Particle Physics at the LHC Era

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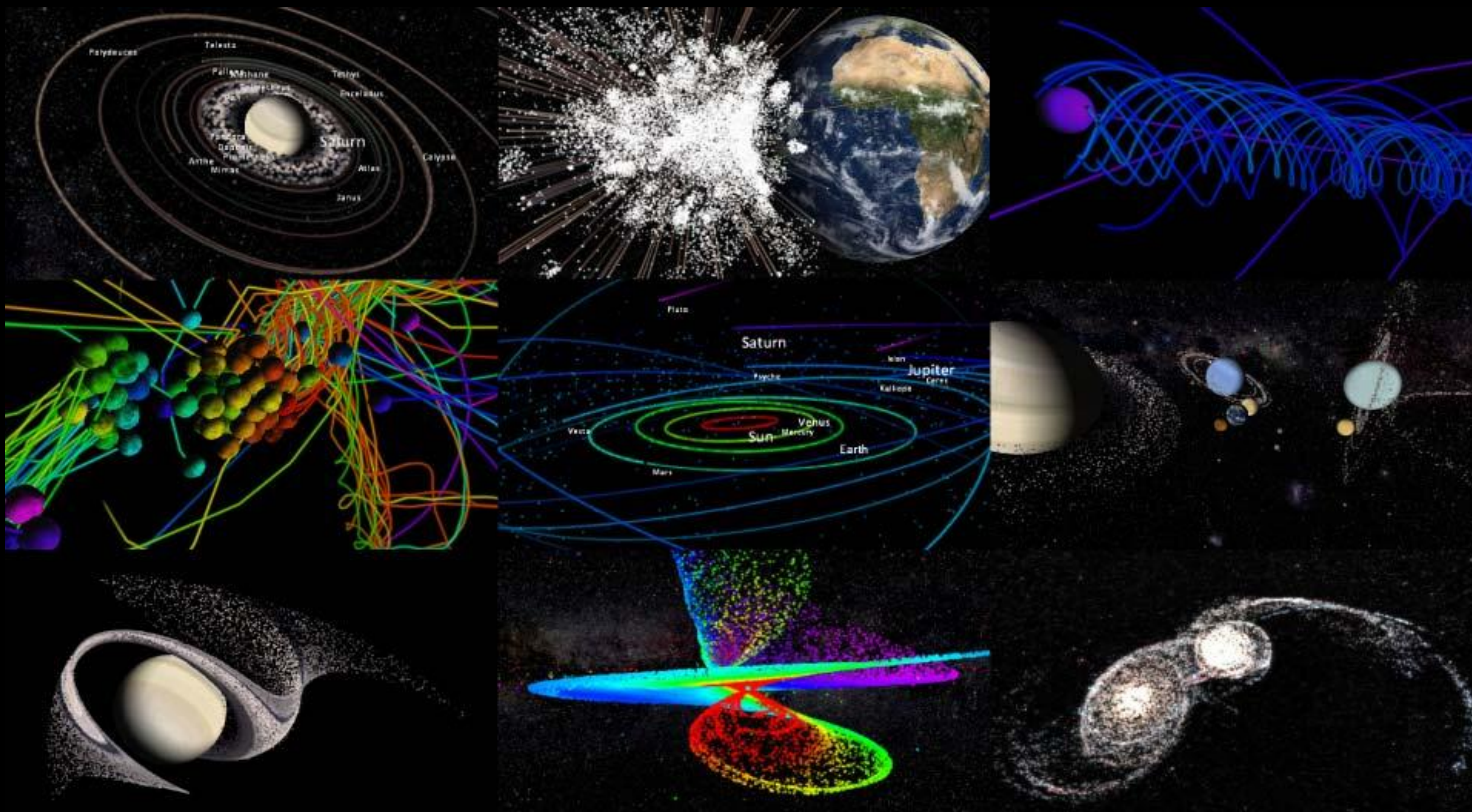
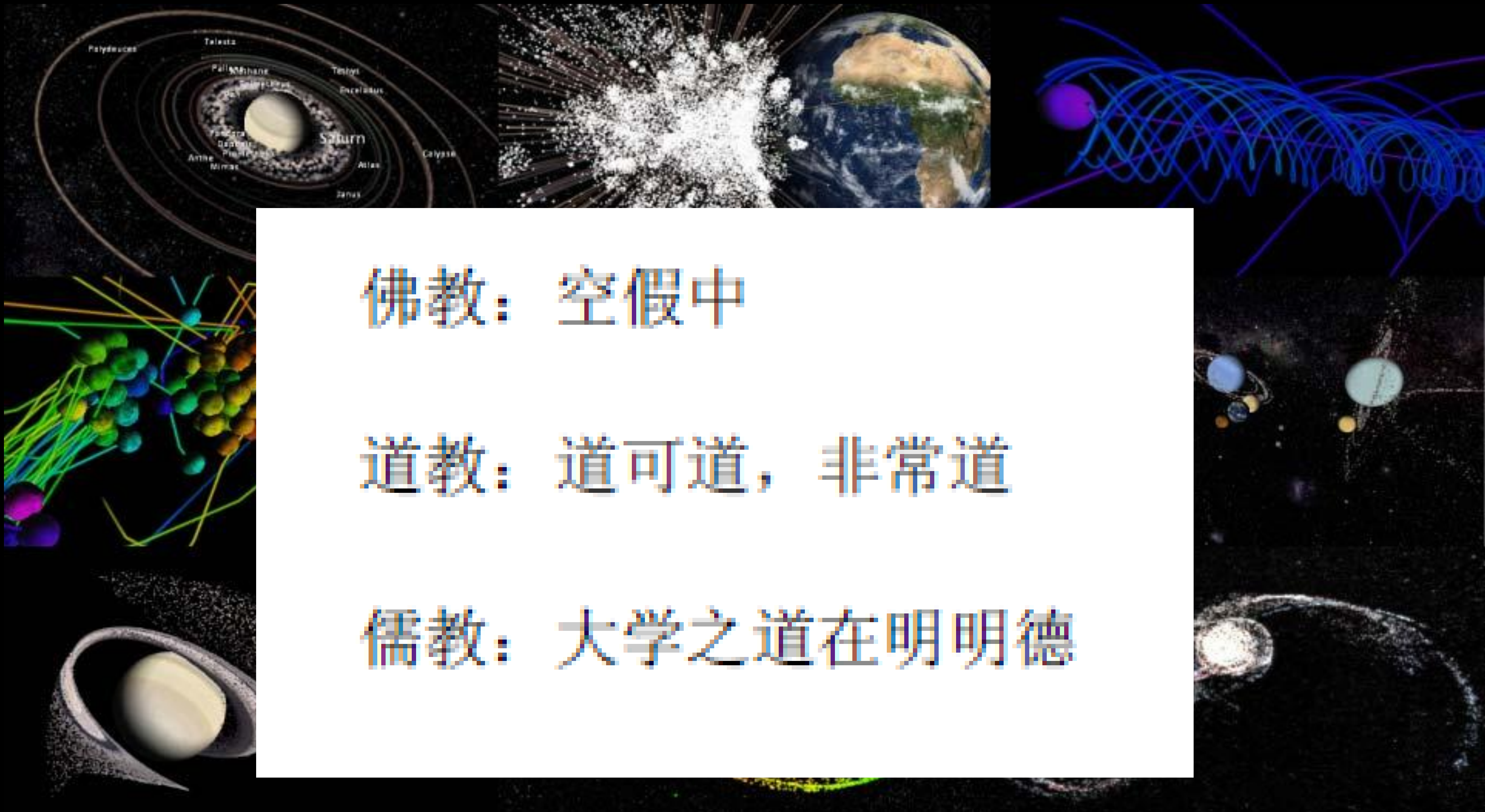
Outline

- Introduction to the Standard Model (SM)
- Theoretical Overiew for New Physics (NP)
- LHC Higgs Searches
- LHC Supersymmetry Searches
- Implications for Supersymmetric SMs
- Summary

I. Introduction to the SM





佛教：空假中

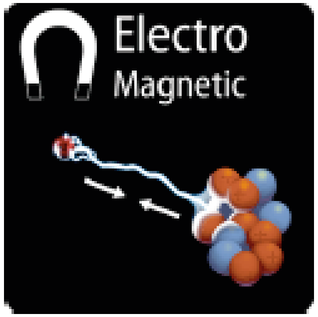
道教：道可道，非常道

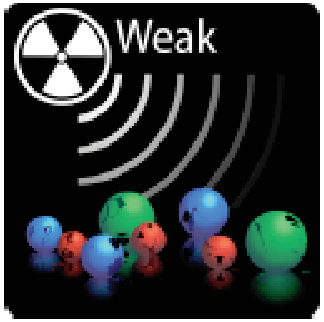
儒教：大学之道在明明德

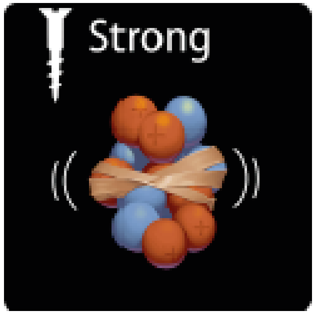
Physicists

Understanding Forces

- Electromagnetism explains electricity and magnetism
- Weak force explains radioactivity
- Strong force explains why quarks are bound in protons
- Gravity seems simple.....

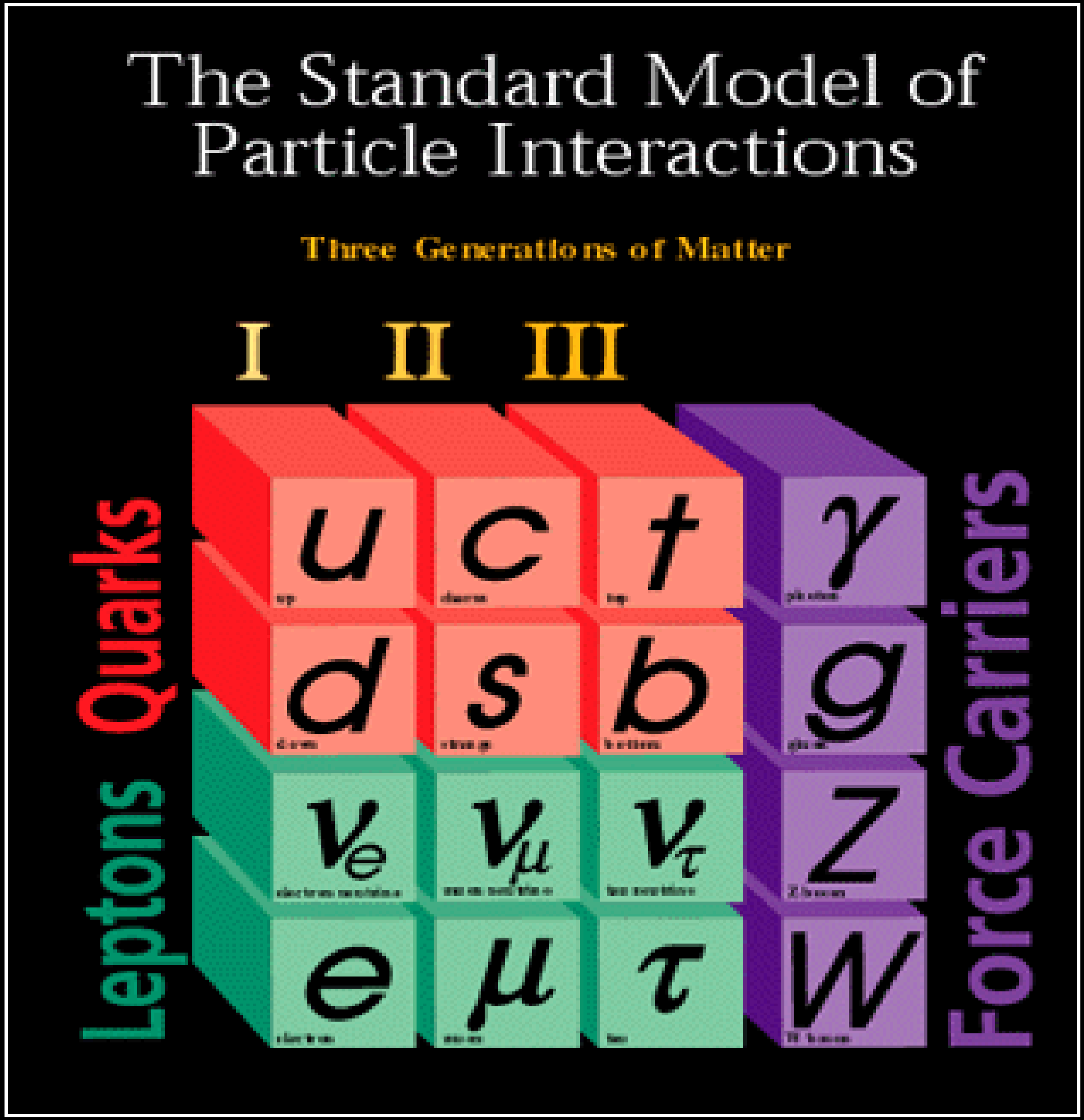






Fundamental Interactions

Interactions	Invariant	Symmetry	Fields	Spin
Gravity	Diffeomorphism		Graviton	2
Strong	Gauge	$SU(3)_C$	Gluon	1
Weak	Gauge	$SU(2)_L$	$W^{\pm}, W^0$	1
Hypercharge	Gauge	$U(1)_Y$	B^0	1


The Standard Model of Particle Interactions
Three Generations of Matter
I
II
III
Quarks
Leptons
Force Carriers
u
c
t
γ
d
s
b
g
νe
νμ
ντ
Z
e
μ
τ
W

Elementary Particles

- Three families of SM fermions:

$$\textbf{Quarks :} \quad Q_1 = \begin{pmatrix} U & U & U \\ D & D & D \end{pmatrix}_{\mathrm{L}} \, , \quad (U \;\; U \;\; U)_R \, , \quad (D \;\; D \;\; D)_R \, .$$

$$\textbf{Leptons :} \quad L_1 = \begin{pmatrix} \nu \\ E \end{pmatrix}_{\mathrm{L}} \, , \quad E_R \, .$$

- One Higgs doublet

$$H \;=\; \begin{pmatrix} H^0 \\ H^- \end{pmatrix} .$$

$$\mathcal{L}_{MSM} = -\frac{1}{2g_s^2}\mathrm{Tr}G_{\mu\nu}G^{\mu\nu} - \frac{1}{2g^2}\mathrm{Tr}W_{\mu\nu}W^{\mu\nu}$$
$$-\frac{1}{4g'^2}B_{\mu\nu}B^{\mu\nu} + i\frac{\theta}{16\pi^2}\mathrm{Tr}G_{\mu\nu}\tilde{G}^{\mu\nu} + M_{Pl}^2 R$$
$$+|D_\mu H|^2 + \bar{Q}_i i\not{D}Q_i + \bar{U}_i i\not{D}U_i + \bar{D}_i i\not{D}D_i$$
$$+\bar{L}_i i\not{D}L_i + \bar{E}_i i\not{D}E_i - \frac{\lambda}{2}\left(H^\dagger H - \frac{v^2}{2}\right)^2$$
$$-\left(h_u^{ij}Q_iU_j\tilde{H} + h_d^{ij}Q_iD_jH + h_l^{ij}L_iE_jH + c.c.\right) ,$$

where $\tilde{H} \equiv i\sigma_2 H^*$.

The SM has 20 parameters (19 without gravity): 3 gauge couplings, 1 Planck scale, 1 strong CP phase, 6 quark masses, 3 charged lepton mass, 3 CKM mixing angles, 1 CKM CP phase, 2 Higgs parameters.

The Higgs potential is

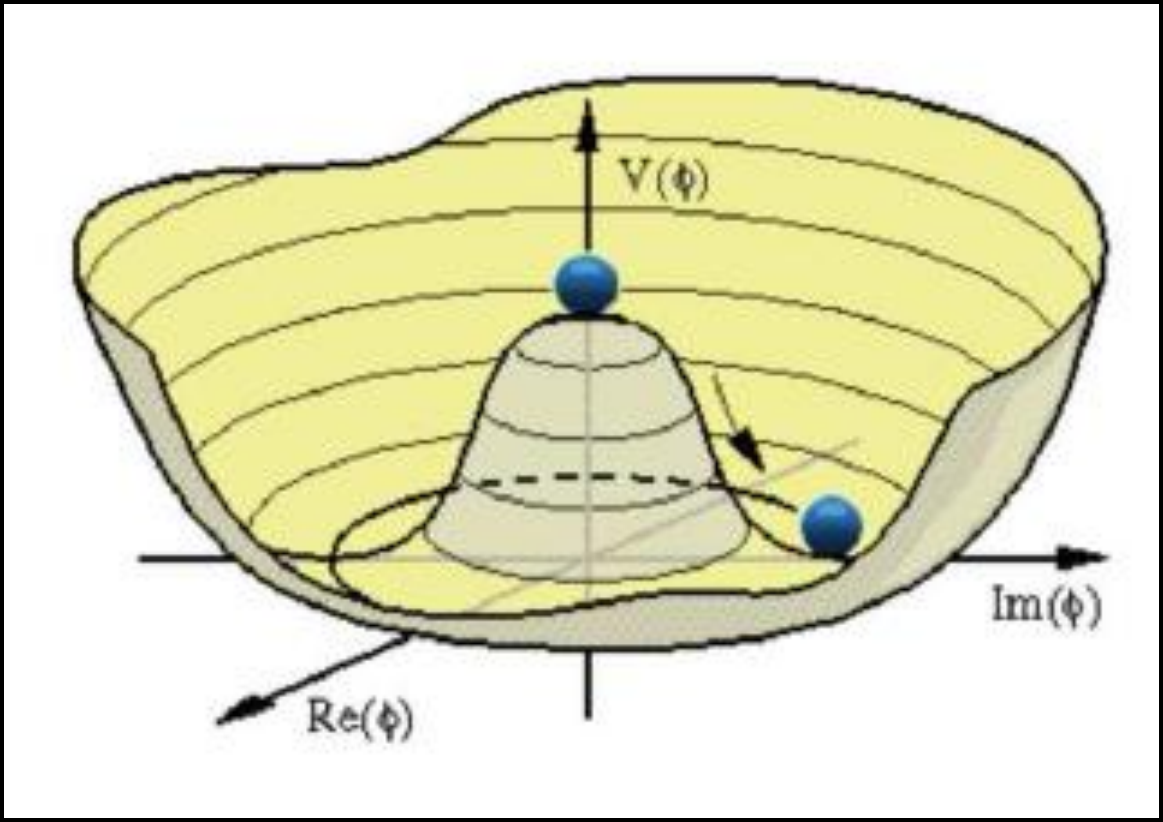
$$V_{\text{Higgs}} = \frac{\lambda}{2}\left(H^\dagger H - \frac{v^2}{2}\right)^2 ,$$

At minimum, Higgs field has a non-zero VEV

$$\langle H^0 \rangle = \frac{v}{\sqrt{2}} .$$

All the gauge symmetries, under which H^0 is charged, are broken after Higgs mechanism.

Higgs Mechanism



3 Goldstone bosons are eaten by gauge bosons

what left is a Higgs boson.

Symmetry Breaking

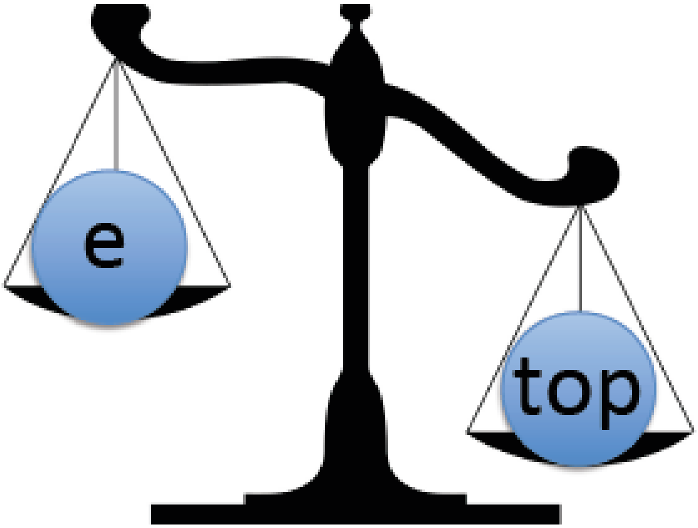
- $SU(2)_L \times U(1)_Y$ is broken down to the $U(1)_{\rm EM}$ symmetry.
- $W^{\pm}$ and Z^0 become massive, and γ is massless

$$Z^0 = \cos\theta_W W^0 - \sin\theta_W B^0\,, \quad \gamma = \sin\theta_W W^0 + \cos\theta_W B^0\,.$$

- The SM quarks and leptons obtain masses via Yukawa couplings, except the neutrinos.
- Higgs boson with mass around 125.5 GeV.

The SM explains existing experimental data very well, including electroweak precision tests.

Masses for particles



The more a particle interacts with the Higgs boson, the heavier it is

The global symmetries in the SM:

- $U(1)_B$ symmetry.
- $U(1)_L$ symmetry.
- Sphaleron process: conserve $B - L$ but violate $B + L$.

Why $U(1)_{B-L}$ is not a gauge symmetry?

The SM is an effective theory which is valid around 100 GeV:

- The high-dimensional operators can violate both baryon and lepton numbers.
- Dimension-5 operators for neutrino mass: $L_i L_j \widetilde{H}\widetilde{H}/M_*$, where $M_* \leq 10^{14}$ GeV.
- Dimension-6 opertors for proton decays: $QQQL/M_*$, $U^c D^c U^c E^c$, $QULD/M_*$, etc, where $M_* \geq 5 \times 10^{15}$ GeV

There may exist a high energy scale, but why the scale to suppress the proton decay is so high?

The convincing evidence for physics beyond the SM:

- Dark matter
- Dark energy
- Neutrino masses and mixings
- Baryon asymmetry
- Inflation

The SM is incomplete!

Major Problems in the SM

- Fine-Tuning Problems
- Aesthetic Problems

Fine-Tuning Problems:

- Cosmological constant problem

$$\Lambda_{\rm CC} \sim 10^{-122} M_{\rm Pl}^4 \, .$$

- Gauge hierarchy problem

$$M_{\rm EW} \sim 10^{-16} M_{\rm Pl} \, .$$

- Strong CP probelm

$$\theta < 10^{-9} \, .$$

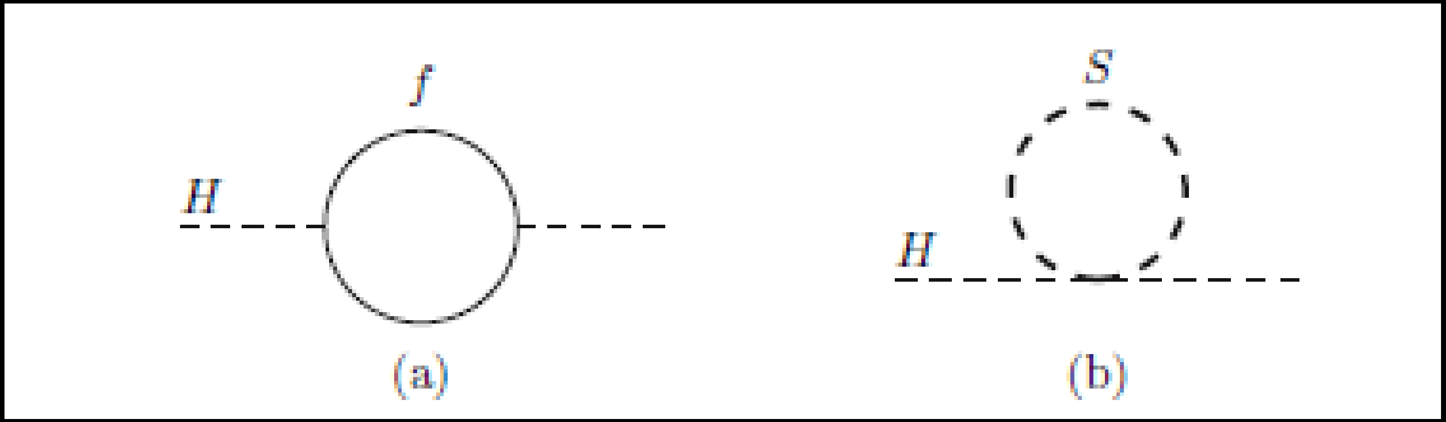
- The SM fermion masses and mixings

$$m_{\rm electron} \sim 10^{-5} m_{\rm top} \, .$$

Gauge Hierarchy Problem

$$-\mathcal{L} = \lambda_f H \bar{f} f + \lambda_S |H|^2 |S|^2 \,.$$

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\rm UV}^2 + \frac{\lambda_S}{16\pi^2}\Lambda_{\rm UV}^2 \,.$$



Aesthetic Problems:

- Interaction unification
- Fermion unification
- Gauge coupling unification
- Charge quantization

The first two prolems can be solved when we embed the SM into the Grand Unified Theories (GUTs) and string models.

II. Theoretical Overview for NP

- New Particles
- New Gauge Symmetries
- Global Symmetry Breaking
- Supersymmetry

New Particles

- Vector-Like Fermions

$$(XQ, \overline{XQ^c}) \text{ and } (XD, \overline{XD^c})$$

- Singlet Boson or Higgs Fields
- Doublet Boson or Higgs Fields
- Triplet Higgs Fields

New Gauge Symmetries

(1) U(1)' Models:

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'$$

$$SU(3)_C \times SU(2)_L \times U(1)_{B-L} \times U(1)_{I3R}$$

$$SU(3)_C \times SU(2)_L \times U(1)_1 \times U(1)_2$$

(2) SU(2)' Models:

$$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_Y$$

$$SU(3)_C \times SU(2)_1 \times SU(2)_2 \times U(1)_Y$$

(3) Top Color Models

$$SU(3)_1 \times SU(3)_2 \times SU(2)_L \times U(1)_Y$$

(4) Top SU(5) Models

$$SU(5) \times SU(3)_C \times SU(2)_L \times U(1)_Y$$

B or L Symmetry Breaking

$$SU(3)_C \times SU(2)_L \times U(1)_{B-L} \times U(1)_{I3R}$$

$$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_Y$$

$$SU(5) \times SU(3)_C \times SU(2)_L \times U(1)_Y$$

Supersymmetry

- A supersymmetry transformation turns a bosonic state into a fermionic state, and vice versa.

$$Q|\text{Boson}\rangle = |\text{Fermion}\rangle, \qquad Q|\text{Fermion}\rangle = |\text{Boson}\rangle.$$

- Algebra: supersymmetry generator Q is a fermionic operator with spin-1/2.

$$\{Q, Q^\dagger\} = P^\mu,$$
$$\{Q, Q\} = \{Q^\dagger, Q^\dagger\} = 0,$$
$$[P^\mu, Q] = [P^\mu, Q^\dagger] = 0.$$

- Each supermultiplet contains an equal number of fermion and boson degrees of freedom.

Supersymmetric Standard Model:

- Four-dimesional $N = 1$ supersymmetry: Kähle potential, superpotential, gauge kinetic function.
- A chiral SM fermion has a complex scalar partner.
- A gauge boson has a spin 1/2 partner.
- A graviton has a spin 3/2 partner.

Supersymmetric Standard Model:

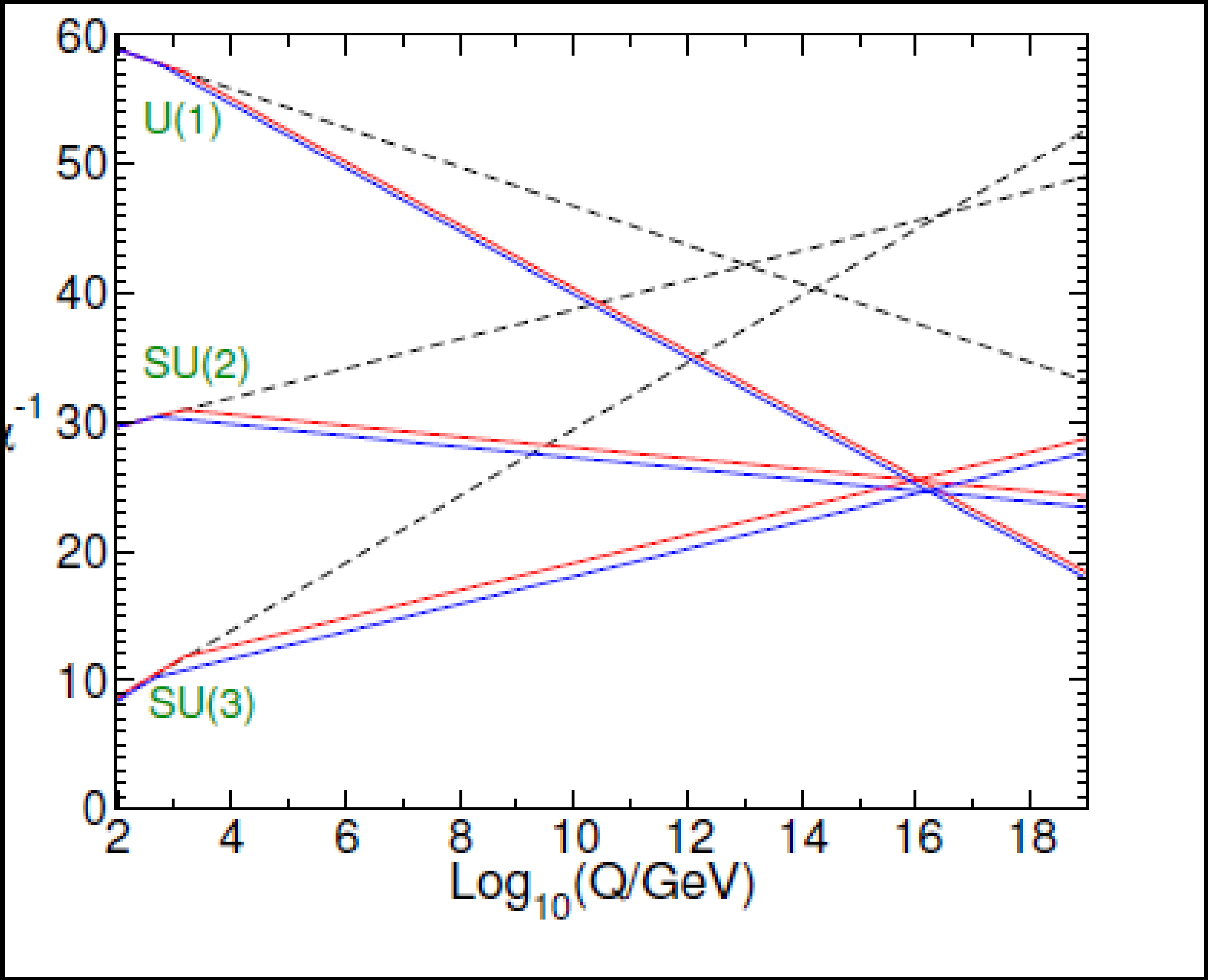
- Two Higgs doublet.
- R symmetry: $R = (-1)^{3B-L+2s}$.
- The SM particle are even while the supersymmetric particles are odd.
- Dark matter: neutralino, sneutrino, gravitino, etc.
- Solution to the proton decay problem.

Particle Spectrum

Names		spin 0	spin 1/2	$SU(3)_C, SU(2)_L, U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L \;\; \widetilde{d}_L)$	$(u_L \;\; d_L)$	$(\,\mathbf{3},\ \mathbf{2}\,,\ \frac{1}{6})$
(×3 families)	$\overline{u}$	$\widetilde{u}^*_R$	$u^\dagger_R$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}^*_R$	$d^\dagger_R$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu} \;\; \widetilde{e}_L)$	$(\nu \;\; e_L)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$
(×3 families)	$\overline{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$	$(\,\mathbf{1},\ \mathbf{1},\ 1)$
Higgs, higgsinos	H_u	$(H_u^+ \;\; H_u^0)$	$(\widetilde{H}_u^+ \;\; \widetilde{H}_u^0)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ +\frac{1}{2})$
	H_d	$(H_d^0 \;\; H_d^-)$	$(\widetilde{H}_d^0 \;\; \widetilde{H}_d^-)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$

Names	spin 1/2	spin 1	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\,\mathbf{8},\ \mathbf{1}\,,\ 0)$
winos, W bosons	$\widetilde{W}^{\pm}\quad \widetilde{W}^0$	$W^{\pm}\quad W^0$	$(\,\mathbf{1},\ \mathbf{3}\,,\ 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\,\mathbf{1},\ \mathbf{1}\,,\ 0)$

Gauge Coupling Unification



Supersymmetric Standard Model:

- Solving the gauge hierarchy problem
- Gauge coupling unification
- Radiatively electroweak symmetry breaking

  Large top quark mass
- Natural dark matter candidates

  Neutralino, sneutrino, gravitino, ...
- Electroweak baryogenesis
- Electroweak precision: R parity

Problems in the MSSM:

- μ problem

  $\mu H_u H_d$

- Little hierarchy problem:

  Fine-tuning for the lightest CP even Higgs mass

- CP violation and EDMs
- FCNC
- Dimension-5 proton decays

The Grand Unified Theories: $SU(5)$, and $SO(10)$, etc.

- Unification of the gauge interactions, and unifications of the SM fermions
- Charge quantization
- Gauge coupling unification in the MSSM, and Yukawa unification $y_t = y_b = y_\tau$
- Radiative electroweak symmetry breaking due to the large top quark Yukawa coupling
- Weak mixing angle at weak scale M_Z
- Neutrino masses and mixings by seesaw mechanism

Problems:

- Gauge symmetry breaking
- Doublet-triplet splitting problem

  Higgs particles do not form complete GUT multiplet at low energy
- Proton decay problem
- Fermion mass problem

  GUT relation $m_e/m_\mu = m_d/m_s$

String Models:

- Calabi-Yau compactification of heterotic string theory
- Orbifold compactification of heterotic string theory

  Grand Unified Theory (GUT) can be realized naturally through the elegant E_8 breaking chain: $E_8 \supset E_6 \supset SO(10) \supset SU(5)$
- D-brane models on Type II orientifolds

  N stacks of D-branes gives us $U(N)$ gauge symmetry: Pati-Salam Models
- Free fermionic string model building

  Realistic models with clean particle spectra can only be constructed at the Kac-Moody level one: the Standard-like models, Pati-Salam models, and flipped $SU(5)$ models.

$\mathcal{F}$-Theory Model Building

- The models are constructed locally, and then the gravity should decoupled, *i.e.*, $M_{\rm GUT}/M_{\rm Pl}$ is a small number.
- The $SU(5)$ and $SO(10)$ gauge symmetries can be broken by the $U(1)_Y$ and $U(1)_X$/$U(1)_{B-L}$ fluxes.
- Gauge mediated supersymmetry breaking can be realized via instanton effects. Gravity mediated supersymmetry breaking predicts the gaugino mass relation.
- All the SM fermion Yuakwa couplings can be generated in the $SU(5)$ and $SO(10)$ models.
- The doublet-triplet splitting problem, proton decay problem, μ problem as well as the SM fermion masses and mixing problem can be solved.

III. LHC Higgs Searches

Compact Muon Solenoid (CMS)

A Toroidal LHC ApparatuS (ATLAS)

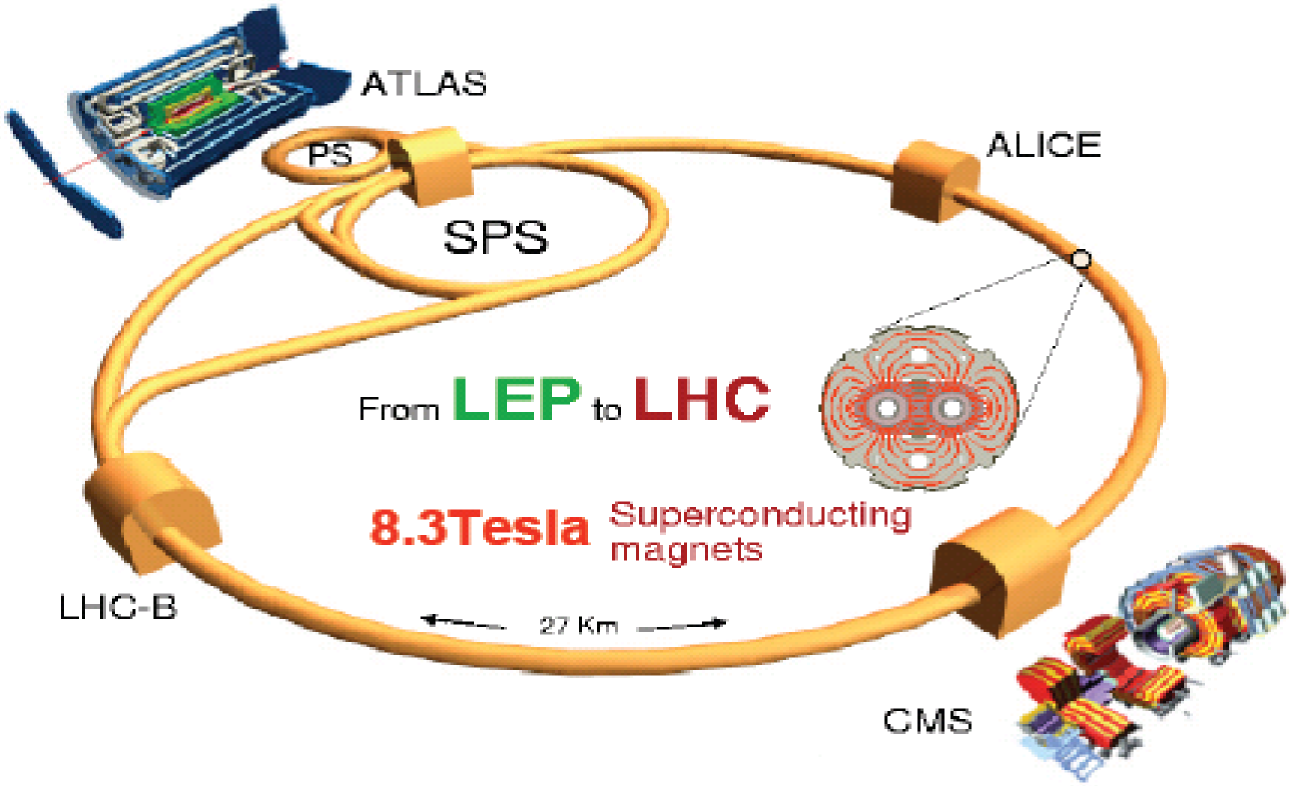
LHC-Beauty (LHCb)

A Large Ion Collider Experiment (ALICE)

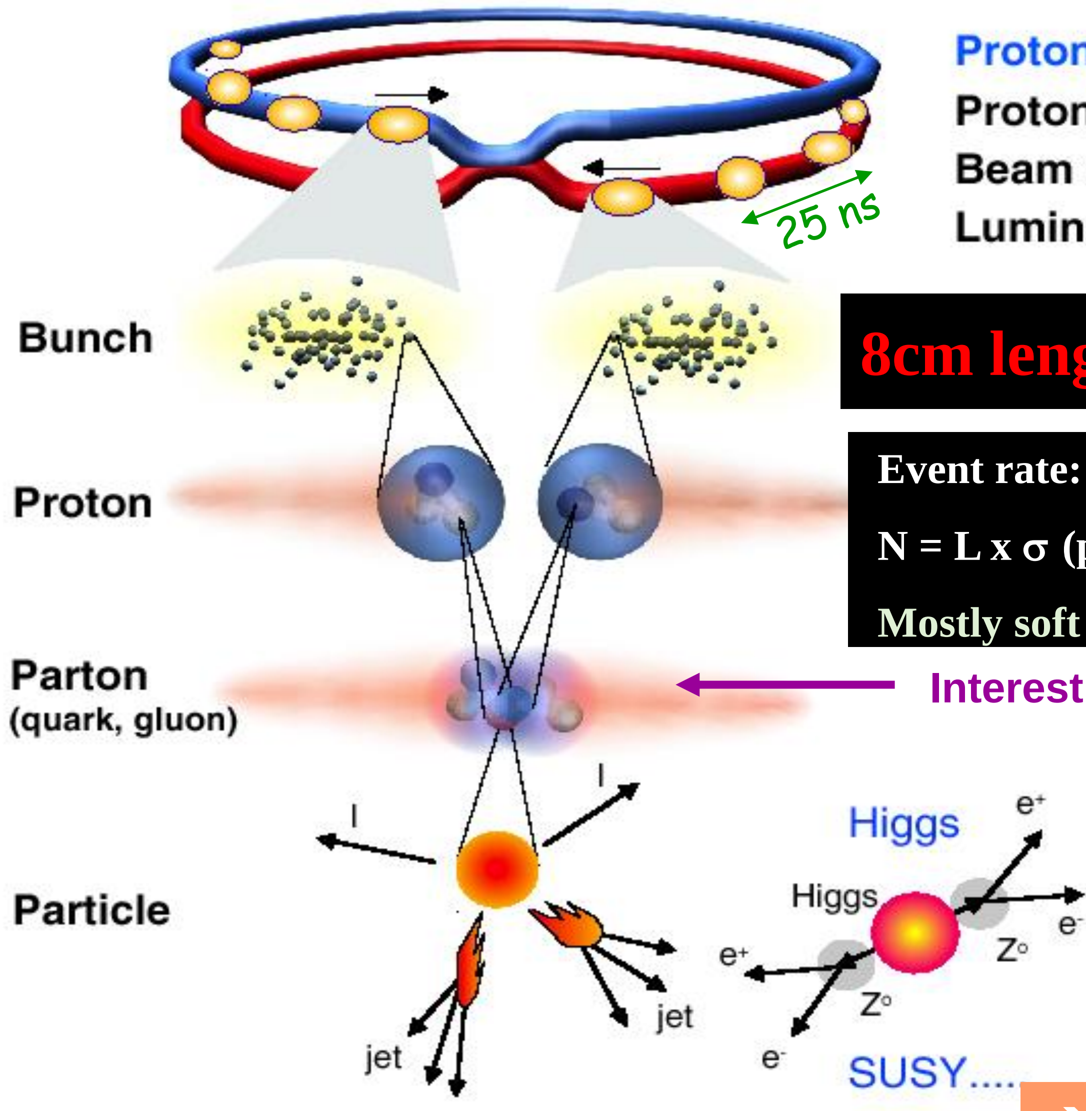
Proton Synchrotron (PS)

Super Proton Synchrotron (PS)

The Large Hadron Collider (LHC)



Collisions at LHC



Proton-Proton	[redacted]
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}

8cm length & 16×10^{-4} cm radius

Event rate:

$N = L \times \sigma$ (pp) ≈ 10^9 interactions/s

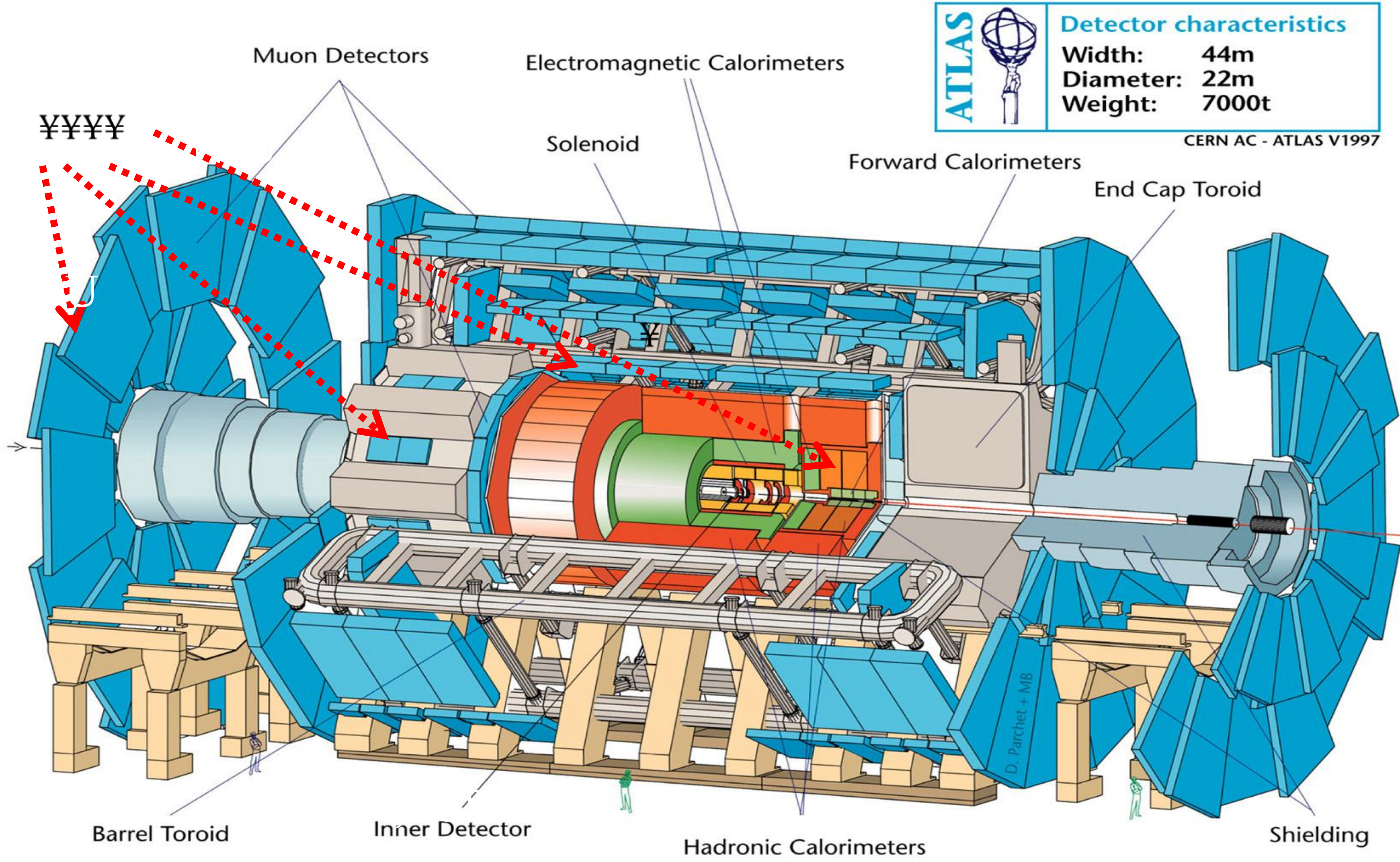
Mostly soft (low p_T) events

Interesting hard (high-p_T) events are rare

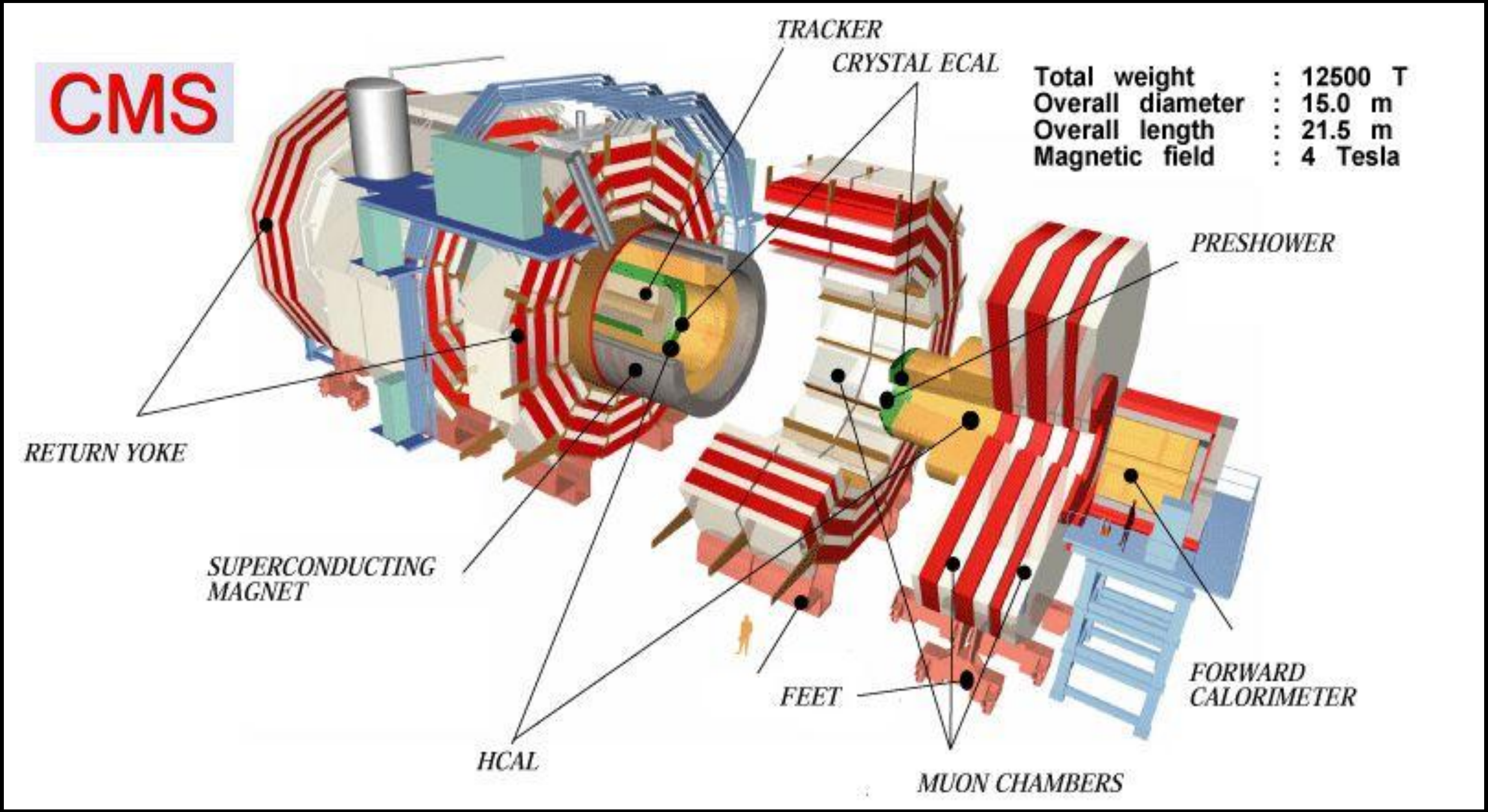
Selection of 1 in
10,000,000,000,000

→ very powerful detectors needed

ATLAS in Brief

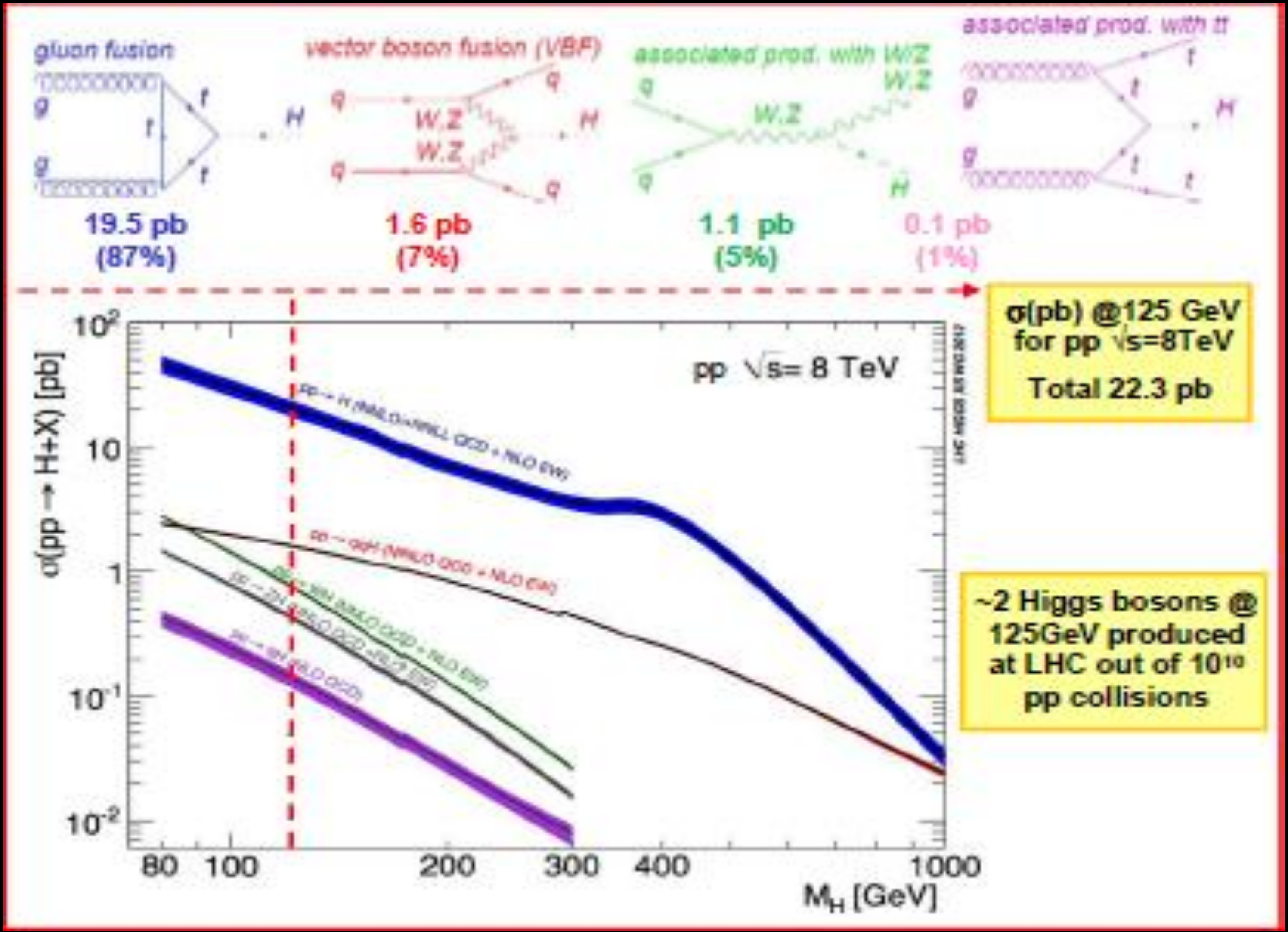


CMS similarities



General purpose CMS designed with equivalent performance as ATLAS while independent cross check is essential

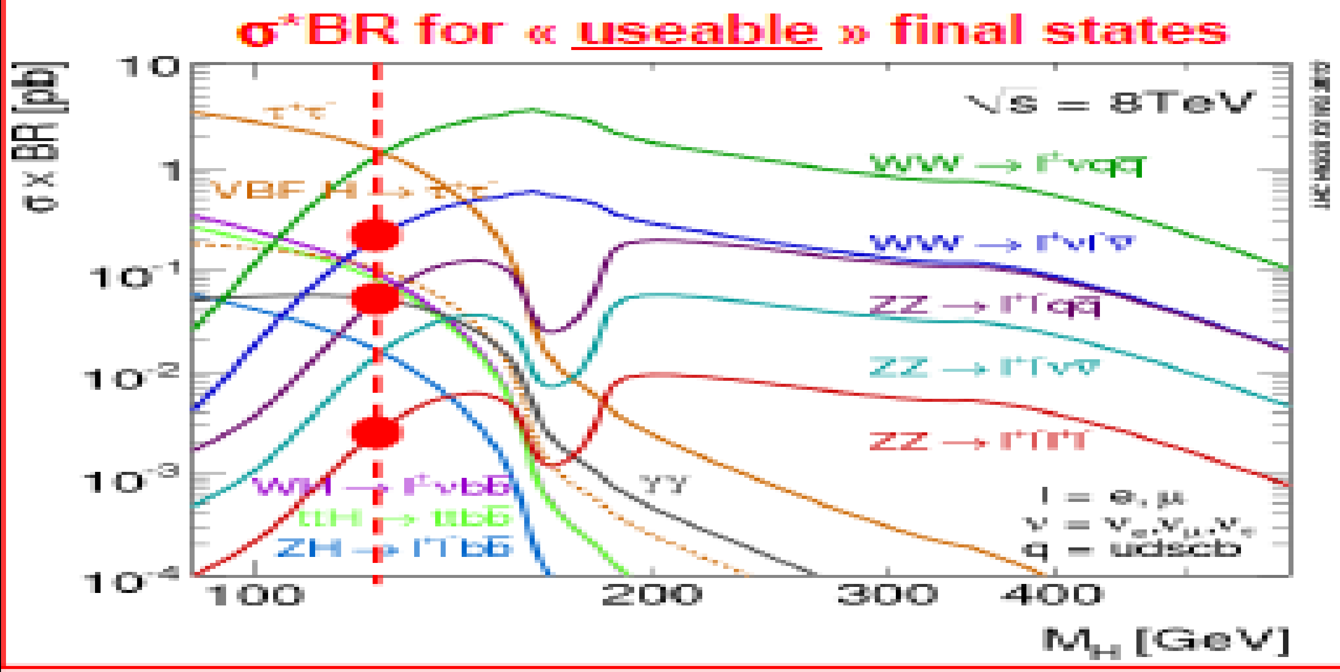
Higgs Production



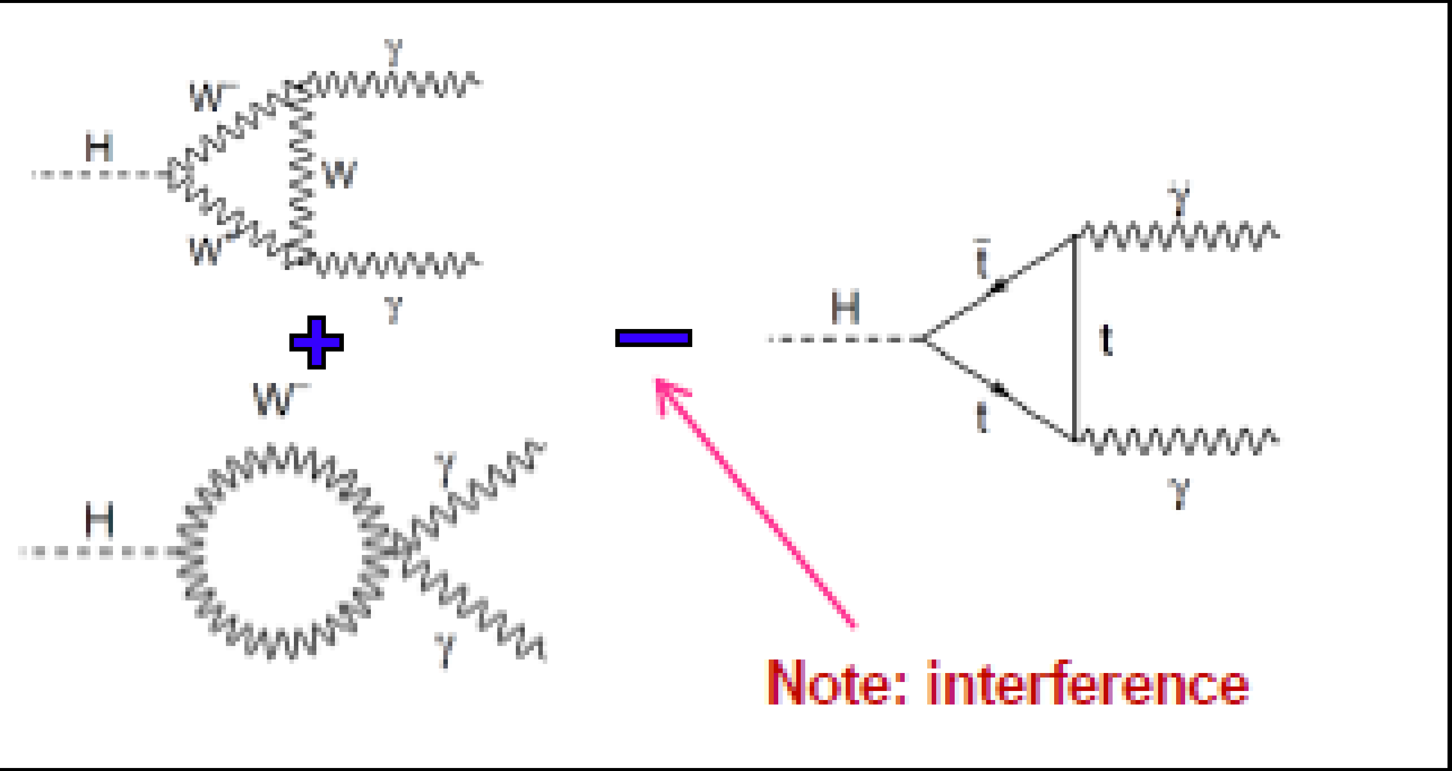
Higgs Decays

Branching ratios at 125 GeV:

bb:	57.7%	ZZ:	2.6%
WW:	21.5%	γγ:	0.23%
ττ:	6.3%		

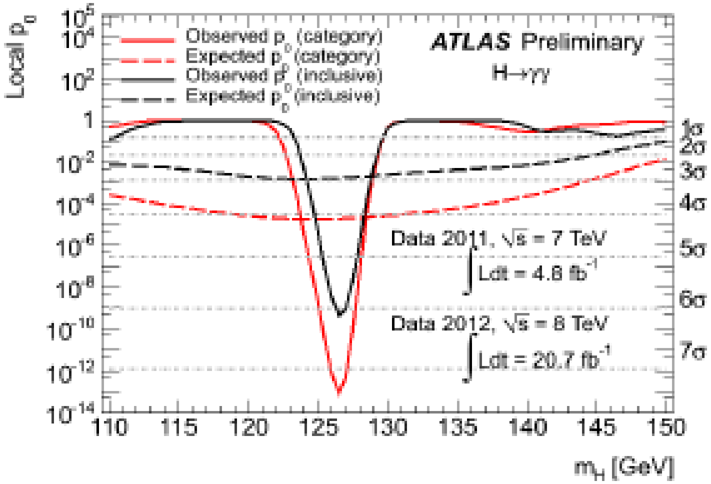


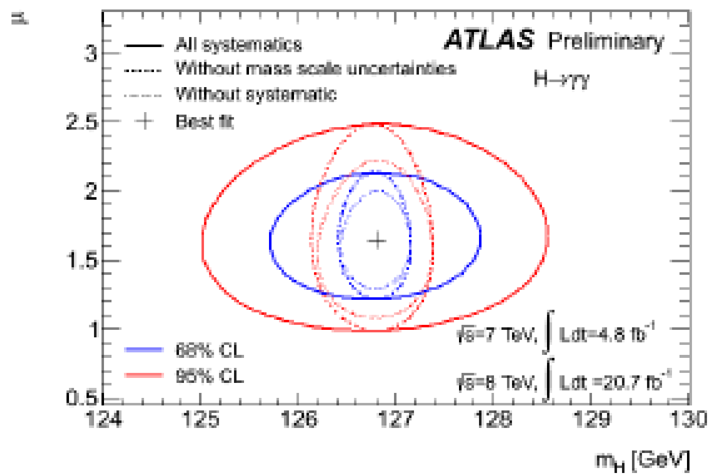
Higgs Decays to Diphoton



H→γγ : mass and signal strength

ATLAS-CONF-2013-012





- Observed local significance of the excess: **7.4σ** (4.1σ expected for SM Higgs)
- Best mass fit: **126.8 ± 0.2 (stat) ± 0.7 (syst) GeV** → Systematics fully dominated by γ-energy scale
- Best fit of signal strength @ this mass **$\mu = 1.65^{+0.34}_{-0.30} = 1.65 \pm 0.24\,(\text{stat})\,^{+0.25}_{-0.18}\,(\text{syst})$**
  [consistent across various categories]

→ 2.3σ from SM Higgs + background hypothesis

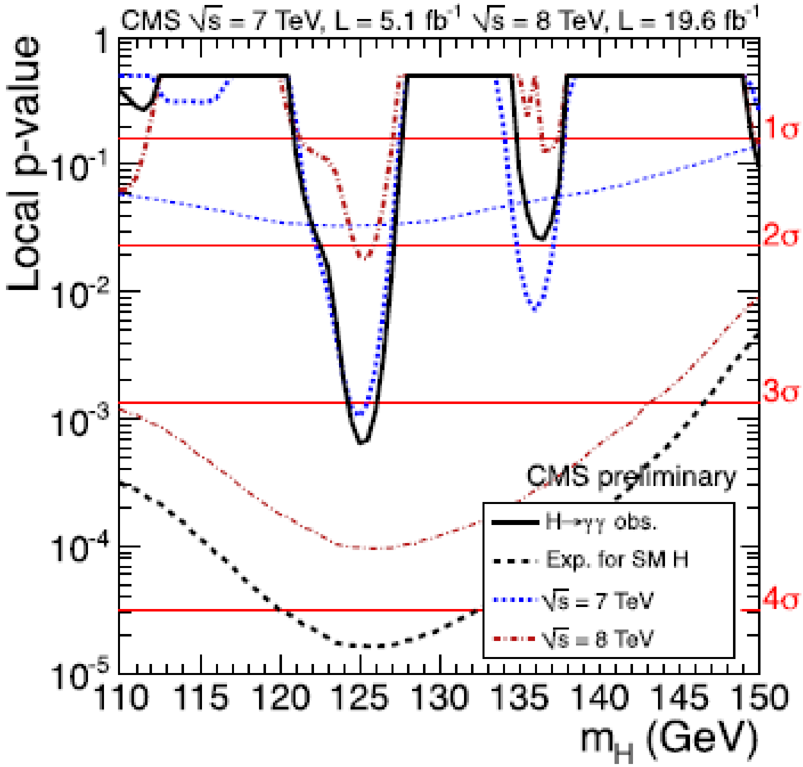
- Inclusive fiducial cross-section of observed particle: **$\sigma_{fid} \cdot BR = 56.2 \pm 12.5$ fb**
  [particle level acceptance cuts: $|\eta^\gamma| < 2.37$, $E_T^\gamma > 40/30$ GeV] [±10.5(stat) ± 6.5(syst) ± 2.0(lumi)]

H→γγ: Results (p-values)

CMS-HIG-13-001

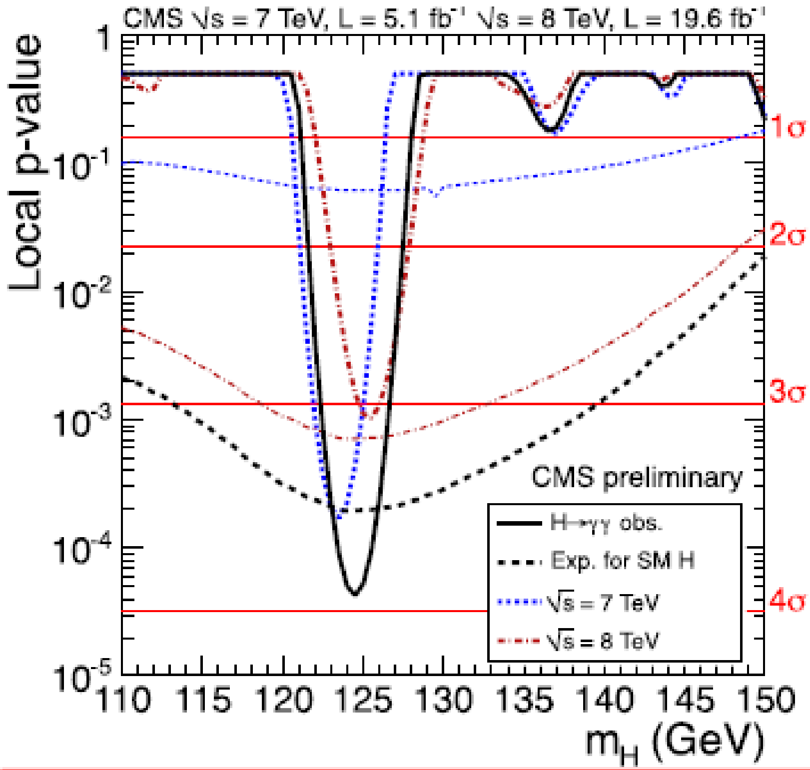
➢ In the following: results of the two analyses are shown side by side

MVA mass-factorized



Significance @ 125.0 GeV: 3.2 σ (4.2 exp.)

Cut-based



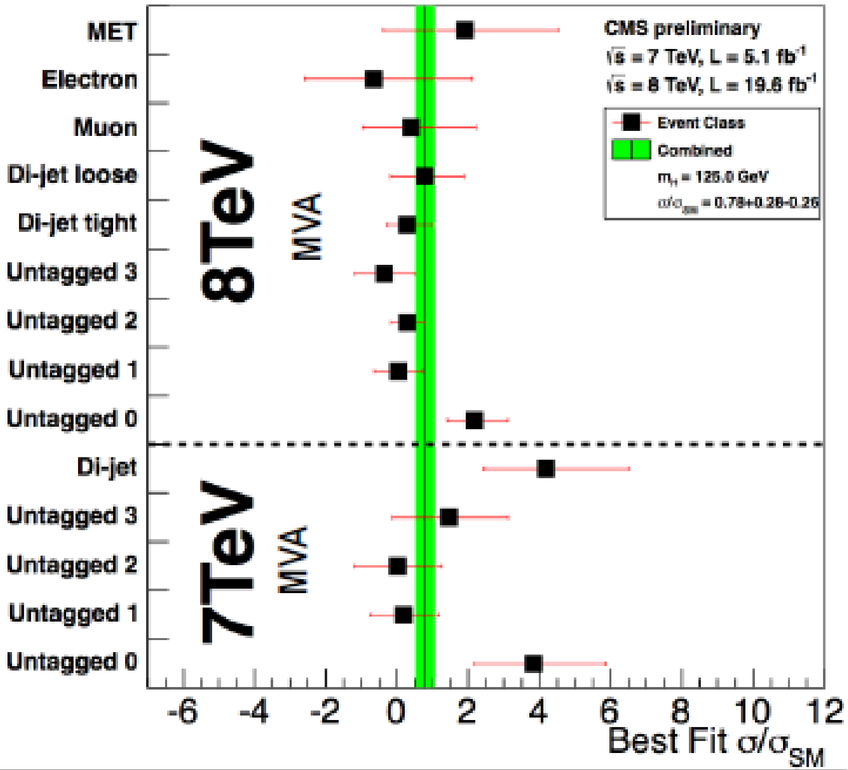
Significance @ 124.5 GeV: 3.9 σ (3.5 exp.)

With additional data and new analysis: significance decreased compared to the published results

H→γγ: Results (channel compatibility)

CMS-HIG-13-001

MVA mass-factorized

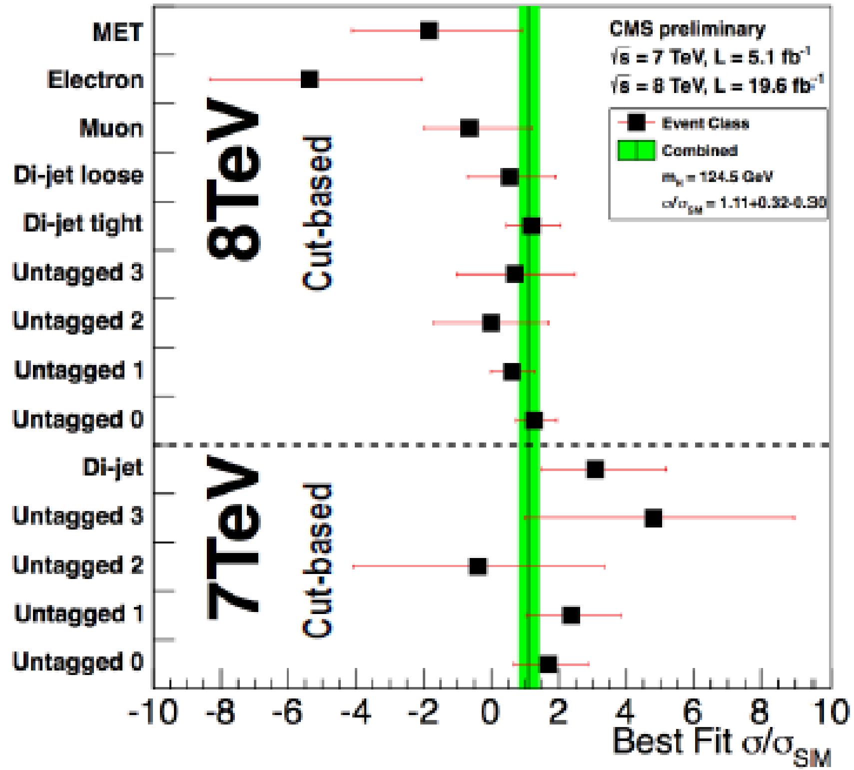


$7+8$ TeV: σ/σ_{SM} @ 125.0 GeV = $0.78^{+0.28}_{-0.26}$

7 TeV: σ/σ_{SM} @ 125.0 GeV = $1.69^{+0.65}_{-0.59}$

8 TeV: σ/σ_{SM} @ 125.0 GeV = $0.55^{+0.29}_{-0.27}$

Cut-based



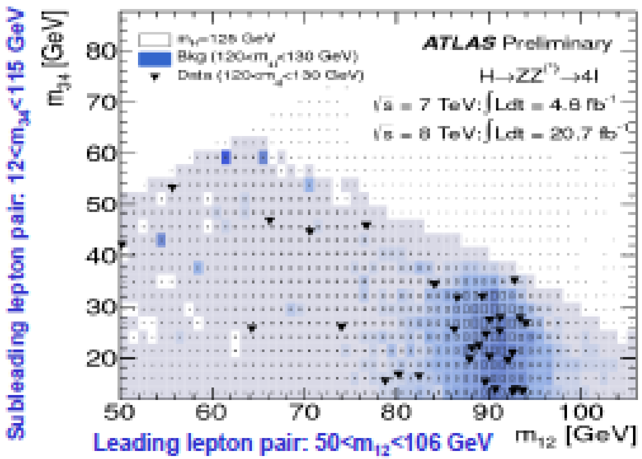
$7+8$ TeV: σ/σ_{SM} @ 124.5 GeV = $1.11^{+0.32}_{-0.30}$

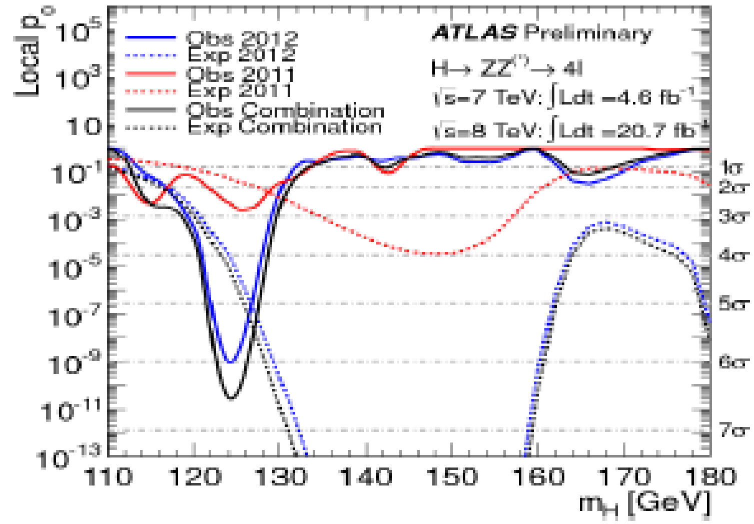
7 TeV: σ/σ_{SM} @ 124.5 GeV = $2.27^{+0.80}_{-0.74}$

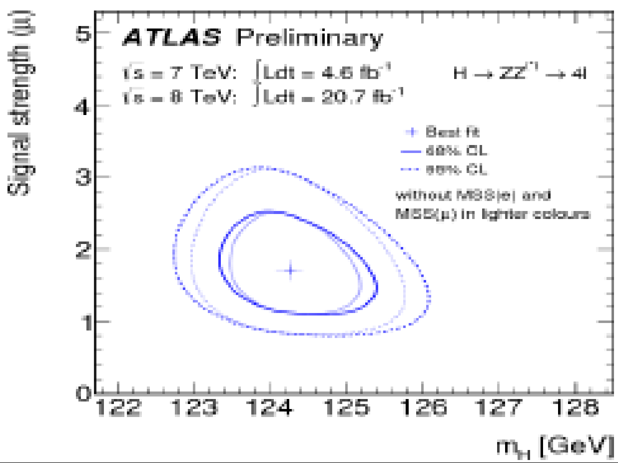
8 TeV: σ/σ_{SM} @ 124.5 GeV = $0.93^{+0.34}_{-0.32}$

H→ZZ$^{(*)}$→4l (l=e,μ) : Results

ATLAS-CONF-2013-013







- Observed local significance of the excess: **6.6σ** (4.4σ expected for SM Higgs)
- Best mass fit **124.3 $^{+0.6}_{-0.5}$ (stat) $^{+0.5}_{-0.3}$ (syst) GeV**

  [measurement dominated by 4**μ** – 0.2% systematics from p_T-scale]
- Signal strength @ this mass: **μ=1.7$^{+0.5}_{-0.4}$**

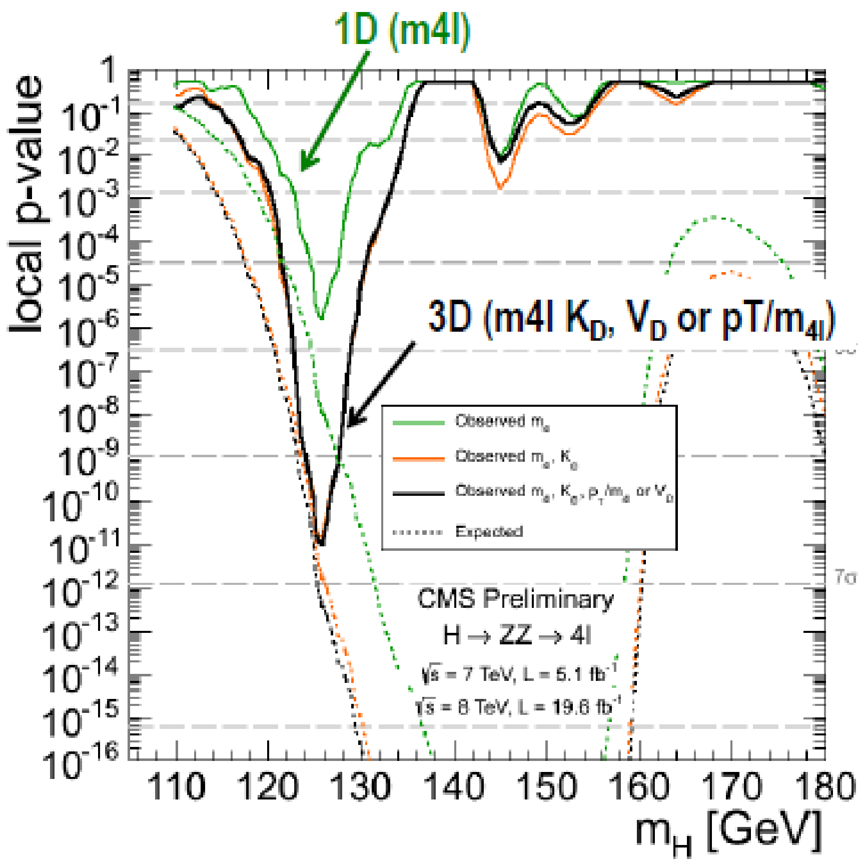
  [@ 125.5 GeV: **μ** =1.5 ± 0.4]

$H \to ZZ \to 4l$: Results

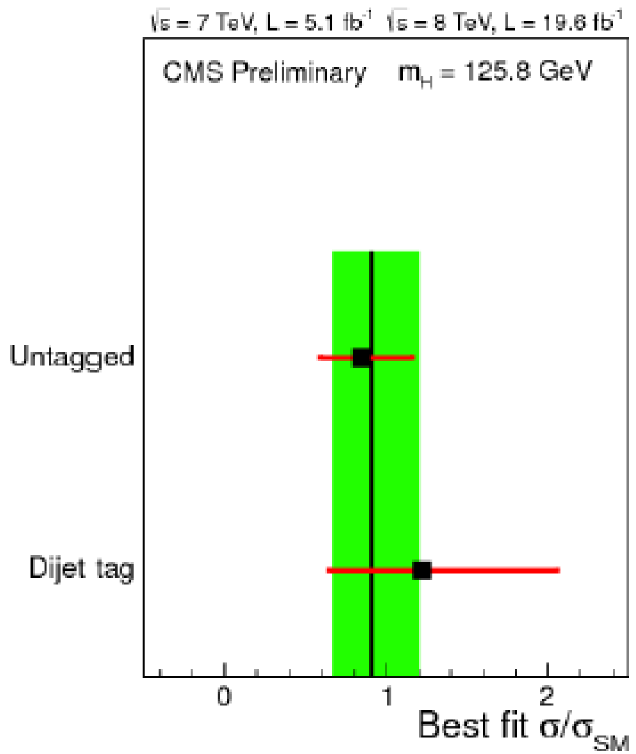
CMS-HIG-13-002

Significance @ 125.8 GeV: 6.7 σ (7.2 expected)
with 3D (m_{4l}, K_D, V_D or pT/m_{4l}) model

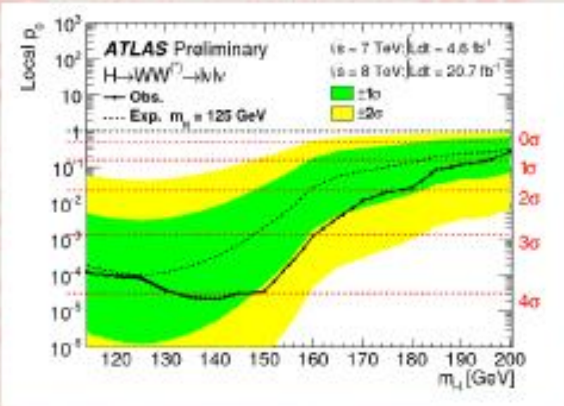
Consistent (but better) wrt 2D (m4l, KD) or 1D (m4l) models.



σ/σ_{SM} @ 125.8 GeV = $0.91^{+0.30}_{-0.24}$



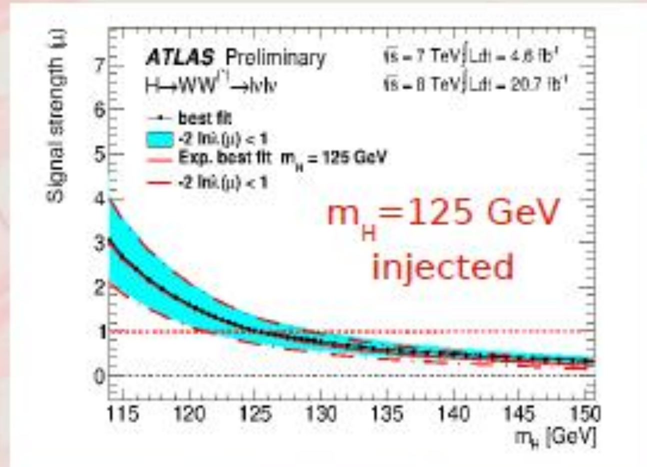
H→$WW^{(*)}$→$l\nu l\nu$: signal strength



Limited mass resolution

Significance at 125 GeV:
- observed: 3.8σ
- expected (SM): 3.7σ

Highest significance:
4.1σ @140 GeV



Signal strength for 0+1+2 jets channels

Signal strength at 125 GeV:
1.01±0.21(stat)±0.19(th)±0.12(syst)±0.04(lumi)

Dominant contribution to the experimental systematic uncertainty from b-tagging efficiency and jet energy scale/resolution.

Inclusive cross section m_H=125 GeV [8TeV]:

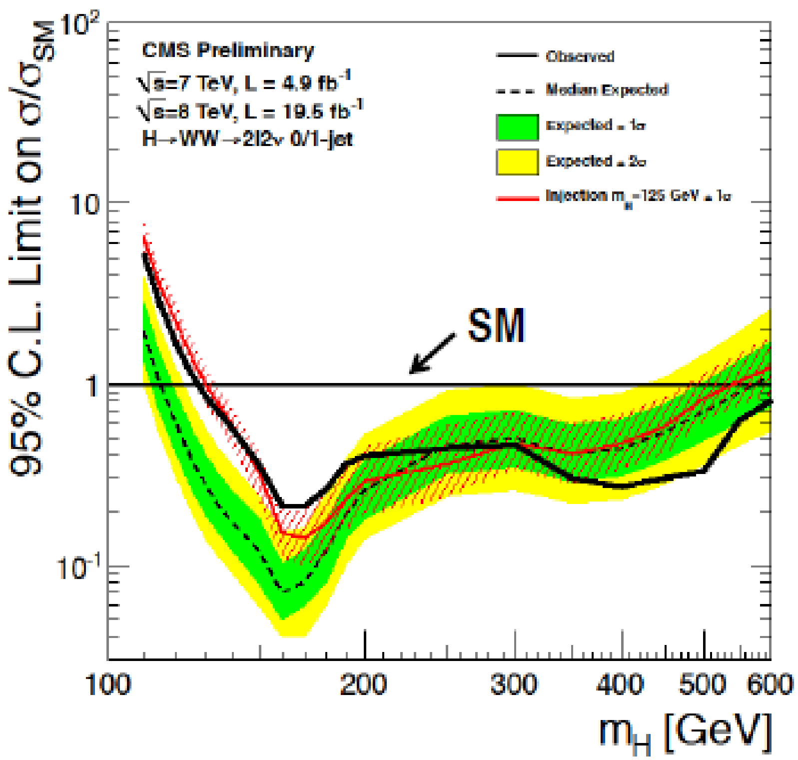
$\sigma_{fid}\cdot BR = 6.0 \pm 1.1(stat) \pm 0.8(theor\ syst) \pm 0.7(exp\ syst) \pm 0.3(lumi)$ **pb**

$H \rightarrow WW \rightarrow 2l2\nu$: Results (2)

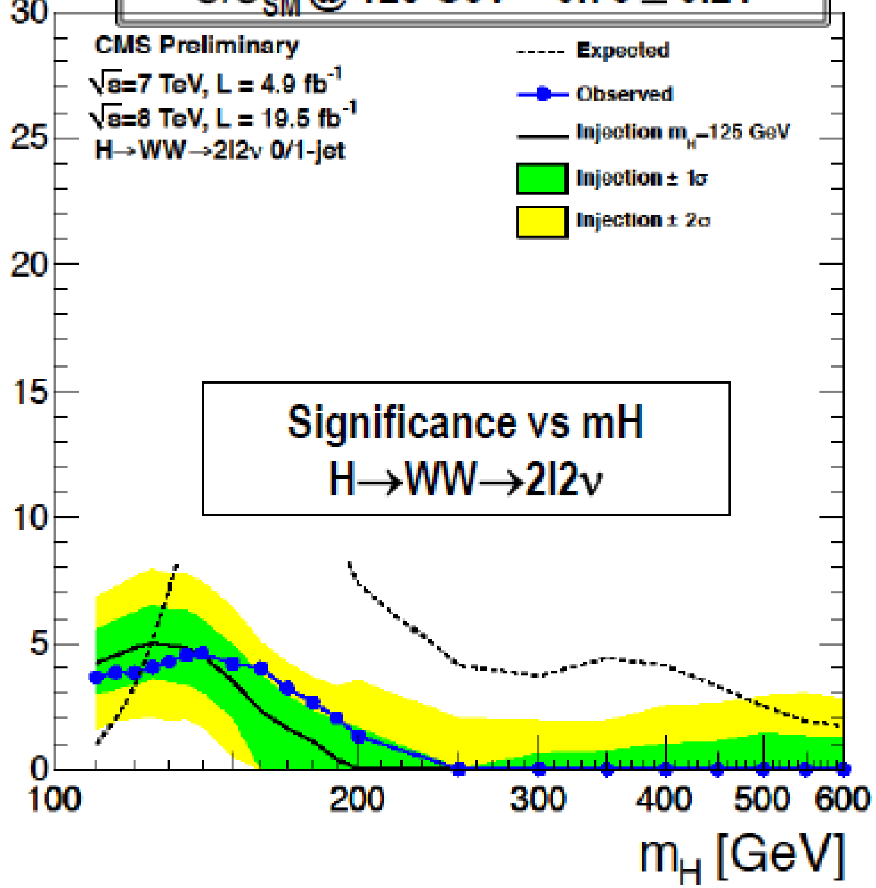
CMS-HIG-13-003

Significance @ 125 GeV: 4.0 σ (5.1 expected)

Large excess at low mass

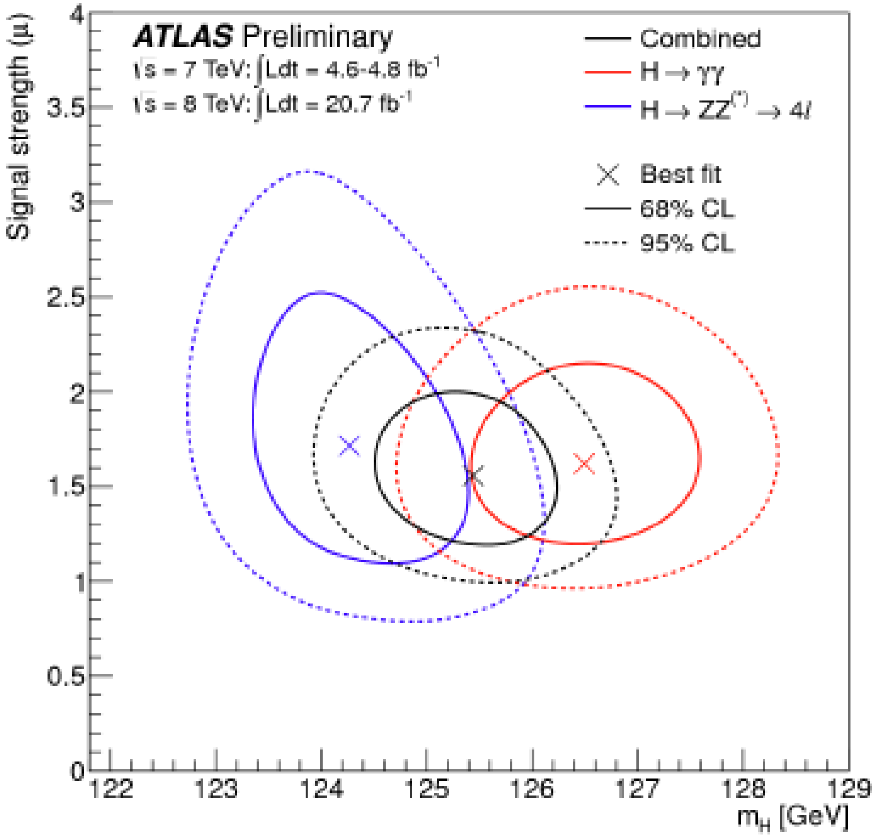


σ/σ_{SM} @ 125 GeV = 0.76 ± 0.21



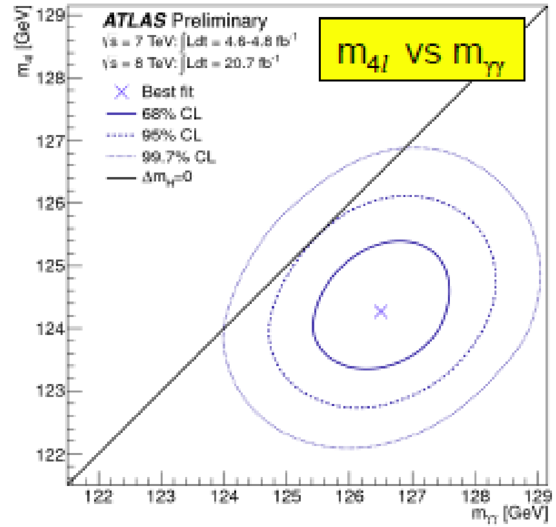
Signal strength vs mass for $\gamma\gamma$ and ZZ

Signal strength $\mu = \sigma/\sigma_{SM}$ vs m_H contours for $\gamma\gamma$ and ZZ and their combination



Comparison of masses from $H\rightarrow\gamma\gamma$ and $H\rightarrow ZZ^{(*)}\rightarrow 4l$

- The individual mass measurements, $m_{\gamma\gamma}$ and m_{4l}, are slightly correlated due to the common EM scale systematic (for photons in $m_{\gamma\gamma}$ and electrons in m_{4l})
  - Pulls $m_{\gamma\gamma}$ down by 350 MeV in combined fit
- Test assumption that both decays come from a common mass
  - $\Delta m_H = m_{\gamma\gamma} - m_{4l}$
    $= 2.3^{+0.6}_{-0.7}\,(stat) \pm 0.6\,(sys)$ GeV
- Consistency Δm_H=0:
  - p-value = 1.5% (2.4σ)
  - More conservative E scale model: allow systematics to vary without constraint ±1σ (rectangular PDF): p-value = 8% (1.7σ)
- Previous measurement, Dec 2012:
  - $\Delta m_H = 3.0 \pm 0.8\,(stat)^{+0.7}_{-0.6}\,(sys)$ GeV



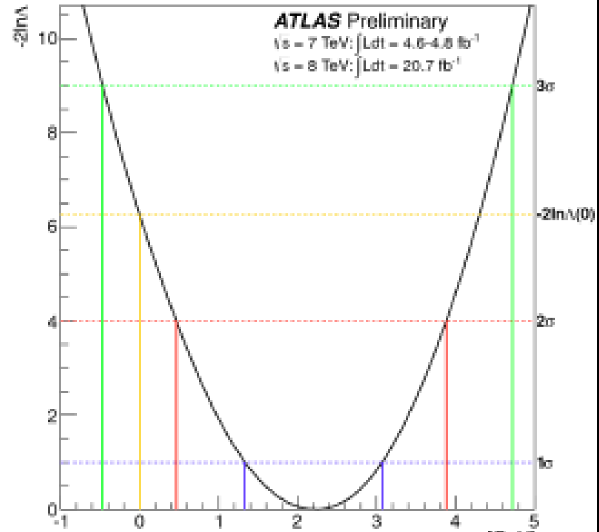


TABLE I: Summary of Higgs decay signal strengthes up to Moriond conference 2013.

CMS	$\mathcal{L}$ (fb^{-1})	μ	M_H (GeV)
$H \to \gamma\gamma$	5.1+19.6	$1.11^{+0.32}_{-0.30}$	124.5
$H \to \gamma\gamma$	5.1+19.6	$0.78^{+0.28}_{-0.26}$	125
$H \to W^+W^-$	4.9+19.5	0.76 ± 0.21	125
$H \to ZZ \to 4l$	5.1+19.6	$0.91^{+0.30}_{-0.24}$	125.8
$H \to b\bar{b}$	5.0+12.1	$1.3^{+0.7}_{-0.6}$	125
$H \to \tau\tau$	4.9+19.4	1.1 ± 0.4	125
ATLAS	$\mathcal{L}$ (fb^{-1})	μ	M_H (GeV)
$H \to \gamma\gamma$	4.8+20.7	$1.65 \pm 0.24^{+0.25}_{-0.18}$	$126.8 \pm 0.2 \pm 0.7$
$H \to W^+W^- \to l\nu l\nu$	4.6+20.7	1.01 ± 0.31	125
$H \to ZZ$	4.6+20.7	$1.7^{+0.5}_{-0.4}$	124.3
$H \to ZZ$	4.6+20.7	1.5 ± 0.4	125.5
$VH \to Vb\bar{b}$	4.7+13.0	$-0.4 \pm 0.7 \pm 0.8$	125
$t\bar{t}H, H \to b\bar{b}$	4.7+13.0	95% CL limit 13.1 measured 10.5 expected	125
$H \to \tau\tau$	4.6+13.0	95% CL limit 1.9 measured 1.2 expected	125
$H \to \tau\tau$	4.6+13.0	0.7 ± 0.7	125
$H \to \mu\mu$	0+20.7	95% CL limit 9.8 measured 8.2 expected	125

IV. LHC Supersymmetry Searches

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$ $\tilde{s}_L\ \tilde{s}_R\ \tilde{c}_L\ \tilde{c}_R$ $\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_L\ \tilde{b}_R$	(same) (same) $\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$
sleptons	0	−1	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$ $\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$ $\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	(same) (same) $\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$
neutralinos	1/2	−1	$\tilde{B}^0\ \tilde{W}^0\ \tilde{H}_u^0\ \tilde{H}_d^0$	$\tilde{N}_1\ \tilde{N}_2\ \tilde{N}_3\ \tilde{N}_4$
charginos	1/2	−1	$\tilde{W}^\pm\ \tilde{H}_u^+\ \tilde{H}_d^-$	$\tilde{C}_1^\pm\ \tilde{C}_2^\pm$
gluino	1/2	−1	$\tilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\tilde{G}$	(same)

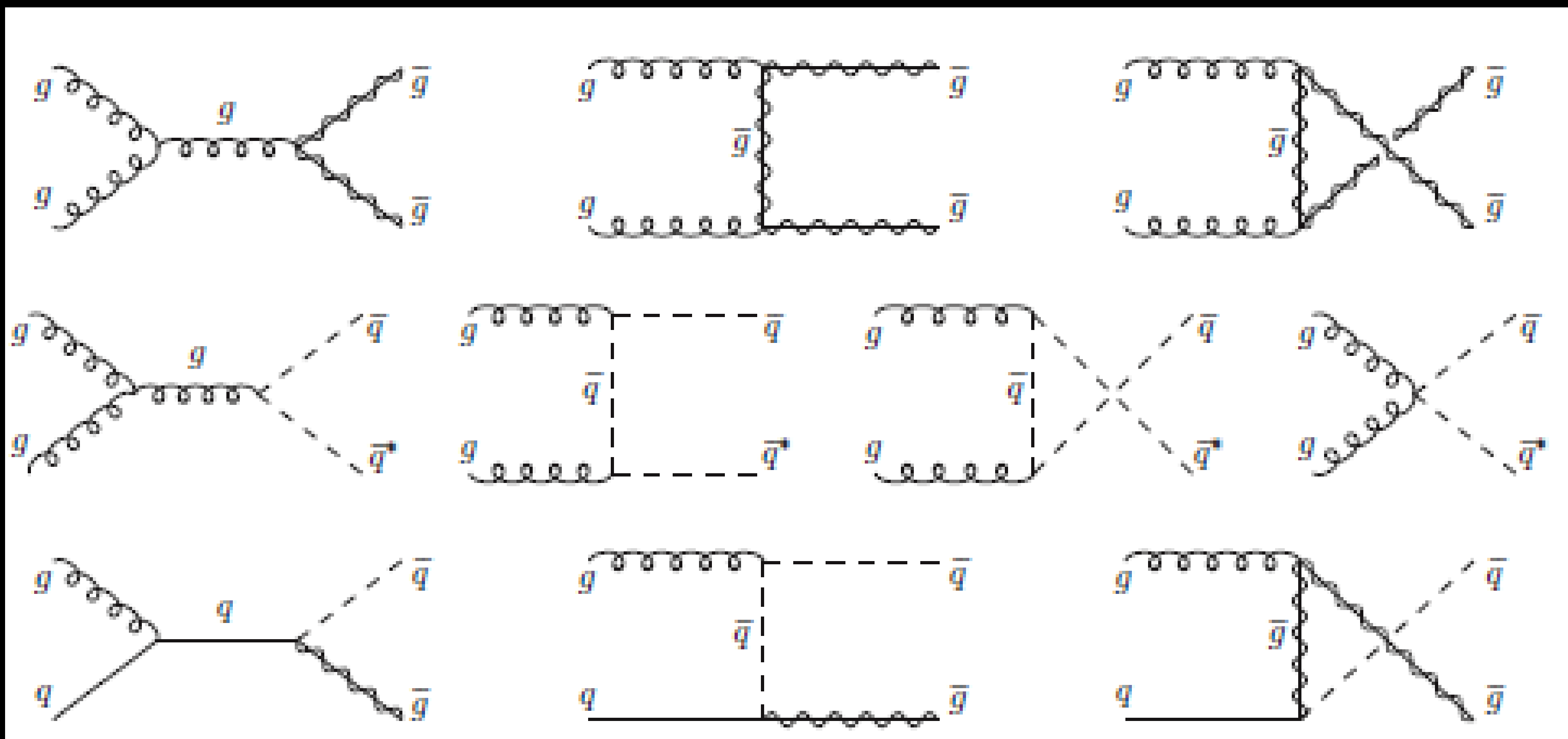
mSUGRA/CMSSM:

- Universal gaugino mass $M_{1/2}$.
- Universal scalar mass M_0.
- Universal trilinear soft term A_0.
- Ratio of the Higgs VEVs

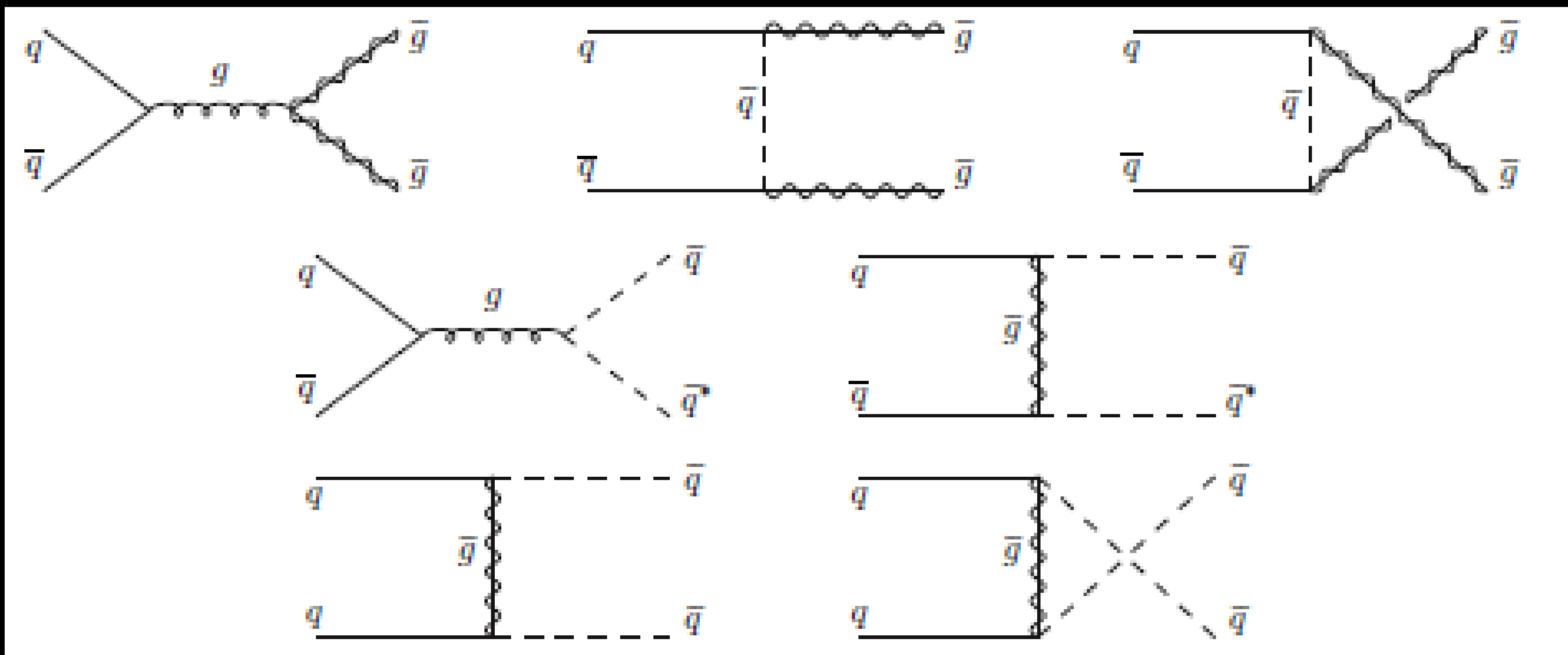
$$\tan\beta = \frac{\langle H_u \rangle}{\langle H_d \rangle}.$$

- The sign of Higgs bilinear mass term μ.

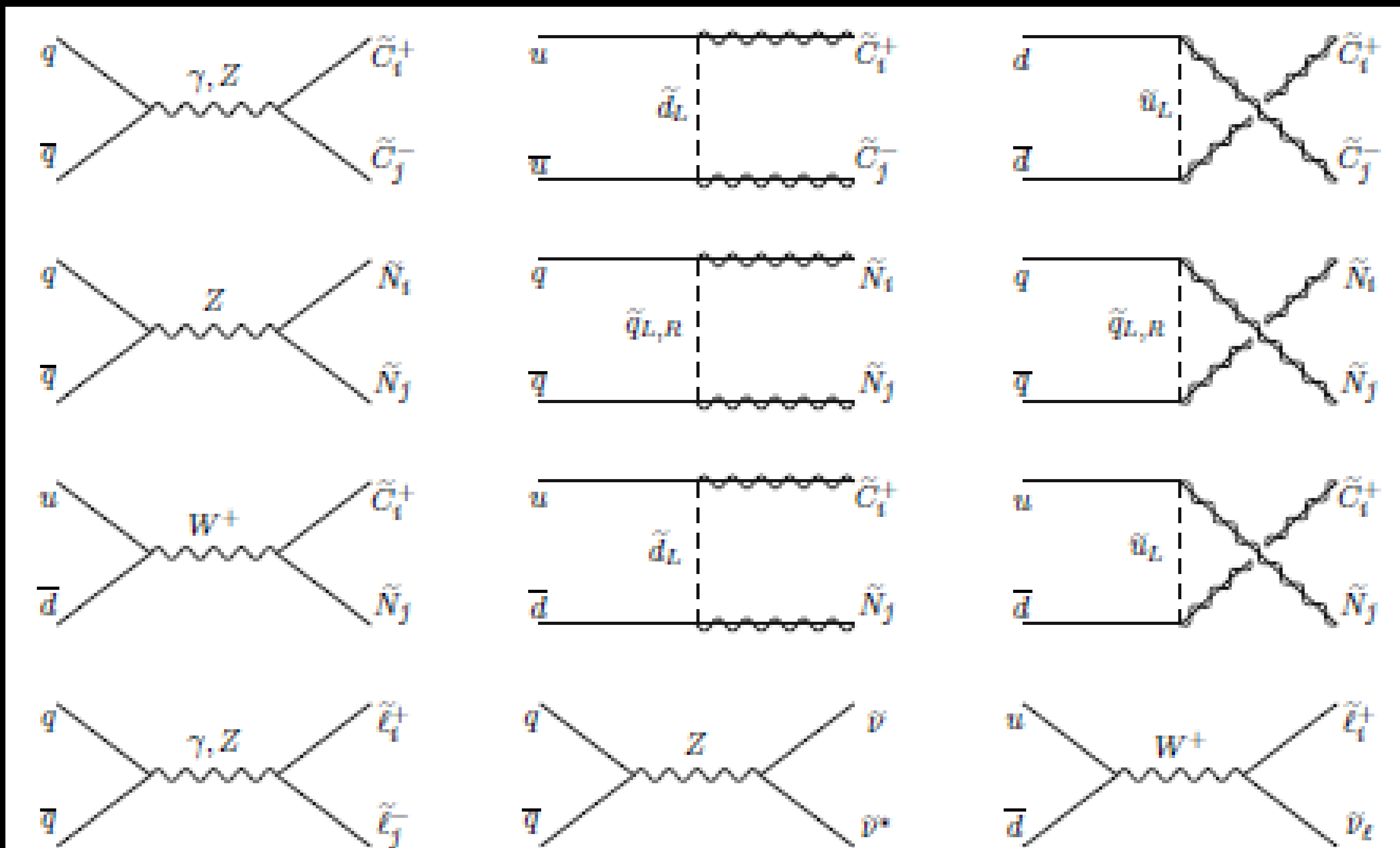
Squarks and Gluino Productions



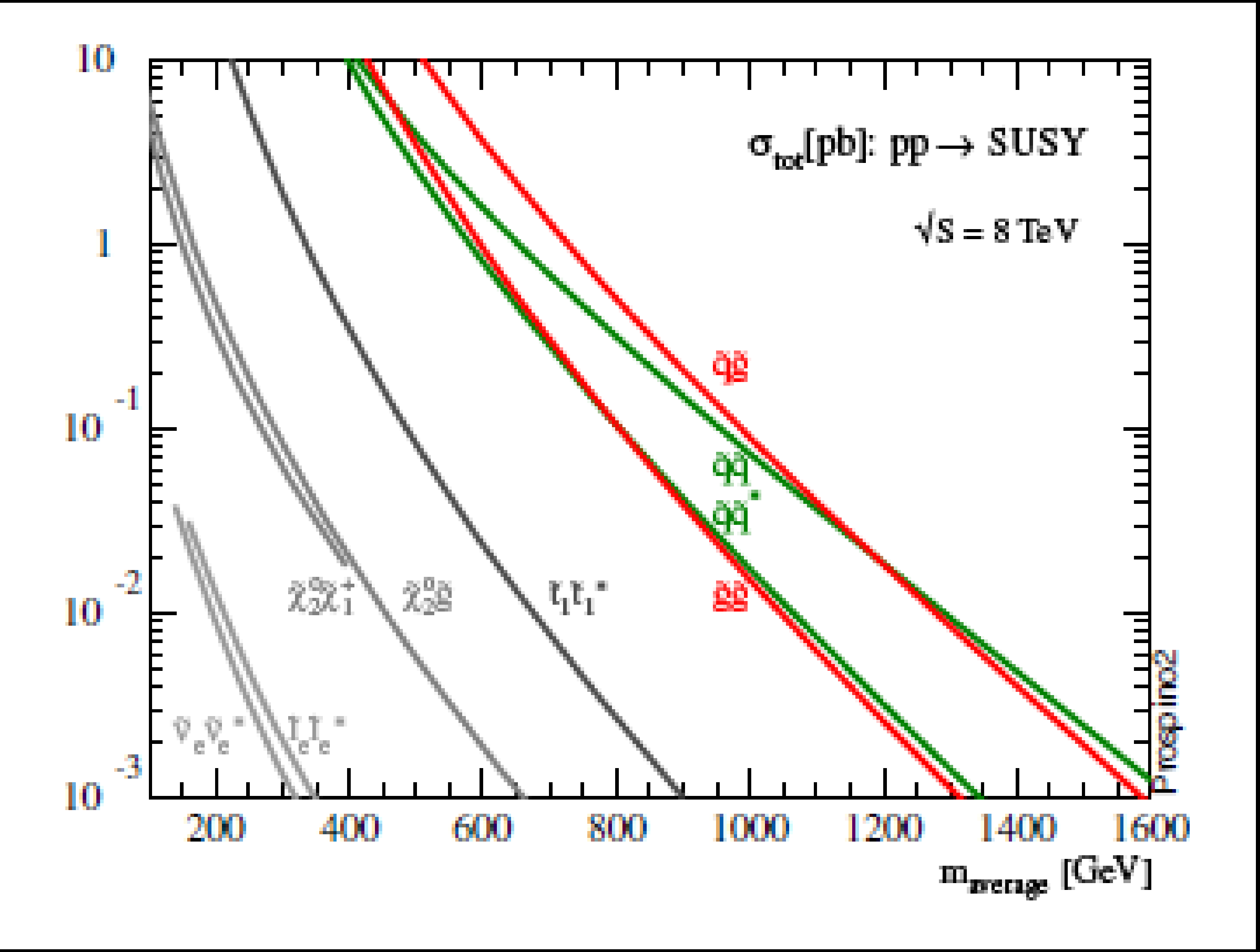
Squarks and Gluino Productions



Electroweak Particle Productions



Production Cross Sections

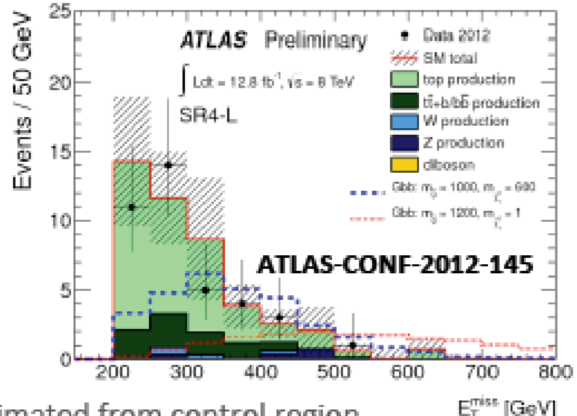


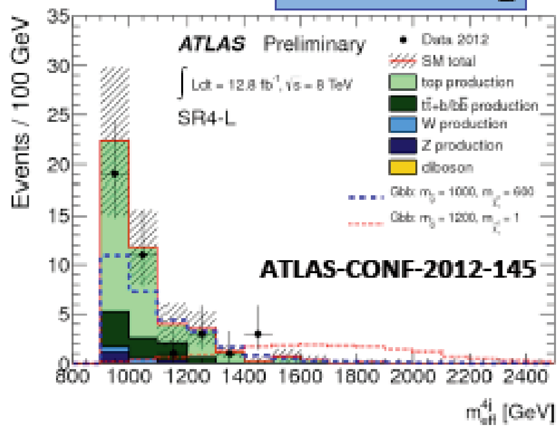
Gluino-mediated sbottom - ATLAS

$\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$

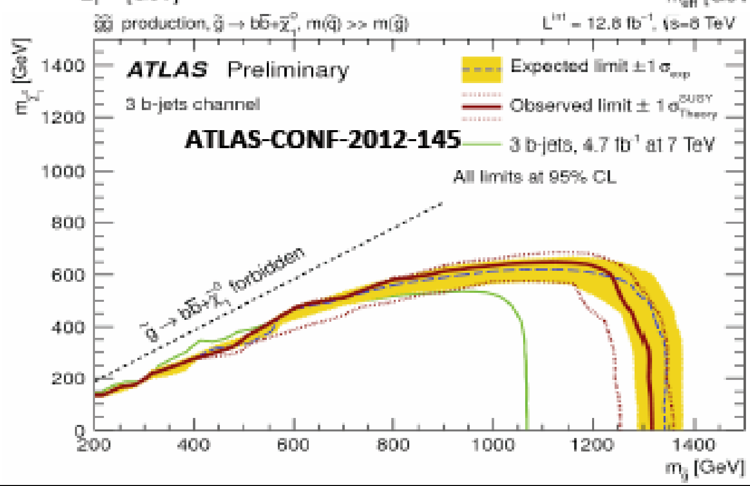
12.8 fb^{-1} @8TeV

0 lep + ≥3 b-jets (4 jets) + E_T^{miss}





- Main backgrounds
  - ttbar+jets: validated and estimated from control region
  - QCD multijet production: estimated from data with two independent methods. Negligible
  - Other backgrounds: ttbar+b/bbar, ttbar+W/Z, W/Z+HF jets. Predicted by MC
- discriminant variables
  - E_T^{miss}, several variants of m_{eff} (scalar sum of E_T^{miss} and jets p_T)
  - $\Delta\phi_{min}^{4j}$ (minimum azimuthal separation between any of the four leading jets and E_T^{miss})



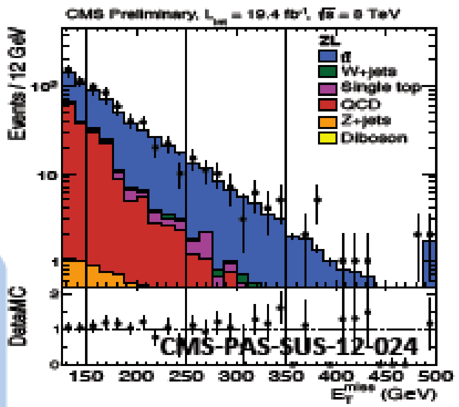
Gluino-mediated sbottom - CMS

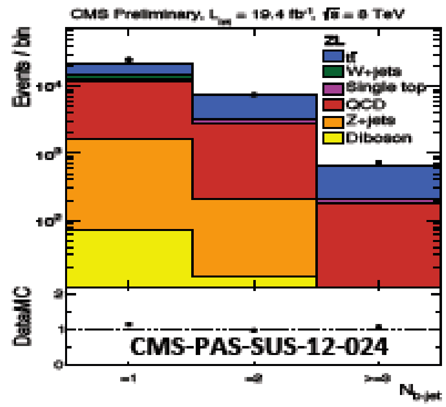
19.4 fb^{-1} @8TeV $\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$

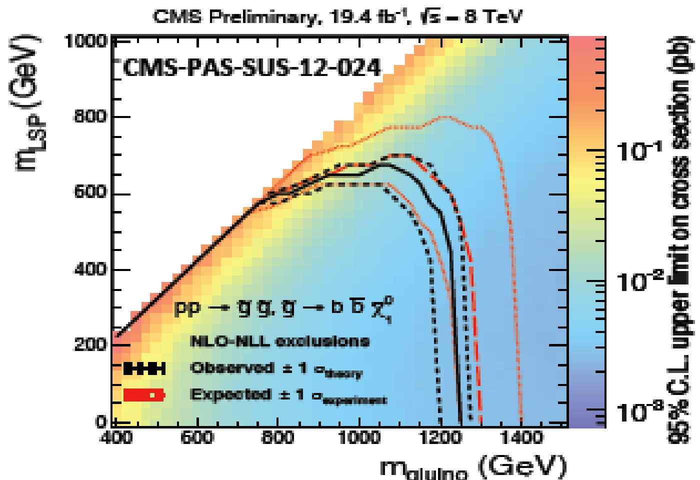
0 lep + ≥3 jets (≥1 b-jets) + E_T^{miss}

NEW!

- Main backgrounds
  - genuine E_T^{miss} bkg: top pairs, single top, W/Z+jets validated and estimated from respective control sample
  - QCD multijet production (data-driven) and dibosons (estimated from MC)
- discriminant variables
  - exclusive bins of H_T (scalar sum of the transverse energy E_T of jets), E_T^{miss}, $N_{b\text{-jets}}$





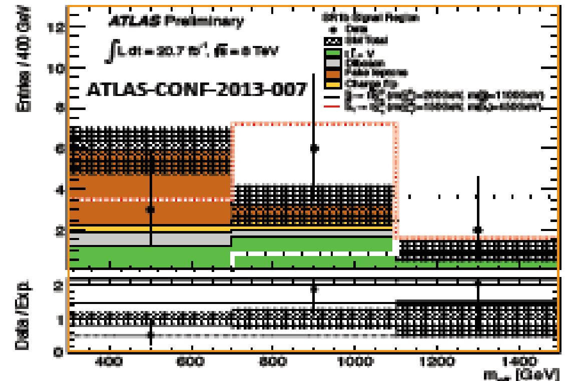


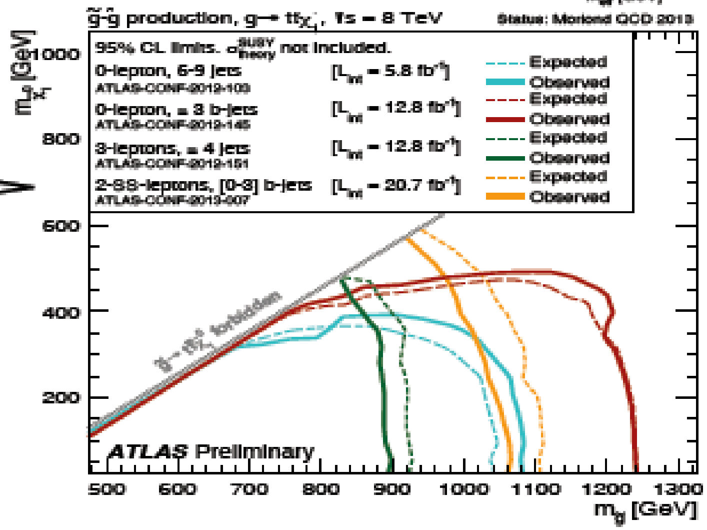
Gluino-mediated stop - ATLAS

8TeV

$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$

- 4 top quarks in decay. Many searches sensitive
  - 0 lep + multi-jet (6-9 jets) + E_T^{miss}. 5.8 fb^{-1}
  - 0 lep + ≥3 b-jets (6 jets) + E_T^{miss}. 12.8 fb^{-1}
  - 2 SS lep + 0,≥1,≥3 b-jets (≥3,4 jets) + E_T^{miss}. 20.7 fb^{-1}
    - NEW!
    - main bkg: ttW/Z, WZ/ZZ+jets (from MC); charge flips, fake leptons (data-driven)
    - discriminant variables: E_T^{miss}, effective mass m_{eff}, lepton-E_T^{miss} transverse mass m_T
  - 3 lep + ≥4 jets + E_T^{miss}. 13.0 fb^{-1}



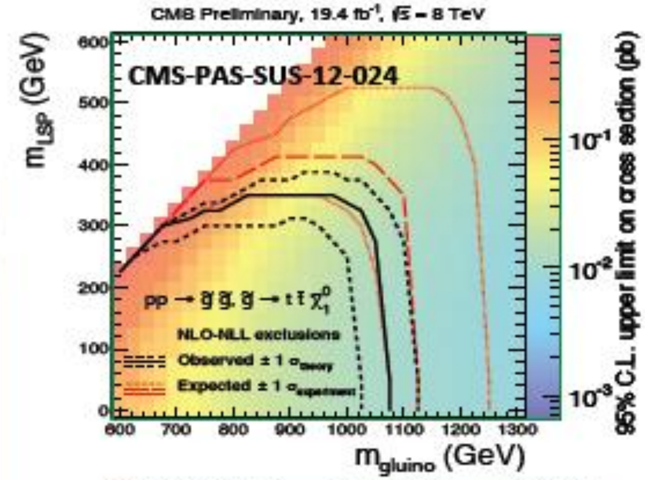


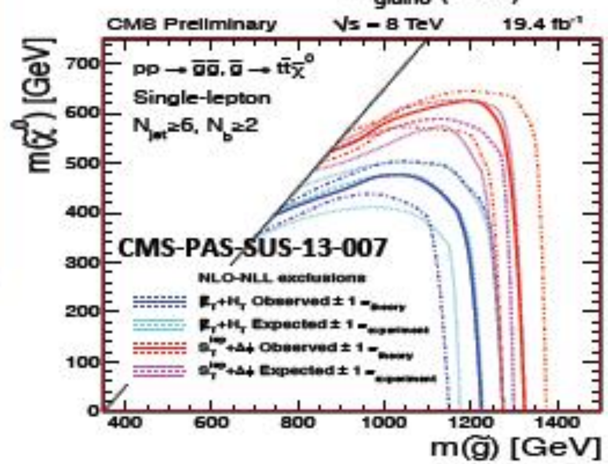
Gluino-mediated stop - CMS

$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$

8TeV

- 4 top quarks in decay. Many searches sensitive
  - 0 lep + ≥3 jets (≥1 b-jets) + E_T^{miss}. 19.4 fb^{-1} **NEW!**
  - 1 lep + ≥6 jets (≥2,≥3 b-jets) + E_T^{miss}. 19.4 fb^{-1} **NEW!**
    - <u>2 complementary methods</u>: *Lepton Spectrum* (LS) and *Delta Phi* (DP)
    - <u>main bkg</u>: top pairs, single top, ttbar+W/Z, W+jets, dibosons, Drell-Yan+jets, QCD multijet production
    - <u>discriminant variables</u>: E_T^{miss}, H_T for LS method; $\Delta\phi(W,l)$, S_T^{lep} for DP method
  - 2 SS lep + ≥2 b-jets + E_T^{miss}. 10.5 fb^{-1}
    - CMS-PAS-SUS-12-029





Direct sbottom - ATLAS

8TeV

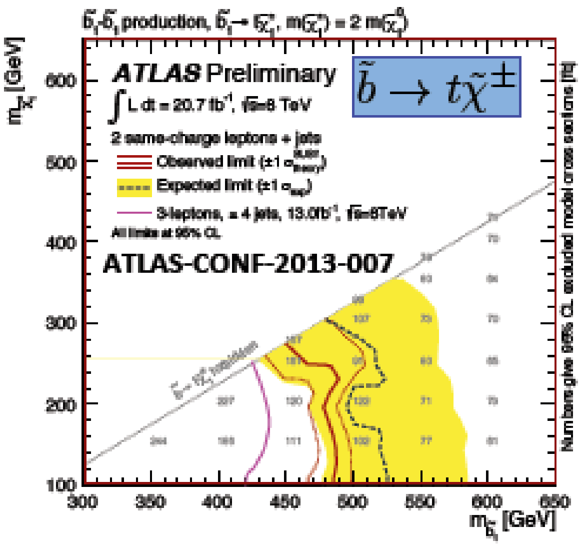
- exploit 2-body decay kinematics for $\tilde{b} \rightarrow b\tilde{\chi}^0$
  - 0 lep +2 b-jets + m_{CT} + E_T^{miss}. 12.8 fb^{-1}

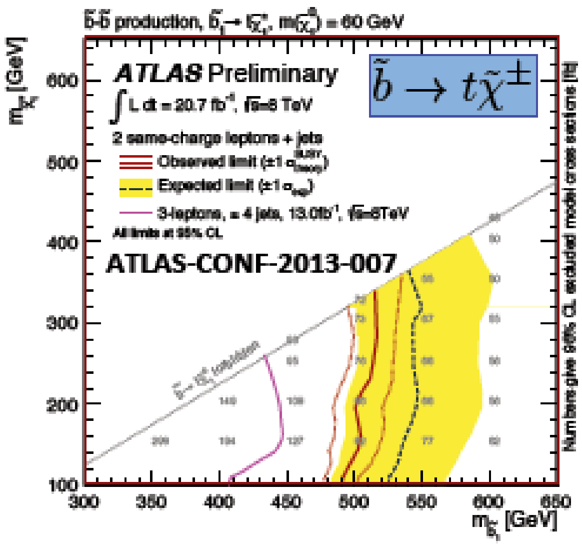
$$m_{CT} = \sqrt{\left(E_T(v_1)+E_T(v_2)\right)^2 - \left(\vec{p}_T(v_1)+\vec{p}_T(v_2)\right)^2}$$

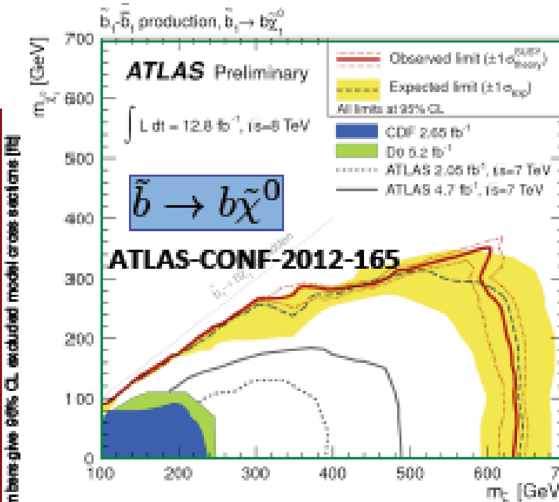
$$m_{CT}^{End} = \frac{m^2(\tilde{b}_1)-m^2(\tilde{\chi}_1^0)}{m(\tilde{b}_1)}$$

NEW!

- use leptonic decay for $\tilde{b} \rightarrow t\tilde{\chi}^{\pm}$
  - 2 SS lep + 0,≥1,≥3 b-jets (≥3,4 jets) + E_T^{miss}. 20.7 fb^{-1}







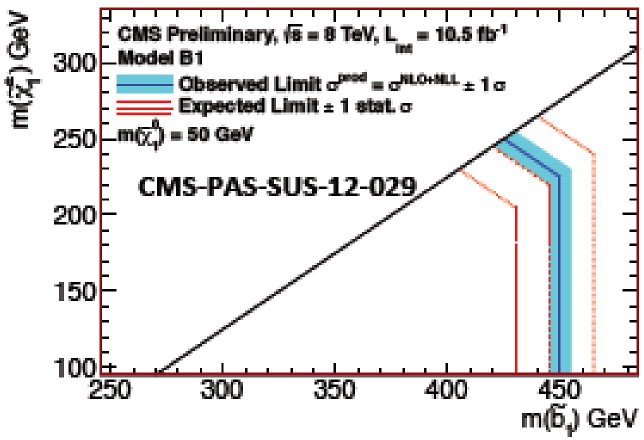
Direct sbottom - CMS

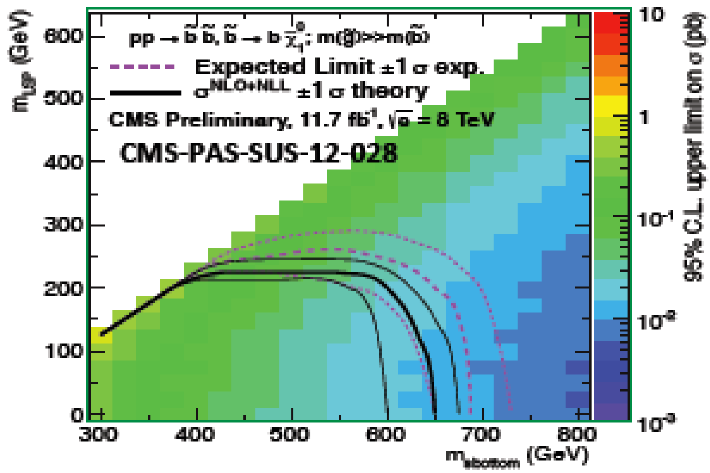
- use leptonic decay for $\tilde{b} \to t\tilde{\chi}^{\pm}$
  - 2 SS lep + ≥2 b-jets + E_T^{miss}. 10.5 fb^{-1}
- exploit 2-body decay kinematics for $\tilde{b} \to b\tilde{\chi}^{0}$
  - 0 lep + 2≤jets≤3 (1,2 b-jets) + E_T^{miss}. 11.7 fb^{-1}
    - main bkg: top pairs, single top, W/Z+jets (validated and estimated from respective control region), QCD multijet production (estimated from MC. Negligible)
    - discriminant variables: H_T, α_T: effective in reducing multijet background

8TeV

$$\alpha_T = \frac{E_T^{j_2}}{M_T} \qquad M_T = \sqrt{\left(\sum_{i=1}^{2} E_T^{j_i}\right)^2 - \left(\sum_{i=1}^{2} p_x^{j_i}\right)^2 - \left(\sum_{i=1}^{2} p_y^{j_i}\right)^2}$$

for N_{jets}=2 E_T^{j2} is the transverse energy of the least energetic jet of the two, and M_T is the transverse mass of the dijet system. For N_{jets}≥2 an equivalent dijet system is formed (combination choosen to minimize ΔH_T)

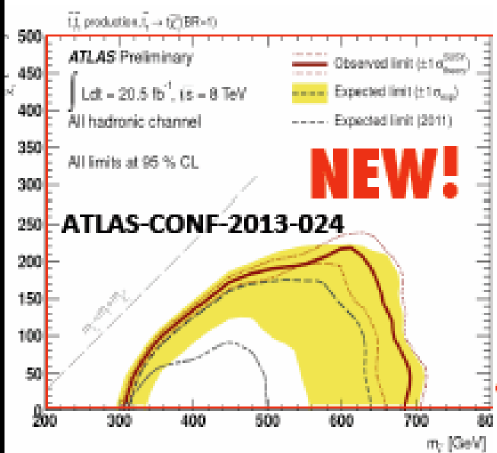


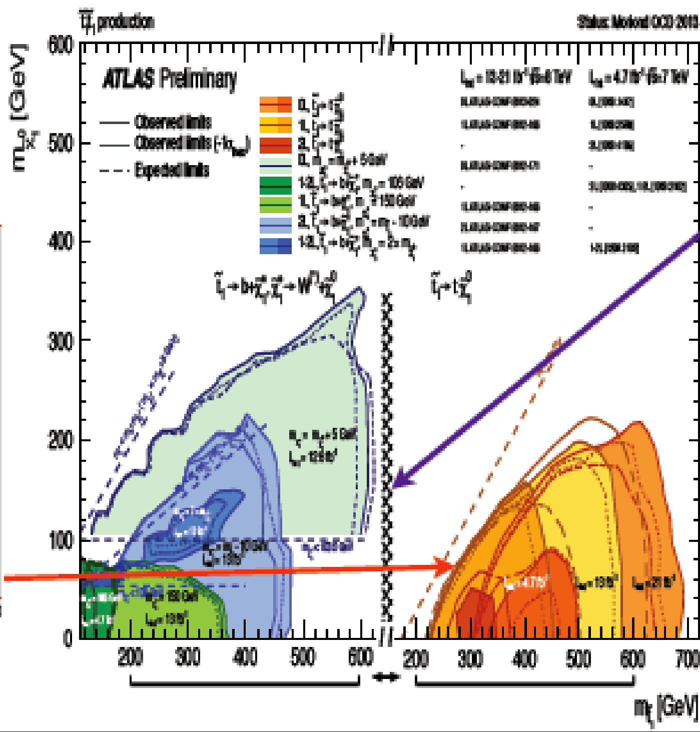


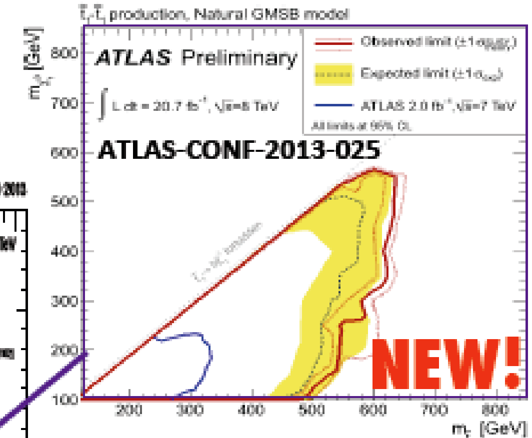
Direct stop - ATLAS

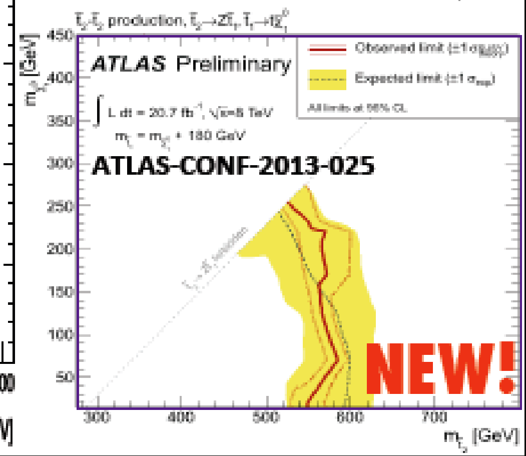
- 2 lep + E_T^{miss}. 13.0 fb^{-1} — $\tilde{t} \to b\tilde{\chi}^{\pm}$; m($\chi^{\pm}$)-m(χ^0)>m(W)
- 1 lep + ≥4 jets (≥1 b-jets) + E_T^{miss}. 13.0 fb^{-1} — $\tilde{t} \to t\tilde{\chi}^0$ — $\tilde{t} \to b\tilde{\chi}^{\pm}$
- 0 lep + 2 b-jets + E_T^{miss}. 12.8 fb^{-1} — $\tilde{t} \to b\tilde{\chi}^{\pm}$; m($\chi^{\pm}$)~m(χ^0)

8TeV





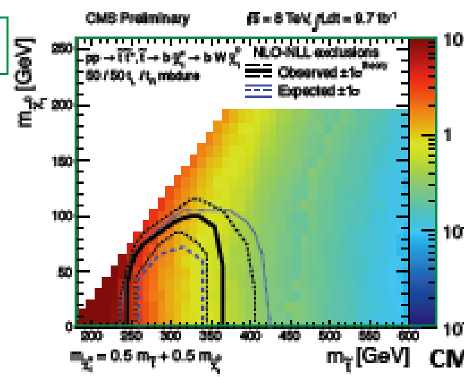


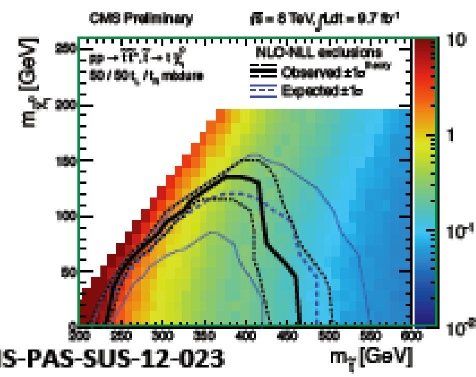


Direct stop - CMS

$\tilde{t} \rightarrow b\tilde{\chi}^{\pm}$ $\tilde{t} \rightarrow t\tilde{\chi}^{0}$

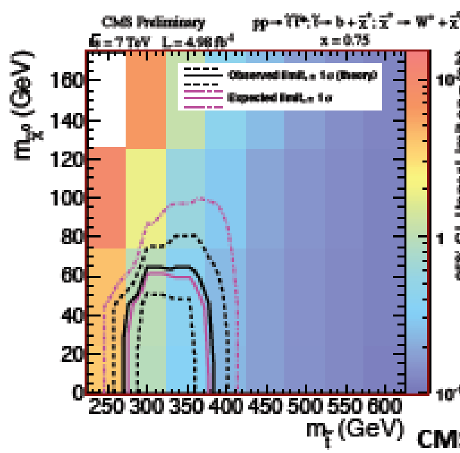
- 1 lep + ≥4 jets (≥1 b-jets) + E_T^{miss}. 9.7 fb^{-1} @8TeV
  - backgrounds: *top pairs, W+jets* (validated and estimated from respective control region); QCD multijet (negligible); dibosons, ttbar+W/Z, single top (from MC)
  - discriminant variables: E_T^{miss}, leptonic transverse mass m_T

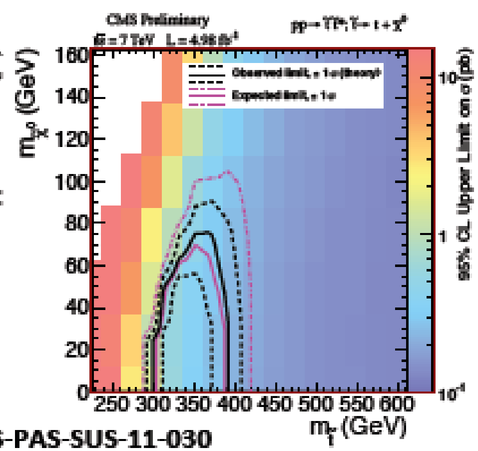




CMS-PAS-SUS-12-023

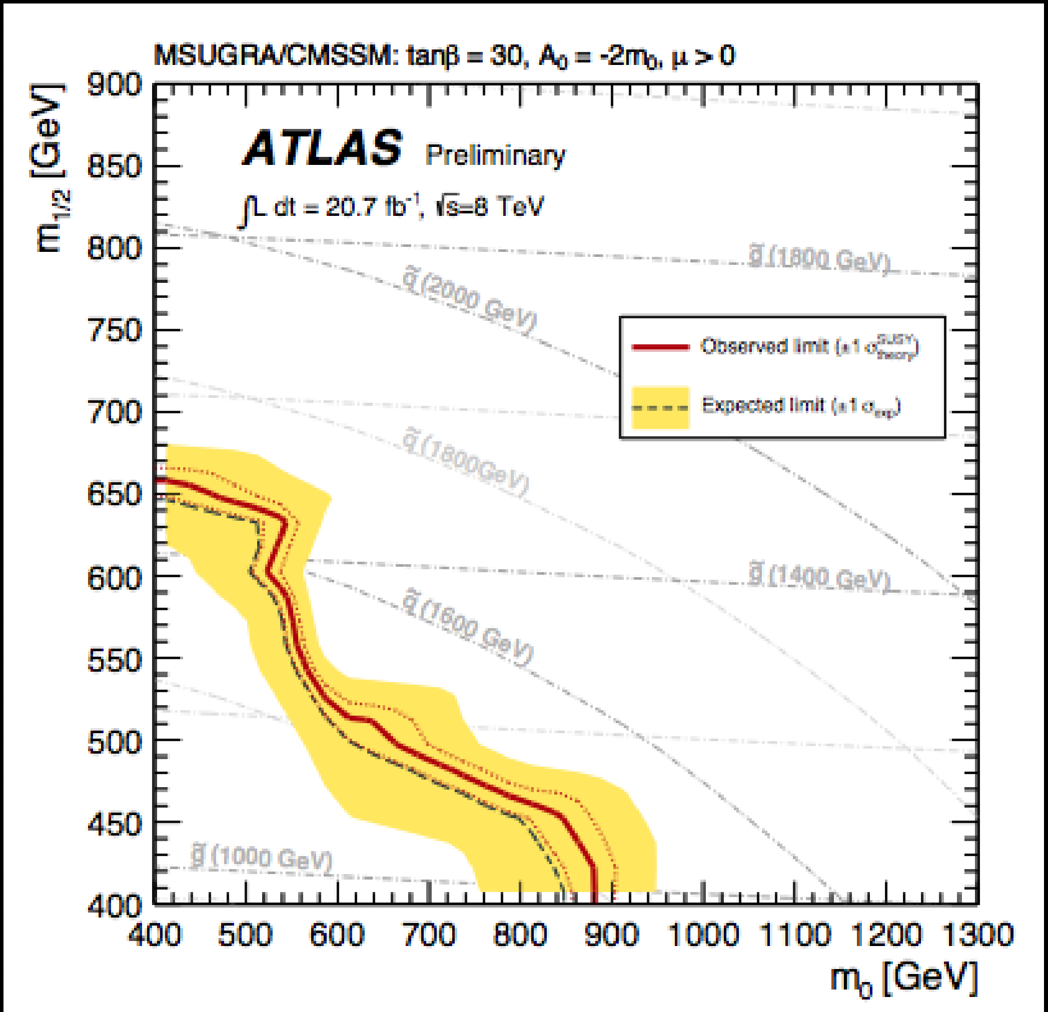
- 0 lep + ≥5 jets (≥1 b-jets) + E_T^{miss}. 4.98 fb^{-1} @7TeV
  - backgrounds: *top pairs, W+jets* (validated and estimated from respective control region); QCD multijet (negligible); dibosons, ttbar+W/Z, single top (from MC)
  - discriminant variables: E_T^{miss}, $\Delta\phi(E_T^{miss}$,three highest-p_T jets), min|$\Delta\phi(E_T^{miss}, p_T^b)$| (enhanced at low angles for top pairs bkg)



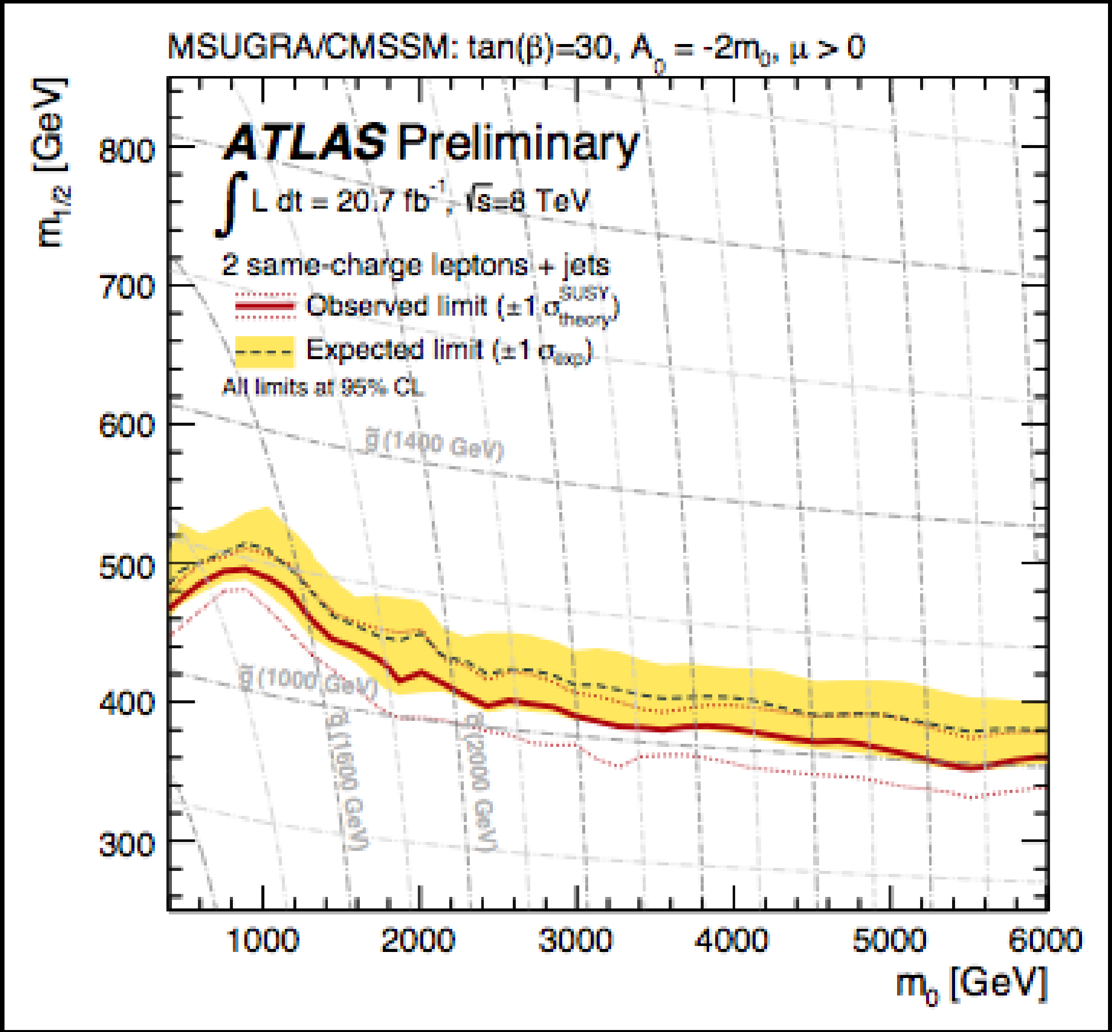


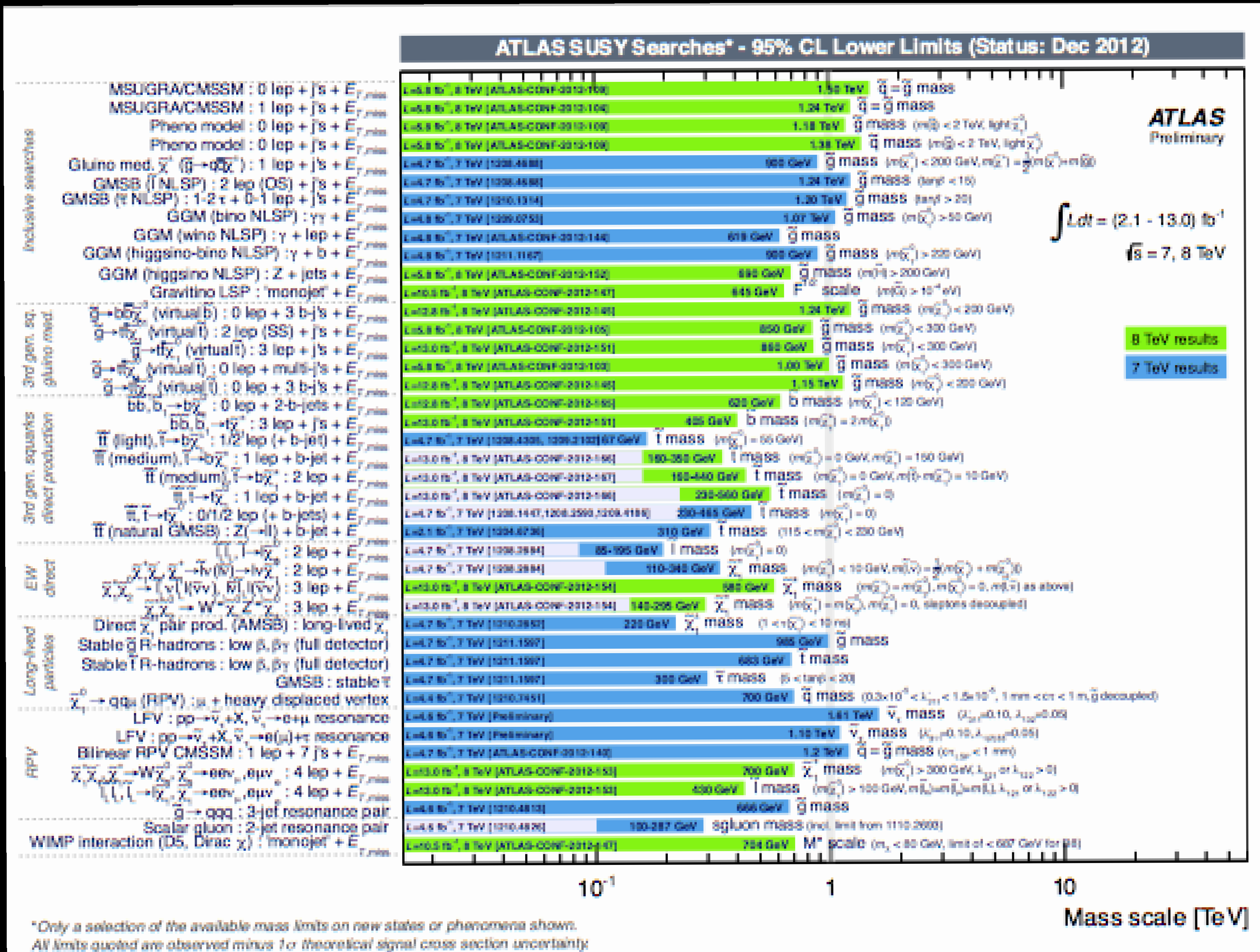
CMS-PAS-SUS-11-030

Tau+Jets+MET(ATLAS-CONF-2013-026) (20.7/fb)



2SSL+Jets+MET(ATLAS-CONF-2013-007)(20.7/fb)





ATLAS SUSY Searches* - 95% CL Lower Limits (Status: Dec 2012)
ATLAS
Preliminary
$\int L dt = (2.1 - 13.0)\ fb^{-1}$
$\sqrt{s}$ = 7, 8 TeV
8 TeV results
7 TeV results
Inclusive searches
3rd gen. sq. gluino med.
3rd gen. squarks direct production
EW direct
Long-lived particles
RPV
10^{-1}
1
10
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

V. Implications for Supersymmetric SMs

Higgs boson mass in the MSSM:

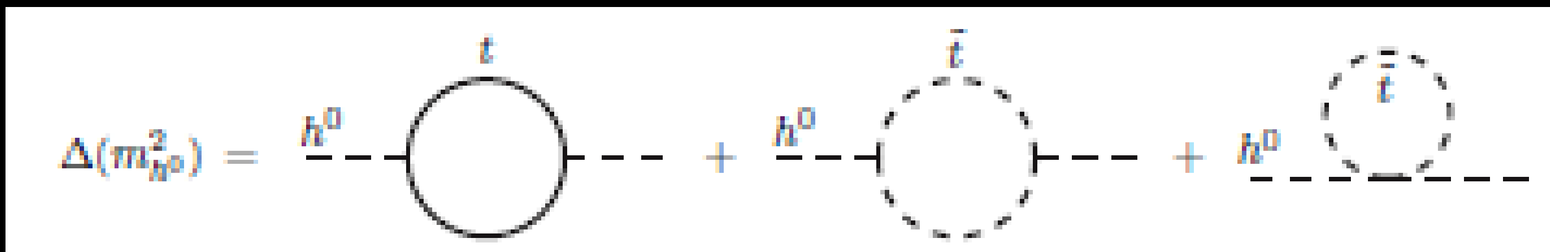
- The bound on the lightest CP-even Higgs boson mass at tree level is

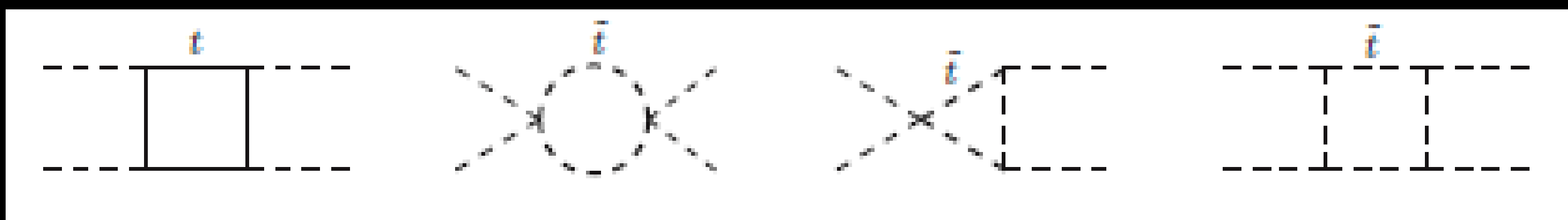
$$M_h \ \leq \ M_Z|\cos 2\beta| \ .$$

- The Higgs boson mass is lifted due to large top quark Yukawa couplings.

- The trilinear soft term A_t should be large to lift the CP-even Higgs boson boson around 125 GeV

$$A_t - \mu \cot \beta \ \simeq \ \sqrt{6 M_{\tilde{Q}_3} M_{\tilde{t}^c}} \ .$$


Δ(m²_{h⁰}) =
h⁰
t
+
h⁰
t̃
+
h⁰
t̃


t
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Higgs boson mass:

- Higgs boson mass lift at tree level: F-term, D-term, mass matrix diagonalization in the NMSSM.
- Higgs mass lift at one loop: vector-like particles.

Supersymmetric SMs:

- Natural supersymmetry [a].
- Supersymmetric models with sub-TeV squarks that can escape/relax the missing energy constraints: R parity violation [b]; compressed supersymmetry [c]; stealth supersymmetry [d]; etc.
- Supersymmetric models with sub-TeV squarks that decrease the cross sections: supersoft supersymmetry [e].

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[a] S. Dimopoulos and G. F. Giudice, Phys. Lett. B **357**, 573 (1995) [hep-ph/9507282]; A. G. Cohen, D. B. Kaplan and A. E. Nelson, Phys. Lett. B **388**, 588 (1996) [hep-ph/9607394].

[b] R. Barbier, C. Berat, M. Besancon, M. Chemtob, A. Deandrea, E. Dudas, P. Fayet and S. Lavignac *et al.*, Phys. Rept. **420**, 1 (2005) [hep-ph/0406039].

[c] T. J. LeCompte and S. P. Martin, Phys. Rev. D **84**, 015004 (2011) [arXiv:1105.4304 [hep-ph]]; Phys. Rev. D **85**, 035023 (2012) [arXiv:1111.6897 [hep-ph]].

[d] J. Fan, M. Reece and J. T. Ruderman, JHEP **1111**, 012 (2011) [arXiv:1105.5135 [hep-ph]]; arXiv:1201.4875 [hep-ph].

[e] G. D. Kribs and A. Martin, arXiv:1203.4821 [hep-ph], and references therein.

Natural Supersymmetry:

- The μ term or effective μ term is smaller than 300 GeV.
- The squar root $M_{\tilde{t}} \equiv \sqrt{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2}$ of the sum of the two stop mass squares is smaller than 1.2 TeV. Consequencely, we can show that the light sbottom mass is smaller than $m_{\tilde{t}_2}$.
- The gluino mass is lighter than 1.5 TeV.

Natural Supersymmetry:

- R-parity violation: supersymmetry is only the solution to the gauge hierarchy problem.
- LHC supersymmetry search constraints can be relaxed.
- An elegant and popular solution to the strong CP problem is the Peccei–Quinn (PQ) mechanism, and the axion can be the cold dark matter candidate.

The NMSSM can still be natural.

Electroweak Supersymmetry [a]

- String model building strongly implies that the three families of the SM fermions have the same origin. Thus, all the squarks may be heavier.
- The LHC supersymmetry and Higgs searches and B physics constraints imply the heavy squarks.
- To explain the $(g_\mu - 2)/2$ results, the smuon may need to be light. Thus, the sletons may be light.
- The observed dark matter density can be realized via the LSP neutralino and stau coannihilations.
- XENON100 constraints: small Higgsino/$\tilde{W}^0$ component for LSP neutralino, and relatively heavy squarks.

[a] T. Cheng, J. Li, TL, D. V. Nanopoulos and C. Tong, arXiv:1202.6088 [hep-ph].

Electroweak Supersymmetry:

The squarks and/or glunios are heavy around a few TeV while the sleptons, bino and winos are light and within one TeV. The Higgsinos (or μ term) can be either heavy or light.

- M_3 is about a few TeV while the squark soft masses are small.
- M_3 is small while the squark soft masses are about a few TeV.
- Both M_3 and squark soft masses are heavy.

GmSUGRA can realize electroweak supersymmetry.

VI. Summary

- The LHC has discovered the Higgs boson with mass around 125 GeV. However, the signal strengths for Higgs boson productions and decays might be deviated from the SM.
- The LHC supersymmetry searches give strong constraints on viable supersymmetry parameter space.
- The supersymmetric SMs can still be natural.

Thank you very much!


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Conclusions

m_H = 125.8 +/- 0.4 (stat) +/- 0.4 (syst) GeV

σ / σ_{SM} = .88 +/- 0.21

- Data consistent with
  - Custodial symmetry
  - Fermion universality tests
  - Fermionic and bosonic couplings expected from SM Higgs
- Data disfavors all alternative models tested thus far at 2σ CL except 0h+

  (0-,1+,1-,gg->2m+,qq->2m+)