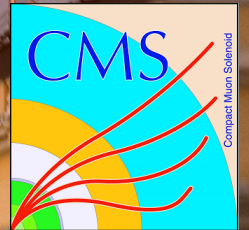
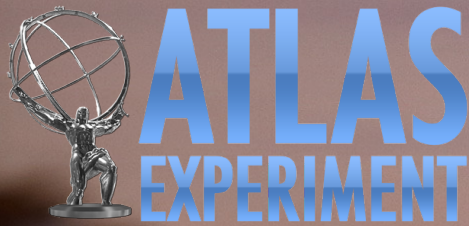


Searches for heavy stable charged particles and other exotic signatures with large ionization at the LHC



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on behalf of the **ATLAS** and * **CMS** Collaborations

 National Centre for Nuclear Research
Warsaw, Poland

LHCP 2015
St. Petersburg, Russia
Aug 31 – Sep 5



Hunting for HSCPs

OUTLINE:

- **Various theoretical models** predict **naturally long-lived** particles: pMSSM, GMSB, AMSB, Split-SUSY (with R-hadrons), RPV SUSY, Hidden Valley (HV), Little Higgs and more
- **Challenging and interesting**
non-standard measurements and techniques of reconstructions, often difficult for triggering
- **Signature based searches**
interpreted in the context of different models
- **Review of EXOTIC HSCP searches in the LHC**
 - Results from ATLAS and CMS data collected in 2012 – **20/fb at 8TeV**



Some EXOTIC Signatures

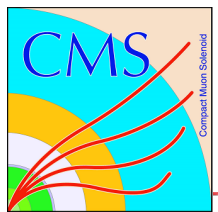
- **Heavy** (meta) **stable** (fractionally, multi-, flip-) **charged particles** → **HSCP**, e.g.:
 - **Stau/slepton** in Gauge-Mediated SUSY breaking
 - **squark LSP** in R-Parity violating SUSY
 - **R-hadrons** decaying via virtual squarks in Split SUSY
 - Nearly mass-degenerate **chargino** & **neutralino** in Anomaly-Mediated SUSY

- **Main signatures:**

While crossing the detector HSCPs may have:

- High/low **ionisation** (dE/dx)
- **Delayed** signal ($\beta < 1$)
extended **time-of-flight** (ToF) vrt SM objects

→ **Mass measurement** from β and p
$$m = \frac{p}{\beta\gamma} = \frac{p}{\beta/\sqrt{1-\beta^2}}$$

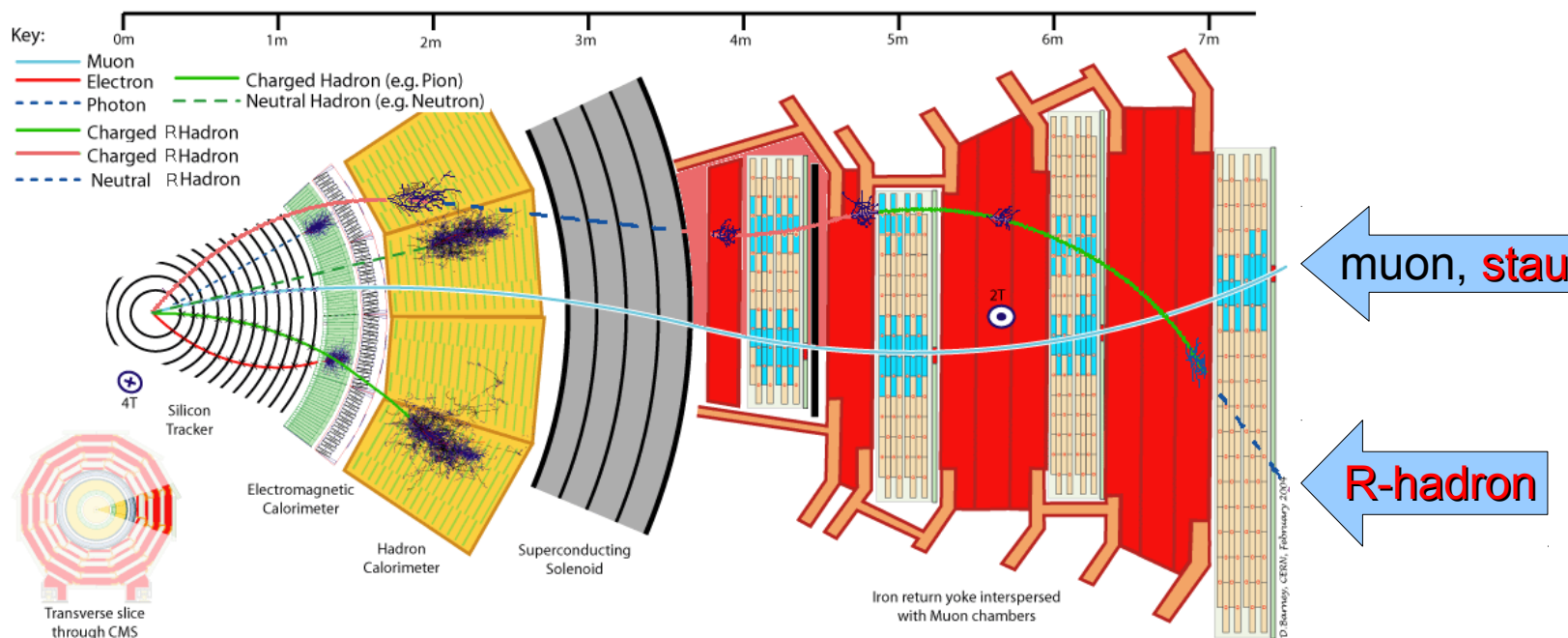


Heavy^{META} Stable Charged Particles in CMS

JHEP 07(2013)122

Signal: Long-Lived Particles from GMSB, Split-SUSY and others:

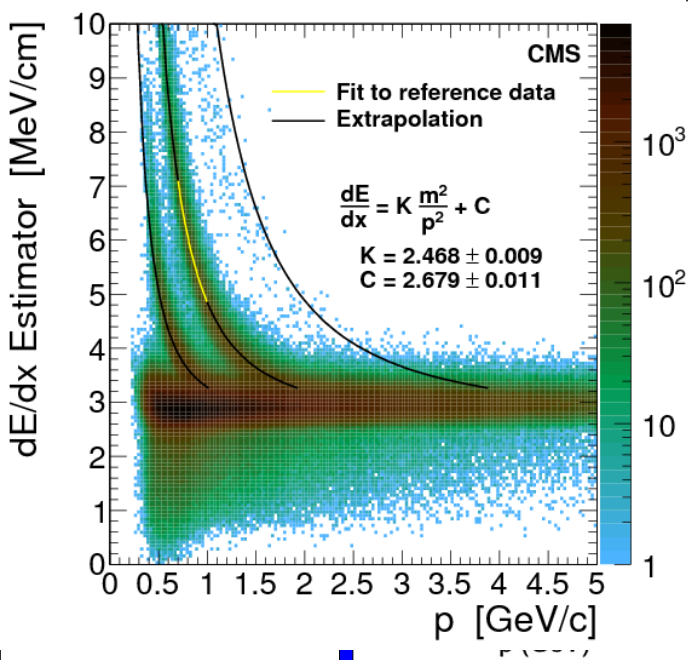
- lepton like (stau)
 - fractional charge ($Q = n \cdot 1/3e$)
 - multiple charge ($Q = n \cdot e$)
- R-hadrons formed from gluino or stop
 - charge can flip while crossing particle interacts with material



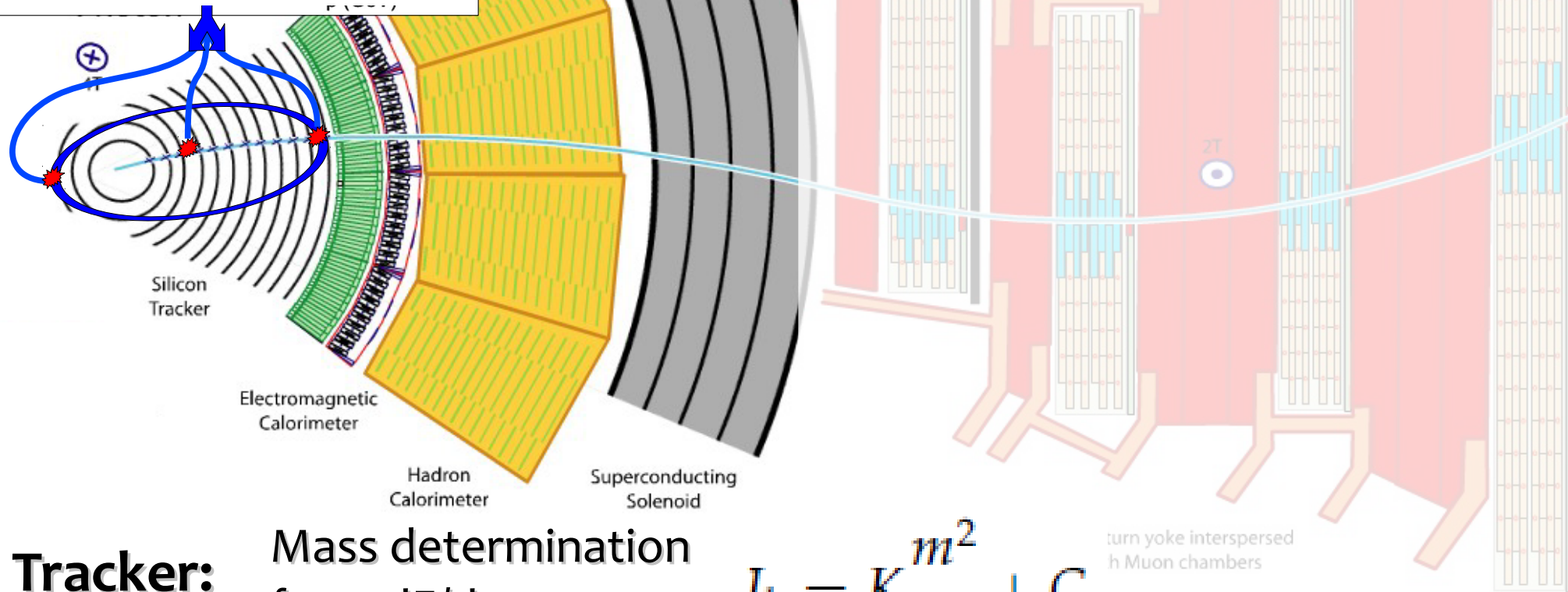
Idea of HSCP Search in CMS

HSCP has high unusual **ionization** related to its mass

JHEP 07(2013)122



$$I_h \sim \frac{dE}{dx}$$



Tracker:

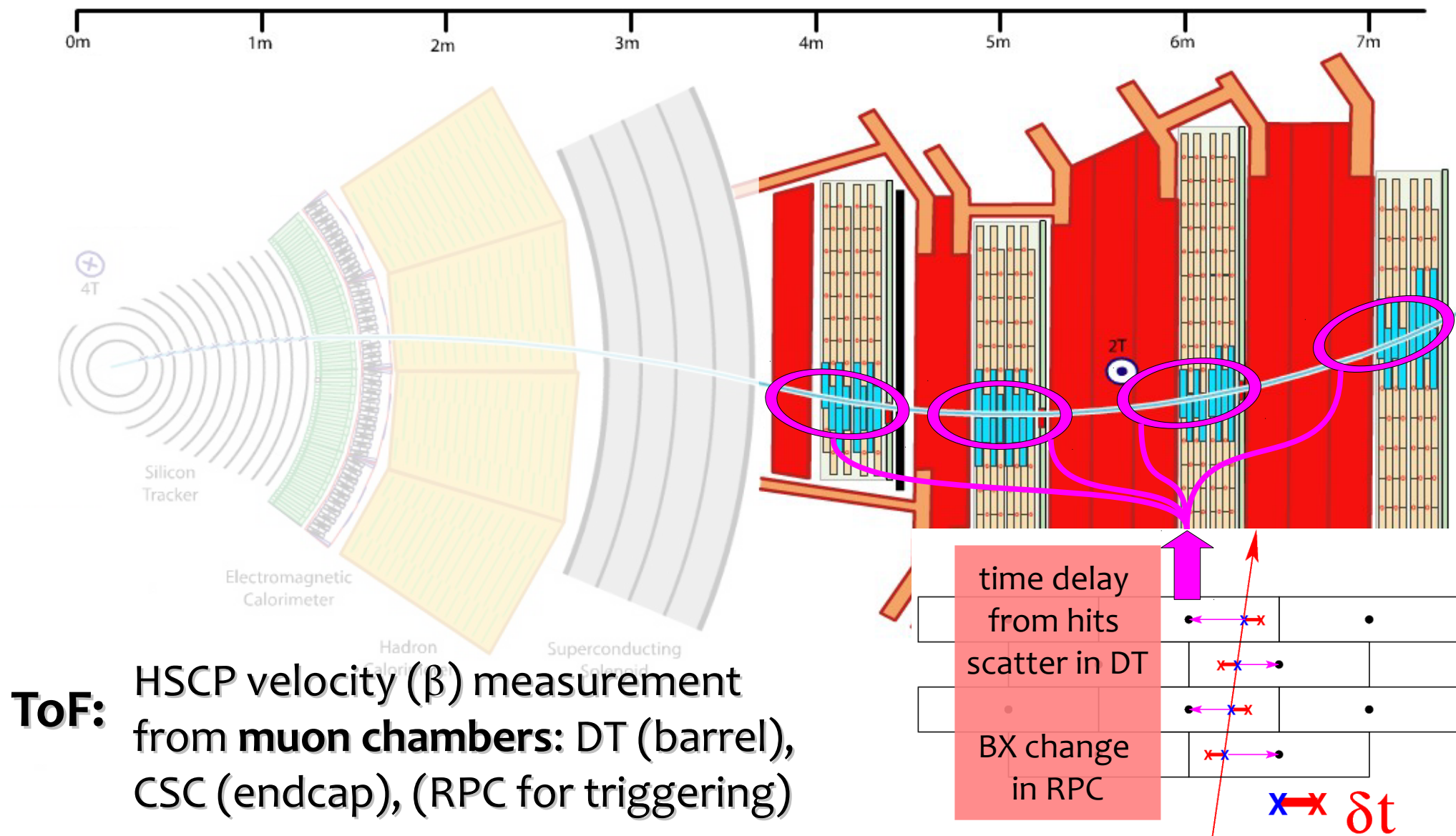
Mass determination
from dE/dx
discriminants

$$I_h = K \frac{m^2}{p^2} + C$$

Idea of HSCP Search in CMS

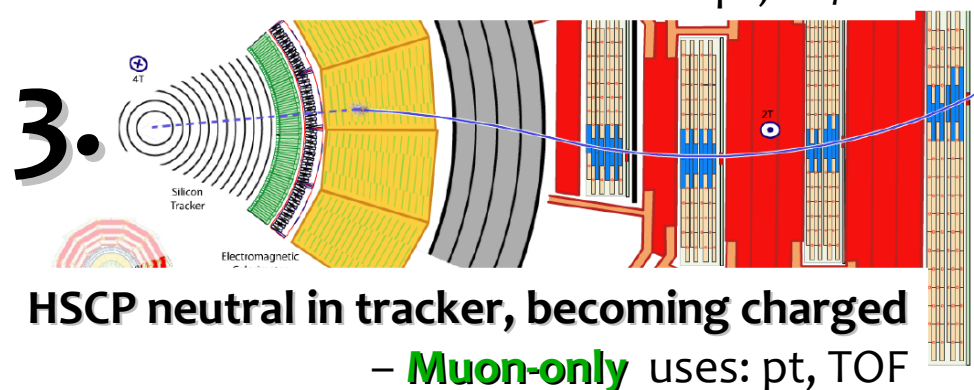
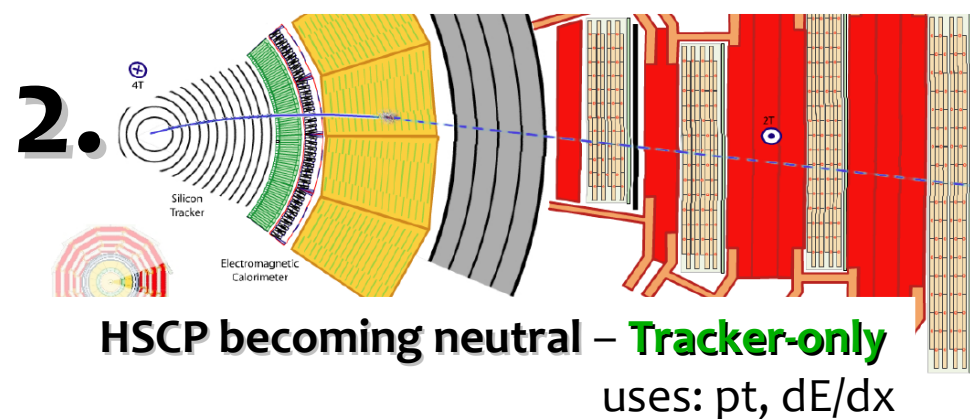
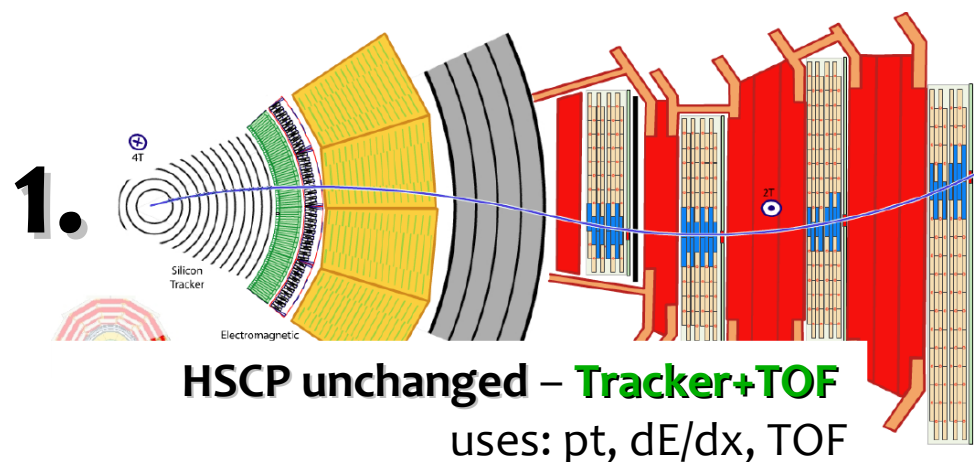
HSCP can be **delayed** with respect to the c -speed SM particle

Muon System: Mass determination from β – ToF

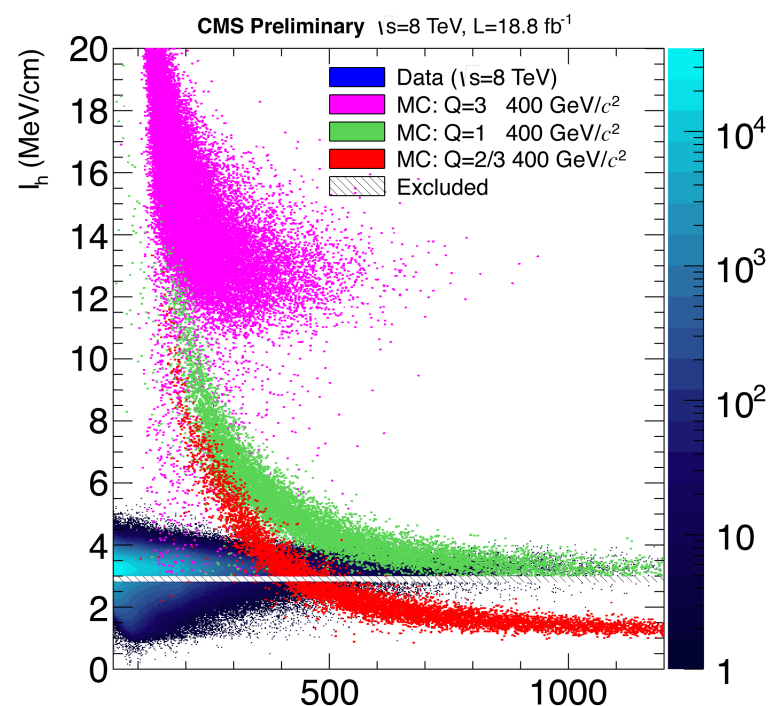


Five HSCP Search Paths in CMS

JHEP 07(2013)122



4. HSCP with $Q = n \cdot e$
Multiply Charged Particles
uses: dE/dx TOF, **do not use pt**,
because reco pt \sim true pt/Q



5. HSCP with $Q = n \cdot 1/3e$
Fractionally Charged Particles
uses: pt, dE/dx, no TOF to be inclusive

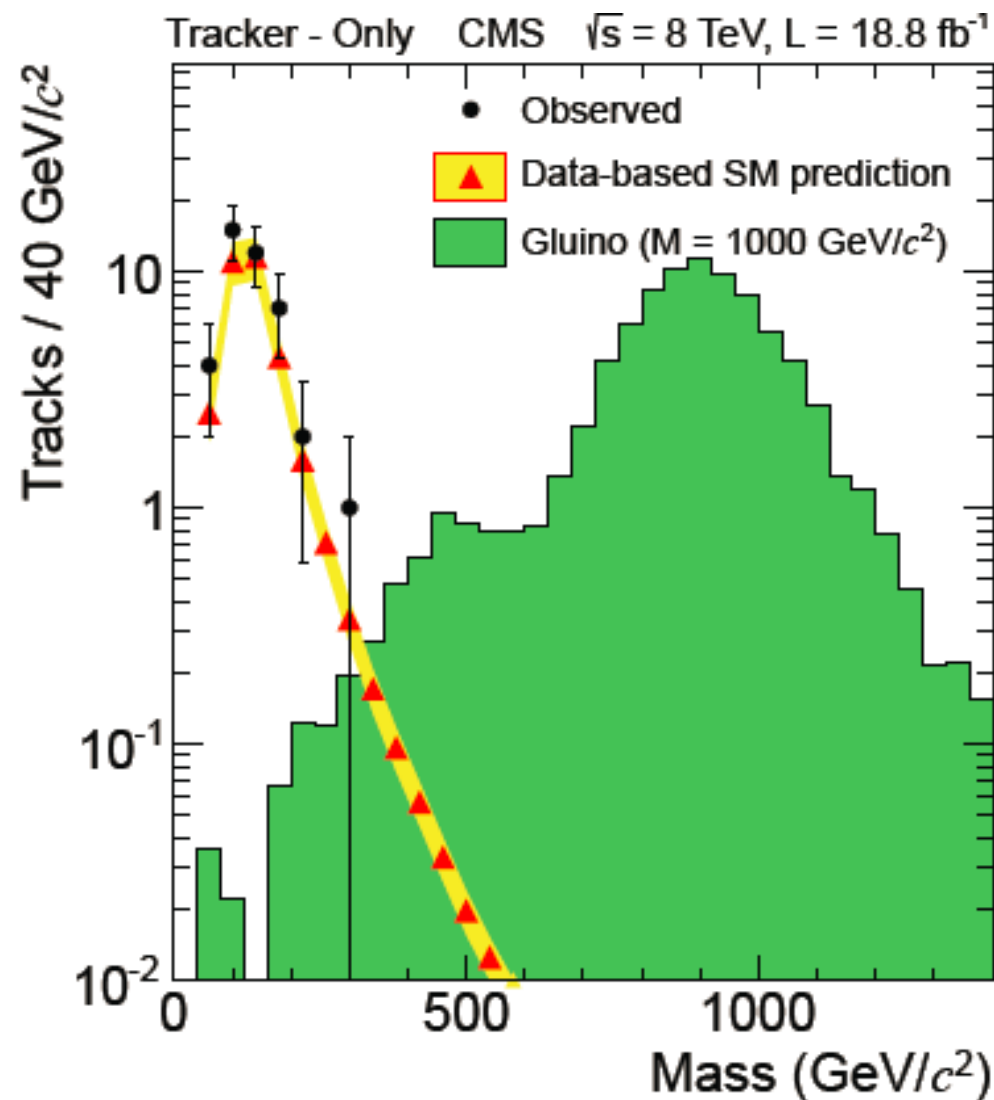
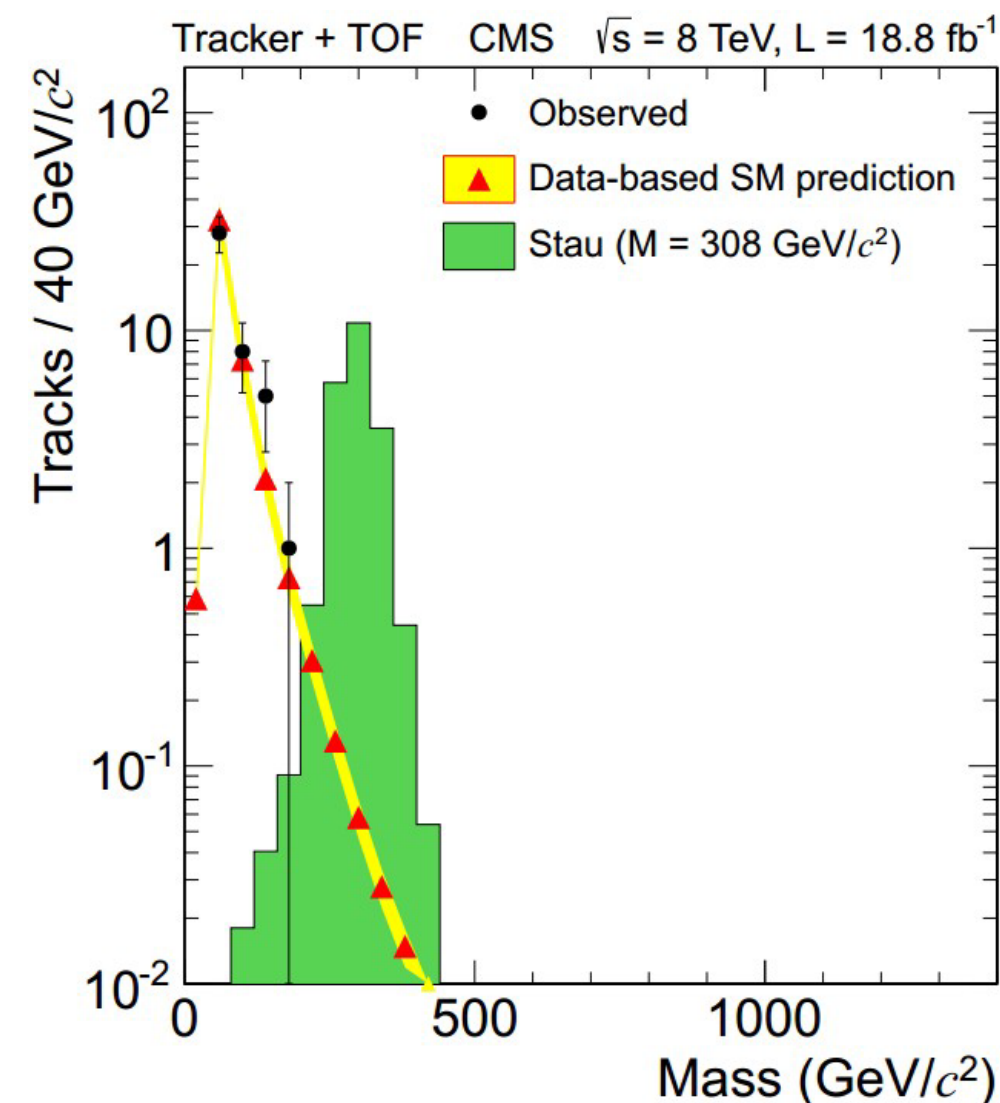


HSCP Results by CMS

JHEP 07(2013)122

dE/dx + TOF

dE/dx



Mass determined from dE/dx

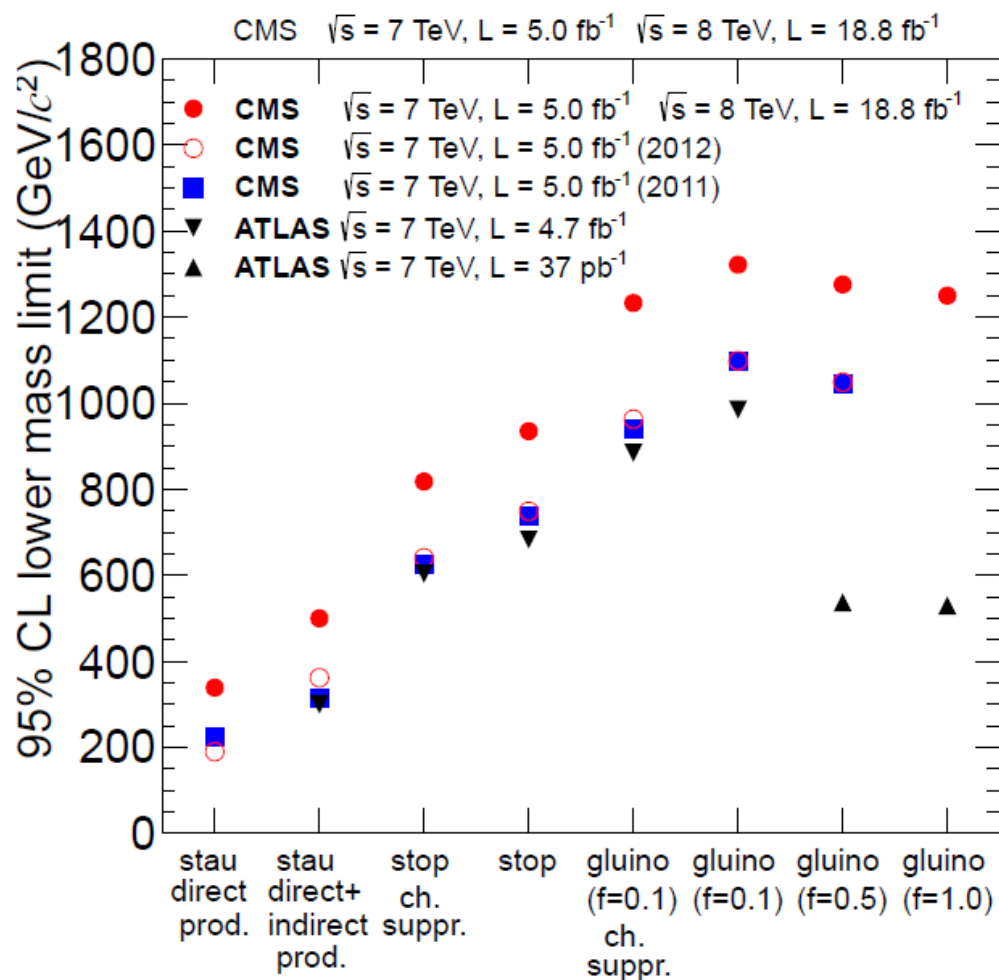


Limits on HSCP by CMS

JHEP 07(2013)122

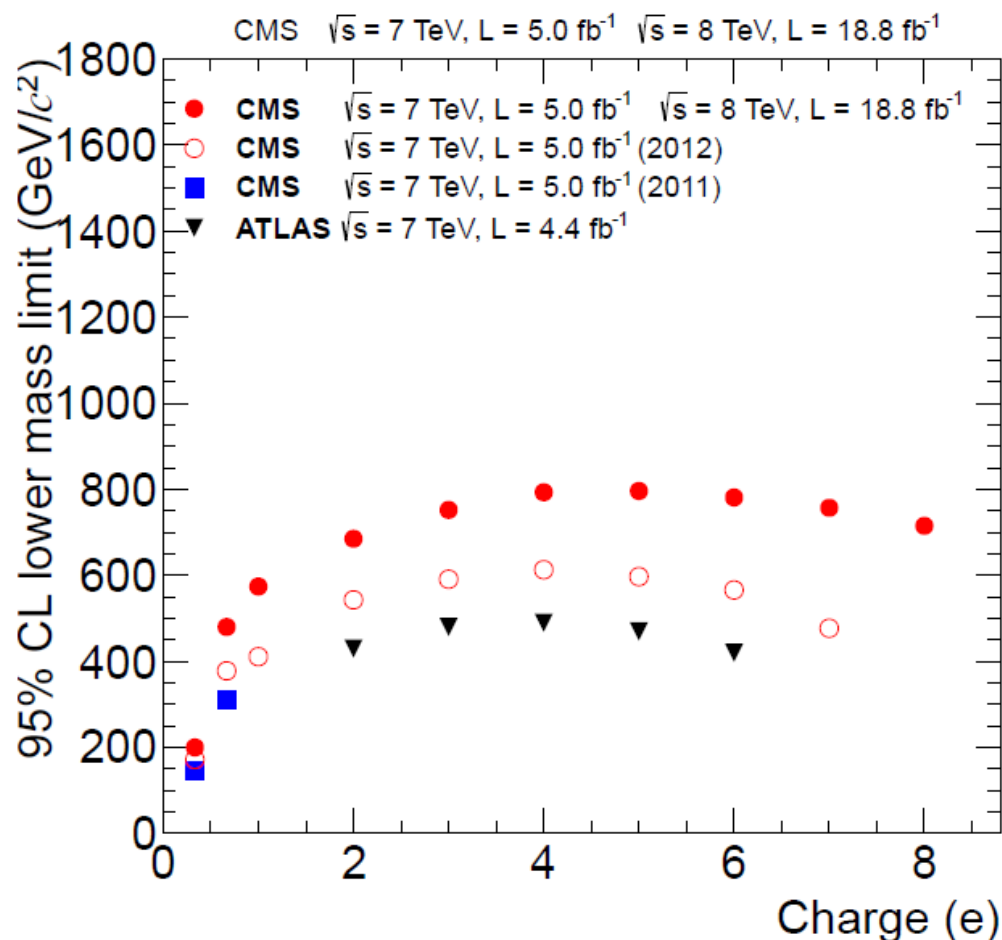
Stau

R-hadrons (stop, gluino)



Multiply Charged Particles

Fractionally Charged Particles

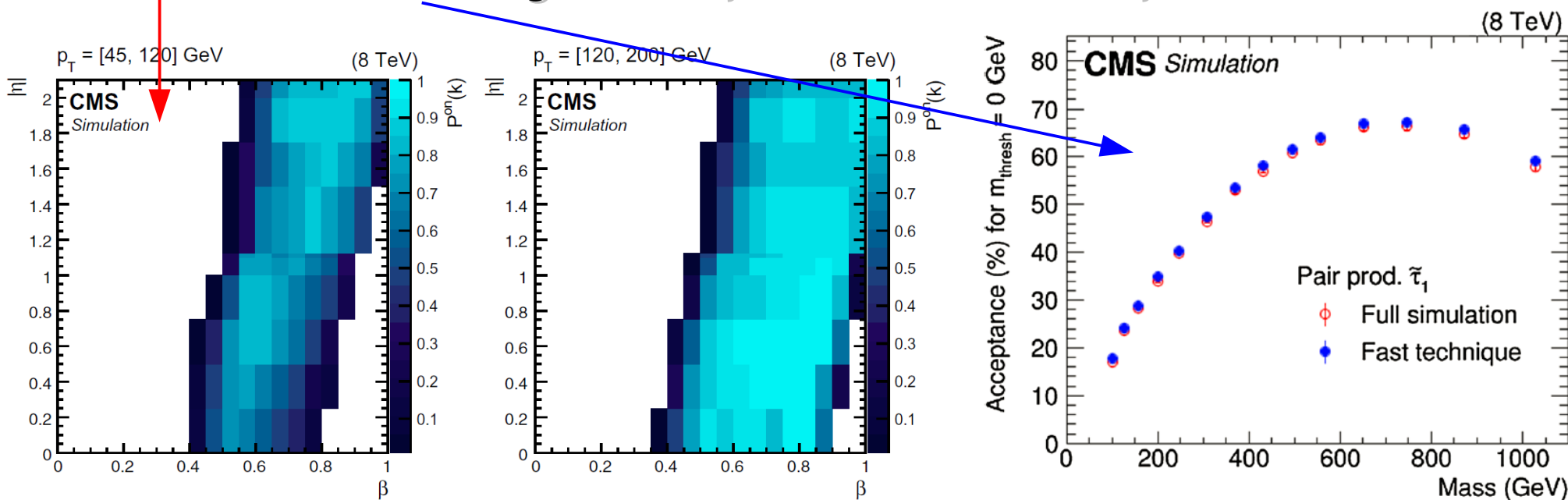


HSCP re-interpretation by CMS

EPJ C (2015) 75:325

- **Reinterpretation of the HSCP search results in context of pMSSM and AMSB**
- Developed a technique to allow anyone to assess CMS sensitivity to any model predicting long-lived lepton-like particles
- The efficiency for HSCP particles is given as a function of β and η in bins of p_T , it can be applied to any model if the kinematics is known

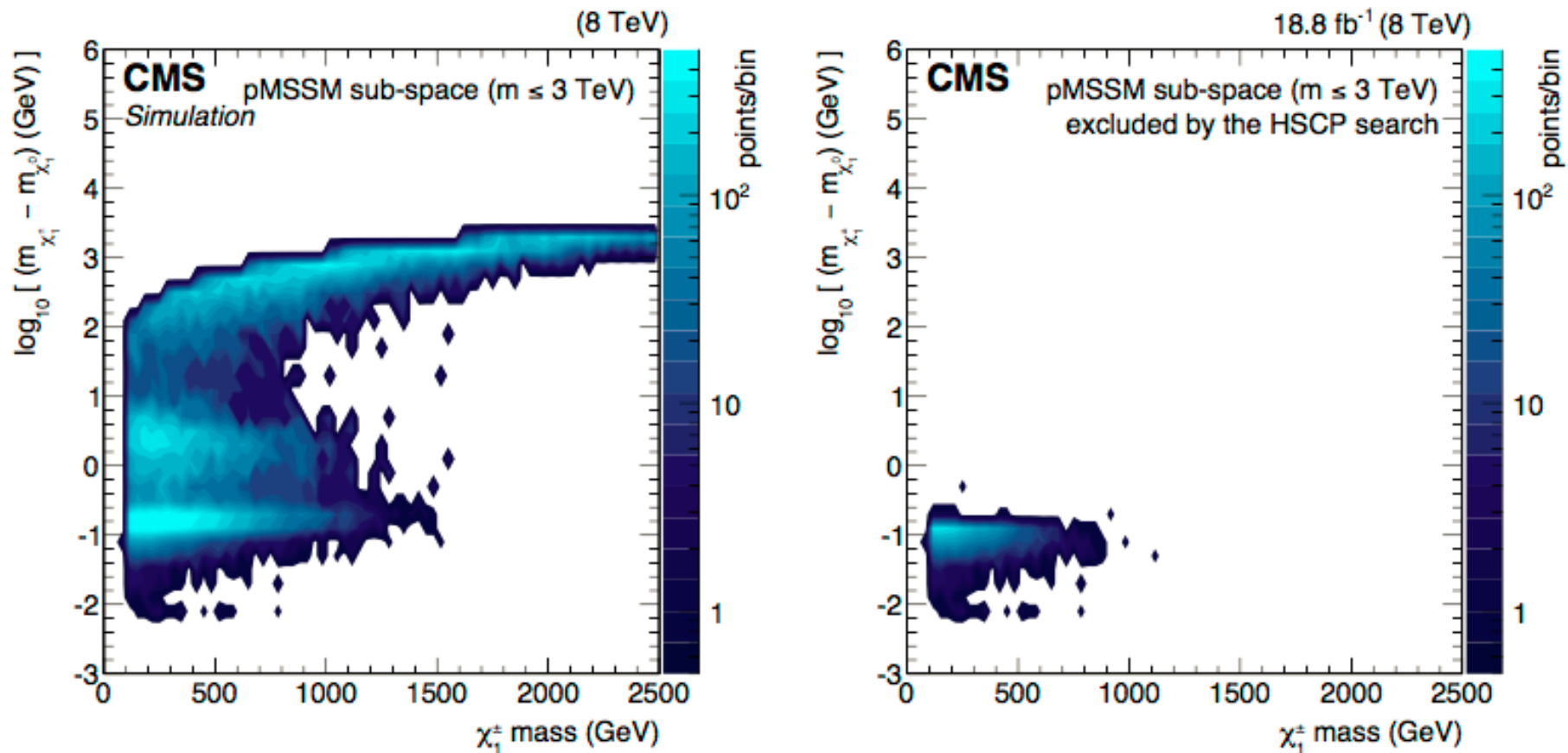
Probability maps of that LLP passes all HSCP cuts are expressed as a $f(\beta, p_T, \eta)$
 Pure **GenLevel MC** enough to verify results of HSCP analysis



HSCP re-interpretation by CMS

EPJ C (2015) 75:325

- Limits on the long-lived sector of the pMSSM sub-space for SUSY particle masses < 3 TeV:
95.9% (100%) of the points with a chargino lifetime $\tau \geq 10$ ns (1000 ns) are **excluded by the present analysis** of the results from the CMS search



- AMSB: **charginos** with lifetimes **100 ns** (3 ns) and masses up to about **800 GeV** (100 GeV) are **excluded** at 95% CL

Analysis strategy

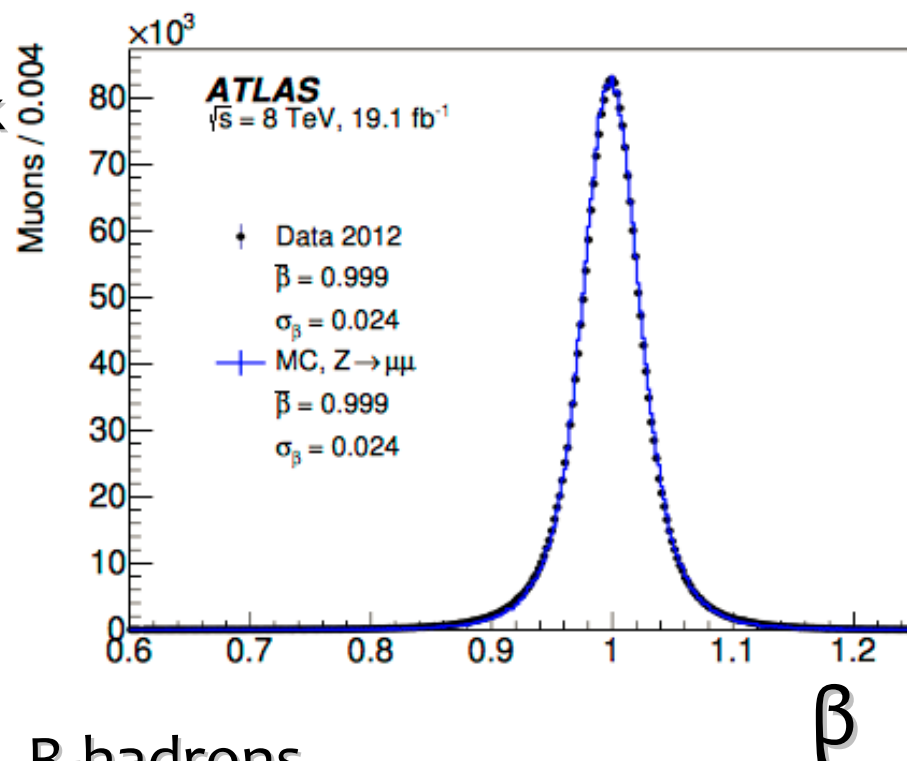
- High p_T muon trigger or missing ET trigger, $MET > 100$ GeV
- Track information ($p_T > 80$ GeV) is used to calculate the candidate mass
 - β calculated from measured **ToF using muon system & calorimeter**
 - $\beta\gamma$ deduced from **Pixel dE/dx**
 - p derived from the candidate track

Background:

- High- p_T muons with large ionization, mis-measured β
- Contribution estimated from data

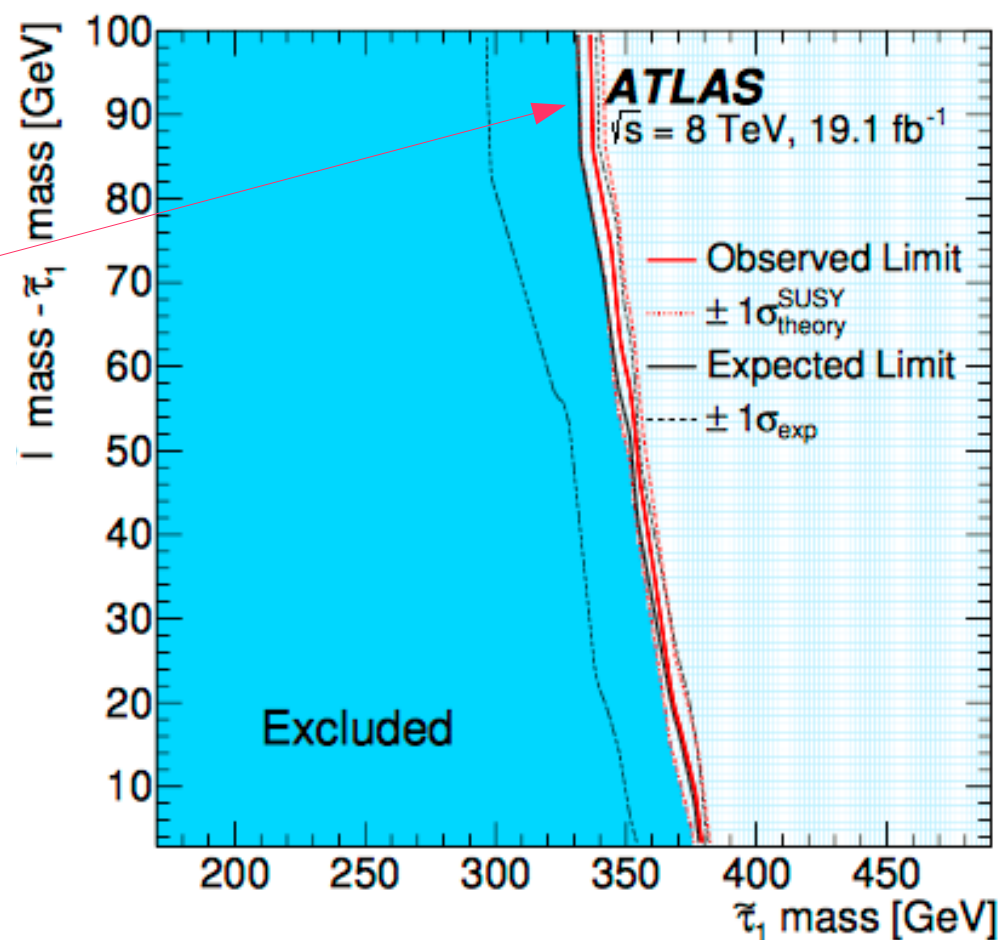
Interpretations:

- stable sleptons, leptoSUSY, charginos, R-hadrons



- Summary of limits reach by ATLAS

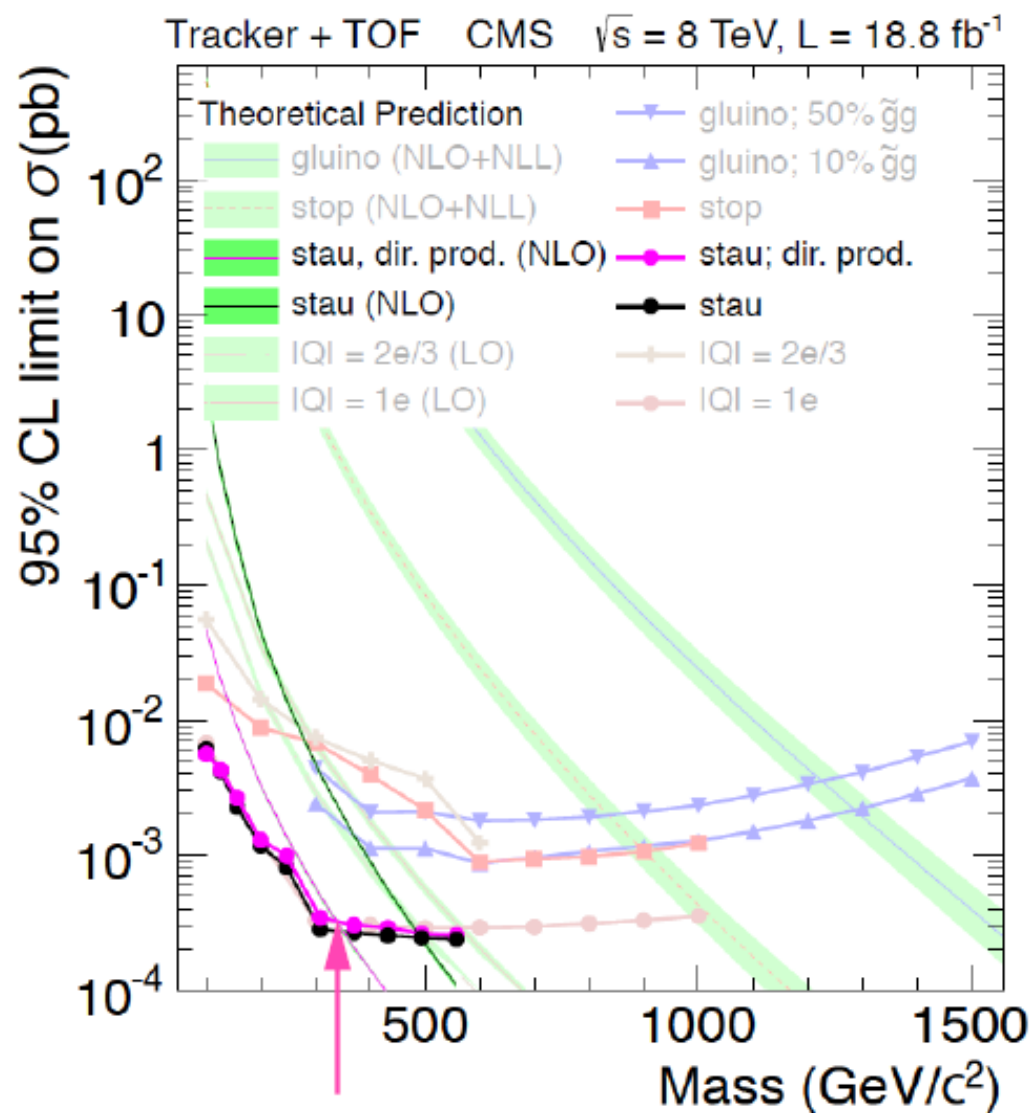
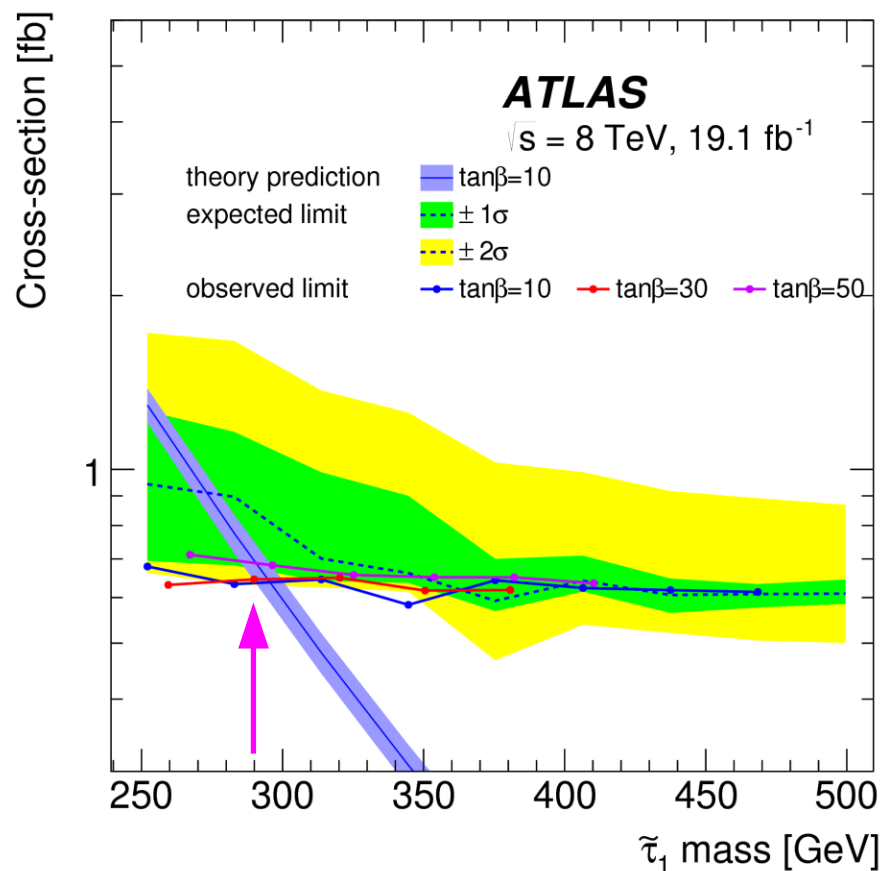
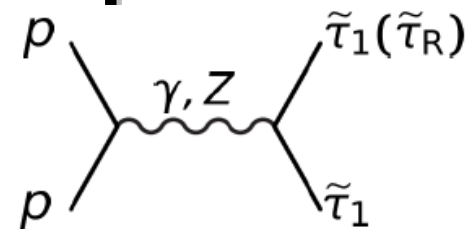
Search	Lower mass limit [GeV]
GMSB sleptons	
· $\tan \beta = 10, 20, 30, 40, 50$	440, 440, 430, 410, 385
· direct $\tilde{\ell}$ production ($m_{\tilde{\ell}} - m_{\tilde{\tau}_1} = 2.7\text{--}93\text{ GeV}$)	377–335
· direct $\tilde{\tau}_1$ production	289
· $\tilde{\chi}_1^0 \tilde{\chi}_1^\pm$ decaying to stable $\tilde{\tau}_1$	537
LeptoSUSY	
· \tilde{q}, \tilde{g}	1500, 1360
Charginos	
· $\tilde{\chi}_1^\pm$	620
<i>R</i> -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



Limits on stau – comparison

- Direct stau production:

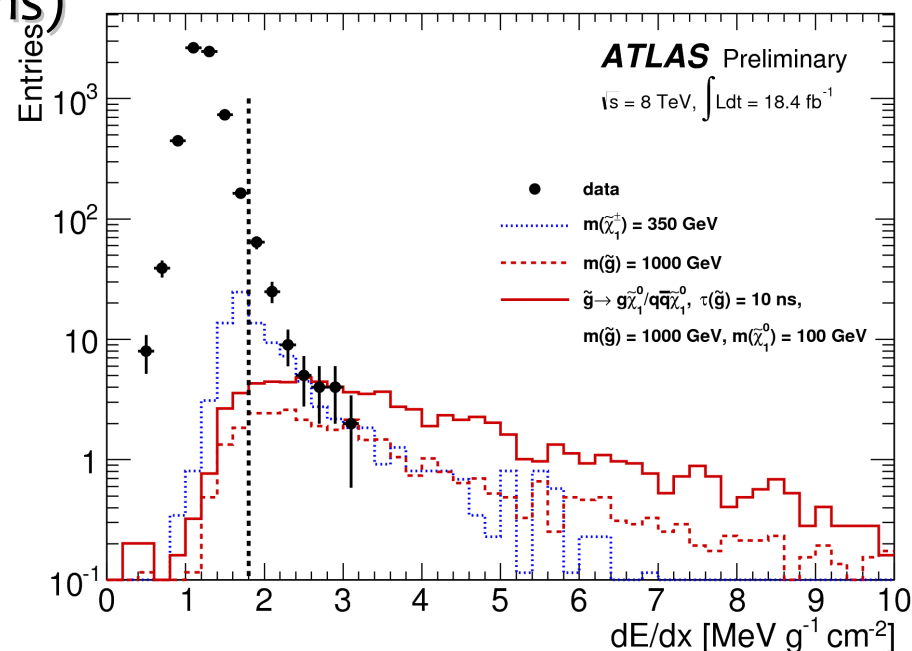
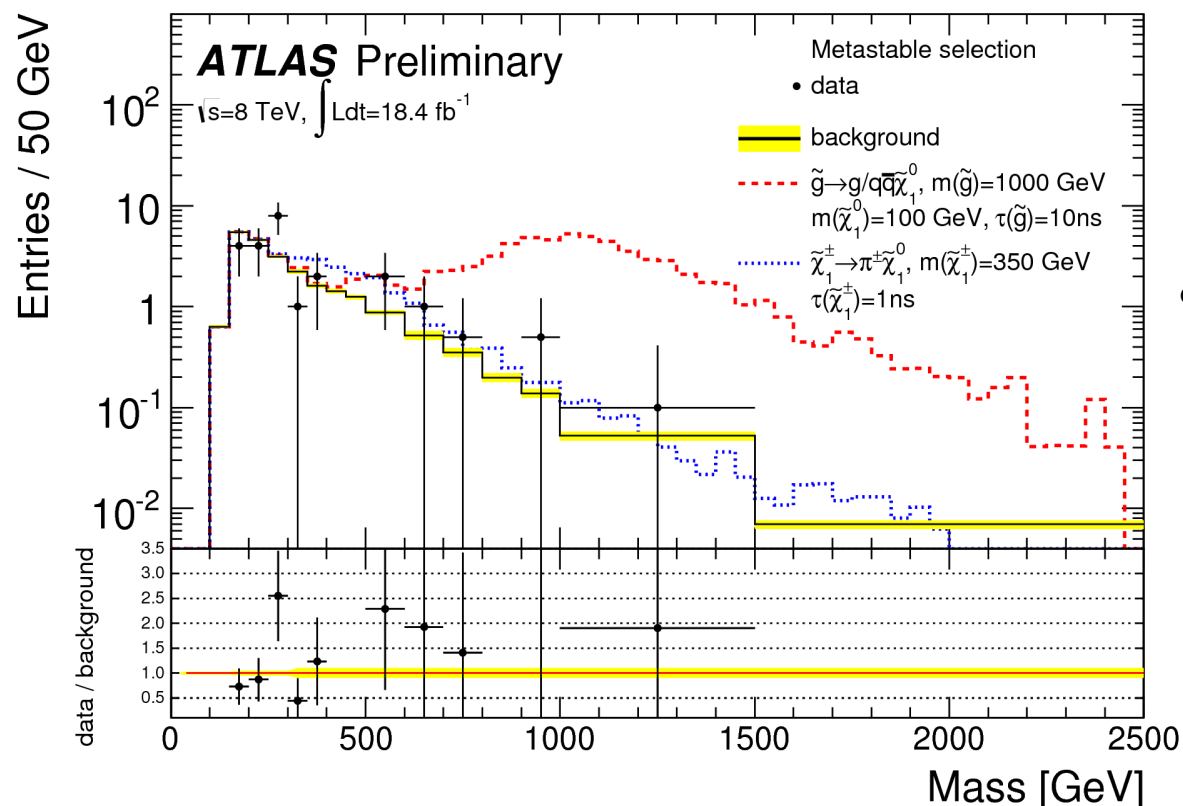
$$m(\tilde{\tau}_1) \begin{cases} > 339 \text{ GeV (CMS)} \\ > 289 \text{ GeV (Atlas)} \end{cases}$$



H(meta)SCP in ATLAS

arXiv:1506.05332

- Updated searches using **Pixel dE/dx only**
→ extend sensitivity to lower lifetimes (1-10 ns)
- Mass from fitting dE/dx and p**
to an empirical Bethe–Bloch function
- MET trigger

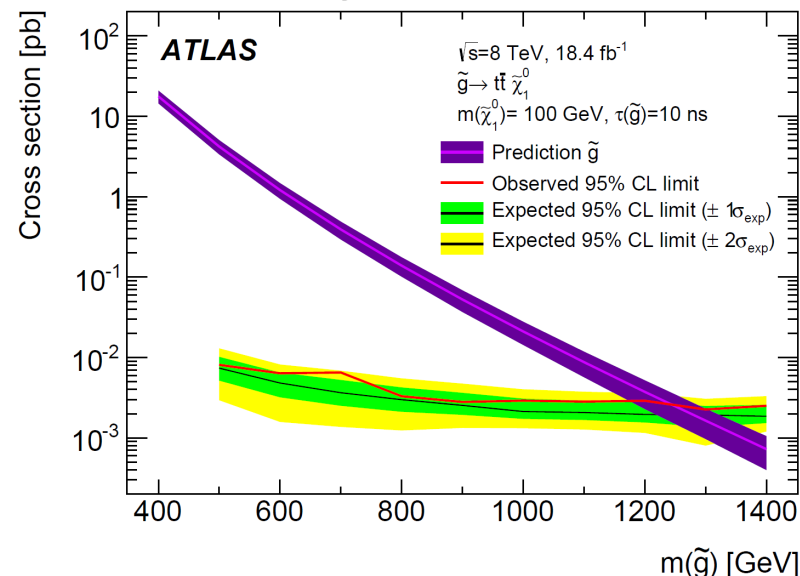


- Offline selection:**
 - track isolation
(ΔR with respect to any other track > 0.25)
 - high (>150 GeV) momentum
 - high ionization (>MIP value)
 - electron veto
 - muon veto if particle is metastable with decay before the muon system

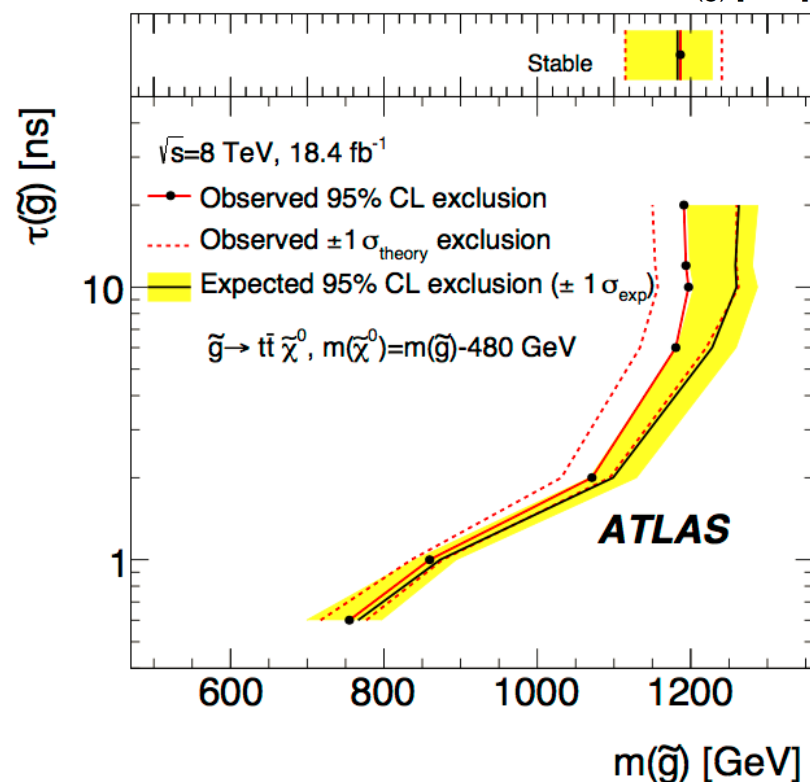
Limits on H(meta)SCP by ATLAS

arXiv:1506.05332

- Interpretations:**
stable and metastable
R-hadrons and charginos

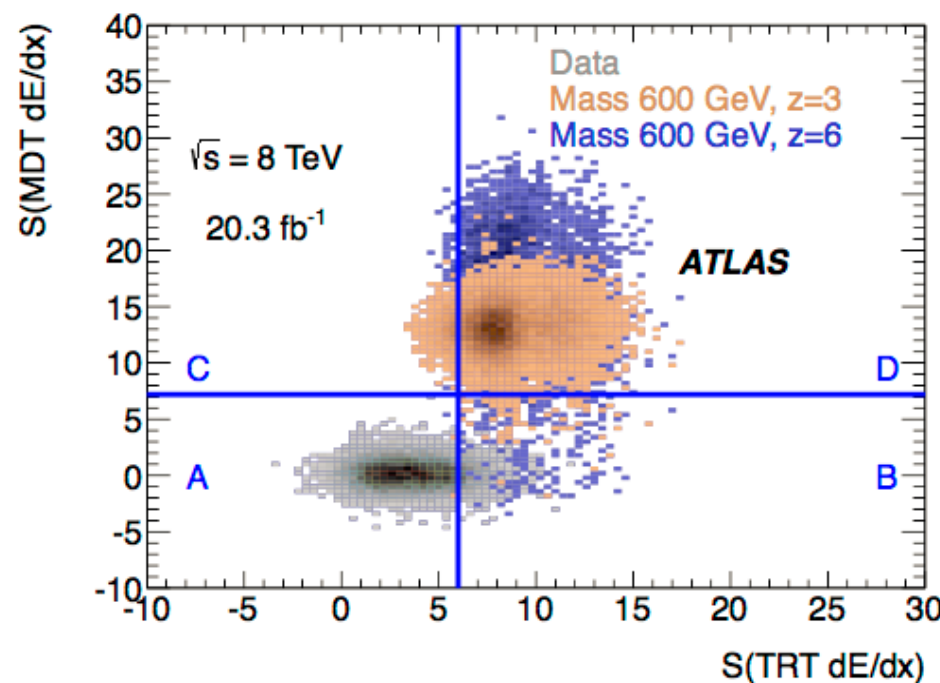
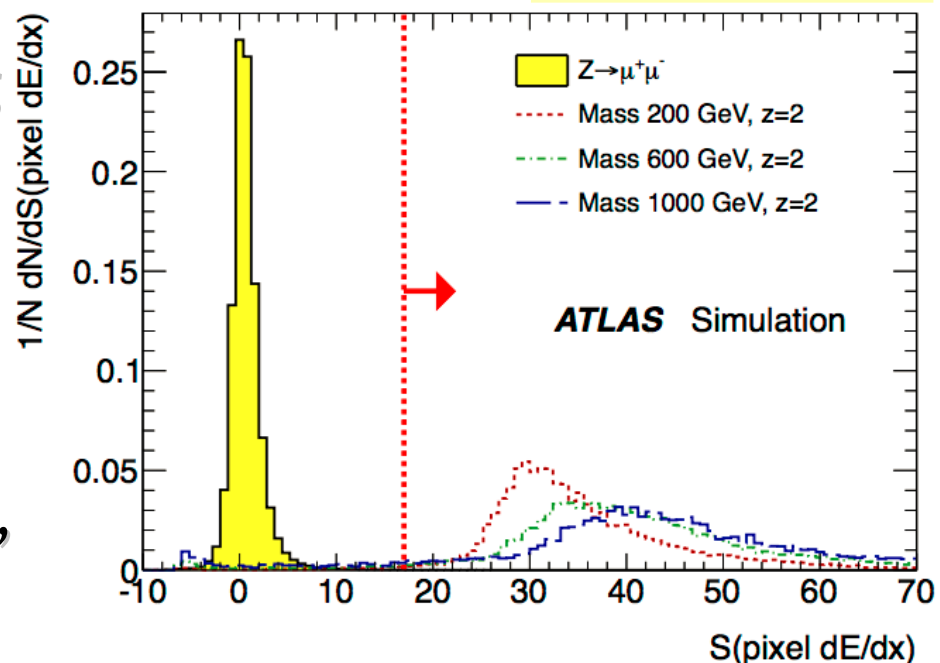


Particle	Decay	$m(\tilde{\chi}_1^0)$ [GeV]	τ [ns]	$m >$ [GeV]
\tilde{g} R-hadron	stable	—	—	1115
\tilde{b} R-hadron	stable	—	—	751
\tilde{t} R-hadron	stable	—	—	766
chargino	stable	—	—	534
\tilde{g} R-hadron	$g/q\bar{q}$	100	10	1185
\tilde{g} R-hadron	$g/q\bar{q}$	$m(\tilde{g}) - 100$	10	1099
\tilde{g}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



- Search for **MCP** – long-lived highly ionizing heavy (mass in 50 - 1000 GeV) particles with **high electric charges ($|q|=2,3,4,5,6 e$)**
- Trigger on high pt muons or MET
- Analysis selection:**
muon-like particles with **high dE/dx in Pixel, Transition Radiation Tracker (TRT) and muon precision chambers (MDT)**
- high fraction of TRT hits passing the high threshold
- Background estimation:**
ABCD method on $S(dE/dx)$ variable

$$S(dE/dx) = \frac{dE/dx_{\text{track}} - \langle dE/dx_{\mu} \rangle}{\sigma(dE/dx_{\mu})}$$

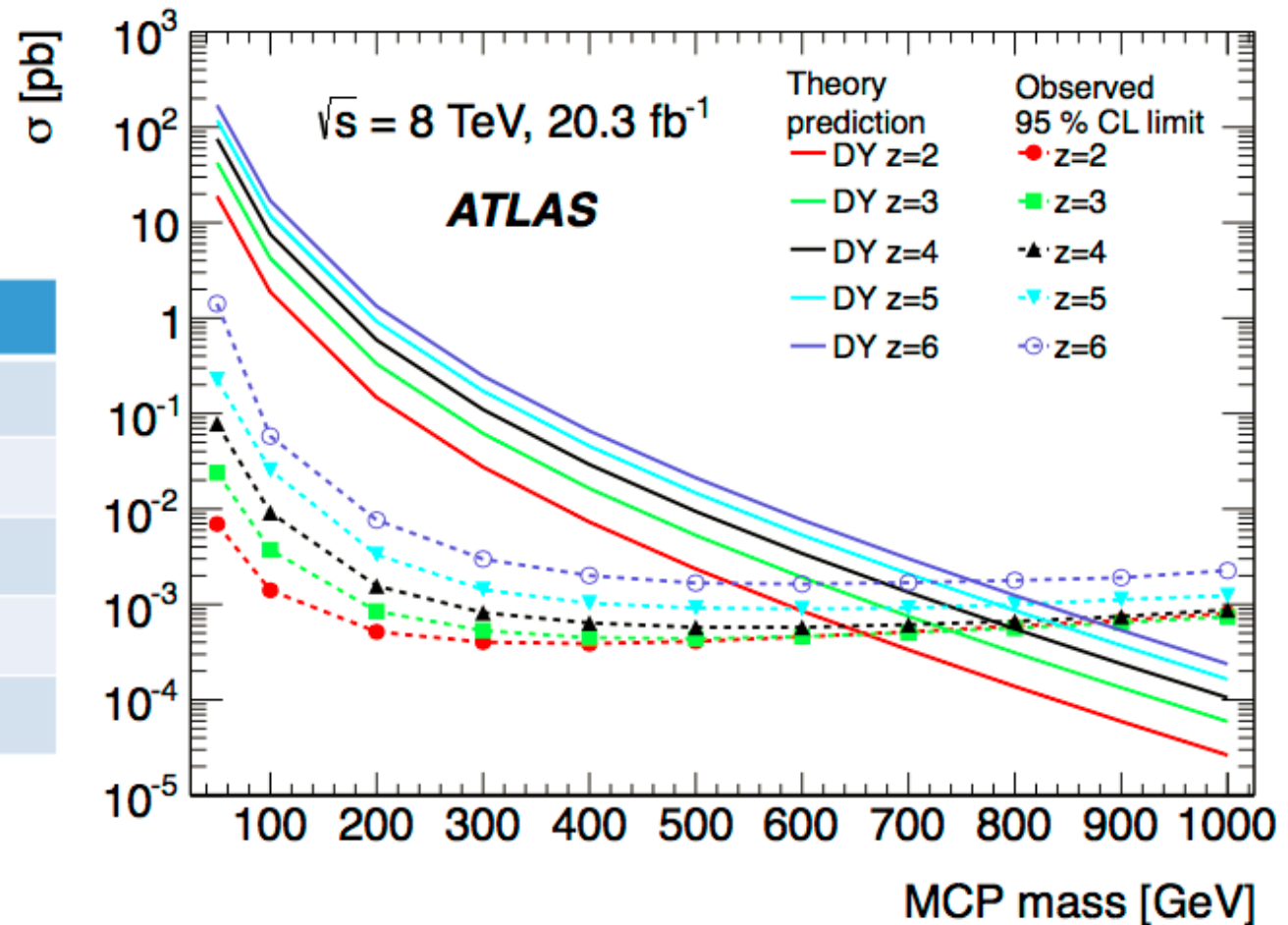


Limits on χ_{CP} by ATLAS

arXiv:1504.04188

- Results: **data in agreement with SM predictions**
→ exclusion limits assuming a Drell-Yan production cross section

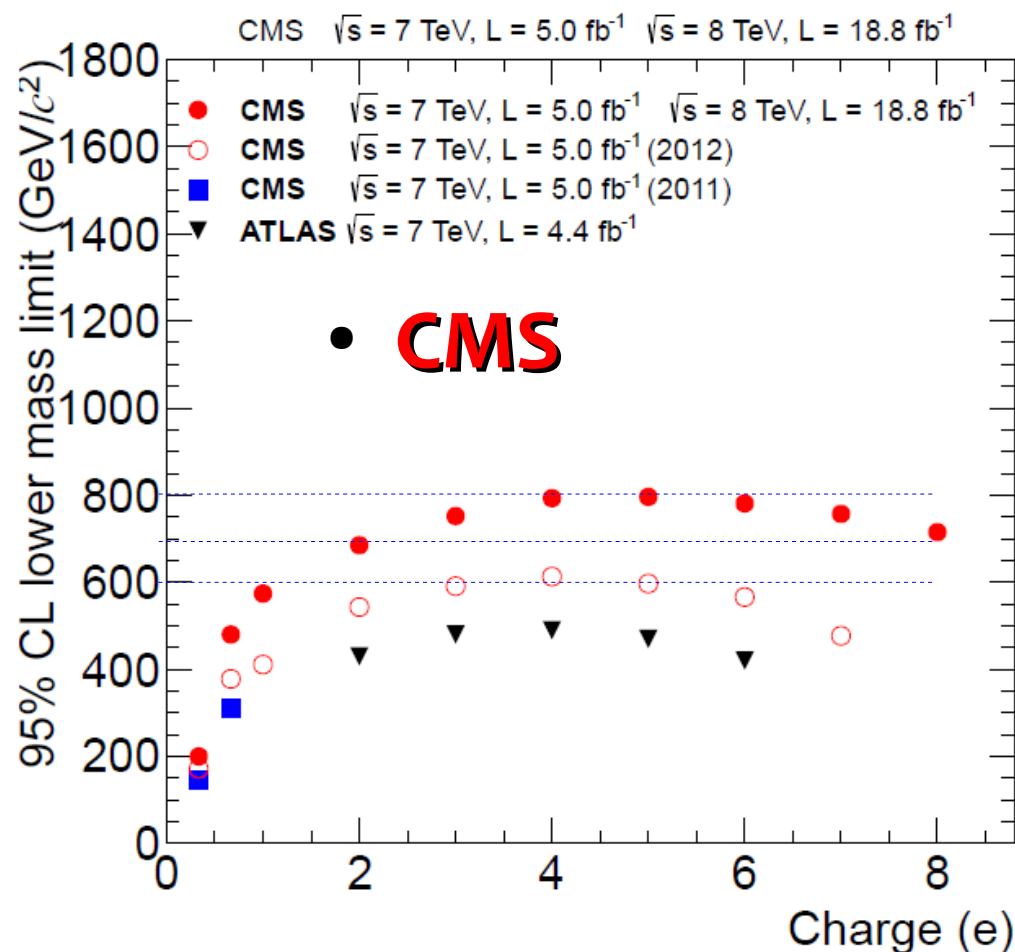
$ q $	Mass limits [GeV]
2e	50-660
3e	50-740
4e	50-780
5e	50-785
6e	50-760



- **Very similar sensitivity** on multi-charged particles of two experiments

- **ATLAS**

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



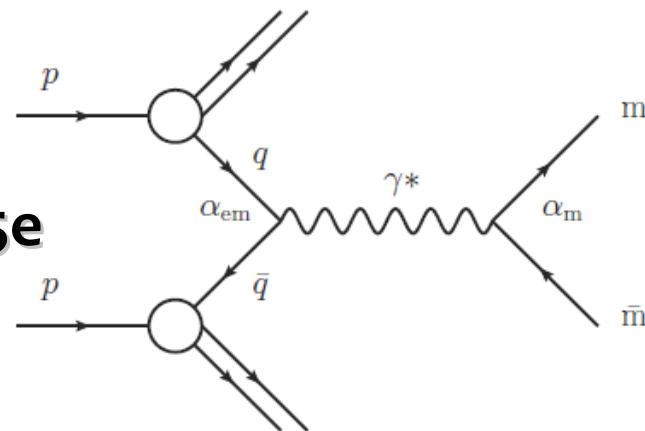
$e/3, 2e/3, 1e, 2e, 3e, 4e, 5e, 6e, 7e, 8e$
 200, 480, 574, 685, 752, 793, 796, 781, 757, 715 GeV

Monopoles in ATLAS

EXOT-2014-16

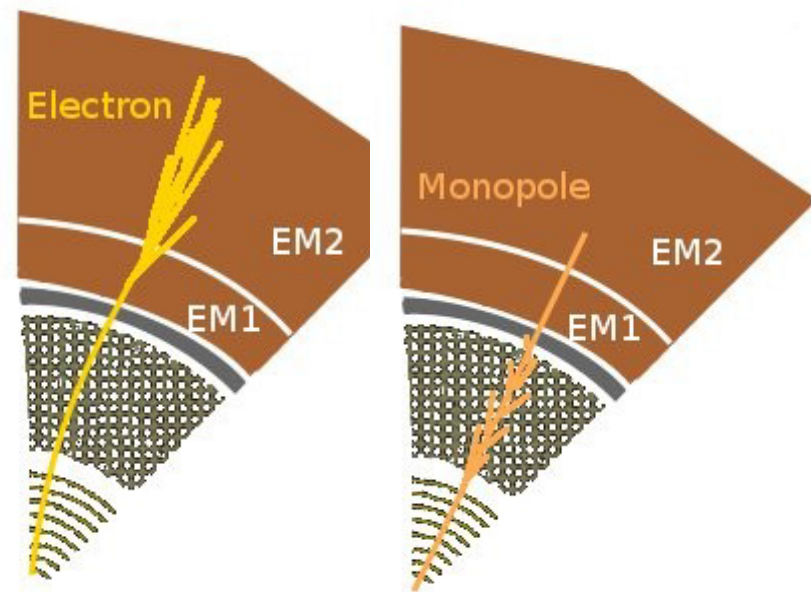
Signal: Massive stable particles with **very high electric charge** predicted by several new models, produced in Drell-Yan process as spin-0 or spin-1/2 particles:

- theories of magnetic **monopoles** with **Dirac magnetic charge** g : $g = n g_D$, where $g_D = 68.5e$
- strange quark matter, Q-balls, stable microscopic black-hole remnants



Signature:
extremely **highly ionization particle (HIP)**,
 $dE/dx \sim g^2$

- high-threshold TRT hits associated to narrow EM cluster



Search for HIPs in mass range 200 – 2500 GeV

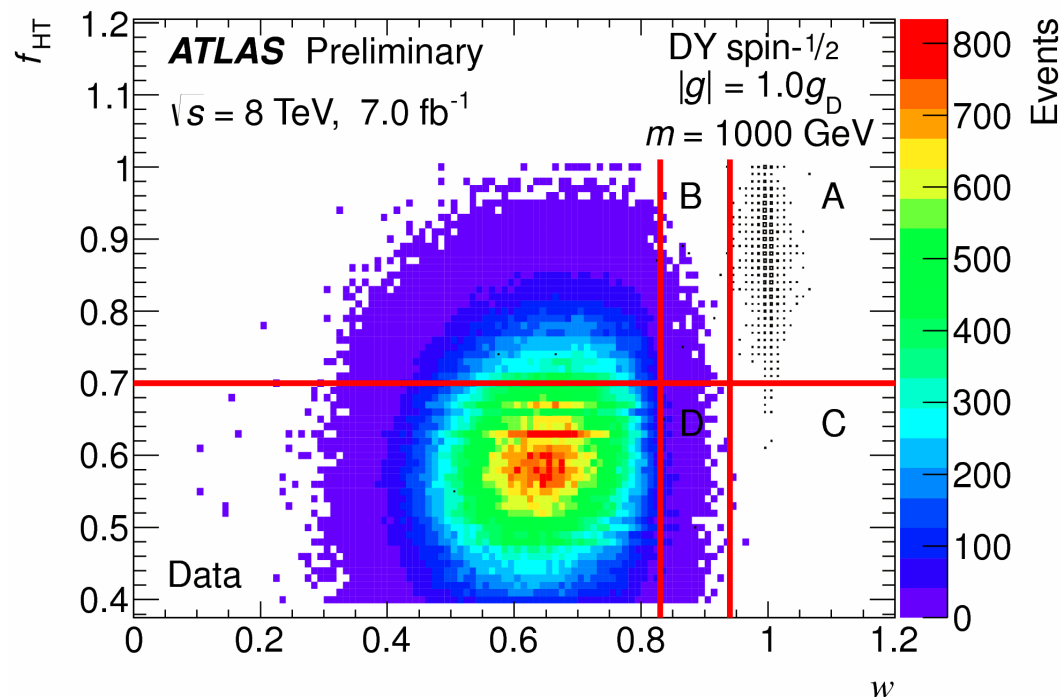
- $10 \leq |z| \leq 60$
- $0.5g_D \leq |g| \leq 2.0g_D$

Triggering: a dedicated (L2) trigger for HIPs, which made monopoles with $|g| > 1.0g_D$ accessible in ATLAS

- EM calorimeter energy deposit with no energy after the first calorimeter layer accompanied by the large fraction of TRT hits passing the high threshold f_{HT}
- Collected luminosity: 7.0/fb

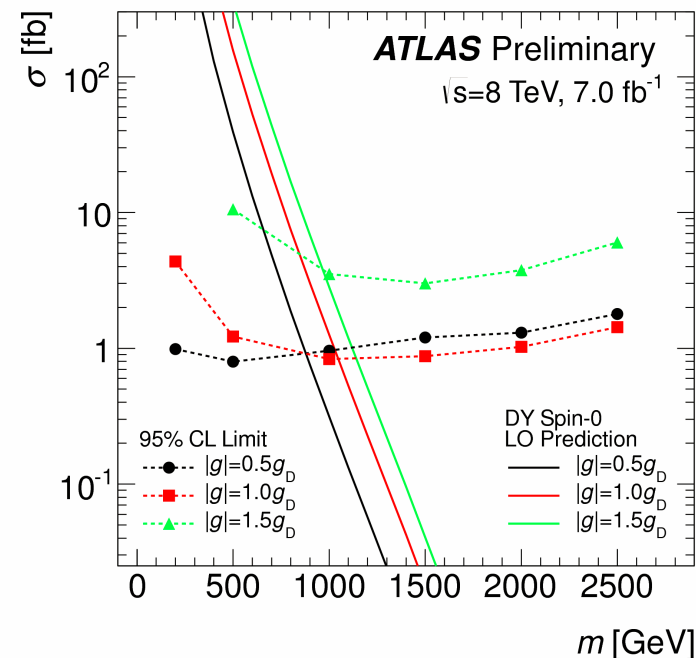
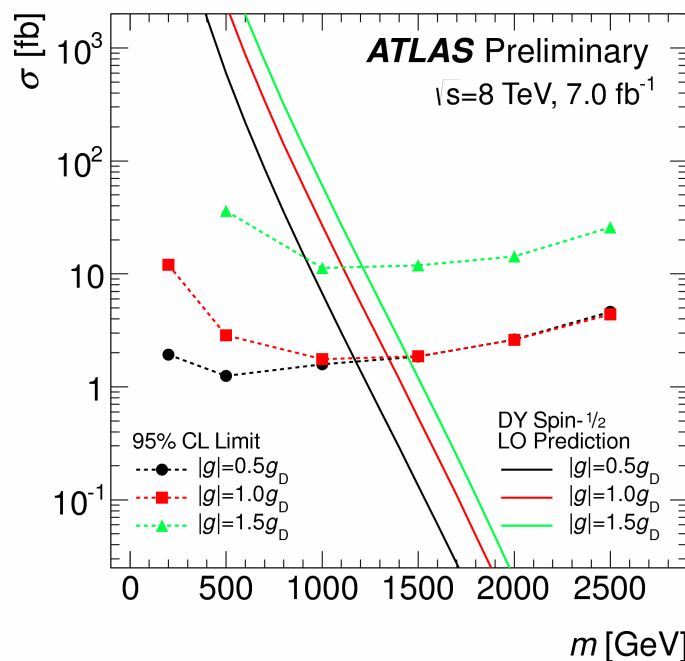
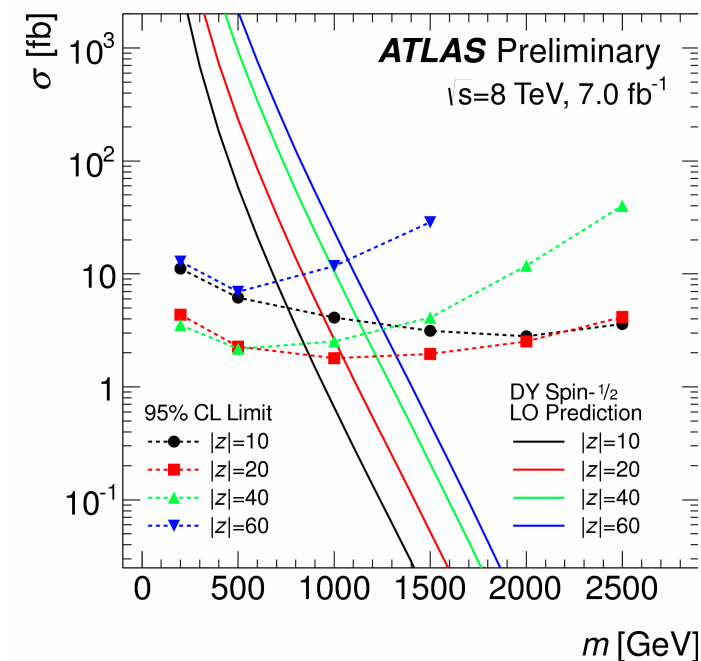
Event selection:

- High f_{HT} matched to EM energy deposit
- Low EM energy deposit dispersion (fraction of EM energy contained in the most energetic cells, w)
- ABCD method used to determine the background from data



- **No events observed in 7 fb @ 8 TeV** → **DY pair production mass limits**
- Results from spin-1/2 extrapolated to spin-0

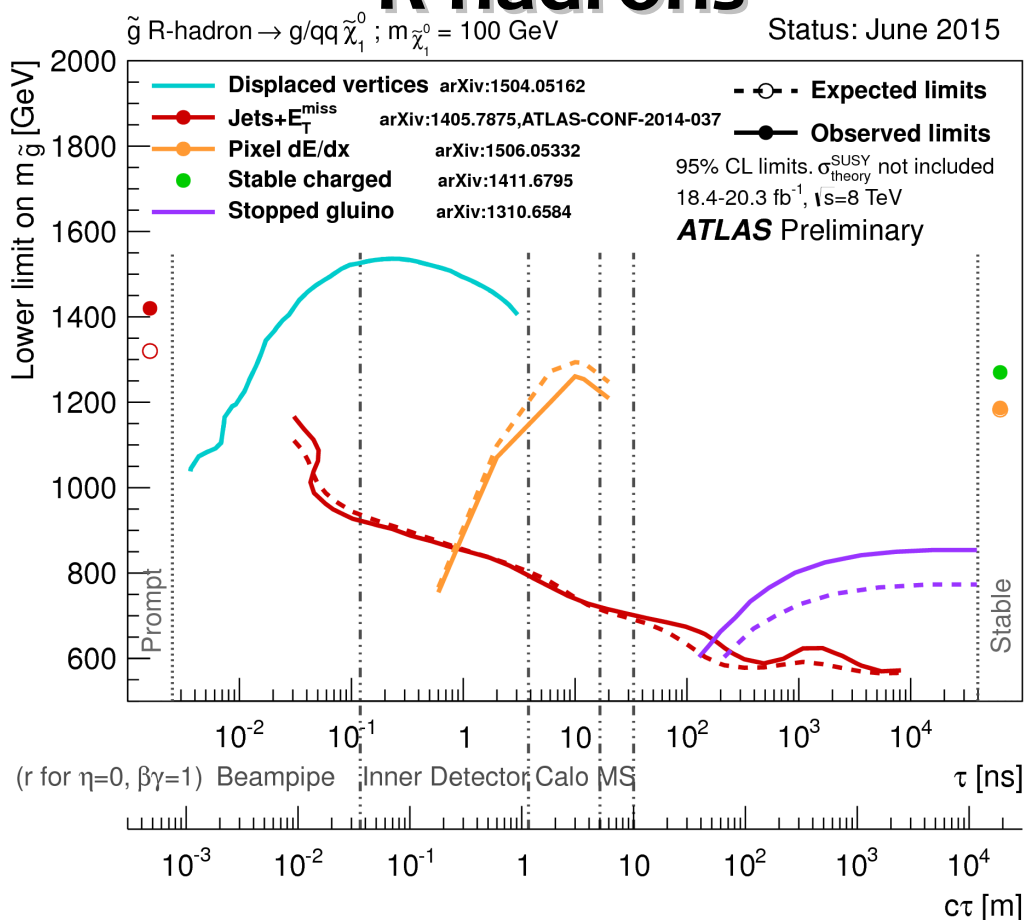
	Drell-Yan Lower Mass Limits [GeV]						
	$ g = 0.5g_D$	$ g = g_D$	$ g = 1.5g_D$	$ z = 10$	$ z = 20$	$ z = 40$	$ z = 60$
spin-1/2	1180	1340	1210	780	1050	1160	1070
spin-0	890	1050	970	490	780	920	880



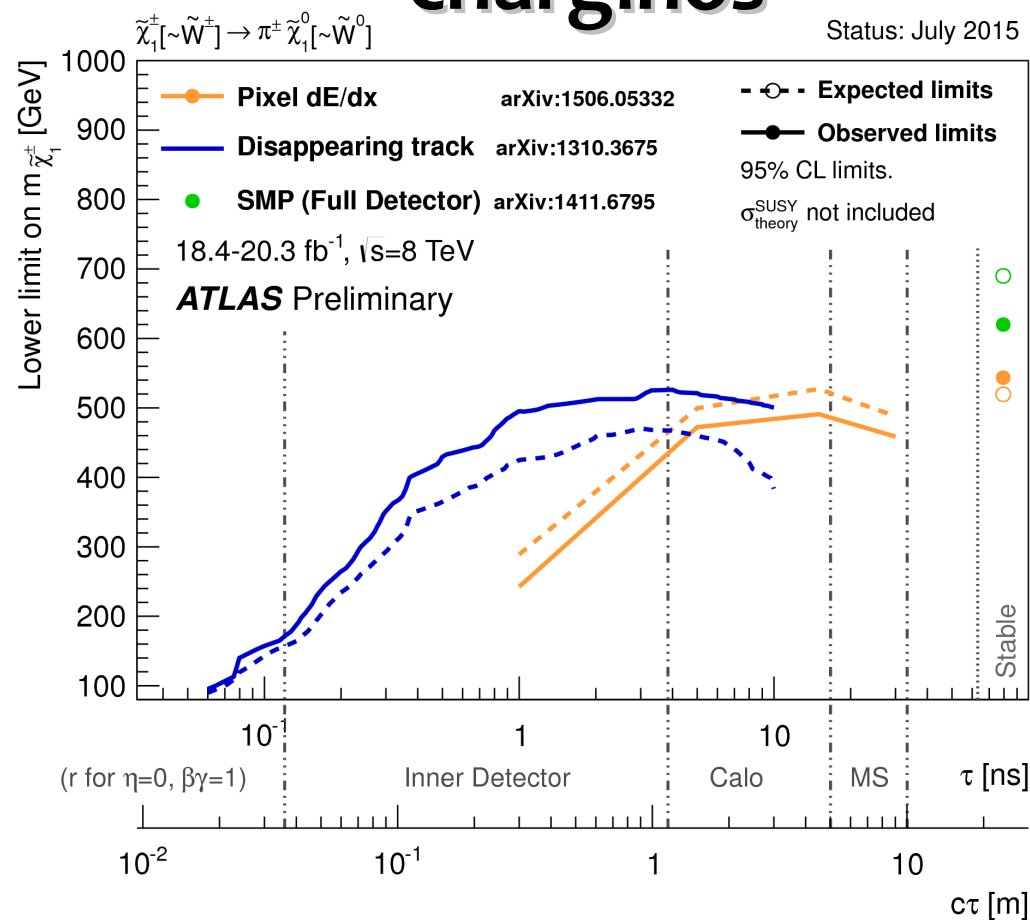
Long lived searches in ATLAS

- Wide coverage of different lifetimes** is achieved by complementary analyses using different detector systems and novel techniques
- Pixel dE/dx covers region of $\tau : 1 - 30$ ns**

R-hadrons



charginos



Conclusions

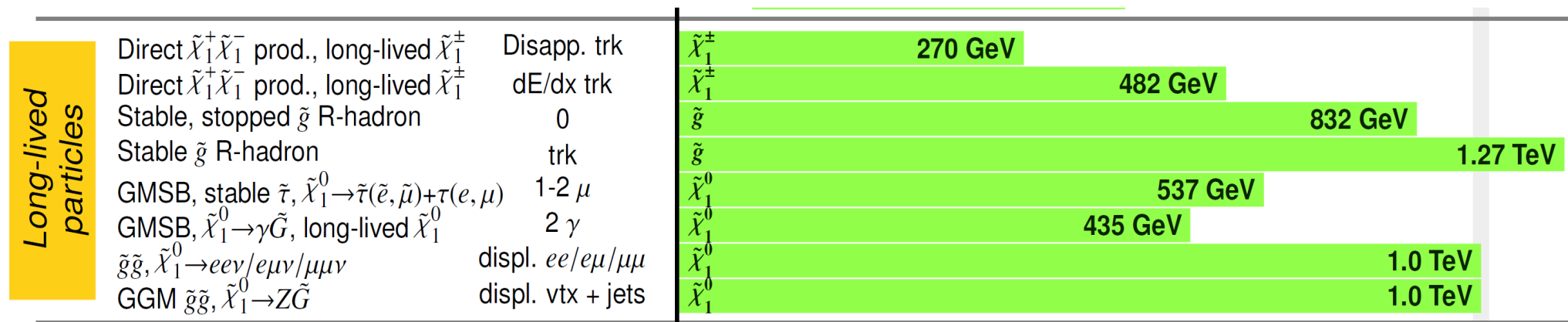
- **No evidence** for new exotic long-lived particles... **yet**
- Data **significantly constrains** many models of BSM
- 2015 pp @ 13 TeV – **hunting for LLPs restarted**
 - Higher energy → wider mass reach
 - More challenging searches with higher luminosity (tracks, isolation, triggering, etc.)
 - 25 ns collision mode → changes in L1 triggers

Work supported by Polish National Science Center
 UMO-2014/14/M/ST2/00428 & UMO-2014/15/B/ST2/03998

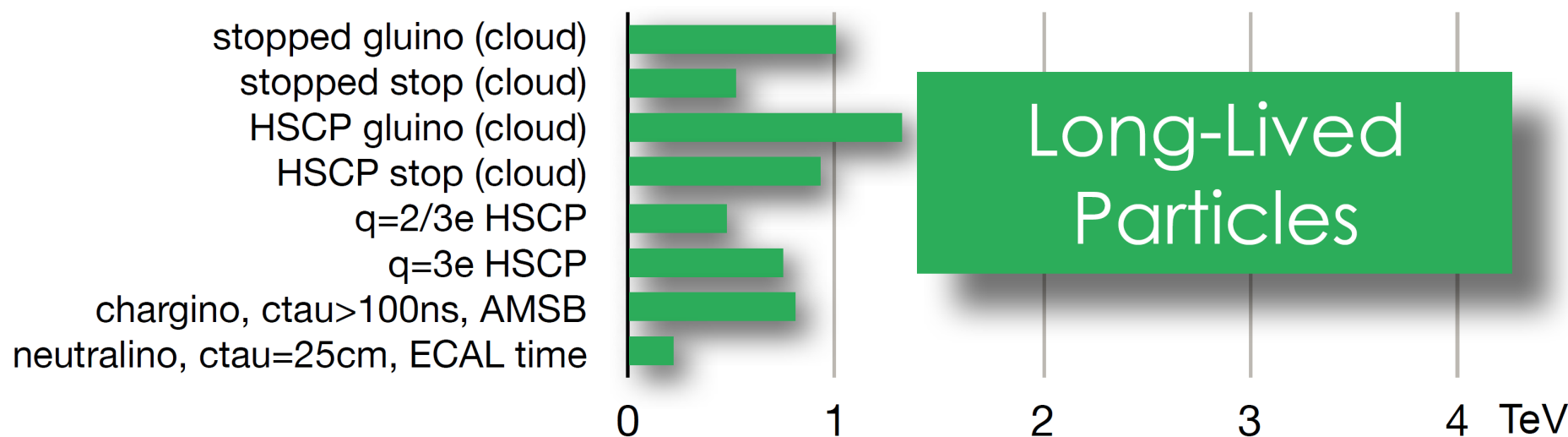


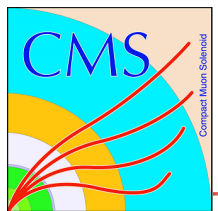
Backup

• ATLAS



• CMS





HSCP Selection

Event selection:

- **Trigger:** muon ($p_T > 40$ GeV) or $MET > 150$ GeV or μ $p_T > 60$ GeV & $MET > 65$ GeV
- **Basic pre-selection:**
 $p_T > 45$ GeV, $|\eta| < 2.1$, $|d_{xy}|$ and $|dz| < 0.5$ cm,
 $\#Hits > 7$, very loose isolation, cosmic veto, etc
- **Selection optimised** to for the best discovery reach for each class of models using **track p_T** , **Muon $1/\beta$** , **Track I_{as}** (dE/dx discriminator)
- **Background** from ABCD method

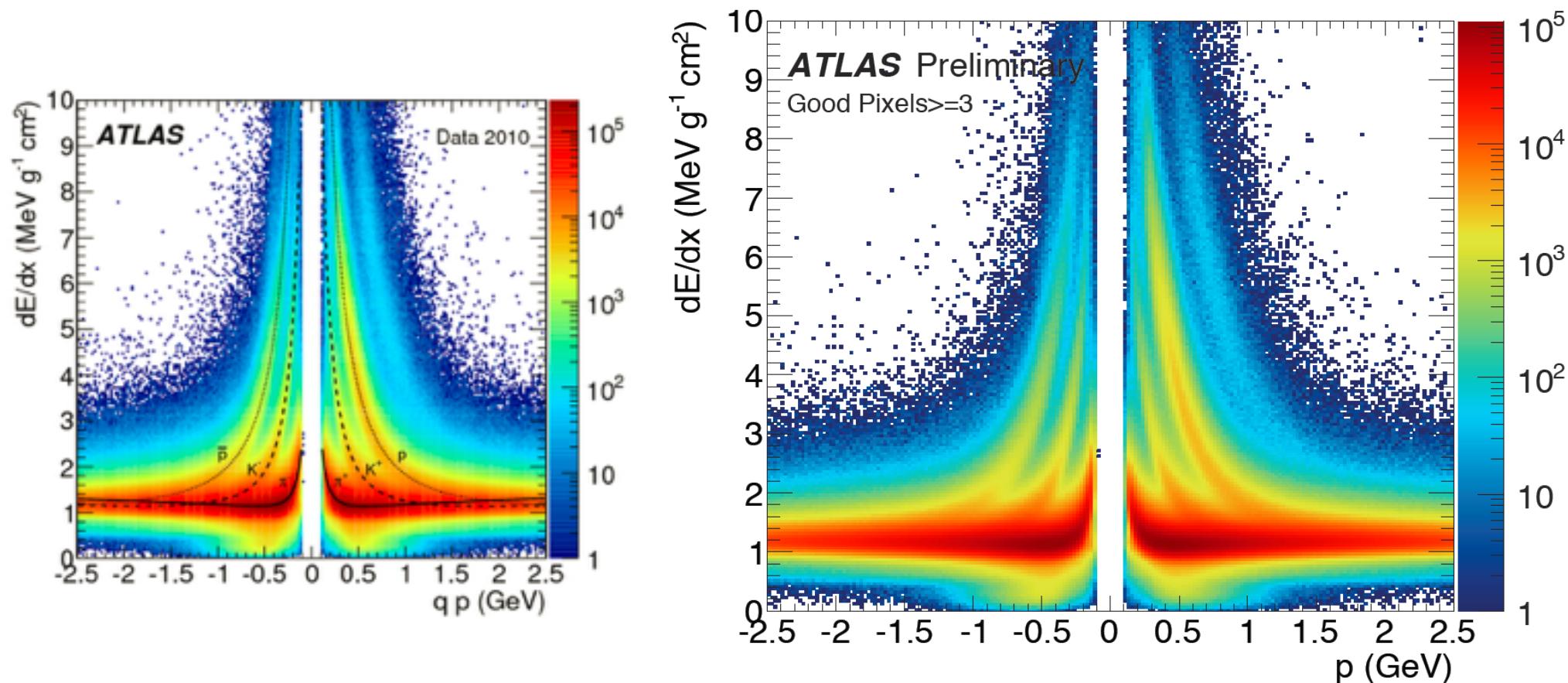
HSCP RESULTS

	Selection criteria				Number of events			
					$\sqrt{s} = 7 \text{ TeV}$		$\sqrt{s} = 8 \text{ TeV}$	
	p_T (GeV/c)	$I_{as}^{(\ell)}$	$1/\beta$	Mass (GeV/c ²)	Pred.	Obs.	Pred.	Obs.
2. 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
1. 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 3.	>230	—	>1.40	—	—	—	6 ± 3	3
$ Q > 1e$ 4.	—	>0.500	>1.200	—	0.15 ± 0.04	0	0.52 ± 0.11	1
$ Q < 1e$ 5.	>125	>0.275	—	—	0.12 ± 0.07	0	1.0 ± 0.2	0

Mass (GeV/c²)

DE/dx in Run 2

ATLAS-PHYS-PUB-2015-011



ATLAS Detector

