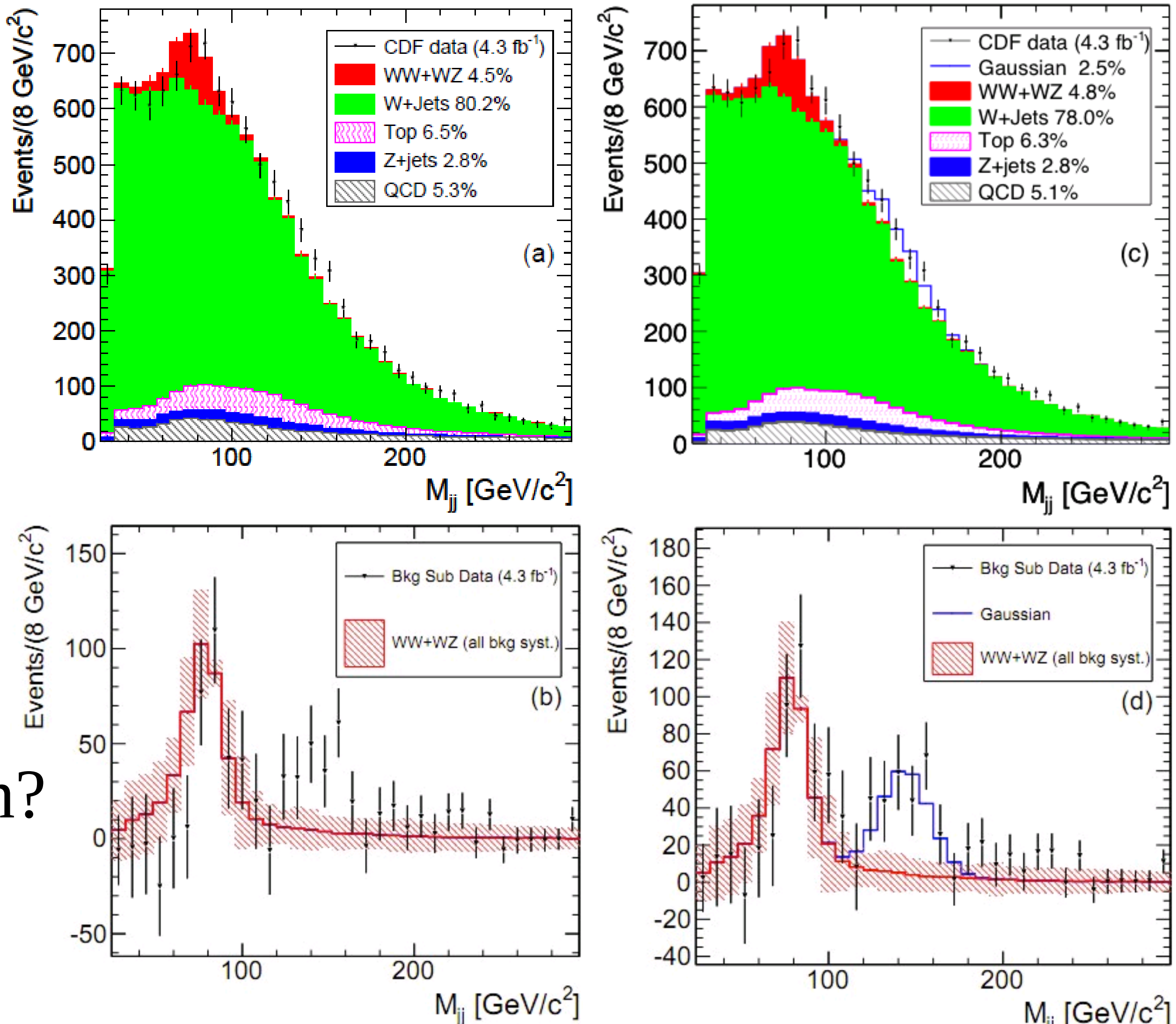
Upsilon (1980 and forward)



Now, a brief tangent



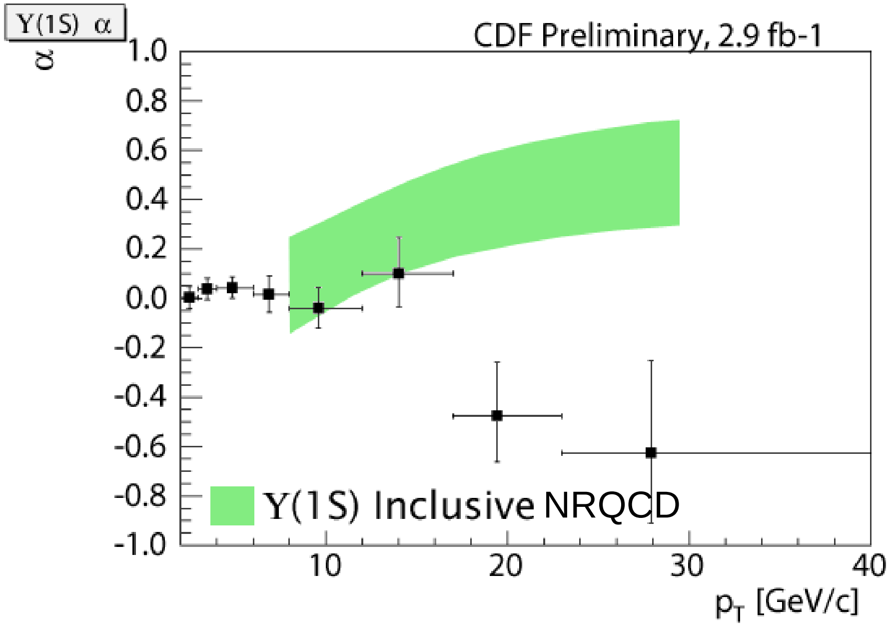
Déjà vu all over again?
No.



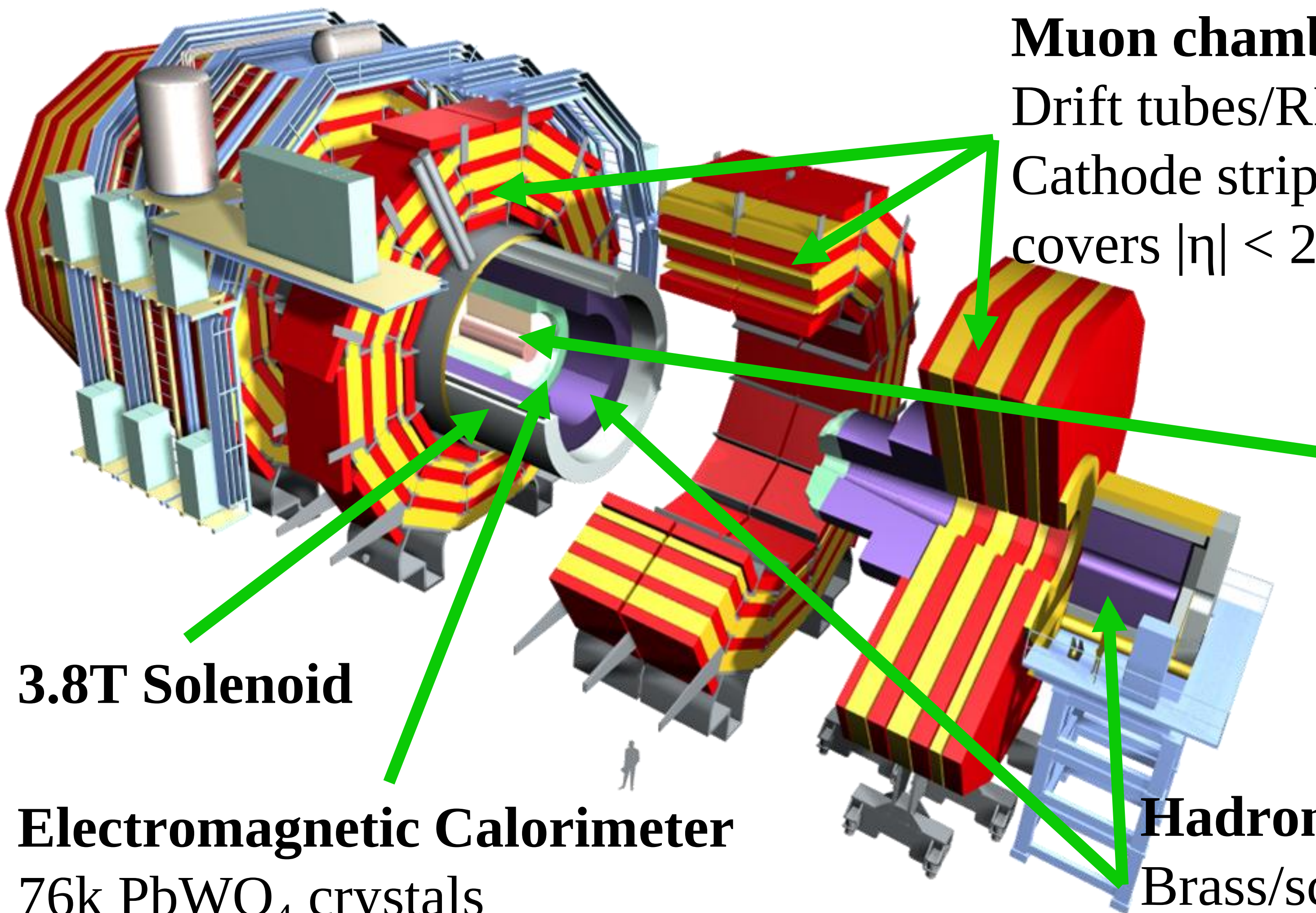
Now back to our regularly scheduled program

Υ Theory

- Quarkonia production at a hadron collider is not theoretically settled.
- Most models fail to simultaneously explain experimental measurements of both cross section and polarization.
- The LHC can provide new measurements to understand quarkonium production including a larger reach in p_T.



The CMS detector



Muon chambers

Drift tubes/RPC in barrel

Cathode strip/RPC in endcaps

covers $|\eta| < 2.4$

Inner tracker

Silicon pixels

Silicon strips

3.8T Solenoid

Electromagnetic Calorimeter

76k $PbWO_4$ crystals

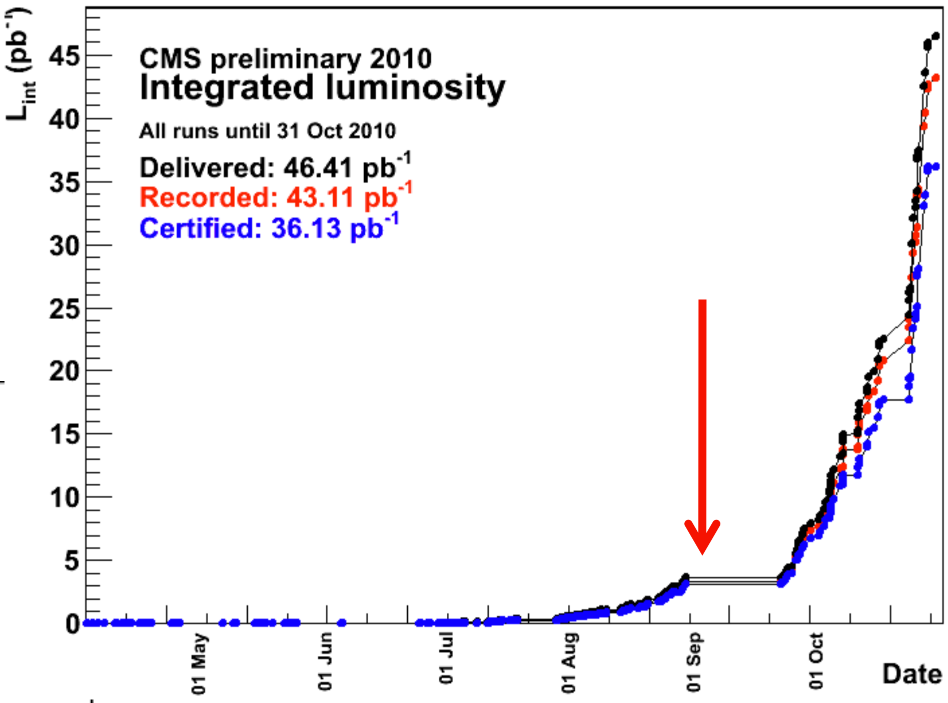
Hadronic Calorimeter

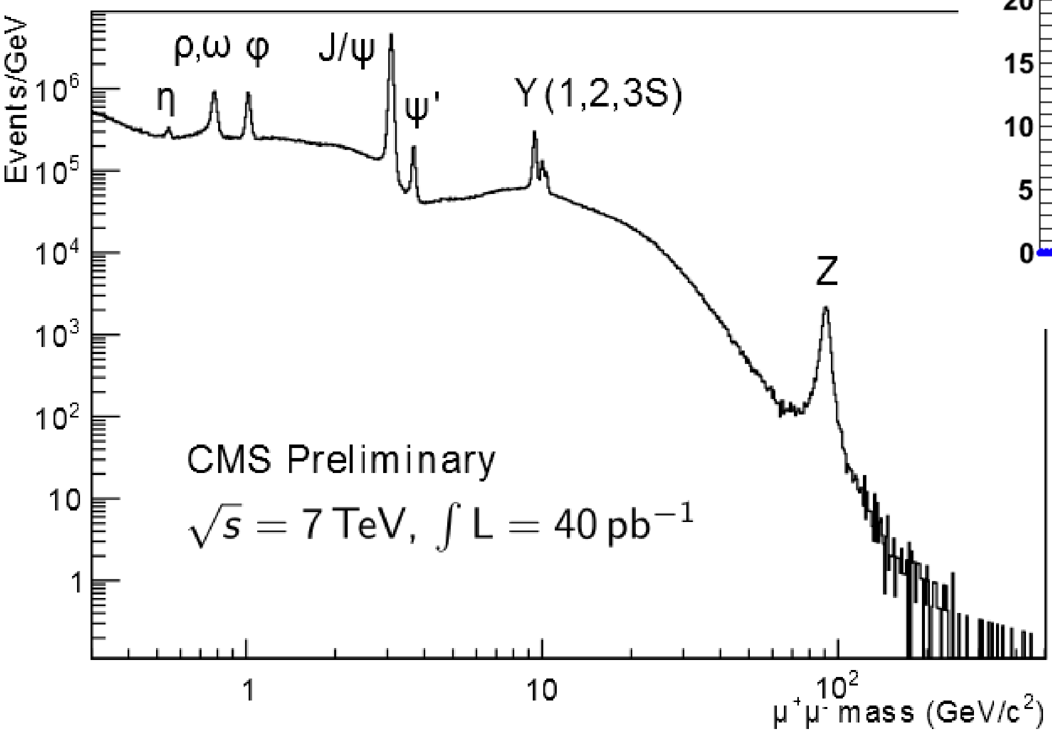
Brass/scintillator

Iron/quartz fiber

The dataset

- Results here are using 3 pb^{-1} of data collected in 2010.
- Full 2010 data set is 40 pb^{-1}.

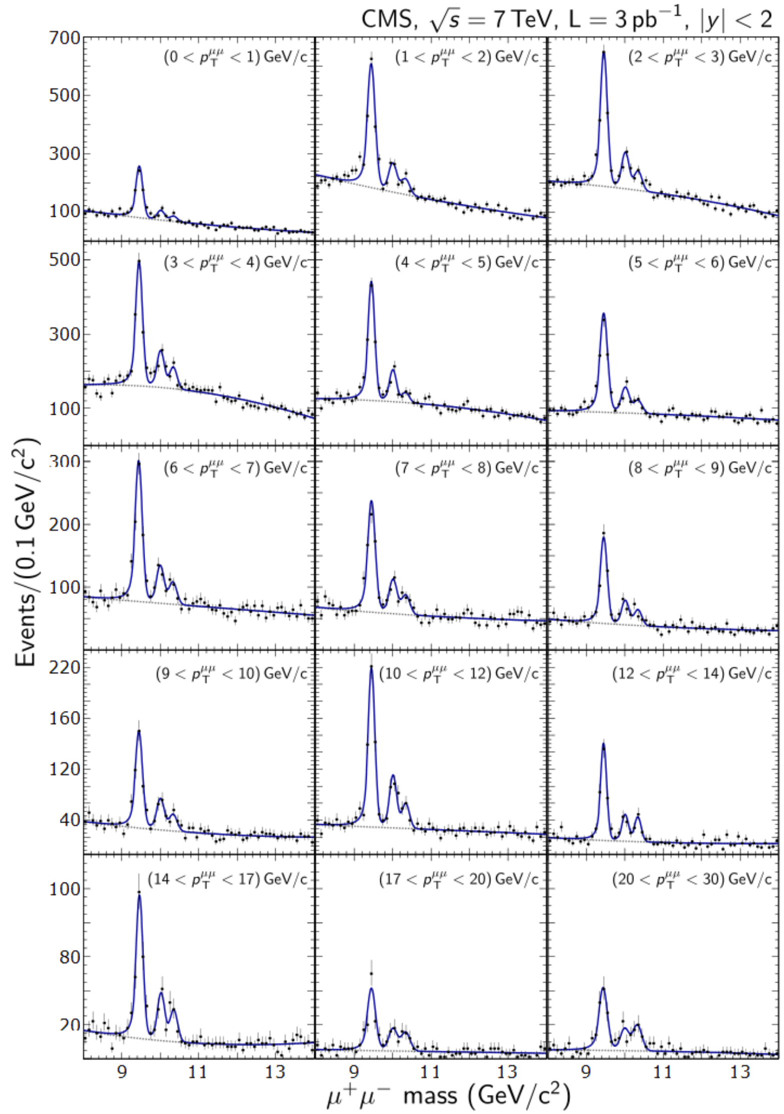




- Heavy ion data is also being analyzed.
- More data is being delivered now.

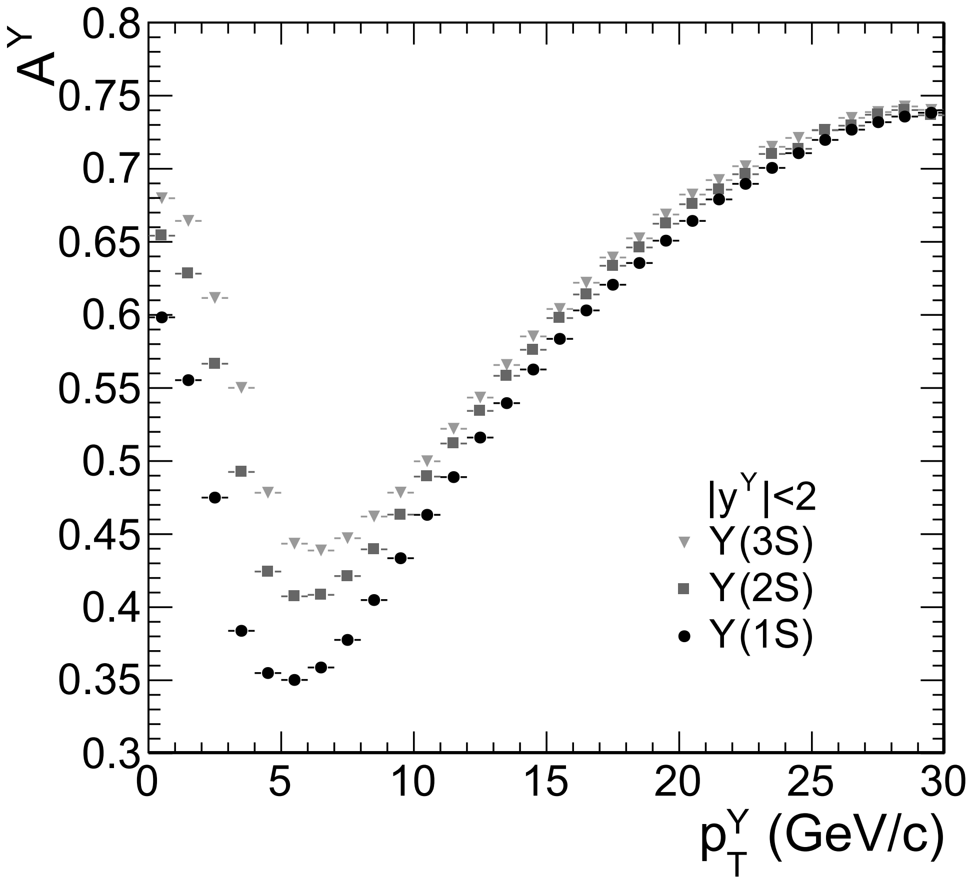
Υ candidate selection

- muon selection
  - Kinematic acceptance
    - $p_T > 3.5$ GeV/c if $|\eta| < 1.6$
    - $p_T > 2.5$ GeV/c if $1.6 < |\eta| < 2.4$
  - track $\chi^2/n_{dof} < 5$
  - $N_{Si\ hits} > 12$
  - tracking parameters and impact parameter consistent with primary vertex
  - muons matched to a dimuon trigger at Level 1
- dimuon selection
  - opposite sign muon pairs
  - vertex probability > 0.1%
  - $|y| < 2.0$



Υ acceptance

- Acceptance is evaluated using MC for its dependence on Υ p_T and *y*
- In addition, the acceptance is strongly dependent on the unknown production polarization.
  - Acceptance changes by as much as 20%.
  - Results are quoted for un-polarized case and for longitudinally and transversely polarized in both the Collins-Soper and helicity frames.

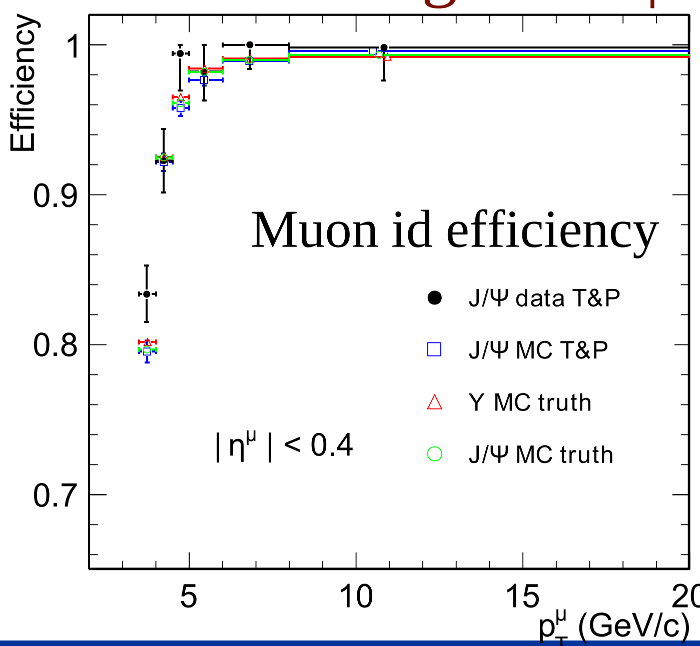


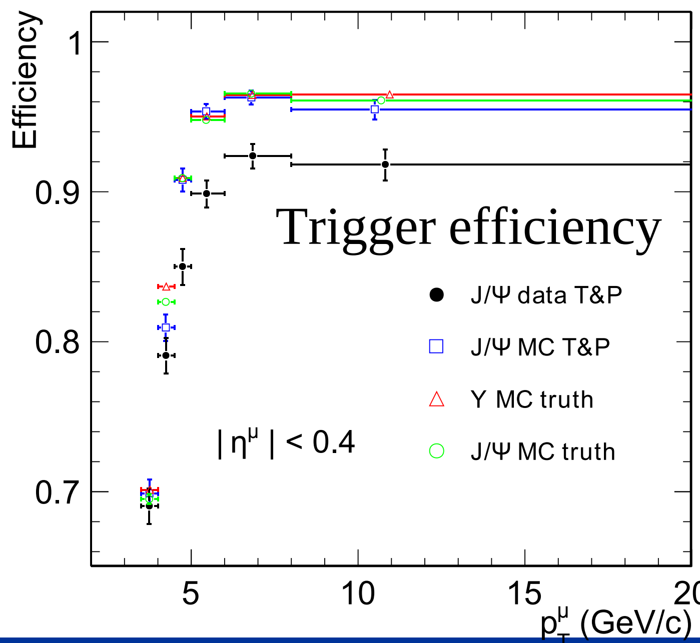
Muon efficiency

- Efficiency is factorized.

$$\varepsilon(\text{total}) = \varepsilon(\text{trigger}|\text{muon}) \times \varepsilon(\text{muon}|\text{track}) \times \varepsilon(\text{track}|\text{accepted})$$

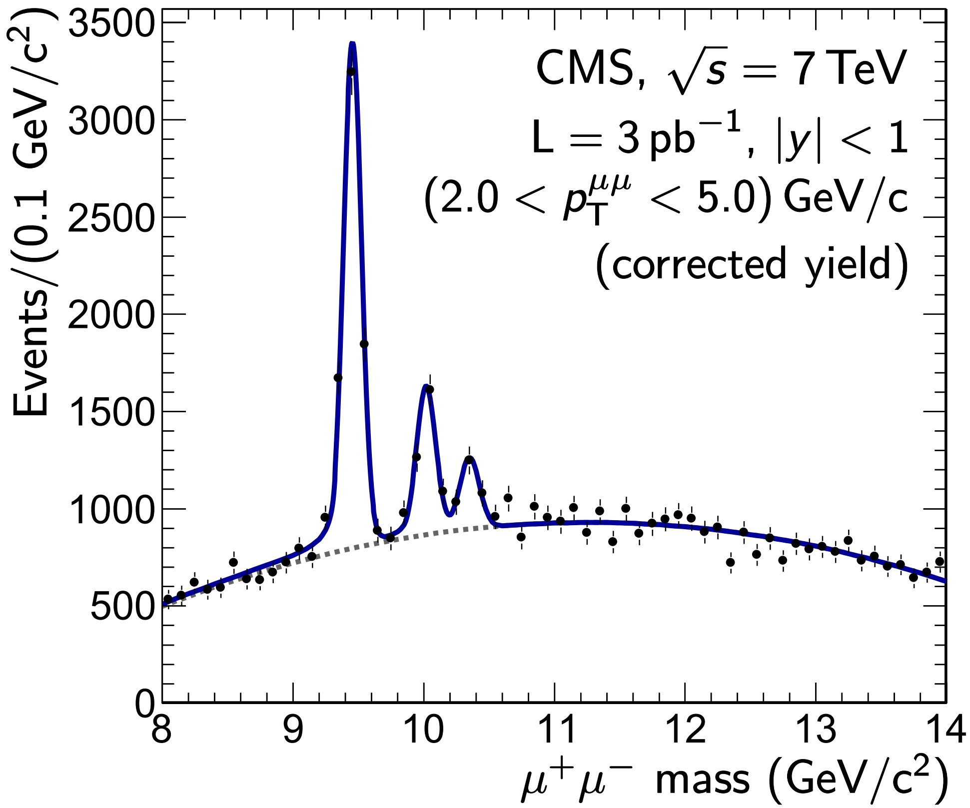
- Tracking efficiency is evaluated using a track-embedding technique to find an efficiency ~98% and flat in p_T and η.
- Muon identification and trigger efficiencies are evaluated from data using the J/ψ resonance.





Bringing it all together

- With the pieces in place we extract the Υ yield in an unbinned maximum likelihood fit to the dimuon mass spectrum from 8GeV – 14 GeV.
  - Signal shape: Crystal Ball shape/resonance
    - 1S mean floating, mass differences fixed to PDG
    - 1S resolution floating, 2S/3S widths fixed relative to 1S
    - tail parameters fixed to MC
  - Background shape: 2nd order polynomial



- Each event is weighted using the acceptance and efficiency measurements.

Results

- Integrated, unpolarized cross section |η| < 2

$$\sigma(\mathrm{pp} \to \Upsilon(1\mathrm{S})X) \cdot \mathcal{B}(\Upsilon(1\mathrm{S}) \to \mu^+\mu^-) = 7.37 \pm 0.13(\mathrm{stat.})^{+0.61}_{-0.42}(\mathrm{syst.}) \pm 0.81(\mathrm{lumi.})\,\mathrm{nb}$$

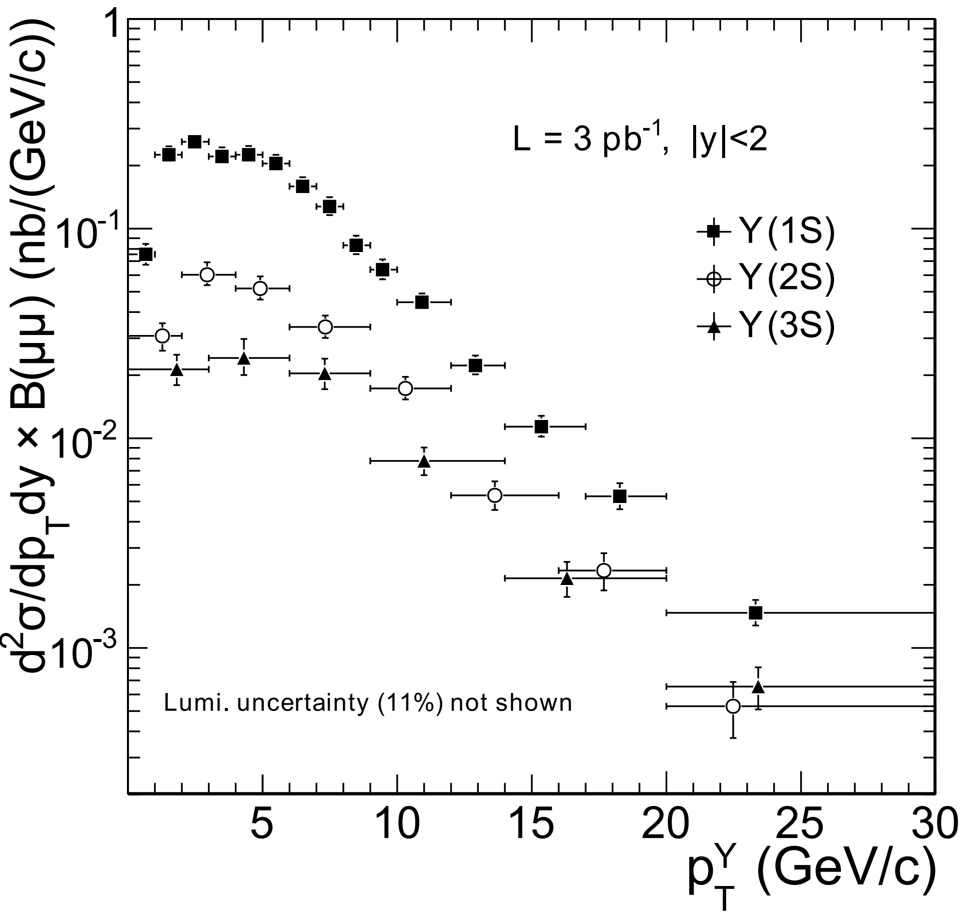
$$\sigma(\mathrm{pp} \to \Upsilon(2\mathrm{S})X) \cdot \mathcal{B}(\Upsilon(2\mathrm{S}) \to \mu^+\mu^-) = 1.90 \pm 0.09(\mathrm{stat.})^{+0.20}_{-0.14}(\mathrm{syst.}) \pm 0.24(\mathrm{lumi.})\,\mathrm{nb}$$

$$\sigma(\mathrm{pp} \to \Upsilon(3\mathrm{S})X) \cdot \mathcal{B}(\Upsilon(3\mathrm{S}) \to \mu^+\mu^-) = 1.02 \pm 0.07(\mathrm{stat.})^{+0.11}_{-0.08}(\mathrm{syst.}) \pm 0.11(\mathrm{lumi.})\,\mathrm{nb}$$

- Dominant systematic uncertainties
  - Luminosity (11%)
  - Muon identification and trigger efficiencies (8%)
- A different polarization can change the cross section by as much as 20%.

Results

dσ/dp$_T$ (unpolarized)

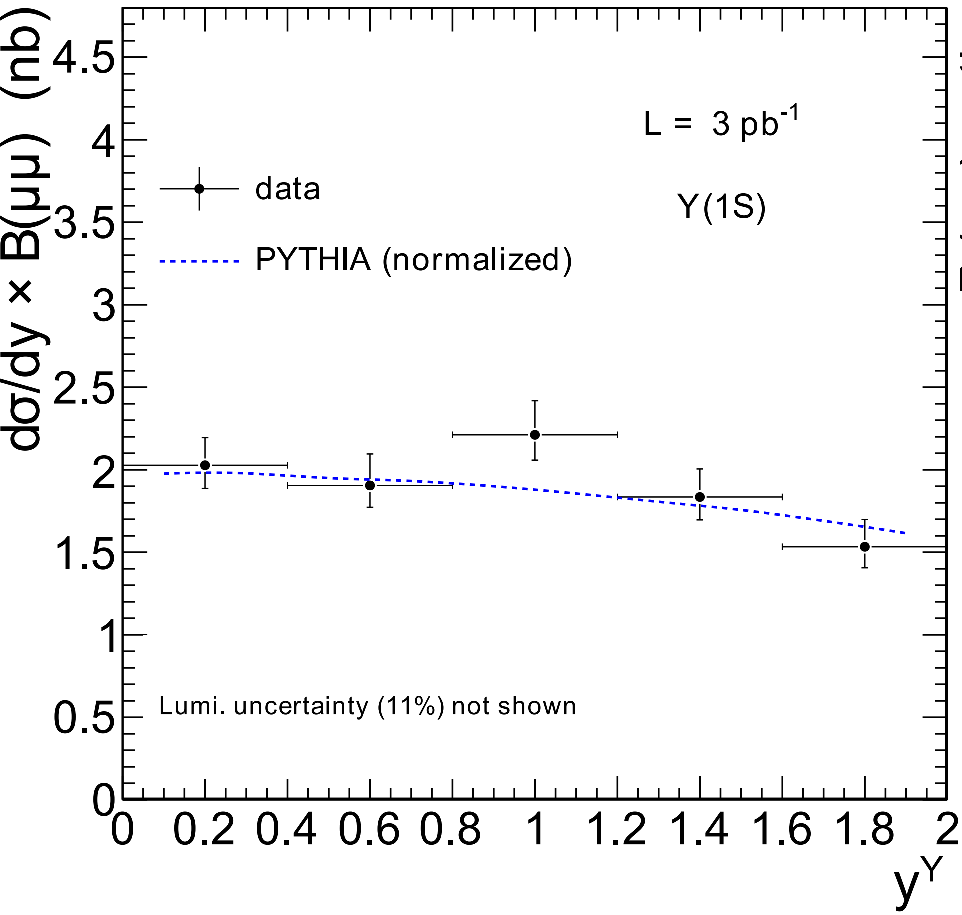


Variation due to polarization

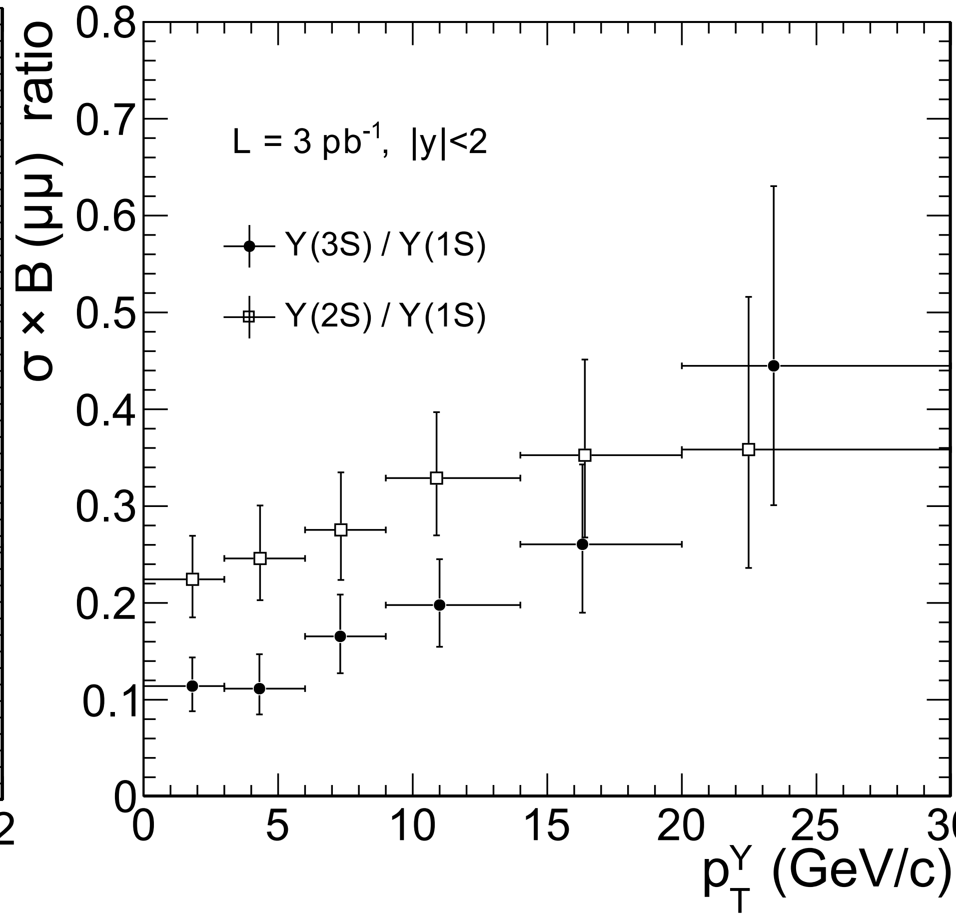
HX-T (%)	HX-L (%)	CS-T (%)	CS-L (%)
< 1			
+16	-22	+13	-16
+14	-19	+18	-24
+14	-20	+18	-23
+18	-23	+8	-12
+18	-23	-1	+2
+18	-23	-4	+10
+15	-20	-5	+12
< 1			
+14	-19	+12	-15
+10	-14	+17	-22
+13	-18	+14	-19
+17	-22	+1	-2
+17	-22	-4	+8
+14	-20	-5	+11
< 1			
+14	-19	+10	-13
+11	-16	+14	-19
+16	-22	+1	-1
+15	-21	-4	+10

Results

dσ/dy

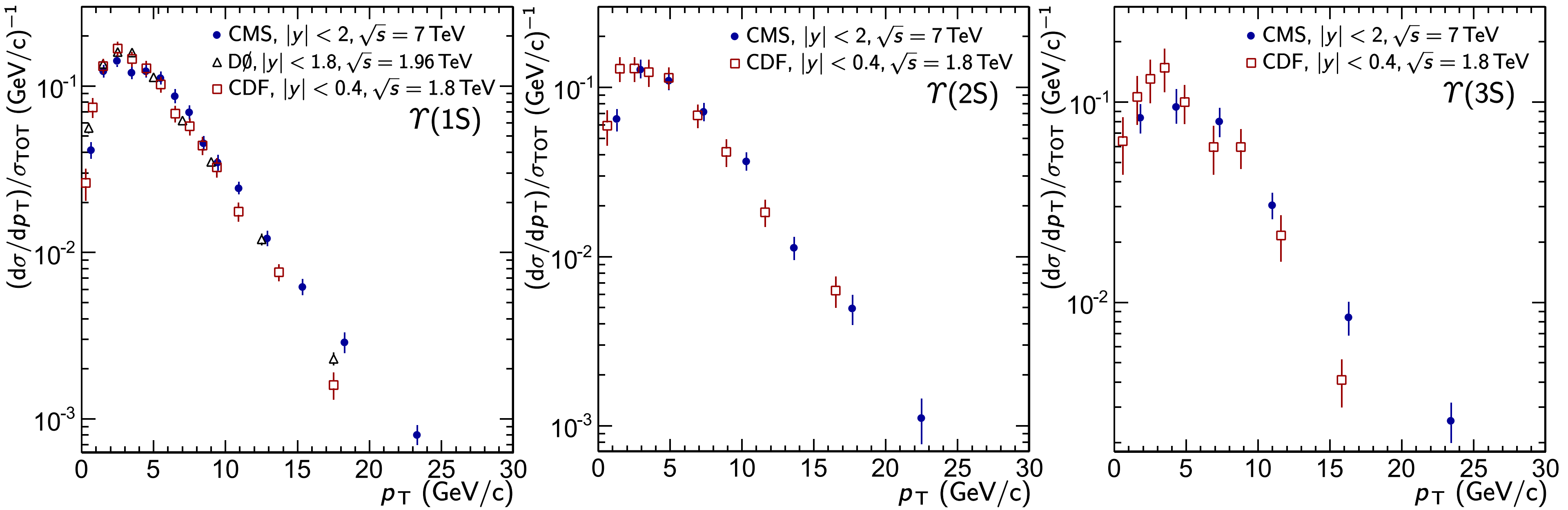


σ(nS)/σ(1S)



Comparison to Tevatron

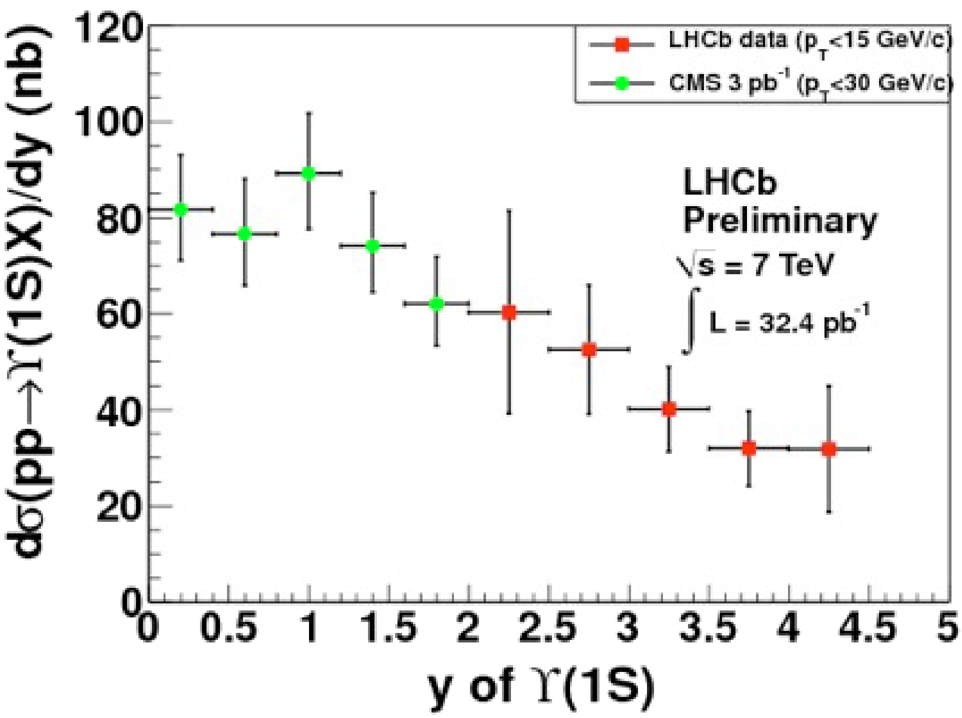
- Good agreement

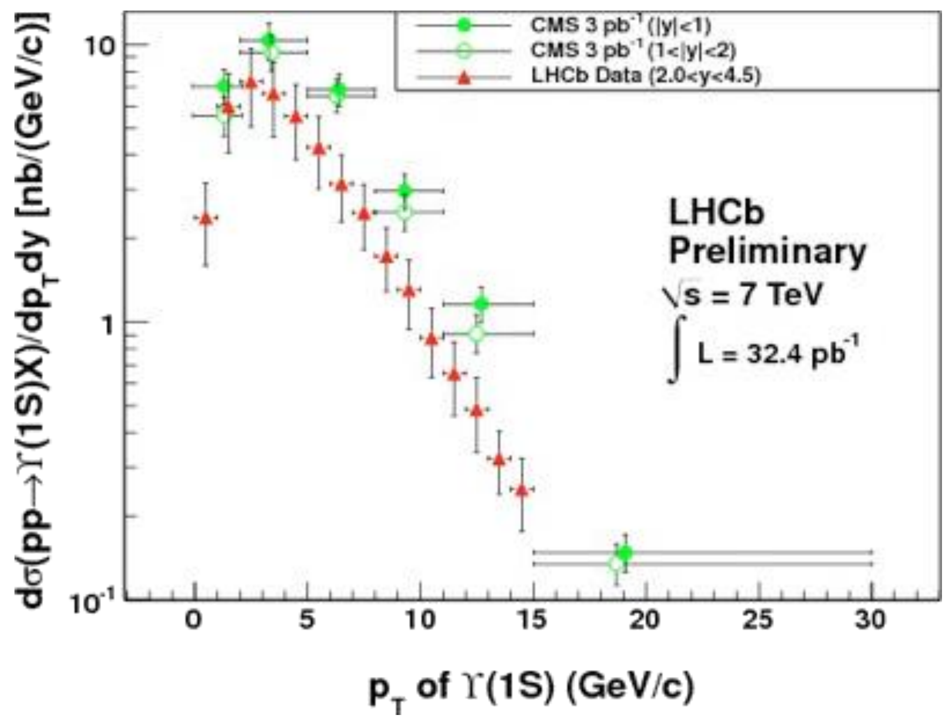


PRL **88** 161802 (2002)
PRL **100** 049902 (2008)

Comparison to LHCb

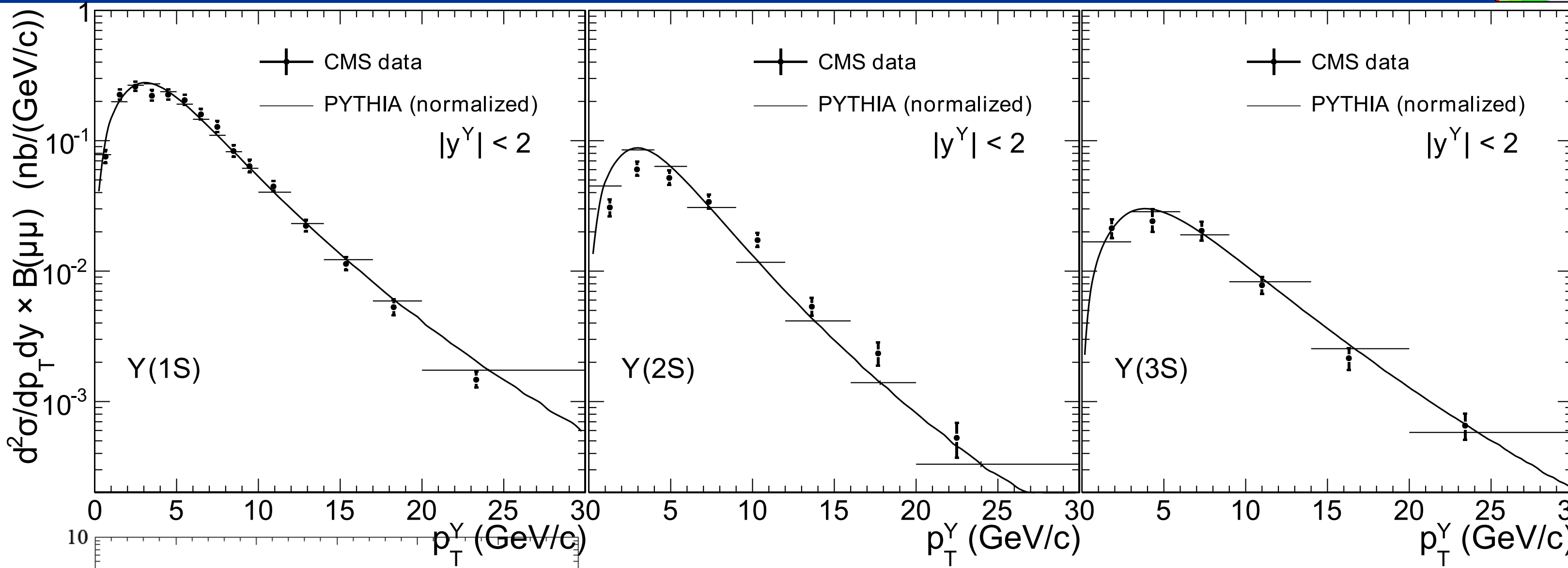
- Complimentary and consistent results

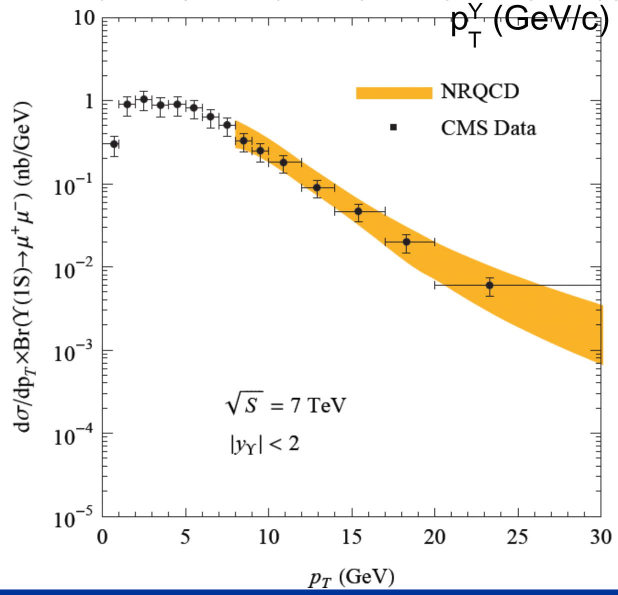




LHCb-CONF-2011-016

Comparison to theory



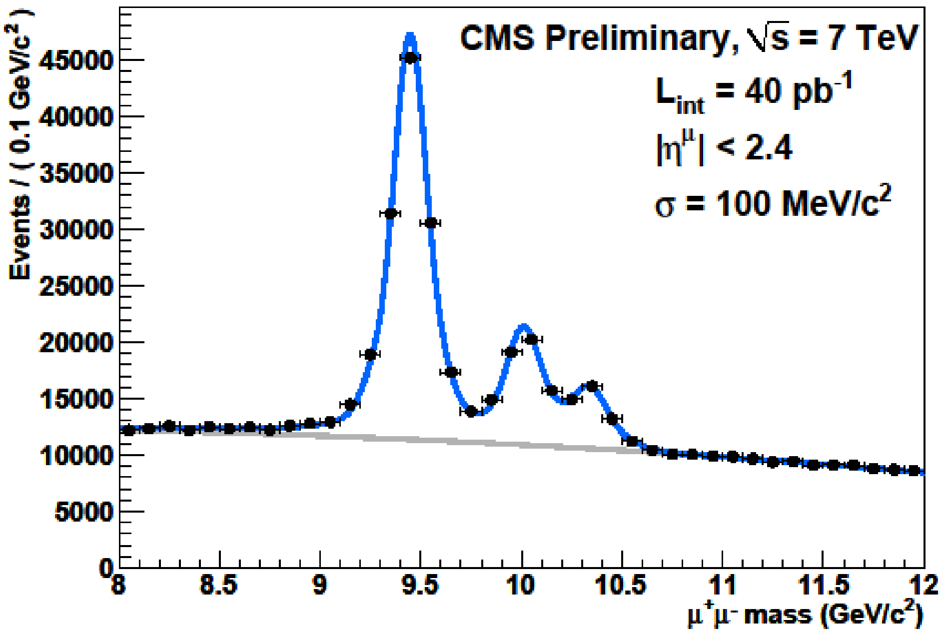


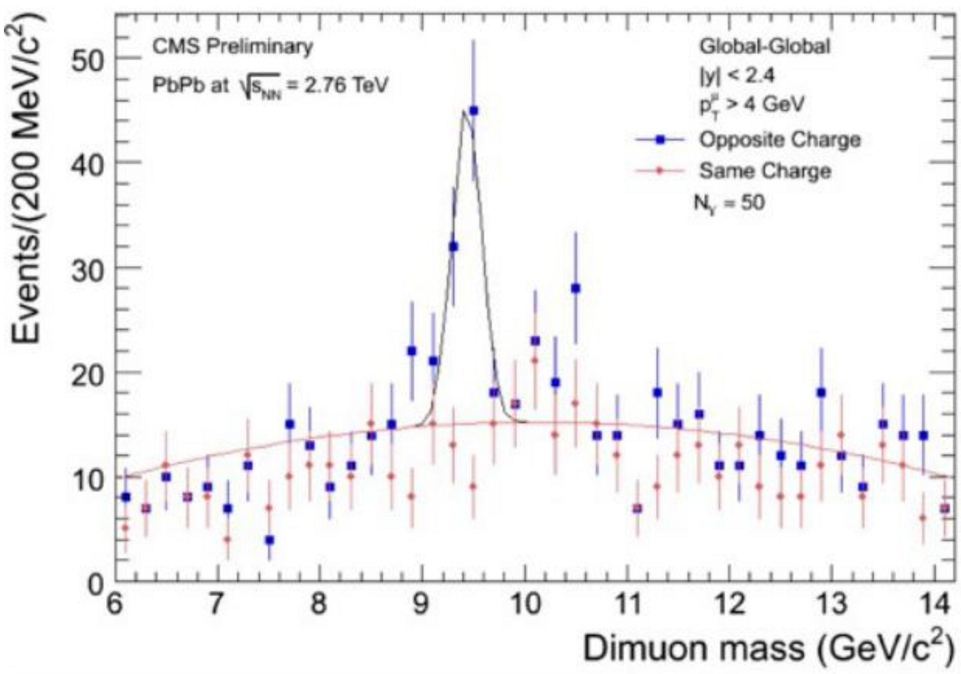
- Reasonable shape agreement with PYTHIA.
- NRQCD give good agreement for large p_T.

Summary and the future

- CMS was the first to measure the Υ(nS) cross section at the LHC and has found it to be compatible with expectations based on experience from the Tevatron and predictions from theory.
- The data volume has significantly increased, and for the future, CMS will update our cross section measurement as well as adding analyses to look at polarization and Υ production in heavy ion collisions.
- **More is yet to come!**

Stay tuned

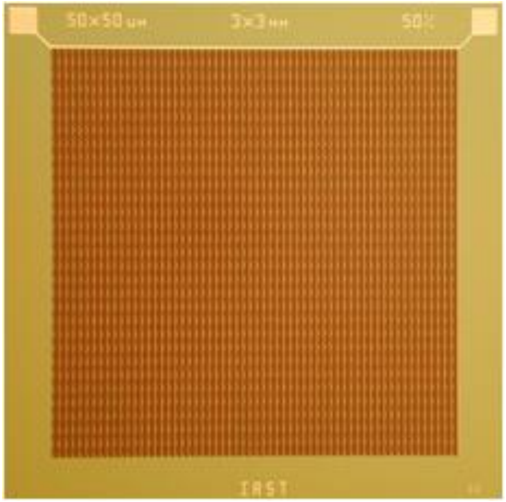

CMS Preliminary, √s = 7 TeV
L_int = 40 pb^-1
|η^μ| < 2.4
σ = 100 MeV/c^2
Events / (0.1 GeV/c^2)
μ+μ- mass (GeV/c^2)

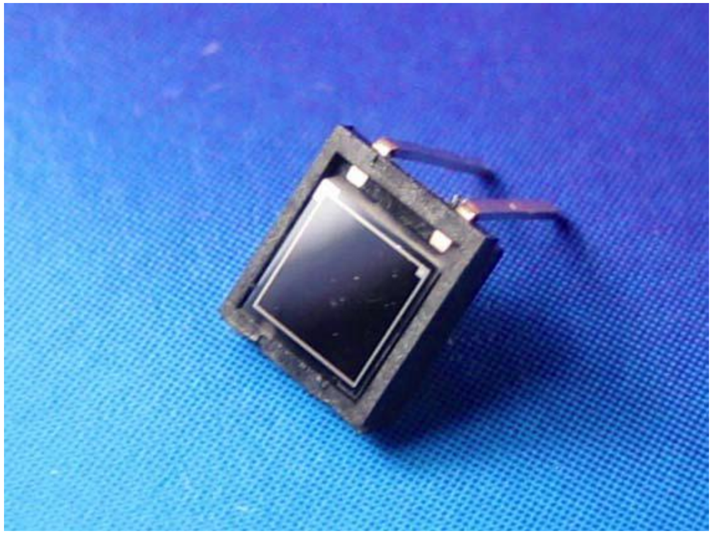

CMS Preliminary
PbPb at √s_NN = 2.76 TeV
Global-Global
|y| < 2.4
p_T^μ > 4 GeV
Opposite Charge
Same Charge
N_Υ = 50
Events/(200 MeV/c^2)
Dimuon mass (GeV/c^2)

G-APD’s and their uses in HEP calorimetry

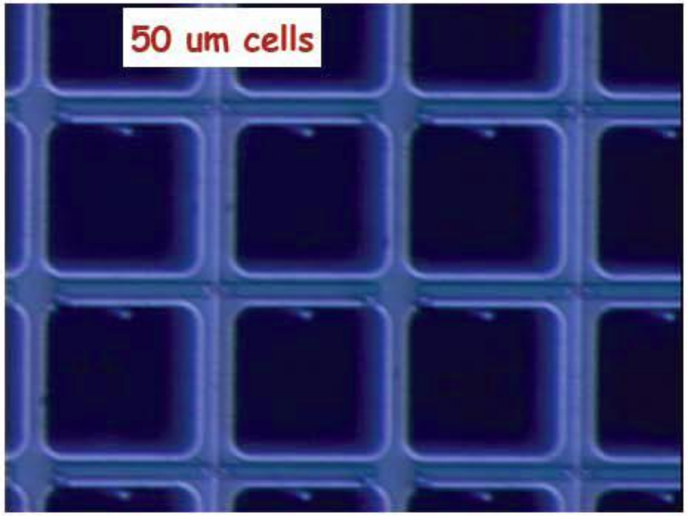
What is a G-APD?

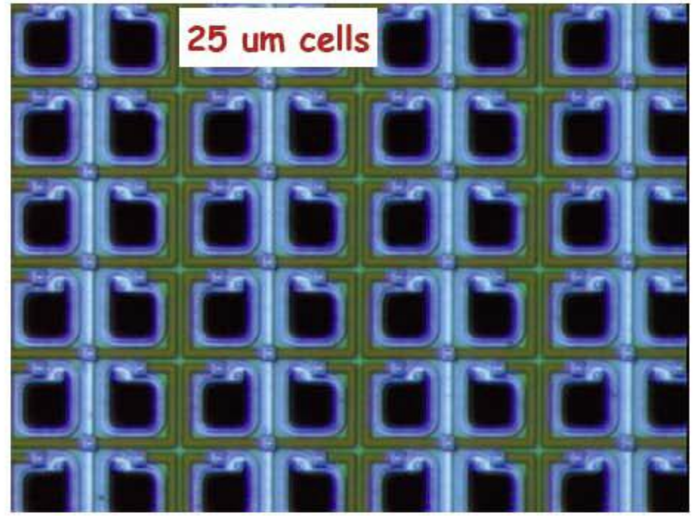
- Geiger mode Avalanche Photo-Diode.
  - generic name for a class of pixilated semiconductor photo-sensors.
  - Other names for the same thing.
    - SiPM (commonly used)
    - MPPC (Hamamatsu)
    - MAPD (Zecotek)
    - I will probably regularly call them SiPM's, but they can be built from other semiconductors.

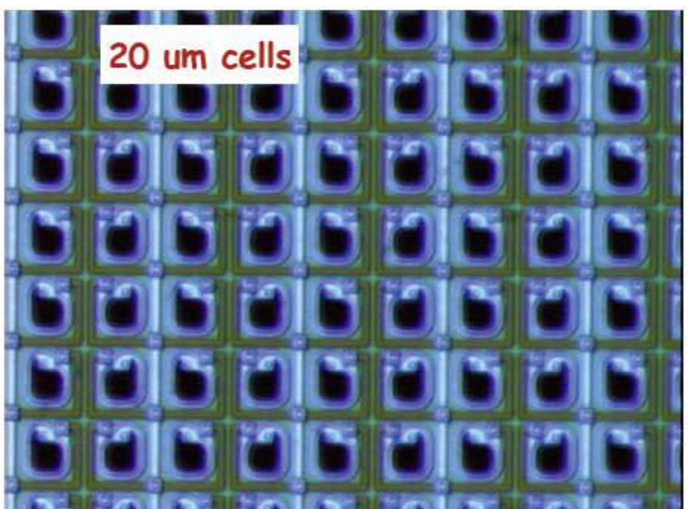


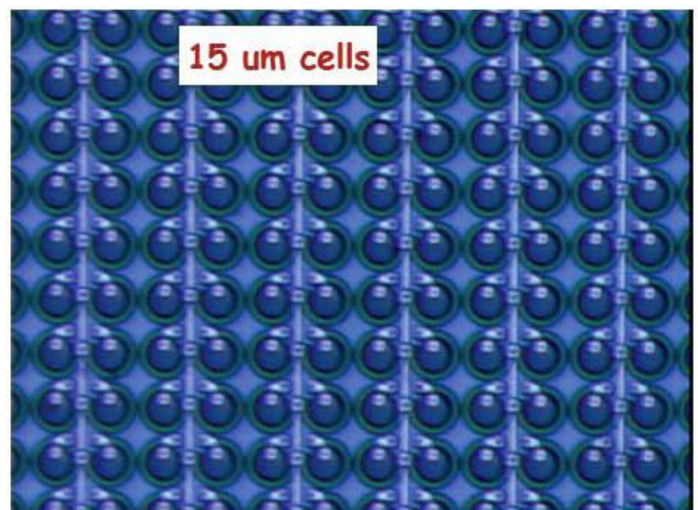


A closer look at an MPPC





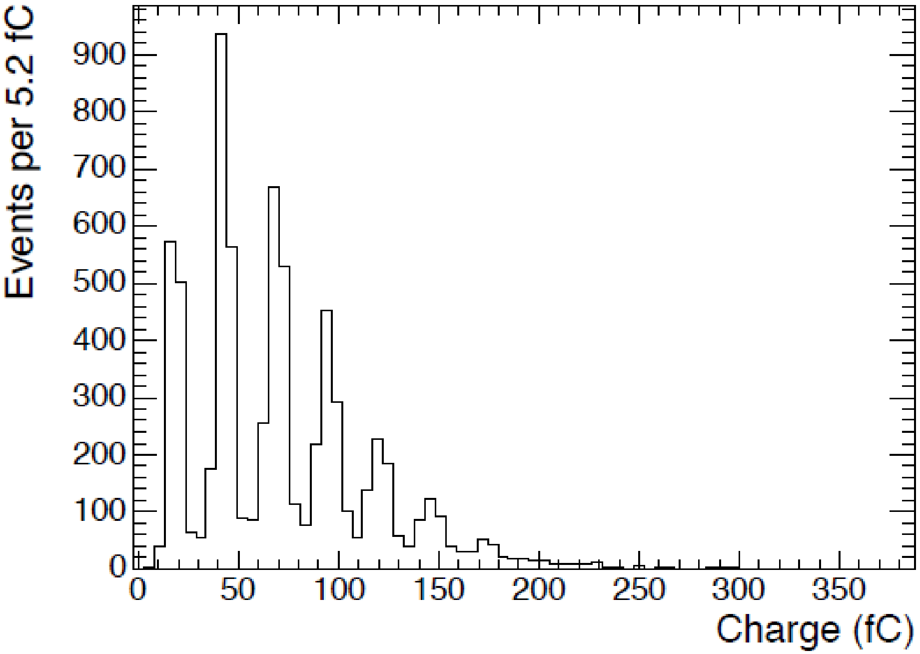




What does it do?

- A G-APD detects photons.

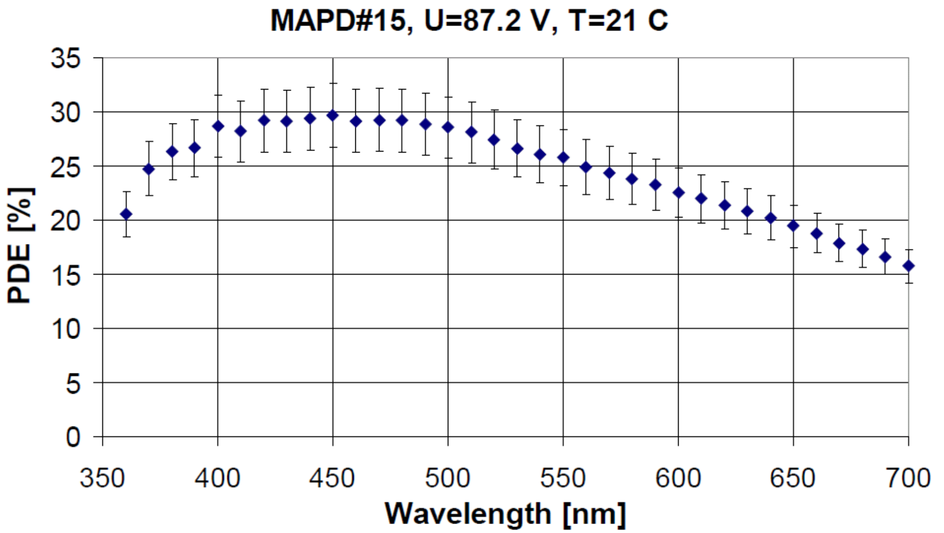
  Each pixel is sensitive to photons. When a photon hits it, it discharges like a capacitor with a gain 10^5-10^6. You can see more than one photon by counting the number of pixels that fire off. The pedestal is dominated by random single pixel discharge.

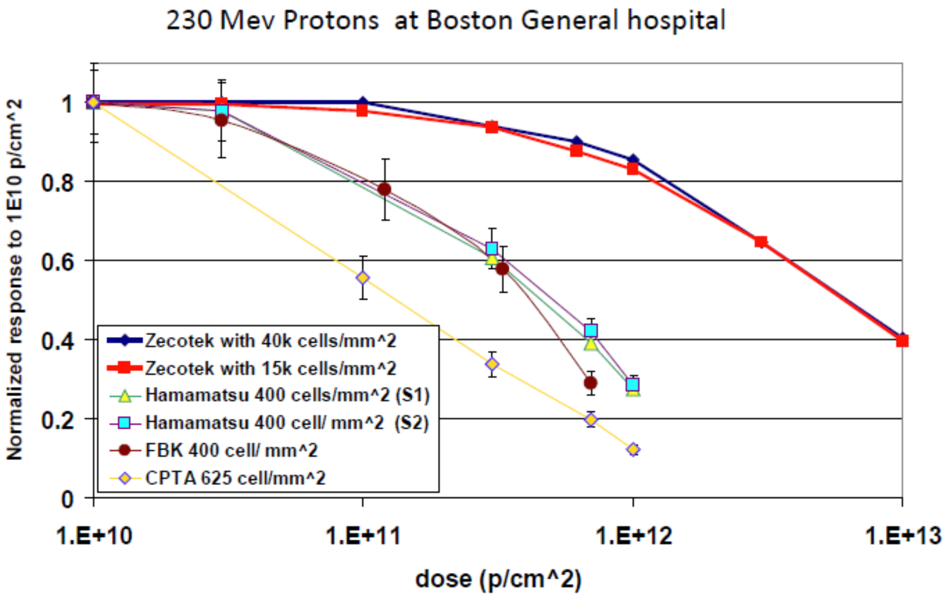


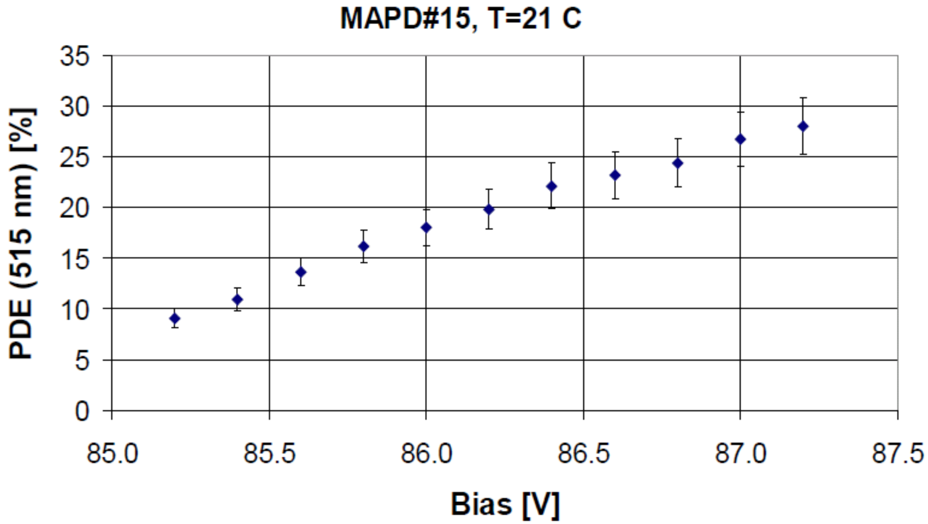
Pulses from an LED observed with the 1-mm^2 SiPM read through the QIE electronics. Charge distribution collected in time samples 5 and 6, showing clear peaks for 0, 1, 2, 3, 4, 5, and 6 photoelectrons.

Additional characteristics

- Can be operated in a magnetic field.
- Good spectral response.
- Relatively radiation hard.
- Fast leading edge.

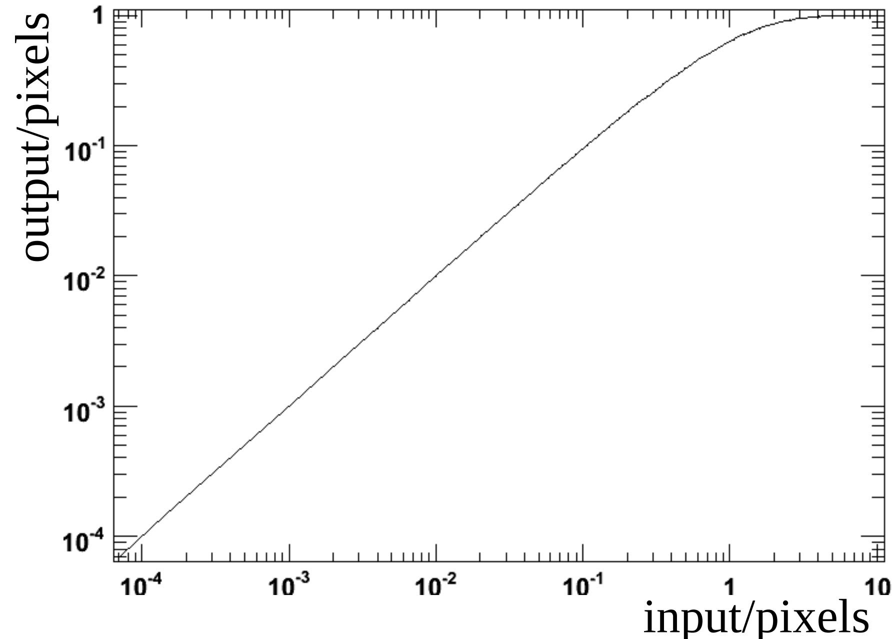






Is there anything else?

- This all sounds really good. Are there drawbacks?
- The dynamic range of the device is determined by the number of pixels that are illuminated.
- A pixel takes some time to "recharge" so that it is sensitive again.
- Temperature sensitivity few-several %/°C



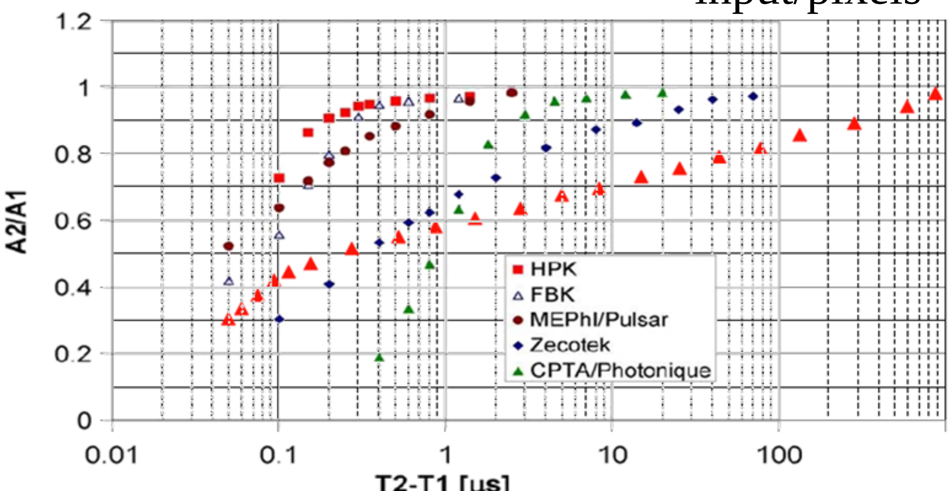
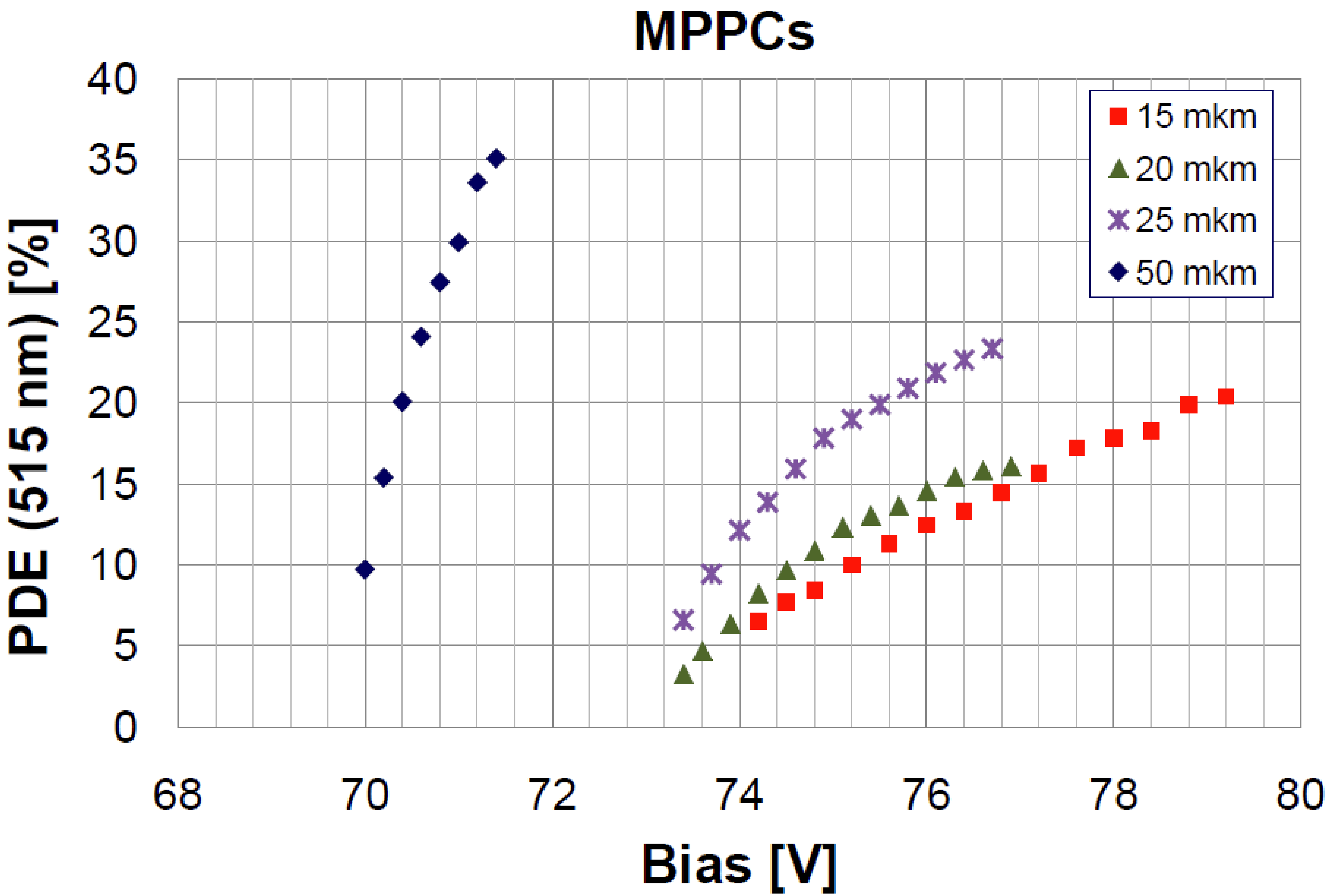
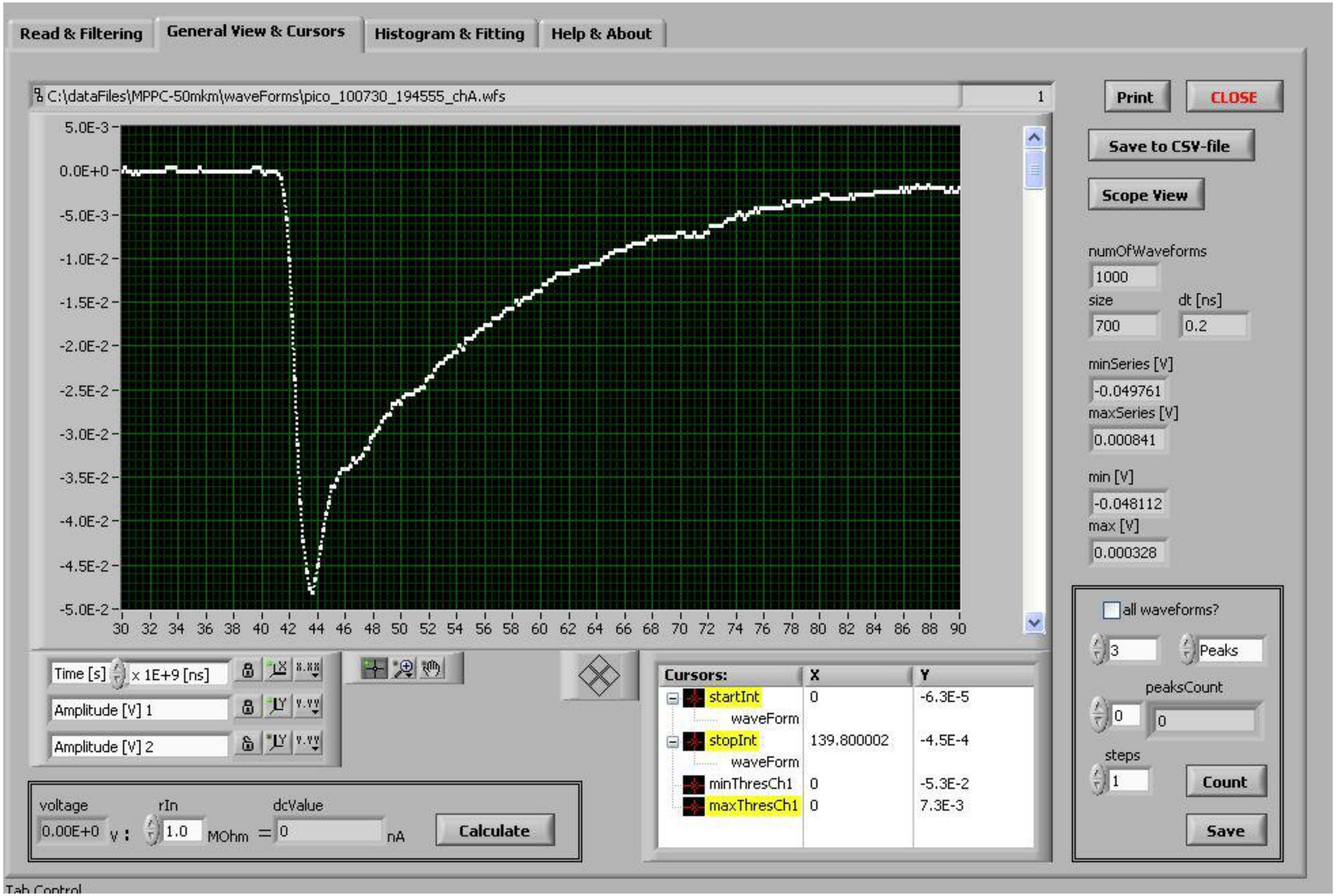


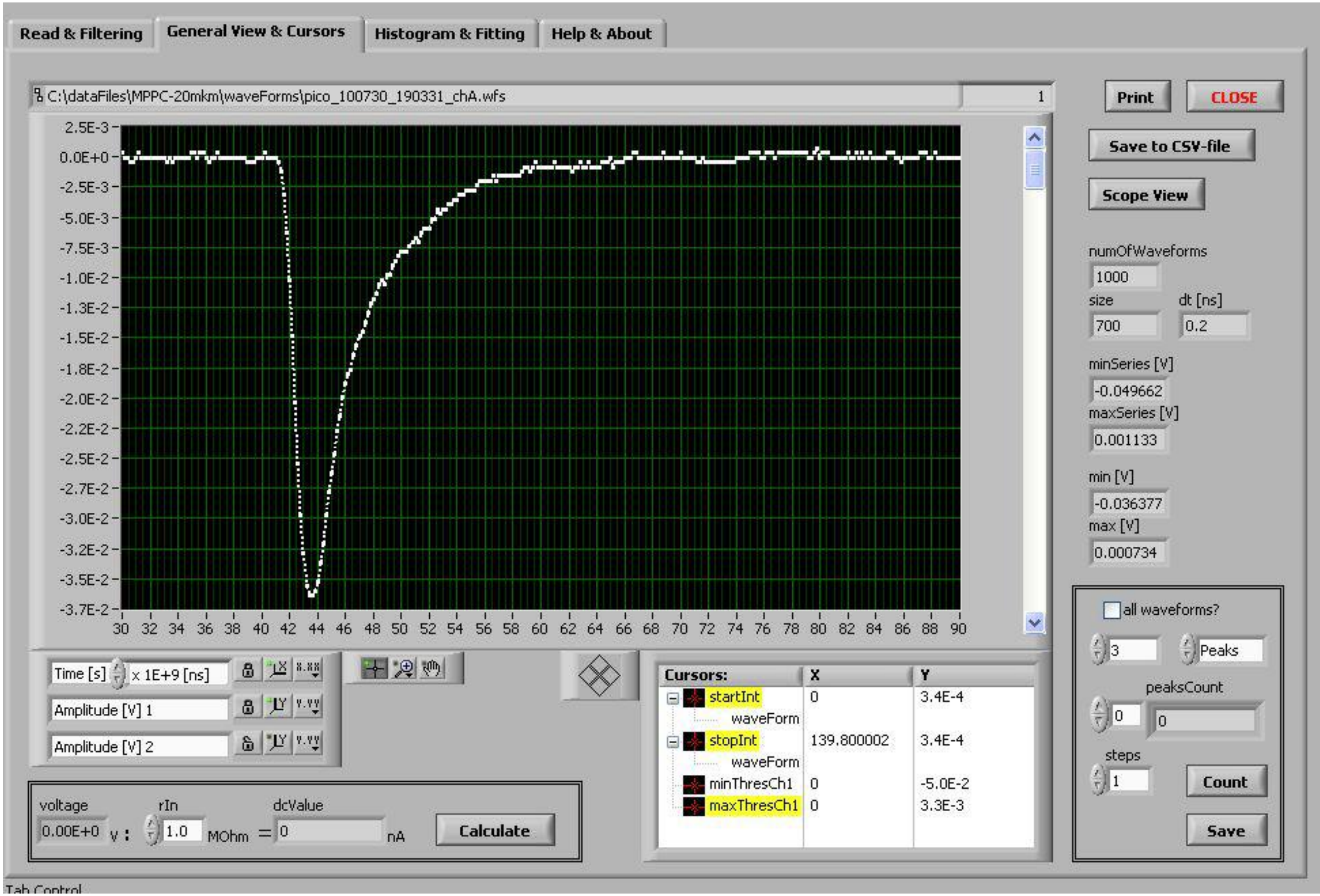
Photo detection efficiency



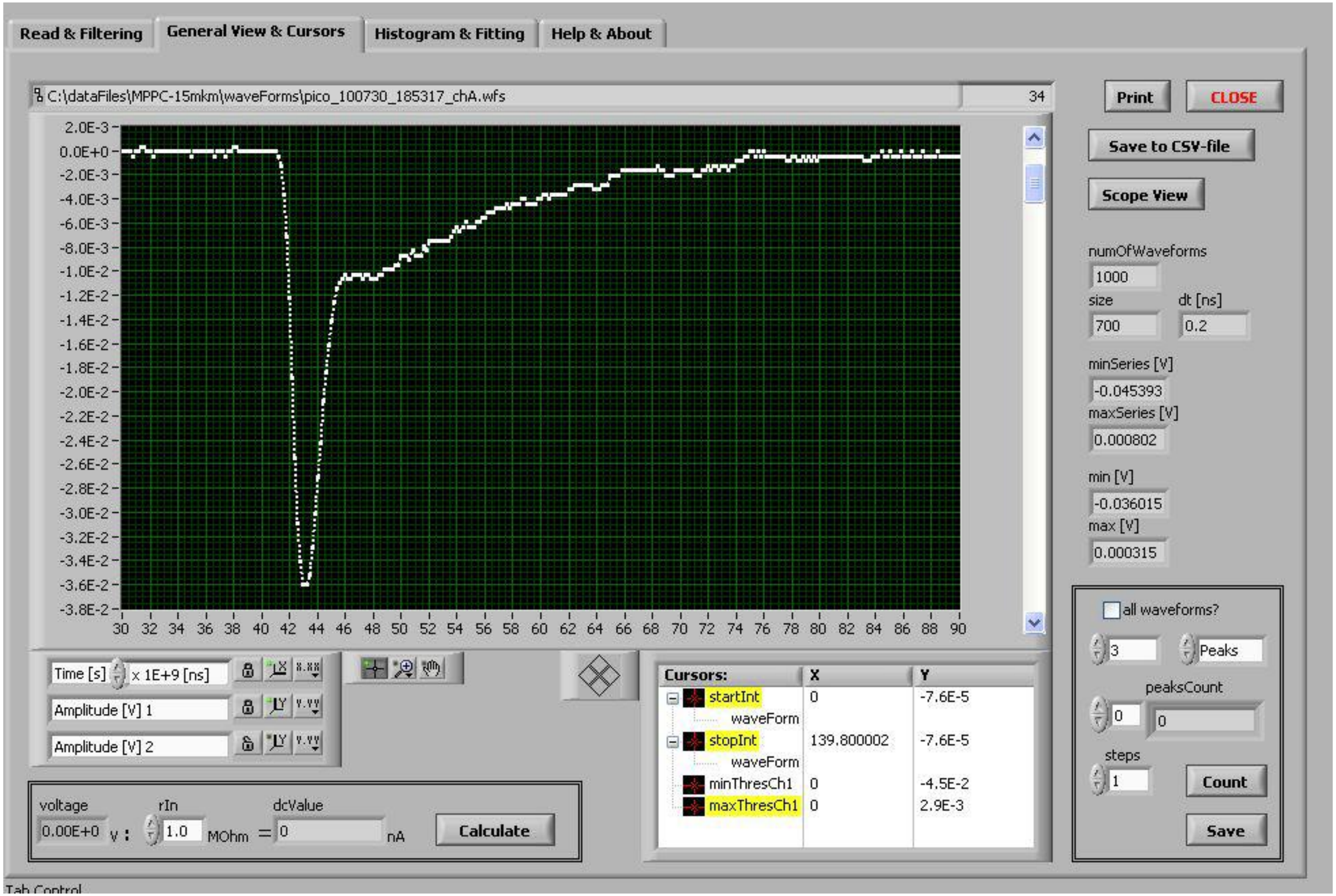
Signal Shape (50 µm)



Signal Shape (20 μm)



Signal Shape (15 μm)

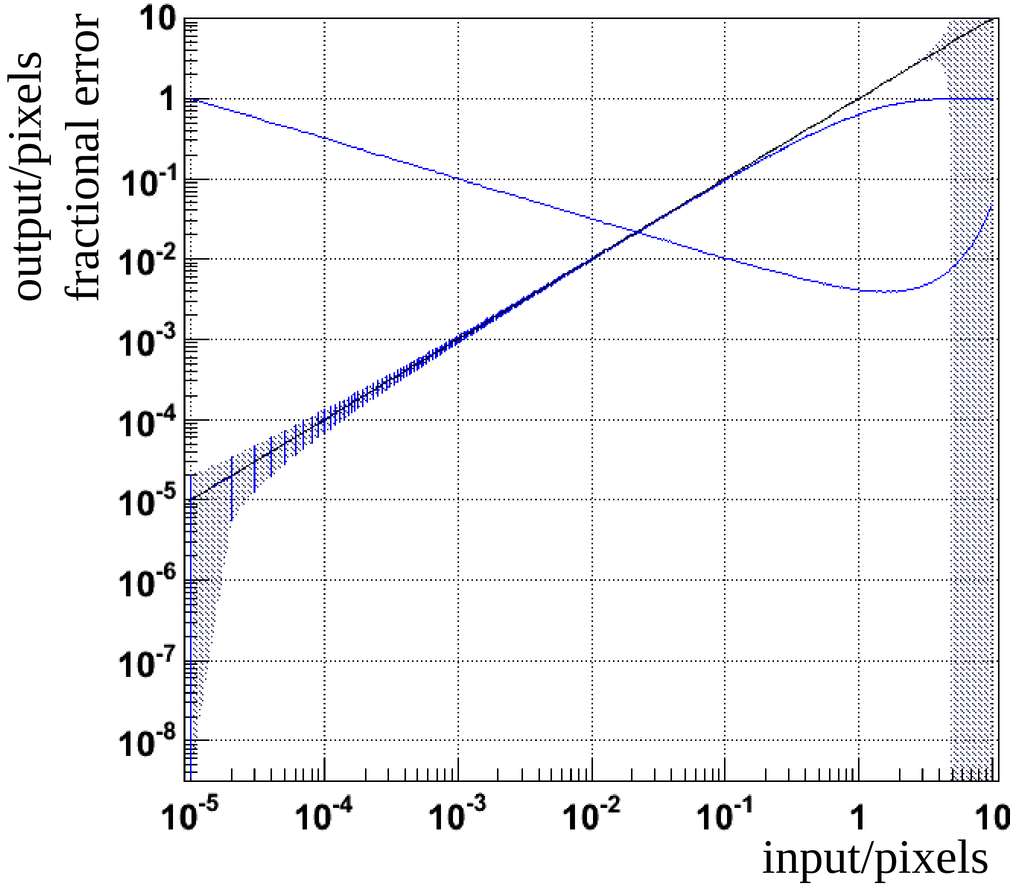


SiPM's in the CMS Hcal

- How does the SiPM map onto the needs of the CMS hadron calorimeter?
  - Large dynamic range (2 GeV – 3 TeV) → lots of pixels
  - High bunch crossing rate → fast pixel recovery
  - Large magnetic field
  - Temperature dependence can be managed.
  - Radiation hardness is ok.
  - No high voltage or vacuum
  - Larger gain than existing HPD
  - Small dimensions

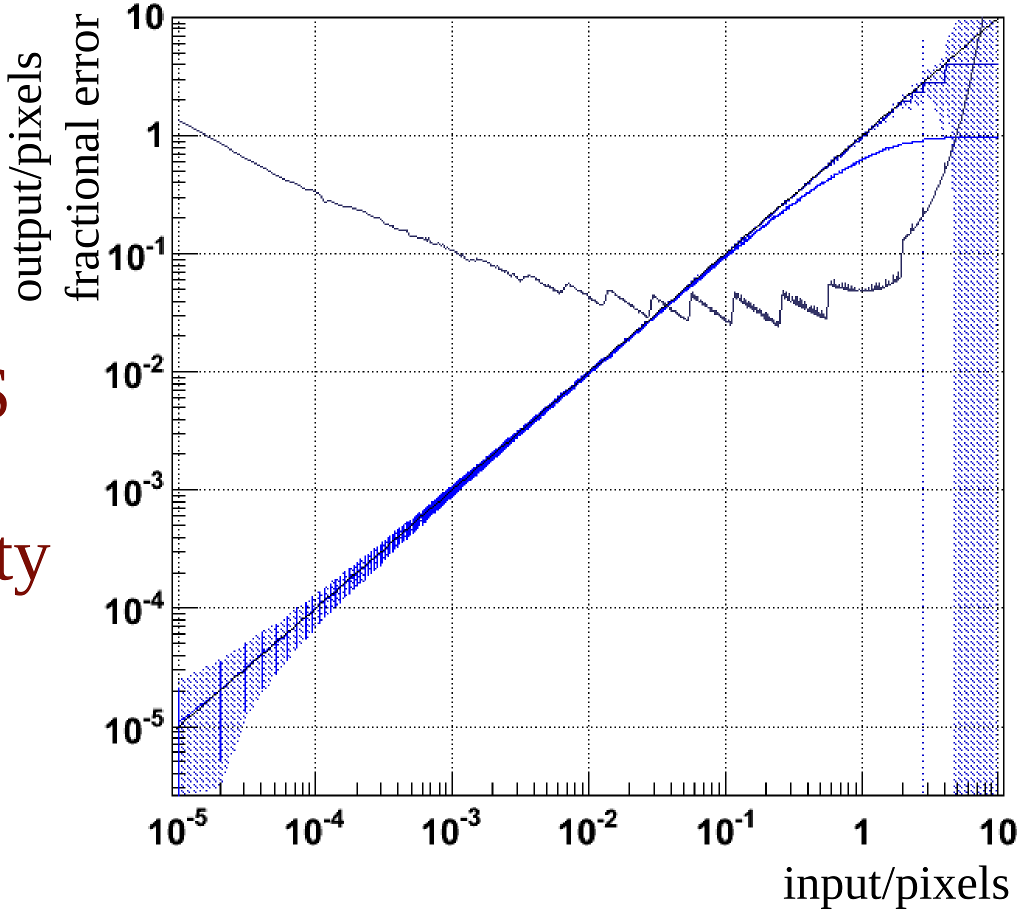
Start with a simple model

- Using basic data from bench tests and a simple model we simulate the SiPM.
- We can see the saturation with more light.
- We can see if we could correct the saturation.
- We see the error on that correction.



Make it slightly more complex

- Add in other factors
  - ADC quantization
  - cross-talk
  - temperature dependence
- So far we found that a SiPM could still be able to meet the needs of the CMS Hcal, but we need to pay attention to the pixel density to make sure it will meet our dynamic range requirements.

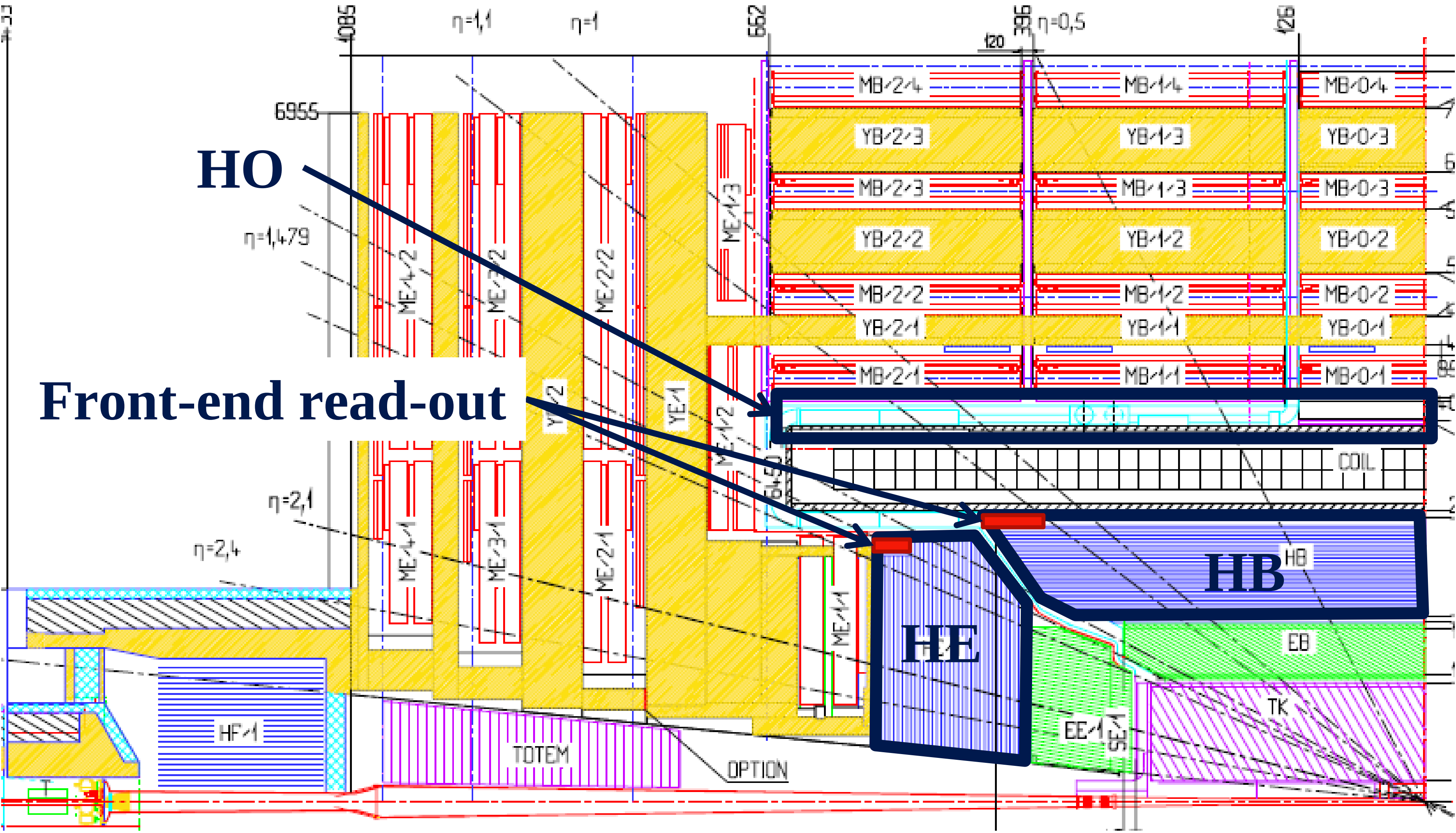


Add something more challenging

- What about the large pileup and high rate at the LHC?
- The Zecotek devices which have the largest dynamic range take ~1 ms for the pixels to “recharge”. That’s 20k bunch crossings. What happens?
  - The device is always in a partially charged state ~70% at <n> = 100 interactions/crossing
- There are faster devices too.
- Using ultra-fast devices it is possible to sample the light from the WLS dye 2-3 times.

MPPC type	# cells 1/mm²	C, pF	R_{cell}, kOhm	C_{cell}, fF	$\tau=R_c x C_c$, ns
15 µm pitch	4444	30	1690	6.75	11.4
20 µm pitch	2500	31	305	12.4	3.8
25 µm pitch	1600	32	301	20	6.0
50 µm pitch	400	36	141	90	12.7

Now to the real world

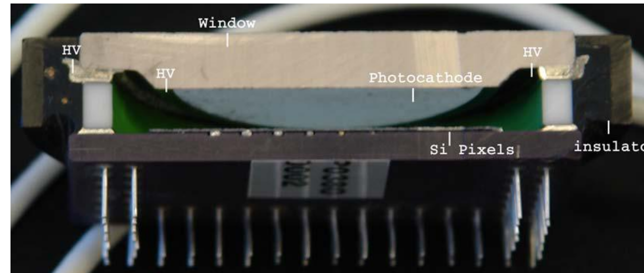


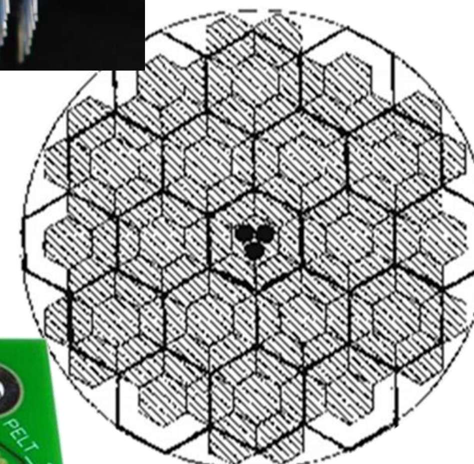
SiPM's in CMS

- The Hcal plans to replace the photo-sensors in the HB, HE and HO with SiPM's.
  - There are two test sectors in HO which are already installed.
  - The rest of HO will be instrumented in the next long shut-down, around 2013.
  - The HB/HE will be upgraded during the following shutdown.
  - All this is subject to change since the LHC has never kept a schedule for very long.

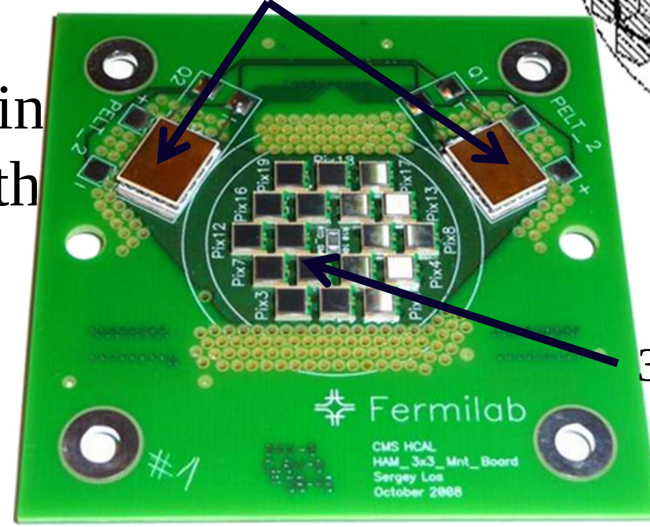
The HO replacement

- The HO is a tail-catcher.
  - 1 or 2 cm of scintillator after the solenoid and right before the muon system.
  - The HPD's haven't worked well in the fringing fields of the flux return.
  - We have developed a drop-in replacement of the HPD with SiPM's.





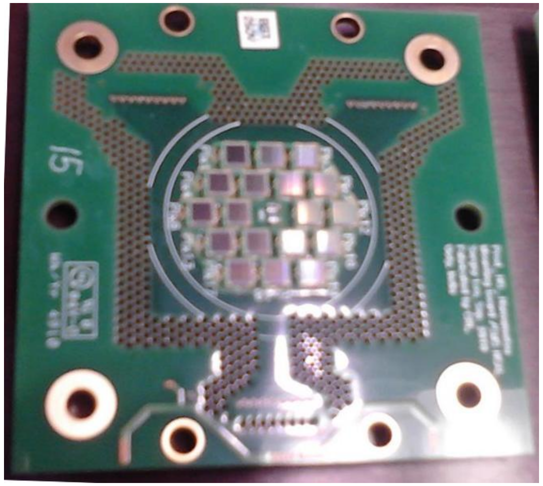
Peltier coolers



3mmx3mm SiPM's

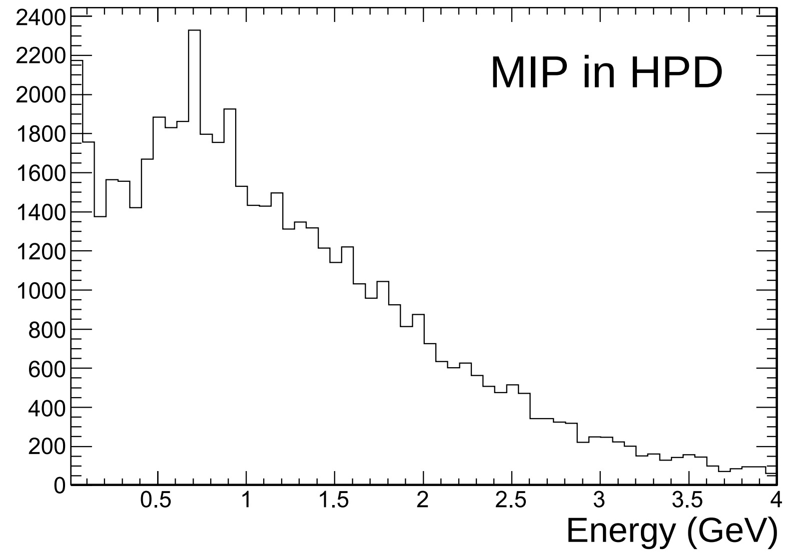
The HO SiPM

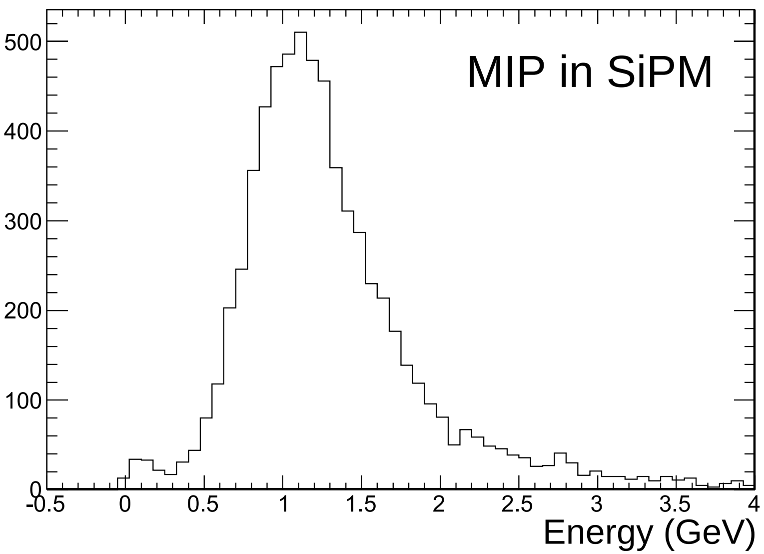
- We are using a Hamamatsu MPPC.
    - cell size: 50μm
    - 3mm x 3mm sensors
- This gives us about 2500 pixels illuminated by our fibers.
    - 1 MIP => ~15 photoelectrons
    - The HO is a low occupancy detector so the dynamic range is not a huge issue.
- Production has already begun on the replacement electronics.
- Will be ready for installation as soon as the LHC is ready.



Significant improvements

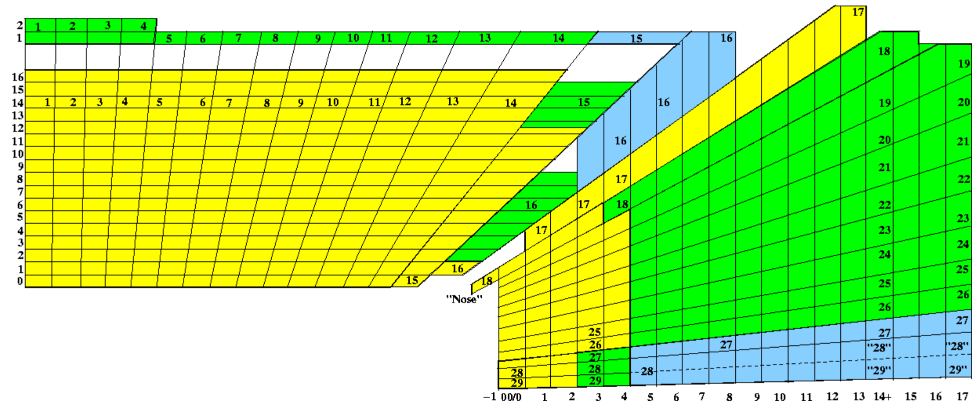
- The MIP signal to noise has gone up by about 20x.
- This has impact on muon identification using the calorimeter energy deposits.
- With better signal to noise the HO can also be better utilized in its original capacity as a tail-catcher to improve the missing E_T distribution.

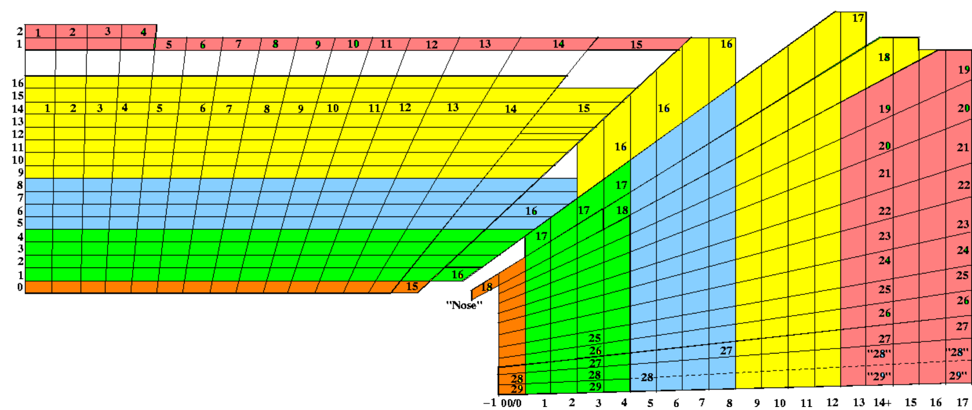




The barrel and endcaps

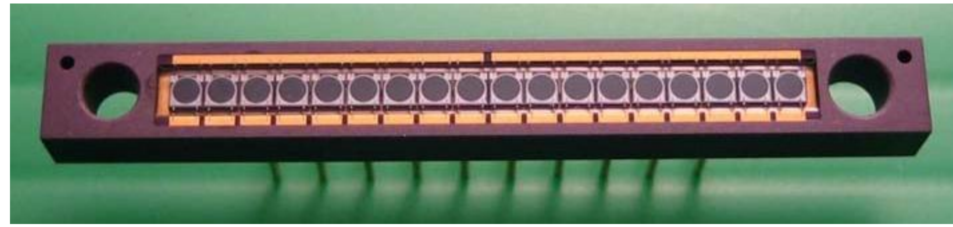
- The hadronic calorimeter upgrade drivers.
  - Make a more robust calorimeter.
  - Make a better calorimeter.
  - Mitigate impact of higher luminosity.
- Compact nature of the SiPM makes it possible to increase the longitudinal segmentation.
  - Improve isolation with high luminosity.
  - Improve calorimetry with weighting EM deposits.
  - Electronics changes will also improve robustness.

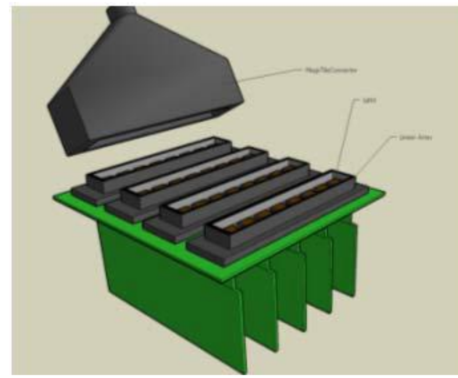


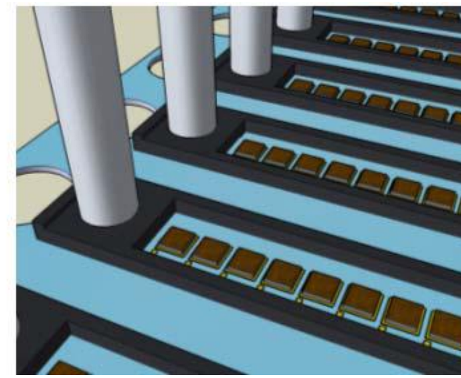


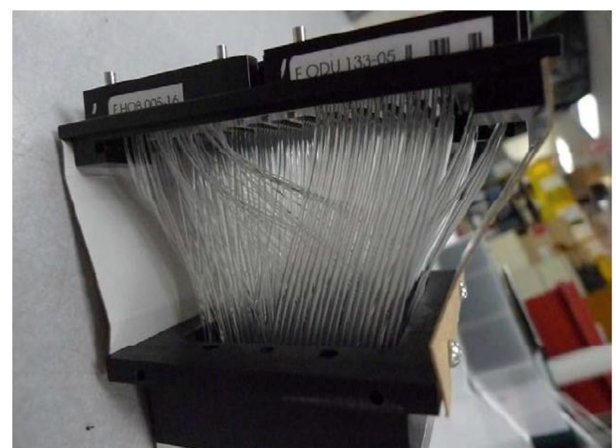
Readout flexibility

- The small SiPM is much more flexible for reading out the fibers from the scintillator layers.
- Two general schemes
  - Each fiber illuminates a 1mm x 1mm SiPM and the signal are electrically grouped into a longitudinal depth for read out.
  - Fibers are grouped and mixed into a longitudinal depths and illuminate a larger SiPM which are directly read out.
  - Hybrids of the two.





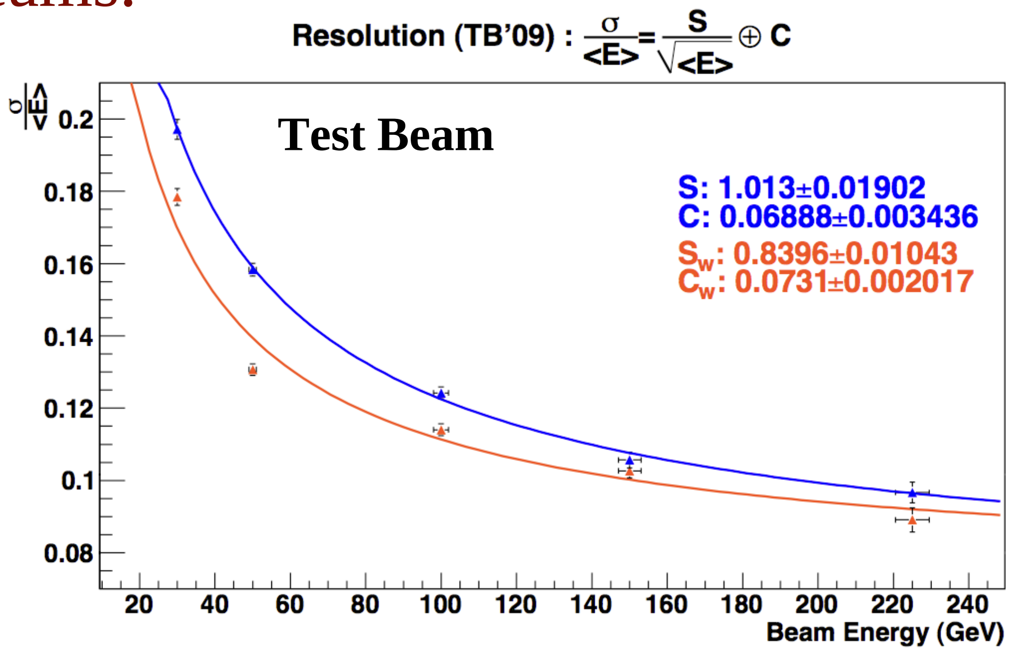


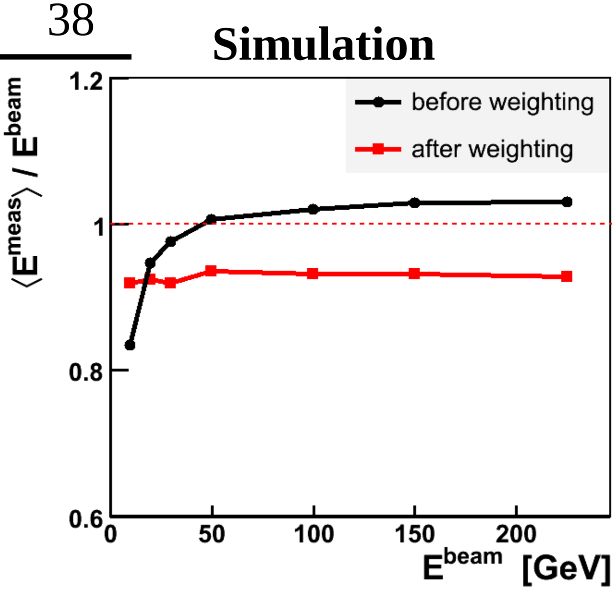


Testing new configurations

- Through simulation we have looked at the detector performance of an upgraded calorimeter.
- Ultimately confirmed using test beams.

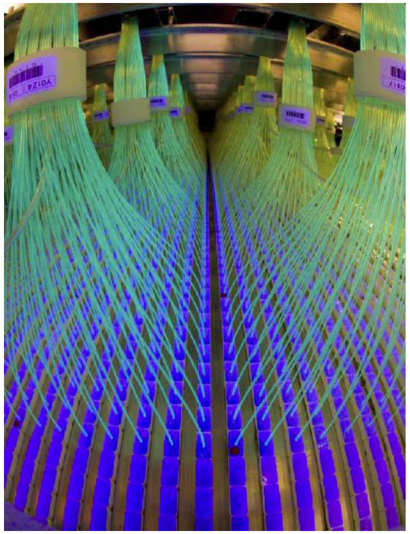
HB Depth	MIP S/N
1	10
2	16
3	16
4	38

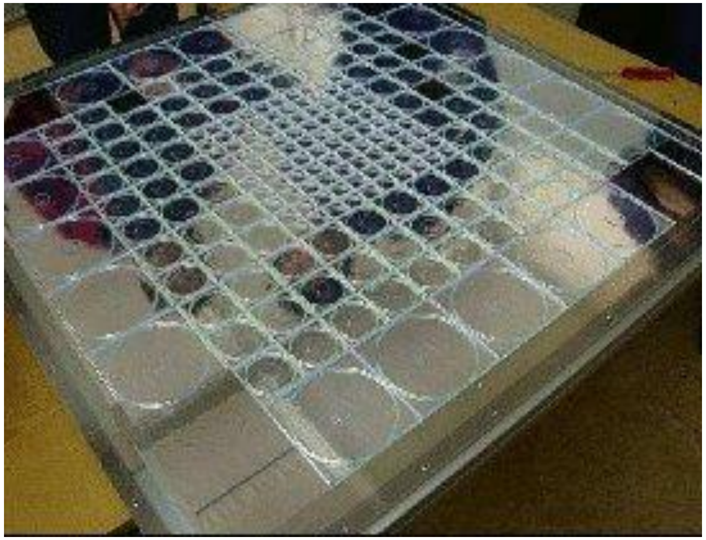




Expanding our view

- Other HEP experiments do too.
  - T2K's near detector uses thousands of MPPC's.
- In a detector for the ILC or other future accelerator, the G-APD will likely play an important role.
  - CALICE makes extensive use of SiPM's
- Building G-APD's from more rad. hard semiconductors may open new applications.





G-APD summary

- G-APD's are a relatively new photo-detection technology.
  - Competitive with PMT on gain and spectral response.
  - Advantages and disadvantages need to be kept in mind.
- Applications to HEP have been found.
  - CMS Hcal
  - T2K
- New applications will probably open up.
  - ILC/CLIC future accelerators
  - New semiconductor materials