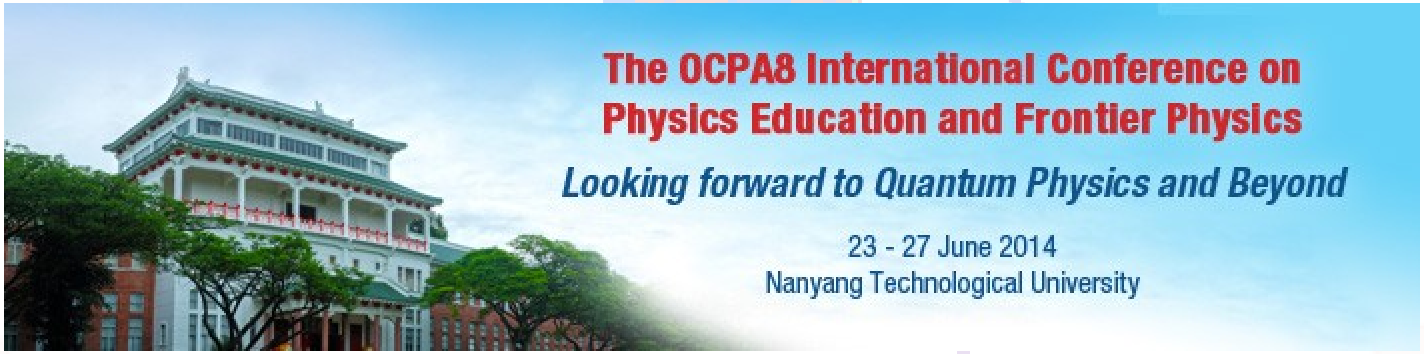
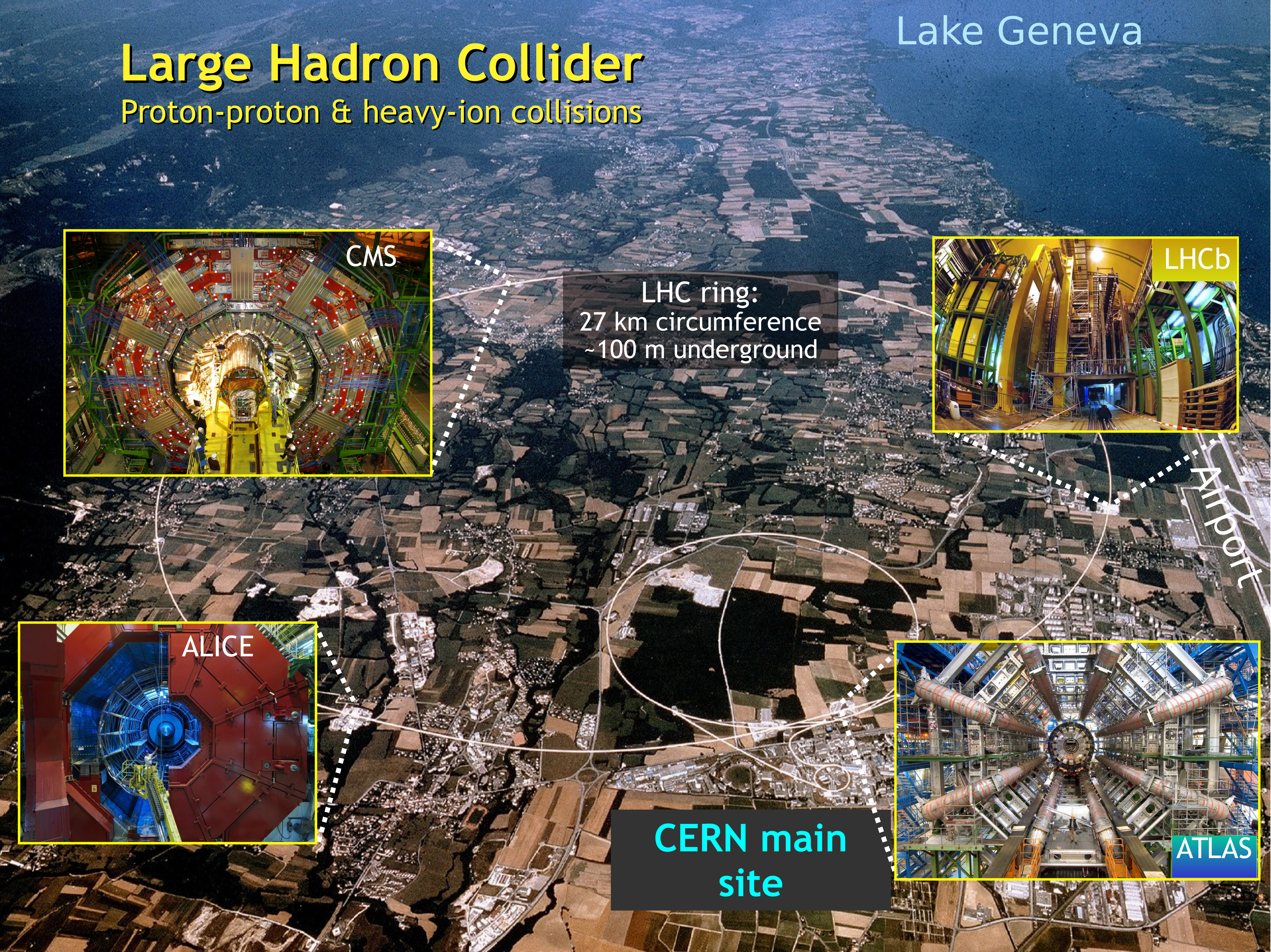
Highlights from ATLAS and CMS at the LHC

Dave Charlton
University of Birmingham
ATLAS Collaboration

OCPA8 Meeting
Nanyang Technological University,
Singapore, 24 June 2014



The LHC, ATLAS and CMS



Large Hadron Collider
Proton-proton & heavy-ion collisions
Lake Geneva
CMS
LHC ring:
27 km circumference
~100 m underground
LHCb
Airport
ALICE
CERN main site
ATLAS

Large Hadron Collider

Proton-proton & heavy-ion collisions

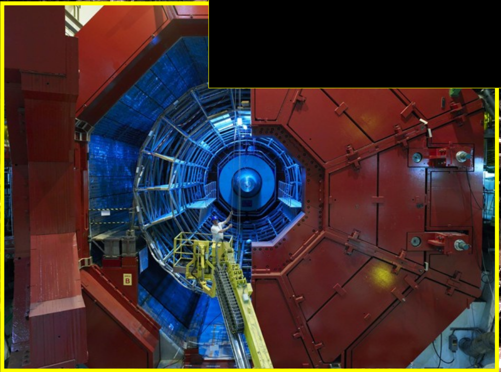
Lake Geneva

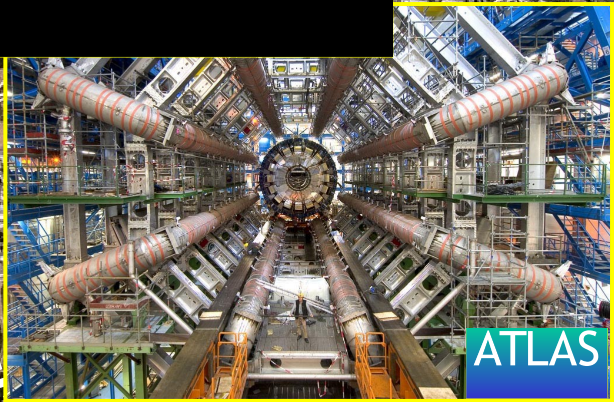
LHC ring:
27 km circumference
~100 m underground

ATLAS and CMS are the two general-purpose discovery experiments

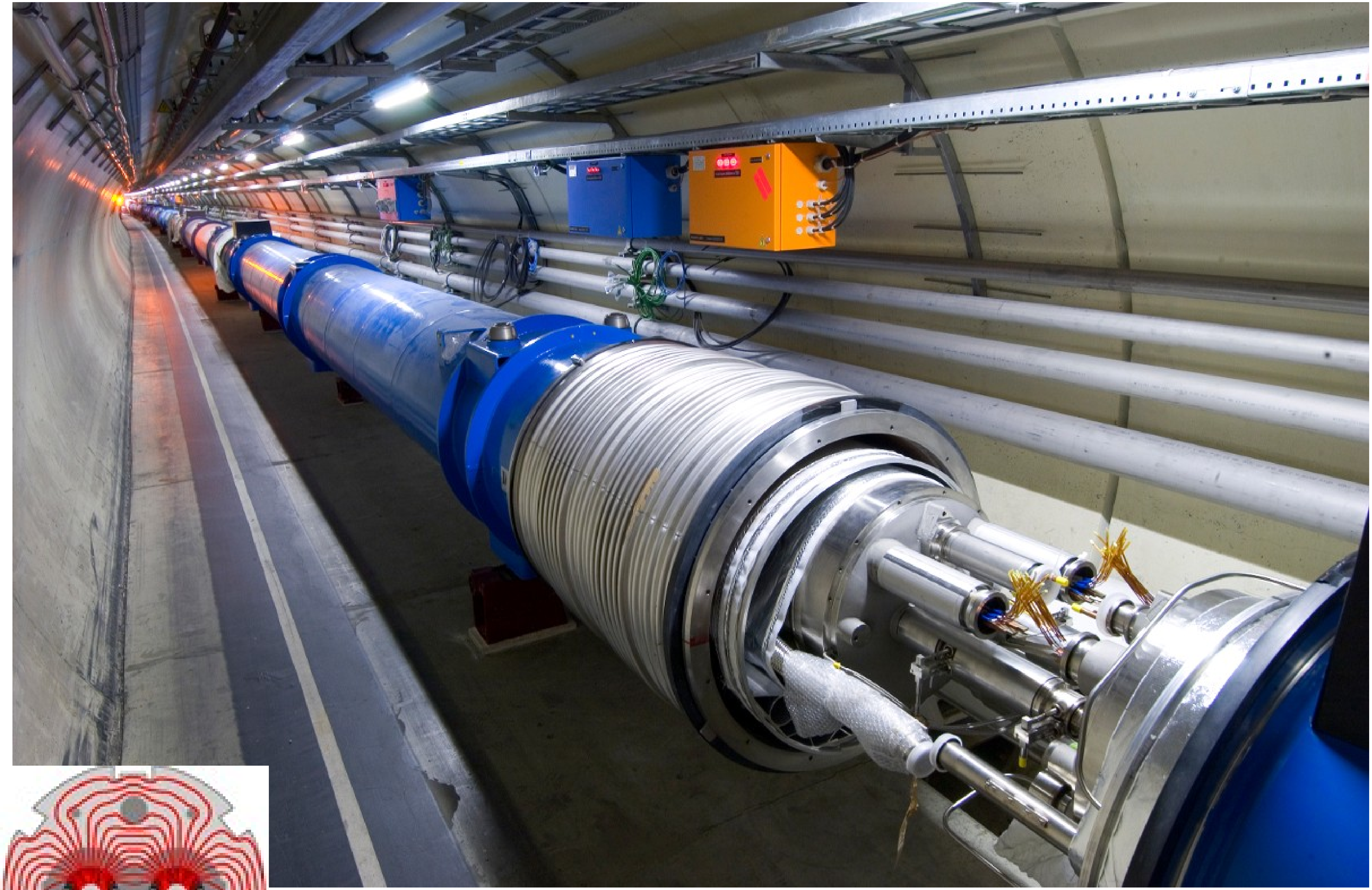
I will only cover a few highlights from these two

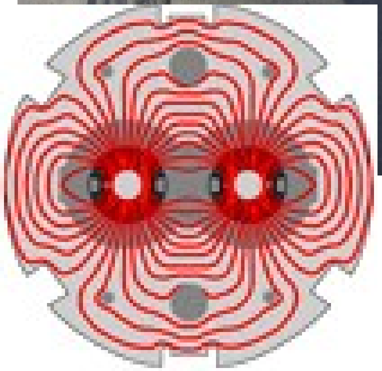
Airport





CERN main site

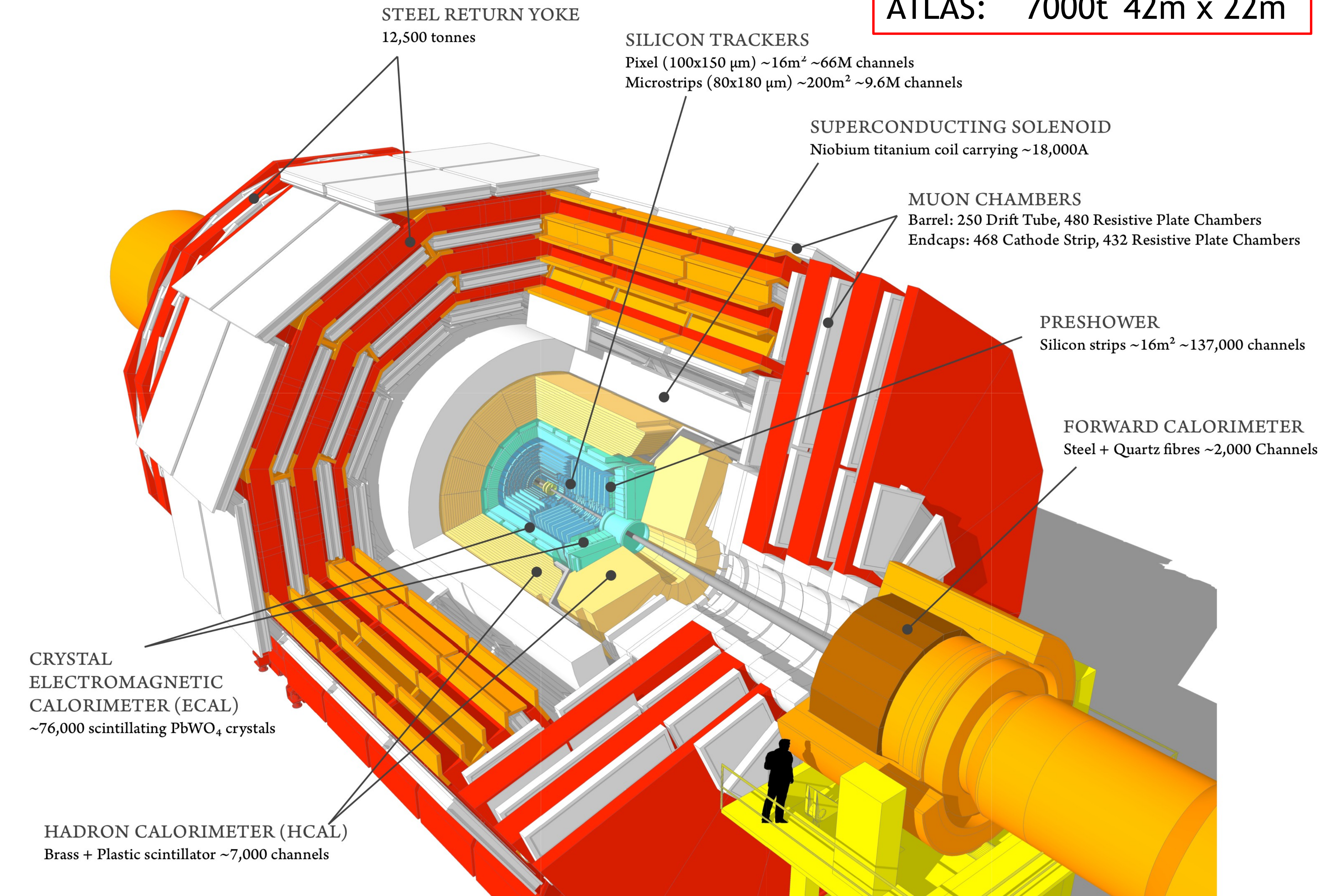




- 1232 14m-long superconducting main dipoles
- Two-in-one coil design
- Maximum field 8.4 T
- Cooled to 1.9K with 90t on LHe

CMS Detector

CMS:	12500t	21m x 15m
ATLAS:	7000t	42m x 22m



Global collaborations

ATLAS: 178 institutions from 38 countries

2900 scientific authors, including 1000 students

Adelaide, Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizona, UT Arlington, Athens, NTU Athens, Baku, IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, HU Berlin, Bern, Birmingham, UAN Bogota, Bologna, Bonn, Boston, Brandeis, Bratislava/SAS Kosice, Brazil Cluster, Brookhaven NL, Buenos Aires, Bucharest, Cambridge, Carleton, CERN, Chinese Cluster, Chicago, Chile, Clermont-Ferrand, Columbia, NBI Copenhagen, Cosenza, AGH UST Cracow, IFJ PAN Cracow, SMU Dallas, UT Dallas, DESY, Dortmund, TU Dresden, JINR Dubna, Duke, Edinburgh, Frascati, Freiburg, Geneva, Genoa, Giessen, Glasgow, Göttingen, LPSC Grenoble, Technion Haifa, Hampton, Harvard, Heidelberg, Hiroshima IT, Hong Kong, Indiana, Innsbruck, Iowa SU, Iowa, UC Irvine, Istanbul Bogazici, KEK, Kobe, Kyoto, Kyoto UE, Kyushu, Lancaster, UN La Plata, Lecce, Lisbon LIP, Liverpool, Ljubljana, QM London, RH London, UC London, Louisiana Tech, Lund, UA Madrid, Mainz, Manchester, CPPM Marseille, Massachusetts, MIT, Melbourne, Michigan, Michigan SU, Milano, Minsk NAS, Minsk NCPHEP, Montreal, McGill Montreal, RUPHE Morocco, FIAN Moscow, ITEP Moscow, MEPhI Moscow, MSU Moscow, Munich LMU, MPI Munich, Nagasaki IAS, Nagoya, Naples, New Mexico, New York, Nijmegen, Northern Illinois University, BINP Novosibirsk, NPI Petersburg, Ohio SU, Okayama, Oklahoma, Oklahoma SU, Olomouc, Oregon, LAL Orsay, Osaka, Oslo, Oxford, Paris VI and VII, Pavia, Pennsylvania, Pisa, Pittsburgh, CAS Prague, CU Prague, TU Prague, IHEP Protvino, Rome I, Rome II, Rome III, RAL-STFC, DAPNIA Saclay, Santa Cruz UC, Sheffield, Shinshu, Siegen, Simon Fraser Burnaby, SLAC, South Africa Cluster, Stockholm, KTH Stockholm, Stony Brook, Sydney, Sussex, AS Taipei, Tbilisi, Tel Aviv, Thessaloniki, Tokyo ICEPP, Tokyo MU, Tokyo Tech, Toronto, TRIUMF, Tsukuba, Tufts, Udine/ICTP, Uppsala, UI Urbana, Valencia, UBC Vancouver, Victoria, Warwick, Waseda, Washington, Weizmann Rehovot, FH Wiener Neustadt, Wisconsin, Wuppertal, Würzburg, Yale, Yerevan

The Worldwide LHC Computing Grid

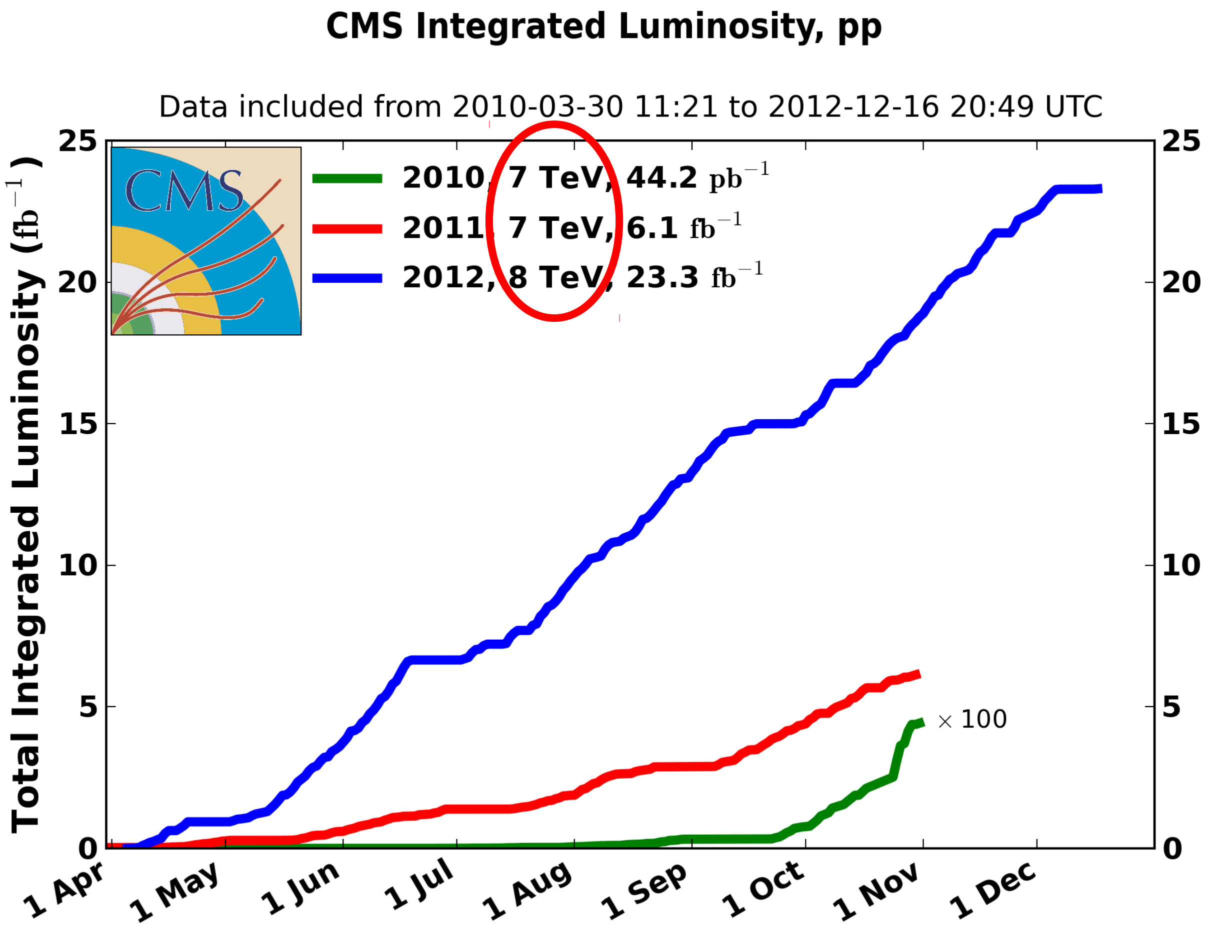
Each year, ATLAS and CMS write 10's PB of data
Around 250 000 CPU cores on the computing Grid are used, spread over ~200 sites, to analyse them

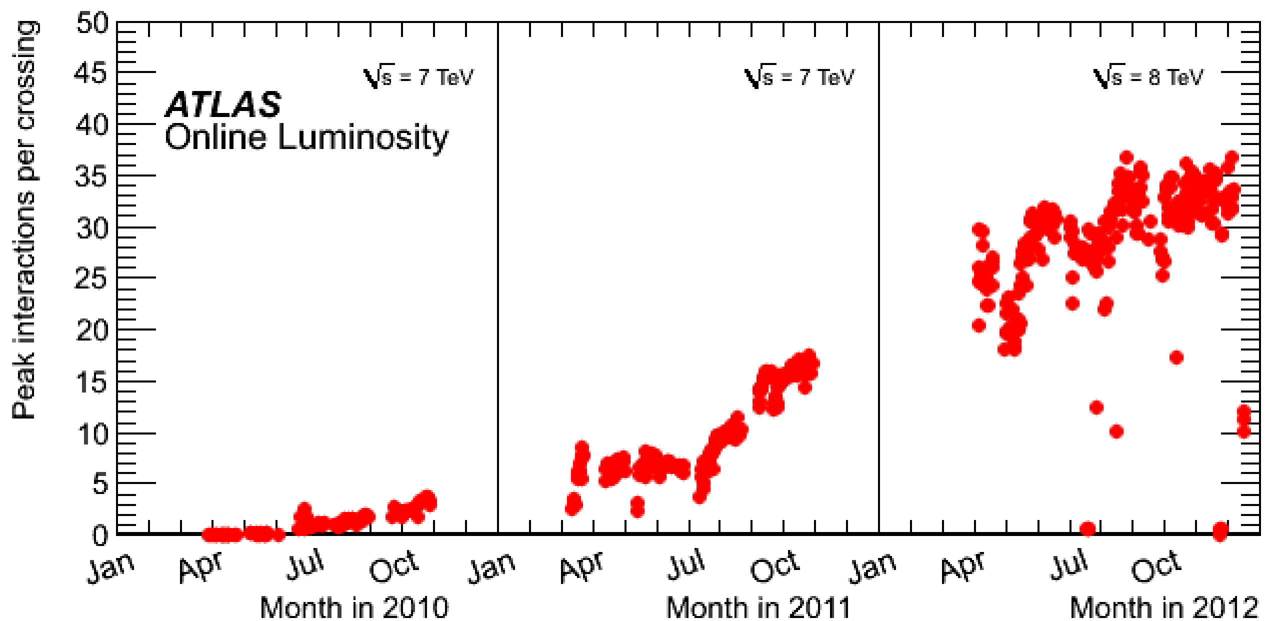
Data collected

Key parameters:
c-of-m energy $\sqrt{s}$ and also integrated luminosity

$$N_{obs} = \sigma \, \varepsilon_{exp} \int L dt$$

The price of high luminosity: pile-up





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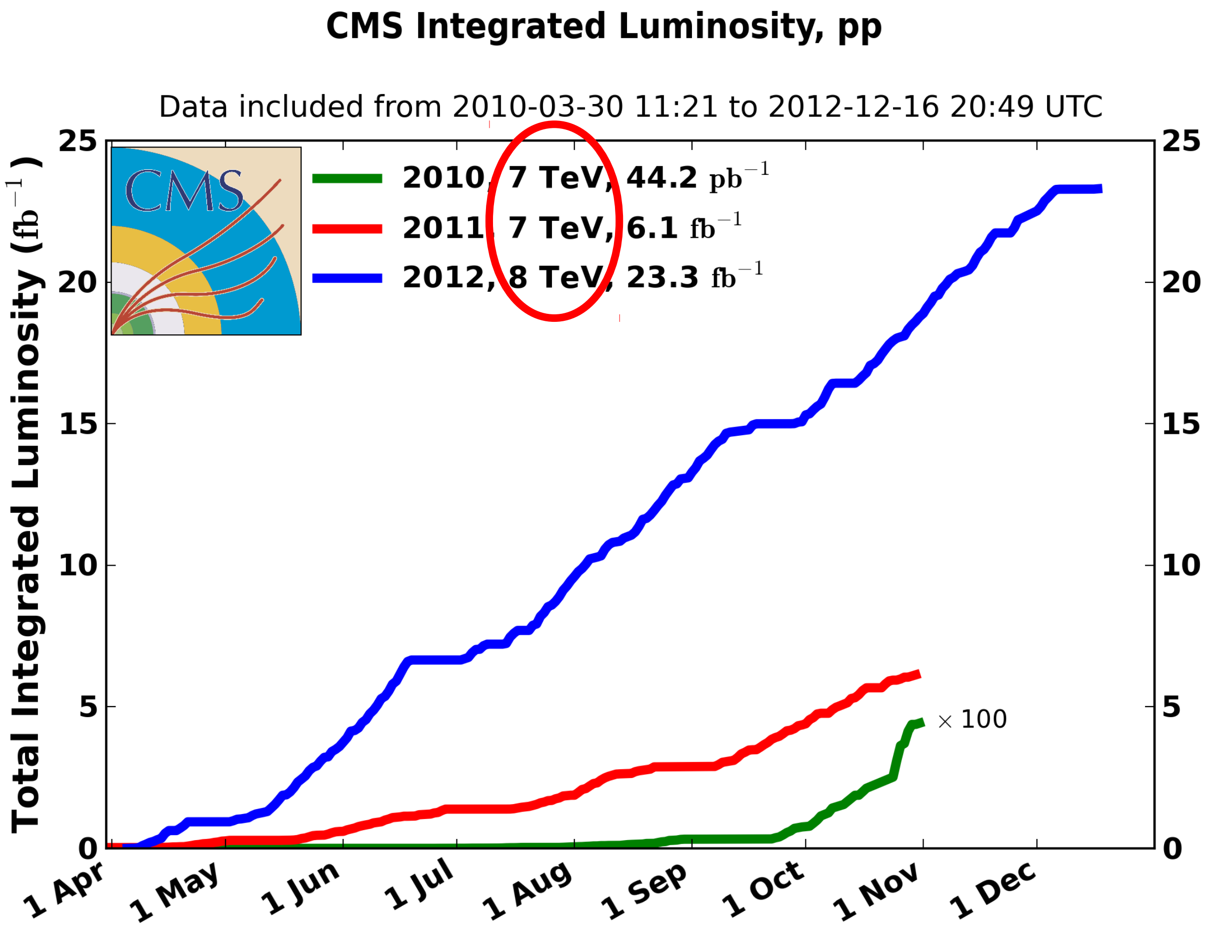
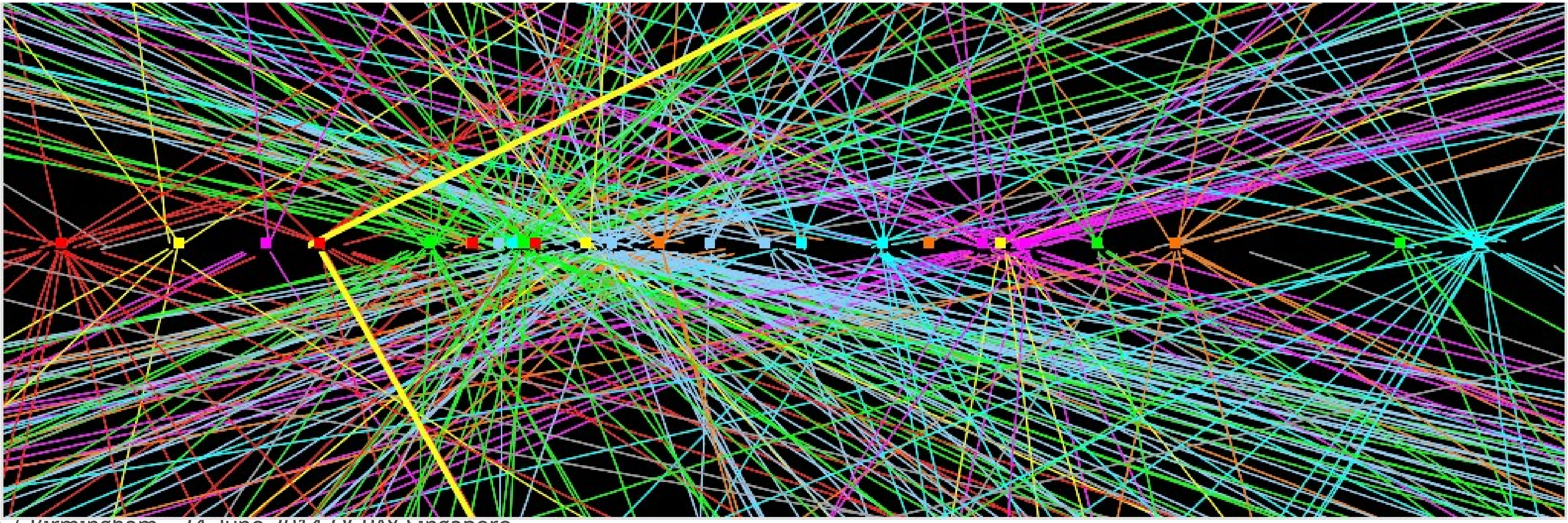
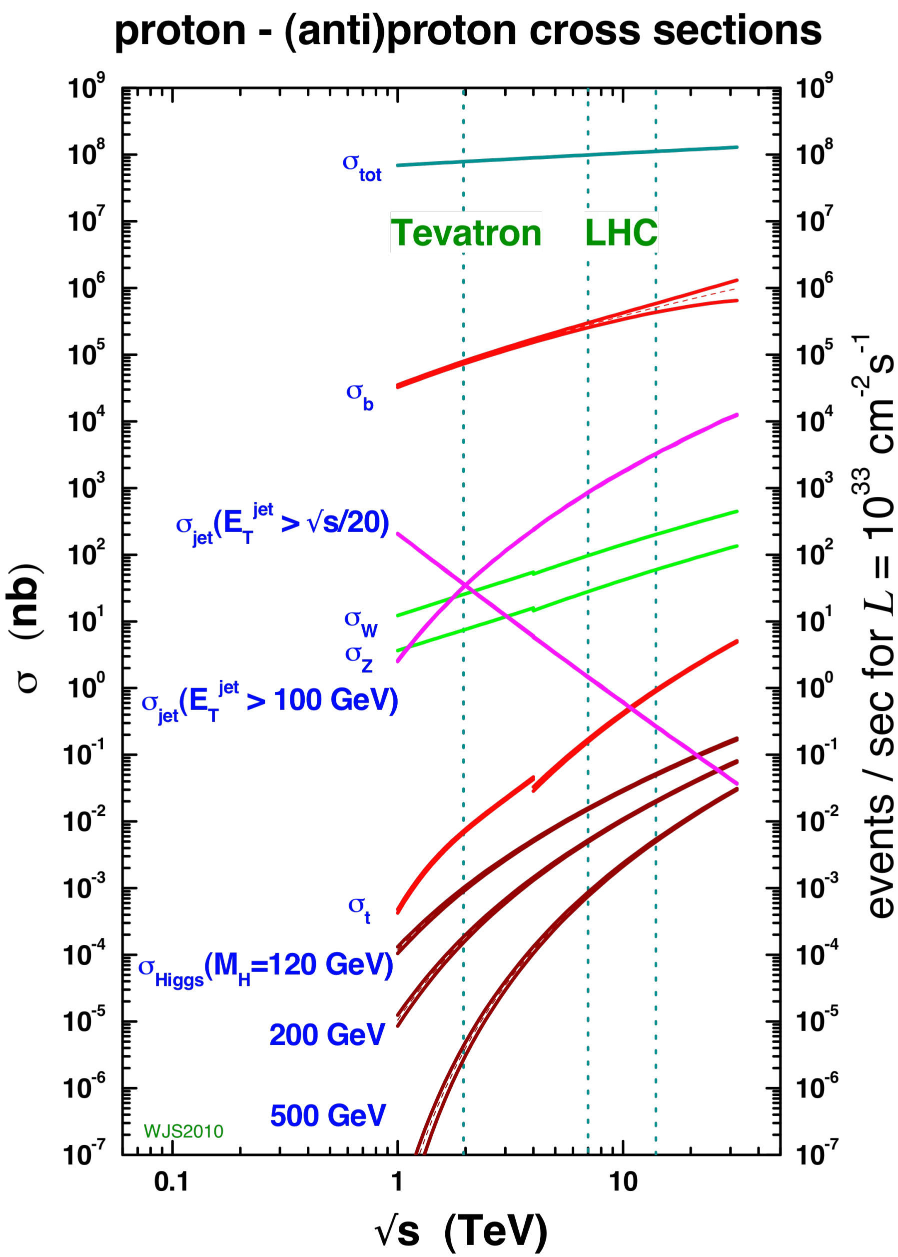


The price of high luminosity: pile-up



Measuring known processes at LHC energies

Physics processes at the LHC



Peak luminosity achieved so far:

$L = 7.7 \times 10^{33}\ cm^{-2}\ s^{-1}$

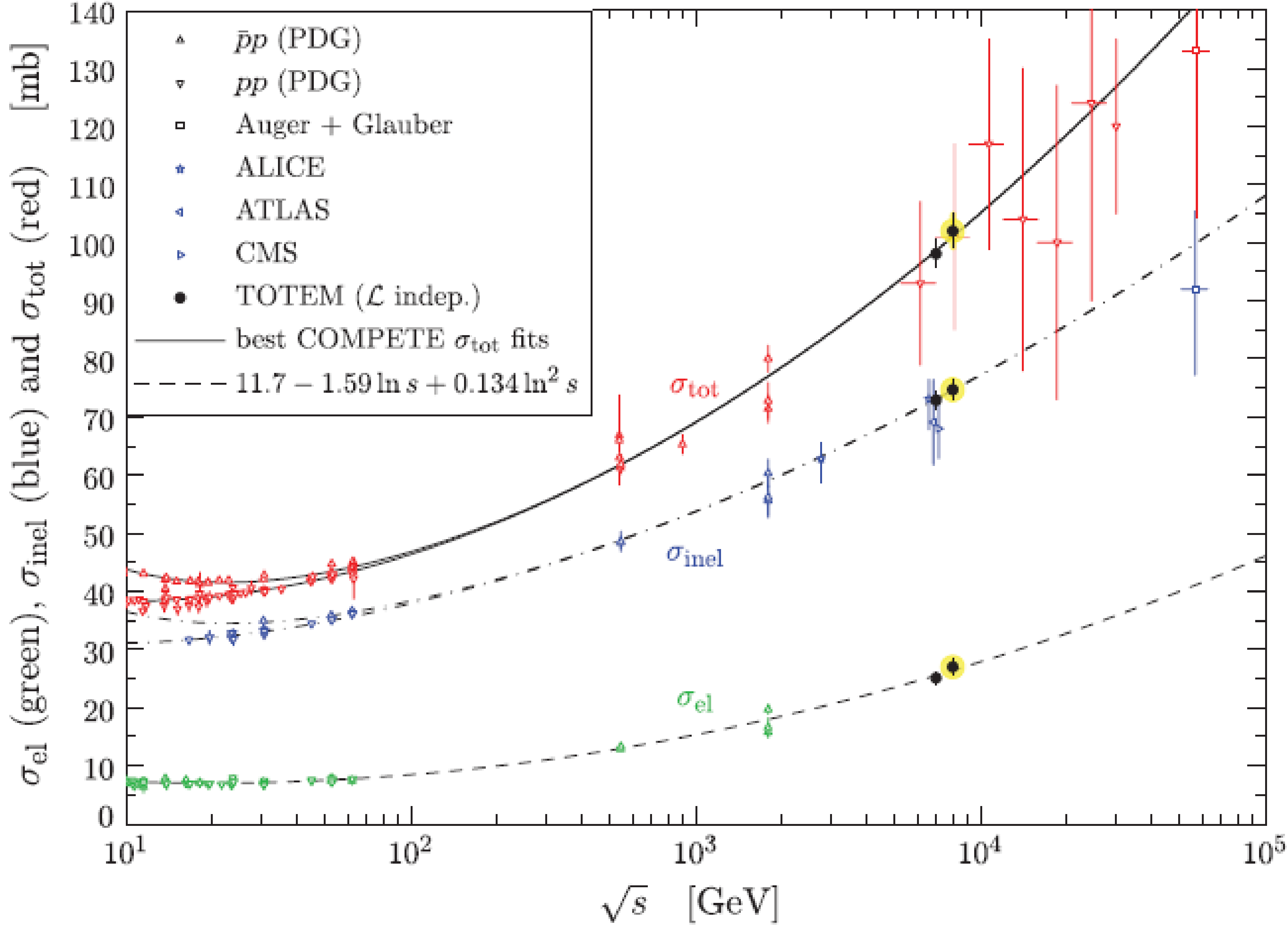
(77% of LHC design luminosity, at 60% of design energy and with half the number of colliding bunches)

process	Rate at L_{peak} (Hz)
any interactions	10^9
Bottom quarks	10^6
Jets with p_T>100 GeV	10^4
W bosons	10^3
Z bosons	10^2
Top quarks	1
H (M=125 GeV)	0.1
H->γγ (M=125 GeV)	2×10^{-4}

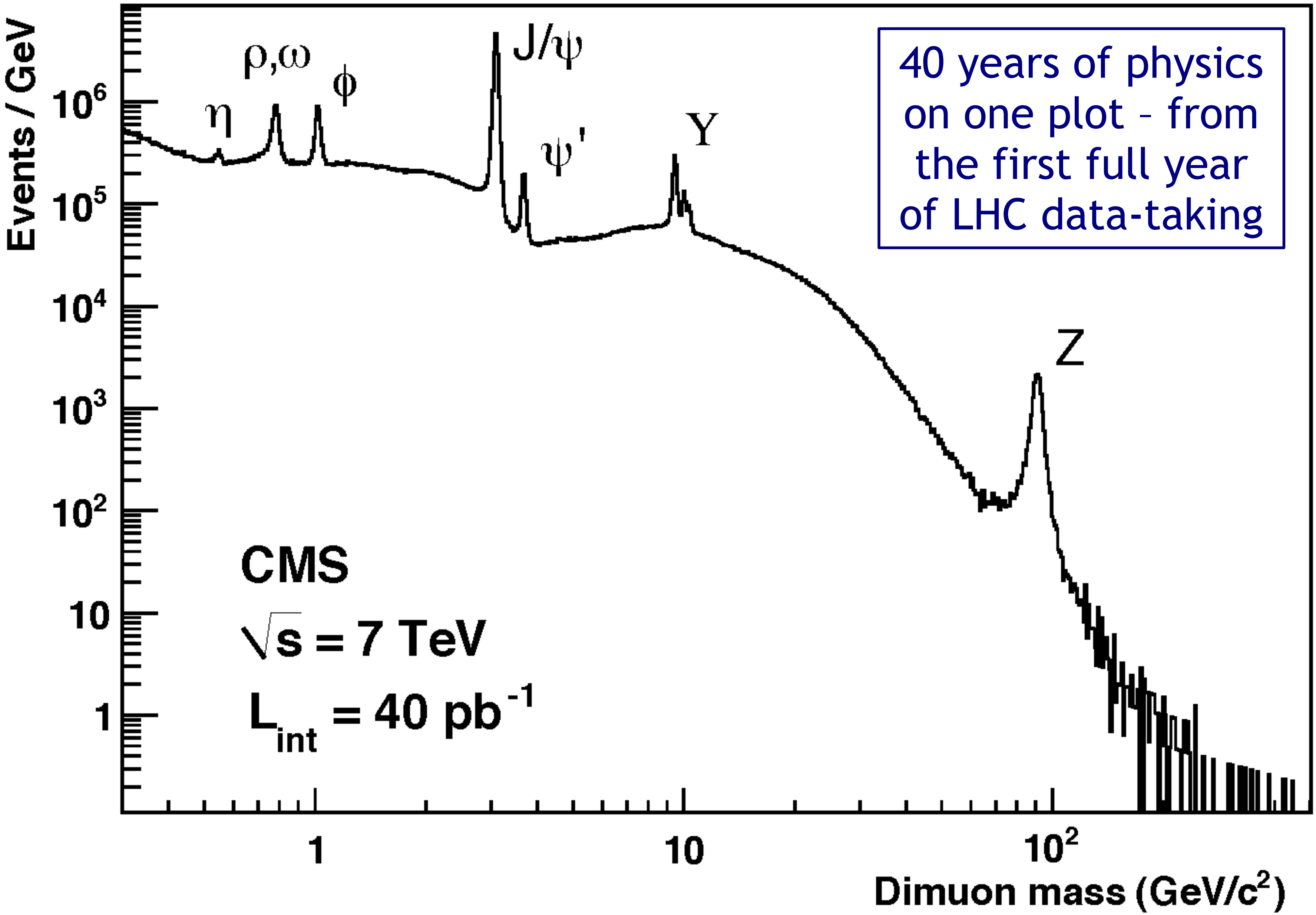
Initially huge QCD backgrounds to rare/ electroweak processes → exceptional detector performance needed (particle ID, resolution ...)

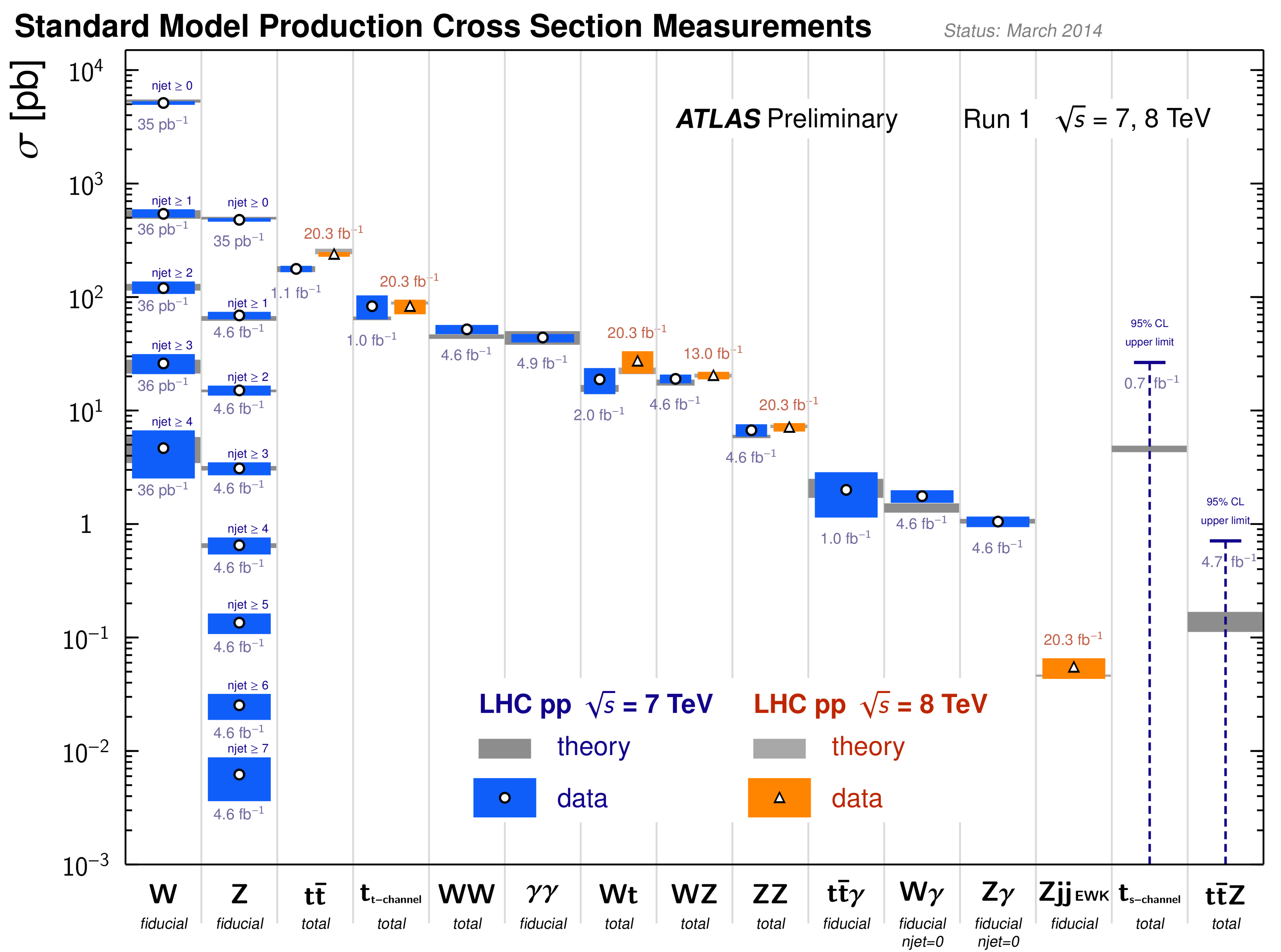
Total cross-section pp→X

Inclusive measurements
Plot from TOTEM, PRL 111 (2013) 012001



Dimuon mass spectrum





Standard Model Production Cross Section Measurements
Status: March 2014
σ [pb]
ATLAS Preliminary
Run 1 √s = 7, 8 TeV
LHC pp √s = 7 TeV
theory
data
LHC pp √s = 8 TeV
theory
data
W fiducial
Z fiducial
tt̄ total
t t−channel total
WW total
γγ fiducial
Wt total
WZ total
ZZ total
tt̄γ fiducial
Wγ fiducial njet=0
Zγ fiducial njet=0
Zjj EWK fiducial
t s−channel total
tt̄Z total
95% CL upper limit

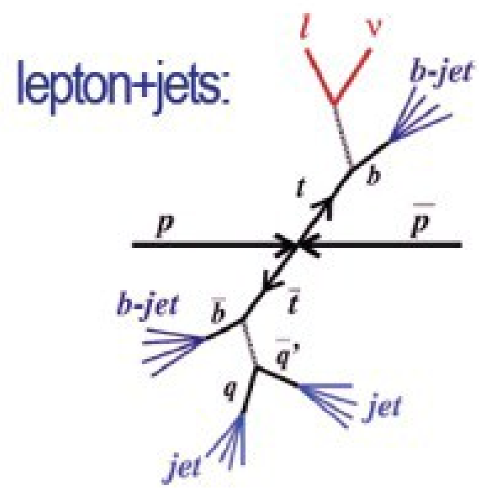
Precision top-quark physics

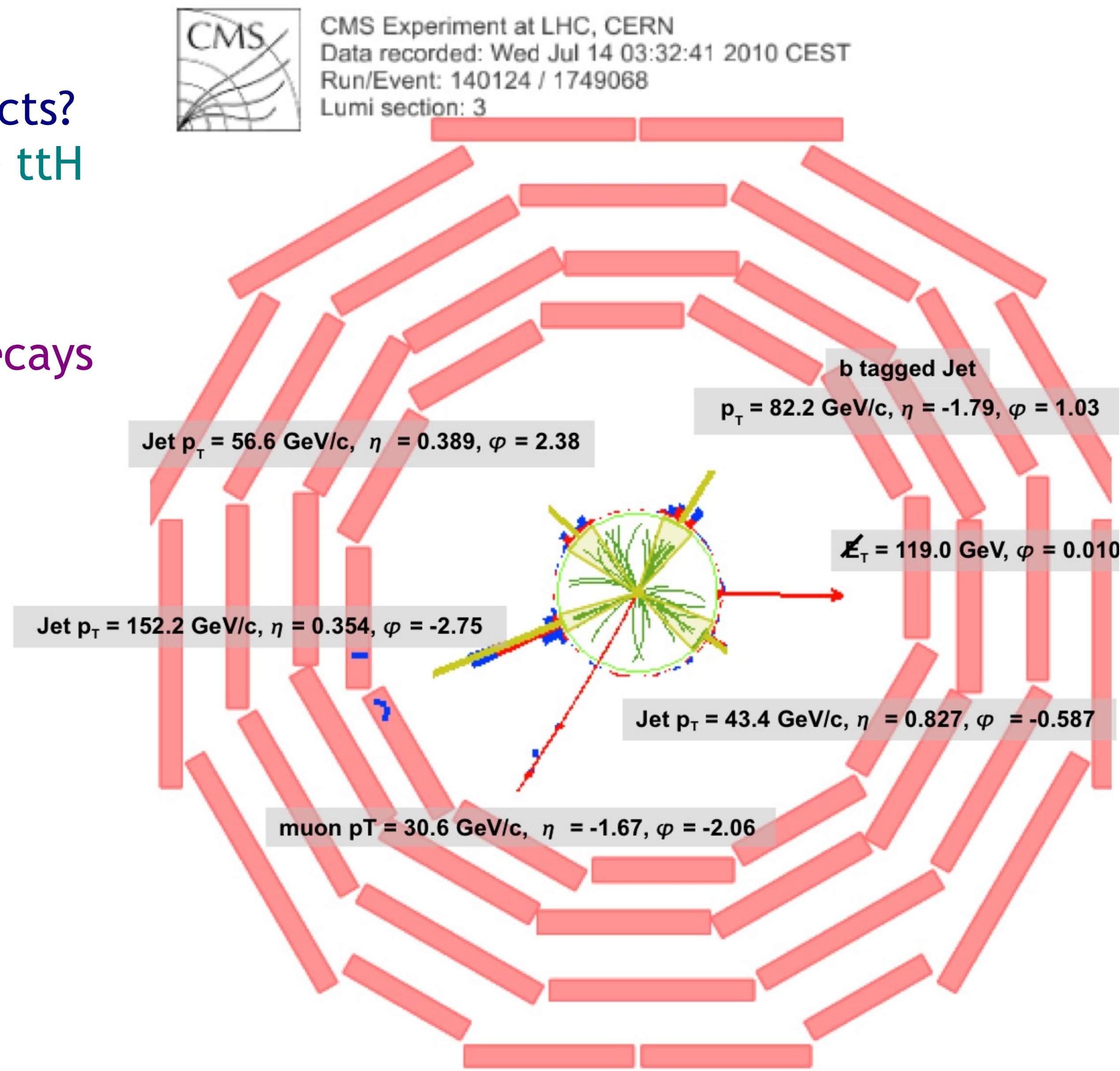
To date around 6M $t\bar{t}$ pairs produced per experiment at the LHC (cf ~75k at Tevatron)

Are top quarks "special" objects?

The Yukawa coupling y_t of the ttH interaction has strength y_t~1

→ Programme to measure top production, properties and decays precisely

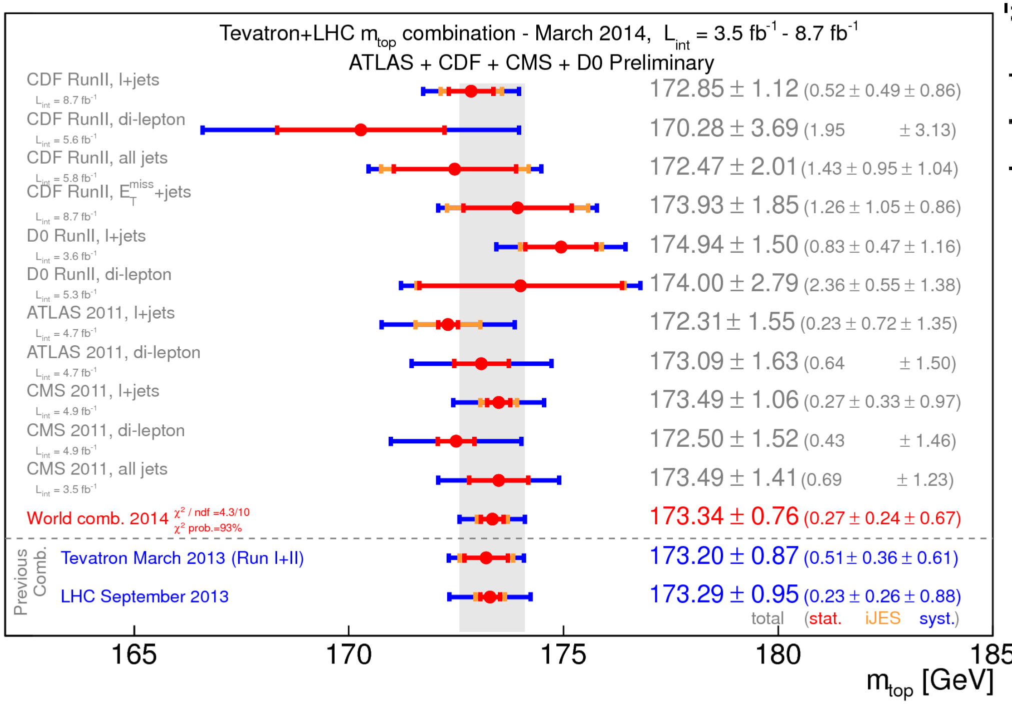




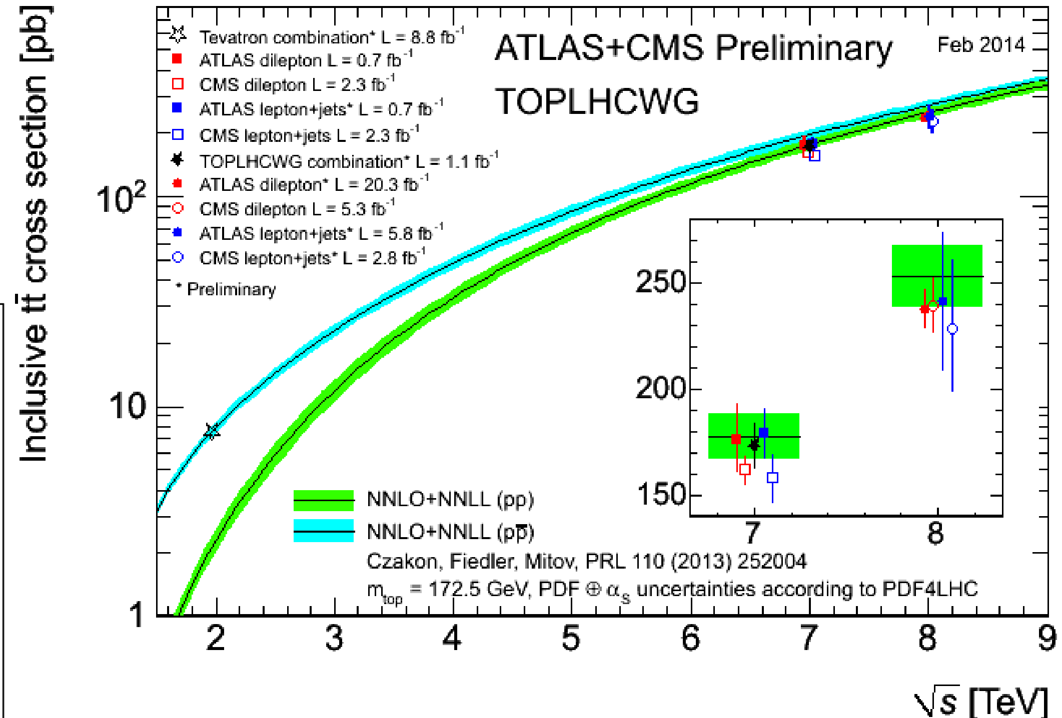
Precision top-quark physics

With 6M $t\bar{t}$ pairs produced, range of precision measurements possible

top-quark mass



$t\bar{t}$ cross-section



LHC+Tevatron combination (03/14)
173.34 ± 0.76 GeV

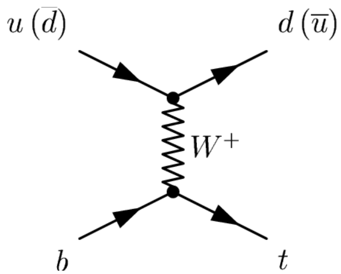
Two more measurements since:

D0	174.98 ± 0.76 GeV
CMS	172.04 ± 0.77 GeV

Uncertainty at level of error in relating measured values to the pole mass

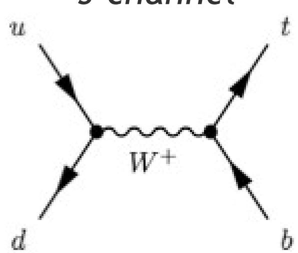
Single top production

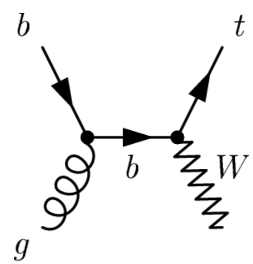
Single top production is an electroweak process: and has a high cross-section at the LHC at 7-8 TeV: σ(single-t)~ ½σ($t\bar{t}$)



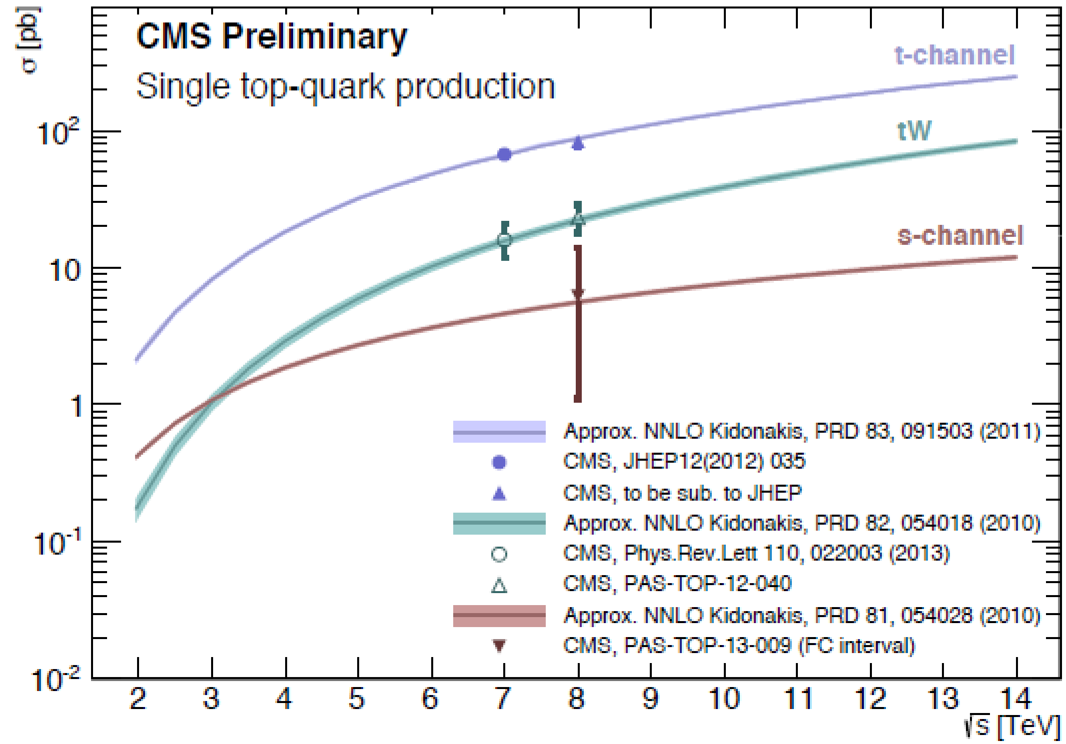
t-channel

s-channel

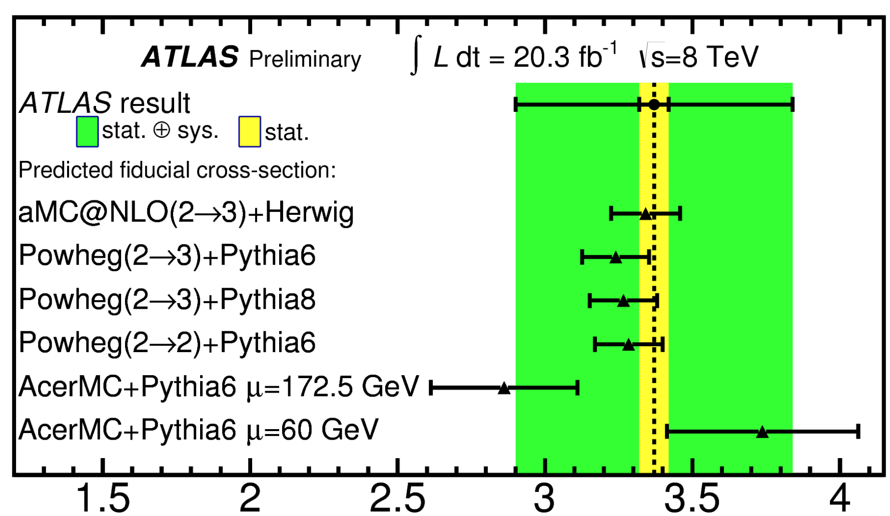




Wt production



New ATLAS t-channel analysis: measure cross-section in a fiducial acceptance corresponding to the experimental cuts, rather than extrapolating to full cross-section → reduces uncertainties and facilitates comparisons with models



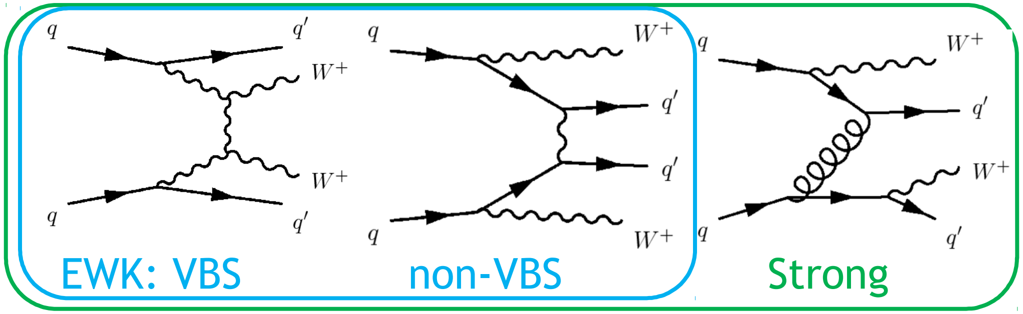
ATLAS-CONF-2014-007

Standard ATLAS approach for measurements, now extended to top (and Higgs) sectors

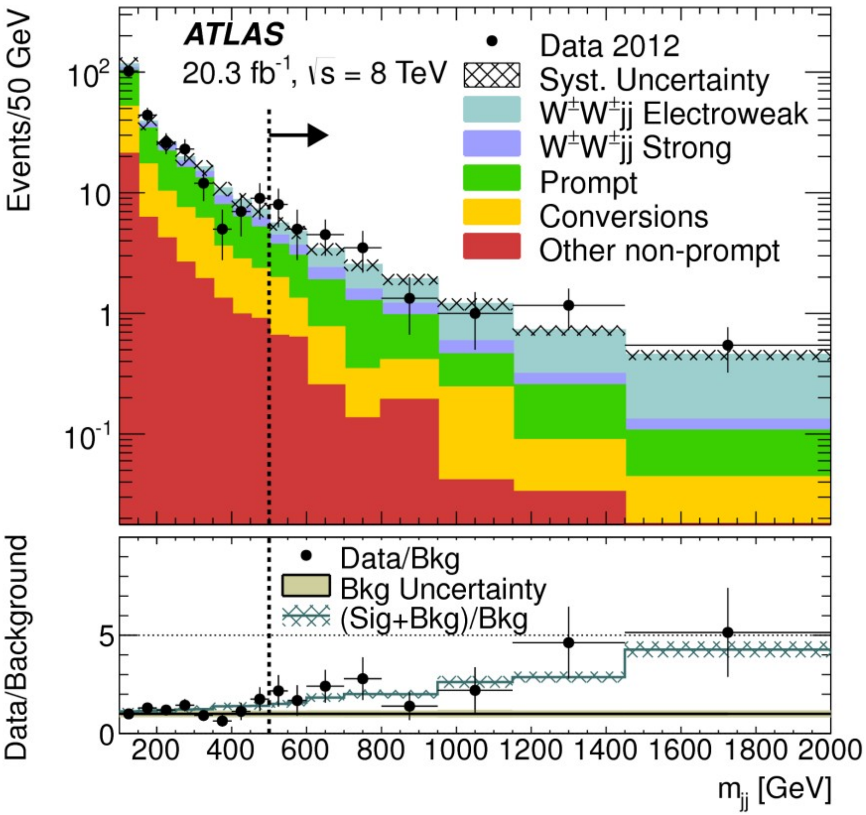
Vector-boson scattering

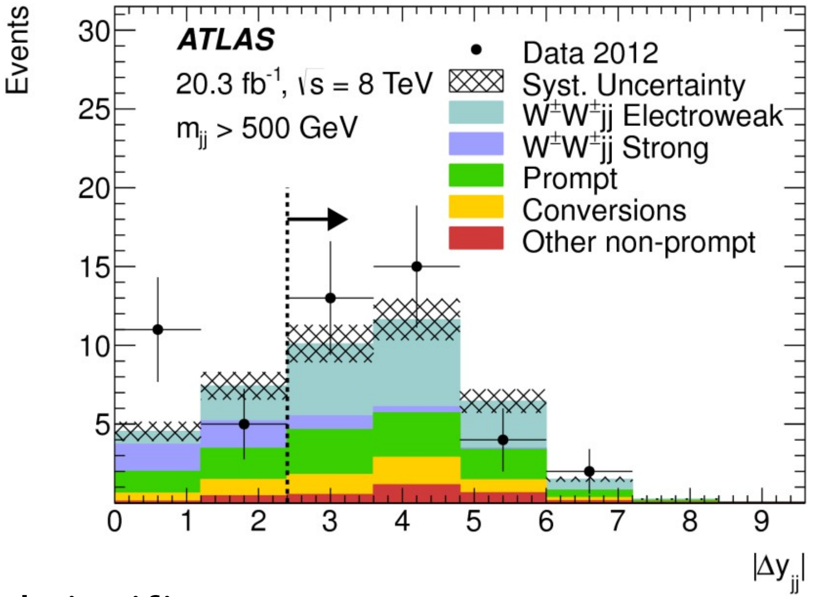
arXiv:1405.6241

Important to probe the scattering of massive electroweak bosons to test for other physics in electroweak symmetry-breaking than the new H(125)



Recent evidence of WW scattering in WW+2 jet final state, with high jet-jet mass and jets well separated in the detector





Combined significance:
4.5 (3.6)σ in the inclusive (VBS) region

Fiducial cross section in VBS region:

$$\sigma^{\text{fid}} = 1.3 \pm 0.4(\text{stat}) \pm 0.2(\text{syst})\ \text{fb}$$

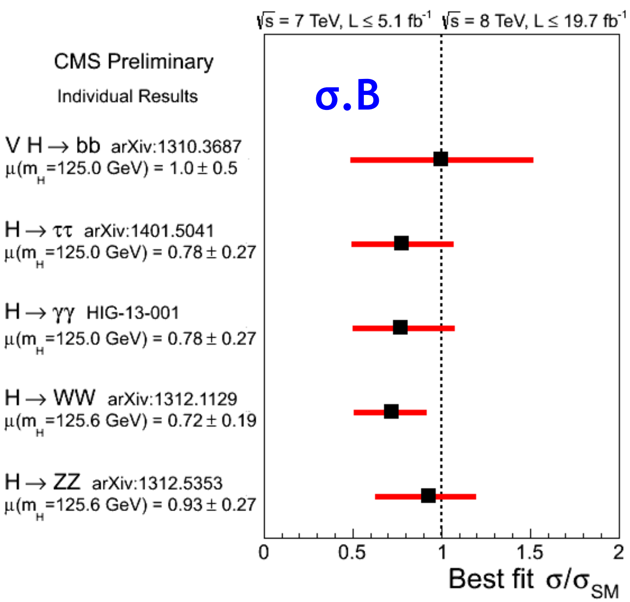
SM: 0.95 ± 0.06 fb

Just the first step of a long-term programme

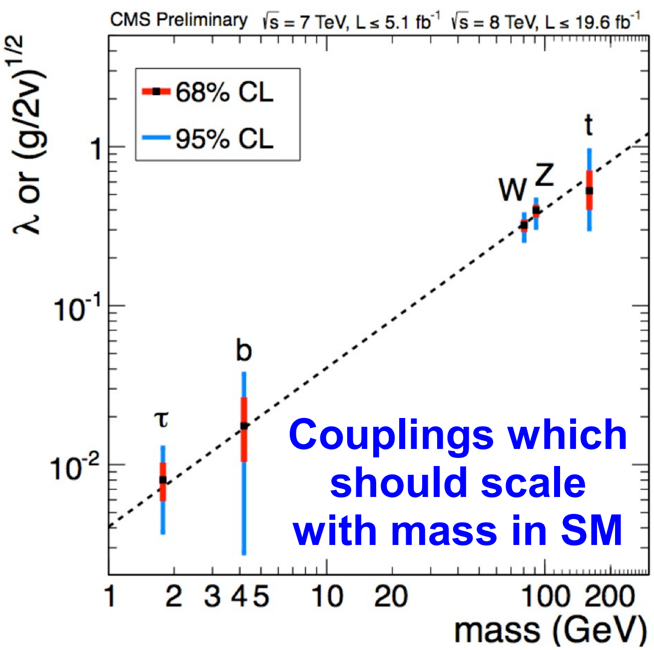
H(125) Update

The H(125) since the discovery

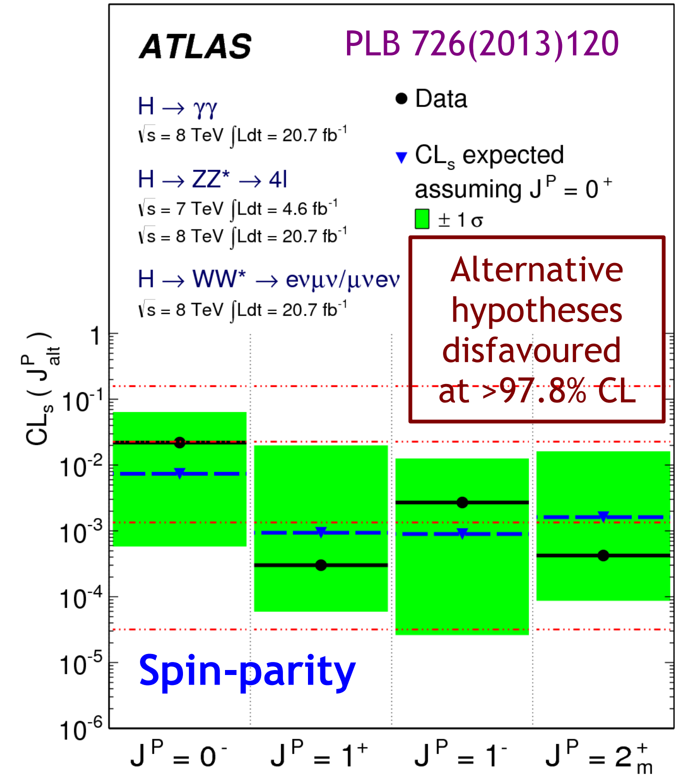
A range of measurements – all so far consistent with the SM H expectations – errors are still large (low statistics)



σ.B



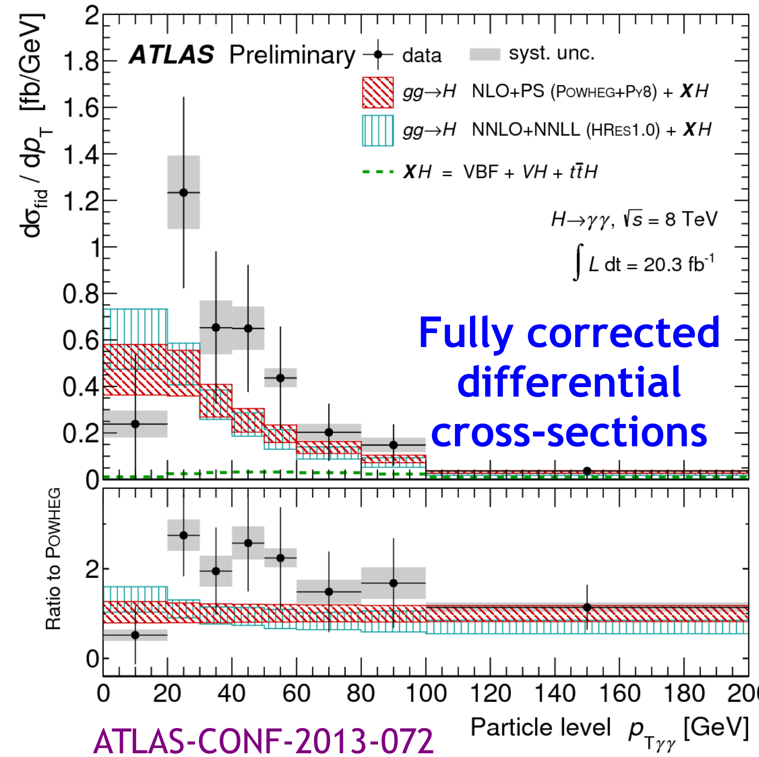
Couplings which should scale with mass in SM



PLB 726(2013)120

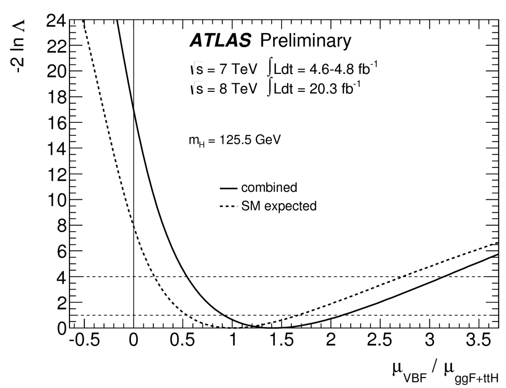
Alternative hypotheses disfavoured at >97.8% CL

Spin-parity



Fully corrected differential cross-sections

ATLAS-CONF-2013-072

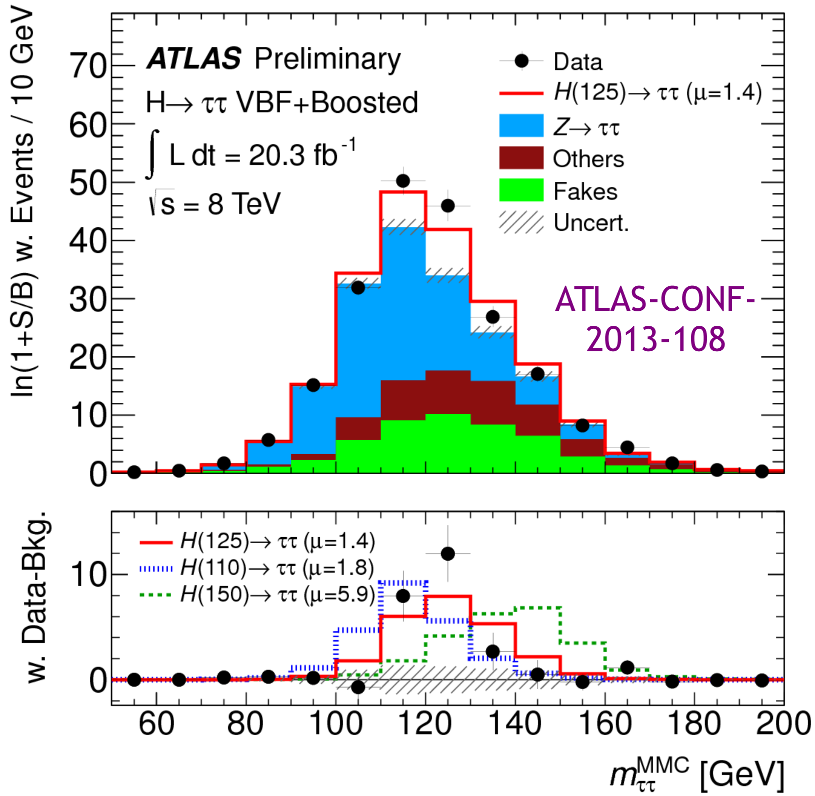


ATLAS-CONF-2014-009

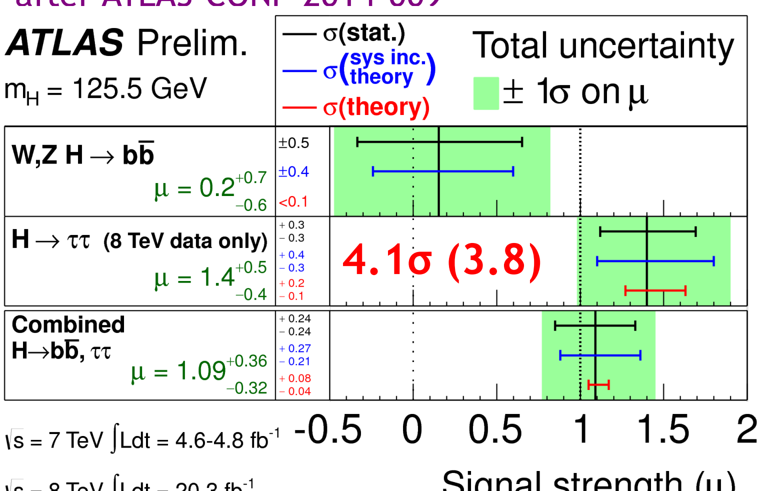
>4σ evidence for VBF production

See also talk by Jianming Qian this afternoon

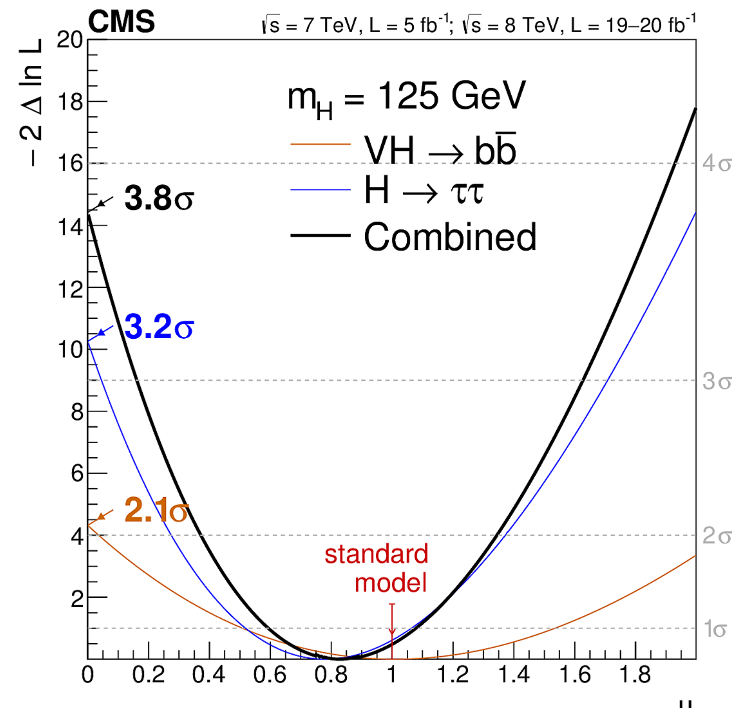
H(125) decays to fermions



after ATLAS-CONF-2014-009



ATLAS and CMS have shown more than 3σ evidence for H(125) decays to fermions (>5σ indirect evidence from production)



Nature Phys 3005

Channel	Significance (σ)		Best-fit
($m_H = 125$ GeV)	Expected	Observed	μ
$VH \to b\bar{b}$	2.3	2.1	1.0 ± 0.5
$H \to \tau\tau$	3.7	3.2	0.78 ± 0.27
Combined	4.4	3.8	0.83 ± 0.24

CMS

Precision H(125) physics: m_H

Very detailed and intricate work to understand the performance of the detector: particle identification performance and energy/momentum scales

Measurements of the Higgs boson mass:

arXiv:1406.3827

ATLAS

Channel	Mass measurement [GeV]
$H \to \gamma\gamma$	$125.98 \pm 0.42\,(\text{stat}) \pm 0.28\,(\text{syst}) = 125.98 \pm 0.50$
$H \to ZZ^* \to 4\ell$	$124.51 \pm 0.52\,(\text{stat}) \pm 0.06\,(\text{syst}) = 124.51 \pm 0.52$
Combined	$125.36 \pm 0.37\,(\text{stat}) \pm 0.18\,(\text{syst}) = 125.36 \pm 0.41$

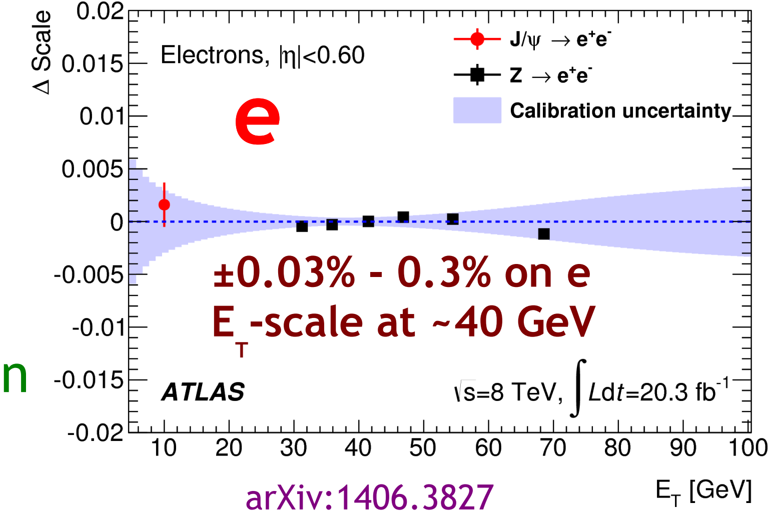
CMS

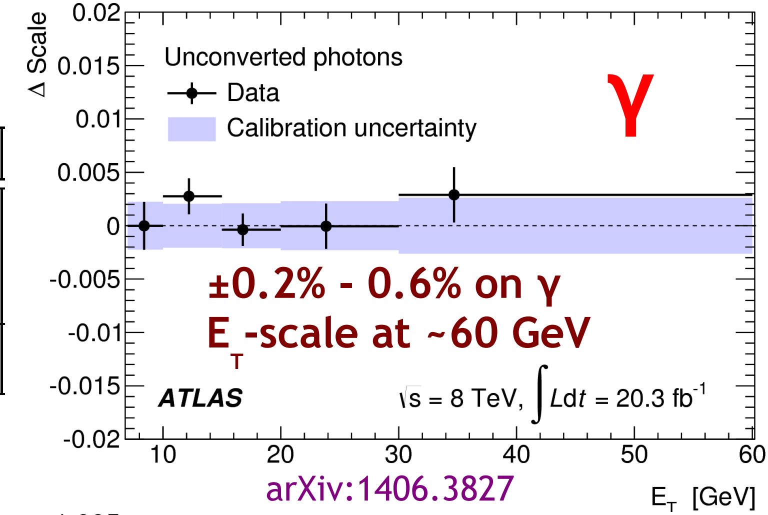
$H \to \gamma\gamma$ 125.4 ± 0.5 (stat) ± 0.6 (syst) GeV

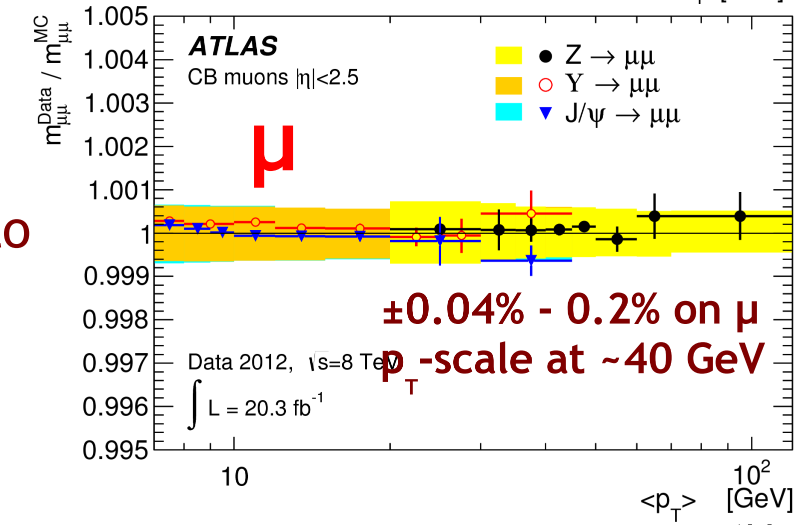
$H \to 4\ell$ 125.6 ± 0.4 (stat) ± 0.2 (syst) GeV

CMS-PAS-HIG-13-001, PRD89.092007

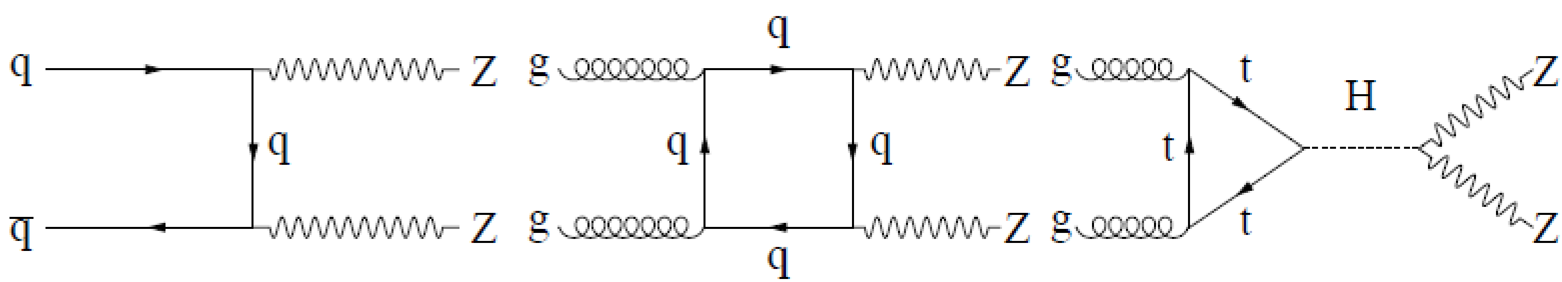
ATLAS analysis indicates that the measurement in the 4ℓ channel will be statistics-limited for years to come – if this superb level of energy/momentum calibration can be maintained







Measuring H propagator at high mass, and Γ_H



arXiv:1405.3455

High mass ZZ production is sensitive to the effect of the Higgs diagram

$$\sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}.$$

(+interference terms)

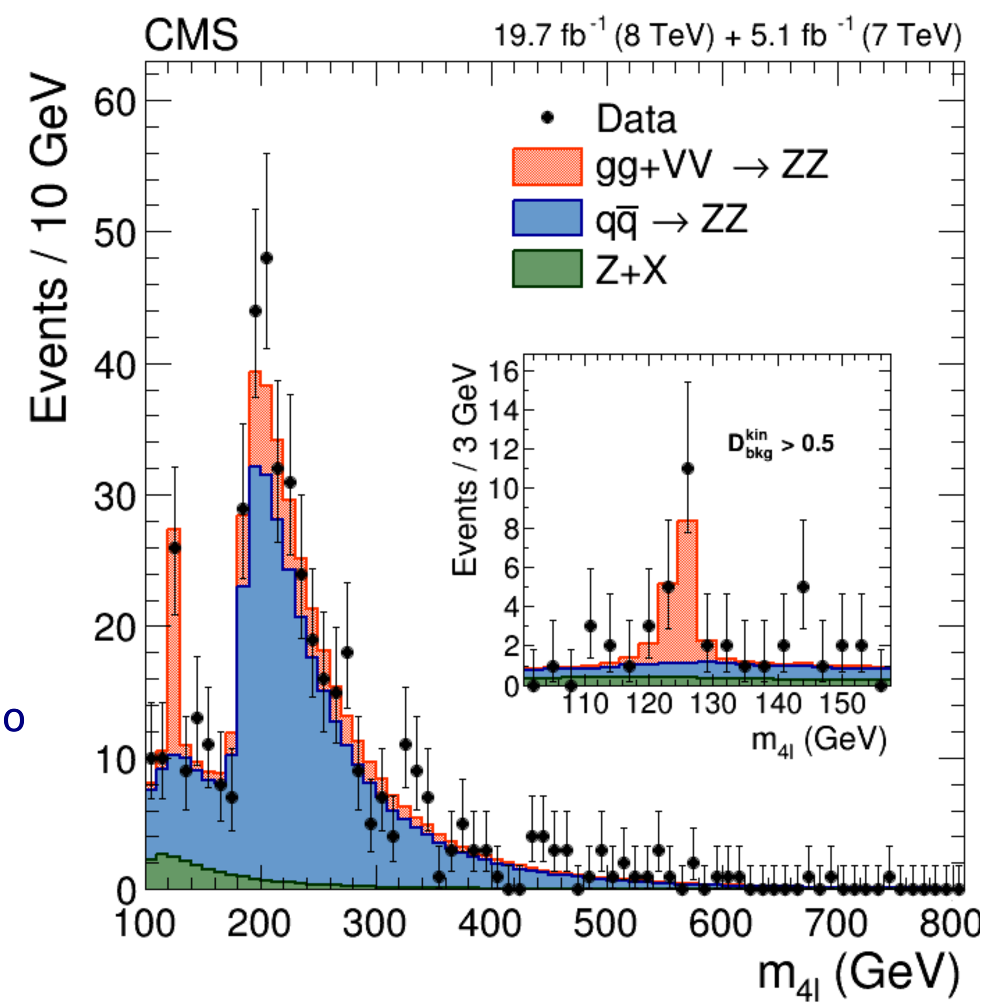
At high-mass, can measure products of H couplings without any assumption about Γ_H.

Now cf:

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}$$

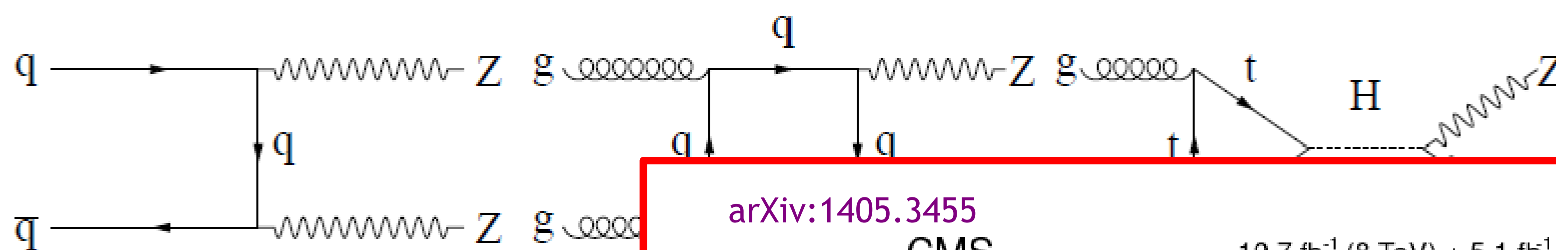
With assumptions (no energy-dependence of g's, no new physics in ZZ production ...)

→ constraint on Γ_H



Kauer & Passarino, Coala & Melnikov, Campbell et al

Measuring H propagator at high mass, and Γ_H



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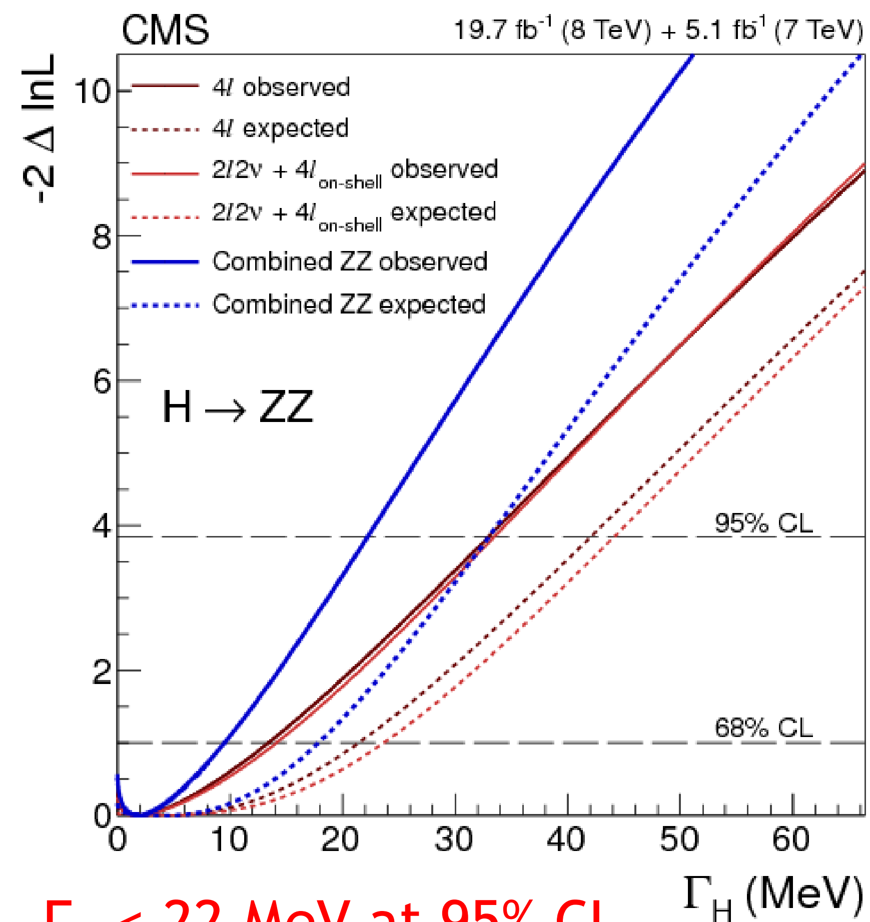
arXiv:1405.3455



Γ_H < 22 MeV at 95% CL

Caution: models with Γ_H differing from SM value (4 MeV) may not be tested

Kauer & Passarino, Coala & Melnikov, Campbell et al

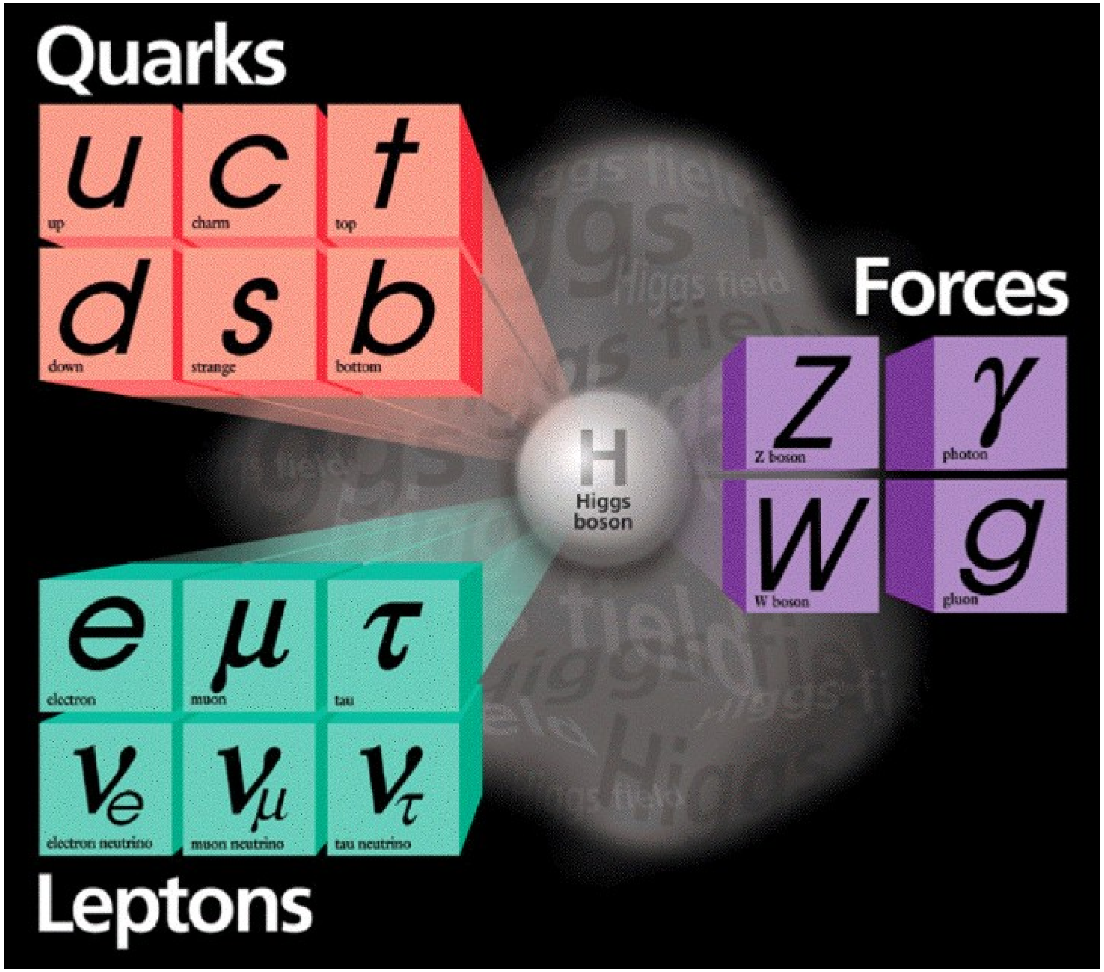
Searching beyond

The end of physics?

The Standard Model works fantastically, and is now completed by the H discovery

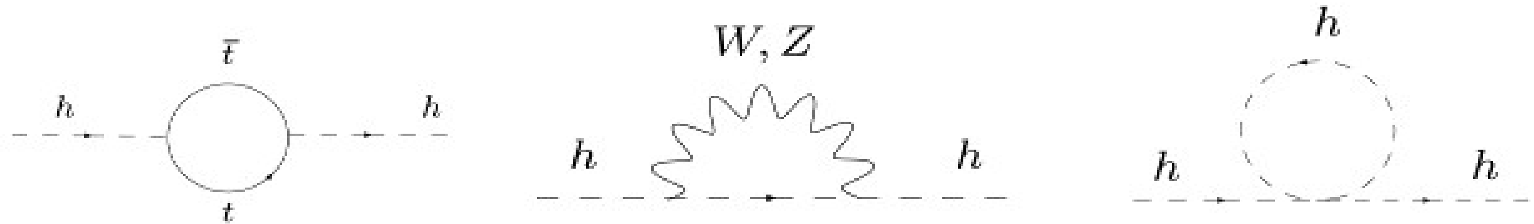
But so many questions are unanswered...

- Why three families?
- Why the huge imbalances in fermion masses?
- What is dark matter?
- Matter-antimatter asymmetry in the universe
- Extra dimensions?



This is not the end of fundamental physics – but where and what comes next?

The hierarchy problem



$$m^2_H = (125\ \text{GeV})^2 = m^2_H{}^{tree} + \delta m^2_H{}^{top} + \delta m^2_H{}^{gauge} + \delta m^2_H{}^{higgs}$$

A low-mass Higgs boson with only the SM particles requires fine-tuning to cancel huge corrections

Huge conceptual puzzle to theorists for many years – now crystallised by the observation of H(125)

Can only be solved by new physics at/near the TeV scale

Supersymmetry

A new symmetry between fermions and bosons

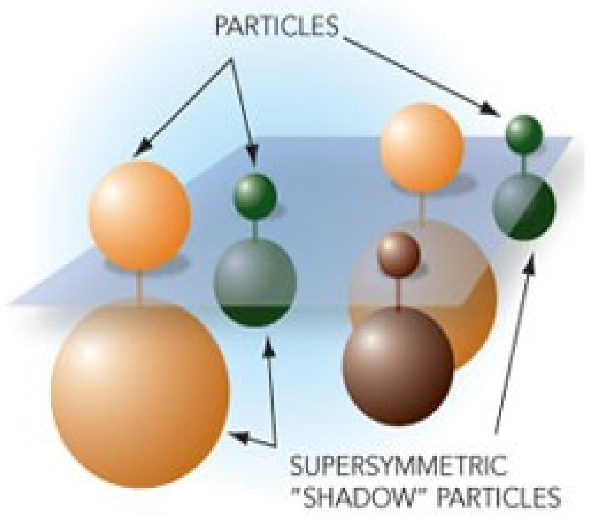
- Each SM particle has a partner with different spin, e.g.:

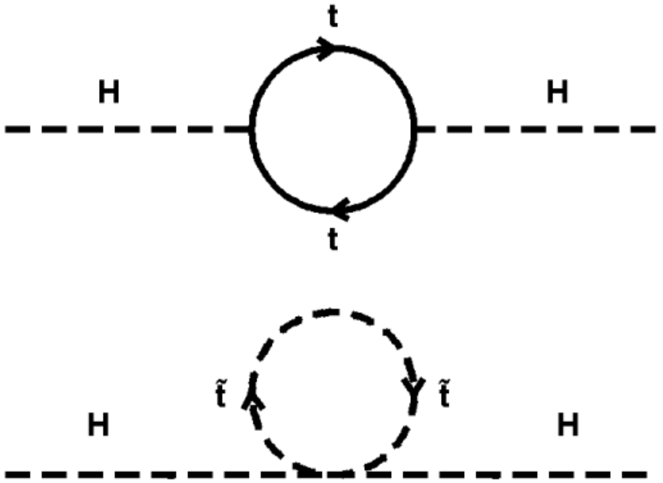
SM	spin	SUSY	spin
electron	1/2	selectron	0
top	1/2	stop	0
gluon	1	gluino	1/2

- SUSY loops cancel SM loops
  - Provided sparticle masses not too high
- No (or few) ad-hoc tuned parameters
- *Natural dark matter candidate in the lightest SUSY particle LSP, mass 0.1-1 TeV*

- SUSY particles should be found at the LHC

Superpartners!





SUSY searches

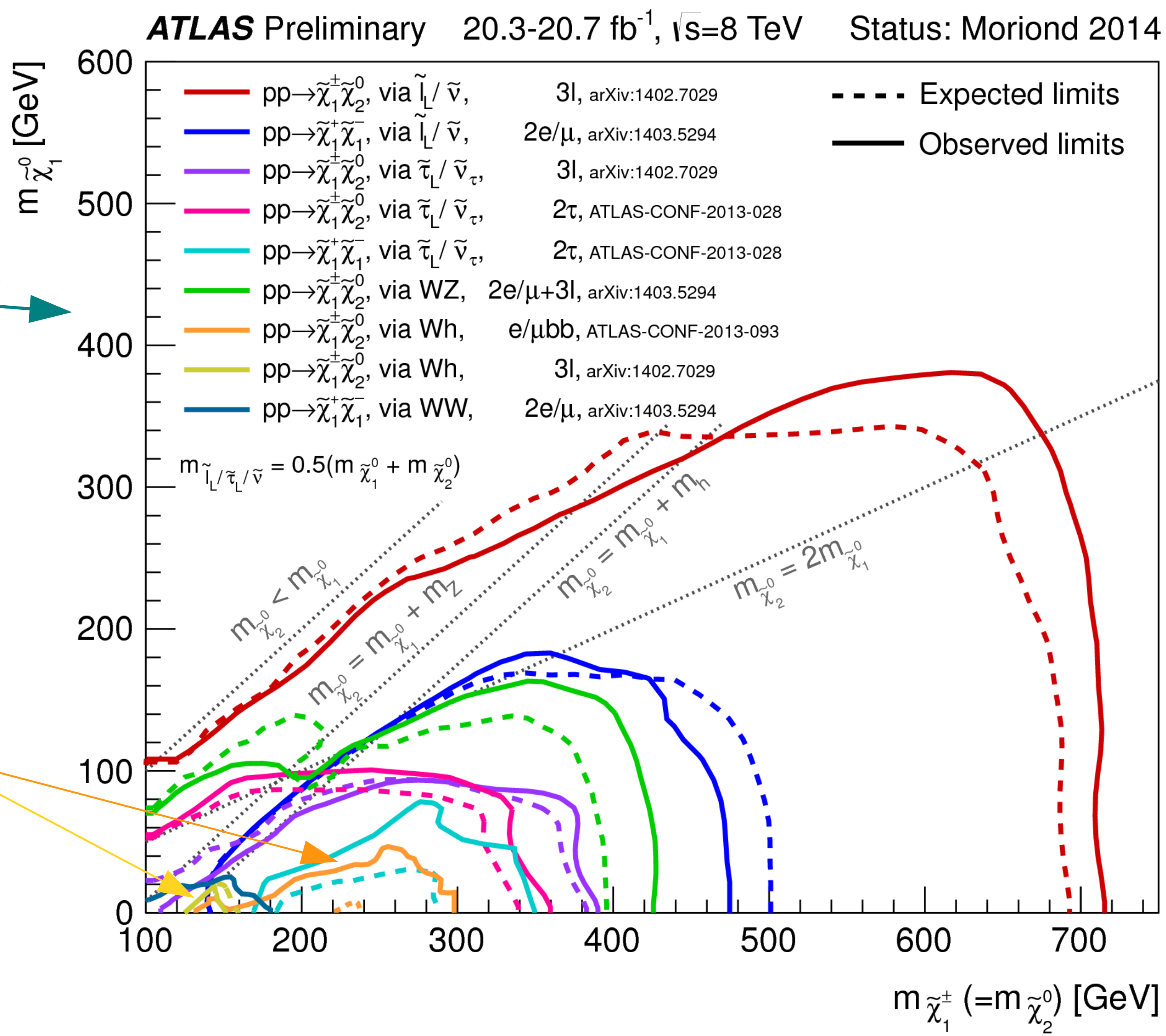
Simplified Model Spectra "SMS"

Plethora of searches for SUSY "leave no stone unturned"

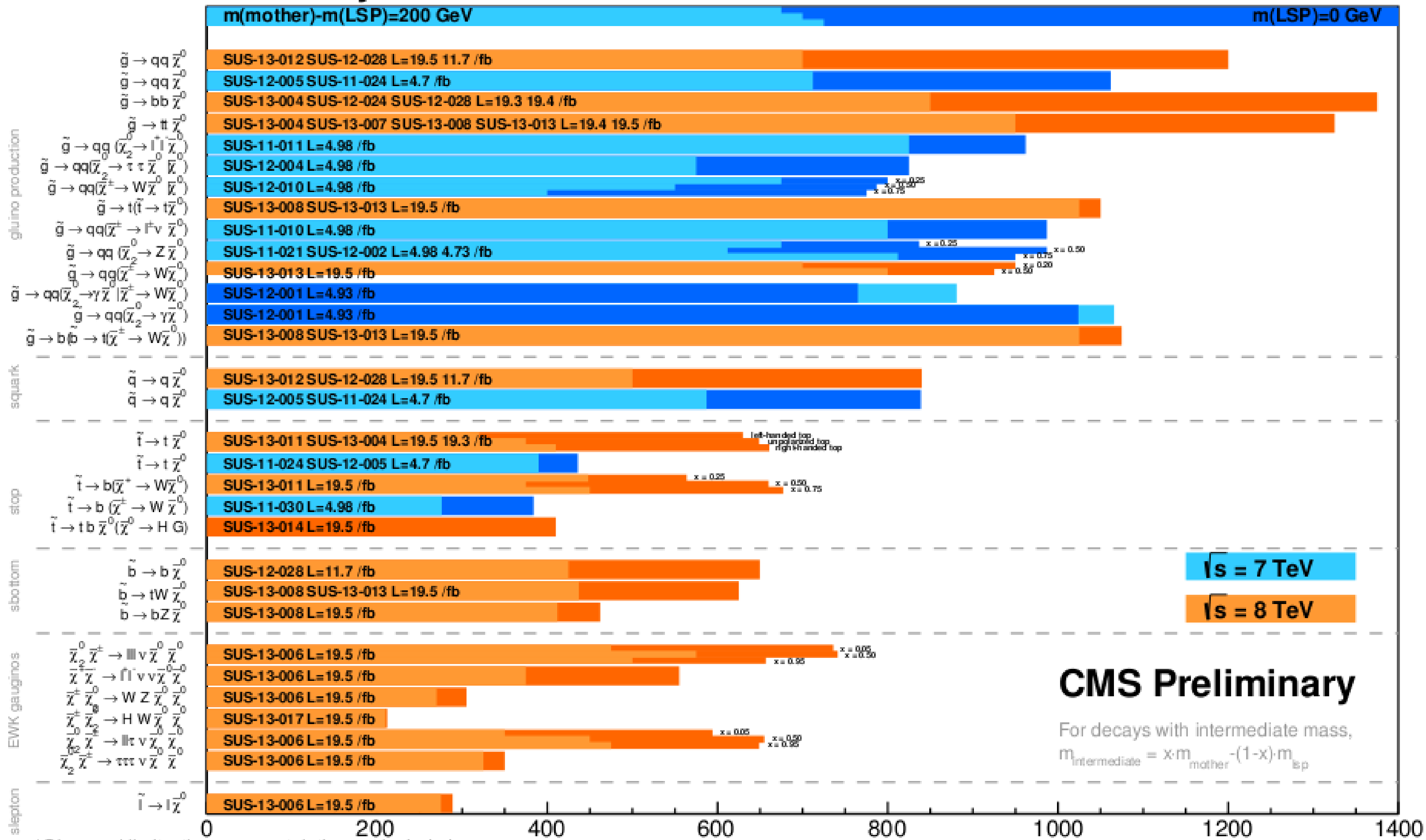
Example: **electroweak production of charginos/neutralinos**

Caution: different decay modes overlaid, curves not directly comparable to each other

Amongst these, searches for neutralinos decaying via the H, charginos via W's as preferred in "natural" SUSY models – challenging analyses!



Summary of CMS SUSY Results* in SMS framework — SUSY 2013

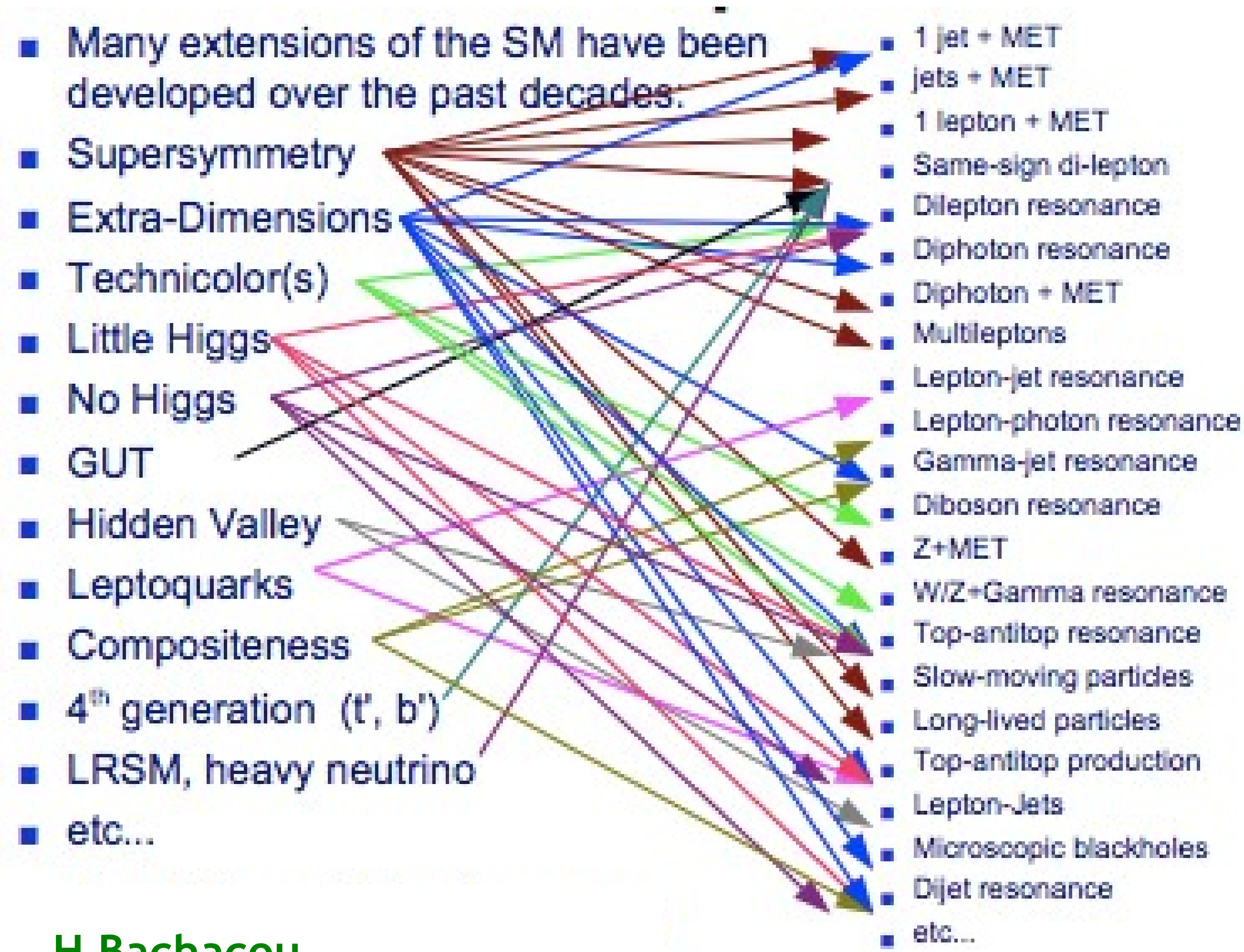


*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

"Exotic" searches

Beyond SUSY, a host of other model possibilities for Beyond the Standard Model physics, with various levels of motivation

- Open perspective – we do not know what we may find
- There are many many possible models – and event signatures
- Models act as benchmarks and guides – but we are open to as much as we can



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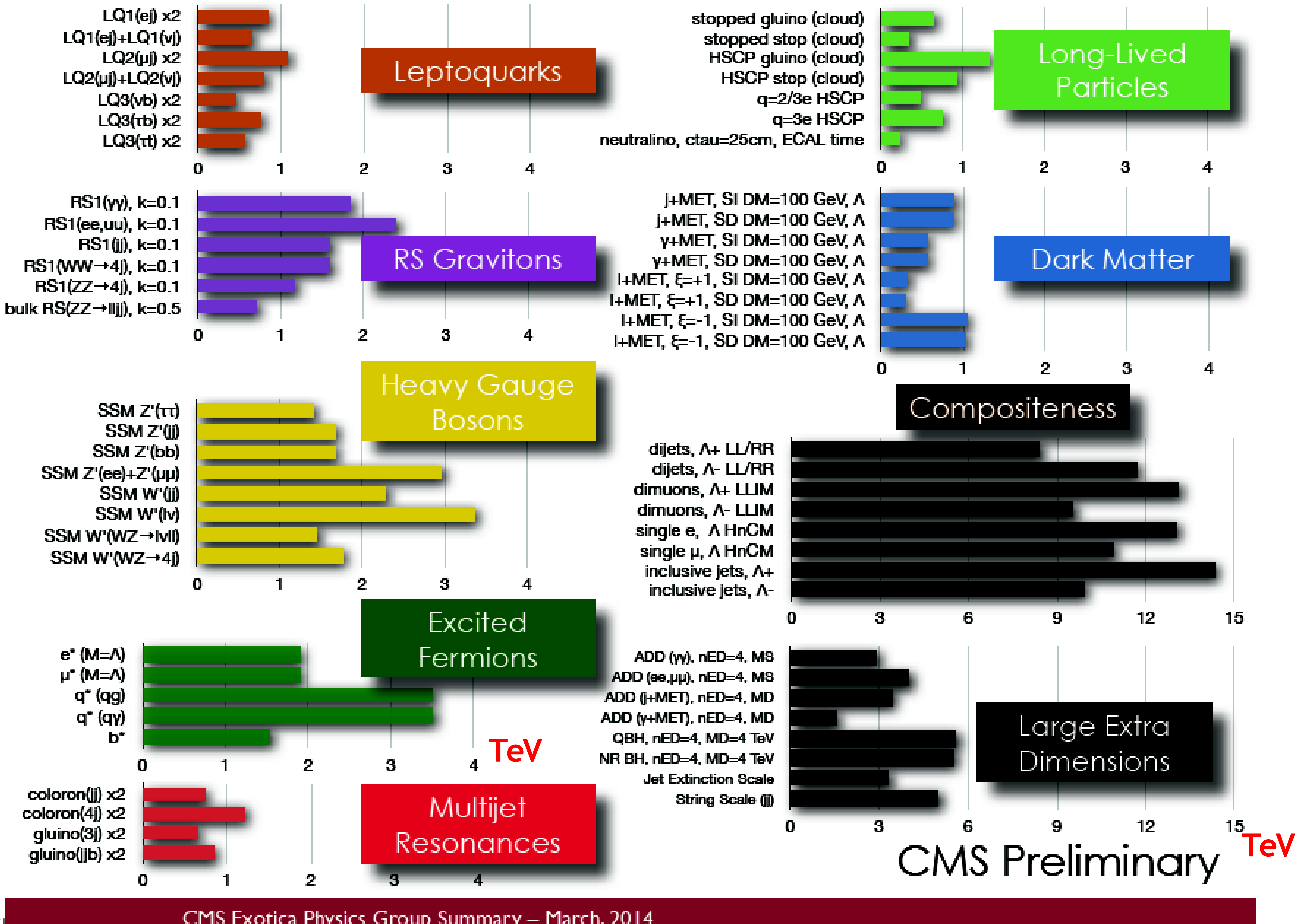
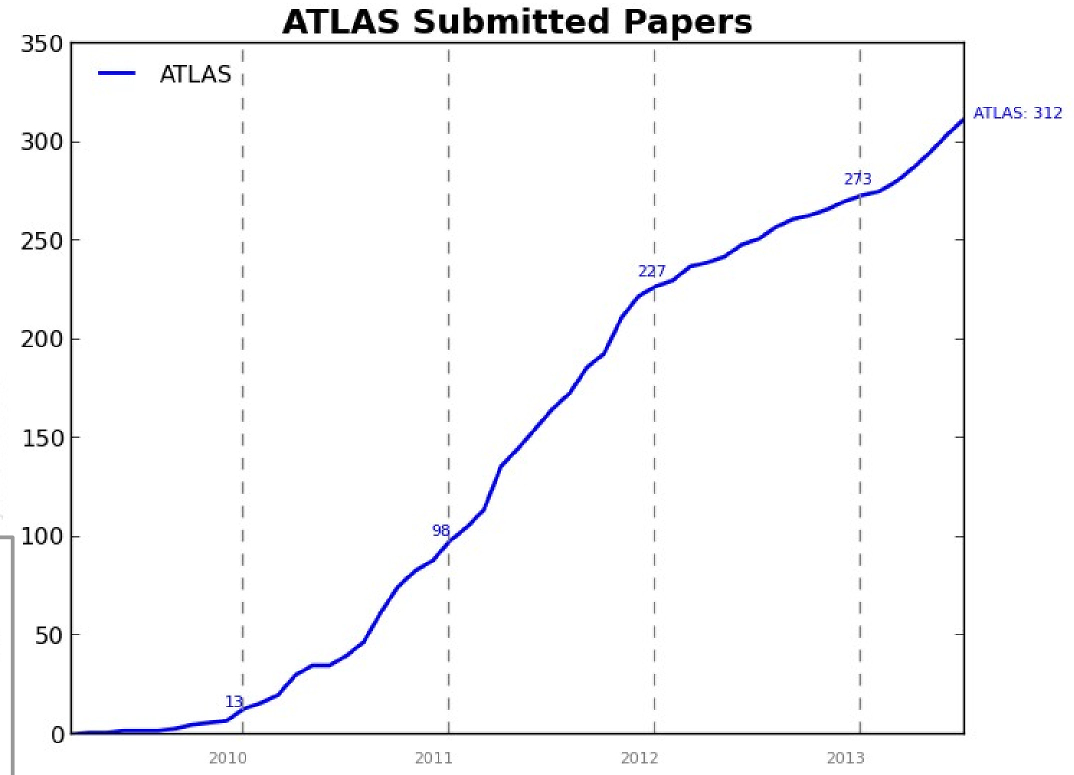
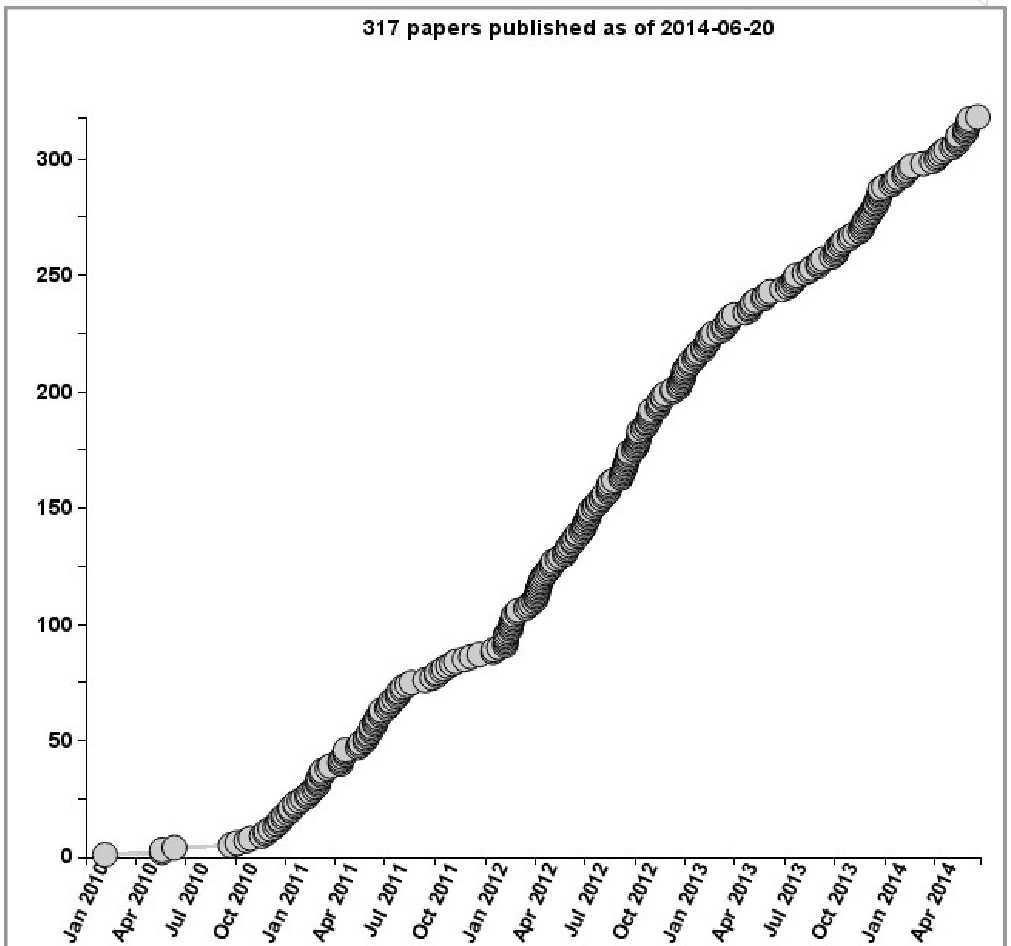
CMS Exotica Limits



Publication Output



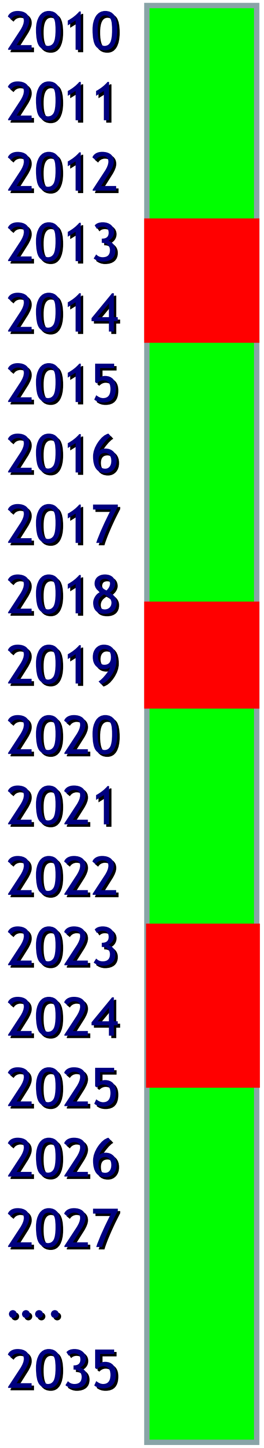


Each experiment now has >300 publications covering a huge range of topics

I could only sample a very few here

Looking Forward

LHC Roadmap



Run 1: energy 7-8 TeV, 25 fb^{-1} of data

Shutdown 1: phase 0 upgrade

Run 2: energy 13+ TeV, ~120 fb^{-1} of data

Shutdown 2: phase 1 upgrade

Run 3: energy 14 TeV, ~350 fb^{-1} of data

Shutdown 3: phase 2 upgrade

HL-LHC: energy 14 TeV, ~3000 fb^{-1} of data

From the White Paper

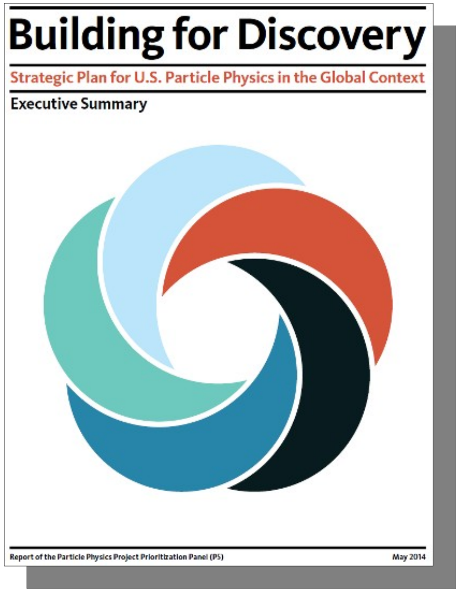
Update of the European Strategy for Particle Physics

c) The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme. *Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*

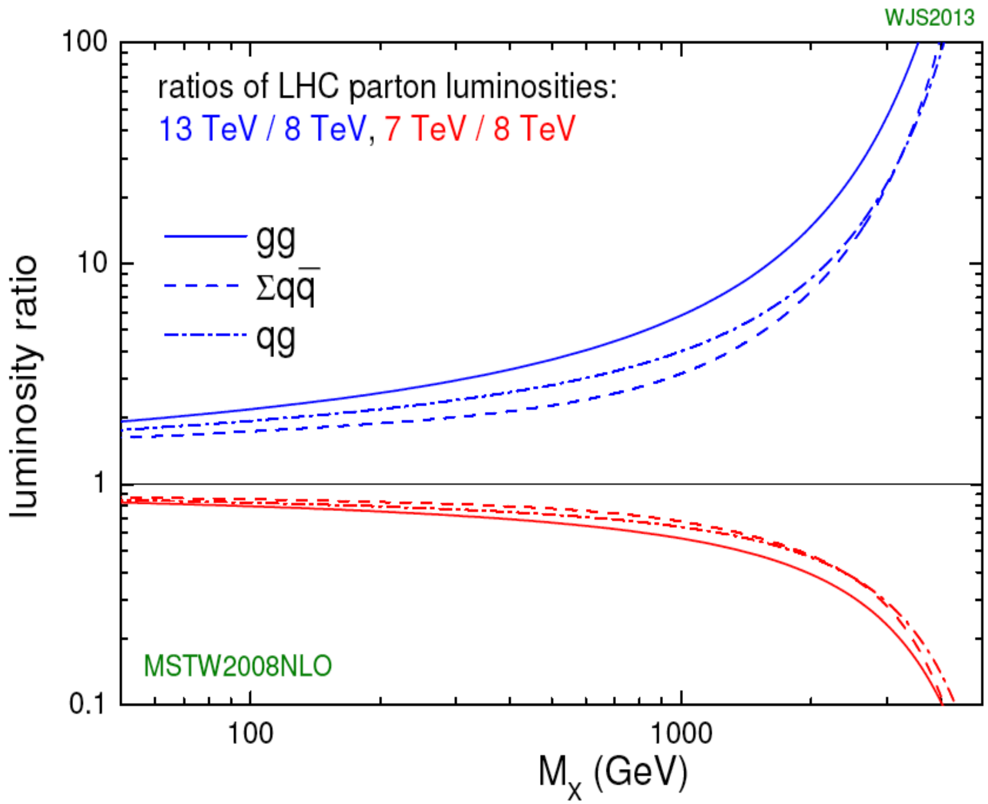
From the US (DOE/NSF) Particle Physics Projects Prioritization Panel (P5) report

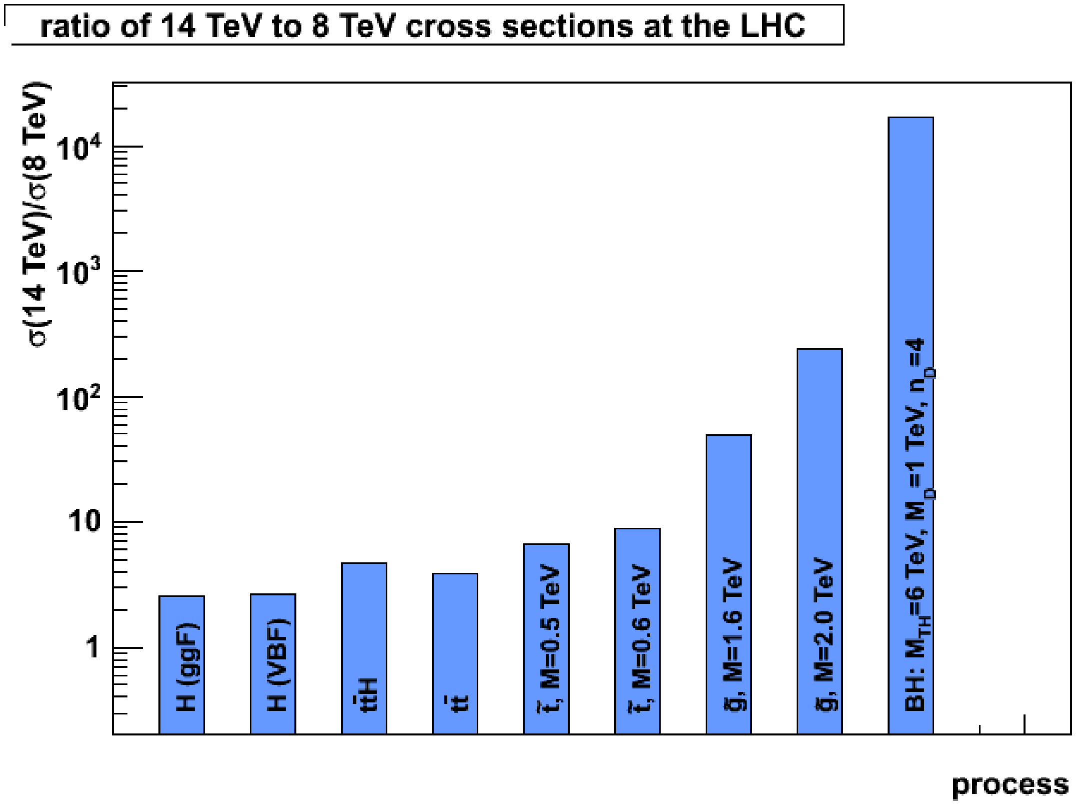
Building for Discovery

Recommendation 10 : Complete the LHC phase-1 upgrades and continue the strong collaboration in the LHC with the phase-2 (HL-LHC) upgrades of the accelerator and both general-purpose experiments (ATLAS and CMS). The LHC upgrades constitute our highest-priority near-term large project.



Run-2 prospects





Run-2 will begin in Spring 2015 and is planned to run to mid-2018

Increase in cross-sections by a factor ~10 for m(system) ~ 2 TeV

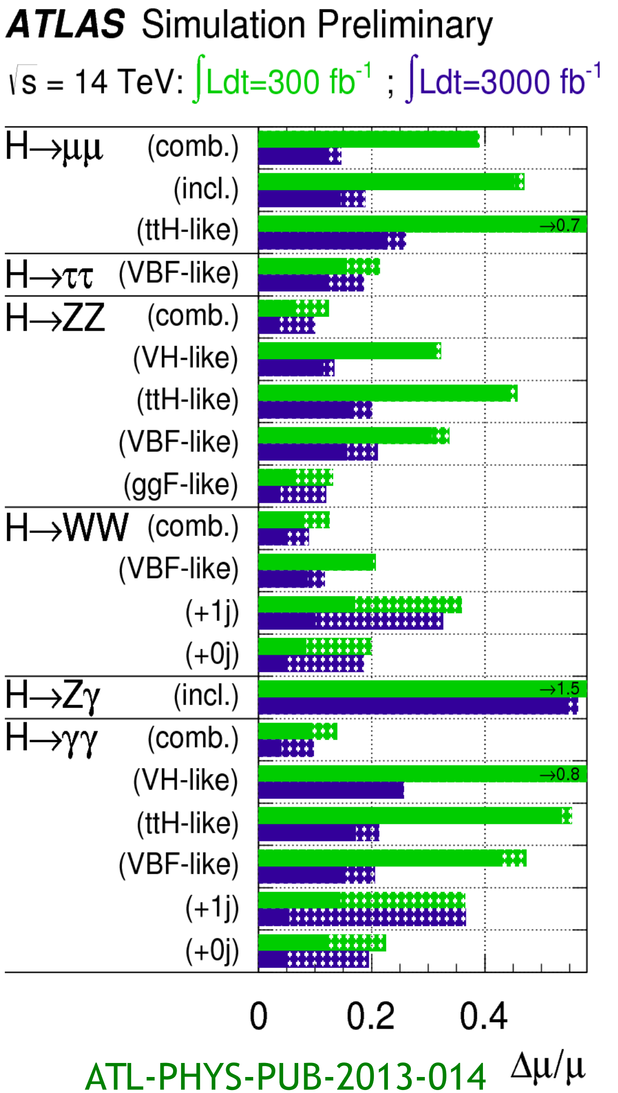
With a few fb^{-1}, discovery of new TeV-scale particles is possible – expect 15-20 fb^{-1} by end 2015, ~100 fb^{-1} in Run-2

Prospects for H(125) measurements

Higgs couplings may indicate new physics: a few percent precision is a good target

Higgs Snowmass report (arXiv:1310.8361)
Deviation from SM due to particles with M=1 TeV

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$



ATL-PHYS-PUB-2013-014

> Future LHC data will allow to measure H couplings at 2-8% level (cf 20-50% today), and to access rare decays such as H→μμ

CMS projections for coupling precision (arXiv:1307.7135)

L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$	BR_{SM}
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]	[7, 11]

Conclusions

The LHC and its large experiments, ATLAS and CMS, are a triumph of global scientific collaboration

A wealth of measurements have established the continuing validity of the SM at LHC energies, and laid the foundation for future searches

The discovery of the Higgs boson at 125 GeV, with close-to-SM properties, has energised, and helped re-focus, searches beyond the Standard Model – but as yet no sustained hints of new physics beyond the Standard Model have been seen

The increase of centre-of-mass energy to 13-14 TeV in 2015 and beyond will extend the mass reach much further, well into the TeV region

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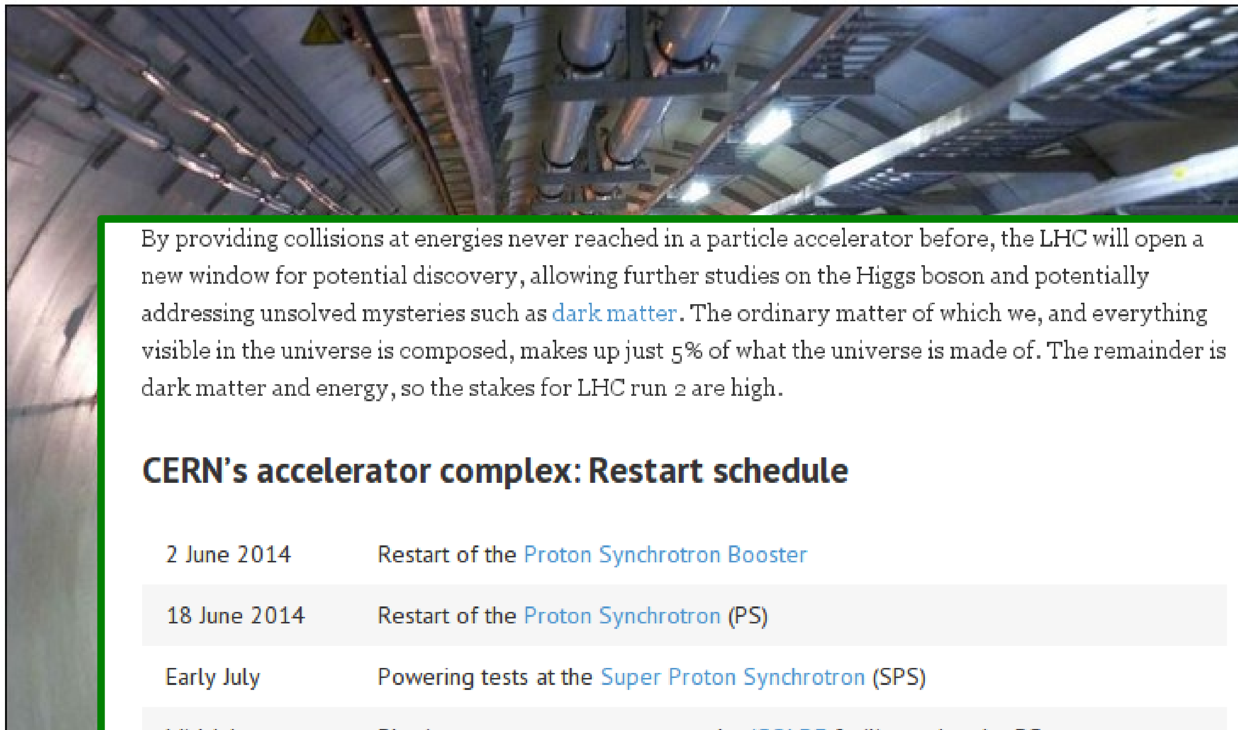
CERN announces LHC restart schedule

Posted by Cian O'Luanaigh on 23 Jun 2014. Last updated 23 Jun 2014, 12.35.



By providing collisions at energies never reached in a particle accelerator before, the LHC will open a new window for potential discovery, allowing further studies on the Higgs boson and potentially addressing unsolved mysteries such as dark matter. The ordinary matter of which we, and everything visible in the universe is composed, makes up just 5% of what the universe is made of. The remainder is dark matter and energy, so the stakes for LHC run 2 are high.

CERN's accelerator complex: Restart schedule

2 June 2014	Restart of the Proton Synchrotron Booster
18 June 2014	Restart of the Proton Synchrotron (PS)
Early July	Powering tests at the Super Proton Synchrotron (SPS)
Mid-July	Physics programme to restart at the ISOLDE facility and at the PS
Mid-August	Antimatter Physics programme to restart at the Antiproton Decelerator
Mid-October	Physics programme to restart at the SPS
Early 2015	Beam back into the Large Hadron Collider (LHC)
Spring 2015	Physics programme to restart at the LHC experiments

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