Search for SUSY R-Hadrons

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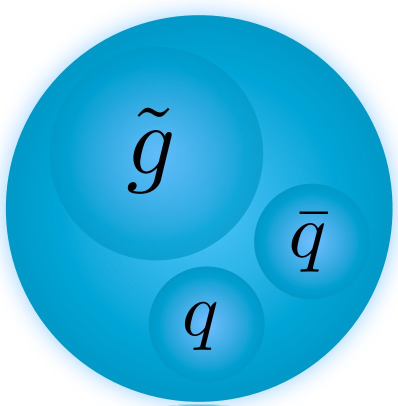
on behalf of the ATLAS Collaboration

Overview

- What are R-Hadrons
- Detection methods
- Latest results

What are R-Hadrons

- Coloured Massive Particles, i.e. gluinos, squarks
- Assumed Long-lived (in our searches)
- Predicted by numerous BSM models including many SUSY scenarios
- Slow moving at LHC energies $\beta < 1$
- Hadronises with light SM quarks into bound states called *R*-Hadrons
  - Electrically charged in specific bound states
  - Nuclear scattering of the light quark system with detector causing electrical charge change
- No interaction between detector and primary parton ($\sigma \propto 1/m^2$) assumed



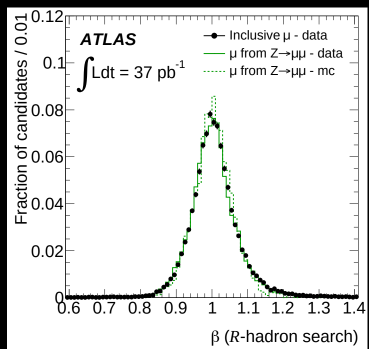
SUSY SMP states
arXiv:hep-ph/0611040

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 $A_b \gg A_t$.

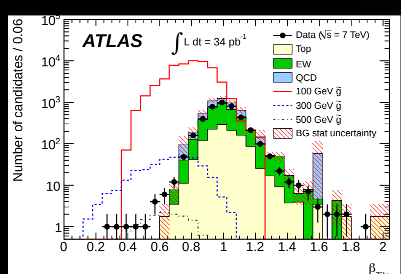
Table 1
Brief overview of possible SUSY SMP states considered in the literature. Classified by SMP, LSP, scenario, and typical conditions for this case to materialise in the given scenario.

R-Hadron detection in ATLAS

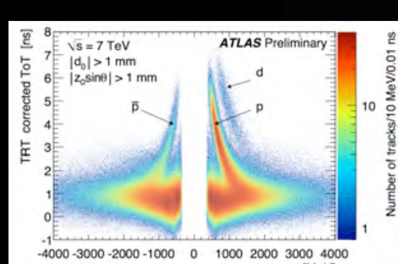
- Velocity as discriminator
- Time of flight
- Specific Energy Loss
- No physics background, only instrumental effects
- Estimate mass by velocity and momentum
- Can become neutral after hadronic interactions
- Unique charge flipping as signature



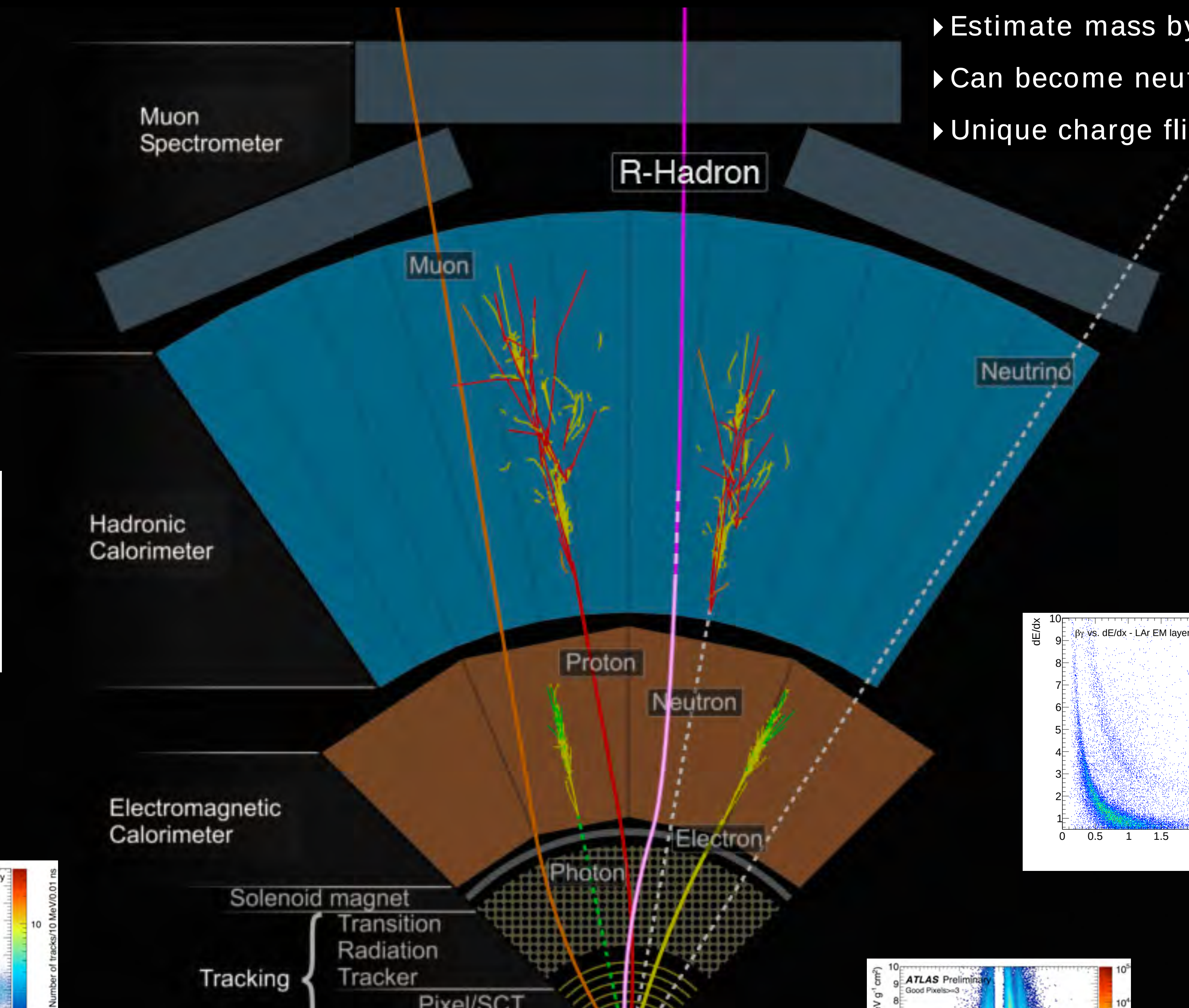
Muon spec. ToF
arXiv:1106.4495

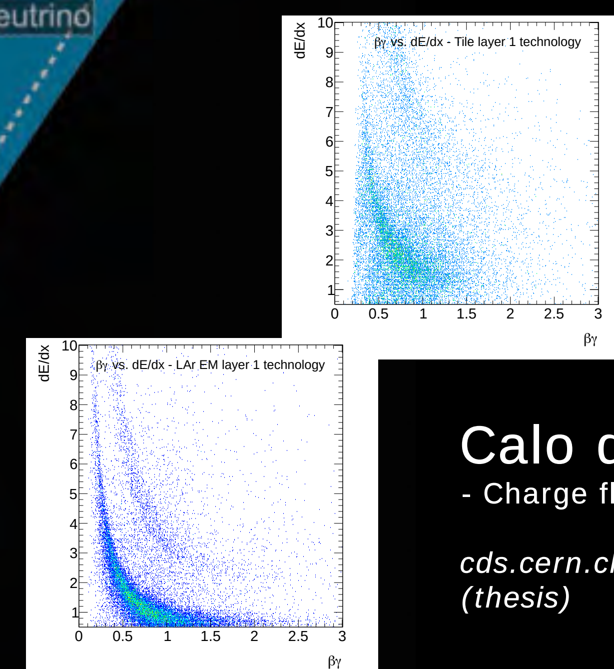


Calo ToF
arXiv:1103.1984



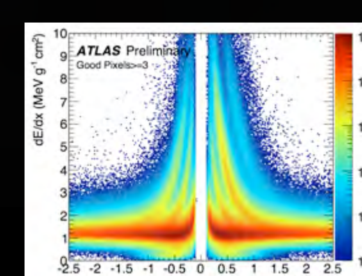
TRT “dE/dx”
arXiv:1103.1984





Calo dE/dx
- Charge flipping

cds.cern.ch:1370233 (thesis)



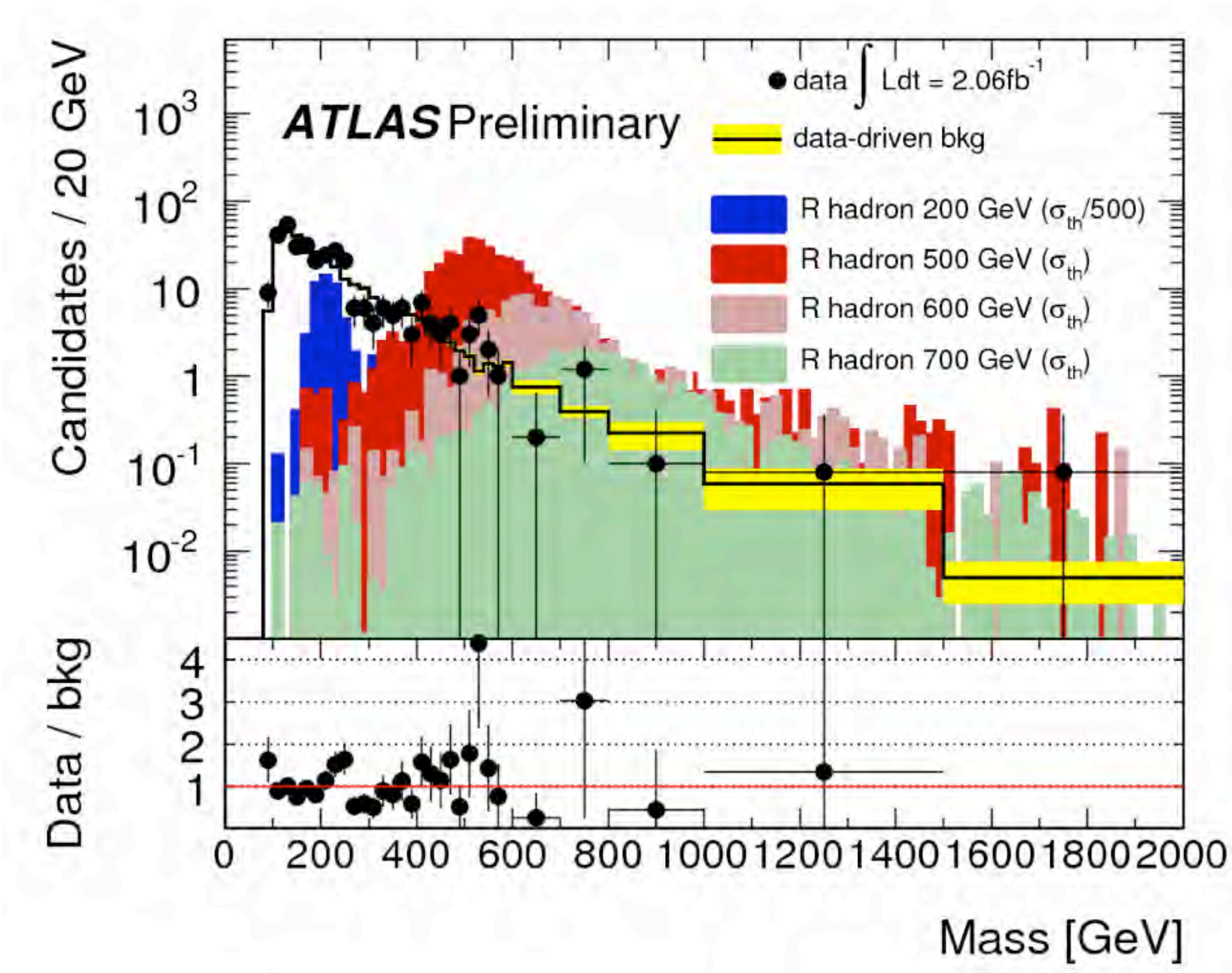
Pixel dE/dx
ATLAS-CONF-2011-016

ATLAS-CONF-2012-022

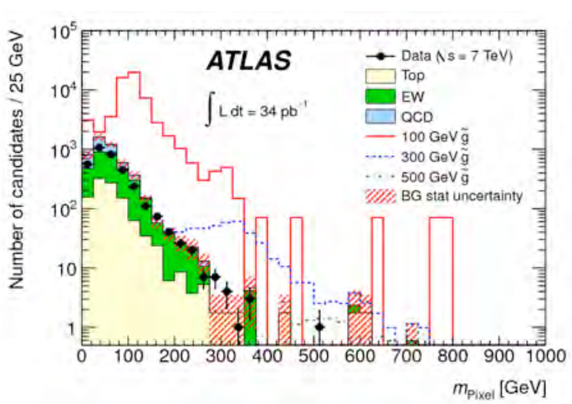
Inner detector only search

- Most recent result (2.06 fb^{-1})
- Pixel dE/dx Estimator
  - Calibrated on slow SM particles

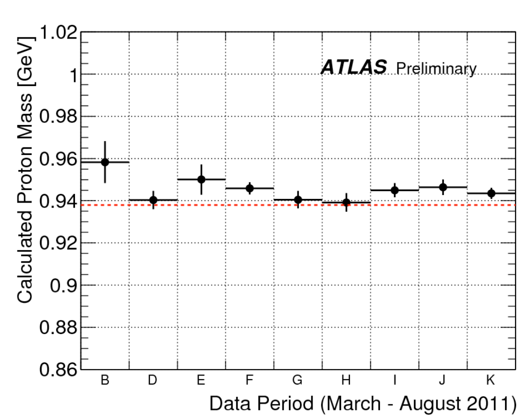
- Missing Energy Trigger MET > 70 GeV
- Offline MET > 85 GeV
- p > 100 GeV
- Pixel dE/dx > 1.8 MeV g^{-1} cm^2
- Distance to nearest track > 0.25
- Distance to nearest jet > 0.3



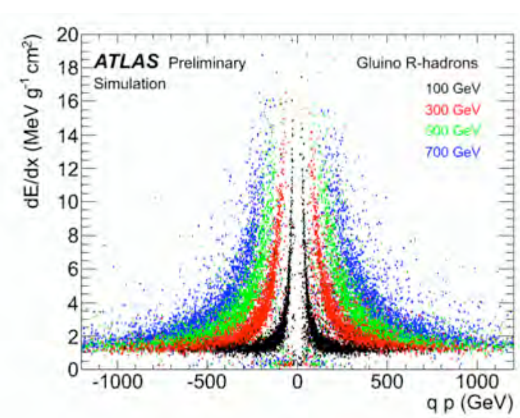
2010 Pixel mass (ID+Calo)



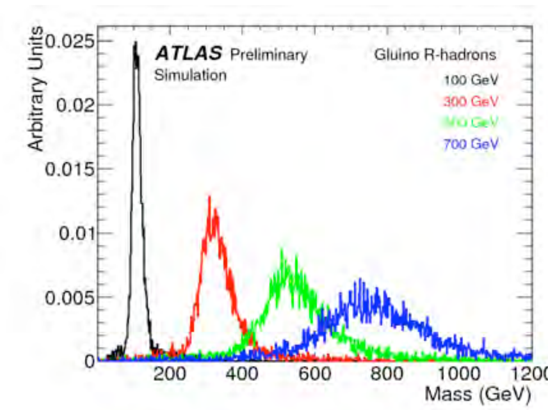
Proton mass run stability



Signal dE/dx response

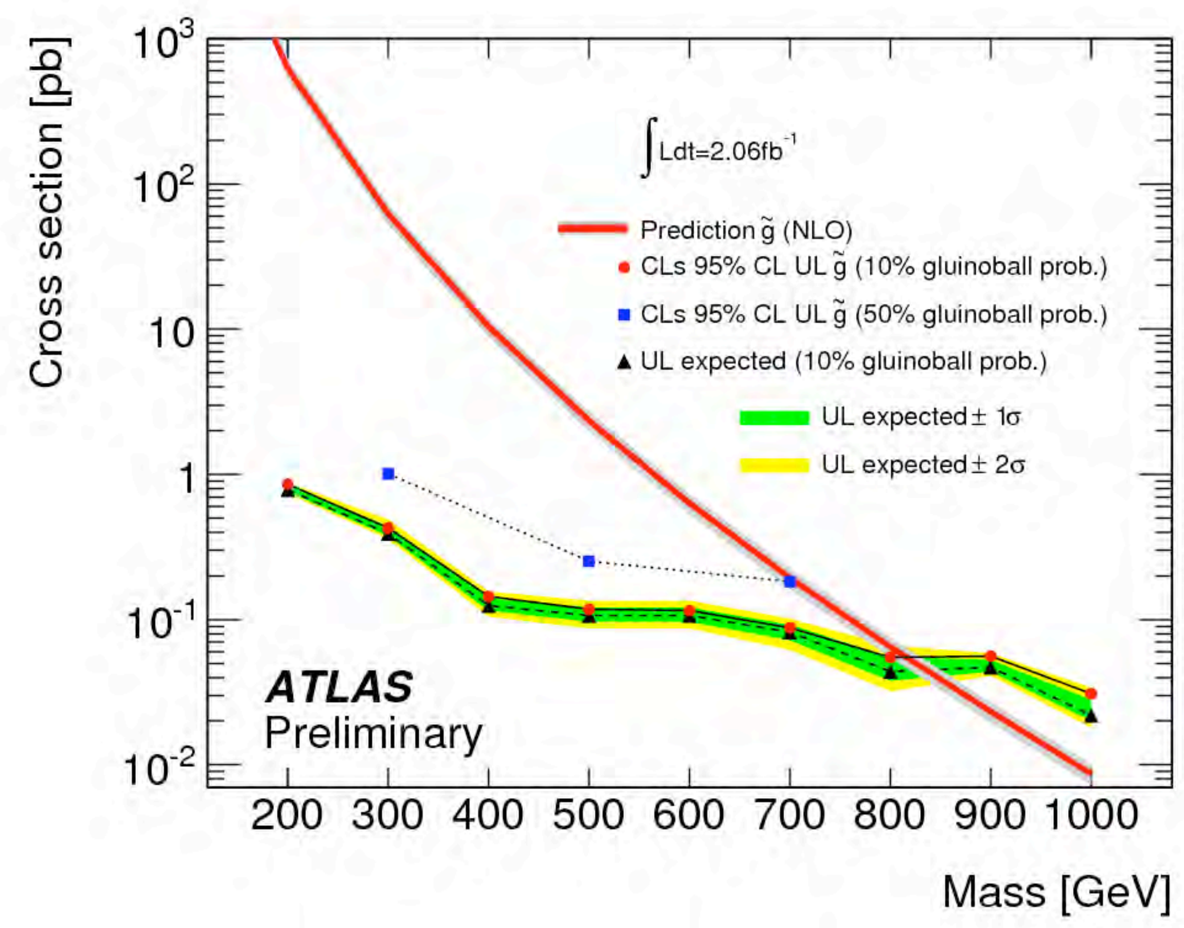


Signal mass estimates



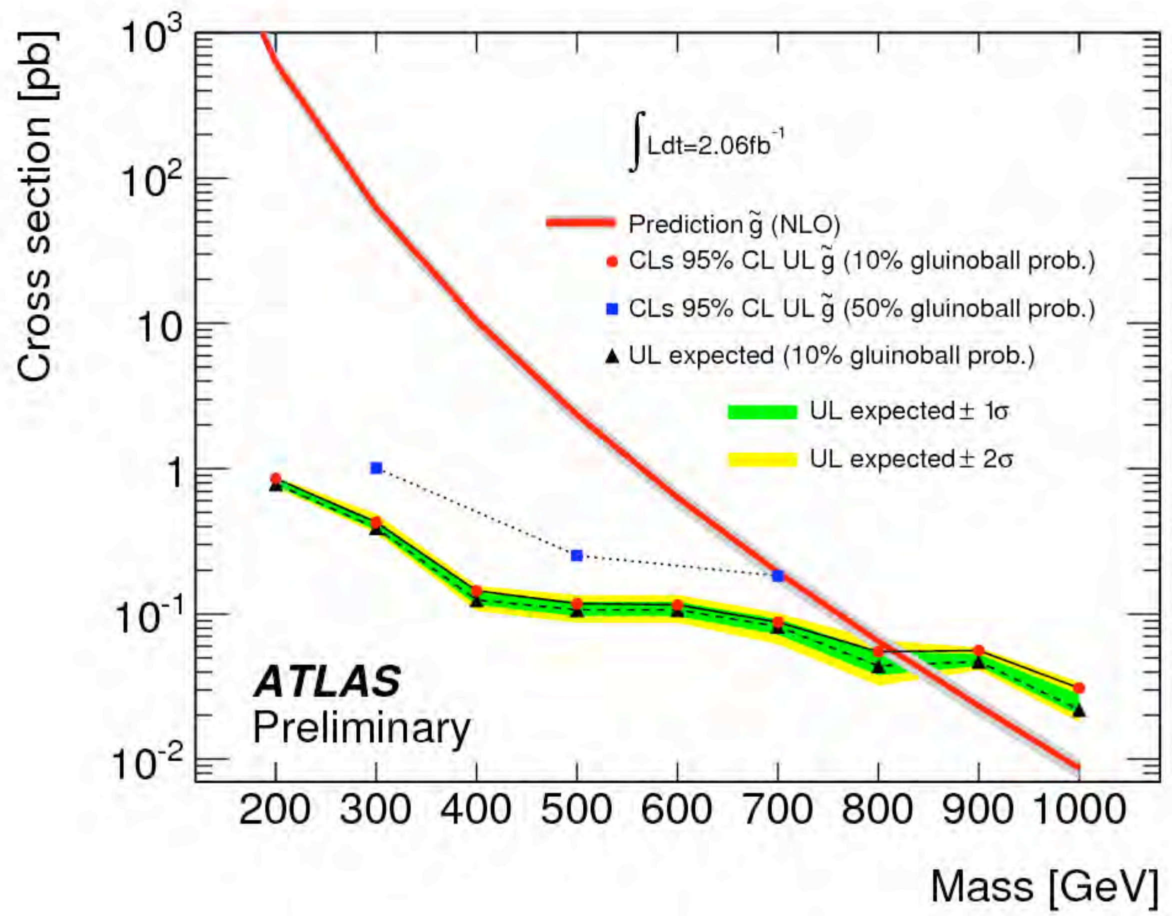
Results

- Increased statistics
- No significant deviation from the Standard Model
- Upper limit: <0.1 pb (CLs method 95% CL)
- Gluino mass exclusion up to 810 GeV for Split-SUSY models (ID+Calo 2010 Limit: ~580 GeV)



Conclusion

- Nearly all sub detectors in ATLAS have R-Hadron discrimination capabilities
- New limit from ATLAS on inner detector only searches for R-Hadrons.
- Many other searches ongoing
- We try to avoid heavy model dependence (beyond nuclear scattering) but input from theorists is welcomed!



Backup slides

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Pixel counting tables

Signal

Cut level	Gluino 400 GeV Cut Eff.	Gluino 400 GeV Total Eff.	Gluino 700 GeV Cut Eff.	Gluino 700 GeV Total Eff.	Gluino 1000 GeV Cut Eff.	Gluino 1000 GeV Total Eff.
Trigger	0.205	0.205	0.219	0.219	0.177	0.177
Offline E_T^{miss}	0.976	0.200	0.987	0.216	0.984	0.175
Primary vtx	0.998	0.200	1.000	0.216	1.000	0.175
High-p_T	0.594	0.120	0.582	0.129	0.592	0.108
Isolation	0.840	0.100	0.838	0.105	0.879	0.091
High-p	0.993	0.099	0.988	0.104	0.999	0.091
ionization	0.663	0.067	0.804	0.085	0.923	0.084

Data

Cut level	# Events	Cut Eff.	Total Eff.
Trigger	2,413,863		
Offline E_T^{miss}	1,421,497	0.589	0.589
Primary vtx	1,368,821	0.963	0.567
High-p_T	212,464	0.155	0.0880
Isolation	32,188	0.151	0.0133
High-p	21,040	0.654	8.7E-03
ionization	333	0.016	1.4E-04

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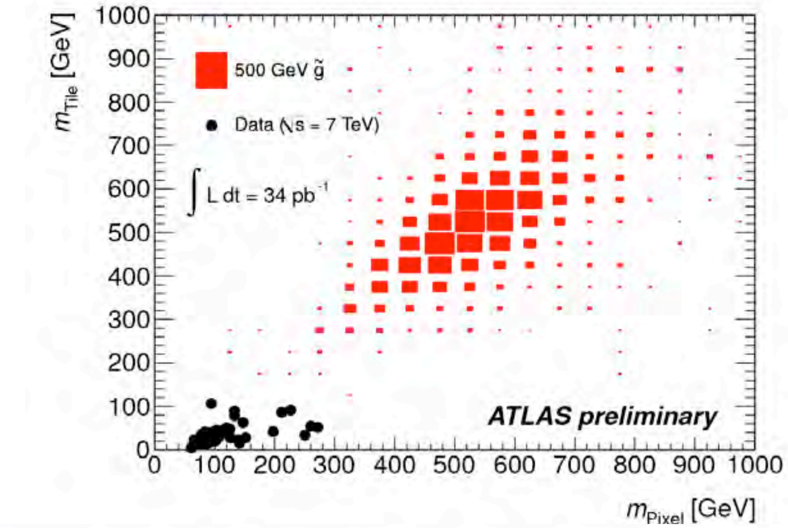
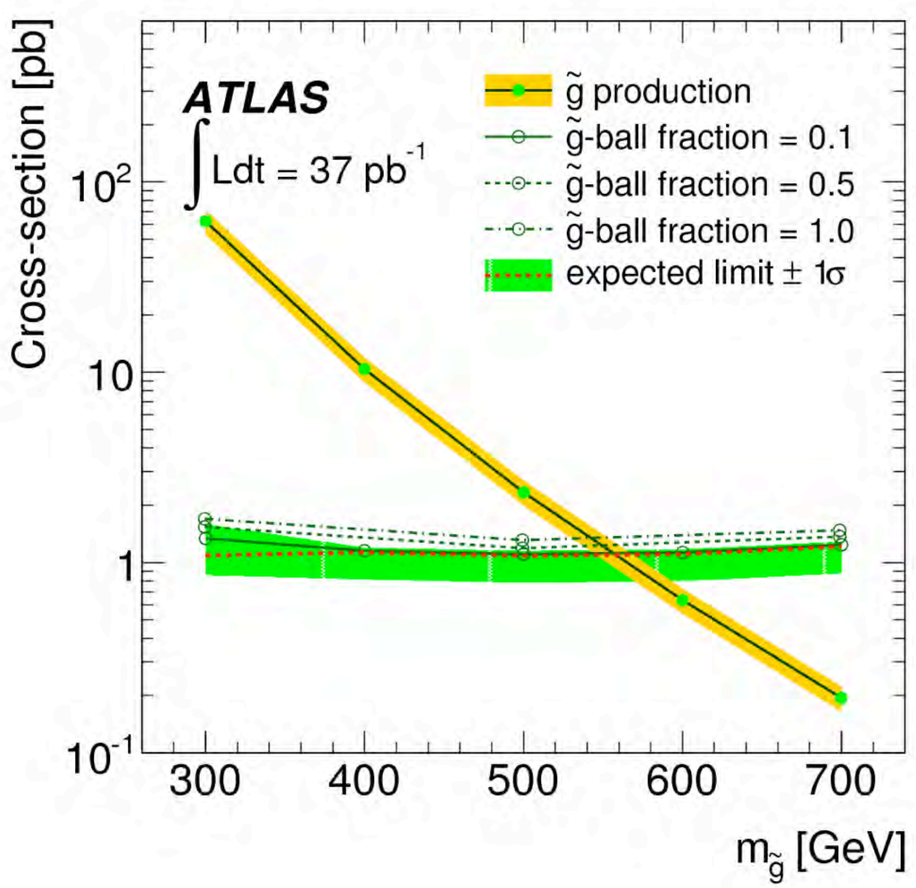
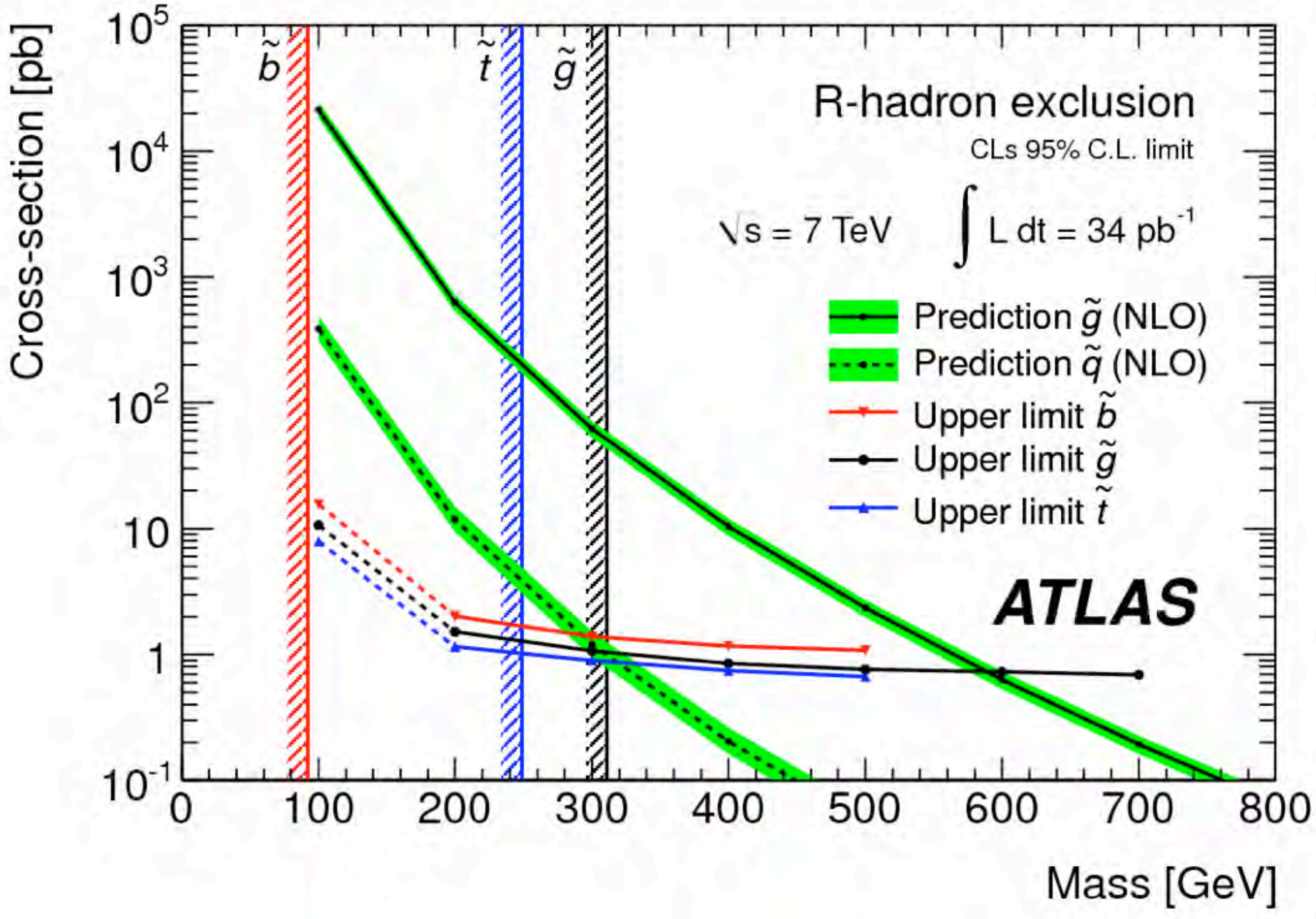
2010

Inner detector &
Calorimeter 2010



Muon Spectrometer, 2010

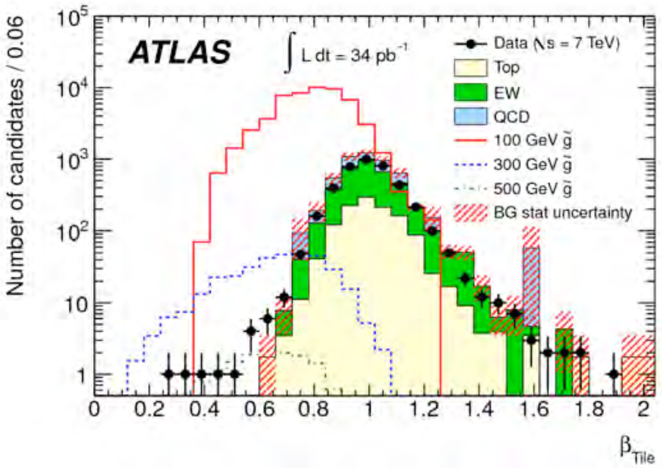




Detection methods

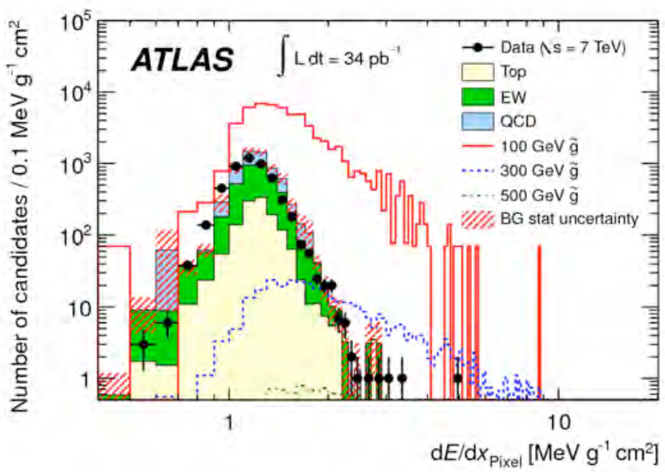
- Velocity as discriminator
  - Time of flight
  - Specific Energy Loss
- No physics background, only instrumental effects
- Estimate mass by velocity and momentum
- Can become neutral after hadronic interactions
- Unique charge flipping as signature

Time of Flight

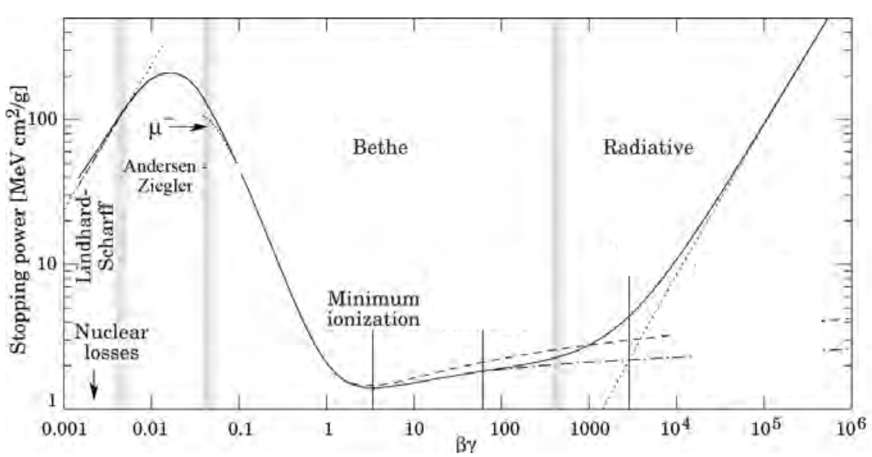


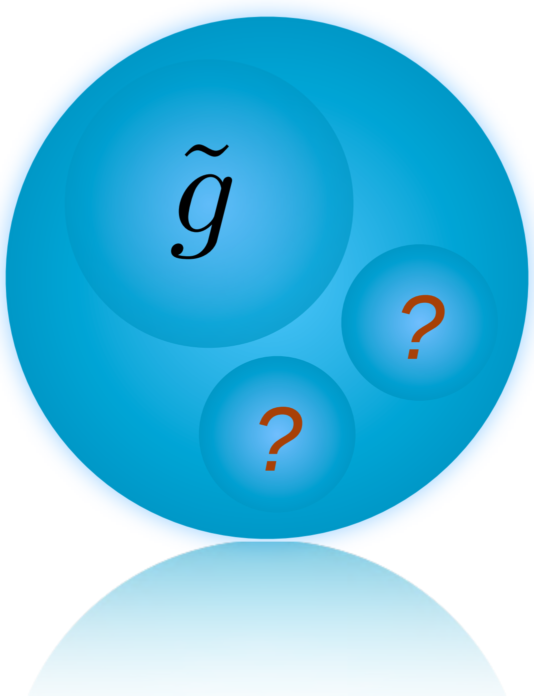
$$m = \frac{p}{\beta}\sqrt{1-\beta^2}$$

Specific Energy Loss



$$m = \frac{p}{\beta\gamma}$$





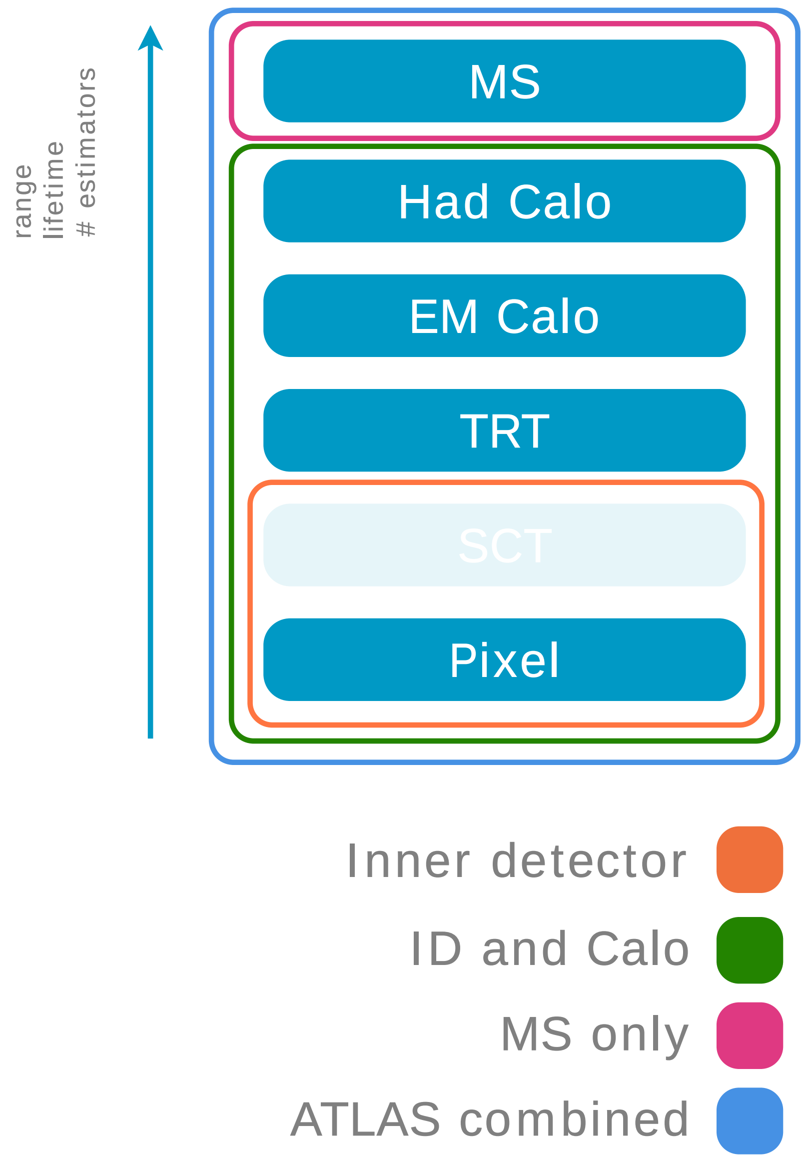
$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A}\frac{1}{\beta^2} \times \left[\frac{1}{2}\ln\frac{2m_e c^2 \beta^2\gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] \sim \frac{1}{\beta\gamma^2}$$

Search strategies in ATLAS

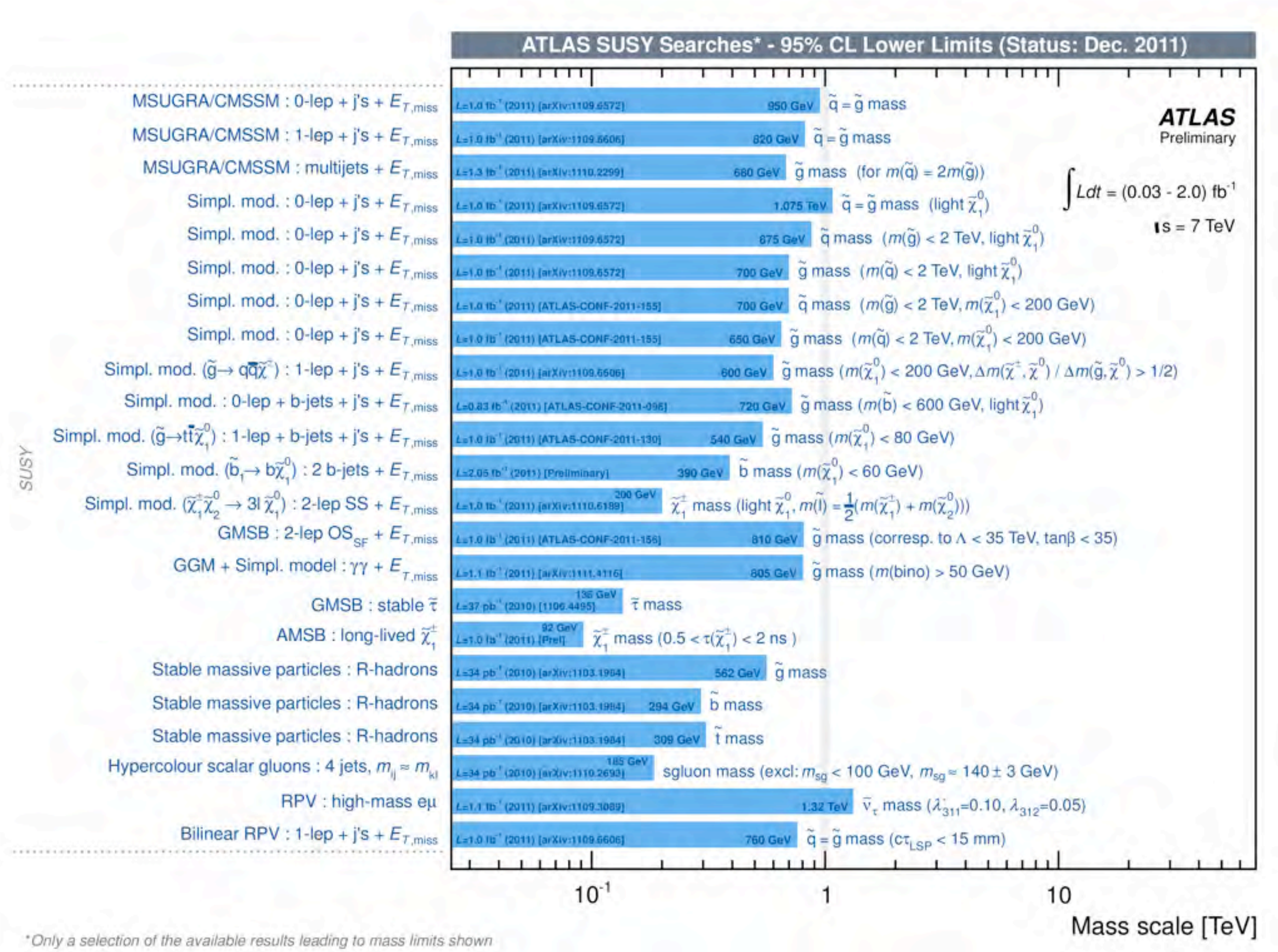
- Multiple searches with variation of sub detectors to maximise model coverage

- **General selection**
  - Trigger (MET or Muons)
  - Momentum cut
  - Isolation (from polluting tracks, jets)
  - Data driven background estimation

- **Search specific selection**
  - *Short lifetime, High hadronic interaction probability*
    ID only: Pixel dE/dx
  - *Intermediate lifetimes, moderate hadronic interaction*
    ID+Calo: Pixel dE/dx and Calo ToF
  - *Long lifetime, low mass*
    MS only: Candidates that where neutral in ID but became charged by interactions.
  - *Inclusive, maximum detector acceptance*
    ID+Calo+MS: Require a minimum of compatible estimates, "semi-multivariate" methodology

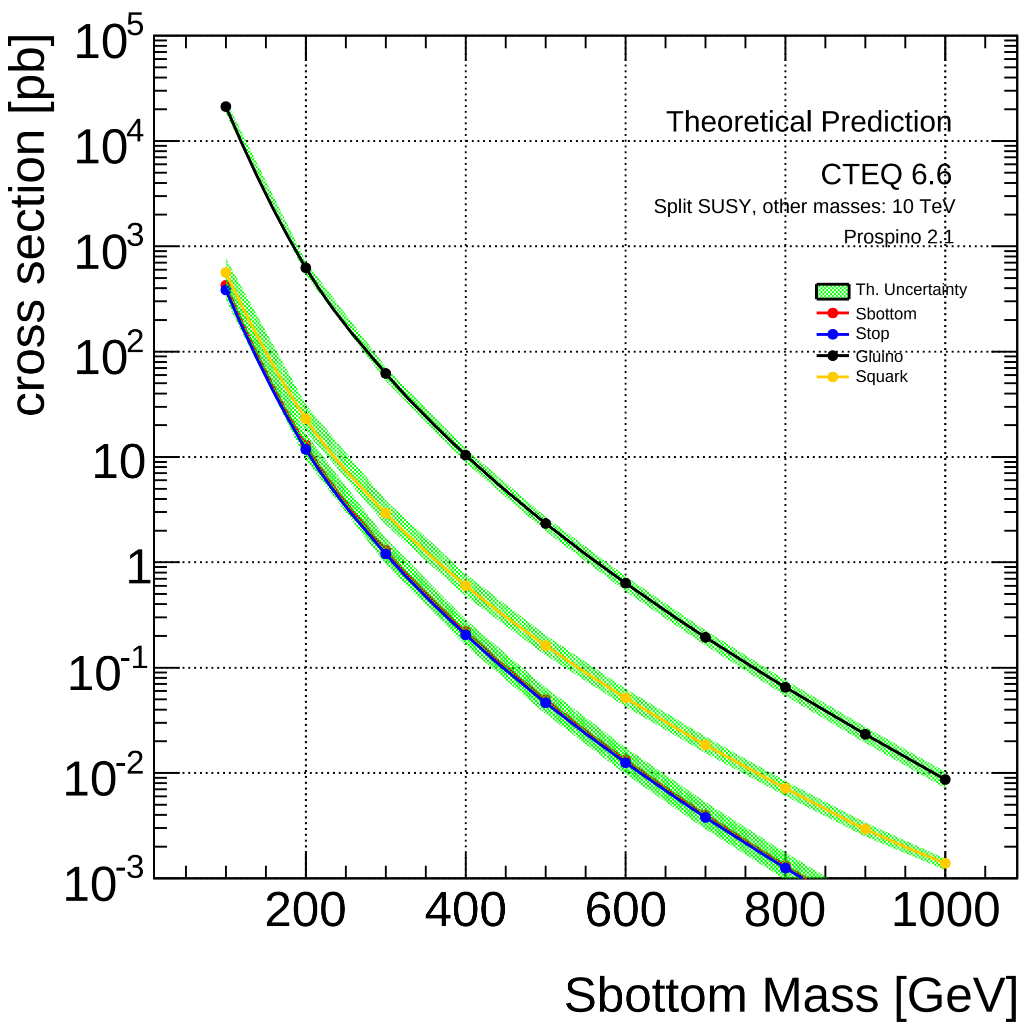


SUSY limits (dec 2011)



Theoretical predictions

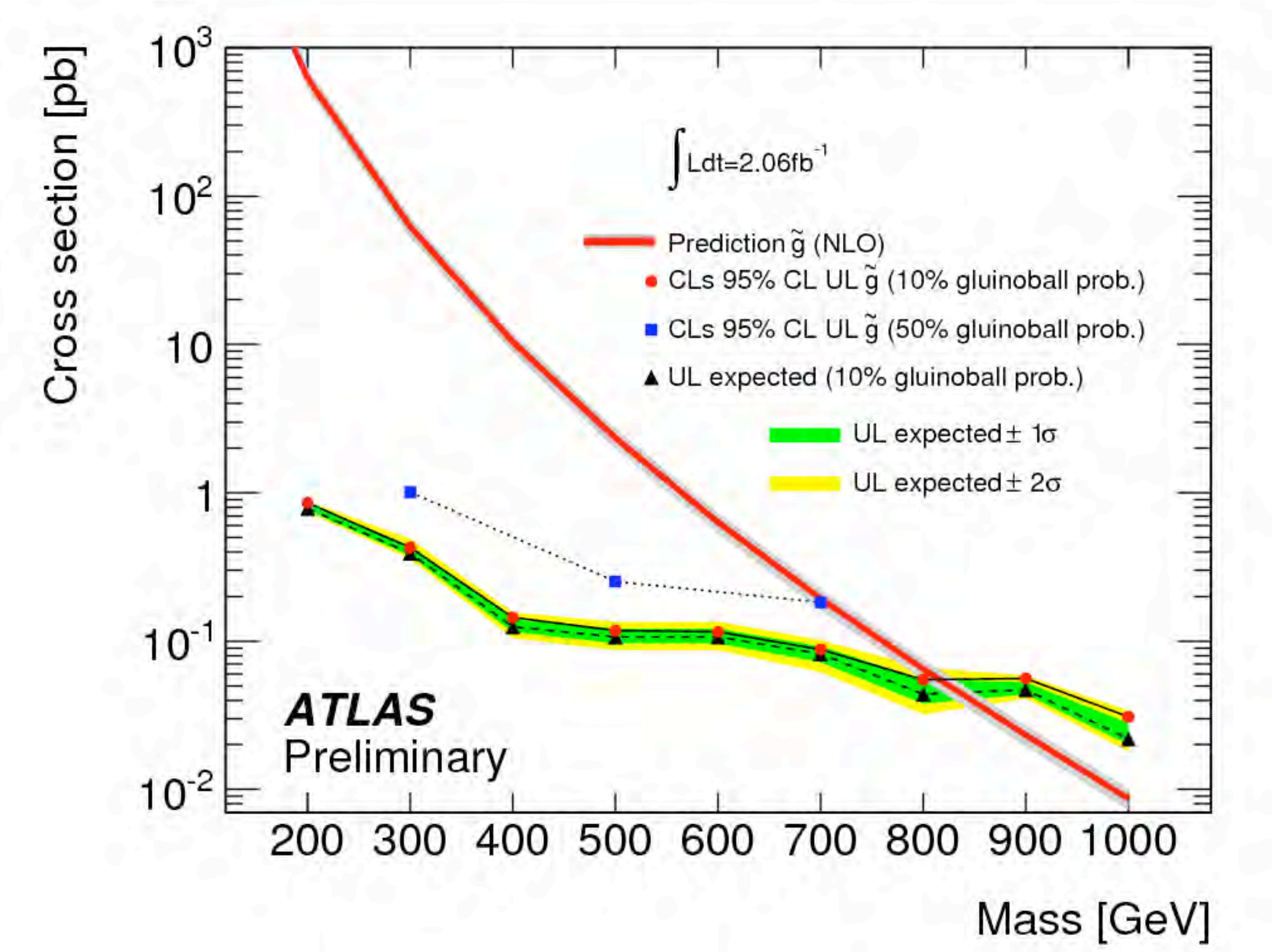
- "Split-SUSY"-like predictions
- Cross sections calculated with Prospino 2.1
- Decoupled mass scales, emulating infinite life-time by decay suppression



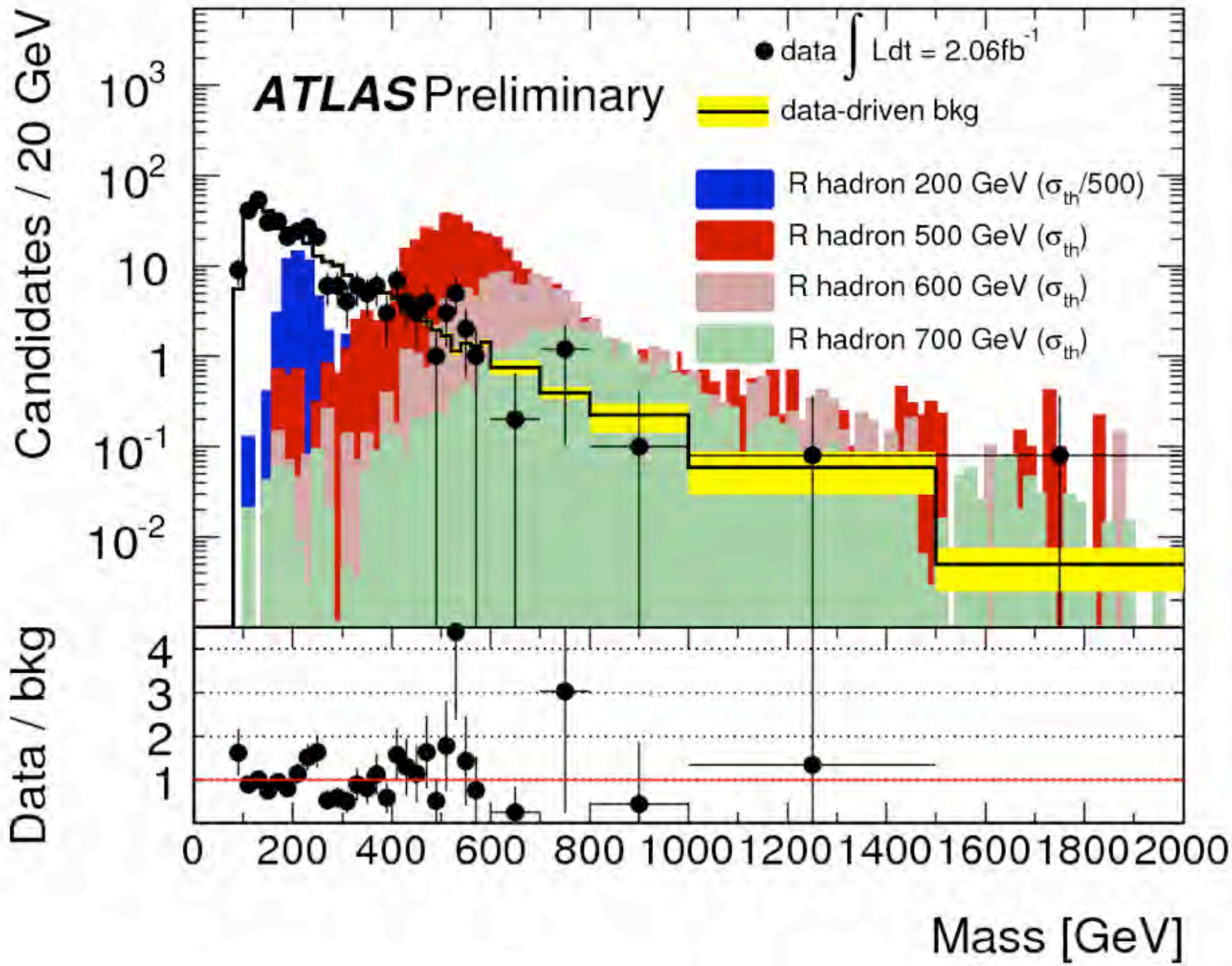
Mass (GeV)	σ (pb)
100	21200
200	625
300	62.1
400	10.4
500	2.34
600	0.634
700	0.194
800	0.0651
900	0.0233
1000	0.00867

Assumptions
Prospino 2.1 NLO
SUSY Splitting scale 10 TeV
$\sqrt{s}$ = 7 TeV
CTEQ 6.6 & MSTW 2008
Th. uncertainty represents
K-factor variation

Limit


Cross section [pb]
10^3
10^2
10
1
10^{-1}
10^{-2}
$\int Ldt=2.06fb^{-1}$
Prediction $\tilde{g}$ (NLO)
CLs 95% CL UL $\tilde{g}$ (10% gluinoball prob.)
CLs 95% CL UL $\tilde{g}$ (50% gluinoball prob.)
UL expected (10% gluinoball prob.)
UL expected ± 1σ
UL expected ± 2σ
ATLAS
Preliminary
200 300 400 500 600 700 800 900 1000
Mass [GeV]

Mass distribution



Pixel dE/dx mass estimator - proton mass stability