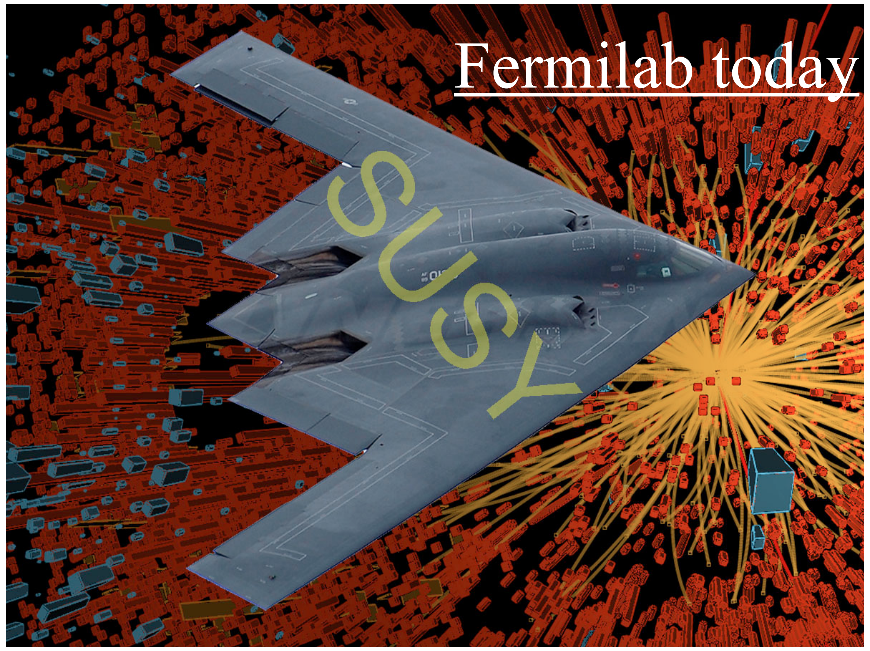
Search for stealth supersymmetry at the LHC

University of Pennsylvania
April 16, 2015

arXiv: 1411.7255
Physics Letters B, 743, 503 (2015)
SUS-14-009 public twiki

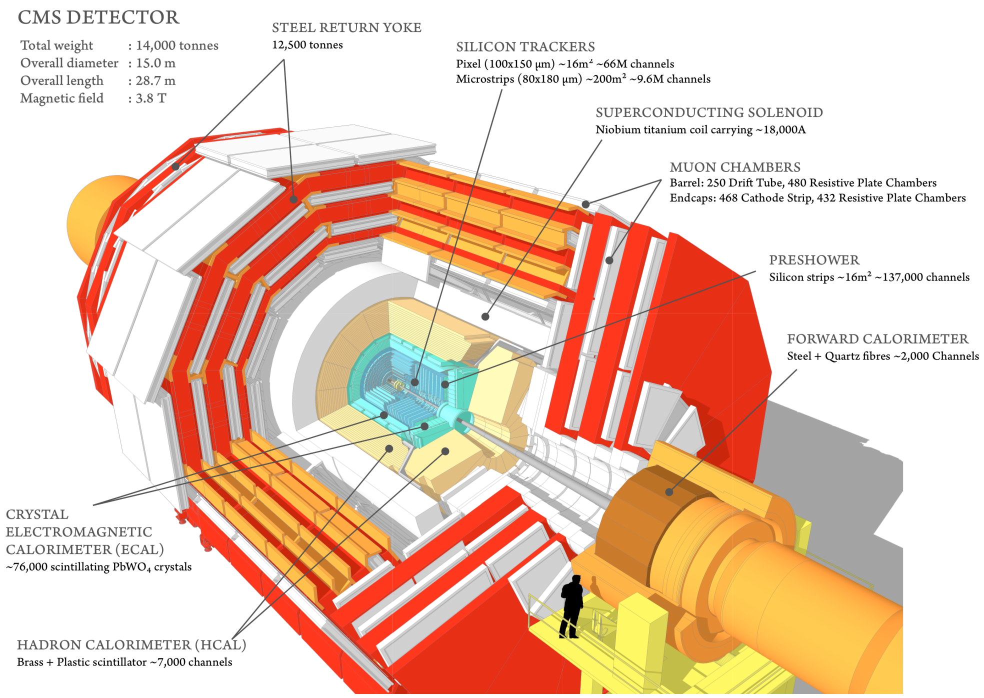


Ben Carlson

bcarlson@cern.ch

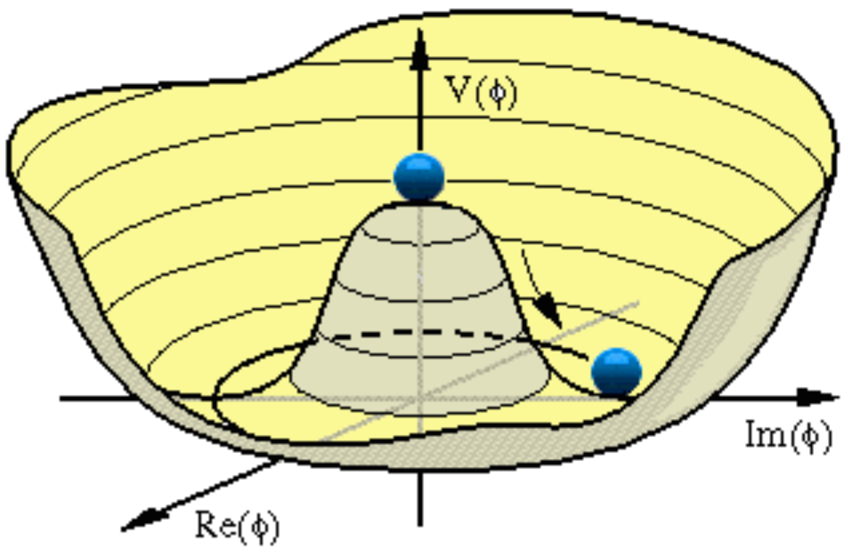
Outline

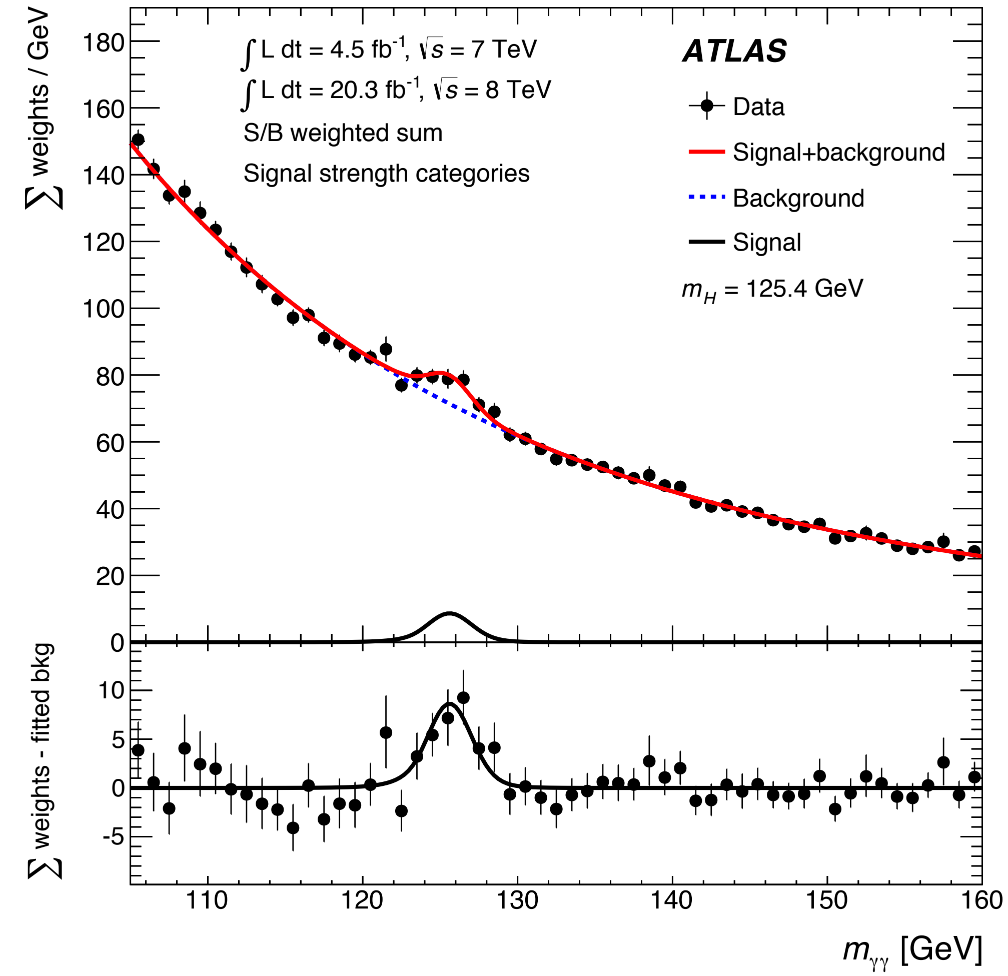
- Motivations for supersymmetry
- Overview of SUSY searches at the LHC
- Stealth SUSY motivation and searches
  - **eμ**, $\gamma\gamma$
- R-parity violation
  - Interpretations and projections
- Discussion for further work at 13 TeV

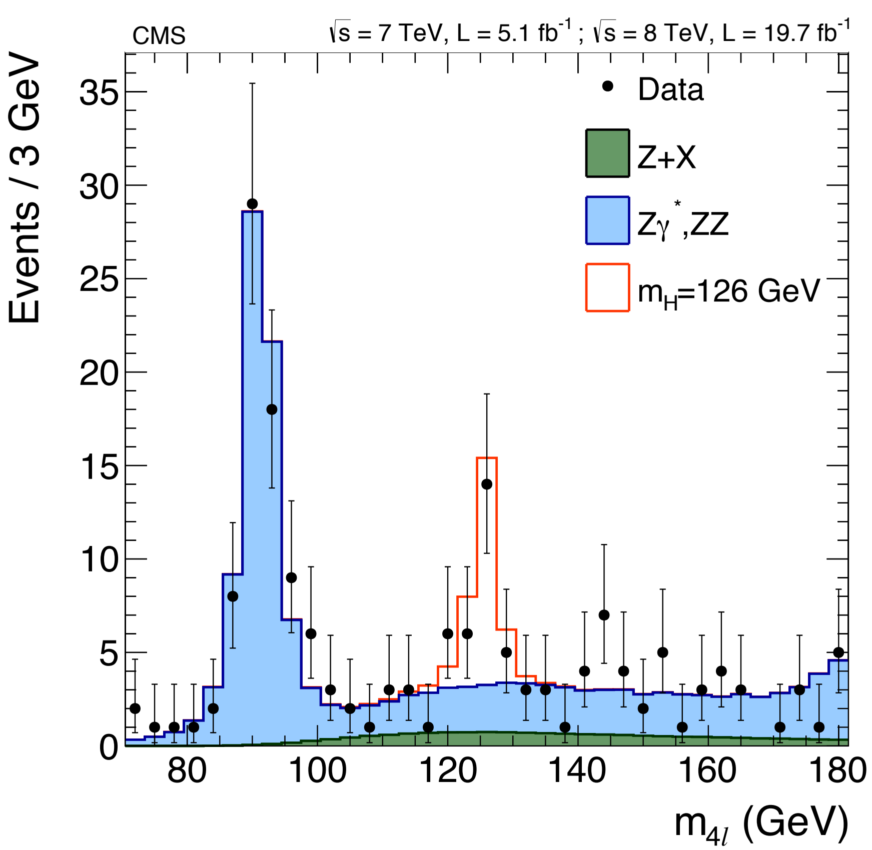


Physics
Carnegie Mellon University

Last piece of the SM: Higgs boson







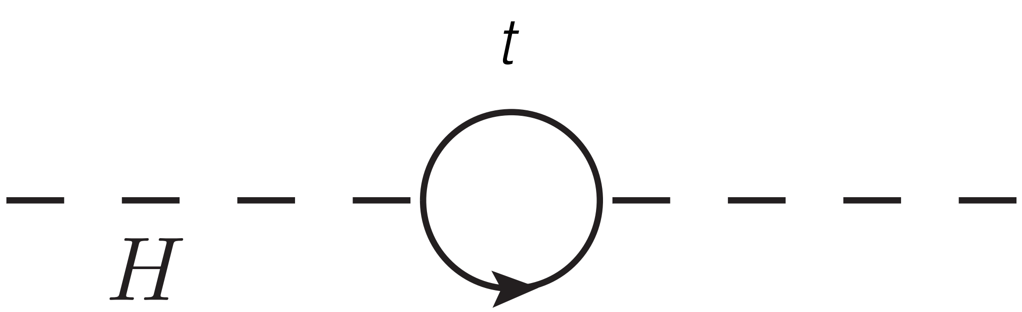
M_H =125 GeV

Hierarchy problem

- Why is $M_H \sim 10^2$ GeV so much less than $M_p \sim 10^{18}$ GeV?

arXiv: hep-ph/9709356

fermion loop corrections
dominated by **top** loops



$$\delta M^2(H) \sim \lambda_f^2 \Lambda^2$$

$\lambda_f \sim$ fermion coupling

Λ: cutoff scale

- Higgs mass is quadratically sensitive to new physics between M_H-M_p
  - Cancelation of divergent terms suggest **new physics** at the **TeV scale**

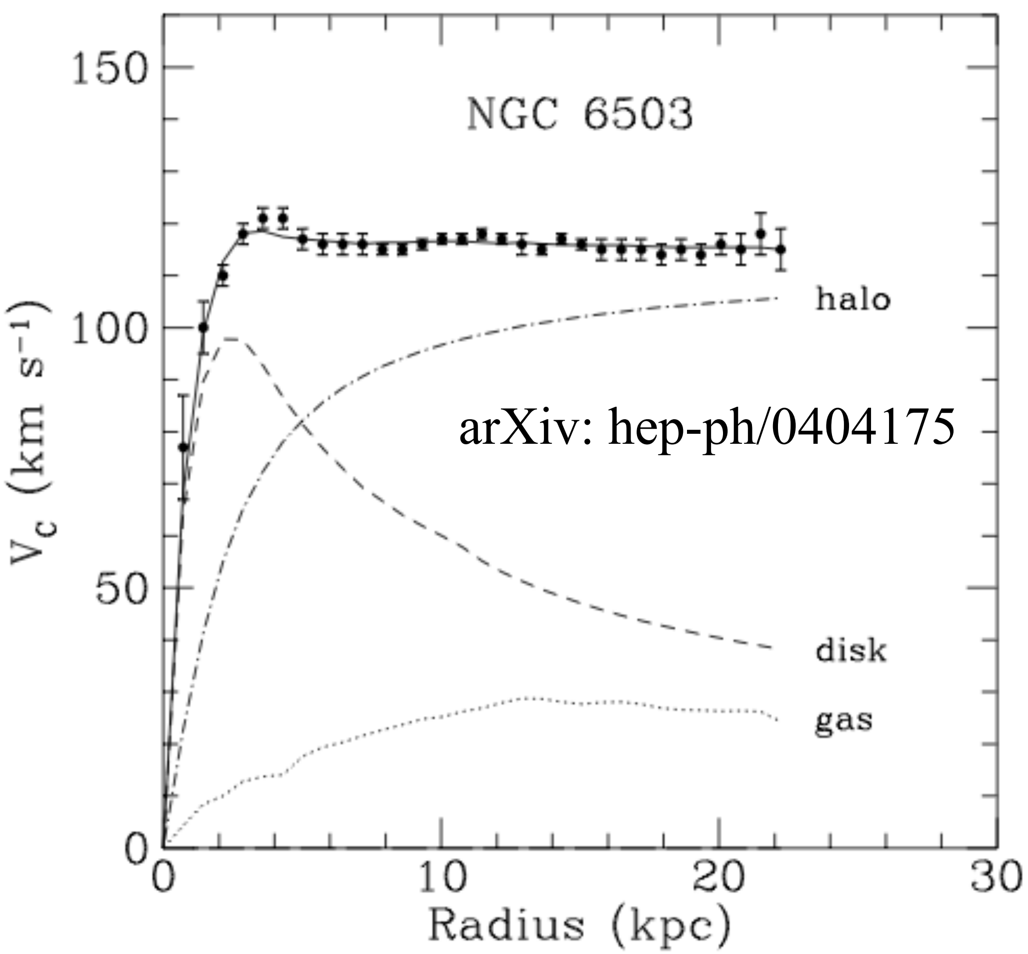
Physics
Carnegie Mellon University

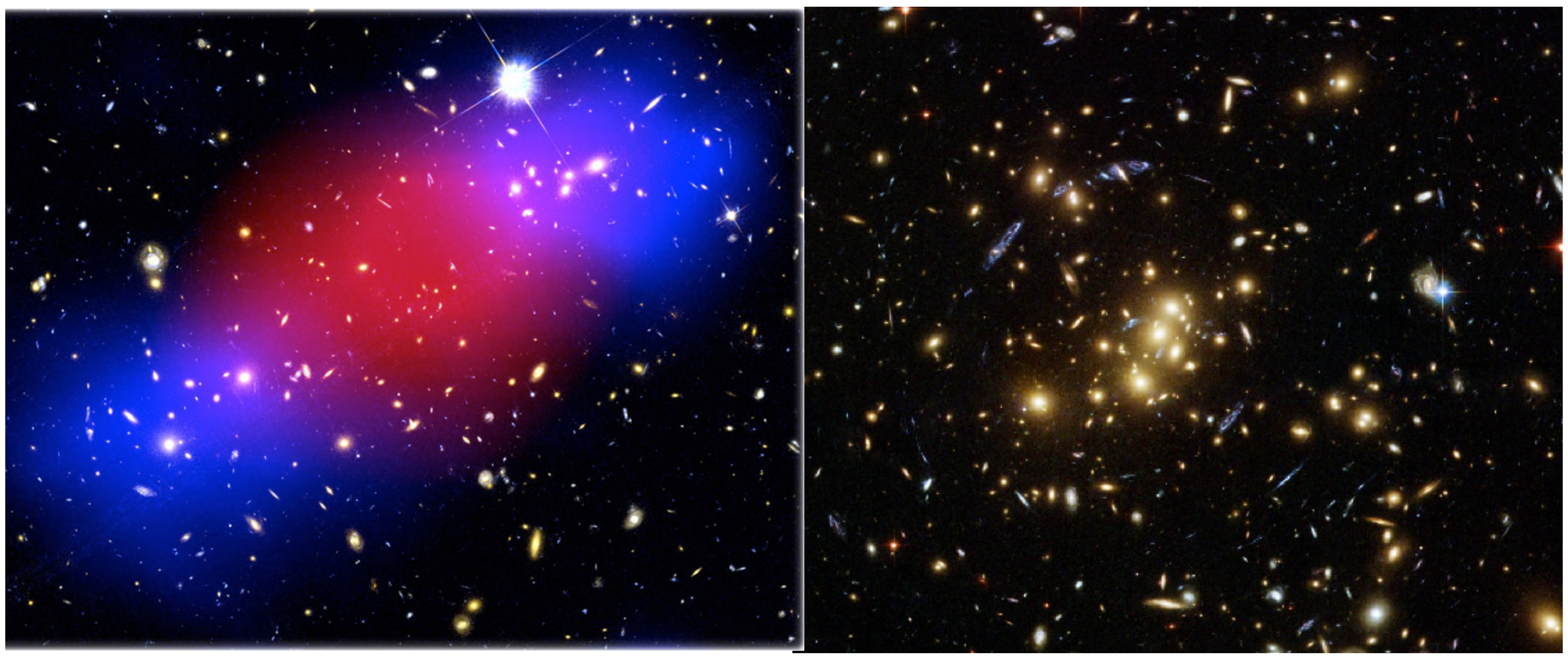
CMS
Compact Muon Solenoid

Dark Matter

- Astrophysical evidence for neutral, non-luminous matter
- Multiple lines of independent evidence

arXiv: 1001.1739





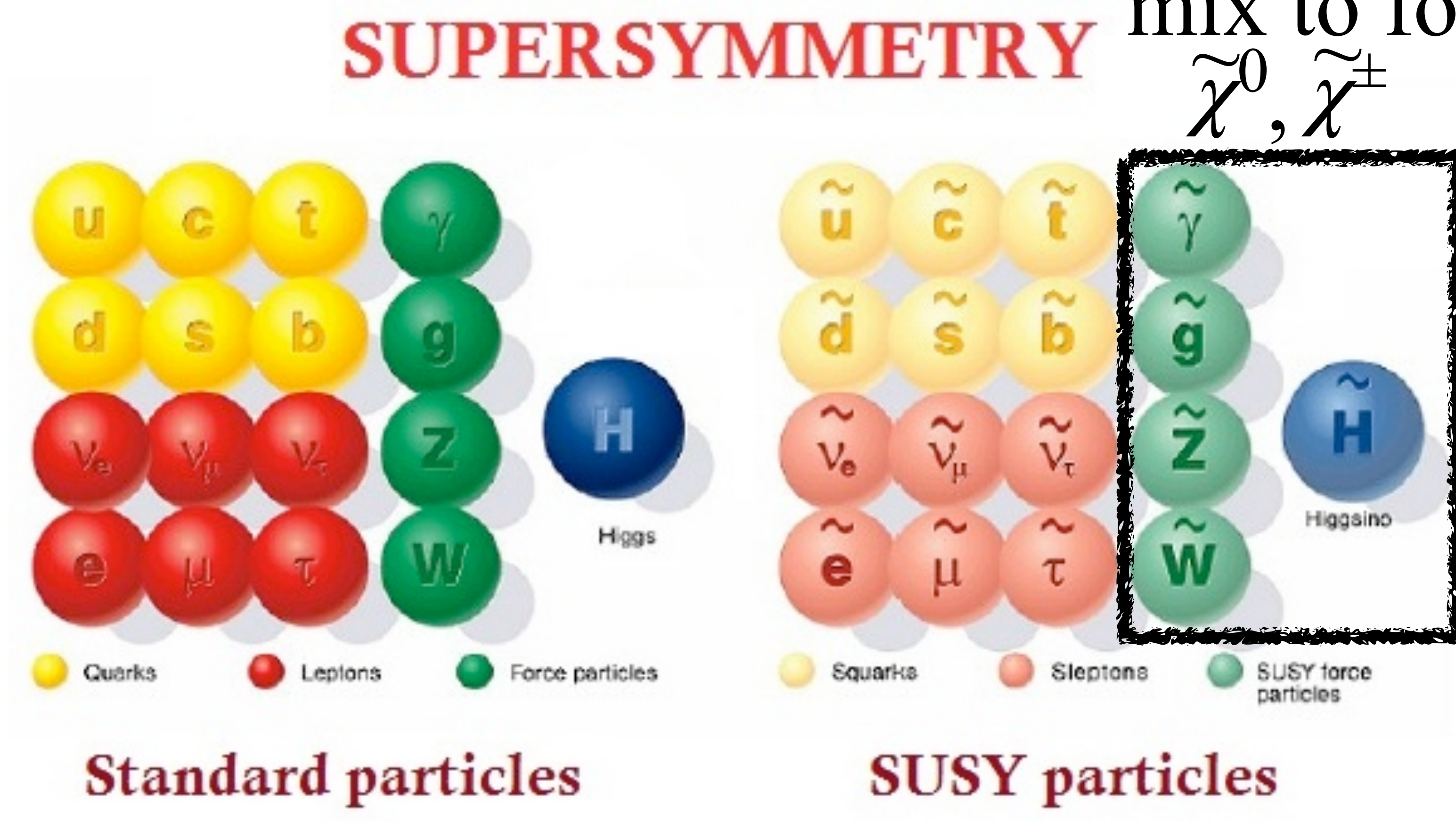
Gravitational lensing

Galactic rotational curves

- DM: not understood in the context of the **standard model**

Physics
Carnegie Mellon University

Supersymmetry



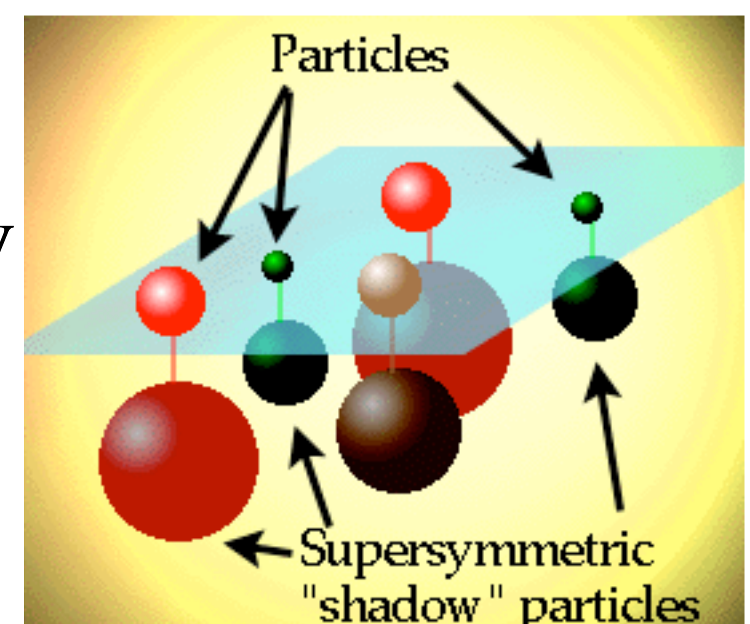
mix to form $\tilde{\chi}^0, \tilde{\chi}^{\pm}$

Provides a neutral, weakly interacting DM candidate

credit: CERN

Supersymmetry: fermion $\Longleftrightarrow$ boson

- Since we do not observe superpartners near SM particle masses, supersymmetry must be a broken symmetry

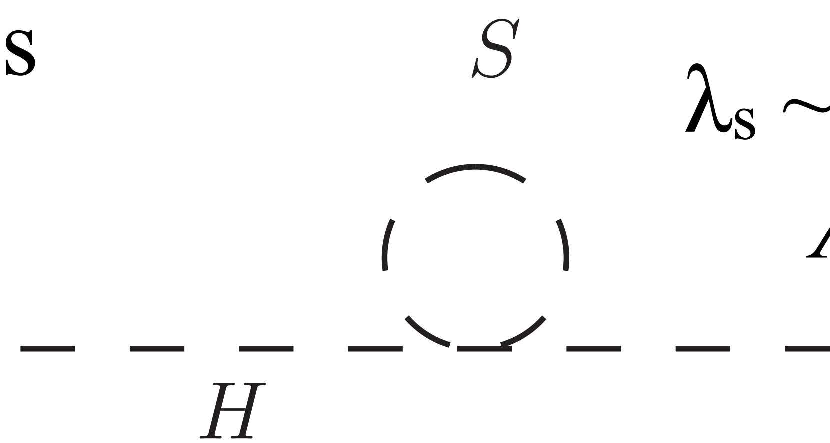


credit: CERN

Supersymmetry: solution to the hierarchy problem

- Supersymmetry introduces a scalar partner that cancels divergent terms

- A scalar partner S cancels corrections to $\delta M^2(H)$



$\delta M^2(H) \sim -\lambda_s \Lambda^2$

$\lambda_s \sim$ scalar coupling

Λ: cutoff scale

- For a (natural)125 GeV Higgs there must be TeV scale supersymmetry
  - top squarks, Higgsinos and gluinos are the lightest candidates

Physics
Carnegie Mellon University

Backgrounds at the LHC

$\sqrt{s}$ = 8 TeV

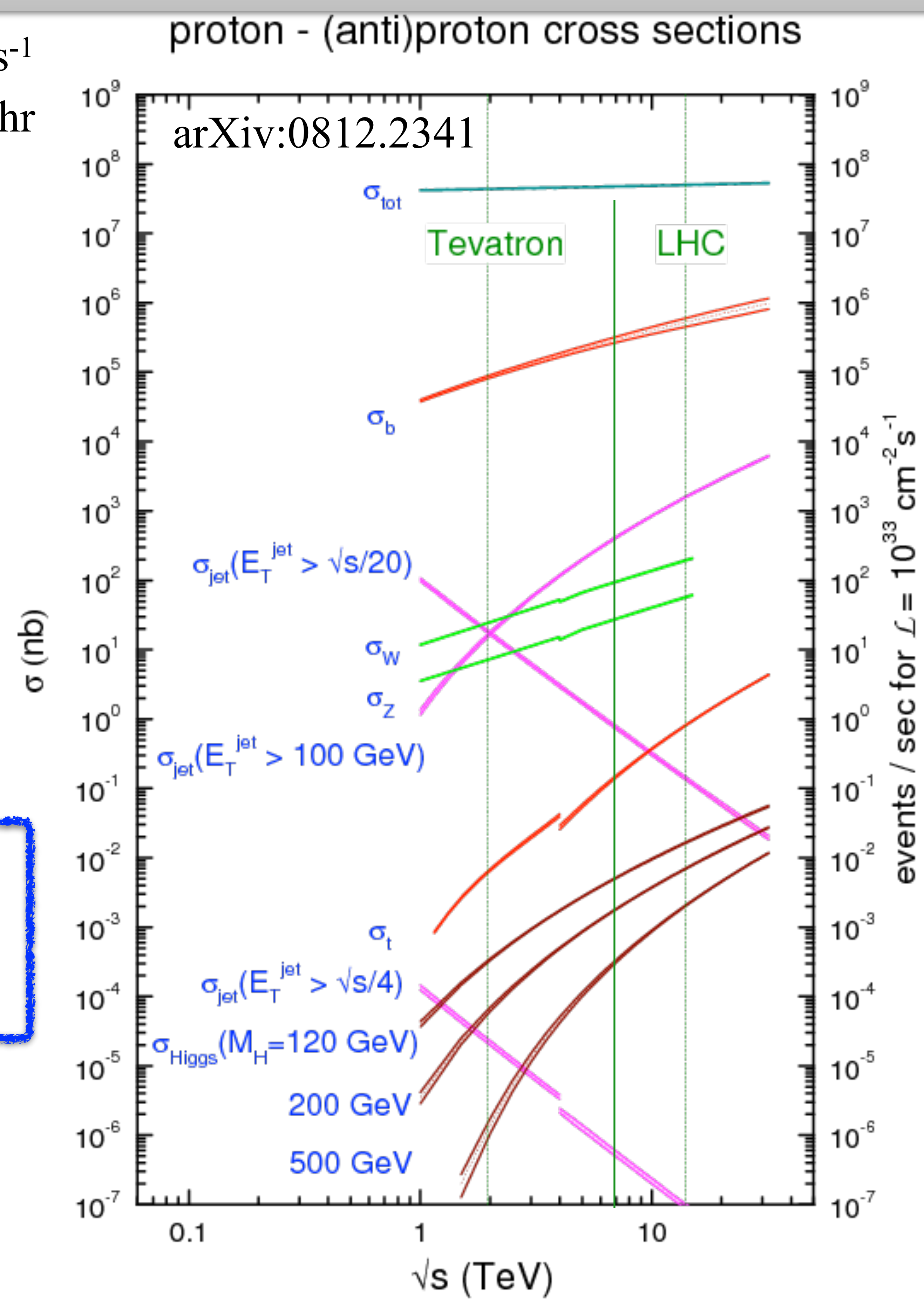
$\mathscr{L} = 10^{34} cm^{-2}s^{-1}$ gives 36 pb^{-1}/hr

Background	Cross section = σ (pb)	Events/hr
QCD	10^7	4×10^8
W+jets	1×10^5	4×10^6
Drell-Yan	4×10^4	1×10^6
ttbar	250	9×10^3
WW(ZZ)	56(33)	$2(1) \times 10^3$
Top squark (500 GeV)	0.08	3

$$N_{events} = \sigma \cdot \mathscr{L} \cdot \varepsilon \cdot \mathscr{A}$$

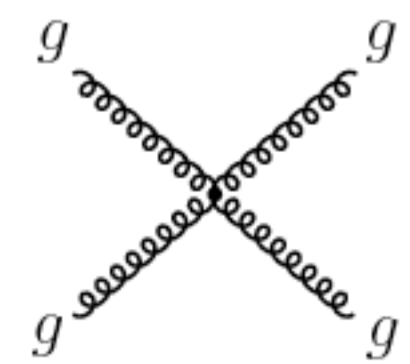
ε = efficiency
$\mathscr{A}$ = Acceptance
$\mathscr{L}$ = Luminosity

- Need handles to reduce SM backgrounds

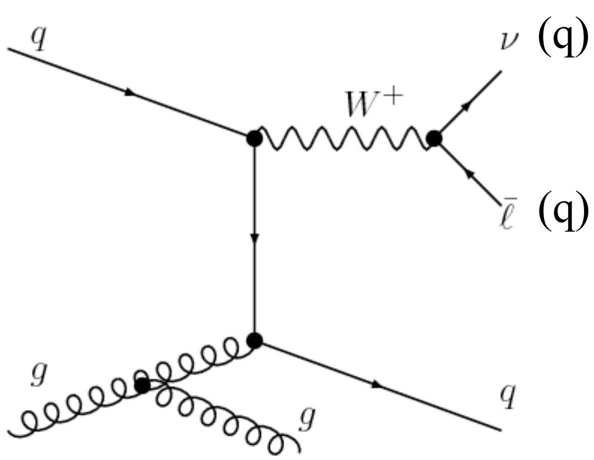


Handles for LHC backgrounds

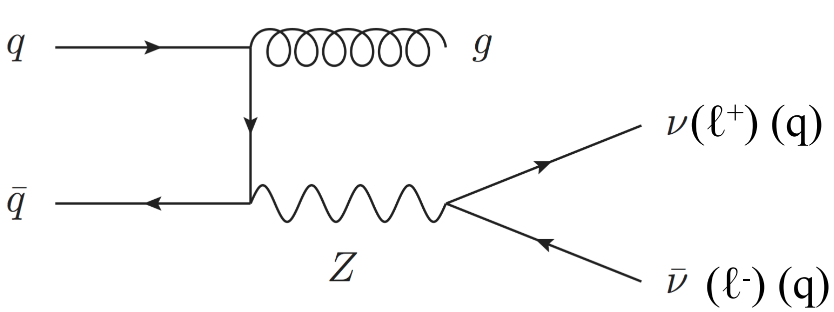
- Sample Feynman diagrams contributing to each process



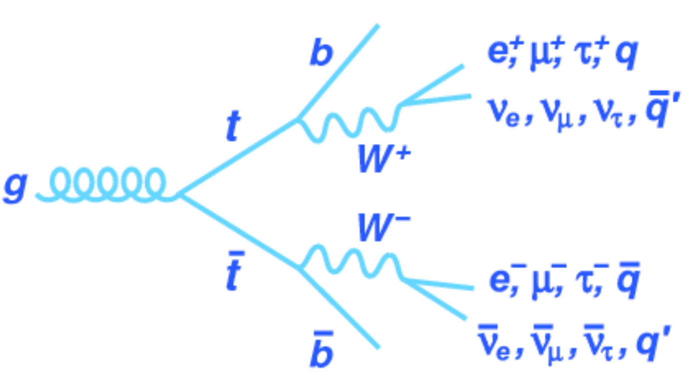
- QCD: multijet events
- Identifiers: jets



- W+jets: multijet events, leptons and neutrinos (jets) from W decay
- Identifiers: one lepton, E_T^{miss}



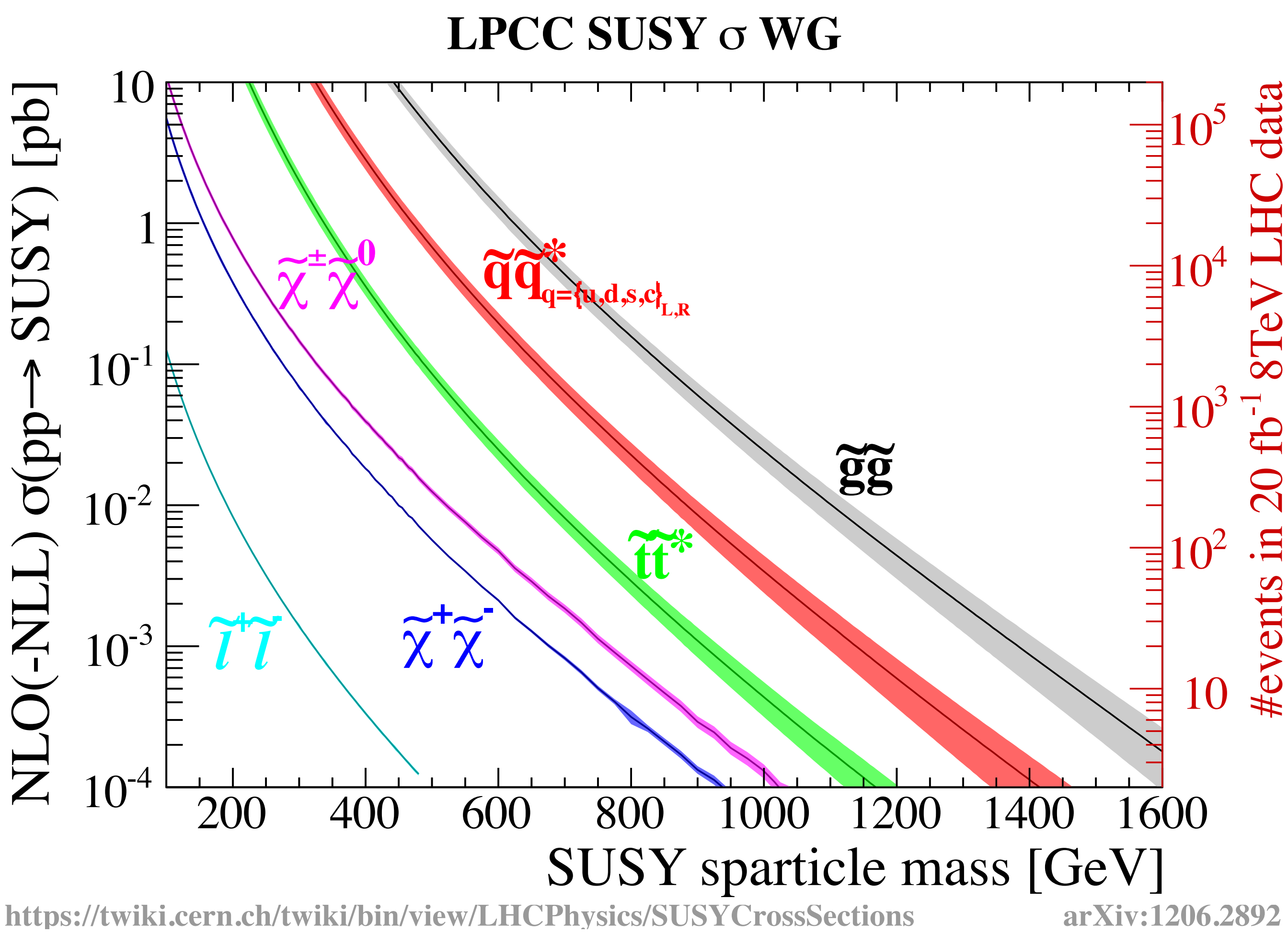
- Drell-Yan: two leptons (neutrinos) (quarks) from Z decay
- Identifiers: two lepton resonance

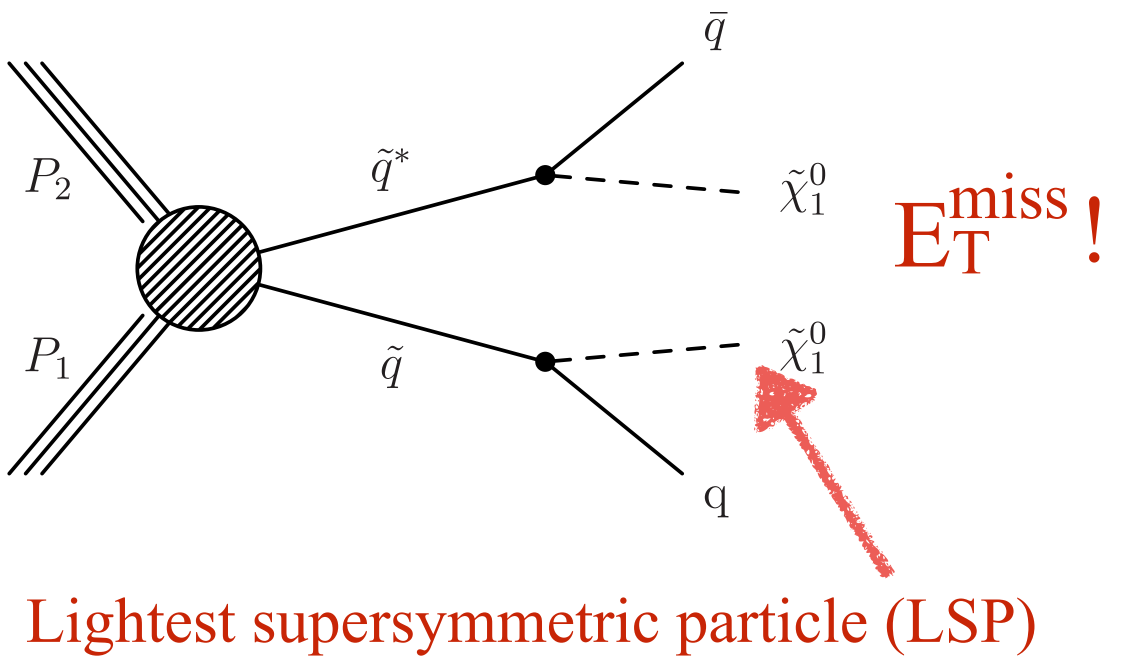


- TTbar: Two b jets, two W's
- Identifiers: b jets, leptons from W's, jets

decreasing cross section

Simplified decay chains at the LHC

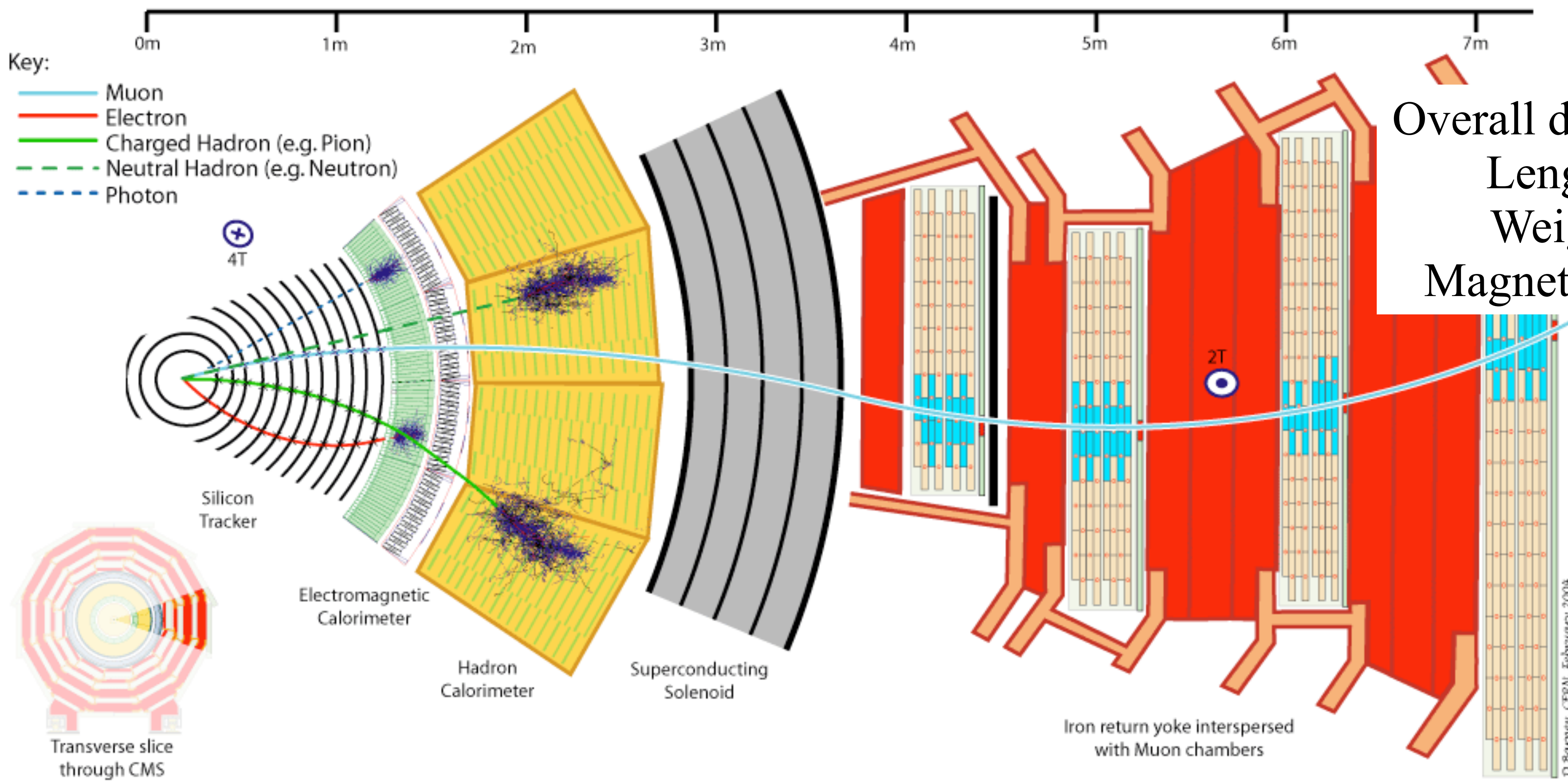




- Common characteristics
  - Assume single dominant decay mode for SUSY particles
  - missing transverse energy from LSP $\tilde{\chi}^0$
- Typically involve X + E_T^{miss}
  - Jets, leptons, photons

Physics
Carnegie Mellon University

The Compact Muon Solenoid

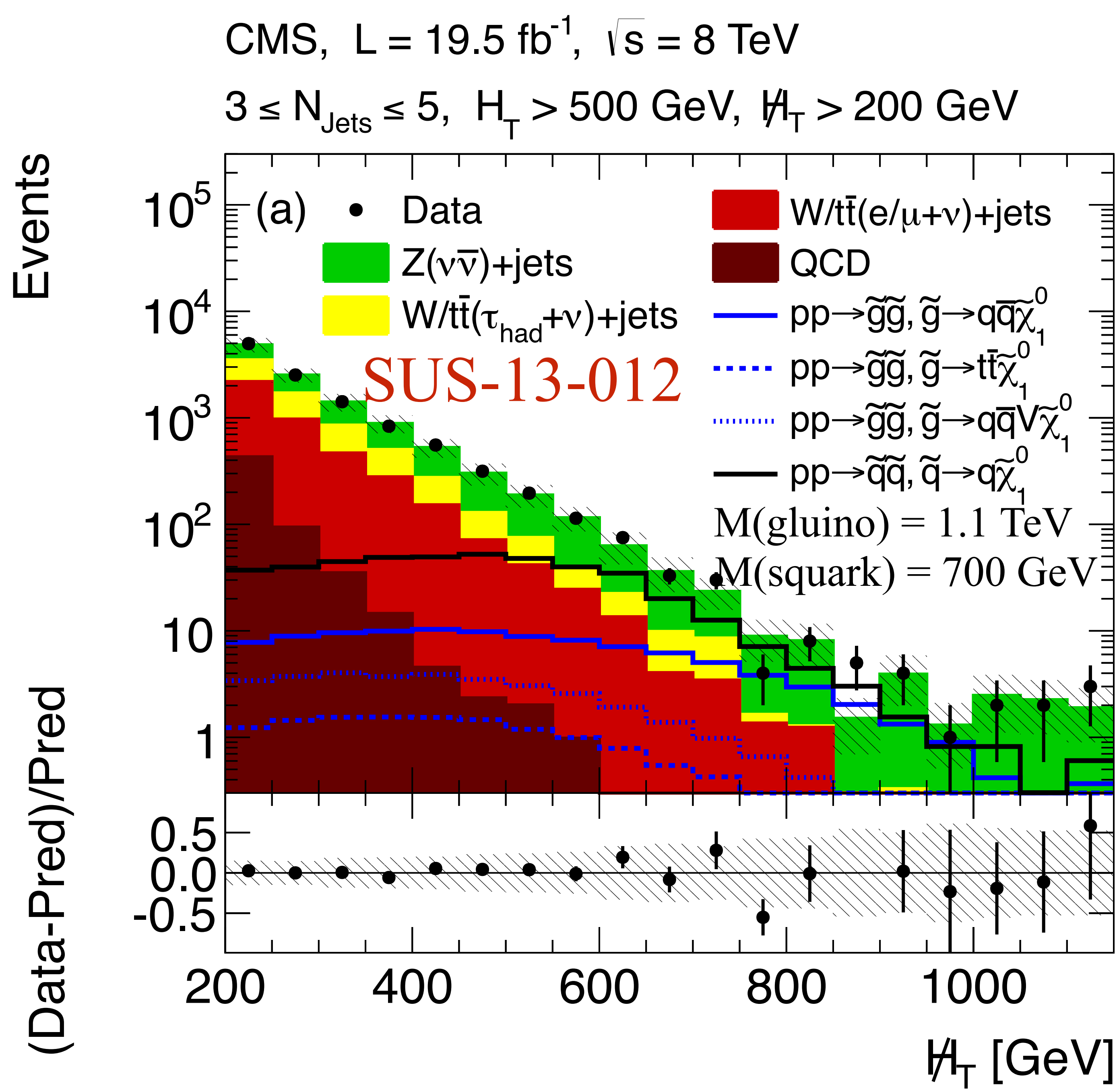


Overall diameter:15.0 m
Length: 28.7m
Weight: 14 kT
Magnetic field: 3.8 T

- **Particle flow** combine information from all subdetectors for object reconstruction: muons, charged and neutral hadrons

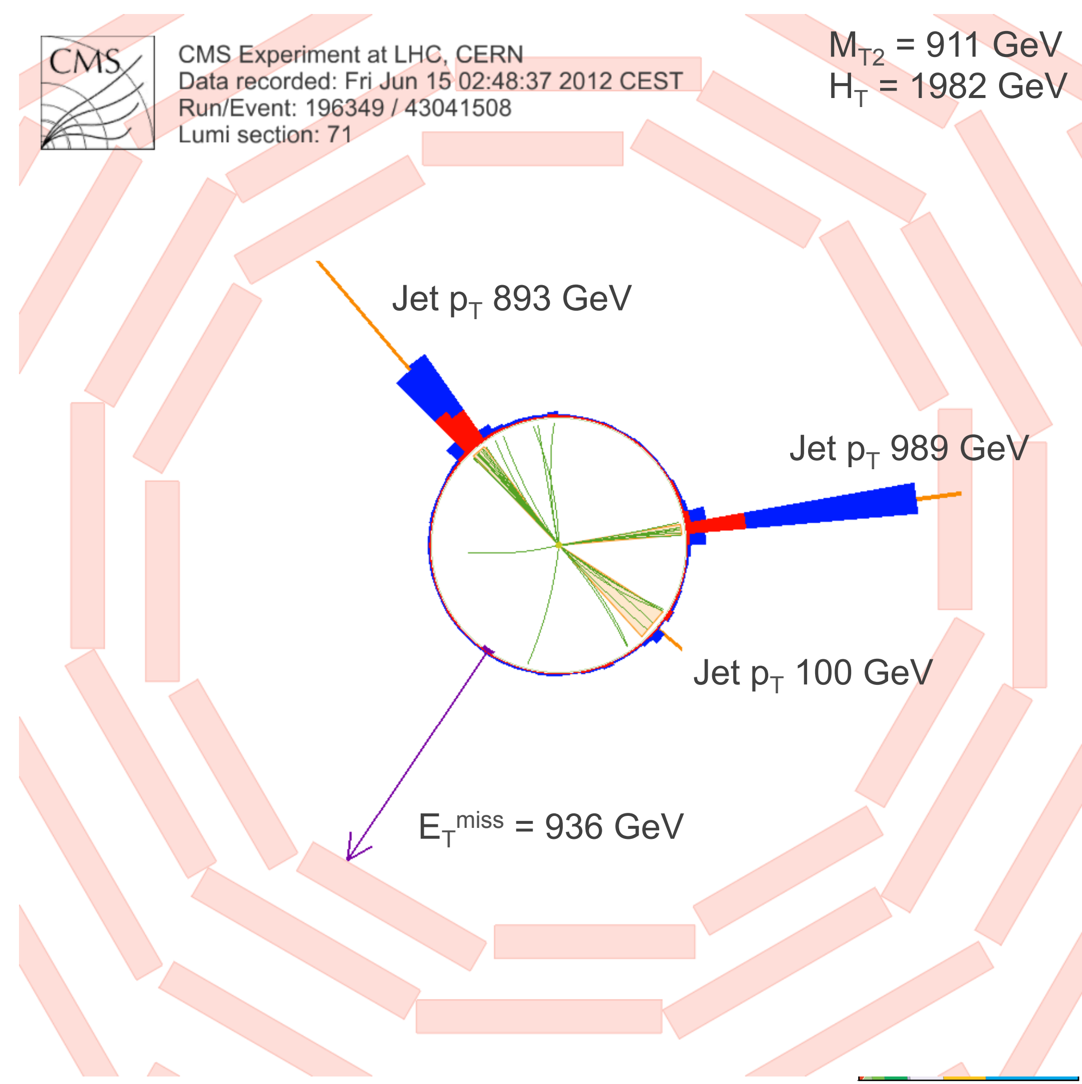
Physics
Carnegie Mellon University

Classic search: jets and E_T^{miss}



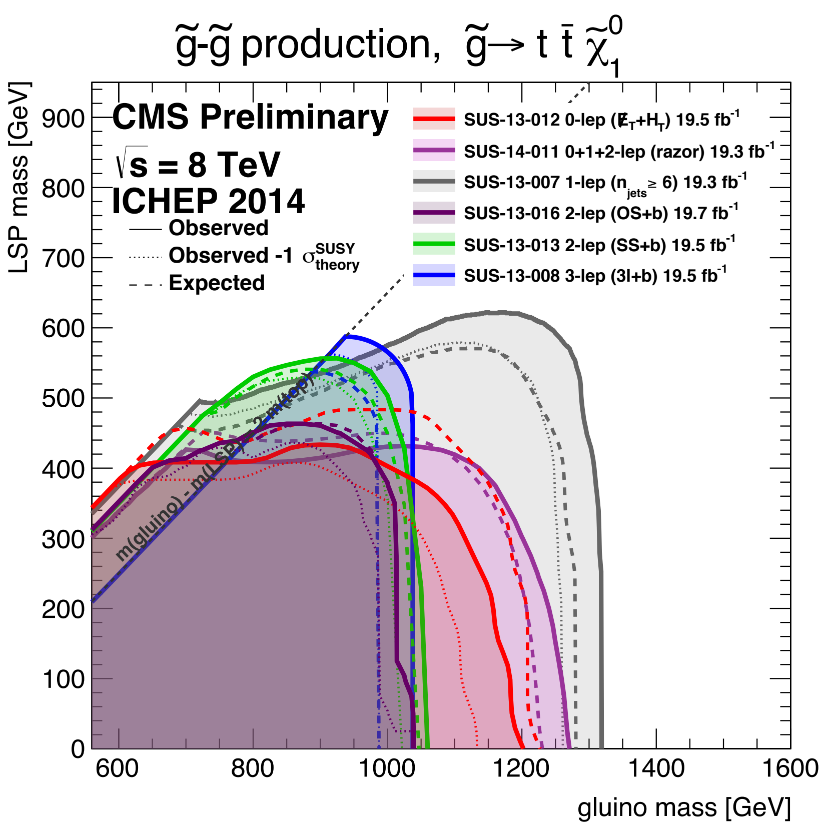
$$\not{H}_T = |\vec{\not{H}}_T| = |-\textstyle\sum_{jets}\vec{p}_T|. \quad H_T = \textstyle\sum_{jets} p_T.$$

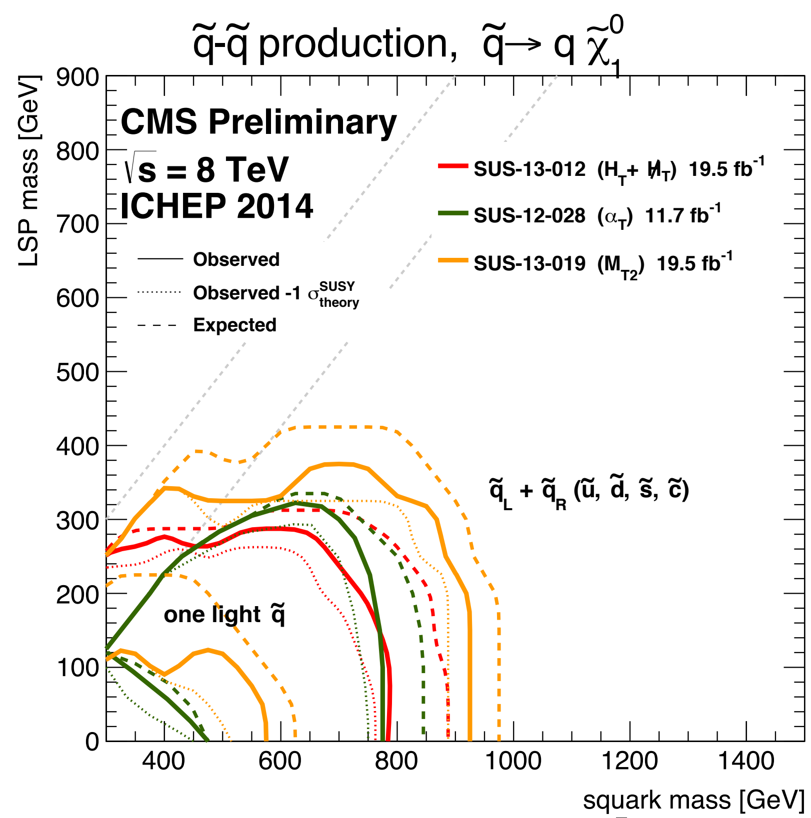
- General, **inclusive** signature
- Sensitive to a broad range of SUSY decays

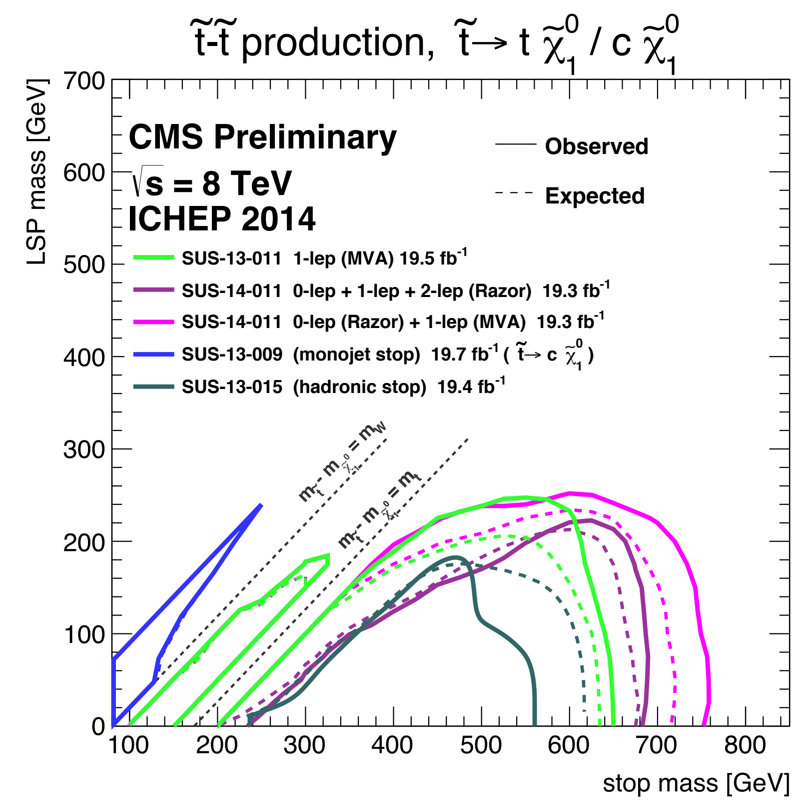


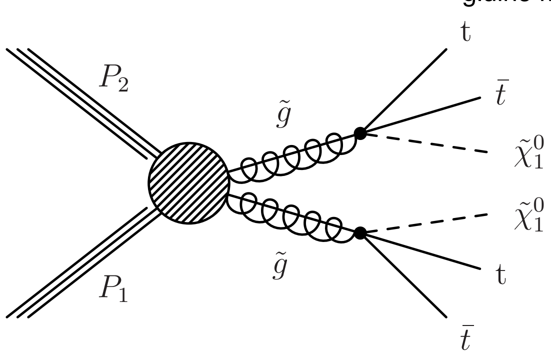
Physics
Carnegie Mellon University

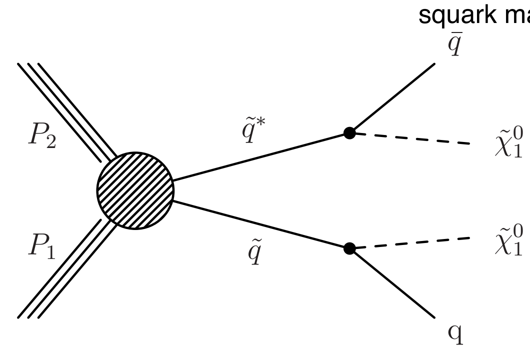
Where we are now: end of Run 1

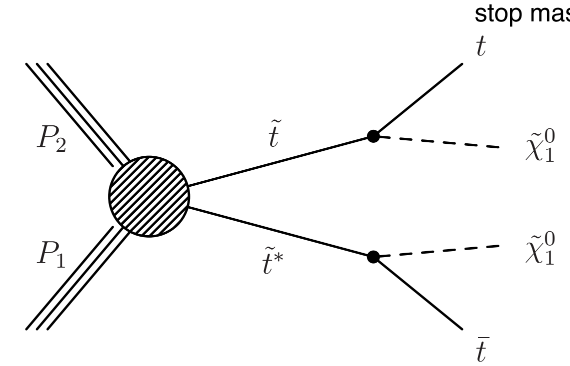










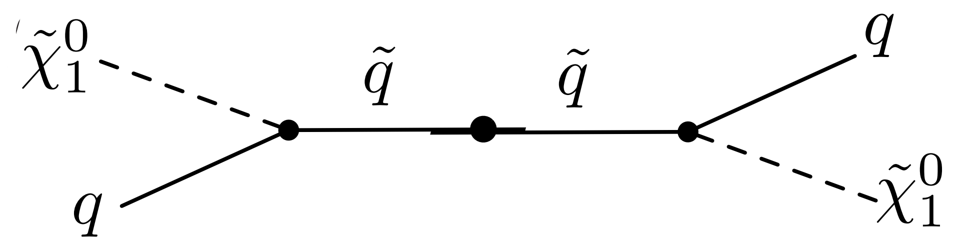


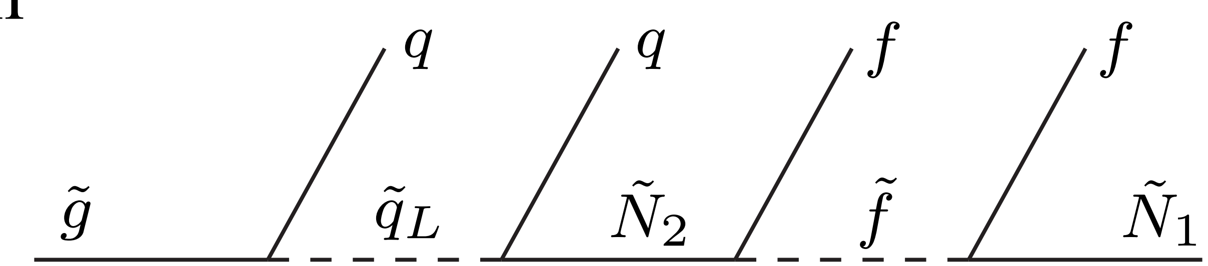
- Where is new physics?
  - Option 1: insufficient sensitivity because of energy or luminosity
  - Option 2: **Not looking in the right place**
    - Nearly all SUSY searches require **substantial E_T^{miss}**

How to hide E_T^{miss}

- There are many examples of models that trade E_T^{miss} for jets

- **Compressed spectra**: coincidental squark-LSP mass degeneracy hides E_T^{miss}, can be revealed by initial state radiation

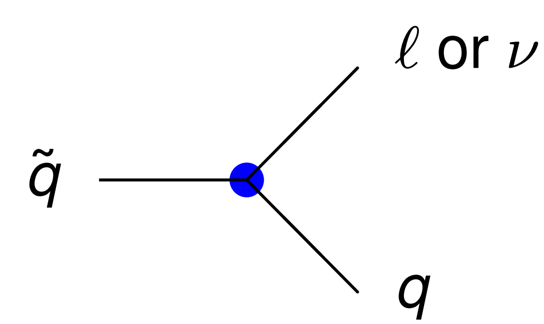




- **Long decay chains**: little p_T remains at end of chain.

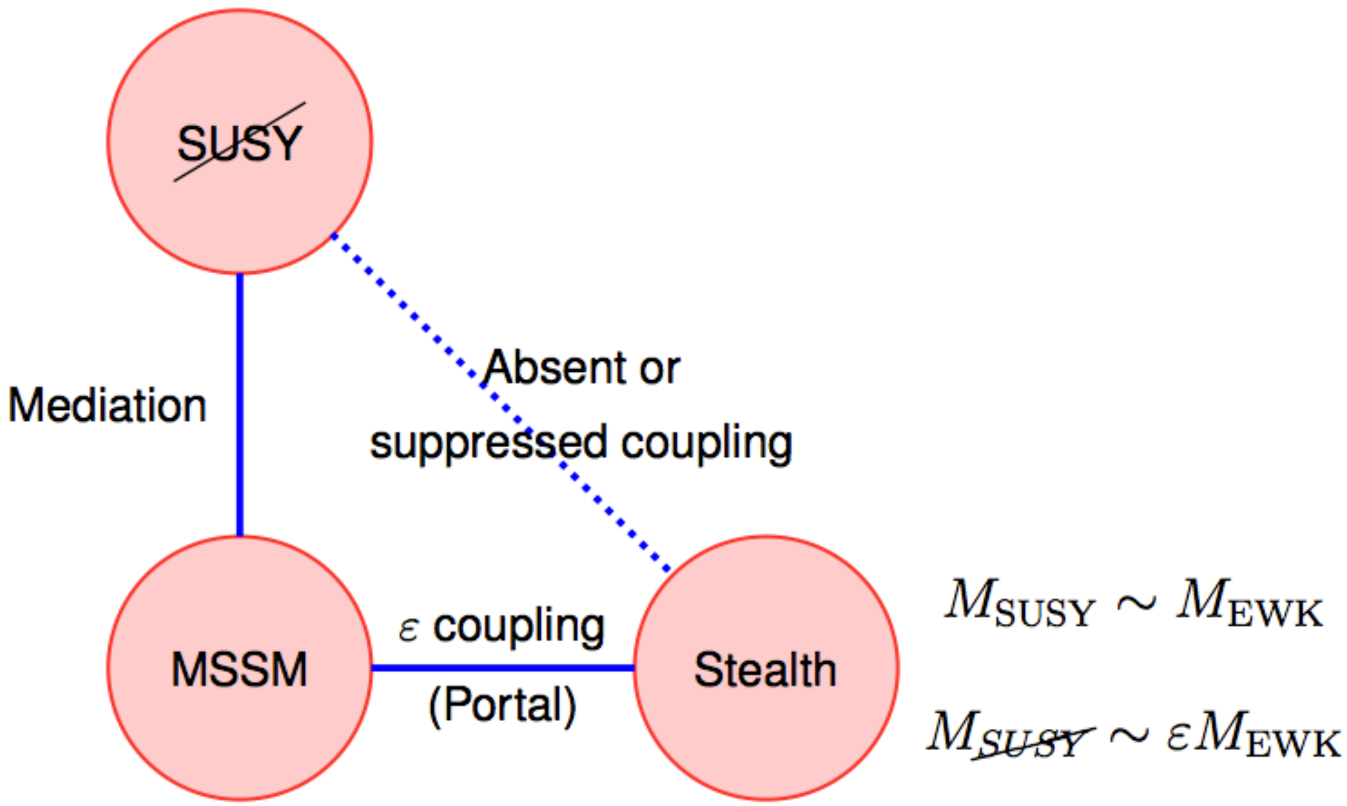
- **Stealth SUSY**: mass degeneracy required by symmetry.

- **R-parity violation**: $W_{\mathrm{RPV}} \supset \lambda'_{ijk} L_i Q_j \bar{D}_k$



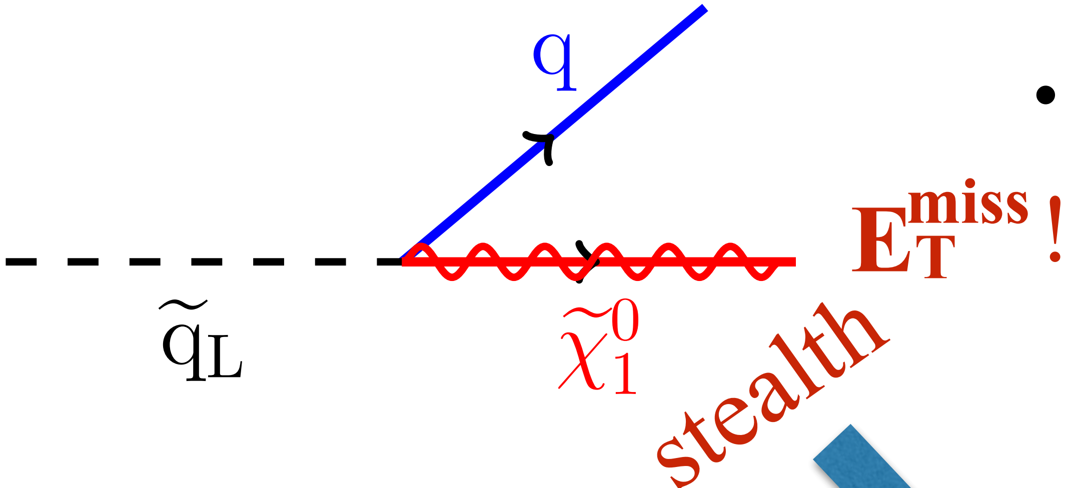
Stealth mechanism

arXiv: 1105.5135, 1201.4875
Fan, Reece, Ruderman

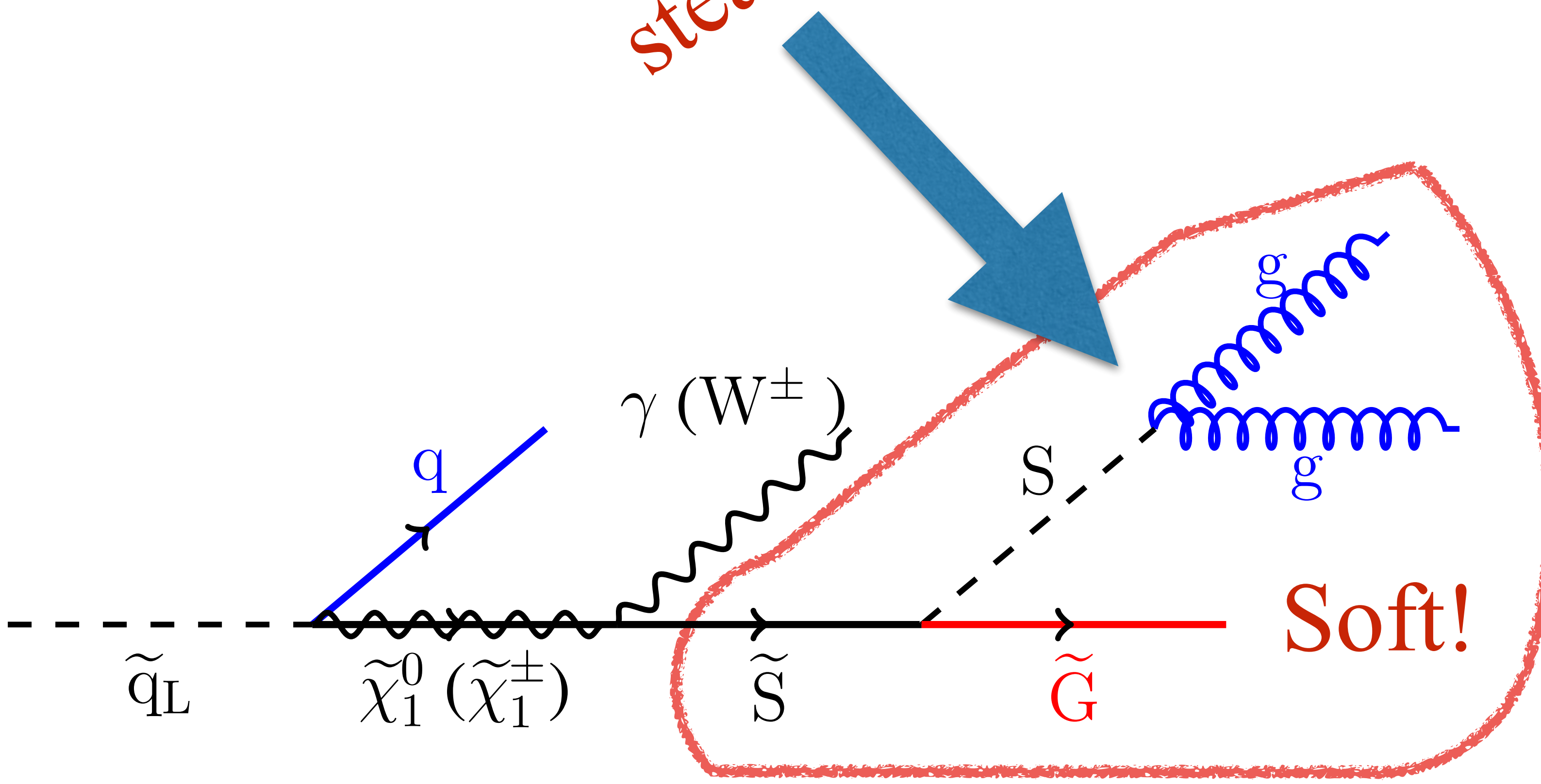


- Assume usual SUSY **breaking sector** with some mediation to **MSSM**
- Introduce hidden sector $\tilde{S}$, S
  - No coupling to SUSY breaking sector
  - SUSY approximately conserved, **enforcing mass degeneracy**
  - $\delta M = M(\tilde{S}) - M(s)$ small

Stealth SUSY



- Typical squark decay that terminates in high p_T, undetected LSP
  - Results in substantial MET



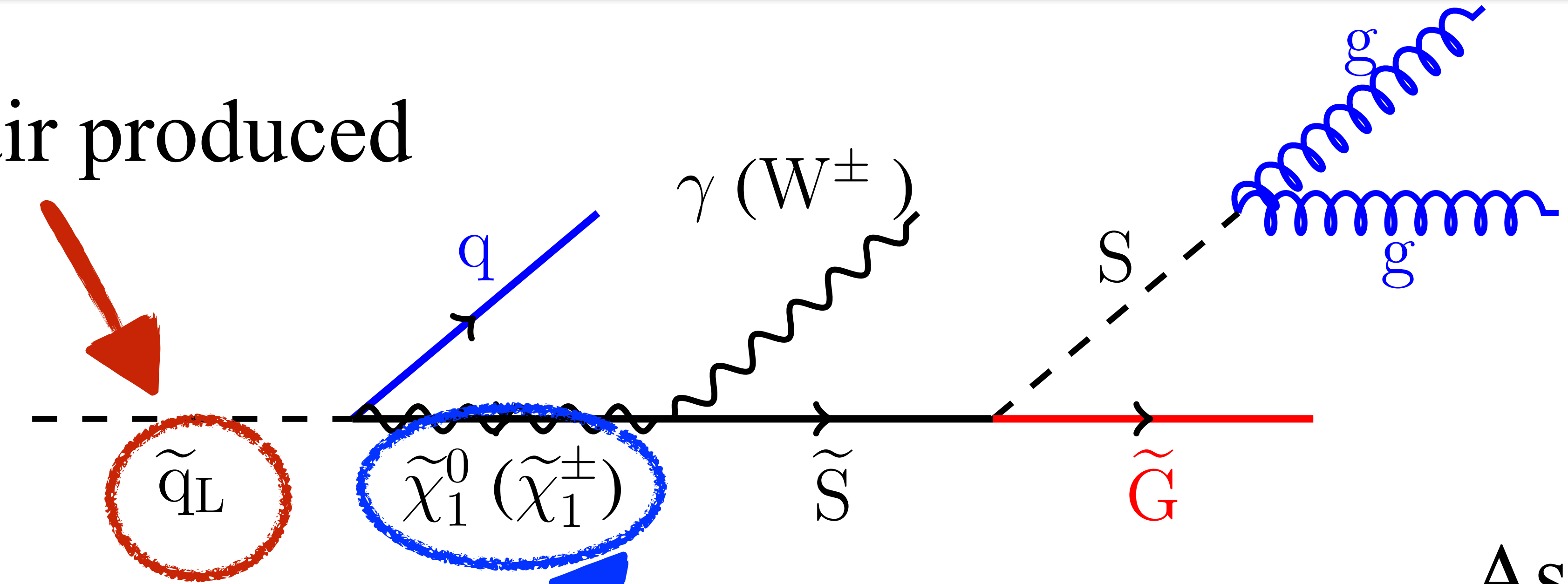
- Allow gaugino to decay to hidden sector with mass degenerate superpartners ($\tilde{S}$,S)

- **Low E_T^{miss}** signature generated naturally from small δM, **required** by the fact that SUSY is conserved in the **stealth sector**

Physics
Carnegie Mellon University

Stealth SUSY signature

Pair produced



$M(\tilde{S}) = 100$ GeV
$\delta M = 10$ GeV

Assume decay to either neutralino or chargino

- Signature: **6 jets** and **WW ($\gamma\gamma$)**
- Analysis targets **general set** of final states with photons or leptons, jets and **no E_T^{miss}** requirement
- Current search strategies are insensitive to this model

Analysis overview

Search separately for WW ($\gamma\gamma$) decays
Use selections:

- **Electron & muon (eμ)**
  - Dominant background: ttbar
  - Selection designed to reduce QCD, W+jets, and DY
- Two **photons ($\gamma\gamma$)**
  - Dominant background: QCD
  - Low cross section from QCD with $\gamma\gamma$

- Use variables: N_{jets}, S_T

S_T: total transverse energy

$$S_T = \sum_{jets} p_T + \sum_{\substack{leptons \\ (Photons)}} p_T + \not{E}_T$$

$S_T \sim 2 \times M_{squark}$

Physics
Carnegie Mellon University

CMS

Selections and trigger

eμ

- Isolated **muon** trigger
- Offline selections:
  - Muon $p_T > 30$ GeV
  - Electron $p_T > 15$ GeV
  - Jet $p_T > 30$ GeV
  - 0 b-tagged* jets

*combined secondary vertex, BTV-13-001

γγ

- Isolated **diphoton** trigger
- Offline selection
  - $p_T(\gamma) > 40$ (25) GeV
  - Jet $p_T > 30$ GeV

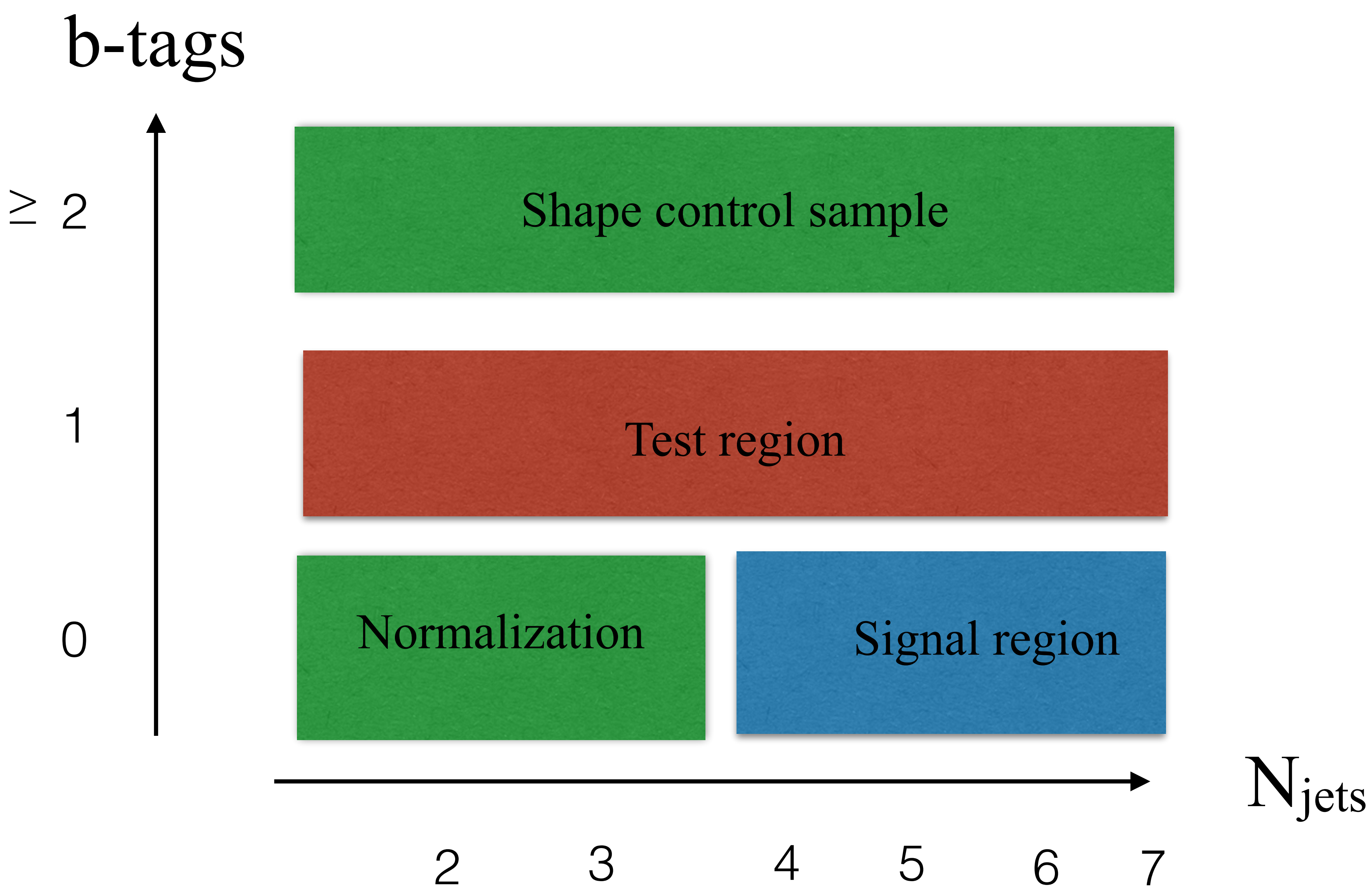
Jets reconstructed using anti-k_T algorithm (R=0.5) from particle flow objects

Physics
Carnegie Mellon University

CMS

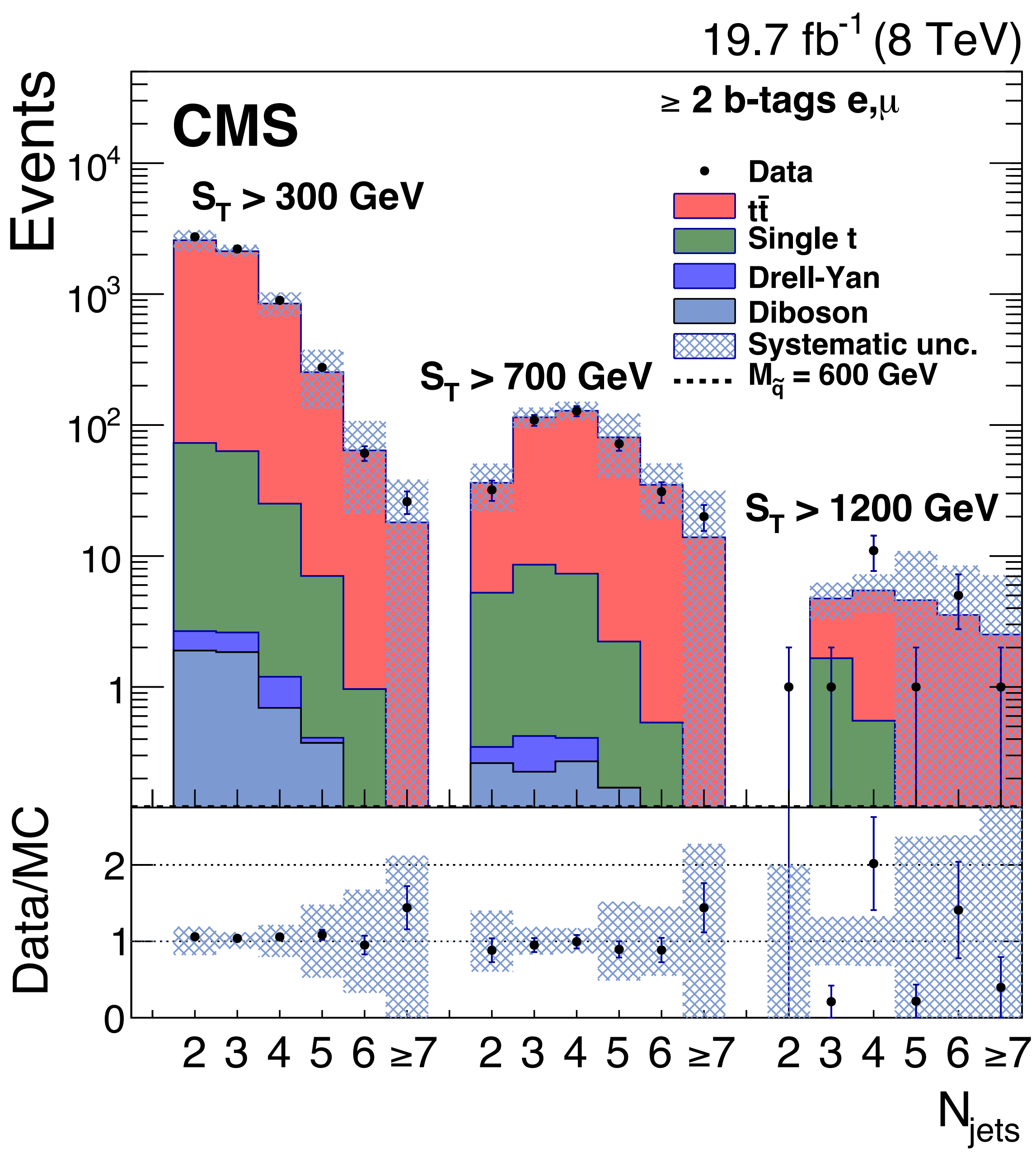
Overview of top background

- Dominant SM background: ttbar
  - Shape from ≥ 2 b-tag
  - Normalization (0 b-tag) from 2-3 jet



Top background estimation for eμ

- Strategy: apply **normalization** and **N_{jets}** shape corrections to MC samples (MadGraph + Pythia) derived from **control samples**



- Shape control sample with ≥ 2 b-tag
- Three (inclusive) S_T bins

- **Jet multiplicity** well modeled by MC
- **Uncertainties** from variation of renormalization/ factorization scales

Background estimation for eμ analysis

- DY contributes to eμ through **$Z \to \tau\tau$**
- **Estimate DY** from dimuon mass < 130 GeV
- Backgrounds with a **non-prompt lepton**: small

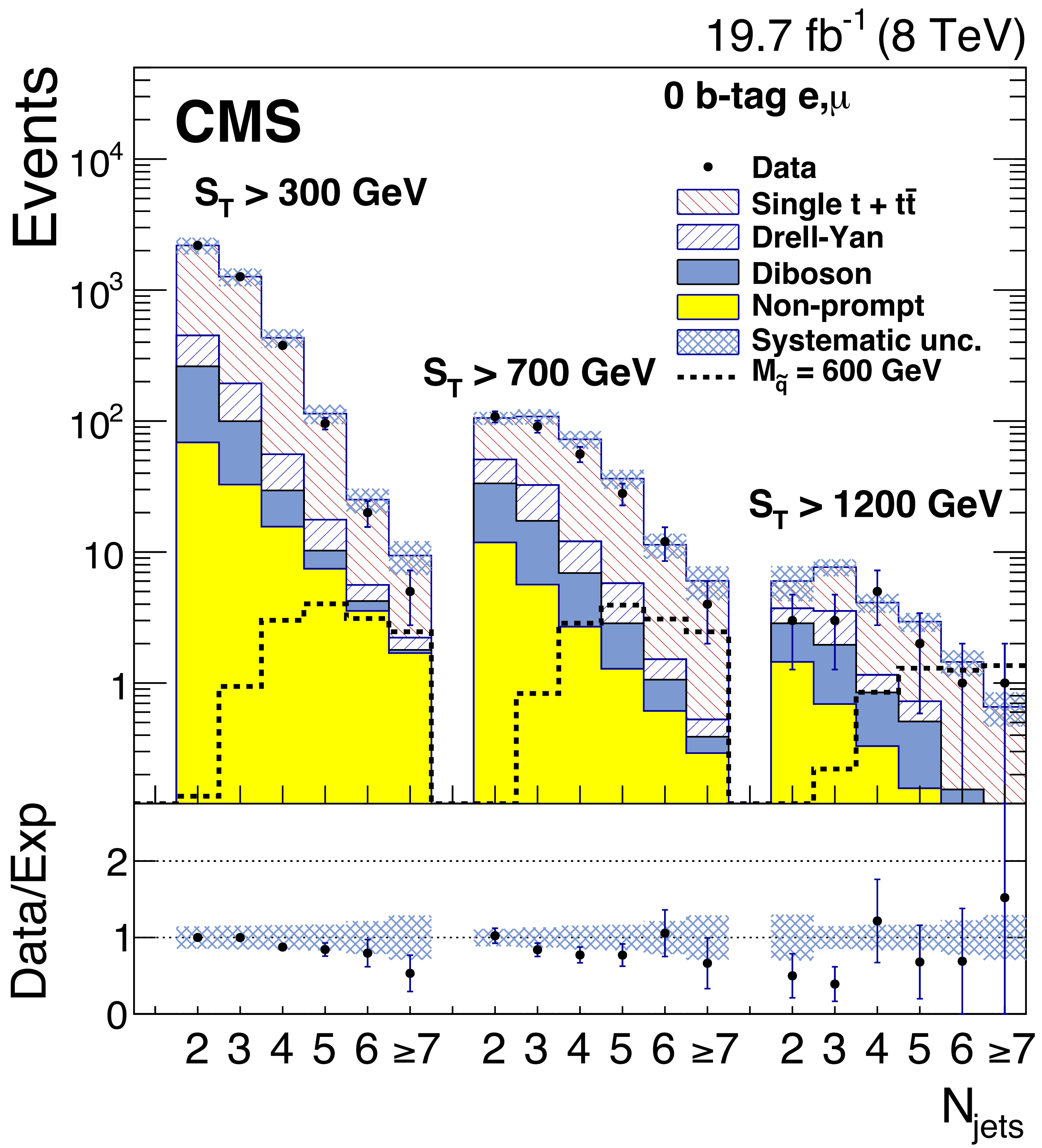
Sample	Leptons	N_{jets}	$N_{\text{b-jets}}$
Search	$e^{\pm}, \mu^{\mp}$	≥ 4	0
Top shape	$e^{\pm}, \mu^{\mp}$	≥ 2	≥ 2
Top normalization	$e^{\pm}, \mu^{\mp}$	<4	0
Drell–Yan	$\mu^{\pm}, \mu^{\mp}$	≥ 2	0
Non-Prompt	$e^{\pm}, \mu^{\pm}$	≥ 2	0

- Validate background estimation in 1 b-tag **validation** control sample

Physics
Carnegie Mellon University

CMS

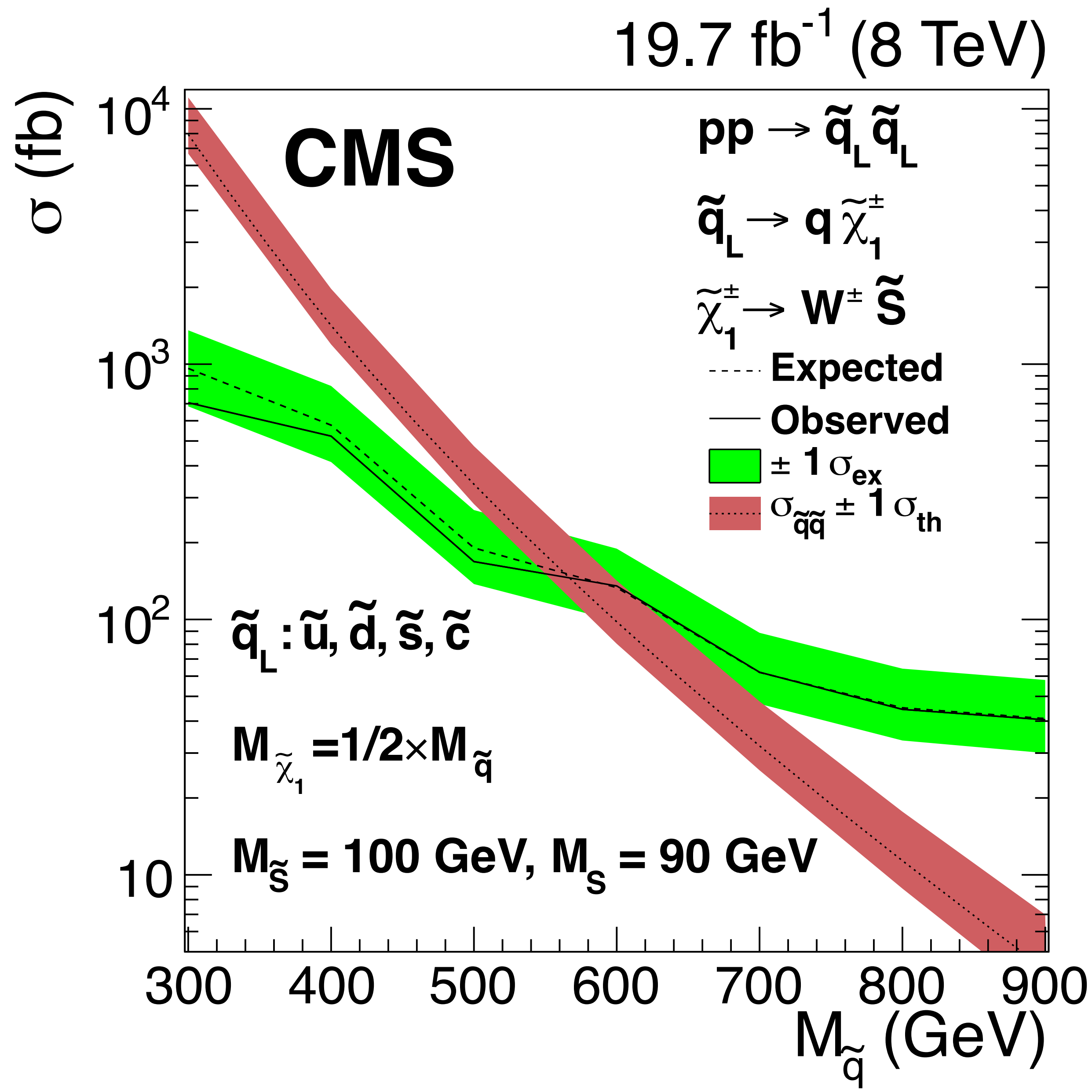
Results 0 b-tag: signal region (eμ)



- Signal tends to produce events with many jets
- Three S_T thresholds (300, 700, 1200 GeV) are optimal for all squark masses
- Dominant systematic uncertainty: statistical uncertainty on **top shape** control sample

Stealth SUSY limits: WW

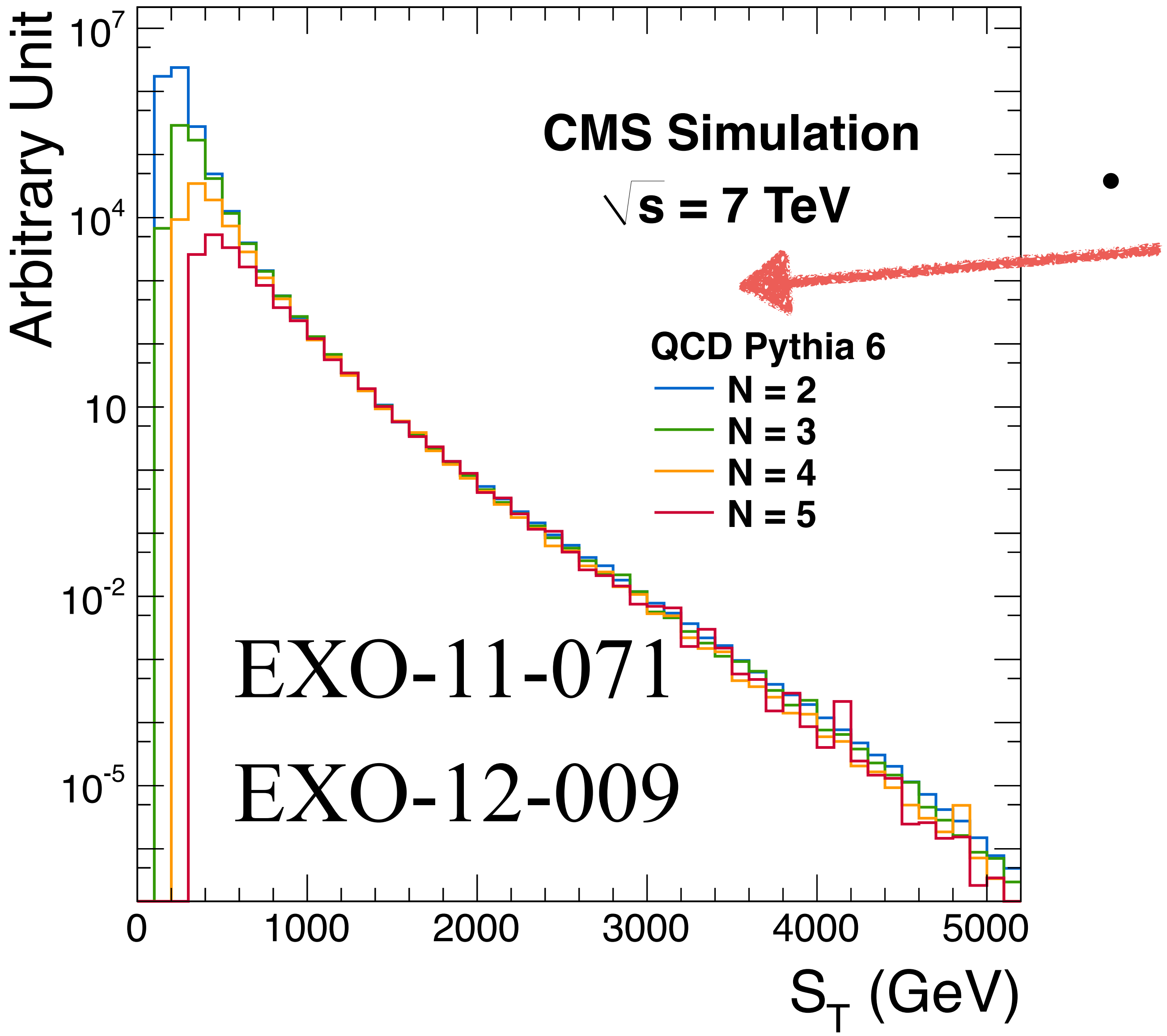
- Set limits on squark mass
- Combine exclusive jet multiplicity bins (4, 5, 6, ≥7)
- Use the S_T threshold with best sensitivity



- Exclude squark masses ~550 GeV

Background estimate ($\gamma\gamma$)

- S_T invariance method: S_T shape independent of N_{jets}

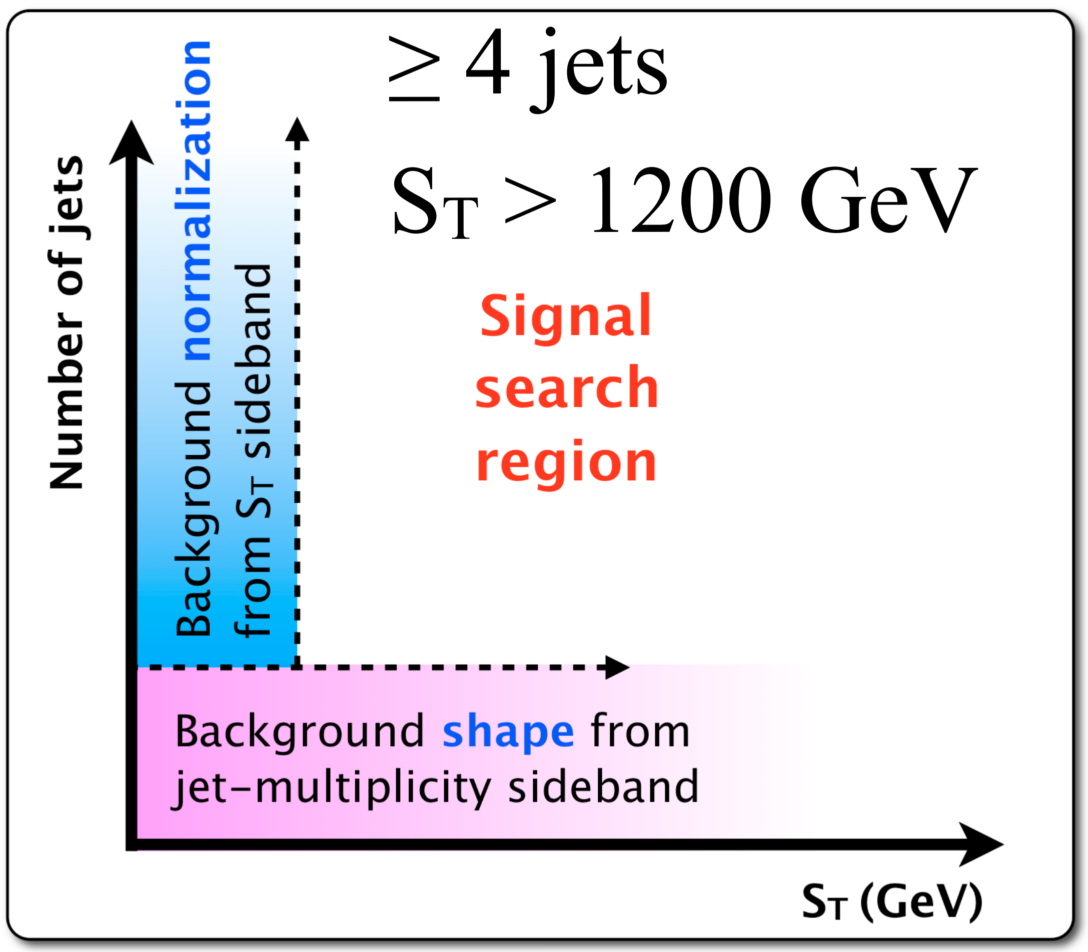


- Validated for:
  - inclusive QCD events (data & simulation)
  - data with 1-γ
  - simulation with $\gamma\gamma$

- Estimate S_T shape from low jet multiplicity

Background estimate ($\gamma\gamma$)

- S_T invariance method: S_T shape independent of N_{jets}



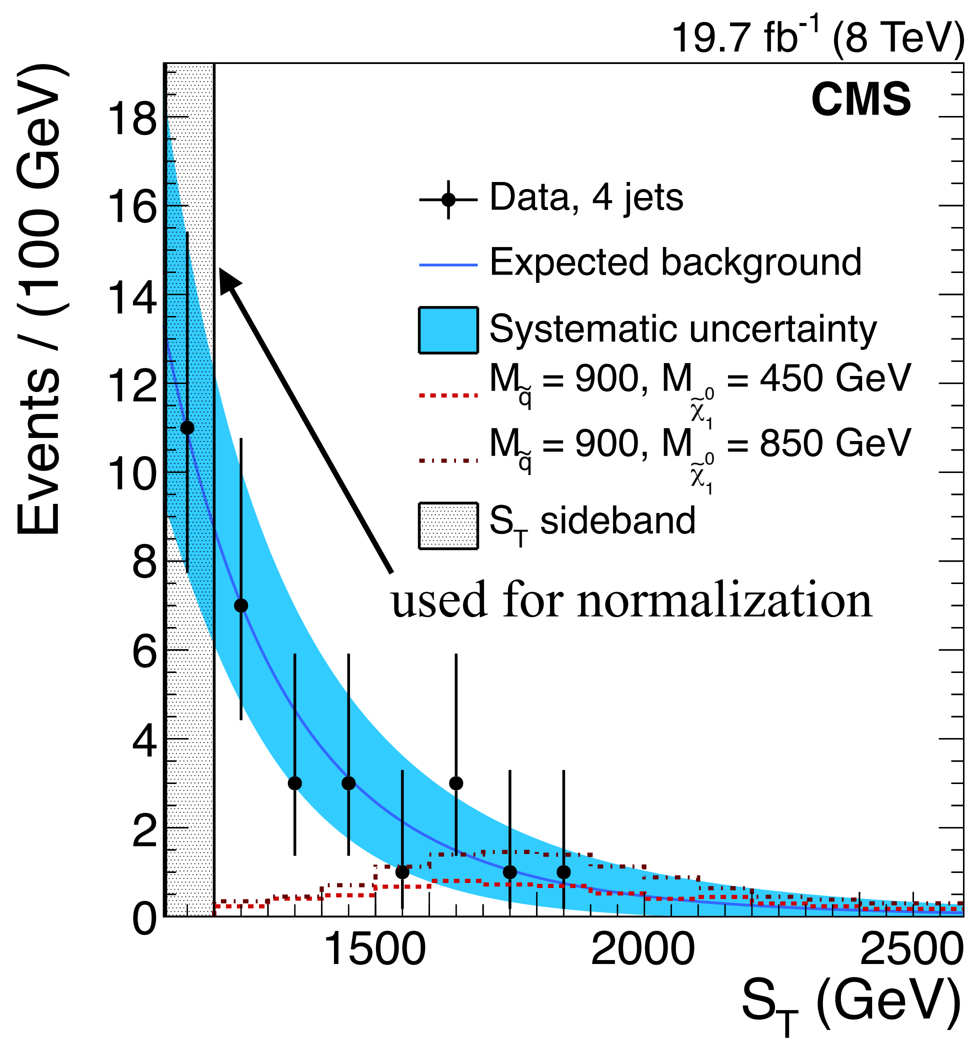
- Shape from 3 jet data using fit
  - Functional form described 1-γ data and $\gamma\gamma$ simulation

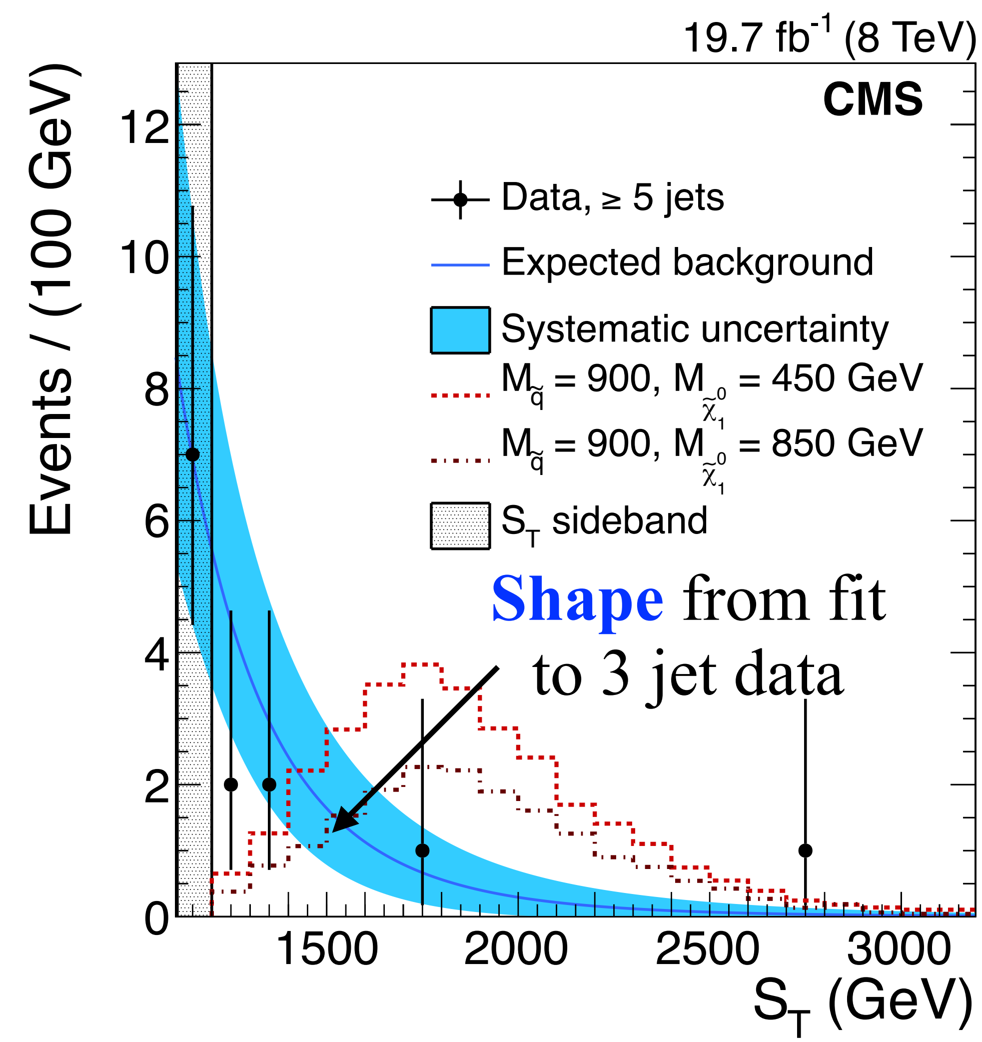
- **Normalize** with an S_T sideband (1100-1200 GeV)

Physics
Carnegie Mellon University

CMS

Results ($\gamma\gamma$)



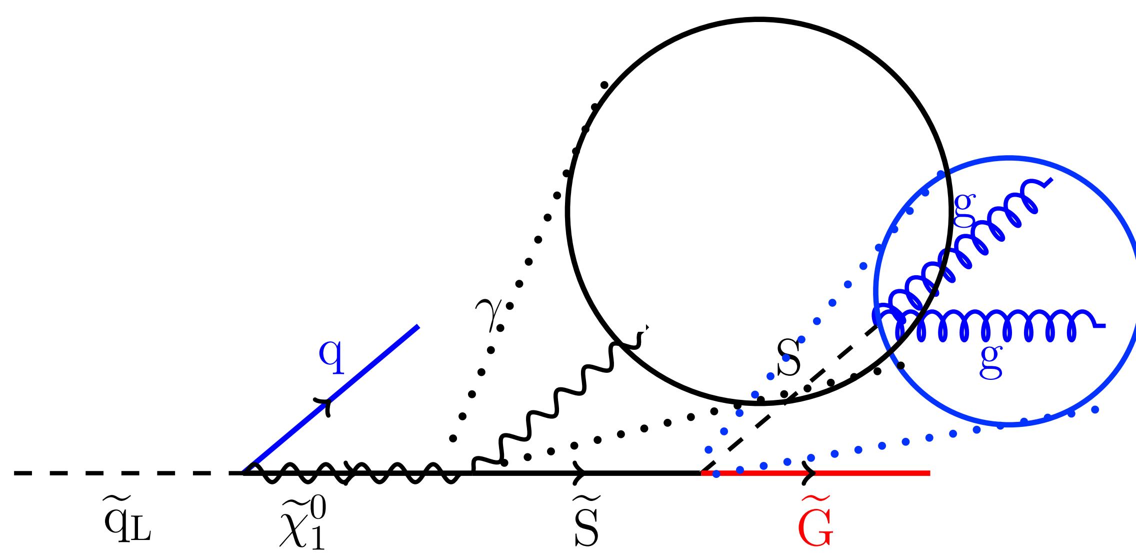


- Systematic uncertainty dominated by **normalization** region statistical uncertainty

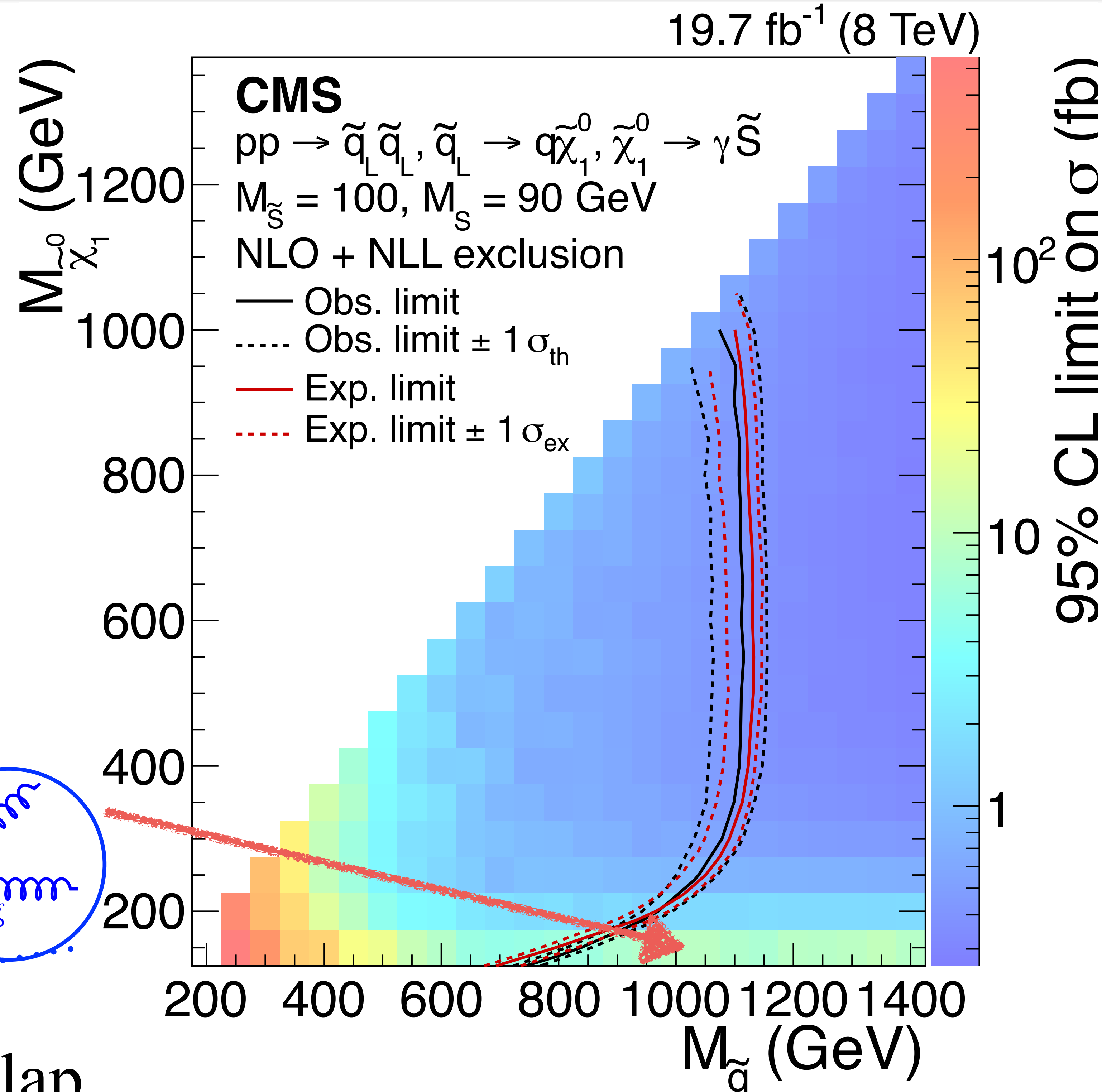
Physics
Carnegie Mellon University

Stealth SUSY limits: $\gamma\gamma$

- Set limits on squark mass
- Combine 4, ≥5 jet bins and all S_T bins in interpretation
- Exclude squark masses ~1050 GeV



Photon/jet overlap



R-parity violation

arXiv: 0406039

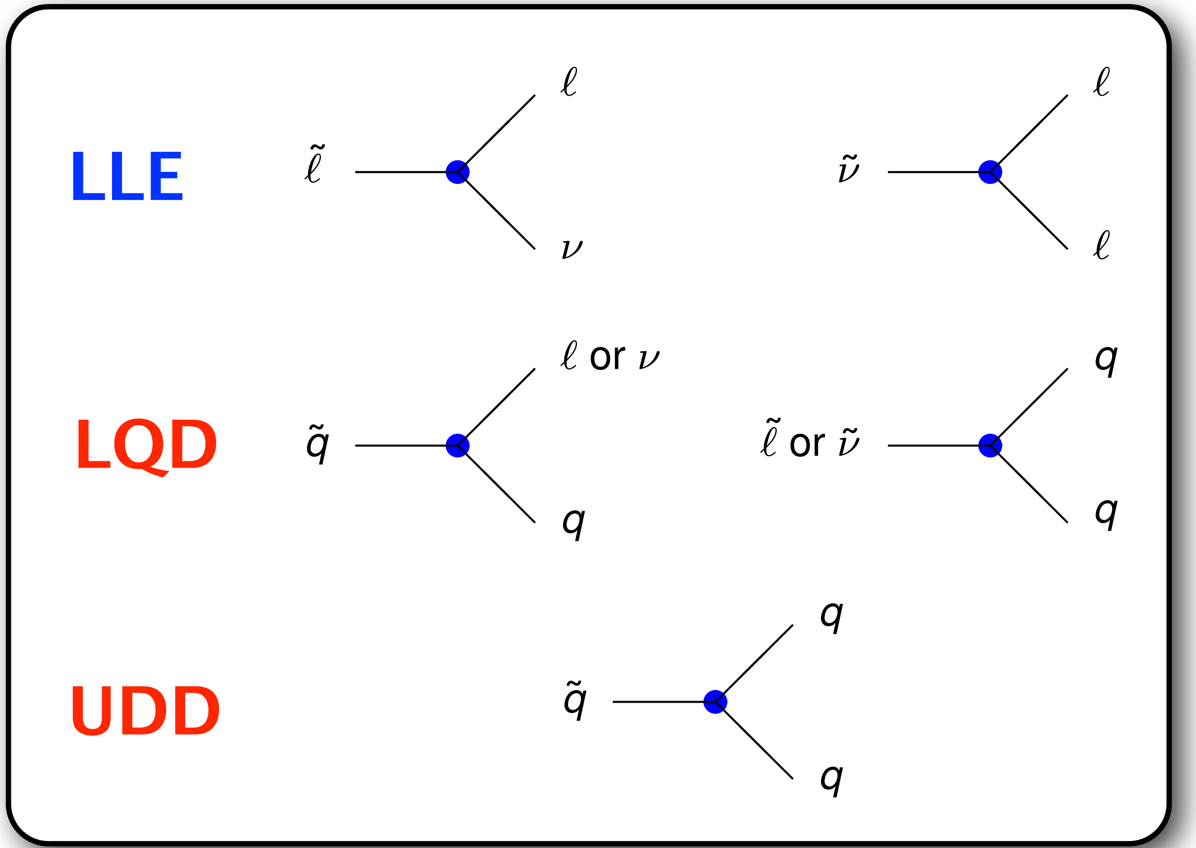
$$W_{\mathrm{RPV}} = \frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k$$

$(\Delta L, \Delta B) = (1, 0)$ $(\Delta L, \Delta B) = (1, 0)$ $(\Delta L, \Delta B) = (0, 1)$

lepton number violating baryon number violating

L = left-handed lepton doublet
Q = left-handed quark doublet
i, j, k = generation indices
E = right-handed lepton singlet
U,D = right-handed quark singlet
$\lambda, \lambda', \lambda''$ = RPV couplings

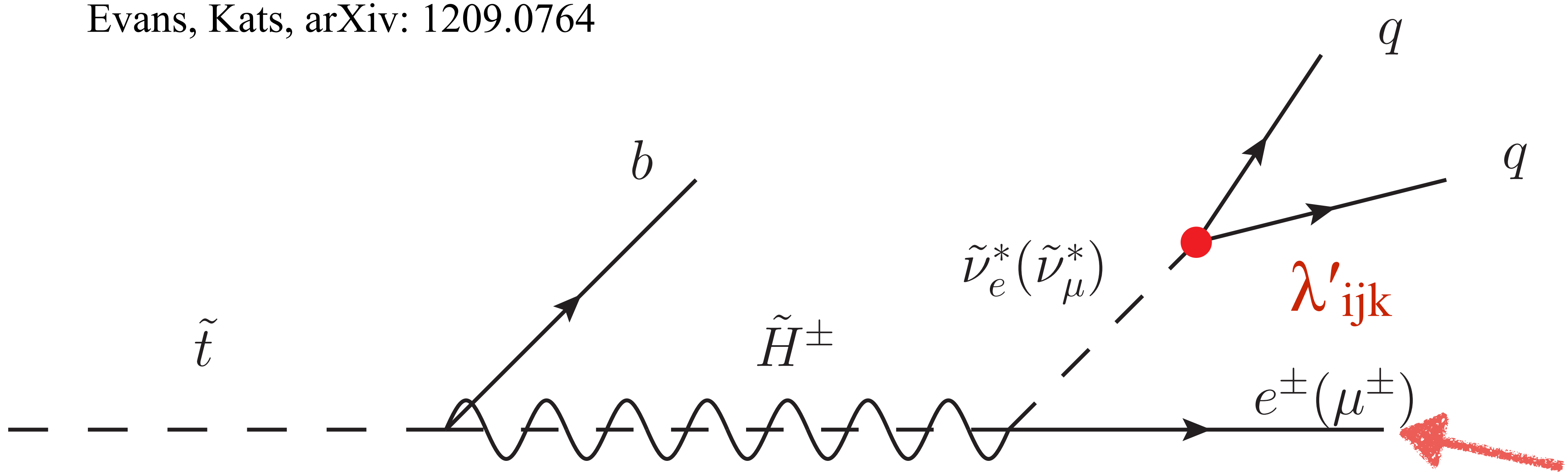
- Allow SUSY particles to decay directly to two SM particles
- Generator of low-E_T^{miss} signatures



Evans, Kats, arXiv:1209.0764

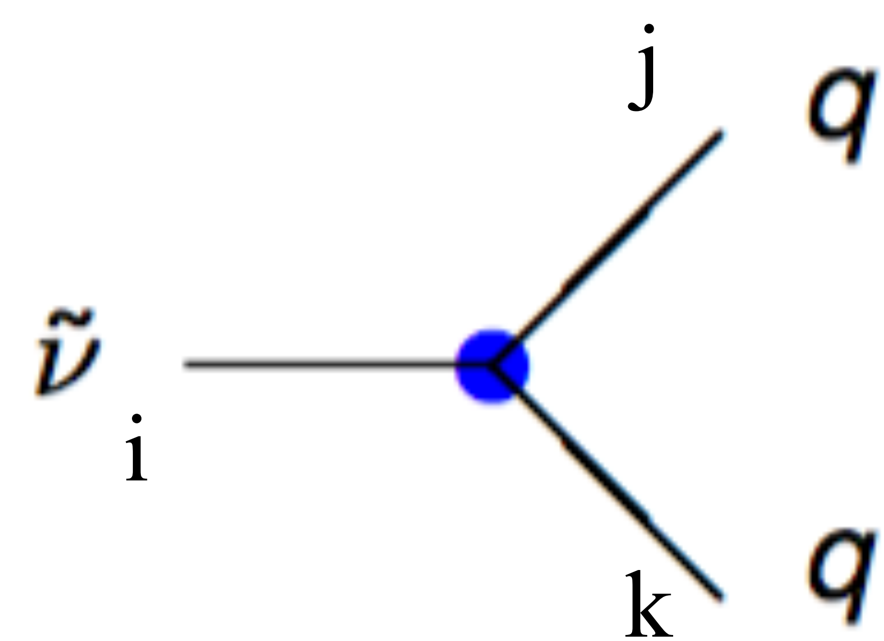
Example higgsino mediated top squark decay

Evans, Kats, arXiv: 1209.0764



Any lepton flavor

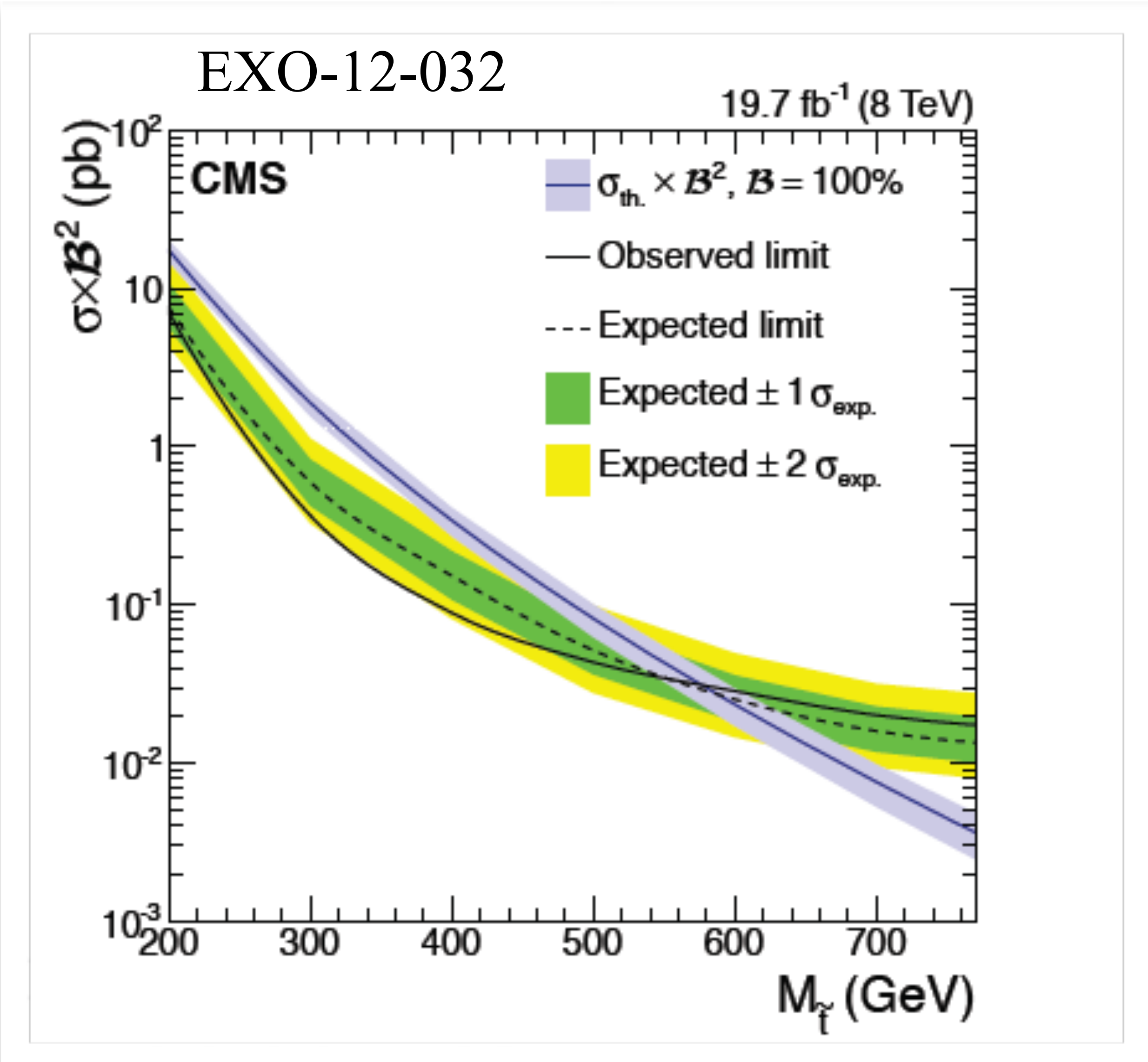
- Both top squark and Higgsino should be light
- Allow R-parity violation in decay chain
- i: lepton generation index
- j,k: quark generation index



Physics
Carnegie Mellon University

Example higgsino mediated top squark decay

- Search using $\tau\tau$ completed EXO-12-032

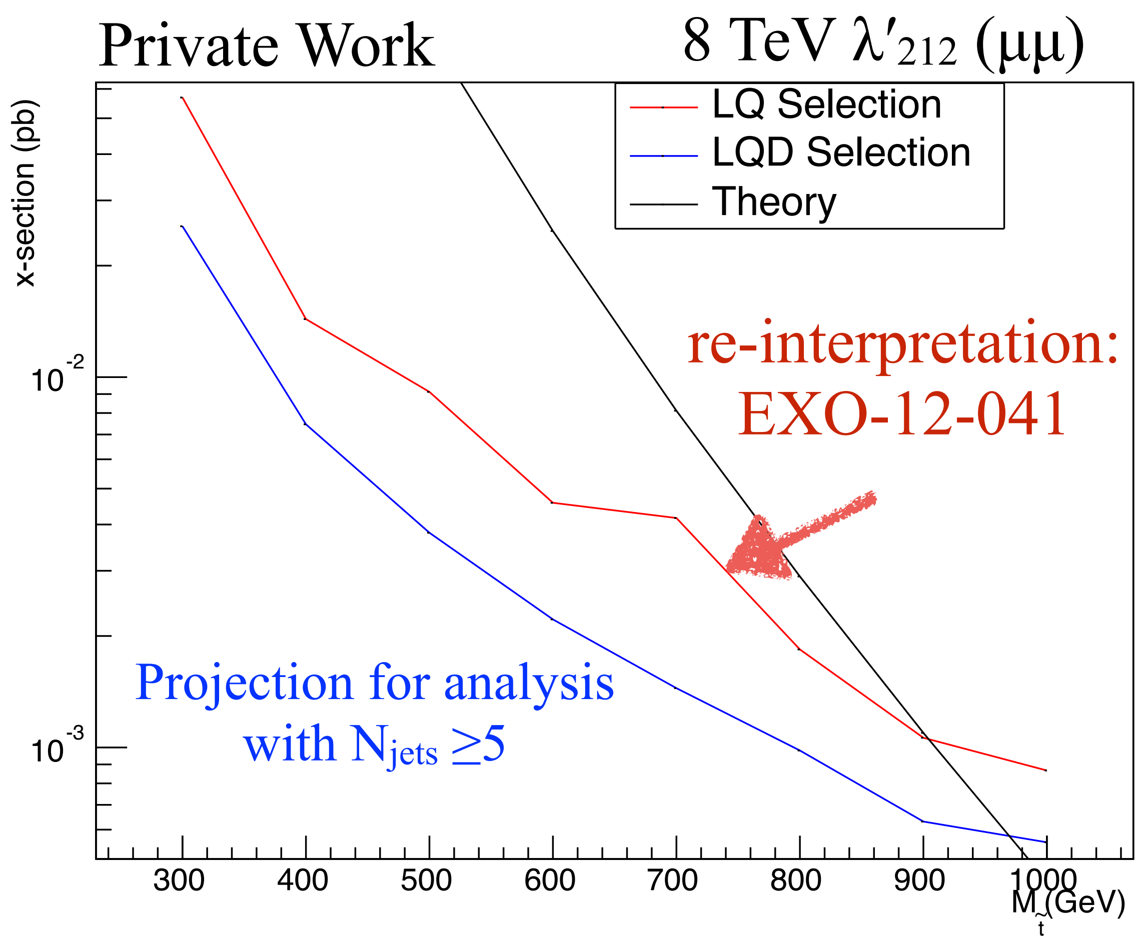


- $N_{jets} \geq 5$ ($\geq$1 b-tag)
- One leptonic τ, one hadronic τ
  - $e(\mu)\tau_h$
- Sensitivity from S_T of events

Physics
Carnegie Mellon University

Example higgsino mediated top squark decay

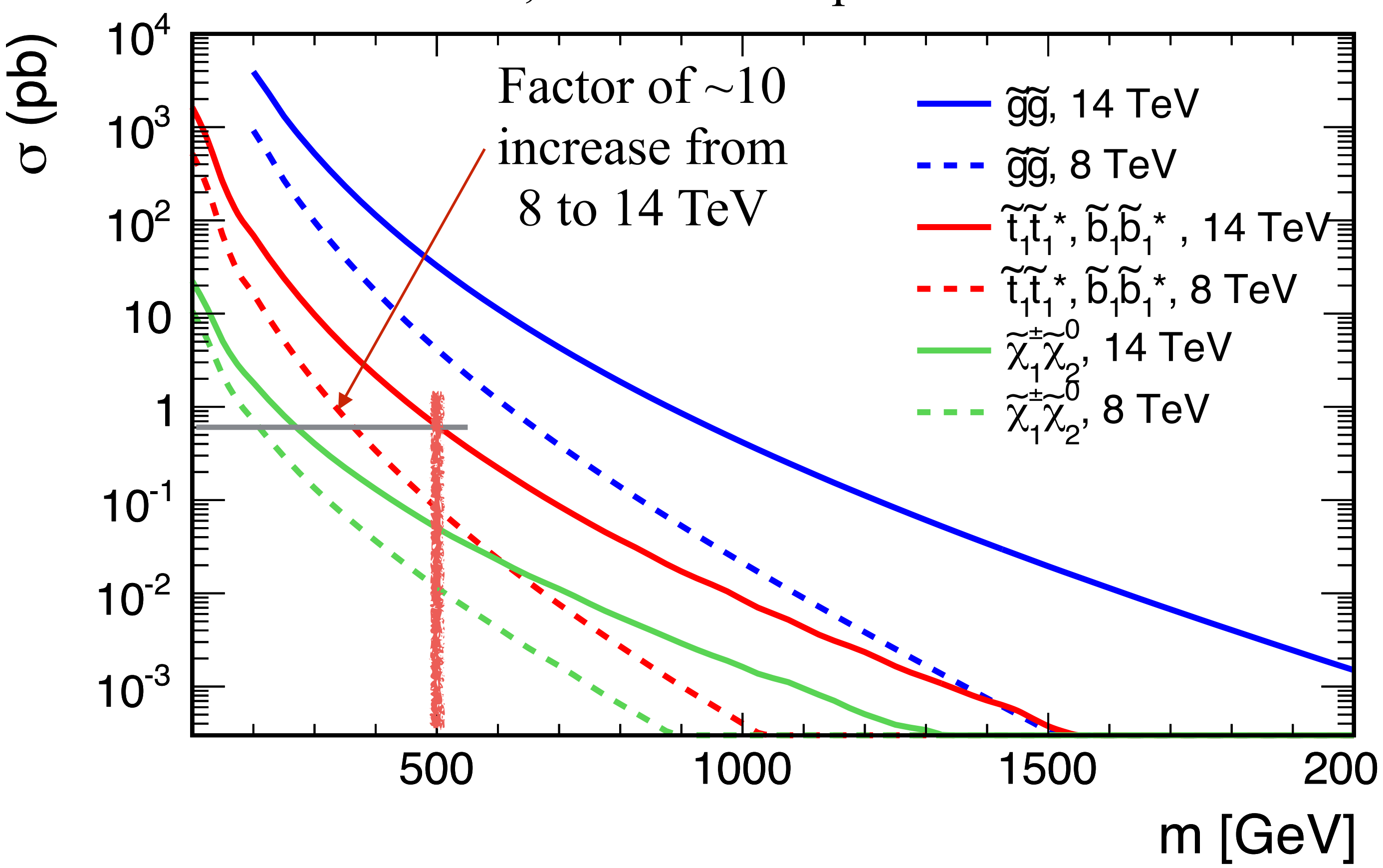
- First (second) generation LQ analyses give some sensitivity
  - Require ee (μμ), at least two jets
    - $M(\ell\ell)$, $M(\ell j)$, S_T



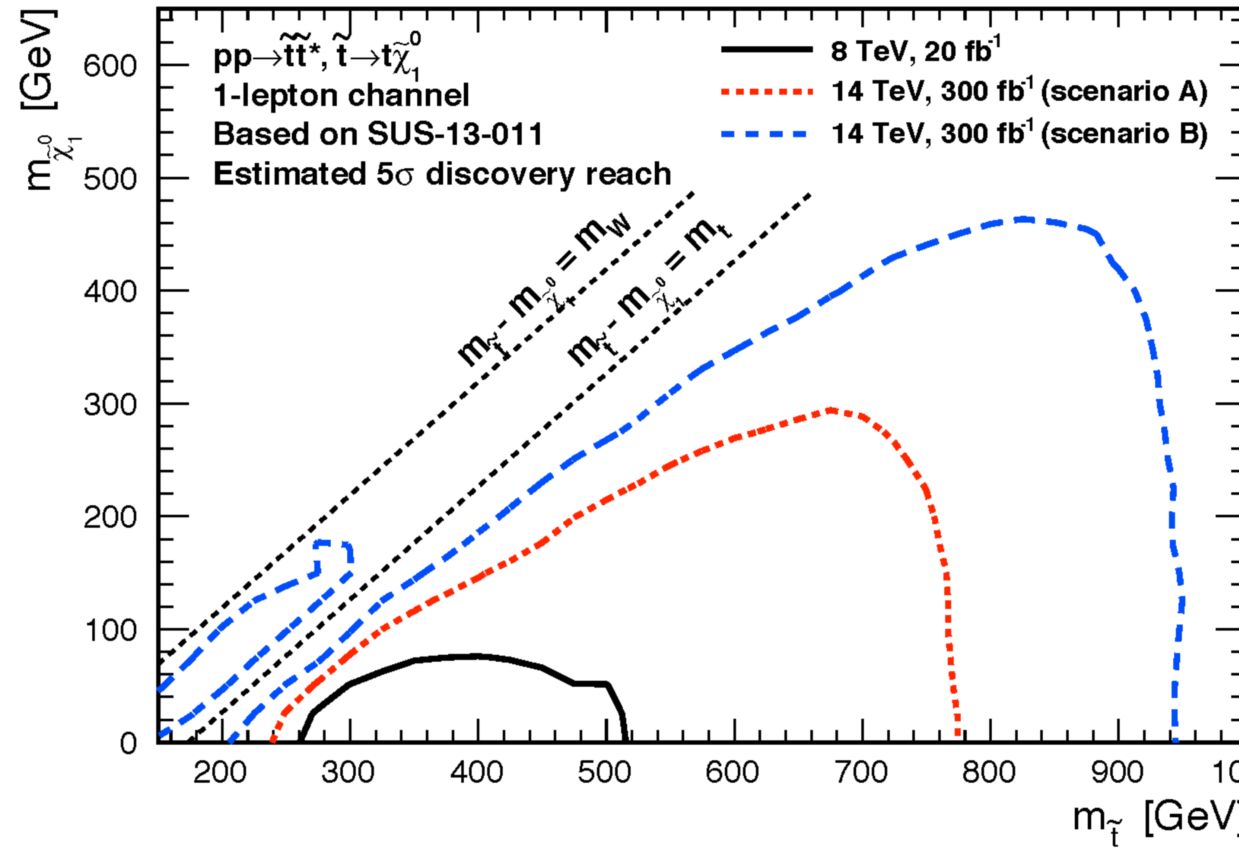
- Dedicated search optimized for this decay
  - $N_{jets} \geq 5$, ≥ 1 b-tag
  - $E_T^{miss} < 100$ GeV
  - $M(\ell\ell) > 130$ GeV
  - S_T optimized for each mass point
- Improve sensitivity by a factor of **2-3 improvement**

Projections for 13 TeV

arXiv: 1307.7135, Snowmass report



Snowmass2013SUS



- Substantial increase in sensitivity to new physics from 8 to 13(14) TeV

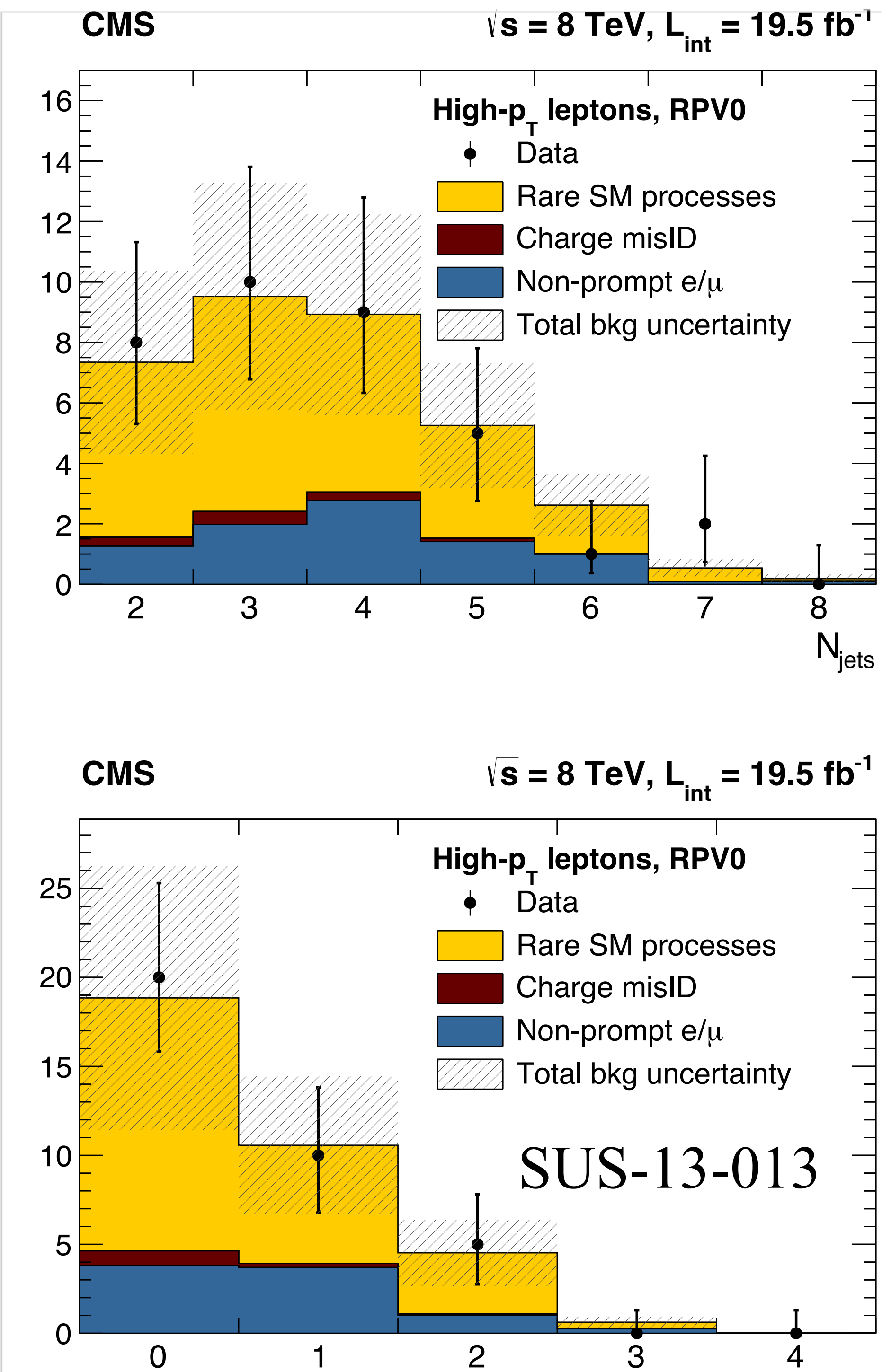
Future directions

- The future direction allow for the possibility that only one squark is light, particularly the top squark
- Strategy:
  1. Address as many models as possible standard SUSY searches with added **low E_T^{miss} bins**
     - **SS dileptons, multileptons**
  2. Design **creative analyses** for challenging (fun) decay chains

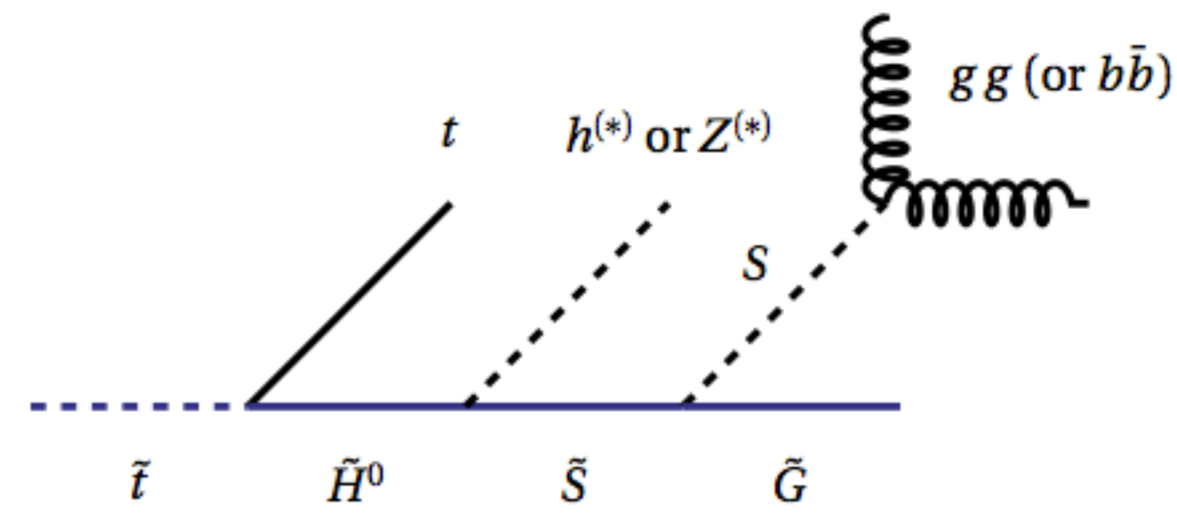
Physics
Carnegie Mellon University

CMS

Same-sign dileptons

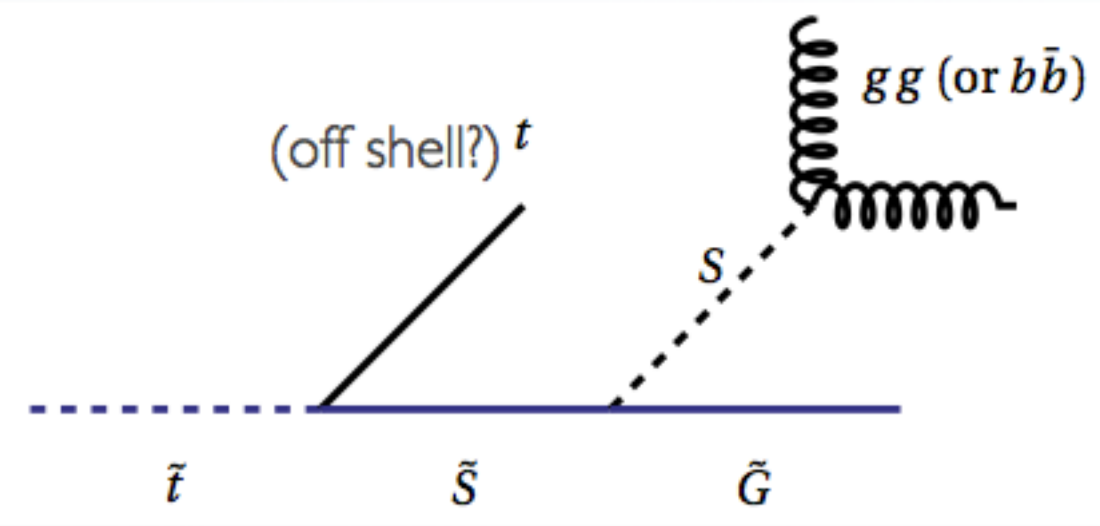


Bin of SS analysis (RPV0):
No MET requirement
$H_T > 500$ GeV



- ttbar background suppressed by same-sign requirement
- SS dileptons background estimation can be modified to search for low E_T^{miss} events
- Dominant backgrounds
  - Rare SM backgrounds (ttW, ttZ)
  - non-prompt leptons

Stealth decays with a dijet resonance



- Allow the top squark to decay directly to stealth singlino

- Signature: **top quarks with additional jets**
  - Could be b jets, but not necessarily
- Challenging signature because of similarity to top quark background
- Search for (paired) **dijet resonance** in top events
  - Select a sample of top quark events using leptons and b jets

Summary

- Low-E_T^{miss} SUSY searches are an important complement to existing searches
  - We search in events that have either two **leptons** or two **photons** plus many jets
- Exclude squark masses below **550 GeV** for stealth decays with **leptons** and **1050 GeV** with **photons**
- Limits on squark masses for stealth models are comparable to those from models with E_T^{miss}
- Future direction: top squarks and Higgsino mediated top squark decays

Physics
Carnegie Mellon University

CMS
Compact Muon Solenoid

Backup

Drell-Yan background

- Estimate DY background (~10%) with a data-driven procedure that accounts for signal contamination
- Fit the **dimuon mass** distribution (50-130 GeV) in **$\mu^+\mu^-$ control region**
  - **DY** shape from MC
  - **Diboson** shape from MC
  - Use first order **polynomial** to describe **non-peaking components** (top, and potential signal)
  - **Floating parameters**: DY normalization (N_{DY}^{fit}), polynomial slope and normalization
- Correct DY MC in search region using $R=N_{DY}^{fit}/N_{DY}^{MC}$ for each N_{jets} bin

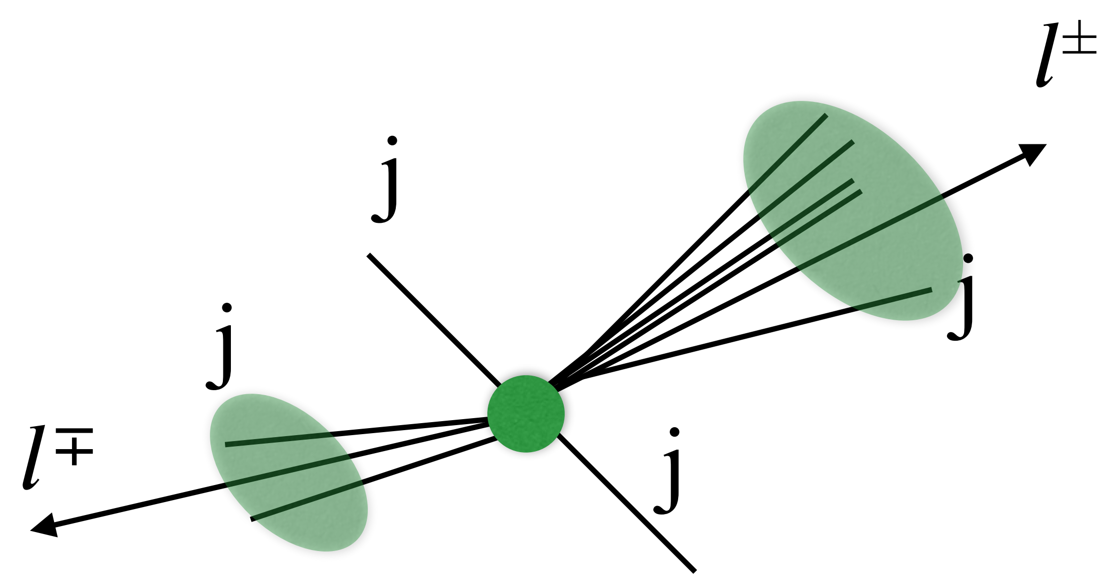
Physics
Carnegie Mellon University

CMS

Non-prompt lepton estimate

Signal produces OS dileptons

- Use **same sign e,μ** pairs to estimate contribution from non-prompt leptons
- **Subtract** background MC from SS data to estimate non-prompt contribution to OS signal region



- Cartoon of sample event with non-prompt leptons

Signal efficiency

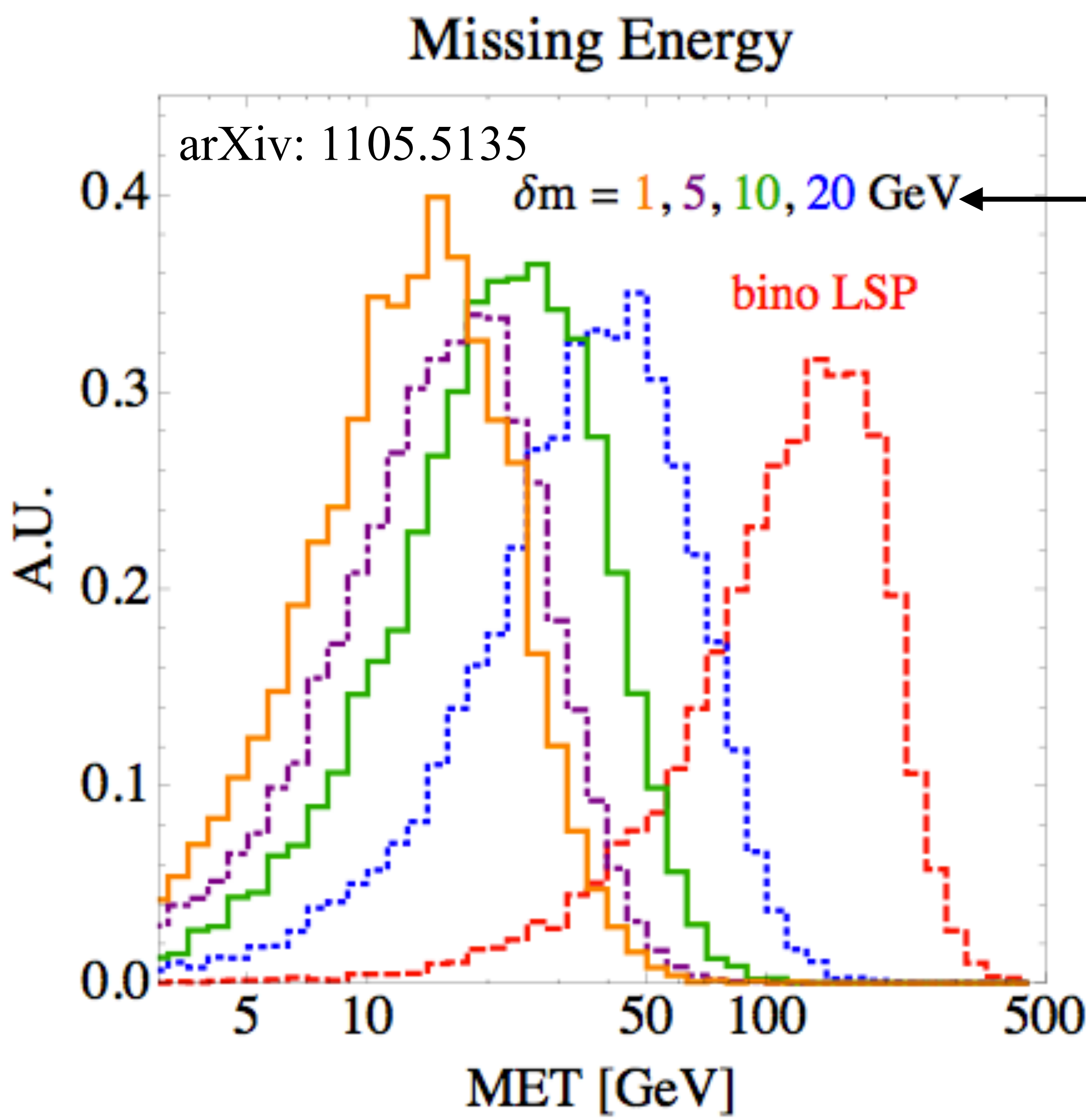
- Sample efficiency for 600 GeV squark
- The nominal branching fraction for W(W)→e(μ) is approximately 2%
- Most significant efficiency reduction comes from **isolation**

Selection	Efficiency [%]
$N_{\text{jets}} \geq 4$, $S_T \geq 300$	99.03 ± 0.05
1 loose μ, 1 loose electron, no isolation	1.70 ± 0.06
1 loose μ, 1 loose electron, loose isolation	1.10 ± 0.05
1 tight μ, 1 tight electron, tight isolation	0.96 ± 0.05
Veto additional loose leptons	0.96 ± 0.05
0 b-tagged jets	0.83 ± 0.04

Physics
Carnegie Mellon University

CMS

No MET handle on stealth

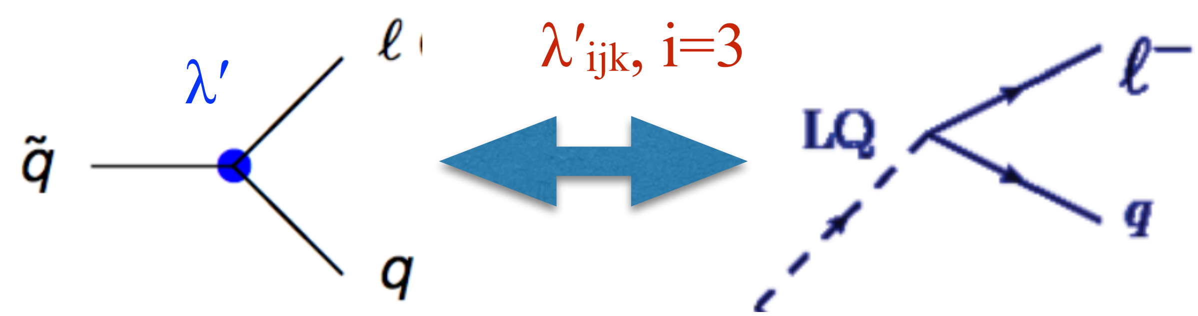


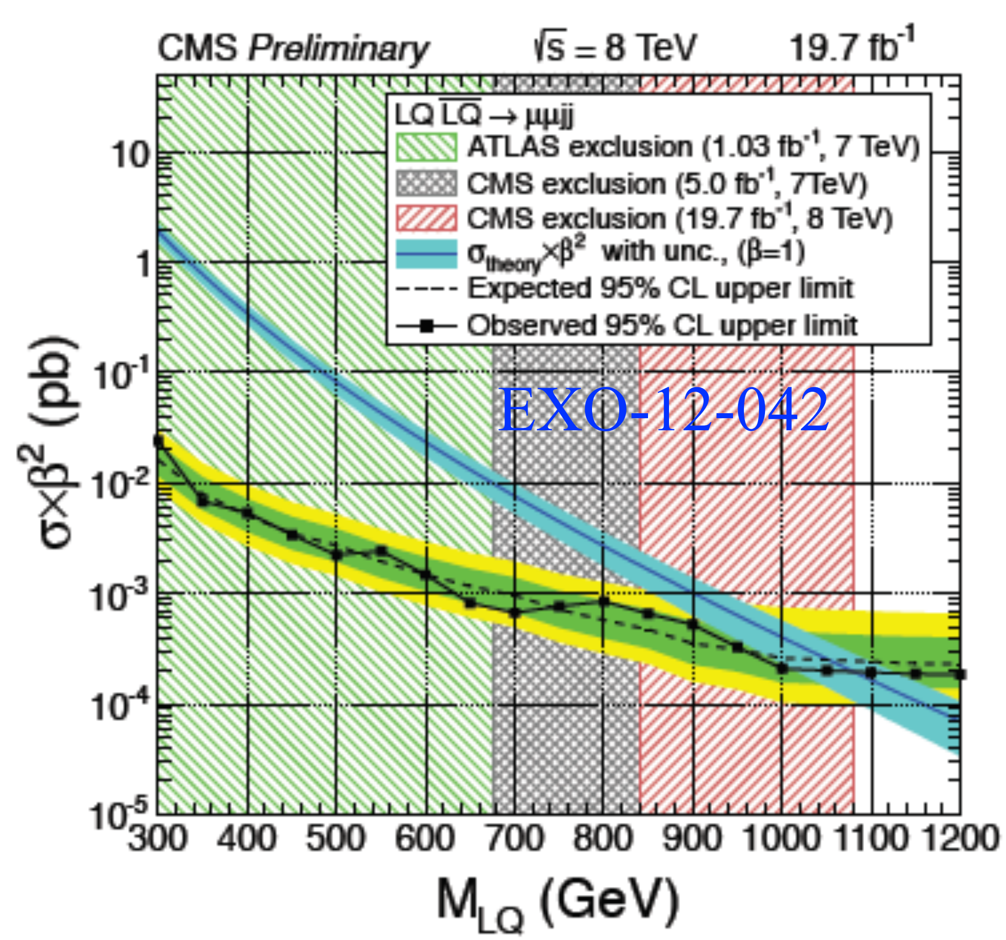
- Mass splitting between $\tilde{S}$ and S controls MET
- As mass splitting goes down, MET goes down

Stealth SUSY has a variety of signatures:
jets, gauge bosons, but…
no MET!

RPV top squark decays

- Direct decay by LQD operator
- Top squark → {(e,j),(μ,j),(τ,b)}
  - Limits from leptoquark searches EXO-12-041(042)(032)
- Selections:
  - Two same flavor leptons ee (μμ)
  - At least two jets
  - Selections on kinematic variables
    - M(ℓℓ), M(ℓj), S_T



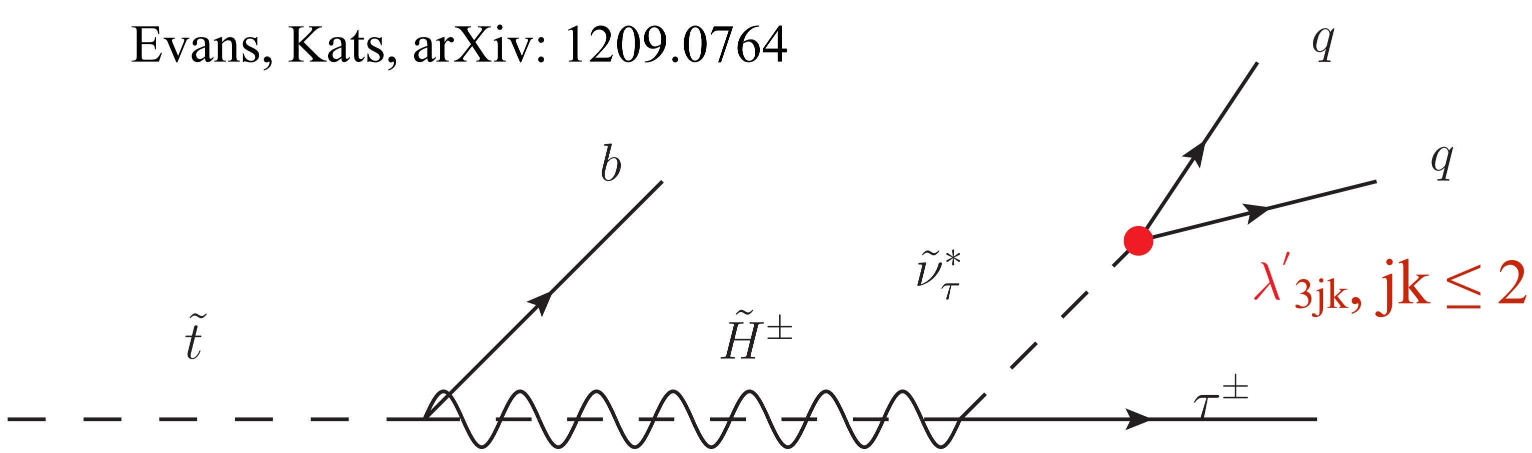


M_{LQ} equivalent to M(top squark)

Physics Carnegie Mellon University

Higgsino mediated top squark decay

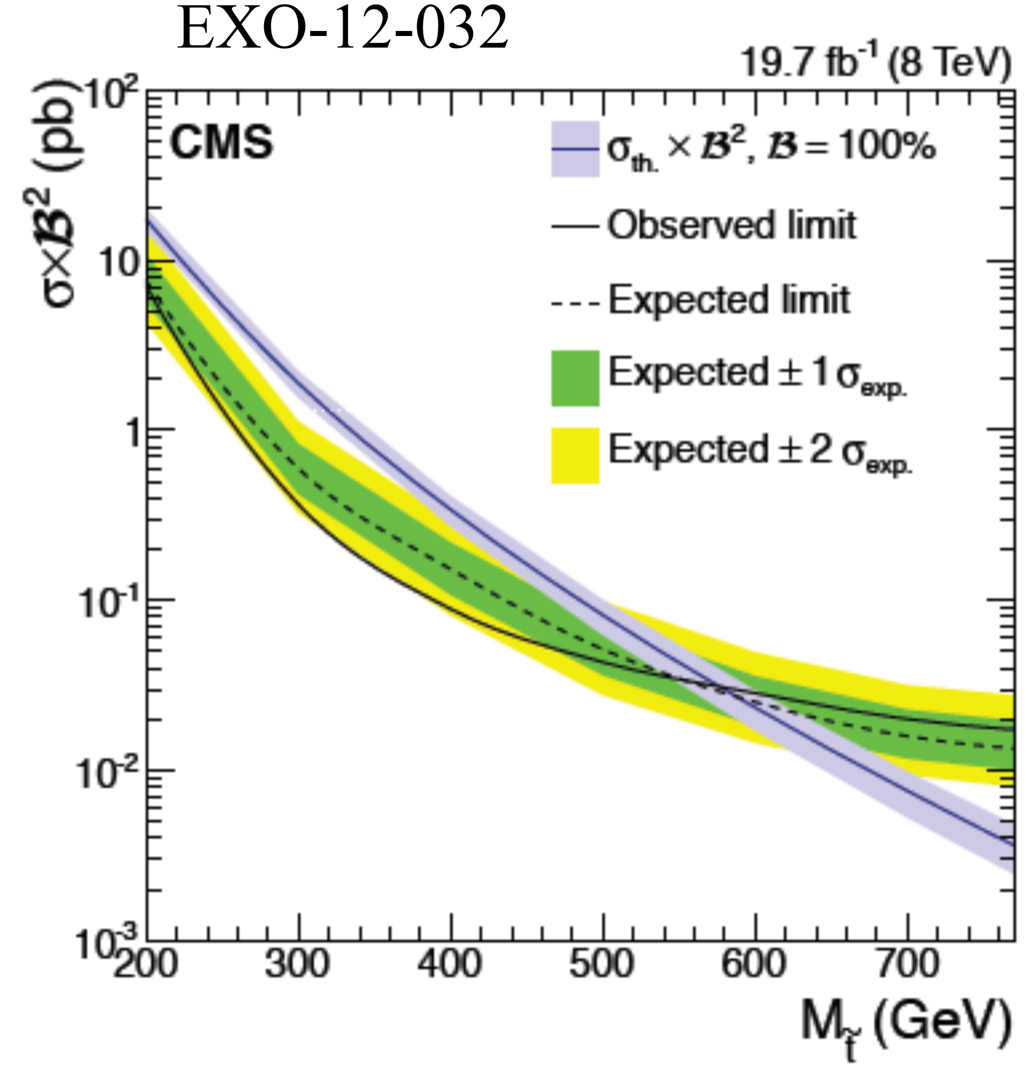
Evans, Kats, arXiv: 1209.0764



- Allow top squark to decay to Higgsino
- Higgsino to decay to SM states by RPV

- Third generation LQ search (τ,b)
  - Two same flavor leptons ($\tau\tau$)
  - Implemented search region with $N_{jets} \geq (2)\ 5$
  - Many jets increase sensitivity to Higgsino mediated decays

EXO-12-032



Physics
Carnegie Mellon University

Indirect limits

	ijk	λ'_{ijk}	ijk	λ'_{ijk}	ijk	λ'_{ijk}	
	111	0.001^{d}	211	0.09^{h}	311	0.16^{k}	**d**
u	112	$0.02^{a\dagger}$	212	0.09^{h}	312	0.16^{k}	**s**
	113	$0.02^{a\dagger}$	213	0.09^{h}	313	0.16^{k}	**b**
	121	$0.035^{e\dagger}$	221	0.18^{i}	321	0.20^{f*}	**d**
c	122	0.06^{c}	222	0.18^{i}	322	0.20^{f*}	**s**
	123	0.20^{f*}	223	0.18^{i}	323	0.20^{f*}	**b**
	131	$0.035^{e\dagger}$	231	$0.22^{j\dagger}$	331	0.26^{g}	**d**
t	132	0.33^{g}	232	0.39^{g}	332	0.26^{g}	**s**
	133	0.002^{c}	233	0.39^{g}	333	0.26^{g}	**b**
	e		**μ**		**τ**		

Limits assume single coupling dominates and $\tilde{M}$=100 GeV.

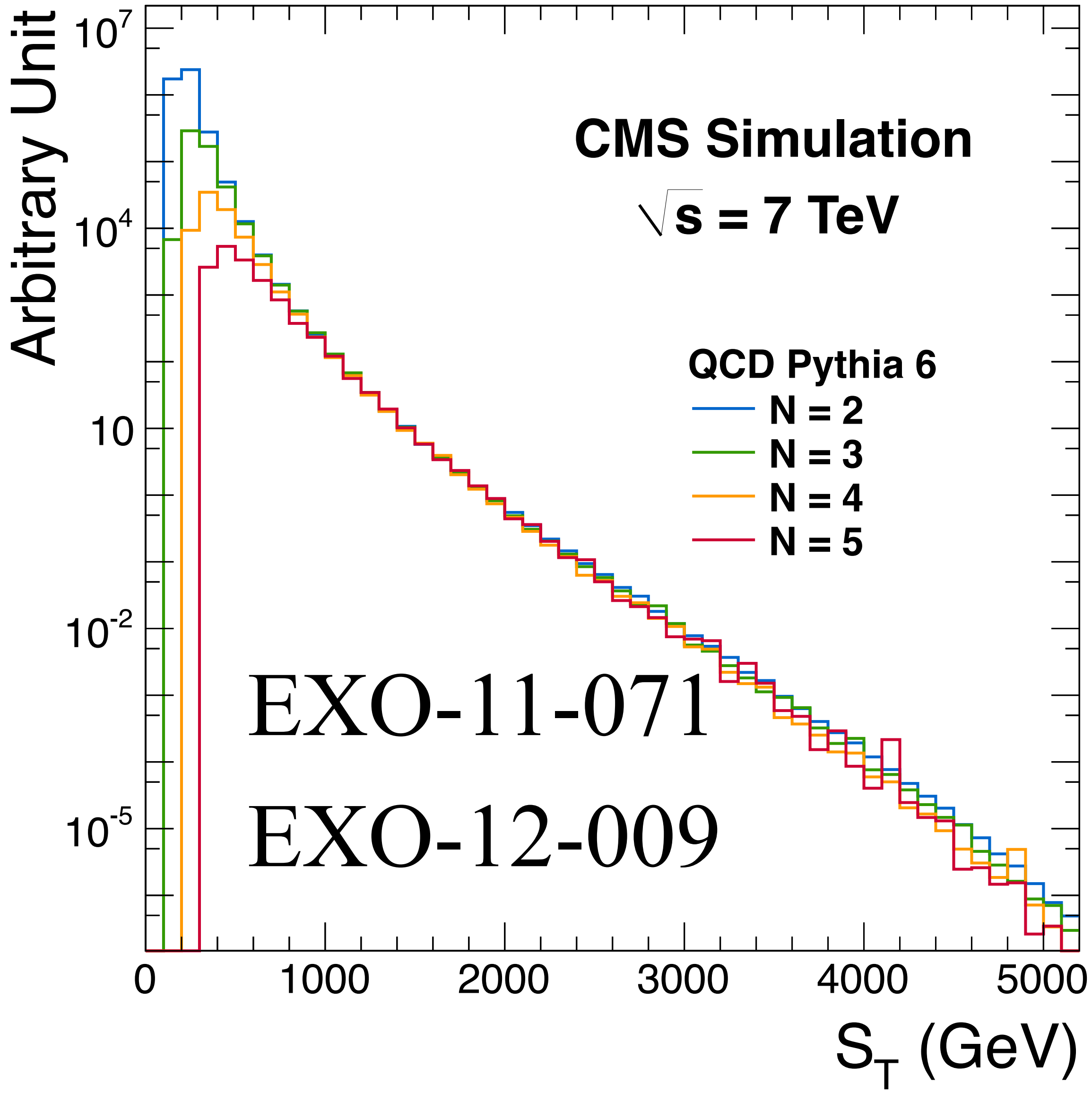
$^{a-h}$ sources of constraint: charged current universality, τ BRs, ν_e mass ν-less double β decay, $D^0 - \bar{D}^0$ mixing, Z, pion, D^+ BRs, etc.

* assume CKM mixing is due to absolute mixing of up-type quarks

† 2σ bound

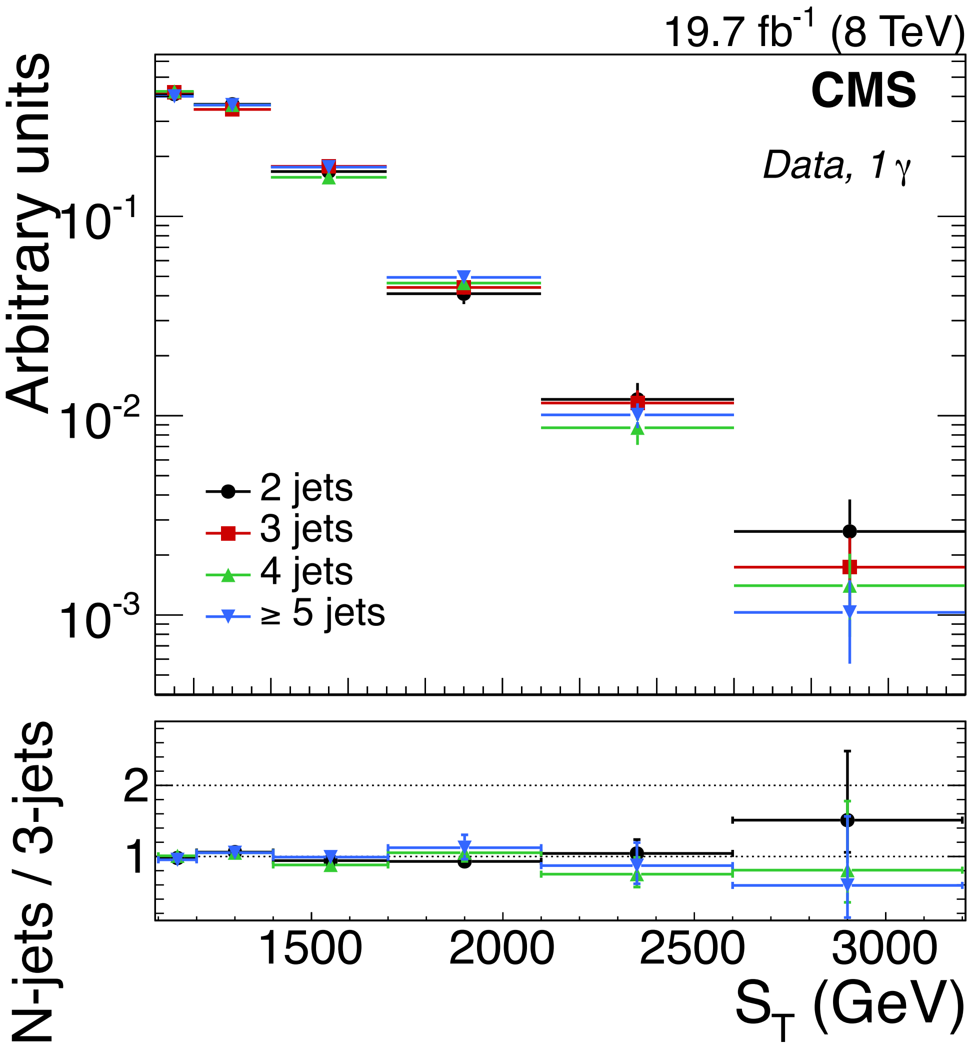
Dreiner, arXiv:hep-ph/9707435

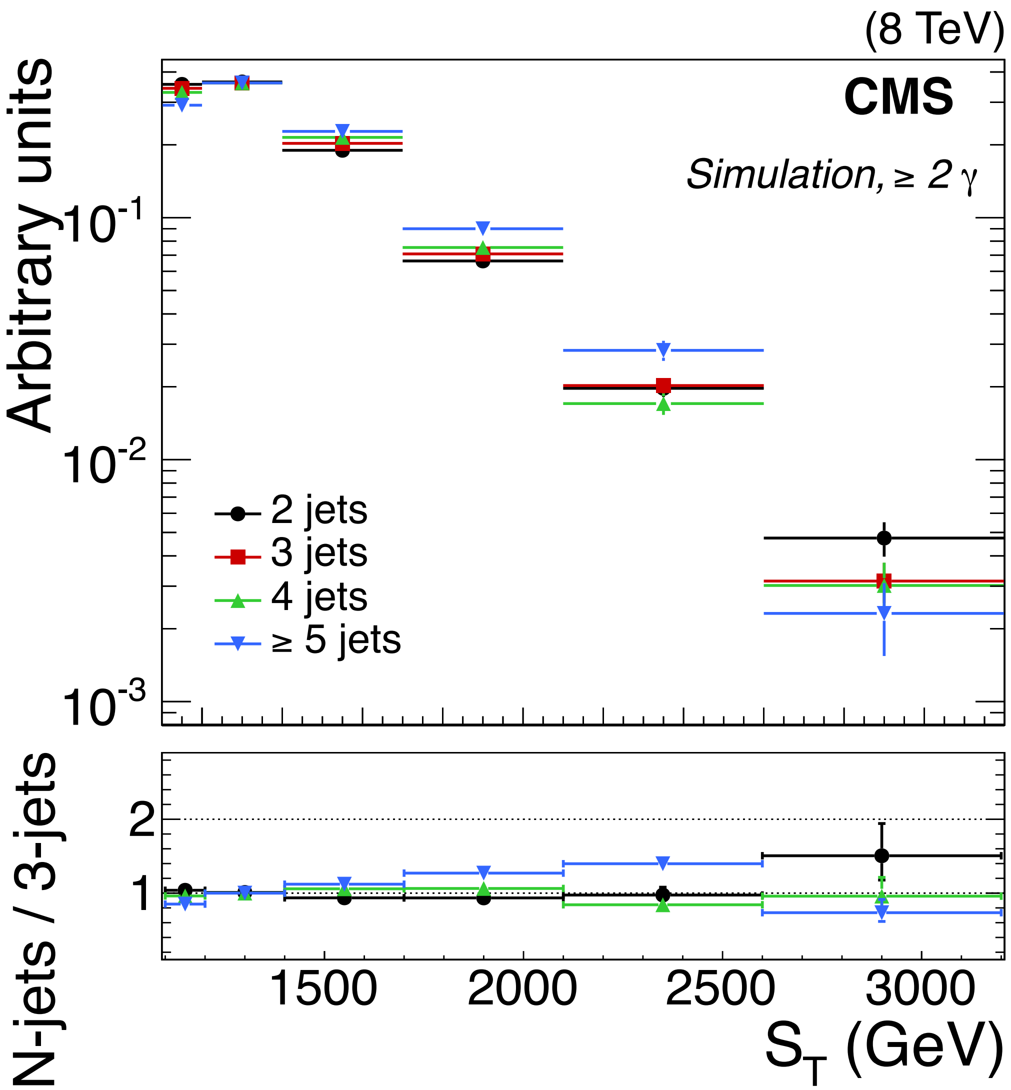
S_T invariance method: inclusive QCD events



- Used in search for black holes to estimate QCD background in all hadronic events
- Also used to estimate QCD events with photons in SUSY search at 7 TeV (SUS-12-014)

S_T invariance with γ or $\gamma\gamma$





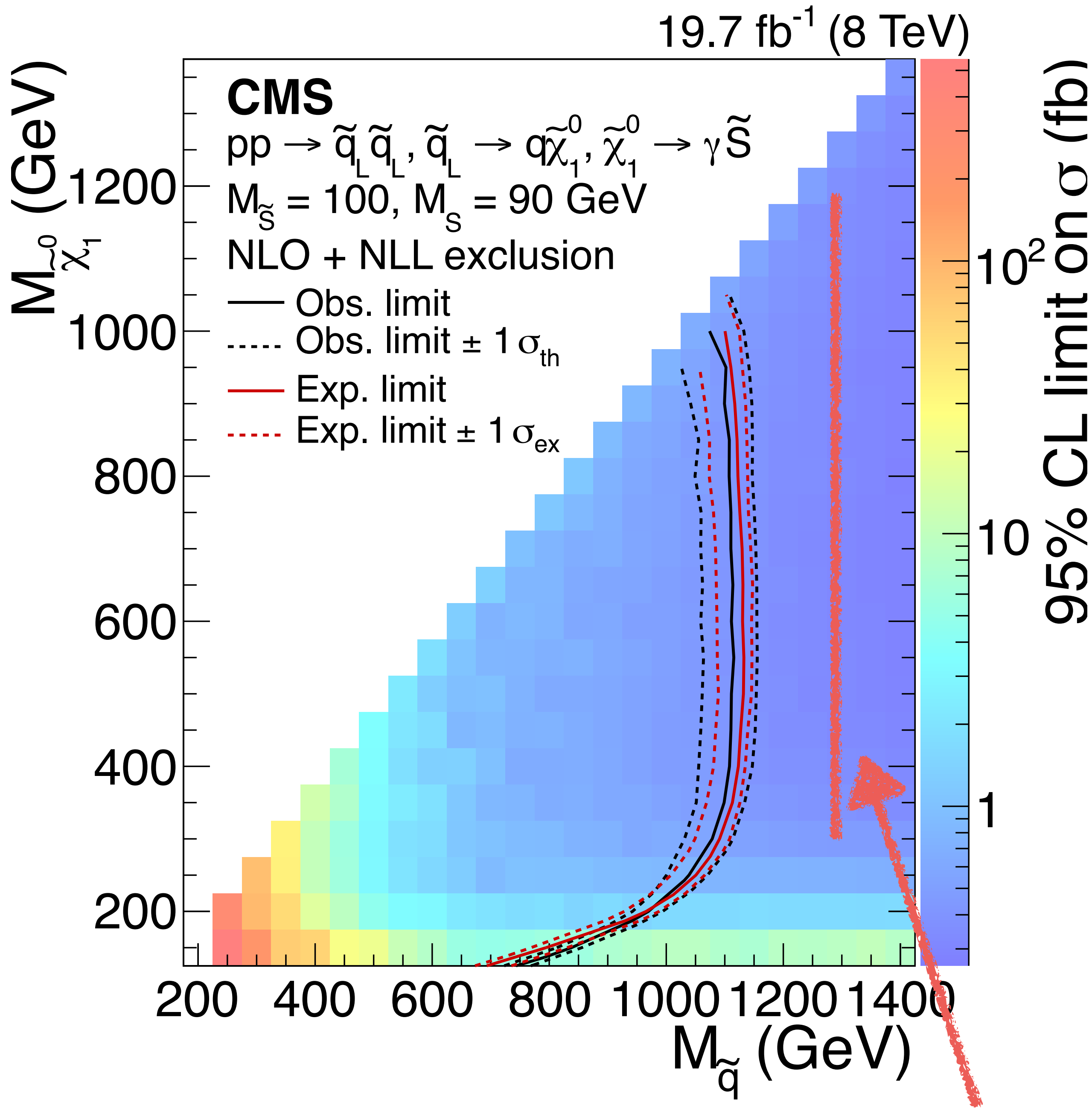
- S_T shapes do not depend on N_{jets}

Region	N_{jets}	S_T (GeV)
Search	≥4	>1200
S_T sideband	≥4	1100–1200
N_{jets} sideband	=3	>1100

Physics
Carnegie Mellon University

Stealth SUSY limits: 13 TeV projections

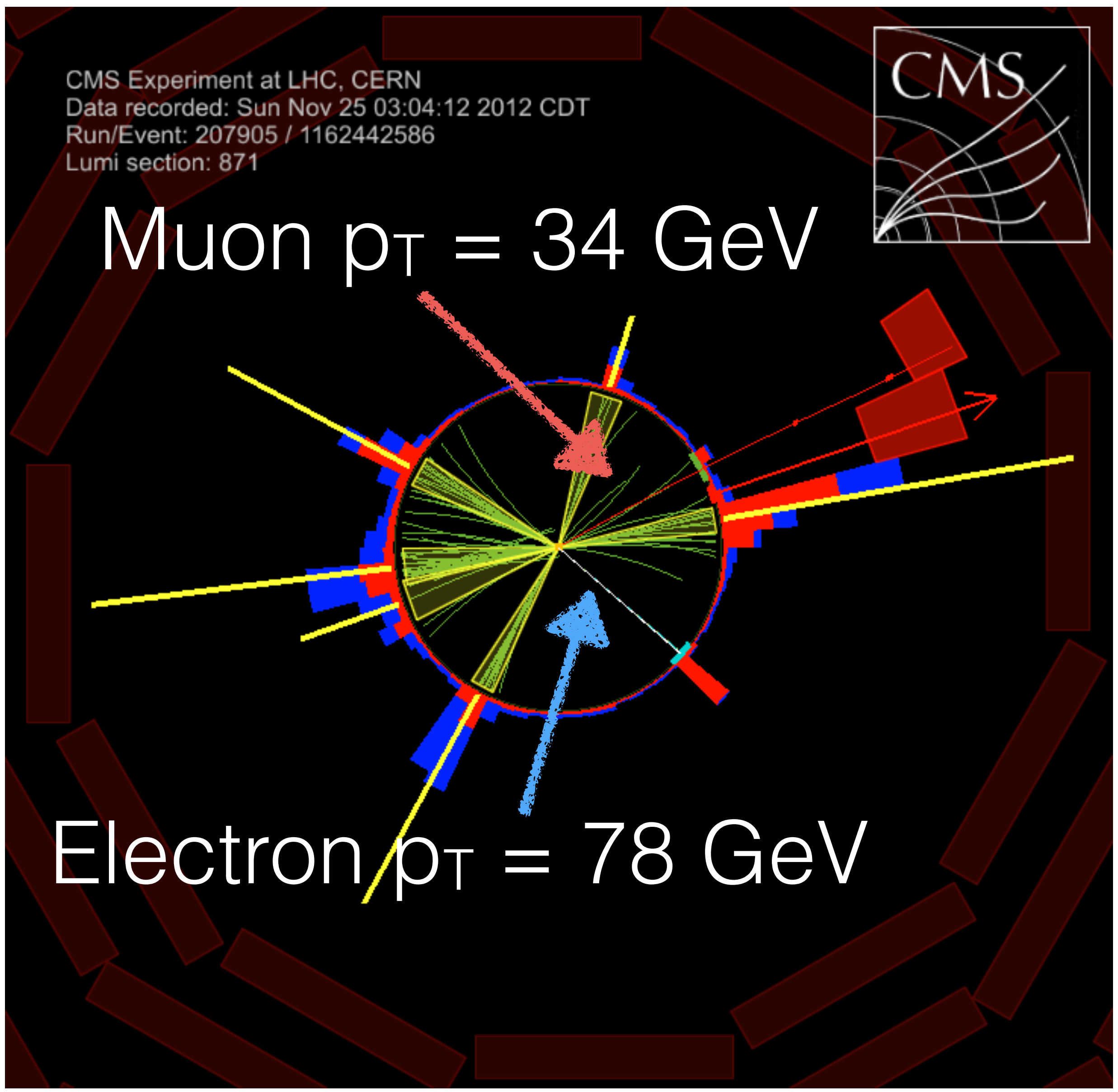
- Backgrounds increase by a factor of two
- Limits based on 10 fb^{-1}
- Photons:
  - Signal efficiency ~30%
  - Exclusion improved to ~1300 GeV
- Leptons:
  - Signal efficiency 2%
  - Exclusion limit improved to ~900 GeV

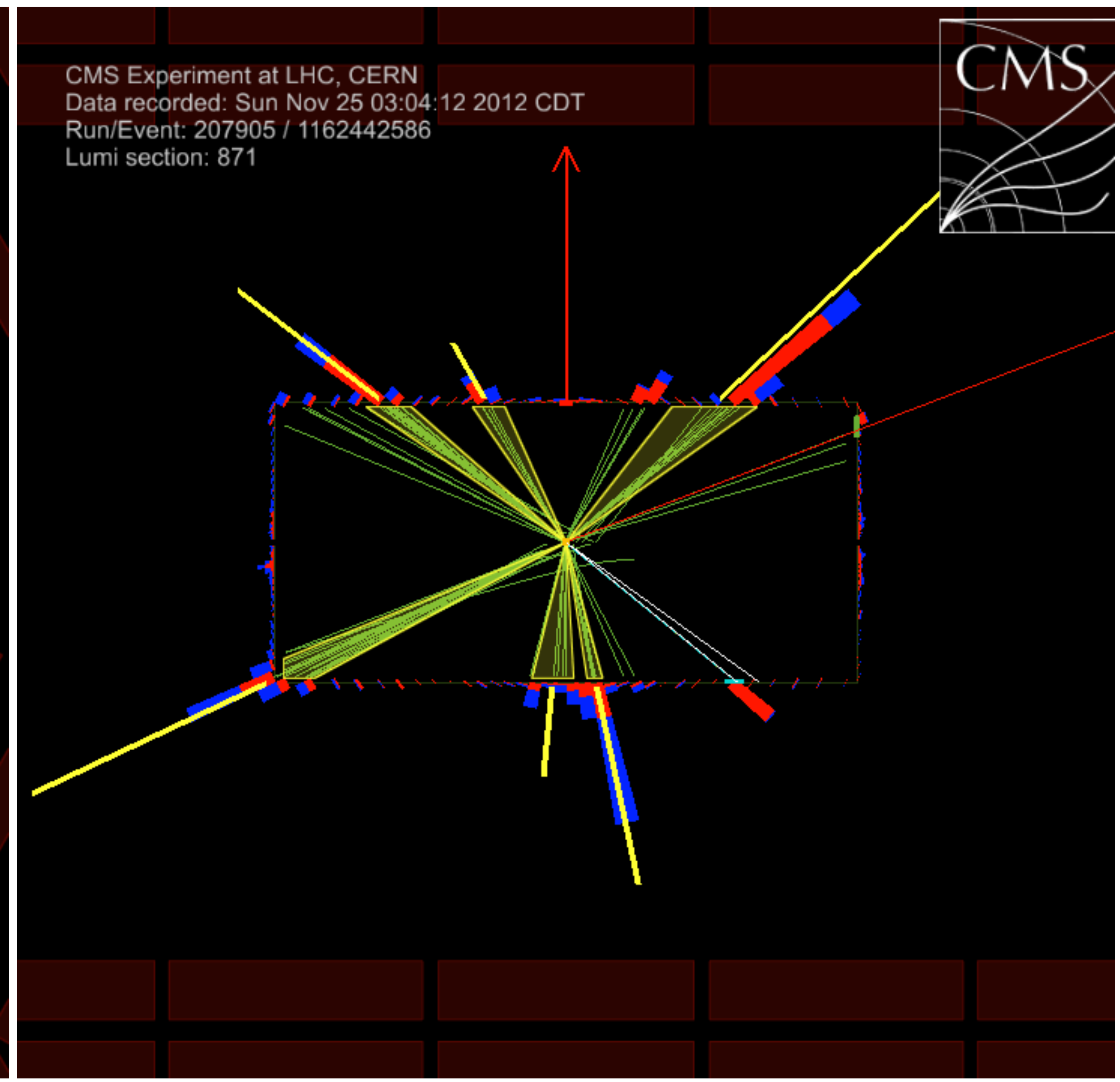


- Projection for 13 TeV

Event display

- S_T = 2200 GeV, 6 jets

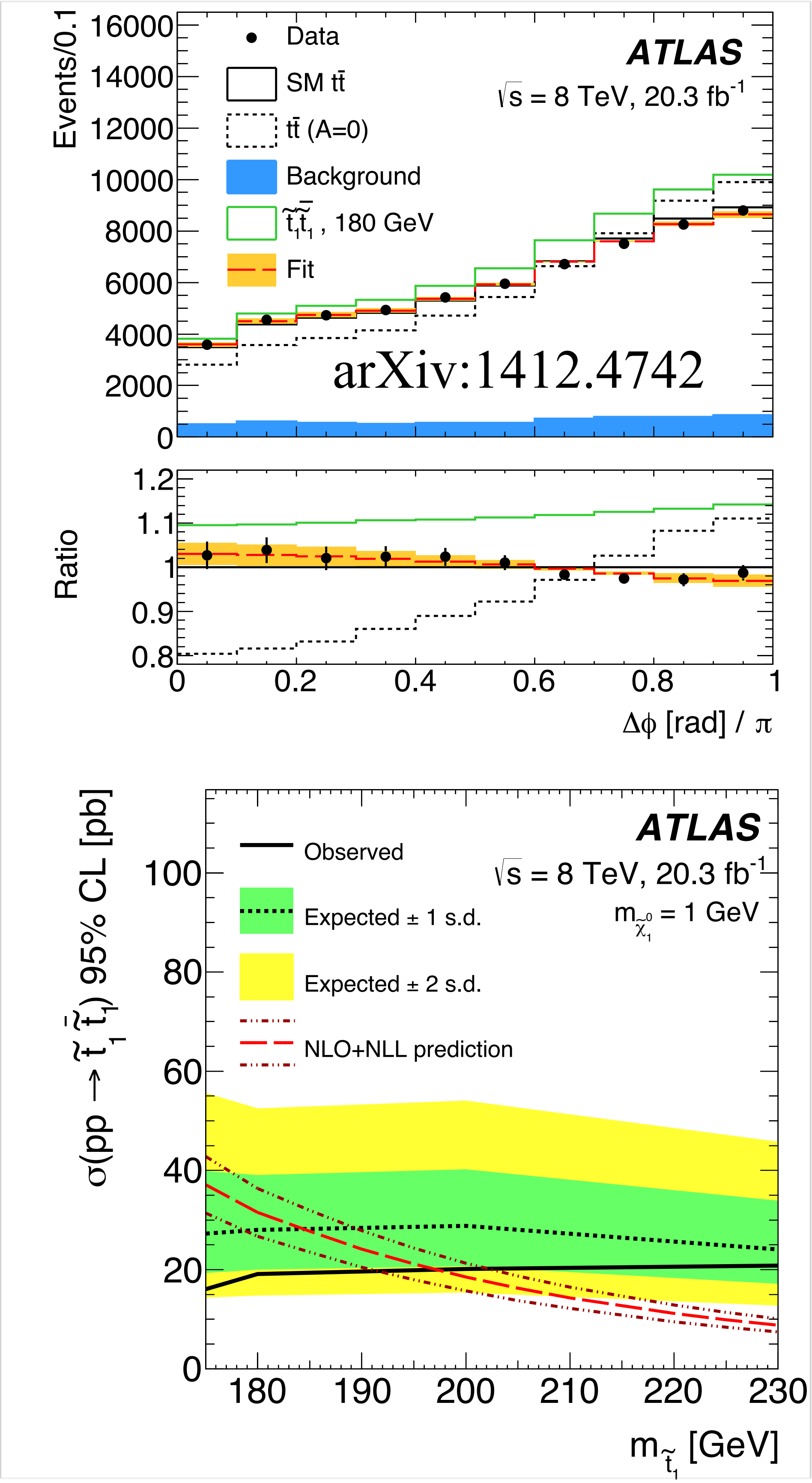




Compressed spectra example

- Small mass splitting
  - e.g. $M(\tilde{t}) - M(t) \sim$ 5-10 GeV
  - Can recover some MET by requiring a hard ISR jet to boost the undetected LSP
- For top squark decays, can utilize the fact that there are **spin correlations** for pair produced top quarks but not top squarks

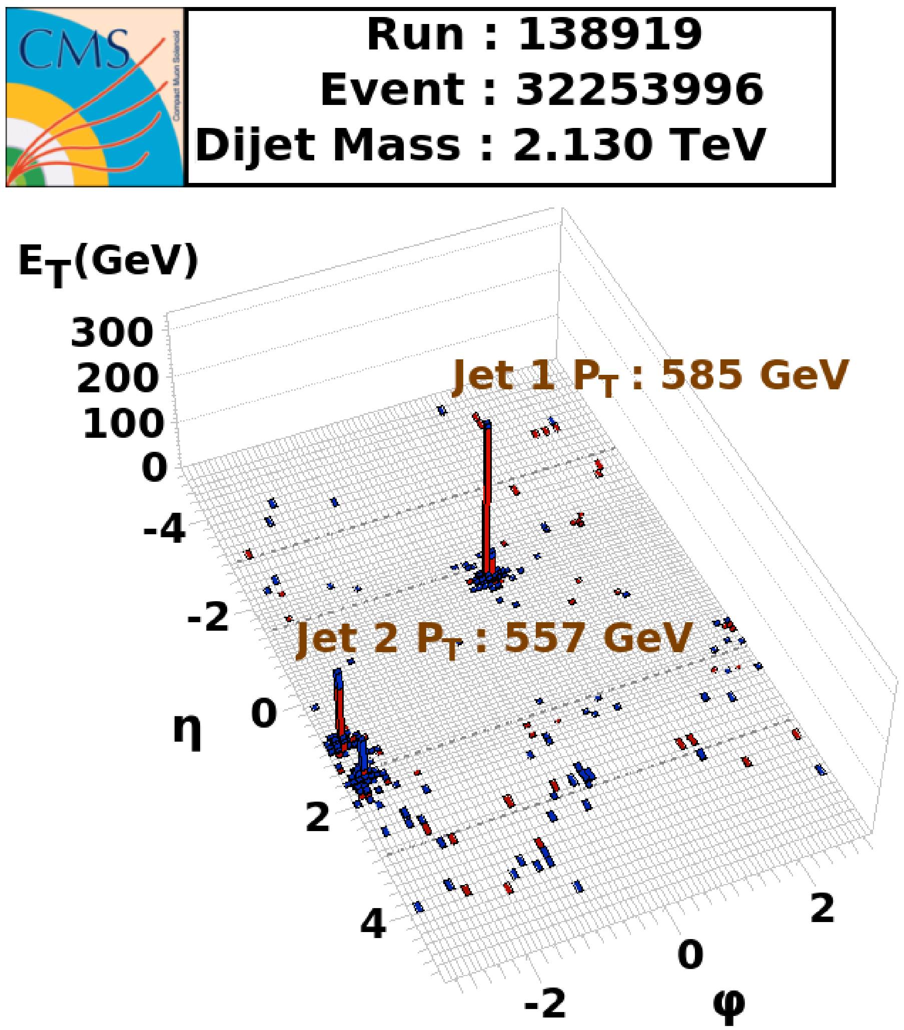
Theory paper, arXiv:1205:5808

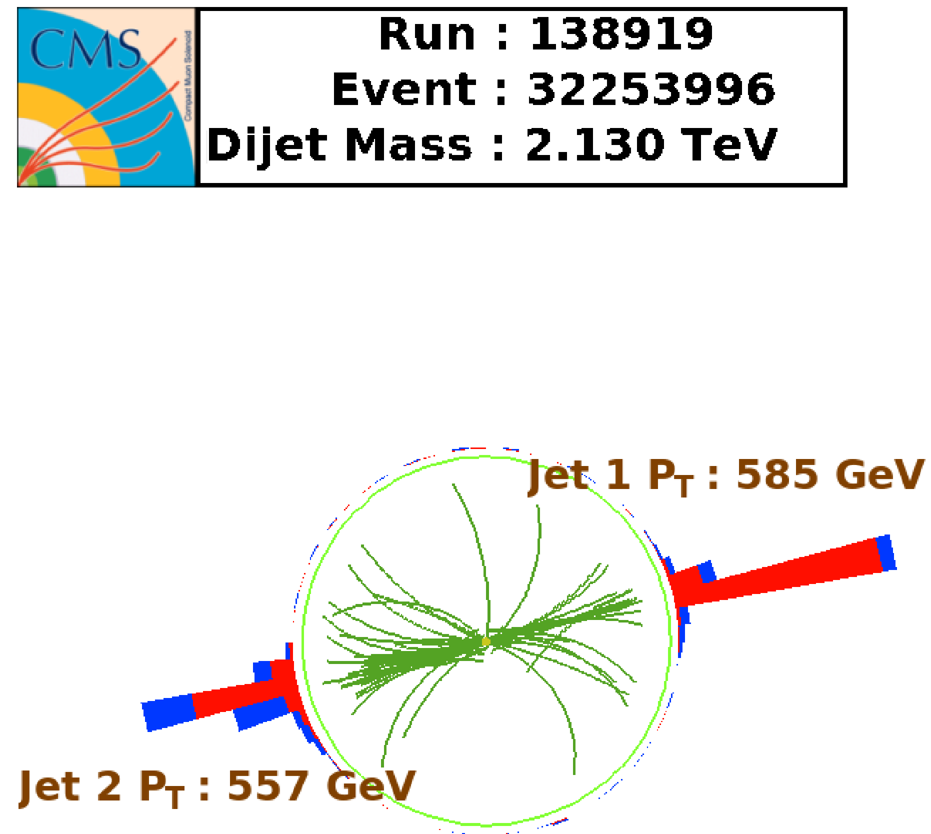


Physics
Carnegie Mellon University

Jets

- Reconstructed jets from quark (gluon) events



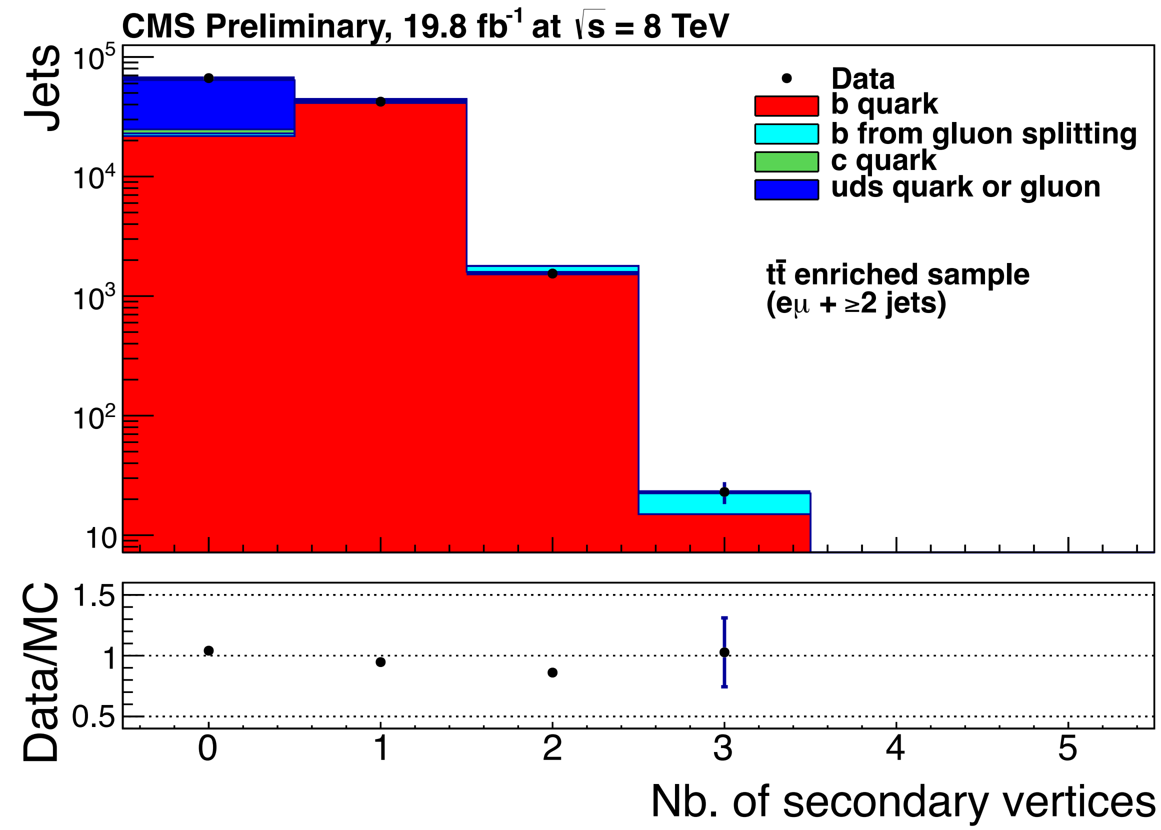


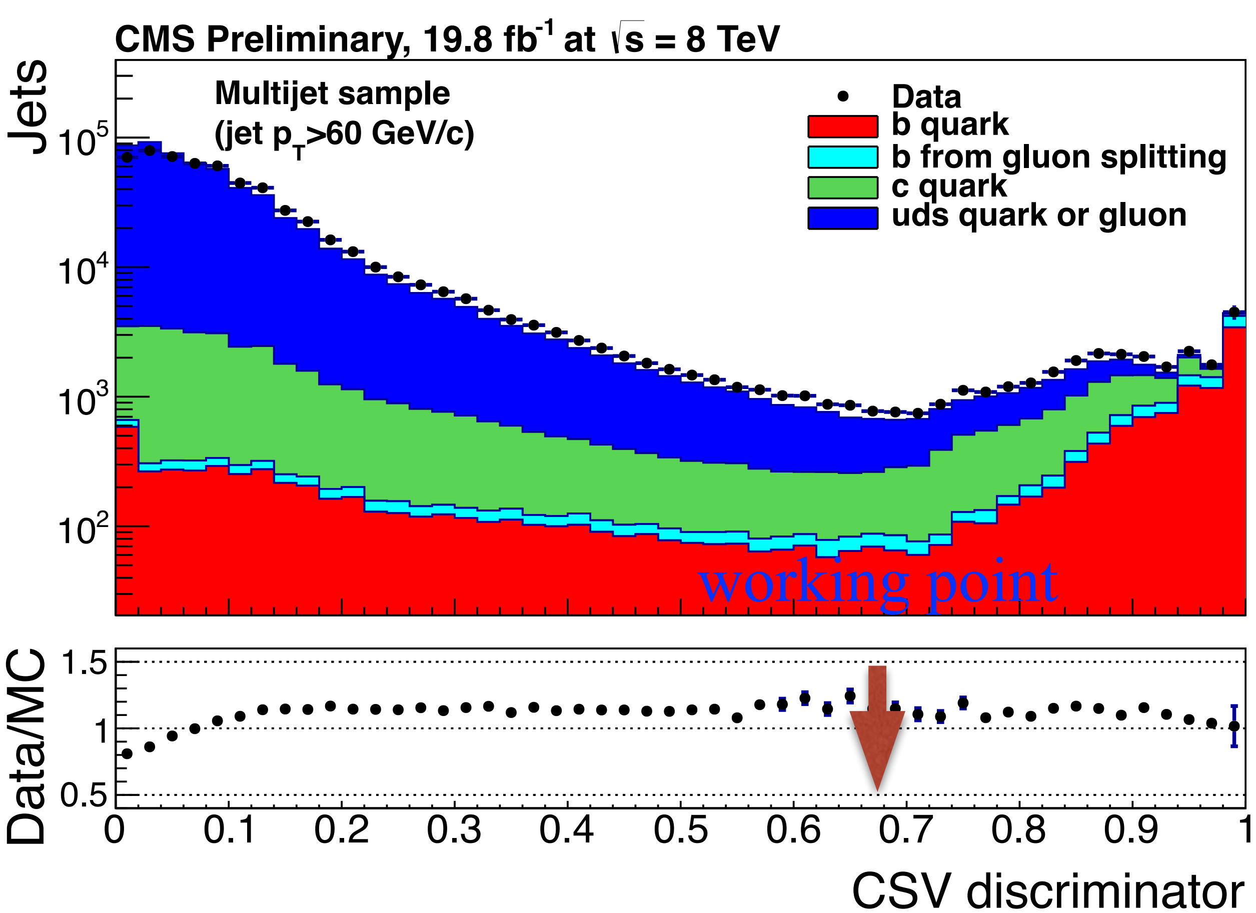
- Jets reconstructed from particle flow objects
- Anti-k_T clustering, radius parameter R=0.5

b jets

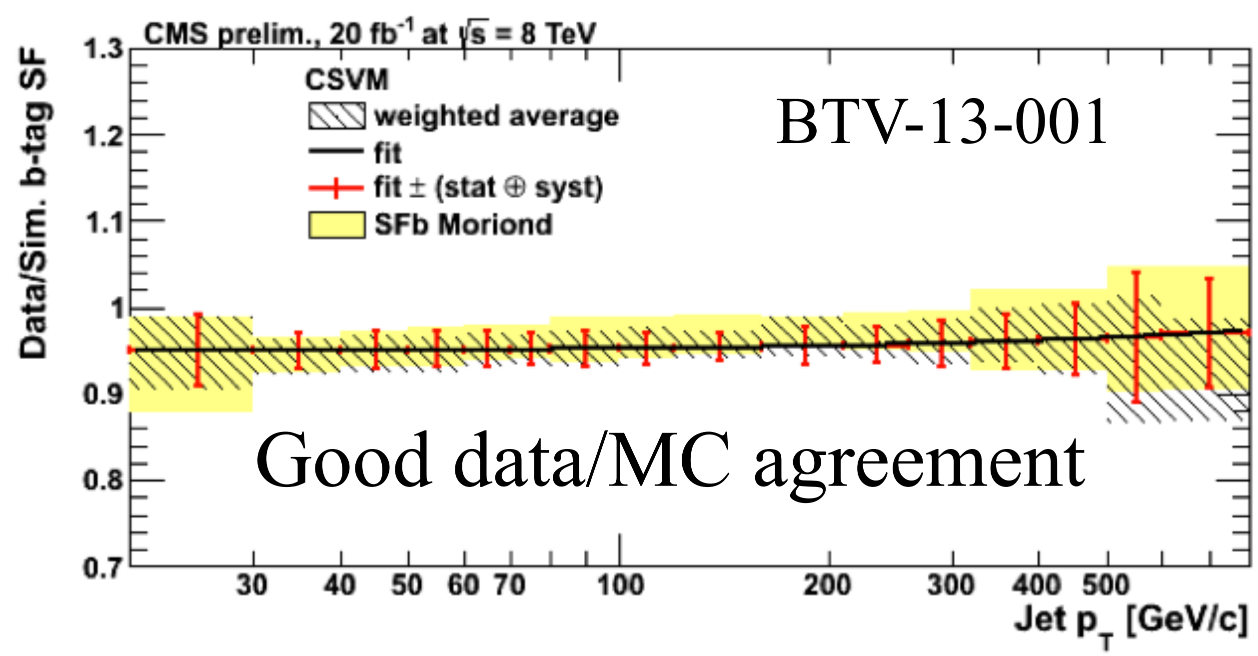
arXiv: 1211.4462

- Identify jets from b quarks
- Separate using track impact parameter and **secondary vertex** information
- Combined secondary vertex (CSV) discriminant





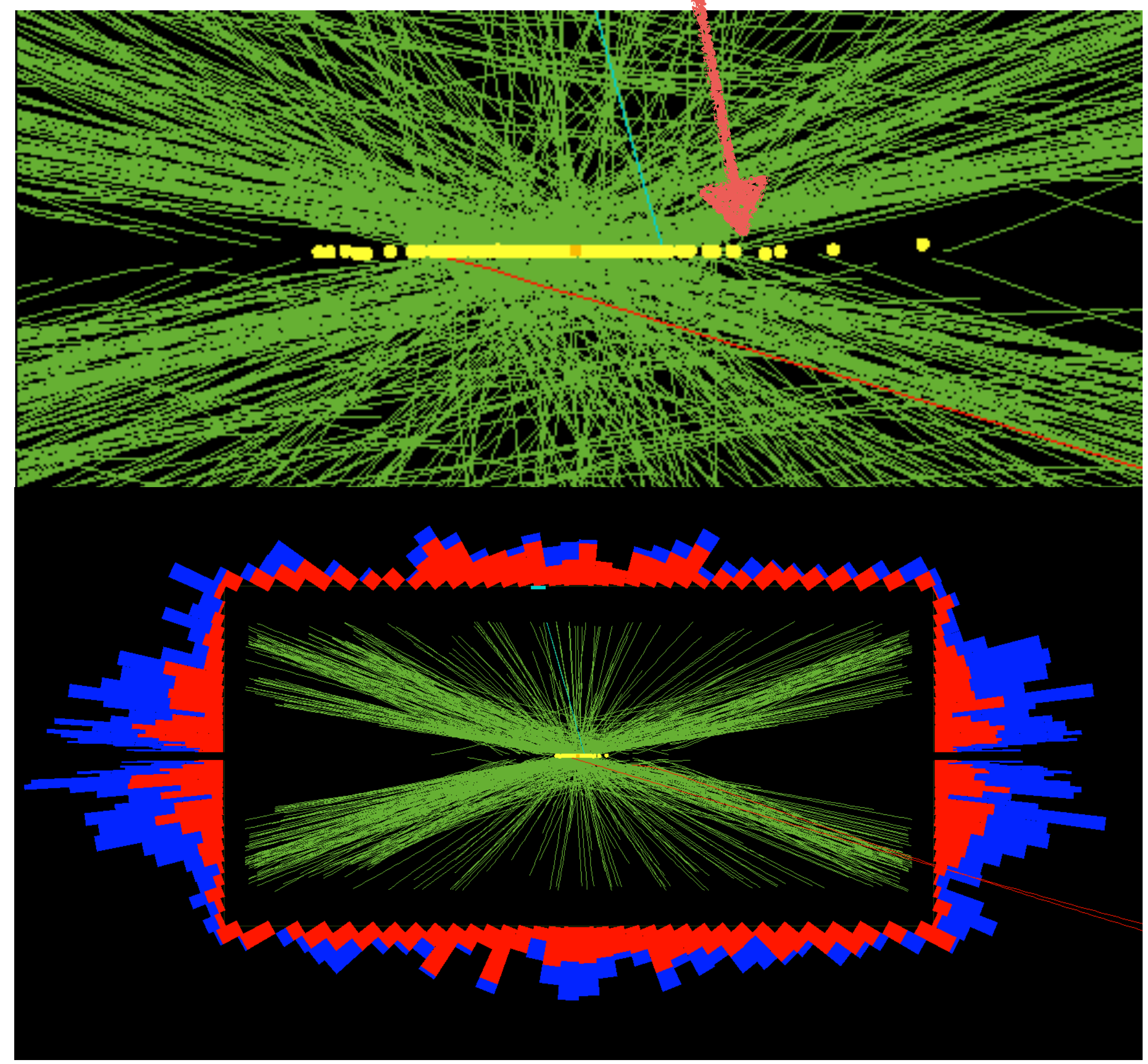
- Efficiency: 70% (b quarks), 20% (c), 1% udsg



The pileup challenge

Year	pileup	bunch spacing (ns)	Integrated luminosity
2010	1-2	150	36 pb
2011	5-10	50-75	5 fb
2012	20-30	50	20 fb
Run 2	~50	50(25)	300 fb

Extreme Run 1 event with ~ 70 vertices!

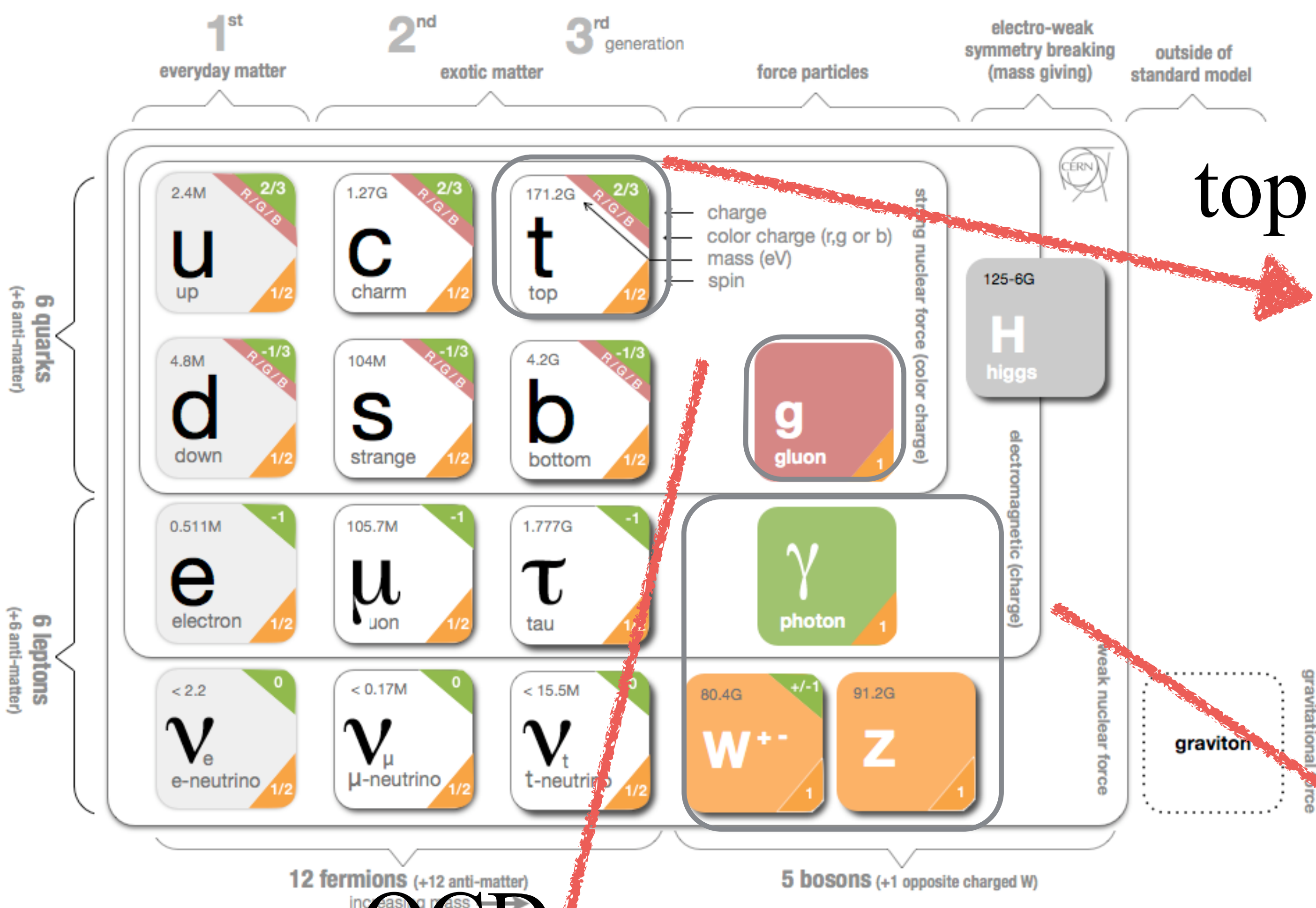


- Object identification must be robust for high pileup events

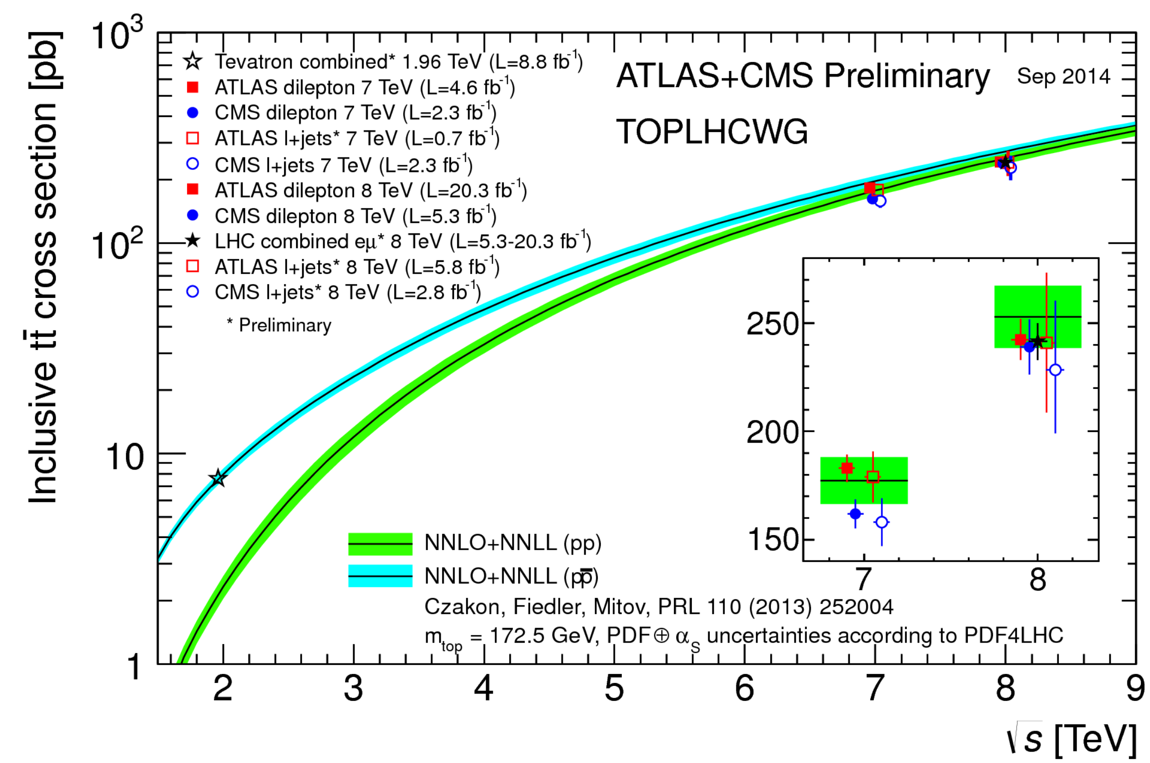
Physics
Carnegie Mellon University

CMS

Success of the SM at the LHC

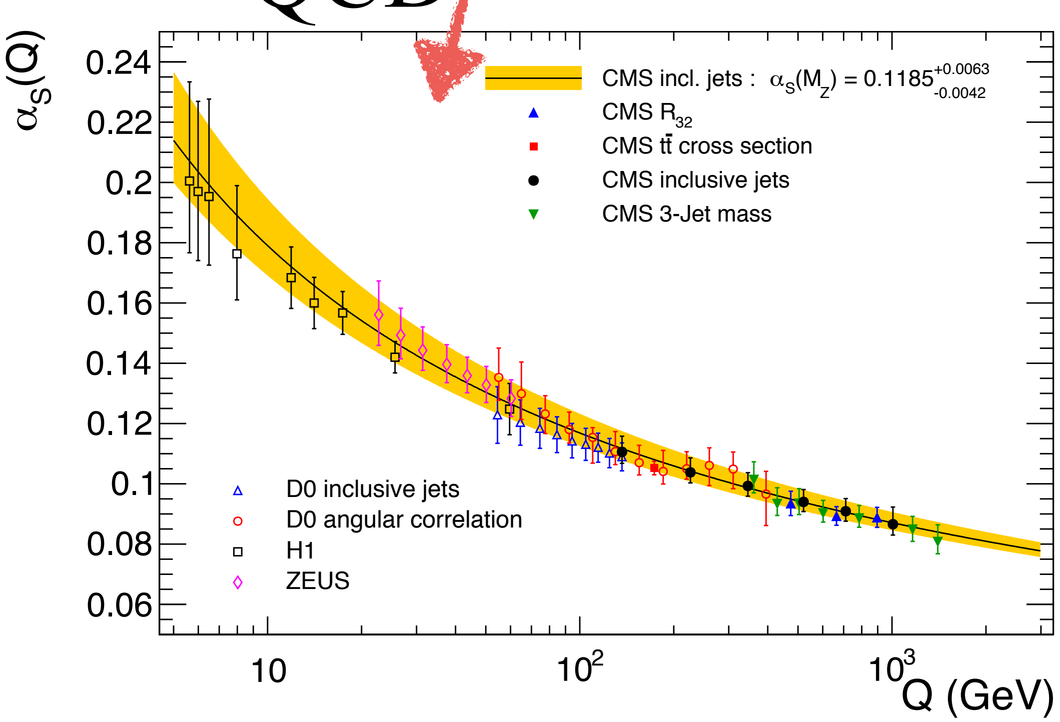


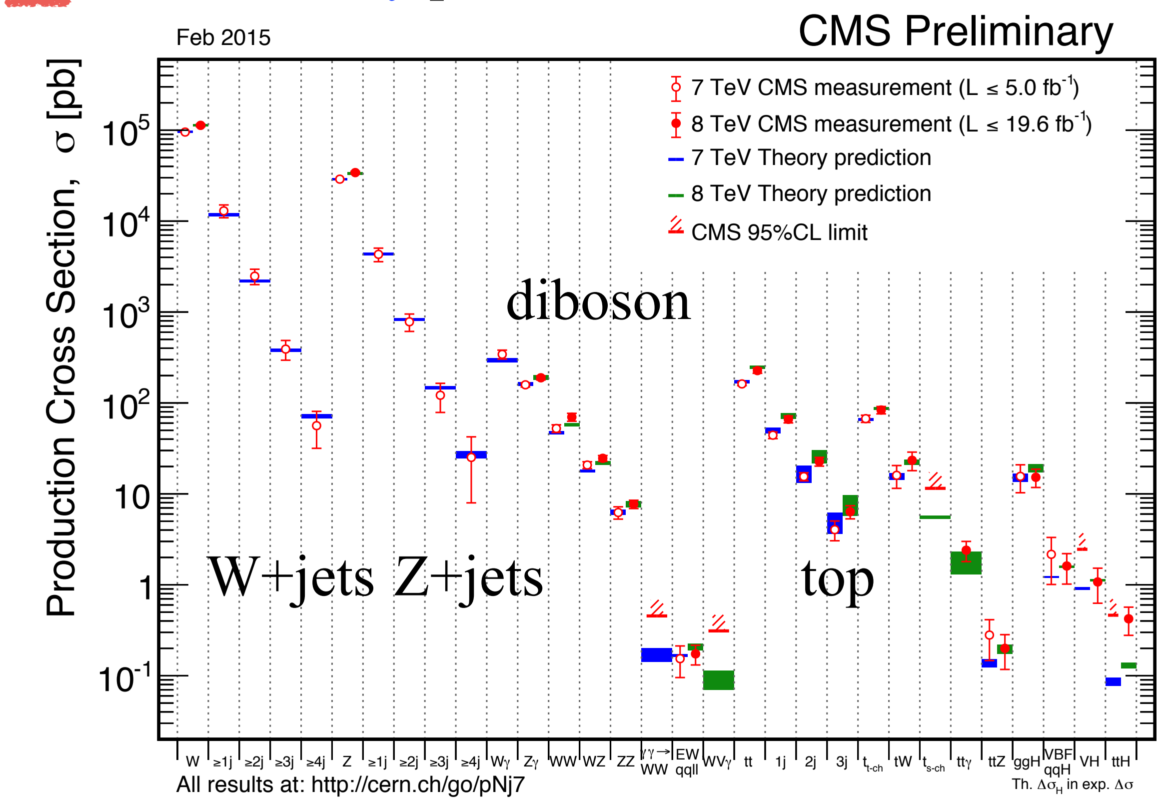
top



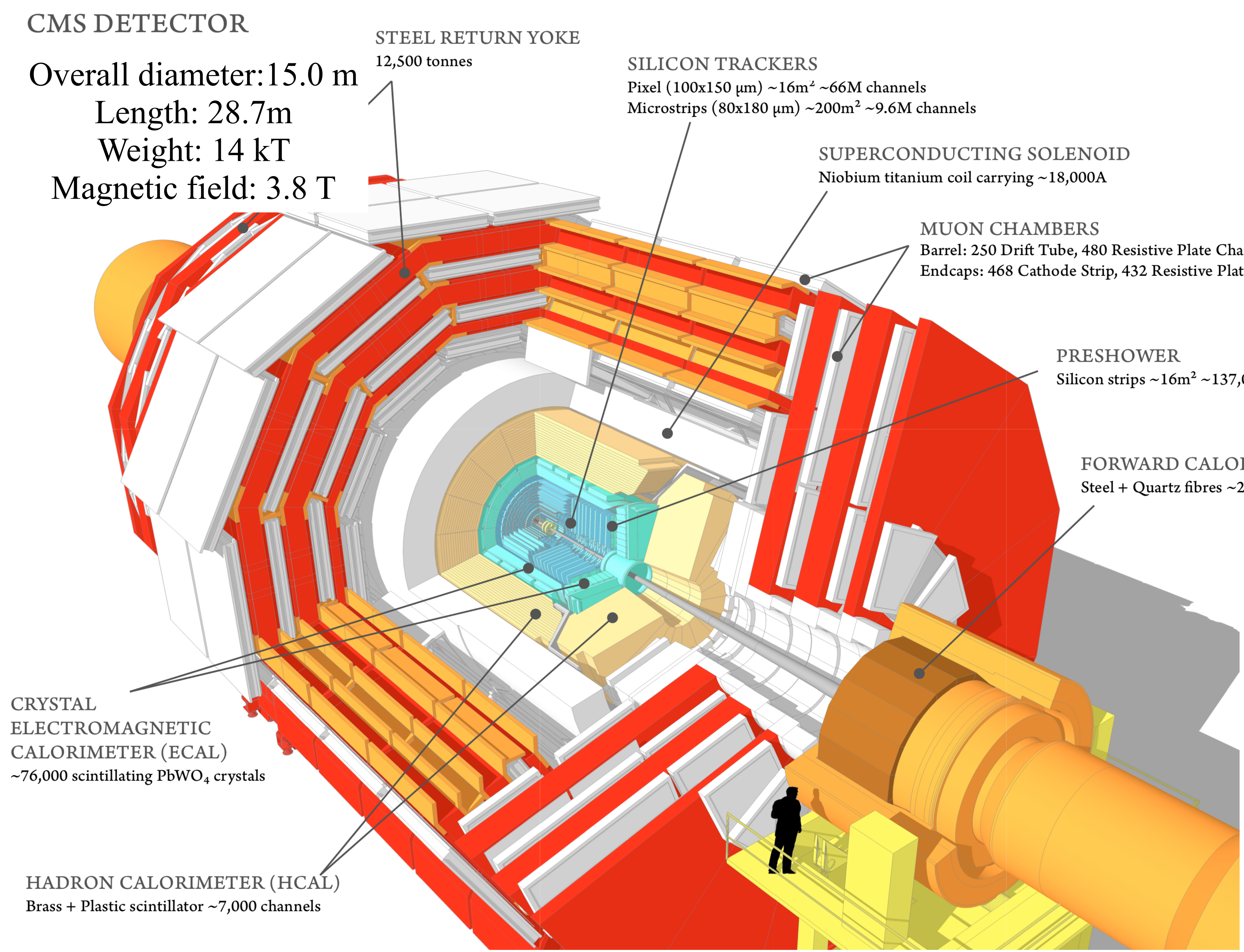
Comparison of measurements and theory predictions

QCD

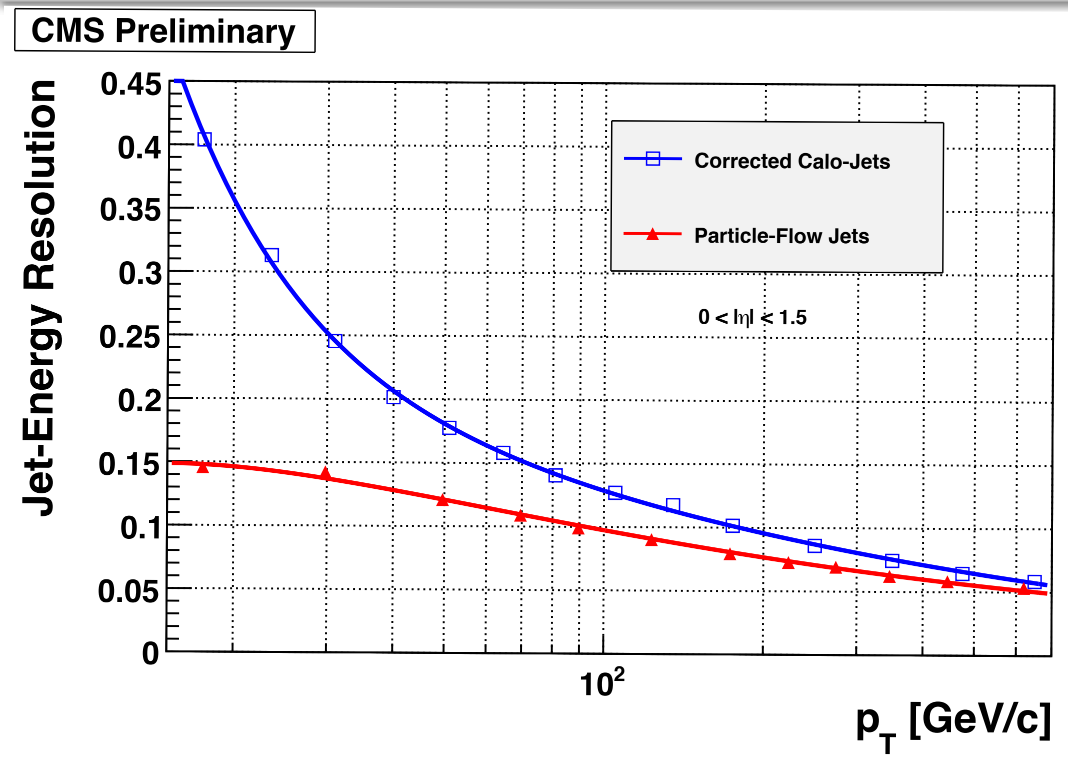


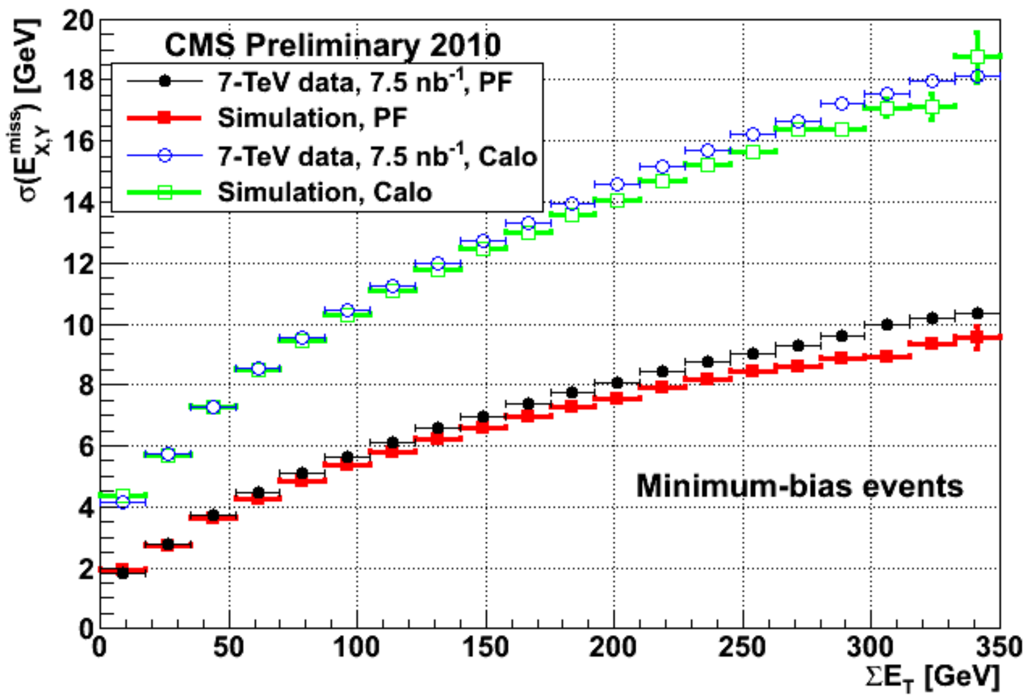


The Compact Muon Solenoid



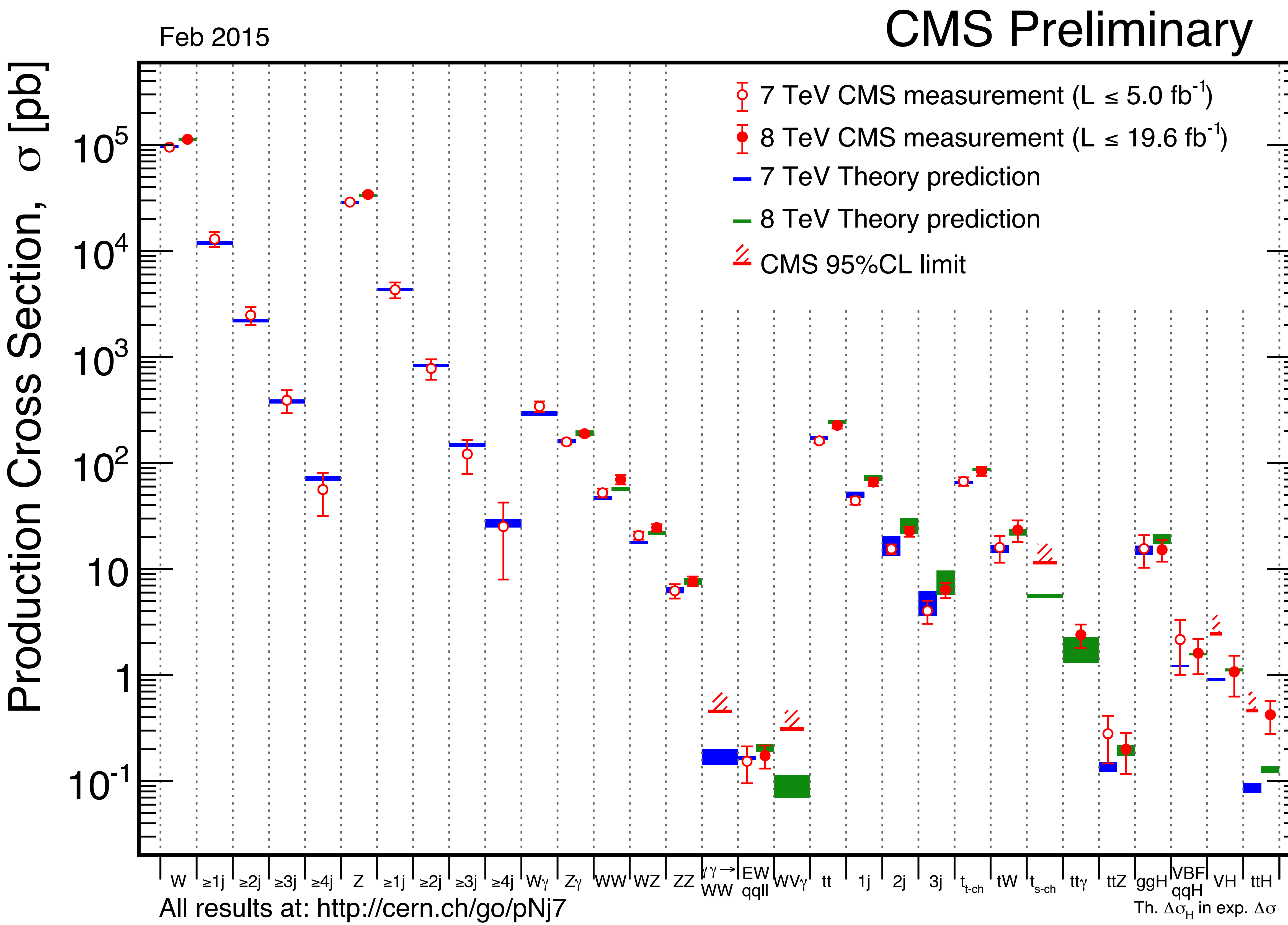
Detector performance with particle flow



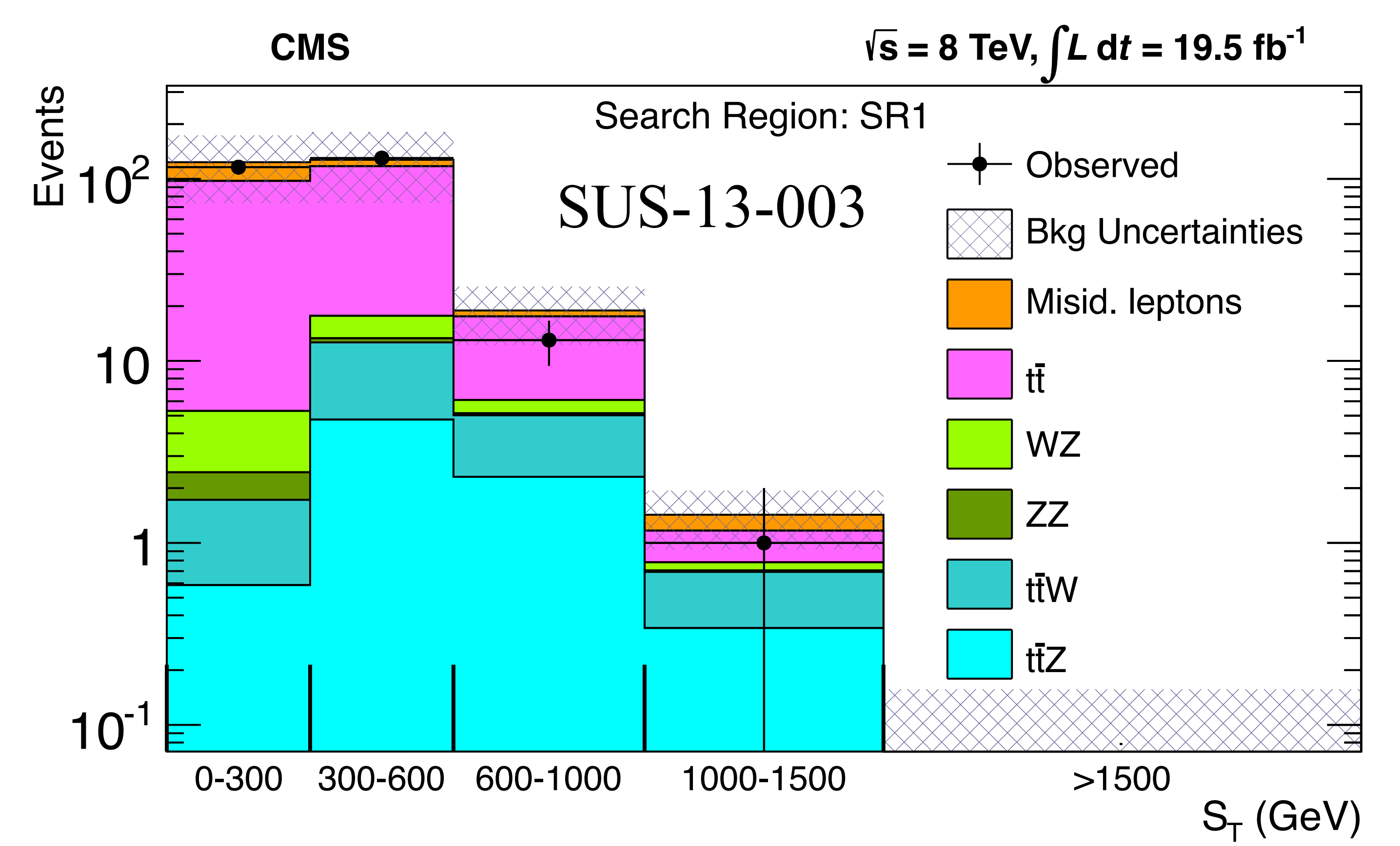


- Improved performance for particle flow objects
- Particularly relevant for jets and MET

SM measurement summary



Multileptons (N_ℓ=3, ≥4)



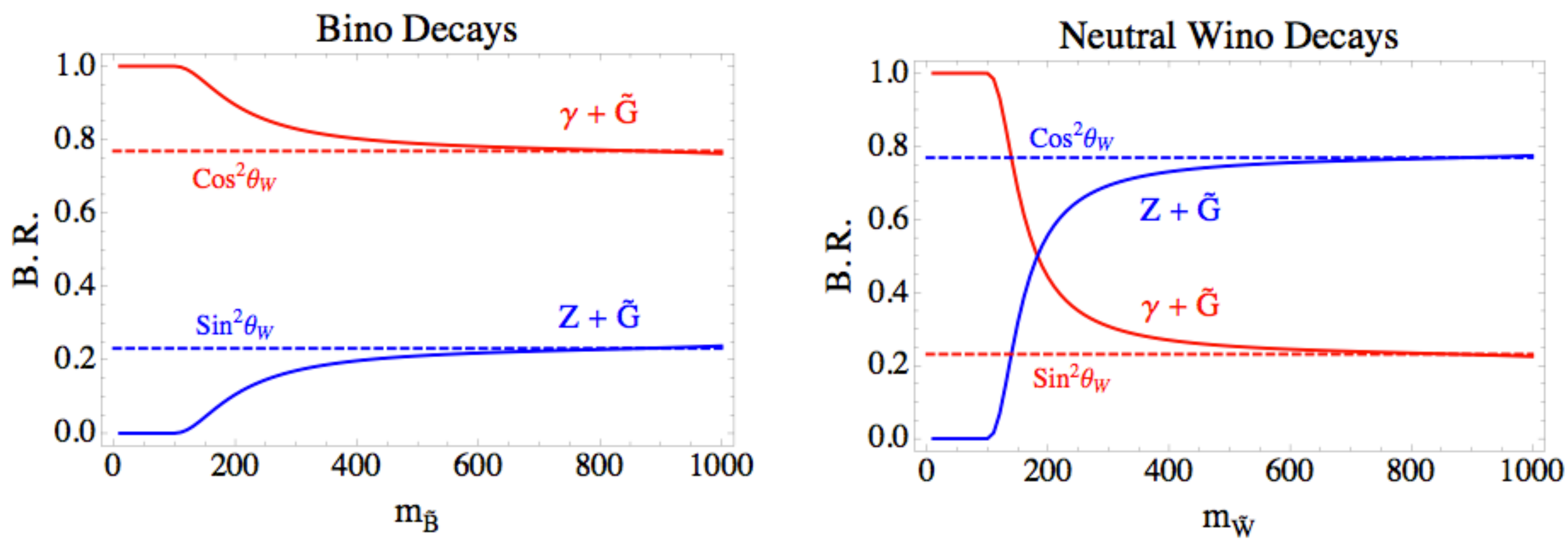
- N_ℓ = 3, no τ's
- No MET requirement

- Use final states with many leptons (N_ℓ)
  - SUS-13-002(003)
- Low SM backgrounds:
  - ttW(Z), WZ, ZZ
  - tt (DY) with a third misidentified lepton
- Known background estimation procedures that can be extended to low-MET bins

Physics
Carnegie Mellon University

Gaugino branching fractions

arXiv: 1103.6083



Unification of couplings

- Running of the strong, weak, and electromagnetic coupling strengths in the SM do not quite converge
- Supersymmetry (colored lines) causes couplings strengths to converge at 10^{16} GeV