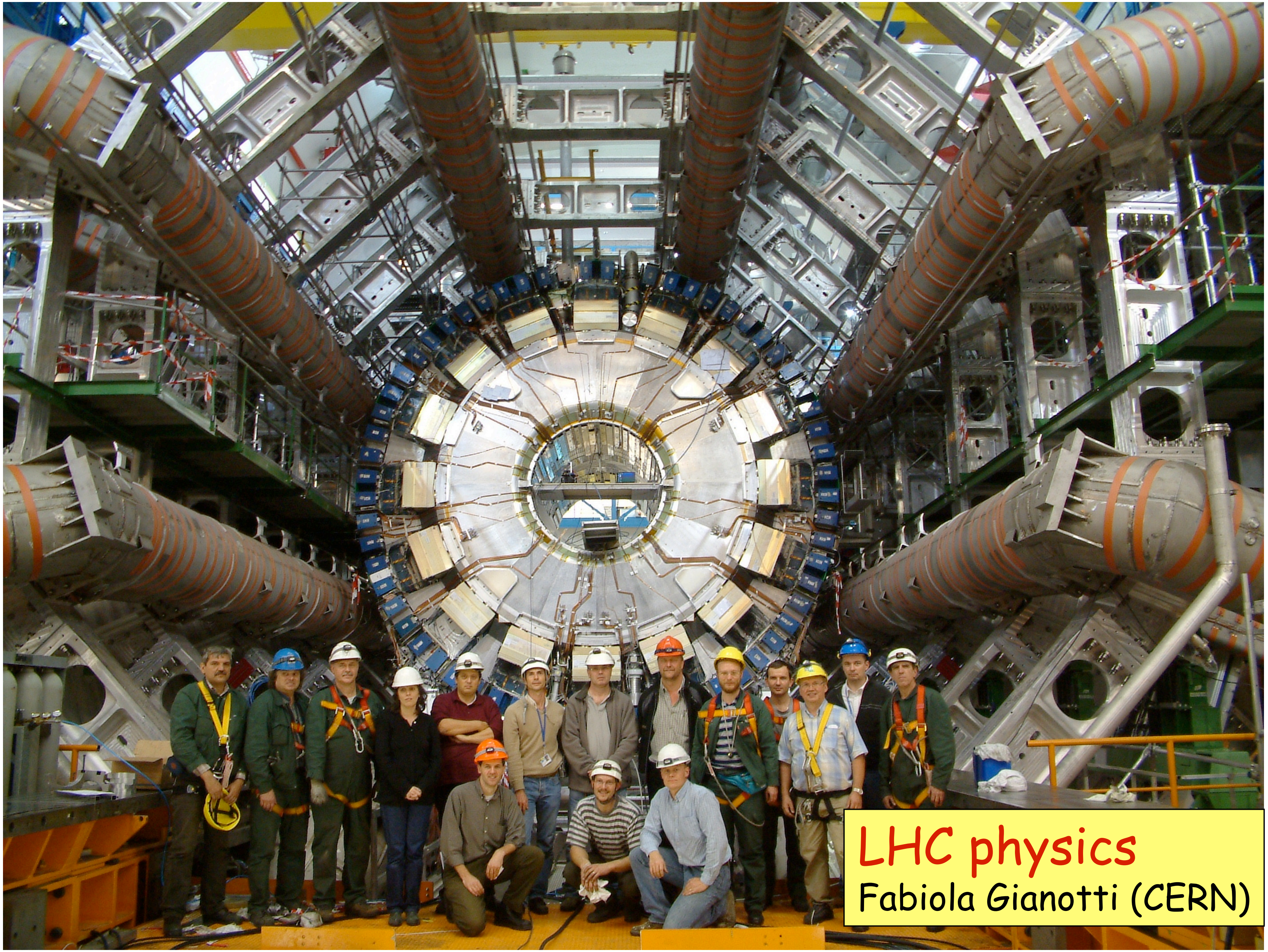


LHC physics

Fabiola Gianotti (CERN)

Layout

- Introduction, machine status
- Physics motivations for the LHC
- Environment, experimental challenges, ATLAS and CMS
- ATLAS detector performance from simulation and test beam
- First collisions and early physics
- Discovery physics (Higgs, SUSY, Extra-dimensions, ..)
- Conclusions

Alla fine: discussione di possibili studi di fisica

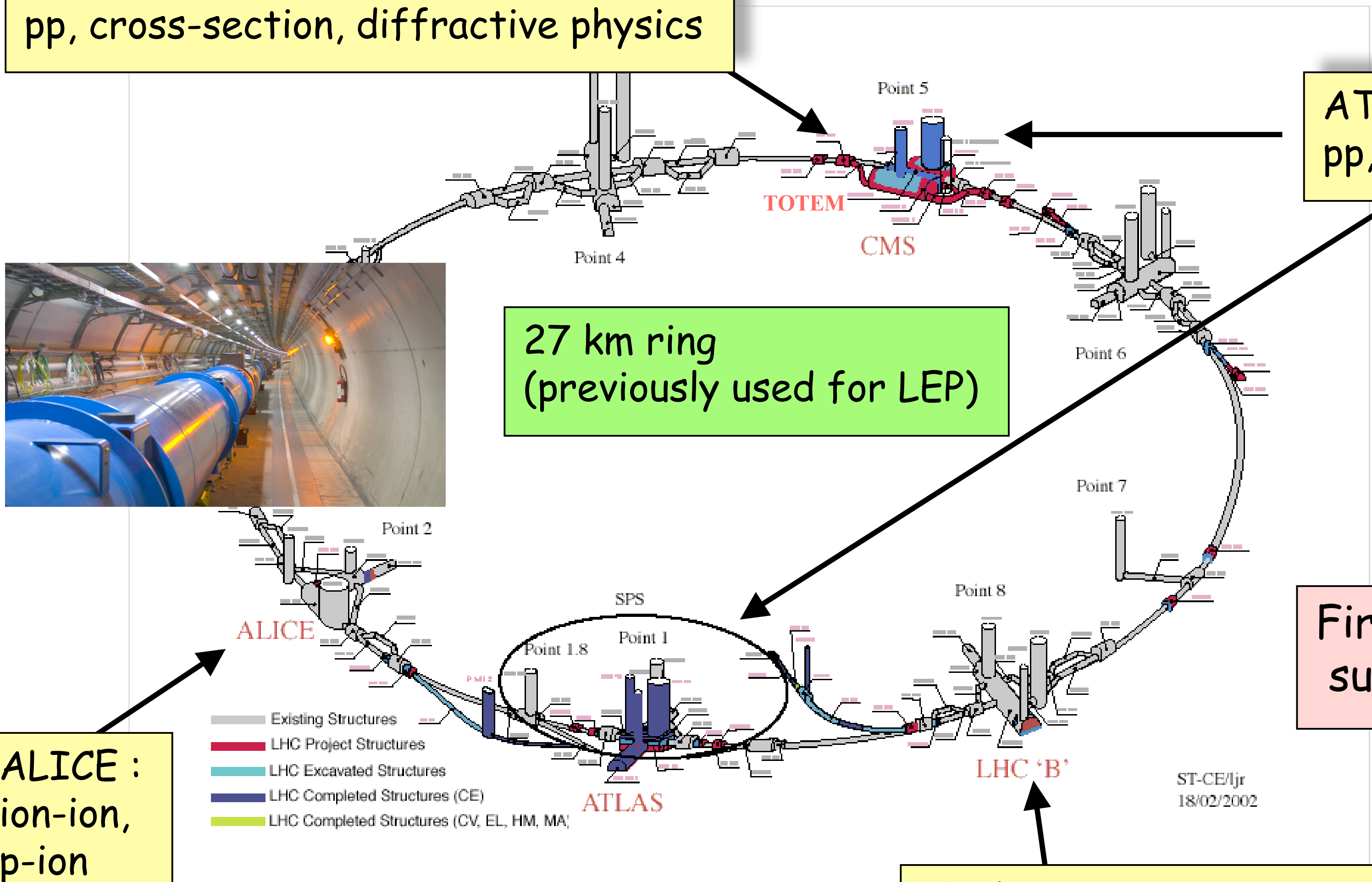
Introduction
Machine main parameters and status

LHC

- pp $\sqrt{s}$ = 14 TeV $L_{design} = 10^{34}$ cm^{-2} s^{-1} (after 2009)
  $L_{initial} \leq$ few x 10^{33} cm^{-2} s^{-1} (until 2009)
- Heavy ions (e.g. Pb-Pb at $\sqrt{s}$ ~ 1000 TeV)

TOTEM (integrated with CMS):
pp, cross-section, diffractive physics

ATLAS and CMS :
pp, general purpose



27 km ring
(previously used for LEP)

First collisions :
summer 2007

ALICE :
ion-ion,
p-ion

LHCb :
pp, B-physics, CP-violation

LHC machine

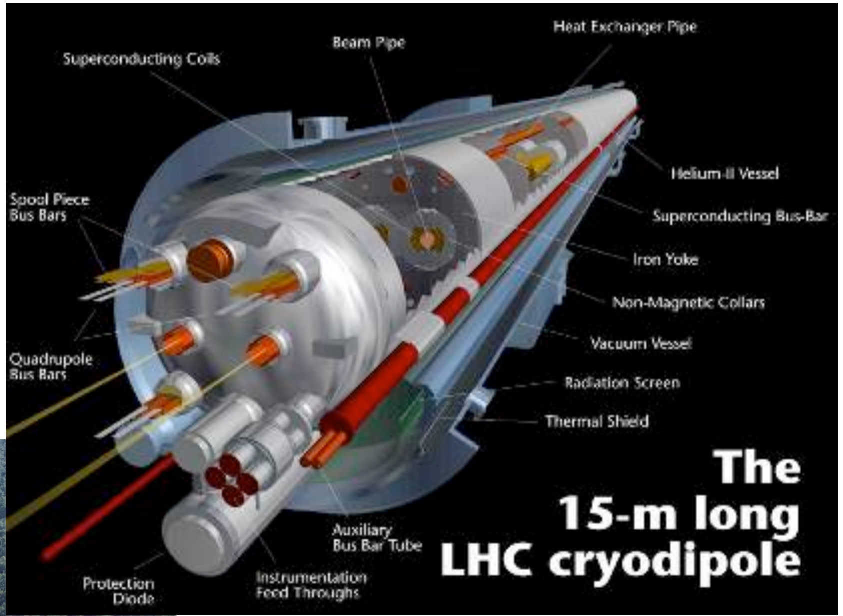
Energy	E	[TeV]	7.0
Dipole field	B	[T]	8.4
Luminosity	L	[cm^{-2} s^{-1}]	10^{34}
Beam–beam parameter	ξ		0.0034
Total beam–beam tune spread			0.01
Injection energy	E_i	[GeV]	450
Circulating current/beam	I_{beam}	[A]	0.53
Number of bunches	k_b		2835
Harmonic number	h_{RF}		35640
Bunch spacing	τ_b	[ns]	24.95
Particles per bunch	n_b		$1.05\ 10^{11}$
Stored beam energy	E_s	[MJ]	334
Normalized transverse emittance $(\beta\gamma)\sigma^2/\beta$	ε_n	[μm.rad]	3.75
Collisions			
β-value at I.P.	β^*	[m]	0.5
r.m.s. beam radius at I.P.	σ^*	[μm]	16
r.m.s. divergence at I.P.	σ'^*	[μrad]	32
Luminosity per bunch collision	L_b	[cm^{-2}]	$3.14\ 10^{26}$
Crossing angle	ϕ	[μrad]	200
Number of events per crossing	n_c		19
Beam lifetime	τ_{beam}	[h]	22
Luminosity lifetime	τ_L	[h]	10

Limiting factor for √s : bending power needed to keep beams in 27 km LEP ring:

p(TeV) = 0.3 B(T) R(km)

with typical magnet packing factor of ~ 70%,
need 1232 dipoles with B=8.3 T for 7 TeV beams

821 out of 1232 superconducting dipoles (B=8.3 T) delivered at CERN as of Monday 21/11/2005



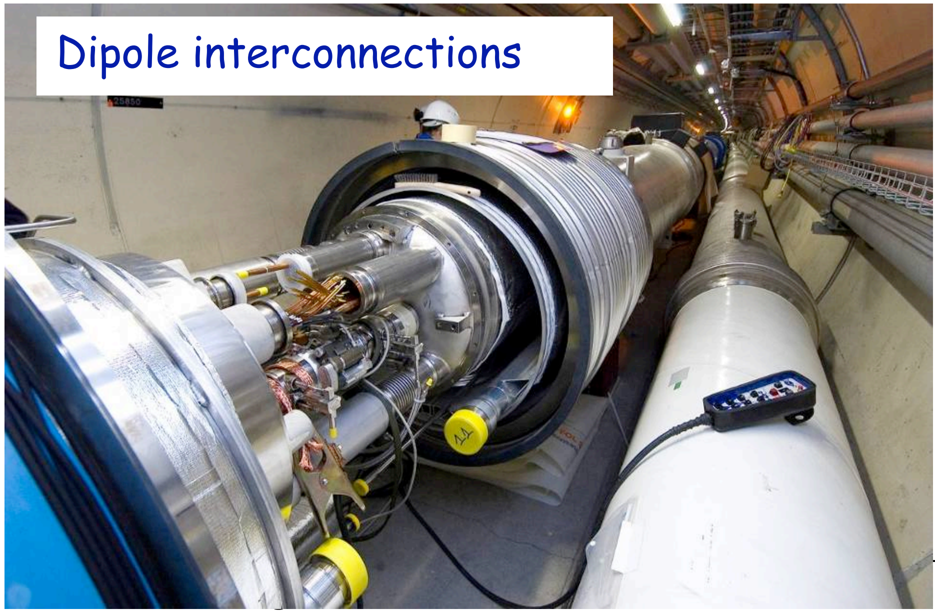
All dipoles tested at warm (magnetic tests) and cold. 15% subject to detailed magnetic tests at cold

Magnet quality is very good

157 dipoles installed
in the underground tunnel
as of Monday 21/11/2005

Installation rate:
10 dipoles/week (goal 20/week)
Limiting factor today:
performance of optical guided vehicles

600 m of cryoline successfully
cooled down on September 14

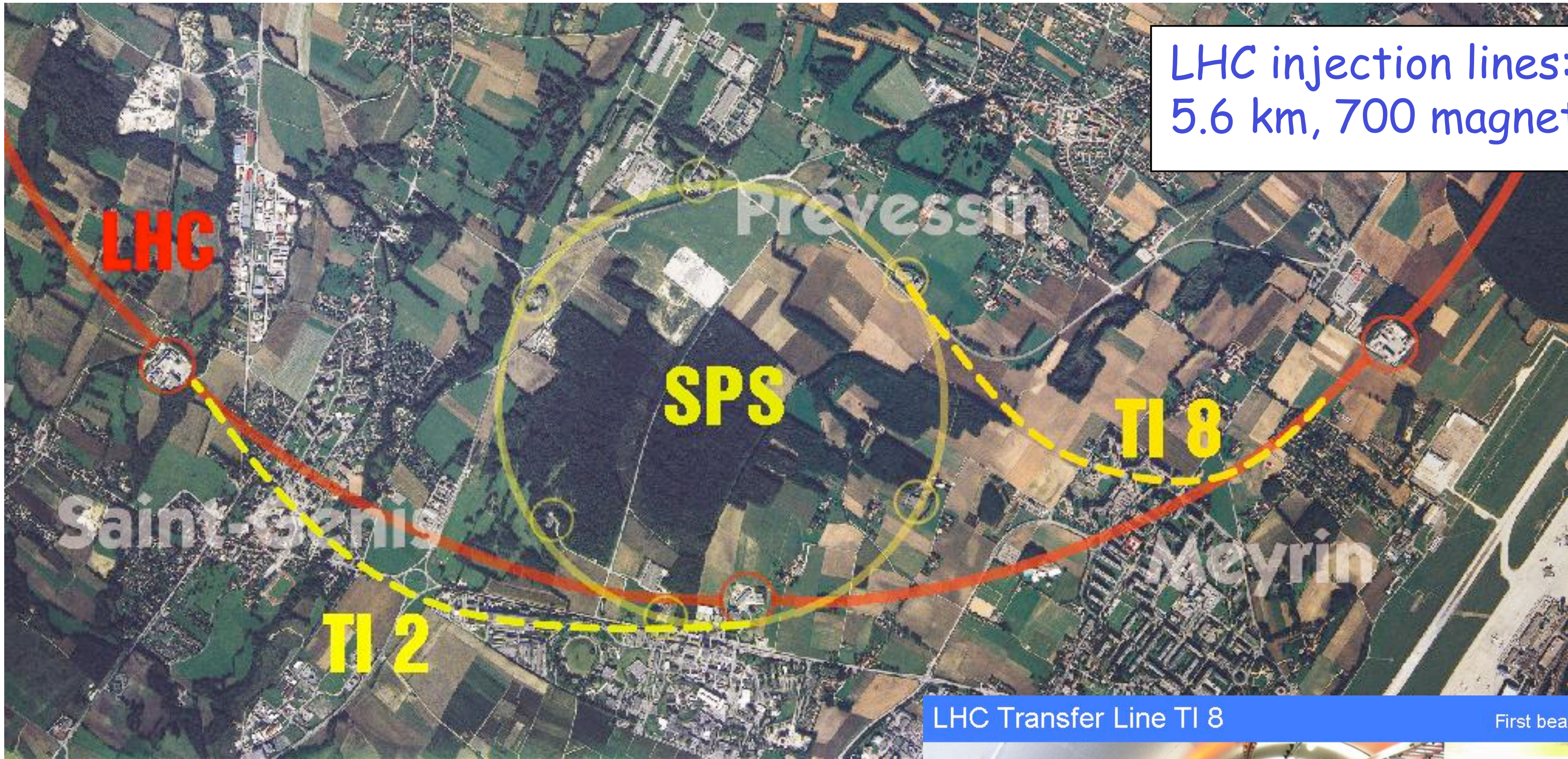

Dipole interconnections

Not only dipoles ….

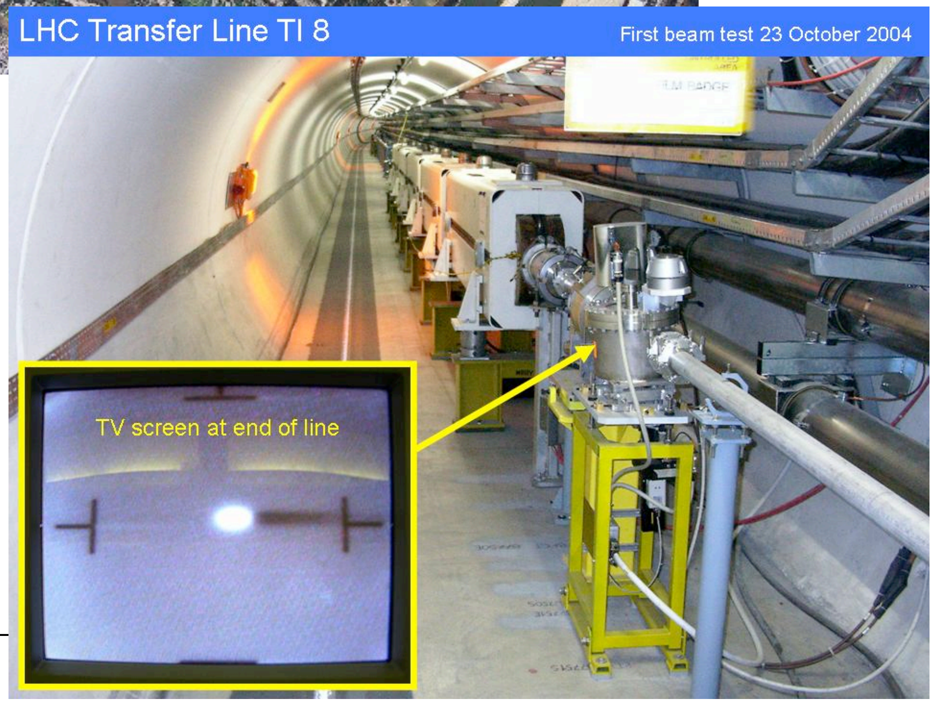
Dipoles	1232
Quadrupoles	400
Sextupoles	2464
Octupoles/decapoles	1568
Orbit correctors	642
Others	376
Total	~ 6700

Assembly of Short Straight Session

Inner triplet quads assembly hall 181



LHC injection lines:
5.6 km, 700 magnets



23/10/2004: first beam injection test from SPS to LHC through TI8 transfer line

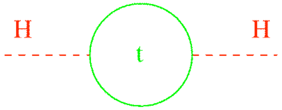
WHY ???

Physics motivations for the LHC

What is wrong with the SM ?

- Origin of particle masses → where is the Higgs boson ?

- "Naturalness" problem :

  radiative corrections 

  $\delta m_H^2 \sim \Lambda^2$ → $\Lambda \equiv$ scale up to which SM is valid

- "Hierarchy" problem : why $M_{EW}/M_{Planck} \sim 10^{-17}$? Is there anything in between ?

- Flavour/family problem, CP-violation, coupling unification, gravity incorporation, ν masses/oscillations, dark matter and dark energy, etc. etc., …. …..

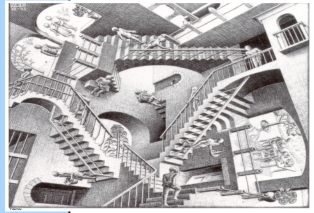
All this calls for

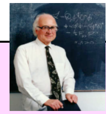
A more fundamental theory of which SM is low-E approximation → **New Physics**

Difficult task : solve SM problems without contradicting (the very constraining) EW data

SUSY
New particles at TeV scale stabilize m_H

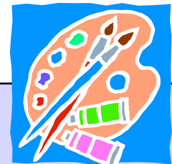
Extra-dimensions
Additional dimensions
$\rightarrow M_{gravity} \sim M_{EW}$
New states at TeV scale



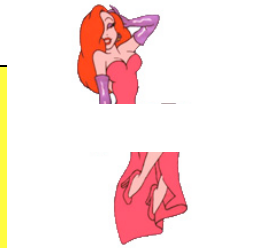


Little Higgs
SM embedded in larger gauge group
New particles at TeV scale, stable m_H

$\delta m_H \sim \Lambda \Rightarrow$ New Physics to stabilize m_H already needed at TeV scale



Technicolour
New strong interactions break EW symmetry
$\rightarrow$ Higgs (elementary scalar) removed
New particles at TeV scale



Split SUSY
Accept fine-tuning of m_H
(and of cosm. constant)
by anthropic arguments
Part of SUSY spectrum at TeV scale
(for couplings unification and dark matter)

strong motivations for a machine able to explore the TeV-scale

LHC

LHC physics goals

Search for the Standard Model Higgs boson over ~ $115 < m_H < 1000$ GeV.

Explore the highly-motivated TeV-scale, search for physics beyond the SM (Supersymmetry, Extra-dimensions, q/l compositness, leptoquarks, W'/Z', heavy q/l, etc.)

Precise measurements :

-- W mass
-- top mass, couplings and decay properties
-- Higgs mass, spin, couplings (if Higgs found)
-- B-physics (mainly LHCb): CP violation, rare decays, B^0 oscillations
-- QCD jet cross-section and α_s
-- etc. ....

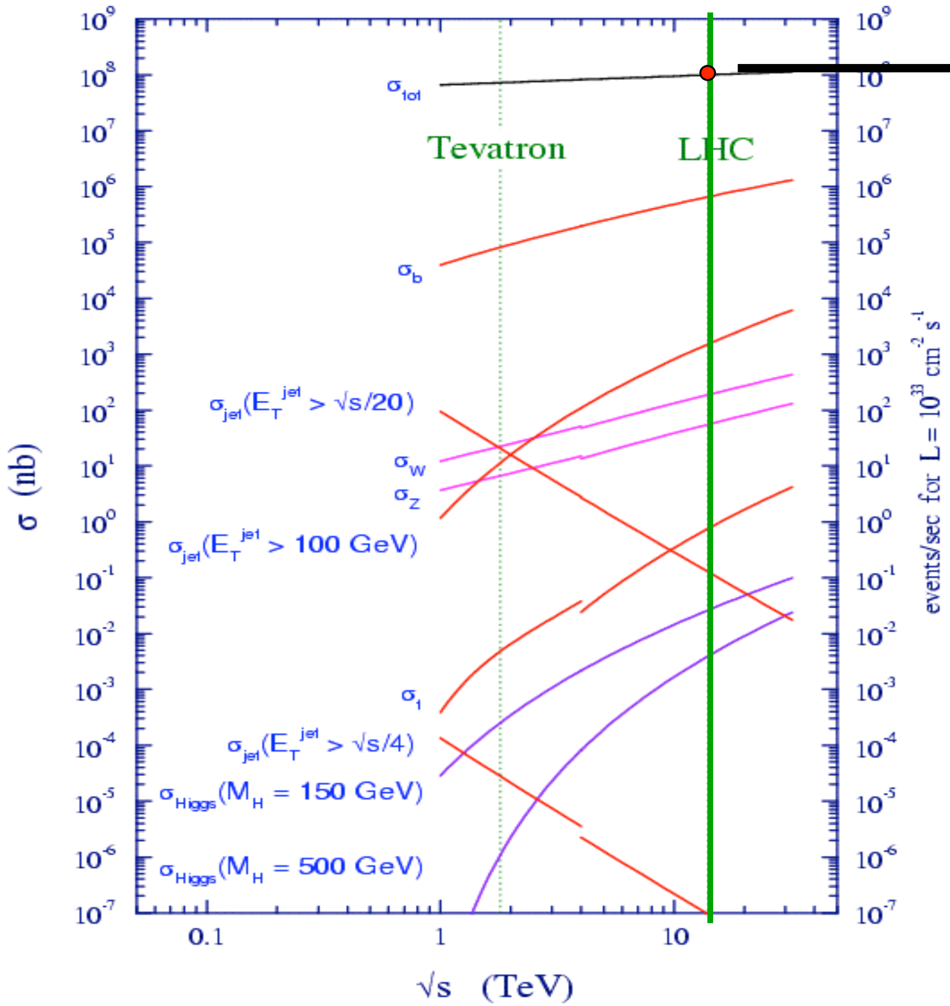
Study phase transition at high density from hadronic matter to quark-gluon plasma (mainly ALICE).

Etc. etc. .....

Here : high-p_T physics (ATLAS and CMS)

The environment and
the experimental challenges,
the performance requirements,
the ATLAS and CMS experiments

Event rate and pile-up (consequence of high luminosity …)



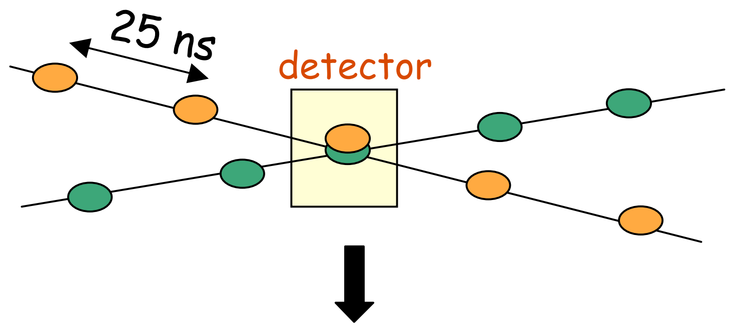
Event rate in ATLAS, CMS :

$N = L \times \sigma_{inelastic}(pp) \approx 10^{34}\ cm^{-2}\ s^{-1} \times 70$ mb

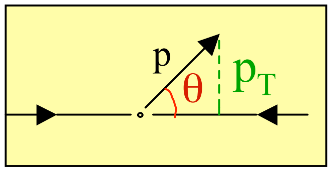
$\approx 10^{9}$ interactions/s

Proton bunch spacing : 25 ns

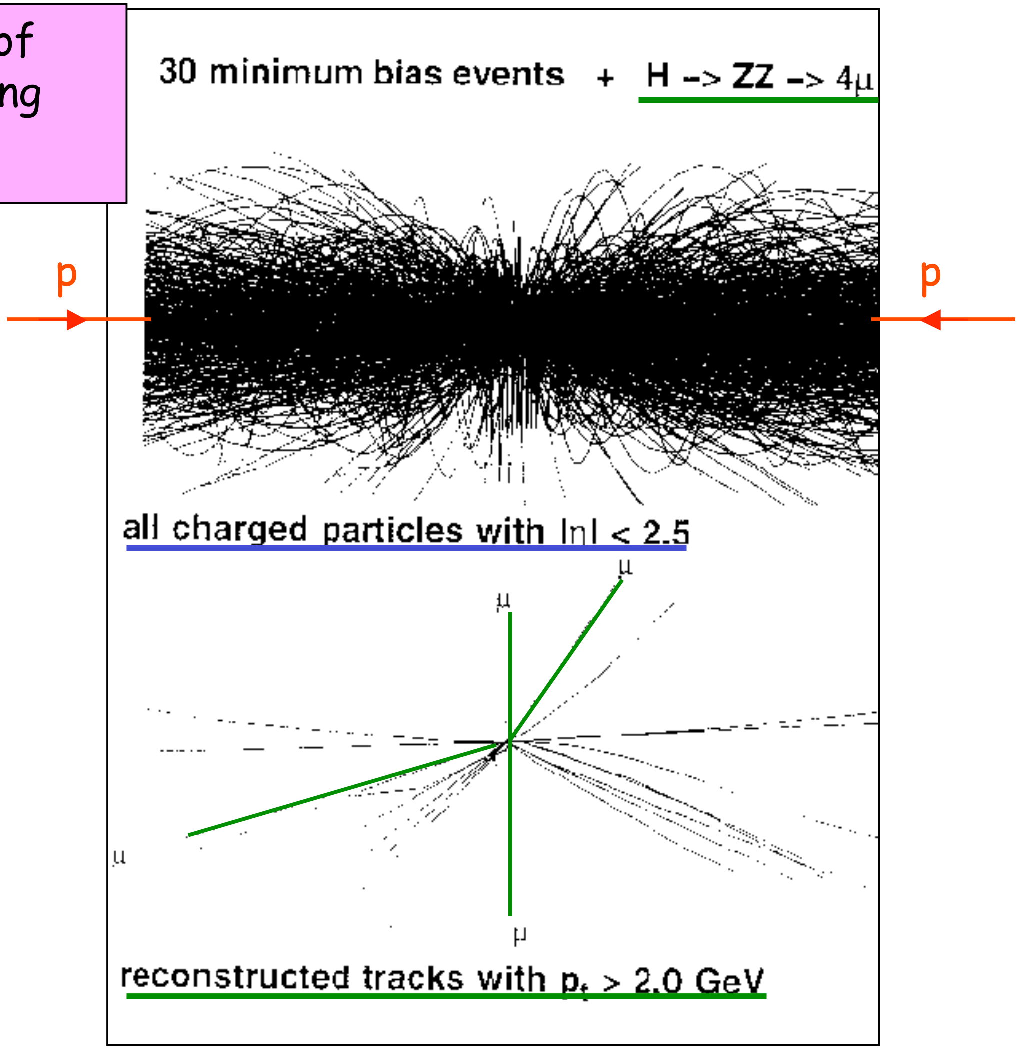
Protons per bunch : 10^{11}



~ 20 inelastic (low-p_T) events ("minimum bias") produced simultaneously in the detectors at each bunch crossing → pile-up



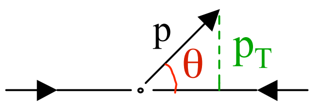
Simulation of CMS tracking detector



At each crossing : ~1000 charged particles produced over $|\eta| < 2.5$ ($10^0 < \theta < 170^0$)

However : $\langle p_T \rangle \approx 500$ MeV

→ applying p_T cuts allows extraction of interesting events



$\eta = -\ln \mathrm{tg}\, \theta/2$

Impact of pile-up on detector requirements and performance:

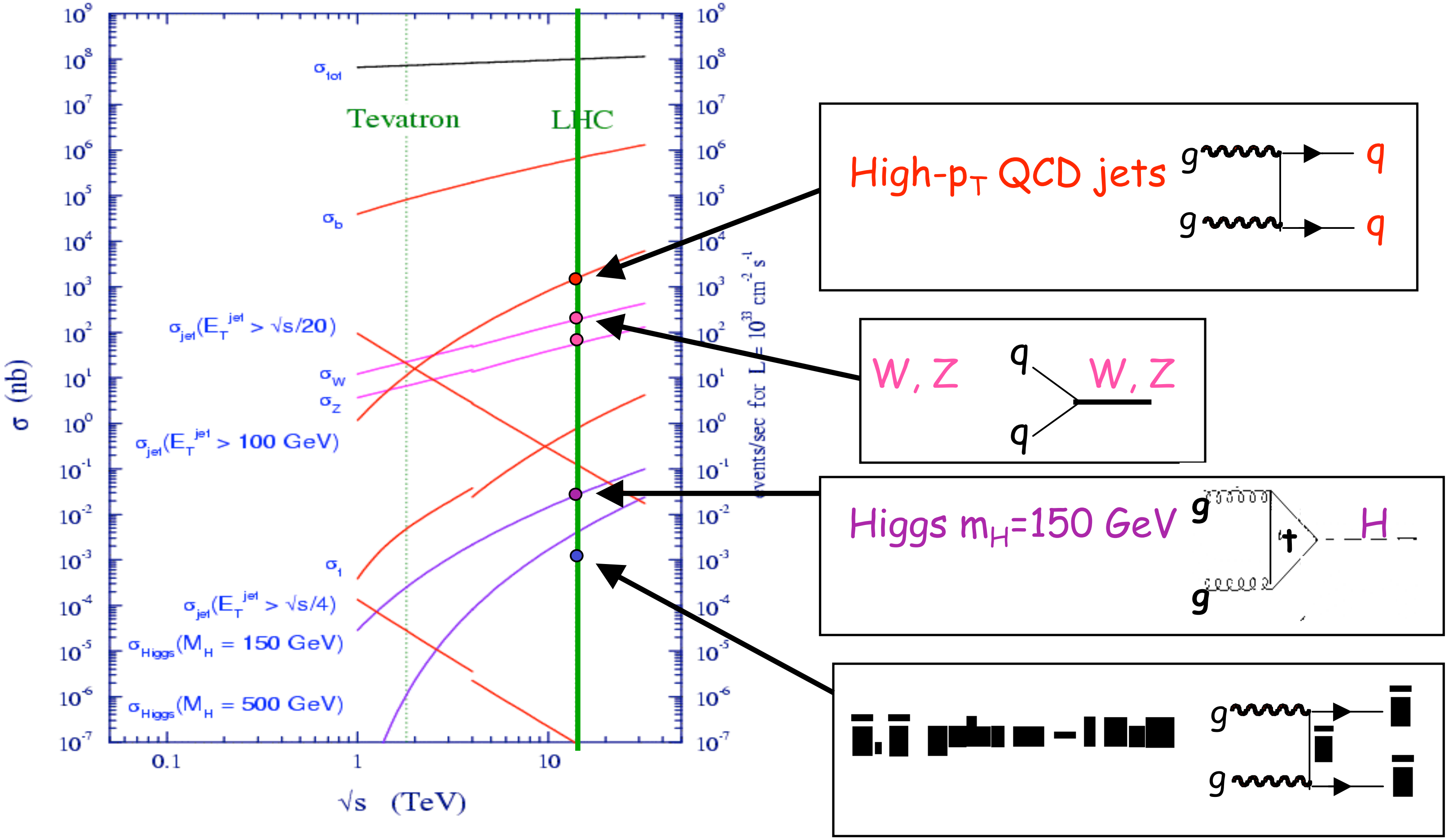
-- fast response : ~ 50 ns

-- granularity : > 10^8 channels

-- radiation resistance (up to 10^{16} n/cm^2/year in forward calorimeters)

-- event reconstruction much more challenging than at previous colliders

Huge (QCD) backgrounds (consequence of high energy …)



- No hope to observe light objects (W, Z, H ?) in fully-hadronic final states → rely on l, γ
- Fully-hadronic final states (e.g. $q^* \rightarrow qg$) can be extracted from backgrounds only with hard O(100 GeV) p_T cuts → works only for heavy objects
- Mass resolutions of ~ 1% (10%) needed for l, γ (jets) to extract tiny signals from backgrounds, and excellent particle identification (e.g. e/jet separation)
- S (EW) /B (QCD) larger at Tevatron than LHC

Examples of detector performance requirements

Don't know how New Physics will manifest → detectors must be able to detect as many particles and signatures as possible: e, μ, τ, ν, γ, jets, b-quarks, ...
→ ATLAS and CMS are general-purpose experiments

Very selective trigger: 40 MHz (interaction rate) → 200 Hz (affordable rate-to-storage)
1 H → 4e event every 10^{13} interactions

Lepton measurement: $p_T \approx$ GeV → 5 TeV (b → l+X, W'/Z', ...)

Mass resolutions:
$\approx$ 1% decays into leptons or photons (Higgs, new resonances)
$\approx$ 10% W → jj, H → bb (top physics, Higgs, ...)

Hadron calorimeter linearity understood to < 1.5 % at E_{jet} ~ 4 TeV (q compositeness)

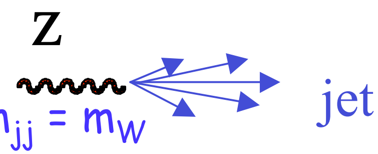
Calorimeter coverage: $|\eta|<5$ (SUSY/E_T^{miss}, Higgs/forward jet tag, ...)

Lepton energy scale

- mainly from $Z \rightarrow ll$ events
- ~ 1 ‰ uncertainty achieved by CDF, D0 (dominated by statistics of control samples)
- goal : 0.2 ‰ , to measure m_W to ~ 15 MeV
- systematics dominated by detector: knowledge of tracker material to 1%, overall alignment to < 1μm, B-field to better than 0.1%, etc.

Jet energy scale

- mainly from $Z (\rightarrow ll) + 1$ jet asking p_T (jet) = p_T (Z)
  and from $W \rightarrow jj$ in $tt \rightarrow bW\, bW \rightarrow bl\nu\, bjj$ events asking $m_{jj} = m_W$

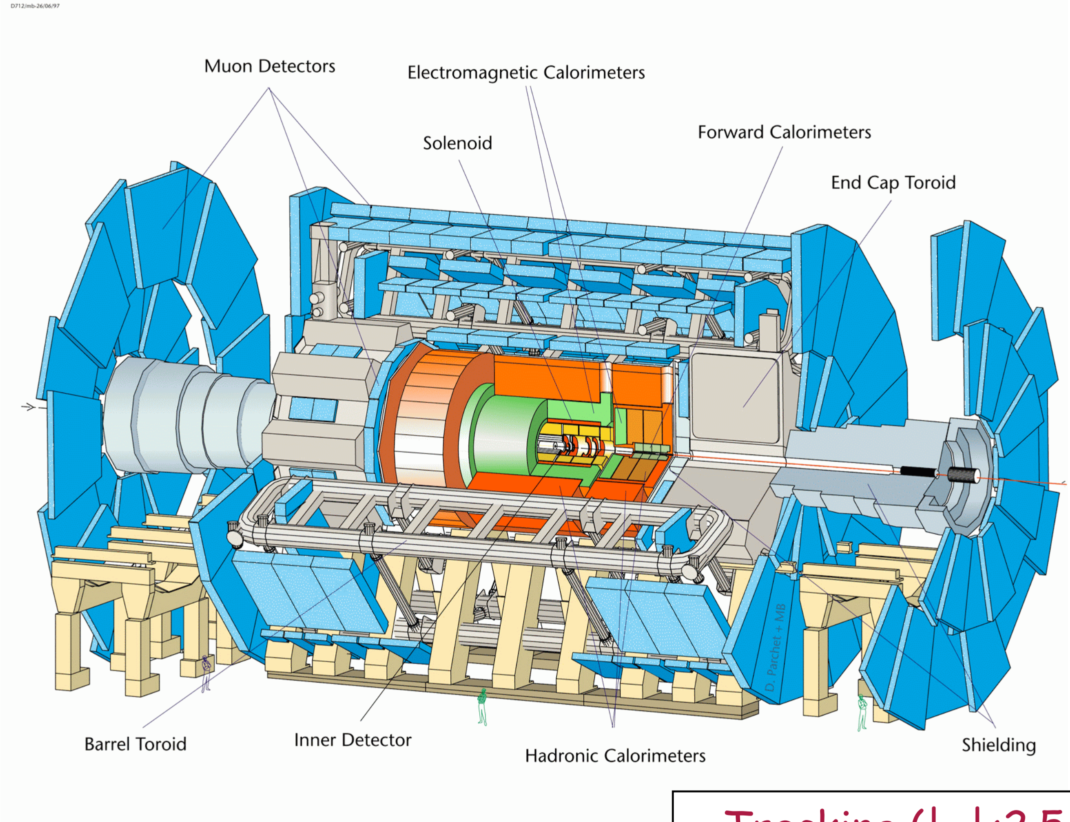


- ~ 3 % uncertainty achieved by CDF, D0 (not enough tt statistics at Tevatron)
- goal : ~ 1 % , to measure m_{top} to ~ 1 GeV, SUSY, …
- systematics dominated by physics : FSR, underlying event, etc.

Particle identification:

- ε (b) ≈ 50% R (jet) ≈ 100 (H → bb, SUSY, 3rd generation !!)
- ε (τ) ≈ 50% R(jet) ≈ 100 (A/H → ττ, SUSY, 3rd generation !!)
- ε (γ) ≈ 80% R(jet) > 10^3 (H → γγ)
- ε (e) > 70% R(jet) > 10^5 (inclusive electron sample)

Absolute luminosity to <5% (W/Z/tt cross-section measurements, new physics through σxBR measurements, ….)



ATLAS

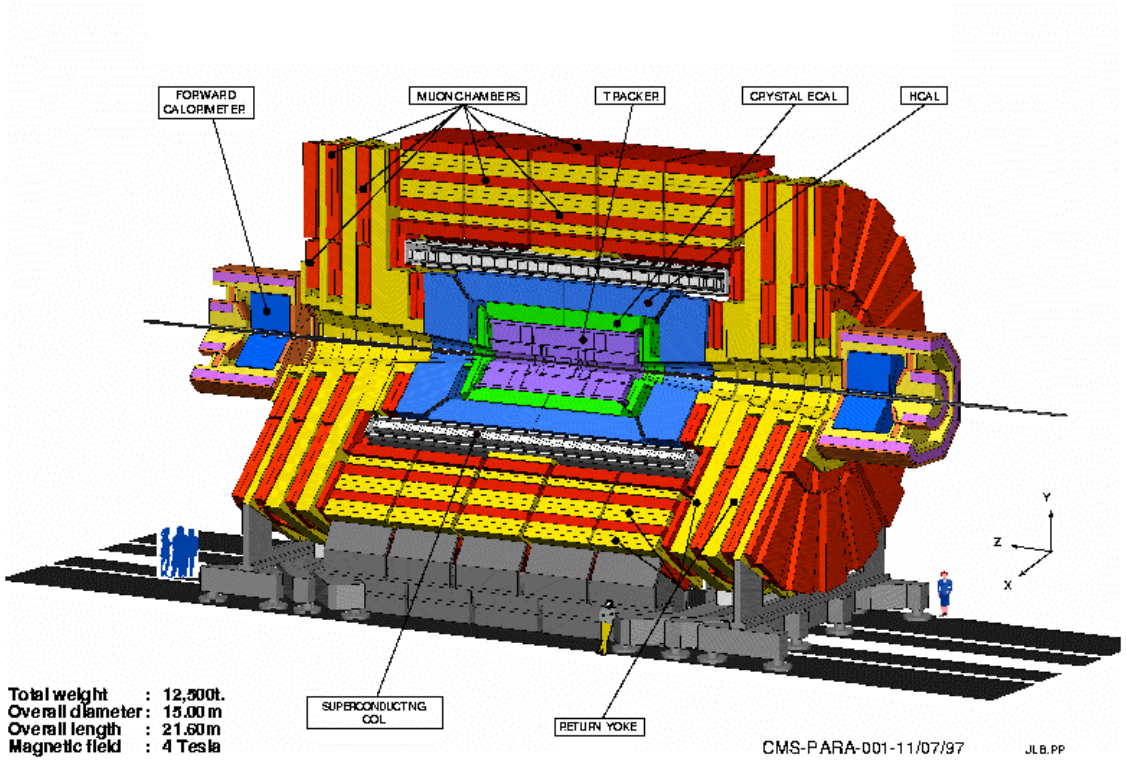
Length : ~45 m
Radius : ~12 m
Weight : ~ 7000 tons
Electronic channels : ~ 10^8

- Tracking ($|\eta|<2.5$, B=2T) :
  -- Si pixels and strips
  -- Transition Radiation Detector (e/π separation)

- Calorimetry ($|\eta|<5$) :
  -- EM : Pb-LAr
  -- HAD: Fe/scintillator (central), Cu/W-LAr (fwd)

- Muon Spectrometer ($|\eta|<2.7$) :
  air-core toroids with muon chambers

CMS



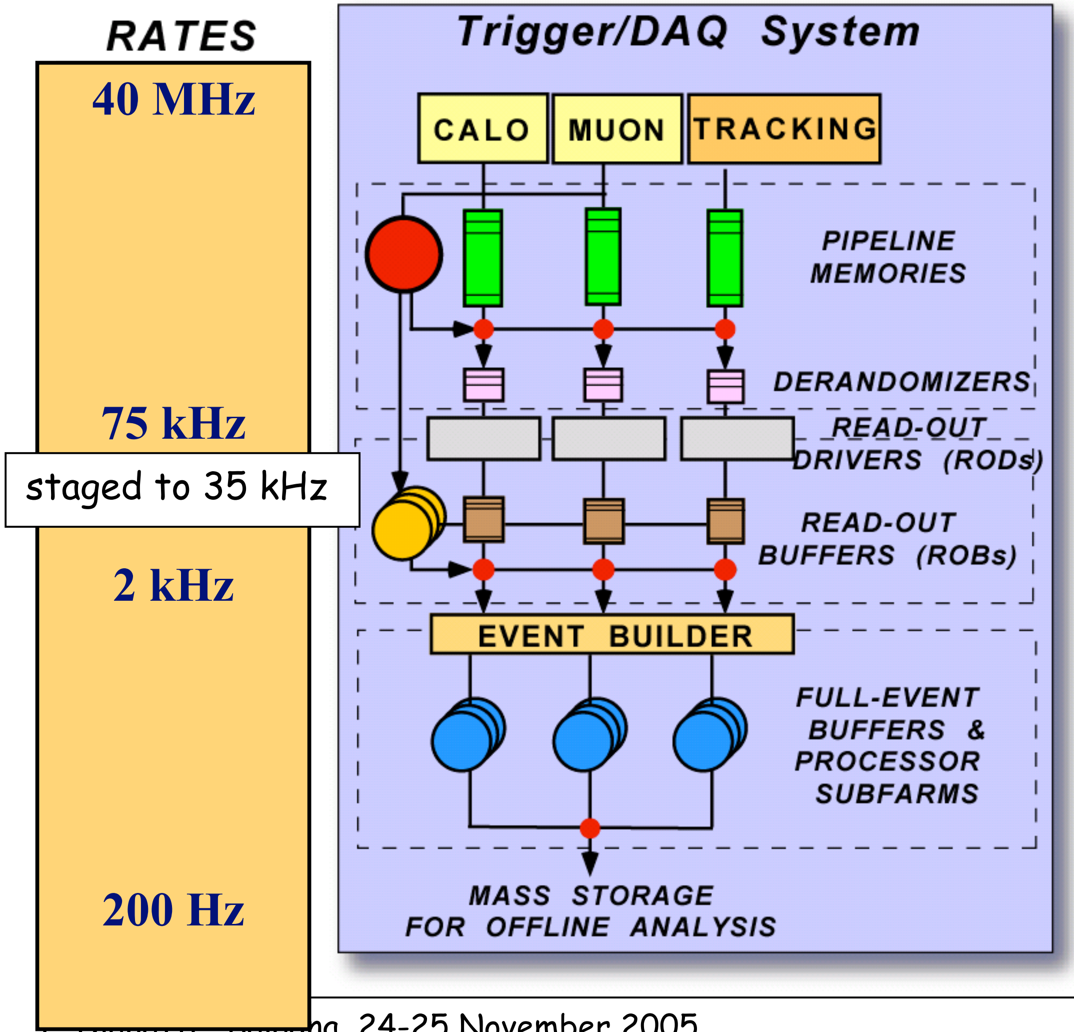
Length : ~22 m
Radius : ~7 m
Weight : ~ 12500 tons

- Tracking ($|\eta|<2.5$, B=4T) : Si pixels and strips
- Calorimetry ($|\eta|<5$) :
  -- EM : $PbWO_4$ crystals
  -- HAD: brass/scintillator (central+ end-cap),
  Fe/Quartz (fwd)
- Muon Spectrometer ($|\eta|<2.5$) : return yoke of solenoid instrumented with muon chambers

	ATLAS	CMS
MAGNET (S)	Air-core toroids + solenoid in inner cavity 4 magnets Calorimeters in field-free region	Solenoid Only 1 magnet Calorimeters inside field
TRACKER	Si pixels+ strips TRT → particle identification B=2T $\sigma/p_T \sim 5\text{x}10^{-4}\, p_T \oplus 0.01$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5\text{x}10^{-4}\, p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$ no longitudinal segm.
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air → $\sigma/p_T \sim 7$ % at 1 TeV standalone	Fe → $\sigma/p_T \sim 5\%$ at 1 TeV only combining with tracker

Trigger: one of the big challenges

Must reduce rate from 40 MHz (interaction rate) to ~ 200 Hz (affordable rate to storage)
Must be very selective: e.g. 1 H → 4e event every 10^{13} interactions
⇒ 3-level system



LEVEL 1 TRIGGER
- Hardware-Based (FPGAs ASICs)
- Coarse granularity from calorimeter & muon systems
- 2 μs latency (2.5 μs pipelines)

LEVEL 2 TRIGGER
- Regions-of-Interest "seeds"
- Full granularity for all subdetector systems
- Fast Rejection "steering"
- O(10 ms) processing time

EVENT FILTER
- "Seeded" by Level 2 result
- Potential full event access
- Offline-like Algorithms
- O(1 s) processing time

High Level Trigger

ATLAS, L = 2x 10^{33}

Examples of possible LVL1 and HLT menus

LVL1

Channel	Threshold [GeV]	Rate [kHz]
Inclusive isolated EM	25	12
Two EM clusters	15	4
Inclusive isolated muon	20	0.8
Di-muons	6	0.2
Tau+E_T^{miss}	25/30	2
1jet or 3jets or 4jets	200 , 90 , 65	0.6
Jet + E_T^{miss}	50 / 60	0.4
Other (calib., pre-scale)		5
Total		**~25 kHz**

HLT (to tape)

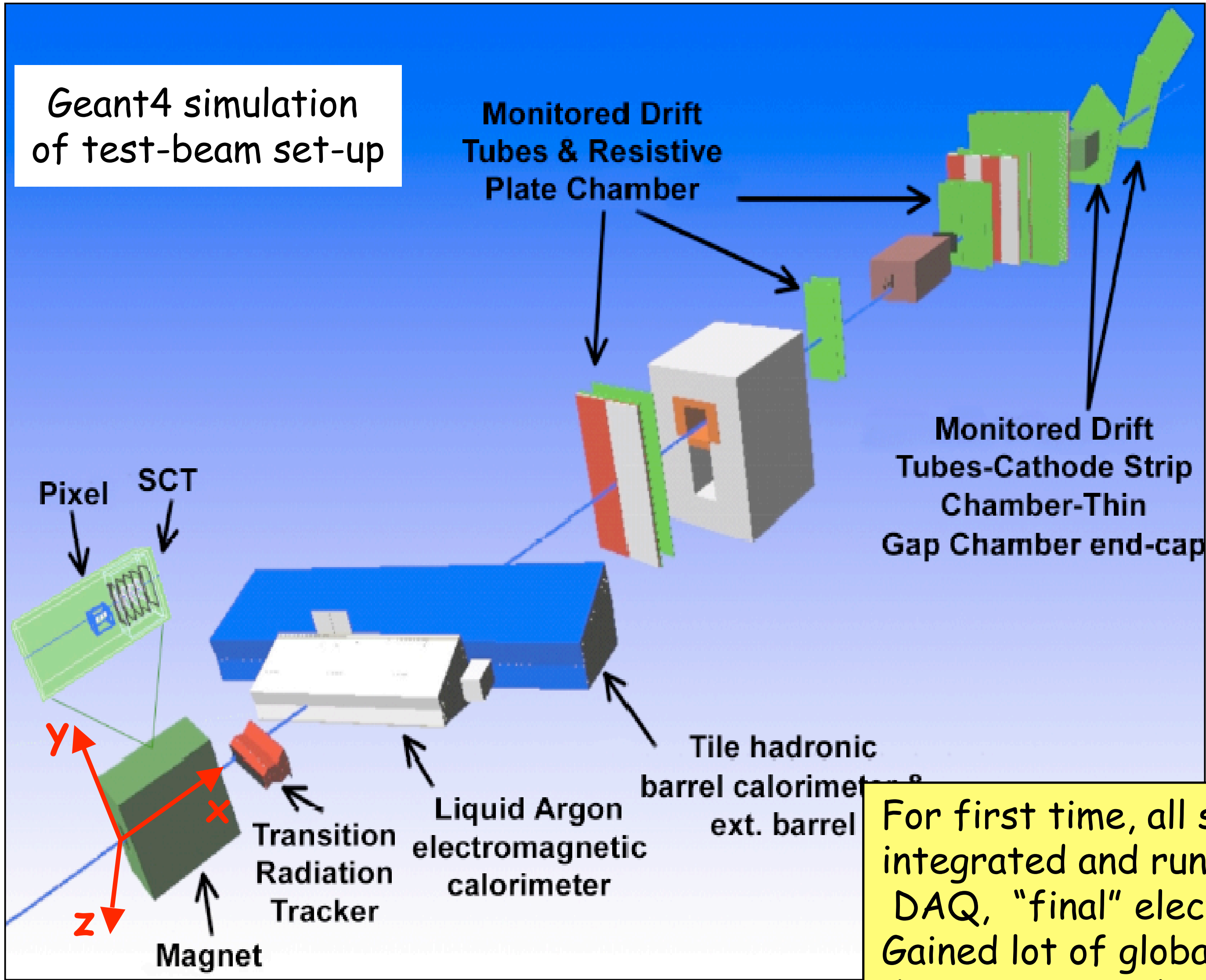
Channel	Threshold [GeV]	Rate [Hz]
1 e, 2 e	25 , 15	40
1 γ, 2 γ	60 , 20	40
1μ, 2 μ–high, 2μ–low	20 , 10 , 6	50
τ +E_T^{miss}	35/45	5
1jet or 3jets or 4jets	400 , 165, 110	25
Jet + E_T^{miss}	70/70	20
Other (calib, …)		20
Total (purity ~50%)		**~200 Hz**

- LVL1 rate limited by staging of HLT processors
- HLT rate by cost of offline computing (1 PB/yr)
- Guiding principles of LHC trigger:
  inclusive approach to the “unknown”, safe overlap with Tevatron reach, avoid biases from exclusive selections, margin for offline optimization and QCD uncertainties, enough bandwidth for calibration/control triggers (esp. at beginning !)

Examples of ATLAS performance from simulations of full experiment and from Combined Test-Beam data

Towards the final experiment : the 2004 ATLAS combined test beam

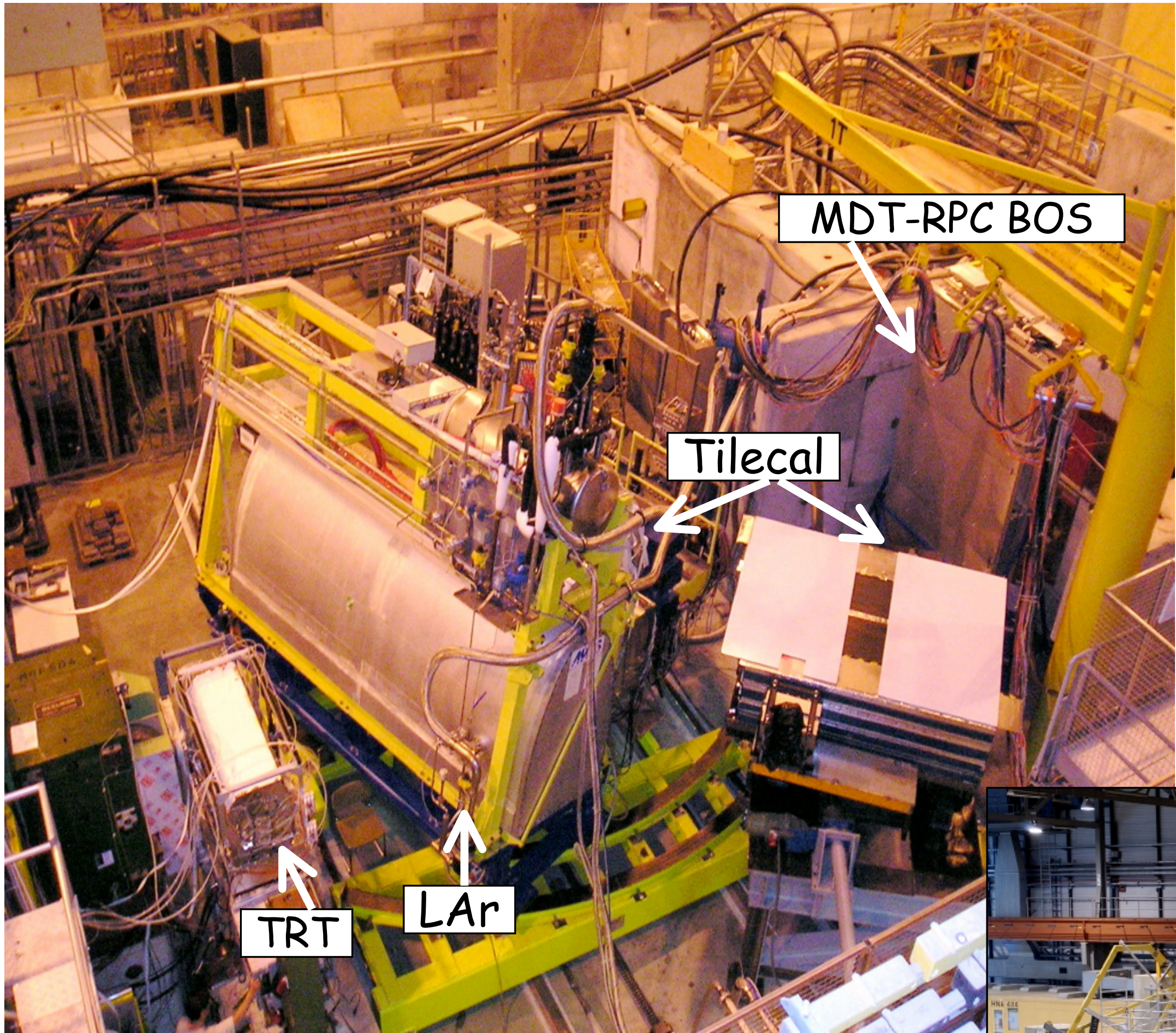
Full "vertical slice" of ATLAS tested on CERN H8 beam line May-November 2004



O(1%) of ATLAS

Production modules in most cases

For first time, all sub-detectors integrated and run together with common DAQ, "final" electronics, slow-control, etc. Gained lot of global operation experience during ~ 6 month run. Common ATLAS software used to analyze the data



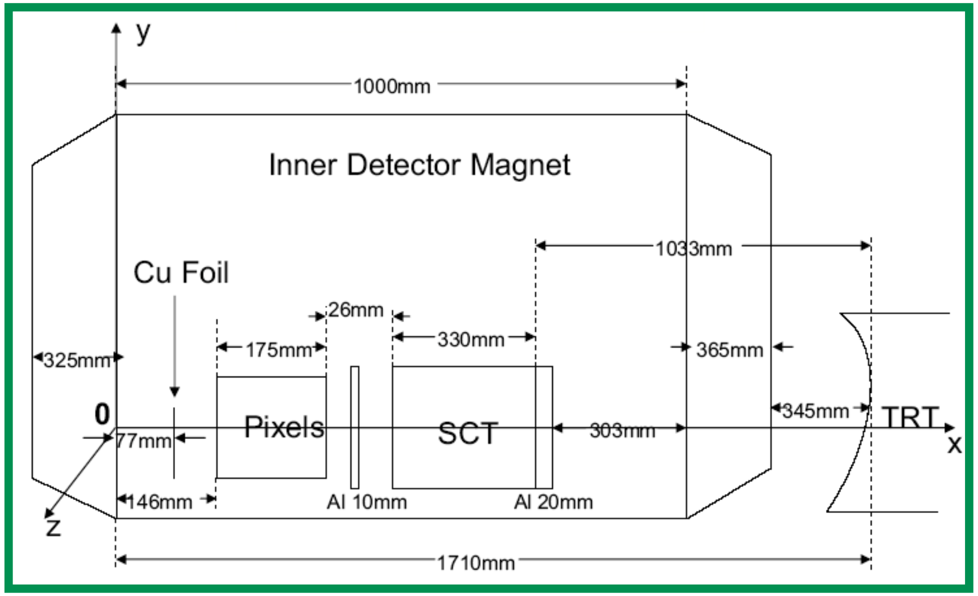
~ 90 million events collected
~ 4.5 TB of data:

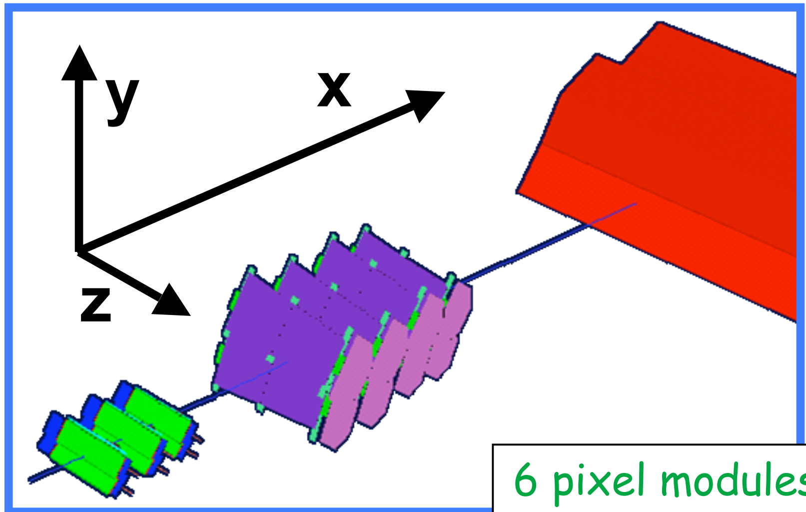
$e^{\pm}$, $\pi^{\pm}$ $1 \rightarrow 250$ GeV
$\mu^{\pm}$, $\pi^{\pm}$, p up to 350 GeV
γ 20-100 GeV
B-field (ID) = $0 \rightarrow 1.4$ T

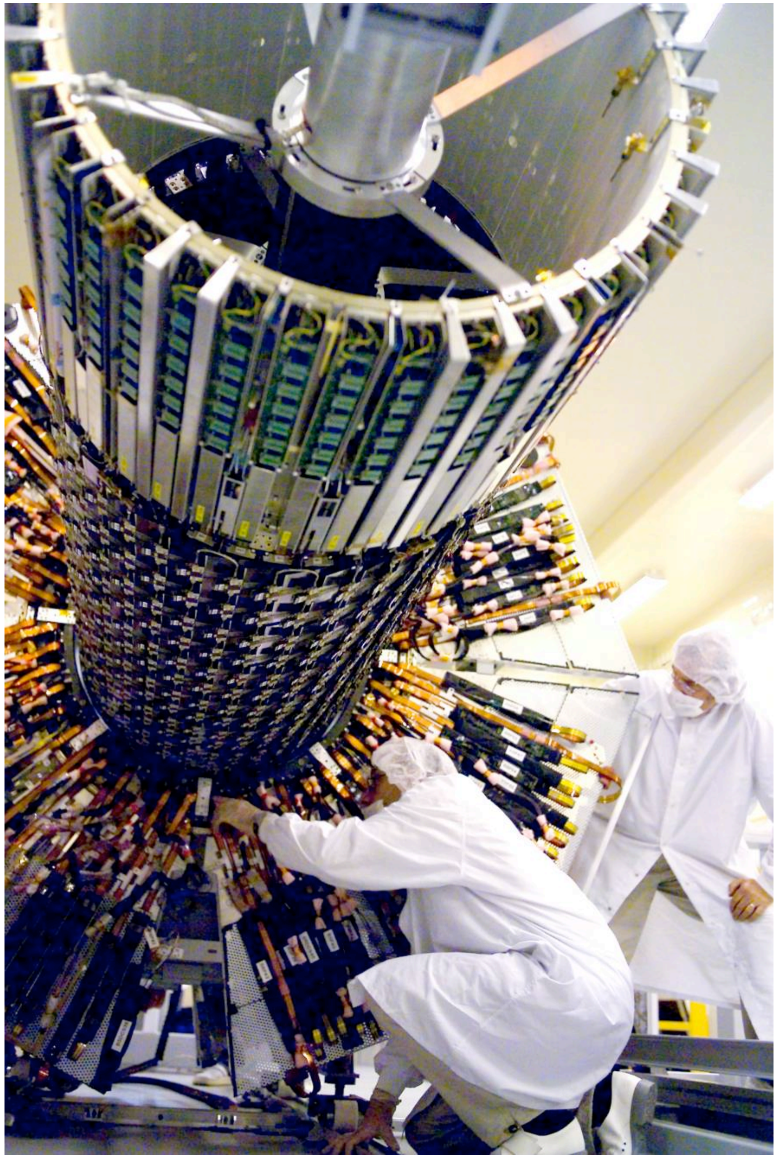
Many configurations
(e.g. additional material in ID,
25 ns runs, etc.)

Last one of a long series of
test-beams for individual
sub-detectors

Tracking and alignment in Inner Detector



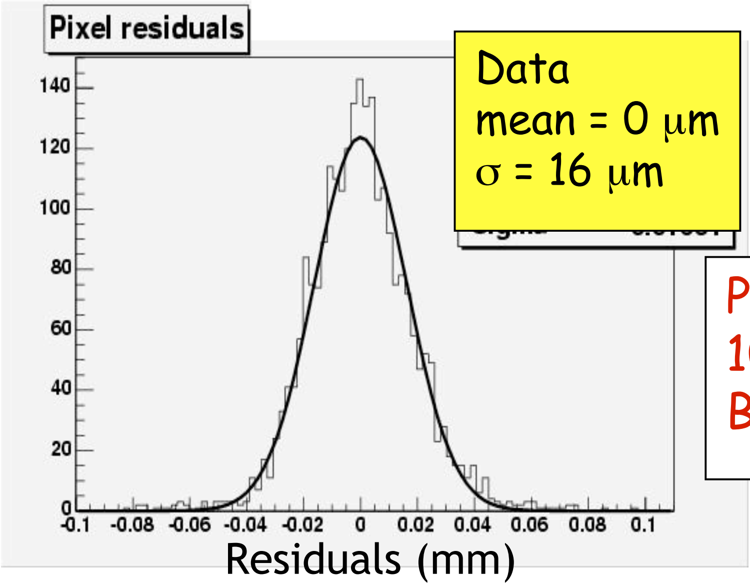




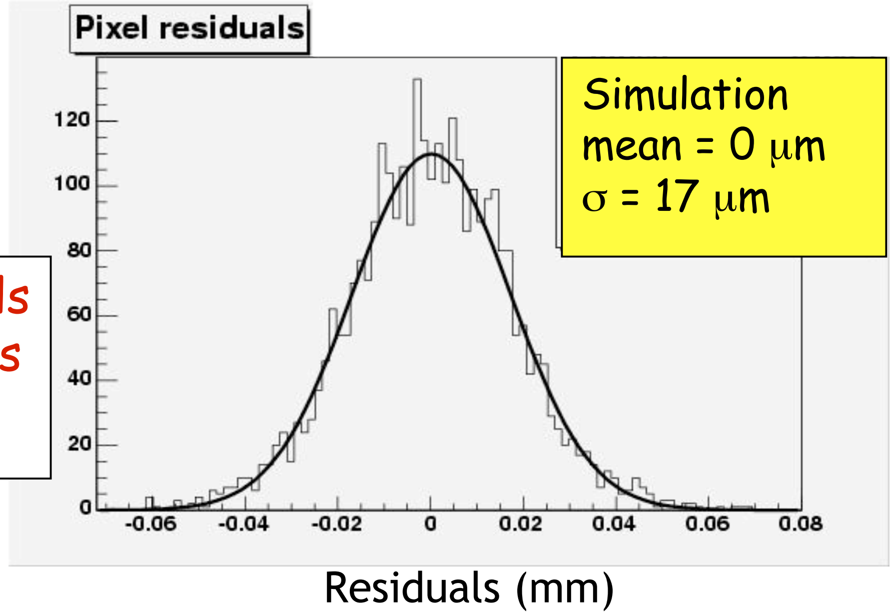
6 pixel modules and 8 SCT modules (inside B=0→1.4 T)
6TRT modules (outside field)

Pixel alignment and position resolution

ATLAS preliminary



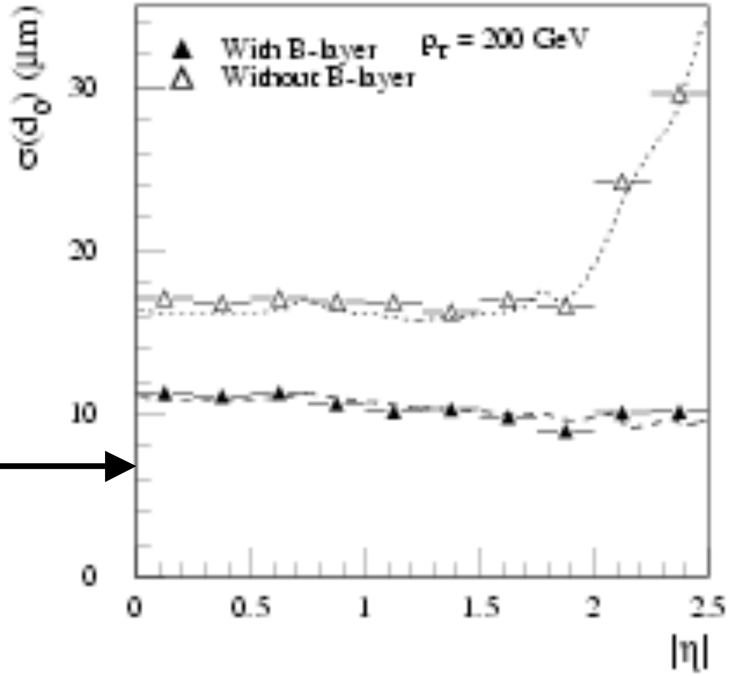
Pixel residuals
100 GeV pions
B = 0



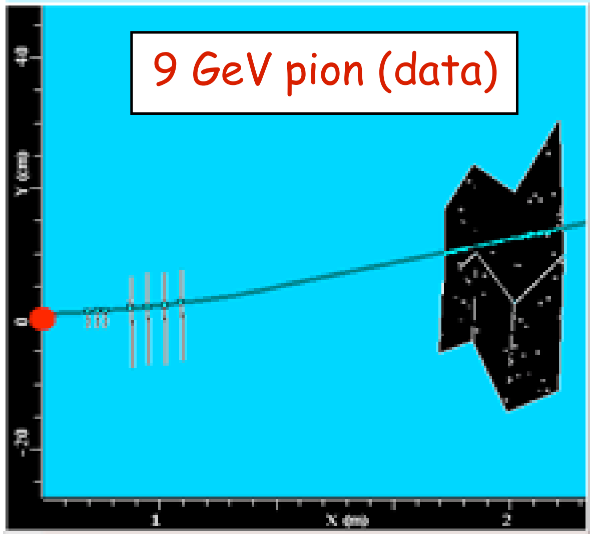
♣ Alignment stability (B=0): within 10 μm over ~ 4 days
(ATLAS goal after few months at LHC: ~ 10-20 μm;
ultimate: 1 μm)

♣ Data with B=1.4 T require more work

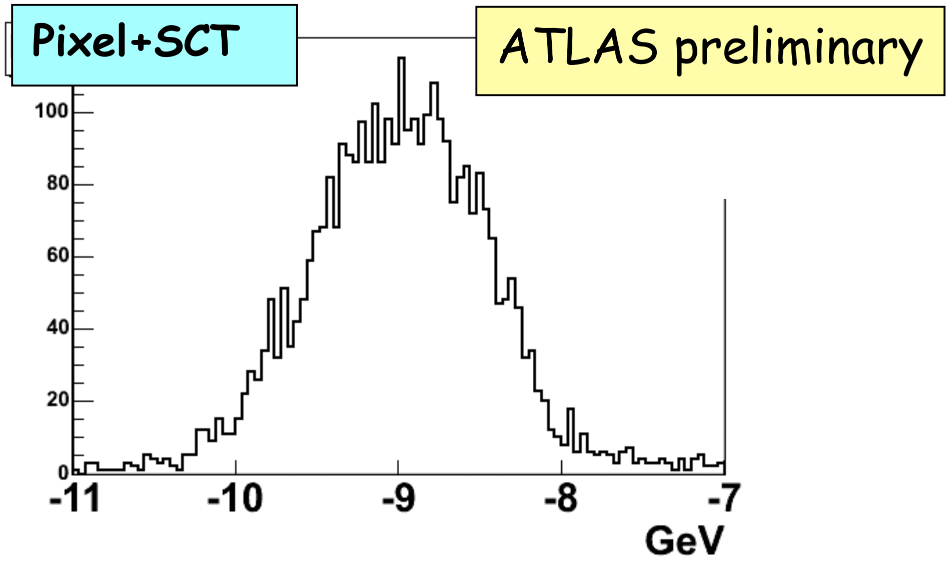
transverse impact parameter resolution from simulation of complete detector

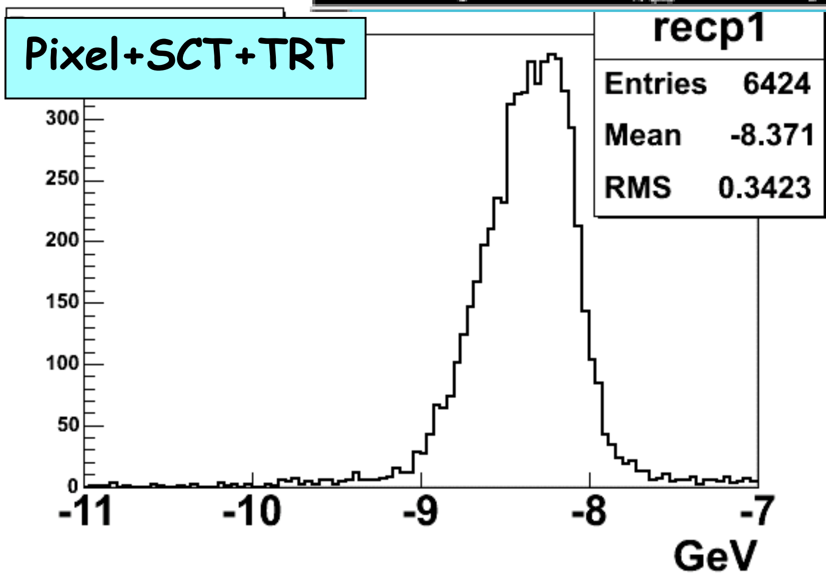


Momentum reconstruction: Pixels + SCT + TRT



9 GeV pion data, B=1.4 T



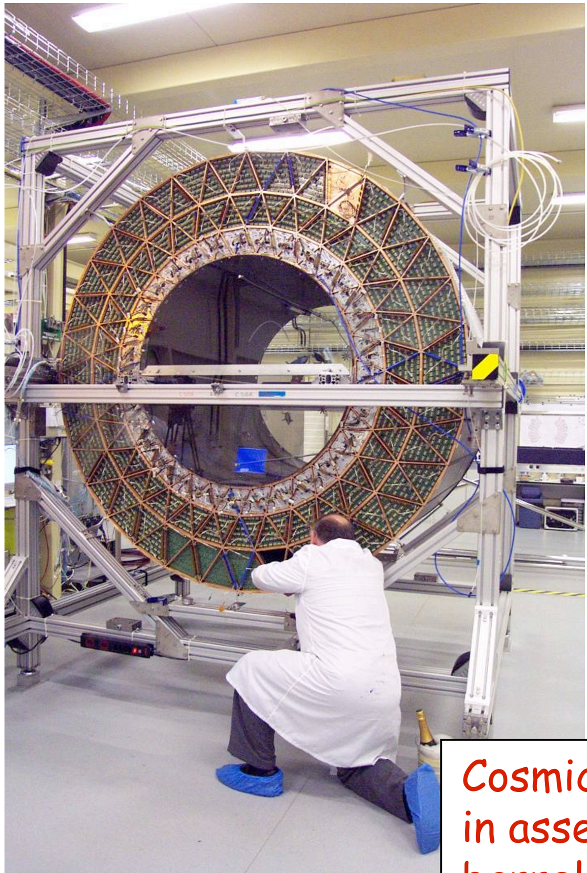


Including TRT improves resolution by ~ 2 as expected, but:

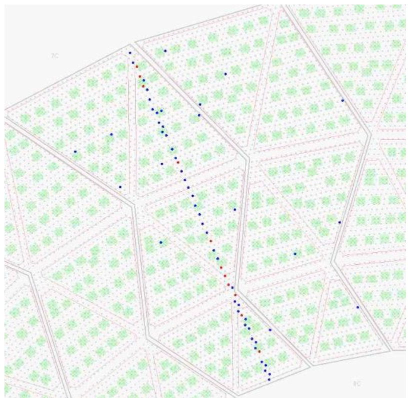
- ♣ mean value shifted by 0.5 GeV
- ♣ momentum resolution (4%) is ~ 2 worse than expected

} alignment, knowledge of B-field and material ?

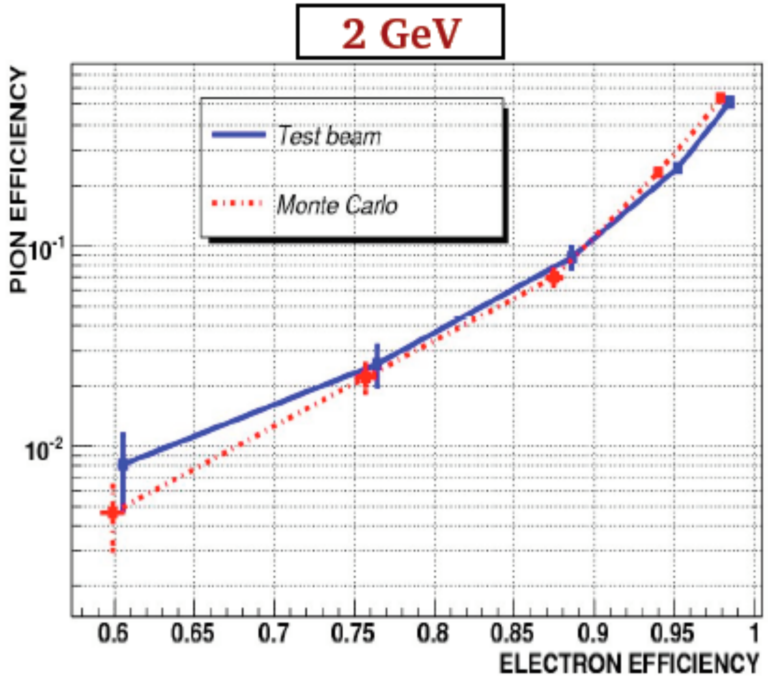
e/π separation with TRT



Cosmics muon in assembled barrel TRT

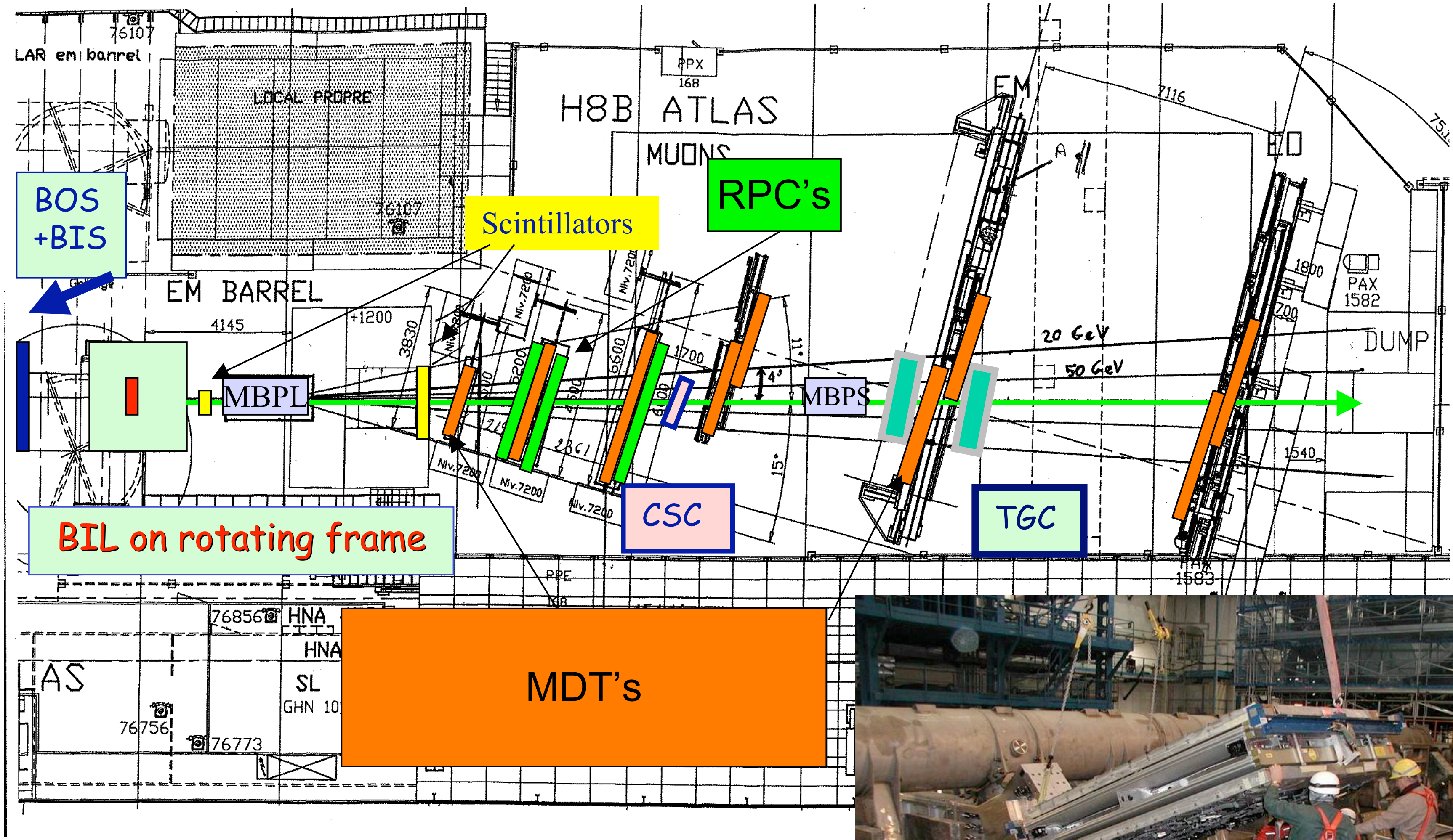


ATLAS preliminary



e/jet (LHC) $\approx 10^{-5}$ (compared to $\approx 10^{-3}$ at Tevatron) at p_T~20 GeV
ATLAS: $R_j \sim 5\times10^4$ after calo+ID cuts; TRT gives additional $R_j > 10$
$\rightarrow$ important handle to extract pure inclusive $e^{\pm}$ sample

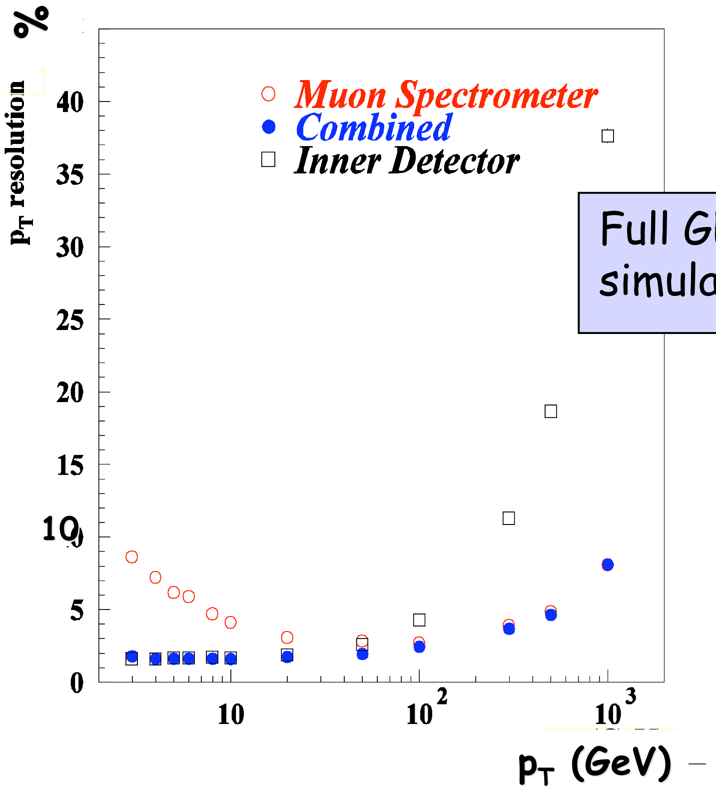
Tracking and momentum resolution in Muon Spectrometer



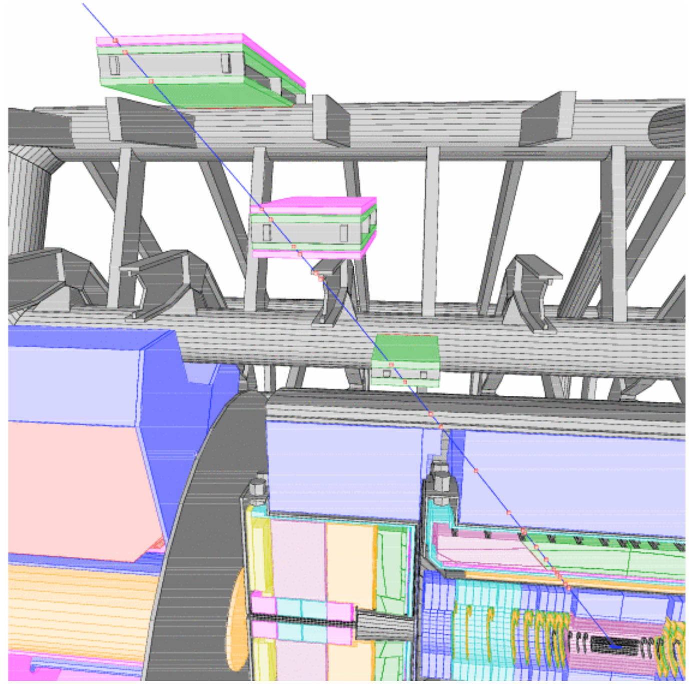
Muon chamber installation in ATLAS pit

Muon momentum resolution in ATLAS

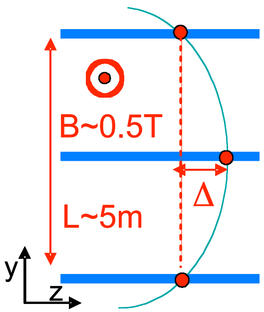
Combining information of Inner Detector and Muon Spectrometer



Full GEANT simulation



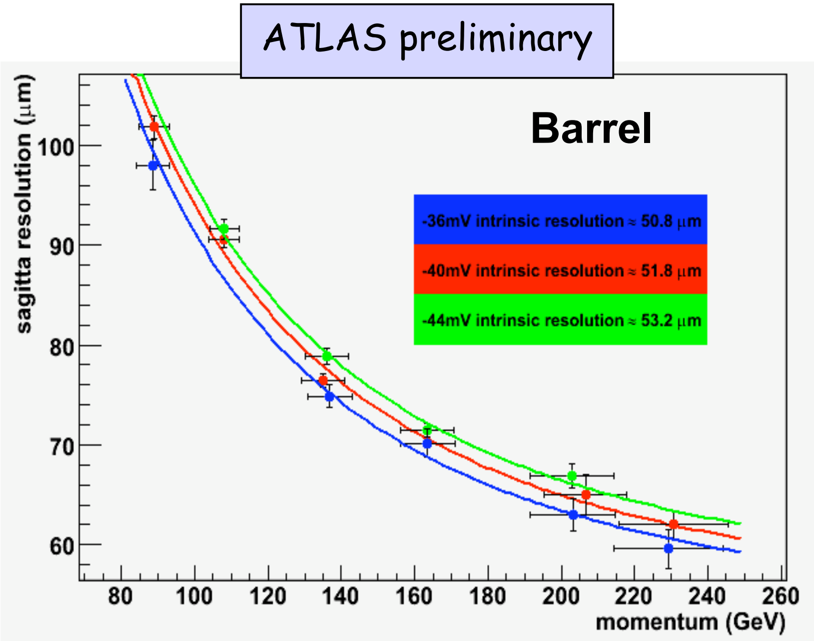
σ/p < 10% for E_μ ~ TeV needed to observe a possible new resonance $X \rightarrow \mu\mu$ as "narrow" peak



ATLAS Muon Spectrometer:
E_μ ~ 1 TeV $\Rightarrow$ Δ~500 μm

– σ/p ~10% $\Rightarrow$ δΔ~50 μm
- alignment accuracy to ~20 μm

Sagitta resolution vs momentum at combined test-beam



Data fitted with:

$$\sigma_{meas} = \sqrt{K_1^2 + (K_2 / P_{meas})^2}$$

K_1 intrinsic resolution term; K_2 multiple scattering

P_{meas} from beam magnet

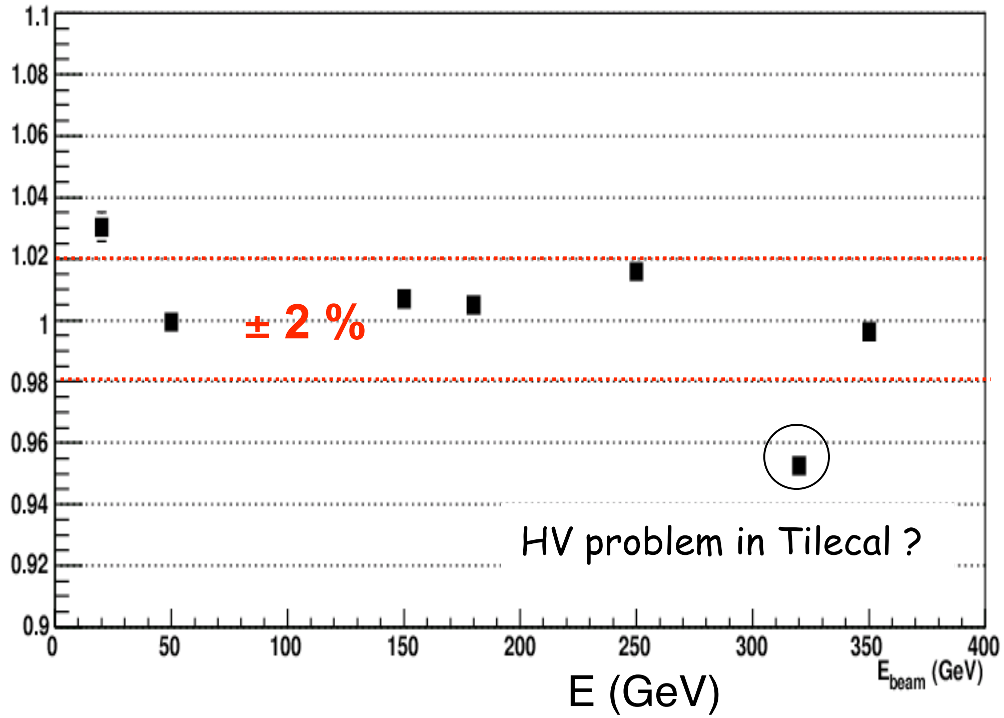
From the fit (36 mV)

Data	Simulation
K_1 = 51±3 μm	K_1 = 40±3 μm
x/X_0~ 0.27±0.04	x/X0~0.32 ±0.03

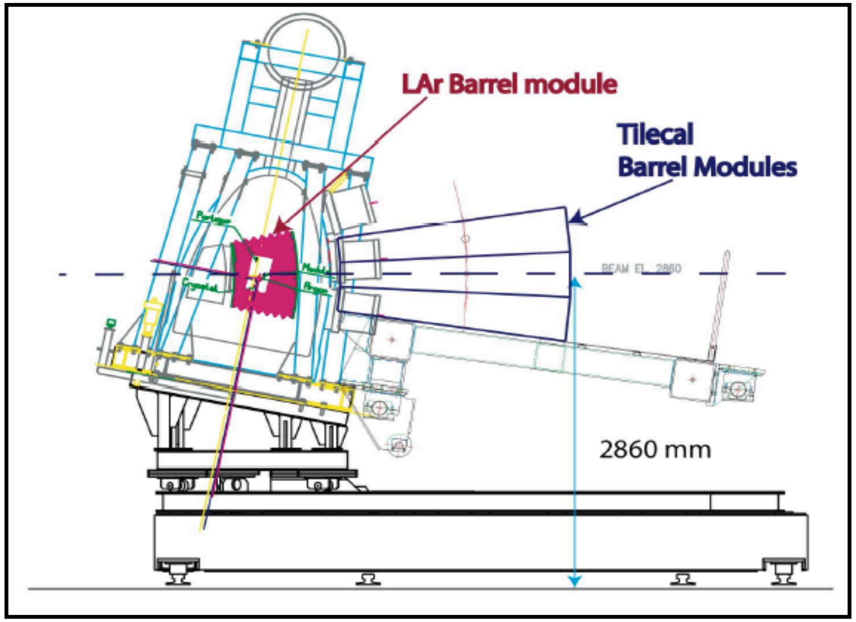
- 50 μm accuracy achieved at high μ momentum
- relative alignment demonstrated to < 20 μm with optical sensors, alignment with straight tracks to < 10 μm
- detector material understood to 15% (from comparison simulation-data)

Combined calorimetry:
data/simulation comparison for pion response in LAR EM + Tilecal

Ratio Data/MC for reconstructed pion energy



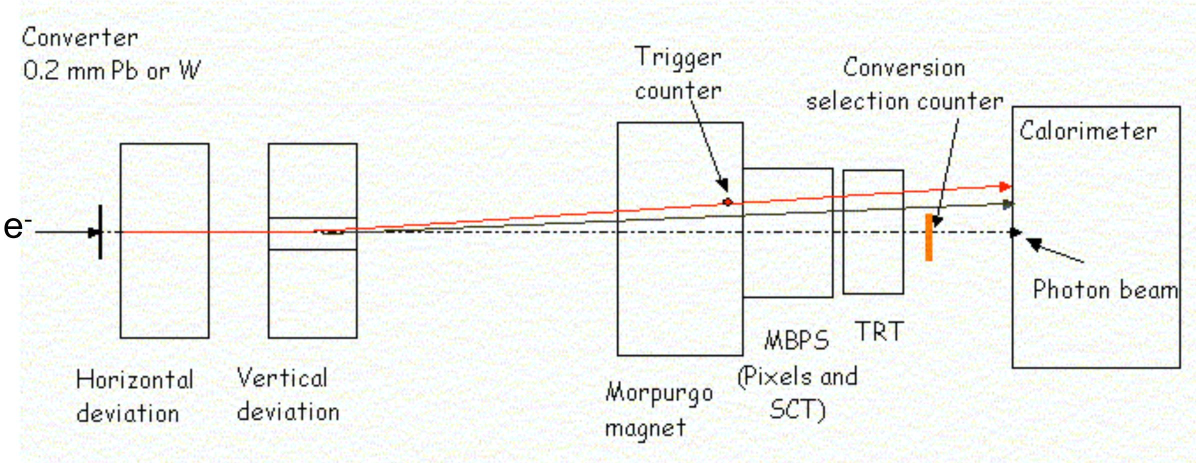
ATLAS preliminary



To understand calorimeter performance for jets at LHC (reconstruction, energy scale, linearity, tails), information from data and Monte Carlo is needed
→ verification and improvement of G4 simulation with test-beam data (single $\pi^{\pm}$) is first step toward extrapolation to ATLAS

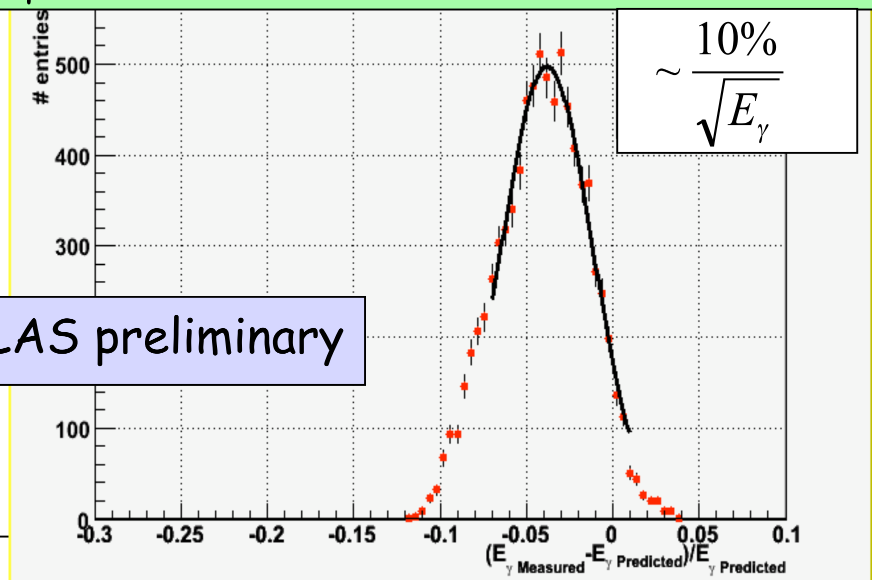
Photon studies

⇒ **reconstruction of conversions in ID**
γ/π^0 separation in ECAL
validation of simulation



- Primary e- bent away from beam line in both directions
- Trigger counter selects e^- angle hence γ energy
  (bulk of γ's have E ~ 60 GeV)
- Conversion $e^{\pm}$ in Pixels, SCT separated by MBPS magnet

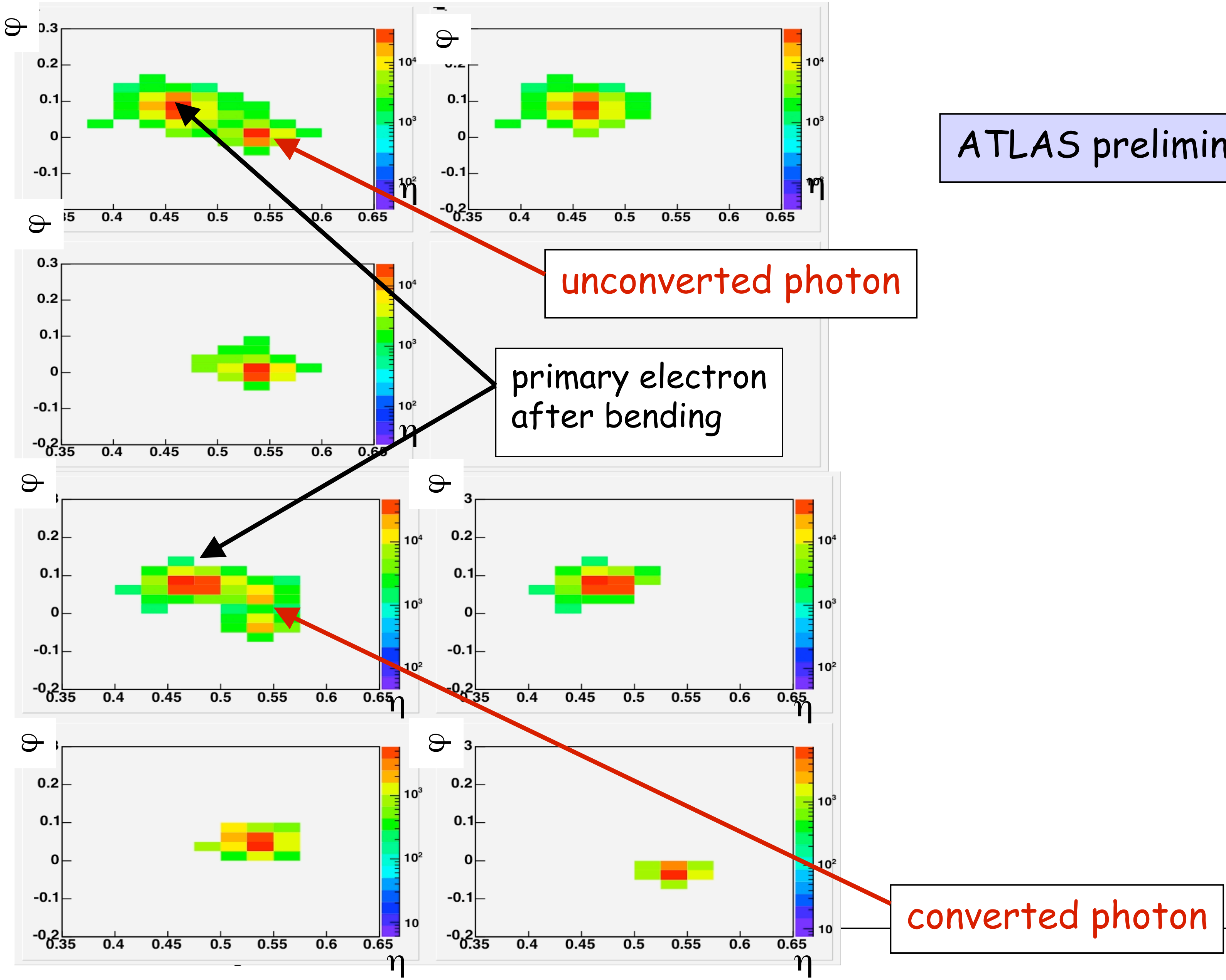
E_γ in ECAL: (measured-predicted)/predicted



$$\sim \frac{10\%}{\sqrt{E_\gamma}}$$

ATLAS preliminary

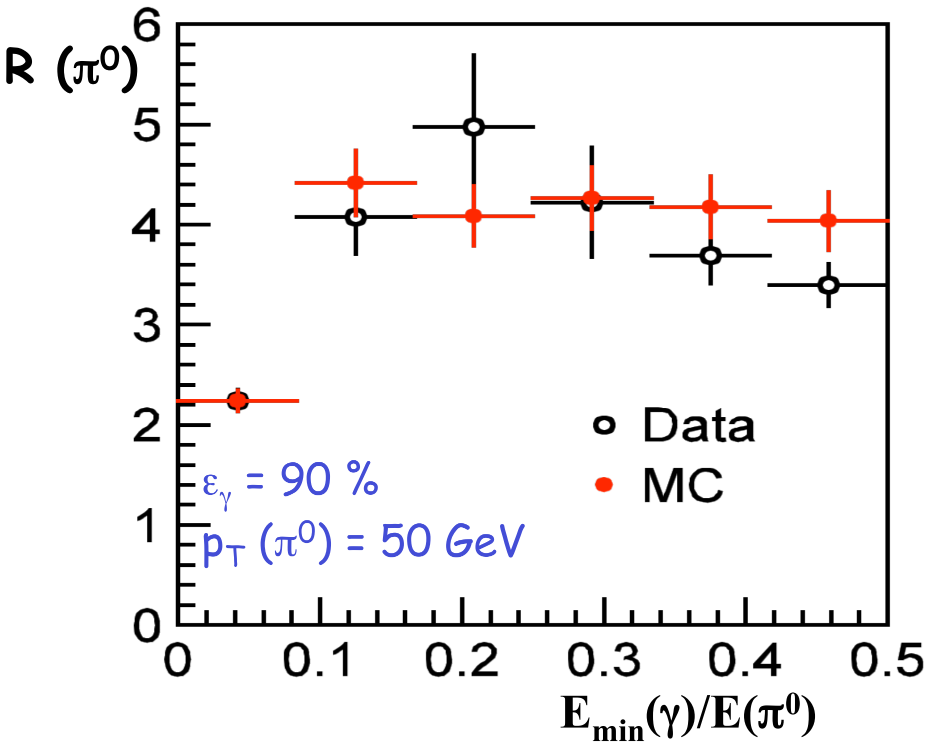
Reconstruction of electron and (un)converted photon in EM calorimeter



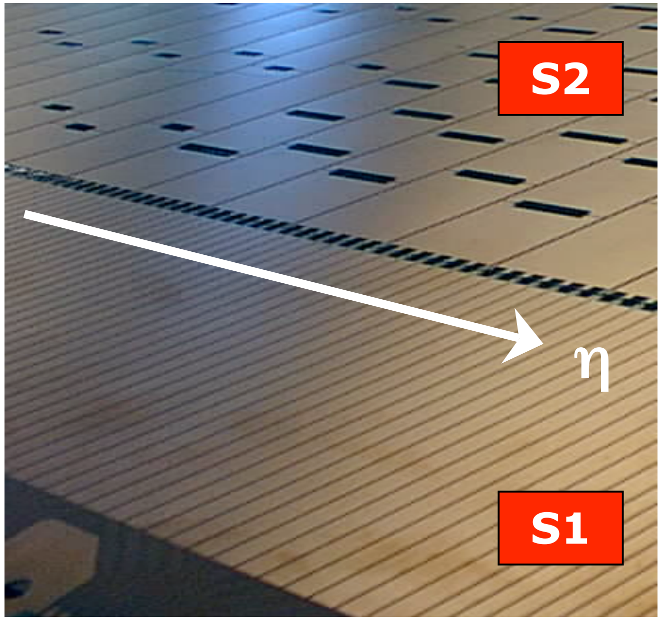
ATLAS preliminary

LHC: $R(\pi^0) \geq 3$ for $\varepsilon(\gamma) \sim 90\%$ needed to reject $\gamma j + jj$ background to $H \rightarrow \gamma\gamma$

From a previous test-beam (1999-2000) with standalone LAr "module zero"



Using 4mm η-strips in 1st ECAL compartment

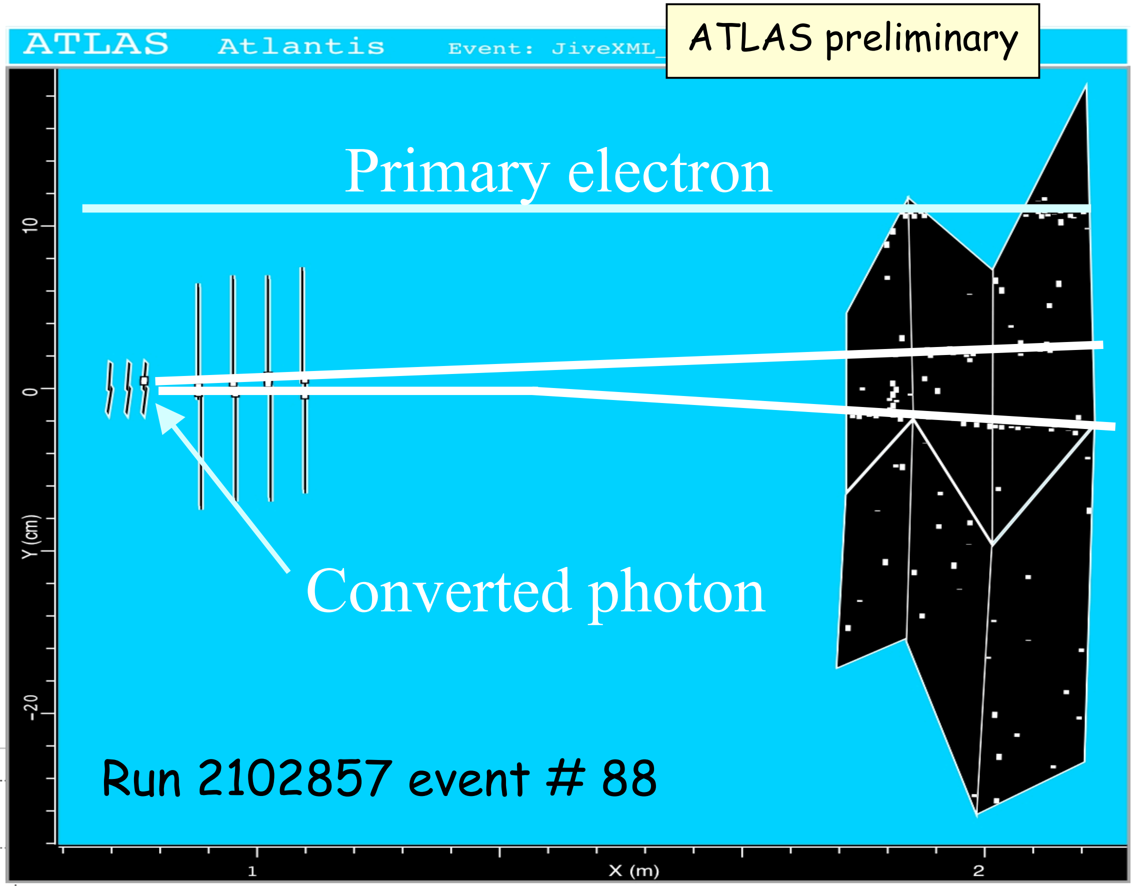


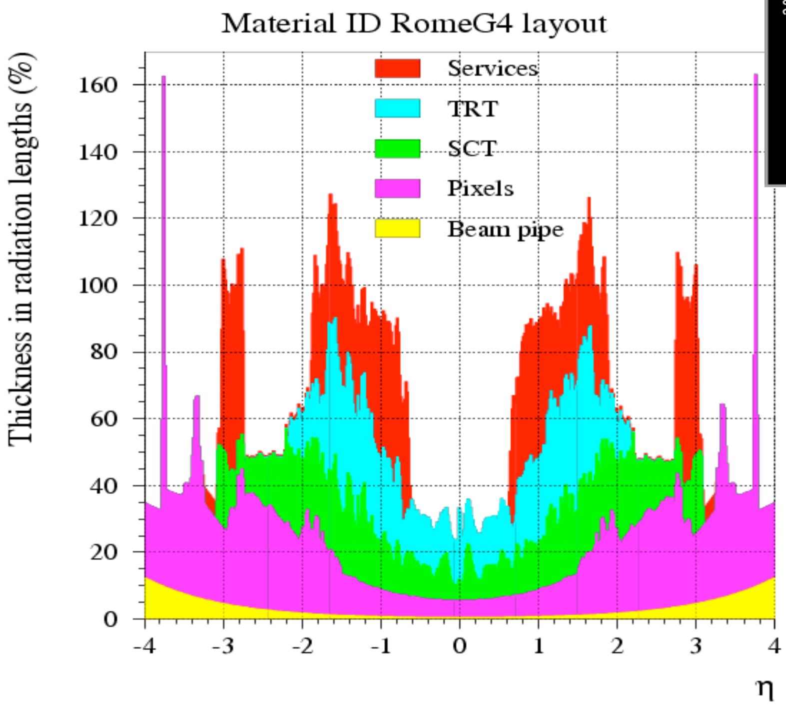
Data:	$\langle R(\pi^0) \rangle = 3.54 \pm 0.12$
MC:	$\langle R(\pi^0) \rangle = 3.66 \pm 0.10$

→ repeat these studies in ATLAS-like environment of combined test-beam (upstream detectors, B-field, ..)

Studies of converted photons

In ATLAS:
γ-conversion probability is > 30% → important to develop (and validate !) efficient reconstruction tools





Work in progress to reconstruct $\gamma \rightarrow e^{+}e^{-}$ in ID

Some conclusions on Combined Test-Beam

- ♣ Preliminary results indicate that the detector performance (individual sub-detectors and combined) in complete ATLAS-like environment is close to expectation

- ♣ Many technical and performance aspects related to data quality and validation (noisy channels, electronics stability with time, etc.) and to alignment and calibration procedures exercised and consolidated

- ♣ G4-based simulation and (combined) reconstruction validated and improved in a realistic environment, with a variety of particles and detector configurations

- ♣ Should be able to understand several detector-related systematic effects
  → disentangle from physics-related effects when LHC operation will start

- ♣ ATLAS has worked as a coherent experiment, using common infrastructure and tools from on-line data taking up to extraction of "physics results"

- ♣ Still a lot of work ahead of us to exploit fully the huge amount of data !

↓

this experience will save a lot of time at LHC/ATLAS start-up

First collisions and early physics

Goal # 1

Understand and calibrate detector and trigger in situ
using well-known physics samples

e.g. - $Z \rightarrow ee, \mu\mu$ tracker, ECAL, Muon chambers calibration/alignment, …
- $tt \rightarrow bl\nu\, bjj$ jet scale from W◊jj, b-tag performance, etc.

Understand basic SM physics at $\sqrt{s}$ = 14 TeV ◊ first tuning of Monte Carlo

Main candles: W, Z, tt, minimum bias, QCD jets
e.g. - measure cross-sections (initially to ~ 20 %),
look at basic event features, first constraints of PDFs, etc.
- measure top mass (to ~ 7 GeV) ◊ give feedback on detector performance
Note : statistical error negligible after few weeks run

will take a lot of time

Goal # 2

Prepare the road to discovery:
measure backgrounds to New Physics : e.g. tt and W/Z+ jets (omnipresent …)

Goal # 3

Look for New Physics potentially accessible in first year(s)
(e.g. $Z' \rightarrow ee$, SUSY, some Higgs ? …)

Expected performance/knowledge of ATLAS detector at the beginning ?

Examples based on experience with test-beams and on simulation studies

	Day 1	After few months	Needed physics samples (examples)
ECAL uniformity e/γ scale	~ 1% ~2 %	~ 0.7 % ~ 0.1% ?	Minimum-bias, $Z \to ee$ ~ 10^5 $Z \to ee$
HCAL uniformity Jet scale	3 % < 10%	~1% <5%	Single pions, QCD jets $Z (\to ll)$ +1j, $W \to jj$ in $t\bar{t}$ events
Tracking alignment (in $R\phi$ Pixels/SCT)	10-200 μm ?	10-20μm	Generic tracks, isolated μ , $Z \to \mu\mu$

(Combined) test-beam, realistic simulations and pre-collision data (cosmics) will help to:

♣ determine detector "operation" parameters: timing, voltages, relative position, initial calibration and alignment, etc.

♣ reach "day 1" performance and understand several systematic effects (material, B-field, ..)

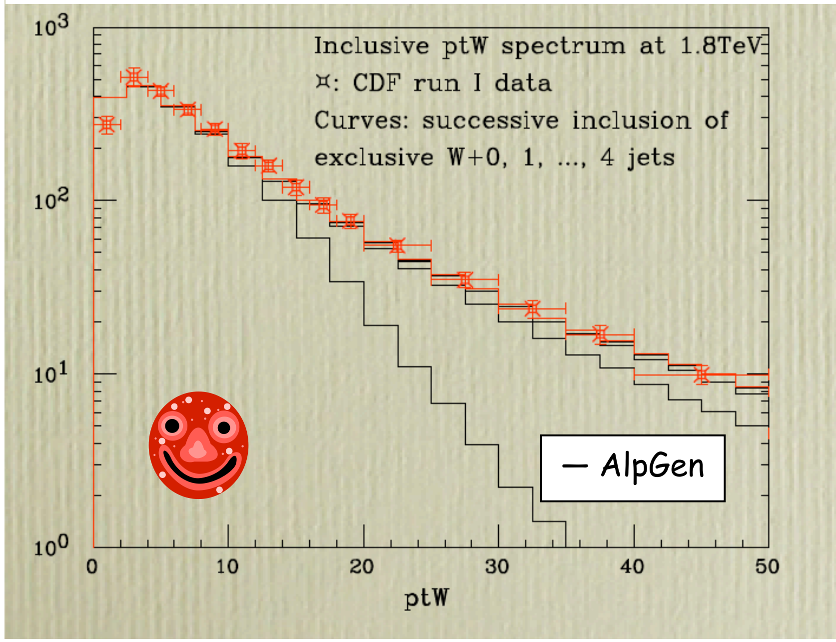
$\Rightarrow$ gain time and experience before commissioning with pp data starts

Knowledge of SM physics at √s = 14 TeV at the beginning ?

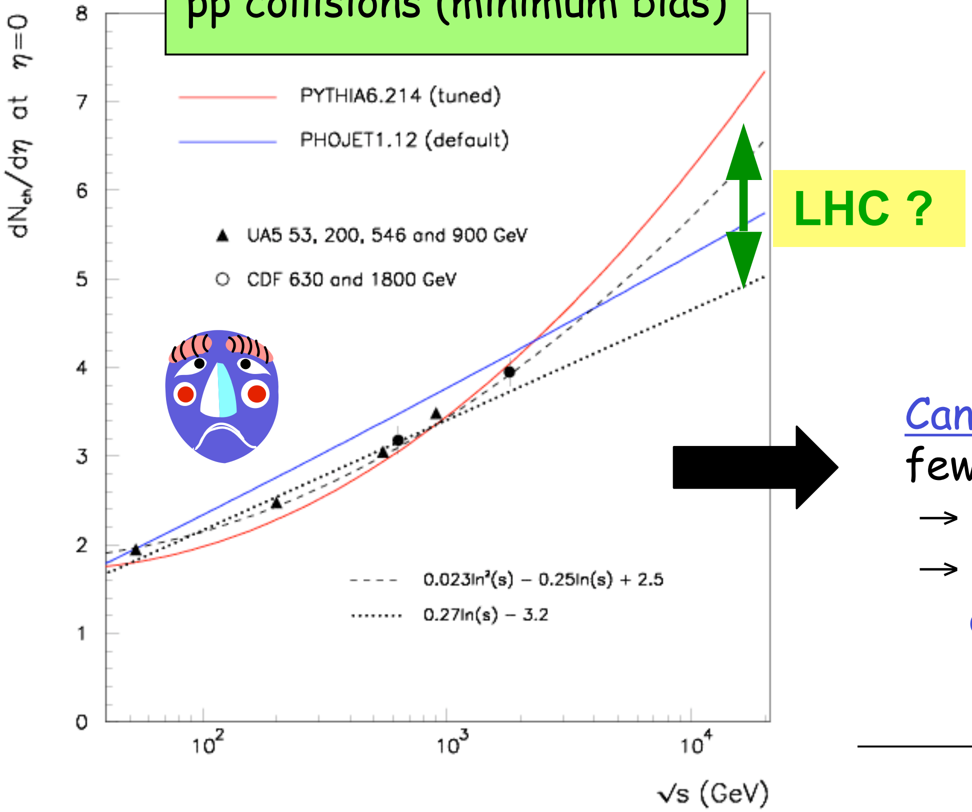
W, Z cross-sections: to 3-4%
(NNLO calculation → dominated by PDF)

tt cross-section to ~7% (NLO+PDF)

Lot of progress with NLO matrix element MC interfaced to parton shower MC (MC@ NLO, AlpGen,..)



$\langle N_{ch}\rangle$ at η =0 for generic pp collisions (minimum bias)



Candidate to very early measurement:
few 10^4 events enough to get $dN_{ch}/d\eta$, dN_{ch}/dp_T
→ tuning of MC models
→ understand basics of pp collisions, occupancy, pile-up, …

LHC start-up scenario

Stage 1 — **2007**

Initial commissioning
43x43 to 156x156, N=3x10^{10}
Zero to partial squeeze

L=3x10^{28} - 2x10^{31}

Stage 2 — **2007 ?/2008**

75 ns operation
936x936, N=3-4x10^{10}
partial squeeze

L=10^{32} - 4x10^{32}

Stage 3 — **2008-2009**

25 ns operation
2808x2808, N=3-5x10^{10}
partial to near full squeeze

L=7x10^{32} - 2x10^{33}

Stage 4 — **2010**

25 ns operation
Push to nominal per bunch
partial to full squeeze

L=10^{34}

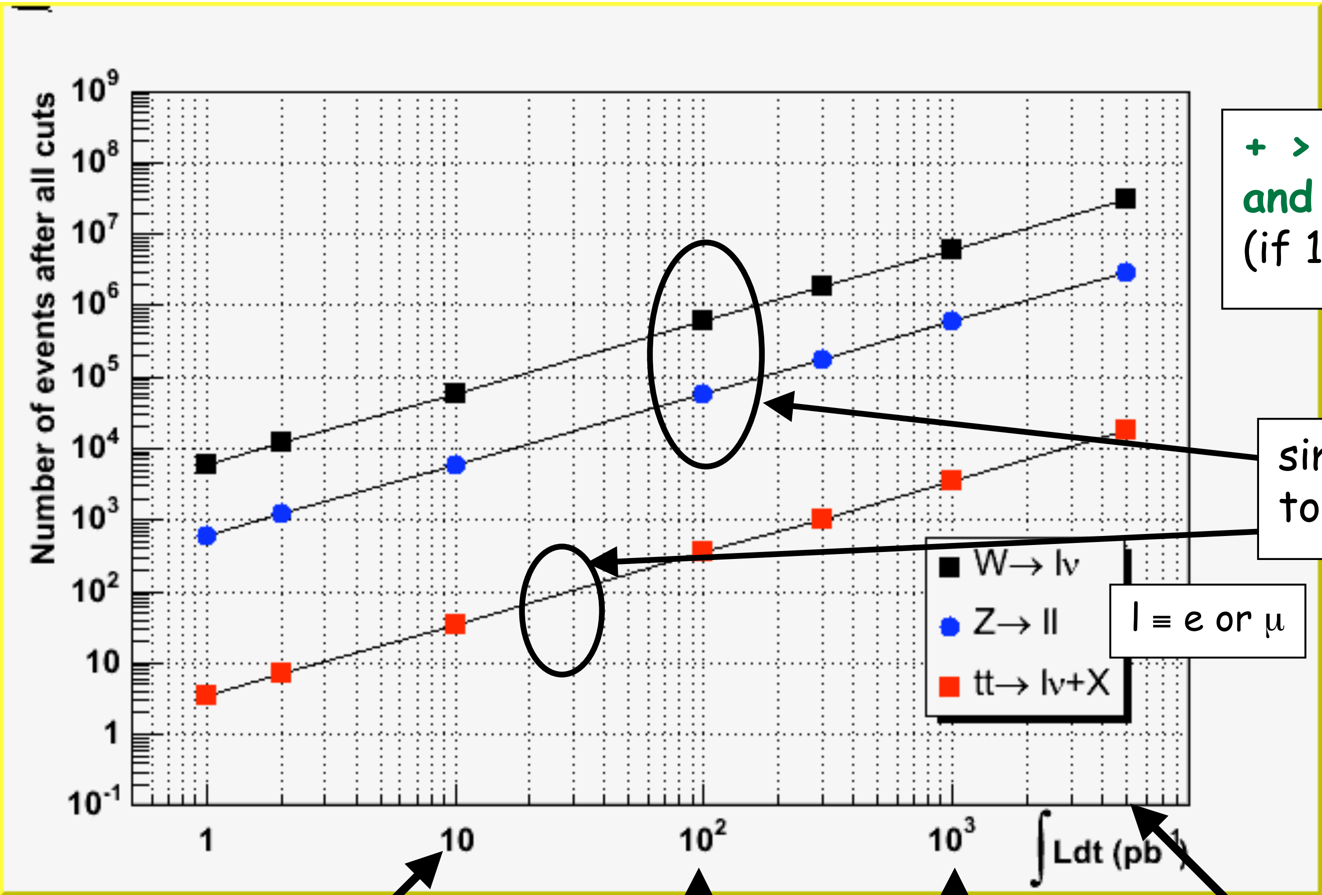
Conservative projections of the Operation Team

" Difficult to speculate further on what the performance might be in the first year. As always, CERN accelerators departments will do their best !"

Lyn Evans, LHC Project Leader

Phase	Months
Hardware commissionin	April, May, June
Machine checkout	July
Beam commissioning	August, September, October
Pilot proton run	November
Shutdown	December, January, February
Machine checkout	March
75ns commissioning	April
First ION run	May
75ns run	June, July
Low intensity 25ns run	August, September, October
Shutdown	November, December, January, February
Machine checkout	March
Startup and scrubbing	April
Half intensity 25ns run	May, June, July, August
Shutdown	September, October, November, December, January, February
Machine checkout	March
Startup and scrubbing	April
Push to nominal 25ns	May, June, July, August, September, October
Shutdown	November, December, January, February
Machine checkout	March
Startup and scrubbing	April
Nominal 25ns	May, June, July, August, September, October
	November, December

How many "candle" events in ATLAS at the beginning ?



l ≡ e or μ

+ > 10^6-10^7 minimum bias and QCD jets p_T > 150 GeV (if 1% of trigger bandwidth)

similar statistics to CDF, D0 today

$10\ pb^{-1} \equiv$ 1 month at 10^{30} + < 2 weeks at 10^{31}, ε=50%

$100\ pb^{-1} \equiv$ few days at 10^{32} , ε=50%

$1\ fb^{-1} \equiv$ 6 months at 10^{32}, ε=50%

$5\ fb^{-1} \equiv$ 3 months at 10^{32} + 3 months at 10^{33}, ε=50%

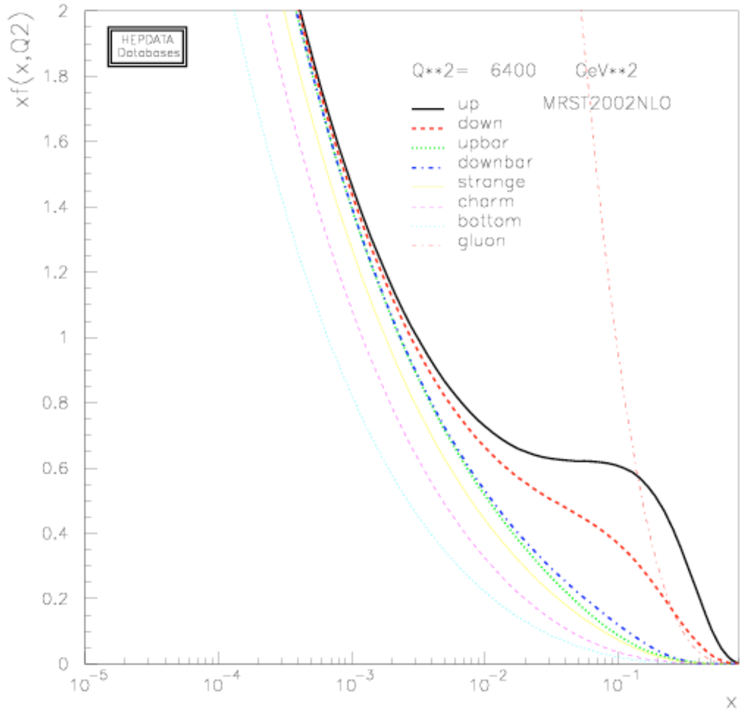
→ end 2007 ?

→ end 2008 ?

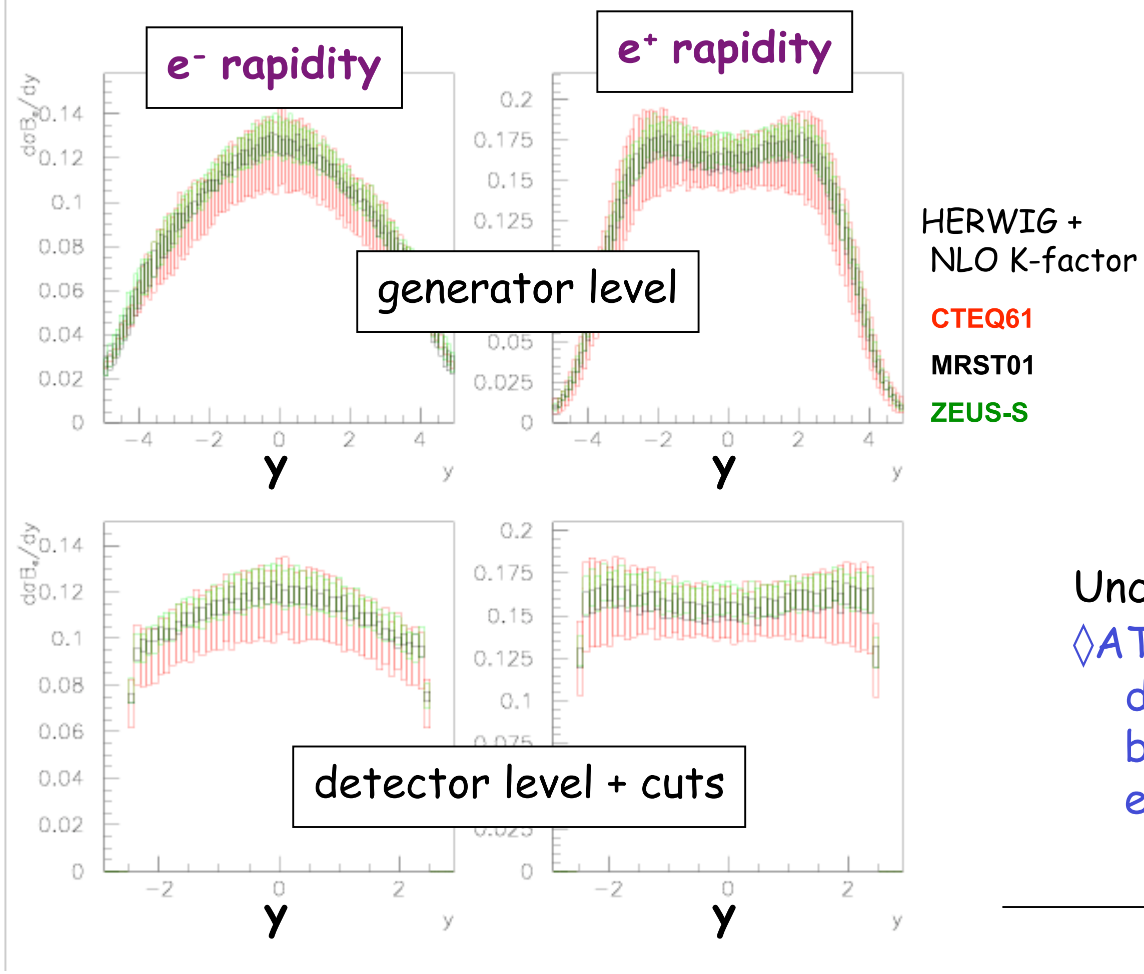
Constraining PDF with early data using $W \rightarrow l\nu$ angular distributions

$$x_{1,2} = \frac{M}{\sqrt{s}} \exp(\pm y)$$ $\Rightarrow$ W production over $|y|<2.5$ at LHC involves $10^{-4} < x_{1,2} < 0.1$

$\Rightarrow$ region dominated by $g \rightarrow qq$



Tricoli et al., ATL-PHYS-CONF-2005-008

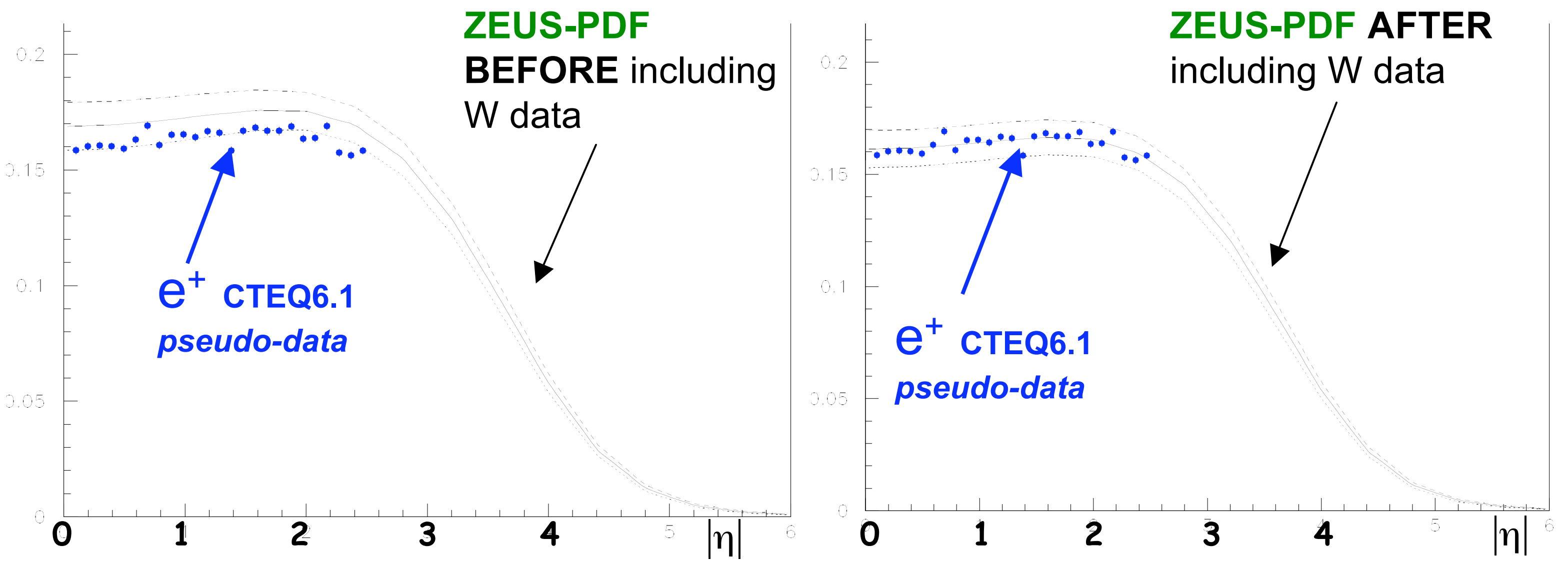


Uncertainties on present PDF: 4-8%

◊ATLAS measurements of $e^{\pm}$ angular distributions provide discrimination between different PDF if experimental precision ~ 3-5%

Effect of including ATLAS data on PDF fits

Sample of 10^6 $W \rightarrow e\nu$ generated with CTEQ6.1 and ATLAS fast simulation
Statistics corresponds to ~ 100 pb^{-1}
4% systematic error included by hand (statistical error negligible)



Tricoli et al.

Central value of ZEUS-PDF prediction shifts and uncertainties is reduced
Error on low-x gluon shape parameter λ ($xg(x) \sim x^{-\lambda}$) reduced by 35%

Systematics (e.g. $e^{\pm}$ acceptance vs η) can be controlled to few percent with $Z \rightarrow ee$
(~ 30000 events for 100 pb^{-1})

Commissioning ATLAS detector and physics with top events

Can we observe an early top signal with limited detector performance ?
Can we use such a signal to understand detector and physics ?

} **YES !** ↕

σ_{tt} (LHC) ≈ 250 pb for gold-plated semi-leptonic channel

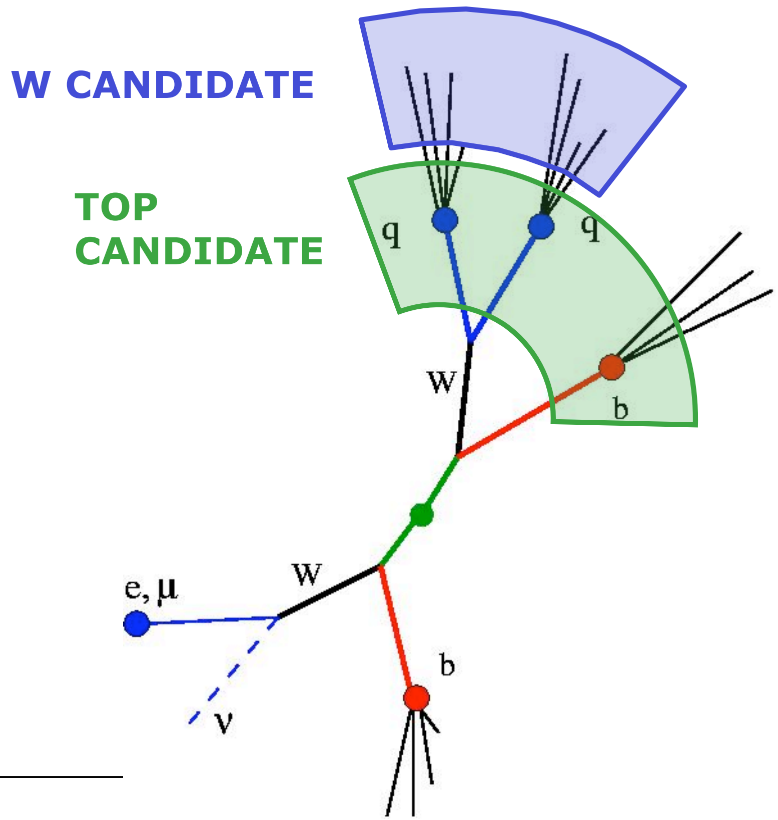
♣ use simple and robust selection cuts:
- p_T (l) > 20 GeV
- E_T^{miss} > 20 GeV
- only 4 jets with p_T > 40 GeV

} $\varepsilon \sim 5\%$

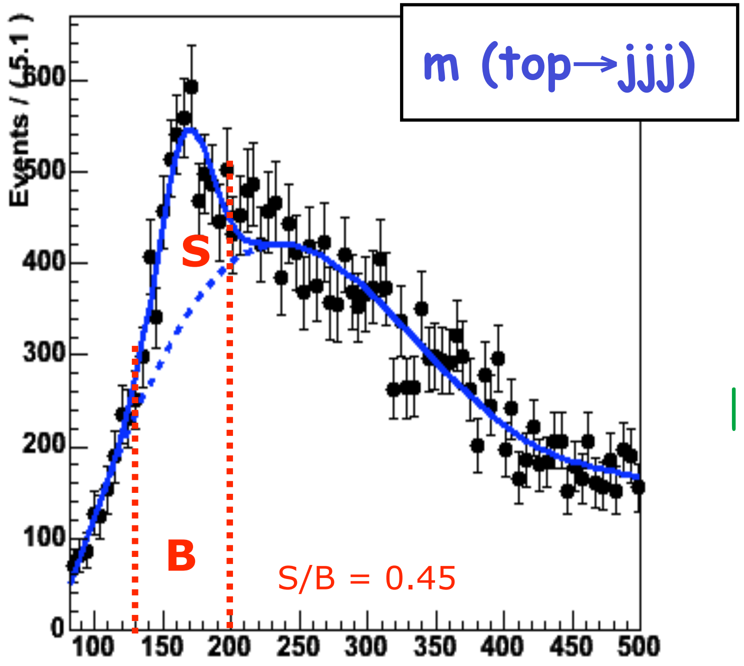
♣ no b-tagging required (early days ...)

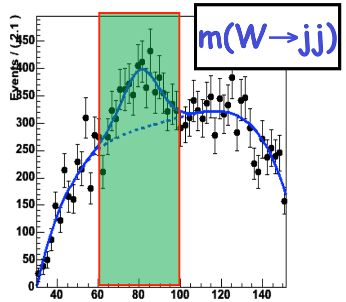
♣ m (top → jjj) from invariant mass of 3 jets giving highest top p_T

♣ m (W→jj) from 2 jets with highest momentum in jjj CM frame

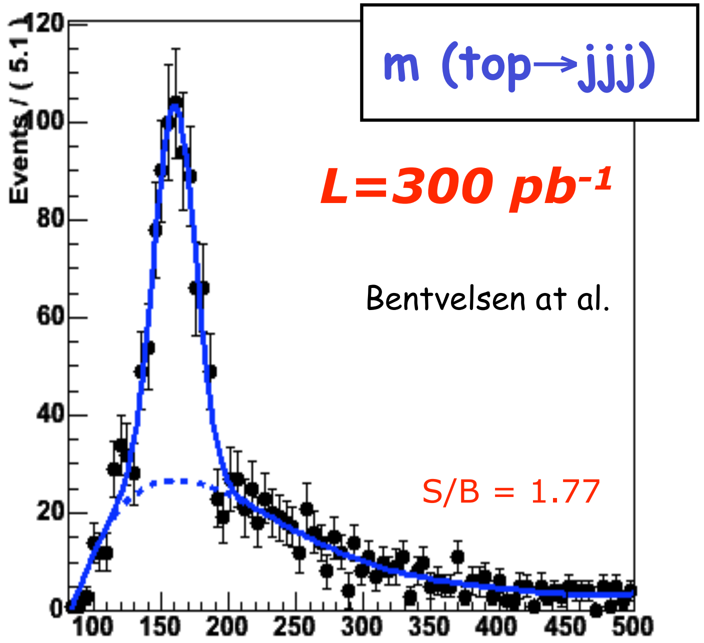


Total efficiency, including m_{jjj} inside m_{top} mass bin : ~ 1.5% (preliminary and conservative ...)





$|m_{jj}-m_W| < 10$ GeV



Background (W+jets, top combinatorics) can be understood with MC+data (Z+jets)

Expect ~ 100 events inside mass peak for 30 pb^{-1}
→ top signal observable in early days with no b-tagging and simple analysis
Cross-section to 20%, m_{top} to 7 GeV (LHC goal ~1 GeV) with 100 pb^{-1} ?

tt is excellent sample to:

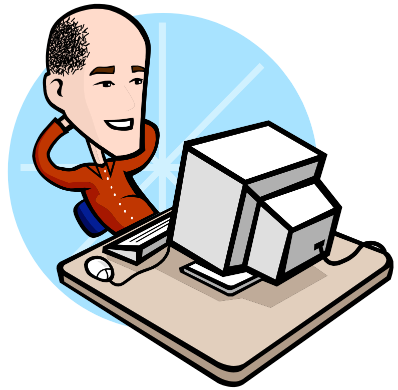
- **commission b-tagging, set jet E-scale using W → jj peak**
- **understand detector performance and reconstruction of several physics objects (e, μ, jets, b-jets, missing E_T, ..)**
- **understand / tune MC generators using e.g. p_T spectra**
- **measure background to many searches**

Discovery physics: 3 examples:

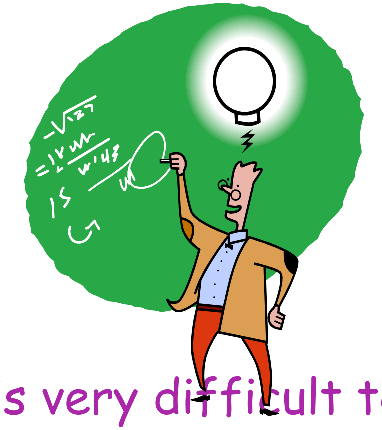
♣ Standard Model Higgs
♣ Supersymmetry
♣ Extra-dimensions

What about early discoveries ?

A new (narrow) resonance of mass ~ 1 TeV decaying into e^+e^-, e.g. a Z′ or a Graviton → e^+e^- might be the easiest new particle to find …

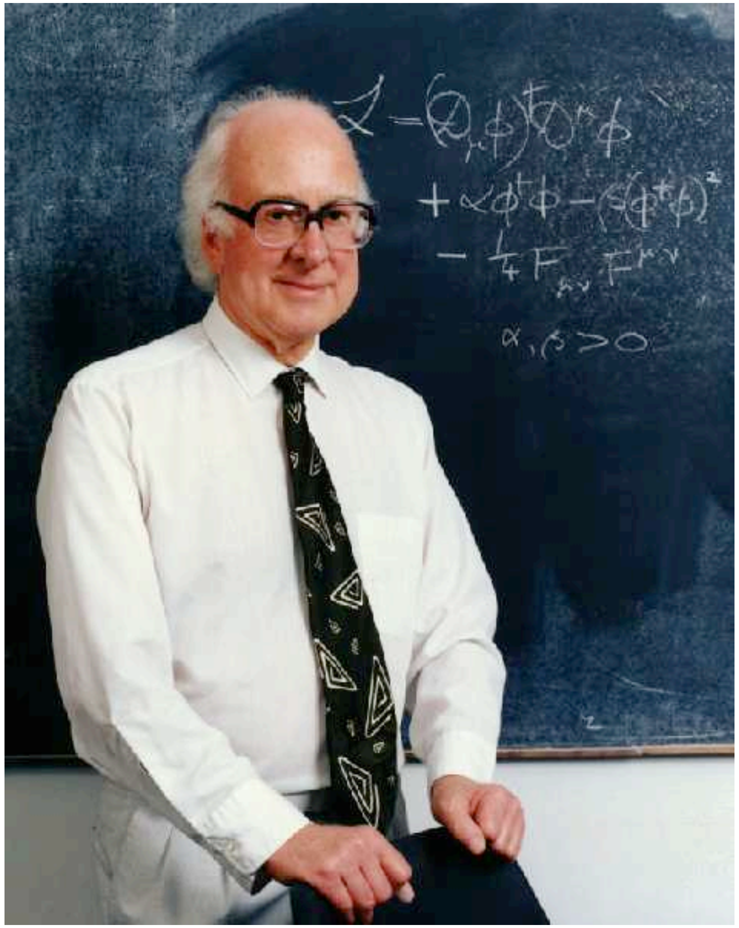


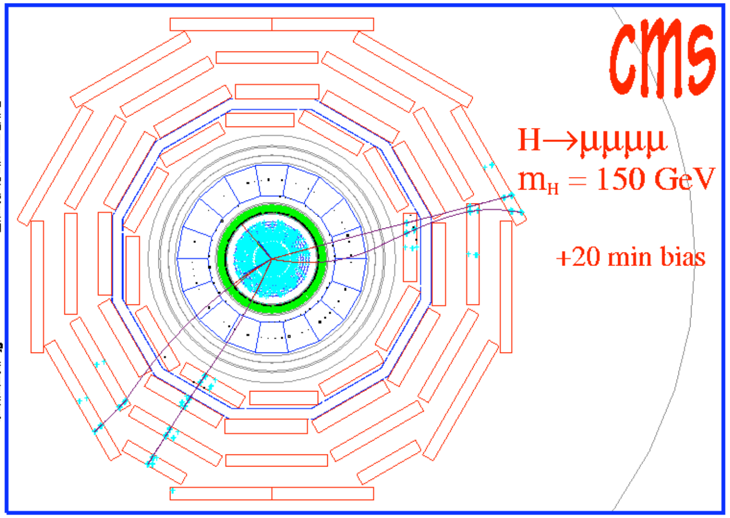
SUSY is more difficult

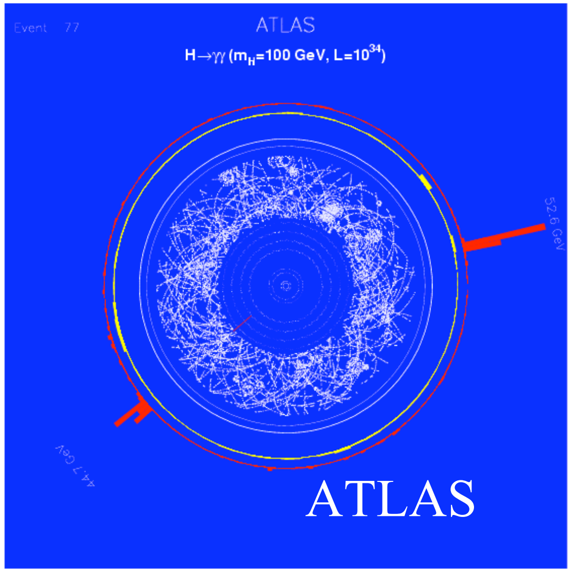


A light Higgs (m_H ~ 115 GeV) is very difficult to find at the beginning

Standard Model Higgs

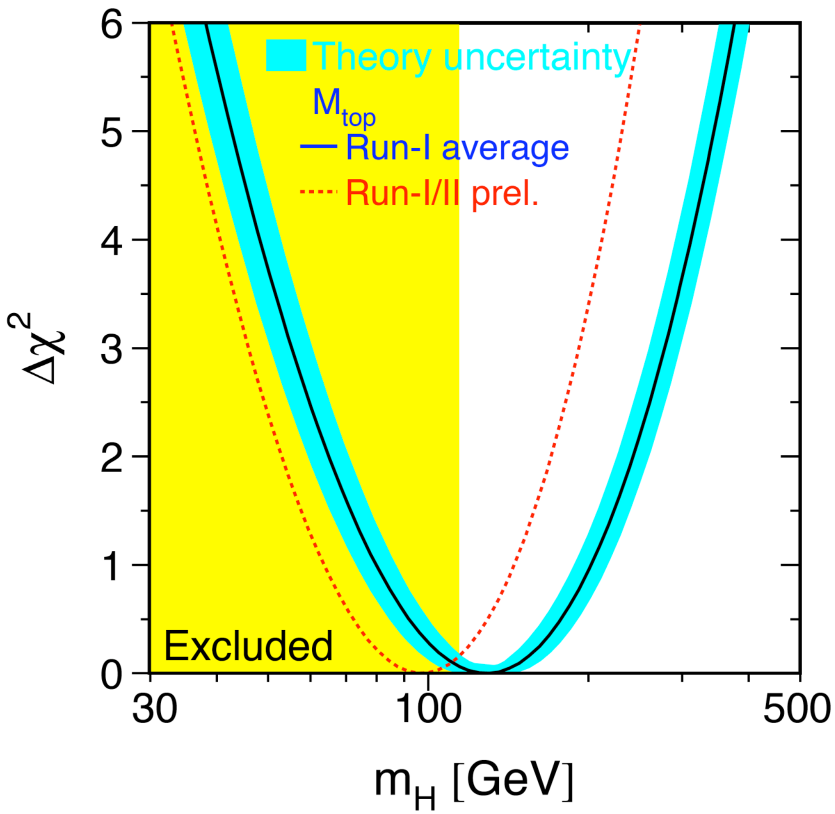


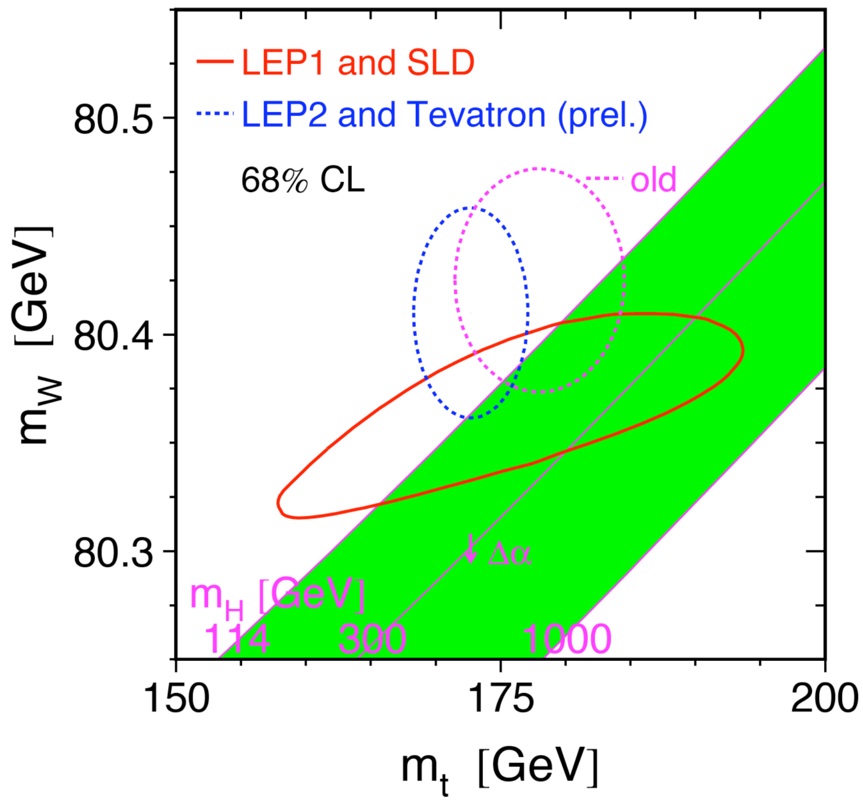




What do we know today ?

m_H > 114.4 GeV (direct searches at LEP)





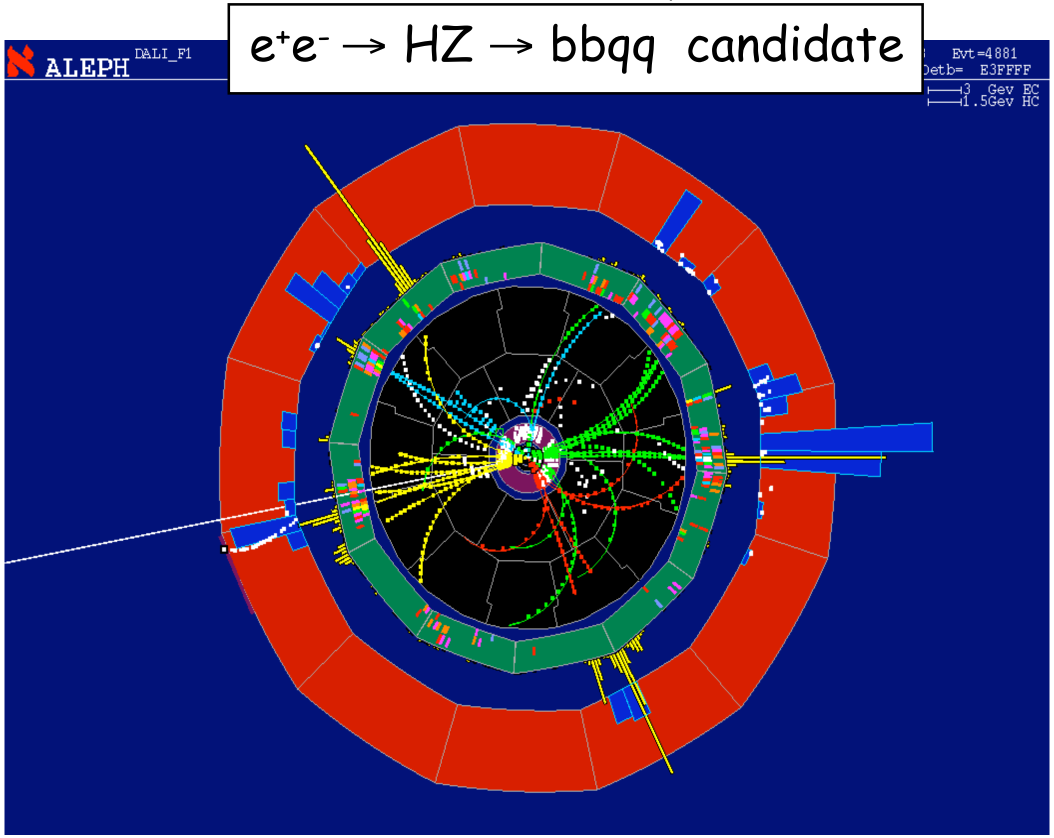
From fit to EW data (LEP, SLD, Tevatron):
m_H < 186 GeV at 95% C.L.

M_{top} = 172.7 ± 2.9 GeV (CDF + D0)
M_W = 80.410 ± 0.032 GeV (world average)

In addition: in 2000 (last year of LEP)

A few Higgs-like events, compatible with m_H ~115 GeV, observed (<2σ "hint")

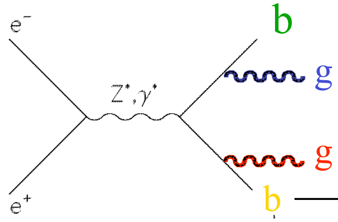
Best candidate : collected by ALEPH on 14/6/2000 at $\sqrt{s}$ = 206.7 GeV



$m(j_1, j_2) = 92.1$ GeV

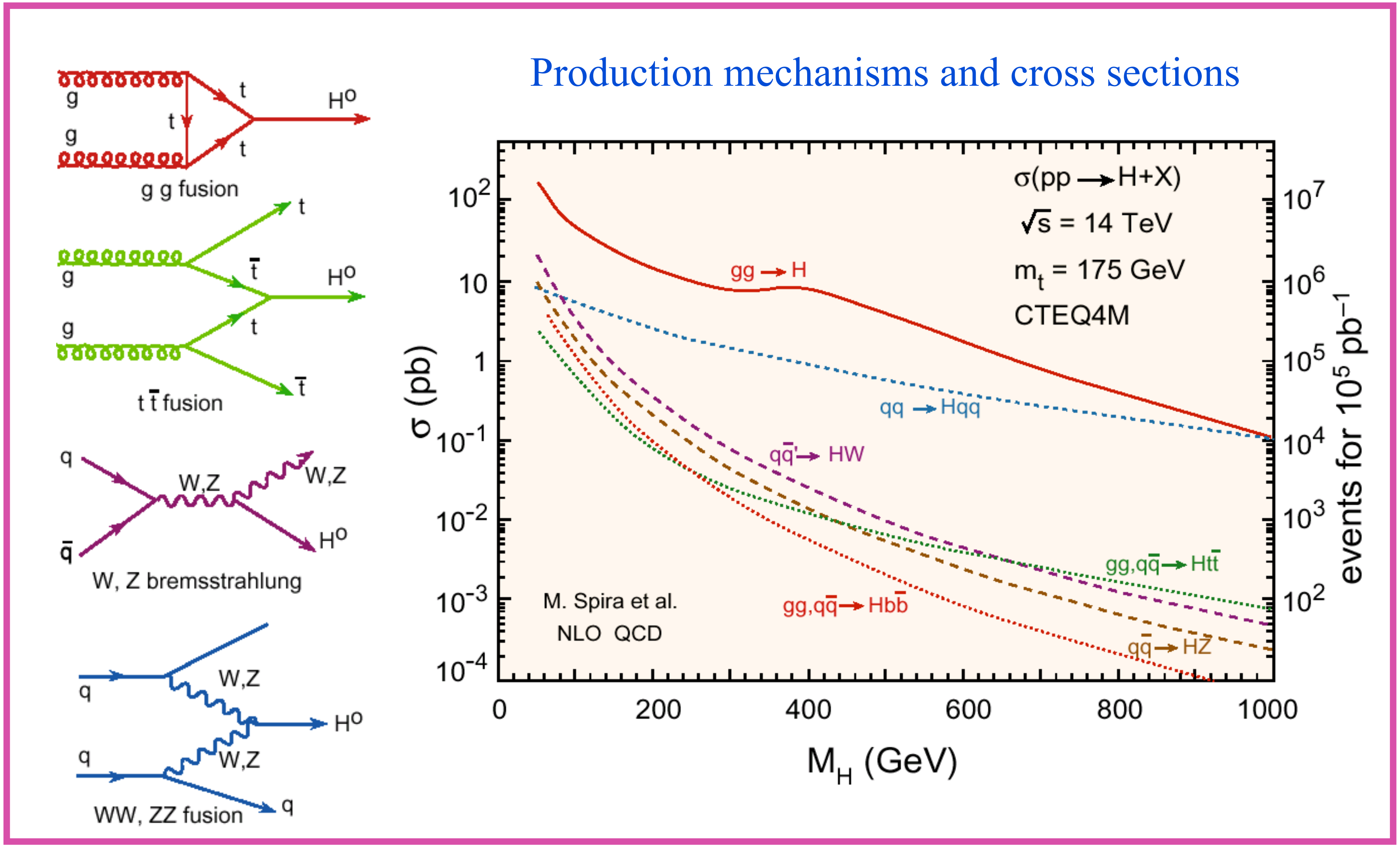
$m_H(j_3 j_4) = 114.3 \pm 3$ GeV

Background interpretation: bbgg

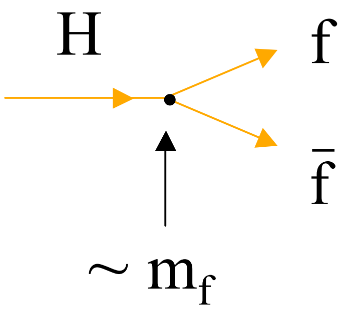


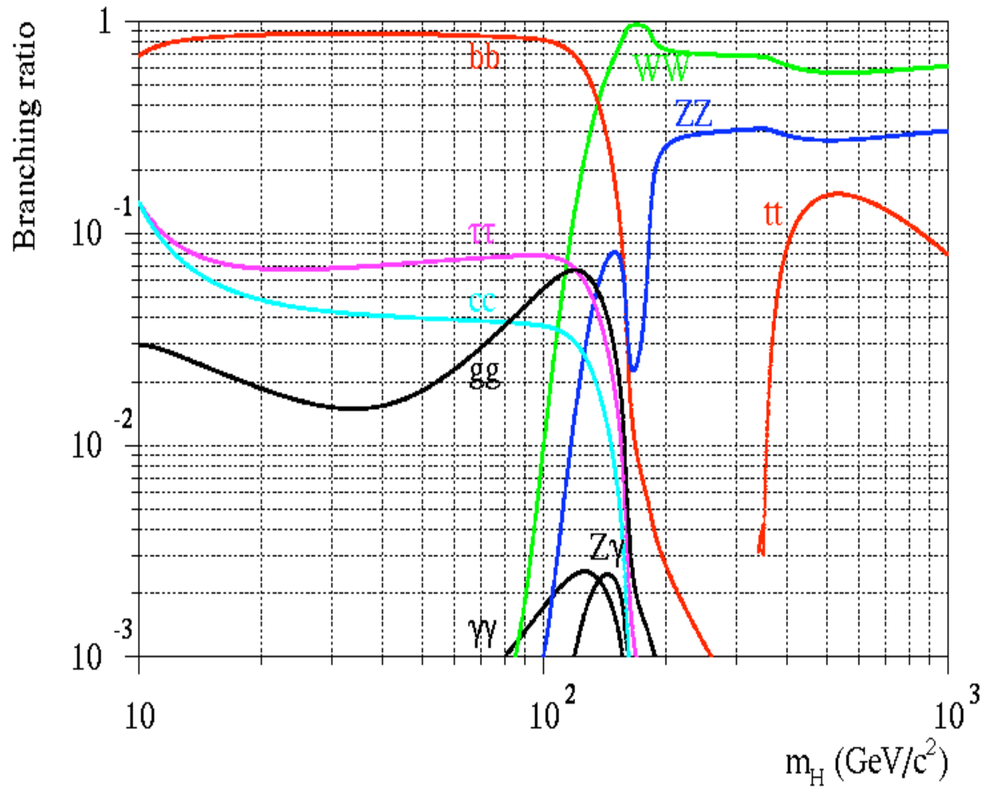
P ~ 1%

Higgs production at LHC



Higgs decays





- m_H < 120 GeV: H → bb dominates
- 130 GeV < m_H < 2 m_Z : H → $WW^{(*)}$, $ZZ^{(*)}$ dominate
- m_H > 2 m_Z : 1/3 H → ZZ
  2/3 H → WW
- important rare decays : H → γγ

N. B.: $\Gamma_H \sim m_H^3 \rightarrow \Gamma_H \sim$ MeV (100 GeV) $\Gamma_H \sim$100 (600) GeV

Main search channels at LHC

Large QCD backgrounds:
e.g. σ (H → bb) ≈ 20 pb direct production, m_H =120 GeV
σ (bb) ≈ 500 μb
→ no hope to trigger / extract fully hadronic final states
→ look for final states with l, γ (l = e,μ)

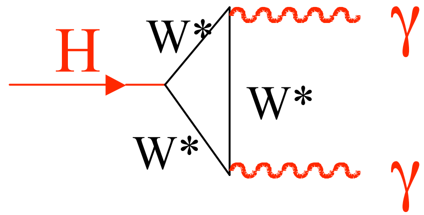
m_H < 130 GeV : [redacted] qqH→ ττ

m_H > 130 GeV : H → ZZ$^{(*)}$ → 4l (gold-plated), H → WW$^{(*)}$ → lν lν
H → ZZ → ll νν
H → ZZ → ll jj
H → WW→ lνjj
} also contribute for m_H > 300 GeV

In the (most motivated) low mass region: S/B <<1, Γ_H << $\Gamma_{detector}$
⇒ Excellent detector performance needed: b-tag, l/γ E-resolution, γ/j separation, E_T^{miss} resolution, forward jet tag, etc. → Higgs searches used as benchmarks for ATLAS and CMS detector design

$H \rightarrow \gamma\gamma$

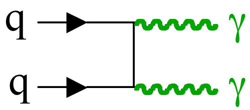
$m_H \lesssim 150$ GeV



- $\sigma \times BR \approx$ 50 fb (BR $\approx 10^{-3}$)

- Backgrounds :

-- $\gamma\gamma$ (irreducible): e.g.

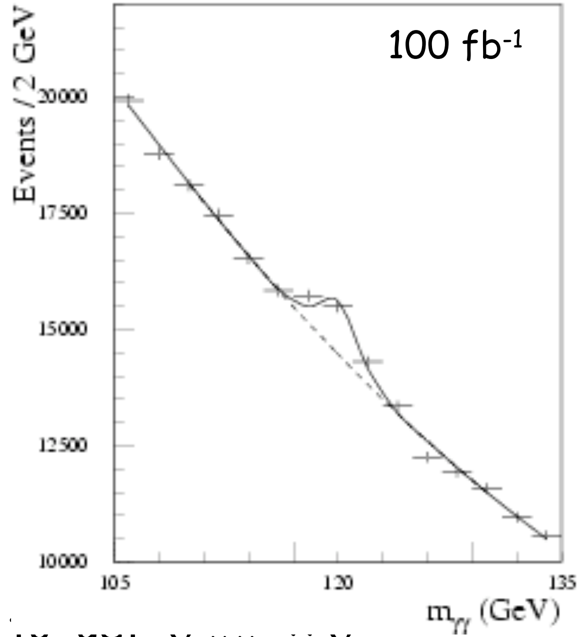


$\sigma_{\gamma\gamma} \approx$ 2 pb / GeV
$\Gamma_H \approx$ MeV
} → need σ (m)/m $\approx$ 1%

-- γj+ jj (reducible):

$\sigma_{\gamma j+jj} \sim 10^6\, \sigma_{\gamma\gamma}$ with large uncertainties

→ need $R_j > 10^3$, including R (π^0) > 3, for $\varepsilon_\gamma \approx$ 80%



→ most demanding channel for EM calorimeter performance:
energy and angle resolution, response uniformity, γ/jet and γ/π^0 separation

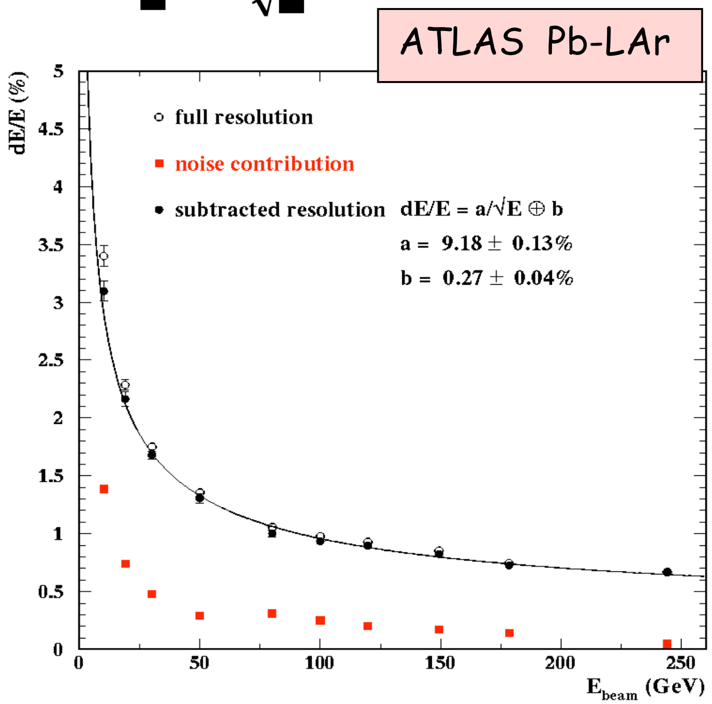
ATLAS and CMS: different technology and design, complementary performance

ATLAS vs CMS ?

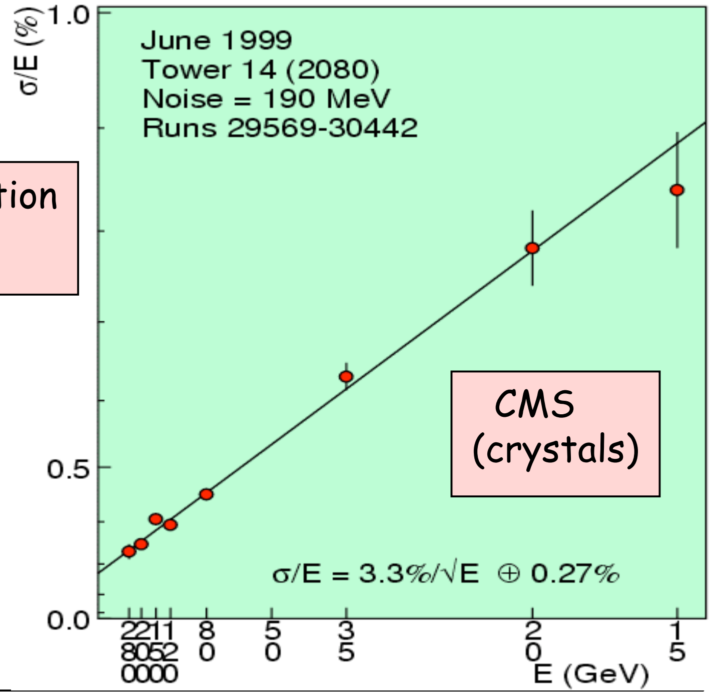
Mass resolution (m_H ~ 100 GeV, high L):

ATLAS : 1.3 GeV (sampling calorimeter)
CMS : 0.7 GeV (homogeneous calorimeter)

$$\frac{S}{\sqrt{B}} \sim \frac{1}{\sqrt{\sigma_m}}$$



electron E-resolution from test beam



ATLAS vs CMS ?

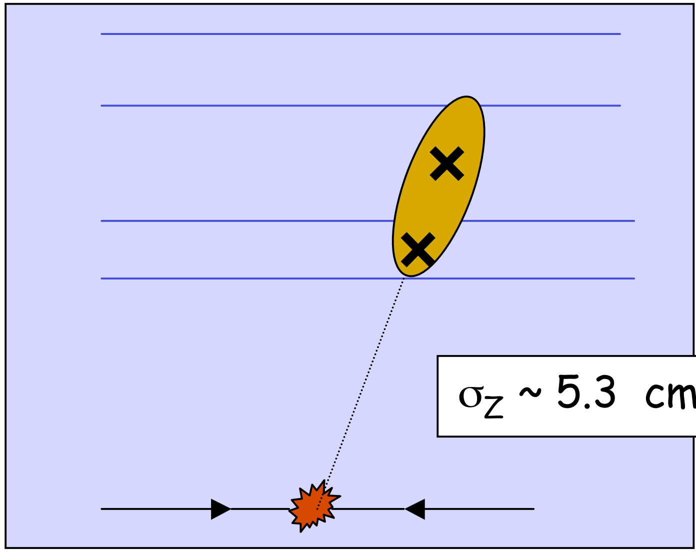
$$\frac{S}{\sqrt{B}} \sim \varepsilon_{\gamma} \times \varepsilon_{mass\ bin}$$

Total acceptance: ≈ 25% larger in ATLAS

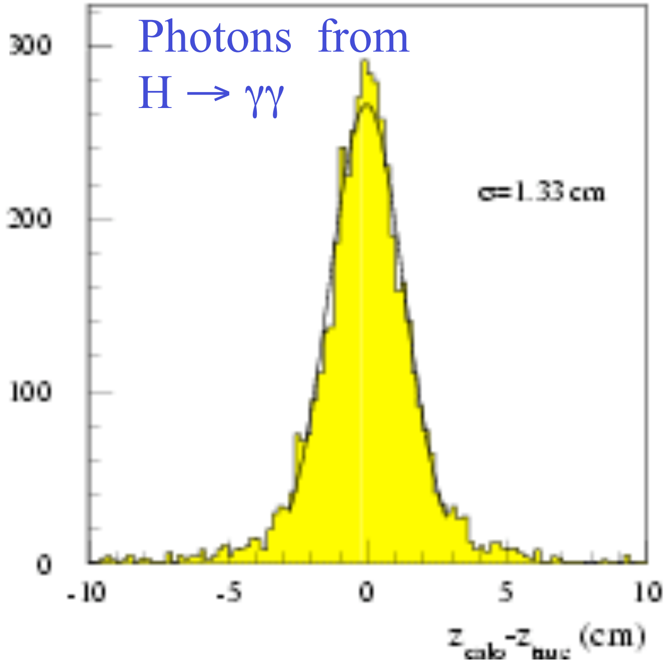
CMS:
- B= 4T : 30% of $\gamma \to e^+e^-$ lost, some others in the tails of mass spectrum
- no ECAL longitudinal segmentation
  → vertex measured using secondary tracks of underlying event → often pick up wrong vertex

→ more tails in the pass spectrum than ATLAS

ATLAS, full simulation
Vertex resolution using EM calo longitudinal segmentation



σ_Z ~ 5.3 cm at LHC



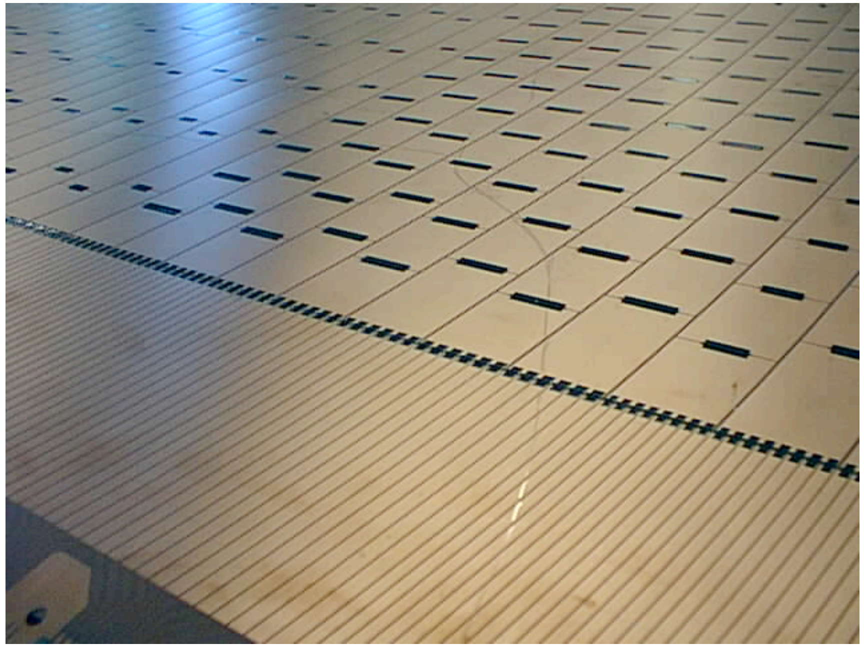
→ [illegible] ≈ [illegible] ≈ 6   100 fb^{-1}

ATLAS vs CMS �

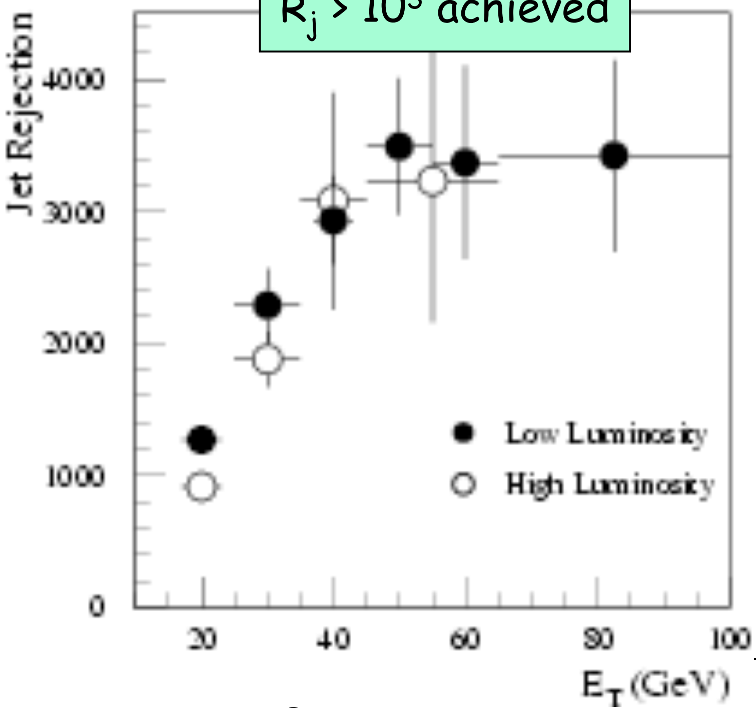
Rejection of γj+jj background

ATLAS EM calorimeter :

- ♣ 4 mm η–strips in first compartment for γ/π^0 separation
- ♣ longitudinal segmentation into 3 compartments



$R_j > 10^3$ achieved

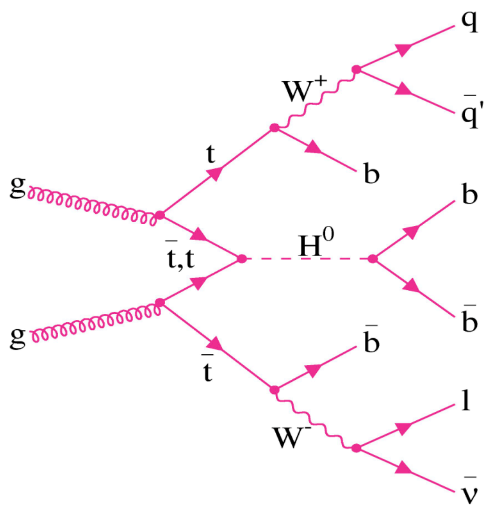


γ/π^0 separation studied also with test-beam data

What about CMS (crystal size ~ 2.5 cm x 2.5 cm, no longitudinal segmentation; preshower only in end-cap) ?

ttH → ttbb

$m_H \leq 130$ GeV



- $\sigma \times BR \approx$ 300 fb
- Complex final state: H ◊ bb, t → bjj, t → blν

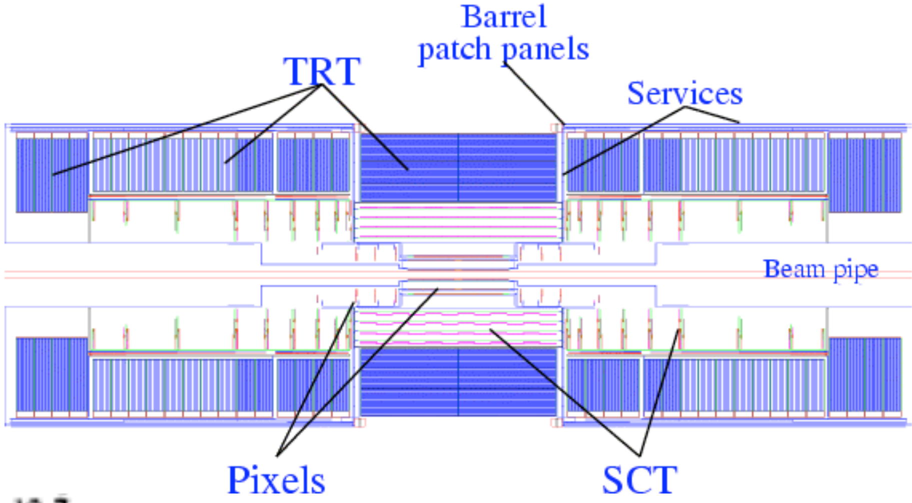
↑

l = e, μ for trigger
and background rejection

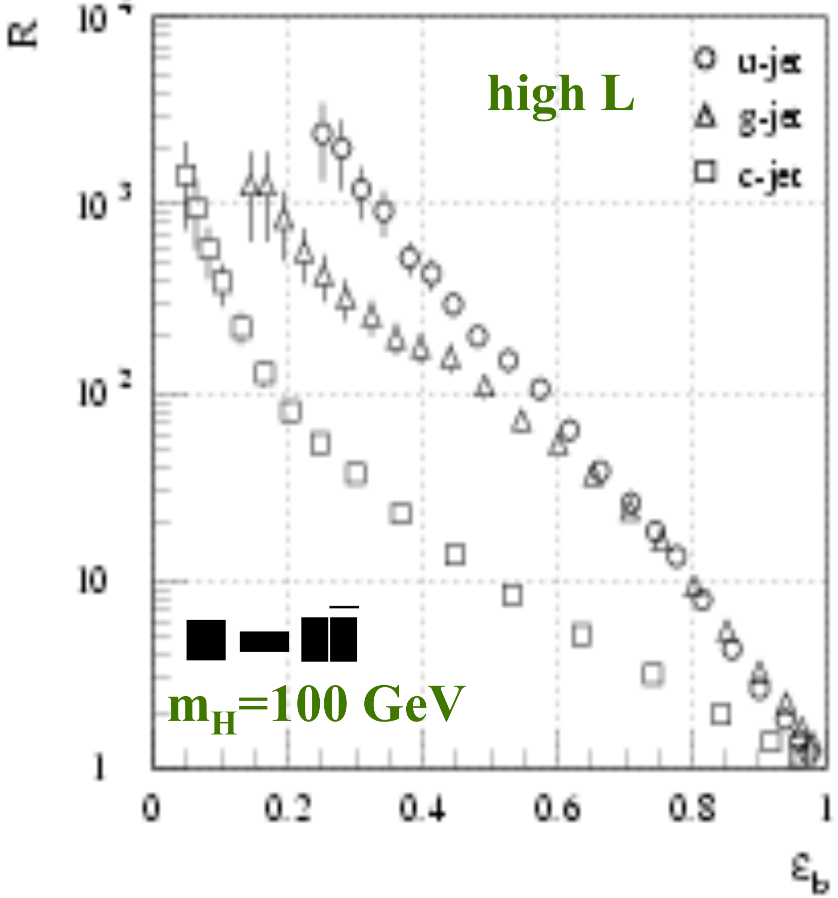
- Main backgrounds:
  -- combinatorial from signal (4b in final state)
  -- Wjjjjjj, WWbbjj, etc.
  -- ttjj (dominant, non-resonant)

} reduced by b-tagging the four b-jets and reconstructing both top quarks

◊ crucial performance aspect : b-tagging



Pixels : ~10^8 channels
First layer at R ~ 5 cm
σ ($R\phi$) ~ 10 μm
σ (z) ~ 60 μm



ATLAS, full simulation

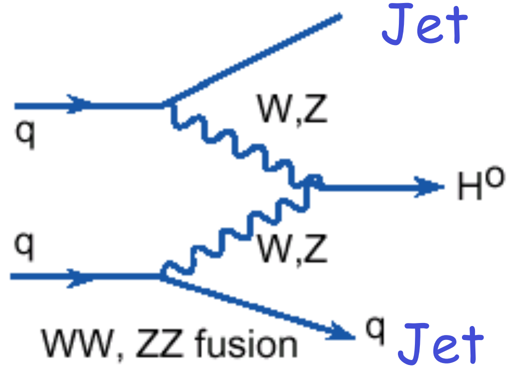
2D b-tag (used here):
ε_b =50% R_j (uds)=100 at high L

3D b-tag: R_j is ~ 2 larger for same ε_b

Note:
-- complementary channel to H → γγ
-- large coverage in MSSM
-- allows measurement of top Yukawa coupling

Vector Boson Fusion qqH → ττ

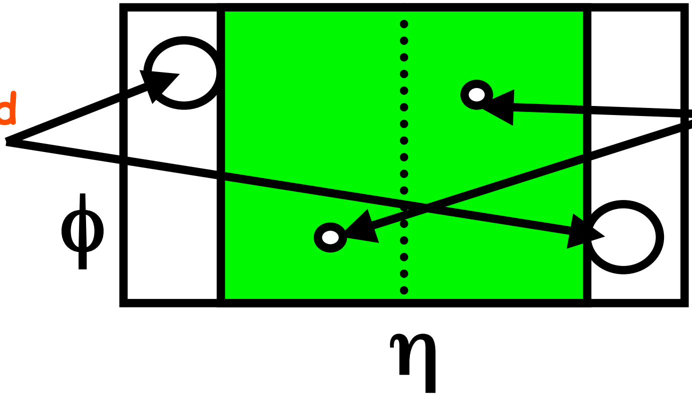
$m_H \leq 200$ GeV



σ = 4 pb (20% of total cross section for m_H = 130 GeV)

Very distinct signature:
♣ two forward jets
♣ little jet activity in central region

Forward tagging jets

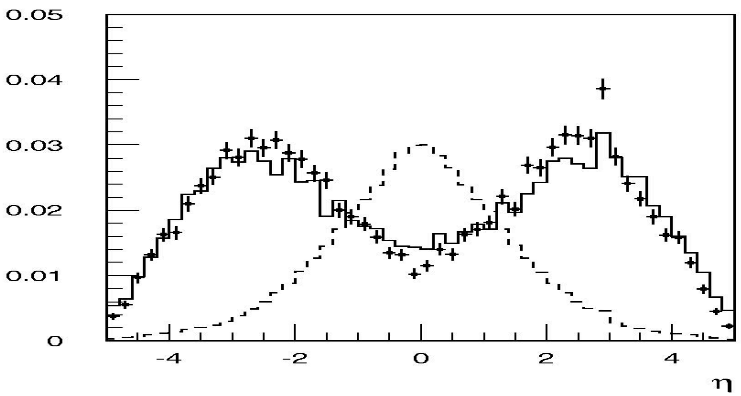


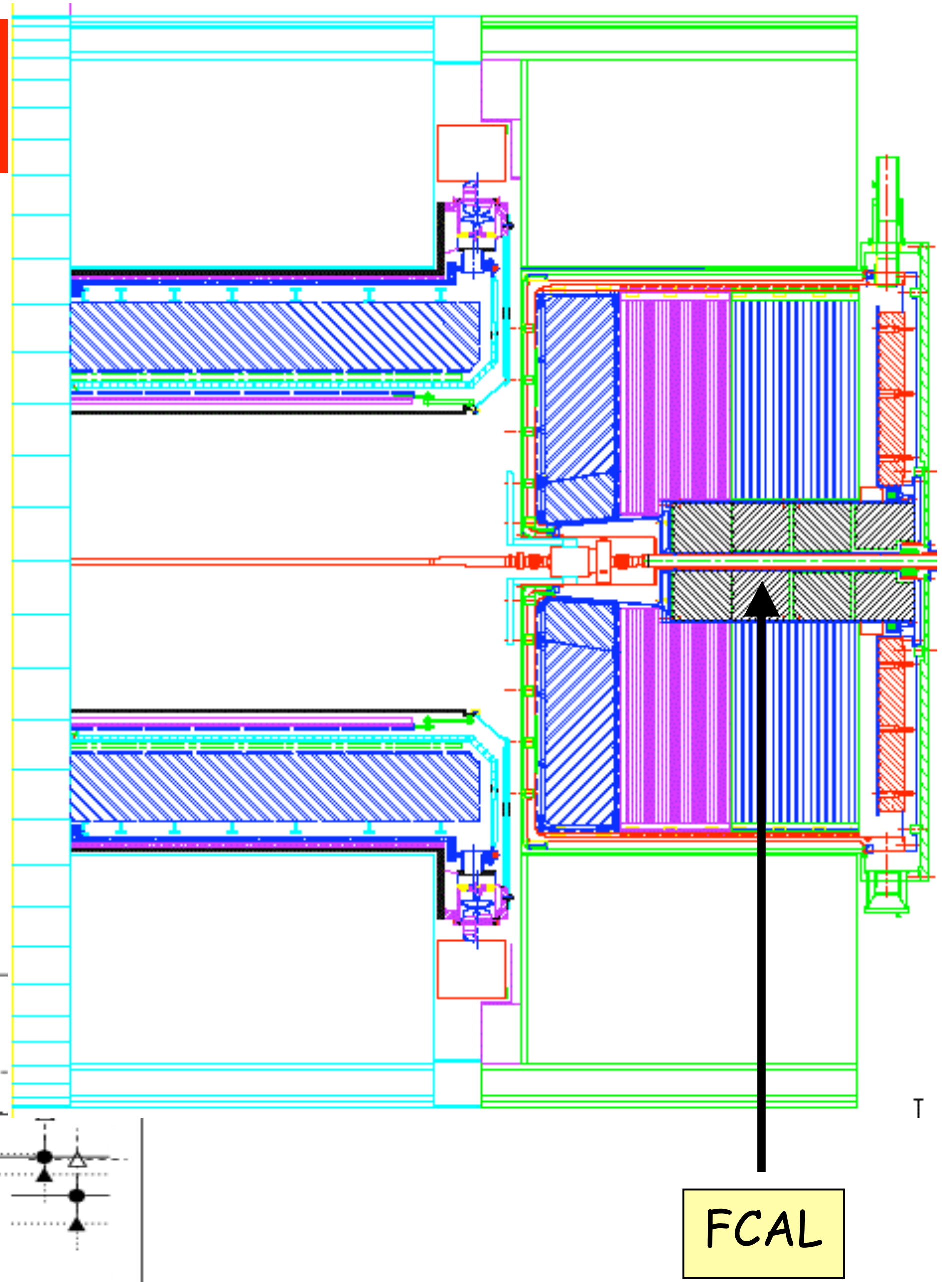
Higgs Decay

Important for the measurement of Higgs boson parameters (couplings to bosons, fermions (taus), total width) and detection of invisible Higgs

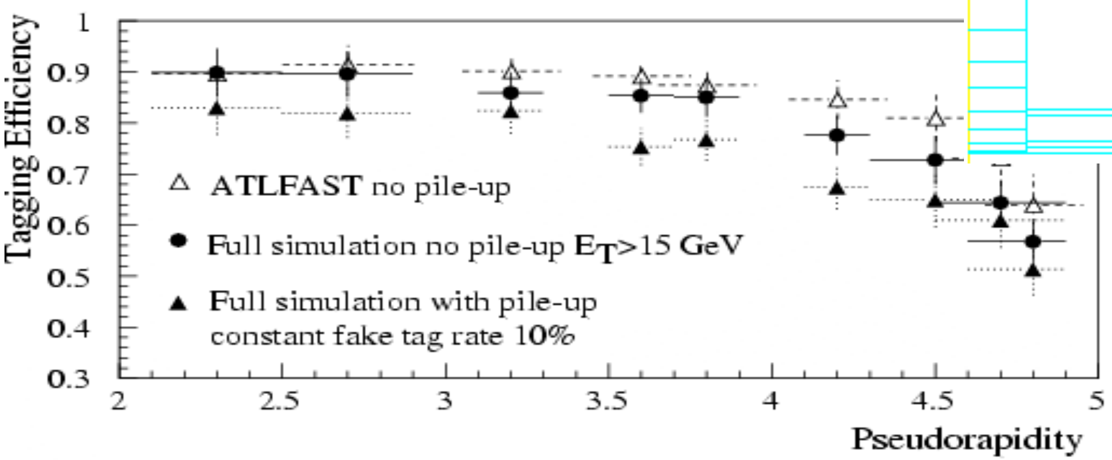
Experimental issues:
forward jet reconstruction (hermetic calorimetry over |η|<5)
jet veto in the central region

Rapidity distribution of most fwd jets VBF Higgs events vs tt background

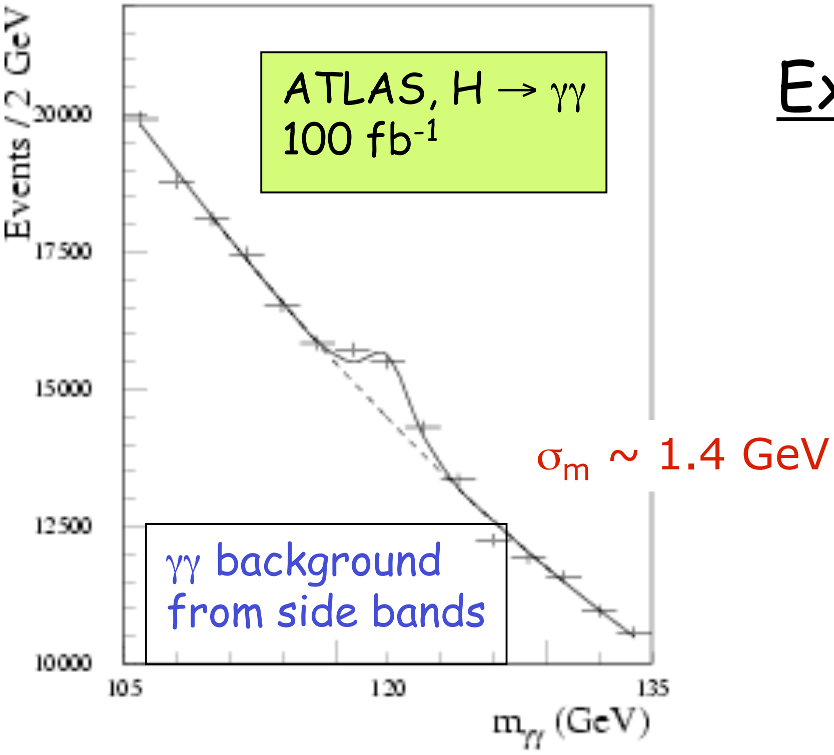


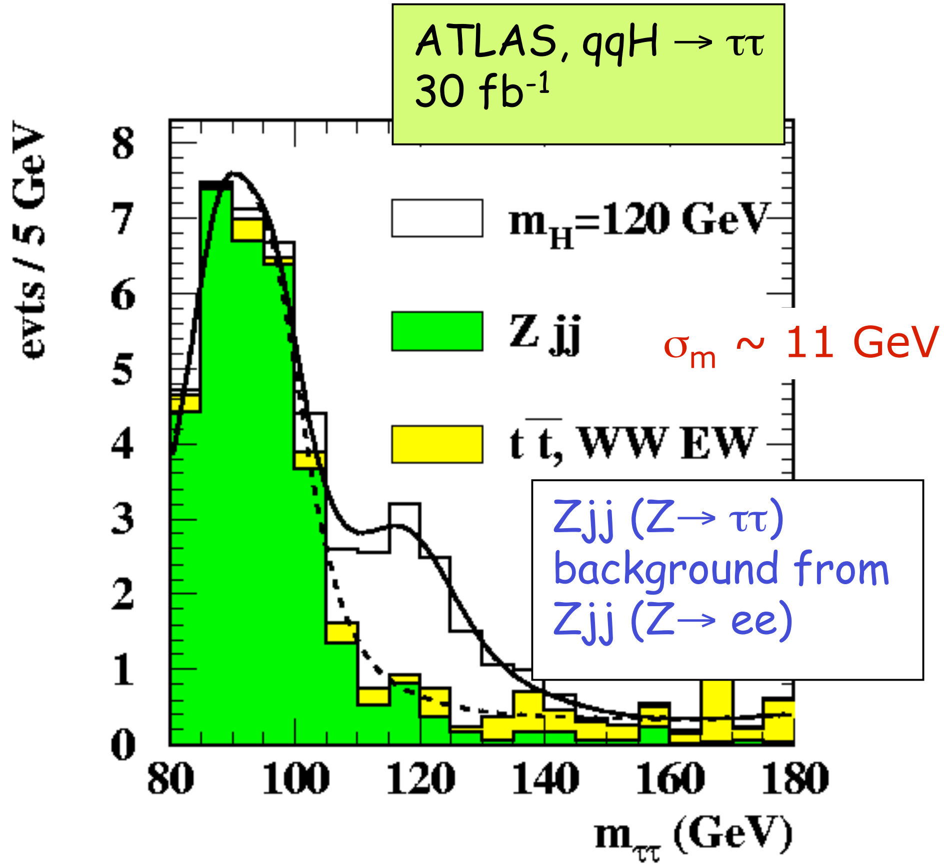


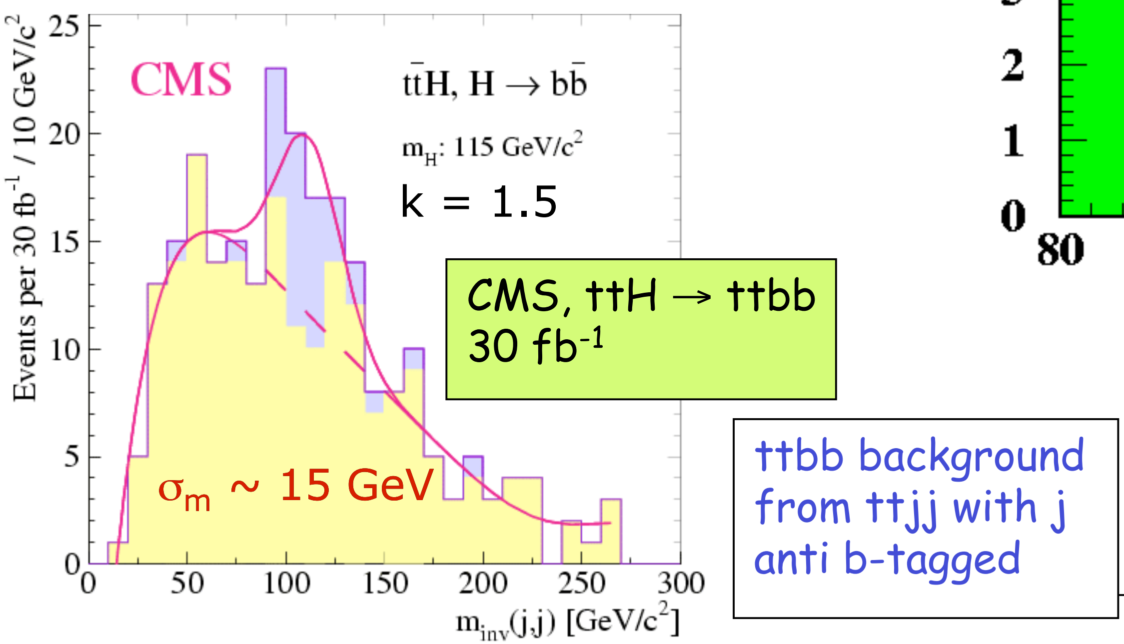
Forward tag jet reconstruction



Expected signals in low-mass region



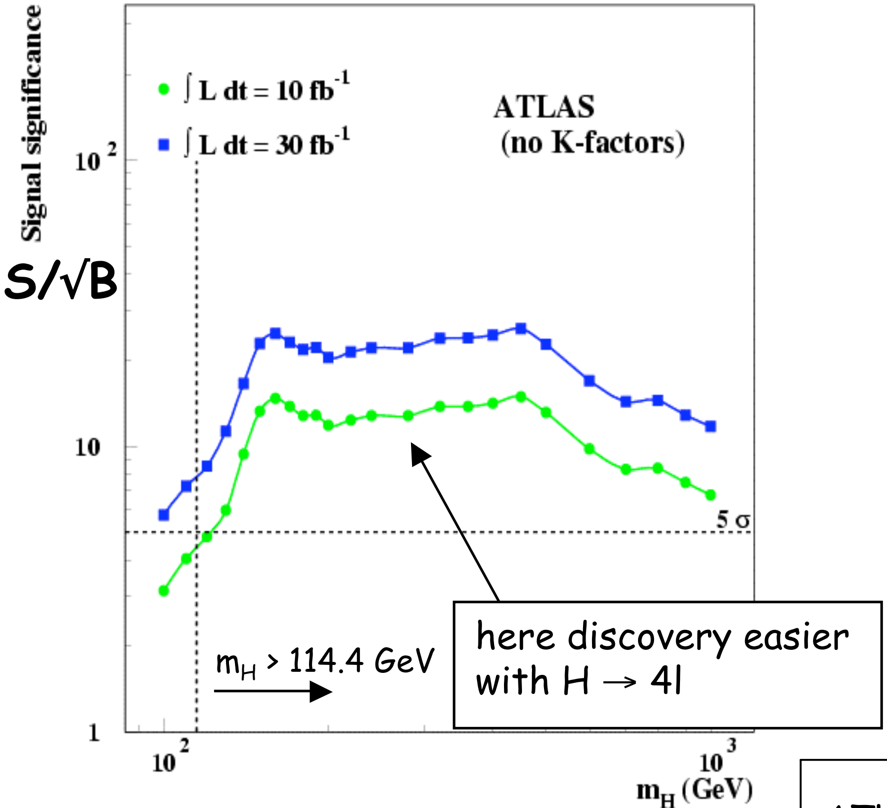


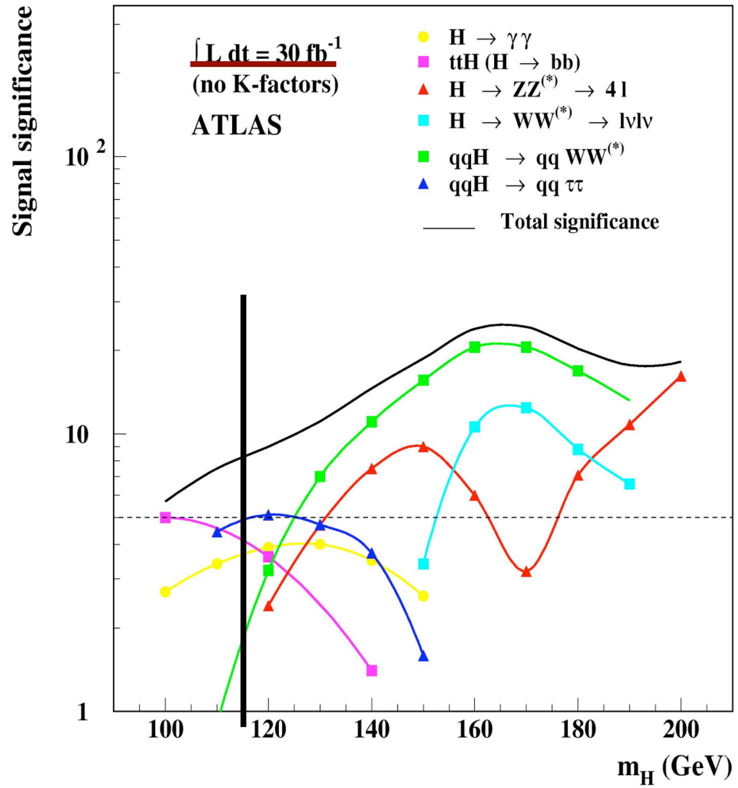


Background dominated by irreducible component in all cases

Summary of SM Higgs discovery potential

What about early discoveries ?





m_H ~ 115 GeV   10 fb^{-1}

total   S/ √B ≈ [redacted]

ATLAS	H → γγ	ttH → ttbb	qqH → qqττ (ll + l-had)
S	130	15	~ 10
B	4300	45	~ 10
S/ √B	2.0	2.2	~ 2.7

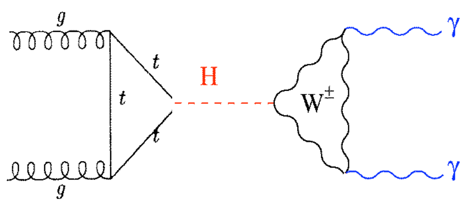
↑ K-factors ≡ σ(NLO)/σ(LO) ≈ 2 not included

<u>Remarks:</u>

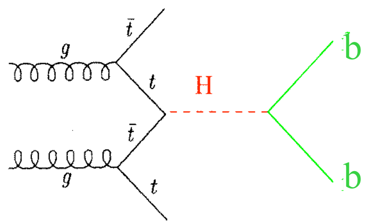
Each channel contributes ~ 2σ to total significance → observation of all channels important to extract convincing signal in first year(s)

The 3 channels are complementary → robustness:

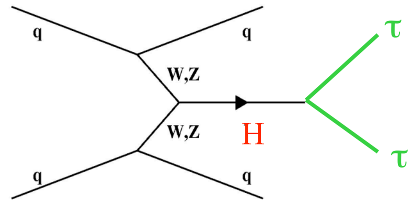
$H \to \gamma\gamma$



$ttH \to tt\ bb \to bl\nu\ bjj\ bb$



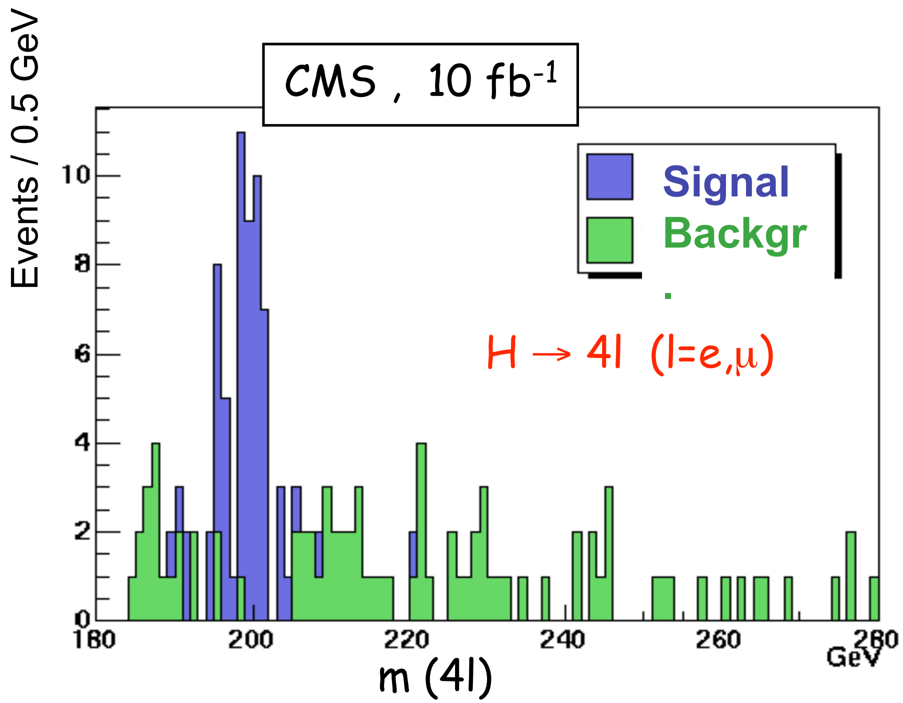
$qqH \to qq\tau\tau$



- different production and decay modes
- different backgrounds
- different detector/performance requirements:
  - -- ECAL crucial for $H \to \gamma\gamma$ (in particular response uniformity) : $\sigma/m \sim 1\%$ needed
  - -- b-tagging crucial for ttH : 4 b-tagged jets needed to reduce combinatorics
  - -- efficient jet reconstruction over $|\eta| < 5$ crucial for $qqH \to qq\tau\tau$: forward jet tag and central jet veto needed against background

Note : -- all require "low" trigger thresholds
E.g. ttH analysis cuts : p_T (l) > 20 GeV, p_T (jets) > 15-30 GeV
-- all require very good understanding (1-10%) of backgrounds

If m_H > 180 GeV : early discovery may be easier with H → ZZ → 4l channel



May be observed with 3-4 fb^{-1} (end 2008 ?)

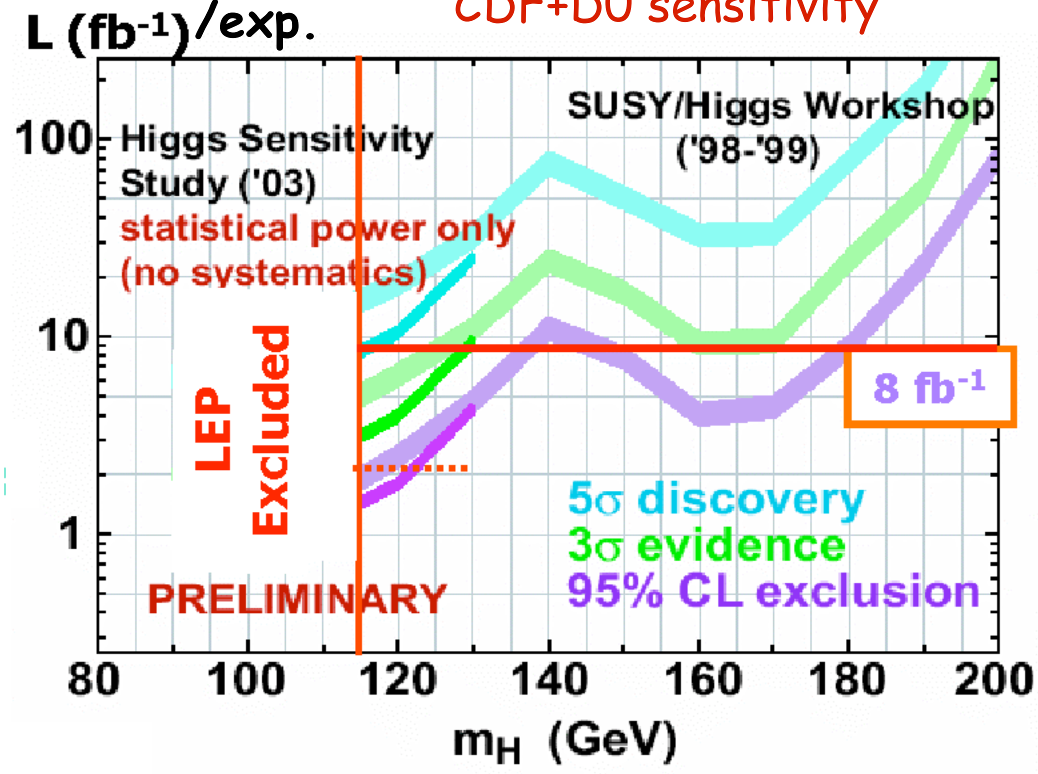
H → 4l : low-rate but very clean : narrow mass peak, small background

- requires:
  ~ 90% e, μ efficiency at low p_T (analysis cuts : $p_T^{1,2,3,4}$ > 20, 20, 7, 7, GeV)
  σ /m ~ 1%, tails < 10% → good quality of E, p measurements in ECAL and tracker
- background dominated by irreducible ZZ production (tt and Zbb rejected by Z-mass constraint, and lepton isolation and impact parameter)

H → WW → lνlν : high rate (~ 100 evts/expt) but no mass peak
→ not ideal for early discovery …

What about the "competition" with the Tevatron ?

CDF+D0 sensitivity



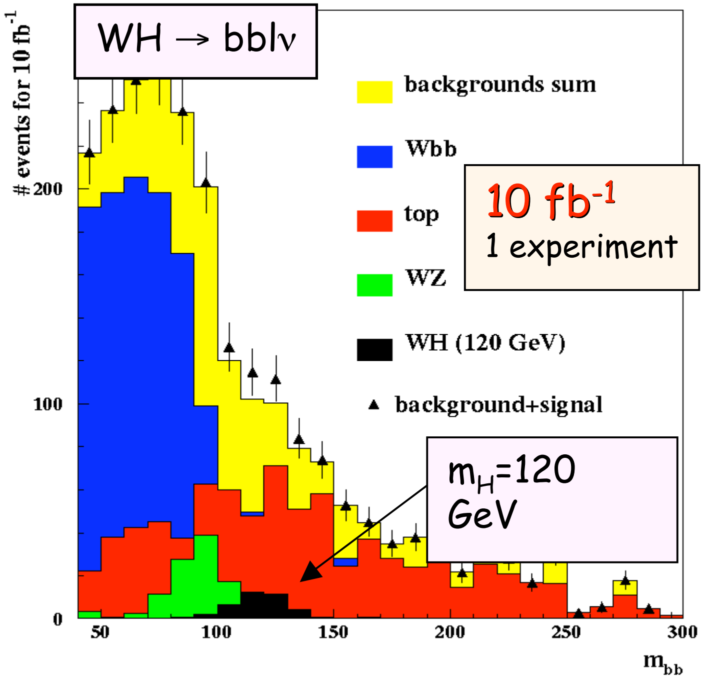
Today : ~ 1 fb^{-1} /exp. on tape
Projections for 2009:
4 fb^{-1} : present machine performance
8 fb^{-1} : electron cooling of pbar and other improvements

With 4 (8) fb^{-1}:
~no 5σ sensitivity
3σ evidence up to 120 (130) GeV
95% C.L. exclusion up to ~ 130 (180) GeV

Tevatron vs LHC after kin. cuts	$WH \to l\nu\, bb$ (m_H=120 GeV)	$H \to WW(^*)$ (m_H = 160 GeV)
S (14 TeV/ 2 TeV)	≈ 5	≈ 17
B (14 TeV/ 2 TeV)	≈ 25	≈ 6
S/B (14 TeV/ 2 TeV)	≈ 0.2	≈ 3
S/√B (14 TeV/ 2 TeV)	≈ 1	≈ 7

Assuming same integrated luminosity and same detector performance at Tevatron and LHC

Best low-mass channel at the Tevatron



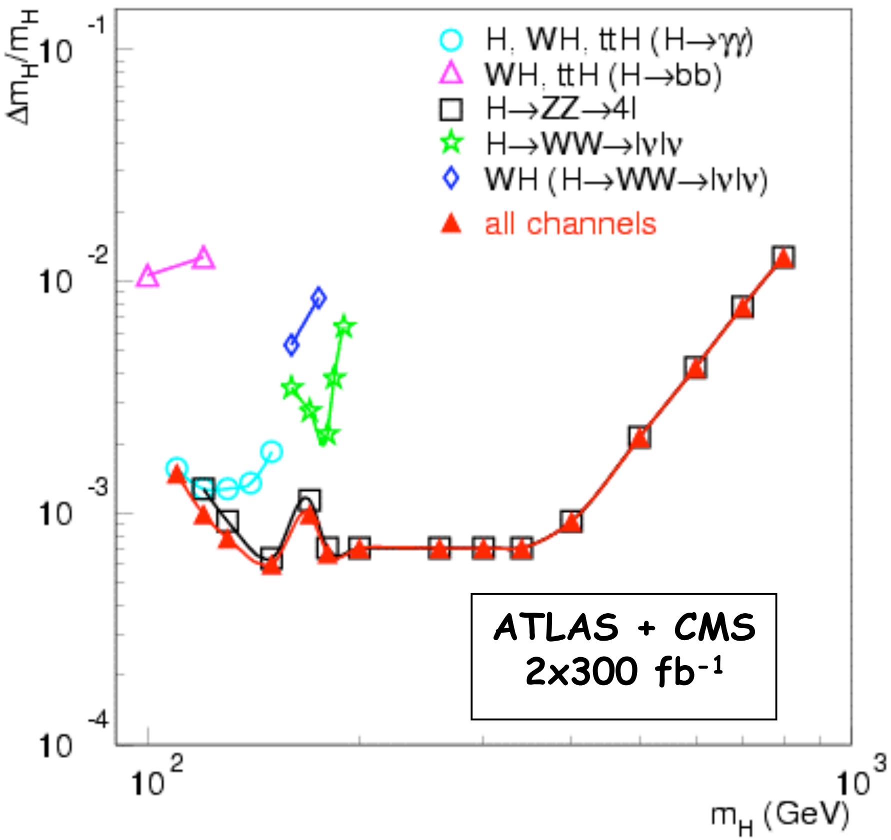
Tevatron projections are quite optimistic:

- ♣ no systematics
- ♣ stretched detector performance (e.g. $H \to bb$ mass resolution)
- ♣ sensitivity from combination of channels with individual significances « 2σ

Still ....

competition between Tevatron and LHC in 2008-2009 if m_H < 130 GeV ?

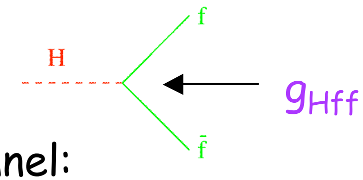
Measurements of the SM Higgs parameters



Dominant systematic uncertainty is
γ /l absolute energy scale:
♣ assumed here: 1‰
♣ goal : 0.2‰ (for m_W measurement)

E-scale from Z → ll events
(close to light Higgs)

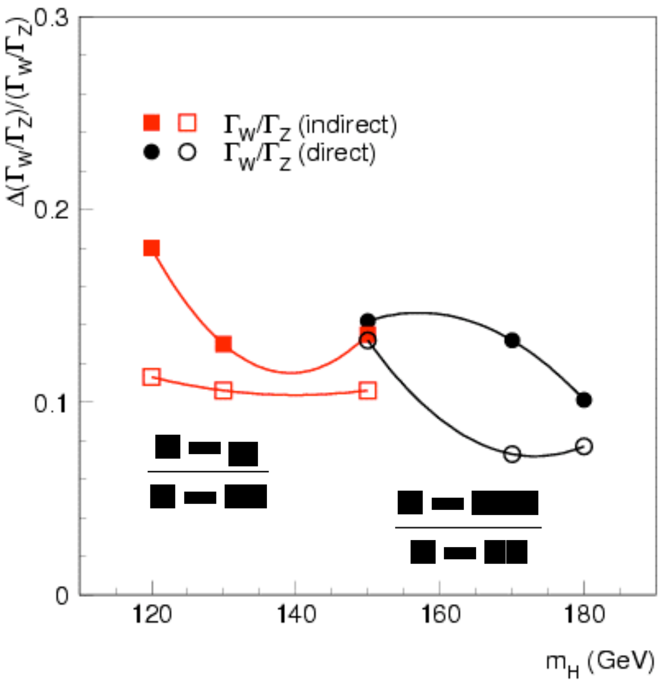
Measurement of the SM Higgs couplings



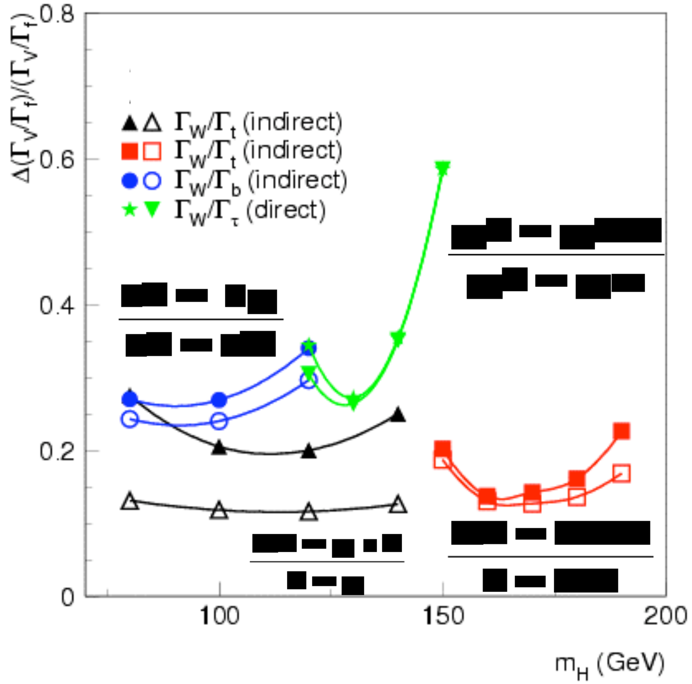
Couplings can be obtained from measured rate in a given production channel:

[illegible] → deduce $\Gamma_f \sim g^2_{Hff}$

Γ_{tot} and σ (pp → H+X) from theory → without theory inputs measure ratios of rates in various channels (Γ_{tot} and σ cancel) → $\Gamma_f/\Gamma_{f'}$ → several theory constraints



Closed symbols:
LHC 600 fb^{-1}
Open symbols:
SLHC 6000 fb^{-1}

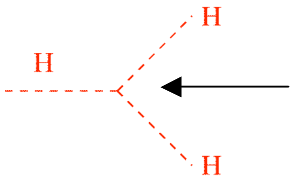


♣ LHC luminosity upgrade (SLHC, L = 10^{35}) could improve LHC precision by up to ~ 2 before first LC becomes operational

♣ Not competitive with LC precision of ≈ %, but useful insight into EWSB mechanism

Higgs self-coupling λ

- not accessible at LHC
- may be constrained to ≈ 20% at SLHC ($L=10^{35}\ cm^{-2}\ s^{-1}$)

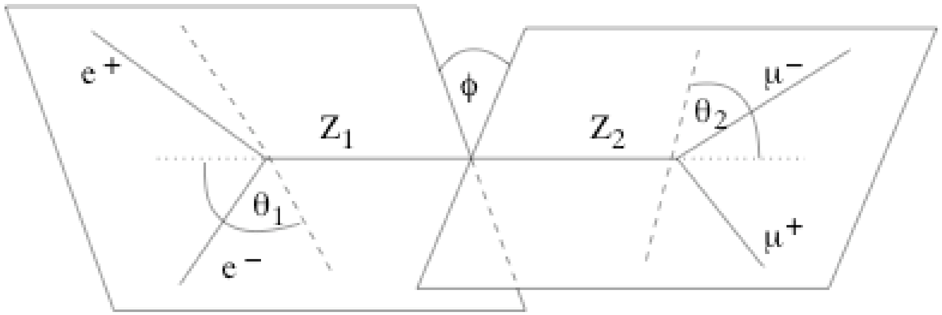


$m_H^2 = 2\lambda v^2$

Buszello et al. SN-ATLAS-2003-025

Higgs spin and CP

Promising for m_H > 180 GeV ($H \to ZZ \to 4l$), difficult at lower masses



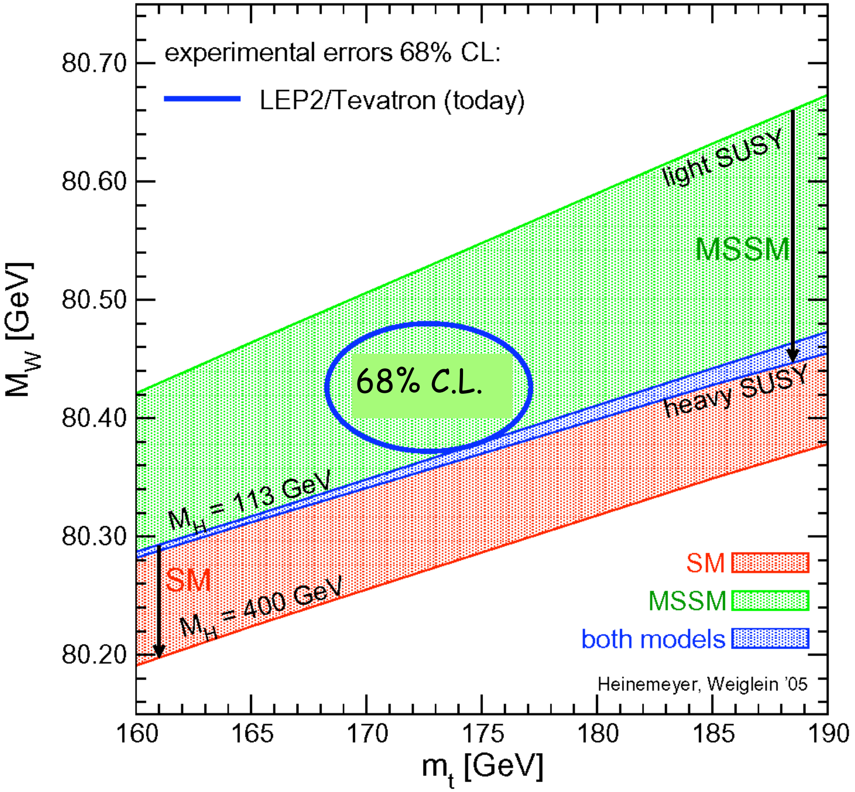
Significance for exclusion of other J^{CP} states than 0^+

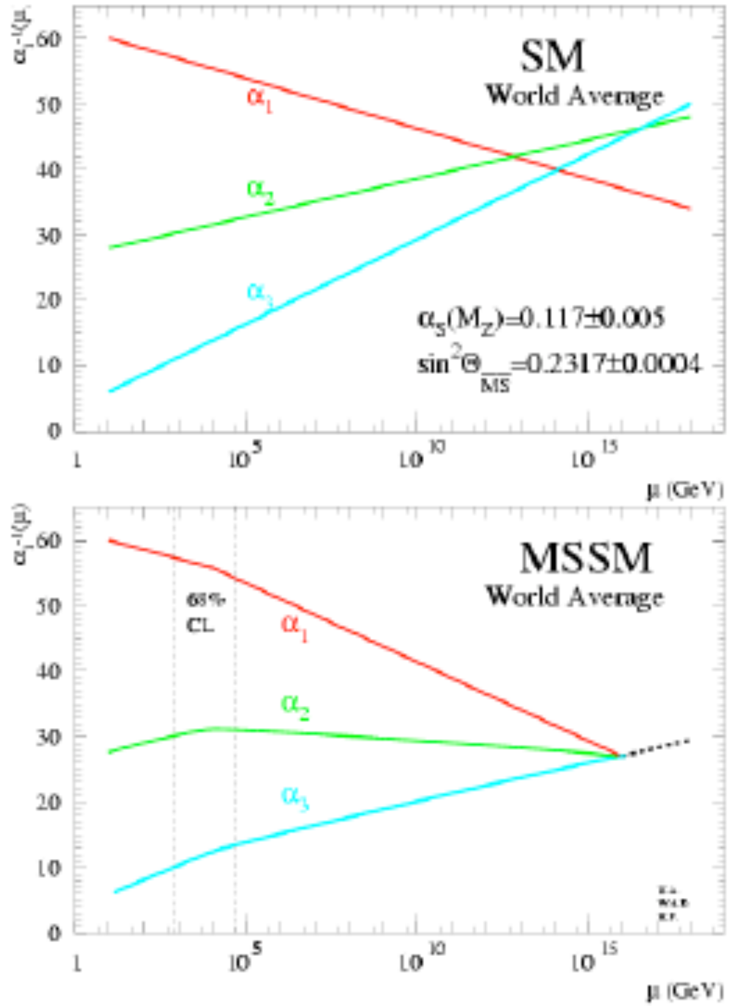
ATLAS + CMS, 2 x 300 fb^{-1}

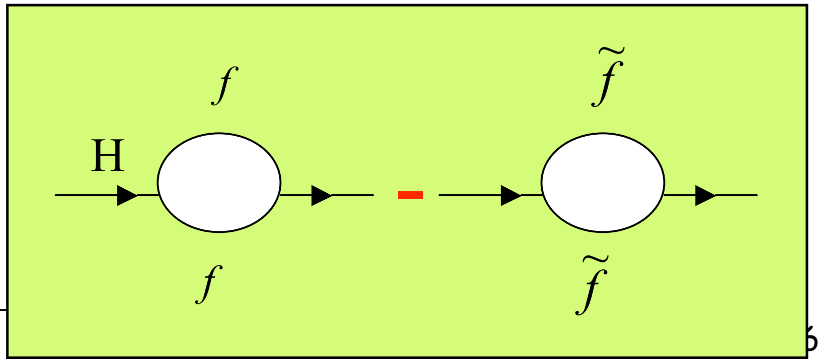
m_H (GeV)	$J^{CP} = 1^+$	$J^{CP} = 1^-$	$J^{CP} = 0^-$
200	6.5 σ	4.8 σ	40 σ
250	20 σ	19 σ	80 σ
300	23 σ	22 σ	70 σ

SUperSYmmetry

Motivations:
- ♣ stabilizes m_H
- ♣ predicts light Higgs (in agreement with EW data)
- ♣ enable gauge-coupling unification
- ♣ provides a dark matter candidate, etc.







SUPERSYMMETRY (SUSY) ≡ symmetry between fermions (matter) and bosons (forces)

- All SM particles p have SUSY partner [redacted] with same couplings and quantum numbers except [redacted]

SM particle	SUSY partner	spin
l	sleptons T	0
q	squarks [redacted]	0
g	gluino [redacted]	1/2
$W^{\pm}$ (+Higgs)	charginos [redacted] $\chi^{\pm}_{1,2}$	1/2
γ, Z (+Higgs)	neutralinos $\chi^{0}_{1,2,3,4}$	1/2

Particle spectrum in minimal models (MSSM)

+ 5 Higgs : h, H, A, $H^{\pm}$

$m_h < 135$ GeV

- No experimental evidence for SUSY → sparticles are heavy

However : to stabilize Higgs mass need : [redacted] ⟶ LHC

- R-Parity (multiplicative quantum number) = + 1 (-1) SM (SUSY) particles

If conserved : -- SUSY particles produced in pairs

-- Lighest Supersymmetric Particle (LSP) is stable

LSP ≡ χ^{0}_{1} weakly interacting ⟷ dark matter candidate

-- all SUSY particles decay to LSP

MSSM (≡ Minimal Supersymmetric extension of the SM) has ~ 120 parameters
→ not very predictive, difficult to use for experimental studies

⬇

Minimal Supergravity (mSUGRA) models have only 5 parameters:
$m_{1/2}$, m_0, $\tan\beta$, sign(μ), A_0

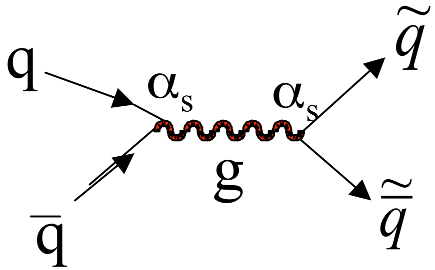
m_0	: universal scalar mass at the GUT scale
$m_{1/2}$	: universal gaugino mass at the GUT scale
$\tan\beta$	: ratio of vacuum expectation values of the two Higgs doublets
μ	: Higgs mixing parameter
A_0	: universal stop/sbottom/stau mixing parameter at GUT scale

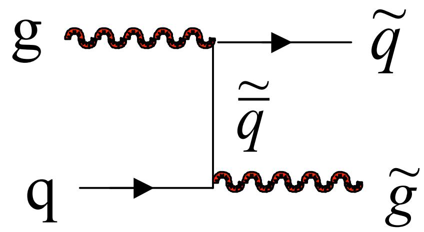
mSUGRA widely used to optimize and interpret experimental studies mainly at hadron colliders. Very predictive but …….. realized in Nature ?

Sparticle production at LHC

- Squarks and gluinos produced via strong processes $\rightarrow$ large cross-section

E.g.:



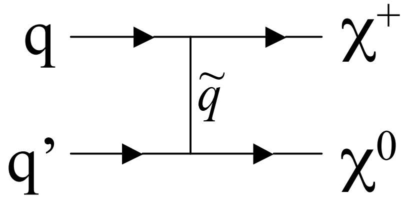


M (GeV)	σ (pb)	Evts/yr
500	100	10^6-10^7
1000	1	10^4-10^5
2000	0.01	10^2-10^3

10^{33}-10^{34}

- Charginos, neutralinos, sleptons direct production occurs via electroweak processes $\rightarrow$ much smaller rate (produced more abundantly in squark and gluino decays)

E.g.

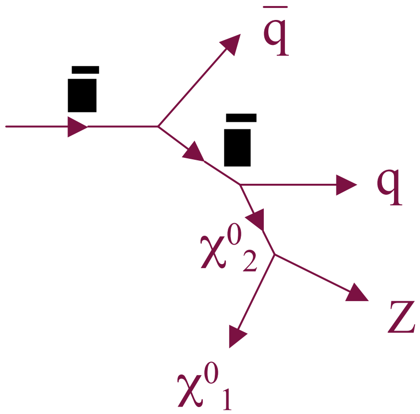


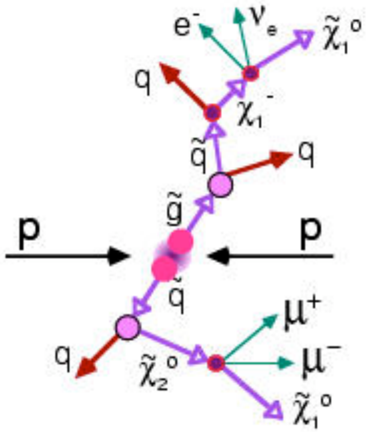
$\sigma \approx$ pb $\quad m_\chi \approx 150$ GeV

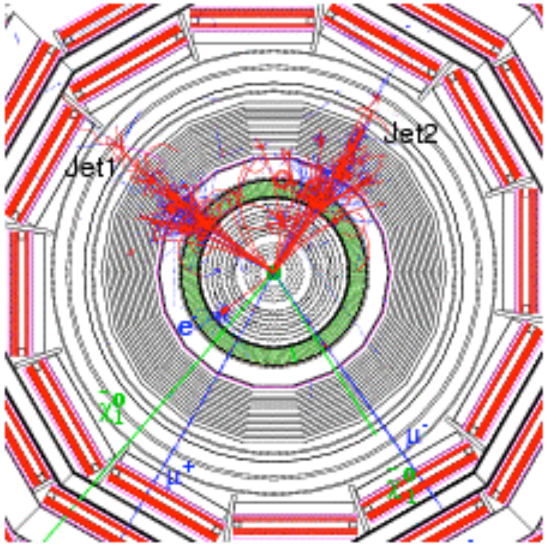
$\tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$ production are dominant SUSY processes at LHC if accessible

■.■ heavy → cascade decays favoured

Example :



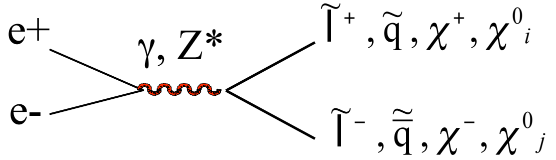
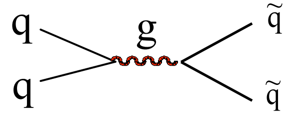




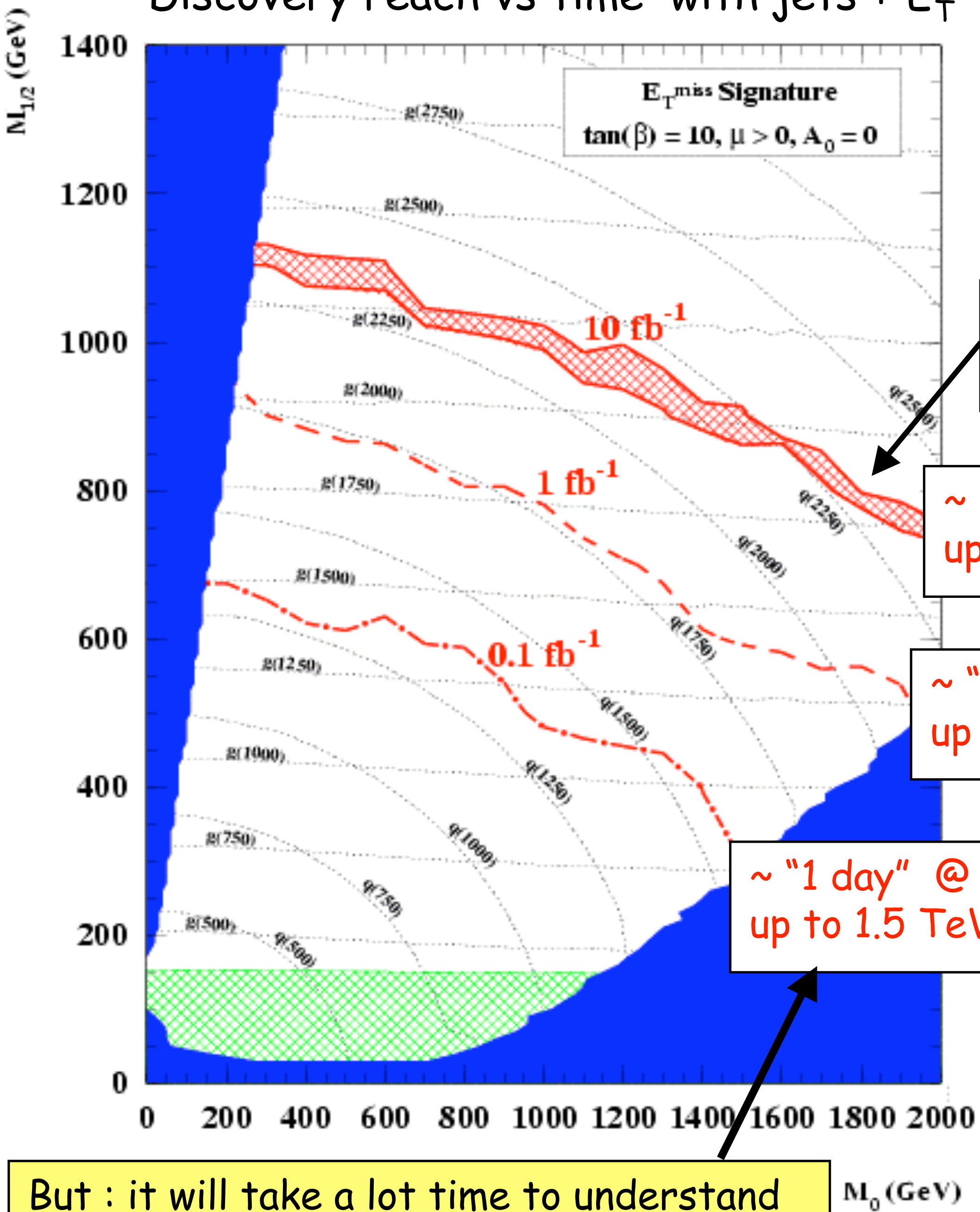
→ spectacular signatures
(many jets, missing transverse energy, leptons)

→ <u>easy</u> to extract SUSY signal
from SM backgrounds at LHC
(in most cases …)

e^+e^- colliders versus hadron colliders

e^+e^- colliders	hadron colliders
Sparticles produced ~ democratically 	[redacted] $\sigma(\tilde{q}, \tilde{g}) \approx 100$ pb $\sigma(\tilde{e}\tilde{e}) \approx 5$ fb m=150 GeV Tevatron 
Direct decays to LSP dominate: e.g. $\tilde{q} \to q\chi^0_1, \tilde{l} \to l\chi^0_1, \chi^\pm \to W^*\chi^0_1$ → main topology is 2 acoplanar objects + missing E	[redacted] e.g. $\tilde{g} \to \tilde{q}q \to qq\chi^0_2 \to qqZ\chi^0_1$ → high multiplicity high p_T final states
Moderate backgrounds (γγ → ff , WW, ZZ)	Huge backgrounds (QCD, W/Z+jets)
Sensitive to: -- ~ all kinematically accessible [redacted] -- ~ all decay modes -- [redacted]	Sensitive to: -- [redacted] (high σ, heavy, clear signature) and $\chi^\pm_1 \chi^0_2 \to 3l$ (clean signature) -- Δ m >>10 GeV (large visible E needed)
Mass reach m ≤ √s /2 for ~ any sparticle over most accessible parameter space	High mass reach for [redacted] but holes in parameter space → ~ no absolute limit
LEP2 : m > 100 GeV for $\chi^\pm$, squarks, sleptons	Tevatron today: [redacted] excluded up to m ~ 330 GeV (Run 2 reach: ~ 400 GeV)

Discovery reach vs time with jets + E_T^{miss} signature (most model-independent)



ATLAS
5σ discovery curves

band indicates factor ± 2 variation in background estimate

~ 100 days :
up to 2.3 TeV

~ "10 days" :
up to 2 TeV

~ "1 day" @ 10^{33}:
up to 1.5 TeV

Discovery reach for squarks/gluinos

But : it will take a lot time to understand the detectors and the backgrounds …

Time	mass reach
1 month at 10^{33}	~ 1.3 TeV
1 year at 10^{33}	~ 1.8 TeV
1 year at 10^{34}	~ 2.5 TeV
ultimate (300 fb^{-1})	~ 2.5-3 TeV

Main backgrounds to SUSY searches in jets + E_T^{miss} topology (one of the most "dirty" signatures …) :

- **W/Z + jets with $Z \to \nu\nu$, $W \to \tau\nu$; tt; etc.**
- **QCD multijet events with fake E_T^{miss} from jet mis-measurements (calorimeter resolution and non-compensation, cracks, …)**
- **cosmics, beam-halo, detector problems overlapped with high-p_T triggers, …**

1) "Clean-up" procedure:

♣ at least 2-3 jets with p_T>80-100 GeV, E_T^{miss} > 80-100 GeV
(for masses at overlap with Tevatron reach, higher otherwise)

♣ good event vertex

♣ no jets in detector cracks

♣ p_T^{miss} vector not pointing along or opposite to a jet in transverse plane

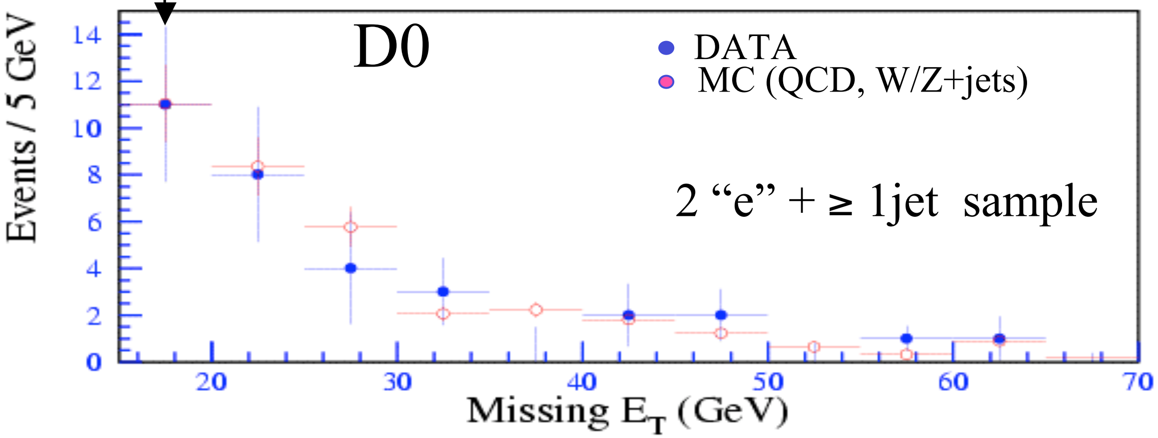
2) Estimate backgrounds using as much as possible data (control samples) and MC

Background process (examples ….)	Control samples (examples ….)
Z (→ νν) + jets W (→ τν) + jets tt→ blνbjj QCD multijets	Z (→ ee, μμ) + jets W (→ eν, μν) + jets tt→ blν blν lower E_T sample

Additional handles from changing (loosening ..) cuts, varying the number of leptons, etc., which will change the background composition.

normalization point

normalise MC to data at low E_T^{miss} and use it to predict background at high E_T^{miss} in "signal" region



Understanding E_T^{miss} spectrum (and tails from instrumental effects) is one of most crucial and difficult experimental issues for SUSY searches at hadron colliders

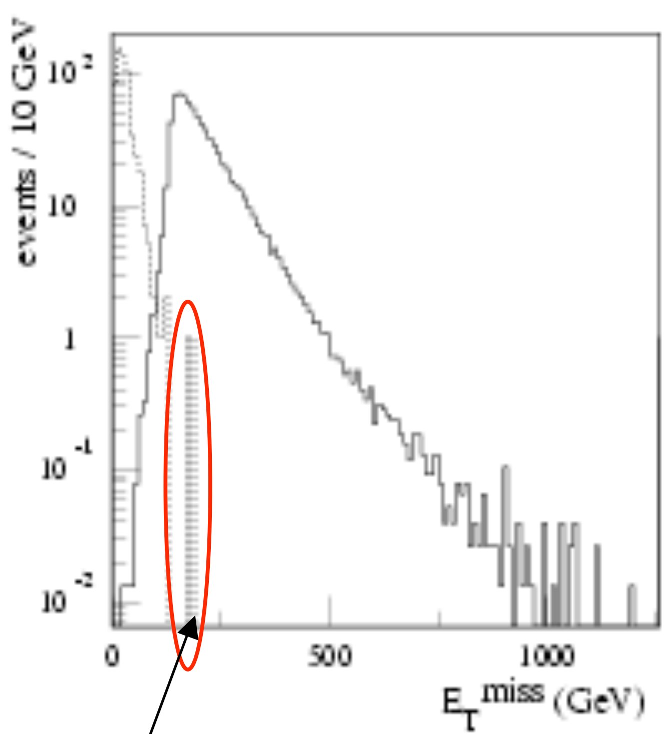
Hermetic calorimetry coverage : $|\eta| < 5$, minimal cracks and dead material

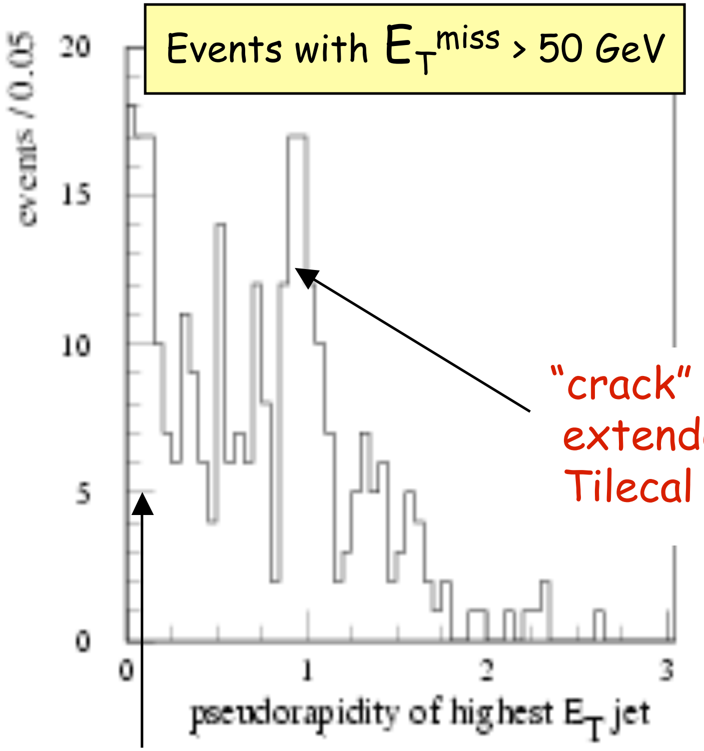
→ minimise fake E_T^{miss} from lost or badly measured jets

ATLAS : full simulation of Z + jet(s) events, with $Z \rightarrow \mu\mu$ and $p_T(Z) > 200$ GeV

.... reconstructed E_T^{miss} spectrum

—— E_T^{miss} spectrum if leading jet is undetected





"crack" barrel/ extended barrel Tilecal

Particles parallel to Tilecal scintillating tiles

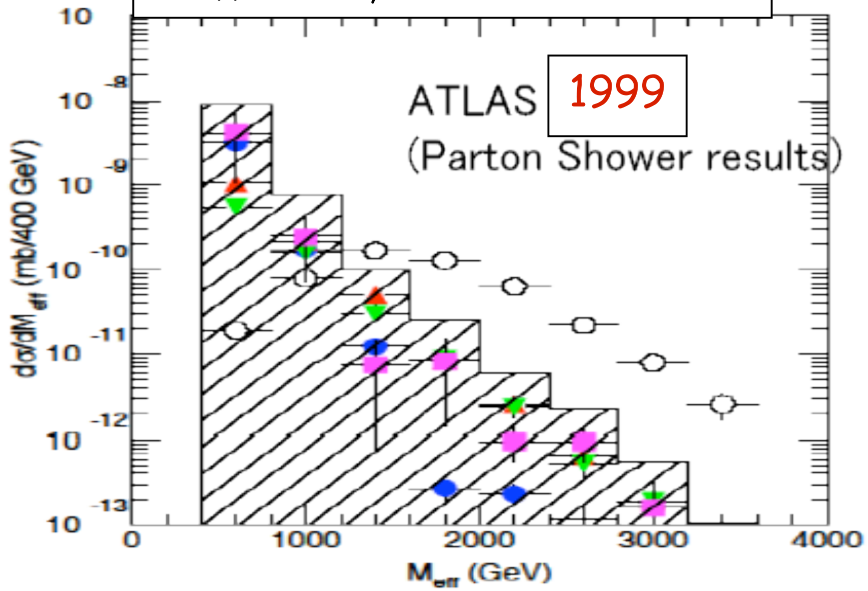
2 events with E_T^{miss} > 200 GeV contain a high-p_T neutrino

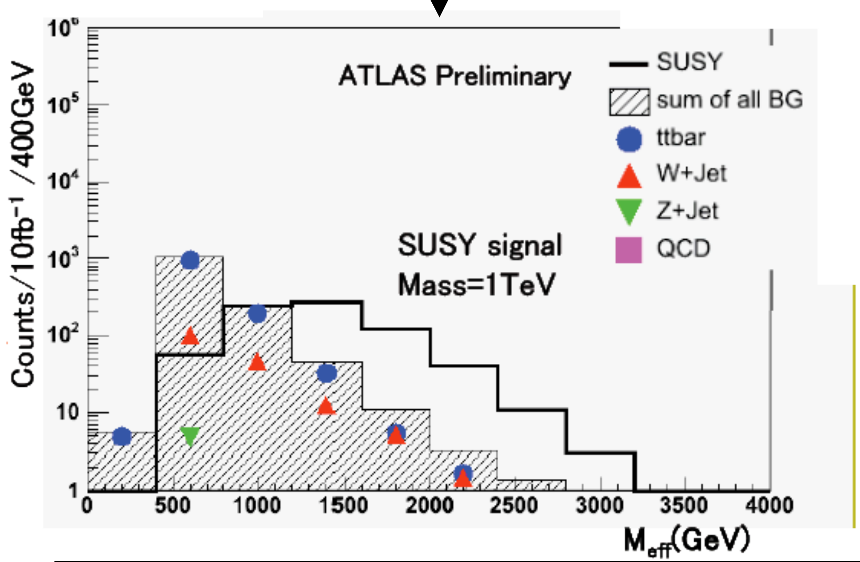
Importance of adequate MC tools to describe the backgrounds

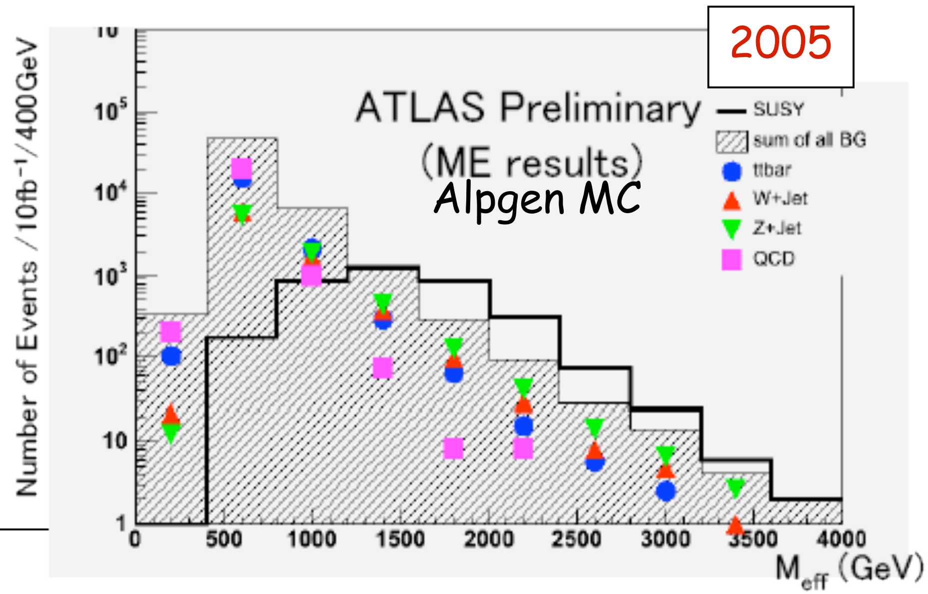
Parton shower MC underestimate
high-p_T region, signal less clear today
with matrix element MC

Will also look for SUSY events with ≥ 1 lepton
(cleaner signature, but more model-dependent)

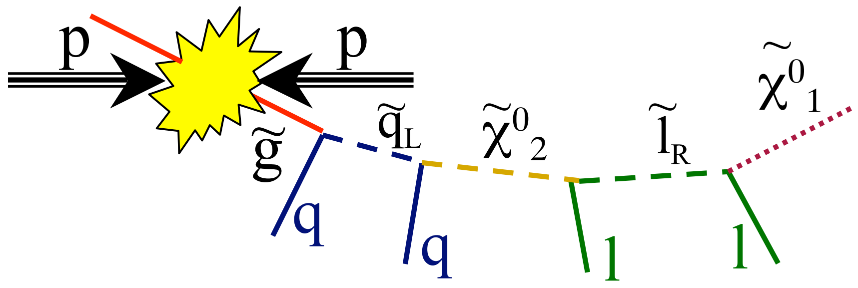
$M_{eff} = \Sigma_{i=1,5}\, E_{Ti}$ (jets) + E_T^{miss}







If SUSY is there …. to progress further and constrain the underlying theory we will need to perform precision measurements (e.g. of sparticle masses)

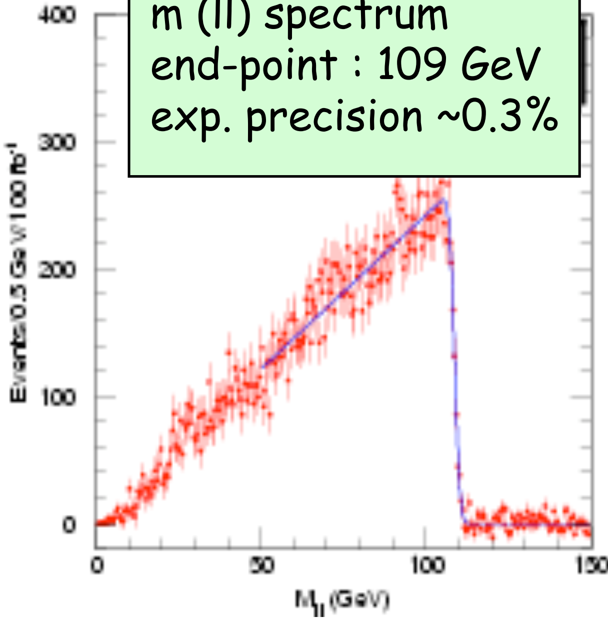


Mass peaks cannot be directly reconstructed (χ^0_1 undetectable)
→ measure invariant mass spectra (end-points, edges,..) of visible particles
→ deduce constraints on combinations of sparticle masses

Ex. : LHC "Point 5" : m_0 = 100 GeV, $m_{1/2}$= 300 GeV, A_0 = 300 GeV, $\tan\beta$ = 2, $\mu > 0$

$m(\tilde{q}) \sim 700$ GeV
$m(\tilde{g}) \sim 800$ GeV
$m(\chi^0_1) \sim 120$ GeV

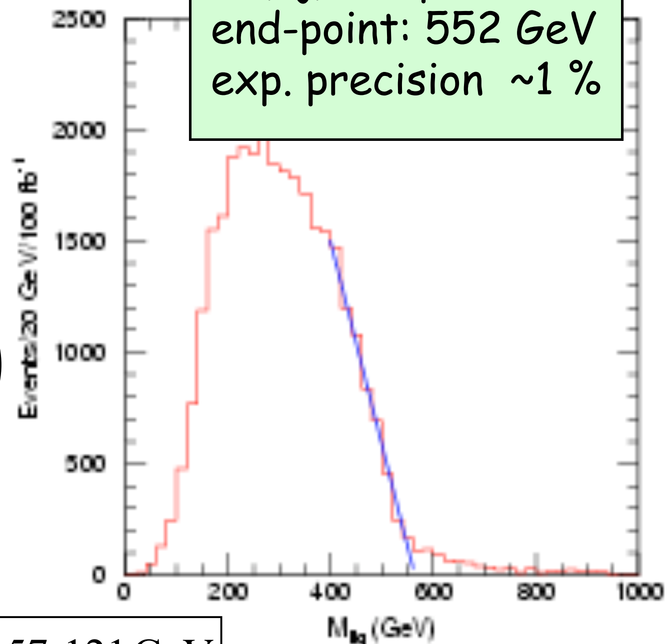
m (ll) spectrum
end-point : 109 GeV
exp. precision ~0.3%



Example of
a typical chain:

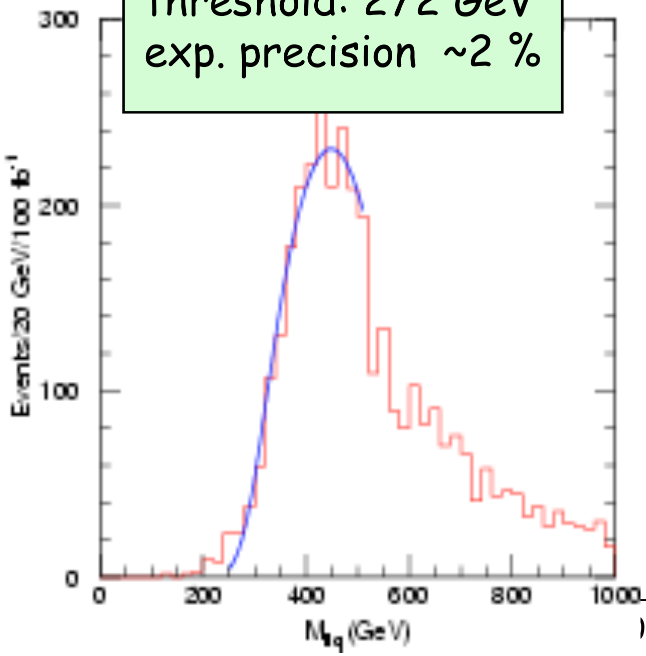
[illegible] → q χ^0_2
↳ T l
↳ l χ^0_1

m $(llj)^{min}$ spectrum
end-point: 552 GeV
exp. precision ~1 %



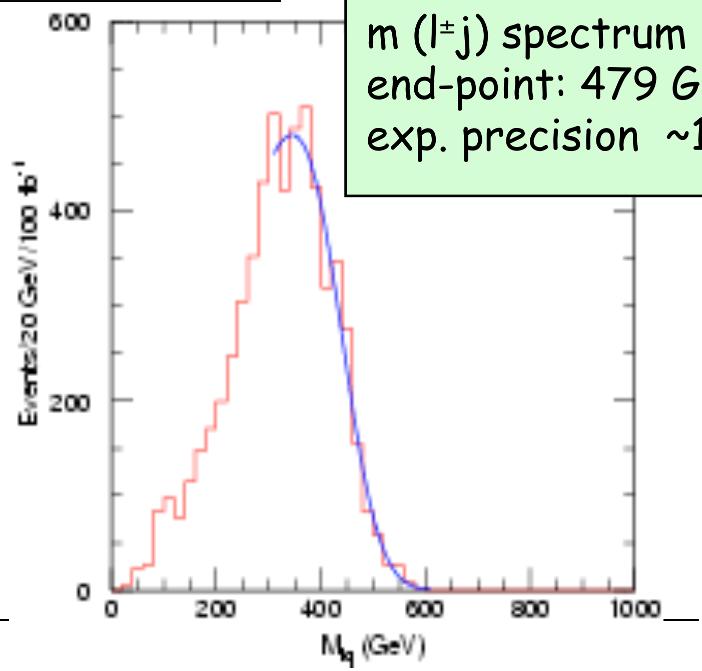
$$m(\tilde{q}_L\ \chi^0_2\ \tilde{l}_R\ \chi^0_1) = 690, 232, 157, 121\,\mathrm{GeV}$$

m $(llj)^{max}$ spectrum
threshold: 272 GeV
exp. precision ~2 %



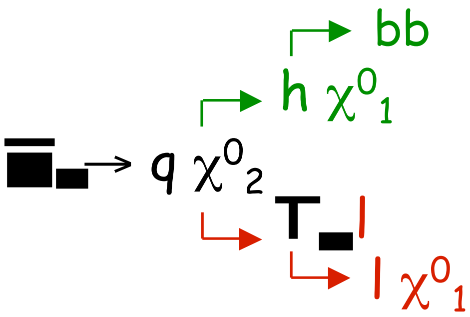
ATLAS
100 fb^{-1}
LHC Point 5

m $(l^{\pm}j)$ spectrum
end-point: 479 GeV
exp. precision ~1 %



Putting all constraints together:

m (bbj), m(ll), m(llj)^{max}, m(llj)^{min}, m(lj)



Sparticle mass	Expected precision 100 fb^{-1}
squark left	± 3%
χ^0_2	± 6%
slepton mass	± 9%
χ^0_1	± 12%

"Model-independent", pure kinematics

Sparticles directly observable at Point 5:

[illegible]

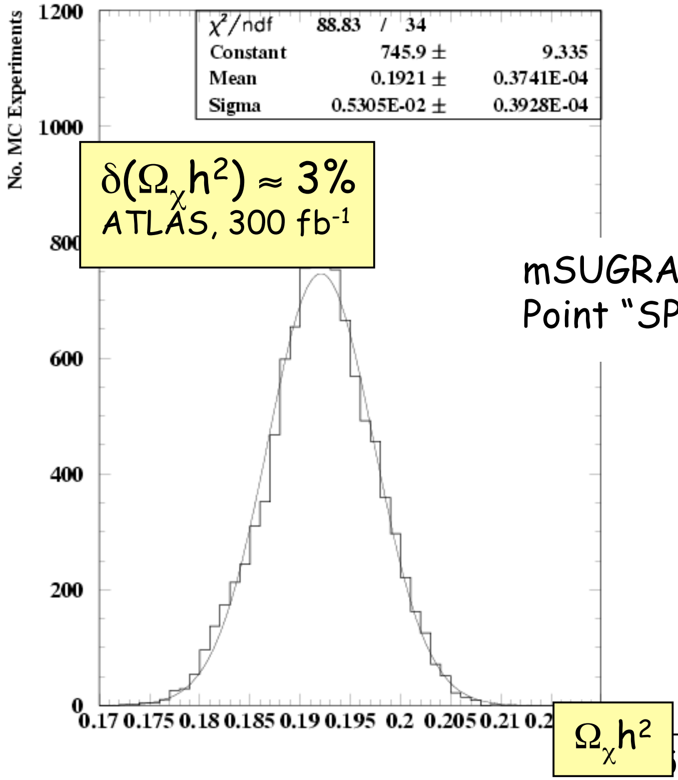
Note: can measure much more than masses: cross-sections, maybe some couplings and branching ratios, etc.

Then, assuming a model and from fit of model to all experimental measurements derive:

- ♣ sparticle masses with higher accuracy
- ♣ fundamental parameters of theory to 1-30%
- ♣ dark matter (χ^0_1) relic density and σ (χ^0_1 - nucleon)

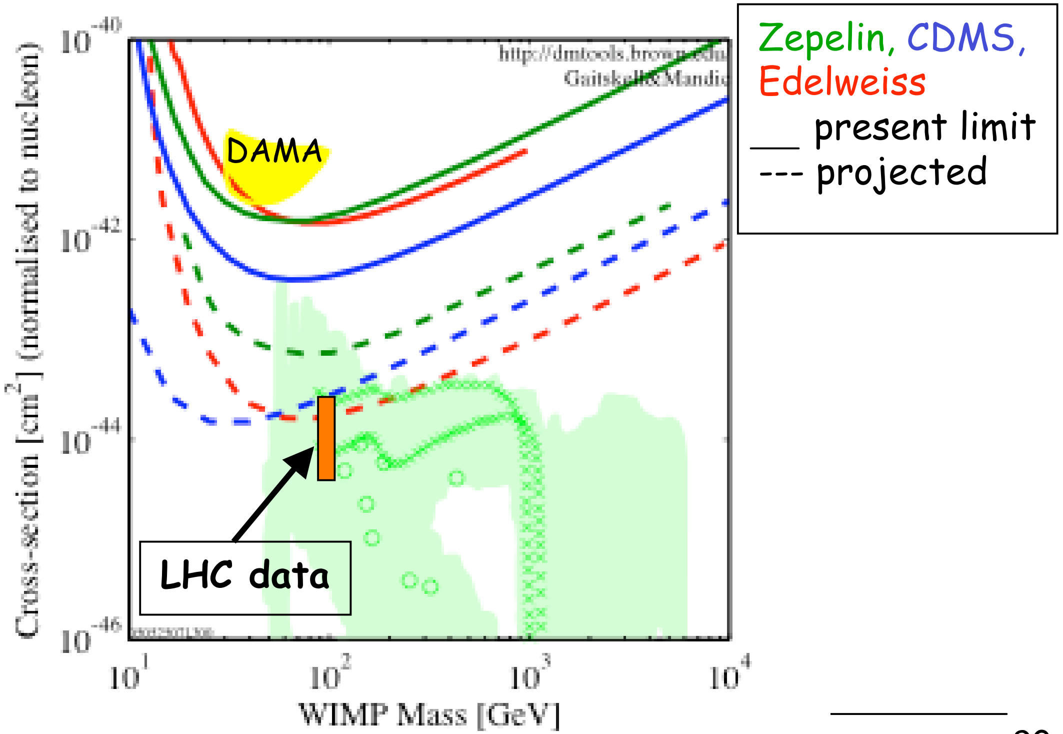
demonstrated so far in mSUGRA (5 param.) and in more general MSSM (14 param.)

As with SM at SLD, LEP, Tevatron



mSUGRA, Point "SPS1A"

Direct Dark Matter searches



General strategy toward understanding the underlying theory
(SUSY as an example …)

Discovery phase: inclusive searches … as model-independent as possible

First characterization of model: from general features: Large E_T^{miss} ? Many leptons ?
Exotic signatures (heavy stable charged particles, many γ's, etc.) ? Excess of b-jets or τ's ? …

Interpretation phase:
- reconstruct/look for semi-inclusive topologies, eg.:
  - -- h $\rightarrow$ bb peaks (can be abundantly produced in sparticle decays)
  - -- di-lepton edges
  - -- Higgs sector: e.g. A/H $\rightarrow \mu\mu, \tau\tau \Rightarrow$ indication about tanβ, measure masses
  - -- tt pairs and their spectra $\Rightarrow$ stop or sbottom production, gluino $\rightarrow$ stop-top
- determine (combinations of) masses from kinematic measurements (e.g. edges …)
- measure observables sensitive to parameters of theory (e.g. mass hierarchy)

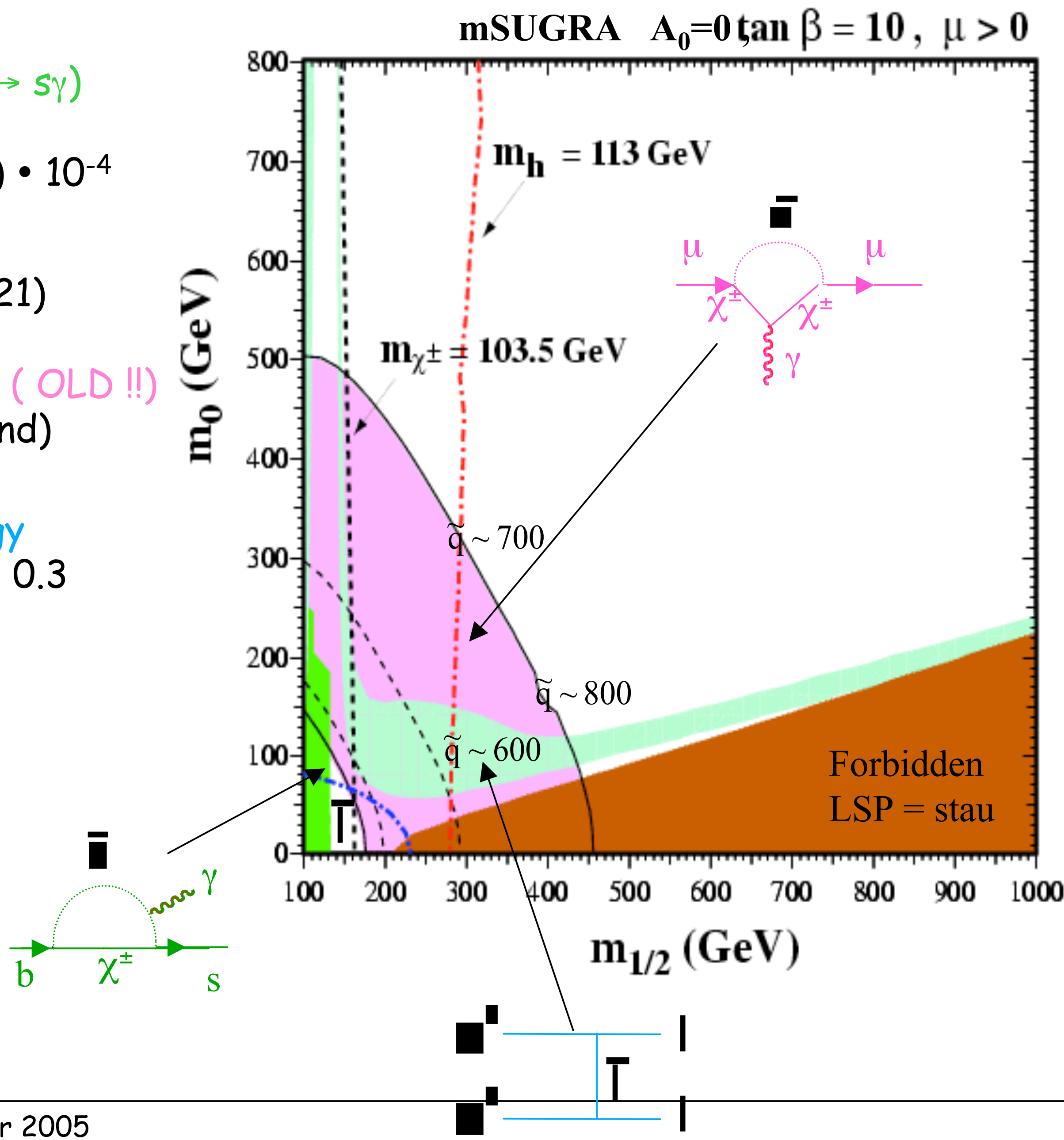
At each step narrow landscape of possible models and get guidance to go on:
- lot of information from LHC data (masses, cross-sections, topologies, etc.)
- consistency with other data (astrophysics, rare decays, etc.)
- joint effort theorists/experimentalists will be crucial

Combining collider data with other "constraints" ....

- Disfavoured by BR ($b \to s\gamma$) from CLEO, BELLE
  BR ($b \to s\gamma$) = $(3.2 \pm 0.5) \cdot 10^{-4}$ used here

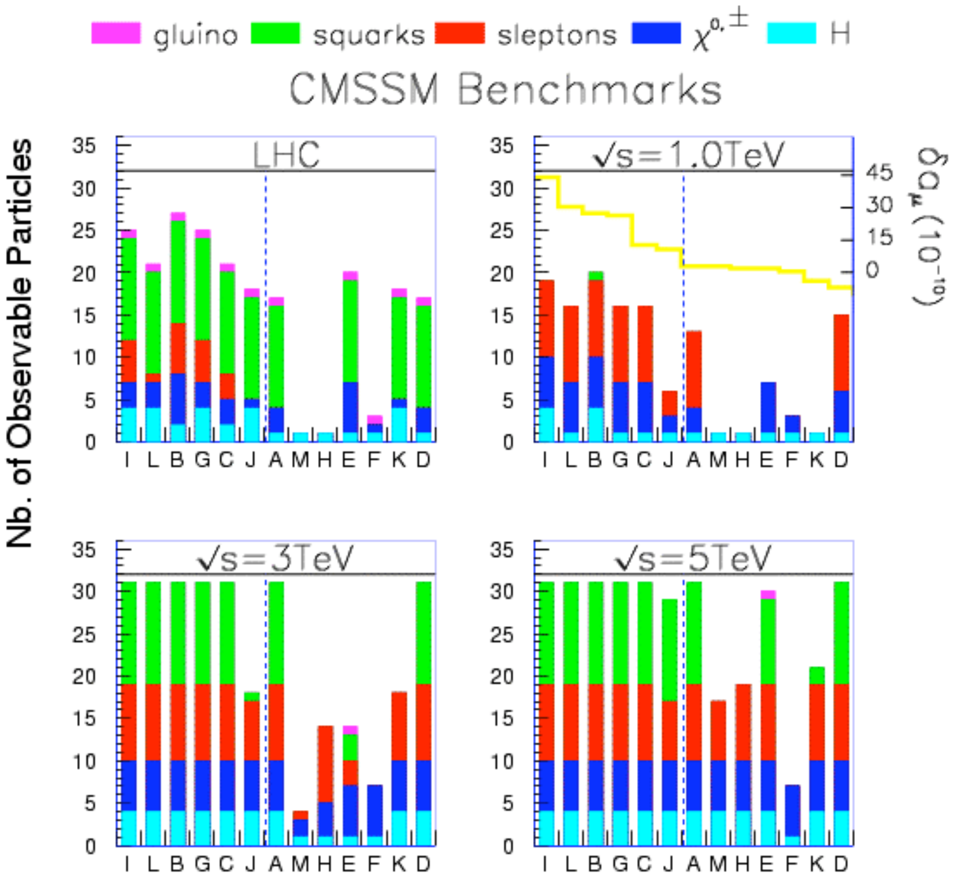
- Favoured by g_μ-2 (E821) assuming that
  $\delta a_\mu = (43 \pm 16) \cdot 10^{-10}$ (OLD !!) is from SUSY ($\pm$ 2 σ band)

- Favoured by cosmology assuming $0.1 \le \Omega_\chi h^2 \le 0.3$



Ellis, Olive

Complementarity between LHC and future e^+e^- Colliders



In general :

- LHC most powerful for ▮ and ▮ (strongly interacting) but can miss some EW sparticles (gauginos, sleptons) and heavy Higgs bosons

- Depending on √s, LC should cover part/all EW spectrum (usually lighter than squarks/gluinos) → should fill holes in LHC spectrum. Squarks could also be accessible if √s large enough.

LC can perform precise measurements of masses (to ~ 0.1%), couplings, field content of sparticles with mass up to ~ √s/2, disentangle squark flavour, etc.

What the LHC can do and cannot do ....

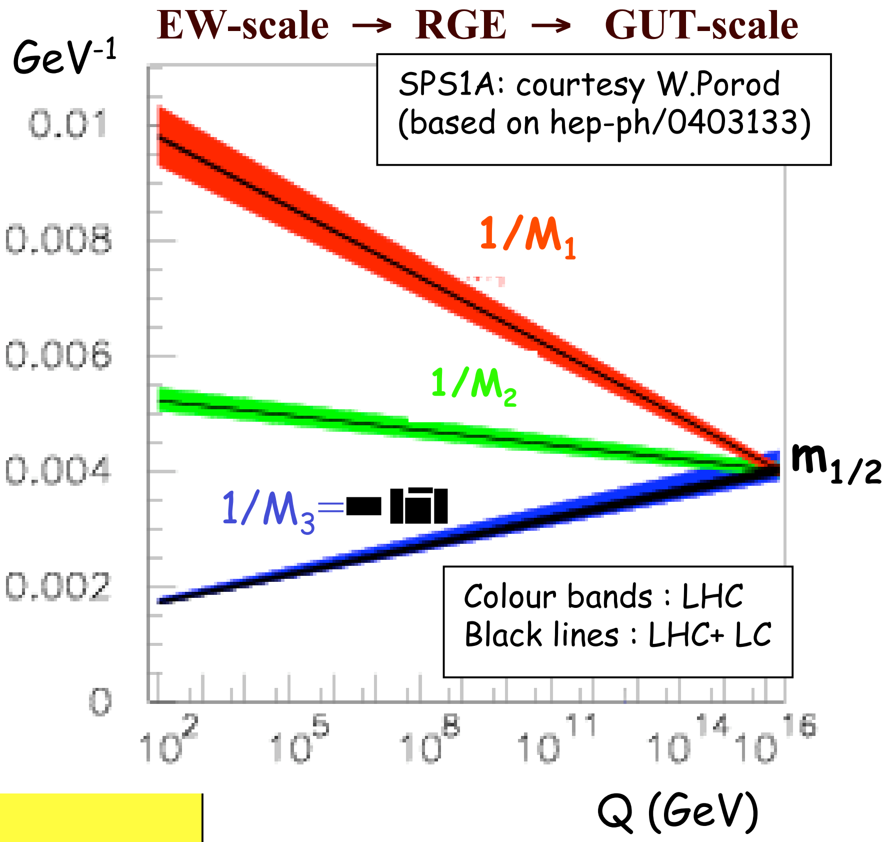
In general the LHC can (examples ...):

- discover SUSY up to m ($\tilde{q}, \tilde{g}$) ~ 2.5 TeV
- measure lightest Higgs h mass to ~ 0.1%
- derive sparticle masses (typically $\tilde{q}, \tilde{g}$, χ^0_2) from kinematic measurements
- constrain underlying theory by fitting a model to the data

More difficult or impossible (examples ...):

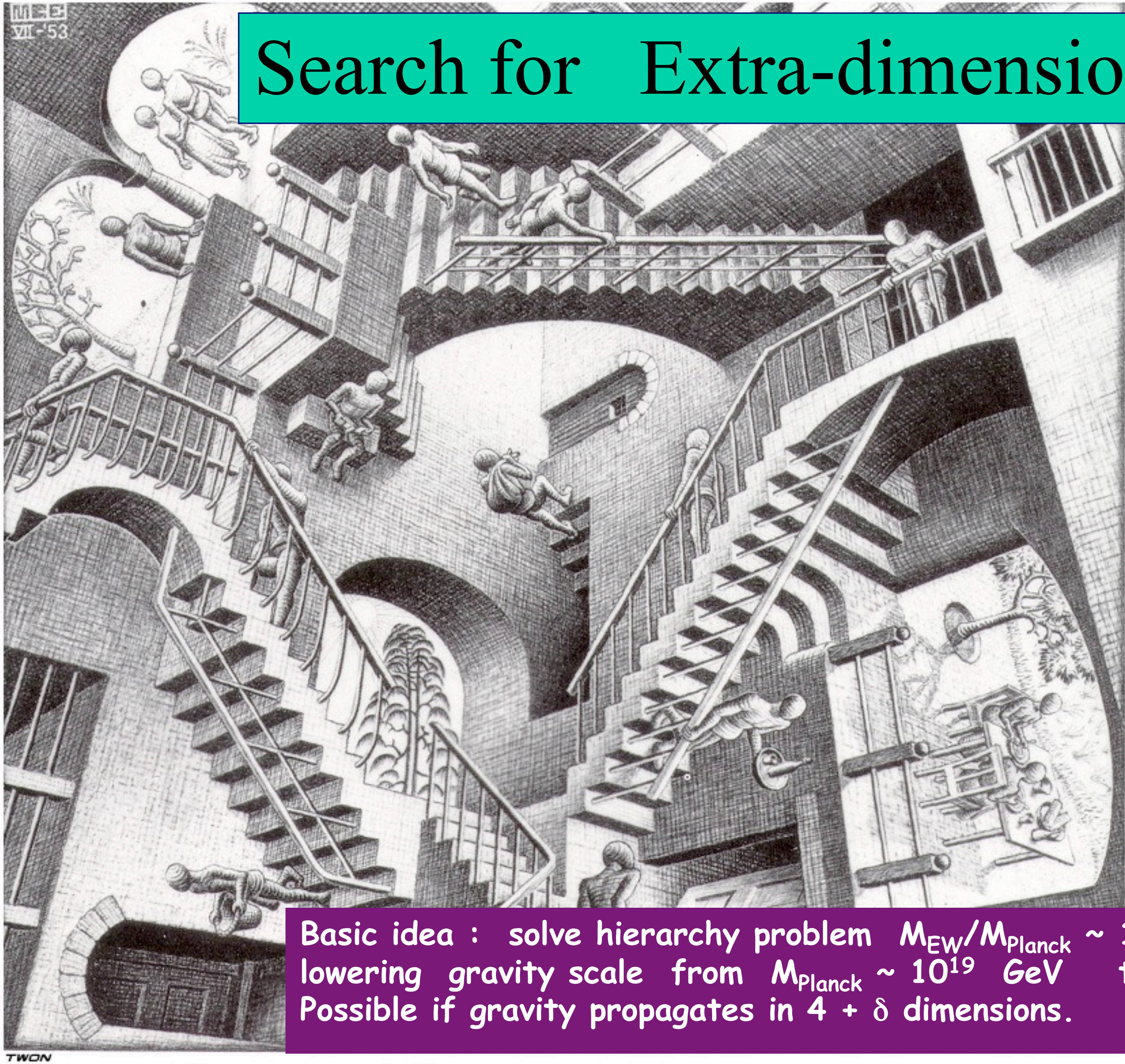
- disentangle squarks of first two generations
- observe / measure sleptons if m > 350 GeV
- measure full gaugino spectrum
- measure sparticle spin-parity and all couplings
- constrain underlying theory in model-indep. way

➡ complementarity with LC

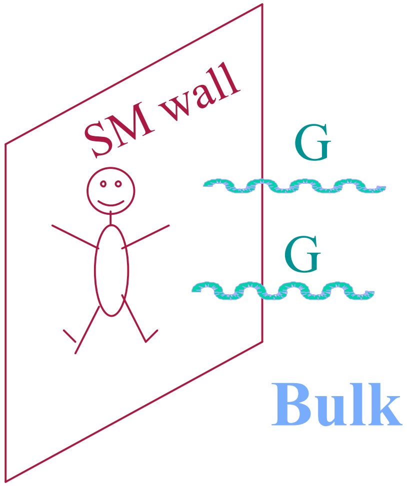


Ultimate goal : from precise measurements of e.g. gaugino masses at the TeV scale reconstruct high-E theory

Search for Extra-dimensions



Basic idea : solve hierarchy problem $M_{EW}/M_{Planck} \sim 10^{-17}$ by lowering gravity scale from $M_{Planck} \sim 10^{19}$ GeV to $M_D \sim 1$ TeV
Possible if gravity propagates in $4 + \delta$ dimensions.



Arkani-Hamed, Dimopoulos, Dvali

If gravity propagates
in $4+\delta$ dimensions,
a gravity scale $\mathbf{M_D \approx 1}$ **TeV** is possible

$$V_4(r) \sim \frac{1}{M_{Pl}^2}\frac{1}{r}$$

[illegible]

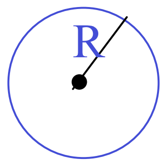
at large distance

$$M_{Pl}^2 \approx M_D^{\delta+2} R^\delta$$

- If $M_D \approx 1$ TeV :

$\delta = 1 \quad R \approx 10^{13}$ m $\rightarrow$ excluded by macroscopic gravity
$\delta = 2 \quad R \approx 0.7$ mm $\rightarrow$ limit of small- scale gravity experiments
....
$\delta = 7 \quad R \approx 1$ Fm

Extra-dimensions are compactified over $R <$ mm

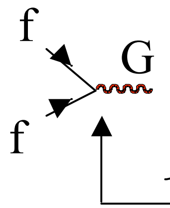


- Gravitons in Extra-dimensions get quantized mass:

[illegible]

$\Delta m \sim \frac{1}{R}$ e.g. $\Delta m \approx 400$ eV $\delta = 3$

→ continuous tower of massive gravitons (Kaluza - Klein excitations)

σ 

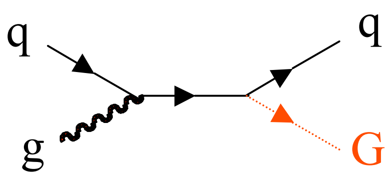
[illegible]

Due to the large number of G_{kk}, the coupling SM particles - Gravitons becomes of EW strength

- Only one scale in particle physics : EW scale
- Can test geometry of universe and quantum gravity in the lab

Extra-dimensions (ADD models)

Look for a continuum of Graviton KK states :



→ topology is jet(s) + missing E_T

Cross-section [illegible]

M_D = gravity scale
δ = number of extra-dimensions

ATLAS, 100 fb^{-1}

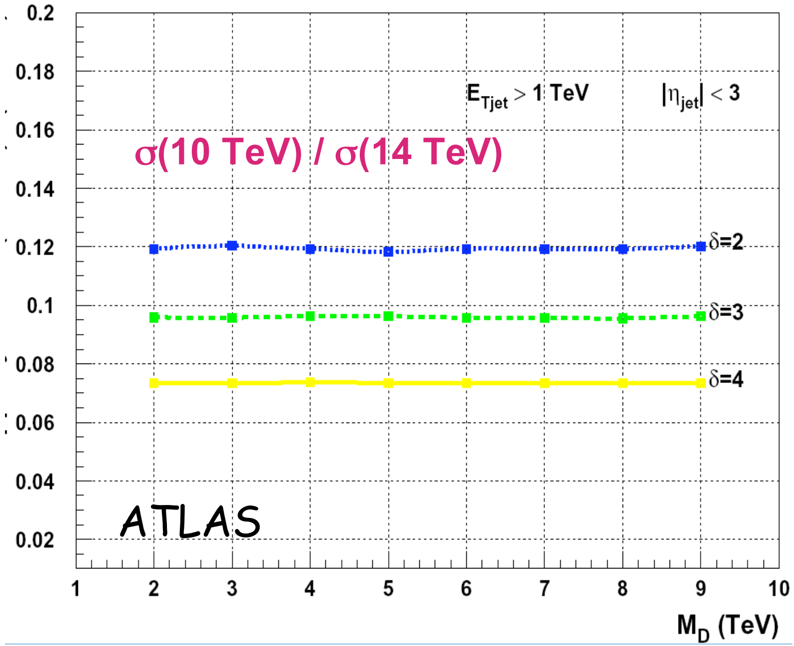
	$\delta = 2$	$\delta = 3$	$\delta = 4$
M_D^{max}	9 TeV	7 TeV	6 TeV

Discriminating between models:
-- SUSY : multijets plus E_T^{miss} (+ leptons, …)
-- ADD : monojet plus E_T^{miss}

To characterize the model need to measure M_D and δ

Measurement of cross-section gives ambiguous results: e.g. δ=2, M_D= 5 TeV very similar to δ=4, M_D= 4 TeV

Solution may be to run at different $\sqrt{s}$:



Good discrimination between various solutions possible with expected <5% accuracy on $\sigma(10)/\sigma(14)$ for 50 fb^{-1}

$G \rightarrow e^+e^-$ resonance with m ~ 1 TeV

The easiest object to discover at the LHC …

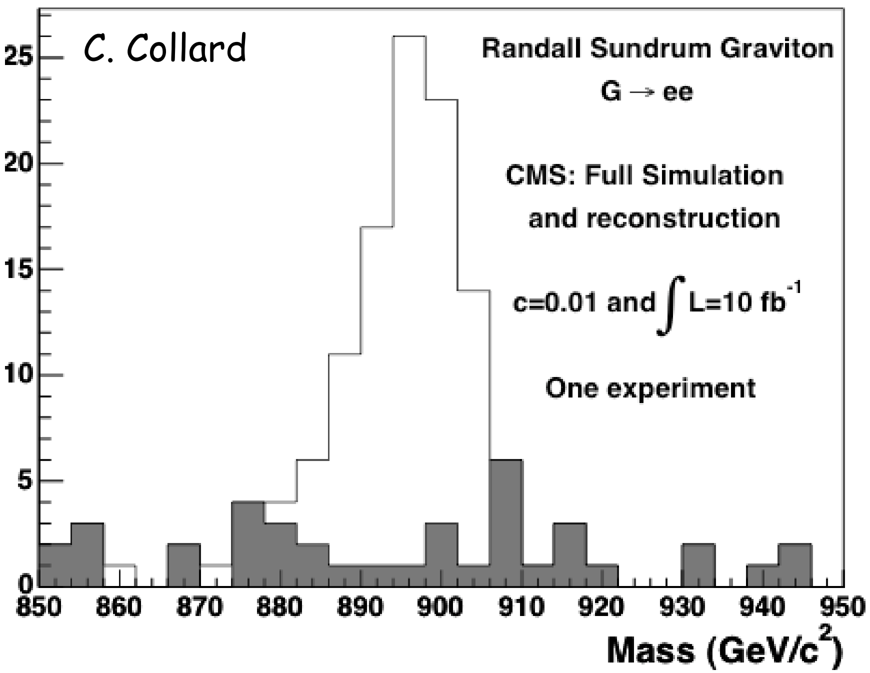
Randall-Sundrum Extra-dimensions

BR ($G \rightarrow ee \approx 2\%$), c = 0.01 (small/conservative coupling to SM particles)

Mass (TeV)	Events for 10 fb^{-1} (after all cuts)	$\int L\,dt$ for discovery ($\geq$ 10 observed events)
0.9	~ 80	~ 1.2 fb^{-1}
1.1	~ 25	~ 4 fb^{-1}
1.25	~ 13	~ 8 fb^{-1}

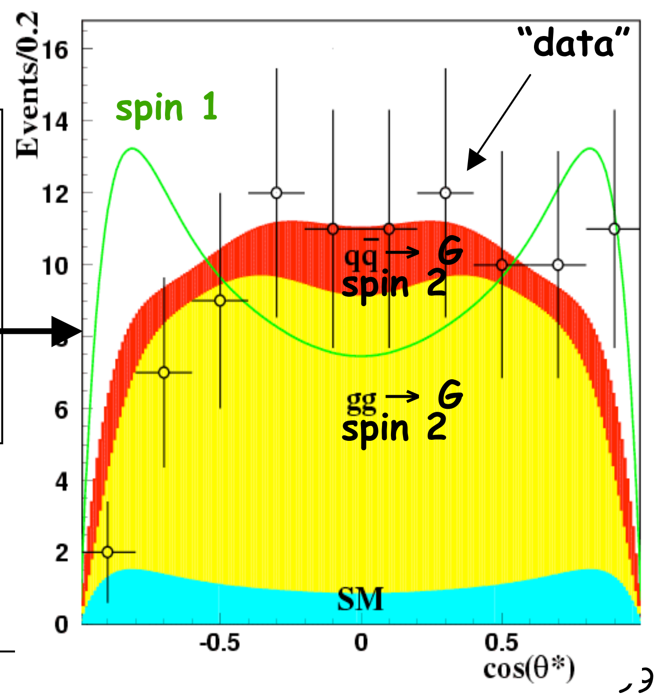
CMS

- large enough signal for discovery with ~ 1 fb^{-1} for m → 1 TeV
- dominant Drell-Yan background small
- signal is <u>mass peak</u> above background



Graviton (s=2) or Z′ (s=1) ?
→ look at $e^\pm$ angular distributions

ATLAS, 100 fb^{-1}, m_G=1.5 TeV



Mini black holes production at LHC ?

… quite speculative for the time being … many big theoretical uncertainties

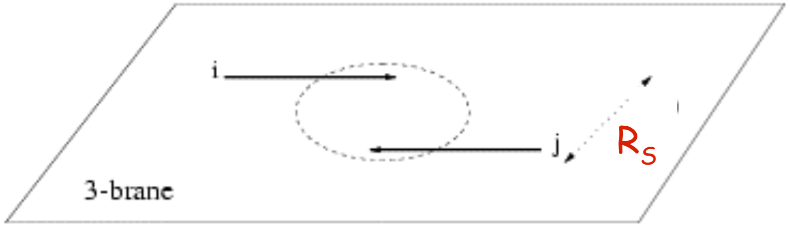
- Schwarzschild radius (i.e. within which nothing escapes gravitational force):

4-dim., $M_{gravity} = M_{Planck}$: [illegible]

4 + δ-dim., $M_{gravity} = M_D \sim$ TeV : [illegible]

⬇

Since M_D is low, tiny black holes of $M_{BH} \sim$ TeV can be produced if partons ij with $\sqrt{s_{ij}} = M_{BH}$ pass at a distance smaller than R_S

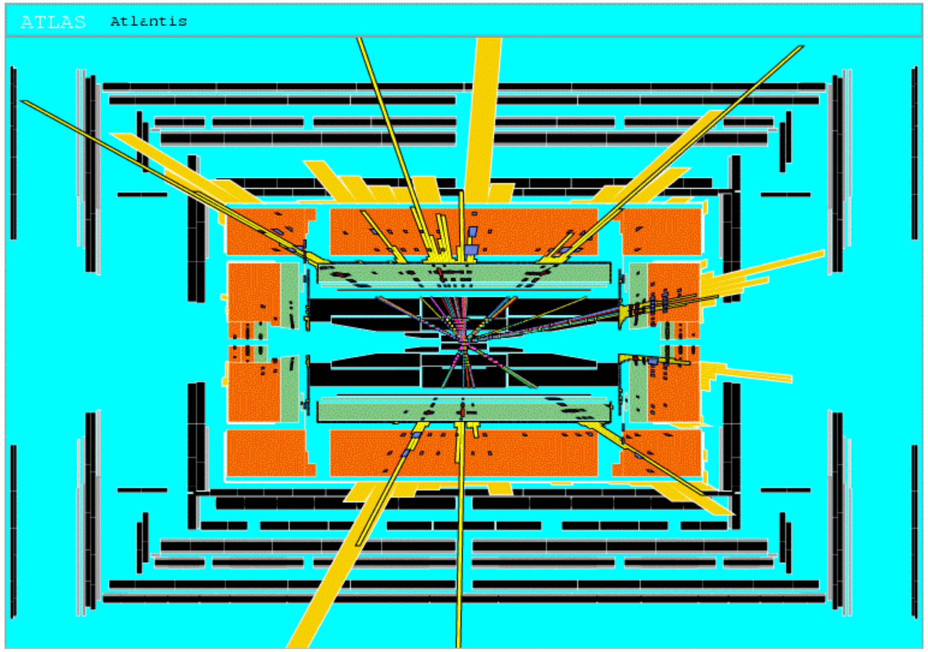


- Large partonic cross-section : $\sigma(ij \to BH) \sim \pi R_S^2$

  e.g. For $M_D \sim 3$ TeV and $\delta = 4$, $\sigma(pp \to BH) \sim 100$ fb $\to$ 1000 events in 1 year at low L

- Black holes decay immediately ($\tau \sim 10^{-26}$ s) by Hawking radiation (democratic evaporation) :
  - -- large multiplicity
  - -- small missing E
  - -- jets/leptons ~ 5

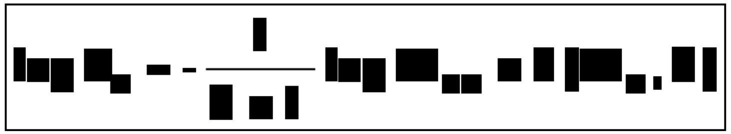
  } expected signature (quite spectacular …)



A black hole event with $M_{BH} \sim 8$ TeV in ATLAS

From preliminary studies : reach is $M_D \sim 6$ TeV for any δ in one year at low luminosity.

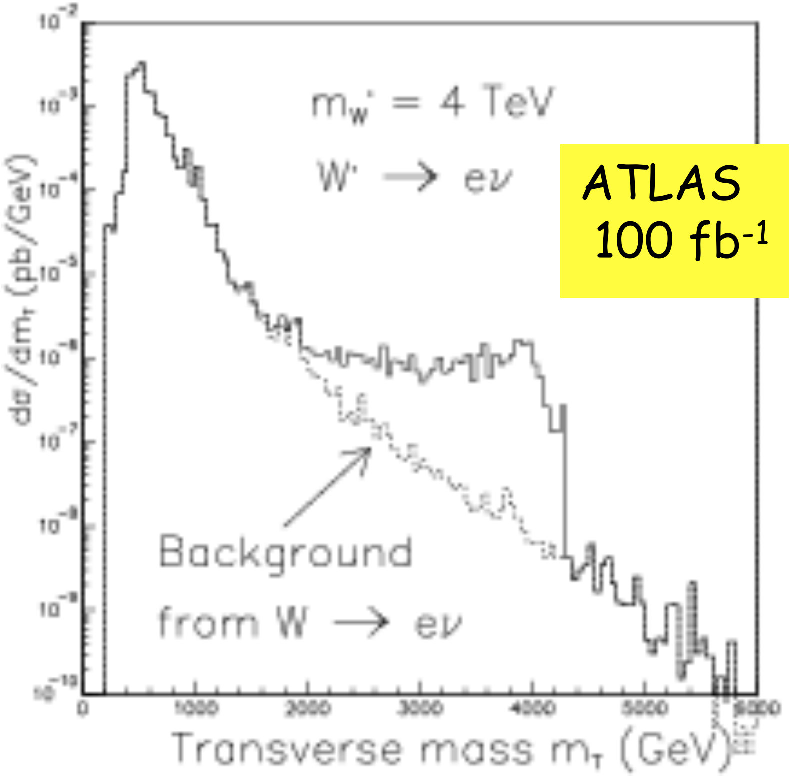
By testing Hawking formula ◊ proof that it is BH + measurement of M_D, δ



precise measurements of M_{BH} and T_H needed (T_H from lepton and photon spectra)

Other examples of reach for Physics beyond SM ...

Excited quarks $q^* \to \gamma q$: up to $m \approx 6$ TeV
Leptoquarks: up to $m \approx 1.5$ TeV
Monopoles $pp \to \gamma\gamma pp$: up to $m \approx 20$ TeV
Compositeness: up to $\Lambda \approx 40$ TeV
$Z' \to ll$, jj: up to $m \approx 5$ TeV
$W' \to l\nu$: up to $m \approx 6$ TeV
etc.... etc....



Large number of scenarios studied:
⇒ demonstrated detector sensitivity to many signatures
→ robustness, ability to cope with unexpected scenarios
⇒ LHC direct discovery reach up to $m \approx$ 5-6 TeV

Conclusions

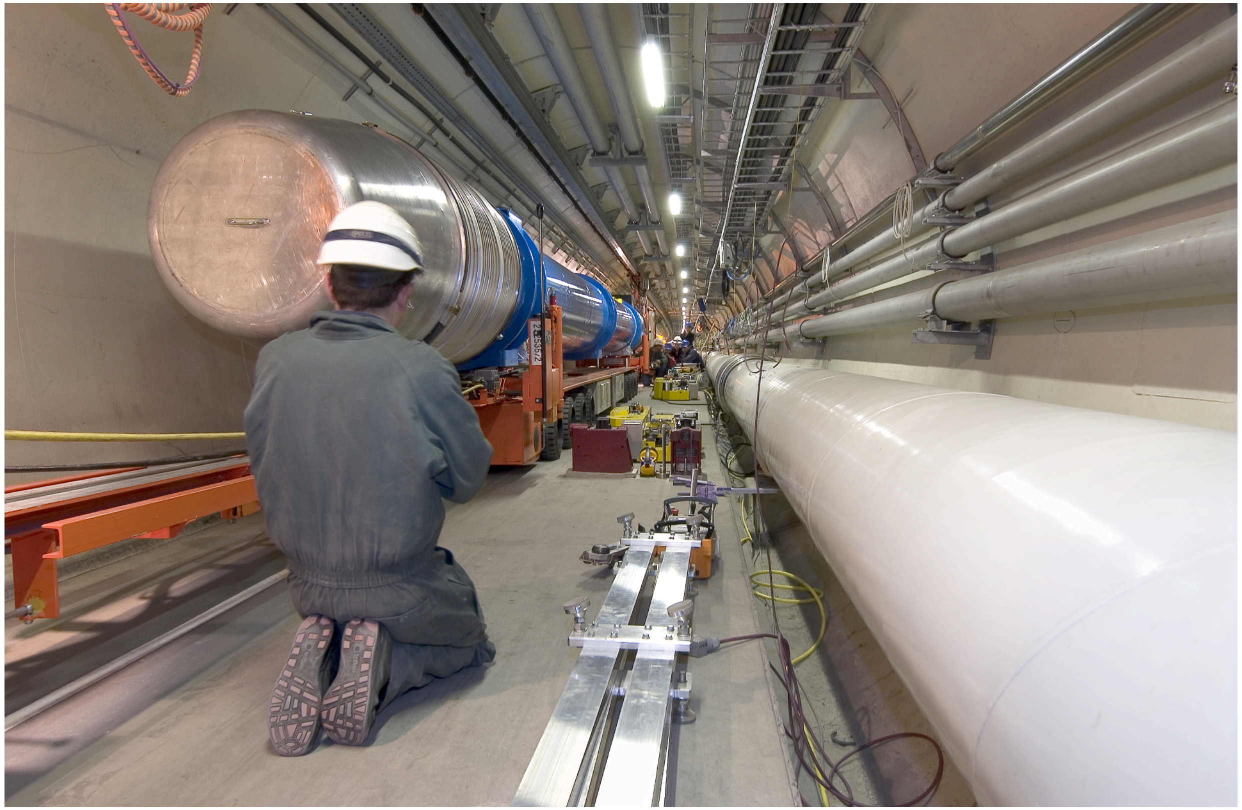
In ~ 2 years from now, the LHC will start operation and particle physics will enter a new epoch, hopefully the most glorious and fruitful of its history.

We can anticipate a profusion of exciting results from a machine able to explore in detail the highly-motivated TeV-scale with a direct discovery potential up to m ≈ 5-6 TeV

→ if New Physics is there, the LHC will find it
→ it will say the final word about the SM Higgs mechanism and many TeV-scale predictions
→ it may add crucial pieces to our knowledge of fundamental physics → impact also on astroparticle physics and cosmology
→ most importantly: it will likely tell us which are the right questions to ask, and how to go on

Sensitivity of experiments to huge numbers of signatures and models demonstrated in 15 years of simulation efforts and test-beam
→ robustness, potential ability to cope with unexpected scenarios

Has Nature prepared a "pleasant" welcome to the TeV-scale (striking signals with limited luminosity and non-ultimate detector performance) or shall we have to sweat through years of data taking and hard work before we can claim a discovery ?



Early determination of scale of New Physics would be crucial for planning of future facilities (ILC ? CLIC ? Underground Dark Matter searches ? ….)
The future of our discipline will benefit from a quick feedback on SUSY and the rest .. !

Next challenge: efficient and as-fast-as-possible commissioning of machine and detectors of unprecedented complexity, technology and performance
Crucial to reach quickly the "discovery-mode" and extract a convincing "early" signal

Spare slides

Magnet Installation

- Installation is progressing in sectors 8-1 and 4-5. More than 100 superconducting magnets have been installed. The installation rate must now ramp up to 20 magnets per week (16 dipoles and 4 SSSs) in the next few weeks.

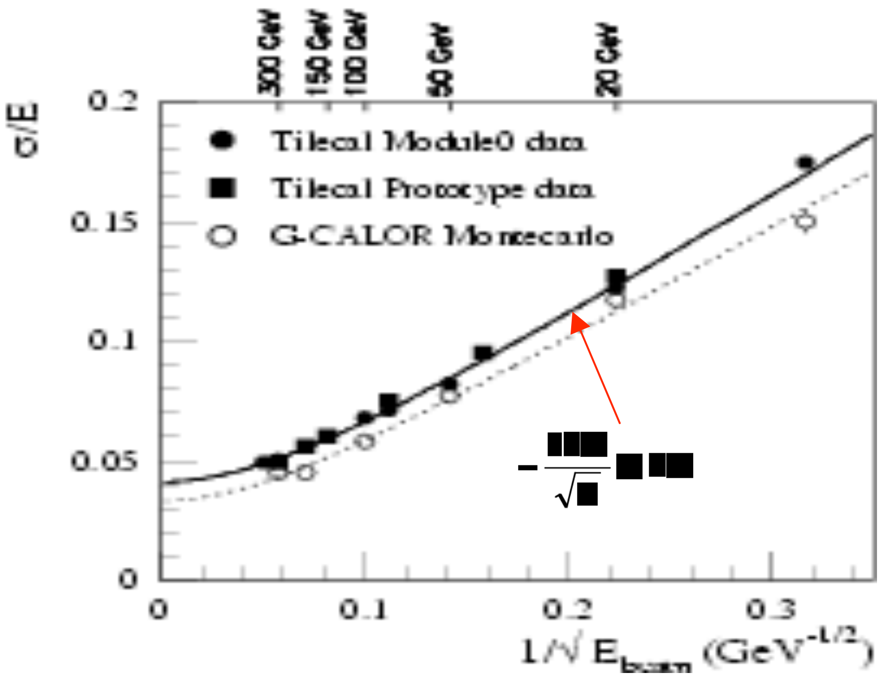
- At the end of October, sector 7-8 will be liberated for magnetic installation. From then on there will be no shortage of slots.

Examples of performance and issues relevant to SUSY studies

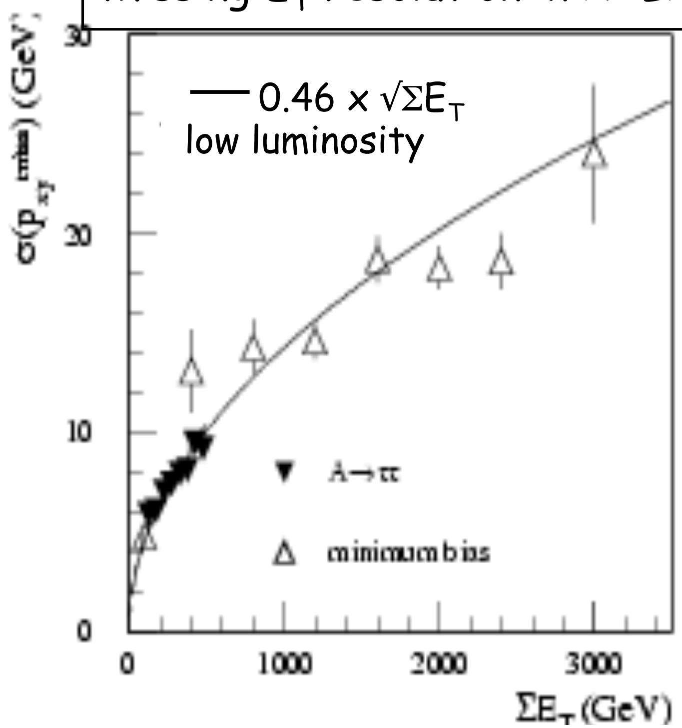
from full sim.

- Good E-resolution of (hadronic) calorimetry:
  - -- reduces fake MET from detector resolution in QCD multijet events
  - -- narrow mass peaks : $W \rightarrow jj$, $h \rightarrow bb$, $t \rightarrow bjj$ from SUSY cascade decays; $A/H \rightarrow \tau\tau$, etc.
  - -- etc.

Pion E-resolution (test-beam data)



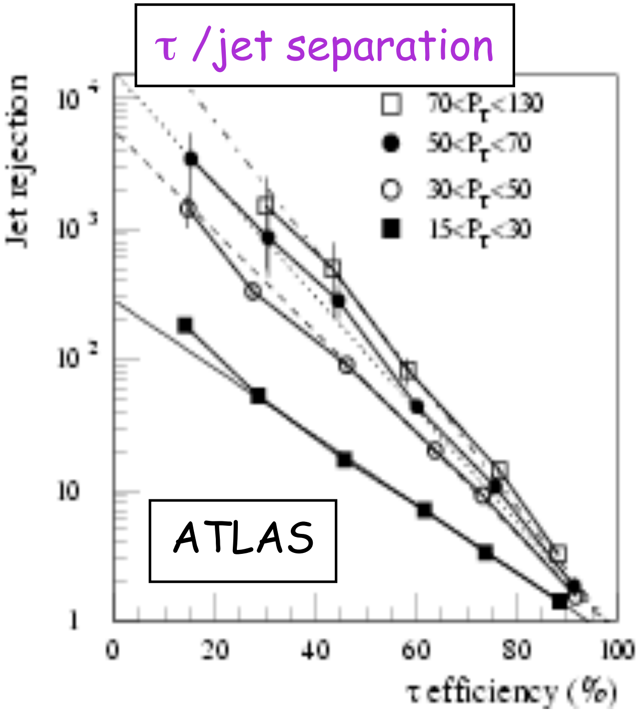
Missing E_T resolution in ATLAS



High lumi : MET resolution is ~ 2 worse

◆ Powerful b-tagging and τ-identification:

-- τ's and b-jets expected in sparticle and SUSY Higgs decays (especially at large tanβ)
-- in general 3rd generation could play a special role in New Physics



From full simulation of τ's from $A \rightarrow \tau\tau$ events and QCD jets

τ's are identified as narrow and low multiplicity jets in calorimeters and tracker

Precise knowledge of absolute lepton, jet and missing E_T energy scales:

→ for precise measurements of SUSY events, e.g. end-points of kinematic distributions, A/H → μμ mass, etc. (in many cases statistical error is negligible)

Can only be achieved with *in situ* calibration with data samples

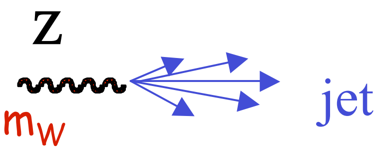
l-scale

- mainly from Z → ll events (1 evt/s per species at 10^{33})
- ~ 1 ‰ uncertainty achieved by CDF, D0 (dominated by statistics of control samples)
- LHC goal : 0.2 ‰ to measure m_W to ~ 15 MeV (1 ‰ assumed here)

↓

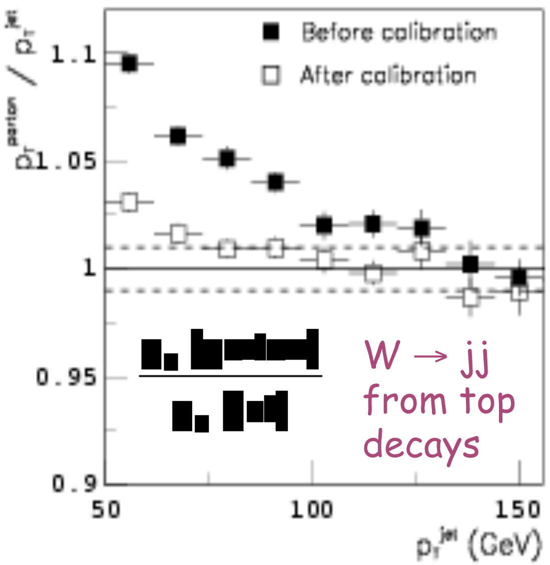
ATLAS: full simulation study of uncertainty on Z → ee scale

Source	Requirement	Uncertainty on scale
Material in Inner Detector	Known to 1%	< 0.01%
Inner bremsstrahlung	Known to 10%	< 0.01%
Underlying event	Calibrate and subtract	<< 0.03%
Pile-up at low luminosity	Calibrate and subtract	<< 0.01%
Pile-up at high luminosity	Calibrate and subtract	<< 0.01%



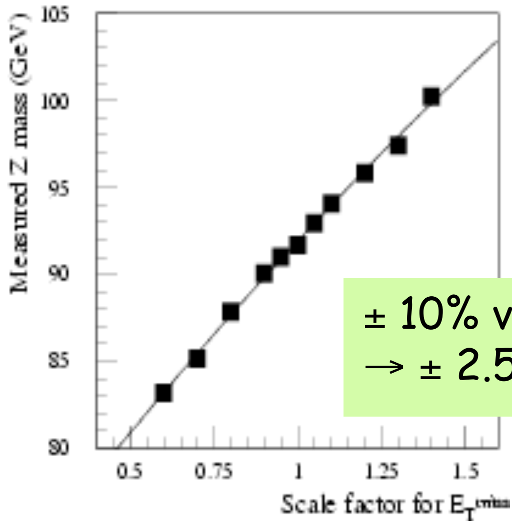
Jet-scale

- mainly from Z (→ ll) + 1 jet asking p_T (jet) = p_T (Z)
  and from W → jj in tt → bW bW → blν bjj events asking $m_{jj} = m_W$
- ~ 3 % uncertainty achieved by CDF, D0 (not enough tt statistics at Tevatron)
- LHC goal : ~ 1 % to measure m_{top} to ~ 1 GeV
- main systematics : FSR, underlying event, etc.



Missing ET scale

- mainly from Z → ττ → l-hadrons + ν 's
- sensitivity of reconstructed Z mass to MET scale



ATLAS,
full simulation

± 10% variation on MET scale
→ ± 2.5 % variation of m_Z

- m_Z can be measured to 1% with 4000 evts (30 fb^{-1})
  → MET scale can be constrained to ~ 5%

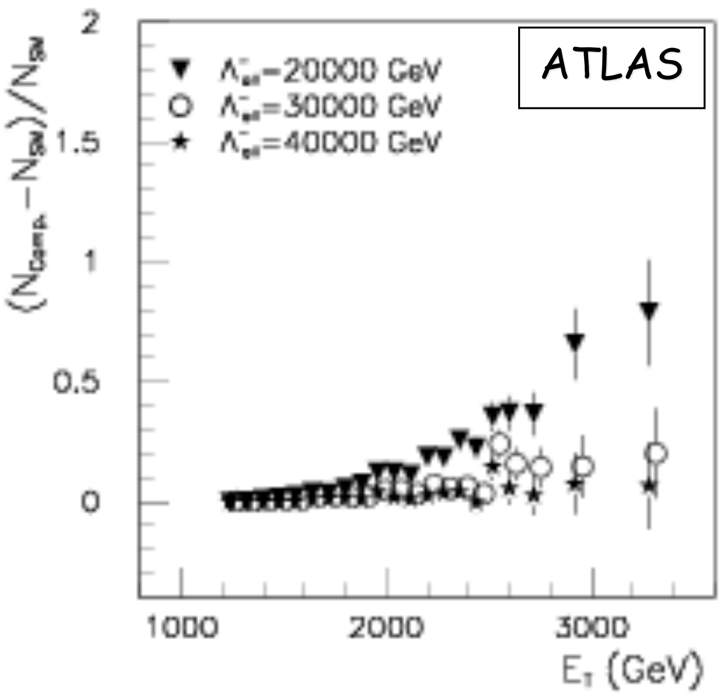
Calorimeters :

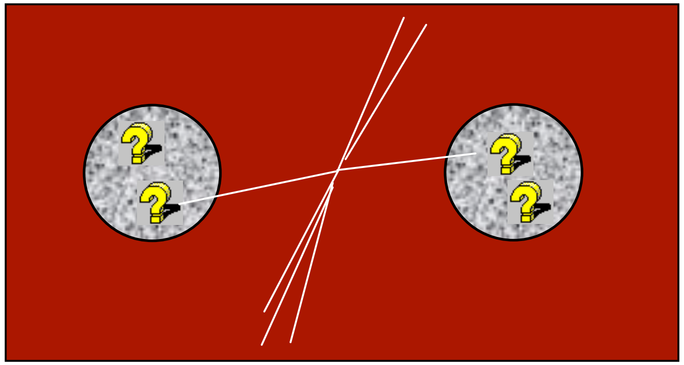
-- $e/\pi/\mu$ test-beam data available for E ~ 1-300 GeV
-- "calibration" samples at LHC, e.g. Z (◊ ll) +jets, cover up to few hundreds GeV

Validate simulation over this range and use it to predict detector response at E ~ TeV (where New Physics is expected !)

Example :

Are quarks really point-like ?

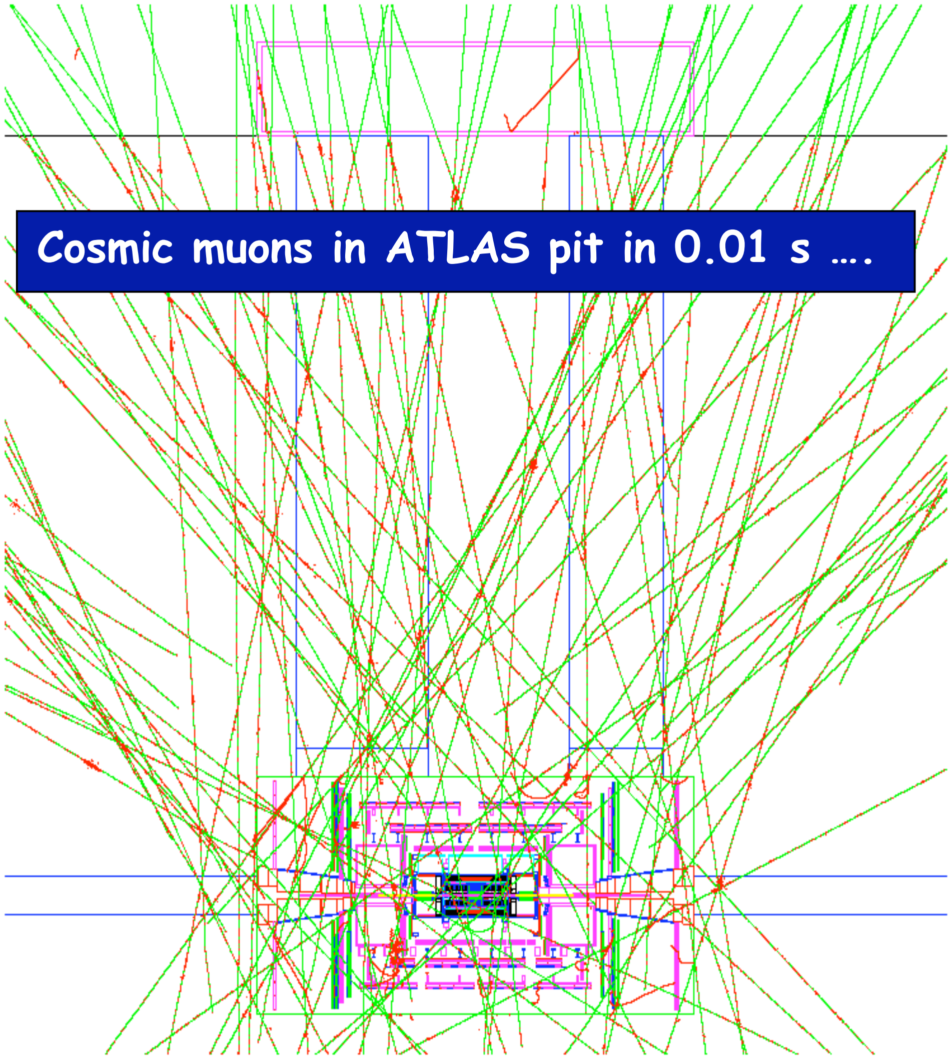




If quarks are composite : new qq → qq interactions with strength ~$1/\Lambda^2$, $\Lambda \equiv$ scale of New Physics.
⇒ expect excess of high-p_T jets compared to SM
The higher Λ the smaller the excess.
LHC sensitivity up to $\Lambda \approx$ 40 TeV

A hadron calorimeter non-linearity of 1.5 % at E_{jet} ~ 4 TeV, not reproduced by simulation, may fake a scale $\Lambda \approx$ 30 TeV ⇒ inadequacy of simulation would limit LHC physics reach

To avoid this : simulation must reproduce e/π response ratio (which governs response non-linearity to jets) to few percent



From full simulation of ATLAS (including cavern, overburden, surface buildings) + measurements with scintillators in the cavern:

Through-going muons	~ 25 Hz
(hits in ID + top and bottom muon chambers)	
Pass by origin	~ 0.5 Hz
(|z| < 60 cm, R < 20 cm, hits in ID)	
Useful for ECAL calibration	~ 0.5 Hz
(|z| < 30 cm, E_{cell} > 100 MeV, ~ 90^0)	

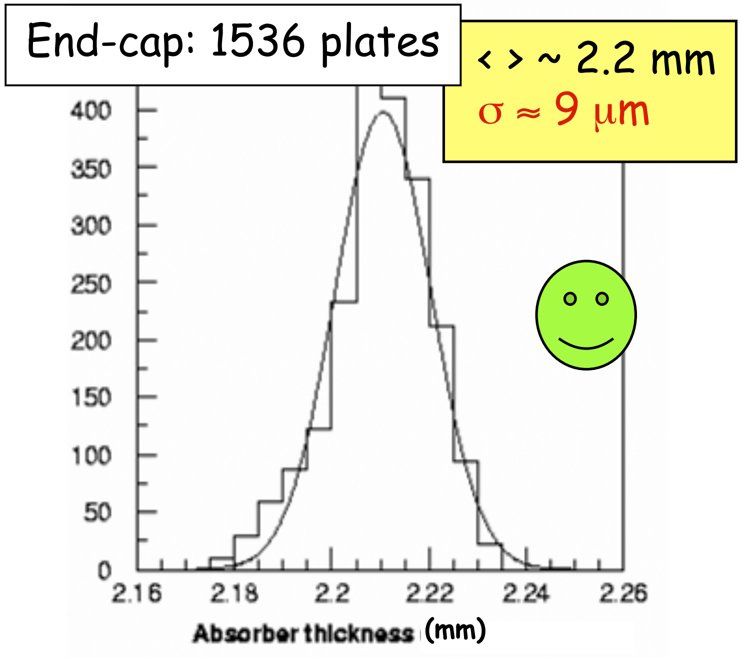
◊ ~ 10^6 events in ~ 3 months of data taking

◊ enough for initial detector shake-down

(catalog problems, gain operation experience, some alignment/calibration, detector synchronization, …)

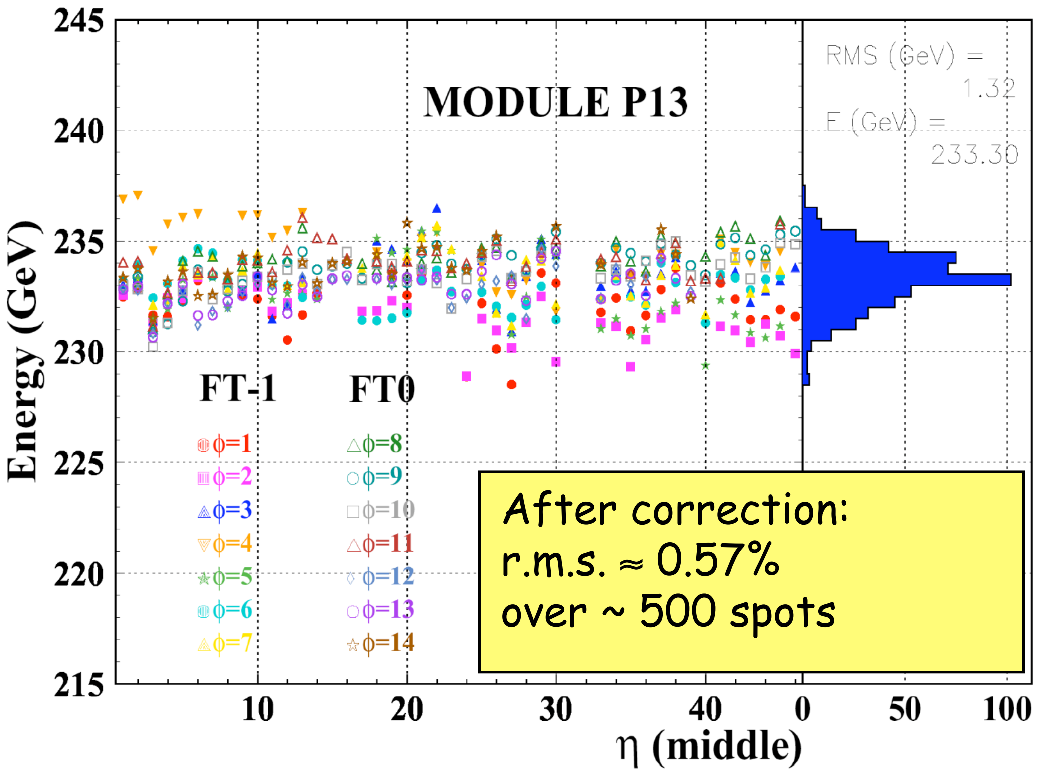
Construction quality

Thickness of Pb plates must be uniform to 0.5% (~10 μm)

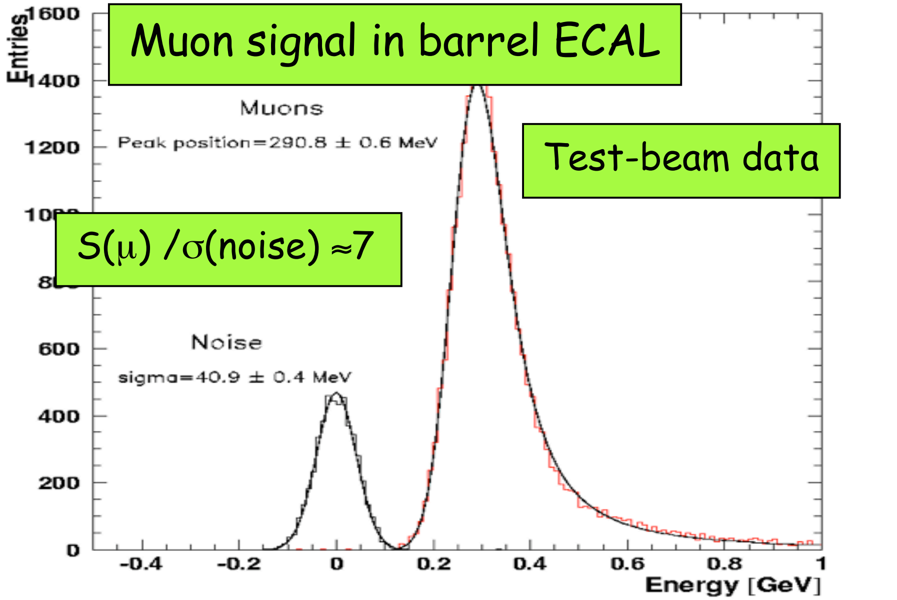


Test-beam measurements

Scan of a barrel module (Δφ×Δη=0.4X1.4) with high-E electrons



Cosmics runs:



Measured cosmic μ rate in ATLAS pit : few Hz

◊ ~ 10^6 events in ~ 3 months of cosmics runs beginning 2007

◊ enough for initial detector shake-down

◊ ECAL : check calibration vs η to 0.5%

First collisions : calibration with $Z \to ee$ events (rate ≈ 1 Hz at 10^{33})

Use Z-mass constraint to correct long-range non-uniformities
(module-to-module variations, effect of upstream material, etc.)
~ 10^5 $Z \to ee$ events (few days data taking at 10^{33}) enough to achieve constant term $c \leq 0.7\%$

Nevertheless, let's consider the worst (unrealistic ?) scenario : no corrections applied

ECAL non-uniformity at construction level, i.e.:
-- no test-beam corrections
-- no calibration with $Z \to ee$

→ $c \approx 2\%$

$H \to \gamma\gamma$ significance m_H~ 115 GeV degraded by ~ 25%
→ need 50% more L for discovery

The first year(s) of data taking

First collisions (Summer 2007) : L ~ 5x 10^{28}
Plans to reach L ~ 10^{33} in/before 2009
Hope to collect few fb^{-1} per experiment by end 2008

Channels (examples ...)	Events to tape for 1 fb^{-1} (per expt: ATLAS, CMS)	Total statistics from previous Colliders
W ◊ $\mu\nu$	7 x 10^6	~ 10^4 LEP, ~ 10^6 Tevatron
Z ◊ $\mu\mu$	~ 10^6	~ 10^6 LEP, ~ 10^5 Tevatron
tt ◊W b W b ◊ $\mu\nu$ +X	~ 10^5	~ 10^4 Tevatron
$\tilde{g}\tilde{g}$ m = 1 TeV	10^2 - 10^3	———

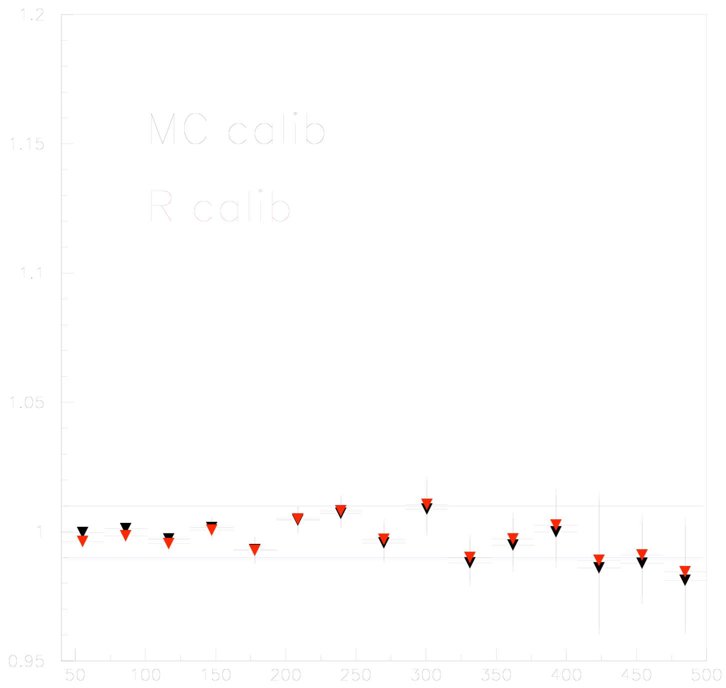
With these data:

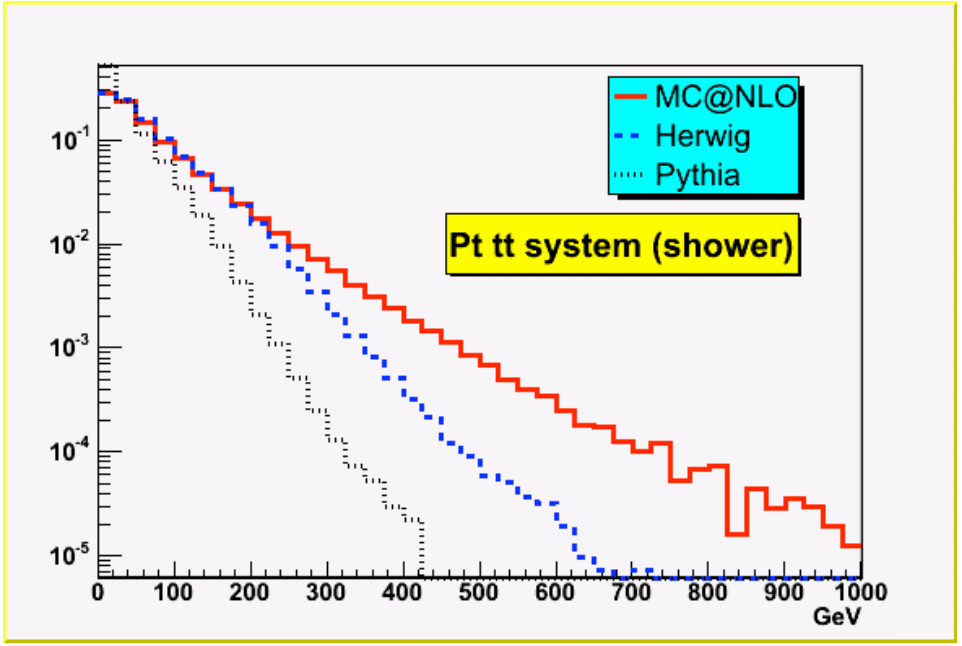
- Understand and calibrate detectors in situ using well-known physics samples
  e.g. - Z → ee, $\mu\mu$ tracker, ECAL, Muon chambers calibration and alignment, etc.
  - tt → blν bjj jet scale from W◊jj, b-tag performance, etc.

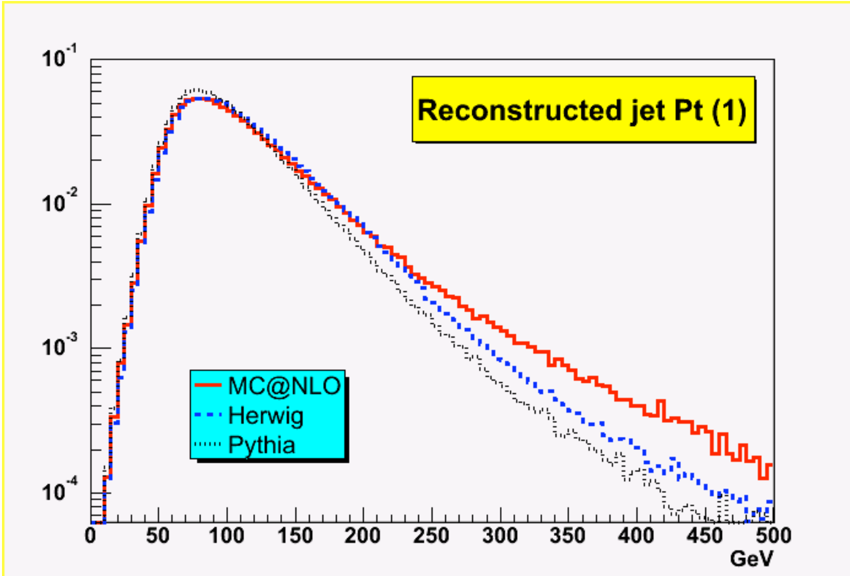
- Measure SM physics at $\sqrt{s}$ = 14 TeV : W, Z, tt, QCD jets ... (omnipresent backgrounds to New Physics)

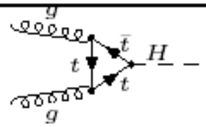
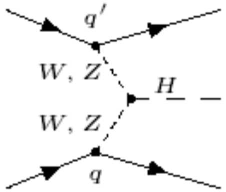
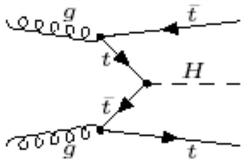
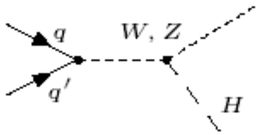
→ prepare the road to discovery .... it will take a lot of time ...

Use the W mass constraint to set the JES.
Rescale jet E and angles to parton energy $\alpha = E_{parton} / E_{jet}$







Production		Decay	mass ranges
	Gluon-Fusion $(gg \to H)$	$H \to ZZ \to 4l$	110 GeV - 200 GeV
		$H \to WW \to l\nu\, l\nu$	110 GeV - 200 GeV
		$H \to \gamma\gamma$	110 GeV - 150 GeV
	WBF $(qq\,H)$	$H \to ZZ \to 4l$	110 GeV - 200 GeV
		$H \to WW \to l\nu\, l\nu$	110 GeV - 190 GeV
		$H \to \tau\tau \to l\nu\nu\, l\nu\nu$	110 GeV - 150 GeV
		$H \to \tau\tau \to l\nu\nu\, \mathrm{had}\nu$	110 GeV - 150 GeV
		$H \to \gamma\gamma$	110 GeV - 150 GeV
	$t\bar{t}H$	$H \to WW \to l\nu\, l\nu\, (l\nu)$	120 GeV - 200 GeV
		$H \to b\bar{b}$	110 GeV - 140 GeV
		$H \to \tau\tau$ (not included)	110 GeV - 150 GeV
		$H \to \gamma\gamma$	110 GeV - 120 GeV
	$W\,H$	$H \to WW \to l\nu\, l\nu\, (l\nu)$	150 GeV - 190 GeV
		$H \to \gamma\gamma$	110 GeV - 120 GeV
	ZH	$H \to \gamma\gamma$	110 GeV - 120 GeV

- Minimal models : 2 Higgs doublets → 5 physical states : h, H, A, $H^{\pm}$

- At tree level SUSY Higgs sector described by two parameters : m_A, tgβ
  Radiative corrections introduce dependence on m_{top}, m_{stop}, stop mixing, etc.

- m_h increases with m_A, tgβ (for m_A < 200, tgβ <10), m_{top}, m_{stop} , mixing

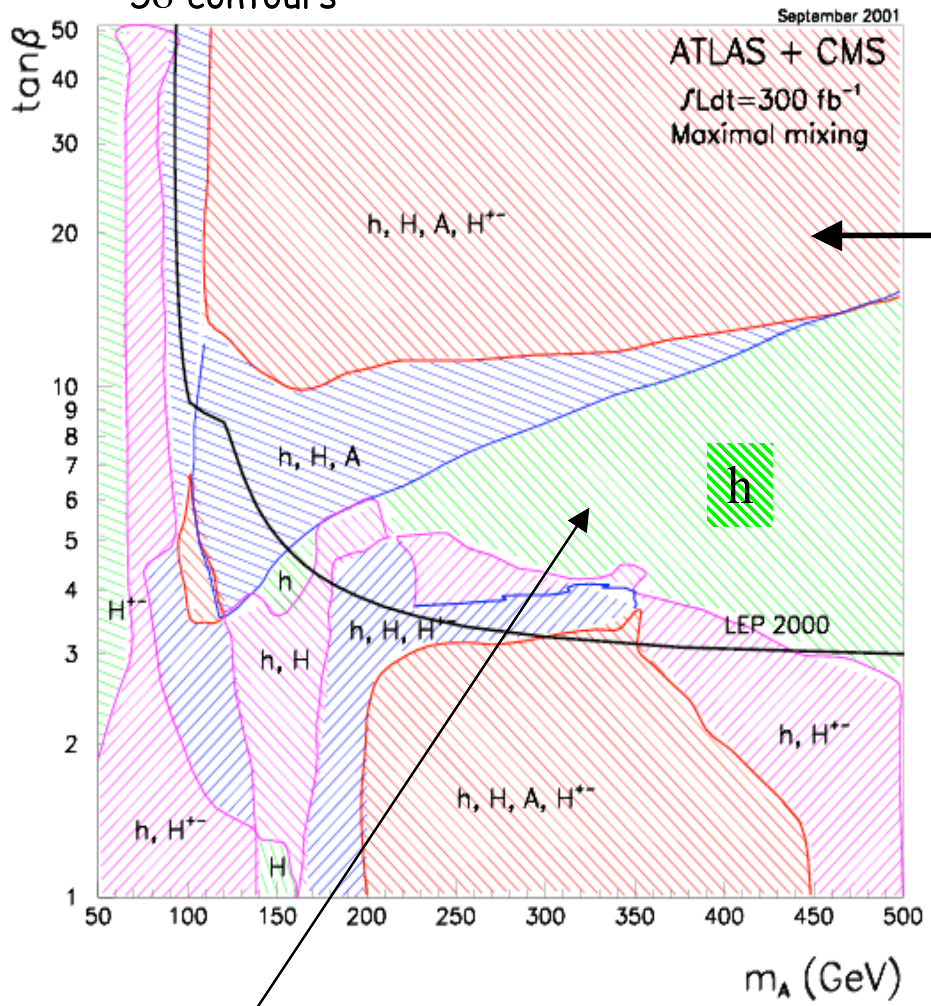
  m_{top}= 174.3 GeV
  - -- no mixing : m_h < 115 GeV → almost fully excluded by LEP
  - -- m_h-max scenario : m_h < 130 GeV

- H, A, $H^{\pm}$ usually heavier and degenerate for m_A > 200 GeV

SUSY Higgs sector : h, H, A, $H^{\pm}$

m_h < 135 GeV , $m_A \approx m_H \approx m_{H^{\pm}}$

5σ contours



H, A → μμ, ττ
$H^{\pm}$ → τν , tb

- 4 Higgs observable
- 3 Higgs observable
- 2 Higgs observable
- 1 Higgs observable

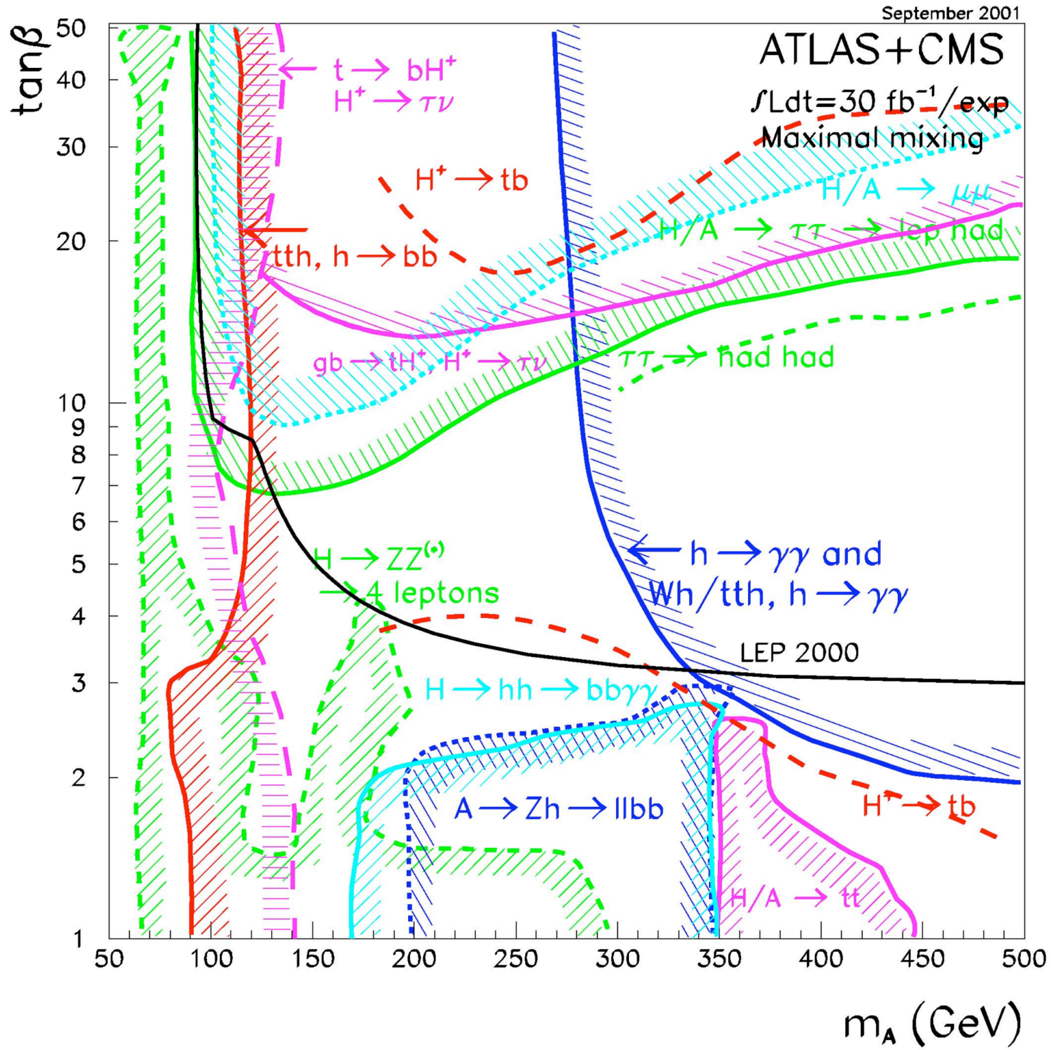
Assuming decays to SM particles only

Here only h (SM - like) observable at LHC, unless A, H, $H^{\pm}$ → SUSY

→ LHC may miss part of the MSSM Higgs spectrum

Observation of full spectrum may require high-E ($\sqrt{s} \approx$ 2 TeV) Lepton Collider

Most of MSSM Higgs plane already covered after 1 year at L= 10^{33} …

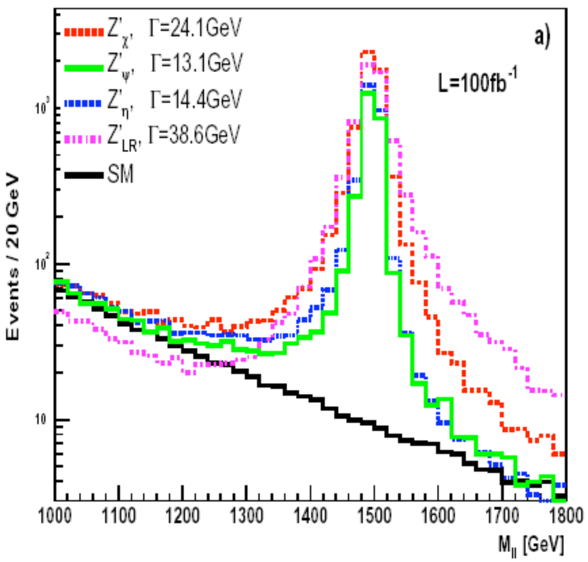


Large variety of channels and signatures accessible

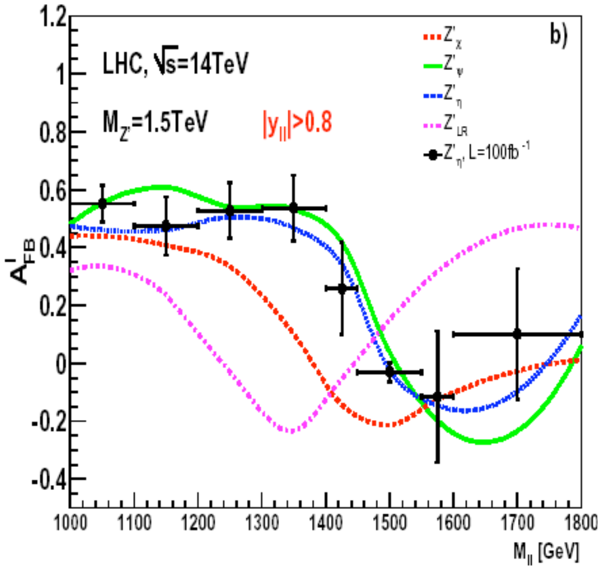
Extended gauge groups : $Z' \rightarrow l^+l^-$

CMS

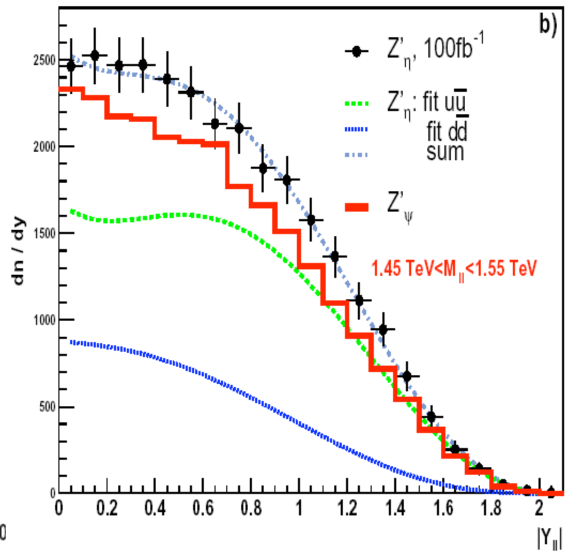
Dilepton invariant mass spectrum



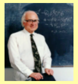
Forward backward asymmetry measurement



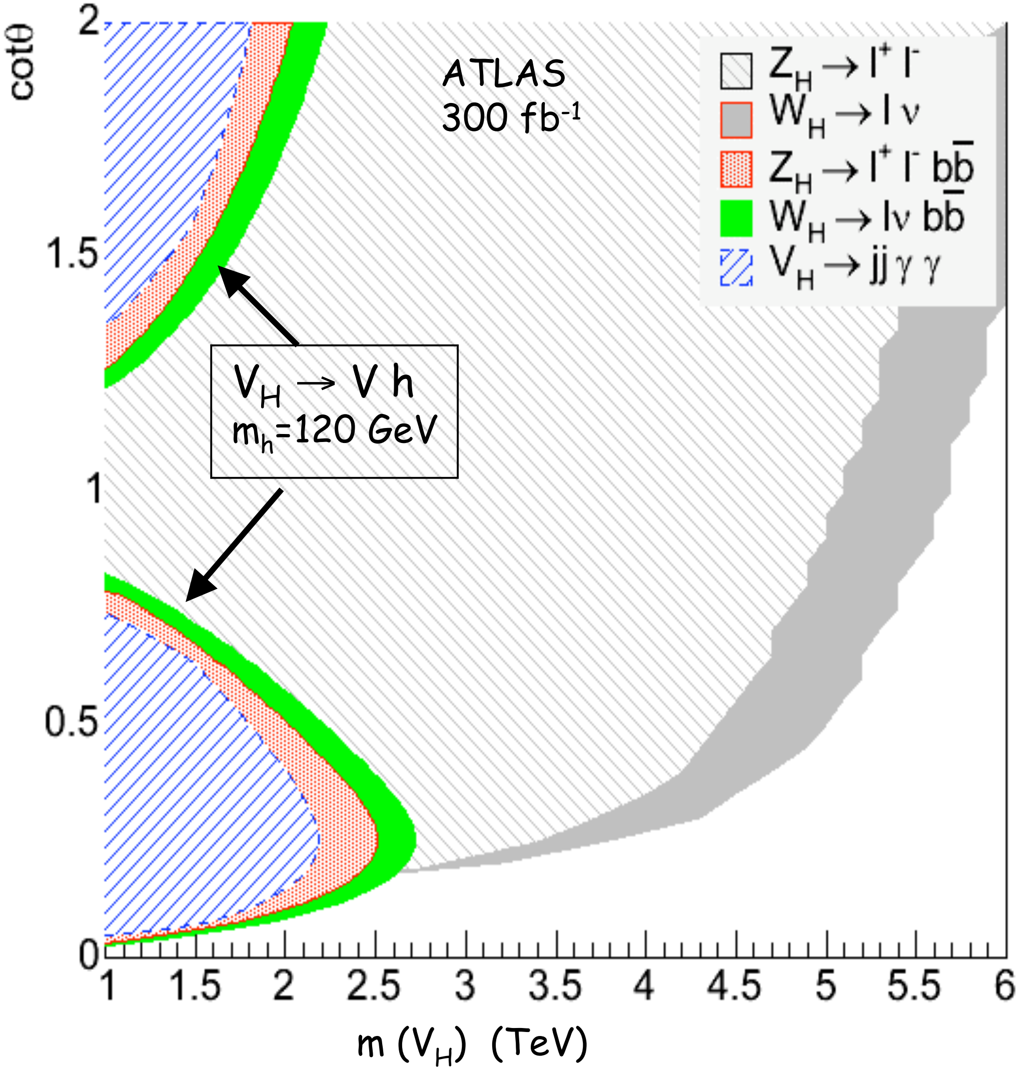
Rapidity distribution



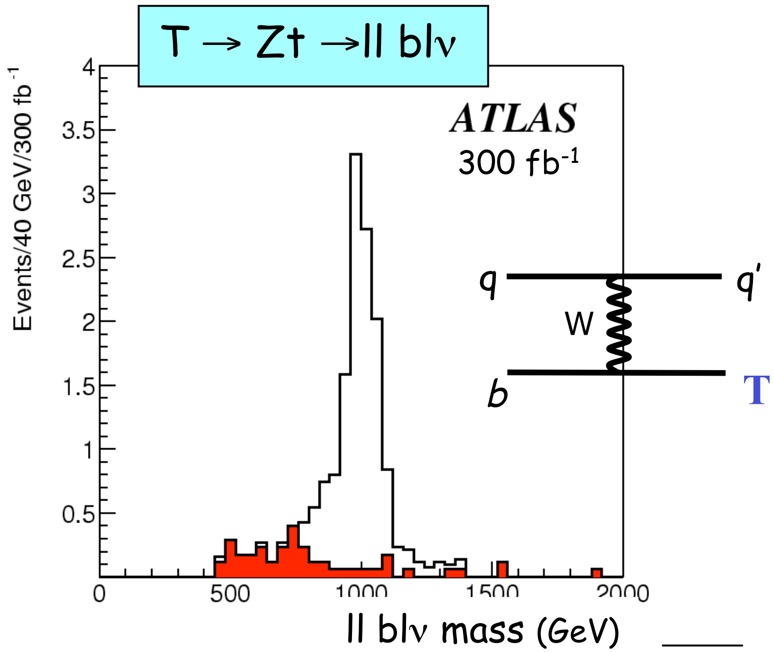
- Reach in 1 year at 10^{34} : 4-5 TeV
- Discriminating between models possible up to m ~ 2.5 TeV by measuring:
  - -- $\sigma x \Gamma$ of resonance
  - -- lepton F-B asymmetry
  - -- Z' rapidity

Little Higgs  models

Alternative approach to the hierarchy problem predicting heavy top T (EW singlet), new gauge bosons W_H, Z_H, A_H and Higgs triplet Φ^0, Φ^+, Φ^{++}

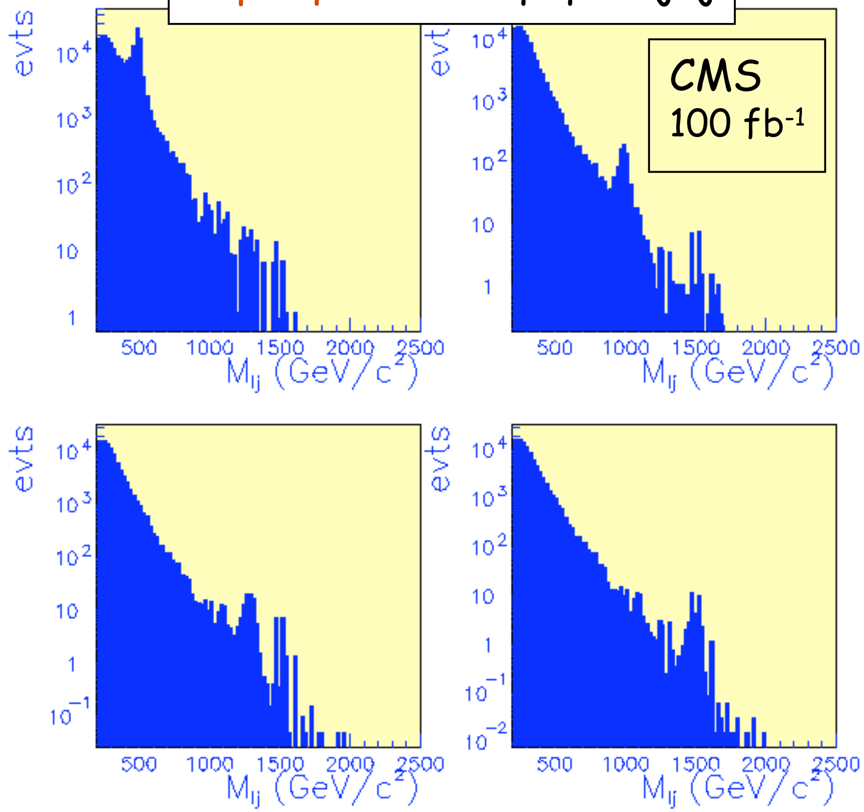


Observation of $T \to Zt$, Wb discriminates from 4th family quarks
Observation of $V_H \to Vh$ discriminates from W′, Z′

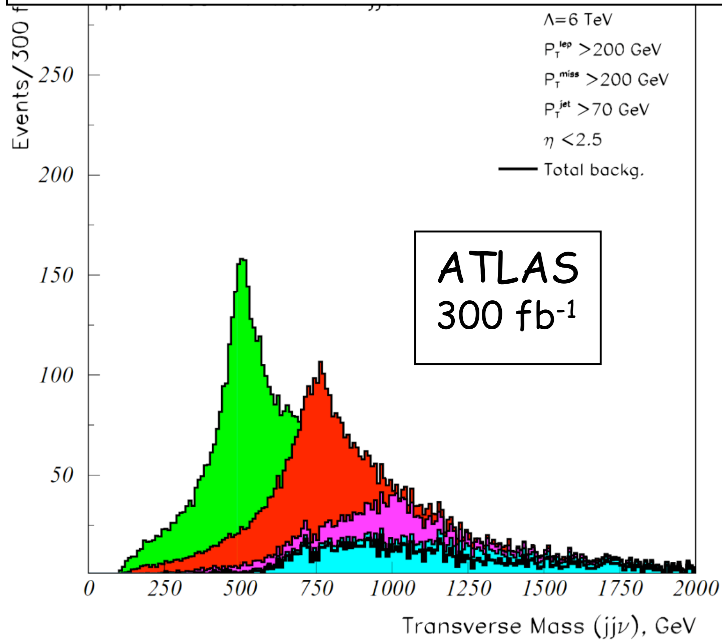


Other scenarios .....

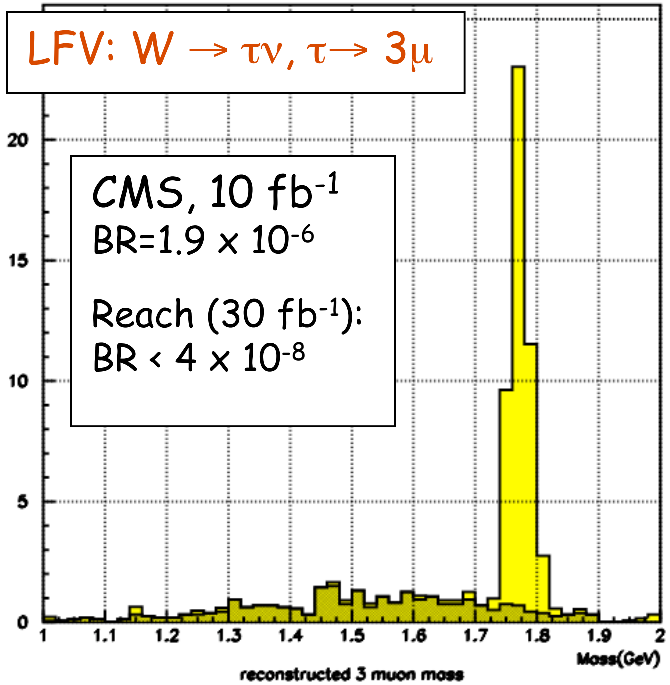
Leptoquarks : lq lq → lj lj



Excited leptons ; e*e, e* → Wν →jj ν



LFV: W → τν, τ→ 3μ



Large number of scenarios studied:

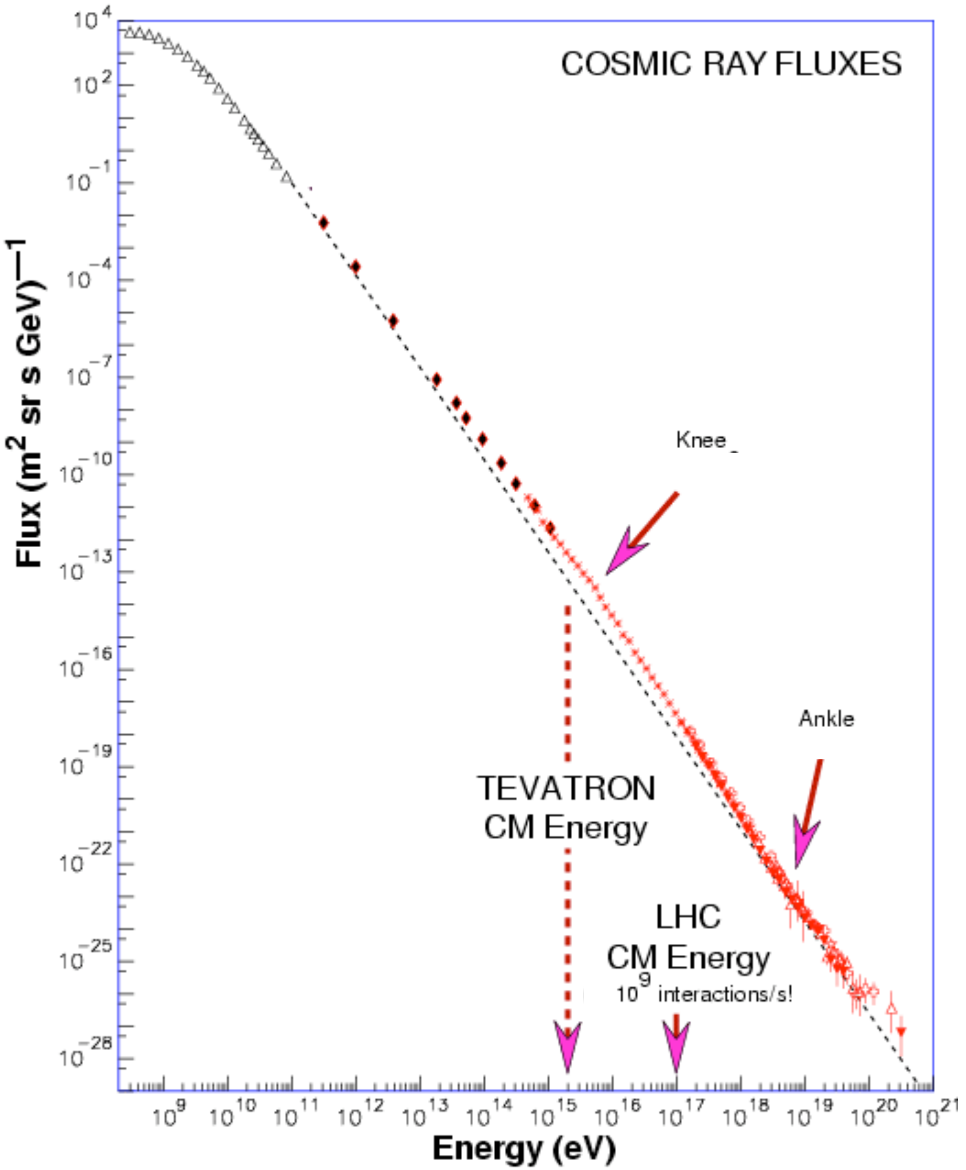
⇒ demonstrated detector sensitivity to many signatures

→ robustness, ability to cope with unexpected scenarios

⇒ LHC direct discovery reach up to m ≈ 5-6 TeV

LHC and high-energy cosmic rays

√s = 14 TeV → corresponds to E ~ 100 PeV fixed target proton beam



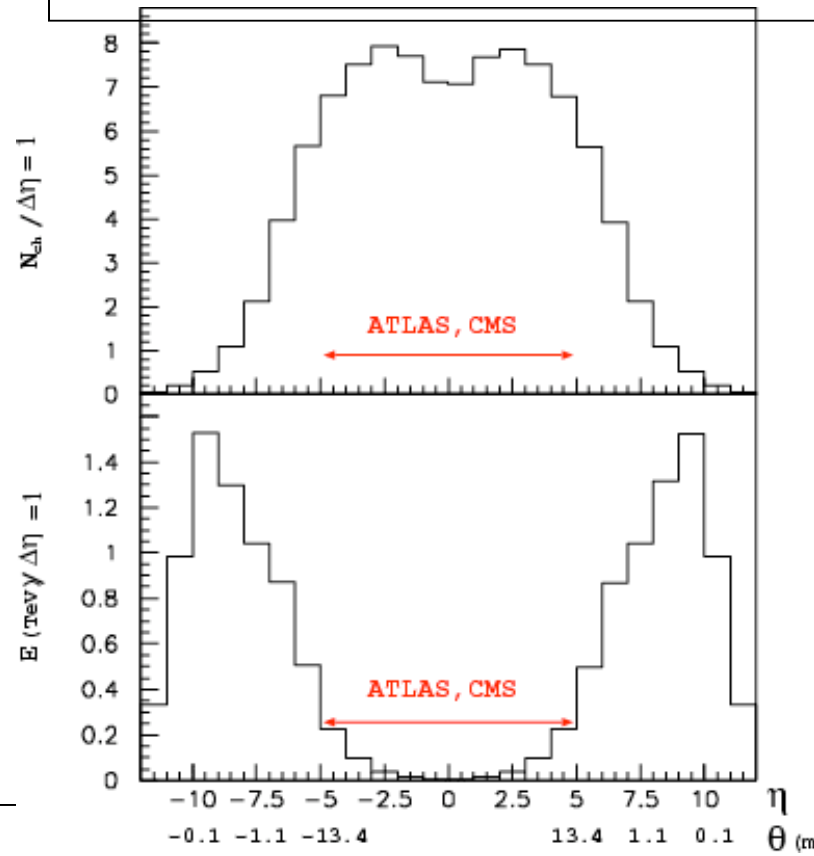
LHC studies most relevant to HECR:

-- most energetic particles from the collisions

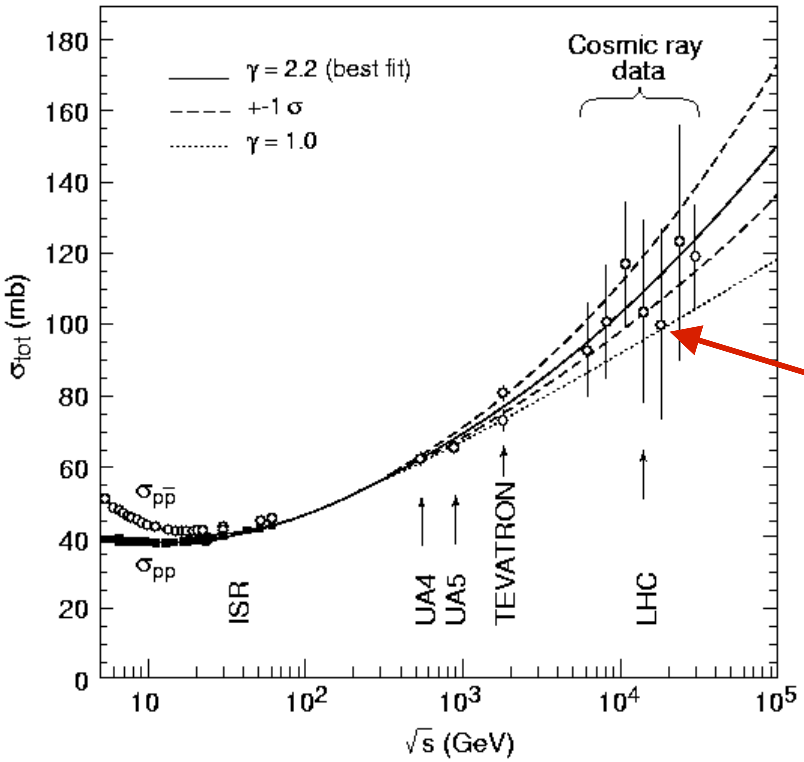
-- pp (and pA, AA) cross-sections

both require detection in the forward region

Charged particle multiplicity and energy in pp inelastic events at √s = 14 TeV



Measurement of σ_{tot} (pp)



Curves are ~ $(\log s)^{\gamma}$

Goal of TOTEM:
~ 1 % precision

TOTEM : 3 stations of detectors ("Roman Pots" RP1, RP2, RP3) at both sides of IP5 (integrated with beam pipe) to measure scattered proton in elastic interactions down
to $\theta_{scat} \approx 20\ \mu$rad