Searches for New Physics with Jets

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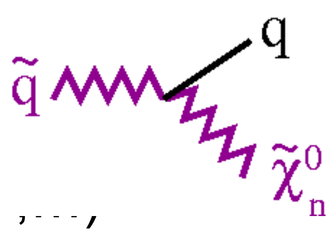
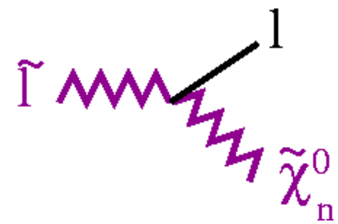
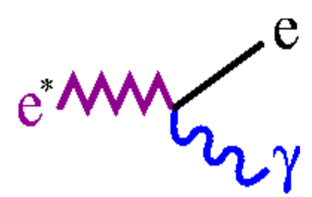
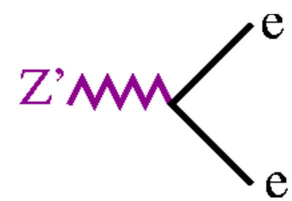
The Unknown beyond the Standard Model

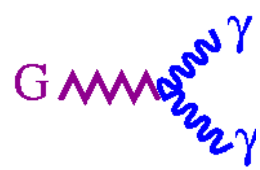
- Many good reasons to believe there is as yet unknown physics beyond the SM:
  - Dark matter + energy, matter/anti-matter asymmetry, neutrino masses/mixing +many more (see 1st lecture)
- Many possible new particles/theories:
  - Supersymmetry:
    - Many flavours
  - Extra dimensions (G)
  - New gauge groups (Z', W' ,…,
  - New fermions (t', b', …)
  - Excited fermions
  - …
- Many signatures involve jets

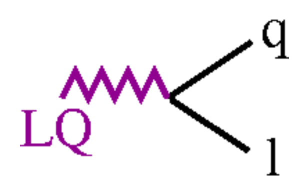




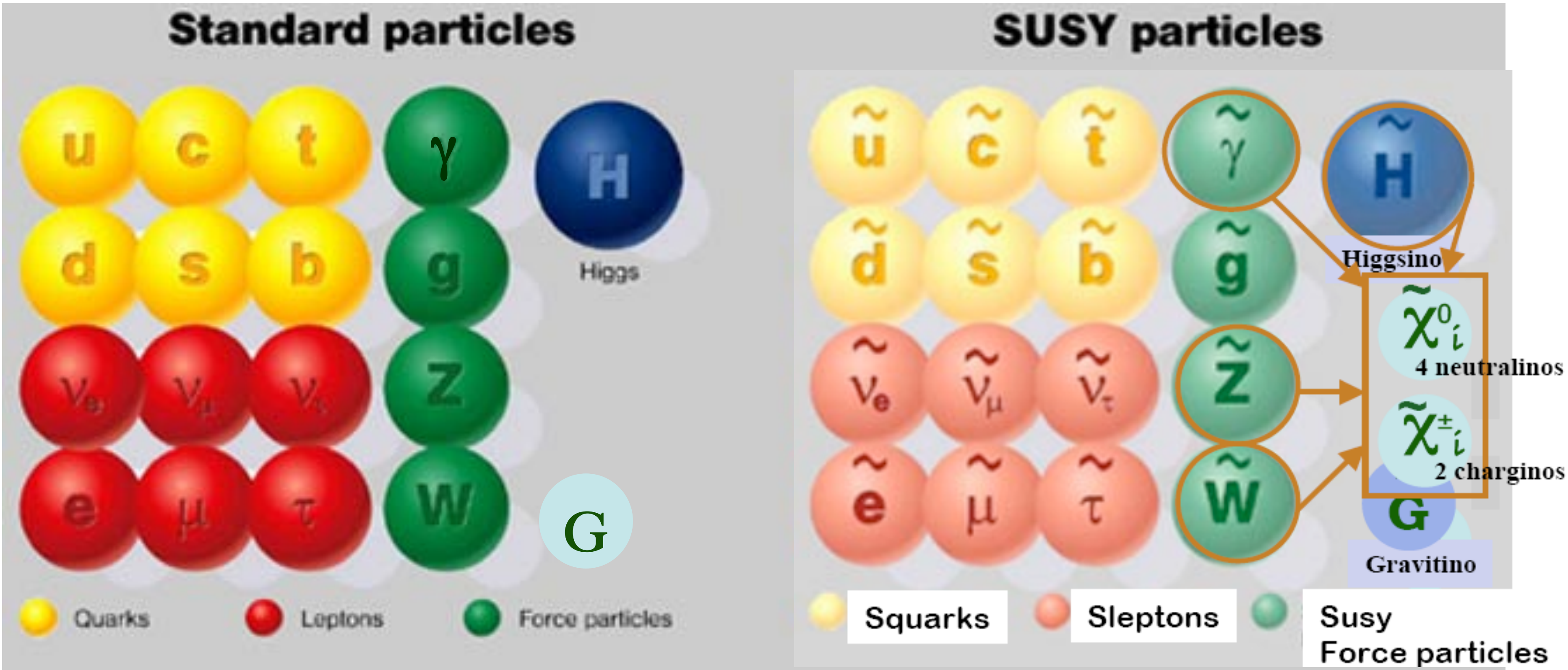








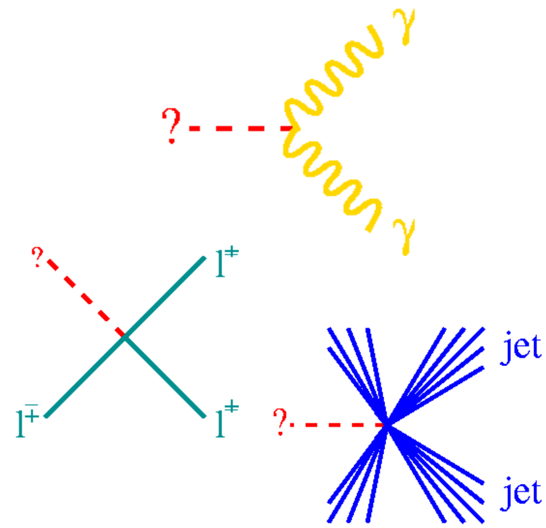
Supersymmetry (SUSY)



- SM particles have supersymmetric partners:
  - Differ by 1/2 unit in spin
    - **Sfermions** (squark, selectron, smuon, ...): spin 0
    - **gauginos** (chargino, neutralino, gluino,…): spin 1/2
- No SUSY particles found as yet:
  - SUSY must be broken: breaking mechanism determines phenomenology
  - More than 100 parameters even in "minimal" models!

SUSY Comes in Many Flavors

- Breaking mechanism determines phenomenology and search strategy at colliders
  - GMSB:
    - Gravitino is the LSP
    - Photon final states likely
  - mSUGRA
    - Neutralino is the LSP
    - Many different final states
    - Common scalar and gaugino masses
  - AMSB
  - Split-SUSY: sfermions very heavy



- R-parity
  - Conserved: Sparticles produced in pairs
    - Yields natural dark matter candidate
  - Not conserved: Sparticles can be produced singly
    - constrained by proton decay if violation in quark sector
    - Could explain neutrino oscillations if violation in lepton sector

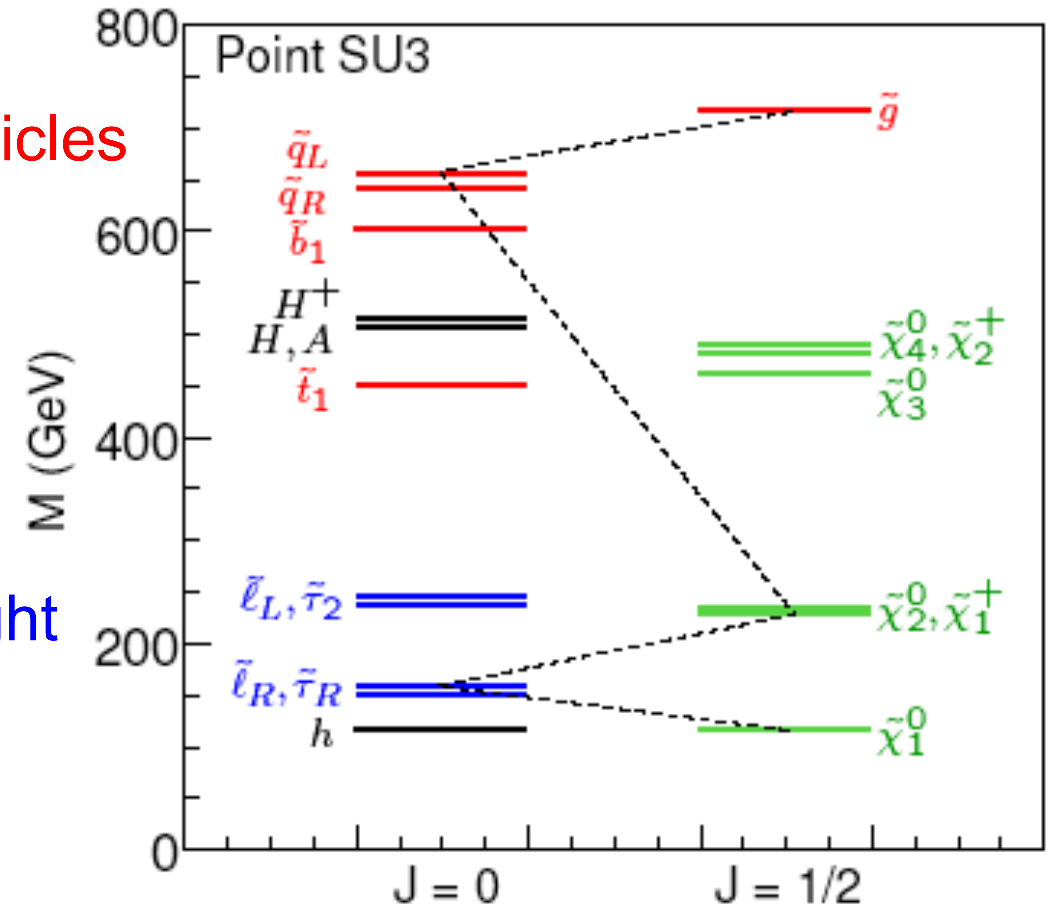
Strategy for SUSY Searches

- *Minimal Supersymmetric Standard Model* (MSSM) has more than 100 parameters
  - Impossible to scan full parameter space
  - Many constraints already from
    - Precision electroweak data
    - Lepton flavour violation
    - Baryon number violation
    - …
- Makes no sense to choose random set
  - Use simplified well motivated "benchmark" models
    - Ease comparison between experiments
- Make interpretation model independent
  - E.g. not as function of GUT scale SUSY particle masses but versus EWK scale SUSY particle masses
  - Mostly using "simplified models"

A Typical Sparticle Mass Spectrum: pre-LHC

Colored particles heavy

Sleptons light

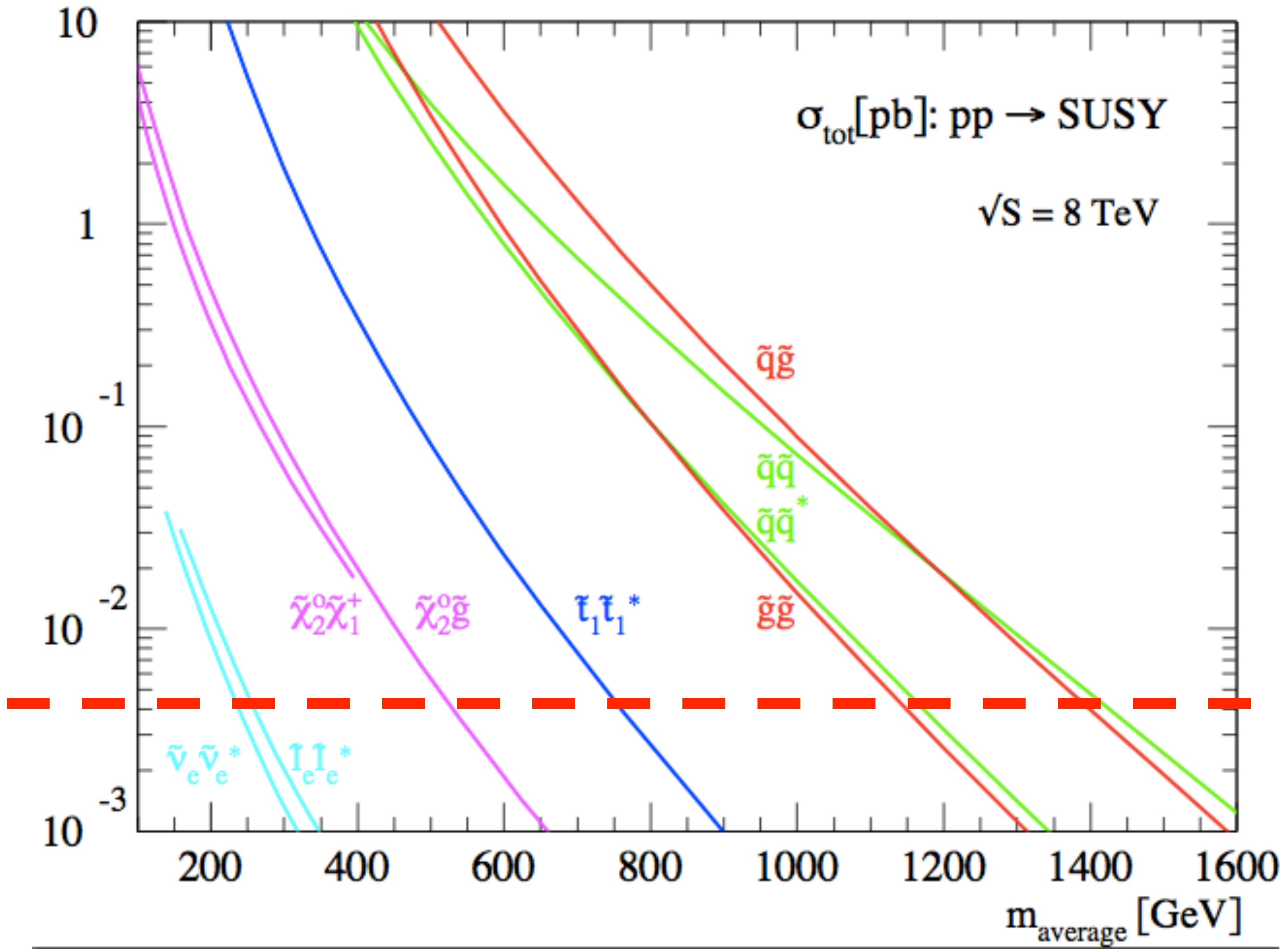


Charginos and neutralinos ~light

- This spectrum is ruled out by LHC data for MANY reasons

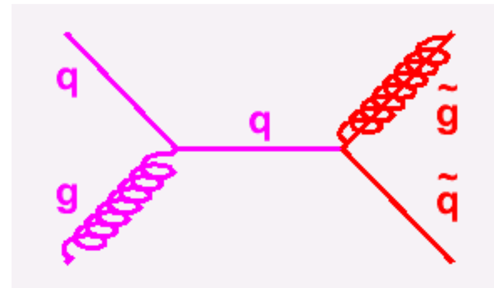
Sparticle Cross Sections

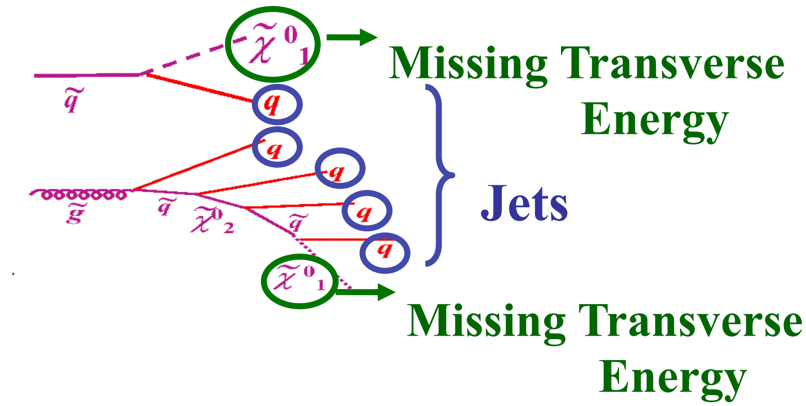
100 events in 20 fb^{-1}

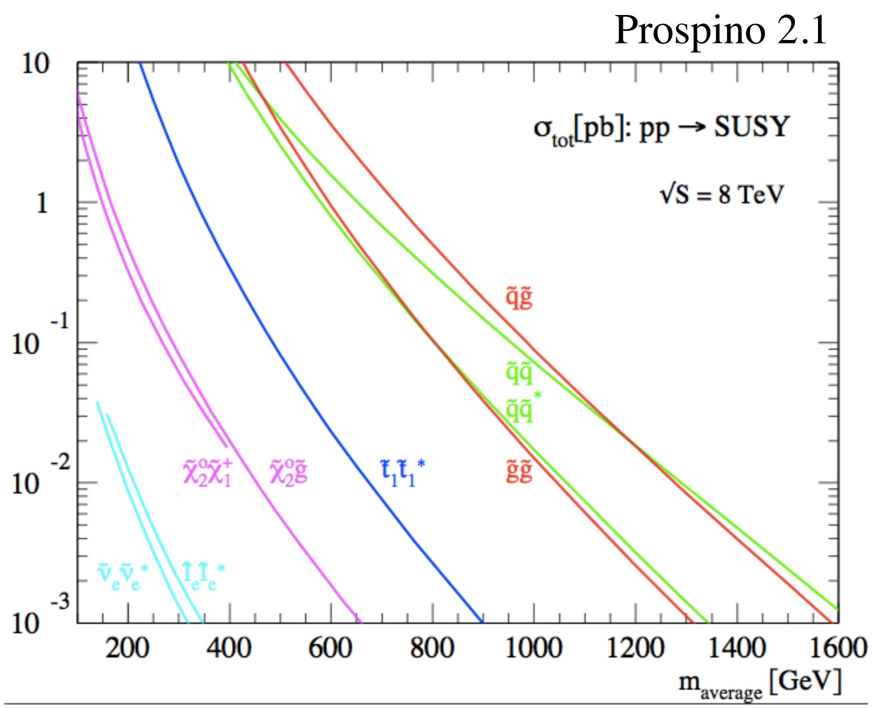


Generic Squarks and Gluinos

- Squark and Gluino production:
  - Signature: jets and $\not{E}_T$







Strong interaction =>
large production cross section

for $M(\tilde{g}) \approx 800$ GeV/c^2:

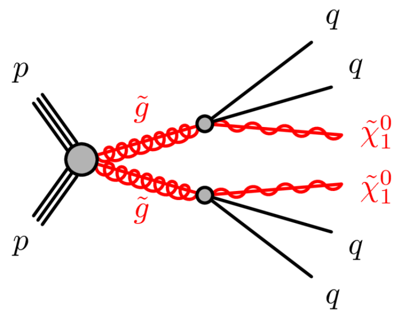
1000 event produced/ fb^{-1}

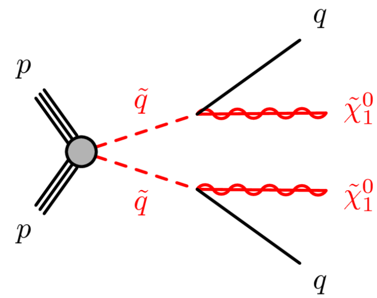
for $M(\tilde{g}) \approx 1600$ GeV/c^2:

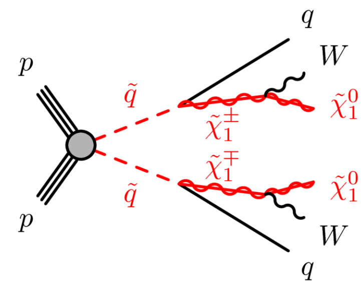
1 event produced/ fb^{-1}

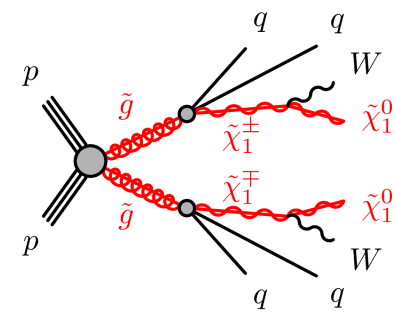
Signature depends many parameters

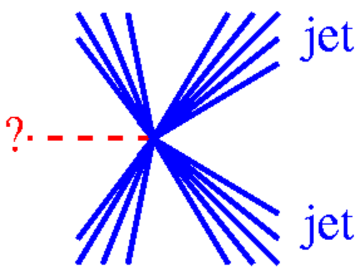
4 jets + E_T^{miss}	2 jets + E_T^{miss}	6 jets + E_T^{miss}	8 jets + E_T^{miss}

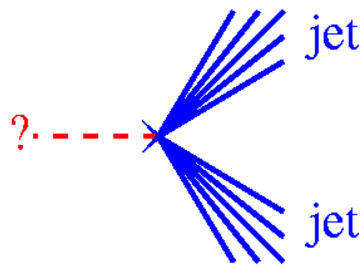


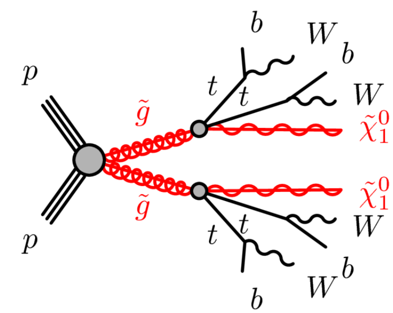












- In any *real* model many signatures may appear at the same time
  - But which exactly and with what strength very unclear
- Strategy is to look for many signatures and to interpret both in **simplified models** and in **mSUGRA**

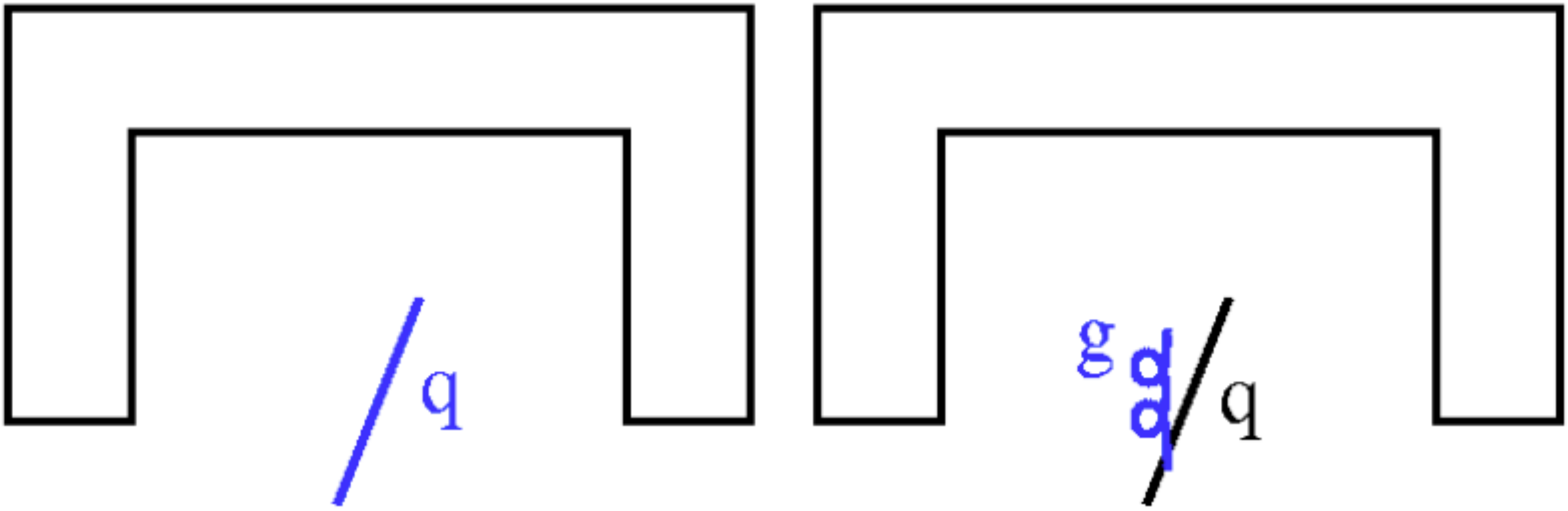
Interlude: Measuring Jets and Missing E_T

- Jets and E_T^{miss} are experimentally among the most challenging quantities to measure
  - Jets are primarily measured by calorimeter but significantly aided by tracker
    - E.g. CMS has so-called "particle flow" algorithm which attempts to use tracker for charged hadrons and calorimeter for neutral hadrons only
  - E_T^{miss} is a derived quantity:

$$E_{\mathrm{x(y)}}^{\mathrm{miss}} = E_{\mathrm{x(y)}}^{\mathrm{miss},e} + E_{\mathrm{x(y)}}^{\mathrm{miss},\gamma} + E_{\mathrm{x(y)}}^{\mathrm{miss},\tau} + E_{\mathrm{x(y)}}^{\mathrm{miss,jets}} + E_{\mathrm{x(y)}}^{\mathrm{miss,softjets}} + (E_{\mathrm{x(y)}}^{\mathrm{miss,calo},\mu}) + E_{\mathrm{x(y)}}^{\mathrm{miss,CellOut}} + E_{\mathrm{x(y)}}^{\mathrm{miss},\mu},$$

$$E_{\mathrm{T}}^{\mathrm{miss}} = \sqrt{(E_{\mathrm{x}}^{\mathrm{miss}})^2 + \left(E_{\mathrm{y}}^{\mathrm{miss}}\right)^2}, \quad \phi^{\mathrm{miss}} = \arctan(E_{\mathrm{y}}^{\mathrm{miss}}/E_{\mathrm{x}}^{\mathrm{miss}}).$$

Partons are Produced in the hard scatter

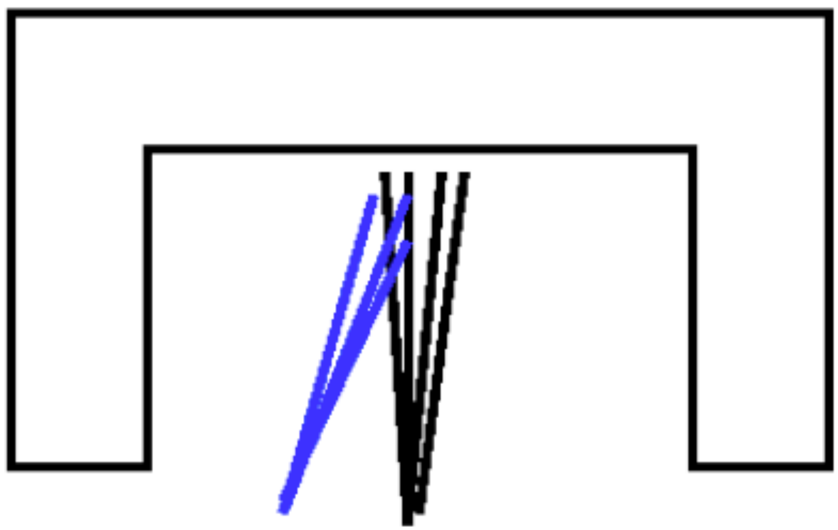


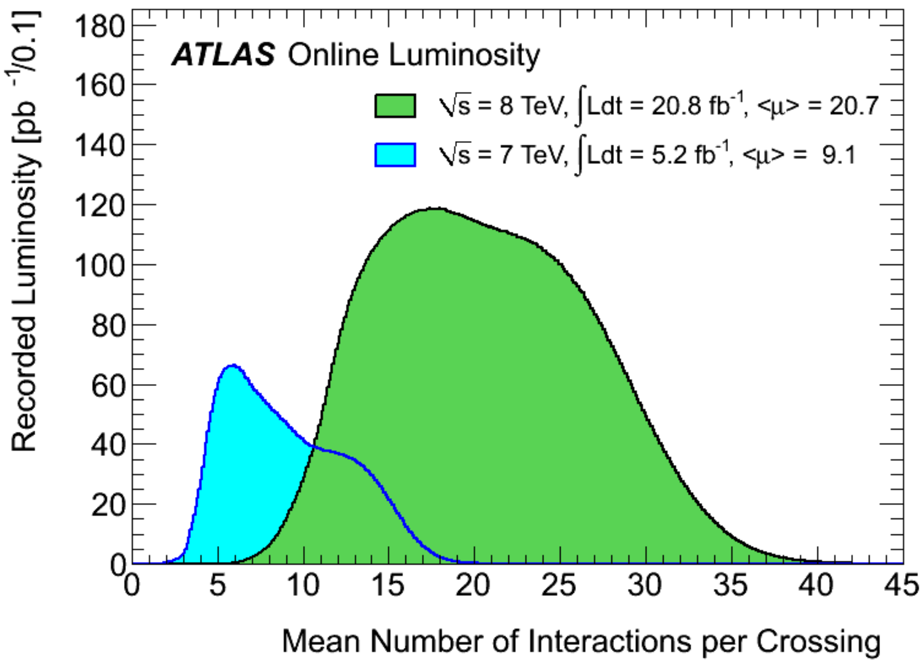
- Would like to know the 4-vector of these partons

Partons hadronize

- Hadronization is non-perturbative QCD phenomenon
  - Phenomenological models implemented in Monte Carlo generators
    - Lund String Model: PYTHIA, SHERPA
    - Cluster fragmentation: HERWIG
- Semileptonic decays of heavy quarks cannot be recovered by experimental technique event by event

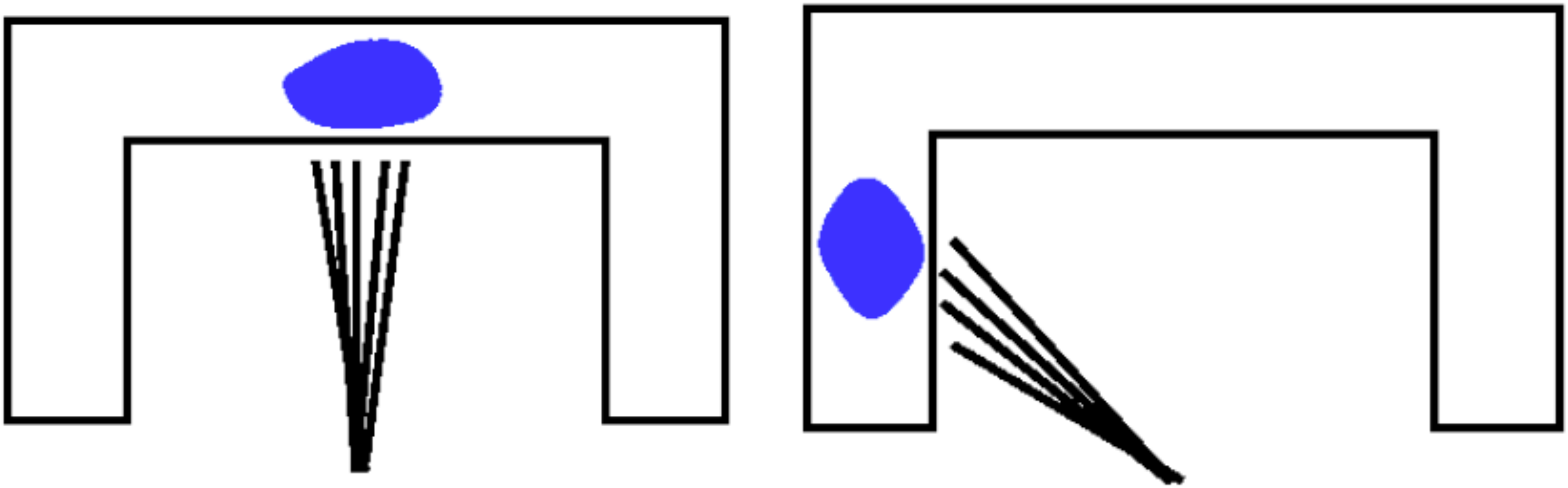
Multiple pp interactions (Pileup)





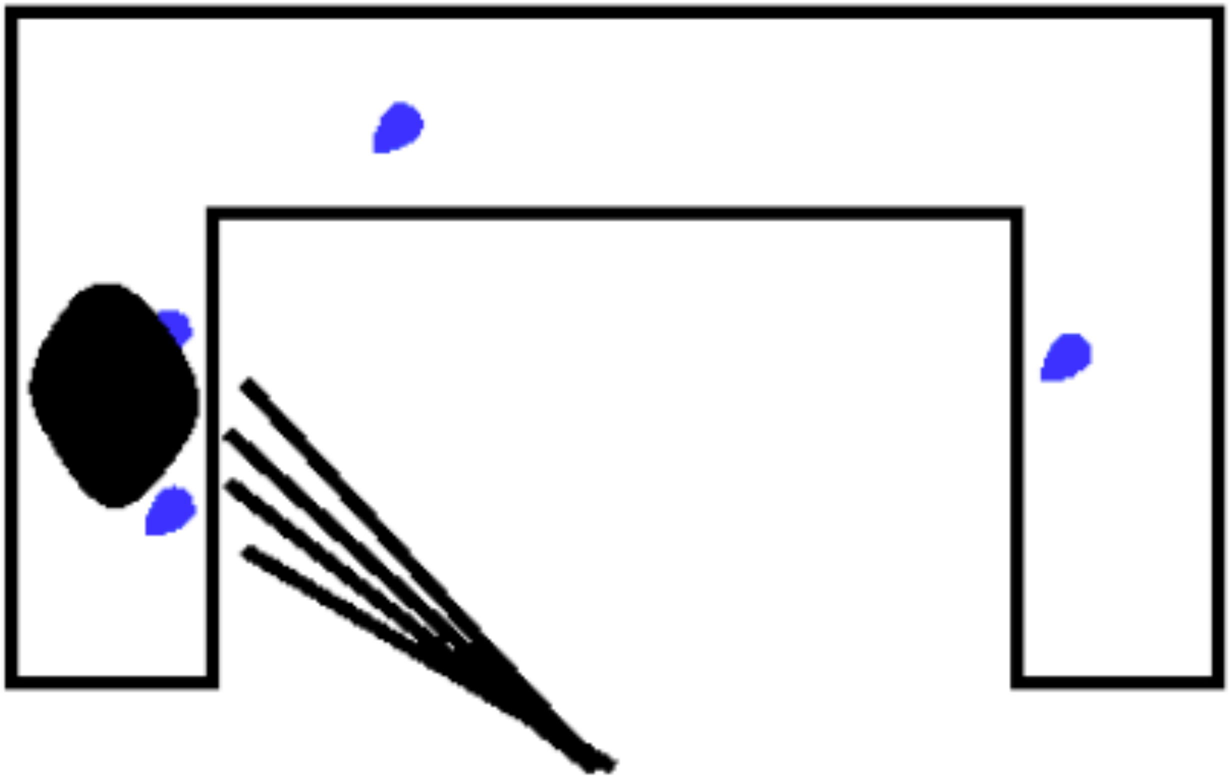
- Particles from additional pp interactions can overlap jet from hard scatter
  - LHC 2012: <μ>=20.7
  - Future LHC: up to ~140 (see tomorrow)
- There is also so-called "out-of-time pileup"
  - ATLAS calorimeter integrates signal from several bunch crossings => see energy from earlier BC's

Hadrons enter Calorimeter



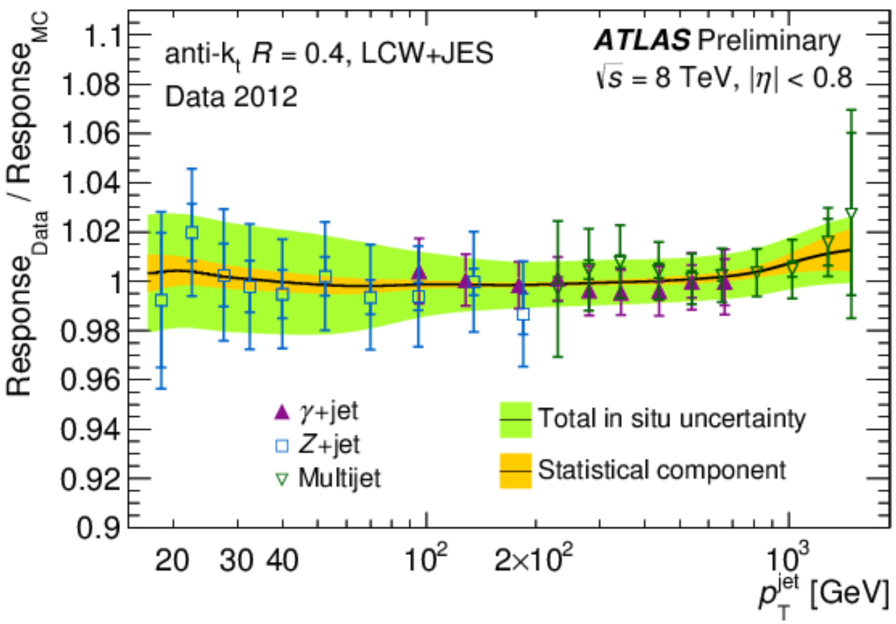
- Calorimeter response to hadrons determines what we measure: typically the resolution is
  - ~1% for pi0's (as they decay to photons)
  - ~10% for charged hadrons (+ significant tail)
- Hadrons can also get stuck before entering calorimeter
- Response may be non-uniform as function of angle
  - There are often "crack" regions with poorer instrumentation

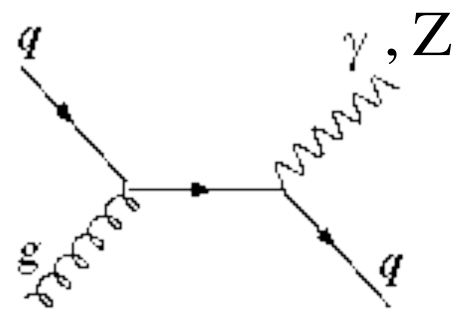
Noise

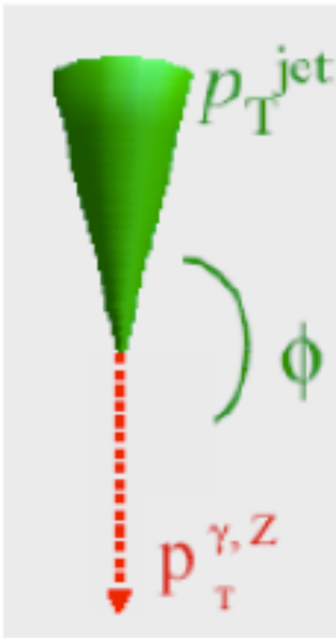


- Noise can overlap the jet in the calorimeter
  - May depend on e.g. instantaneous luminosity
  - Must be subtracted from jet on average

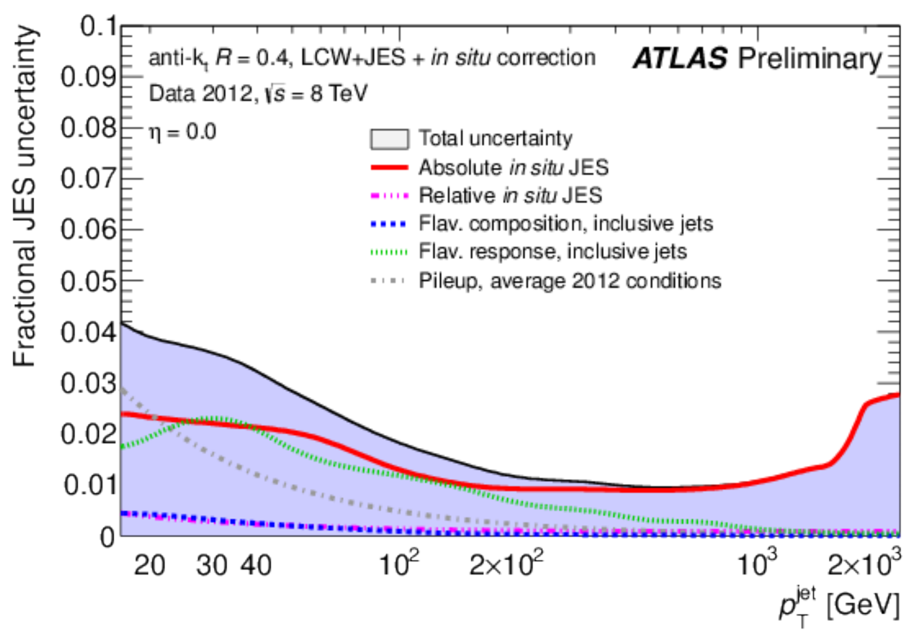
Jet Energy Scale



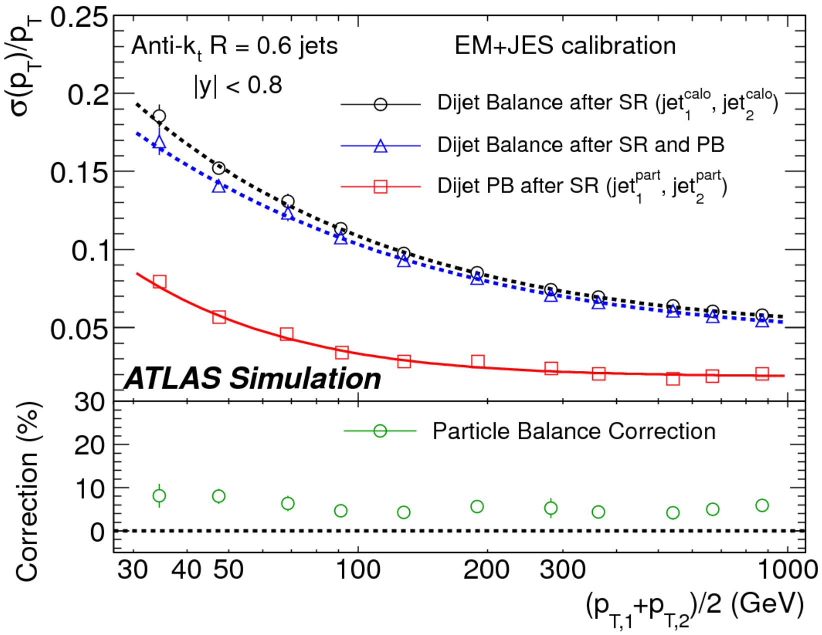


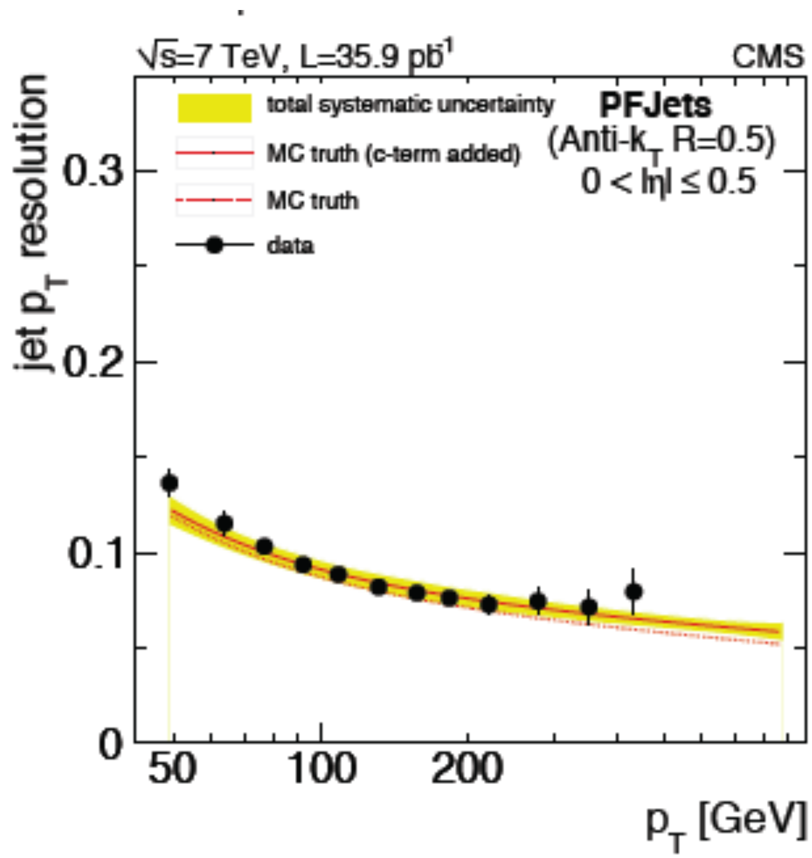


- Jets are calibrated *in situ* with calibration processed:
  - photon+jet, Z+jet, multijet
- Systematic uncertainty due to understanding of
  - calibration procedure
  - Jet flavor composition/response
  - pileup



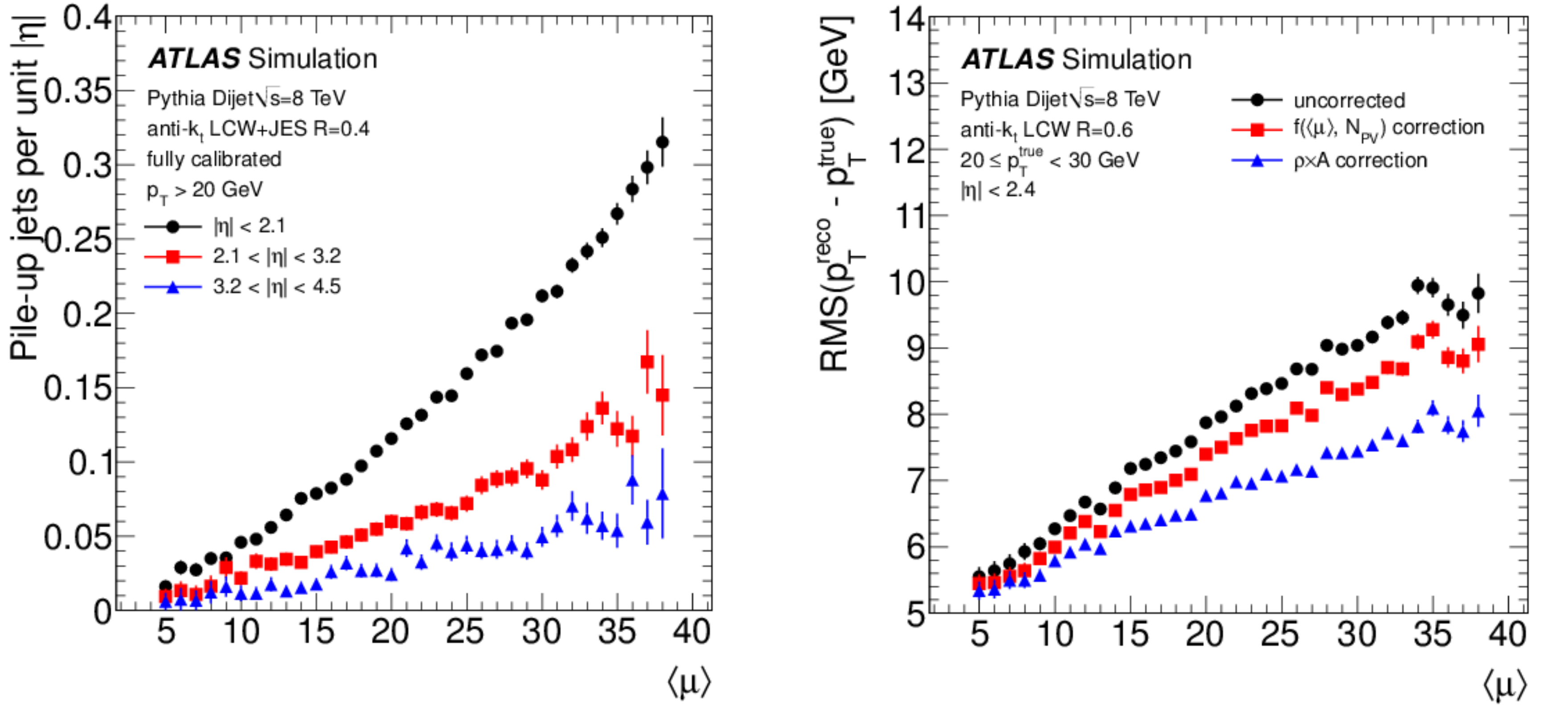
Jet Energy Resolution





- Jet energy resolution
  - p_T=50 GeV: σ~12-15%
  - p_T=200 GeV: σ~8%
- Deteriorates with pileup (see tomorrow's lecture)

Impact of Pileup

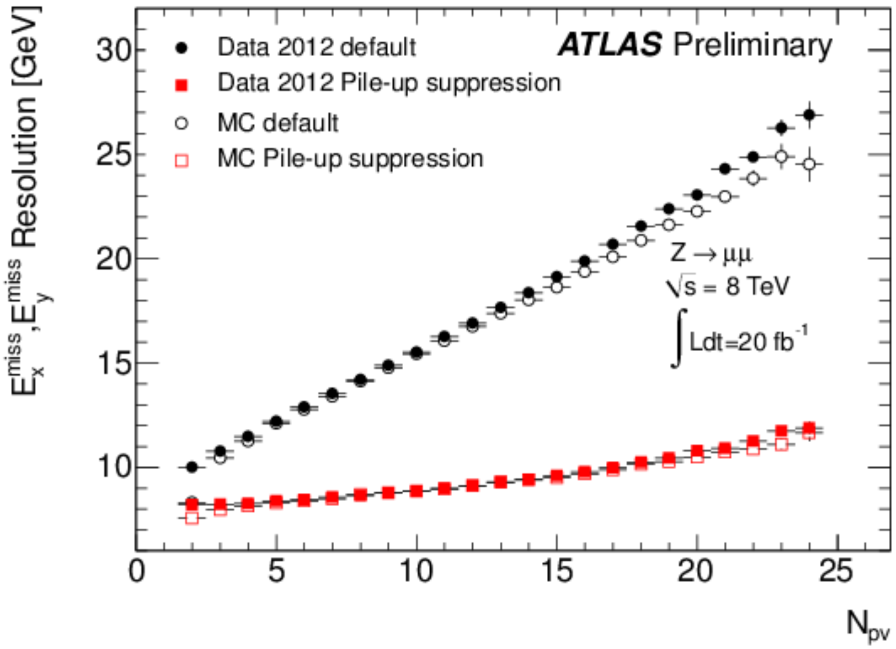


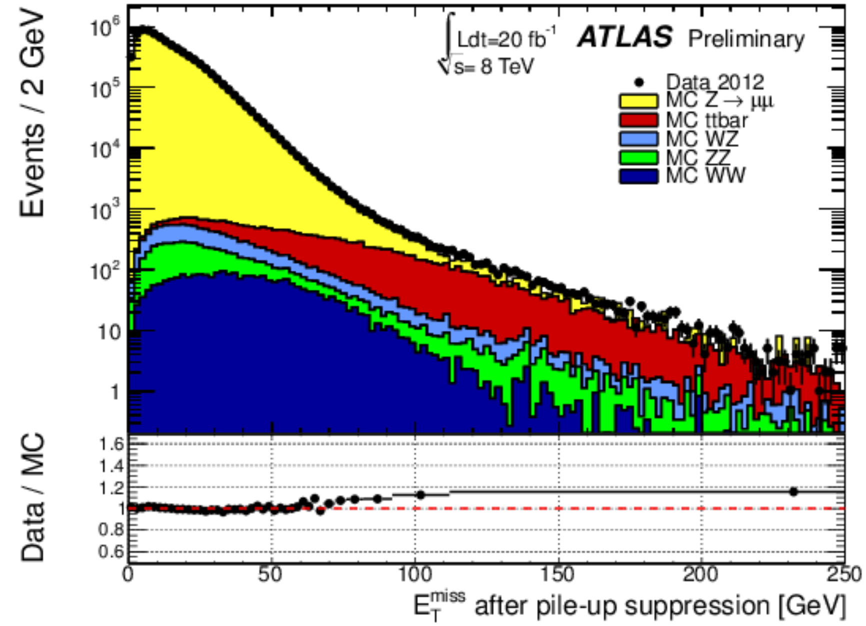
- Pileup can create jets and degrades resolution
- Several correction methods exist
  - All work on average but fluctuations are large
- "Jet Area Correction" by M. Cacciari and G. Salam works best

$$p_T^{jet,corr} = p_T^{jet} - \rho \times A_T^{jet}$$

arXiv:0707.1378

Missing E_T





- Pileup suppression important to retain missing ET resolution
  - Resolution typically 5-10 GeV (for events with no E_T^{miss})
- Long tails can cause up to ~100 GeV of E_T^{miss}

End of Interlude =>
Back to Searches with Jets

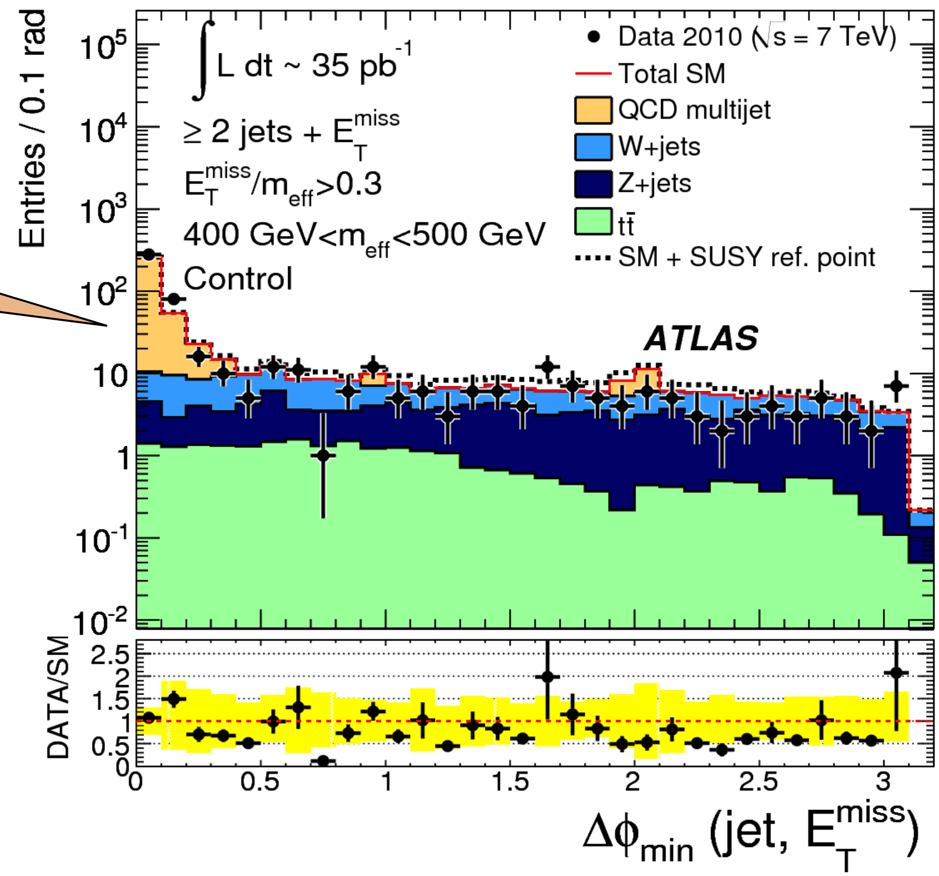
Selection and Procedure

- Selection:
  - Large missing E_T
    - Due to neutralinos
  - Large H_T
    - $H_T = \sum E_T^{jet}$
  - Large $\Delta\phi$
    - Between missing E_T and jets and between jets
    - Suppress QCD dijet background due to jet mismeasurements
  - Veto leptons:
    - Reject W/Z+jets, top

- Procedure:
  1. Define signal cuts based on background and signal MC studies
  2. Select control regions that are sensitive to individual backgrounds
  3. Keep data "blind" in signal region until data in control regions are understood
  4. Open the blind box!

QCD Dijet Rejection Cut

QCD multijet background

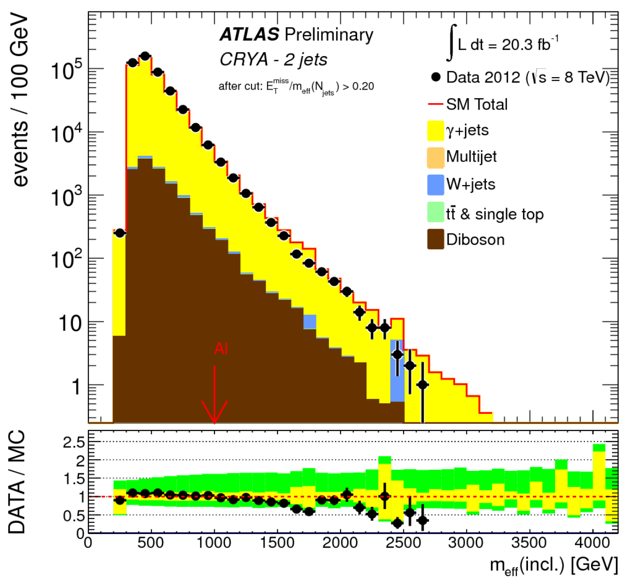


- Cut on $\Delta\phi$(jet, E_T^{miss})
- Used to suppress and to understand and reject QCD multi-jet background

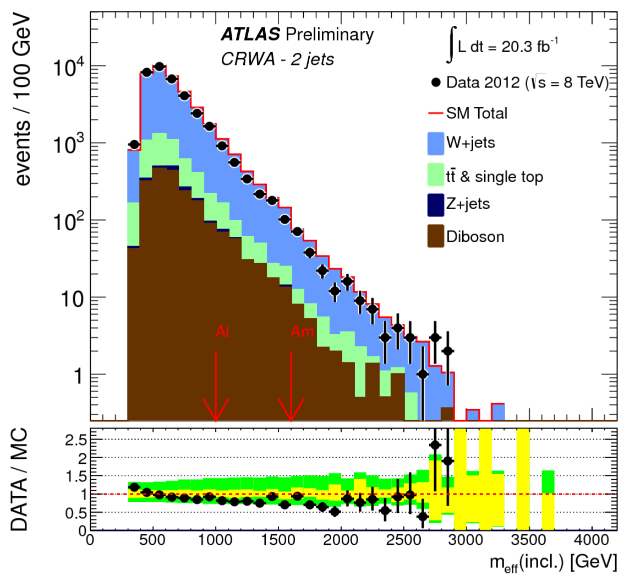
Control Regions to check backgrounds

CR	SR background	CR process	CR selection
CRY	$Z(\to \nu\nu)$+jets	γ+jets	Isolated photon
CRQ	multi-jets	multi-jets	Reversed $\Delta\phi(\text{jet}, E_T^{\text{miss}})_{\text{min}}$ and $E_T^{\text{miss}}/m_{\text{eff}}(Nj)$ requirements[a]
CRW	$W(\to \ell\nu)$+jets	$W(\to \ell\nu)$+jets	$30\text{ GeV} < m_T(\ell, E_T^{\text{miss}}) < 100\text{ GeV}$, b-veto
CRT	$t\bar{t}$ and single-t	$t\bar{t} \to bbqq'\ell\nu$	$30\text{ GeV} < m_T(\ell, E_T^{\text{miss}}) < 100\text{ GeV}$, b-tag

γ+jets



W+jets



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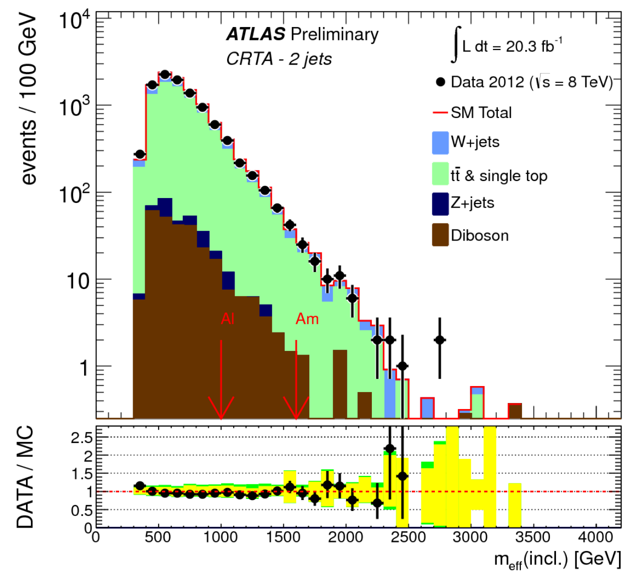


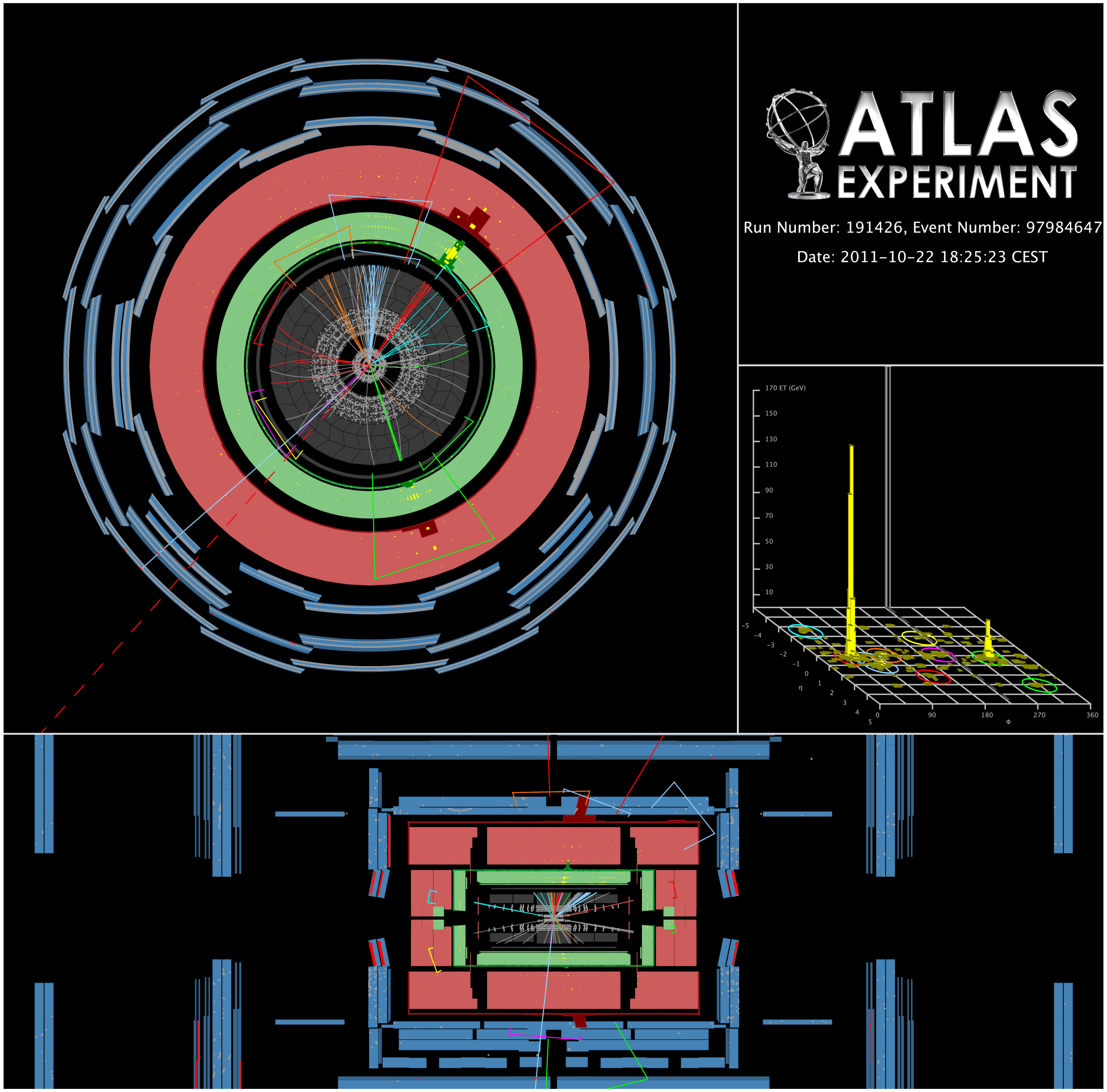
- Adjust background normalization if disagreement observed
- Next: look at the signal region!

A Nice Candidate Event!

4 jets: p_T=974, 276, 146 and 61 GeV

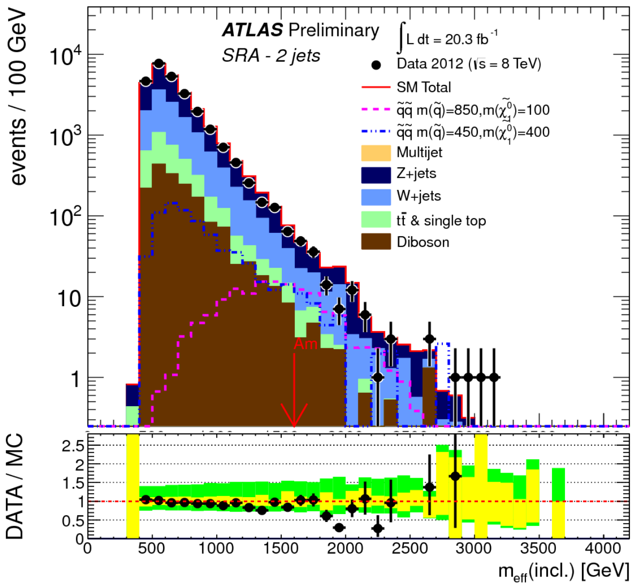
E_T^{miss}=984 GeV

M_{eff}=2441 GeV

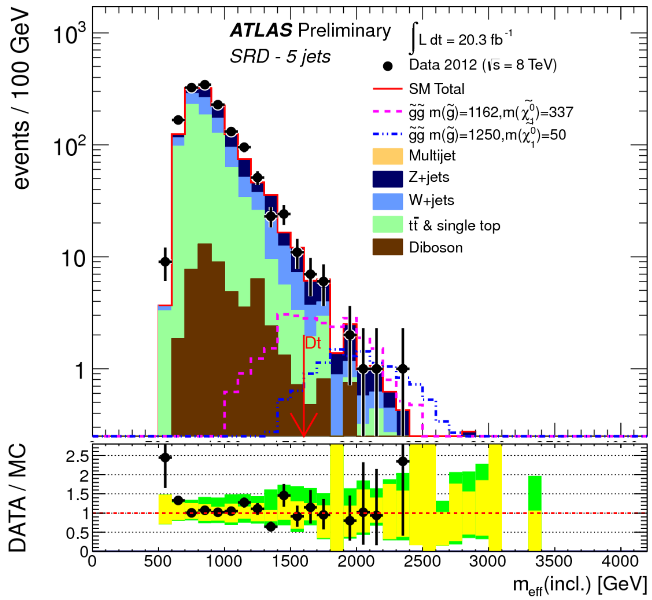


Data in the Signal Regions

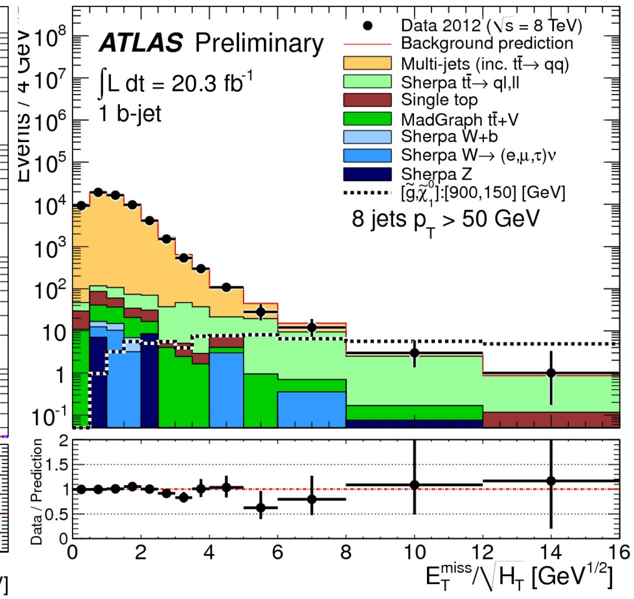
2 jets + E_T^{miss}



5 jets + E_T^{miss}



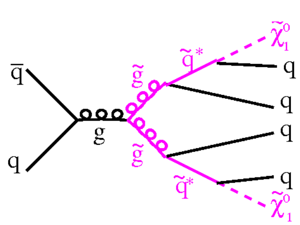
8 jets + E_T^{miss}

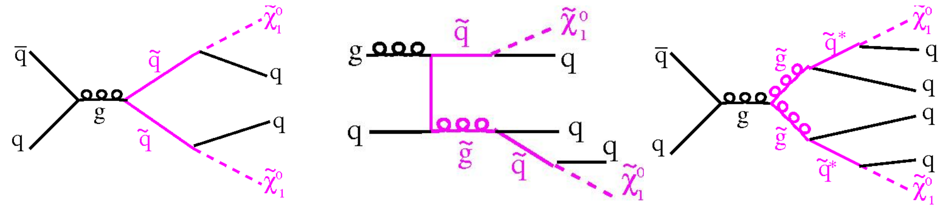


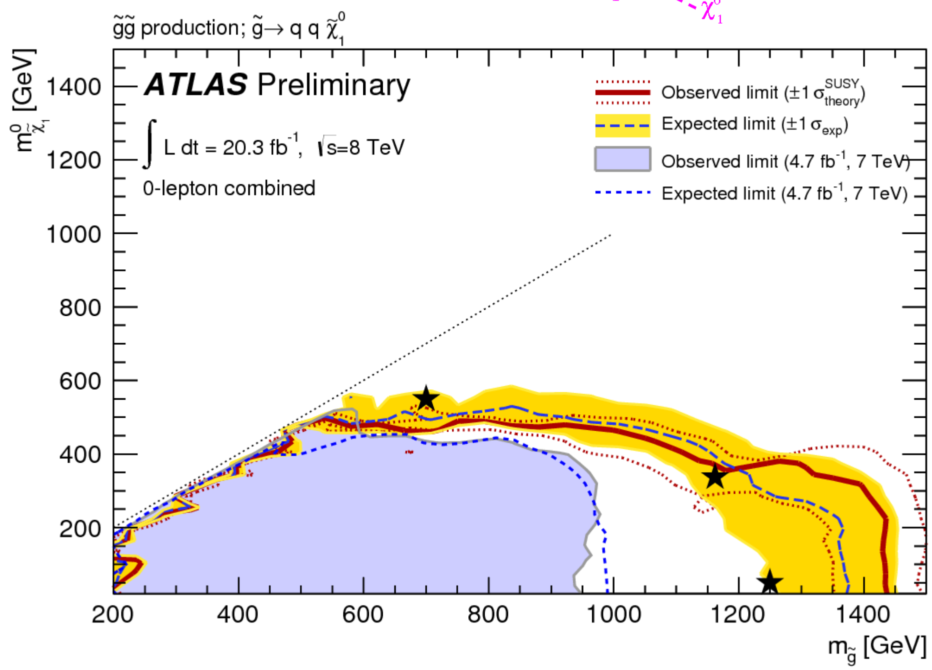
- Many signal regions defined and looked at
- No significant excess observed yet
- Set limits in benchmark models

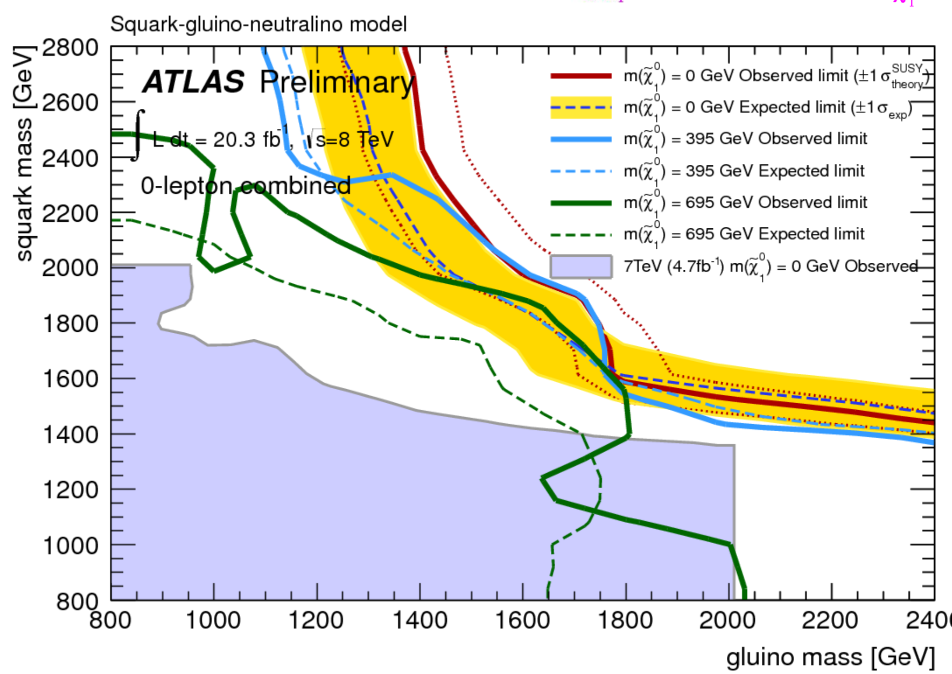
Constraints on Simplified Model

$m(\tilde{q})>m(\tilde{g})$



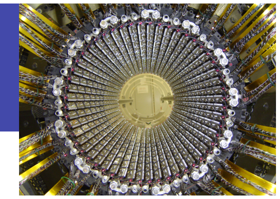




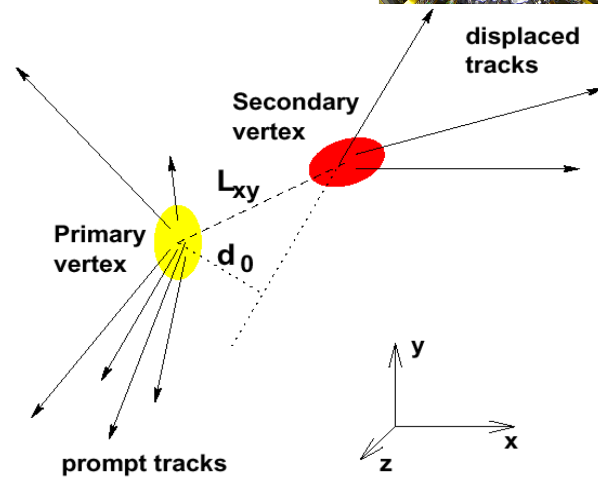


- Limits exclude gluinos up to 1.4 TeV for LSP masses < 300 GeV
- Limits much weaker for larger LSP masses

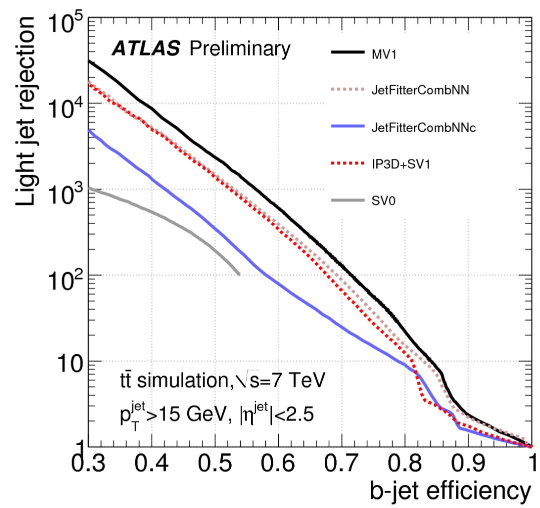
Finding the b-jets

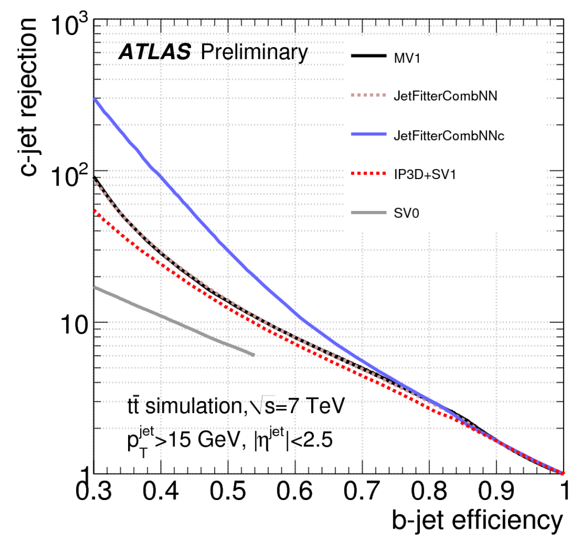


- Exploit large lifetime of the b-hadron
  - B-hadron flies before it decays: d=cτ
    - Lifetime τ =1.5 ps^{-1}
    - d=cτ = 460 μm
    - Can be resolved with silicon detector resolution



- Combined with other properties in an neural network (or other similar algorithm)



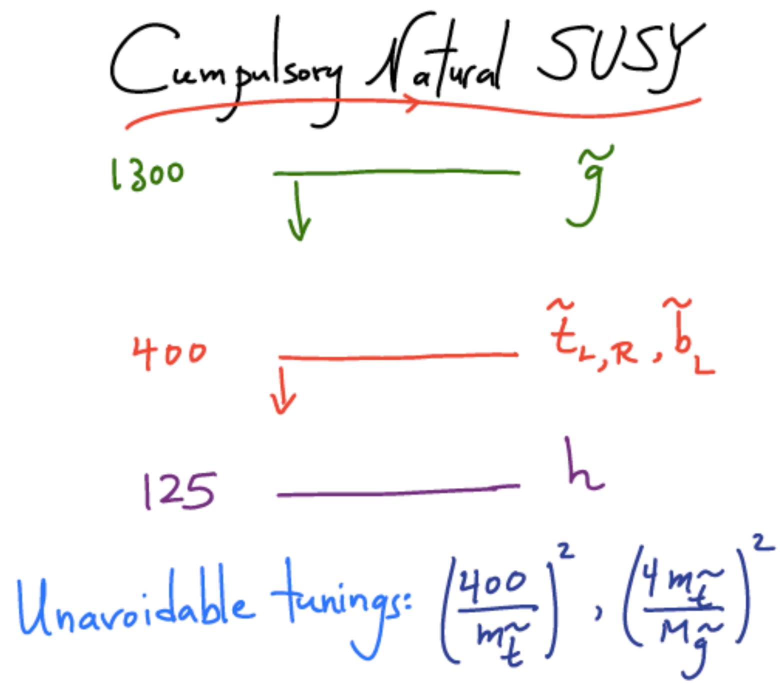


- Typical performance:
  - Efficiency=70%
  - "Light jet rejection": 140
    - Means that 1% of light jets are tagged as b-jets by algorithm
  - Charm jet rejection: 5

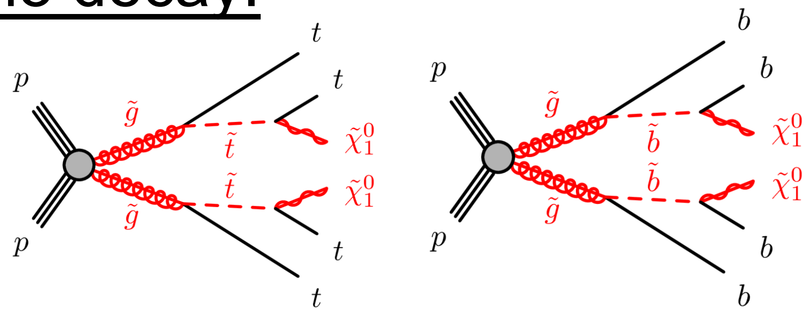
Searches with b-jets

- Strong theoretical motivation for searches with b-jets from naturalness arguments
  - Sbottom and stop should be “light”
  - Both decay via b-jets!

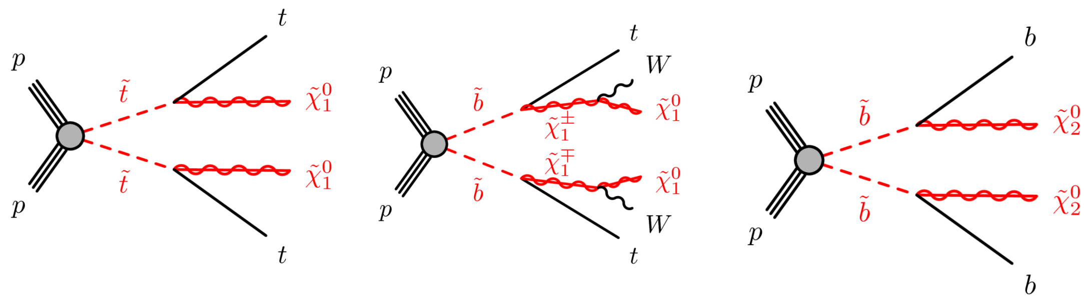
N. Arkani-Hamed



Gluino decay:

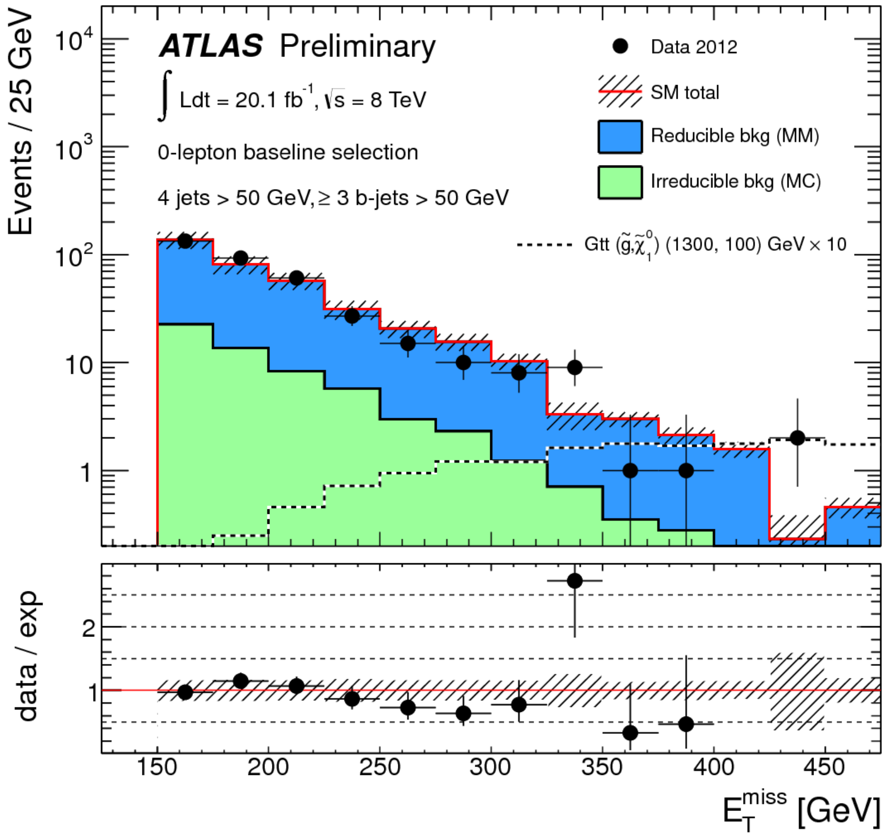


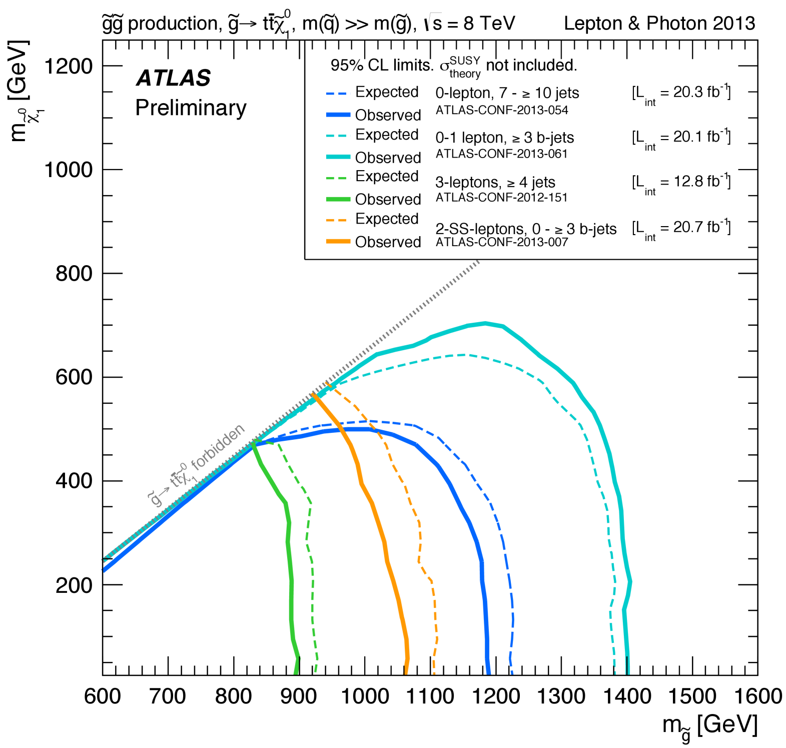
Direct pair production:



3 b-jets + missing ET

- Several signal regions with varying number of jets and 0 or 1 lepton
- Main background: top
- Sensitive to gluinos decaying via top or b quarks





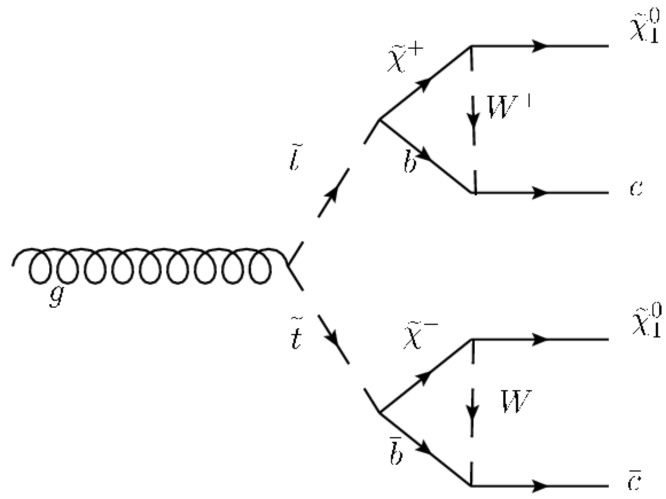
Excludes gluino mass <1.4 TeV for LSP mass < 500 GeV

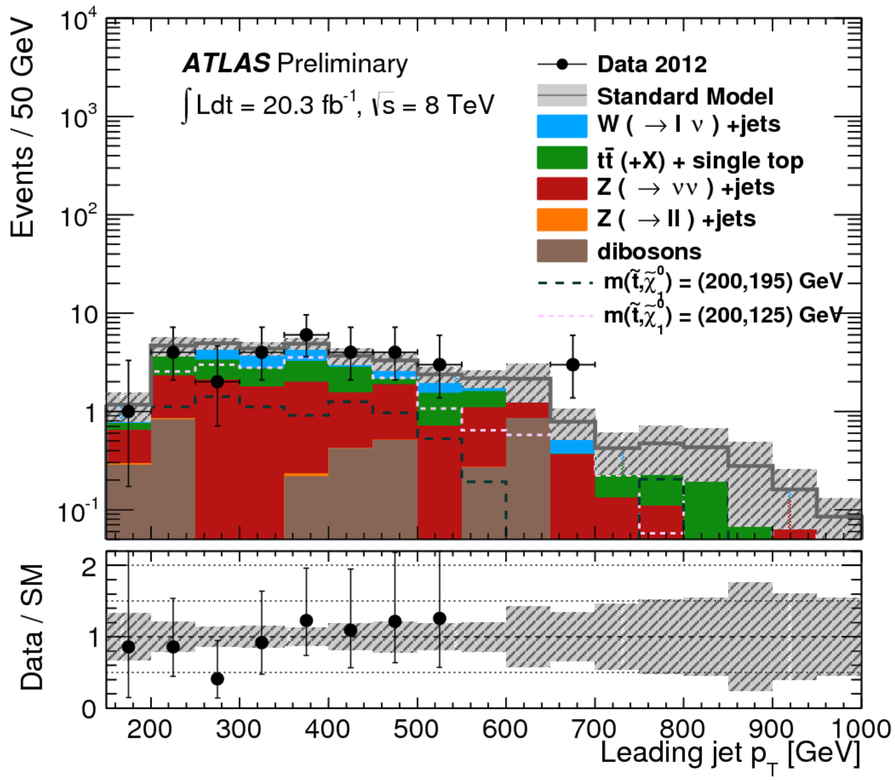
What about charm jets?

- Much harder to identify as they have shorter lifetime than b's
  - Contaminated both by light and by b backgrounds
  - Efficiency for charm: 20%
  - Rejection: factor 5 for b's, factor 140 for light
- Could be important though
  - E.g. stop could decay to charm + LSP
    - If other decays not open

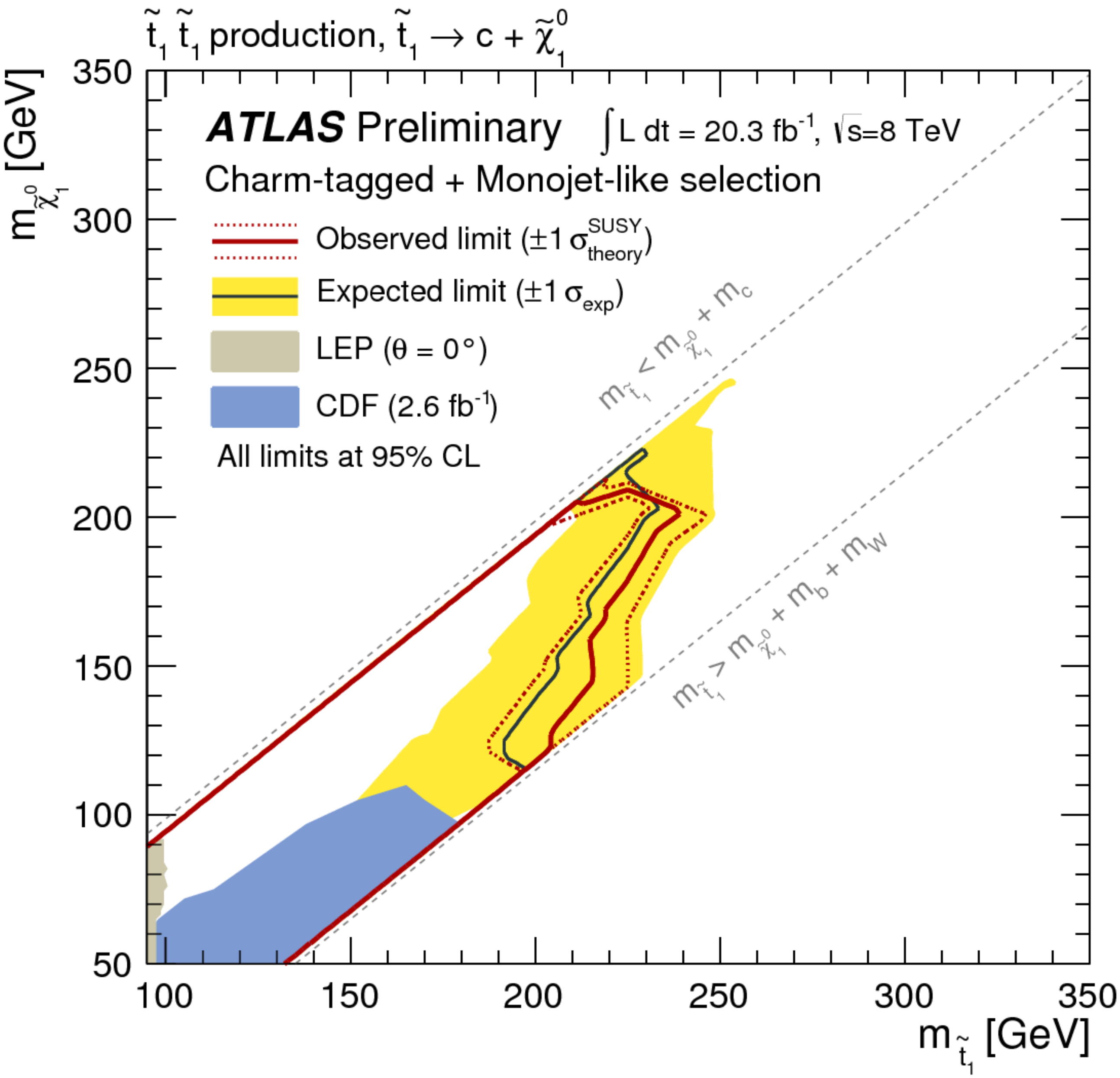
Stop search with monojet+charm

- Signature contains 2 charm jets
  - Both are quite soft and not hard enough to trigger
- Require a hard jet from ISR for trigger
  - E_T^{miss}>150 GeV
  - p_T(lead jet)>120 GeV
  - At most 3 more jets with p_T>30 GeV
    - Various tagging requirements to reject b's and select c's
  - Several signal regions

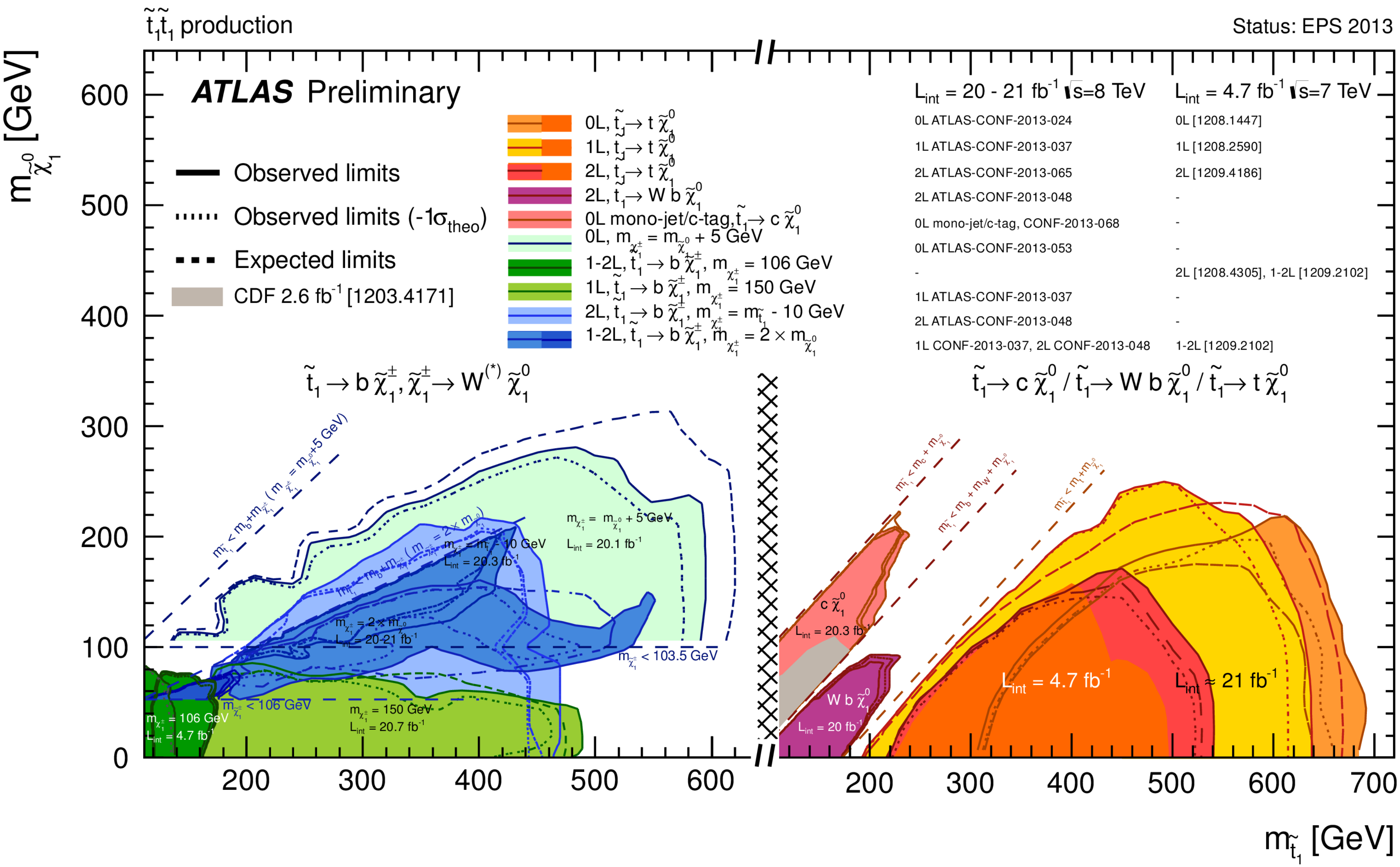




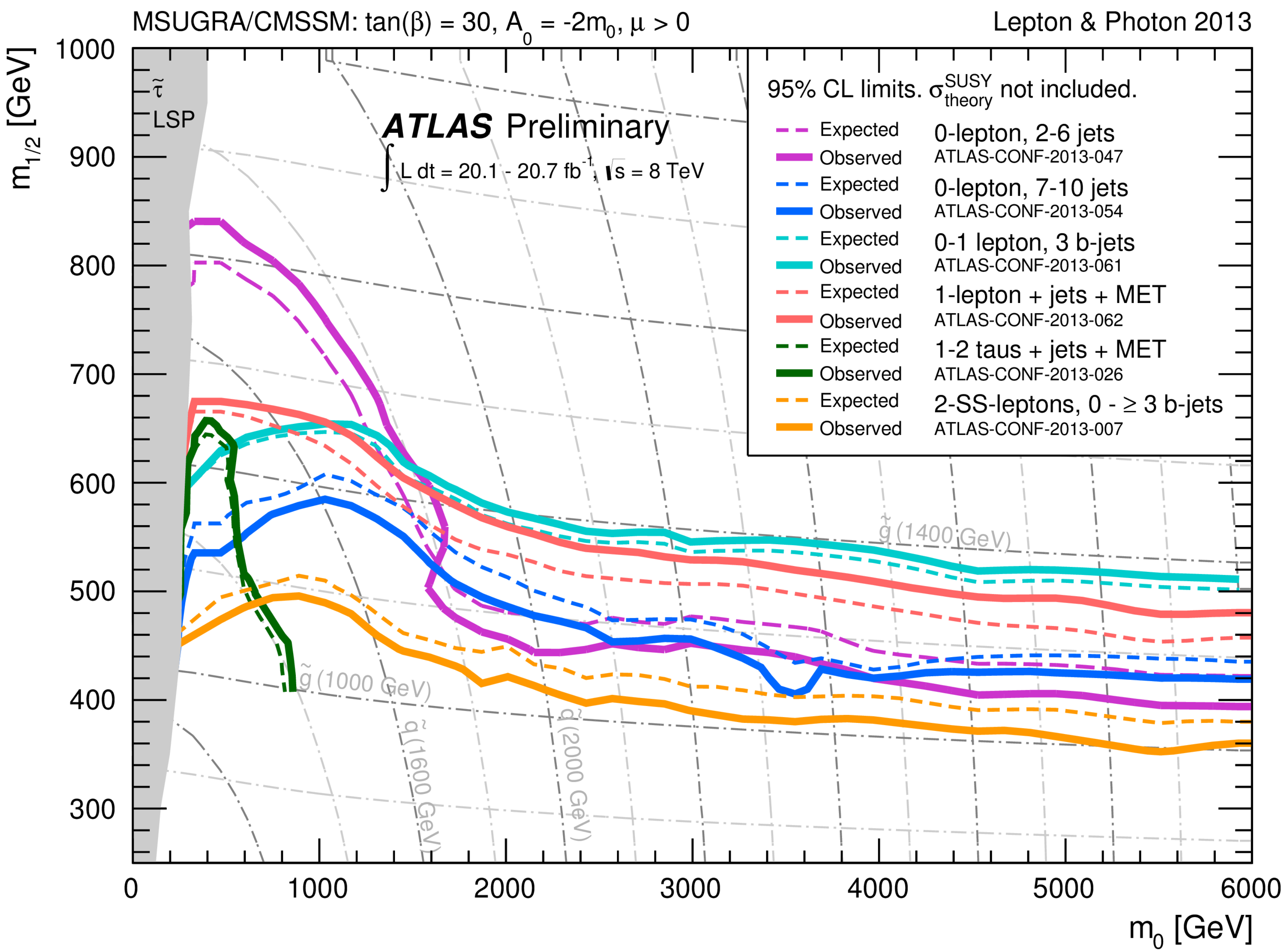
Constraints on stop -> c+LSP



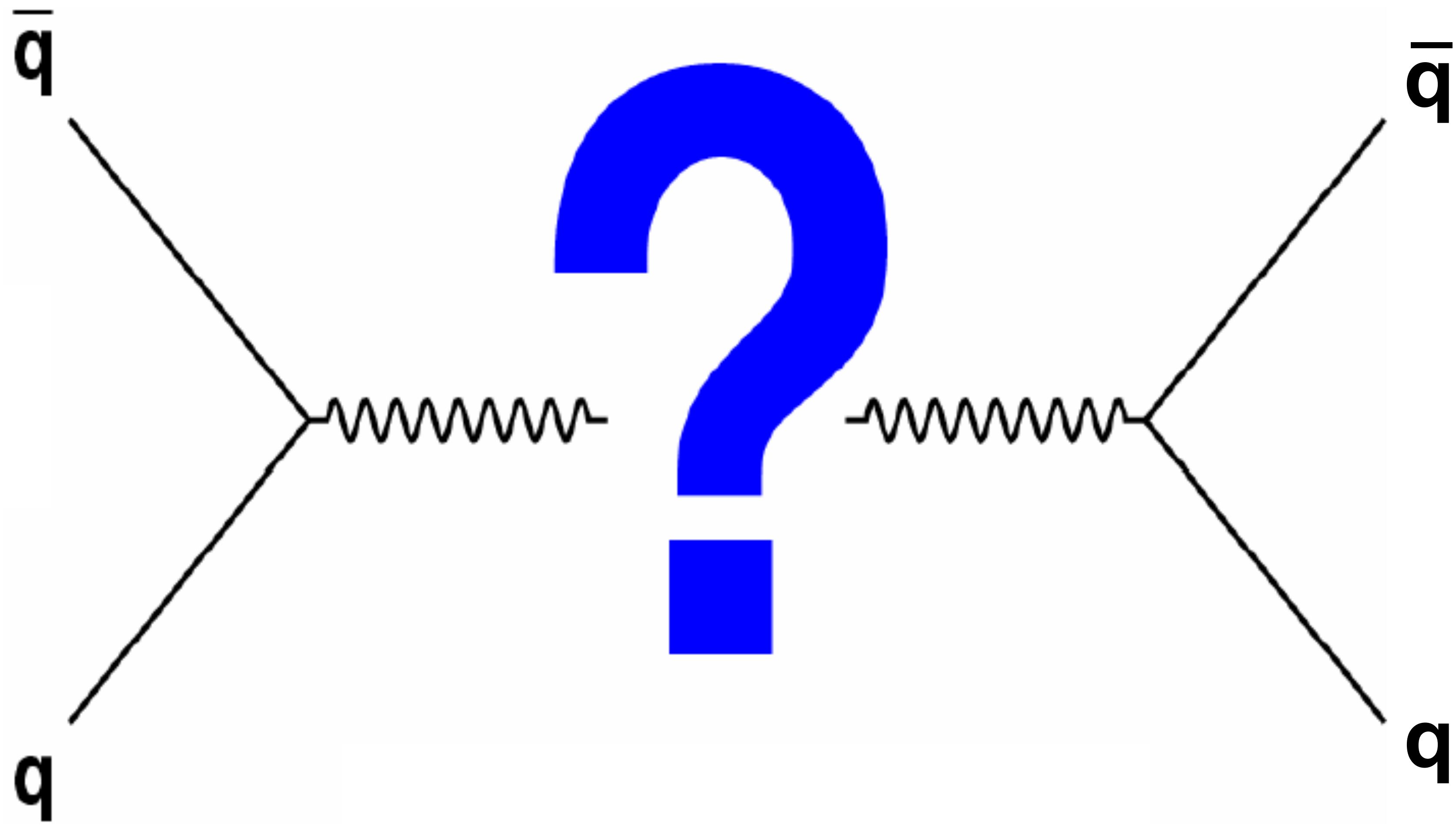
All stop constraints



mSUGRA Constraints

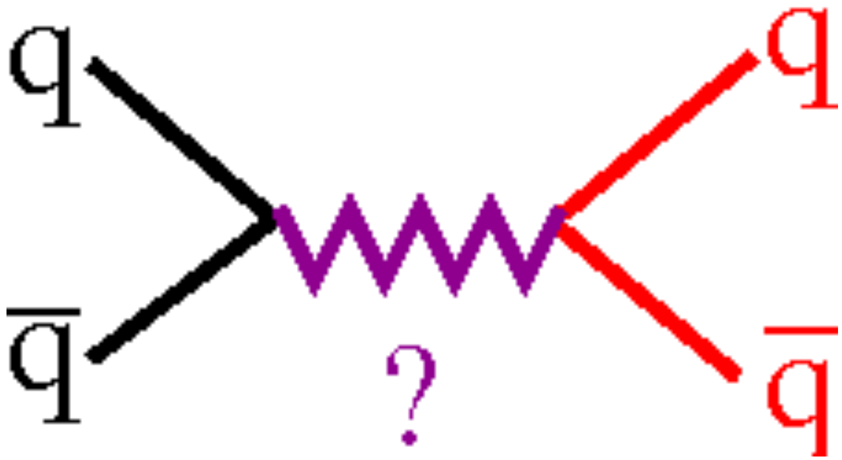


High Mass Resonances

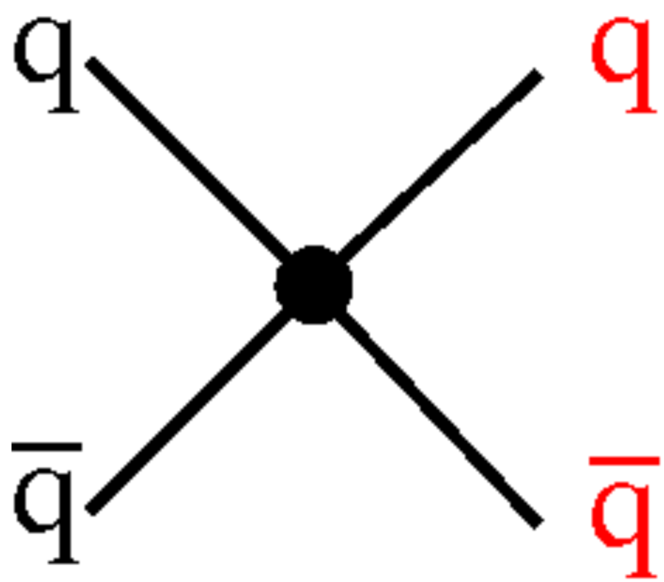


Resonances or Tails

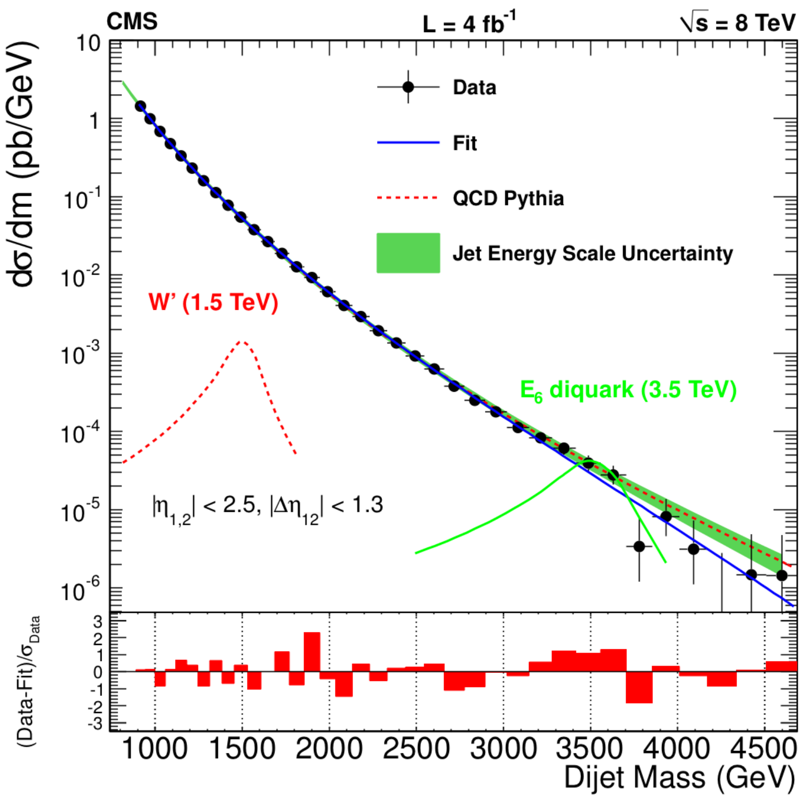
- New resonant structure:
  - X →jj,bb,tt,tb
  - *E.g.*
    - *excited quark*
    - *Randall Sundrum KK gluon*
    - *Z' or W'*
    - *charged or neutral Higgs*
    - *.....*

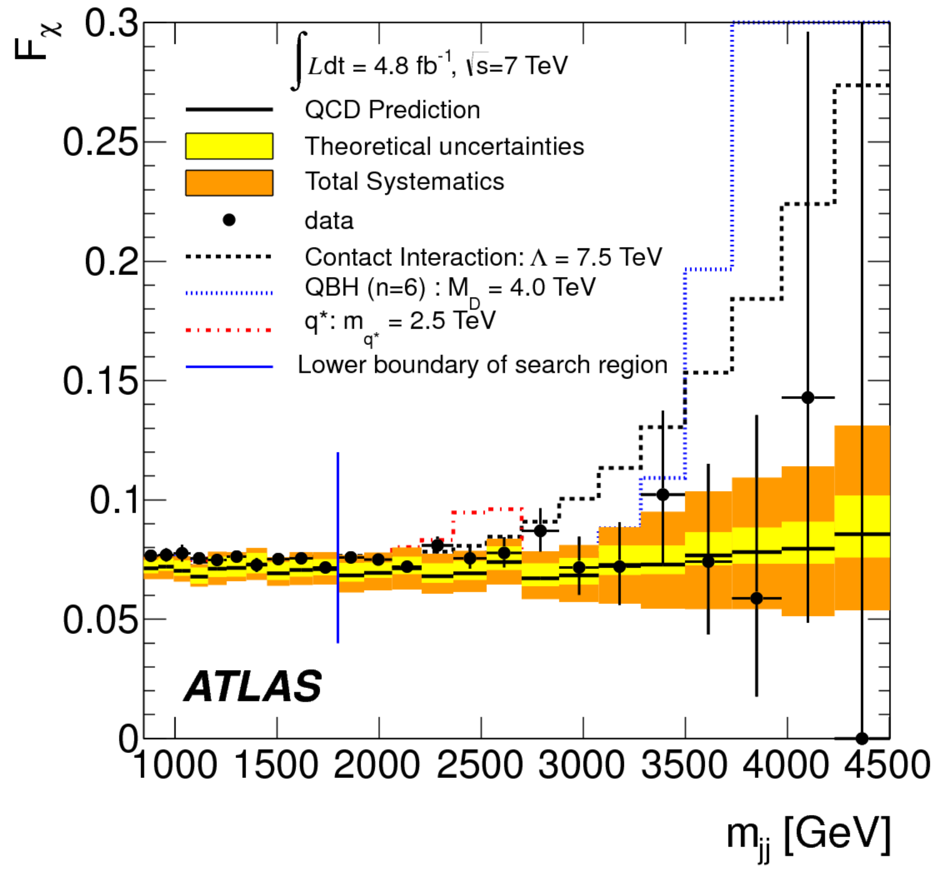


- Hard tail:
  - Quantum black hole
  - Contact interaction
    - Effective 4-point vertex like Fermi's β-decay
      - E.g. via t-channel exchange of very heavy particle



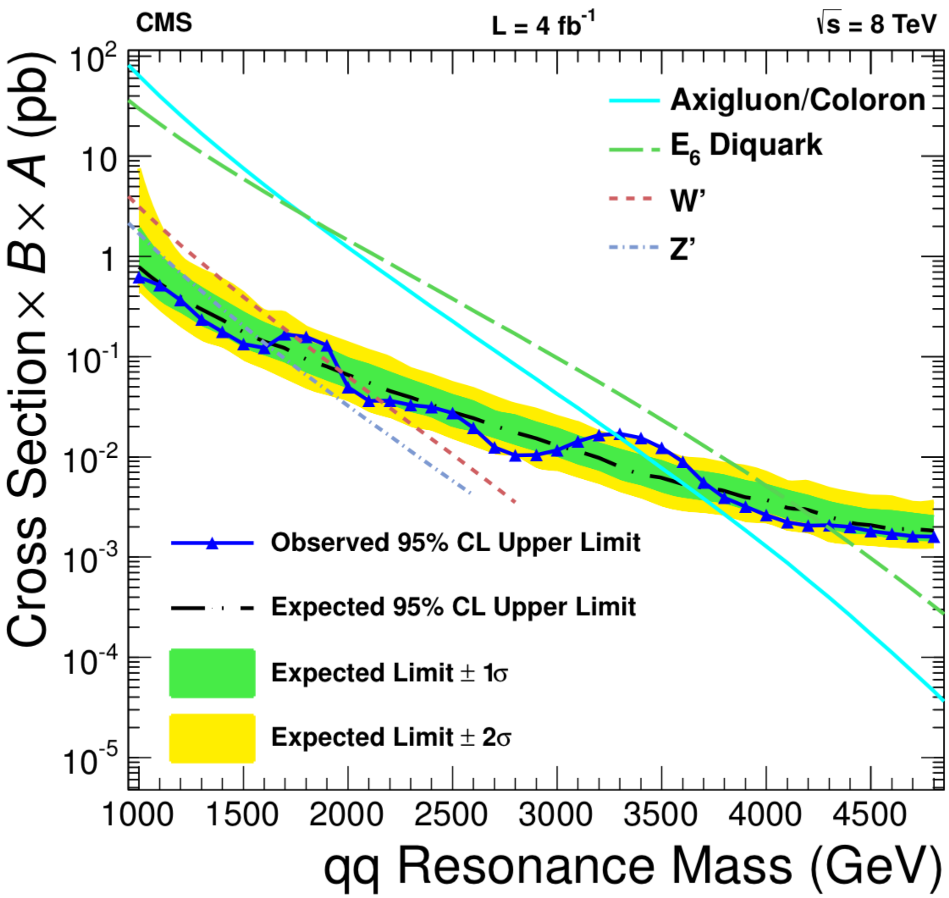
Dijet Resonance Searches

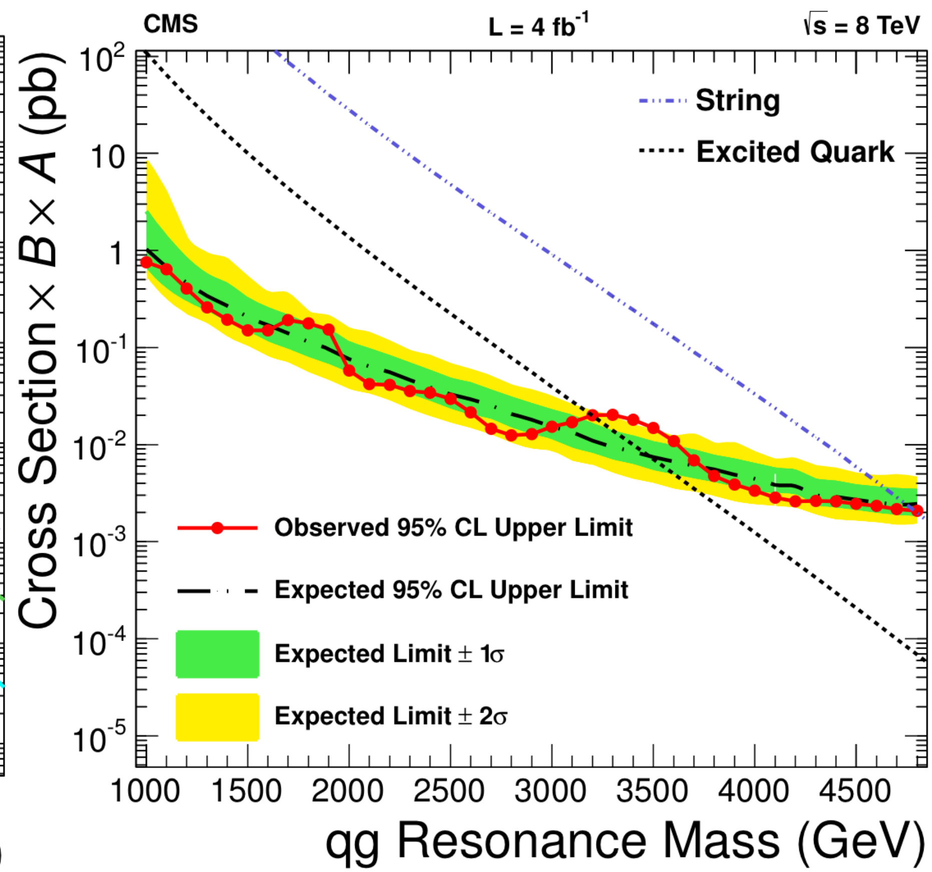




- Dijet resonance search extends to masses up to 4.5 TeV
- Define variable: $$F_\chi(m_{jj}) \equiv \frac{\mathrm{d}N_{\mathrm{central}}/\mathrm{d}m_{jj}}{\mathrm{d}N_{\mathrm{total}}/\mathrm{d}m_{jj}}$$
  - Reduces sensitivity to systematic uncertainties

Limits on qq and qg resonances

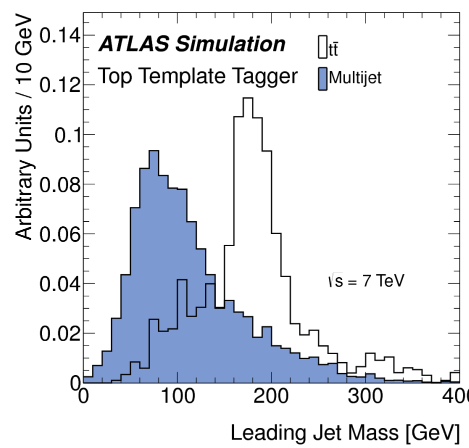


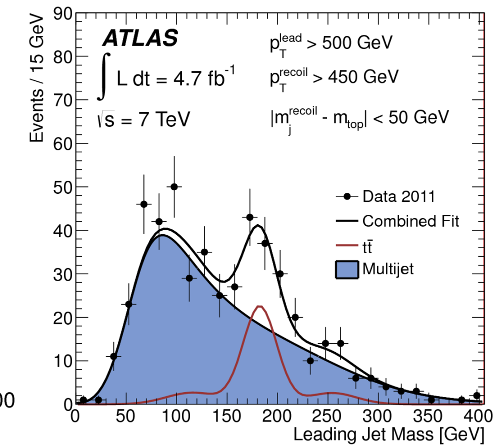


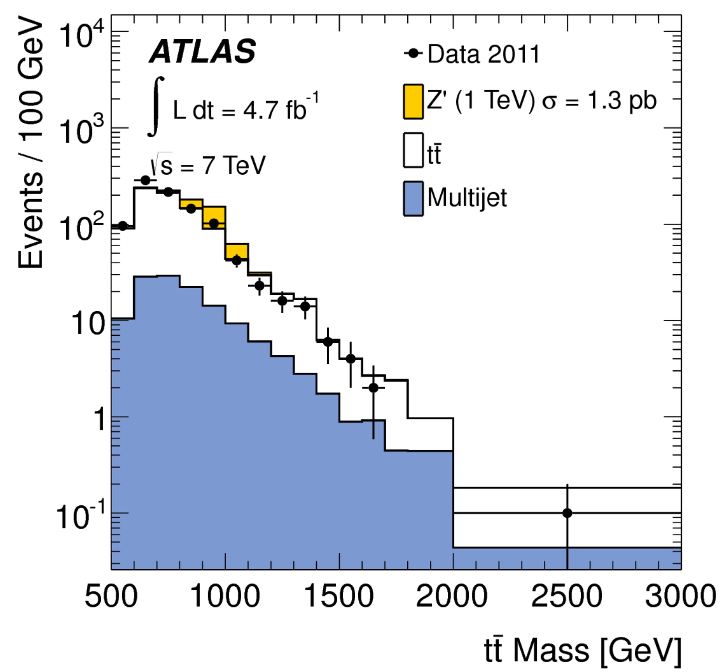
- Probe cross section of 10-100 fb
- No resonance structures seen

$t\bar{t}$ resonance search

- If $m_X >> m_{top}$ the top quarks will be highly boosted
  - E.g. for m=2 TeV ~70% of top quarks are not resolved as three separate jets
  - Requires special techniques to reconstruct them
- Use “Fat jets” and analyze their substructure
  - much innovation from theorists in this area!
    - Trimming, Nsubjettiness,…
    - HepTopTagger (Plehn *et al.*)
    - TopTemplateTagger (Perez *et al.*)
    - …

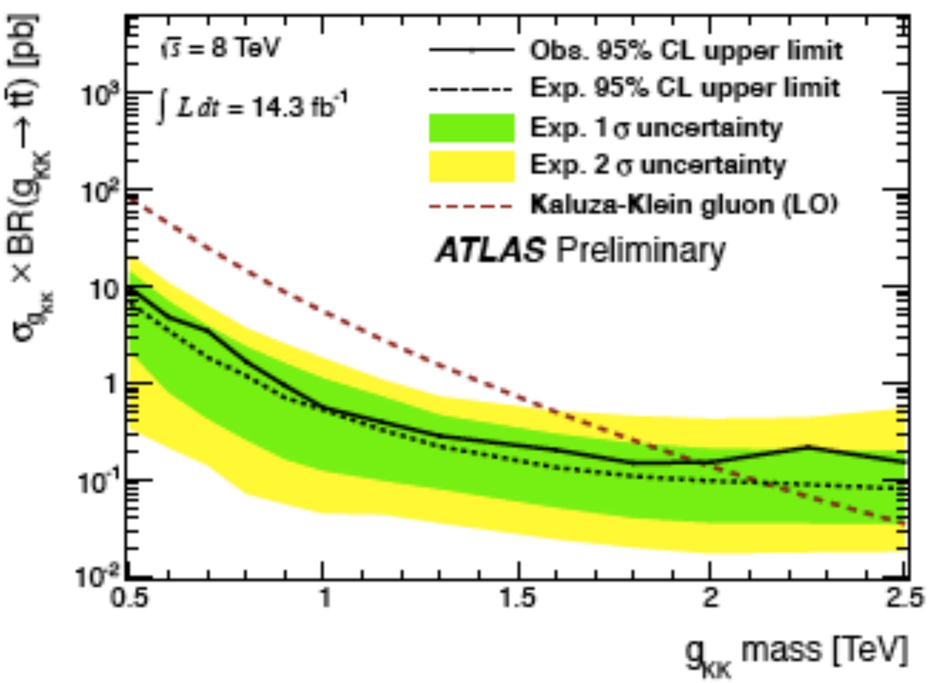


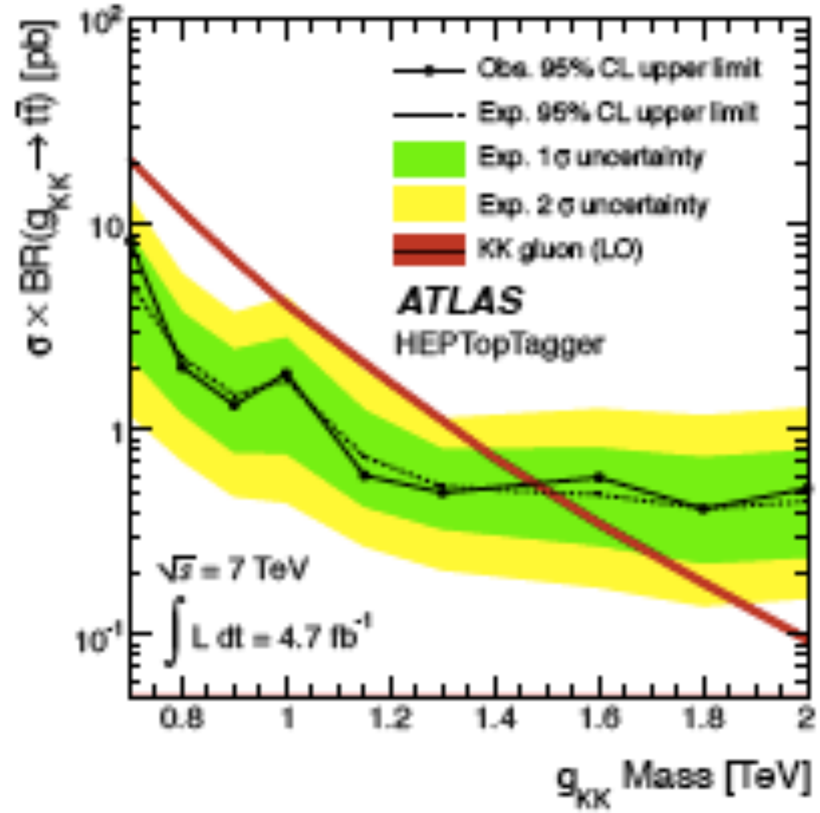




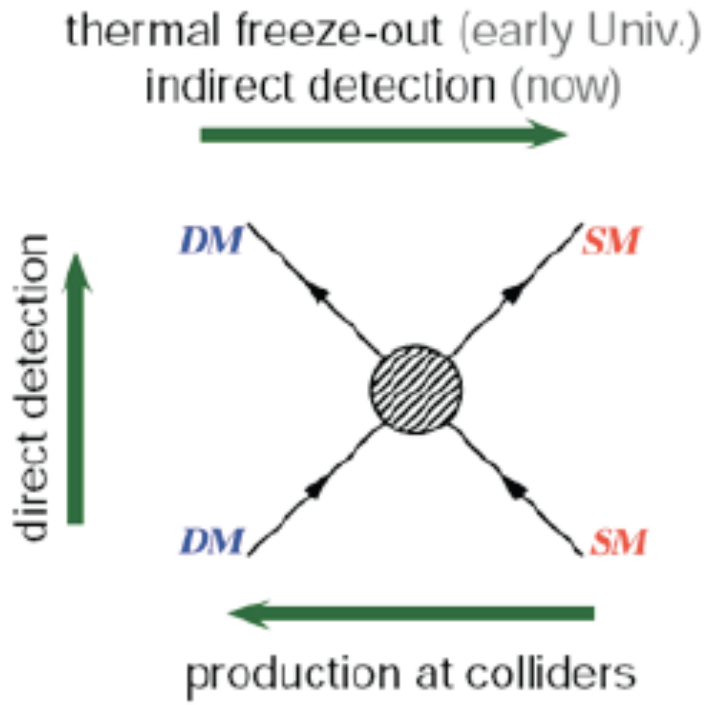
tt̄ resonance search results

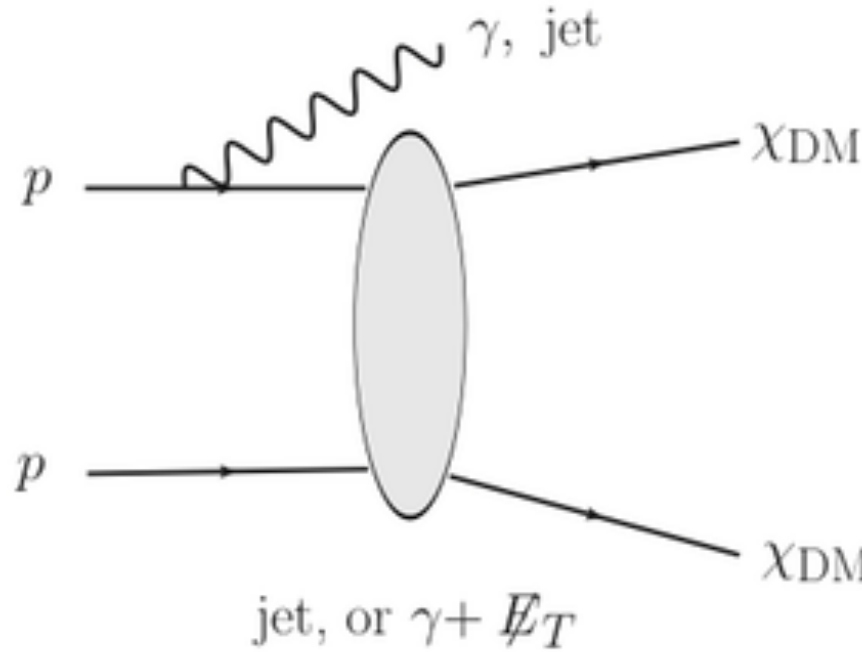
- Searches in both all-hadronic and semileptonic tt decay signatures
- Cross section limits approaching 0.1 pb at high mass





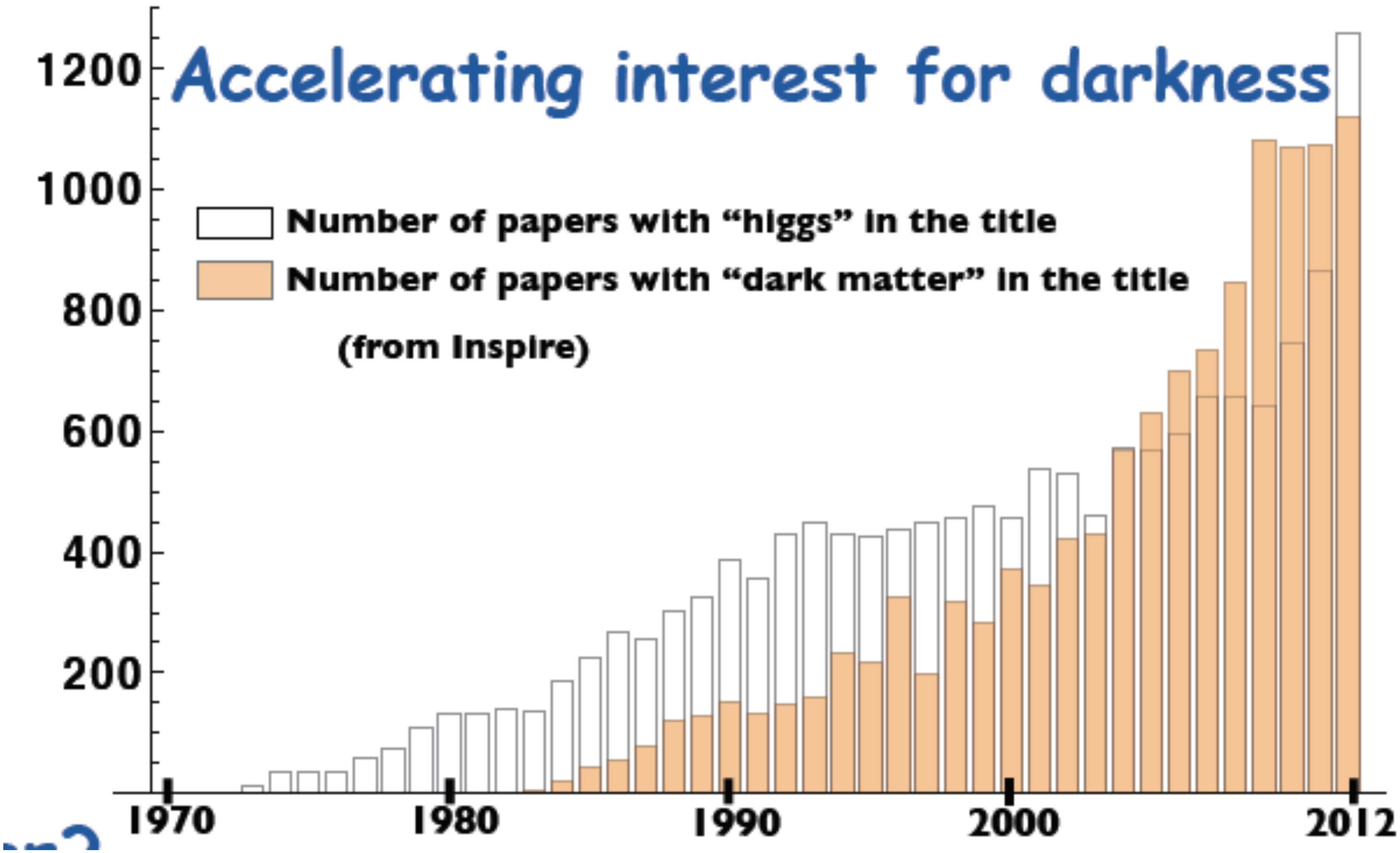
Monojets and Dark Matter





- Dark matter pair production at LHC possible via tagging of ISR jet or photon
- Complements program of direct and indirect detection experiments

Dark Matter Interest



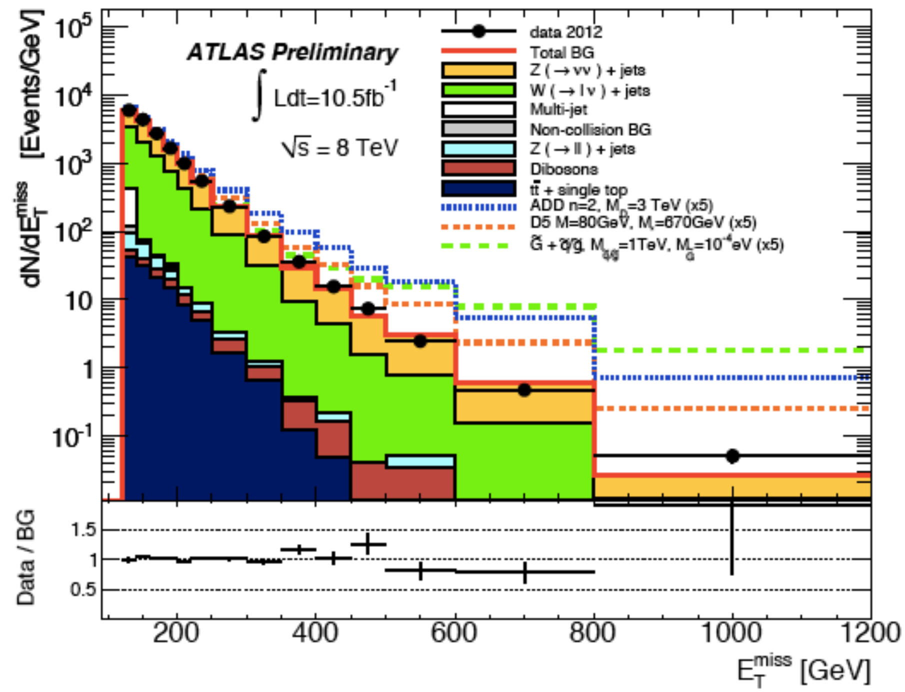
Géraldine Servant, EPS 2013

Monojet Analysis

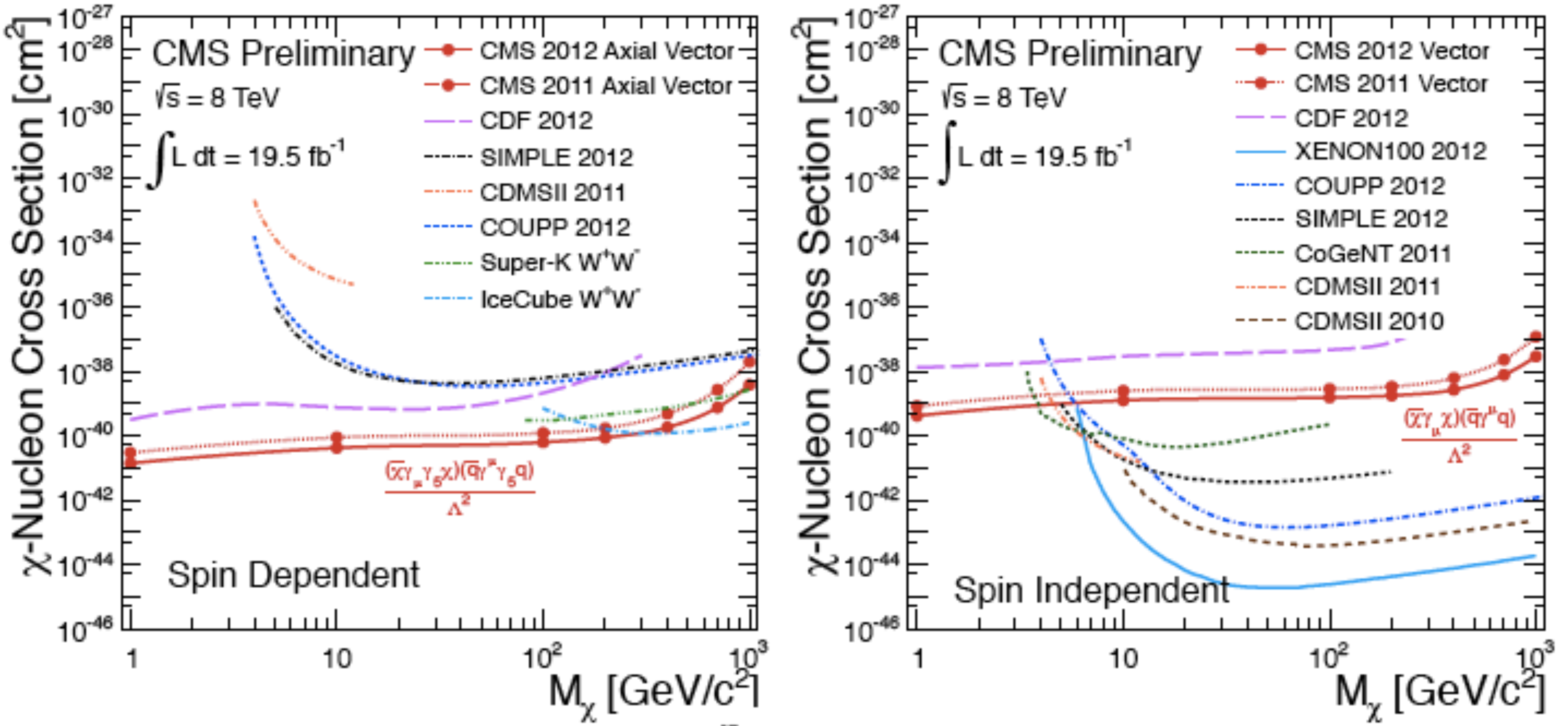
Event Selection

$E_T^{miss} > 120$ GeV
Jet cleanup requirements
Leading jet with $p_T > 120$ GeV and $|\eta| < 2.0$
At most two jets with $p_T > 30$ GeV and $|\eta| < 4.5$
$\Delta\phi(\text{jet}, E_T^{miss}) > 0.5$ (second-leading jet)
Lepton vetoes
+ several signal regions for various E_T^{miss} and jet p_T cuts

- Main backgrounds
  - Z->vv
  - W->lv where l=τ



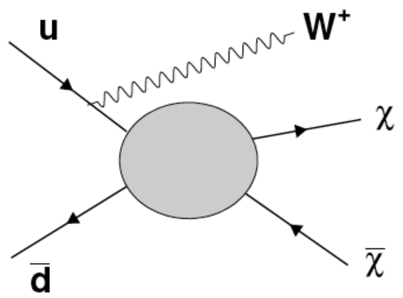
Results

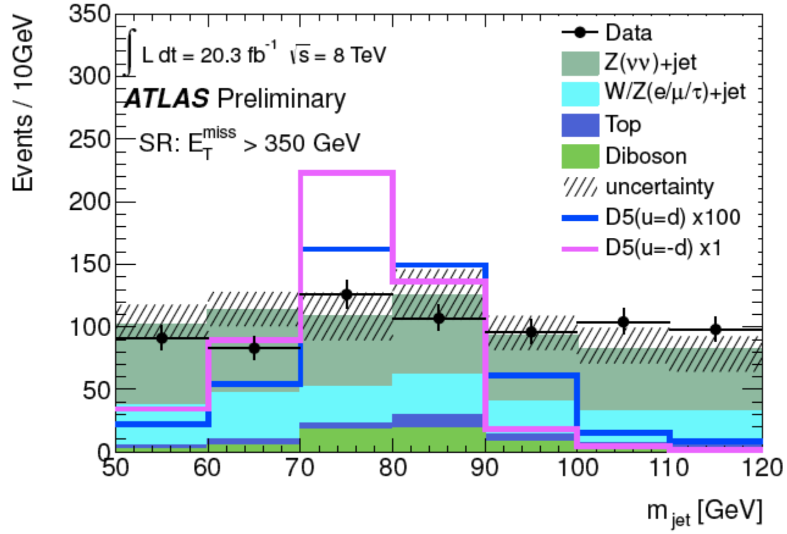


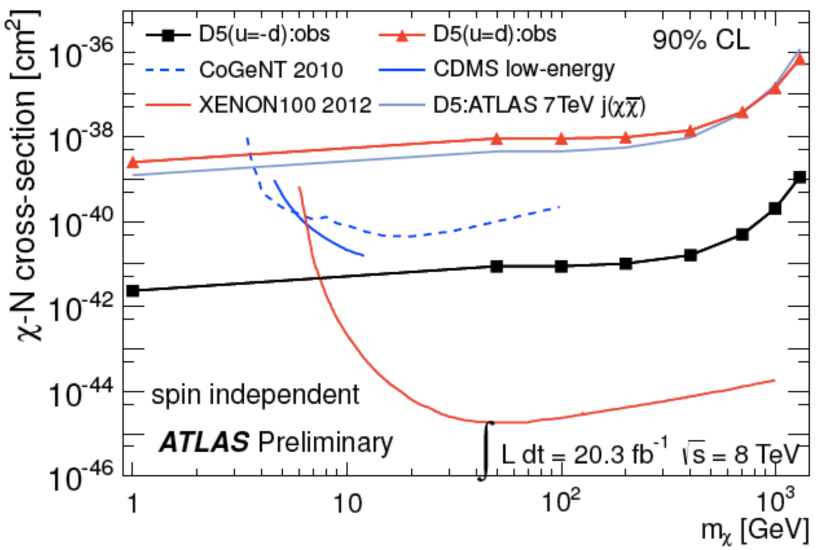
- Sensitivity nearly independent of WIMP mass
- Very constraining for spin dependent cas
  - Not competitive with direct detection for spin independent case at m>10 GeV

Mono-W

- Instead of searching for mono-"jet" can look for mono-W or mono-top
  - W or top is "fat jet" with mass ~mW or mtop using again substructure techniques
  - Brand new analysis from ATLAS was just released
    - More sensitive to spin independent process if DM couples with opposite sign to up and down quarks







Conclusions

- Many viable scenarios of new physics predict signatures involving jets at hadron colliders in both strong and weak production processes
  - SUSY, Extra dimensions, … and even Dark Matter production
- Jets are complex and difficult to understand
  - Systematic uncertainties on jet energy typically 2-5%
- b-jets are of particular interest to probe new physics coupling to third generation
  - Can be resolved experimentally with efficiency of ~70%
- Innovation in area of top and W/Z tagging via fat jets
  - Strong collaboration between theorists and experimentalists
- Many searches for new physics with jets at the LHC with 25 fb^{-1} of 7 and 8 TeV data
  - None showed any signs of new physics yet
- Searches with jets will again be in the lime light in 2015 when $\sqrt{s}\approx 13$ TeV!