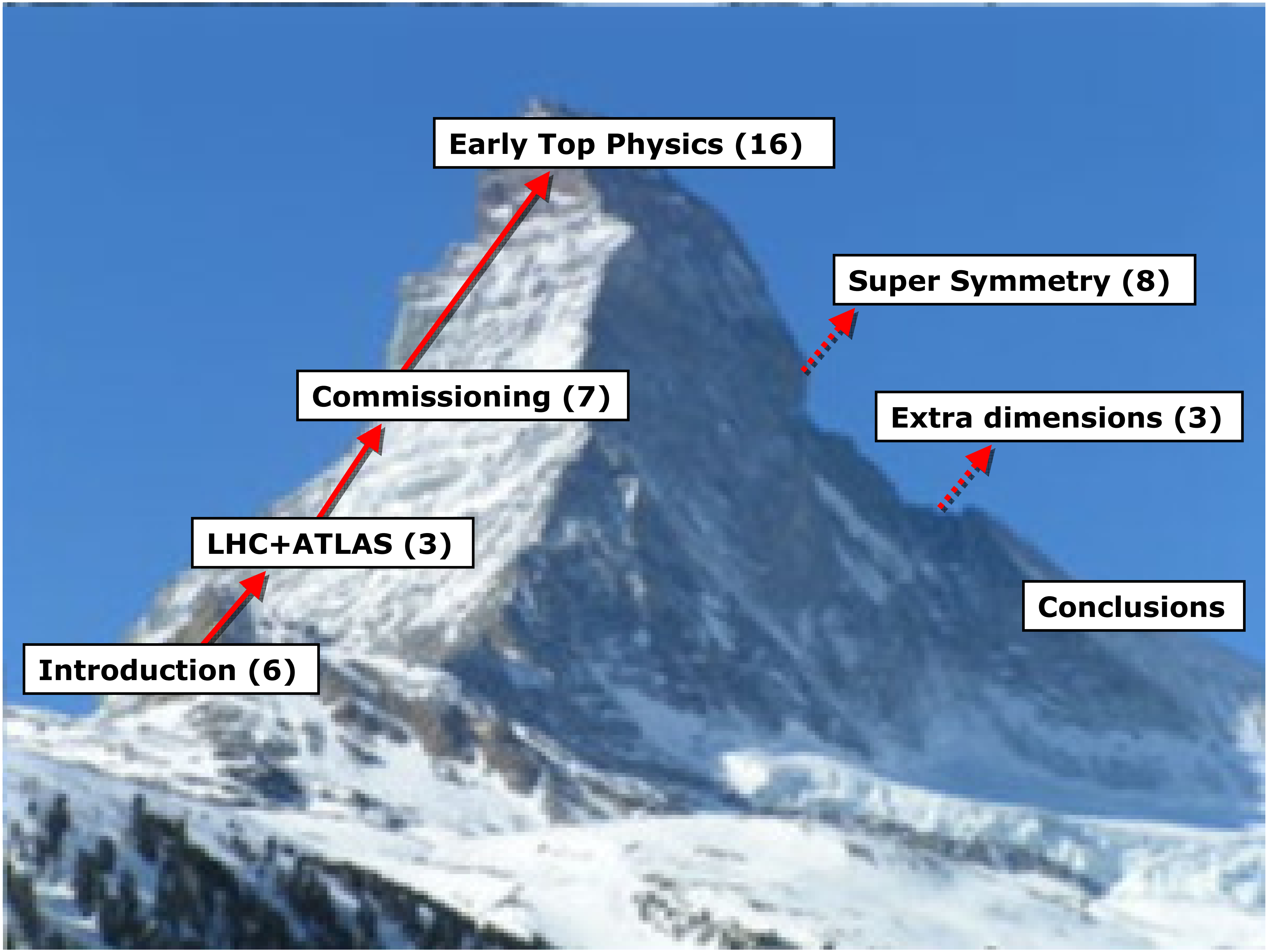
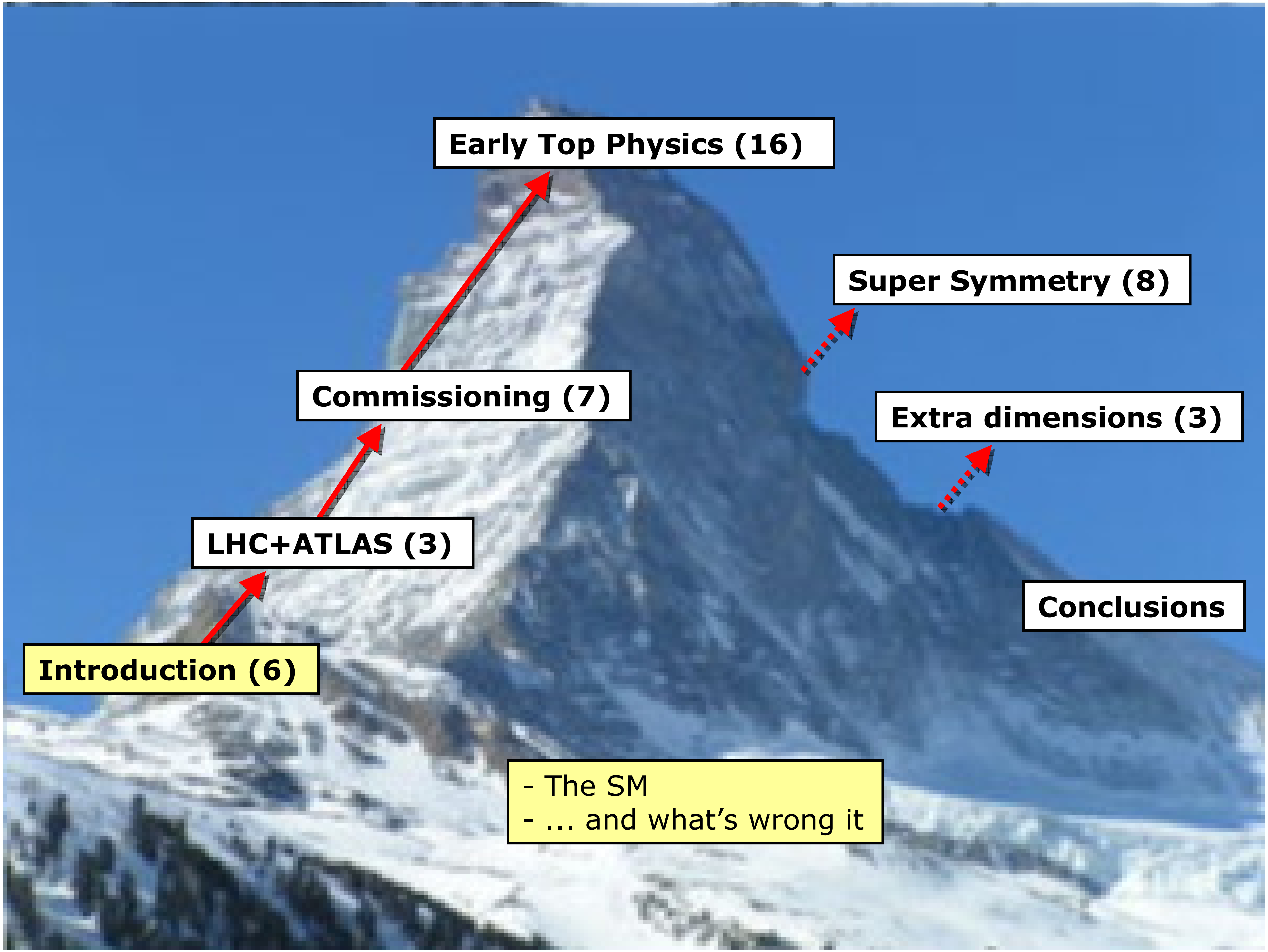
Preparing for first physics at the LHC

Ivo van Vulpen
(NIKHEF)

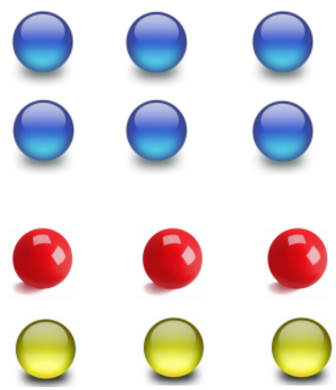

Early Top Physics (16)
Super Symmetry (8)
Commissioning (7)
Extra dimensions (3)
LHC+ATLAS (3)
Conclusions
Introduction (6)


Early Top Physics (16)
Super Symmetry (8)
Commissioning (7)
Extra dimensions (3)
LHC+ATLAS (3)
Conclusions
Introduction (6)
- The SM
- … and what’s wrong it

Particles

Quarks

Leptons



Forces

1) Electromagnetism

2) Weak nuclear force

3) Strong nuclear force

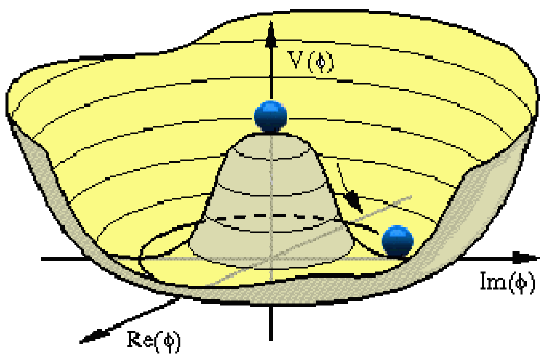
The Standard Model:

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

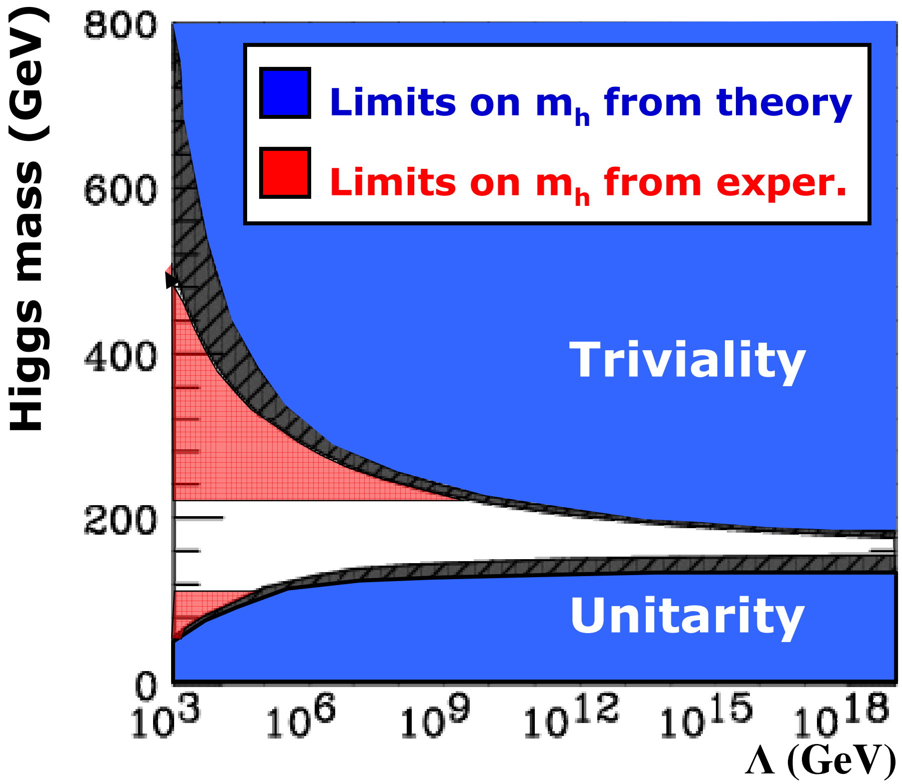
Electro-Weak Symmetry Breaking: (Higgs mechanism)

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

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

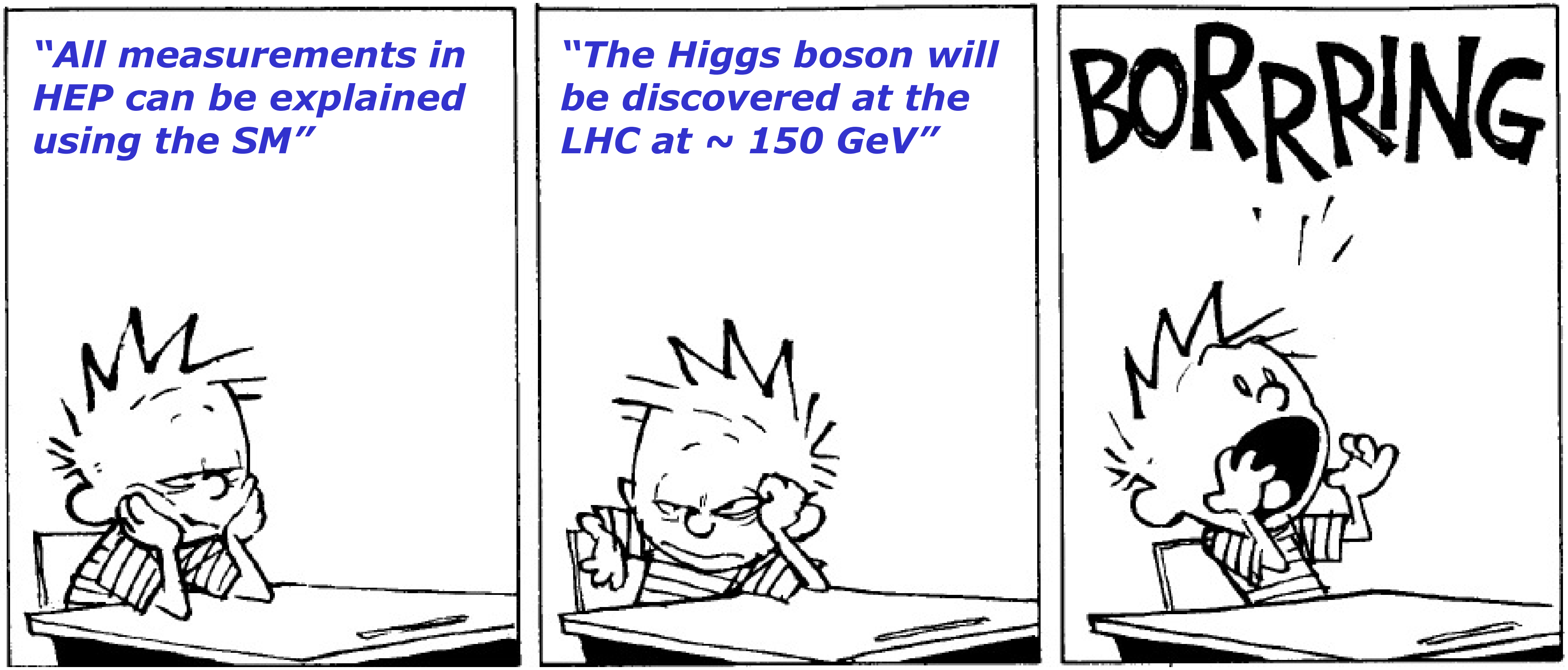


$$V = -\mu^2|\Phi|^2 + \lambda^2|\Phi|^4$$

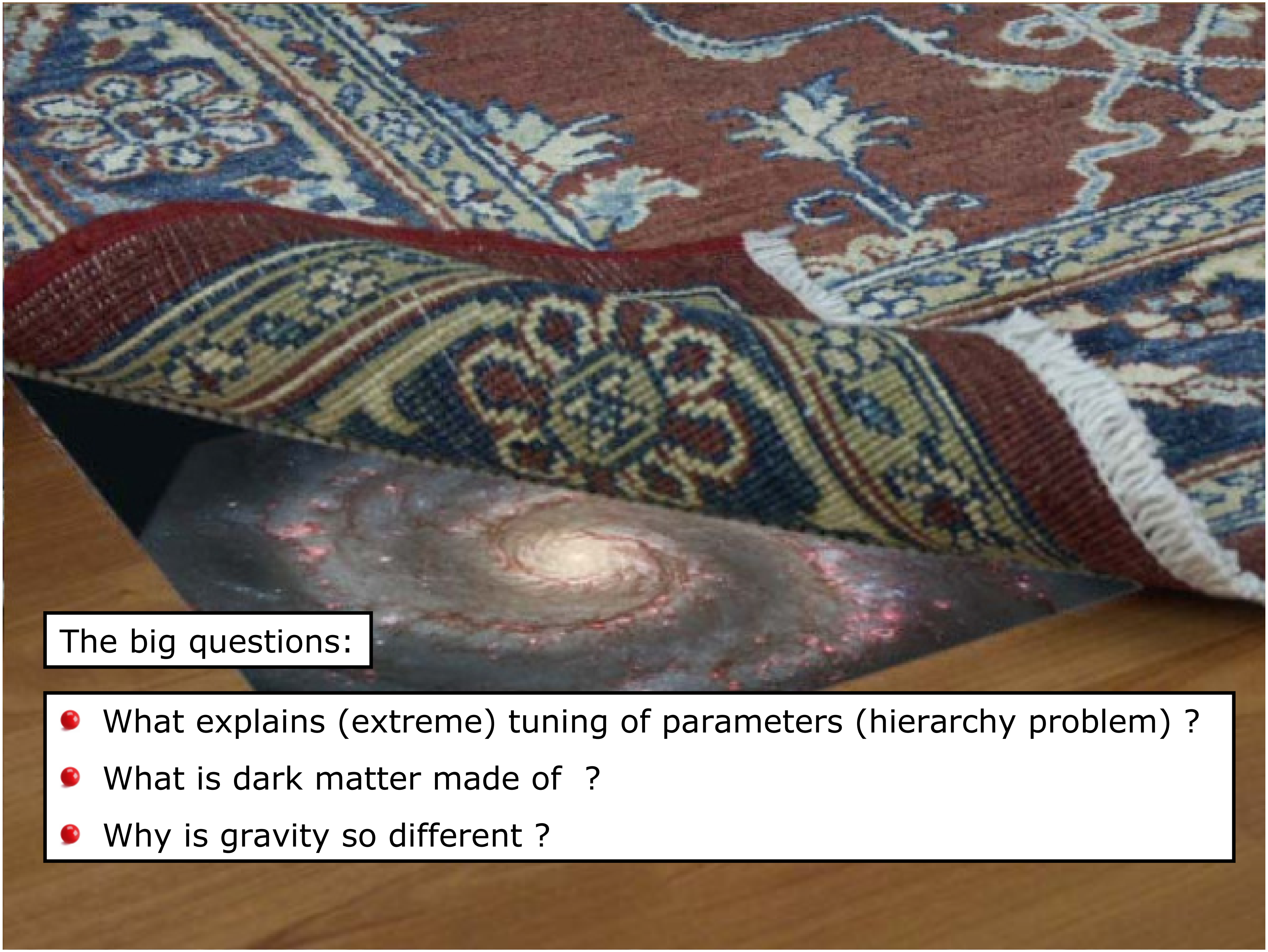


λ describes Higgs's self-couplings (3h, 4h)

The standard model … boring ?



No. … there are many mysteries left!



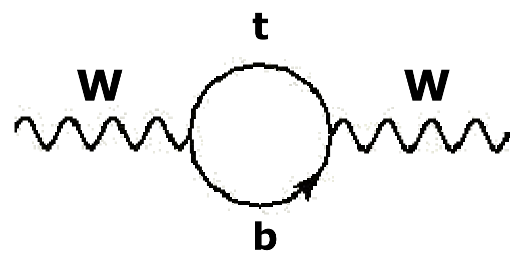
The big questions:

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

The 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:

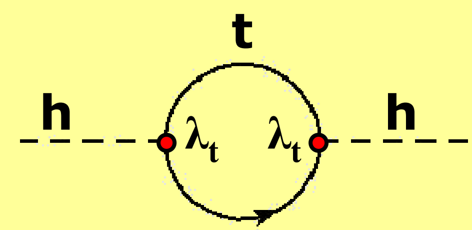
$$m_h \quad = \quad m_{h_{bare}} + \delta m_{h,top} + \ldots$$

150 = 1354294336587235150
−1354294336587235000

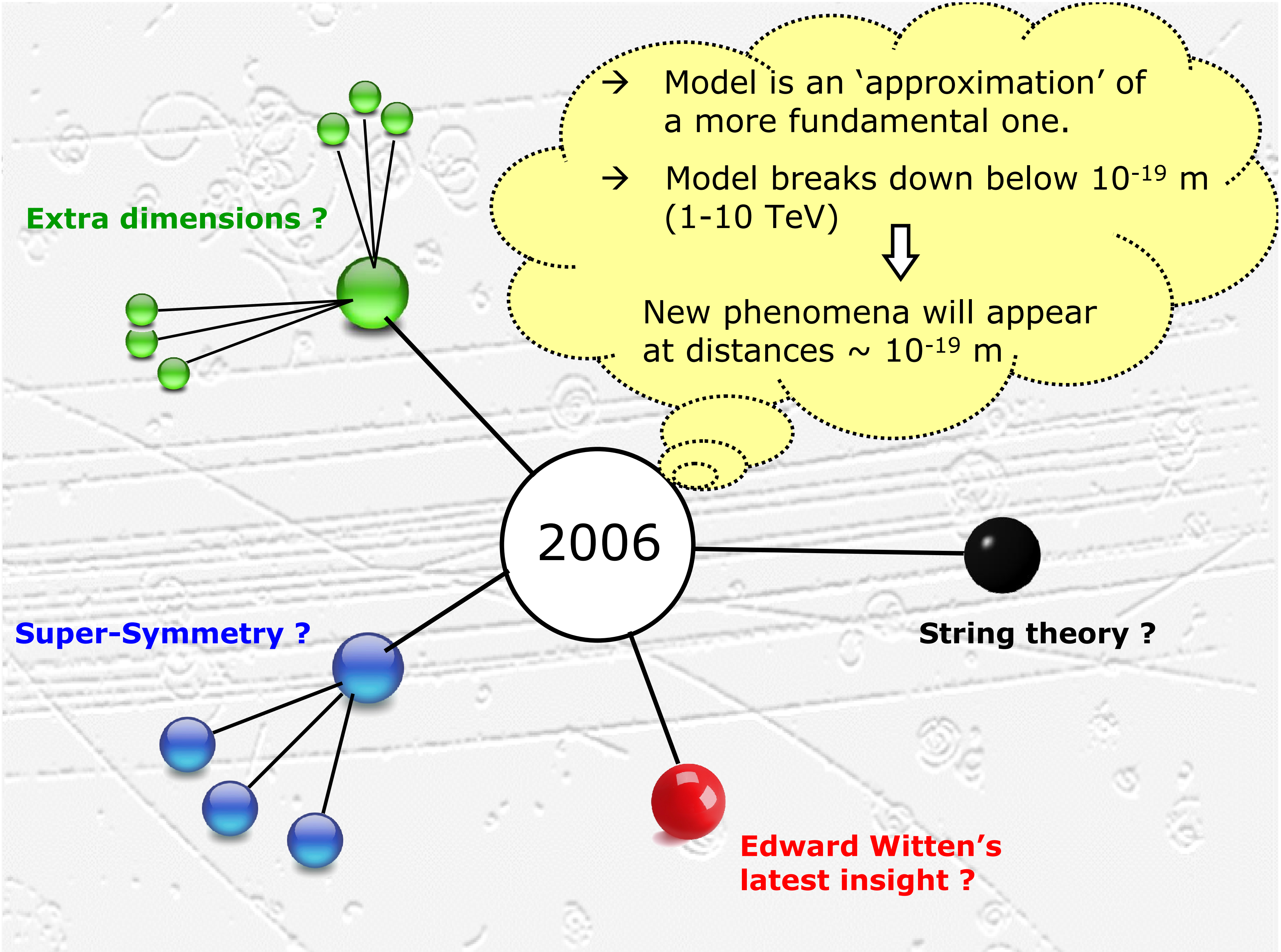
Hierarchy problem:

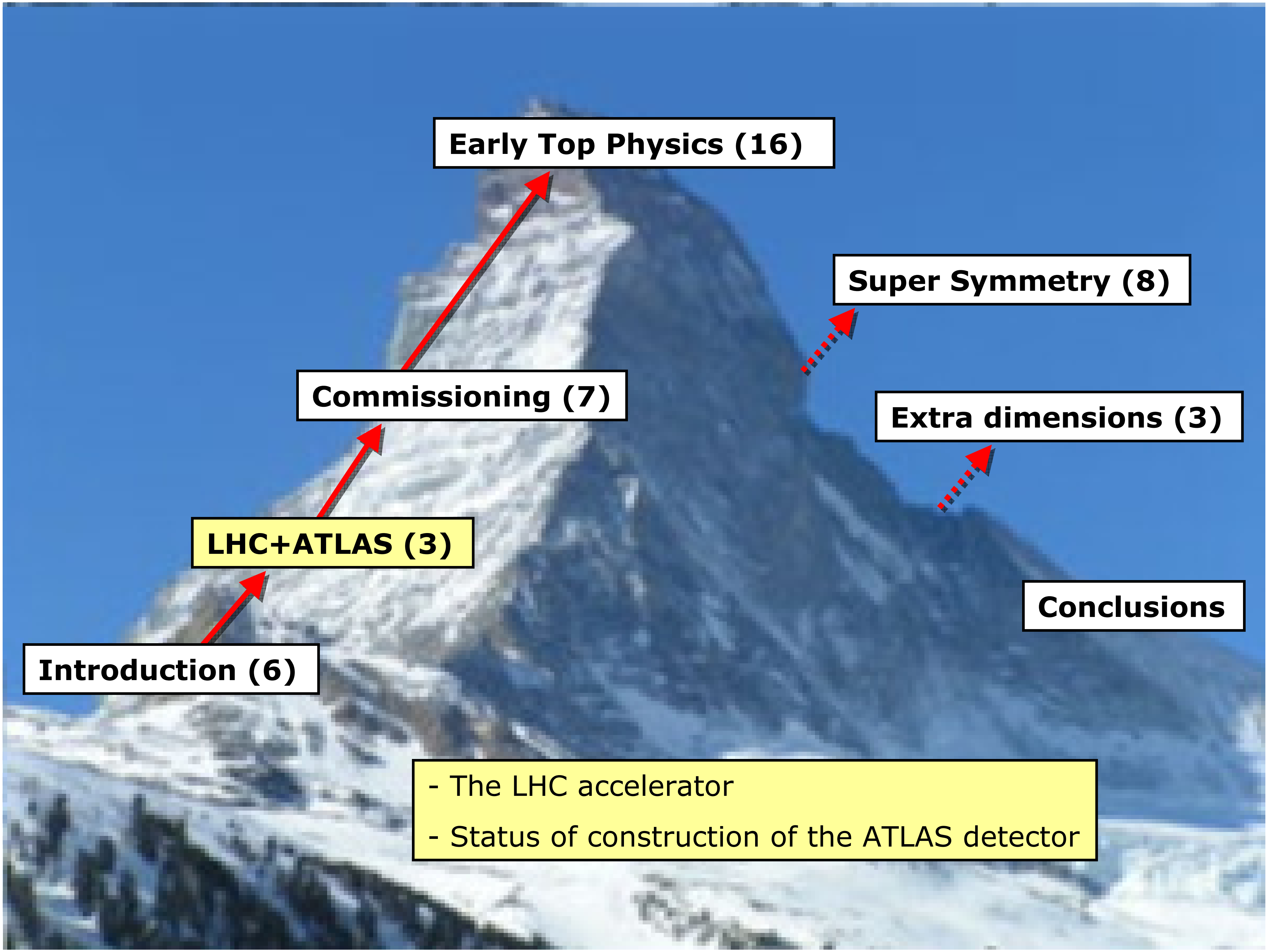
→ 'Conspiracy' to get $m_h \sim M_{EW}$ ($\ll M_{PL}$)
→ Biggest troublemaker is the top quark!

Radiative corrections from top quark



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


→ 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
2006
Extra dimensions ?
Super-Symmetry ?
String theory ?
Edward Witten's latest insight ?


Early Top Physics (16)
Super Symmetry (8)
Commissioning (7)
Extra dimensions (3)
LHC+ATLAS (3)
Conclusions
Introduction (6)
- 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} $cm^{-2}s^{-1}$

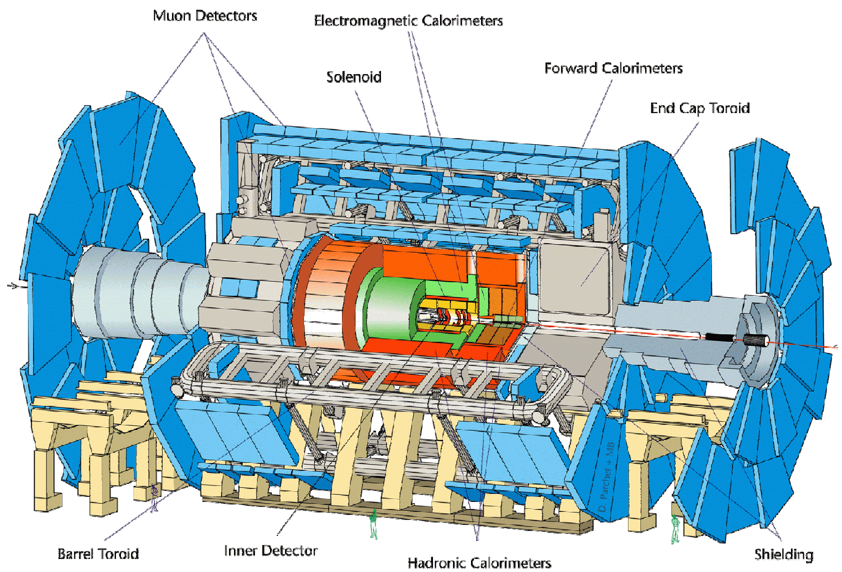
Phase 1: (low luminosity) 2007-2009
Integrated luminosity ~ 10 fb^{-1}/year
Phase 2: (high luminosity) 2009-20xx
Integrated luminosity ~ 100 fb^{-1}/year

→ Search for rare processes

7 x Tevatron

100 x LEP & Tevatron

The ATLAS detector



~1000 charged particles produced over |η|<2.5 at each crossing.

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

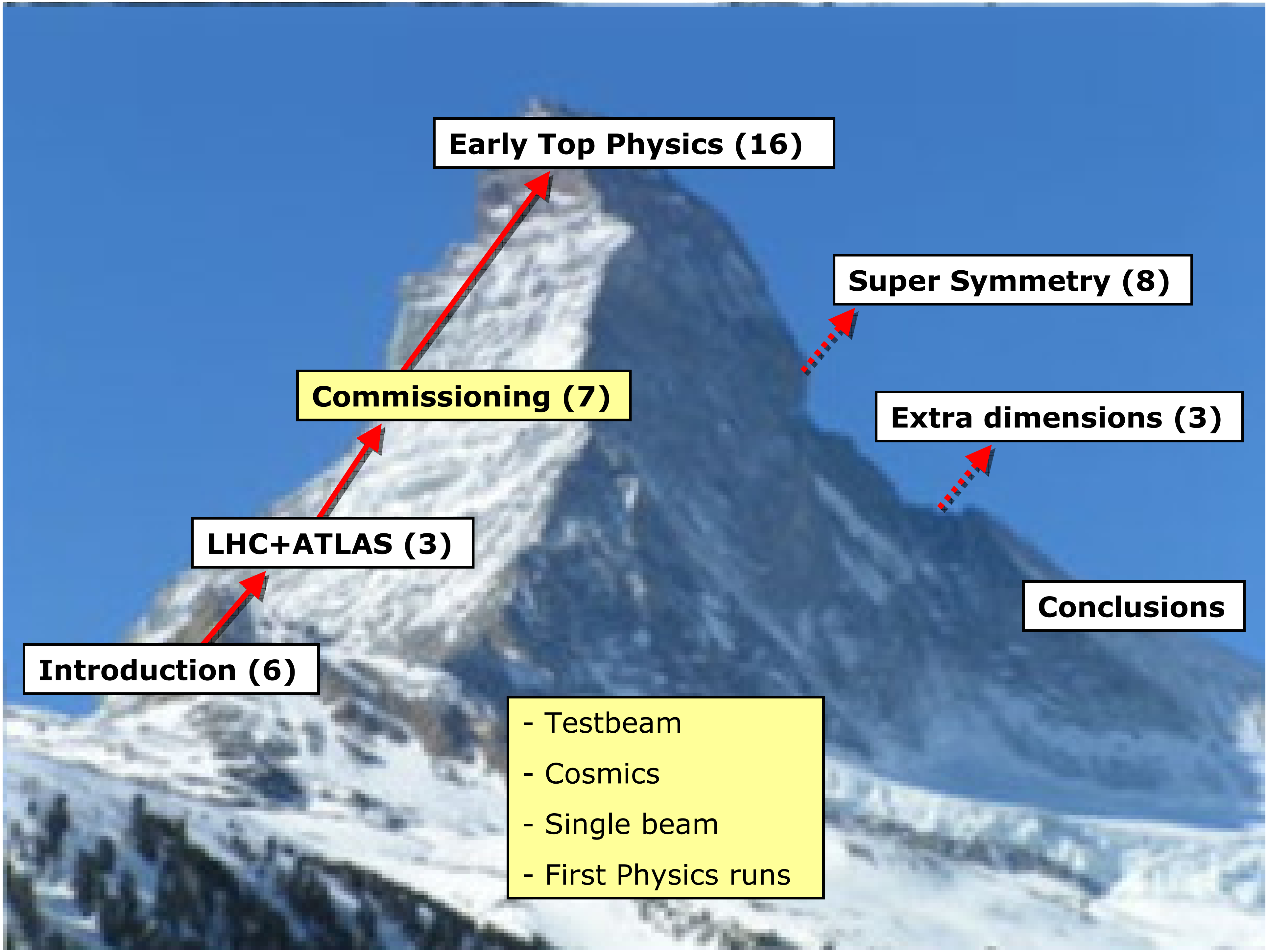
- **Tracking (|η|<2.5, B=2T) :**
  - Silicon pixels and strips
  - Transition Radiation Detector (e/π separation)
- **Calorimetry (|η|<5) :**
  - EM : Pb-LAr
  - HAD: barrel: Fe/scintillator
    forward: Cu/W-LAr
- **Muon Spectrometer (|η|<2.7) :**
  - air-core toroids with muon chambers

ATLAS floats, … but CMS doesn't

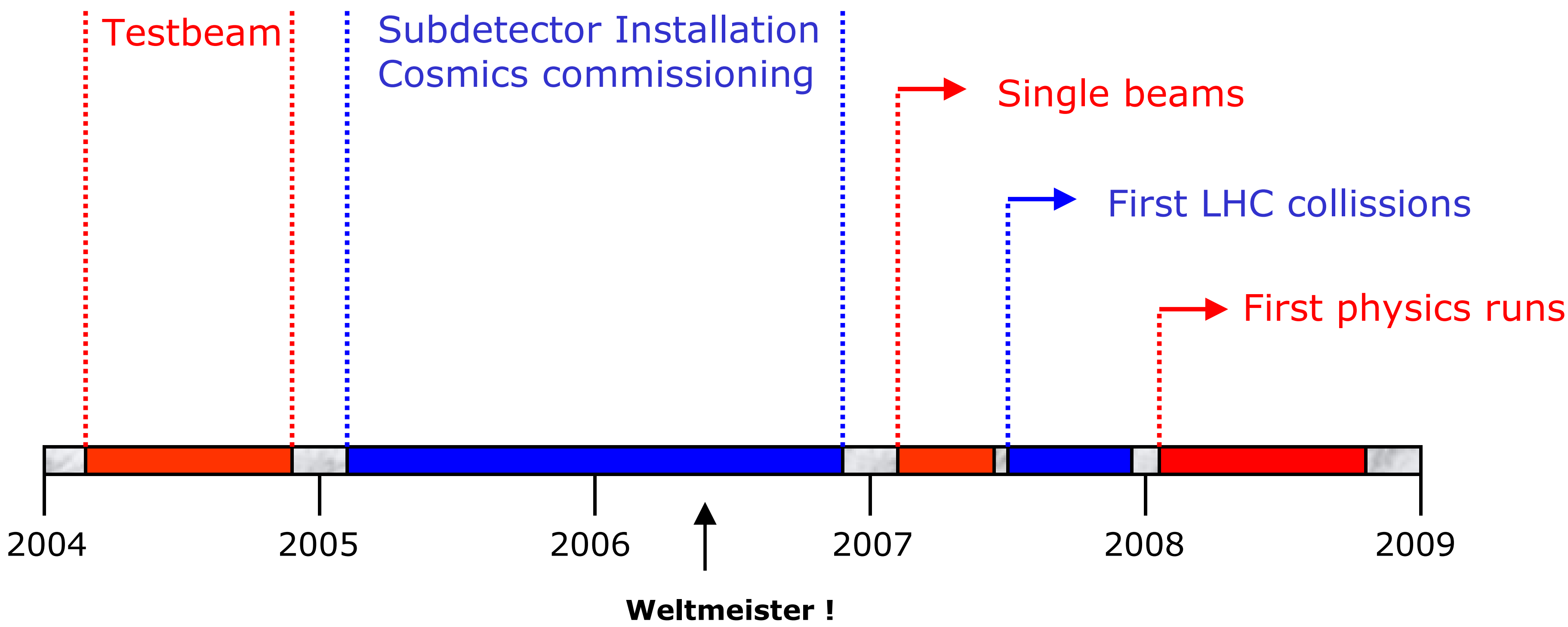
The ATLAS detector today

Last Friday 10:30 hours

http://atlaseye-webpub.web.cern.ch/atlaseye-webpub/web-sites/pages/UX15_webcams.htm


Early Top Physics (16)
Super Symmetry (8)
Commissioning (7)
Extra dimensions (3)
LHC+ATLAS (3)
Conclusions
Introduction (6)
- Testbeam
- Cosmics
- Single beam
- First Physics runs

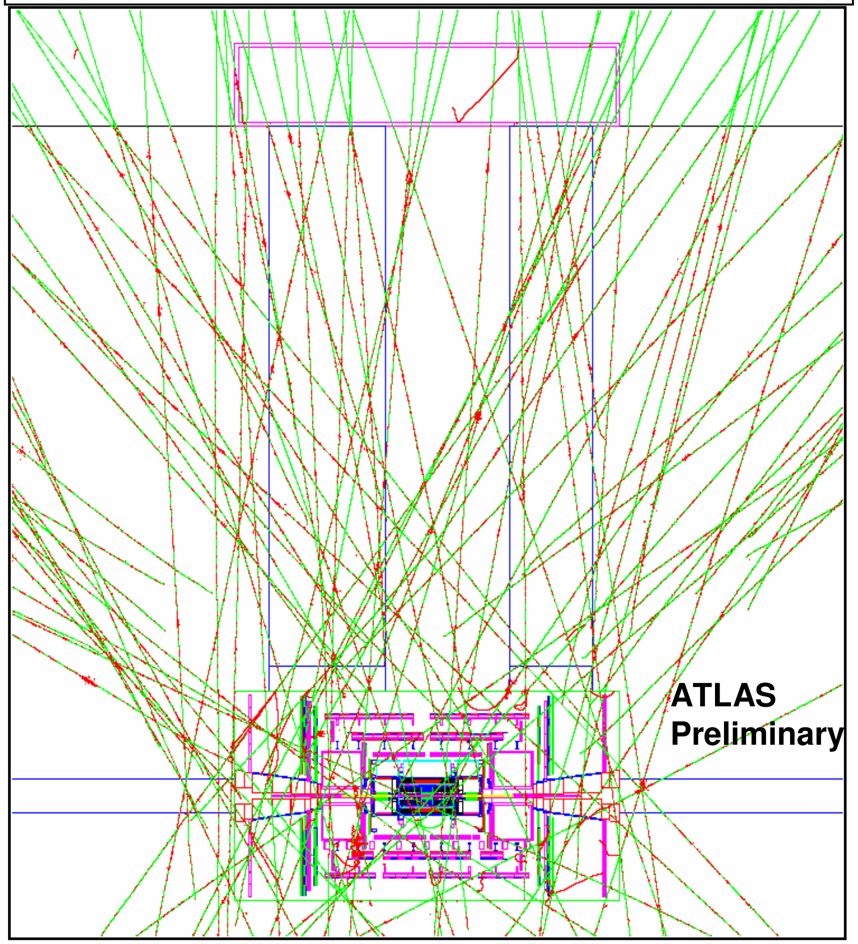
Time-line for LHC machine and ATLAS preparation

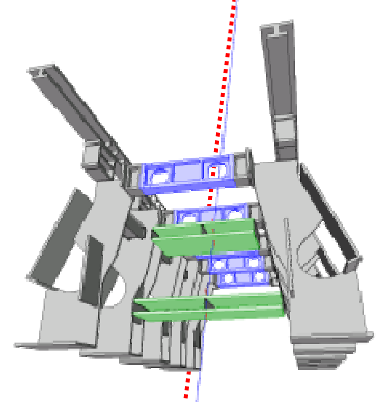


Muons in the ATLAS cavern

~ 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

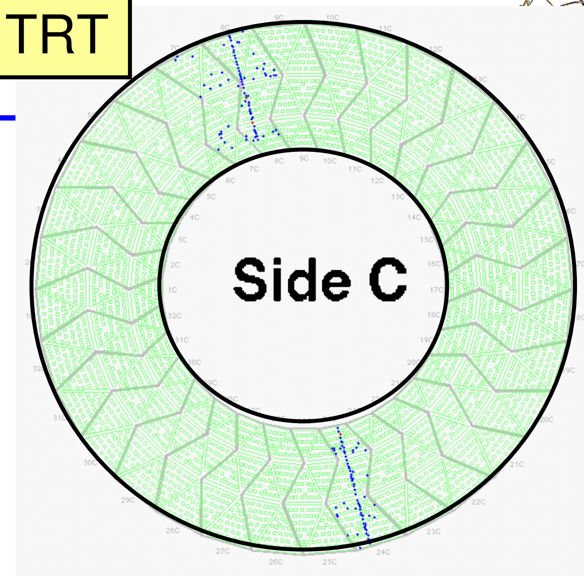
Cosmics : tracks in Pixels+SCT+TRT

- 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

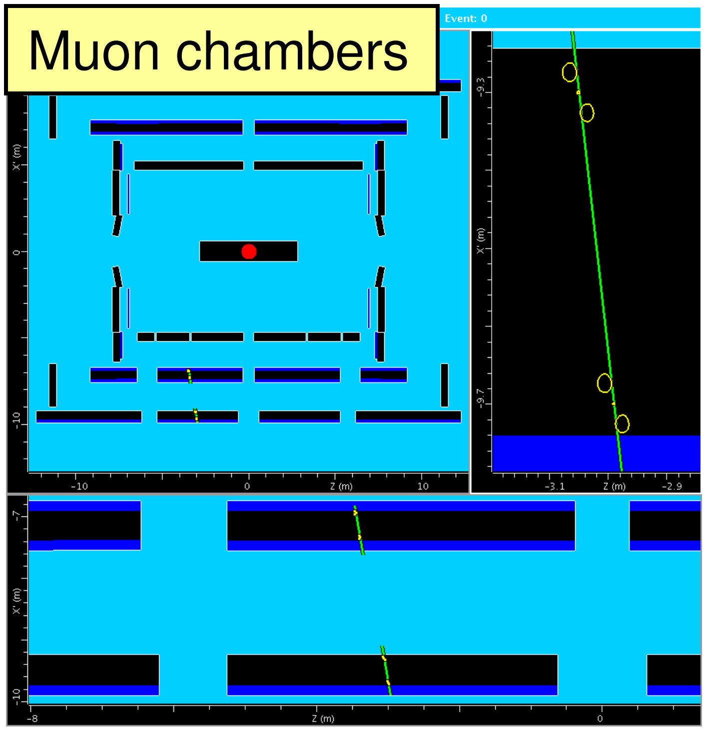
We can reconstruct these muons!

Muons seen by individual sub-detectors
(ATLAS' first events)

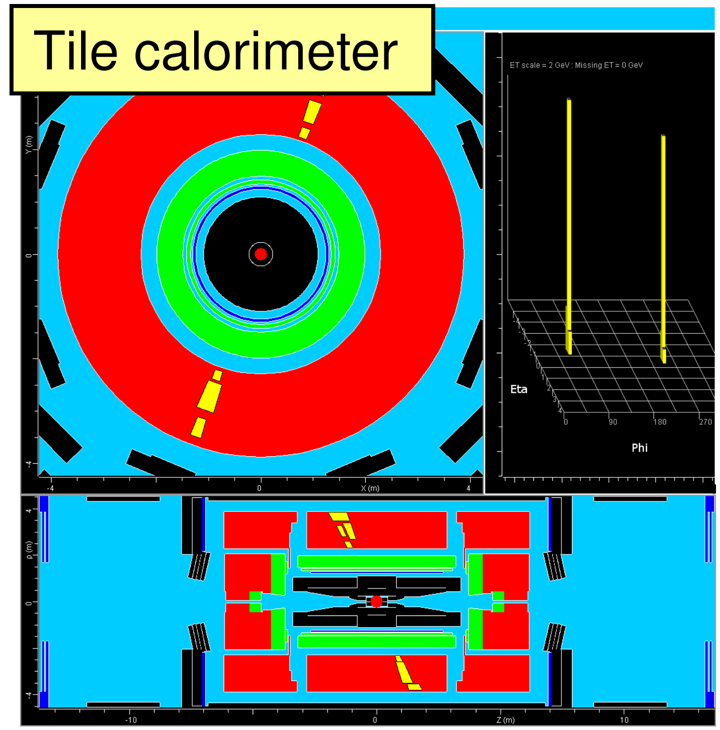
TRT



Muon chambers



Tile calorimeter

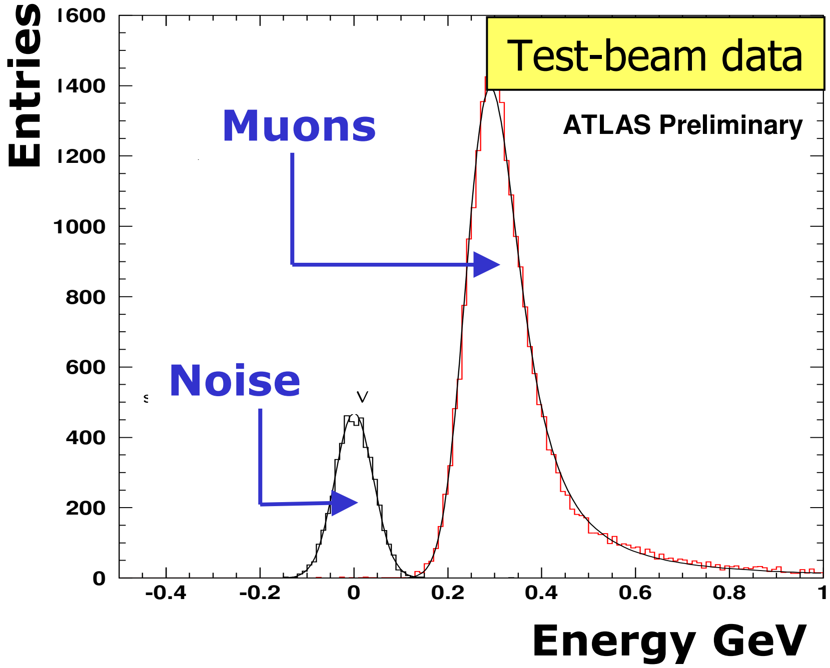


Using cosmics to calibrate the EM Calorimeter

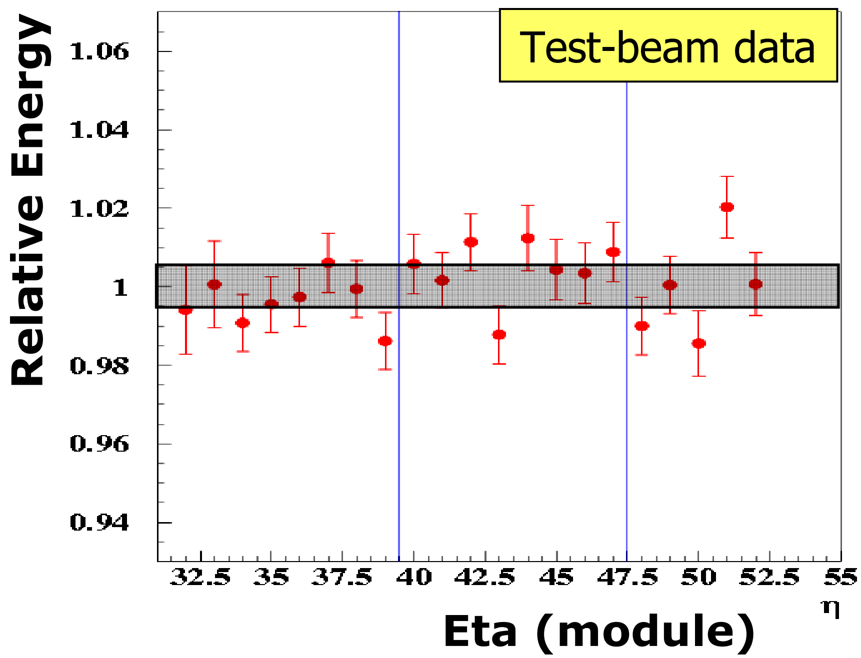
What can we do with 100 days of cosmics in the ECAL ?

In 3 months (50% eff.): 100 muons/cell
(over |η| <=1 and 70 % of φ coverage)

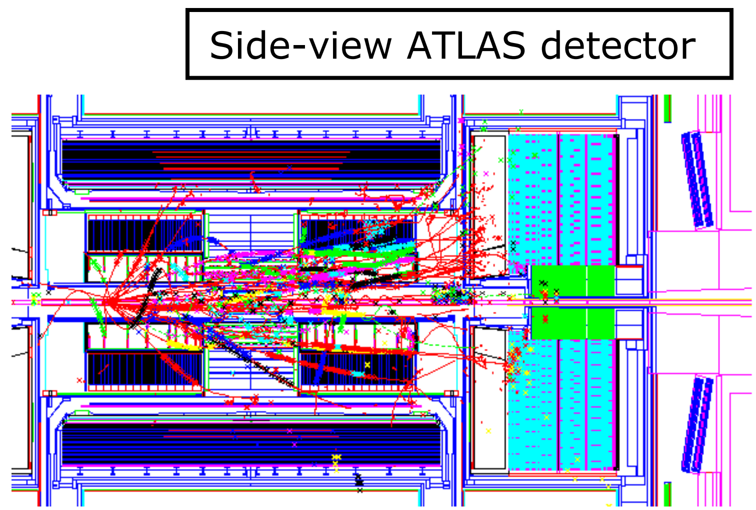
A muon deposit ~ 300 MeV in ECAL cell (S/N~ 7)



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



Single beams in LHC

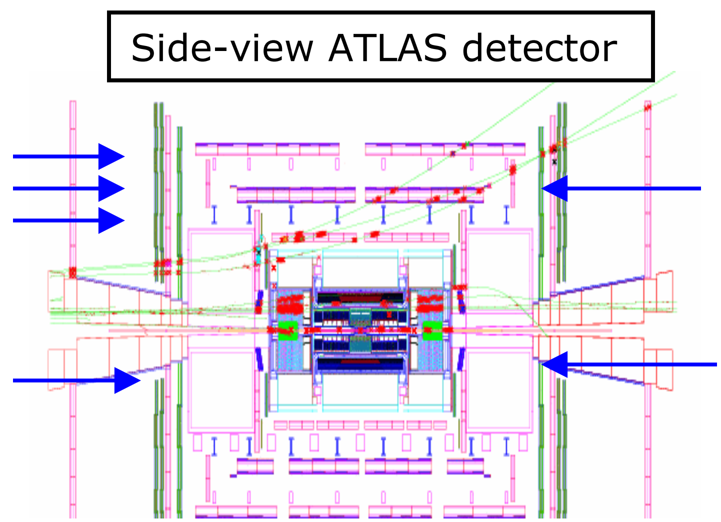


Beam gas:

- 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

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 Rφ	Generic tracks, isol. muons, $Z \rightarrow \mu^+\mu^-$

Plan-de-campagne during first year

First year:

A new detector AND *a new energy regime*

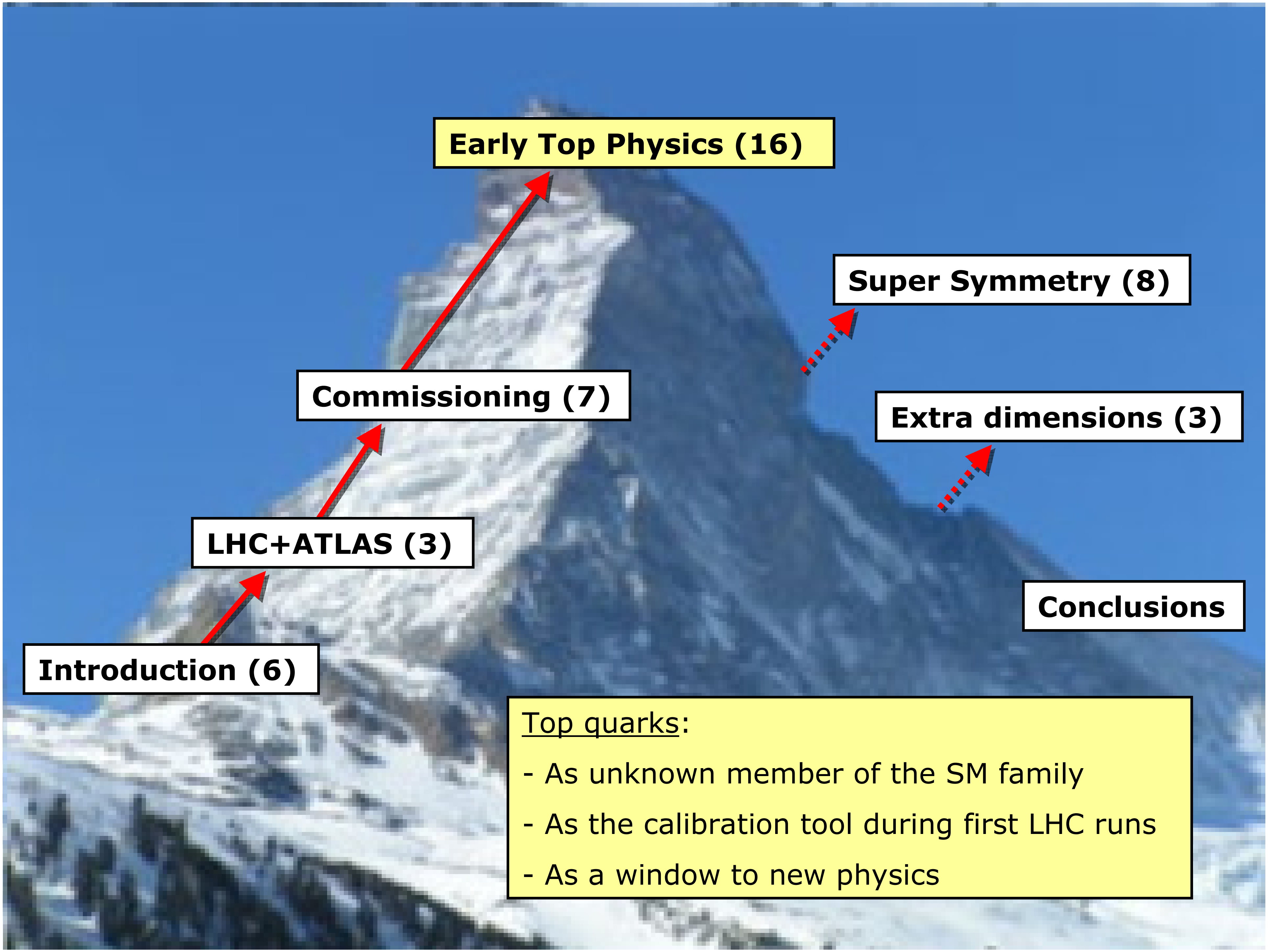
0 Understand ATLAS using cosmics

1 Understand SM+ATLAS in *simple* topolgies

2 Understand SM+ATLAS in *complex* topologies

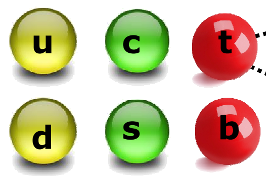
3 Look for *new physics* in ATLAS at 14 TeV

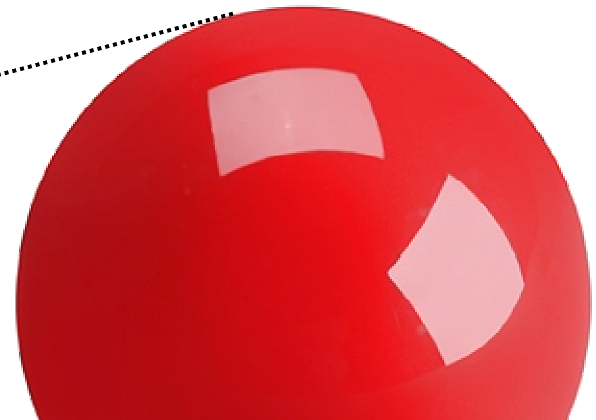
Process	#events 10 fb^{-1}
$b\bar{b}$	10^{12}
$W \rightarrow e\nu$ (1)	10^{8}
$Z \rightarrow e^{+}e^{-}/\mu^{+}\mu^{-}$	10^{7}
$t\bar{t}$ (2)	10^{7}
Min. bias	10^{7}
QCD jets $P_T > 150$ GeV	10^{7}
h (m_h = 130 GeV)	10^{5}
$\tilde{g}\tilde{g}$ ($m_{\tilde{g}}$ = 1 TeV) (3)	10^{4}


Early Top Physics (16)
Super Symmetry (8)
Commissioning (7)
Extra dimensions (3)
LHC+ATLAS (3)
Conclusions
Introduction (6)
Top quarks:
- As unknown member of the SM family
- As the calibration tool during first LHC runs
- As a window to new physics

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

We still know little about the top quark





- Mass	precision <2%
- 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	??

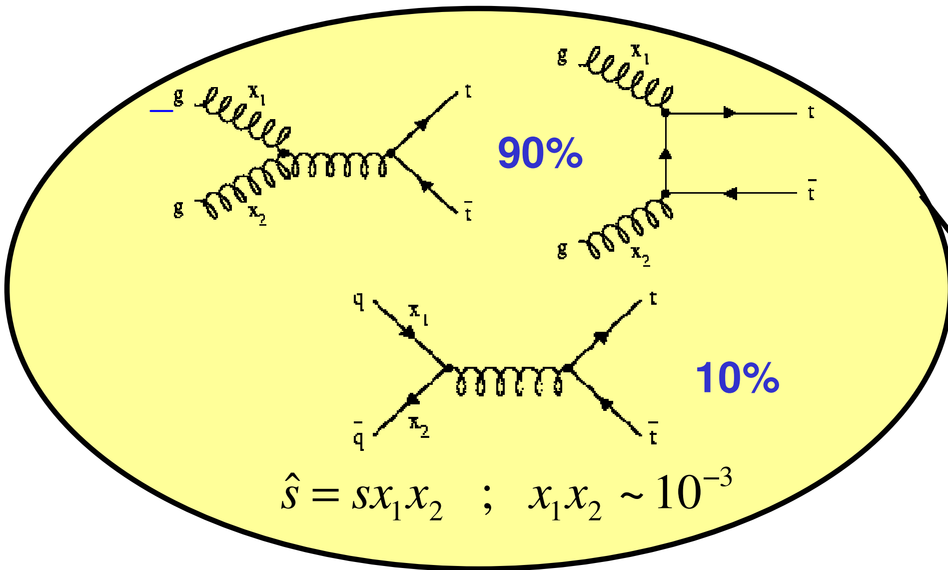
- The LHC offers an opportunity for **precision measurements**

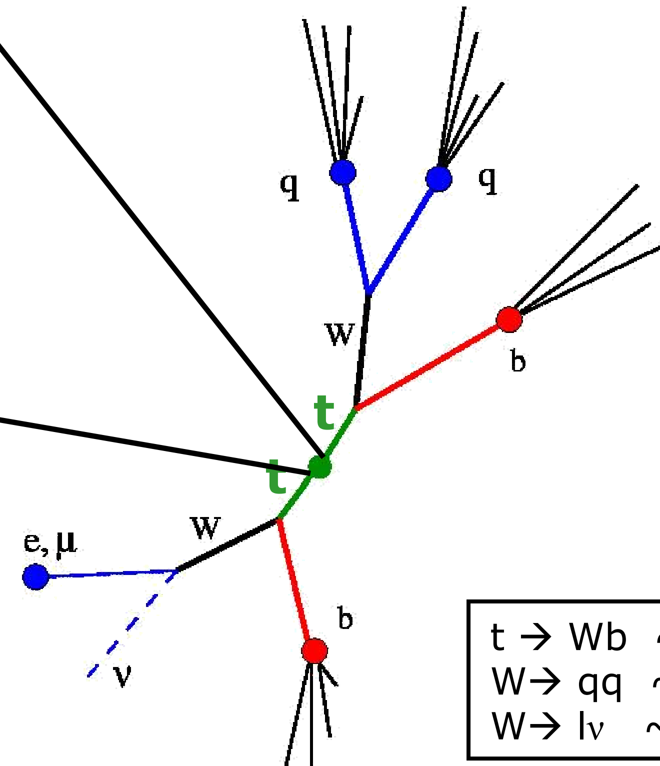
Top quark production at the LHC

<u>Production</u>: σ_{tt}(LHC) ~ 830 ± 100 pb

→ 1 tt-event per second

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





t → Wb ~ 1
W→ qq ~ 2/3
W→ lν ~ 1/3

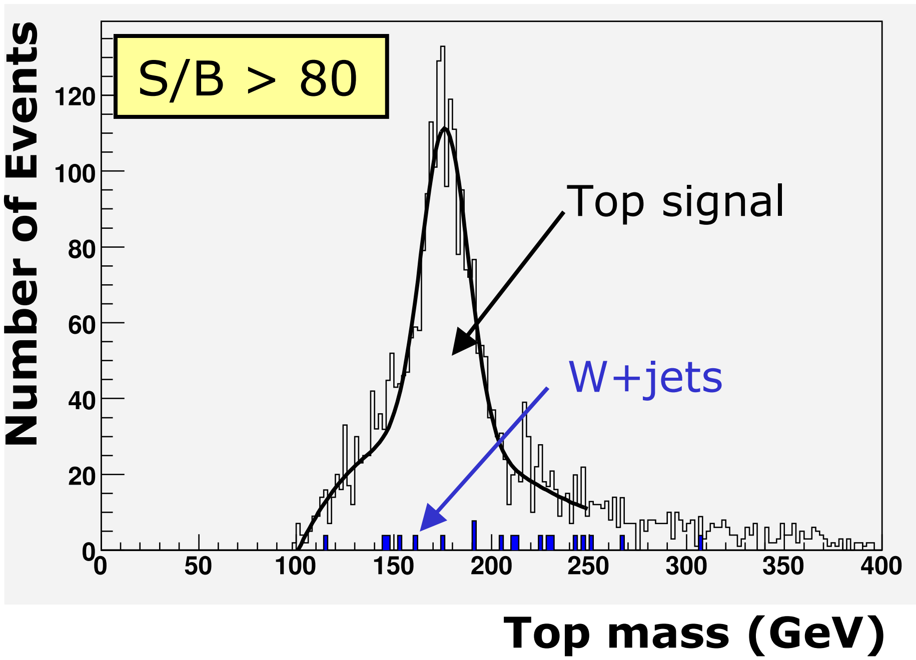
<u>Final states</u>:

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

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/%**
Final State Radiation	**0.5**
Light jet scale (±1%)	**0.2**
b-quark fragmentation	**0.1**
Initial State Radiation	**0.1**
Combinatorial bkg	**0.1**
TOTAL: Stat ⊕ Syst	**1.3**

hep-ex/0403021

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
4 jets(R=0.4)	P_T > 40 GeV

Selection efficiency = 5.3%

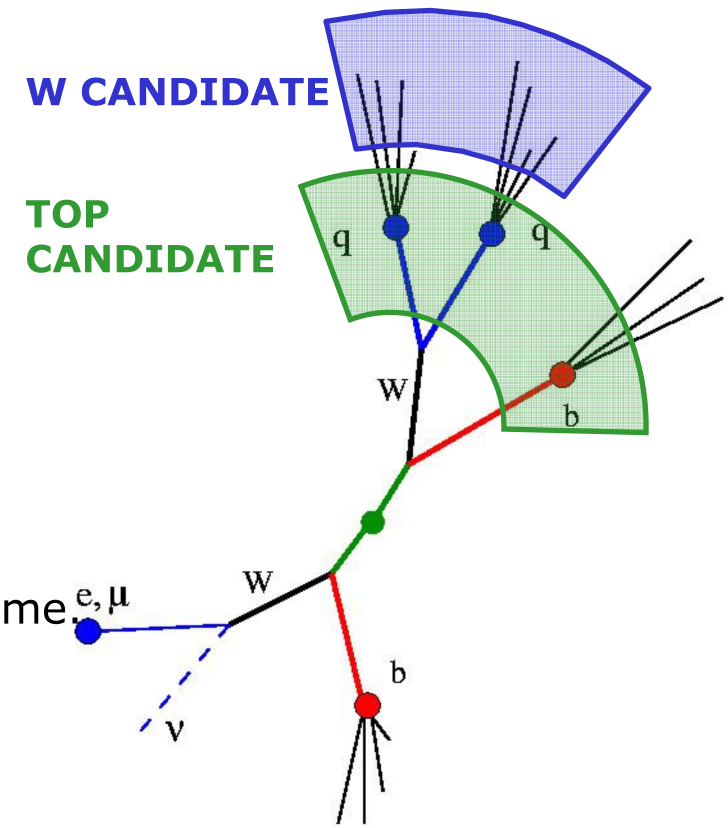
- Assign jets to W, top decays

1) Hadronic top:

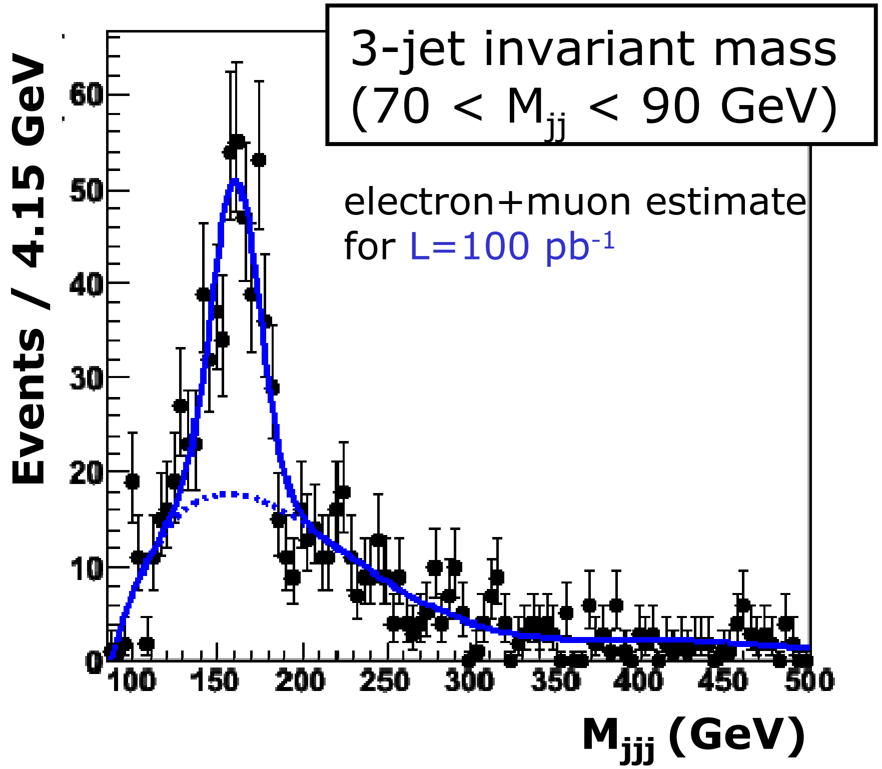
Three jets with highest vector-sum p_T as the decay products of the top

2) W boson:

Two jets in hadronic top with highest momentum. in reconstructed jjj C.M. frame.



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

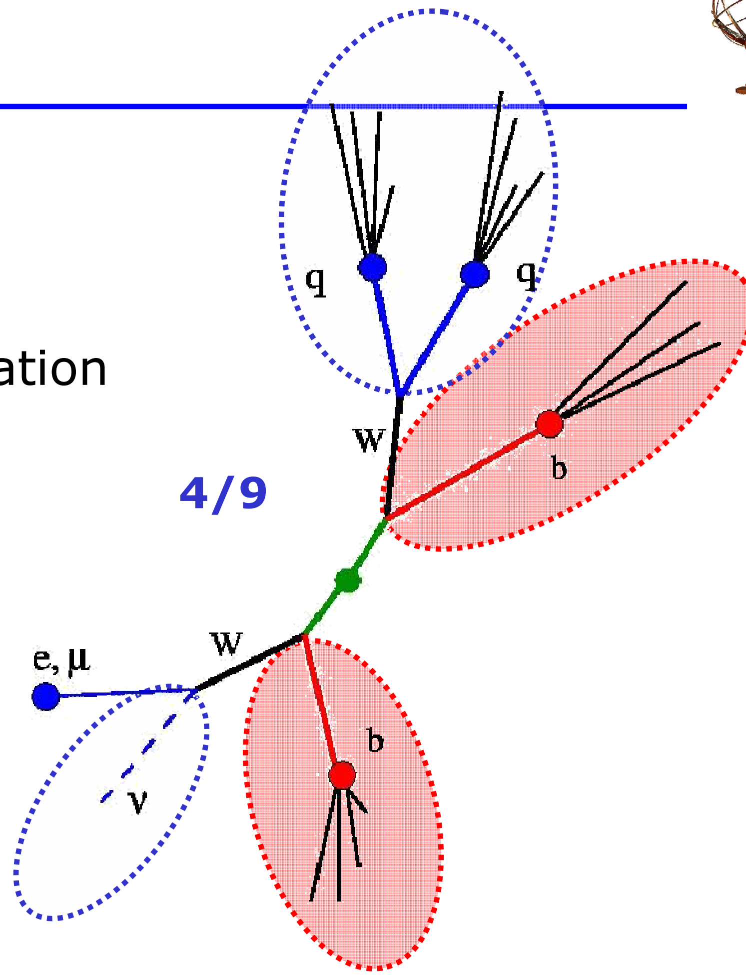


100 fb^{-1} is a few days of nominal low-lumi LHC operation

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



A candle for complex topologies:

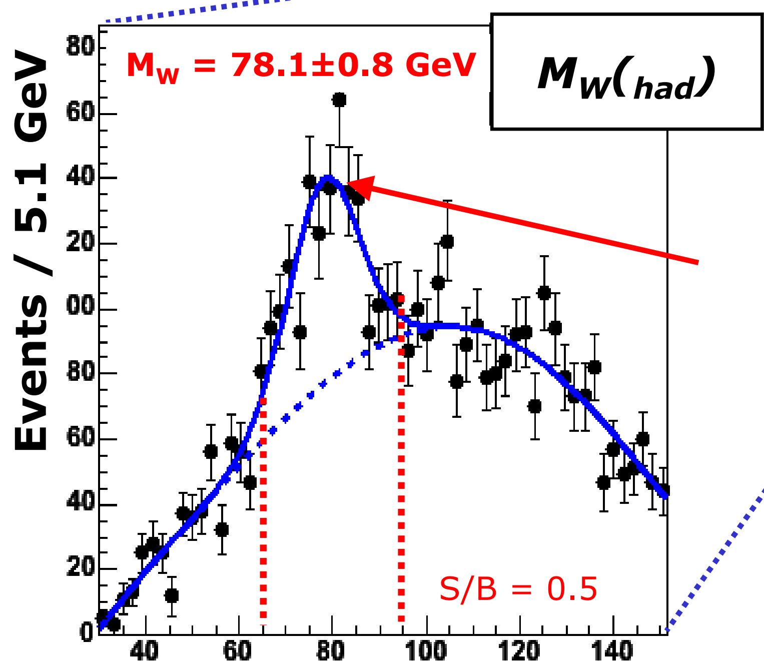
- Calibrate light jet energy scale
- Calibrate missing E_T
- Obtain enriched b-jet sample
- Leptons & Trigger

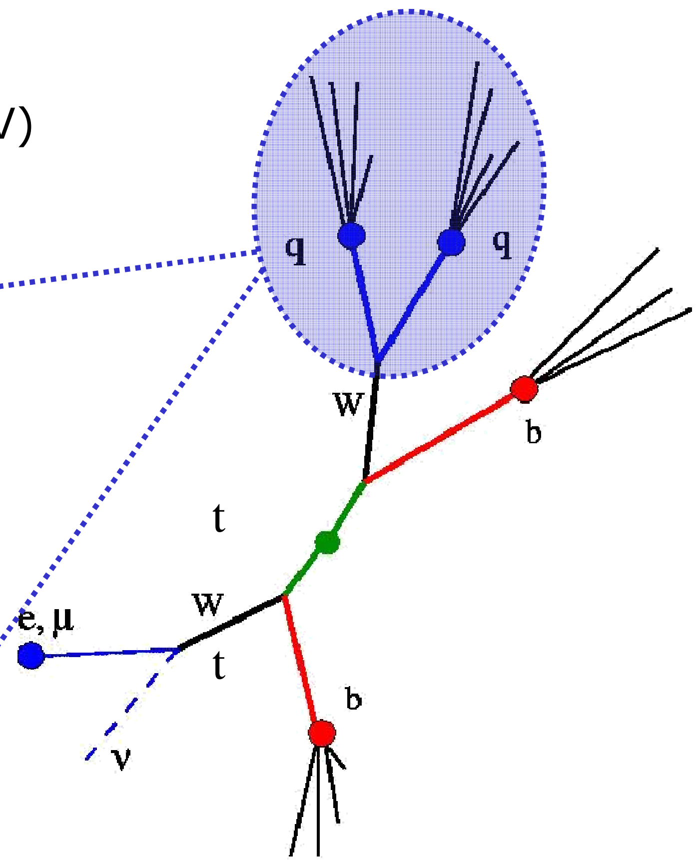
Note the 4 candles:

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

- (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

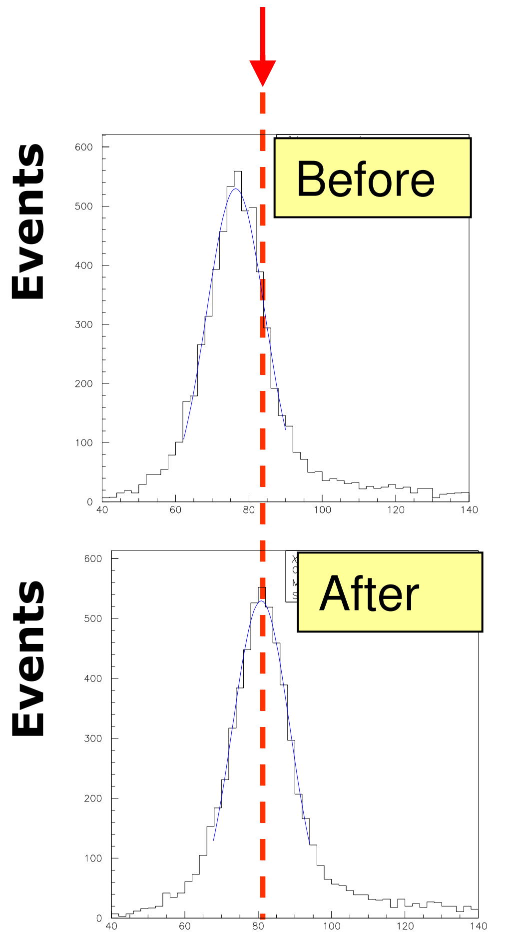




Translate jet 4-vectors to parton 4-vectors

Jet energy scale (using hadronic W-boson)

M_W (PDG) = 80.425 ± 0.038 GeV



Di-jet mass(GeV)

Use the known W-boson mass
to calibrate the Jet energy scale

$$M_{jj} = \sqrt{2E_{j1}E_{j2}(1-\cos\theta_{j1j2})} = M_W$$

$E_{jet} = \alpha \times E_{parton}$

Rescale jet energy and angles, with correction $\alpha(P_T,\eta)$ such that mass of 2 partons gives M_W

Pro:

- Large event sample
- Easy to trigger
- Small physics backgrounds

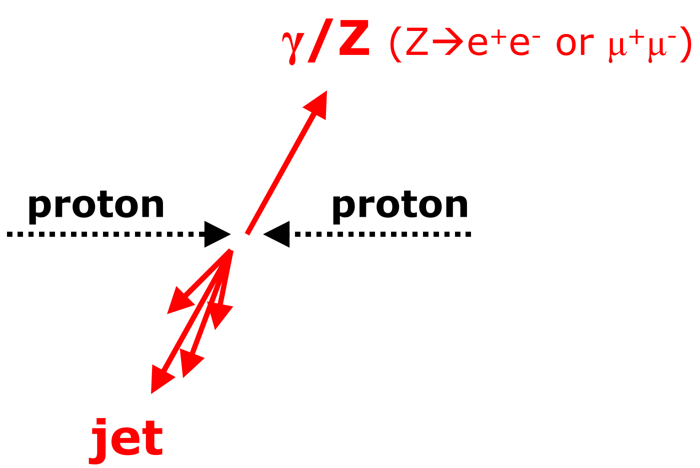
Con:

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

Jet Energy Scale (Alternative calibration method)

Use the p_T balance between Z/γ and highest p_T-jet

Rate per hour	γ+jet	Z+jet
P_T > 20 GeV	6×10^5	--
P_T > 50 GeV	7×10^3	2×10^3



Pro:

- Enlarged P_T and η range
- Includes 6% of b-jets
- Large statistics

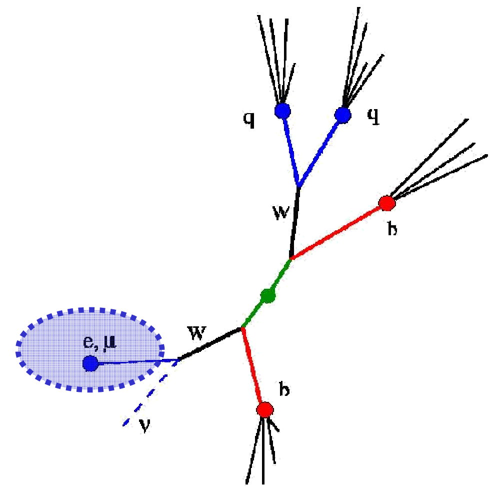
Con:

- Biases from selection / ISR and Z/γ background
- Statistics at large P_T limited
- Pre-scaled trigger

Measuring lepton trigger efficiency from data

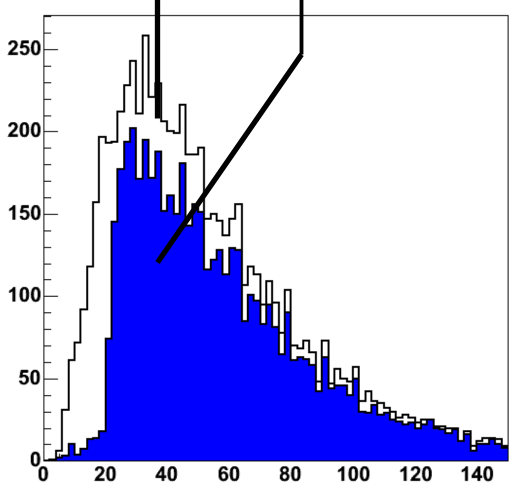
- (2) e/γ reconstruction and trigger

- Triggers: 2E15i, E25i, E60
- Lepton reconstruction in 'busy' events

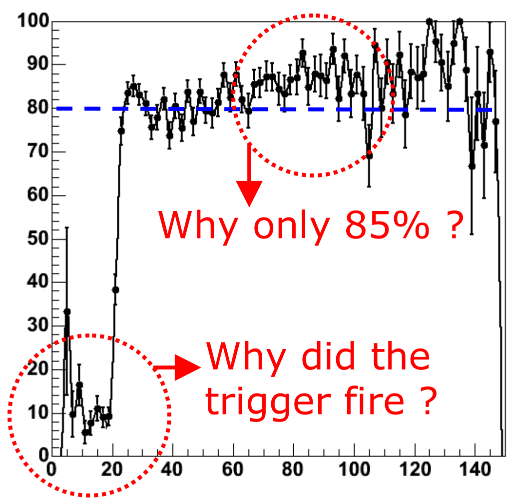


White: reconstructed electons

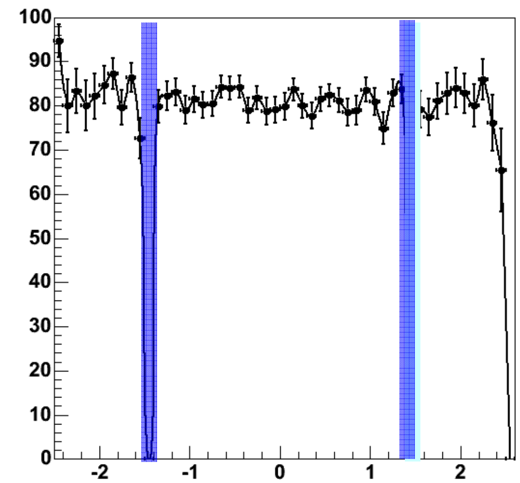
Blue: reconstructed electons + trigger



Electron p_T (GeV)



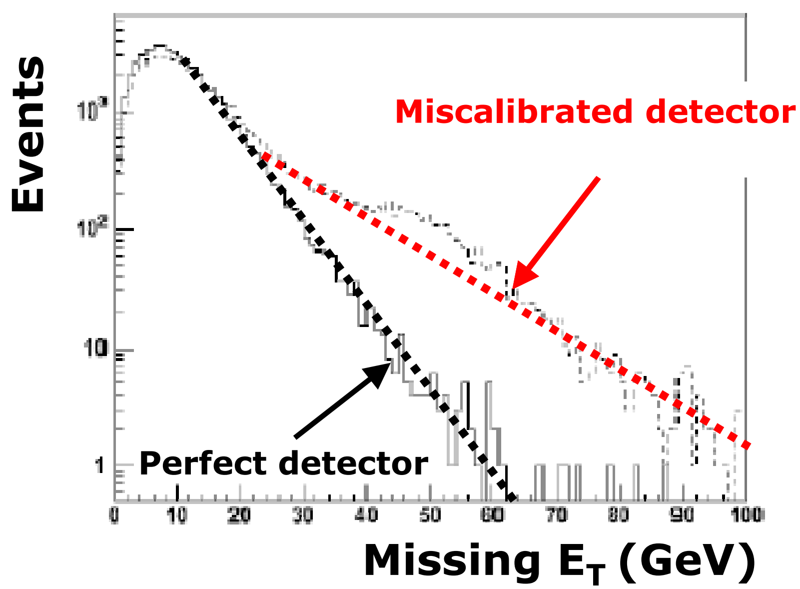
e/γ trig eff (pT)

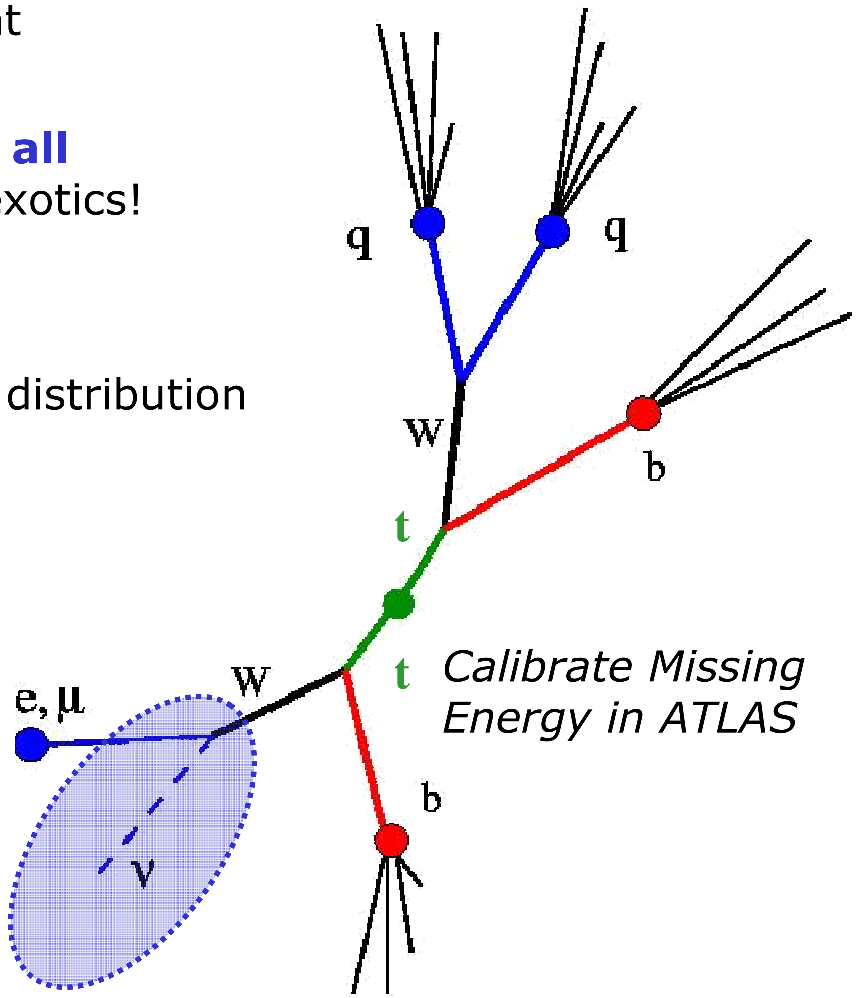


e/ γ trig eff (η)

- (3) 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

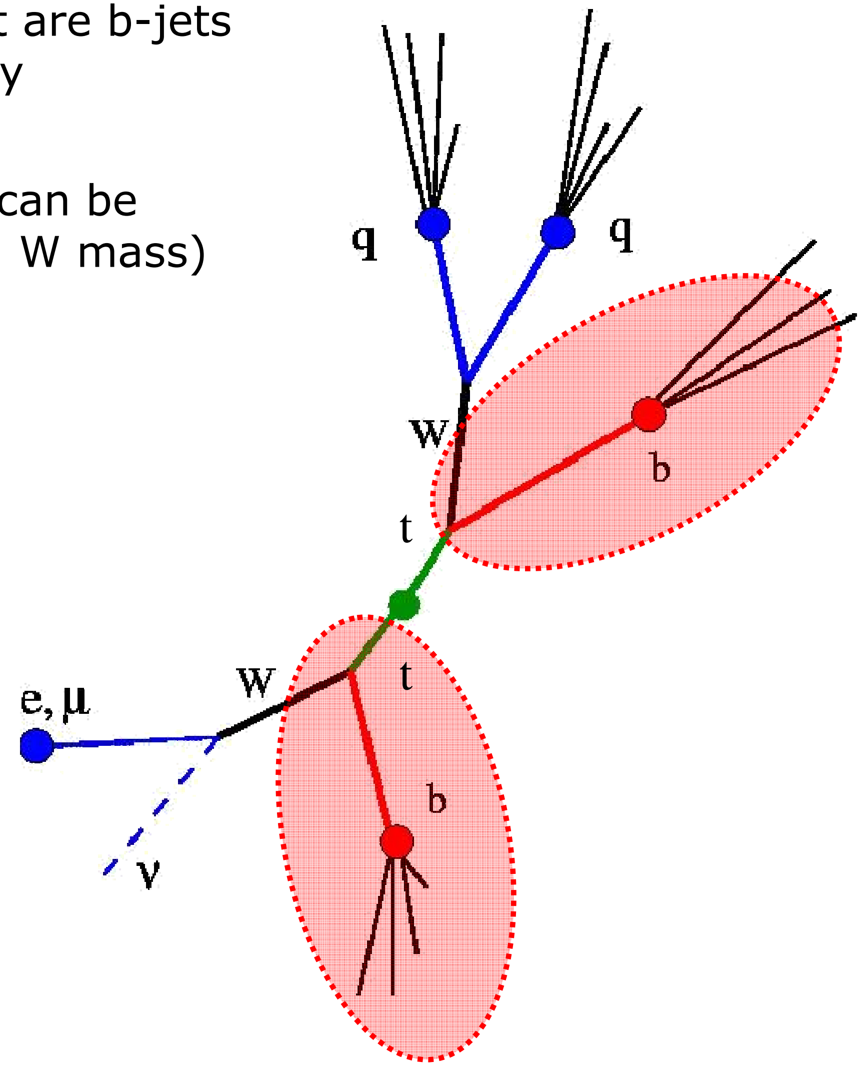




Calibrate Missing Energy in ATLAS

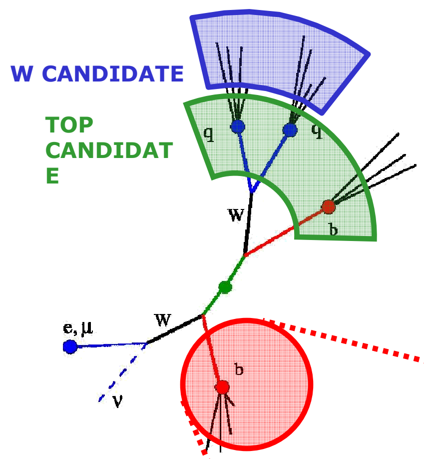
Using top quark events to obtain a clean sample of b-quarks

- (4) 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

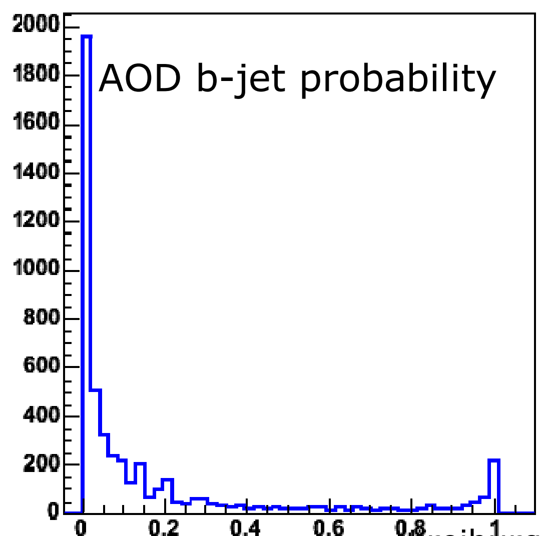
Using top quark events to get clean sample of b-quarks



- Use of ttbar sample to provide *b* enriched jet sample
  - Cut on M_W(had) and M_{top}(had)
  - Look at b-jet prob for 4th jet
    (must be b-jet if all assignments are correct)

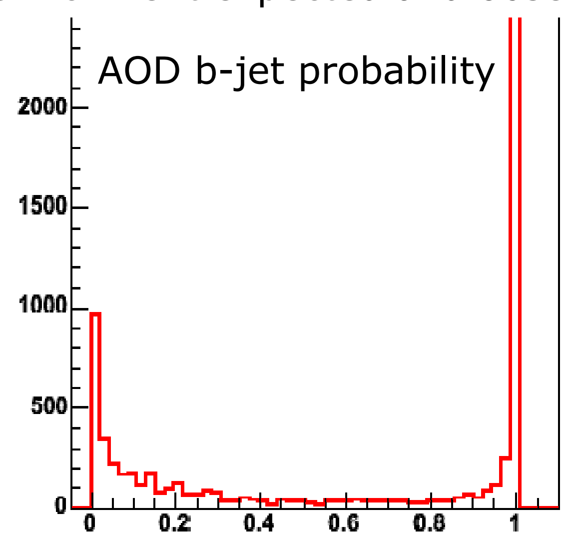
W+jets (background)

'random jet',
no b-enhancement expected



ttbar (signal)

'always b jet if all jet assignment are OK'
B-enrichment expected and observed



Clear enhancement observed!

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***

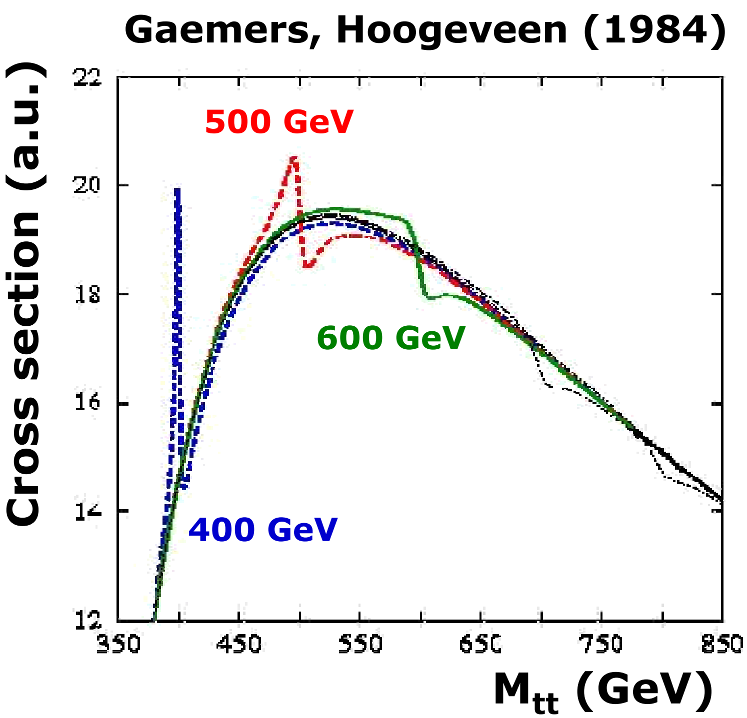
Top quarks as a window to new physics

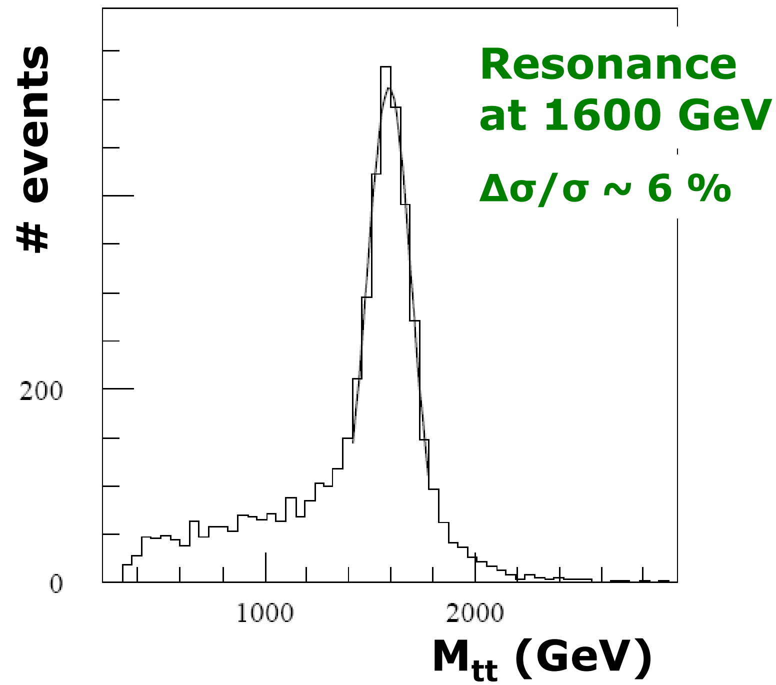
- Structure in M_{tt}

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

- Resonances in M_{tt}

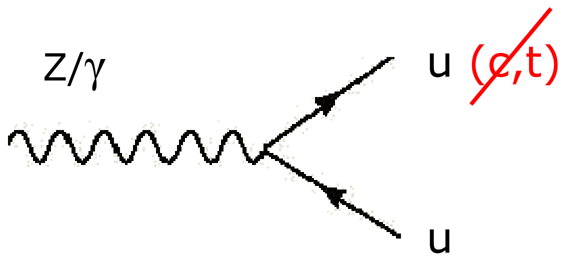
$$\underbrace{pp \rightarrow X \rightarrow t\bar{t}}_{Z', Z_H, G^{(1)}, \text{SUSY}, ?}$$





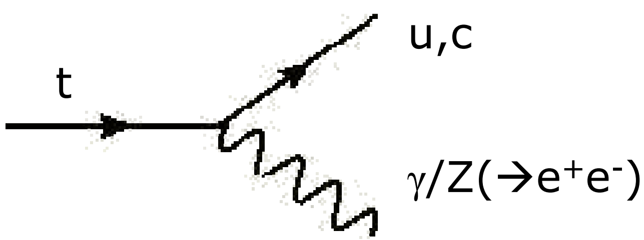
Flavour changing neutral currents

- No FCNC in SM:



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

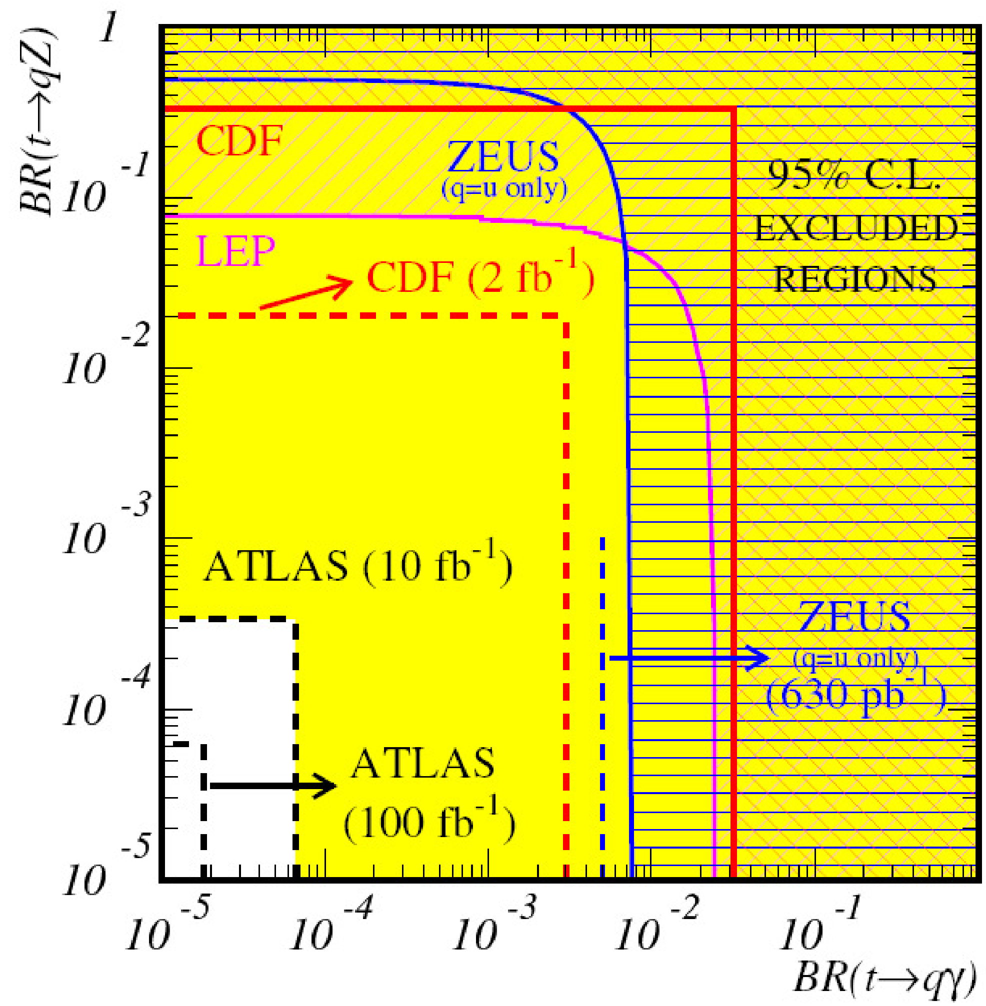
- Look for FCNC in top decays

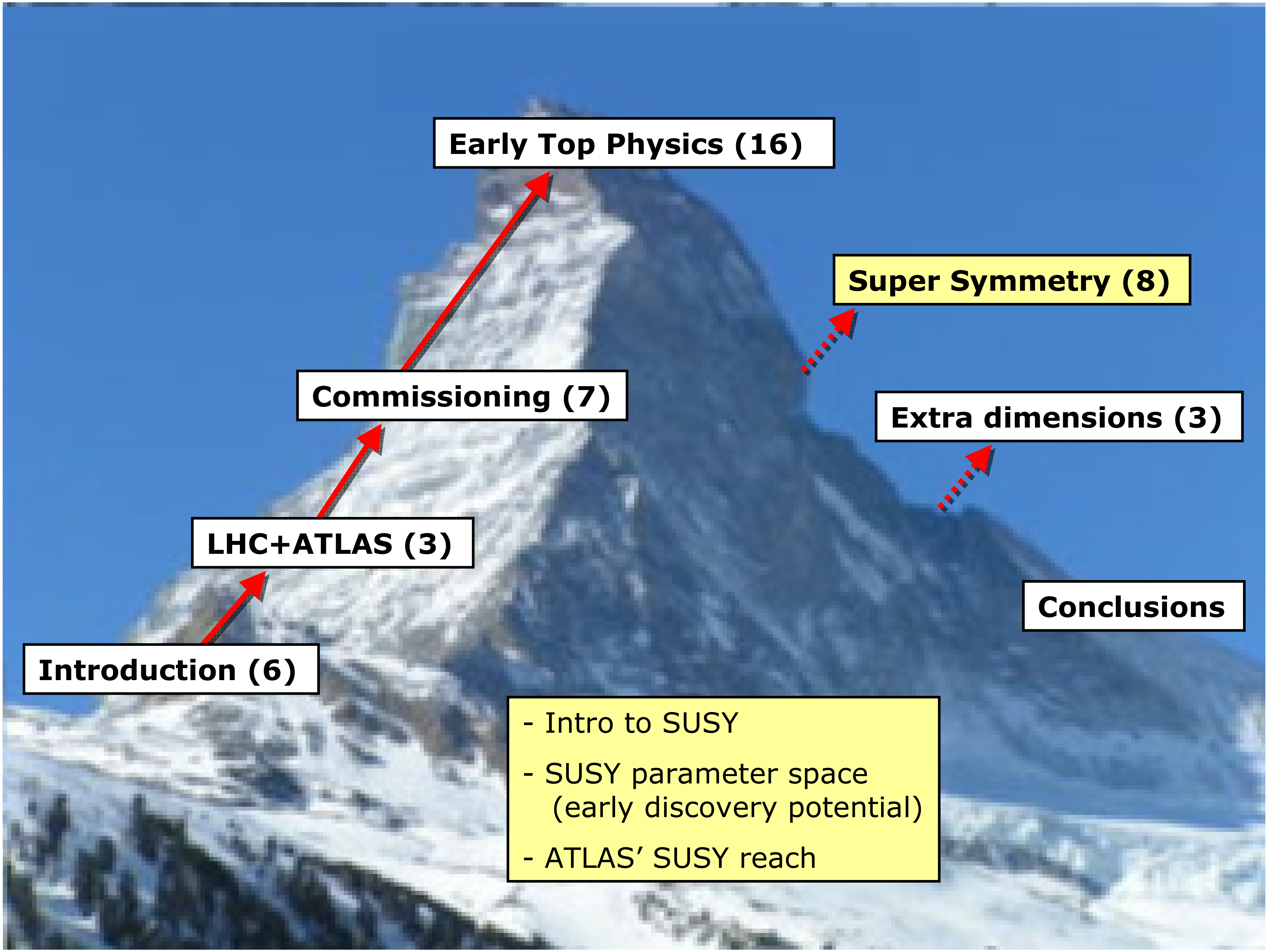


Expected limits on FCNC for ATLAS:

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

ATLAS 5σ sensitivity



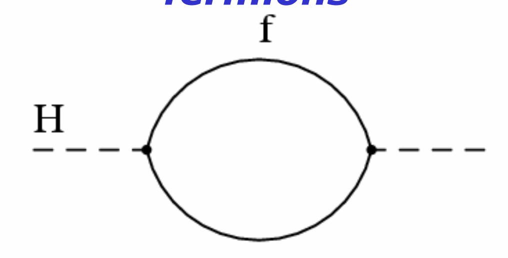

Early Top Physics (16)
Super Symmetry (8)
Commissioning (7)
Extra dimensions (3)
LHC+ATLAS (3)
Conclusions
Introduction (6)
- Intro to SUSY
- SUSY parameter space
(early discovery potential)
- ATLAS' SUSY reach

Fixing the hierarchy problem

SUSY: solves the hierarchy problem:

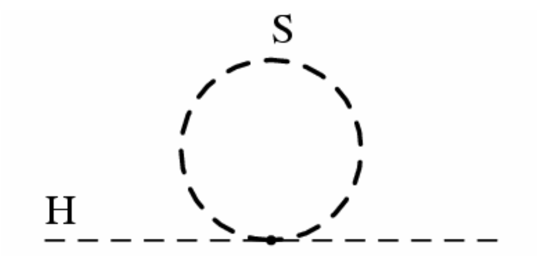
All ΔM_h terms between particles and super-partners magically cancel

fermions



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

Notice minus sign
Note 2 bosonic partners per fermion



bosons

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

- If masses SUSY partners of SM particles (sparticles) not too heavy
  → 'natural' solution to Hierarchy problem

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

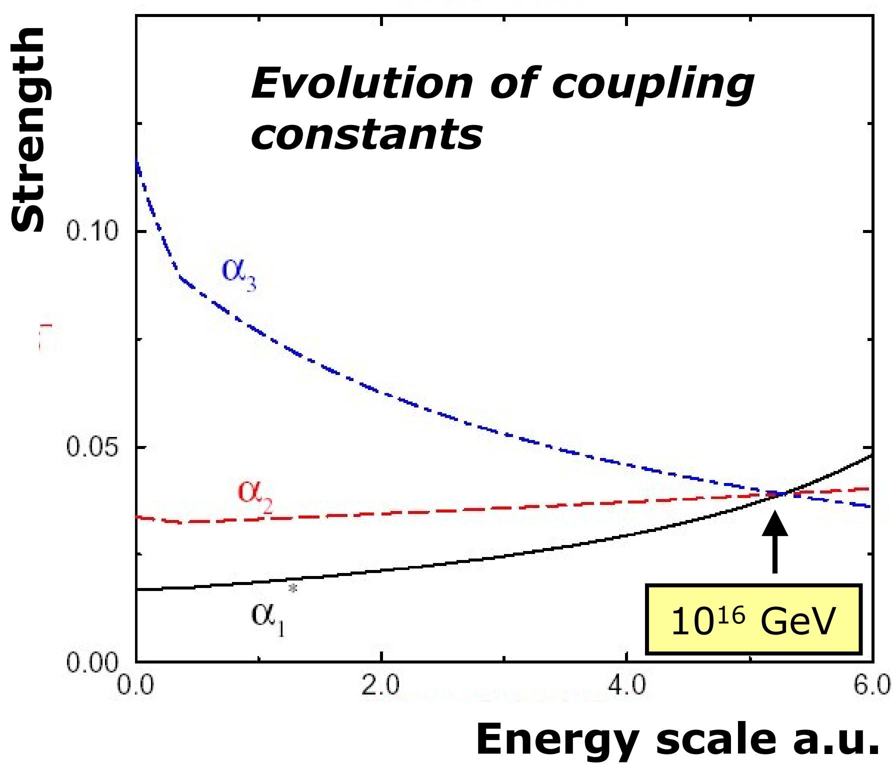
Assumptions (mSUGRA):

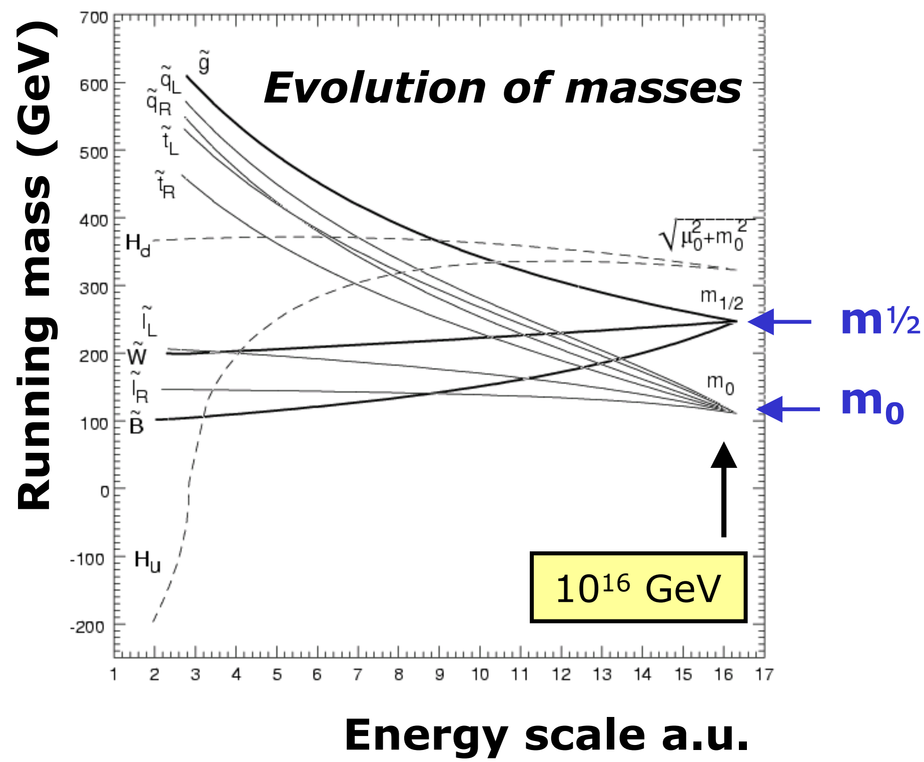
→ R-parity is conserved
There is a (stable) Lightest Supersymmetric Particle: LSP

→ 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

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



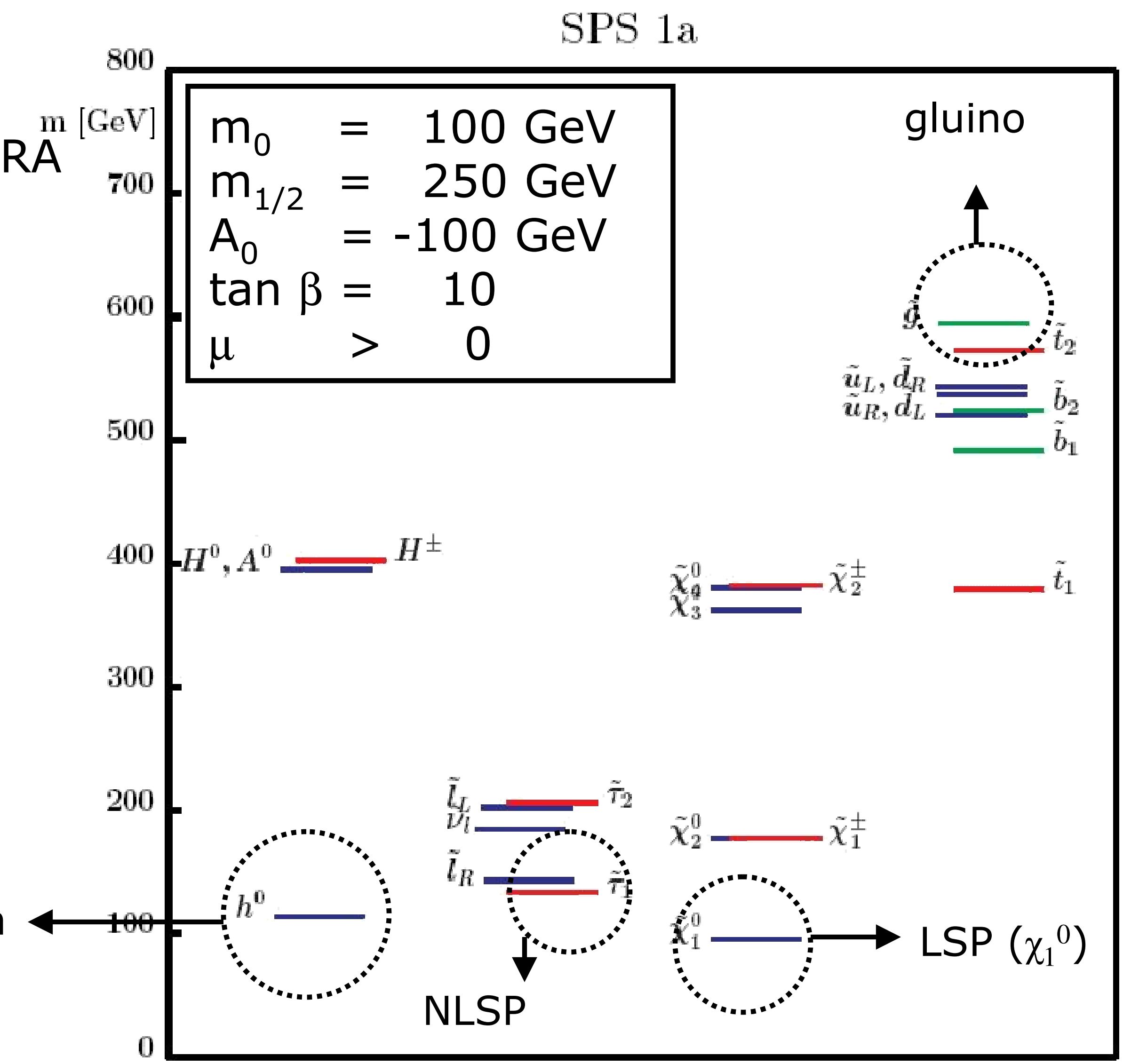


Particle (mass) spectrum predicted for each mSUGRA parameter point

Not all mSUGRA points (mass spectra) allowed:

LEP:
- $M_h > 114.4$ GeV

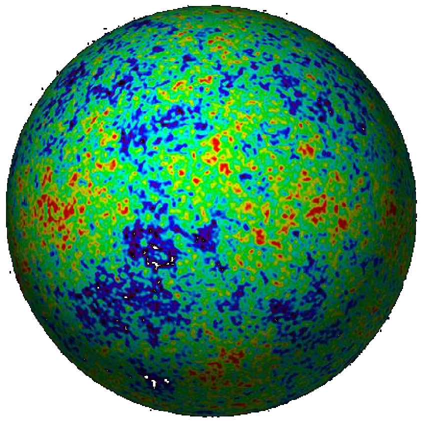
Cosmology:
- LSP is neutral
- Limits on LSP mass (upper/lower)



Higgs boson

Cosmology and SUSY

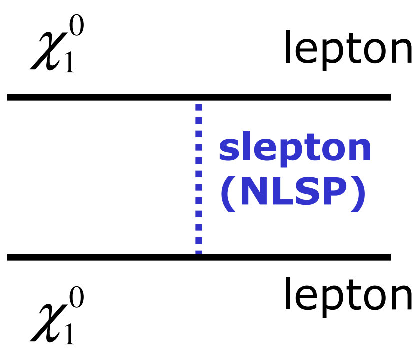
dark matter



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.



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

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

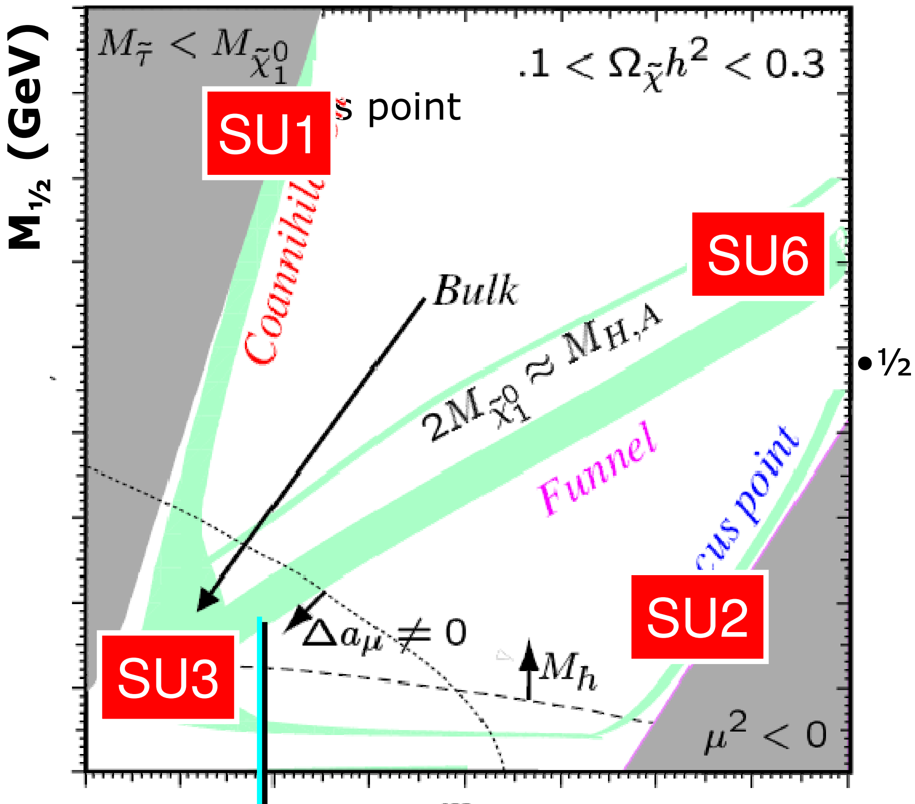
$$\approx m_\chi^3$$

Upper AND lower limits on LSP mass

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

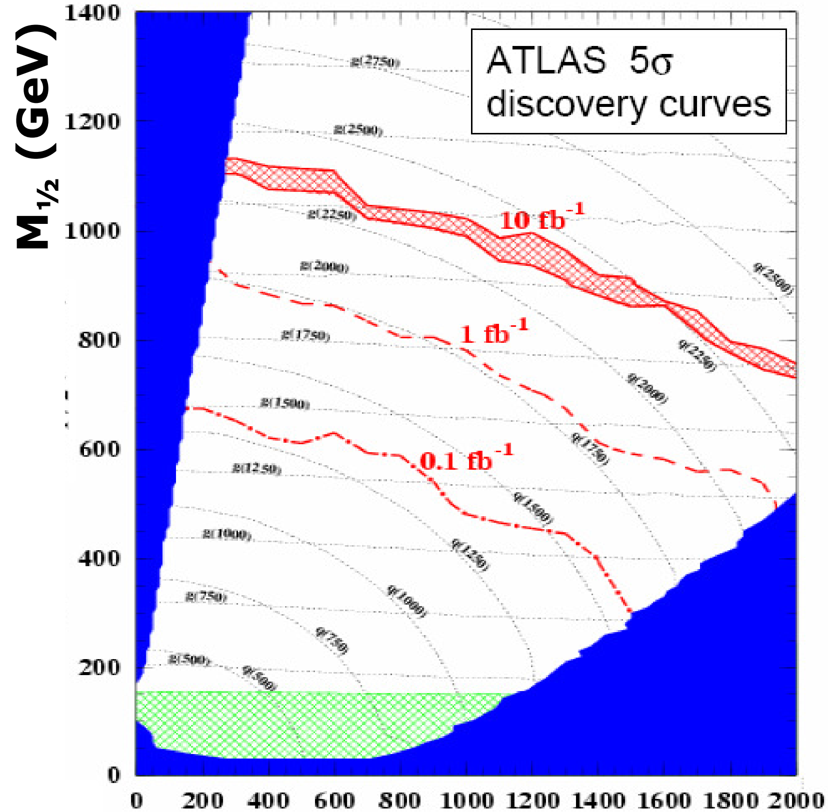
mSUGRA space

Allowed mSUGRA space (post WMAP)



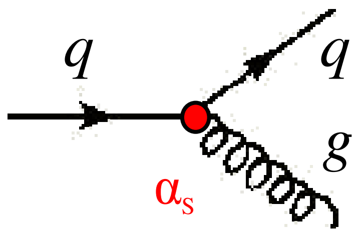
Allowed mSUGRA space
Very different exp. signatures

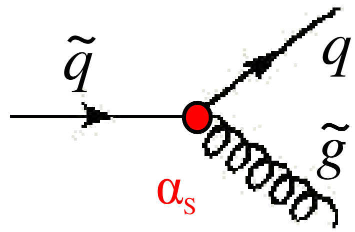
ATLAS reach in mSUGRA space



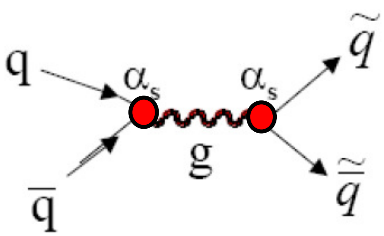
M = 1.3 TeV (1 week)
M = 1.8 TeV (1 month)
M = 3 TeV (300 fb^{-1})

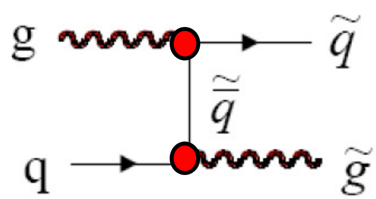
- Superpartners have same gauge quantum numbers as SM particles → interactions have same couplings

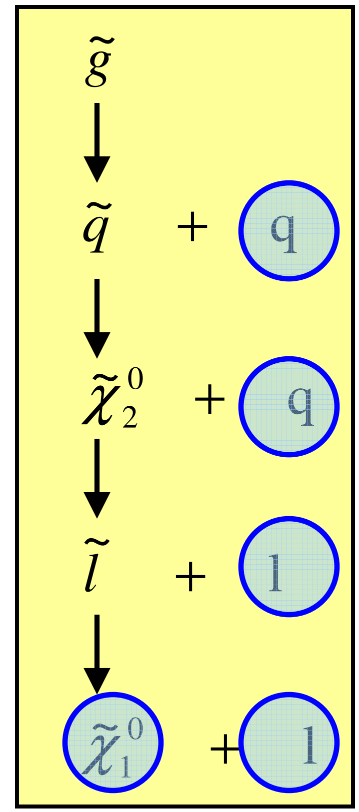




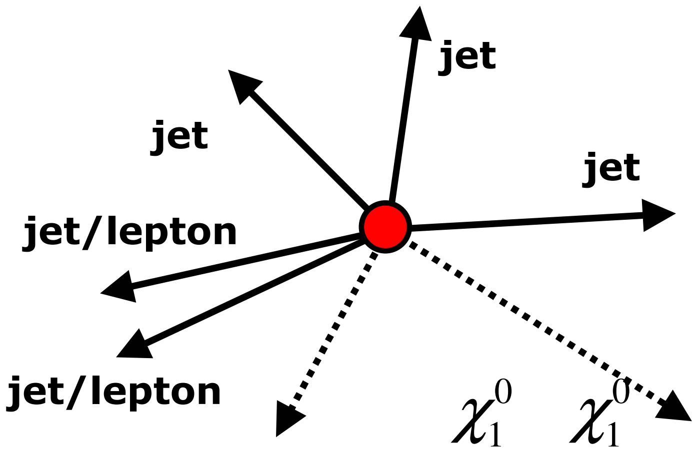
Gluino’s / squarks are produced copiously
(rest SUSY particles in decay chain)







In this example:
Gluino → 2 jets + 2 leptons
+ LSP (missing energy)



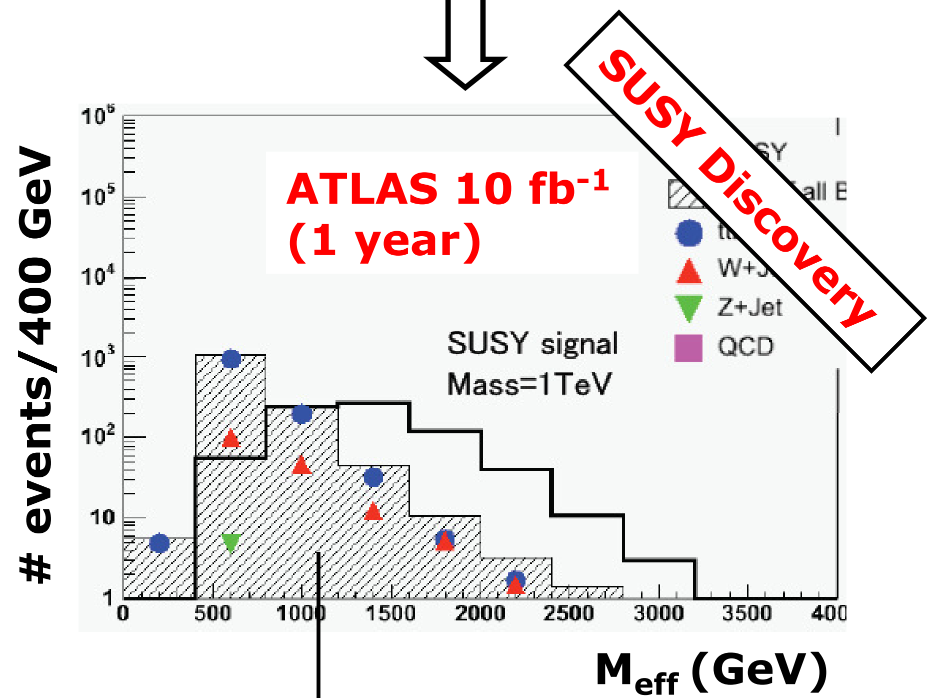
In R-parity conserving models the LSP is stable and escapes detection (mSUGRA)

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

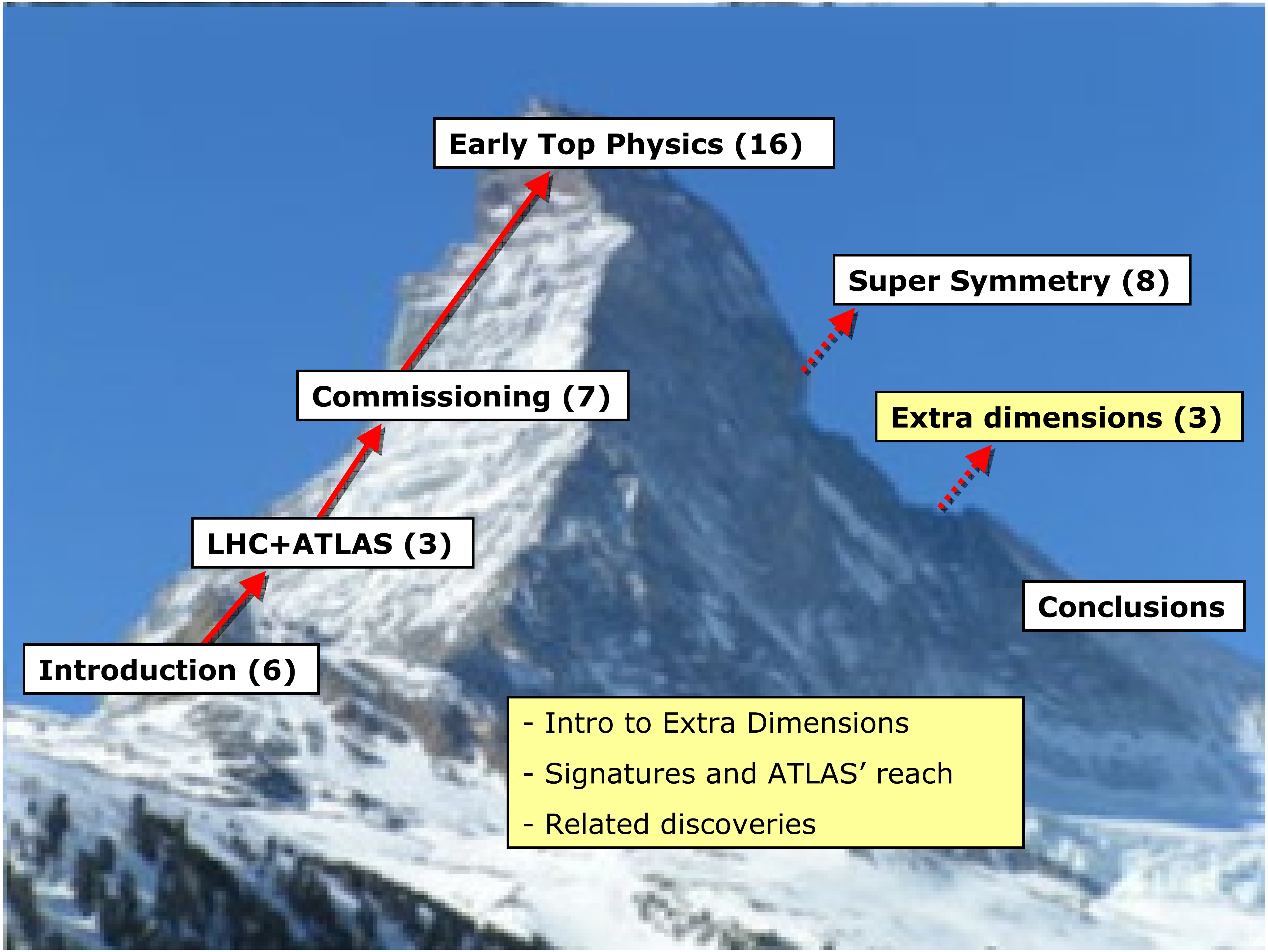
SUSY events look like top events

- **Sensitive to hard scale**:

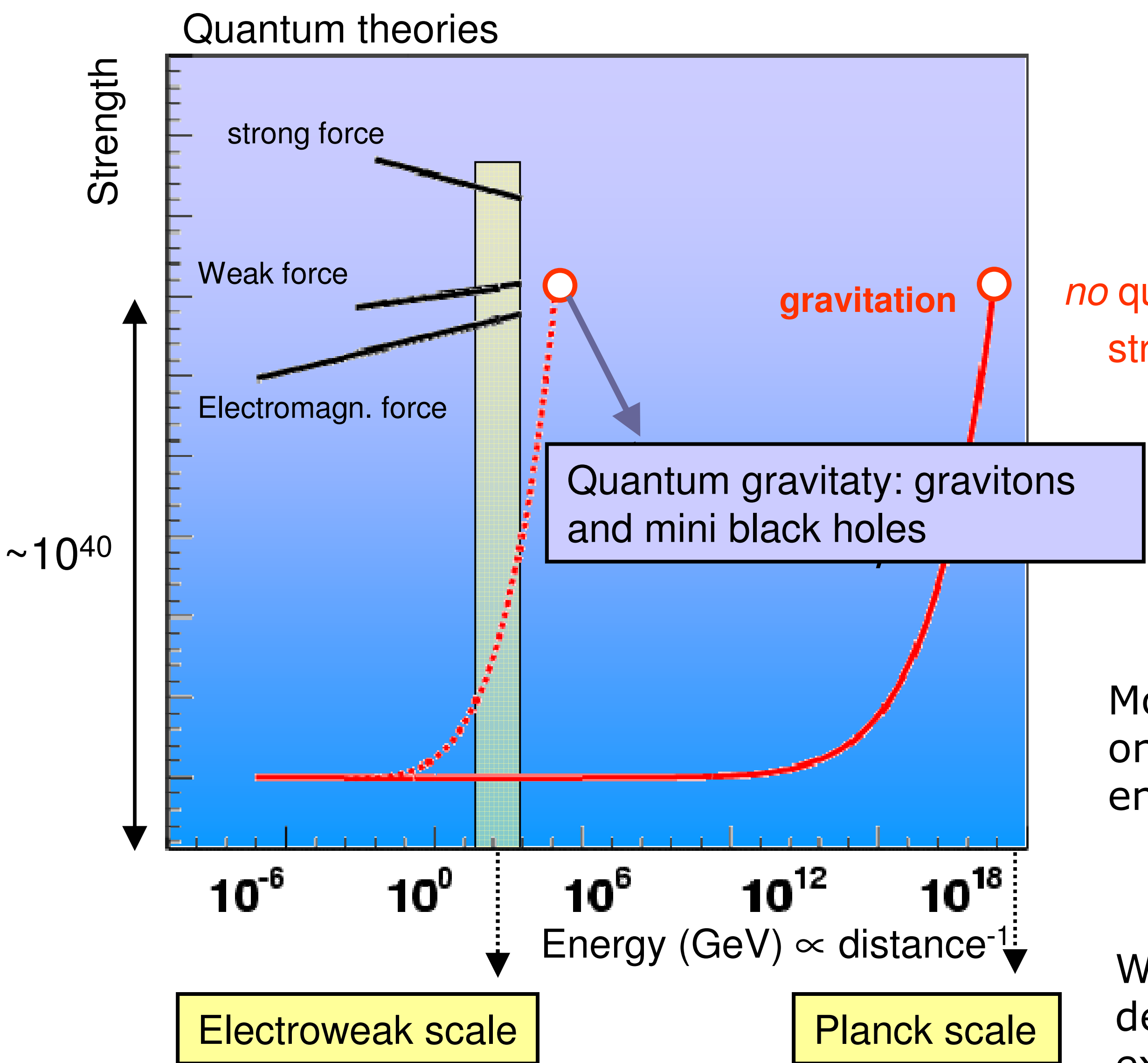
$$M_{eff} = \not{E}_T + \sum_{i=1}^{N_{jets}} (P_T)_i$$



tt production dominant background
remember: we understand this


Early Top Physics (16)
Super Symmetry (8)
Commissioning (7)
Extra dimensions (3)
LHC+ATLAS (3)
Conclusions
Introduction (6)
- Intro to Extra Dimensions
- Signatures and ATLAS’ reach
- Related discoveries

The 3+1 forces of nature



no quantum theory
string theory?

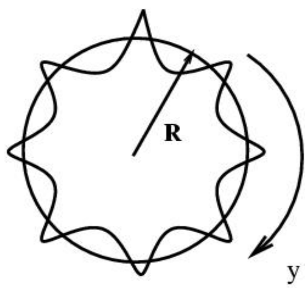
Most models predict only gravitons can enter extra dimension

↓

We should observe decays of Kaluza-Klein excitations of gravitons

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

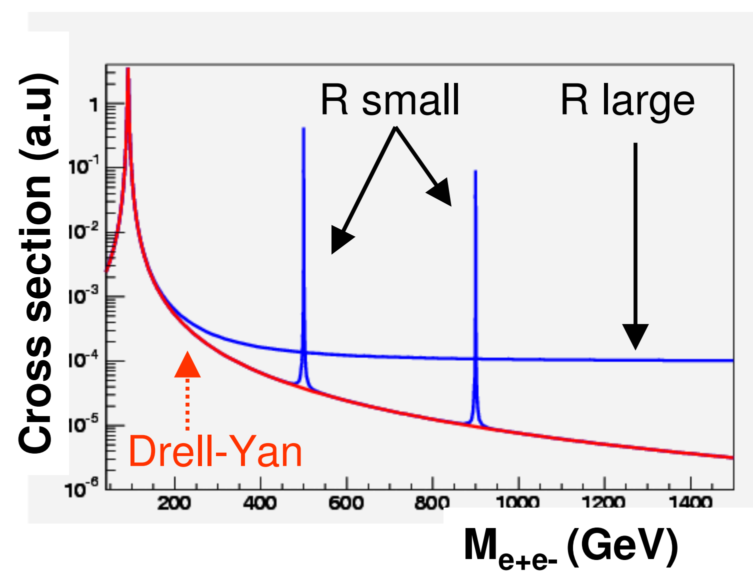
Momentum quantized in the extra dimension. $P_{xd} = i \times \Delta P$, with i = 1,2,3,4,5, …

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

(4+n)-dim.

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

(4)-dim.



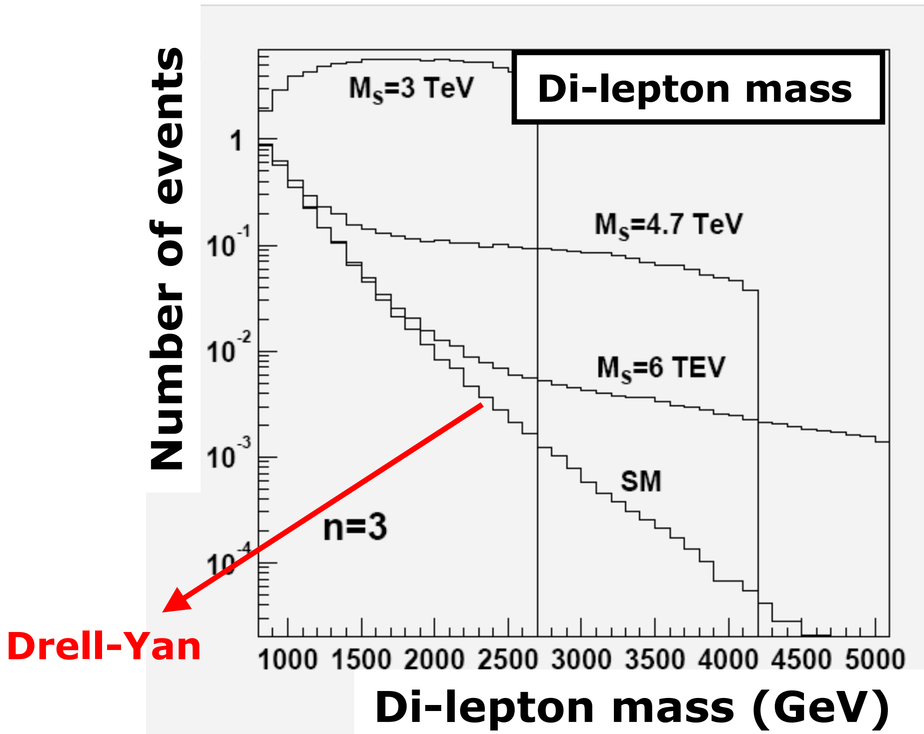
Note: other model can have fermions or gauge bosons in the bulk ($Z^{(i)}$, $W^{(i)}$)

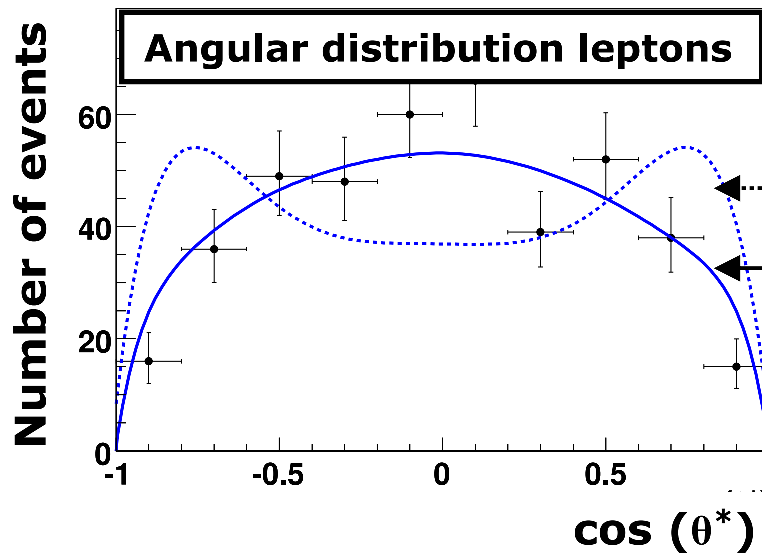
Graviton in the XD:

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

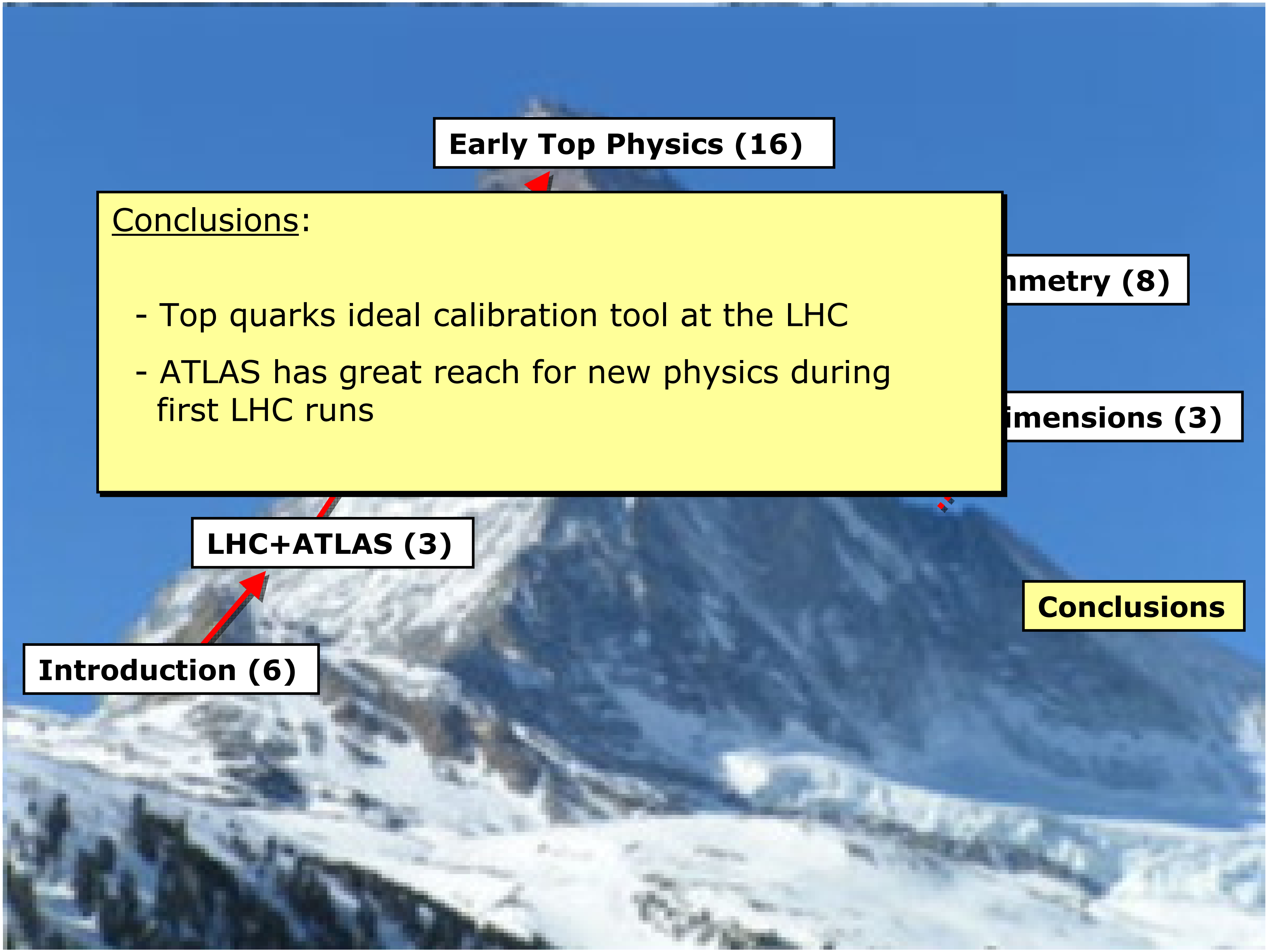
Use spin-2 nature of graviton:

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