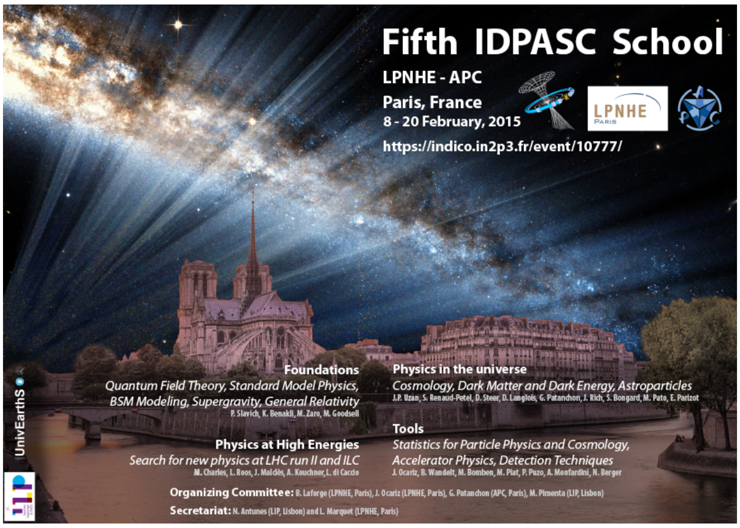
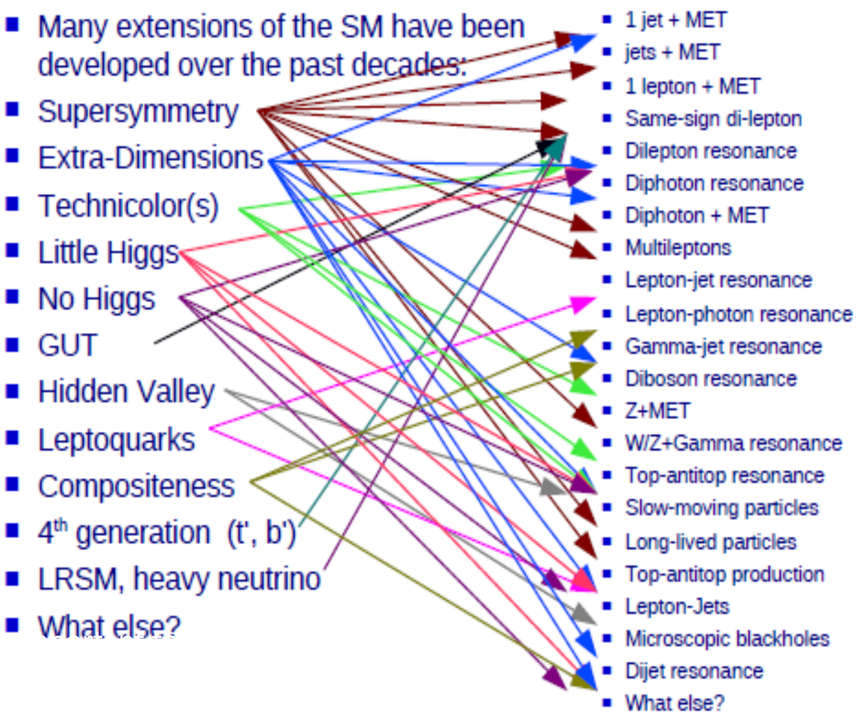
Beyond the Standard Model @ ATLAS & CMS

Lucia Di Ciaccio

Université de Savoie & CNRS/IN2P3-LAPP



A very long list of models & signatures



- **Complex 2D problem**

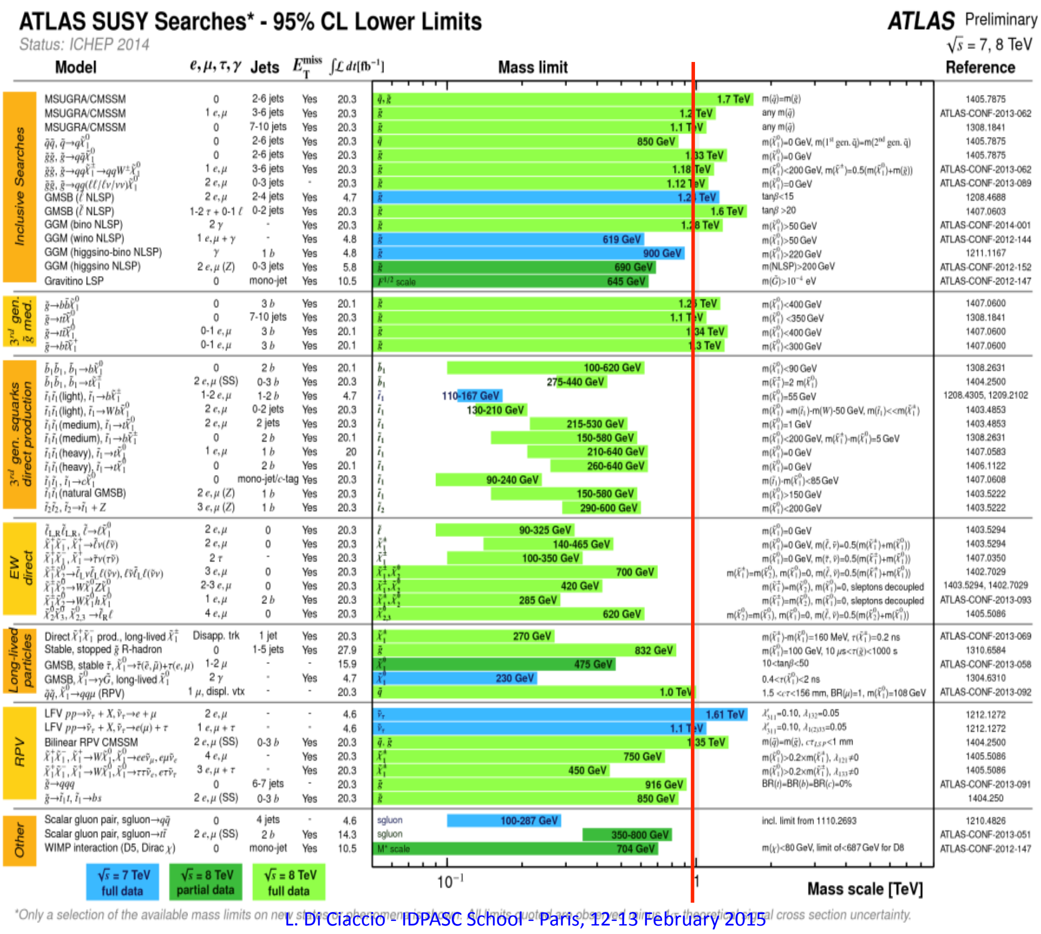
I'll proceed :
* **SUSY searches**
* **Exotics searches**

then I'll follow

- *Signature approach*:
  - Practical
  - Less model dependent

- **Important to investigate as many signatures as possible and to be in the first step of the search model independent**

SUSY searches



SUSY Searches

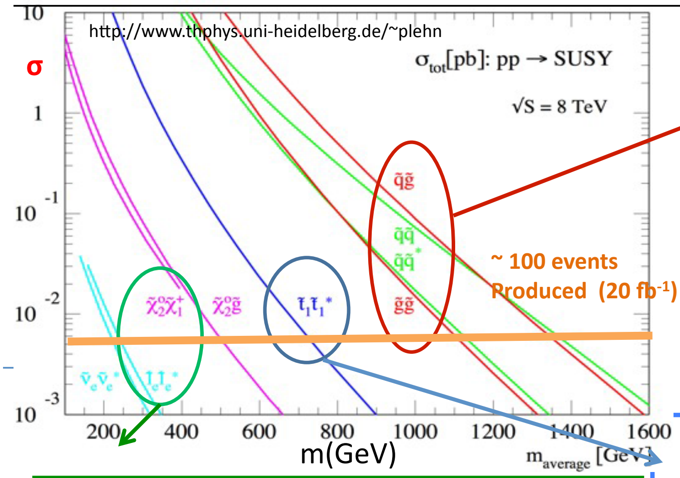
Too many results, impossible to show everything!

- Strong production of squarks and gluinos
- Third Generation searches includes: stops and sbottoms
- Electroweak production and R-parity violation

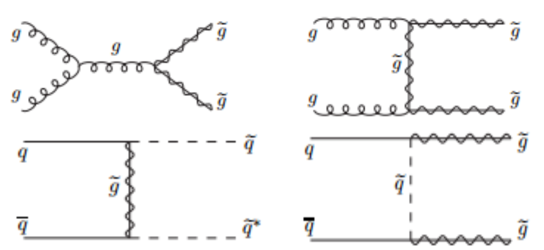
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

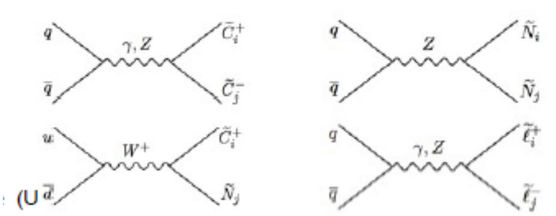
Production of SUSY particles @LHC



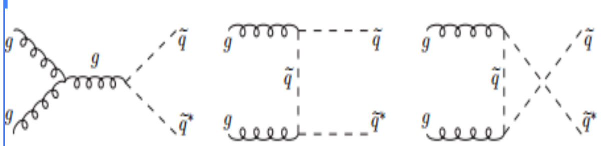
Strong production of gluinos, 1st/2nd generation squarks
expected sensitivity up to ~ 1.2TeV



Electro-weak production of charginos, neutralinos and sleptons
(reach ~ 0.2-0.5 TeV)

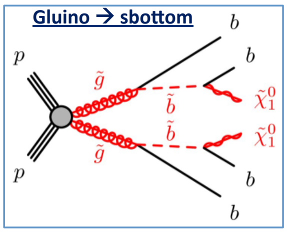


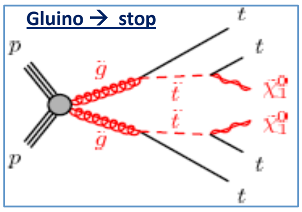
Strong production of 3rd generation squarks (s-top & s-bottom) gg->squark-squark
(up to 0.7 TeV)



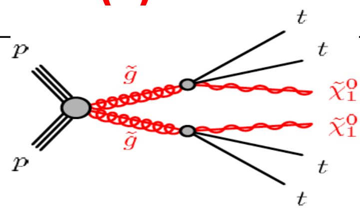
“Typical” SUSY Search: multijet+MET+0(1) l

Large cross-section





LSP = χ^0_1

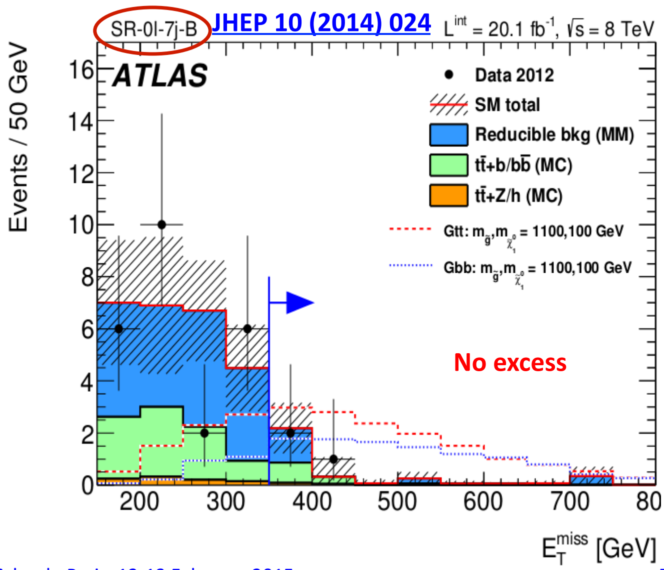


Gluino production with off-shell stops

ATLAS: Events with

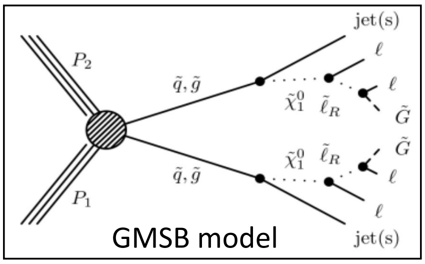
* 0 or 1 lepton (e^- or μ)
* Large E_t^{miss}
* ≥4 or ≥7 jets (of which ≥3 b-jets)
* kinematic variables combining E_t^{miss}, jet p_T, lepton p_T

After selection, events are classified into **9 SR** (sensitivity to kinematics of different models)



“Typical” SUSY Search: 3 leptons + MET

PRD 90,032006 (2014)



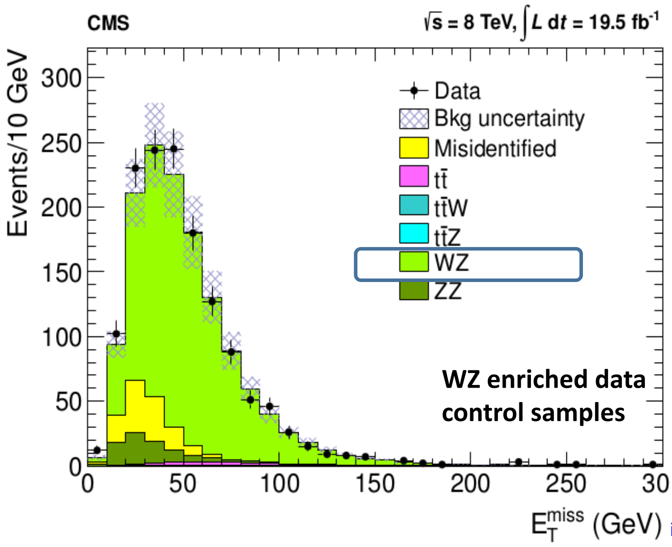
LSP = $\check{G}$

NLSP = $\tilde{l}_R$

CMS: Events with

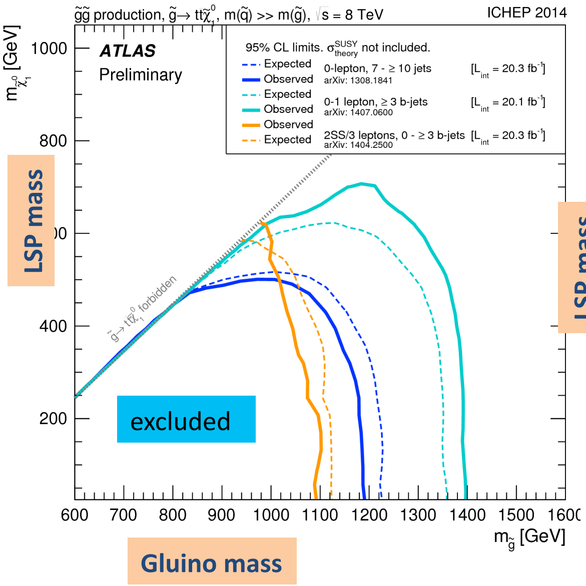
* ≥3 leptons (rare in SM)
* E_t^{miss}

* Sign and flavour of lepton pairs define categories
* Irreducible background from WZ & ZZ
* Lepton isolation requirements (against leptons from heavy flavours)
* E_T^{miss} & H_T (scalar sum of jet transverse momentum) used

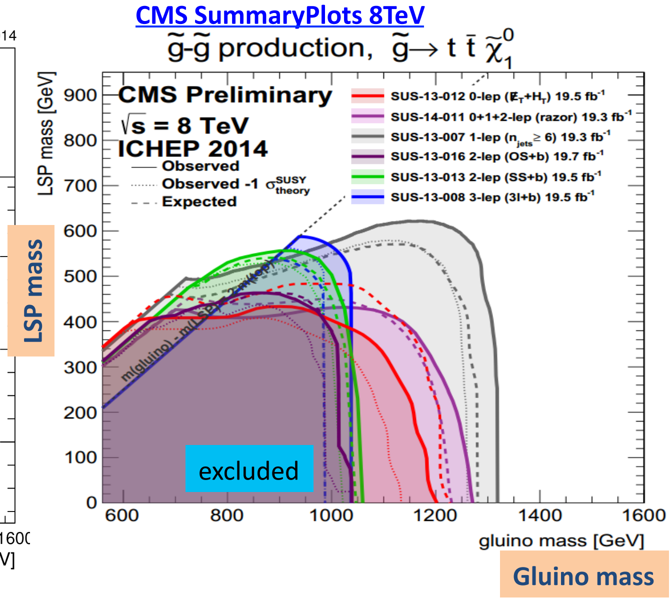


Gluino summary (simplified model)

[ATLAS SummaryPlots 8TeV]



[CMS SummaryPlots 8TeV]

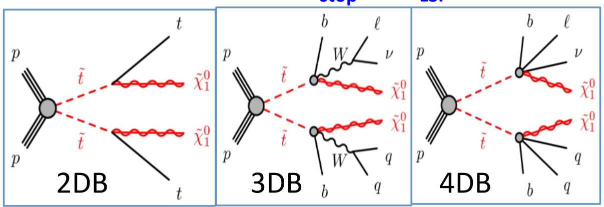


Mass (gluino)> 1340 GeV (for M_{LSP} < 200 GeV)

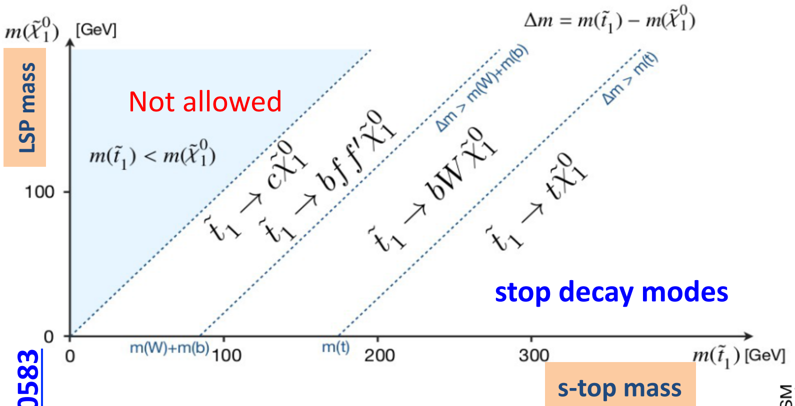
Third Generation: direct pair production of stops

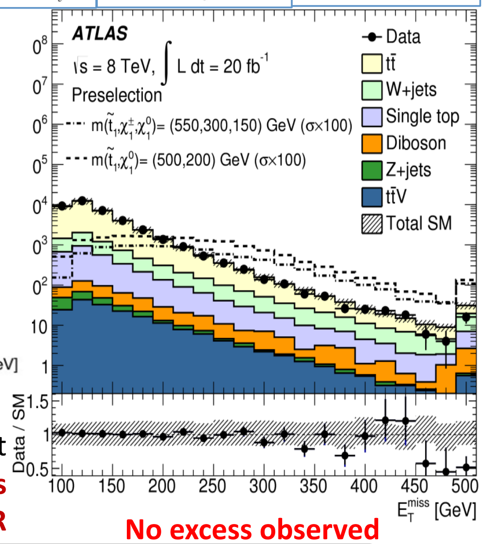
ATLAS: 1 lepton, E_t^{miss} and 4 (one b-) jets

Depend upon m_{stop} & m_{LSP}



* Target 2,3,4 **b**ody stop **d**ecays **t** + χ_1^0 as well as **b** **stop decays.** Different mass splitting χ_1 assumptions.
* Uses both cut and count and shape methods to search for deviations from the Standard Model





arxiv:1407.0583

To enhance sensitivity, various variables target different kinematic regions, e.g. **m_T** combinations, **soft leptons** for low mass stop / compressed scenarios and **large- R jets** for heavy stop (boosted)

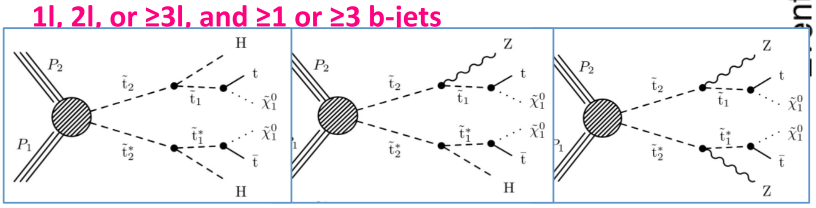
No excess observed

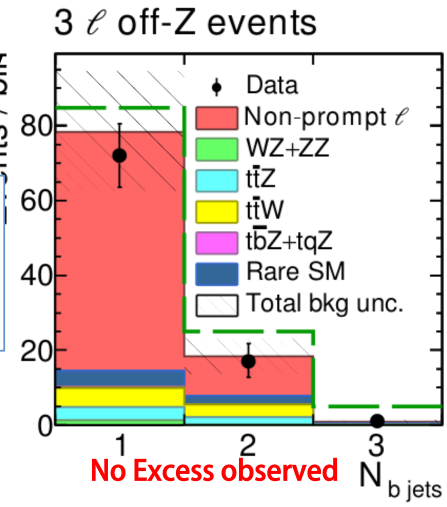
$$m_T = \sqrt{2 \cdot p_T^\ell \cdot E_T^{miss}\,(1 - \cos\Delta\phi(\vec\ell, \vec p_T^{miss}))}$$

Third Generation: direct pair production of stops

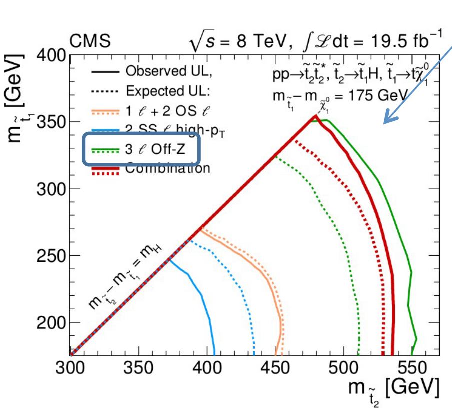
* **CMS:** direct pair production of top squarks, with **Higgs (H) or Z bosons** in the decay chain→ targets Heavier stop decay
* Select events containing leptons & b-jets.

1l, 2l, or ≥3l, and ≥1 or ≥3 b-jets





No Excess observed



stop2→stop1

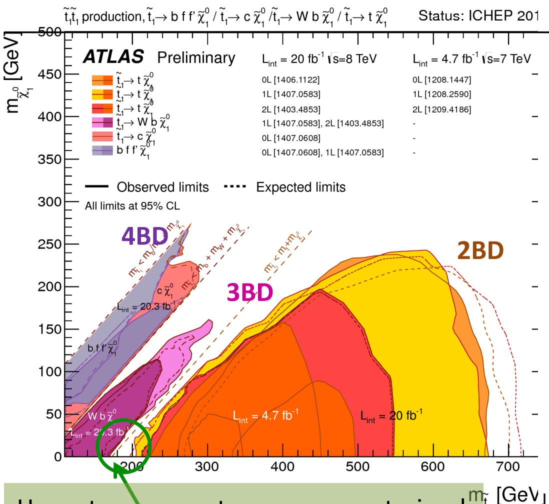
Analysis:

- Split by number of leptons and b-jets
- Use multiple kinematic variables for bkg suppression e.g E_t^{miss}, p_T, $m_T = \sqrt{2 p_T^{\ell} E_T^{miss} (1 - \cos\Delta\phi(\ell, E_T^{miss}))}$.

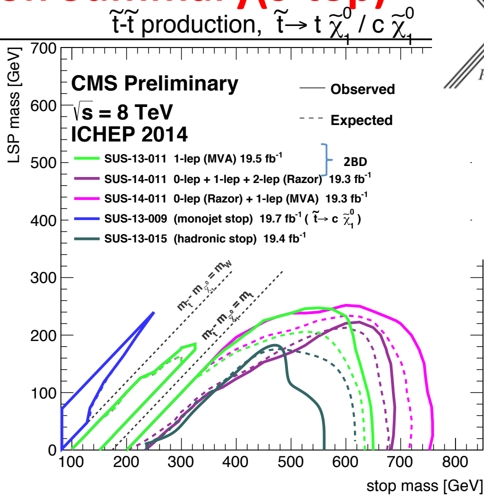
[Phys. Lett. B 736 (2014) 371]

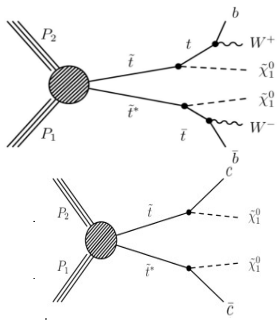
- 96 SRs
- Limits in $stop_1$, $stop_2$ mass plane, but indirectly probes difficult region of $stop_1$ χ_1^0 mass plane

Third Generation Summary(s-top)



Here stop mass ≈ top mass, constrained by tt cross-section measurement



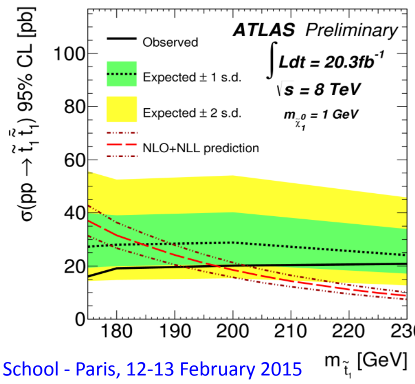


Many different stop decay channels, different sparticle mass hierarchies, and simplified decay scenarios

Spin correlation in tt-bar
[arXiv 1406.5375]

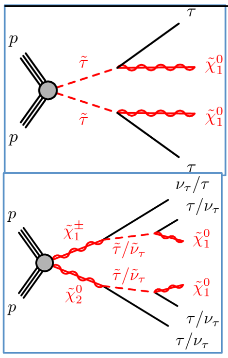
- Based on tt production in opposite dilepton channel

*Δϕ between 2 lepton used to extract correlation between t and t-bar spins



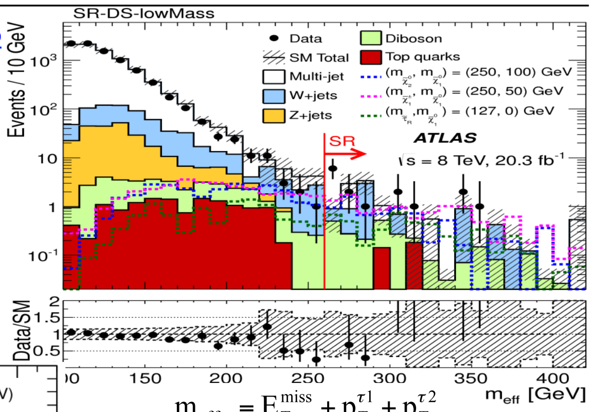
m_{stop} between m_{top} & 191 GeV excluded

Electroweak Searches (ATLAS): 2 $\tau + E_T^{miss}$

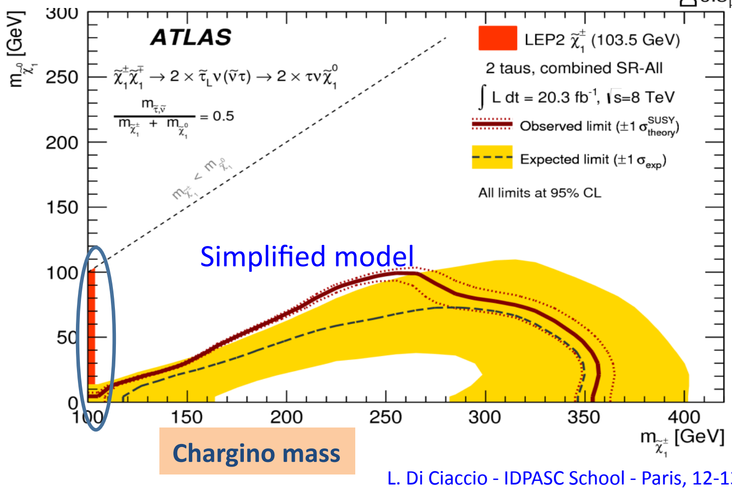


$2\,\tau + E_T^{miss}$ JHEP 10 (2014) 096

Analysis:
direct stau production and stau via **Chargino-neutralino** Decays



$$m_{eff} = E_T^{miss} + p_T^{\tau 1} + p_T^{\tau 2}$$



* 4 SRs
*2 opposite sign taus is req. in all SR + jet veto
* cuts on E_T^{miss}, m_T comb. or m_{eff}

No excess observed

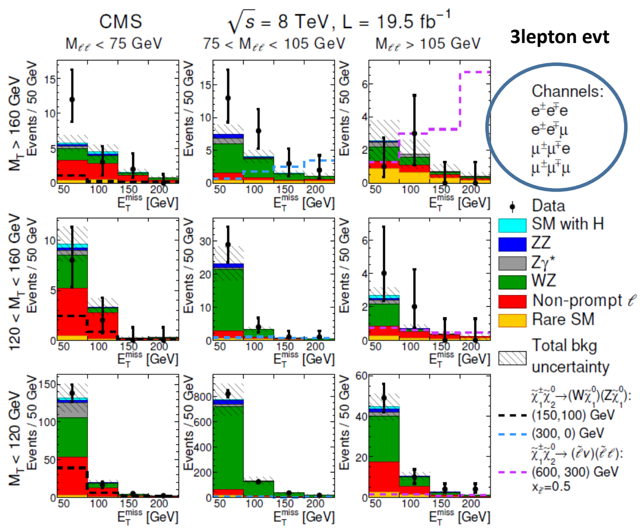
Limits on chargino mass 350 GeV

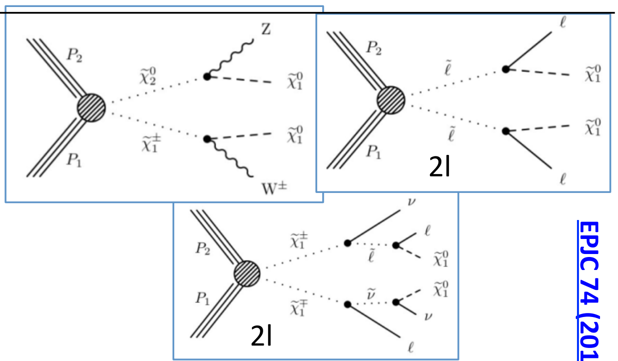
Electroweak Searches (CMS):multilepton

One, two, three or four leptons and E_T^{miss}

* Search charginos/neutralinos/sleptons in signatures with leptons/WZ/Higgs
* Events are split by number of lepton, some use "**binned**" signal regions

No excess





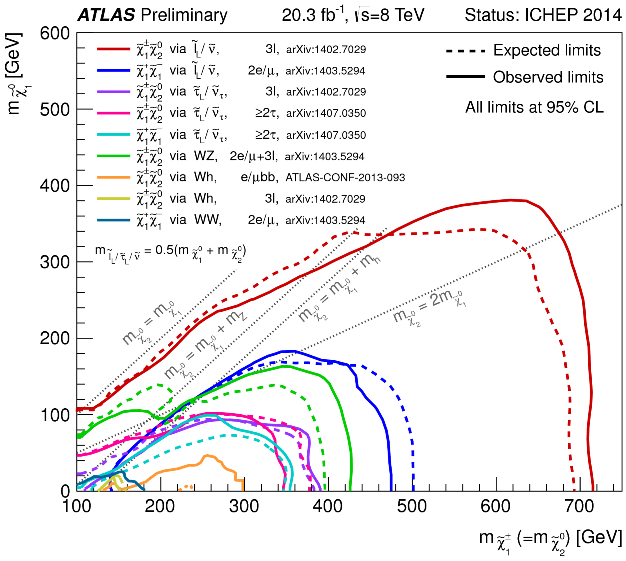
EPJC 74 (2014) 3036

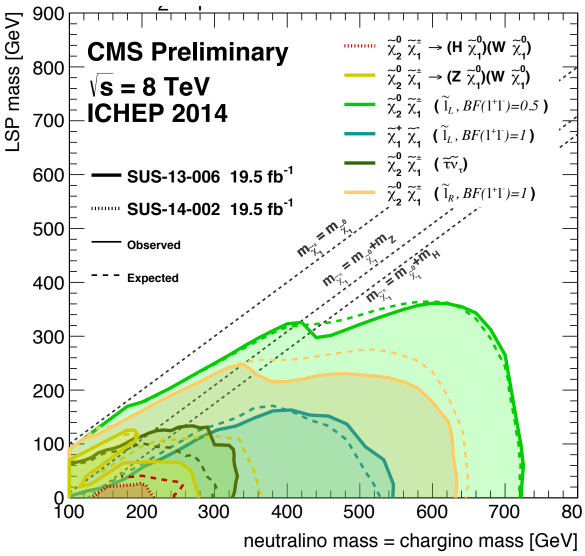
- **One** lepton targets $\chi_1^{\pm}\chi_2^{0} \to$ WH
- **Two** lepton targets direct slepton production (and three lepton scenarios where one lepton is lost)
- **Three** leptons target $\chi_1^{\pm}\chi_2^{0}$ through sleptons or to ZH/ZZ/ WH
- Four lepton is interpreted in Gauge Mediated Symm. Breaking(GMSB)

Probe charginos and neutralinos with masses **up to 720 GeV**, and sleptons up to **260 GeV**, depending on the model

Electroweak Summary ($\tilde{\chi}_2^0\tilde{\chi}_1^\pm$)

* Analyses cover wide range of possible decays of **neutralino & chargino production**





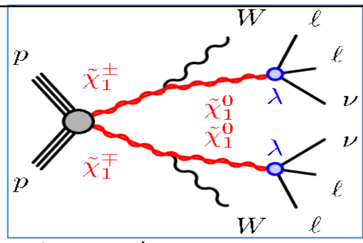
* **Limits depend on final states (weaker for tau final states)**
* **Probing chargino-neutralino masses up to 200-700 GeV**
* **Also Higgsino masses probed up to 210 GeV (380 GeV in GMSB model)**

R-Parity Violation (RPV): 4l + MET

R-Parity
***R* =+1 for particles, -1 for sparticles**

If RPV, LSP decays to SM particle

Products of LSP decay depend on λ coupling



* R-Parity violating simplified models with decays lightest SUSY particle to e⁻ /μ

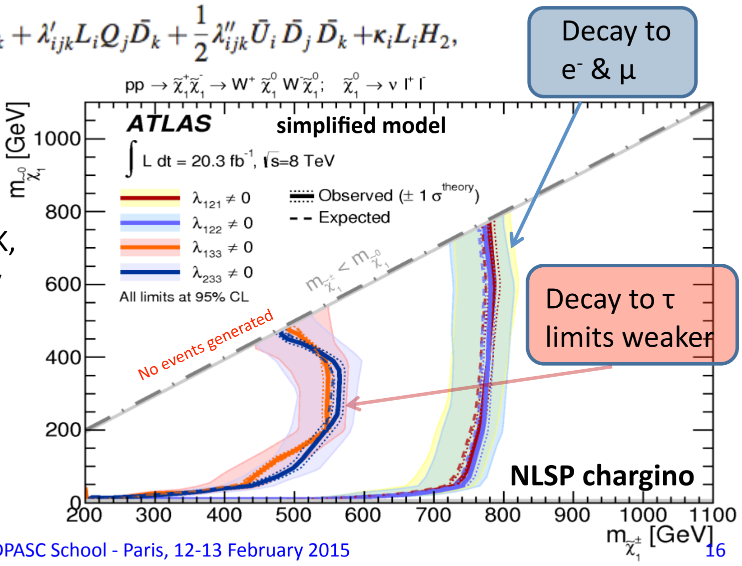
RPV superpotential $\frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k + \kappa_iL_iH_2,$

L,Q, E = superfield, *i,j,k*=generation

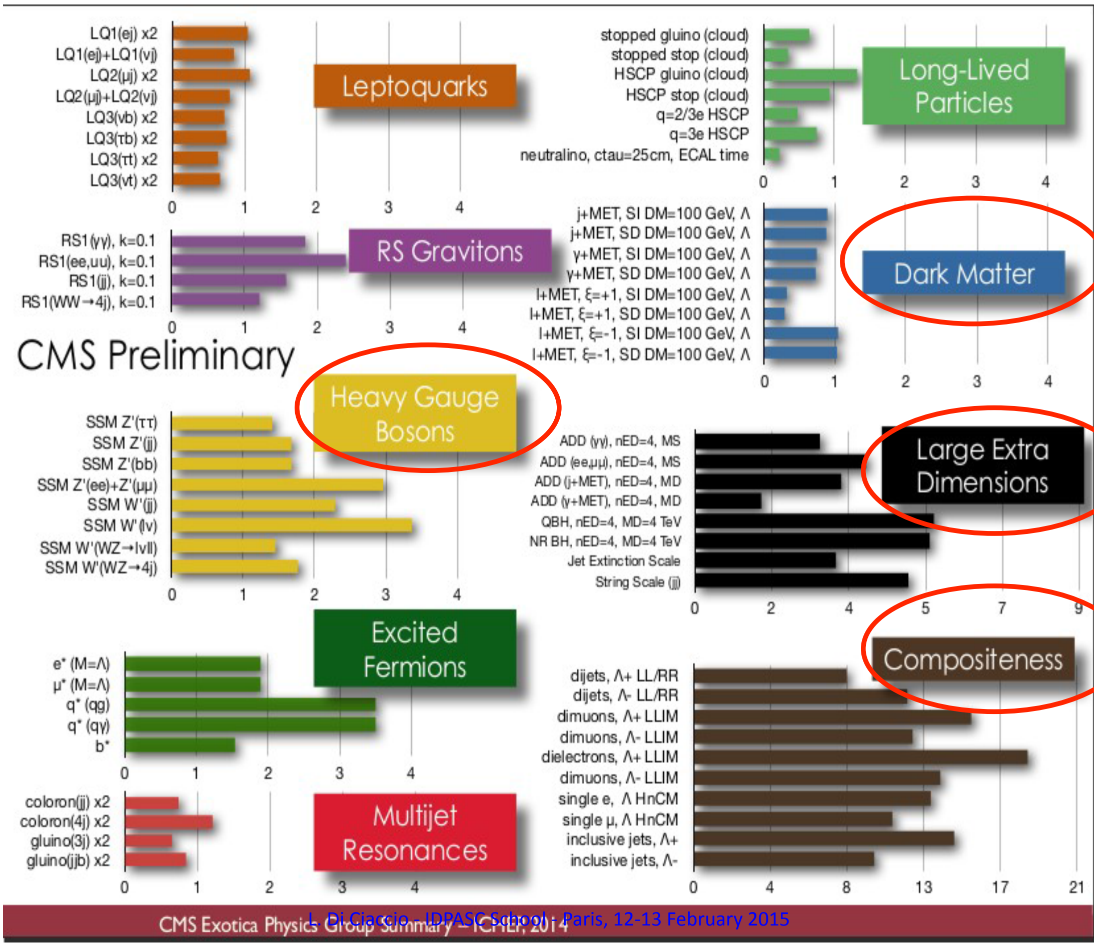
- **ATLAS : four leptons and E_T^{miss}**
  PRD.90,052001(2014)

* Versatile analysis–interpreted in EWK, general gauge mediated and R-parity violating (mostly EWK) models
* Very low backgrounds
* **9 SRs** containing **0,1** or **2** taus

No excess observed



Exotic searches



Exotic Searches

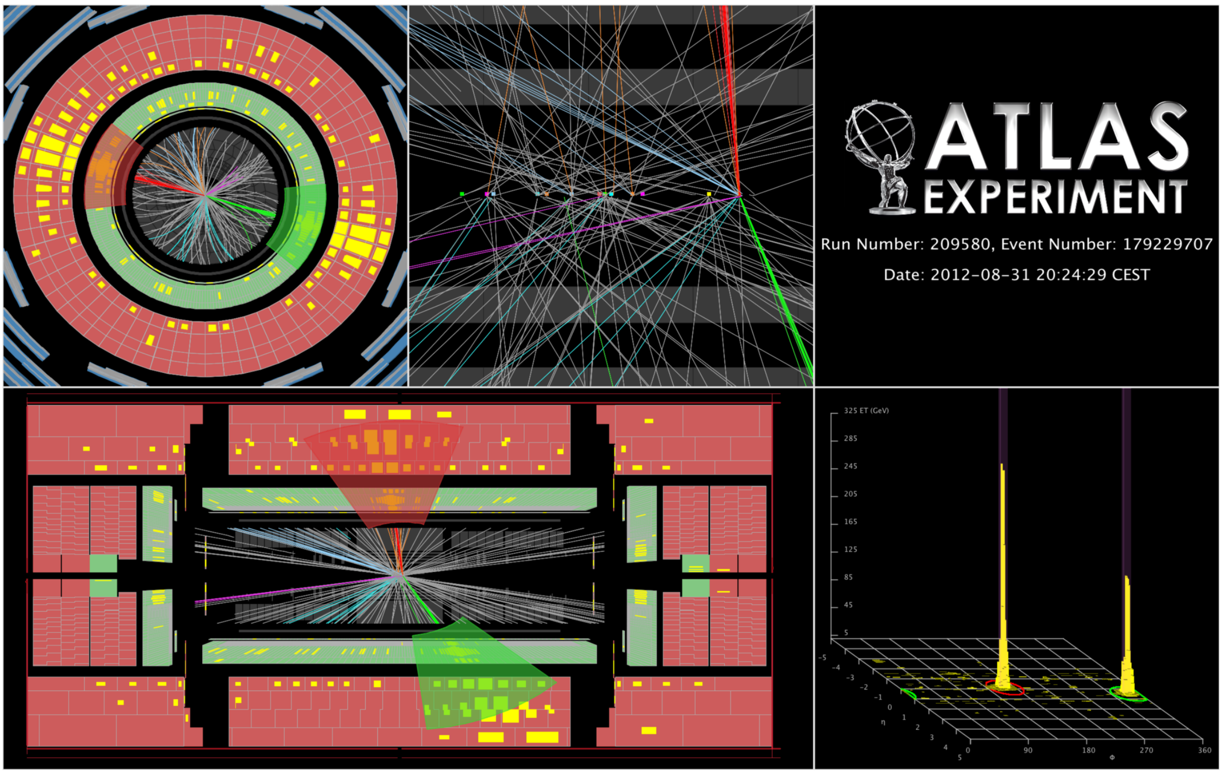
- Heavy resonance : dijet
- Dark Matter & Extra Dimensions (Mono X, X= jet,γ)
- Vector like Quarks

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G

Dijet Event (mass=4.69TeV)



Heavy Resonance: Dijets channel

Heavy Resonance in dijet channel :
very early search for numerous resonances BSM: excited quarks, string resonance, axi-gluons, colorons, E6 diquarks, W' & Z', RS gravitons

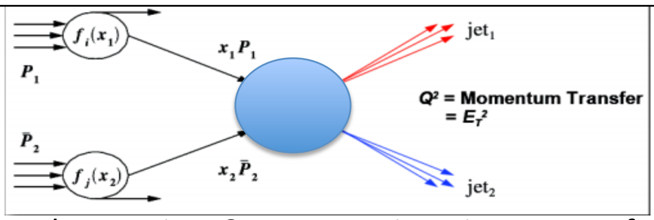
- **If quarks are composite**, then there will be excited states, **q***, which would decay to a quark and a neutral boson (gluon, photon or Z)

  Look for following decays: q*→qg; q*→qγ, q*→qZ
  Signature: **resonance in di-jet**, photon+jet or Z+jet mass spectrum

- More generally the scattering of two quarks (and gluons, and quarks against gluons) will not follow QCD but will show deviations from the exchange of a new boson

  Signature: the angular distribution of two-jet events will look different from "Rutherford scattering with scaling violations"

Heavy Resonance: Dijets channel

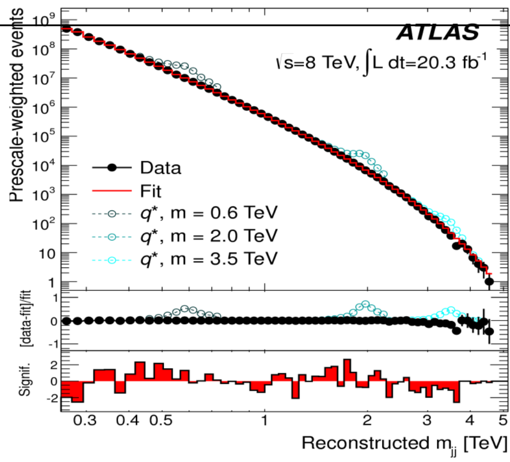


- Select ≥ 2 jets & construct invariant mass of 2 highest p_T jets
- Look for resonance above phenomenological fit of data

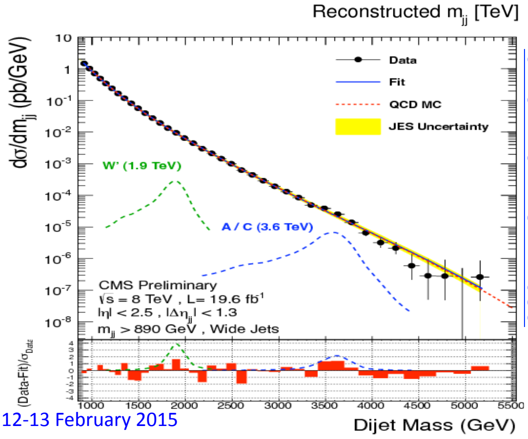
$$f(x) = p_1(1-x)^{p_2}\, x^{p_3 + p_4 \ln x}$$
$$x = m_{jj}/\sqrt{s}$$

❖ **ATLAS vs CMS analysis**
- **Combination of pre-scaled jet triggers vs H_T/m_{jj} at HLT**
- **Anti-k_T R=0.6 jets** Vs **wider jets (R~1.1**

❖ **Both Experiments:**
- Rapidity cuts to enhance scattering (Δη) & M_{jj}

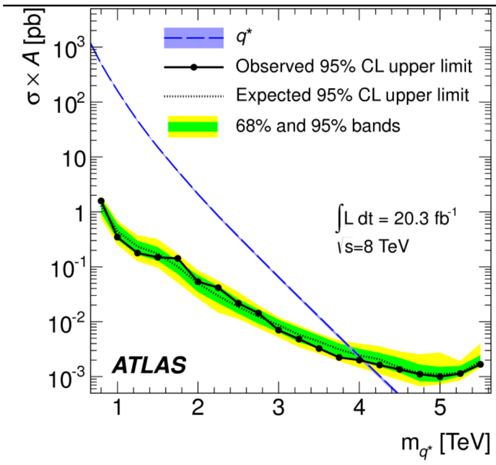


arxiv:1407.1376



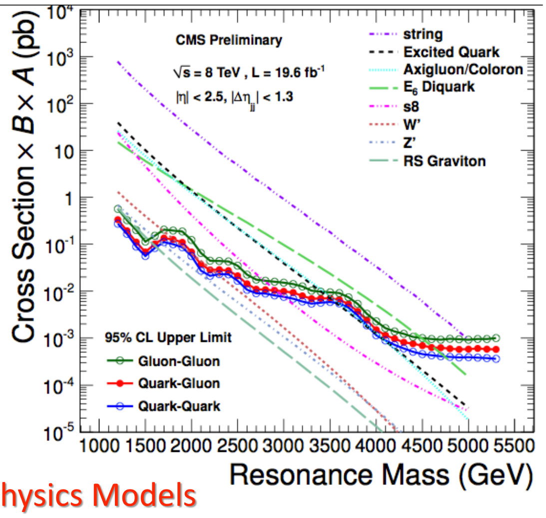
CMS-PAS-EXO-12-059

Heavy Resonance: Dijets



arXiv:1407.1376

CMS-PAS-EXO-12-059



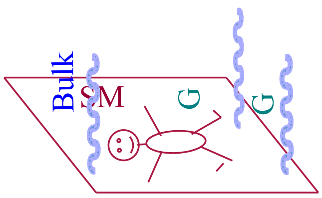
95% C.L Limit on various physics Models

Model and Final State	95% CL Limits [TeV] Expected	Observed
$q^* \to gg$	3.99	4.09
$s8 \to gg$	2.83	2.72

Model	Final State	Obs. Mass Excl. [TeV]	Exp. Mass Excl. [TeV]
String Resonance (S)	qg	[1.20,5.08]	[1.20,5.00]
Excited Quark (q^*)	qg	[1.20,3.50]	[1.20,3.75]

Extra-dimensions?

why gravity is so weak ? $M_{W/Z}/M_{Planck} \approx 10^2$ GeV/10^{19} GeV $G_F/G_N \approx 10^{32}$



Extra-Dimensions

Proposed answer :

- gauge and gravity **unify** at a **fundamental scale M_D** $\approx$ 1 TeV
- observed weakness of gravity **at distance R** due to **$n \geq 2$ new spatial dimensions**

$$V_4(r) \sim \frac{1}{M_{Pl}^2}\frac{1}{r} \longrightarrow V_{4+n}(r) \sim \frac{1}{M_D^{n+2}R^n}\frac{1}{r} \quad @\ r >> R \qquad M_{Planck}^2 \approx M_D^{n+2} R^n$$

If $M_D \approx$ 1 TeV then

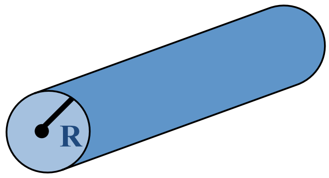
n=1 $R \approx 10^{13}$ m $\rightarrow$ excluded by macroscopic gravity

n=2 $R \approx 0.7$ mm $\rightarrow$ limit of small- scale gravity experiments

….

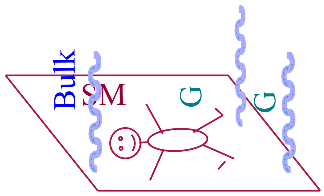
→ A **gravity scale** as low as M_D **~ 1** TeV is possible, provided that there exist n additional dimensions with $n \geq 2$ **compactified/curled-up** over R < mm

Graviton field has excitation states due to finite size of compactified space ('Kaluza Klein towers')



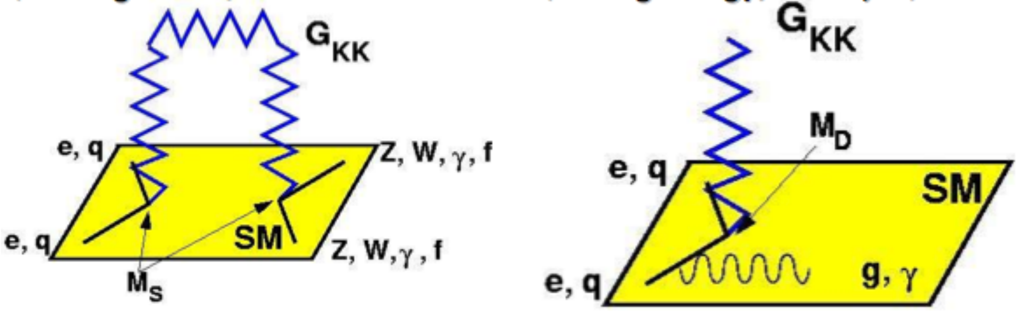
Extra-Dimensions(ED)

- gravitons move freely in all dimensions
- SM fields localized to 4-dim. space-time



Indirect effects
(virtual graviton)

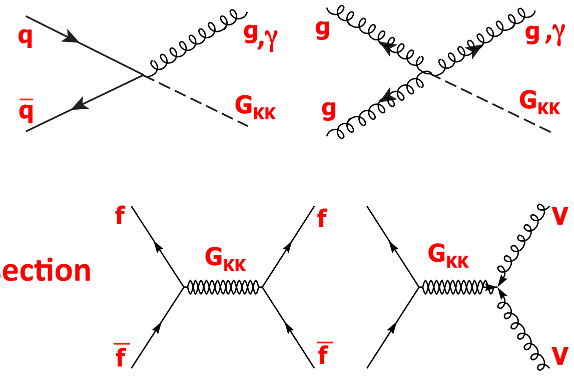
Direct effects
(missing energy, mono-jets)



(Some) Extra-Dimension signatures

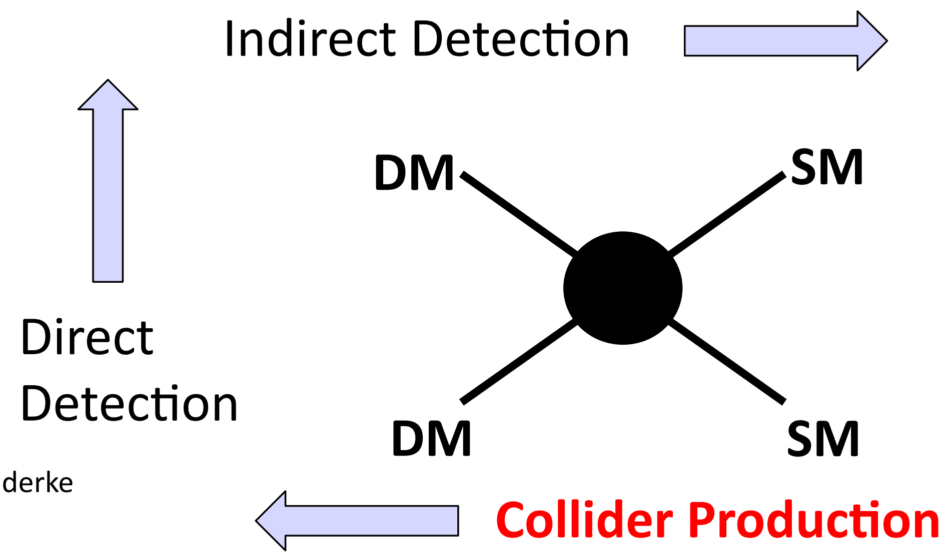
Many models(*) (**ADD, RS, TeV^{-1}, UED**) --> different signatures :

- **single photon/jet + MET** (real G_{KK})
  - direct graviton production in **ADD**
- **di-lepton, di-photon, di-jets resonances**
  - **RS** model (Z_{kk} decays)
- **modifications di-lepton, dijet SM cross-section**
  - virtual graviton exchange in **ADD**
- **single leptons + MET**
  - W_{kk} decays
- **back to back energetic jets + MET**
  - **UED**
- **high multiplicity/sphericity**
  - microscopic back holes in LargeED scenarios



(*)
ADD=Arkani-Hamed, Dimopoulos, Dvali (LargeED)
RS= Randal Sundrum
UED=Universal Extra Dimension

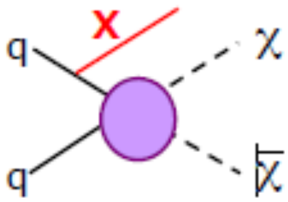
Dark Matter?



M. Fedderke

Dark Matter @ LHC

- DM has no known interactions beyond gravity
  → assume it interacts "weakly" (WIMP= weakly Interactive Massive Particle)
  → DM particles could be produced in collisions at LHC and escape detector unobserved)



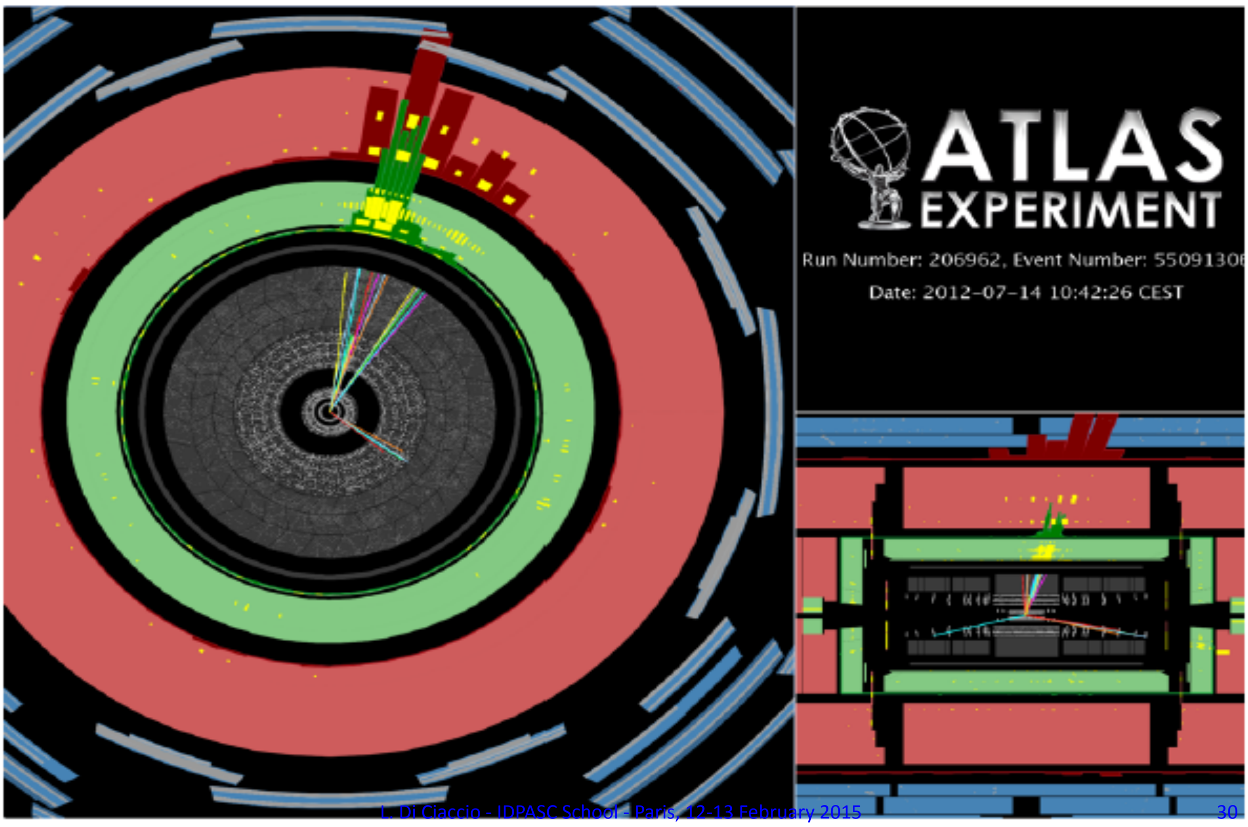
Detection @ LHC

→ **"X(s)+ missing E_T "**

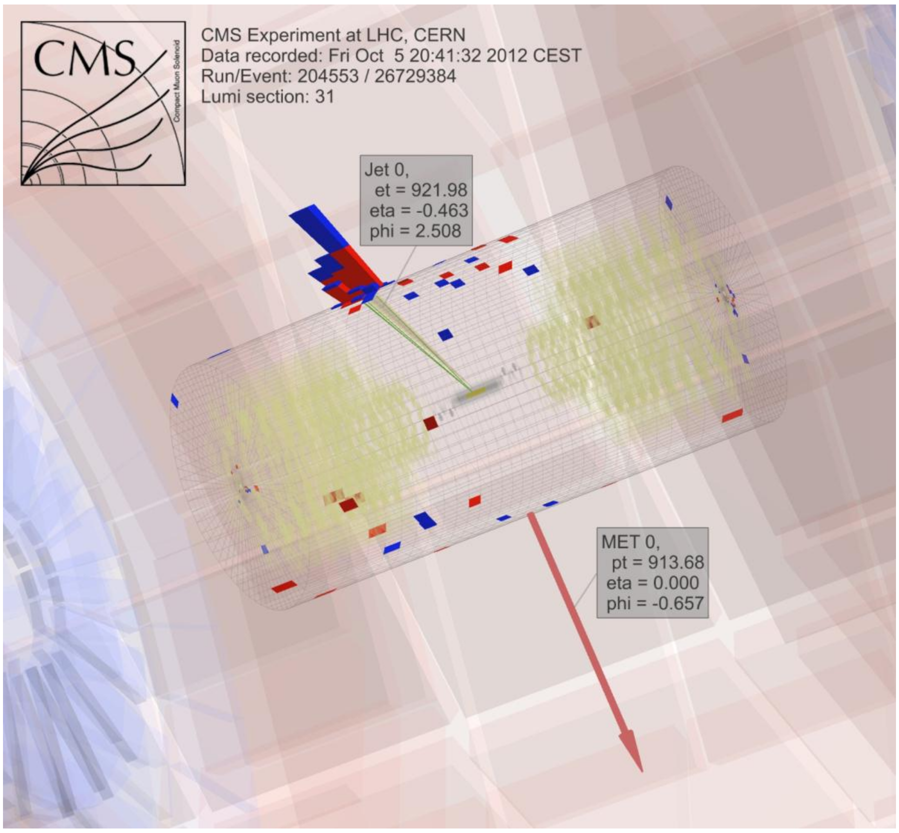
X: quark/gluon (Jet), γ, W/Z radiated from incoming quark/gluon

Large E_T^{miss} indicates presence of non-interacting particles (perhaps Dark Matter ?)

Mono-jet event (high-p_T jet and E_t^{miss}) in ATLAS



Mono-jet event (high-p_T jet and E_t^{miss}) in CMS



Mono-jet search (X=q/g)

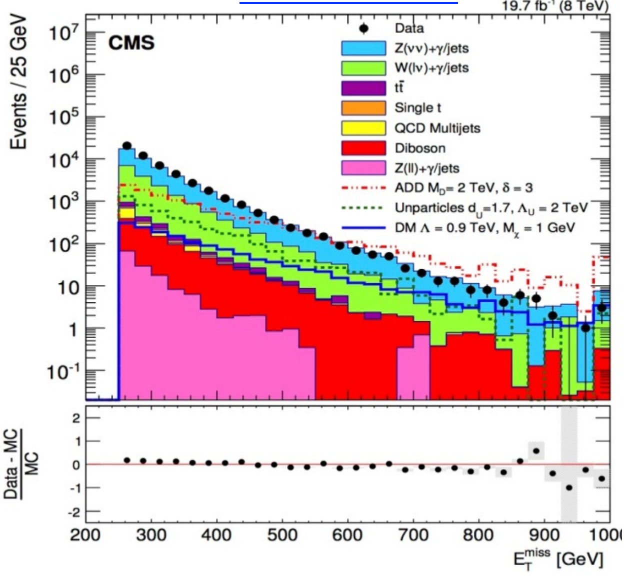
❖ **(Typical) Monojet Selection**

- Leading jet **p_T > 120 GeV, |η|<2.4, Njet ≤ 2**
- Topological cuts against QCD : $\Delta\Phi(E_t^{miss}$, jet2)< 0.5
- Veto events with isolated leptons

❖ **Background from Data-Driven and MC**

- Measure **Z(μμ)+jets**: predict Z(νν)+jets
- Measure **W+jets**: predict W(lν) +jets (l fake)
- Smaller backgrounds from top, QCD, non-collision

arXiv: 1408.3583

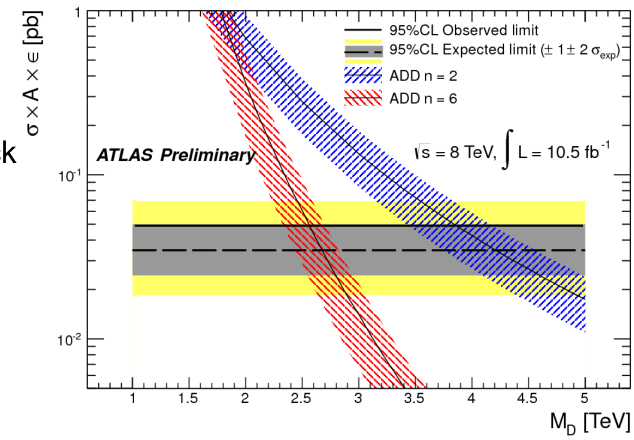


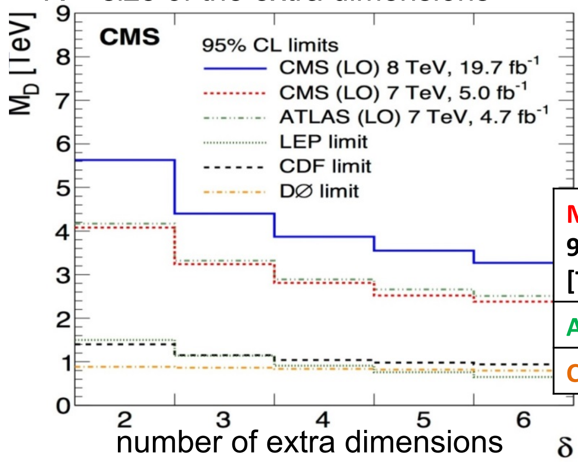
Mono-jet search (X=q/g)

Large Extra Dimensions:
Arkani-Hamed, Dimopoulos, Dvali (ADD)

M_{Pl} = 4-dimensional Planck scale
M_D = fundamental(4+n) dimensional Planck scale

δ,n = number of extra dimensions
R = size of the extra dimensions

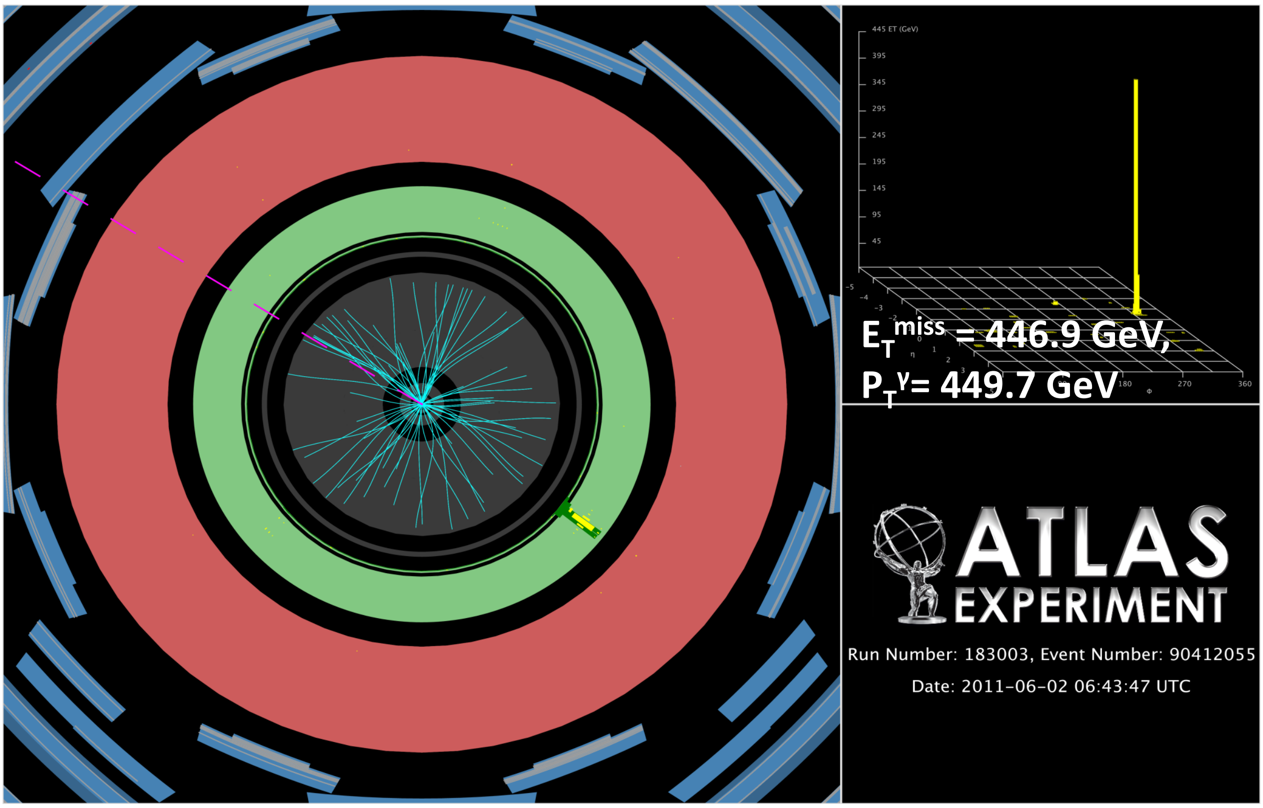




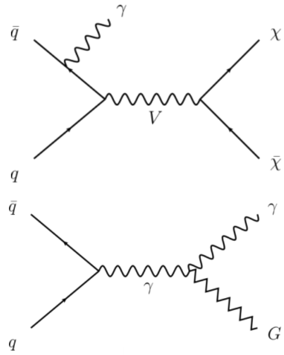
M_D (ADD) at LO 95% CL limits [TeV]	√s [TeV]	Lumi [fb^{-1}]	δ = 3 Exp	δ = 3 Obs.	δ = 6 Exp	δ = 6 Obs.
ATLAS Monojet	8	10.5	3.39	3.16	2.69	2.58
CMS Monojet	8	19.7	4.38	3.96	2.95	3.26

Limits on M_D in the range of ~ 3 – 4 TeV

Mono-photon event (high-p_T photon and E_t^{miss})



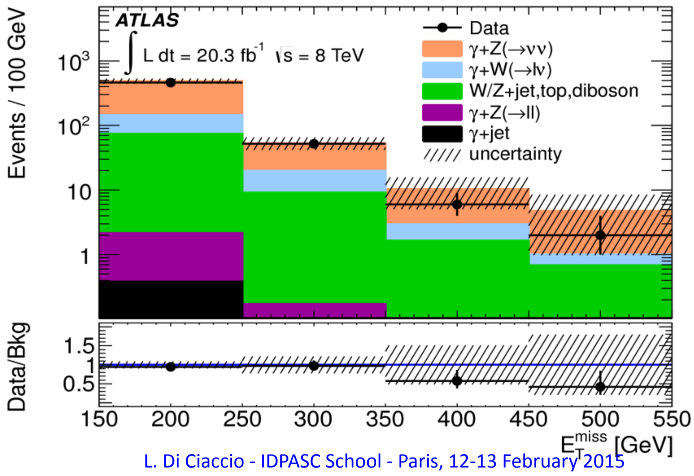
Mono-photon (high-p_T photon and E_t^{miss})



- Large Extra Dimension, Dark matter or SUSY partners of the quarks (squarks) predict the production of **Photon +E_t^{miss}**

- **Event Selection**
- E_t^{miss} >150 GeV & p_T^{γ} >125GeV
- (η<1.37) & $\Delta\phi(\gamma, E_t^{miss})$>0.4.

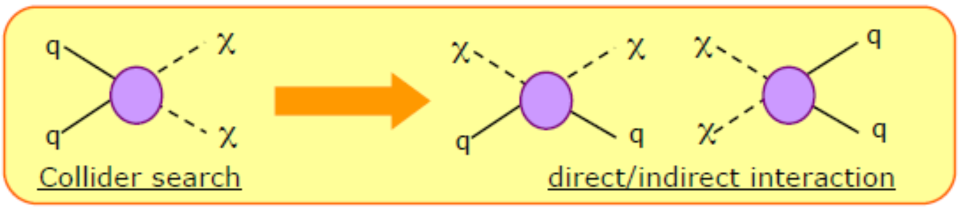
arxiv1411.1559



Dark Matter Interpretation

No excess has been observed

Compare sensitivity with existing direct/indirect searches



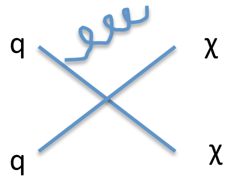
Model Independent:

* SM- χ mediator very heavy → Contact Interaction (CI)
* Effective field theory approach: CI ($\Lambda = M^*/\sqrt{g_q\, g_\chi}$)
* χ is Dirac fermion
* Cross-section depends on the scale Λ and m_{DM}

$$\sigma \propto (\mu/\Lambda^2)^2 , \ \mu = m_{DM} m_p/(m_{DM}+m_p)$$

M* is the mass of the heavy mediator
χ DM candidate

$$\mathcal{L} \supset \frac{1}{\Lambda_V^2}\bar{\Psi}\gamma_\mu\Psi\bar{q}\gamma^\mu q + \frac{1}{\Lambda_A^2}\bar{\Psi}\gamma_\mu\gamma_5\Psi\bar{q}\gamma^\mu\gamma_5 q$$



$$\frac{g_q\, g_\chi}{M^2} \sim \frac{1}{\Lambda^2}$$

Lorentz structure of SM (q and g) currents and DM Dirac fermions **in CI**

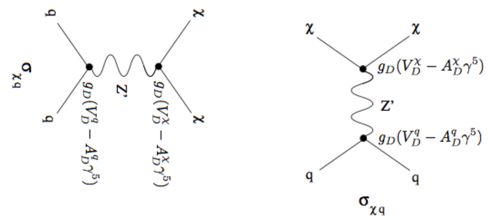
1210.4491v2

Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G_{\mu\nu}^a)^2$

Mono-photon

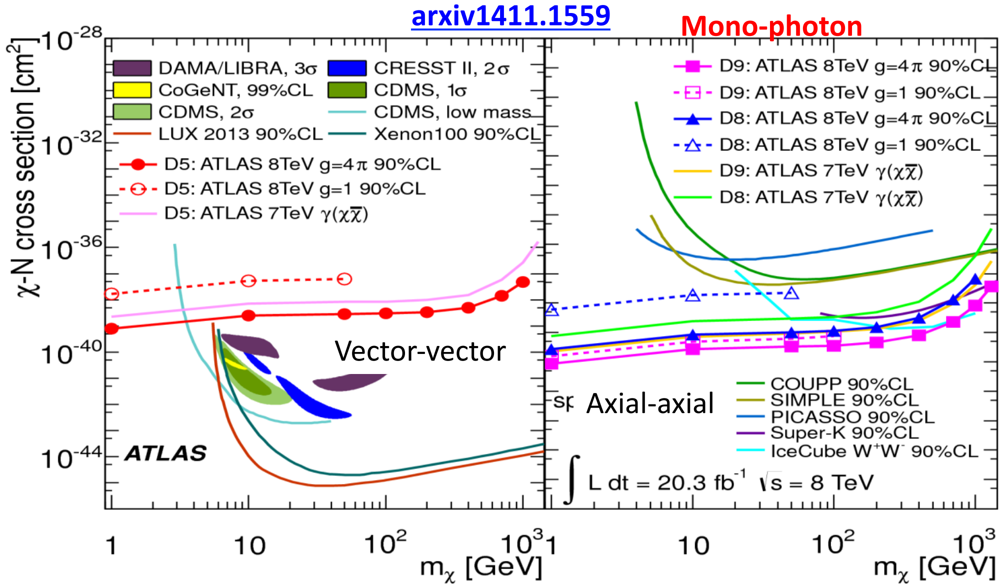
Expected (observed) upper limits on the cross section and on the M are set

* Lower limits on M* can be converted into upper limits on WIMP-Nucleon scattering cross section:



arxiv1411.1559

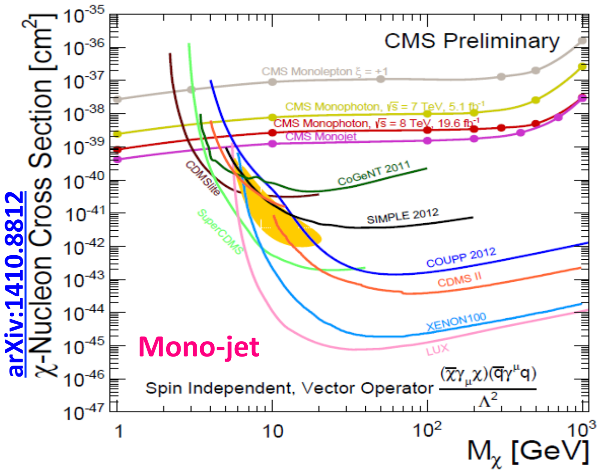
Mono-photon

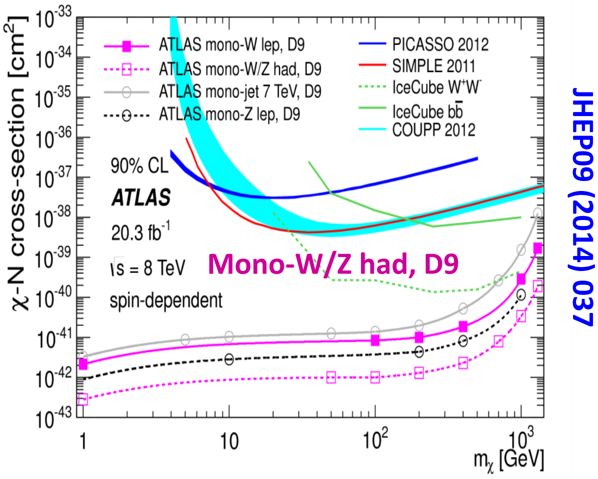


DM interpretation: limits on WIMP-Nucleon cross section

- ❑ Lower limits on M_* are converted into upper limits on WIMP-Nucleon scattering cross section
- ❑ In general: Most powerful in mono-jet (or mono W if constructive interference)

➢ Limits on dark matter-nucleon scattering cross-sections are also provided for low mass(m_χ<10GeV) region where direct detection experiments have less senstivity





Exotic Heavy Quark (Motivation)

❑ Little-Higgs models

➡ existence of fermionic partners of t/b quarks

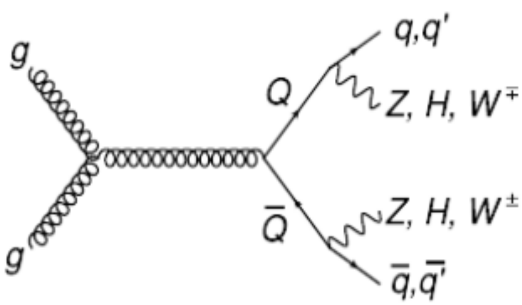
Alternatives to solve the Hierarchy problem

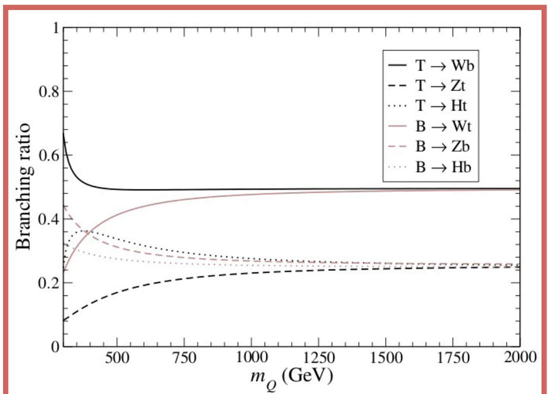
Constraints from the discovery of the Higgs Boson:

➢ **4^{th} generation: disfavoured** (should enhance $H\to\tau\tau$ and suppress $H\to\gamma\gamma$)

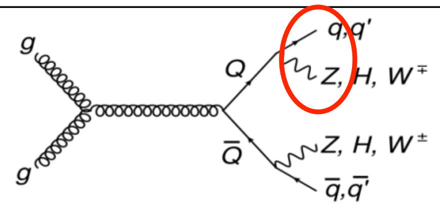
➢ **Vector like Quarks(VLQ):**

- Left & right-handed chirality's transform in the same way under SU(2)xU(1)
- Mass independent from the Higgs boson coupling
- No constraint from Higgs discovery

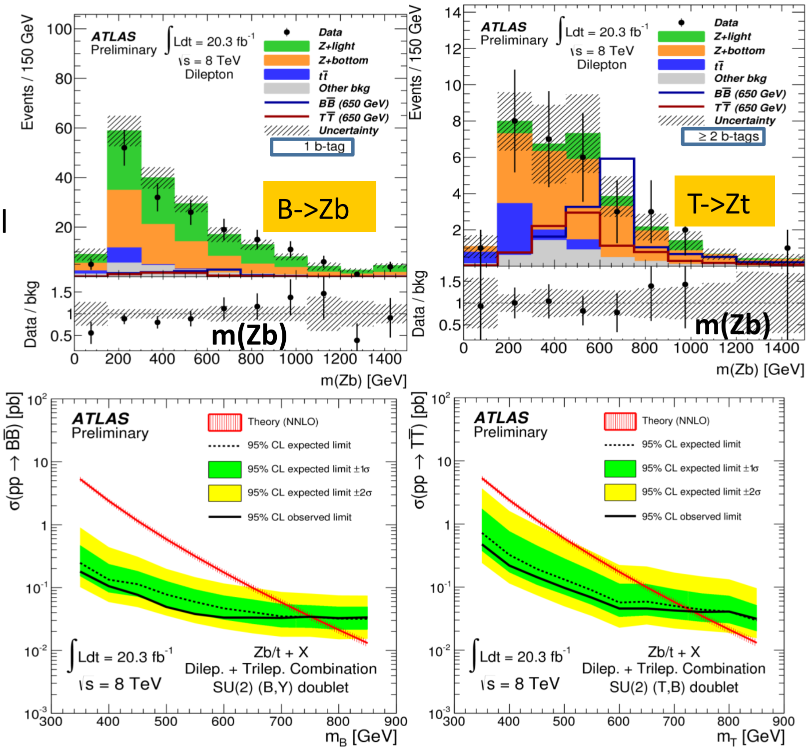




Vector-like Quarks (T/B) →Z(t/b)



arXiv:1409.5500



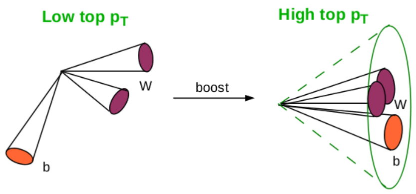
* The invariant mass of Z & highest pt b-jet, used as final discriminant in dilepton channel

* The dist. m(Zb) is peaked at heavy quark mass (B) & peaks at a lower value & is wider in case of (T)

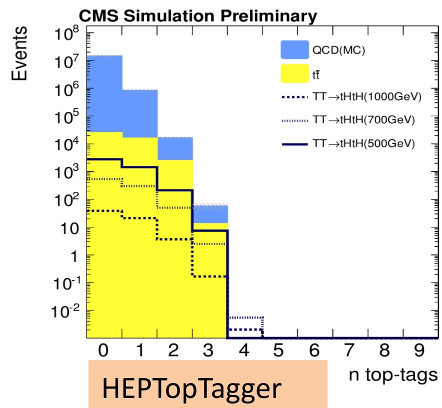
❖ Limits on SU(2) doublet vector-quark mass:
T=735 GeV, B=755GeV

VLQ (top-Higgs resonance) T'→ tH (H → bb)

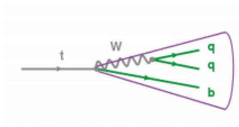
- ❑ LittleHiggs model, Extra Dim, Composite Higgs predicts pair produced Heavy Quark decaying into top & Higgs.
- ❑ T' →$b\bar{b}bjj$ is the main final state.
- ❑ Attempt to probe this **all hadronic** final state
- ❑ Highly boosted topology
- ❑ Top and Higgs tagging combined to b-tagging



CMS PAS B2G-14-002

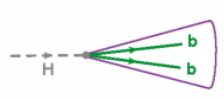


Select events with ≥ 1 top tags and ≥ 1 Higgs tags



Boosted top-quark jets are identified using Top-tagging:

- HEPTopTagger
- Subjet b-tag



Boosted Higgs boson jets are identified using Higgs-tagging:

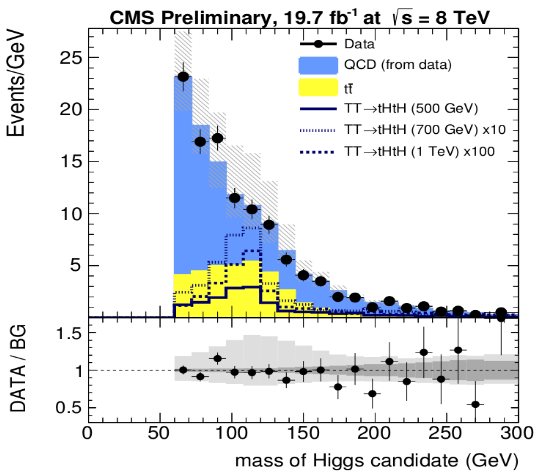
- Based on 2 subjet b tags
- Invariant mass of b jets > 60 GeV

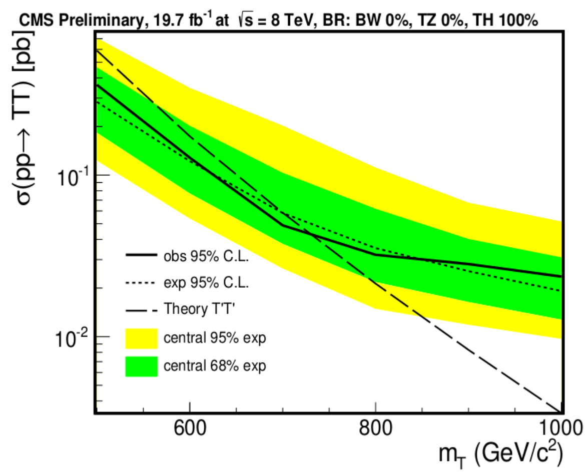
Backgrounds reduced very effectively using substructure tools

VLQ T’→ tH (H → bb)

Sensitive variables: H_T & m_H distinguish signal from bkg.
→ These two variables are used in the statistical analysis for setting limits on T production cross-section.

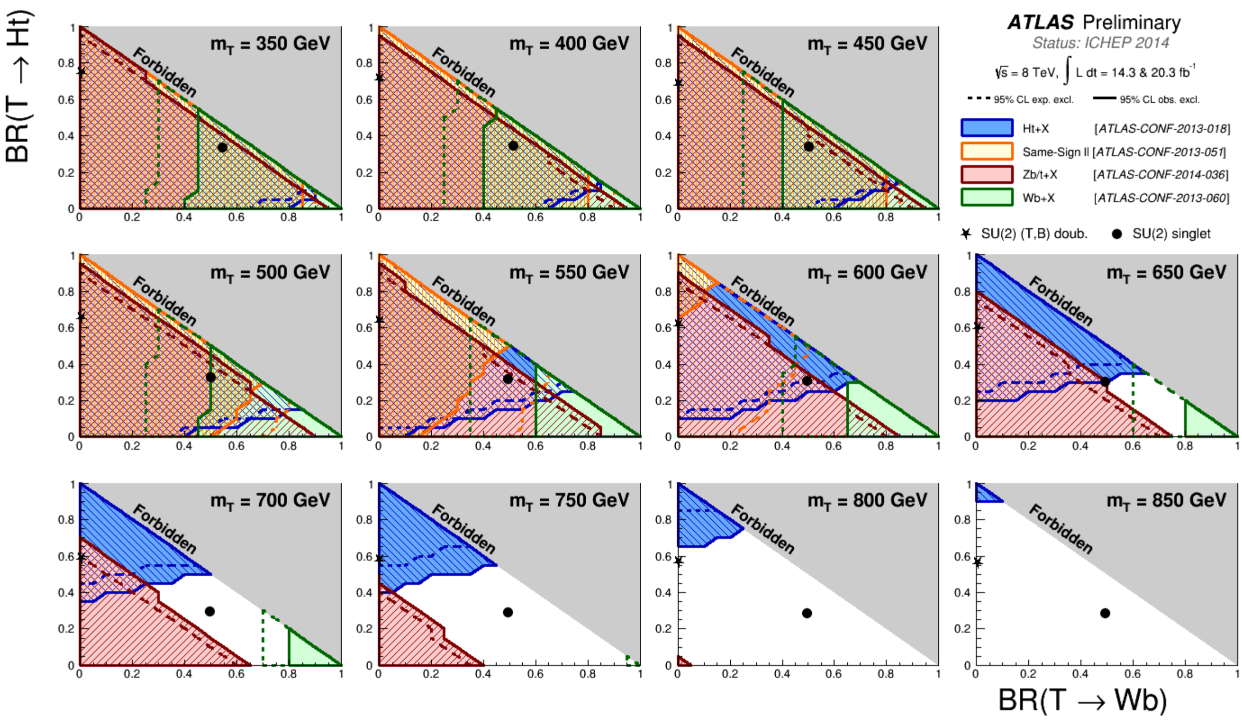
CMS PAS B2G-14-002



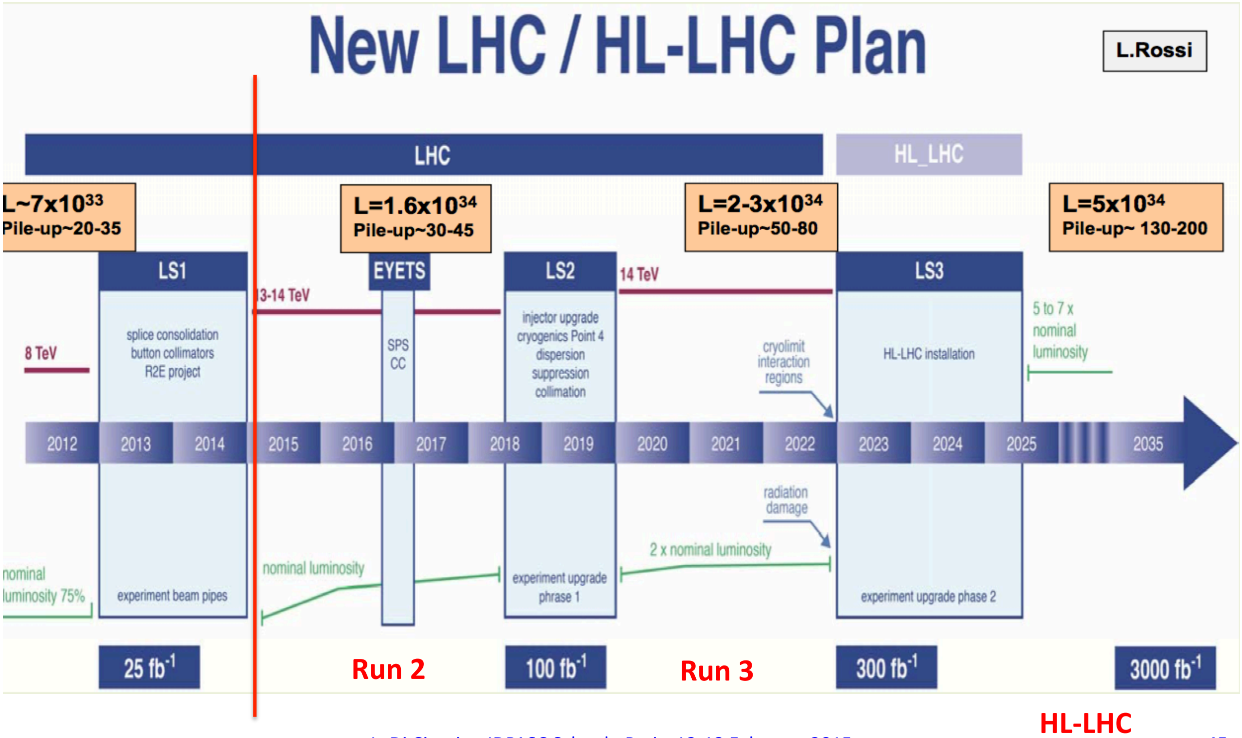


Mass limit for 100% T’ → tH: Expected 701 GeV
Observed 747 GeV

Exclusion Limits for Vector Like T Quark



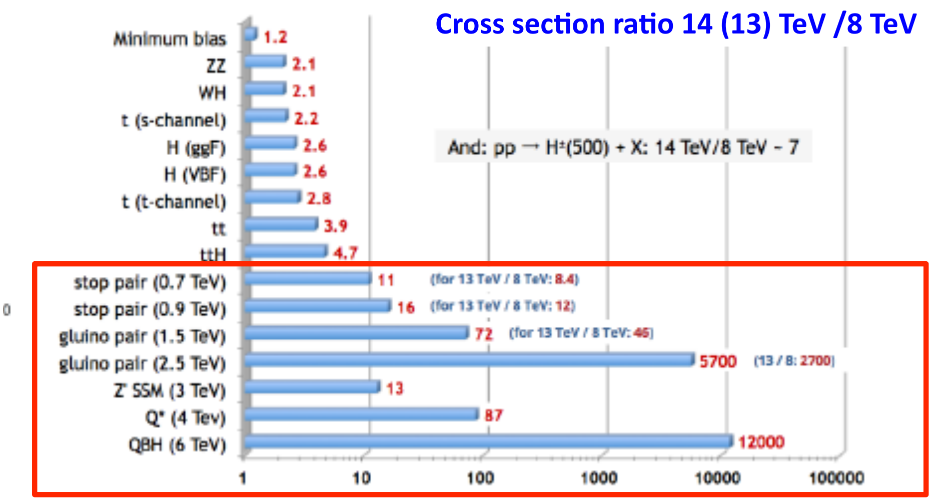
Outlook



HL-LHC

The next steps for the LHC

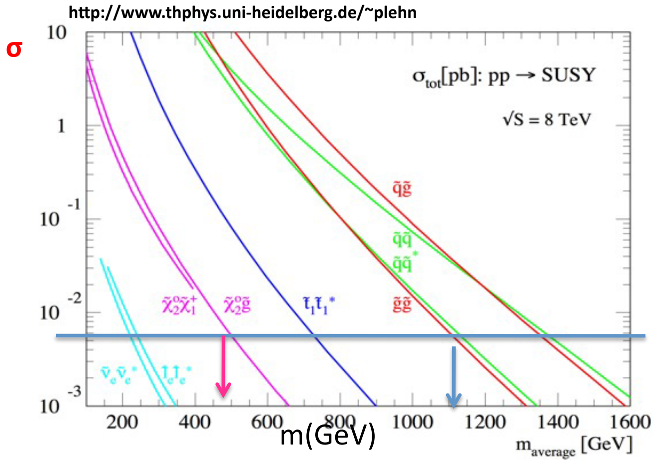
- **LHC Runs 2 (100 fb^{-1}) and 3,** up to **300 fb^{-1}** at **√s =13/14** TeV
  → Huge increase wrt Run 1 in sensitivity in multi-TeV region



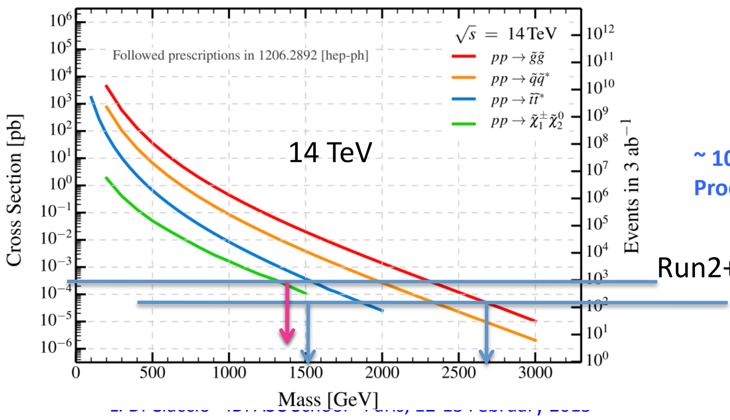
- **High Luminosity (HL)-LHC :** up to **3000 fb^{-1}** at **√s = 14** TeV

→factor 10 luminosity crucial for new Physics processes with low cross section (eg. EWK SUSY, 3rd generation squarks)

SUSY
X-sections



~ 100 events
Produced (20 fb-1)



~ 100 events
Produced

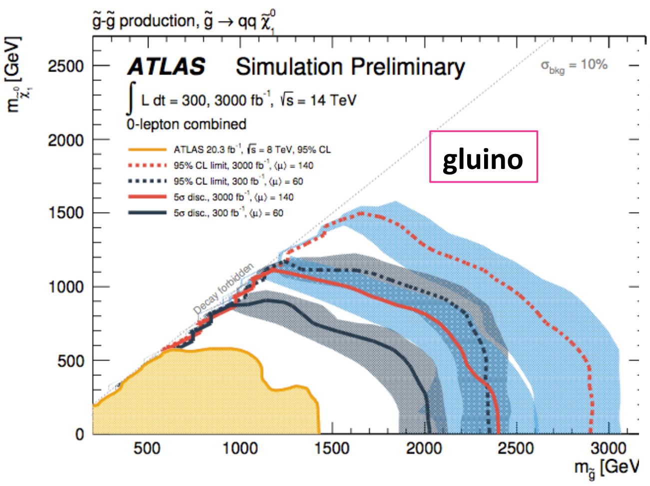
Run2+3

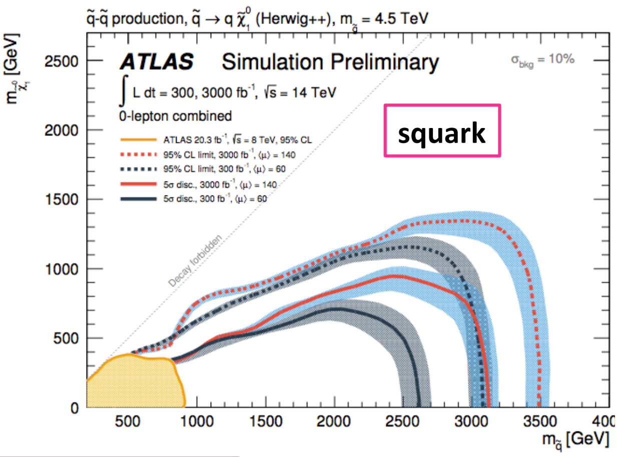
HL-LHC

Outlook for ATLAS SUSY: Squark & gluinos @ HL-LHC

Striking improvements to limits in strong searches and EWK with 300 fb^{-1} and 3000 fb^{-1} . Possibility of discovery

Will we be able to keep a good control of the background (and of the detector response)?





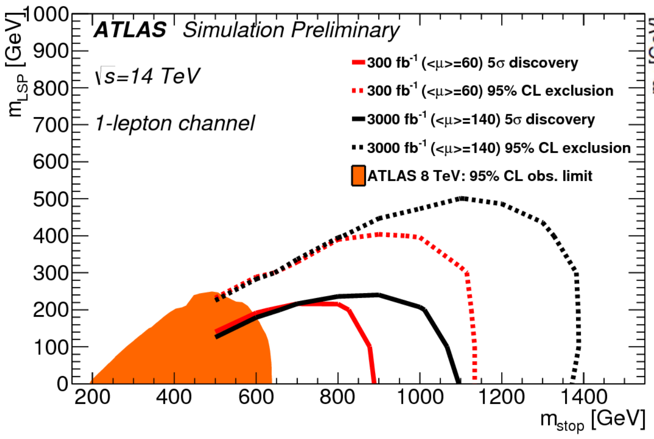
Discovery reach up to 2.5-3 Tev

Outlook for ATLAS SUSY: Stop and chargino

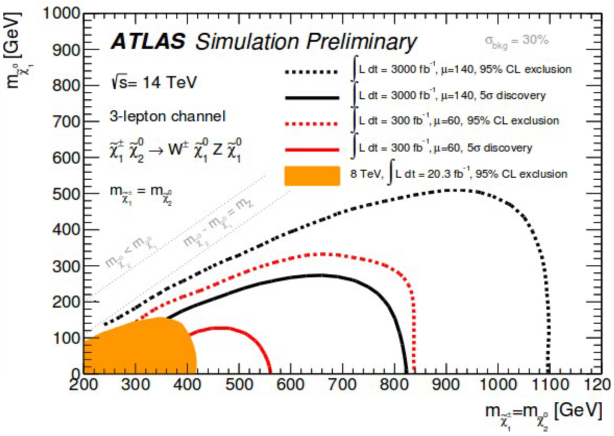
Striking improvements to limits in strong searches and EWK with 300 fb^{-1} and 3000 fb^{-1}. Possibility of discovery

Will we be able to keep a good control of the background (and of the detector response)?

ATLAS-PHYS-PUB_2013-011



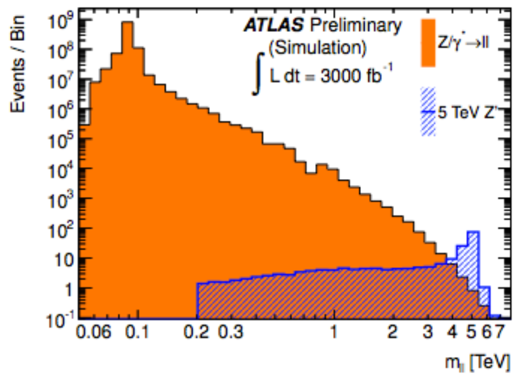
ATLAS-PHYS-PUB-2014-010



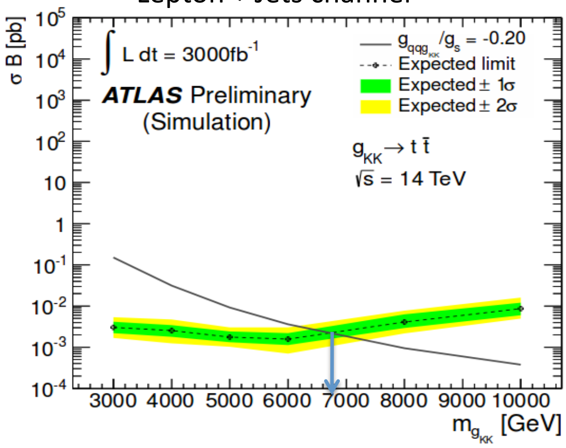
Outlook ATLAS Exotic

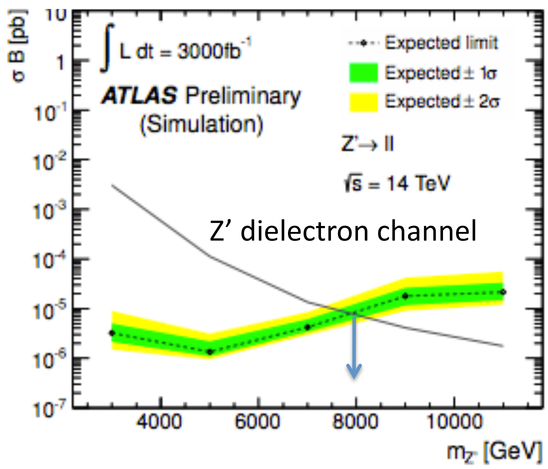
Similar study for two exotics searches dilepton resonances ttbar and can be probed up to **6.7** TeV and **7.8** TeV with 3000 fb-1

ATLAS-PHYS-PUB-2013-003



Lepton + Jets channel

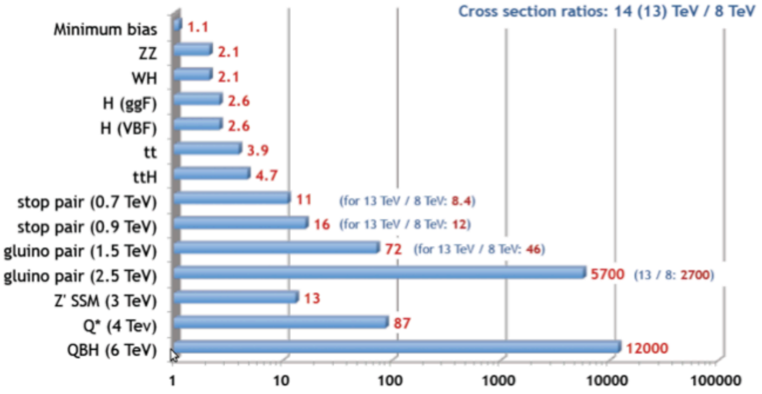




Conclusions

- Run 1 was a great success:
  with the long awaited discovery of the Higgs boson
  and provided with new understanding on where New Physics is not

- Run 2 is quickly approaching
  The experiments are preparing for its start
  Run 2 will collect data at an **unprecedented reached energy**
  Uncharted territory will be reached. This will allow to explore in detail remote a new vast phase space looking for “new-physics”
  → **New Physics** discoveries could be made even at early Run 2



THE END