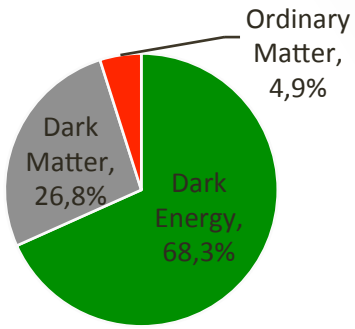
Searches for Dark Matter in events with long-lived particles at the LHC

Marco Schioppa

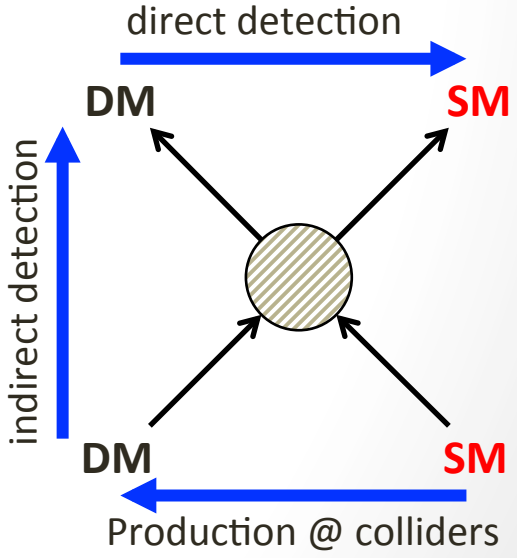
INFN and University of Calabria

On behalf of ATLAS, CMS and LHCb Collaborations

Dark Matter …

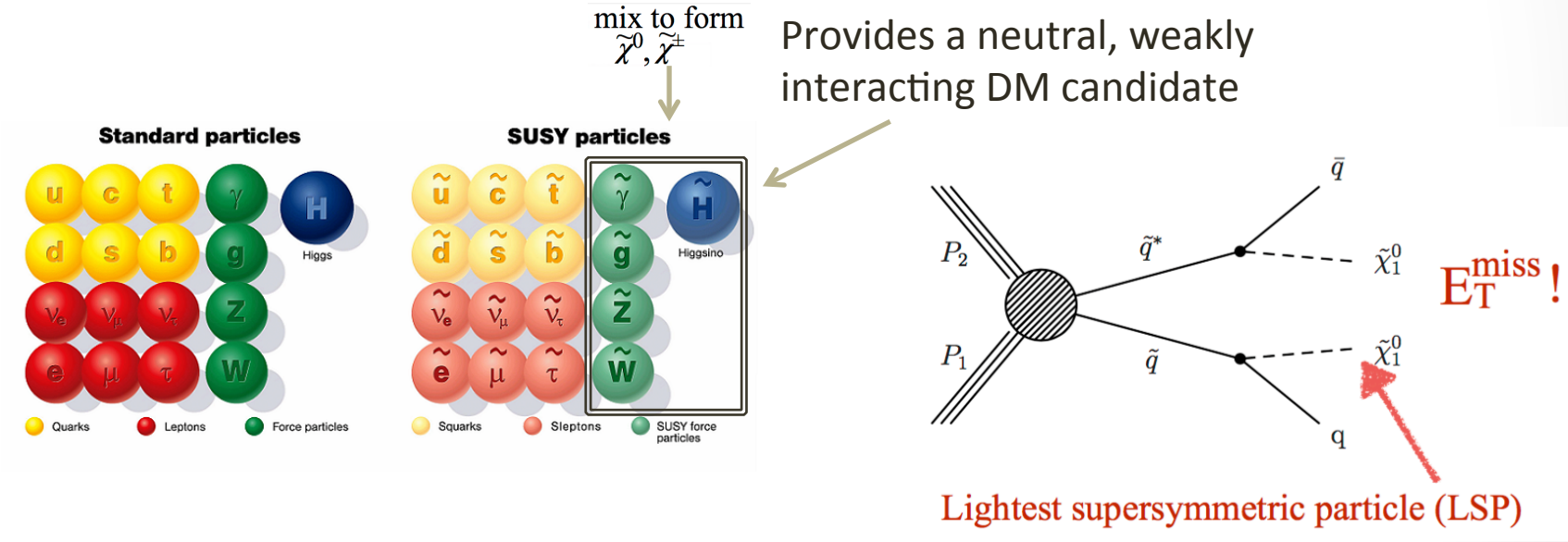


- There is a variety of evidence in favor of the existence of dark matter but only through its gravitational influence. Its **identity** is **unknown**
  - If DM particles are produced at accelerators, we can determine its mass and interactions
- **LHC** is the frontier probing physics at unexplored energies with unprecedented rates of pp collisions
- If DM interacts with Standard Model hadrons (e.g. DM scatter off nuclei in direct detection experiments) then proton colliders will directly produce DM particles
  - Many model producing **long-lived particles** (**LLP**) include DM candidates (produced in association with the LLP, mediate interactions, result from a charged LLP decay)



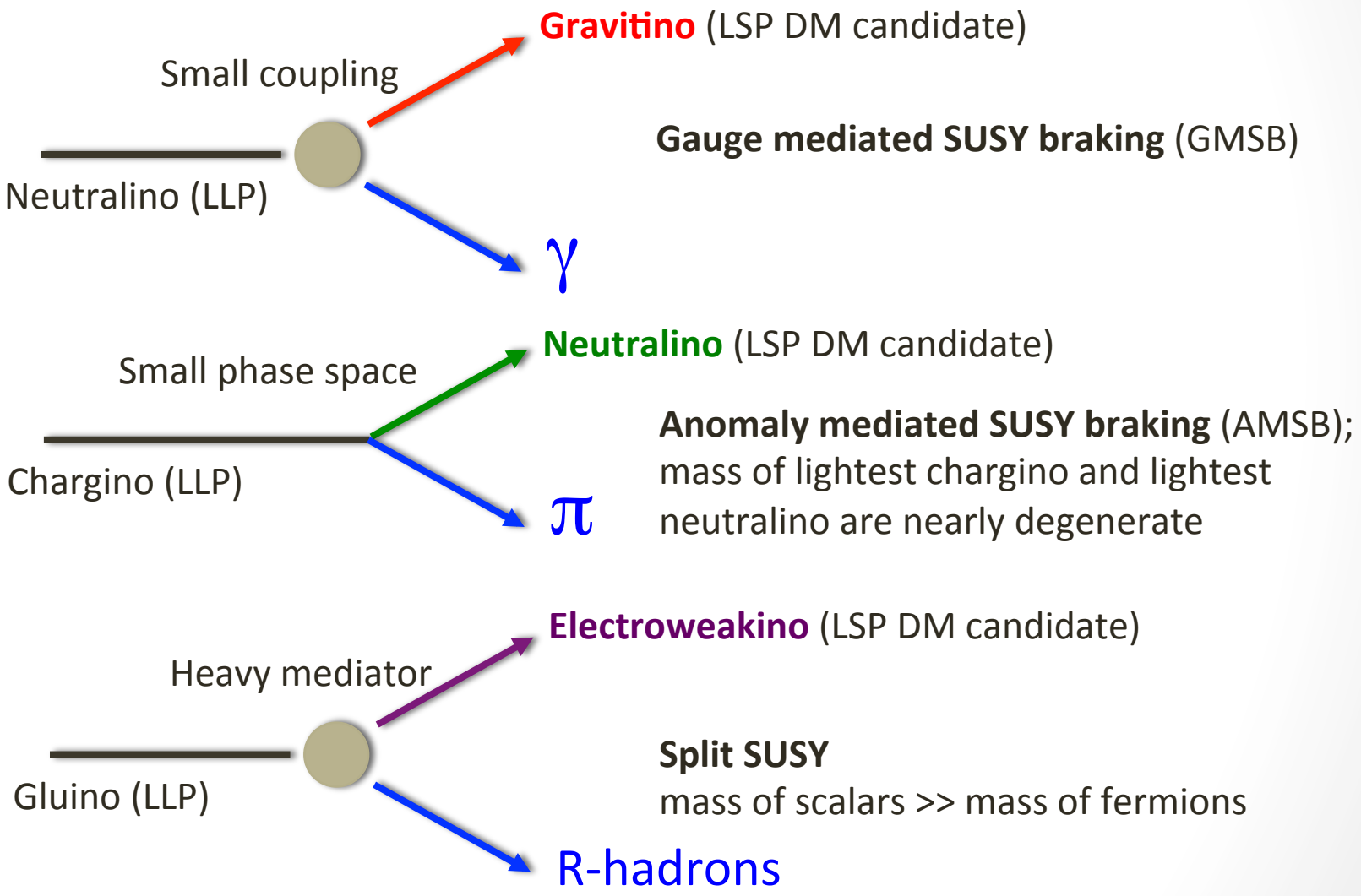
… candidates from SUSY …

- The currently best motivated DM candidate in SUSY theory is the lightest superparticle (LSP)



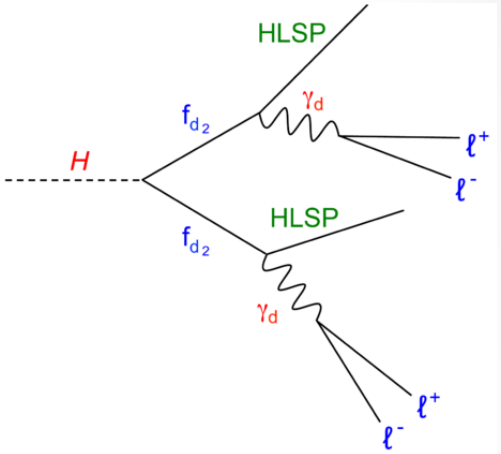
- The decay chain can contain particles with long lifetime (LLP) if
  - very small coupling in decay chain
  - heavy particle mediates the decay
  - no much phase space for decay

… candidates from SUSY …

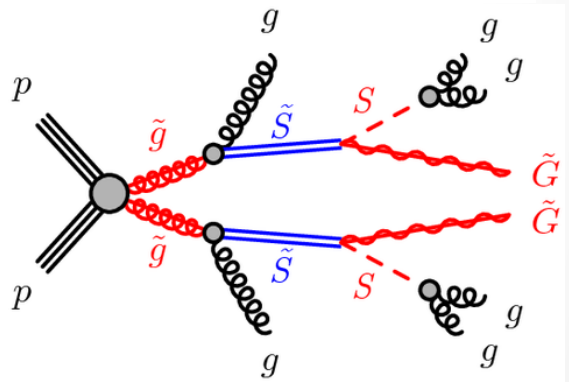


… candidates from hidden sectors/stealth SUSY …

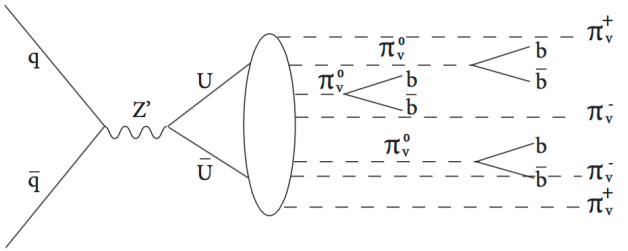
- A scalar boson decays to a pair of prompt hidden sector fermions that in turn decay in long-lived neutral particles (the dark photon) and an hidden LSP



- A pair of gluinos decay to long-lived singlinos, which in turn each decay to a low-mass gravitino and a pair of hadronic jets

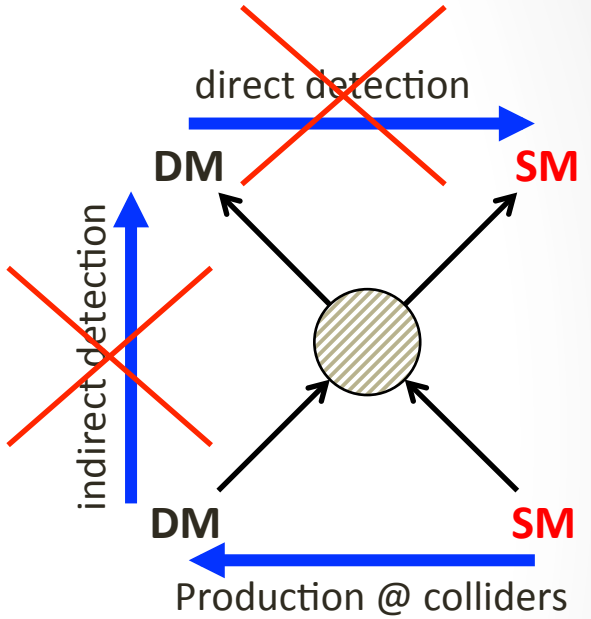


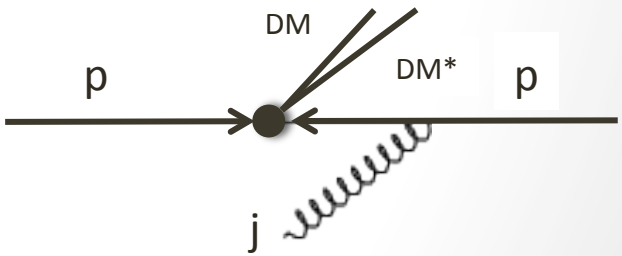
- The $\pi_v^{\pm}$ (LSP) are v-charged, but neutral under the SM electrical charge. The π_v^0 are the long-lived particles that decay to SM quark pairs.



… inelastic Dark Matter (iDM)…

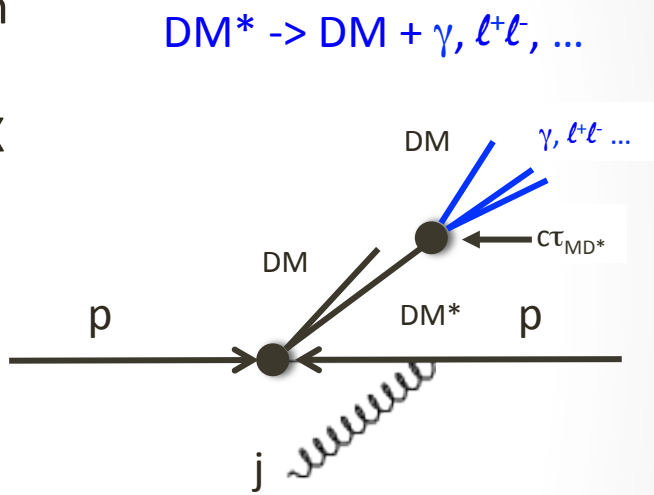
- DM could live in a dark sector (DS) with additional particles and forces. In the iDM scenario the heavier particles were abundant in the early universe and the coannihilation of DM with SM was dominant. The current universe would show only the lightest DM states that has no interaction with SM suppressing indirect and direct detection signatures
- By contrast colliders like LHC can produce both lighter and heavier DM particles. In the iDM scenario both lighter and heavier DM particles are produced simultaneously. When the heavier DM state (excited) decays into the lighter (ground) some SM particles are produced





… inelastic Dark Matter …

- The characteristic iDM signature is the production of DM+DM* in association with a hard SM object X, followed by the subsequent decay of DM*->DM+Y : pp -> X +DM+(DM*->DM+Y)=X+Y+missET
  - X is any SM state (jet for hadron machines) that can be used to trigger the event
  - Y is any SM state which nature depends on the mode by which DM couples inelastically to the SM. The most promising modes are photon and pair of leptons



- If DM and DM* are O(100 MeV) – O(10 GeV) mass range, the soft SM decay products of DM* are typically aligned with missing momentum
- The mass splitting between DM* and DM allows a non-prompt decay of DM* leading to a **displaced decay**

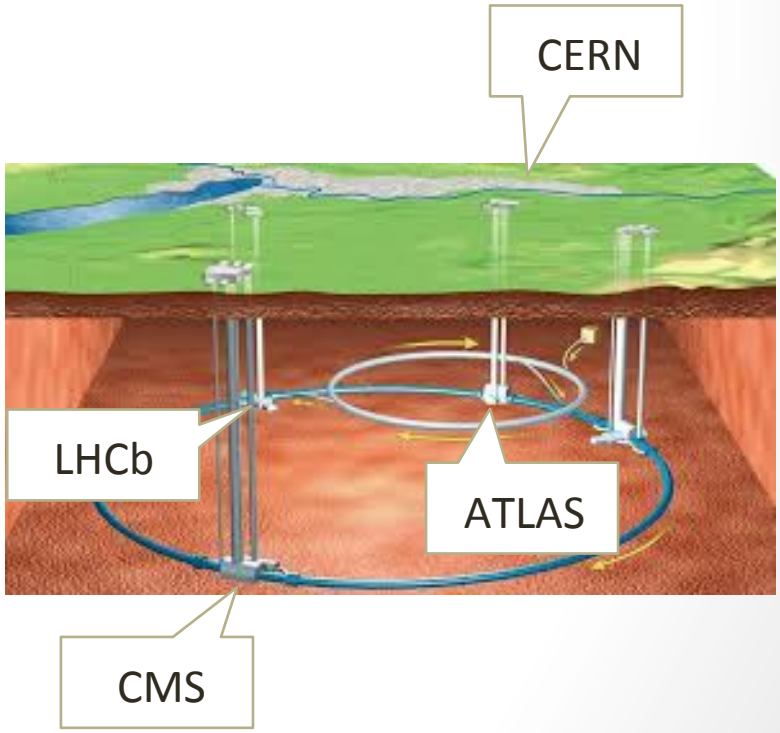
Summary

- LHC machine
- ATLAS, CMS and LHCb experiments
- Signatures and results for
  - Heavy stable charged particles
  - Disappearing track + MET
  - Photons + MET
  - Displaced jets
  - Lepton Jets
- Conclusions

LHC machine

LHC is a proton-proton collider at CERN of Geneva

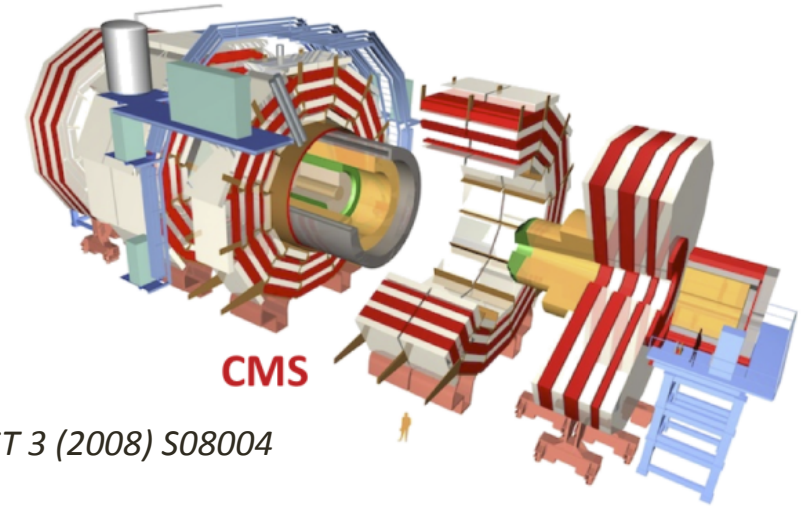
- $\sqrt{s}$=13 TeV (at present)
- 40MHz bunch crossing
- 1232 superconducting dipole magnet 8.3T max magnetic field
- 1.9K operation temperature



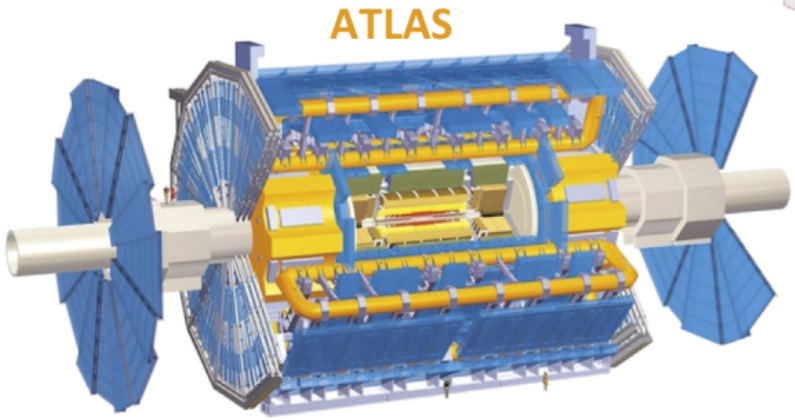
In this talk I present results from 3 main detectors: **two** multi-purpose detectors and **one** designed to the study of particles with b/c-quark, located 100 m underground

- **ATLAS**
- **CMS**
- **LHCb**

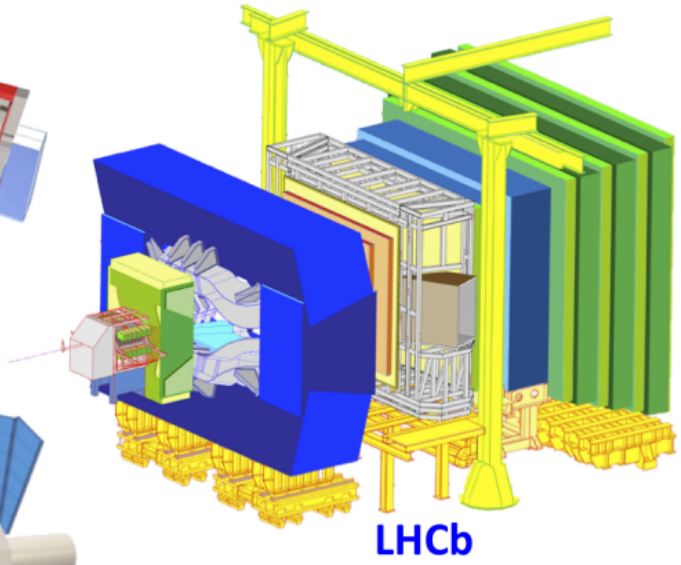
The experiments



JINST 3 (2008) S08004



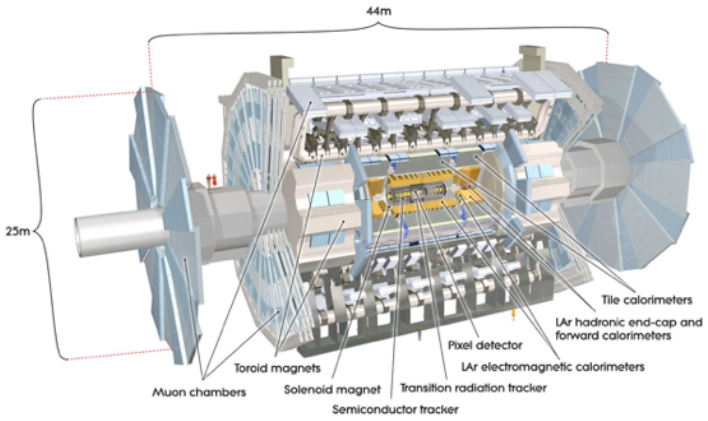
JINST 3 (2008) S08003

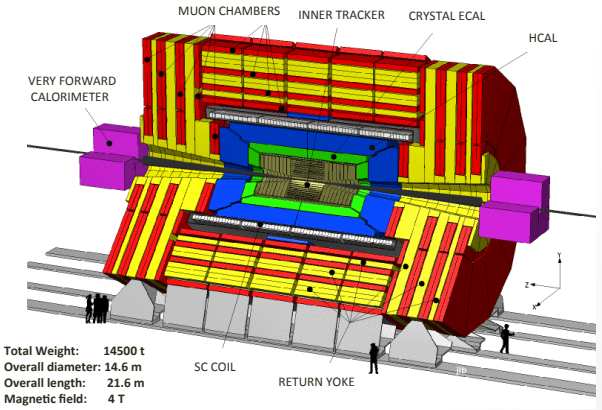


JINST 3 (2008) S08005

ATLAS and CMS experiments

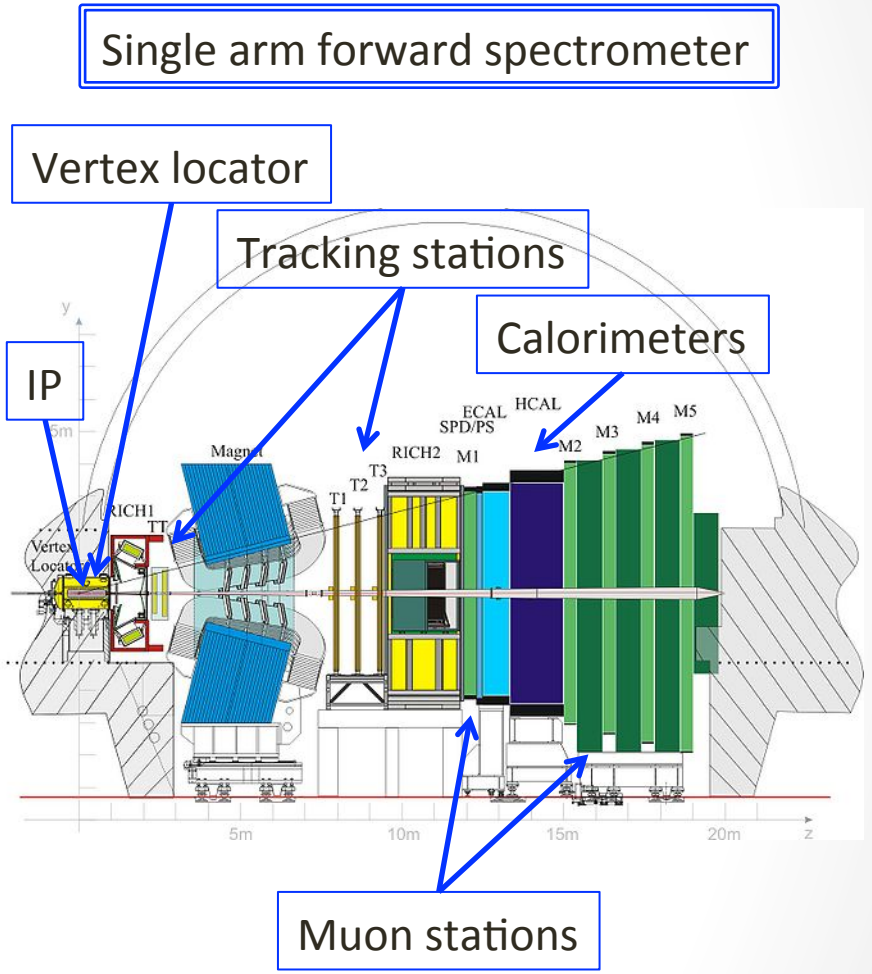
	ATLAS	CMS
Magnetic field	2T solenoid + toroid (0.5T barrel, 1T endcap	4T solenoid + return yoke
Tracker	Si pixel, strips + TRT $\sigma/p_T \approx 5 \bullet 10^{-4}\ p_T + 0.01$	Si pixel, strips $\sigma/p_T \approx 1.5 \bullet 10^{-4}\ p_T + 0.005$
EM calorimeter	Pb + Lar $\sigma/E \approx 10\% / \sqrt{E} + 0.007$ GeV	PbWO4 crystals $\sigma/E \approx 3\% / \sqrt{E} + 0.003$ GeV
H calorimeter	Fe + scint. / Cu + Lar (10λ) $\sigma/E \approx 50\% / \sqrt{E} + 0.03$ GeV	Brass + scint. (7λ+catcher) $\sigma/E \approx 100\% / \sqrt{E} + 0.05$ GeV
Muon	$\sigma/p_T \approx 2\%$ @ 50GeV to 10% @ 1TeV	$\sigma/p_T \approx 1\%$ @ 50GeV to 10% @ 1TeV (DT/ CSC+Tracker)
Trigger	L1 + RoI-based HLT (L2+EF)	L1 + HLT (L2+L3)





LHCb experiment

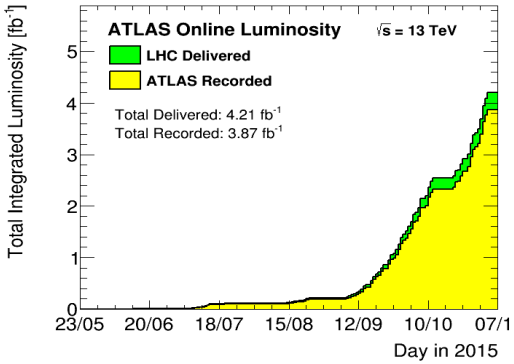
	LHCb
Magnetic field	Bending power of 4Tm
Tracker	Si strips + straw drift tubes $\sigma/p_T \approx 1 \bullet 10^{-2}\ p_T$ @200GeV
EM calorimeter	Pb + sci. pads ($25X_0$) $\sigma/E \approx 10\% / \sqrt{E} + 0.01$ GeV
H calorimeter	Fe + scint. (5.6λ) $\sigma/E \approx 69\% / \sqrt{E} + 0.09$ GeV
Muon	Iron and MWPC
Trigger	L0 + HLT

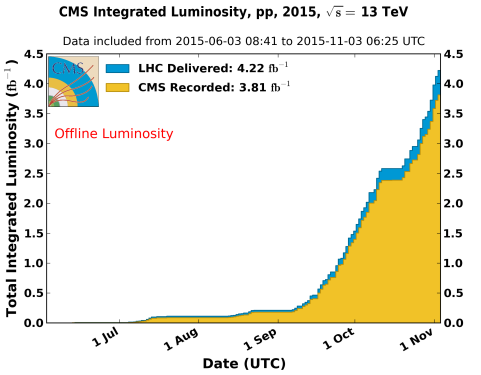


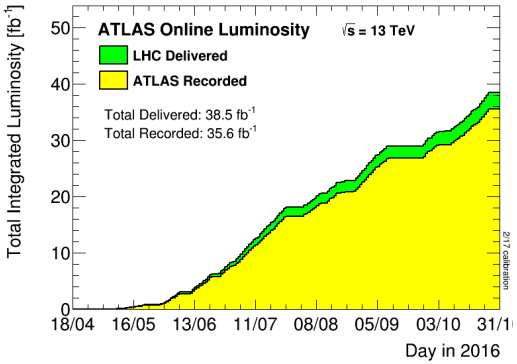
Data taking in Run II

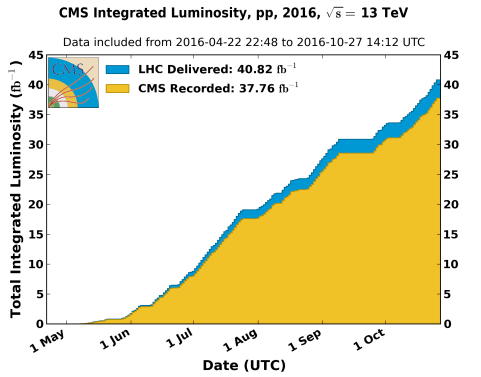
During **Run II** the collected data refers to 13 TeV pp collisions recorded in **2015** and **2016**:

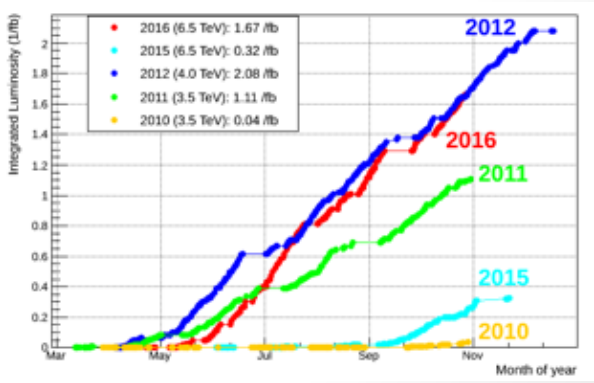
- **ATLAS**
  - 13.7 (2015) and 24.2 (2016) interactions per crossing
  - 3.87 (2015) 35.6 (2016) fb^{-1} total recorded luminosity
- **CMS**
  - 14 (2015) and 27 (2016) interactions per crossing
  - 3.81 (2015) 37.8 (2016) fb^{-1} total recorded luminosity
- **LHCb**
  - 1.67 (2016) fb^{-1} total recorded luminosity









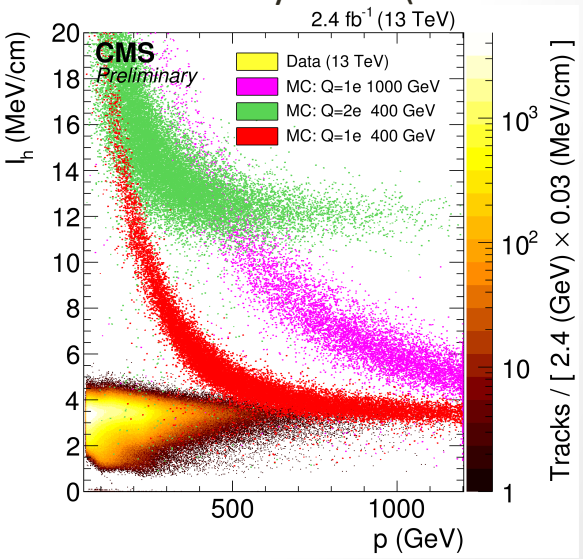


Efficiencies ⟹ All good for physics close to 96%

Search for Heavy Stable Charged Particles in CMS (1/2)

CMS PAS EXO-15-010

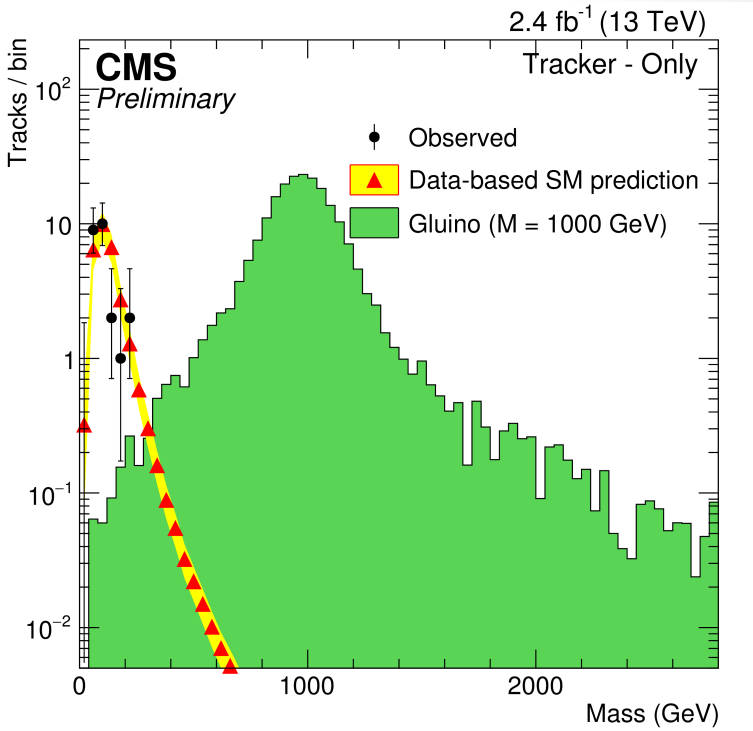
- **Model context**:
  - Different models for strong interaction of R-hadron with detector material :
    - R-hadron composed of a spectator HSCP surrounded by cloud of colored, light constituents (cloud model)
    - Charge-suppressed model "CS" (almost all R-hadrons flip to neutral)
  - HSCP type hadron like:
    - Pair-production of gluino or stop
    - Form R-hadrons (bound state with q or g)
  - HSCP type lepton like:
    - Stau long-lived that decays to gravitino LSP
      - Heavier SUSY particles leading to >=1 stau(s) at the end of the decay chain (GMSB benchmark)
      - Direct pair production
- **Background:**
  - Mainly from instrumental sources
- **Event selection**:
  - Heavy: slow moving -> long TOF to the muon detector
  - Stable (wrt detector): long-lived ($\tau > 1$ ns)
  - Charged: |Q| >= 1 -> high dE/dx in Si tracker



Search for Heavy Stable Charged Particles in CMS (2/2)

CMS PAS EXO-15-010

- "tracker-only" analysis - require tracks be reconstructed in the silicon detectors
- "tracker+TOF" analysis - requiring tracks reconstructed in both silicon detectors and muon system



Results for |Q| = 1e

Model	Analysis	Limits
gluino (*)	Tracker only	M > 1590 GeV
stop	Tracker only	M > 1020 GeV
stau	Tracker+TOF	M > 480 GeV

(*) How often gluino forms neutral hadron with gluon? f=0.1 considered

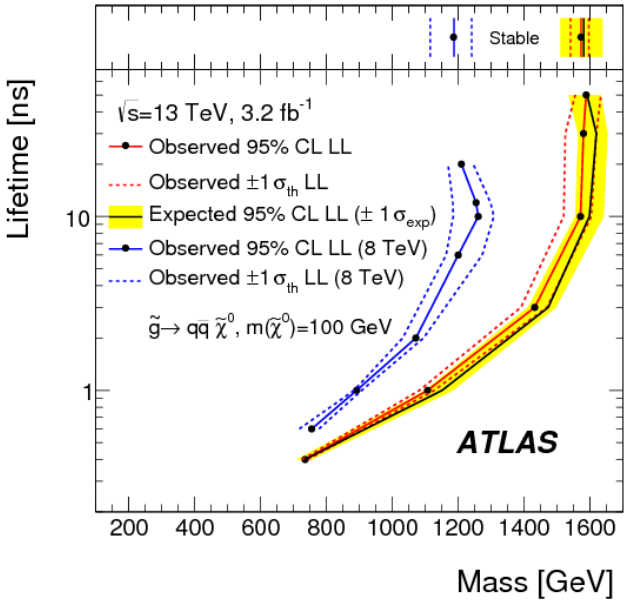
- **Results**:
  - Data-driven background estimation
  - Mass estimated from dE/dx and *p*
  - Data agrees well with SM background

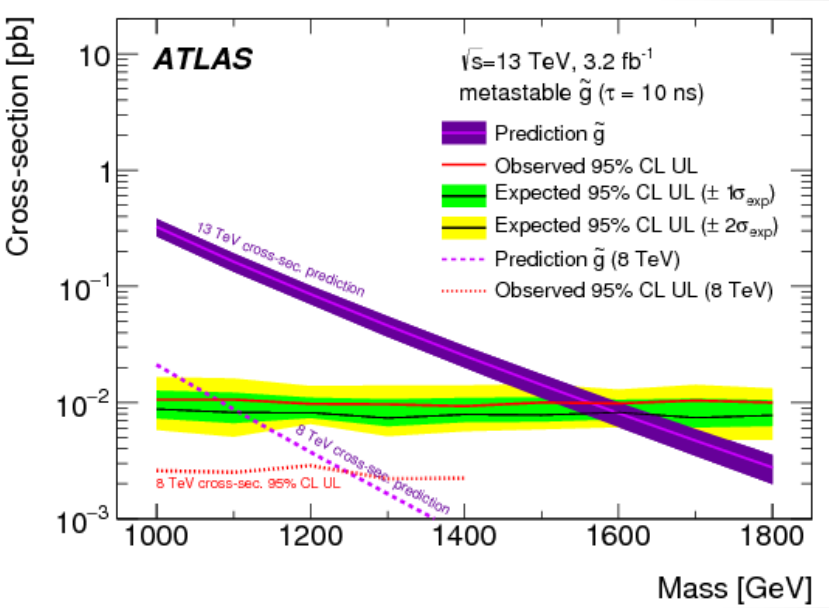
ATLAS limit gluino/sbottom/stop>1580/805/890 GeV with 3.2 fb^{-1} @ √s=13TeV
PLB 760 (2016) 647-665

Metastable heavy charged particle search in ATLAS

Phys.Rev. D 93 112015 (2016)

- **Model context**:
  - Split-SUSY and AMSB: NLSP Gluino long-lived
  - Gluino → Neutralino (LSP, DM candidate)
- **Background**
  - SM processes
  - Overlapping tracks (high ionization)



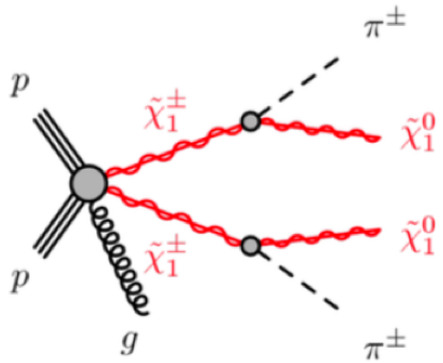


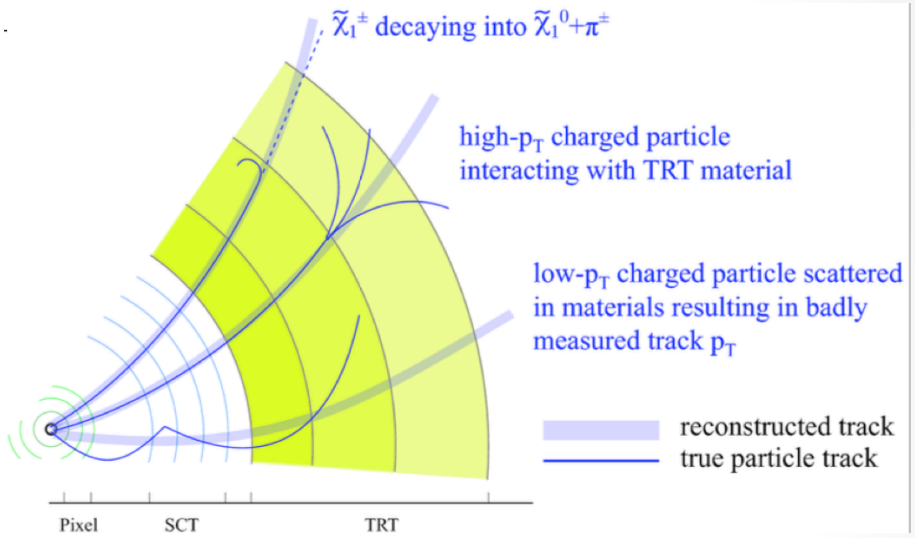
- **Event selection**:
  - Missing ET > 130 GeV
  - At least one high-pT (150 GeV), isolated, good track
  - Anomalously large energy loss in pixel detector
- **Results**
  - No evidence of a signal above the background is observed

Long-lived chargino search in ATLAS (1/2)

Phys.Rev. D 88 112006 (2013)

- **Model context**:
  - AMSB: lightest chargino slightly heavier than lightest neutralino (LSP)
  - Chargino predominantly decays to neutralino (missing ET) and soft pion
  - Constrained phase space: chargino long-lived ($\tau > 0.2$ns)



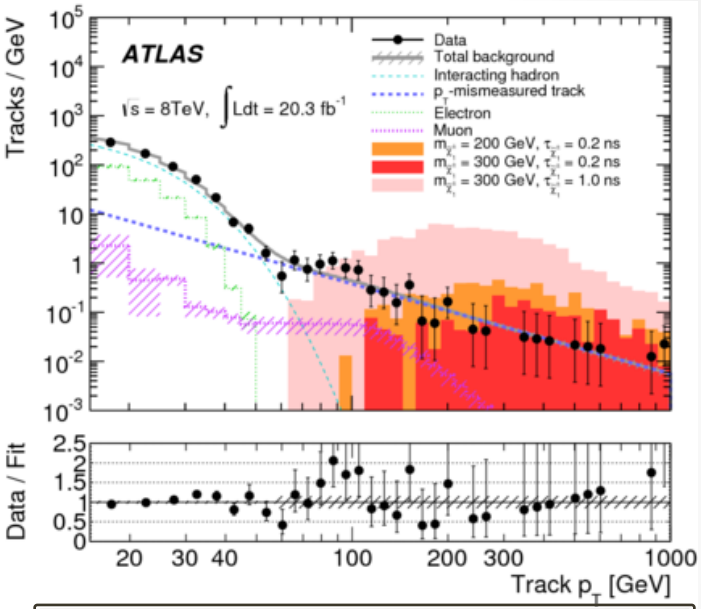


- **Background** (mimic disappearing tracks)
  - Charged hadrons interacting with tracker material
  - Charged leptons losing momenta in tracker due to scattering or bremsstrahlung -> not correctly identified
  - Tracks with mis-measured p_T

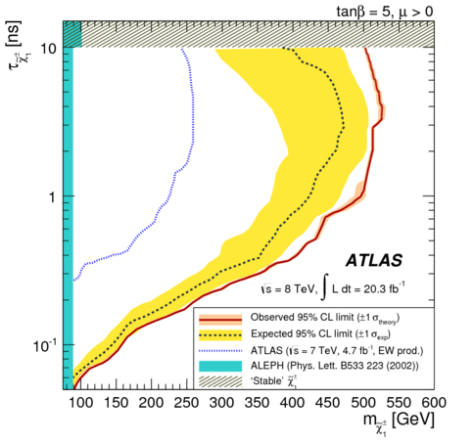
Long-lived chargino search in ATLAS (2/2)

Phys.Rev. D 88 112006 (2013)

- **Event selection**:
- Dedicated trigger to suppress background
  - >= one high-p_T jet (ISR-jet), large missing ET, $\Delta\phi$(jet,MET)>1
- One or two **disappearing track(s)**
  - High-pT, isolated track, missing hits in outer layer of tracker
  - No matching hit in muon detector
  - Small or no calorimeter energy deposit
- Missing E_T (DM candidate)



~2σ excess around 90 GeV. Discrepancy is not consistent with any signal hypothesis studied in this analysis



Tanβ is the ratio of Higgs vacuum expectation values at electroweak scale, M is the sign of the higgsino mass term

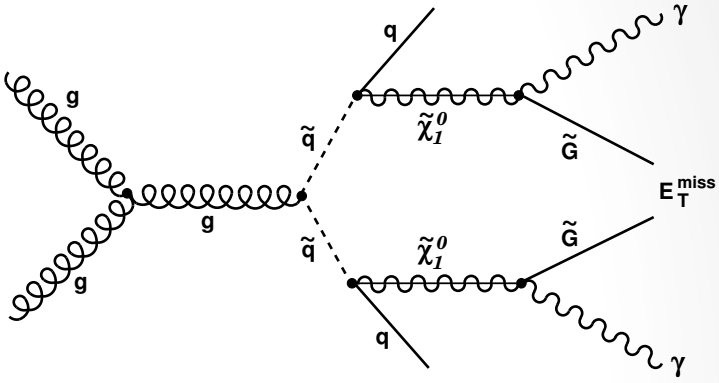
- **Results:**
  - Chargino excluded up to 270 GeV for lifetime=0.2 ns in AMSB scenario

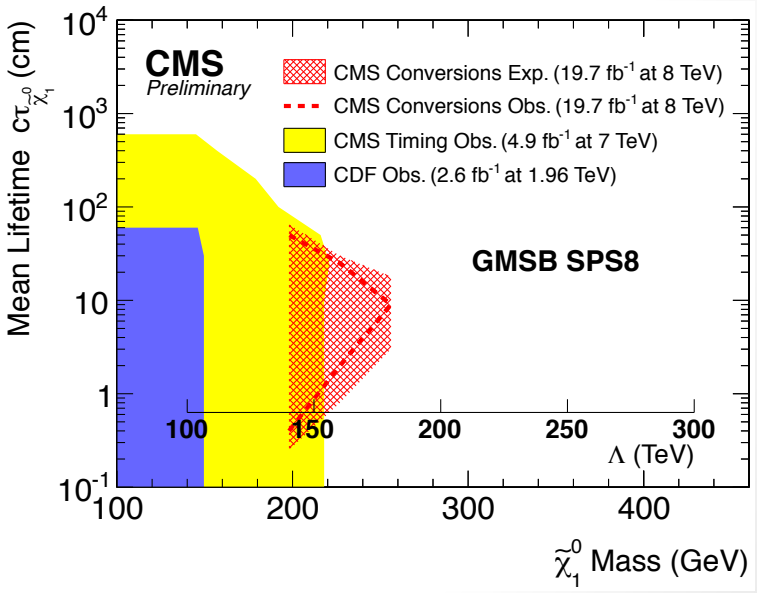
CMS limit 260 GeV with 19.5 fb^{-1} data JHEP 01 (2015) 096

LLP search in photons+MET final state in CMS

CMS PAS EXO-14-017

- **Model context**:
  - GMSB with lightest neutralino is long-lived
  - Pair production of neutralino -> decay to gravitino (LSP=DM candidate) and photon
  - Consider $c\tau$ of neutralino between 0.4 to 100 cm
- **Background**: mainly from SM γ+jet
- **Event selection**:
  - >= 2 high-p_T, isolated, good photons (>=1 γ converted in e^+e^-)
  - >= 2 jets
  - Missing E_T (DM candidate)
- **Results**:
  - No excess observed in data
  - Neutralino excluded up to 250 GeV for $c\tau$=10 cm in GMSB

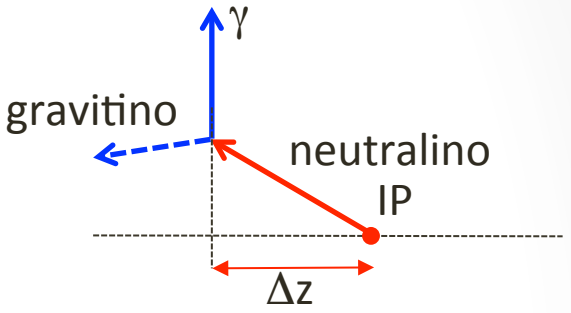


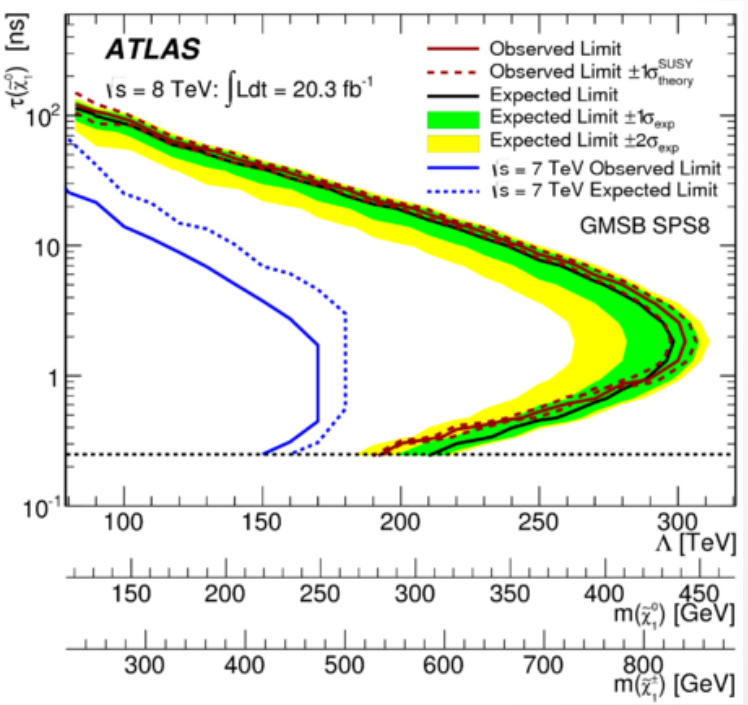


LLP search in photons+MET final state in ATLAS

Phys. Rev. D 90, 112005 (2014)

- **Model context**:
  - GMSB with neutralino is long-lived
  - Pair production of neutralino -> decay to gravitino+γ (gravitino=LSP DM candidate)
- **Background:**
  - prompt γ, e/jet misidentified as a γ
- **Event selection**:
  - Two non-pointing and delayed photons + MET
- **Results**:
  - Data are in good agreement with the background only fit and no evidence for non-pointing and delayed photons is observed



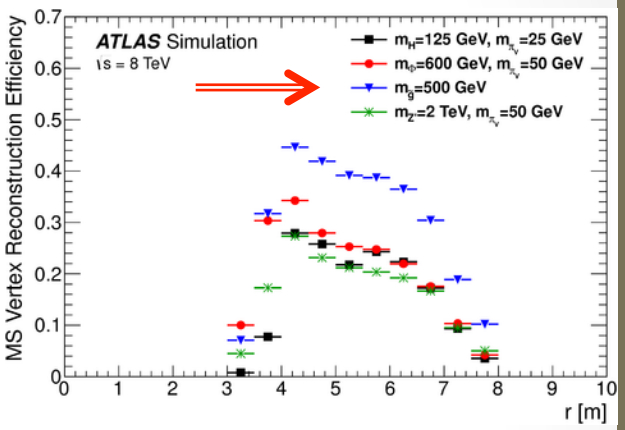


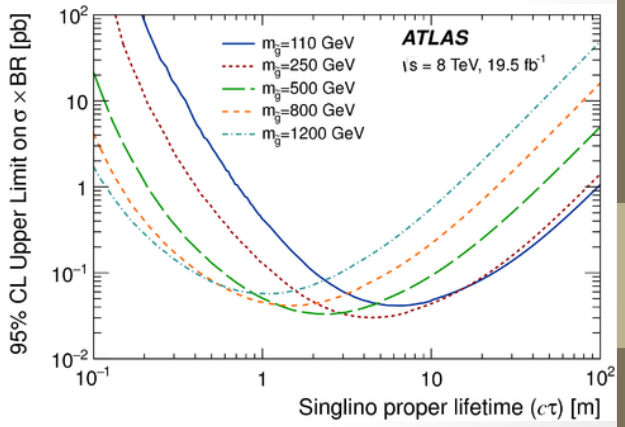
ATLAS limits stronger than CMS due its LAr ECAL's ability to reconstruct the γ direction

Searches for long-lived weakly interacting particle decaying to displaced jets

Phy. Rev D 92 (2015) 012010

- **Model context**:
  - Stealth-SUSY in which a pair of gluinos decay to long-lived singlinos, which in turn each decay in gravitino (LSP) and a pair of hadronic jets
- **Background:**
  - ID fake vertex from jets with high track multiplicity
  - MS fake vertex
- **Event selection**:
  - Muon RoI Cluster trigger in a cone $\Delta R=0.4$ with poor activity in ID and CAL
  - Require 2 DV (IDVx+MSVx or 2MSVx)
- **Results**
  - Limits are set on σxBR of the signal as a function of the singlino proper lifetime

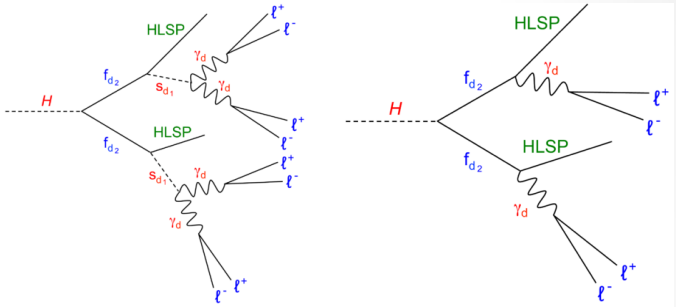


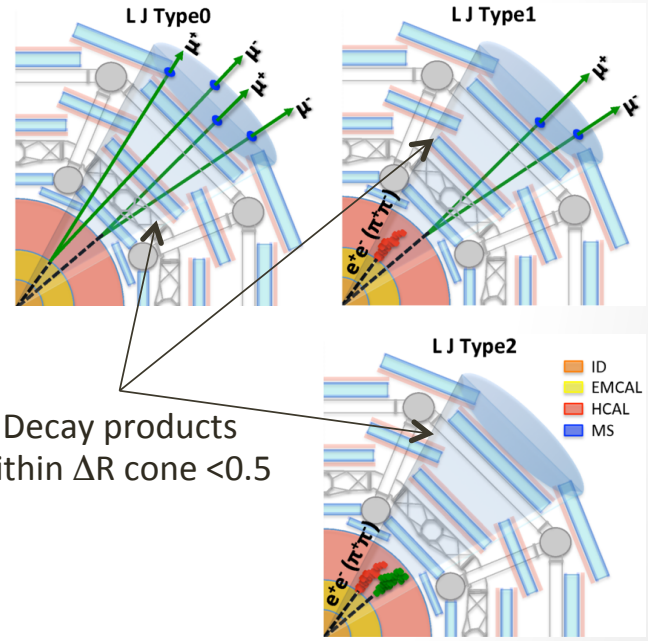


Searches for LLNP decaying in displaced Lepton-Jets (LJ)

ATLAS-CONF-2016-42

- **Model context**:
  - Hidden-Sector (HS) in which a Higgs-like boson decays to HS fermions/scalars that in turn decay in long-lived neutral dark photons (γ_D) decaying to LJ
- **Background**
  - SM-multijets estimated with data-driven method
  - cosmics and beam-induced background
- **Event selection**:
  - Dedicated triggers for displaced objects
  - >= 2 collimated μ without match with ID track or jets with low electro-magnetic energy fraction (Lepton-Jet=LJ)
  - The search requires 2 LJs in all possible combinations of e/jets and/or muons
- **Results**
  - Limits are set on σxBR of the signal as a function of the proper lifetime of the long-lived particle

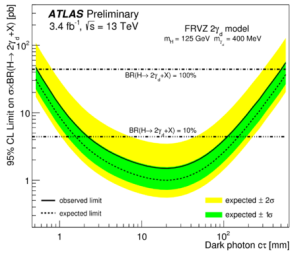




Decay products within ΔR cone <0.5

Jets lacks energy deposits in inner layers

FRVZ model	m_H (GeV)	Excluded $c\tau$ [mm]
Higgs → $2\gamma_d + X$	125	$2.2 \leq c\tau \leq 111.3$
Higgs → $4\gamma_d + X$	800	$3.8 \leq c\tau \leq 163.0$
Higgs → $2\gamma_d + X$	125	$0.6 \leq c\tau \leq 63$
Higgs → $4\gamma_d + X$	800	$0.8 \leq c\tau \leq 186$



Some other LLP searches

(not covered in this talk)

- **LLP pair-produced, decays to ee/ μμ/ eμ**
  - displaced di-lepton vertex
    - [CMS PRD 91 (2015) 052012]
    - [CMS Phys. Rev. Lett. 114 no. 6, (2015) 061801]
    - [ATLAS Phys. Rev. D 92, 072004 (2015)]
    - [ATLAS-CONF-2017-026]
- **Search for decays of stopped LLP**
  - gluino, stop, sbottom (R-hadron) : Low kinetic energy, come to rest within detector
    - [CMS EPJC 75 (2015) 151]
    - [ATLAS Phys. Rev. D 88, 112003 (2013)]

- **NO Searches for DM with LLP published by LHCb**

Conclusions

- Both ATLAS and CMS have made great effort to search for DM with LLP
- Wide range of analyses, looking for many different signatures and often using the detector in interesting and “non-standard” ways
- Various models used for interpretation. No evidence for new physics so far
- Limits are put on these new models : best limits till now
- New promising searches are ongoing
- High expectation from 2017-18 Run (100/fb expected for ATLAS / CMS):

the goal is discovery!

- ATLAS Recent results https://twiki.cern.ch/twiki/bin/view/Atlas/AtlasResults
- CMS Recent results http://cms-results.web.cern.ch/cms-results/public-results/publications/
- LHCb Recent results http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_QEE.html