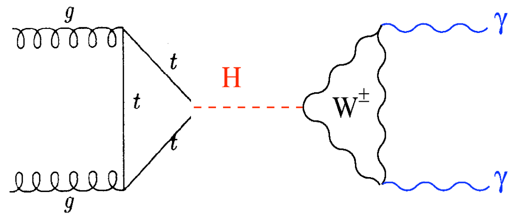
Spare slides

$H \rightarrow \gamma\gamma$

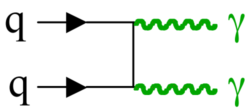
$m_H \leq 150$ GeV



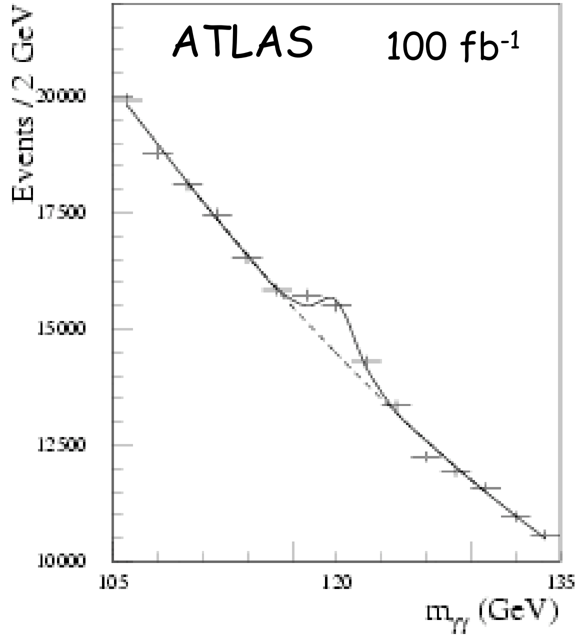
- σ x BR ≈ 50 fb   (BR ≈ 10^{-3})

- Backgrounds :

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



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



-- γj+ jj (reducible):

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

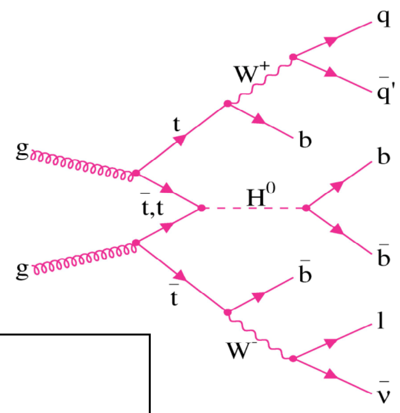
→ need $R_j > 10^3$, including R (π^0) > 3, for $\varepsilon_\gamma \approx$ 80% to get $\sigma_{\gamma j+jj} \ll \sigma_{\gamma\gamma}$

→ 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

$t\bar{t}H \rightarrow t\bar{t}b\bar{b}$

$m_H \leq 130$ GeV



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

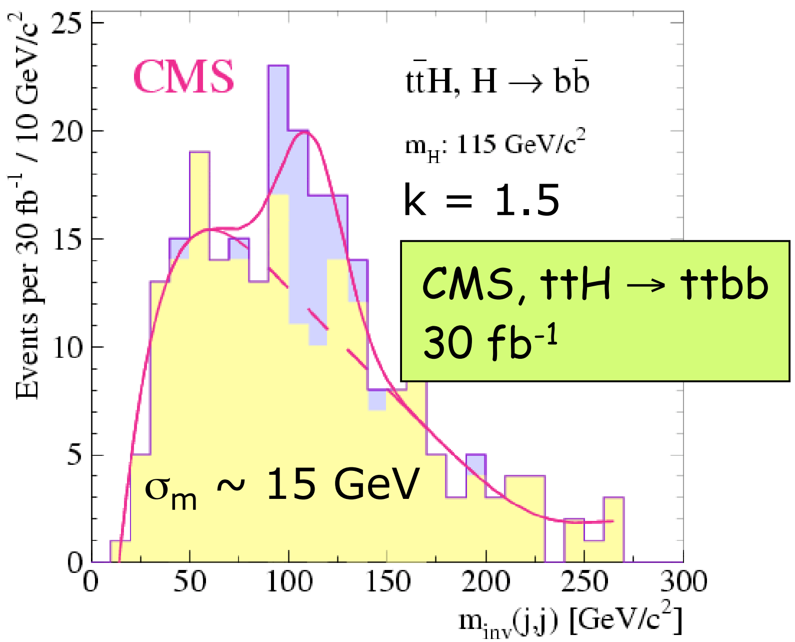
l = e, μ for trigger
and background rejection

- 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

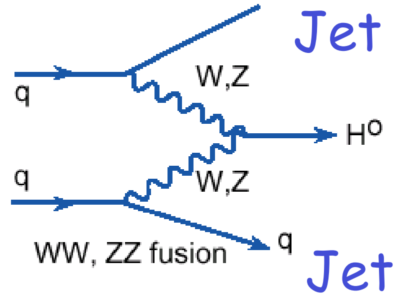
→ crucial performance aspect : b-tagging

ttbb background from ttjj with j anti b-tagged



Vector Boson Fusion qqH → ττ

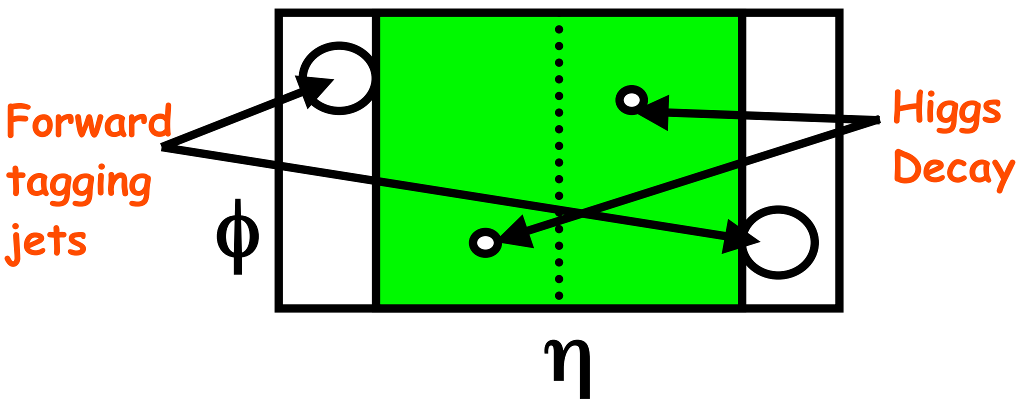
$m_H \leq 200$ GeV

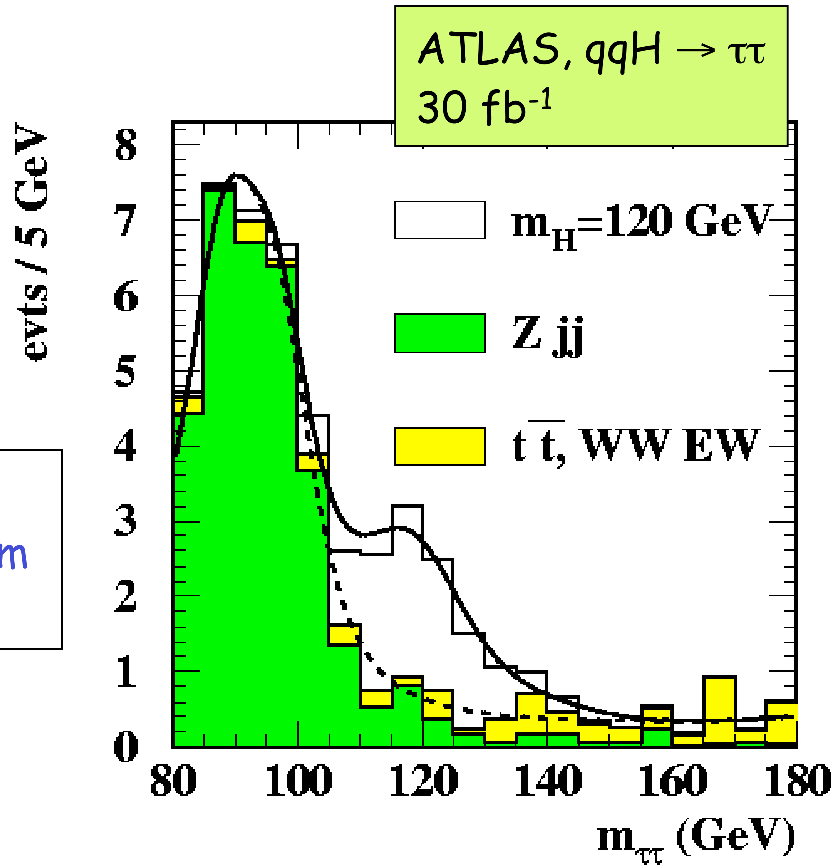


σ = 4 pb (20% of total cross section for m_H = 130 GeV)

Very distinct signature:

- two forward jets
- little jet activity in central region





Zjj (Z→ ττ)
background from
Zjj (Z→ ee)

Experimental issues:

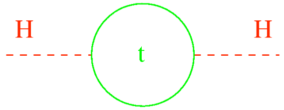
forward jet reconstruction
(hermetic calorimetry over |η|<5)

jet veto in the central region

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

Examples of detector performance requirements

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:
≈ 1% decays into leptons or photons (Higgs, new resonances)
≈ 10% W → jj, H → bb (top physics, Higgs, ...)

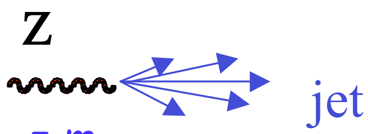
Hadron calorimeter linearity understood to < 1.5 % at E_{jet} ~ 4 TeV (q compositeness)

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

Lepton energy scale

- mainly from Z → 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 (→ 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)
- 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)

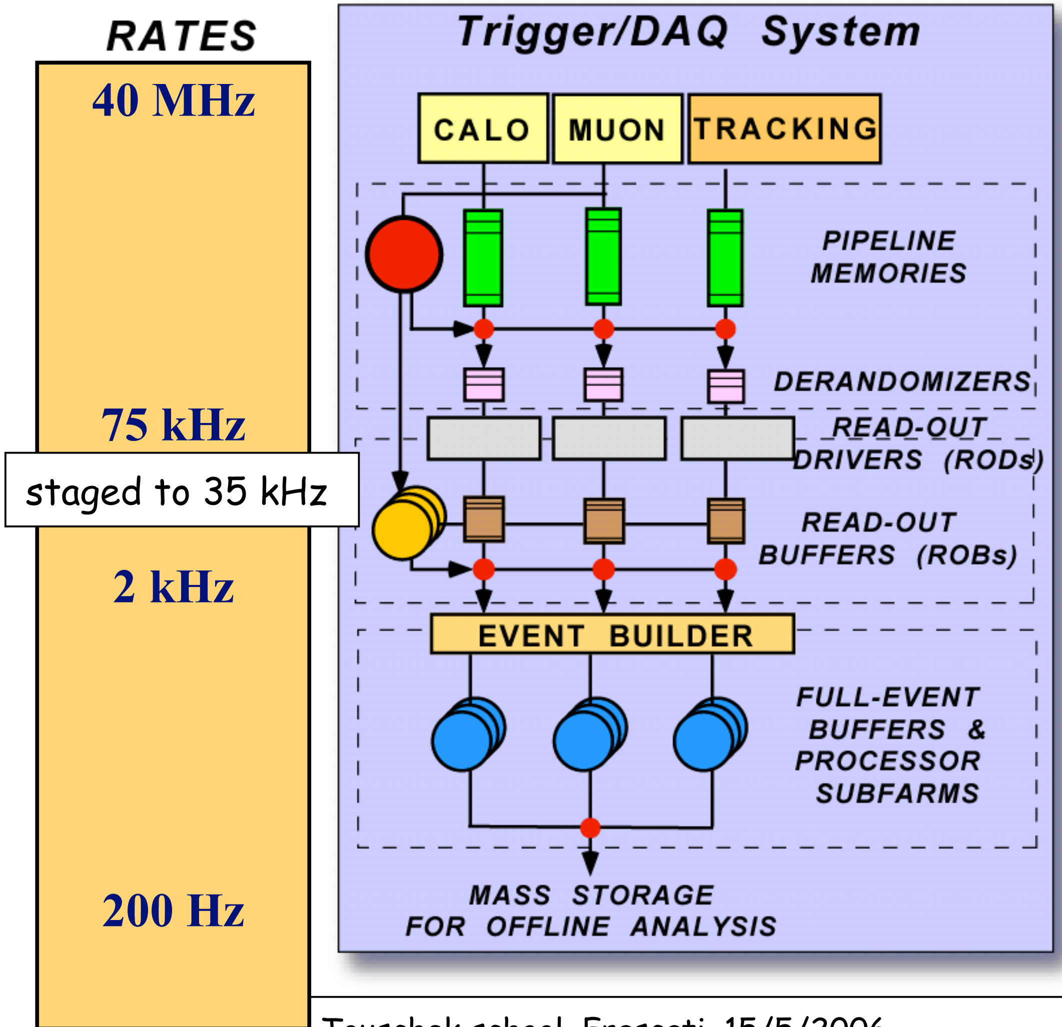
Absolute luminosity to <5% (W/Z/tt cross-section measurements, new physics through σxBR measurements, ….)

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 !)

ATLAS vs CMS ❶

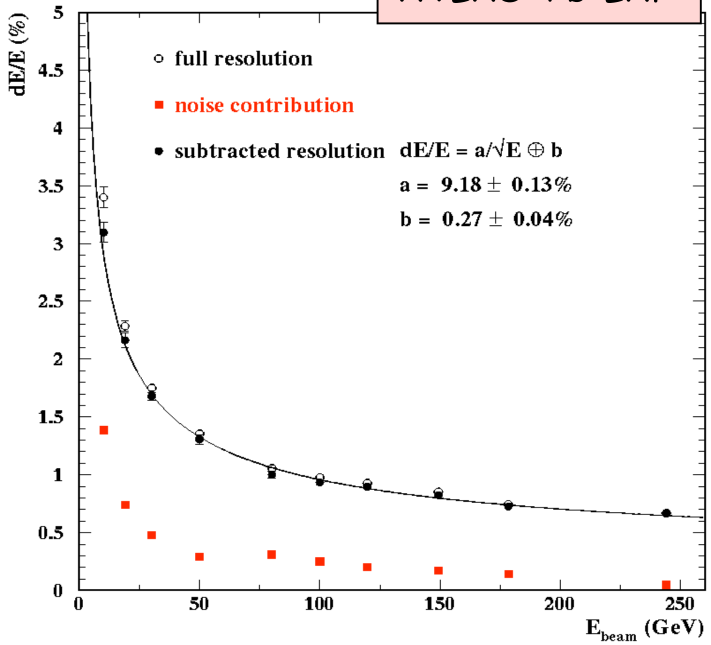
Mass resolution (m_H ~ 100 GeV, high L):

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

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

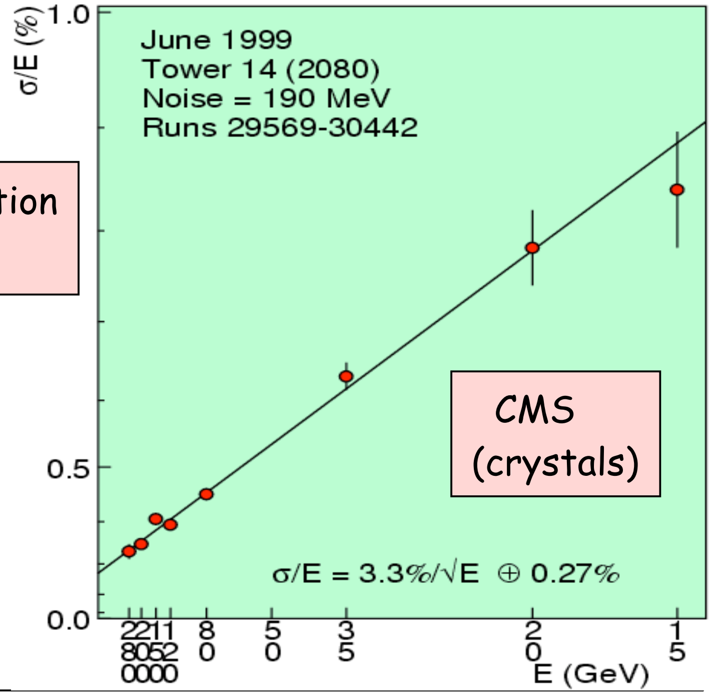
$$\frac{\sigma(E)}{E} \approx \frac{10\%}{\sqrt{E}}$$

ATLAS Pb-LAr



electron E-resolution from test beam

$$\frac{\sigma(E)}{E} \approx \frac{2-5\%}{\sqrt{E}}$$



CMS (crystals)

ATLAS vs CMS ❷

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

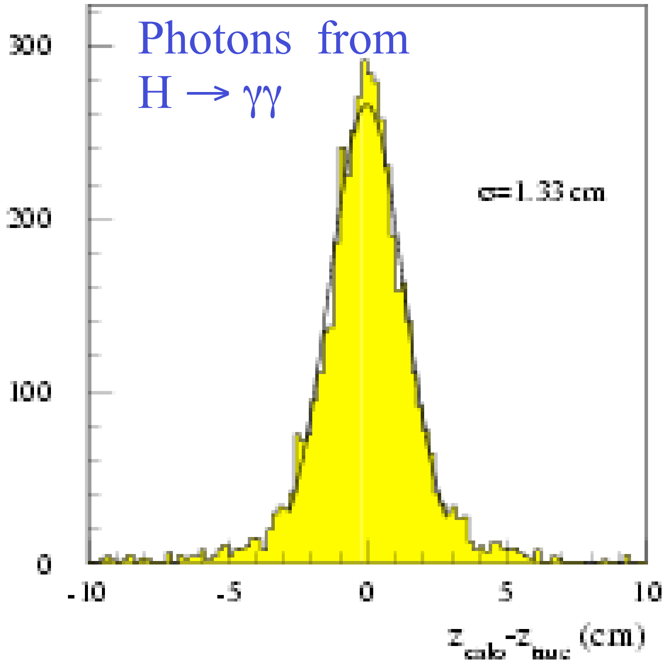
Total acceptance: ≈ 25% larger in ATLAS

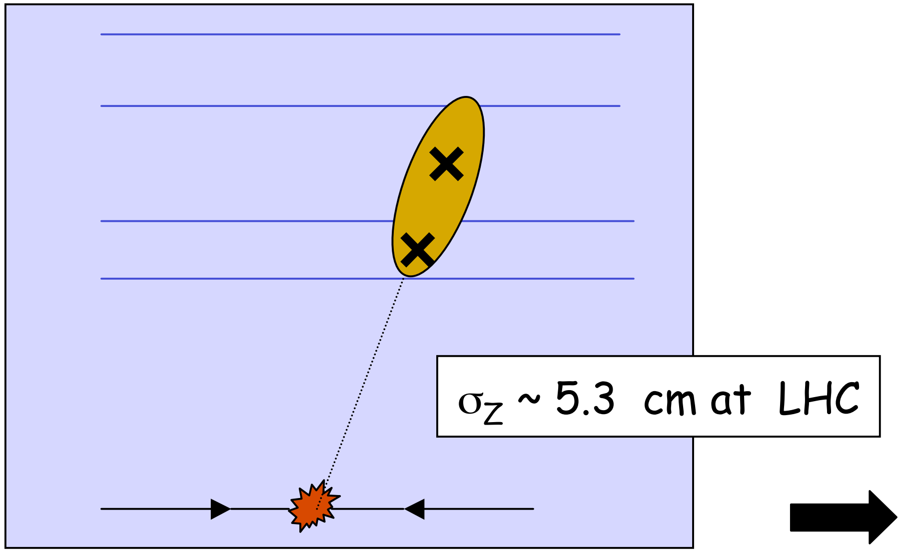
CMS:

- 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

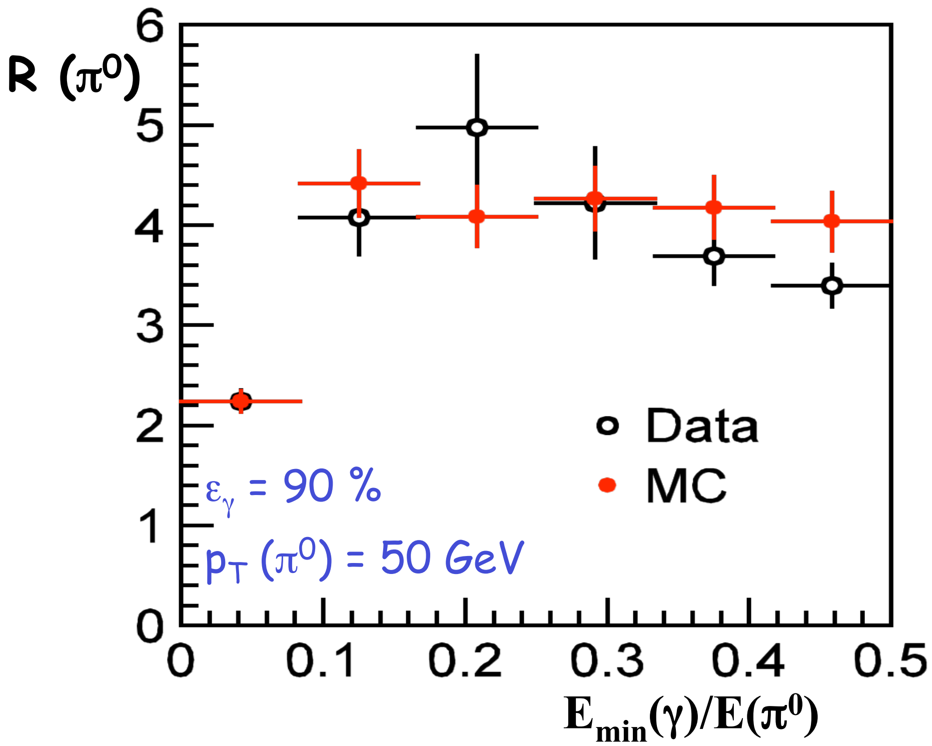
ATLAS, full simulation
Vertex resolution using EM calo longitudinal segmentation



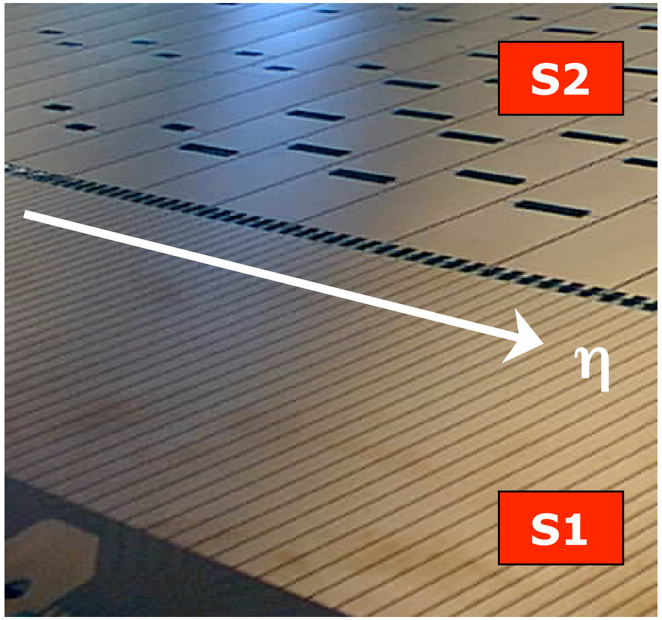


$$\Rightarrow \frac{S}{\sqrt{B}}(\text{CMS}) \approx \frac{S}{\sqrt{B}}(\text{ATLAS}) \approx 6 \quad 100\ \text{fb}^{-1}$$

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



Using 4mm η-strips in 1st ECAL compartment



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

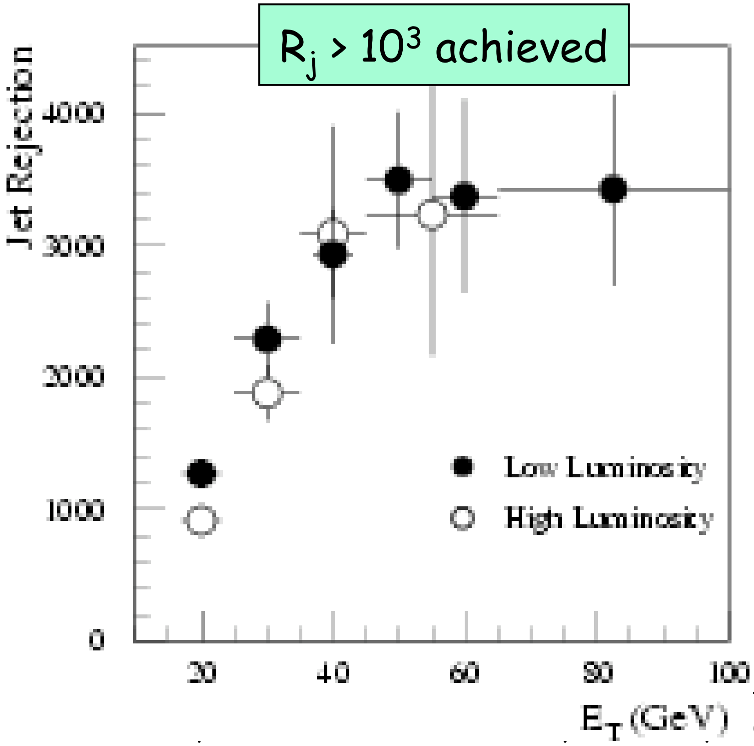
MC: $\langle R(\pi^0)\rangle = 3.66 \pm 0.10$

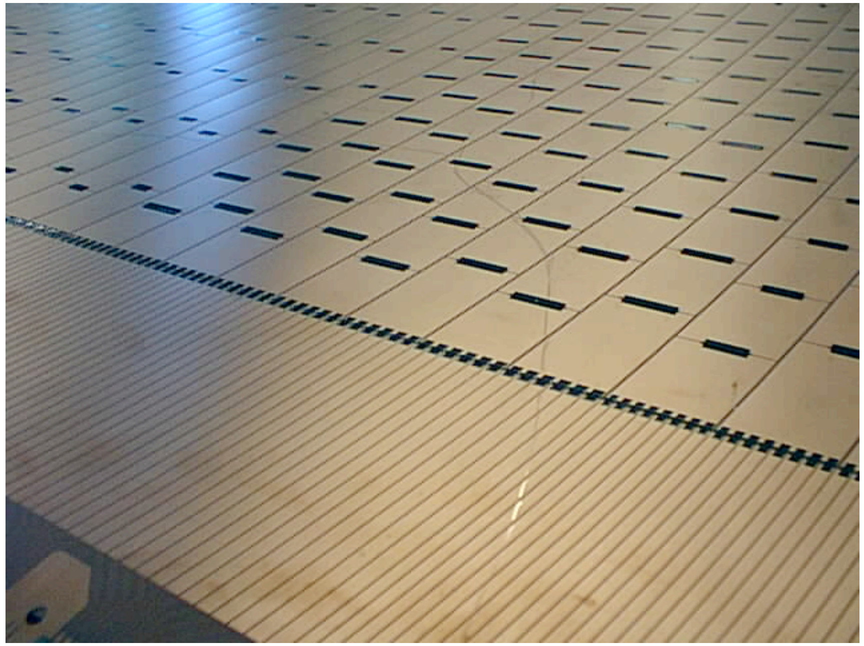
ATLAS vs CMS ❸

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

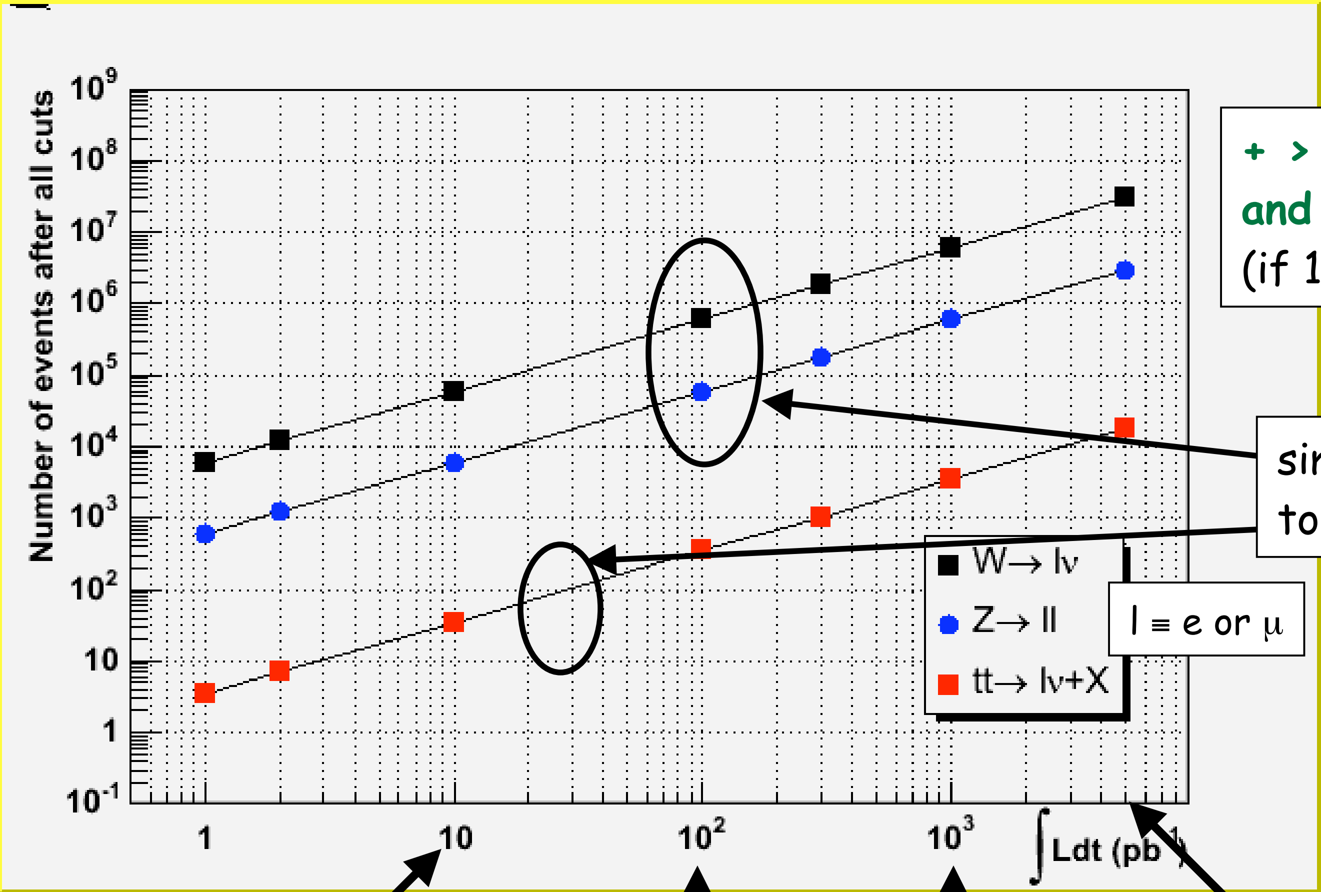




γ/π^0 separation studied also with test-beam data

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

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



+ > 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} ≡ 1 month at 10^{30} + < 2 weeks at 10^{31}, ε=50%

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

→ end 2007 ?

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

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

→ end 2008 ?

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 !** ↕

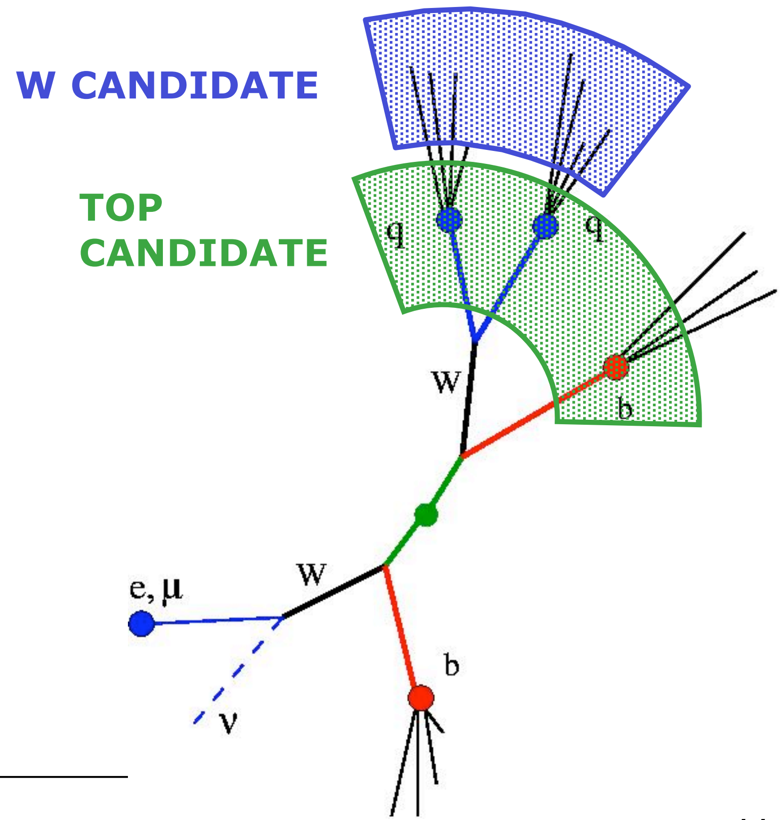
σ_{tt} (LHC) ≈ 250 pb
for gold-plated
semi-leptonic channel

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

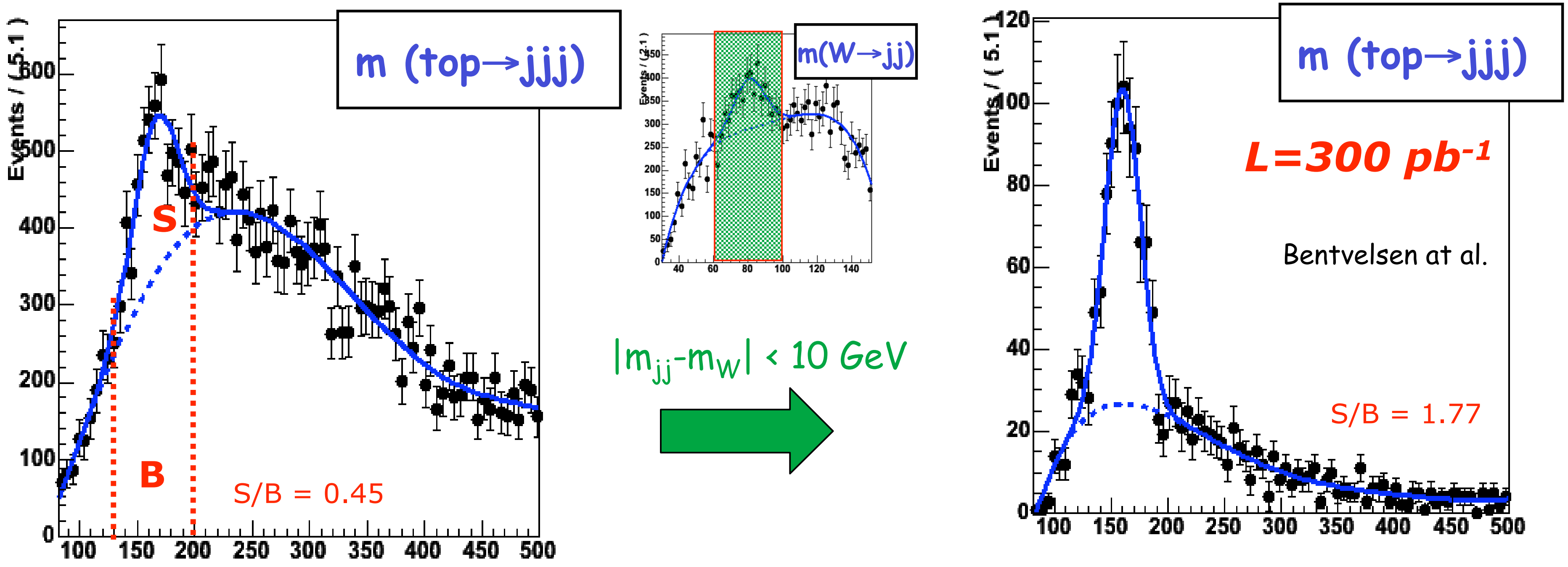
  } $\varepsilon \sim 5\%$

- 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 …)



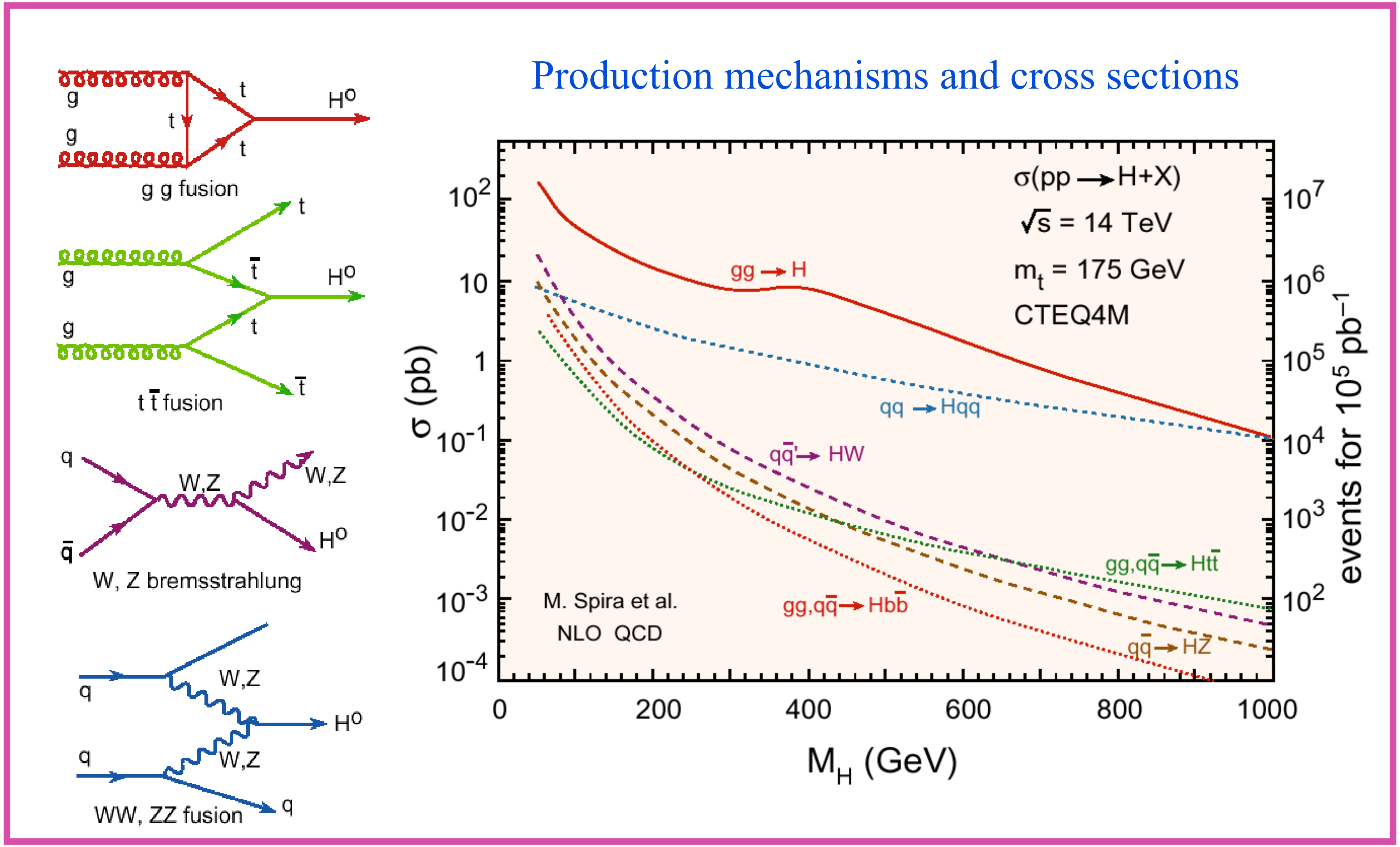
Background (W+jets, top combinatorics) can be understood with MC+data (Z+jets)

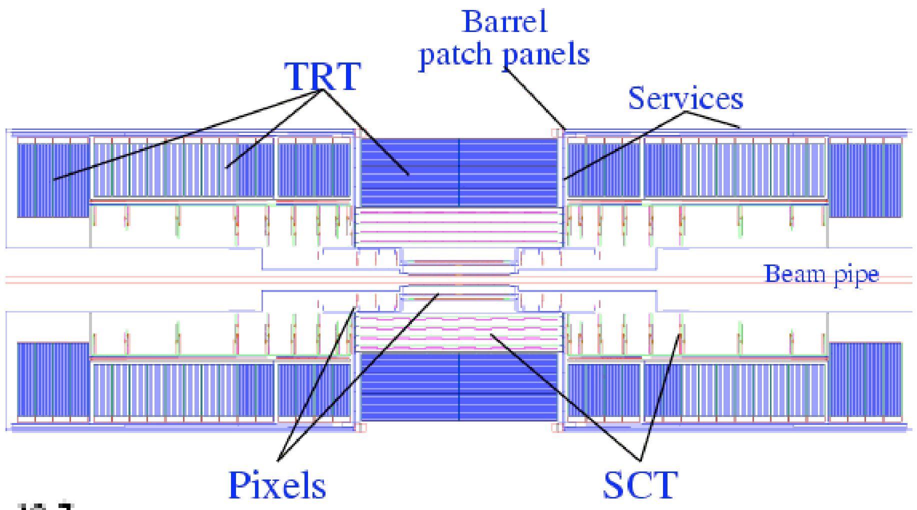
Expect ~ 100 events inside mass peak for 30 pb^{-1}
→ top signal observable in early days with no b-tagging and simple analysis
Cross-section to 20%, m_{top} to 7 GeV (LHC goal ~1 GeV) with 100 pb^{-1} ?

tt is excellent sample to:

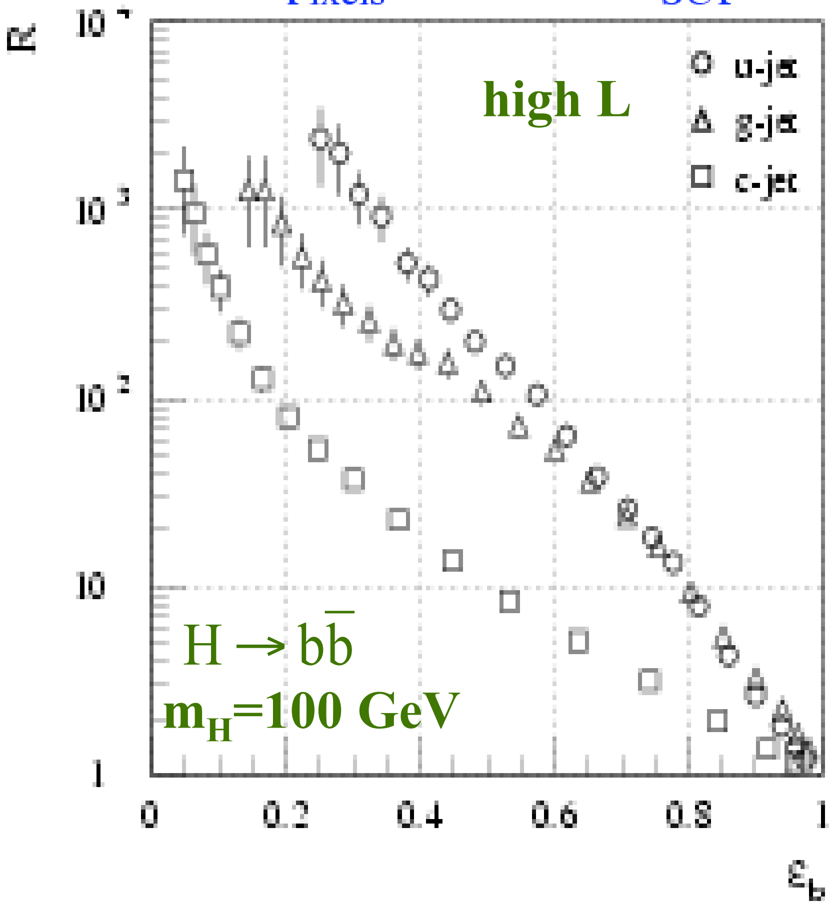
- **commission b-tagging, set jet E-scale using W → jj peak**
- **understand detector performance and reconstruction of several physics objects (e, μ, jets, b-jets, missing E_T, ..)**
- **understand / tune MC generators using e.g. p_T spectra**
- **measure background to many searches**

Higgs production at LHC





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



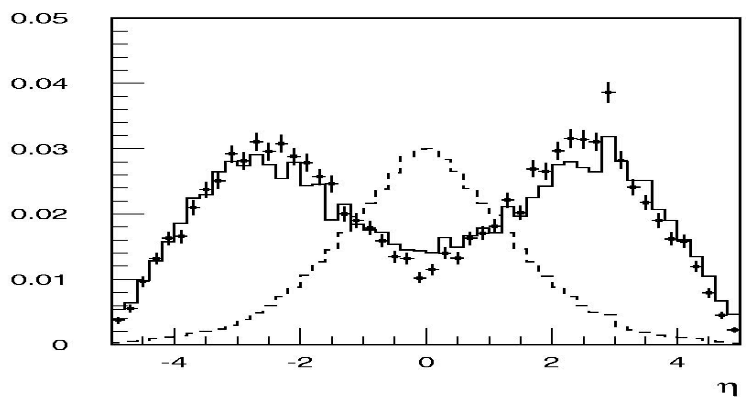
ATLAS, full simulation

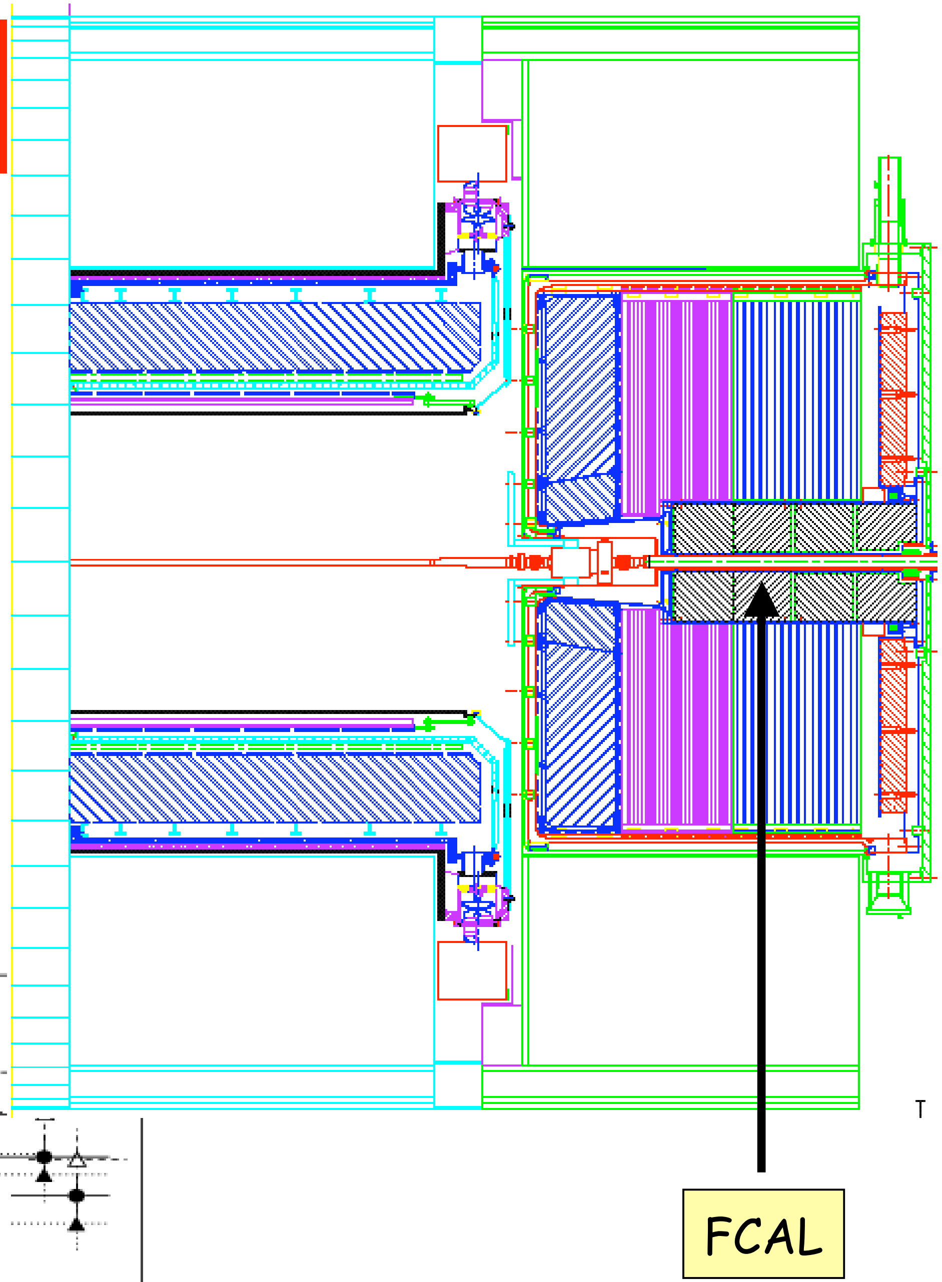
2D b-tag (used here):
ε_b =50% R_j (uds)=100 at high L

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

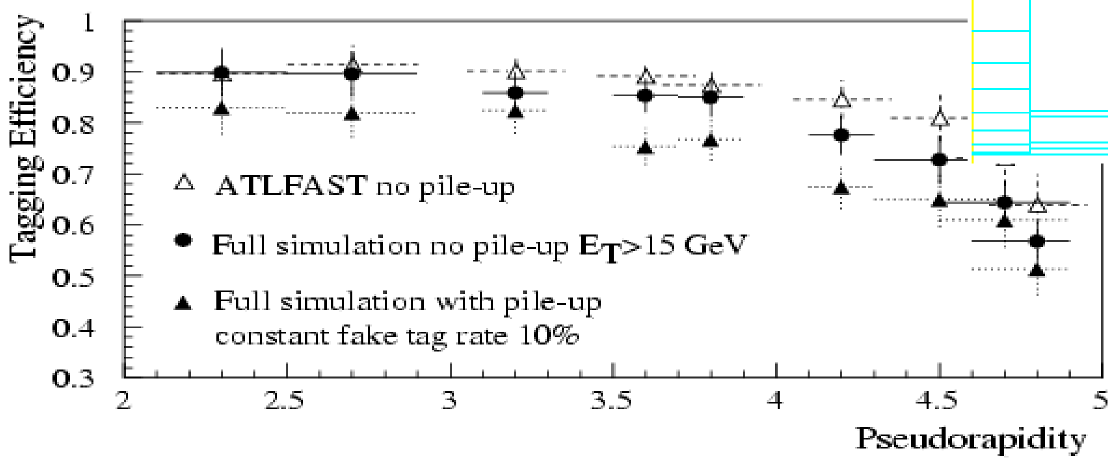
Note:
-- complementary channel to $H \rightarrow \gamma\gamma$
-- large coverage in MSSM
-- allows measurement of top Yukawa coupling

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

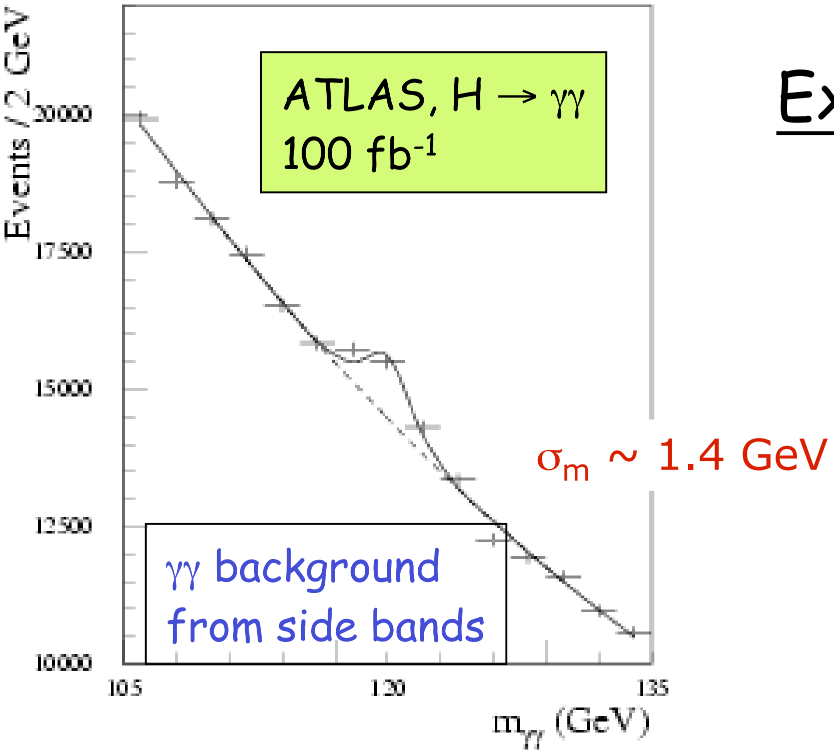


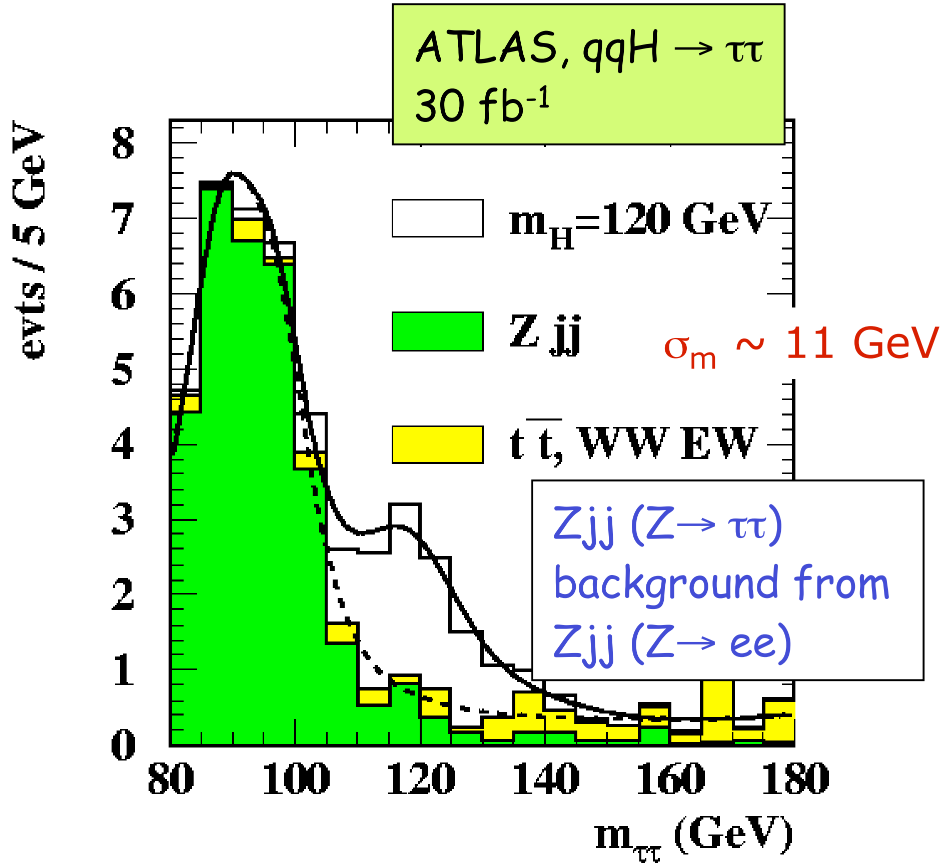


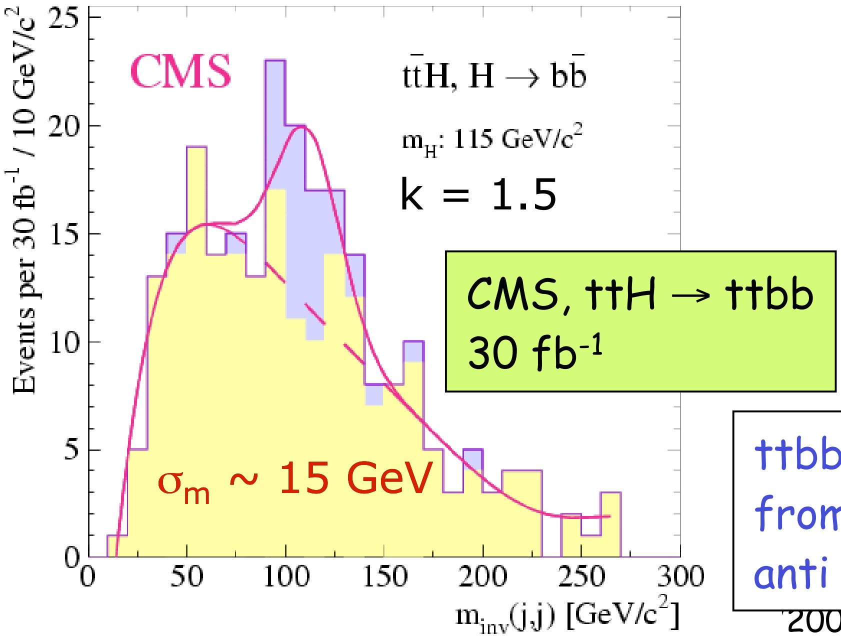
Forward tag jet reconstruction



Expected signals in low-mass region



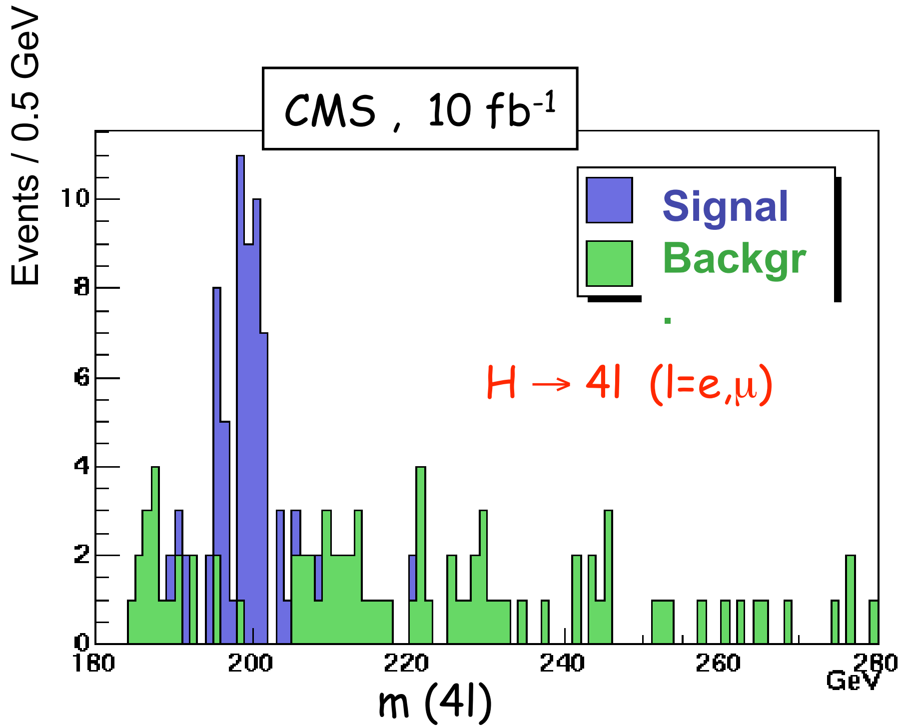




ttbb background from ttjj with j anti b-tagged

Background dominated by irreducible component in all cases

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



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

$H \to 4l$: 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)

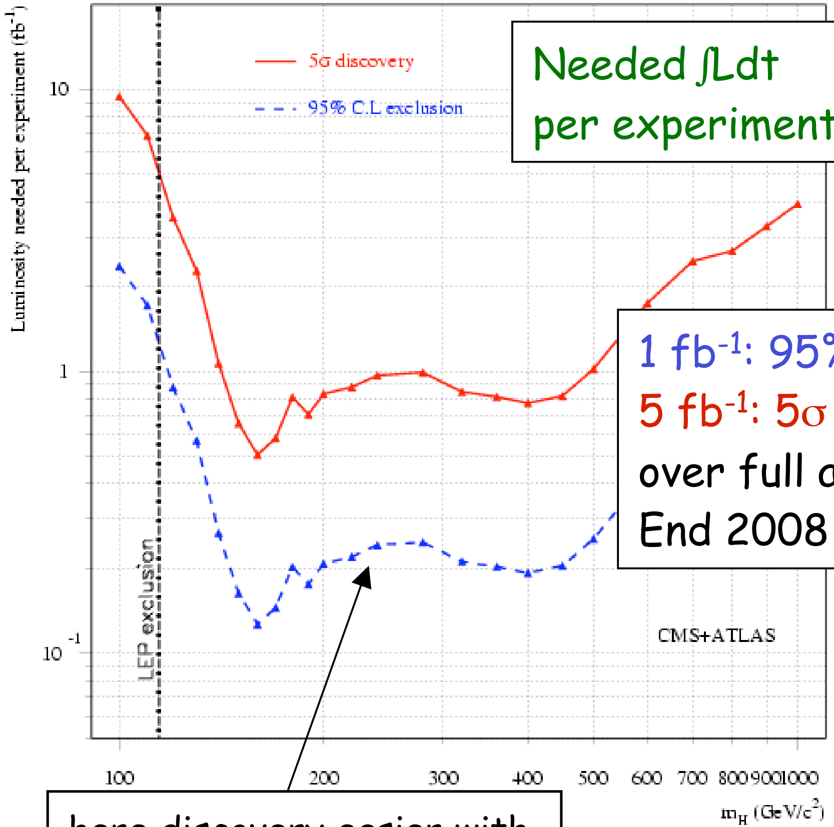
  σ /m ~ 1%, tails < 10% → good quality of E, p measurements in ECAL and tracker

- background dominated by irreducible ZZ production (tt and Zbb rejected by Z-mass constraint, and lepton isolation and impact parameter)

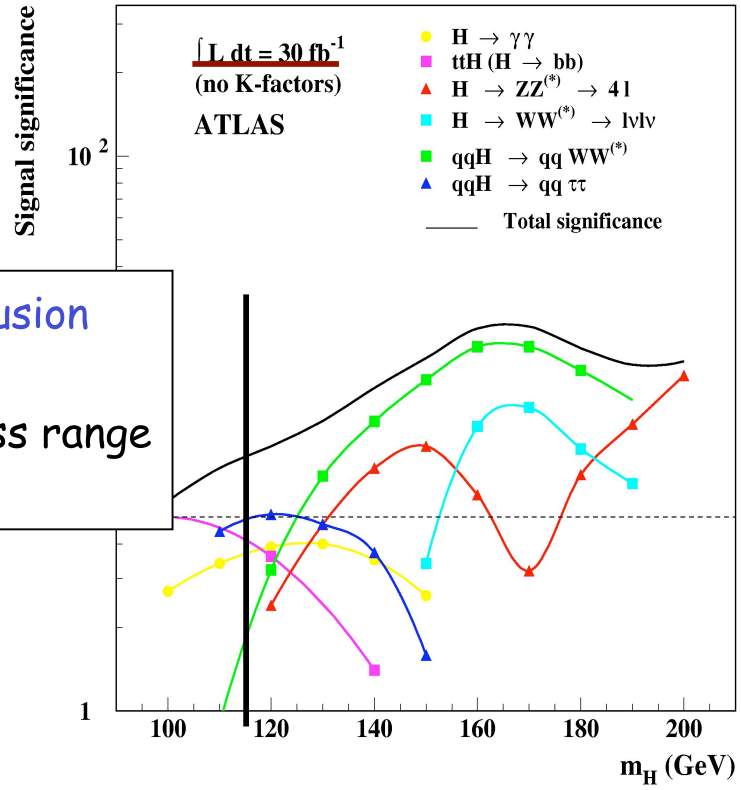
$H \to WW \to l\nu l\nu$: high rate (~ 100 evts/expt) but no mass peak

→ not ideal for early discovery …

A difficult case: a light Higgs (m_H ~ 115 GeV) ...



Needed ∫Ldt per experiment



1 fb^{-1}: 95% C.L. exclusion
5 fb^{-1}: 5σ discovery
over full allowed mass range
End 2008 ?

here discovery easier with gold-plated H → ZZ → 4l

m_H ~ 115 GeV   10 fb^{-1}

total $S/\sqrt{B} \approx 4^{+2.2}_{-1.3}$

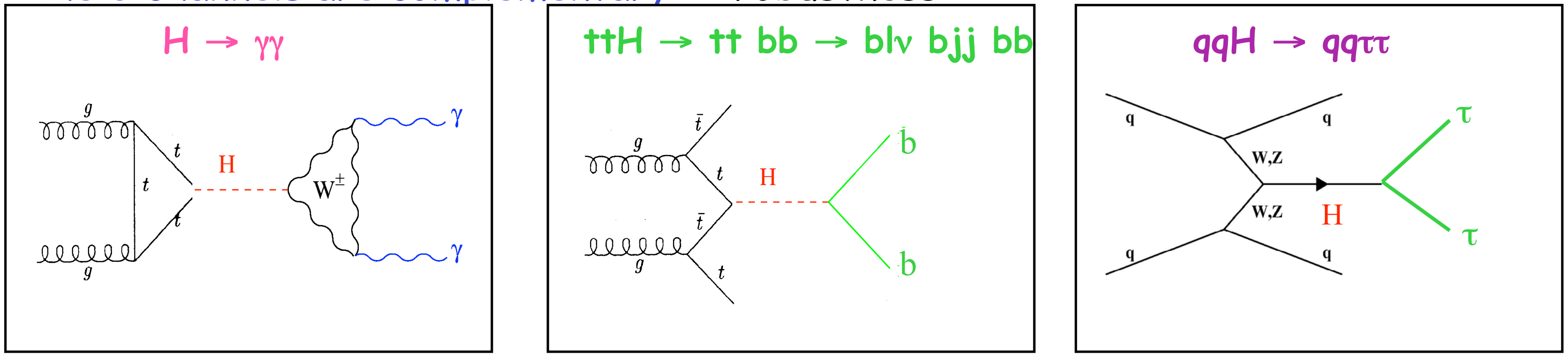
ATLAS	H → γγ	ttH → ttbb	qqH → qqττ (ll + l-had)
S	130	15	~ 10
B	4300	45	~ 10
S/ √B	2.0	2.2	~ 2.7

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

Remarks:

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:



- 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

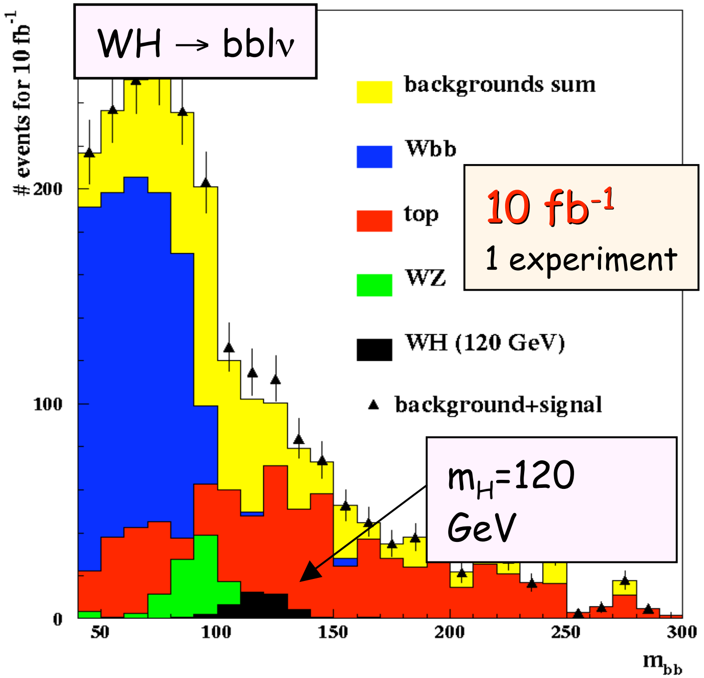
E.g. ttH analysis cuts : p_T (l) > 20 GeV, p_T (jets) > 15-30 GeV

-- all require very good understanding (1-10%) of backgrounds

Tevatron vs LHC after kin. cuts	WH → lν bb (m_H=120 GeV)	H → 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 <u>same</u> integrated luminosity and <u>same</u> detector performance at Tevatron and LHC

Best low-mass channel at the Tevatron



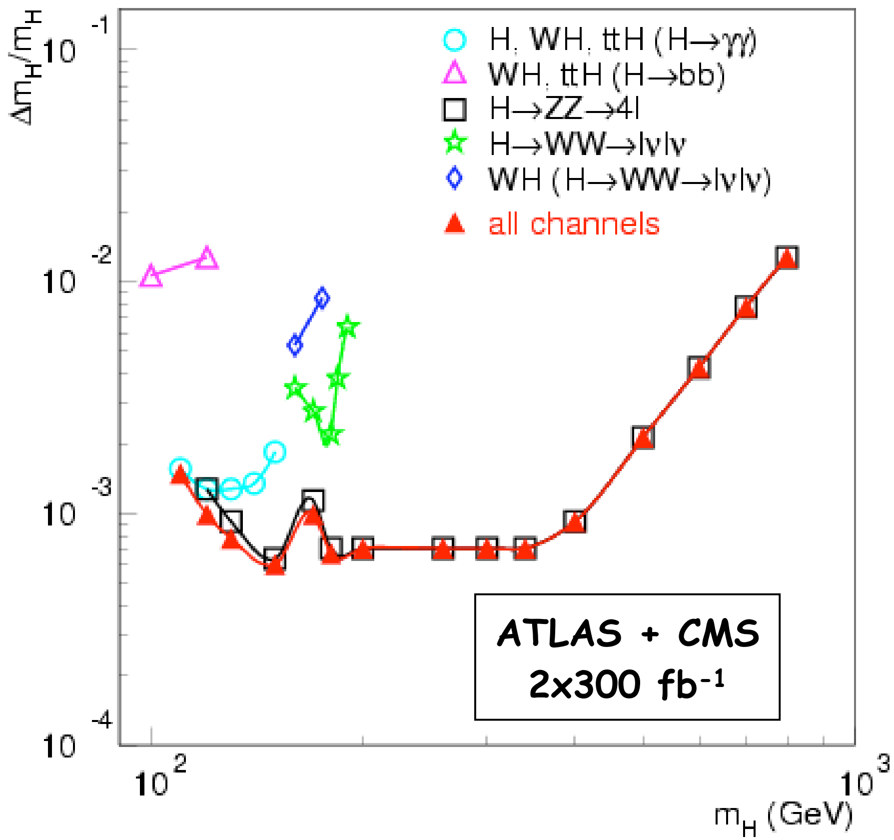
Tevatron projections are a bit optimistic:

- no systematics
- optimistic detector performance (e.g. H → 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



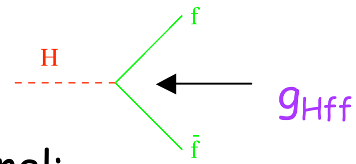
Dominant systematic uncertainty is

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)

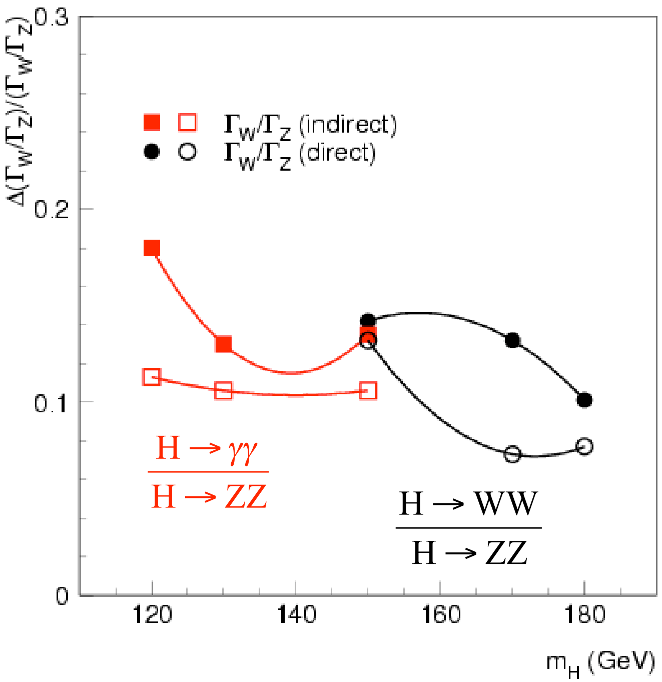
Measurement of the SM Higgs couplings



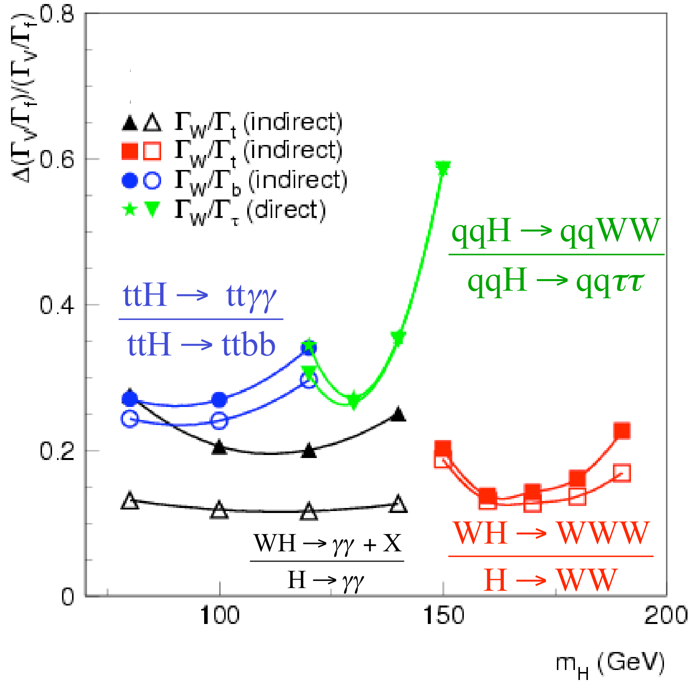
Couplings can be obtained from measured rate in a given production channel:

$R_{ff} = \int L\, dt \bullet \sigma(pp \to H + X) \bullet BR(H \to ff)$ $\quad BR(H \to ff) = \frac{\Gamma_f}{\Gamma_{tot}}$ $\quad \to$ 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



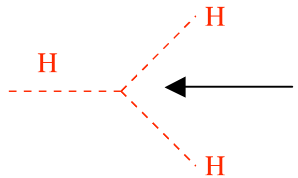
Closed symbols:
LHC 600 fb^{-1}
Open symbols:
SLHC 6000 fb^{-1}



- 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 ($L=10^{35}\ cm^{-2}\ s^{-1}$)



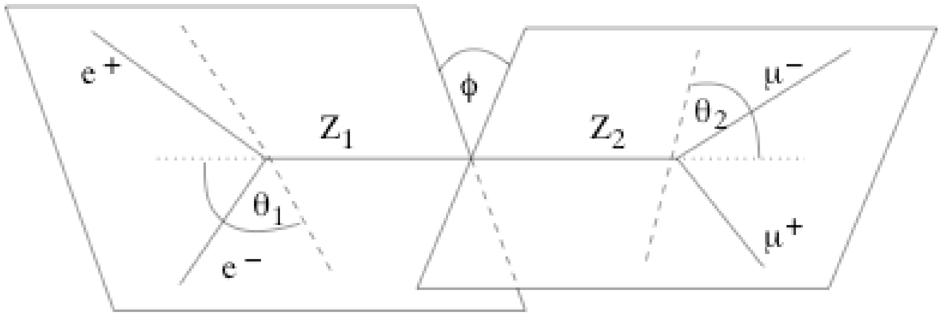
$\sim \lambda v$

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

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



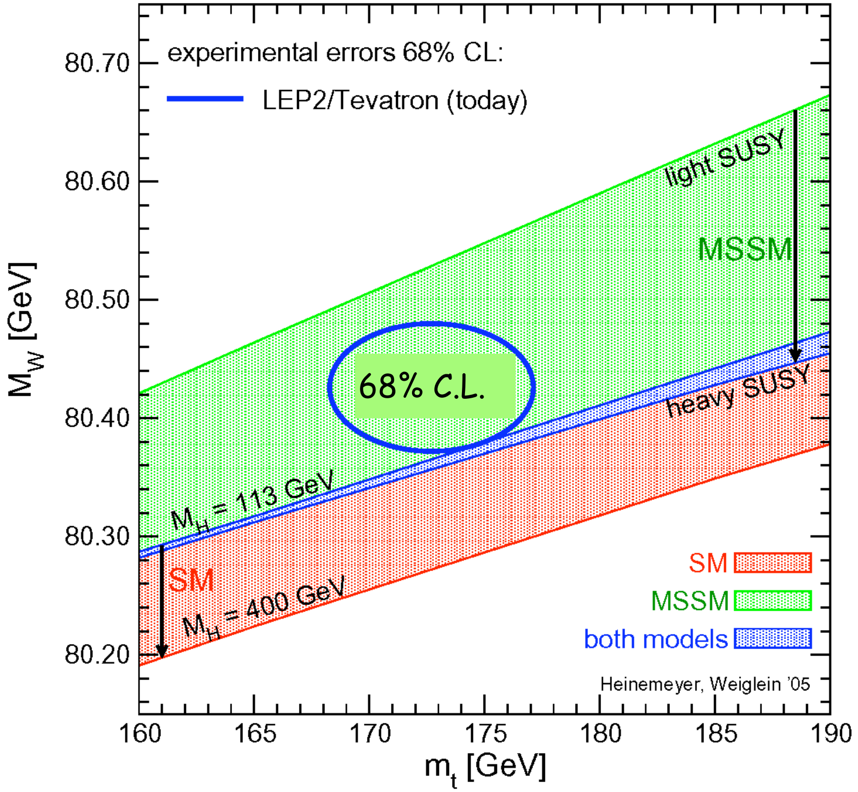
Significance for exclusion of other J^{CP} states than 0^+

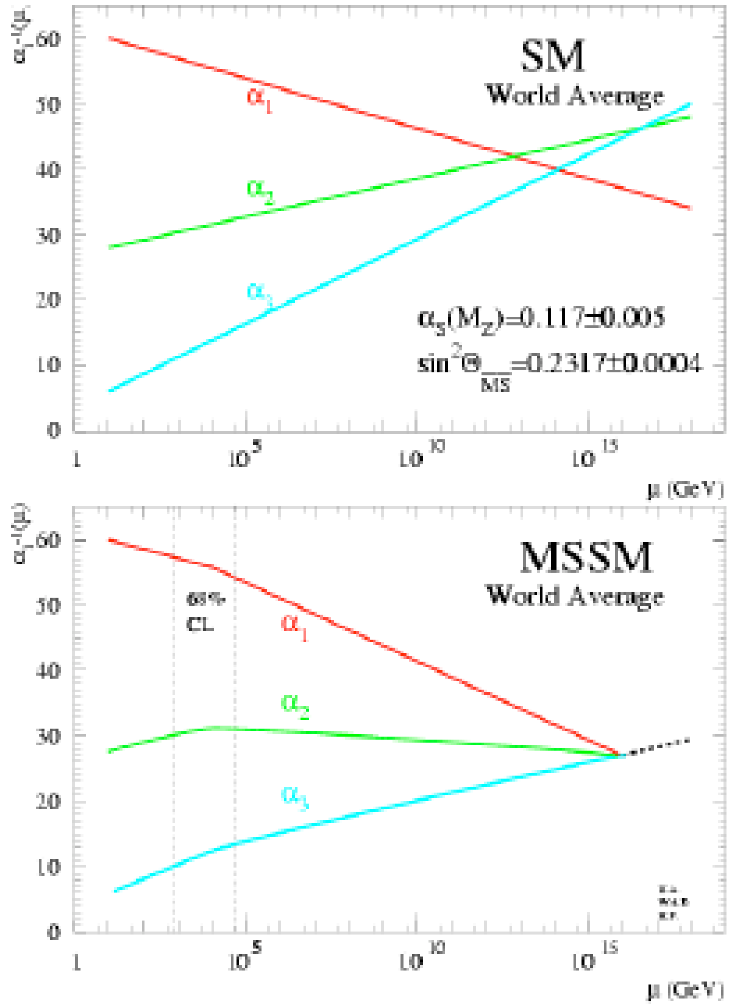
m_H (GeV)	$J^{CP} = 1^+$	$J^{CP} = 1^-$	$J^{CP}=0^-$
200	6.5 σ	4.8 σ	40 σ
250	20 σ	19 σ	80 σ
300	23 σ	22 σ	70 σ

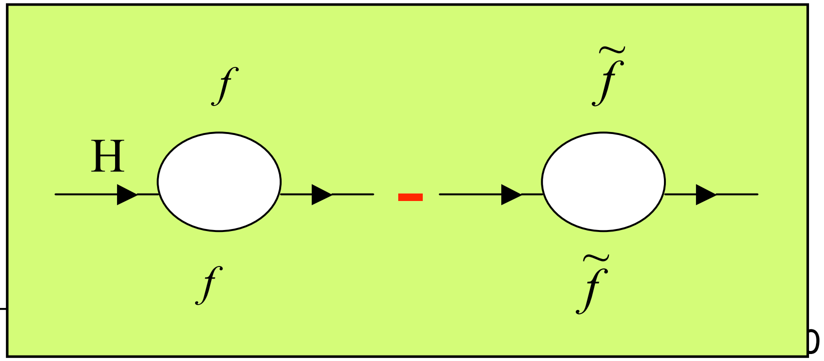
ATLAS + CMS, 2 x 300 fb^{-1}

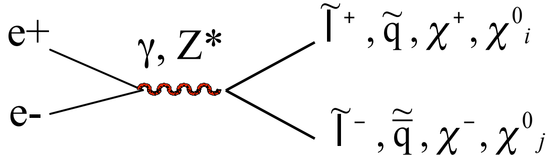
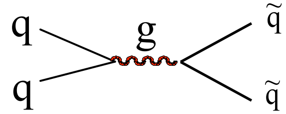
SUperSYmmetry

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

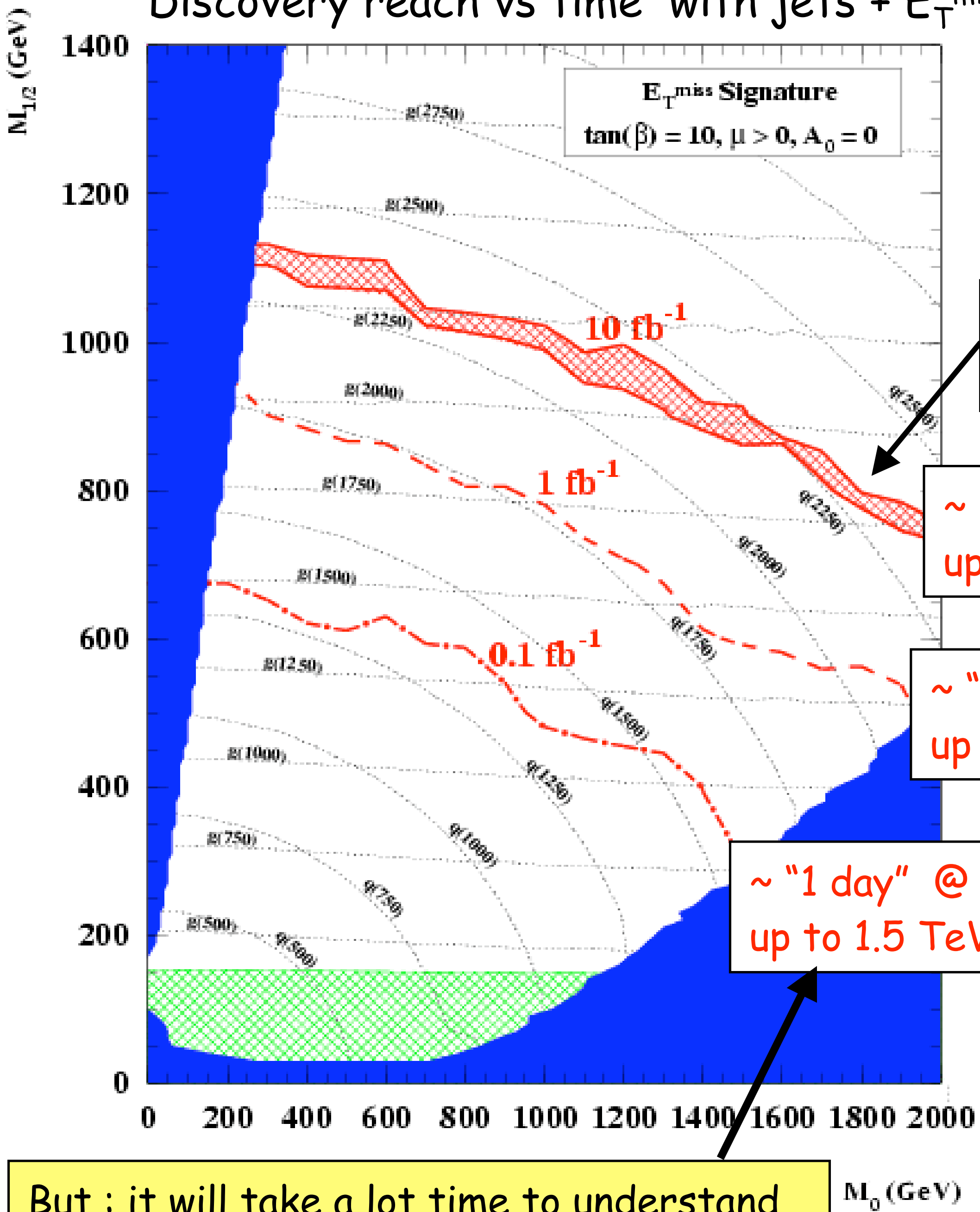






e^+e^- colliders	versus hadron colliders
Sparticles produced ~ democratically  	$\tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$ dominates  $\sigma(\tilde{q}, \tilde{g}) \approx 100$ pb $\sigma(\tilde{e}\tilde{e}) \approx 5$ fb } m=150 GeV Tevatron
Direct decays to LSP dominate: e.g. $\tilde{q}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

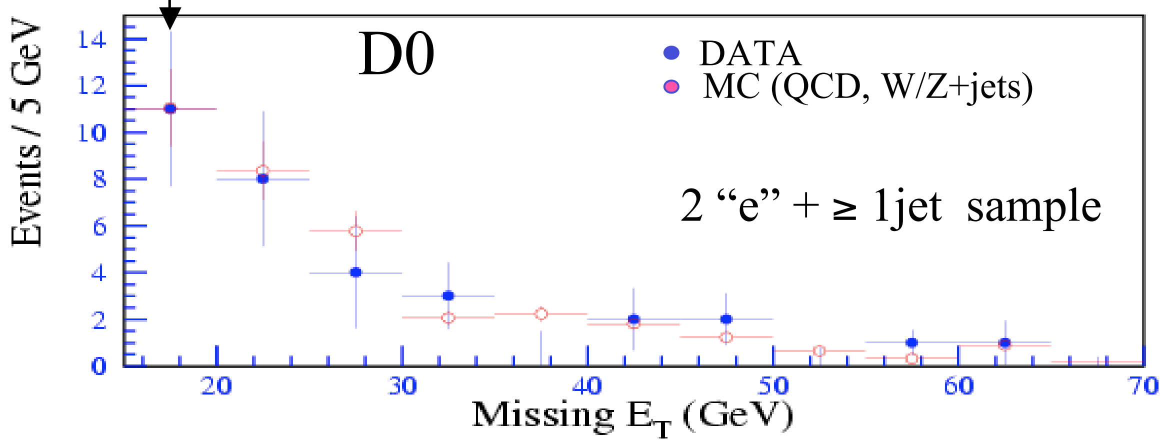
2) Estimate backgrounds using as much as possible data (control samples) and MC

Background process (examples ….)	Control samples (examples ….)
Z ($\rightarrow \nu\nu$) + jets	Z ($\rightarrow$ ee, $\mu\mu$) + jets
W ($\rightarrow \tau\nu$) + jets	W ($\rightarrow$ eν, $\mu\nu$) + jets
tt$\rightarrow$ blνbjj	tt$\rightarrow$ blν blν
QCD multijets	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

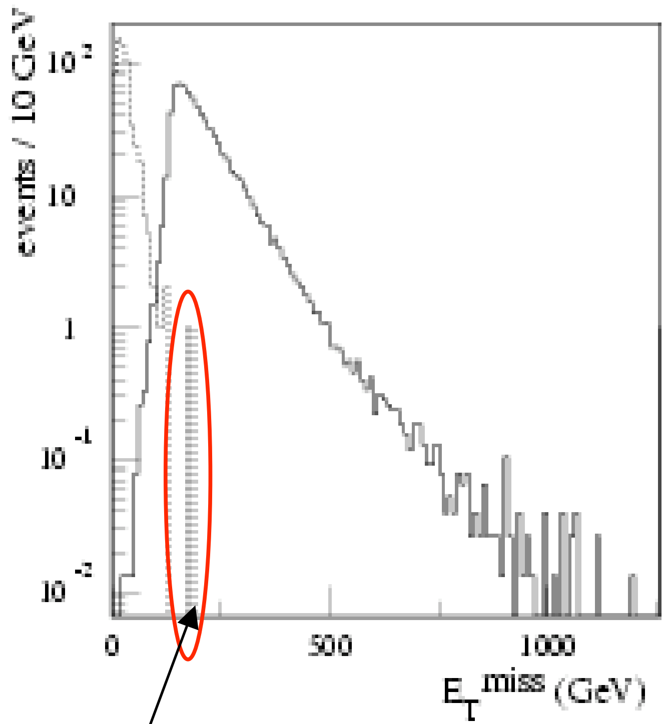
Hermetic calorimetry coverage : $|\eta| < 5$, minimal cracks and dead material

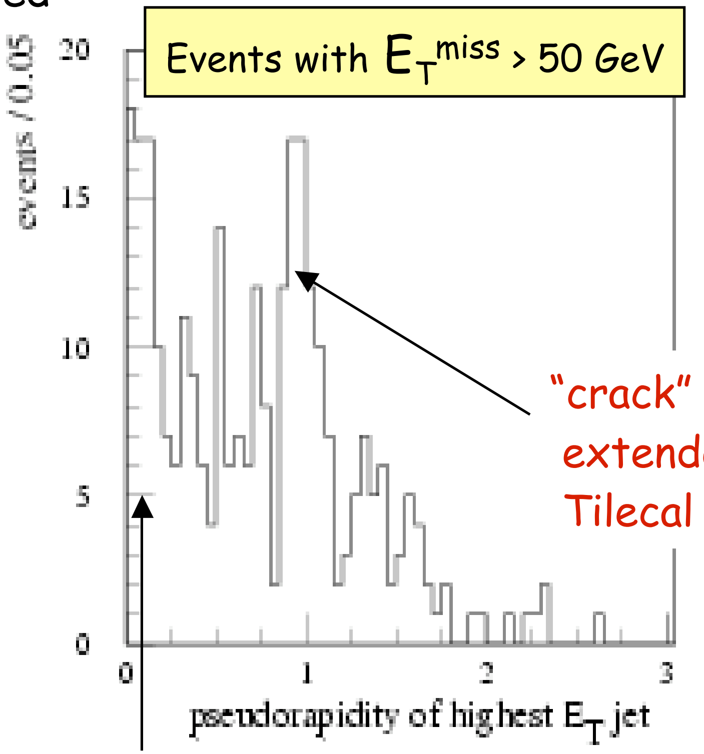
→ minimise fake E_T^{miss} from lost or badly measured jets

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

.... reconstructed E_T^{miss} spectrum

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



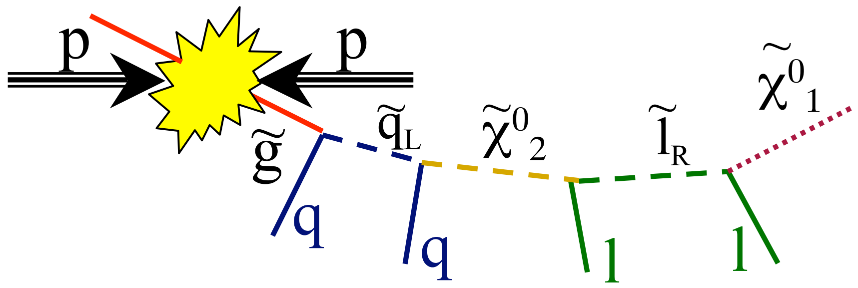


"crack" barrel/
extended barrel
Tilecal

Particles parallel
to Tilecal scintillating tiles

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

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

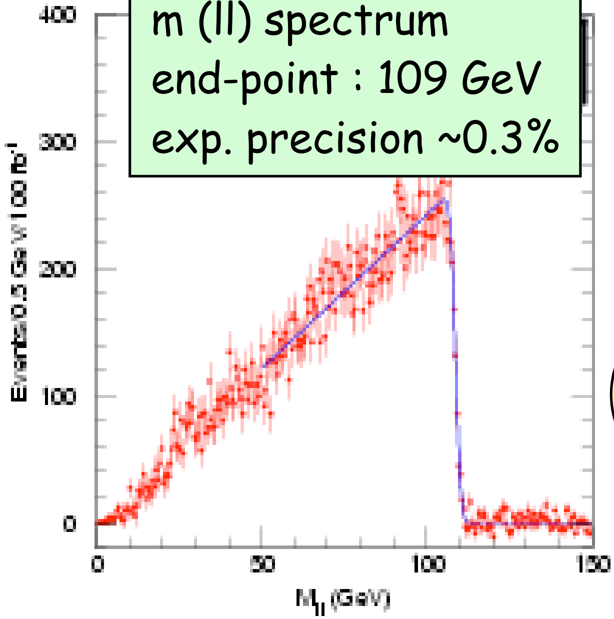
Ex. : LHC "Point 5" : $m_0 = 100$ GeV, $m_{1/2} = 300$ GeV, $A_0 = 300$ GeV, $\tan\beta = 2$, $\mu > 0$

$m(\tilde{q}) \sim 700$ GeV

$m(\tilde{g}) \sim 800$ GeV

$m(\chi^0_1) \sim 120$ GeV

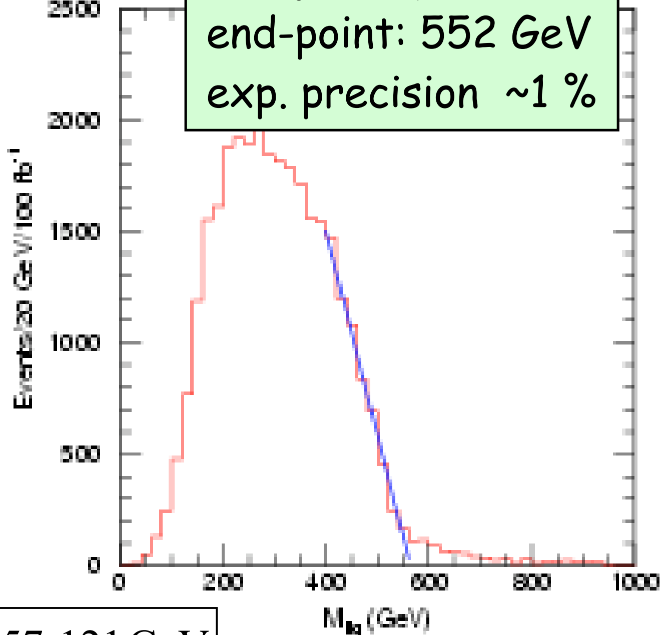
m (ll) spectrum
end-point : 109 GeV
exp. precision ~0.3%



Example of
a typical chain:

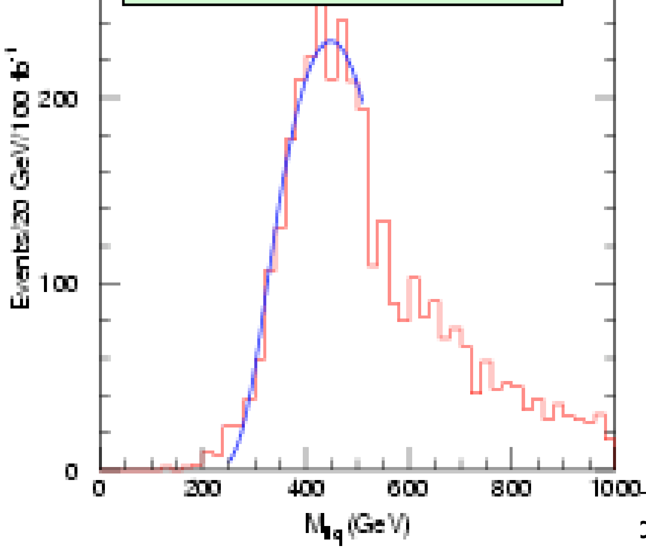
$\tilde{q}_L \to q\, \chi^0_2$
$\quad \hookrightarrow \tilde{l}\; l$
$\qquad \hookrightarrow l\, \chi^0_1$

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



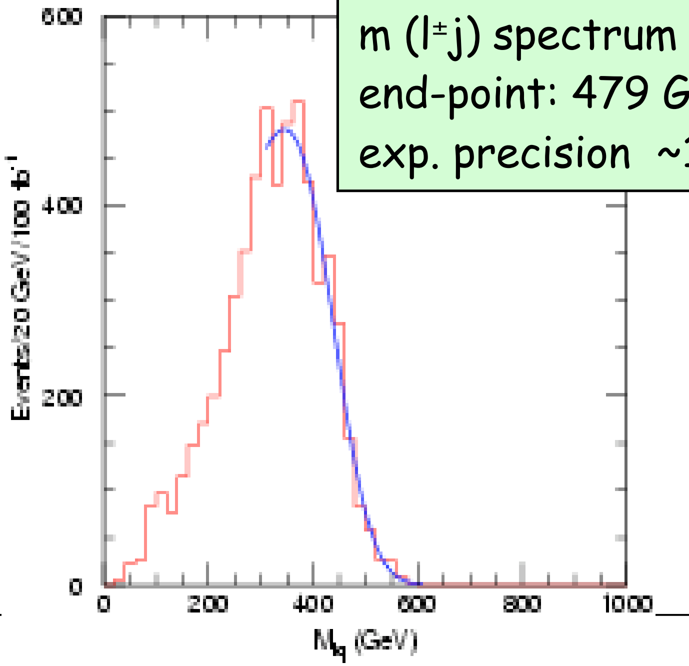
$m(\tilde{q}_L\ \ \chi^0_2\ \ \tilde{l}_R\ \ \chi^0_1\ ) = 690, 232, 157, 121\ \mathrm{GeV}$

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)

$\tilde{q}_L \rightarrow q\, \chi^0_2$

$\chi^0_2 \rightarrow h\, \chi^0_1$, $h \rightarrow bb$

$\chi^0_2 \rightarrow \tilde{\ell}_R\, l$, $\tilde{\ell}_R \rightarrow l\, \chi^0_1$

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:
$\tilde{q}_L$, $\tilde{q}_R$, $\tilde{g}$, $\tilde{t}_1$, $\tilde{\ell}_R$, $\tilde{\ell}_L$, h, χ^0_2

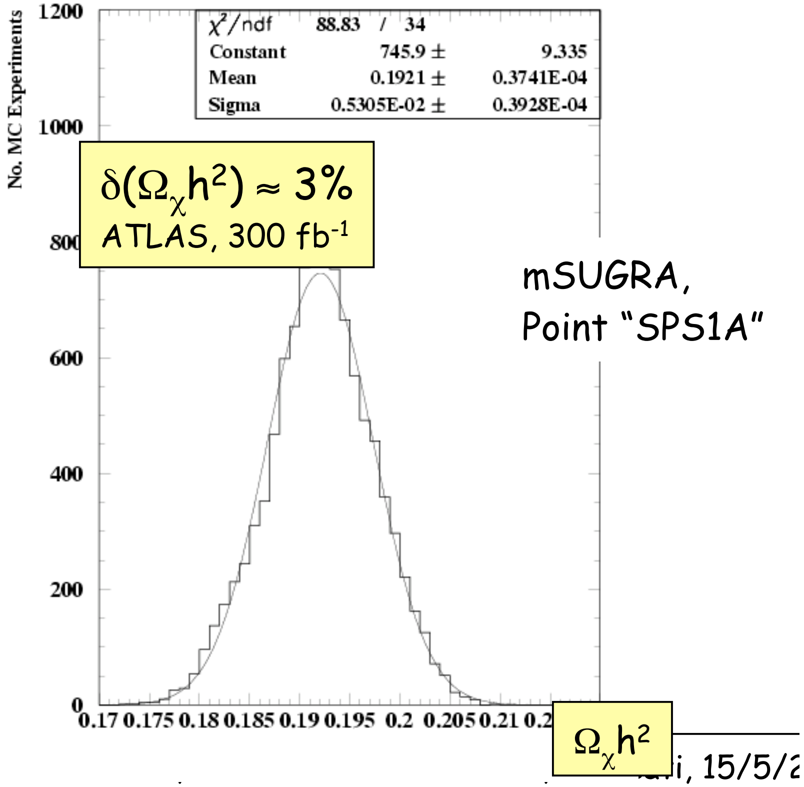
Note: can measure much more than masses: cross-sections, maybe some couplings and branching ratios, etc.

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

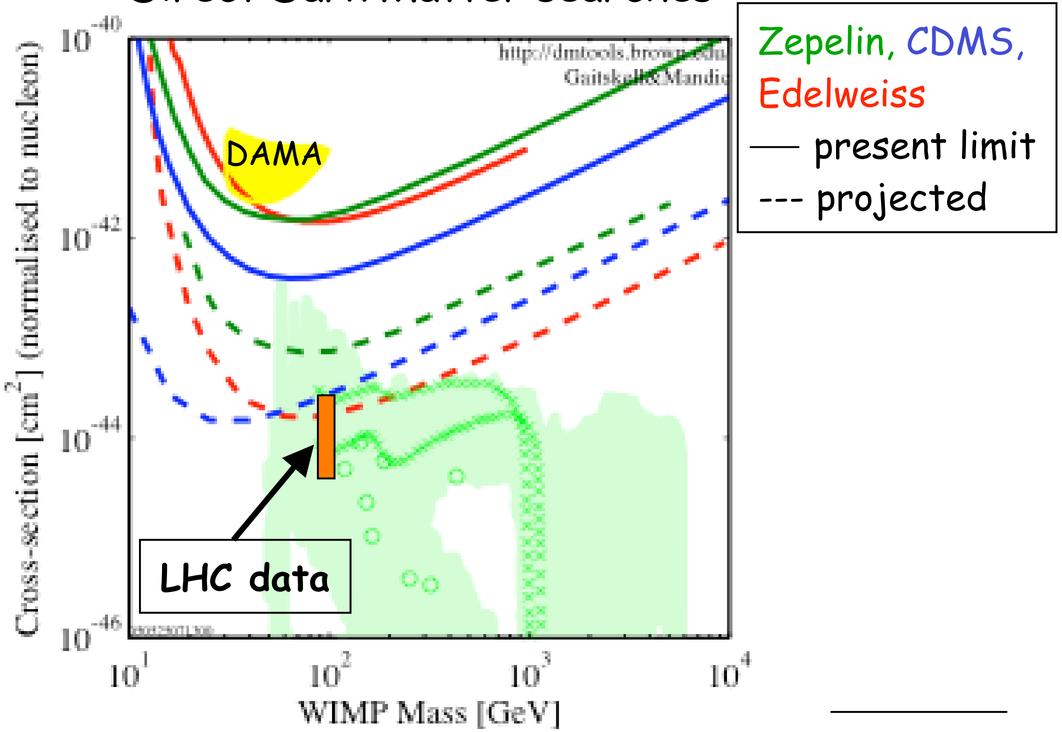
- sparticle masses with higher accuracy
- fundamental parameters of theory to 1-30%
- dark matter (χ^0_1) relic density and σ (χ^0_1 - nucleon)

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

As with SM at SLD, LEP, Tevatron



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:

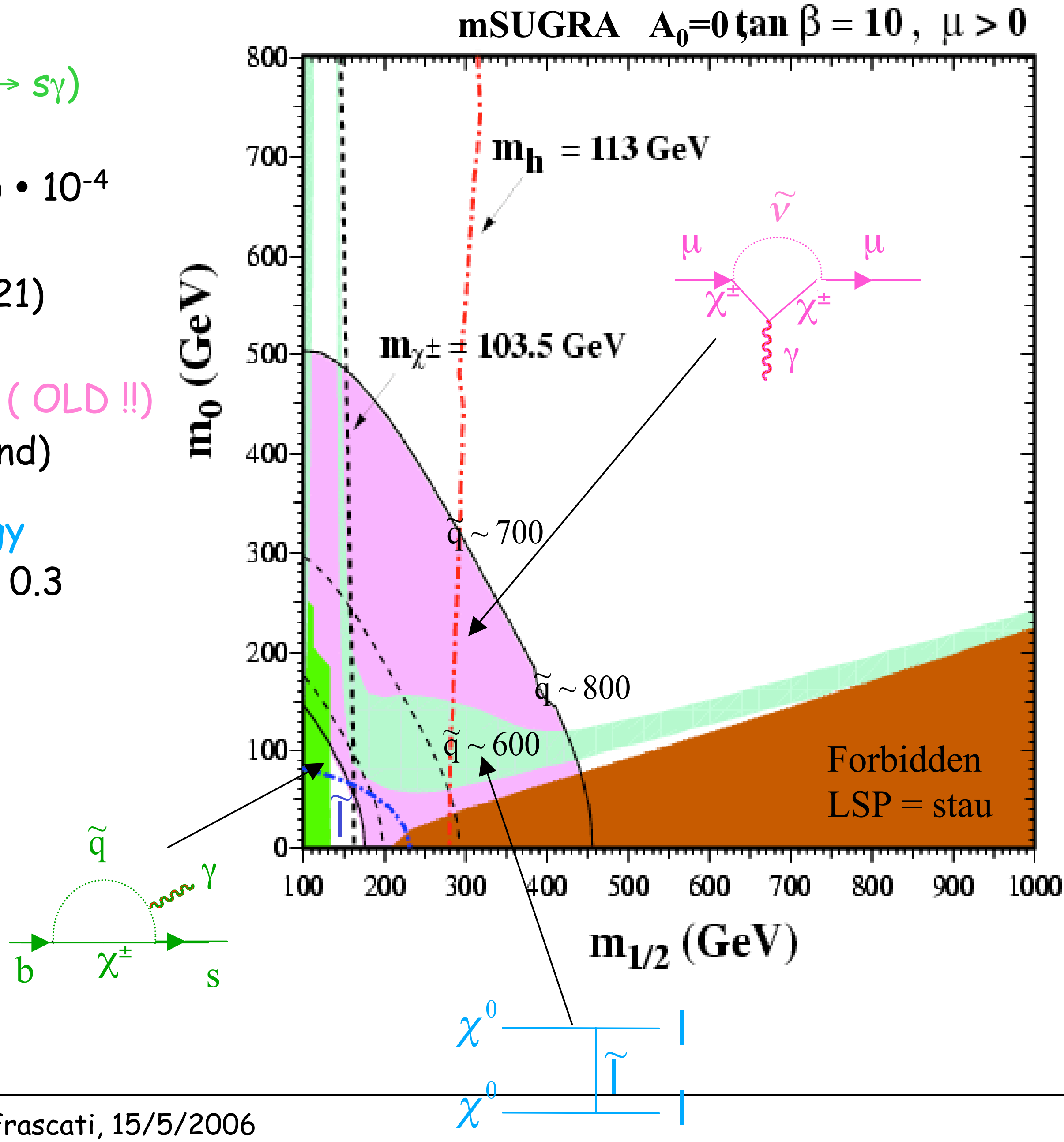
- reconstruct/look for semi-inclusive topologies, eg.:
  - -- h $\rightarrow$ bb peaks (can be abundantly produced in sparticle decays)
  - -- di-lepton edges
  - -- Higgs sector: e.g. A/H $\rightarrow$ $\mu\mu$, $\tau\tau$ $\Rightarrow$ indication about tanβ, measure masses
  - -- tt pairs and their 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

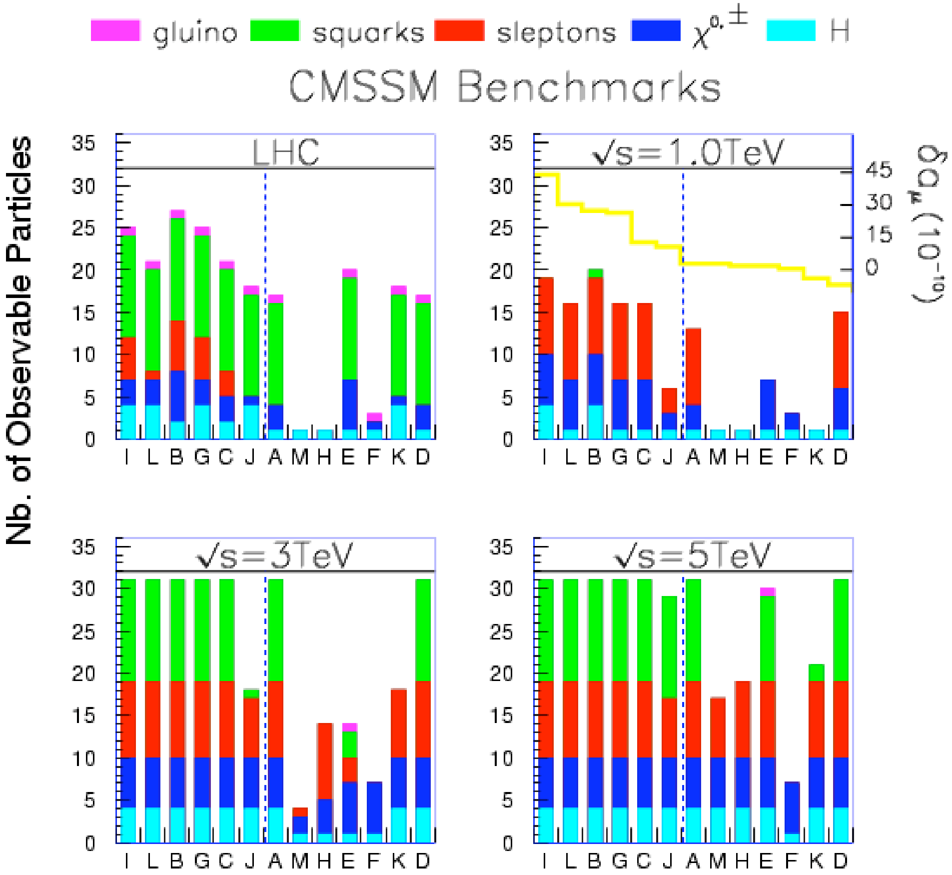
Combining collider data with other "constraints" ….

- Disfavoured by BR (b → sγ) from CLEO, BELLE
  BR (b → sγ) = (3.2 ± 0.5) • 10^{-4} used here
- Favoured by g_μ-2 (E821) assuming that
  $\delta\alpha_\mu$ = (43 ± 16) • 10^{-10} (OLD !!) is from SUSY (± 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 $\tilde{q}$ and $\tilde{g}$ (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 ….

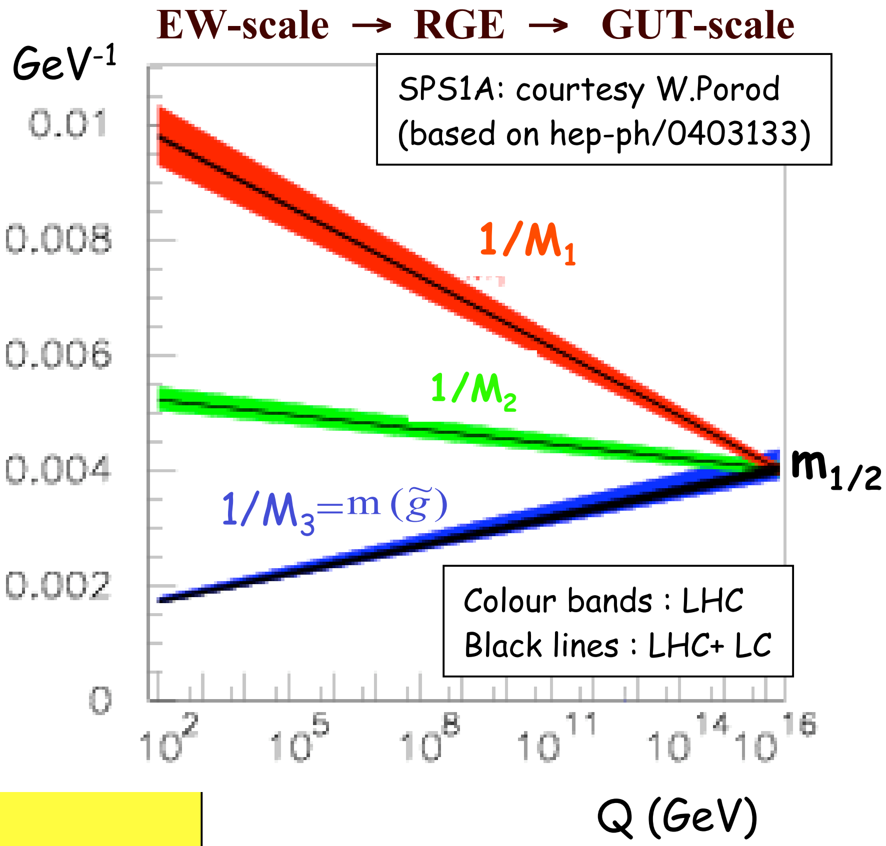
In general the LHC can (examples …):

- 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

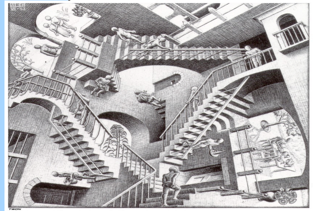
➡ complementarity with LC



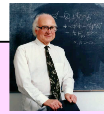
Ultimate goal : from precise measurements of e.g. gaugino masses at the TeV scale reconstruct high-E theory

SUSY
New particles at TeV scale
stabilize m_H

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



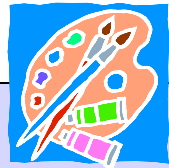
Little Higgs



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

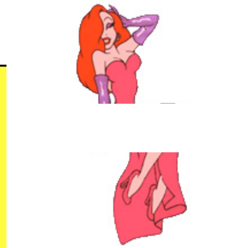
$\delta m_H \sim \Lambda \Rightarrow$ New Physics to stabilize m_H already needed at TeV scale

Technicolour



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

Split SUSY



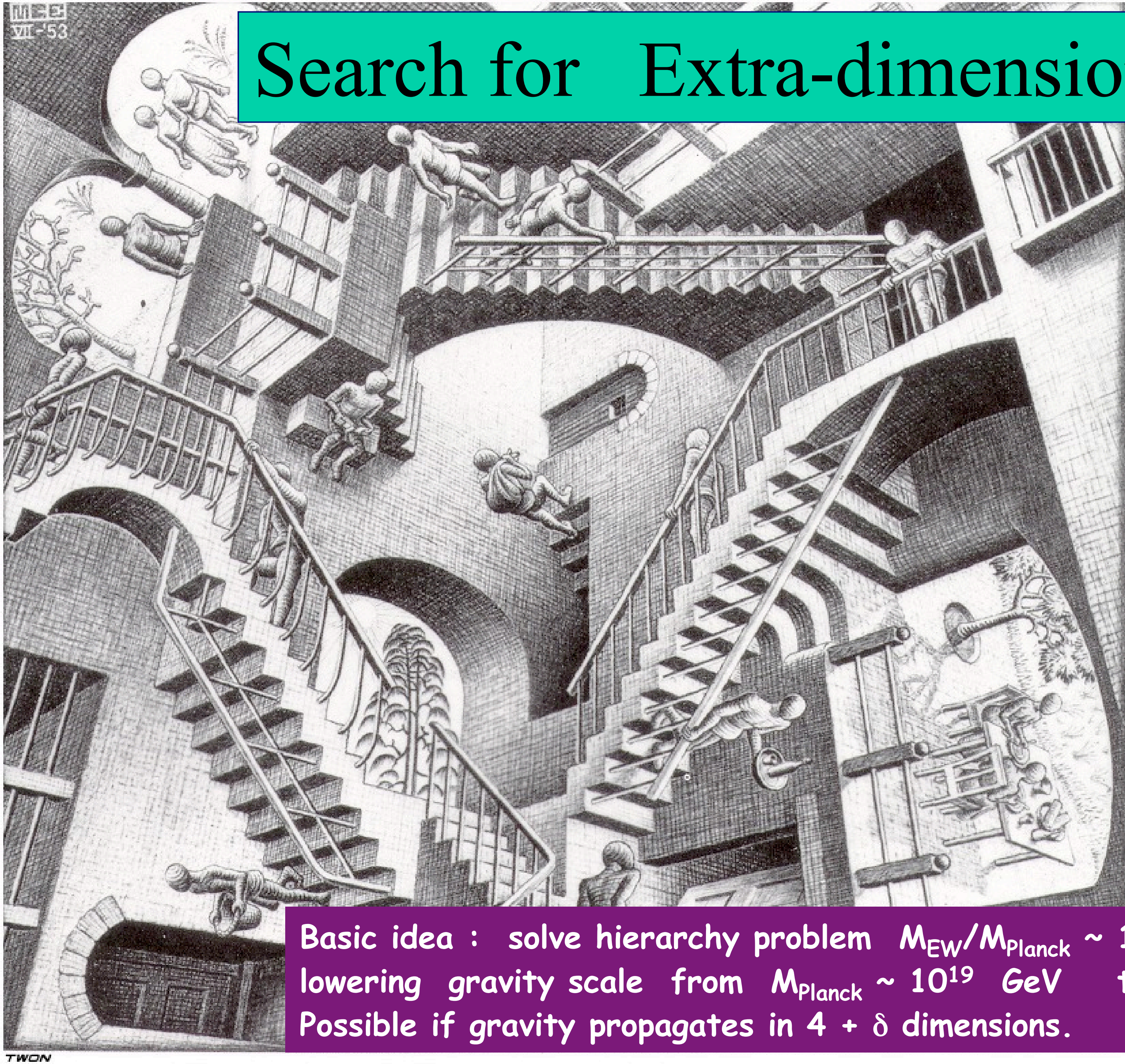
Accept fine-tuning of m_H
(and of cosm. constant)
by anthropic arguments
Part of SUSY spectrum at TeV scale
(for couplings unification and dark matter)

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

⬇

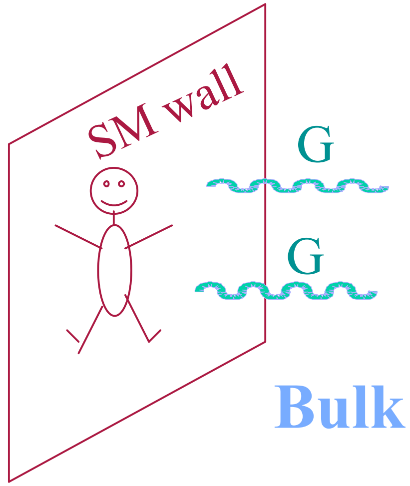
LHC

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 + δ dimensions.

Arkani-Hamed, Dimopoulos, Dvali



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

$$V_4(r) \sim \frac{1}{M_{Pl}^2}\frac{1}{r}$$
$$V_{4+\delta}(r) \sim \frac{1}{M_D^{\delta+2} R^\delta}\frac{1}{r}$$
at large distance

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

- If $M_D \approx 1$ TeV :

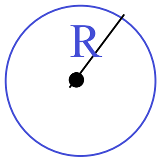
$\delta = 1$ $R \approx 10^{13}$ m → excluded by macroscopic gravity

$\delta = 2$ $R \approx 0.7$ mm → limit of small- scale gravity experiments

….

$\delta = 7$ $R \approx 1$ Fm

Extra-dimensions are compactified over R < mm



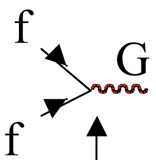
- Gravitons in Extra-dimensions get quantized mass:

$$m_k \sim \frac{k}{R} \qquad k = 1, \dots \infty$$

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

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

σ (



)

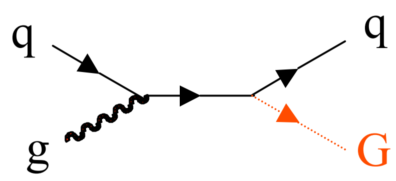
$$\approx \frac{1}{M_{Pl}^2} N_{kk} \approx \frac{1}{M_{Pl}^2} \left(\frac{\sqrt{s}}{\Delta m} \right)^{\delta} \approx \frac{1}{M_{Pl}^2} \sqrt{s}^{\,\delta} R^{\delta} \approx \boxed{\frac{\sqrt{s}^{\,\delta}}{M_D^{\delta+2}}}$$

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 $\approx \frac{1}{M_D^{\delta+2}}$

M_D = gravity scale

δ = number of extra-dimensions

ATLAS, 100 fb^{-1}

	δ = 2	δ = 3	δ = 4
M_D^{max}	9 TeV	7 TeV	6 TeV

Discriminating between models:

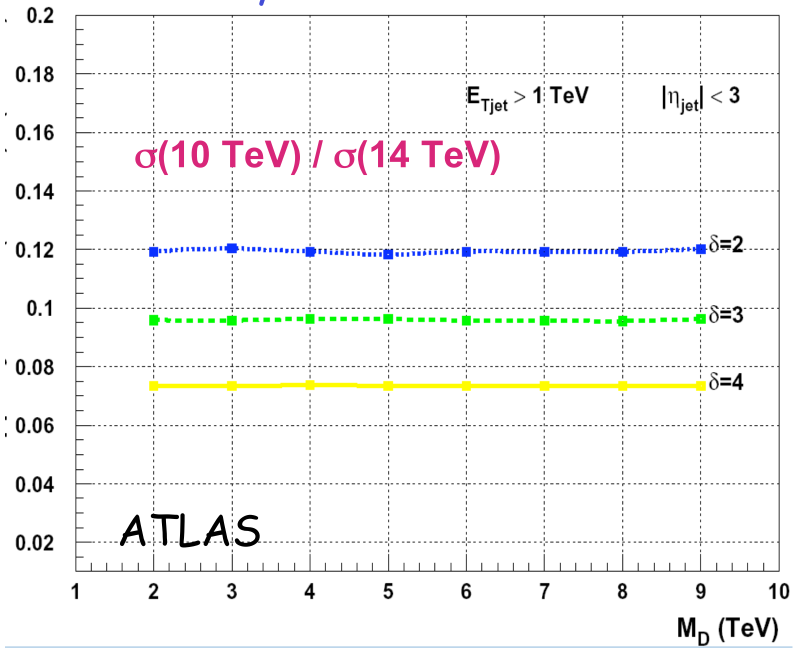
-- SUSY : multijets plus E_T^{miss} (+ leptons, …)

-- 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}

$G \to e+e-$ resonance with $m \sim 1$ TeV

The easiest object to discover at the LHC …

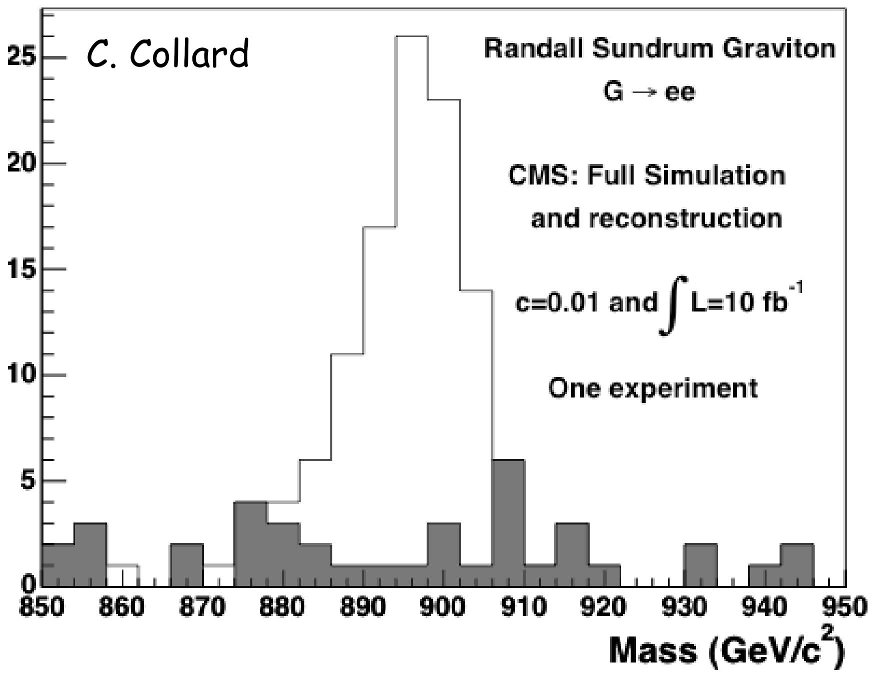
Randall-Sundrum Extra-dimensions

BR ($G \to ee \approx 2\%$), 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}

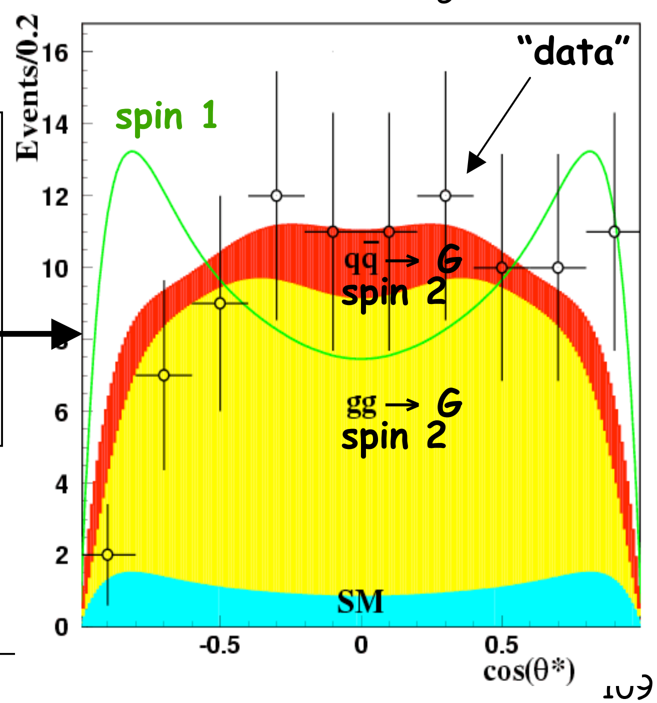
CMS

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

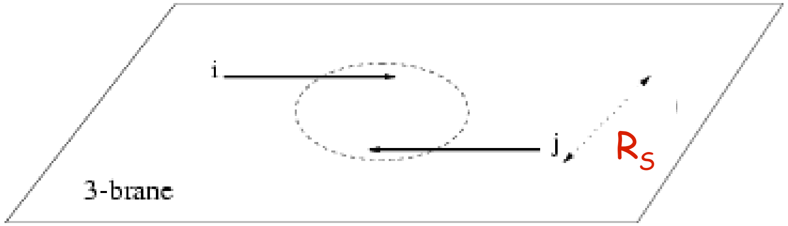
- Schwarzschild radius (i.e. within which nothing escapes gravitational force):

4-dim., $M_{gravity} = M_{Planck}$: $R_S \sim \frac{2}{M_{Pl}^2} \frac{M_{BH}}{c^2}$

4 + δ-dim., $M_{gravity} = M_D \sim$ TeV : $R_S \sim \frac{1}{M_D} \left(\frac{M_{BH}}{M_D} \right)^{\frac{1}{\delta+1}}$

⬇

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

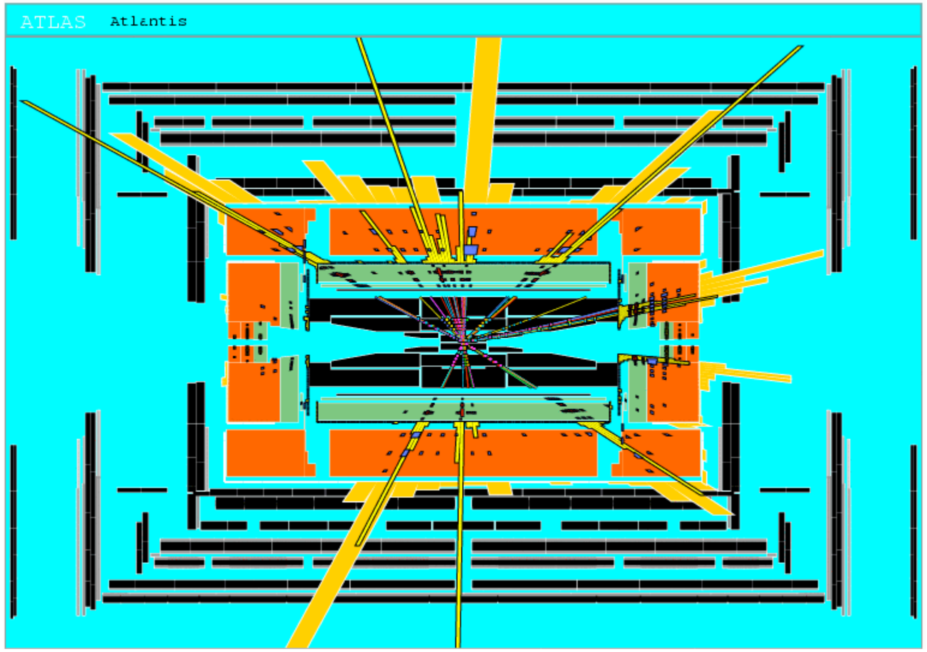


- Large partonic cross-section : $\sigma(ij \to BH) \sim \pi R_S^2$

  e.g. For $M_D \sim 3$ TeV and $\delta = 4$, $\sigma(pp \to BH) \sim 100$ fb → 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} ~ 8 TeV in ATLAS

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

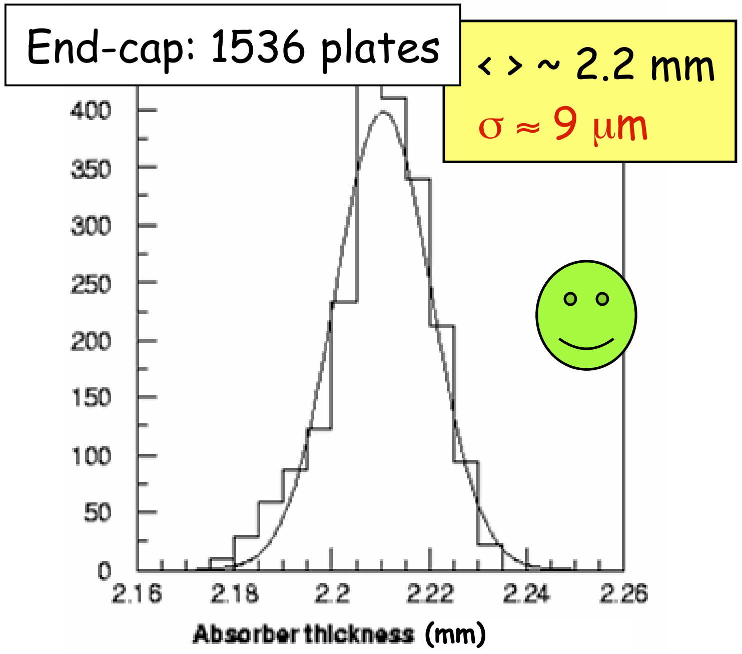
By testing Hawking formula → proof that it is BH + measurement of M_D, δ

$$\log T_H = -\frac{1}{\delta + 1} \log M_{BH} + f(M_D, \delta)$$

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

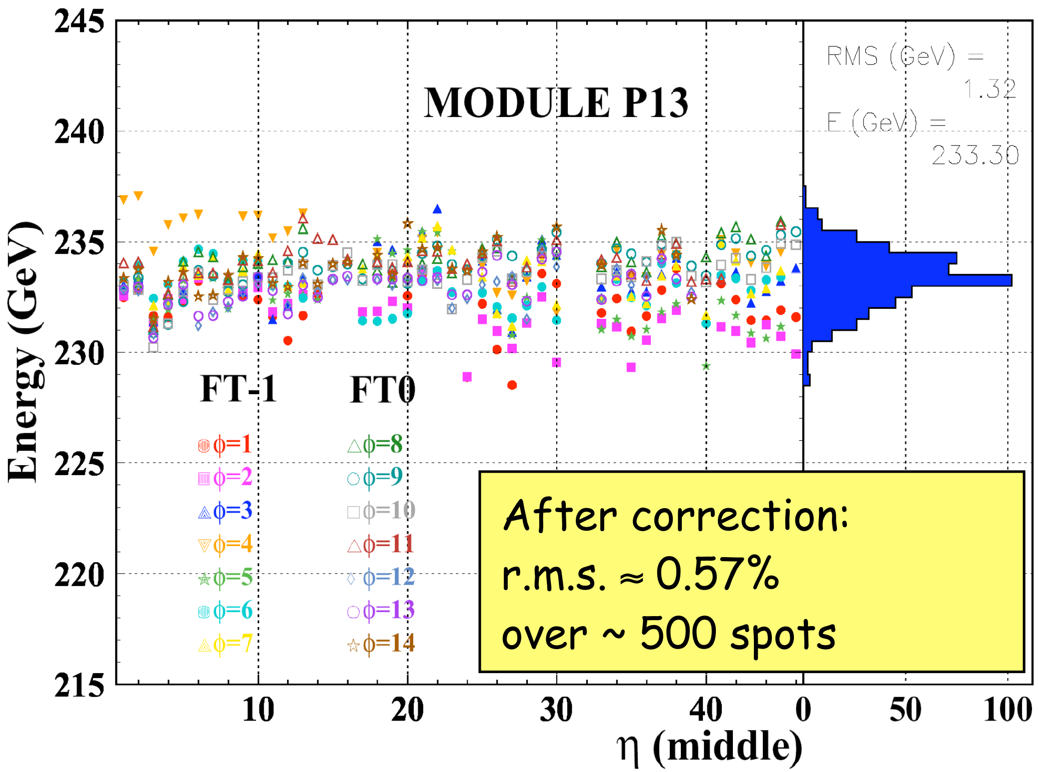
❶ Construction quality

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



❷ Test-beam measurements

Scan of a barrel module ($\Delta\varphi \times \Delta\eta$=0.4X1.4) with high-E electrons



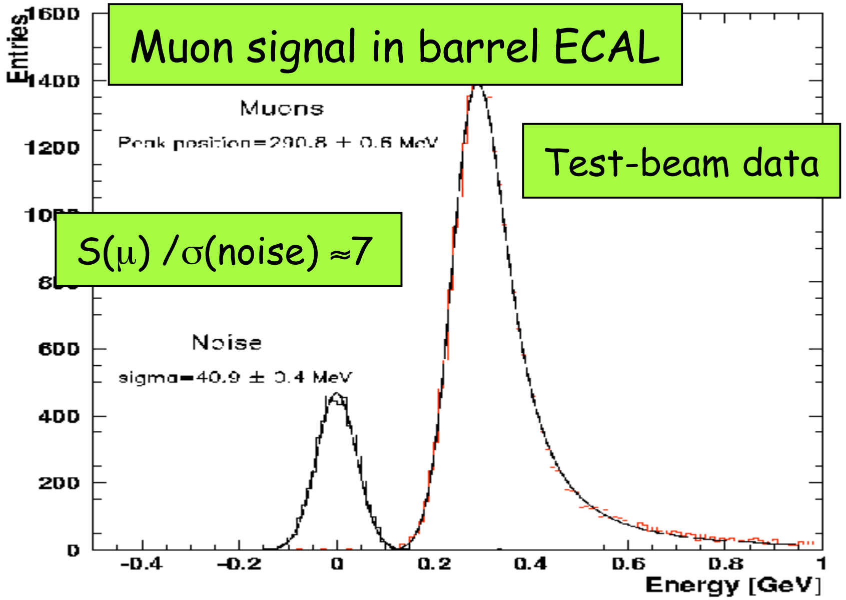
❸ Cosmics runs:

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%



❹ 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

❷ 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
$W \to \mu \nu$	7 x 10^6	~ 10^4 LEP, ~ 10^6 Tevatron
$Z \to \mu \mu$	~ 10^6	~ 10^6 LEP, ~ 10^5 Tevatron
$tt \to W b W b \to \mu \nu + X$	~ 10^5	~ 10^4 Tevatron
$\tilde{g}\tilde{g}$ m = 1 TeV	10^2 - 10^3	———

With these data:

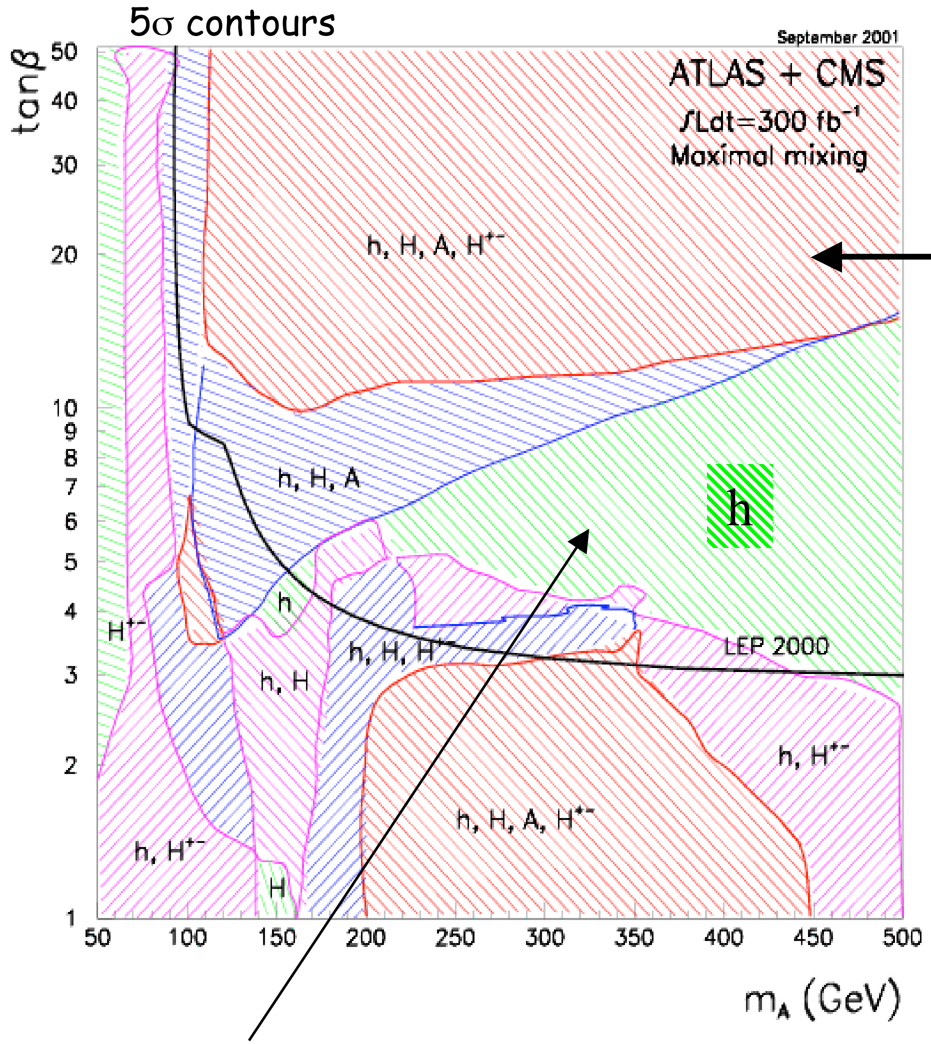
- Understand and calibrate detectors in situ using well-known physics samples
  e.g. - $Z \to ee, \mu\mu$ tracker, ECAL, Muon chambers calibration and alignment, etc.
  - $tt \to bl\nu\ bjj$ jet scale from $W \to jj$, b-tag performance, etc.

- 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 …

SUSY Higgs sector : h, H, A, H±

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



H, A → μμ, ττ
H± → τν , tb

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

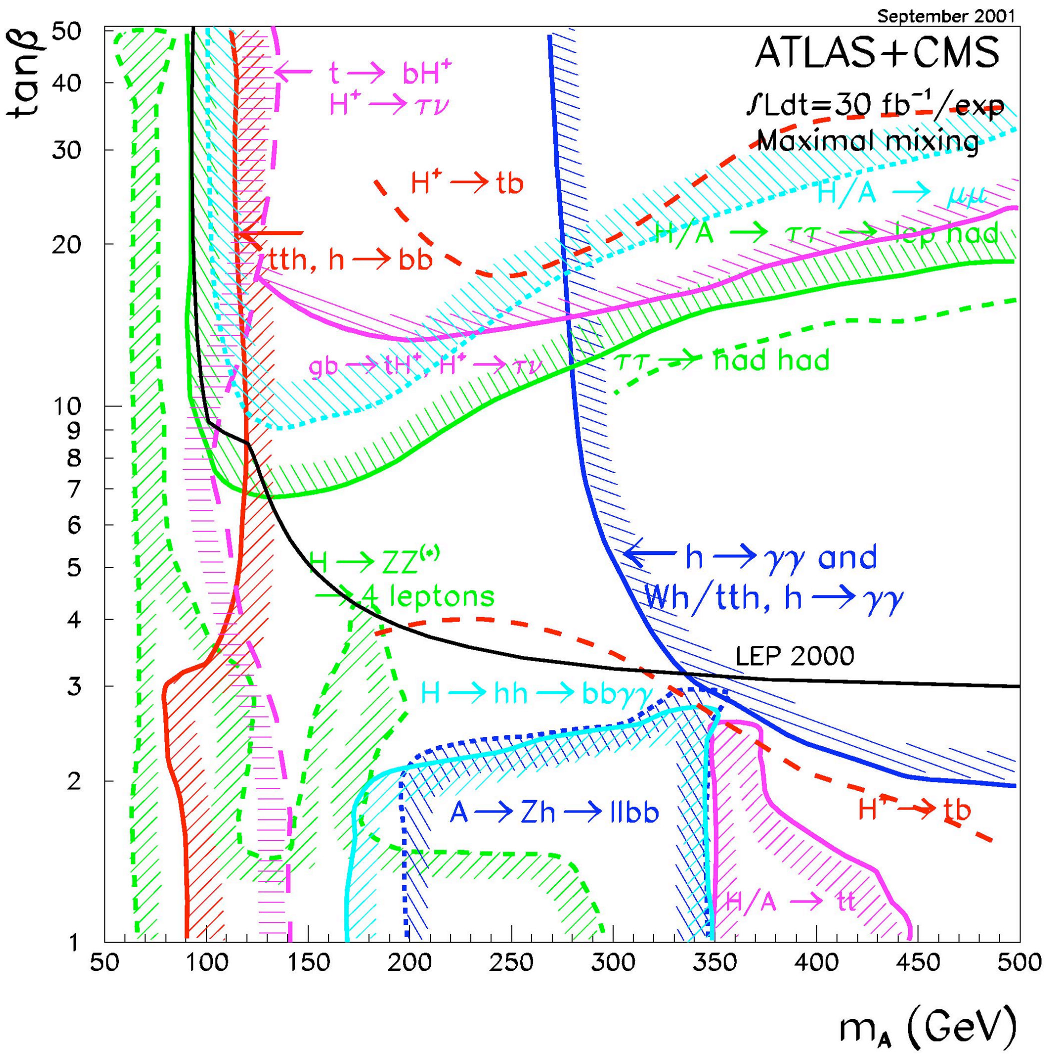
Assuming decays to SM particles only

Here only h (SM - like) observable at LHC, unless A, H, H± → 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

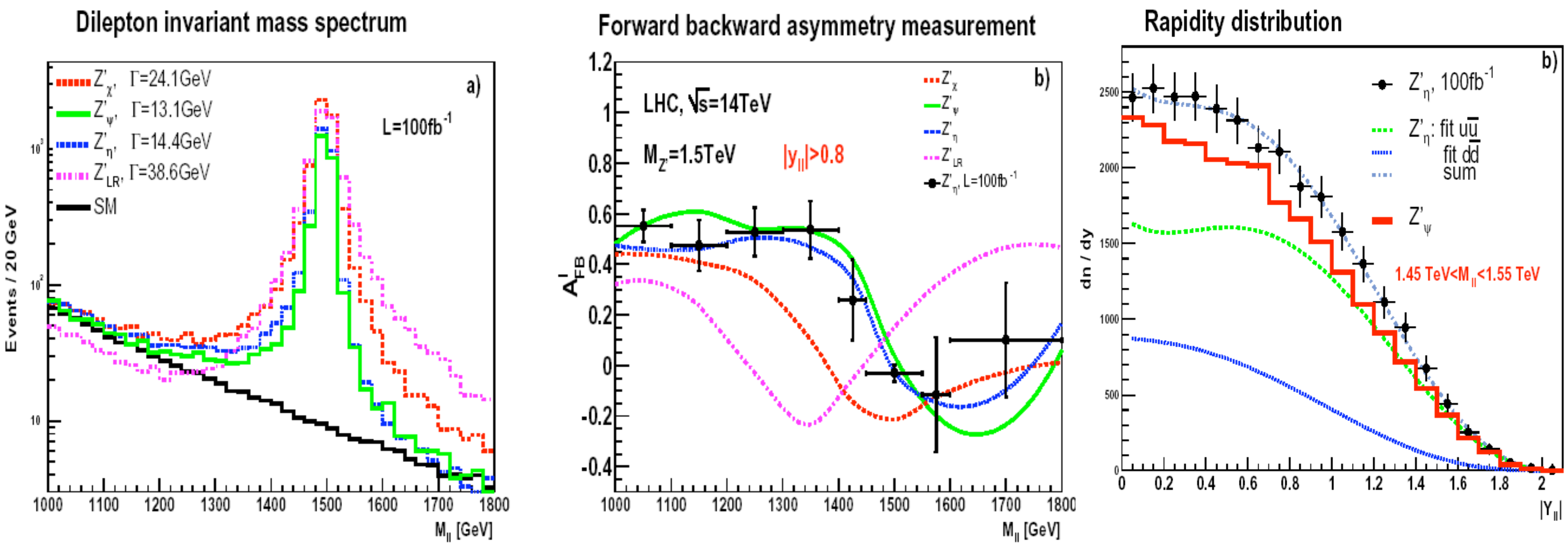
Most of MSSM Higgs plane already covered after 1 year at L= 10^{33} …



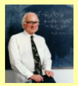
Large variety of channels and signatures accessible

Extended gauge groups : Z′ → l^+l^-

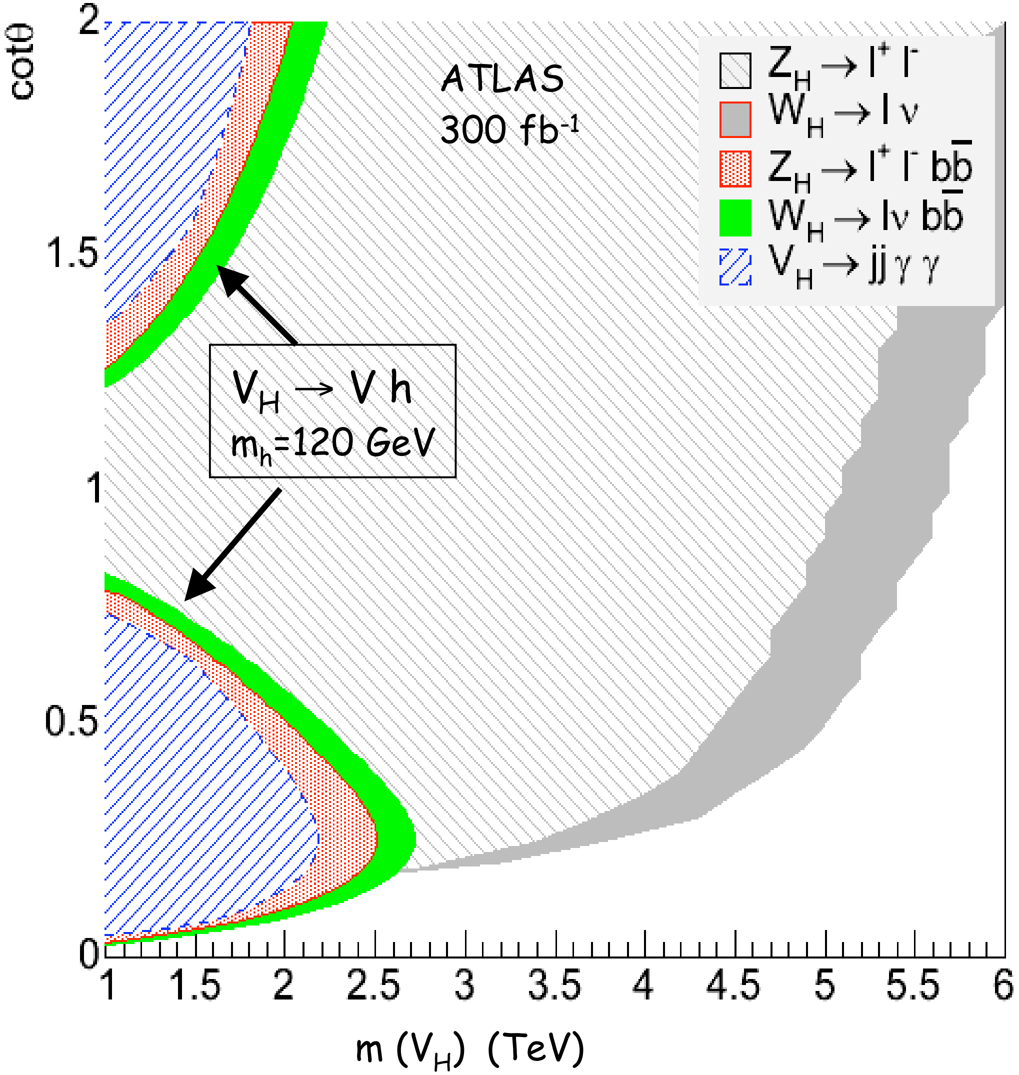
CMS



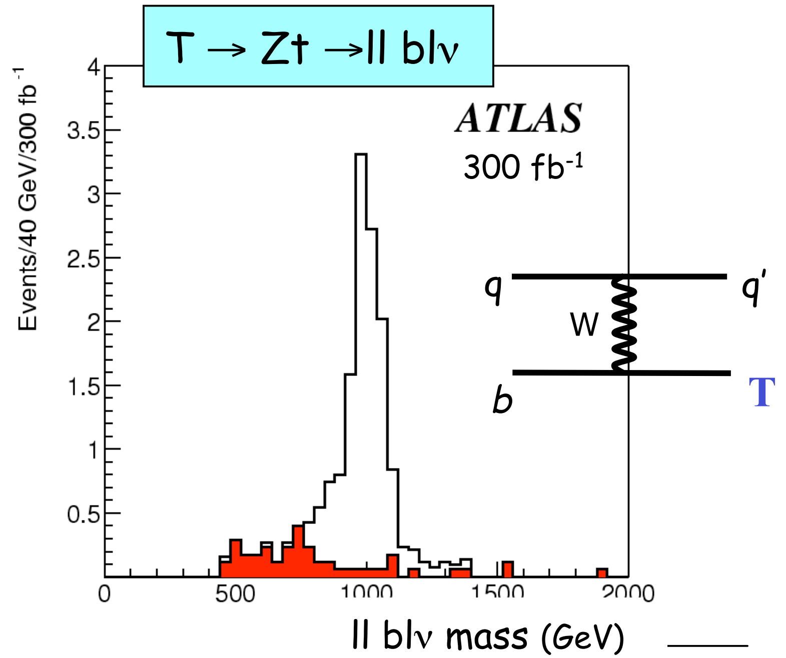
- Reach in 1 year at 10^{34} : 4-5 TeV
- Discriminating between models possible up to m ~ 2.5 TeV by measuring:
  - -- $\sigma x \Gamma$ of resonance
  - -- lepton F-B asymmetry
  - -- Z′ rapidity

Little Higgs  models

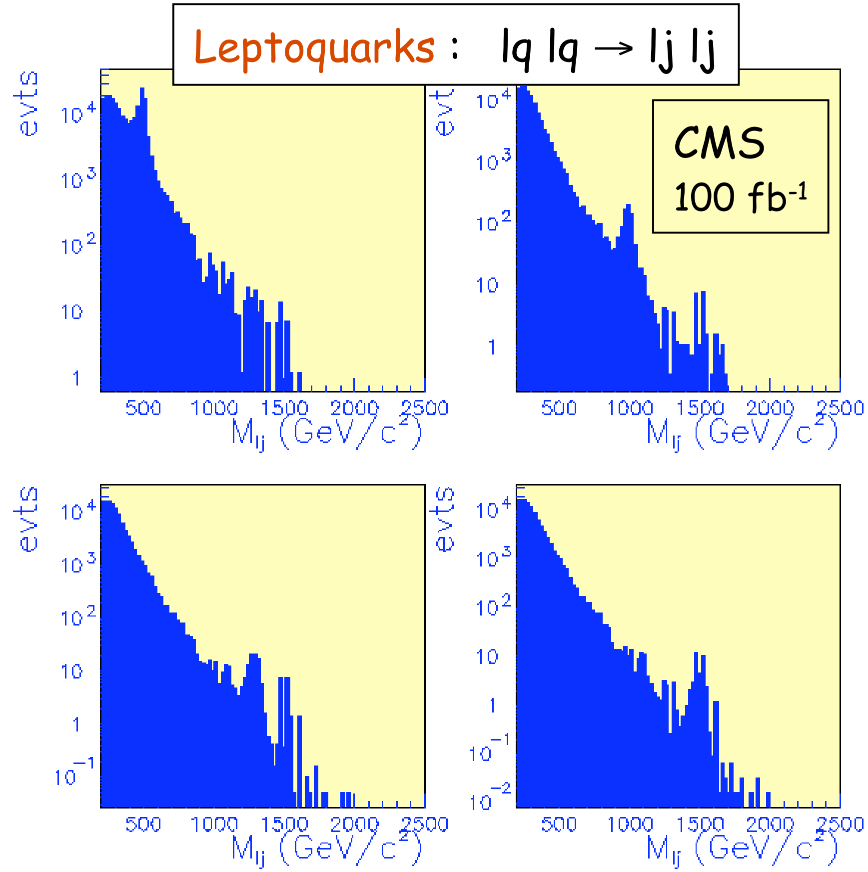
Alternative approach to the hierarchy problem predicting heavy top T (EW singlet), new gauge bosons W_H, Z_H, A_H and Higgs triplet Φ^0, Φ^+, Φ^{++}

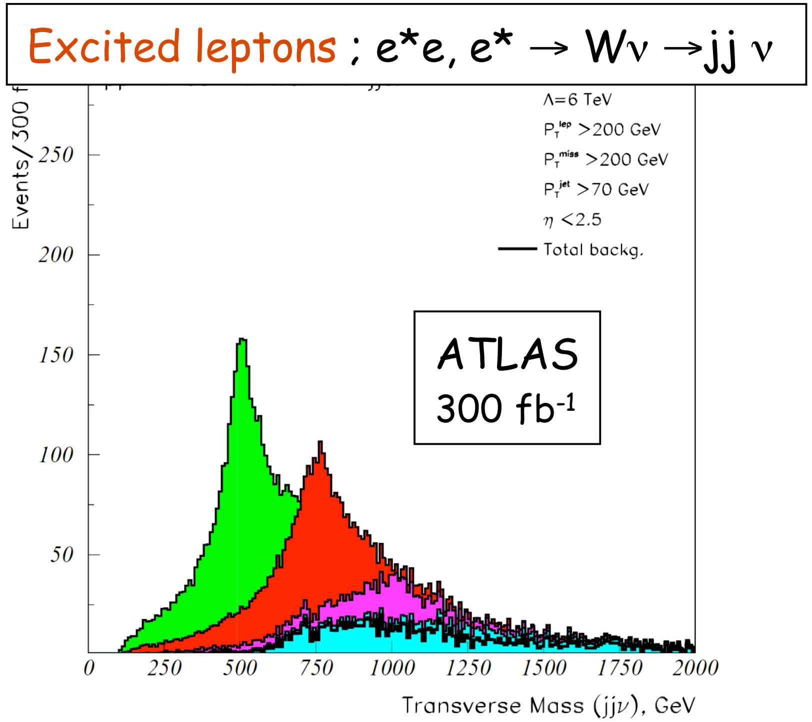


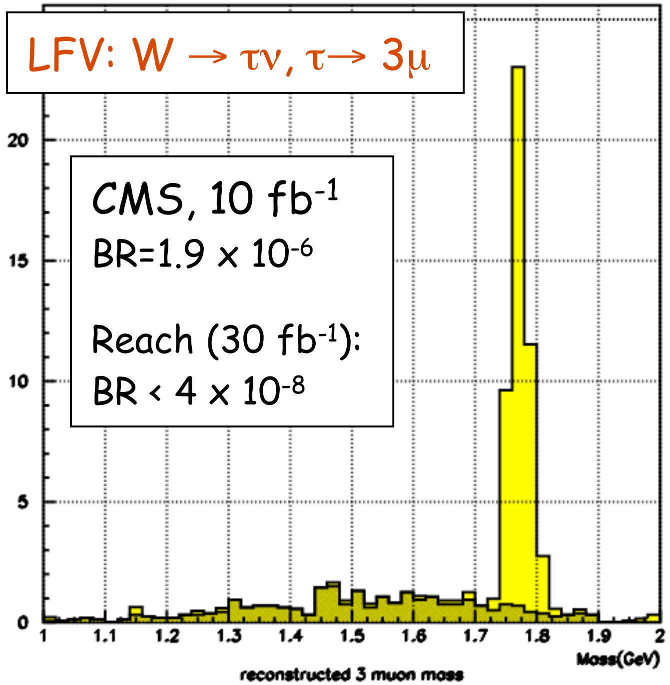
Observation of $T \to Zt$, Wb discriminates from 4th family quarks
Observation of $V_H \to Vh$ discriminates from W', Z'



Other scenarios .....







Large number of scenarios studied:

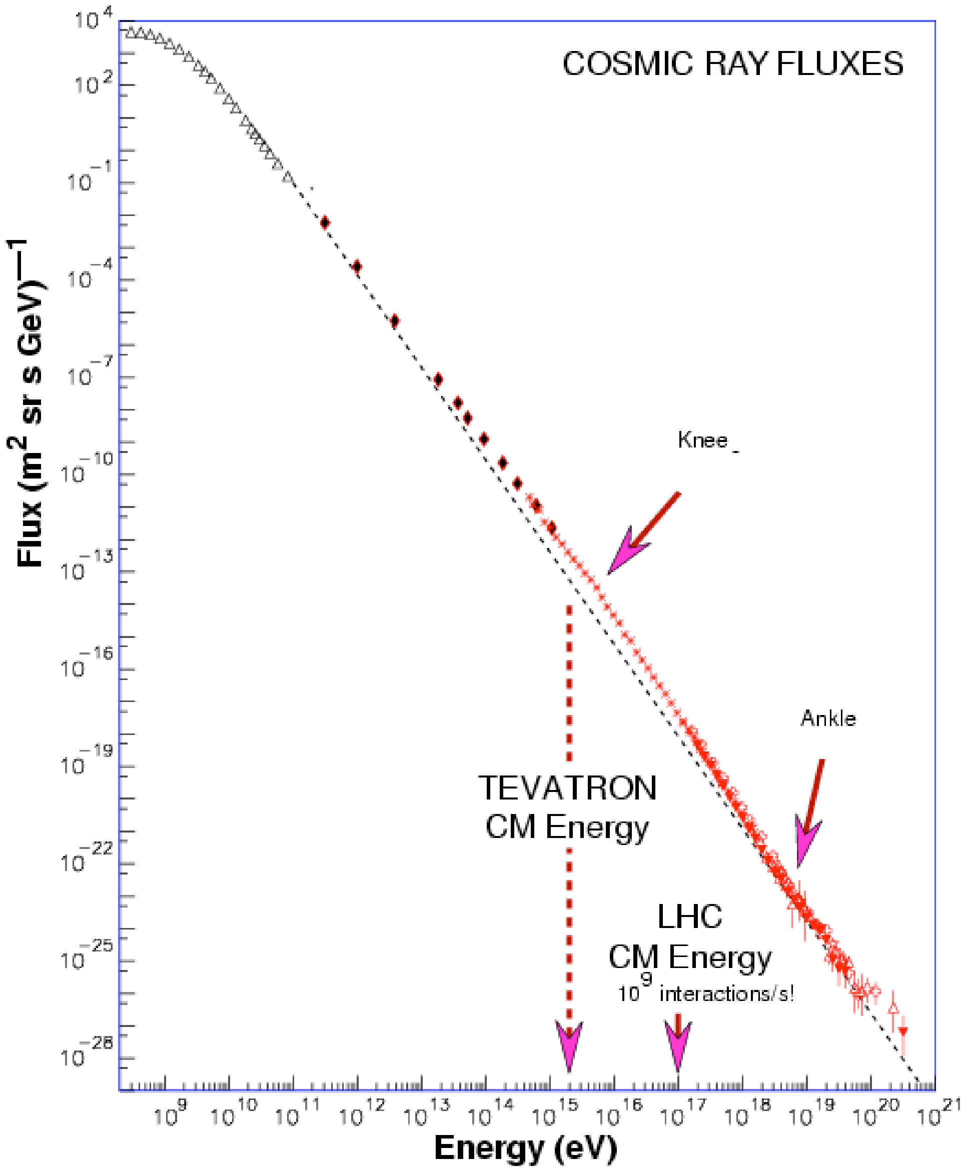
⇒ demonstrated detector sensitivity to many signatures

→ robustness, ability to cope with unexpected scenarios

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

LHC and high-energy cosmic rays

$\sqrt{s}$ = 14 TeV → corresponds to E ~ 100 PeV fixed target proton beam



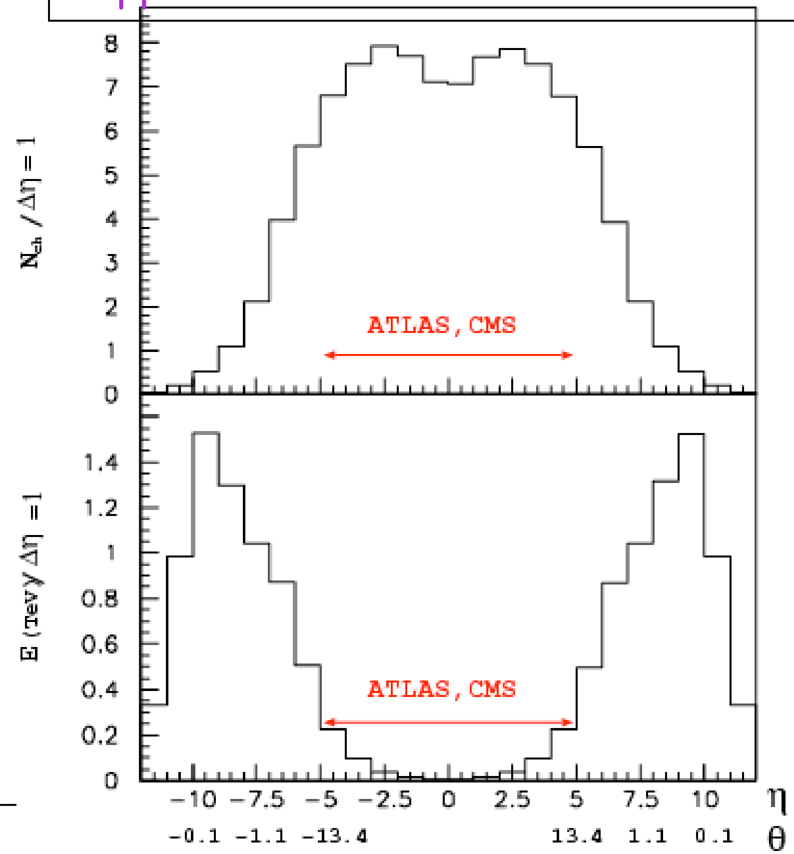
LHC studies most relevant to HECR:

-- most energetic particles from the collisions

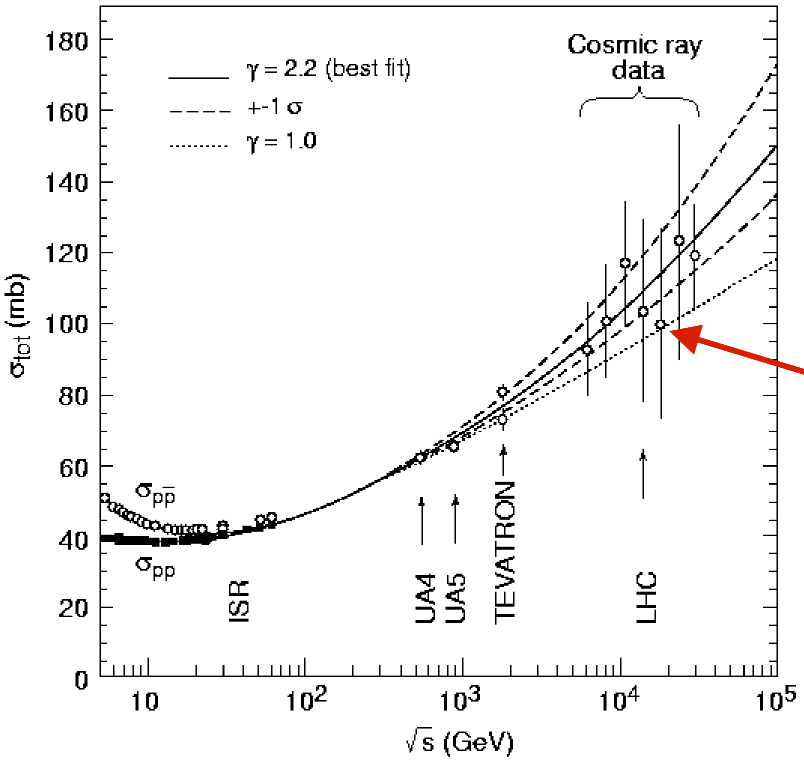
-- pp (and pA, AA) cross-sections

both require detection in the forward region

Charged particle multiplicity and energy in pp inelastic events at $\sqrt{s}$ = 14 TeV



Measurement of σ_{tot} (pp)

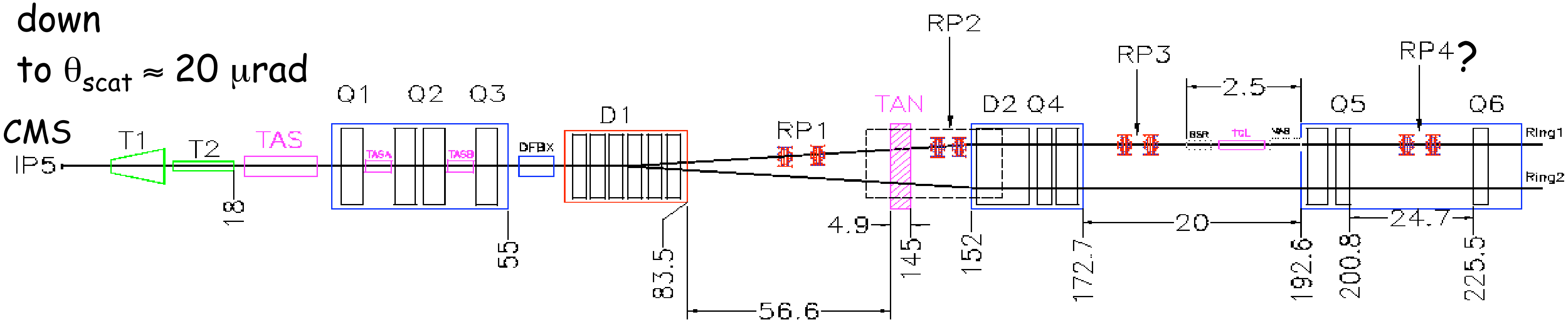


Curves are ~ $(\log s)^{\gamma}$

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



With the first collision data (1→ 100 pb^{-1} ?)

- understand detector performance in situ ⇔ physics (the two are correlated !)
- measure particle multiplicity in minimum bias (a few hours of data taking …)
- measure QCD jets (>10^3 events with E_T (j) > 1 TeV with 100 pb^{-1}) and their underlying event
- measure W,Z cross-sections: to 15% with <10 pb^{-1} and 10% with 100 pb^{-1}?
- observe a top signal with ~ 30 pb^{-1}
- measure tt cross-section to 20% and m(top) to 7-10 GeV with 100 pb^{-1} ?
- improve knowledge of PDF (low-x gluons !) with W/Z: with O(100) pb^{-1} ?
- first tuning of MC (minimum bias, underlying event, tt, W/Z+jets, QCD jets,…)

And, more ambitiously:

- discover SUSY up to squark and gluino masses of ~ 1.3 TeV ?
- discover a Z' up to masses of ~ 1.3 TeV ?
- surprises ?