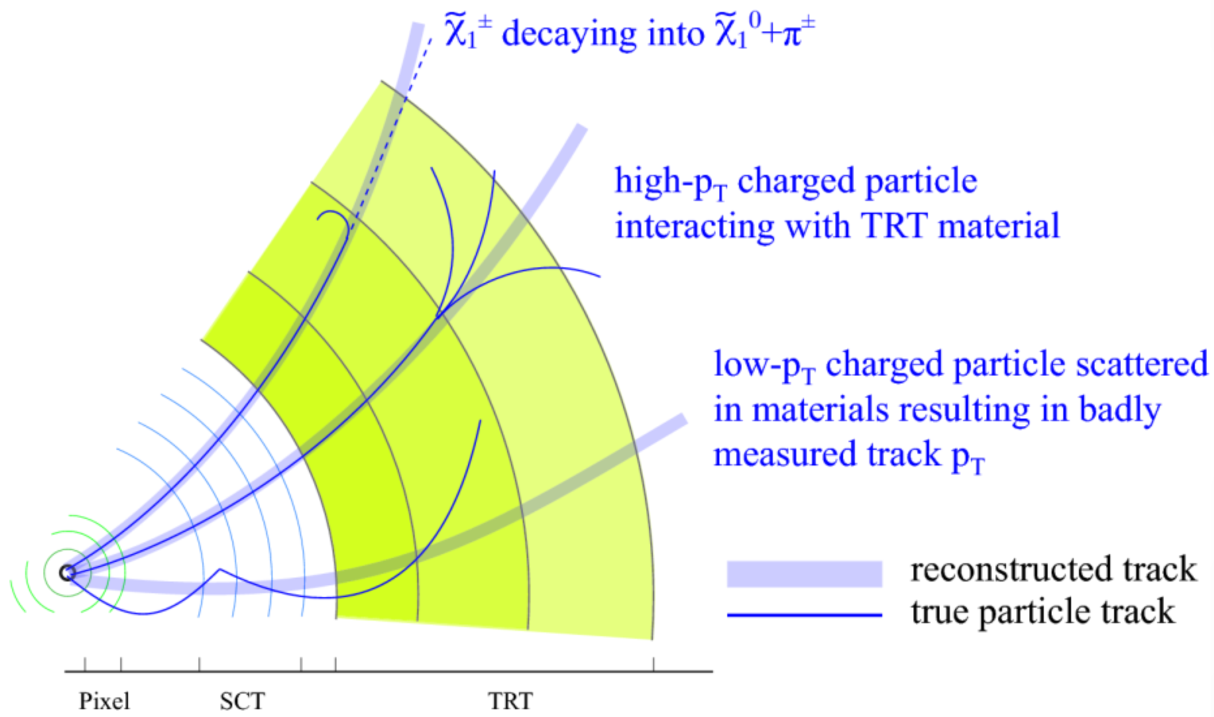
Searches for RPV-SUSY and Long-Lived particles in ATLAS



Monica D'Onofrio

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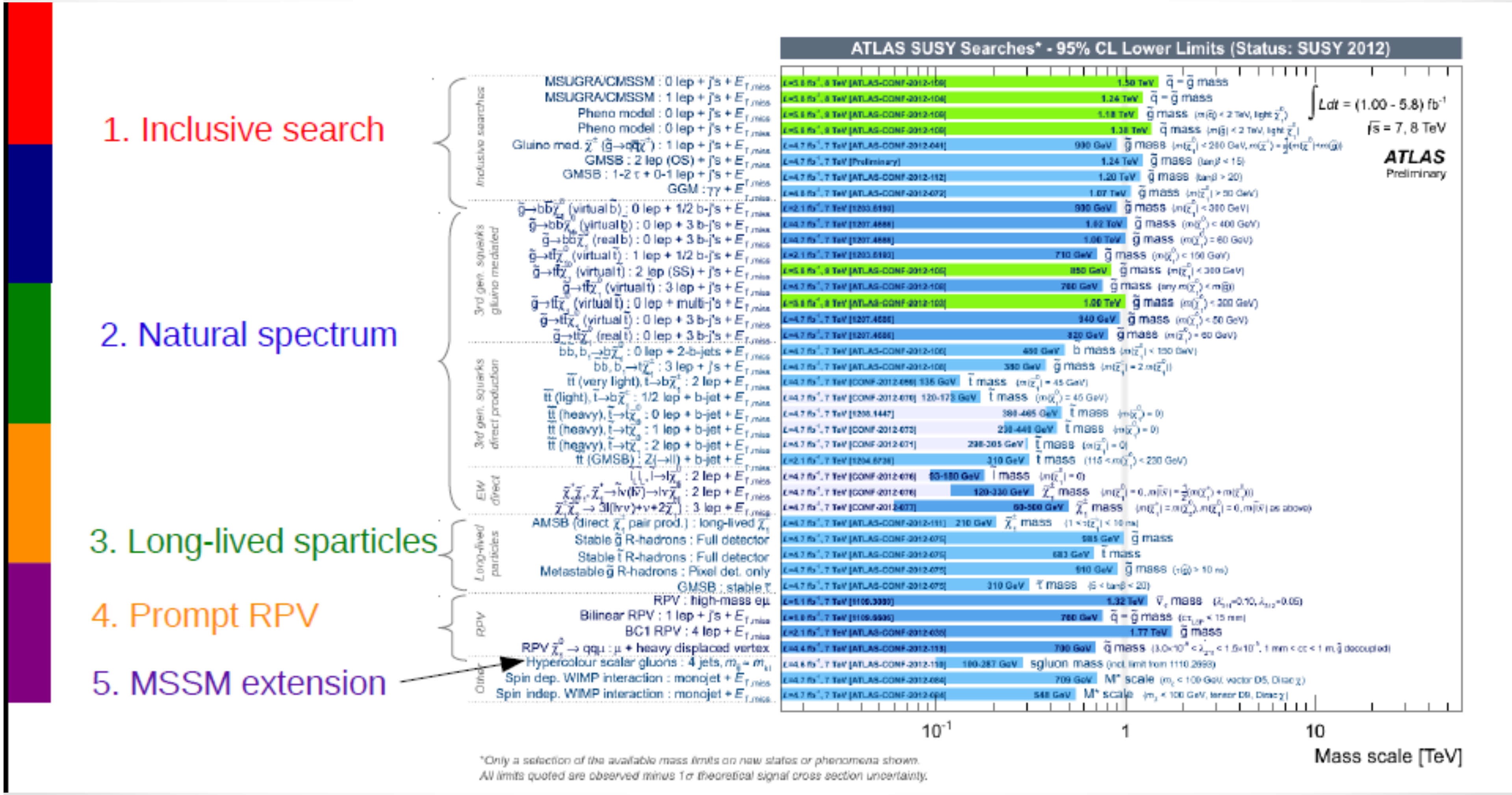
GGI Meeting, Florence, 23 Oct. 2012

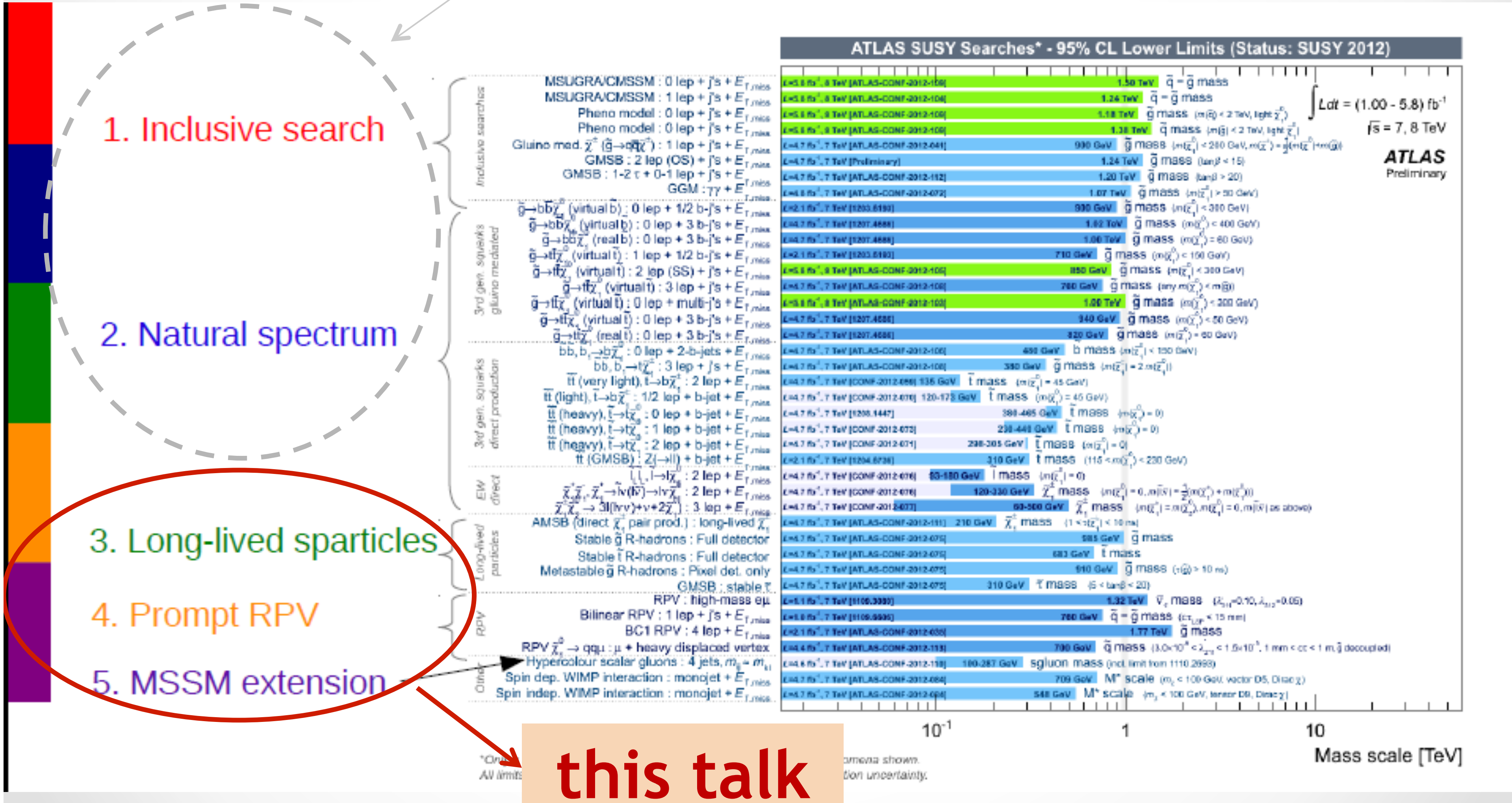
Searches for SUSY @ ATLAS

- Broadly and deeply cover the SUSY signature space



Searches for SUSY @ ATLAS

Giacomo's talk yesterday



R-parity

- Define R-parity = $(-1)^{3(B-L)+2s}$
  - R = 1 for SM particles
  - R = -1 for MSSM partners

If conserved (RPC), sparticles pair produced and Lightest SUSY Particle is stable (MET signatures)

If not conserved (RPV)→ different terms, couplings constraint by proton decay

L-number violating terms

$$W_{\not R p} = \lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E}^C_k + \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}^C_k + \epsilon_i\hat{L}_i\hat{H}_u + \lambda''_{ijk}\hat{U}^C_i\hat{D}^C_j\hat{D}^C_k$$

bilinear terms

B-number violating terms

ΔL =1, 9 λ couplings, 27 λ′ couplings

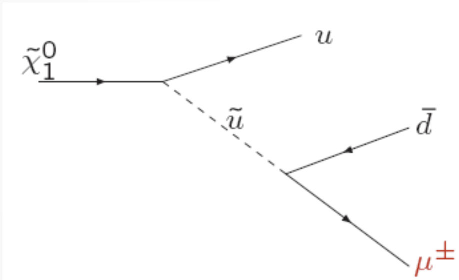
Pletora of new couplings, only partially constraints (m/100 GeV)

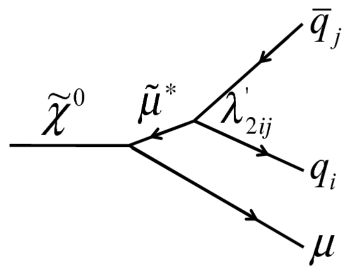
	$\lambda_{ijk}L_iL_j\bar{E}_k$	$\lambda'_{1jk}L_1Q_j\bar{D}_k$	$\lambda'_{2jk}L_2Q_j\bar{D}_k$	$\lambda'_{3jk}L_3Q_j\bar{D}_k$
weakest	0.07	0.28	0.56	0.52
strongest	0.05	$5.\cdot 10^{-4}$	0.06	0.11

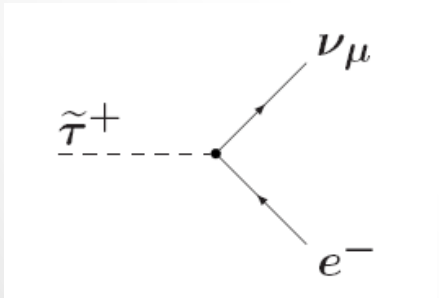
RPV scenarios

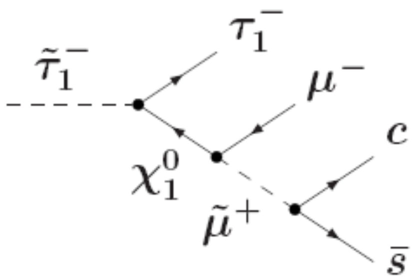
- Many final states to explore and not yet searched for:
  - LSP no longer stable

$$\begin{pmatrix} \text{pair production: } \tilde{q}\tilde{q},\ \tilde{q}\tilde{g},\ \tilde{g}\tilde{g} \\ \text{resonant } \tilde{\ell} \text{ production} \end{pmatrix} \otimes \begin{pmatrix} \underline{\text{LSP}} \\ \tilde{\chi}_1^0 \\ \tilde{\chi}_1^\pm \\ \tilde{\nu}_L \\ \tilde{\ell}^\pm_{L,R} \\ \tilde{\tau}_1^\pm \\ \tilde{q}_{L,R} \\ \tilde{t}_1 \\ \tilde{g} \end{pmatrix} \otimes \begin{pmatrix} \underline{\text{Operator}} \\ L_1 L_2 \bar{E}_1 \\ \vdots \\ L_2 L_3 \bar{E}_3 \\ L_e Q_1 \bar{D}_1 \\ \vdots \\ L_\mu Q_1 \bar{D}_1 \\ \vdots \\ L_\tau Q_3 \bar{D}_3 \\ \bar{U}_i \bar{D}_j \bar{D}_k \end{pmatrix}$$







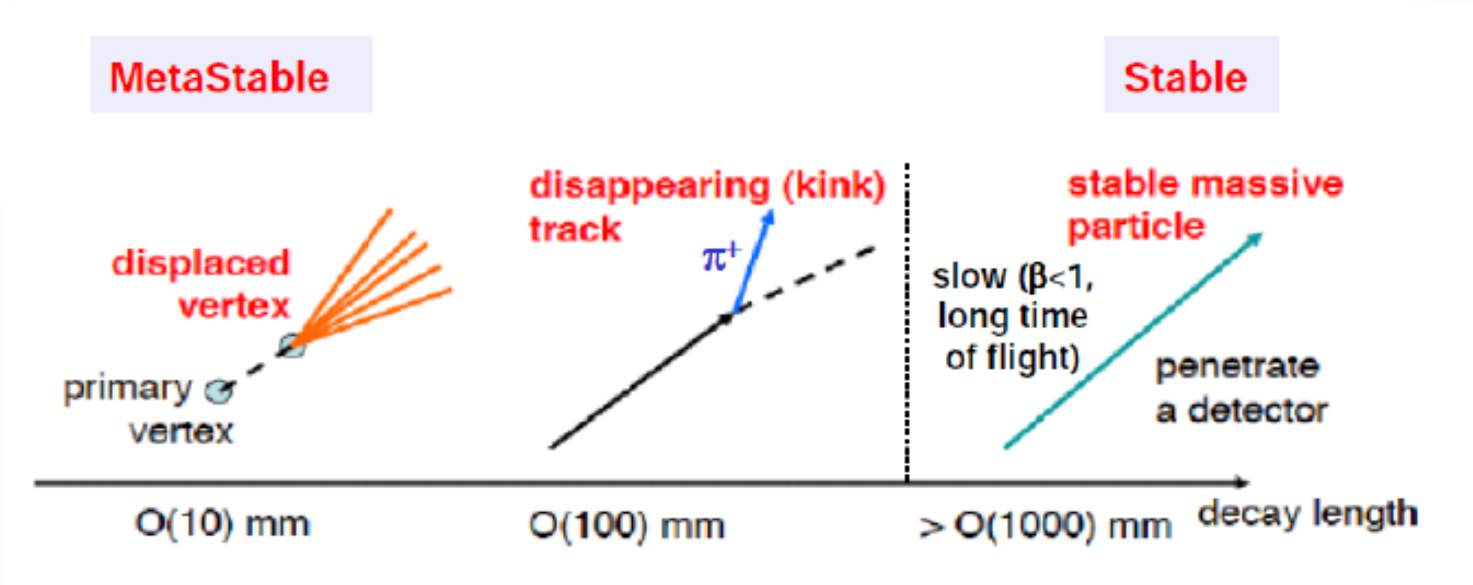


- **Something like > 700 possibilities, with final state signatures involving leptons and/or jets**

- **If λ, λ’,λ’’ very small, can lead to long-lived LSP**

Long-Lived particles in SUSY

- Several new physics models could give raise to new, massive particles with long-lifetime. Long-lived (LL) particles in RPC scenarios:
  - If ΔM(chargino-neutralino) ≈ 100 MeV (eg. in AMSB):
    - Long-lived charginos → disappearing tracks
  - If very heavy squarks mediate gluinos decay (strong virtuality):
    - Long-lived gluinos → R-hadrons (eg. Split SUSY)
  - If NLSP-gravitino GMSB couplings are weak: long-lived sleptons



- ‘prompt’ RPV SUSY:
  - **Leptonic RPV** **(production and/or decay):**
    - search for multilepton final states
    - emu resonances and continuum
  - **Hadronic RPV:**
    - search for 2x3jet resonances
    - search for 2x2jet resonances (currently focusing on scalar gluons searches)
- **Long-lived SUSY:**
  - Displaced vertex
  - Disappearing tracks
  - R-hadrons and sleptons

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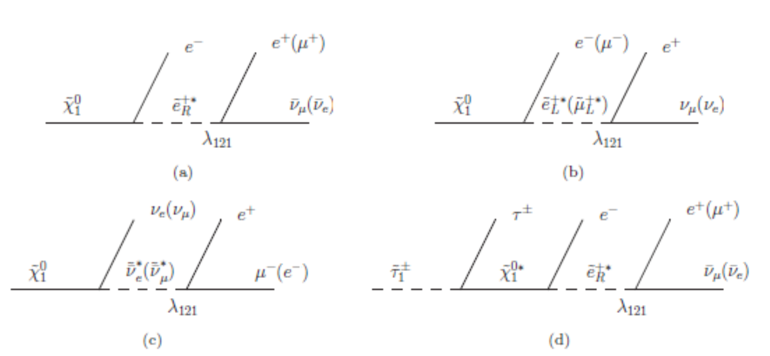
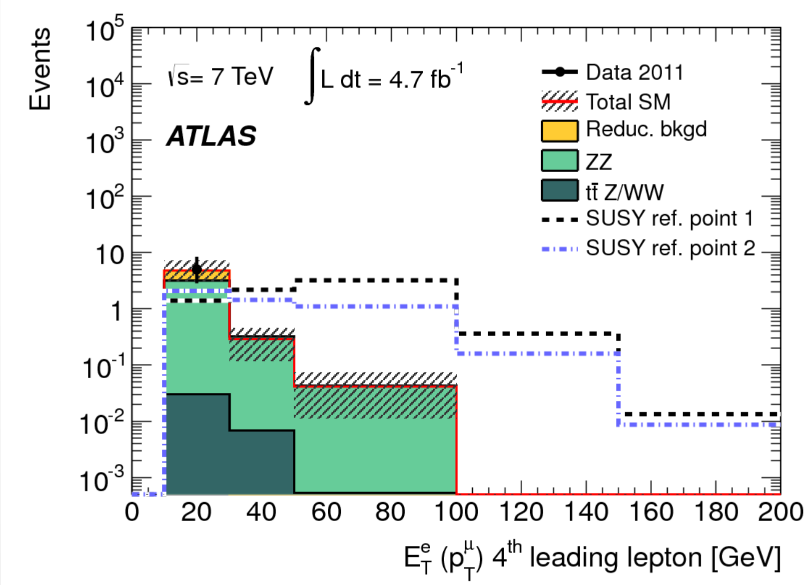
RPV@decay: Multilepton

- Signature expected in case of RPV in the lepton sector

$$W_{RPV} = \lambda_{ijk} L_i L_j \bar{E}_k$$

- High p_T leptons, possibly non large missing E_T





- Two SR defined based on MET and total tranverse energy (m_eff)
- Validation regions used for SM background checks:
  - Reducible bkg (fakes, from data)
  - Irreducible bkg (ZZ, ttZ, ttWW): from MC

Selection	SR1	SR2	VR1	VR2	VR3
Number of leptons	≥ 4	≥ 4	3	≥ 4	≥ 4
Z-candidate	veto	veto	veto	requirement	veto
E_T^{miss}/GeV	> 50	–	> 50	–	< 50
m_{eff}/GeV	–	> 300	–	–	< 300

$$m_{eff} = E_T^{miss} + \sum_\mu p_T^\mu + \sum_e E_T^e + \sum_j E_T^j.$$

Multilepton: background

- **Reducible background (WZ, ttW,tt,WW):**
  - Events with 3 real and one fake leptons, or 2 real and 2 fake (3,4 fakes negligible)
  - Estimated with a *weighting method*

$$[N_{\rm data}(3\ell_S+\ell_L)-N_{\rm MCirr}(3\ell_S+\ell_L)]\times F(\ell_L)$$
$$-[N_{\rm data}(2\ell_S+\ell_{L_1}+\ell_{L_2})-N_{\rm MCirr}(2\ell_S+\ell_{L_1}+\ell_{L_2})]\times F(\ell_{L_1})\times F(\ell_{L_2})$$

$$F=\sum_{i,j}(\alpha^i\times R^{ij}\times f^{ij})$$

Fake ratio:
→ l_S and l_L: signal and loose leptons
→ i: type of fakes (HF,conversion)
→ j: process category
→ f^{ij} : fake rate of fake type I process j
F weighted for the fractional contribution of each process

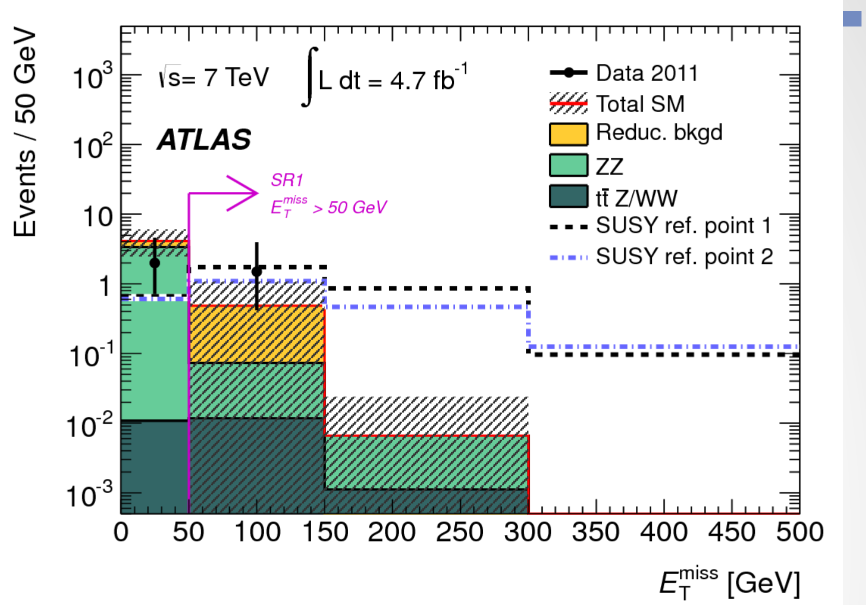
Selection	VR1	VR2	VR3
SUSY ref. point 1	4.6 ± 0.5	1.38 ± 0.16	0.004 ± 0.006
SUSY ref. point 2	3.5 ± 0.4	2.32 ± 0.34	0.120 ± 0.029
ZZ	3.2 ± 1.9	38 ± 7	2.9 ± 1.5
$t\bar{t}Z$	0.70 ± 0.35	0.64 ± 0.32	$(3.5\pm3.6)\times10^{-3}$
$t\bar{t}WW$	0.08 ± 0.06	$(1.3\pm1.0)\times10^{-3}$	$(2.2\pm2.1)\times10^{-4}$
WZ (†)	34.6 ± 6	–	–
$t\bar{t}W$ (†)	2.6 ± 0.8	–	–
Σ Irreducible	41 ± 8	38 ± 7	2.9 ± 1.5
Reducible	95 ± 32	-0.25 ± 0.96	1.3 ± 1.3
Σ SM	136 ± 33	38 ± 7	4.2 ± 1.8
Data	152	40	2
p_0-value (σ)	0.33 (0.45)	0.42 (0.21)	0.80 (−0.85)

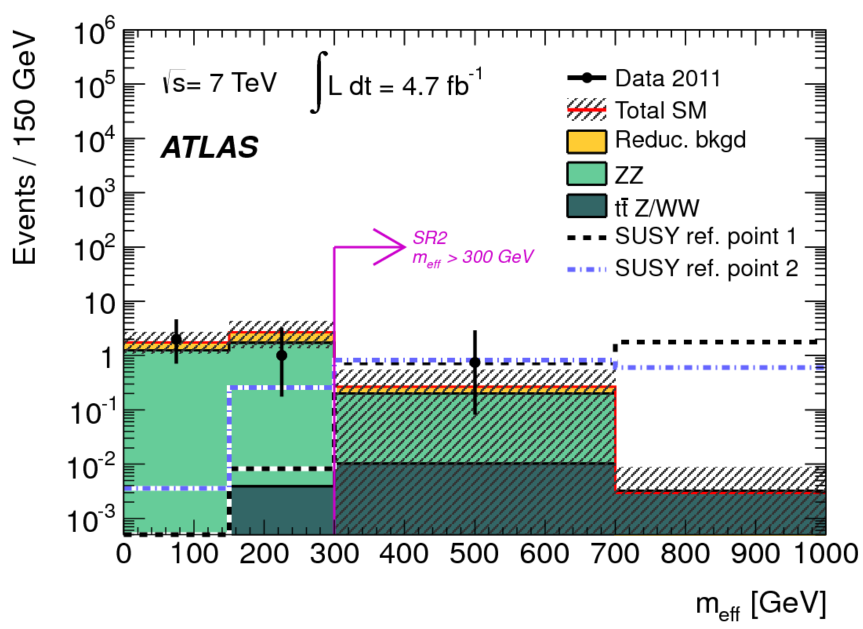
- **Irreducible background:**
  - **ZZ, ttZ, ttWW**

Multilepton: results

- Major uncertainties:
  - Irreducible bkg: generator uncertainties on ZZ MC modeling
  - Reducible bkg: dominated by unc. on contributions from each process

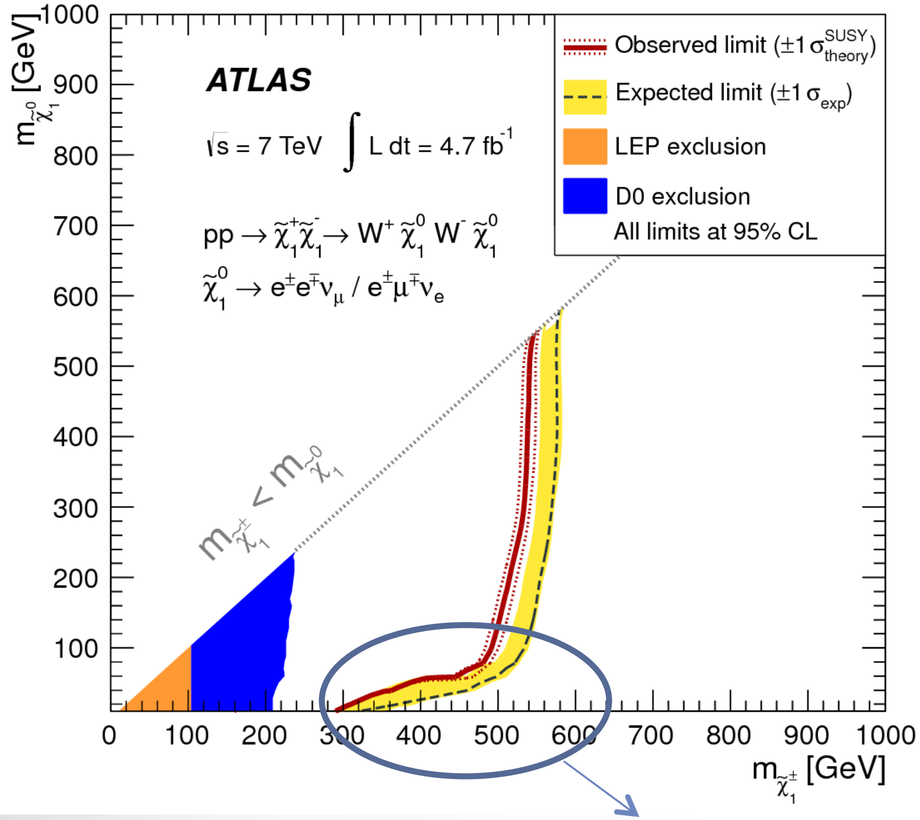
Selection	SR1	SR2
SUSY ref. point 1	6.5 ± 0.6	7.1 ± 0.7
SUSY ref. point 2	4.2 ± 0.6	4.5 ± 0.6
ZZ	0.14 ± 0.11	0.51 ± 0.30
$t\bar{t}Z$	0.023 ± 0.014	0.029 ± 0.016
$t\bar{t}WW$	0.0044 ± 0.0035	0.005 ± 0.004
Σ Irreducible	0.17 ± 0.12	0.54 ± 0.31
Reducible	0.8 ± 0.8	0.18 ± 0.26
Σ SM	**1.0 ± 0.8**	**0.7 ± 0.4**
Data	**3**	**2**
p_0-value (σ)	0.05 (1.7)	0.07 (1.5)
σ_{vis} obs (exp)	1.3 (0.8)	1.1 (0.7)



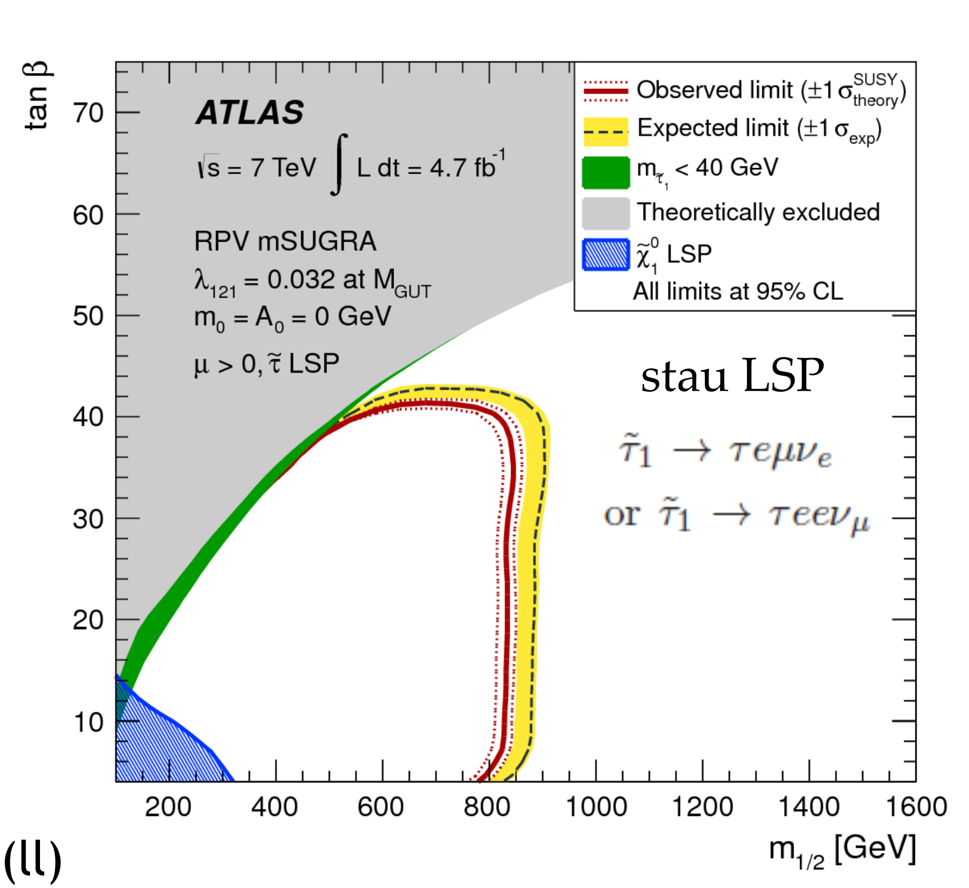


Multilepton: interpretation

- Interpretation in simplified models for chargino pair production as well as mSUGRA/cMSSM breaking models

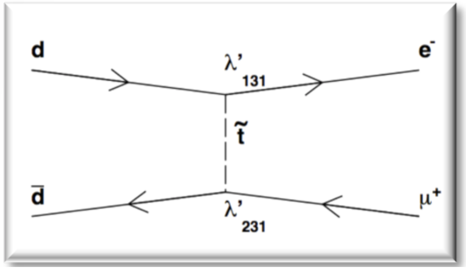


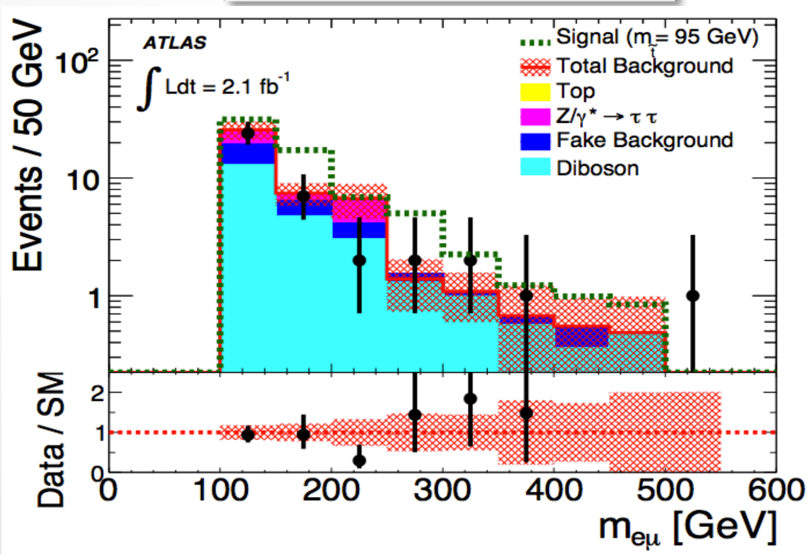
Low ΔR(leptons) and low m(ll)

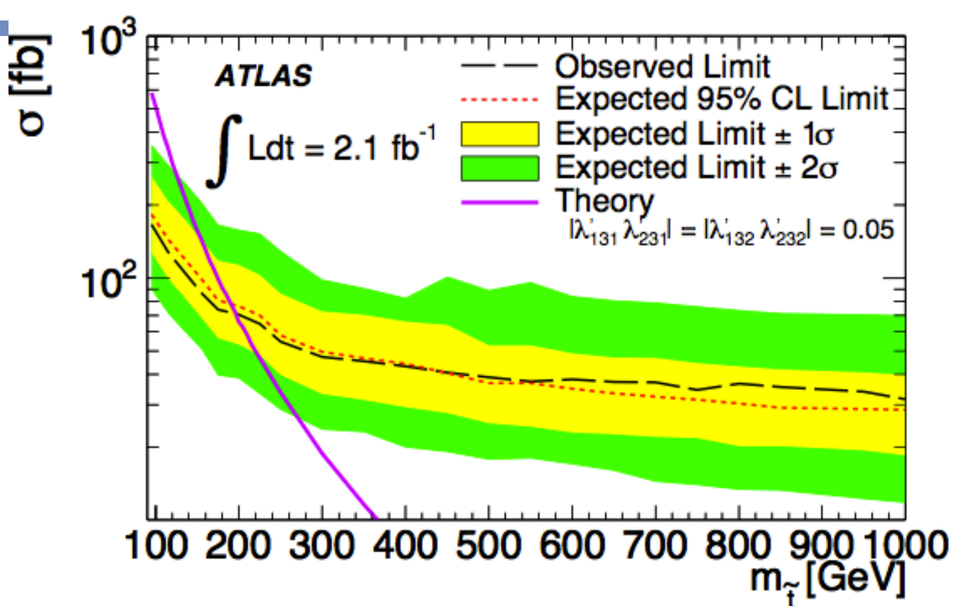


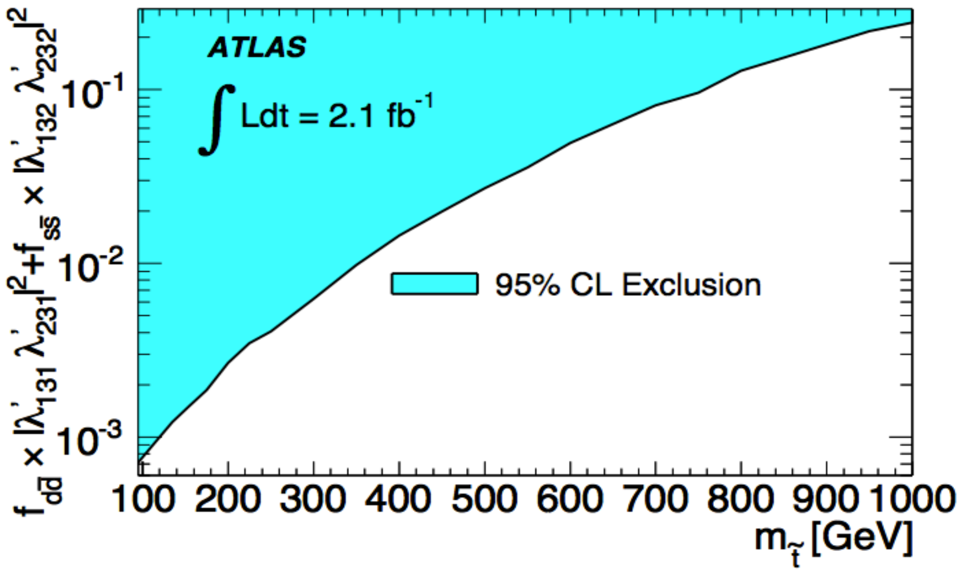
RPV@Production

- Look for excess in the tail of different flavor di-leptons
- **In this case: eμ invariant mass**
  - **No jets, low E^{T}_{miss}**





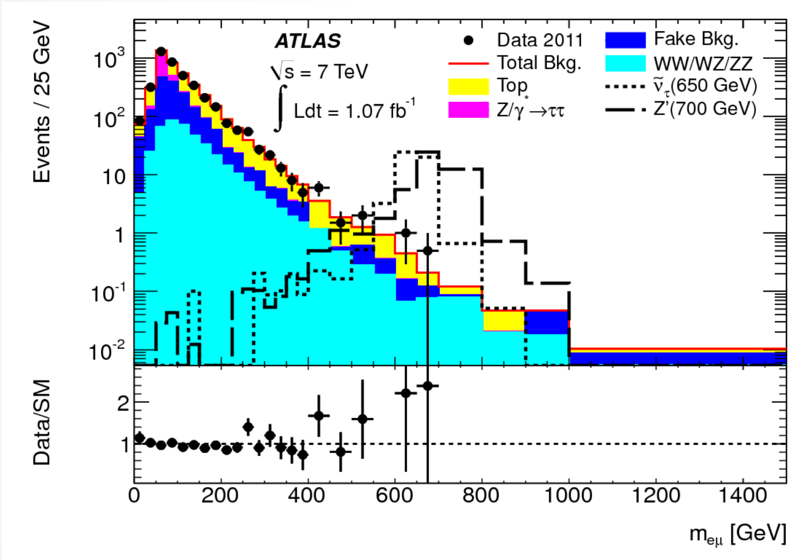


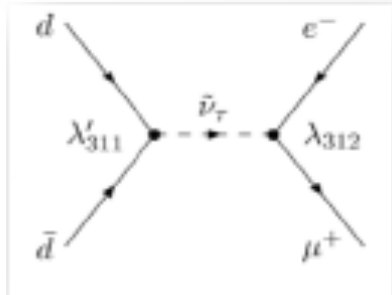


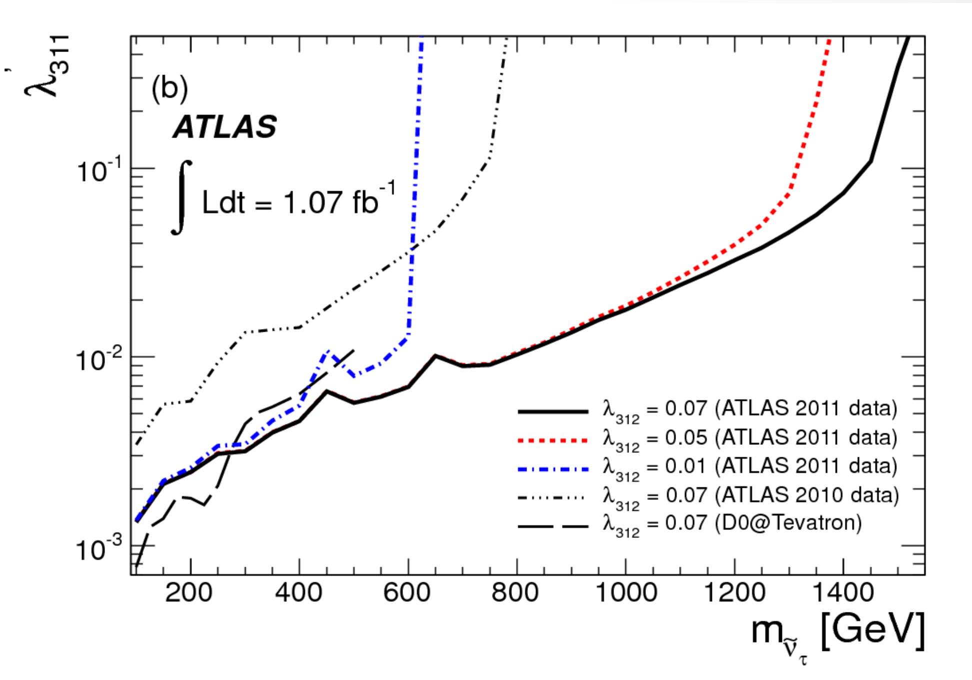
e-mu resonances: sneutrinos

RPV couplings at production and decay

- SM background dominated by fakes and ttbar







Scan in
eμ mass

$m_{e\mu}$	Data	SM prediction
> 200 GeV	286	288 ± 22
> 250 GeV	152	136 ± 11
> 300 GeV	70	67 ± 6
> 350 GeV	35	34.0 ± 3.0
> 400 GeV	22	17.7 ± 1.7
> 450 GeV	10	10.5 ± 1.2
> 500 GeV	7	6.8 ± 0.9
> 550 GeV	3	4.3 ± 0.6
> 600 GeV	3	2.4 ± 0.4
> 650 GeV	1	1.49 ± 0.31
> 700 GeV	0	1.07 ± 0.25

- ‘prompt’ RPV SUSY:
  - Leptonic RPV:
    - search for multilepton final states
    - emu resonances and continuum
  - Hadronic RPV:
    - search for 2x3jet resonances
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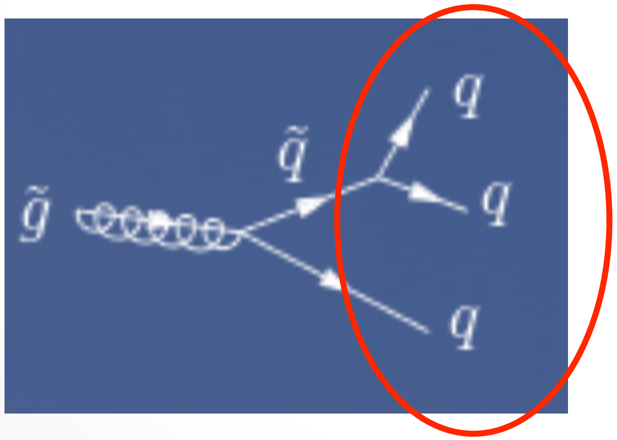
- Long-lived SUSY:
  - Displaced vertex
  - Disappearing tracks
  - R-hadrons and sleptons

‘Hadronic’ RPV: 2x3jets

- UDD couplings least constrained via collider experiments
  - Very hard given the all-hadonic decays and overwhelming multijet bkg
- Several interesting possibilities:
  - Here, consider **2 x 3jets** for gluino pair production focusing on uds λ’’couplings

$$W_{R_p} = \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k$$



2 analyses:
- **Resolved**
- **Boosted**

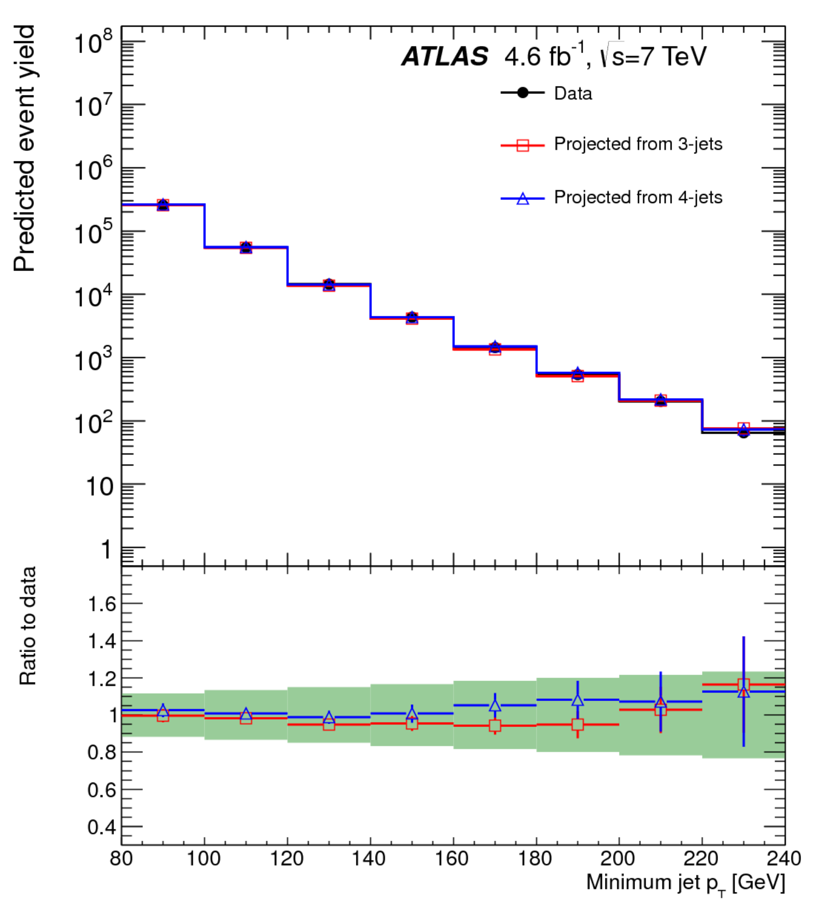
2x3jets: resolved

- signal discriminated from multijet background by exploiting the large p_T of jets produced in gluino decays.

- p_T of 6th leading jets used to discriminate signal from bkg:
  - Three selections used: **> 80 GeV, 120 GeV and 160 GeV**
- **Multijet bkg** estimated using normalization procedure from low to high N jets

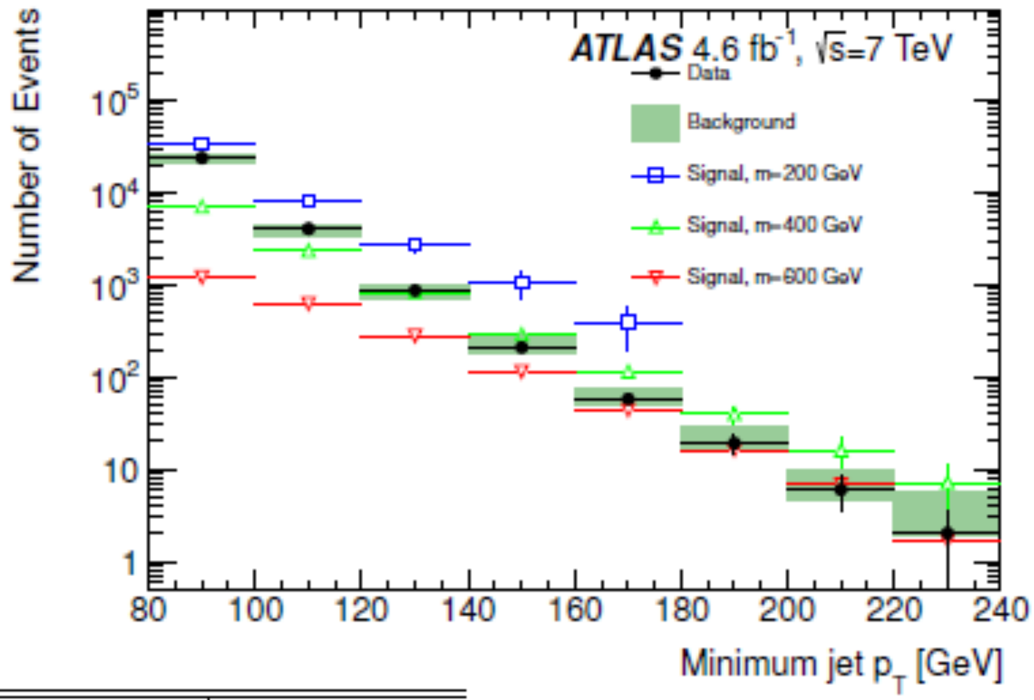
$$N_{data}^{n-jet} = N_{data}^{m-jet} \frac{N_{MC}^{n-jet}}{N_{MC}^{m-jet}}$$

  - Tested from 3j / 4j → 5j (signal depleted)
  - Final estimate using 3 jets → ≥ 6 jets



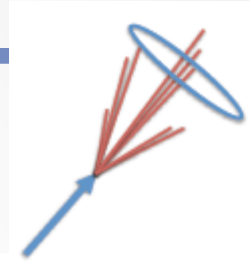
2x3jets: resolved (II)

- Good agreement between data and SM expectation
- Systematic uncertainties mostly from JES and JER, followed by PDF
  - Systematics on color flow and QCD radiation not considered due to the poor knowledge in case of RPV-vertex



Model ($m_{\tilde{g}}$)	$p_{T,min}^{6th-jet}$	Data	Background	Signal bias [%]	Signal
100 GeV	80 GeV	23600	23500 ± 2800	8.5	99200 ± 20000
200 GeV	120 GeV	856	851 ± 140	3.7	2700 ± 500
300 GeV	120 GeV	856	851 ± 140	1.0	1460 ± 240
400 GeV	160 GeV	57	62 ± 13	0.8	110 ± 13
500 GeV	160 GeV	57	62 ± 13	0.3	67 ± 9
600 GeV	160 GeV	57	62 ± 13	0.1	43 ± 7
800 GeV	160 GeV	57	62 ± 13	0.0	20 ± 3

2x3jets: boosted jets



- Jet shape variable sensitive to the N-body structure from jets containing boosted-gluino decay products.

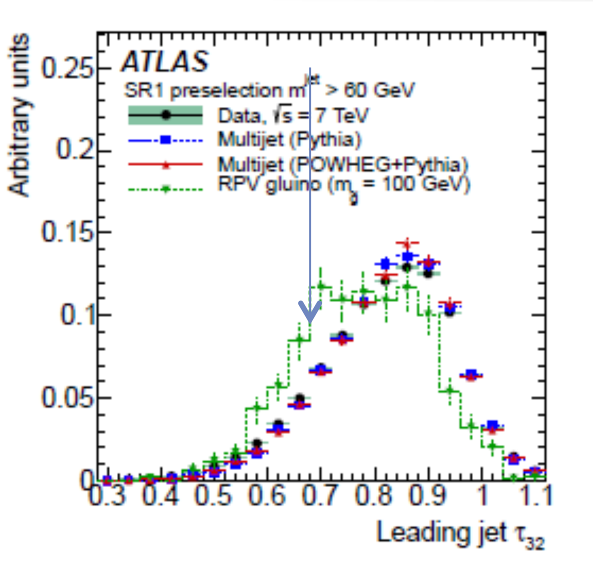
N-subjettiness $\tau_N = \frac{1}{d_0} \sum_k p_{Tk} \times \min(\delta R_{1k}, \delta R_{2k}, ..., \delta R_{Nk})$, with $d_0 \equiv \sum_k p_{Tk} \times R$

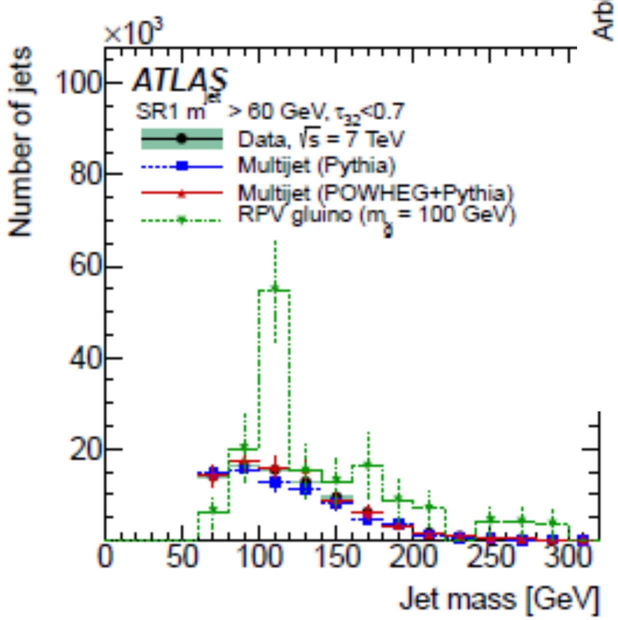
- $\tau_{32} = \tau_3 / \tau_2$

→ if ≈ 1(0), jet well described by 2(3)-subjets

After that, the trimming procedure is applied:

- Soft radiation removed
- Invariant mass of the jet considered (if τ_{32}<0.7)





2x3jets: boosted (II)

- Select events with two massive large-R jets and τ_{32}<0.7
- High normal jet muliplicity also required to reduce multijet bkg
  - Use ABCD method

Selection	Baseline Selection	SR1	SR2
Small-R ($R=0.4$) jet p_T^{jet}	$p_T^{jet} > 30$ GeV	$p_T^{jet} > 30$ GeV	$p_T^{jet} > 30$ GeV
Large-R ($R=1.0$) jet p_T^{jet}	$p_T^{jet} > 200$ GeV	$p_T^{jet} > 200$ GeV	$p_T^{jet} > 350$ GeV
Scalar sum $\sum_{i=1}^{N_{jet}^{R4}=4} p_T^{jet}$	(—)	600 GeV	(—)
Small-R jet multiplicity	(—)	$N_{jet}^{R4} \geq 4$	$N_{jet}^{R4} \geq 4$
Large-R jet multiplicity	$N_{jet} \geq 2$	$N_{jet} \geq 2$	$N_{jet} \geq 2$
Large-R jet mass	(—)	$m_{J_1,J_2}^{jet} > 60$ GeV	$m_{J_1,J_2}^{jet} > 140$ GeV
Large-R jet τ_{32}	(—)	$\tau_{32} < 0.7$	$\tau_{32} < 0.7$

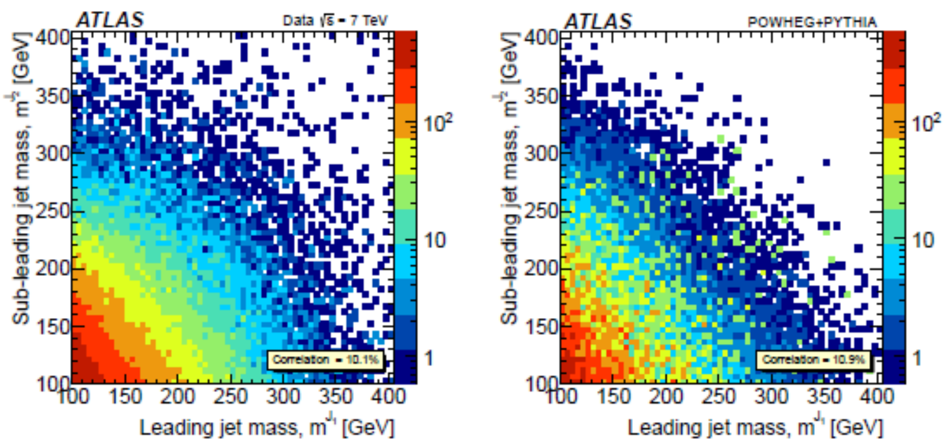
Region	Jet (J_1) selections	Jet (J_2) selections	Description
CR-A	$m^{jet} < M_{threshold}$	$m^{jet} < M_{threshold}$	Low-mass jets, to validate τ_{32} shape
CR-B	$m^{jet} > M_{threshold}$ $\tau_{32} < 0.7$	$m^{jet} < M_{threshold}$	Signal-like leading jet, to validate m^{jet}
CR-C	$m^{jet} < M_{threshold}$	$m^{jet} > M_{threshold}$ $\tau_{32} < 0.7$	Signal-like subleading jet, to validate m^{jet}

$$N_{SR} = N_{CR-C} \times \left(\frac{N_{CR-B}}{N_{CR-A}}\right) \times \alpha$$

$$\alpha = \left(\frac{N_{SR}/N_{CR-C}}{N_{CR-B}/N_{CR-A}}\right)\Bigg|_{MC}$$

α = correlation factor , evaluated from MC

Data *MC (POWHEG+PYTHIA*

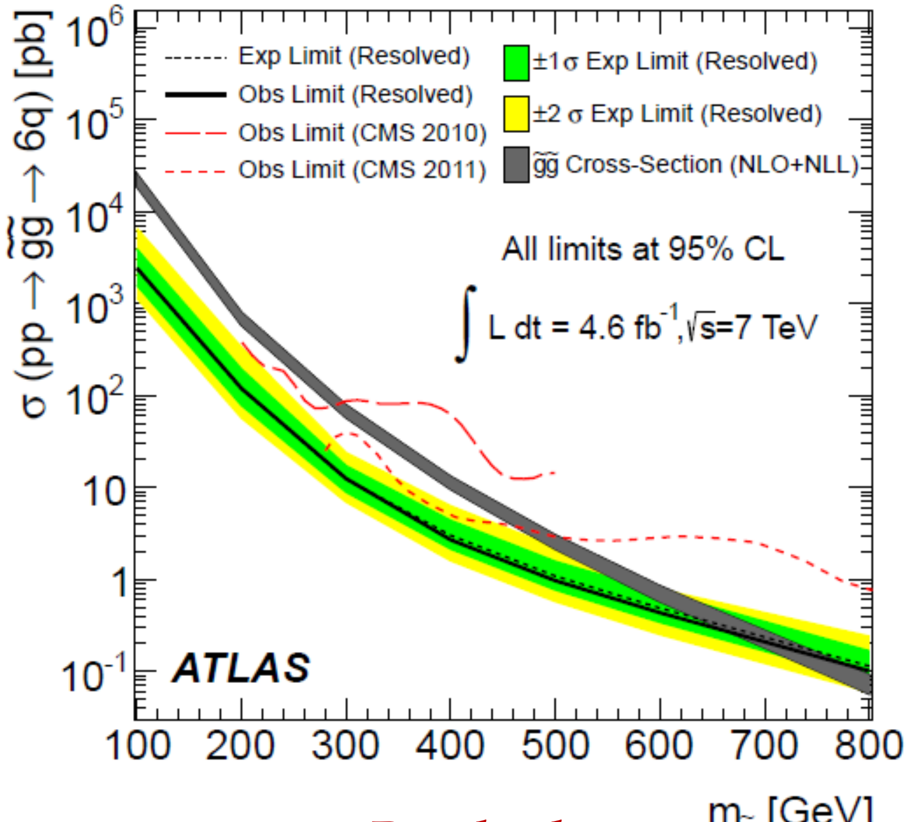


(c) Data, $m^{jet} > 100$ GeV (d) POWHEG+PYTHIA, $m^{jet} > 100$ GeV

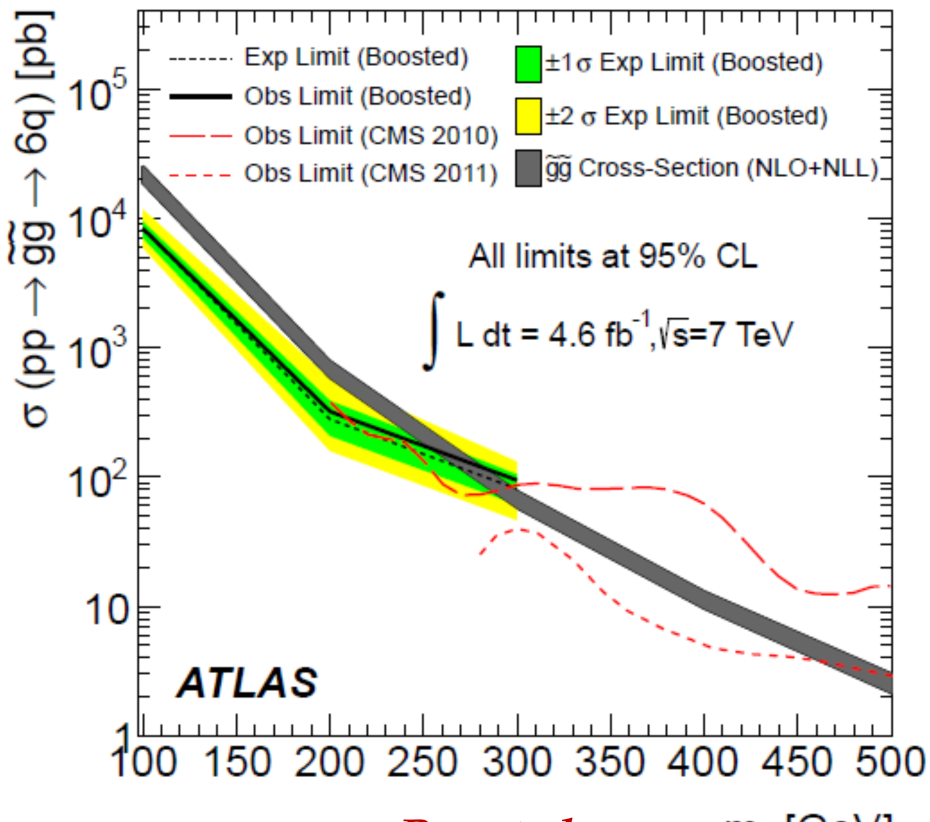
Agreement with data is tested looking at correlations of 1st and 2nd leading jet M

2x3jets: results

- Boosted analysis sensitive for m(gluinos) up to 300 GeV
- Resolved analysis excludes m(gluinos) < 670 GeV



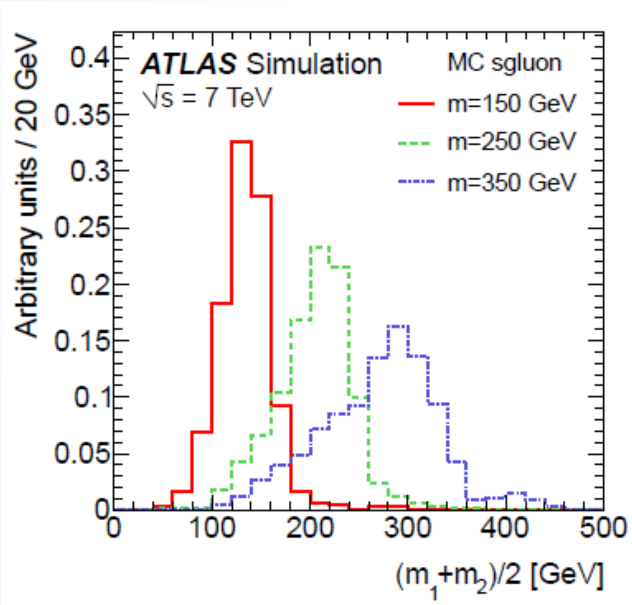
Resolved

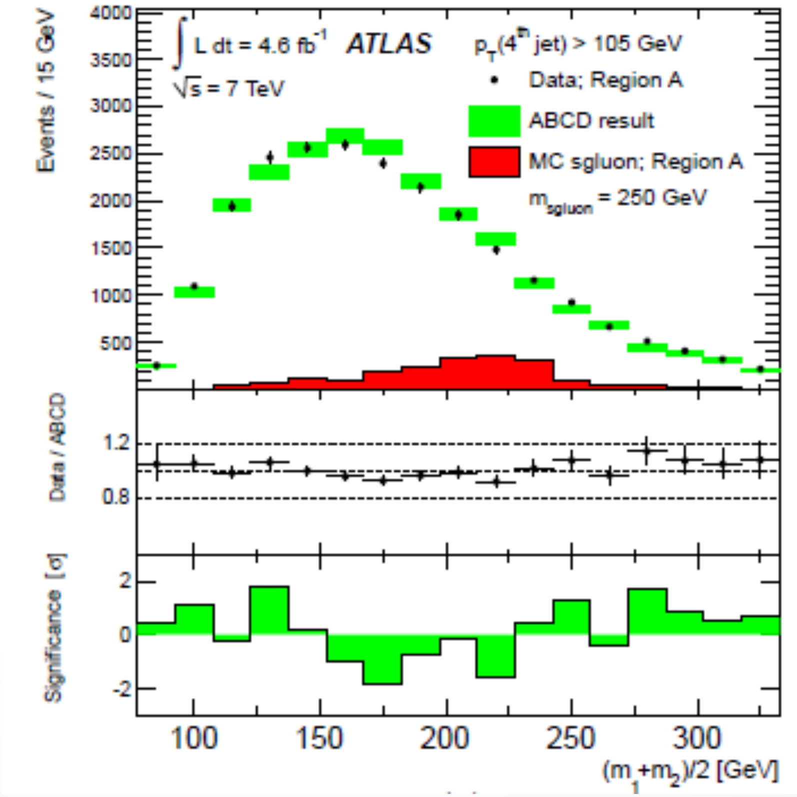


Boosted

2x2jets

- Searches for 2jets resonances potentially sensitive also to RPV sparticle production (→jj final states)
  - In this case, search for pair-produced massive coloured scalars in four-jet
  - Background estimate using **ABCD method**:
    - Regions defined by m1,m2 and scattering angle, cos(θ*)





Exclude sgluons between 150 and 290 GeV

- ‘prompt’ RPV SUSY:
  - Leptonic RPV:
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    - emu resonances and continuum
  - Hadronic RPV:
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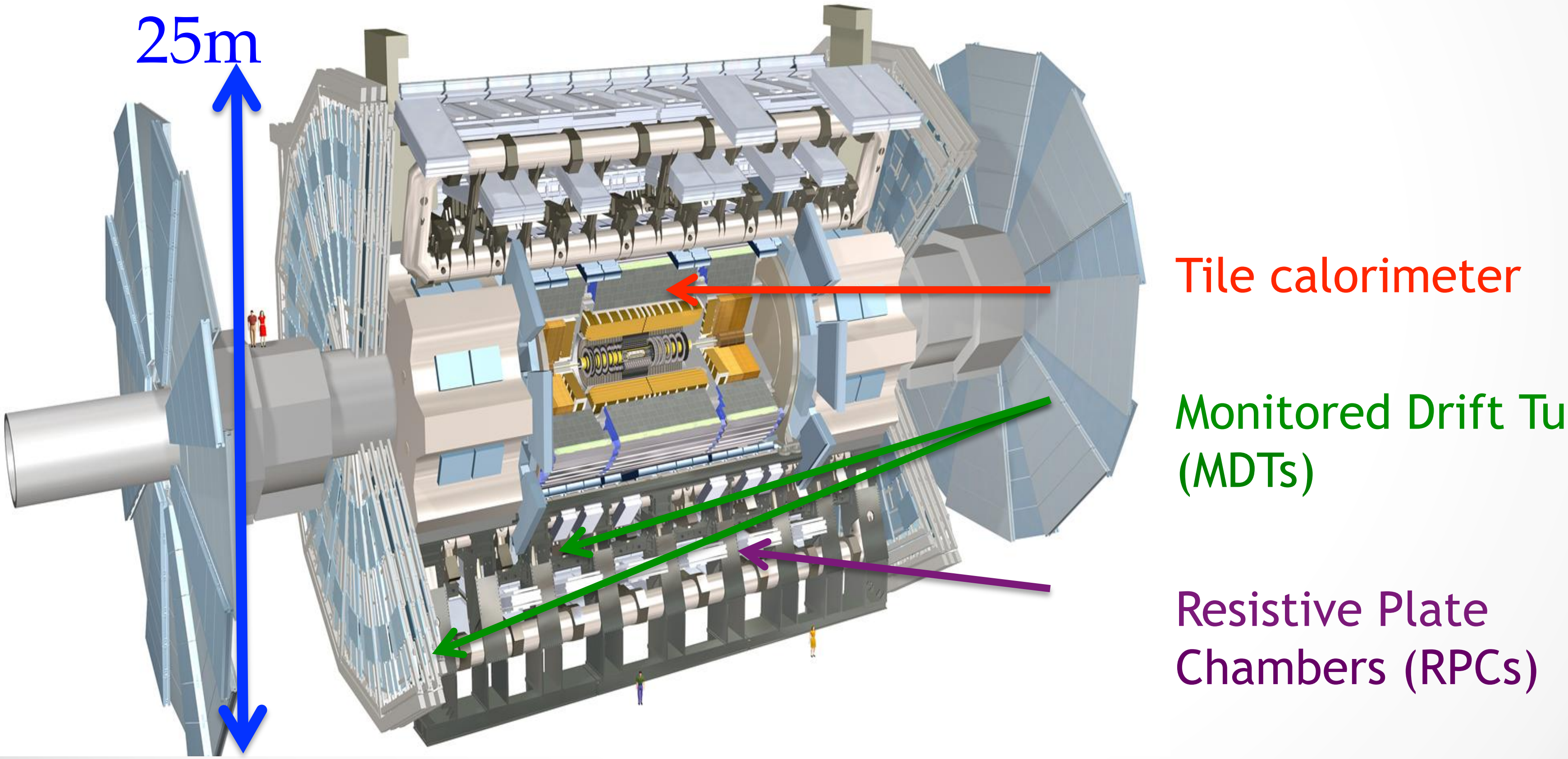
    - search for 2x2jet resonances (currently focusing on scalar gluons searches)
- Long-lived SUSY:
  - Displaced vertex
  - Disappearing tracks
  - R-hadrons and sleptons

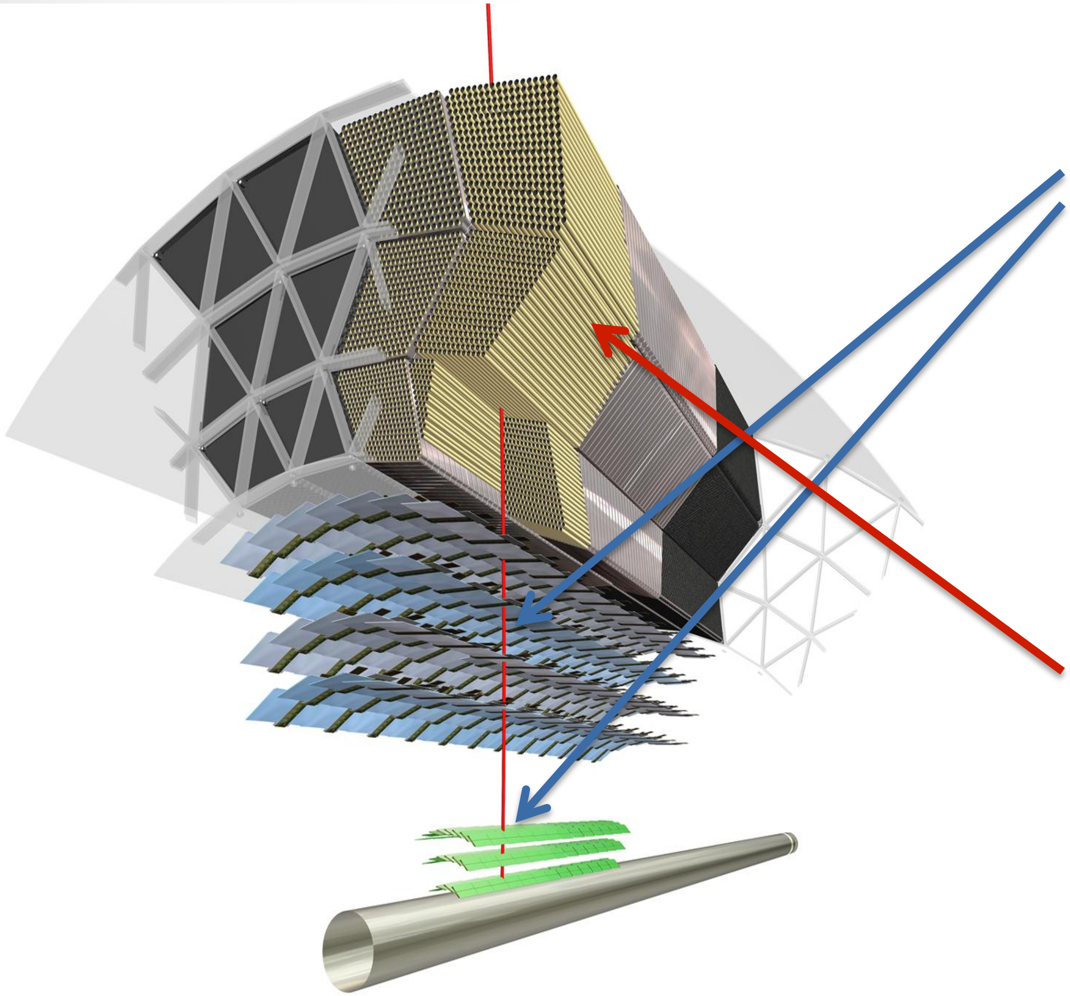
To make it possible: ATLAS detector

Several sub-detectors with excellent time resolution, including (but not only):



Can measure time-of-flight

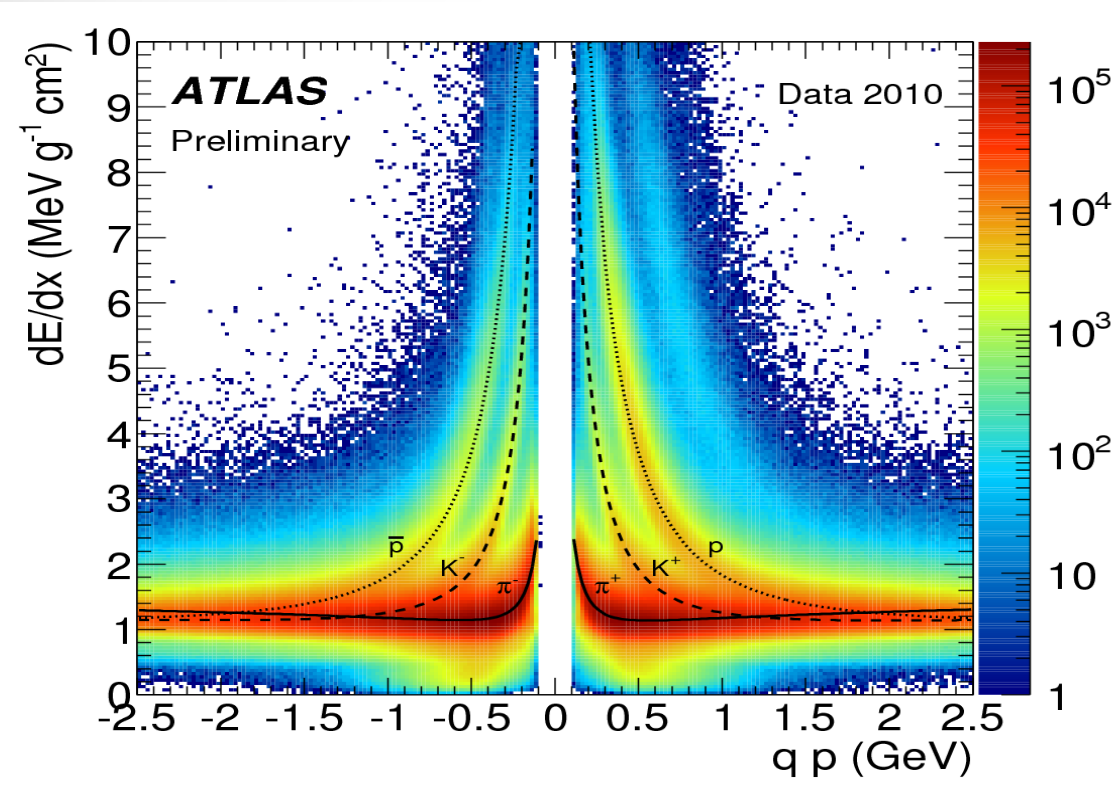
The ATLAS Inner Detector (ID)



- Pixel detector
- Semiconductor Tracker (SCT)
  - Good for finding vertices
- Transition Radiation Tracker (TRT) → a continuous tracker
  - Can detect kinked or disappearing tracks

All within a 2T solenoidal B-field

dE/dx measurements

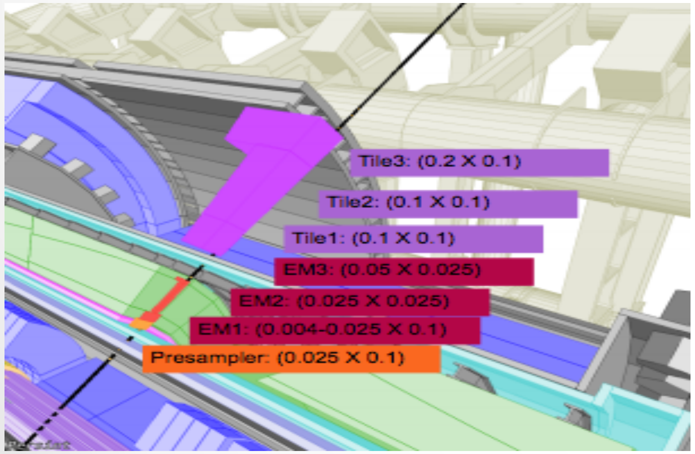


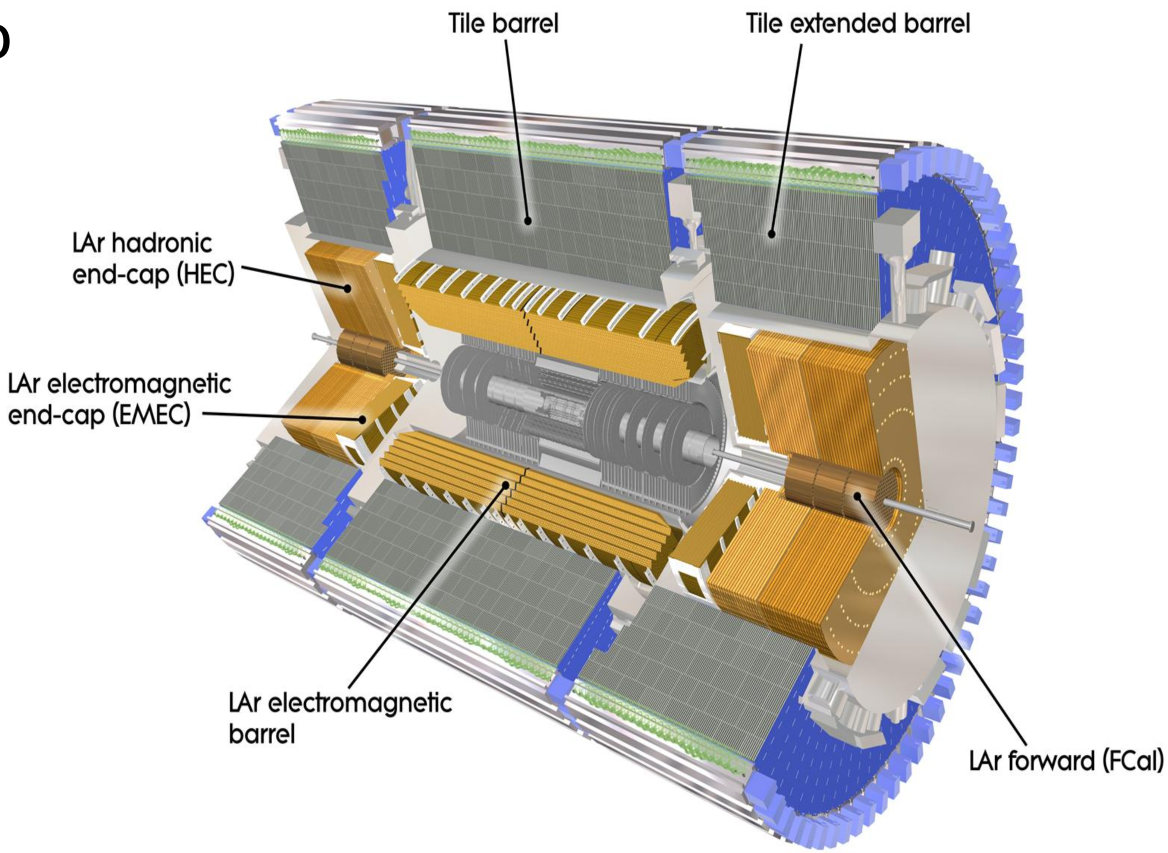
Pixel detector can measure ionization energy loss *dE/dx* via charge deposited (calculated from Time-over-Threshold)

TRT can also measure *dE/dx* via Time-over-Threshold

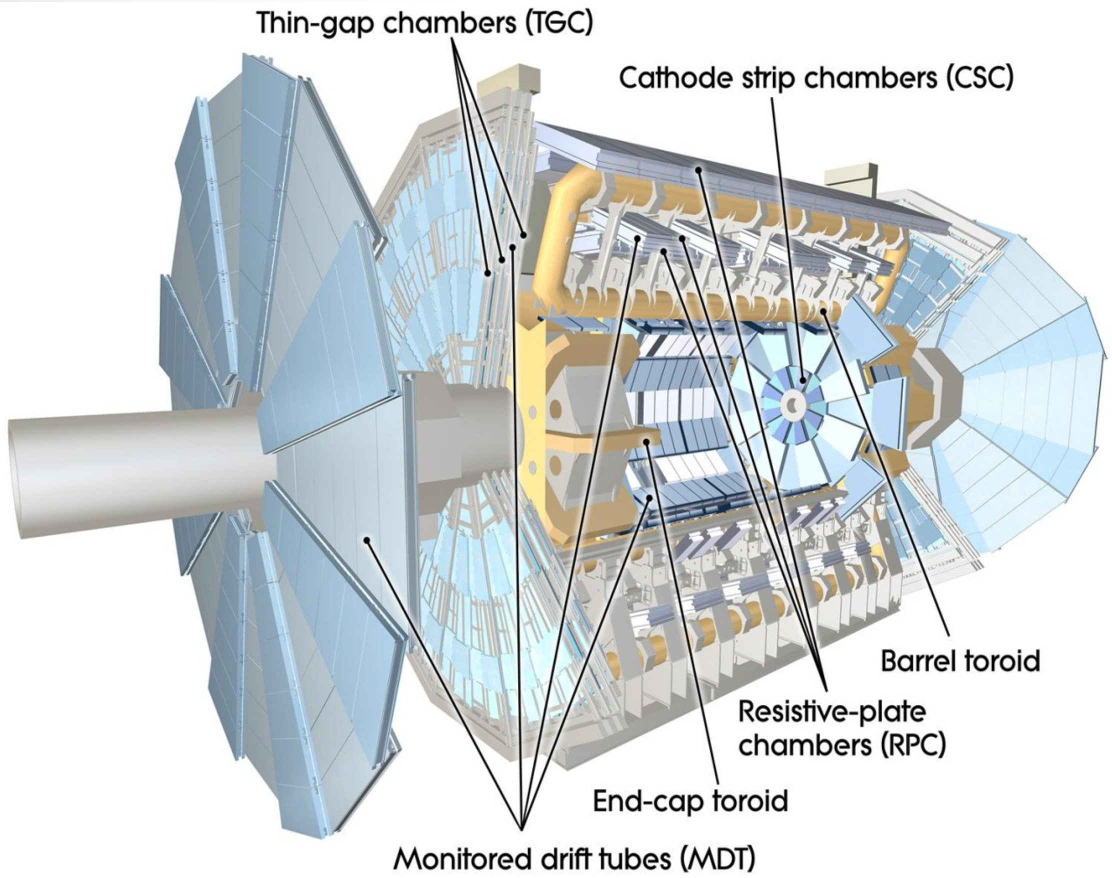
The ATLAS Calorimeters

- Both LAr and Tile calorimeters can also measure *dE/dx* by summing energy deposits over path length.





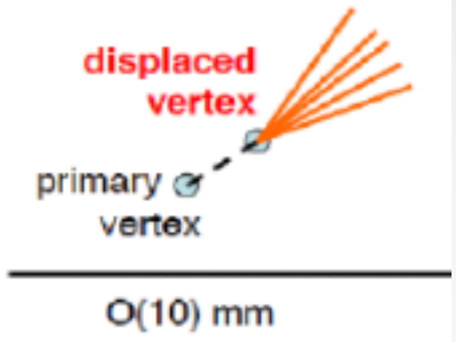
The ATLAS Muon Spectrometer



- Precision muon chambers can reconstruct "standalone" tracks
  - i.e. can find particles that did not leave tracks in Inner Detector (e.g. decay products of LLPs)
- MDTs can also measure *dE/dx* (similar principle to TRT).

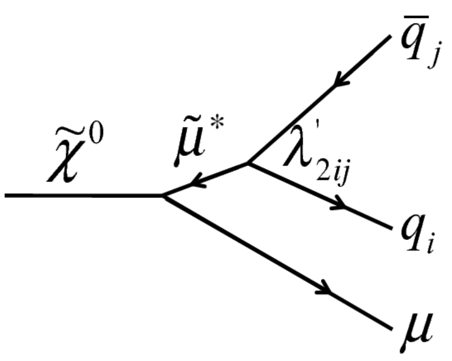
Displaced vertices in ID

- Particles with lifetimes of order a few picoseconds could decay within the inner tracking detector, giving rise to displaced vertices



→ *Here:* consider **muon+jets** topology, i.e. from RPV neutralinos decay with a non-zero (but small) λ'_{211} coupling

- Presence of a muon useful for triggering and background rejection
- High track multiplicity helps vertex reconstruction

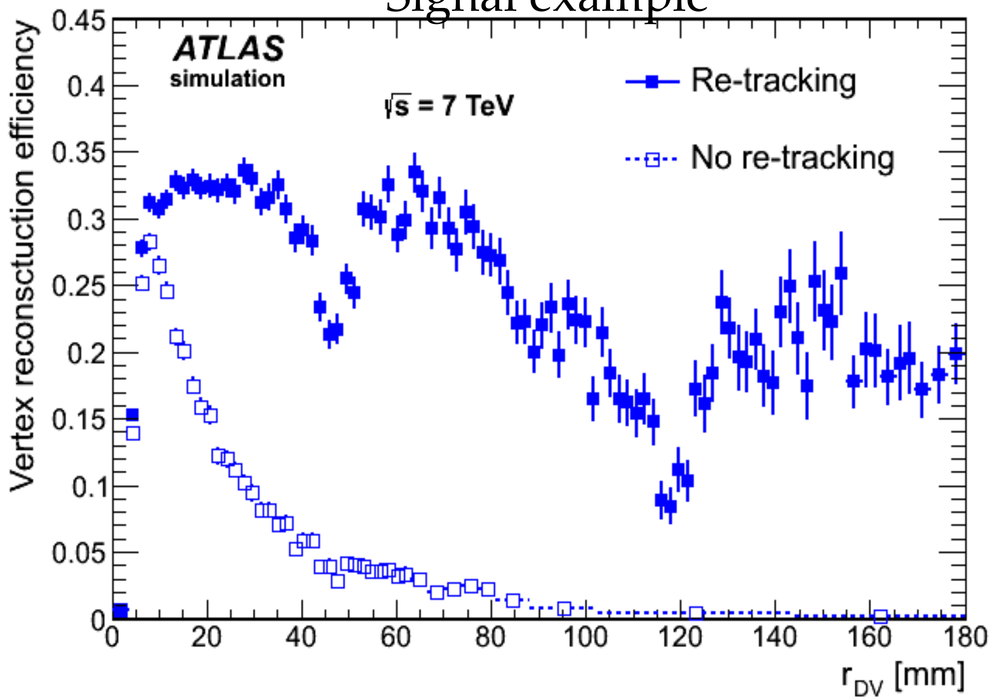


track and vertex reconstruction

- Standard ATLAS tracking is highly optimized for tracks coming from the primary interaction point (IP)
- To increase efficiency for secondary tracks

  → re-run Silicon-seeded tracking algorithm, with looser cuts on transverse impact parameter, using "left-over" (shared) hits from Standard tracking.

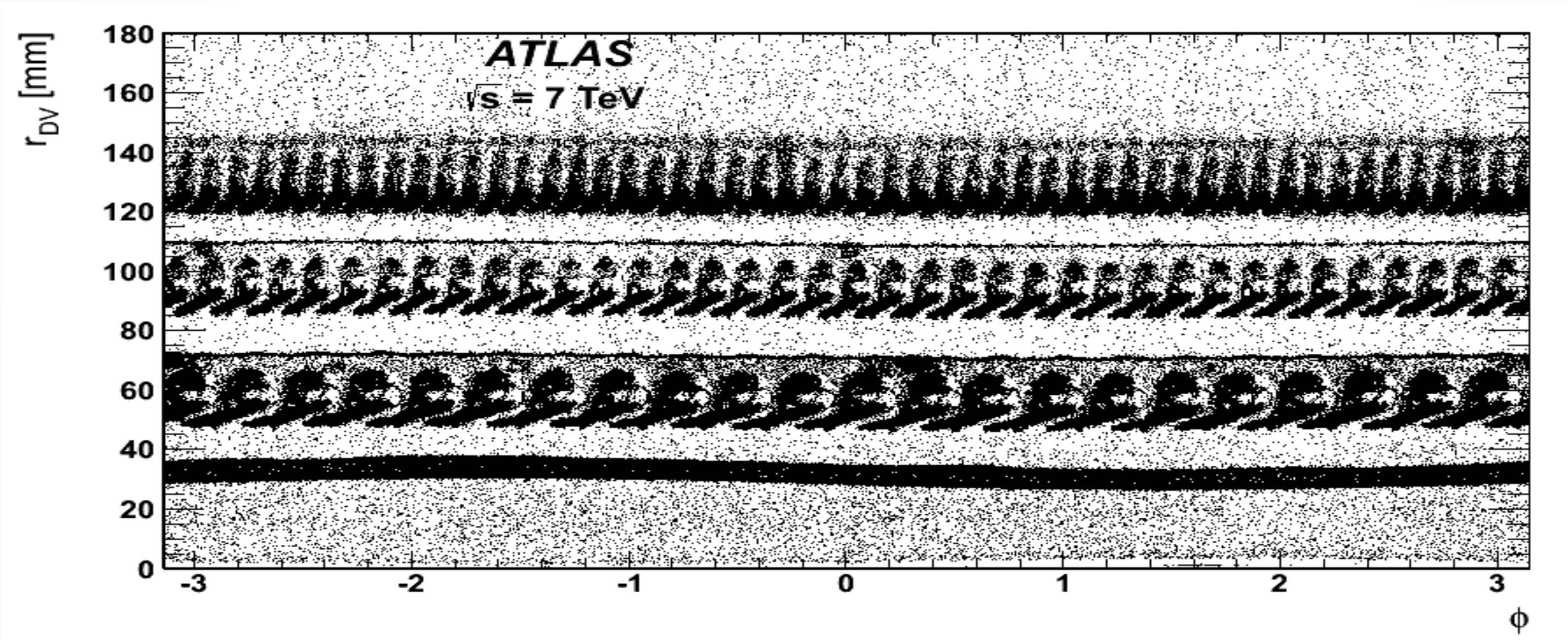
Signal example



- Vertex-finding algorithm based on an iterative disambiguation process
- then splits/merges/refits vertices until no tracks are shared between vertices.

Displaced vertices - selection

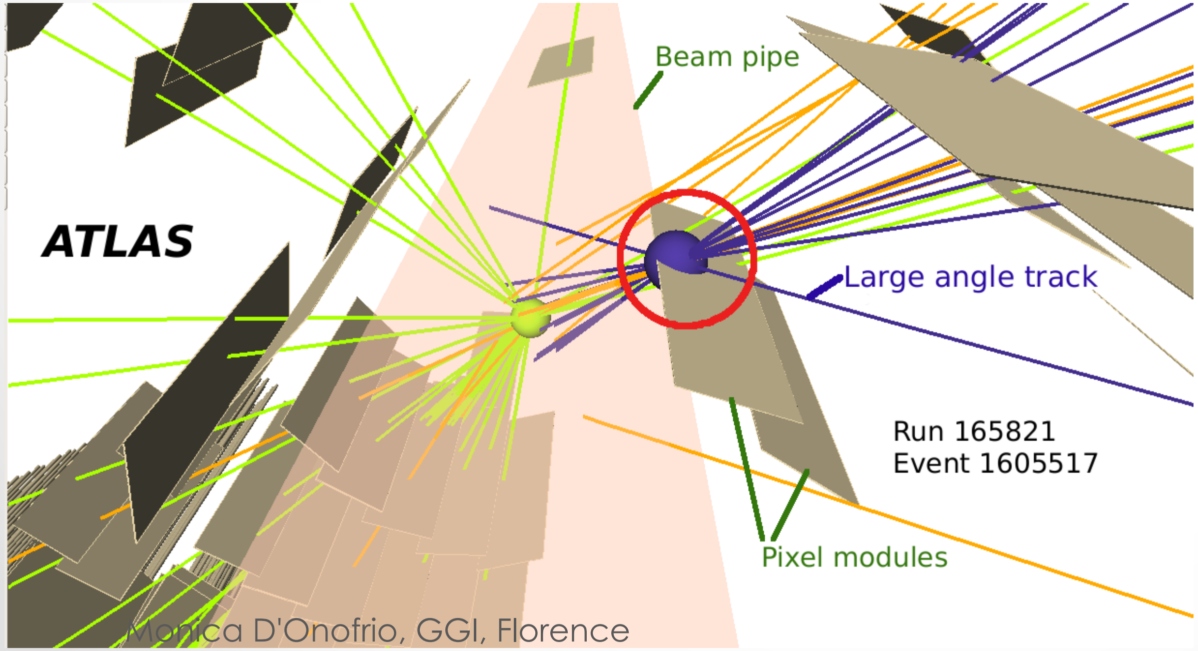
- Events triggered by high-p_T muon trigger, with no ID track requirement.
- Use tracks with $|d_0|>2mm$, $p_T>1$ GeV as input to vertexing
- Look in fiducial volume roughly corresponding to Pixel barrel
- Require at least 5 tracks in vertex, and mass > 10 GeV.
- Require high-p_T muon passing within 0.5mm of reco vertex



→ Veto vertices reconstructed in regions with high material density

Displaced vertices - backgrounds

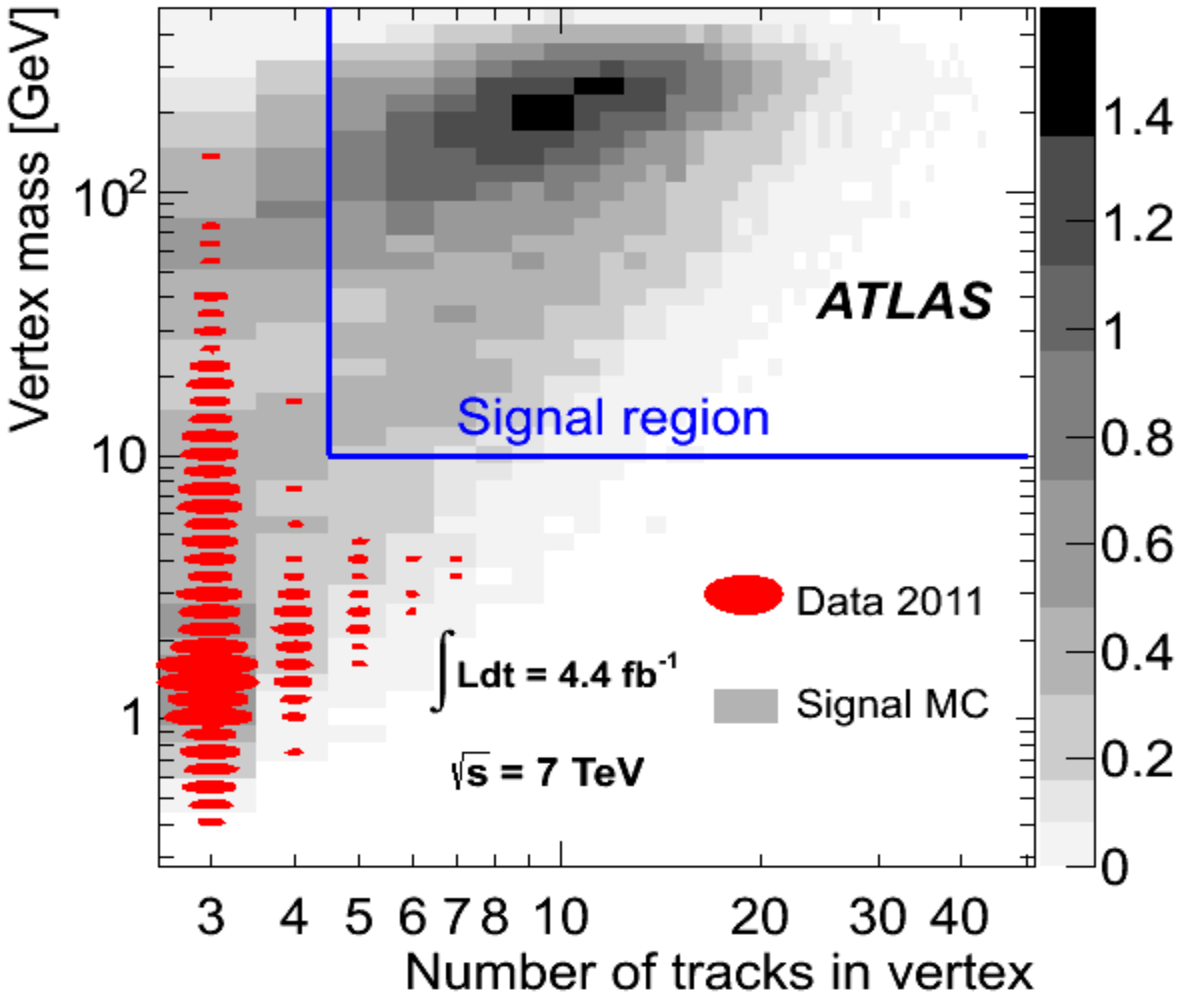
- Two sources of background vertices considered:
  - Purely random combinations of tracks inside the beampipe (where vacuum is good, but track density is high).
  - High-mass tail of distribution of real vertices from hadronic interactions with gas molecules.
    - Particularly if vertex is crossed by random (real or fake) track at large angle.



- Use different data-driven method for each source: total estimate is $(4 \pm 60)*10^{-3}$ vertices

Displaced vertices - results

- Zero vertices passing selection requirements observed in 4.4 fb^{-1} data sample.

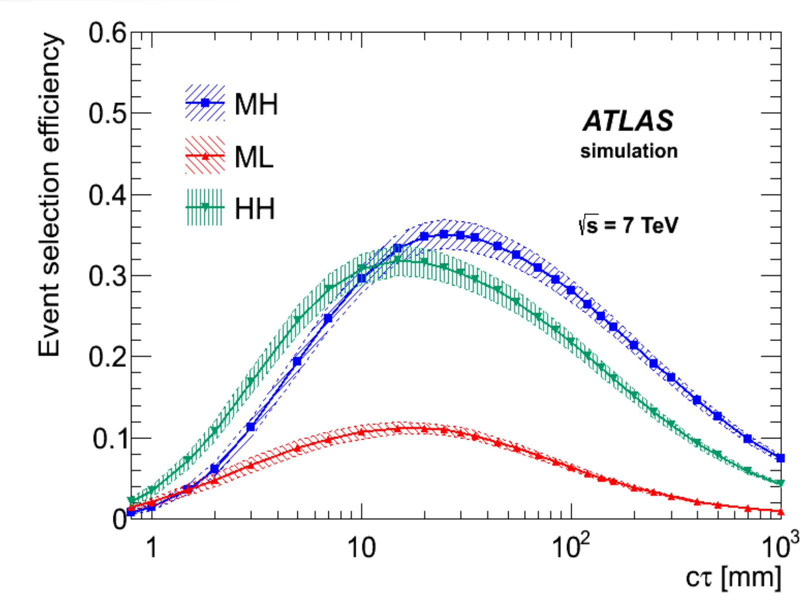


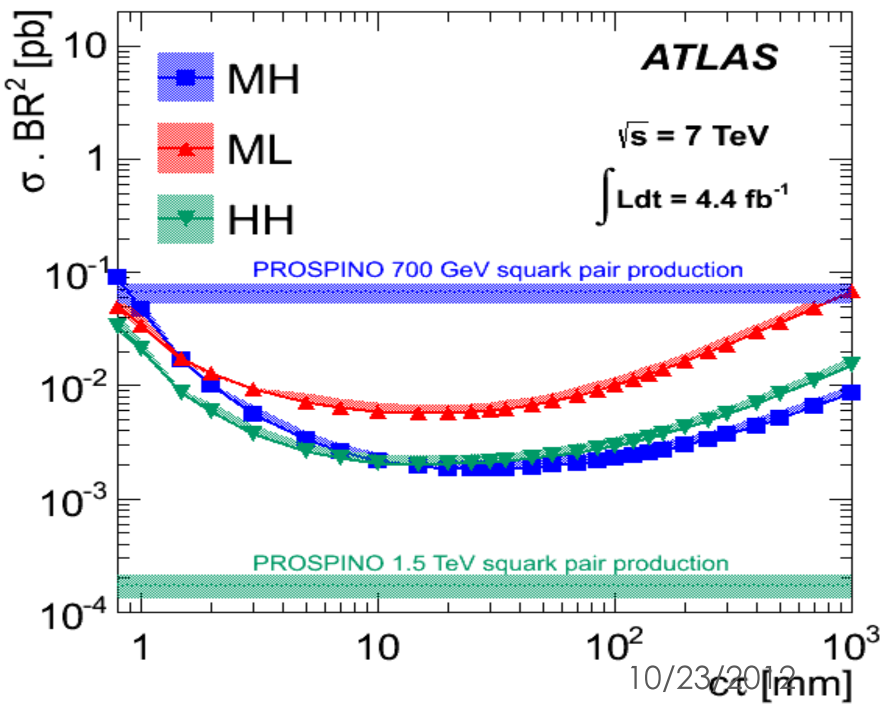
Displaced vertices - interpretation

- Exclusion limits set on squark pair production
  - Assume squark decays directly to LL neutralino, which decays to muon plus jets.
- Three combinations of squark and neutralino masses considered, to study the effect of LLP mass and boost on reconstruction efficiency

Sample	$m_{\tilde{q}}$ [GeV]	$m_{\tilde{\chi}_1^0}$ [GeV]	$c\tau$ [mm]
MH	700	494	78
ML	700	108	101
HH	1500	494	82

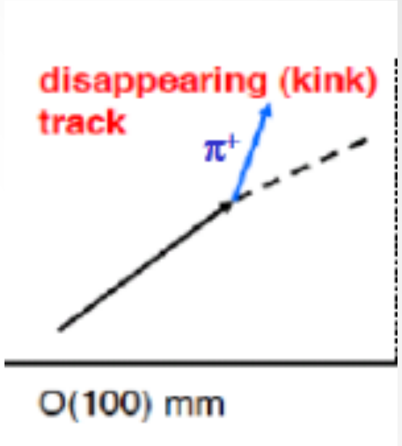
efficiency-vs-$c\tau$





Disappearing tracks

- In AMSB model, could have long-lived charginos decaying to neutralino and soft pion
- Look for production processes as:



$$pp \rightarrow \tilde{\chi}_1^{\pm}\tilde{\chi}_1^{0}j, \quad pp \rightarrow \tilde{\chi}_1^{+}\tilde{\chi}_1^{-}j$$

$\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_1^{0}\pi^{\pm}$ branching ratio set to 100%

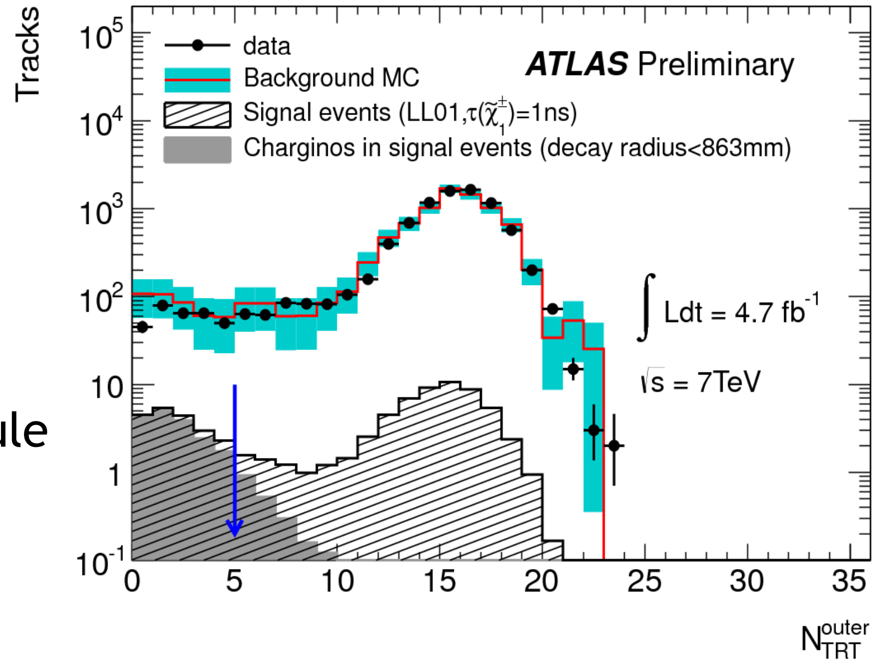
Use jet from ISR to trigger on events

- Resulting final state:
  - High p_T jet + large missing ET
  - High-p_T disappearing track (or "kinked" track):
    - Isolated tracks that stop in outer TRT

Disappearing tracks - selection

- Event selection:
  - missing E_T > 90GeV and ≥ 1 jet with p_T > 90GeV
  - Jets well separated from missing E_T direction in φ (Δφ > 1.5)
  - Veto events with reconstructed ele or μ candidates.
- Disappearing track candidate selection:
  - Track must be isolated
  - have p_T > 10GeV,
  - at least 1 Pixel hit and 6 SCT hits,
  - originate from primary vertex,

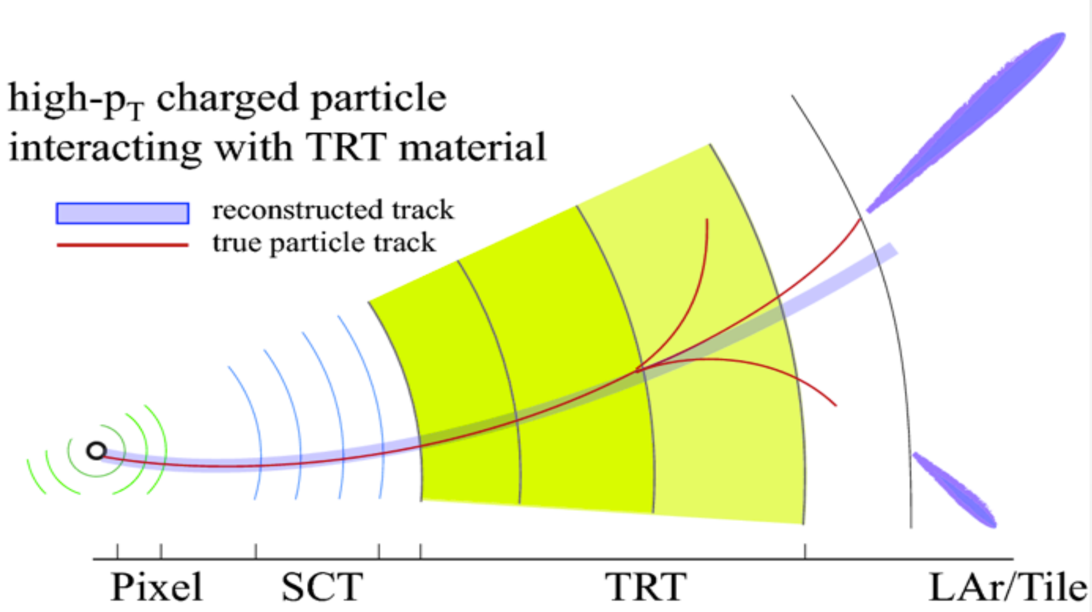
  and point to TRT barrel (but not region around |η|=0)
  - Fewer than 5 hits in TRT outer module

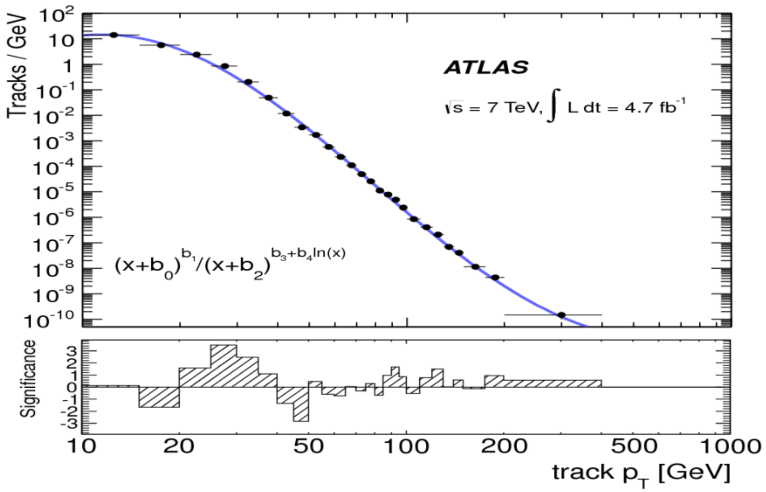


Disappearing tracks - backgrounds

- Potential background sources are:

Charged hadrons interacting with detector material (80%)





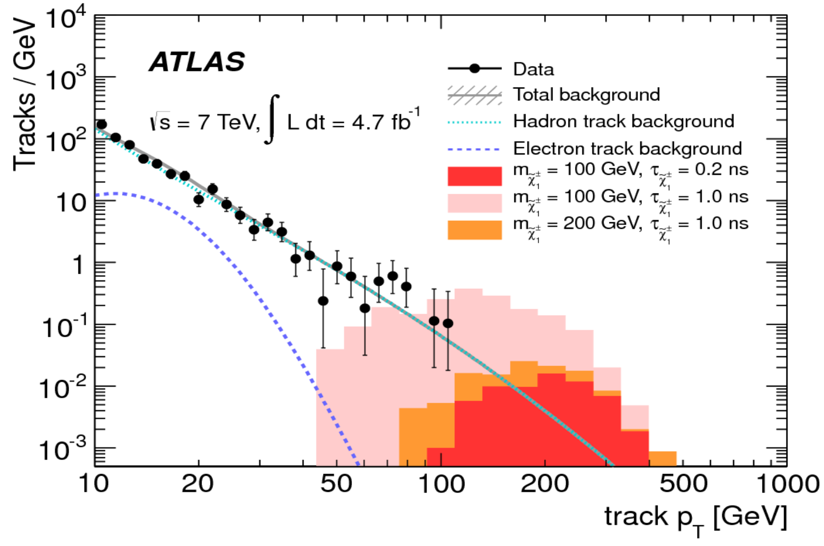
Electrons surviving lepton veto, undergoing bremsstrahlung

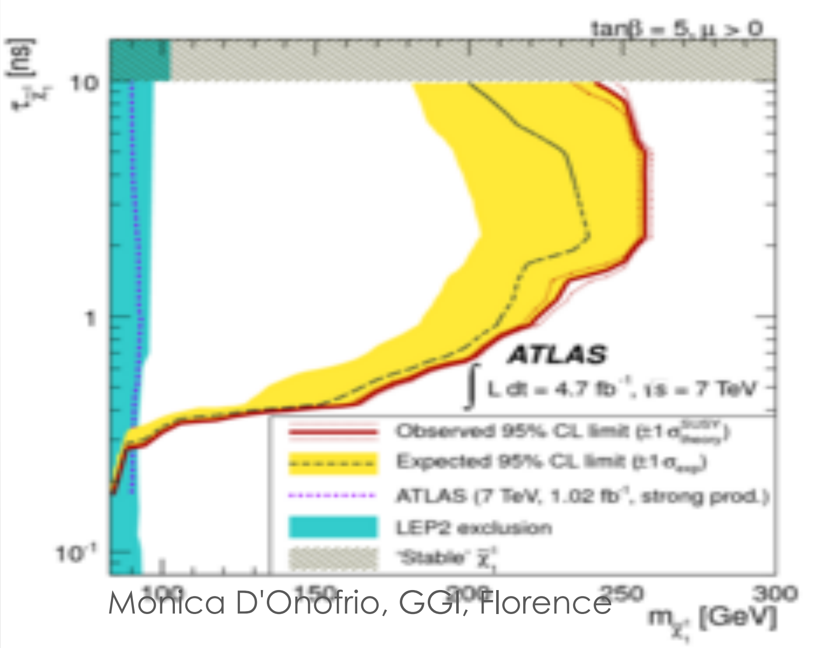
Obtain p_T spectrum for both sources of background using data control samples

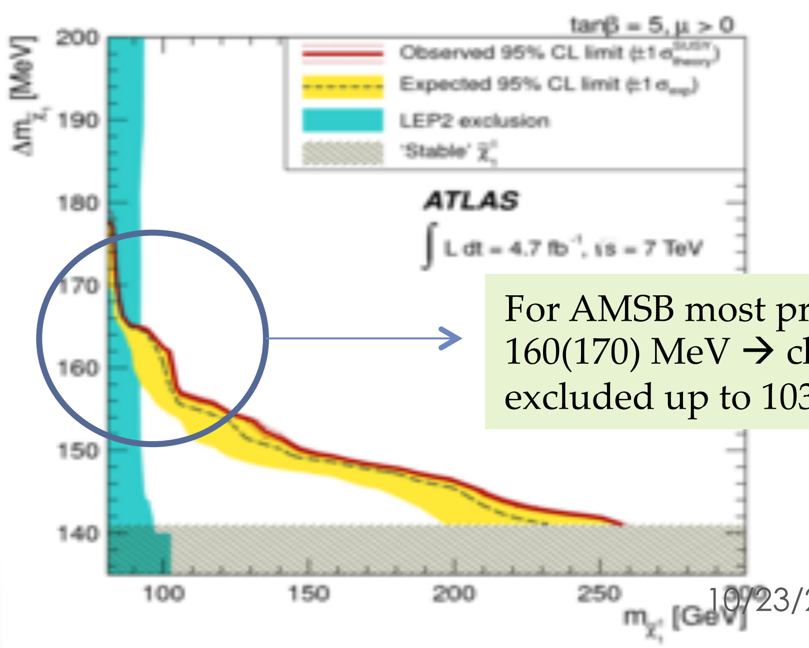
Disappearing tracks - results

- Use signal+background likelihood fit to track p_T spectrum, to test different signal hypotheses

- No significant excess found → Set limits on chargino mass and lifetime and charg-neut ΔM:







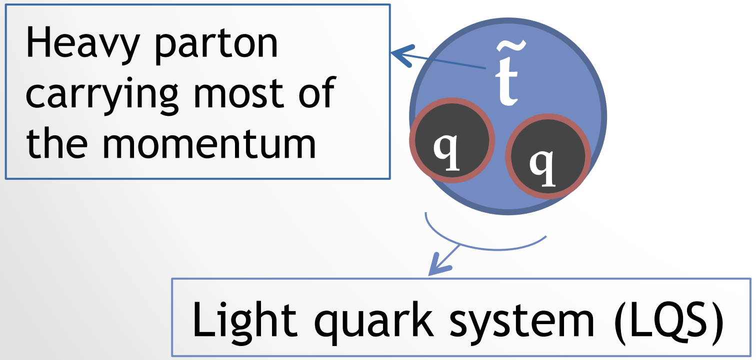
For AMSB most prob value 160(170) MeV → chargino mass excluded up to 103 (85) GeV

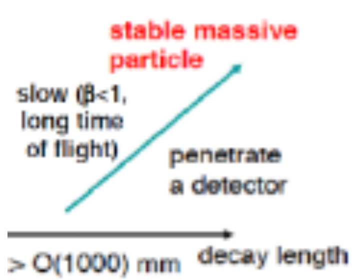
Stable Massive Particles (SMPs)

- SMPs predicted in SUSY several other BSM scenarios
- Stable → $c\tau \geq$ size of detector
- Produced with $\beta<1$
- *Within SUSY:*
  - $\tilde{l}$ and $\tilde{\chi}^+$
  - **$\tilde{q}/\tilde{g}$ (bound states)**

Colored sparticles can hadronise into long-lived bound hadronic states

R-hadrons





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 $A_b \gg A_t$.

Table 1
Brief overview of possible SUSY SMP states considered in the literature. Classified by SMP, LSP, scenario, and typical conditions for this case to materialise in the given scenario.

SMPs: how-to

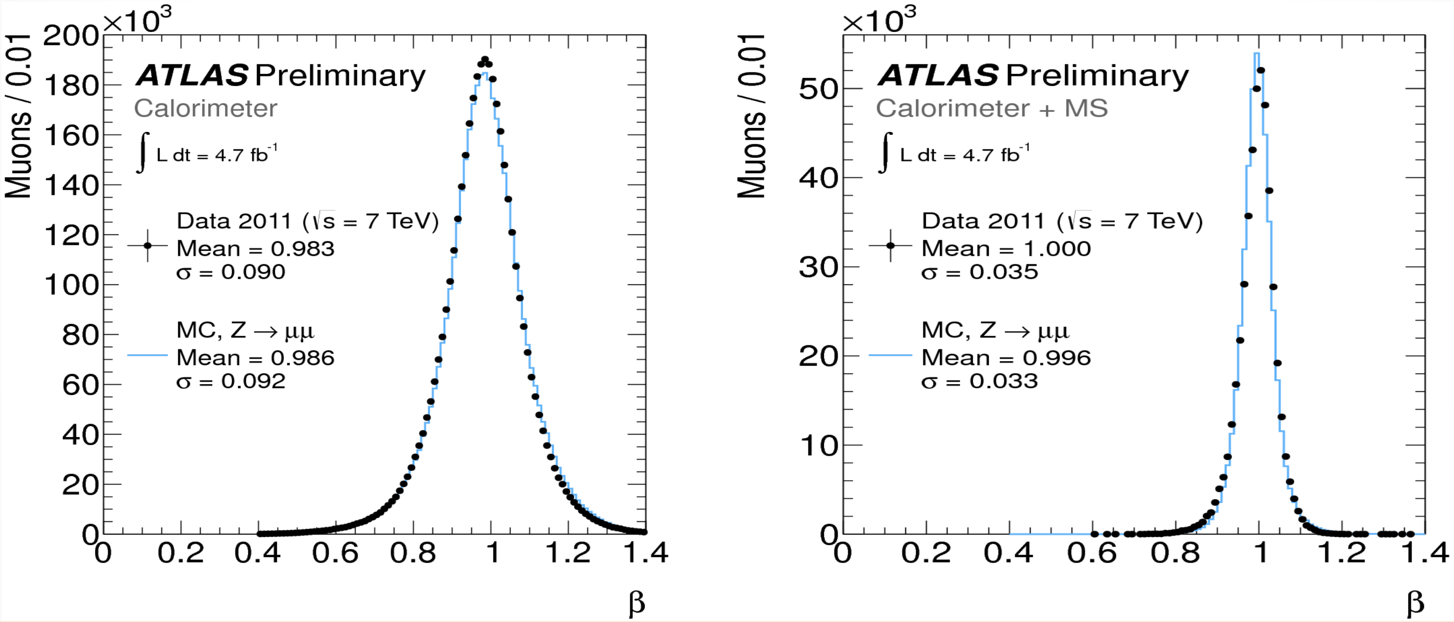
- Particles with $c\tau \geq$ size of detector:
  - If neutral and weakly interacting → missing E_T
  - If charged (at any point!) or strongly interacting → can detect them directly
  - If massive, could be produced with low velocities: $\beta < 1$
- Mass of SMPs:

- measure charged particle momentum *p* in ID and MS
- measure energy loss *dE/dx* in several subdetectors
  - For these analyses, use Pixel
  - *dE/dX* is related to relativistic boost factor $\beta\gamma$
- measure time-of-flight in several sub-detectors
  - For these analyses, use Tile, RPC, MDT
  - Can measure velocity β

→ $p = \beta\gamma m$

β measurements and bkg

- Use Z→μμ events to calibrate β measurements
- If β measurements from different systems are > 0.2 and internally consistent → combined in a weighted average.



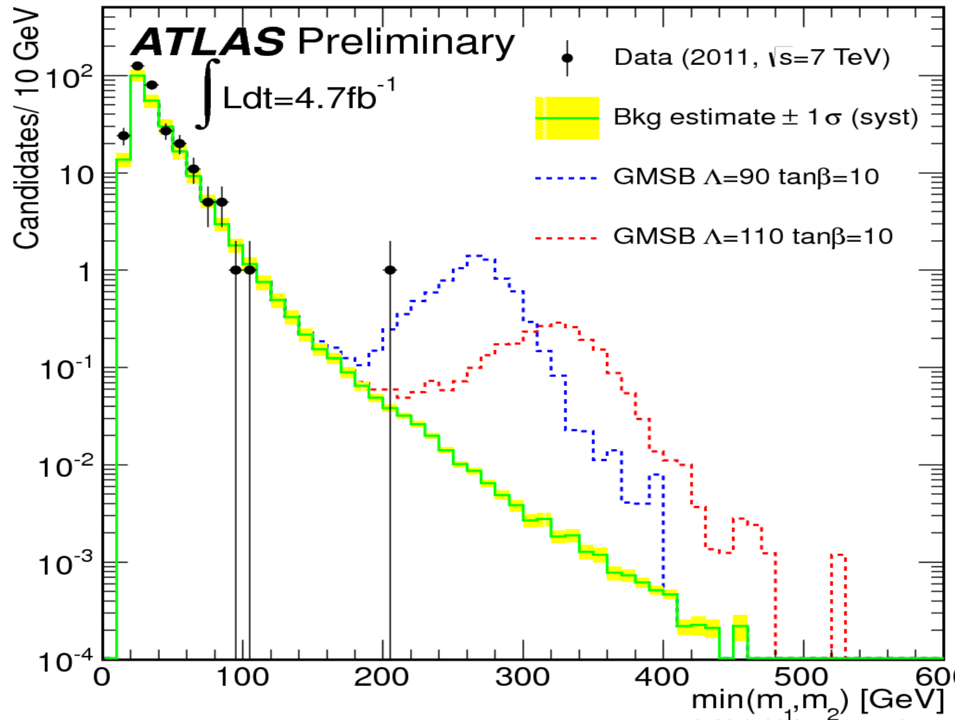
Main background are high-p_T muons with mismeasured β.

- Exploit fact that mis-measurements of β or βγ in different subdetectors are uncorrelated.
- Use data-driven method based on randomly sampling β or βγ values from CR distributions.

Long-lived sleptons - selection

- "Heavy muons"-like, releasing energy throughout detector
- Use single μ trigger (70-85% efficiency for GMSB slepton events):
  - Efficiency for particles arriving late at MS estimated from MC signal
- 2 μ candidates per event, $p_{T\ loose(tight)}$ > 50(70) GeV.

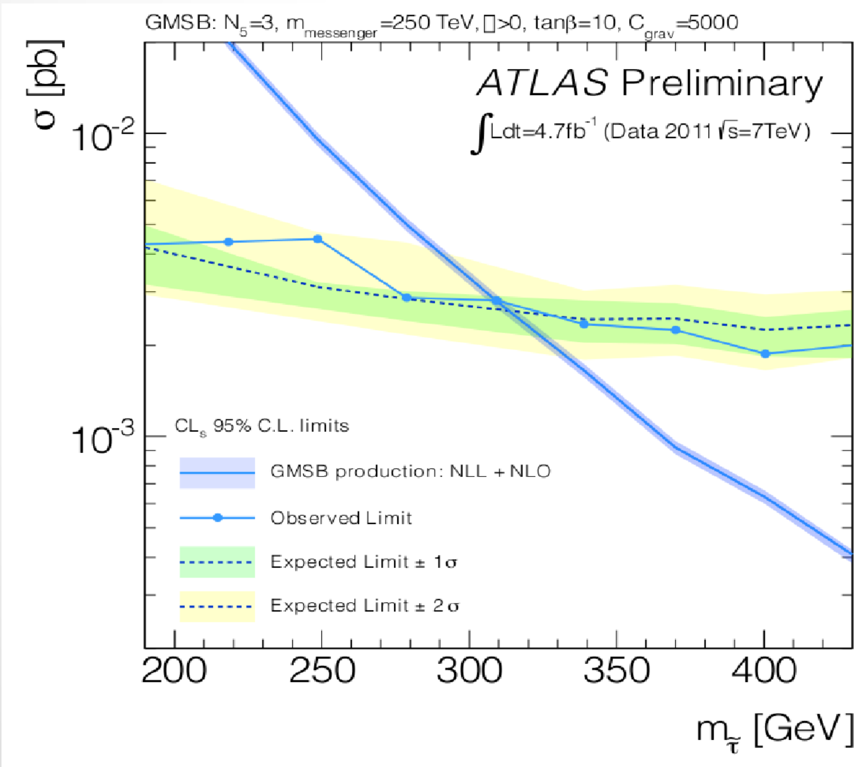
- Either two loose candidates or one must pass tight selection.
- Bkg estimate: from iterative procedure based on muon-β PDF:
  - Assume bkg is due to measurement resolution
- Apply cut on candidate mass $m_\beta = p/\gamma\beta$ (depending on stau mass hypothesis: 122 – 465 GeV range)



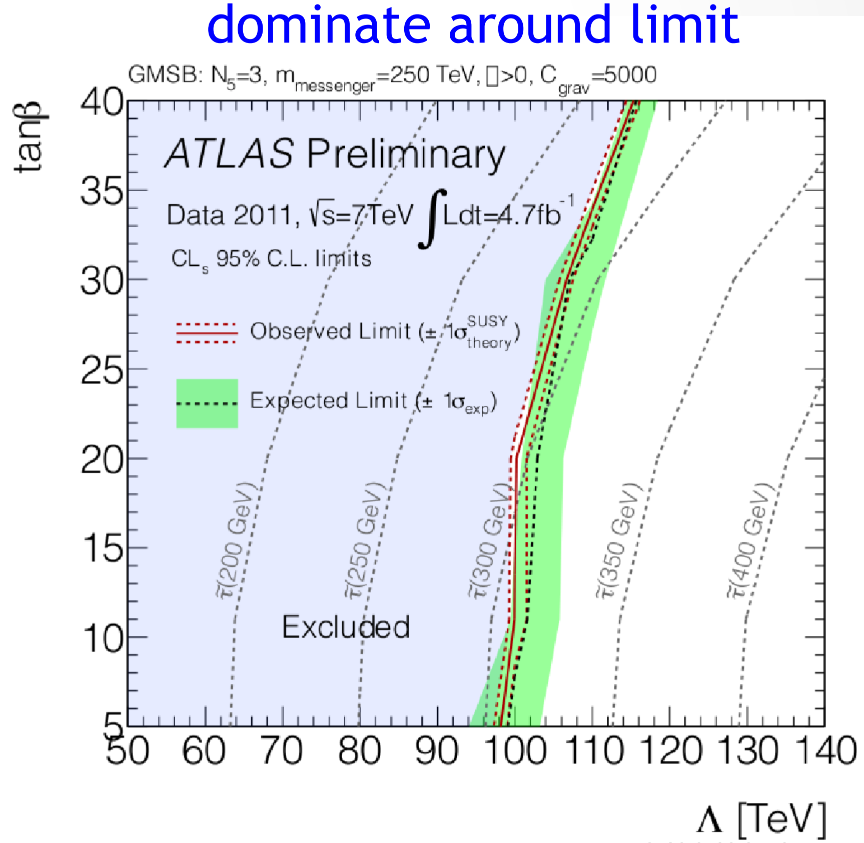
Slepton search - results

- No excess above background expectation

- Constraints on stau mass in GMSB scenario

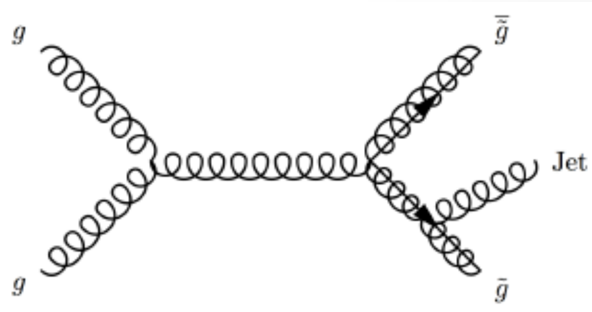


- Constraints in tanβ vs Λ in GMSB scenario
  - Direct sleptons production dominate around limit



R-hadrons - selection

- Undergo interactions with detector material
  ➔can also change charge as it moves through detector
- If β is too low, particle might be associated with following bunch crossing by the time it gets to MS.
- Due to both these effects, efficiency for single muon trigger can be quite low.
  ➔use also missing E_T trigger
    - Exploit possible additional jets from ISR.



- **Three different analyses:**
  - **“Full detector”**
  - **“ID only”**
  - **“MS agnostic”**

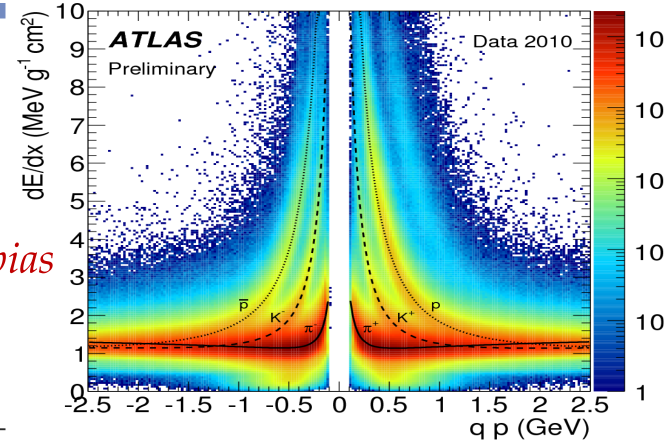
Cover the lack of knowledge of R-hadron interactions with the detector and the lifetimes for which they would not reach the calorimeters

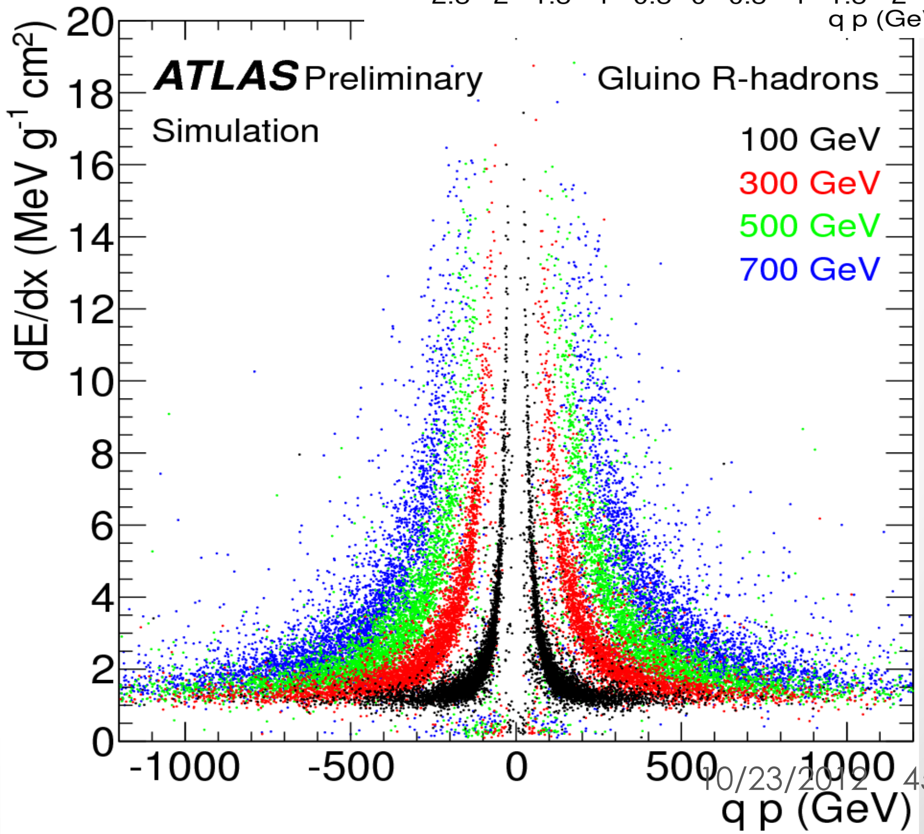
R-hadrons - selection (2)

- All three analyses require good quality, isolated, high-momentum ID track.
- **"MS agnostic":**
  - missing E_T triggers
  - calorimeter-only timing measurement

  → require ID trk pT>140 GeV
- **"ID only":**
  - Offline missing E_T cut
  - Tighter cuts on isolation and number of silicon hits

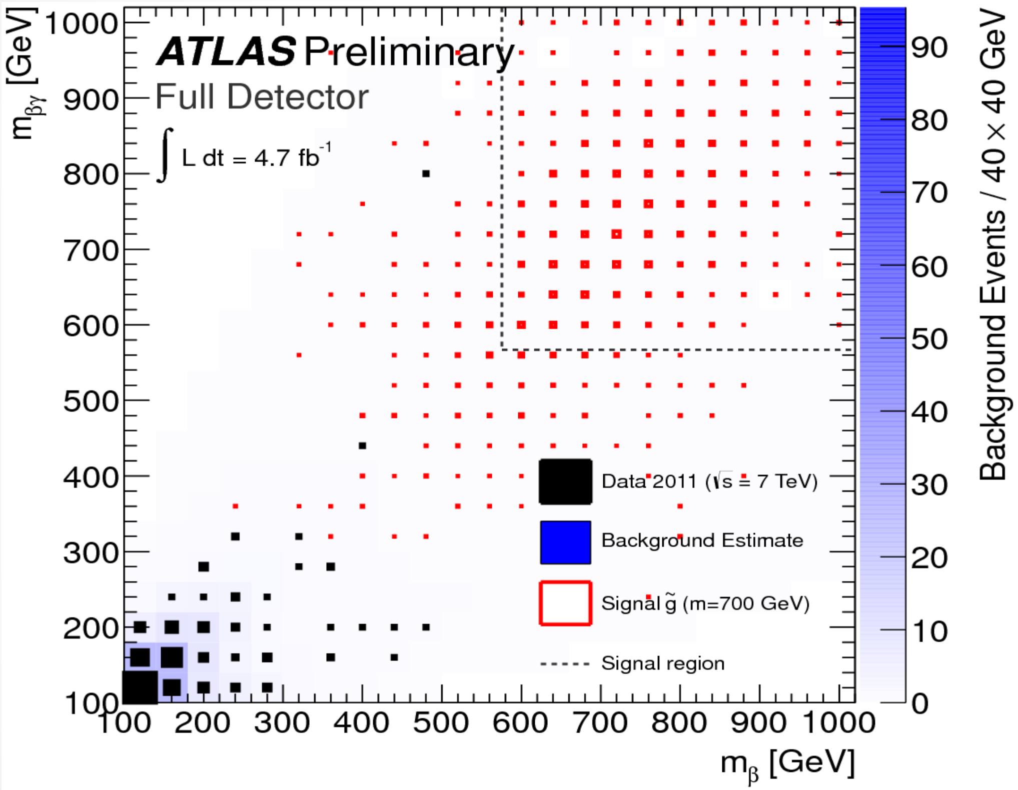
Data minimum bias

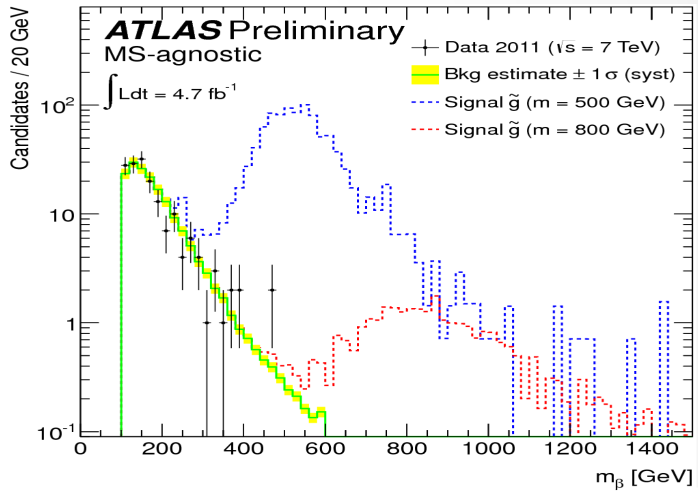


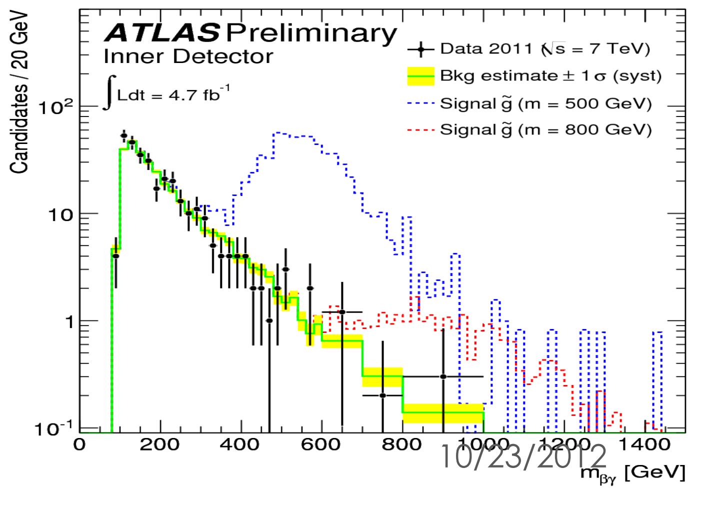


R-hadron searches - results

- MS-agnostic and FD: final selection based on requirements on $\beta\gamma$ and β



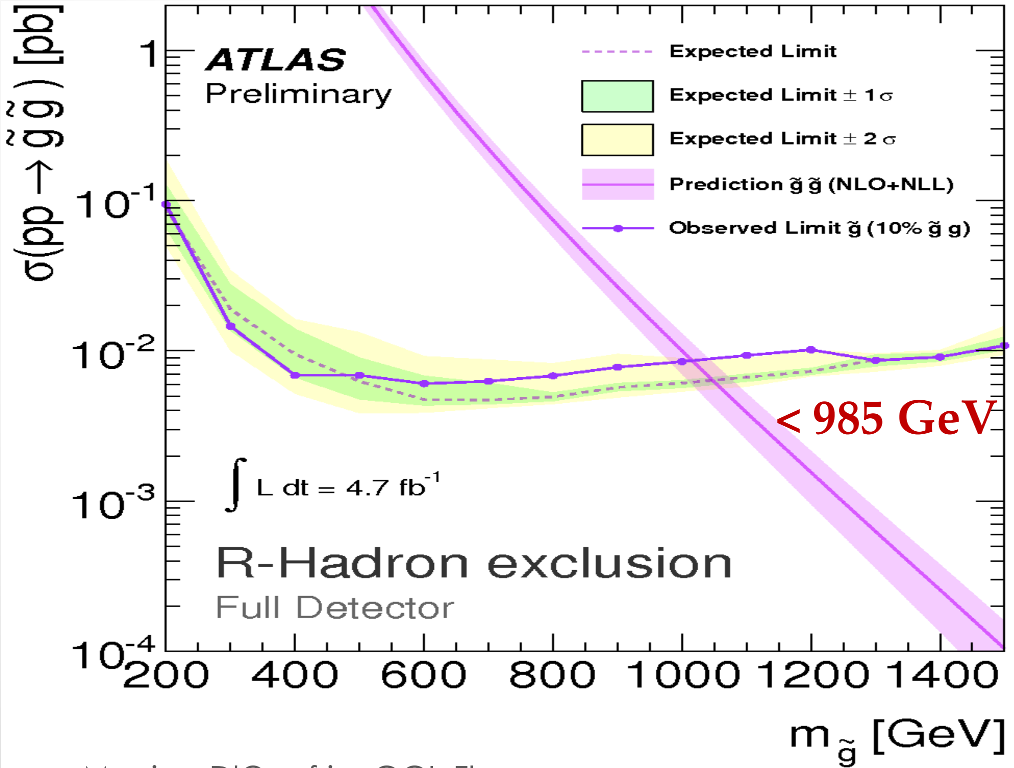


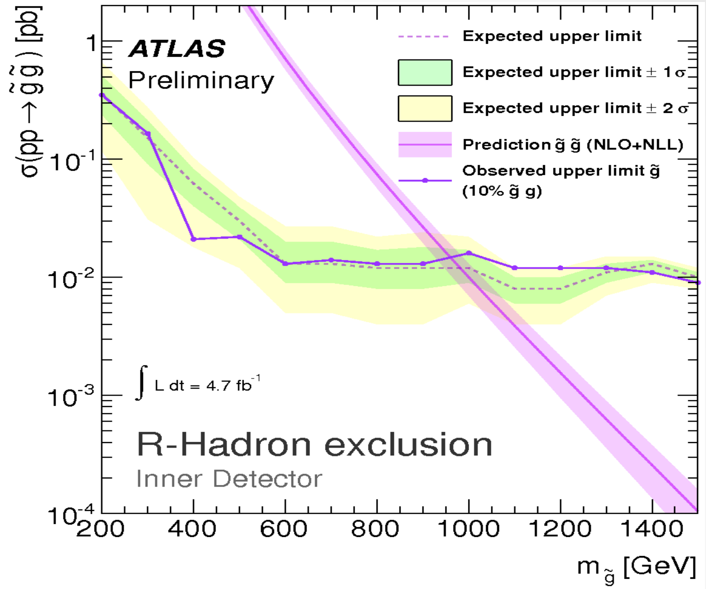


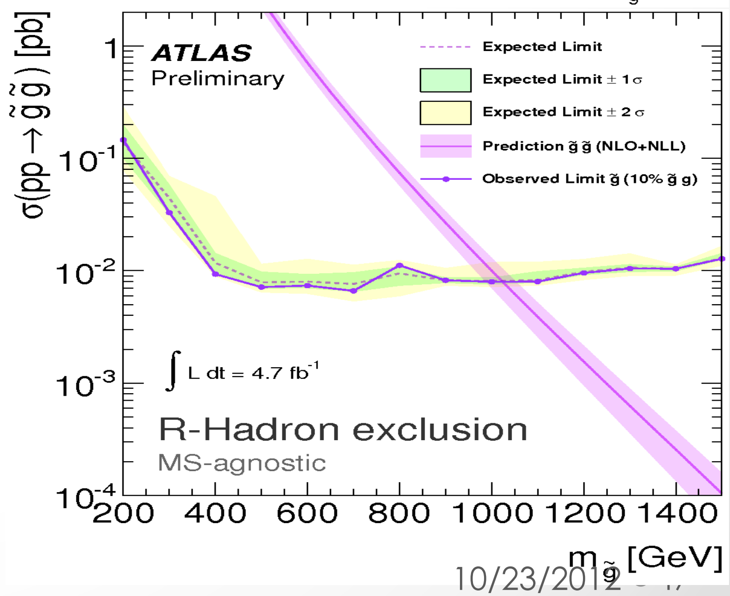
- ID-only: selection based on exceeding dE/dx thresholds

R-hadron searches - results

- No excess above background expectation seen in any of the three analyses
- Limits set by counting N events passing model-dependent mass cuts
- gluino R-hadrons:

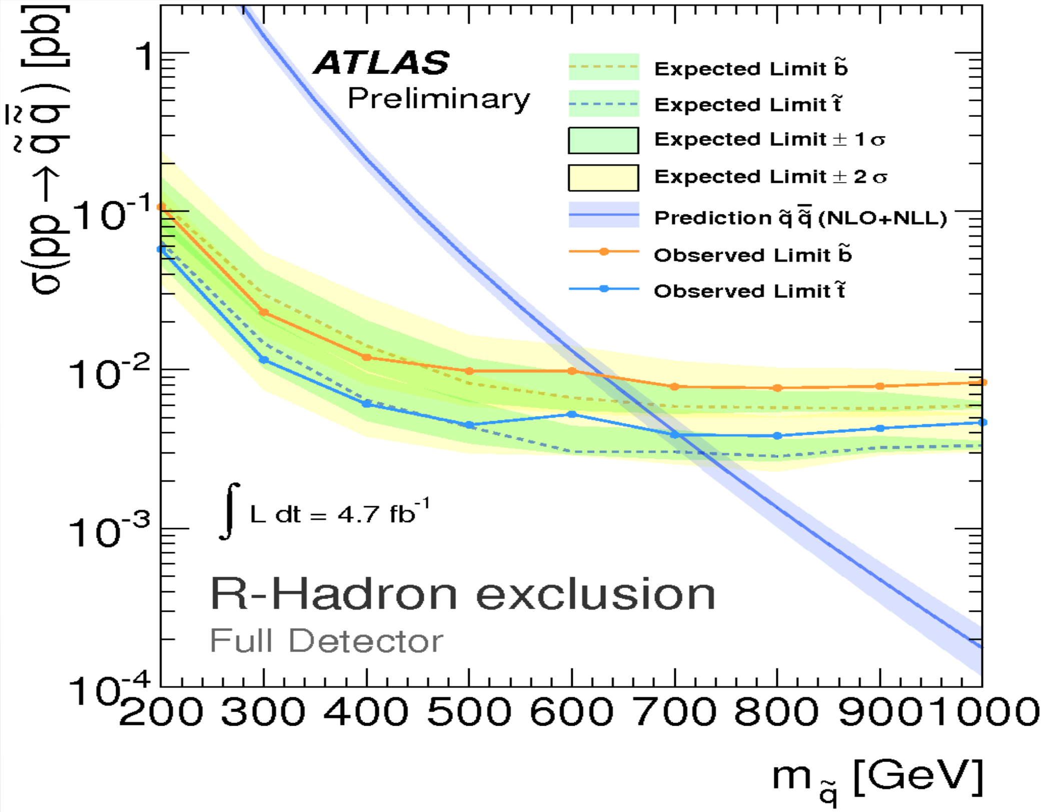


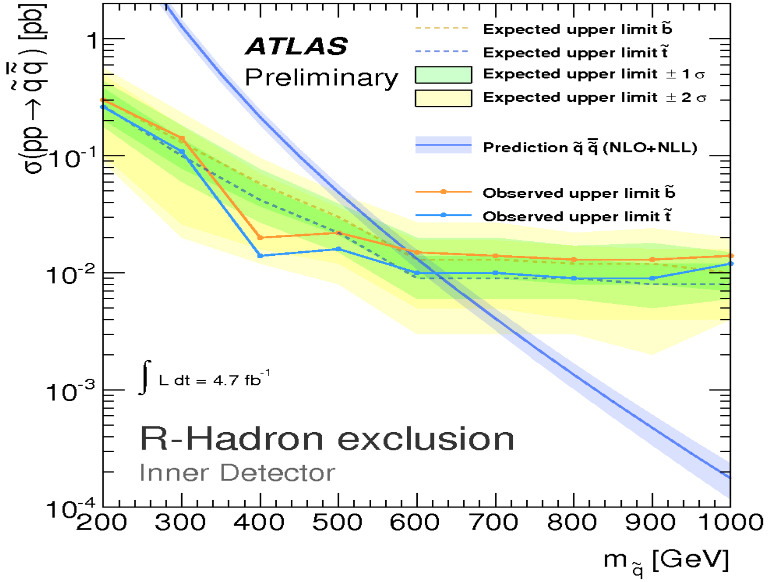


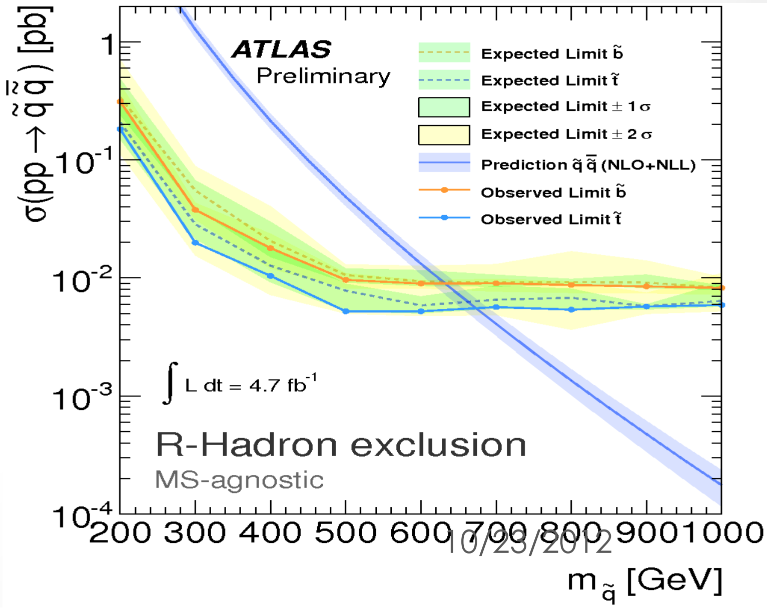


R-hadron searches - results

- squark (stop & sbottom) R-hadrons:



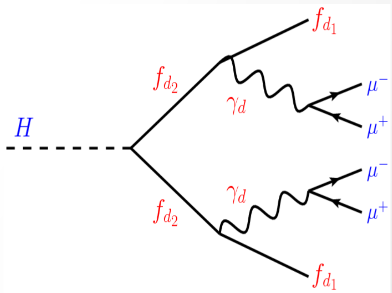




Other searches for LL particles

Several New Physics models (well beyond SUSY) could give rise to new massive particles, with long lifetimes:

- Hidden sector interacts with SM via (heavy) Communicator particle(s)
  - light Higgs-to-LLP search:
    - look for displaced vertices at larger radii, near outer radius of hadronic calorimeter, or in the MS
    - Use specially developed trigger algorithm, and specialized tracking and vertexing, to reconstruct vertices in MS
  - Higgs decay to hidden-sector fermions → decay to a (potentially long-lived) neutral hidden-sector particle γ_d and a stable hidden sector fermion
    - those escape detection
    - Decay of γ_d could give rise to collimated pairs of leptons



- Magnetic monopoles:
  - Experimental signature → large, localized energy deposit in EM calorimeter, associated with region of high ionization in TRT.

Conclusions

- Several SUSY models lead to hard to constrain or 'unconventional' signatures:
  - RPV multilepton or multijet scenarios
  - Long-lived particles
- Wide range of analyses, looking for many different signatures, sometimes using the detector in interesting and "non-standard" ways.
- No sign of New Physics so far….
- BUT:
  - All these analyses are being updated (and improved) with 2012 data.
  - More to come

Doing our best to cover as much parameter space as possible, as well as and get maximum possible value out of our fantastic ATLAS detector