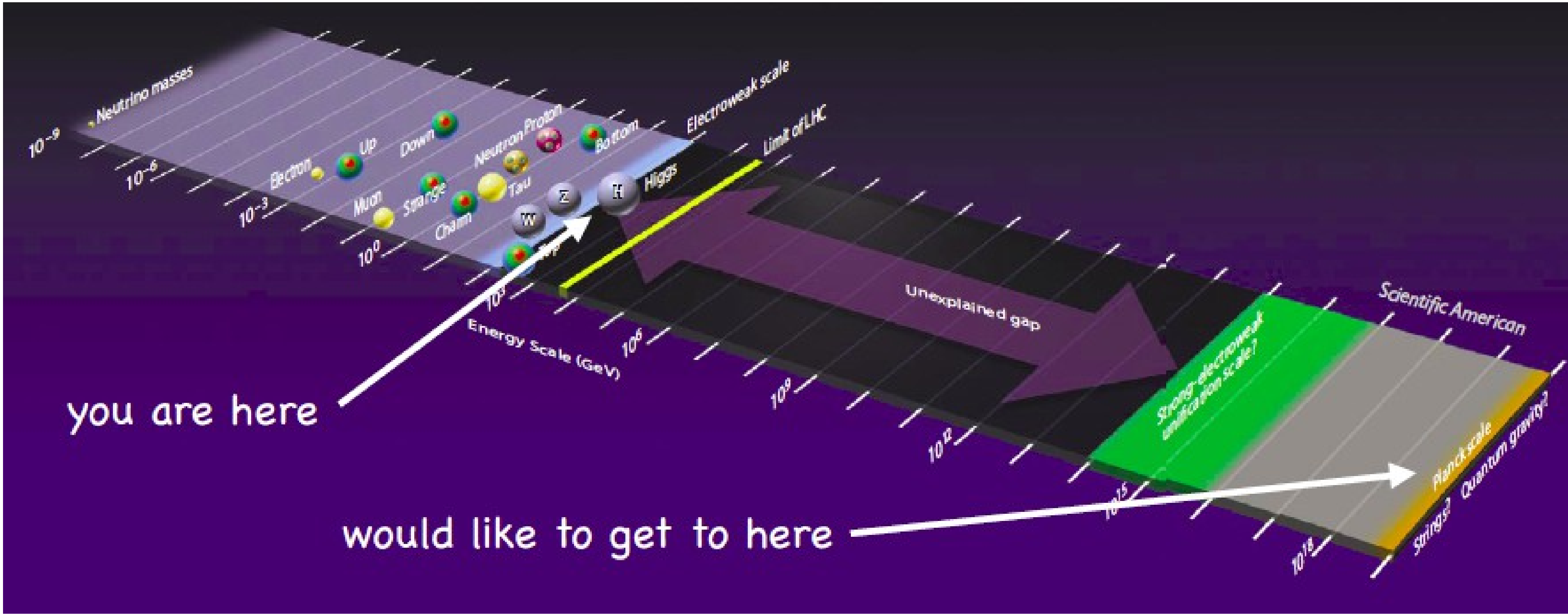
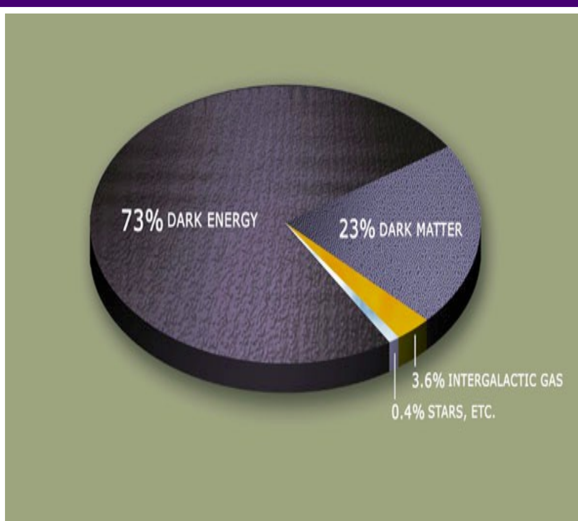
LHC SUSY searches: Pulling out all the stops

Andy Haas (NYU)

Workshop on Frontiers of New Physics: Colliders and Beyond
ICTP, Trieste - June 23-27, 2014
http://cdsagenda5.ictp.it/full_display.php?email=0&ida=a13203

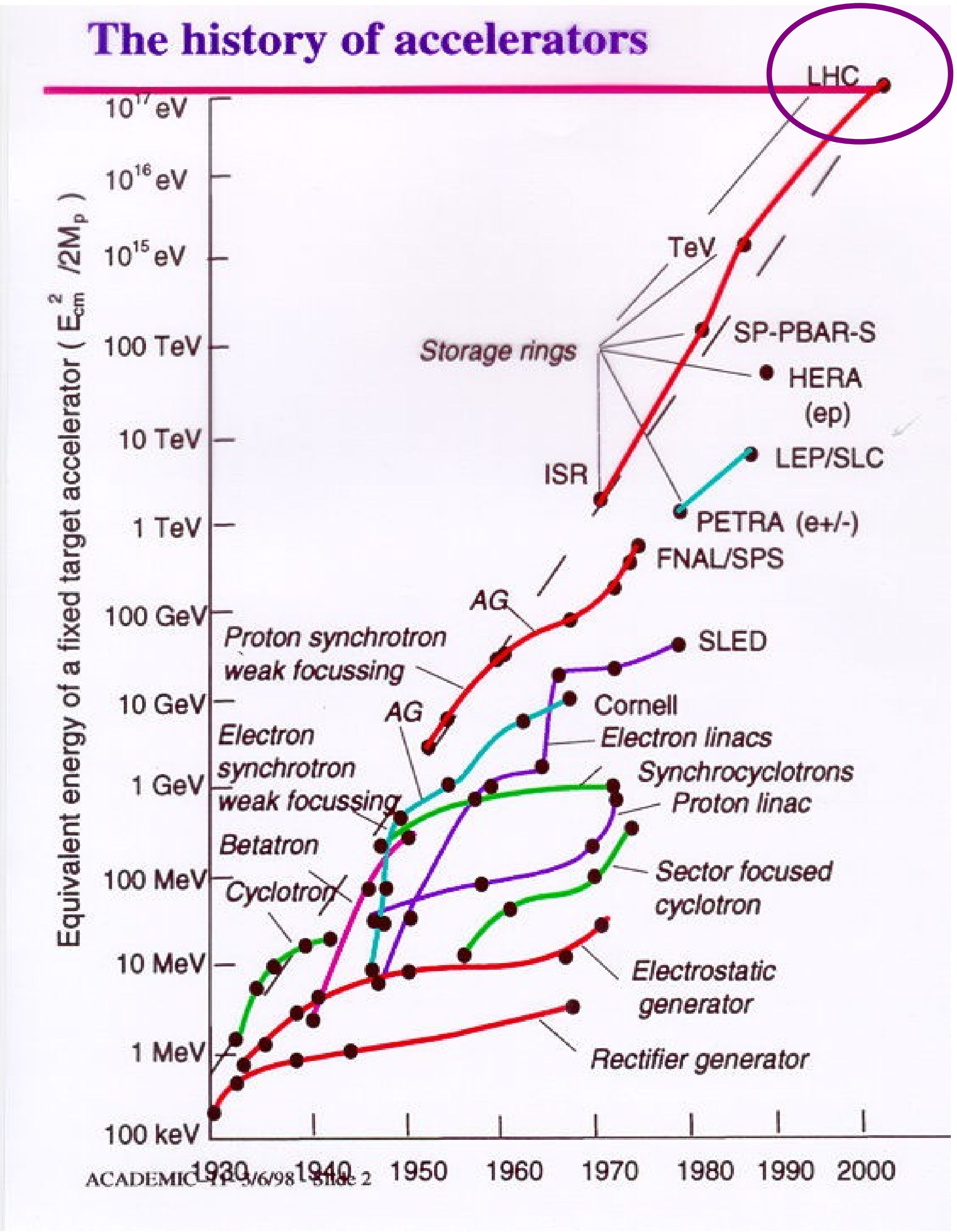
“Science Drivers”

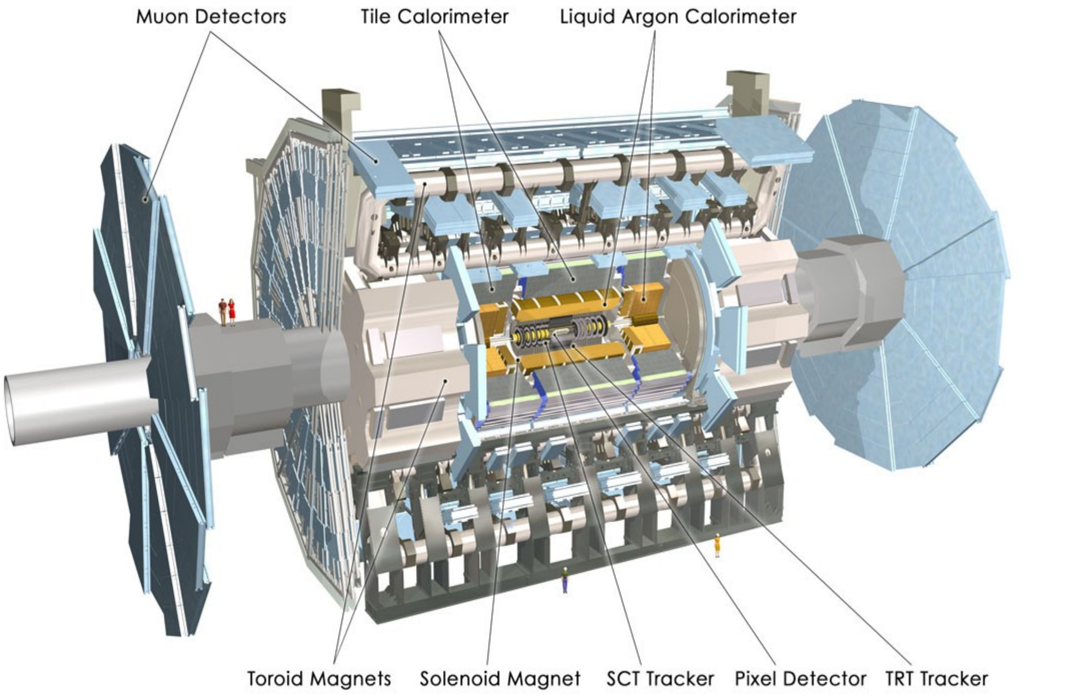




- Hierarchy problem
- Force unification
- Dark matter
- ...
- Should find SUSY near the EW scale?!
  (Many other solutions too... almost all predict new physics there!)

Directly Probing the EW Scale (and just beyond)



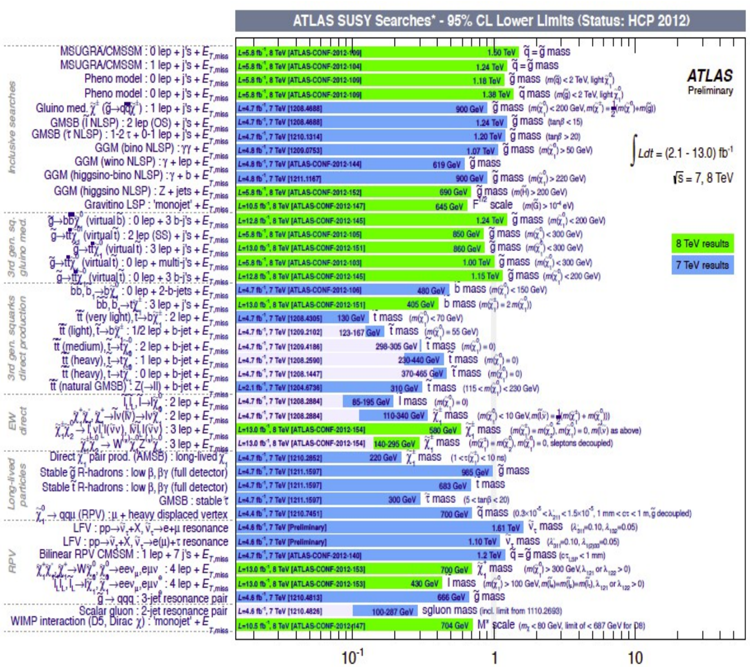


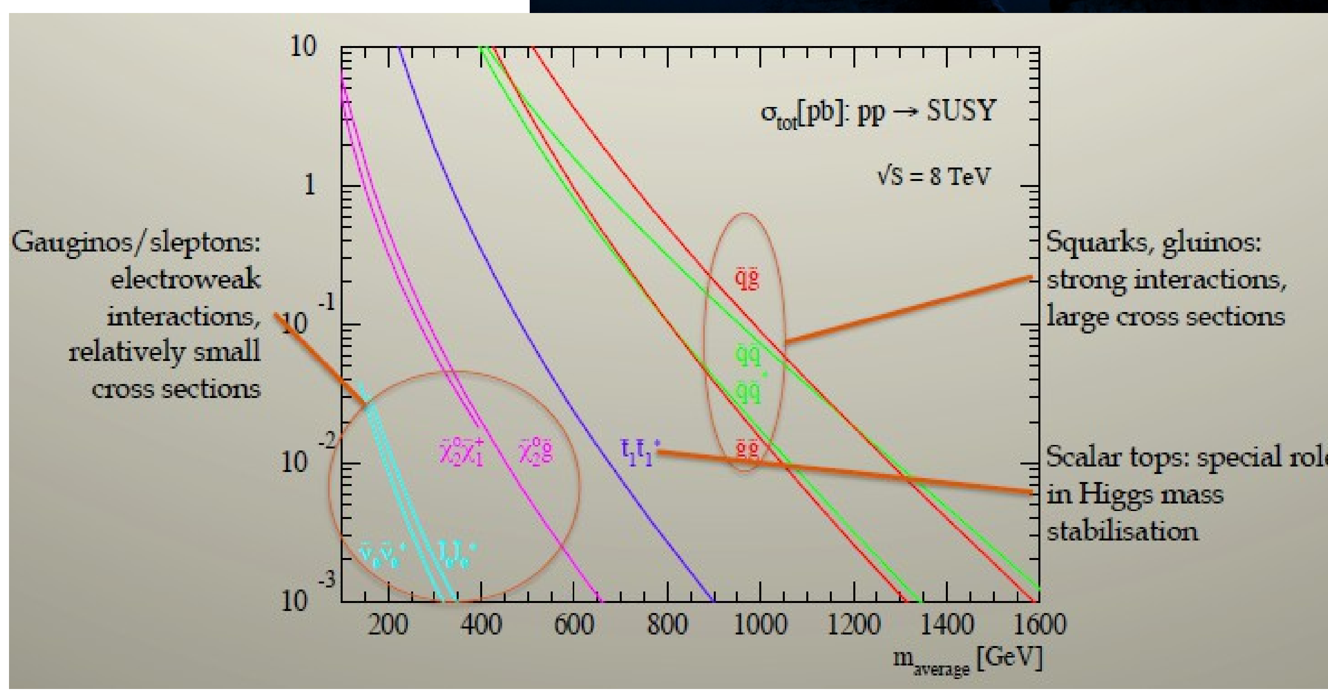
Center-of-mass energy
7-8 TeV (13-14 soon!)

~1 billion proton collisions / second
~100 Z bosons / second
~1 Higgs boson / minute
~1 Neutralino / day ?

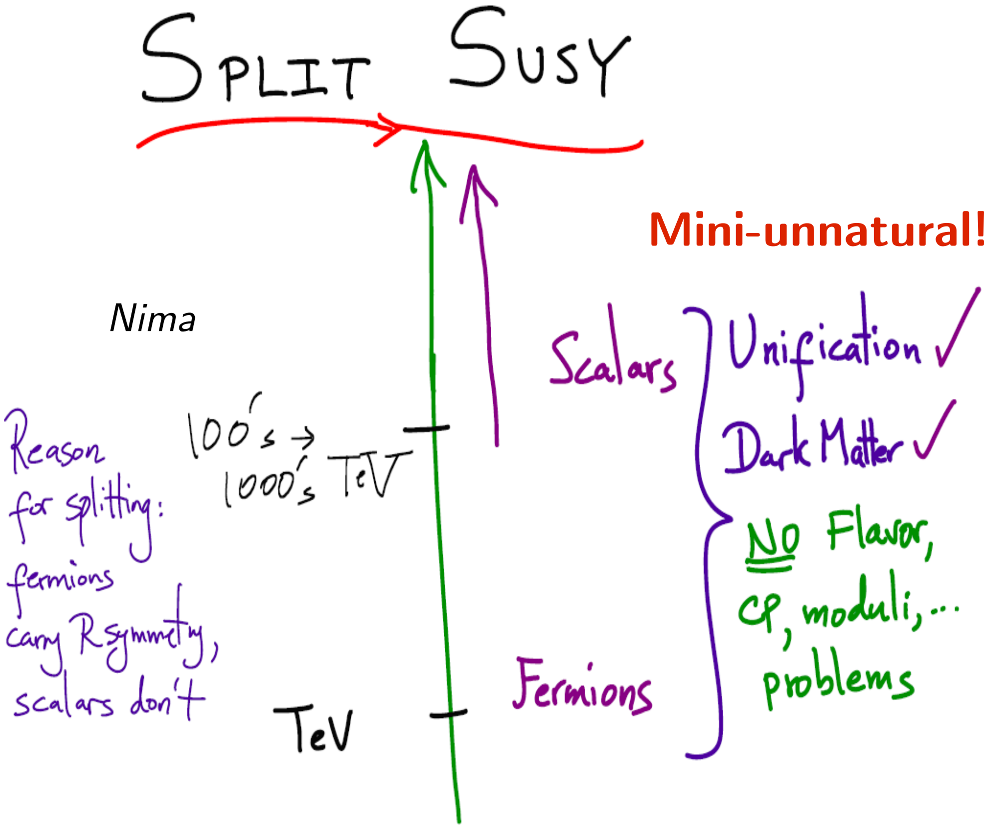
Introduction

- SUSY is complicated – many new particles and parameters
- For the first time in 40 years (?), no well-defined target in particle physics
- Must perform many many searches, find SUSY wherever it can be hiding
- **I'll discuss *some* trickier searches underway and potential improvements**



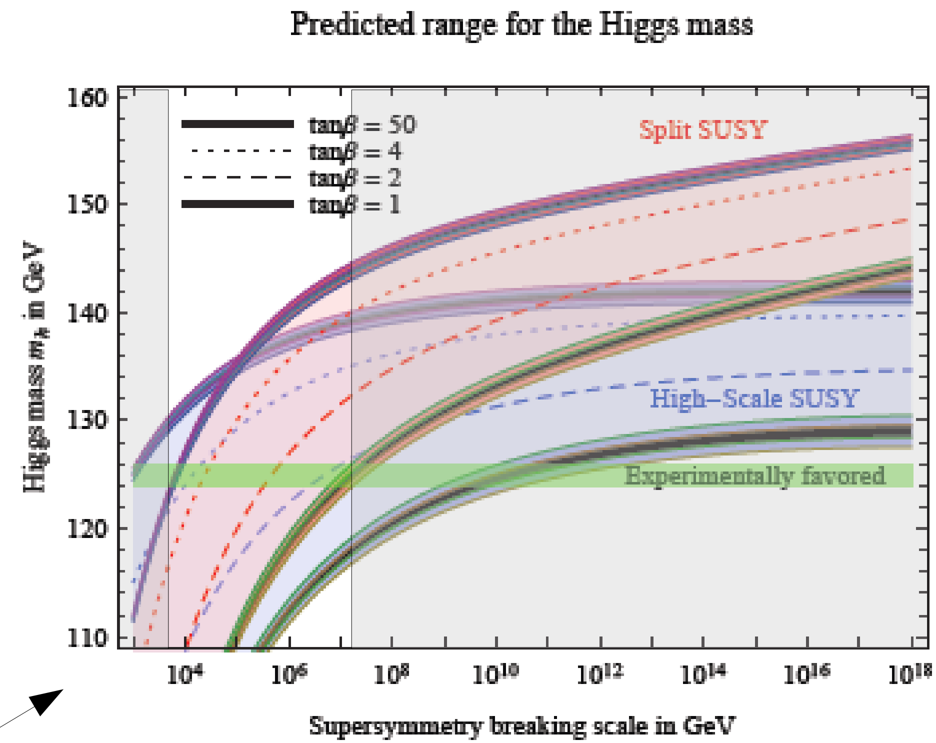


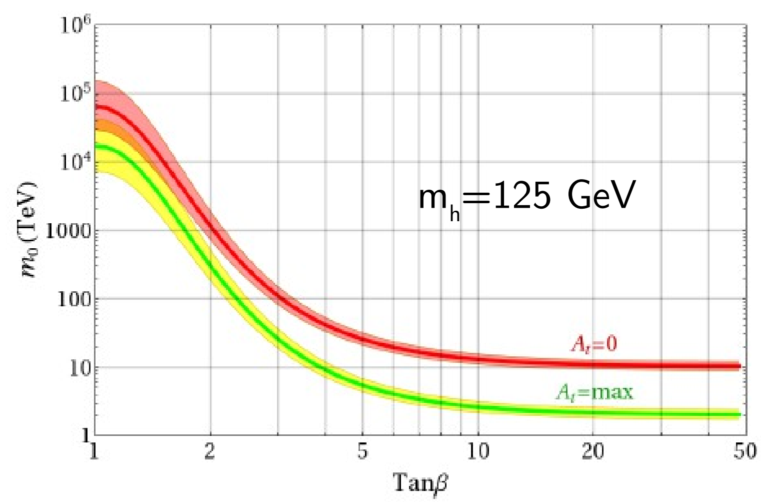
Mini-split SUSY



$$M_S \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}},\ X_t \equiv A_t - \mu \cot\beta$$

$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{2\pi^2 v^2}\left\{\ln\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right) + \frac{1}{16\pi^2}\left(\frac{3m_t^2}{v^2} - 32\pi\alpha_s\right)\left[\frac{2X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\ln\frac{M_S^2}{m_t^2} + \left(\ln\frac{M_S}{m_t^2}\right)^2\right]\right\}$$

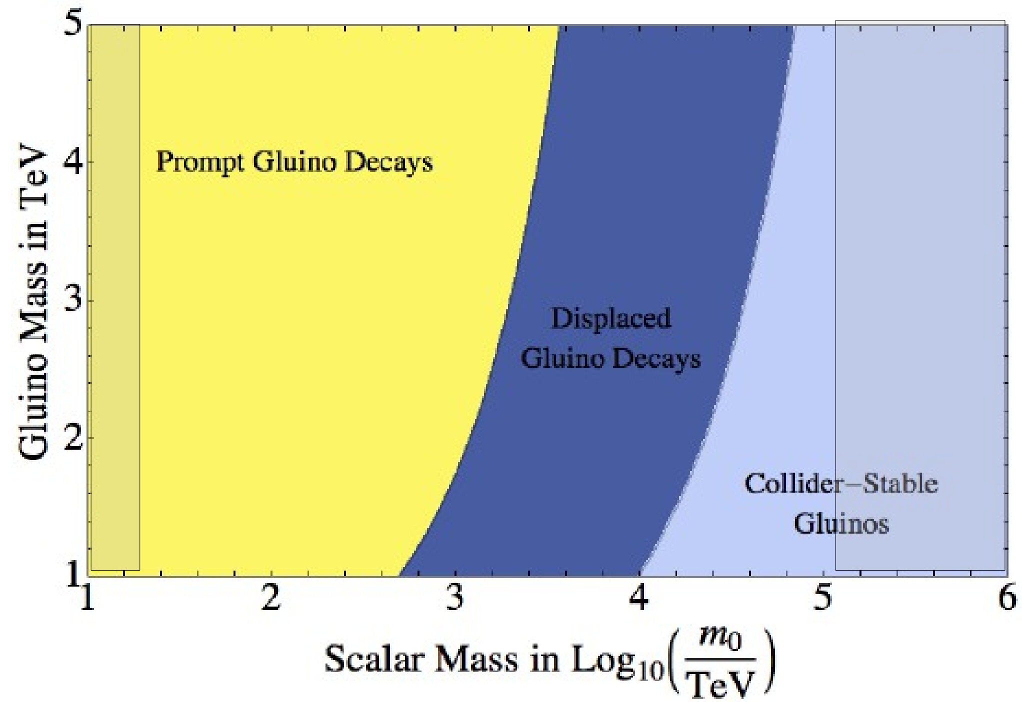




"Mini-split", arXiv:1210.0555
A. Arvanitaki, N. Craig, S. Dimopoulos, G. Villadoro
"Simply Unnatural SUSY", arXiv:1212.6971
N. Arkani-Hamed, A. Gupta, D.E. Kaplan, N. Weiner, T. Zorawski

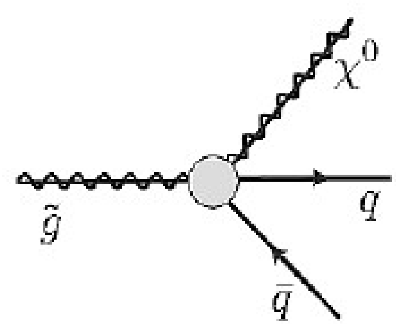
Searches for mini-split

- Only the sfermions (Gauginos and Higgsinos) are within LHC reach
  - Can go after gluinos or EW-inos



- Gluino lifetime depends on the squark masses (m_0)
- Gluino searches:
  - Prompt (standard!)
  - Displaced (*Rhadron*)
    - Mini-displaced + MET
    - Displaced jet + MET
    - Large dE/dx
  - Detector-stable
    - Escaping Rhadron
    - Stopped Rhadron

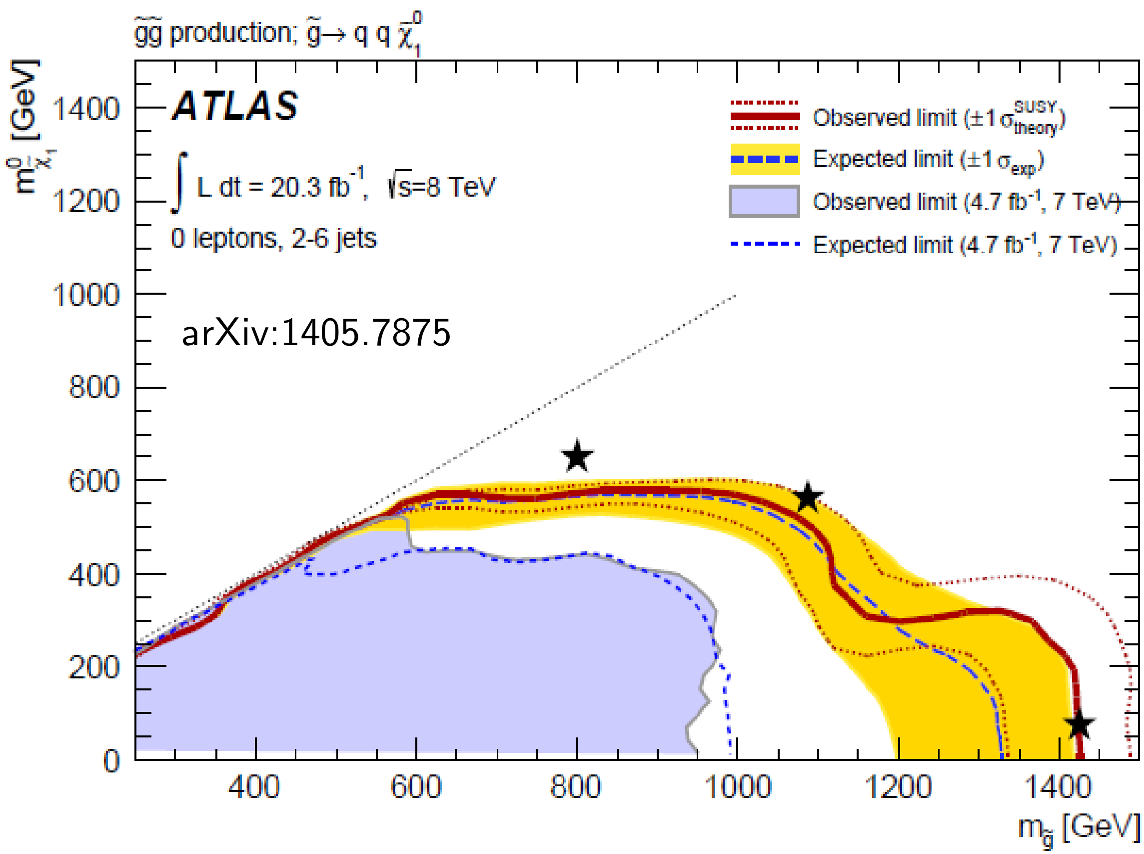
$$c\tau \approx 10^{-5}\text{m}\left(\frac{m_{\tilde{q}}}{\text{PeV}}\right)^4\left(\frac{\text{TeV}}{m_{\tilde{g}}}\right)^5$$

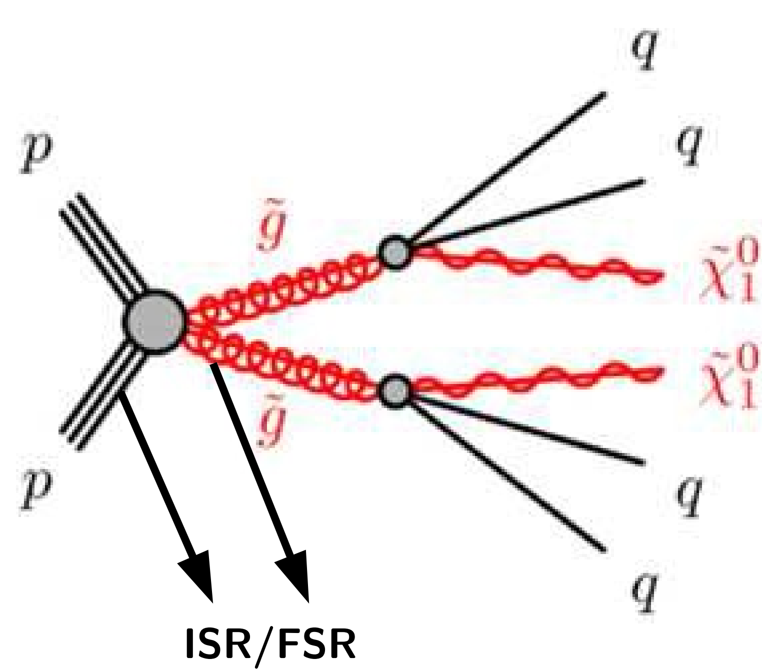


- *Will talk about EW-ino searches later...*

Prompt gluino decay + MET searches

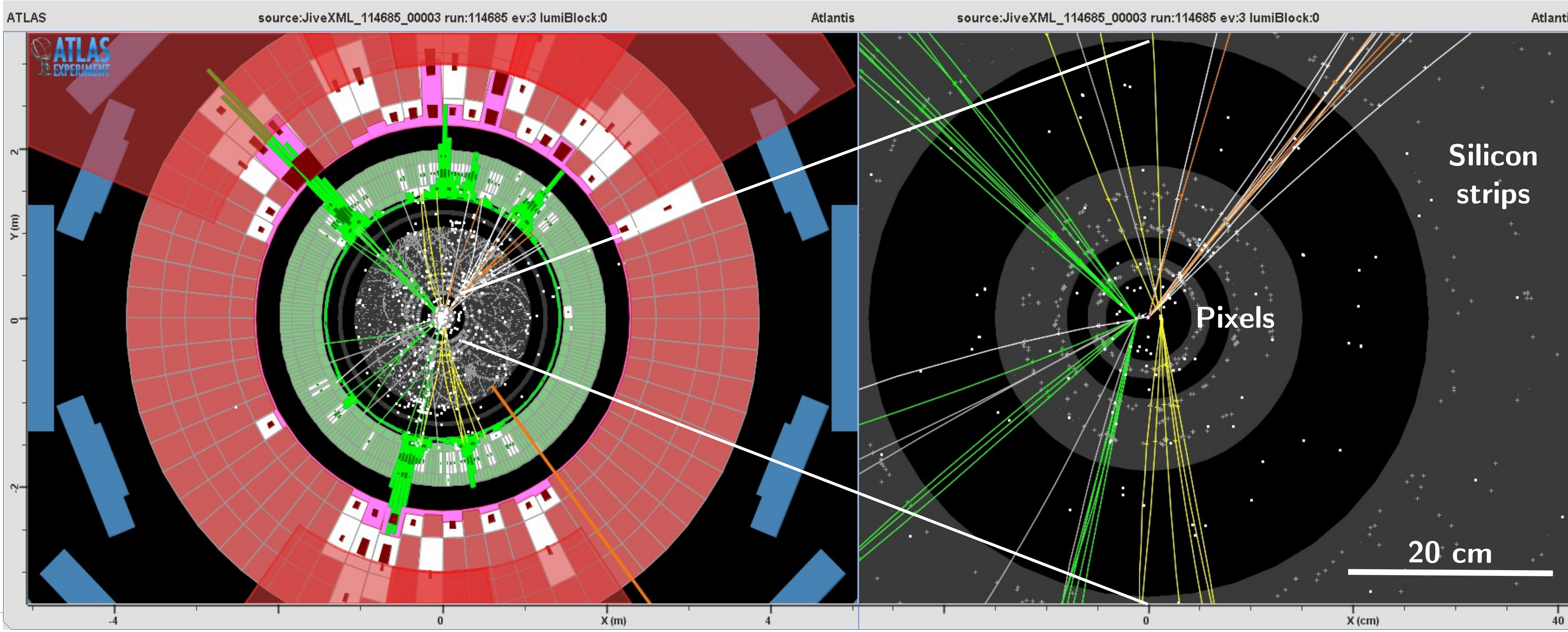
- Gluinos are pair-produced
- Each gluino decays (promptly) to jets + MET
  - Possibly to ttbar + MET if top squark is a bit lighter than other squarks Can look for lepton(s), same-sign leptons, and/or b-jets + MET
- Limits on gluino mass: ~600–1400 GeV (depending on neutralino mass)





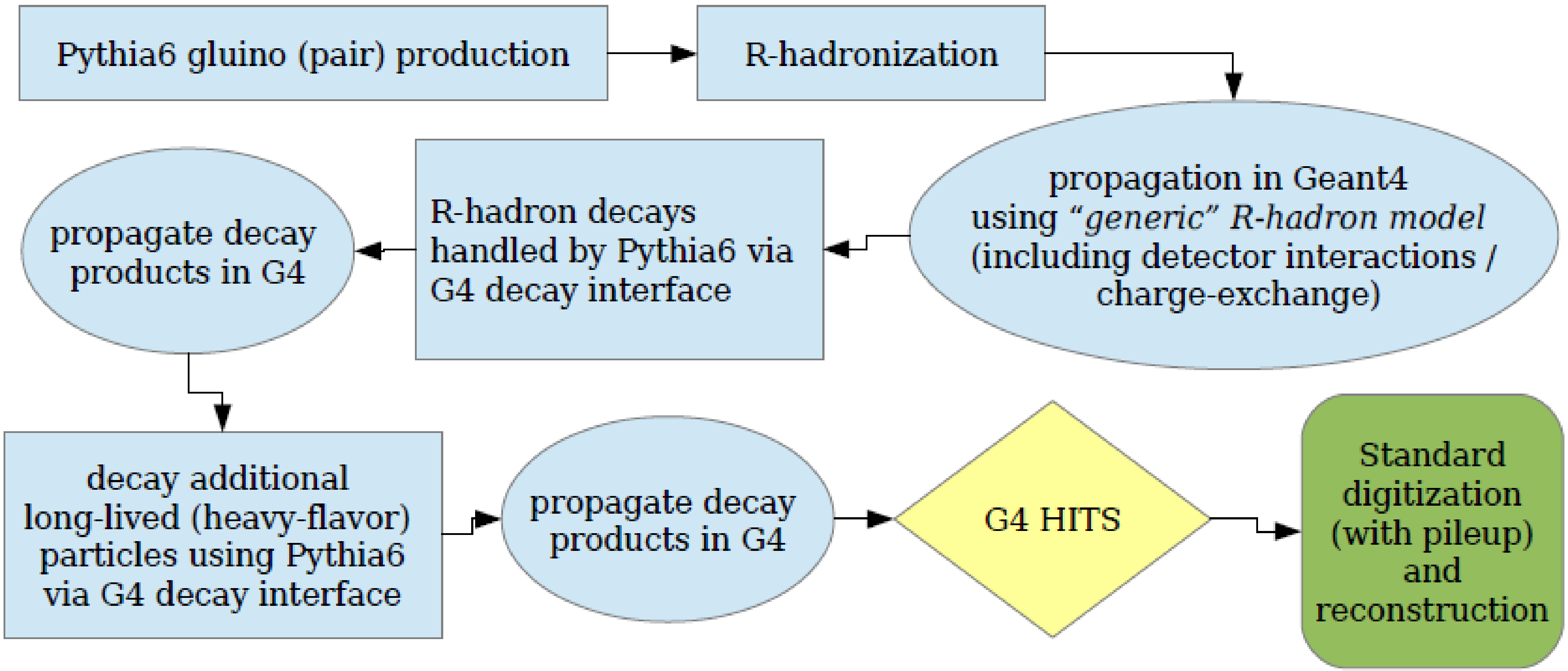
Mini-displaced gluino decays

- What if gluino (Rhadron) is just a little long-lived (~1 ns)?
  - Standard jets+MET searches 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 using track pT fraction, EM fraction (when?)
- *So far, no explicit limits on gluinos with intermediate lifetimes...*



Mini-displaced gluino decays

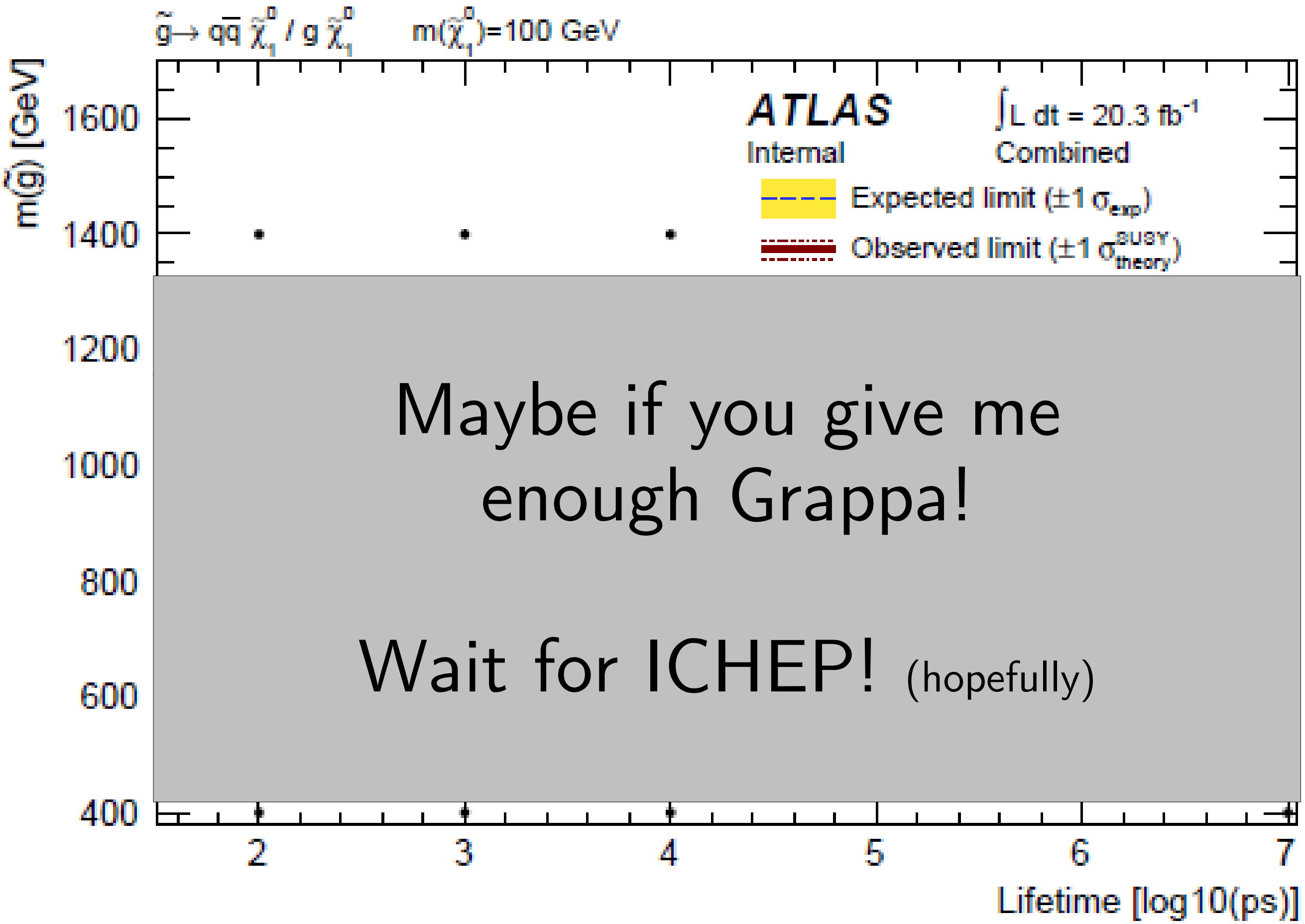
- Generated fullly-simulated MC of decaying Rhadrons at ATLAS



- Reinterpretation of existing ATLAS 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*

Mini-displaced gluino decays

- Will have limits on gluino mass vs. lifetime
- Also scan neutralino mass
- Study ~g→qqX/gX and ~g→ttX decays separately

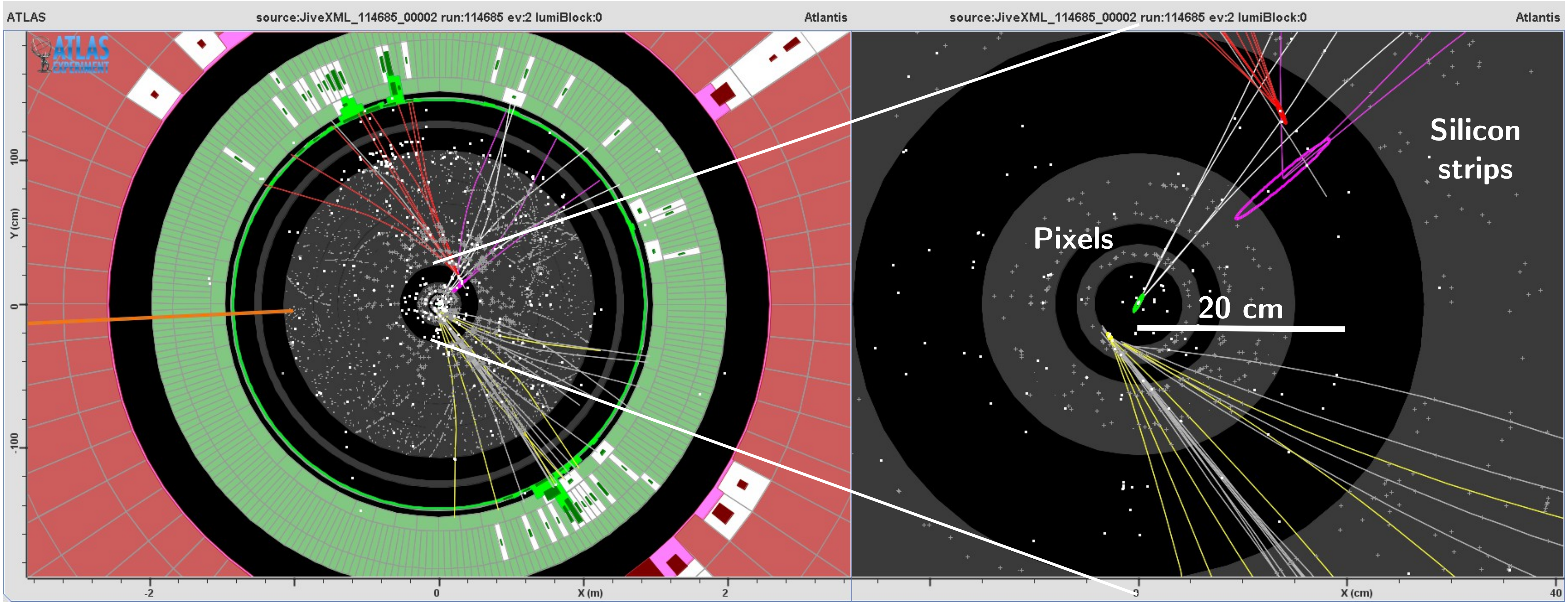


Displaced jet search

ATLAS-CONF-2013-092

- <u>Would like to actually find them – not exclude them!</u>

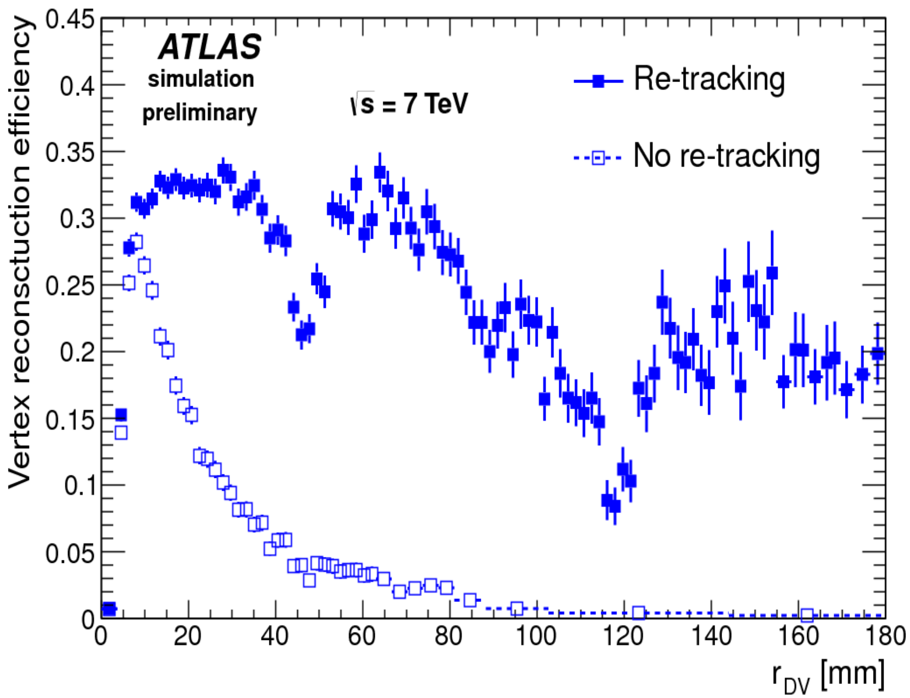
- For moderate lifetimes, reconstruct the **displaced vertex in tracker**
- Current analysis requires a **high-pt muon** to trigger on and reduce backgrounds... sensitive to gluino $\rightarrow$ ttbar decays
  - *Now adding analysis based on MET trigger, for g $\rightarrow$ qq+x_1^0 decays*

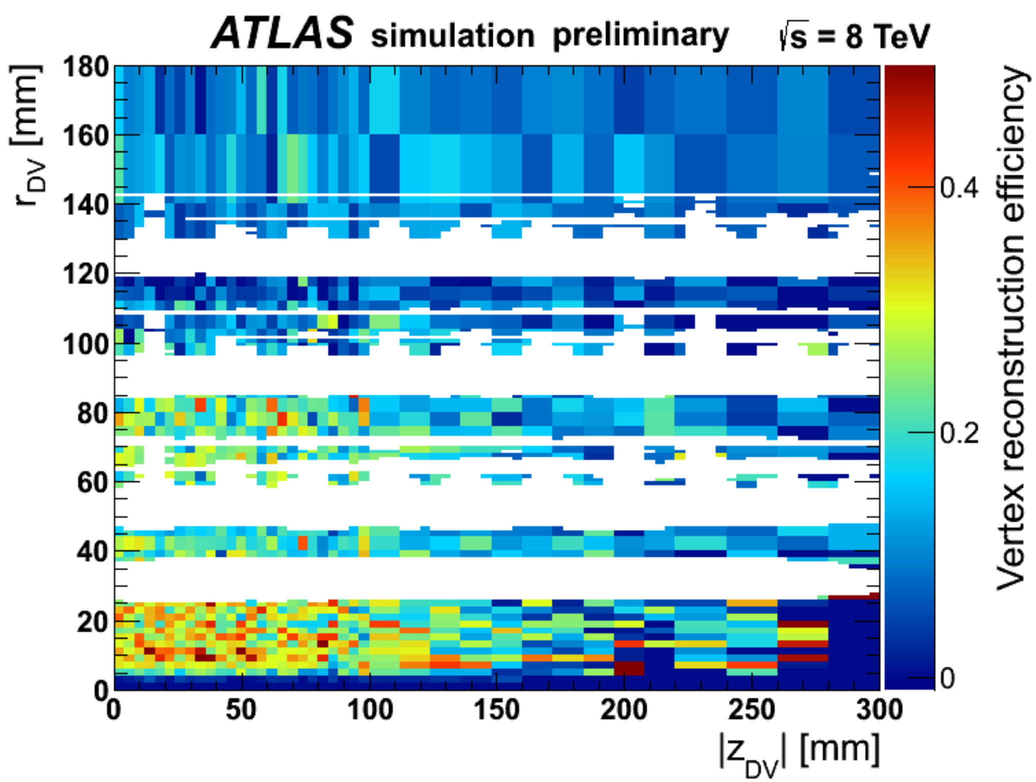


Displaced jet search

- ATLAS default impact parameter cut in tracking is 10 mm (for speed)
  - Tracking is re-run with looser impact parameter requirements
  - Need access to special reconstruction output with all tracker hits saved

- Special secondary vertexing reconstructs displaced vertices
  - Good efficiency out to a radius of ~18 cm…

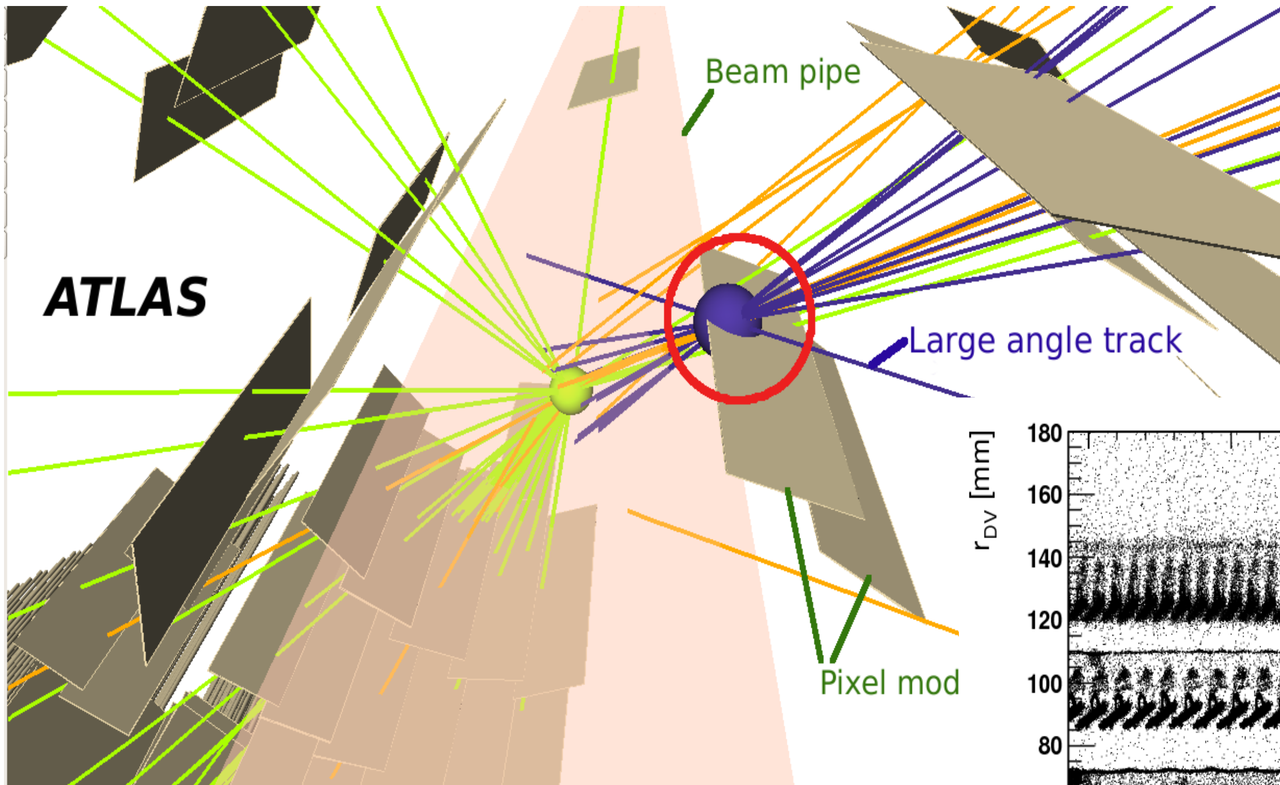




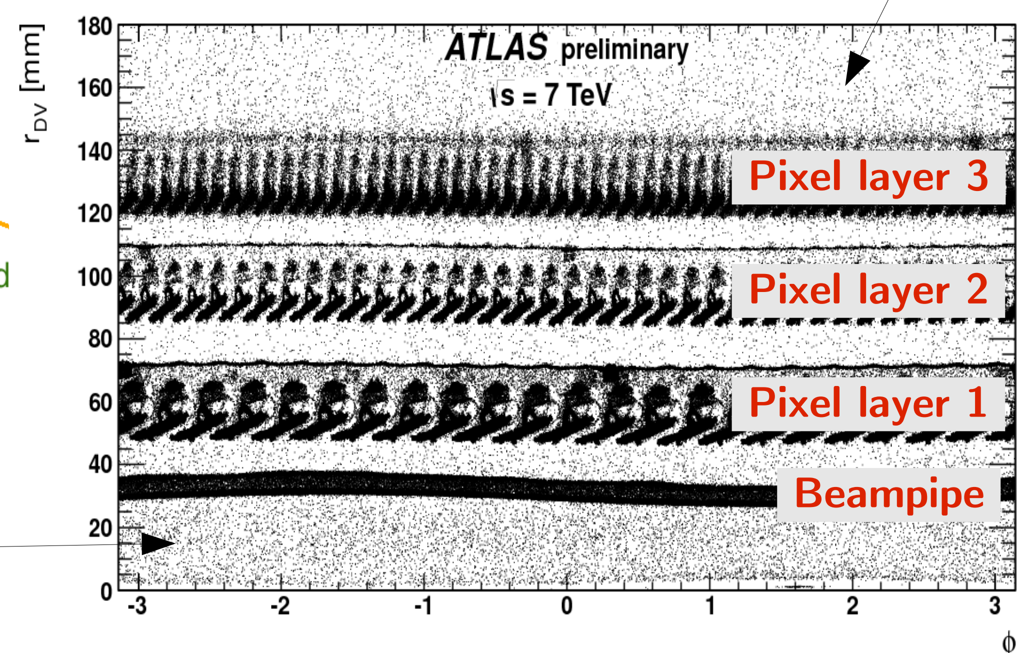
Displaced jet search

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

Crazy 2018 upgrade idea: Vacuum in part of tracker?



3-track vertices with low mass

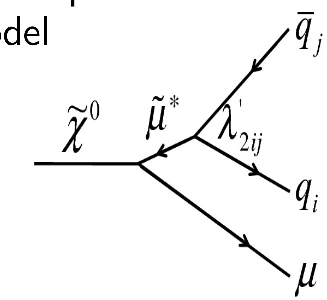


- Also background from random track crossings / pileup (no air in the beampipe)

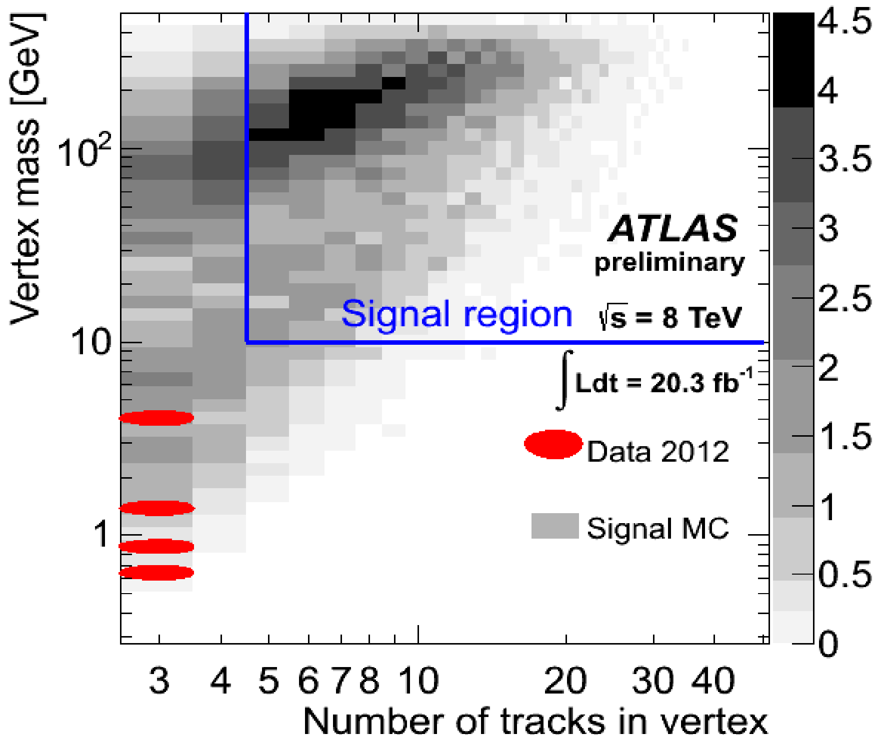
Displaced jet search

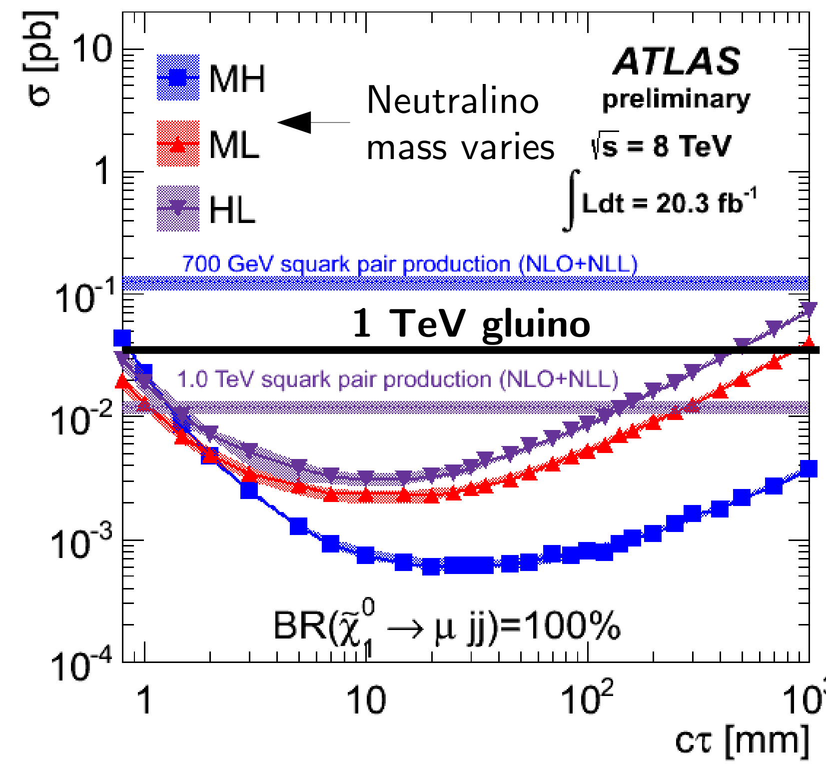
- Require vertex to have at least 5 tracks and (visible) mass >10 GeV
- Total background expected: 0.02 events
- 0 events observed in signal region

RPV squark model



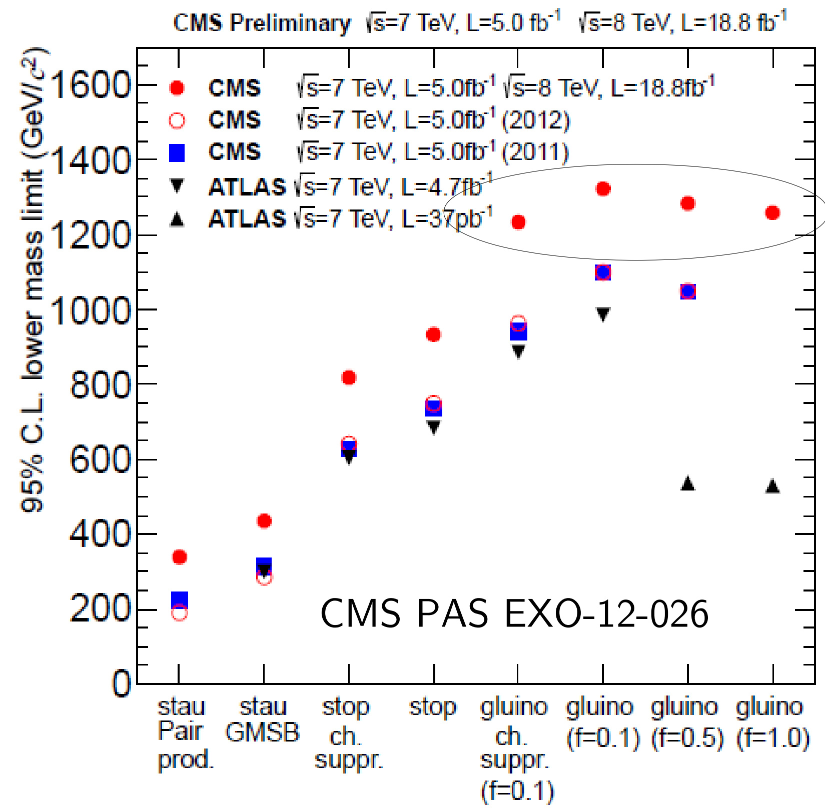
- *Sensitive to ~1–1.4 TeV gluino→tt+x_1^0 for ctau ~1 ns?*

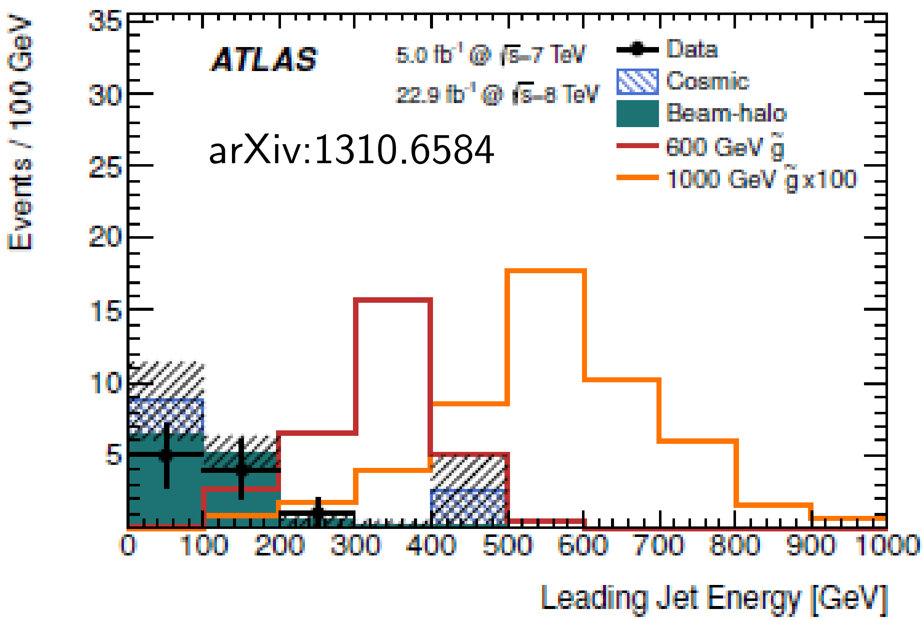




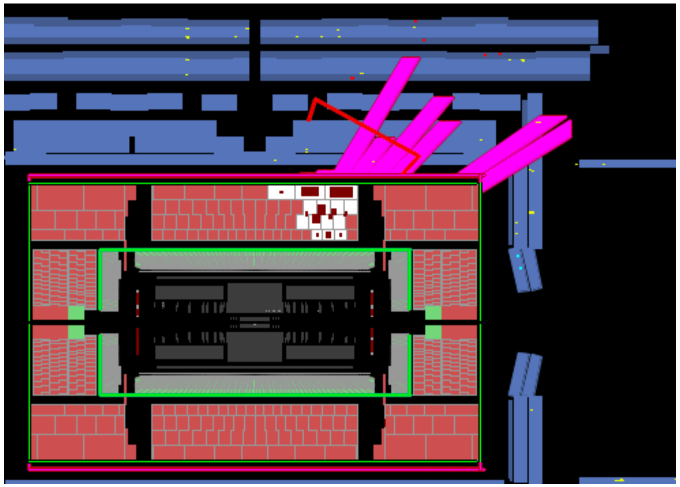
Detector-stable Rhadron searches

- Rhadron escapes the detector, can use timing in the calorimeter and/or muon system, gluino >1200 GeV
- Some stop in detector and decay later
  - Gluino >~800 GeV, lifetime 10us – 10 h
- *Need to continue in Run 2, and improve!*
  - *Data after/between runs*
  - *New "late" triggers (later slides)*





Could study gluino decay!
(somewhat)

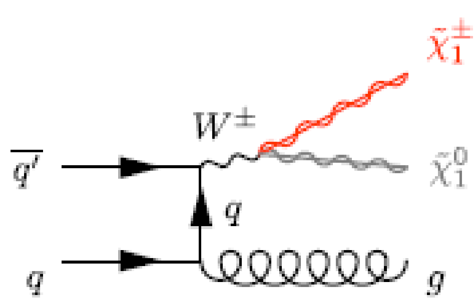


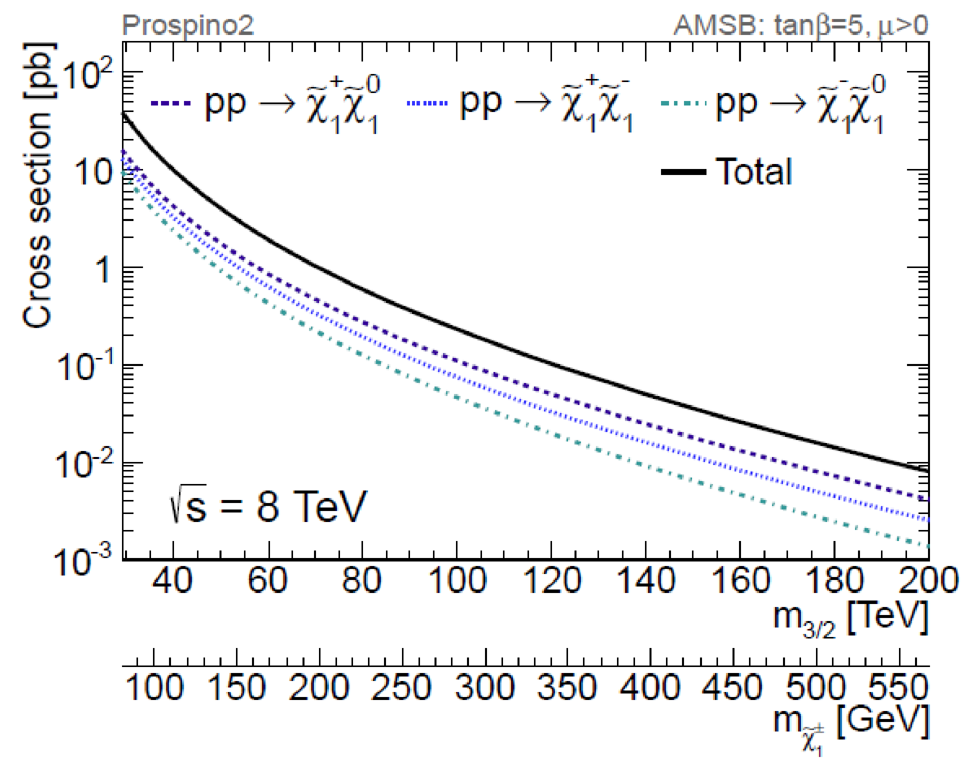
Long-lived Chargino

- Chargino becomes long-lived when nearly-degenerate with the LSP
- 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= $\frac{1}{2}\,\alpha\,m_Z$ = ~355 MeV

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

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

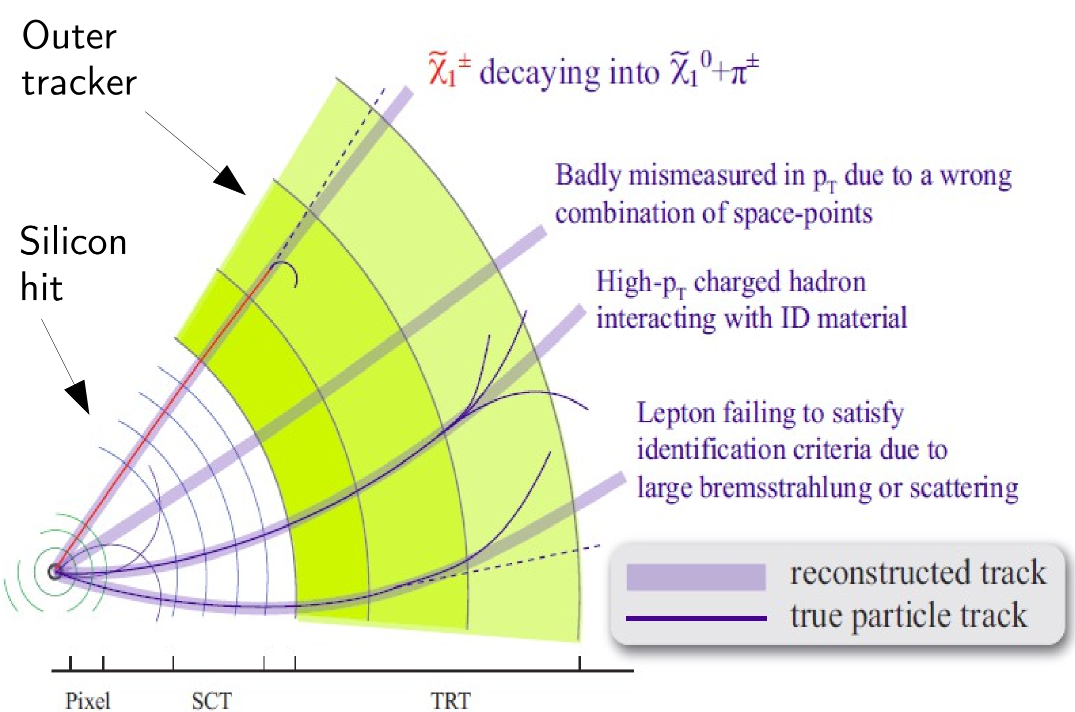


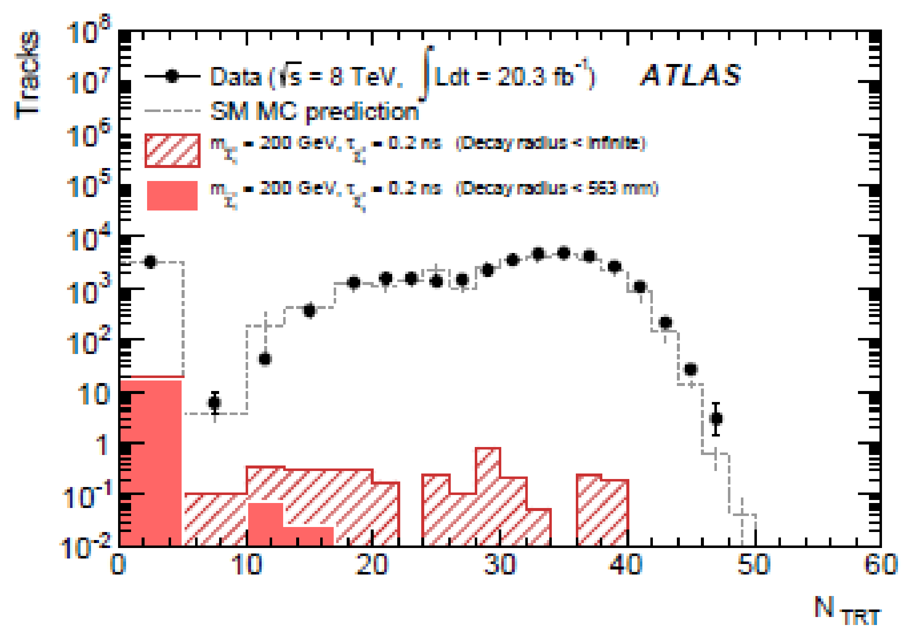


Disappearing track search

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

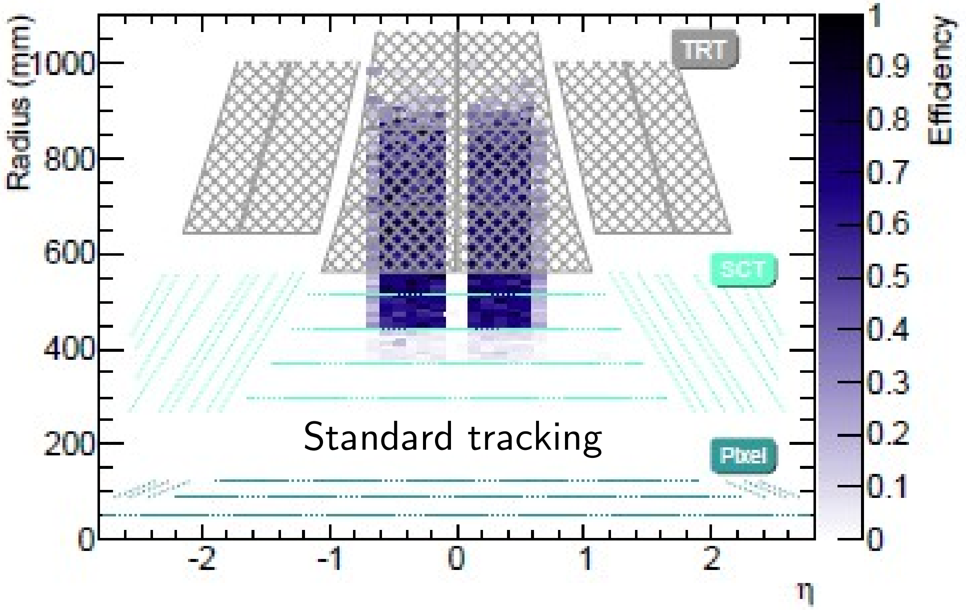


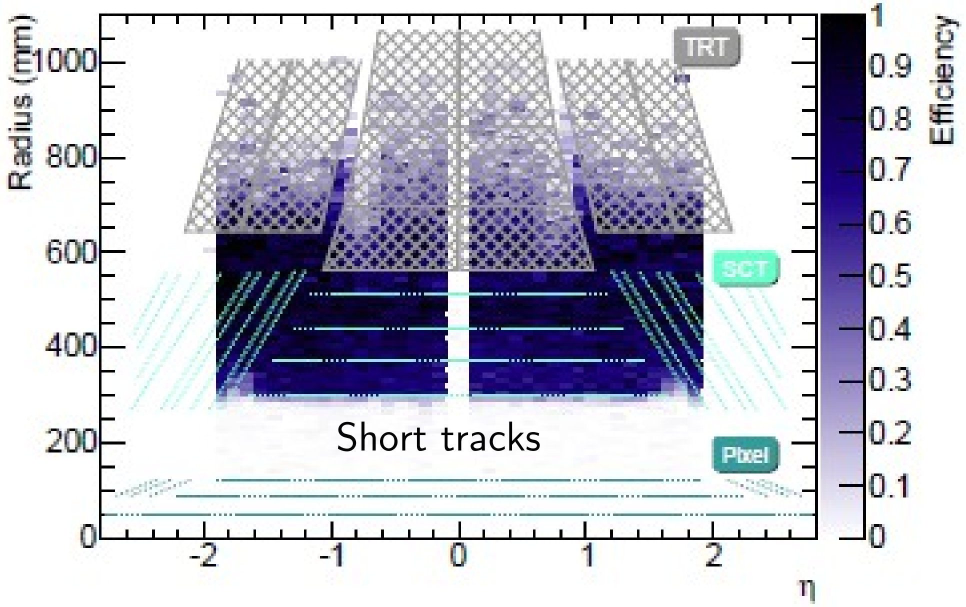


Improved disappearing track search

- Large improvement from customized track reconstruction
  - *(Needs access to data with all tracker hits saved...)*

- Require just 1 Si strip layer (instead of 3) and no TRT
  - Decay volume moves to r>~300 mm and widens
  - Efficiency 100x larger for cτ=100mm (165 MeV)

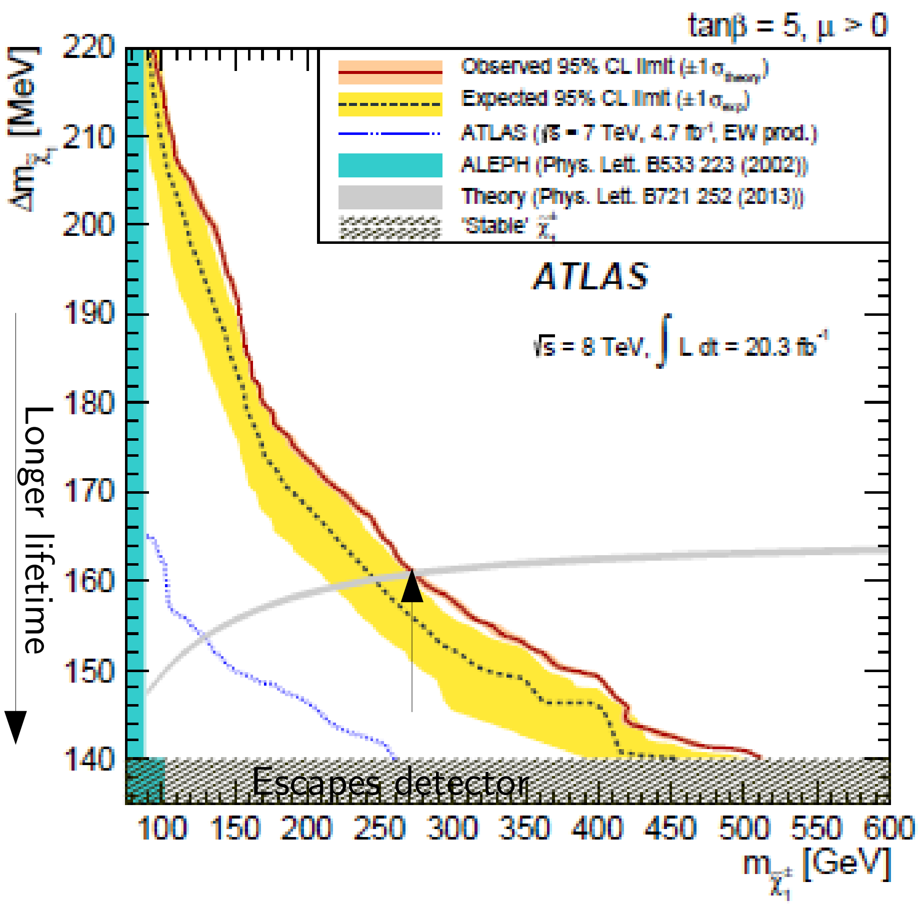


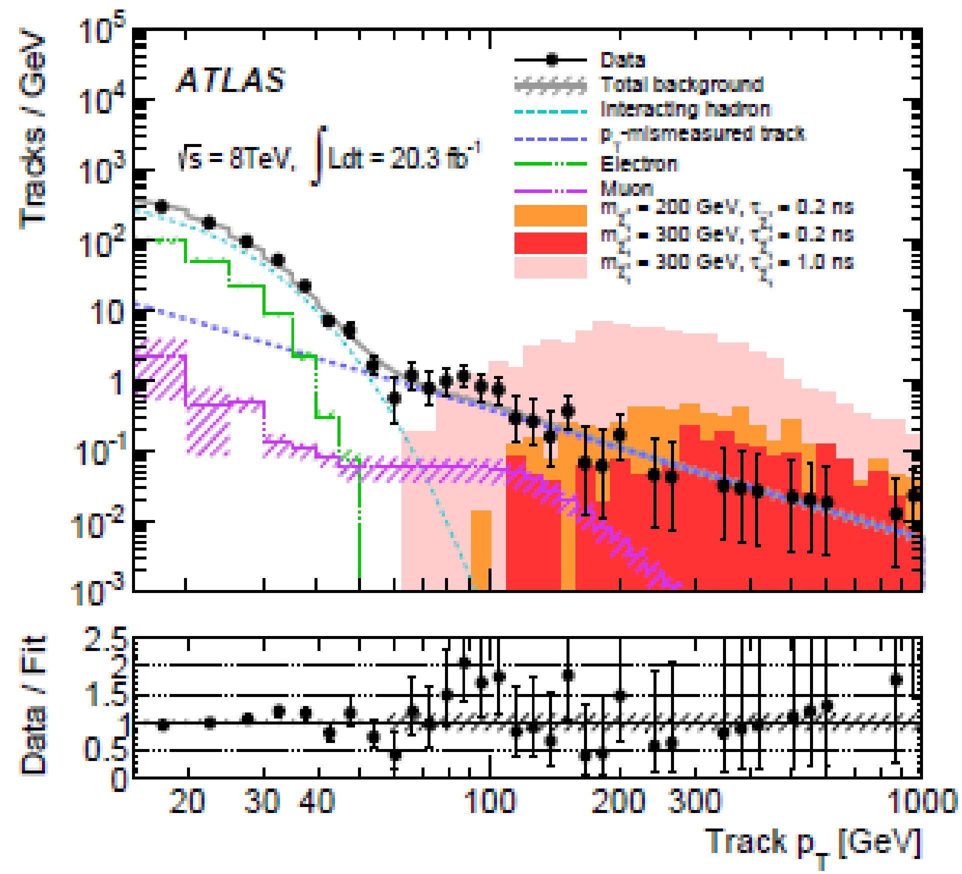


Disappearing track search

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

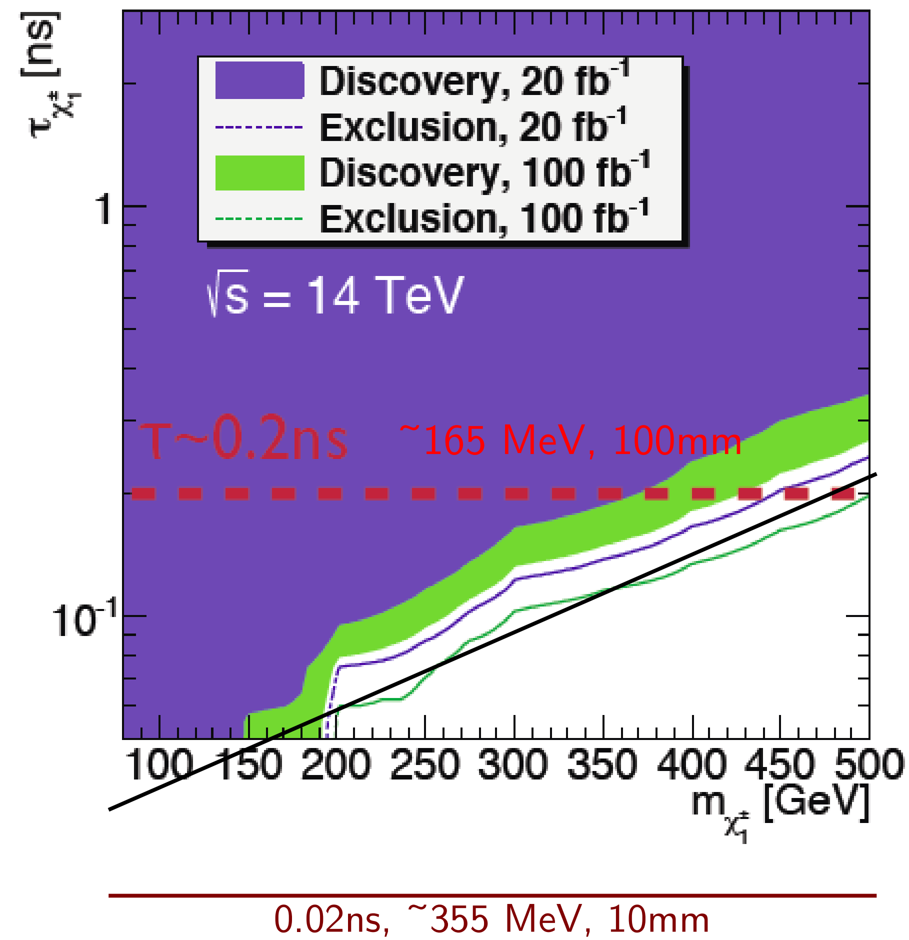
- Exclude chargino <270 GeV in AMSB with Δm~165 MeV





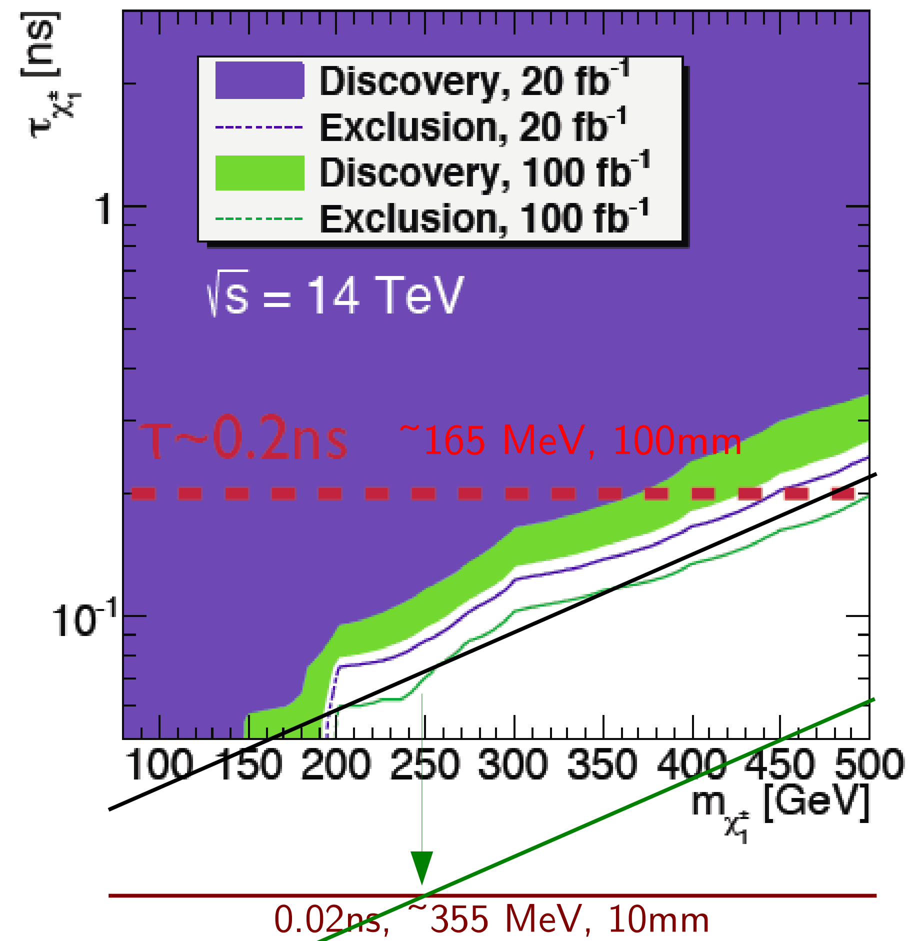
Improved disappearing track search

- 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 ~10 mm lifetime case...

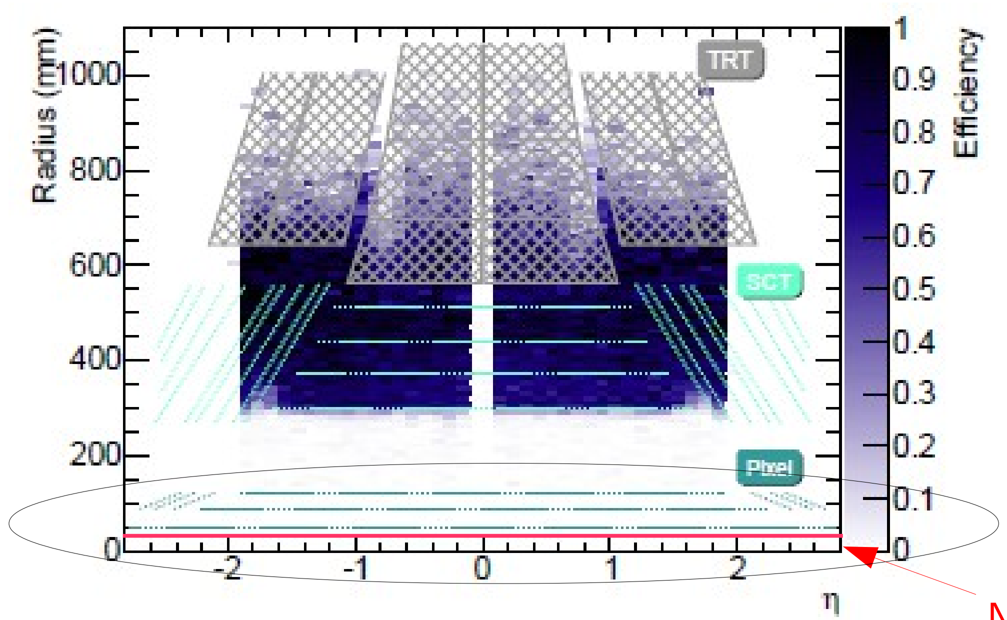


Improved disappearing track search

- 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 ~10 mm lifetime case
  - Insertable B-Layer (IBL) added
  - Could have r>150 mm tracks using just 4 pixel hits?!

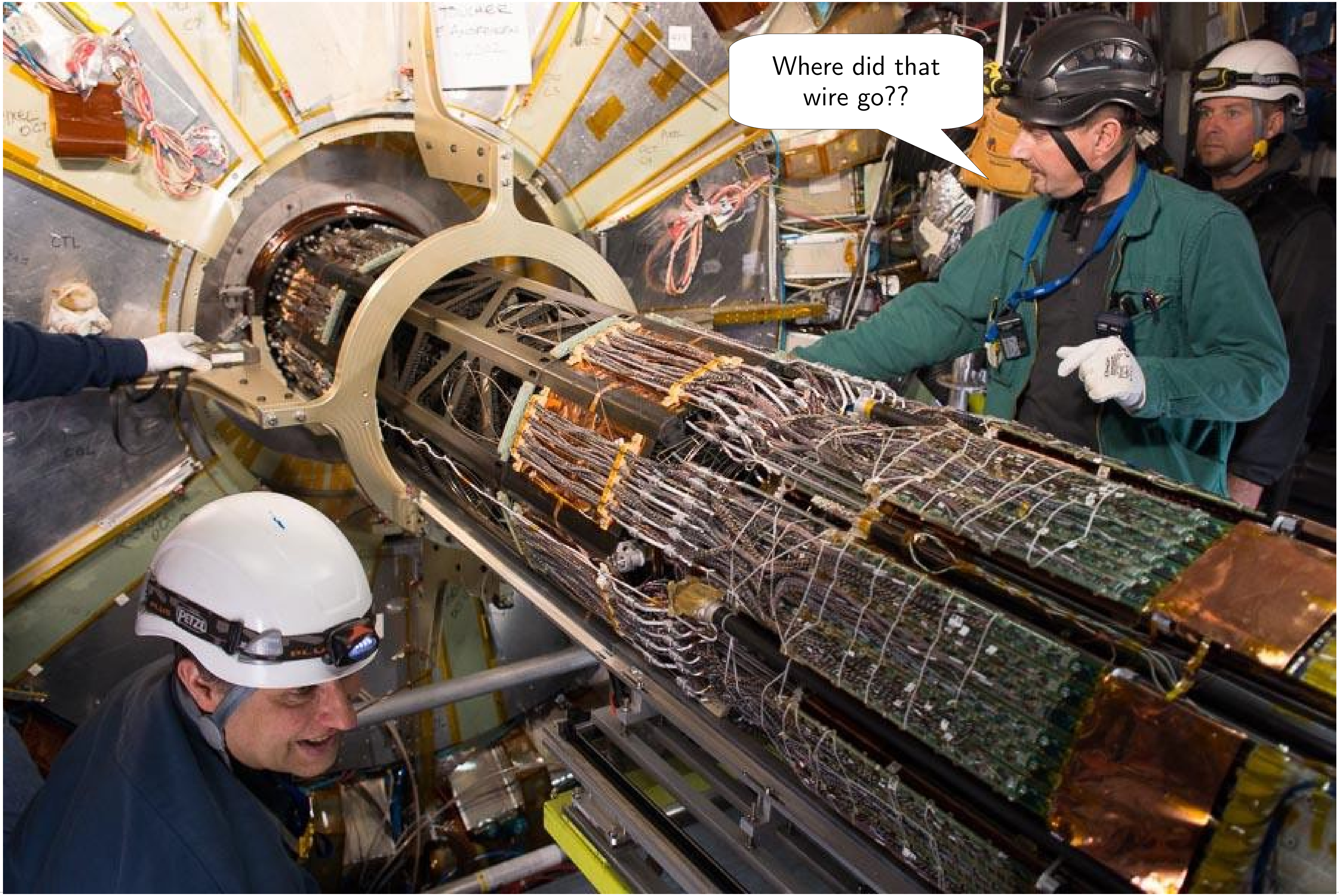


Sensitive up to ~800 GeV for 100mm and ~250 GeV for 10mm lifetime using 4-pixel IBL tracks?



New IBL pixel layer at radius of ~26mm

IBL installation!

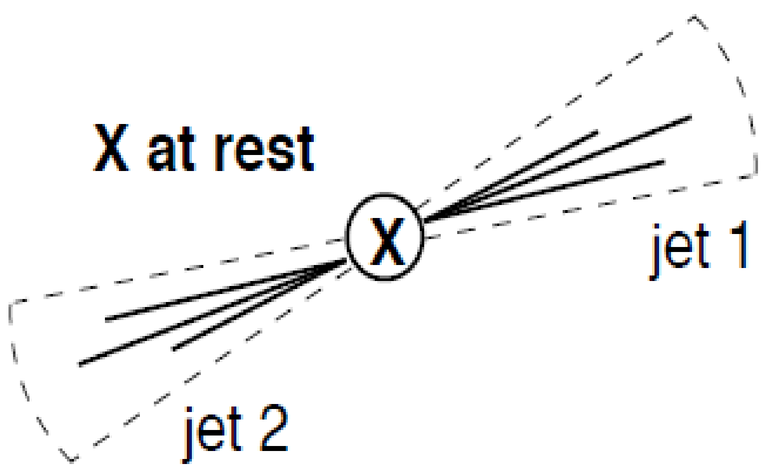


IBL installation!

Boosted Stuff

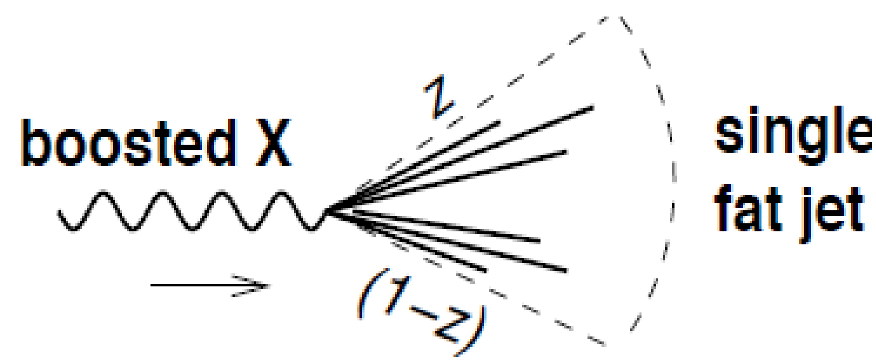
- Boosted particle $\rightarrow$ collimated decay products in detector

Normal analyses: two quarks from $X \rightarrow q\bar{q}$ reconstructed as two jets



Gavin Salam

High-p_t regime: EW object X is boosted, decay is collimated, $q\bar{q}$ both in same jet



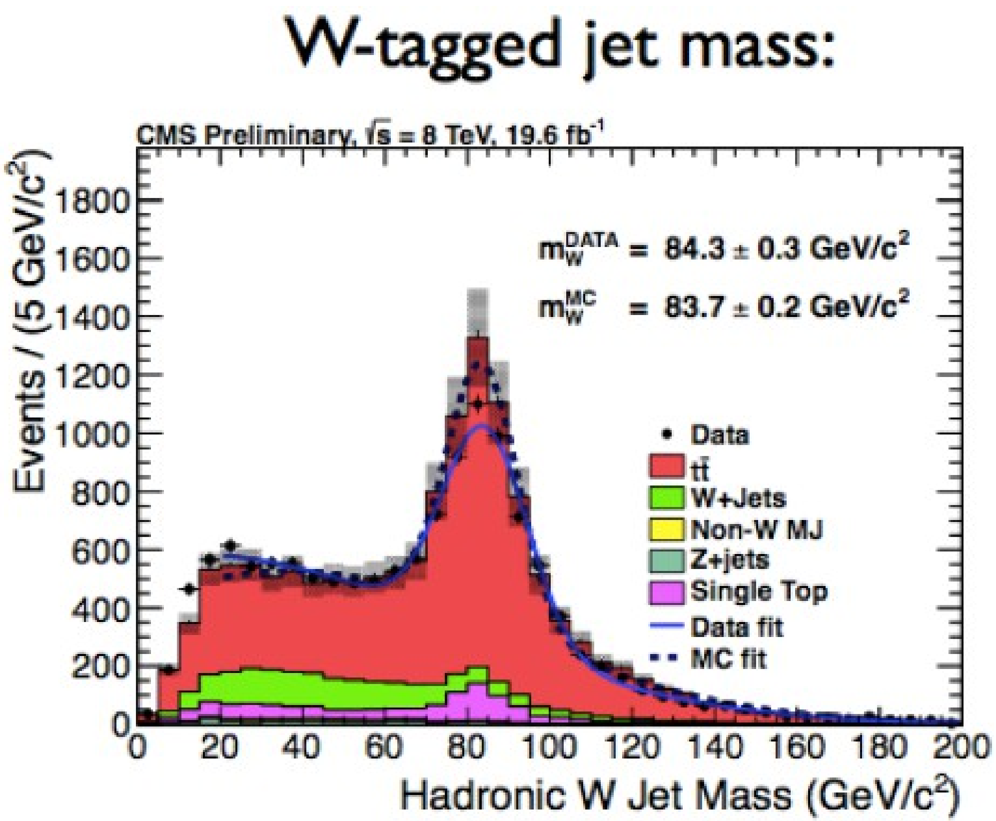
Happens for $p_t \gtrsim 2m/R$

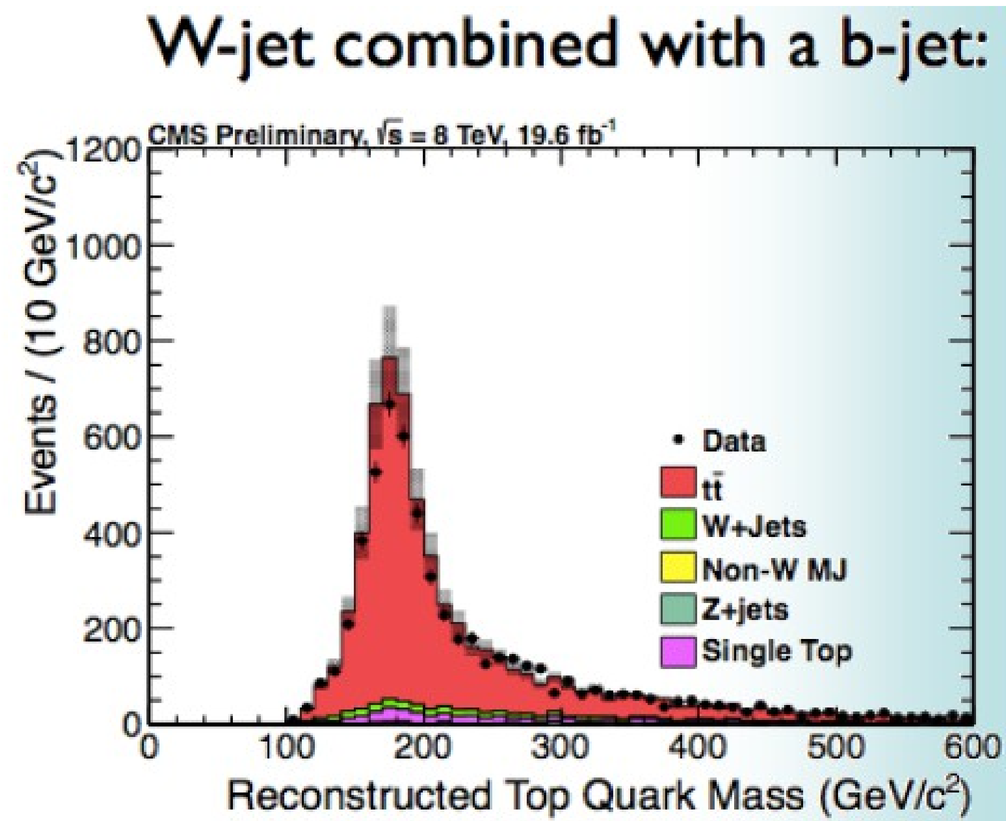
$p_t > 400$ GeV for $m = m_W$, $R = 0.4$

"Giving New Physics a Boost" aka "BOOST"
http://www-conf.slac.stanford.edu/Boost2009/
and each year following!

Fat jets

- Can look for boosted W and top-quark decays to hadrons
- *Nicely calibrated in ttbar events at ATLAS and CMS*



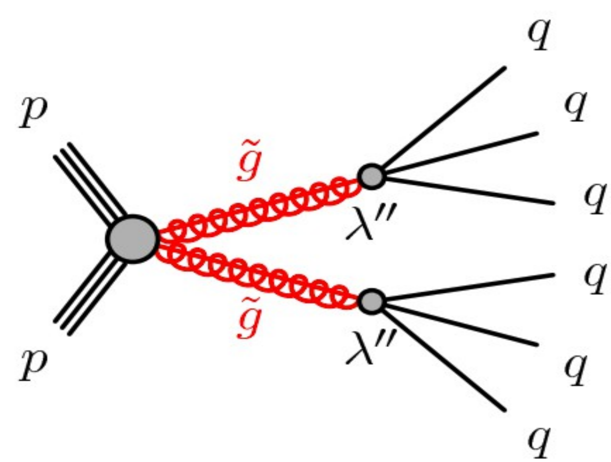


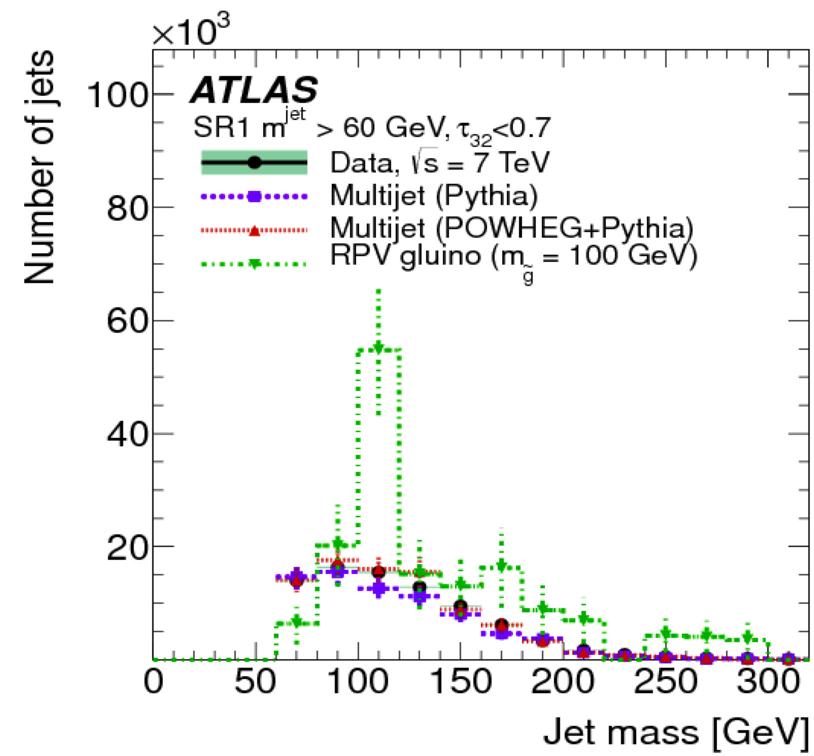
Boosted gluino → jets decays JHEP12 (2012) 086

- If the gluino is highly boosted, all the decays can be recombined in a "fat" jet.
  - Use "N-subjettiness" substructure variables, τ_N to characterize how well a jet can be described as containing *N* or fewer k_t subjets

$$\tau_N = \frac{1}{d_0} \sum_k p_{Tk} \times \min(\delta R_{1k}, \delta R_{2k}, ..., \delta R_{Nk}) \;, \quad \text{with} \quad d_0 \equiv \sum_k p_{Tk} \times R$$

  - τ_{32} (= τ_3 / τ_2) measures how well the "fat" jet can be as containing 3 (τ_{32}≈1) or 2 (τ_{32}≈0) jets. Require τ_{23}>0.7.
  - Use the mass of each fat jets to select gluino candidates.
- Main background: multi-jet, estimated data-driven.
  - Estimated using the "ABCD" method: event yields in orthogonal control regions in m_{J1} and/or m_{J2} are used to predict the total number of events expected in the signal region.
- Looking for a peak in the jet mass spectrum.





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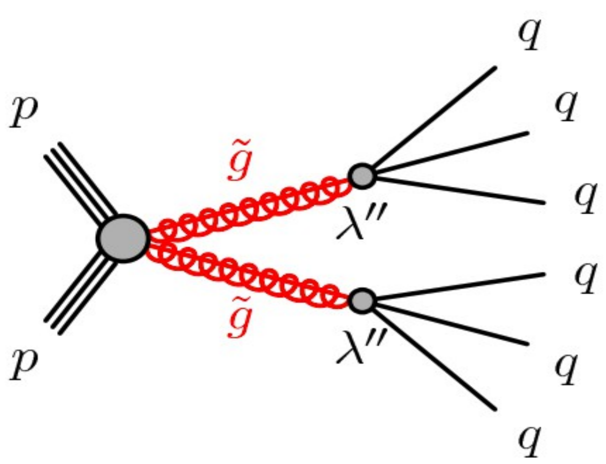
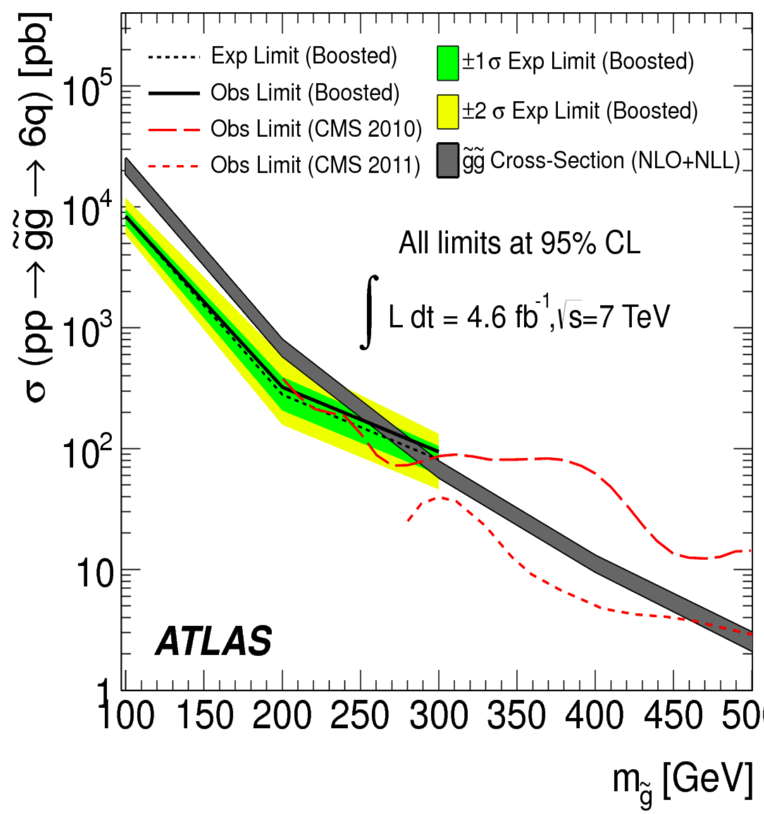
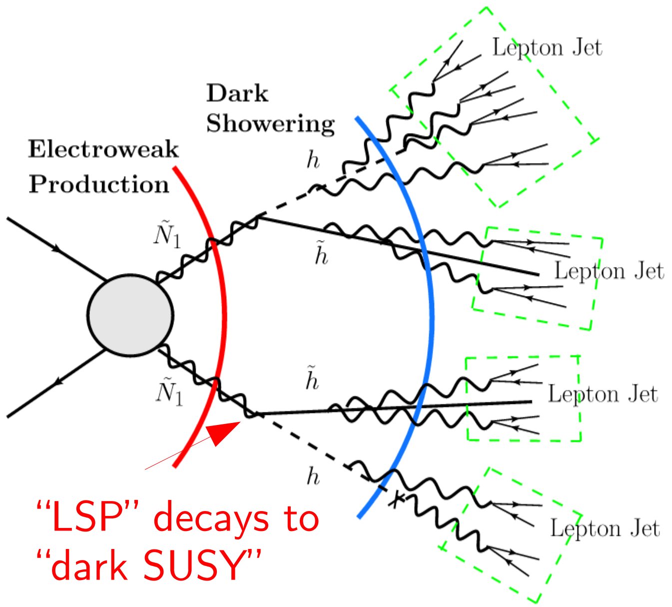


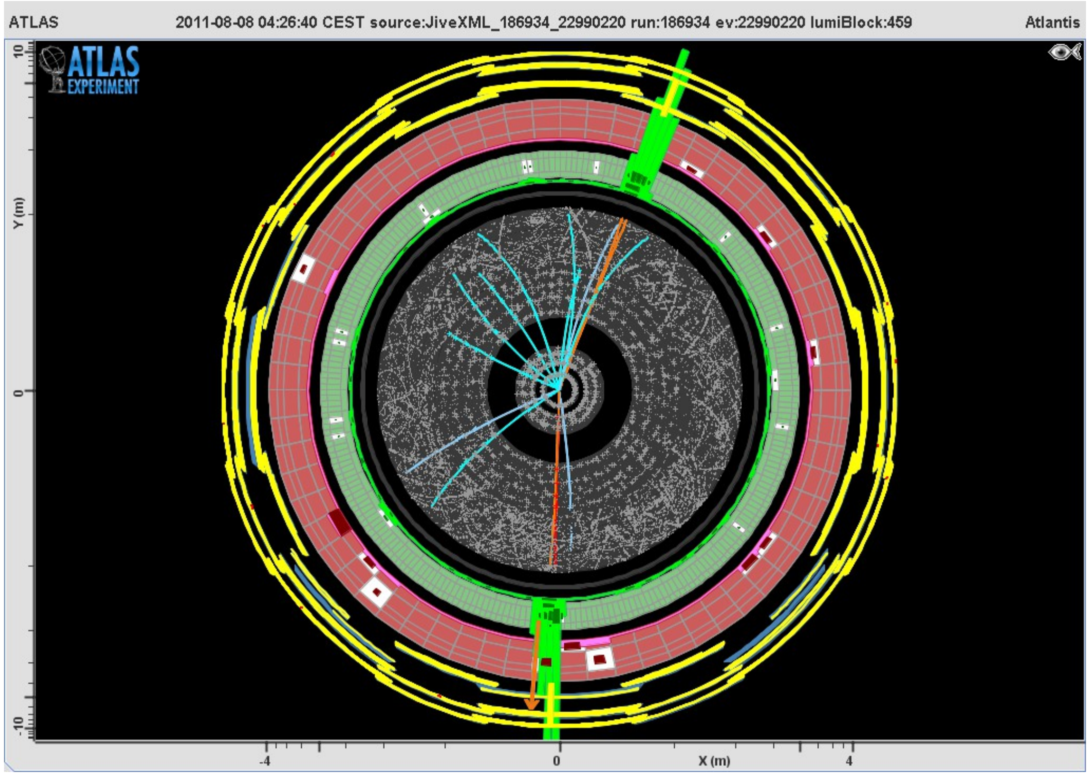


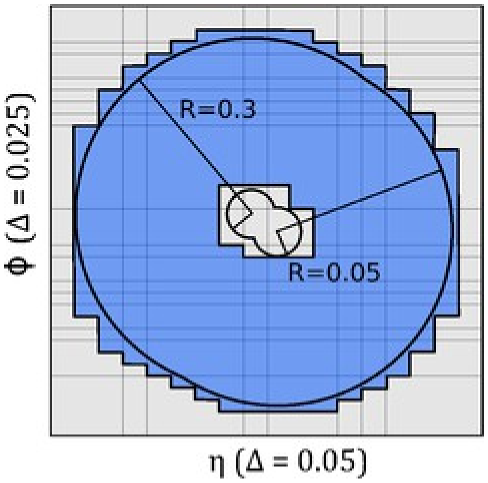
Collimated Leptons

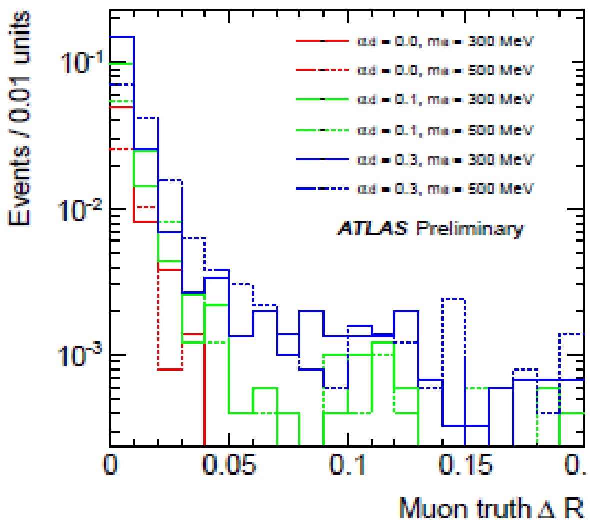
Lepton jets: muon/electron jets

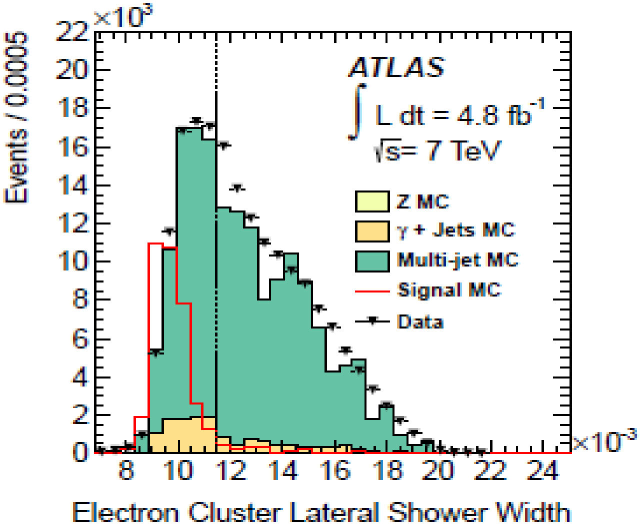


arXiv:0909.0290, et. al

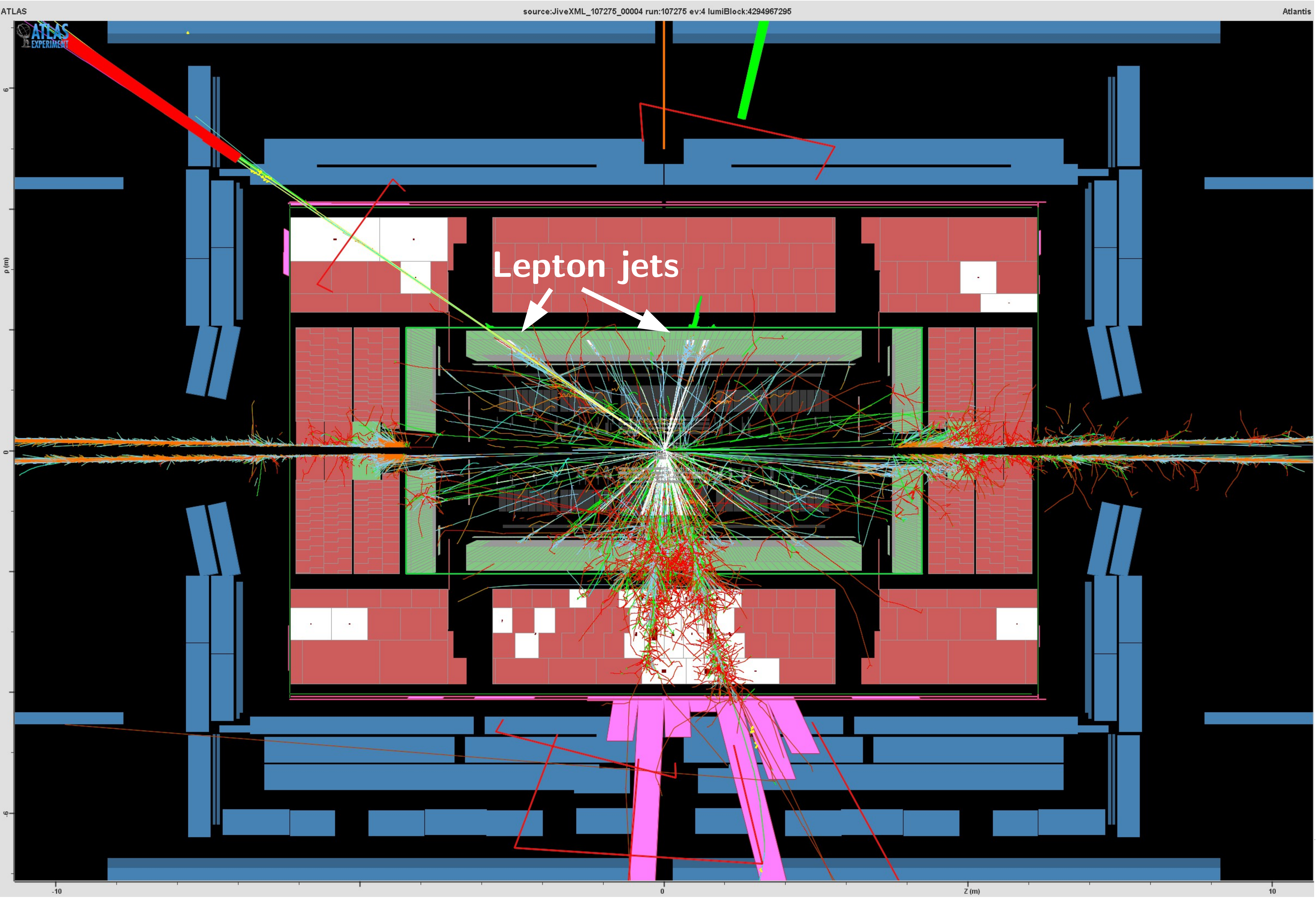




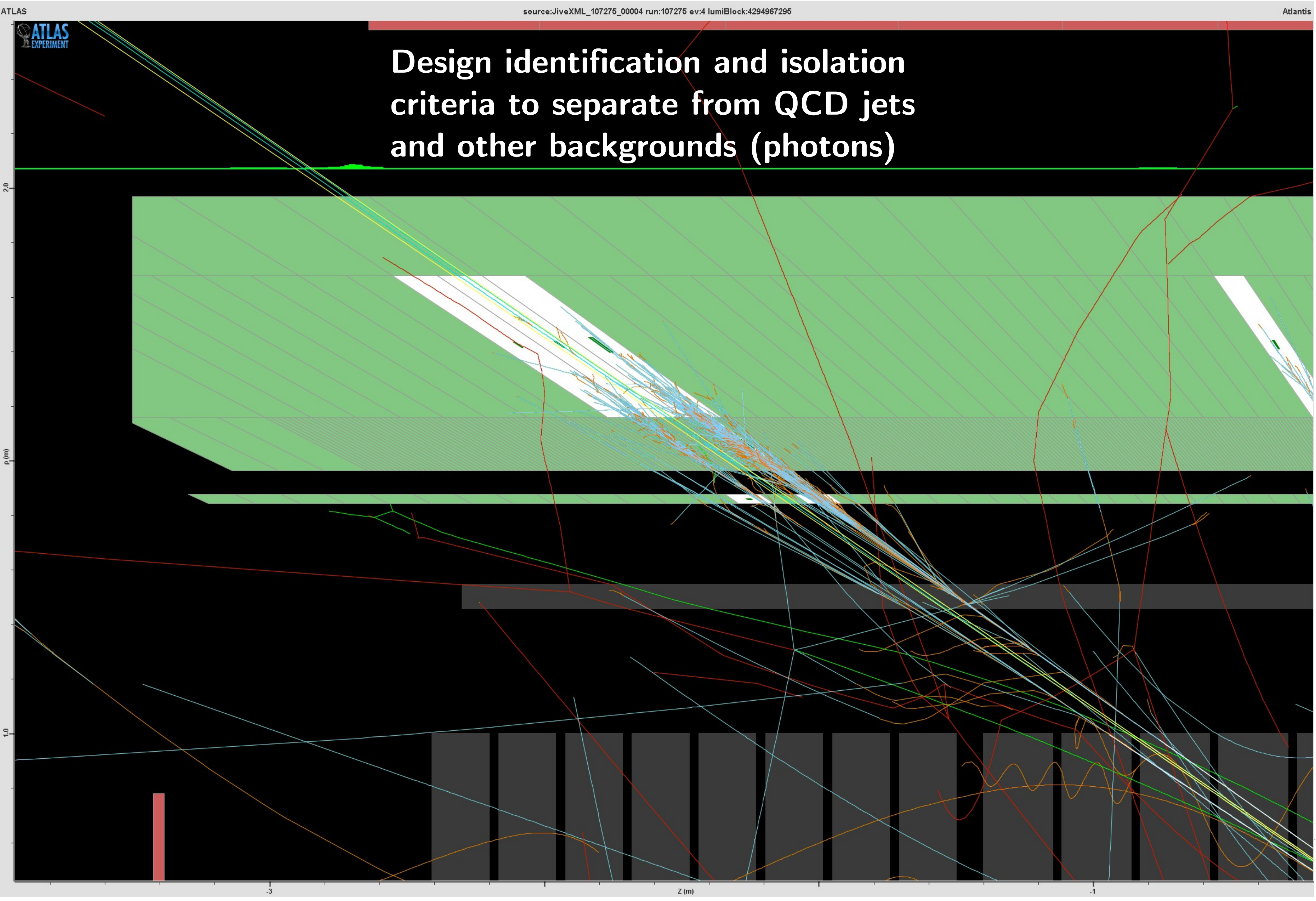




Collimated Leptons

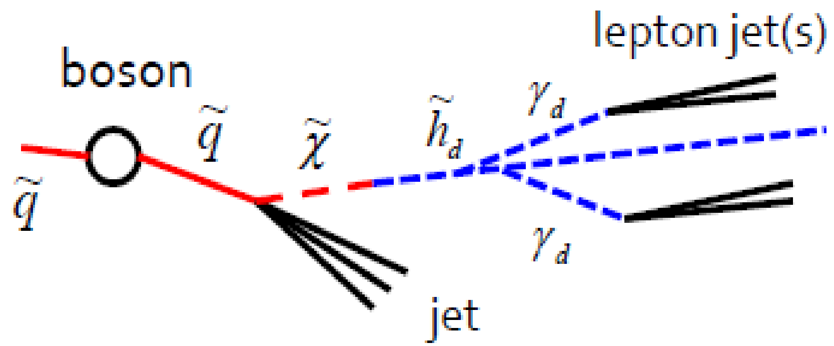


Collimated Leptons



Collimated Leptons

- In the analysis model; pairs of squarks cascade decay through a dark sector into lepton jets



- Lepton pairs are produced from dark photons
  - Energy and quantity of leptons in jet depend on:
    - **Dark photon mass**
    - **Dark sector gauge coupling α_d** (higher coupling → more overlapping dark photons)
- Analysis uses 3 channels:
  - Single muon-jet with ≥4 muons
  - Pairs of muon-jets with ≥2 muons
  - Pairs of electron-jets with ≥2 electrons

	2 e-jet	1 mu-jet	2 mu-jet
Data	15	7	3
bkgd (ABCD)	15.2±2.7	3.0±1.0	0.5±0.3
bkgd (tag-probe)	14.55±0.23		2.2±0.9

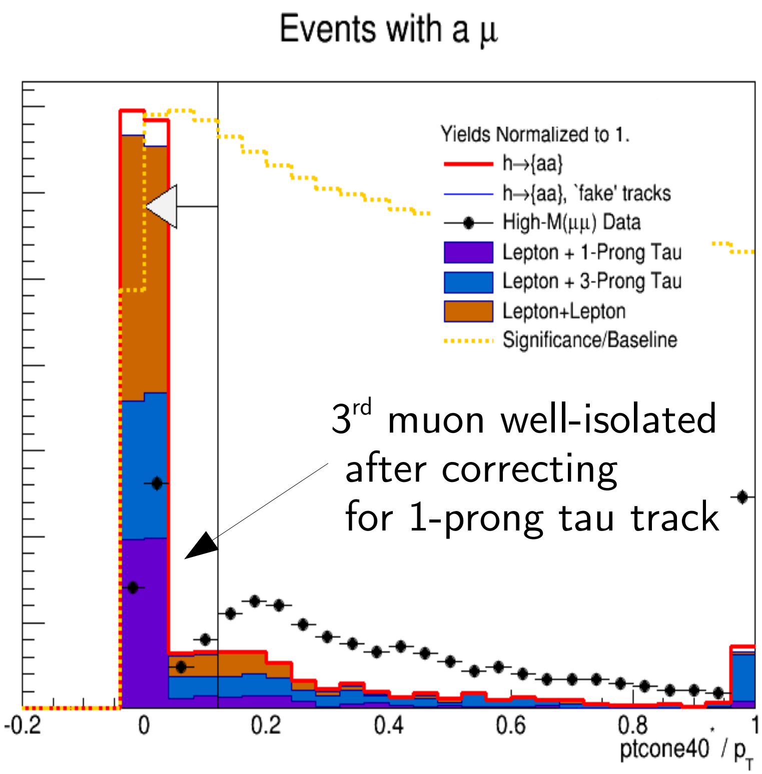
- Main background contribution from fake muon-jets in multi-jet events
  - Limits on applicable HV model couplings set: (value depends on model parameters)

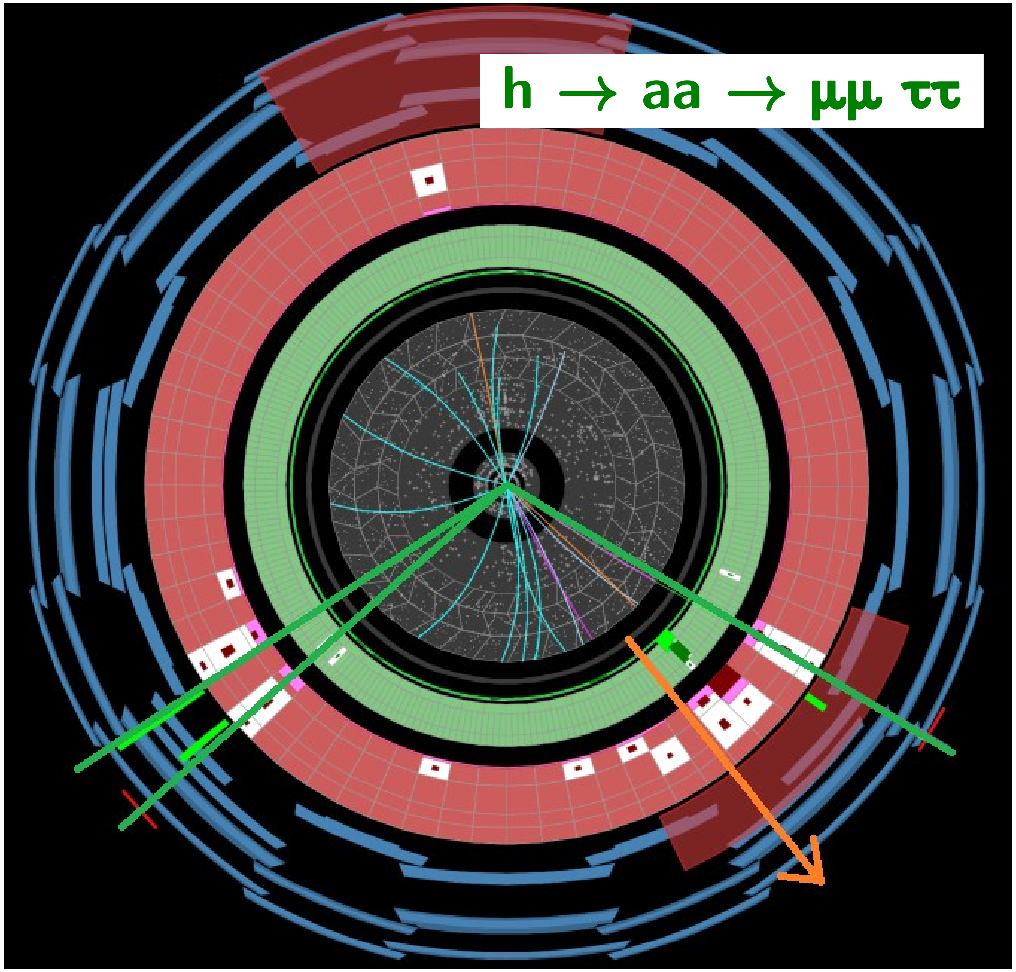
Excluded:
$\sigma \times BR > 0.017 — 1.2$ pb

Collimated Taus

- Special case: *taus are more complicated*
  - Two overlapping hadronic tau decays looks very much like QCD jet

- Good separation when one tau (or both) decays leptonically (especially muon)

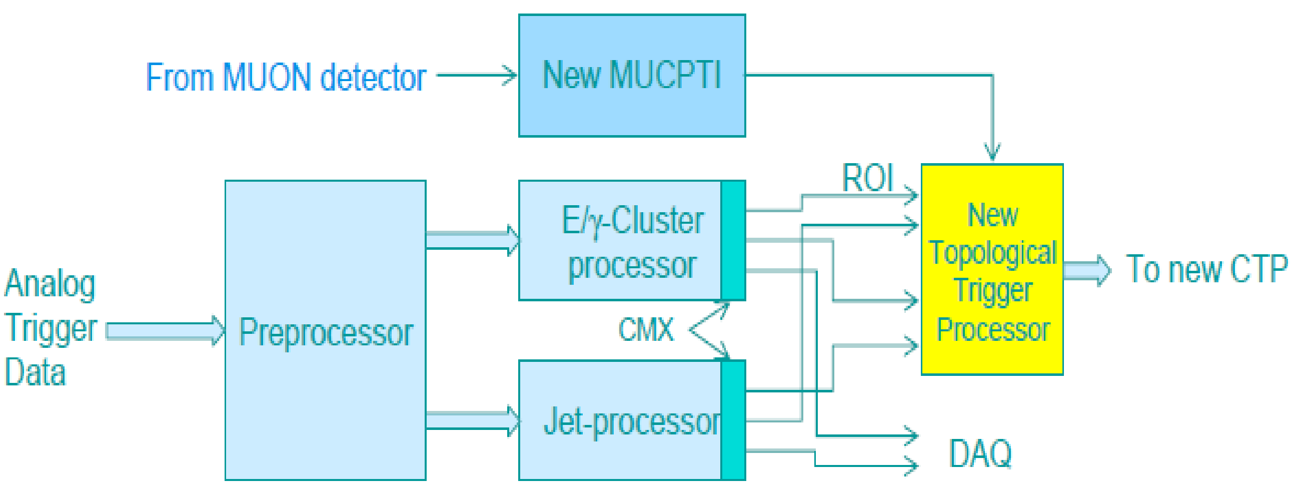


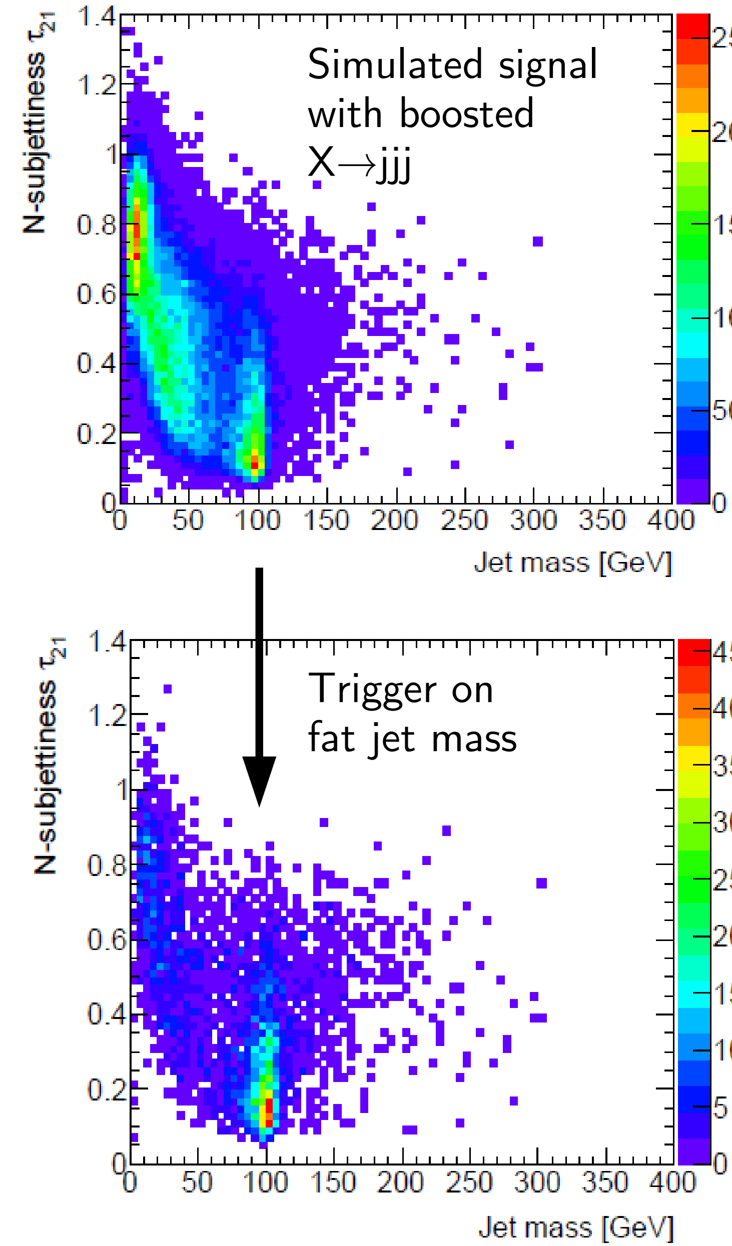


Upgraded (ATLAS) Trigger

- New Run 2 L1 capabilities for topological combinations of objects and kinematics

Overlap removal em, jets
$\Delta\phi$
$\Delta\eta$ ← **VBF!**
R — Angular distance
Back to back
Not back to back
M ← **VBF!** — Reconstructed mass

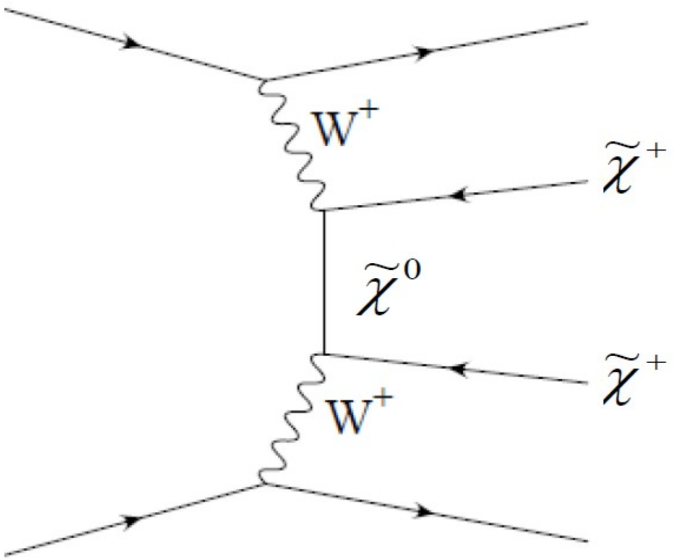




VBF SUSY

- Vector-Boson Fusion (VBF) isn't just for Higgs anymore!

- VBF SUSY xs is reasonable at 13-14 TeV, and *we'll be able to trigger on it*



arXiv:1210.0964

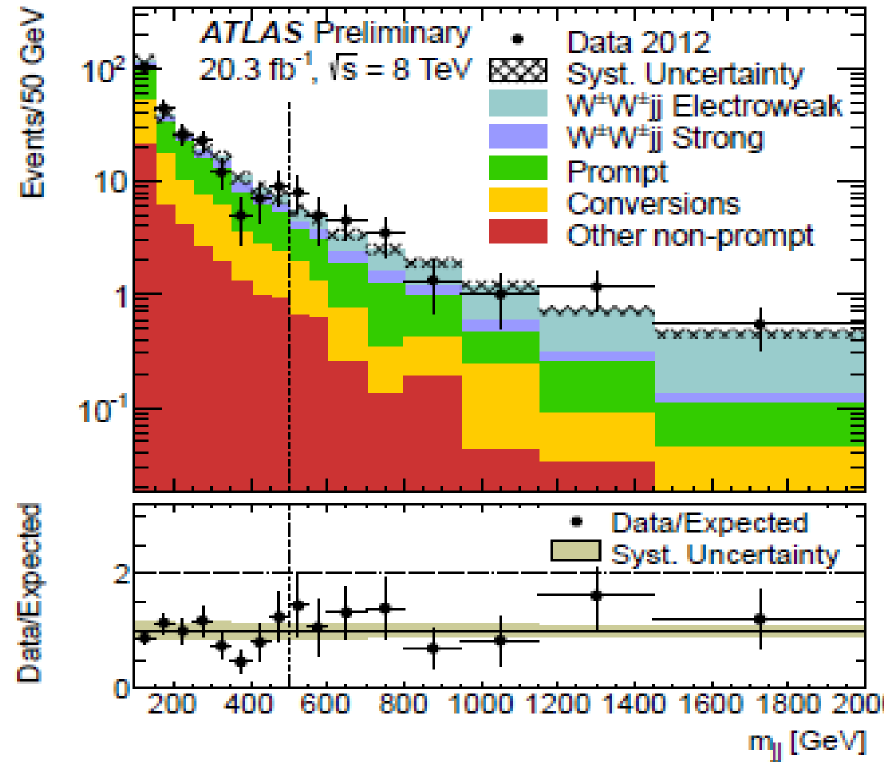
- Can help the disappearing track search:
  - Total signal x-sec @14TeV (m_{wino}~400GeV): ~10fb
    - The ISR requirement reduces the signal efficiency down to 10~20% (w/o track requirements)
  - VBF @14TeV (m_{wino}~400GeV, Deta(jj)>4.2): ~1fb
    - Orthogonal to the ISR signal events and small efficiency loss due kinematic selection cuts.
    - Di-chargino events enhanced

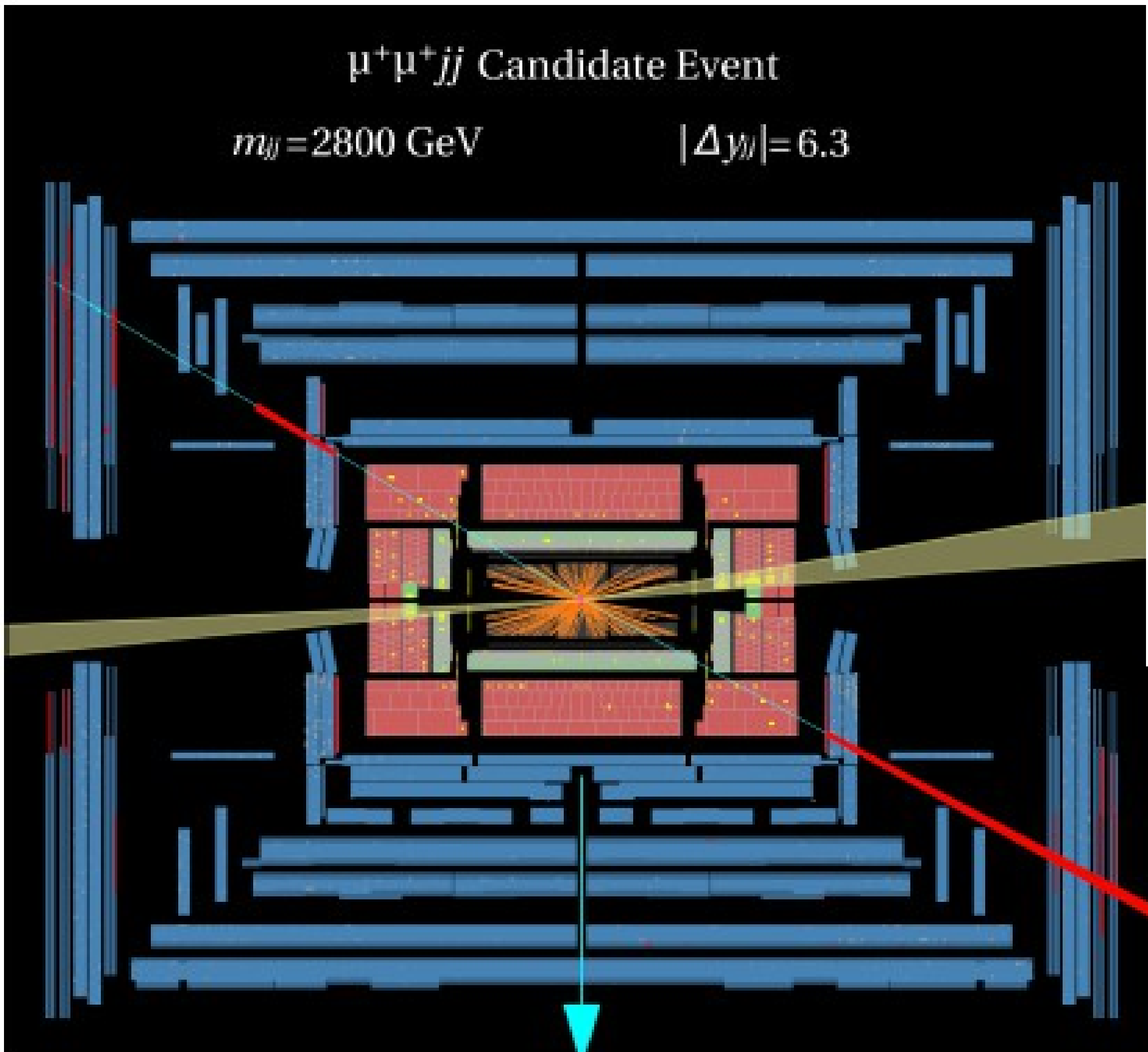
- Also a new handle for *compressed EW SUSY spectra*
  - Trigger on VBF, look for soft leptons, like-sign, some MET, etc.

VBF SUSY

- Nice measurement of SM backgrounds in this channel

ATLAS-CONF-2014-013

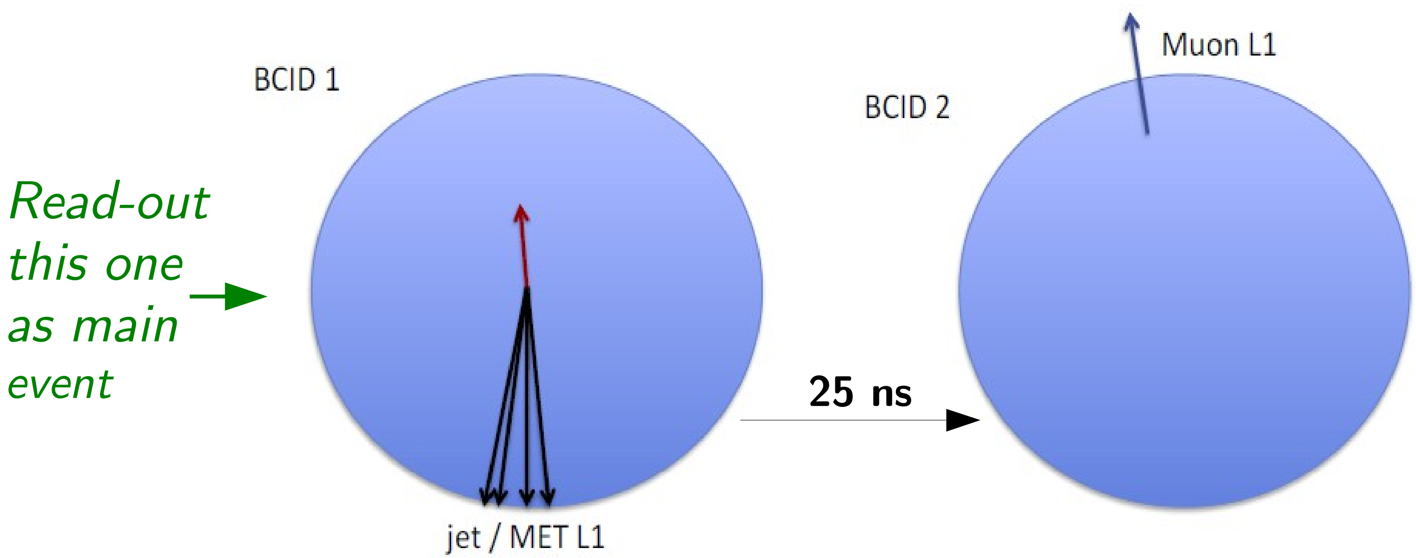




“Late” triggers

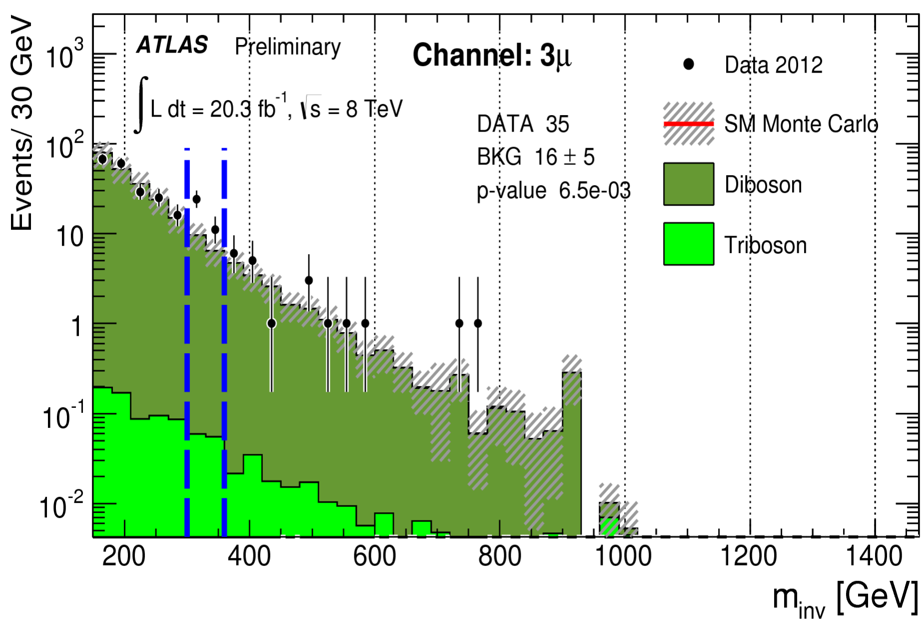
- Can also combine info from *multiple bunch crossings* in Run2 trigger
  - Recall, bunch spacing will be just 25 ns in Run2 (was 50 ns)

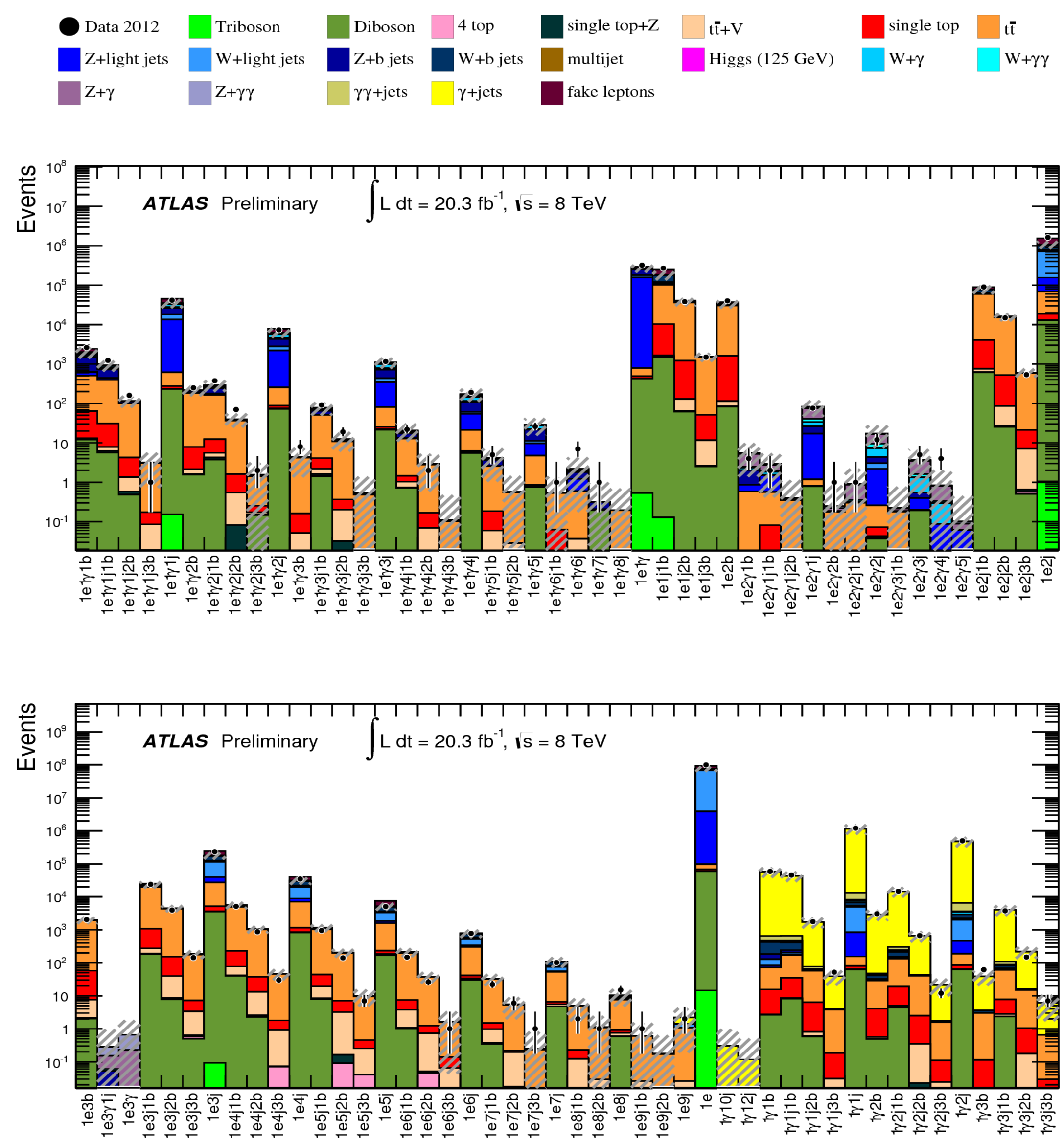
- Heavy, slow (beta~0.5), charged long-lived particle (like Chargino)
  - Too slow to reach muon trigger in bunch 1 (production crossing)
  - Reaches muon trigger in next bunch
  - Would not fire muon trigger by itself
  - *Can combine with jet/MET in previous bunch crossing*



General Search Methods

- Look in every final-state possible… as theory-blind *(theorist-deaf?)* as possible
- Compare data/backgrounds:
  - Number of events
  - Excesses in Meff, Minv, or MET distributions
- ***697 final-states…***

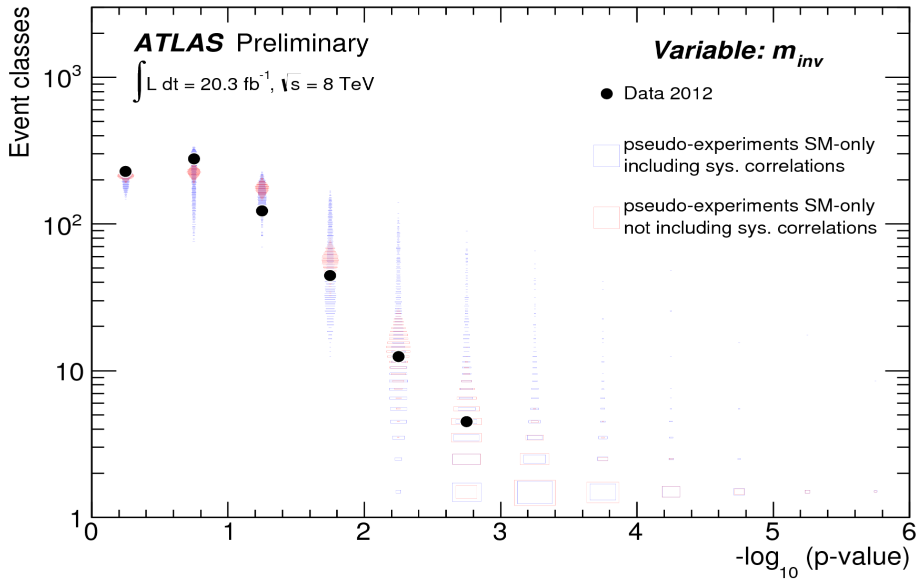


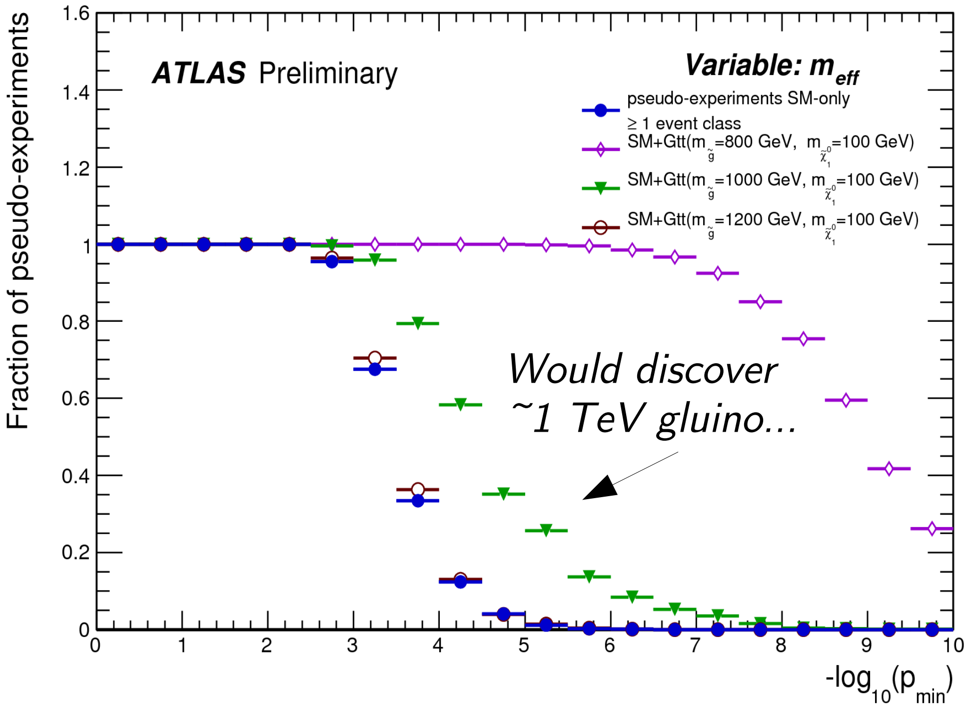


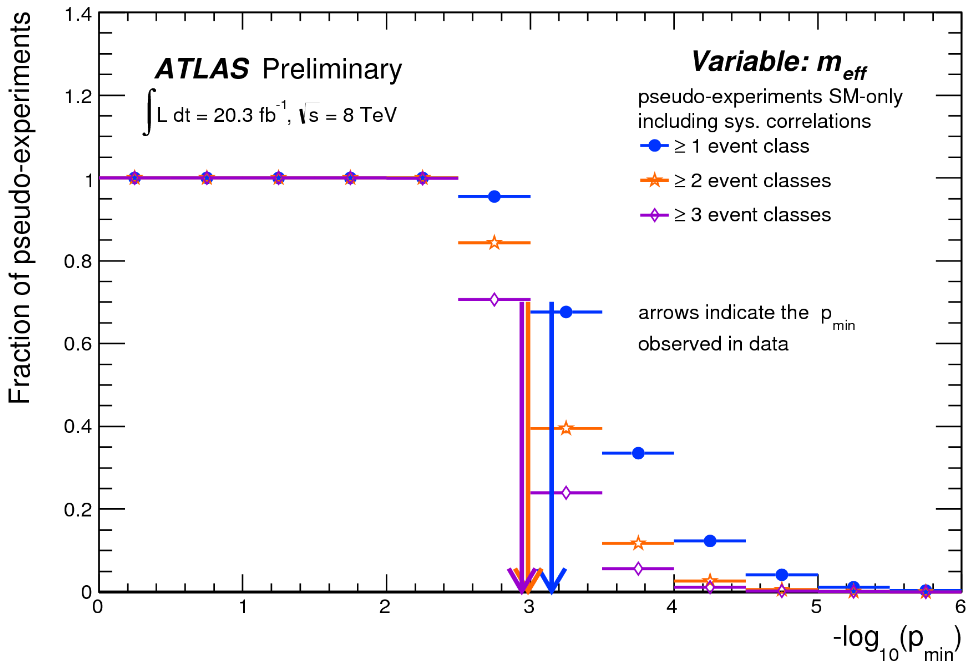
General Search Methods

- Compare to "look-elsewhere" effect
- Sensitive to new physics...

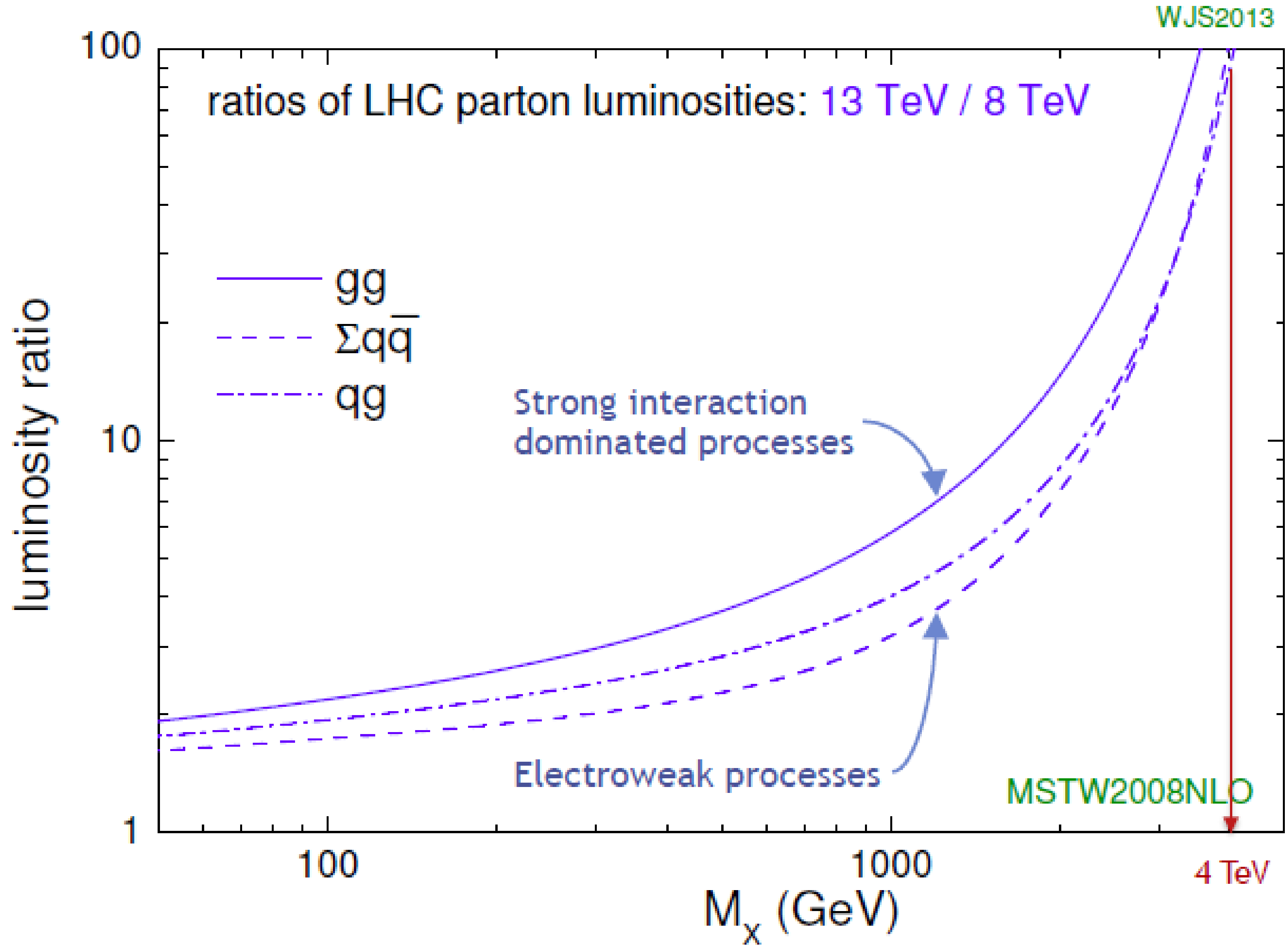
- Good way to search when you don't know what to look for!
- ***How to improve for Run2?***







Higher Energy – Next Year !

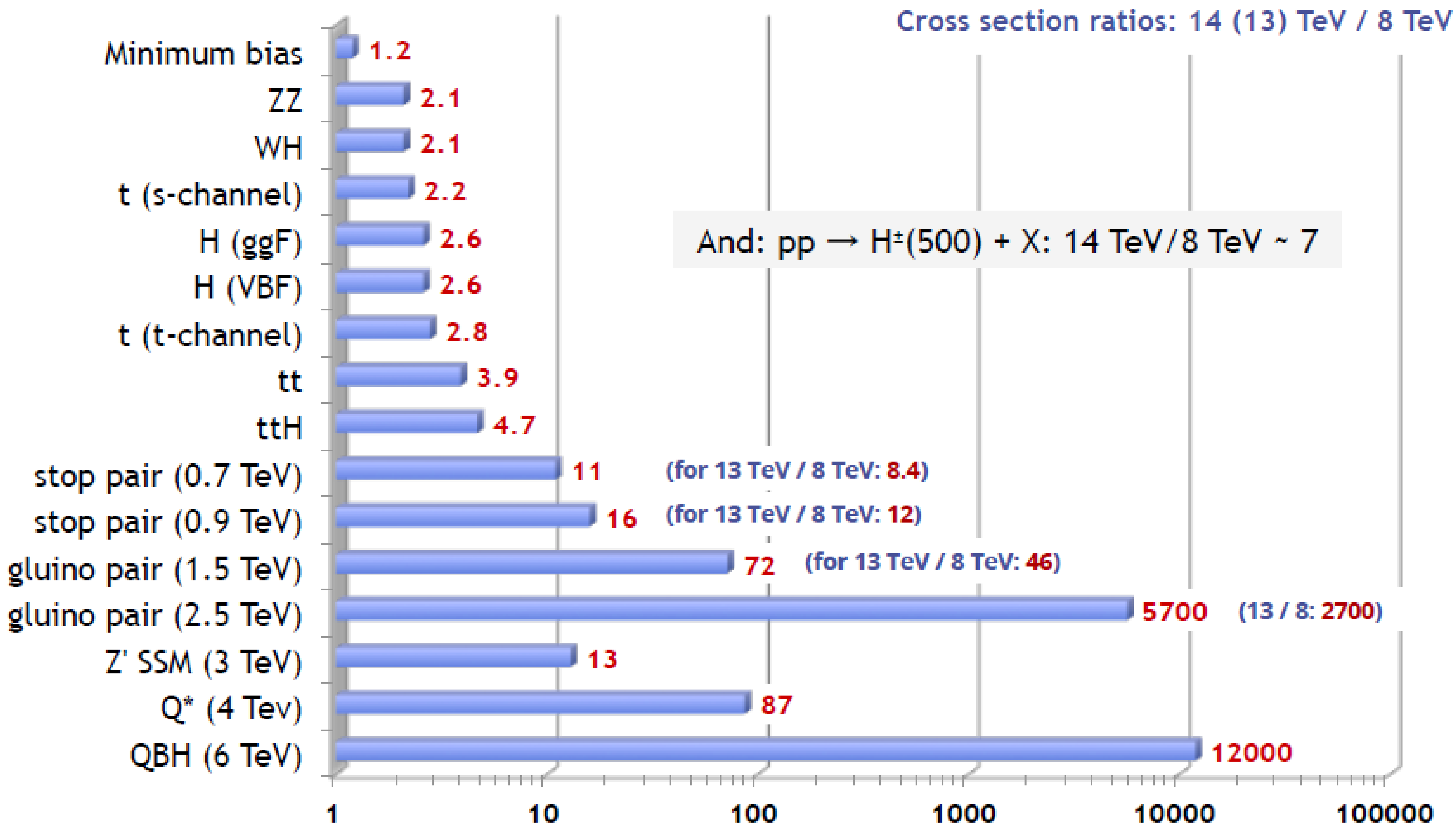


Higher Energy – Next Year !

Cross section ratios

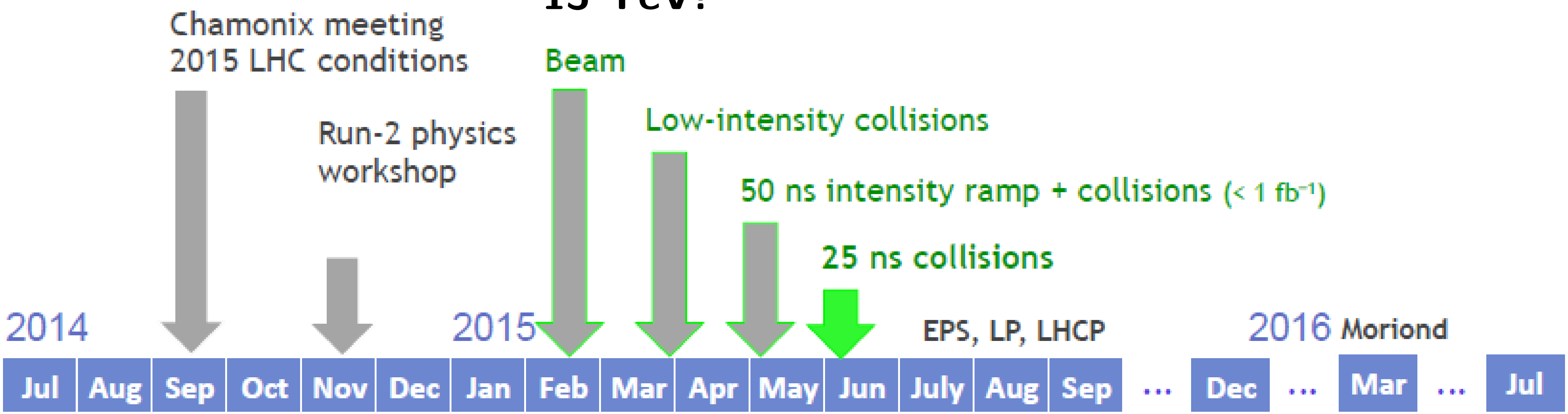
Hugely increased potential for discovery of heavy particles at 13~14 TeV

But life can become harder for states lighter than tt



Higher Energy – Next Year !

13 TeV!



← **~25/fb @ 50ns, 8TeV**

1–5/fb

15-30/fb

↓

14 TeV?

2018 ~100/fb
2022 ~300/fb
2035 ~3000/fb?

Summary

- To find SUSY at the LHC, we might have to look harder (smarter)!
  (Or maybe we just need 13-14 TeV? Or 100 TeV? Or 1000 TeV?)

- Let's keep working on *new ways* to find new physics at the LHC
  - New final-state signatures
  - New triggers
  - Even new (sub-)detectors!

- Gave *some* examples of new and improved SUSY searches underway

- Have to find SUSY by ~2018...

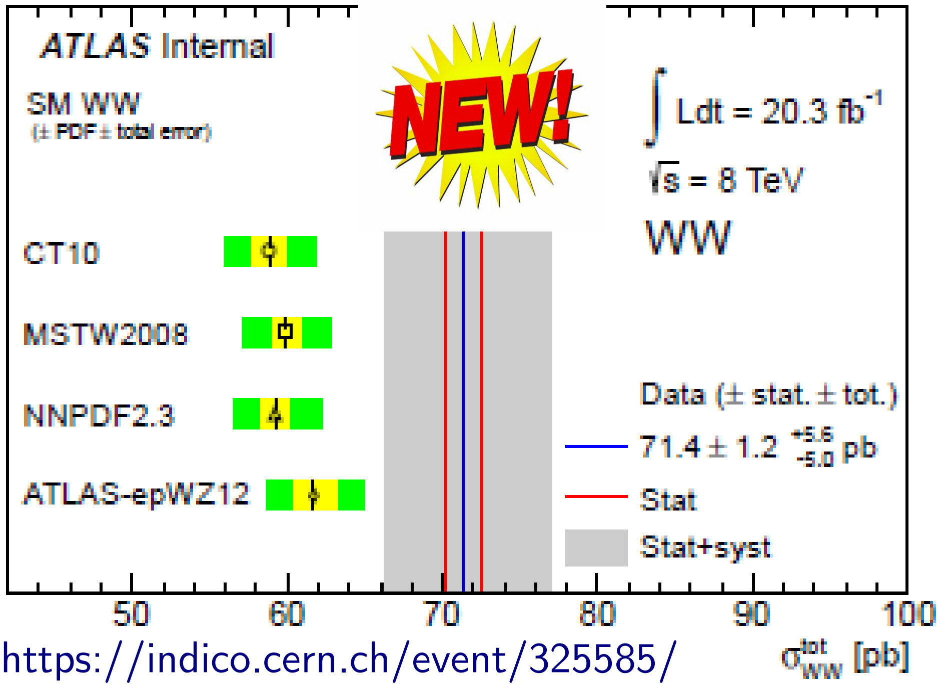
- ***... the studios are pushing for a sequel!***

The good stuff (backup)

What's up with WW?

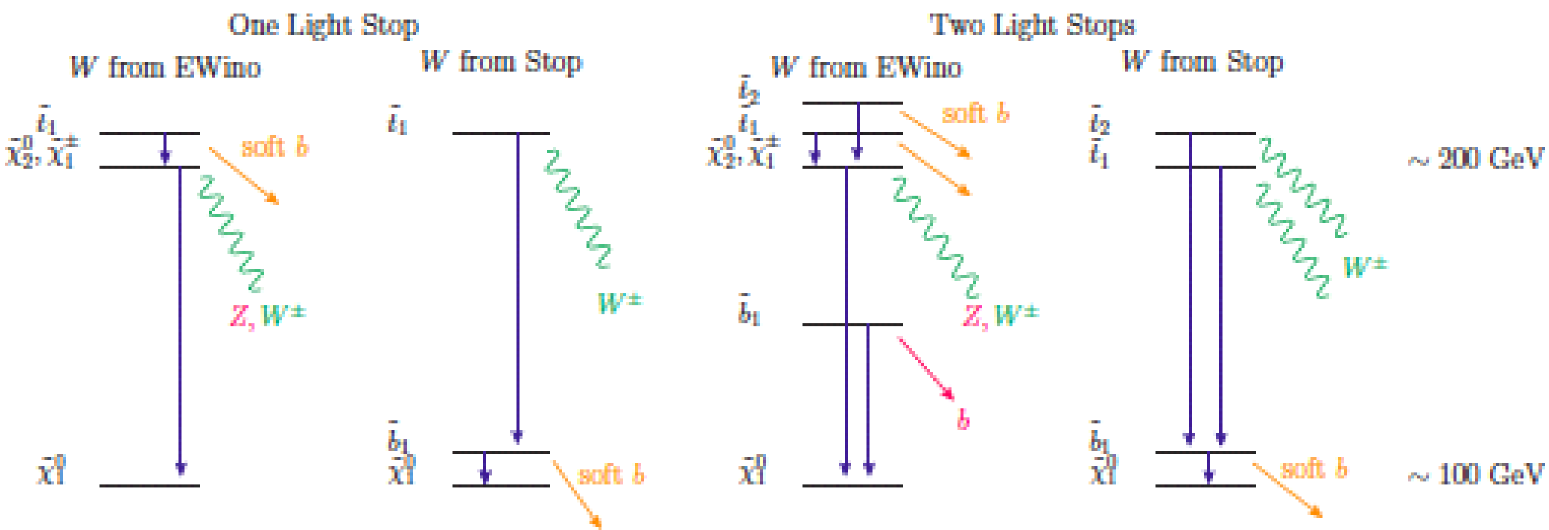
- Has always been high at LHC (ATLAS and CMS)
- (N)NLO corrections needed?
- Stop / Chargino production?!

Curtin, Meade, Tien: arXiv:1406.0848;
Kim, Rolbiecki, Sakurai, Tattersall: arXiv:1406.0858



https://indico.cern.ch/event/325585/

ATLAS-CONF-2014-033



What's up with WW?

- If you want to sound smart in an Astronomy seminar...

  "So have you checked for complications from *dust* ?"

What's up with WW?

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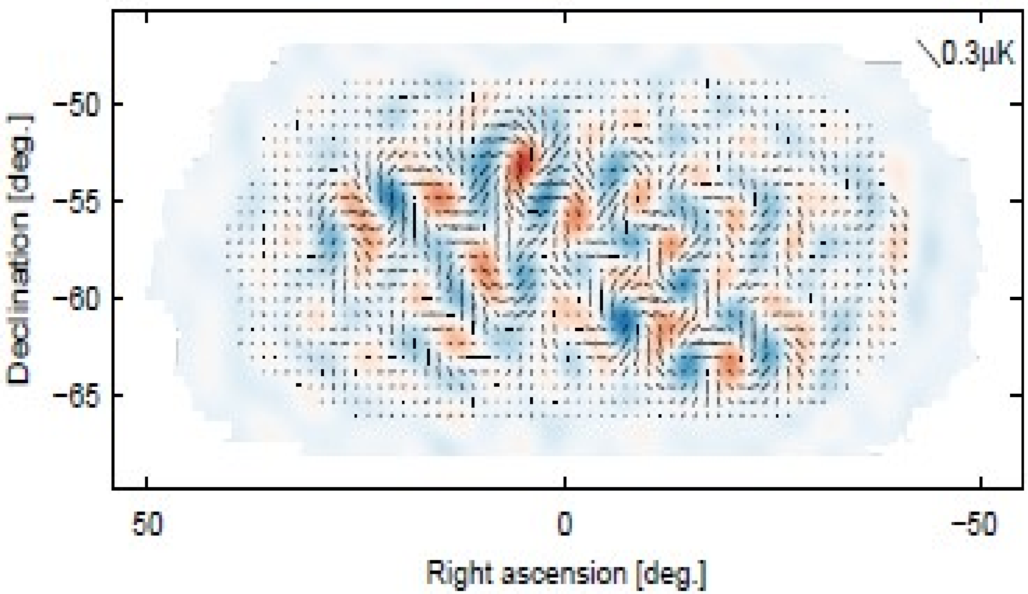
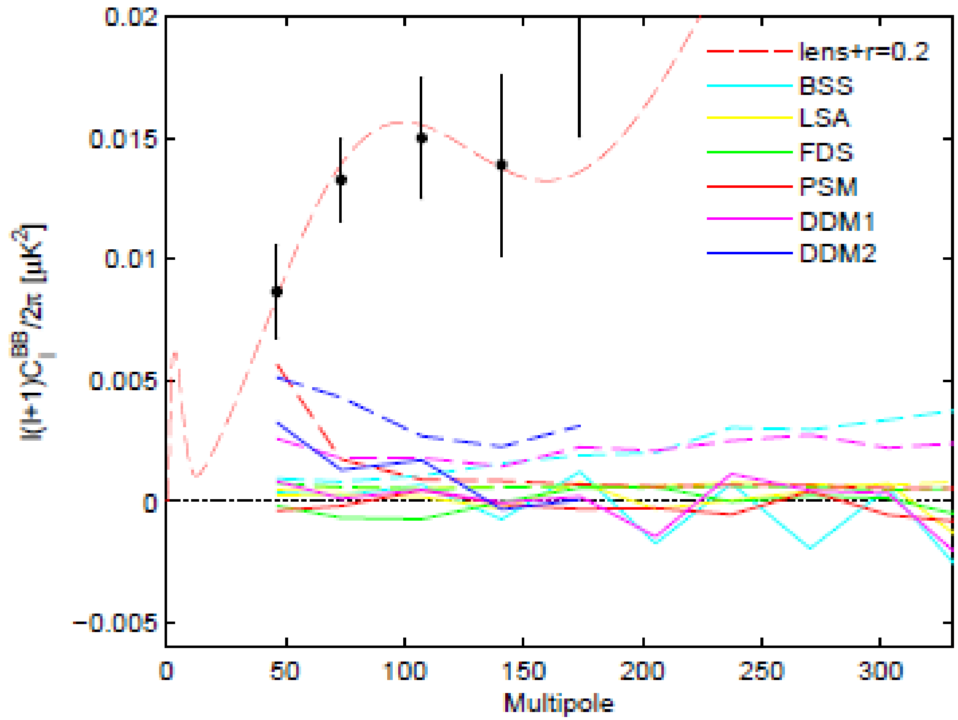
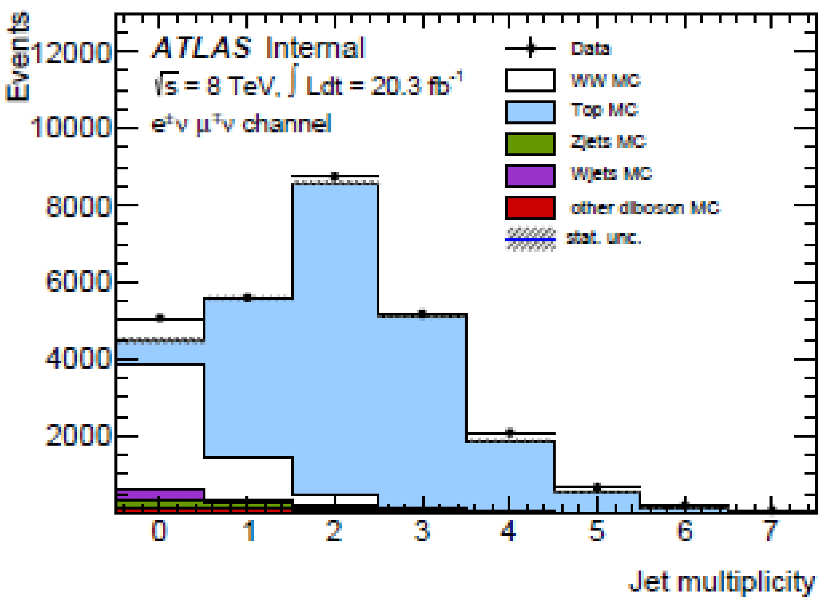


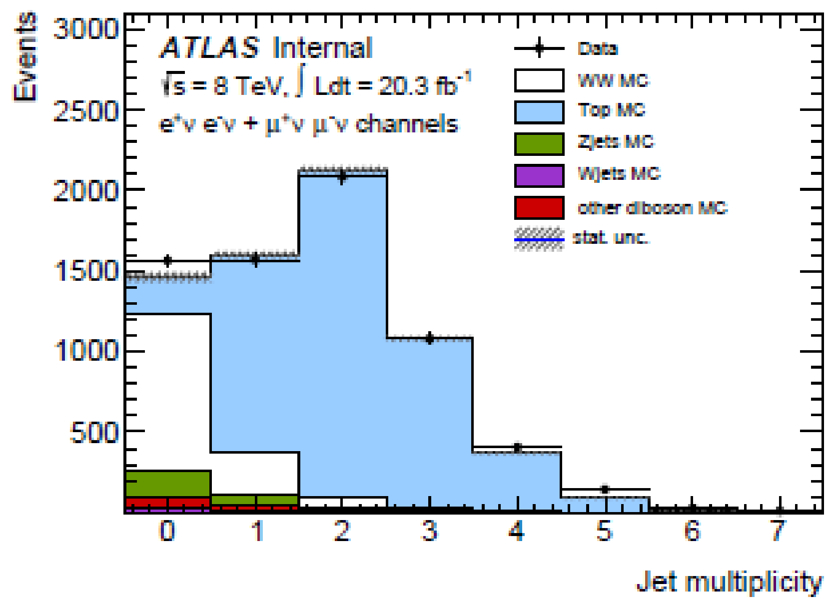


What's up with WW?

- If you want to sound smart in a High-Energy Physics seminar...

  “So have you checked for systematics arising from your *jet veto* “?

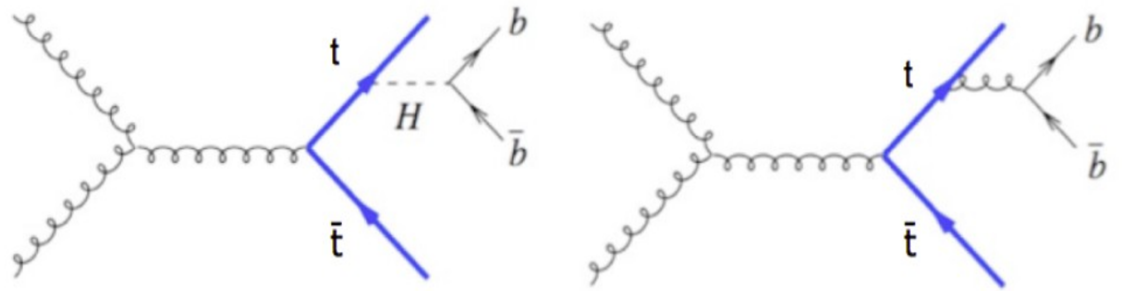


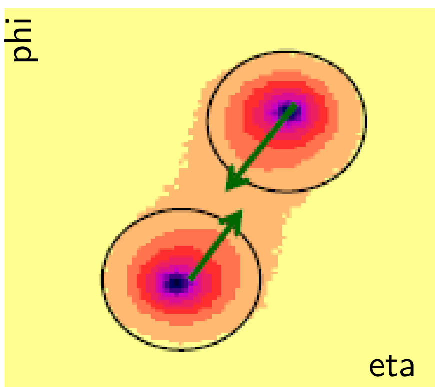


- Dominant experimental systematic uncertainty...

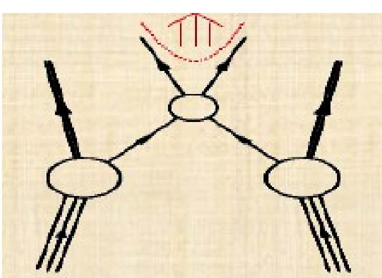
Color flow

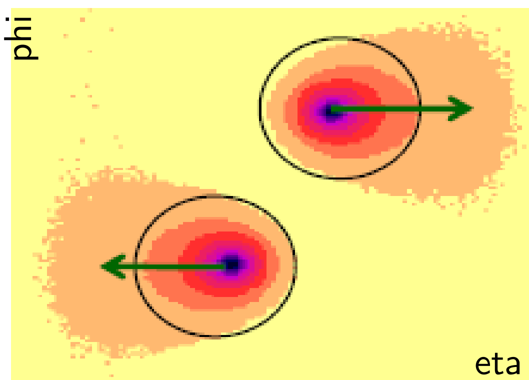
- Higgs is color-singlet
- H $\rightarrow$ jets:
  color-singlet configuration
  - Backgrounds often not…
    e.g. gluon splitting



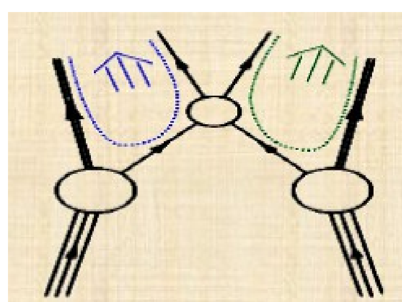


SINGLET





OCTET



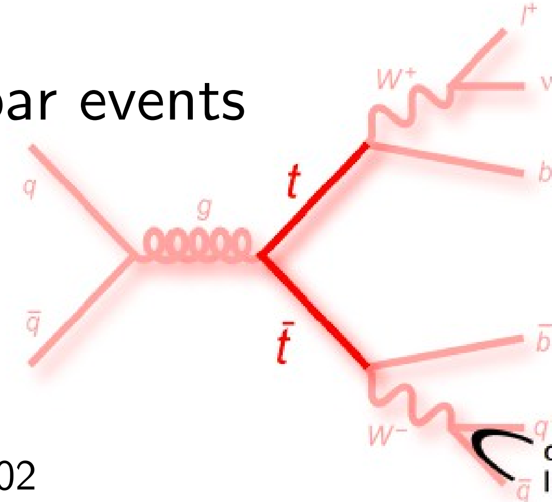
- Useful as additional variable for separating signal from backgrounds

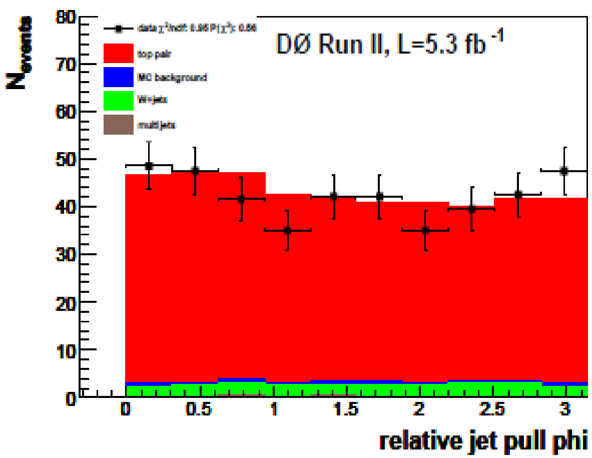
- Does not bias jet kinematics to 1st order
  - Can perhaps be used to measure background shapes with small syst.

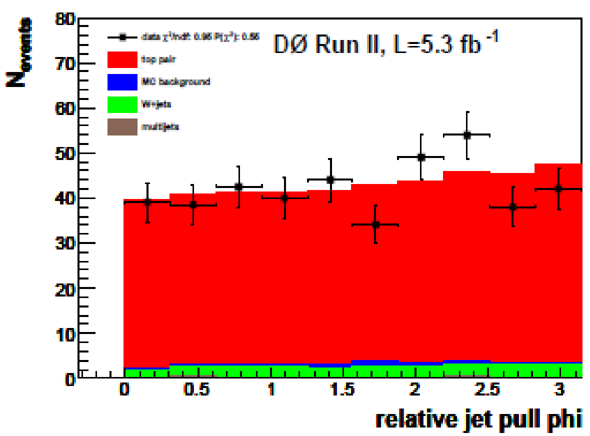
Phys.Rev.Lett.105:022001

Color flow

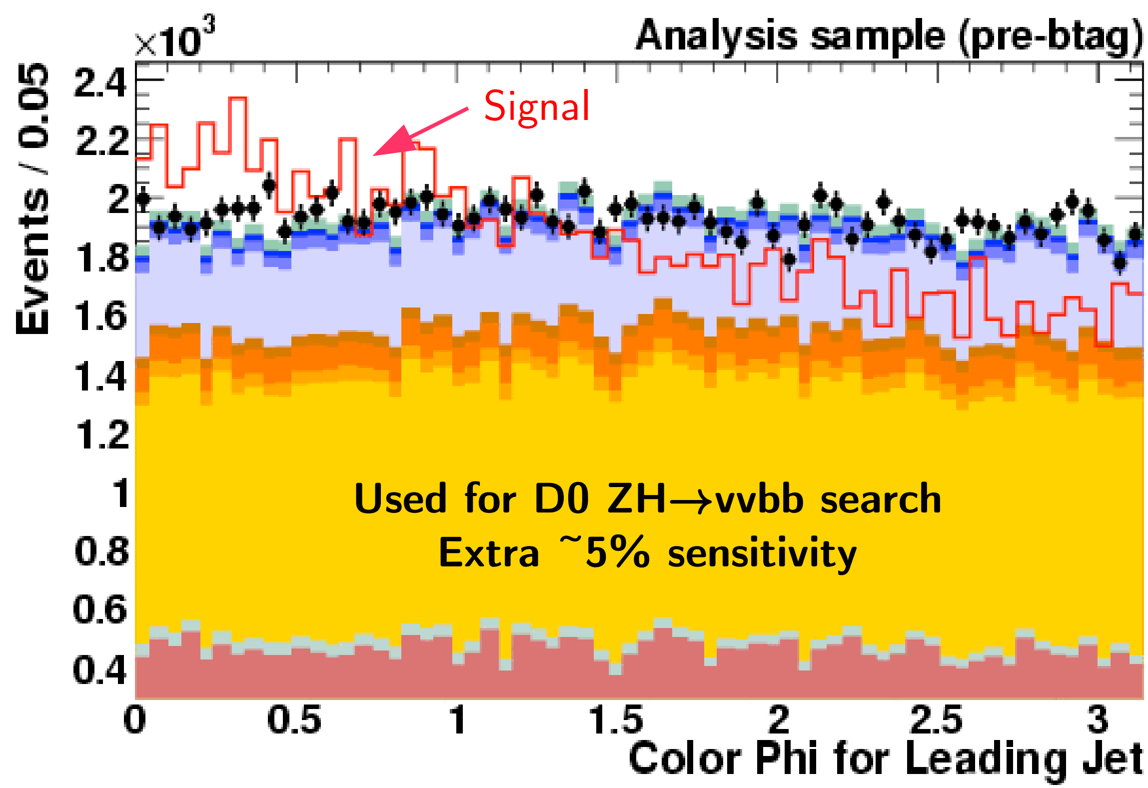
- Method was tested at D0 (Tevatron) using ttbar events
- Successfully used in D0 Higgs→bb search
- Will soon be tested with large statistics at ATLAS



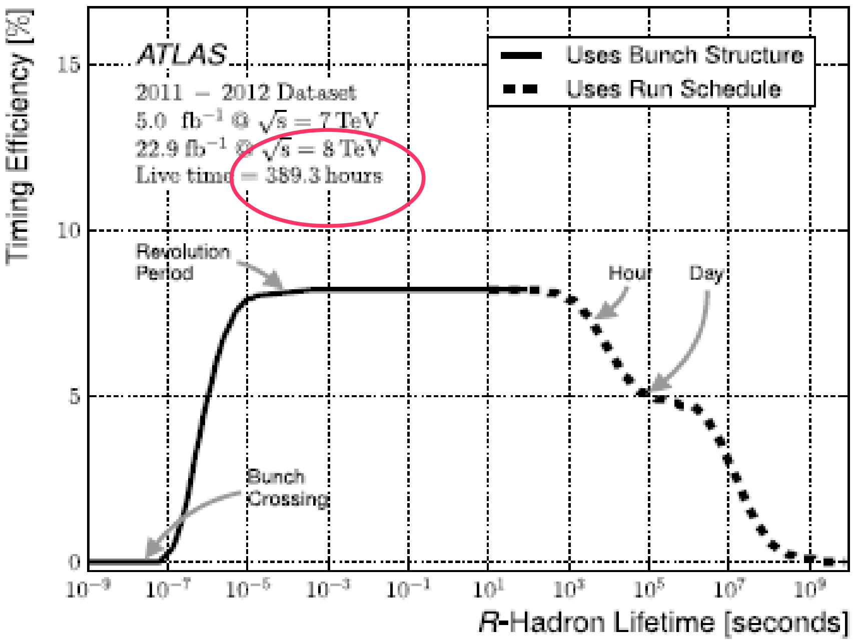


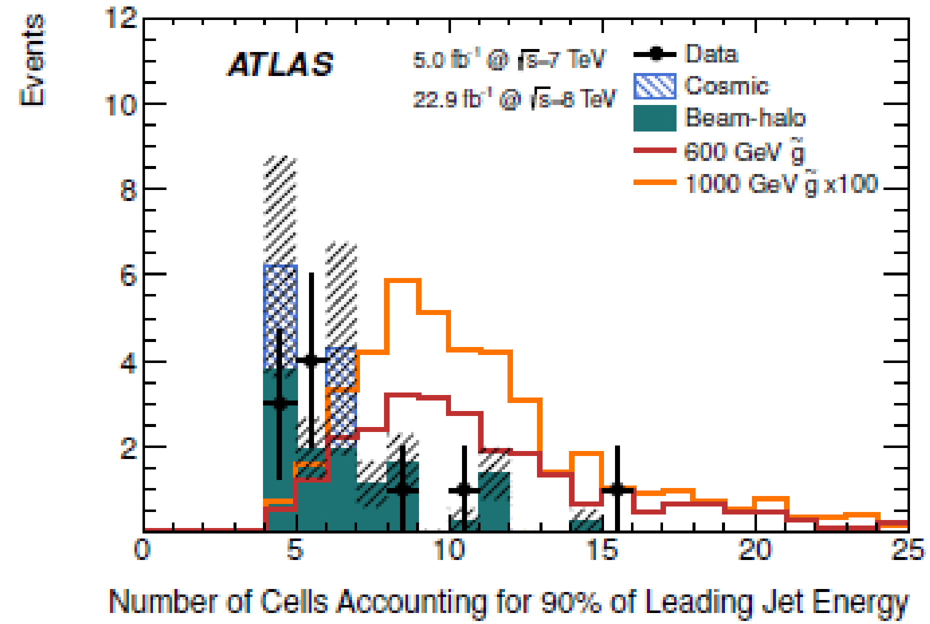


Phys.Rev.D 83:092002



Stopped Gluino





Leading jet energy (GeV)	R-hadron model	Gluino/squark decay	Neutralino mass (GeV)	Gluino/squark mass limit (GeV) Expected	Observed
100	Generic	$\tilde{g} \to g/q\bar{q} + \tilde{\chi}^0$	$m_{\tilde{g}} - 100$	526	545
100	Generic	$\tilde{g} \to t\bar{t} + \tilde{\chi}^0$	$m_{\tilde{g}} - 380$	694	705
300	Generic	$\tilde{g} \to g/q\bar{q} + \tilde{\chi}^0$	100	731	832
300	Generic	$\tilde{g} \to t\bar{t} + \tilde{\chi}^0$	100	700	784
300	Intermediate	$\tilde{g} \to g/q\bar{q} + \tilde{\chi}^0$	100	615	699
300	Regge	$\tilde{g} \to g/q\bar{q} + \tilde{\chi}^0$	100	664	758
100	Generic	$\tilde{t} \to t + \tilde{\chi}^0$	$m_{\tilde{t}} - 200$	389	397
100	Generic	$\tilde{t} \to t + \tilde{\chi}^0$	100	384	392
100	Regge	$\tilde{t} \to t + \tilde{\chi}^0$	100	371	379
100	Regge	$\tilde{b} \to b + \tilde{\chi}^0$	100	334	344