Collider searches for long-lived particles

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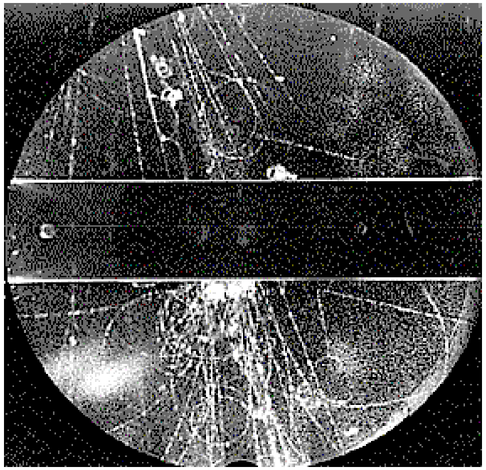
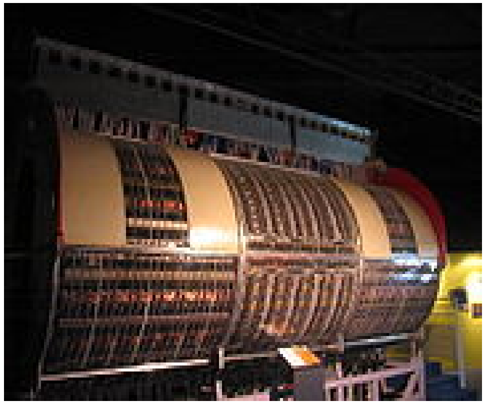
Particle Physics Seminar
Oxford, 9 March 2010

- Fundamental physics puzzles
- Split-SUSY and long-lived gluinos
- Magnetic Monopoles
- Past searches – LEP, Tevatron
- ATLAS search plans

Brief history of new particle discoveries





- 1950-1974:
  - hadron jungle, neutrino
  - quark model confirmed
- 1974-1994:
  - heavy quarks, tau, *W* and *Z*...
  - 3 generations, EW unification confirmed
- 2010 and onward:
  - Expect heavy and short-lived particles (e.g., Higgs boson)
  - Long-lived ? (e.g., WIMP)

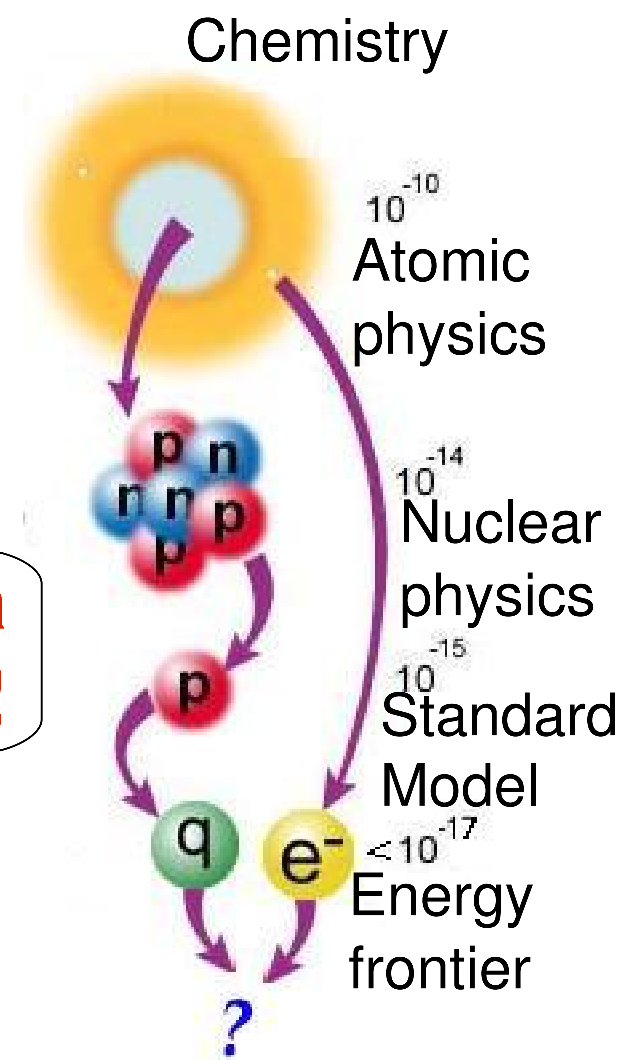
Today's particle physics puzzles

- Origin of mass, mass hierarchy
- Unification of forces
- Matter-antimatter asymmetry
- Dark matter

Proposed searches

New data needed !

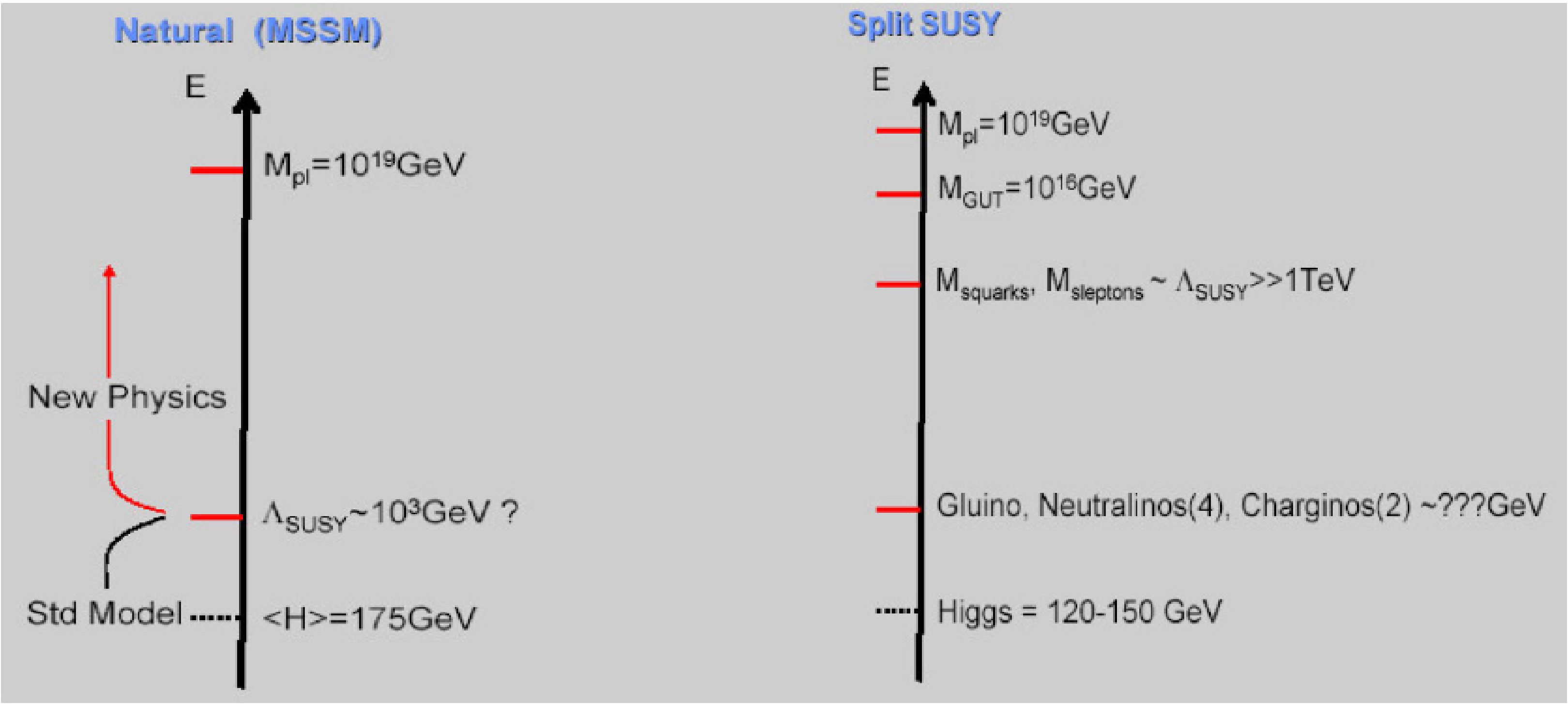
- Higgs boson
- Precision measurements
- Exotic phenomena, e.g., Supersymmetry



Split-SUSY

arXiv:hep-th/0405159

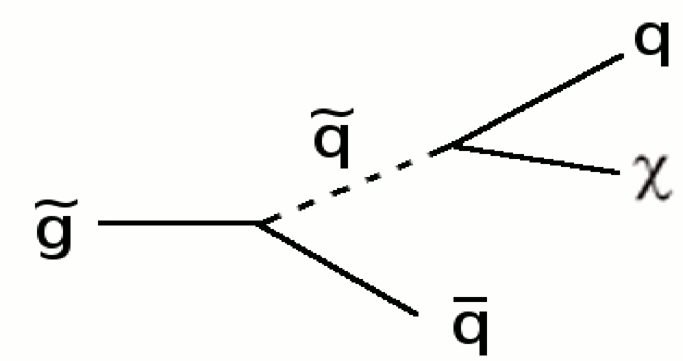
- Accept the unnaturalness of the Higgs mass
- Supersymmetry breaking occurs at $M_s >> 1$ TeV
  - Scalars have mass at this scale

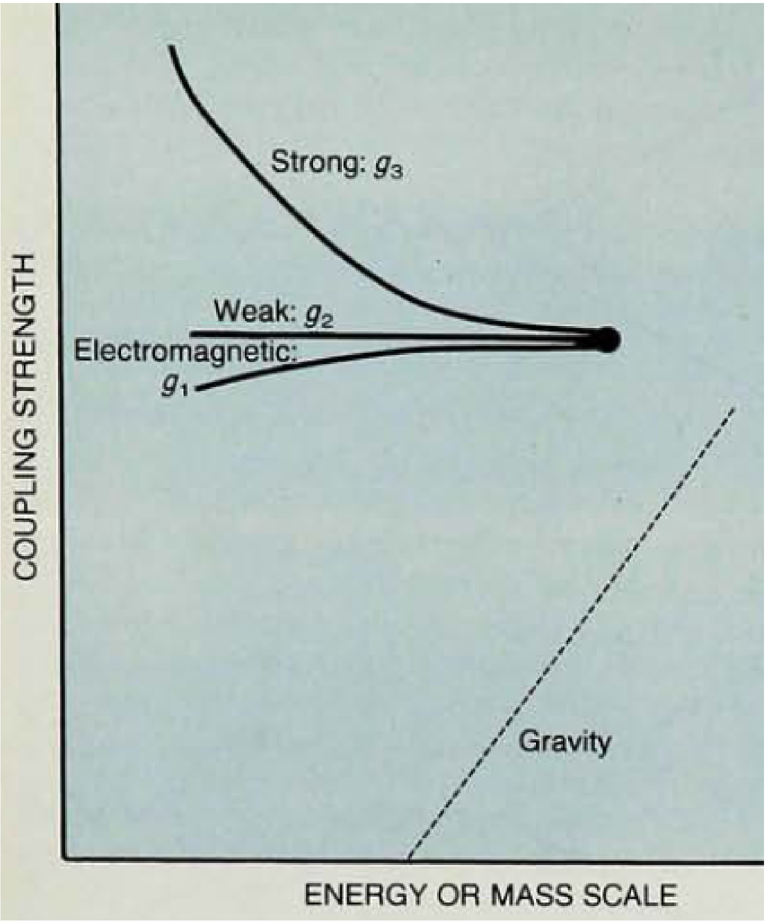


Nice features of split-SUSY

- Unification of couplings
- Long proton lifetime
- Long-lived gluino

→ R-Hadrons !



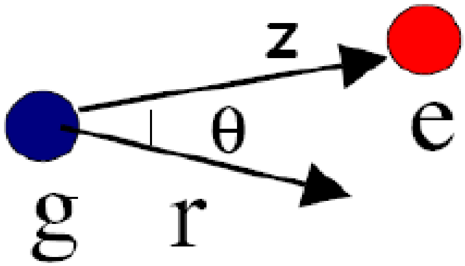


Examples of well-motivated exotic long-lived particles

- Neutral LSP dark matter (*R*-parity conservation)
- Metastable stau NLSP (LSP gravitino)
- Metastable squark or gluino (kinematics)
- Leptoquark (weak coupling)
- Magnetic Monopole (charge conservation)

Magnetic Monopoles

- Dirac's argument (1931)
  - Angular momentum of field of electron-monopole system :



$$L = \int r \times E \times B dr d\theta d\phi$$

$$= \frac{\mu_0 e g}{4\pi}\hat{z} \Rightarrow e = \frac{nh}{g\mu_0} \quad g_D = \frac{h}{e\mu_0}$$

- “explain” charge quantization
- Symmetrize Maxwell Equations
- Ingredient in Grand Unification Theories

Monopoles: ionization

- Stopping power for electrically charged particle

$$\frac{dE}{dx} = \frac{4\pi e^4 Z_1^2}{m_e c^2 \beta^2} n \left(\frac{1}{2} \ln \left(\frac{2 m_e c^2 \beta^2 \gamma^2 T_{max}}{I_e^2} \right) - \beta^2 - \frac{\delta}{2} \right)$$

- Stopping power for monopole (charge g)

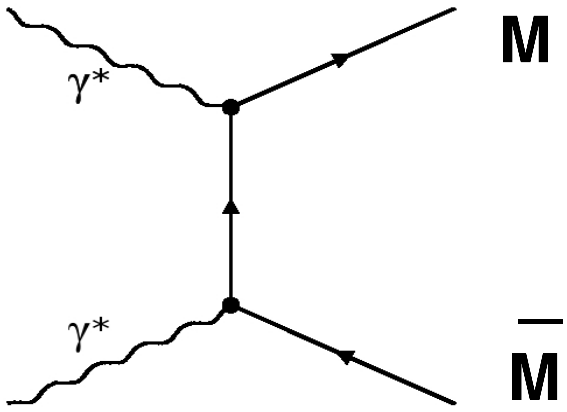
$$\frac{dE}{dx} = \frac{4\pi e^2 g^2}{m_e c^2} n \left(\frac{1}{2} \ln \left(\frac{2 m_e c^2 \beta^2 \gamma^2 T_{max}}{I_m^2} \right) - \frac{1}{2} - \frac{\delta}{2} + \frac{K(|g|)}{2} - B(|g|) \right)$$

- $g \approx 137/2$ e : several thousand times greater dE/dX

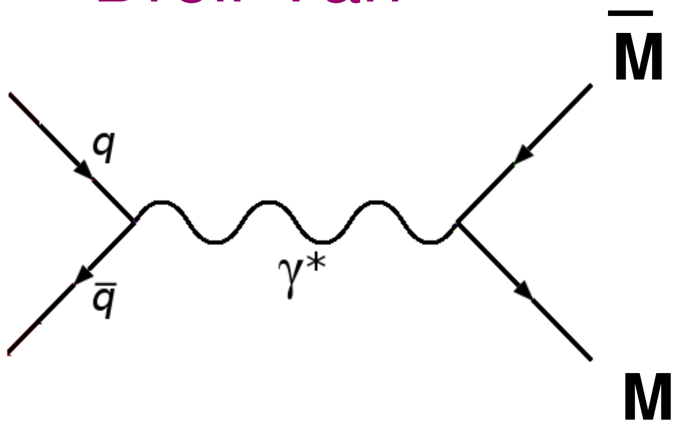
Monopoles: kinematics

- Direct pair production processes at colliders:

photon fusion

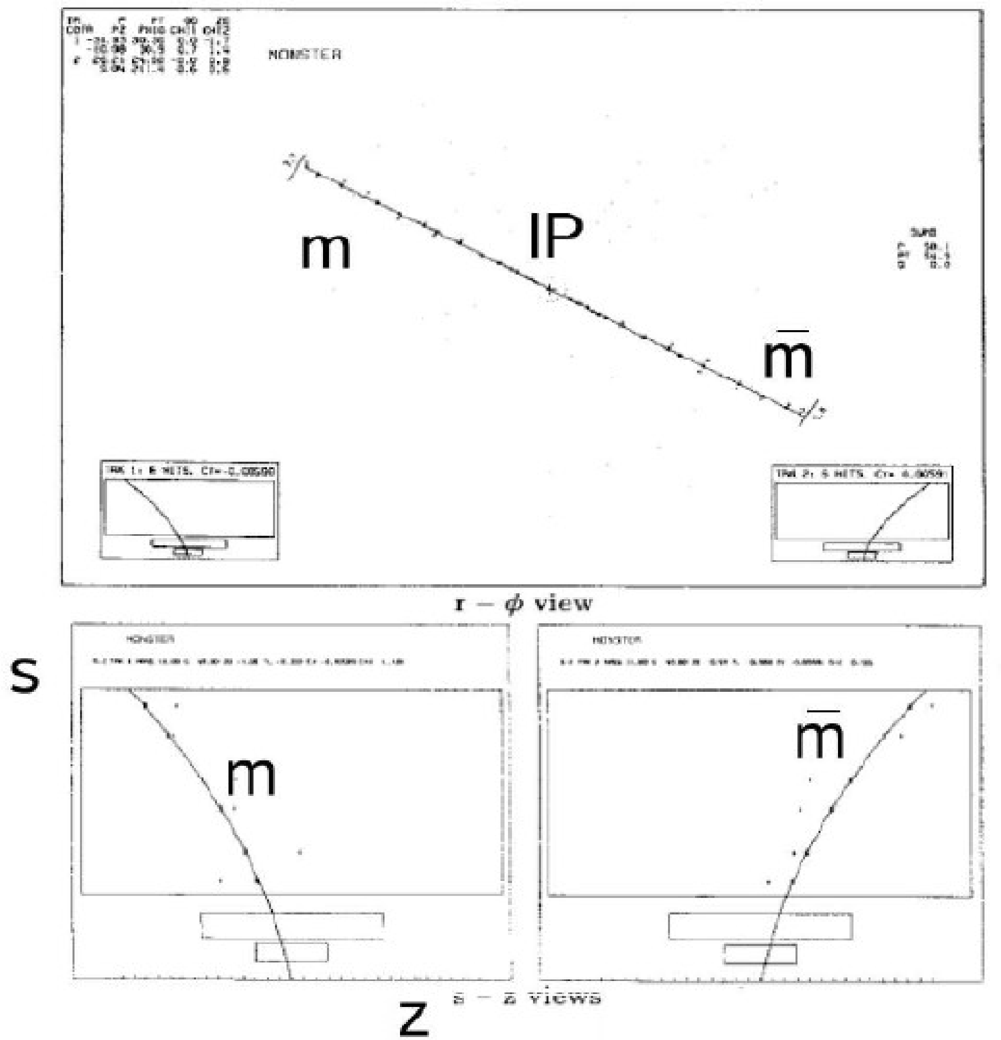


Drell-Yan



- Higher-order corrections ?
  - Strong g coupling → **non-perturbative dynamics !!!**
  - No reliable model for cross sections and kinematics !

Monopoles: bending in magnetic field

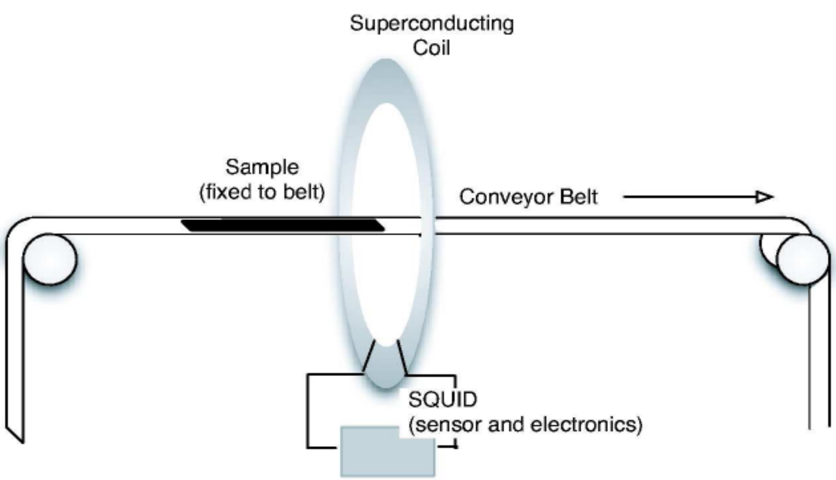


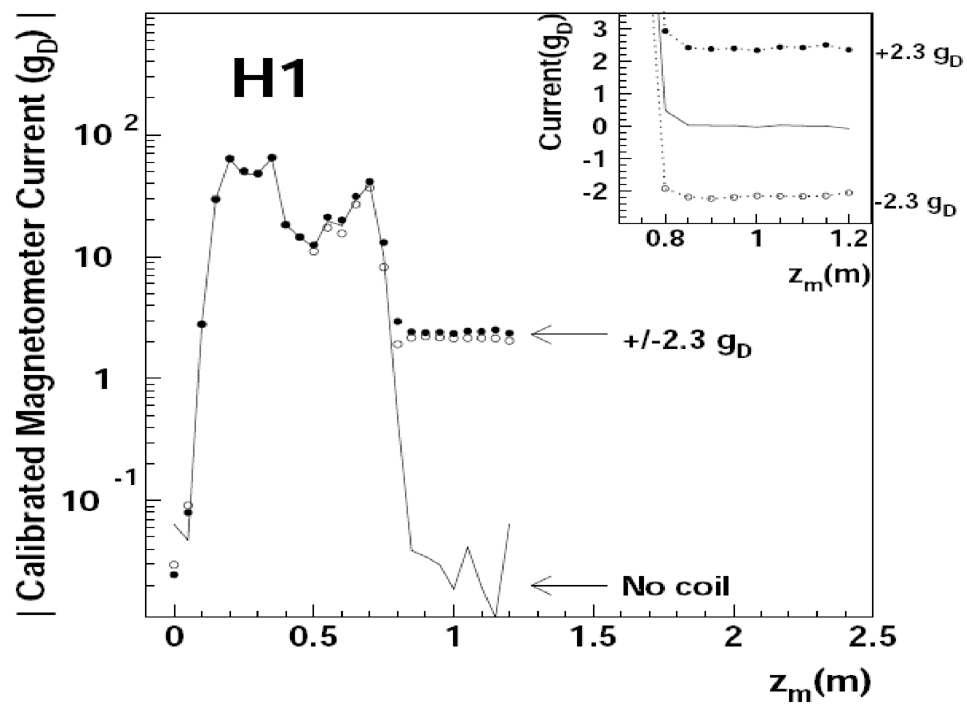
- Acceleration along beam axis
- Straight trajectory in xy plane
- Parabolic trajectory in rz plane

Tasso : W. Braunschweig et al., Z. Phys. C38 (1988) 543

Direct search: SQUID technique

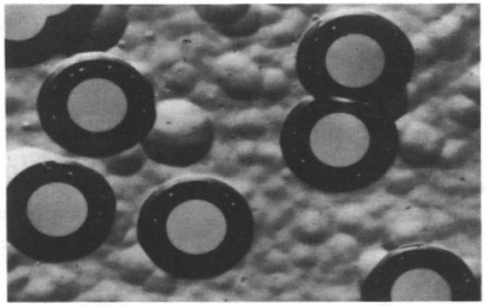
- At HERA (H1) and the Tevatron (E882)
- Beam pipe and detector material cut into strips
  - Passed through superconducting coil to sense induced current
  - Long solenoid used for calibration
- Trapped Monopoles
  - Model dependence





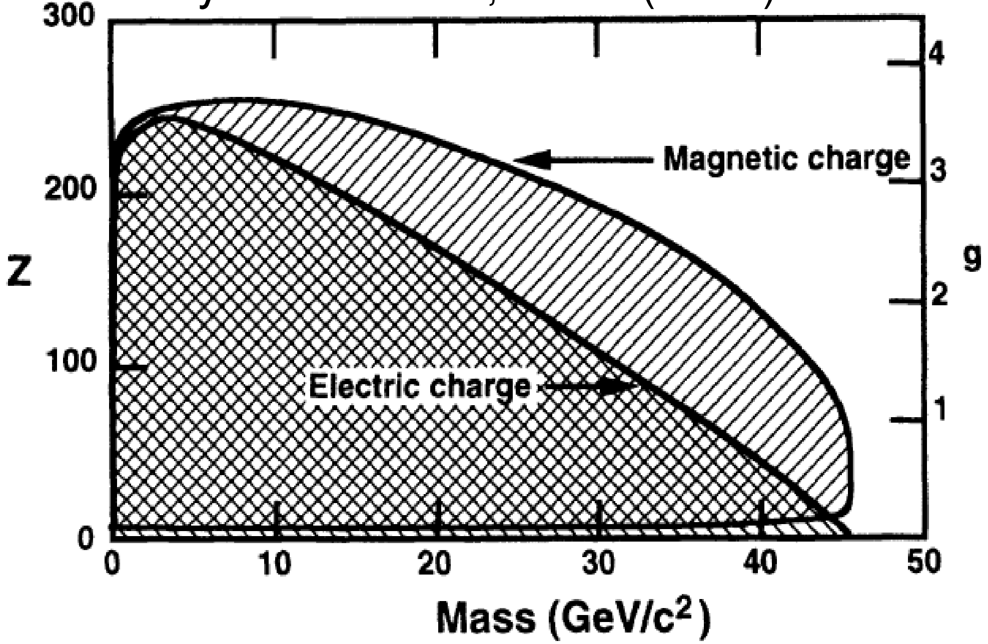
Direct search: track-etch detectors

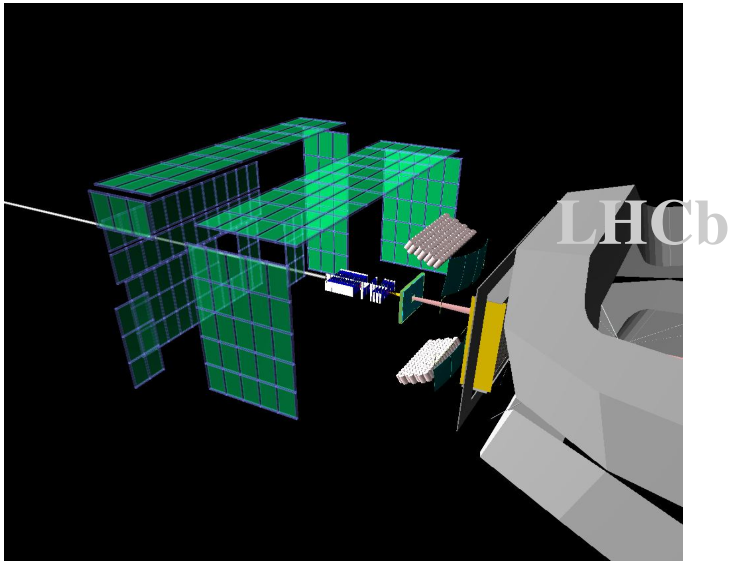
- Pits due to highly-ionizing particles
- Tevatron
- LEP: (MODAL)



- LHC: MOEDAL
  - At Point 8
  - Run in 2010 ?

Phys. Rev. D 46, R881 (1992)

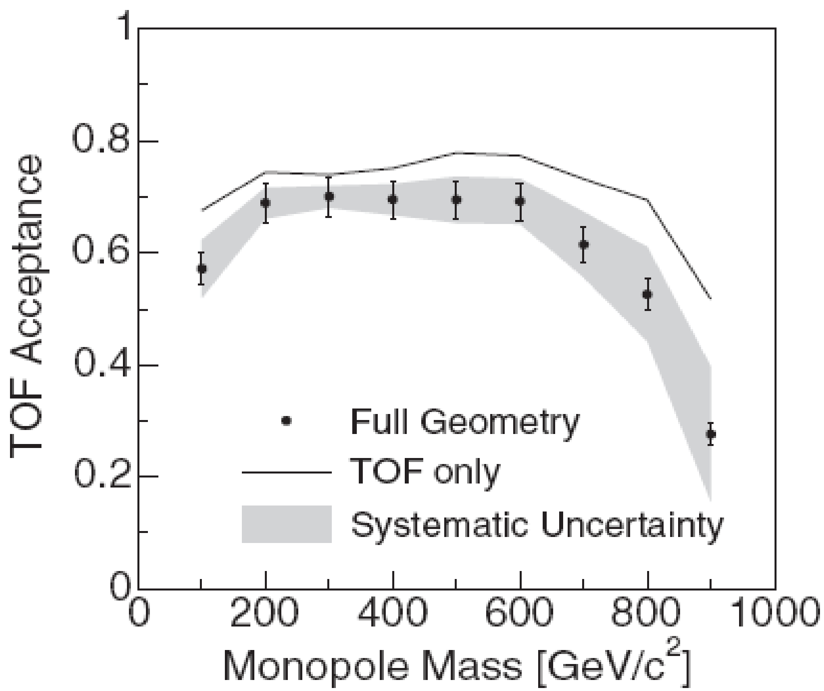


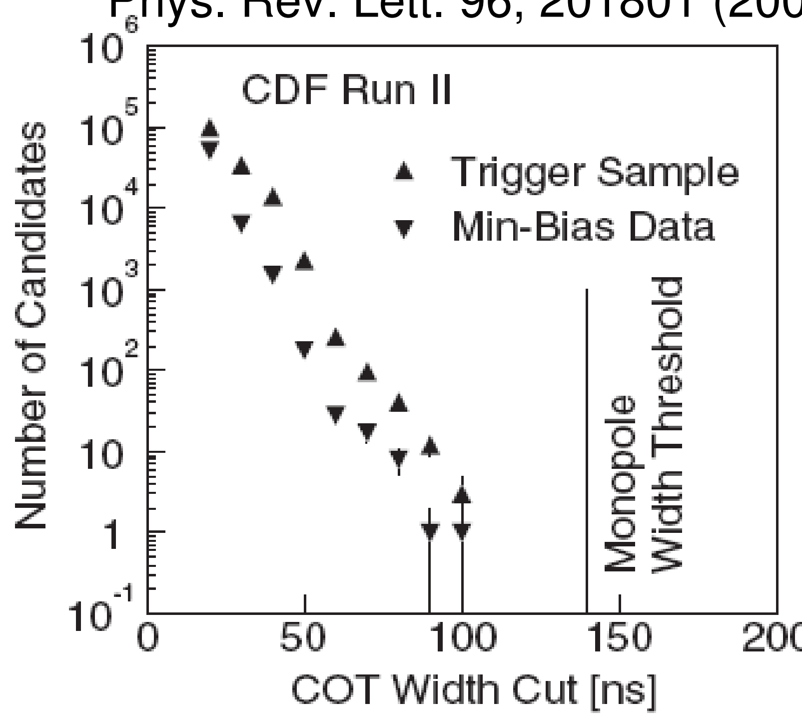


Direct search: CDF

- Special trigger requiring high pulse in TOF scintillator
- High-ionization hits in tracker, straight line in xy plane
- 0.2 pb limit (200 to 700 GeV Dirac monopole)

Phys. Rev. Lett. 96, 201801 (2006)

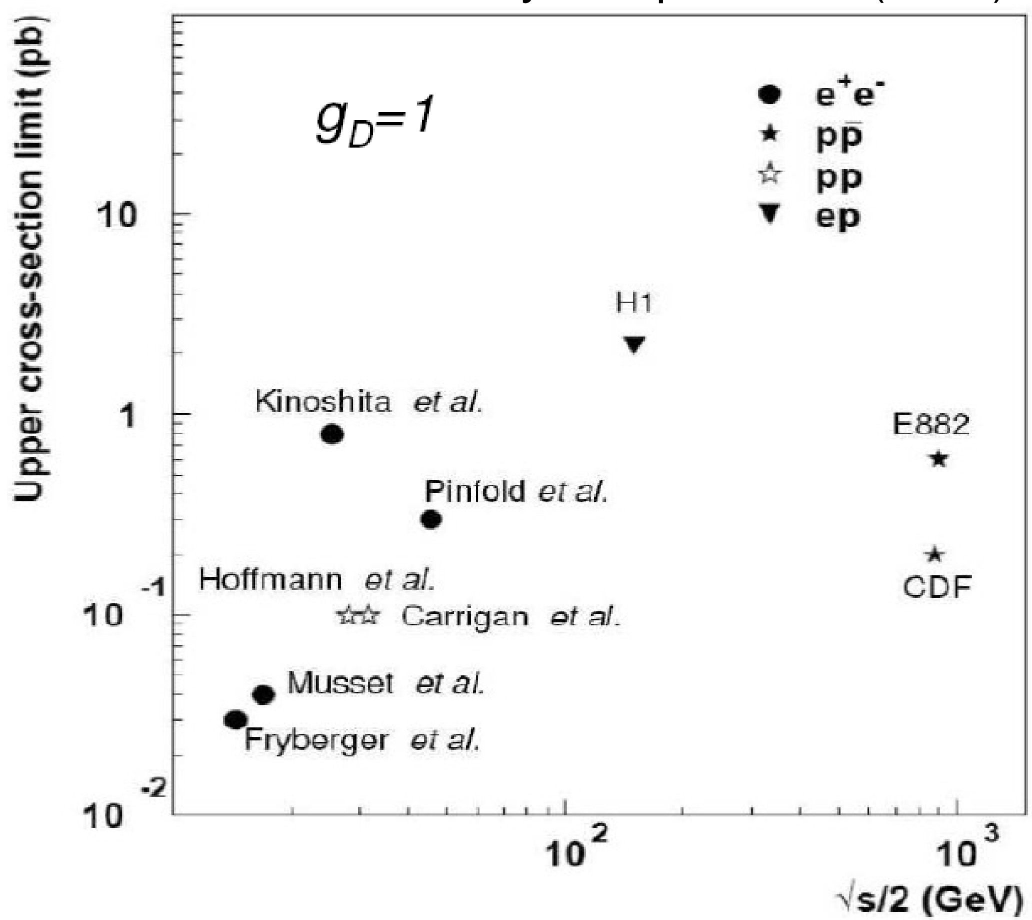




Direct searches: current cross section limits for a Dirac Monopole

Phys. Rept. 438, 1 (2007)

- Each limit valid in a given mass range
- Unwise to quote mass limits (must assume production model)

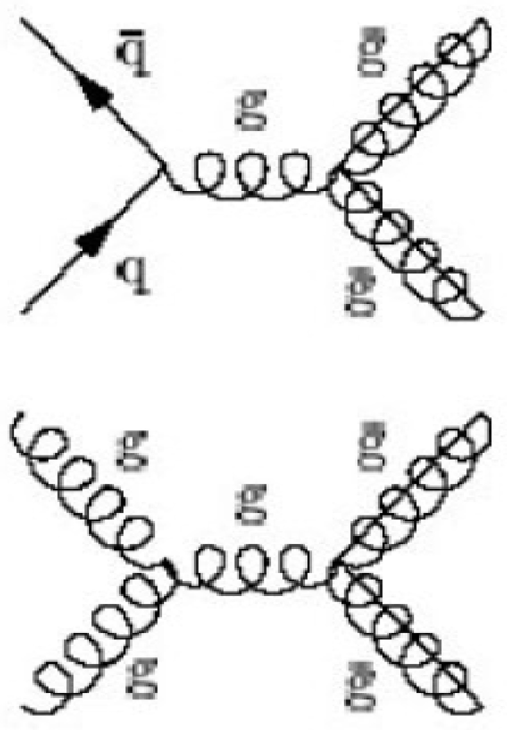


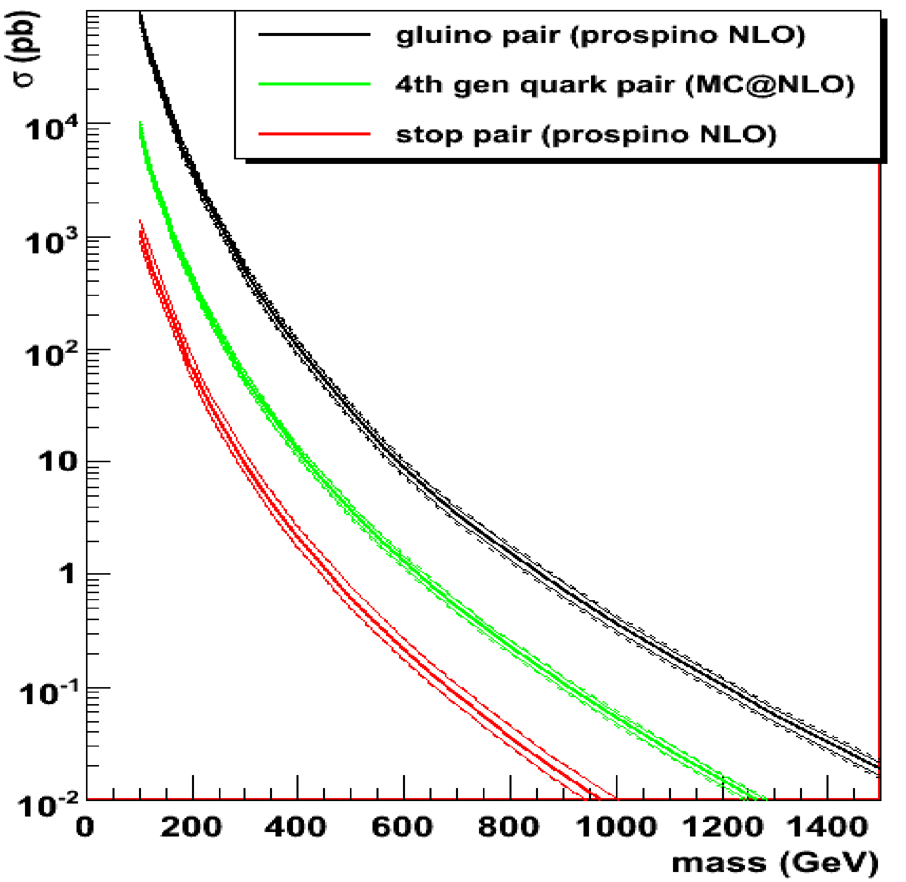
Long-lived particles carrying colour charge

- Colour-triplets:
  - Spin-0: leptoquark, squark
  - Spin-1/2: KK-quark, 4th gen quark
- Colour-octets:
  - Spin-1/2: gluino
  - Spin-1: KK-gluon
- R-Hadrons with integer electric charges

Heavy Coloured objects at the LHC

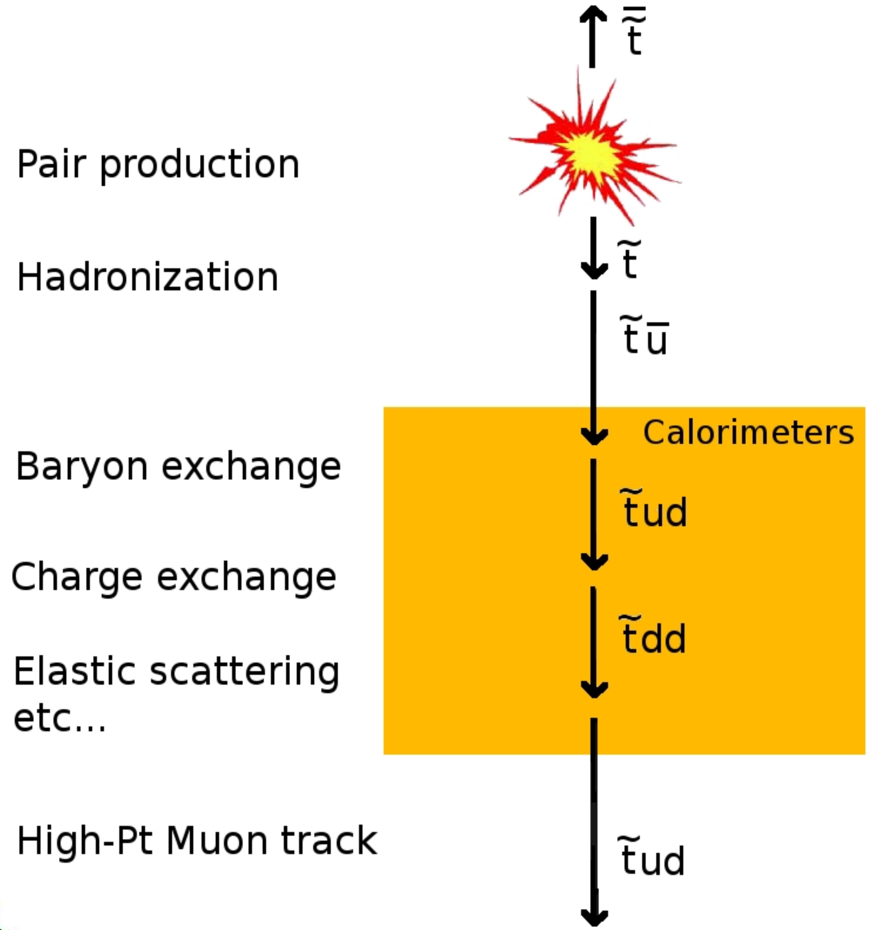
- Strong process, e.g. direct gluino pair production
  - mass 300 GeV → more than 100000/fb^{-1} (14 TeV pp collisions)

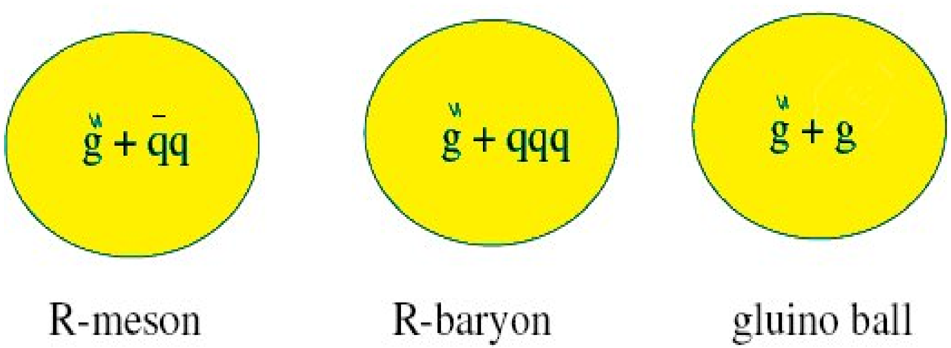




R-Hadrons

- *Coloured*
- *Long-lived* > 50 ns
  (size of detector)
- **Heavy** > 250 GeV
  (current limit)





Generic signature :
slow and high momentum

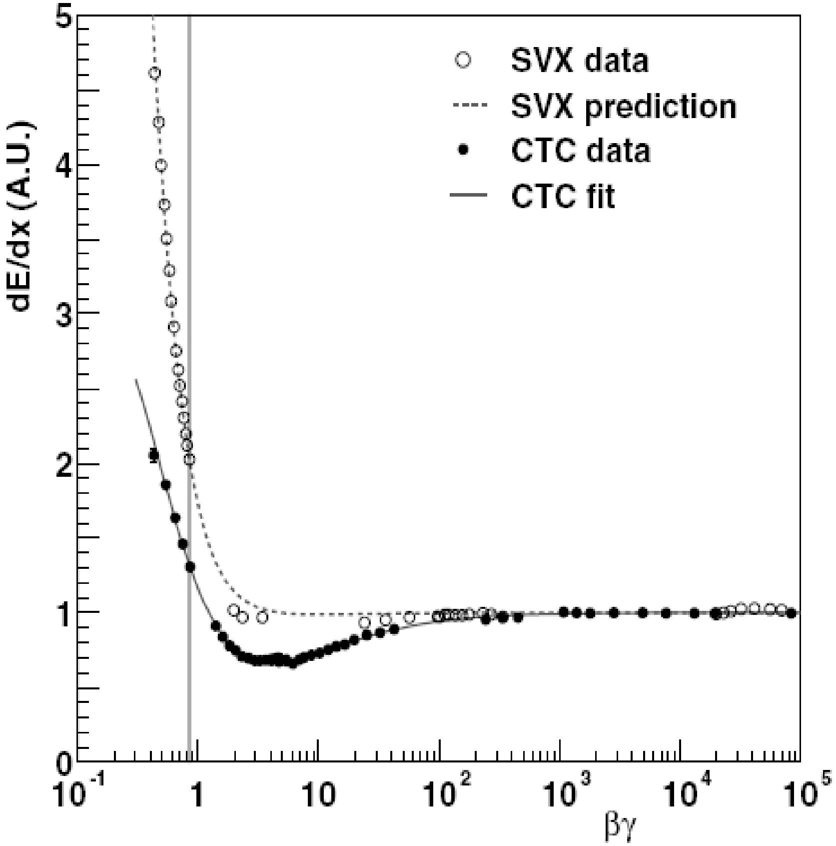
R-Hadrons : mass spectra

- Quark-like : similar to charmed and bottomed hadrons (e.g. Λ_c^+)
- Gluon-like : assume a model
  - Lightest state → neutral or charged ?
  - Gluino balls ?

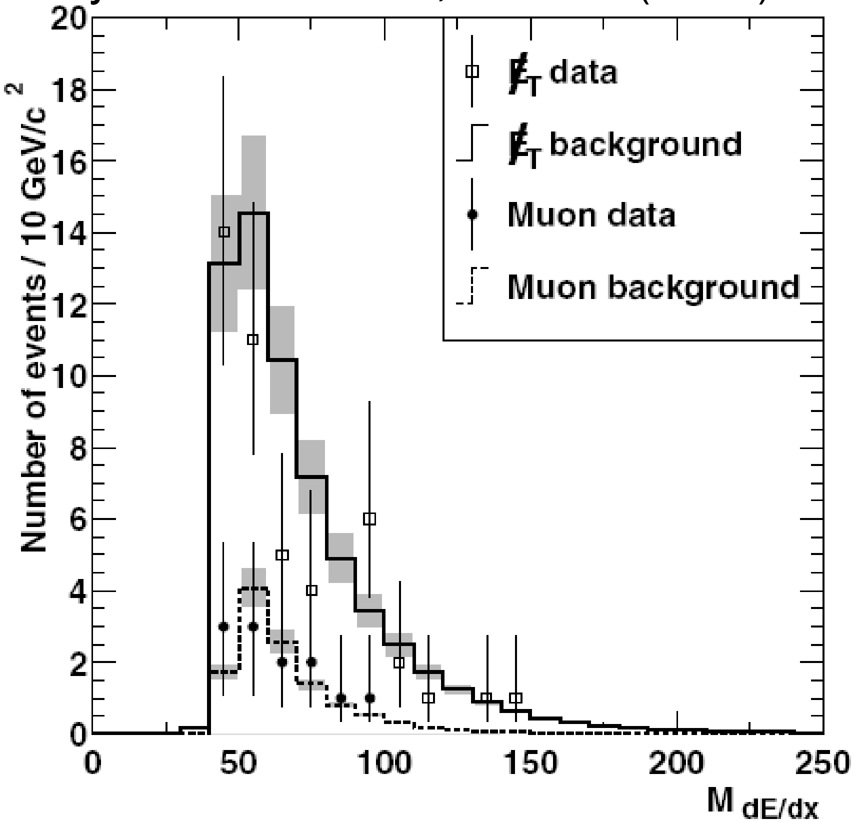
Heavy Parton	States	Mass (GeV)
Squark	$\tilde{q}\bar{u}, \tilde{q}\bar{d}$	$m_{\tilde{q}} + 0.3$
	$\tilde{q}ud$	$m_{\tilde{q}} + 0.7$
Gluino	$\tilde{g}q\bar{q}, \tilde{g}u\bar{d}, \tilde{g}d\bar{u}, \tilde{g}g$	$m_{\tilde{g}} + 0.7$
	$\tilde{g}uds$	$m_{\tilde{g}} + 0.7$

arXiv:0908.1868

CDF search using dE/dx in inner detector



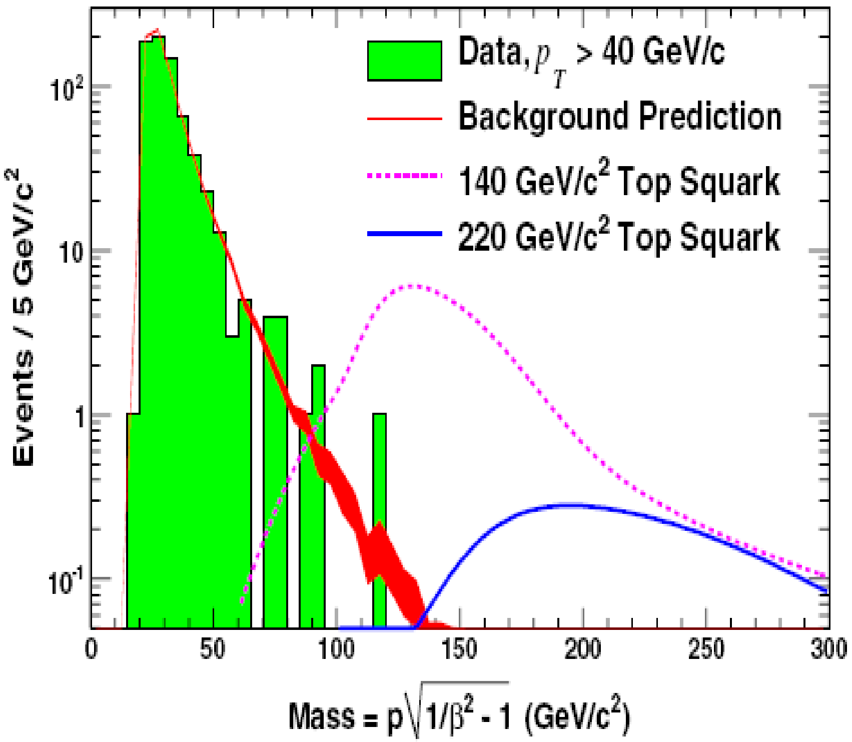
Phys. Rev. Lett. 90, 131801 (2003)

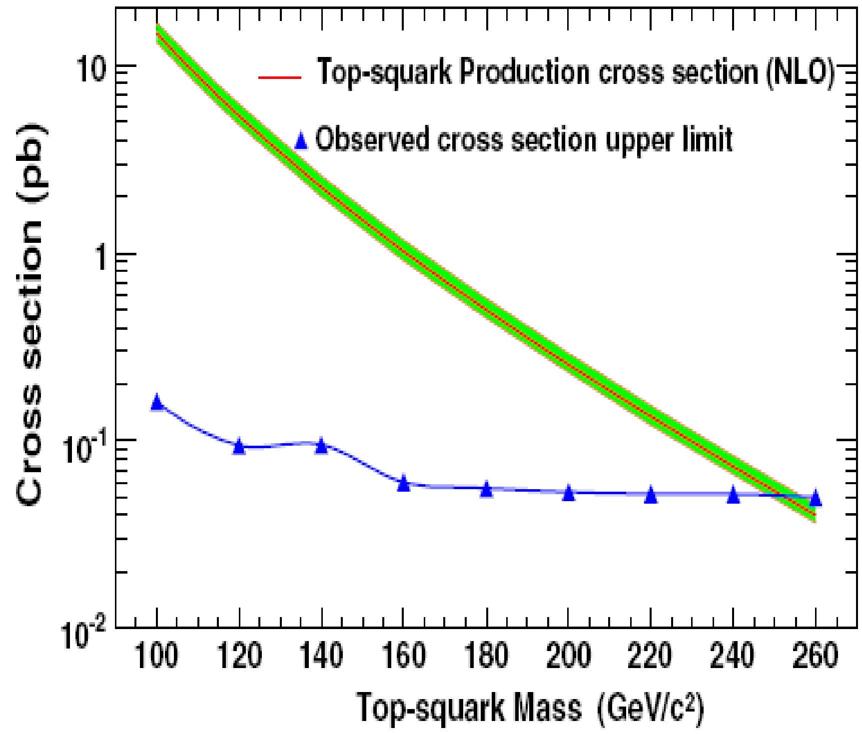


- ~200 GeV mass limit for long-lived 4th gen quark

CDF search using TOF in muon detector

Phys. Rev. Lett. 103, 021802 (2009)

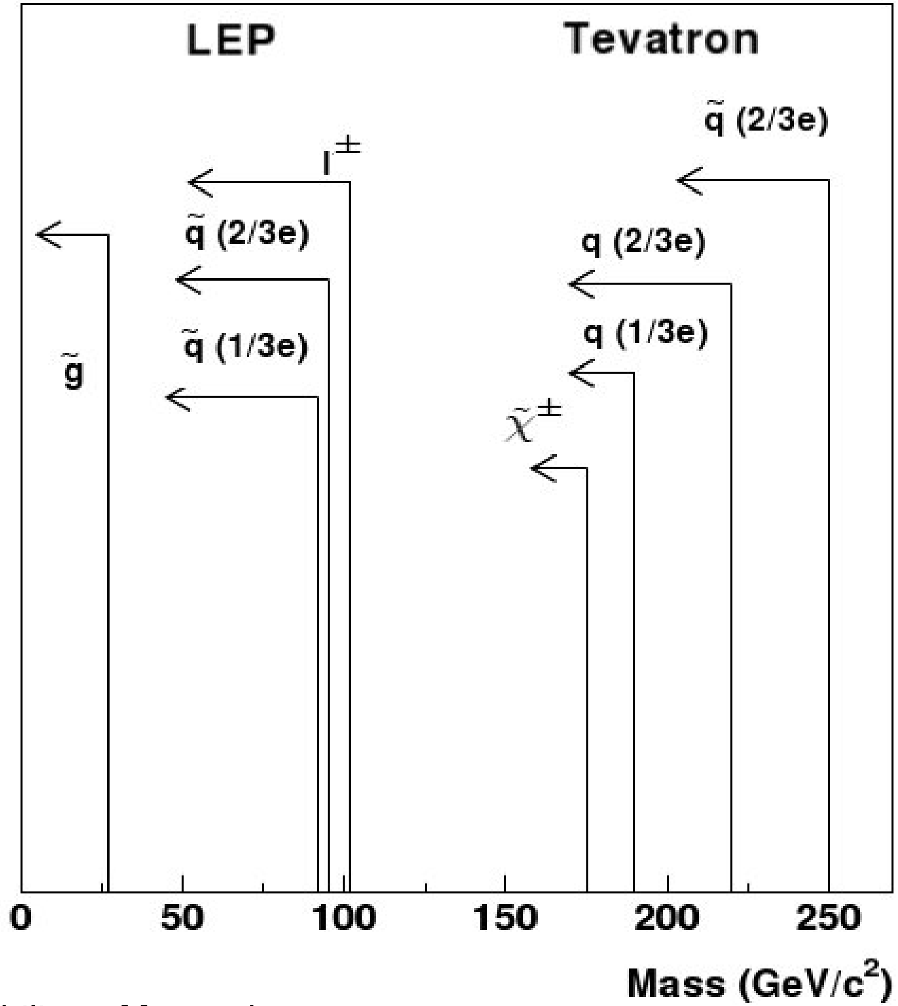




- 250 GeV mass limit for long-lived scalar top quark

R-Hadrons and long-lived leptons: published exclusion limits

- Assume standard couplings
- What are the limits for a color-octet ?



Signature-based long-lived particle searches in ATLAS

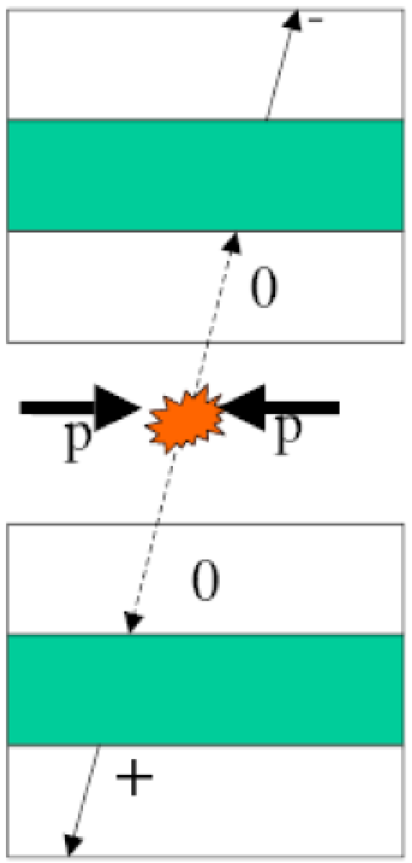
- Displaced vertices / kinks
- Non-pointing photons
- Low EM calorimeter fraction
- Jets in empty bunches
- Slow tracks
- High invariant mass dimuons
- Highly ionizing tracks

} decaying (first four items)

} non-decaying (last three items)

Early data: Generic & Simple

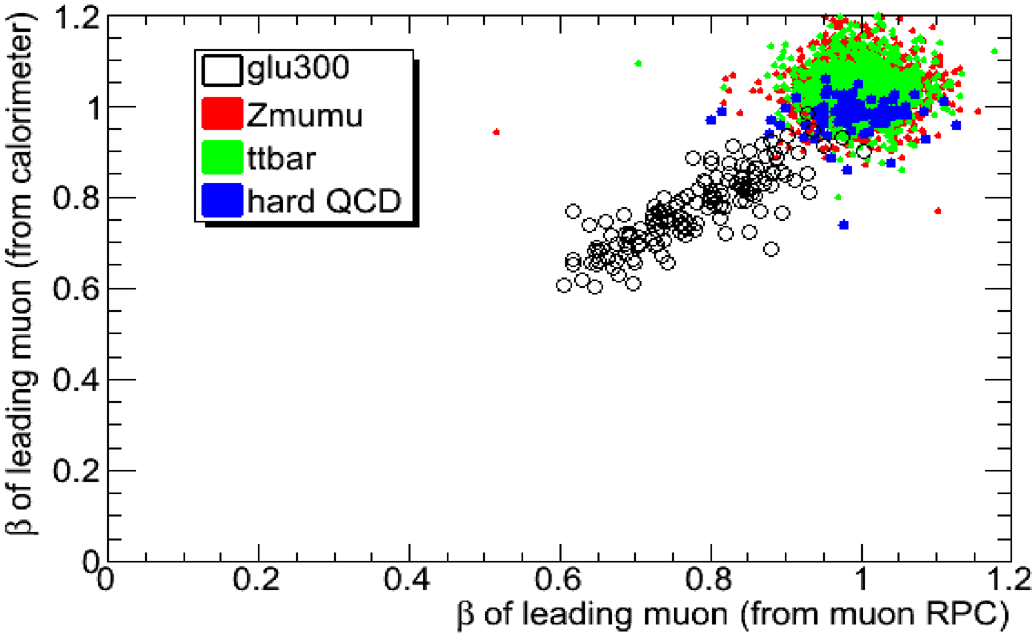
- Systematics
  - Efficiency
  - Robustness
  - Backgrounds
- Non-optimum conditions
- Look for extreme signatures
- Use several independent variables



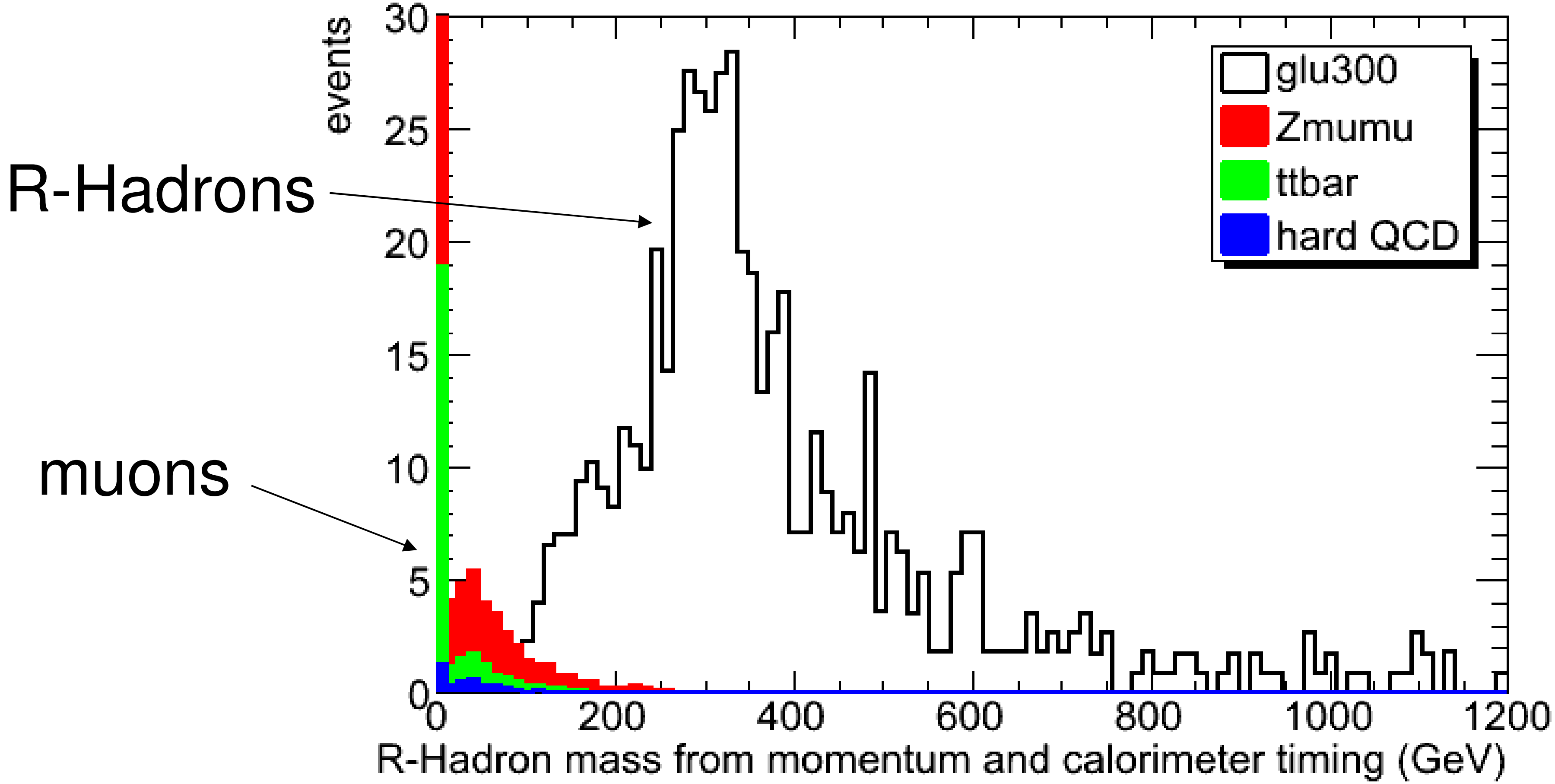
R-Hadrons and long-lived leptons in ATLAS: low speed

(From this point, plots are approximative and shown only for illustration)

- Measure time-of-flight of high-momentum objects
  - Calorimeter
  - muon RPC
- If correlation
  - Slow massive particle !

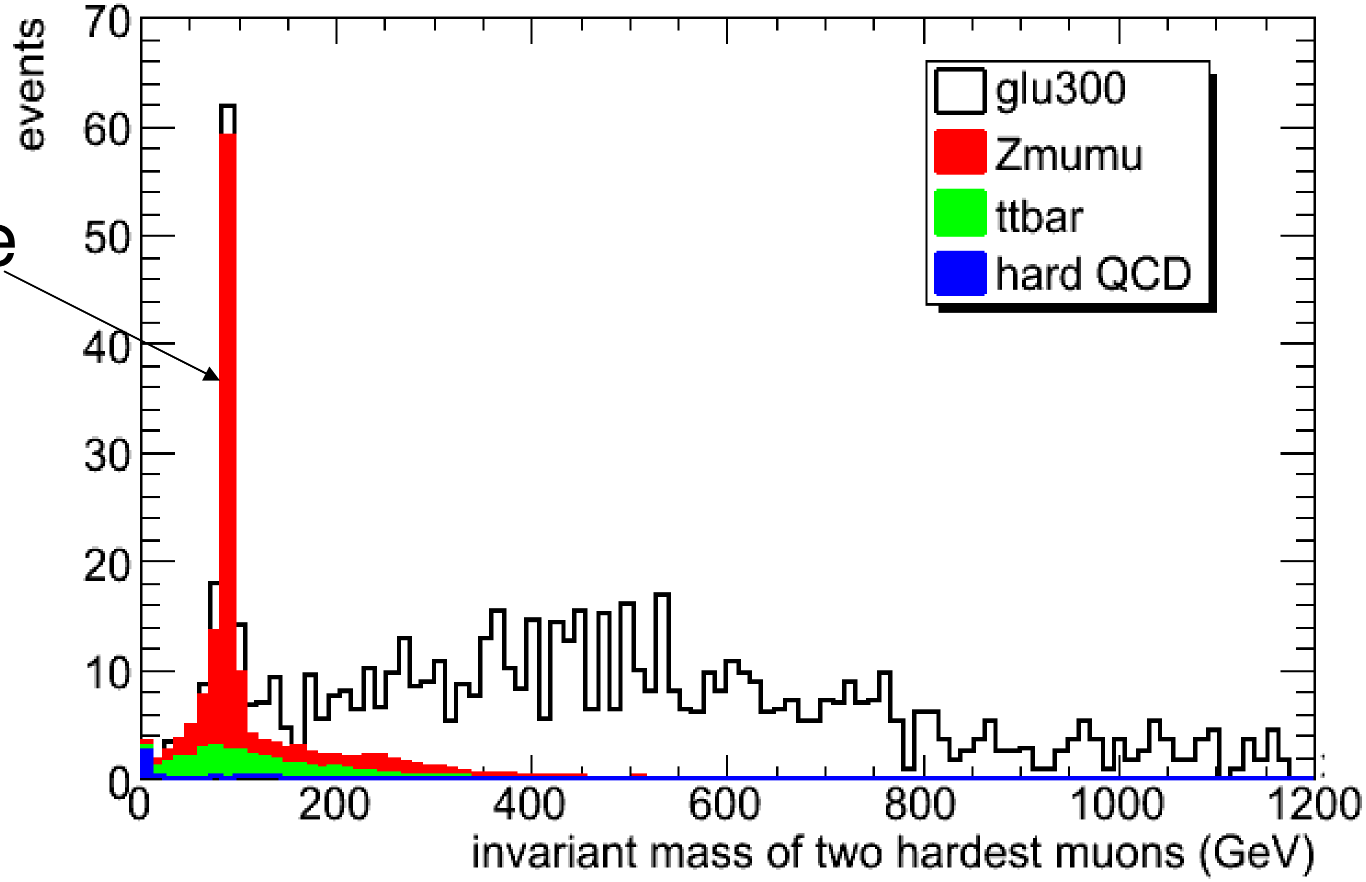


R-Hadrons: reconstructed mass



R-Hadrons: invariant mass two muon objects

Z resonance

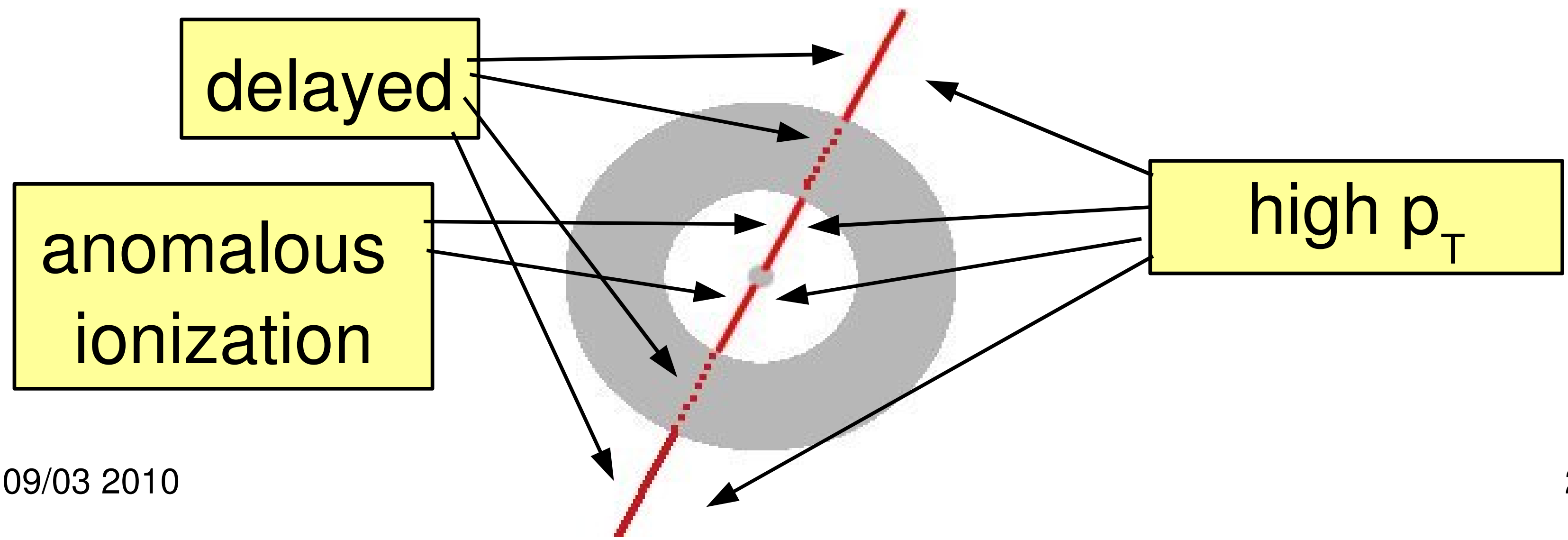


R-Hadrons summary: possible selection criteria

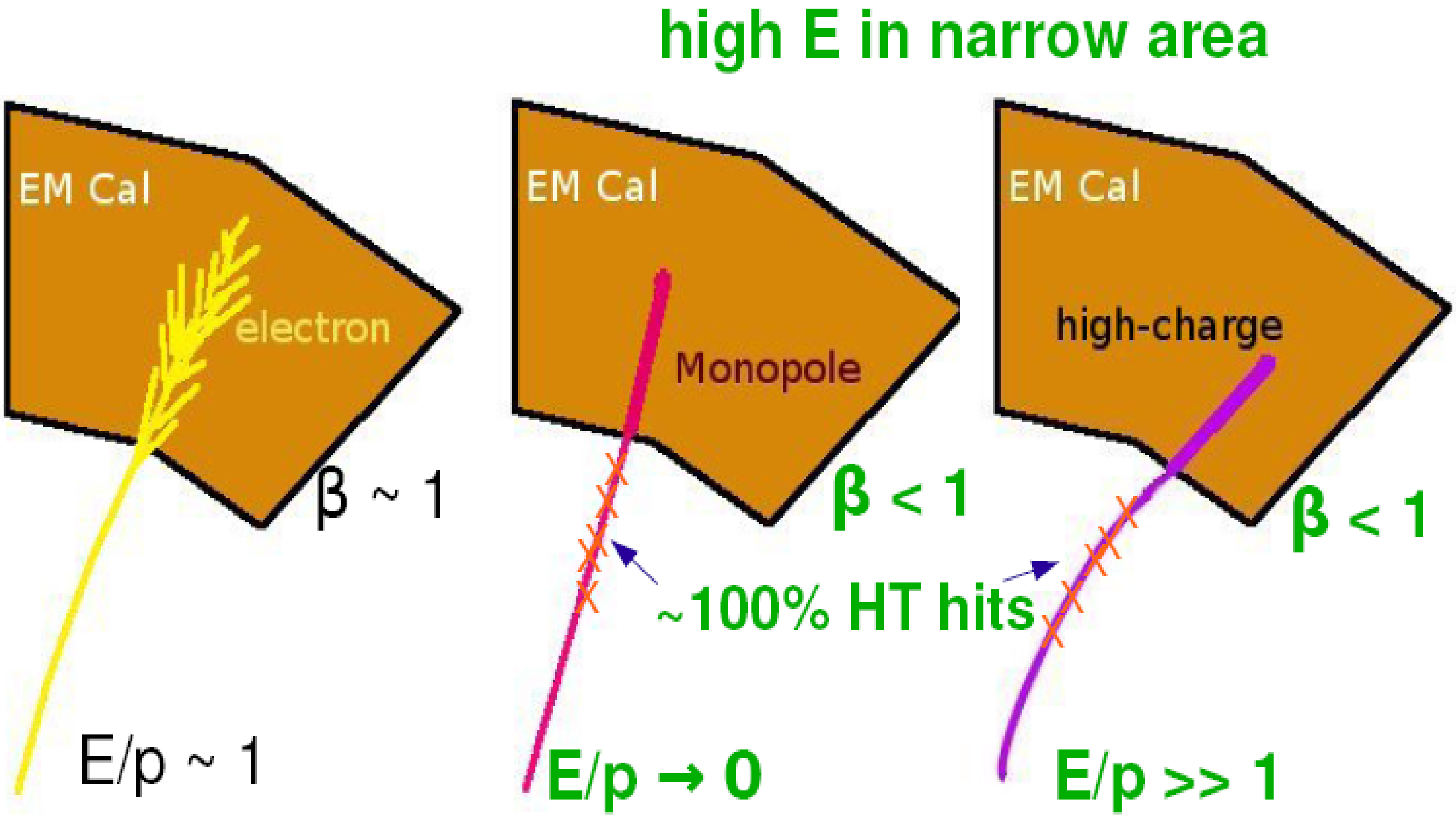
1. Low β in muon system and/or calorimeter
   - Fakes : tails in muon β distributions, cosmics
2. High-p_T muon track without associated ID track
   - Fakes : ID inefficiencies
3. Additional muon and high invariant mass
   - Fakes : high-p_T tails
4. A combination of the above

R-Hadrons: unmistakable events

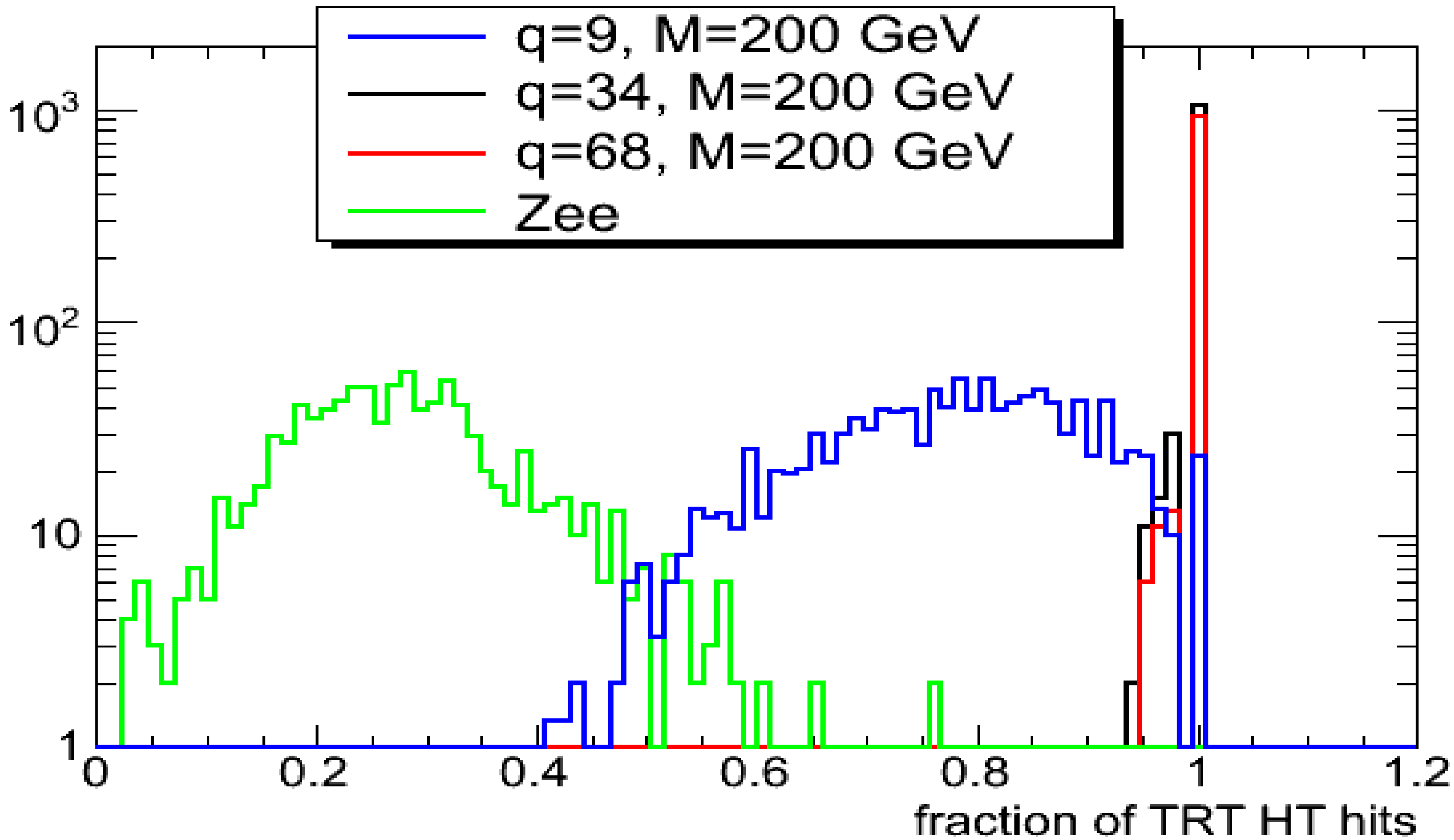
- Look for anomalies in spectra of muon objects
  - All variables behave as expected for ordinary muons
    → cross section and mass limits
  - Excess → Detector effect ? Unexpected backgrounds ? New physics ?
- Combine all variables



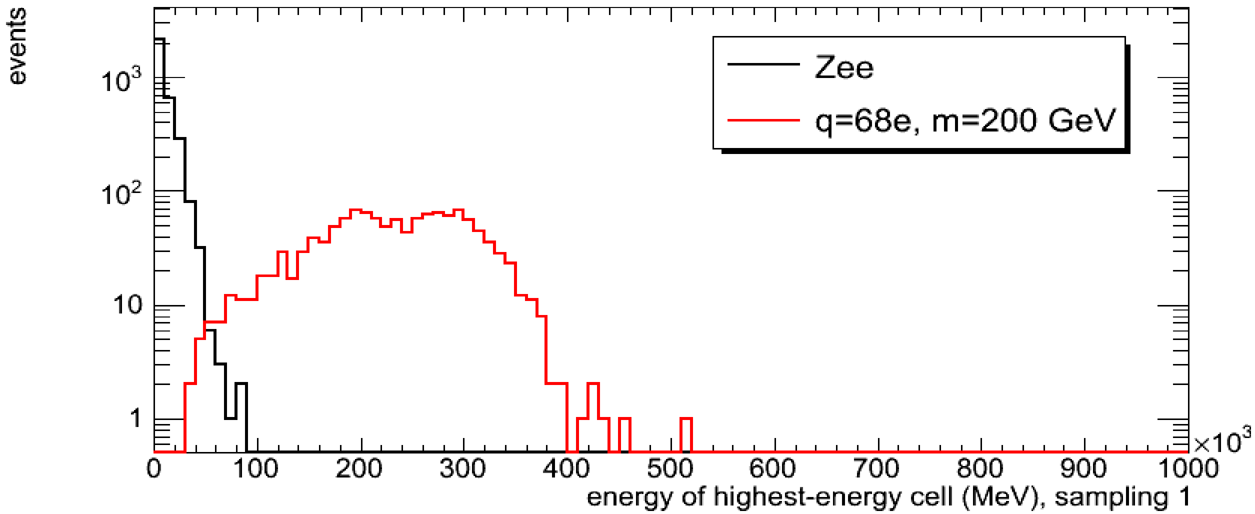
Highly ionizing particles (HIPs) in ATLAS



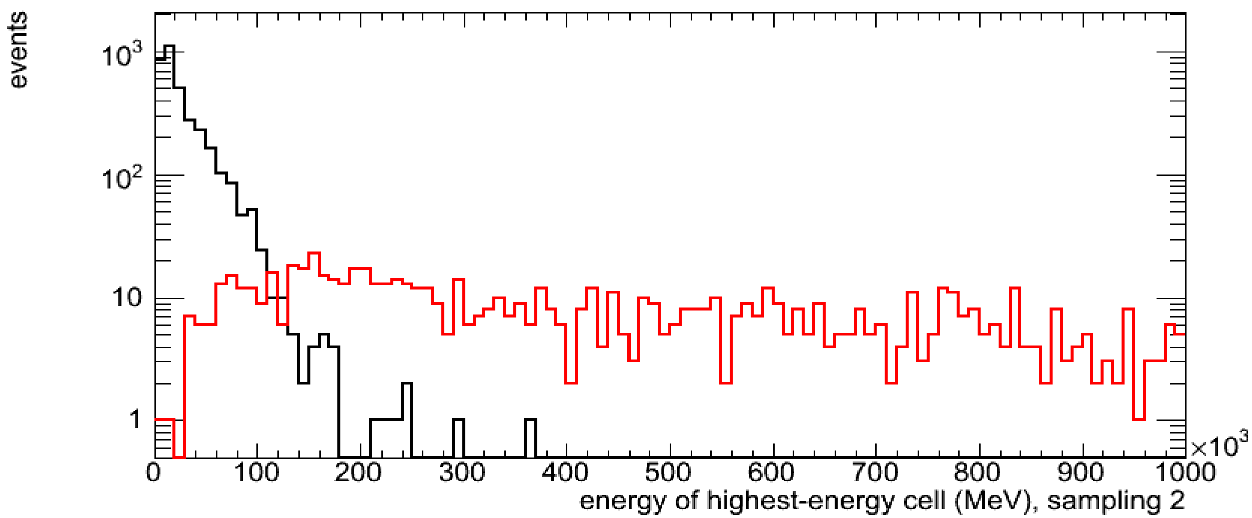
HIPs: TRT


q=9, M=200 GeV
q=34, M=200 GeV
q=68, M=200 GeV
Zee
10^3
10^2
10
1
0
0.2
0.4
0.6
0.8
1
1.2
fraction of TRT HT hits

HIPs: EM calorimeter cell energy

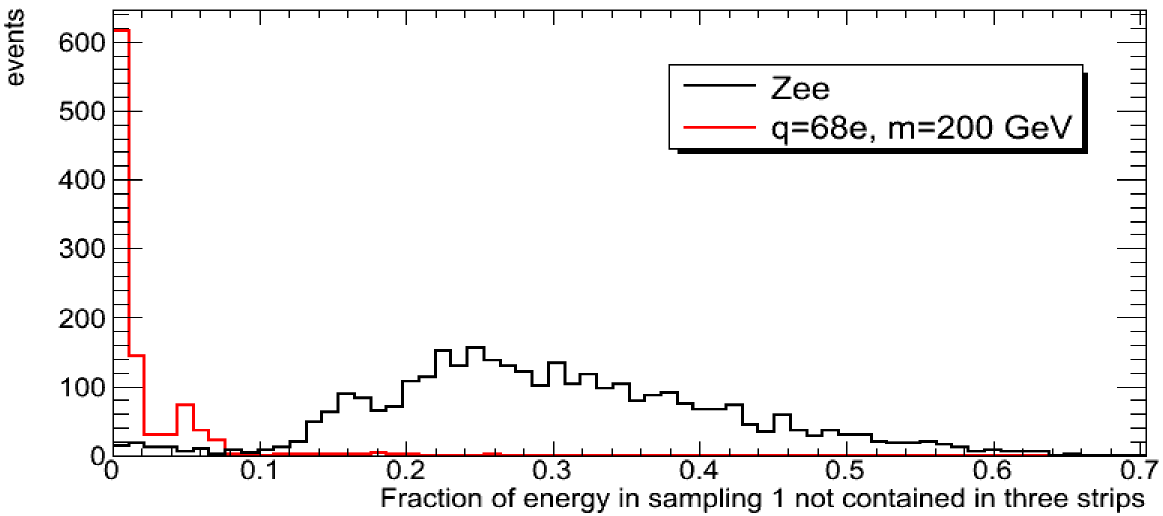


First layer

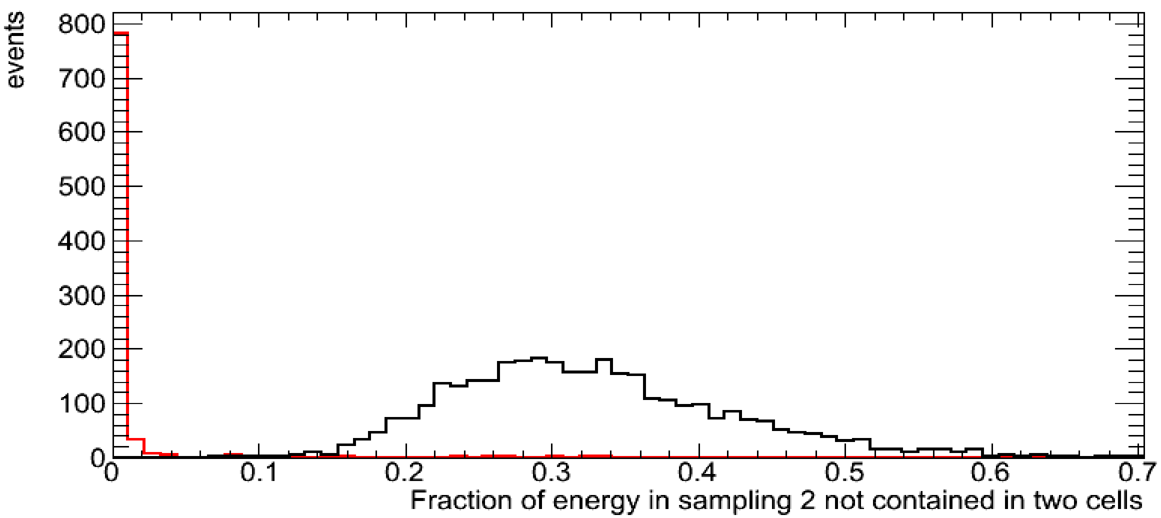


Second layer

HIPs: EM shower shape



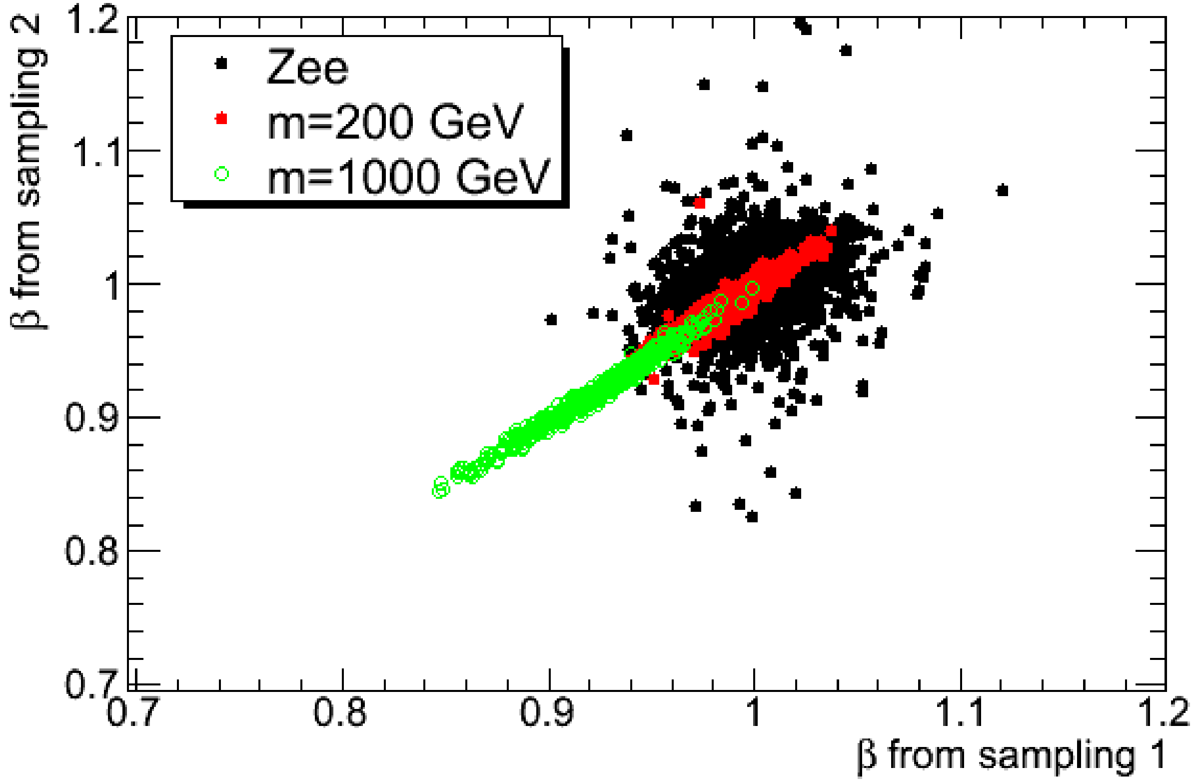
First layer
(3 cells)



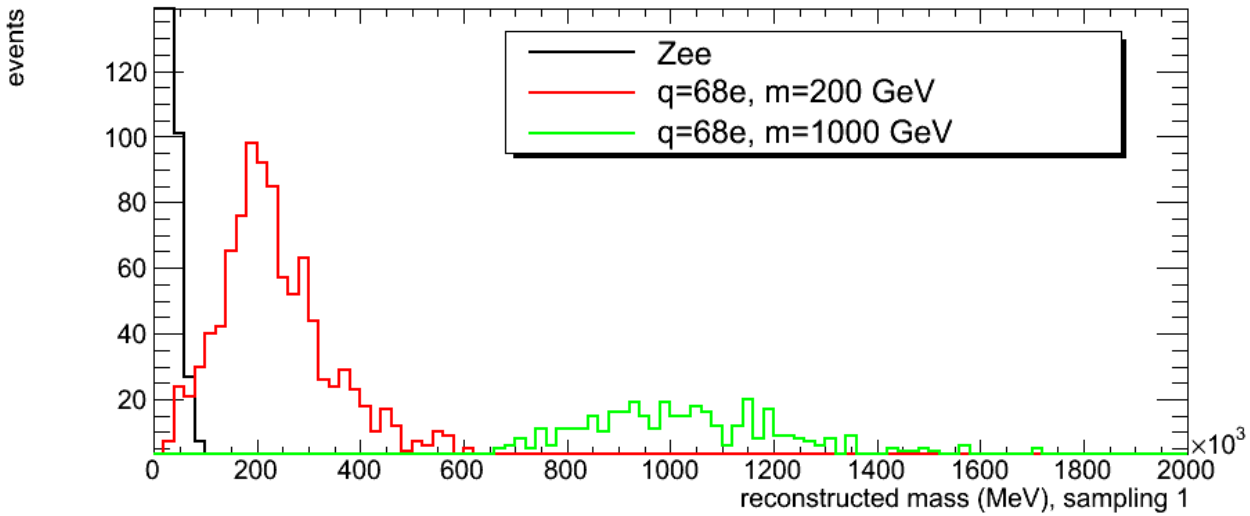
Second layer
(2 cells)

HIPs: low speed

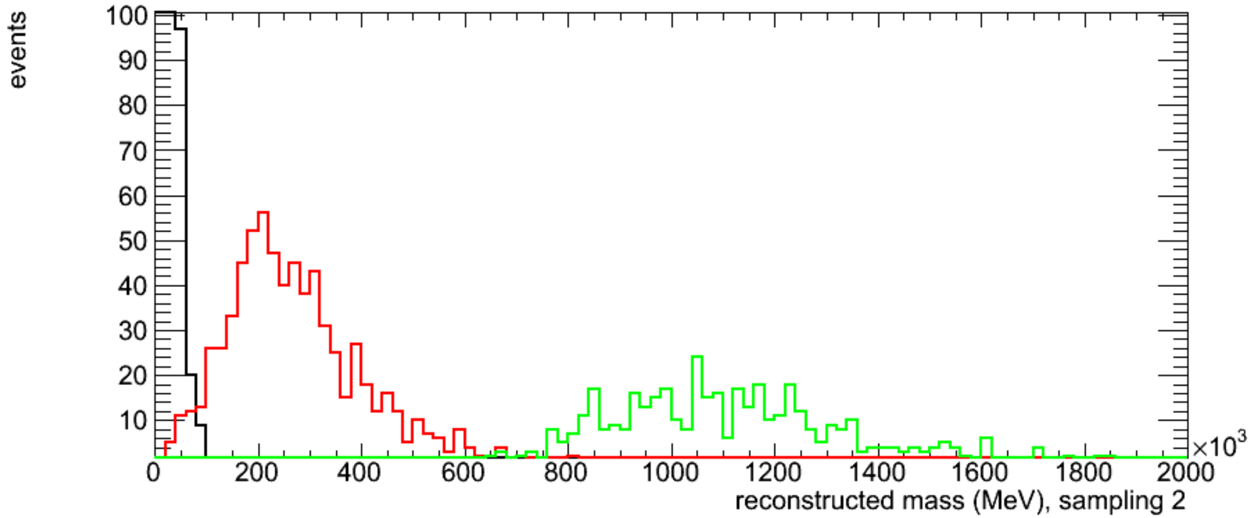
- Measure time-of-flight with calorimeter cells
  - EM layer 1
  - EM layer 2
- If correlation
  - Slow massive particle !



HIPs: reconstructed mass



First layer



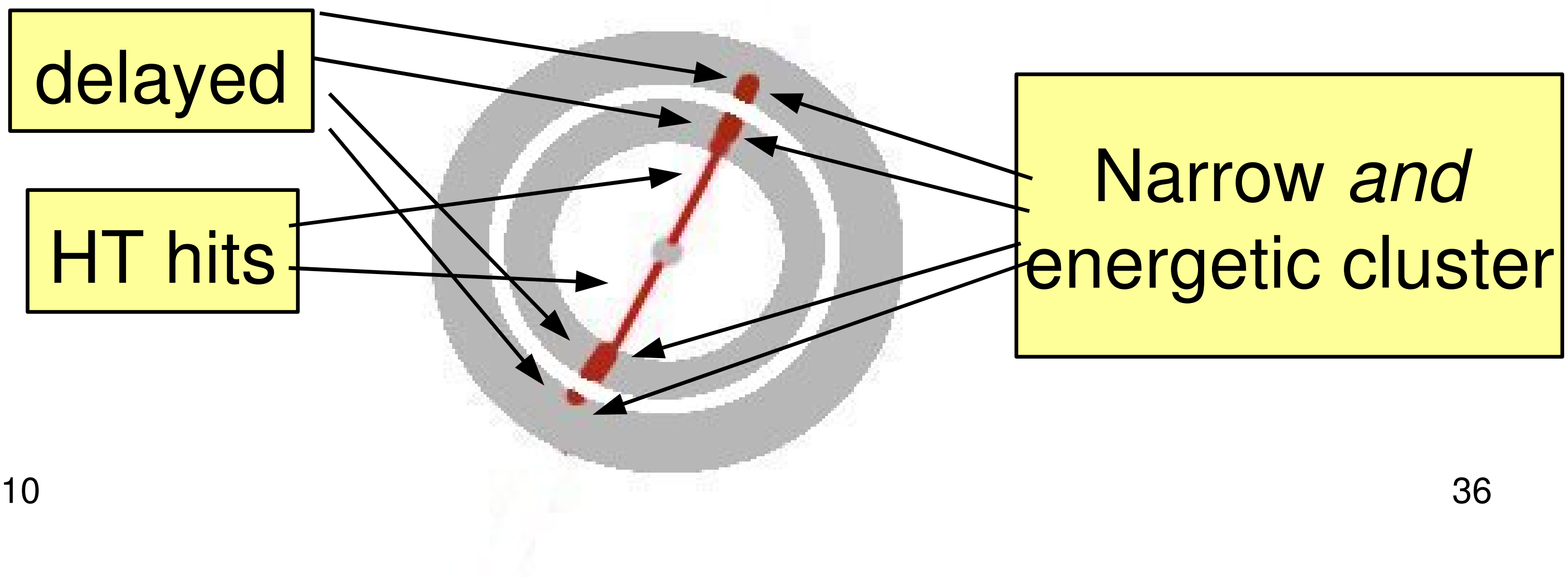
Second layer

HIPs summary: possible selection criteria

1. High fraction (>90%) of TRT HT hits along track
   - Fakes : high-energy electrons, low-energy deuterons and alphas
2. Large energy deposition in most energetic cell in both EM calorimeter layers
   - Fakes : high-energy electrons
3. Narrow EM shower in both EM calorimeter layers
   - Fakes : hot cells
4. A combination of the above

HIPs: unmistakable events

- Look for anomalies in spectra of EM objects
  - All variables behave as expected for ordinary electrons and photons → cross section and mass limits
  - Excess → Detector effect ? Unexpected backgrounds ? New physics ?
- Combine all variables



Summary

- Fundamental physics puzzles
  - We expect new physics at the TeV scale
  - LHC will probe these regions
  - Signatures : electrons, jets, missing energy, long-lived particles
- Search techniques with general-purpose experiments (experience from LEP and Tevatron)
  - Late arrival / late decays
  - Energy loss
  - Special event topologies

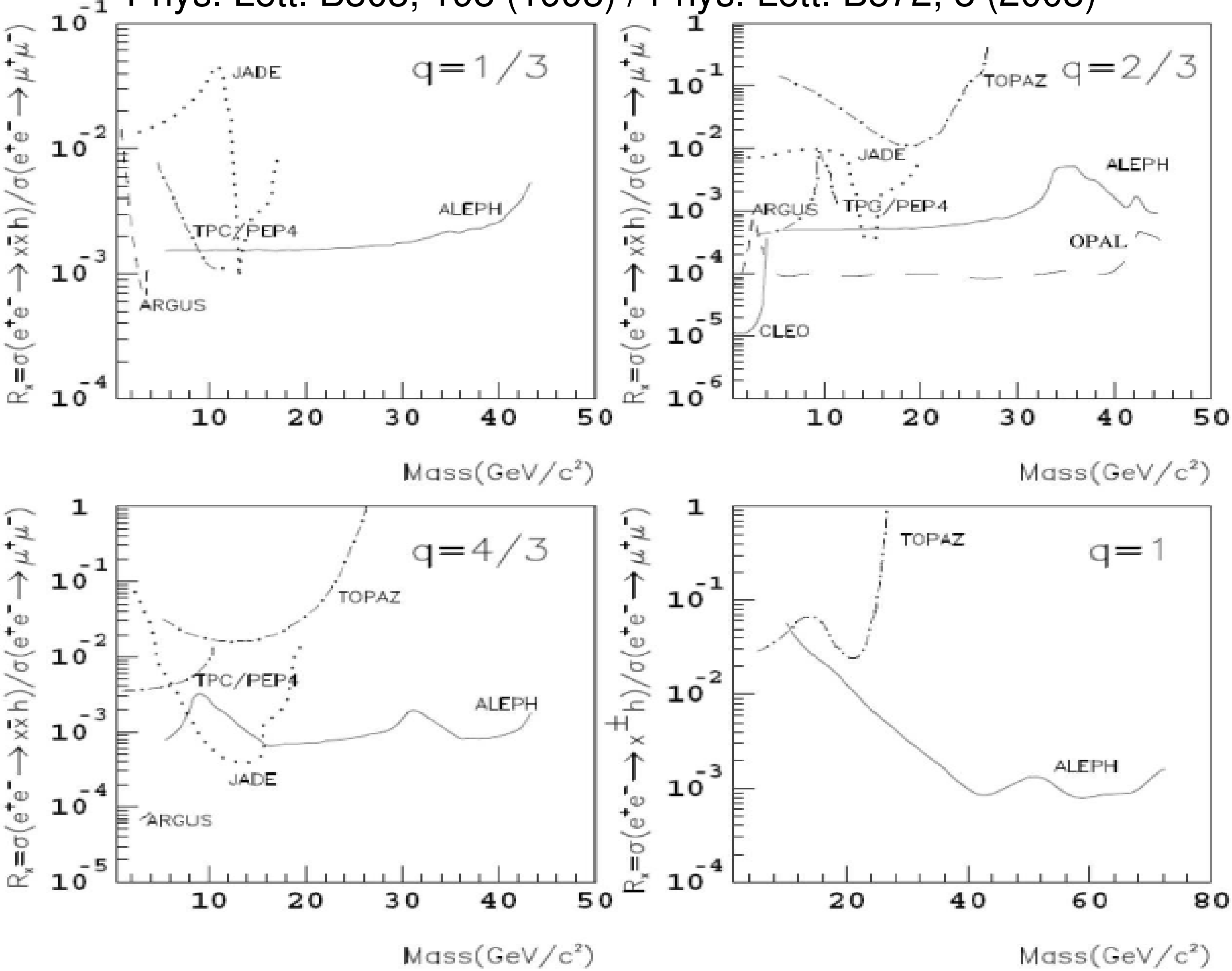
Outlook

- As soon as the LHC runs at 7 TeV collision energy (which should be pretty soon)
  - Look at all possible signatures
  - Can we do exciting physics even with non-optimized data ?
  - e.g. R-Hadrons, Monopoles in ATLAS → striking events
  - Possibly large cross sections → high masses accessible early

Extra slides

Free quarks / low-charge objects

Phys. Lett. B303, 198 (1993) / Phys. Lett. B572, 8 (2003)



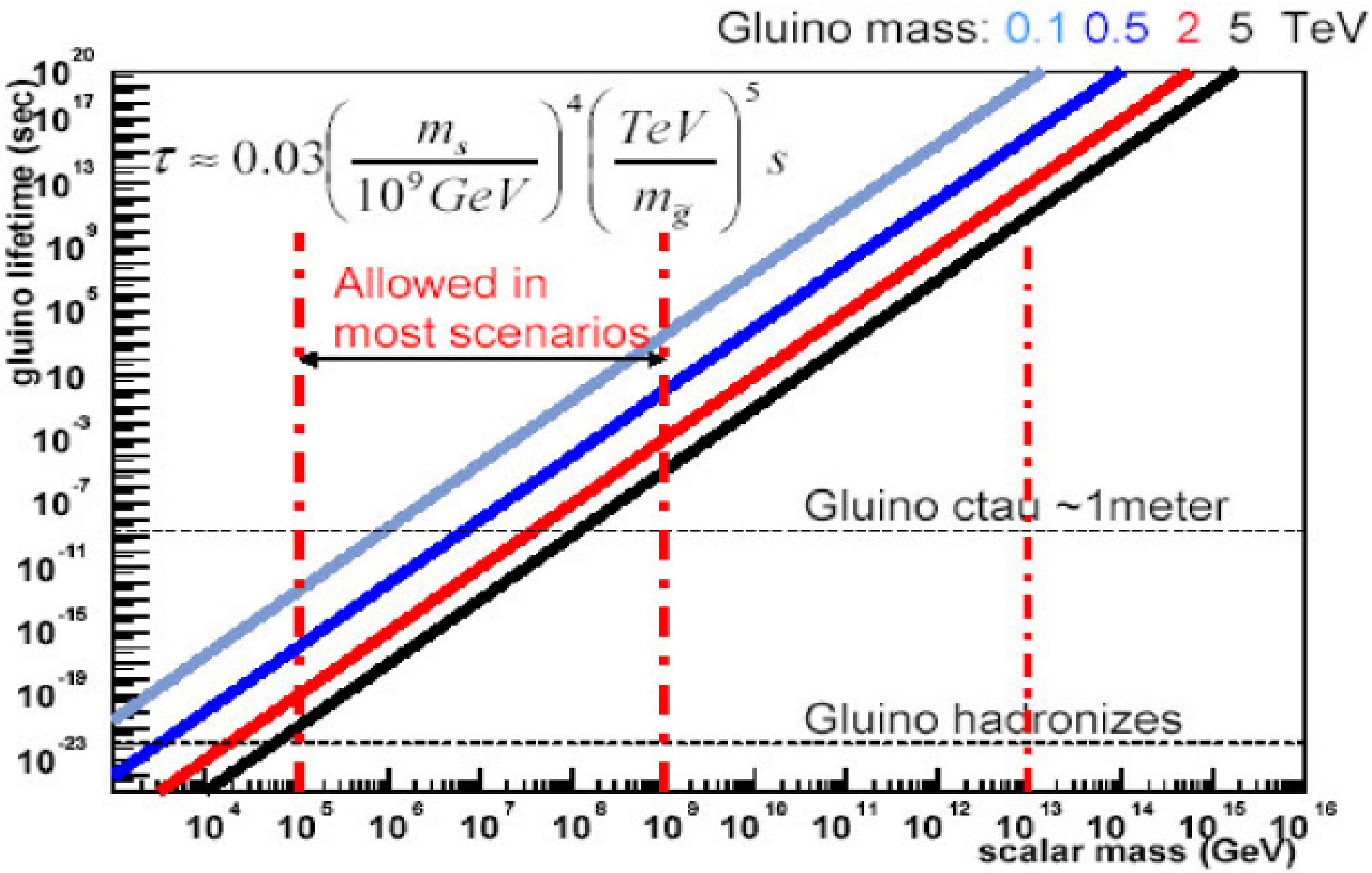
SUSY models giving rise to SMPs

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.
$\tilde{\ell}_{s1}$	$\tilde{G}$	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.

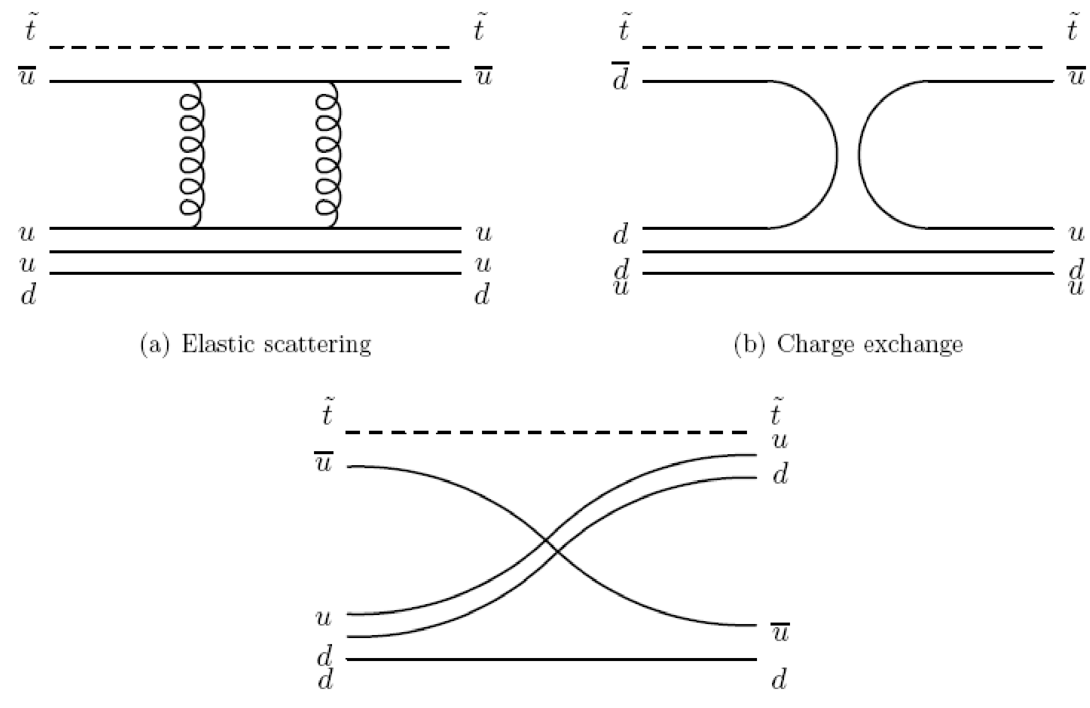
arXiv:hep-ph/0611040v2

Gluino lifetime sin split-SUSY



Interactions of R-Hadrons with detector material

- Heavy parton unlikely to interact (cross section suppressed by $1/m^2$)
- Effectively low-energy (~GeV) interactions involving light quarks
  - Regge Theory
- Light quark flavor can change several times during the passage through the detector



(a) Elastic scattering

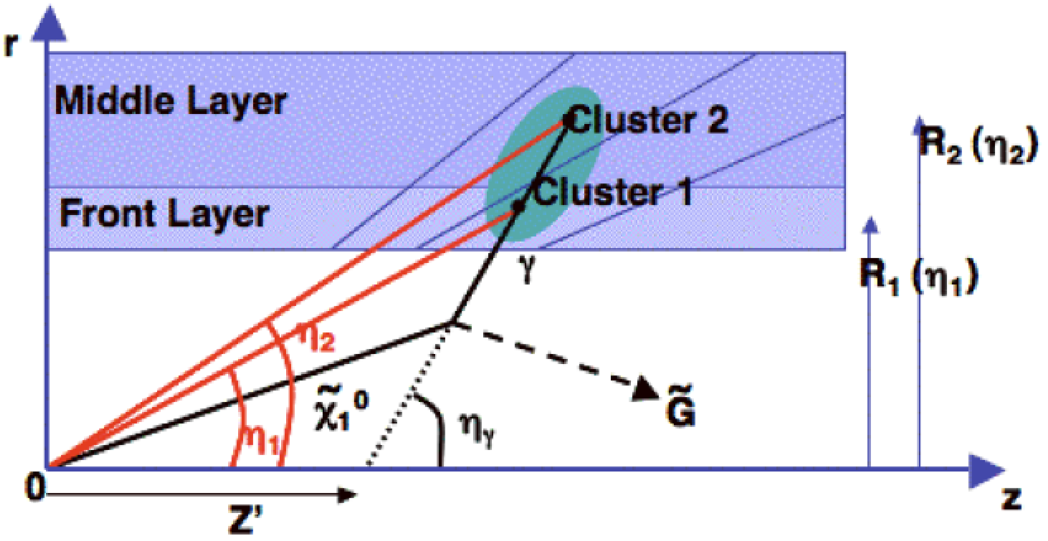
(b) Charge exchange

(c) Baryon exchange

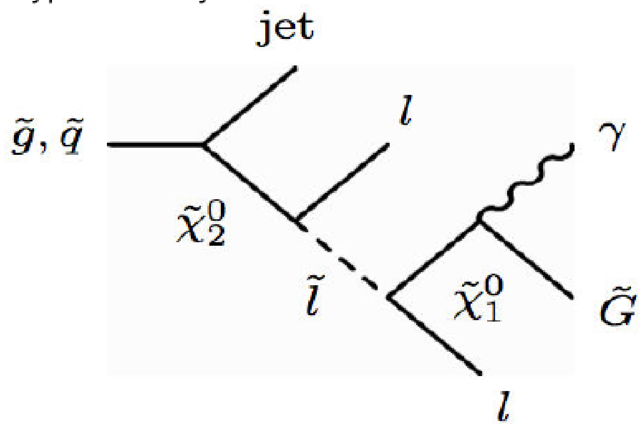
(Details of scattering model and GEANT4 implementation: R. Mackeprang, A. Rizzi, Eur. Phys. J. C50 (2007) 353-362)

Non-pointing photons

•In GMSB, the symmetry is broken by gauge interactions through messenger gauge fields.
If decay length of the neutralino is comparable to the size of the ATLAS inner detector, high pT photons could enter the calorimeter at angles (ηϒ) deviating significantly from the nominal pointing angle (η2).
i.e. ηϒ != η2

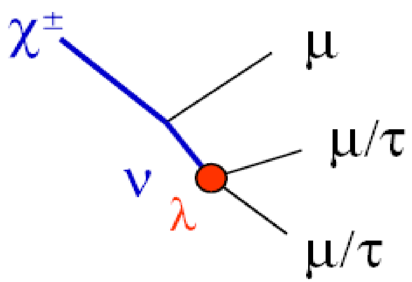


typical decay chain for Neutralino NLSP

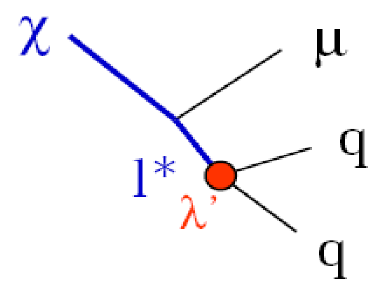


Displaced vertices

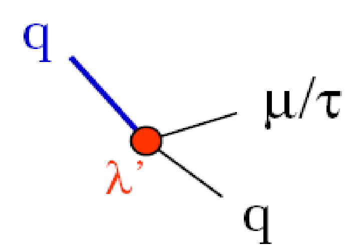
Late decays into muons and taus via RPV:



Most similar



We are looking for DV with muons.



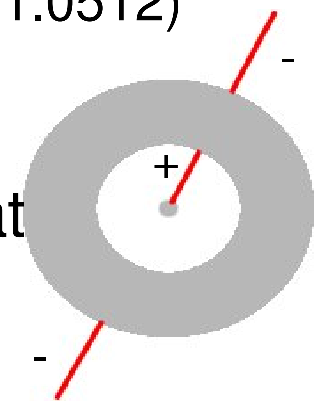
BR very small

Are CDF ghost events due to RPV SUSY: probably not

Are we sensitive to this kind of events: yes

R-Hadron event selection

(SUSY chapter in CERN-OPEN-2008-020, arXiv:0901.0512)



Search for stop and gluino R-Hadrons, optimized for 1 fb^{-1} of integrated luminosity for pp collisions at 14 TeV

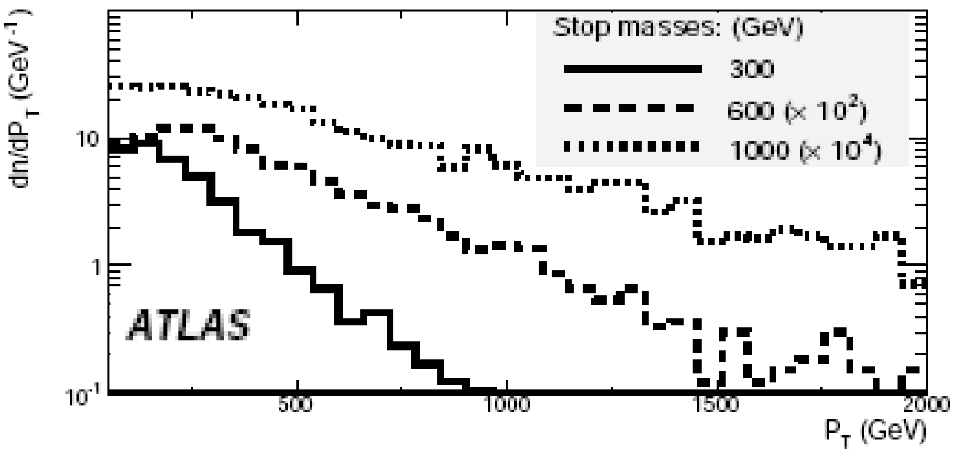
- Trigger : muon trigger
- Selection : jet veto + one of the following criteria
  - Hard (p_T>250 GeV) muon track lacking inner track
  - Two hard back-to-back inner tracks with few high-threshold (HT) hits
  - Two hard back-to-back like-sign muon tracks
  - One hard muon track with inner track of opposite charge

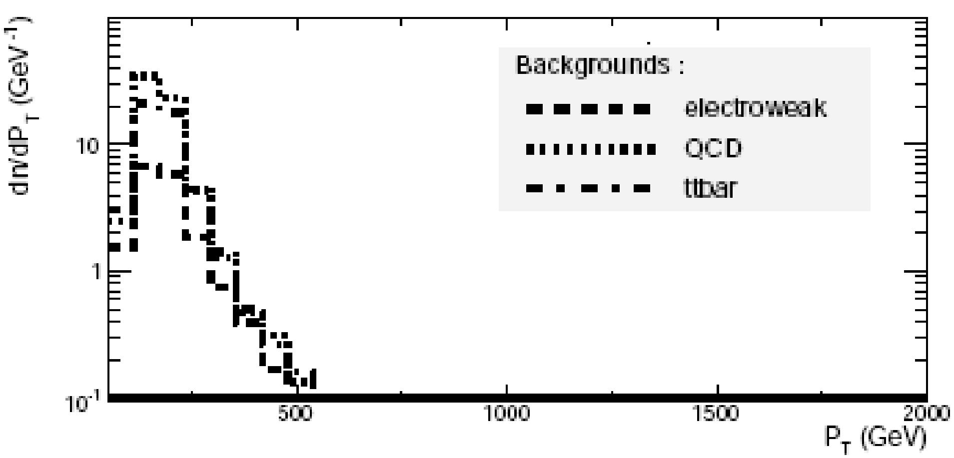
Simulated data

- Signal samples
  - Gluinos 300, 600, 1000, 1300, 1600, 2000 GeV
  - Stops 300, 600, 1000 GeV
- Background samples
  - QCD dijets (PYTHIA) with $p_T > 140$ GeV
  - Top pairs (semi-leptonic)
  - W and Z with muons in final state
- Full ATLAS simulation
- Standard ATLAS reconstruction

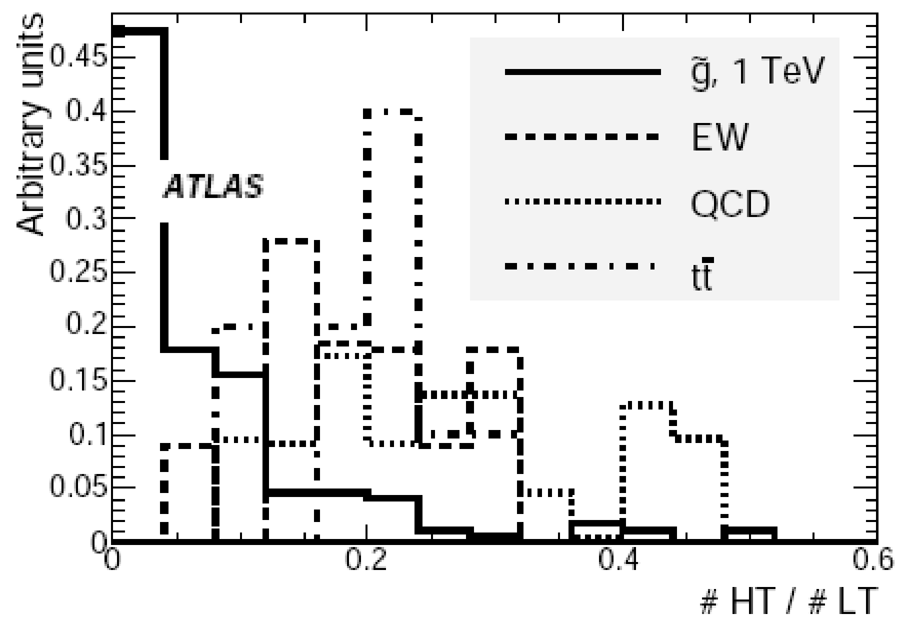
Final state observables

- p_T of muon tracks
  (normalized to 1 fb^{-1})



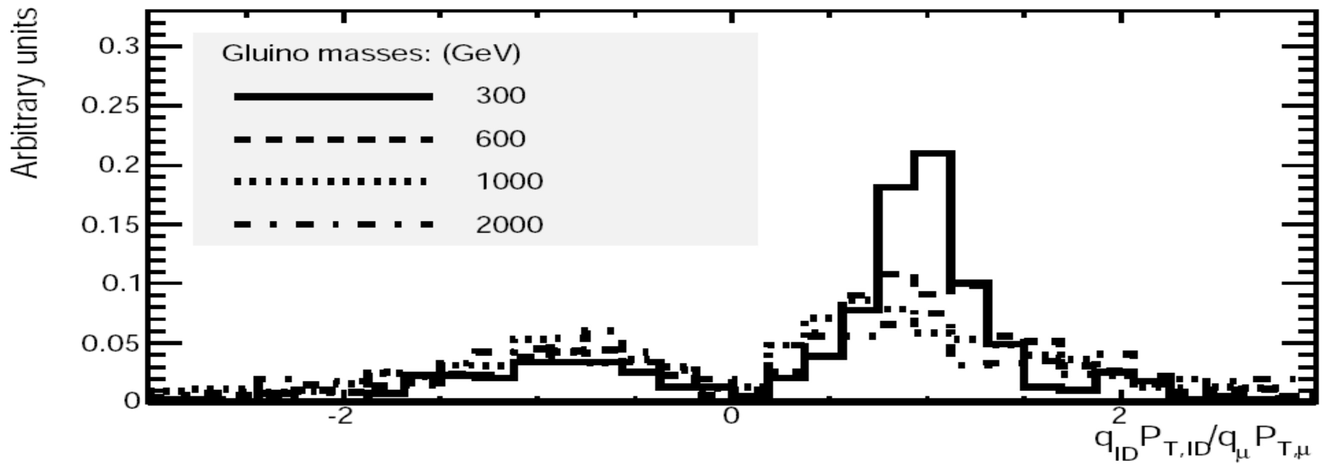


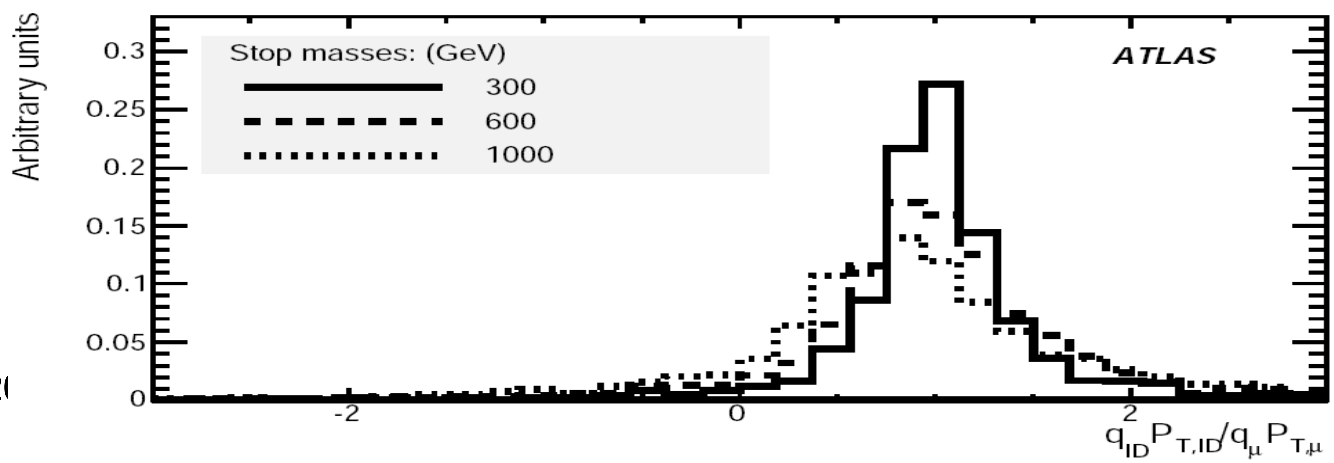
- High-threshold (HT) hits in inner tracker



Charge-flipping signature

$q_{ID}p_{T,ID}/q_{\mu}p_{T,\mu}$

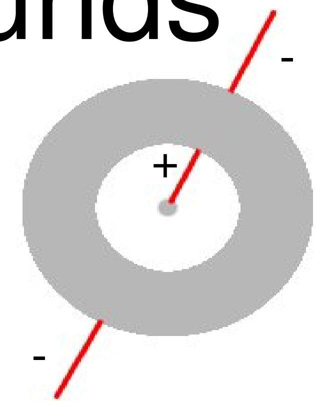




Results

Sample	Mass [GeV]	Event Rate / fb^{-1}
$\tilde{g}$	300	6400
	600	270
	1000	11
$\tilde{t}_1$	300	70
	600	4
BG	QCD di-jet	0.9
	$Z \rightarrow \mu\mu$	0.8

Instrumental backgrounds



- Use Z→μμ *tag-and-probe*
  - High-p_T tail fractions
  - Charge misidentification probability
  - Standalone track reconstruction efficiency
- *In situ* determination of both ID and muon system performances at high p_T