Beyond The Standard Model LHC Results and Prospects

Prof. Albert De Roeck CERN, Geneva, Switzerland Antwerp University Belgium UC-Davis California USA IPPP, Durham-UK NTU, Singapore

September 14-18 Split, Croatia

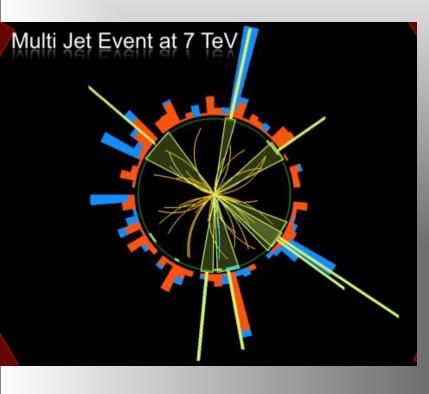
Split School of High Energy Physics 2015



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

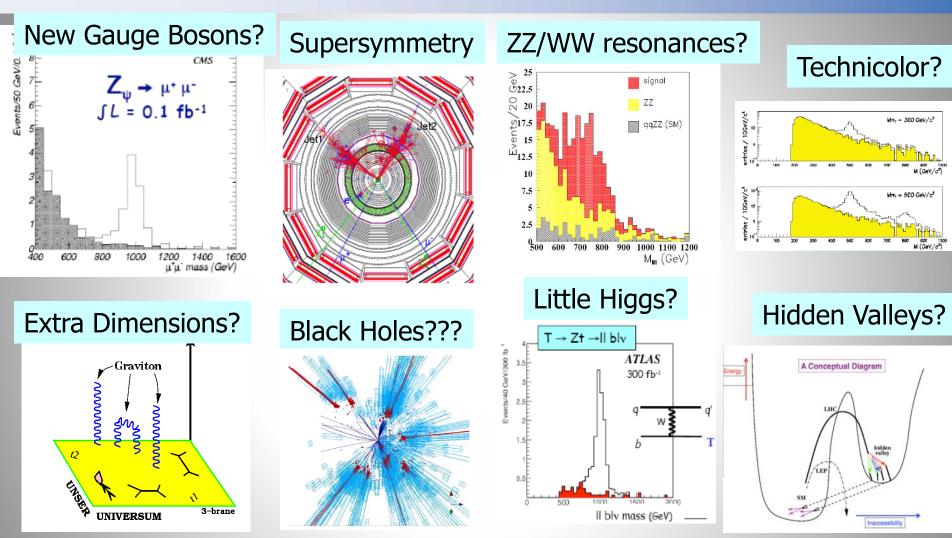
- Search for SupersymmetryThe connection with dark matter
- Outlook for Run-II
- Far Future Outlook
- Summary

Searches for New Physics

Important SM parameter \rightarrow stability of EW vacuum Precise measurements 180 arXiv:1205.6497 of the top quark and first measurements of the 178 arXiv:1403.6535 Higgs mass Top pole mass Mt in GeV 176 We also know that: **Universe content** 170 visible matter 5% 168 128 120 122 124 126 130 132 Higgs pole mass M_h in GeV dark matter 27% New Physics inevitable? But at which scale/energy? dark energy 68% Where Is t Veryba

N. Arkani-Hamed

New Physics?



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
- Origin of matter
- Masses of neutrinos
- Hierarchy problem
- Inflation
- Quantum gravity

SUSY SUSY

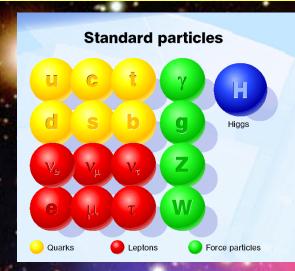
SUSY SUSY SUSY

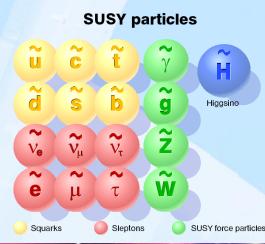
The Standard Model

John Ellis BUSSTEPP August 2015

Is Not E

Supersymmetry: a new symmetry in Nature?

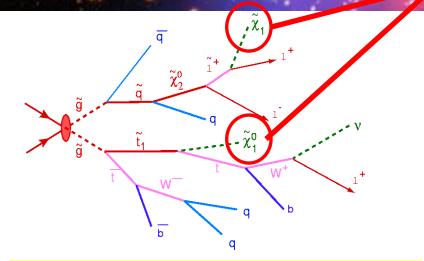






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Candidate particles for Dark Matter \Rightarrow Produce Dark Matter in the lab

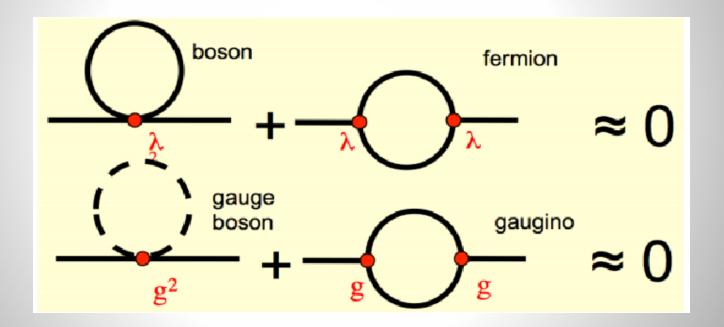


SUSY particle production at the LHC

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

Supersymmetry

Supersymmetry (SUSY) \rightarrow 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



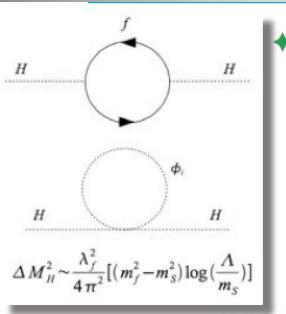
Fermion and boson loops cancel, provided $m_{\tilde{f}} \leq \text{TeV}$.

Why weak-scale SUSY ?

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

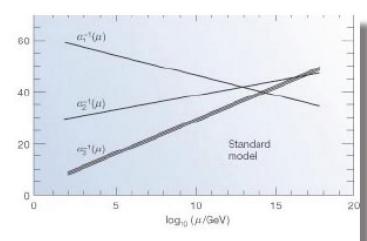
Discovering SUSY – A revolution in particle physics!!

Summary: Why SUSY is good for you!!

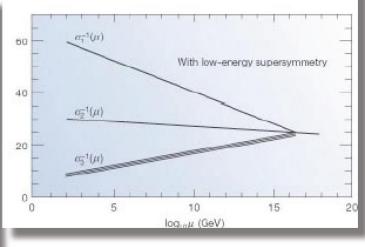


Elegant solution to the hierarchy problem (i.e., why the Higgs mass is not at the Planck scale)

Gauge unification

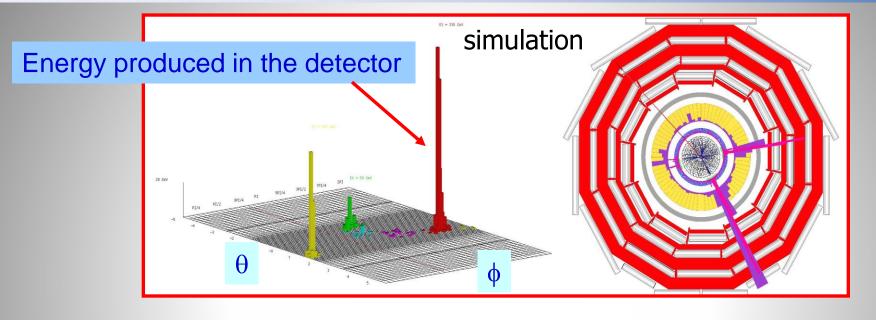


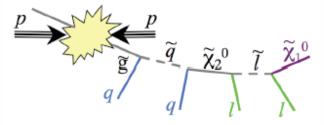




Dark matter candidate with the right abundance

Detecting Supersymmetric Particles



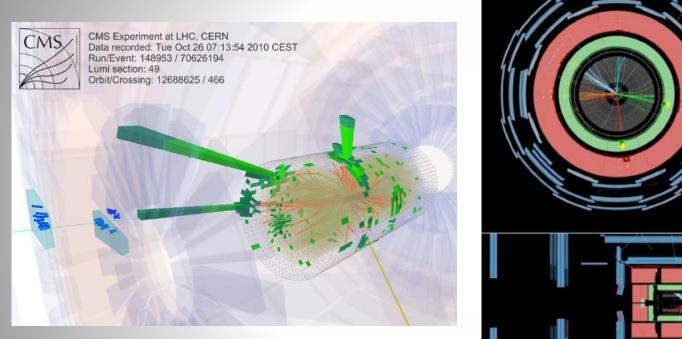


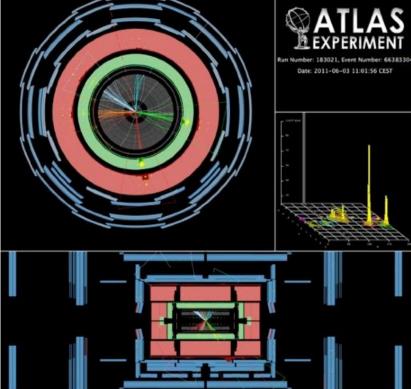
Supersymmetric particles decay and produce a cascade of jets, leptons and missing transverse energy (MET) due to escaping 'dark matter' particle candidates

Very prominent signatures in CMS and ATLAS

...Some Interesting Collisions...

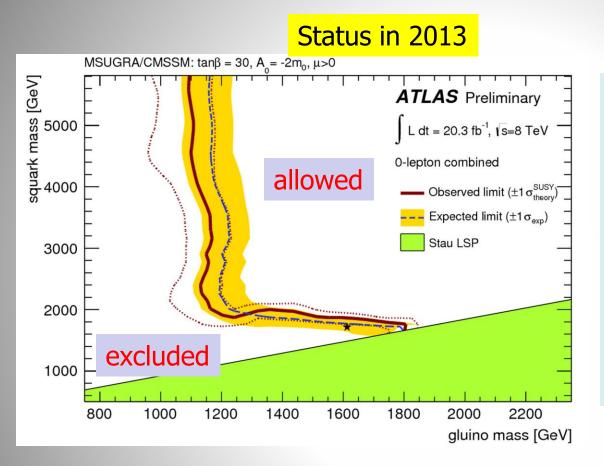
...already in 2010...





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...



•So far NO clear signal of supersymmetric particles has been found

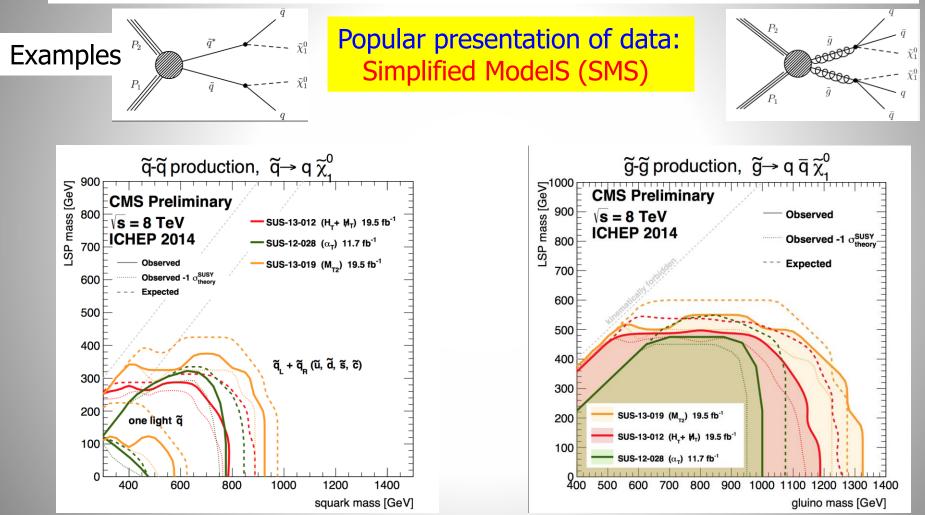
•We can exclude regions where the new particles could exist.

•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.



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

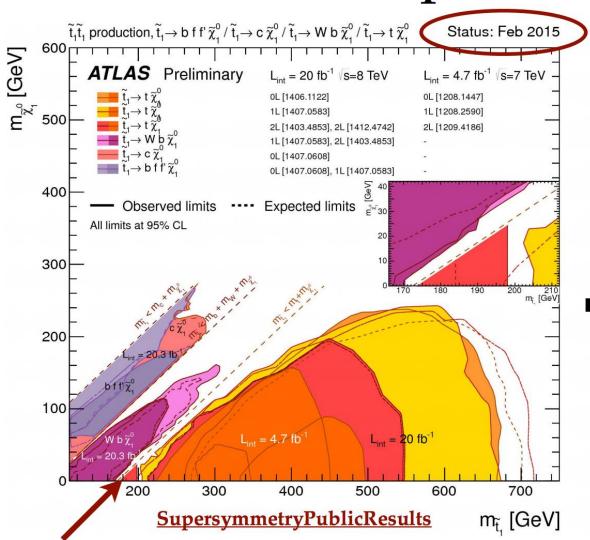
Moving away from constrained SUSY models to 'natural' models

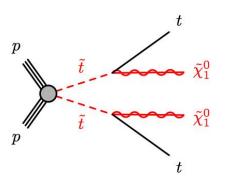
Natural SUSY survived LHC so far, but we are getting close to push it to its limits!

Cumpulsory Natural SUSY 1500 Ĩt.R,b 400 120 Unavoidable tunings: $\left(\frac{400}{m_{1}^{2}}\right)^{2}$, $\left(\frac{4m_{1}^{2}}{M_{q}^{2}}\right)^{2}$

Natural SUSY?

Direct Stop Searches

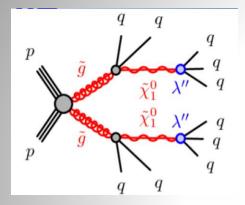




Stealth stop region ($m_{\tilde{t}} \sim m_t$) nearly closed by precision tt measurements!

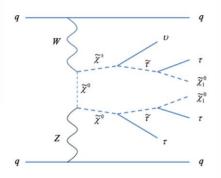
Recent New Directions...

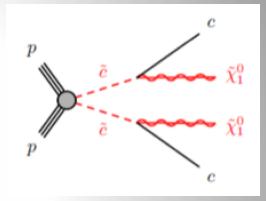
Multi-jet (≥6), no MET

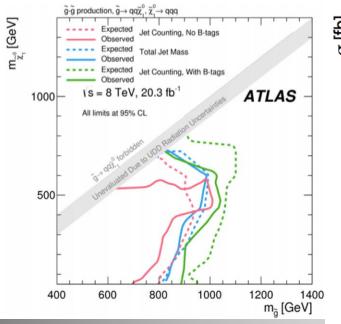


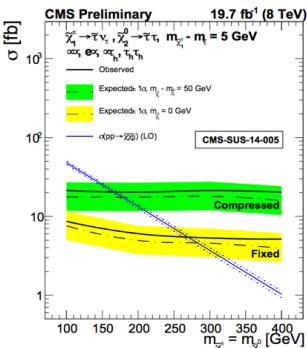
VBF EWKino production

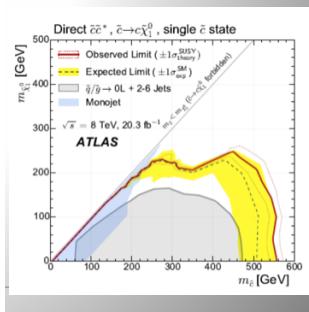
Scalar charm quark











Summary of SUSY Searches

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

ATLAS Preliminary ATLAS SUSY Searches* - 95% CL Lower Limits Status: Feb 2015 $\sqrt{s} = 7, 8 \text{ TeV}$ e, μ, τ, γ Jets $E_{T}^{\text{miss}} \int \mathcal{L} dt [\text{fb}^{-1}]$ Model Reference Mass limit MSUGRA/CMSSM $m(\tilde{q})=m(\tilde{g})$ 0 2-6 jets Yes 20.3 1.7 TeV 2-6 jets Yes 20.3 850 GeV $m(\tilde{\chi}_1^0)=0$ GeV, $m(1^{st} \text{ gen. } \tilde{q})=m(2^{nd} \text{ gen. } \tilde{q})$ $\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ 0 THIS WASN'T PREDICTED STORY 0-1 jet Yes 20.3 250 GeV $m(\tilde{q})-m(\tilde{\chi}_1^0) = m(c)$ Searches $\tilde{q}\tilde{q}\gamma, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ (compressed) 1γ 2-6 jets 20.3 $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_{1}^{0}$ 0 Yes 1.33 TeV $m(\tilde{\chi}_1^0)=0 \text{ GeV}$ IN OUR MODEL - WHAT @ 2009 3-6 jets $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_1^{\pm} \rightarrow qqW^{\pm}\tilde{\chi}_1^0$ $1e, \mu$ Yes 20 1.2 TeV $m(\tilde{\chi}_{1}^{0}) < 300 \text{ GeV}, m(\tilde{\chi}^{\pm}) = 0.5(m(\tilde{\chi}_{1}^{0}) + m(\tilde{g}))$ SHOULD WE DO? $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$ $2e,\mu$ 0-3 jets 20 1.32 TeV $m(\tilde{\chi}_{1}^{0})=0$ GeV Inclusive GMSB (Ĩ NLSP) $1-2\tau + 0-1\ell$ 0-2 jets Yes 20.3 1.6 TeV $tan\beta > 20$ 2γ GGM (bino NLSP) Yes 20.3 1.28 TeV $m(\tilde{\chi}_1^0) > 50 \text{ GeV}$ GGM (wino NLSP) $1 e, \mu + \gamma$ Yes 4.8 619 GeV $m(\tilde{\chi}_1^0) > 50 \text{ GeV}$ GGM (higgsino-bino NLSP) γ 1bYes 4.8 900 GeV $m(\tilde{\chi}_{1}^{0})>220 \, GeV$ GGM (higgsino NLSP) 2 e, µ (Z) 0-3 jets Yes 5.8 m(NLSP)>200 GeV 690 GeV LARGE DON T SAY ANYTHING. Gravitino LSP mono-jet $m(\tilde{G}) > 1.8 \times 10^{-4} \text{ eV}, m(\tilde{g}) = m(\tilde{q}) = 1.5 \text{ TeV}$ 0 Yes 20.3 865 GeV $F^{1/2}$ scale HADRON MAYBE NO ONE WILL COLLIDER $\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_{1}^{0}$ 0 3bYes 20.1 1.25 TeV $m(\tilde{\chi}_1^0) < 400 \text{ GeV}$ CER NOTICE. gen. 7-10 jets $m(\tilde{\chi}_{1}^{0}) < 350 \, GeV$ $\tilde{g} \rightarrow t \bar{t} \tilde{\chi}_{1}^{0}$ 0 Yes 20.3 1.1 TeV 0-1 e,µ 1.34 TeV $\tilde{g} \rightarrow t \bar{t} \tilde{\chi}_1^0$ 3bYes 20.1 $m(\tilde{\chi}_1^0) < 400 \text{ GeV}$ ã r 0-1 e,μ $\tilde{g} \rightarrow b \bar{t} \tilde{\chi}_1^{\dagger}$ Yes 20.1 1.3 TeV m(X10)<300 GeV 3b100-620 GeV $\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_1^0$ 0 2bYes 20.1 $m(\tilde{\chi}_1^0) < 90 \text{ GeV}$ squarks 2 e, µ (SS) 275-440 GeV $\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow t \tilde{\chi}_1^{\pm}$ 0-3 b Yes 20.3 $m(\tilde{\chi}_{1}^{\pm})=2 m(\tilde{\chi}_{1}^{0})$ 230-460 GeV $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow b \tilde{\chi}_1^{\pm}$ 1-2 e, µ 4.7 ĩ₁ 110-167 GeV $m(\tilde{\chi}_{1}^{\pm}) = 2m(\tilde{\chi}_{1}^{0}), m(\tilde{\chi}_{1}^{0}) = 55 \text{ GeV}$ 1-2 b Yes $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0$ or $t \tilde{\chi}_1^0$ $2e,\mu$ 0-2 jets Yes 20.3 90-191 GeV 215-530 GeV $m(\tilde{\chi}_1^0)=1 \text{ GeV}$ 0-1 e,µ gen. 210-640 GeV $m(\tilde{\chi}_1^0)=1 \text{ GeV}$ $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$ 1-2 b Yes 20 ĩ $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow c \tilde{\chi}_1^0$ 0 mono-jet/c-tag Yes 20.3 90-240 GeV $m(\tilde{t}_{1})-m(\tilde{\chi}_{1}^{0}) < 85 \, GeV$ $\tilde{t}_1 \tilde{t}_1$ (natural GMSB) 2 e, µ (Z) 1bYes 20.3 ĩ 150-580 GeV $m(\tilde{\chi}_{1}^{0}) > 150 \text{ GeV}$ $\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$ $3 e, \mu (Z)$ 1bYes 20.3 290-600 GeV m(X10)<200 GeV ----- $\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell \tilde{\chi}_1^0$ $2e,\mu$ 0 Yes 20.3 90-325 GeV $m(\tilde{\chi}_{1}^{0})=0 \text{ GeV}$ 1403.5294 $\tilde{\chi}_1^+ \tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow \tilde{\ell} \nu(\ell \tilde{\nu})$ $2e,\mu$ 0 Yes 20.3 $\tilde{\chi}_{1}^{\pm}$ 140-465 GeV $m(\tilde{\chi}_{1}^{0})=0 \text{ GeV}, m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_{1}^{\pm})+m(\tilde{\chi}_{1}^{0}))$ 1403.5294 $\tilde{\chi}_1^+ \tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow \tilde{\tau} \nu(\tau \tilde{\nu})$ 2τ 20.3 100-350 GeV Yes $m(\tilde{\chi}_{1}^{0})=0 \text{ GeV}, m(\tilde{\tau}, \tilde{\nu})=0.5(m(\tilde{\chi}_{1}^{\pm})+m(\tilde{\chi}_{1}^{0}))$ 1407.0350 Ň $\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{2}^{0} \rightarrow \tilde{\ell}_{L} \nu \tilde{\ell}_{L} \ell(\tilde{\nu}\nu), \ell \tilde{\nu} \tilde{\ell}_{L} \ell(\tilde{\nu}\nu)$ 3 e, µ 0 Yes 20.3 $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^{0}$ 700 GeV $m(\tilde{\chi}_{1}^{\pm})=m(\tilde{\chi}_{2}^{0}), m(\tilde{\chi}_{1}^{0})=0, m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_{1}^{\pm})+m(\tilde{\chi}_{1}^{0}))$ 1402.7029 2-3 e, µ $\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{2}^{0} \rightarrow W \tilde{\chi}_{1}^{0} Z \tilde{\chi}_{1}^{0}$ 0-2 jets Yes 20.3 $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 420 GeV $m(\tilde{\chi}_1^{\pm}) = m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 0$, sleptons decoupled 1403.5294, 1402.7029 $\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{2}^{0} \rightarrow W \tilde{\chi}_{1}^{0} h \tilde{\chi}_{1}^{0}, h \rightarrow b \bar{b} / W W / \tau \tau / \gamma \gamma$ e, μ, γ 0-2 b Yes 20.3 250 GeV $m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0)=0$, sleptons decoupled 1501.07110 $4 e, \mu$ $m(\tilde{\chi}_{2}^{0})=m(\tilde{\chi}_{3}^{0}), m(\tilde{\chi}_{1}^{0})=0, m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_{2}^{0})+m(\tilde{\chi}_{1}^{0}))$ $\tilde{\chi}_{2}^{0}\tilde{\chi}_{3}^{0}, \tilde{\chi}_{2}^{0}, \tilde{\chi}_{2}^{0}, \rightarrow \tilde{\ell}_{R}\ell$ 0 Yes 20.3 620 GeV 1405.5086 Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$ Disapp. trk 1 jet Yes 20.3 270 GeV $m(\tilde{\chi}_{1}^{\pm})-m(\tilde{\chi}_{1}^{0})=160 \text{ MeV}, \tau(\tilde{\chi}_{1}^{\pm})=0.2 \text{ ns}$ 1310.3675 ong-lived Stable, stopped g R-hadron 0 1-5 jets Yes 27.9 832 GeV $m(\tilde{\chi}_1^0)=100 \text{ GeV}, 10 \,\mu\text{s} < \tau(\tilde{g}) < 1000 \text{ s}$ 1310.6584 Stable @ R-hadron 19.1 1411.6795 trk 1.27 TeV 537 GeV 10<tanβ<50 GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(\tilde{e}, \tilde{\mu}) + \tau(e, \mu)$ 1-2 µ 19.1 1411.6795 GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$, long-lived $\tilde{\chi}_1^0$ 2γ Yes 20.3 435 GeV $2 < \tau(\tilde{\chi}_1^0) < 3$ ns. SPS8 model 1409.5542 $\tilde{q}\tilde{q}, \tilde{\chi}_{1}^{0} \rightarrow qq\mu$ (RPV) 1 μ, displ. vtx 20.3 1.0 TeV 1.5 <cτ<156 mm, BR(μ)=1, m(χ̃⁰₁)=108 GeV ATLAS-CONF-2013-092 LFV $pp \rightarrow \tilde{v}_{\tau} + X, \tilde{v}_{\tau} \rightarrow e + \mu$ $\lambda'_{211} = 0.10, \lambda_{132} = 0.05$ $2e,\mu$ 4.6 1.61 TeV 1212.1272 LFV $pp \rightarrow \tilde{\nu}_{\tau} + X, \tilde{\nu}_{\tau} \rightarrow e(\mu) + \tau$ $\lambda'_{211}=0.10, \lambda_{1(2)33}=0.05$ $1 e, \mu + \tau$ 4.6 1.1 TeV 1212.1272 Bilinear RPV CMSSM Yes $m(\tilde{q})=m(\tilde{g}), c\tau_{LSP}<1 \text{ mm}$ 2 e, µ (SS) 0-3h20.3 1.35 TeV 1404.2500 $\tilde{\chi}_1^+ \tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow W \tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow e e \tilde{v}_{\mu}, e \mu \tilde{v}_e$ $4 e, \mu$ Yes 20.3 750 GeV $m(\tilde{\chi}_1^0) > 0.2 \times m(\tilde{\chi}_1^{\pm}), \lambda_{121} \neq 0$ 1405 5086 $\tilde{\chi}_1^+ \tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow W \tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tau \tau \tilde{\nu}_e, e \tau \tilde{\nu}_\tau$ $3e, \mu + \tau$ Yes 20.3 450 GeV $m(\tilde{\chi}_1^0) > 0.2 \times m(\tilde{\chi}_1^{\pm}), \lambda_{133} \neq 0$ 1405.5086 $\tilde{g} \rightarrow qqq$ 0 6-7 jets 20.3 916 GeV BR(t)=BR(b)=BR(c)=0%ATLAS-CONF-2013-091 $\tilde{g} \rightarrow \tilde{t}_1 t, \tilde{t}_1 \rightarrow bs$ 2 e, µ (SS) 0-3 b 20.3 850 GeV 1404.250 Yes Other Scalar charm, $\tilde{c} \rightarrow c \tilde{\chi}_{1}^{0}$ 0 2 c Yes 20.3 490 GeV m(X10)<200 GeV 1501.01325 $\sqrt{s} = 7 \text{ TeV}$ $\sqrt{s} = 8 \text{ TeV}$ $\sqrt{s} = 8 \text{ TeV}$ 10^{-1} 1 Mass scale [TeV] full data partial data full data

Dark Matter: Complementary Searches?

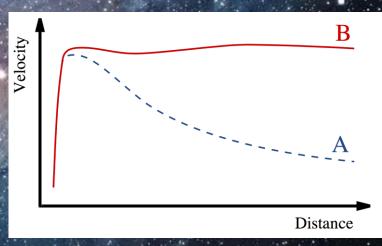
After the discovery of the Higgs particle @ the LHC: Dark matter is the next important physics problems to tackle for the LHC

The search is complementary to other experimental techniques used.



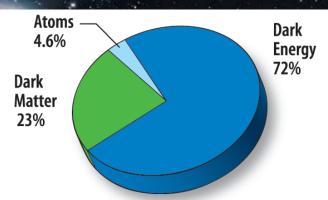
Dark Matter: The Next Challenge !?!

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



'Supersymmetric' particles ?



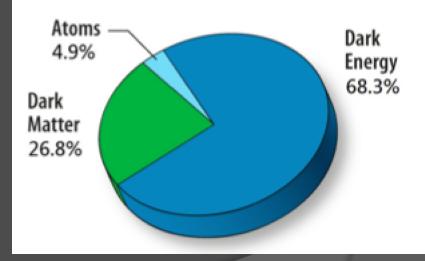


F. Zwicky 1898-1974

Particle Dark Matter?

The Dark Matter Candidate Zoo

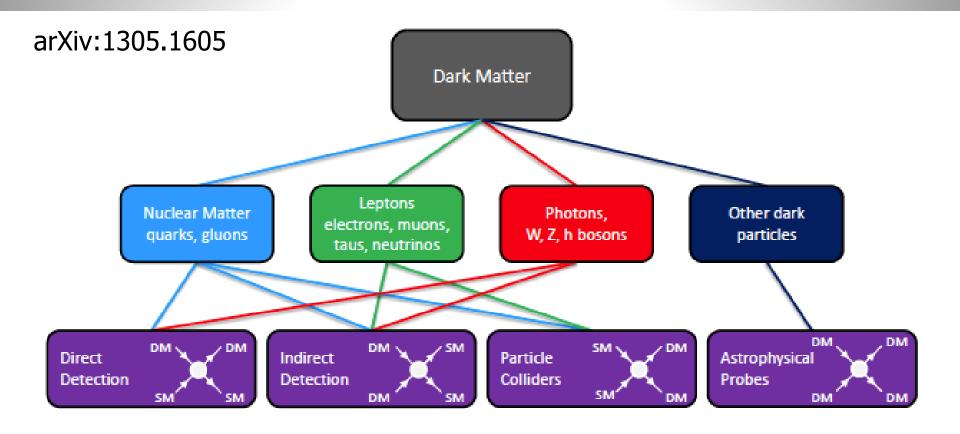
- Neutralinos (higgsino, bins, winos, singlinos)
- Axinos
- Gravitinos
- Sneutrinos
- Axions
- Sterile neutrinos
- 4th generation neutrinos
- Kaluza-Klein photons
- Kaluza-Klein gravitons
- Brane world dark matter/D-matter
- Little higgs dark matter
- Light scalars
- Superheavy states (*ie.* "WIMPzillas")
- 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...



From D. Hooper

Dark Matter @ LHC?

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



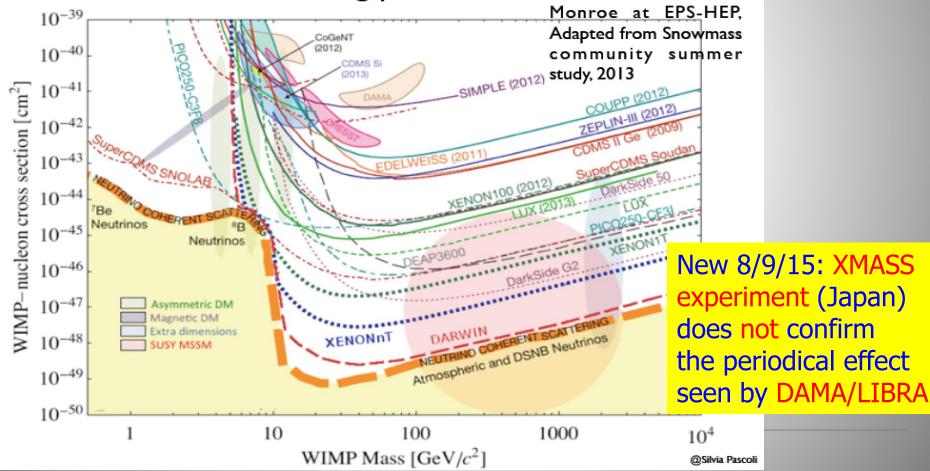
+ CAST experiment, searching for axion DM

Direct Searches for Dark Matter

Underground low noise experiments

No non-ambiguous signal yet!!

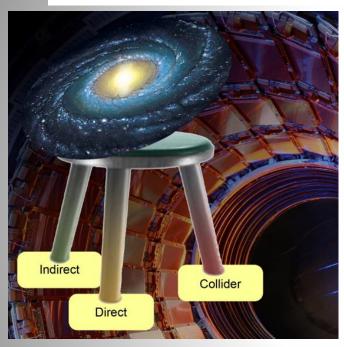
There is a very large number of projects which are under construction or being planned for the future.



The Generic Dark Matter Connection

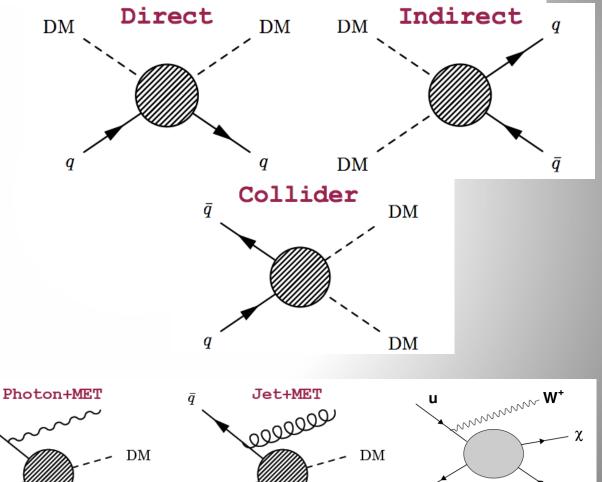
Searches for mono-jets and mono-photons can be used to search for Dark Matter (DM)

DM



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

 \bar{q}



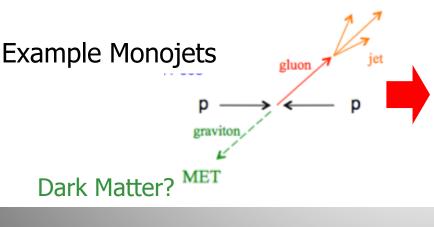
DM

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Mono-object Searches in CMS

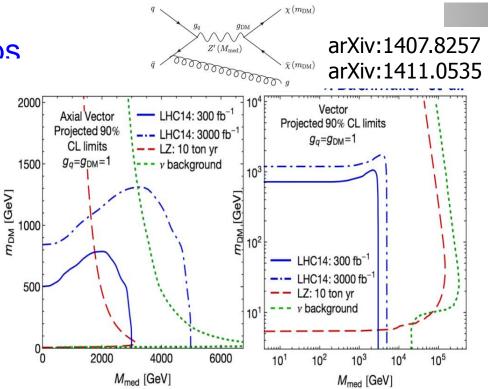


- Mono-photons: First used for dark matter Searches
- Mono-Ws: Distinguish dark matter couplings to u- and d-type of quarks
- Mono-Zs: Clean signature
- Mono-Tops: Couplings to tops
- Mono-Higgs: Higgs-portals
- Higgs Decays?

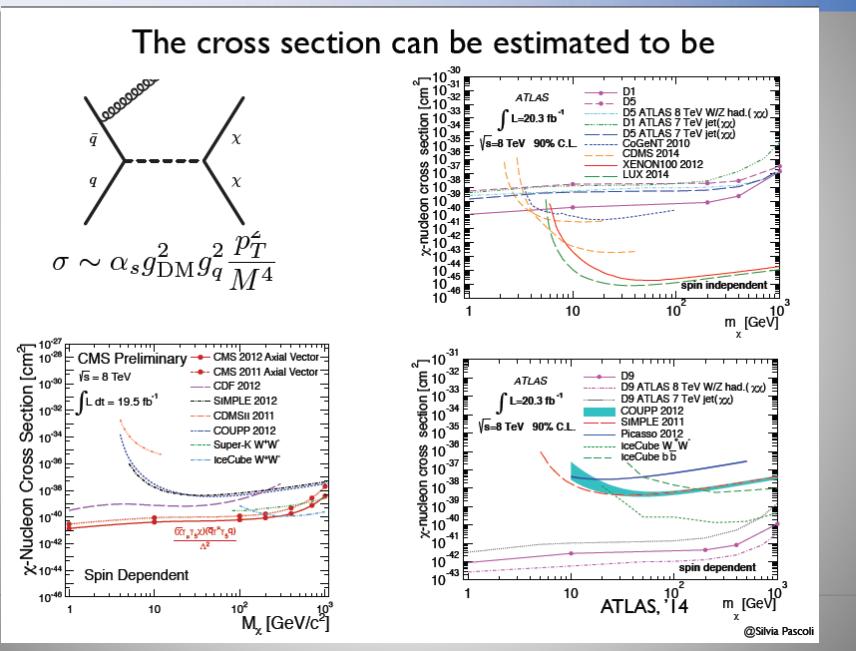


Effective Field Theories for DM interpretation are under scrutiny! Alternatives such as SMS proposed

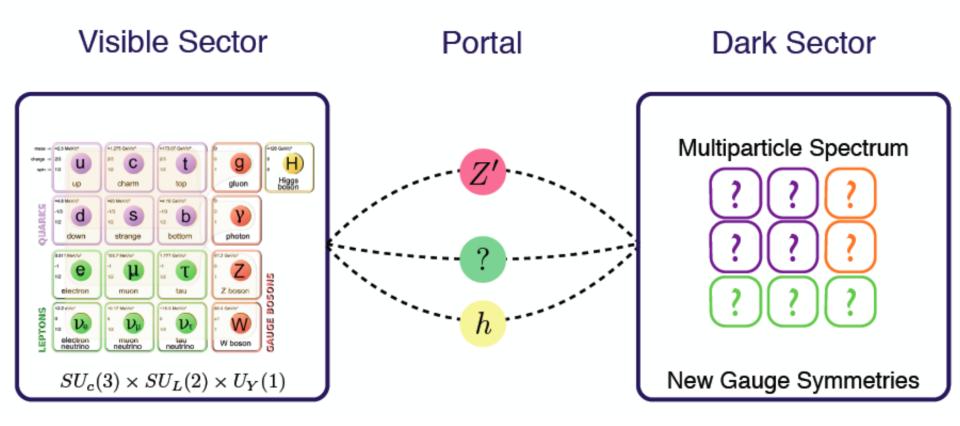
PhD: Elsayed Tayel (Alex)



Some Recent Results (EFTs)

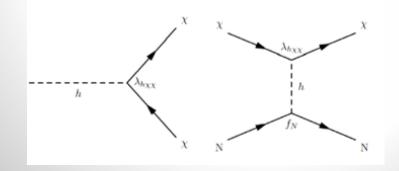


Cite: "Why should 5% of the mass density have all the fun?"



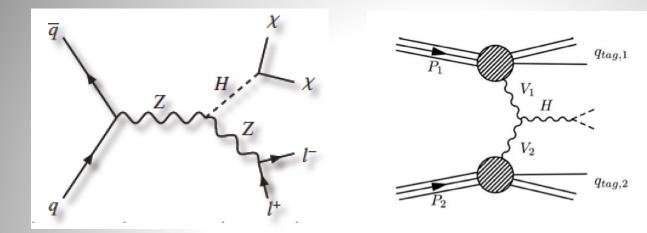
Can motivate alternative searches to MET + X from dark sector

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 coordinate

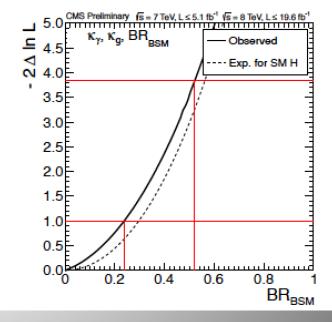
• Different searches:

-Direct search

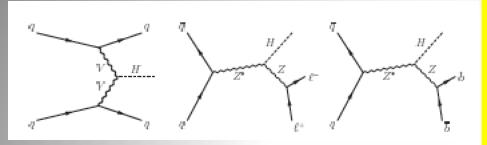
Look for the invisible decay channels

-Indirect search

Make a global fit of all production and decays (and some modest assumptions)

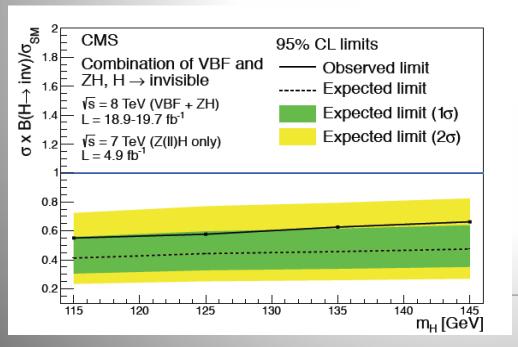


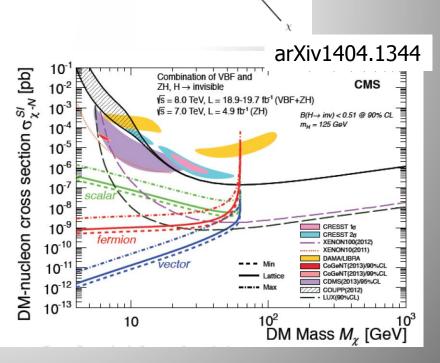
Invisible Higgs Decay Channel



Search for invisible Higgs decays using $Z+H \rightarrow 2$ leptons + missing E_T VBF H $\rightarrow 2$ jets + missing E_T Possible decay in Dark Matter particles (if M<M_H/2): Higgs Portal Models

Combined result from the three channels $BR(H \rightarrow invisible) < 58\%(44\% exp)$ at 95% CL. for a Higgs with a mass of 125 GeV





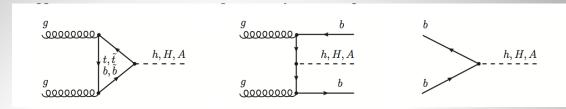
Searches for BSM Higgses

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

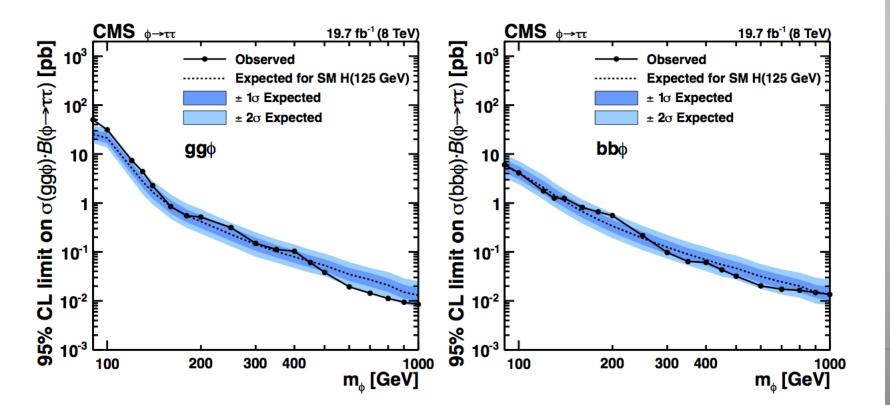
- No significant signal to report so far
- Exclusions of BSM space

MSSM Neutral Higgs Tau Tau

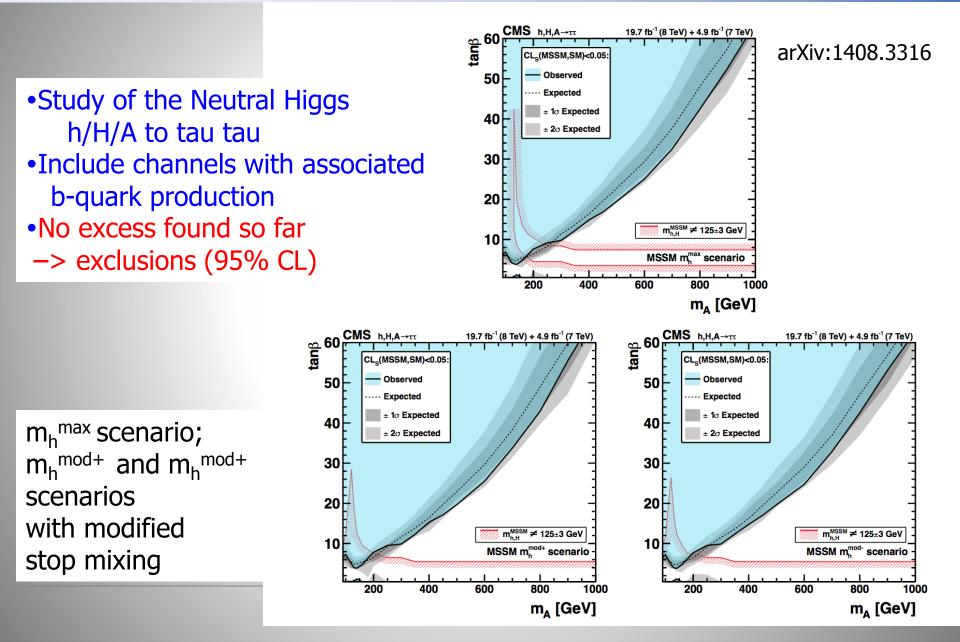
arXiv:1408.3316



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)



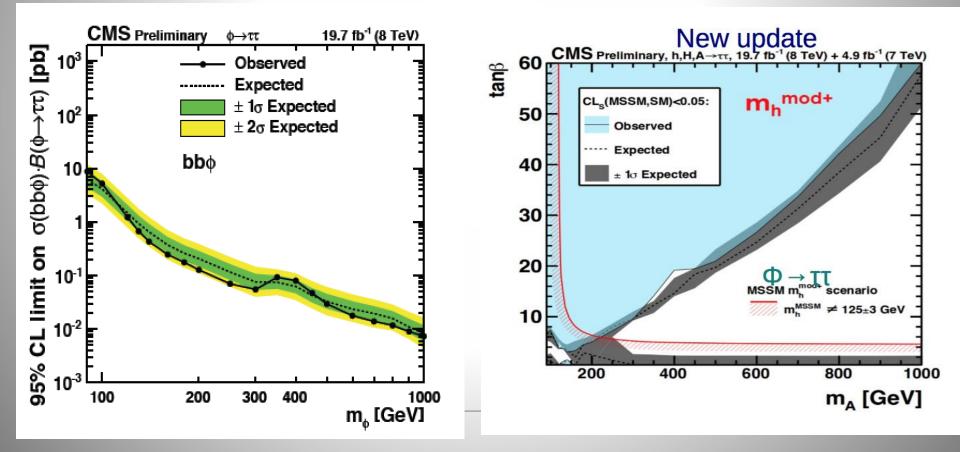
$MSSM Neutral Higgs \rightarrow Tau Tau$



$MSSM Neutral Higgs \rightarrow Tau Tau$

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

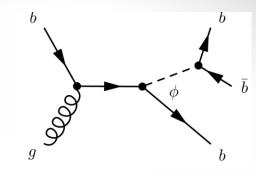
Huge gain ~70%! i.e. like 3x the lumi

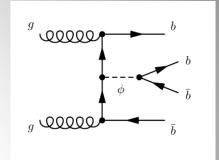


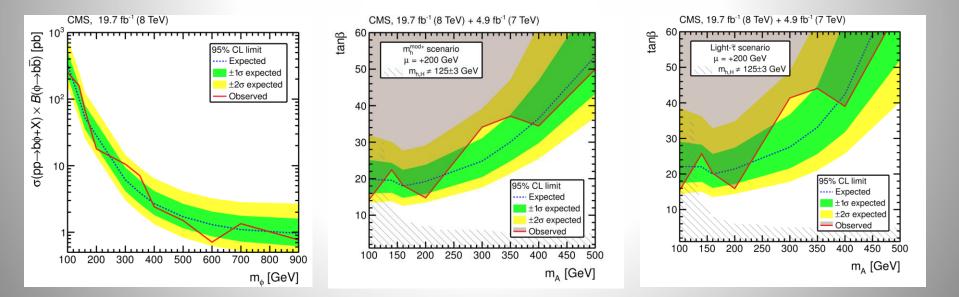
$NSSW Neutral Higgs \rightarrow DD$

arXiv:1506.08329

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







Exclusion limits for different MSSM scenarios

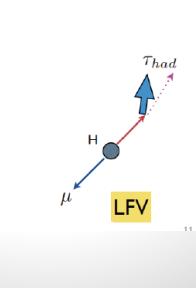
Search for LFV Decays: $H \rightarrow \mu \tau$

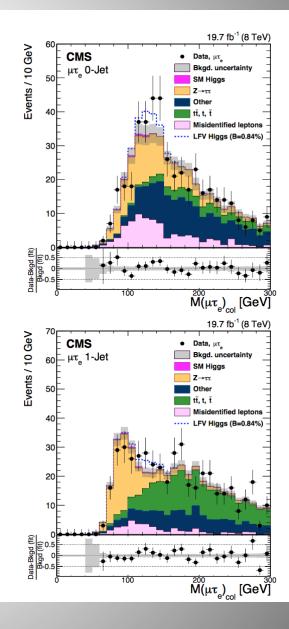
arXiv:1502.07400

- Previous best limits on $B(H \rightarrow \mu \tau) <~ 10\%$ from reinterpretation of LHC $H \rightarrow \tau \tau$ searches and from $\tau \rightarrow \mu \gamma$ 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 τ_{had}

 τ_{μ}

- $\Delta \phi$ between μ , τ_h / τ_e , missing energy vector

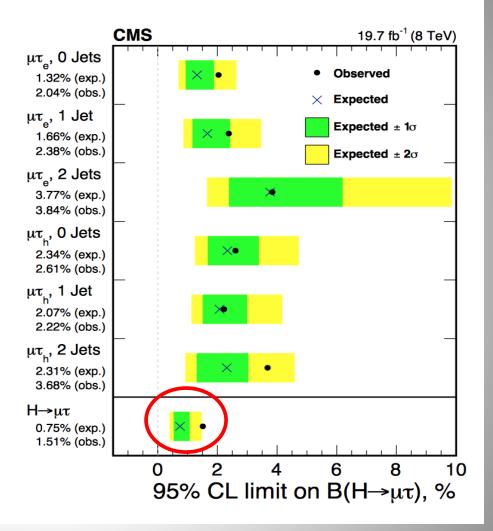




Search for LFV Decays: $H \rightarrow \mu \tau$

- Comparable sensitivity from all channels
- $\mathcal{B}(\mathrm{H}
 ightarrow \mu au) < 1.51\%$ at 95%

- Large improvement of previous limits
- Background-only
 p-value of 0.010 (2.4 σ)
 - Best fit $\mathcal{B}(H \to \mu \tau) = (0.84^{+0.39}_{-0.37})\%.$



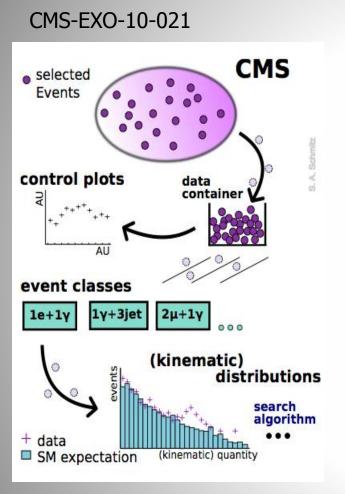
Mild excess giving a 2.4 σ effect... To be watched!!! Not contradicted by ATLAS at EPS... 3

What Deviations did we Observe?

March 2015		B. H	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	~3 0	PRD 90, 032006 (2014)
Higgs $\rightarrow \mu \tau$ (lepton flavor violation)	CMS 8 TeV	2.5σ	CMS-PAS-HIG-14-005
1 st 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
32+E _T ^{miss} electroweak SUSY	ATLAS 8 TeV	2.2σ	PRD 90, 052001 (2014)
Soft 22+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→h(bb)h(γγ)	ATLAS 8 TeV	2.4σ	arXiv:1406.5053 [hep-ex]

+ WH (2.8σ) +LHCb (3.7σ?)

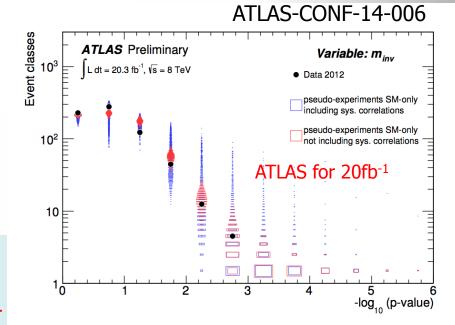
A Global View!



Model independent searchDivide events into exclusive classesStudy deviations from SM predictions in a statistical way

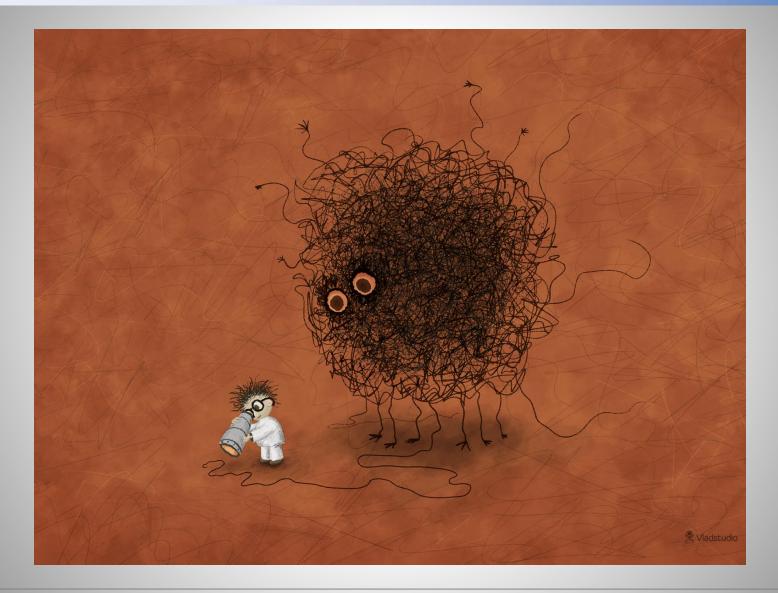
Distributions in each class

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



Probability distribution as expected for 35 pb⁻¹ for CMS \rightarrow muons, electrons, photons, (b)jets, MET

Are we looking at the right place??



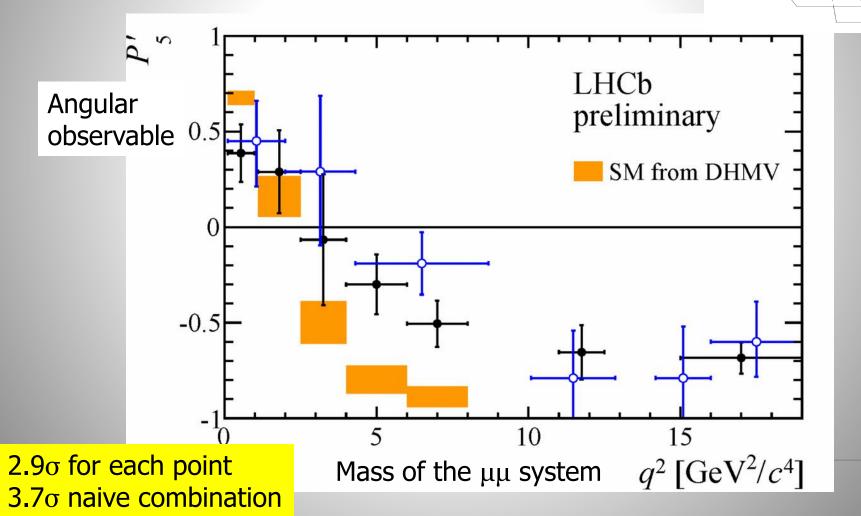
New Physics in Rare Decays?

z

B

Analysis of the B0 \rightarrow K^{*} μ + μ - decay (full run-I data-set)

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



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)

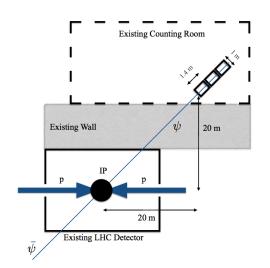
A "new" idea -> Hunting for particles with charges ~ 0.1-0.001e arXiv:1410.6816

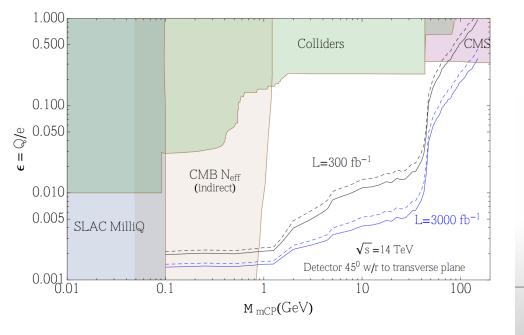
Looking for milli-charged particles with a new experiment at the LHC

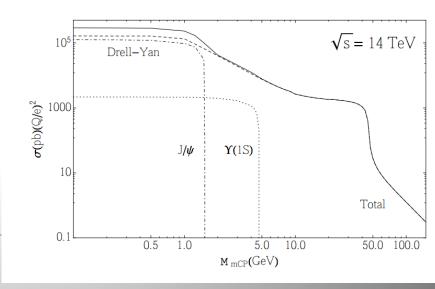
Andrew Haas, Christopher S. Hill, Eder Izaguirre, Itay Yavin

(Submitted on 24 Oct 2014)

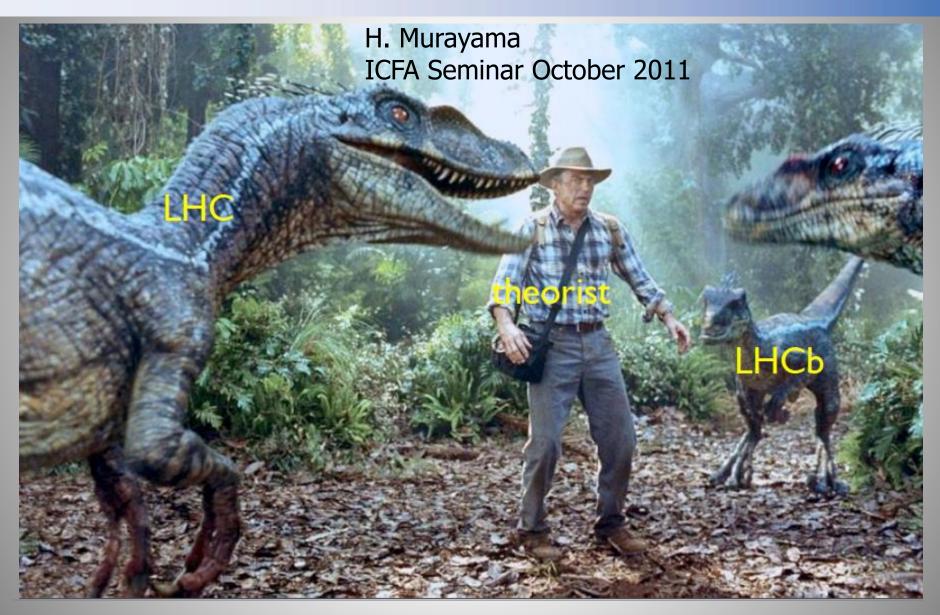
We propose a new experiment at the Large Hadron Collider (LHC) that offers a powerful and model-independent probe for milli-charged particles. This experiment could be sensitive to charges in the range $10^{-3}e - 10^{-1}e$ for masses in the range 0.1 - 100 GeV, which is the least constrained part of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







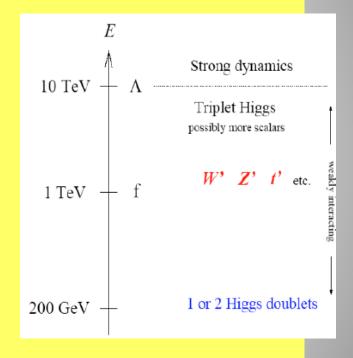
How does it feel to be a (BSM) Theorist?



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...

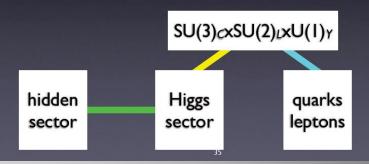
The Future: Studying the Higgs...



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

Higgs as a portal

- having discovered the Higgs?
- Higgs boson may connect the Standard Model to other "sectors"

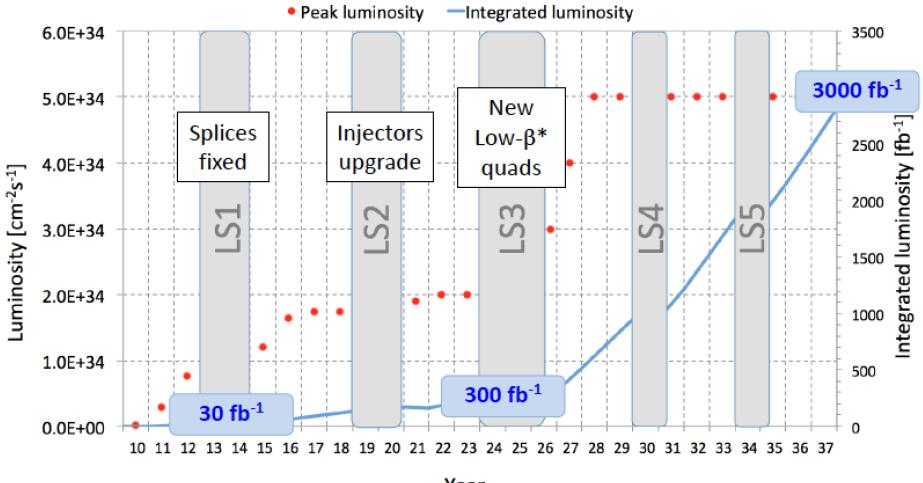


Many questions are still unanswered: •What explain a Higgs mass ~ 125 GeV? •What explains the particle mass pattern? •Connection with Dark Matter?

•Where is the antimatter in the Universe?

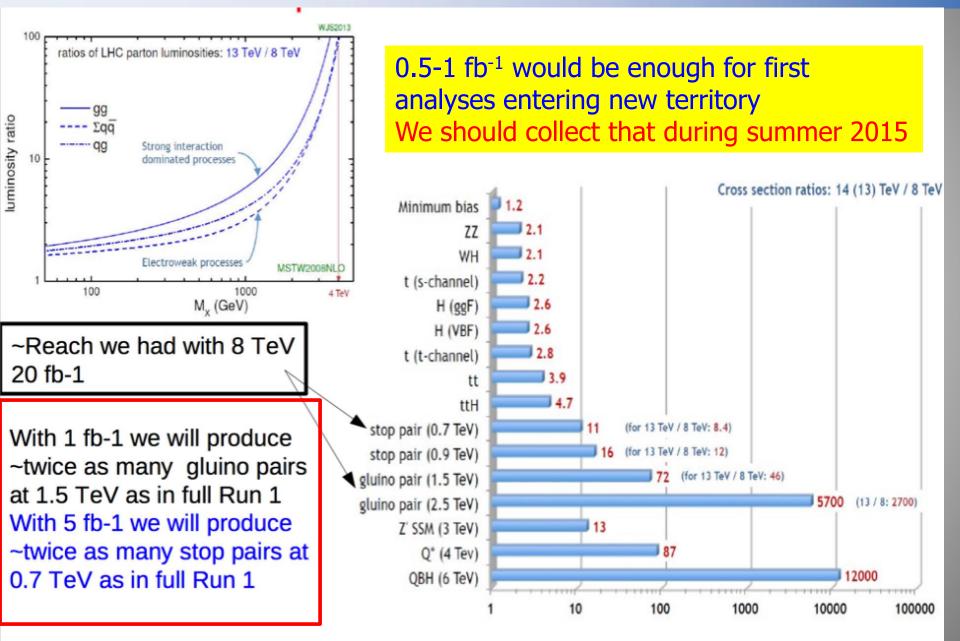
• (5)

The Future Program of the LHC



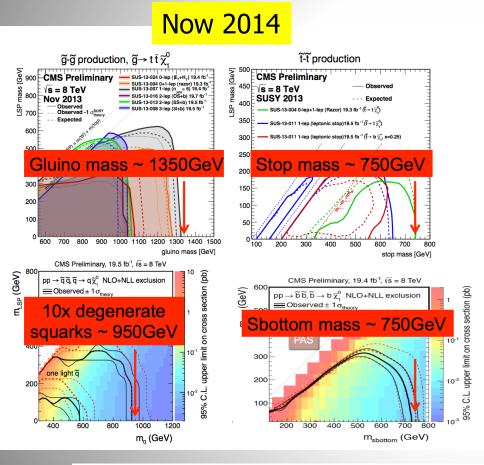
Year

Prospects for Searches at 14 TeV



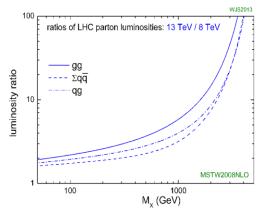
SUSY Prospects @ 2015/2016

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



2015-2016

Cross Section Scaling 8 -> 13 TeV



Xsection Ratios 13/8 TeV

1350GeV gluino: x30 950GeV squark: x20 750GeV squark: x9 350GeV X⁺⁻X⁰: 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)

Future Circular Collider Study Kick-off Meeting

EUCARD

12-15 February 2014, University of Geneva, Switzerland LOCAL ORGANIZING COMMITTEE University of Geneva C. Blanchard, A. Blondel, C. Doglioni, G. Iacobucci, M. Koratzinos CERN M. Benedikt, E. Delucinge,

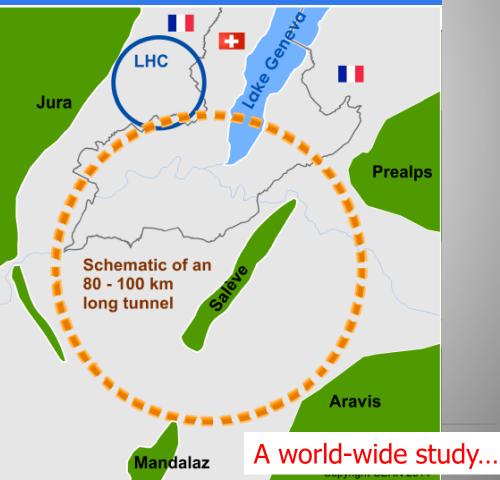
J. Gutleber, D. Hudson, C. Potter, F. Zimmermann

SCIENTIFIC ORGANIZING

FCC Coordination Group A. Ball, M. Benedikt, A. Blondel, F. Bordry, L. Bottura, O. Brüning, P. Collier, J. Ellis, F. Gianotti, B. Goddard, P. Janot, E. Jensen, J. M. Jimenez, M. Klein, P. Lebrun, M. Mangano, D. Schulte, F. Sonnemann, L. Tavian, J. Wenninger, F. Zimmermann

http://indico.cern.ch/

e/fcc-kickoff



A High Energy Proton-Proton Collider

"High Energy LHC"

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 Nb₃Sn dipoles

 100 TeV with 20 T based on HTS dipoles

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

"Machine Options" HE-LHC :33 TeV with 20T magnets Canton of Vaud **C** 3 LHC ette Genete Jura Prealps Canton of Geneva ute-Savoie Departmer

Aravis

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 \sqrt{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)*</l>	Rate (Hz) ee>hadrons	Years	Statistics
90	5.6	2 104	1	2 10 ¹¹ Z decays
160	1.6	25	1-2	2 107 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

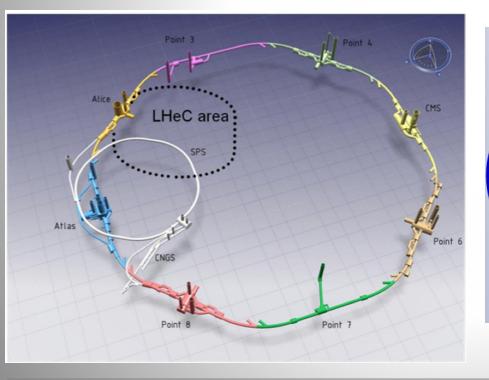
The Physics Case includes

- Precise measurement (0.1% to 1%) of the Higgs Couplings
- Improve precision (statistics x 10⁵) 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)

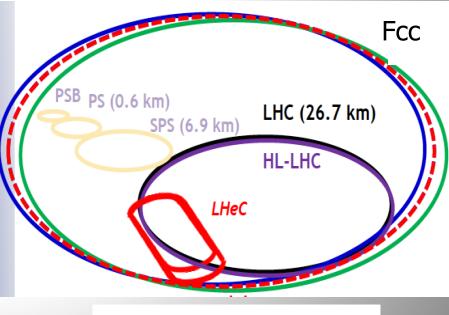
FCC-he: The Electron-Proton Option

Future possible hadron and lepton colliders will be excellent QCD explorers
 High luminosity (10³⁴-10³⁵) 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

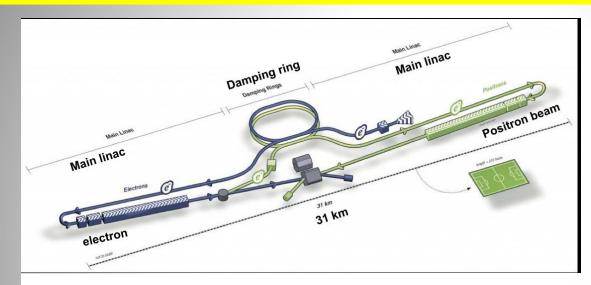
Linear e+e- Colliders

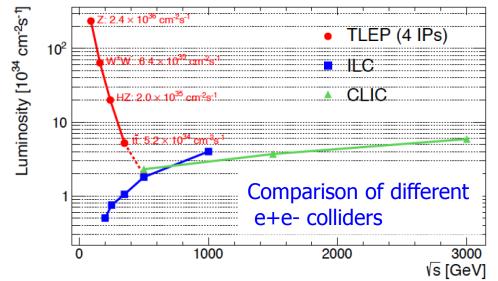
Electron-positron machines for high precision and possibly high energy (few TeV) ... Avoid Synchrotron radiation from a circular machine

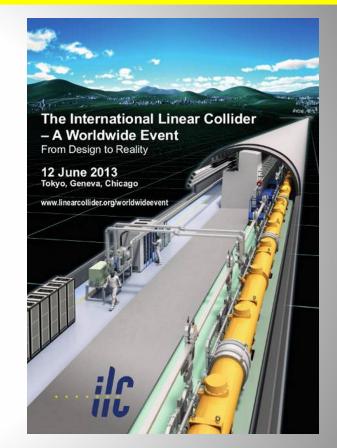
Studies and R&D work on linear colliders started in the '90's and they have achieved a very high level of maturity now...

ILC Layout

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

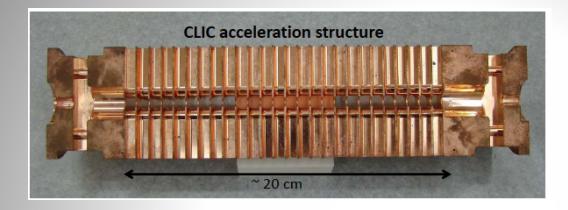


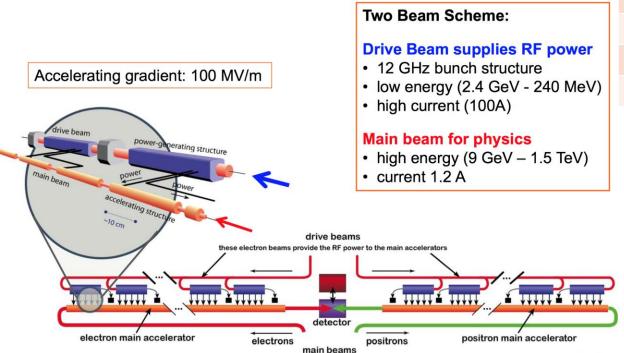




Note: in 2013 ILC produced a plan to double the luminosity (not included in the figure)

CLIC: Two Beam Acceleration





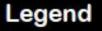
CLIC parameters

	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

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

~1 km

CLIC Layout @ CERN



Potential underground siting :

CLIC 500 Gev CLIC 1.5 TeV CLIC 3 TeV

Jura Mountains



Lake Geneva

Tunnel implementations (laser

straig

Geneva

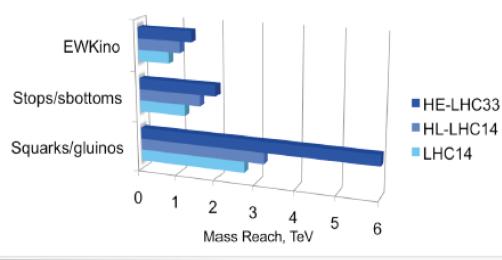
(P)



Central MDI & Interaction Region

FCC-hh: Searches for New Particles

Searches for pair produced SUSY particles



E.g. 2HDM in SUSY

 m_h, m_H, m_A, m_{H^\pm}

 $an eta \equiv \langle \Phi_2 \rangle / \langle \Phi_1 \rangle$

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

$$\Delta \approx \sin^2(2\beta) \frac{m_H^2}{m_h^2}$$

$$\Delta(\tan\beta=50)\leq 1-m_H\lesssim 3.1~{
m TeV}$$

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

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 4x10⁻²¹ m

-Discovery of resonances up to masses of 40-50 TeV

Upper limit for higher Higgs mass in 2HDM models?

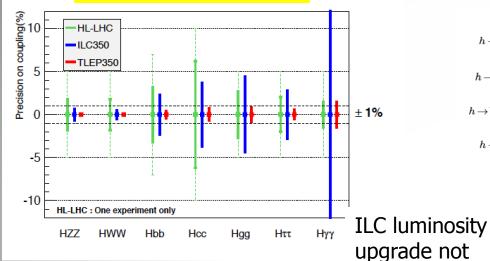
• Why 100 TeV ?

 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

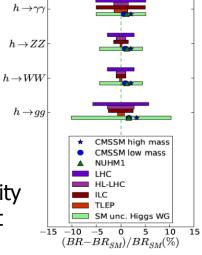
Physics at e+e- Colliders

included

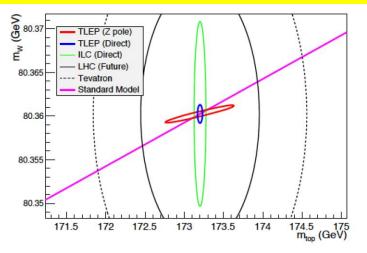
Higgs Boson Couplings



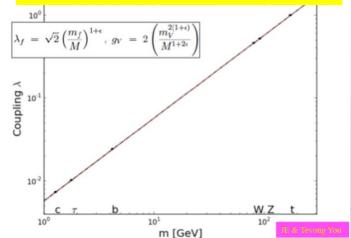
Higgs Boson decays

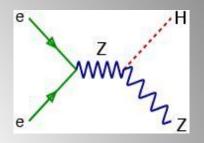


Fit to all EWK precision measurements



Higgs couplings vs particle mass





arXiv1308.6176

First look at the physics case of TLEP



The TLEP Design Study Working Group

M. Dicer,⁴ H. Duran Yildiz,⁴ I. Yildiz,⁴ G. Colgnet,⁴ M. Deimi C. Grejean, J S. Antusch, J T. Sen, h H.-J. He, K. Potamianos, J S. Haug A. Moreno,¹ A. Heister,⁴⁶ V. Sanz,⁴ G. Gomez-Ceballos,⁶ M. Klute,⁶ M. Zanetti, L.-T. Wang,^p M. Dam,⁴ C. Boehm,[†] N. Glover,[†] F. Krauss,[†] A. Lerz,[†] M. Syphers, Ropostos,¹ V. Chill,¹¹ P. Lenzi,¹¹ G. Sguarzoni,¹¹ M. Antonelli,¹ U. Dostell,¹ O. Frascielo,¹ C. Miardi,¹ G. Venanzoal,¹ M. Zaboz,¹ J. van der Bil.¹ M. de Gruttola,² D.,W. Kim,³ M. Bachtis,² A. Butterworth,² C. Bernet,² C. Botta Carminati,⁷ A. David,⁷ L. Denlau,⁷ D. d'Enterria,¹ G. Ganis,⁷ B. Goddard, G. Gludice,² P. Janot,² J. M. Jowett,² C. Lourenco,² L. Malgerl,² E. Meschi, F. Montrat.² P. Musela.² J. A. Osborne.² J. Perrozt.² M. Pierini.² J. Binnill. A. de Reeck,^c J. Rojo,^z G. Roy,^z A. Sclabà,^z A. Valassi,^c C.S. Waaijer, Weininger,² H. Woenri,² F. Zimmermann,² A. Phonel.²⁴ M. Kovatzinos¹ od,⁶⁶ Y. Onel,⁶⁰ R. Talman,⁶² E. Castanoda Miranda,⁶³ E. Bulyak,⁶ ak^{4/} D. KevaseyL^{4/} S. PadhL^{4/} P. FaccolL^{4/} J. R. Ells.^{4/} M. Cam Y. Bal,⁴⁸ M. Chamico,⁴⁶ R.B. Appleby,⁶⁰¹ H. Owen,⁶⁰¹ H. Maury Cuna,⁴⁰ C. Gractos, ^{do} G. A. Munoz, Hernandez,^{do} L. Trentadue,^{do} E. Torrente, Lujan, 5. Wang,⁴⁹ D. Bertsche,⁴⁴ A. Gramolin,⁴¹ V. Telnov,⁴¹ M. Kado,⁴⁴¹ P. Petroff,⁴ P. Azzl,^{av} O. Nicrosini,^{av} F. Picchini,^{av} G. Monta W. da Silva ^{ay} N. Gizard ^{at} N. Craiz ^{ba} T. Han ^{bb} C. Luci ^{be} B. Mein ^{be} L. Silvestrici M. Cluchini,⁶⁶ R. Cakir,⁶⁶ R. Aleksan,⁶⁷ F. Couderc,⁶⁷ S. Ganjour,⁶⁷ E. Lançon,⁶ E LOCA.^M P. SOWER ing.⁶ M. Spiro.⁴ C. Tanguy.⁶ J. Zinn-Justin.⁶ S. Moretti,⁶ M. Kikuchi,³⁶ H. Kolso,⁵⁶ K. Ohmi,⁴⁶ K. Olde,³⁵ G. Pauletta,⁸ R. Ruiz de Austri,⁵ M. Gouzevitch^{ik} and S. Chattonadhvay ⁴Faculty of Science, Ankara University, Ankar

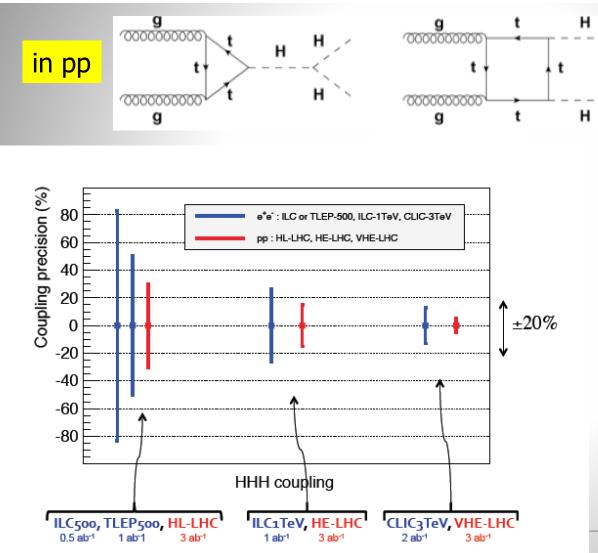
⁴Pacaky of Science, Ankara University, Ankara, Tarkey ⁵DAT, Ankara University, Ankara, Tarkey ⁶Meddle Bail Tochnical University, Inkore, Tarkey ⁶Laboratore at Ausory-Lo-View de Tayloue des Particulo INSP3/CNES, Antony-Lo-View, Pharee

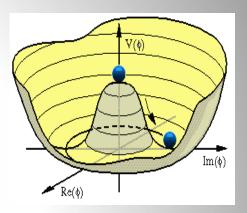
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FCC-ee delivers very precise measurements

The Higgs Self Coupling!

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





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