Overview of

ATLAS Supersymmetry searches

with 2010 LHC data

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Outline of presentation

Motivations for searches:
- Why Jets + Missing Transverse Energy (MET)?
- What else to search for?

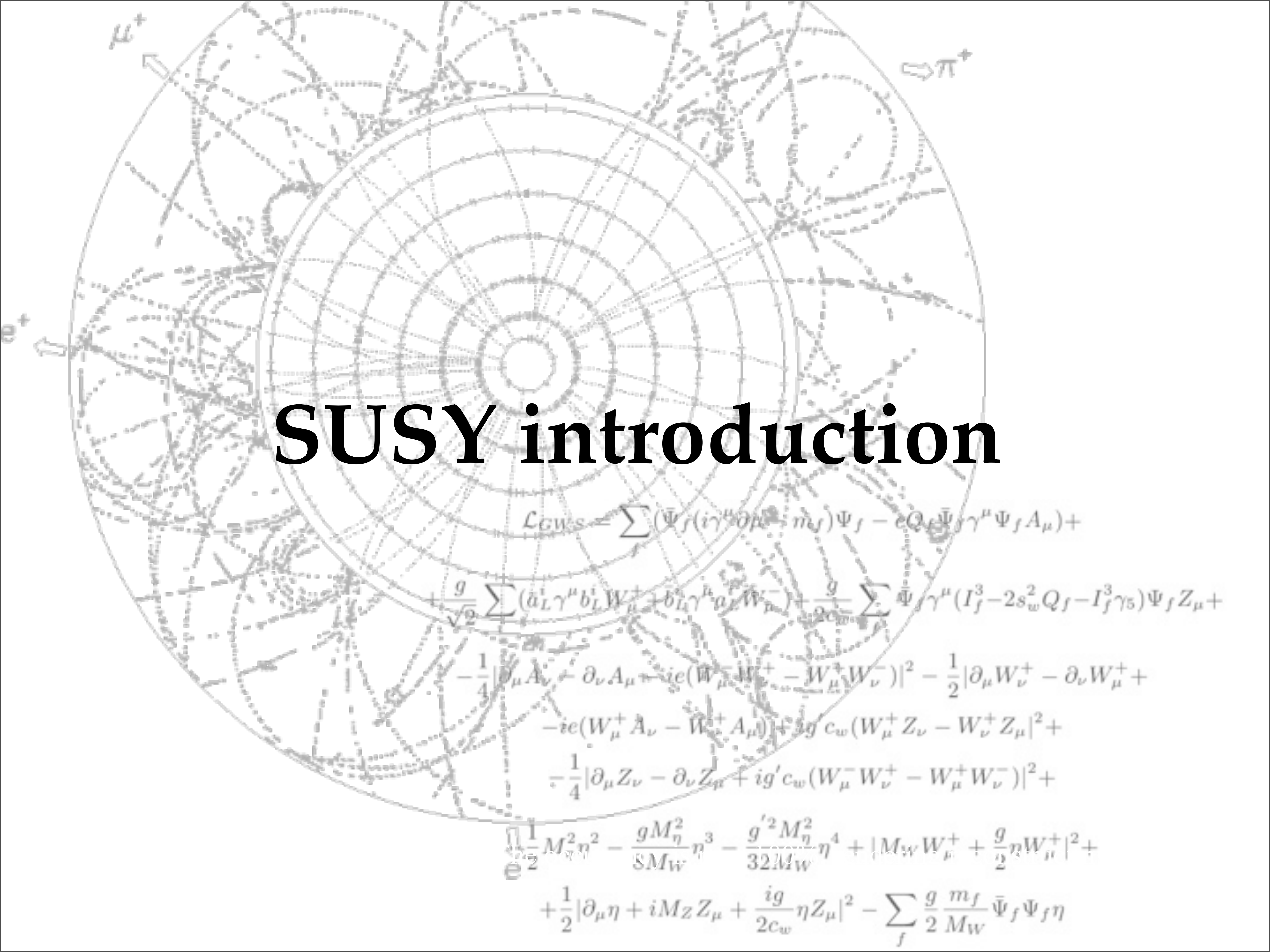
The ATLAS detector

SUSY searches:
- Jets + MET (0+1 lepton)
  (for 2011 update, see talk by **Michael Rammensee**)
- Di-leptons + MET
- Multi-lepton + MET
- eμ resonance search
- Meta-stable SUSY candidates
  (also, see talk by **Simon Owen**)

Conclusions and outlook

<u>Notes on limited warrenty:</u>
I will assume general knowledge of LHC running and ATLAS in general.
Covering broadly (13+ analysis),
I will occasionally be short/undetailed.

SUSY introduction



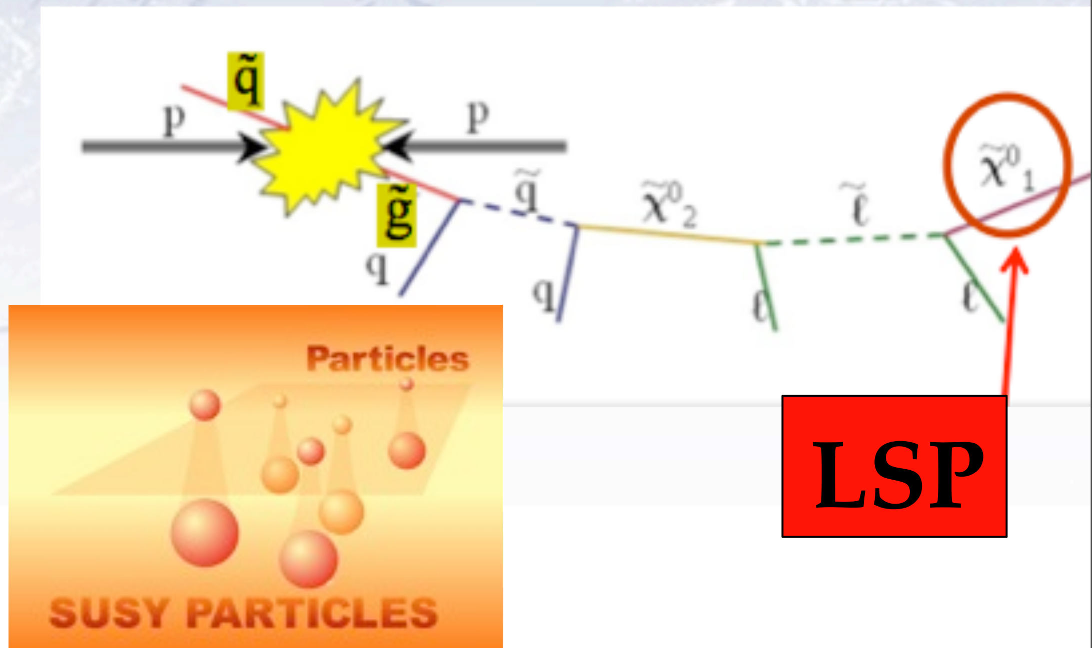
Super Symmetry (SUSY) shortly

SUSY postulates "superpartners" to each SM particle and R-parity:

$$R = (-1)^{2j+3B+L}$$

If R-parity is conserved, SUSY particles are pair produced.

Unknown mass hierarchy determines decay chains and (possibly long) lifetimes...



This forces SUSY searches to be broad!

So where to start?

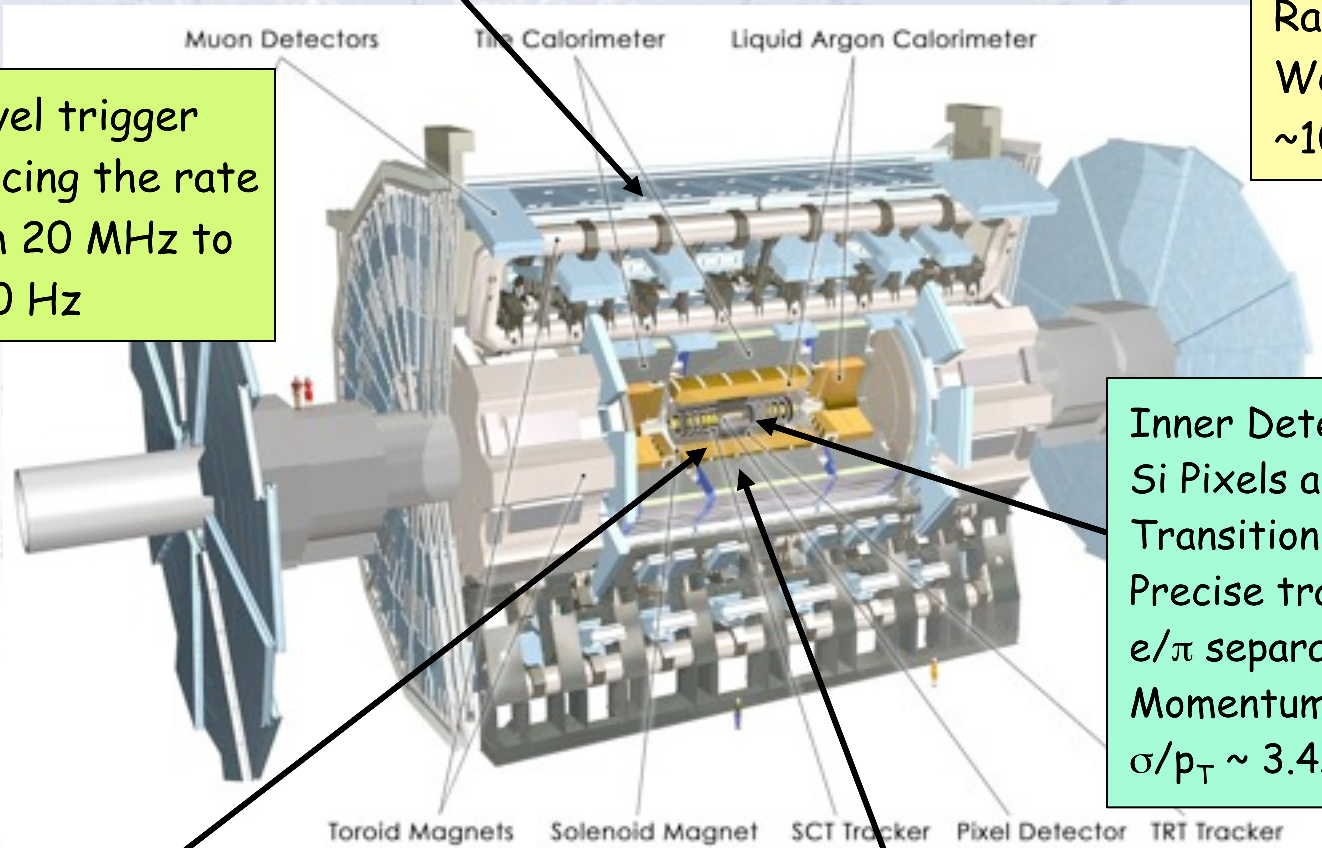
- Gluinos and squarks couple strongly ⇒ dominant SUSY production at LHC.
- Lightest SUSY Particle (LSP) creates Missing E_T (MET).
- Assumptions simplify ⇒ From 100+ SUSY parameters to "a few".

The ATLAS detector

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based chambers
Muon trigger and measurement with momentum resolution < 10% up to E_μ ~ TeV

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels

3-level trigger reducing the rate from 20 MHz to ~200 Hz



Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels and strips (SCT) +
Transition Radiation straws
Precise tracking and vertexing,
e/π separation (TRT).
Momentum resolution:
$\sigma/p_T \sim 3.4\times10^{-4}\, p_T(\mathrm{GeV}) \oplus 0.015$

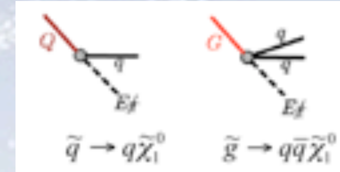
EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: ~ 1% at 100 GeV, 0.5% at 1 TeV

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Tilecal Fe/scintillator (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

ATLAS SUSY searches

arXiv:1102.5290

Jets + MET



To maximize ($m_{\tilde{g}}$,$m_{\tilde{q}}$) coverage, ATLAS defines 4 signal regions:

A: Light squark pairs.

B: Heavy squark pairs.

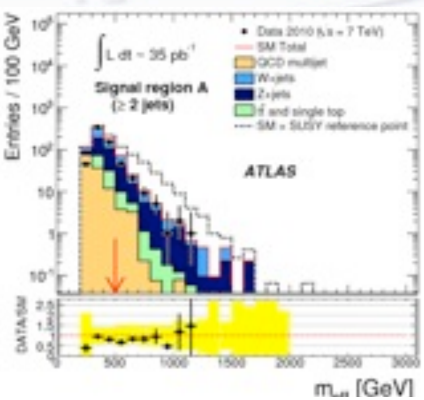
C: Gluino pairs.

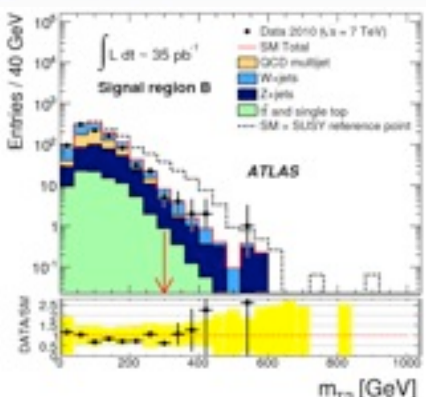
D: Squark+gluino production.

		A	B	C	D
Pre-selection	Number of required jets	≥ 2	≥ 2	≥ 3	≥ 3
	Leading jet p_{T} [GeV]	> 120	> 120	> 120	> 120
	Other jet(s) p_{T} [GeV]	> 40	> 40	> 40	> 40
	$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 100	> 100	> 100	> 100
Final selection	$\Delta\phi(\mathrm{jet}, \vec{P}_{\mathrm{T}}^{\mathrm{miss}})_{\mathrm{min}}$	> 0.4	> 0.4	> 0.4	> 0.4
	$E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$	> 0.3	–	> 0.25	> 0.25
	m_{eff} [GeV]	> 500	–	> 500	> 1000
	m_{T2} [GeV]	–	> 300	–	–

$$m_{\mathrm{eff}} \equiv \sum_{i=1}^{n} |\mathbf{p}_{\mathrm{T}}^{(i)}| + E_{\mathrm{T}}^{\mathrm{miss}}$$

$$m_{\mathrm{T2}}(\mathbf{p}_{\mathrm{T}}^{(1)}, \mathbf{p}_{\mathrm{T}}^{(2)}, \not{\mathbf{p}}_{\mathrm{T}}) = \min_{\mathbf{q}_{\mathrm{T}}^{(1)} + \mathbf{q}_{\mathrm{T}}^{(2)} = \mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}} \left\{ \max\left(m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}^{(1)}, \mathbf{q}_{\mathrm{T}}^{(1)}), m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}^{(2)}, \mathbf{q}_{\mathrm{T}}^{(2)}) \right) \right\}$$



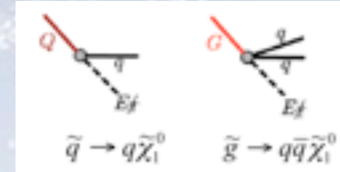


Events w. leptons ($p_T > 10$ GeV) are discarded.

	Signal region A	Signal region B	Signal region C	Signal region D
QCD	$7\ ^{+8}_{-7}$[u+j]	$0.6\ ^{+0.7}_{-0.6}$[u+j]	$9\ ^{+10}_{-9}$[u+j]	$0.2\ ^{+0.4}_{-0.2}$[u+j]
W+jets	50 ± 11[u] $^{+14}_{-10}$[j] $\pm\ 5[\mathcal{L}]$	4.4 ± 3.2[u] $^{+1.5}_{-0.8}$[j] $\pm\ 0.5[\mathcal{L}]$	35 ± 9[u] $^{+10}_{-8}$[j] $\pm\ 4[\mathcal{L}]$	1.1 ± 0.7[u] $^{+0.2}_{-0.3}$[j] $\pm\ 0.1[\mathcal{L}]$
Z+jets	52 ± 21[u] $^{+15}_{-11}$[j] $\pm\ 6[\mathcal{L}]$	4.1 ± 2.9[u] $^{+2.1}_{-0.8}$[j] $\pm\ 0.5[\mathcal{L}]$	27 ± 12[u] $^{+10}_{-6}$[j] $\pm\ 3[\mathcal{L}]$	0.8 ± 0.7[u] $^{+0.6}_{-0.0}$[j] $\pm\ 0.1[\mathcal{L}]$
$t\bar{t}$ and t	10 ± 0[u] $^{+3}_{-2}$[j] $\pm\ 1[\mathcal{L}]$	0.9 ± 0.1[u] $^{+0.4}_{-0.3}$[j] $\pm\ 0.1[\mathcal{L}]$	17 ± 1[u] $^{+6}_{-4}$[j] $\pm\ 2[\mathcal{L}]$	0.3 ± 0.1[u] $^{+0.2}_{-0.1}$[j] $\pm\ 0.0[\mathcal{L}]$
Total SM	118 ± 25[u] $^{+32}_{-23}$[j] $\pm\ 12[\mathcal{L}]$	10.0 ± 4.3[u] $^{+4.0}_{-1.9}$[j] $\pm\ 1.0[\mathcal{L}]$	88 ± 18[u] $^{+26}_{-18}$[j] $\pm\ 9[\mathcal{L}]$	2.5 ± 1.0[u] $^{+1.0}_{-0.4}$[j] $\pm\ 0.2[\mathcal{L}]$
Data	87	11	66	2

arXiv:1102.5290

Jets + MET



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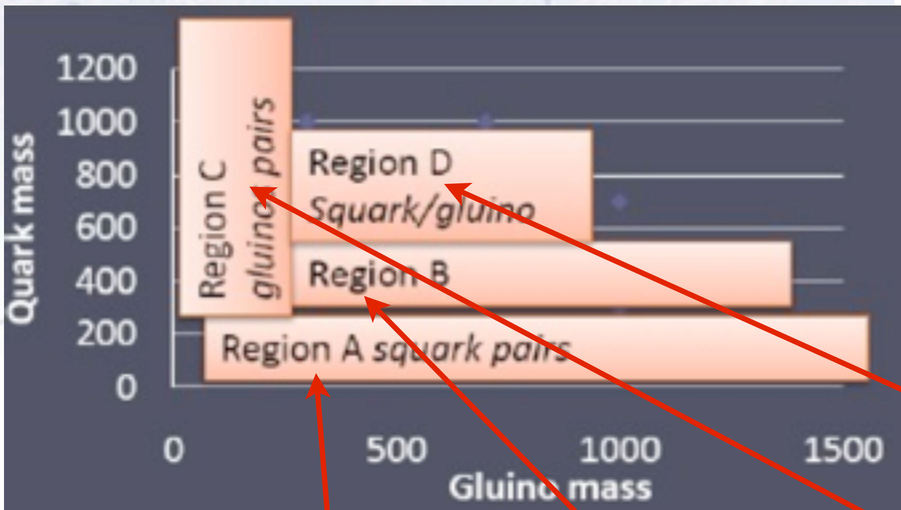
	E_T^{miss}/m_{eff}	> 0.3	–	> 0.25	> 0.25
	m_{eff} [GeV]	> 500	–	> 500	> 1000
	m_{T2} [GeV]	–	> 300	–	–



(figure: S. Caron)

$$m_{eff} \equiv \sum_{i=1}^{n} |\mathbf{p}_T^{(i)}| + E_T^{miss}$$

$$m_{T2}(\mathbf{p}_T^{(1)}, \mathbf{p}_T^{(2)}, \mathbf{p}_T) \equiv \min_{\mathbf{q}_T^{(1)}+\mathbf{q}_T^{(2)}=\mathbf{E}_T^{miss}} \left\{ \max\left(m_T(\mathbf{p}_T^{(1)}, \mathbf{q}_T^{(1)}), m_T(\mathbf{p}_T^{(2)}, \mathbf{q}_T^{(2)}) \right) \right\}$$

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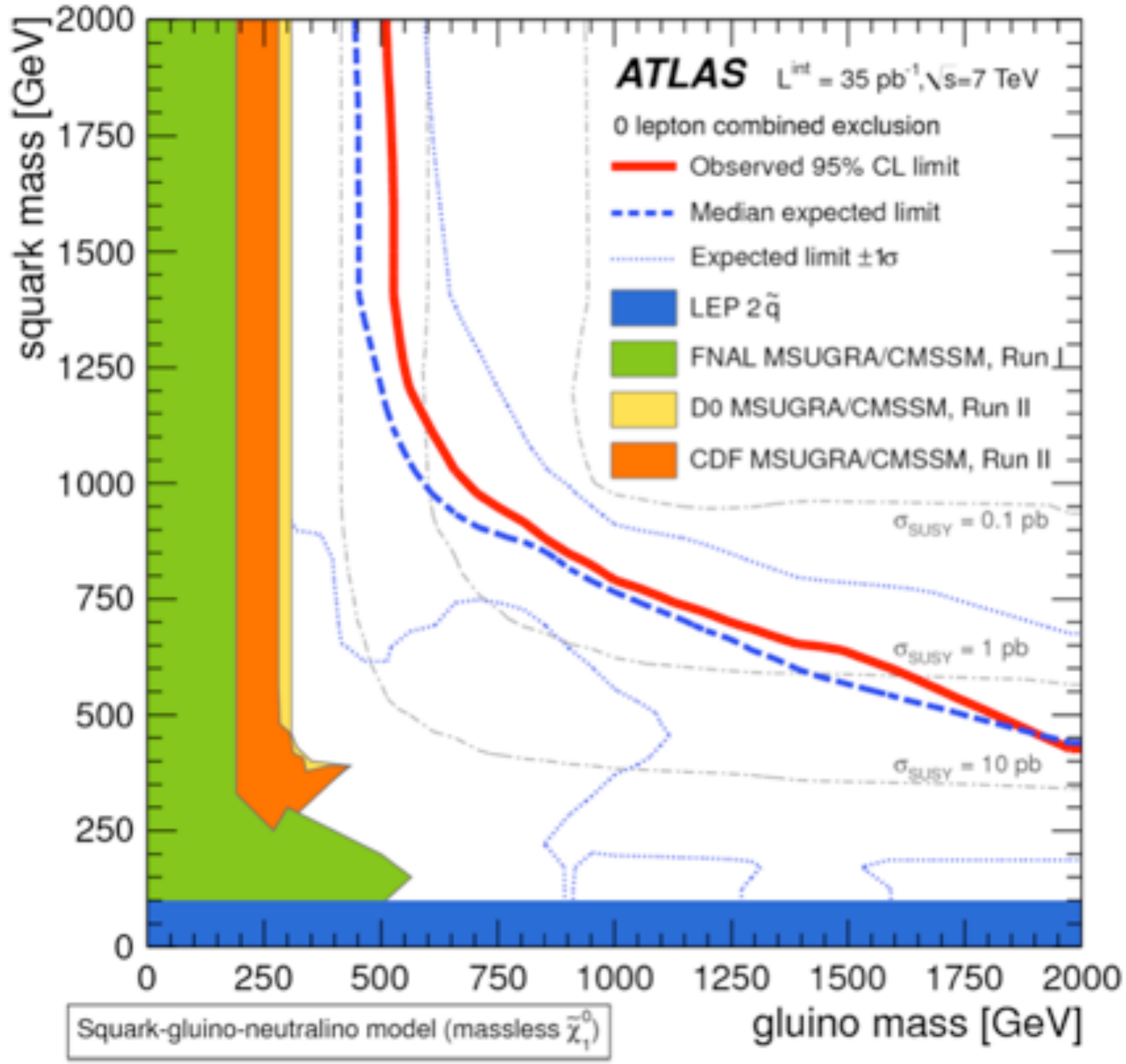
Data	87	11	66	2

arXiv:1102.5290

Jets + MET

Using a simplified MSSM model (2 squark gen. and massless neutralino) limits can be set as shown.



First conclusions:

- SUSY not seen.
- Limits extend quite far beyond earlier limits.
- If taken literally, SUSY "does not like color"!

However, this is still at low luminosity.

For 2011 update, see talk of Michael Rammensee.

arXiv:1

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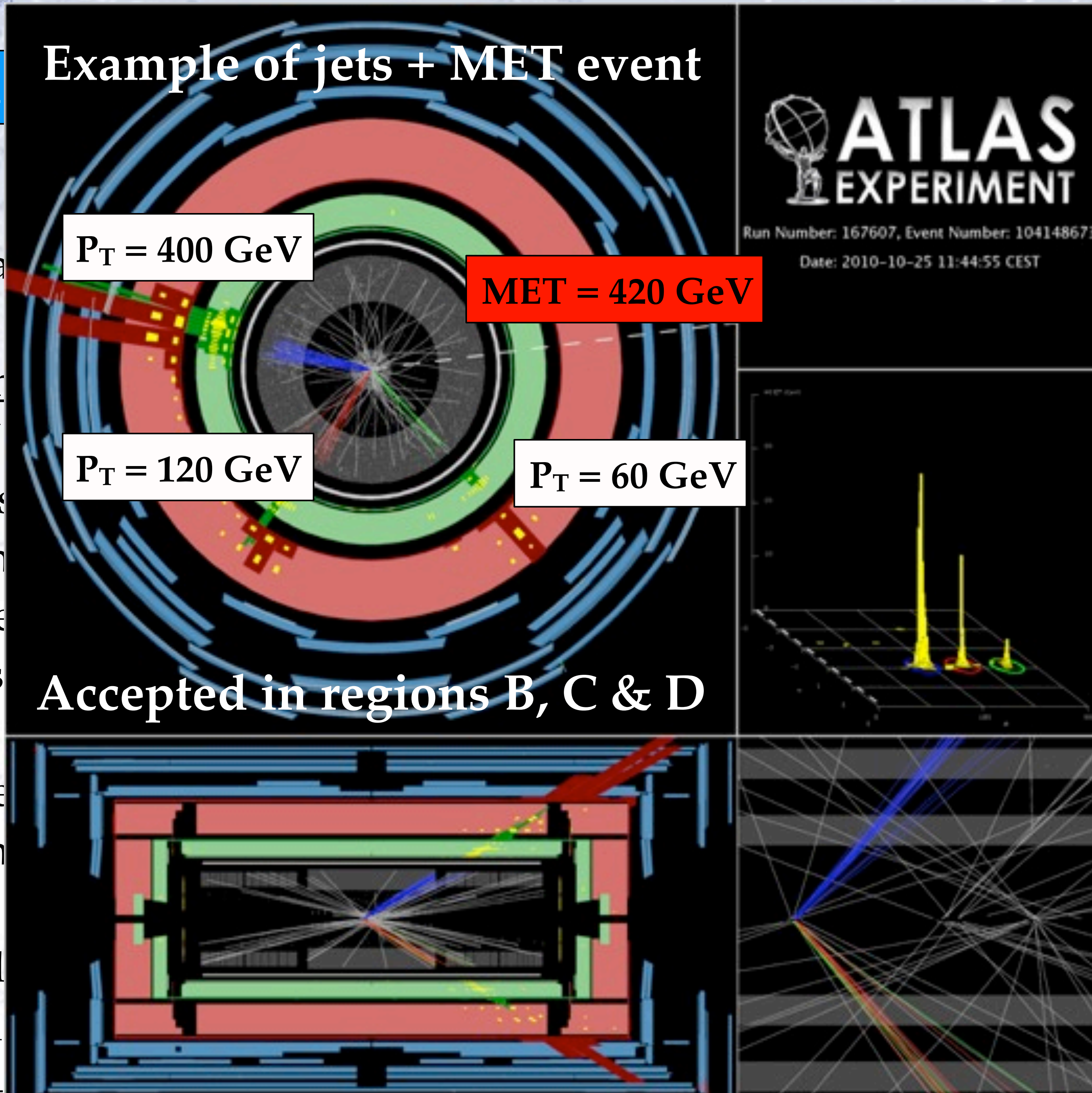
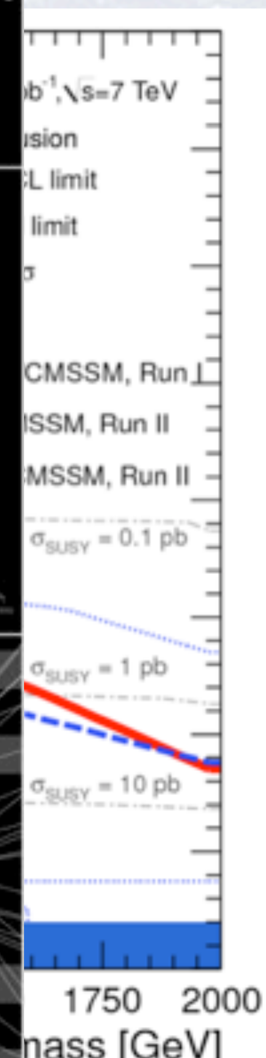
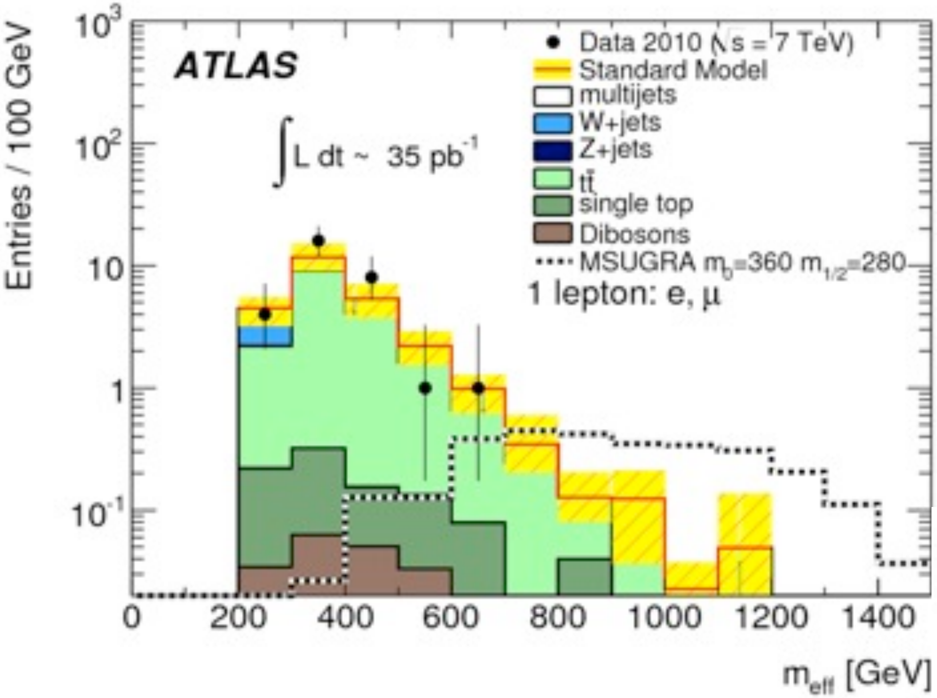




Including a lepton...

arXiv:1102.2357

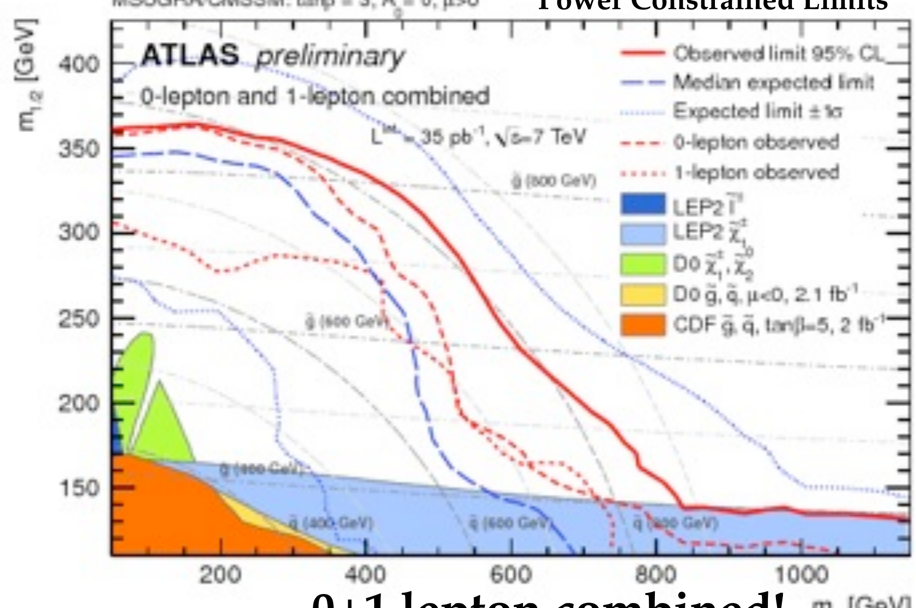


Including a lepton in the event selection (higher trigger eff.):

- e or μ (p_T > 20 GeV)
- ≥ 3 jets (p_T > 60, 30, 30 GeV)
- MET > 125 GeV
- M_{eff} > 500 GeV

The limits COMBINED with previous analysis (jets + MET) are shown.
Combination improves limits at at large m_0 (and low $m_{1/2}$).

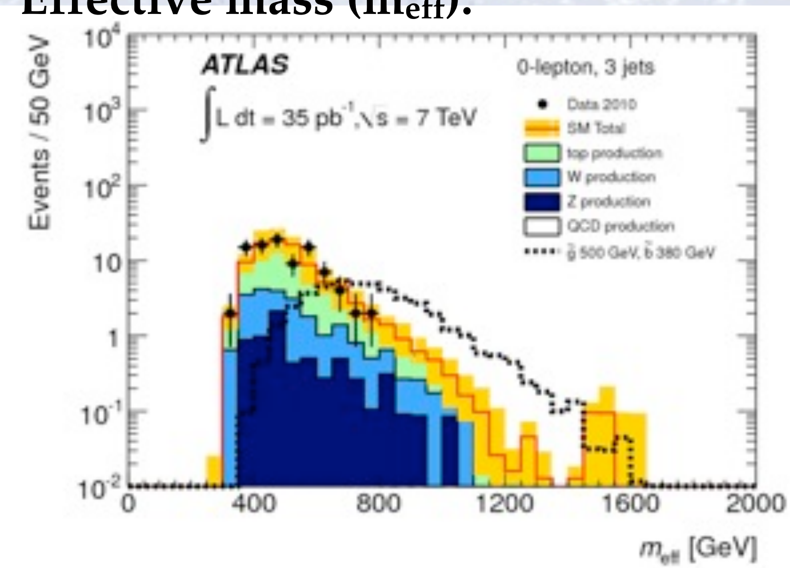
Power Constrained Limits



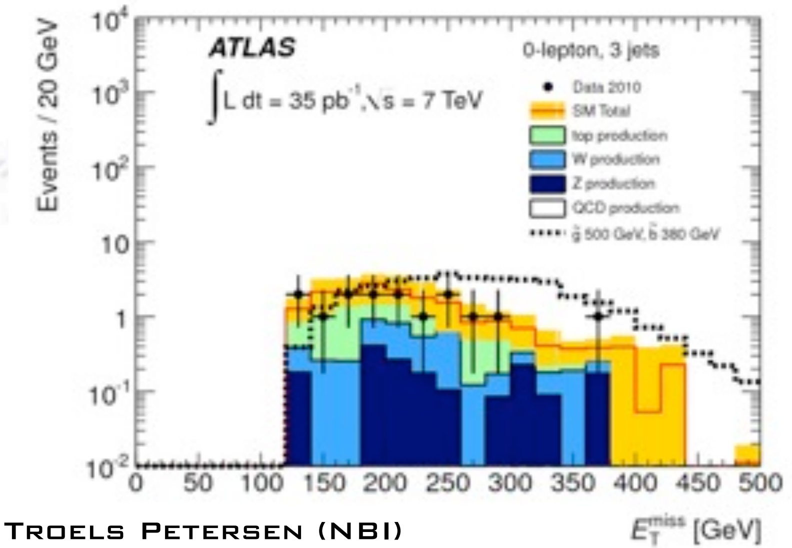
0+1 lepton combined!

b-jets + MET (+ 1 lepton)

Effective mass (m_{eff}):



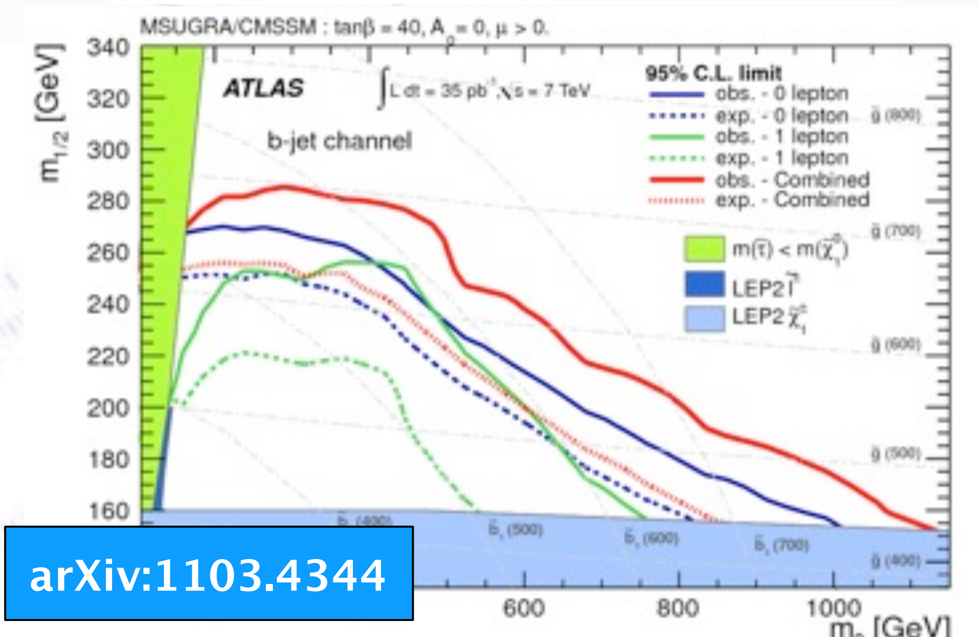
Missing energy (m_{eff} > 600 GeV):



If heavy flavors are SUSY favorites:

- ≥ 3 jets (p_T > 120, 30, 30 GeV) and ≥ 1 b-tag.
- m_{eff} & MET define signal region.

	0-lepton	1-lepton Monte Carlo	1-lepton data-driven
$t\bar{t}$ and single top	12.2 ± 5.0	12.3 ± 4.0	14.7 ± 3.7
W and Z	6.0 ± 2.0	0.8 ± 0.4	-
QCD	1.4 ± 1.0	0.4 ± 0.4	$0^{+0.4}_{-0.0}$
Total SM	19.6 ± 6.9	13.5 ± 4.1	14.7 ± 3.7
Data	15	9	9

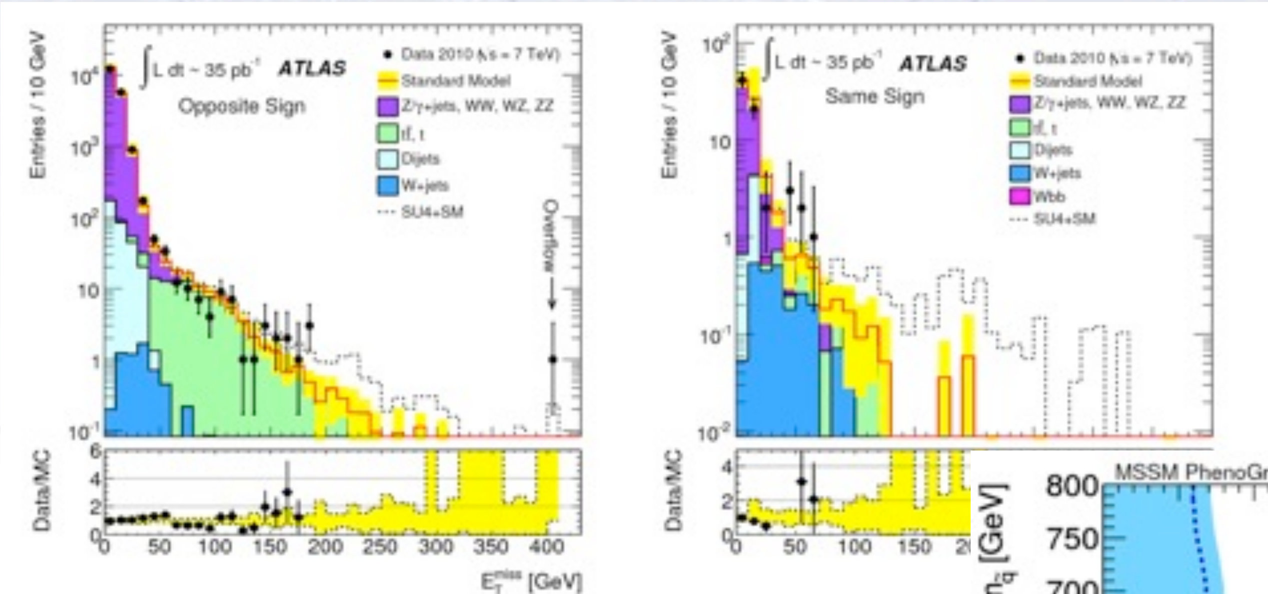


arXiv:1103.4344

Di-lepton + MET

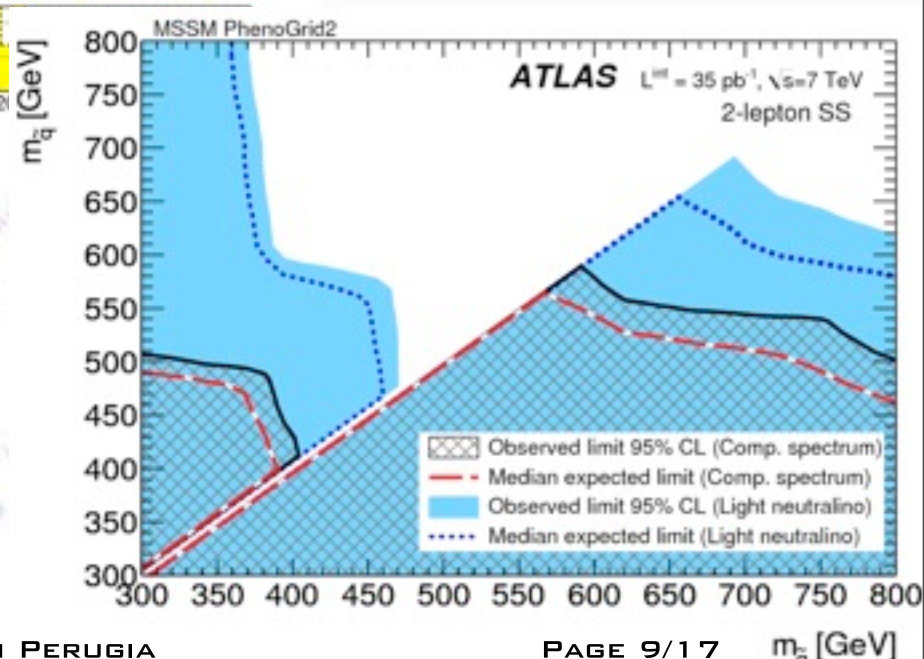
Search with same and opposite charge leptons (e & μ).

arXiv:1103.6214
(arXiv:1103.6208)



Note:
Large difference in SS and OS statistics.

In OS, tail is ttbar!!!



Other analysis uses different flavor combination as control channel.

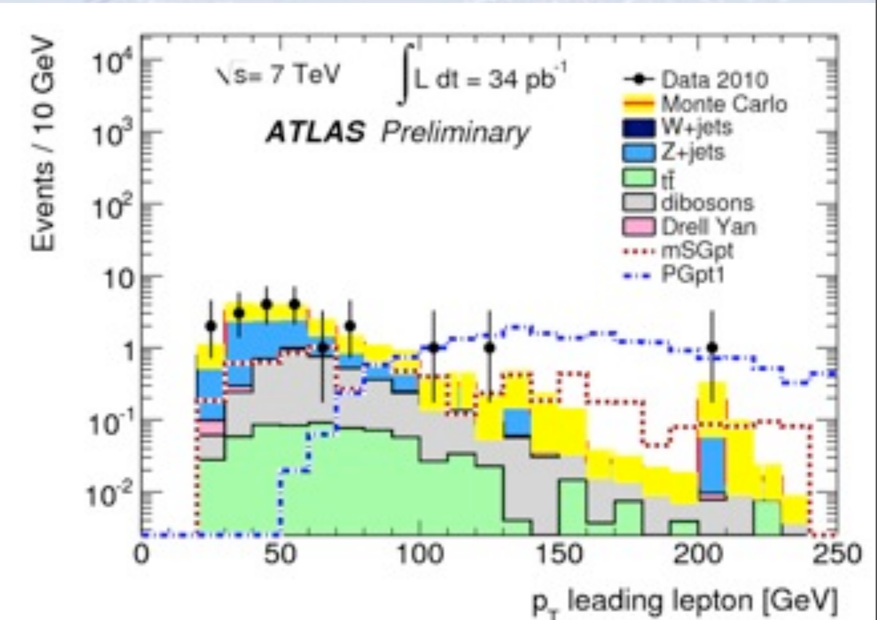
Limits obtained depend on SUSY mass hierarchy, but are in the range: **m(squark) > 450-690 GeV.**

Multi-lepton + MET

If **gauginos/neutralinos** are abundent, then one should see many leptons:

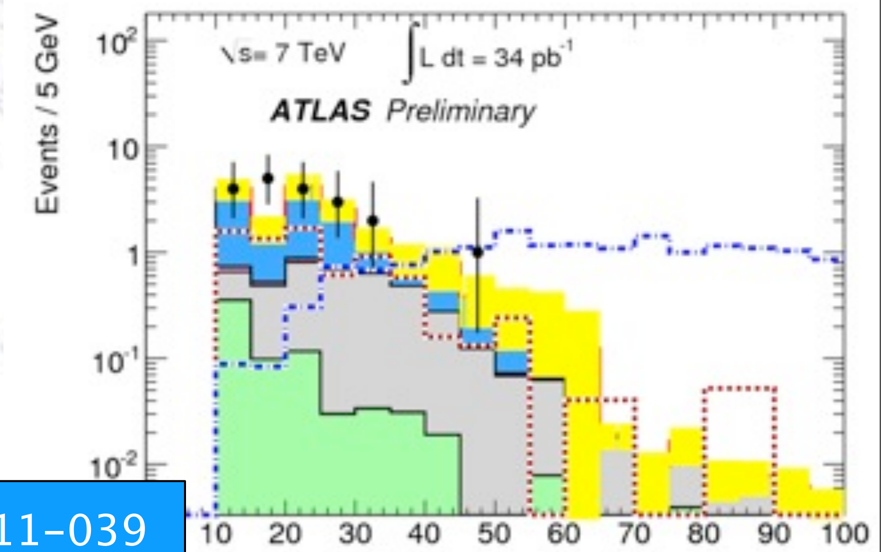
- ≥ 3 e/μ ($p_T > 20, 20, 20/10$ GeV).
- Two jets ($p_T > 50$ GeV).
- MET (> 50 GeV).
- SFOS: m(ll) > 20 GeV and Z-veto.

(SFOS: Same Flavor Opposite Sign)



Before MET, jet, and inv. mass cuts:

- 3-lepton events: **19** (SM: 16.6 ± 1.3).
- 4-lepton events: **0**



After cuts, SM (ttbar) events expected:

0.109 ± 0.023 (stat) $^{+0.036}_{-0.025}$ (syst)

None are observed!

ATLAS-CONF-2011-039

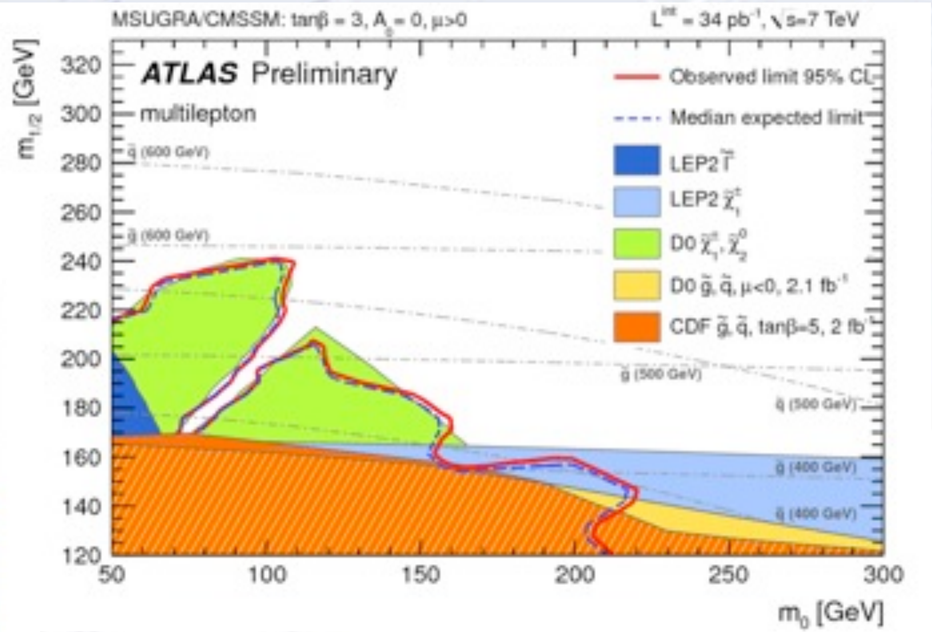
Multi-lepton + MET

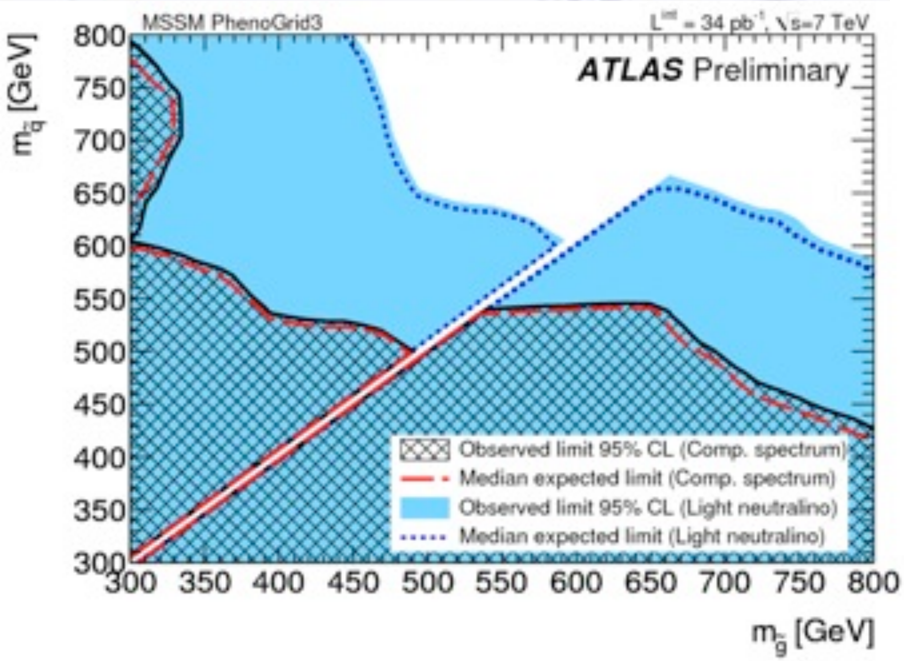
This result has two interpretations, either **MSUGRA** or **MSSM-Grid**.

<ins>MSUGRA interpretation:</ins>

Generally, mass limits are low.

Close to those from Tevatron.





Pheno-grids reduce MSSM to signatures.
Useful for optimisation of signal regions.

<ins>MSSM-Grid interpretation:</ins>

Assuming $m_{gluino} = m_{squark} + 10$ GeV the squark mass limit become:

540 GeV ("compressed spectrum")

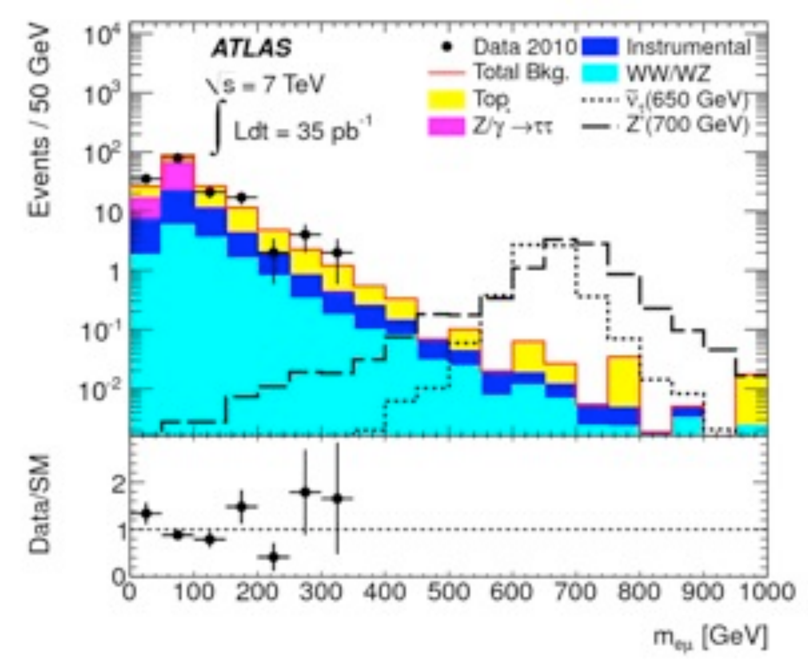
670 GeV ("light neutralino")

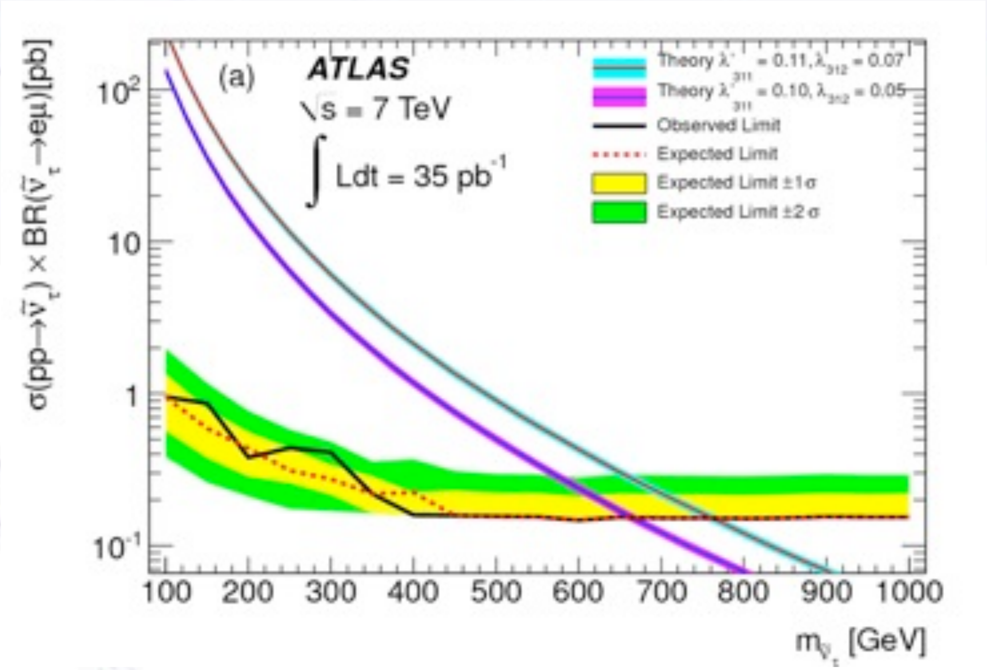
eμ resonance search

(e.g. R-parity violating $\tilde{\nu}_\tau \rightarrow e\mu$)

arXiv:1103.5559

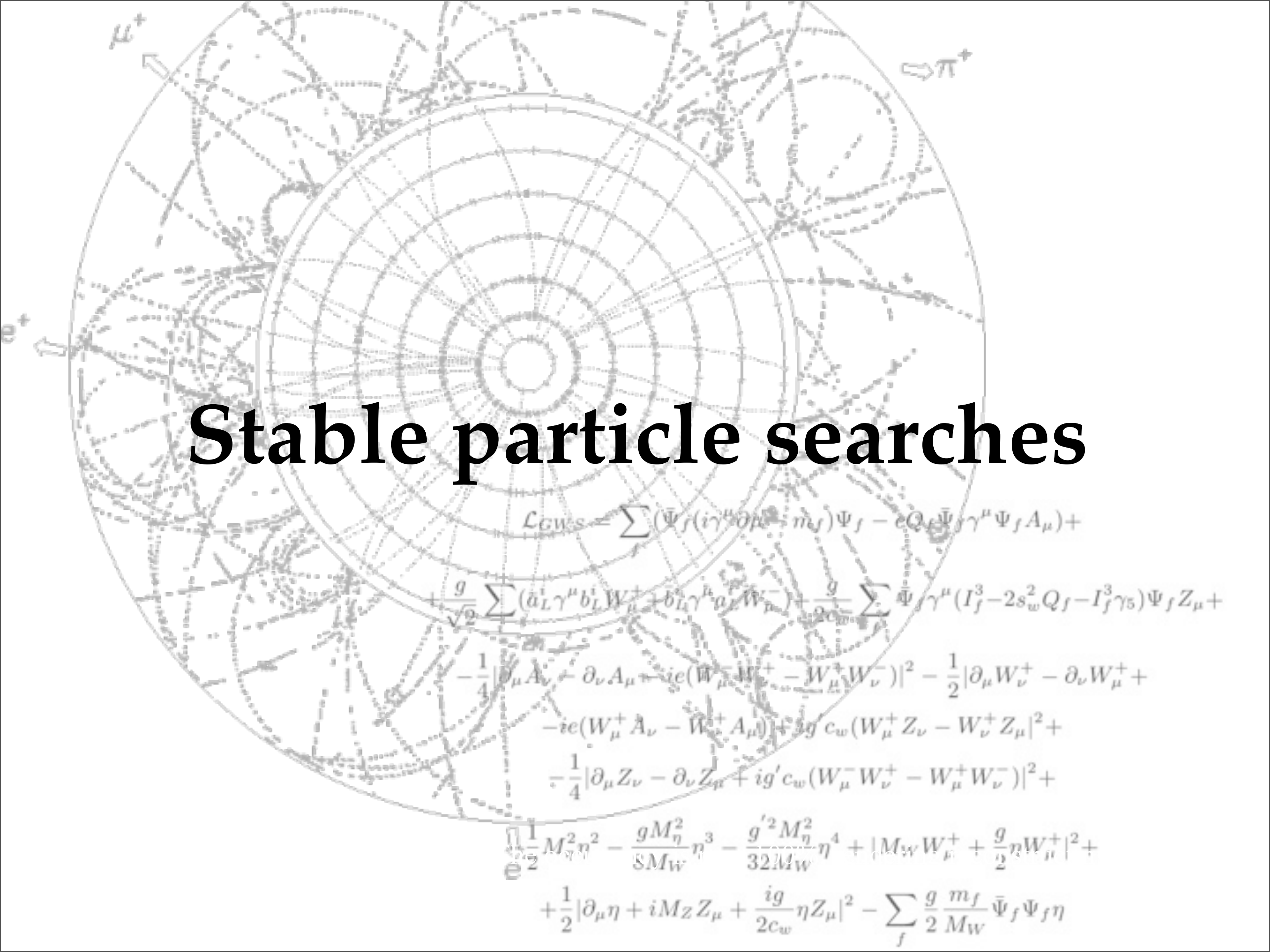
This is a fabulous dream channel! Looking for a peak in clean events!!





Lepton requirement:
$p_T > 20$ GeV + isolation

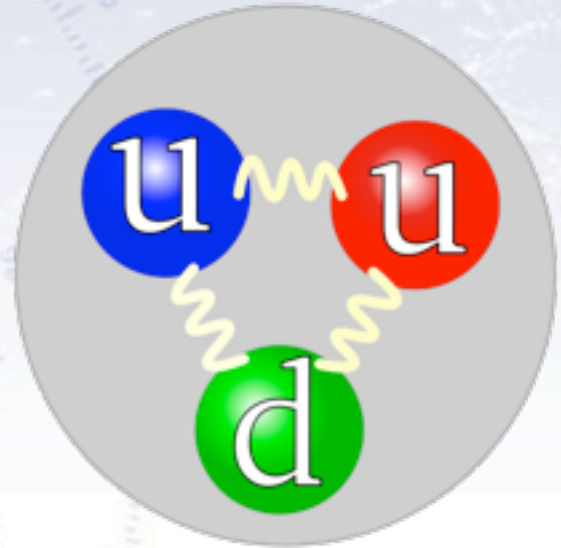
Limit:
$m(\tilde{\nu}_\tau) < 750$ GeV



Stable particle searches

Motivation and theory

Stable Massive Particles (SMPs) are predicted in most SUSY scenarios (**hep-ph/0611040**).



For gluinos and squarks consider a hadron, with a gluon or quark SUSY exchanged (R-hadron).

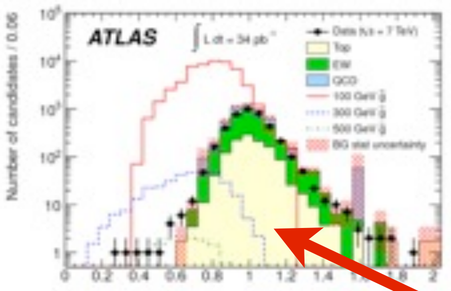
Generally, only the quarks and gluons interact with detector.

Hadronic scattering can lead to different event topologies (e.g. change of charge!).

Scenario	Possible signatures
Stop	Mostly muon-like
Sbottom	Mostly neutral in muon system
Gluino	Possibly muon-like
	Mostly neutral in muon system

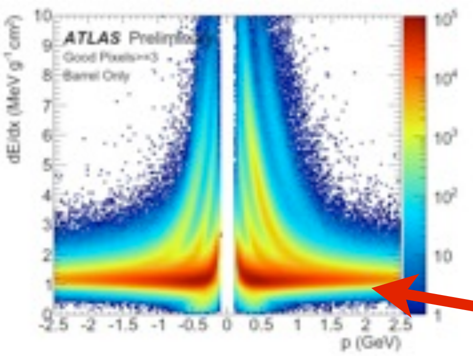
Stable heavy particles in a detector

Tile:

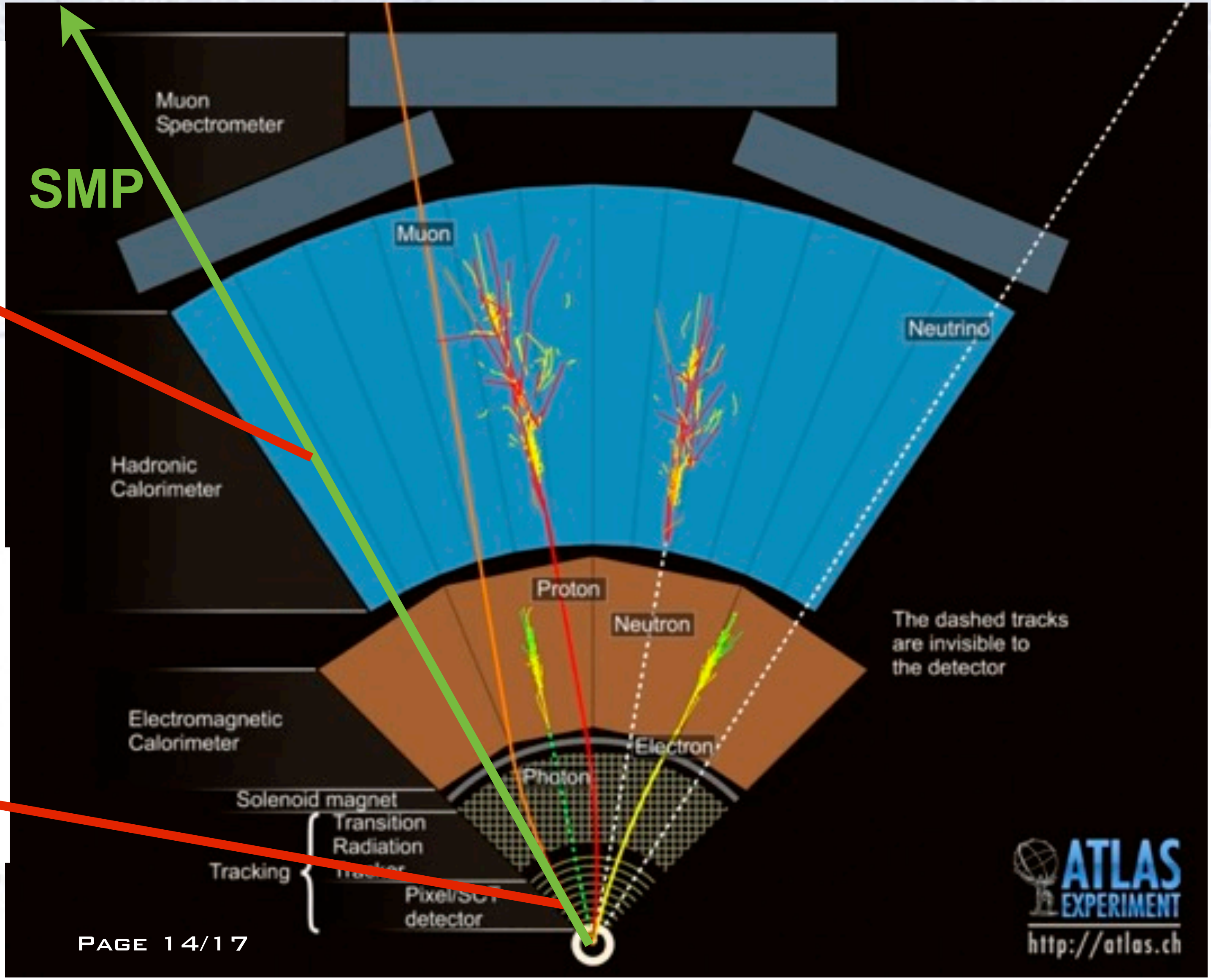


Observable:
Delayed signal

Pixel:

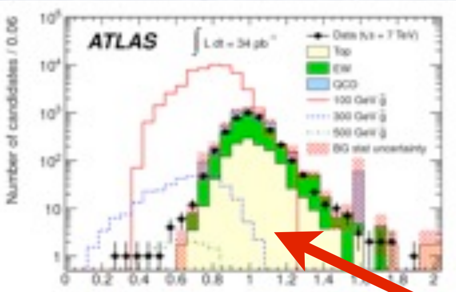


Observable:
High Ionization



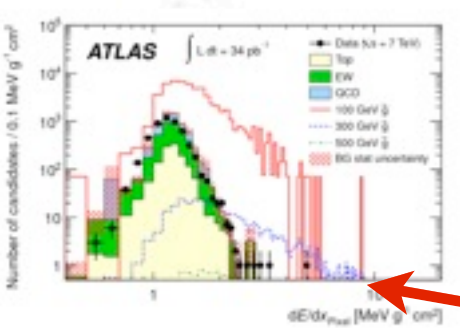
Stable heavy particles in a detector

Tile:



Observable:
Delayed signal

Pixel:



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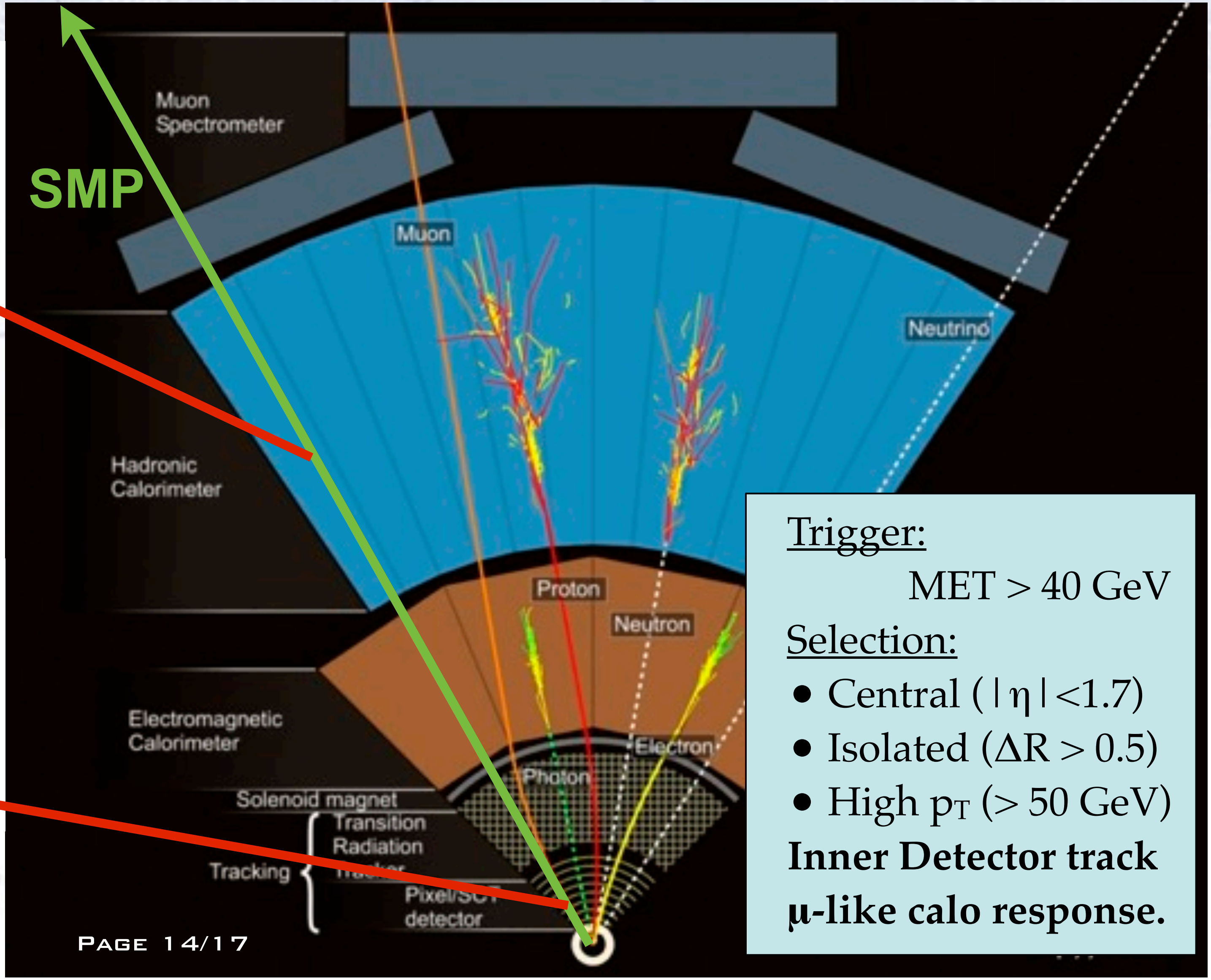


<u>Trigger:</u>

MET > 40 GeV

<u>Selection:</u>

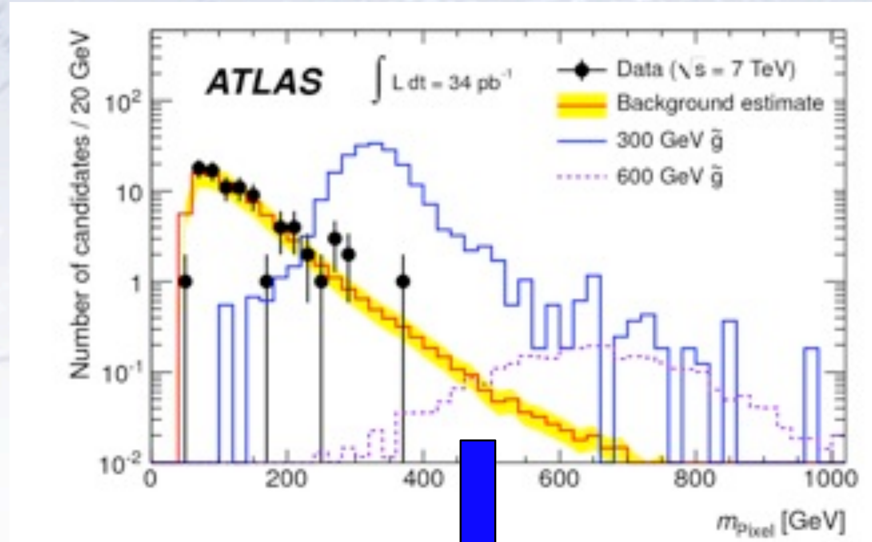
- Central (| η | <1.7)
- Isolated (ΔR > 0.5)
- High p_T (> 50 GeV)

Inner Detector track
μ-like calo response.

Mass reconstruction

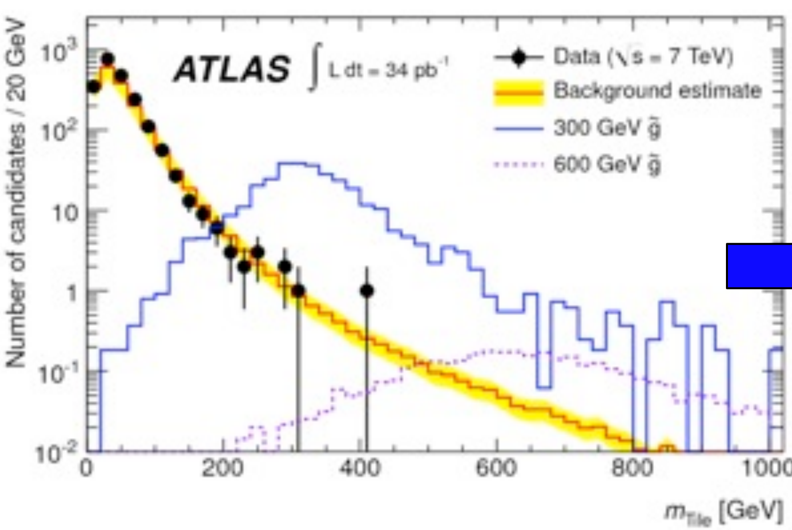
Use β (tile) and βγ (pixel) to get mass estimate:

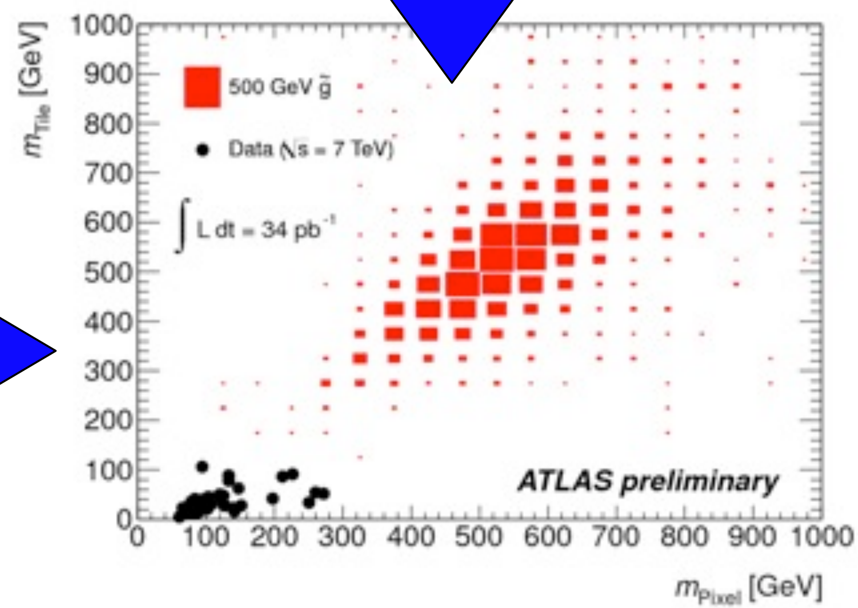
$$m = p / \beta\gamma$$



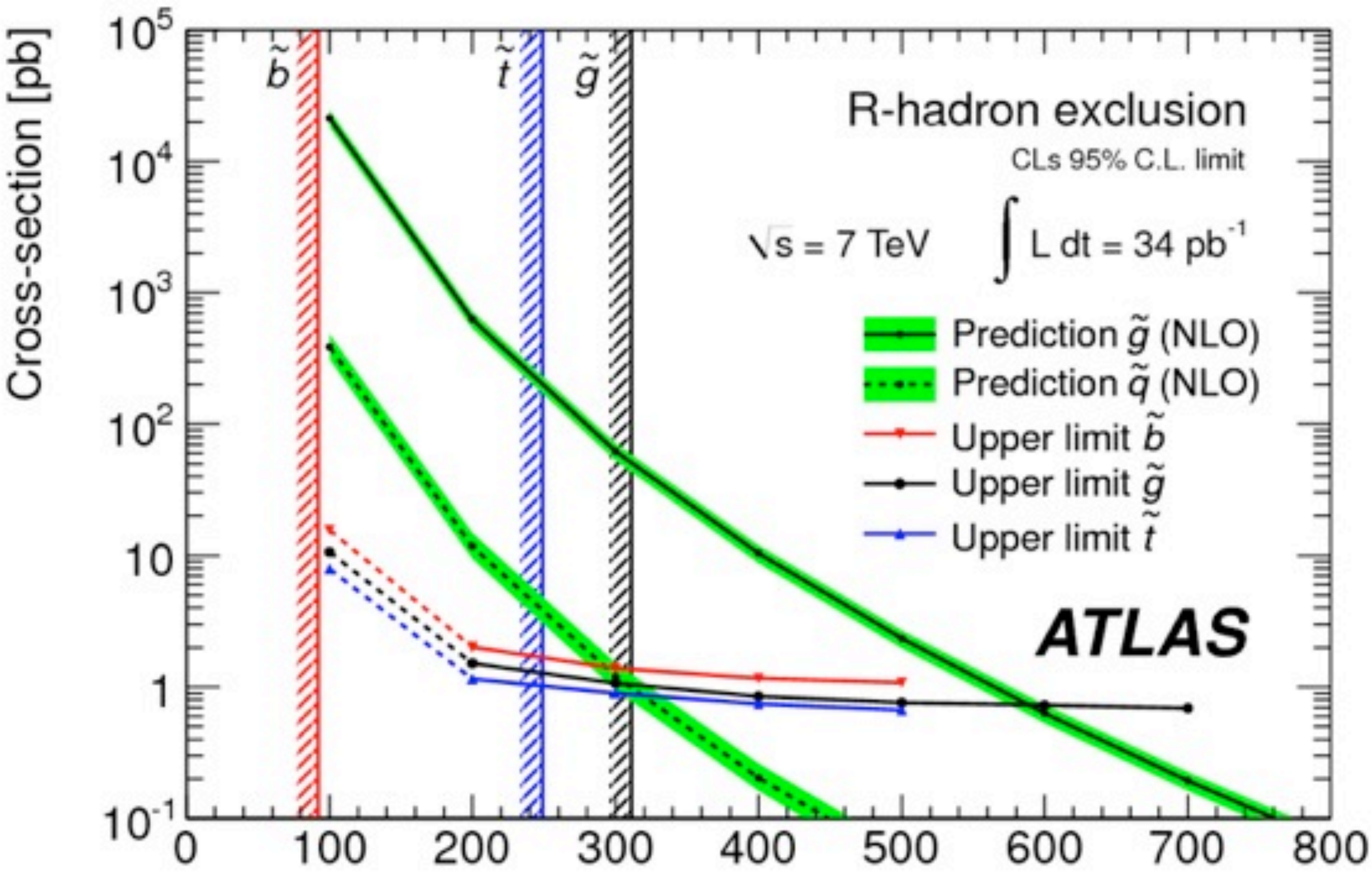
Using two **independent** detectors greatly reduces backgrounds.

(estimated using random combination technique).





Mass reconstruction



m(gluino) > 562-586 GeV

m(stop) > 309 GeV, m(sbottom) > 294 GeV

arXiv:1103.1984

Conclusions

Many SUSY searches done - SUSY was **NOT** "just around the corner"! Limits have already surpassed several of those from Tevatron and LEP.

Luminosity increases incredibly (thank you very much LHC), and so the searches continue (see following talks).

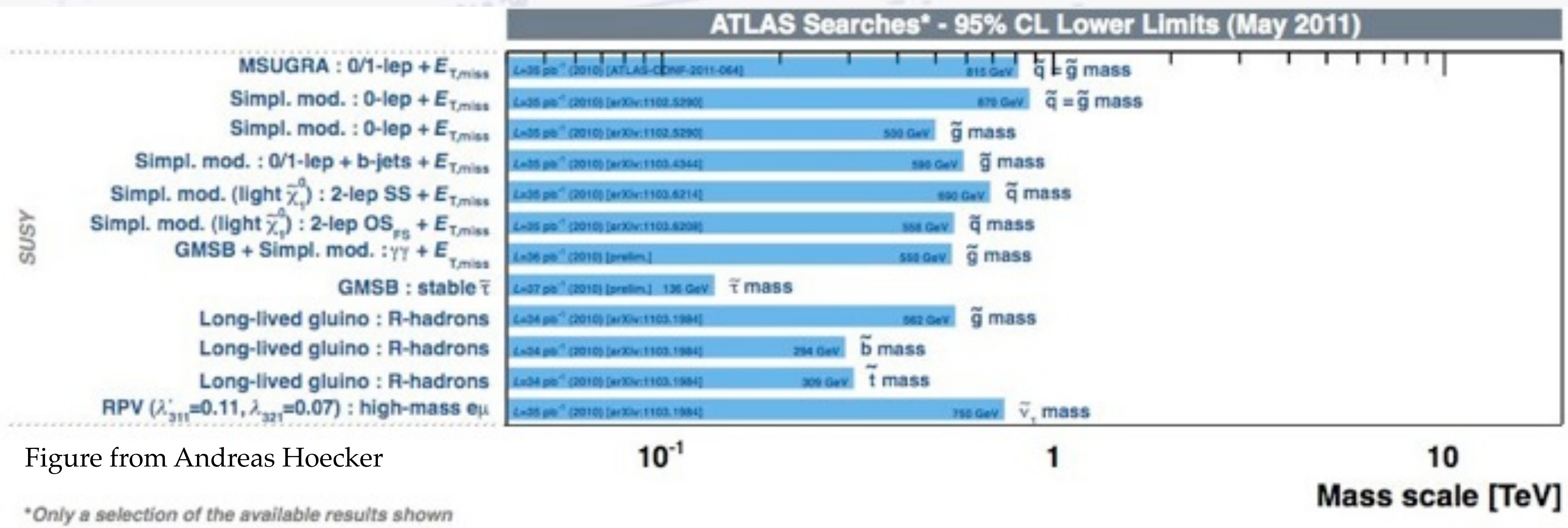


Figure from Andreas Hoecker

Maybe we are just chasing ghosts...

...but it's the "maybe" that keeps the chase on.

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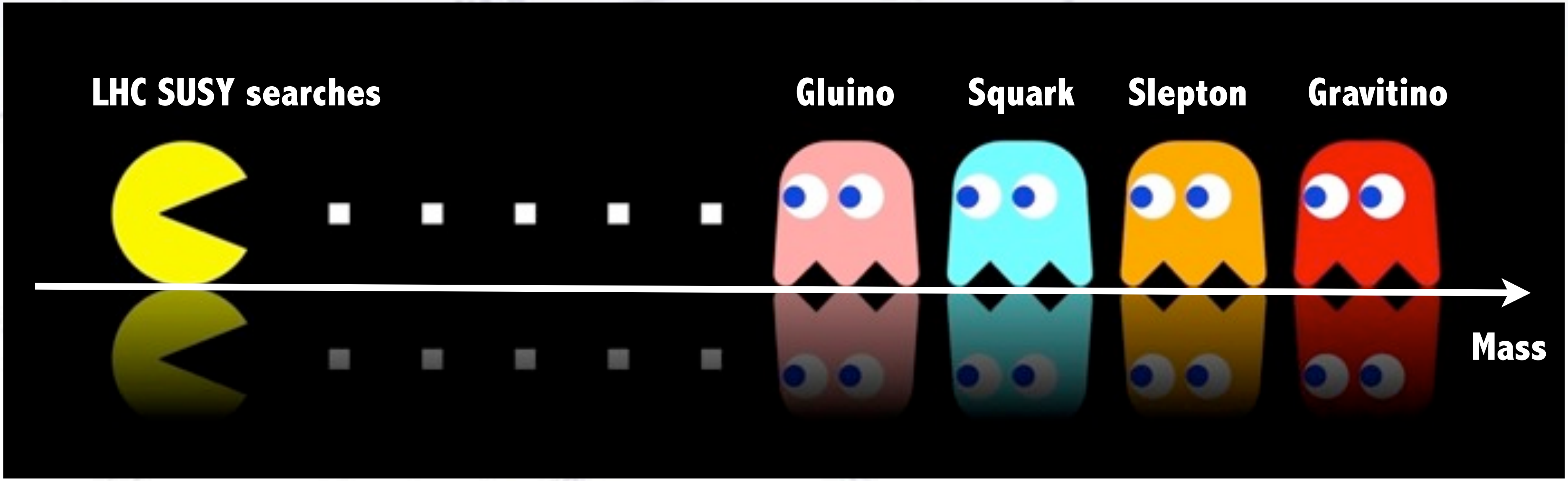

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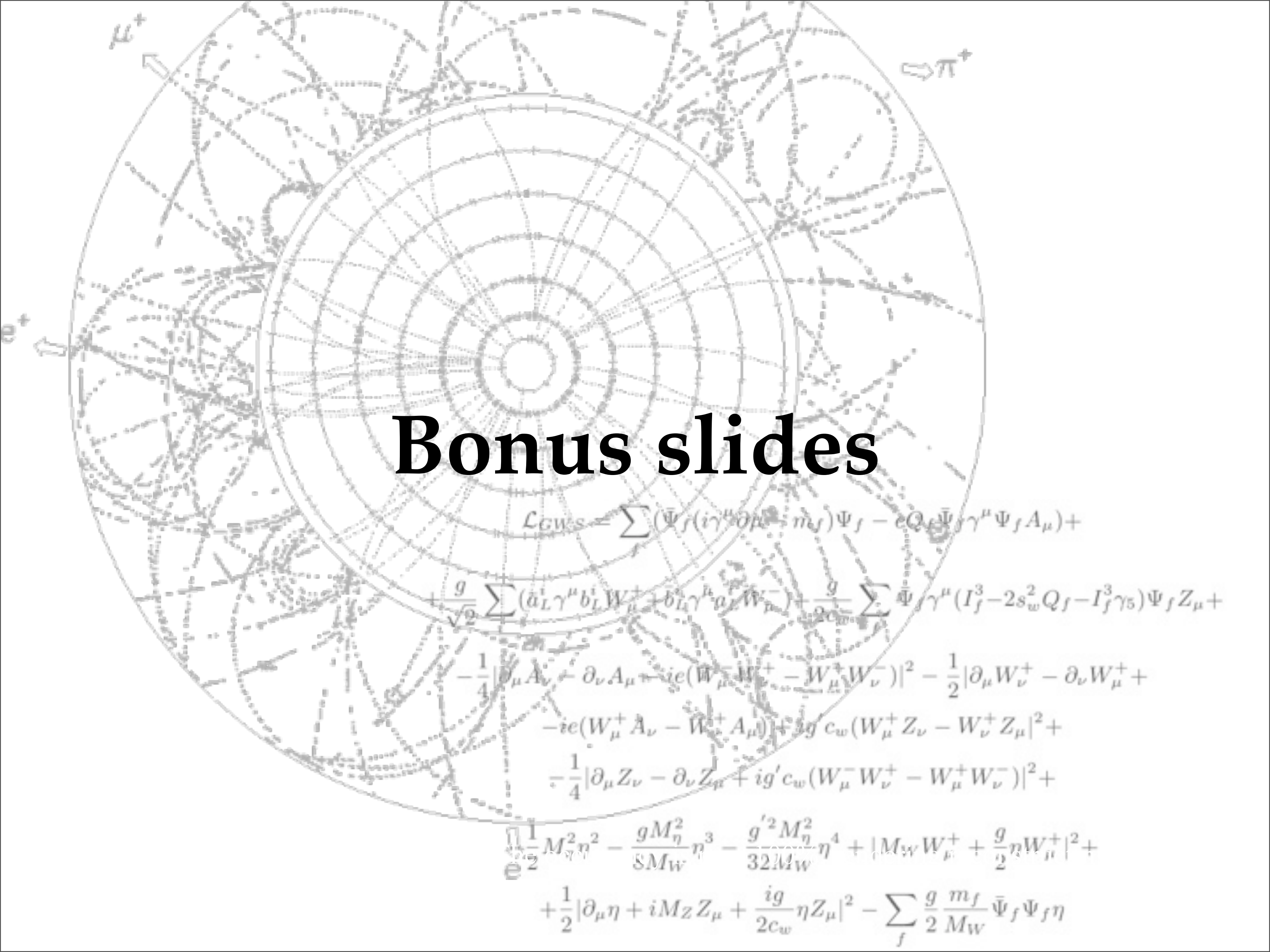
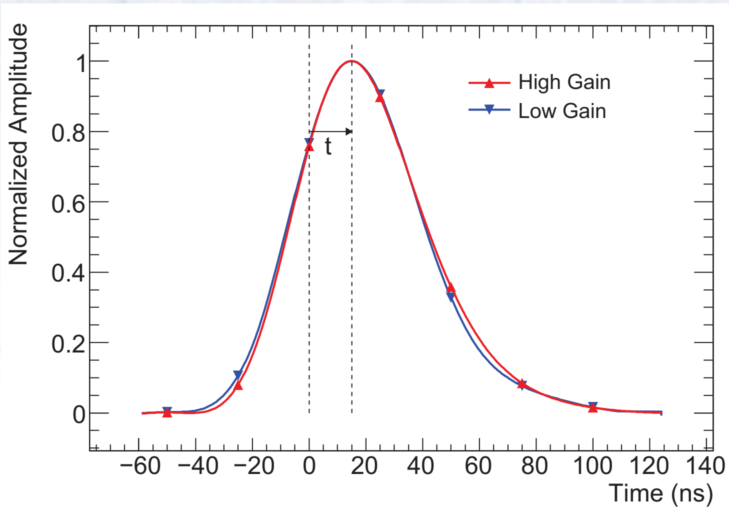
Bonus slides



Perhaps still the best estimate of what lies beyond...

Mass reconstruction - Tile

The typical time resolution of a single cell is 1-2 ns (@ 1 GeV) depending on E. Cells are combined, using the energy as weight (resolution improves with E).

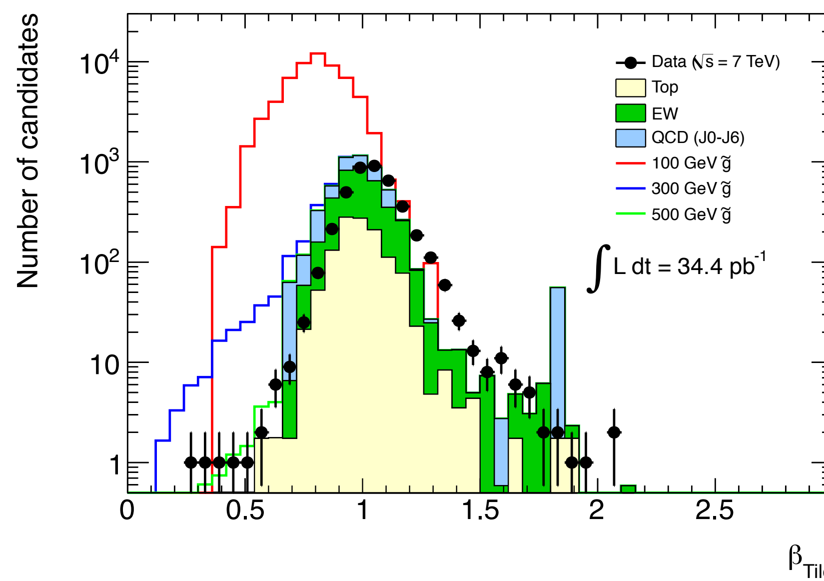


$$\beta_{cell} = \frac{v}{c} = \frac{d_{cell}}{t_{true} c} = \frac{d_{cell}}{(t_{reco} + \frac{d_{cell}}{c})c} = \frac{d_{cell}}{t_{reco} c + d_{cell}}$$

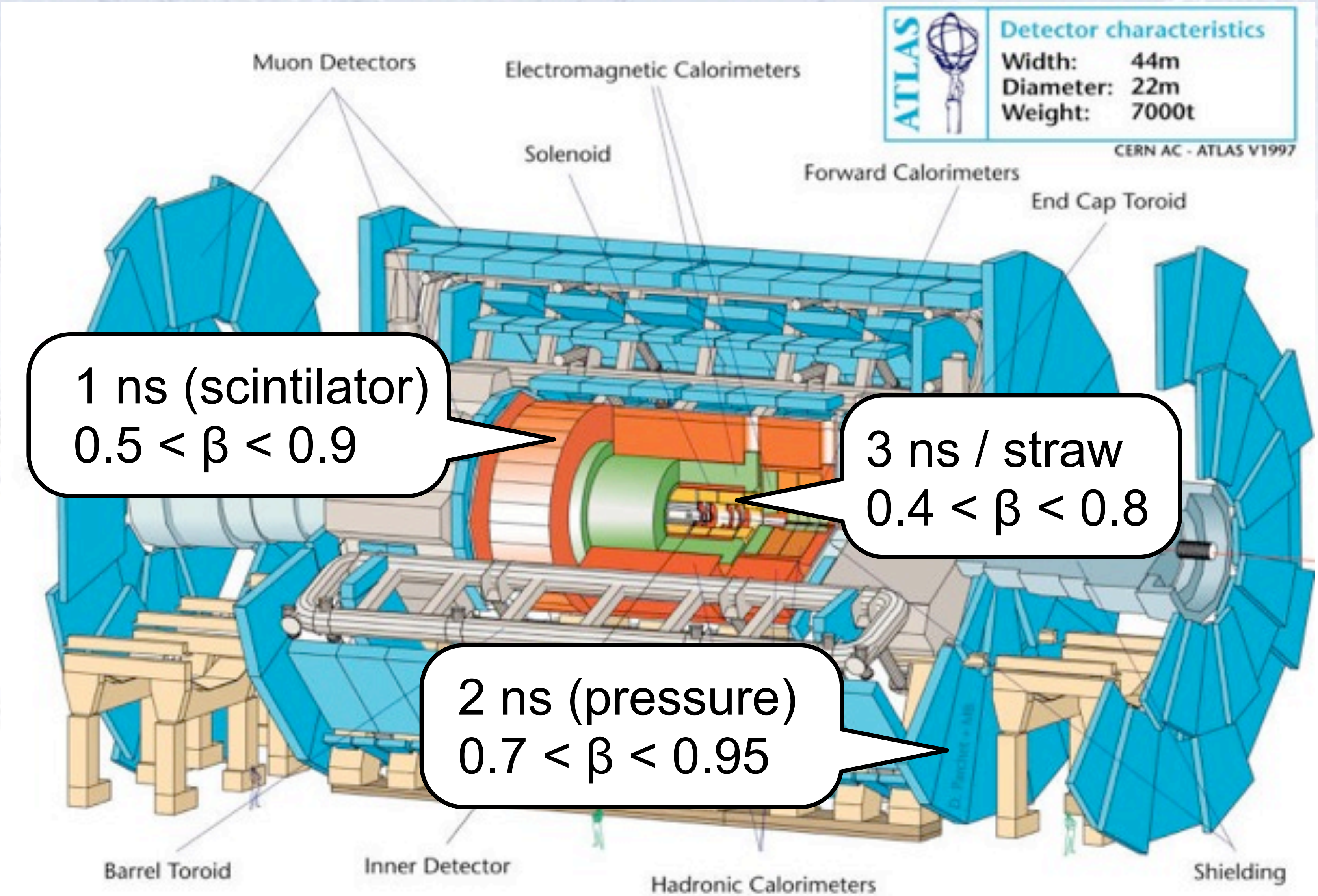
$$\beta_{reco} = \frac{\sum_{i=0}^{n} w_i \beta_i}{\sum_{i=0}^{n} w_i} \qquad w(E_i) = E_i$$

The β_{reco} distribution is centered at 1.00 for data and 0.97 for simulation.
The slight shift is a systematic error in time (of 100ps) between BPTX and calo.

We require $\beta < 1$ for mass reconstruction.



Observing heavy particles



For new search results using muon spectrometer, see talk by Simon Owen.