Beyond The Standard Model
LHC Results and Prospects

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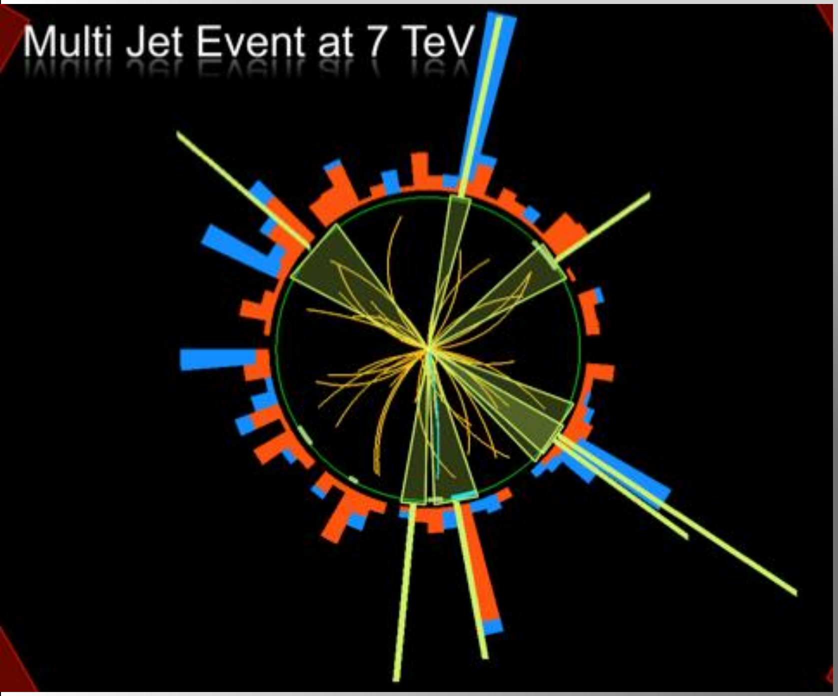
Split School of High Energy Physics 2015

Lecture Plan

Overview of the two lectures in the next two days at this school

- Lecture 1: Introduction to physics Beyond the Standard Model (BSM) and searches for exotic phenomena at the LHC
- Lecture 2: Searches for Supersymmetry, the connection to dark matter searches and an outlook for the future.

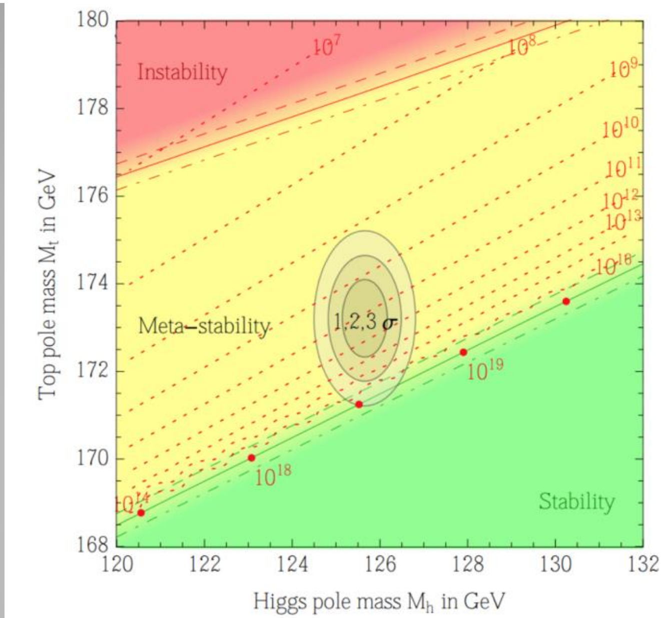


Outline

- Search for Supersymmetry
- The connection with dark matter
- Outlook for Run-II
- Far Future Outlook
- Summary

Searches for New Physics

Important SM parameter → stability of EW vacuum

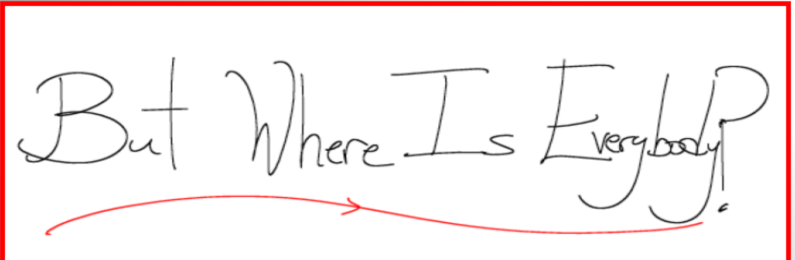


arXiv:1205.6497

arXiv:1403.6535

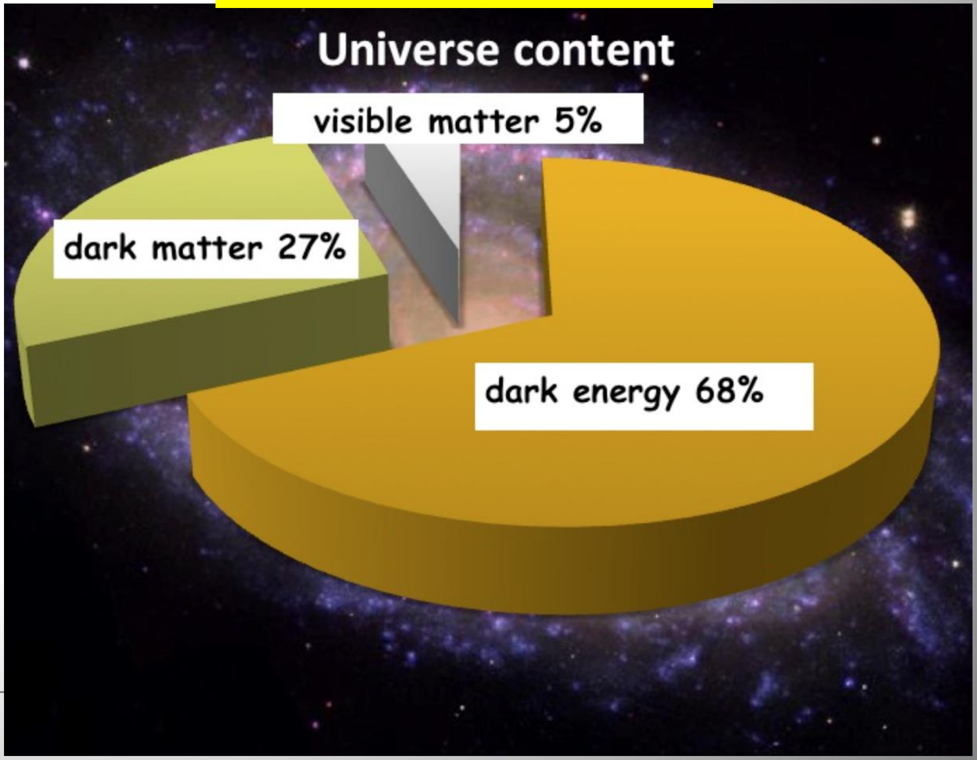
Precise measurements of the top quark and first measurements of the Higgs mass

New Physics inevitable?
But at which scale/energy?



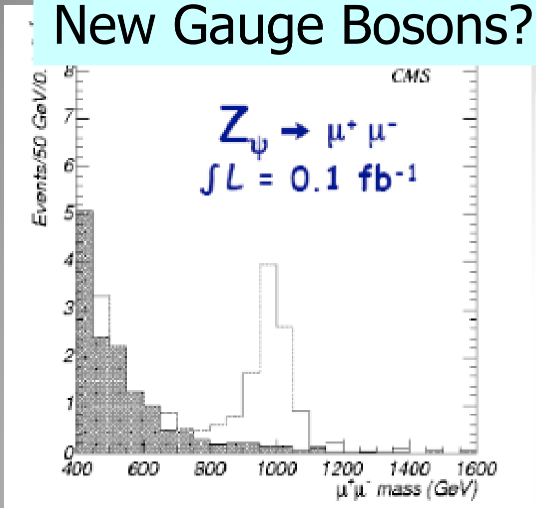
N. Arkani-Hamed

We also know that:

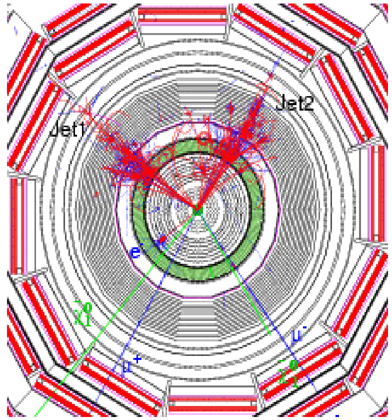


New Physics?

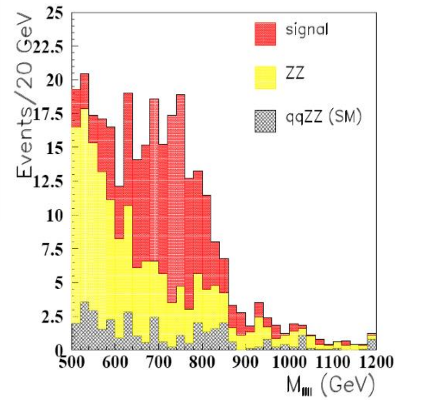
New Gauge Bosons?



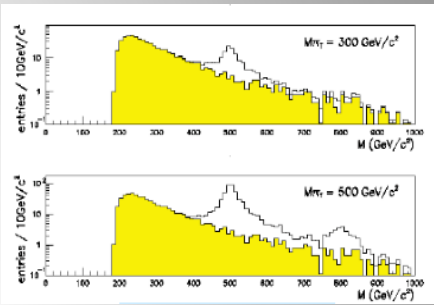
Supersymmetry



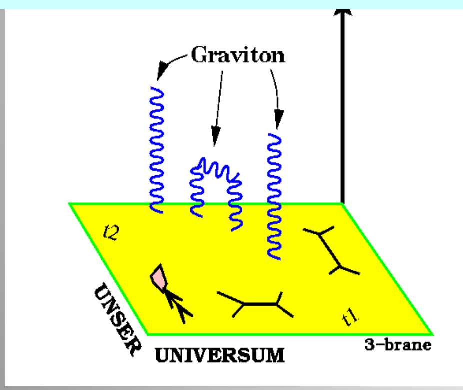
ZZ/WW resonances?



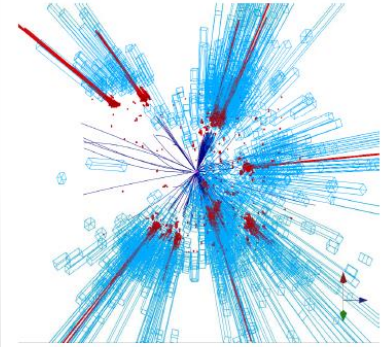
Technicolor?



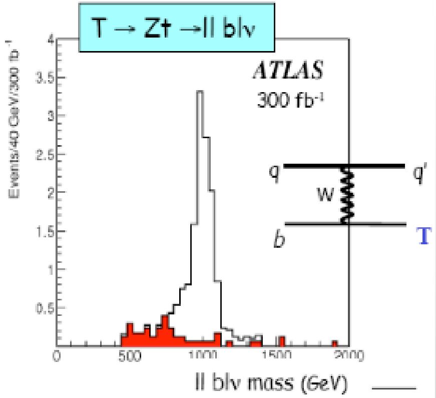
Extra Dimensions?



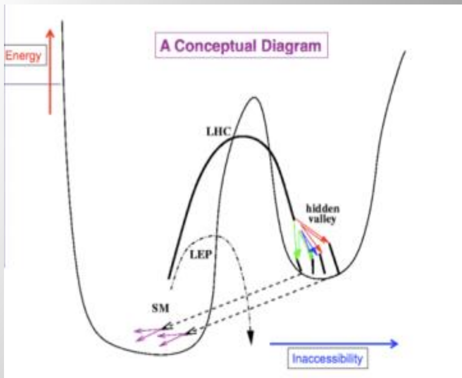
Black Holes???



Little Higgs?



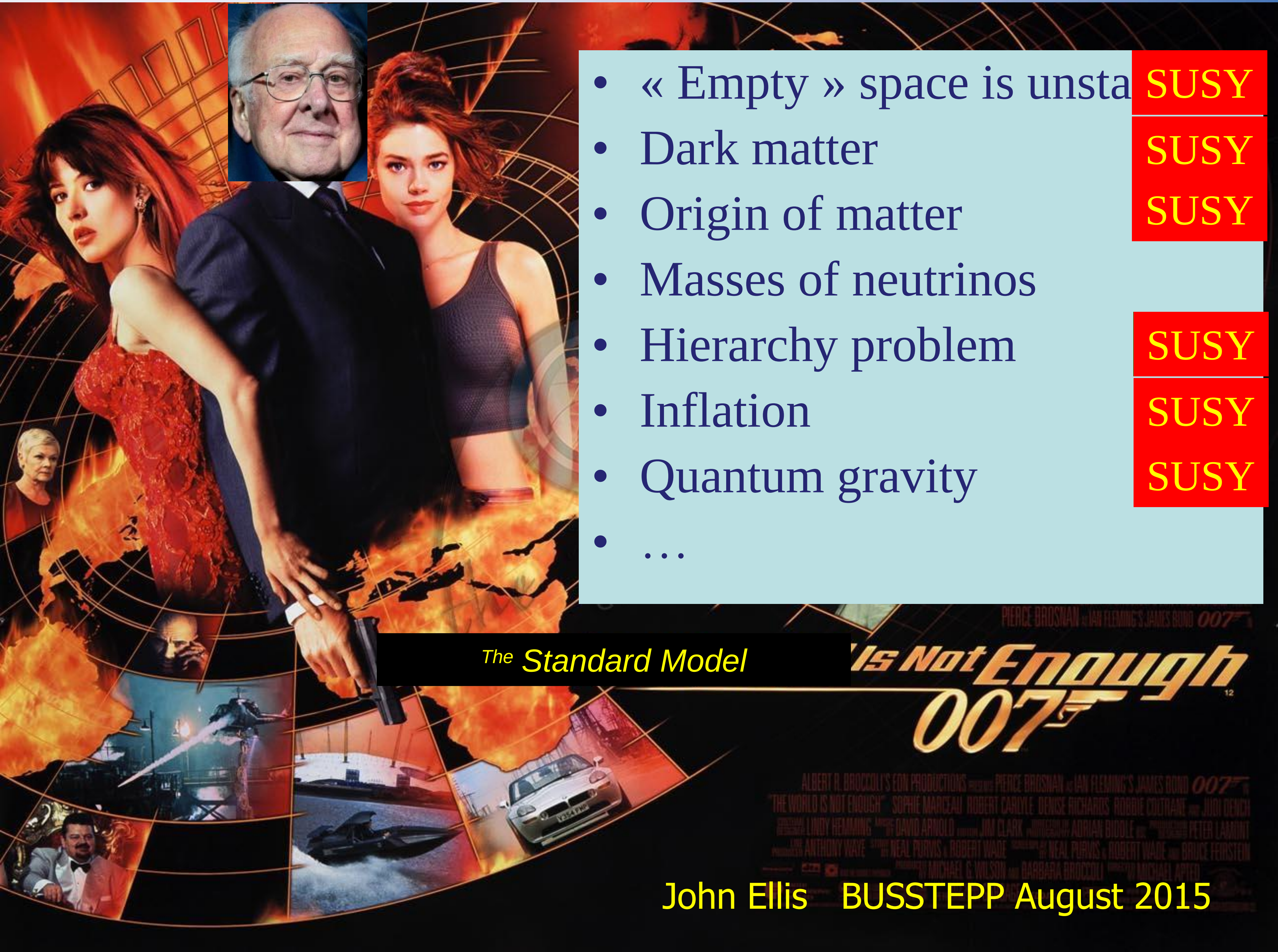
Hidden Valleys?



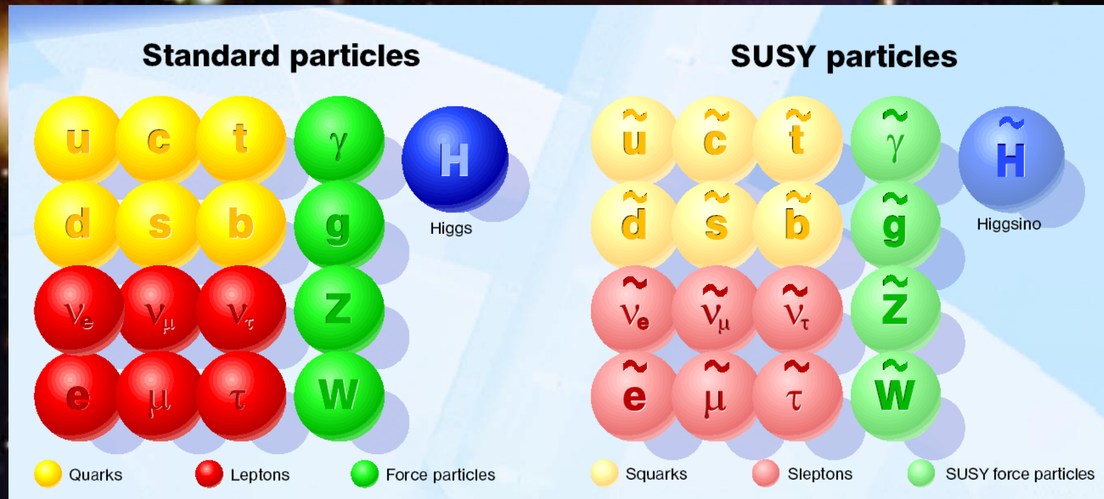
What stabelizes the Higgs Mass? Many ideas, not all viable any more

A large variety of possible signals. We have to be ready for that

- « Empty » space is unsta SUSY
- Dark matter SUSY
- Origin of matter SUSY
- Masses of neutrinos
- Hierarchy problem SUSY
- Inflation SUSY
- Quantum gravity SUSY
- …

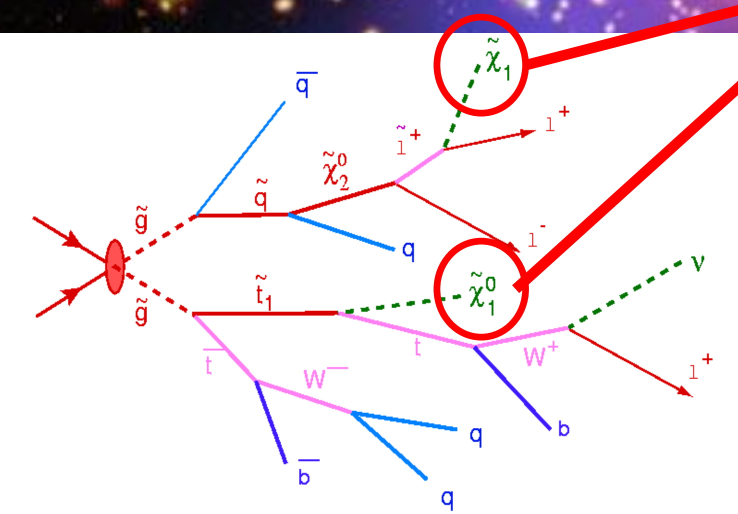


Supersymmetry: a new symmetry in Nature?



Candidate particles for Dark Matter
⇒ Produce Dark Matter in the lab

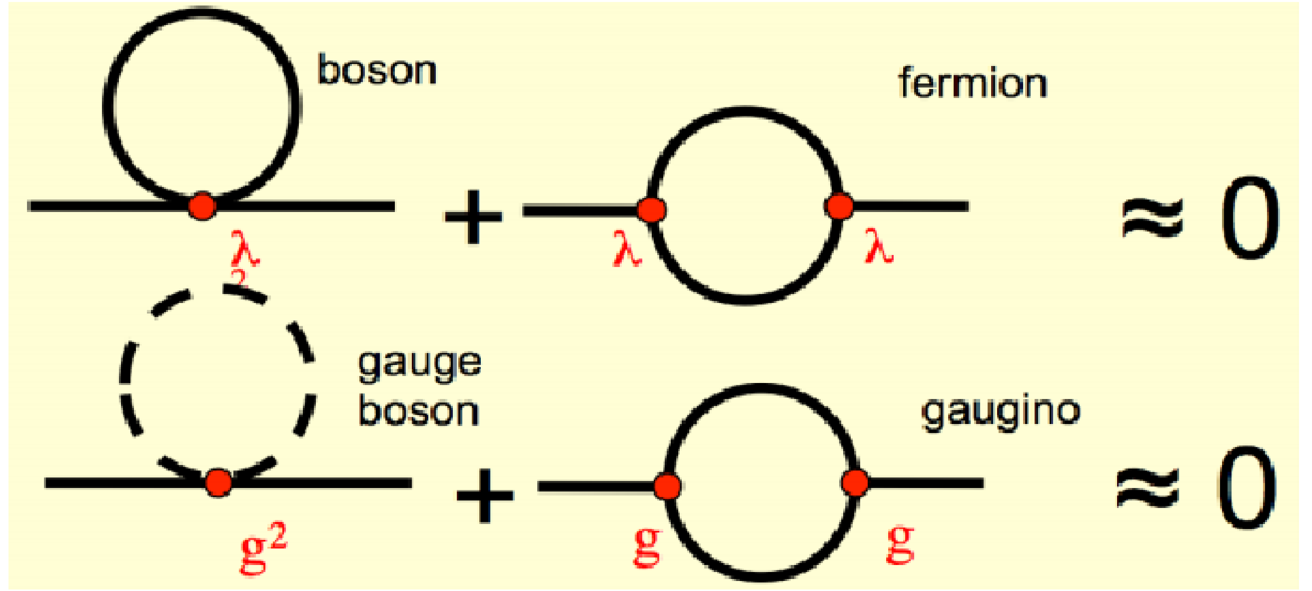
"One day all these trees will be SUSY phenomenology papers"



SUSY particle production at the LHC

Supersymmetry

Supersymmetry (SUSY) → assumes a new hidden symmetry between the bosons (particles with integer spin) and fermions (particles with half integer spin). Stabelize the Higgs mass up to the Planck scale



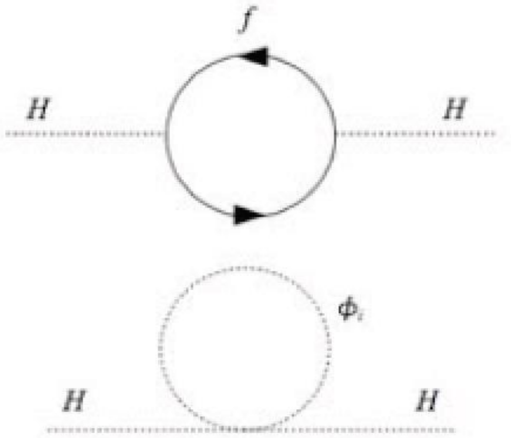
Fermion and boson loops cancel, provided $m_{\tilde{f}} \leq$ TeV.

Why weak-scale SUSY ?

- stabilises the EW scale: $|m_F - m_B| < O(1\ \text{TeV})$
- predicts a light Higgs $m_h < 130$ GeV
- accomodates gauge unification
- accomodates heavy top quark
- dark matter candidate: neutralino, sneutrino, gravitino, ...
- consistent with EW precision tests

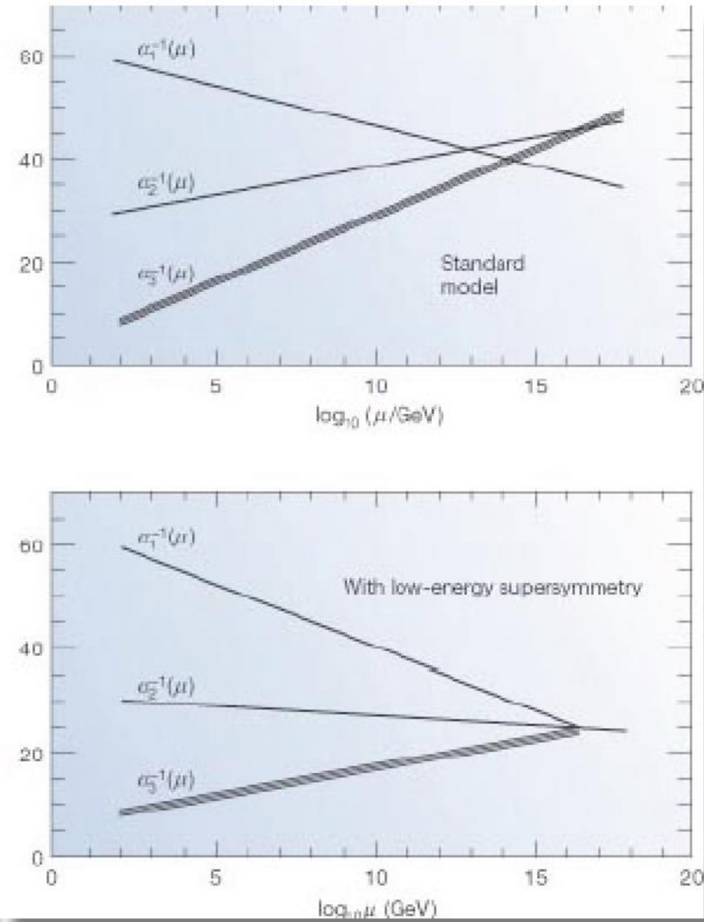
Discovering SUSY – A revolution in particle physics!!

Summary: Why SUSY is good for you!!



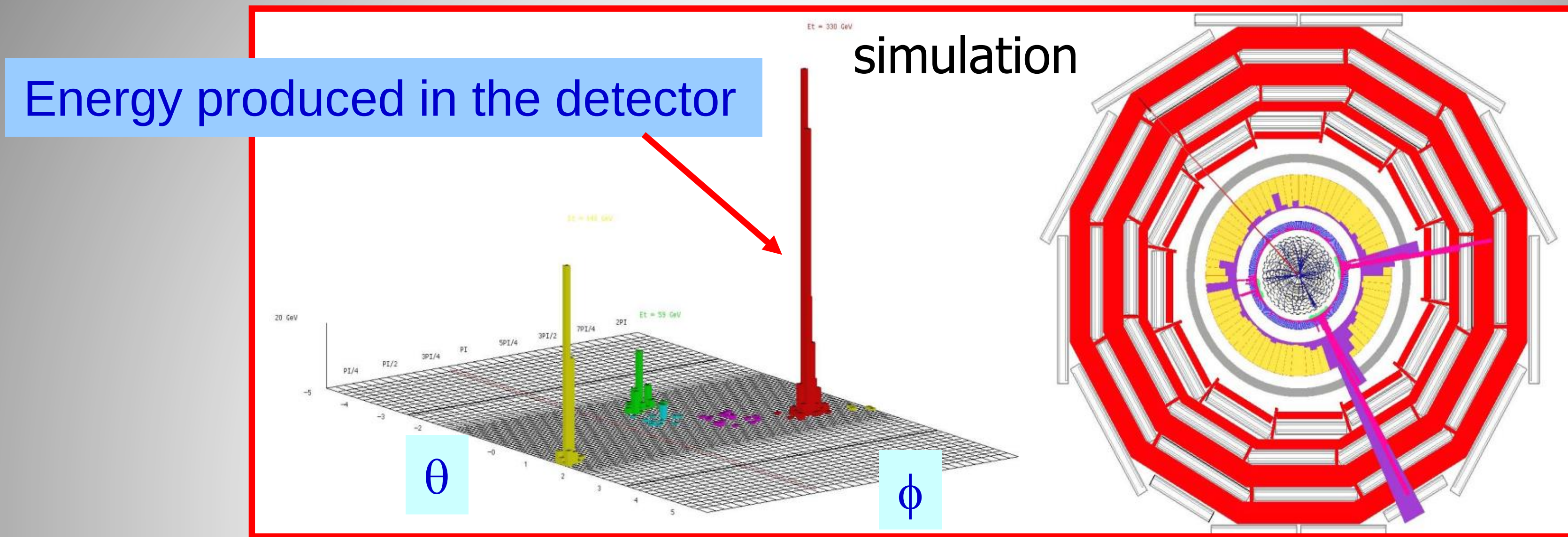
$$\Delta M_H^2 \sim \frac{\lambda_f^2}{4\pi^2}[(m_f^2 - m_S^2)\log(\frac{\Lambda}{m_S})]$$

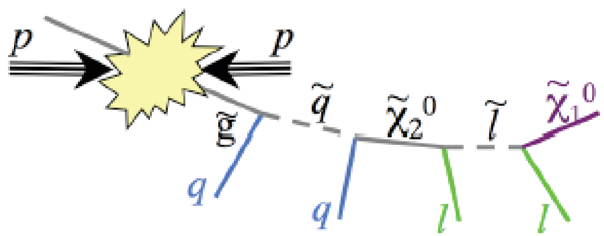
- Elegant solution to the hierarchy problem (i.e., why the Higgs mass is not at the Planck scale)
- Gauge unification



- Dark matter candidate with the right abundance

Detecting Supersymmetric Particles



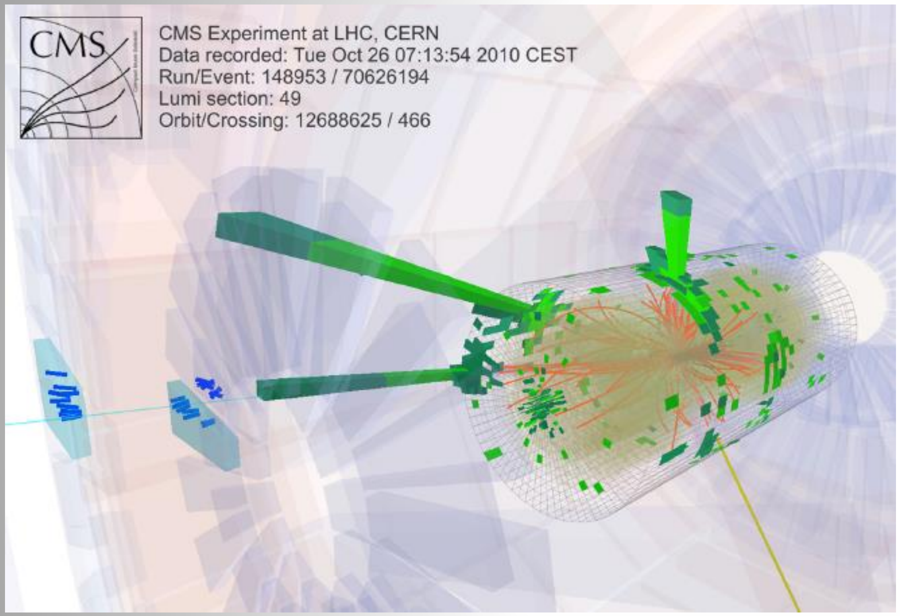


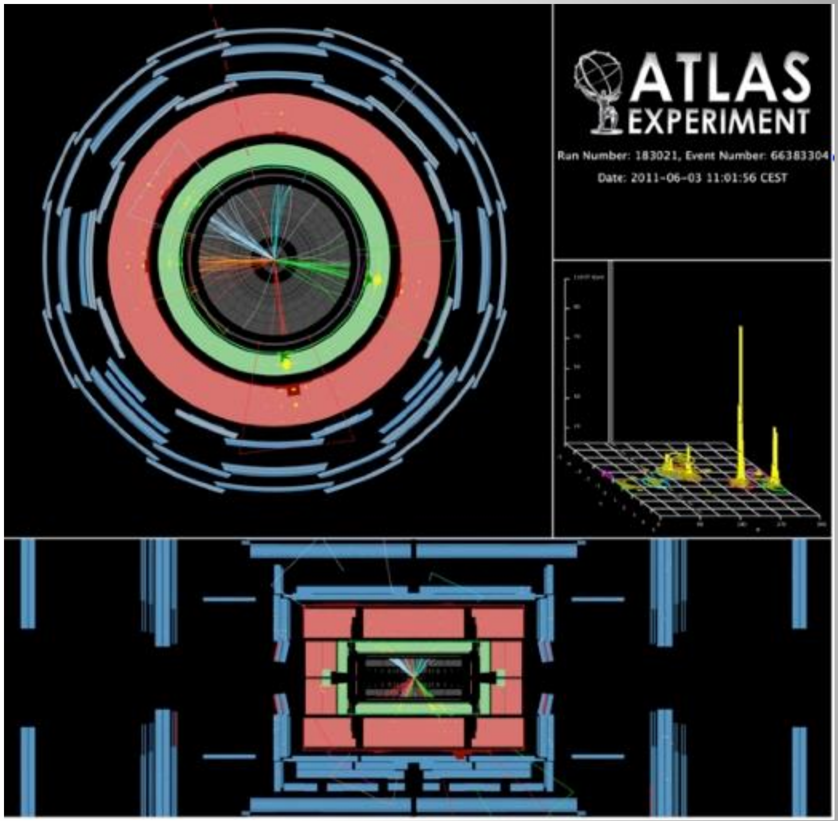
Supersymmetric particles decay and produce a cascade of jets, leptons and missing transverse energy (MET) due to escaping 'dark matter' particle candidates

➡ Very prominent signatures in CMS and ATLAS

…Some Interesting Collisions…

…already in 2010…

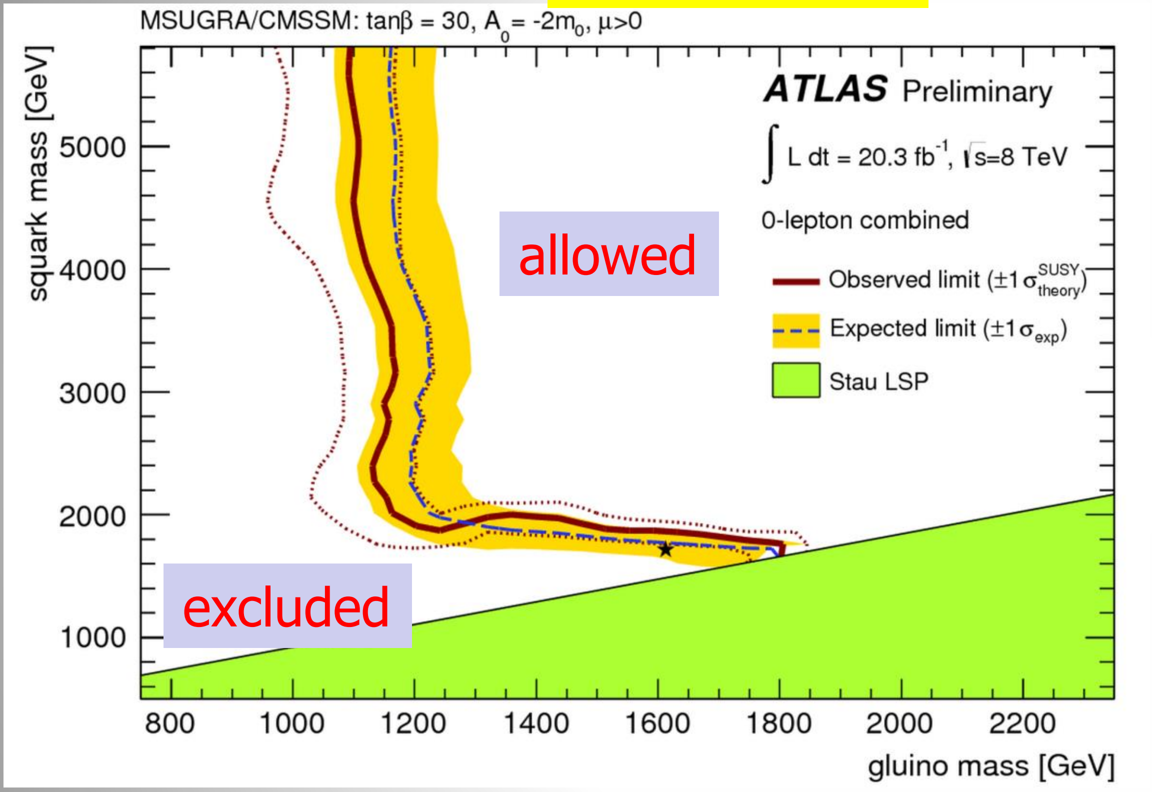




- Events with five jets of particles and large missing energy which could come from a possible dark matter particle
- But a few events is not enough too prove we have something new
  No visible excess has been building up with time…

SUSY Searches: No signal yet to date…

Status in 2013



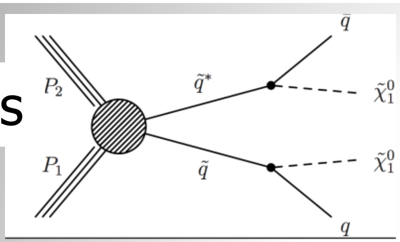
- So far NO clear signal of supersymmetric particles has been found
- We can exclude regions where the new particles could exist.
- Searches will continue for the higher energy in 2015

Plenty of searches ongoing: with jets, leptons, photons, W/Z, top, Higgs, with and without large missing transverse energy
Also special searches for contrived model regions

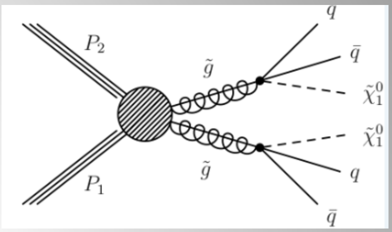
Limits on Squarks and Gluinos

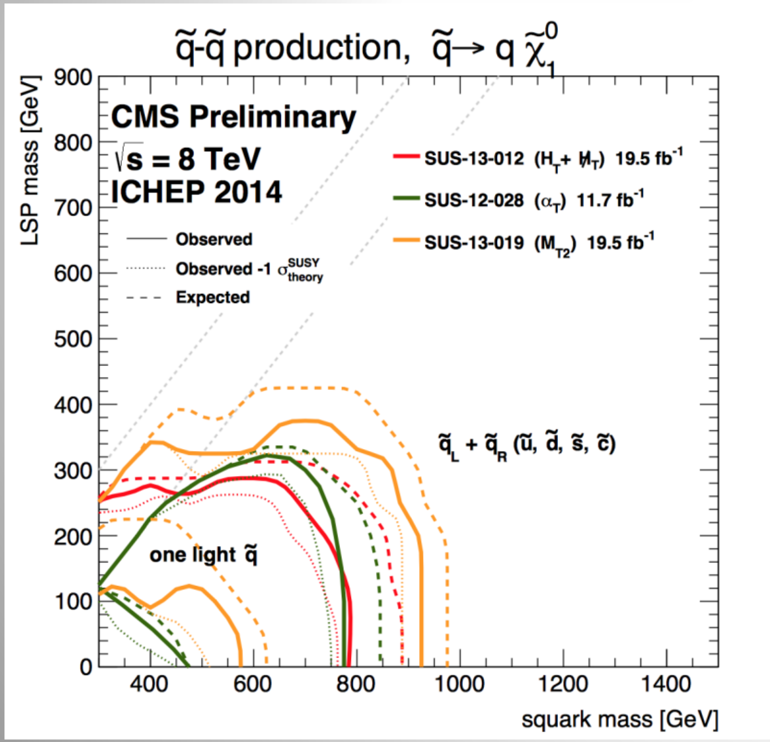
Results depend on the topologies studies, assumed mass of the LSP etc.

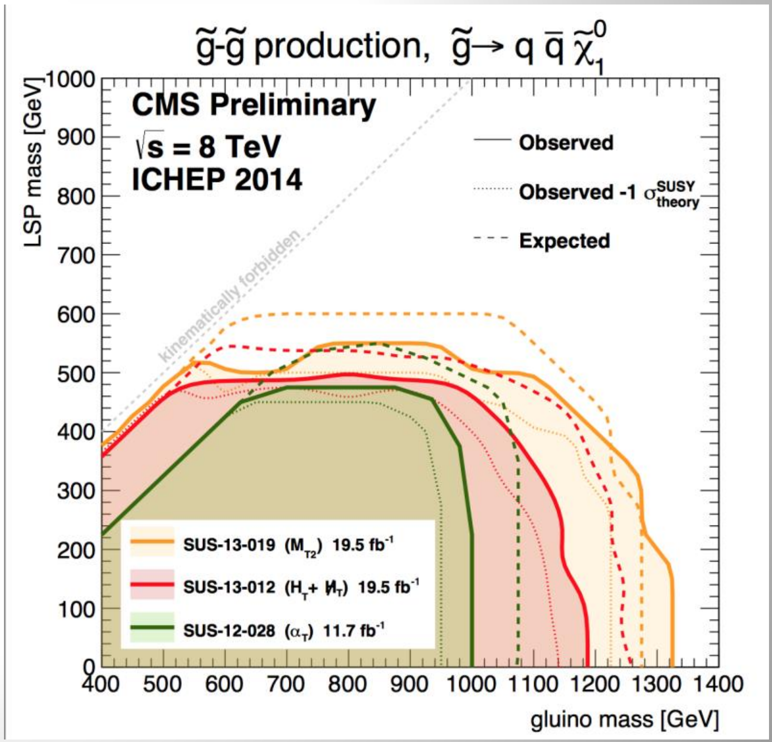
Examples



Popular presentation of data:
Simplified ModelS (SMS)







Combined limits typically > 1-1.3 TeV on sparticle masses

What is really needed from SUSY?

End 2011: Revision!

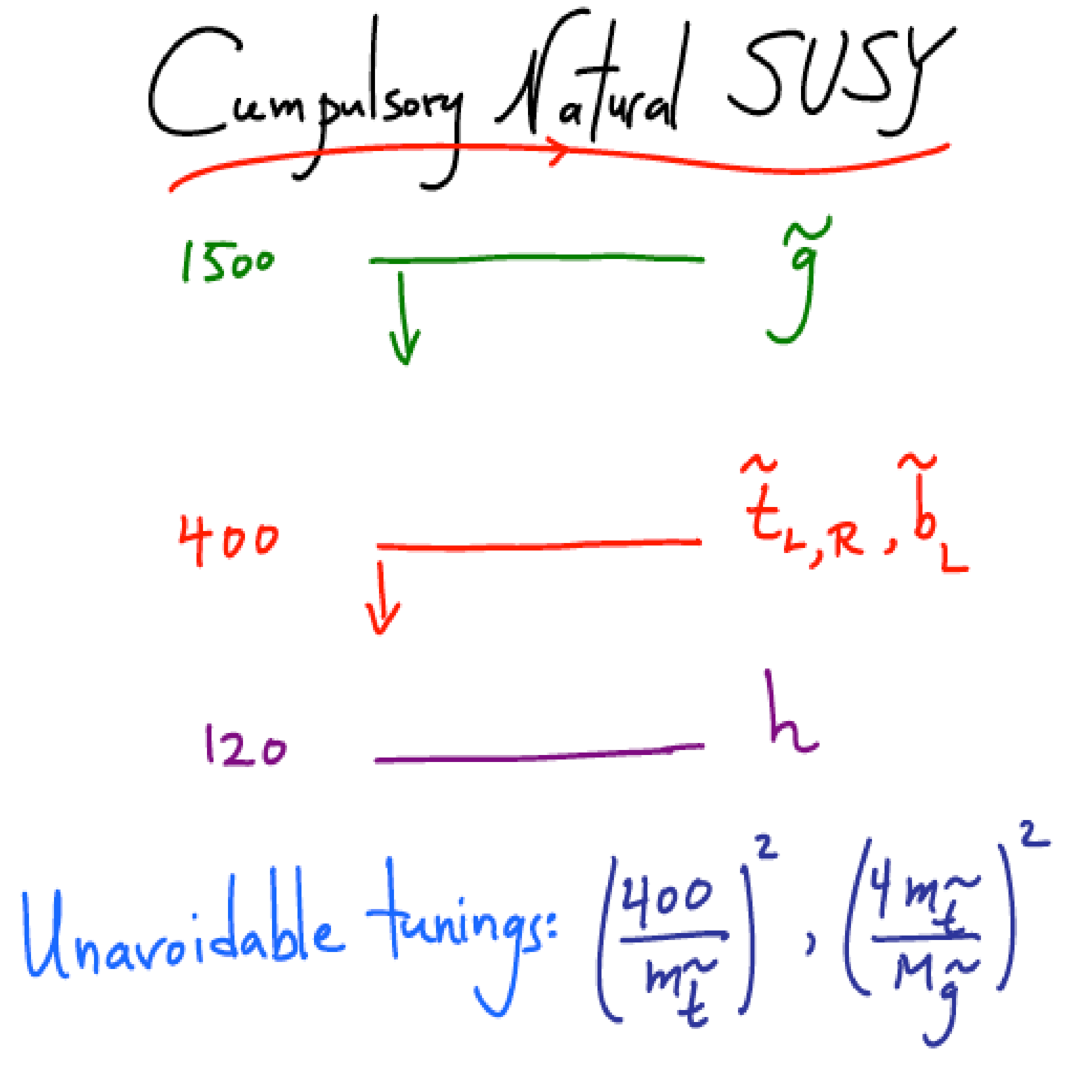
N. Arkani-Ahmed
CERN Nov 2011

Papucci, Ruderman,
Weiler arXiv:1110.6926

LHC data end 2011
Stops > 200-300 GeV
Gluino > 600-800 GeV

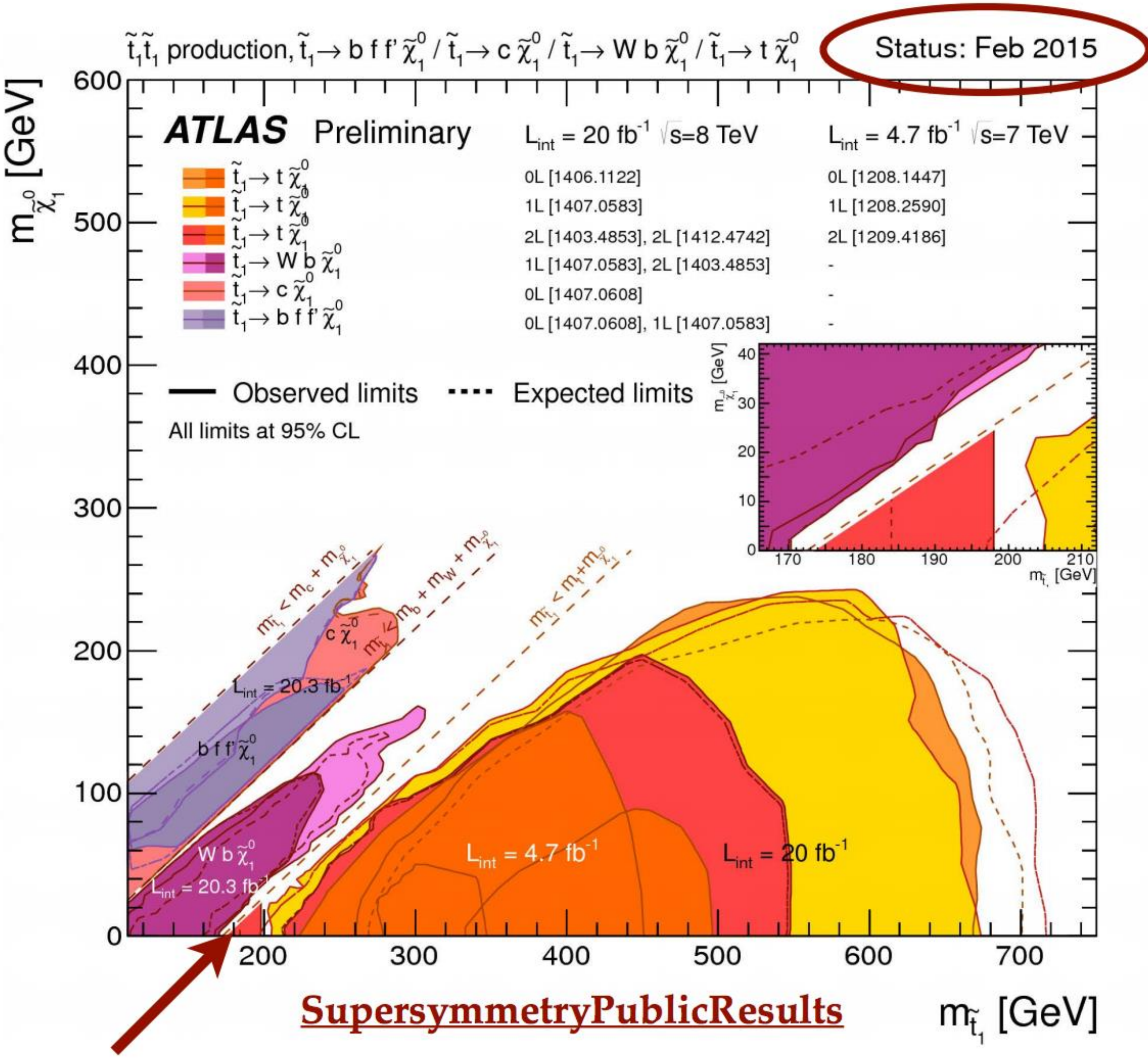
Moving away from constrained SUSY models to 'natural' models

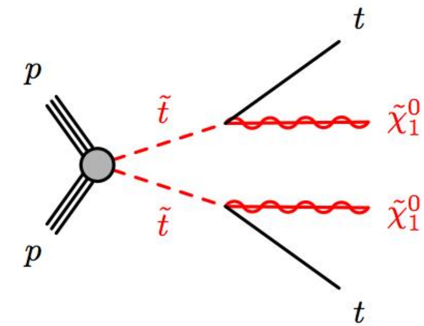
Natural SUSY survived LHC so far, but we are getting close to push it to its limits!



Natural SUSY?

Direct Stop Searches

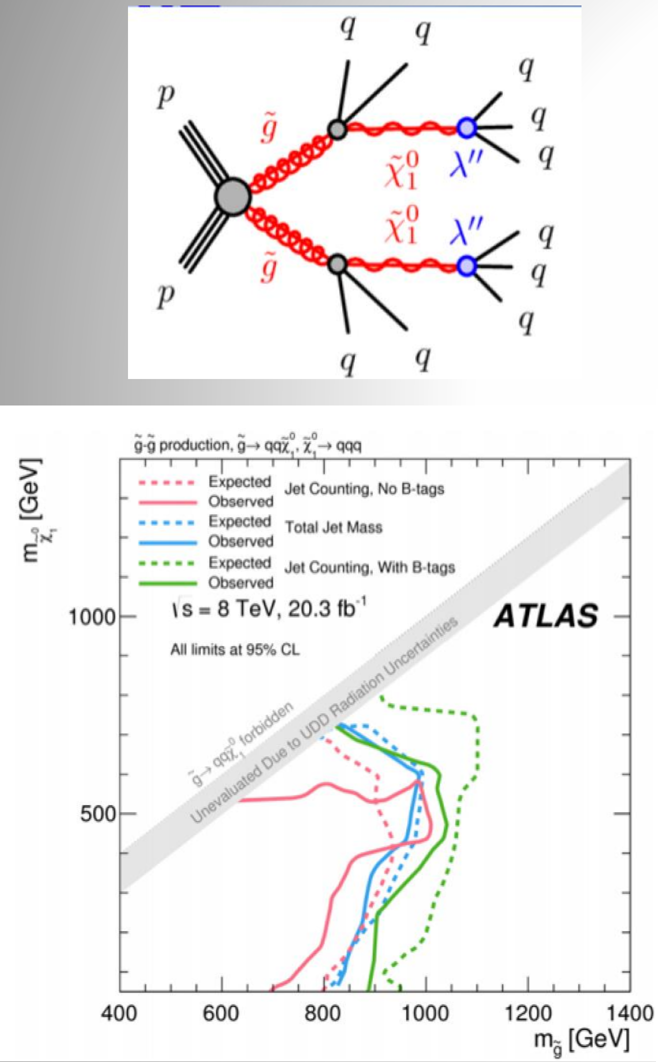




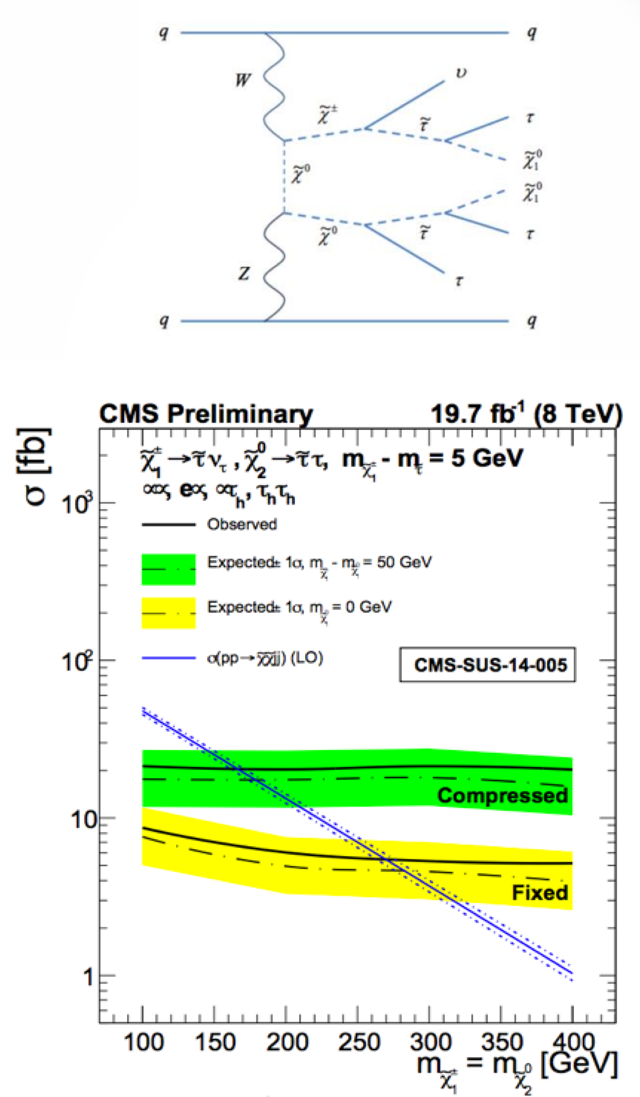
- Stealth stop region ($m_{\tilde{t}} \sim m_t$) nearly closed by precision $t\bar{t}$ measurements!

Recent New Directions…

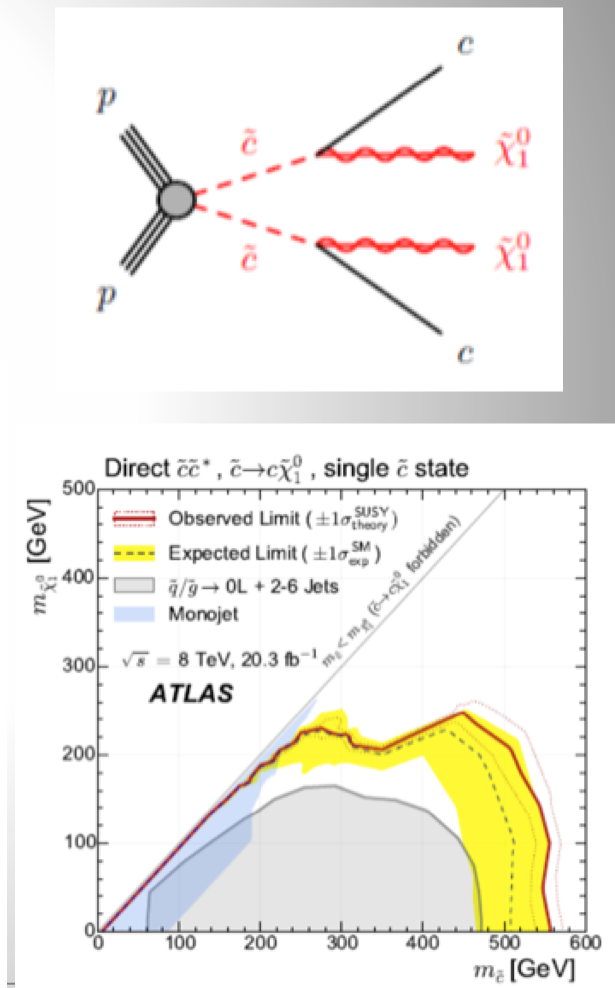
Multi-jet (≥6), no MET



VBF EWKino production

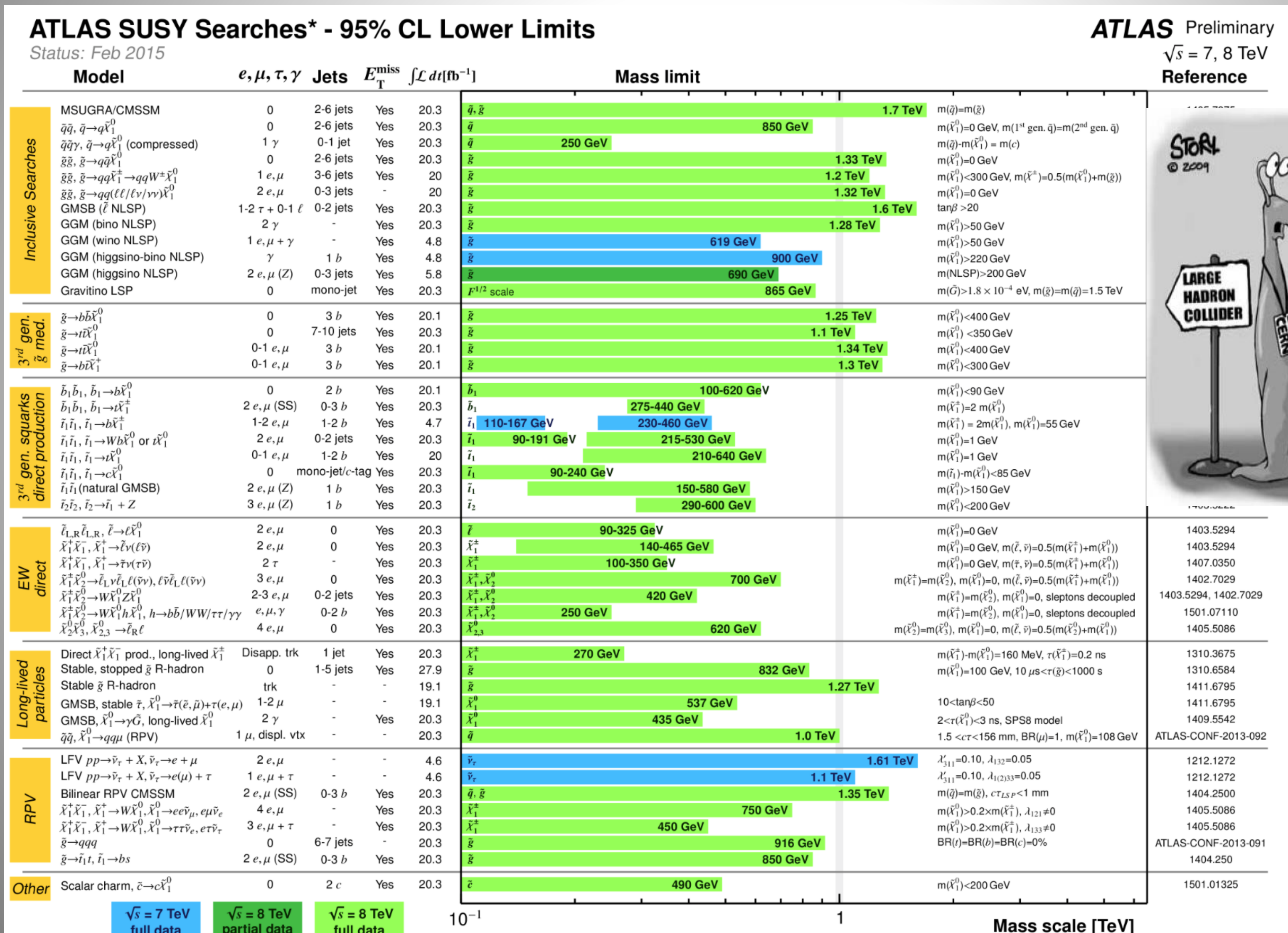


Scalar charm quark



Summary of SUSY Searches

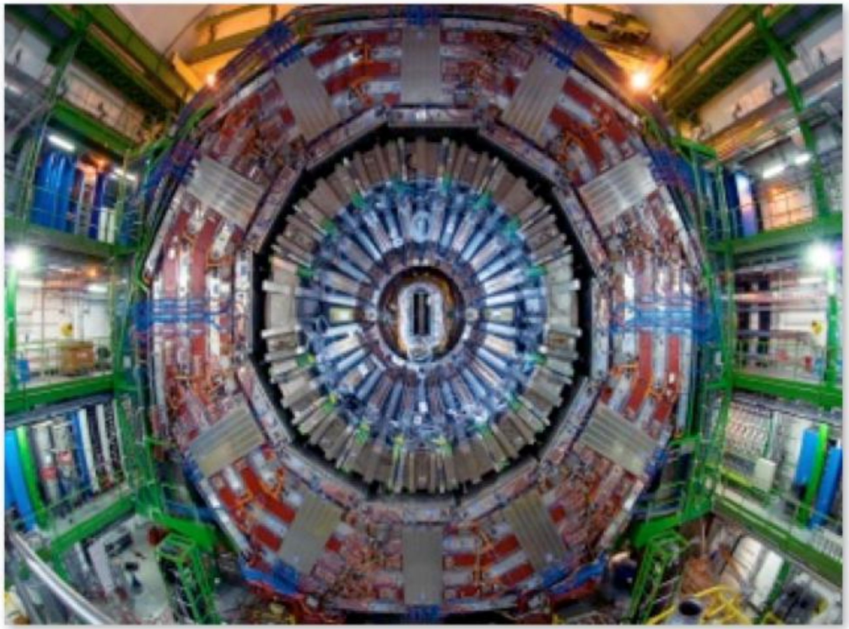
In short: no sign of SUSY with the data collected so far (similar for CMS)



Dark Matter: Complementary Searches?

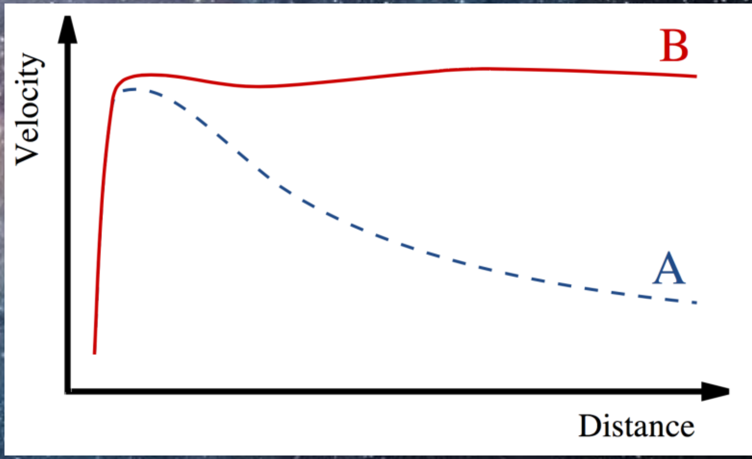
After the discovery of the Higgs particle @ the LHC:
Dark matter is the next important physics problems to tackle for the LHC

The search is complementary to other experimental techniques used.



Dark Matter: The Next Challenge !?!

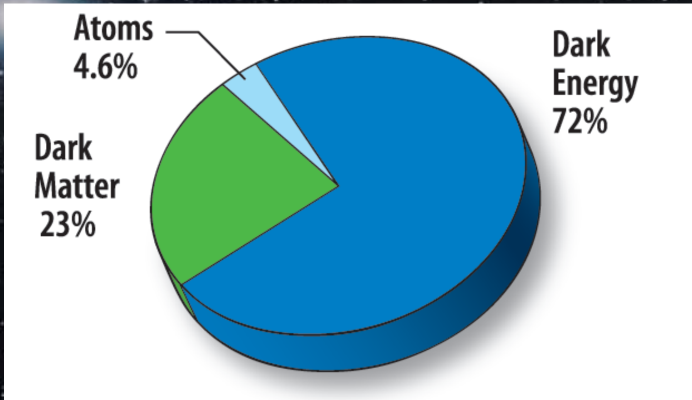
Astronomers found that most of the matter in the Universe must be invisible Dark Matter



'Supersymmetric' particles ?


F. Zwicky 1898-1974


Vera Rubin ~ 1970

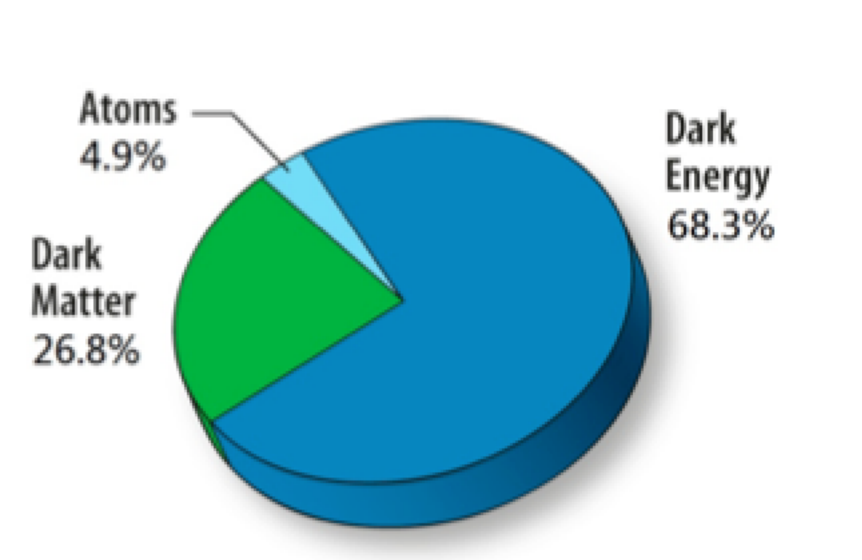


Particle Dark Matter?

The Dark Matter Candidate Zoo

From D. Hooper

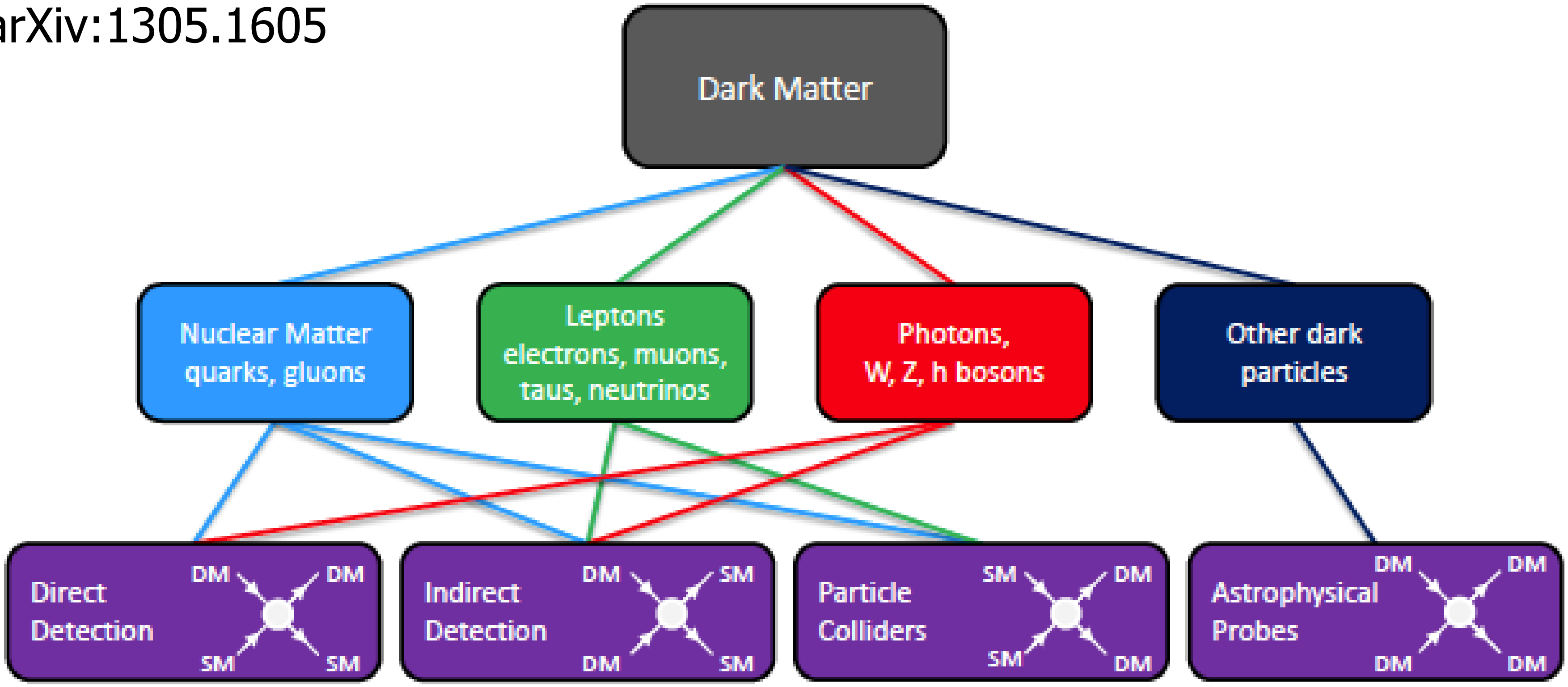
- Neutralinos (higgsino, bins, winos, singlinos)
- Axinos
- Gravitinos
- Sneutrinos
- Axions
- Sterile neutrinos
- 4^{th} generation neutrinos
- Kaluza-Klein photons
- Kaluza-Klein gravitons
- Brane world dark matter/D-matter
- Little higgs dark matter
- Light scalars
- Superheavy states (*ie.* "WIMPzillas")
- Self-interacting dark matter
- Super-WIMPs
- Asymmetric dark matter
- Q-balls (and other topological states)
- CHAMPs (charged massive particles)
- Cryptons, mirror matter, and many, many, many others…



Dark Matter @ LHC?

Search for WIMP candidates in events with Missing Transverse Momentum
EG: SUSY searches, monojet and mono-photon searches, W' searches…

arXiv:1305.1605



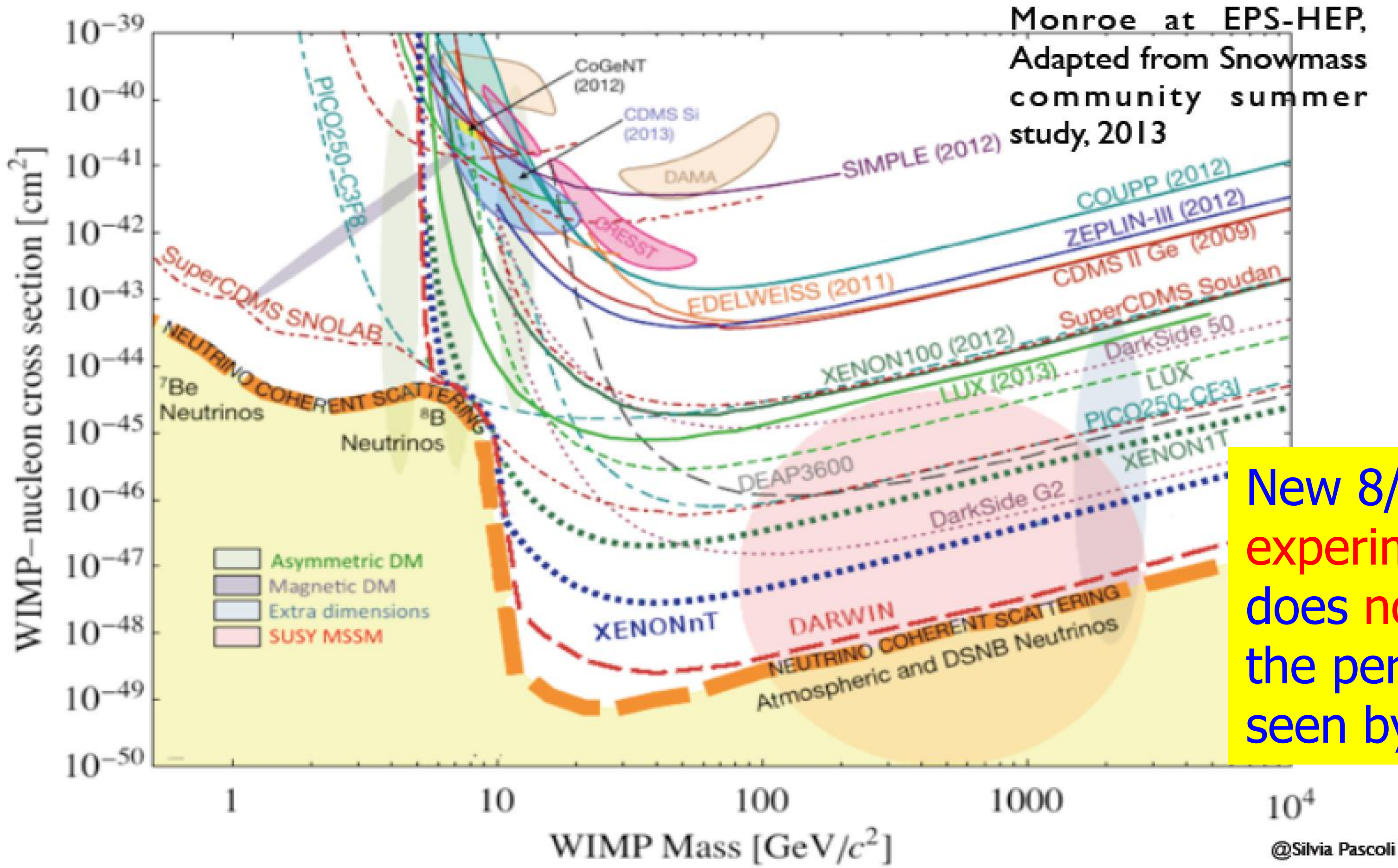
+ CAST experiment, searching for axion DM

Direct Searches for Dark Matter

Underground low noise experiments

No non-ambiguous signal yet!!

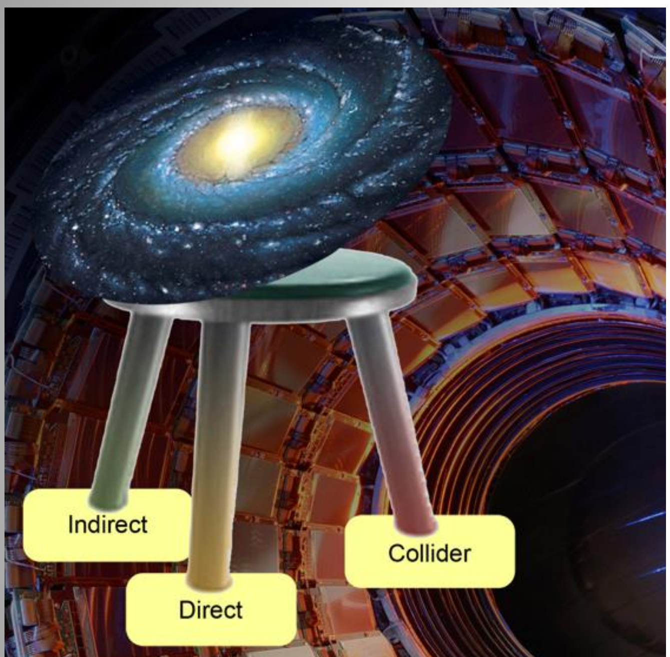
There is a very large number of projects which are under construction or being planned for the future.

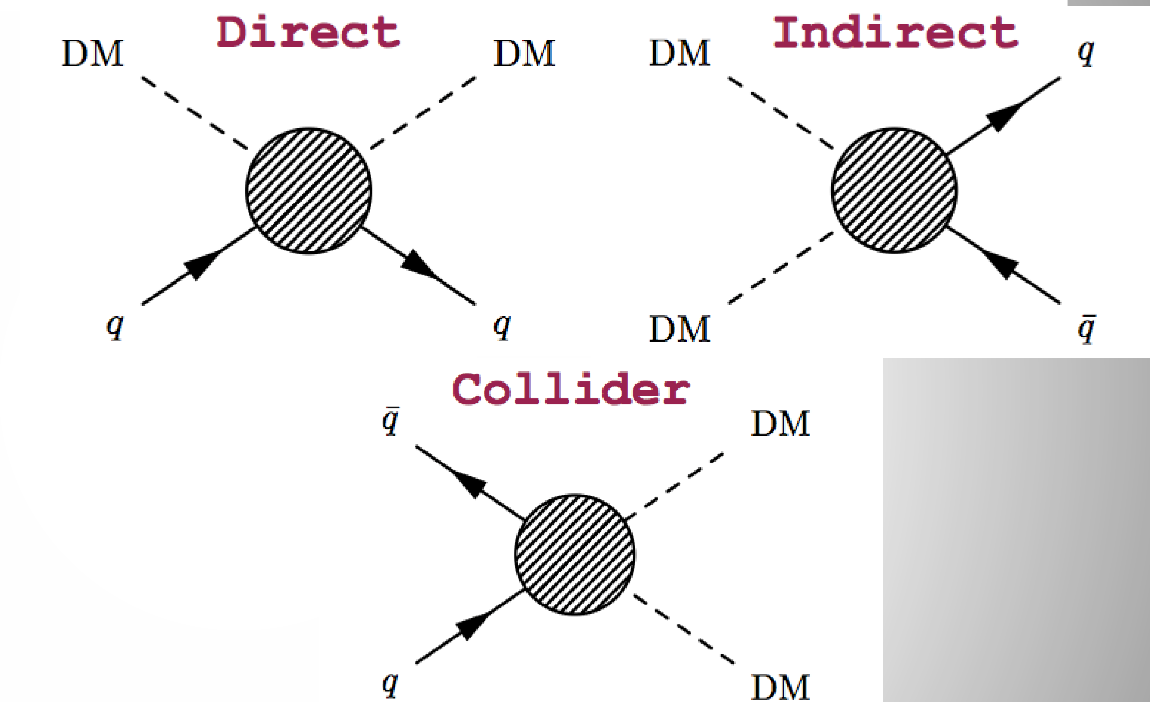


New 8/9/15: XMASS experiment (Japan) does not confirm the periodical effect seen by DAMA/LIBRA

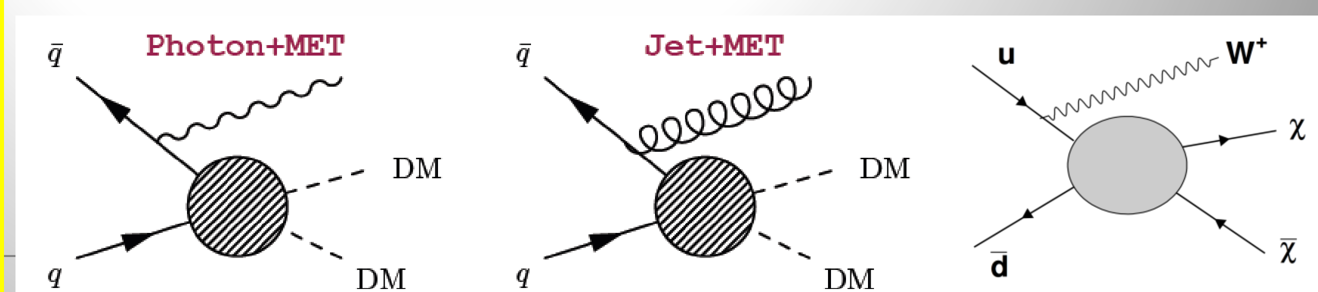
The Generic Dark Matter Connection

Searches for mono-jets and mono-photons can be used to search for Dark Matter (DM)





Use effective theory or better simplified models to relate measurements to Dark Matter studies

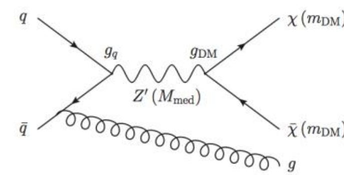


Mono-object Searches in CMS

PhD: Elsayed Tayel (Alex)

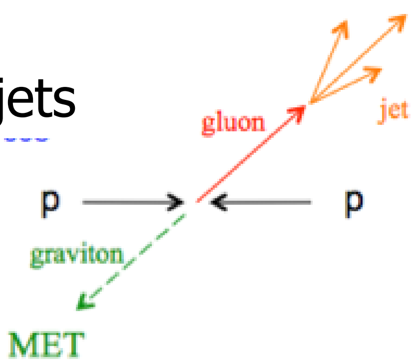
- Mono-jets: Generally the most powerful
- Mono-photons: First used for dark matter Searches
- Mono-Ws: Distinguish dark matter couplings to u- and d-type of quarks
- Mono-Zs: Clean signature
- Mono-Tops: Couplings to tops
- Mono-Higgs: Higgs-portals
- Higgs Decays?

Effective Field Theories for DM interpretation are under scrutiny!
Alternatives such as SMS proposed

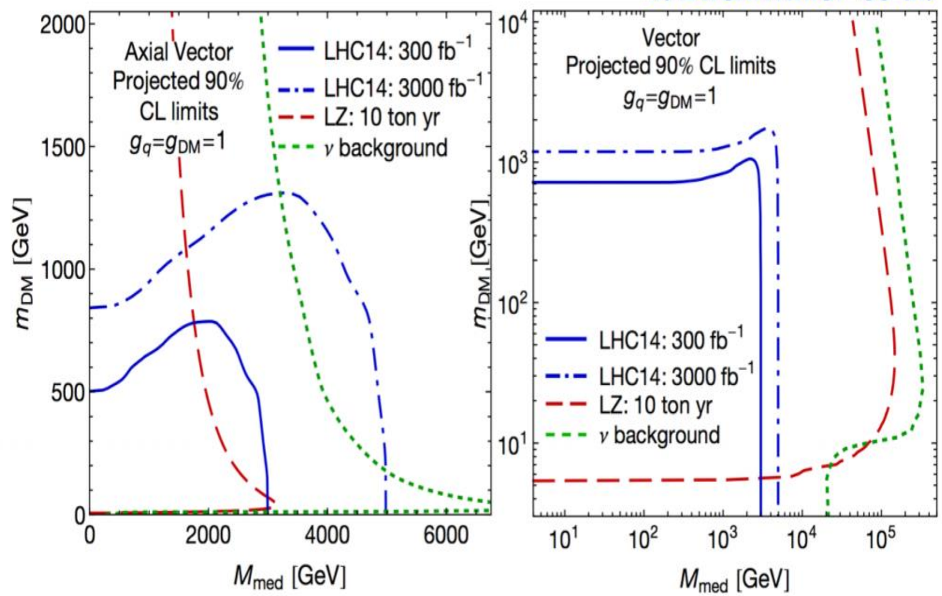


arXiv:1407.8257
arXiv:1411.0535

Example Monojets

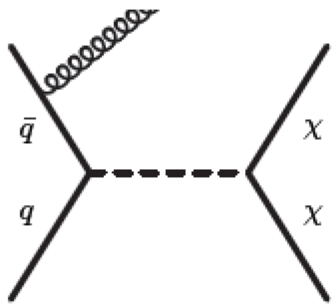


Dark Matter?

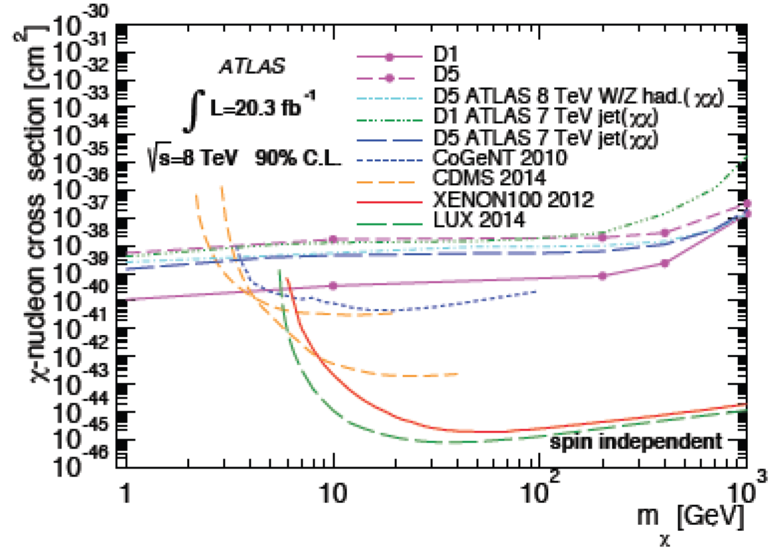


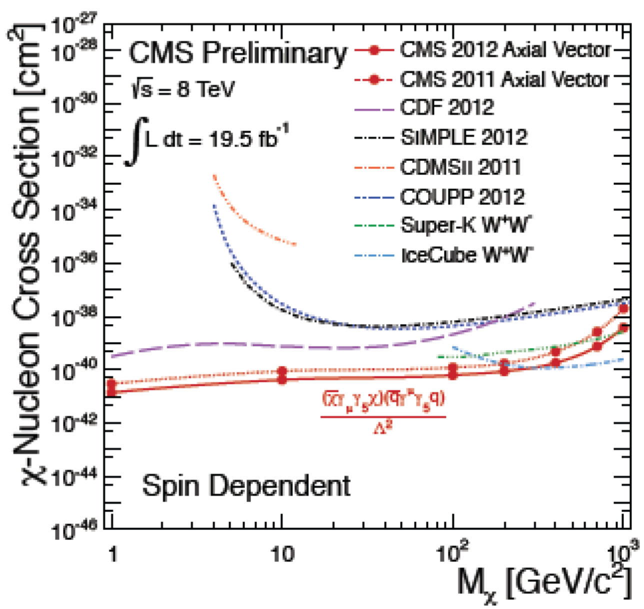
Some Recent Results (EFTs)

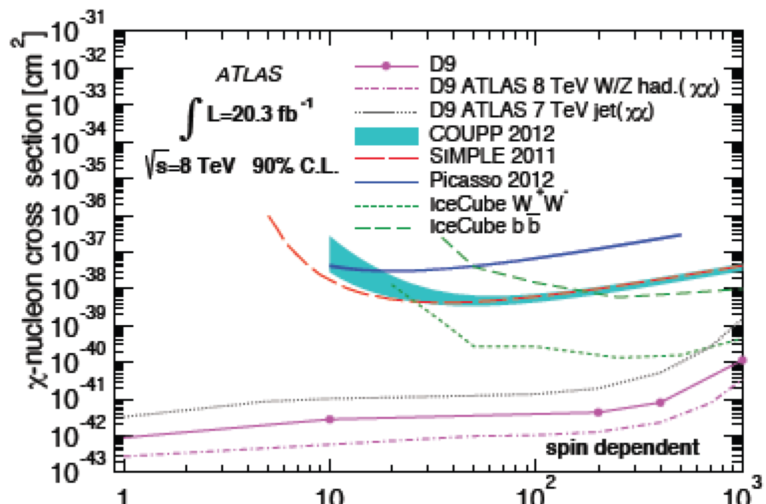
The cross section can be estimated to be



$$\sigma \sim \alpha_s g_{\rm DM}^2 g_q^2 \frac{p_T^2}{M^4}$$



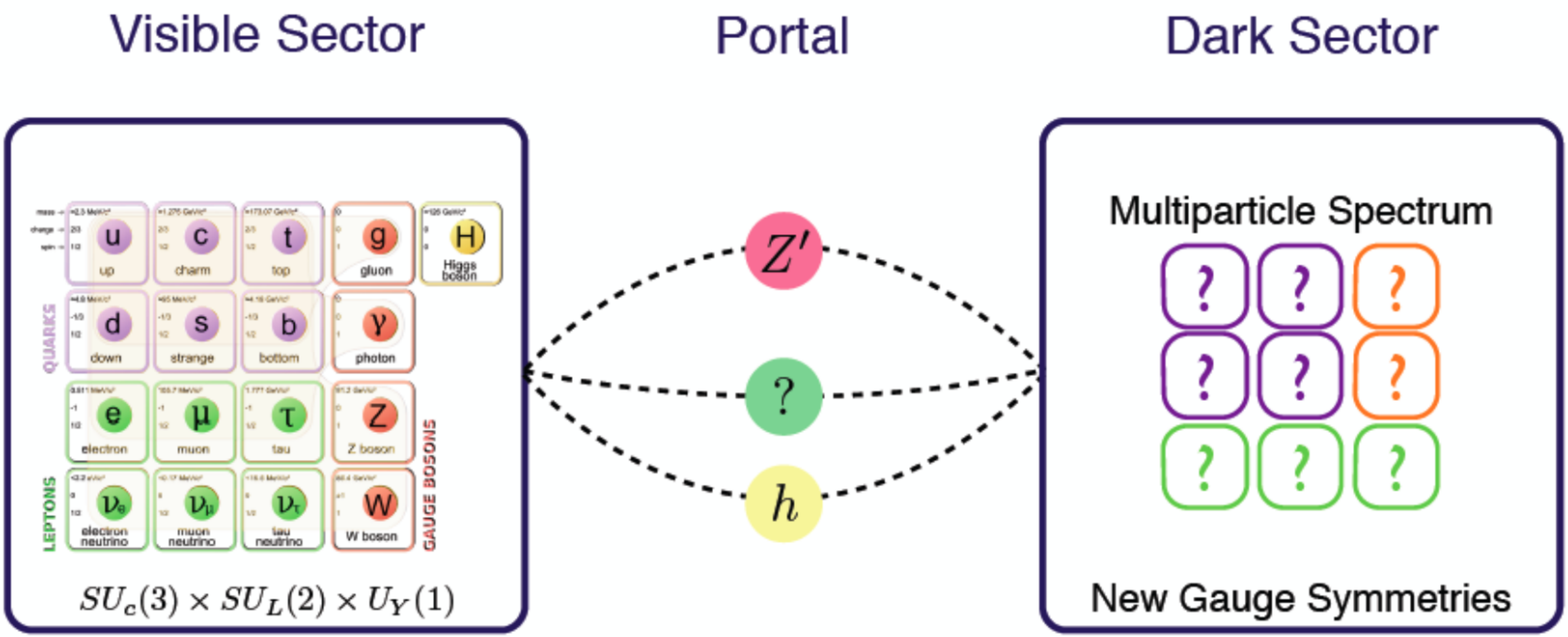




ATLAS, '14

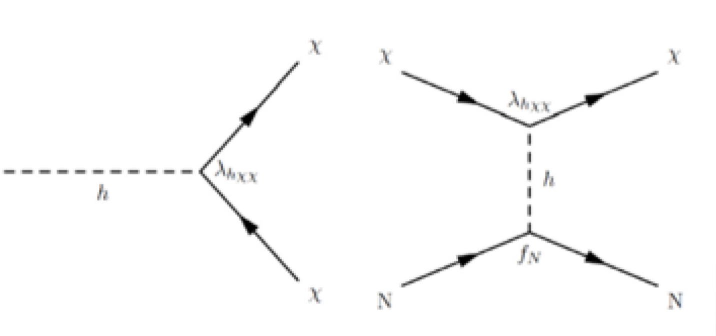
@Silvia Pascoli

Cite: “Why should 5% of the mass density have all the fun?”



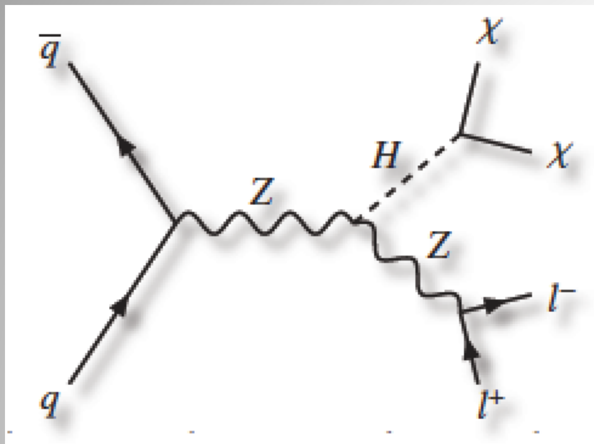
Can motivate alternative searches to MET + X from dark sector

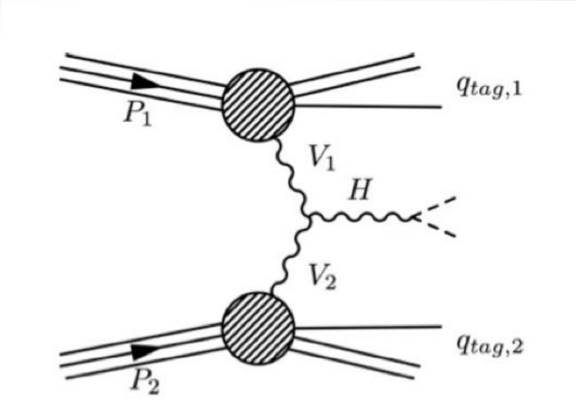
Dark Matter and the Higgs



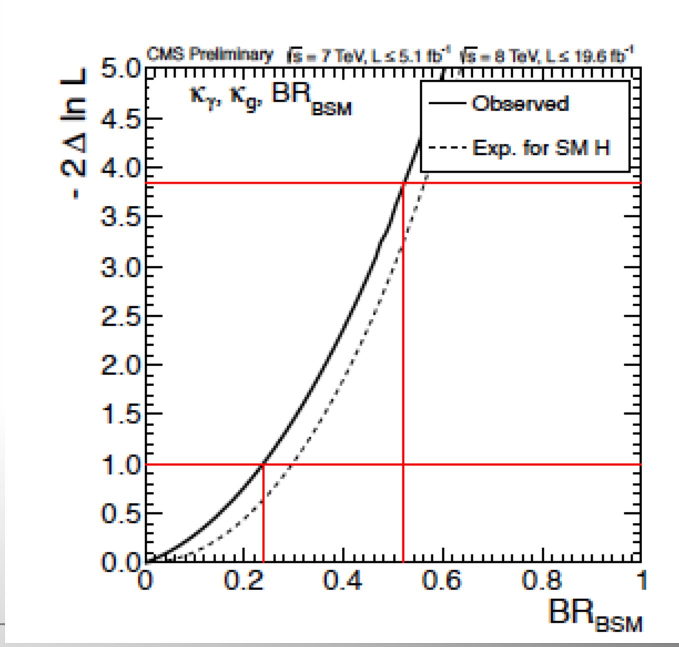
"higgs portal models"
Eg: arXiv:1205.3169

Invisible Higgs Decay Channel



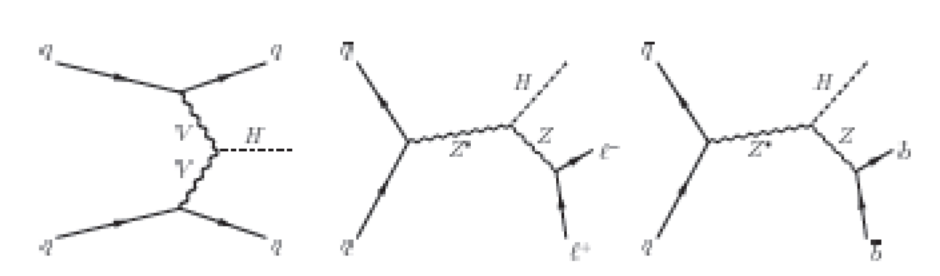


CMS-PAS-HIG-13-005



- Possible decay of the Higgs in Dark Matter particles (if $M<M_H/2$)
- Different searches:
  - -Direct search
    Look for the invisible decay channels
  - -Indirect search
    Make a global fit of all production and decays (and some modest assumptions)

Invisible Higgs Decay Channel



Search for invisible Higgs decays using

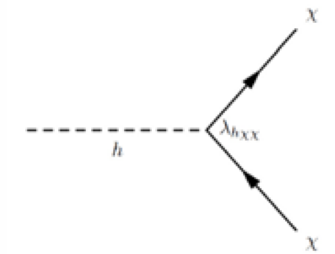
- Z+H → 2 leptons + missing E_T
- VBF H → 2 jets + missing E_T

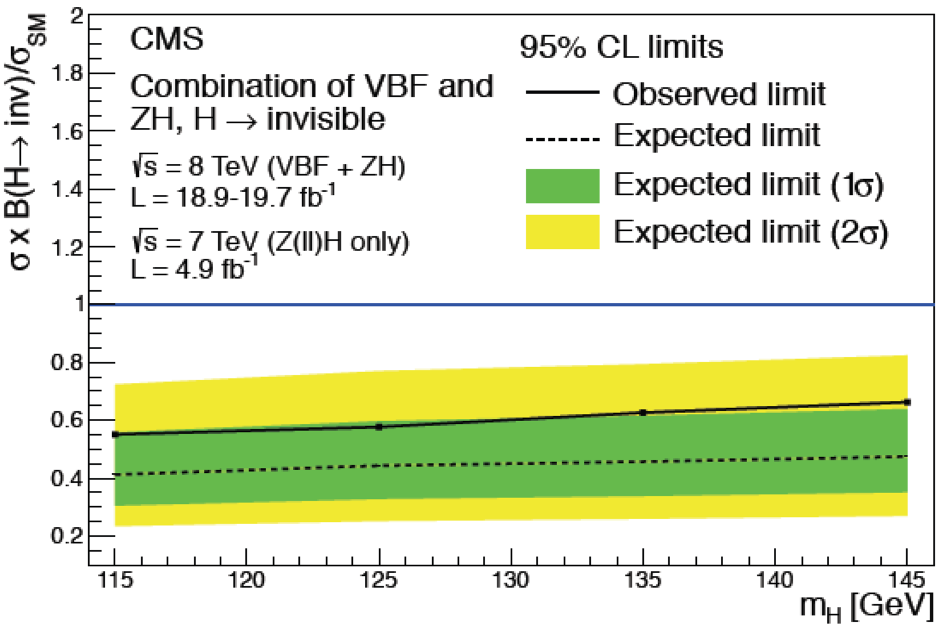
Possible decay in Dark Matter particles (if $M<M_H/2$): Higgs Portal Models

Combined result from the three channels

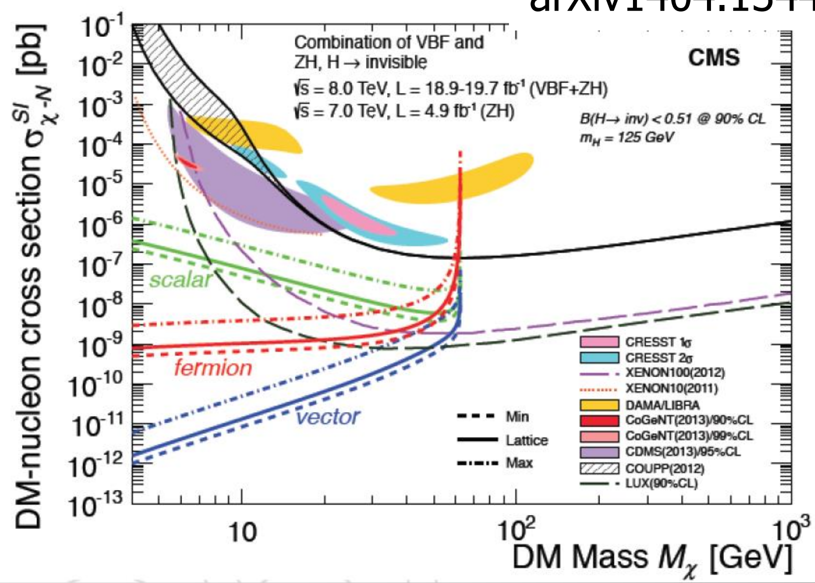
BR(H→invisible)<58%(44% exp) at 95% CL.

for a Higgs with a mass of 125 GeV





arXiv1404.1344



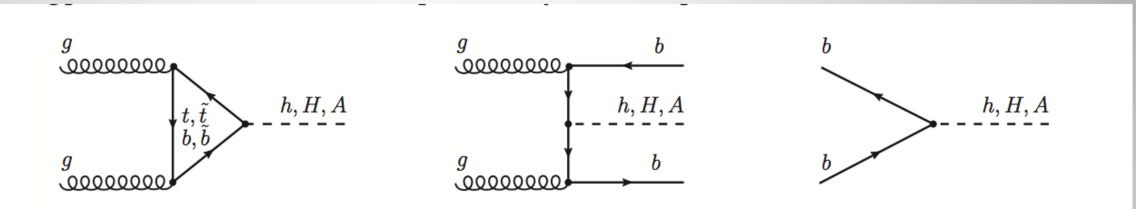
Searches for BSM Higgses

- Exotic Higgs Decays
- Search for new Higgses: high and low mass
  - 2HDM, MSSM, NMSSM…
- Charged Higgs searches
- Summary

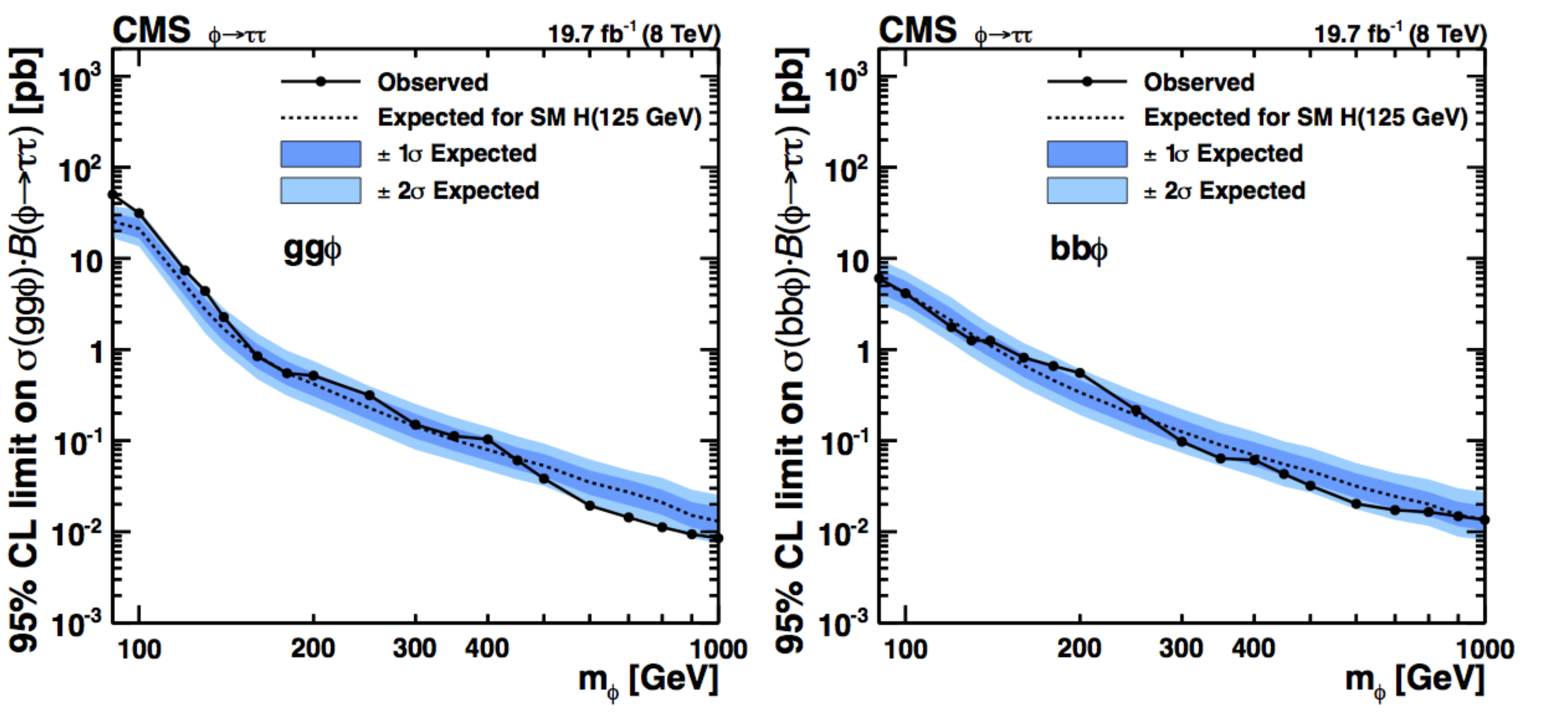
- No significant signal to report so far
- Exclusions of BSM space

MSSM Neutral Higgs → Tau Tau

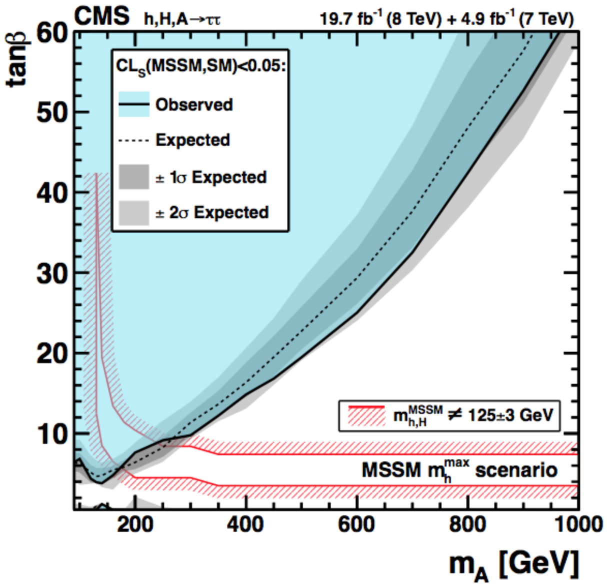
arXiv:1408.3316



- Study of the Neutral Higgs h/H/A to tau tau
- Include channels with associated b-quark production
- Upper limits on σ.BR (95% CL)



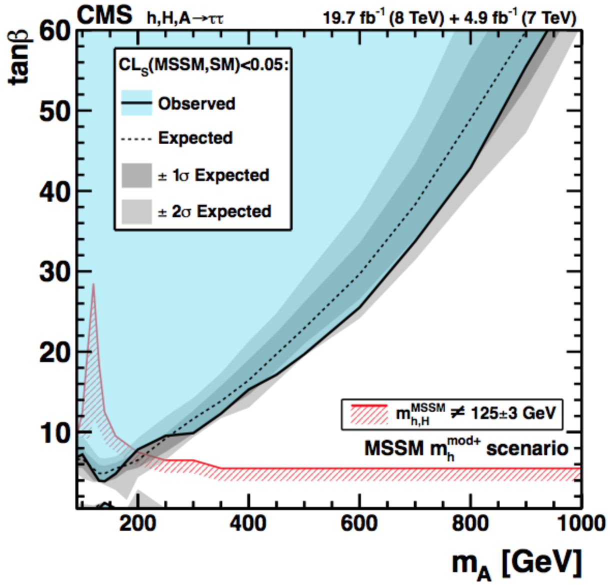
MSSM Neutral Higgs → Tau Tau

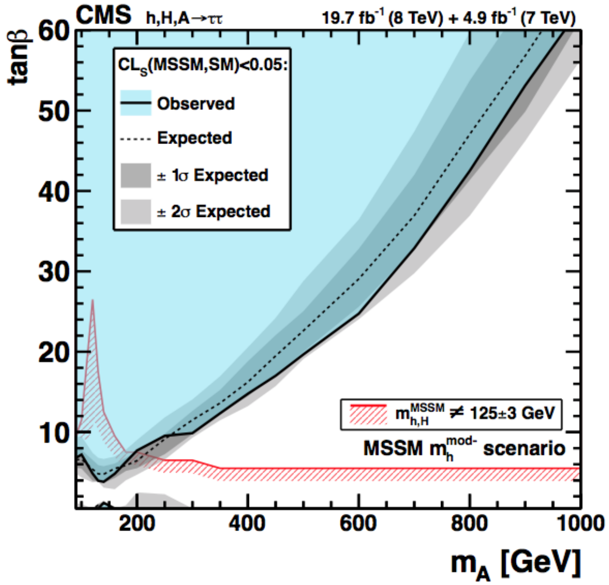


arXiv:1408.3316

- Study of the Neutral Higgs h/H/A to tau tau
- Include channels with associated b-quark production
- No excess found so far –> exclusions (95% CL)

m_h^{max} scenario; m_h^{mod+} and m_h^{mod+} scenarios with modified stop mixing



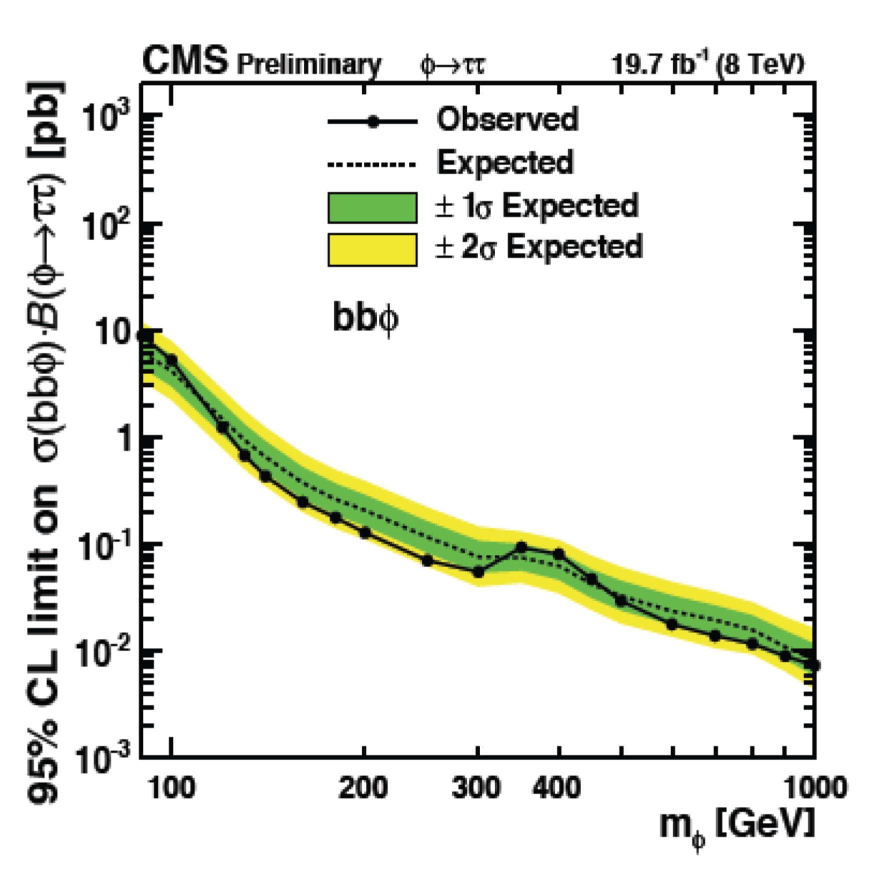


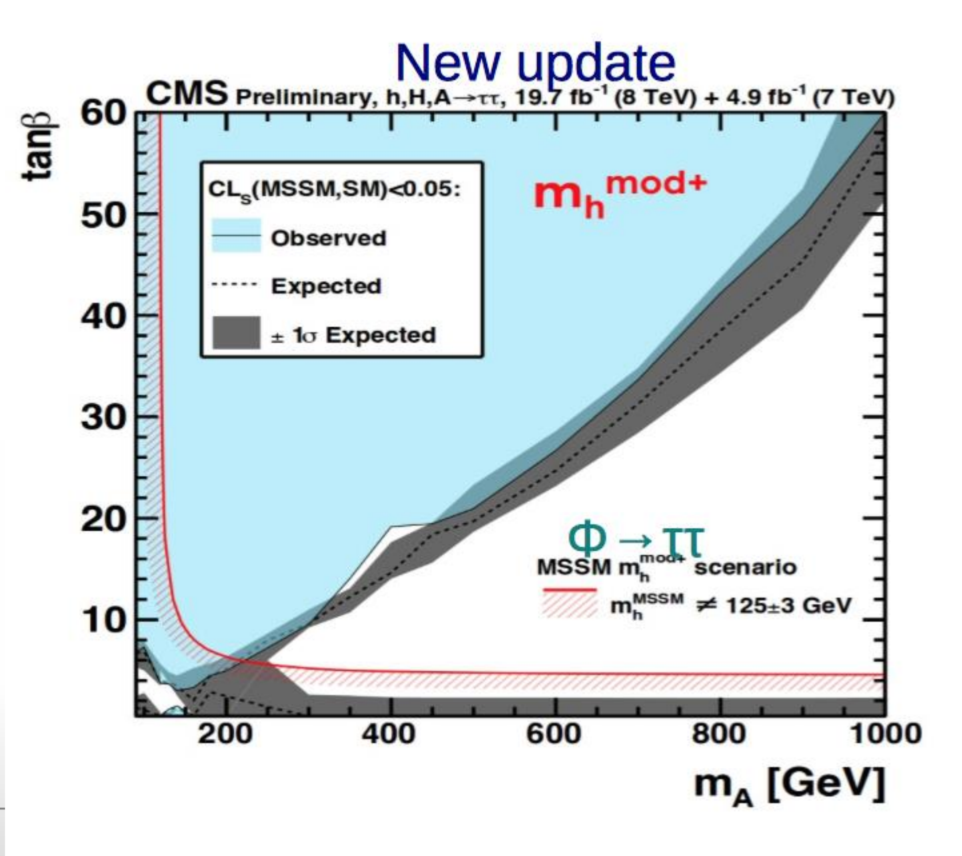
MSSM Neutral Higgs → Tau Tau

NEW: Update of the MSSM results with new tau finder
Reanalysis of the 2011/12 data.
MVA hadronic tau analysis, b-quark categories and hadronic tau p_T categories…

HIG-14-029

Huge gain ~70%!
i.e. like 3x the lumi

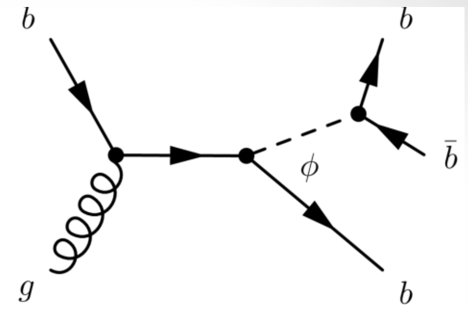


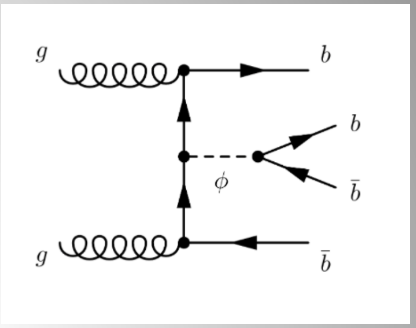


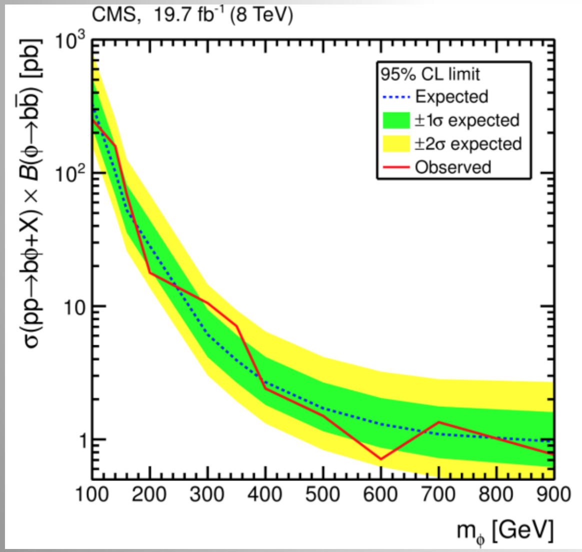
MSSM Neutral Higgs → bb

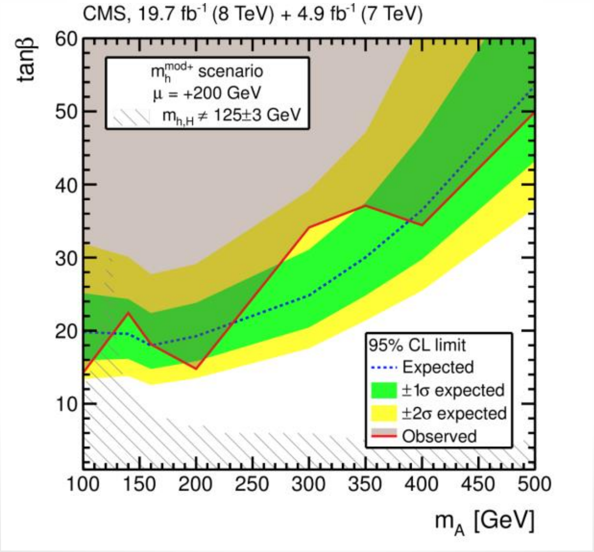
arXiv:1506.08329

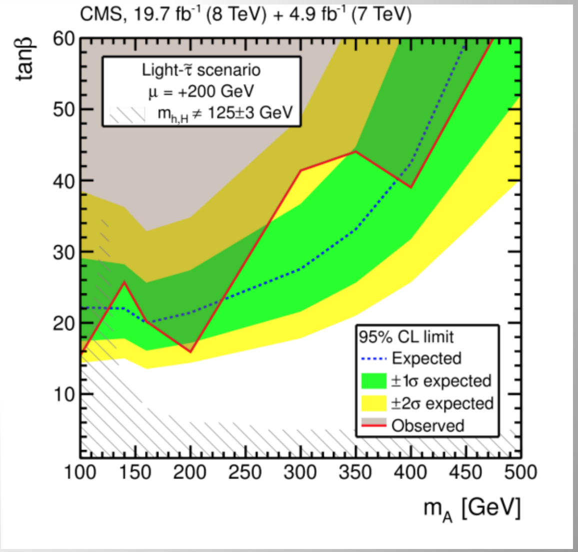
Search for H->bb with one or two b-quarks associated









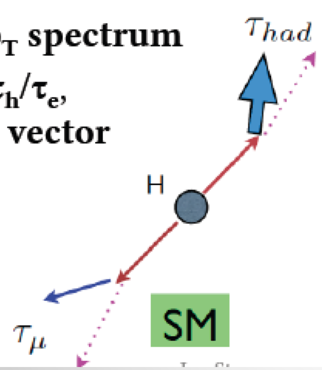


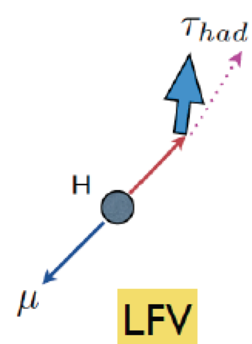
Exclusion limits for different MSSM scenarios

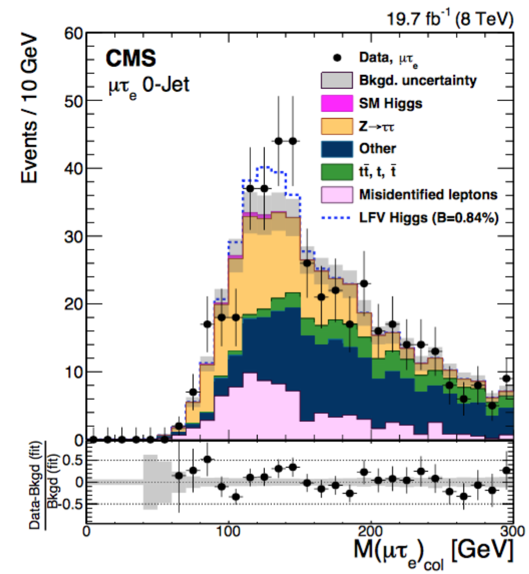
Search for LFV Decays: H →μτ

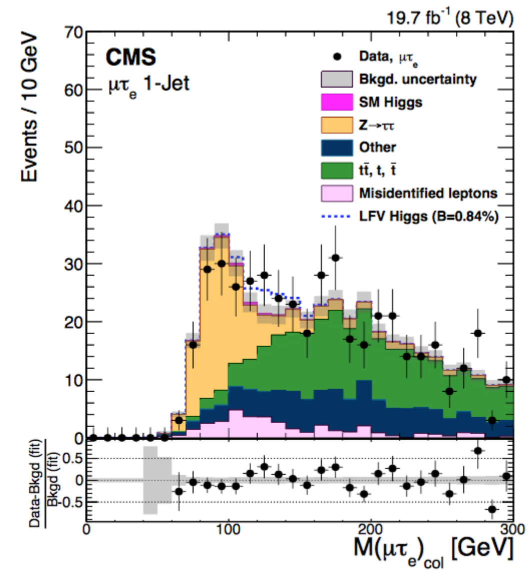
arXiv:1502.07400

- Previous best limits on B(H→μτ) <~ 10% from reinterpretation of LHC H→ττ searches and from τ→μγ arXiv:1209.1397
  - **Can do better with first dedicated search**
- Consider hadronic (τ_h) and electron (τ_e) tau decays
- Same basic event selection and jet categories as SM H→ττ analysis (0-jet, 1-jet, VBF-tag)
- Differences in kinematics
  - **Harder muon p_T spectrum**
  - **Δφ between μ, τ_h/τ_e, missing energy vector**



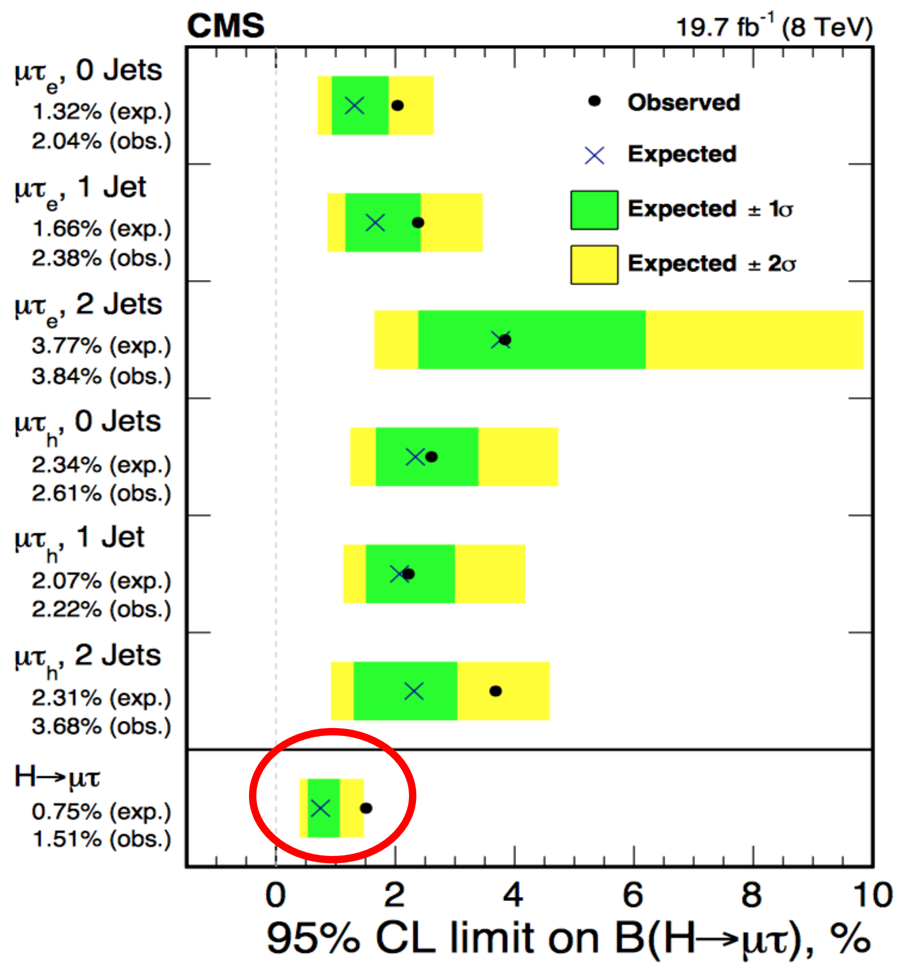






Search for LFV Decays: H →μτ

- Comparable sensitivity from all channels
- $\mathcal{B}(\mathrm{H} \to \mu\tau) < 1.51\%$ at 95%
- **Large improvement of previous limits**
- Background-only p-value of 0.010 (2.4 σ)
  - Best fit $\mathcal{B}(\mathrm{H} \to \mu\tau) = (0.84^{+0.39}_{-0.37})\%$.



Mild excess giving a 2.4σ effect… To be watched!!!
Not contradicted by ATLAS at EPS… ☺

What Deviations did we Observe?

March 2015

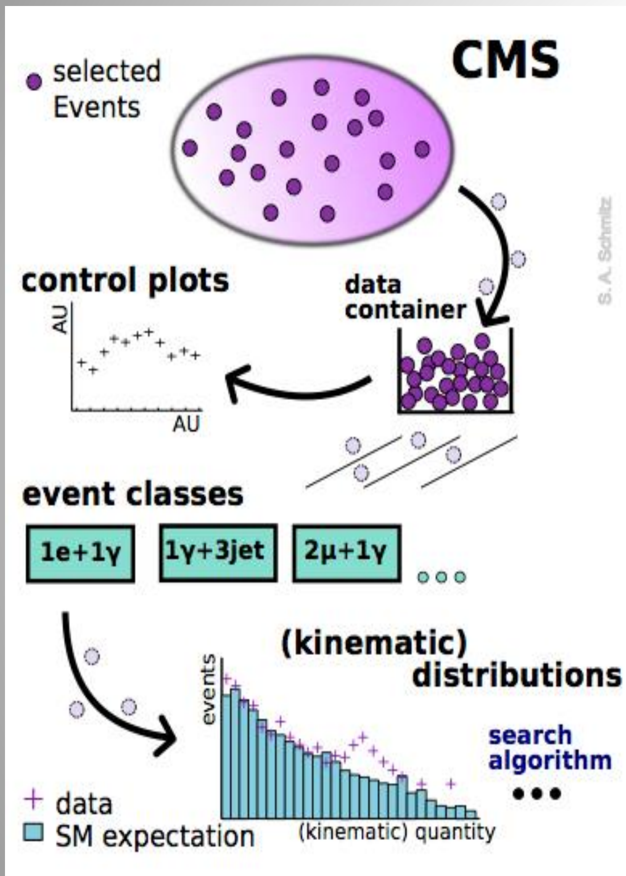
B. Hooberman

Search	Dataset	Max Significance	Reference
Dilepton mass edge	CMS 8 TeV	**2.6σ**	CMS-PAS-SUS-12-019
WW cross section	CMS 7 TeV	**1.0σ**	EPJC 73 2610 (2013)
WW cross section	CMS 8 TeV	**1.7σ**	PLB 721 (2013)
$3\ell+E_T^{miss}$ electroweak SUSY	CMS 8 TeV	**~2σ**	EPJC 74 (2014) 3036
$4\ell+E_T^{miss}$ electroweak SUSY (see backup)	CMS 8 TeV	**~3σ**	PRD 90, 032006 (2014)
Higgs$\rightarrow\mu\tau$ (lepton flavor violation)	CMS 8 TeV	**2.5σ**	CMS-PAS-HIG-14-005
1st gen. leptoquarks (eejj / evjj channels)	CMS 8 TeV	**2.6σ / 2.4σ**	CMS-PAS-EXO-12-041
ttH with same-sign muons	CMS 8 TeV	$\mu_{ttH} = 8.5^{+3.5}_{-2.7}$	arXiv:1408.1682v1 [hep-ex]
Dijet resonance search	CMS 8 TeV	**~2σ**	arXiv:1501.04198 [hep-ex]
Heavy right-handed neutrinos	CMS 8 TeV	**2.8σ**	EPJC 74 (2014) 3149
$3\ell+E_T^{miss}$ electroweak SUSY	ATLAS 8 TeV	**2.2σ**	PRD 90, 052001 (2014)
Soft $2\ell+E_T^{miss}$ strong SUSY	ATLAS 8 TeV	**2.3σ**	ATLAS-CONF-2013-062
WW cross section	ATLAS 7 TeV	**1.4σ**	PRD 87, 112001 (2013)
WW cross section	ATLAS 8 TeV	**2.0σ**	ATLAS-CONF-2014-033
Z+jets+E_T^{miss}	ATLAS 8 TeV	**3.0σ**	arXiv:1503.03290 [hep-ex]
Monojet search	ATLAS 8 TeV	**1.7σ**	arXiv:1502.01518 [hep-x]
$H\rightarrow h(bb)h(\gamma\gamma)$	ATLAS 8 TeV	**2.4σ**	arXiv:1406.5053 [hep-ex]

\+ WH (2.8σ) +LHCb (3.7σ?)

A Global View!

CMS-EXO-10-021



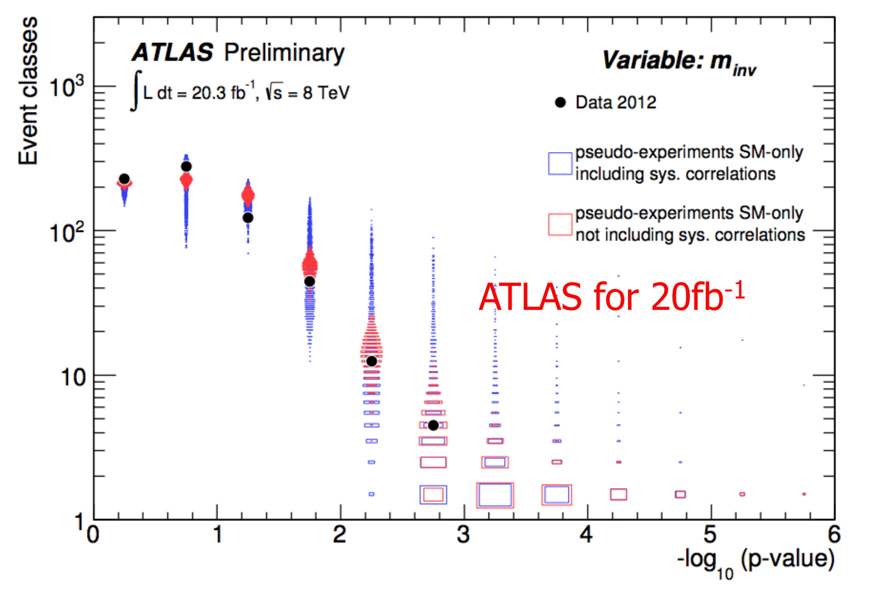
Model independent search

- Divide events into exclusive classes
- Study deviations from SM predictions in a statistical way

Distributions in each class

- $\sum p_T$ - Most general
- $M_{inv}^{(T)}$ - Good for resonances
- MET - Escaping particles

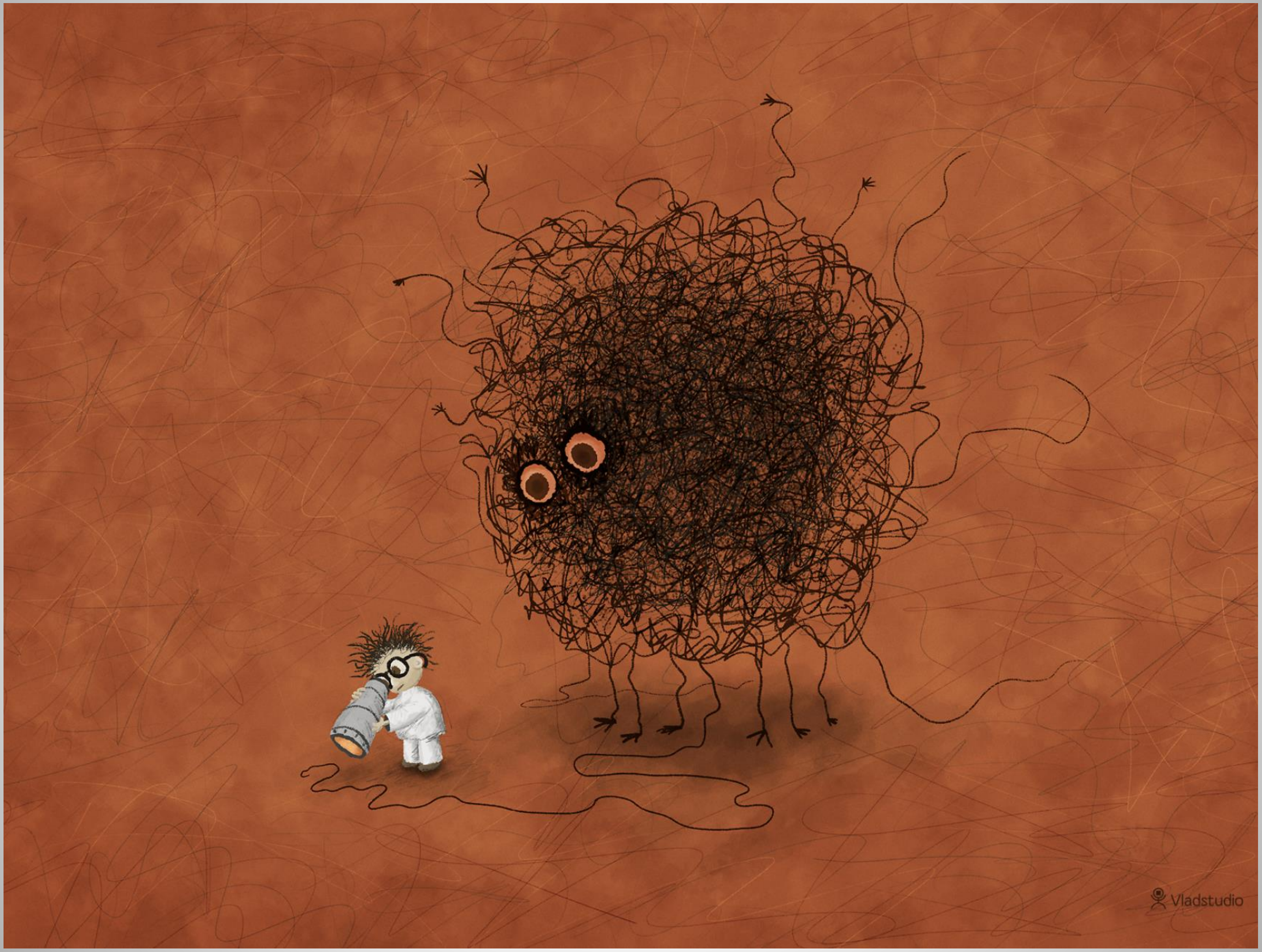
ATLAS-CONF-14-006



Probability distribution as expected for 35 pb^{-1} for CMS

→muons, electrons, photons, (b)jets, MET

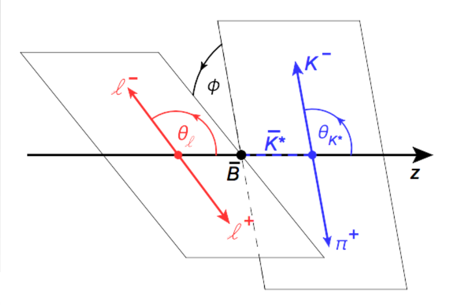
Are we looking at the right place??



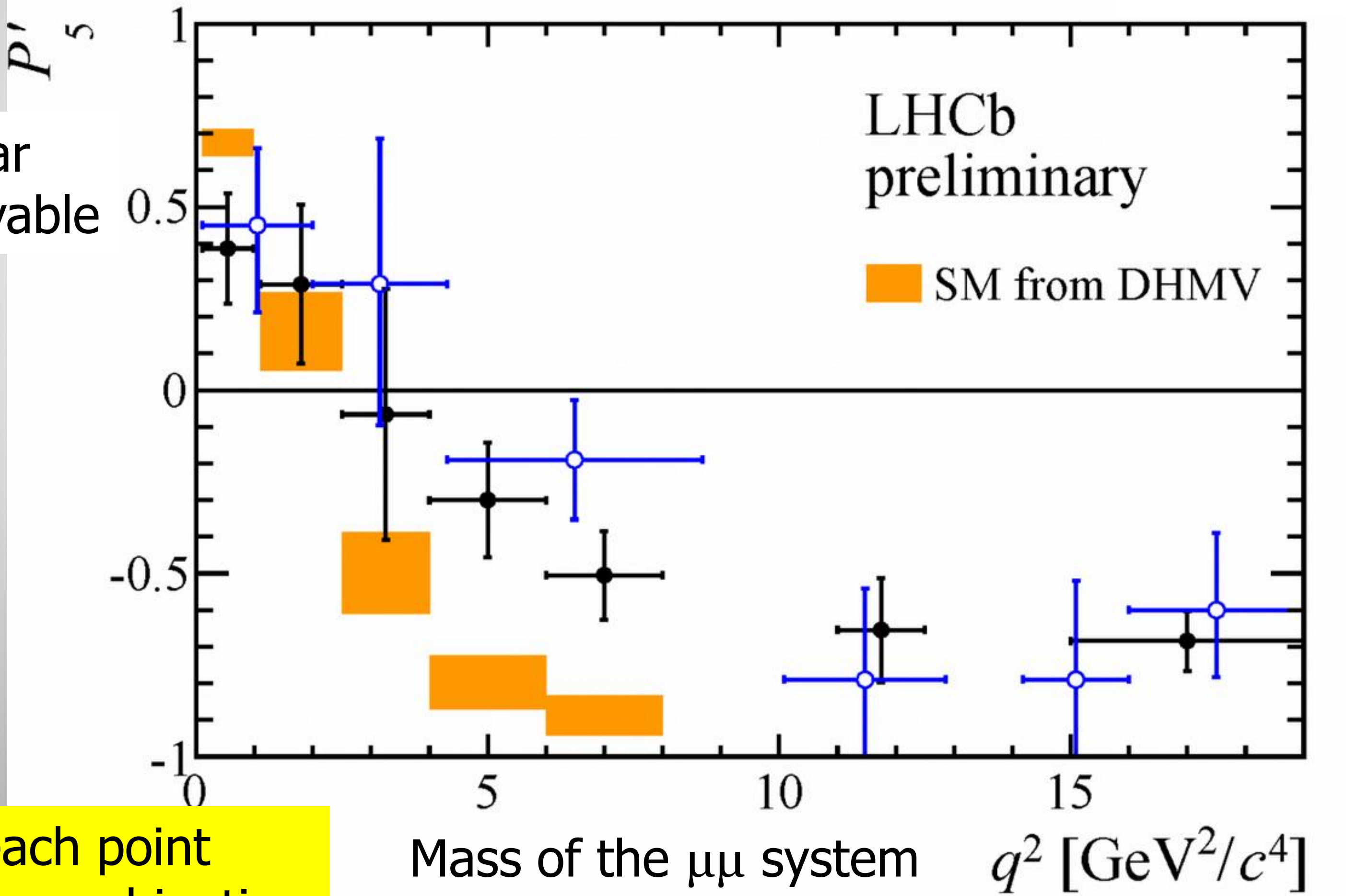
New Physics in Rare Decays?

Analysis of the $B0 \to K^*\mu+\mu-$ decay (full run-I data-set)

http://lhcb-public.web.cern.ch/lhcb-public/Welcome.html#P5p



Angular observable



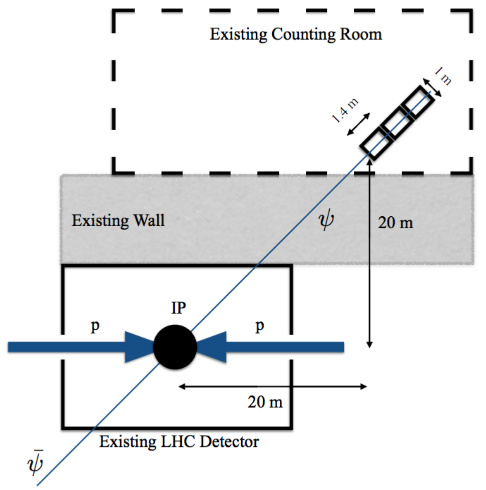
Mass of the μμ system

2.9σ for each point
3.7σ naive combination

Particles with Milli-Charges?

CMS search for fractional charged particle arXiv:1210.2311
Q=1/3e > 140 GeV; Q=2/3e >310 GeV (95% CL. dE/dx)

A "new" idea -> Hunting for particles with charges ~ 0.1-0.001e arXiv:1410.6816

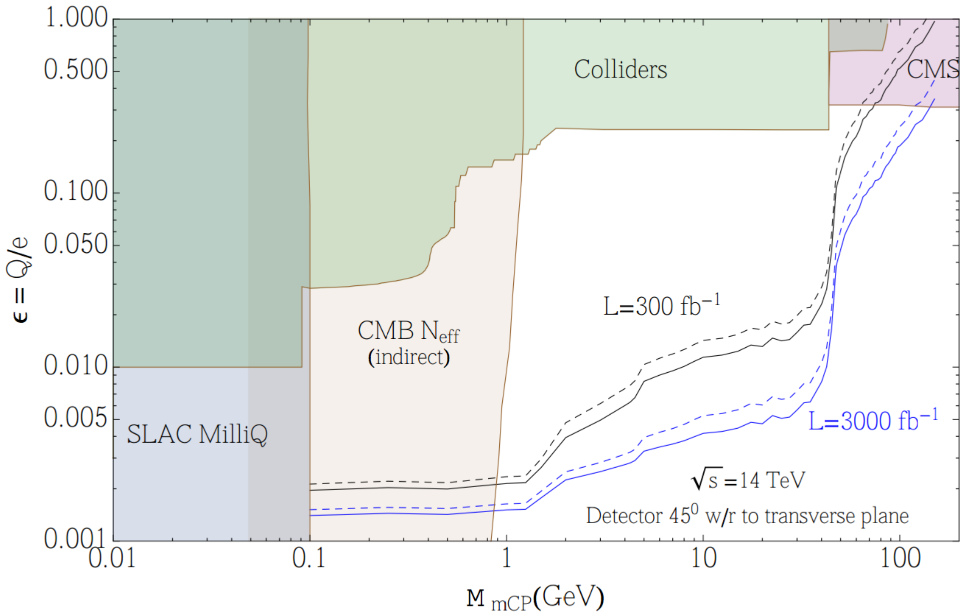


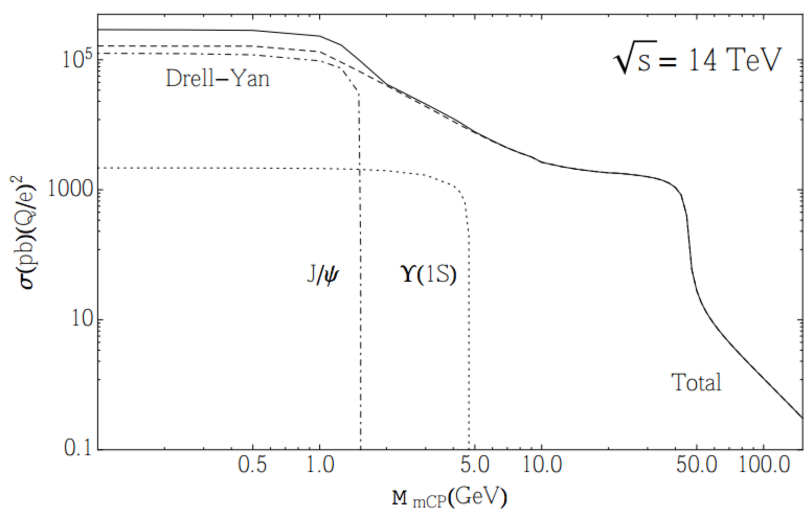
Looking for milli-charged particles with a new experiment at the LHC

Andrew Haas, Christopher S. Hill, Eder Izaguirre, Itay Yavin

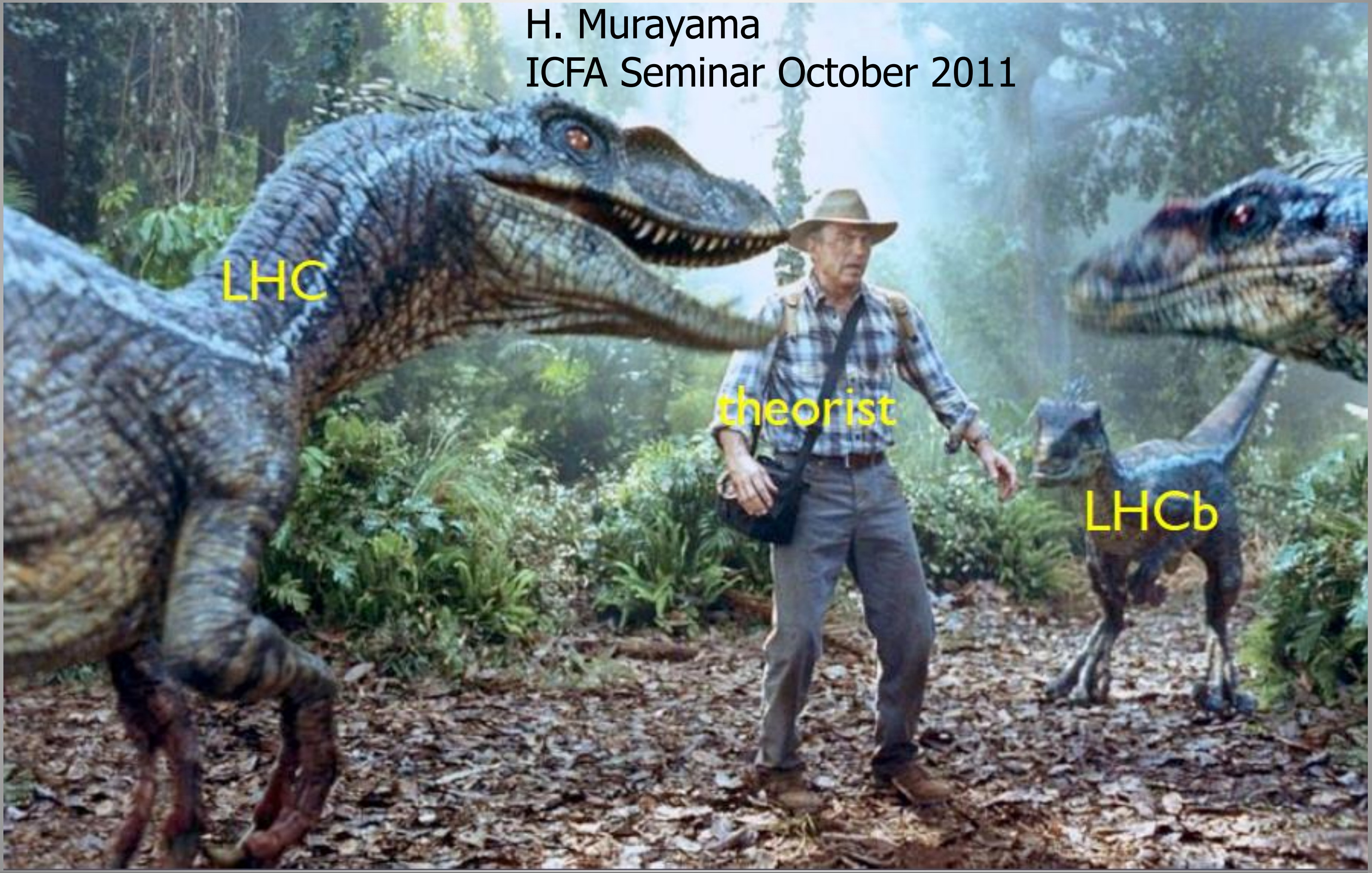
(Submitted on 24 Oct 2014)

We propose a new experiment at the Large Hadron Collider (LHC) that offers a powerful and model-independent probe for milli-charged particles. This experiment could be sensitive to charges in the range $10^{-3}e - 10^{-1}e$ for masses in the range $0.1 - 100$ GeV, which is the least constrained part of the parameter space for milli-charged particles. This is a new window of opportunity for exploring physics beyond the Standard Model at the LHC.



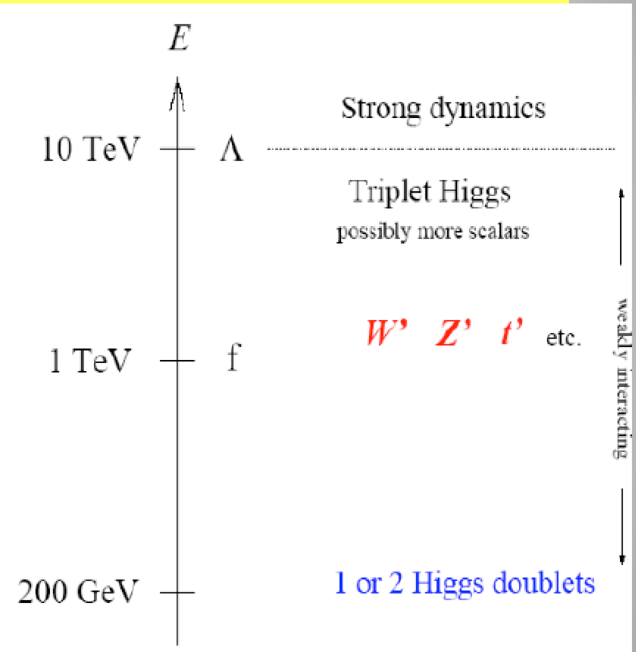


How does it feel to be a (BSM) Theorist?



Other New Physics Ideas…

- Plenty!
  - Compositeness/excited quarks & leptons
  - Little Higgs Models
  - leptoquarks
  - String balls/T balls
  - Bi-leptons
  - RP-Violating SUSY
  - SUSY+ Extra dimensions
  - Unparticles
  - Classicalons
  - Dark/Hidden sectors
  - Colored resonances
  - And more….

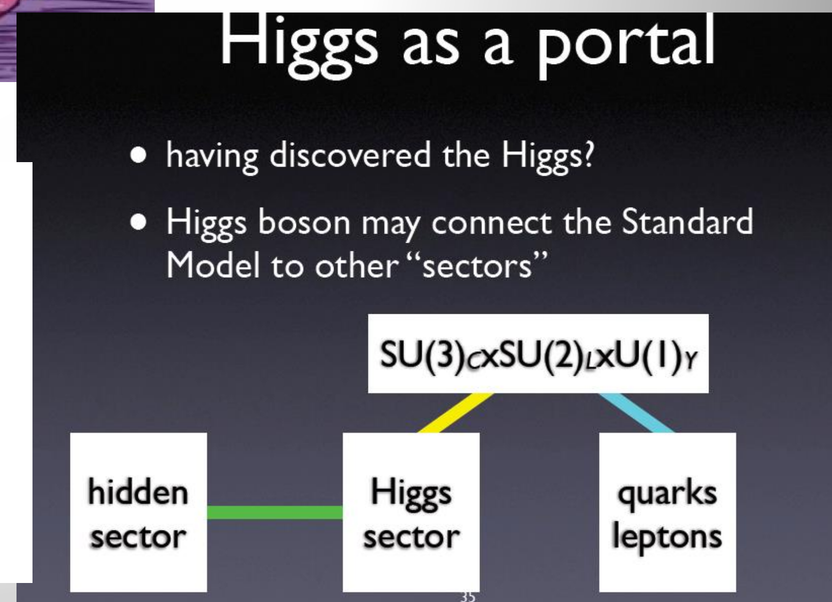


Have to keep our eyes open for all possibilities:
Food for MANY PhD theses!!

The Future…

The Future: Studying the Higgs…

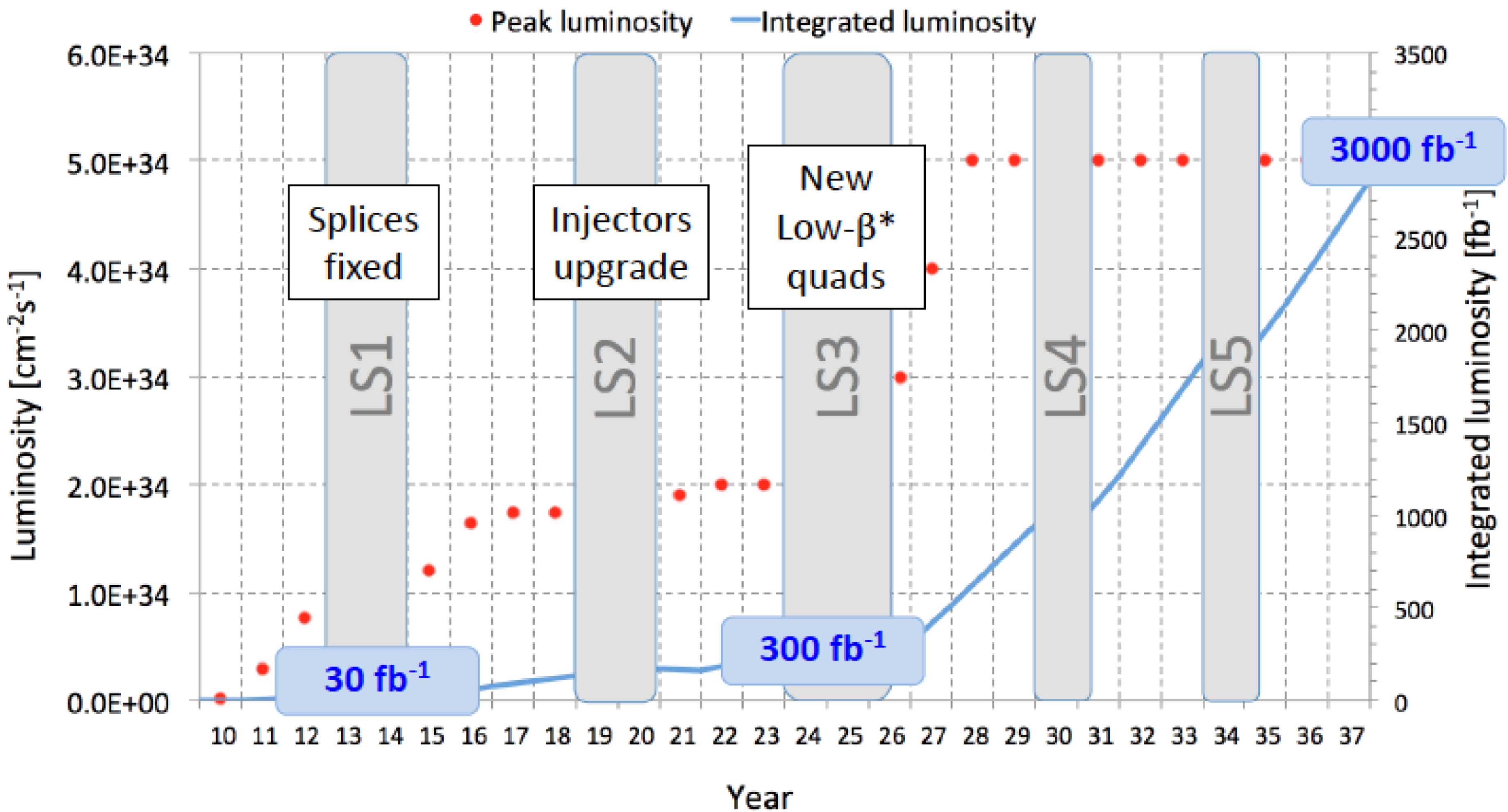
The Higgs is the new particle that may give us crucial insight into the new physics world
We will have to study it!!



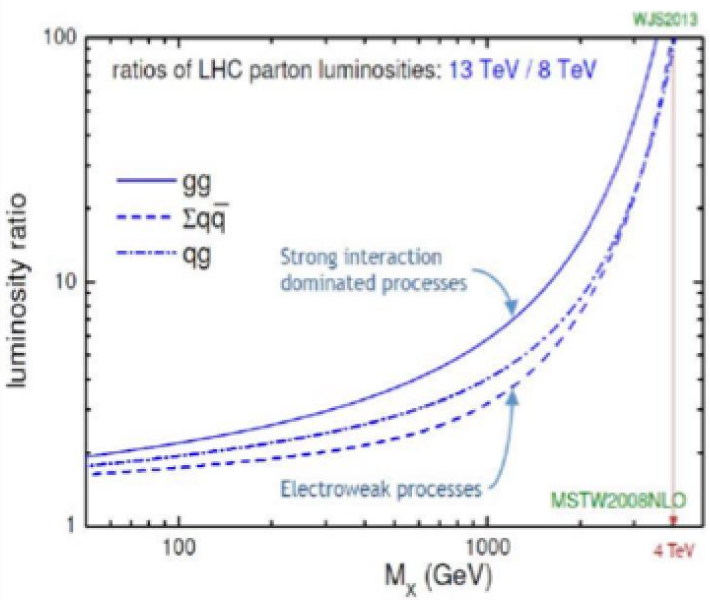
Many questions are still unanswered:

- What explain a Higgs mass ~ 125 GeV?
- What explains the particle mass pattern?
- Connection with Dark Matter?
- Where is the antimatter in the Universe?
- ⑤

The Future Program of the LHC



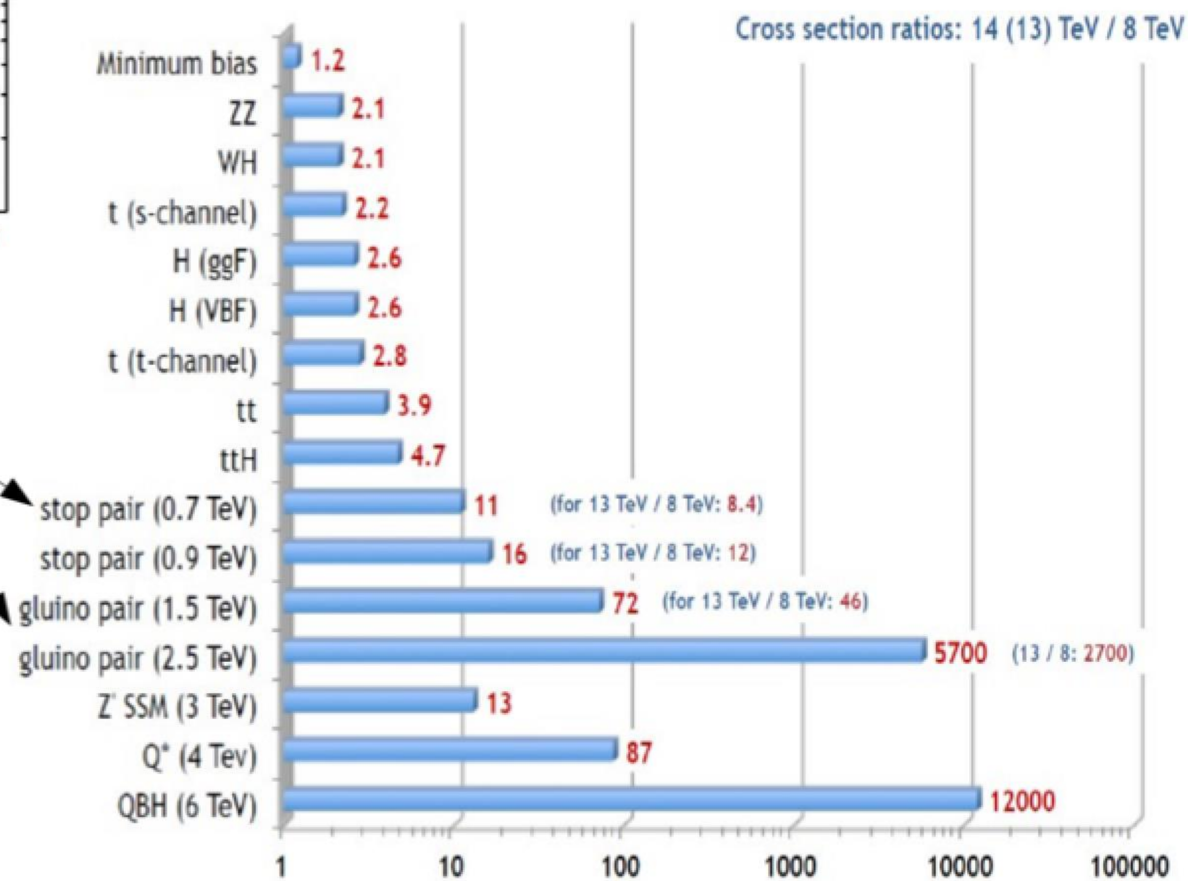
Prospects for Searches at 14 TeV



0.5-1 fb^{-1} would be enough for first analyses entering new territory
We should collect that during summer 2015

~Reach we had with 8 TeV 20 fb-1

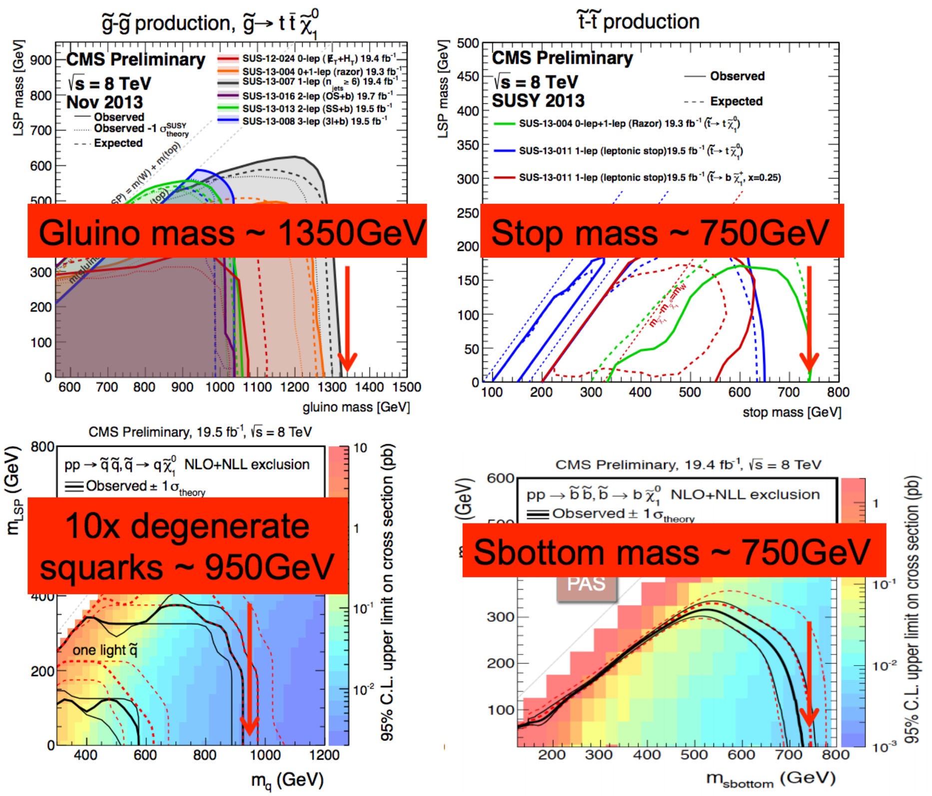
With 1 fb-1 we will produce ~twice as many gluino pairs at 1.5 TeV as in full Run 1
With 5 fb-1 we will produce ~twice as many stop pairs at 0.7 TeV as in full Run 1



SUSY Prospects @ 2015/2016

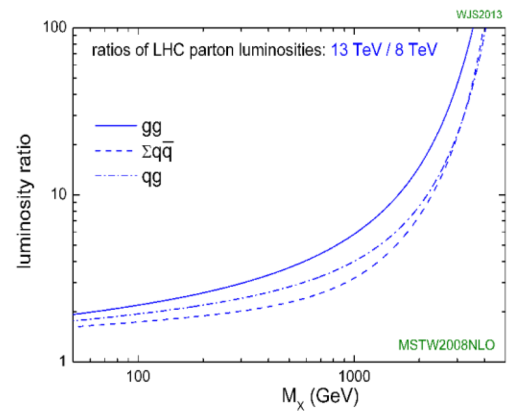
Expect ~ 10-20 fb^{-1} in 2015 & 40 fb^{-1} in 2016 (present guestimates)

Now 2014



2015-2016

Cross Section Scaling 8 -> 13 TeV



Xsection Ratios 13/8 TeV

1350GeV gluino: x30
950GeV squark: x20
750GeV squark: x9
350GeV $X^{+-}X^0$: x3
top pairs: x4

~1/fb of 13TeV data surpasses our best gluino limits.
~3/fb of 13TeV data surpasses our sbottom and stop limits.
There will be no relevant SM measurements at 13TeV by the time we have already stepped well into new territory!!!

0.5-1 fb^{-1} would be enough for first analyses entering new territory
We expect that have such a sample by Summer 2015!!

Beyond the LHC

- Proton-proton machines at higher energy…

- Electron-positron machines for high precision…

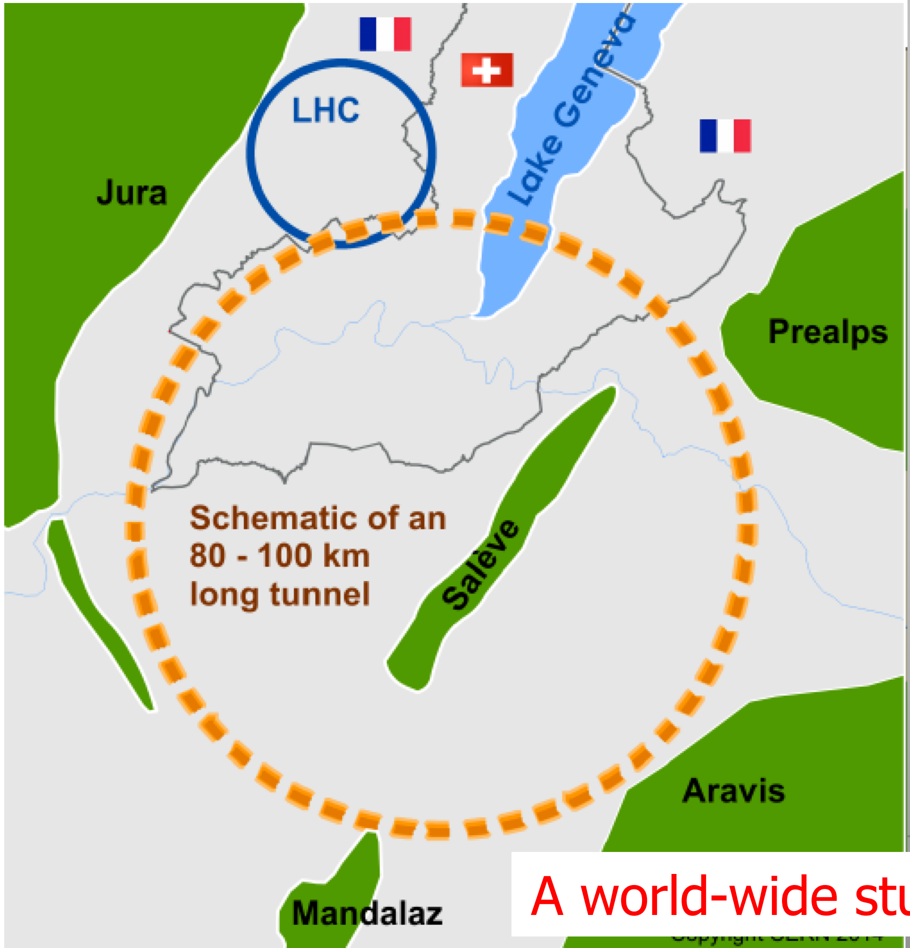
- Both? And allowing for electron-proton collisions..?

New projects will take 10-20 years before they turn into operation, hence need a vision & studies now!

The FCC Project

Future Circular Colliders: The return of studies for circular machines!

80-100 km tunnel infrastructure in Geneva area – design driven by pp-collider requirements (FCC-hh)
with possibility of e+-e- (FCC-ee) and p-e (FCC-he)



A world-wide study…

A High Energy Proton-Proton Collider

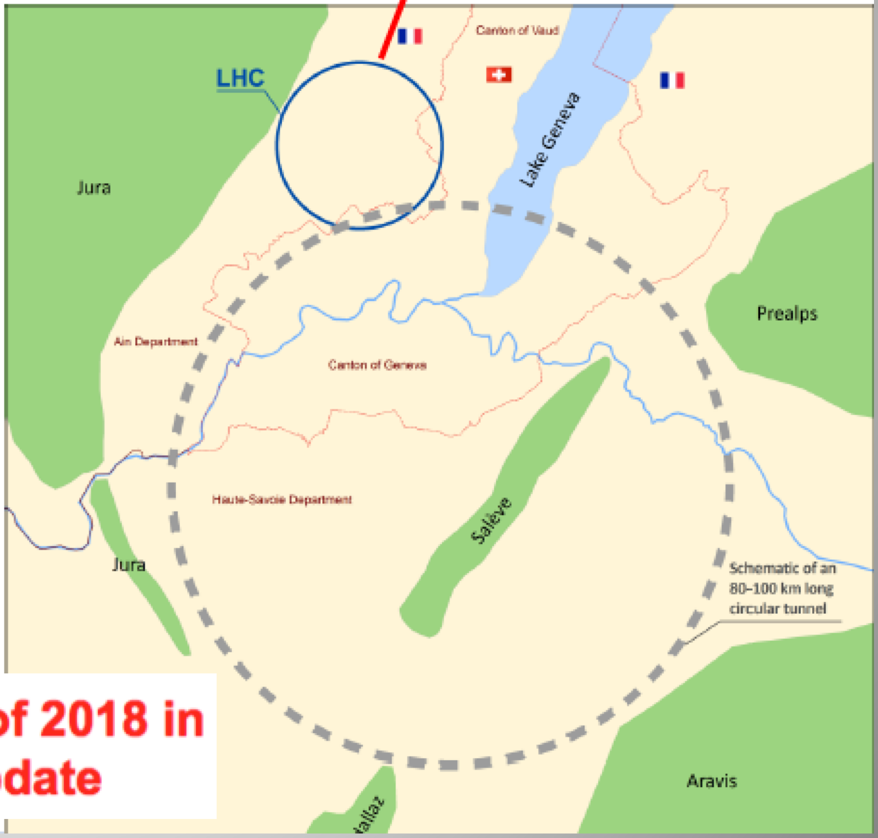
"Machine Options"

"High Energy LHC"

HE-LHC :33 TeV with 20T magnets

First studies on a new 80 km tunnel in the Geneva area

- 42 TeV with 8.3 T using present LHC dipoles
- 80 TeV with 16 T based on Nb_3Sn dipoles
- 100 TeV with 20 T based on HTS dipoles



Conceptual Design Report by end of 2018 in time for next European Strategy Update

FCC-ee: The Electron-Positron Option

- In July 2011 a proposal was made to (re)install a 120 GeV / beam e^+e^- collider in the LEP-LHC tunnel – named LEP3. Work on LEP3 started in a series of workshops.
- The 80 km TLEP machine appeared in 2012 in parallel with the feasibility study for a 80 km ring for a future hadron collider around CERN. TLEP and LEP3 were presented in September 2012 at the European Strategy meeting in Krakow.
- In October 2013 TLEP was integrated into the FCC study and is now known as FCC-ee.

Circular e+e- collider with √s energy in the range of 90-350 GeV

Can serve 4 experiments simultaneously!

Challenging but no showstoppers!! (2 rings)
Energy loss/turn ~ 8 GeV

√s (GeV)	<L >(ab-1/year)*	Rate (Hz) ee—>hadrons	Years	Statistics
90	5.6	$2\ 10^4$	1	$2\ 10^{11}$ Z decays
160	1.6	25	1-2	$2\ 10^7$ W pairs
240	0.5	3	5	$5\ 10^5$ HZ events
350	0.13	1	5	$2\ 10^5$ ttbar

* each interaction point

Tera-Z, Oku-W, Mega-H, Mega-top

The Physics Case includes

- Precise measurement (0.1% to 1%) of the Higgs Couplings
- Improve precision (statistics x 10^5) on the measurements of the Z parameters [M_Z, Γ_Z , R_ℓ, R_b, R_c, Asymmetries & weak mixing angle]. Z rare decays.
- Scan W threshold (aiming at 0.5 MeV precision). W rear decays
- Scan ttbar threshold (aiming at 10 MeV)

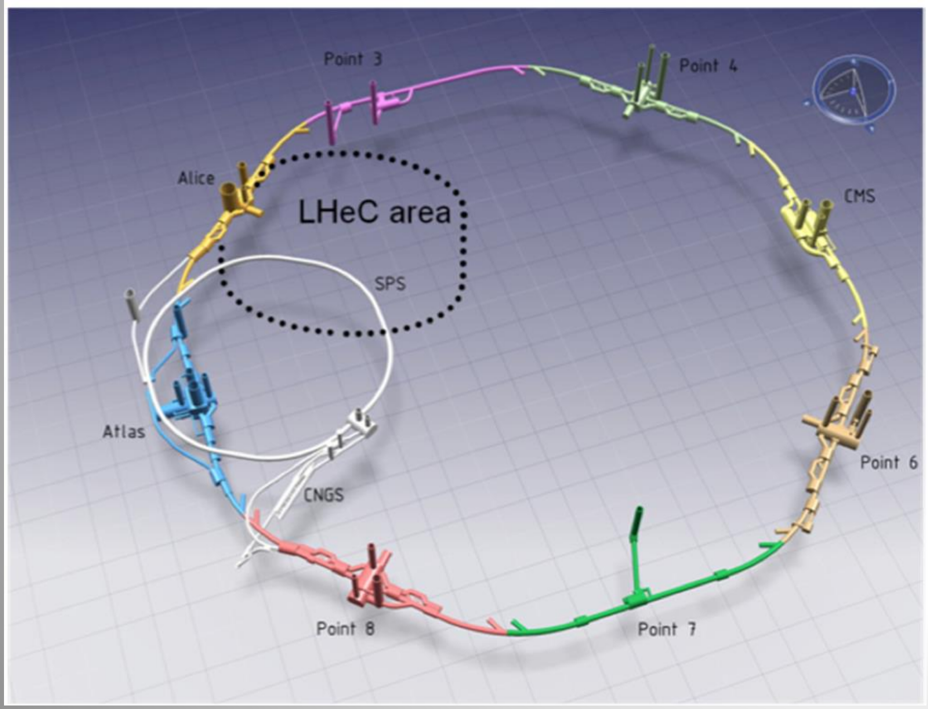
FCC-he: The Electron-Proton Option

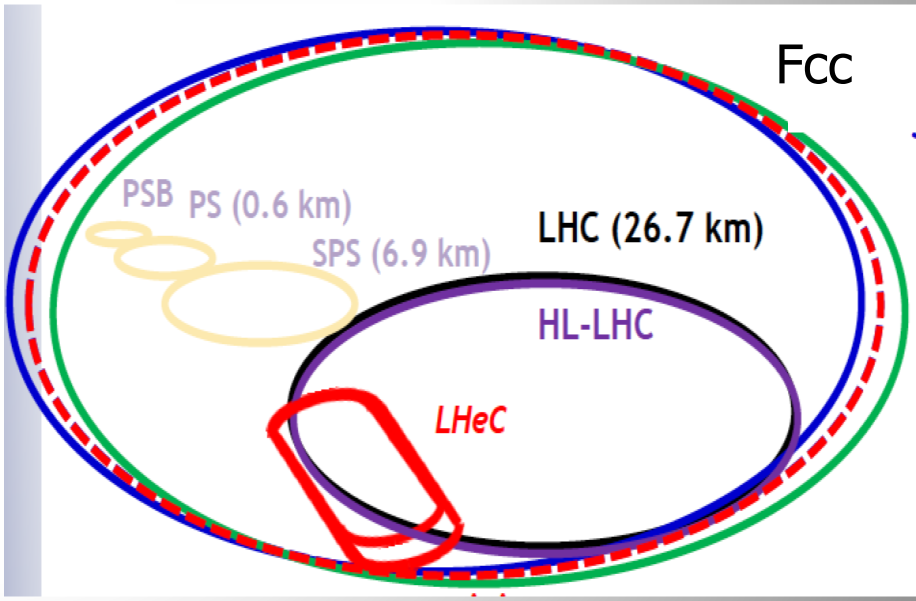
- Future possible hadron and lepton colliders will be excellent QCD explorers
- High luminosity (10^{34}-10^{35}) and/or energy lepton-hadron colliders

->Dedicated facilitie studies include the LHeC (Europe) and EIC (US) projects and now FCC-he

ep: 60 GeV x 7 TeV

ep: 60-175 GeV x 50 TeV





Use FCC-ee ring or Energy Recovery Linac

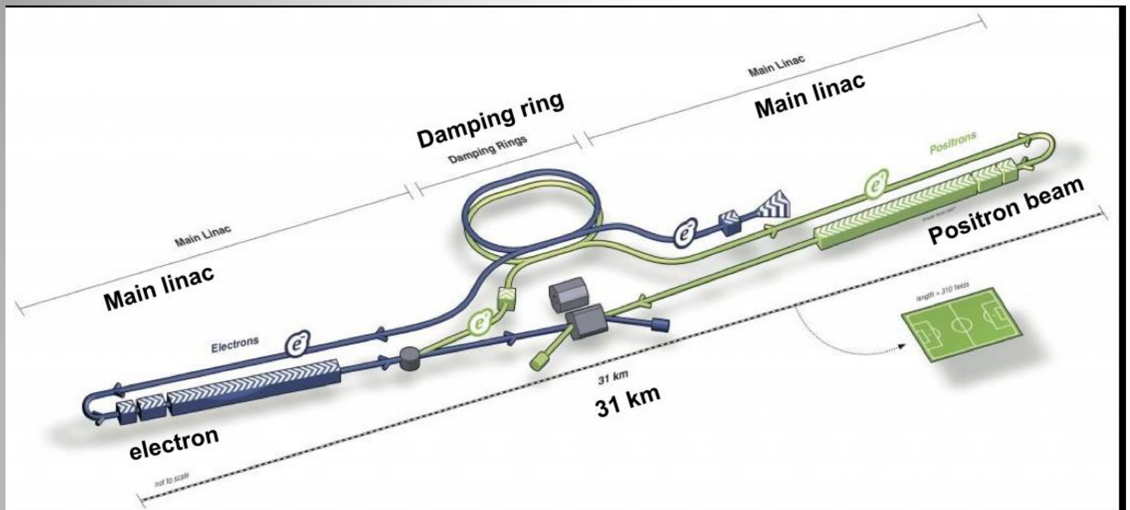
Linear e+e- Colliders

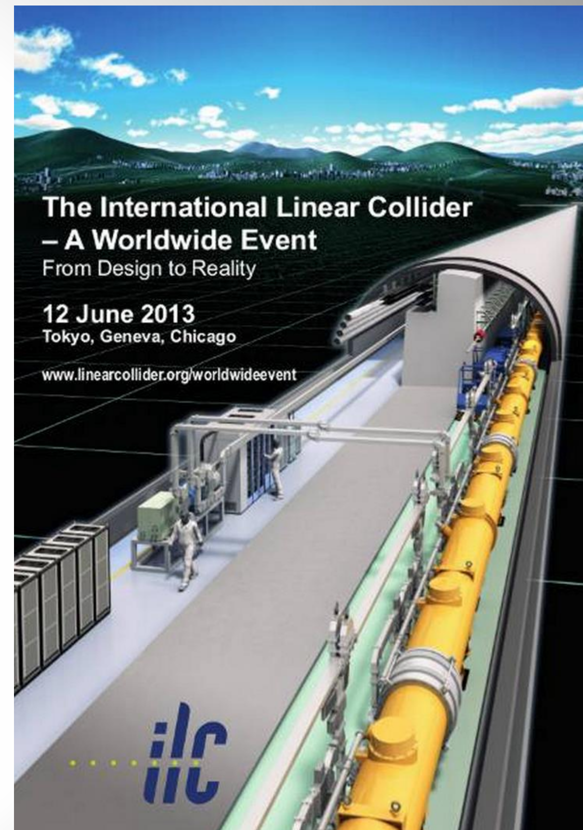
Electron-positron machines for high precision and possibly high energy (few TeV) …
Avoid Synchrotron radiation from a circular machine

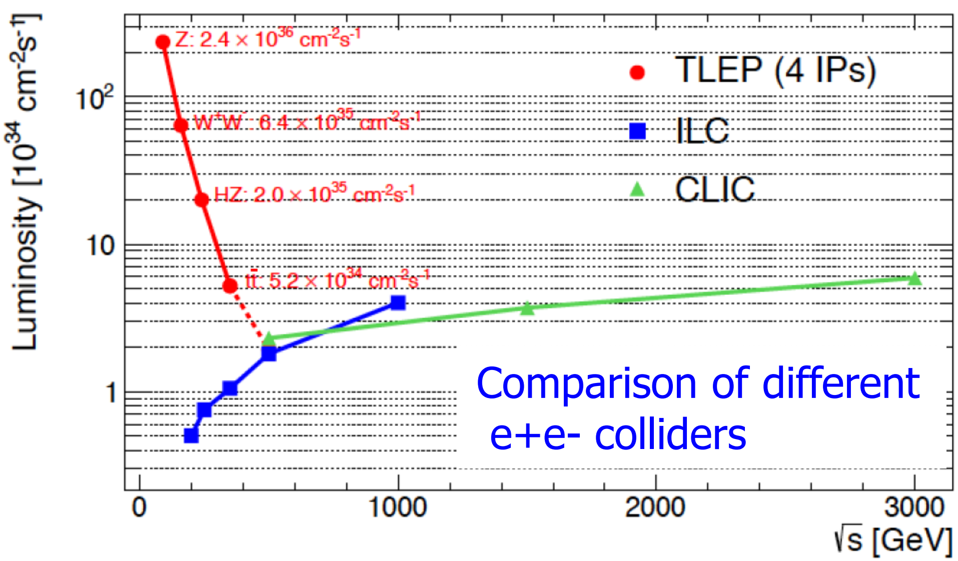
Studies and R&D work on linear colliders started in the '90's and they have achieved a very high level of maturity now…

ILC Layout

Japan has expressed a strong interest to host this collider! Under discussion…



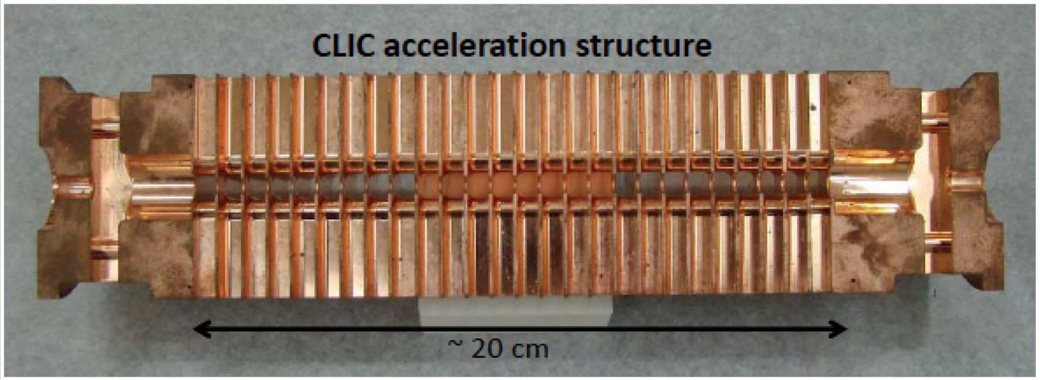




Comparison of different e+e- colliders

Note: in 2013 ILC produced a plan to double the luminosity (not included in the figure)

CLIC: Two Beam Acceleration



CLIC parameters

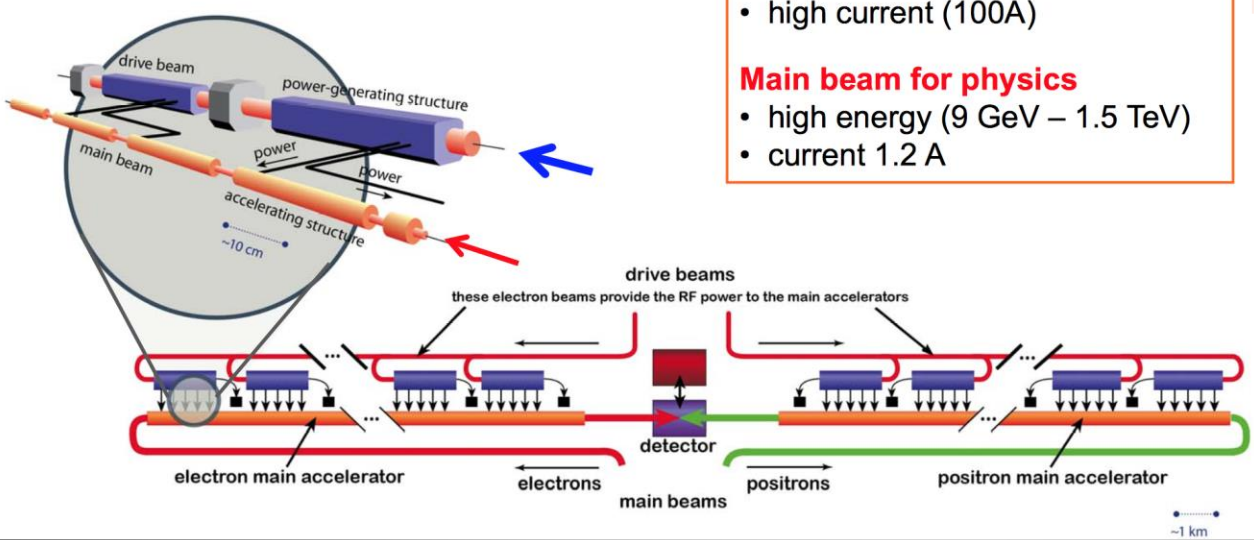
	CLIC at 3 TeV
L ($cm^{-2}s^{-1}$)	5.9×10^{34}
BX separation	0.5 ns
#BX / train	312
Train duration (ns)	156
Rep. rate	50 Hz
Duty cycle	0.00078%
σ_x / σ_y (nm)	≈ 45 / 1
σ_z (μm)	44

Accelerating gradient: 100 MV/m

Two Beam Scheme:

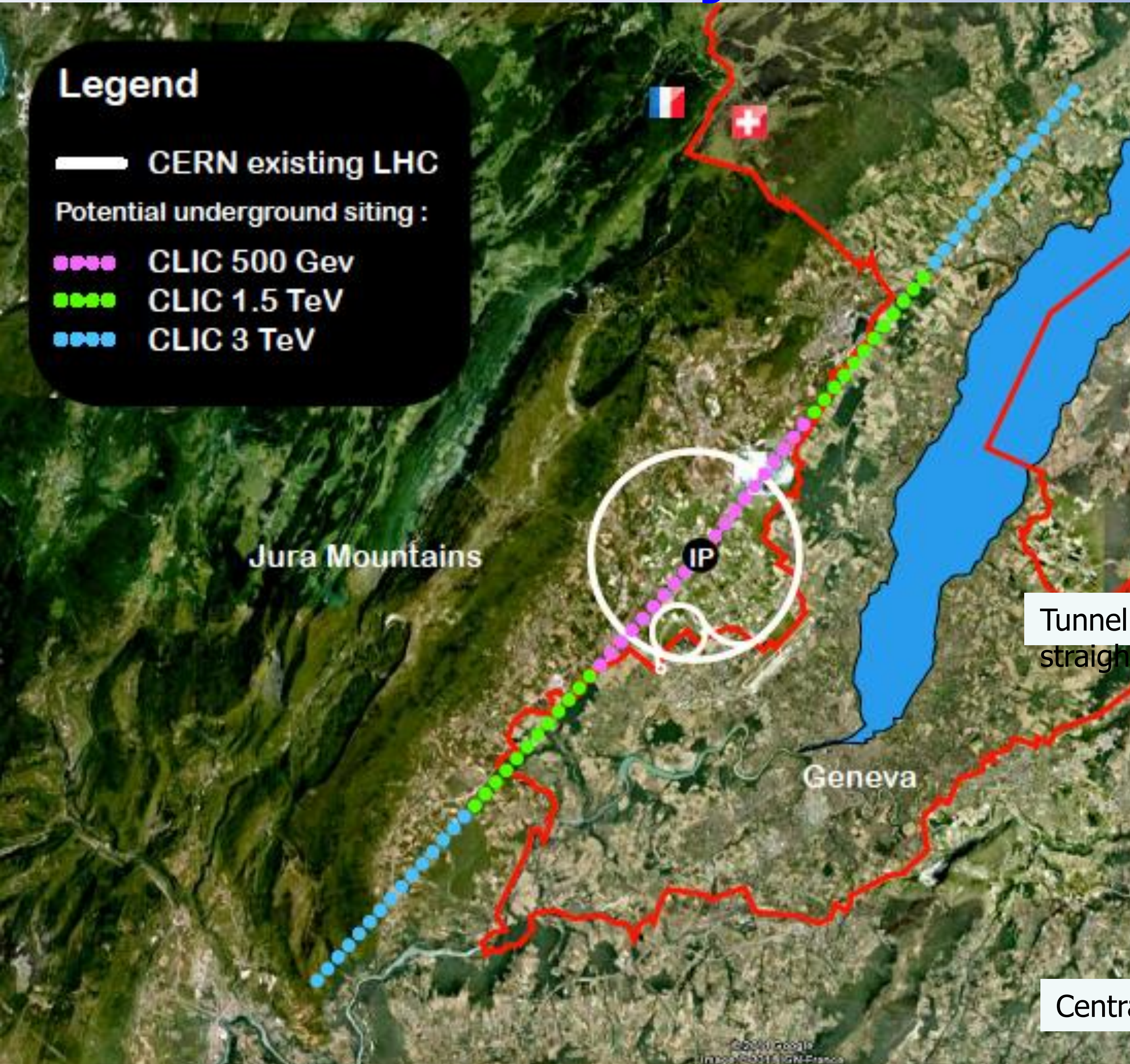
Drive Beam supplies RF power
- 12 GHz bunch structure
- low energy (2.4 GeV - 240 MeV)
- high current (100A)

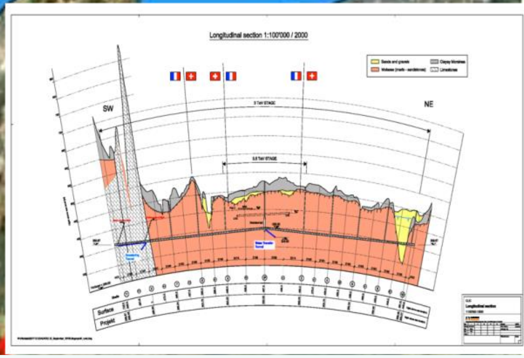
Main beam for physics
- high energy (9 GeV – 1.5 TeV)
- current 1.2 A



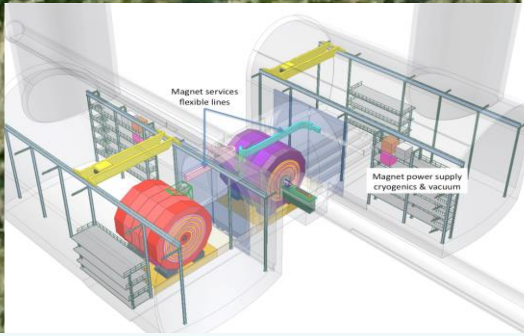
Parameters for √s
- 500 GeV
- 1.4 TeV
- 3 TeV

CLIC Layout @ CERN





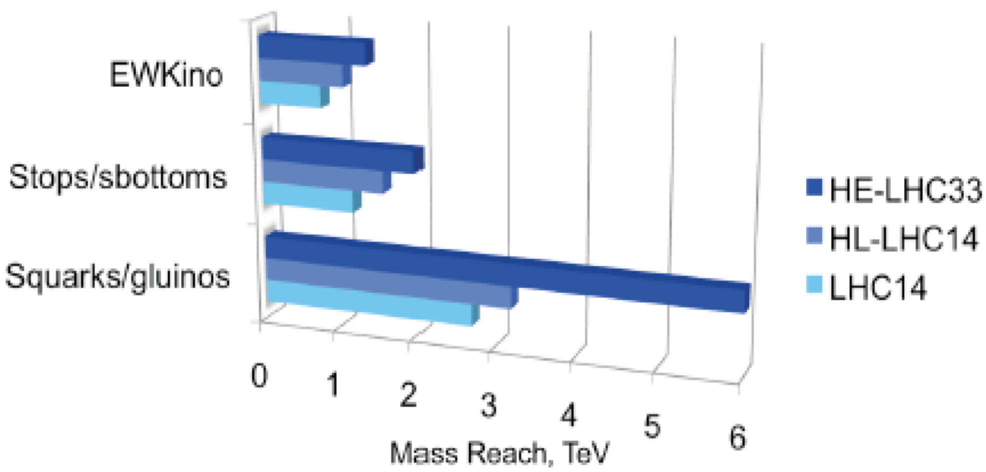
Tunnel implementations (laser straight)



Central MDI & Interaction Region

FCC-hh: Searches for New Particles

Searches for pair produced SUSY particles



FCC-hh

- -Reach sparticle masses search up to about 16 TeV for squarks of light quarks and 7 TeV for stops
- -Excited quarks probe the structure of quarks down to 4×10^{-21} m
- -Discovery of resonances up to masses of 40-50 TeV

E.g. 2HDM in SUSY

$m_h, m_H, m_A, m_{H^\pm}$ $\tan\beta \equiv \langle\Phi_2\rangle/\langle\Phi_1\rangle$

Fine tuning and naturalness: (N.Craig, BSM@100 Wshop)

$\Delta \approx \sin^2(2\beta)\frac{m_H^2}{m_h^2}$ $\Delta(\tan\beta = 50) \leq 1 \rightarrow m_H \lesssim 3.1\ \text{TeV}$

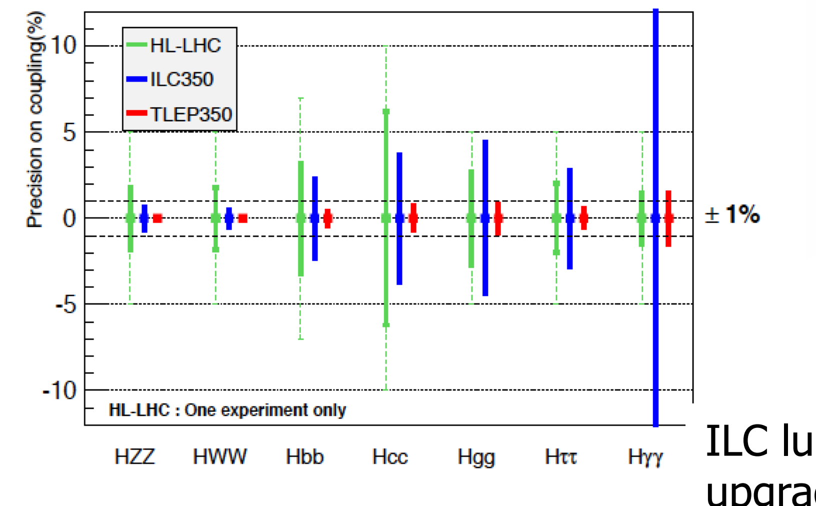
Extra H can be heavy, well above LHC reach, but cannot be arbitrarily heavy

Upper limit for higher Higgs mass in 2HDM models?

- **Why 100 TeV ?**
  - Need for O(100 TeV) in the cards since the SSC days: fully explore EWSB, probing in particular unitarization of WW scattering at m(WW)> TeV, and explore dynamics well above EWSB

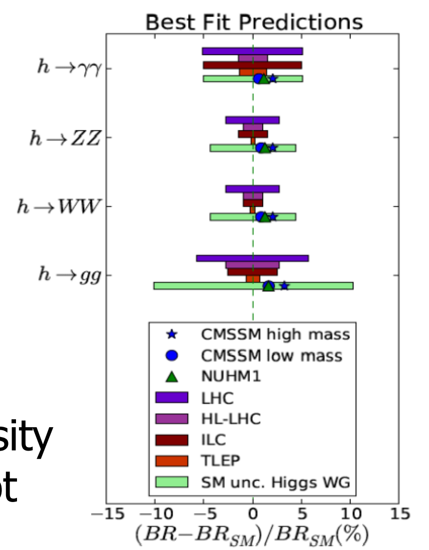
Physics at e+e- Colliders

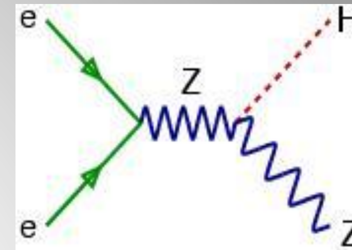
Higgs Boson Couplings



ILC luminosity upgrade not included

Higgs Boson decays



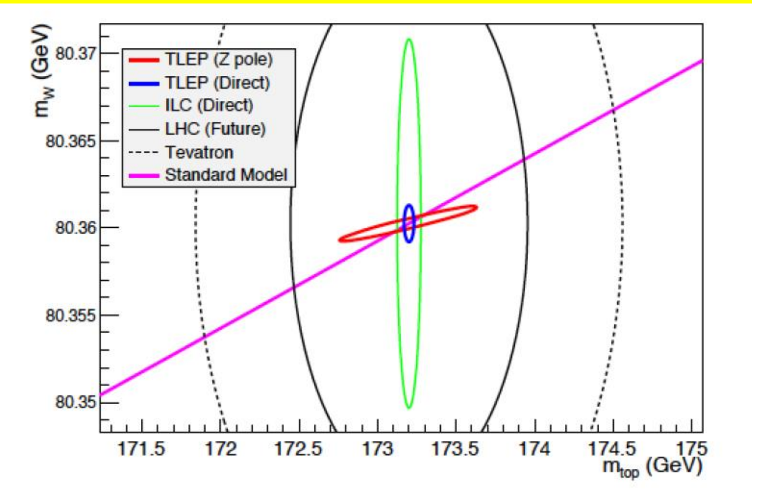


arXiv1308.6176

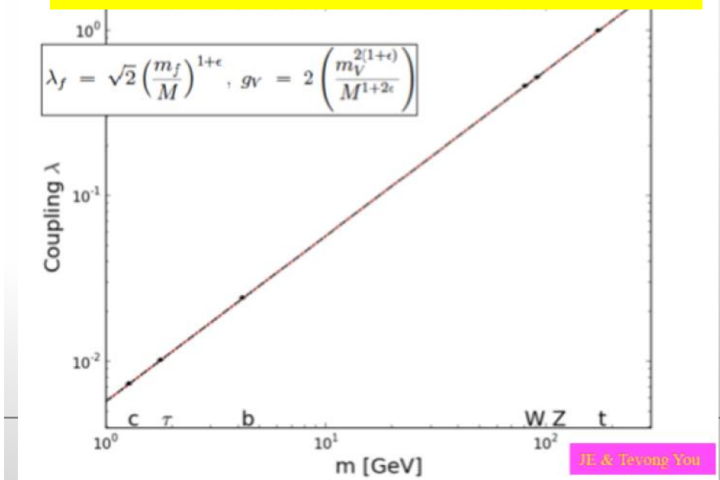
First look at the physics case of TLEP

The TLEP Design Study Working Group

Fit to all EWK precision measurements



Higgs couplings vs particle mass

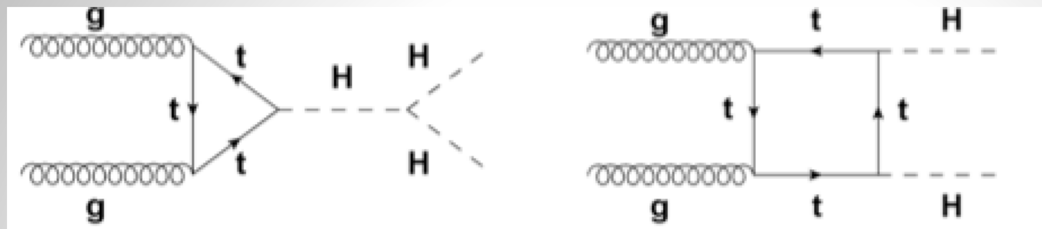


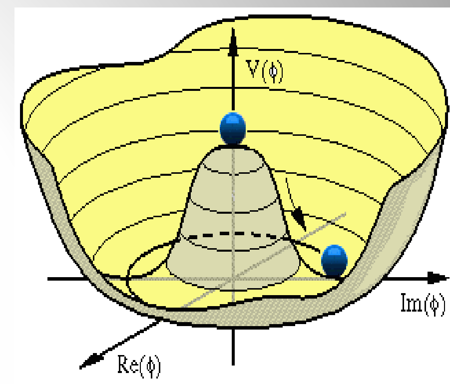
FCC-ee delivers very precise measurements

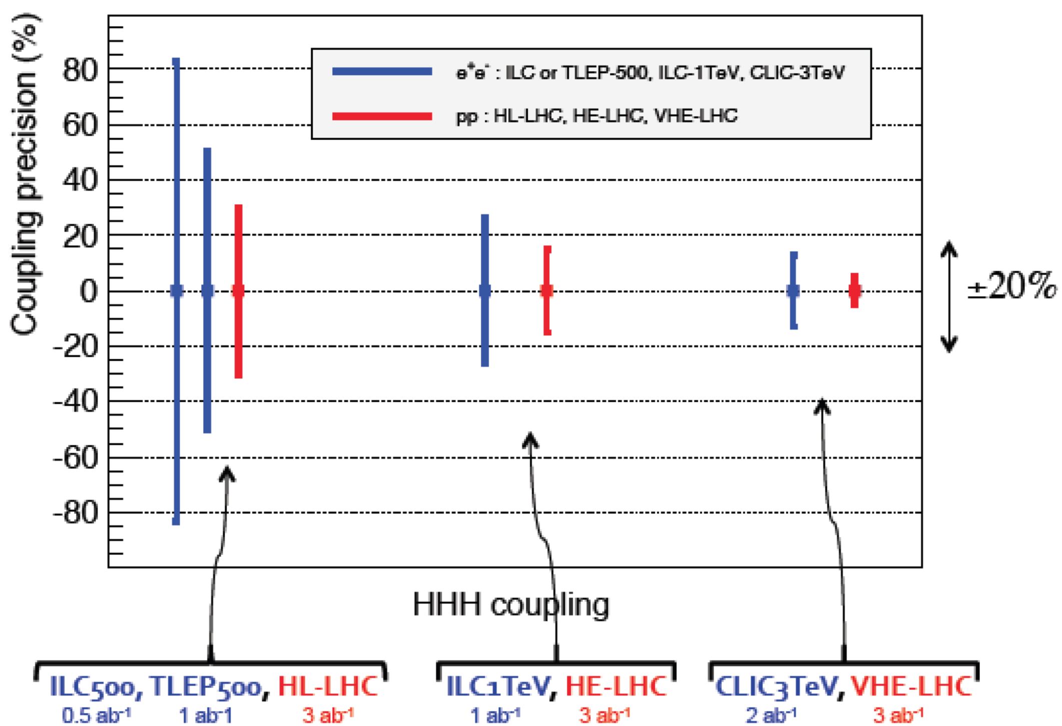
The Higgs Self Coupling!

A key measurement for our understanding of the Higgs field potential!

in pp







Difficult measurements!!:
Evaluation till ongoing for HL-LHC sensitivity

e+e- machines with sufficient energy and FCC-hh can measure this process precisely

Summary: The Searches are on!

- The LHC has entered a new territory. The ATLAS and CMS experiments are heavily engaged in searches for new physics. The most popular example is Supersymmetry, but many other New Physics model searches are covered.
- No sign of new physics yet in the first 20 fb^{-1} at 8 TeV with the analyses reported in this lecture… This starts to cut into the 'preferred regions' for a large number of models, like SUSY
- More exotic channels are now being covered: monopoles, fractional or multiple charged particles, long lived particles… Still many unexplored channels left to explore
- The LHC did its part so far with a great run in 2
Collected about 20 fb^{-1}@ 8 TeV by end of 2012
- In 2015 the energy will be 13/14 TeV, excellent
- And maybe one day soon:

End of Lecture II