ATLAS Experiment & Physics at the LHC

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How do we do Physics?

In our endeavor to understand reality, we are somewhat like a man trying to understand the mechanisms of a closed watch.

He sees the face and moving hands, even hears its ticking,

but he has no way of opening the case.

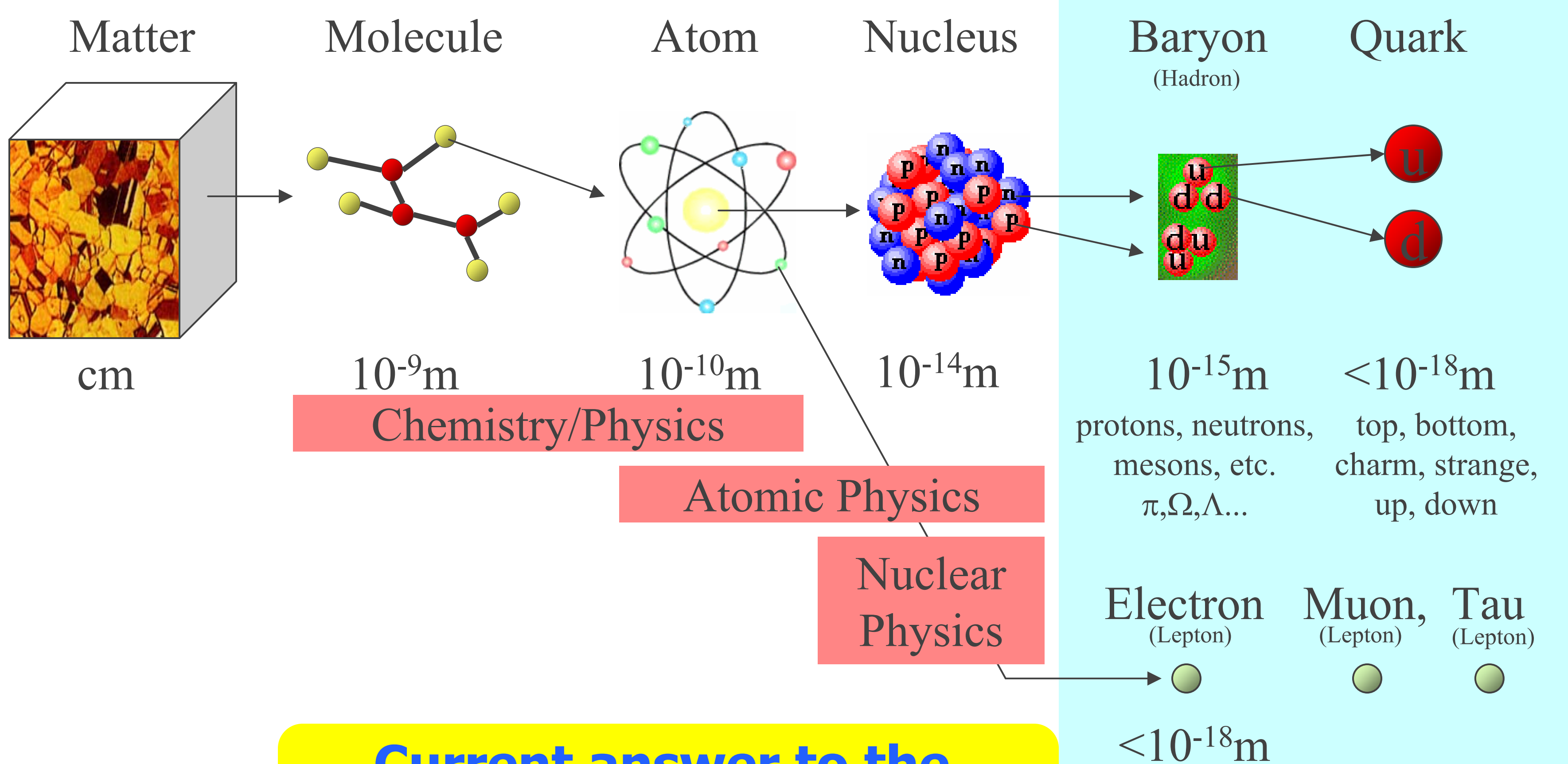
If he's ingenious, he may form some picture of a mechanism which could be responsible for all the things he observes,

But he may never be quite sure his picture is the only one which could explain his observations

— Albert Einstein in 1938

What is the Universe made of?

Some Recent Answers

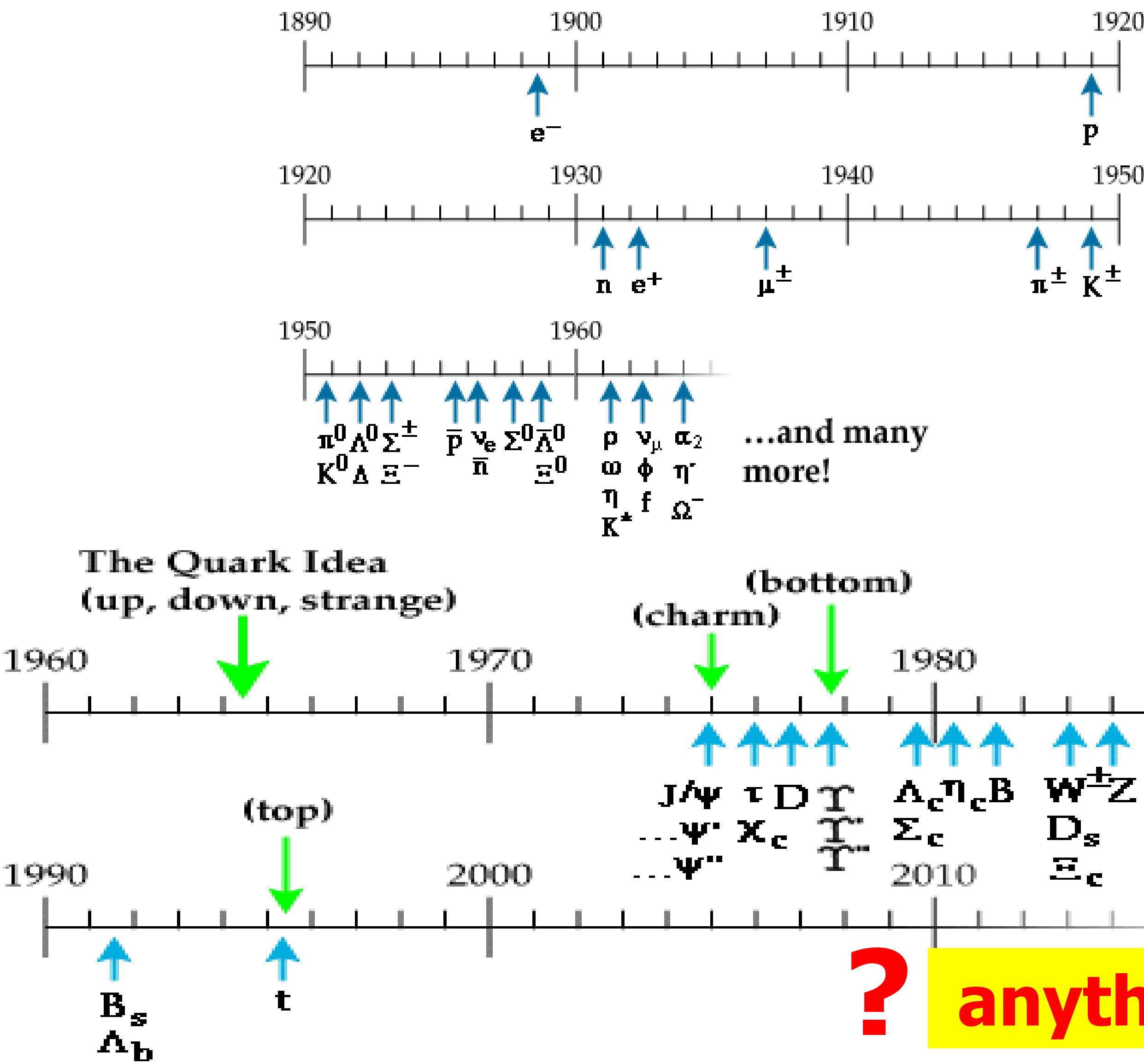


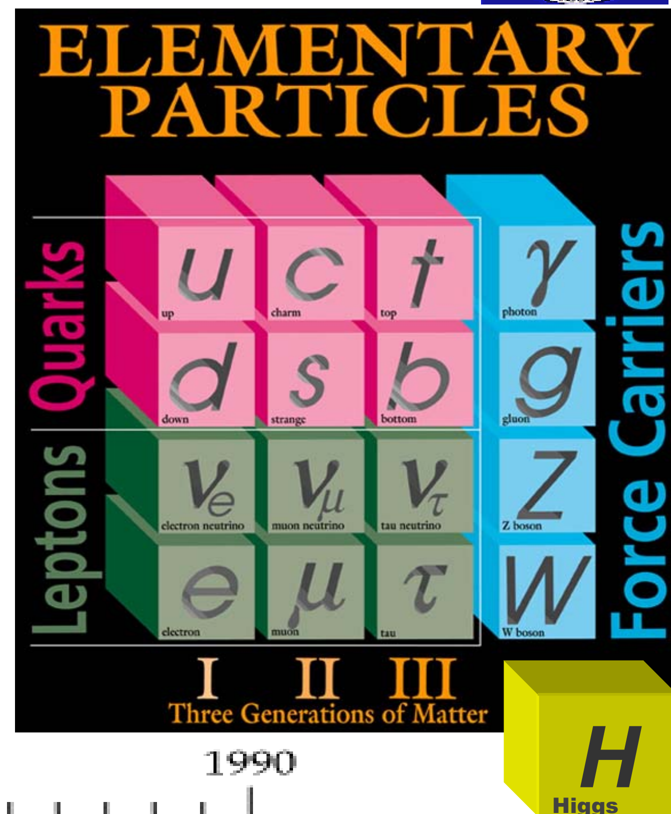
Current answer to the thousand-year old question:

Quarks & Leptons

High Energy Physics

SM & Past HEP Discoveries





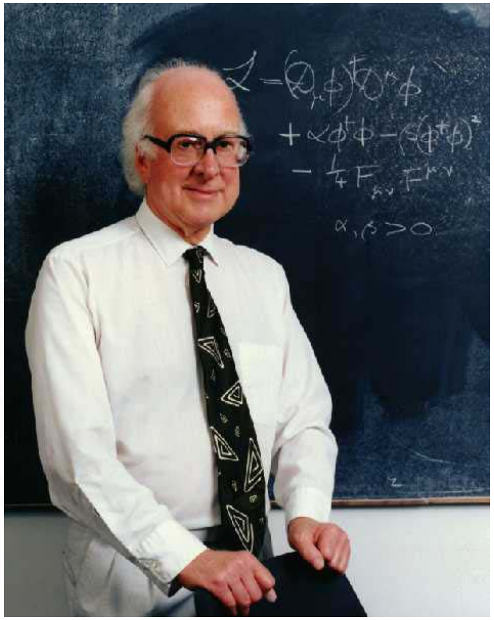
? **anything left???**

SM: A successful story, BUT

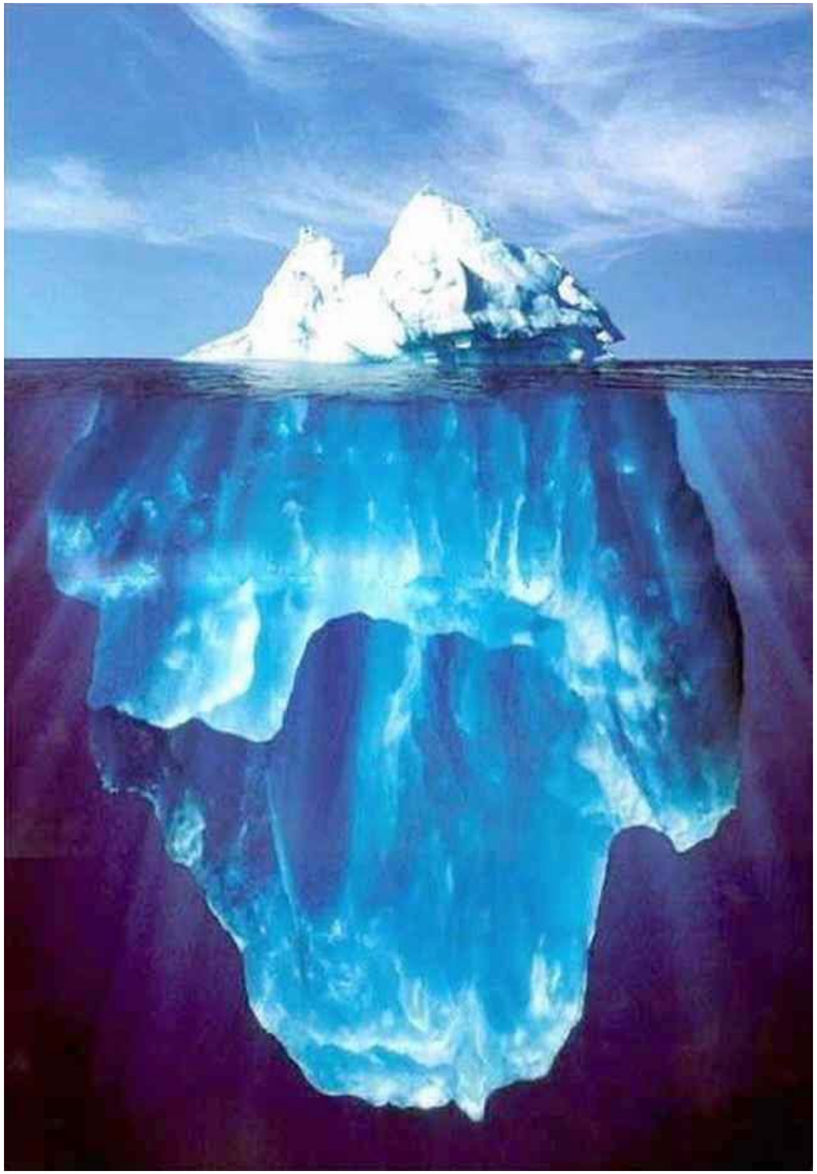
- Why are there **three** families?
- Why **asymmetry** between **matter/anti-matter**?
- Where is the **Higgs** particle?
- Are there **higher symmetry** beyond SM?
- Where does **dark matter/energy** fit in?

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

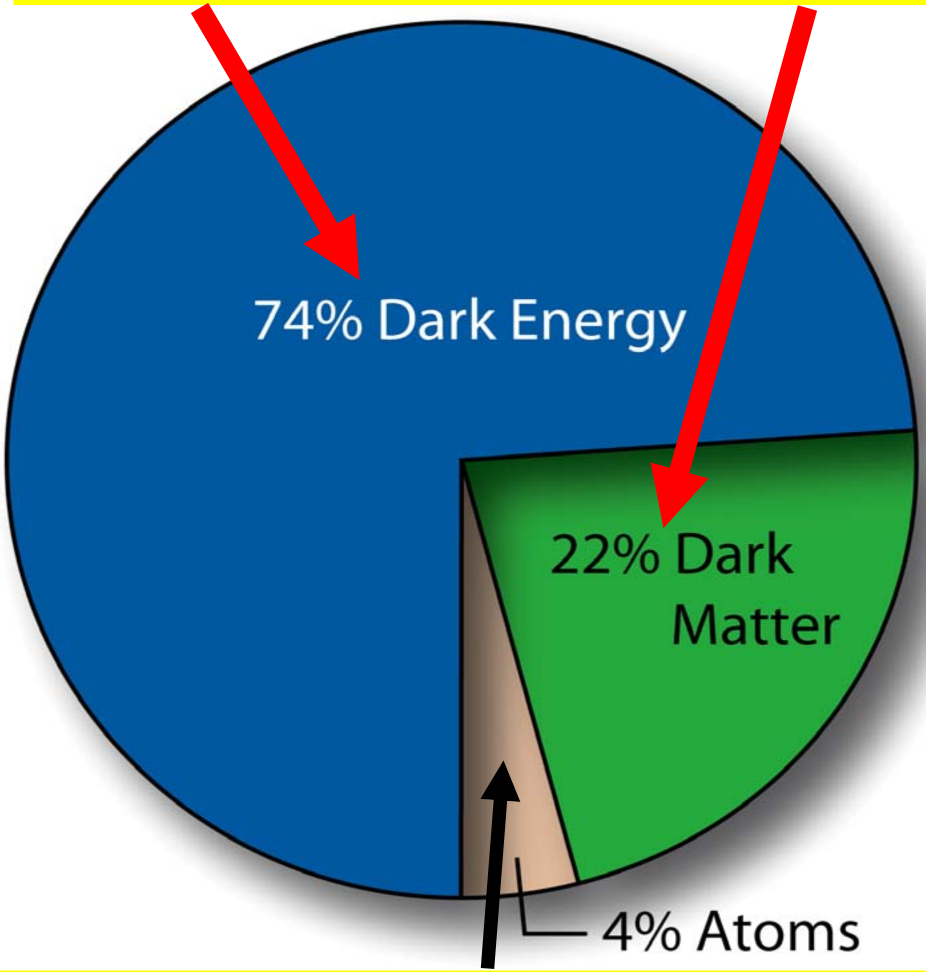
$$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix}$$



Why New Physics Beyond SM?



New Physics (NP)



What Standard Model is about

Current Situation about SM and NP:

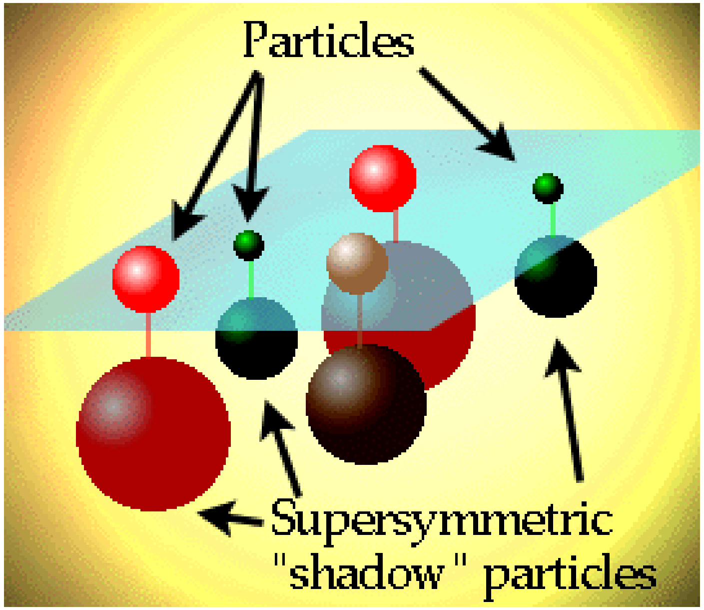
"There are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns - the ones we don't know we don't know"

Donald Rumsfeld's remark which won a Foot in Mouth award in 2003

Ideas of New Physics

Supersymmetry (SUSY)

Symmetry between **fermions (matter)** and **bosons (forces)**



It stabilizes the Higgs mass, fits as dark matter, ……

However, none of the SUSY particles has been observed.

Hidden Extra-Dimensions, Little Higgs,

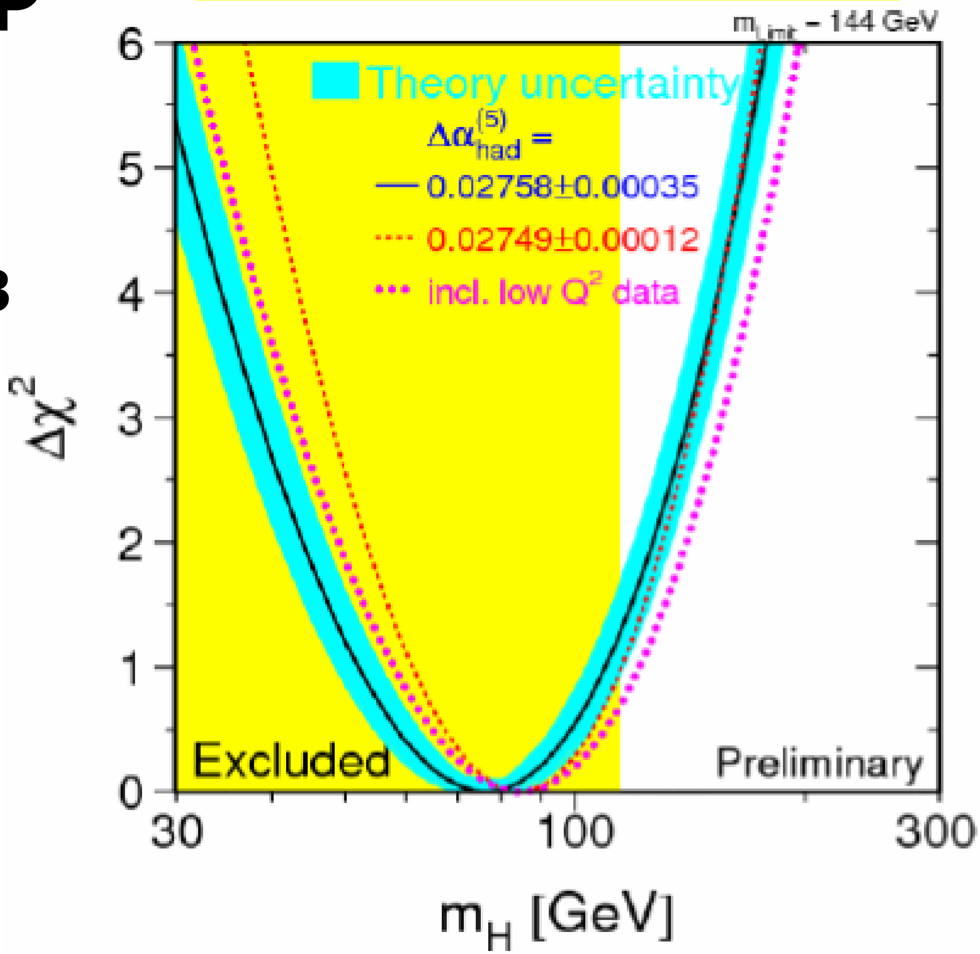
Heavier W,Z, other Exotics particles, ……

None has been experimentally verified

New Physics at TeV scale

SM confirmed by LEP Tevatron, SPS, SLC, PEP-II, KEK-B,…… with precision ~10^{-3}

Lepton Photon 2007



Electroweak Fit:

$M_{Higgs} = 76^{+33}_{-24}$ GeV

$M_{Higgs} < 144$ GeV @ 95% C.L.

SUSY, ED, etc. → NP ~ TeV scale

Facilities for TeV Physics

Tevatron at Fermilab:

- **pp collider, Ecm= 2 TeV**

LHC at CERN:

- **pp collider, Ecm=14 TeV**

Future Possibilities

e+e- Linear Collider:

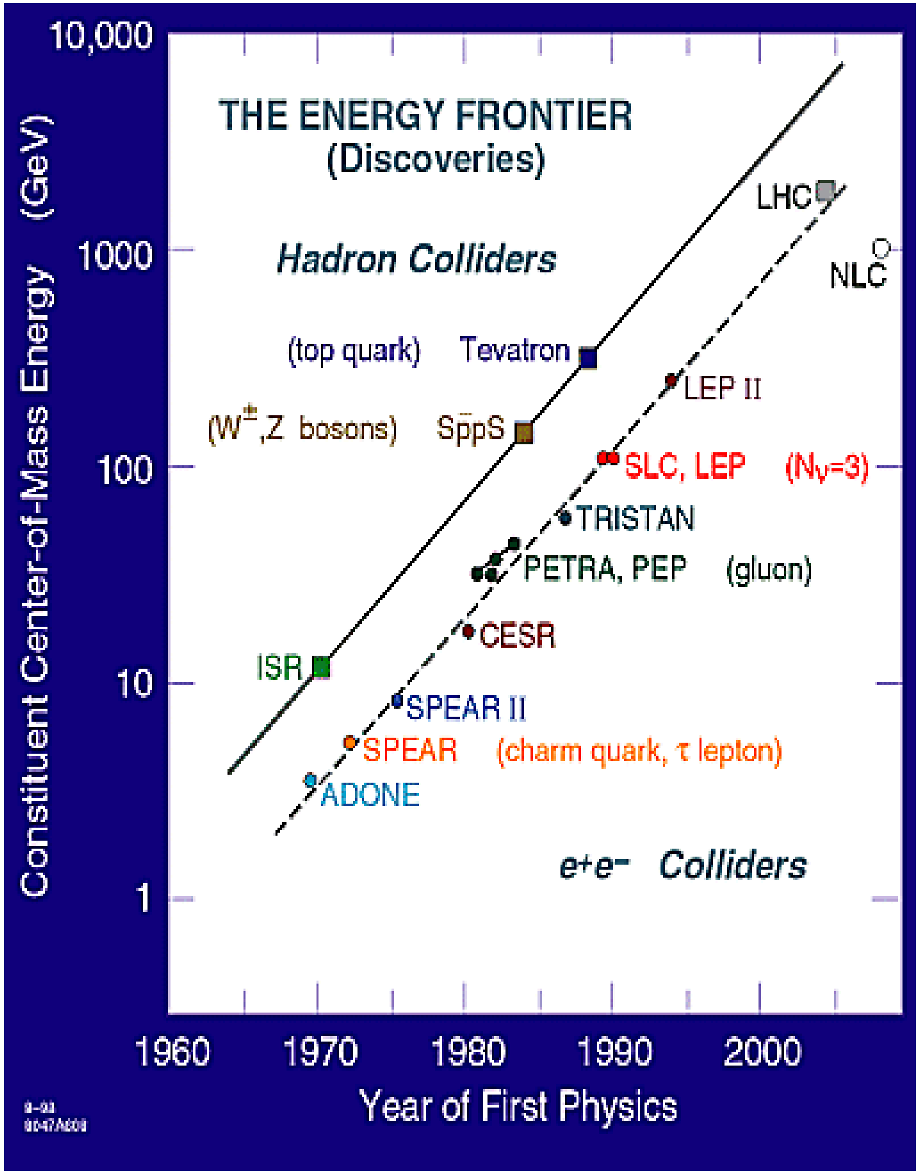
- ILC (SLAC, Fermilab, KEK, ???)
- CLIC (CERN)

μ+μ- Collider:

- Ecm ~ few TeV

VLHC:

- Ecm = 50 to 400 TeV



Large Hadron Collider (LHC)

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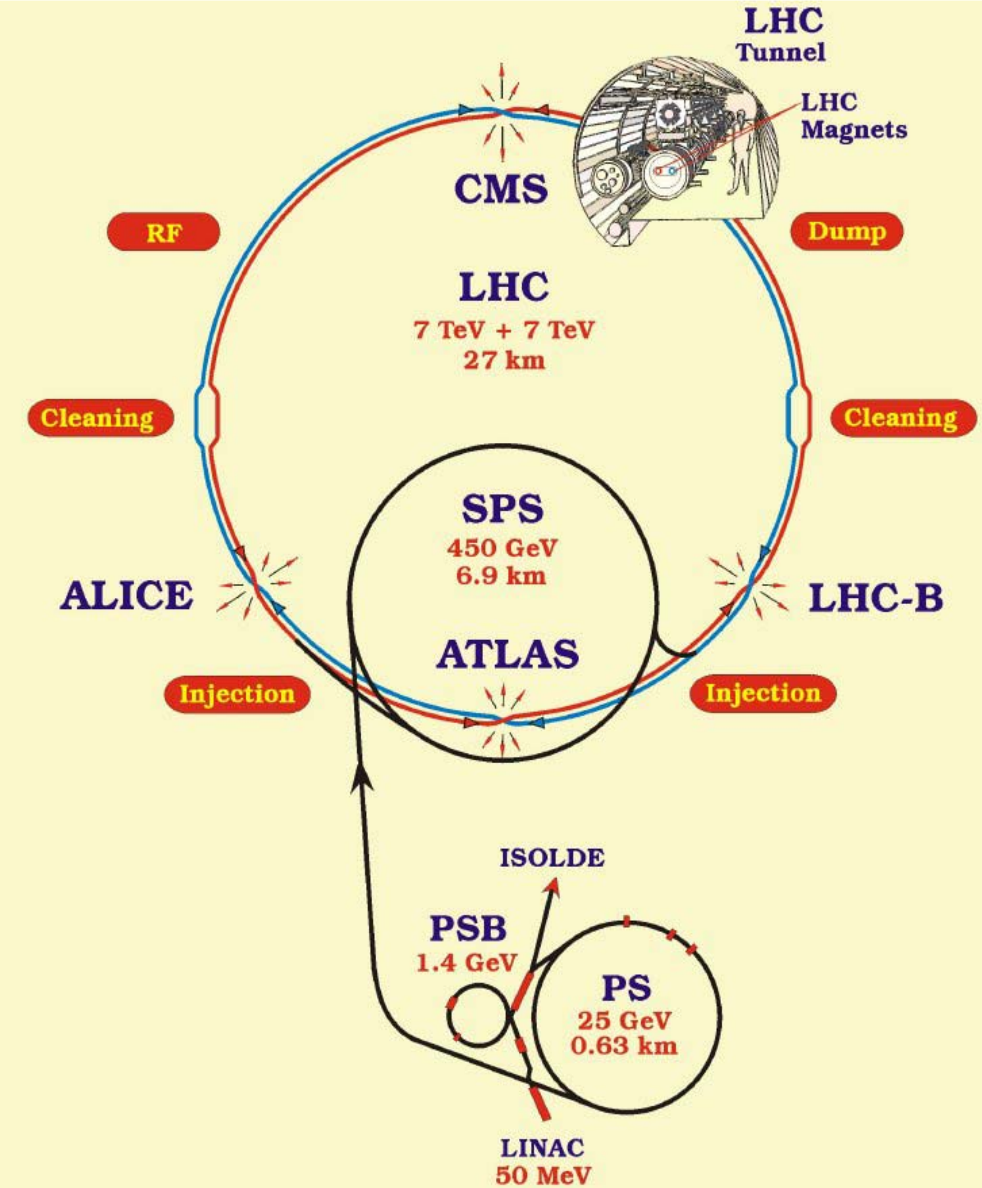
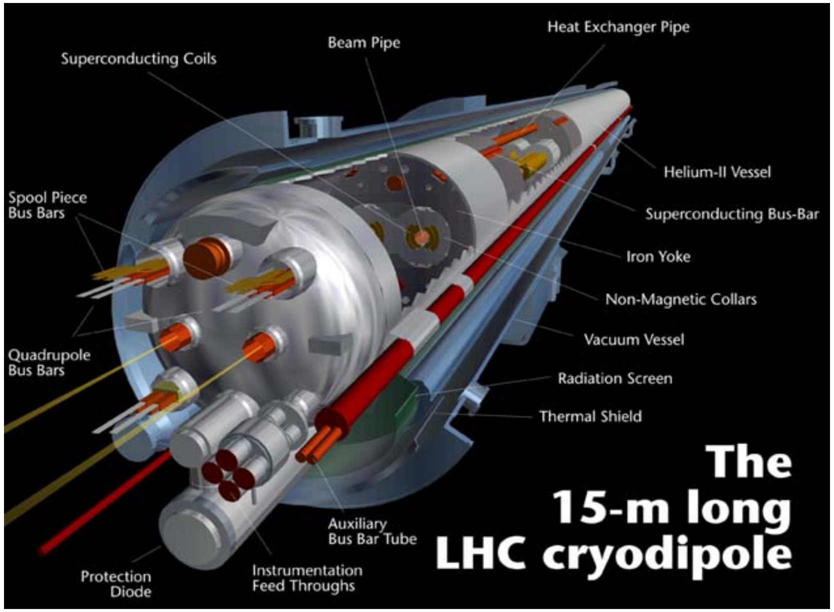


6 Billion Dollars LHC has been under construction since 1994

Start in the fall of 2008, world's most powerful collider until at least 2020



Superconducting magnet

Large Hadron Collider (LHC)

Rest mass of LHC proton beam bunch: ~2×10^{-10}g

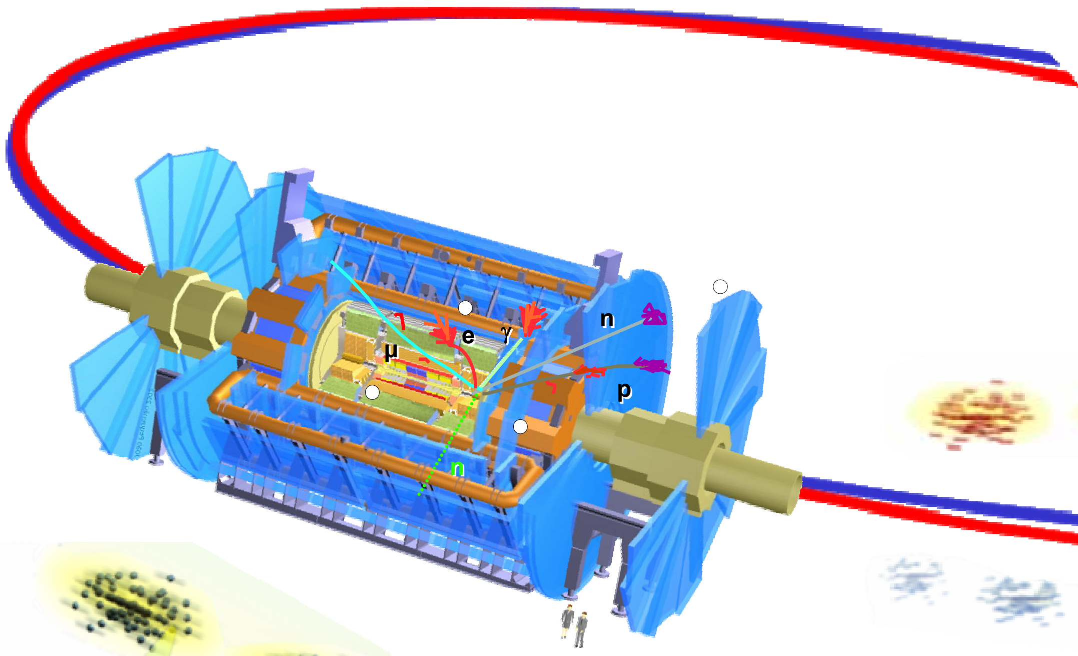
However, LHC beams carries an energy of

10^{14} protons $\times$ 14×10^{12} eV $\cong 10^{8}$ J

or, if you like

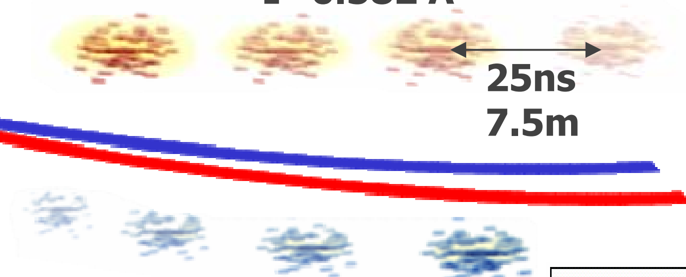
One 100 Ton truck at 100 km/h

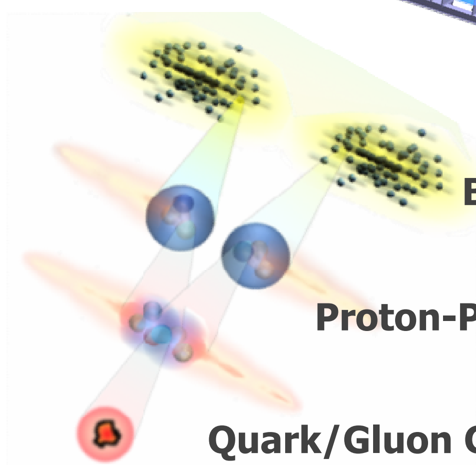
Large Hadron Collider (LHC)



Nominal LHC Parameters:

7 TeV	Proton Energy
$10^{34} cm^{-2}s^{-1}$	Luminosity
2808	Bunches per Beam
10^{11}	Protons per Bunch



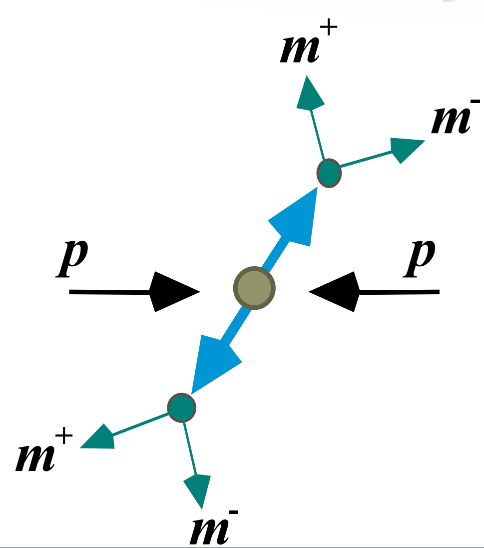


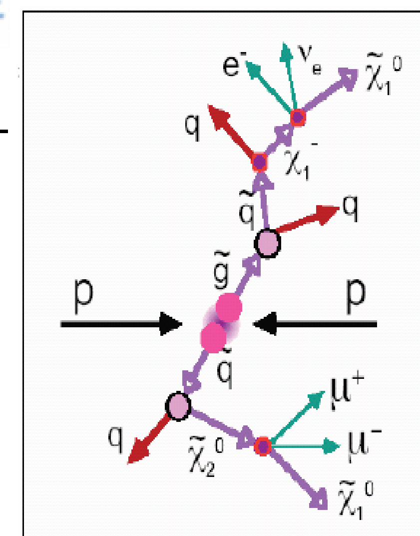
Bunch Crossings $4x10^7$ Hz

Proton-Proton Collisions 10^9 Hz

Quark/Gluon Collisions

Heavy particle production $10^{+3...-6}$ Hz
(W, Z, top, Higgs, SUSY, ...)



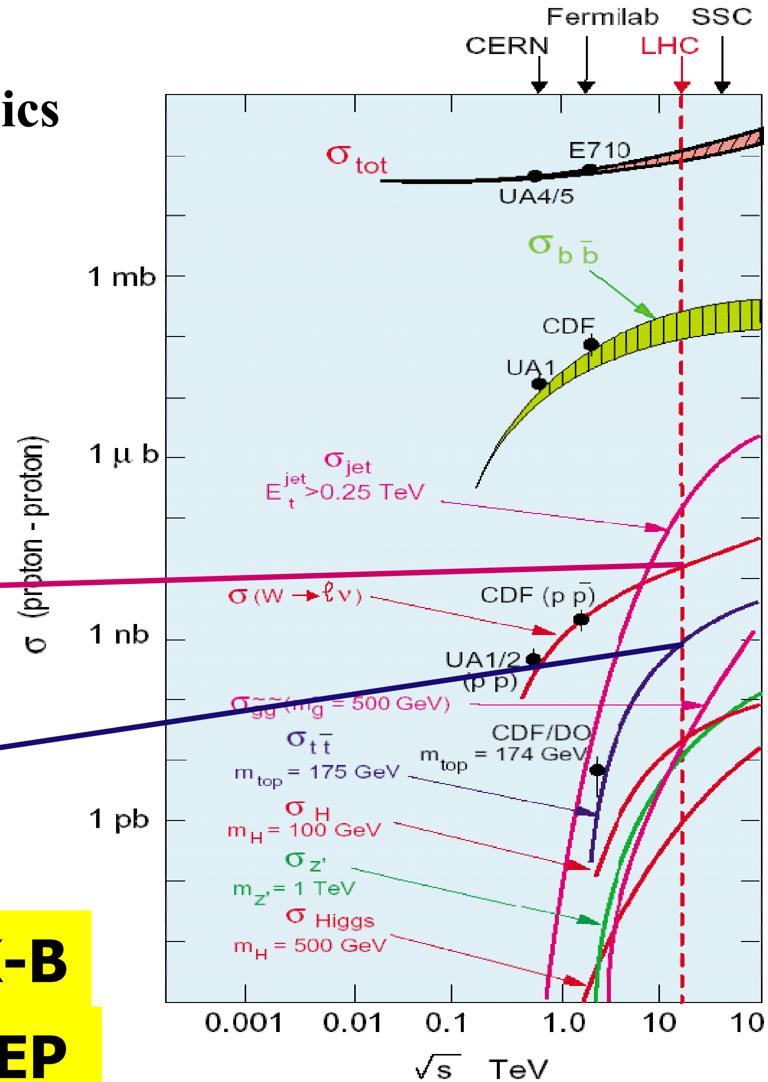


LHC tunnel (2006/9)

Rich & Exciting Physics

Expected event rates for representative physics processes at low luminosity ($L=10^{33}$ cm^{-2} s^{-1})

process	σ(pb)	Event /sec	Event /year
bb	5×10^{8}	10^{6}	10^{12}
Z→ee	1.5×10^{3}	~3	10^{7}
W→eν	1.5×10^{4}	~30	10^{8}
WW→eνX	6	10^{-2}	6×10^{3}
tt	830	~2	10^{7}
H(700GeV)	1	2×10^{-3}	10^{4}

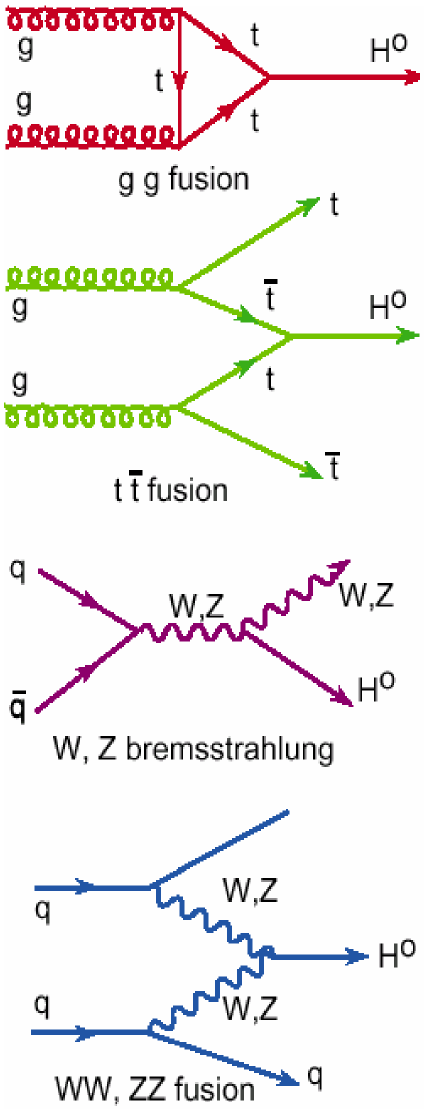


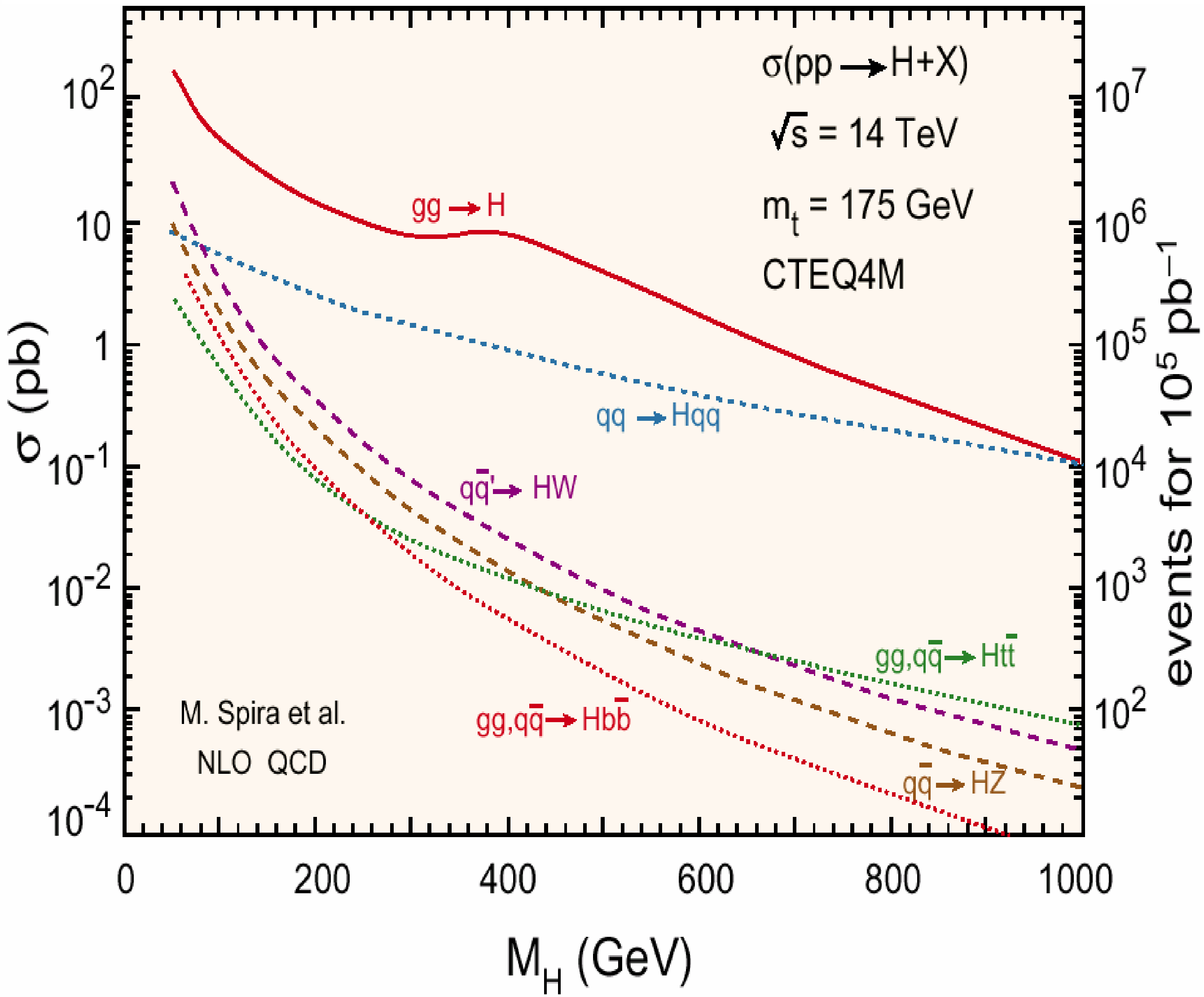
LHC is a B-factory: ~10^{8} PEP/KEK-B

W/Z factories: ~10^{7} Tevatron & LEP

Top factory: ~10^{4} Tevatron, and also Higgs/SUSY factory

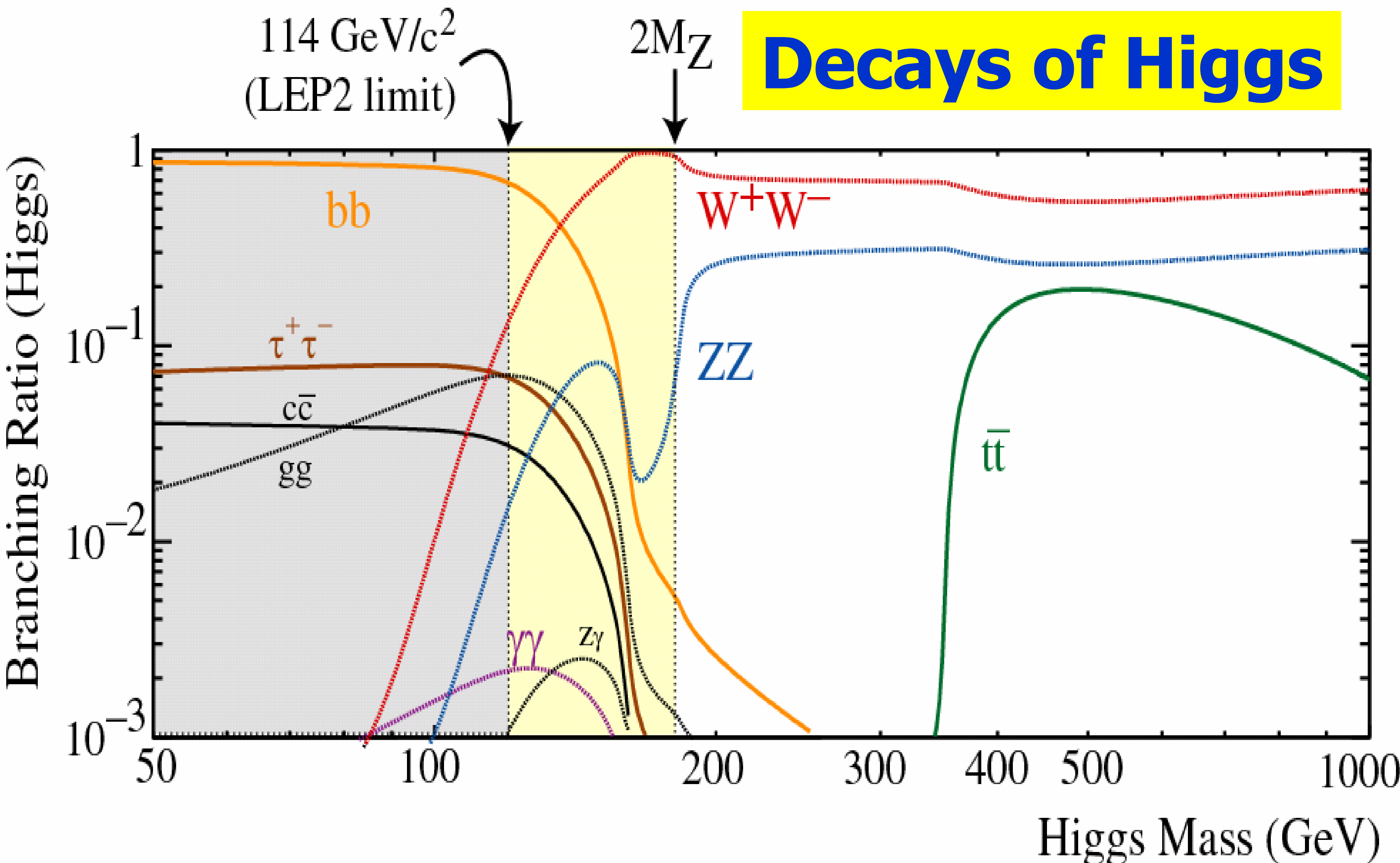
Higgs Production at LHC



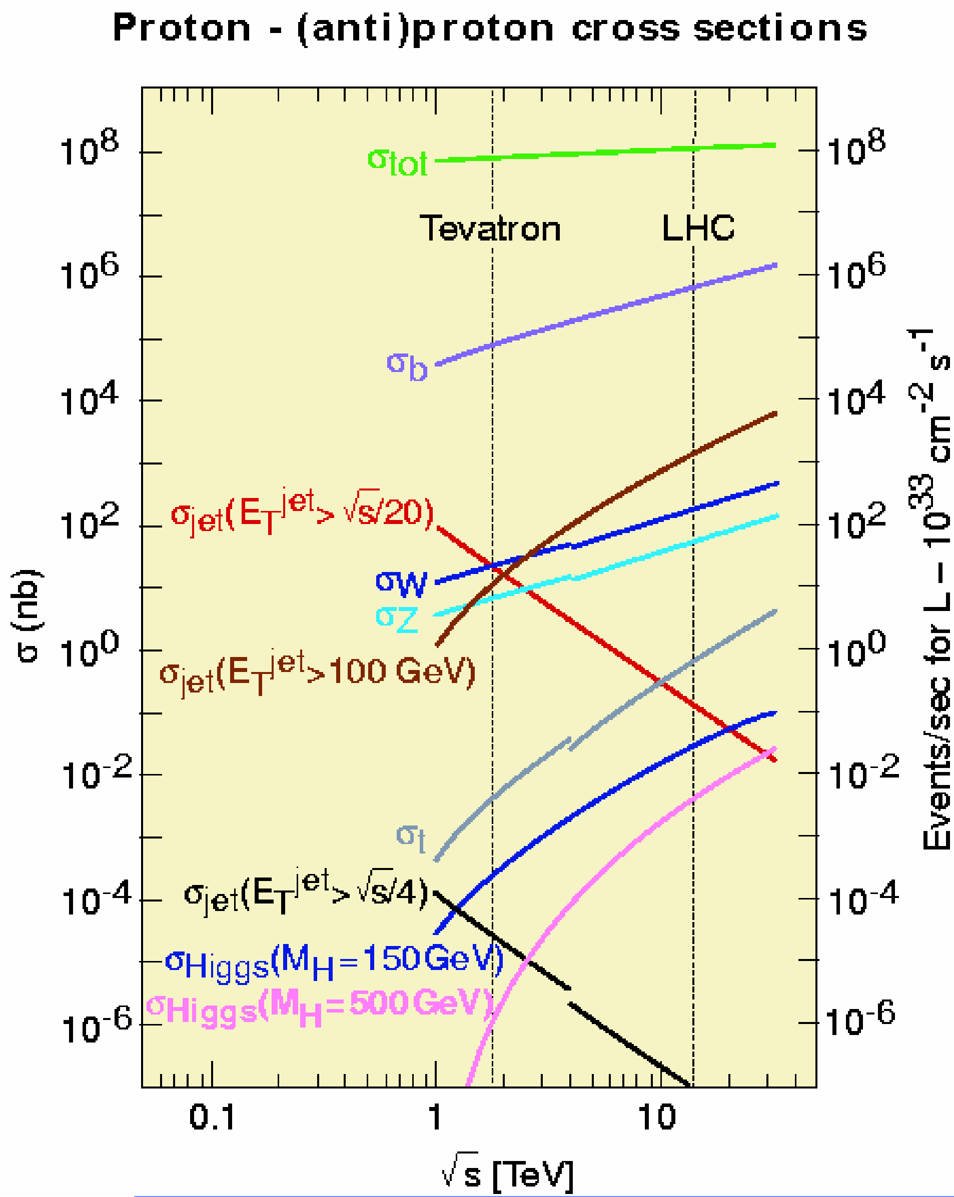


SM Higgs in LHC/ATLAS data

Decays of Higgs



SM Higgs in LHC/ATLAS data



Cross-section/Rates:

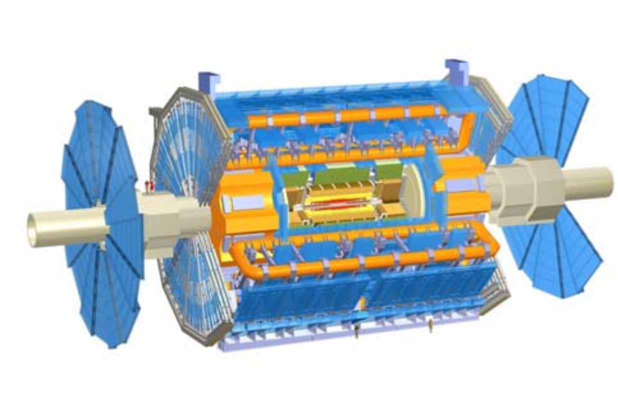
- Total
  - $\sigma \approx 100$ mb (10^9 Hz)
- W/Z production
  - $\sigma \approx 200/60$nb (2/0.6 kHz)
- Top production
  - $\sigma \approx 0.8$ nb (80 Hz)
- SM Higgs (m_H=150GeV)
  - $\sigma \approx 30$ pb (3 Hz)

BR included (10fb^{-1}):

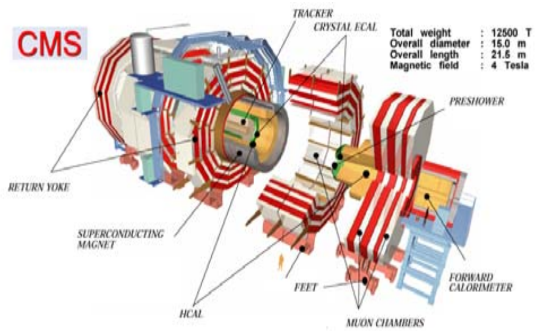
- $H \rightarrow bb$ ~90,000 events
- $H \rightarrow \tau\tau$ ~9,000 events
- $H \rightarrow \gamma\gamma$ ~600 events

LHC and LHC Experiments

ATLAS



CMS

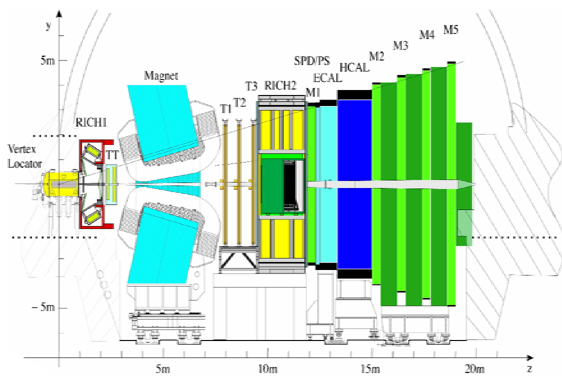


ALTAS and **CMS** have same physics goals: **concentrate on "high-p_T" discovery physics**

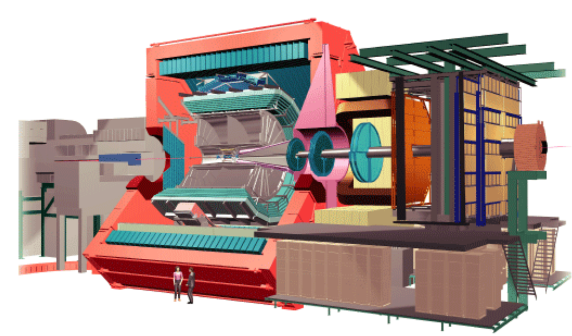
The detector concepts are however different: this provides necessary redundancy and fruitful competition

LHCb

LHCb looks like a fixed-target experiment (though it is not!), because it concentrates on low-p_T B physics



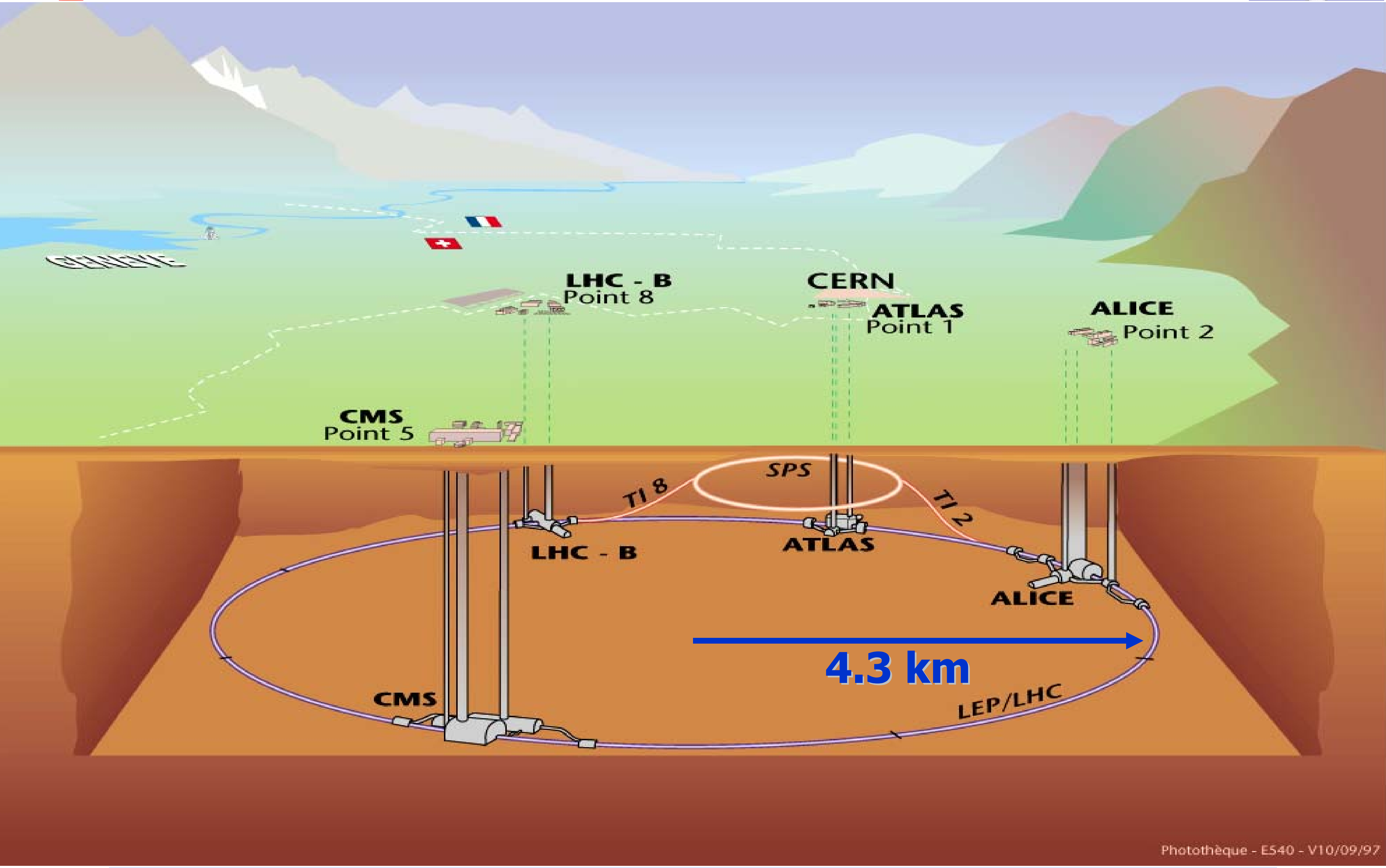
ALICE



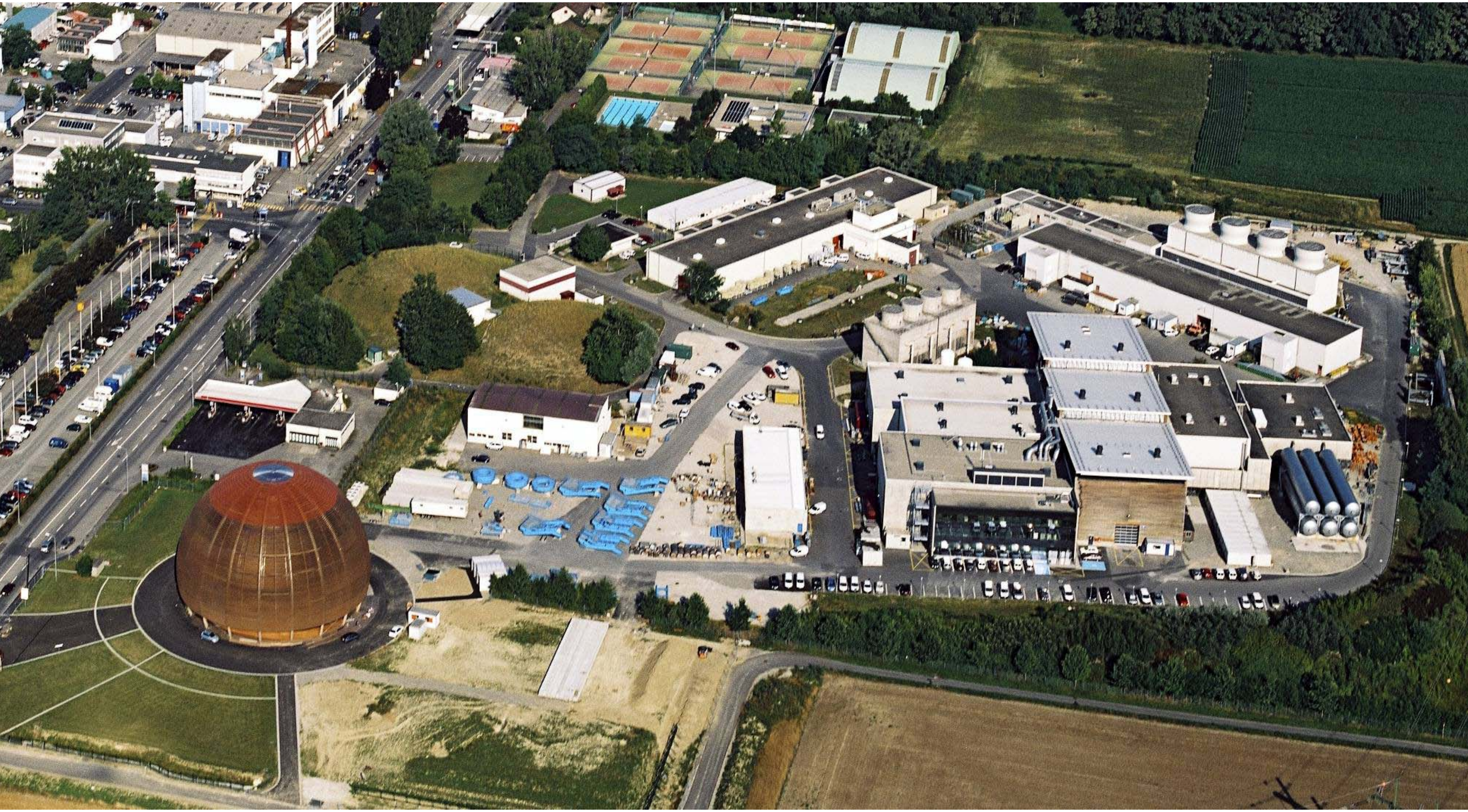
ALICE will exploit high-energetic nucleus-nucleus ("heavy-ion") collisions

There are two more (much smaller) experiments at the LHC: TOTEM (measuring elastic and diffractive processes), and LHCf (testing cosmic shower models)

LHC and LHC Experiments

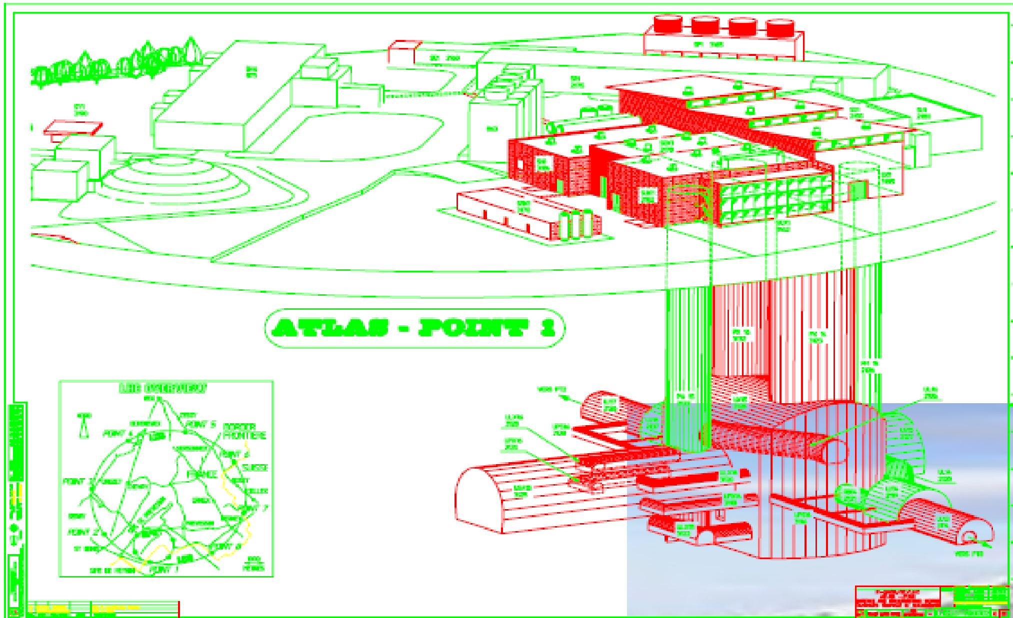


An Aerial View of Point-1

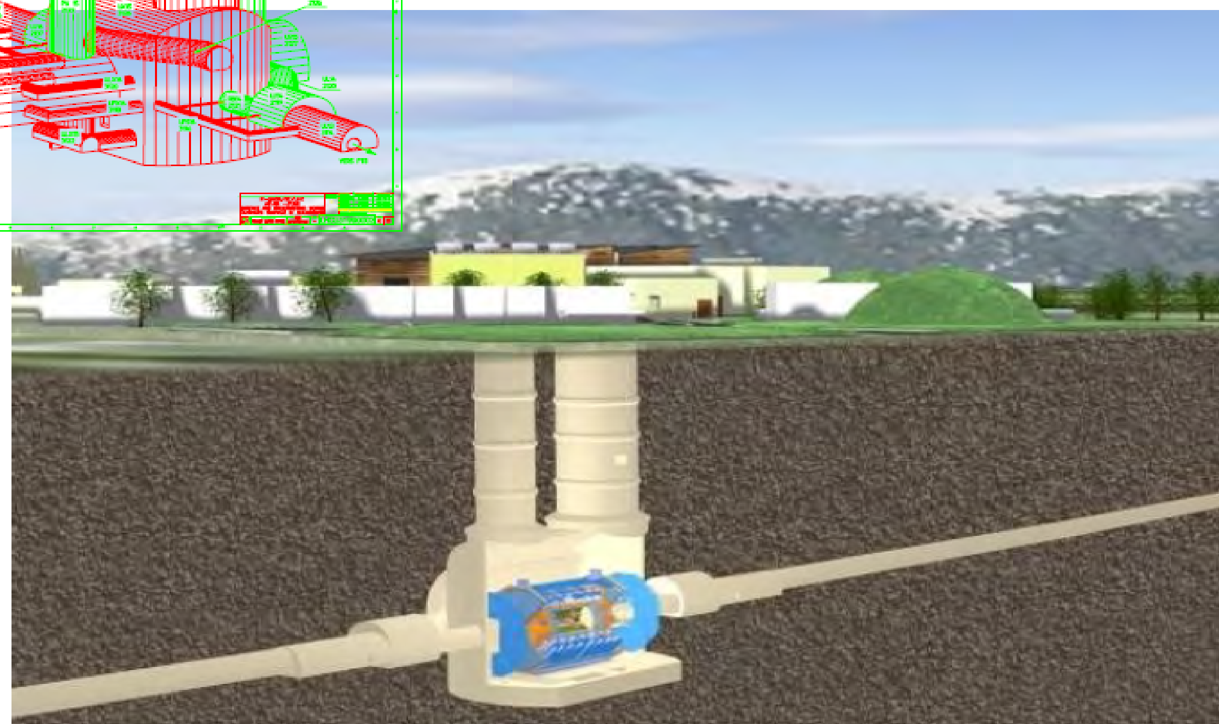


(Across the street from the CERN main entrance)

Pit-1 & ATLAS Detector



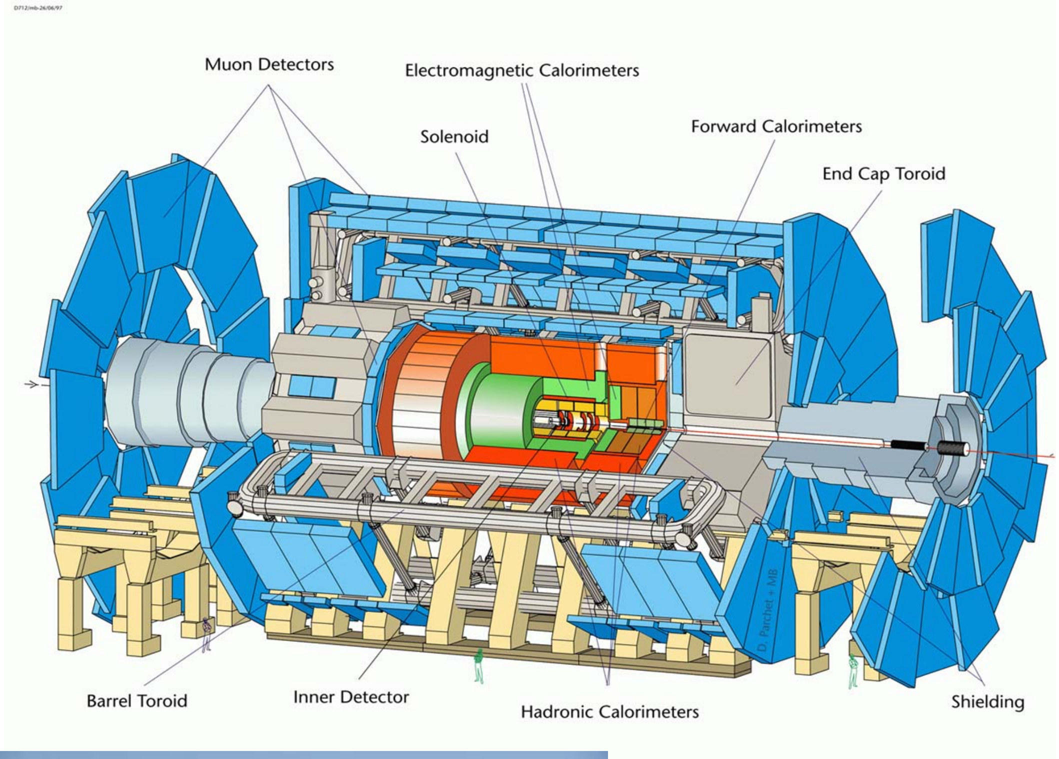
The Underground Cavern at Pit-1 for the ATLAS Detector



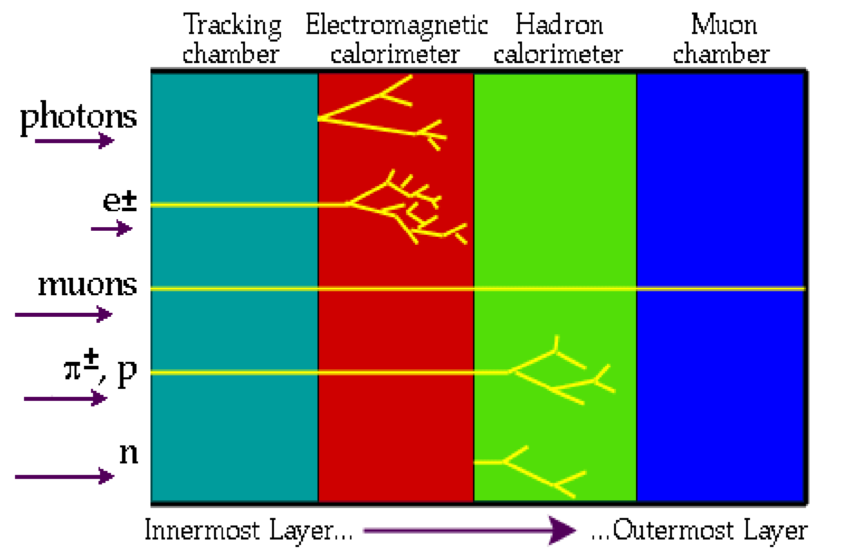
Length = 55 m
Width = 32 m
Height = 35 m

Depth =100 m

ATLAS Detector

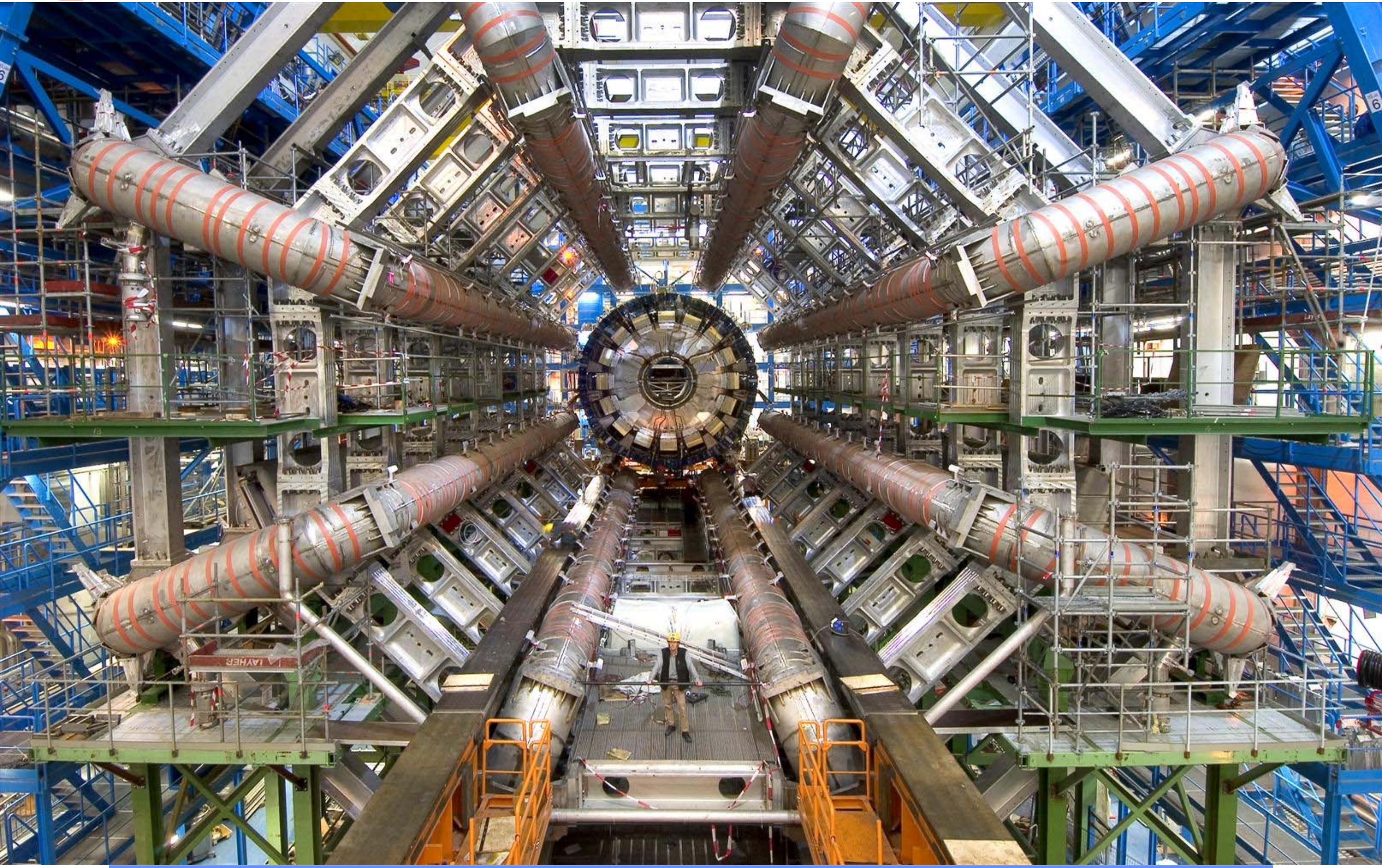


~ 10^8 electronic channels
~ 3000 km of cables



Detector component	resolution	η coverage
Tracking	$\sigma_{p_T}/p_T = 0.05\%\ p_T \oplus 1\%$	$\lvert\eta\rvert < 2.5$
EM calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	$\lvert\eta\rvert < 3.2$
Hadronic calorimetry (jets)		
barrel and end-cap	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$	$\lvert\eta\rvert < 3.2$
forward	$\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$	$3.1<\lvert\eta\rvert<4.9$
Muon spectrometer	$\sigma_{p_T}/p_T = 10\%/p_T$ @ p_T=1 TeV	$\lvert\eta\rvert < 2.7$

ATLAS Detector (2005/11)

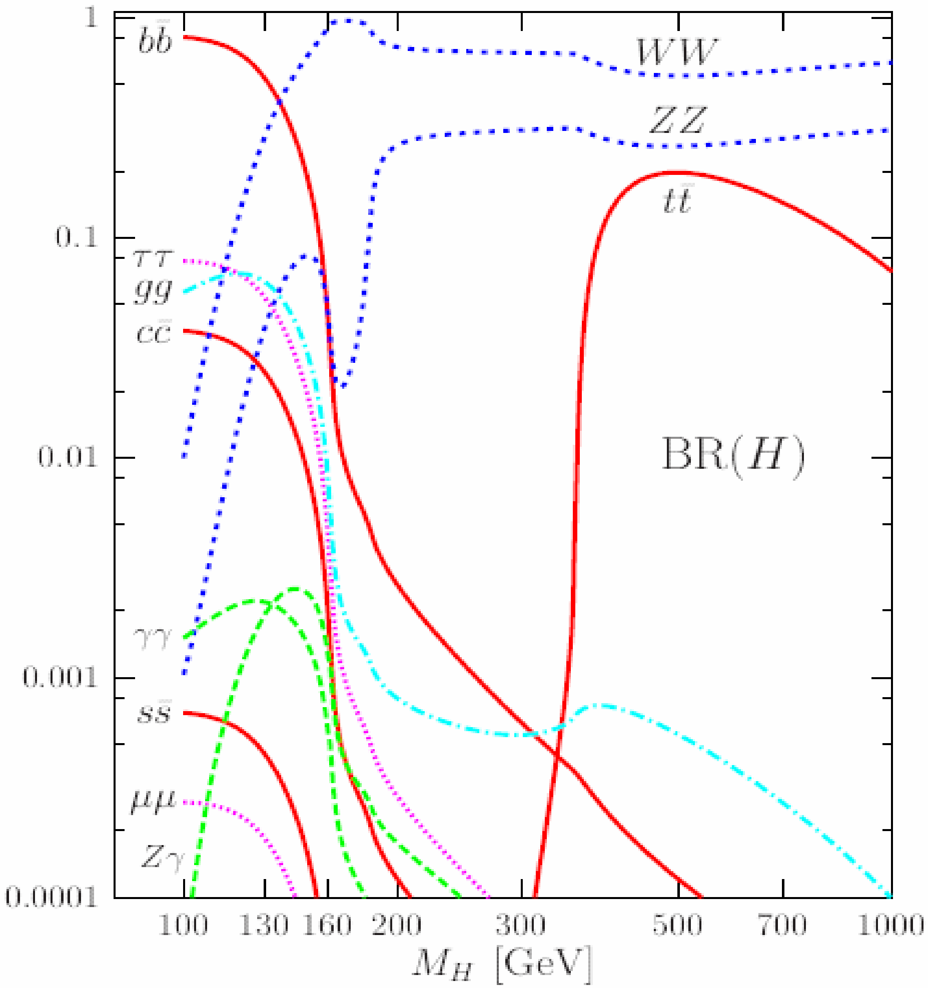


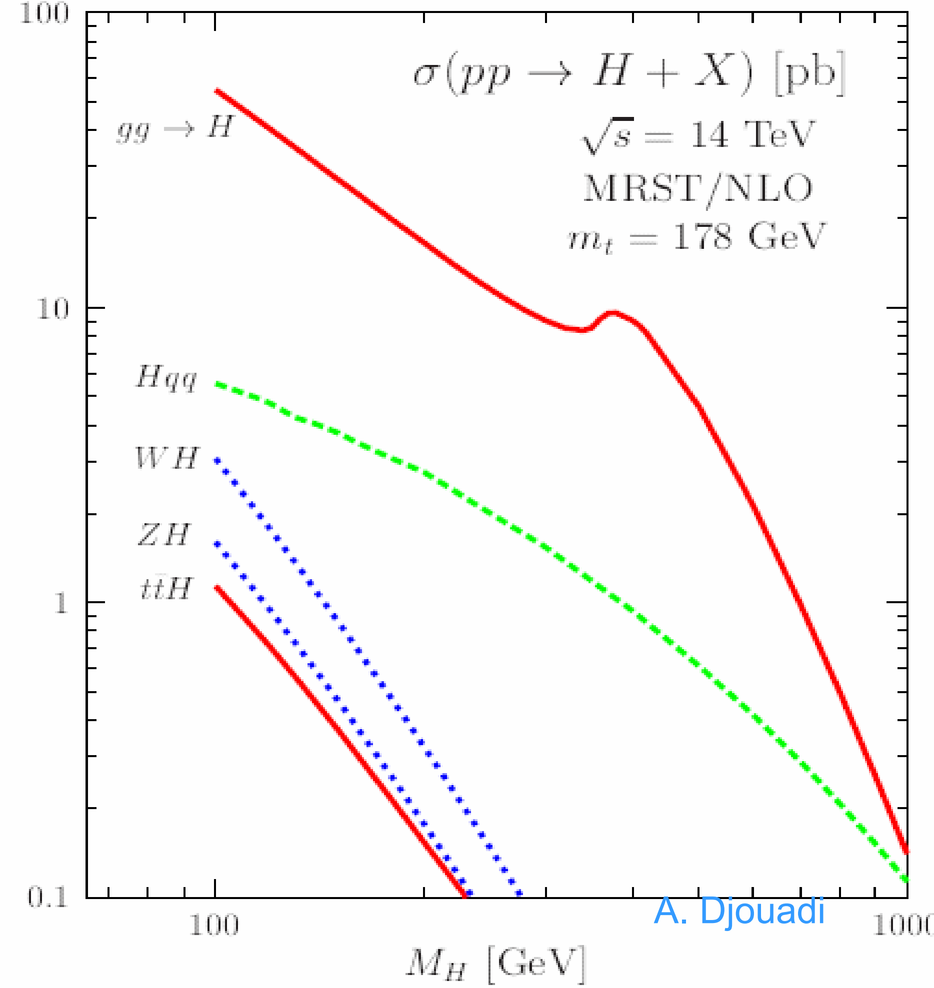
ATLAS Collaboration

~2000 physicists, ~170 institutions, 35 countries

~400 US physicists from ~40 universities/national labs

Higgs Physics





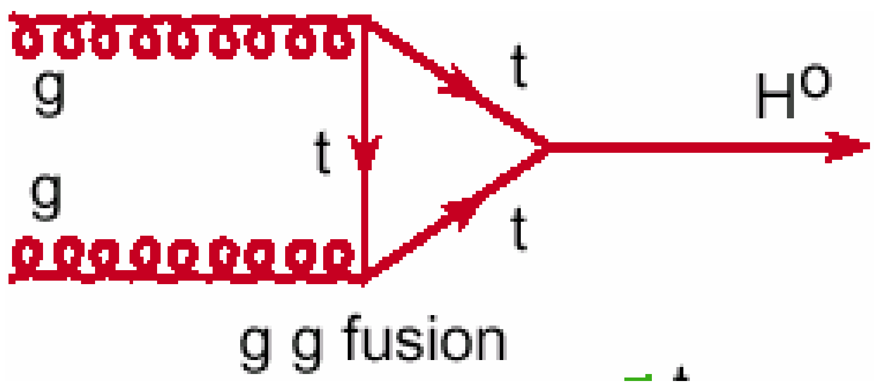
"Compromise" of various factors: production mechanism, decay mode, trigger & background.

Inclusive Higgs Searches

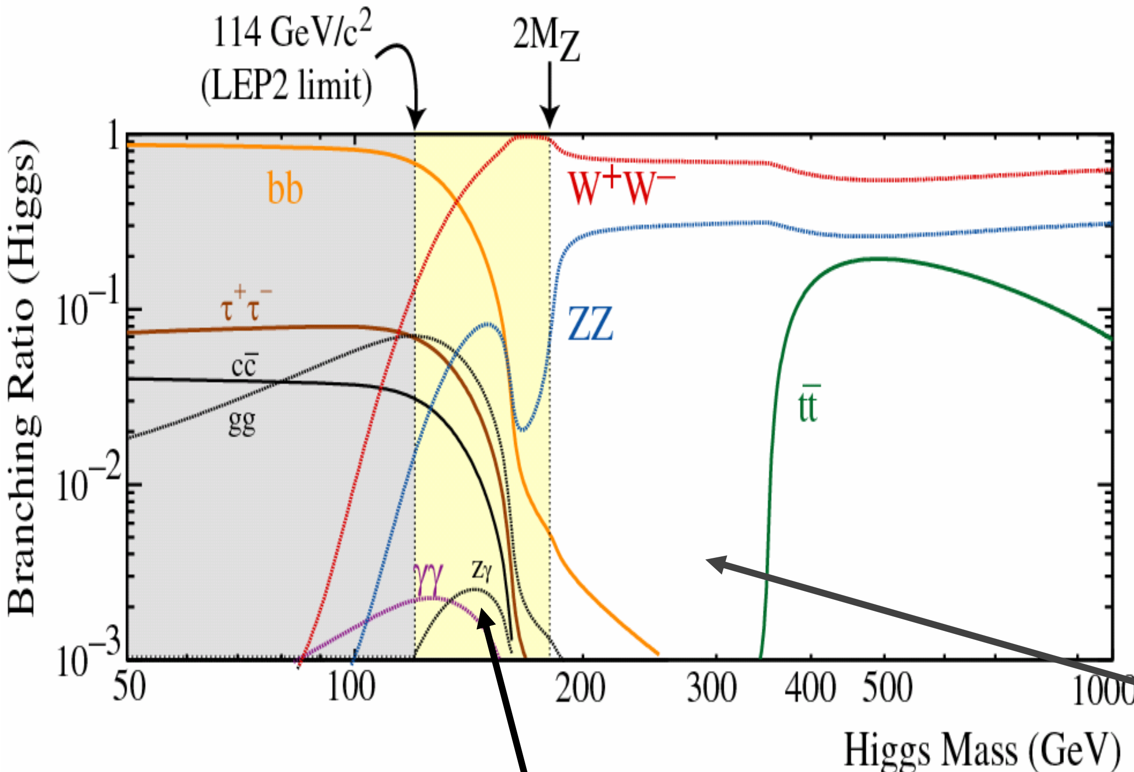
Do not use any feature of the production mechanism.

One makes less assumptions than in other search strategies. However to reduce the backgrounds need to have a clean final state with leptons or photons.

The gluon-gluon fusion channel has the highest rate.



Higgs Searches at LHC



Dominant BR for $m_H<2m_Z$:

σ (H → bb) ≈ 20 pb;

σ (bb) ≈ 500 μb

for m(H) = 120 GeV

→ no hope to trigger or extract fully hadronic final states

→ look for final states with ℓ, γ (ℓ = e,μ)

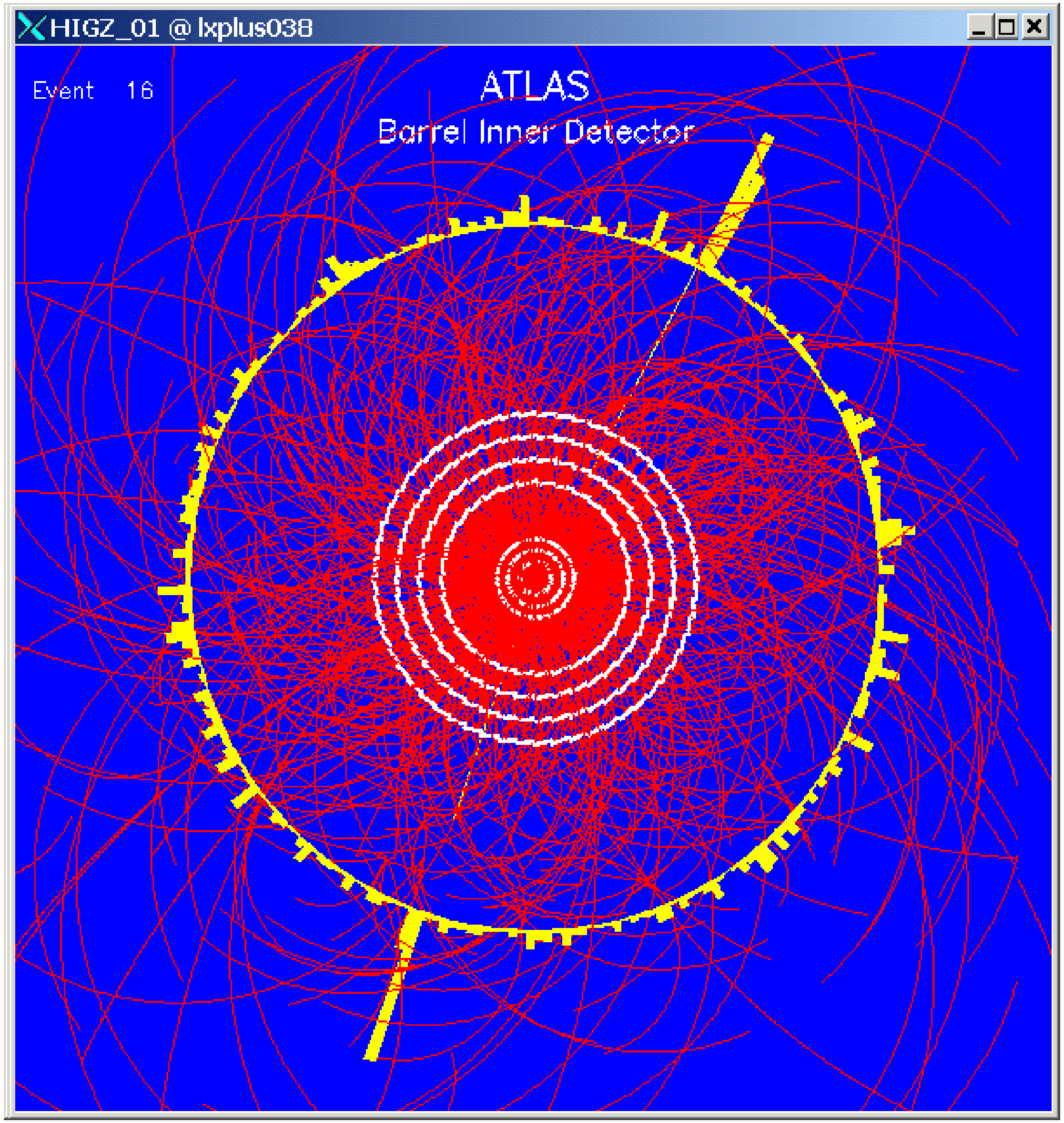
Low mass region: m(H) < 2 m_Z :

- H → $\gamma\gamma$: small BR, but best resolution
- H → bb : good BR, poor resolution: ttH, WH
- H → ZZ* → 4ℓ
- H → WW* → $\ell\nu\ell\nu$ or $\ell\nu$jj : via VBF
- H → $\tau\tau$: via VBF

m(H) > 2 m_Z :

- H → ZZ → 4ℓ
- qqH → ZZ → $\ell\ell$ $\nu\nu$
- qqH → ZZ → $\ell\ell$ jj
- qqH → WW → $\ell\nu$jj

H → γγ in ATLAS



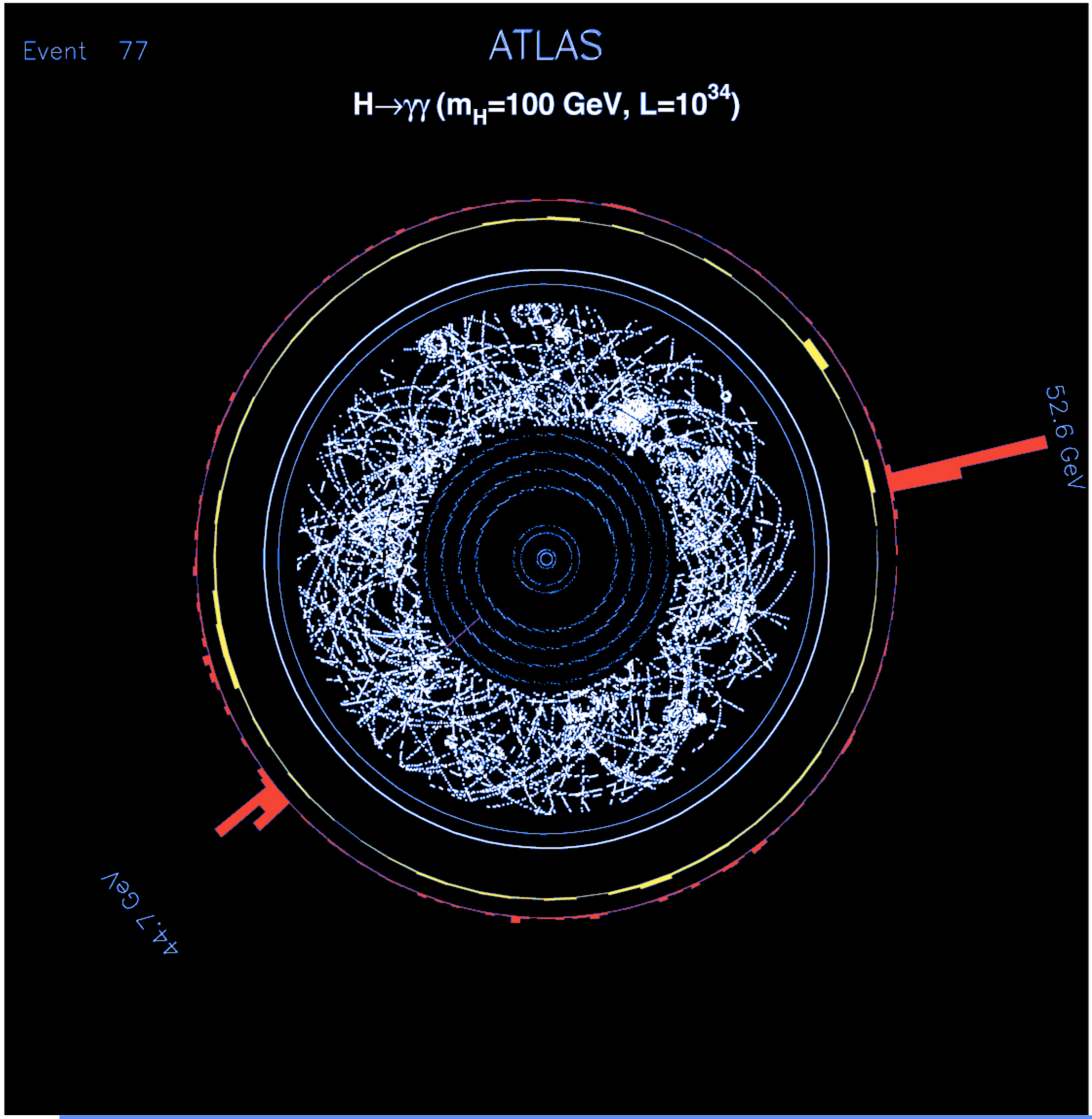
H → γγ
high luminosity
($L=10^{34}$ $cm^{-2}s^{-1}$)

23 interactions per bunch crossing

~1000 charged tracks

Expect one such event per billions of other similar events

$H \to \gamma\gamma$ in ATLAS



One photon converts to e^+e^- in ID material.

Note high number of low momentum tracks

($L=10^{34}$ cm^{-2} s^{-1})

Higgs Search: $H \rightarrow \gamma\gamma$

Features: Low mass range: <140 GeV; small BR (~2×10^{-3}) but over a smooth background; background can be estimated from data (side bands)

Trigger: High P_T di-photon trigger, single photon trigger

Backgrounds: Irreducible: 2γ production
Reducible: γ+jet , di-jet, etc

Analysis: Need good mass resolution of ~1%:
1. EM energy resolution
2. Primary vertex determination

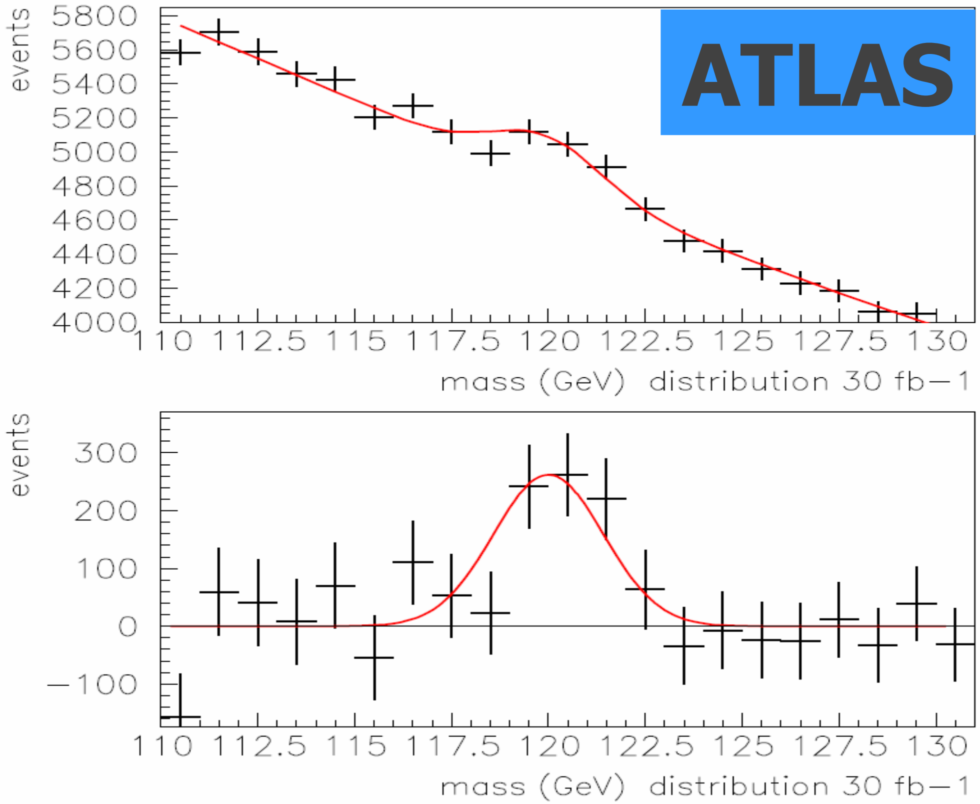
Higgs Search: H→γγ

Excellent photon ID essential (Rejection factor of ~10^3 for $e_\gamma \approx 80\%$). Make good use of:

1. **Photon isolation (tracker and calorimeter)**
2. **Study of shower shapes in calorimeter**

Photon conversion recovery important:

~50% γ convert before the calorimeter in the tracker material.



Higgs Search: H→ZZ*→4l

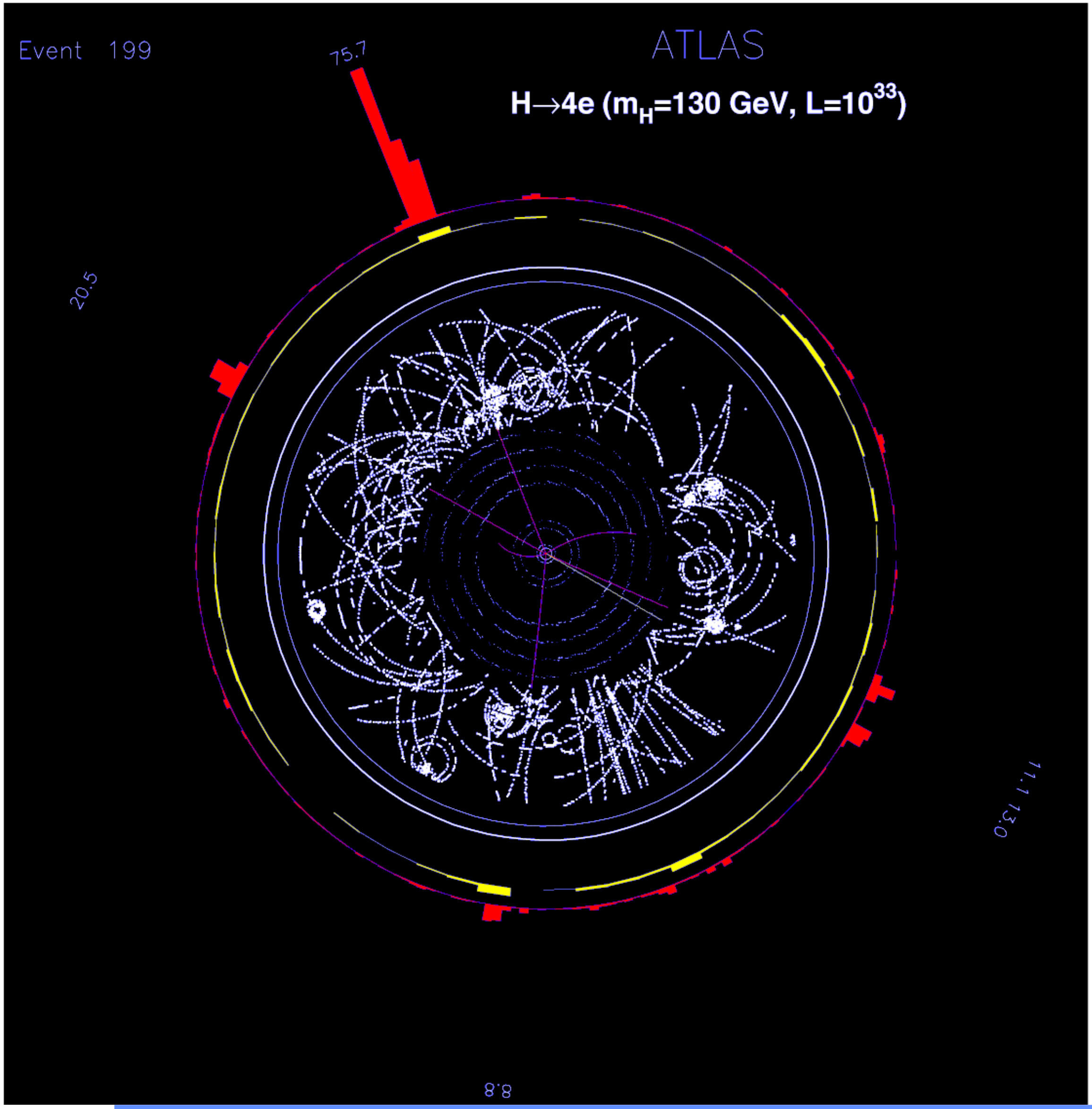
Features: Golden channel: for high mass;
low statistic for M_H<130 GeV,
Can use 4e, 4μ, 2e2μ.

Trigger: High P_T single and dilepton triggers

Backgrounds: Irreducible: qq,gg$\rightarrow$ZZ*/γ*$\rightarrow$4l
Reducible: Zbb$\rightarrow$4l, tt$\rightarrow$4l

Analysis: Reconstruction of low P_T e & μ
Good e & μ energy resolution (1-2%);
Recover e bremstralung effects
Background: lepton isolation (tracking and calorimeter) & impact parameter,
Can be estimated from sidebands

H → 4 e in ATLAS



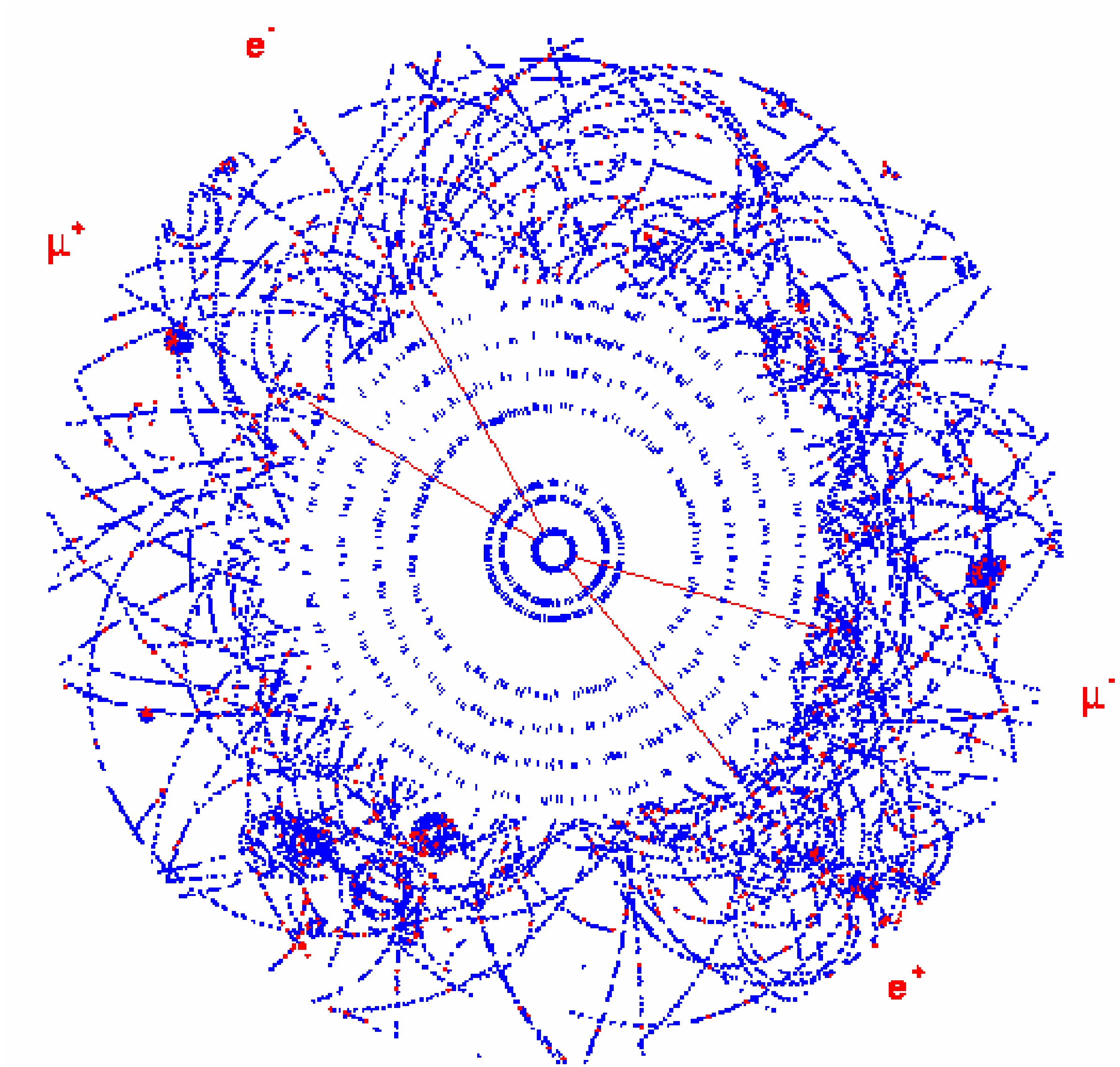
H → 4e event.

One electron emits high energy photon in beam pipe.

Only electron tracks shown in ID.

($L=10^{33}\ cm^{-2}\ s^{-1}$)

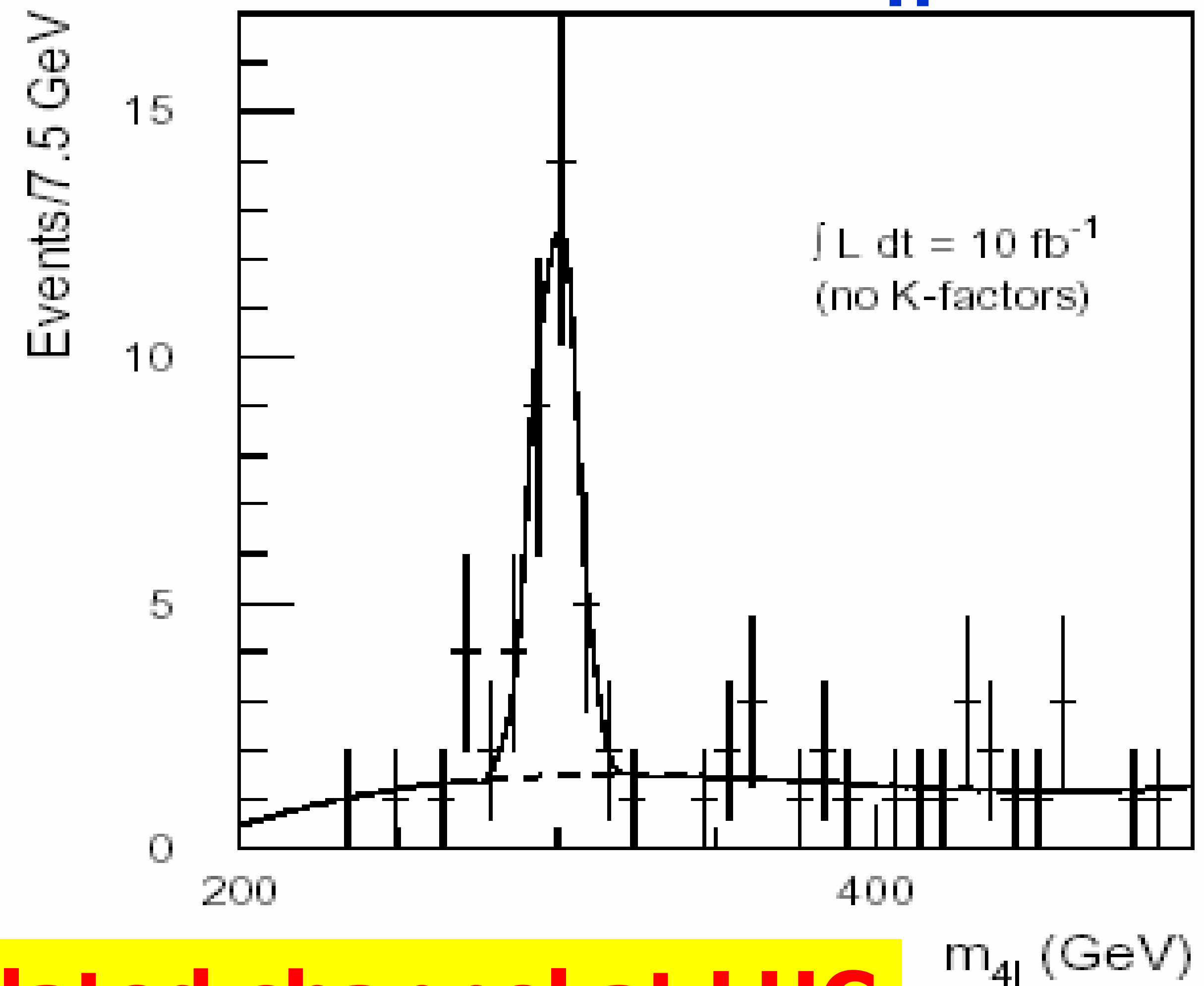
$H \rightarrow e^+e^-\mu^+\mu^-$ in ATLAS



Inner detector resolves high energy tracks in high occupancy environment

Higgs Search: H→ZZ*→4l

$H \rightarrow ZZ^{(*)} \rightarrow 4l$ with m_H = 300 GeV



Gold-plated channel at LHC

Higgs Search: $H \rightarrow WW^* \rightarrow 2l2\nu$

Features: Particularly interesting: $2M_W < M_H < 2M_Z$
2μ, 2e, eμ + E_T^{miss}.
No mass peak and high background that needs to be well understood.

Trigger: High P_T dilepton & single lepton triggers

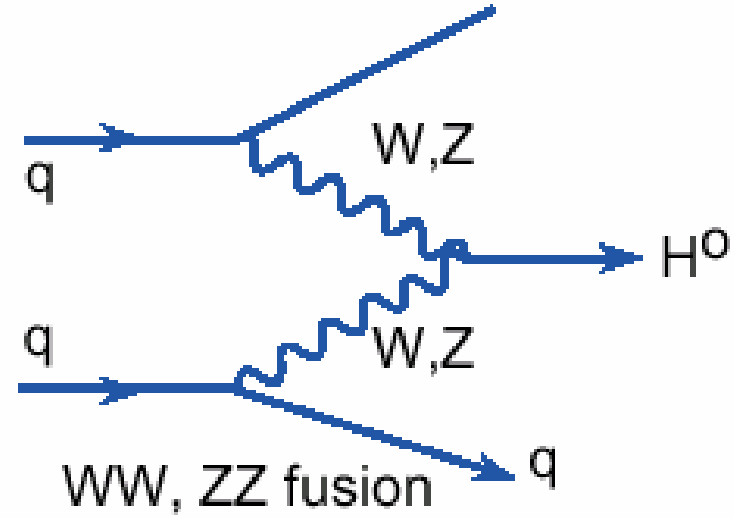
Backgrounds: Continuum WW, WZ, ZZ
tt production and single top production tWb, etc.

Analysis: Two isolated (tracking & calorimeter) opposite sign primary leptons & E_T^{miss}
Apply jet veto in the event.

Other Higgs Searches

Vector Boson Fusion

Lower rate than gluon-gluon fusion but clear signature.



Signatures

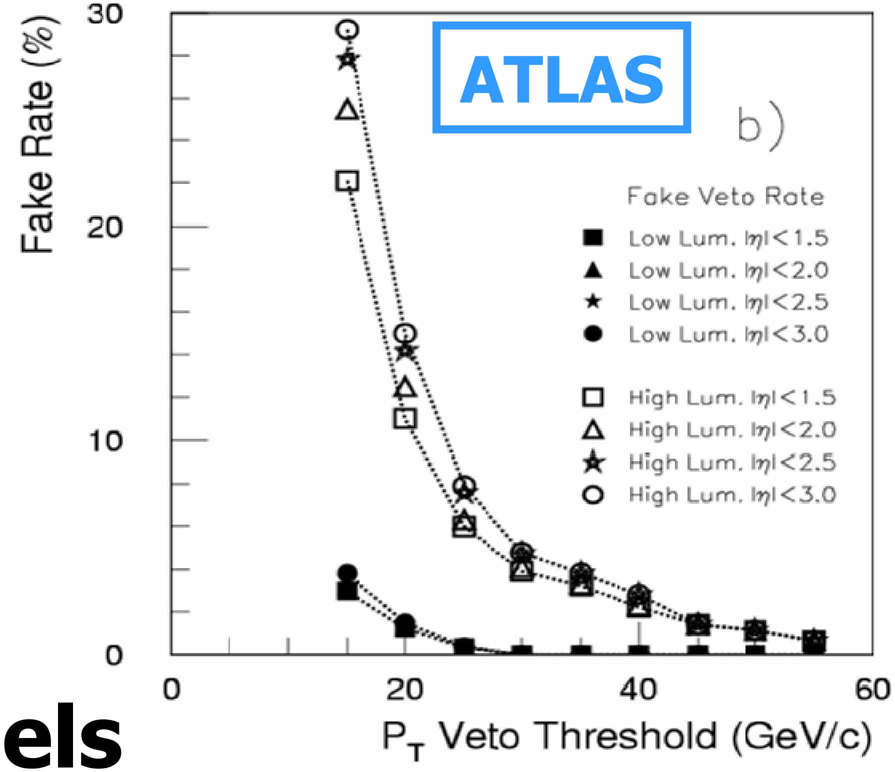
1. Two forward "tag" jets (large η separation with high-p_T) with large M_{jj}
2. No jet activity in the central region

• Tag jets are assumed to be the highest E_T jets in opposite hemispheres, with E_T>~40 GeV, $\Delta\eta_{jj}$>~4, M_{jj}>500-1000 GeV.

Experimental Issues in VBF

Good reconstruction efficiency for forward jet

Uncertainties on the robustness of jet veto in the presence of pile-up



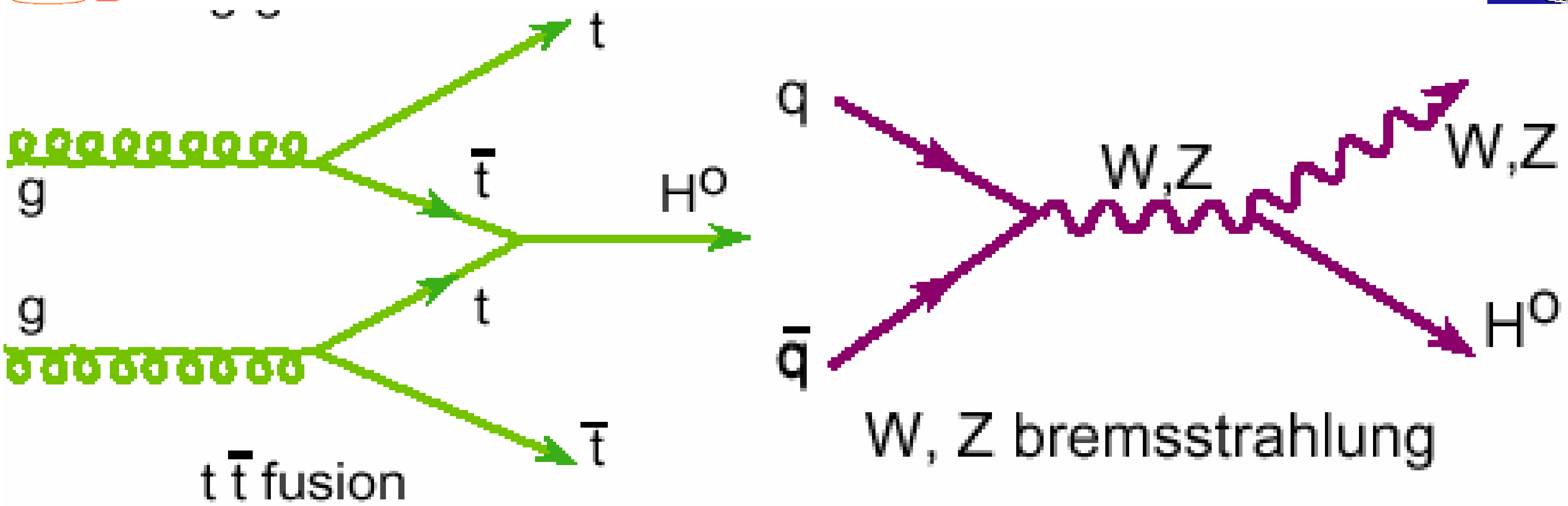
VBF Decay Channels

$qqH \rightarrow qq\gamma\gamma$

$qqH \rightarrow qqWW^{(*)}$ where $WW^{(*)} \rightarrow l\nu\ l\nu$ and $l\nu\ jj$

$qqH \rightarrow qq\tau\tau$ where $\tau\tau \rightarrow l\nu\nu\ l\nu\nu$, $l\nu\nu$ had ν and hadhad

Associated Production



pp $\rightarrow$ WH, ZH, ttH with W $\rightarrow$ lν, Z $\rightarrow$ ll or Z $\rightarrow$ $\nu\nu$

Dispite low rate, the leptons from W, Z and t$\rightarrow$Wb$\rightarrow$lνb can provide trigger and discrimination from background. Provide useful channels with higher integrated luminosity (~100 fb^{-1}).

Associated Production channels

pp → WH, ZH, ttH with H→γγ

WH → WWW(*)

ttH → ttbb (with one t decaying semileptonically)

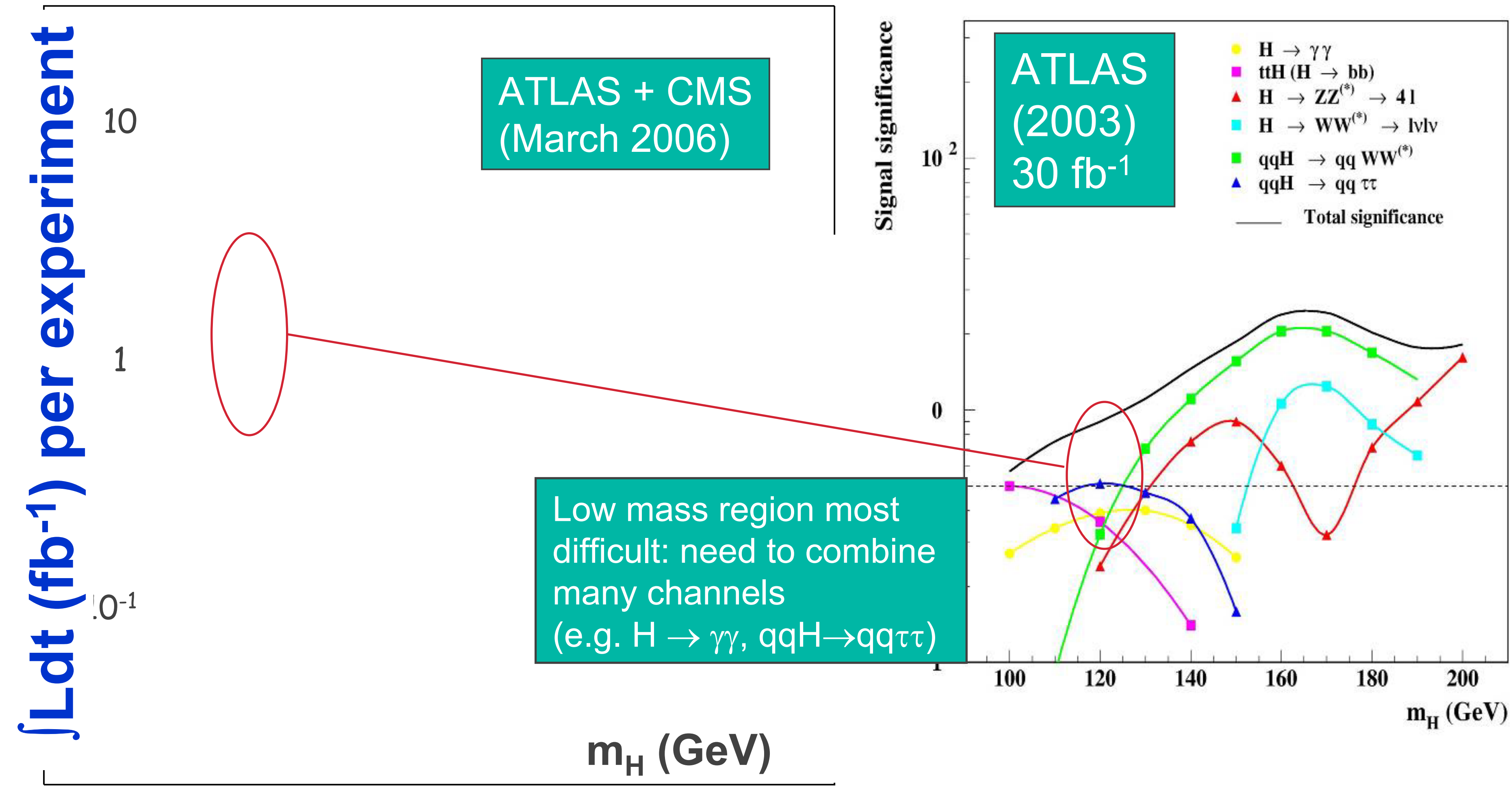
ZH → ll + invisible H decay products

After Higgs is discovered?

- **Precise measurements of Higgs Mass**
- **Higgs Decay Width, BRs, Spin, CP**
- **Yukawa Coupling**
- **Higgs Self-coupling**
- **……**

Higgs Discovery at LHC

Require ~~~~ <u>~fb^{-1} of well understood data</u>, with a light Higgs being the most difficult to observe: final word in 2010?



Why Supersymmetry (SUSY)?

SUSY ≡ symmetry bw fermions (matter) and bosons (forces)

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

$$\text{spin}\,(\tilde{p}) = \text{spin}\,(p) - 1/2$$

Higgs in minimal models (MSSM): h, H, A, $H^{\pm}$

Supersymmetry (SUSY)

R-Parity definition: $(-1)^{3(B-L)+2s}$

R-Parity = +1 (-1) for SM (SUSY) particles

If R-Parity is conserved :

-- **SUSY particles produced in pairs**

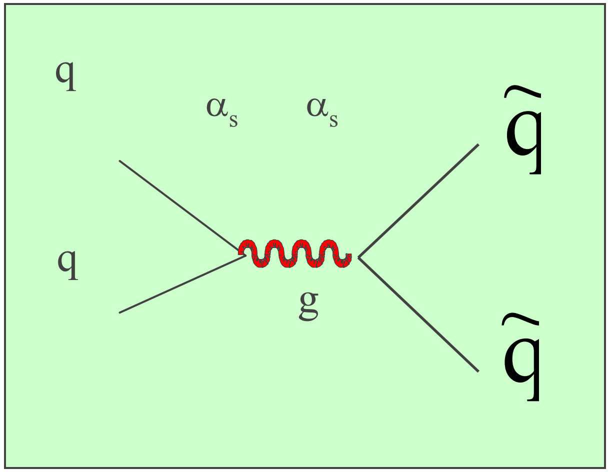
-- **Lightest SUSY Particle (LSP) is stable**
LSP: χ^0_1 weakly interacting
(natural dark matter candidate)

-- **all SUSY particles decay to LSP**

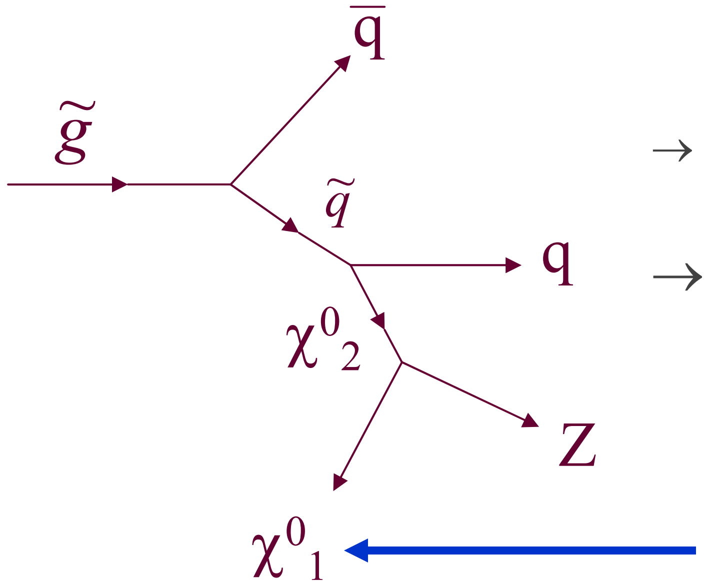
SUSY Search at LHC/ATLAS

- **Dominant processes :** $\tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$ **production**
  strong production $\rightarrow$ **huge cross-section**

  e.g. for $m(\tilde{q}, \tilde{g}) \sim 1$ TeV **~ 10^4 events produced in one year at low L**



- $\tilde{q}, \tilde{g}$ **heavy** $\rightarrow$ **cascade decays**



$\rightarrow$ **spectacular signatures with many jets, leptons + missing E**

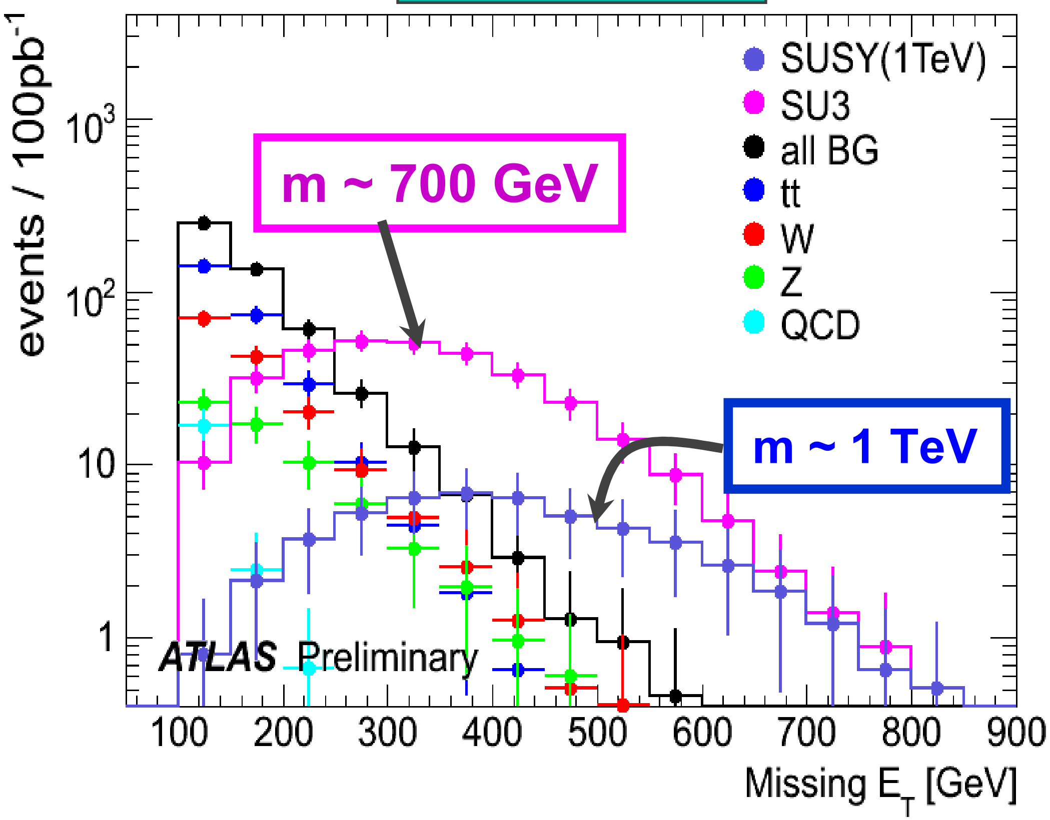
$\rightarrow$ **EASY to extract SUSY signal from SM backgrounds at LHC**

weakly interacting $\rightarrow$ **not detected**
$\rightarrow$ **missing energy in final state!**

SUSY Search at LHC/ATLAS

For squarks and gluinos with M ~ 1TeV, hints of a signal can already show up with 100pb^{-1}

100 pb^{-1}

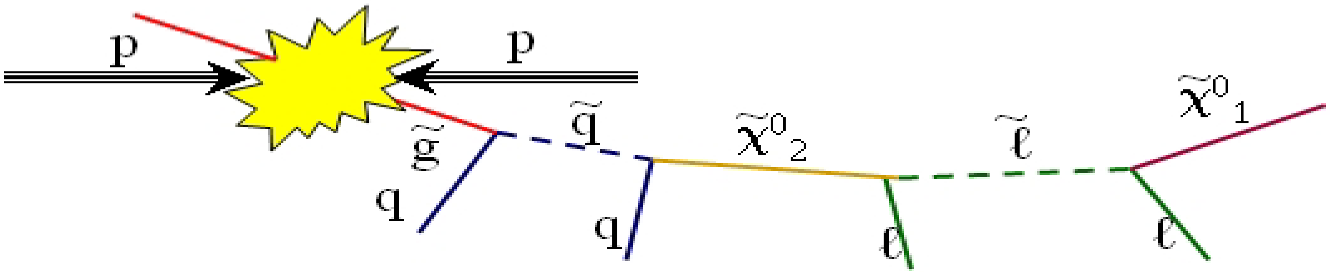


...but...

will need ~fb^{-1} of data to understand the backgrounds which could fake this:

- **W/Z + jets with Z → νν, W → τν; tt**
- **QCD multijet events with fake E_T^{miss} (calorimeter resolution, cracks, …)**
- **cosmics, beam-halo, detector problems overlapped with high-p_T triggers…**

Early SUSY Searches



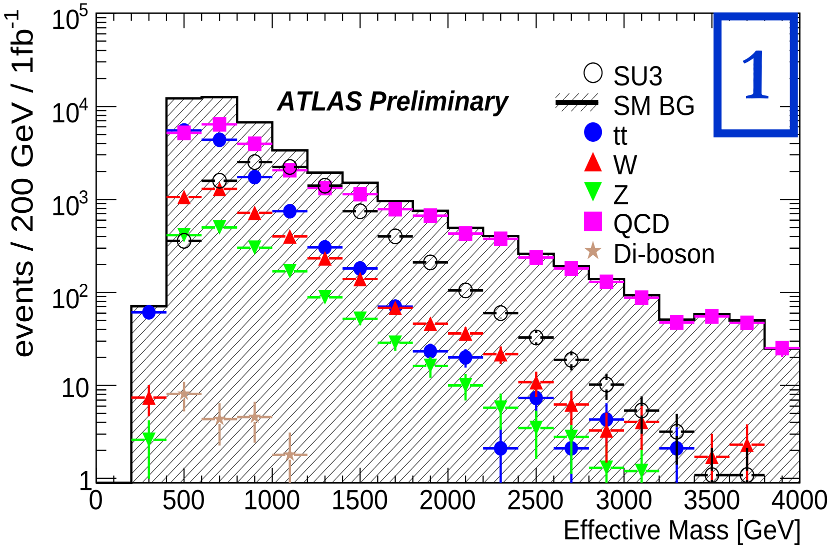
1. squark and gluino production ⇨ cascade decay ⇨ high Pt jets
2. LSP stable ⇨ large missing Et
3. Possibly some leptons

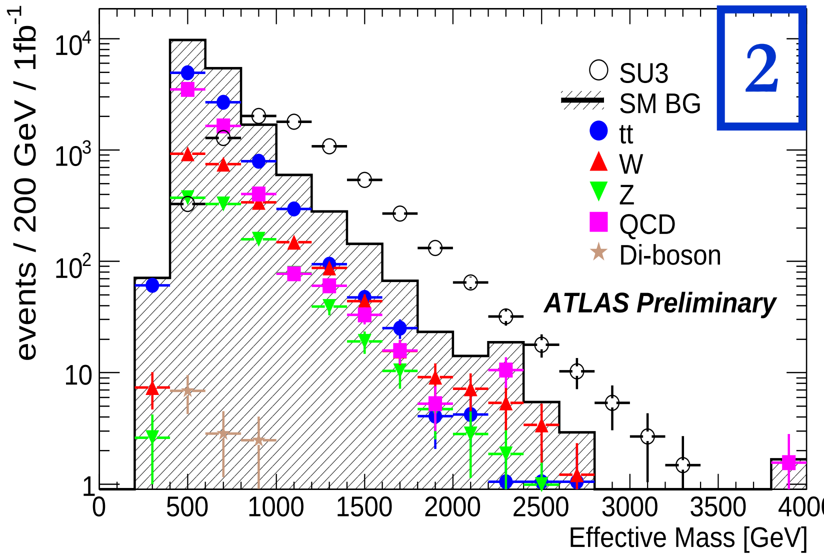
Large MET + multi-jets + multi-leptons

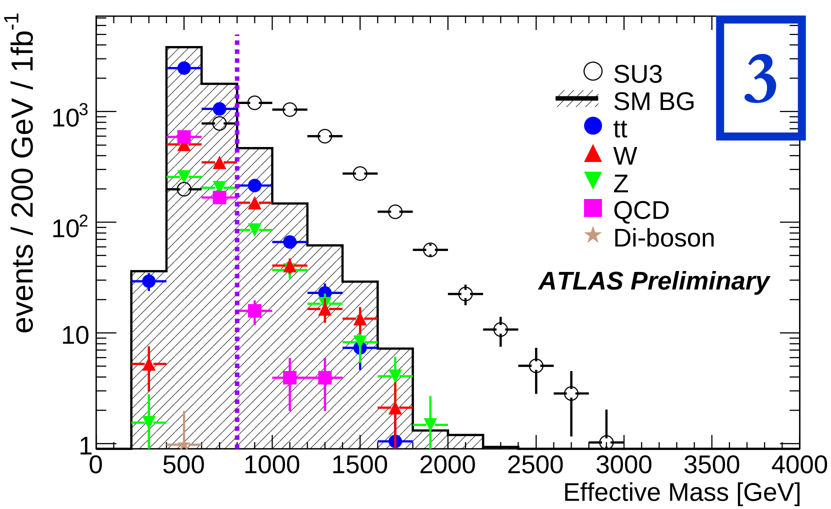
Data-driven determination of backgrounds

- Poor understanding of detector (missing Et tails, …) with early data
- Large theoretical uncertainties on background

Jets + MET + 0-Lepton







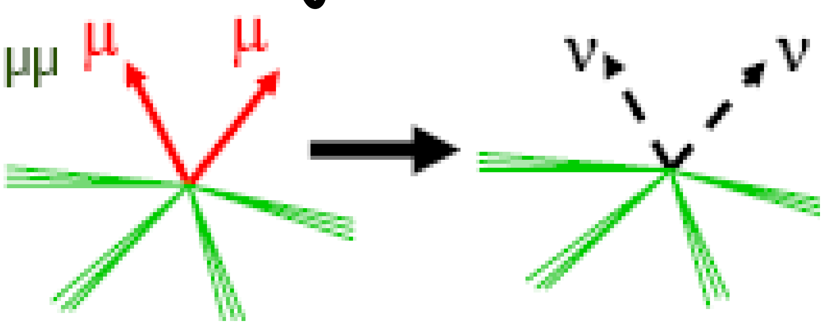
$$M_{eff} = MET + \Sigma P_T(jet)$$

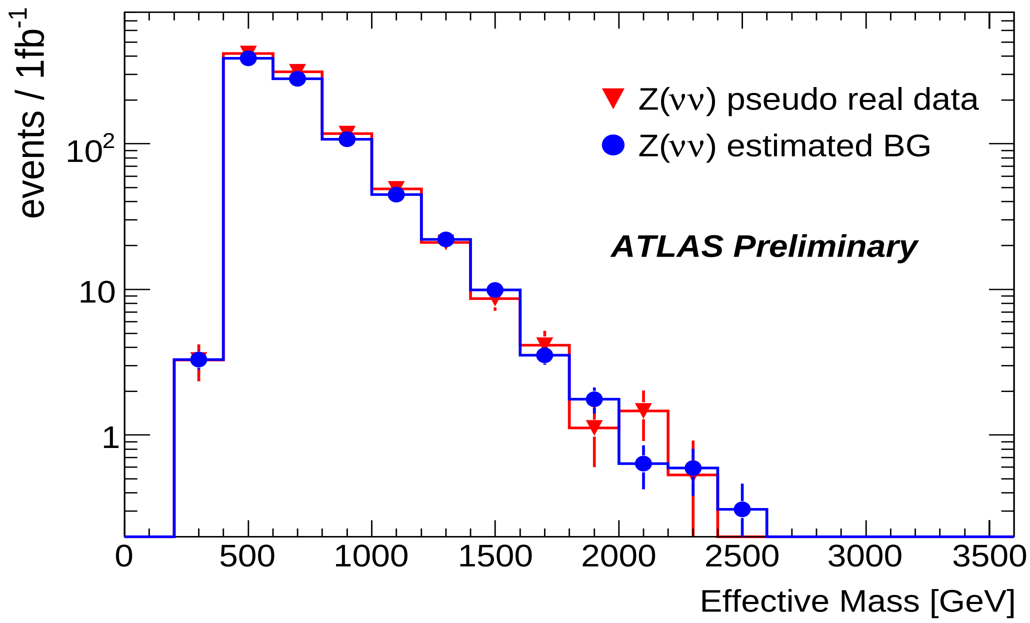
ATLAS selection cuts:

1. 4 jets, Pt(Jet1)>100GeV, Pt(Jet4)>50GeV, MET>100GeV
2. MET > $0.2 \times M_{eff}$
3. Transverse sphericity > 0.2
   $\Delta\varphi(MET, jet_{1,2,3}) > 0.2$
   no isolated e or μ (Pt>20GeV)
   J70_X70 combined trigger

Z/W+Jets BKG Estimation

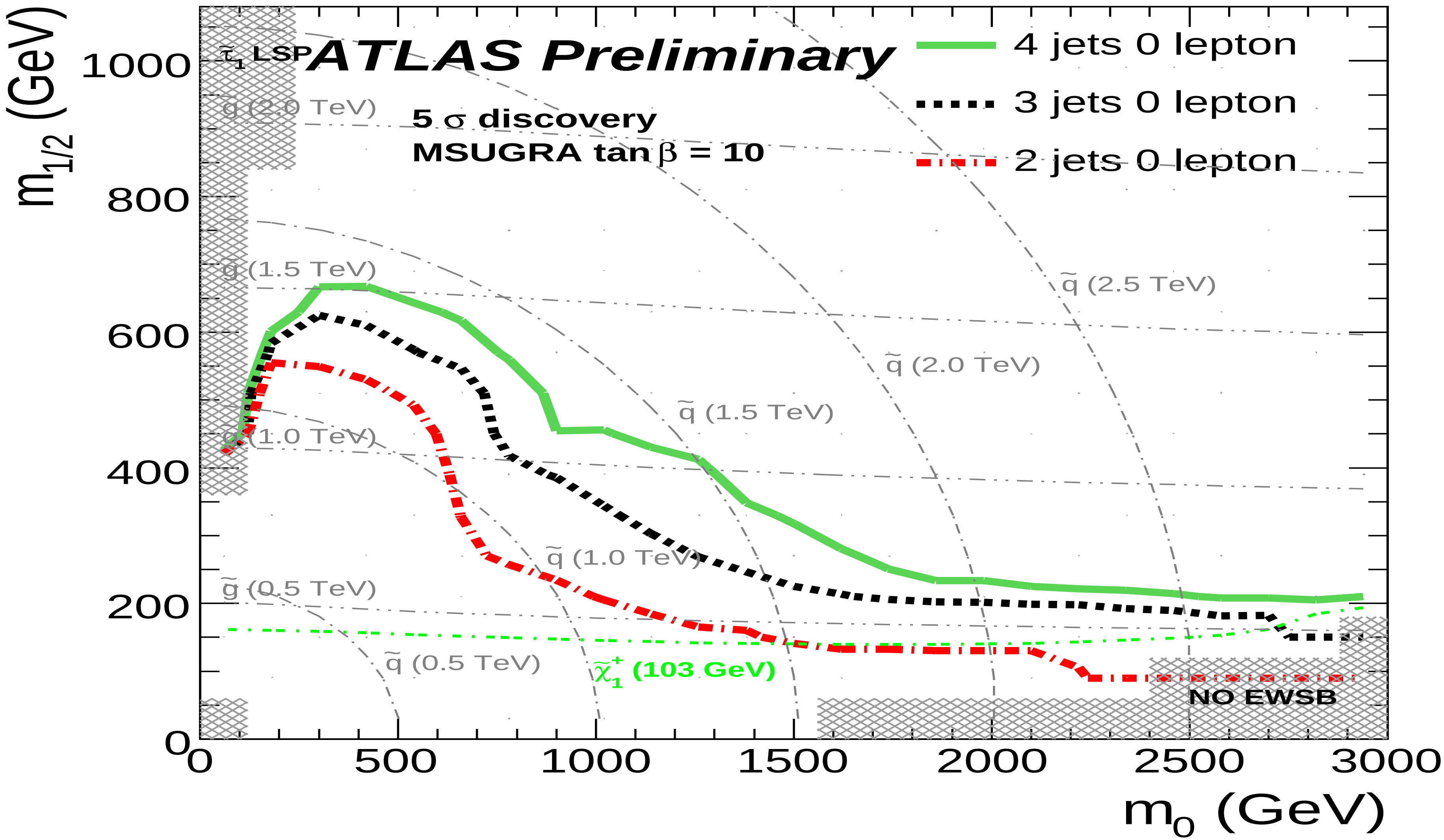
- $Z\to\nu\nu$ + jets is irreducible BKG in 0-lepton channel
- Can be estimated with $Z\to l^+l^-$ + jets



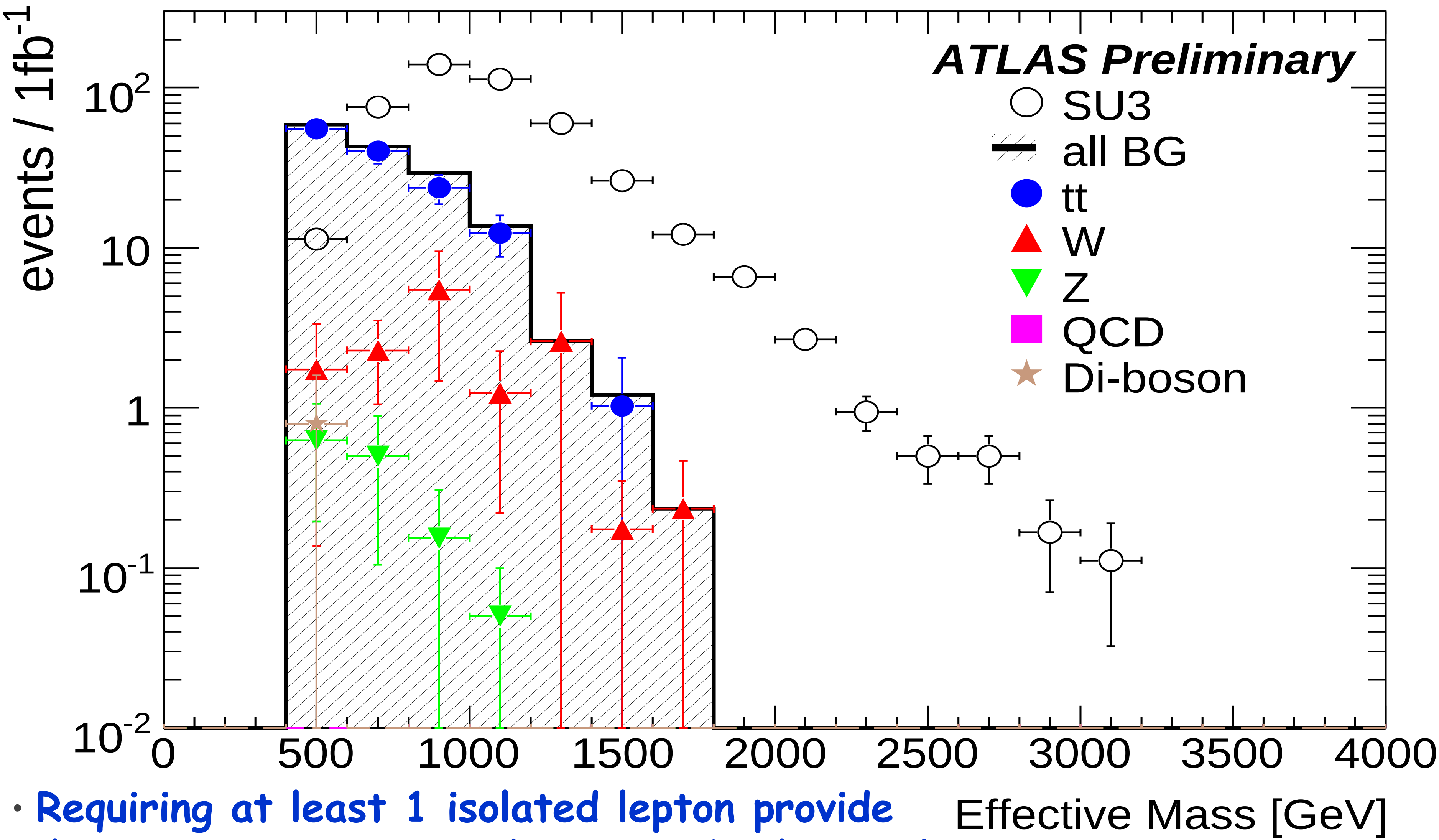


- **Main limiting factor: control sample statistics ($Br(Z\to l+l-)/Br(Z\to\nu\nu)\sim 0.17$)**
- **A good tail description requires MC or extrapolation methods**
  - W + jets background is due to $W\to\tau\nu\to$hadrons (42%) or $W\to e/\mu\nu$ with lepton out of acceptance (41%) or $W\to e/\mu\nu$ with non-selected lepton (17%)
  - it can be estimated from $Z\to l+l-$ + jets or $W\to l\nu$ + jets control samples

Jet+MET+0-l Discovery Reach



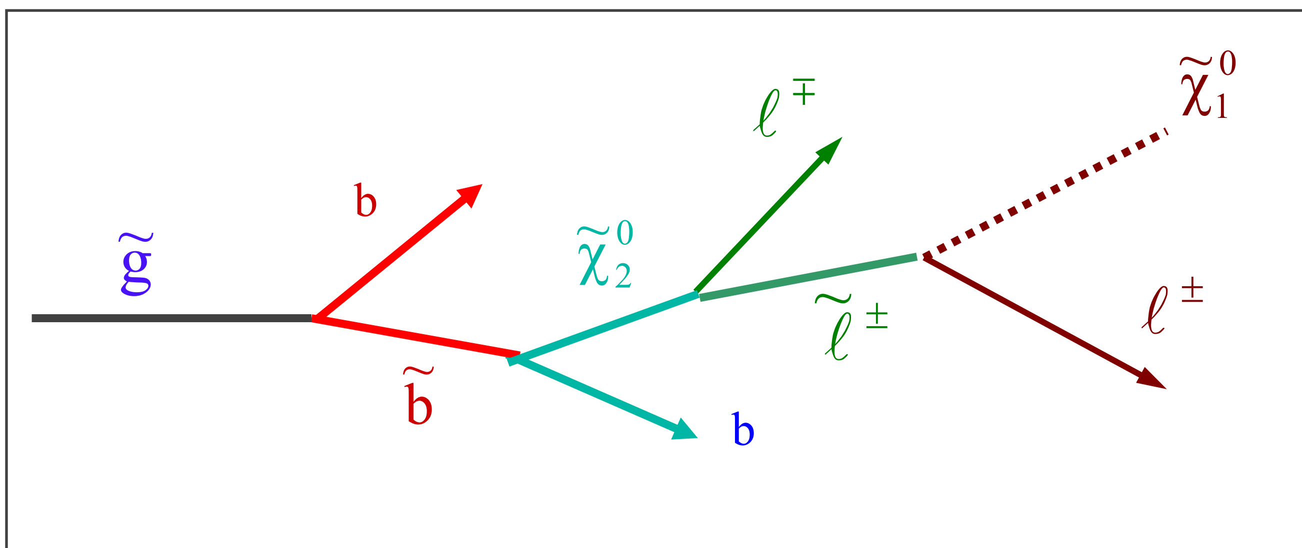
Jets + MET + 1-Lepton



- Requiring at least 1 isolated lepton provide clean signature as it reduce QCD background

After SUSY is found ……

- End-points (pure kinematics) of reconstructed mass spectra at each step of (long) squark/gluino decay chains.
- LSP's mass can be constrained indirectly from other measurements in the final state Impossible with one channel along



Road map for SUSY

Signatures: Jets + n leptons + E_T^{miss}

SUSY discovery potential

- SUSY @ 1 TeV with 0.1 fb^{-1}
- SUSY @ 2 TeV with (1 – 10) fb^{-1}
    - within 1 year of data taking
    - ~1 fb^{-1} well understood data crucial!

After inclusive SUSY events found

- Cannot claim SUSY without further precision measurement – may have found other BSM physics instead

What I haven't covered

- Top Physics
- Electroweak measurements
- B-Physics
- Extra Dimensions
- Black Holes, Gravitons,
- ......

The Road to Discovery

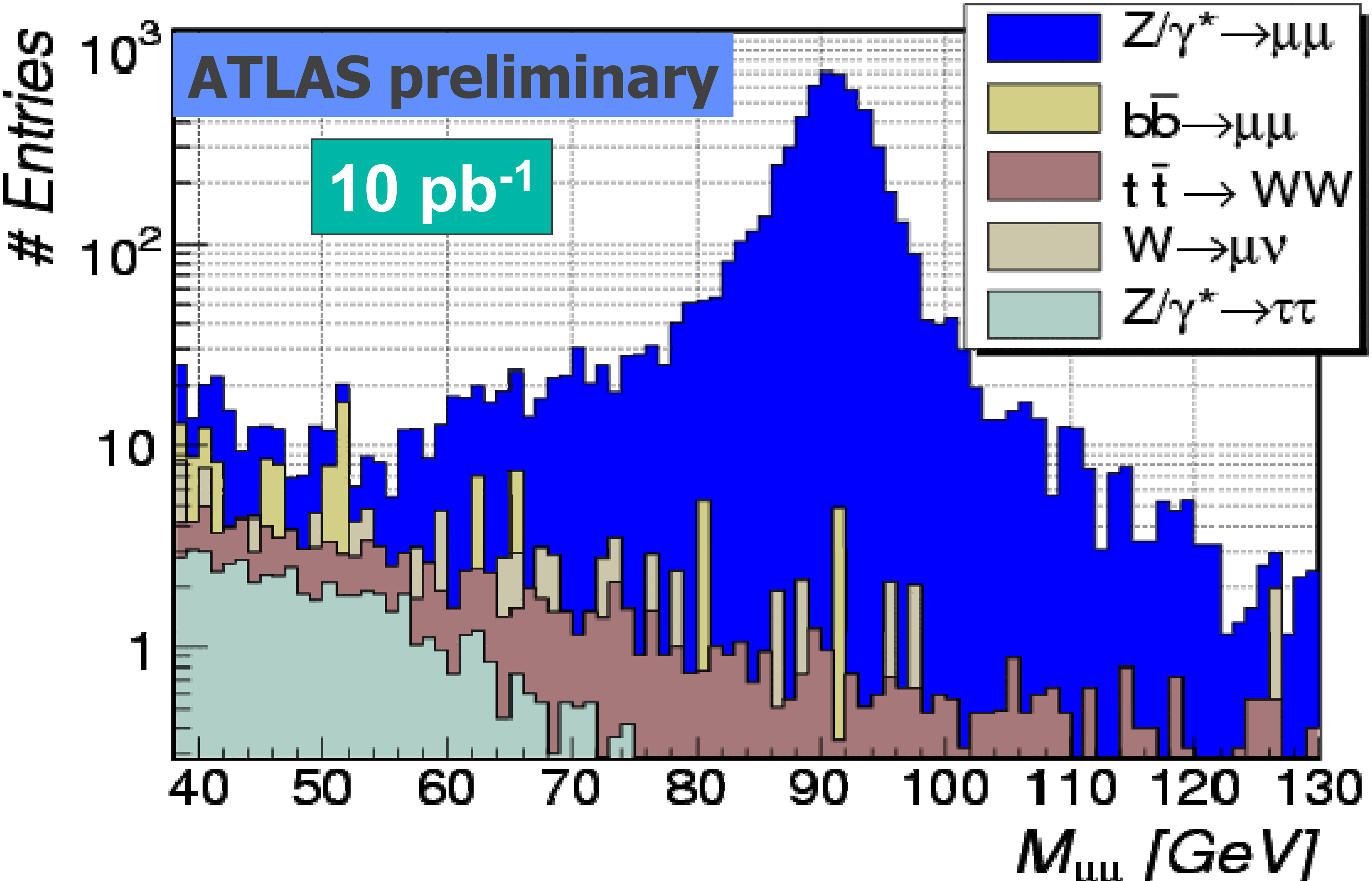
Step #1 **Understand/calibrate detector in situ using well-known processes (W, Z, top, etc) at 14TeV**

Channel	Events/ $100pb^{-1}$	Comparison	Leads to understanding of
$Z \rightarrow ee, \mu\mu$	$\sim10^4$	$\sim10^6$ LEP $\sim10^5$ Tevatron	ECAL energy scale and uniformity Tracking alignment
$W \rightarrow e\nu, \mu\nu$	$\sim10^5$	$\sim10^4$ LEP $\sim10^6$ Tevatron	ECAL energy scale Tracking alignment Constrain PDFs
$tt \rightarrow WbWb \rightarrow \mu\nu + X$	$\sim10^2$	$\sim10^4$ Tevatron	Jet scale from $W \rightarrow jj$ B tagging performance

Step #2 **Understand backgrounds to New Physics, e.g. tt and W/Z+ jets, ……**

Step #3 **Look for New Physics potentially accessible in first year(s), e.g. $Z' \rightarrow ee/\mu\mu$, SUSY, Higgs…?**

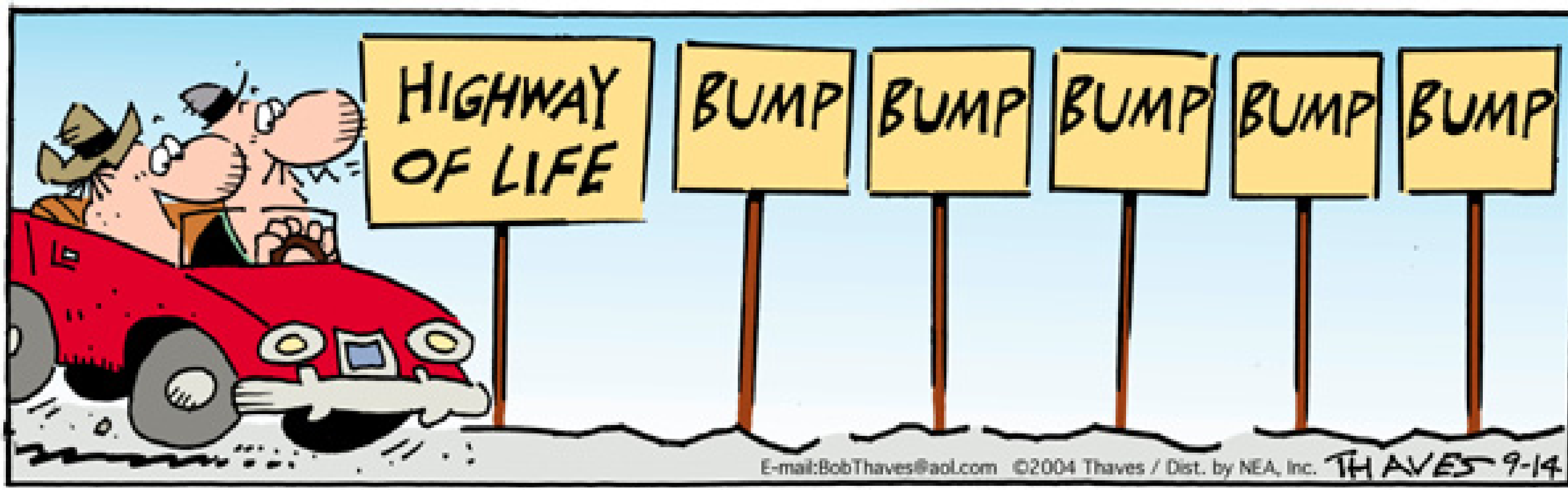
First peaks to search for ...

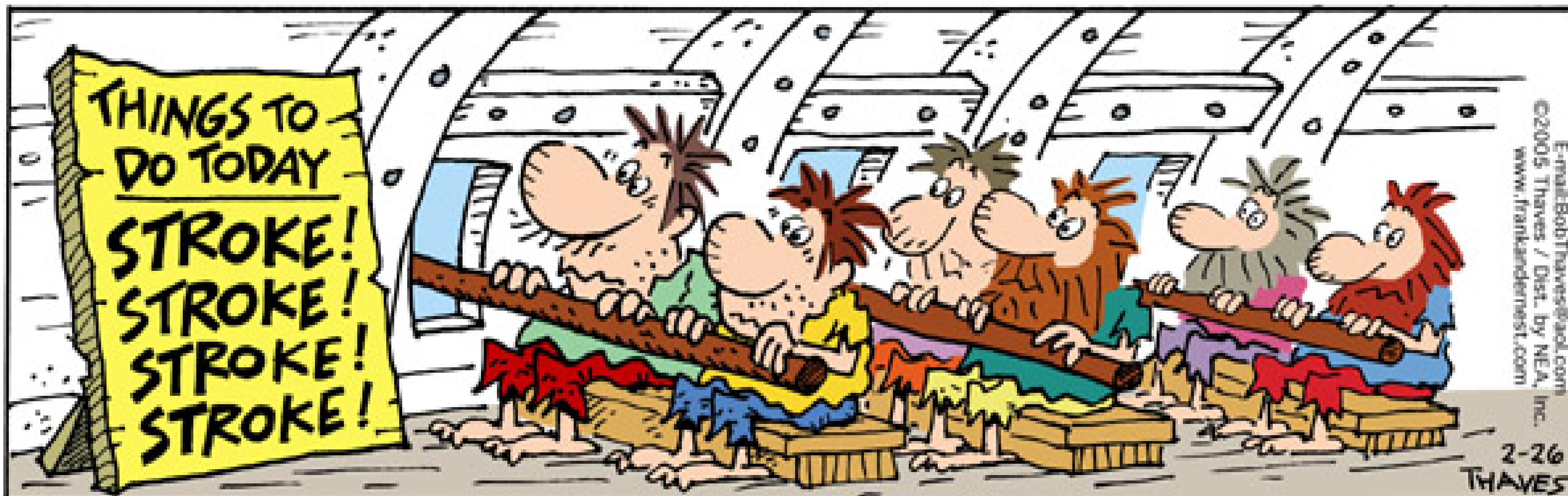


LHC Physics Program

- ATLAS/CMS: HUGE discovery potential for NP
  - -- SM Higgs : full mass range
  - -- SUSY up to m ~ 2 TeV
  - -- Beyond SUSY (LQ, W′, Z′, etc.) : up to m ~ 5 TeV
  - -- Many other New Physics at TeV scale
- Great potential for precise measurements:
  - -- m_W to ≈ 15 MeV
  - -- many measurements in top sector (precision ~ %)
  - -- Higgs mass : 1 ‰ (SM, h) to 1% (A/H)
  - -- many SUSY measurements
    → fundamental parameters to ≈ %
- Lot of challenges and hard work ahead of us!

Conclusion/Future Outlook





Conclusion/Future Outlook