Physics with muons at the Large Hadron Collider

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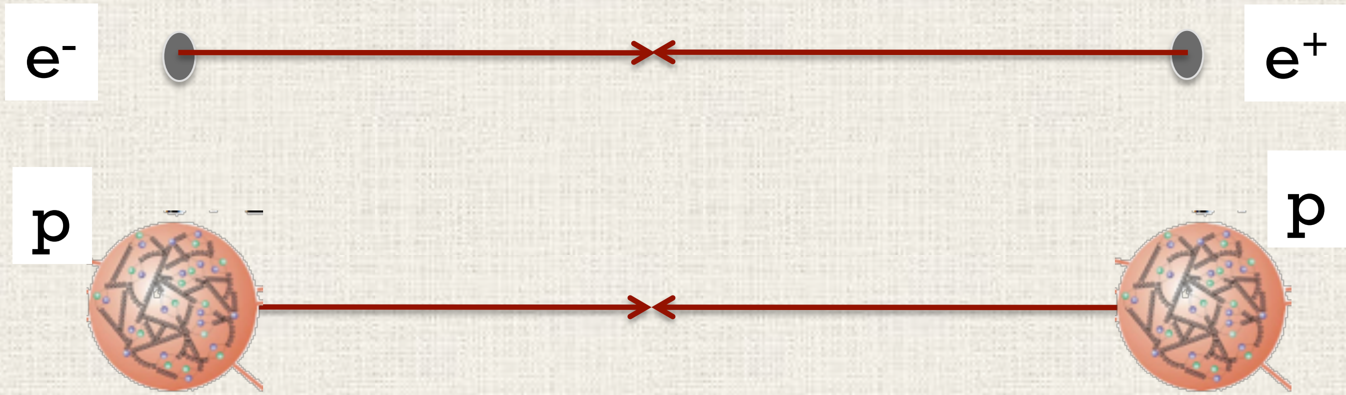
Outline

1. Introduction, p-p collisions at the energy frontier: the LHC.
2. Detectors for LHC: general ideas.
3. How muons are detected at LHC.
4. The ATLAS muon spectrometer
5. First physics results with muons from ATLAS.
6. Prospects.

1. Introduction, p-p collisions at the energy frontier: the LHC

- p-p collisions are the roadmap for the energy frontier.
  - Protons can be accelerated to higher energies wrt electrons;
  - It is easier to accumulate high intensity proton beams than antiprotons beams;
  - pp and p-antip asymptotically equal at high energies.
- BUT protons are more difficult to manage wrt electrons ➔ the life is difficult for the researcher.



The proton is a complex object done by “partons”:

valence quarks / *sea quarks* / *gluons*

s = (center of mass energy of interaction)^2

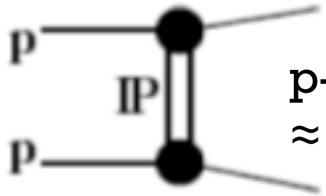
$\hat{s}$ = (center of mass energy of *elementary* interaction)^2

e^+e^-: interactions btw point-like particles with $\sqrt{\hat{s}} \approx \sqrt{s}$

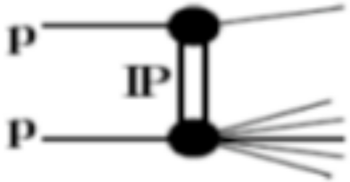
pp: interactions between groups of partons with $\sqrt{\hat{s}} << \sqrt{s}$

A detailed look at a p-p collision. What really happens ?

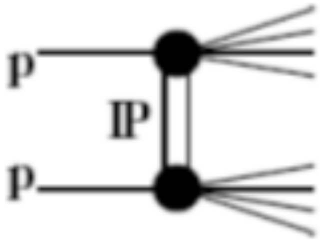
(A) "Real" proton-proton collision
(*pomeron exchange*): 40% of the times



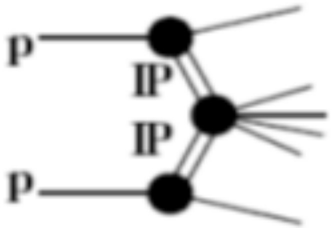
p-p elastic scattering
≈ 25%



Single diffraction
≈ 10%



Double diffraction
≈ 1%



Central diffraction
≈ 1%

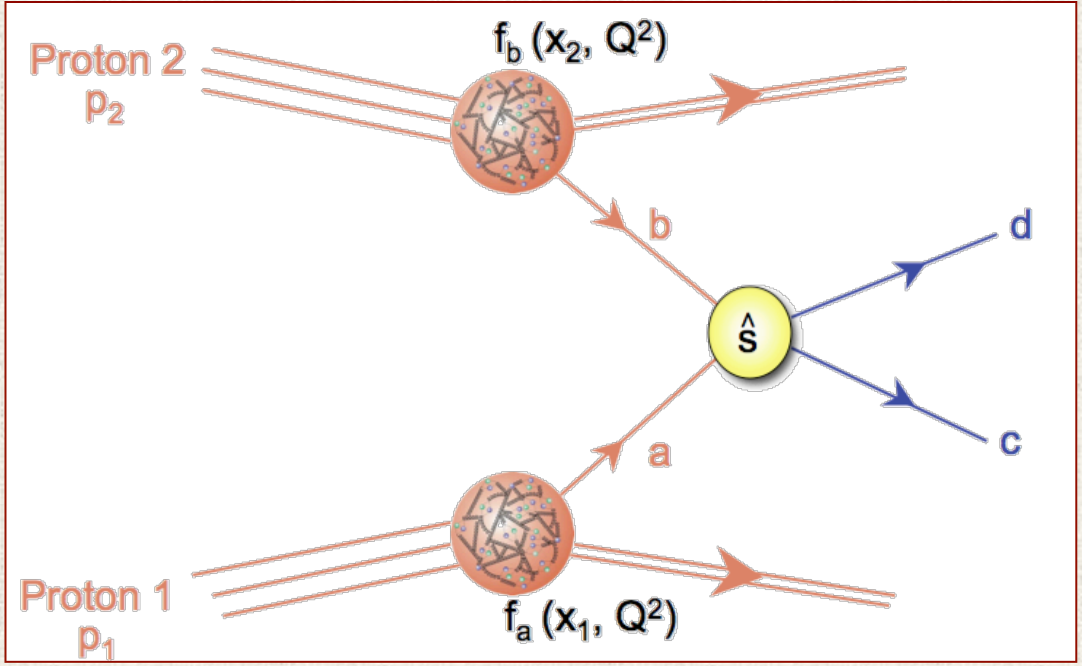
(B) Inelastic non-diffractive:
60% of the times

Where is the *fundamental physics* in this picture ?
Among non-diffractive collisions **parton-parton collisions**.
Signatures:

proton-proton collision
➔ "forward"

parton-parton collision
➔ "transverse"

Parton-parton collision: a+b → d+c.



a,b = quarks or gluons;
d,c = quarks, gluons, or leptons, vector bosons,…;
x = fraction of proton momentum carried by each parton;
ŝ = parton-parton c.o.m. energy = x_1x_2s;

Theoretical method: the ***factorization theorem***

$$d\sigma(pp \to cd) = \int_0^1 dx_1 dx_2 \sum_{a,b} f_a(x_1,Q^2) f_b(x_2,Q^2) d\hat{\sigma}(ab \to cd)$$

Two ingredients to predict pp cross-sections:

→ proton pdfs (f_a and f_b)

→ $\hat{\sigma}$ "fundamental process" cross-section

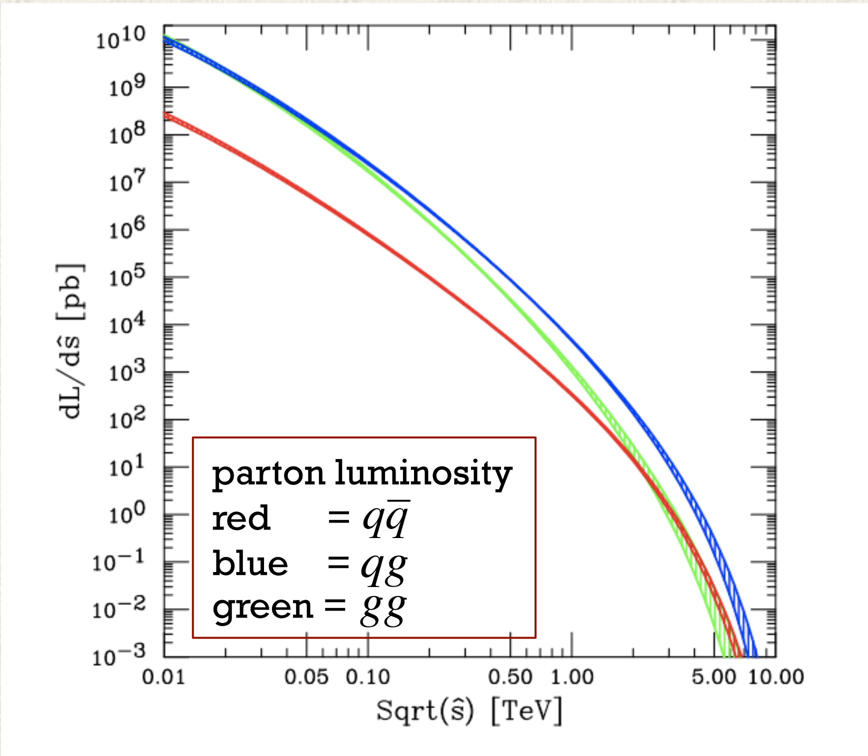
Order of magnitude estimate of cross-sections:

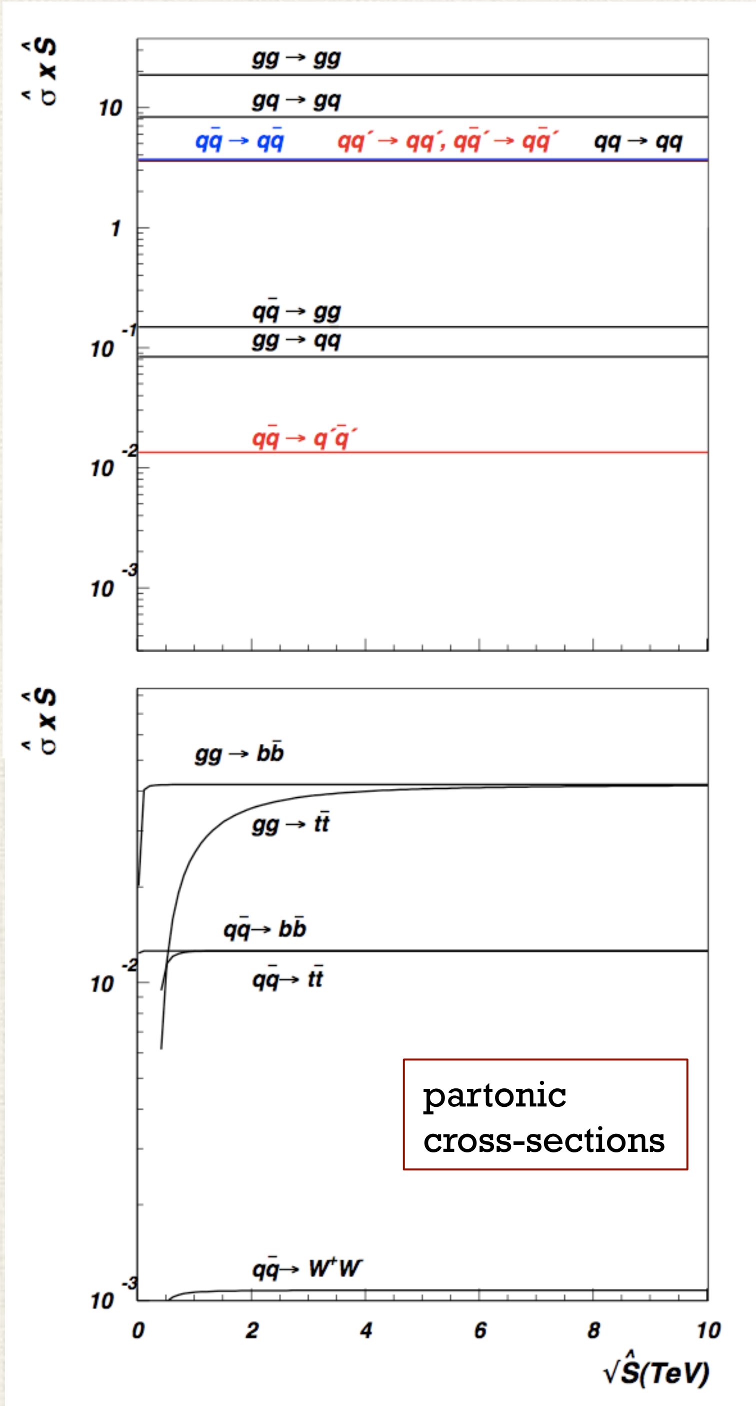
$$\sigma = \int \frac{d\hat{s}}{\hat{s}} \frac{dL}{d\hat{s}} (\hat{s}\hat{\sigma})$$

where:

$dL/d\hat{s}$=parton luminosity (pb)

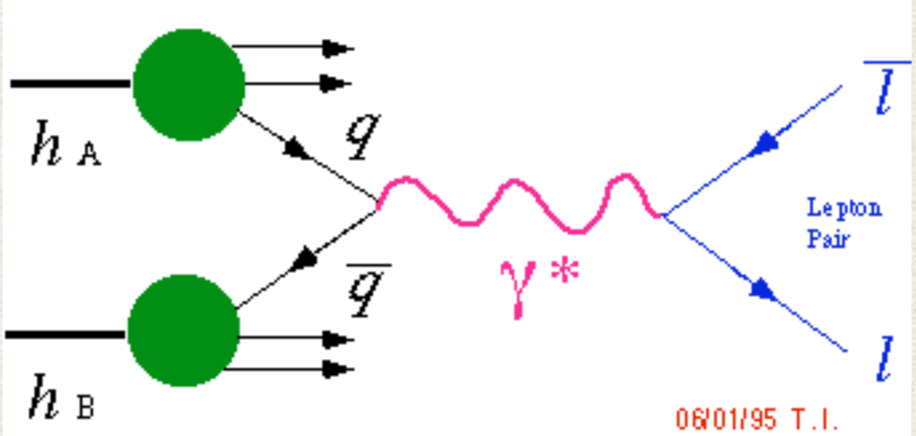
$(\hat{s}\hat{\sigma})$= partonic cross-section





J.M.Campbell, J.W.Huston, W.J.Stirling
Rept.Prog.Phys. 70 (2007) 89

“Classical” example: the *Drell-Yan* process:



The “fundamental processes are:

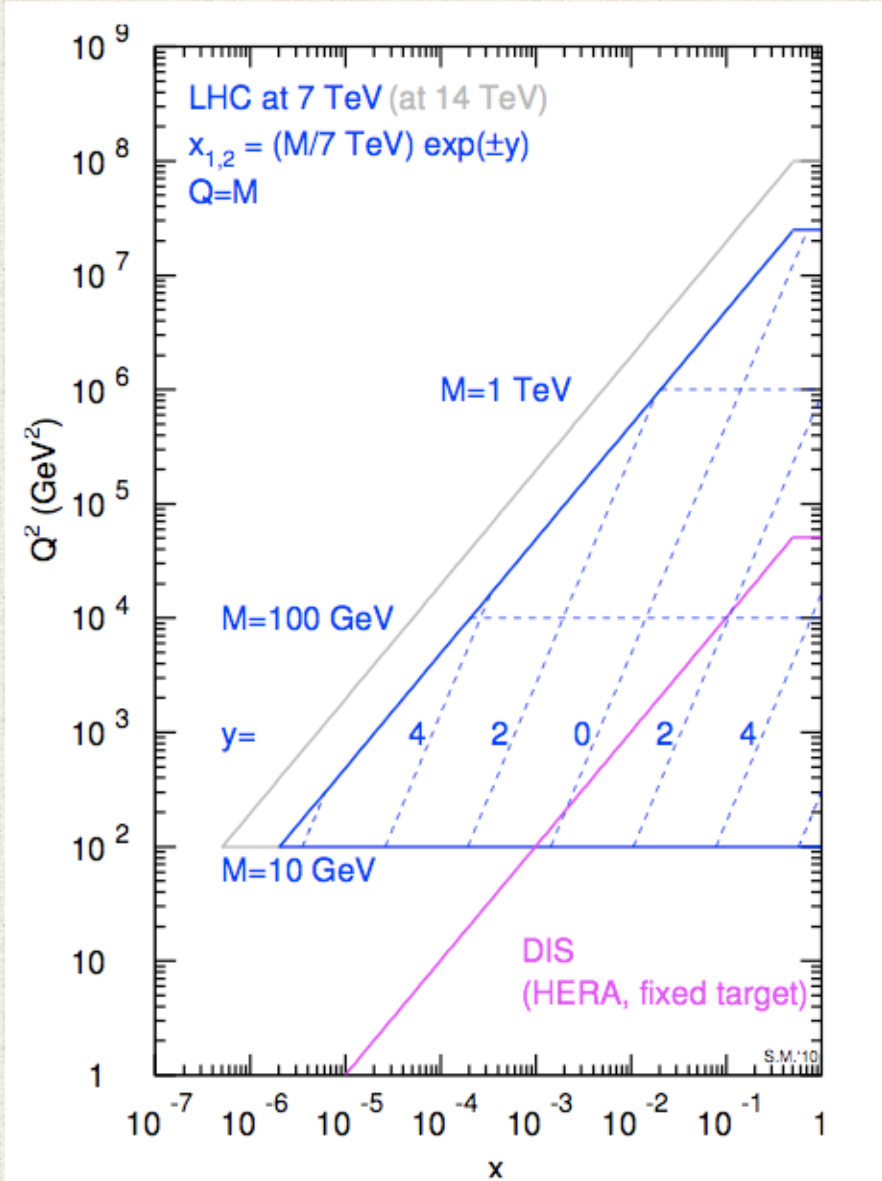
$$q\bar{q} \rightarrow e^+e^-$$

$$q\bar{q} \rightarrow \mu^+\mu^-$$

very well known from QED / EW physics
BUT we need to know the pdfs $f_q(x,Q^2)$.
How well do we know them ?

(1) DGLAP equations ➔ pdf sets
(2) from processes where the fundamental processes are “known” ➔ new constraints

$x - Q^2$ plane:
LHC vs. previous experiments

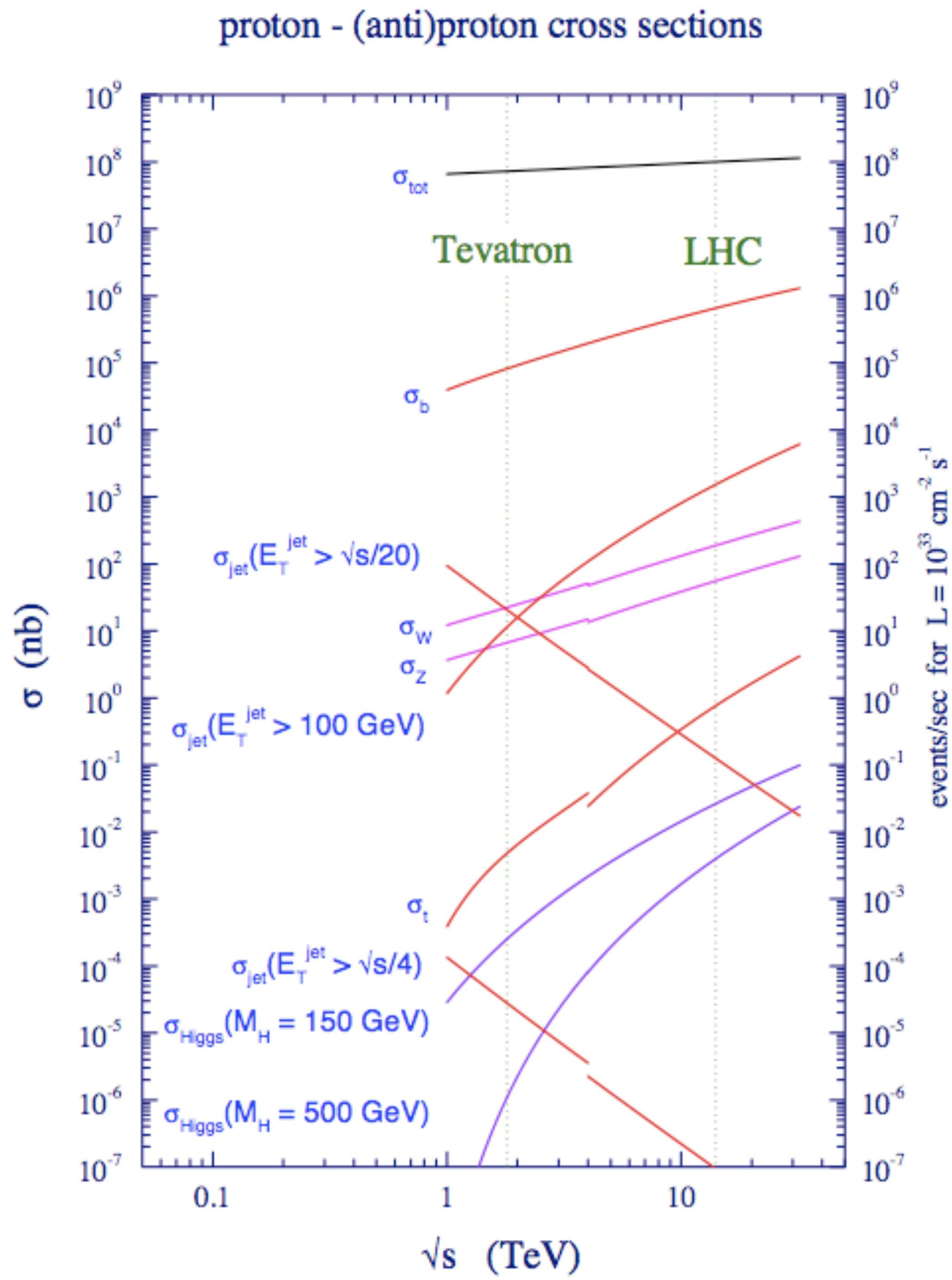


Cross-sections vs. √s
High luminosities
➔ sensitivity for "rare" processes

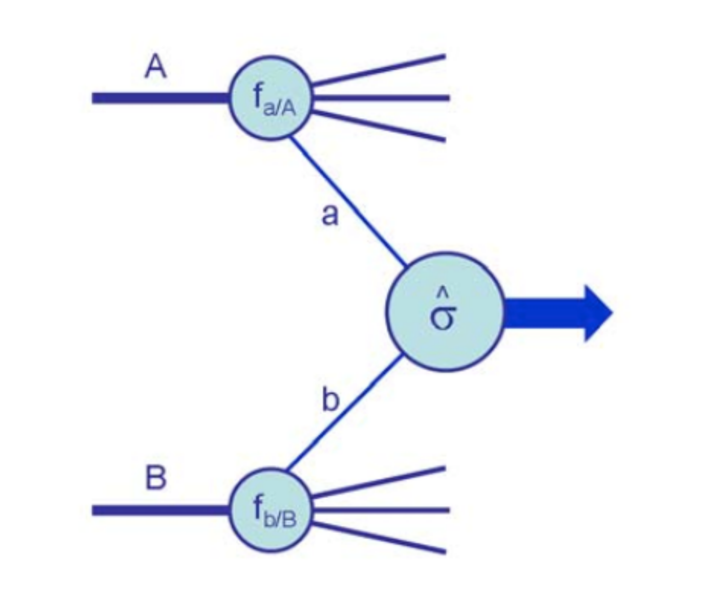
$$\dot{N}_{events} = \sigma \varepsilon L$$

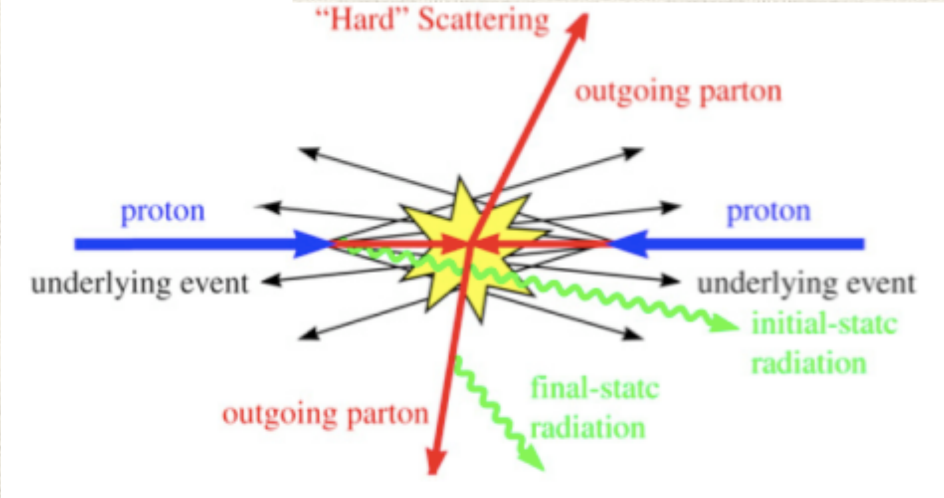
2010 data: ≈ 40 pb^{-1}
- ➔ physics of Jets;
- ➔ W/Z physics;
- ➔ top observation.

2011-2012 data: × 100 ?
- ➔ Higgs physics
- ➔ Extend BSM



A hard inelastic non-diffractive Event at LHC





→ Interesting objects to detect are:

- **leptons**
  - *electrons*
  - *muons*
  - *taus* (through their decays)
- **photons**
- **partons** (through jets)
- **neutrinos** (missing energy)

→Interesting objects are at ***high p_T***

The kinematics of each object is defined by:

p_T = transverse momentum = |p|sinθ
ϕ = polar angle
θ = azimuthal angle
y = rapidity
η = pseudorapidity (=y assuming m=0)

$$y = \frac{1}{2}\log\frac{E+p_L}{E-p_L} = \frac{1}{2}\log\frac{x_1}{x_2}$$

$$\eta = -\log\tan\frac{\theta}{2}$$

2. Detectors for LHC: general ideas

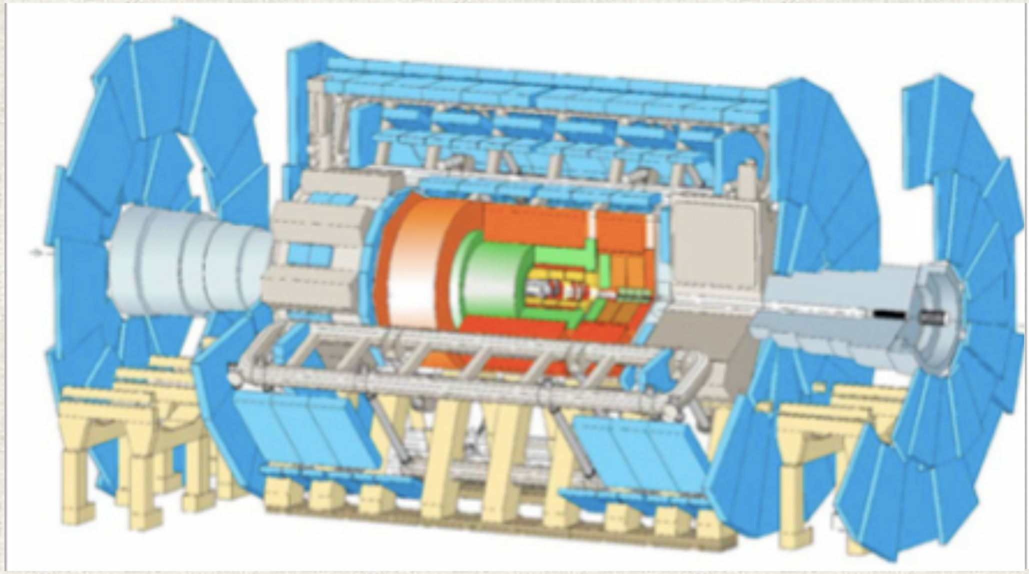
LHC parameters

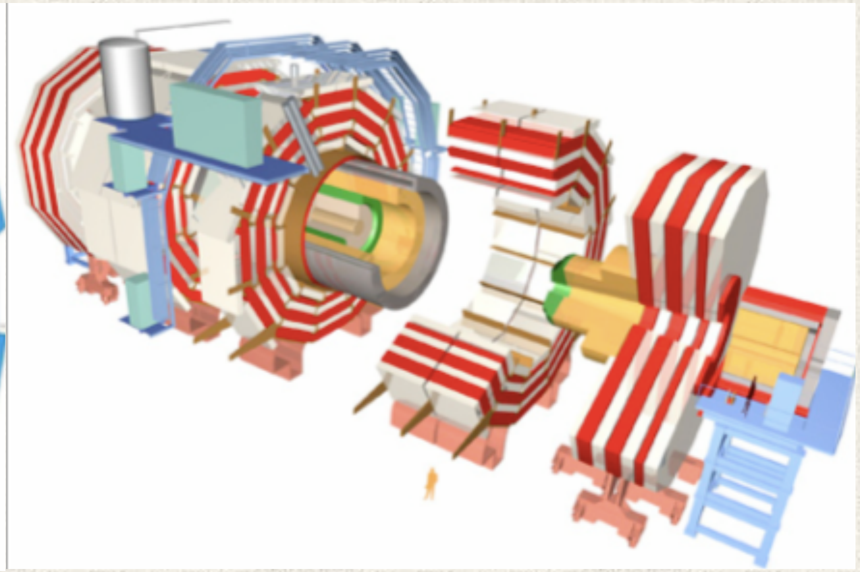
	project	2010 run
$\sqrt{s}$ (TeV)	14	7
L ($cm^{-2}s^{-1}$)	10^{34}	2×10^{32}
N_{bunch}	≈4000	≤ 368
T_{bunch} (ns)	25	≥ 150
Length (km)	27	27

LHC experiments

→ ALICE (HI, quark-gluon plasma)
→ ATLAS (SM, Higgs, SUSY, Exotics)
→ CMS (SM, Higgs, SUSY, Exotics)
→ LHCb (B-physics, CP violation)
→ TOTEM (Total cross-section)

The Giants: ATLAS & CMS



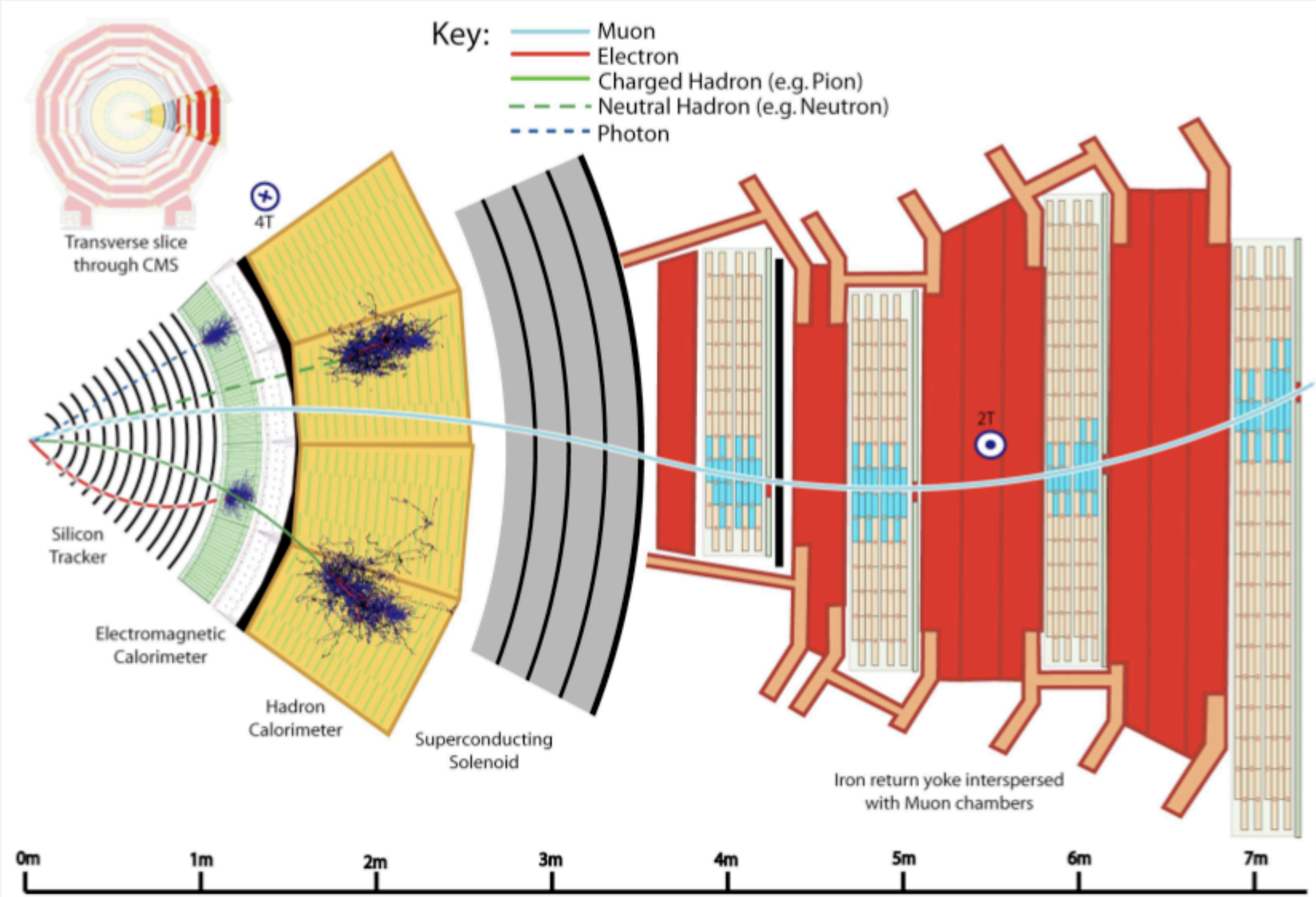


ATLAS (the largest): 46 x 25 m

CMS (the heaviest): 12500 tonn

Common structure:	e	μ	Jet	γ	$\not{E}_T$
→ Magnetic Field system	✗	✗			
→ Inner Detector	✗	✗			
→ Electromagnetic Calorimeter	✗		✗	✗	✗
→ Hadronic Calorimeter			✗		✗
→ Muon Spectrometer		✗			

Example: overall structure of the CMS detector

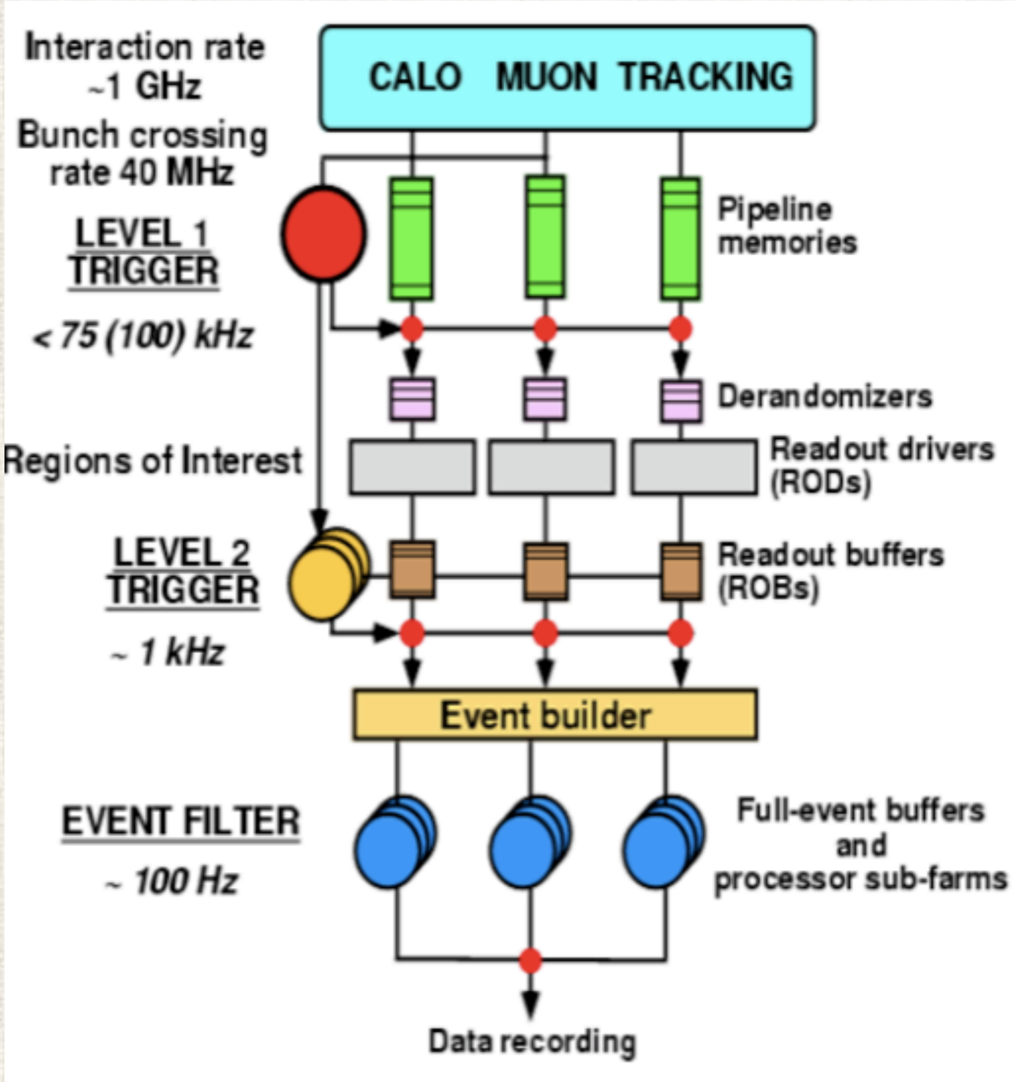


An important quest for pp experiments: the ***Trigger***

$$\dot{N} = \sigma_{tot} L \approx 10^{-25} cm^2 \times 10^{32 \div 34} cm^{-2} s^{-1} = 10 MHz \div 1 GHz$$

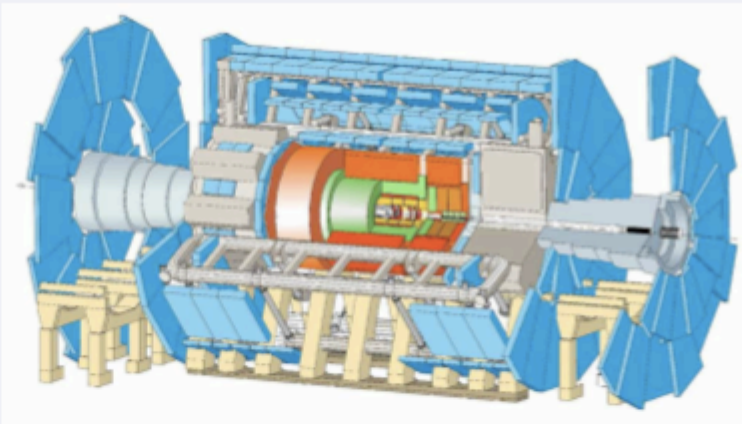
bunch crossing rate = 40 MHz
➔ every b.c. contains at least an interaction (25/b.c. at max L)

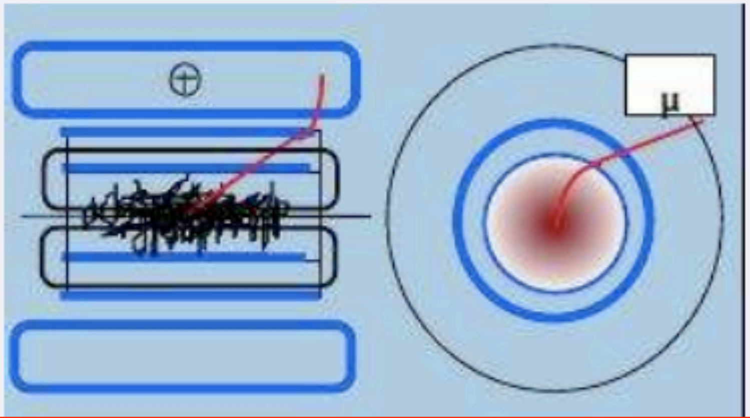
• Technically impossible and physically not interesting to register all b.c.s
• Retain only "interesting" b.c.
➔ TRIGGER = online decision: take or reject the b.c.
• ***Decision has to be fast;***
• ***Criteria have to be flexible and scalable;***
• ***Thresholds have to be defined.***



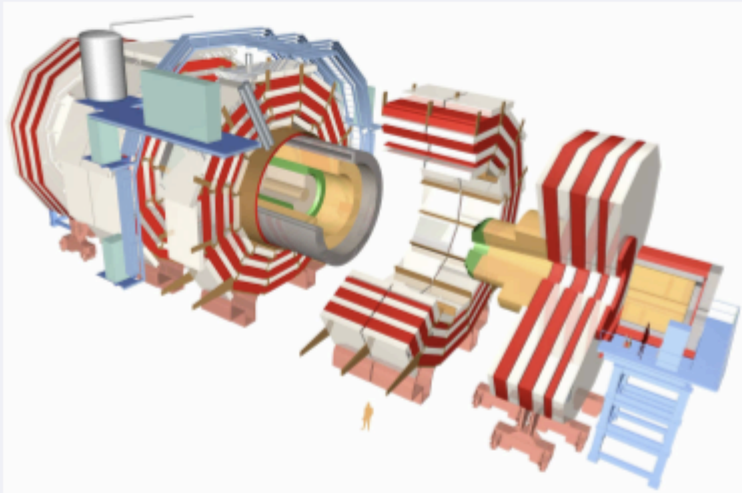
3. How muons are detected at LHC

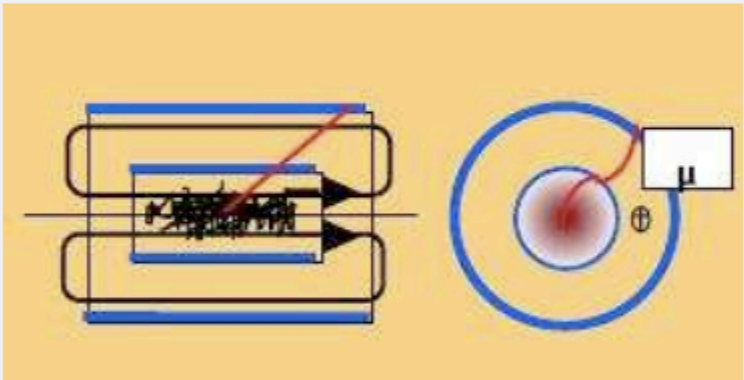
→ The calorimeters provide a "natural" muon filter;
→ The magnetic field system. ATLAS and CMS have different approaches





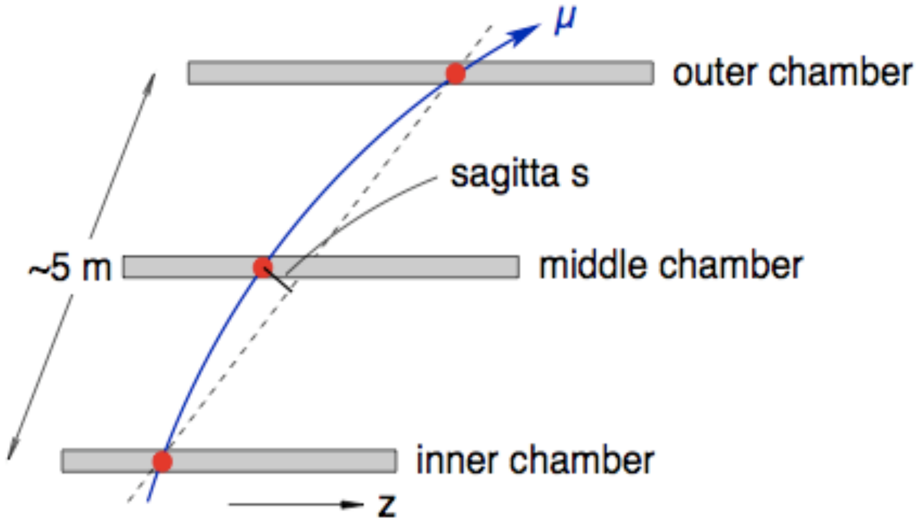
ATLAS: inner solenoid + outer toroids



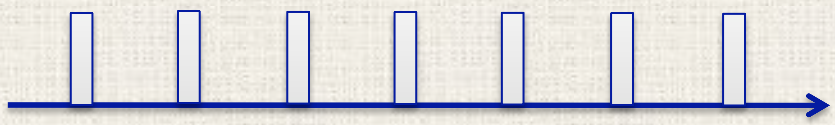


CMS: one solenoid inner + outer (reversed direction)

→ Further question: you need both *high space precision* (for tracking) and *high response velocity* (for trigger)



Bunch crossing structure: 25 ns



The trigger aims to determine the correct bunch crossing:
➔ $\sigma(t) \approx$ few ns << 25 ns

Precision needed. Assuming:

$B = 1$ T

$p = 1$ TeV

➔ sagitta $s \approx 500$ μm

If the required resolution is

$\sigma(p_T)/p_T < 10\%$ @ $p_T = 1$ TeV

➔ $\sigma(s) < 50$ μm

Hit resolutions ≈ tens μm

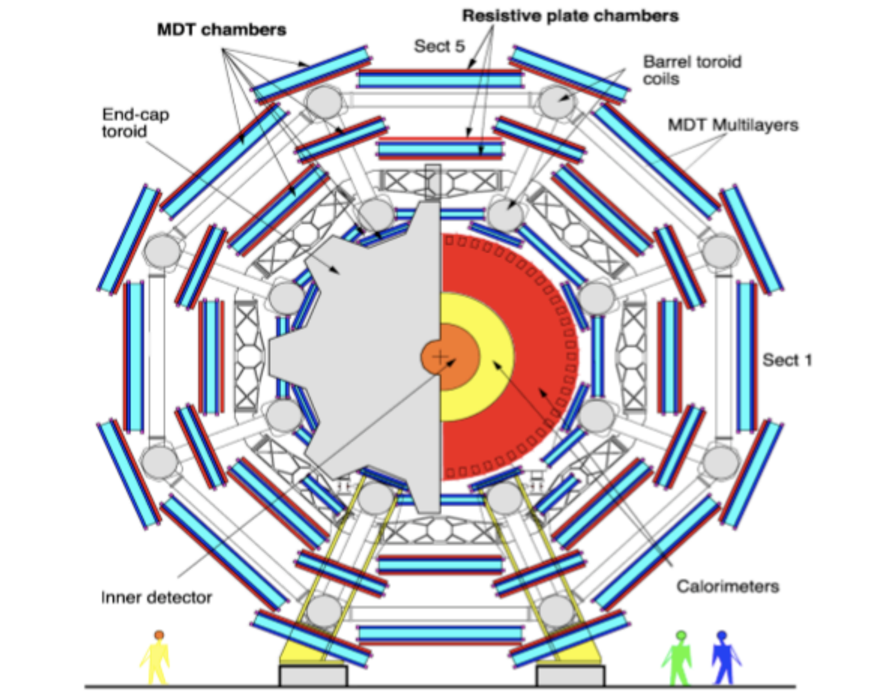
Detector aligned at the same level

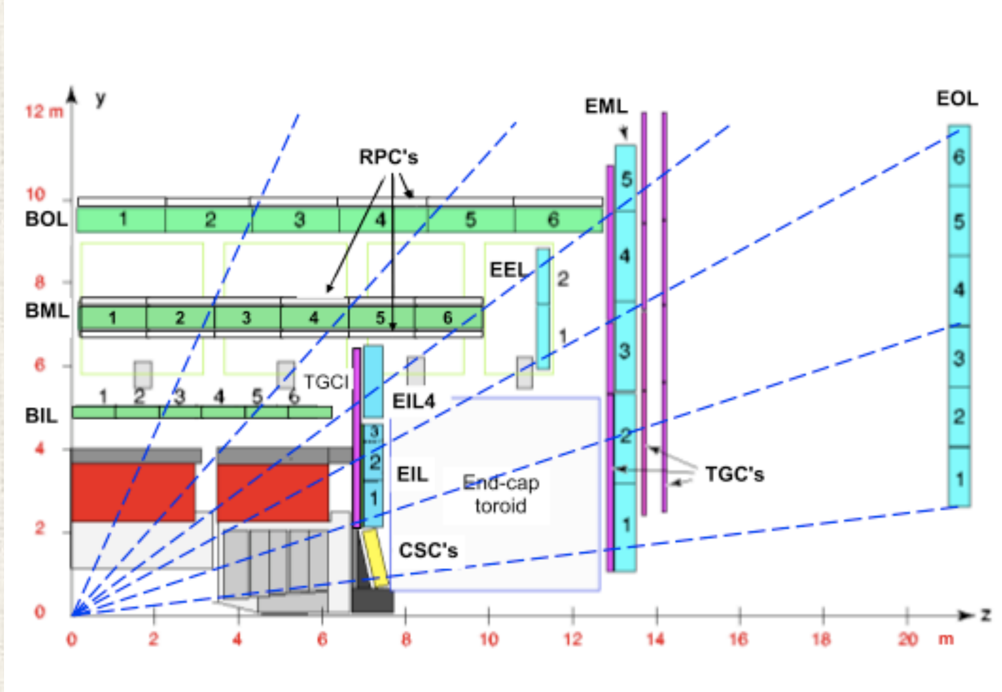
Additional requirements:

→very large surfaces;
→large η coverage;
→high rate environment tolerance.

➔"very challenging enterprise"

4. The ATLAS Muon Spectrometer



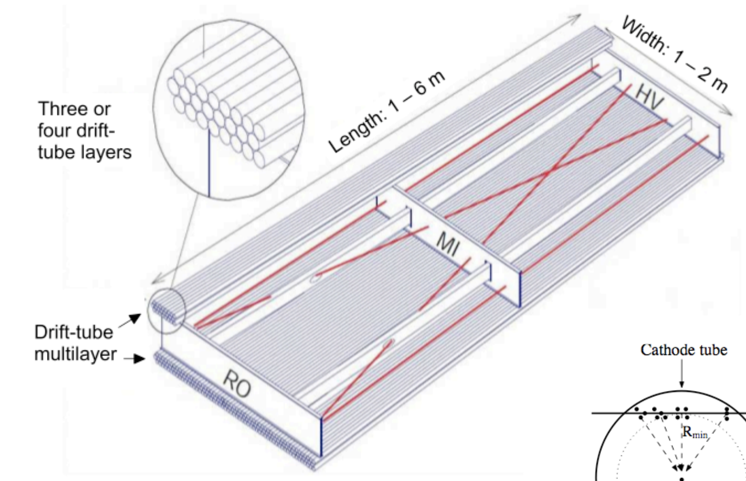


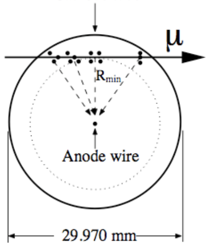
		Chamber resolution (RMS) in			Measurements/track		Number of	
Type	**Function**	z/R	ϕ	time	barrel	end-cap	chambers	channels
MDT	tracking	35 μm (z)	—	—	20	20	1088 (1150)	339k (354k)
CSC	tracking	40 μm (R)	5 mm	7 ns	—	4	32	30.7k
RPC	trigger	10 mm (z)	10 mm	1.5 ns	6	—	544 (606)	359k (373k)
TGC	trigger	2–6 mm (R)	3–7 mm	4 ns	—	9	3588	318k

ATLAS muon spectrometer: detectors overview

Precision chambers

(1) Monitored Drift Tubes (MDT)

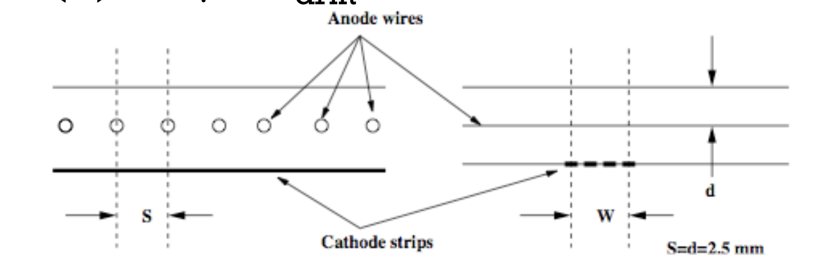




High-pressure drift tubes
$\sigma(R) \approx 100\mu m, T_{drift} \approx 700ns$

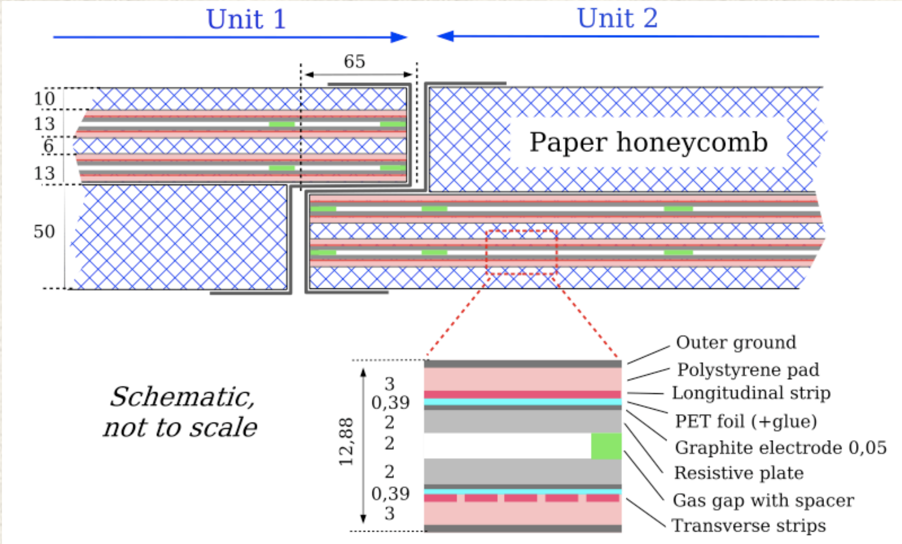
(2) Cathode Strip Chambers (CSC)

Operation in high rate environment
$\sigma(R) \approx 60\mu m T_{drift} \approx 20ns$

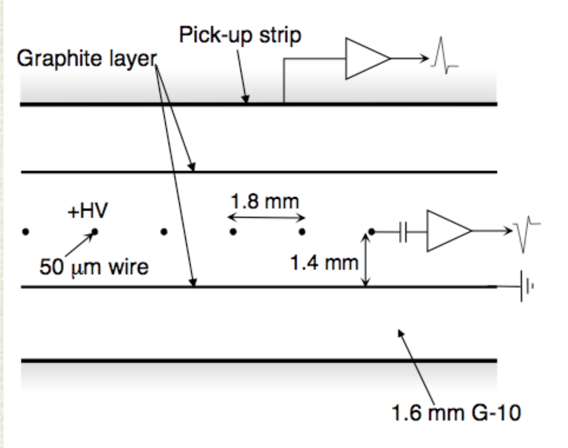


Trigger chambers

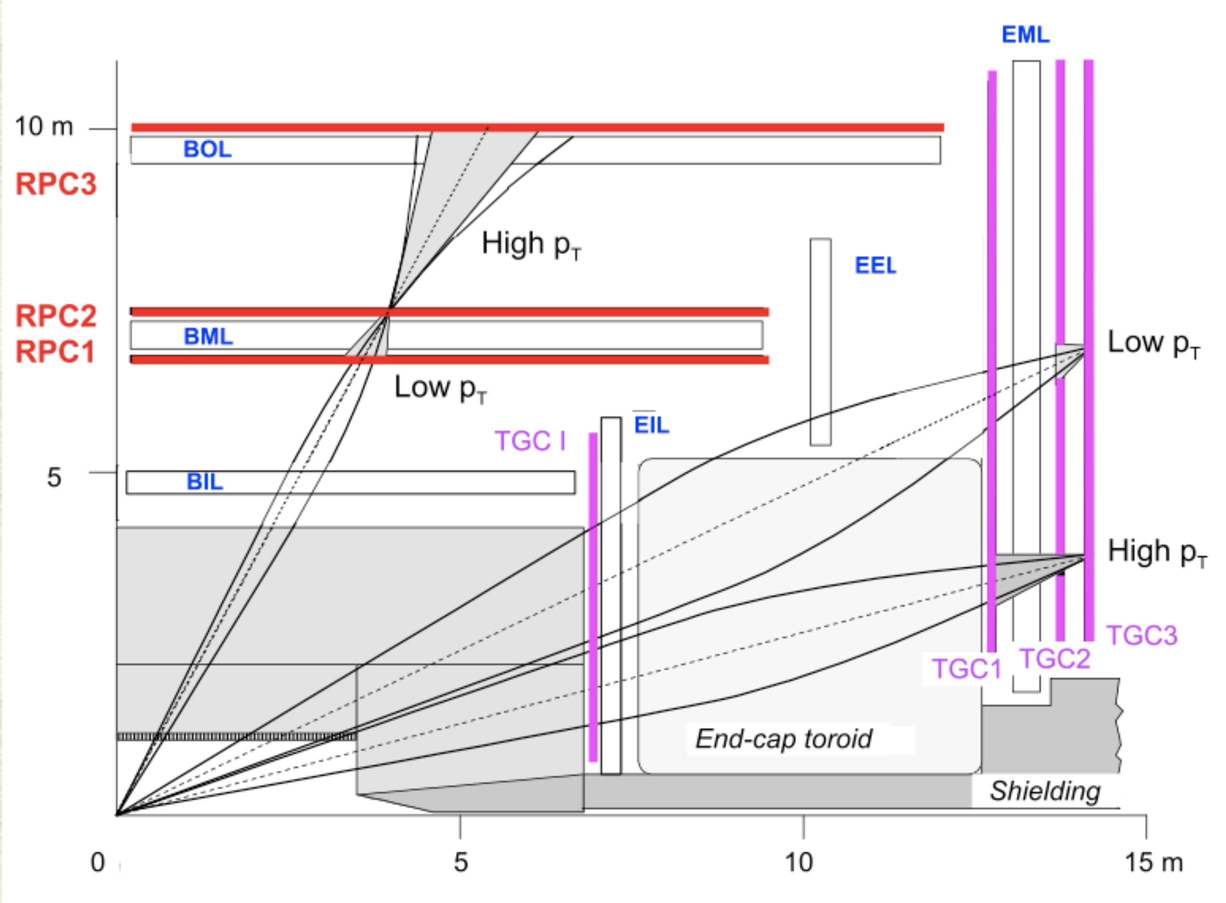
(1) Resistive Plate Chambers (RPC)



(2) Thin Gap Chambers



ATLAS Muon Trigger concept



Level-1: fully hardware trigger, simply based on RPC or TGC coincidences, with up to 6 p_T thresholds with full η coverage;

Level-2: software trigger using precision chambers with coarse granularity

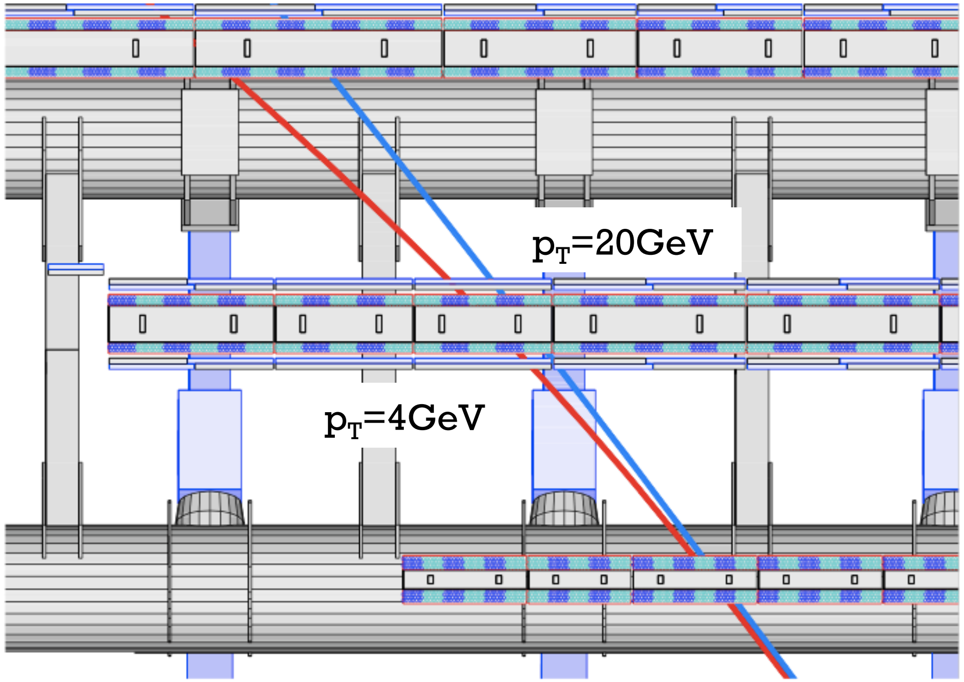
Event-Filter: software trigger using quasi-offline track reconstruction

ATLAS Muon Tracking concept

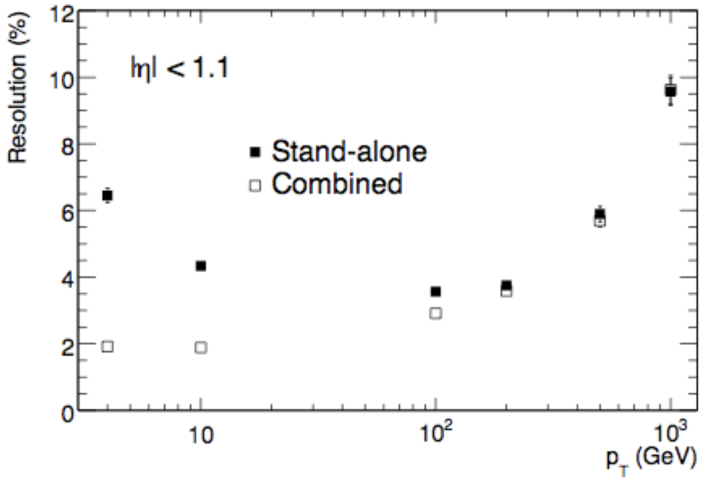
A typical track in MS has ≈ 20 hits
A muon tracks can be:
- "standalone" purely based on MS
- "combined" btw MS and ID

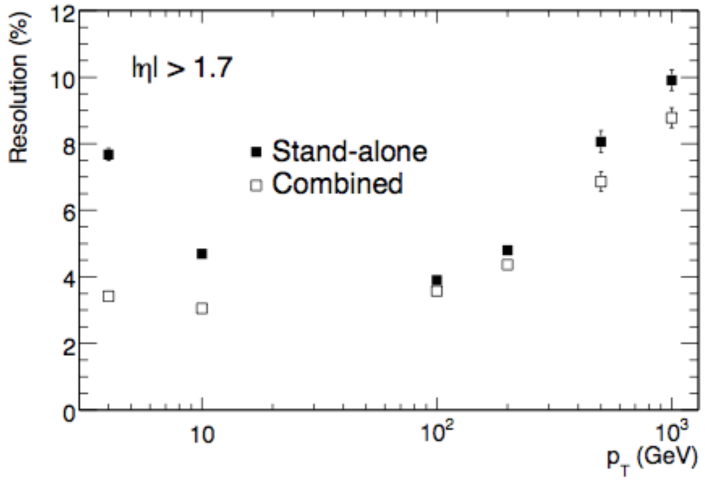
The standalone capability can be crucial at high luminosity when ID is "very crowded"

The momentum measurement is dominated by
- ID @ low p_T
- MS @ high p_T

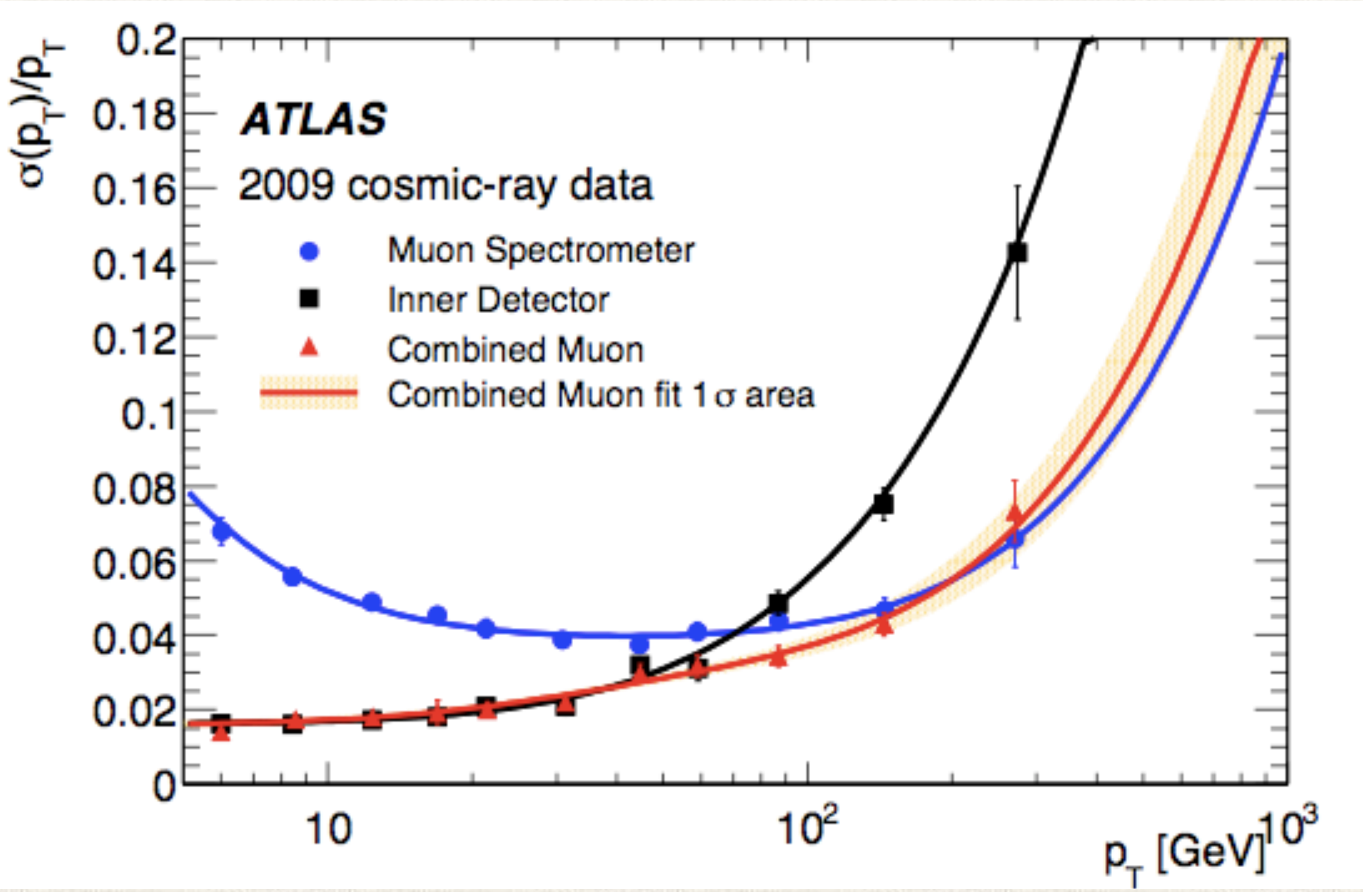


Project p_T resolutions: standalone and combined





Study of Muon Detection performance with 2009 cosmic ray data



Muon Spectrometer Resolution: still higher than expectations due to misalignement. Now much better agreement.

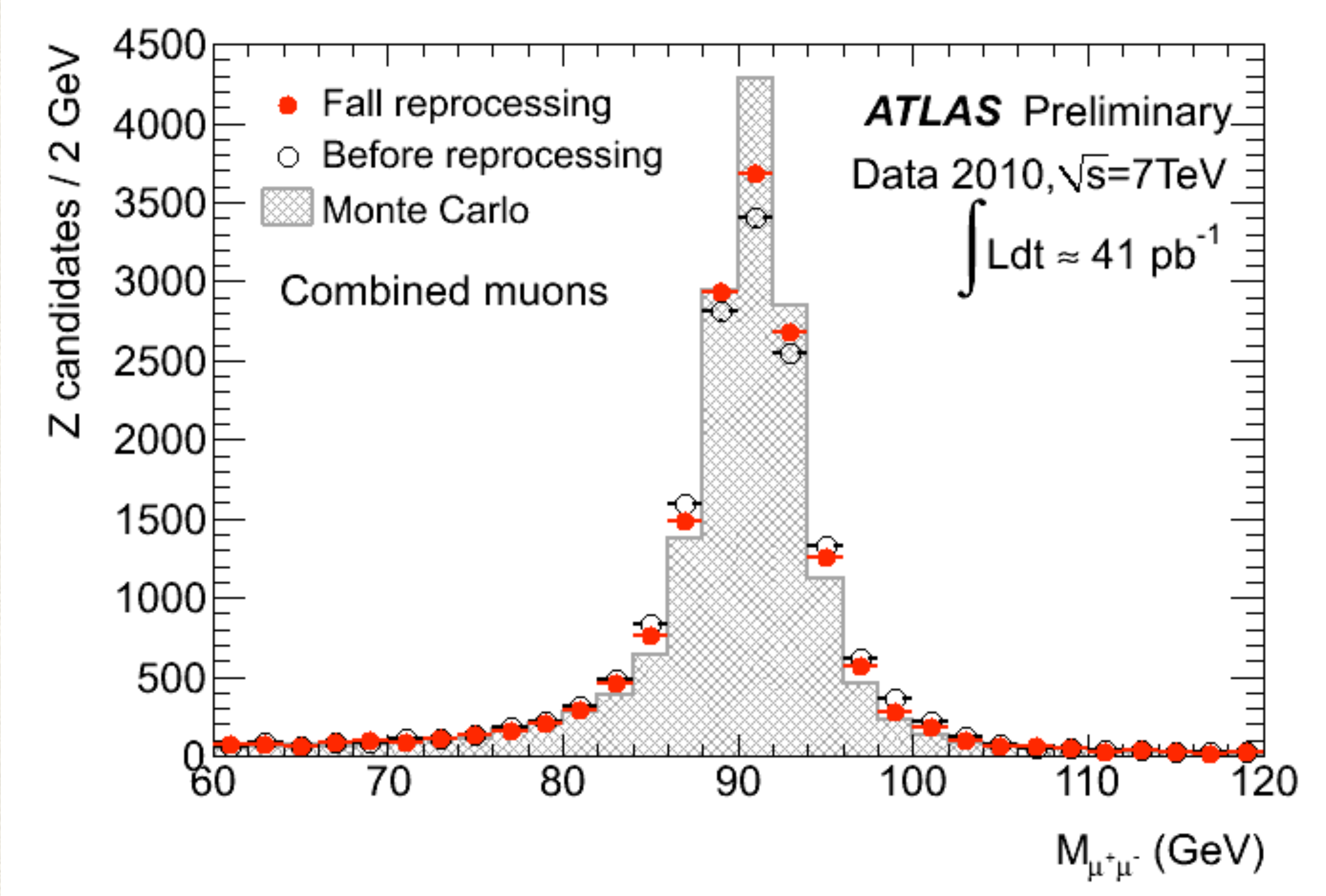
$$\frac{\sigma_{p_T}}{p_T} = \frac{P_0}{p_T} \oplus P_1 \oplus P_2 \times p_T.$$

P_0=0.29 ± 0.03 ± 0.01 GeV (0.35)

P_1=0.043 ± 0.002 ± 0.002 (0.035)

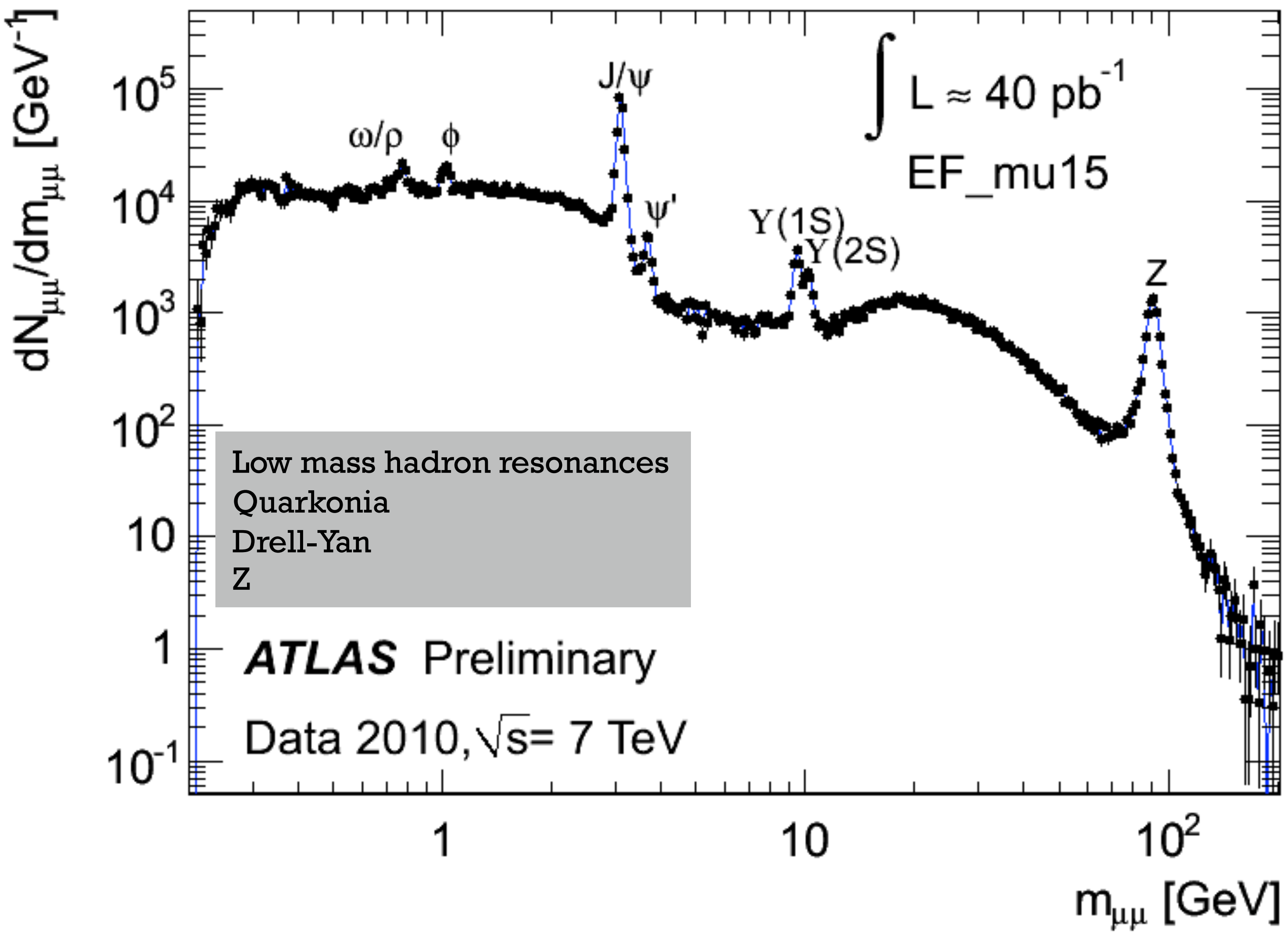
P_2=(4.1 ± 0.4 ± 0.6) × 10^{-4} GeV^{-1} (2.1× 10^{-4})

Study of Muon Detection performance with 2010 collision data
The Z lineshape (mass and width) is the “standard candle” used to understand the muon spectrometer performance.
Work in progress to finely tune the MonteCarlo.

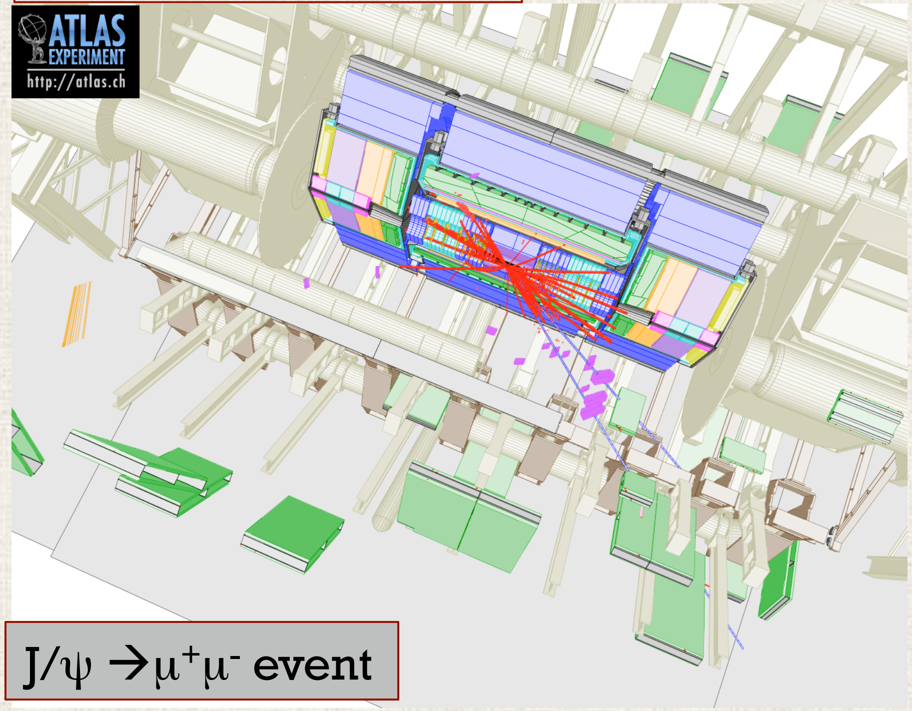


5. First physics results with muons from ATLAS

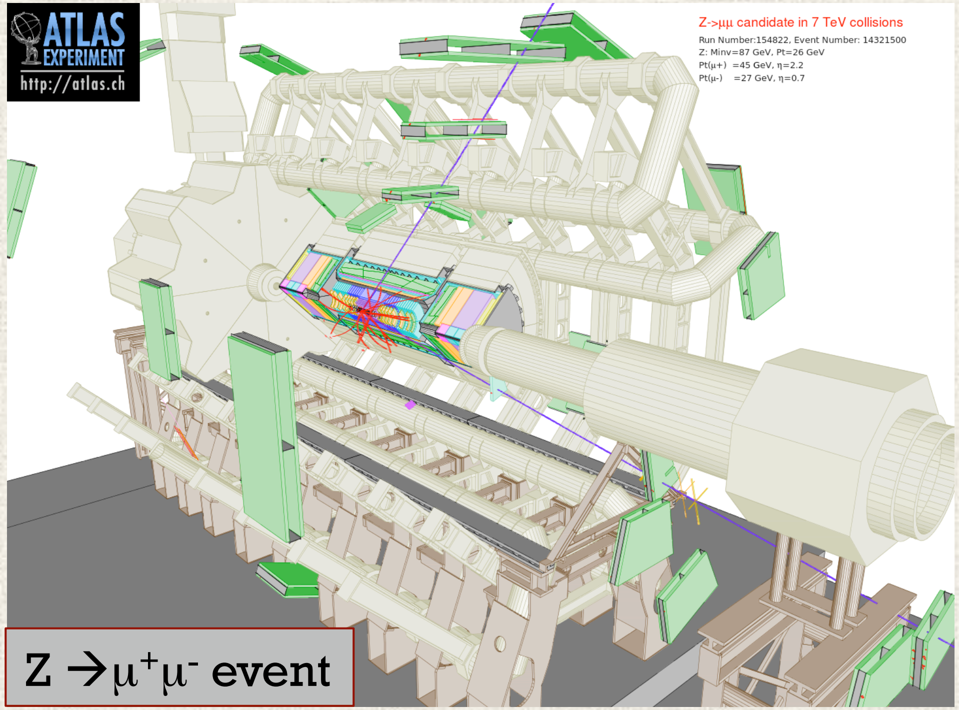
"Dimuon" invariant mass spectrum: a lot of physics



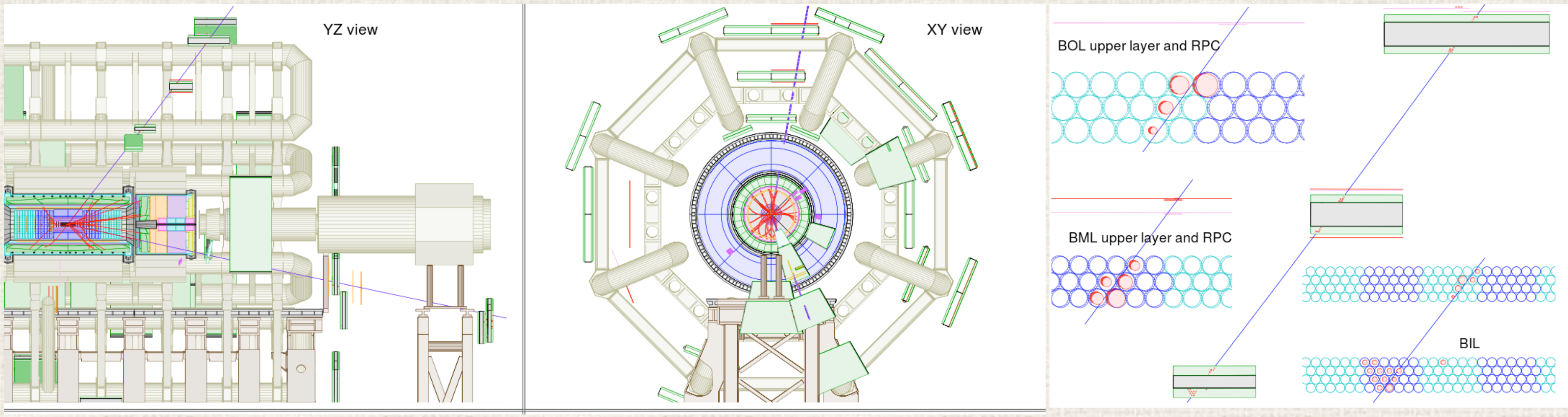
Di-Muon Events



$J/\psi \rightarrow \mu^+\mu^-$ event



$Z \rightarrow \mu^+\mu^-$ event



Three analyses already published:

(1) Measurement of the ***$W \rightarrow l\nu$ and $Z/\gamma^* \rightarrow ll$ production cross sections*** in proton-proton collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector

JHEP 12 (2010) 060 (11 Oct 2010)

(2) Measurement of the ***top quark-pair production cross section*** with ATLAS in pp collisions at $\sqrt{s}$=7 TeV

accepted by EPJC (submitted 8 Dec 2010)

(3) Measurement of ***the centrality dependence of J/ψ yields and observation of Z production in lead-lead collisions*** with the ATLAS detector at the LHC

accepted by Phys Lett. B (submitted 24 Dec 2010)

(1) ***W → lν and Z/γ* → ll production cross sections***: comparison with theory

$W^{\pm}$ and Z production at LHC: "elementary" cross-section predicted from EW theory - test of PDFs and factorization scheme

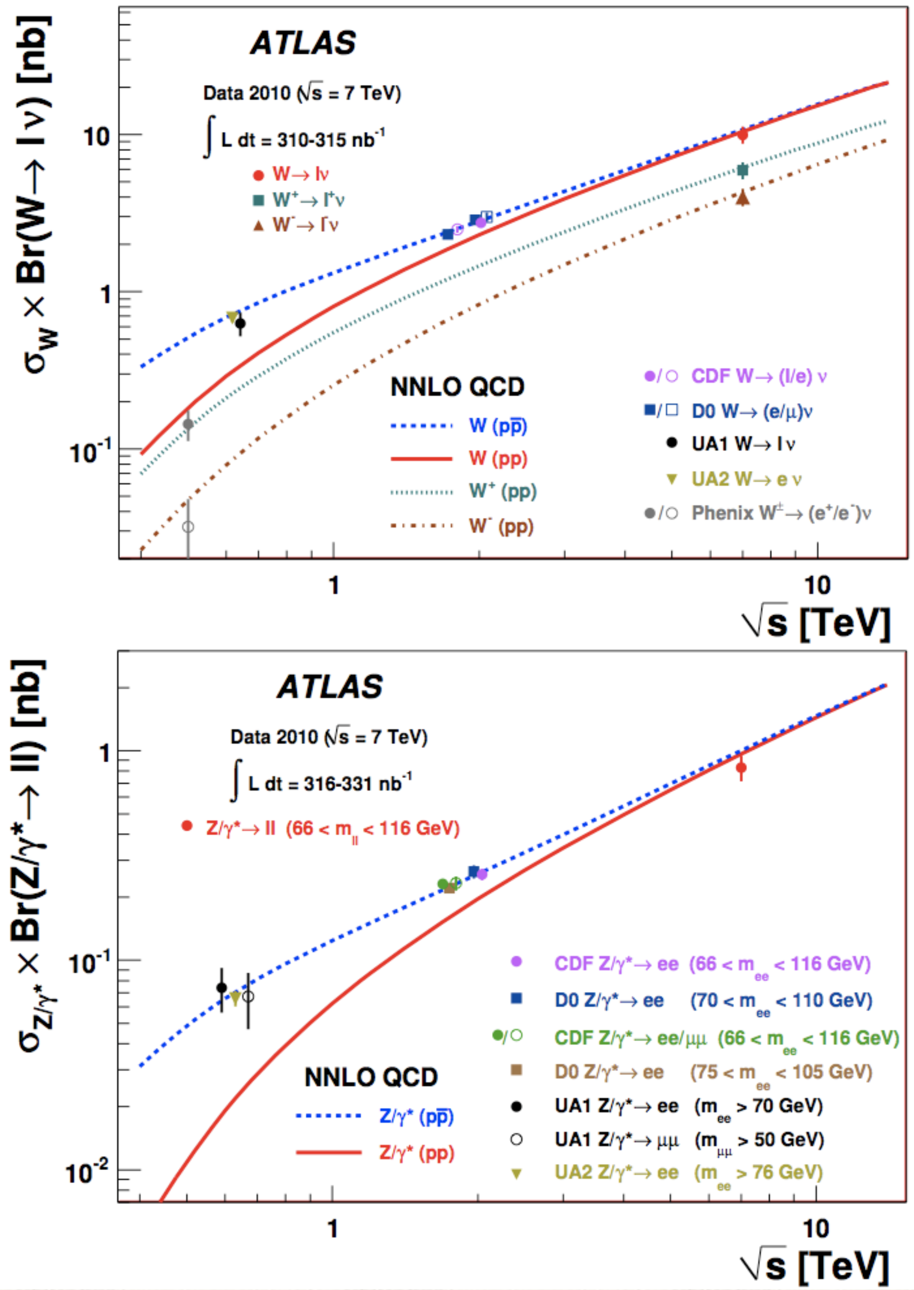
Results published from 0.3 pb^{-1} using both electron and muon channel
≈ 1000 W→lν events / flavour
≈ 100 Z→ll events / flavour

Total uncertainty on inclusive cross-sections:

- ±11% from luminosity
- ≈ (few – 10)% statistics
- ≈ few% systematics

Agreement with NNLO QCD

Prospects: analyses on 40 pb^{-1} almost completed.
Total uncertainty below 4%
p_T and rapidity studies



(2) ***top quark-pair production cross section***

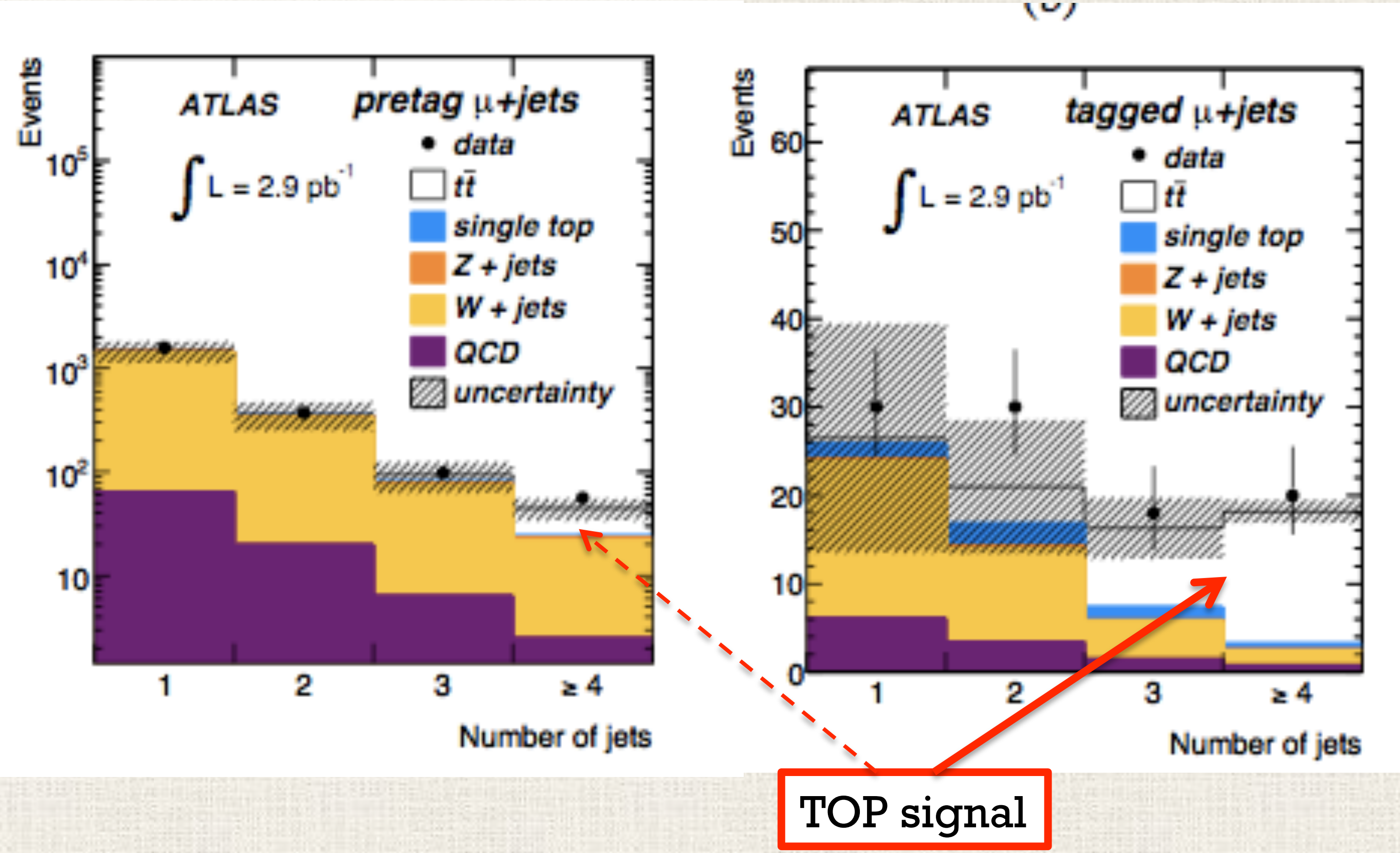
ATLAS has observed top quark pair production with the first data through the "single-lepton" final state (l = e, μ):

$$pp \rightarrow t\bar{t} \rightarrow W^{\pm}W^{\mp}b\bar{b} \rightarrow l\nu jjbb$$

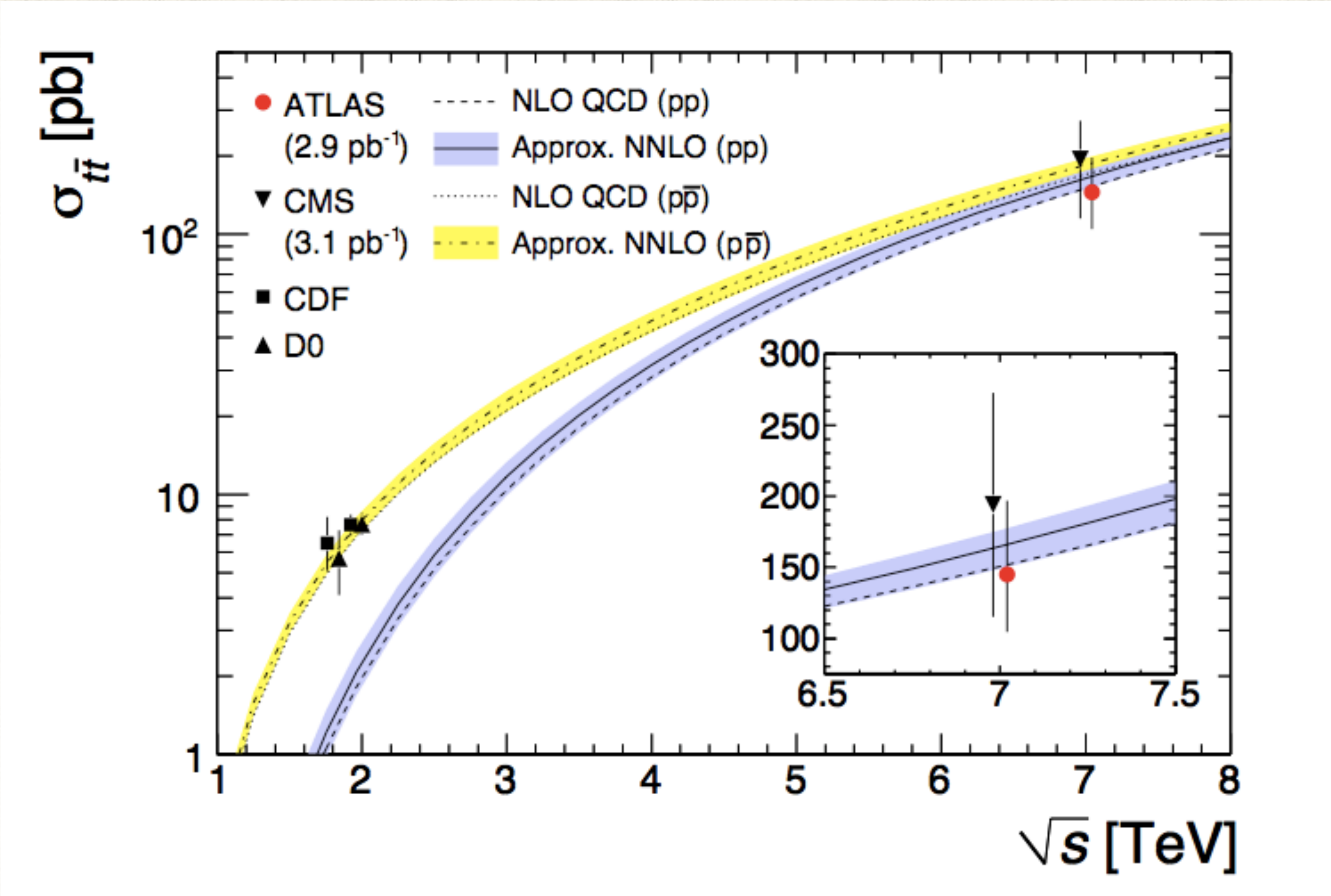
Strategy:

select (W→μν)+Njets;   at least 1 b-jet;

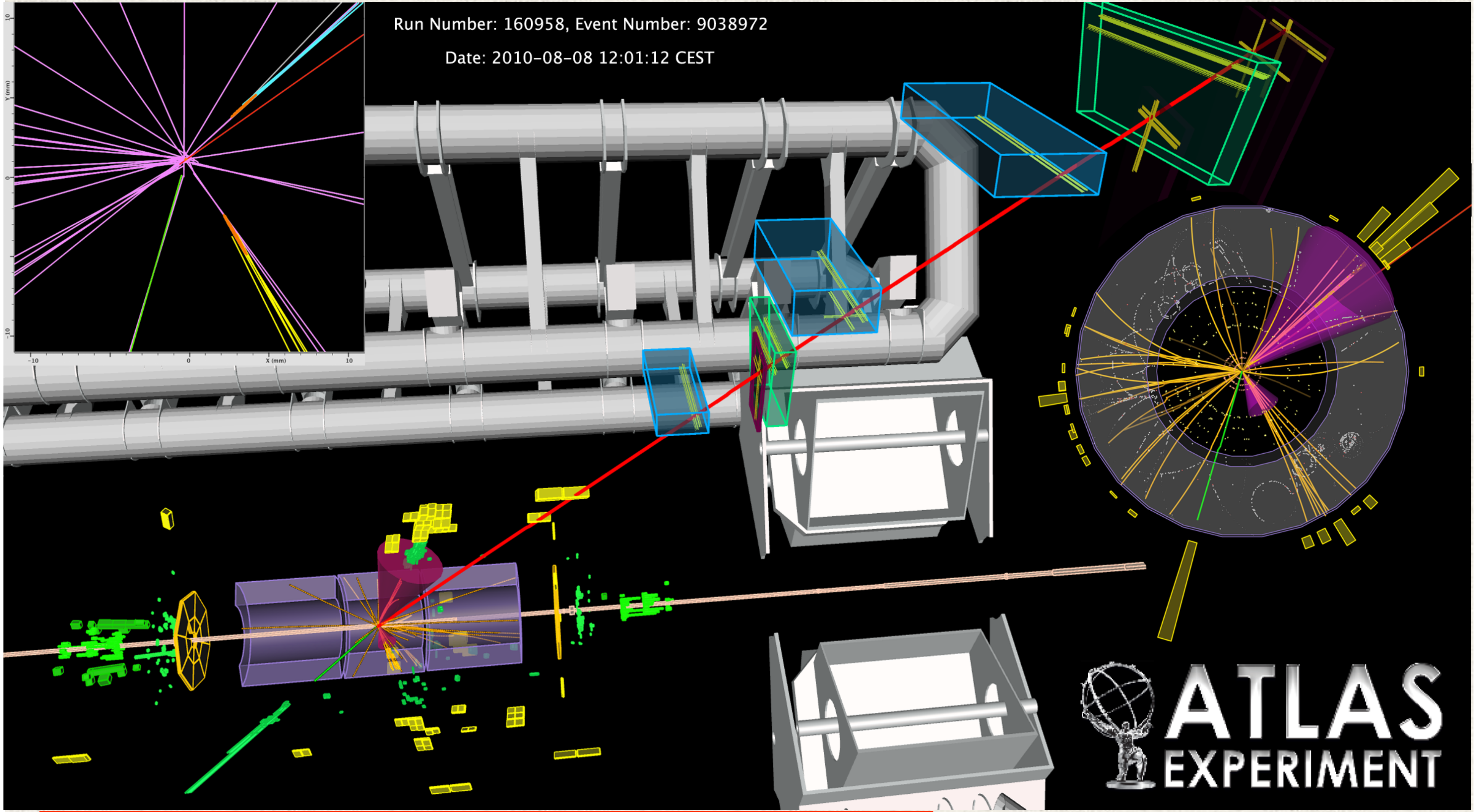
➔ excess of events with N=4 jets in the b-tagged sample



First cross-section measurements of ATLAS and CMS (30% uncertainties) in agreement with predictions



TOP di-lepton candidate event: 1 μ, 1 e, Missing ET and 2 b-jets



Prospects: analysis with 40 pb^{-1} almost completed.

- Di-leptons become important
- Cross-section measurement (10% uncertainty)
- Estimate of the top mass

(3) ***Centrality dependence of J/ψ yields and observation of Z production in lead-lead collisions***

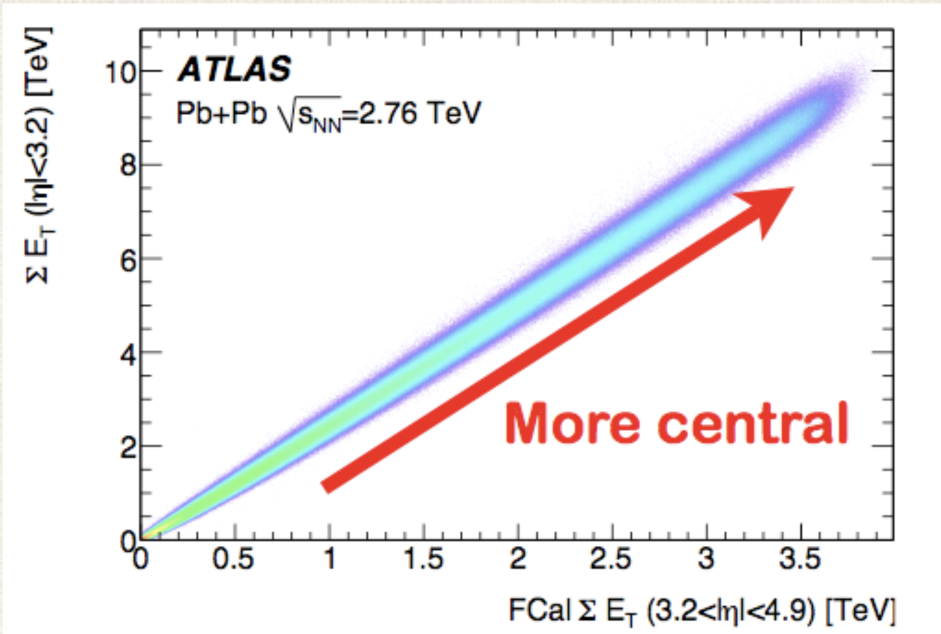
Lead nuclei with p = 3.5 TeV × 82 = 287 TeV = 1.4 TeV/nucleone
➔ $\sqrt{s_{NN}}$=2.76 TeV/nucleon ; extremely high nuclear density

"Central" collision:
very high energy density

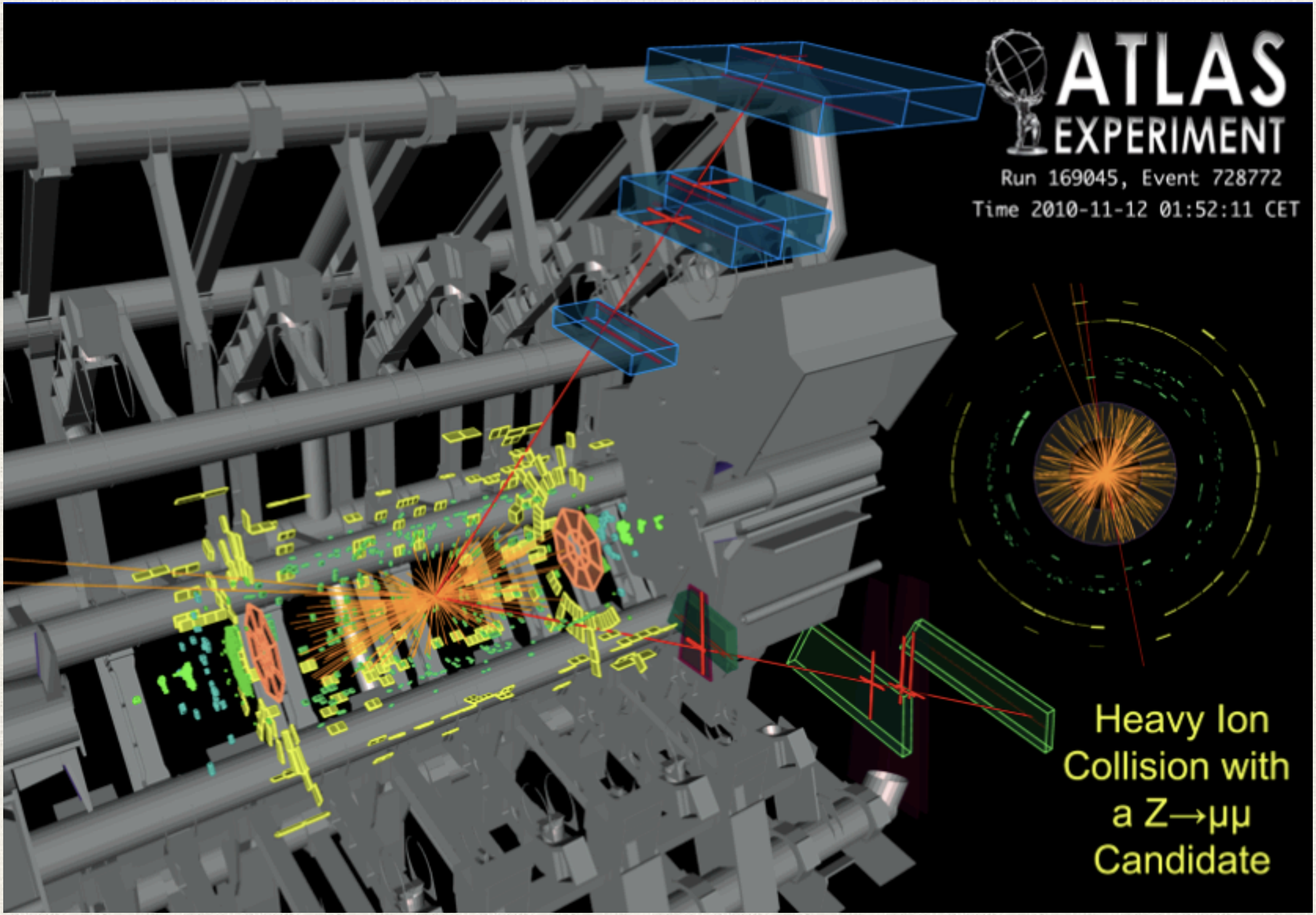
"Peripheral" collision:
moderate energy density

The sum of the energies measured by the calorimeters is strongly correlated to the "centrality" of the collision.

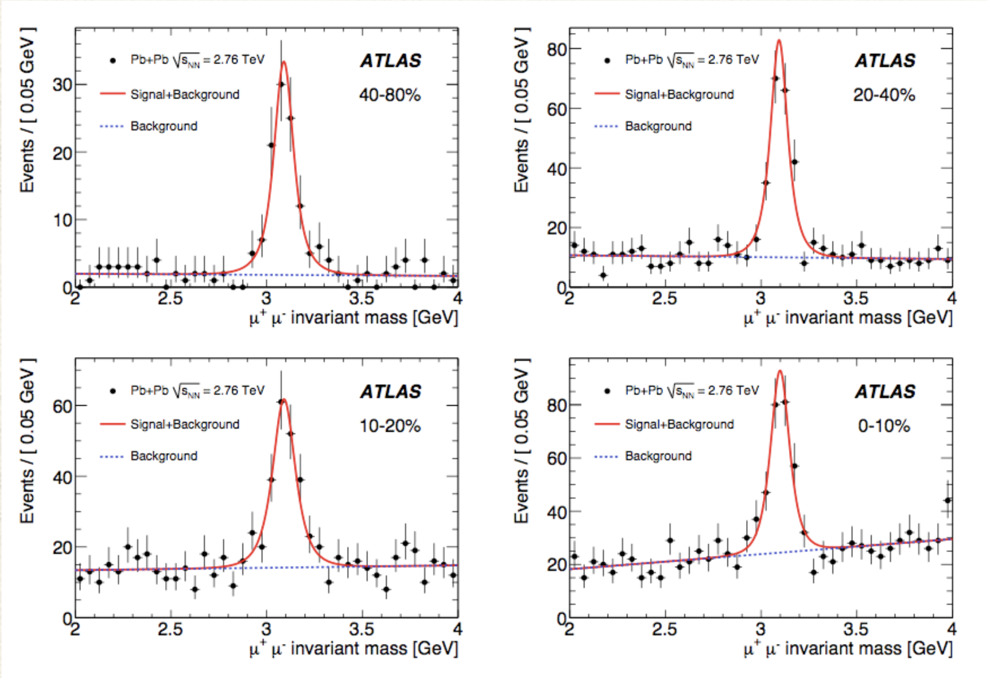
It is possible to select event samples with different degrees of energy densities

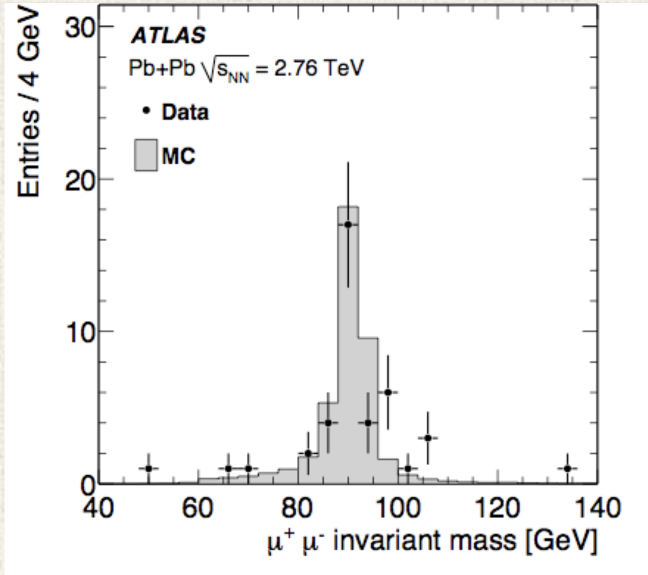


Heavy Ion event: large ID and calorimeter occupancies BUT clean muons



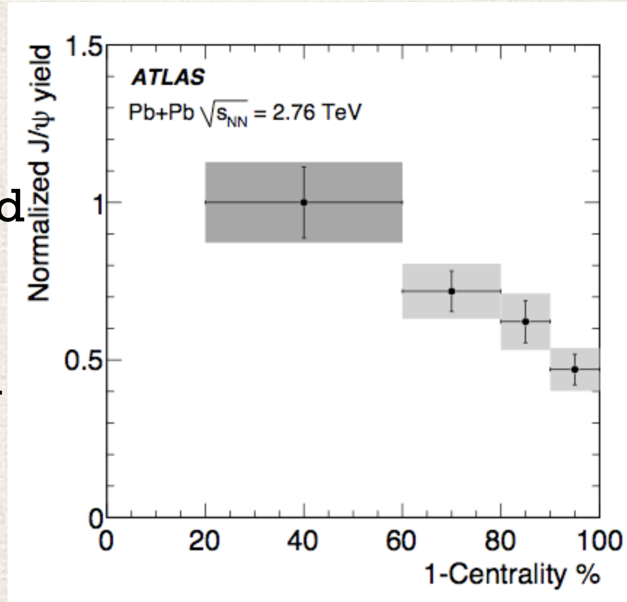
ATLAS has studied J/ψ and Z production through their →$\mu^+\mu^-$ decay as a function of the event centrality

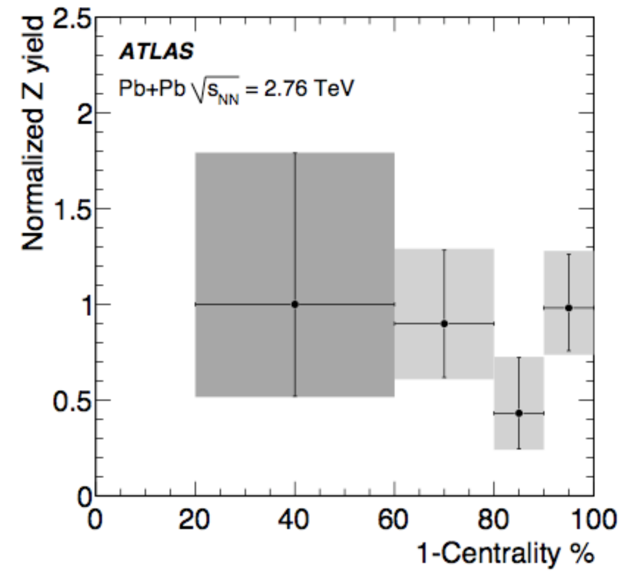




Result: J/ψ suppression is clearly observed
Z suppression not observed (but limited statistics).

Previous results (NA50 and PHENIX) are confirmed at much higer $E_{c.m.}$





6. Prospects

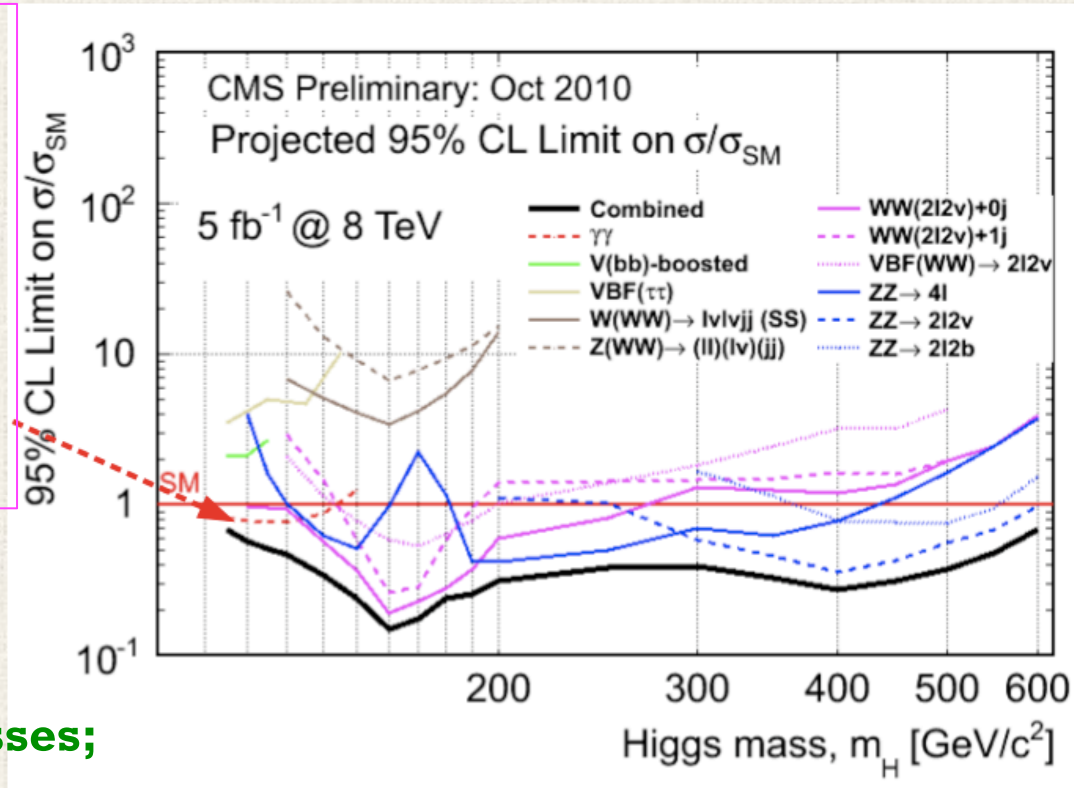
CERN decision: 2011 + 2012 two years LHC run.

$E_{c.m.}$ = 7 TeV in 2011; possible upgrade to 8 TeV in 2012

Expected integrated luminosity: 1 fb^{-1} in 2011, >5 fb^{-1} in 2012

Higgs boson discovery potential with 2011+2012 run:

"***5fb^{-1} @ 8TeV should give ATLAS/CMS at least 3 σ Higgs evidence PER EXPERIMENT***"
(official statement of LHC experiments at Chamonix)



Main discovery channels are:

H→γγ @ very low masses;
WW → (2l2ν) + 0,1j @ interm. masses;
ZZ → 4l, 2l2ν @ large masses.
l = muon or electron

→MUON DETECTION CRUCIAL FOR HIGGS DISCOVERY