Searches for highly ionizing particles in ATLAS and CMS

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Introduction

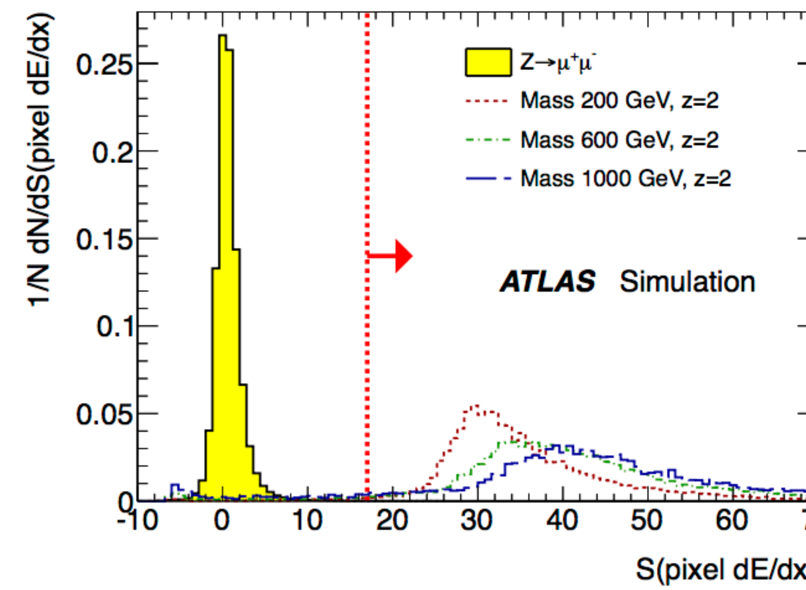
- High-mass, long-lived charged particles predicted by various extensions of the Standard Model
- If such particles have a mass lighter than a few TeV they could be produced by the CERN LHC
- Massive particles with lifetime greater than O(1) ns could be observed with the ATLAS and CMS detectors as high-momentum tracks with anomalously large rates of energy loss through ionization
- These particles could also be highly penetrating such that the fraction reaching the muon system of the detectors would be sizeable
  - The muon system could therefore be used to help in identification and in the measurement of the time-of-flight (TOF) of the particles
- In this talk results are presented of some specific BSM searches for high-mass, long-lived charged particles. Results are interpreted in terms of
  - the production of new particles with a fractional or multiple value of the charge of the electron
  - the production of high mass stable charged particles (HSCP), also reinterpreted in the context of supersymmetric scenarios that predict stable or pseudo-stable charged particles in the final state
  - the presence of magnetic monopoles

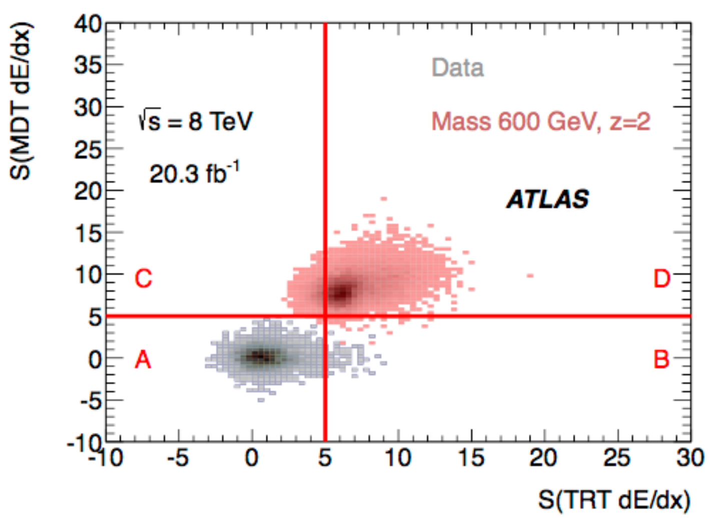
Multi-Charged Particles (MCP) in ATLAS

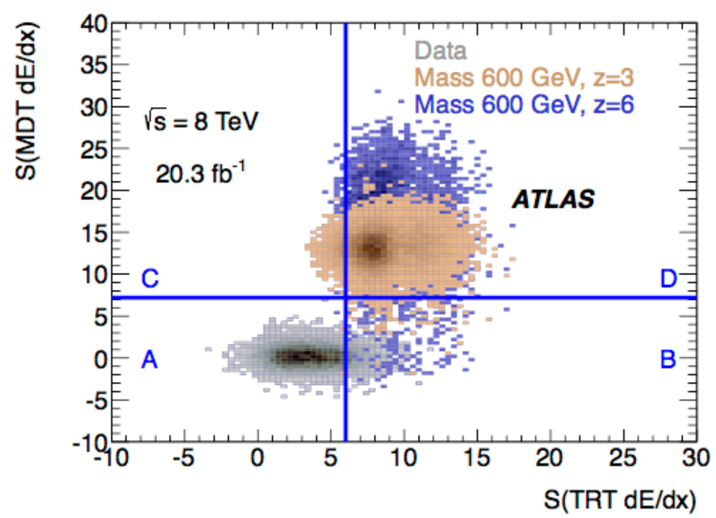
arXiv:1504.04188 submitted to EPJ C

- Search for long-lived highly ionizing heavy (mass in 50 - 1000 GeV) particles with high electric charges (|q|=2,3,4,5,6 e)
- "Blue-sky" search, but some models predict new particles with charge greater than one
  - Almost Commutative Geometry model (AC-leptons): extends SM by two heavy particles with $|q| \geq e$
  - Walking Technicolor Model (techni-leptons): production of 3 particle pairs with q+e, q, q-e ($|q| \geq e$)
- Analysis features
  - Long-lived particles → high p_T muon trigger or missing E_T trigger
  - Selection
    - muon-like particles with high ionization losses in Pixel, Transition Radiation Tracker (TRT) and muon precision chambers (MDT)
    - high fraction of TRT hits passing the high threshold, f_{HT}
  - Background estimation: ABCD method

$$S(\mathrm{d}E/\mathrm{d}x) = \frac{\mathrm{d}E/\mathrm{d}x_{\mathrm{track}} - \langle \mathrm{d}E/\mathrm{d}x_{\mu} \rangle}{\sigma(\mathrm{d}E/\mathrm{d}x_{\mu})}$$

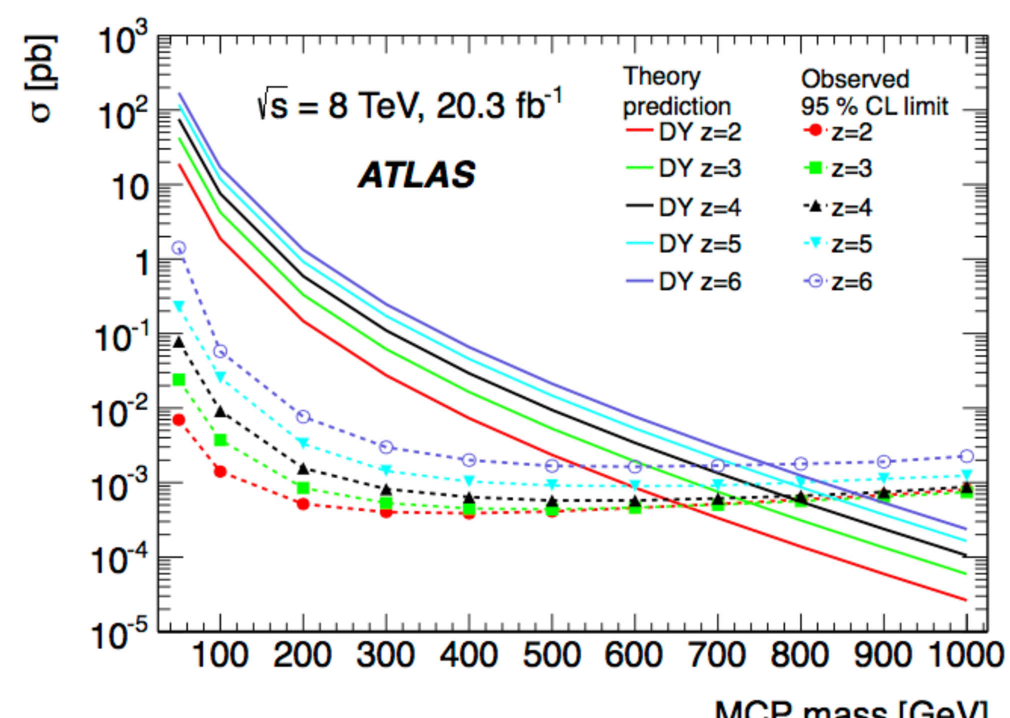






- Results: no candidate events observed in data → exclusion limits assuming a Drell-Yan production cross-section

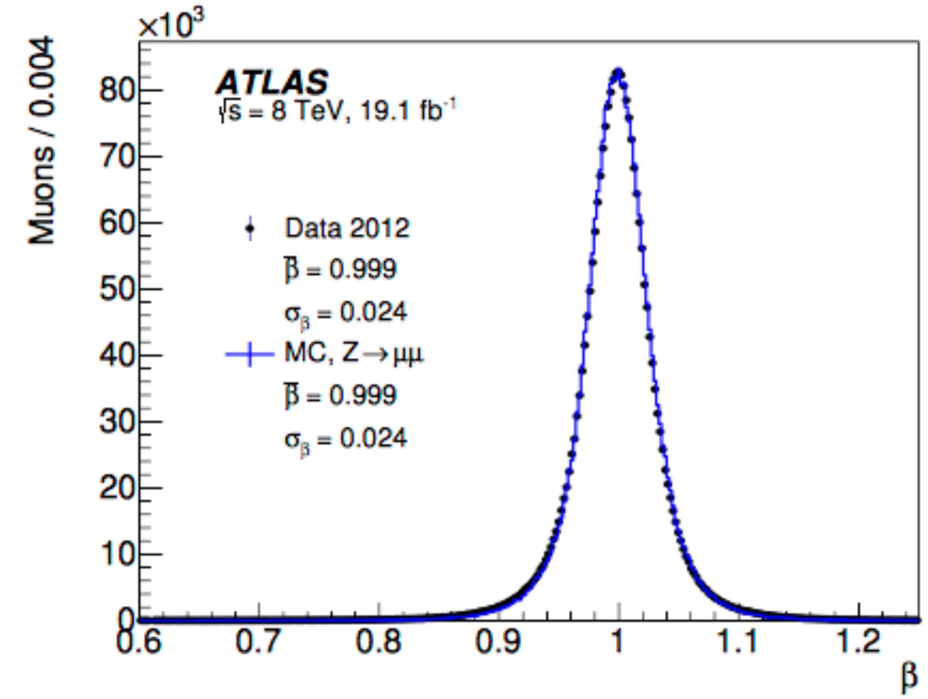
|q|	Mass limits [GeV]
2e	50-660
3e	50-740
4e	50-780
5e	50-785
6e	50-760

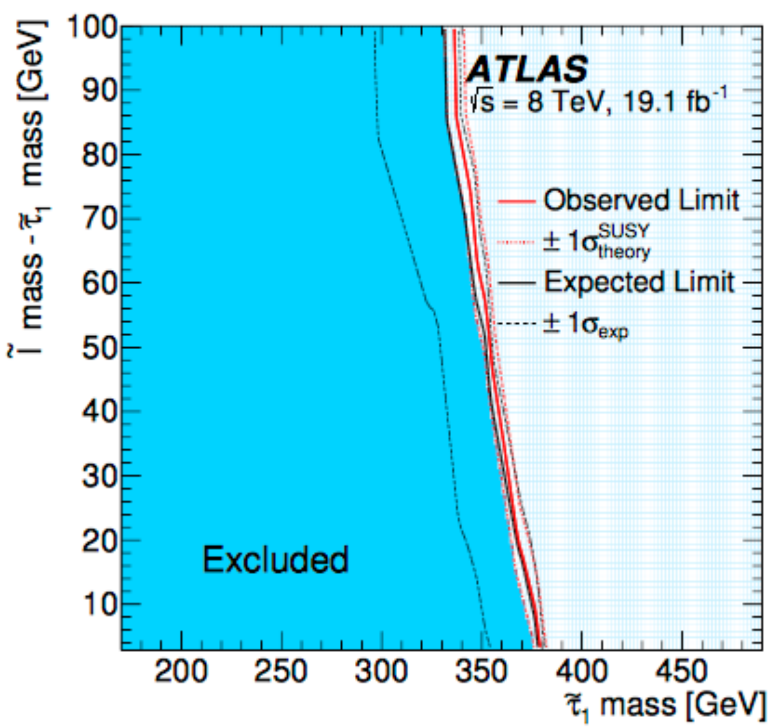


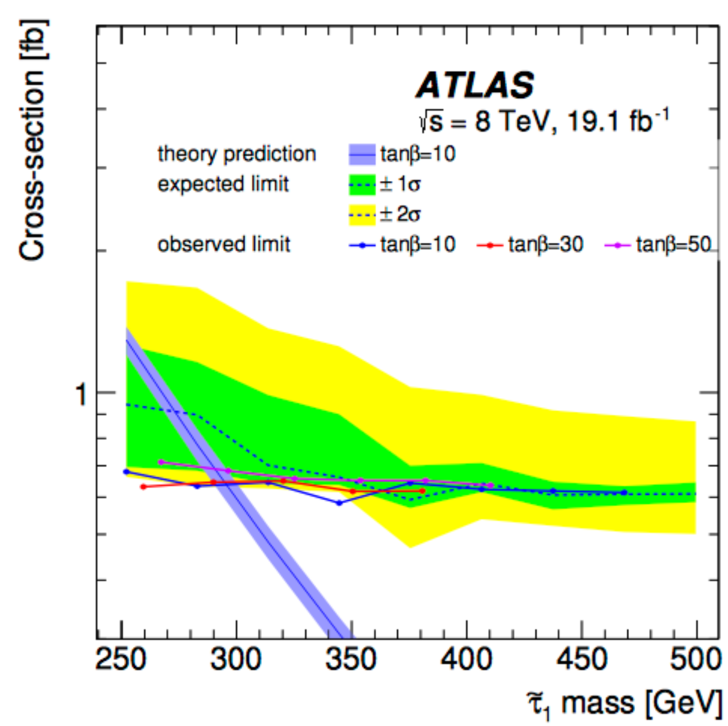
Stable heavy charged particles in ATLAS

JHEP01 (2015) 068

- Search for heavy, charged, stable, slow-moving ($\beta < 1$) particles
- Analysis strategy
  - High p_T muon trigger or missing E_T trigger
  - Track information is used to calculate the candidate mass
    - p derived from the candidate track
    - β calculated from measured ToF (using muon system and calorimeter)
    - $\beta\gamma$ deduced from Pixel dE/dx
- Background: high-p_T muons with large ionization, mis-measured β
  - Contribution estimated from data
- Interpretations: stable sleptons, leptoSUSY, charginos, R-hadrons





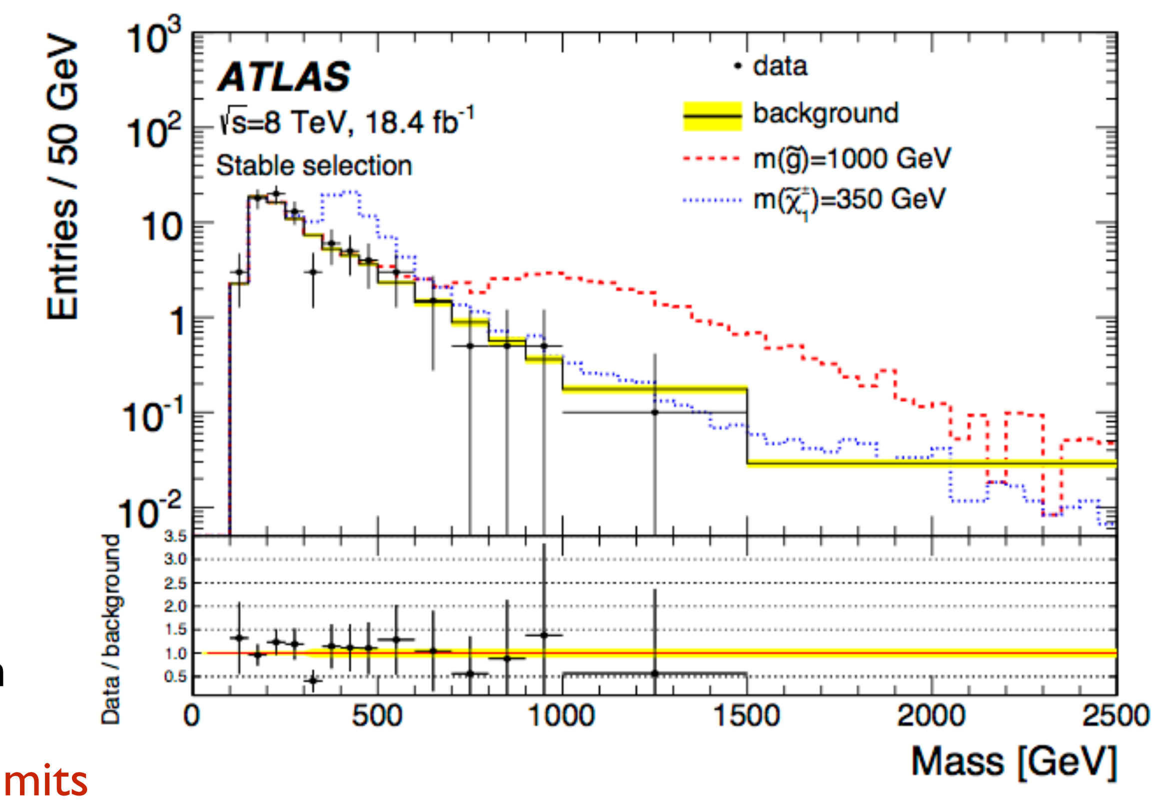


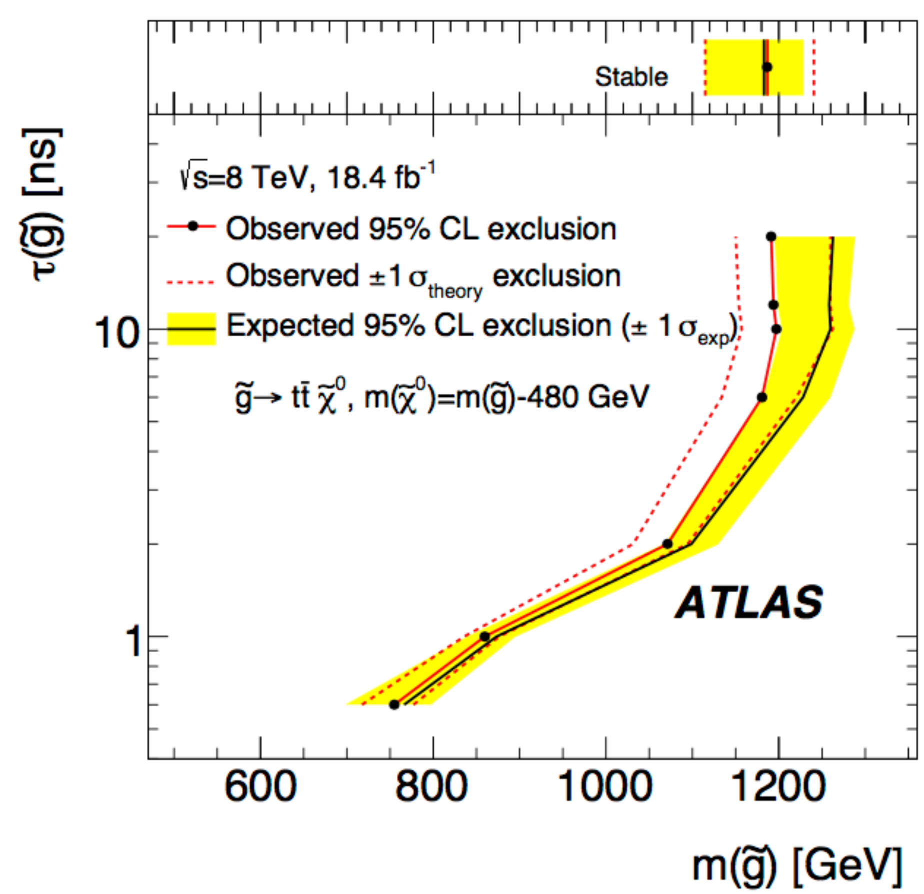
Search	Lower mass limit [GeV]
GMSB sleptons	
· $\tan\beta = 10, 20, 30, 40, 50$	440, 440, 430, 410, 385
· direct $\tilde{\ell}$ production ($m_{\tilde{\ell}} - m_{\tilde{\tau}_1} = 2.7$–$93$ GeV)	377–335
· direct $\tilde{\tau}_1$ production	289
· $\tilde{\chi}_1^0\tilde{\chi}_1^\pm$ decaying to stable $\tilde{\tau}_1$	537
LeptoSUSY	
· $\tilde{q}, \tilde{g}$	1500, 1360
Charginos	
· $\tilde{\chi}_1^\pm$	620
R-hadrons	
· $\tilde{g}, \tilde{b}, \tilde{t}$ (full-detector)	1270, 845 and 900
· $\tilde{g}, \tilde{b}, \tilde{t}$ (MS-agnostic)	1260, 835 and 870

Metastable heavy charged particles in ATLAS

arXiv:1506.05332 submitted to EPJ C

- Updated searches using Pixel dE/dx only → extend sensitivity to lower lifetimes
- Mass obtained by fitting energy loss and momentum to an empirical Bethe–Bloch distribution
- Events selected by missing transverse energy trigger
- Offline selection:
    - track isolation (ΔR with respect to any other track > 0.25)
    - electron veto
    - high (>150 GeV) momentum
    - high ionization (>MIP value)
    - muon veto if particle is metastable with decay before the muon system
- No events observed in data over the estimated background → lower limits on particles mass



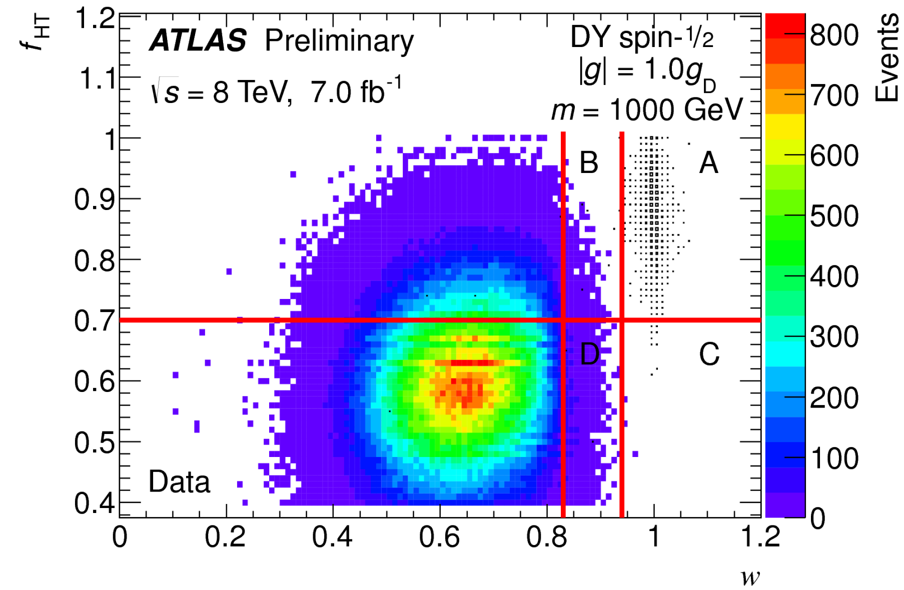


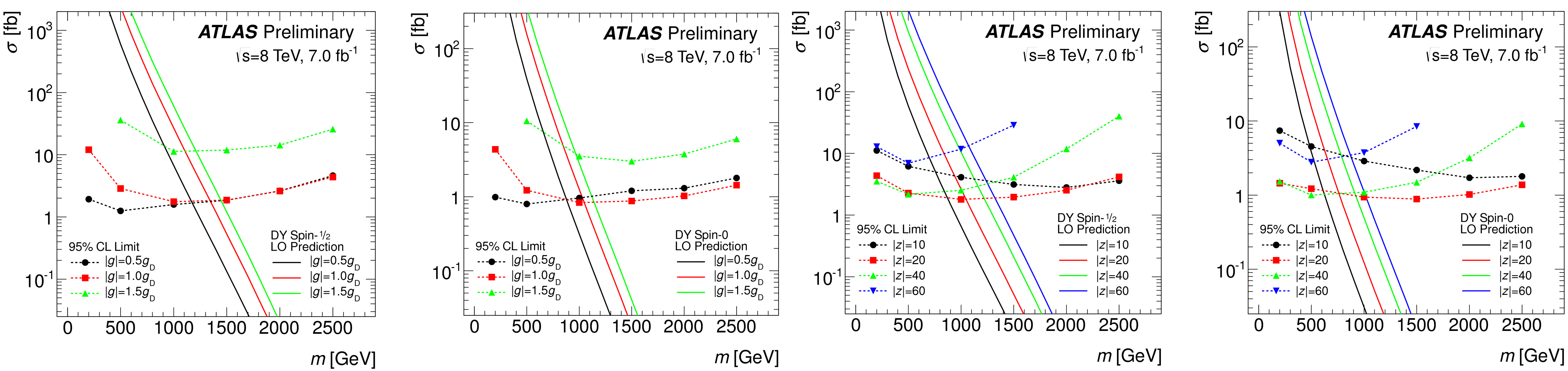
Particle	Decay	$m(\tilde{\chi}^0_1)$ [GeV]	τ [ns]	$m >$ [GeV]
$\tilde{g}$ R-hadron	stable	–	–	1115
$\tilde{b}$ R-hadron	stable	–	–	751
$\tilde{t}$ R-hadron	stable	–	–	766
chargino	stable	–	–	534
$\tilde{g}$ R-hadron	$g/q\bar{q}$	100	10	1185
$\tilde{g}$ R-hadron	$g/q\bar{q}$	$m(\tilde{g}) - 100$	10	1099
$\tilde{g}$ R-hadron	$t\bar{t}$	100	10	1182
$\tilde{g}$ R-hadron	$t\bar{t}$	$m(\tilde{g}) - 480$	10	1157
$\tilde{g}$ R-hadron	$g/q\bar{q}$	100	1.0	869
$\tilde{g}$ R-hadron	$g/q\bar{q}$	$m(\tilde{g}) - 100$	1.0	821
$\tilde{g}$ R-hadron	$t\bar{t}$	100	1.0	836
$\tilde{g}$ R-hadron	$t\bar{t}$	$m(\tilde{g}) - 480$	1.0	836
chargino	$\tilde{\chi}^0_1 + \pi^\pm$	$m(\tilde{\chi}^\pm_1) - 0.14$	1.0	239
chargino	$\tilde{\chi}^0_1 + \pi^\pm$	$m(\tilde{\chi}^\pm_1) - 0.14$	15	482

Search for monopoles and stable particles with high electric charges in ATLAS

to be submitted to PRD

- Massive stable particles with very high electric charge predicted by several new physics models: theories of magnetic monopoles (carry magnetic charge g, g = n x g_D, where g_D = 68.5e), strange quark matter, Q-balls, stable microscopic black-hole remnants
- Signature to maximise the acceptance for particles predicted by the models (energy in 100 - 500 GeV): **large localised energy deposit in the Electromagnetic calorimeter + a region of high ionisation density in the TRT (f_{TH})**
- Event selection
  - dedicated trigger: EM calorimeter energy deposit with no energy after the first calorimeter layer + large f_{HT}
  - high f_{HT} matched to EM energy deposit
  - EM energy deposit dispersion (fraction of EM energy contained in the most energetic cells, w)
  - ABCD method used to determine the background from data
- Results: no events observed in 7 fb^{-1} @ 8 TeV → DY pair production mass limits



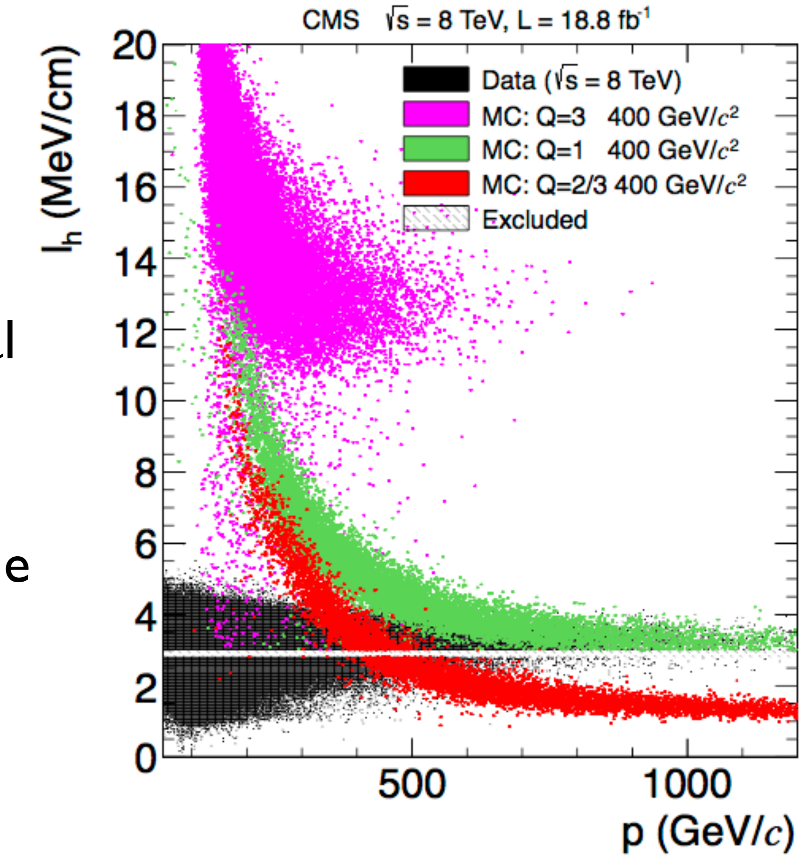


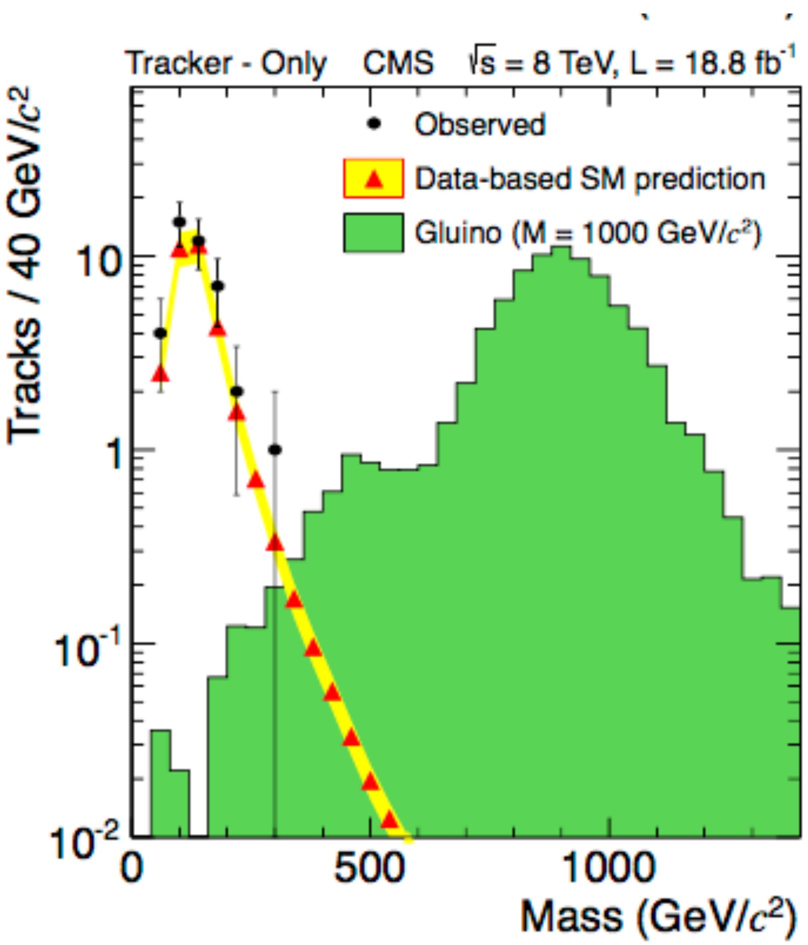
	Drell-Yan Lower Mass Limits [GeV]						
	$\|g\| = 0.5g_D$	$\|g\| = g_D$	$\|g\| = 1.5g_D$	$\|z\| = 10$	$\|z\| = 20$	$\|z\| = 40$	$\|z\| = 60$
spin-1/2	1180	1340	1210	780	1050	1160	1070
spin-0	890	1050	970	490	780	920	880

High mass Stable Charged Particles (HSCP) in CMS

JHEP07 (2013) 122

- Search for particles with significant lifetime (≳a few ns), $\beta<1$, and possibly $|q| \neq 1$
- High p_T muon trigger plus missing E_T trigger
- Use dE/dx in tracker and TOF to muon system to distinguish HSCP signal
- Five channels: single charge in tracker+TOF, tracker only, muon only, fractional-charge (tracker only), and multiple charge
- Smirnov–Cramer–von Mises discriminator, I_{as} used to separate SM particle from candidates with large (small) dE/dx
- Background estimation: ABCD method

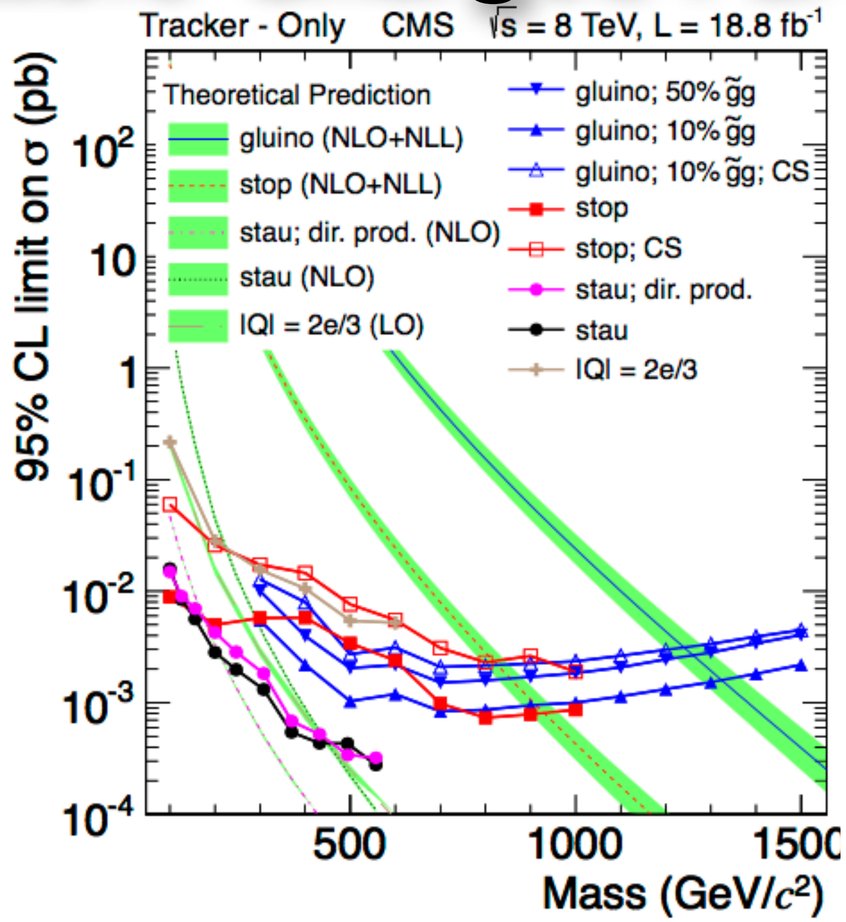


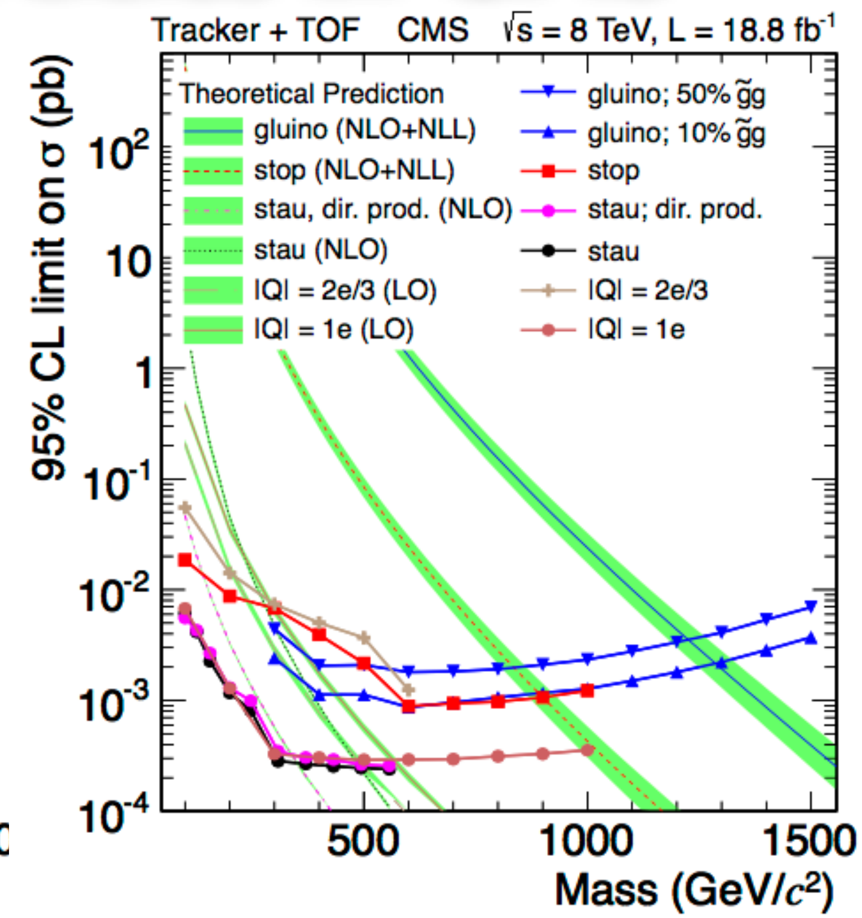


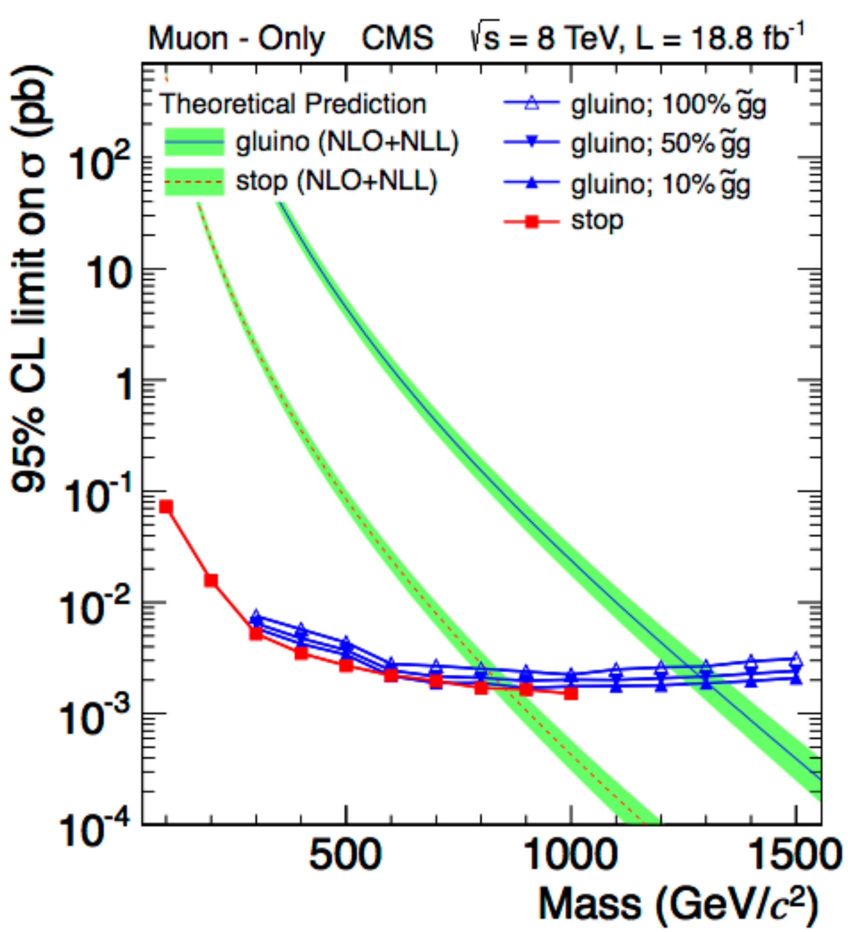
	Selection criteria				Number of events			
					$\sqrt{s}=7$ TeV		$\sqrt{s}=8$ TeV	
	p_T (GeV/c)	$I_{as}^{(\prime)}$	$1/\beta$	Mass (GeV/c^2)	Pred.	Obs.	Pred.	Obs.
Tracker-only	>70	>0.4	–	>0	7.1 ± 1.5	8	33 ± 7	41
				>100	6.0 ± 1.3	7	26 ± 5	29
				>200	0.65 ± 0.14	0	3.1 ± 0.6	3
				>300	0.11 ± 0.02	0	0.55 ± 0.11	1
				>400	0.030 ± 0.006	0	0.15 ± 0.03	0
Tracker+TOF	>70	>0.125	>1.225	>0	8.5 ± 1.7	7	44 ± 9	42
				>100	1.0 ± 0.2	3	5.6 ± 1.1	7
				>200	0.11 ± 0.02	1	0.56 ± 0.11	0
				>300	0.020 ± 0.004	0	0.090 ± 0.02	0
Muon-only	>230	–	>1.40	–	–	–	6 ± 3	3
$\lvert Q \rvert > 1e$	–	>0.500	>1.200	–	0.15 ± 0.04	0	0.52 ± 0.11	1
$\lvert Q \rvert < 1e$	>125	>0.275	–	–	0.12 ± 0.07	0	1.0 ± 0.2	0

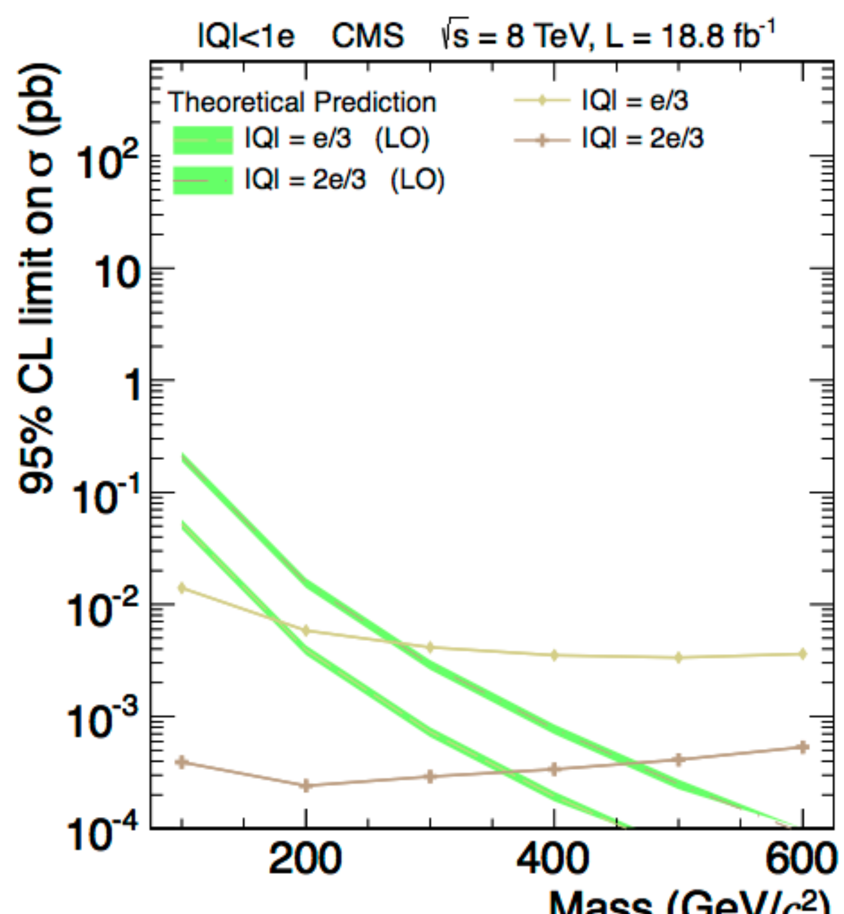
High mass Stable Charged Particles in CMS

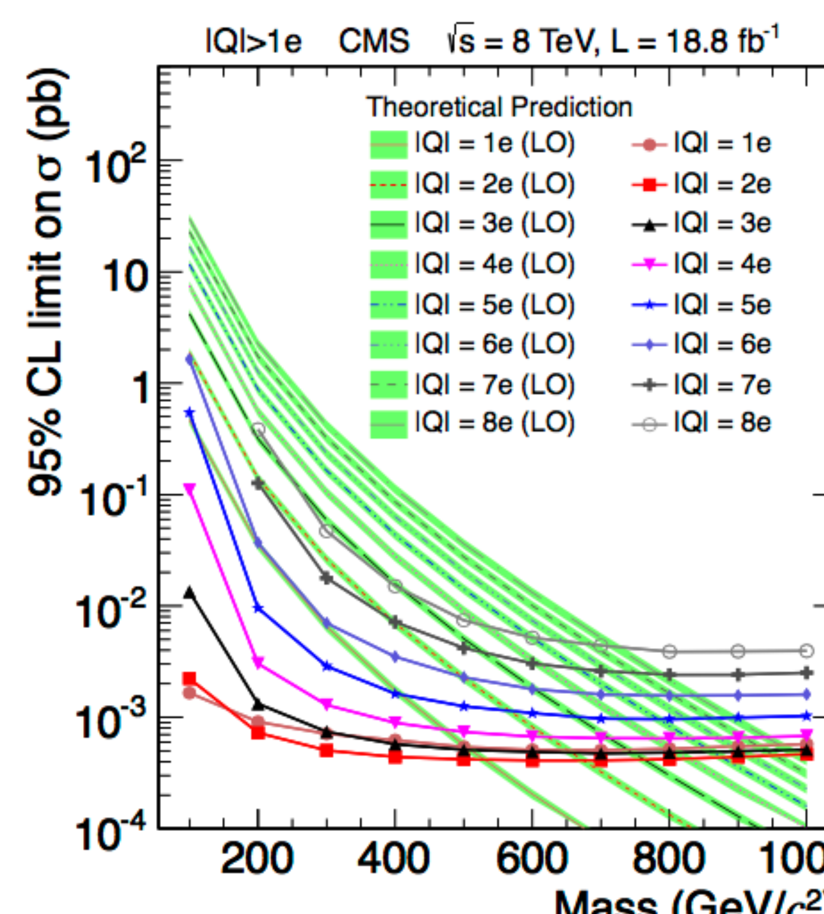
- Limits on cross sections are given for models with the production of gluinos, scalar tops, and staus, and for Drell–Yan like production of fractionally, singly, and multiply charged particles











High mass Stable Charged Particles in CMS

- Summary of exclusion limits

particle	mass limit
gluino (f = 0.5)	< 1276 GeV
gluino (f = 1.0)	< 1250 GeV
gluino (f = 0.1) cloud Interaction model	< 1322 GeV
gluino (f = 0.1) charge-suppressed model	< 1233 GeV
stop cloud Interaction model	< 935 GeV
stop charge-suppressed model	< 818 GeV
stau direct+indirect production	< 500 GeV
stau direct only production	< 339 GeV

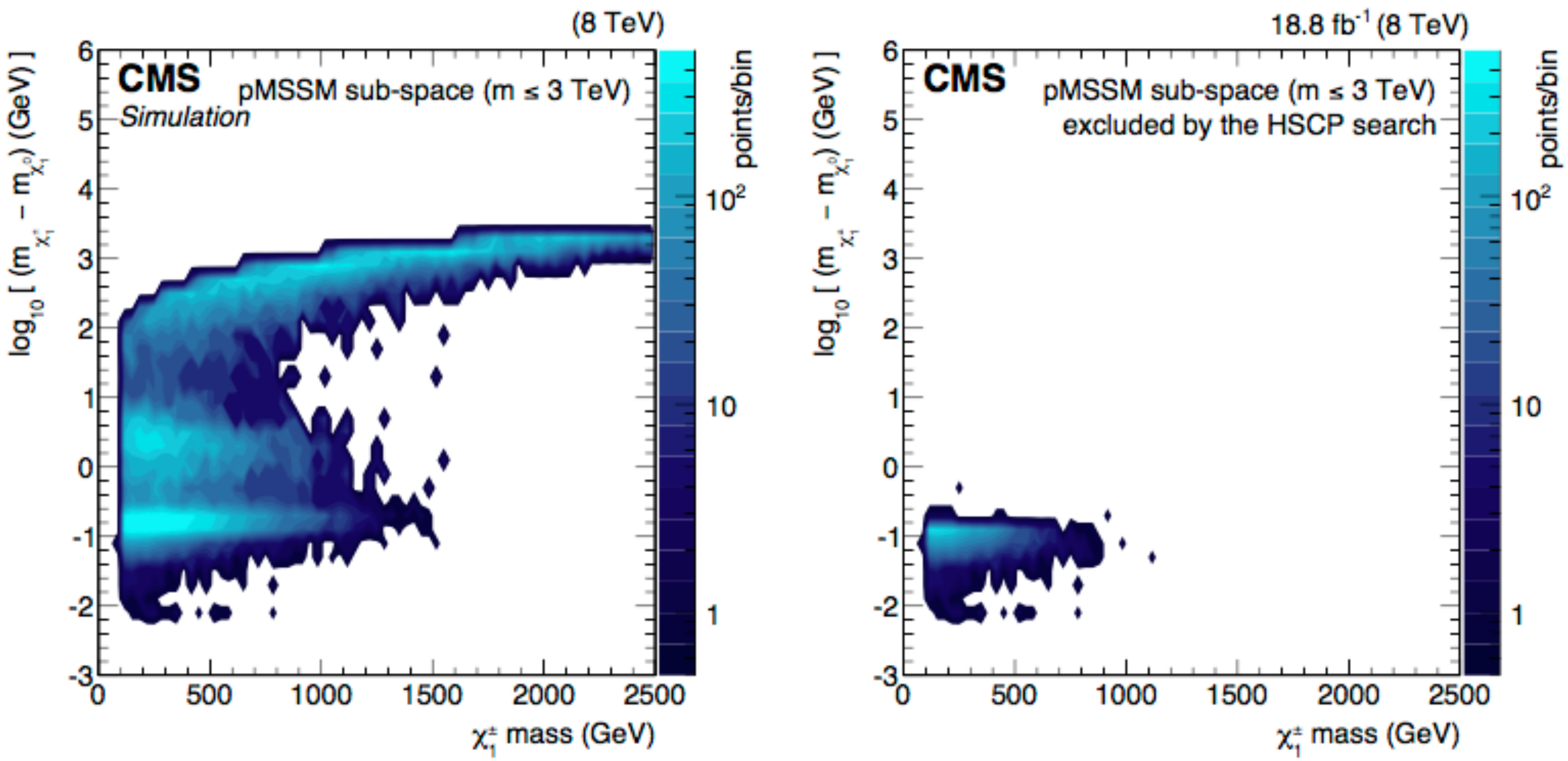
f is the fraction of gluinos hadronizing into $\tilde{g}$-gluon bound states

- Drell–Yan like signals with |Q| = e/3, 2e/3, 1e, 2e, 3e, 4e, 5e, 6e, 7e, and 8e are excluded with masses below 200, 480, 574, 685, 752, 793, 796, 781, 757, and 715 GeV/c^2, respectively

High mass Stable Charged Particles in CMS

arXiv:1502.02522 submitted to EPJ C

- Reinterpretation of the search results
  - Developed a technique to allow anyone to assess CMS sensitivity to any model predicting long-lived lepton-like particles
  - Main principle: measure the efficiency for these particles as a function of β and η in bins of p_T; then one just needs the predicted kinematics from the model
  - Example: reinterpret results in the context of the phenomenological minimal supersymmetric standard model (pMSSM) and the anomaly-mediated supersymmetry breaking (AMSB) model
  - The most stringent limits to date are set on the long-lived sector of the pMSSM sub-space that covers SUSY particle masses up to about 3 TeV: 95.9% (100%) of the points with a chargino lifetime τ ≥ 10 ns (1000 ns) are excluded by the present analysis of the results from the CMS search



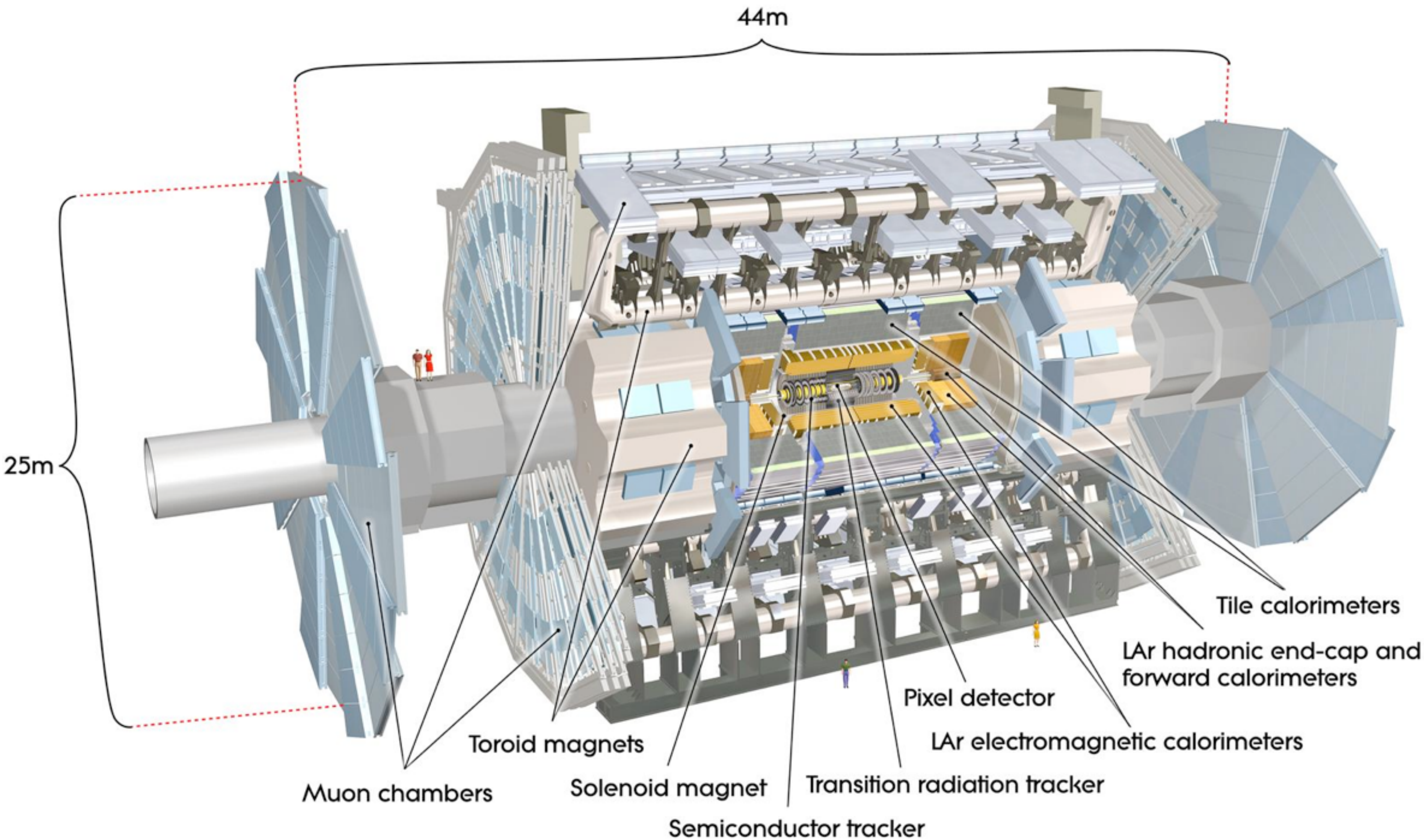
- In the context of the AMSB model, charginos with lifetimes 100 ns (3 ns) and masses up to about 800 GeV (100 GeV) are excluded at 95% CL

Conclusions

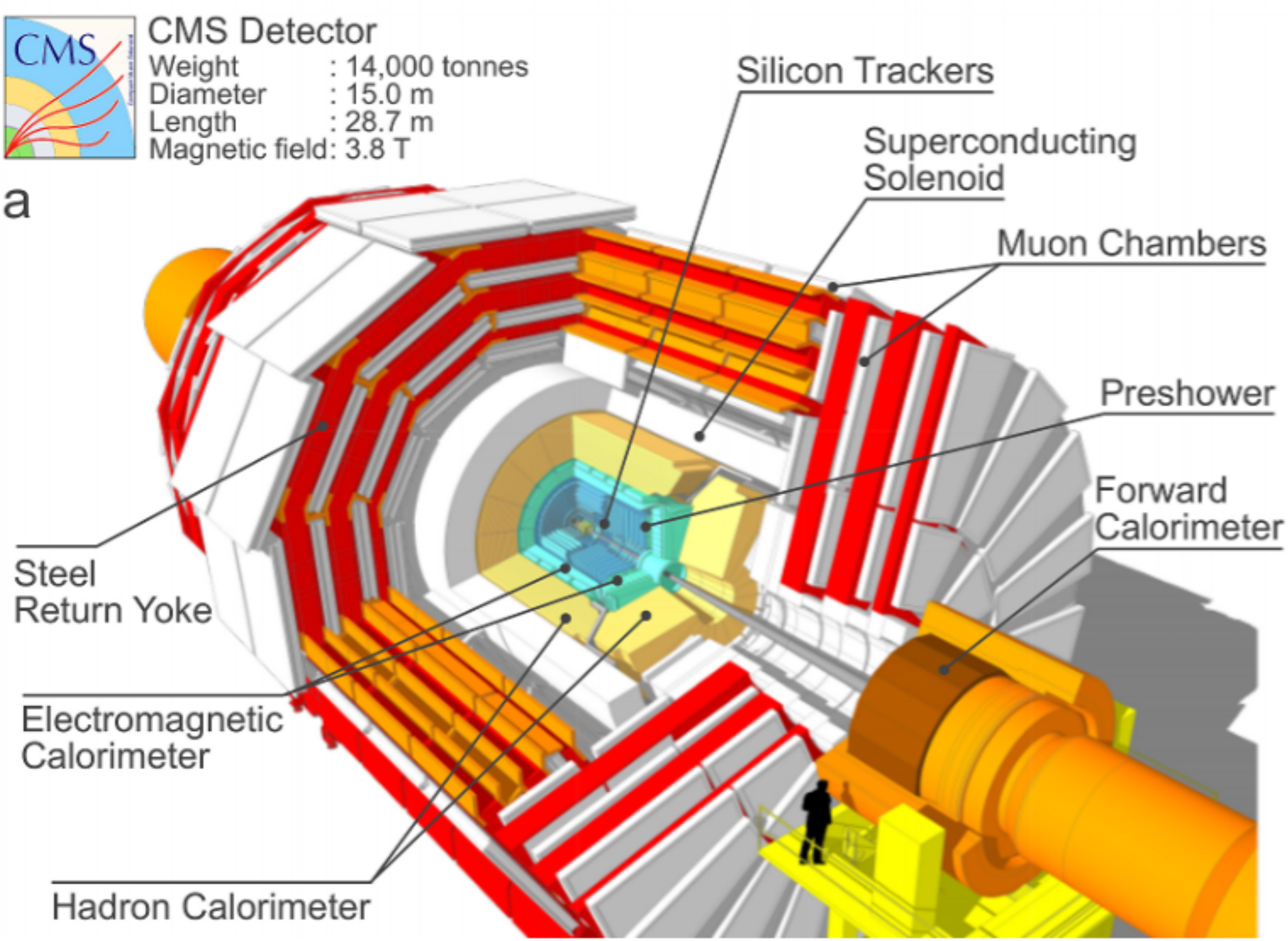
- With no sign of new physics, there has been much speculation that BSM signals could be hiding in stable, meta-stable heavy charged particles
- ATLAS and CMS Run1 searches for highly ionizing particles at the LHC were very successful
- Long list of new physics analyses and results presented in this talk
- New or stronger limits have been established by the two experiments
- While we complete the Run1 program, data at higher energy are being collected
- We are looking forward to the increased discovery potential of Run2

Extra

The ATLAS detector

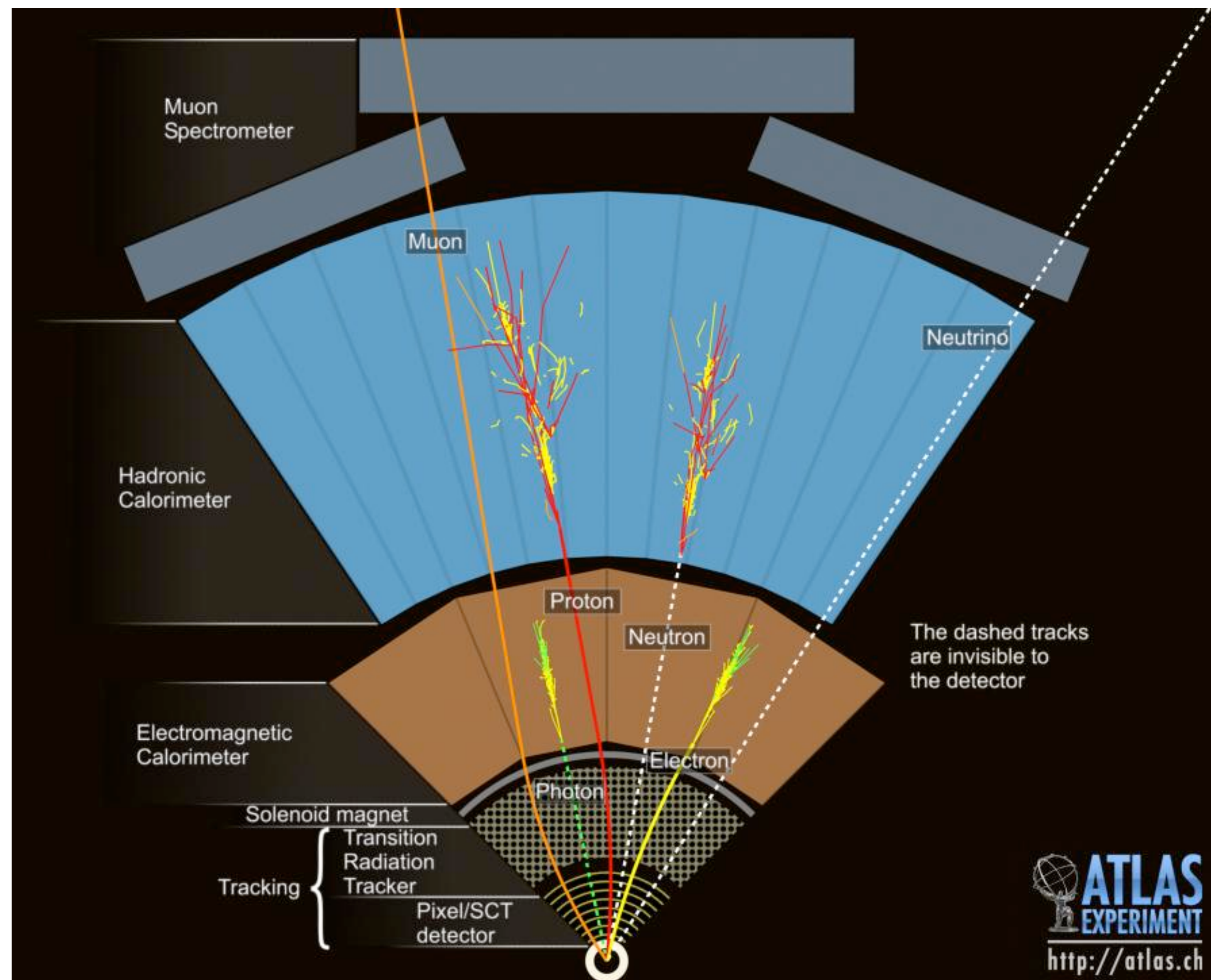


The CMS detector

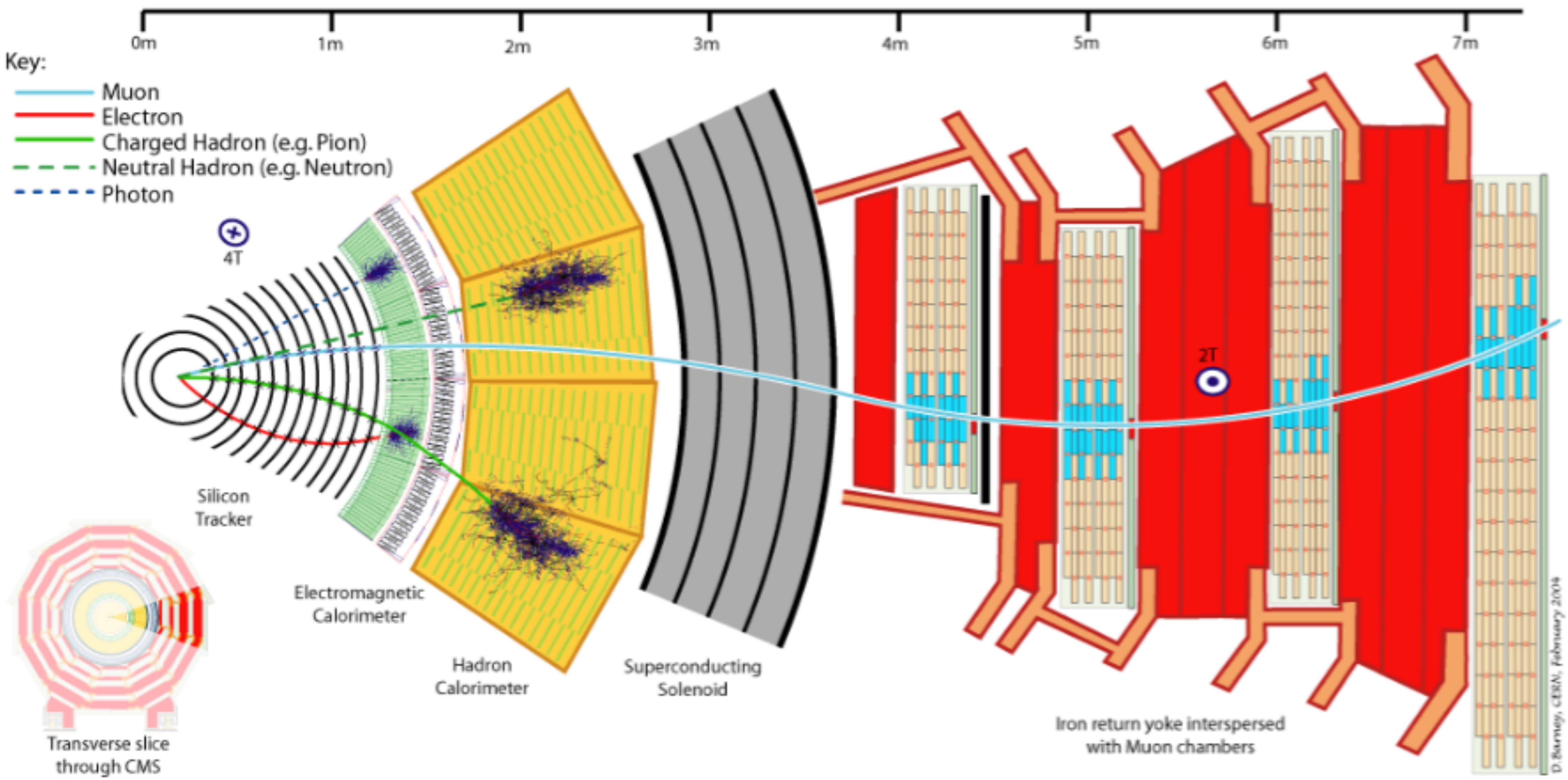


Physics objects

- Jet: cluster in EM and hadronic calorimeters (and Inner Detector)
- Photon: EM cluster without matching track
- Electron: EM cluster with matching track
- Muon: matching tracks in inner and muon trackers, or muon standalone
- Tau: Narrow jet with matching track(s)
- MET (missing E_T): p_T required to balance all of the above (and more)



Physics objects



ATLAS and CMS: more details

	ATLAS	CMS
B-field	2T solenoid (Inner Tracker inside, HCAL outside of B-field) + toroid: 0.5T (barrel), 1T (endcap) → **good for jet resolution, worse for e/γ**	4T solenoid + return yoke (ECAL and part of HCAL inside) → **good for e/γ resolution, worse for jet**
Tracker	Si pixels and strips + transition radiation tracker → **high resolution, granularity, "continuous" tracking at large radii**	Si pixels and strips (fully Silicon) → **high resolution, granularity**
	$\sigma/p_T \sim 5 \times 10^{-4} p_T + 0.01$	$\sigma/p_T \sim 1.5 \times 10^{-4} p_T + 0.005$
π with pT=1GeV	84% reco efficiency (material budget, B-field)	80% reco efficiency
e with pT=5GeV	90% reco efficiency	85% reco efficiency
EM calo	Liquid argon + Pb absorbers → **high granularity**	$PbWO_4$ crystals → **high resolution**
	$\sigma/E \sim 10\%/\sqrt{E} + 0.007$	$\sigma/E \sim 3\%/\sqrt{E} + 0.003$
100 GeV γ	1.0 - 1.5% E resolution	0.8% E resolution
50 GeV e	1.3 - 2.3% E resolution	2.0% E resolution
Had calo	Fe + scintillator / Cu+Lar (10λ)	Brass + scintillator (7λ + catcher)
	$\sigma/E \sim 50\%/\sqrt{E} + 0.03$ GeV	$\sigma/E \sim 100\%/\sqrt{E} + 0.05$ GeV
1000 GeV jets	2%	5%
2000 GeV MET	20 GeV	40 GeV
Muon	σ/p_T~2% at 50 GeV to 10% at 1 TeV (Inner Tracker + muon system)	σ/p_T~1% at 50 GeV to 10% at 1 TeV (Inner Tracker + muon system)

Stable Massive Particles

- **Stable Massive Particles** (SMPs) predicted by many BSM scenarios, including several different SUSY models
- sleptons are massive, charged and metastable in GMSB
- R-hadrons are **colored** SMPs: bound states formed by **squarks and gluinos** hadronizing with a light SM quarks system, several **electric charges** (and the electric charge can change due to nuclear scattering in the detector)
- **Long-lived** for this search

	composition	notation
R-mesons	$R = \tilde{g}q\bar{q}, (\tilde{q}\bar{q})$	R^+, R^-, R^0
R-baryons	$R = \tilde{g}qqq, (\tilde{q}qq)$	R^{++}, R^+, R^-, R^0
R-gluinoballs	$R = \tilde{g}g$	R^0

arXiv:hep-ph/0611040

SMP	LSP	Scenario	Conditions
$\tilde{\tau}_1$	$\tilde{\chi}_1^0$	MSSM	$\tilde{\tau}_1$ mass (determined by $m^2_{\tilde{\tau}_{L,R}}$, μ, $\tan\beta$, and A_τ) close to $\tilde{\chi}_1^0$ mass.
	$\tilde{G}$	GMSB	Large N, small M, and/or large $\tan\beta$.
		$\tilde{g}$MSB	No detailed phenomenology studies, see [23].
		SUGRA	Supergravity with a gravitino LSP, see [24].
	$\tilde{\tau}_1$	MSSM	Small $m_{\tilde{\tau}_{L,R}}$ and/or large $\tan\beta$ and/or very large A_τ.
		AMSB	Small m_0, large $\tan\beta$.
		$\tilde{g}$MSB	Generic in minimal models.
$\tilde{\ell}_{i1}$	$\tilde{G}$	GMSB	$\tilde{\tau}_1$ NLSP (see above). $\tilde{e}_1$ and $\tilde{\mu}_1$ co-NLSP and also SMP for small $\tan\beta$ and μ.
	$\tilde{\tau}_1$	$\tilde{g}$MSB	$\tilde{e}_1$ and $\tilde{\mu}_1$ co-LSP and also SMP when stau mixing small.
$\tilde{\chi}_1^+$	$\tilde{\chi}_1^0$	MSSM	$m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0} \lesssim m_{\pi^+}$. Very large $M_{1,2} \gtrsim 2$ TeV $\gg |\mu|$ (Higgsino region) or non-universal gaugino masses $M_1 \gtrsim 4M_2$, with the latter condition relaxed to $M_1 \gtrsim M_2$ for $M_2 \ll |\mu|$. Natural in O-II models, where simultaneously also the $\tilde{g}$ can be long-lived near $\delta_{GS} = -3$.
		AMSB	$M_1 > M_2$ natural. m_0 not too small. See MSSM above.
$\tilde{g}$	$\tilde{\chi}_1^0$	MSSM	Very large $m^2_{\tilde{q}} \gg M_3$, e.g. split SUSY.
	$\tilde{G}$	GMSB	SUSY GUT extensions [25–27].
	$\tilde{g}$	MSSM	Very small $M_3 \ll M_{1,2}$, O-II models near $\delta_{GS} = -3$.
		GMSB	SUSY GUT extensions [25–29].
$\tilde{t}_1$	$\tilde{\chi}_1^0$	MSSM	Non-universal squark and gaugino masses. Small $m^2_{\tilde{q}}$ and M_3, small $\tan\beta$, large A_t.
$\tilde{b}_1$			Small $m^2_{\tilde{q}}$ and M_3, large $\tan\beta$ and/or large $A_b \gg A_t$.

dE/dx measurement in CMS

from JHEP07 (2013) 122

As in Ref. [19], dE/dx for a track is estimated as:

$$I_h = \left(\frac{1}{N}\sum_i c_i^{-2}\right)^{-1/2}, \quad (1)$$

where N is the number of measurements in the silicon-strip detectors and c_i is the energy loss per unit path length in the sensitive part of the silicon detector of the ith measurement; I_h has units MeV/cm. In addition, two modified versions of the Smirnov–Cramer–von Mises [54, 55] discriminator, I_{as} (I'_{as}), are used to separate SM particles from candidates with large (small) dE/dx. The discriminator is given by:

$$I_{as}^{(\prime)} = \frac{3}{N} \times \left(\frac{1}{12N} + \sum_{i=1}^{N}\left[P_i^{(\prime)} \times \left(P_i^{(\prime)} - \frac{2i-1}{2N}\right)^2\right]\right), \quad (2)$$

where P_i (P'_i) is the probability for a minimum ionizing particle (MIP) to produce a charge smaller (larger) or equal to that of the ith measurement for the observed path length in the detector, and the sum is over the measurements ordered in terms of increasing $P_i^{(\prime)}$.

As in Ref. [19], the mass of a $|Q| = 1e$ candidate particle is calculated based on the relationship:

$$I_h = K\frac{m^2}{p^2} + C, \quad (3)$$

where the empirical parameters $K = 2.559 \pm 0.001\,\text{MeV} \cdot c^2/\text{cm}$ and $C = 2.772 \pm 0.001\,\text{MeV/cm}$ are determined from data using a sample of low-momentum protons in a minimum-bias dataset.

The number of silicon-strip measurements associated with a track, 15 on average, is sufficient to ensure good dE/dx and mass resolutions.