New long-lived particles at future circular colliders

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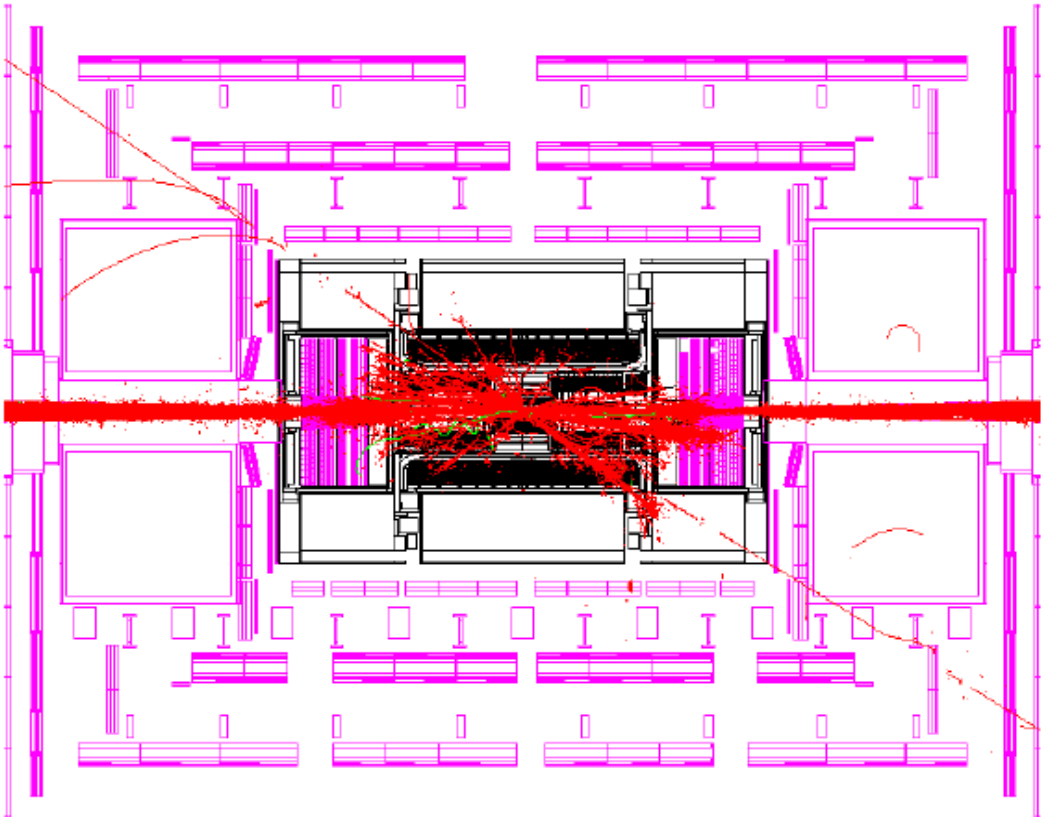
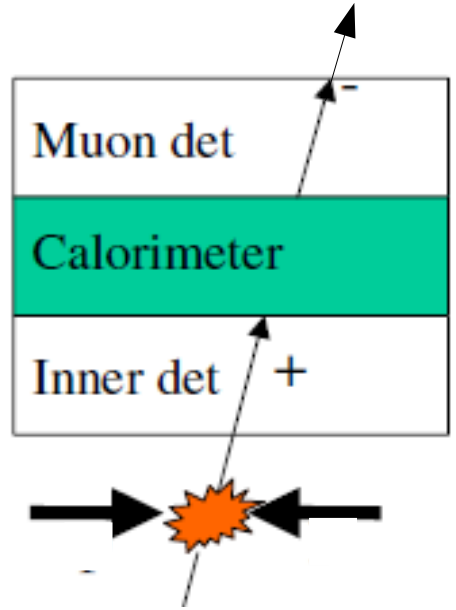
Exploring the Physics Frontiers with Circular Colliders
Aspen - Jan 30, 2015

https://indico.cern.ch/event/336571/

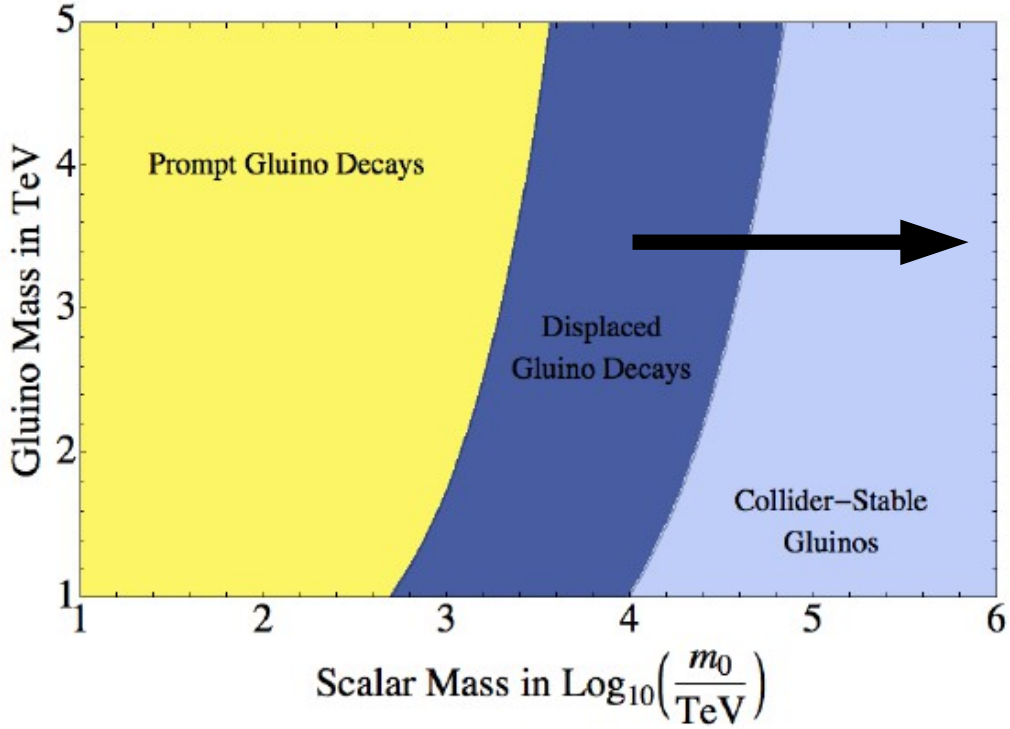


Introduction / Motivation



- New particles will either be
  - Prompt decays
  - *Semi-stable, decay in detector*
  - *Detector-stable, decay outside the detector*
    (or get stopped in the detector and decay later)

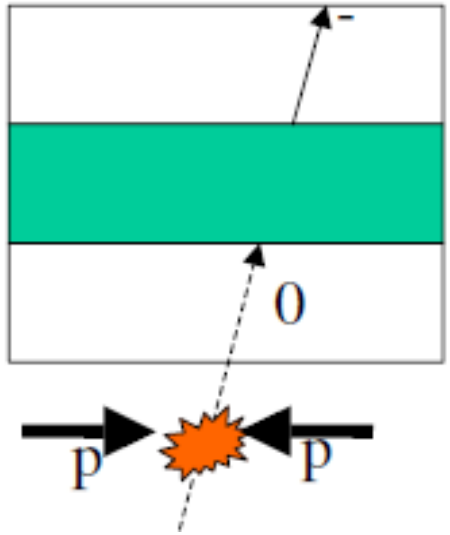
- **Must ensure sensitivity to semi-stable and detector-stable cases!**



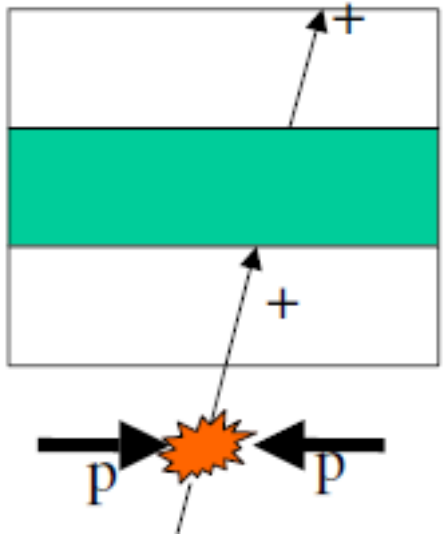
- Very well-motivated
  - NLSP → LSP with small Δm
    - AMSB Wino/Higgsino, etc.
  - Split / mini-split SUSY
    - mH=125 GeV → 10-10^4 TeV squarks
    - Off-shell gluino decay through heavy squarks → long lifetime!

Benchmark Scenarios

- 1) Colored (gluino, stop, sbottom, …)
  - Pair-produced via strong-interaction or Drell-Yan
  - Hadronizes into **“R-hadron”**
  - Electrically charged or neutral at production
  - Charge exchange through nuclear interactions with detector material
  - “Generic, Regge, or Intermediate” benchmark R-hadron spectra / interaction models



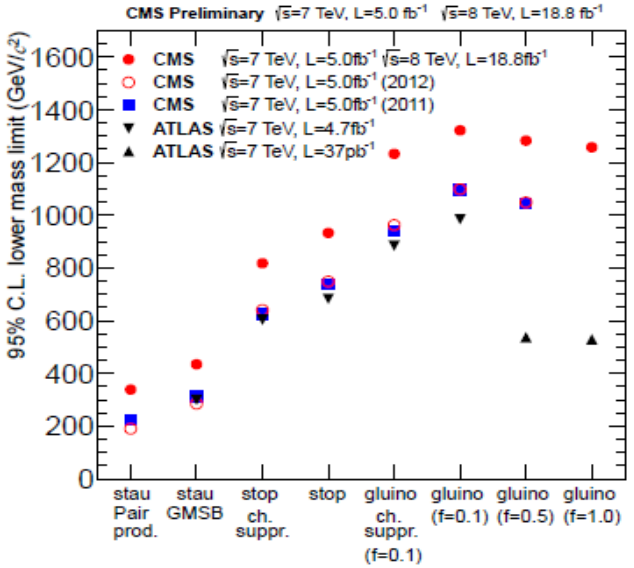
- 2) Not colored, but electrically charged (stau, chargino, …)
  - Pair-produced via Drell-Yan
  - Always charged, escapes the detector like a **“heavy muon”**

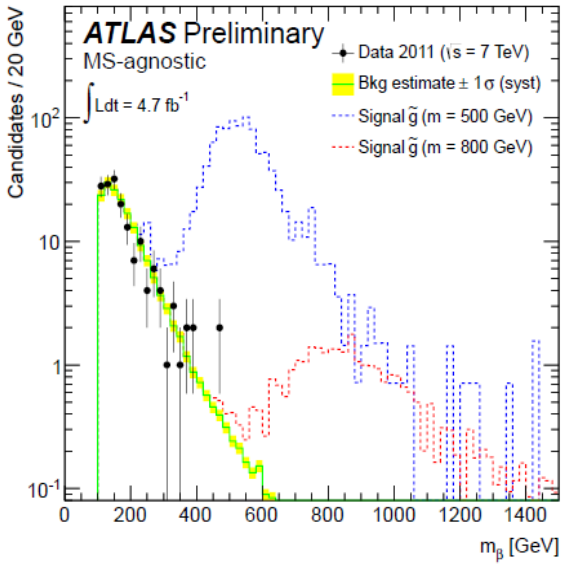


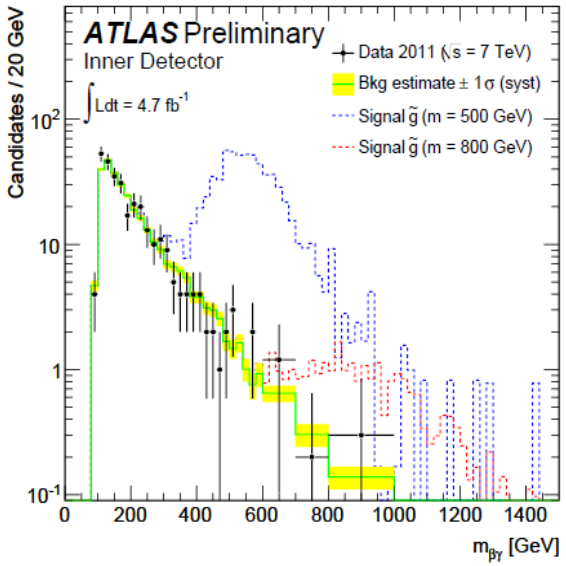
Stable R-hadron: Previous Searches

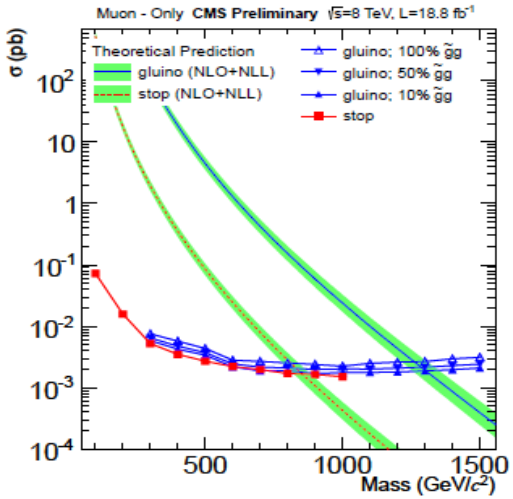
- LHC 8 TeV has best sensitivity so far…
- Look for ***slow***, highly ionizing, high-pT track:
  - Become neutral in detector
    - Inner-track only (use dE/dx only)
    - Inner-track only + calorimeter timing
  - Start neutral, get charged in calorimeter
    - Muon-track only, muon timing
- **m(stop/sbottom)>~800 GeV**
  m(gluino)>~1200 GeV

ATLAS-CONF-2012-075
CMS PAS EXO-12-026



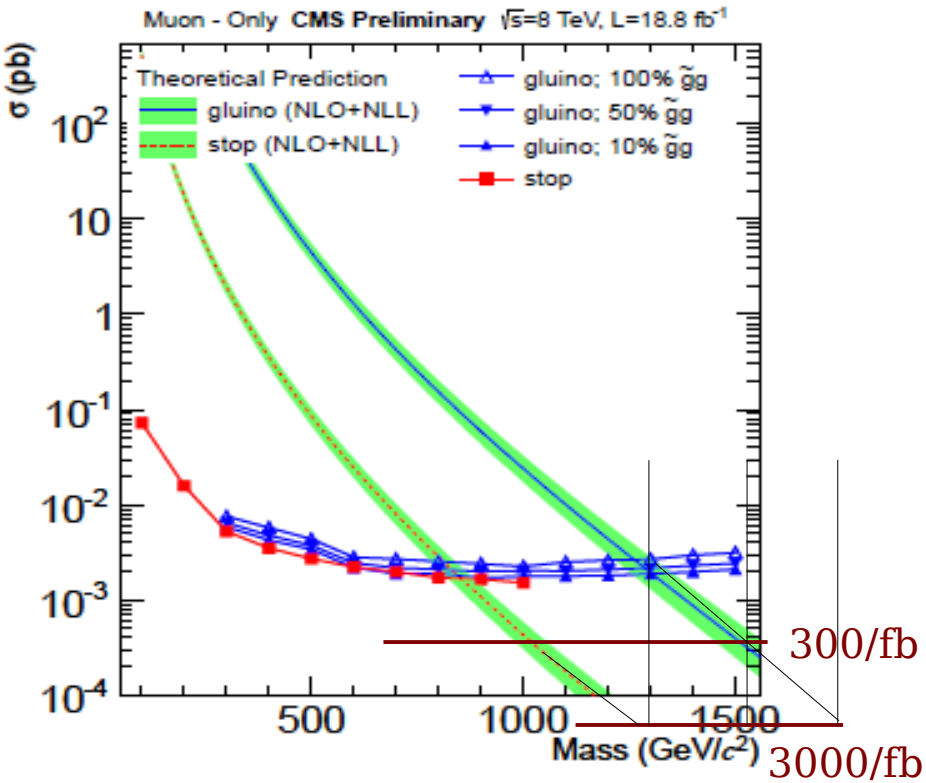


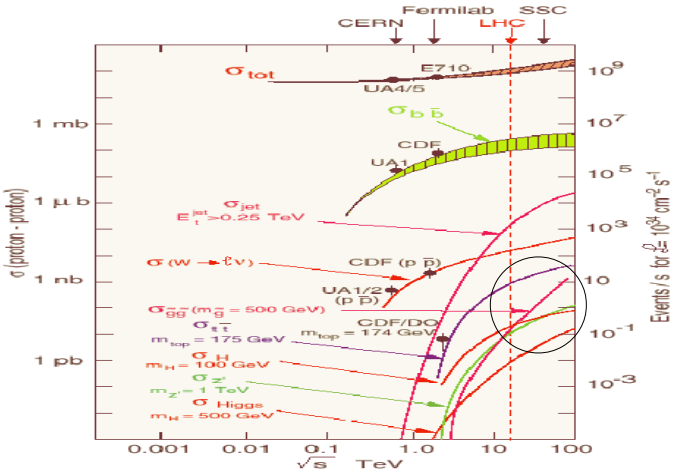




Stable R-hadron: Future Proton Collider Reach

- Luminosity doesn't buy much…
  - Cross-section falls fast!
  - S/sqrt(B) → sqrt(L)
  - Gluino R-hadron:
    - 8 TeV 30/fb: 1.3 TeV
    - 8 TeV 300/fb: 1.5 TeV
    - 8 TeV 3000/fb: 1.7 TeV
- But CM energy is nice!
  - S and B both scale ~linearly
  - Gluino R-hadron:
    - 14 TeV 300/fb: 2.8 TeV
    - 14 TeV 3000/fb: 3.3 TeV
    - 33 TeV 3000/fb: ~7 TeV
    - 100 TeV 3000/fb: ~20 TeV
- *Squark: ~2/3 of gluino reach*



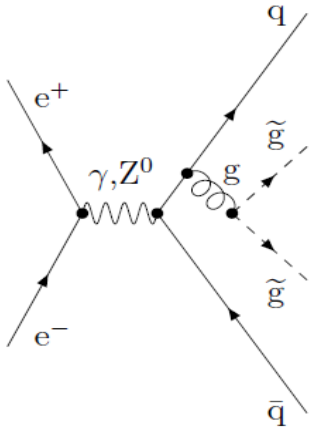


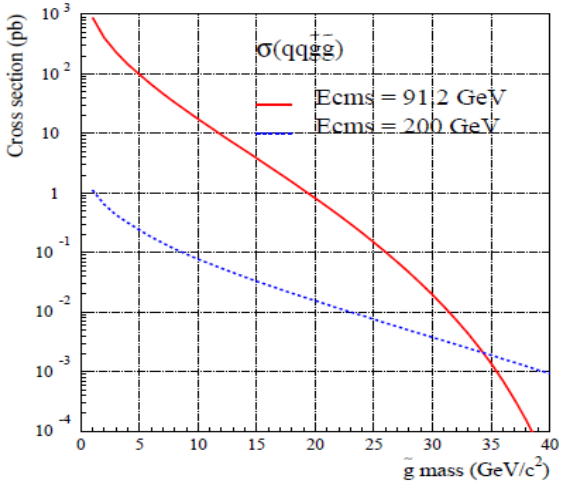
http://www.snowmass2013.org/tiki-index.php?page=EF+Facilities+List

Stable R-hadron: Future Lepton Collider Reach

- Look at LEP searches…

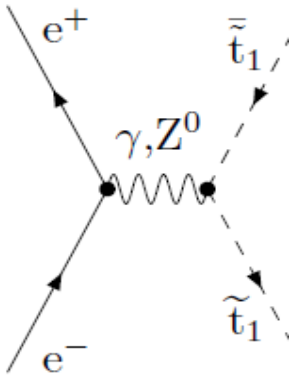
- Not as easy to make gluinos
  - Have to make quarks first!
  - Sensitive up to **~CM/4**

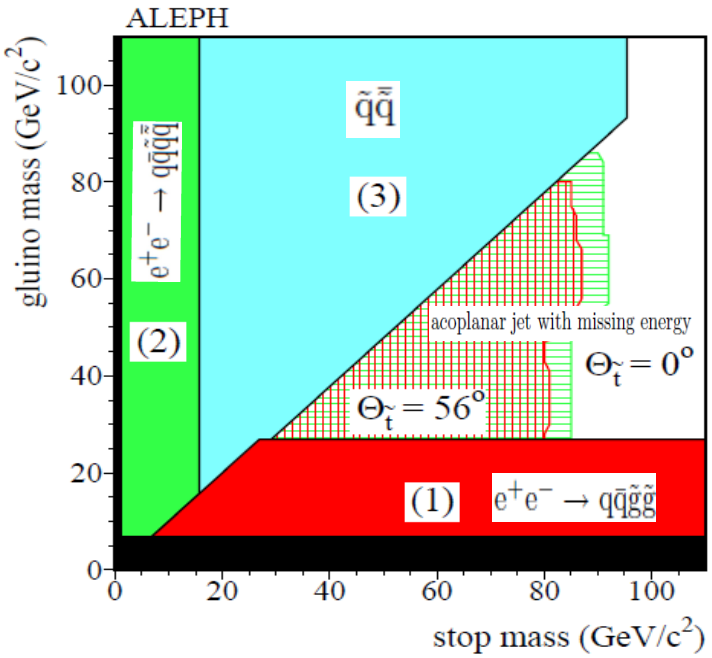




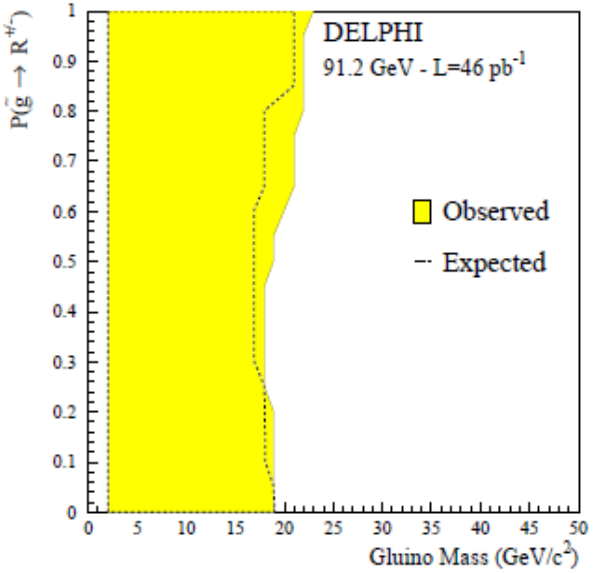
arXiv:hep-ex/0303024
arXiv:hep-ex/0305071

- But can produce squarks via Drell-Yan up to **~CM/2**





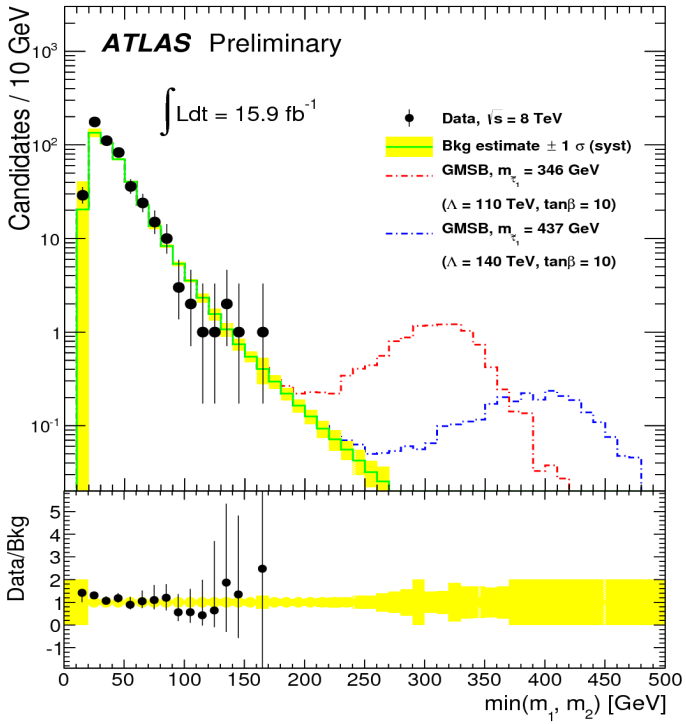
m(squark)>~90 GeV



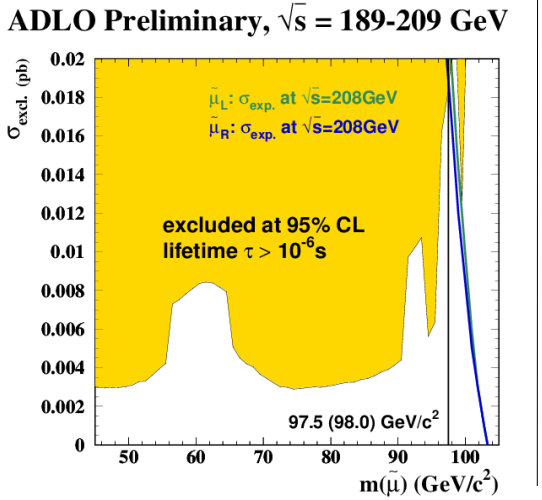
m(gluino)>~20 GeV

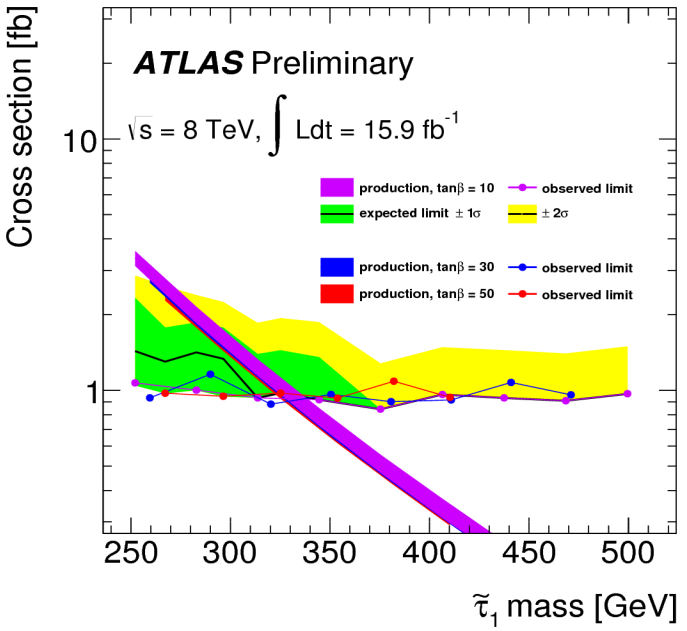
Heavy-muon: Previous Searches

- LHC 8 TeV has best sensitivity so far…
  - High-pT, isolated track
  - Measure *velocity* of track via
    - dE/dx (inverting Bethe-Block) (measured best in silicon)
    - Precise timing (measured in calorimeters and muon systems)
  - Background: mis-measured leptons
  - **m(stau)>~340 GeV**



- LEP was sensitive to long-lived charged particles up to **~CM/2**

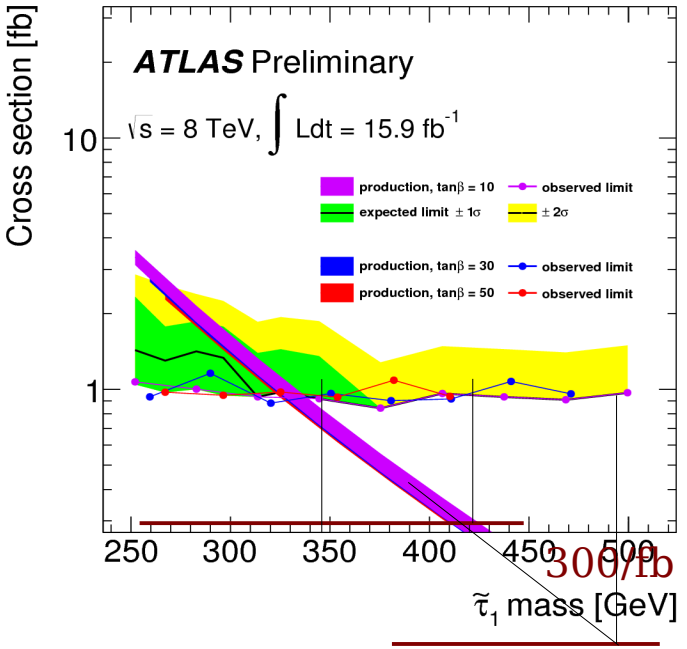


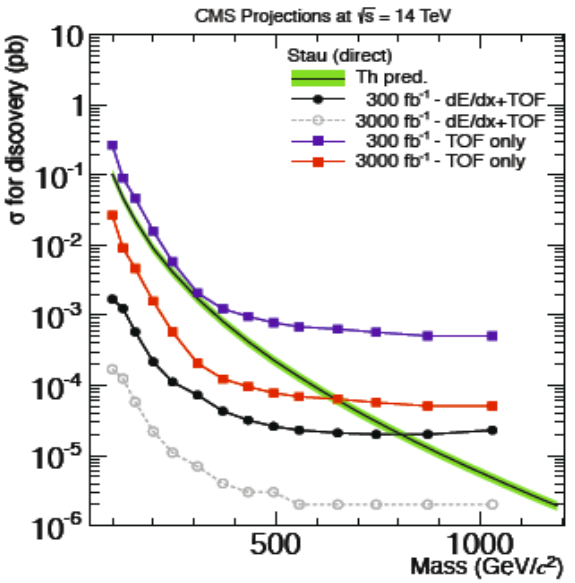


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-058/
http://lepsusy.web.cern.ch/lepsusy/www/gmsb_summer02/lepgmsb.html

Heavy Muon: Future Collider Reach

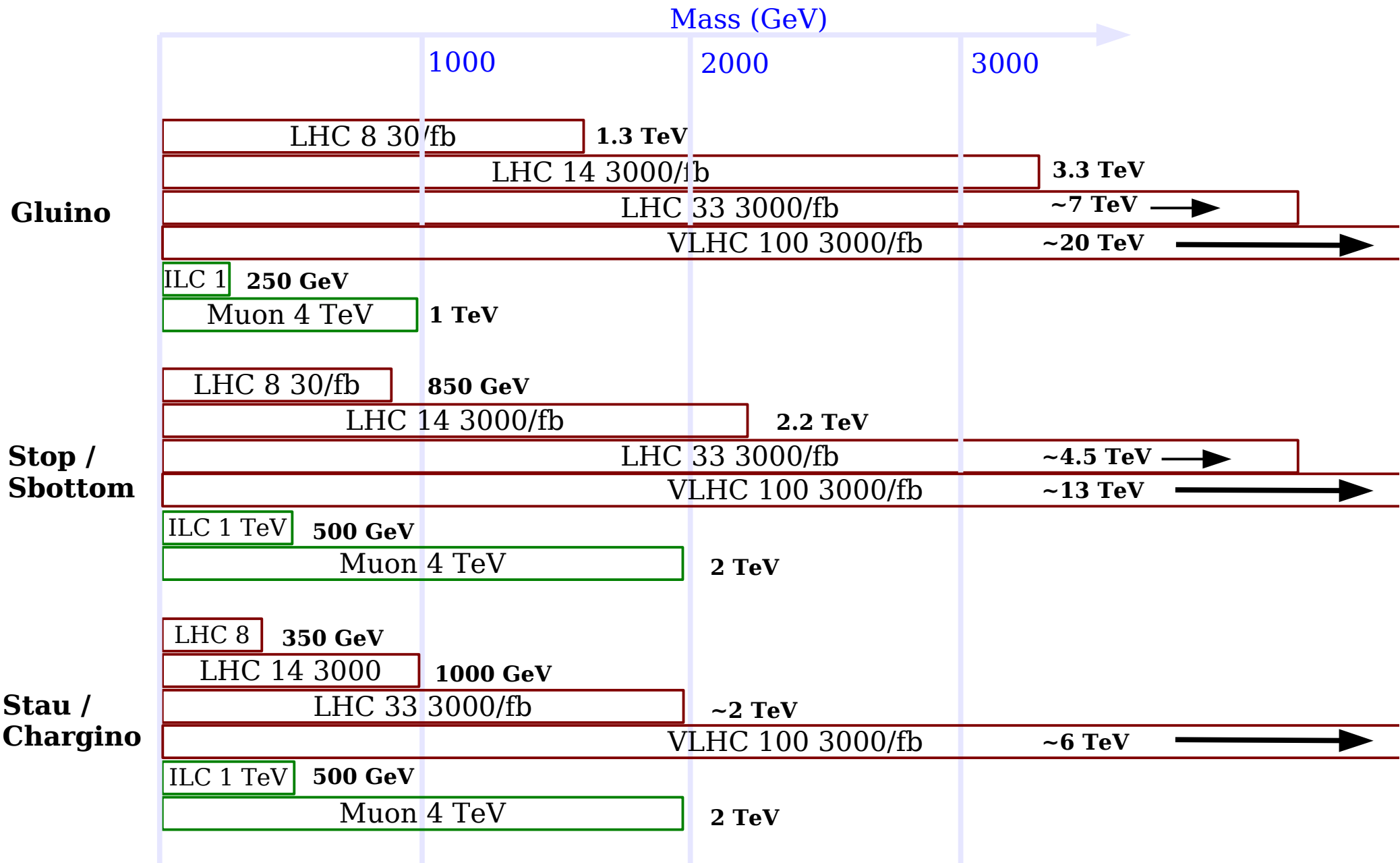
- Proton colliders:
  - S/sqrt(B) → sqrt(L)
  - S and B both scale ~linearly with CM
  - Heavy-muon reach:
    - 8 TeV 30/fb: 350 GeV
    - 8 TeV 300/fb: 425 GeV
    - 8 TeV 3000/fb: 500 GeV
    - 14 TeV 300/fb: 700 GeV
    - 14 TeV 3000/fb: ~1000 GeV
    - 33 TeV 3000/fb: ~2 TeV
    - 100 TeV 3000/fb: ~6 TeV
- Lepton colliders:
  - Heavy-muon reach ~CM/2:
    - ILC e^+e^- 1 TeV: 500 GeV
    - Muon collider 4 TeV: 2 TeV





3000/fb

Detector-Stable Particles: Estimated Mass Reach

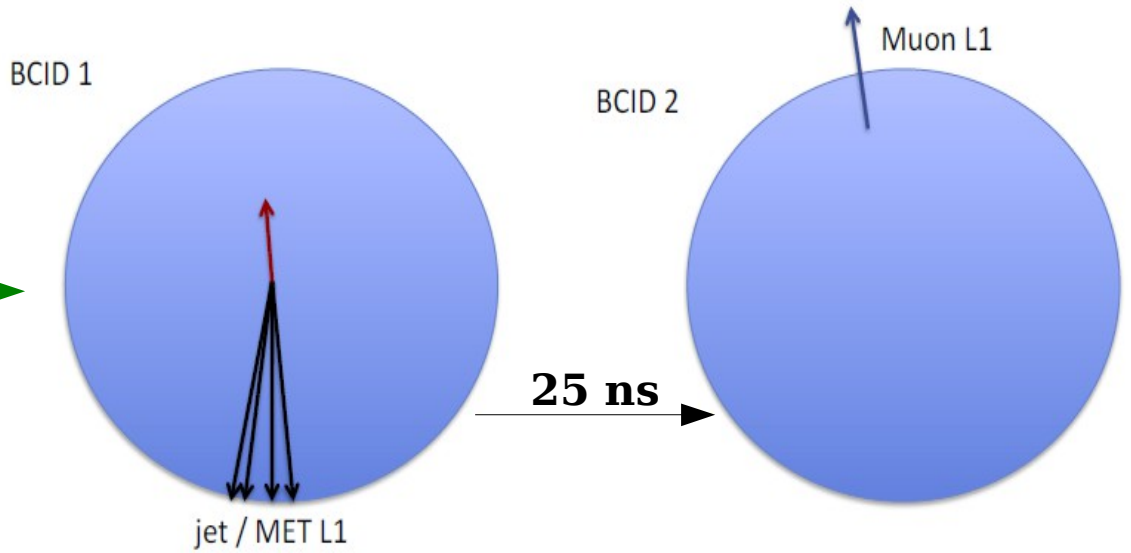


“Late” triggers

- Combine info from *multiple bunch crossings* in ATLAS Run2 trigger
  - Recall, bunch spacing will be just 25 ns in Run2 (was 50 ns)

- Heavy, slow (β<~0.5), charged long-lived particle
  - Too slow to reach muon trigger in bunch 1 (production crossing)
  - Reaches muon trigger in next bunch crossing
  - Would not fire muon trigger by itself
  - *Combine with jet/MET in <u>previous</u> bunch crossing*

Read-out this one as main event →



Could be an important technique if bunch spacing gets shorter… 5 ns ?

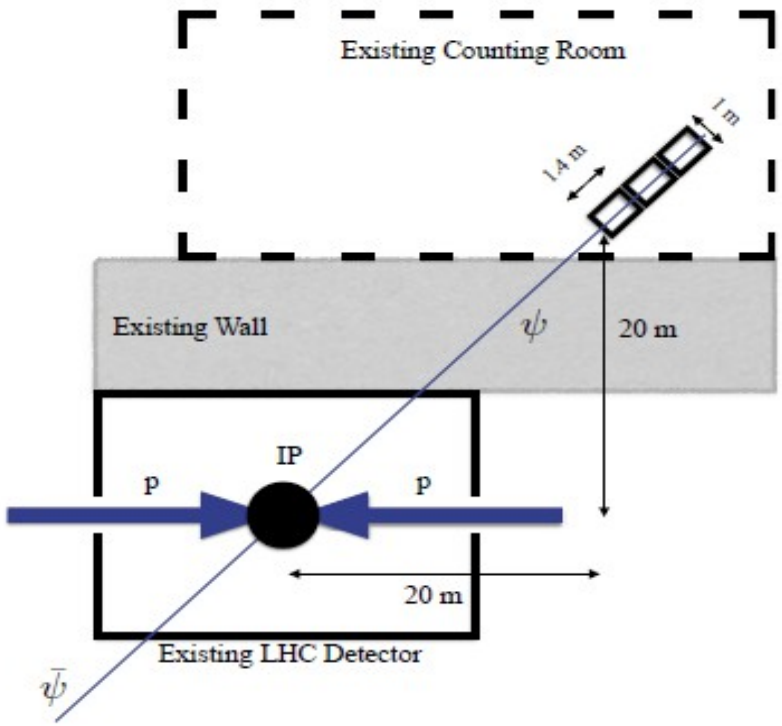
Milli-charged Particles

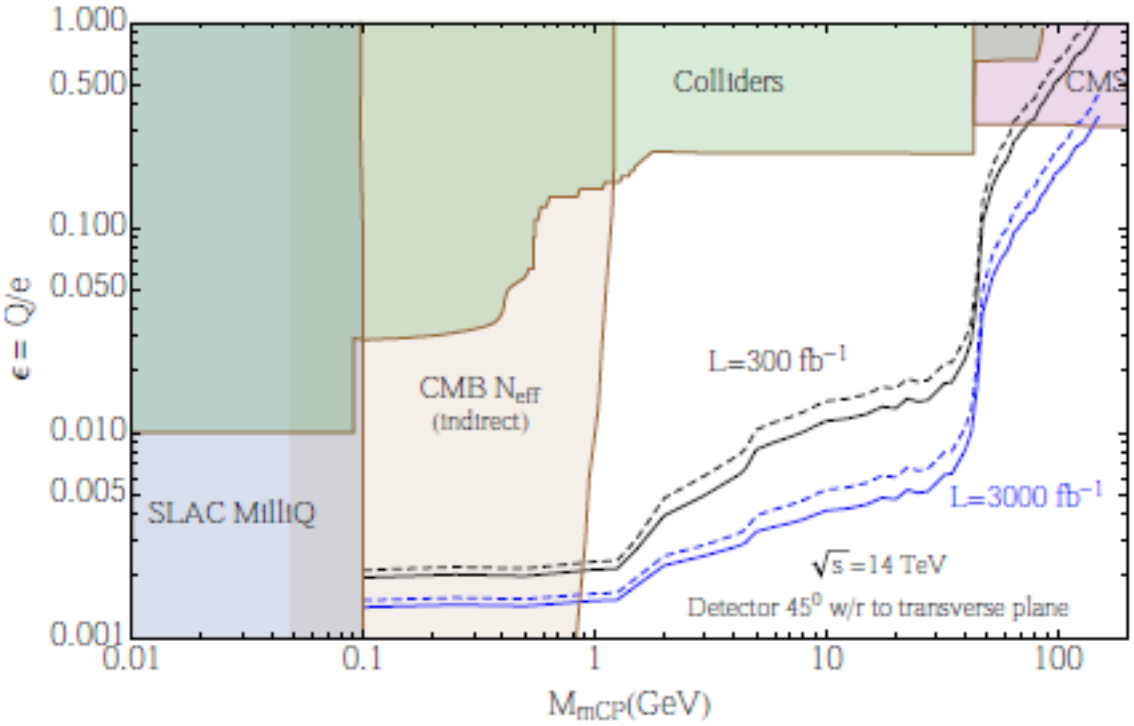
- New dark sectors can have new particles which appear "milli-charged" to the SM
- Electric charge ~10^{-3} – ~10^{-1}
- No direct constraints above 100 MeV

arXiv:1410.6816 [hep-ph]

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\psi}\left(\partial\!\!\!/ + ie'A\!\!\!/' - i\kappa e'B\!\!\!/ + iM_{\rm mCP}\right)\psi$$

- ***A new LHC experiment (mQ@LHC) could probe up to ~100 GeV***
  - *Scintillator coincidence "telescope" sensitive to single photo-electrons*



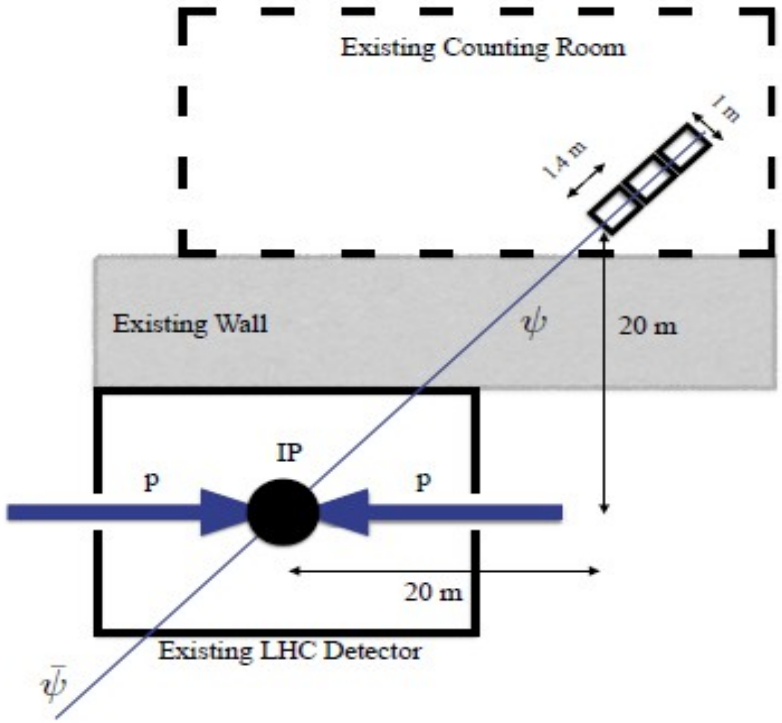


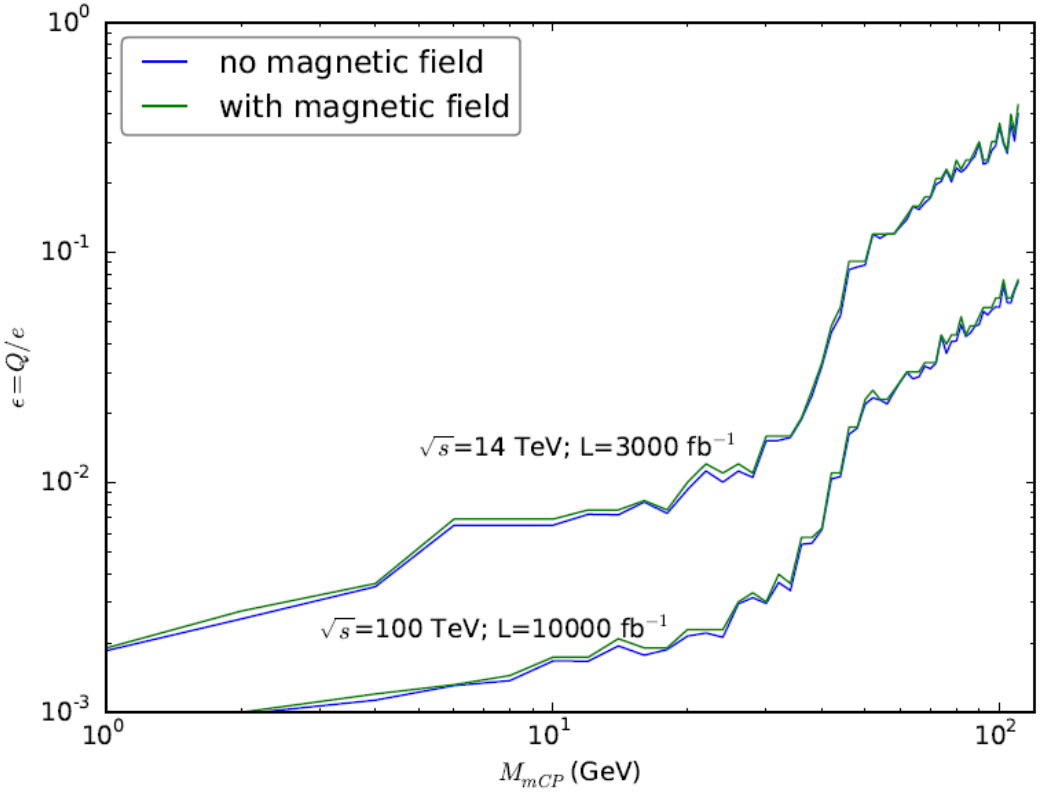
Milli-charged Particles

- New dark sectors can have new particles which appear "milli-charged" to the SM
- Electric charge ~10^{-3} – ~10^{-1}
- No direct constraints above 100 MeV
- ***Future 100 TeV reach about 5x lower in charge and out to ~500 GeV mass***

arXiv:1410.6816 [hep-ph]

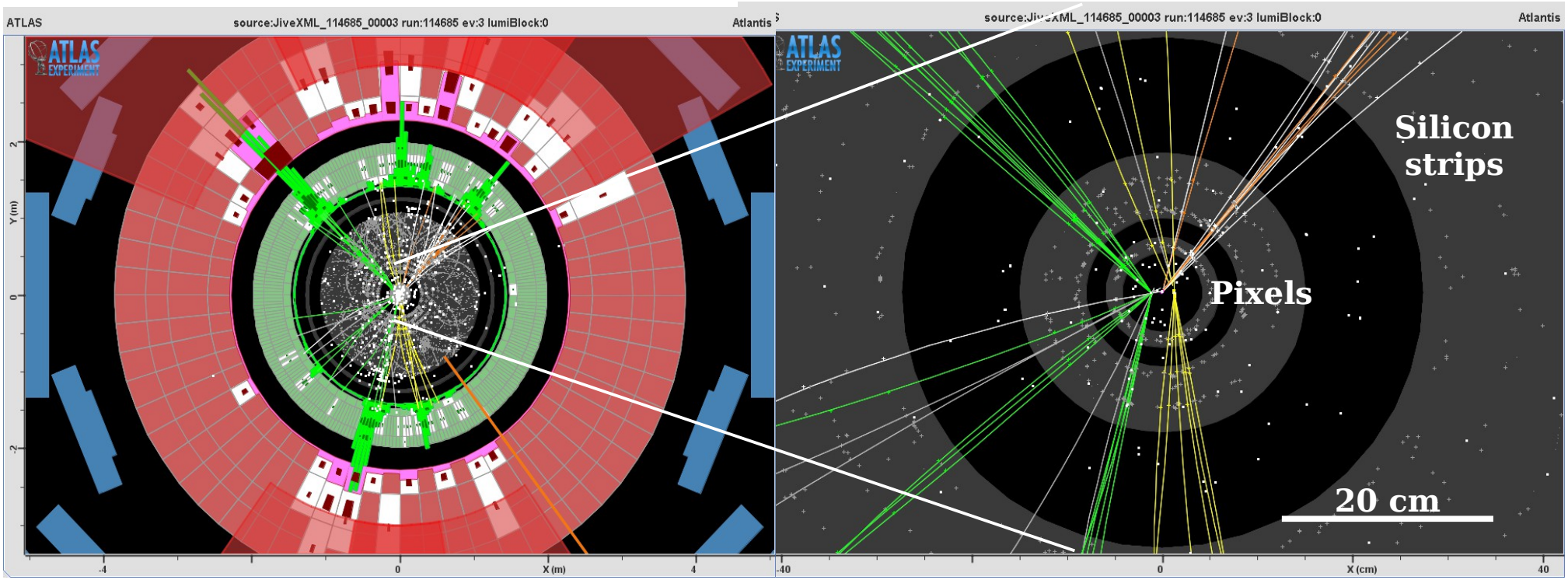
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\psi}\left(\partial\!\!\!/ + ie'A\!\!\!/' - i\kappa e'B\!\!\!/ + iM_{\rm mCP}\right)\psi$$





Semi-stable R-hadron Decays

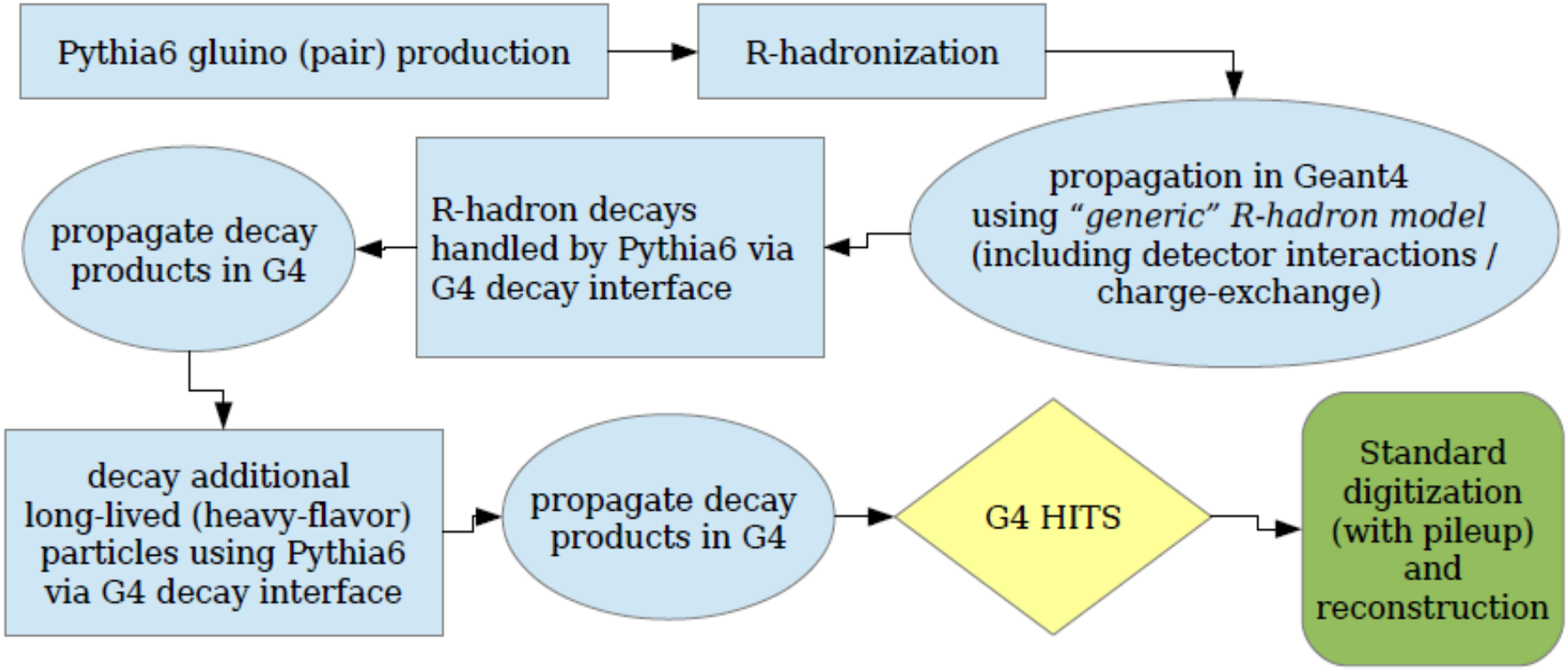
- What if gluino (R-hadron) is just a little long-lived (~1 ns)?
  - Displaced jets (+MET) from R-hadron decays in the detector



- Standard jets+MET search should still apply (up to what lifetime?)
  - Leptons vetos may start to fail impact-parameter cuts (when?)
  - Jets will start to be identified as b-jets (when?)
  - Jets may fail cleaning cuts, e.g. track pT fraction, EM fraction (when?)

Prompt search reinterpretations

- *First explicit limits on gluinos with intermediate lifetimes from reinterpretation of prompt SUSY searches*
  - 7-10 jets and 0,1,2 b-jets and MET
  - 2-6 jets and MET
  - *3 b-jet and SS/3L searches also considered but don't add sensitivity*
- Generated fullly-simulated MC of decaying Rhadrons at ATLAS

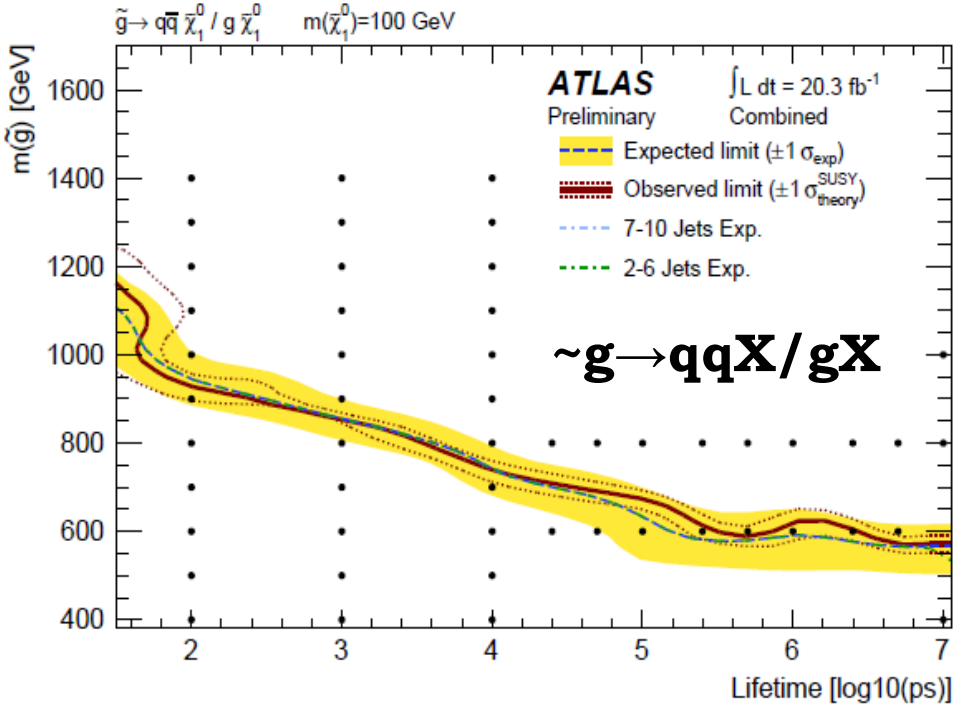


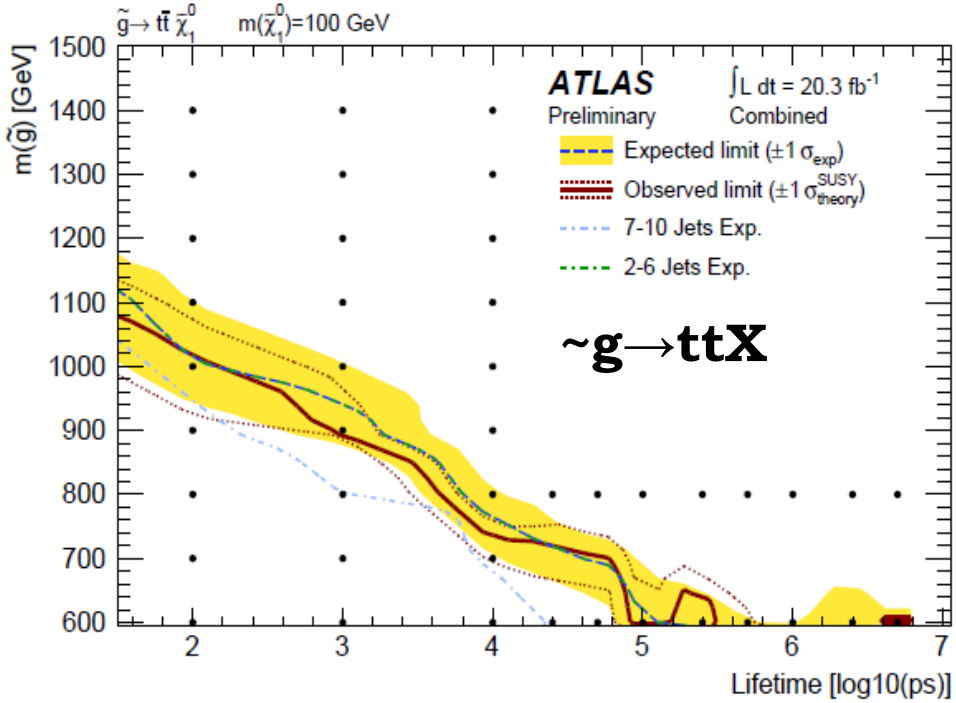
Prompt search reinterpretations

- Limits on gluino mass vs. lifetime
  - Also scan neutralino mass

ATLAS-CONF-2014-037

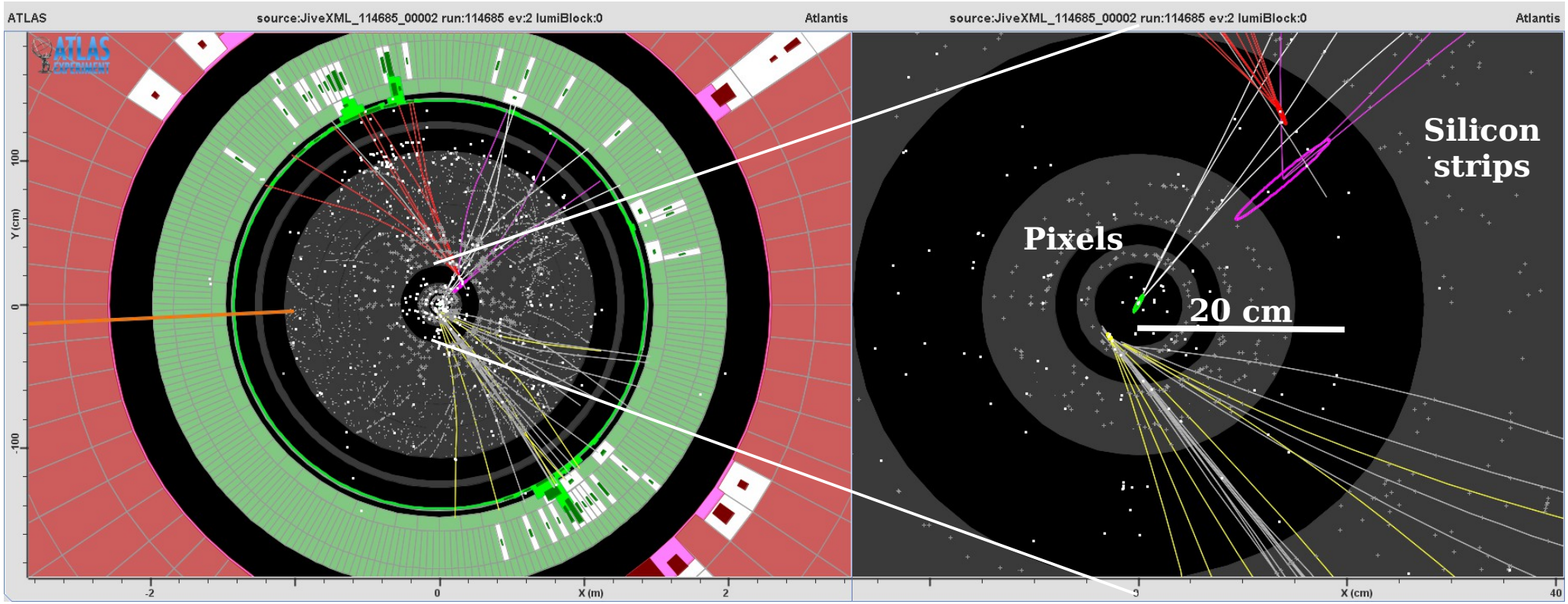
- Gluino with lifetime of 1 ns excluded up to ~900 GeV, for $m(\chi_1^0)$=100 GeV





Displaced vertex searches

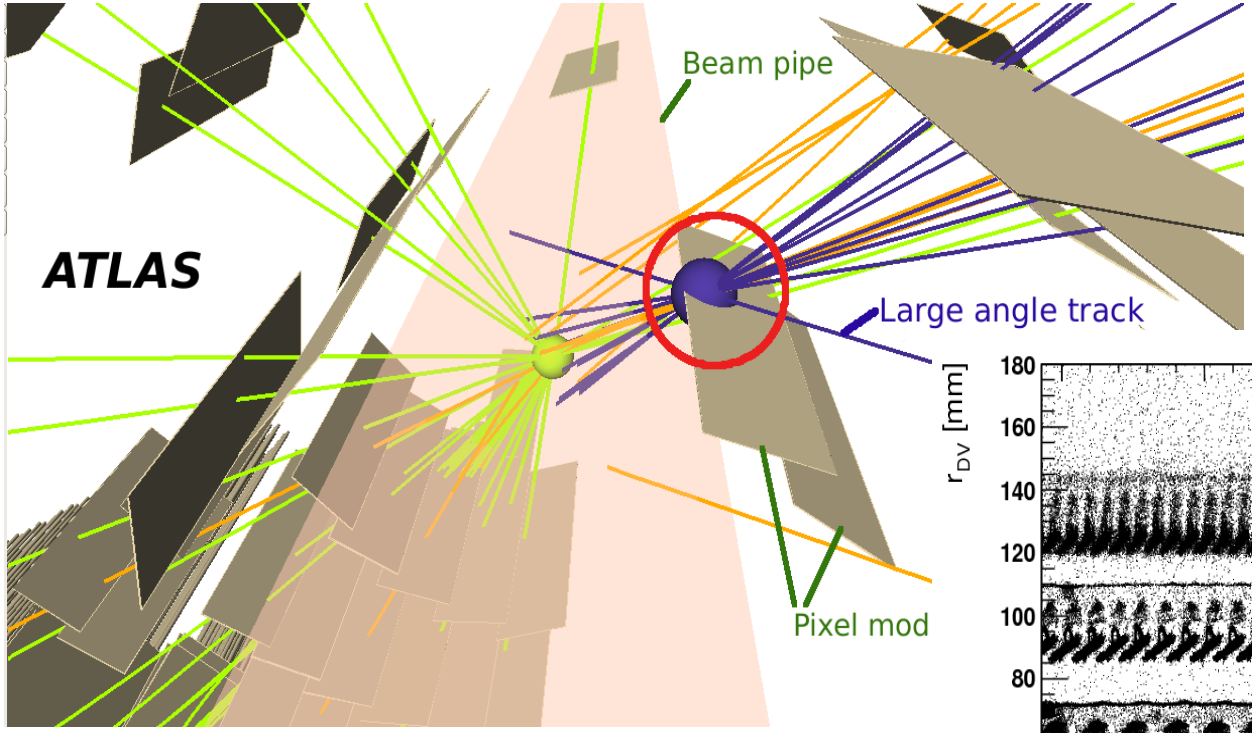
- For moderate lifetimes, ~1 – 1000 ns, can reconstruct the **displaced vertex in the tracker**
- Current ATLAS analysis requires a *high-pt muon* to trigger on and reduce backgrounds… sensitive to gluino → ttbar decays
  - *Adding analysis based on jet and MET triggers, for g → qq+x_1^0 decays*



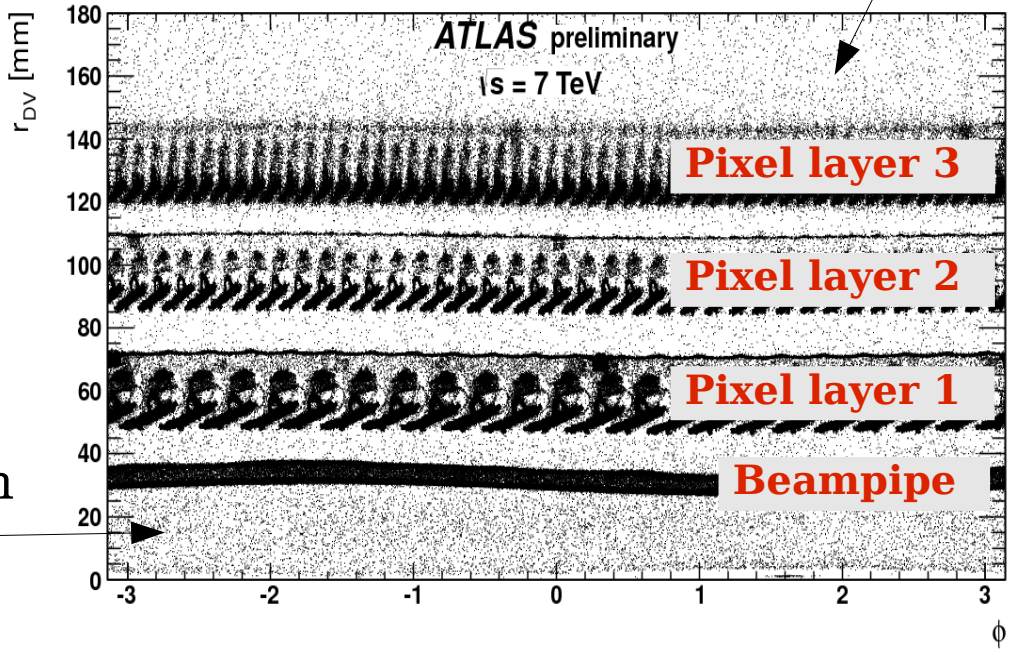
Displaced vertex searches

ATLAS-CONF-2013-092

- Background from hadronic interactions with material (or air!)
  - Find where material is (from data) and reject the regions



3-track vertices with low mass



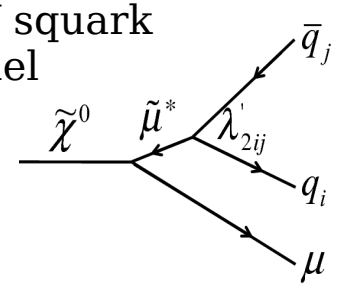
  - Also background from random track crossings / pileup (no air in the beampipe)

Displaced vertex searches

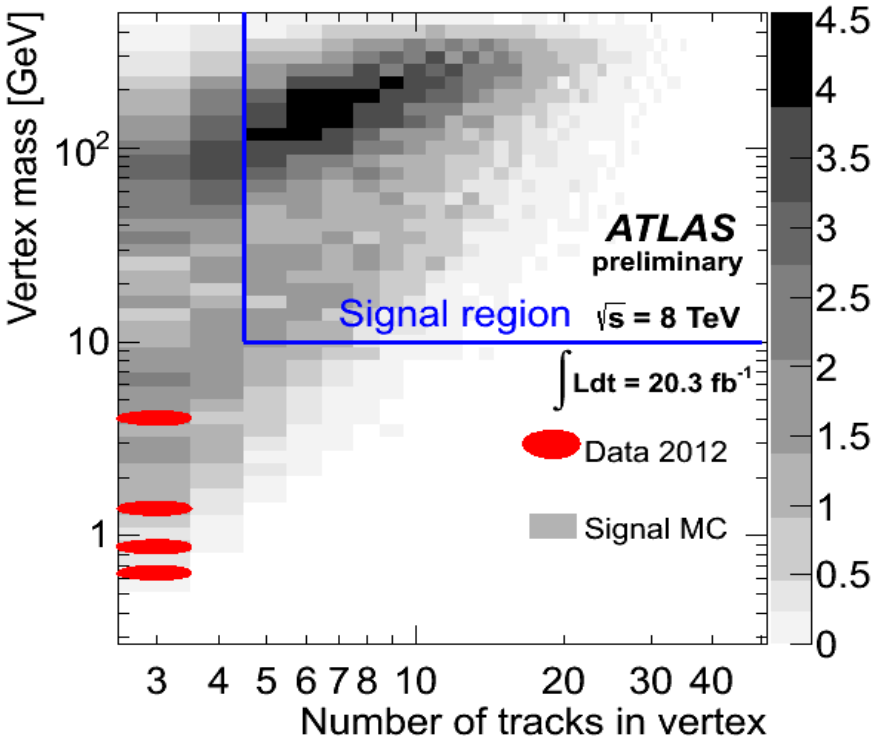
- Require vertex to have at least 5 tracks and (visible) mass >10 GeV
- Total background expected: 0.02 events
- Observed in signal region: 0 events

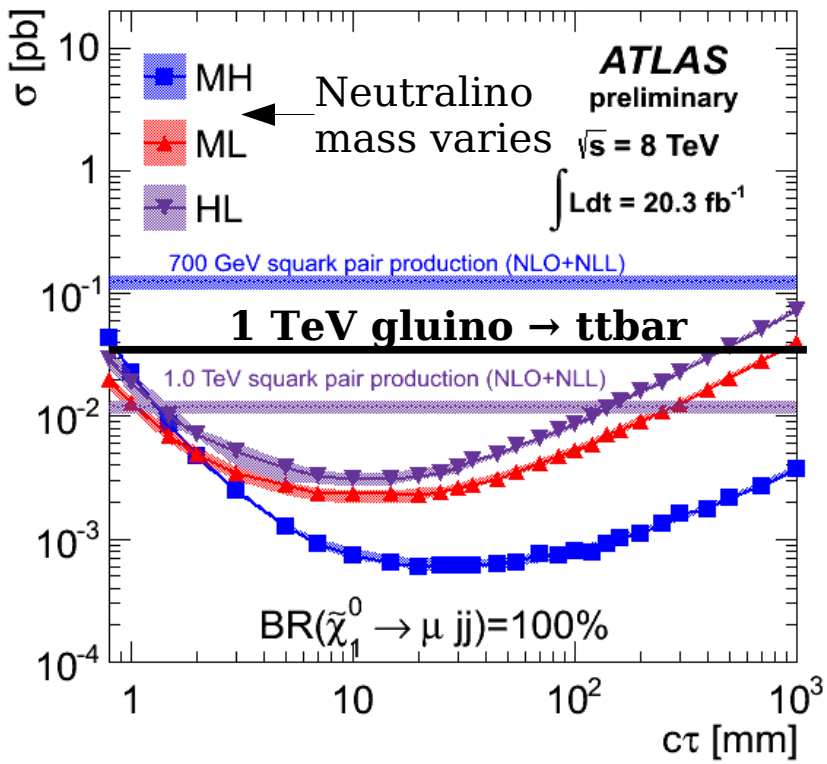
ATLAS-CONF-2013-092

RPV squark model



- *Sensitive to ~1–1.4 TeV gluino→tt+x_1^0 for cτ ~1-1000 ns*



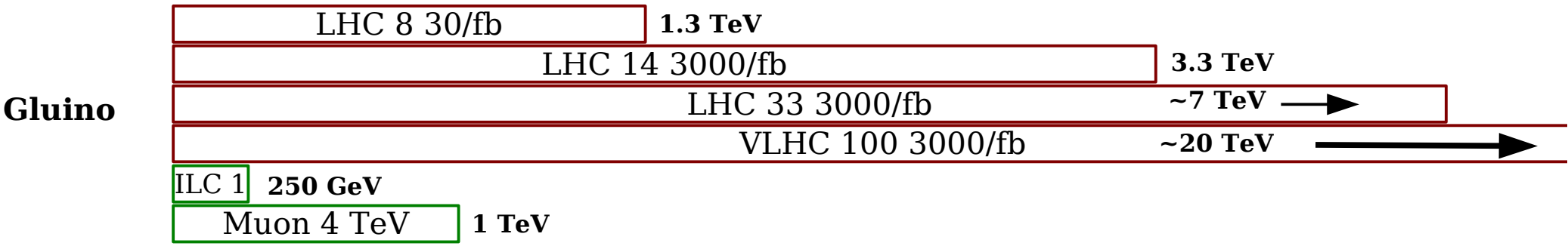


(Far-)Future of Displaced Vertex Searches

- Direct search for displaced vertices is more sensitive than relying on jets and MET (prompt reinterpretations), for lifetimes > ~1 mm
- "Detector-stable" searches more sensitive for lifetimes > ~300 mm

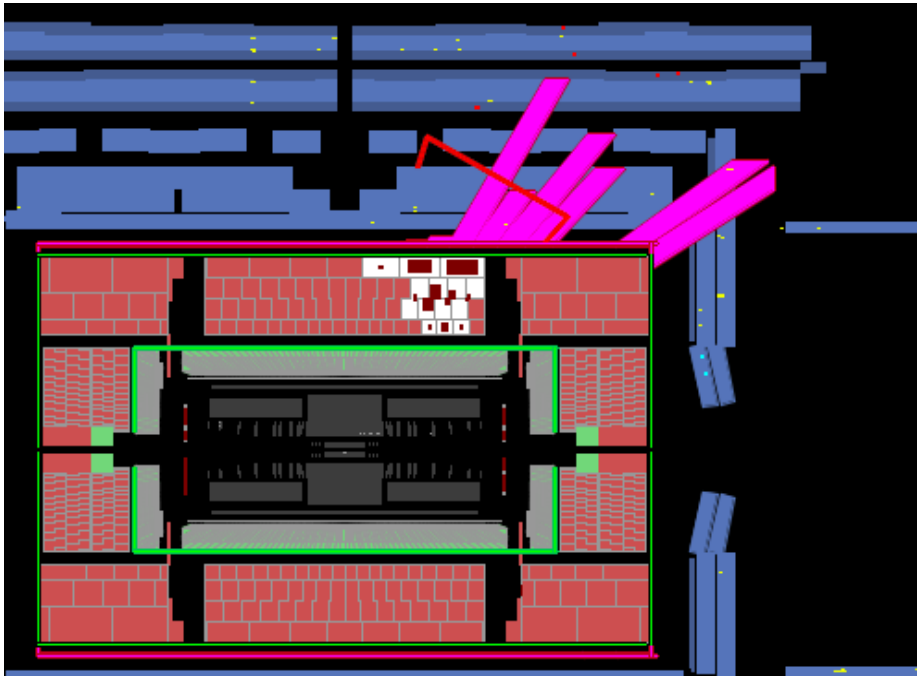
- *Must ensure future detectors can still reconstruct tracks starting ~100 mm from the beamspot with impact parameters up to ~50 mm*
- *Must ensure there are still sufficient air-gaps (or vacuum?) between inner detector tracker material*

- Assuming detectors perform well, sensitivity is limited only by production cross-section, reach is similar to detector-stable case:

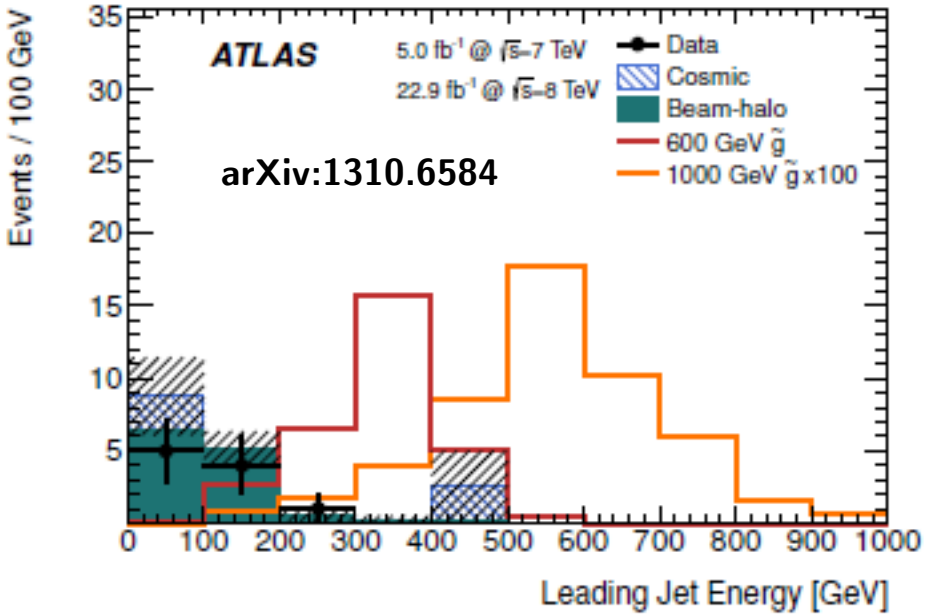


Out-of-time Decays (Stopped R-hadrons)

- Can also detect decay of R-hadron that has *stopped* in the calorimeter
- D0, ATLAS, CMS have searched…
- Limits usually slightly weaker than dE/dx + timing searches for escaping R-hadrons
  (assuming it's often charged in the tracker)
- But offers possibility to *study the R-hadron decay*



- Should ensure this remains possible at future collider detectors
  - Need abort gap without collisions
  - Need good calorimeter timing and shower-shape discrimination
  - Need efficient muon vetos for cosmics and beam-halo



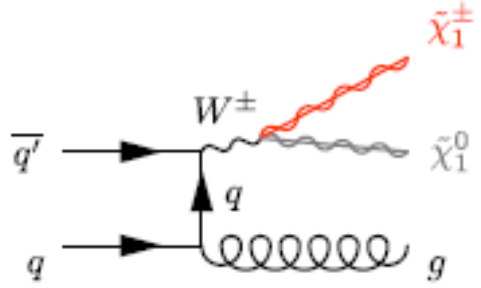
Semi-stable Charged Particle Decays

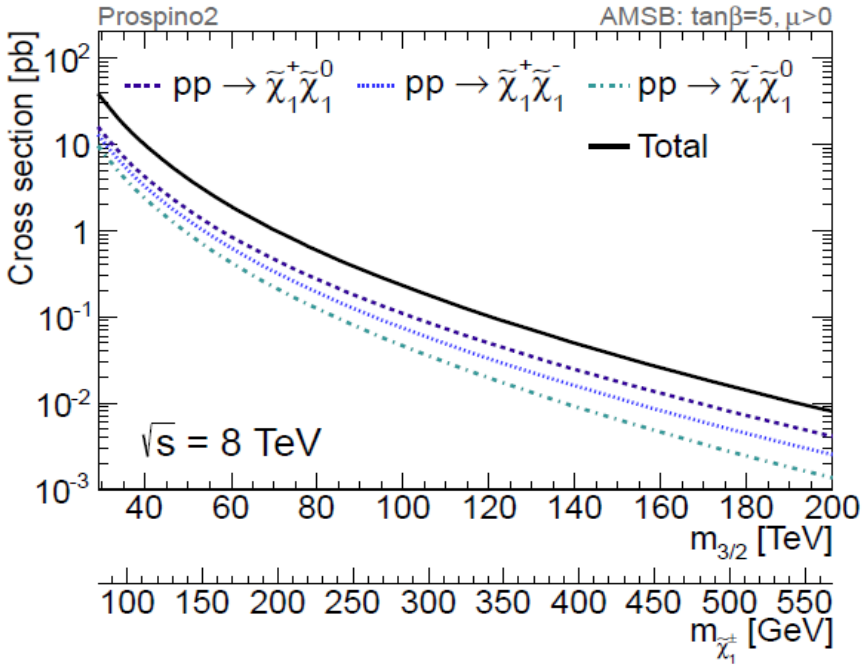
- Chargino becomes long-lived when nearly-degenerate with the LSP
- Kinked-tracks from chargino → neutralino (and soft pion/lepton)

- Light Wino and Bino, heavy Higgsinos, Wino LSP
  - Lifetime ~50 mm, Δm~165 MeV from EW contribution
- Higgsino LSP, only light Higgsinos
  - Lifetime ~5 mm, Δm= ½ α m_Z = ~355 MeV

$pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_1^0 + \text{jet}$, $pp \to \tilde{\chi}_1^+\tilde{\chi}_1^- + \text{jet}$

Need pT>90 GeV ISR for MET trigger:
~15% of cross-section



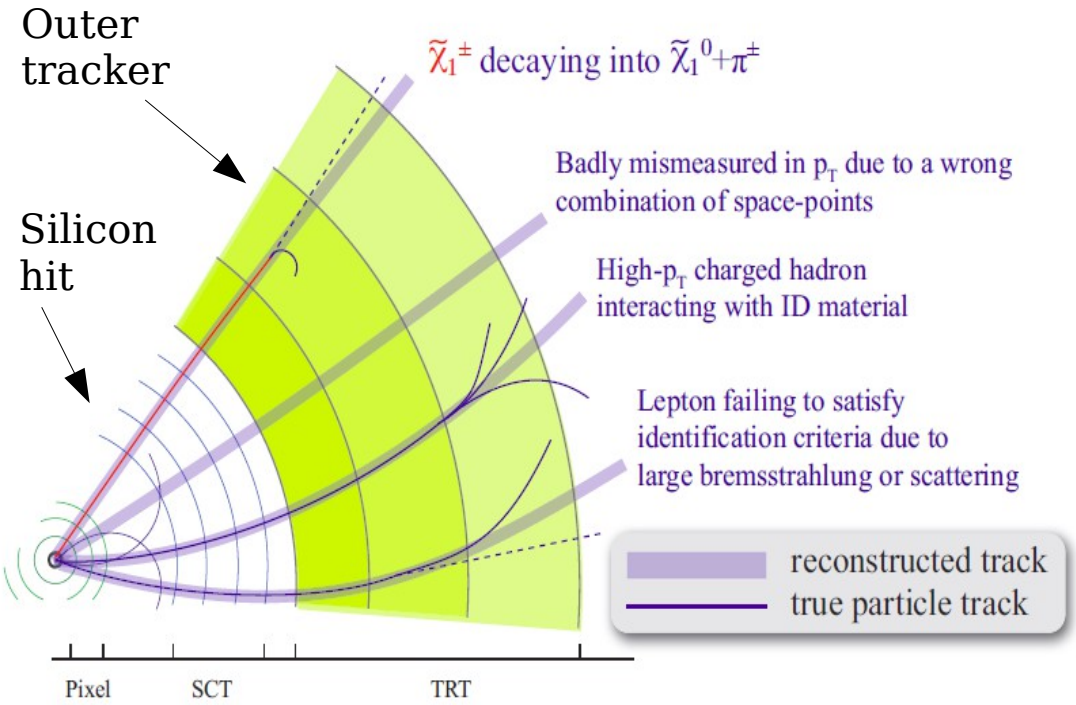


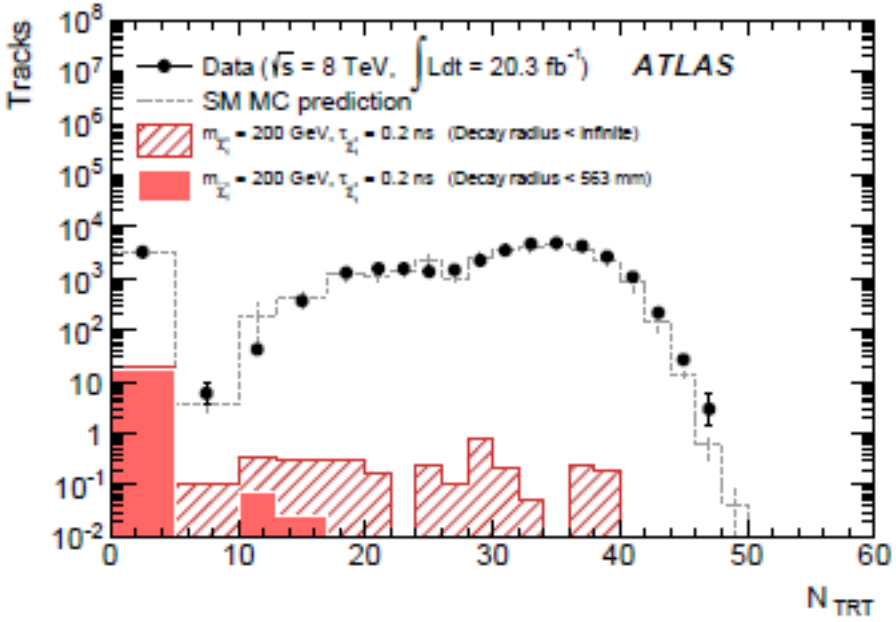
Semi-stable Charged Particle Decays

arXiv:1310.3675

- Chargino travels through some layers
  then decays to a soft pion (not reconstructed) + MET

- Look for high-pt isolated track with few hits in outer tracking layer
  - Track needs at least 3 inner pixel hits and 1 silicon strip hit
  - Require <5 outer-tracker (TRT) hits

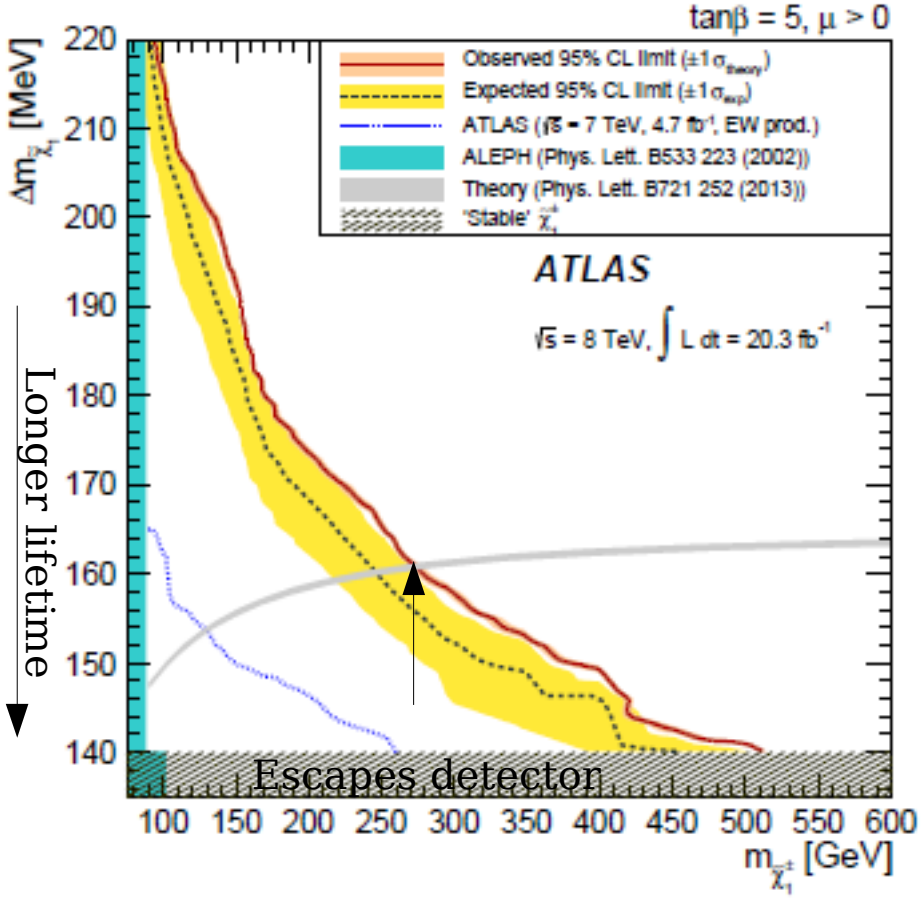


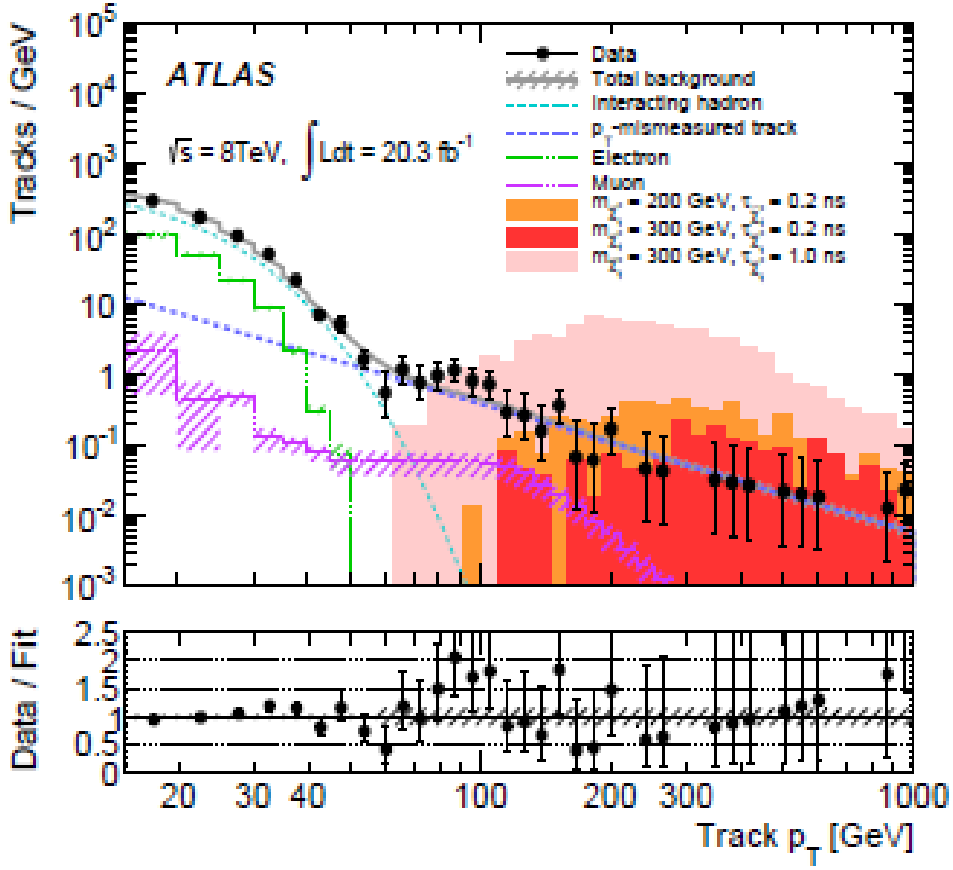


Semi-stable Charged Particle Decays

- Background track pT shapes fit to data
  - No excess seen at high pT

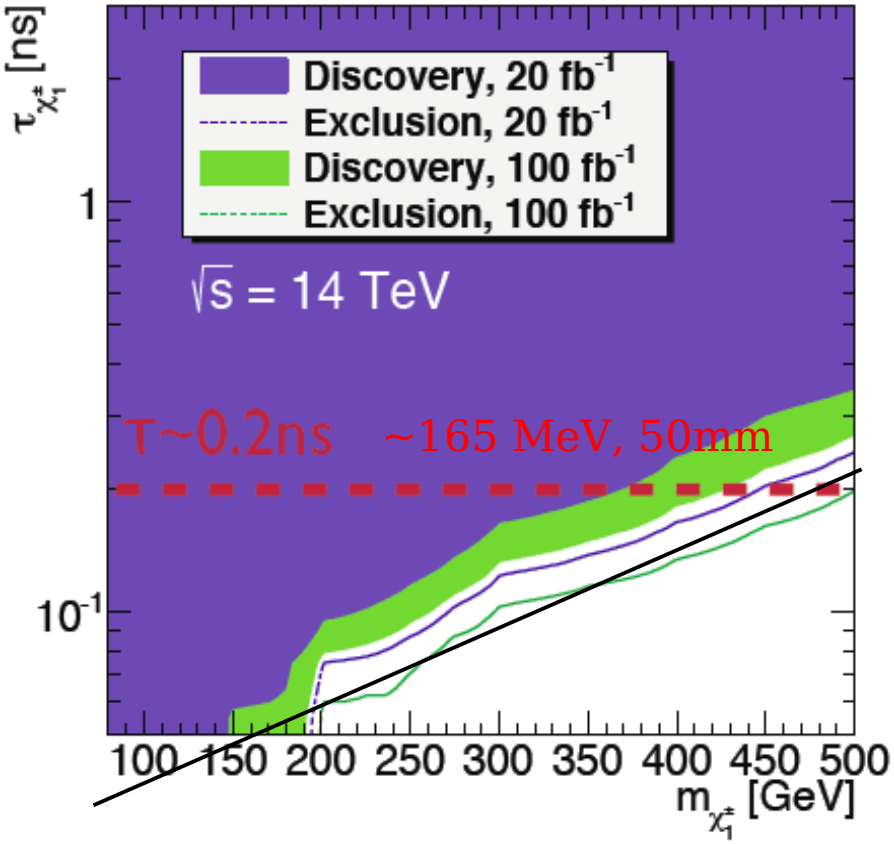
- Exclude chargino <270 GeV in AMSB with Δm~165 MeV





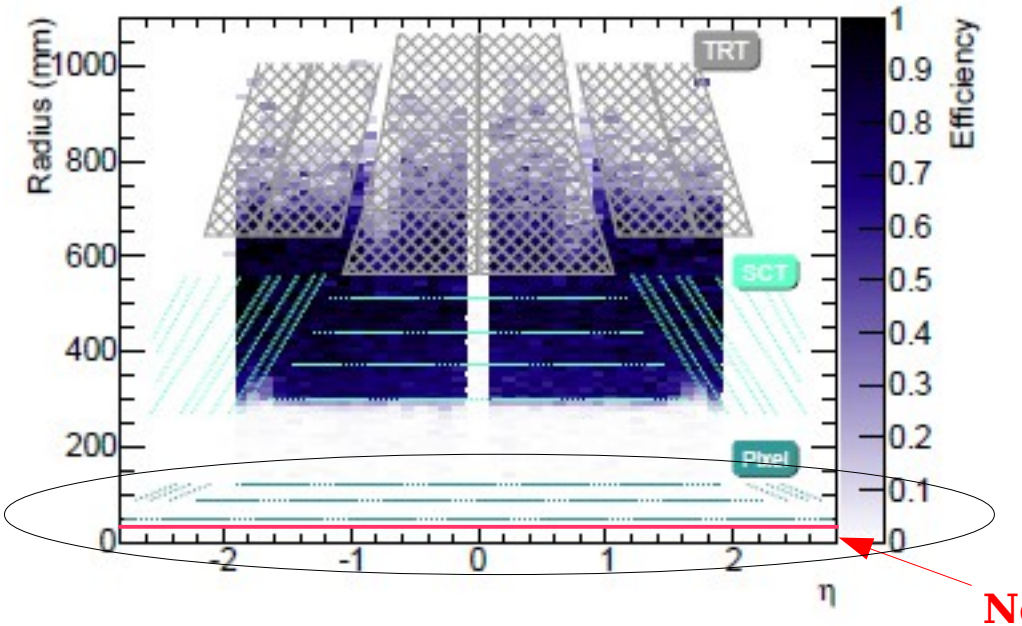
Improved Disappearing Track Search

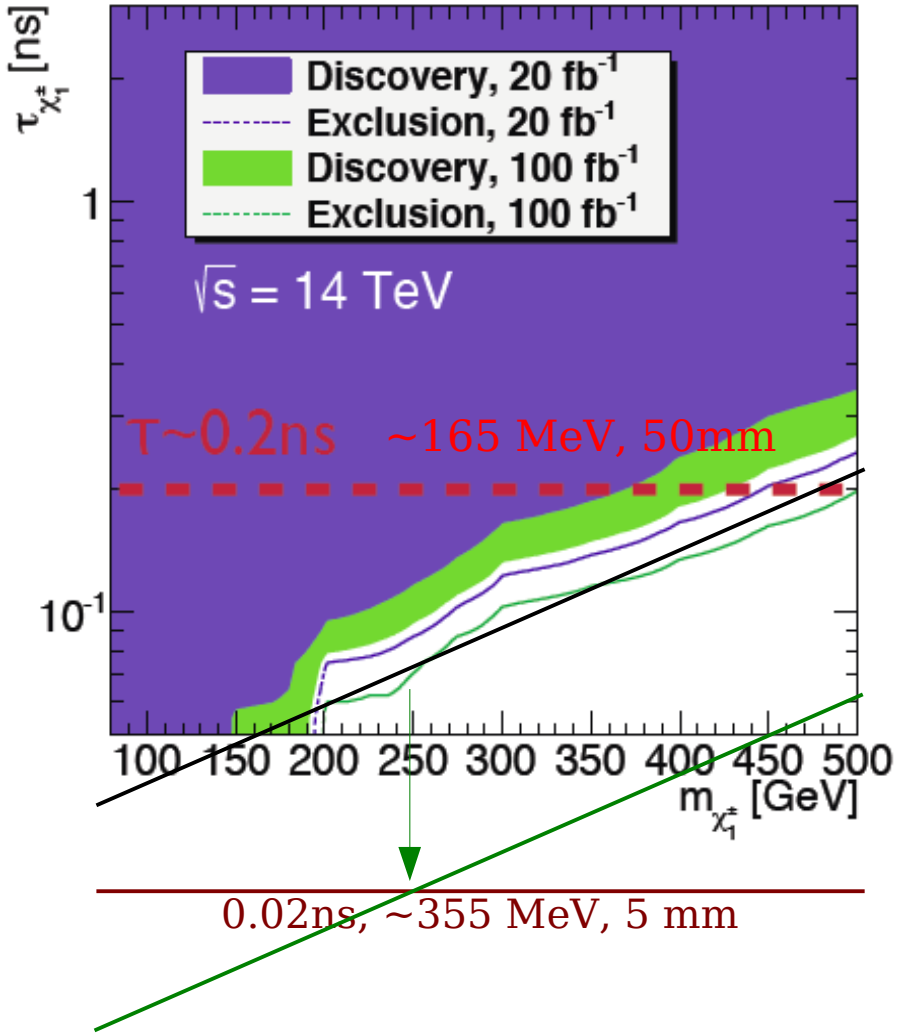
- Eventual sensitivity with 14 TeV and same short-track analysis ~500 GeV for Δm~165 MeV
- Going to need even shorter tracks to reach the ~5 mm lifetime case…



Improved Disappearing Track Search

- Eventual sensitivity with 14 TeV and same short-track analysis ~500 GeV for Δm~165 MeV
- Going to need even shorter tracks to reach the ~5 mm lifetime case
  - Insertable B-Layer (IBL) added
  - Could have ~150 mm tracks using just 4 pixel hits?!





Sensitive up to ~800 GeV for 50 mm and ~250 GeV for 5 mm lifetime using 4-pixel IBL tracks?

New IBL pixel layer at radius of ~26mm

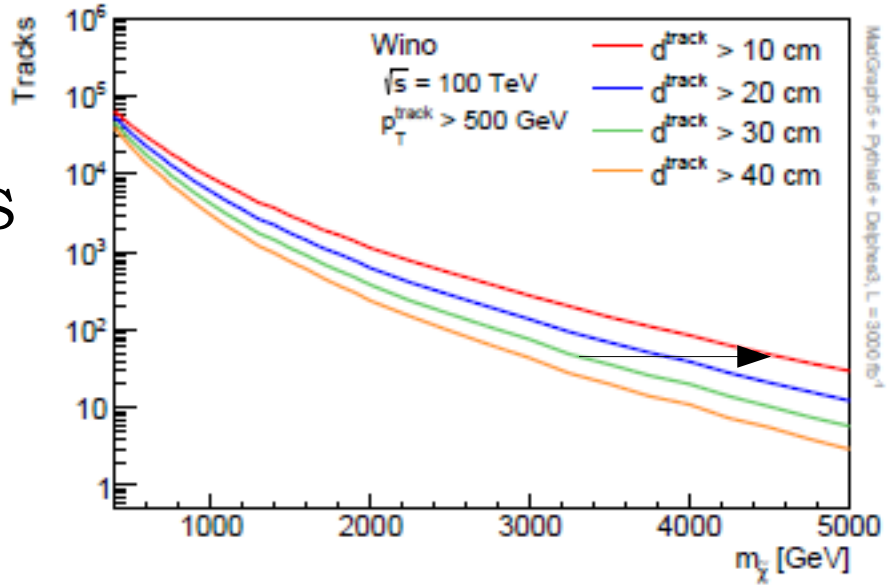
(Far-)Future of Disappearing Track Searches

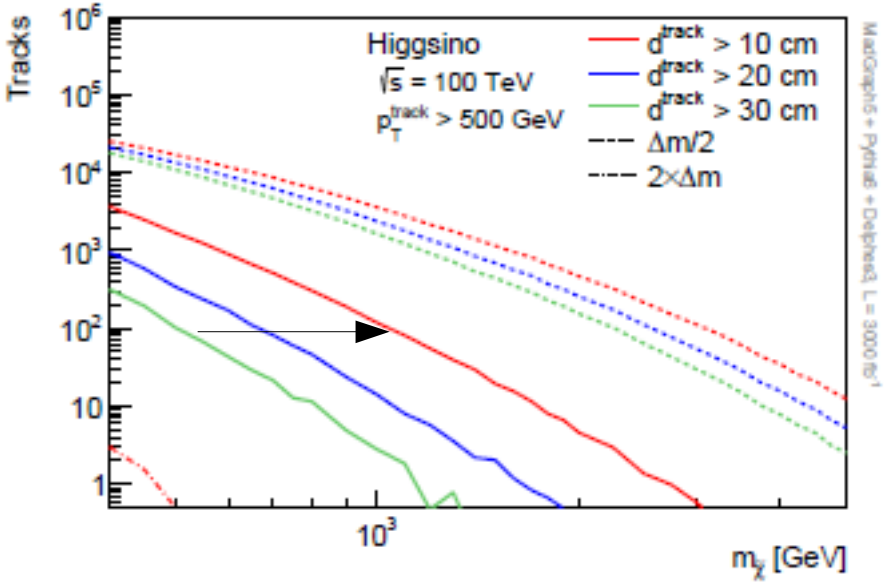
- Reconstructing very short tracks (with good momentum resolution!) is essential for mass reach
- 15 cm tracks seem possible at ATLAS

- If we could reconstruct 10 cm tracks at a 100 TeV detector:
  - Wino sensitivity from 3.5 → 4.5 TeV
  - Higgsino from ~600 GeV → 1 TeV !

- *Short tracks should perhaps be a design goal of future detectors (and accelerators?)*

M. Low and L.T. Wang
arXiv: 1404.0682





Conclusions

- Semi-stable and detector-stable particles are highly-motivated targets for beyond-SM discoveries at future (or current!) colliders

- Discussed several important searches – skipped many… (displaced photons, leptons, light resonances, etc.)

- Distinct signatures and low backgrounds – sensitivity often up to kinematic limits of production rate
  - Long-lived gluino mass reach ~7x greater at 100 TeV than 14 TeV
- Must ensure detectors (and accelerators) continue to allow good triggering on and reconstruction of:
  - escaping, slow, and stopping charged (and milli-charged?) particles
  - displaced tracks (and vertices in air/vacuum gaps)
  - very short tracks (with good momentum resolution)
- And of course we must build future accelerators and detectors!!!