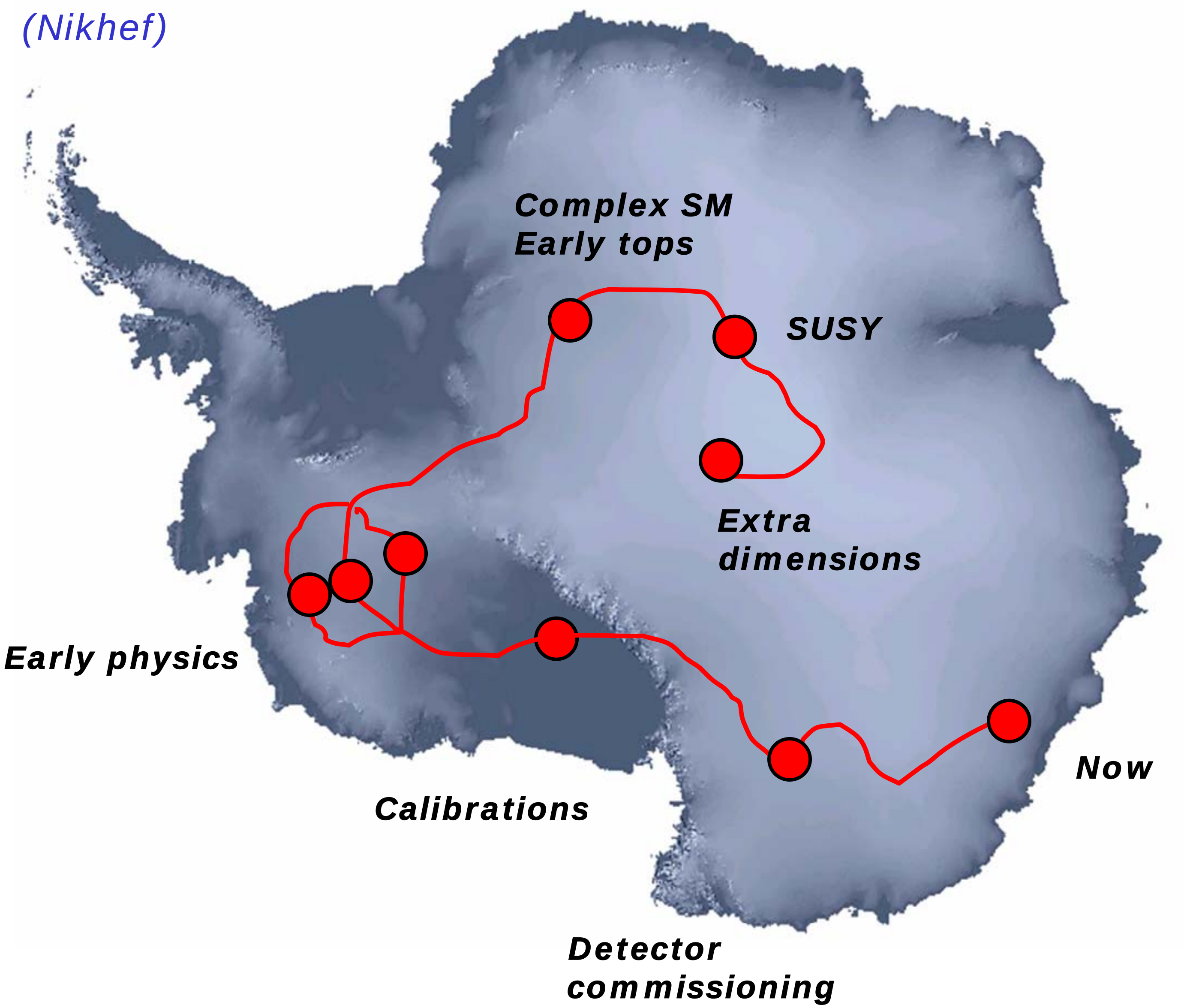
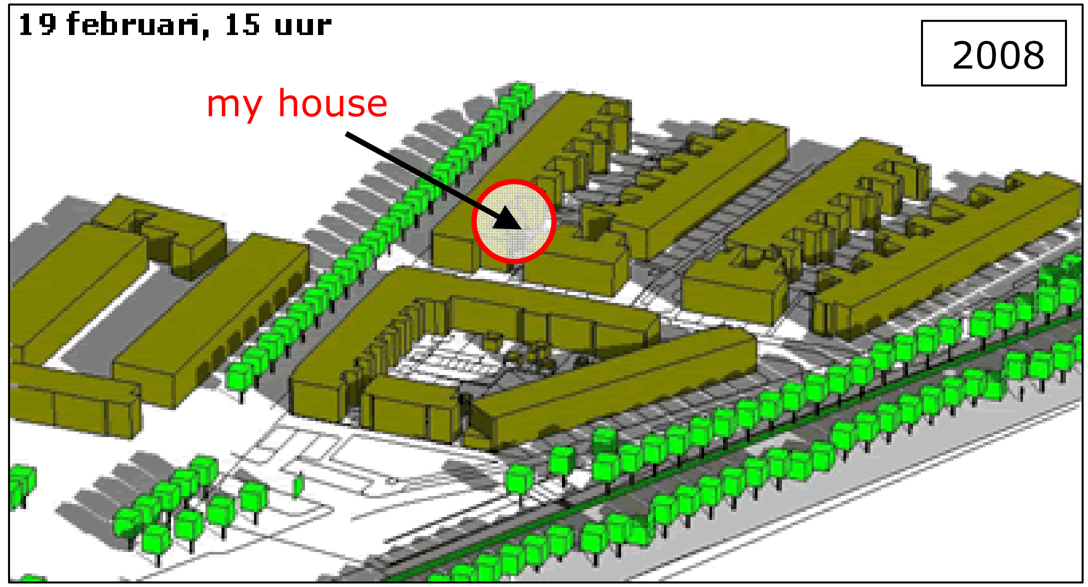
Preparing for first physics at the LHC

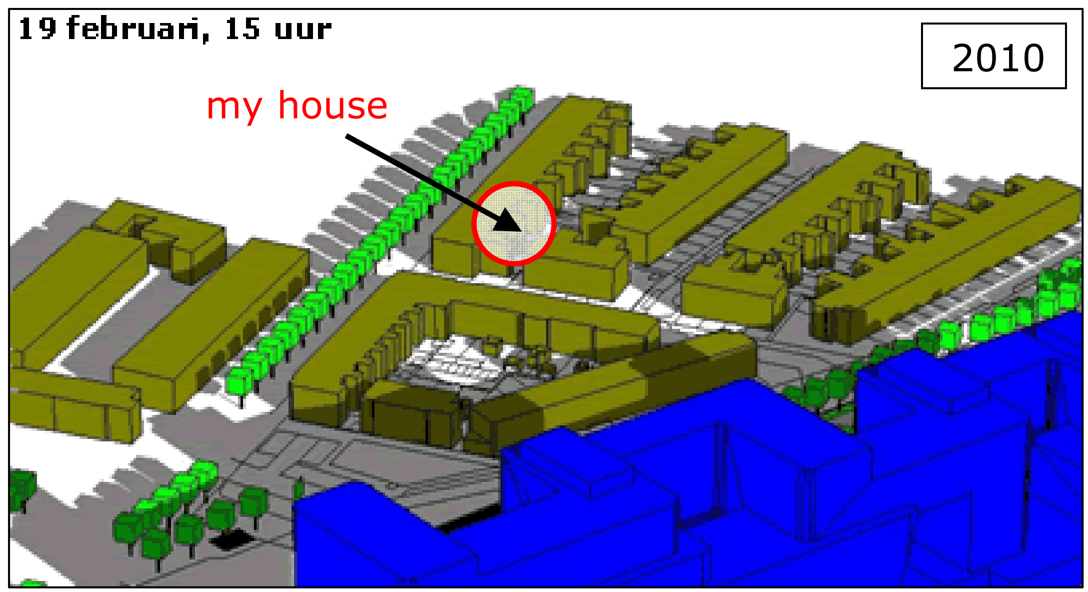
Ivo van Vulpen (Nikhef)

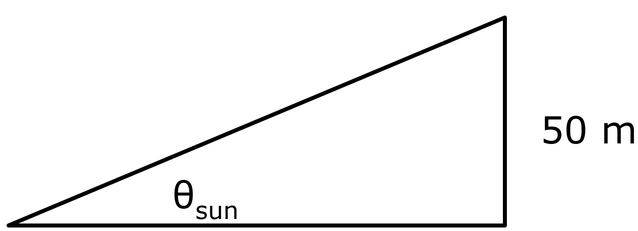


Athens: 'the place where I bought my first house'



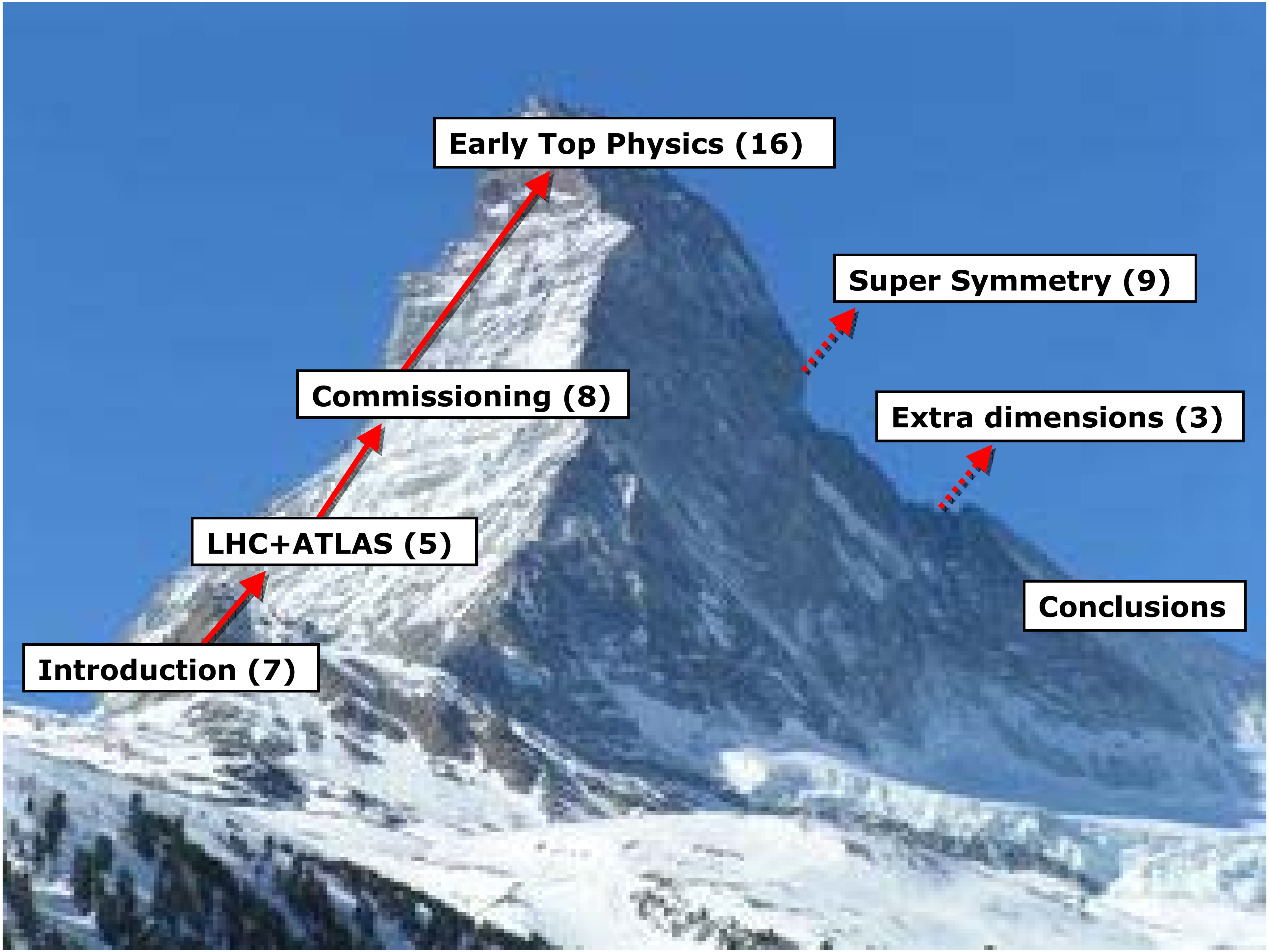
Yesterday: 'they'll build a school for 3000 pupils, a building 50 m high'

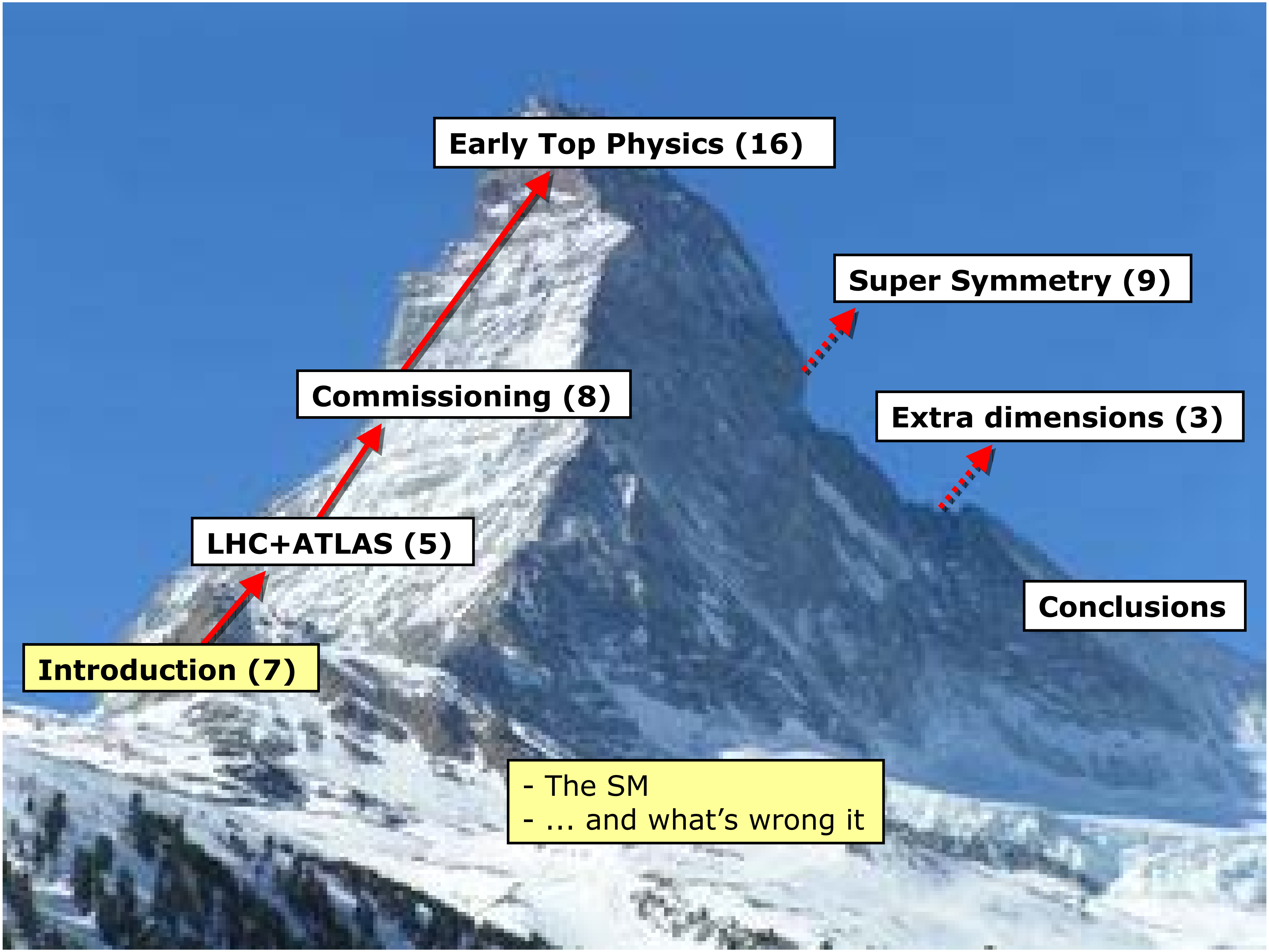




x = maps.google.com

θ_{sun} = 15°/20°/61° at 21-dec/1-feb/21-jun


Early Top Physics (16)
Super Symmetry (9)
Commissioning (8)
Extra dimensions (3)
LHC+ATLAS (5)
Conclusions
Introduction (7)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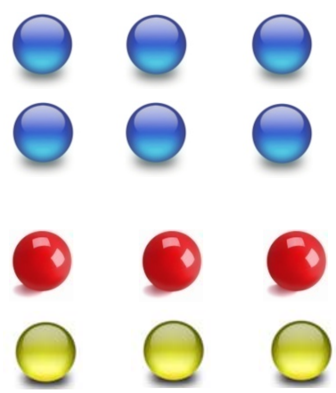
- The SM
- ... and what's wrong it

Particles

Quarks

Leptons



Forces

1) Electromagnetism

2) Weak nuclear force

3) Strong nuclear force

The Standard Model:

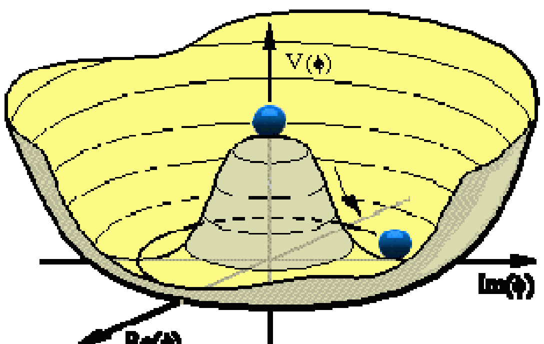
Describes all measurements down to distances of 10^{-19} m

Electroweak Symmetry breaking

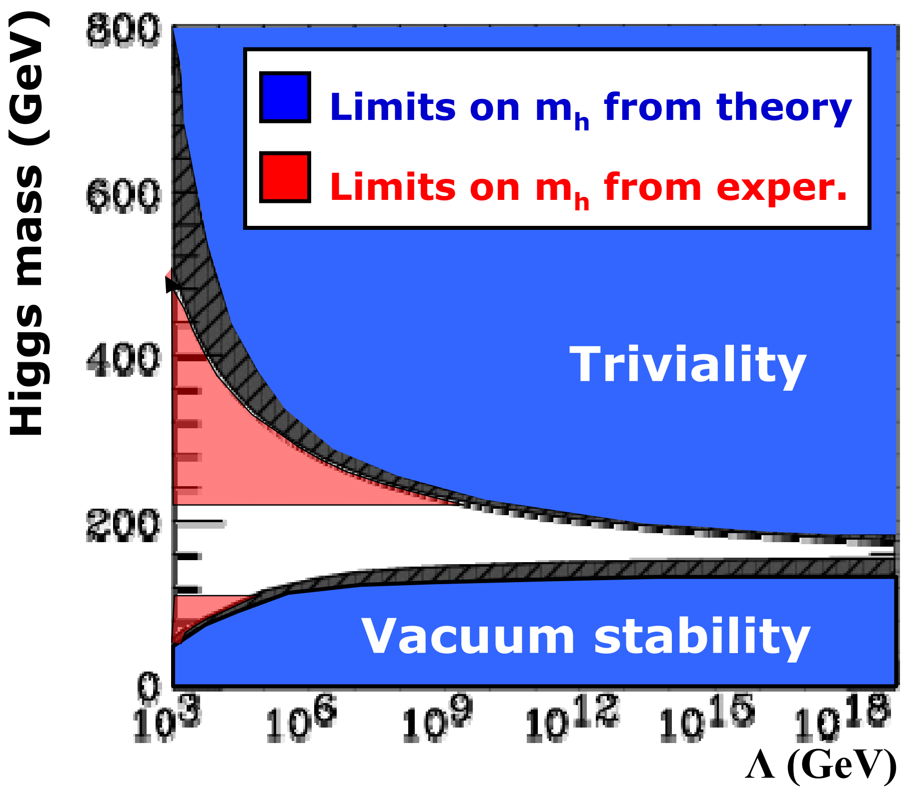
<u>Electro-Weak Symmetry Breaking:</u> (Higgs mechanism)

- Weak gauge bosons and particles have mass
- Regulate WW/ZZ scattering

"We know everything about the Higgs boson except its mass"

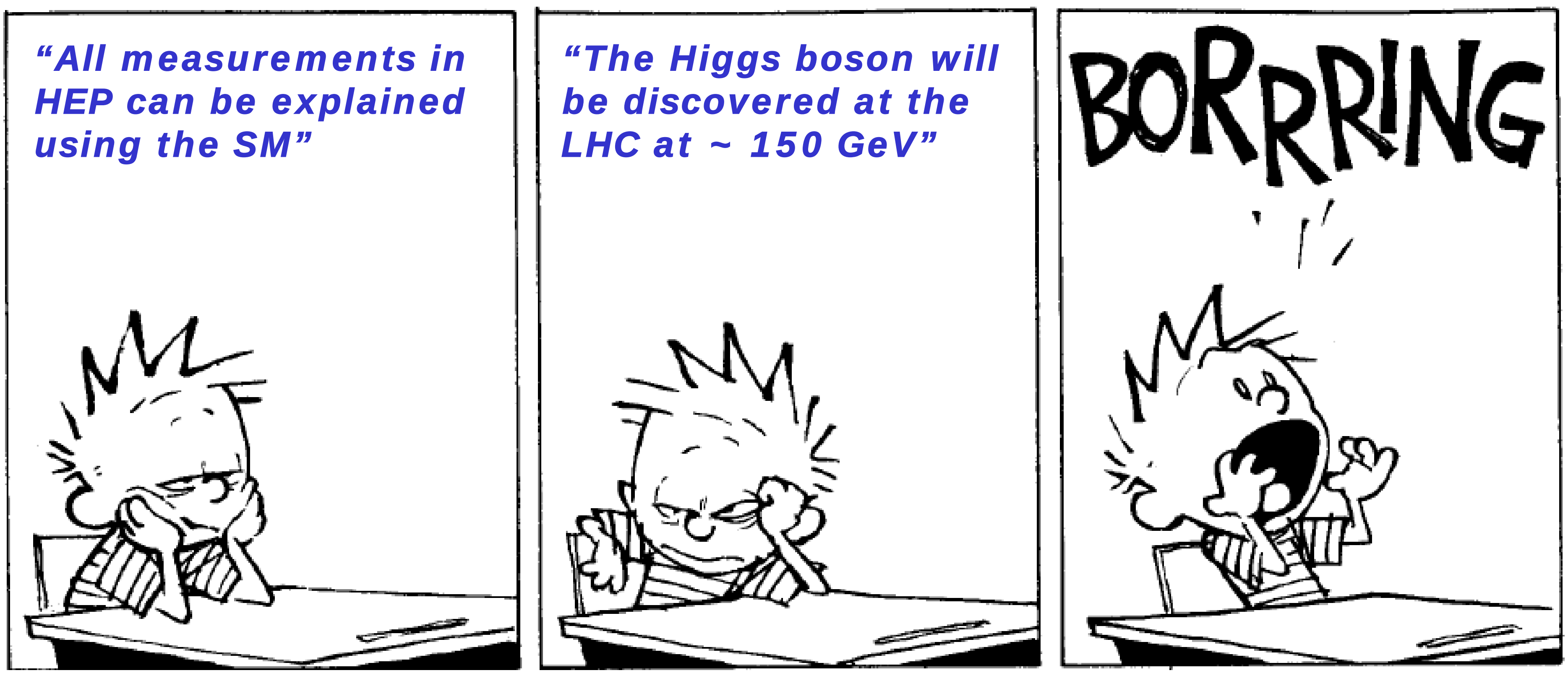


$$V = -\mu^2 |\Phi|^2 + \lambda^2 |\Phi|^4$$

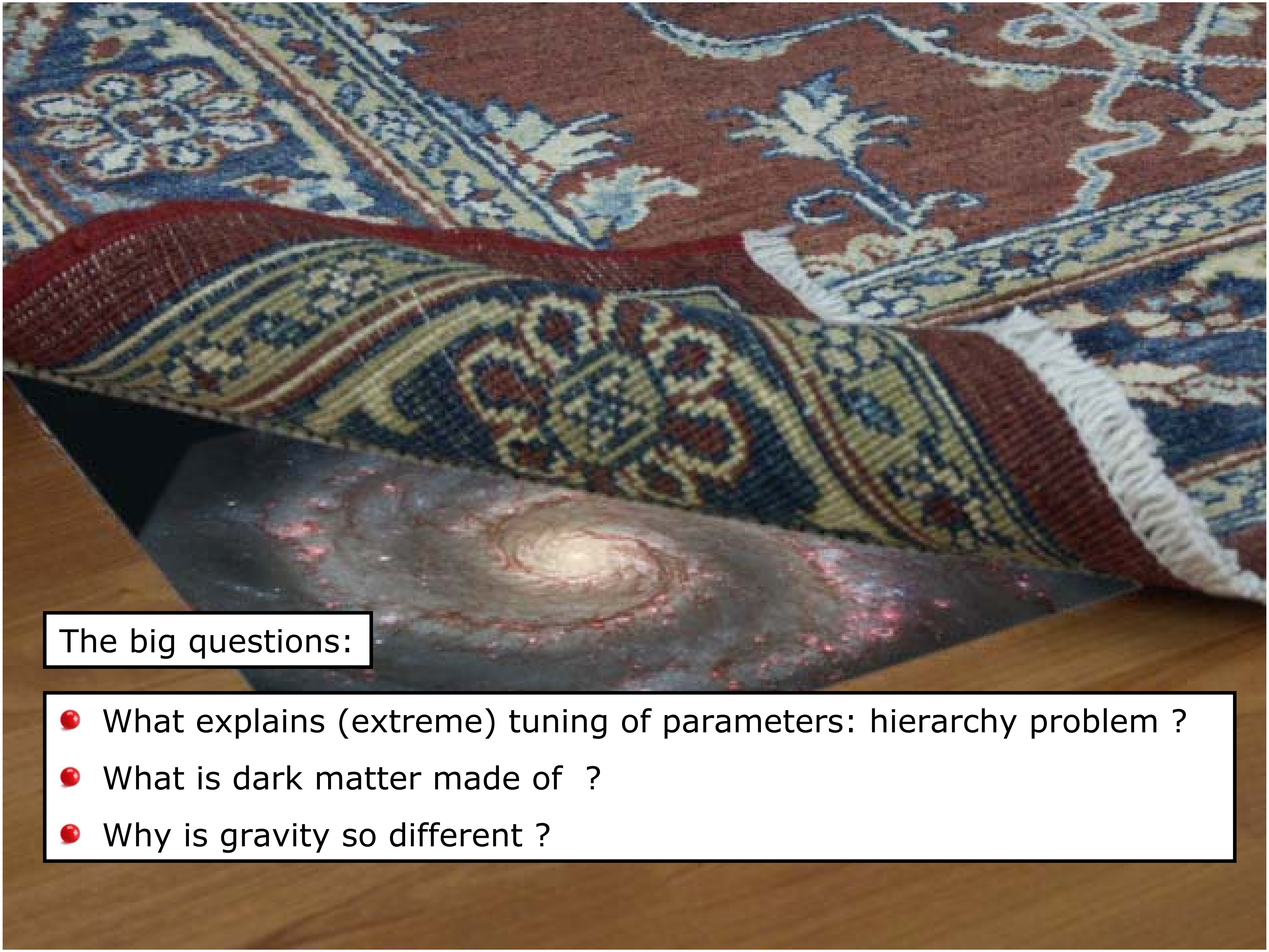


λ describes Higgs's self-couplings (3h, 4h)

The standard model … boring ?



No. … there are many mysteries left!



The big questions:

- What explains (extreme) tuning of parameters: hierarchy problem ?
- What is dark matter made of ?
- Why is gravity so different ?

The mysteries of the SM

- Why is gravity not a part of the Standard Model ?
- What is the origin of particle mass ? (Higgs mechanism)
- In how many dimensions do we live ?

XD — 1

- Are the quarks and leptons really the fundamental particles ?
- Are there *new symmetries* in nature ?
- Why are there only *3* families of fermions ?
- Are protons really stable ?
- Why is electric charged quantized ?

GUT — 2

- Why is there more matter than anti-matter in our universe ?
- What is the nature of *dark matter* and dark energy ?
- Do *quantum corrections explode* at higher energies ?

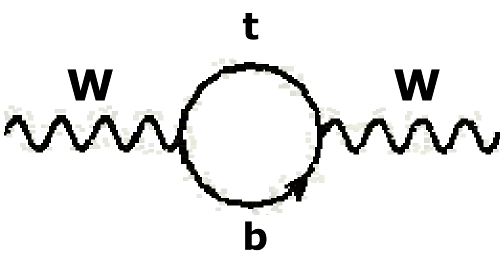
SUSY — 3

- Why are neutrino masses so small ?

The hierarchy problem in the SM

- **Success** of radiative corr. in the SM:

	predicted	observed
top quark	179^{+12}_{-9}	172.7 ± 2.9
Higgs boson	91^{+45}_{-32}	**?**



- **Failure** of radiative corr. in Higgs sector:

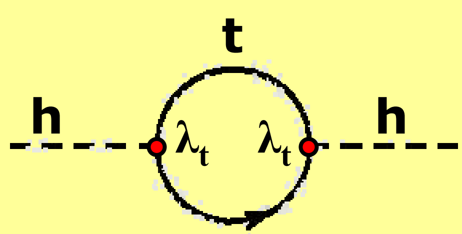
$$m_h = m_{h(bare)} + \delta_{h(top)} + \ldots$$

150 = 135429433658723515**0**
−13542943365872350**00**

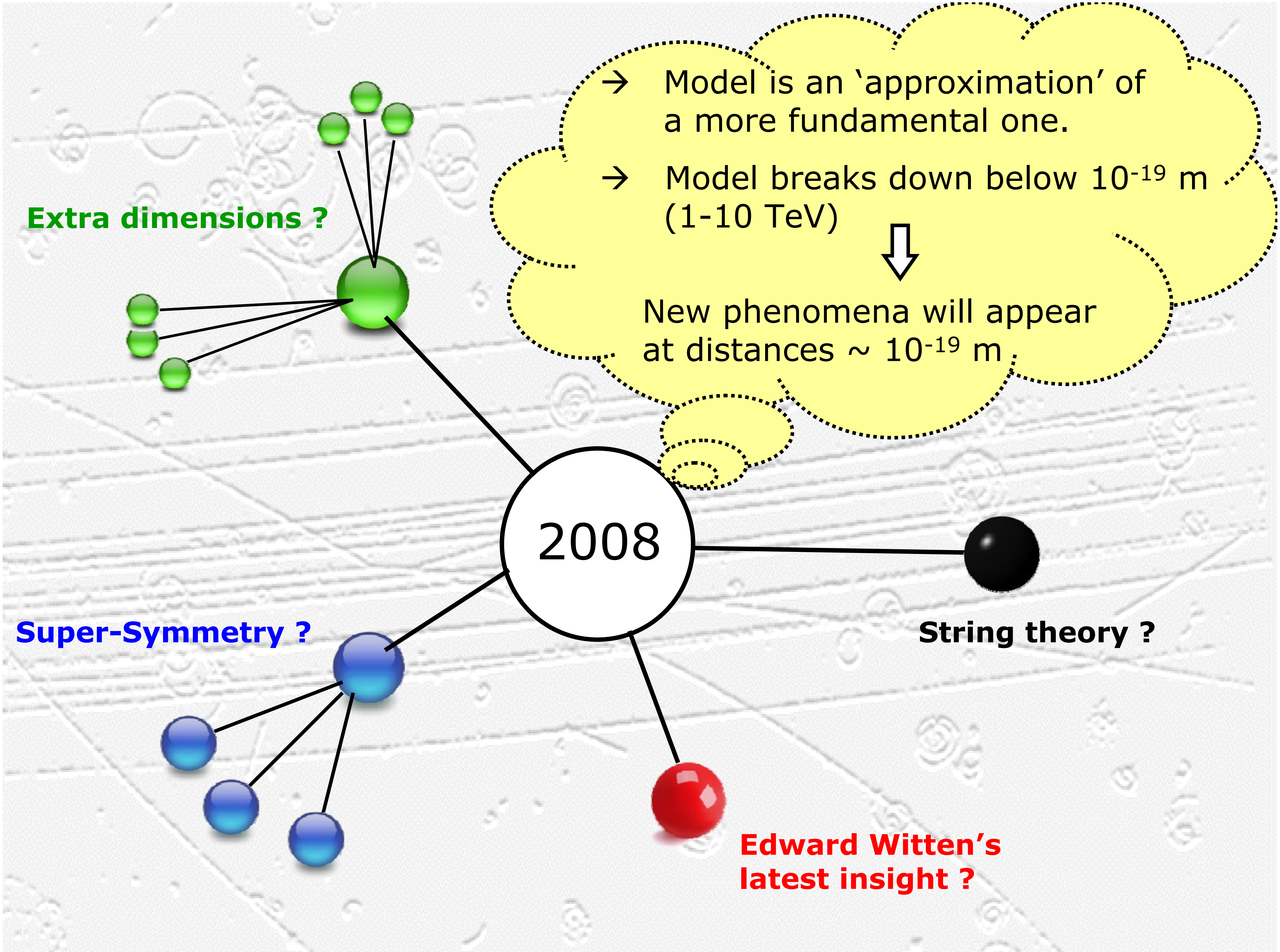
Hierarchy problem:

→ 'Conspiracy' to get $m_h \sim M_{EW}$ (« M_{PL})
→ Biggest troublemaker is the top quark!

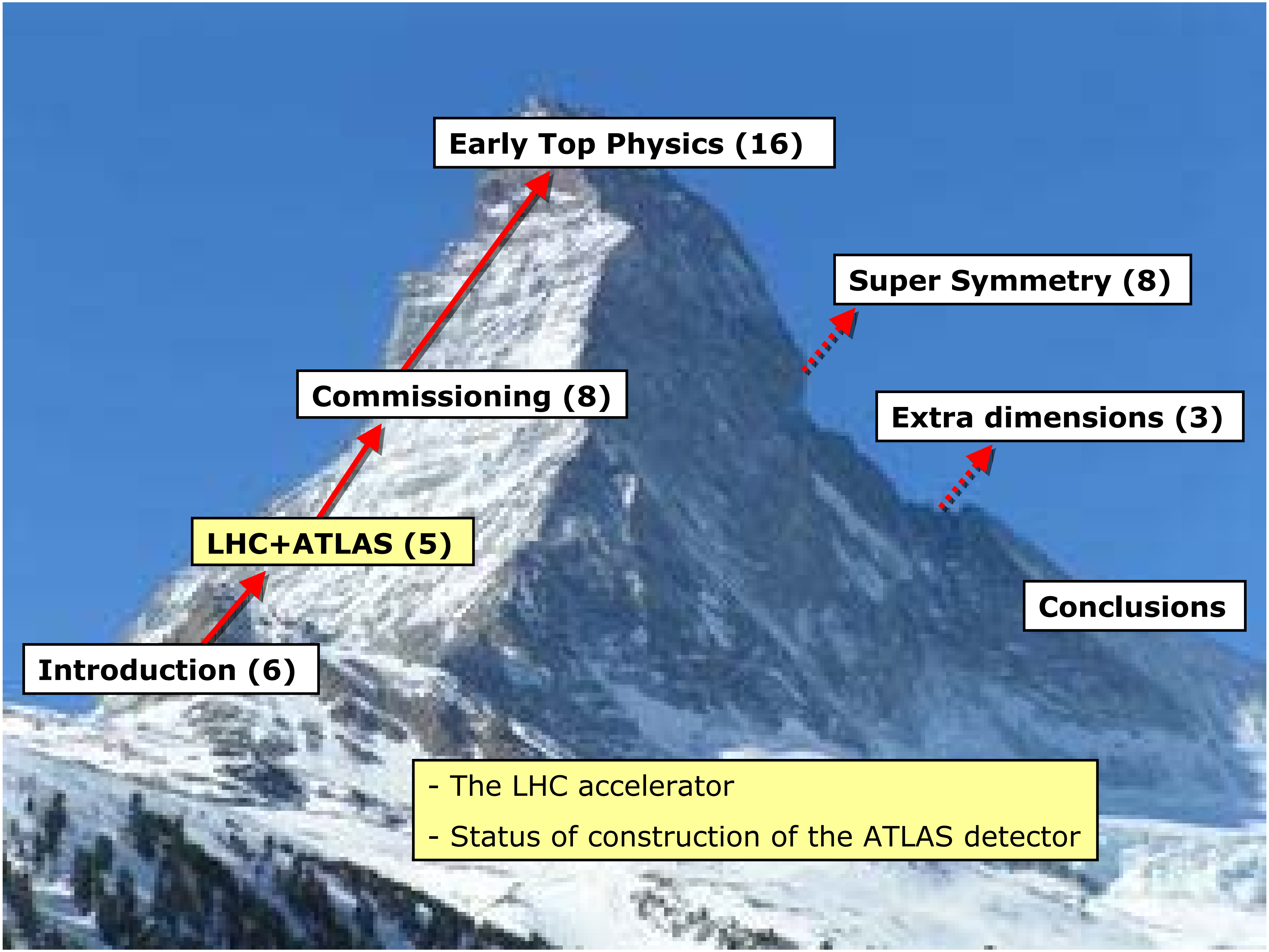
Radiative corrections from top quark



$$\delta^2_{h(top)} = -\frac{3}{8\pi^2}\lambda_t^2 \, \Lambda^2$$



→ Model is an 'approximation' of a more fundamental one.
→ Model breaks down below 10^{-19} m (1-10 TeV)
⇩
New phenomena will appear at distances ~ 10^{-19} m
Extra dimensions ?
2008
String theory ?
Super-Symmetry ?
Edward Witten's latest insight ?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- The LHC accelerator
- Status of construction of the ATLAS detector

The LHC machine

<u>Centre-of-mass energy</u>: 14 TeV

Energy limited by bending power dipoles
1232 dipoles with B= 8.4 T working at 1.9k

→ *Search for particles with mass up to 5 TeV*

<u>Luminosity</u>: 10^{33}-10^{34} $cm^{-2}s^{-1}$

Phase 1: (low luminosity) 2008-2009
Integrated luminosity ~ 10 fb^{-1}/year
Phase 2: (high luminosity) 2010-20xx
Integrated luminosity ~ 100 fb^{-1}/year

→ *Search for rare processes*

→ 7 x Tevatron

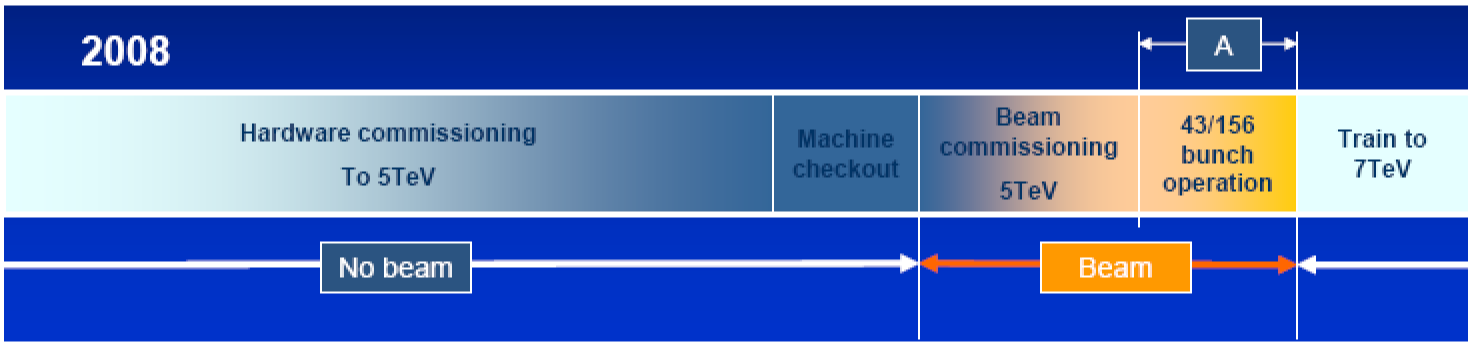
→ 100 x LEP & Tevatron

R. Bailey Top2008

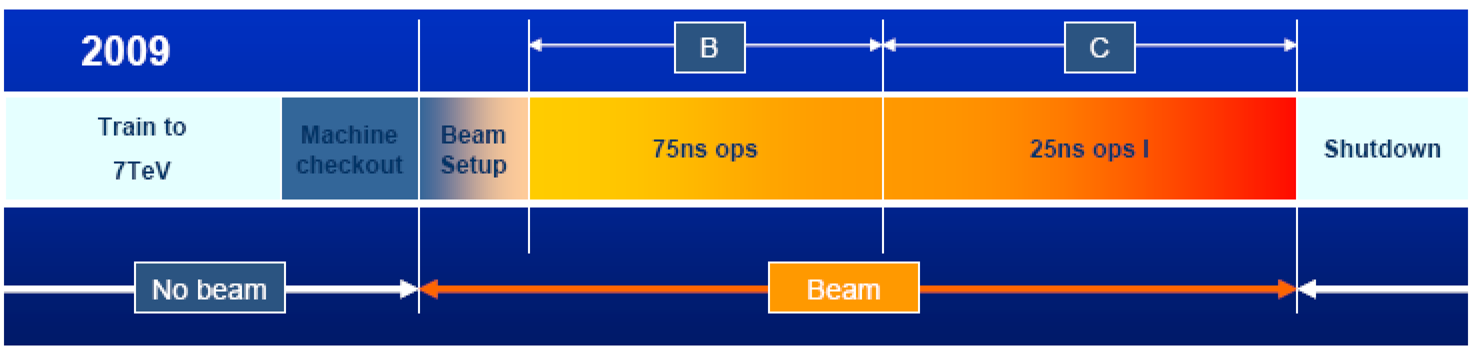
Strategy for 2008 and 2009

[A] pilot run: - first collissions
- 43 bunches
- few times 10^{31}

5 TeV



7 TeV



[B] - 75 ns
- Squeeze beam
- few times 10^{33}

[C] 25 ns operation
50% nominal operation

R. Bailey Top2008

Expected luminosity in first 2 years

LHC operators:

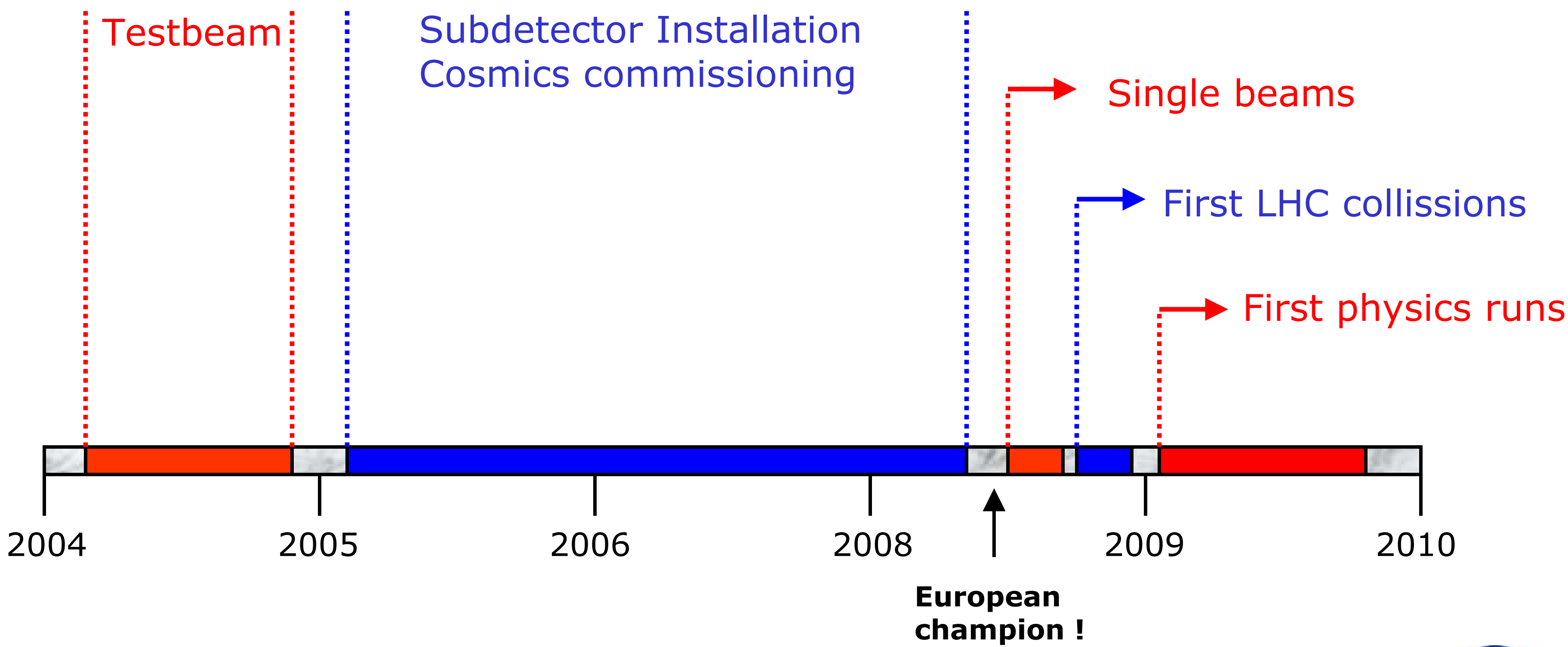
- "we need 44 days from first injection to first physics pilot run"
- estimated efficiency from LEP and Tevatron operation

	days of physics	Efficiency	Peak Luminosity	Integrated Luminosity
2008	40	0.1	5×10^{31}	20 pb^{-1}
2009	150	0.2	10^{33}	2.5 fb^{-1}

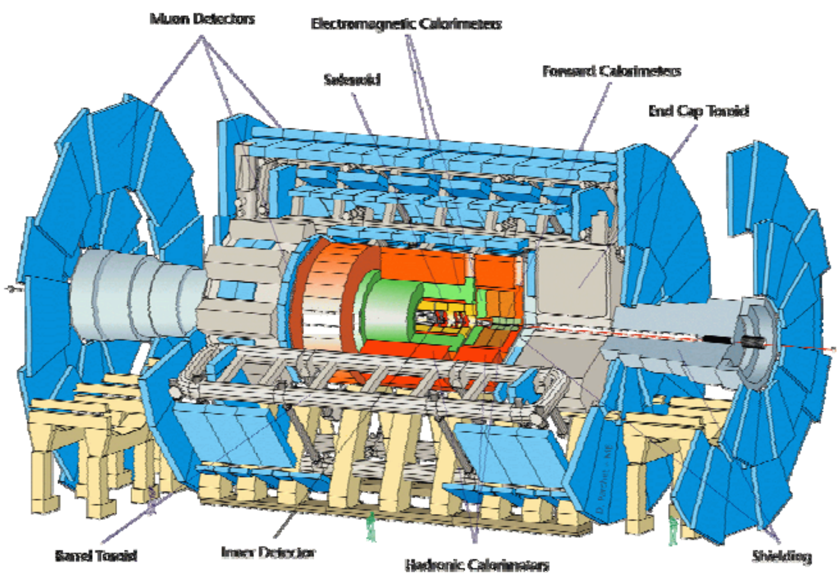
CMS and ATLAS prepared 'Physics readiness report ':
Analysis potential with ~100 pb^{-1}

The road to physics from ATLAS' point of view

Time-line for LHC machine and ATLAS preparation



The ATLAS detector

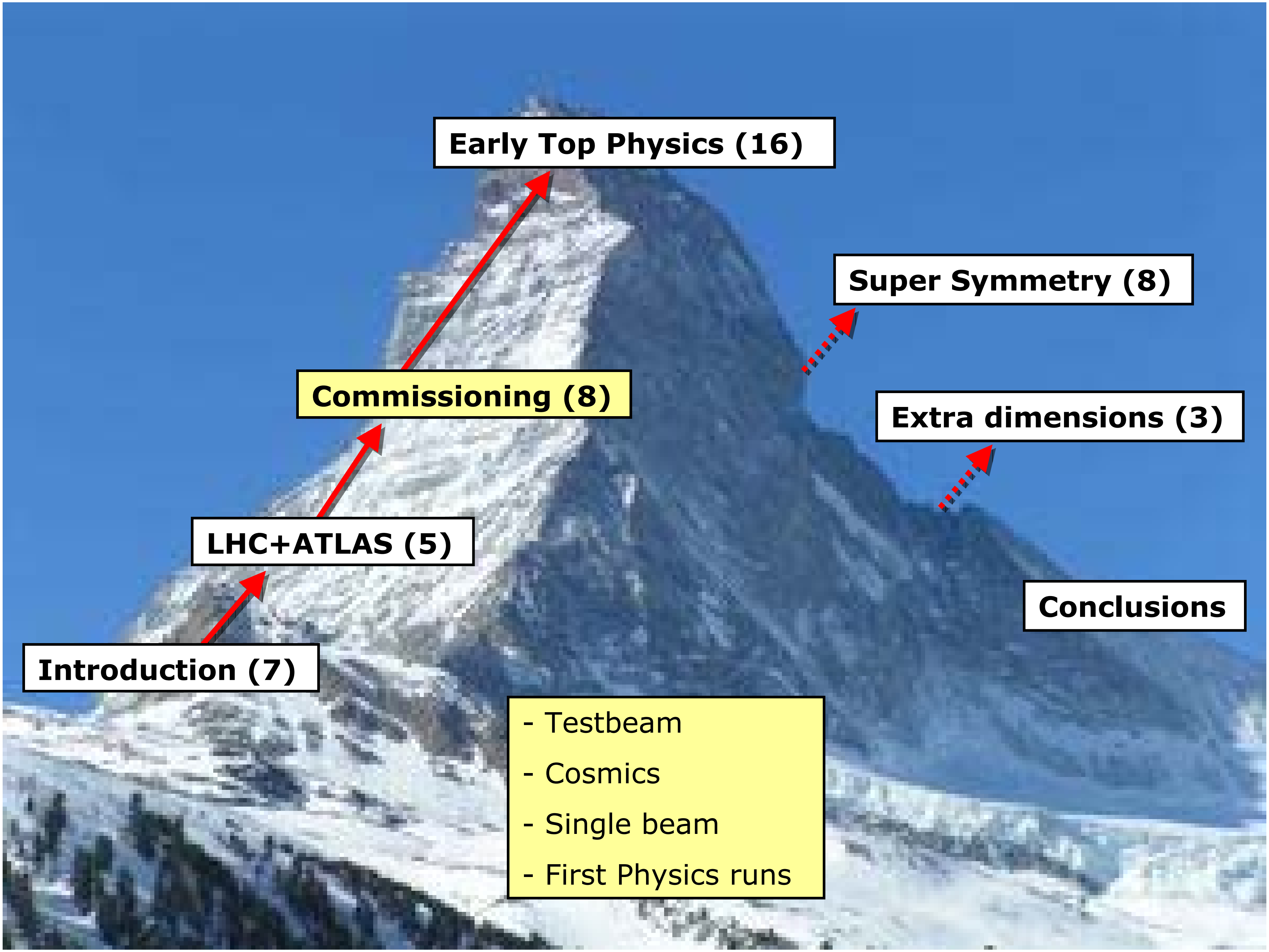


~1000 charged particles produced over $|\eta|<2.5$ at each crossing.

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

- **Tracking ($|\eta|<2.5$, B=2T) :**
  - Silicon, pixels and strips
  - Transition Radiation Detector (e/π separation)
- **Calorimetry ($|\eta|<5$) :**
  - EM : Pb-LAr
  - HAD: barrel: Fe/scintillator
    forward: Cu/W-LAr
- **Muon Spectrometer ($|\eta|<2.7$) :**
  - air-core toroids with muon chambers

ATLAS floats, … but CMS doesn’t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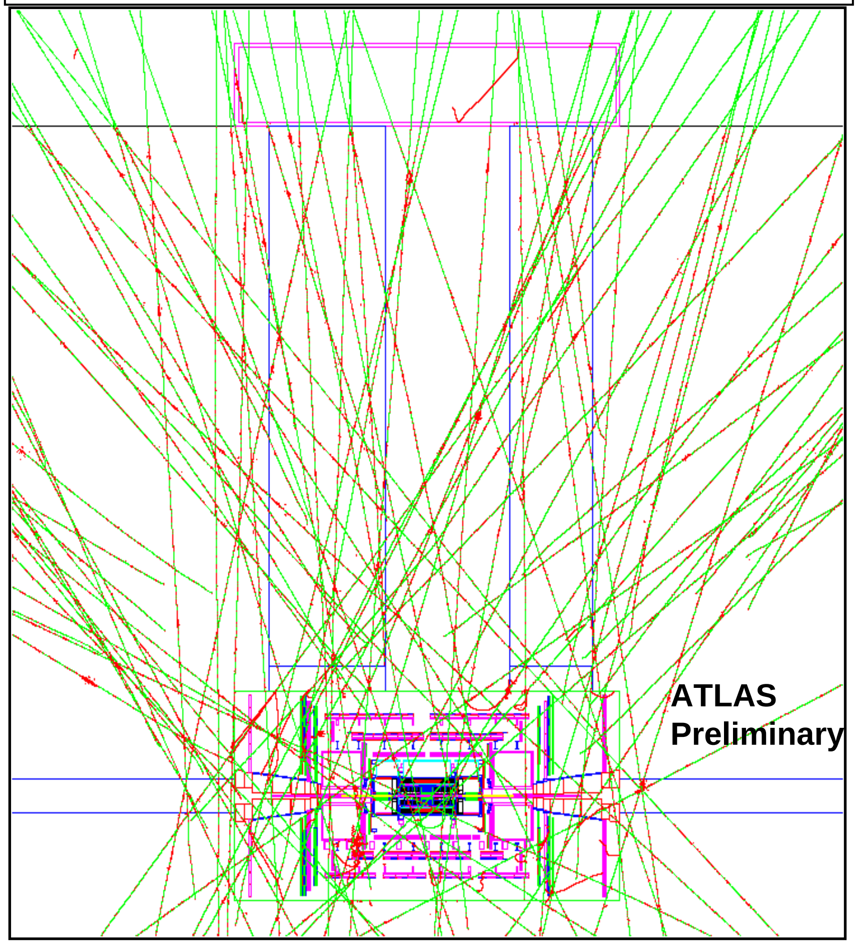
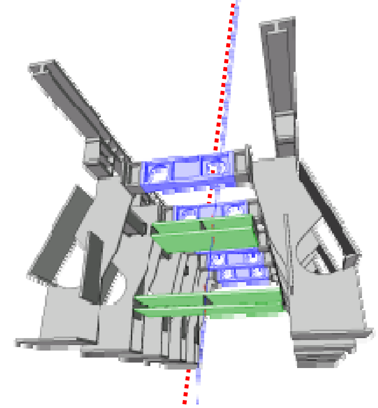
- Cosmics
- Single beam
- First Physics runs

Muons in the ATLAS cavern

~ 20 million muons enter cavern per hour

Simulation ATLAS cavern 0.01 seconds





Rate:

Cavern	5000 Hz
and in ATLAS	25 Hz
and go through origin	0.5 Hz

→ 10^6 events in 3 months

Cosmics : tracks in Pixels+SCT+TRT

- Useful statistics for debugging .
- Check relative position
- First alignment studies:
  (down to ~ 10 μm in parts of Pixels/SCT)
- First calibration of R-t relation in straws

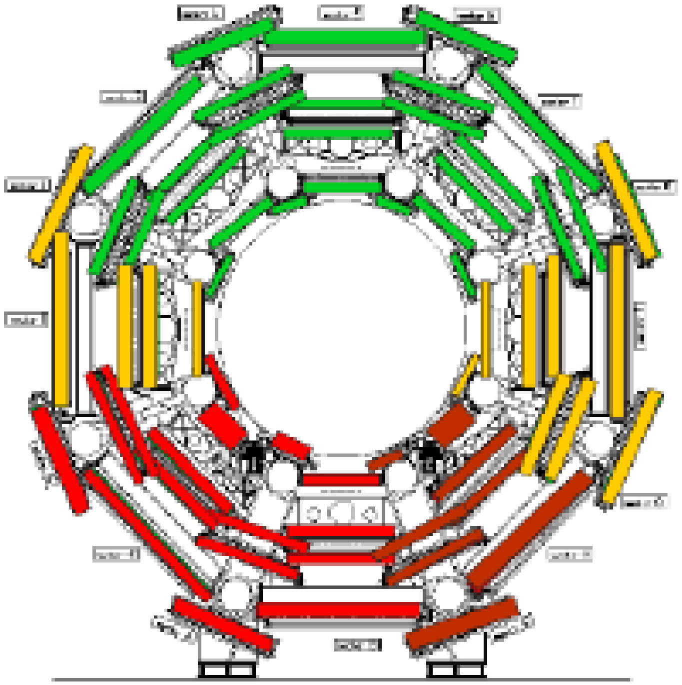
Commisisoning the muon detectors

Instrumented for
Commissioning

All chambers installed

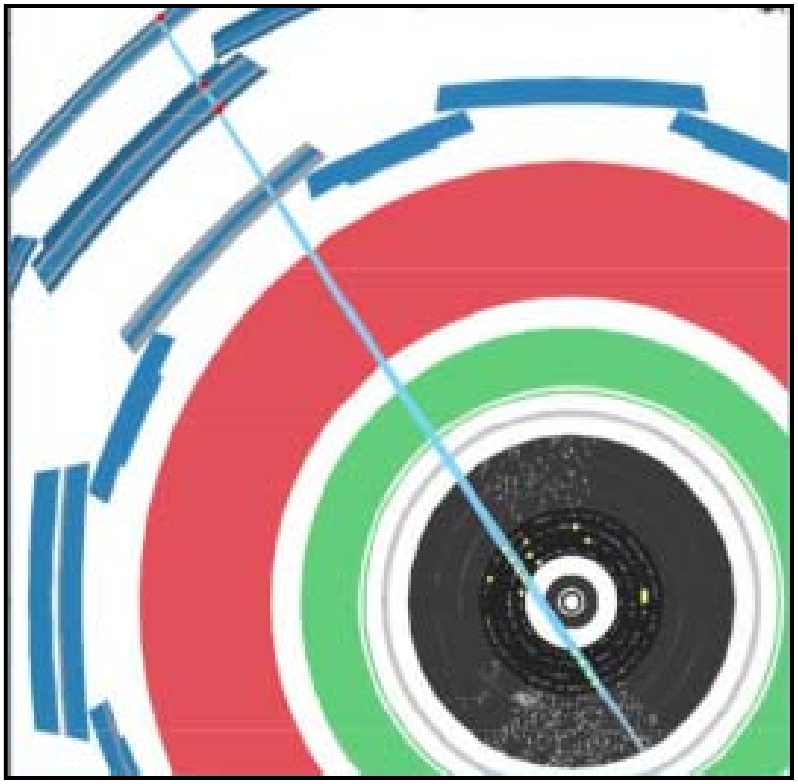
Full DAQ system ready

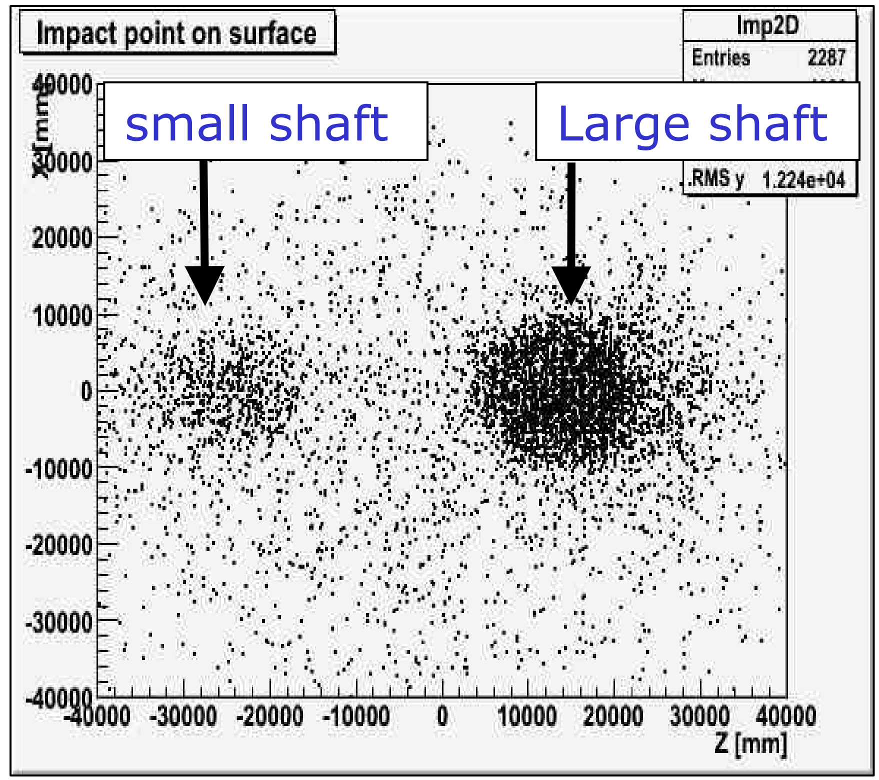
Dead tubes < 0.01%



Commissioning the muon detectors

Full chain of muon reconstruction in ATLAS
Standalone tracking using cosmic rays



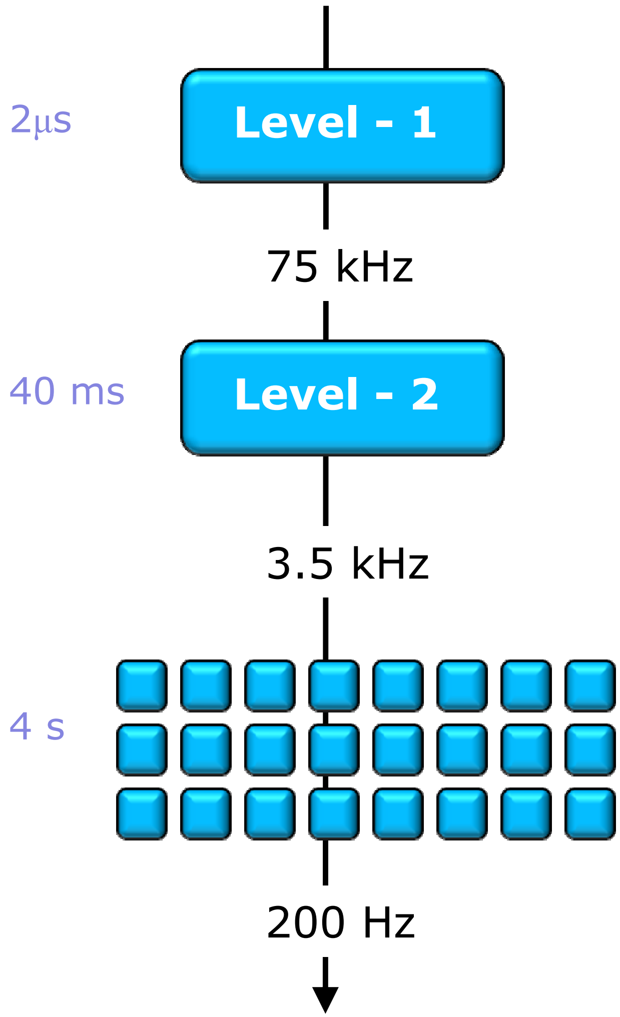


origin cosmic rays

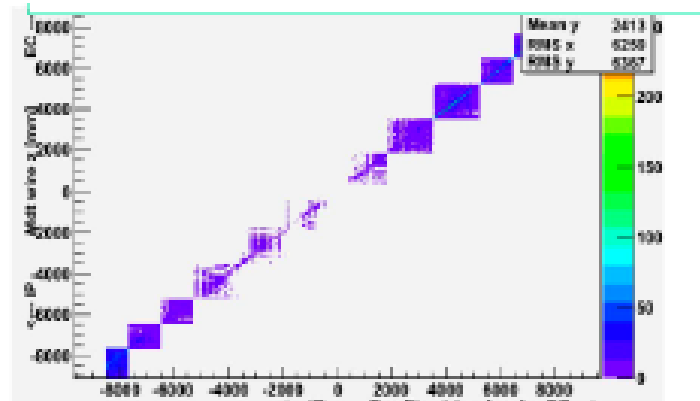
J. Thomas, HCP2008
C. Schiavi, Top2008

Testing trigger set-up

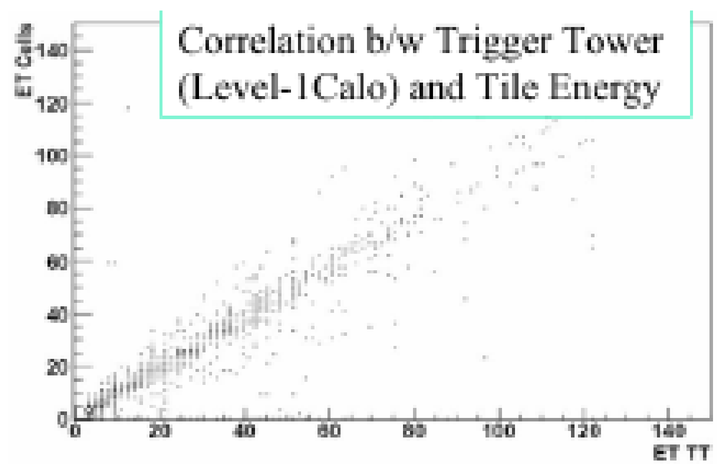
LHC interaction rate ~ 1 GHz
Output rate ~ 200 Hz (300 Mb/s)



Position: trigger chambers –vs- muon chambers



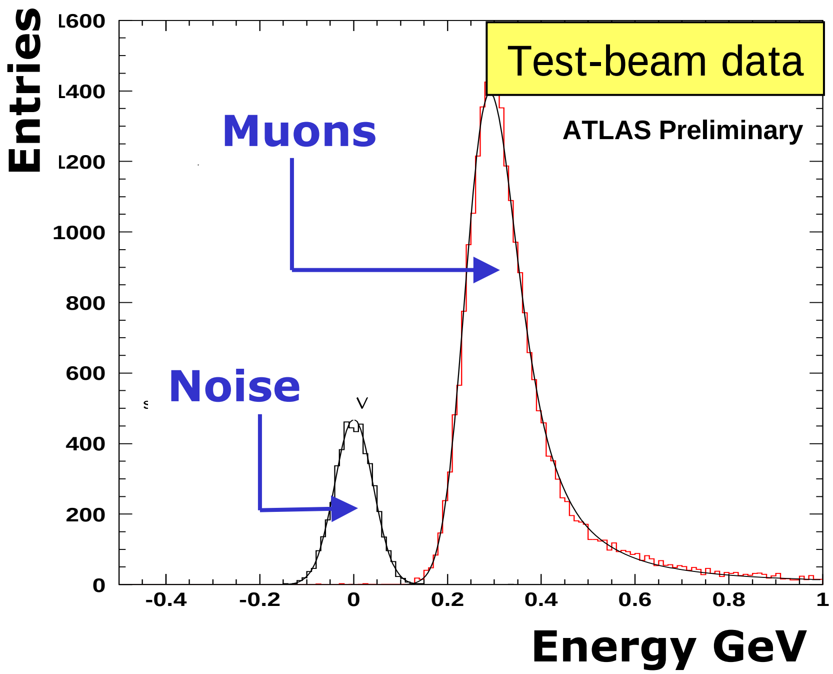
Energy: trigger tower -vs- tile calorimeter energy



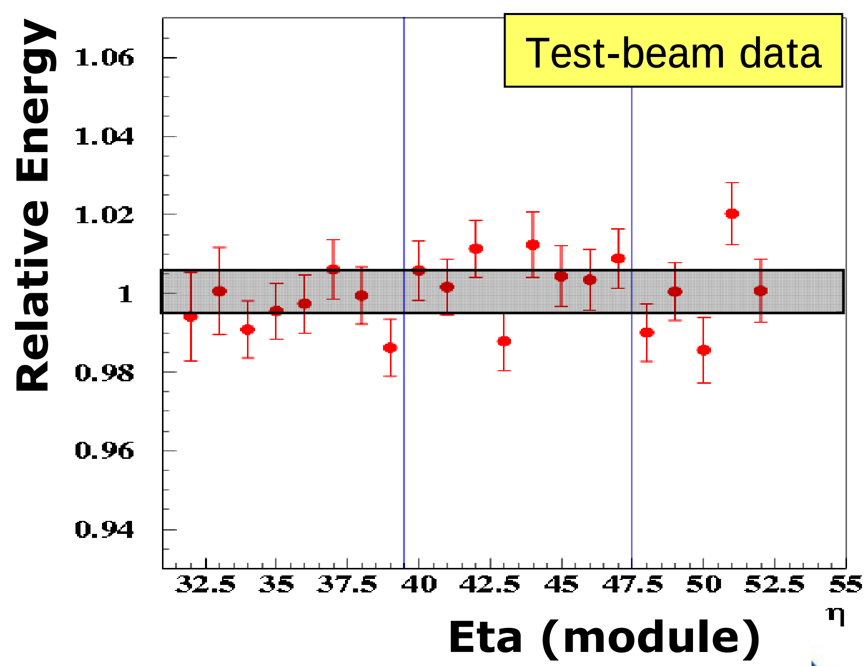
Using cosmics to calibrate the EM Calorimeter

What can we do with 100 days of cosmics in the ECAL ?

A muon deposit ~ 300 MeV in ECAL cell (S/N~ 7)



check (+ correct) ECAL response uniformity vs η to ~ 0.5%

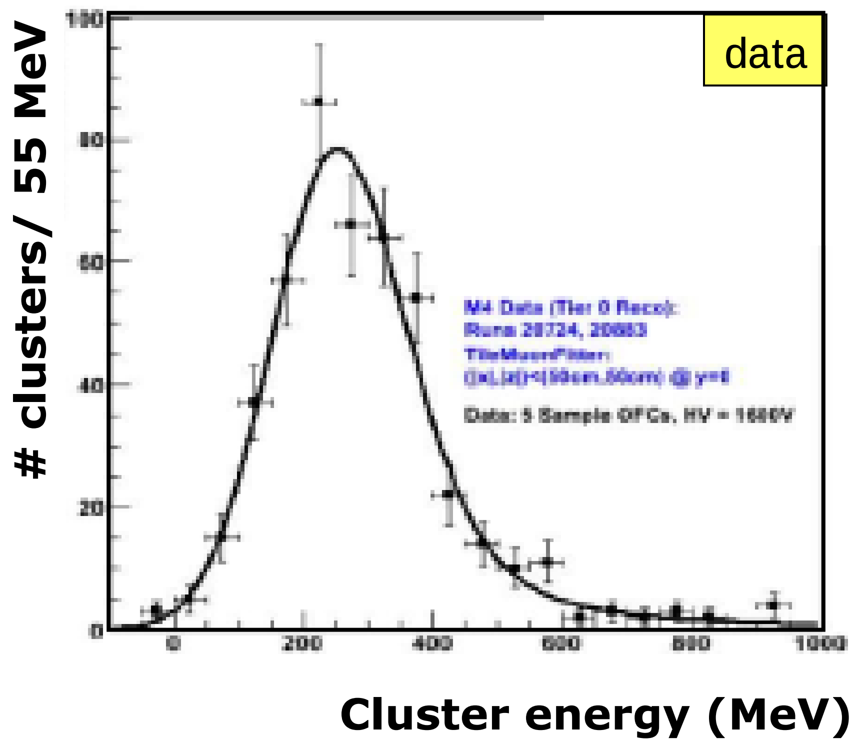


Commissioning the Liquid Argon Calorimeter

C. Schiavi, Top2008

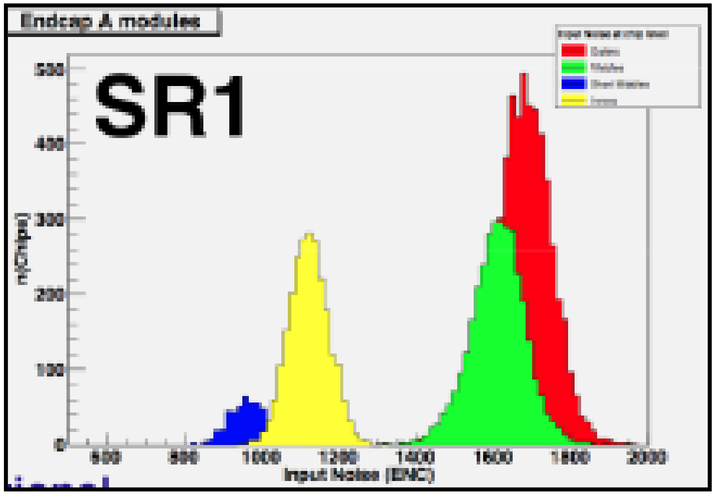
Cryostat temperature stable (Δ< 10 mK)
500k events since august 2006

Liquid Argon
3x3 cluster Energy

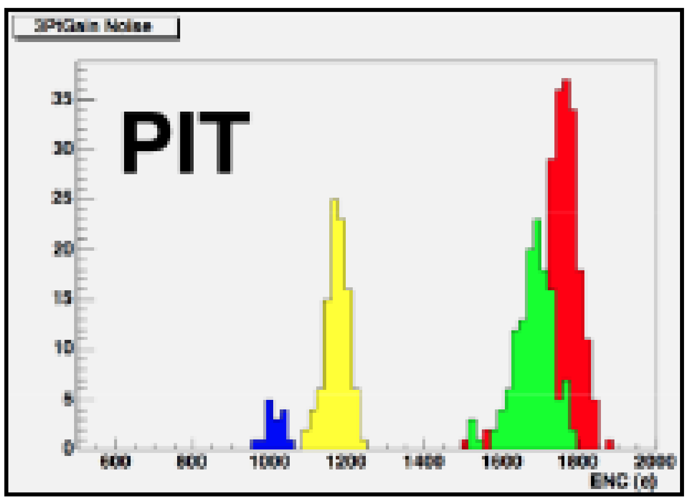


Noise levels in the SCT and 'the full thing'

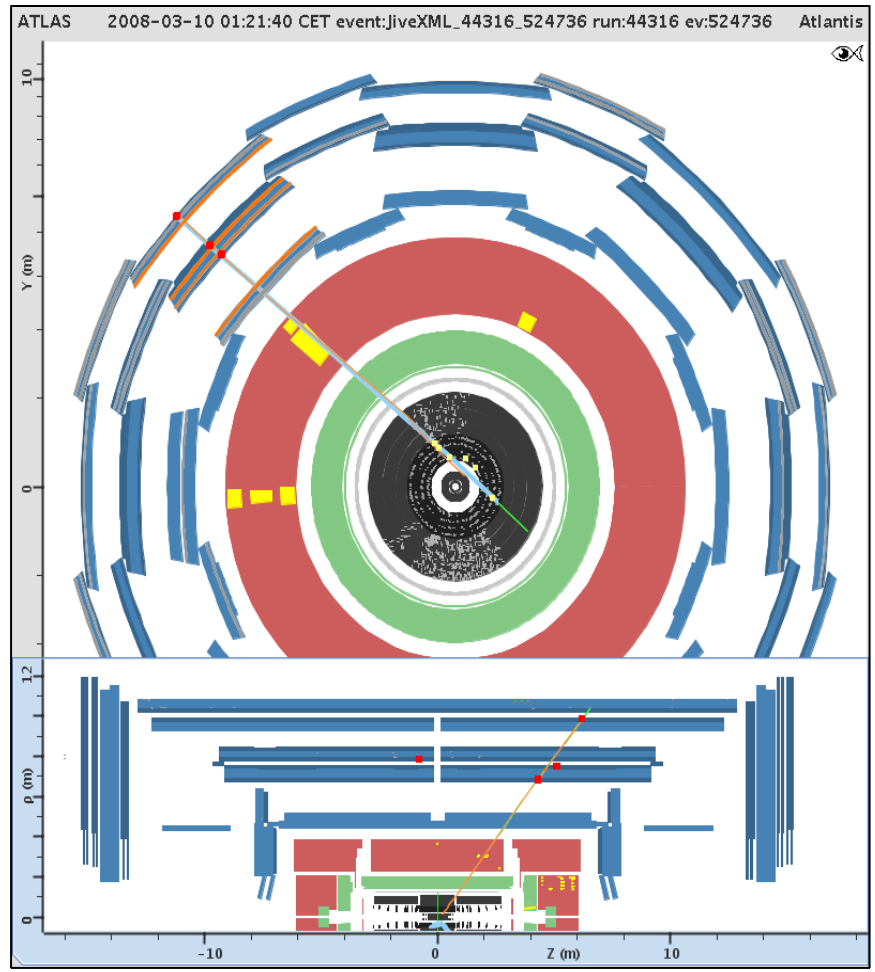
SCT modules noise levels *on surface*



SCT modules noise levels *in the pit*



Cosmic data using: TRT+SCT+Muon



Agree nicely (taking temperature effects into account)

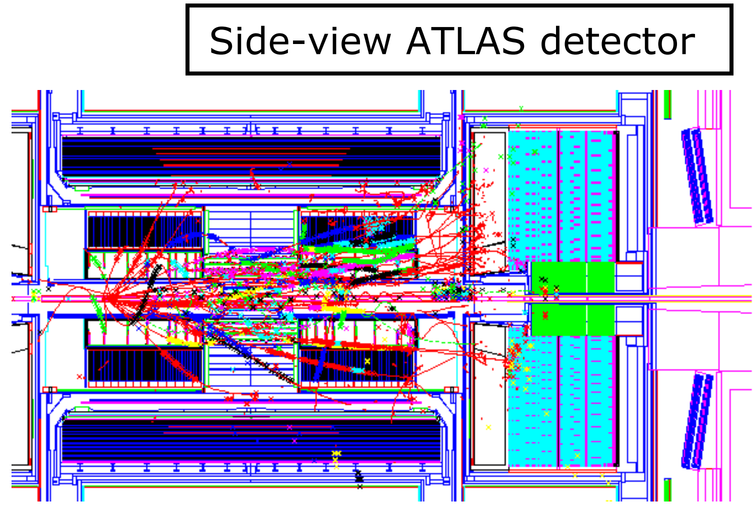
Single beams in LHC

Beam gas:

- 7 TeV protons on residual gas in vacuum

Low-P_T particles
25 Hz tracks with P_T> 1 GeV and |z|<20 cm
Vertices uniform over ±23 m

→ Timing/Trigger/Tracking Alignment

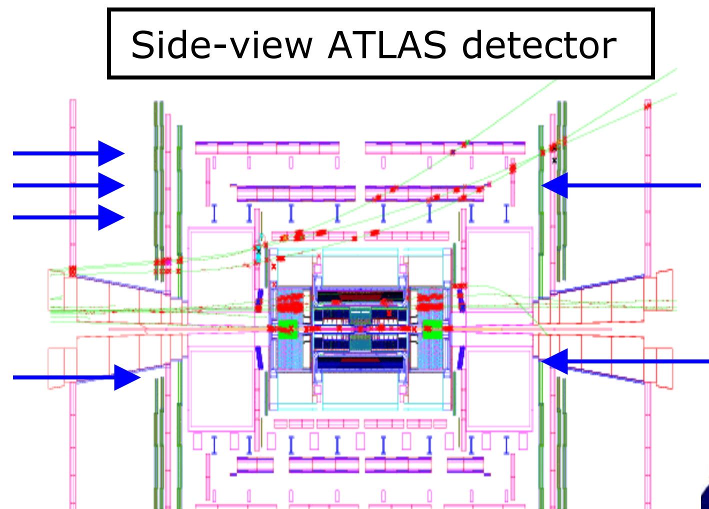


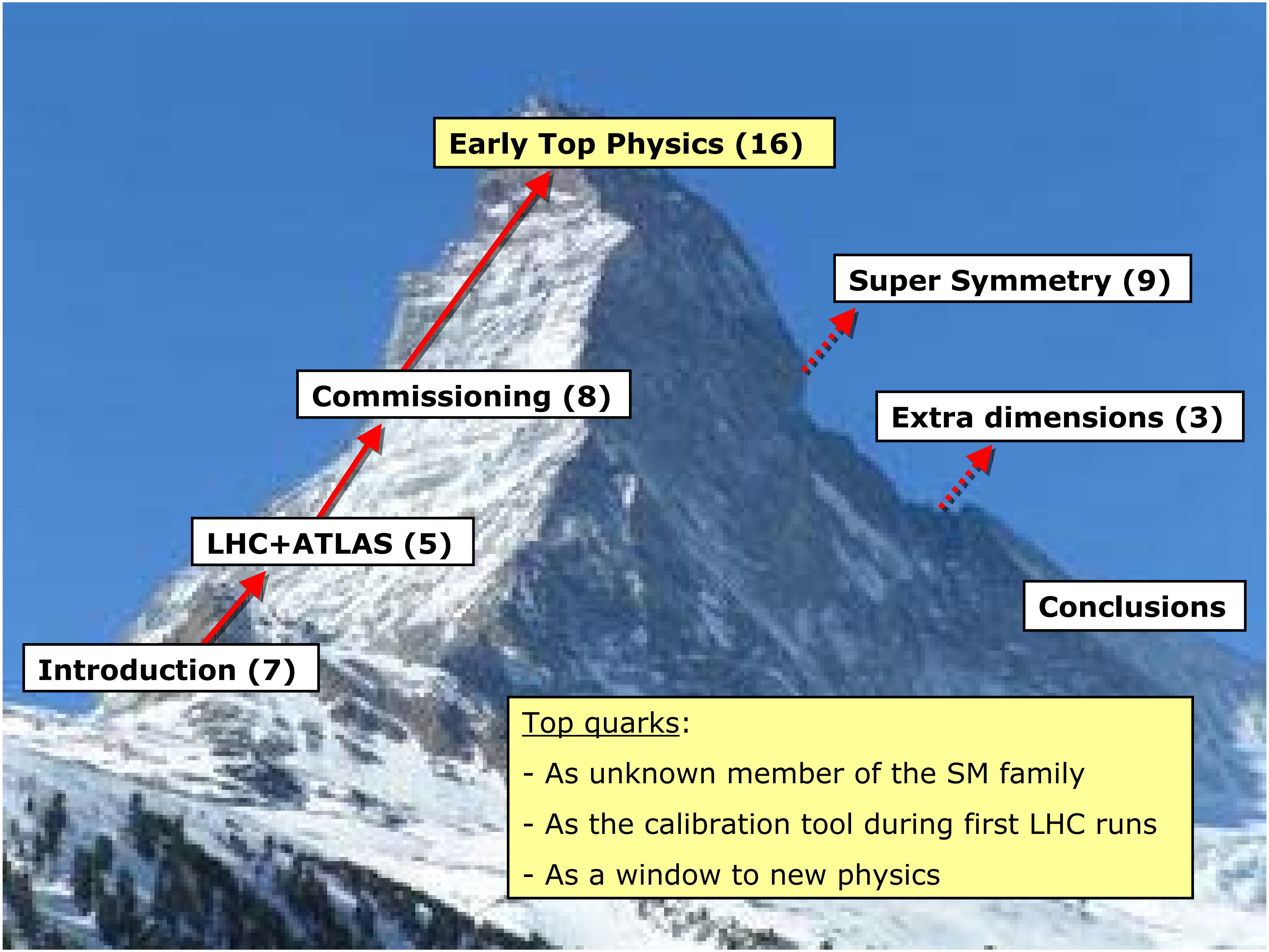
Beam halo:

- Straight tracks accompanying beam

Rate: 1 kHz with E > 100 GeV
10 Hz with E > 1 TeV
10^6-10^7 μ in 2 months (30% eff.)

→ Alignment in Muon Endcaps

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Top quarks:
- As unknown member of the SM family
- As the calibration tool during first LHC runs
- As a window to new physics

ATLAS detector performance on day-1

- Reconstruct (high-level) physics objects:

Electrons/photons: Electromagnetic Energy scale

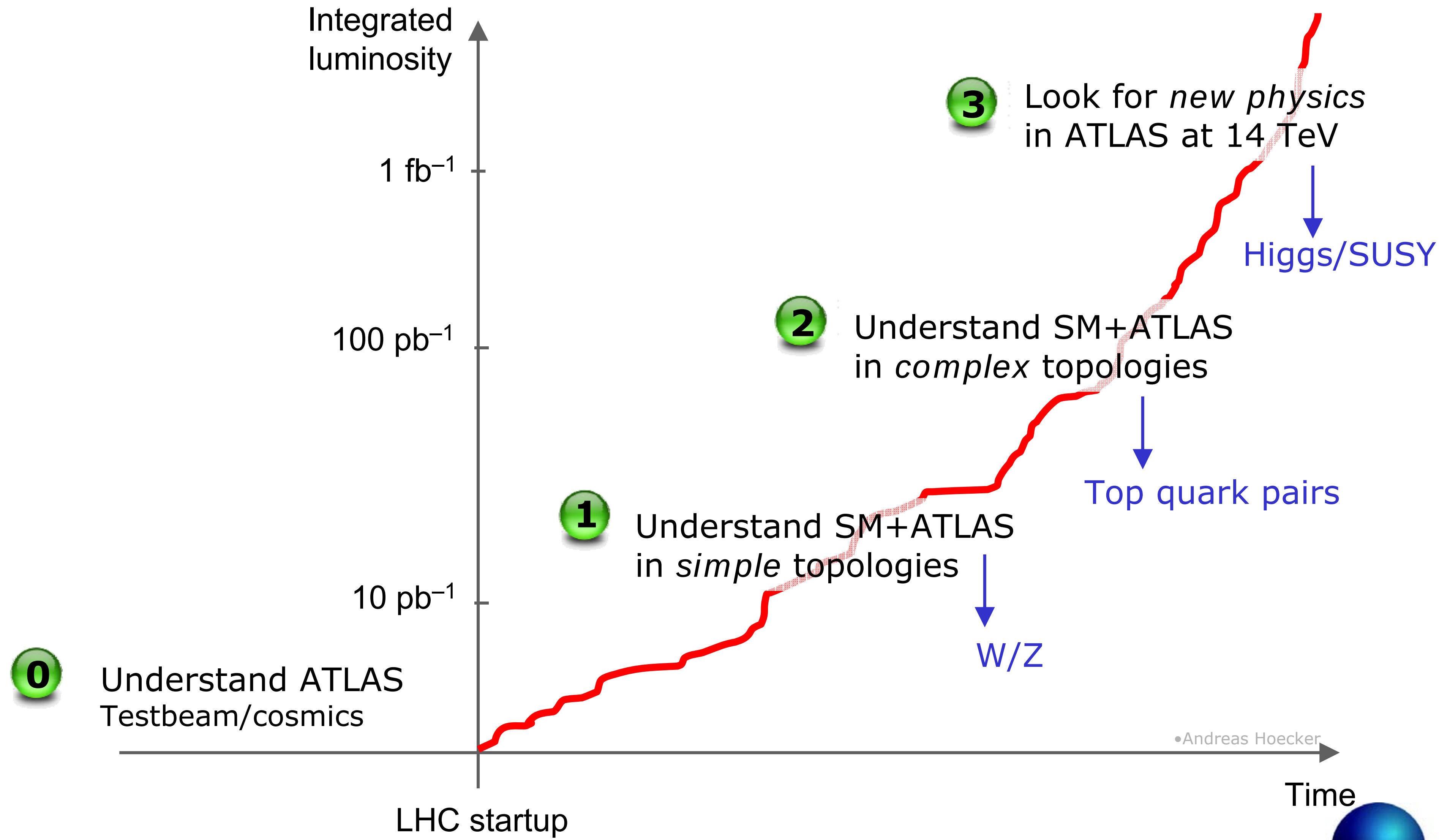
Quarks/Gluons: Jet Energy scale + b-tagging

Neutrino's/LSP?: Missing Energy reconstruction

Expected detector performance from ATLAS
(based on Testbeam and simulations)

Performance	Expected day-1	Physics samples to improve
ECAL uniformity	1%	Min. bias, $Z \rightarrow e^+e^-$ (10^5 in a few days)
e/γ scale	1-2%	$Z \rightarrow e^+e^-$
HCAL uniformity	2-3%	single pions, QCD jets
Jet scale	<10%	γ/Z ($Z \rightarrow l^+l^-$) + 1 jet or $W \rightarrow jj$ in tt
Tracking alignment	20-500 μm $R\varphi$	Generic tracks, isol. muons, $Z \rightarrow \mu^+\mu^-$

LHC start-up programme



Plan-de-campagne during first year

First year:

A new detector AND *a new energy regime*

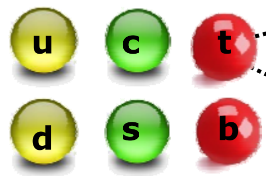
0. Understand ATLAS using cosmics
1. Understand SM+ATLAS in *simple* topolgies
2. Understand SM+ATLAS in *complex* topologies
3. Look for *new physics* in ATLAS at 14 TeV

Process	#events 10 fb^{-1}
$b\bar{b}$	10^{12}
$W \rightarrow e\nu$ (1)	[illegible]
$Z \rightarrow e^+e^-/\mu^+\mu^-$	10^7
$t\bar{t}$ (2)	10^7
Min. bias	10^7
QCD jets $P_T > 150$ GeV	10^7
h (m_h = 130 GeV)	10^5
$\tilde{g}\tilde{g}$ ($m_{\tilde{g}}$ = 1 TeV) (3)	10^4

Talk by David tomorrow

The top quark: ‘old-physics’, … but not well known

We still know little about the top quark



- Mass	precision ~1%
- Electric charge ⅔	-4/3 excluded @ 94% C.L. (preliminary)
- Spin ½	not really tested – spin correlations
- Isospin ½	not really tested
- BR($t \rightarrow Wb$) ~ 100%	at 20% level in 3 generations case
- V−A decay	at 20% level
- FCNC	probed at the 10% level
- Top width	??
- Yukawa coupling	??

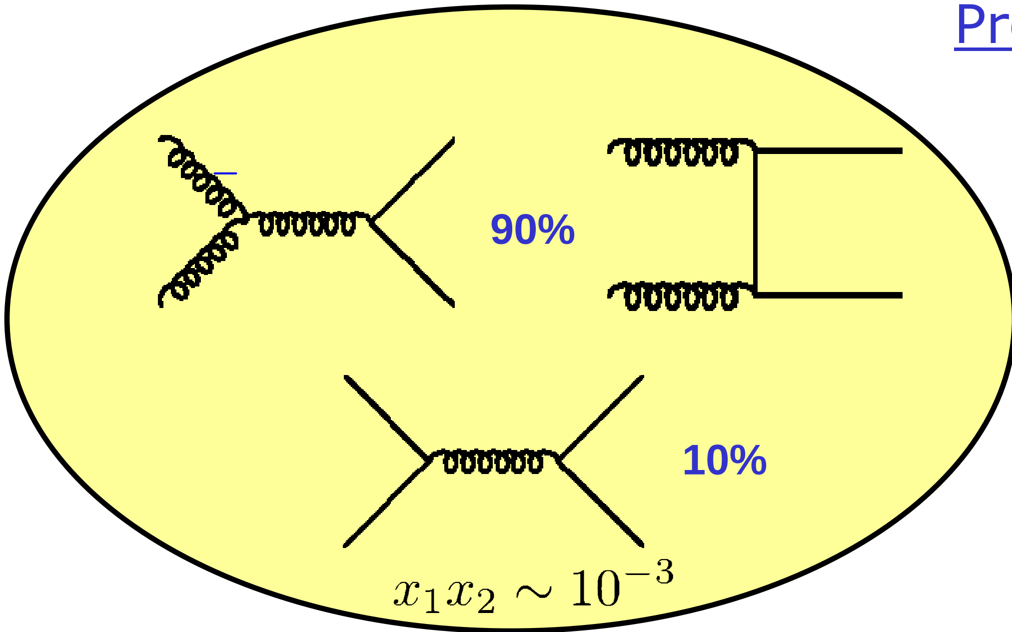
- The LHC offers an opportunity for **precision measurements**

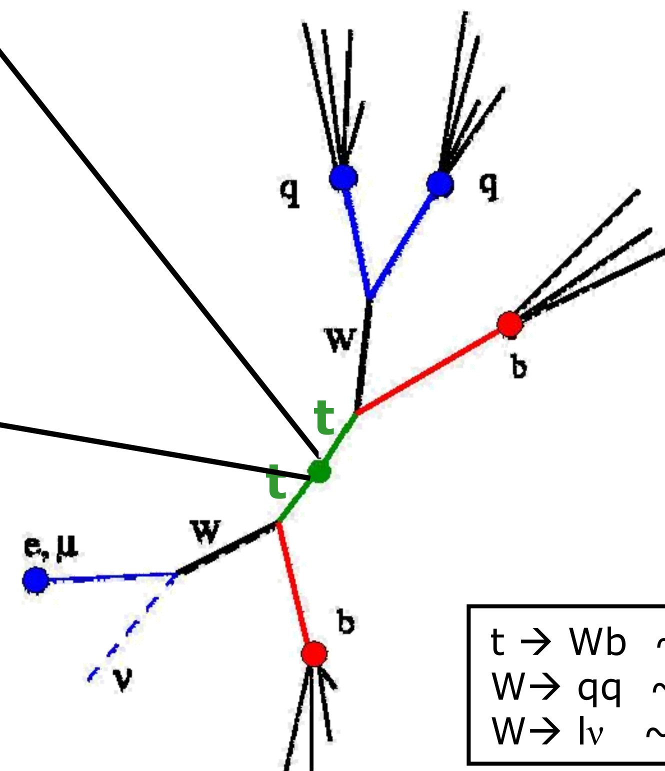
Top quark production at the LHC

Production: σ_{tt}(LHC) ~ 830 ± 100 pb

→ 1 tt-event per second

Cross section LHC = 100 x Tevatron
Background LHC = 10 x Tevatron





Final states:

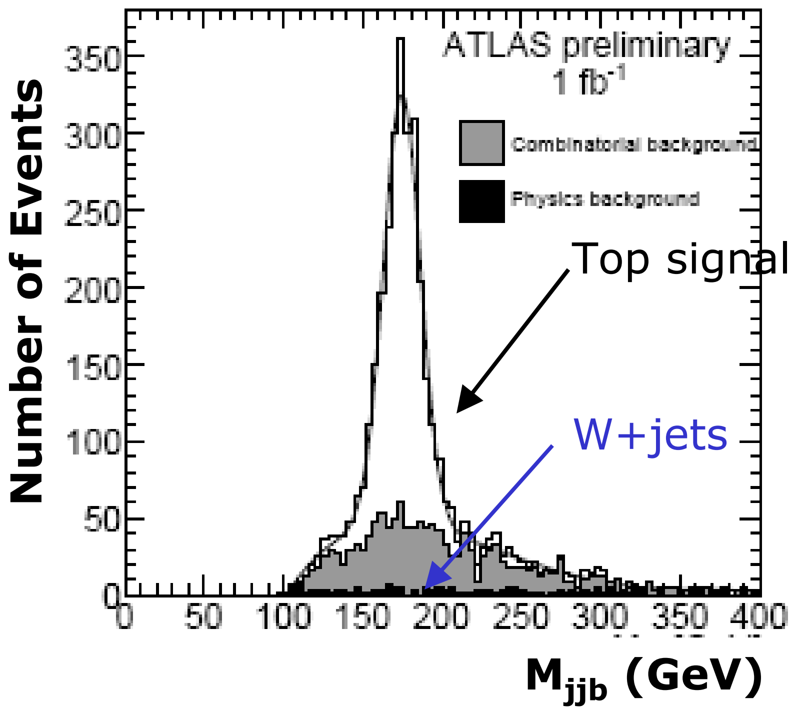
1) Full hadronic (4/9) 6 jets
2) Semi-leptonic (4/9): 1l + 1ν + 4 jets
3) Full leptonic (1/9): 2l + 2ν + 2 jets

→ *Golden channel* (l=e,μ)→ 2.5 million events/year

t → Wb	~ 1
W→ qq	~ 2/3
W→ lν	~ 1/3

Top physics is 'easy' at the LHC

Selection: Lepton + multiple jets + 2 b-jets kills the dominant background from W+jets



Systematic errors on M_{top} (GeV) in semi-leptonic channel

Source	Error 10 fb^{-1}
b-jet scale (±1%)	0.7
ISR/FSR Radiation	0.3
Light jet scale (±1%)	0.2
b-quark fragmentation	0.1
TOTAL: Stat ⊕ Syst	~ 1 GeV

Could we see top quarks when selection is not based on b-tag ?
If so: we could use top quark production to calibrate ATLAS.

Selecting Top quark events without b-tag information

- Robust selection cuts

Missing	E_T > 20 GeV
1 lepton	P_T > 20 GeV
3 jets	P_T > 40 GeV
4 jets with	P_T > 30 GeV

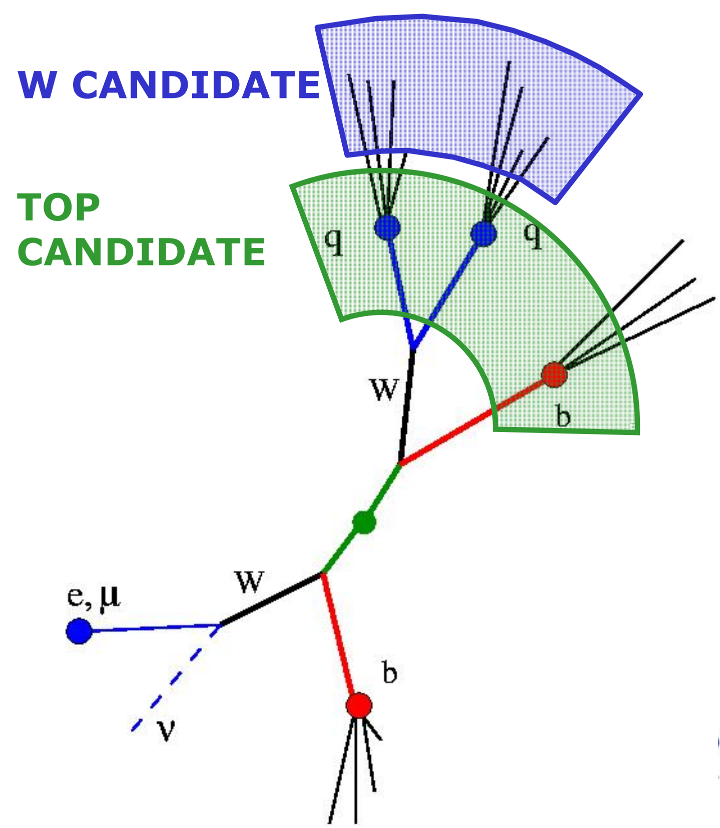
	Effic (%)	# signal	#bckg
Muon	23.6	3274	1497
Electron	18.2	2555	1144

- Assign jets to top decays

> Note: In 70% of events there is an extra jet with P_T > 30 GeV
>
> → jet pairings ?

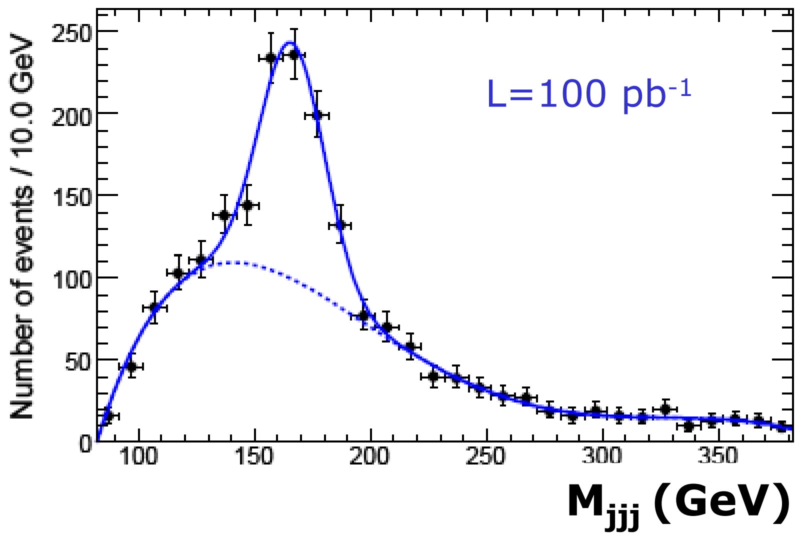
Hadronic top:
three jets with highest vector-sum p_T

Extra: Require a jj-pair in top quark candidate with |Mjj-80.4| < 10



Results for a 'no-b-tag' analysis: 100 pb^{-1}

Hadronic 3-jet mass

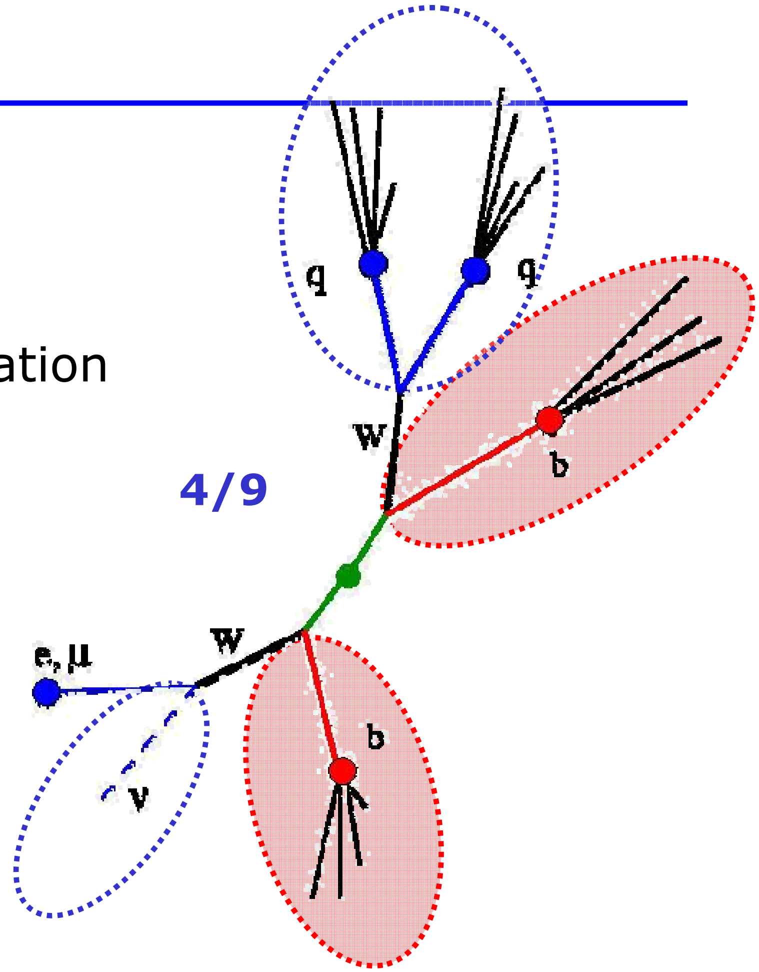


100 fb^{-1} is a few days of nominal low-lumi LHC operation

Yes, we can see top peak (even without b-tag requirement) during first LHC runs

“Top quark pair production has it all”:

≥ 4 jets, b-jets, neutrino, lepton
several mass constraints for calibration



<u>A candle for complex topologies</u>:

- Calibrate light jet energy scale
- Calibrate missing E_T
- Obtain enriched b-jet sample
- Leptons & Trigger

<u>Note the 4 candles</u>:

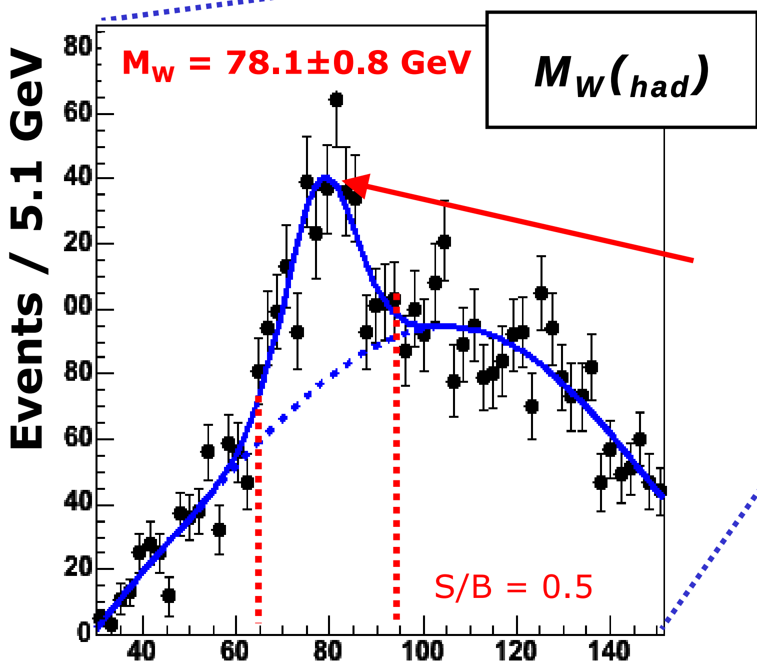
- 2 W-bosons $M_W = 80.4$ GeV
- 2 top quarks & $M_t = M_{t\text{-bar}}$

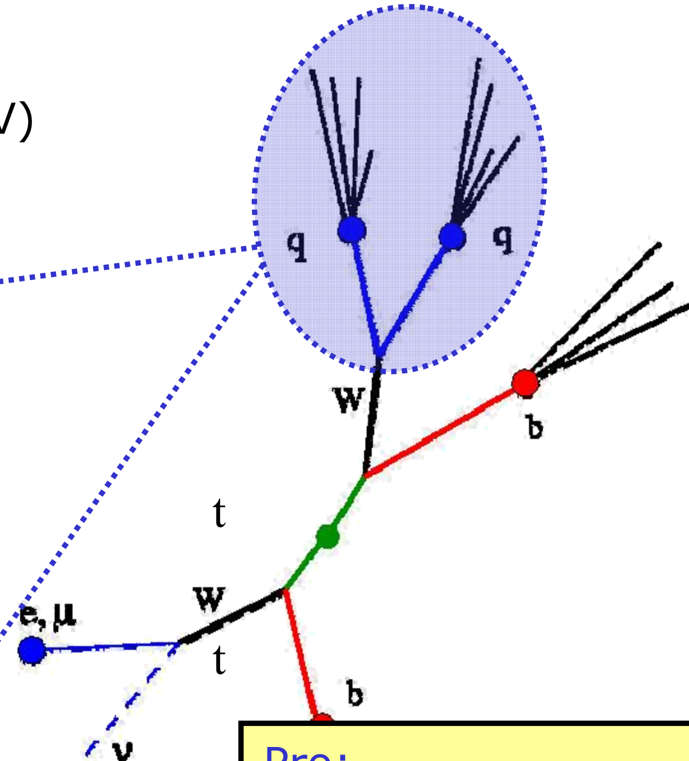
Jet energy scale

(1) Abundant source of W decays into light jets

- Invariant mass of jets should add up to well known W mass (80.4 GeV)
- W-boson decays to light jets only
  → Light jet energy scale calibration
  (target precision 1%)

Determine Light-Jet energy scale





Pro:
- Large event sample
- Small physics backgrounds

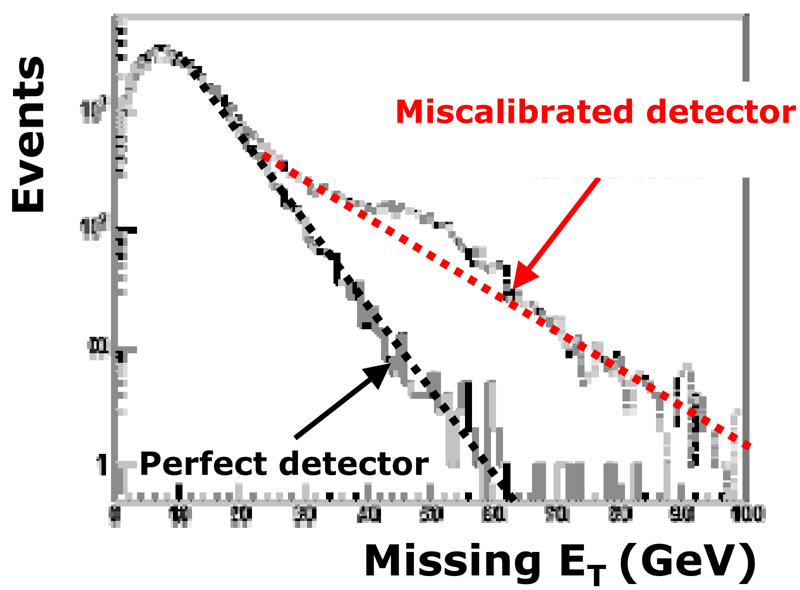
Con:
- Only light quark jets
- Limited Range in P_T and η

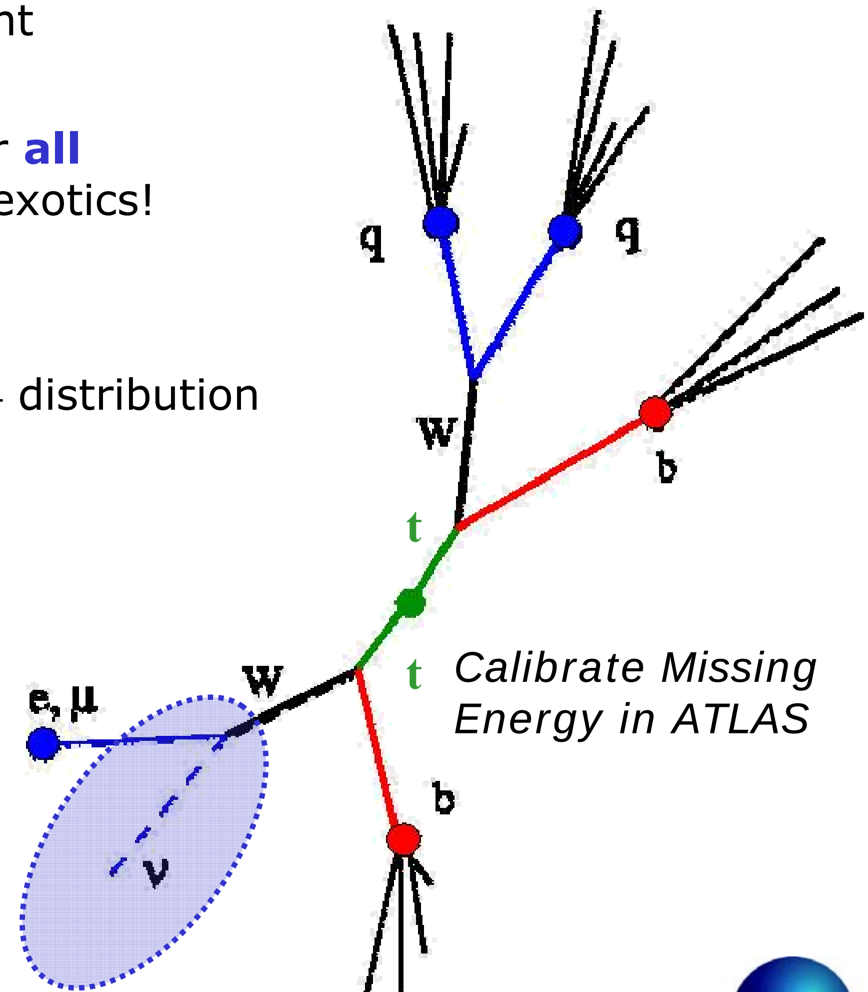
Using top quark events to calibrate missing energy

(2) Known amount of missing energy

- 4-momentum of neutrino in each event can be constrained from kinematics
- Calibration of missing energy **vital** for **all** (R parity conserved) SUSY and most exotics!

Effect of 3-4 % dead cells on missing E_T distribution



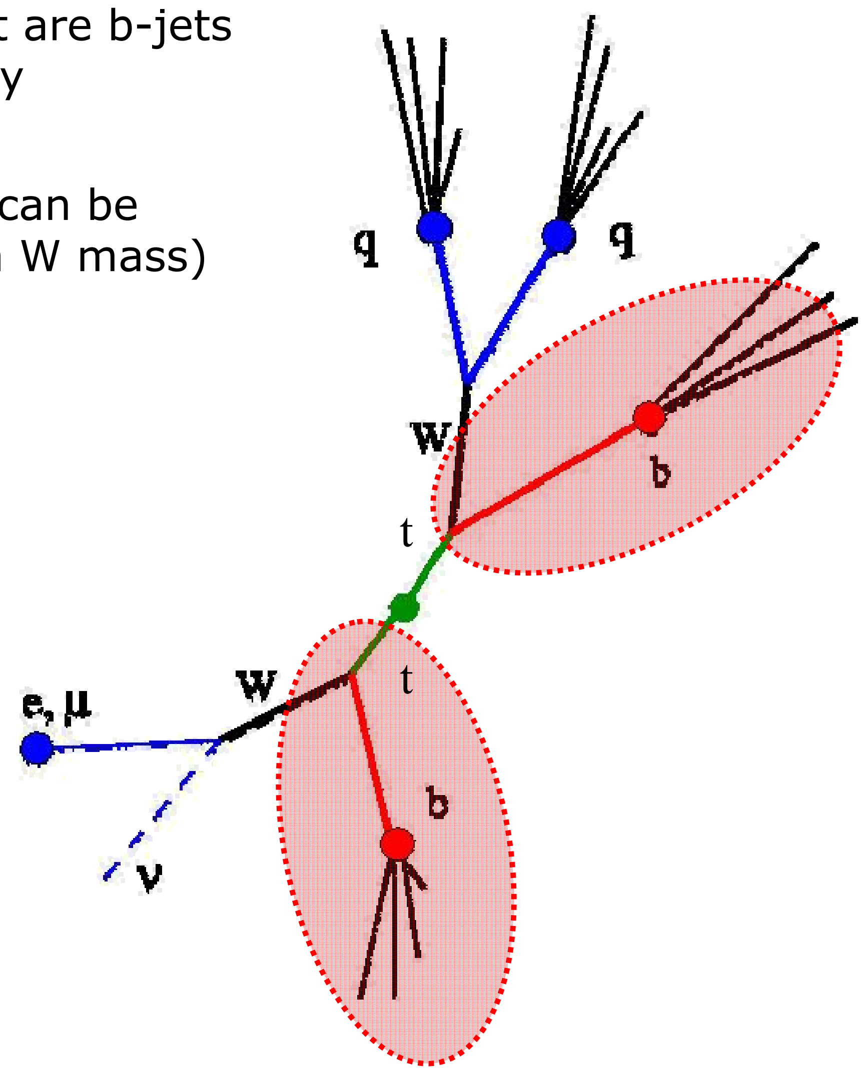


Calibrate Missing Energy in ATLAS

Using top quark events to obtain a clean sample of b-quarks

(3) Abundant clean source of b-jets

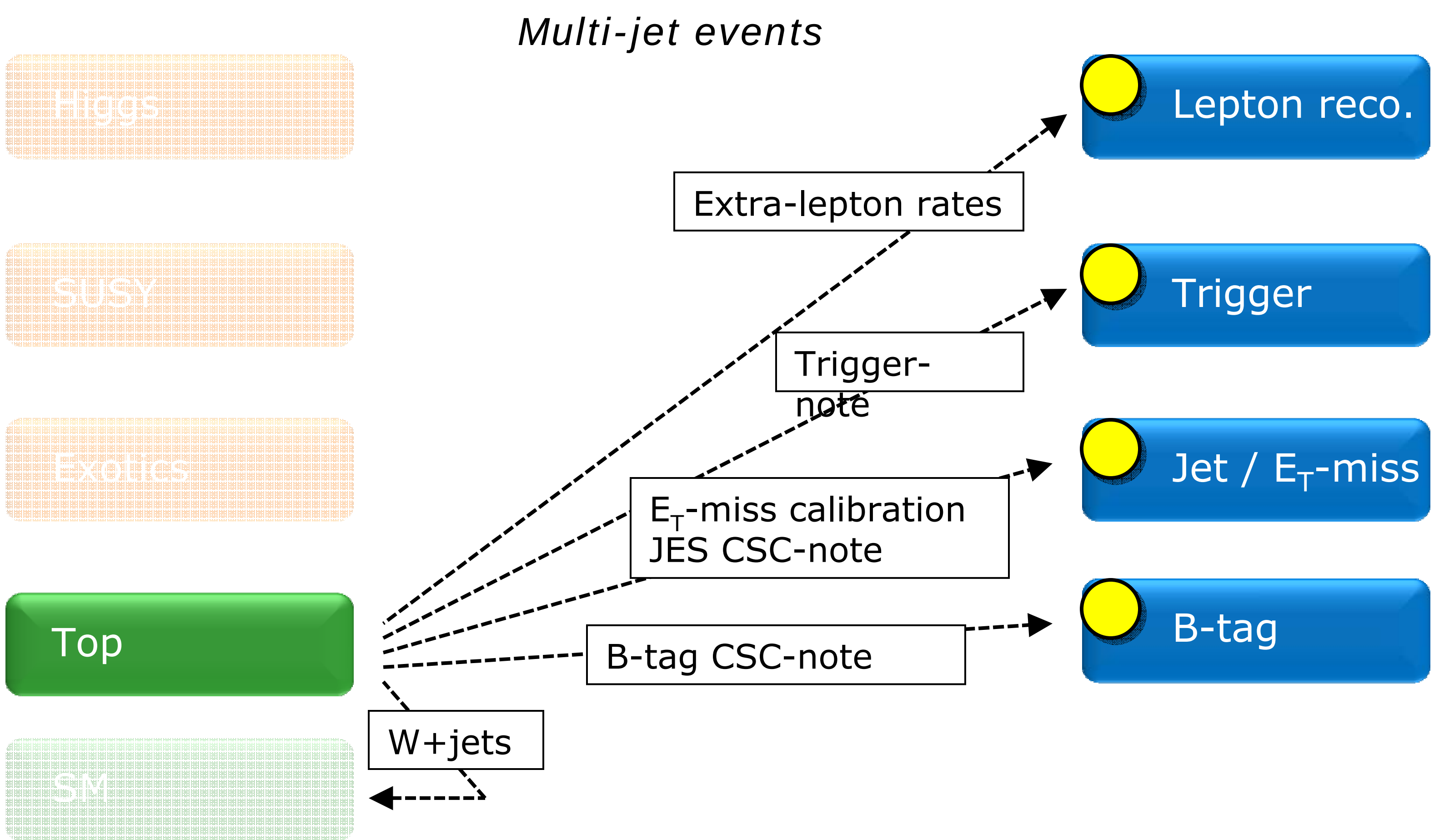
- 2 out of 4 jets in event are b-jets
  ➔ ~50% a-priori purity
  (extra ISR/FSR jets)
- The 2 light quark-jets can be identified (should form W mass)



Calibrate/test b-tagging in complex event topology

Top reconstruction (I)

Physics groups *Performance groups*



Summary: top physics during commissioning

Inputs

- Single lepton trigger efficiency
- Lepton identification efficiency
- Integrated luminosity
  - At startup around 10-20%.
  - Ultimate precision < 5%

What we can provide

- Top enriched samples
- Estimate of a light jet energy scale
- Estimate of the b-tagging efficiency
- Estimate of M_{top} and σ_{top} ~20% accuracy. One of ATLAS' first physics measurements?

Can reconstruct top and W signal after ~ one week of data taking ***without using b tagging***

Top quarks as a window to new physics

- Structure in M_{tt}

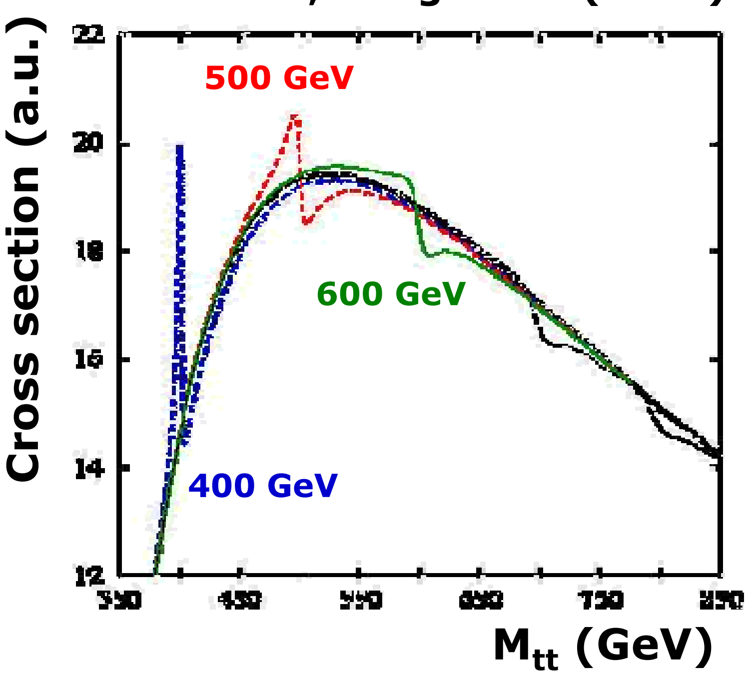
- Interference from MSSM Higgses
  H,A→ tt (can be up to 6-7% effect)

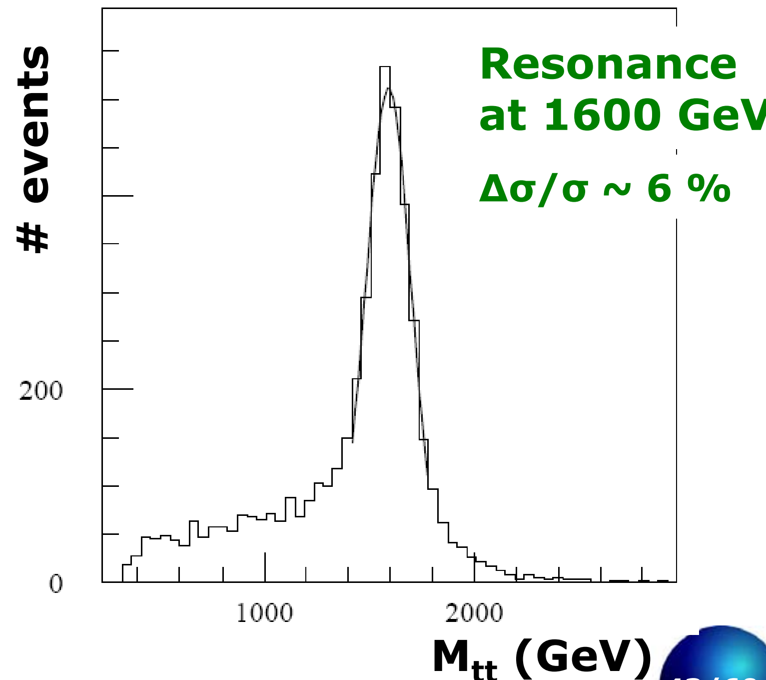
- Resonances in M_{tt}

$$pp \rightarrow X \rightarrow t\bar{t}$$

Z′, Z_H, $G^{(1)}$, SUSY, ?

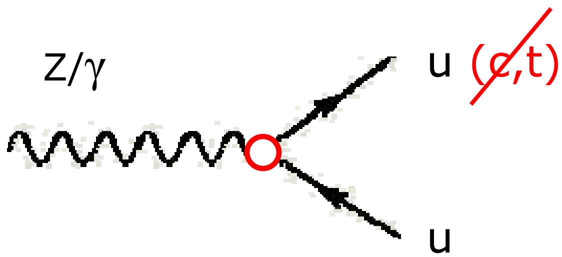
Gaemers, Hoogeveen (1984)





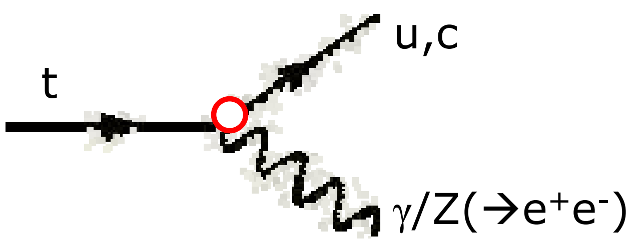
Flavour changing neutral currents

- No FCNC in SM:



SM: 10^{-13}, other models up to 10^{-4}

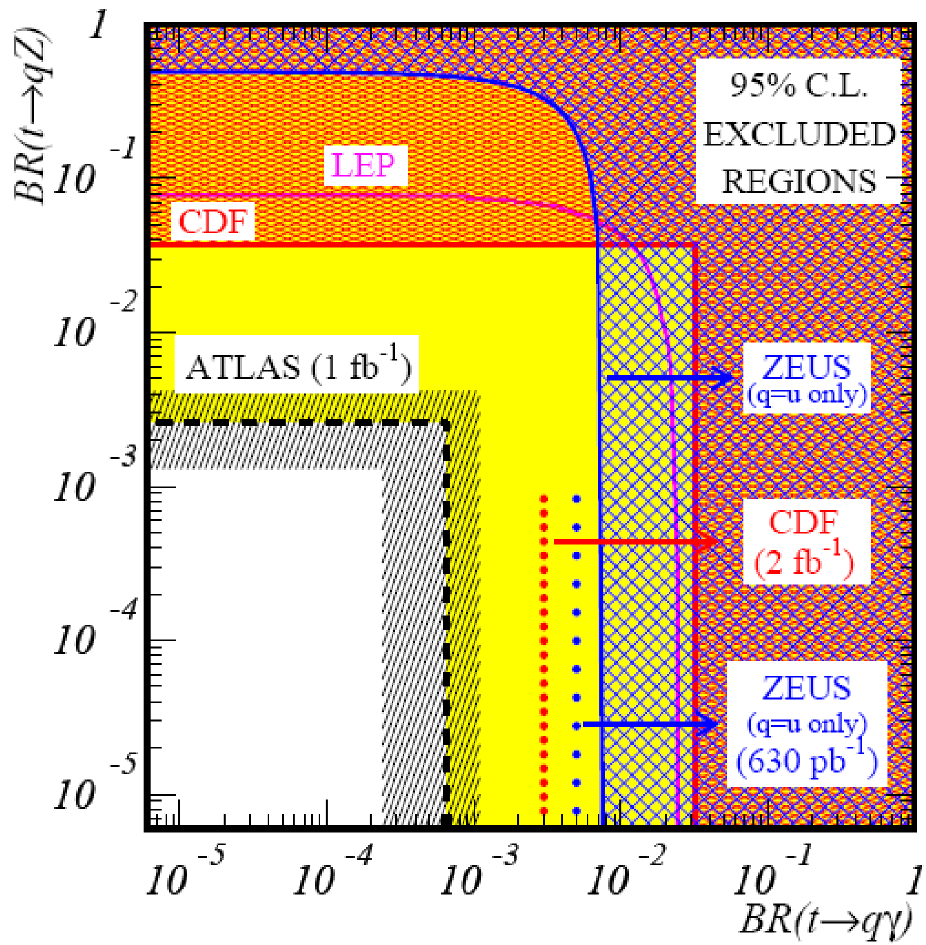
- Look for FCNC in top decays

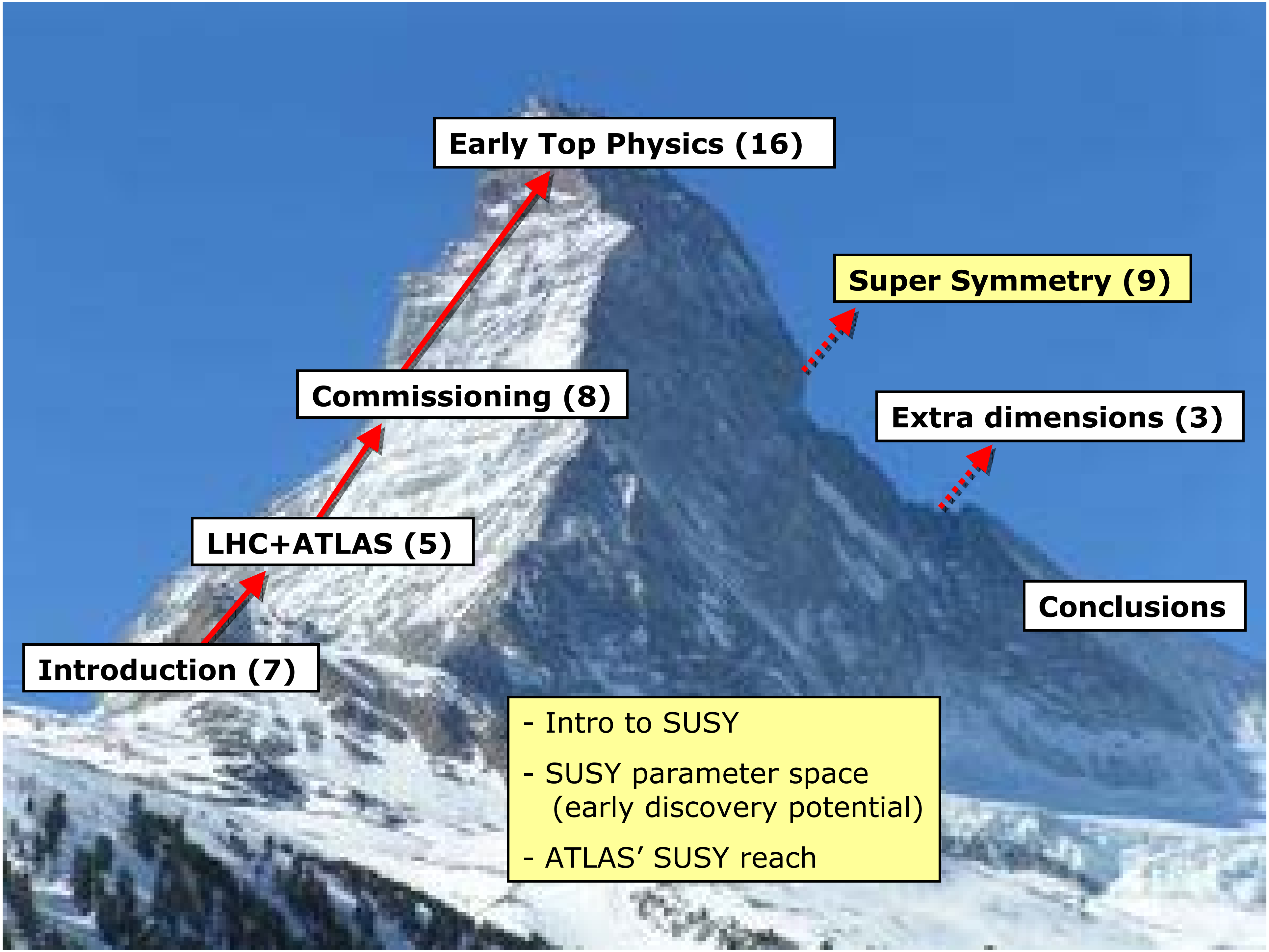


Expected limits on FCNC for ATLAS:

- Results statistically limited
- Sensitivity at the level of SUSY and Quark singlet models

ATLAS 5σ sensitivity




Early Top Physics (16)
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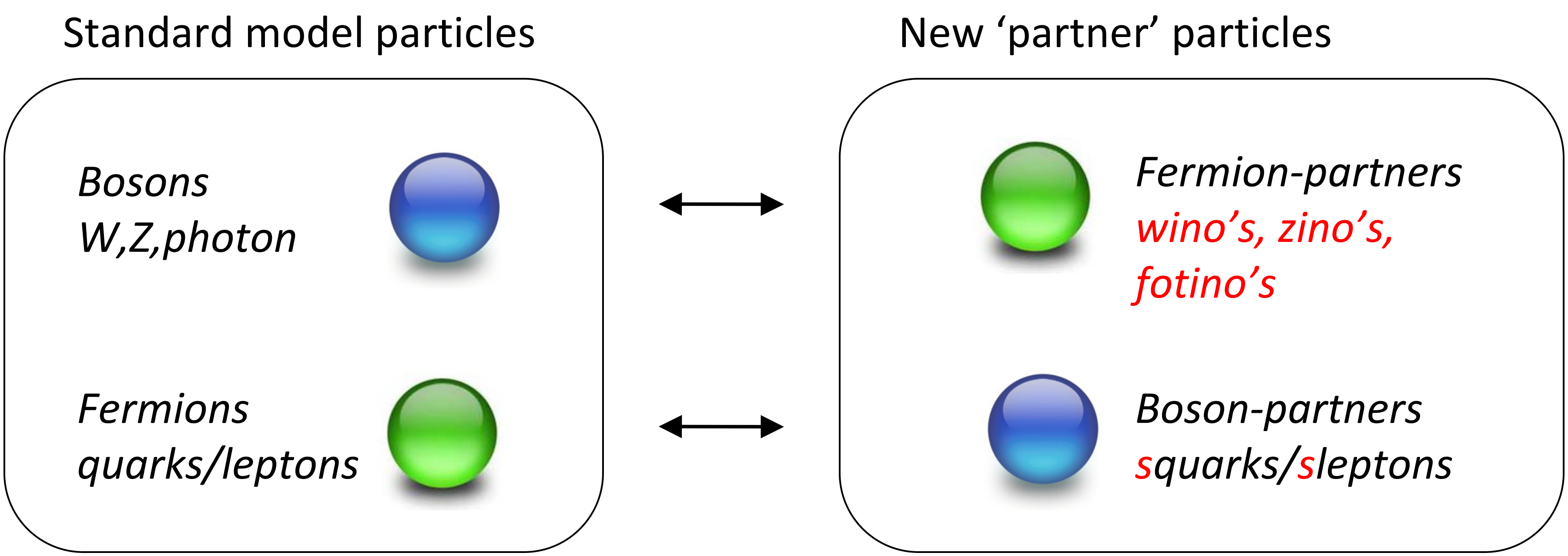
- Intro to SUSY
- SUSY parameter space (early discovery potential)
- ATLAS' SUSY reach

A new symmetry: supersymmetry

Symmetry between bosons and fermions



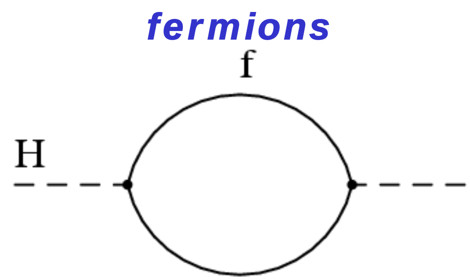
Nice symmetry: Regulate quantum corrections

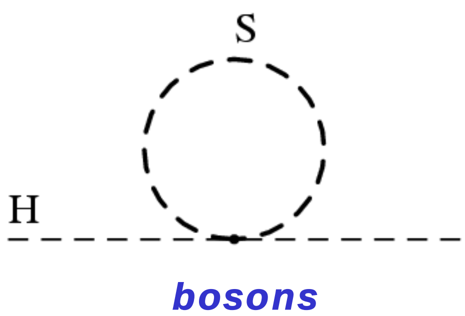
If lightest particle stable → dark matter candidate

Fixing the hierarchy problem

SUSY: ‘solves’ the hierarchy problem:

All ΔM_h terms between particles and super-partners magically cancel





$$\Delta m_H^2 = \frac{|\lambda_f|^2}{16\pi^2}\left[-2\Lambda_{UV}^2 + 6m_f^2 \ln(\Lambda_{UV}/m_f) + \ldots\right]$$

Notice minus sign

Note 2 bosonic partners per fermion

$$\Delta m_H^2 = \frac{|\lambda_S|^2}{16\pi^2}\left[\Lambda_{UV}^2 - s m_S^2 \ln(\Lambda_{UV}/m_S) + \ldots\right]$$

Note: This works if the masses of the SUSY particles (sparticles) are close to those of their SM particles partners

SUSY also: Gauge Unification and dark matter candidate

SUSY parameter space

SUSY is concept and *a-priori* not very predictive (many parameters)

SUSY has quite a few constraints from data:
no sparticles observed yet (SUSY is broken) and cosmology

Assumptions (mSUGRA):

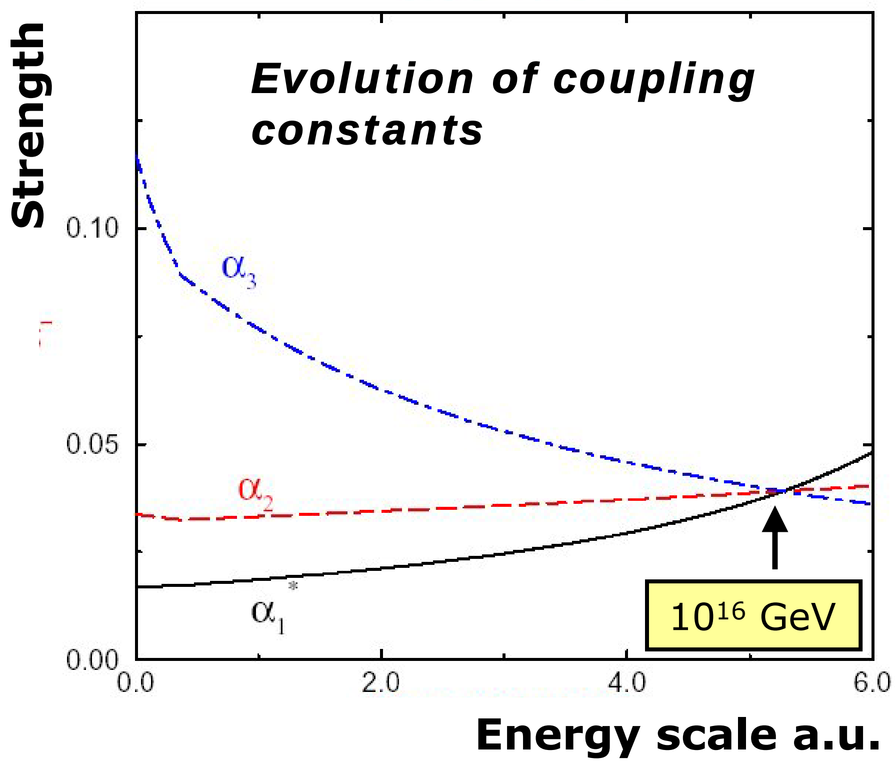
→ R-parity is conserved
There is a (stable) Lightest Supersymmetric Particle: LSP

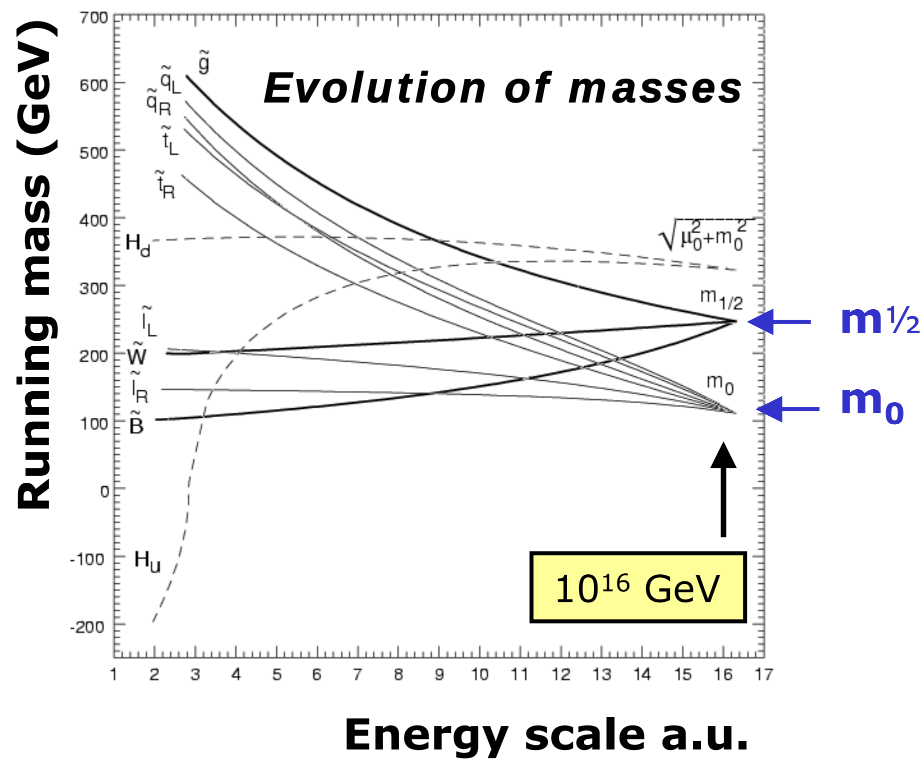
→ mSUGRA

- m_0: universal scalar mass (sfermions)
- $m_{1/2}$: universal gaugino mass
- A_0: trilinear Higgs-sfermion coupling
- sgn(μ): sign of Higgs mixing parameter
- tan(β): ratio of 2 Higgs doublet v.e.v

SUSY stuff

Fixing parameters at 10^{16} GeV, the renormalization group equations will give you all sparticle masses at LHC!





SUSY mass spectra

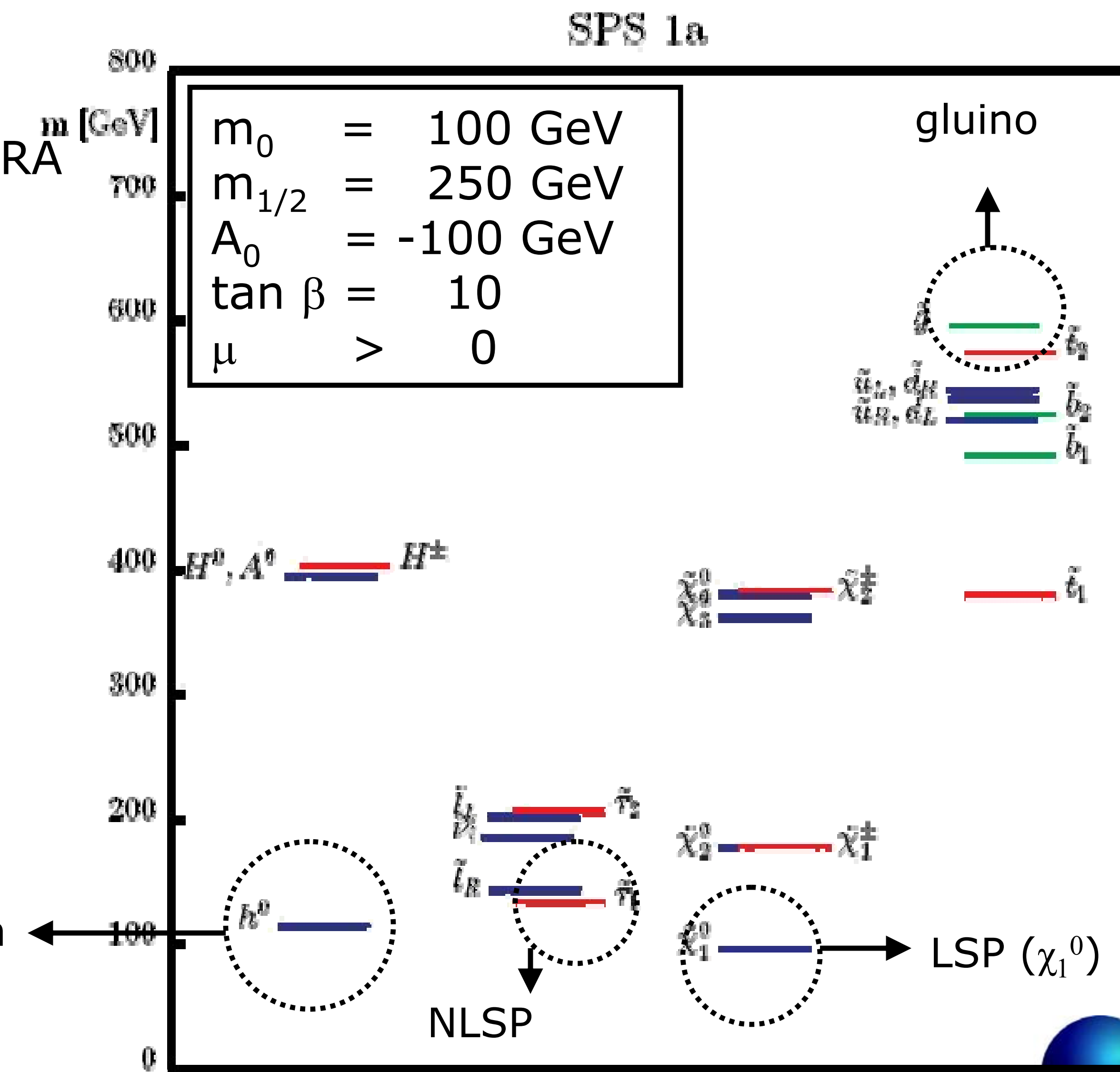
Particle (mass) spectrum predicted for each mSUGRA parameter point

Not all mSUGRA points (mass spectra) allowed:

LEP:
- $M_h > 114.4$ GeV

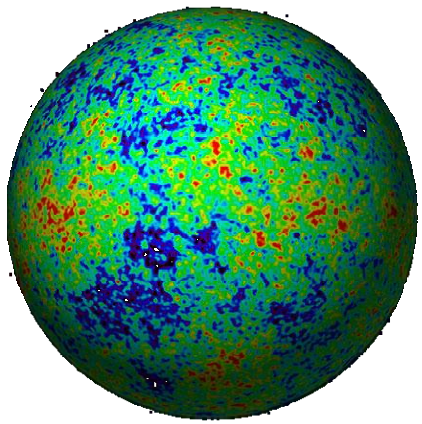
Cosmology:
- LSP is neutral
- Limits on LSP mass (upper/lower)

Higgs boson



Cosmology and SUSY

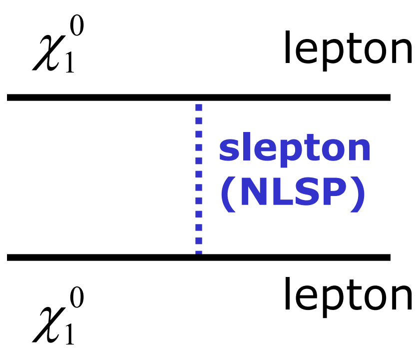
dark matter



WMAP III: $0.121 < \Omega_m h^2 = n_{LSP} \times m_{LSP} < 0.135$

ρ_{LSP} = Relic LSP density x LSP mass

The relic LSP density depends on LSP mass:
LSP stable, but they can annihilate, so density decreases when LSP annihilation cross section increases.



$$\sigma(\chi_1^0\chi_1^0 \to ff) \propto m_\chi^2/(m_\chi^2 + m_{\tilde{f}}^2)^2$$

$$\rho_{LSP} \propto (m_\chi^2 + m_{\tilde{f}}^2)^2 / m_\chi$$

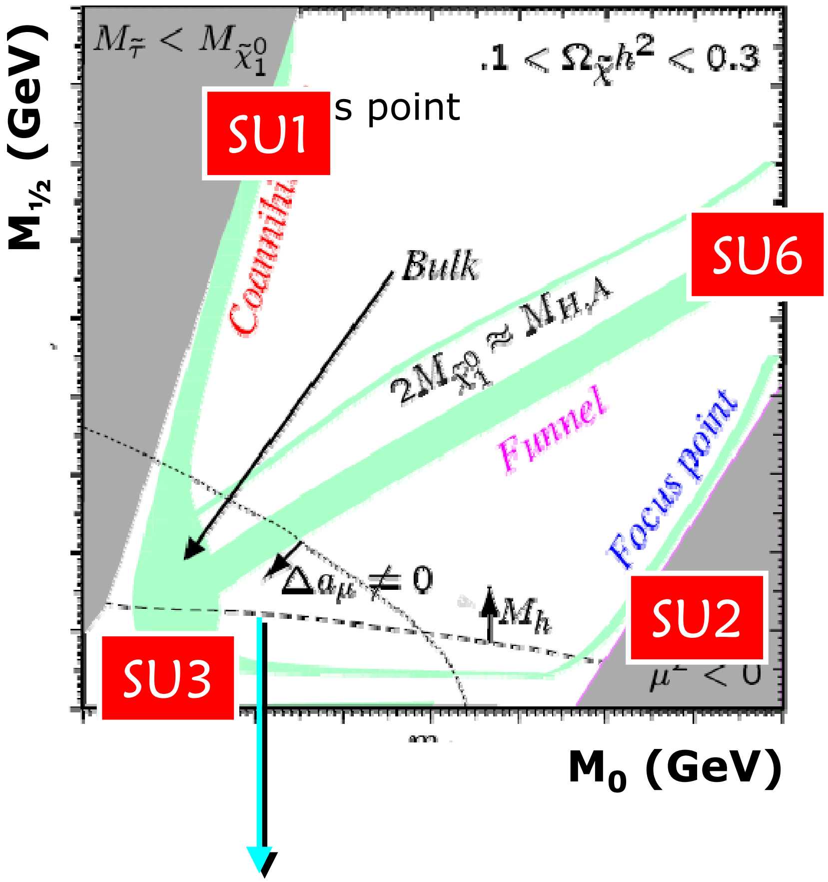
$$\approx m_\chi^3$$

Upper AND lower limits on LSP mass

SUSY might be one of the first signals to be observed at the LHC

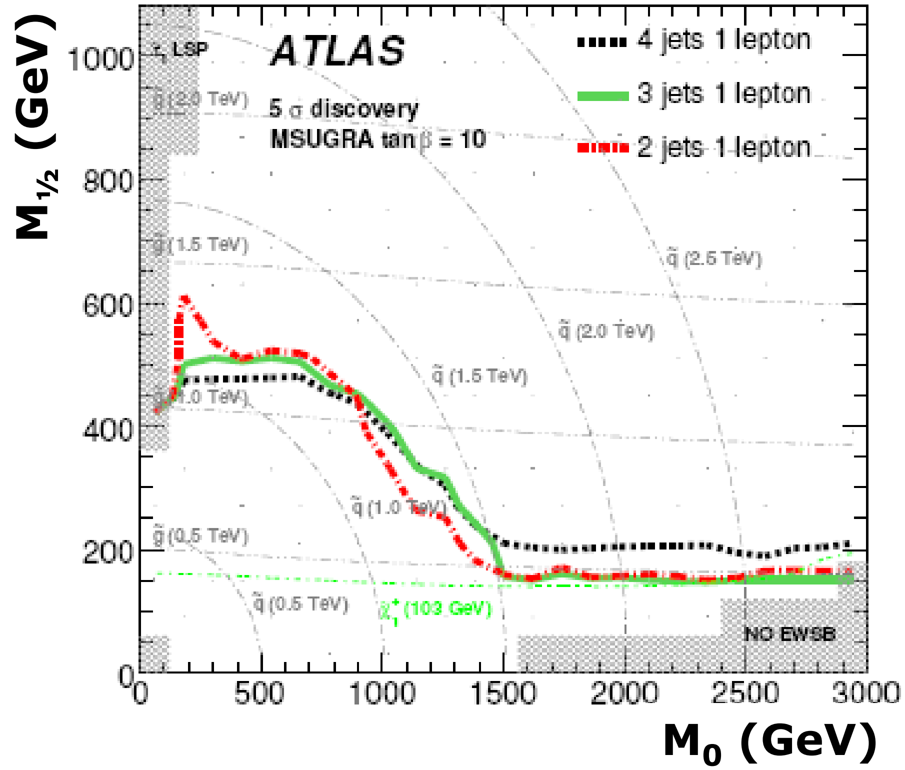
mSUGRA space

Allowed mSUGRA space (post WMAP)



Allowed mSUGRA space
Very different exp. signatures

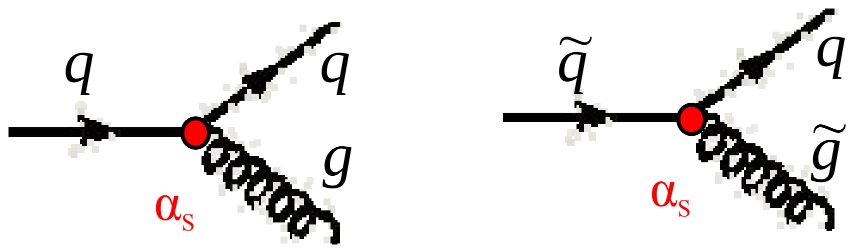
ATLAS reach in mSUGRA space (1-lepton)



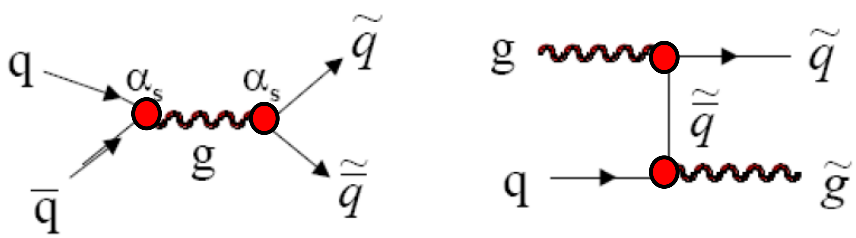
M = 1.3 TeV (1 week)
M = 1.8 TeV (1 month)
M = 3 TeV (300 fb^{-1})

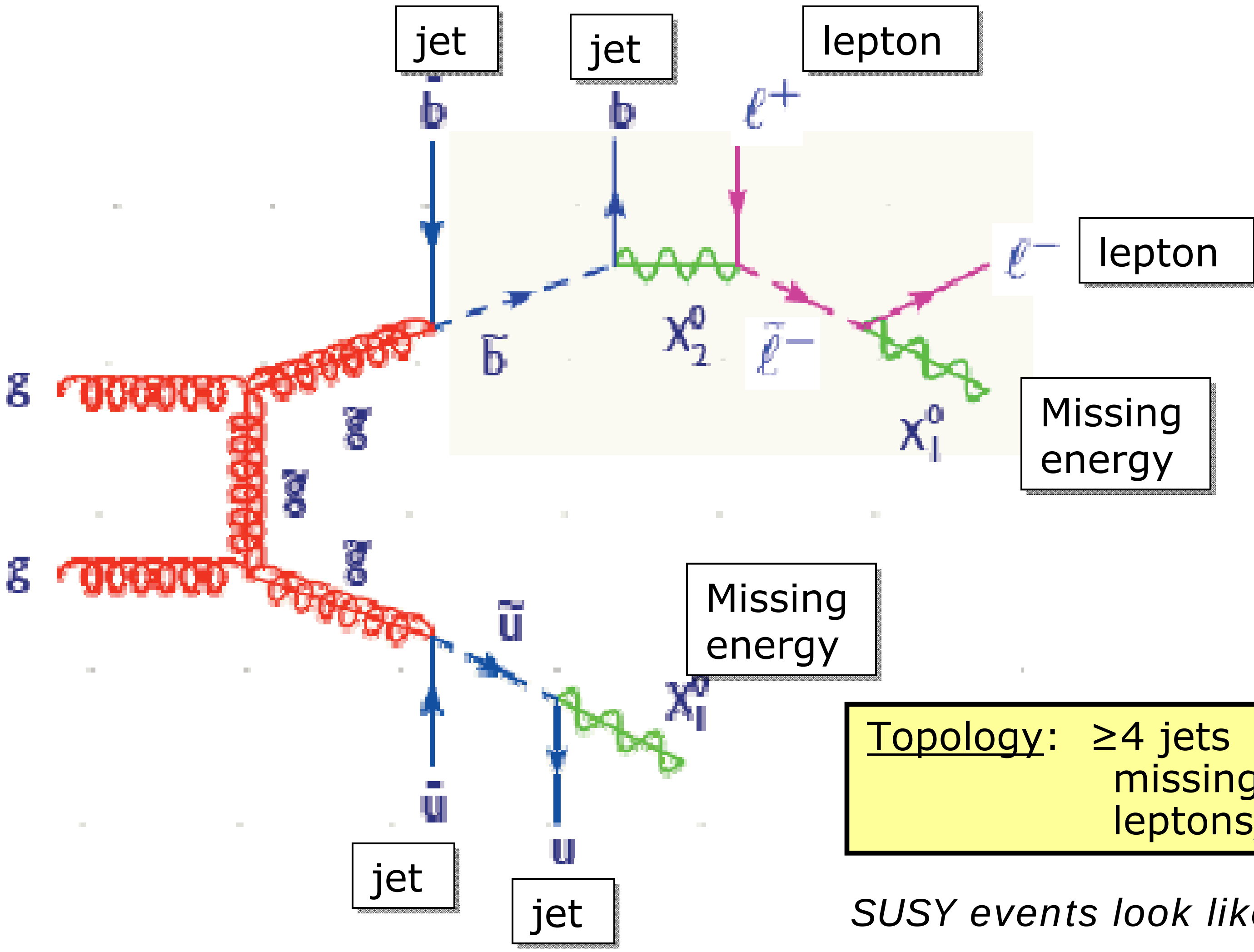
Production of SUSY particles at the LHC

- Superpartners have same gauge quantum numbers as SM particles → interactions have same couplings



Gluino's / squarks are produced copiously
(rest SUSY particles in decay chain)

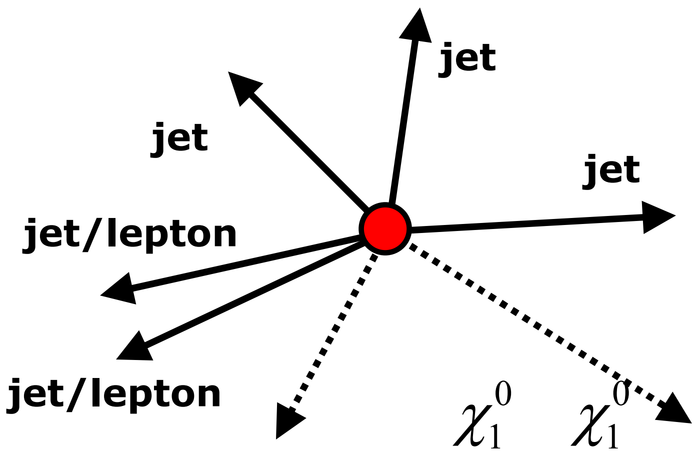




<u>Topology</u>: ≥4 jets
missing E_T (large)
leptons/photons

SUSY events look like top events

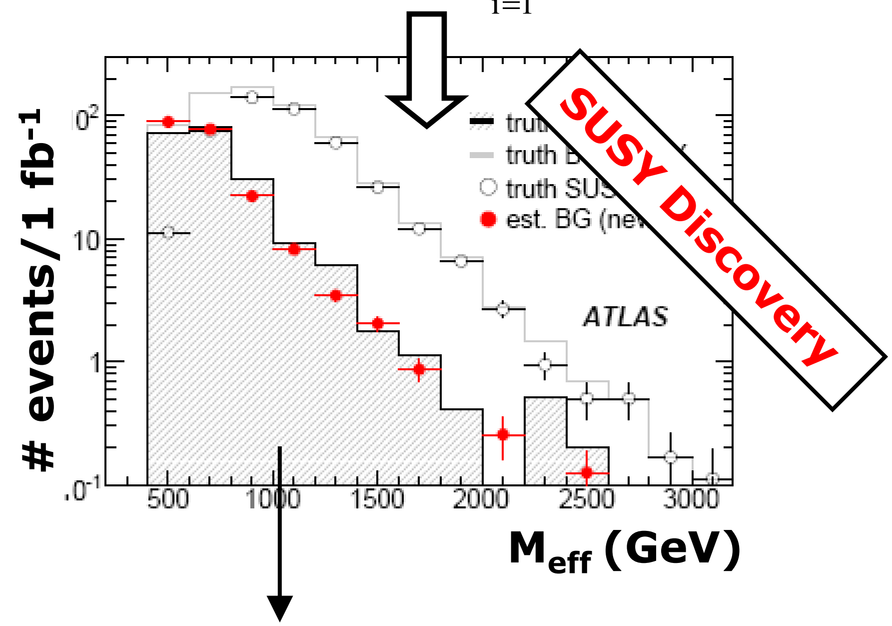
Common signature large fraction SUSY events



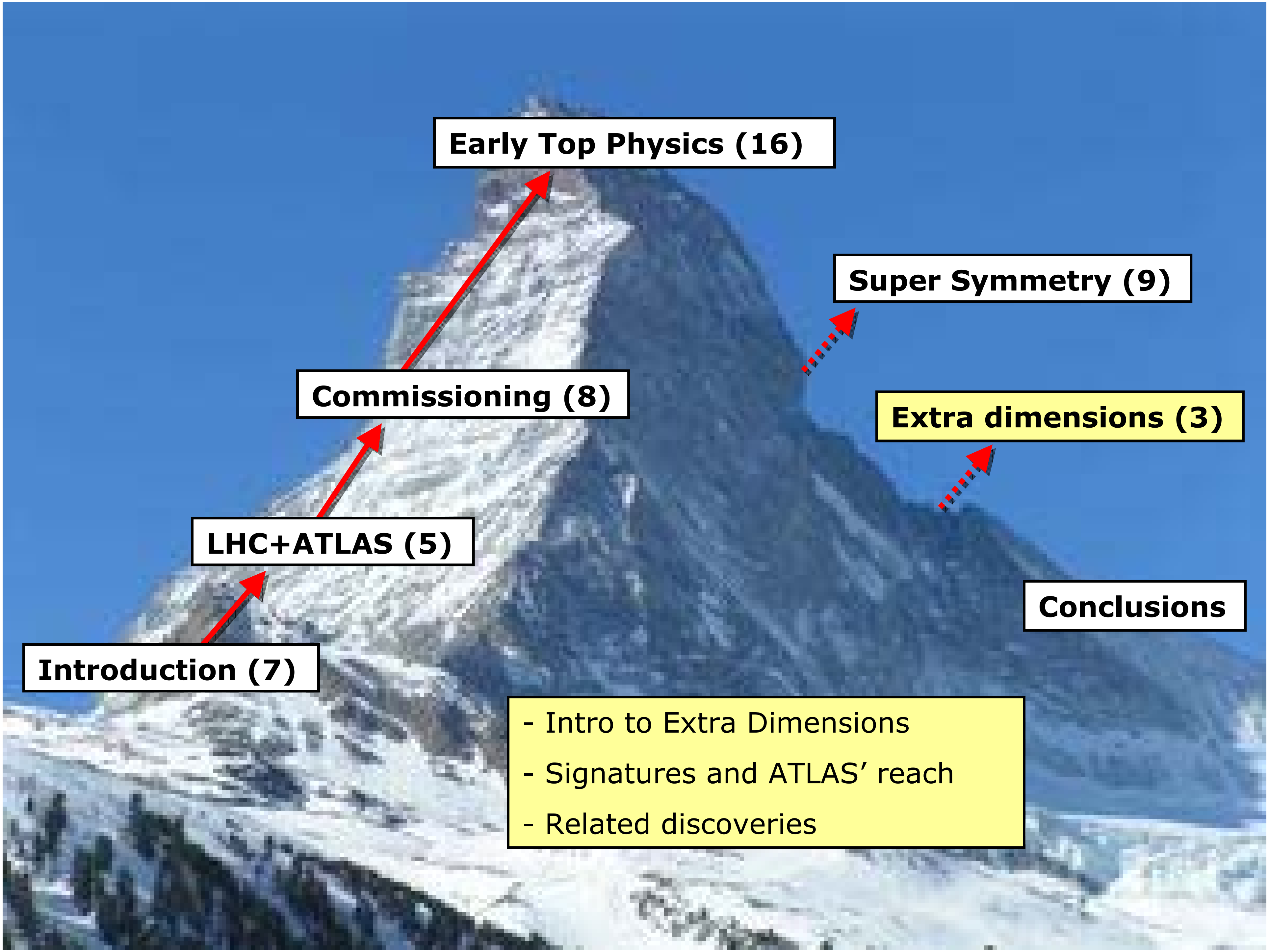
In R-parity conserving models the LSP is stable and escapes detection (mSUGRA)

- **Sensitive to hard scale:**

$$M_{eff} = \not{E}_T + \sum_{i=1}^{N_{jets}} (P_T)_i$$



tt production dominant background
remember: we understand this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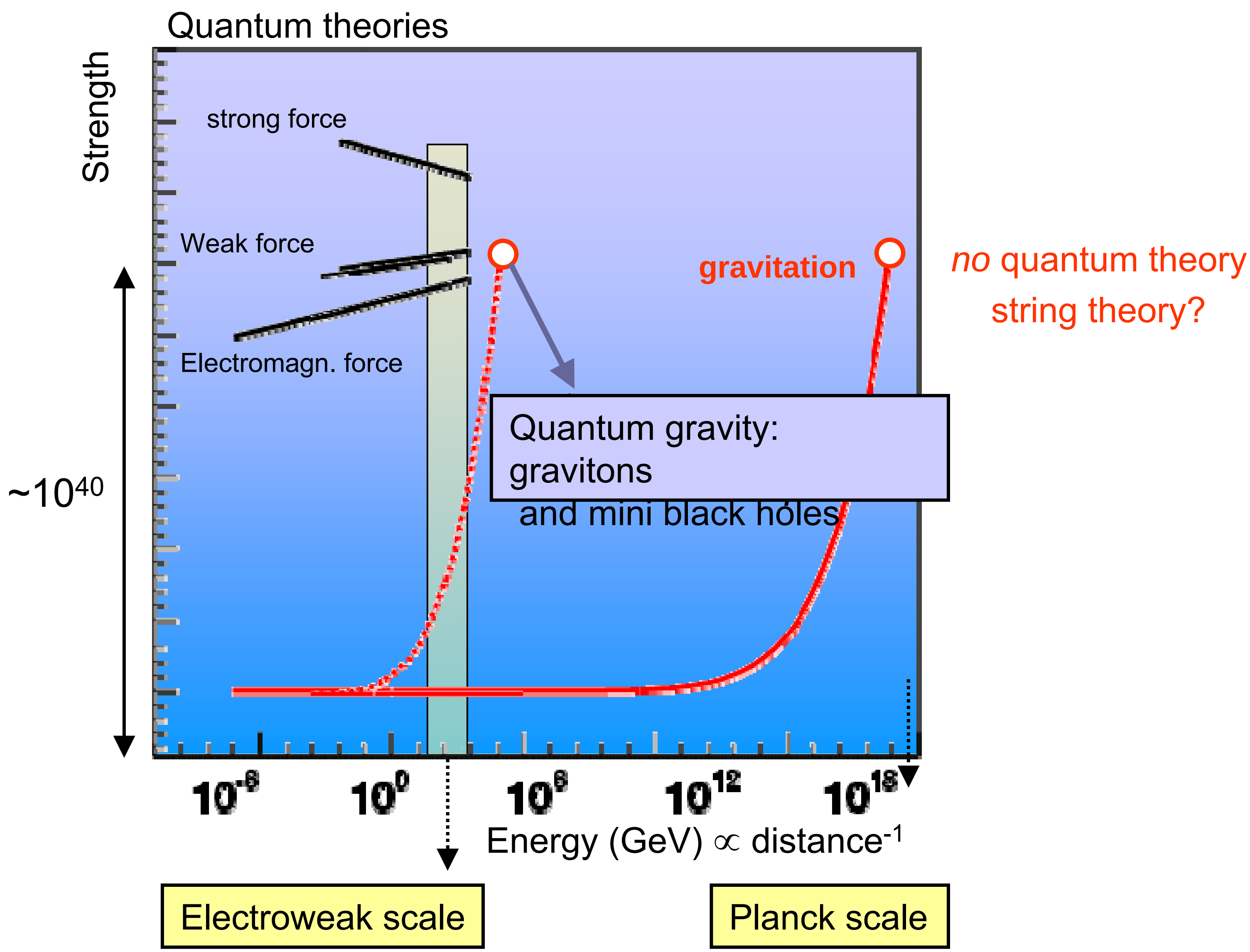
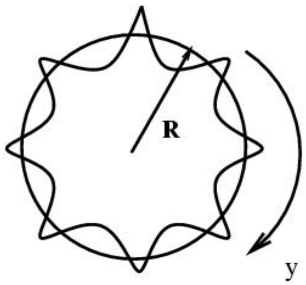
- Signatures and ATLAS’ reach
- Related discoveries

The 3+1 forces of nature



Kaluza-Klein excitations

Each particle that can 'enter' the extra dimension (bulk) will appear in our 4 dimensions as a ***set*** *of massive states (Kaluza-Klein tower)*



$$(M_{real})^2 = E^2 - p_x^2 - p_y^2 - p_z^2 - p_{xd}^2$$
$$= (m_{4d})^2 - p_{xd}^2$$

$$\boxed{(m_{4d})^2 = (M_{real})^2 + p_{xd}^2}$$

Depends on size/shape XD

Momentum quantized in the extra dimension. $P_{xd} = i \times \Delta P$, with i = 1,2,3,4,5, …

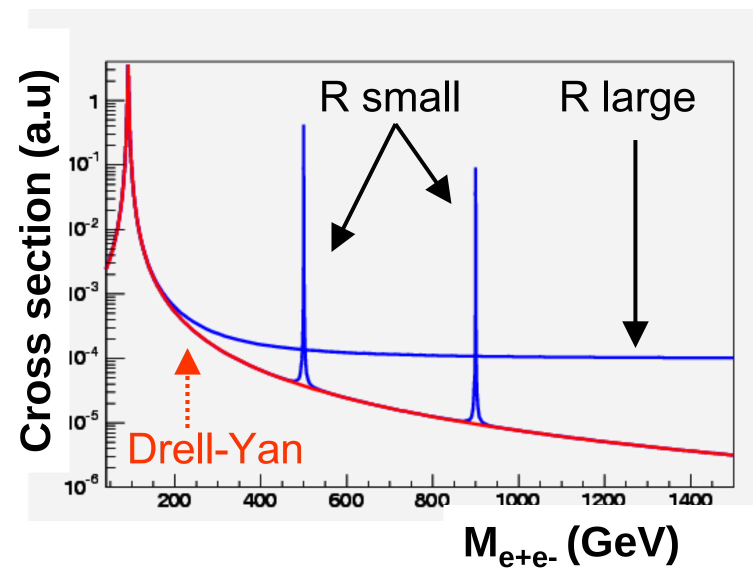
(4+n)-dim.

massless graviton G
momentum p_0 p_1, p_2, …, p_i in extra dimension

⇓

(4)-dim.

massive gravitons
with mass m_0, m_1, m_2, …. m_i
with name $G^{(0)}$, $G^{(1)}$, $G^{(2)}$, …$G^{(i)}$



Note: other model can have fermions or gauge bosons in the bulk ($Z^{(i)}$, $W^{(i)}$)

Graviton in the XD:

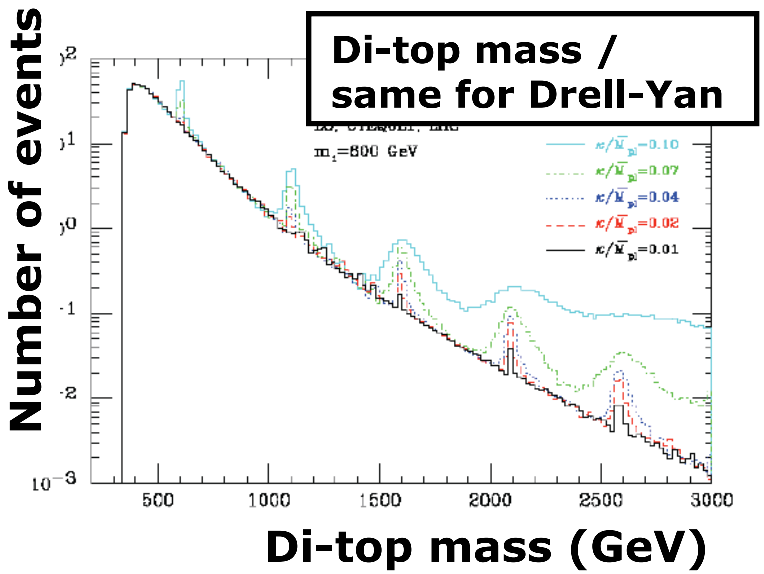
In 4-dimensions: KK excitations $G^{(0,1,2,3,4)} \rightarrow e^+e^-/\mu^+\mu^-$

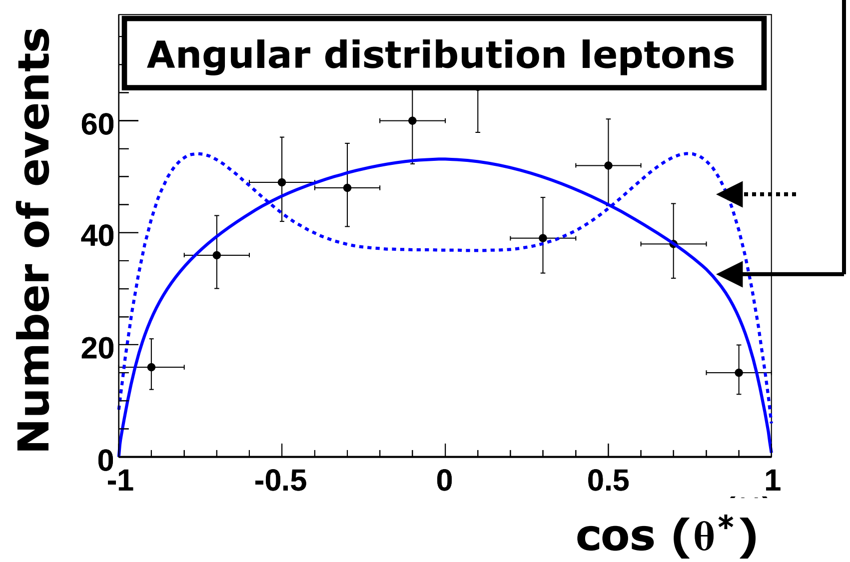
Use spin-2 nature of graviton:

- $gg \rightarrow G \rightarrow e^+e^-$: $1 - \cos^4\theta^*$
- $qq \rightarrow G \rightarrow e^+e^-$: $1 - 3\cos^2\theta^* + 4\cos^4\theta^*$
- $qq \rightarrow \gamma/Z \rightarrow e^+e^-$: $1 + \cos^2\theta^*$

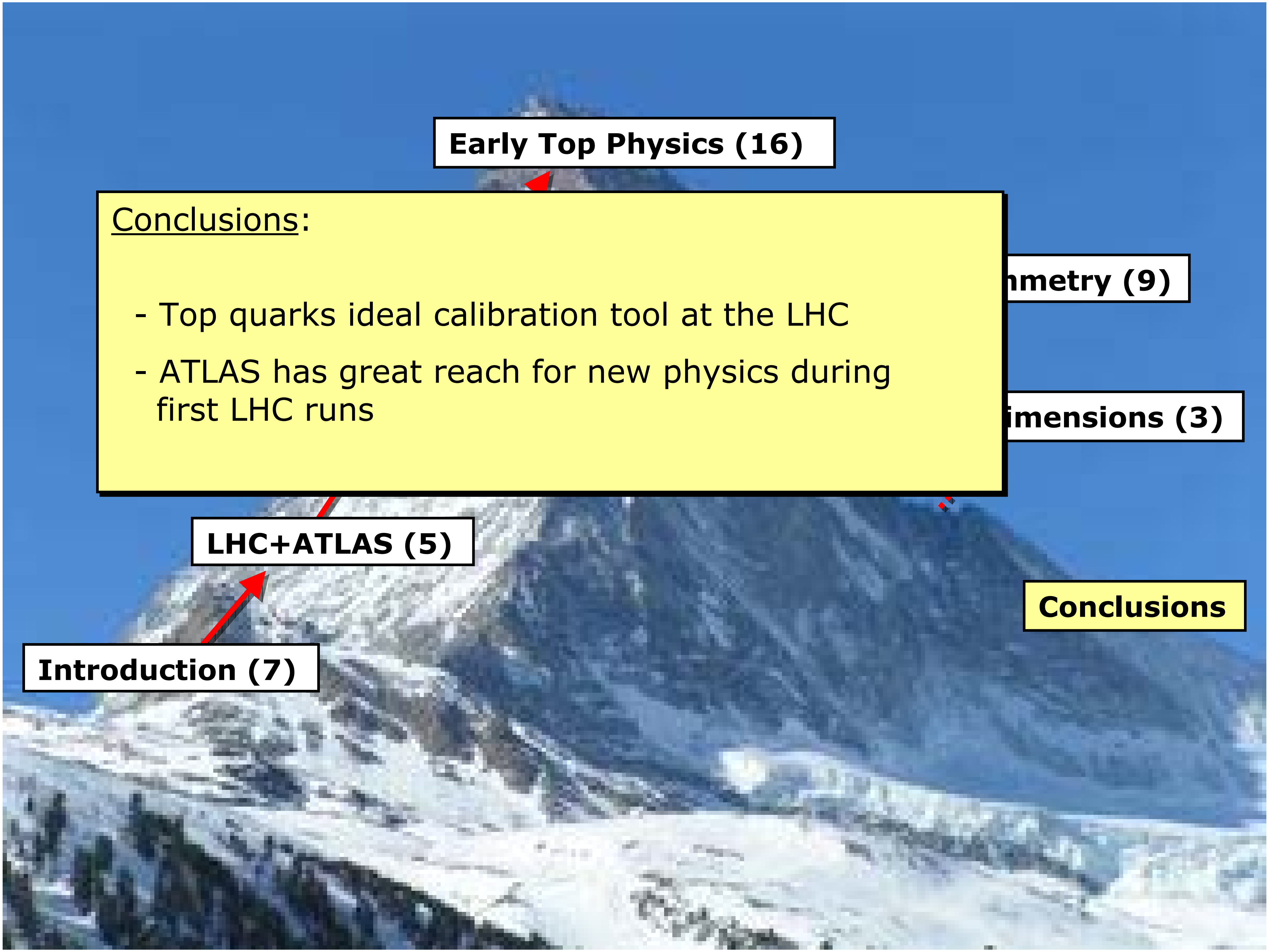
spin-2

spin-1





ATLAS extra dimension reach:
M_s =5.4 (7) TeV for 10(100) fb^{-1}



Conclusions:

- Top quarks ideal calibration tool at the LHC
- ATLAS has great reach for new physics during first LHC runs

Backup slides

Top reconstruction (I)

Physics groups

- Higgs
- SUSY
- Exotics
- Top
- SM

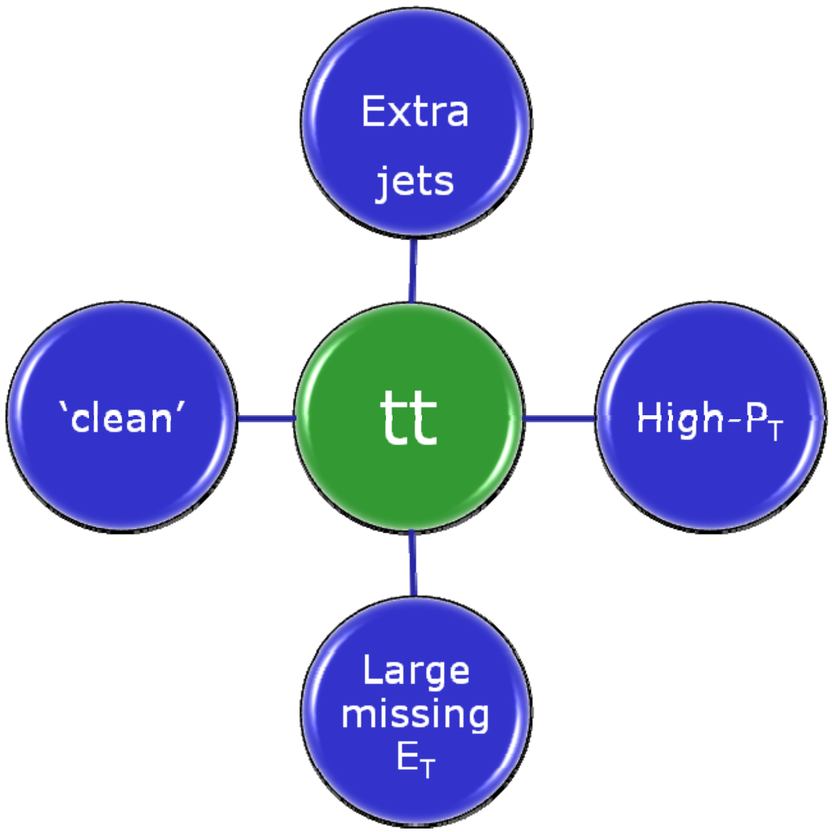
Performance groups

- Lepton reco.
- Trigger
- Jet / E_T-miss
- B-tag

Extrapolating in top phase space

Top group (all)
ttH

low 'ISR-FSR'
Top mass
Cross-section



Exotics, SUSY
Top group:

$$\frac{d\sigma}{dP_T} \text{ or } \frac{d\sigma}{dM_{tt}}$$

SUSY

Example of multi-jet issues: Isolated leptons

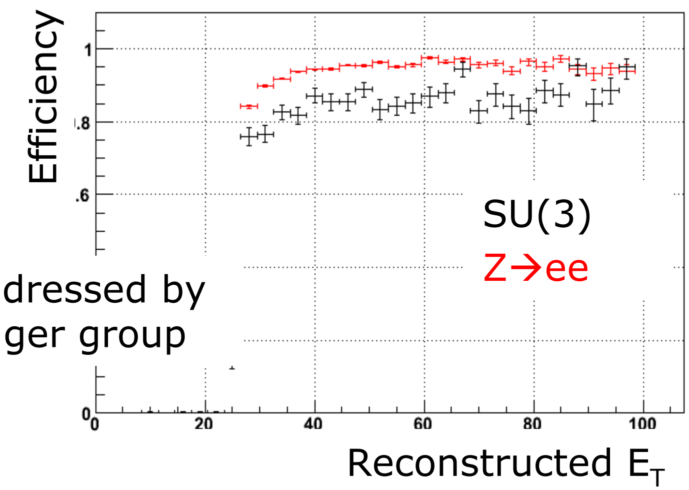
Lepton Trigger & reconstruction:

Dependence on jet multiplicity ?

Data: Z: tag-probe

tt: trigger degeneracy

Procedure to arrive at robust understanding & correction

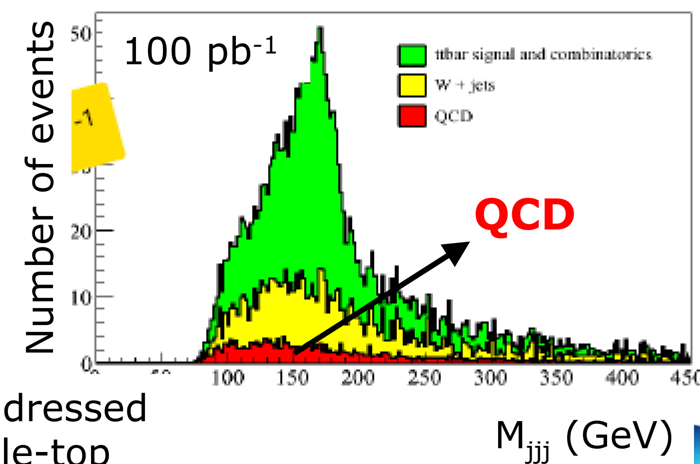


Also addressed by top trigger group

Isolated extra leptons:

Fake and non-prompt (semi-leptonic)

f (lepton definition, P_T, η, jet-type, jet multiplicity, …)



Also addressed by single-top and SUSY group