Long-lived Particle Searches at Colliders

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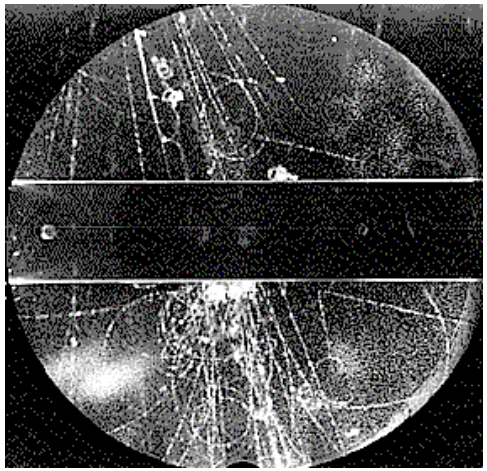
Seminar DPNC

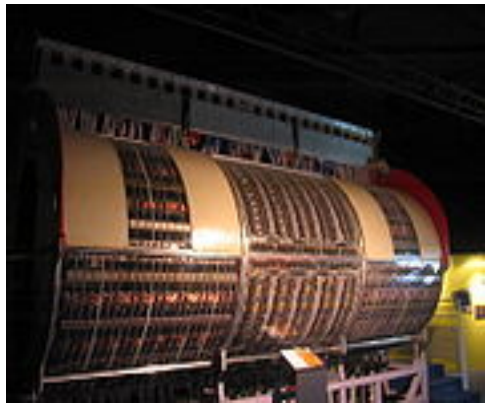
Geneva, 14 October 2009

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

History of new particles

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





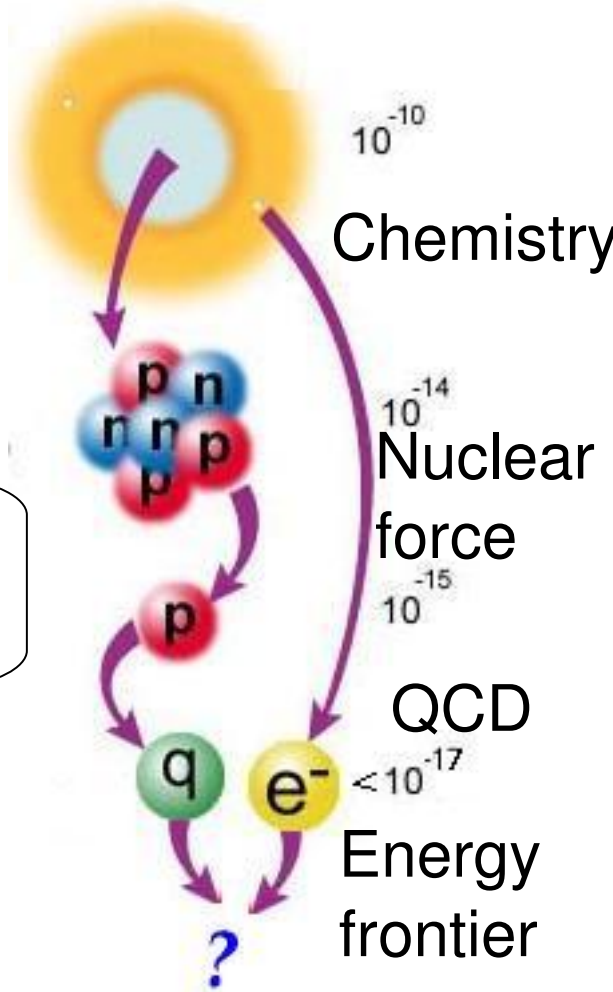
Today's particle physics puzzles

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

Proposed searches

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

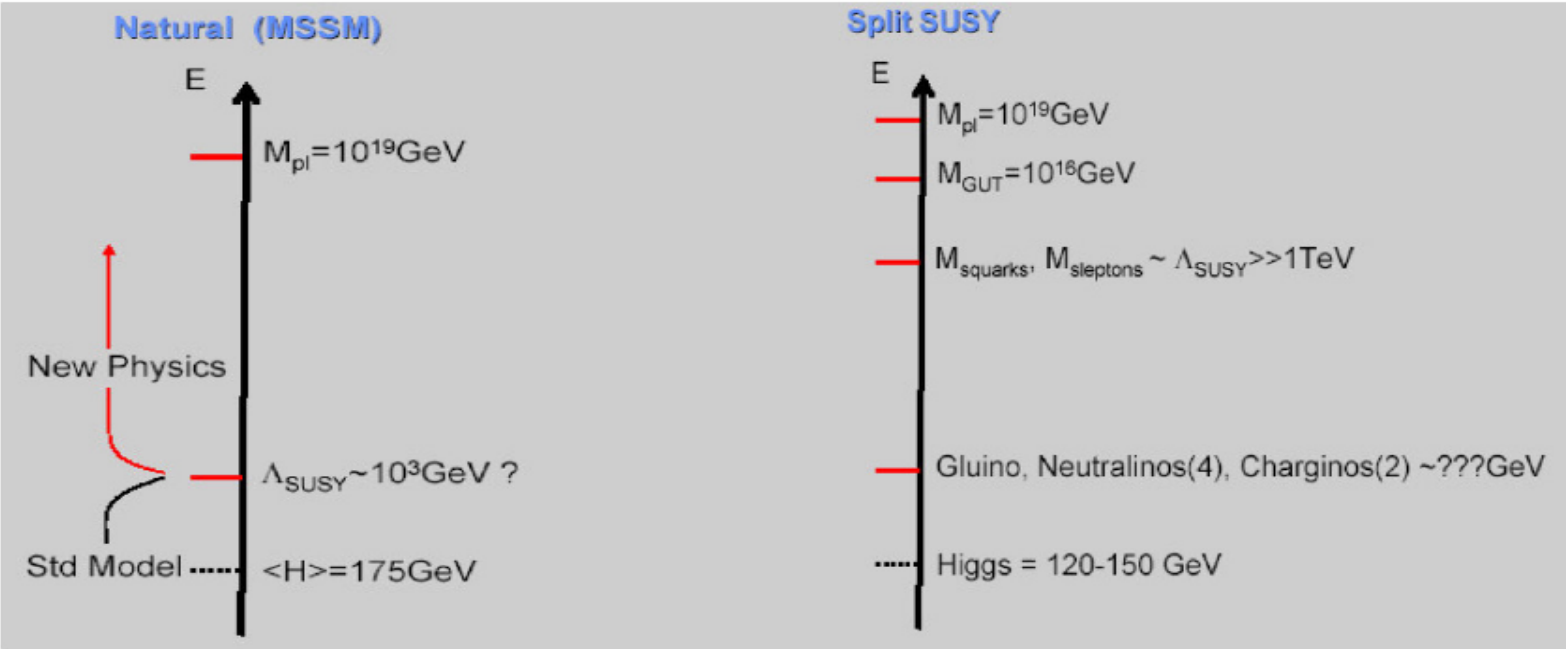
New data needed !



Split-SUSY

arXiv:hep-th/0405159

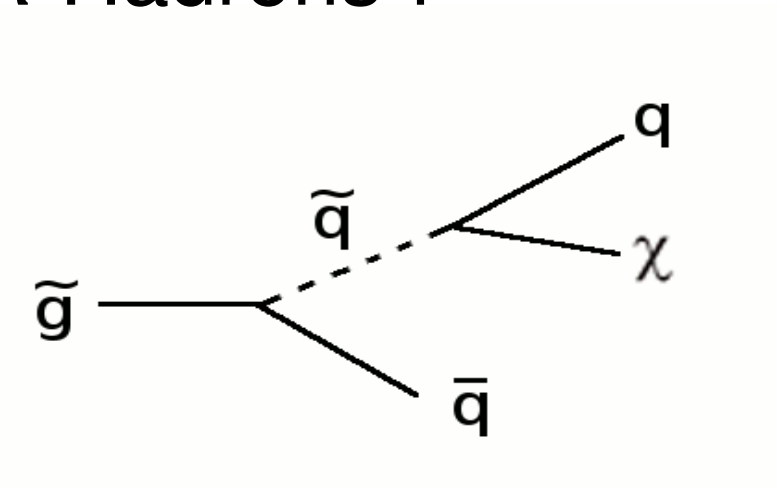
- Accept the unnaturalness of the Higgs mass
- Supersymmetry breaking occurs at M_s >> 1 TeV
- Scalars have mass at this scale

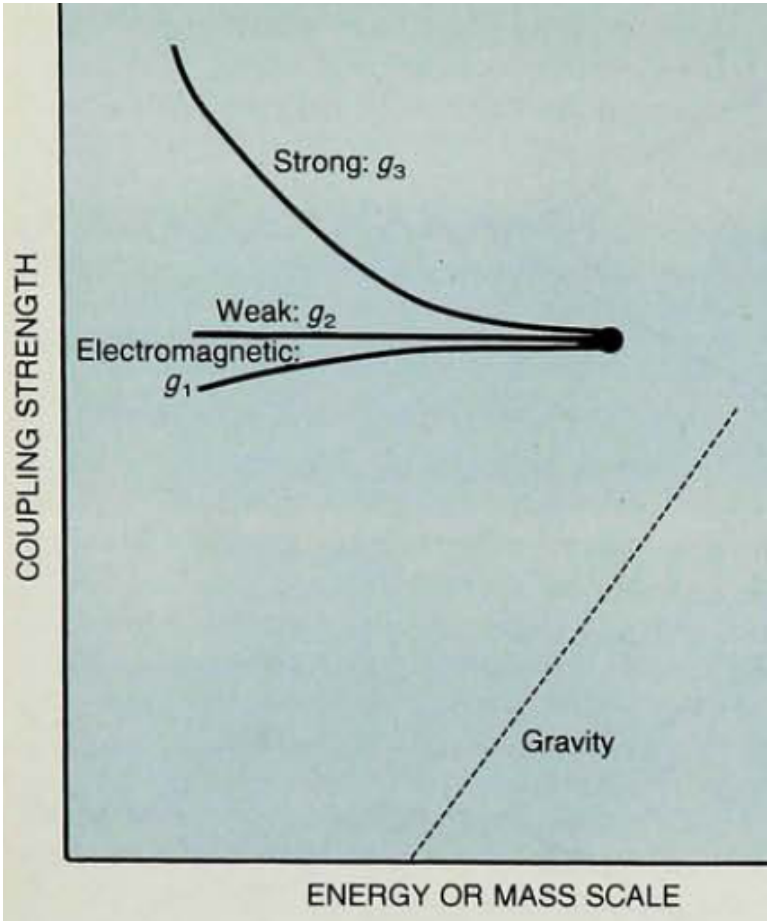


Nice features of split-SUSY

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

→ R-Hadrons !



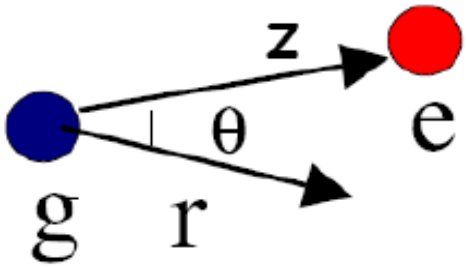


Examples of well-motivated exotic long-lived particles

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

Magnetic Monopoles

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



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

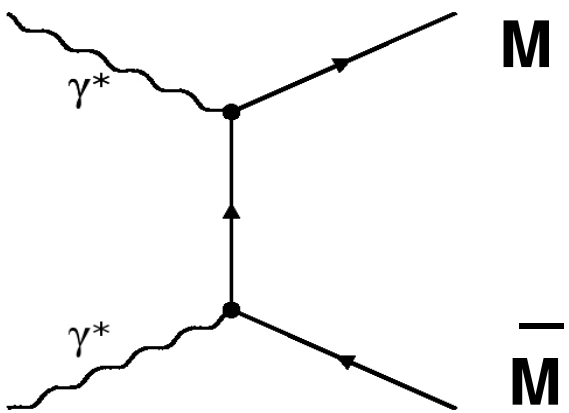
$$= \frac{\mu_0 e g}{4\pi} \hat{z} \Rightarrow e = \frac{nh}{g\mu_0} \quad g_D = \frac{h}{e\mu_0}$$

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

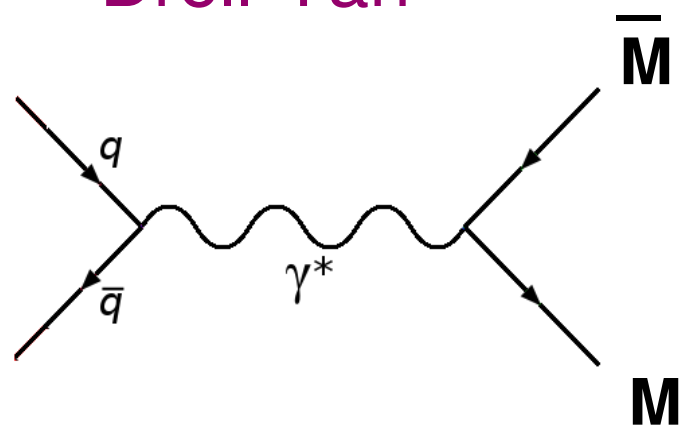
Monopoles – kinematics

- Direct pair production processes at colliders :

photon fusion



Drell-Yan



- Higher-order corrections ?
  - Strong g coupling → **non-perturbative dynamics !!!**
  - Must rely on models for the cross section and kinematics calculations !

Monopoles - ionization

- Stopping power for electrically charged particle

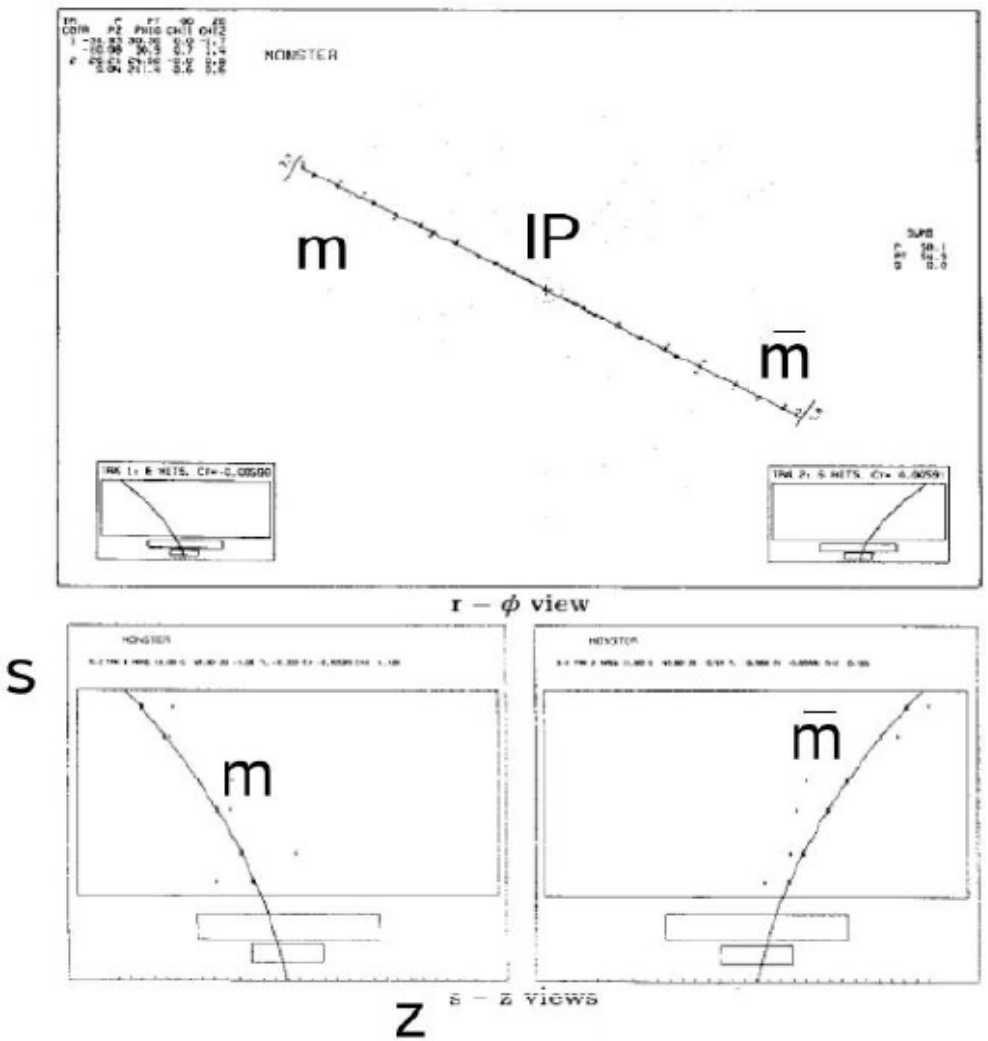
$$\frac{dE}{dx} = \frac{4\pi e^4 Z_1^2}{m_e c^2 \beta^2} n \left(\frac{1}{2} \ln \left(\frac{2 m_e c^2 \beta^2 \gamma^2 T_{max}}{I_e^2} \right) - \beta^2 - \frac{\delta}{2} \right)$$

- 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≈137/2 e : several thousand times greater dE/dX

Monopole bending in a magnetic field

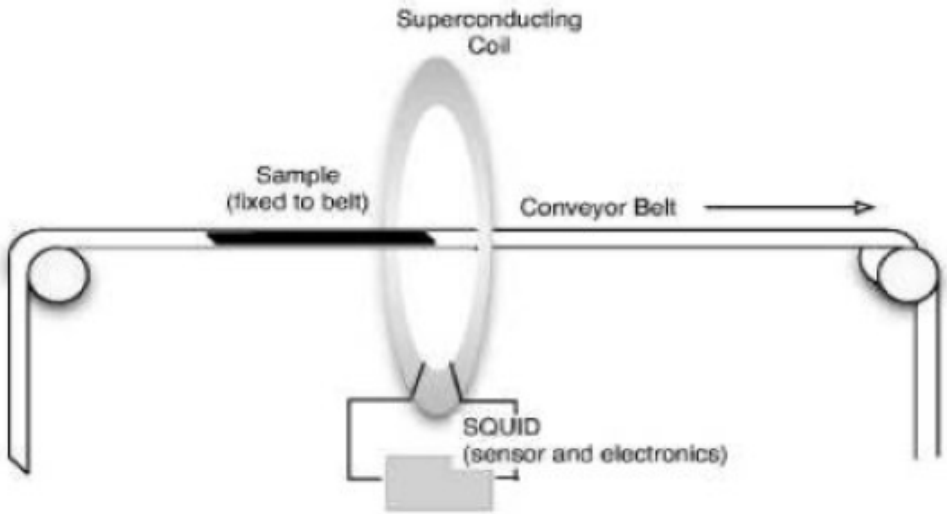


- Acceleration along beam axis
- Parabolic trajectory in rz plane

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

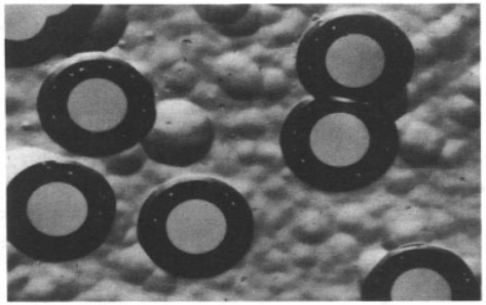
SQUID technique

- At HERA and the Tevatron
- Search for trapped Monopoles
- Old beam pipe and detector material in a superconducting coil to sense flux jump



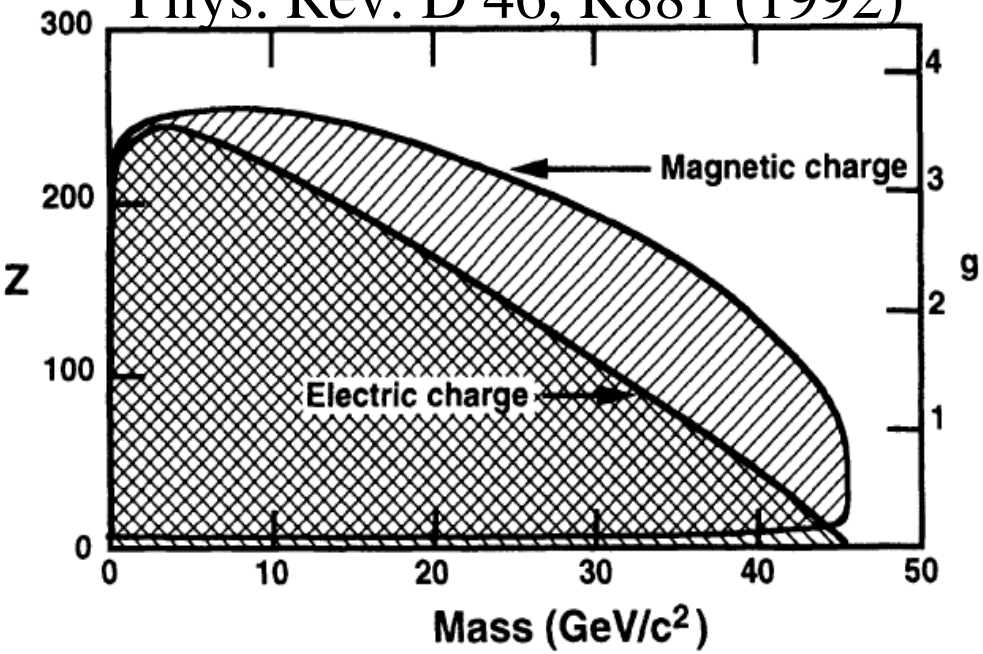
Plastic track-etch detectors

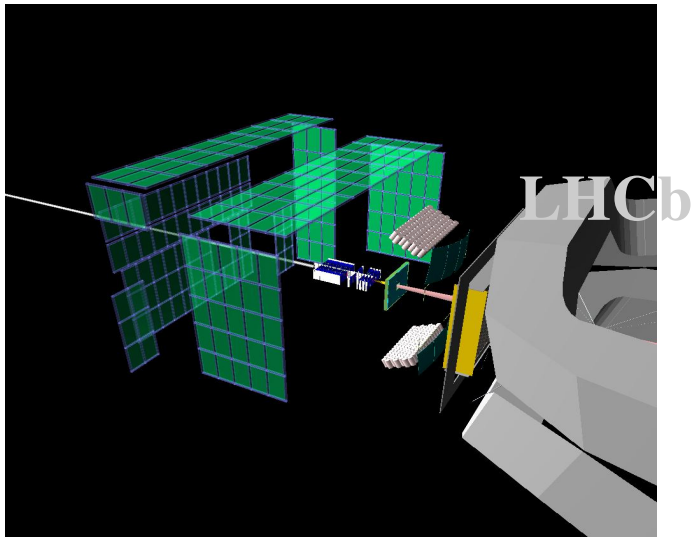
- Pits due to highly-ionizing particles
- Tevatron
- LEP



- MoEDAL (LHC)
  - At Point 8
  - Run in 2010

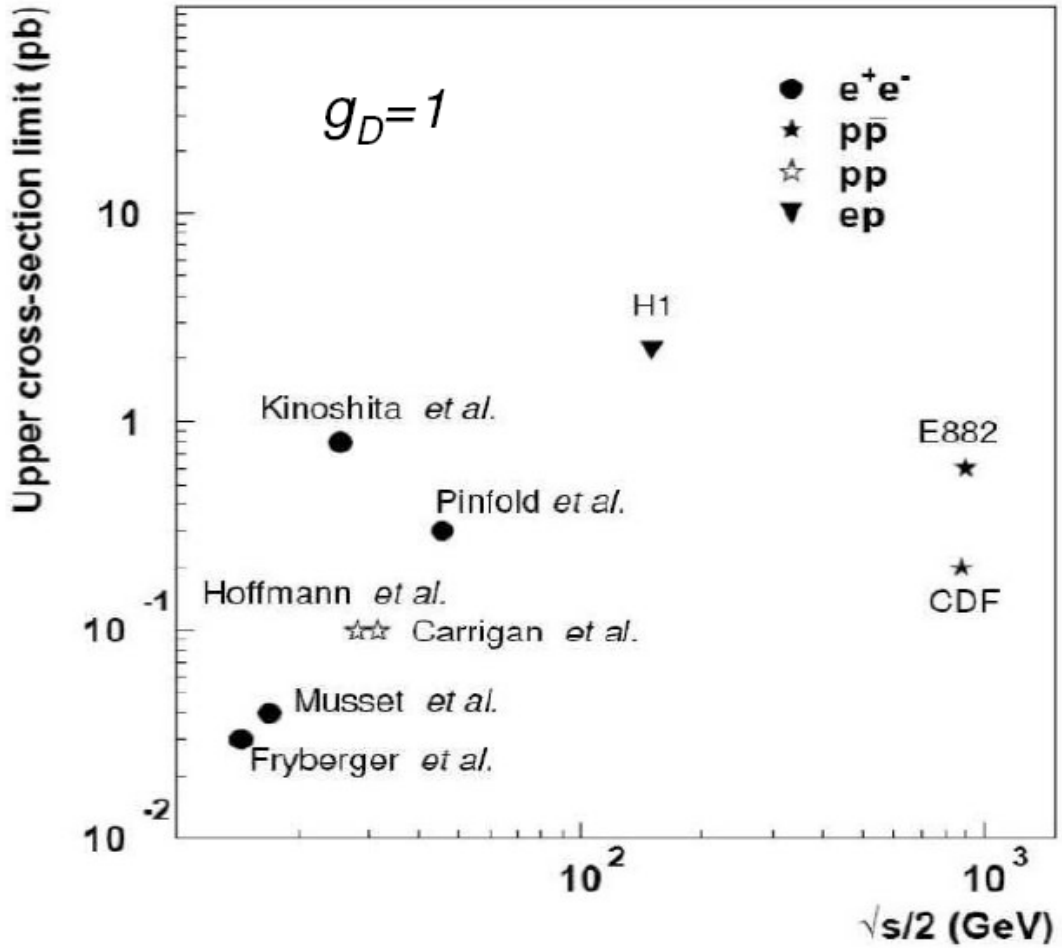
Phys. Rev. D 46, R881 (1992)





Current cross section limits for Dirac Monopoles

- Limits only valid for given mass ranges
- Unwise to quote mass limits (must assume production model)

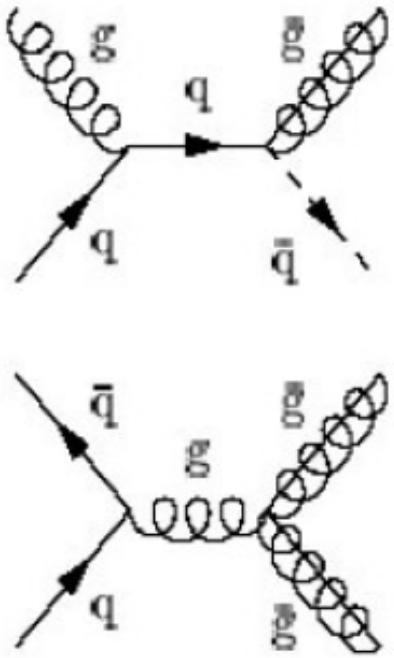


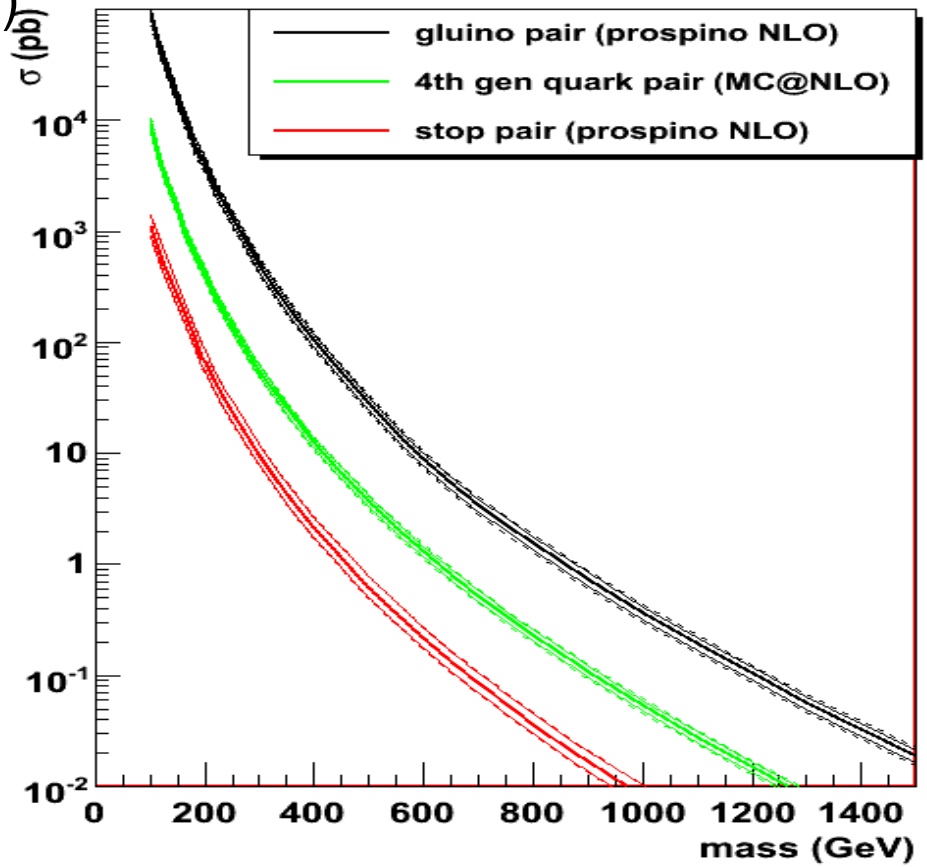
Long-lived particles carrying colour charge

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

Heavy Coloured objects at the LHC

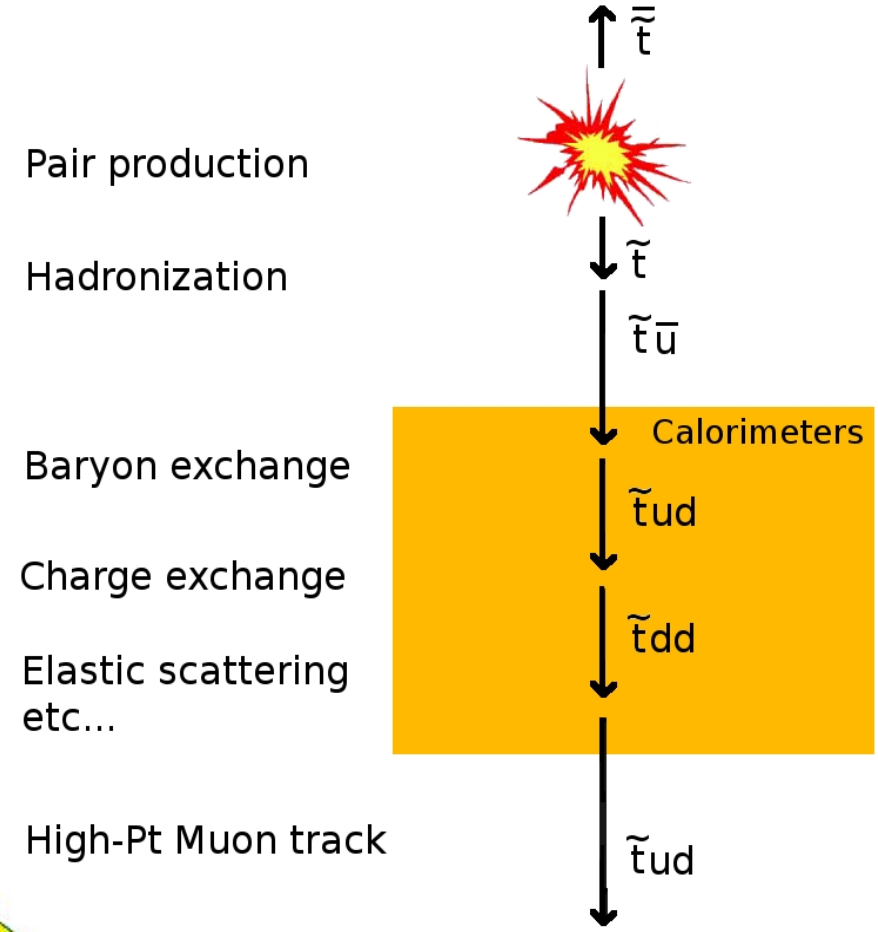
- Strong process, e.g. gluino pair production
  - mass 300 GeV → more than 100000/fb^{-1} (14 TeV pp collisions)

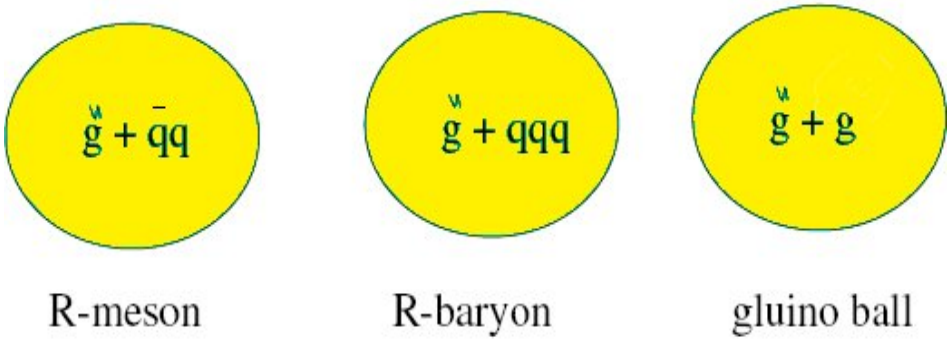




R-Hadrons

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





Generic signature : slow and high momentum

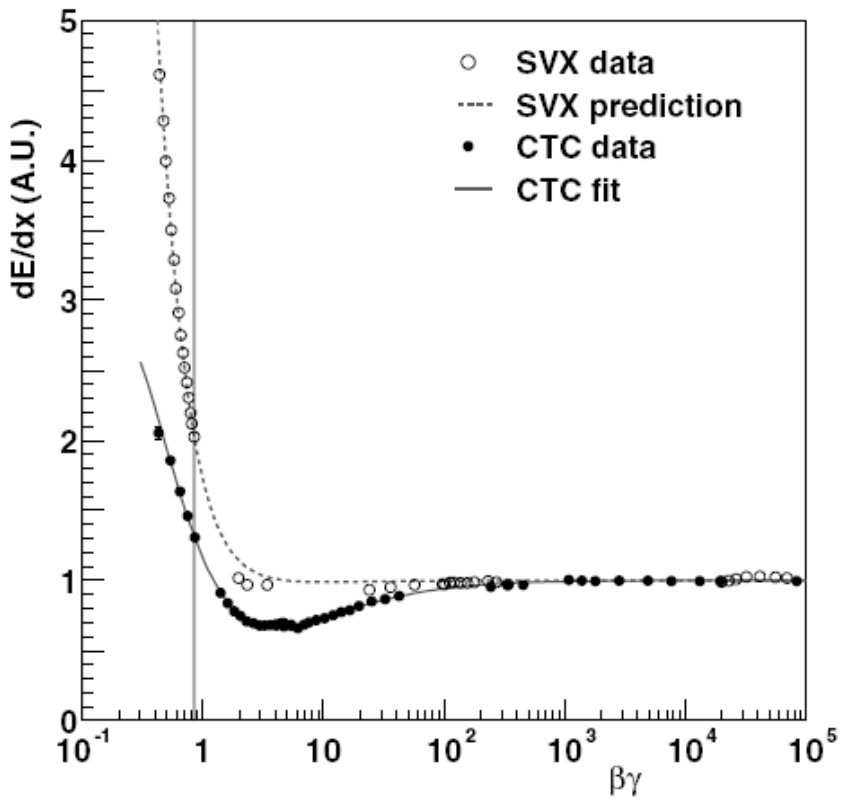
R-Hadrons : mass spectra

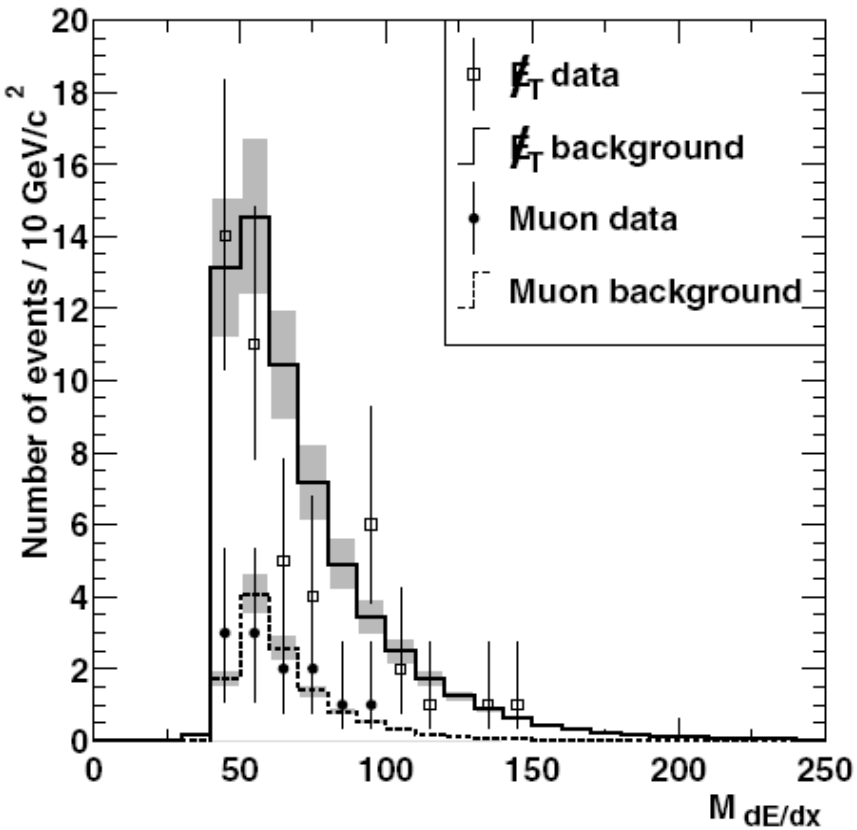
- Quark-like : similar to charmed and bottomed hadrons (e.g. Λ_c^+)
- Gluon-like : assume a model
  - Lightest state → neutral or charged ?
  - Gluino balls ?

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

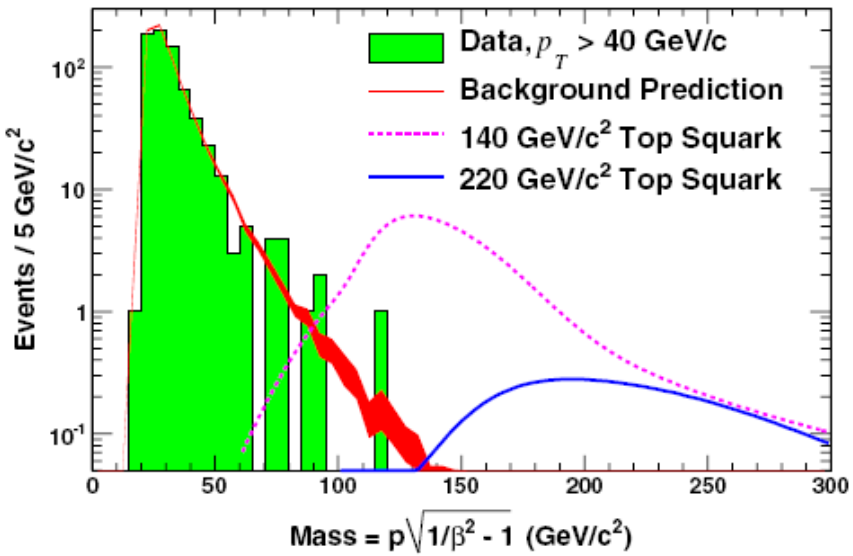
CDF search using dE/dx in inner detector

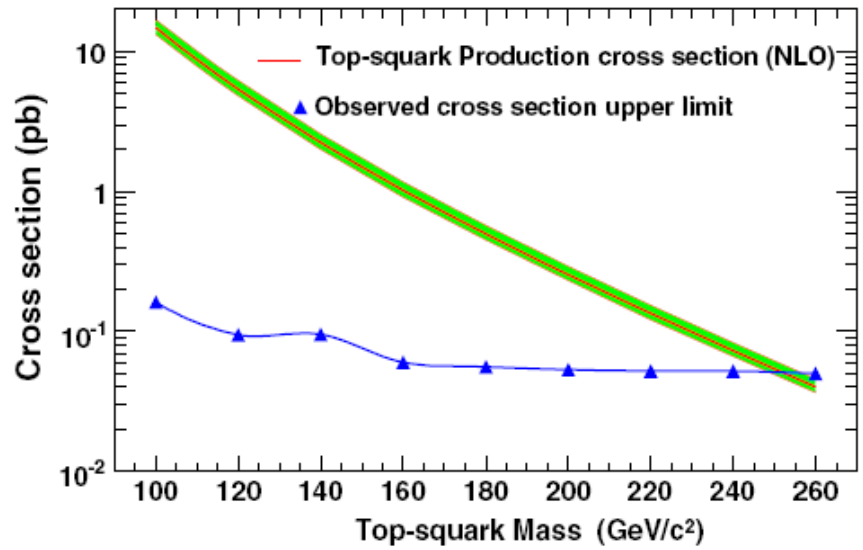




Phys. Rev. Lett. 90, 131801 (2003)

CDF search using TOF in muon detector



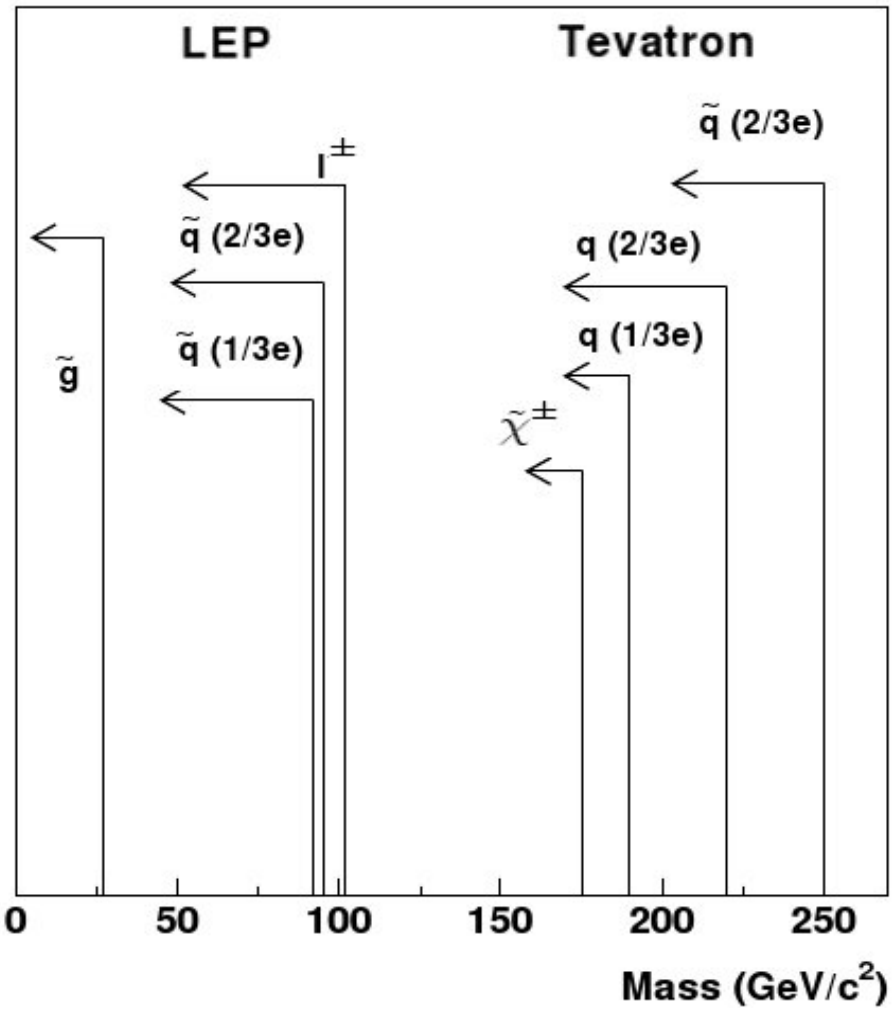


Phys. Rev. Lett. 103, 021802 (2009)

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

Published mass limits

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



Generic signature-based long-lived particle searches in ATLAS

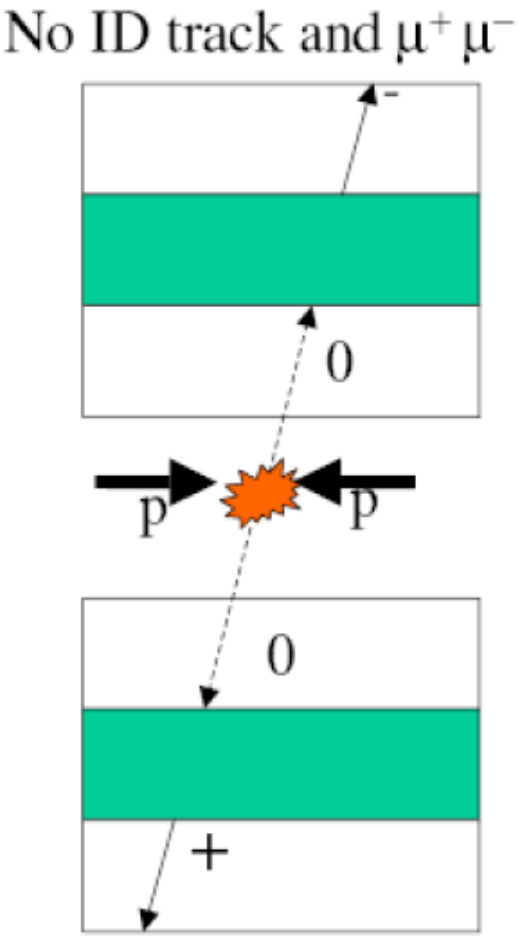
- Displaced vertices / kinks
- Non-pointing photons
- Low EM calorimeter fraction
- Out-of-bunch-crossing
- Slow tracks
- High invariant mass dimuons
- Highly ionizing tracks

decaying

non-decaying

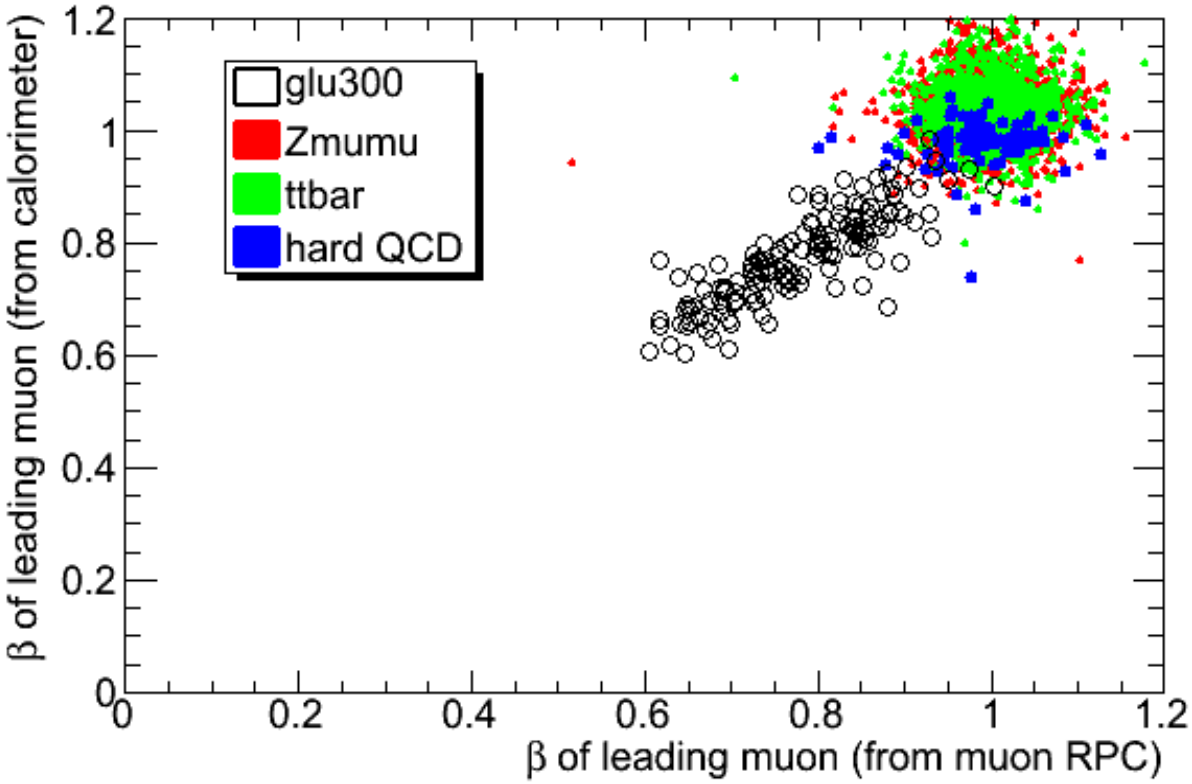
Early data : Generic & Simple

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

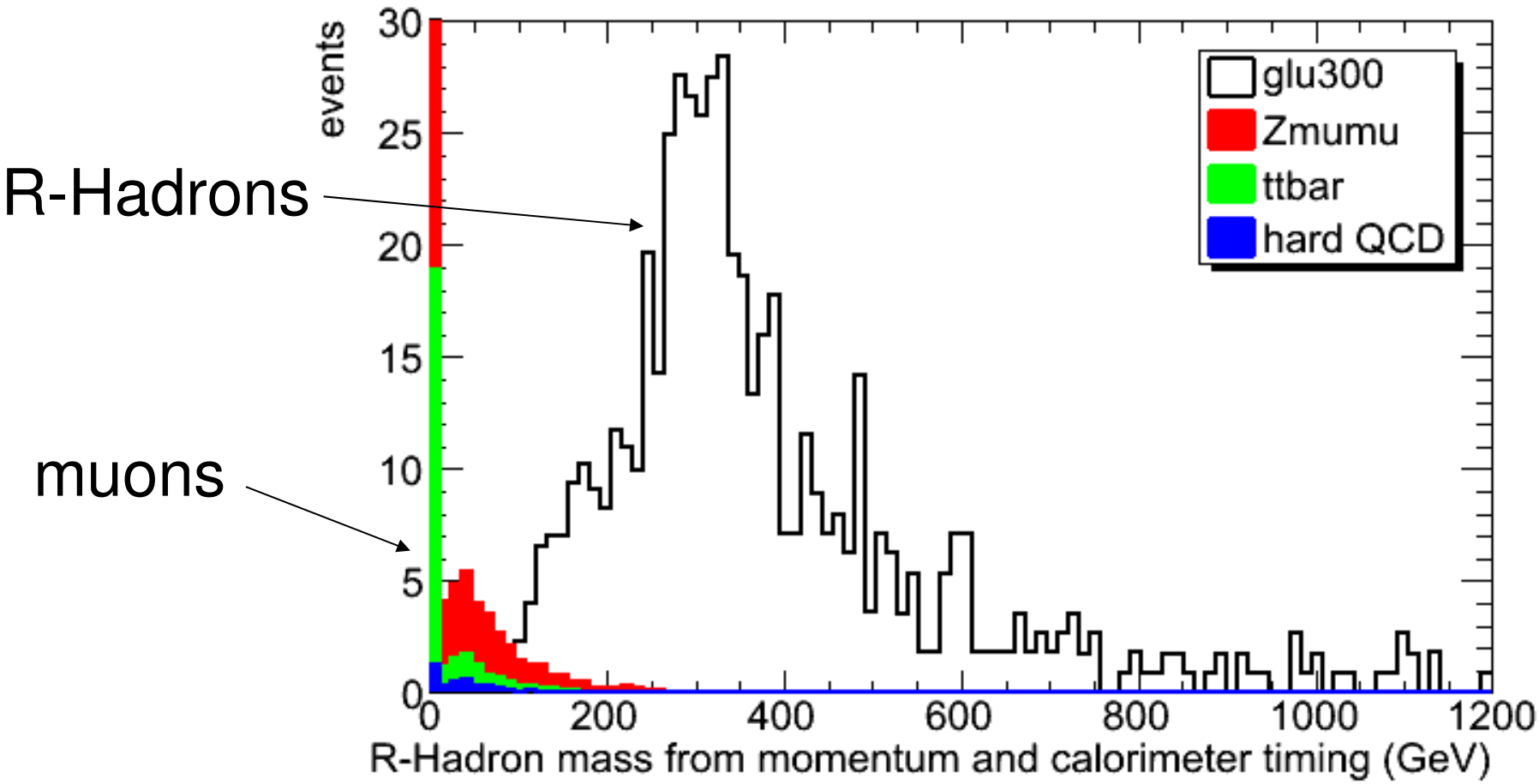


Expected signature : low speed

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

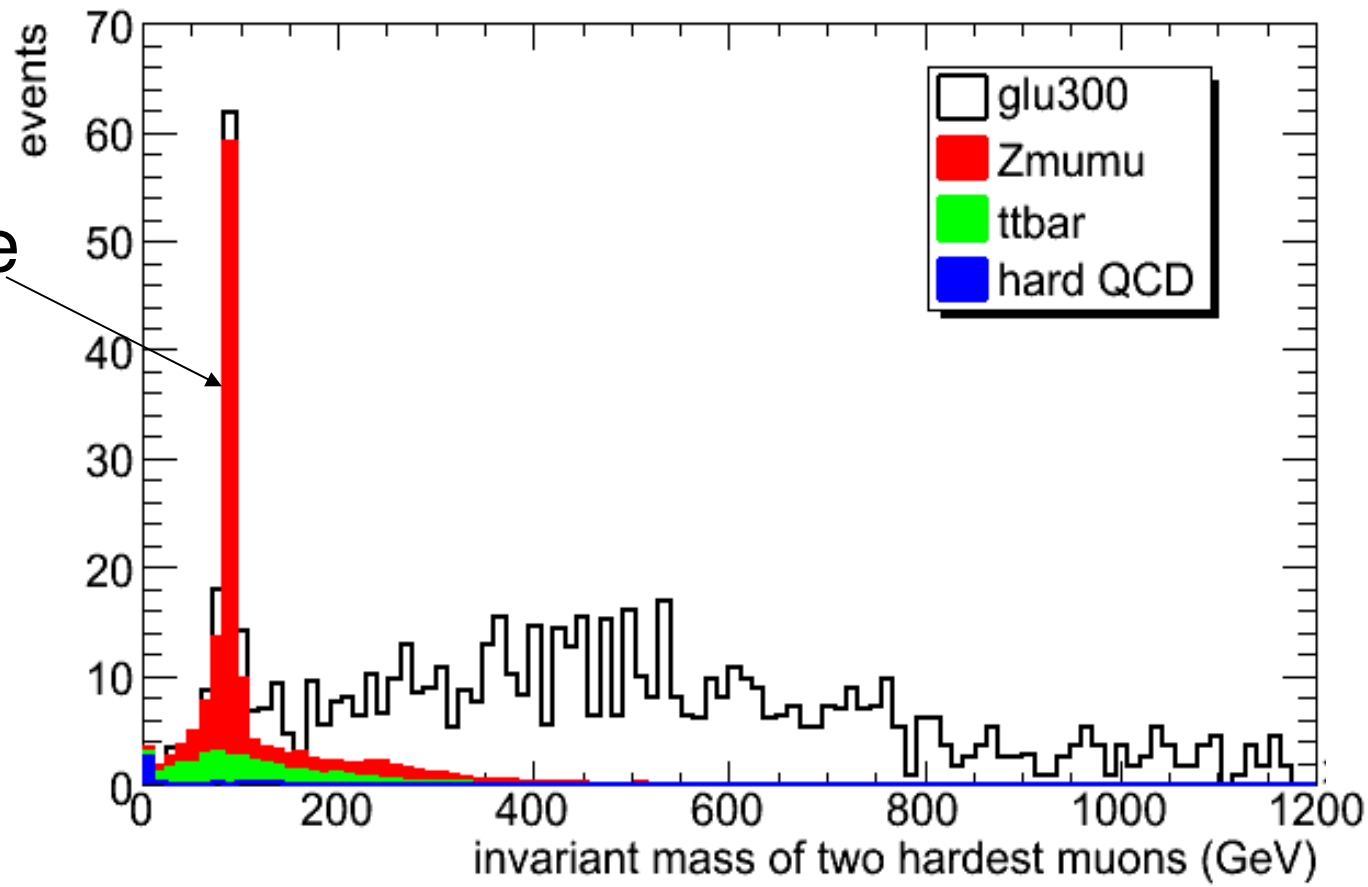


Expected signature : reconstructed mass



Expected signature : invariant mass of two muons

Z resonance

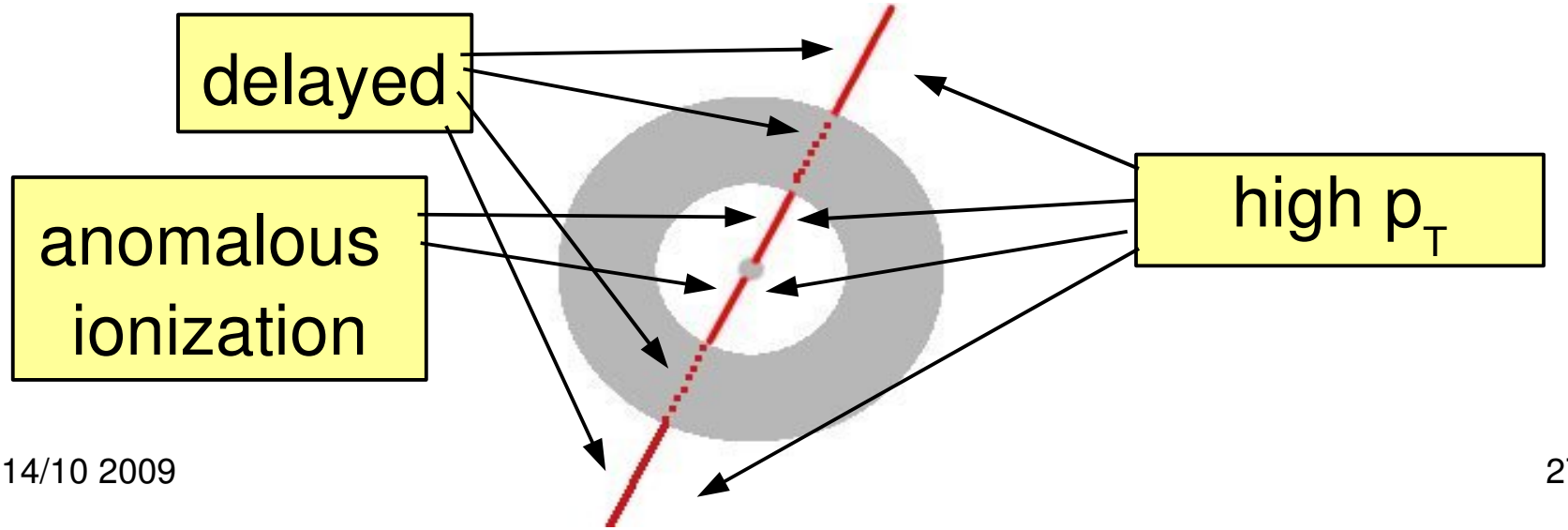


R-Hadrons : possible selection criteria

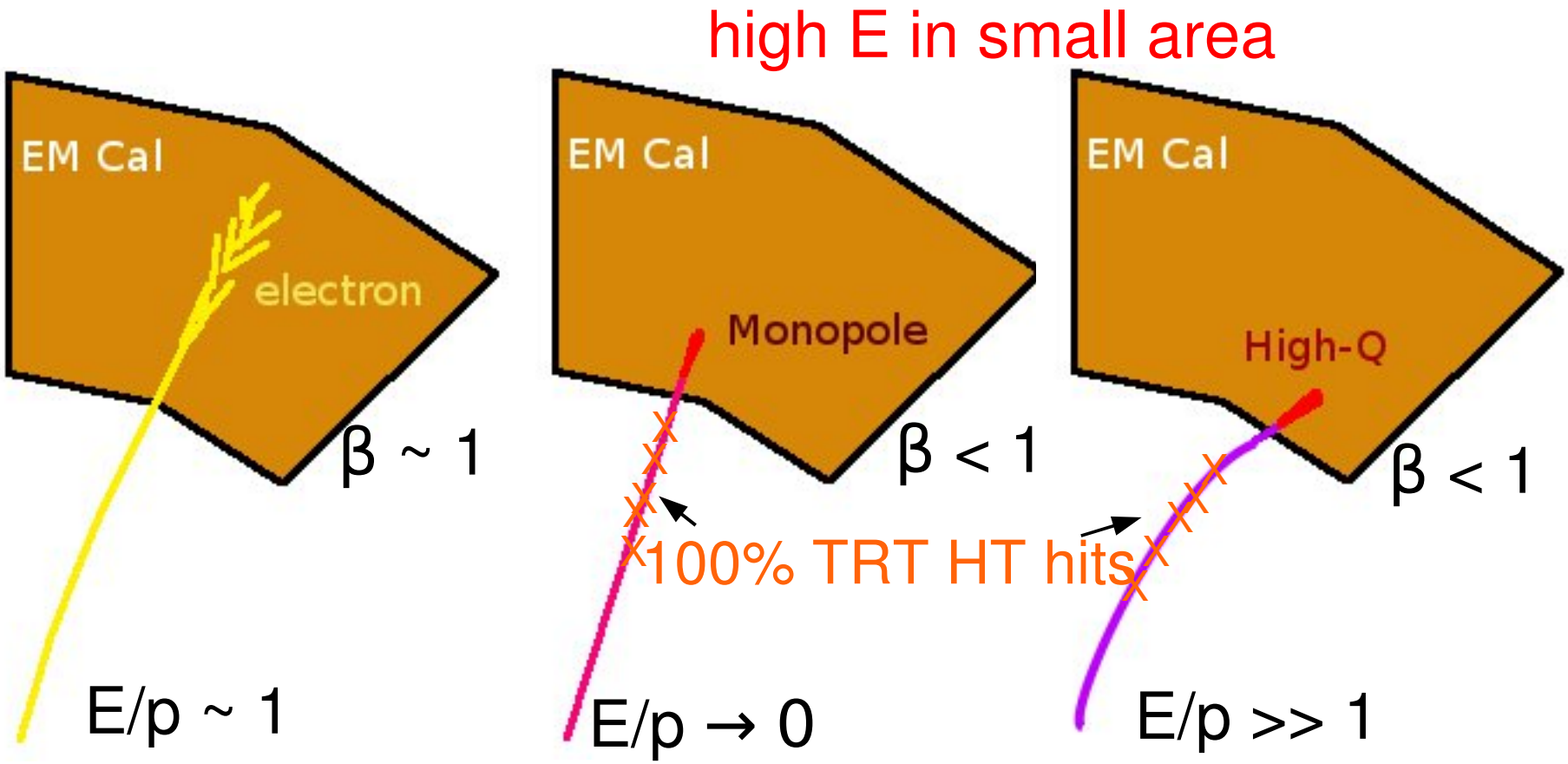
1. Low β in muon system and/or calorimeter
   - Fakes : muon β distributions obtained from $Z \rightarrow \mu\mu$
2. High-p_T muon track without associated ID track
   - Fakes : ID efficiency vs. p_T obtained from $Z \rightarrow \mu\mu$
3. Additional muon and high invariant mass
   - Fakes : high-p_T tails obtained from $Z \rightarrow \mu\mu$
4. A combination of the above

What could happen

- 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 : unmistakable events ?



High-Q/Monopoles in ATLAS



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

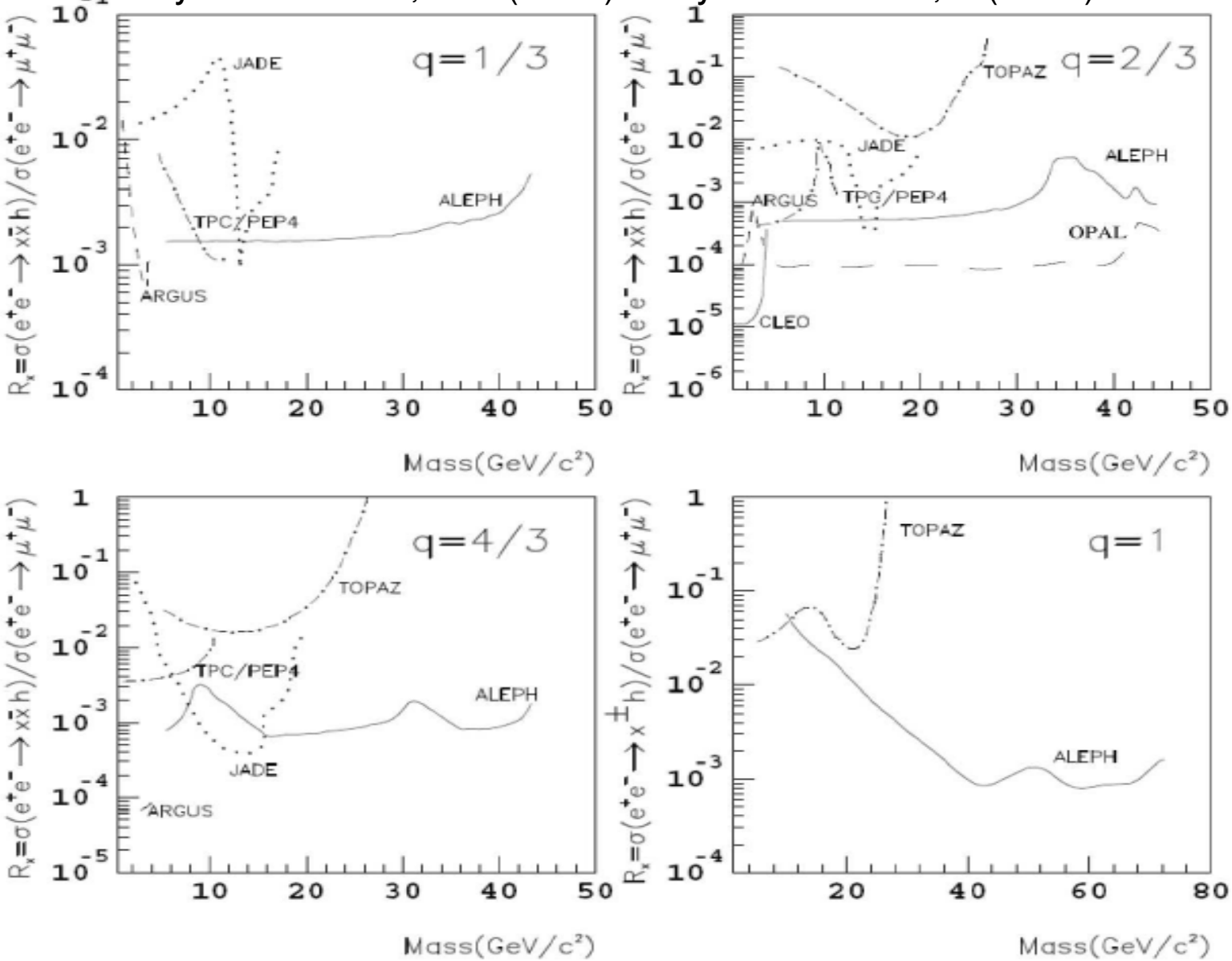
Outlook

- As soon as the LHC machine runs at high energies
  - Look at all possible signatures
  - Can we do something 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)



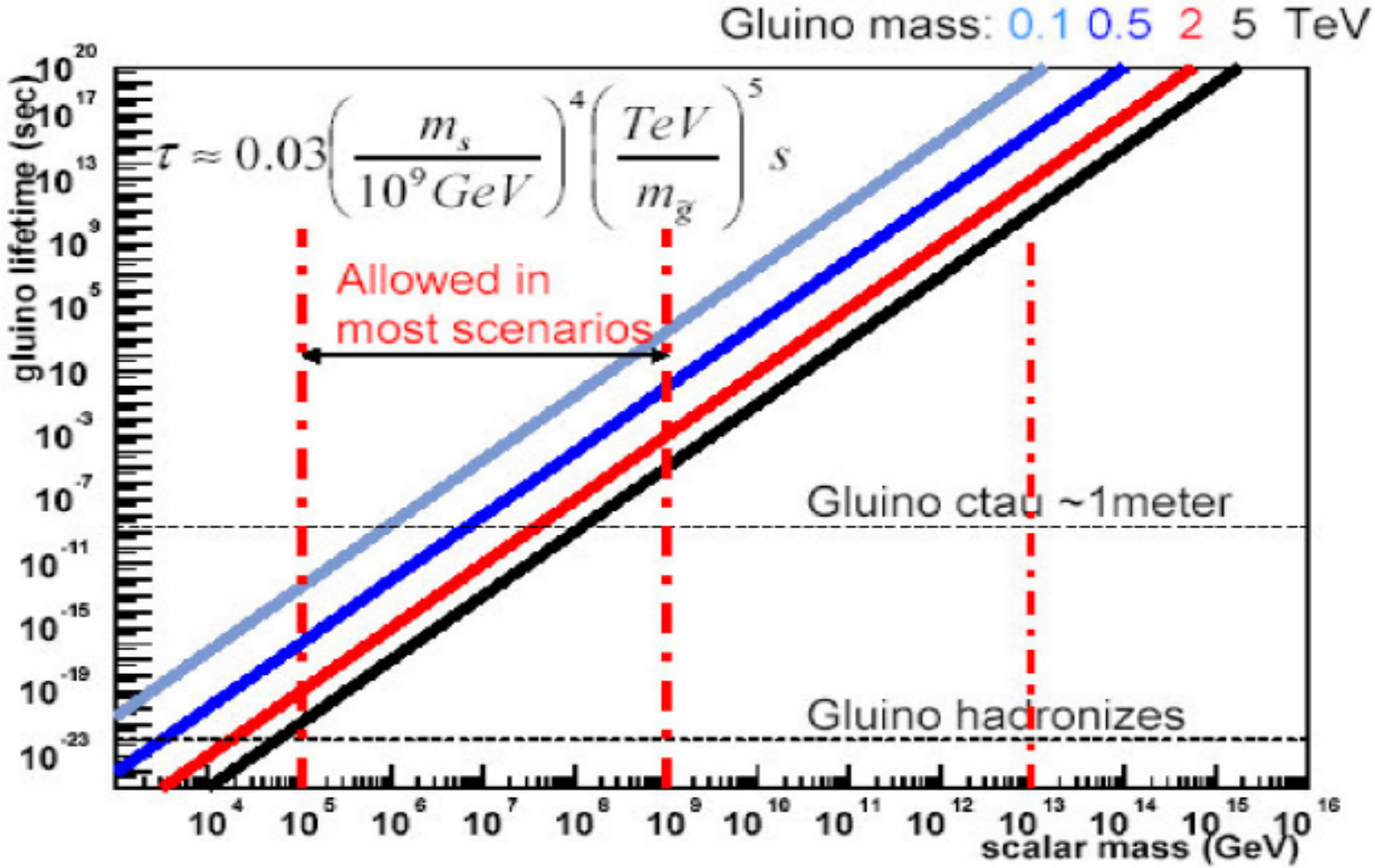
SUSY models giving rise to SMPs

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.
$\tilde{\ell}_{i1}$	$\tilde{G}$	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 $\gg \lvert\mu\rvert$ (Higgsino region) or non-universal gaugino masses $M_1 \gtrsim 4M_2$, with the latter condition relaxed to $M_1 \gtrsim M_2$ for $M_2 \ll \lvert\mu\rvert$. Natural in O-II models, where simultaneously also the $\tilde{g}$ can be long-lived near $\delta_{CS} = -3$.
		AMSB	$M_1 > M_2$ natural. m_0 not too small. See MSSM above.
$\tilde{g}$	$\tilde{\chi}_1^0$	MSSM	Very large $m_{\tilde{q}}^2 \gg M_3$, 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 $\delta_{CS} = -3$.
		GMSB	SUSY GUT extensions [25–29].
$\tilde{t}_1$	$\tilde{\chi}_1^0$	MSSM	Non-universal squark and gaugino masses. Small $m_{\tilde{q}}^2$ and M_3, small $\tan\beta$, large A_t.
$\tilde{b}_1$			Small $m_{\tilde{q}}^2$ 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.

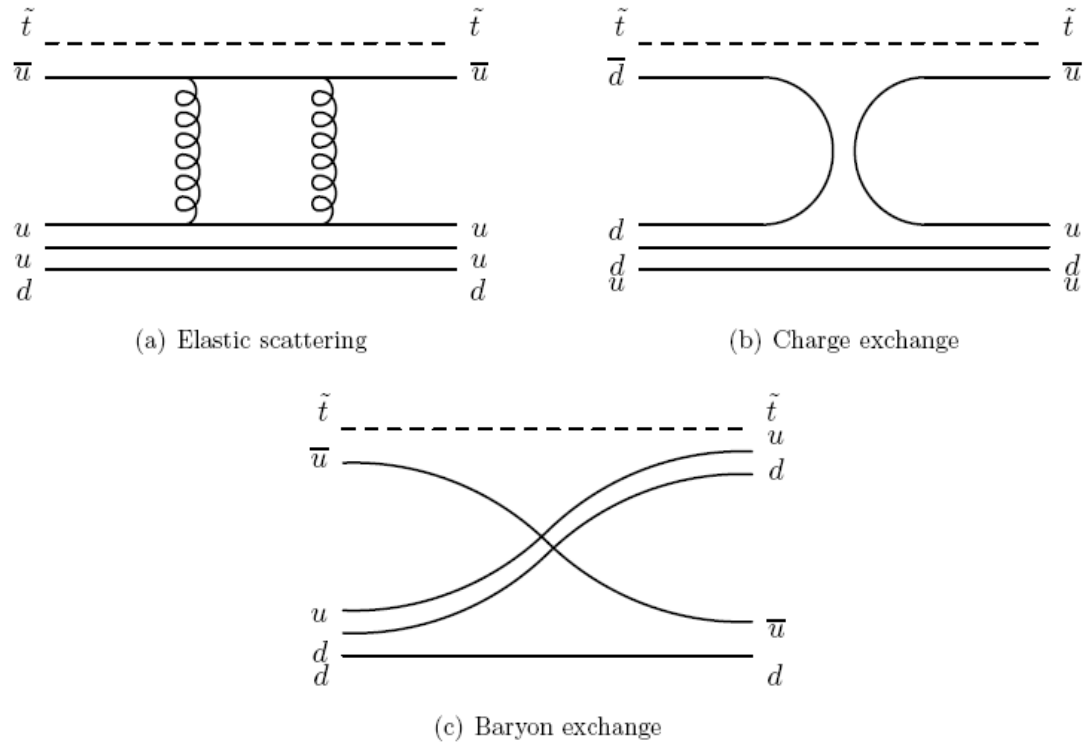
arXiv:hep-ph/0611040v2

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

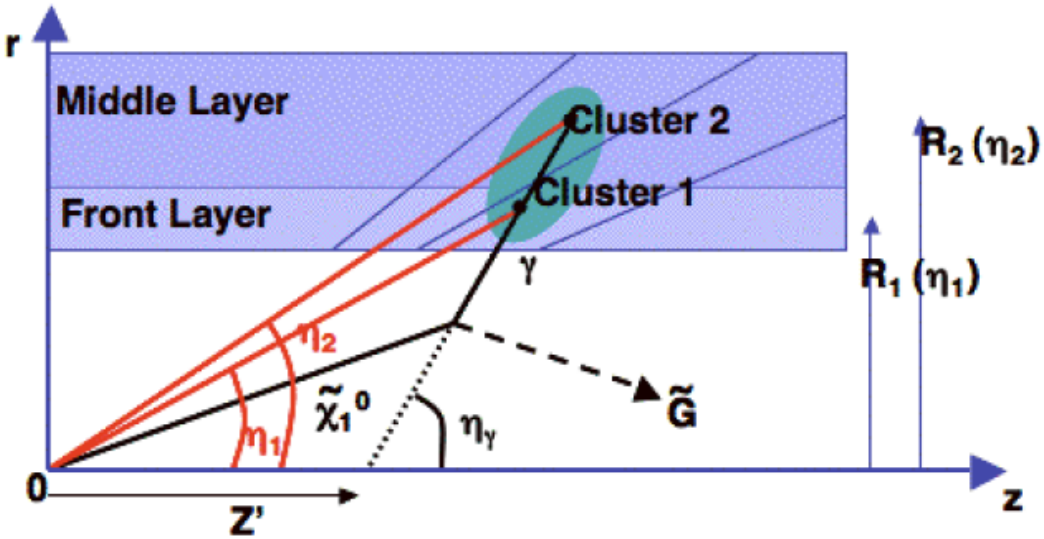


(a) Elastic scattering (b) Charge exchange (c) Baryon exchange

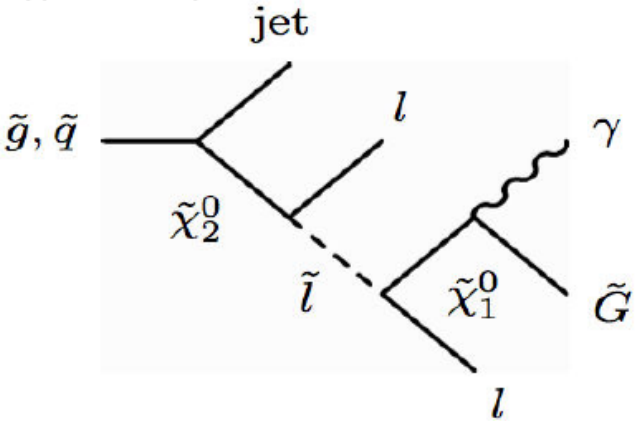
(Details of scattering model and GEANT4 implementation: R. Mackeprang, A. Rizzi, Eur. Phys. J. C50 (2007) 353-362)

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 ($\eta\Upsilon$) deviating significantly from the nominal pointing angle ($\eta 2$).
i.e. $\eta\Upsilon$!= $\eta 2$

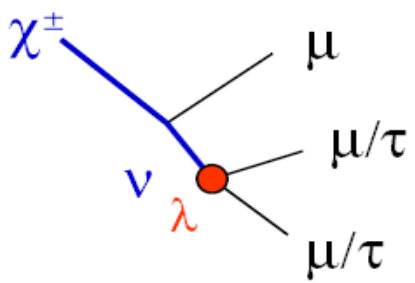


typical decay chain for Neutralino NLSP

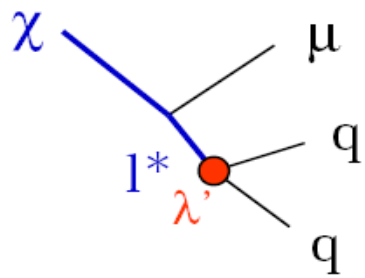


Displaced vertices

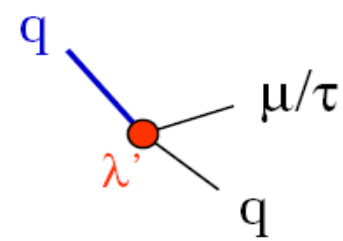
Late decays into muons and taus via RPV:



Most similar



We are looking for DV with muons.



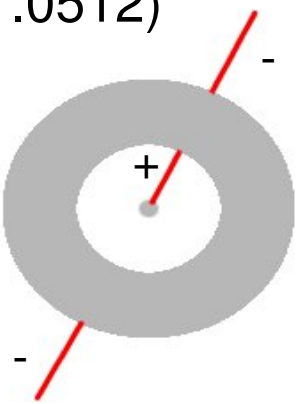
BR very small

Are CDF ghost events due to RPV SUSY: probably not

Are we sensitive to this kind of events: yes

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

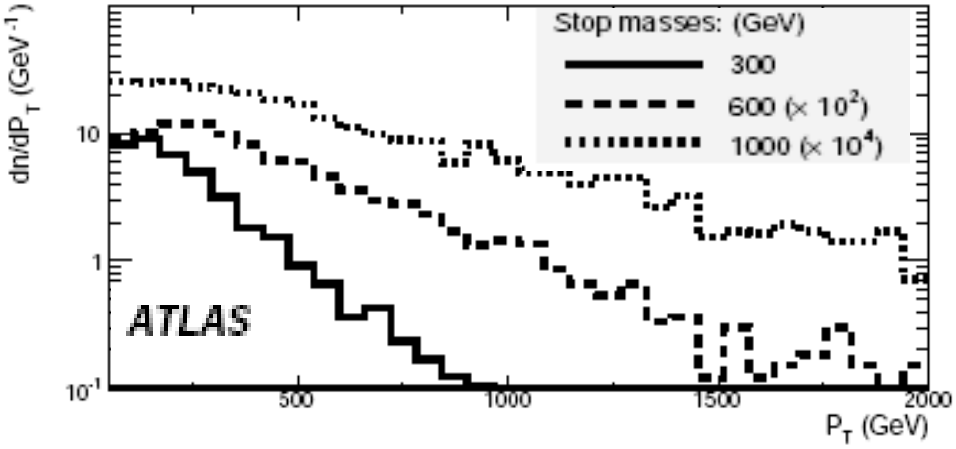
- Trigger : muon trigger
- Selection : jet veto + one of the following criteria
  - Hard (p_T>250 GeV) muon track lacking inner track
  - Two hard back-to-back inner tracks with few high-threshold (HT) hits
  - Two hard back-to-back like-sign muon tracks
  - One hard muon track with inner track of opposite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

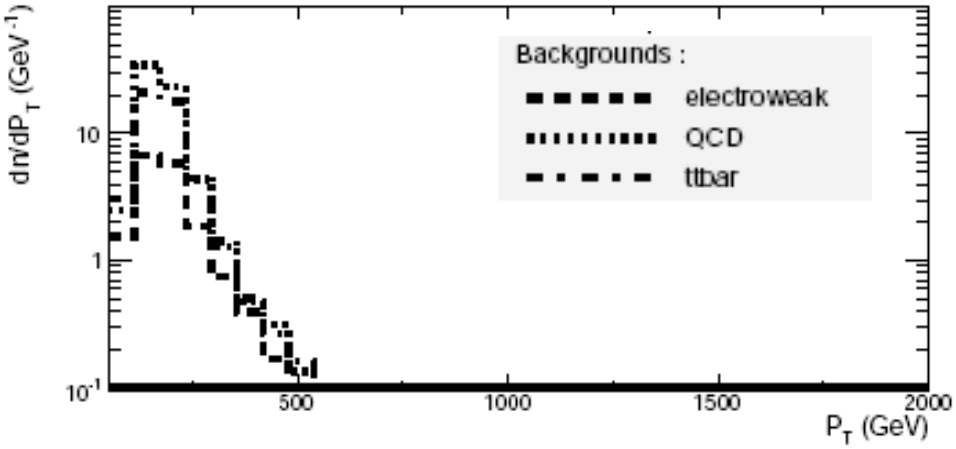
Simulated data

- 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

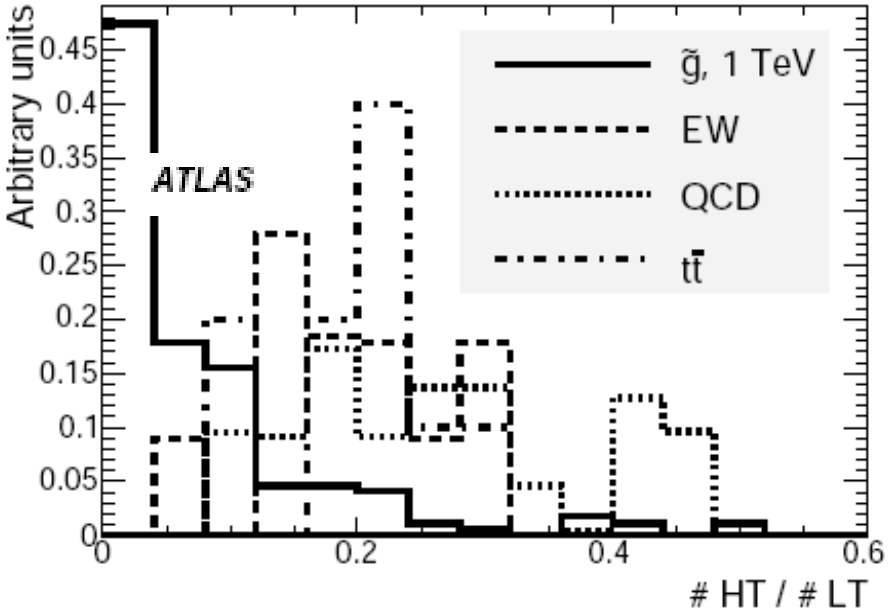
Final state observables

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



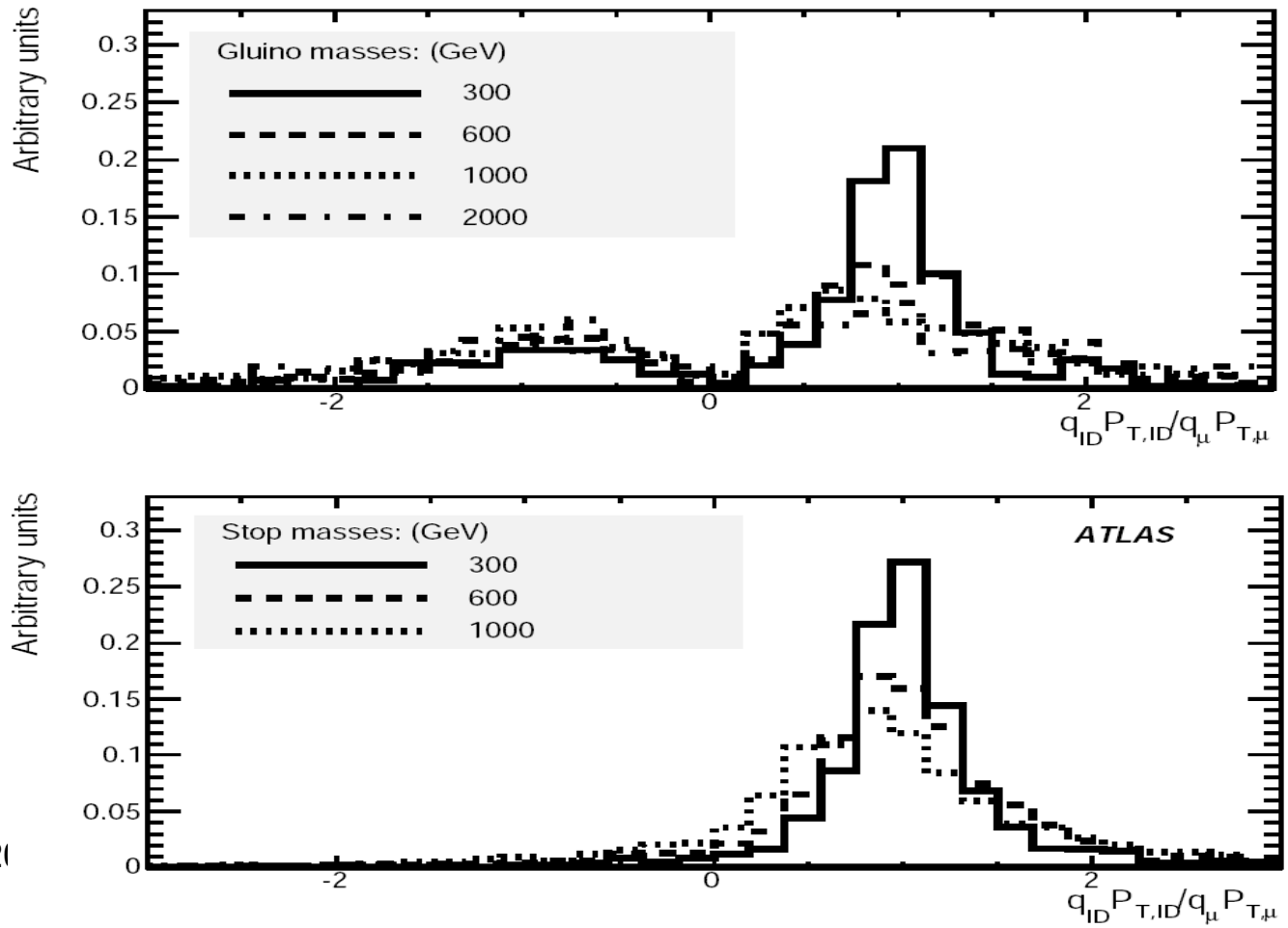


- High-threshold (HT) hits in inner tracker



Charge-flipping signature

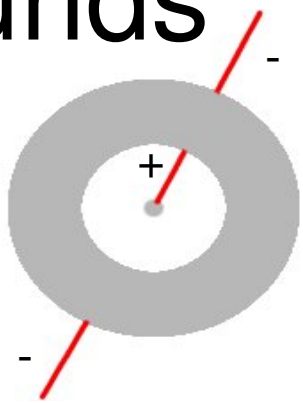
$q_{ID}p_{T,ID}/q_{\mu}p_{T,\mu}$



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