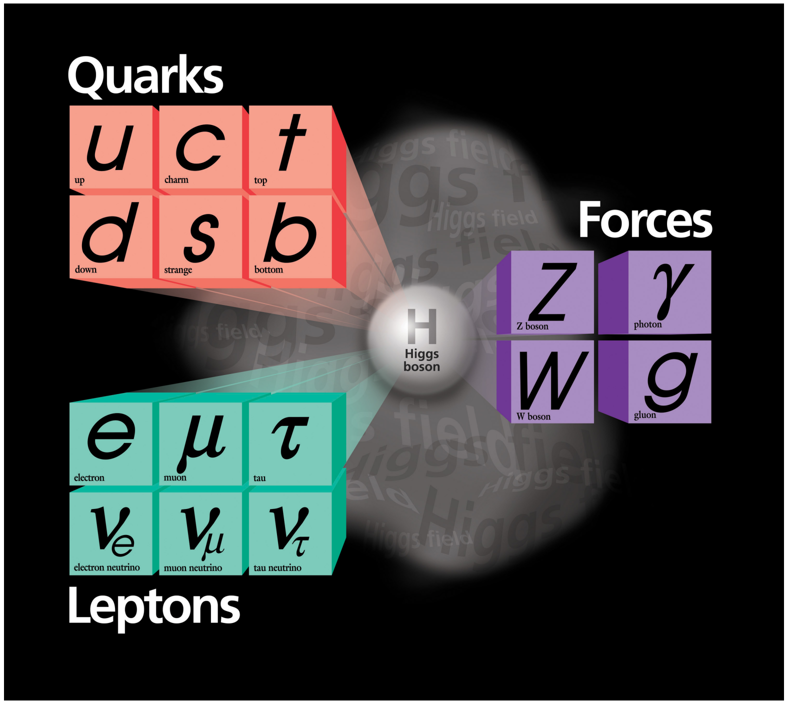
What -- in my personal opinion -- should be the highest level conclusions of the Energy Frontier report?

B. Heinemann

(LBNL and UC Berkeley)

Seattle, July 2nd 2013

The Standard Model



$$\begin{aligned}\mathcal{L} \;=\; & -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\,\bar{\psi}D\!\!\!/\,\psi \\ & + \psi_i\lambda_{ij}\psi_j h + \text{h.c.} \\ & + |D_\mu h|^2 - V(h) \\ & + \frac{1}{M}L_i\lambda^\nu_{ij}L_j h^2 \text{ or } L_i\lambda^\nu_{ij}N_j\end{aligned}$$

- In the past 116 years we have discovered all the fundamental particles and their interactions
  - Electron discovery 1897 => Higgs discovery 2013
  - Amazing theoretical and experimental success!
- We now have a self-consistent theory that ***can*** be extrapolated to the Planck scale without breaking down
  - However, many questions are open which likely means there is some new physics between EWK and Planck scale

QUANTUM UNIVERSE

THE REVOLUTION IN 21ST CENTURY PARTICLE PHYSICS

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What does "Quantum Universe" mean?

To discover what the universe is made of and how it works is the challenge of particle physics. Quantum Universe presents the quest to explain the universe in terms of quantum physics, which governs the behavior of the microscopic, subatomic world. It describes a revolution in particle physics and a quantum leap in our understanding of the mystery and beauty of the universe.

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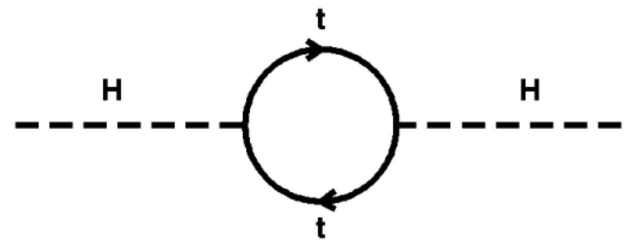
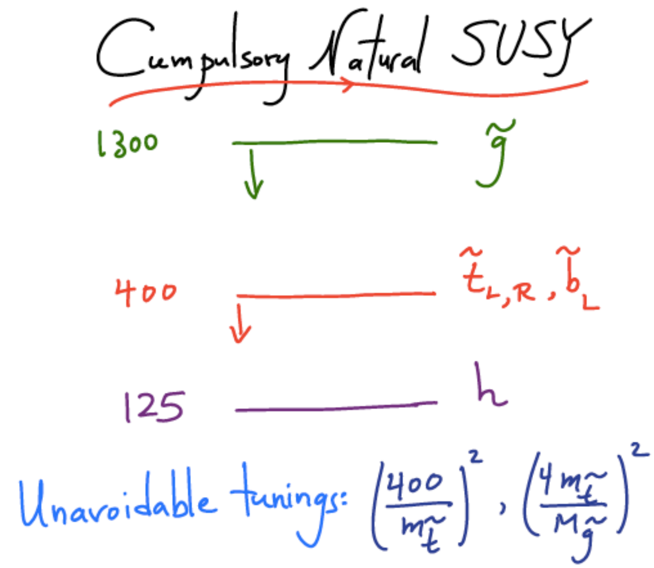
Higgs Discovery

- Higgs discovery raises more detailed questions
  - What protects its mass being much higher?
  - Is it the only (fundamental) scalar particle?
    - Is it a fundamental particle of composite?
  - Does it fully unitarize longitudinal WW scattering?
- Two strategies at the energy frontier
  - Directly search for new particles
    - Particles related to symmetry which protects mass
    - Particles related to composite structure (aka "new rho meson")
  - Precision measurement of Higgs boson properties

What protects its mass from being higher?

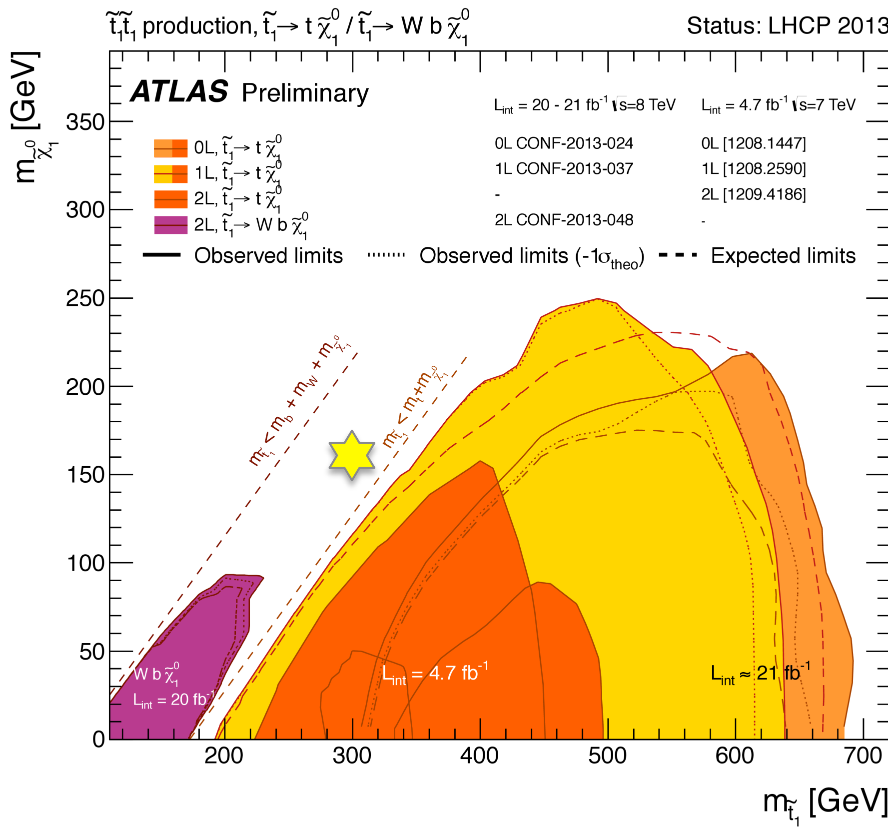
- Known possible answers:
  - SUSY: top squark at m<400 GeV
    - and gluino with m<1.6 TeV
  - vector-like top quarks
    - E.g. Little Higgs theories
  - extra spatial dimensions or some other dramatic new physics at a mass scale of a few TeV
  - weak scale is fine-tuned at ~1%
- Gia Dvali (ATLAS week, Oct. 2012): *"there must be some other stuff at $M \sim m_H$ … or at $M \sim 4\pi\, m_H$ … or at $M \sim 16\, \pi^2\, m_H$"*
  - This implies between 100 GeV and 20 TeV!
- Can directly search for these particles at colliders

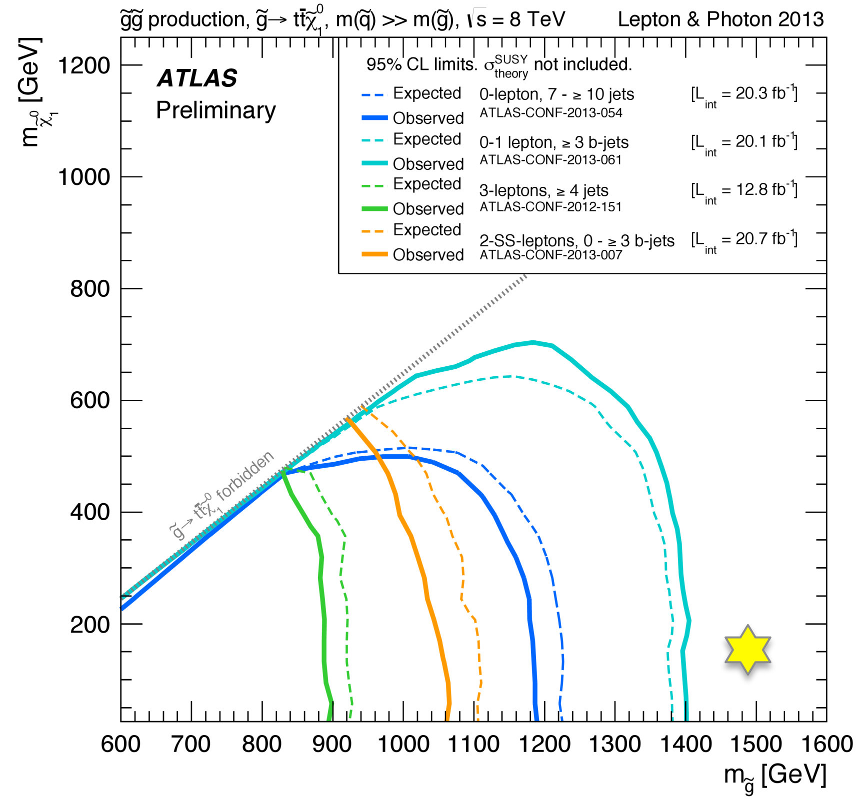




N. Arkani-Hamed

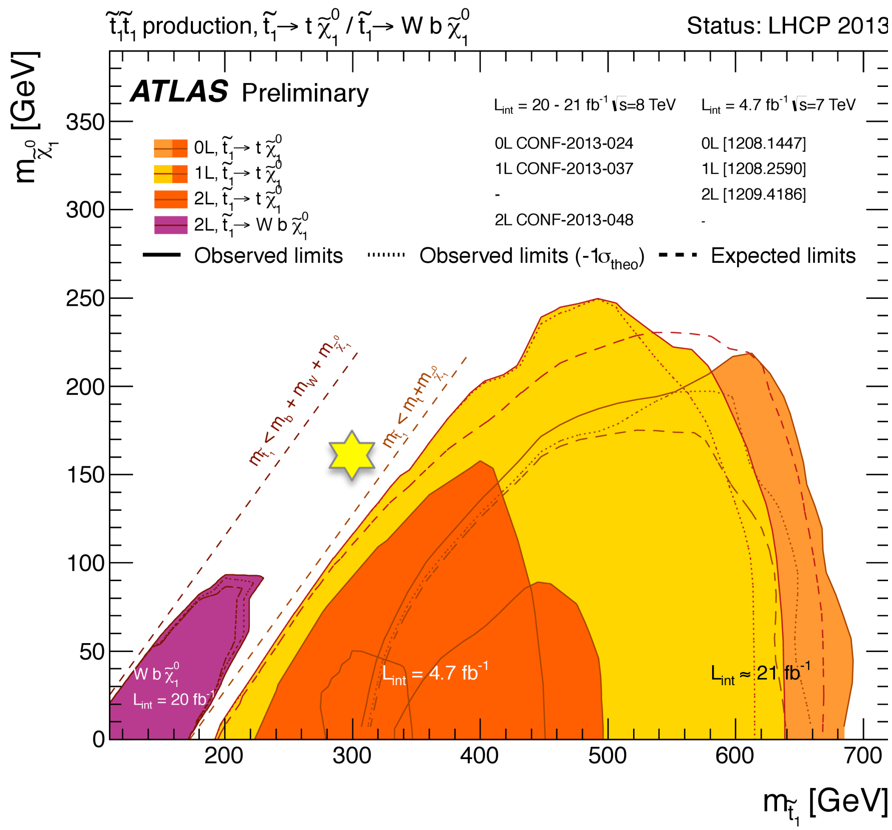
Constraints on top squarks

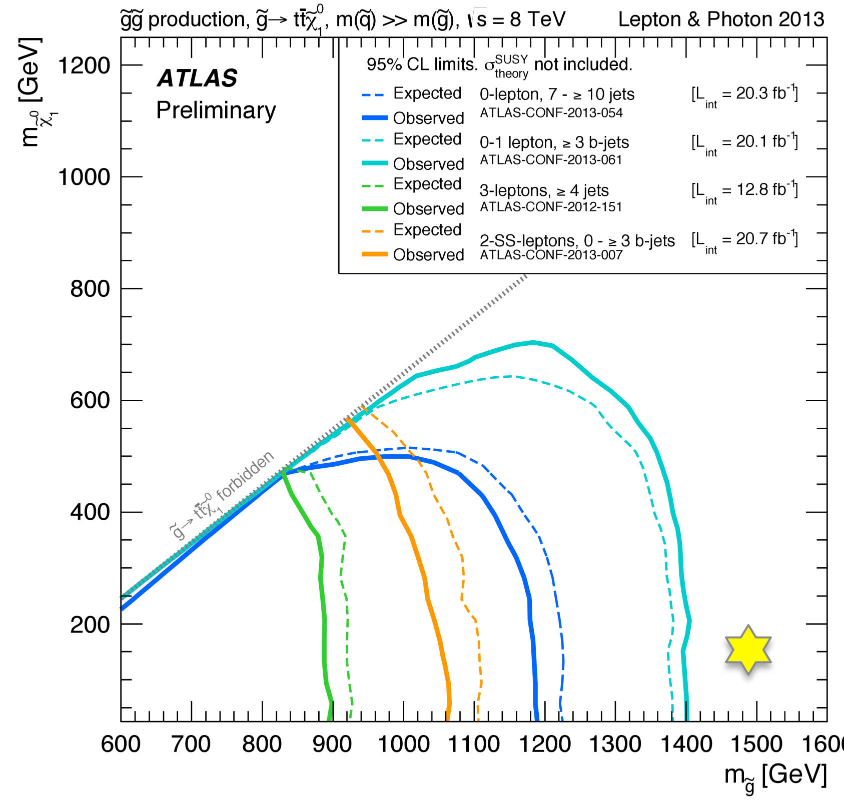




- Constraints ever improving from both ATLAS and CMS

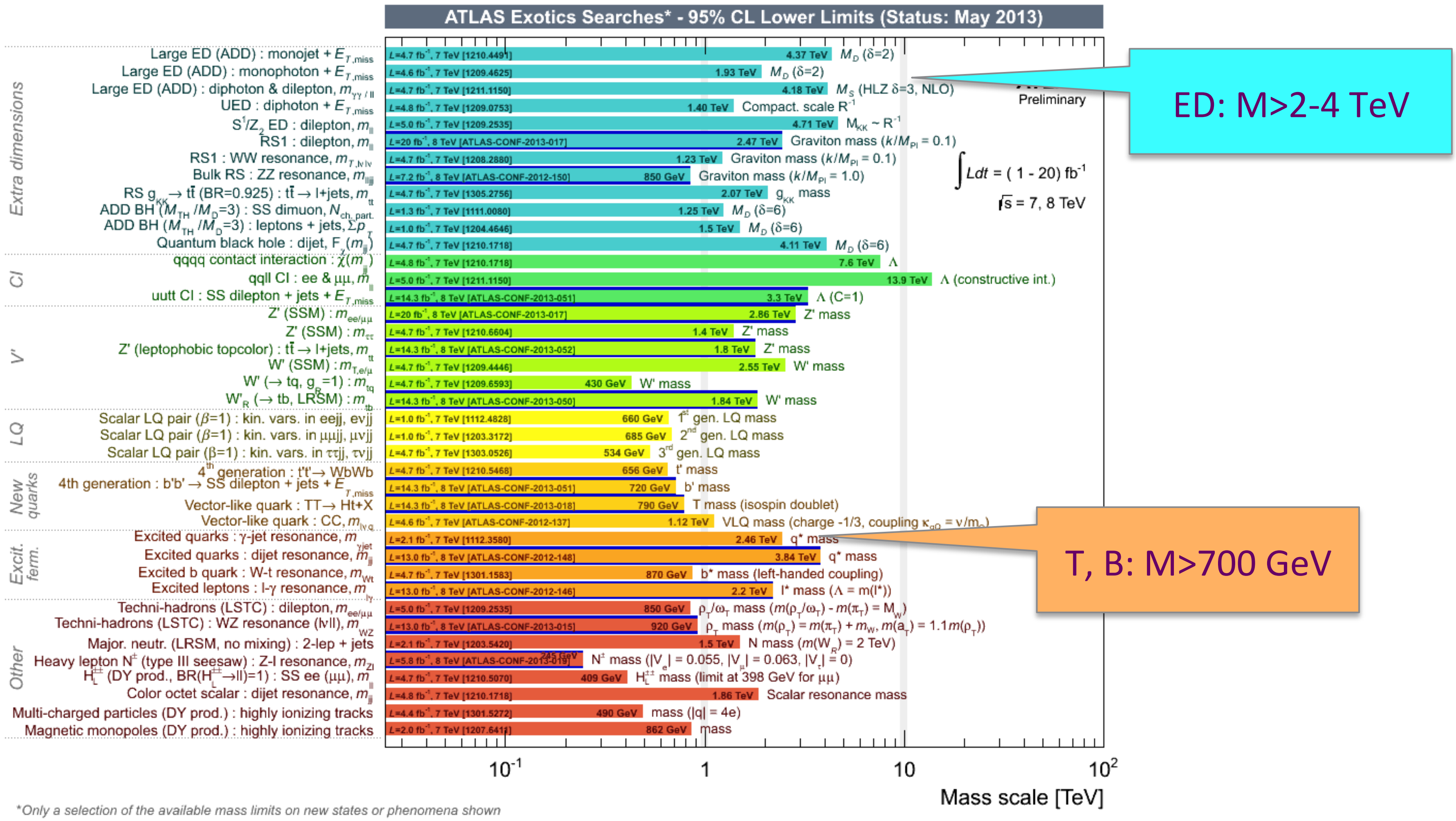
Constraints on top squarks





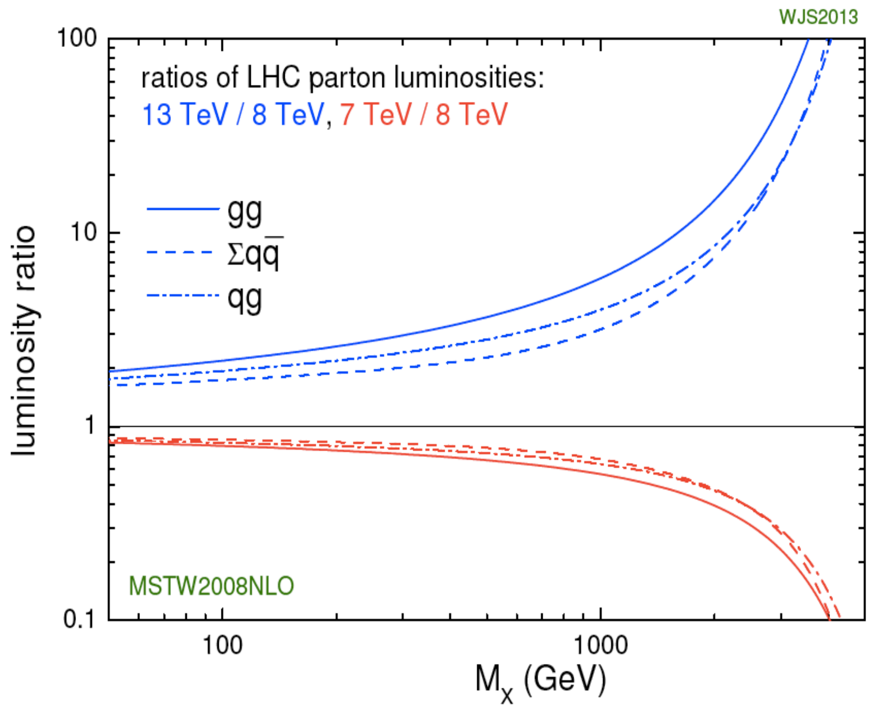
- Constraints ever improving from both ATLAS and CMS
- However, **pretty natural** scenarios still allowed, e.g
  - M(gluino)=1.5 TeV, m(stop)=300 GeV, m(LSP)=150 GeV
- LHC (and HL-LHC) will be able to discover such scenarios

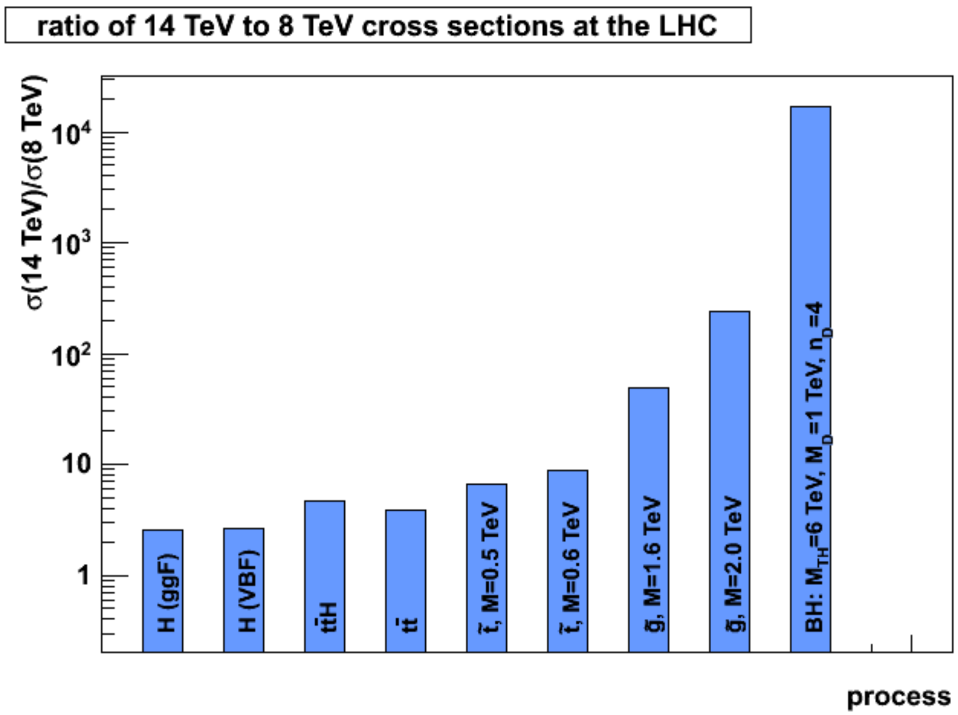
Other New Particles



- Reach for such particles will be approximately doubled or even tripled in future LHC running

Run-2 Physics Cross Sections

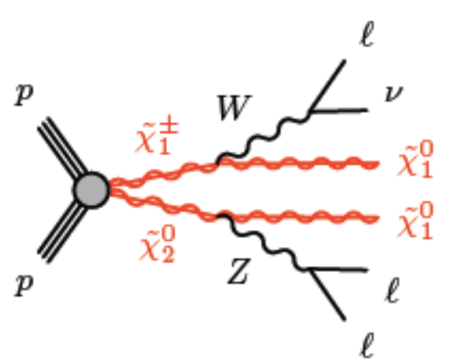


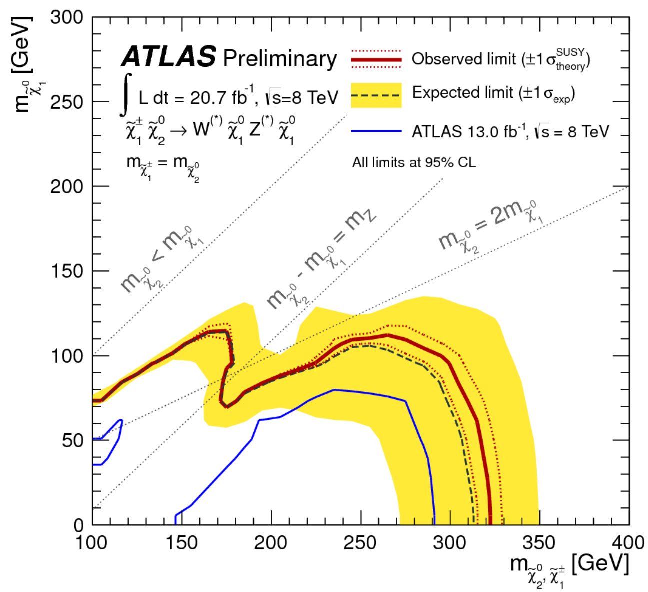


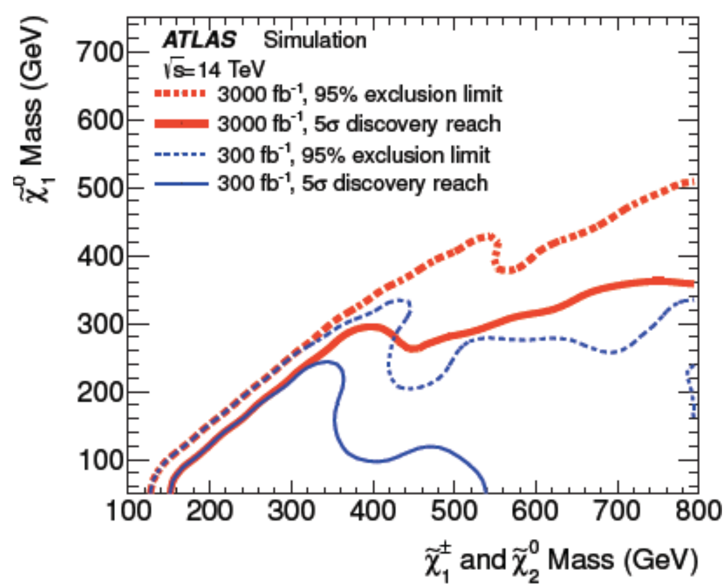
- Increase in cross section by factor ~10 for M~2 TeV
- Discovery of TeV scale particles possible with a few fb^{-1}

New physics at the weak scale

- Even if Nature is finetuned and stop is heavy we have other reasons for new physics at weak scale
  - Unification of couplings, Dark Matter, …
- E.g. in "split-SUSY" other scalars are all heavy but gauginos are at ~low mass







Dramatic improvement in reach by HL-LHC: probing ~1 TeV charginos!

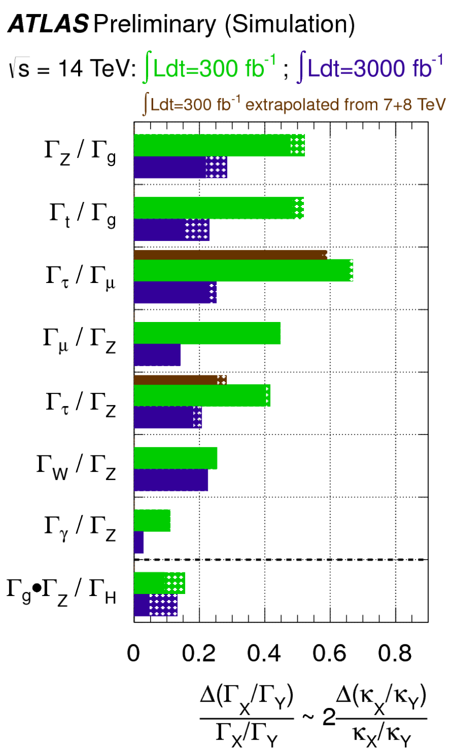
Is it a fundamental particle or composite?

- Should observe deviation in Higgs branching ratios

	ΔhVV	$\Delta h t\bar{t}$	Δhbb
Mixed-in Singlet	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
Minimal Supersymmetry	$< 1\%$	3%	$10\%^a$, $100\%^b$

R. Gupta et al., arXiv: 1206.3560

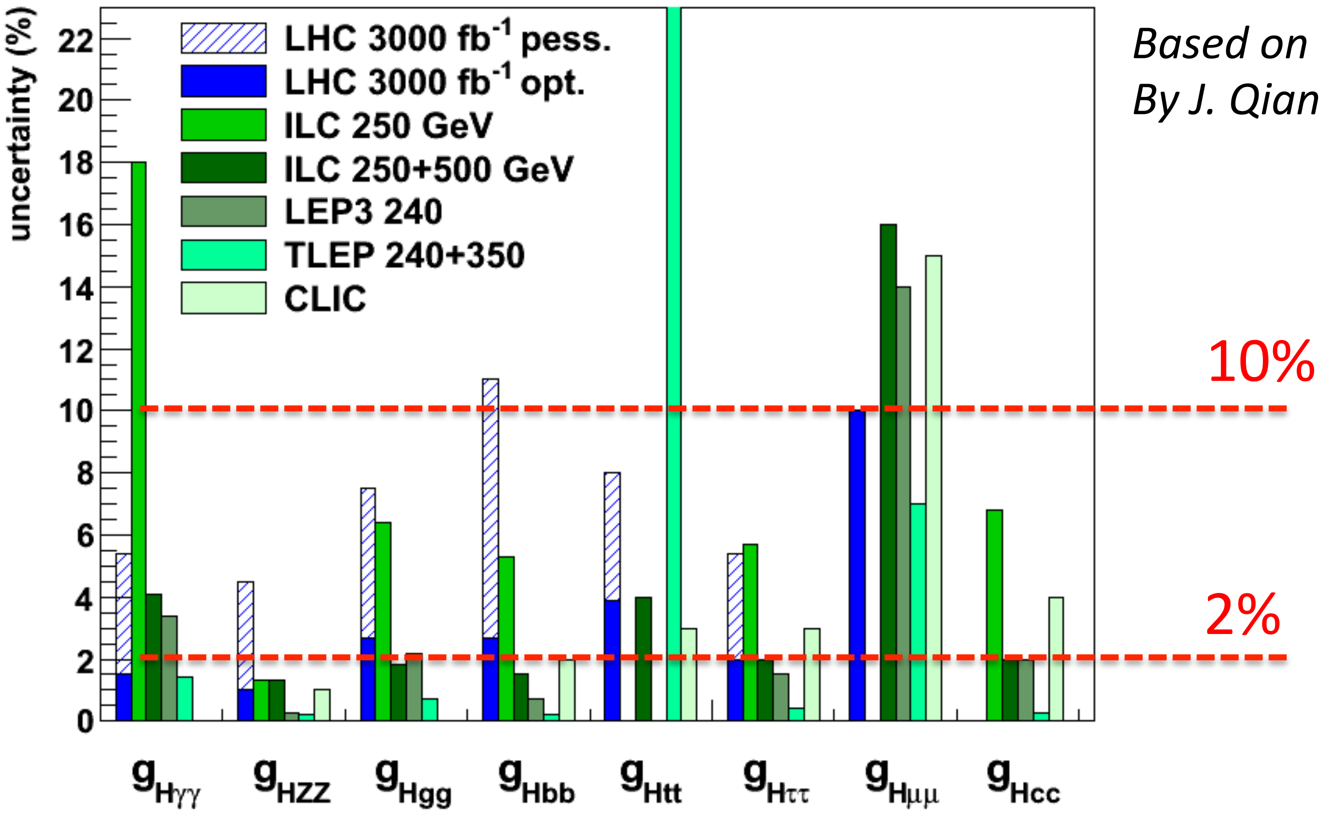
J. Qian



Facility	LHC	HL-LHC	ILC	Full ILC	CLIC	LEP3 (4 IP)	TLEP (4 IP)
Energy (GeV)	14,000	14,000	250	250+500+1000	350+500+1500	240	240+350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250	250+500+1000	500+500+1500	2000	10000+1400
N_H produced	1.7×10^7	1.7×10^8	80,000	370,000	618,000	600,000	3,200,000
				Measurement precision			
m_H (MeV)	100	50	35	35	70	26	7
$\Delta\Gamma_H$	–	–	11%	6%	6%	4%	1.3%
$\mathrm{BR}_{\mathrm{inv}}$	NA	NA	<0.8%	<0.8%	NA	<0.7%	<0.3%
$\Delta g_{H\gamma\gamma}$	5.1 – 6.5%	1.5 – 5.4%	18%	4.1%	NA	3.4%	1.4%
Δg_{Hgg}	5.7 – 11%	2.7 – 7.5%	6.4%	1.8%	NA	2.2%	0.7%
Δg_{HWW}	2.7 – 5.7%†	1.0 – 4.5%†	4.8%	1.4%	1%	1.5%	0.25%
Δg_{HZZ}	2.7 – 5.7%†	1.0 – 4.5%†	1.3%	1.3%	1%	0.25%	0.2%
$\Delta g_{H\mu\mu}$	< 30%	< 10%	–	16%	15%	14%	7%
$\Delta g_{H\tau\tau}$	5.1 – 8.5%	2.0 – 5.4%	5.7%	2.0%	3%	1.5%	0.4%
Δg_{Hcc}	–	–	6.8%	2.0%	4%	2.0%	0.25%
Δg_{Hbb}	6.9 – 15%	2.7 – 11%	5.3%	1.5%	2%	0.7%	0.22%
Δg_{Htt}	8.7 – 14%	3.9 – 8.0%	–	4.0%	3%	–	30%
Δg_{HHH}	–	30%‡	–	26%	16%	–	–

Note: with the luminosity upgrade, the ILC coupling precision improves by a factor of ∼ 2.
† assuming the same deviation for the HWW and HZZ couplings. ‡ two experiments.

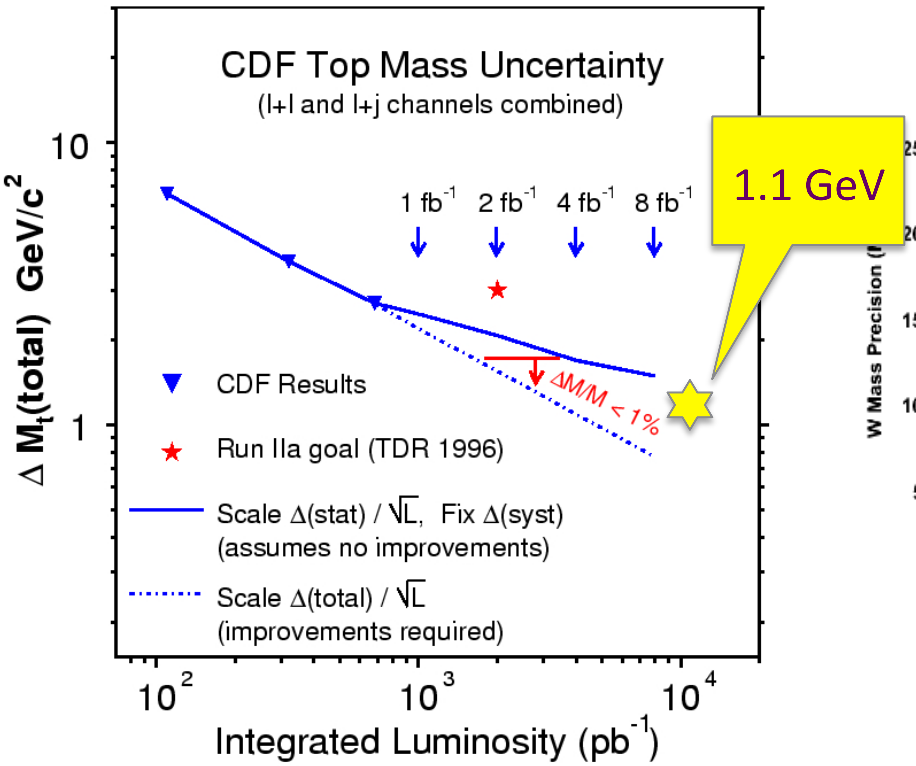
Higgs Boson Coupling Precision

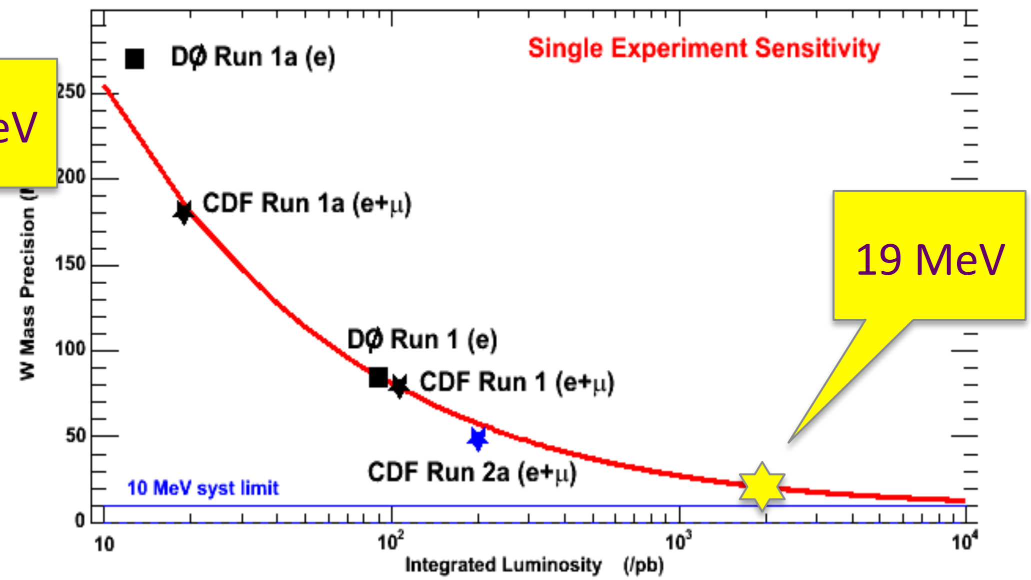


Based on table shown
By J. Qian

- HL-LHC will test couplings at a few % precision (albeit some model-dependence)
  - ILC precision comparable and model-independent, TLEP best
- "Optimistic" HL-LHC scenario involves scaling all experimental errors by sqrt(L) and assuming theoretical precision improves by factor 2
  - Progress on theoretical cross section precision has also been HUGE in the past decade ("**NLO revolution**") => Thanks!!! Hope (and believe) it continues!

Comment on Hadron Collider Projections





- I personally think that assuming sqrt(L) data scaling is reasonable (definitely not crazy!)
  - Having large statistics allows to select the "best events"
  - Data can be used to constrain systematics *in situ*

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- EWK scale is probed **directly** at the energy frontier via the on-shell production of weak scale particles
  - There is a fantastic opportunity of discovering new physics directly in LHC's future running
    - HL-LHC critical to fully explore highest mass scales and/or new physics found earlier
    - Lepton colliders can complement LHC in specific scenarios
  - Higgs boson needs to be studied in detail
    - HL-LHC will probe it with few % precision (needs theory work)
    - ILC achieves similar precision to HL-LHC / TLEP ~10 times better
  - We should plan to build a 100 TeV hadron collider (and/or multi-TeV lepton collider)
    - R&D should be strongly supported to enable this (at all and at lowish cost)

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- The interest in energy frontier is HUGE
  - theoretical interest is HUGE
    - ATLAS has 30 papers (all <3 years old) with >100 citations (Higgs paper has >1000)
    - ATLAS+CMS have 500 papers
  - interest from the general public is HUGE
    - Public lectures, events at school, media (TV and print), movies,…

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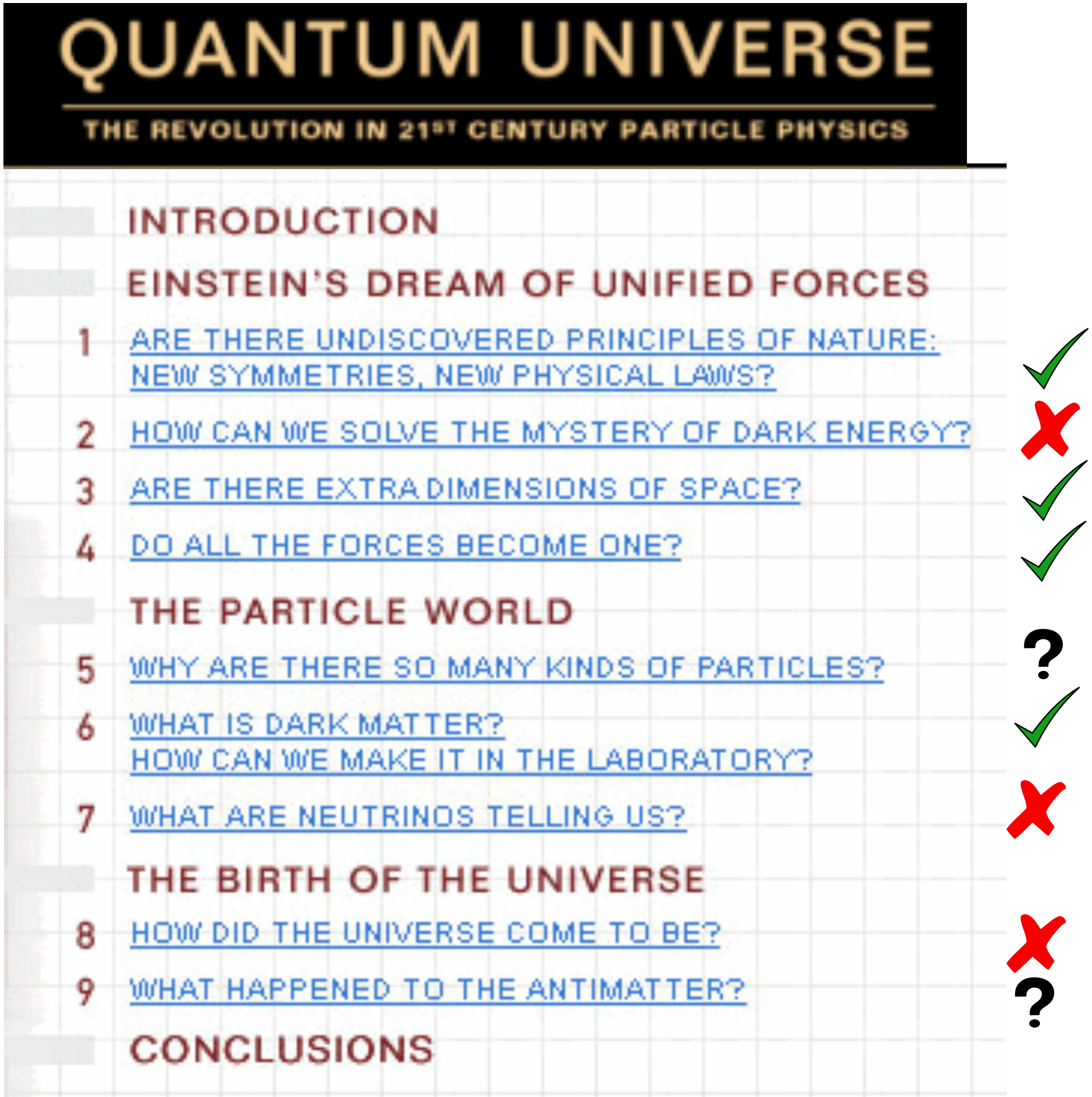
Which big questions are addressed by the energy frontier?



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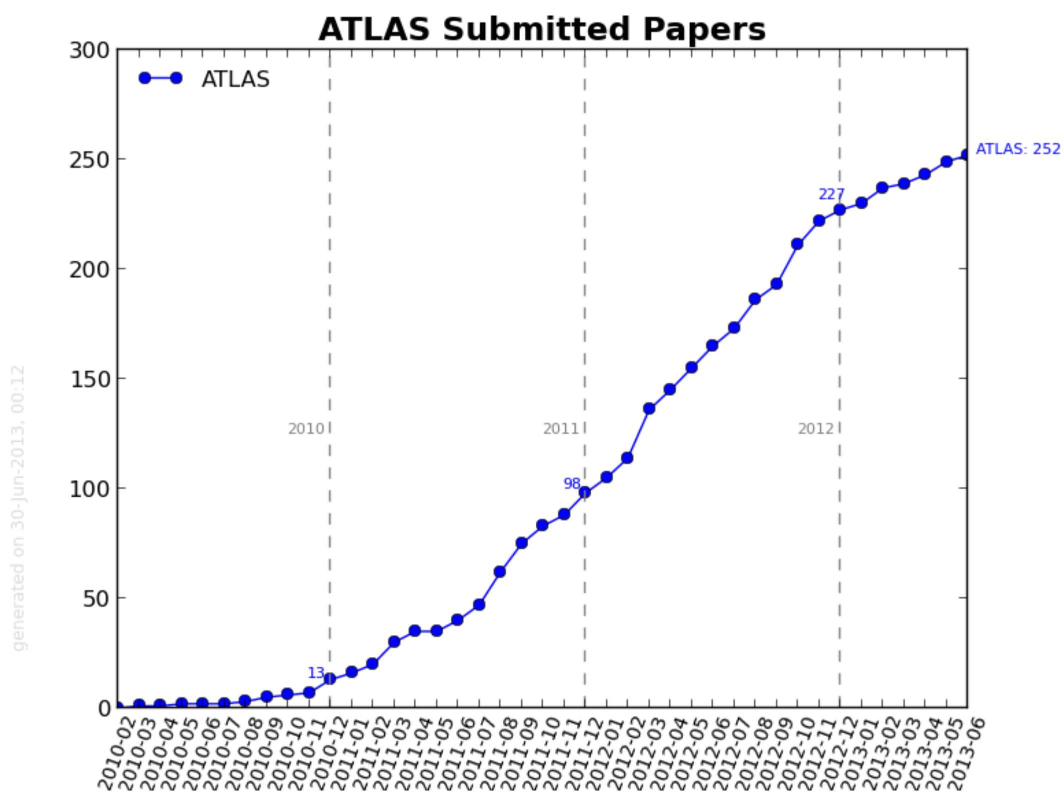
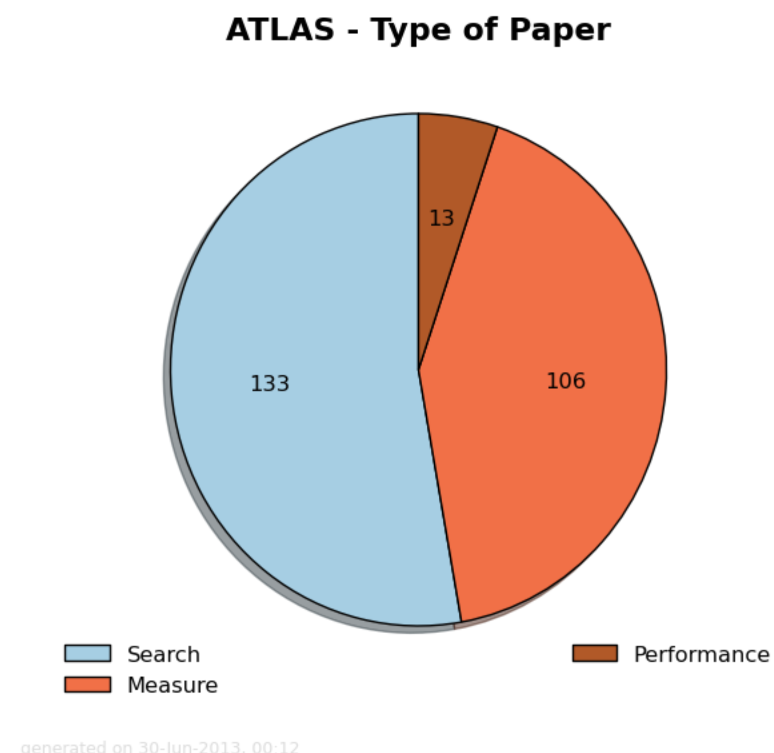
Backup Slides

ATLAS submitted papers





In addition ATLAS has released 497 conference notes (!)