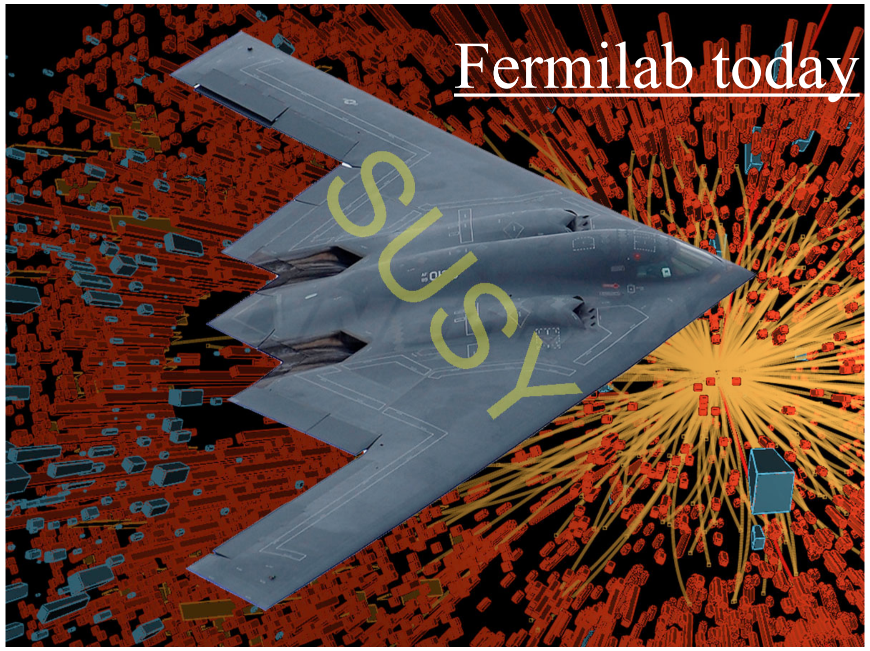
Search for stealth supersymmetry at the LHC

Cornell University
March 20, 2015

arXiv: 1411.7255
SUS-14-009 public twiki



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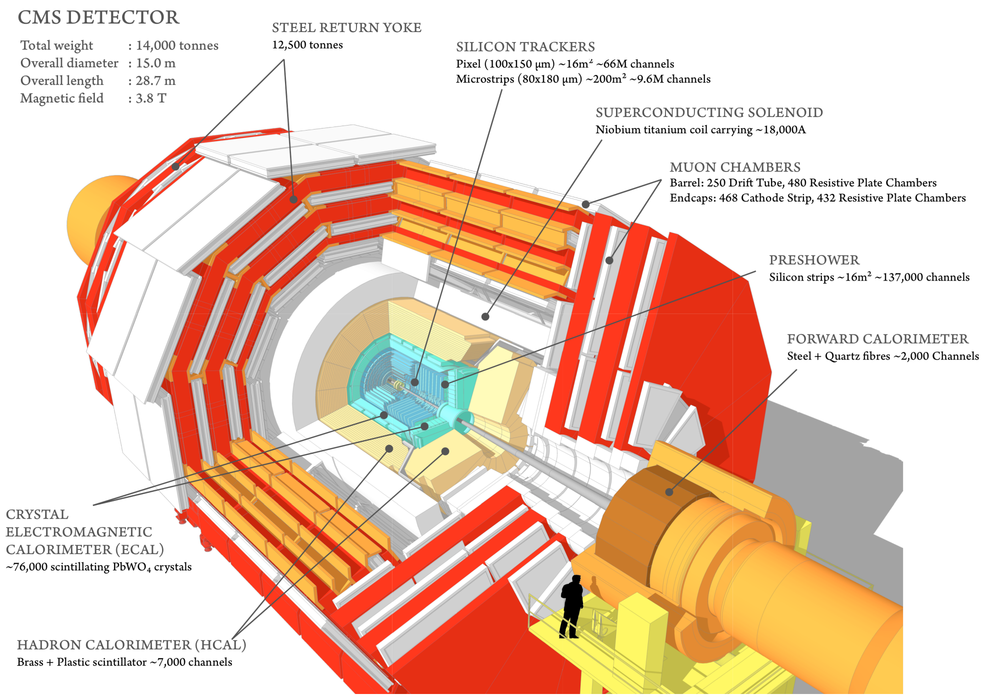
Outline

- 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



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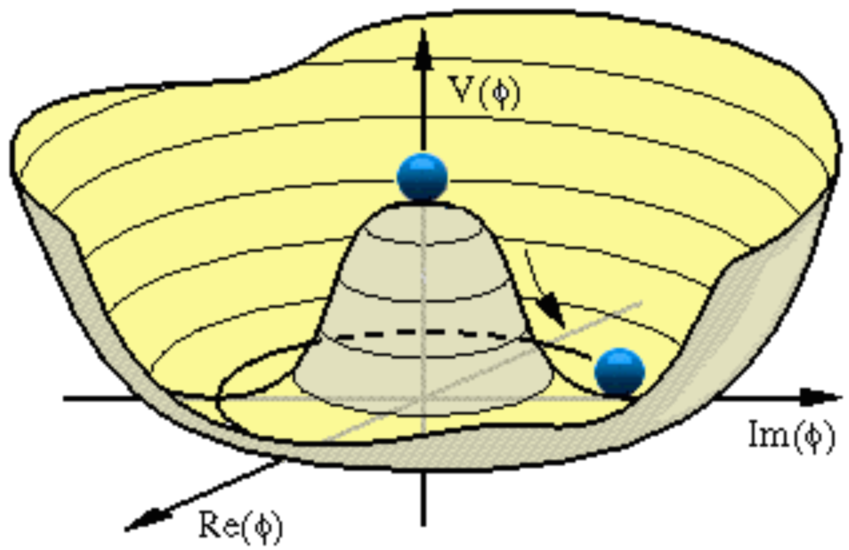
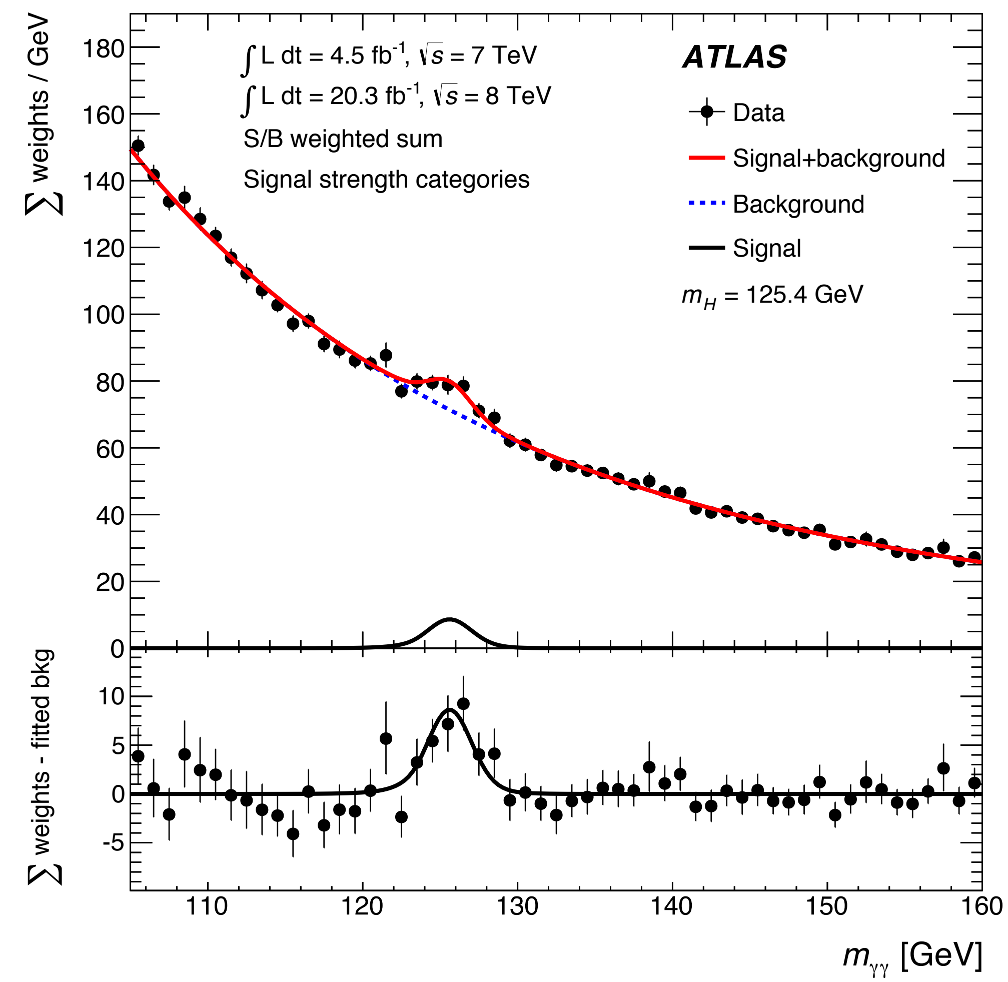
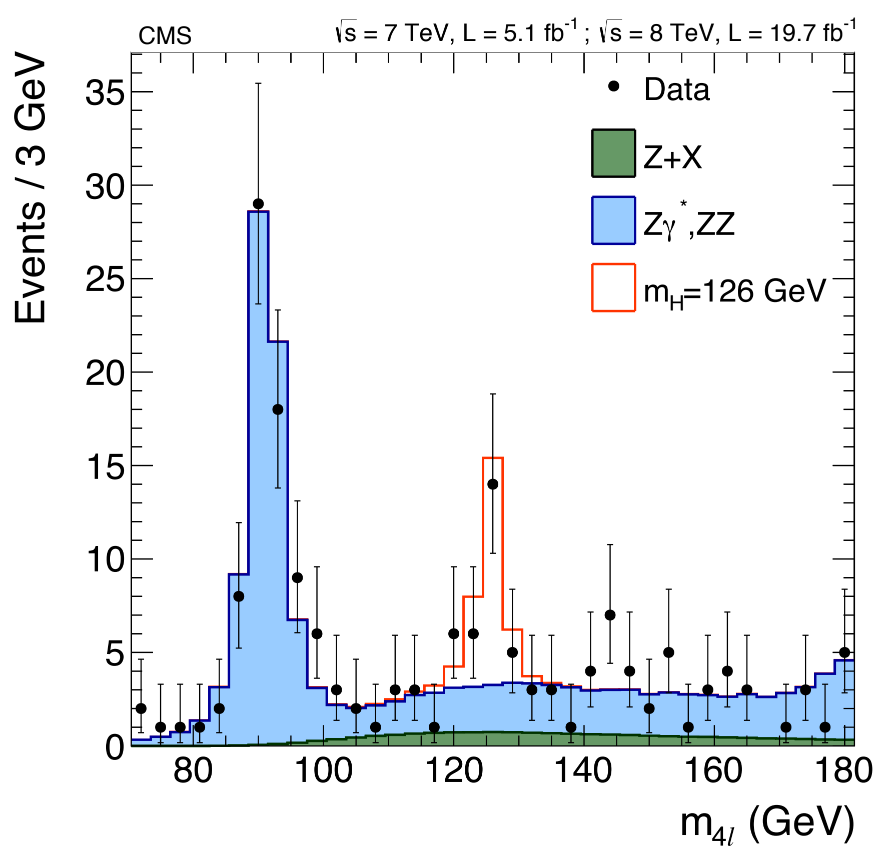
Last piece of the SM: Higgs boson







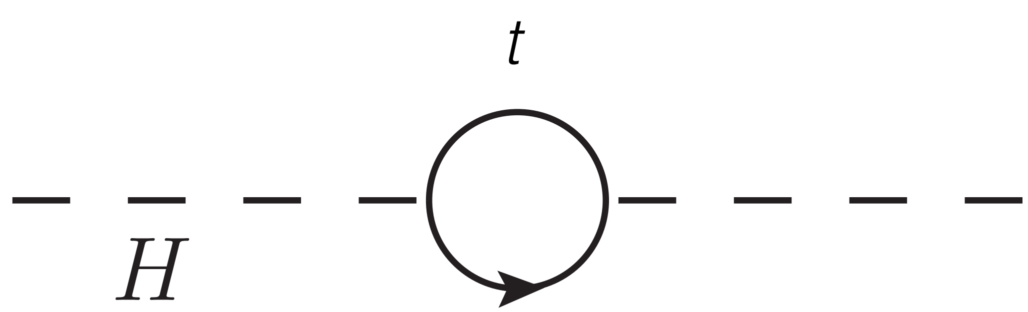
$M_H = 125$ GeV

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**

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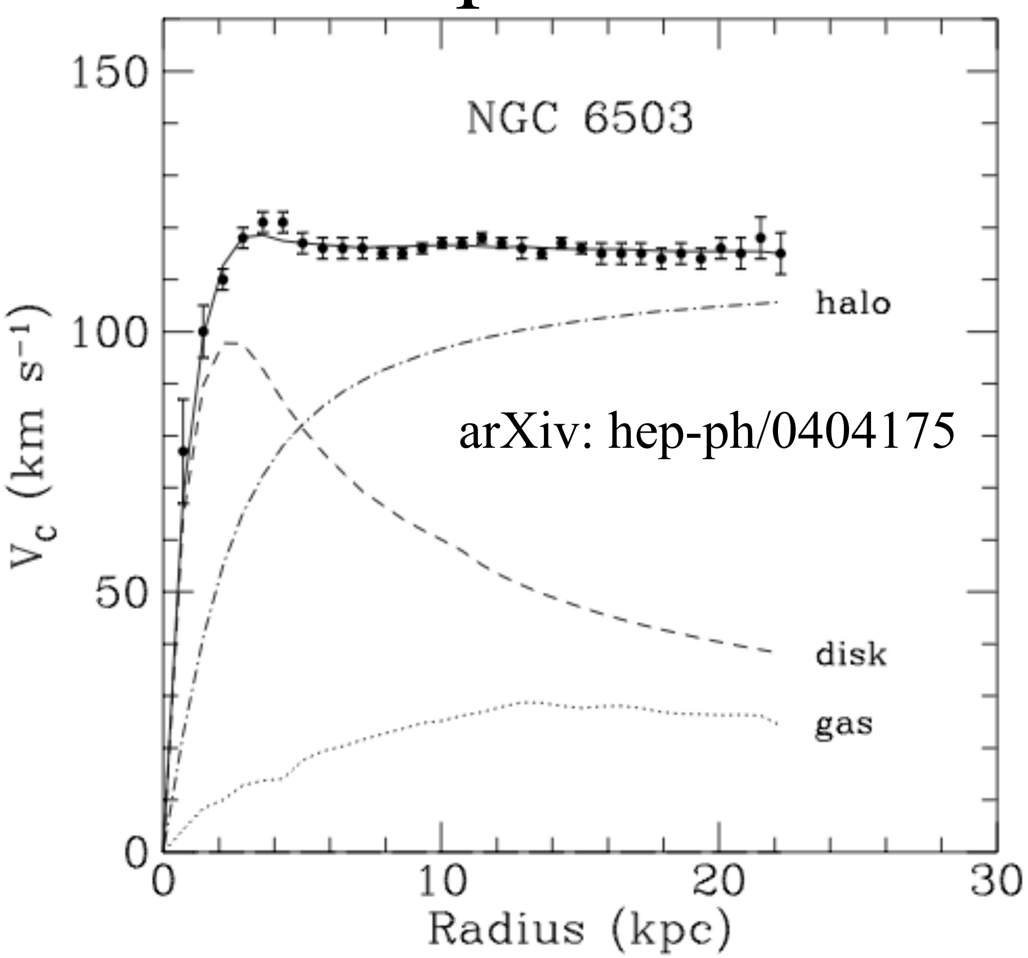
Dark Matter

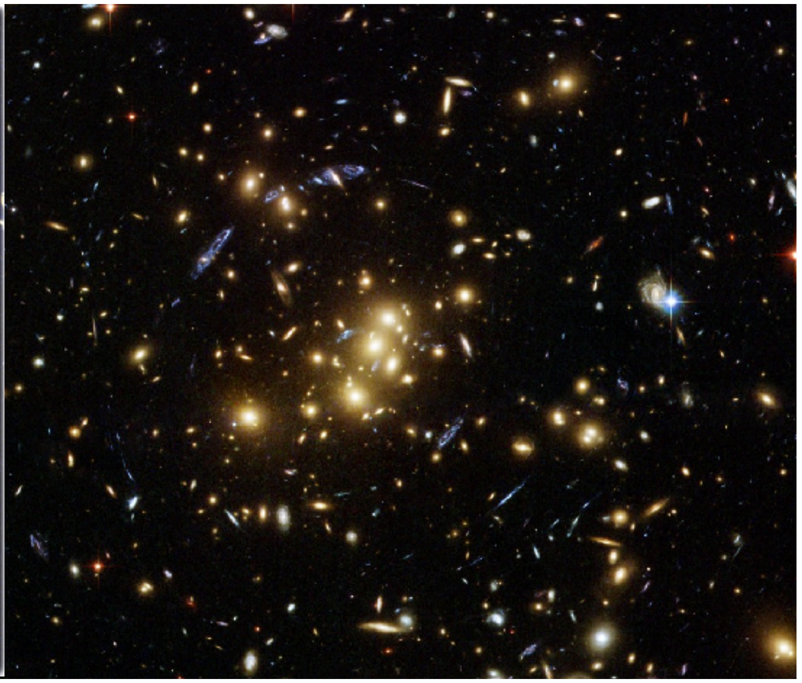
- Astrophysical evidence for neutral, weakly interacting non-luminous matter
- Multiple lines of independent evidence

arXiv: 1001.1739



arXiv: hep-ph/0404175

Galactic rotational curves



Gravitational lensing

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

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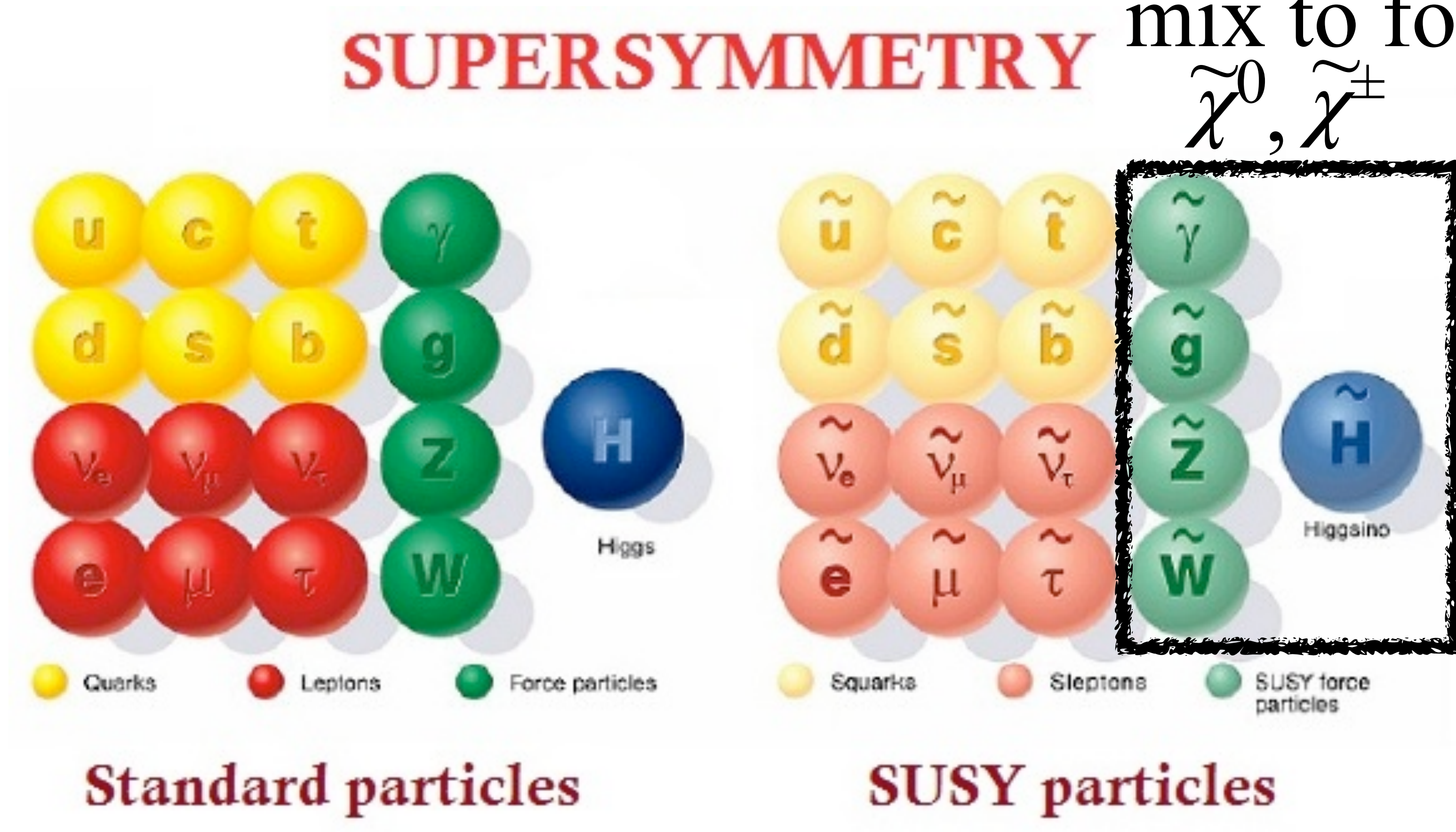
Supersymmetry



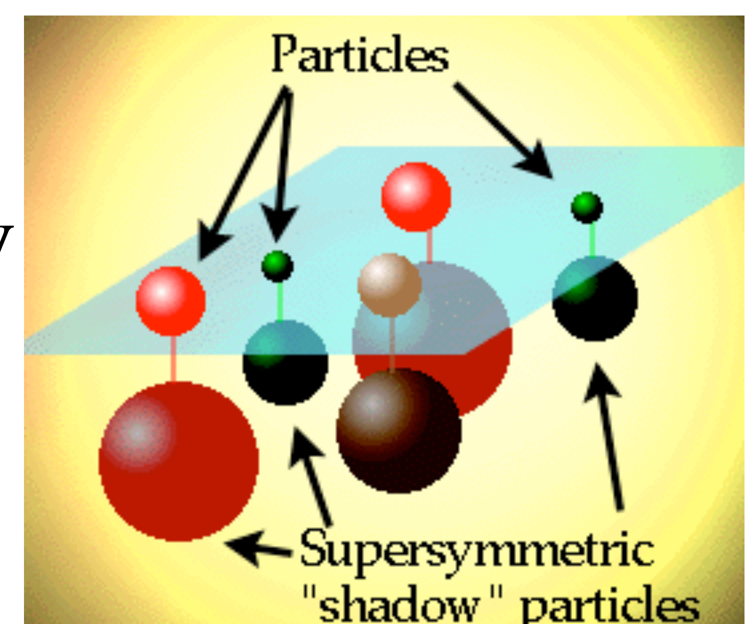
mix to form $\tilde{\chi}^0, \tilde{\chi}^{\pm}$

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

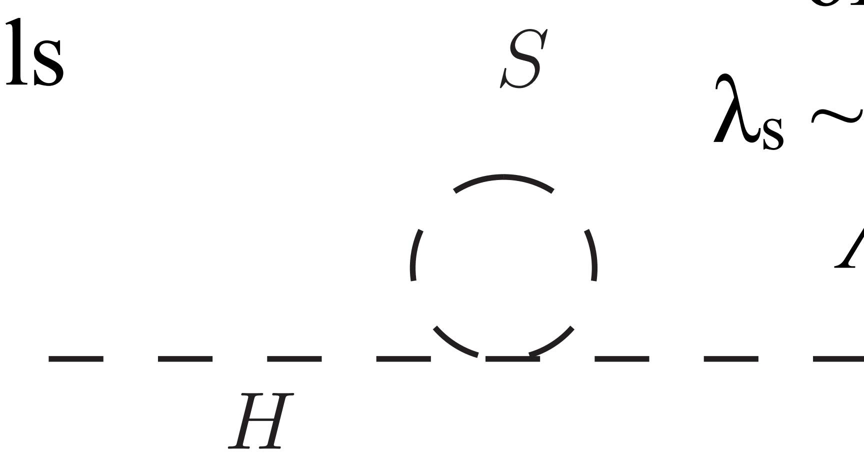


credit: CERN

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

Backgrounds at the LHC

$\sqrt{s}$ = 8 TeV

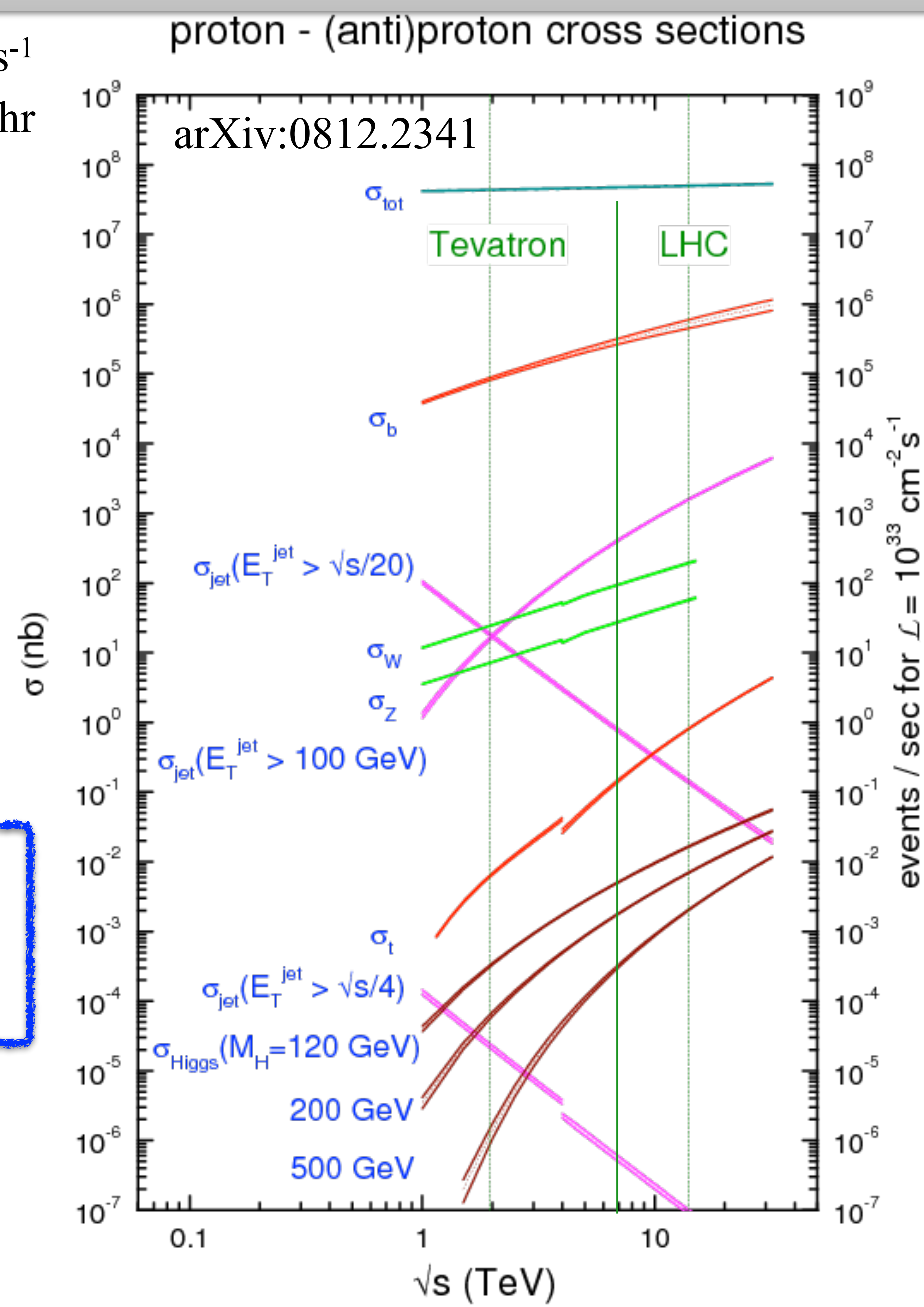
$\mathscr{L} = 10^{34}\,cm^{-2}s^{-1}$ gives 36 pb^{-1}/hr

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)	$2(1)\times10^3$
Top squark (500 GeV)	0.08	3

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

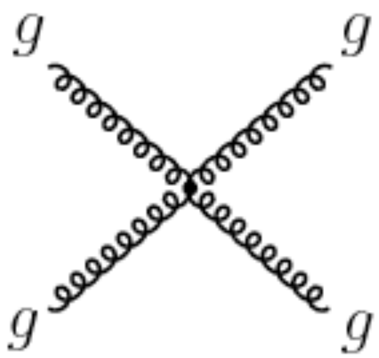
ε = efficiency
$\mathscr{A}$ = Acceptance
$\mathscr{L}$ = Luminosity

- Need handles to reduce SM backgrounds

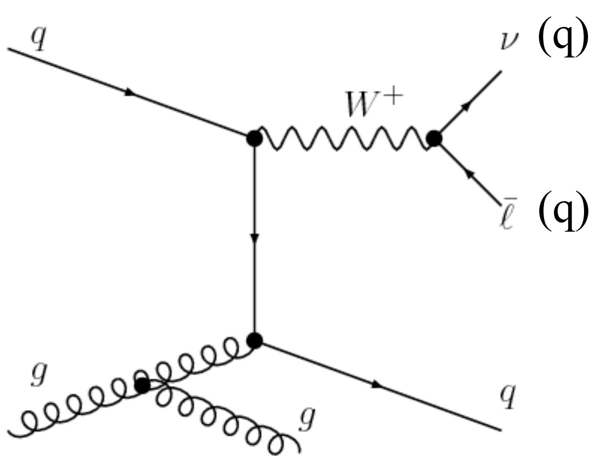


Handles for LHC backgrounds

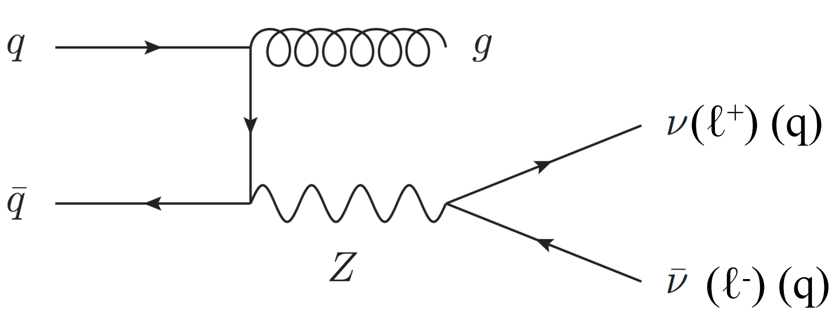
- Sample Feynman diagrams contributing to each process



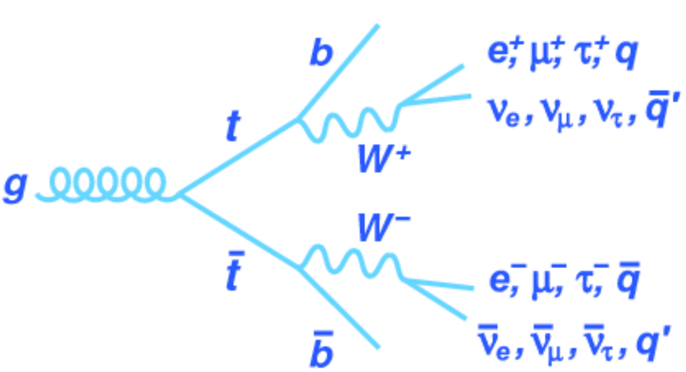
- QCD: multijet events
- Identifiers: jets



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



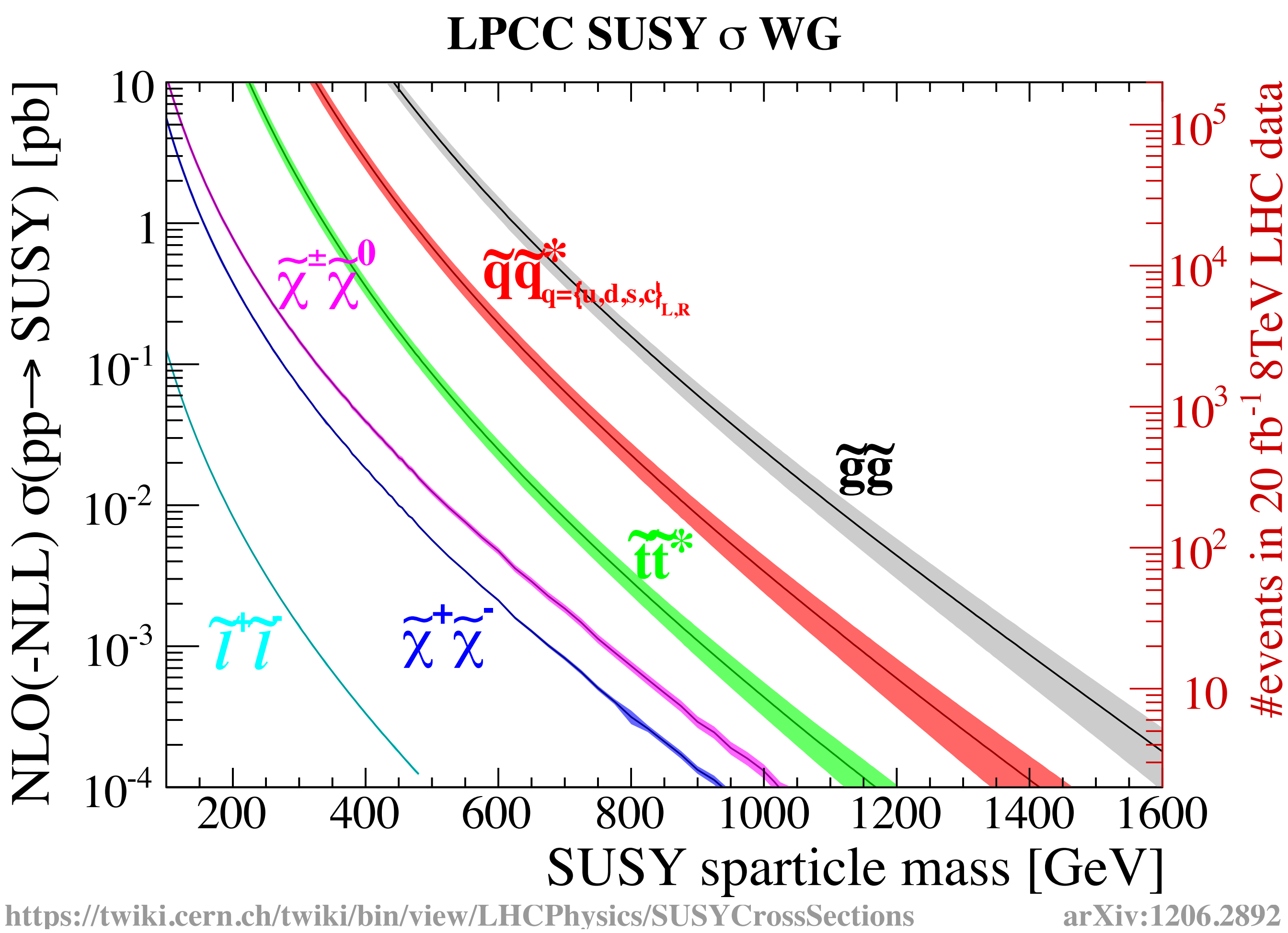
- Drell-Yan: two leptons (neutrinos) (quarks) from Z decay
- Identifiers: two lepton resonance

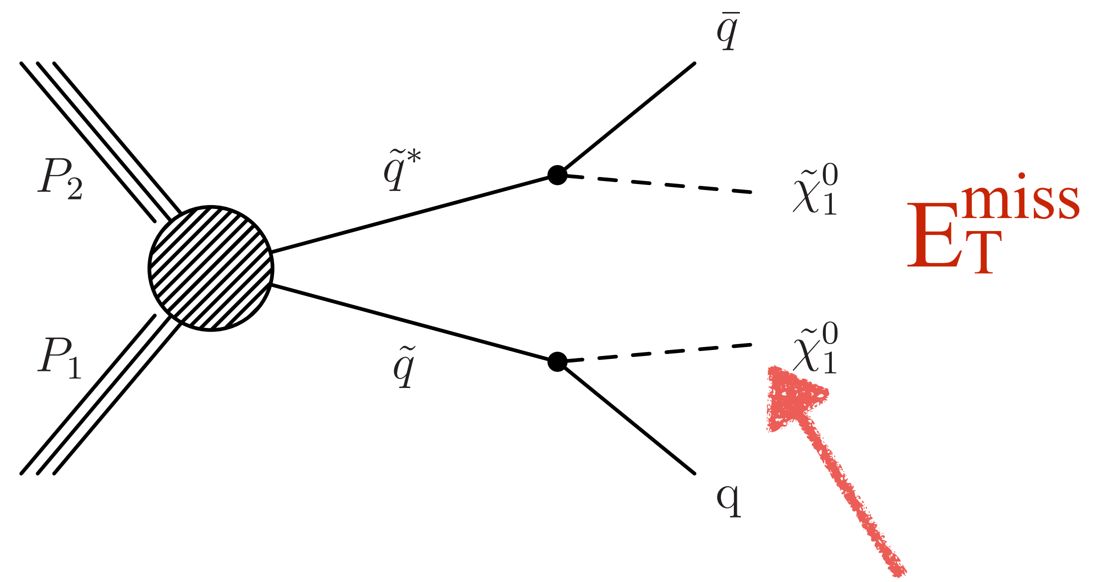


- TTbar: Two b jets, two W's
- Identifiers: b jets, leptons from W's, jets

decreasing cross section

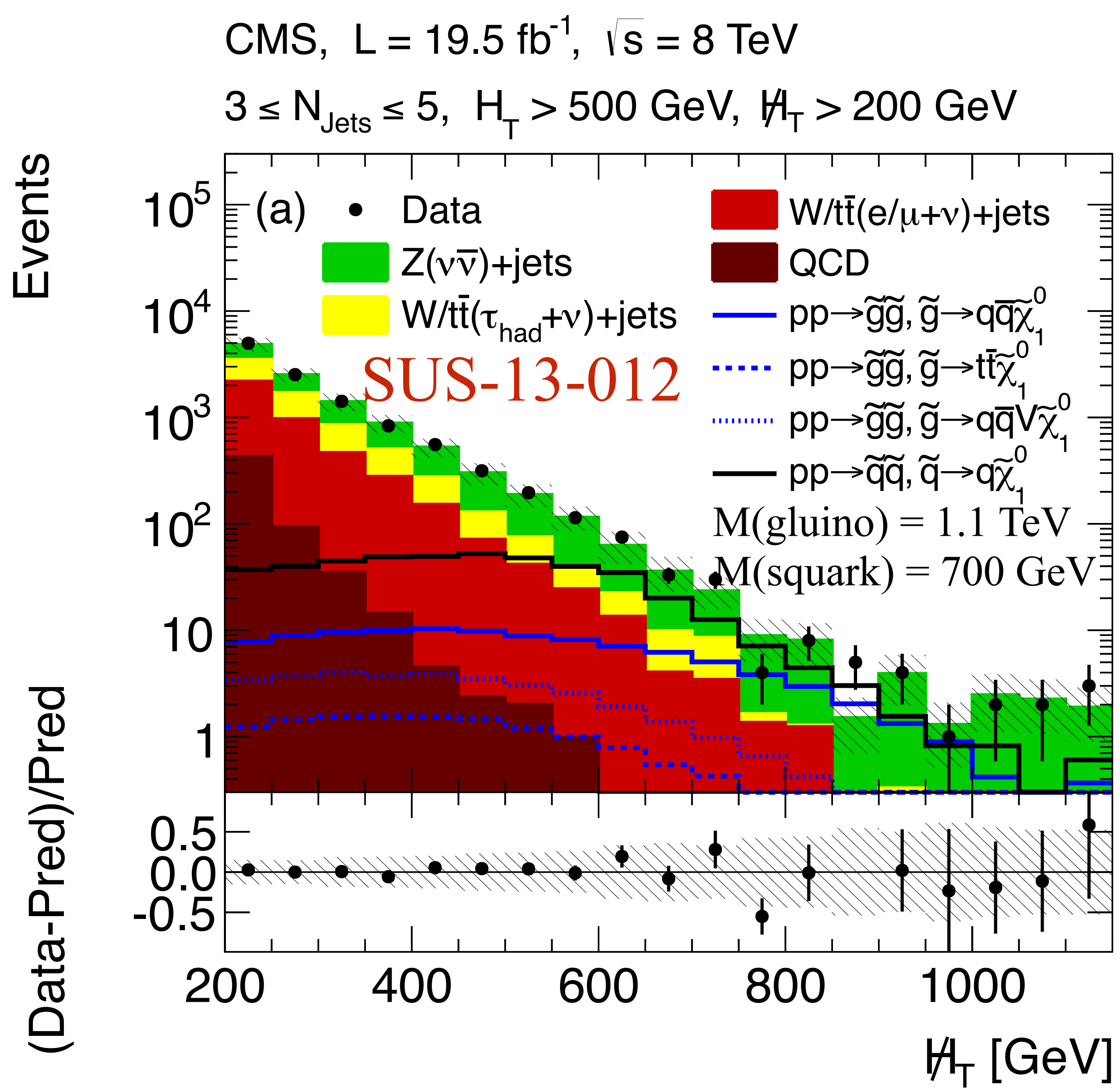
Simplified decay chains at the LHC





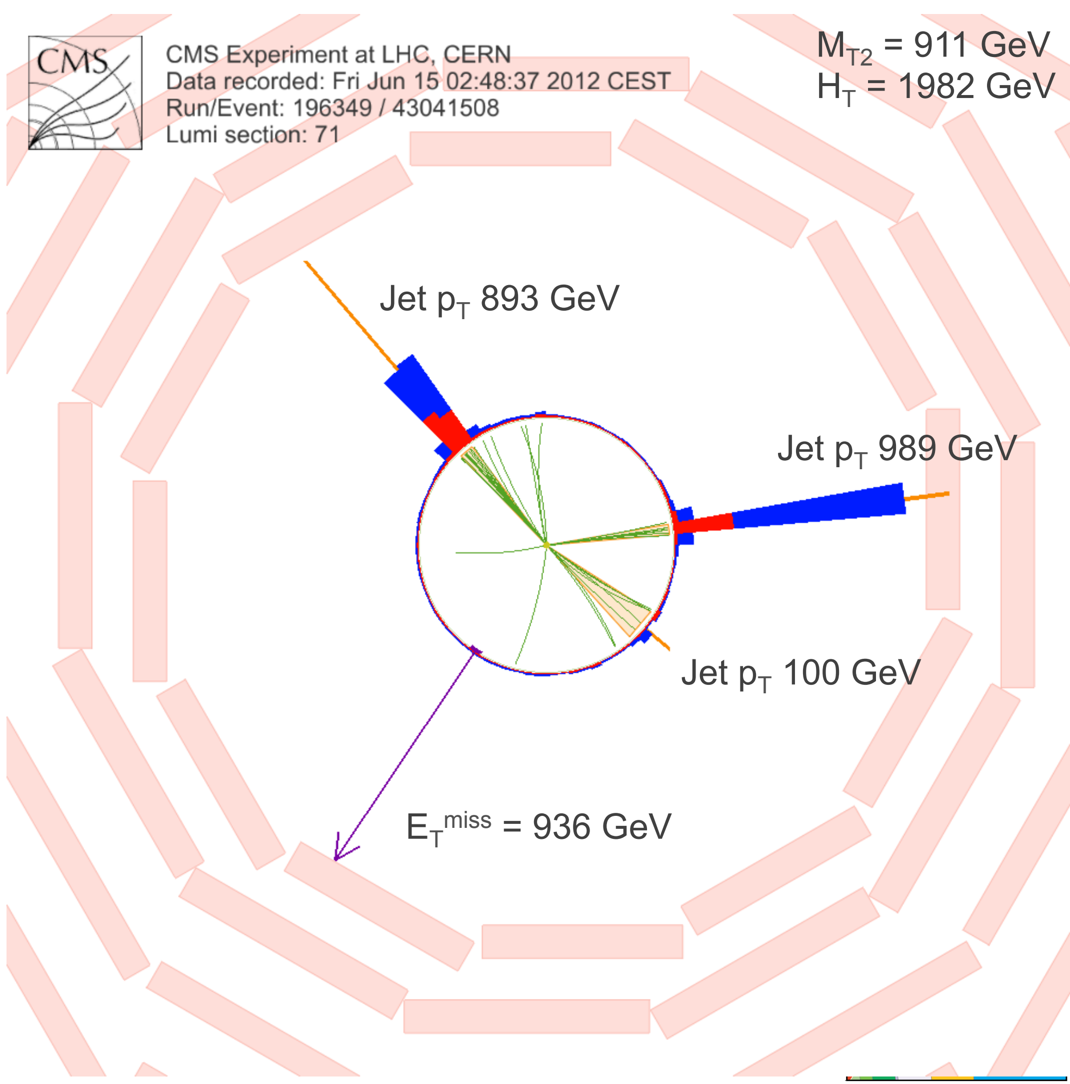
- Common characteristics
  - Assume single dominant decay mode for SUSY particles
  - missing transverse energy from LSP $\tilde{\chi}^0$
- Typically involve $X + E_T^{miss}$
  - Jets, leptons, photons

Classic search: jets and E_T^{miss}



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

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



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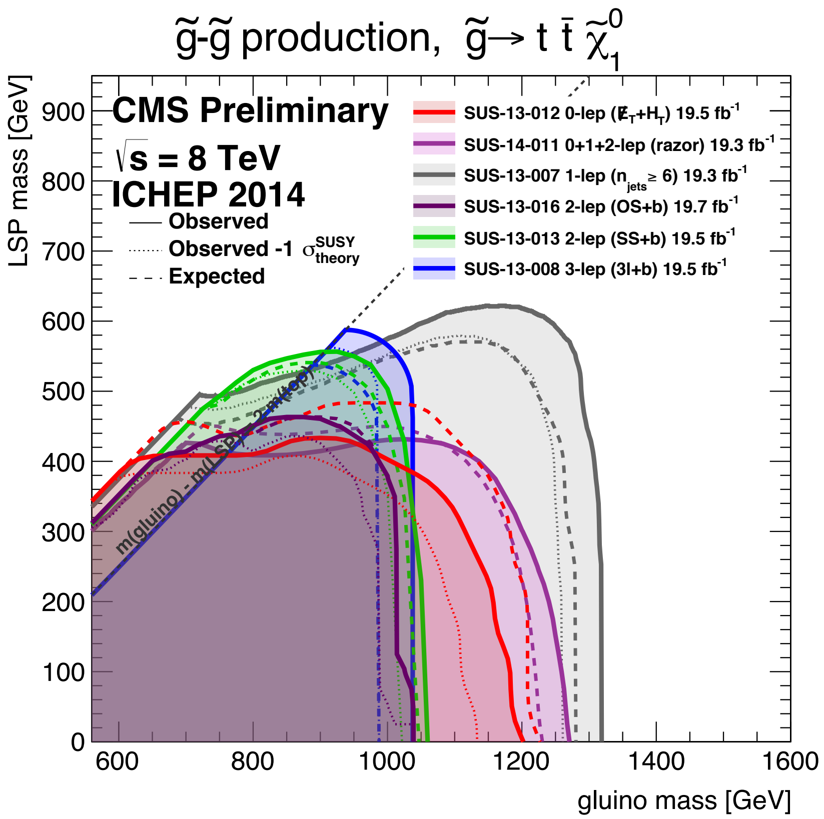
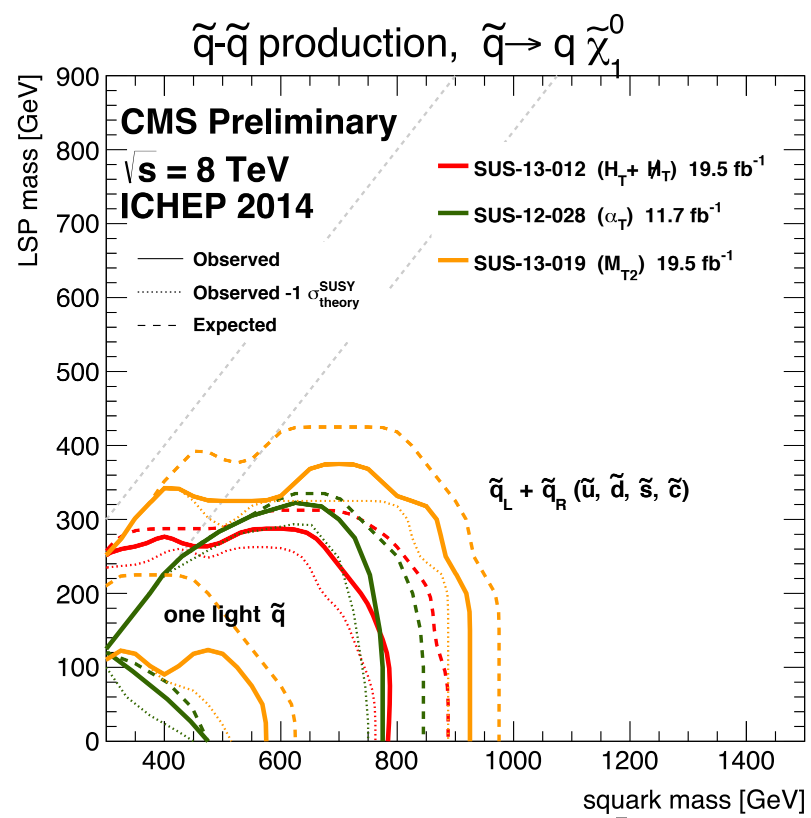
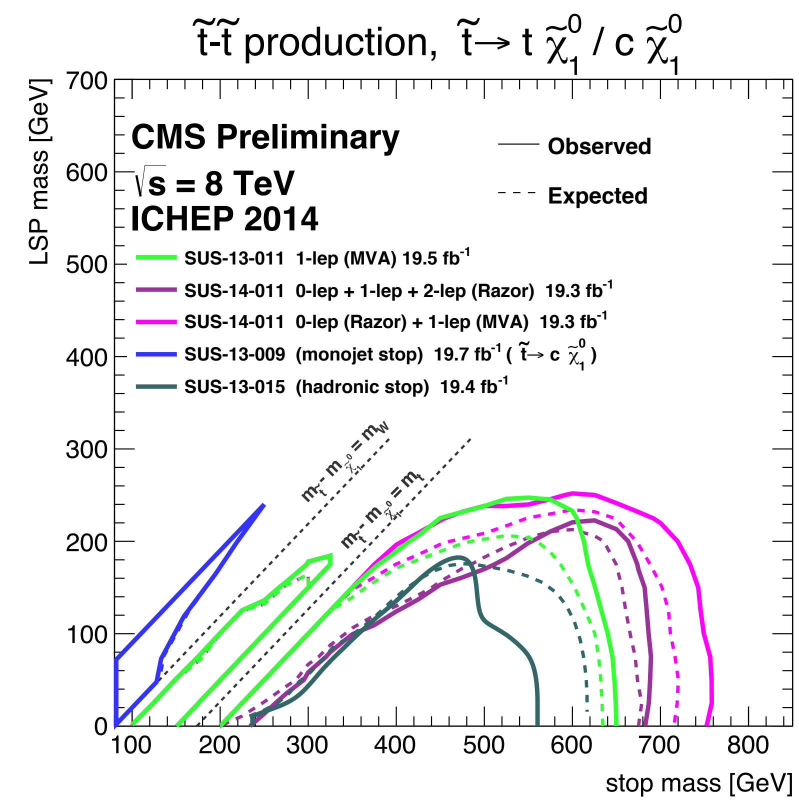
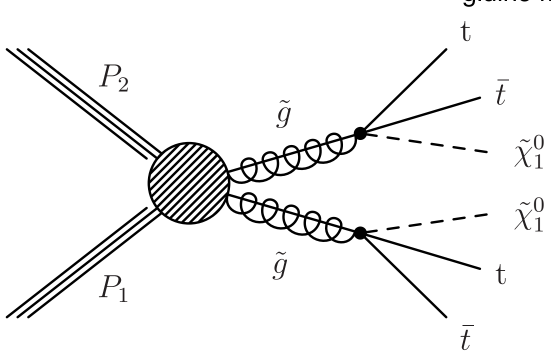
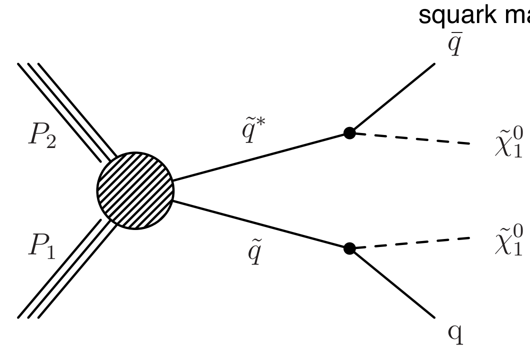
Where we are now: end of Run 1

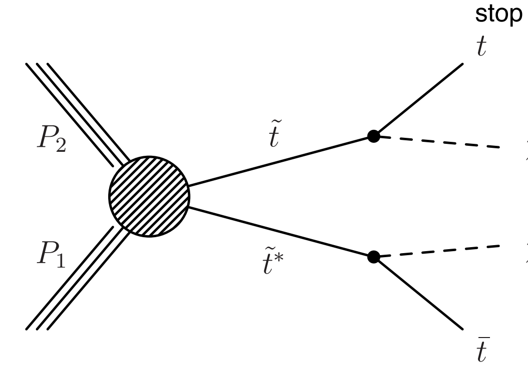










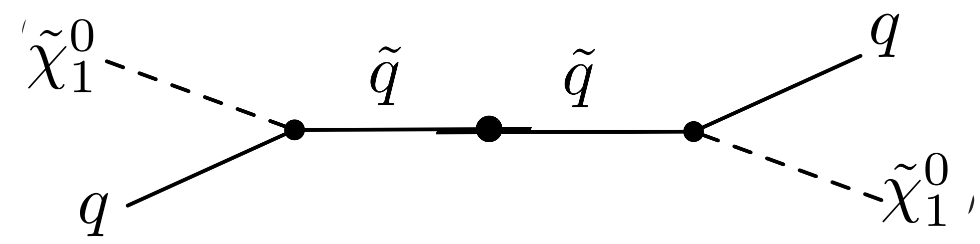


- Where is new physics?
  - Option 1: insufficient sensitivity because of energy or luminosity
  - Option 2: **Not looking in the right place**
    - Nearly all SUSY searches require **substantial E_T^{miss}**

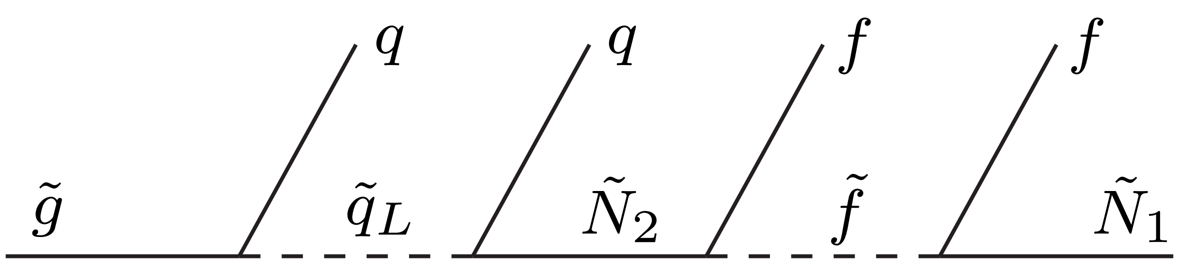
How to hide E_T^{miss}

- 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

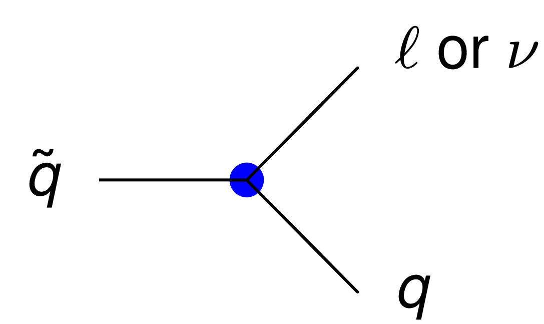


- **Long decay chains**: little p_T remains at end of chain.



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

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



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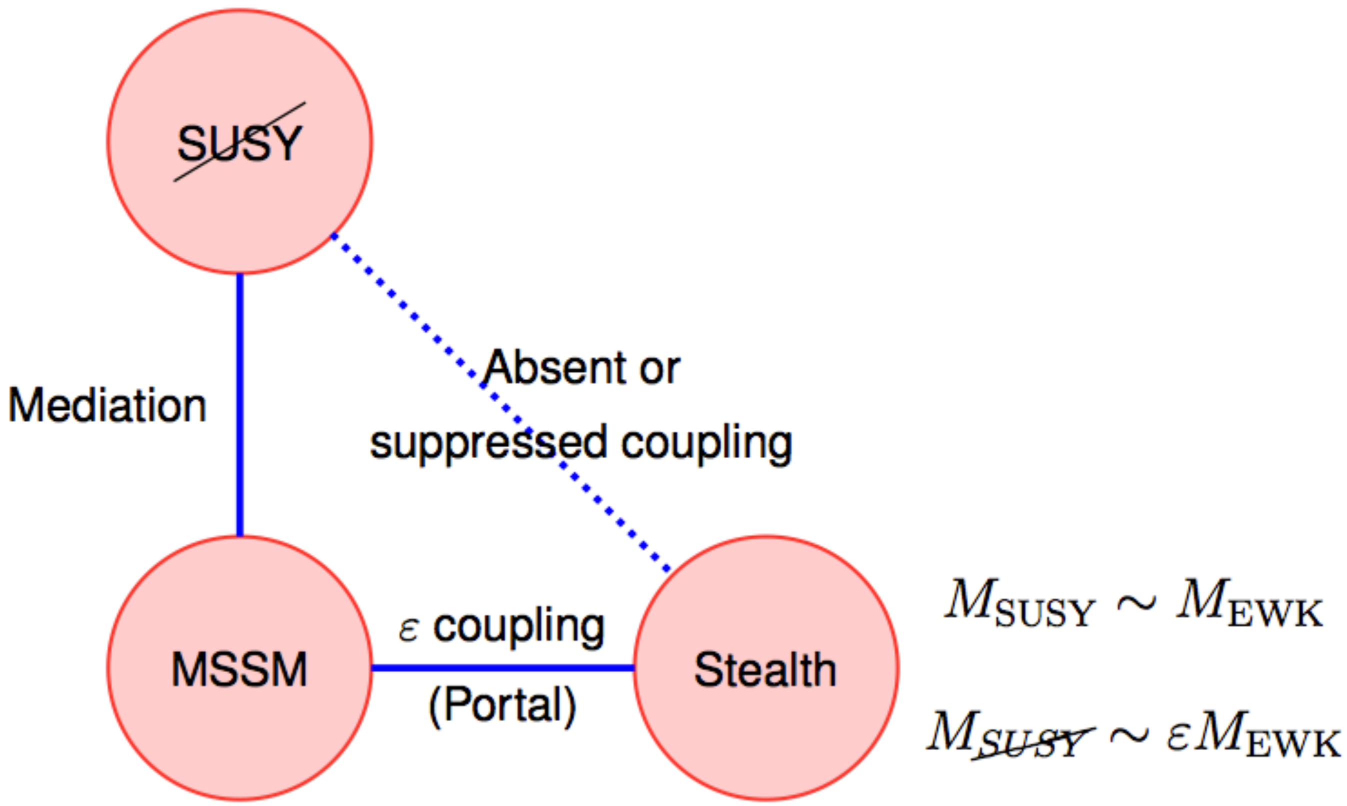
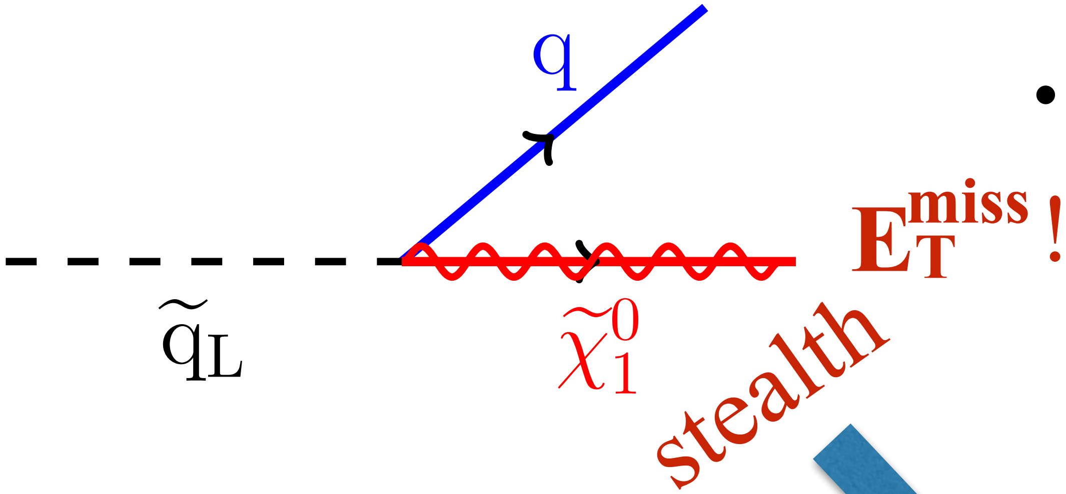
Stealth mechanism

arXiv: 1105.5135, 1201.4875
Fan, Reece, Ruderman

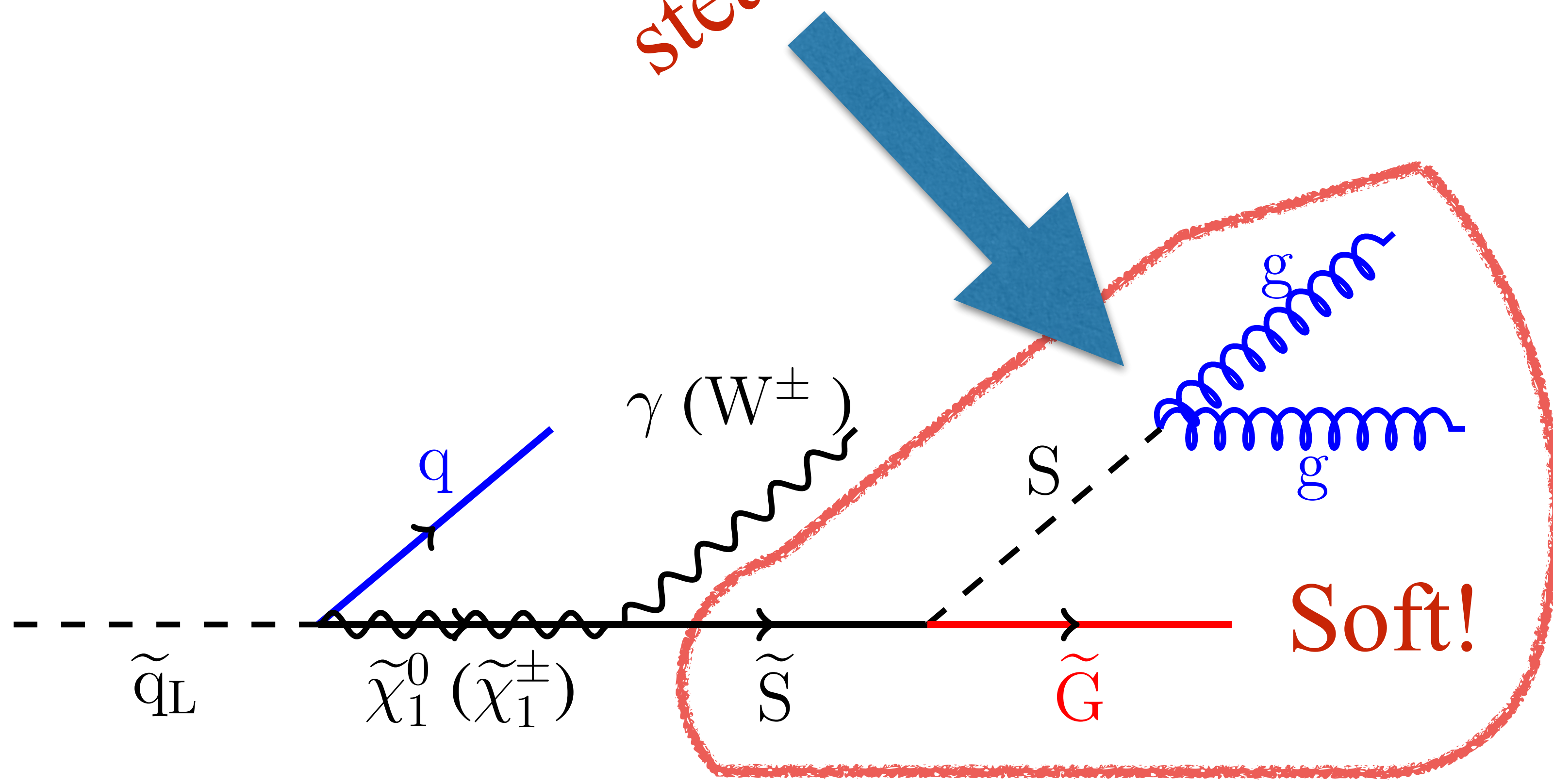


- Assume usual SUSY **breaking sector** with some mediation to **MSSM**
- Introduce hidden sector $\tilde{S}$, S
  - No coupling to SUSY breaking sector
  - SUSY approximately conserved, **enforcing mass degeneracy**
  - $\delta M = M(\tilde{S})\text{-}M(s)$ small

Stealth SUSY



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

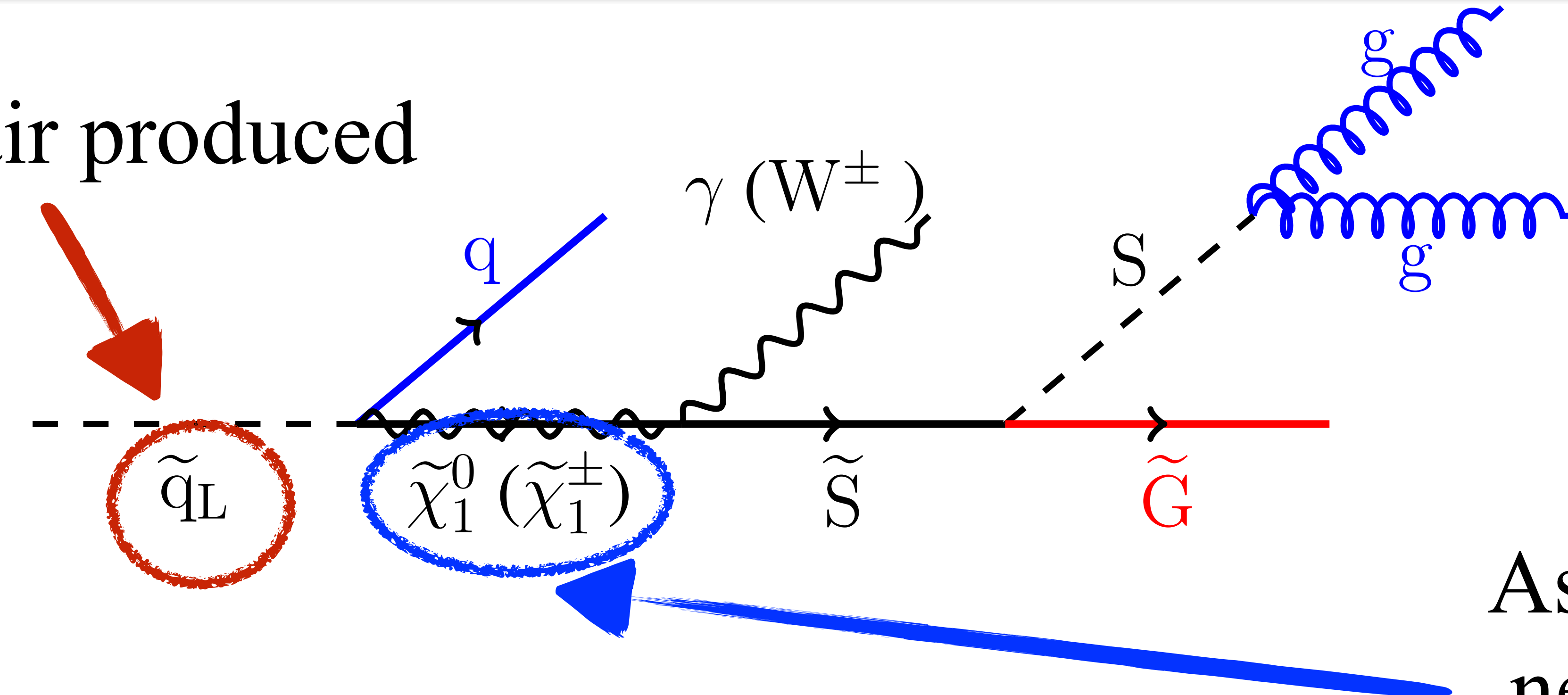


- Allow gaugino to decay to hidden sector with mass degenerate superpartners ($\tilde{S}$,S)

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

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

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

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

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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

$\gamma\gamma$

- 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

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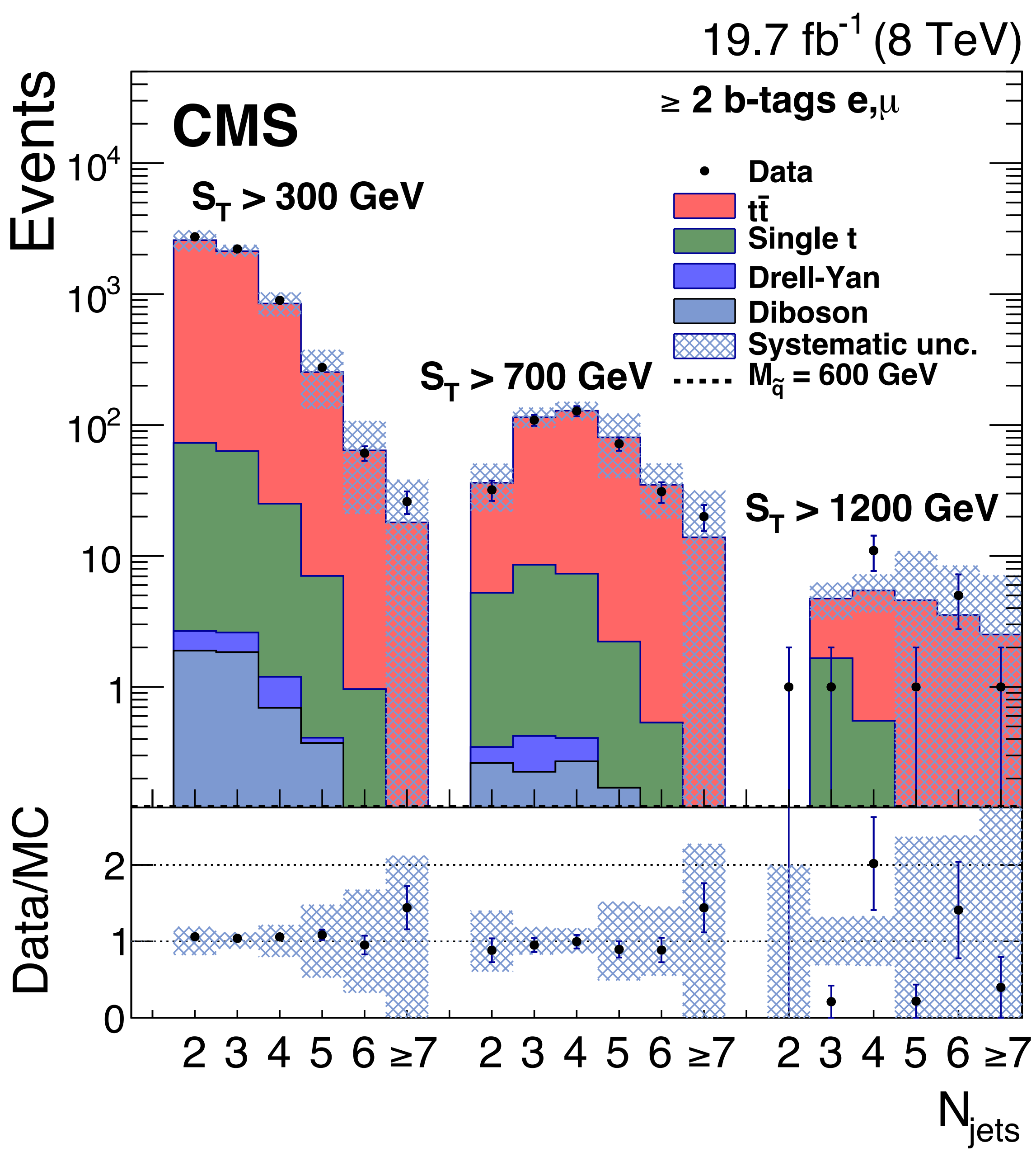
Top background estimation for eμ

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



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

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

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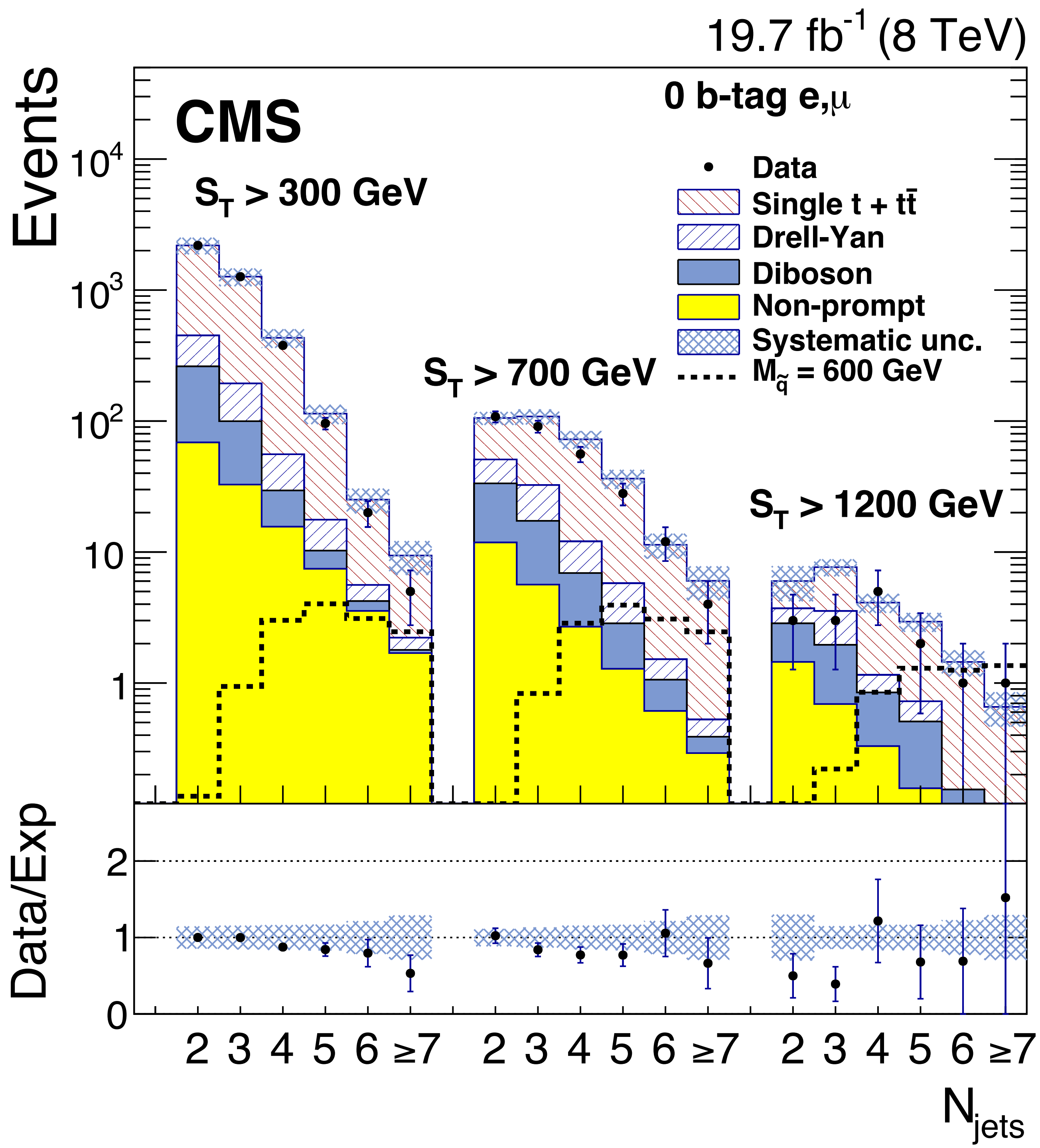
Background estimation for eμ analysis

- DY contributes to eμ through **$Z \rightarrow \tau\tau$**
- **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

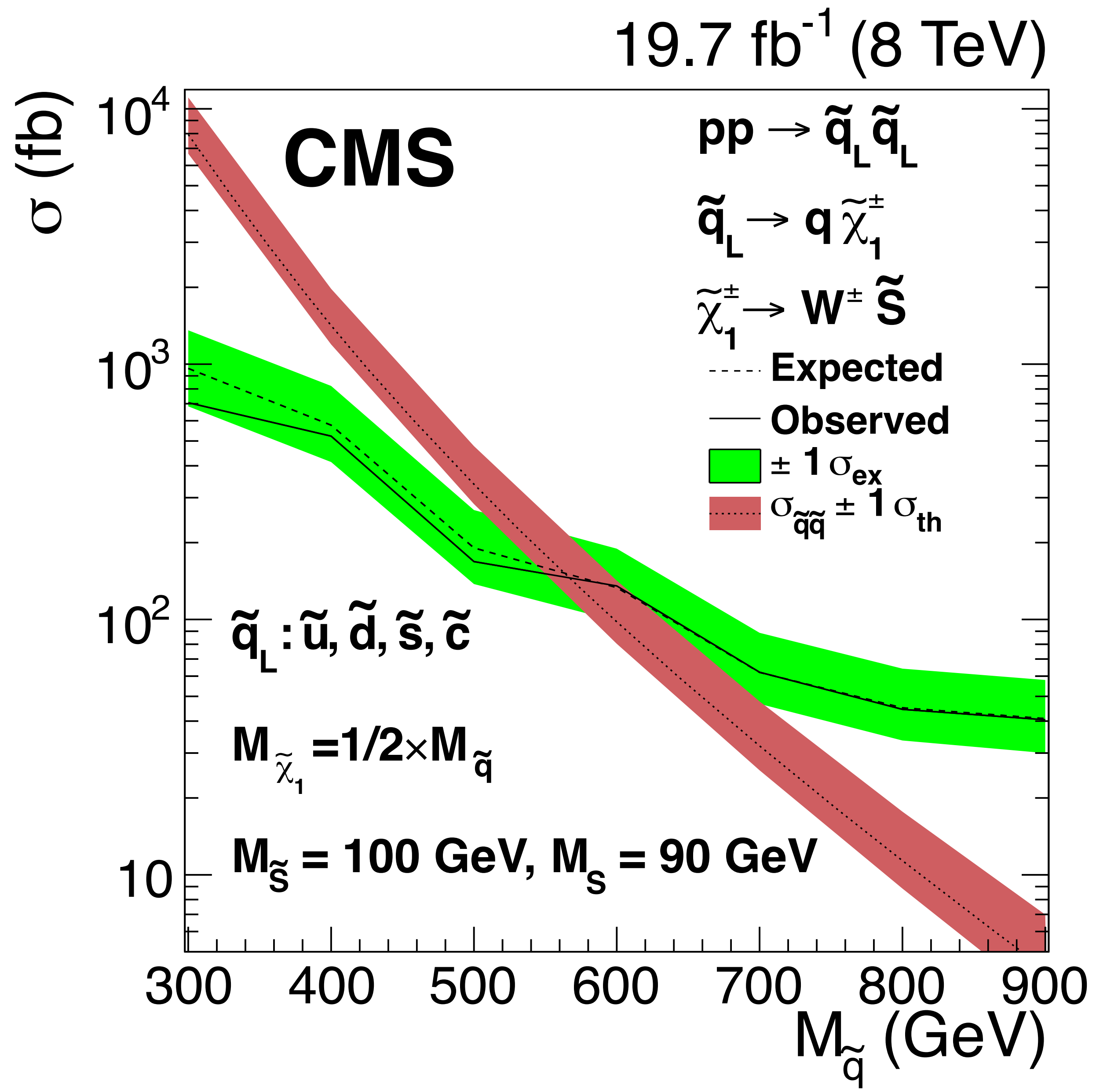
Results 0 b-tag: signal region (eμ)



- 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

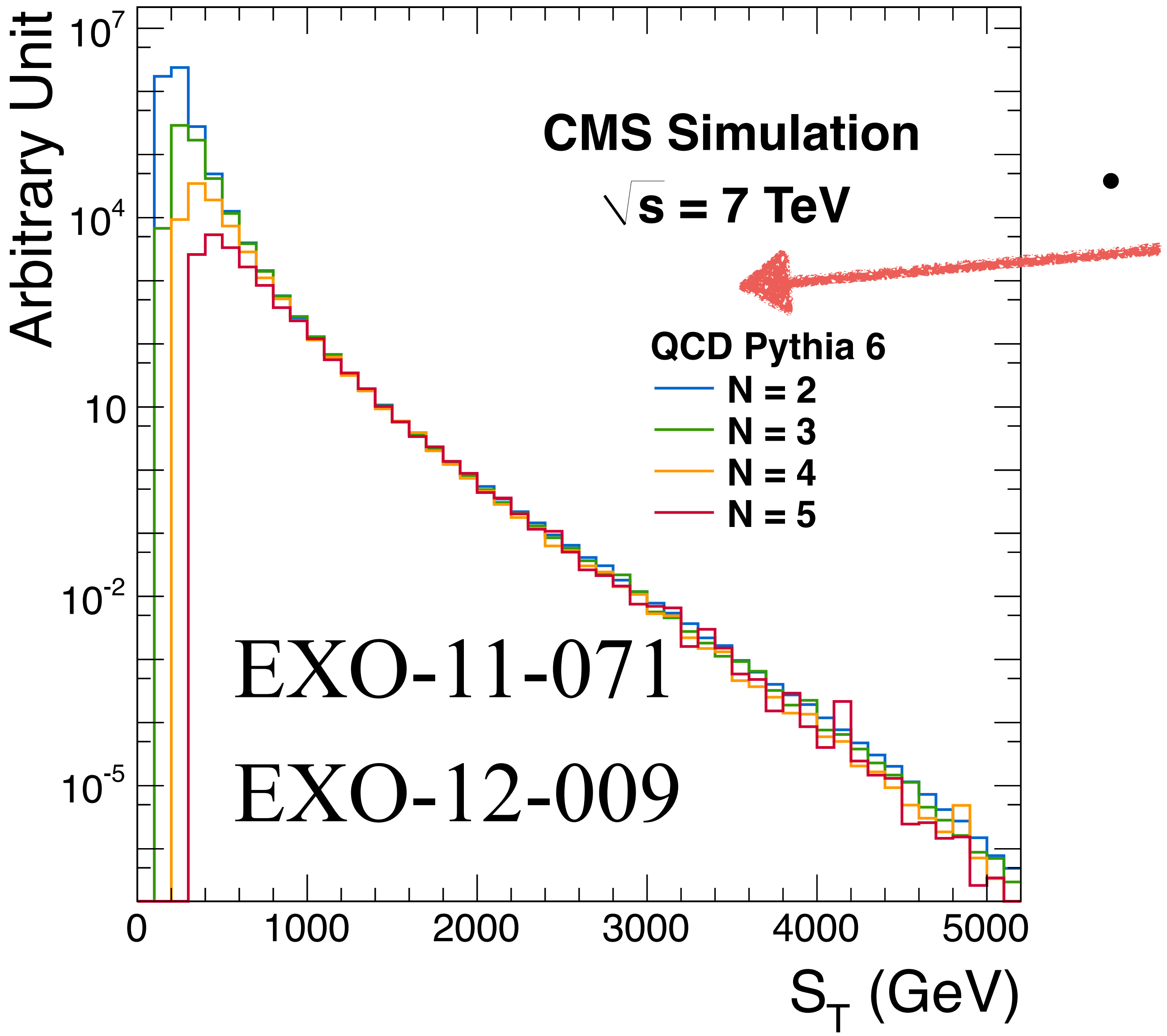
- Set limits on squark mass
- Combine exclusive jet multiplicity bins (4, 5, 6, ≥7)
- Use the S_T threshold with best sensitivity



- 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

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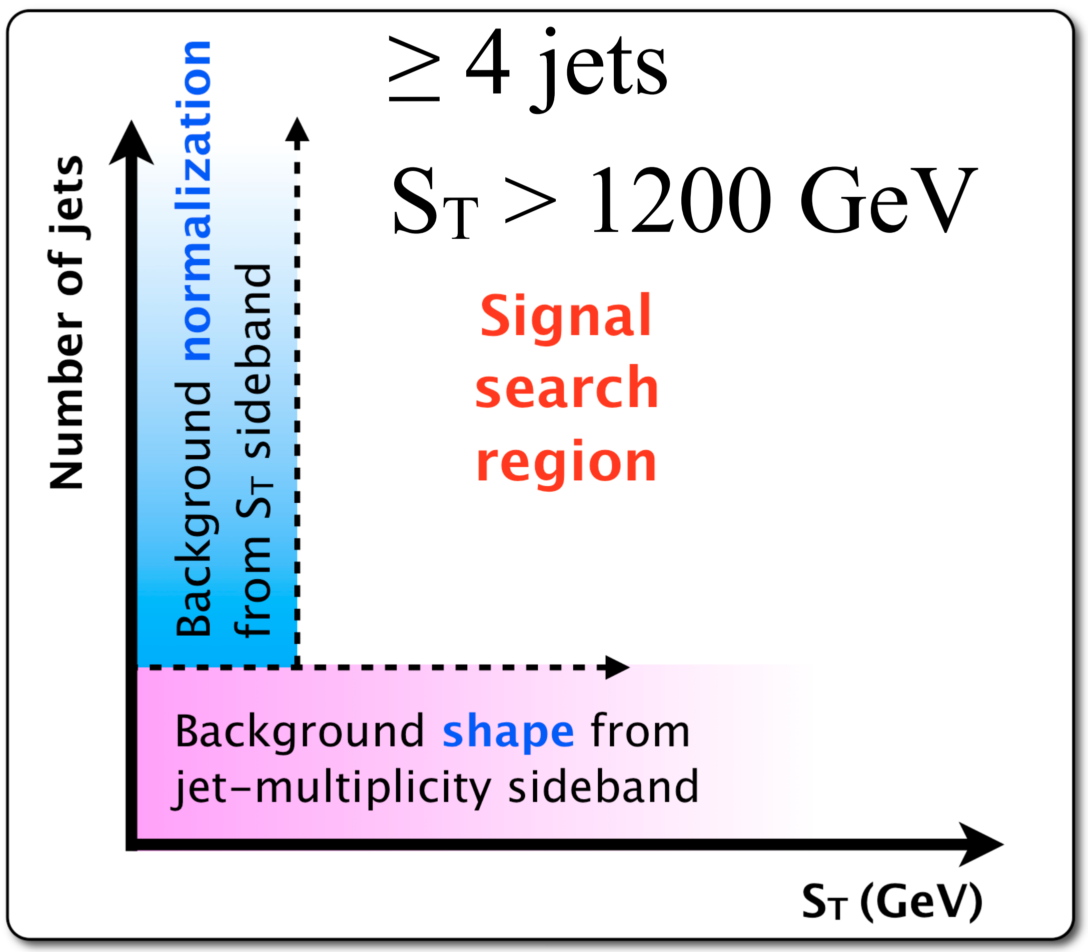
Background estimate ($\gamma\gamma$)

- 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** in S_T sideband (1100-1200 GeV)

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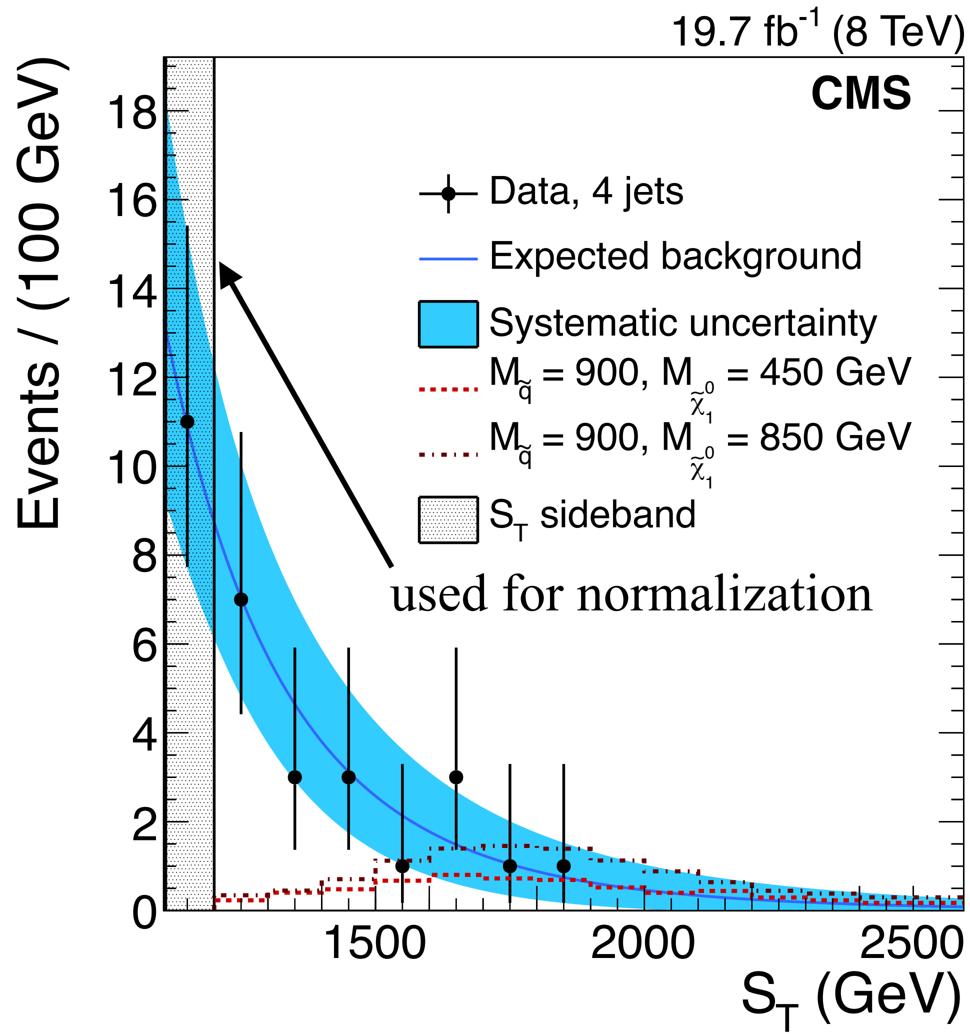
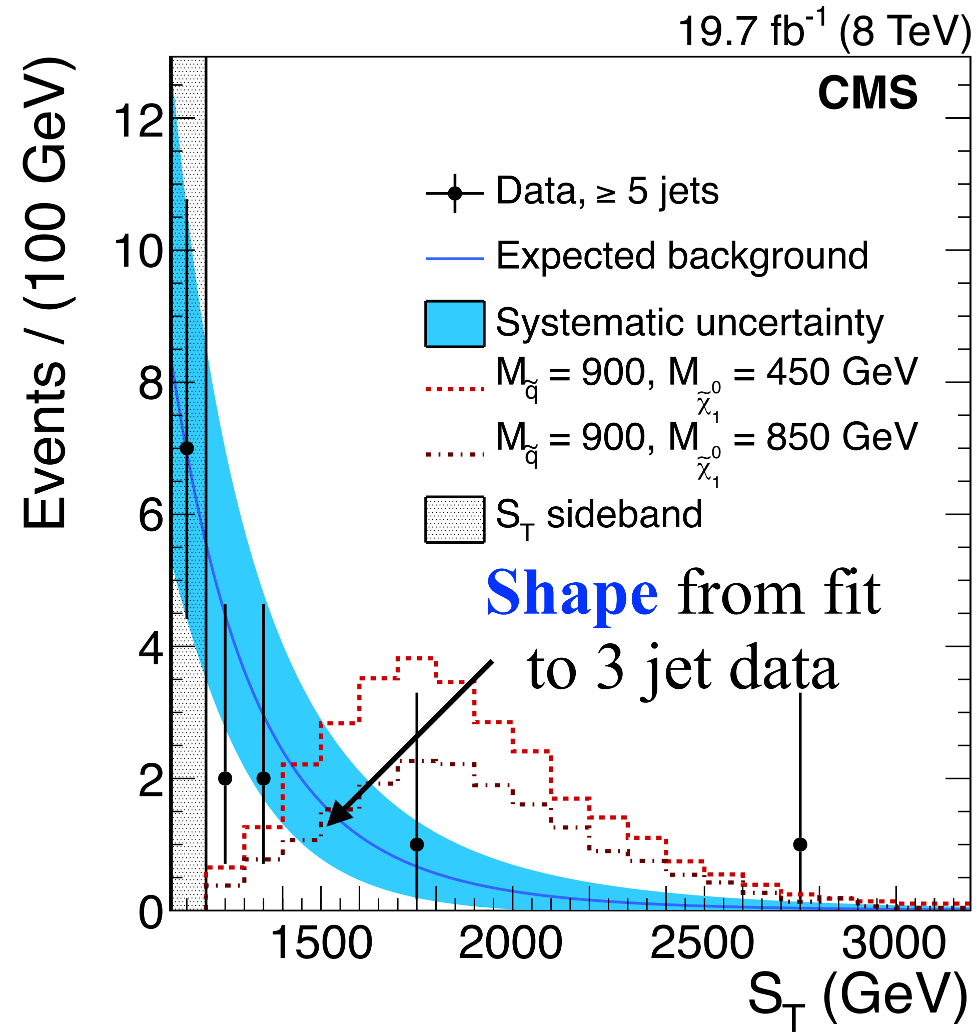
Results ($\gamma\gamma$)





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

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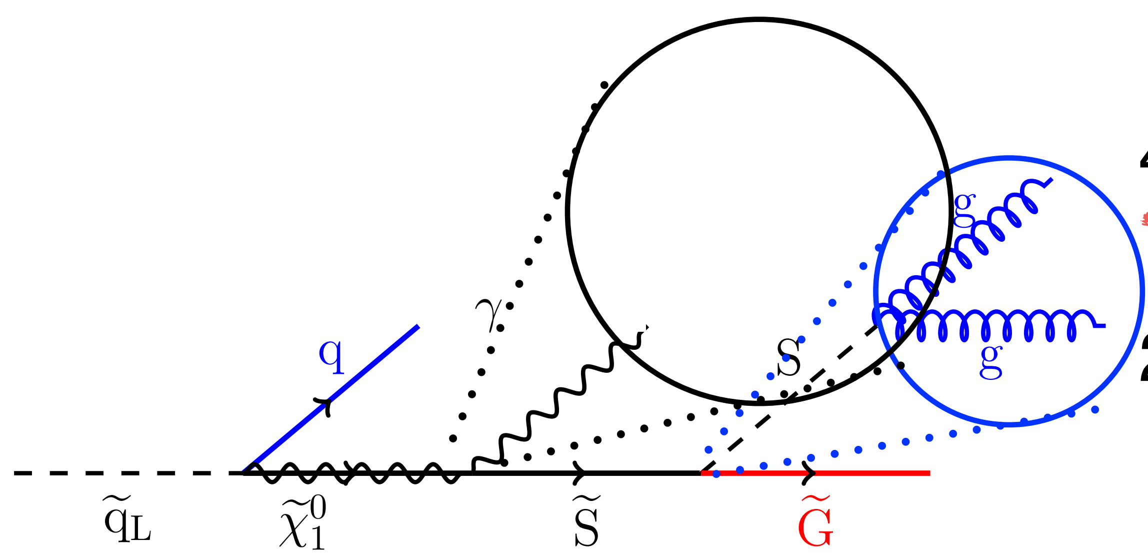
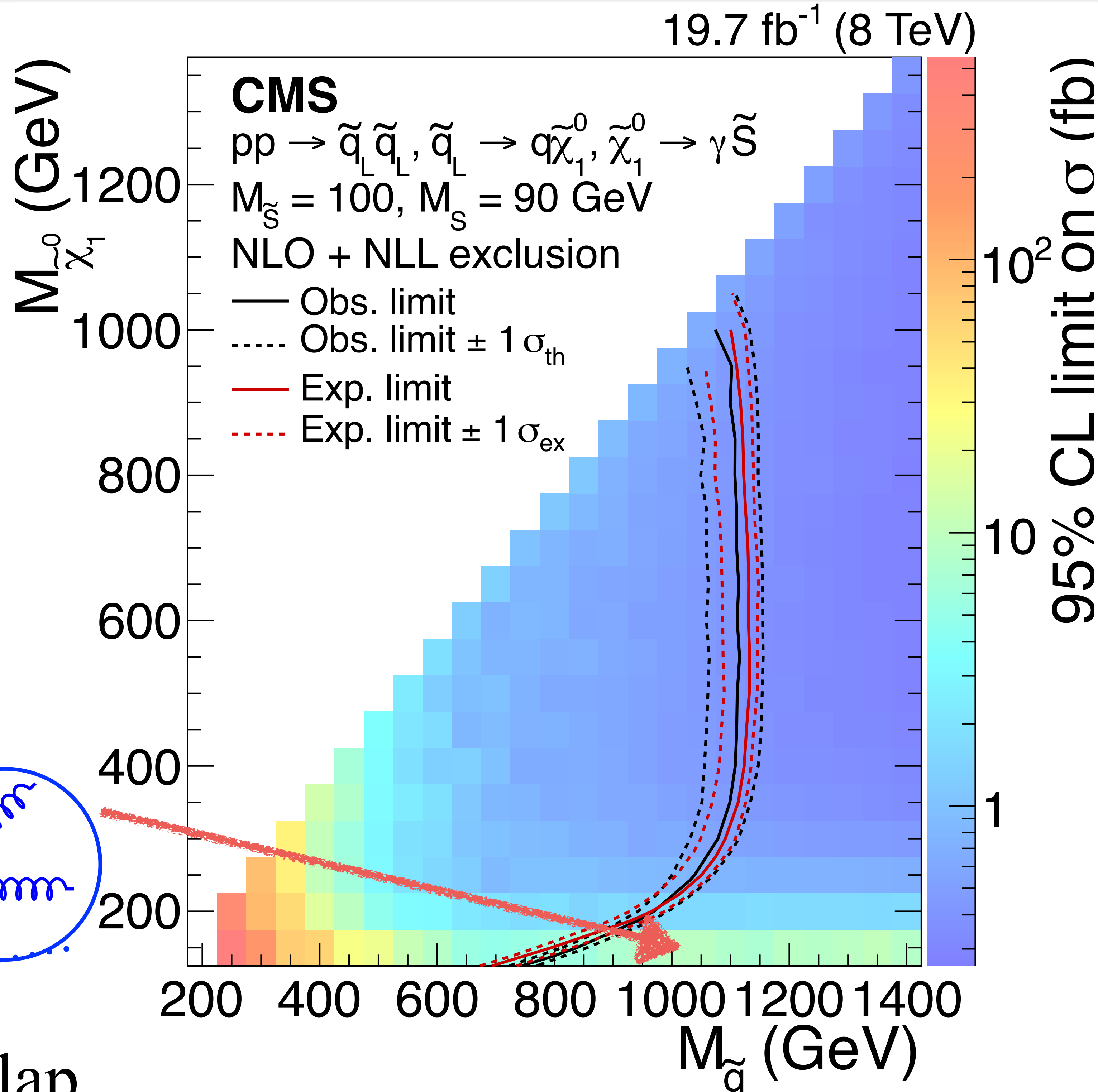
Stealth SUSY limits: $\gamma\gamma$

- 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

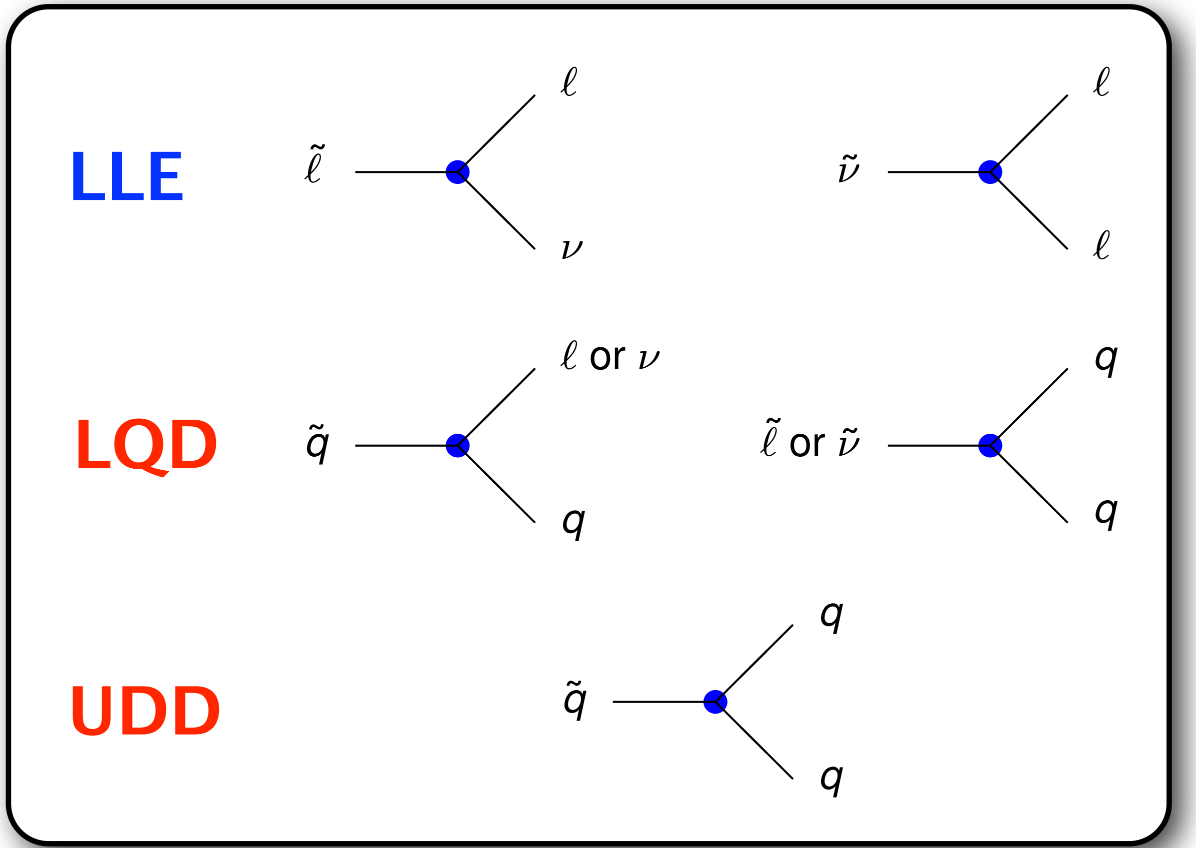
$$W_{\rm RPV} = \frac{1}{2}\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{1}{2}\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

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

lepton number violating baryon number violating

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

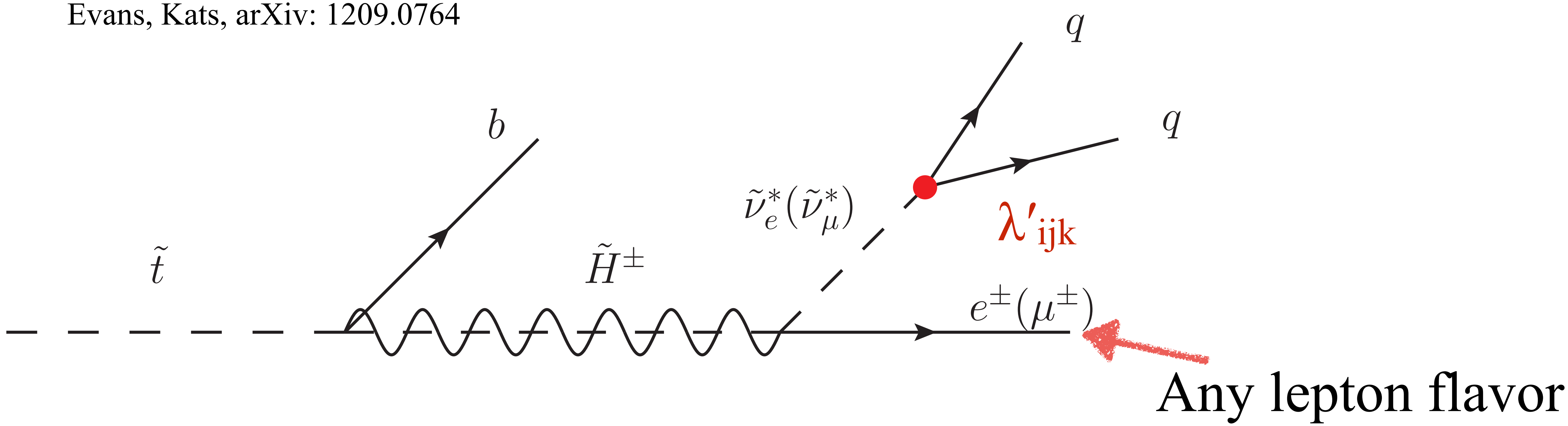
- Allow SUSY particles to decay directly to two SM particles
- Generator of low-E_T^{miss} signatures



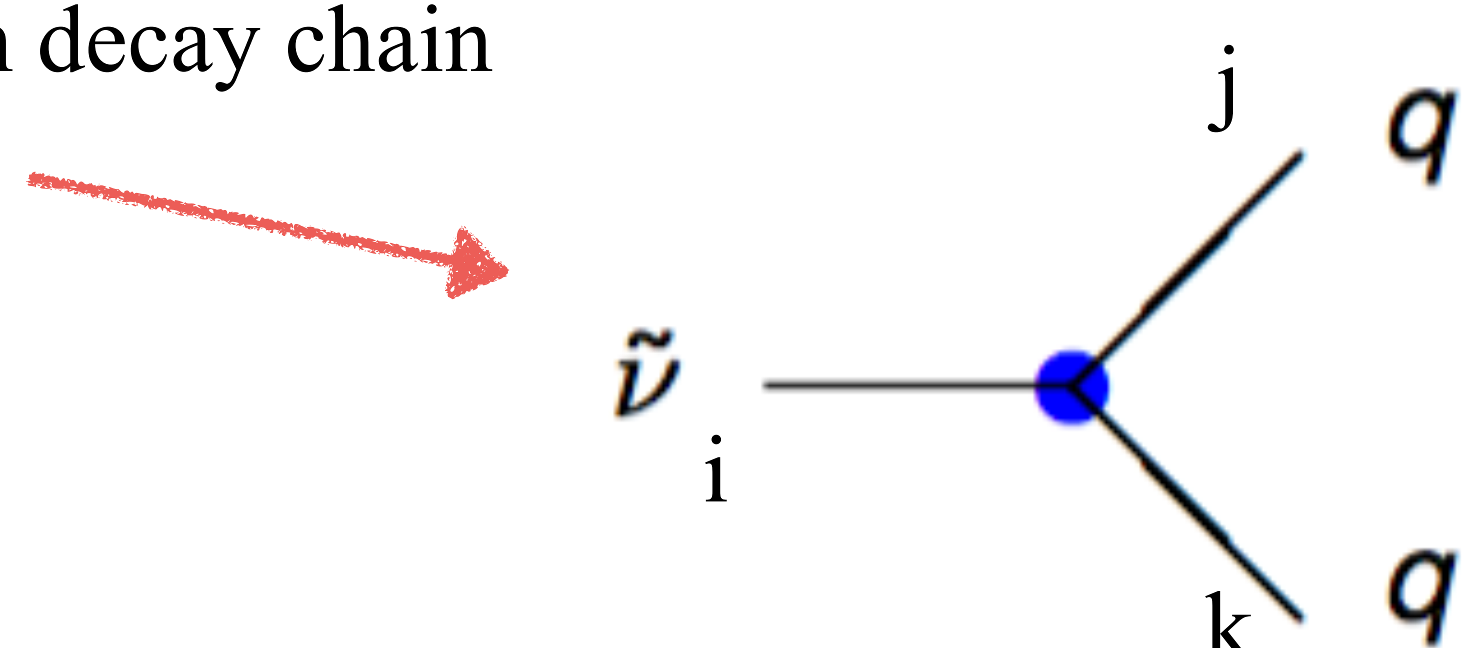
Evans, Kats, arXiv:1209.0764

Example higgsino mediated top squark decay

Evans, Kats, arXiv: 1209.0764



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



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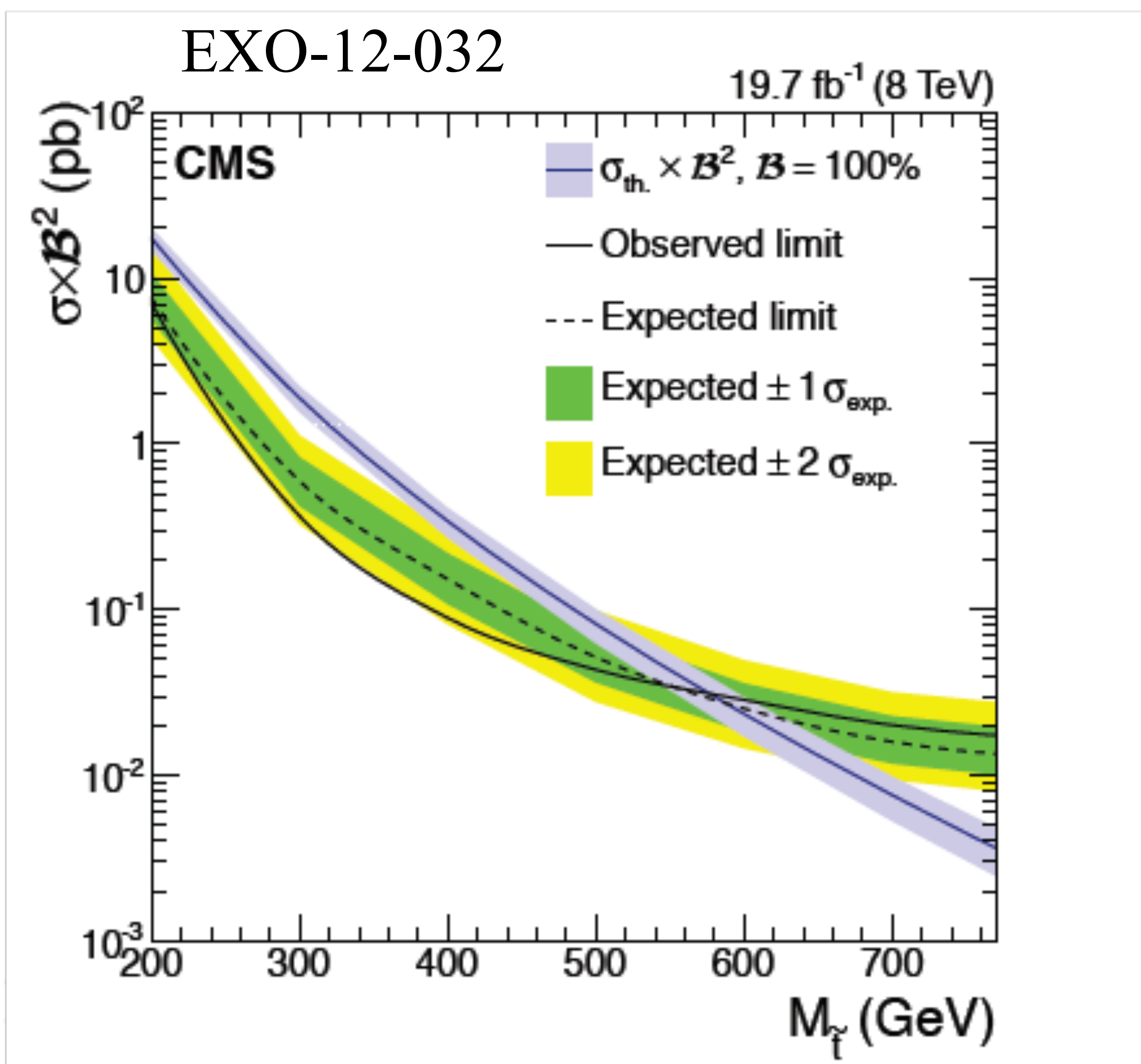
Example higgsino mediated top squark decay

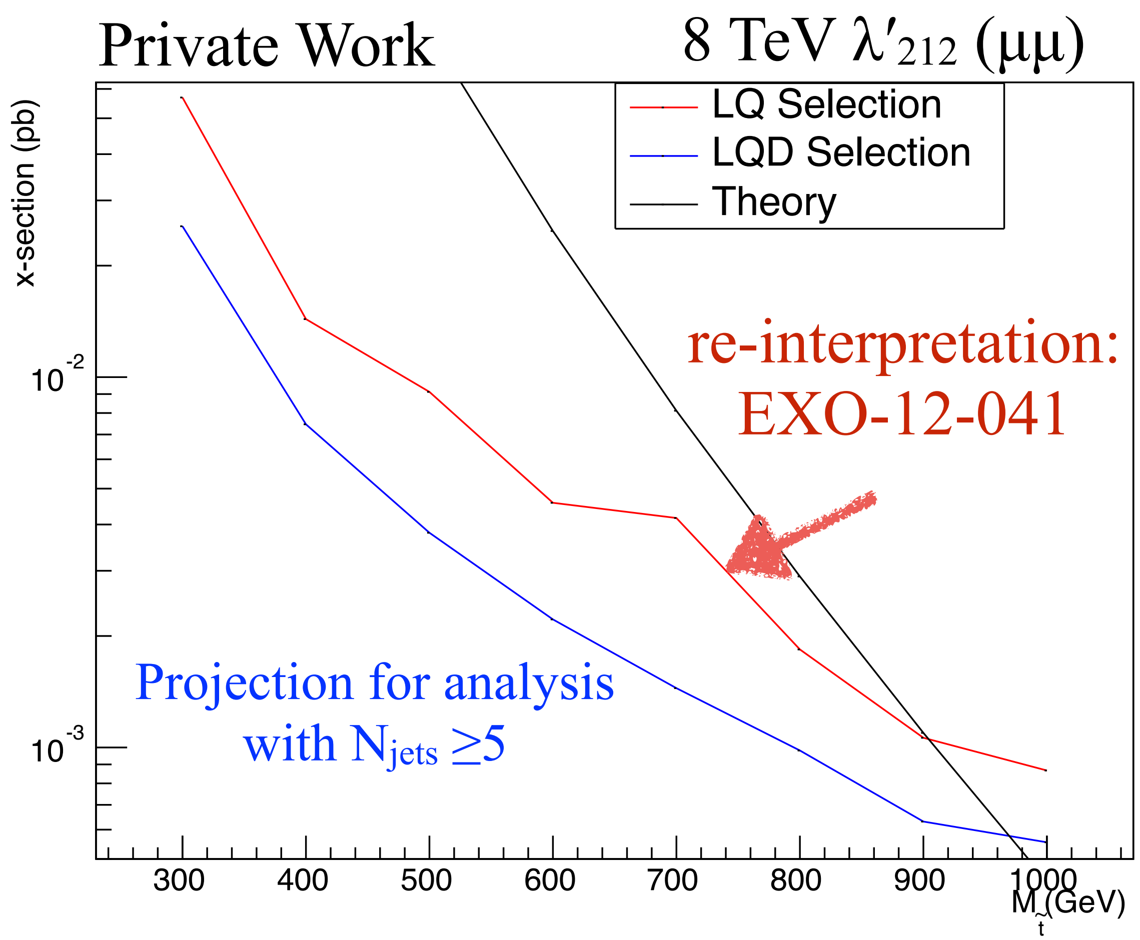
- Search using $\tau\tau$ completed EXO-12-032



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

Example higgsino mediated top squark decay

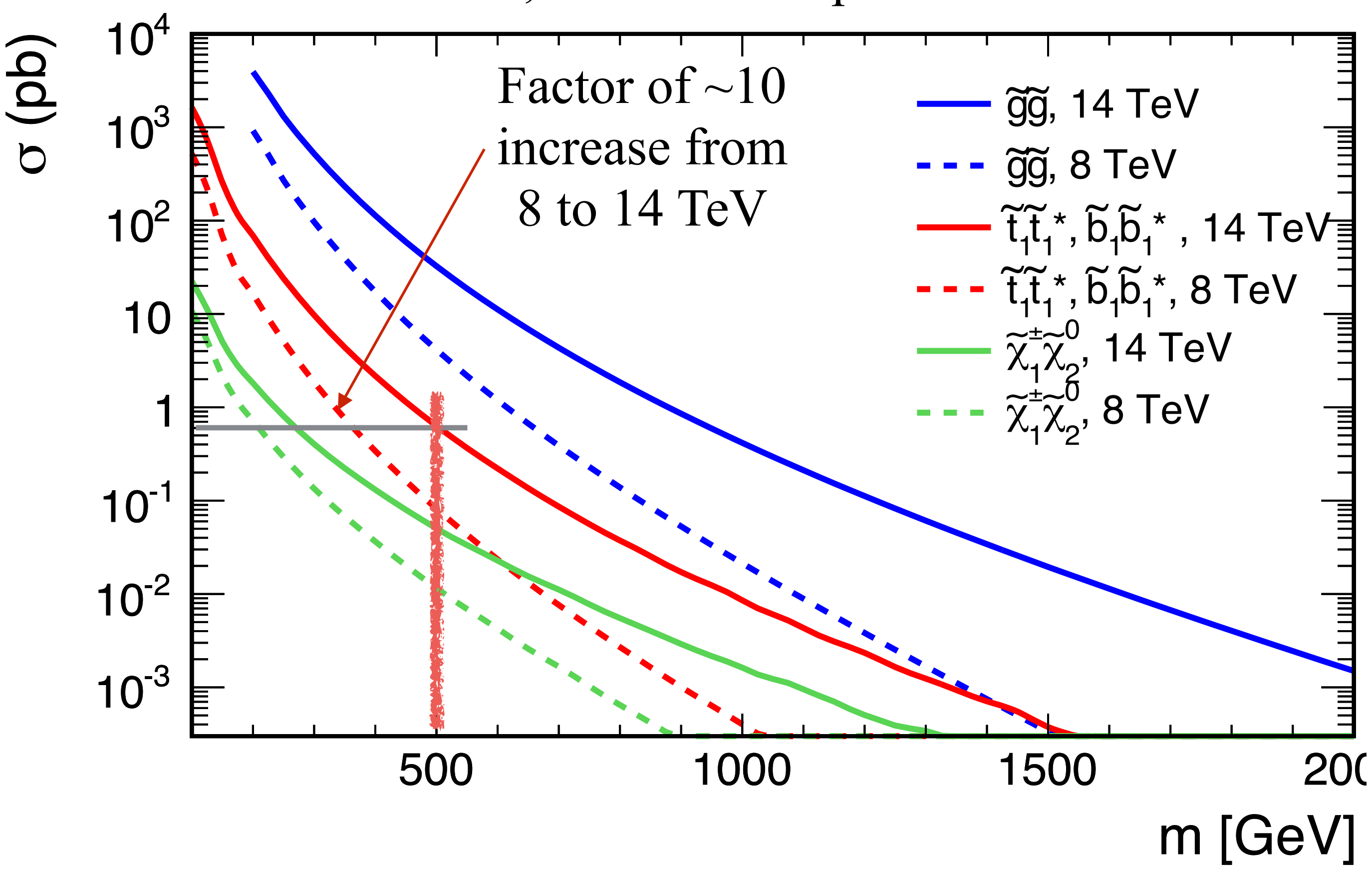
- First (second) generation LQ analyses give some sensitivity
  - Require ee (μμ), at least two jets
    - $M(\ell\ell)$, $M(\ell j)$, S_T



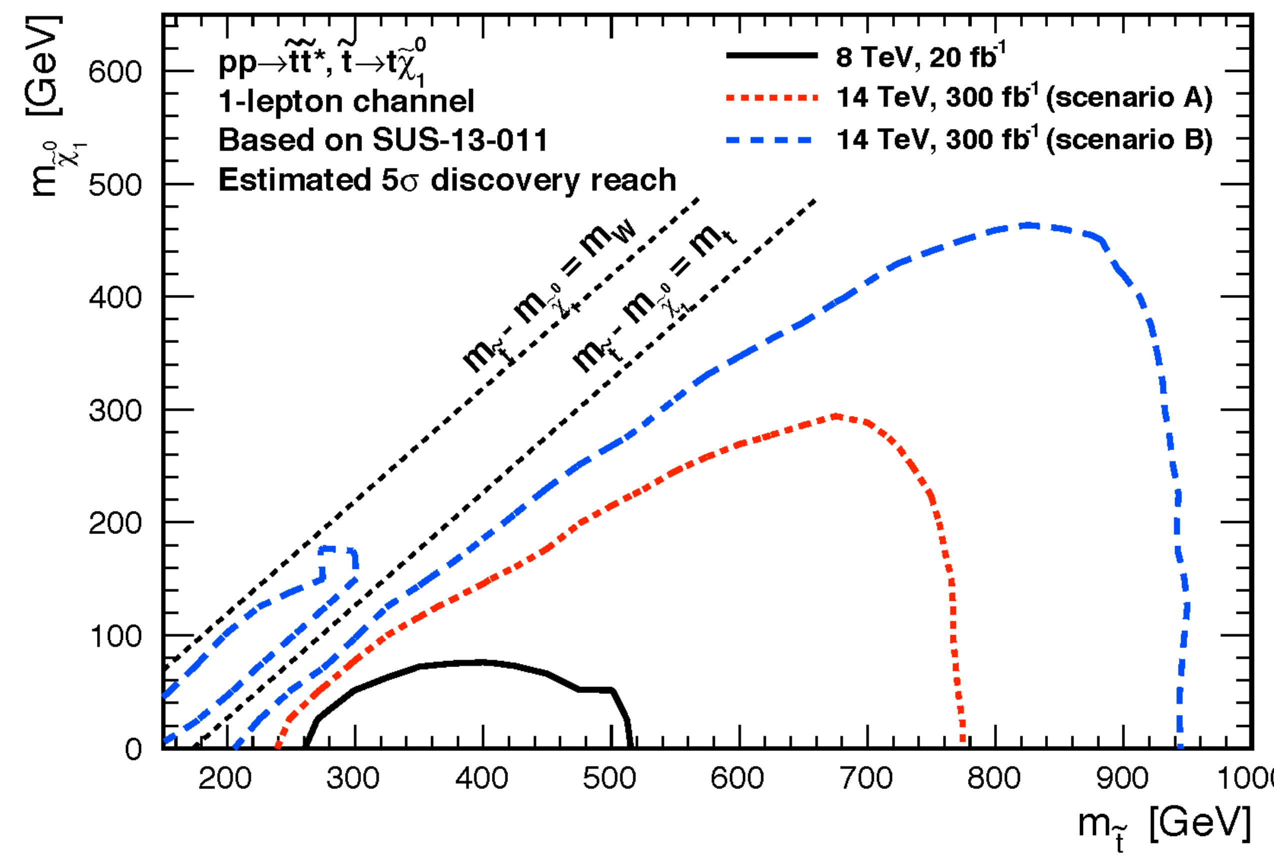
- Dedicated search optimized for this decay
  - $N_{jets} \geq 5$, ≥ 1 b-tag
  - $E_T^{miss} < 100$ GeV
  - $M(\ell\ell) > 130$ GeV
  - S_T optimized for each mass point
- Improve sensitivity by a factor of **2-3 improvement**

Projections for 13 TeV

arXiv: 1307.7135, Snowmass report



Snowmass2013SUS



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

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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

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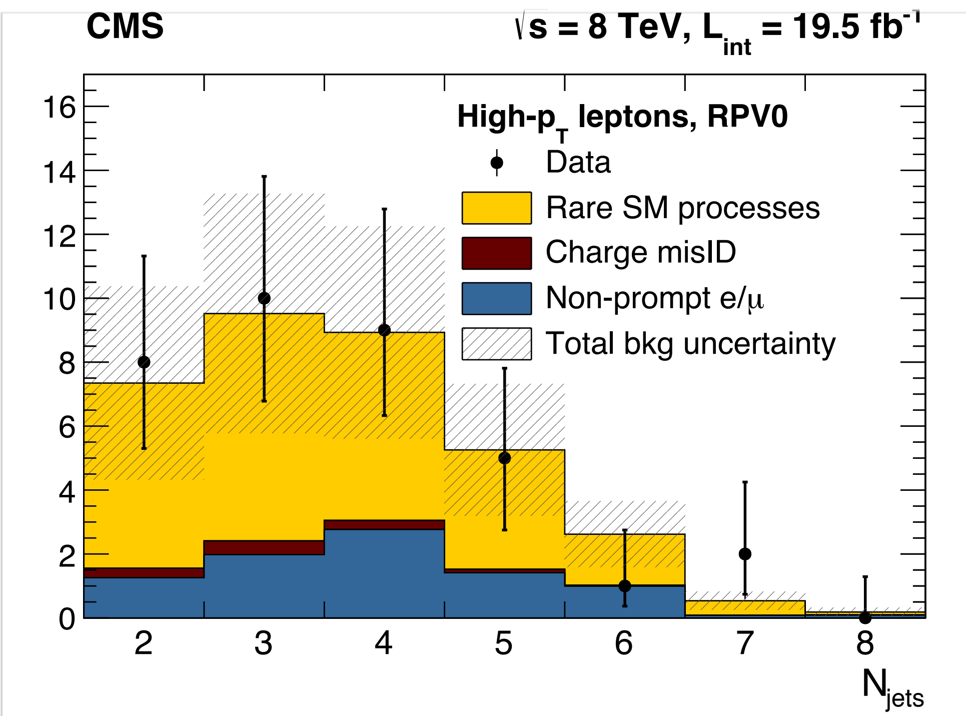
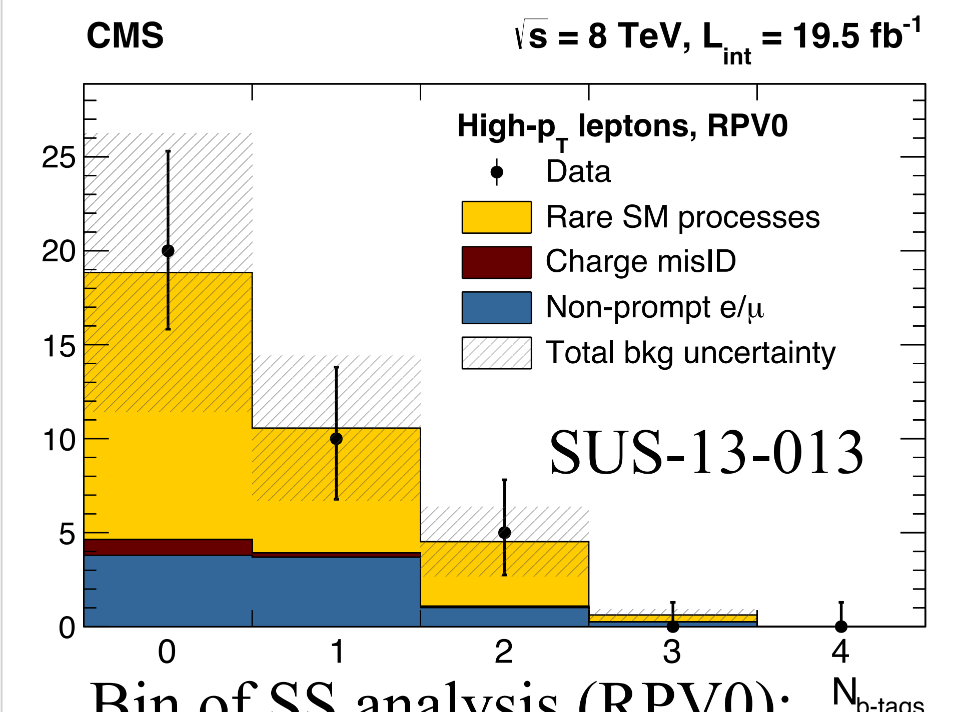
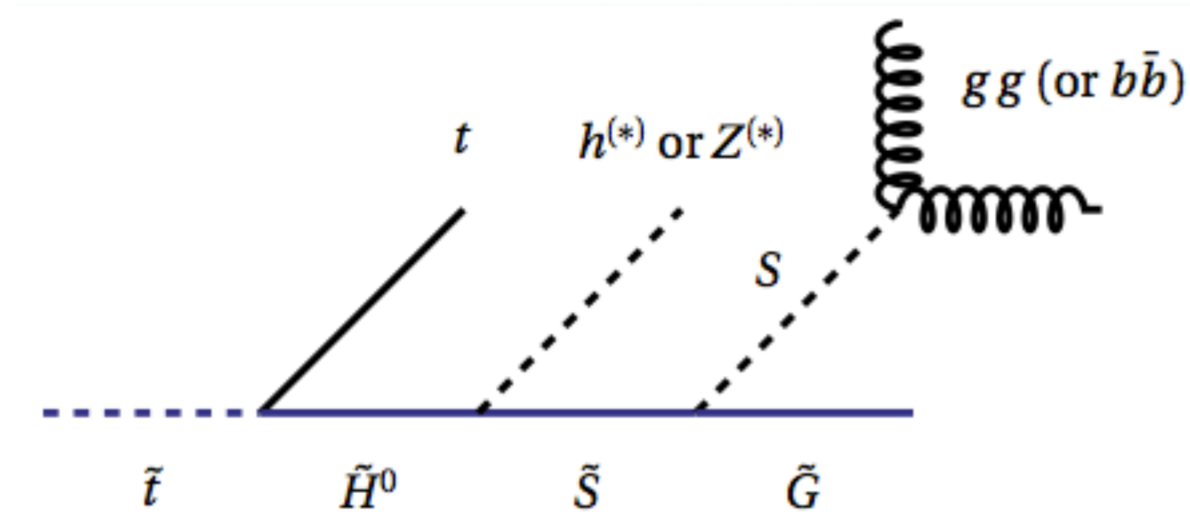
Same-sign dileptons



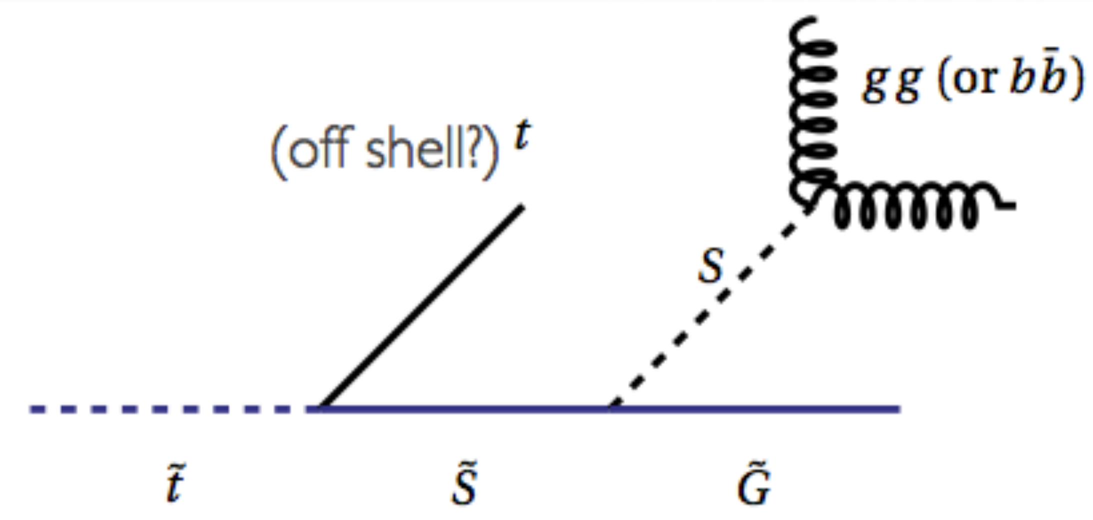


Bin of SS analysis (RPV0):
No MET requirement
$H_T > 500$ GeV



- 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

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Backup

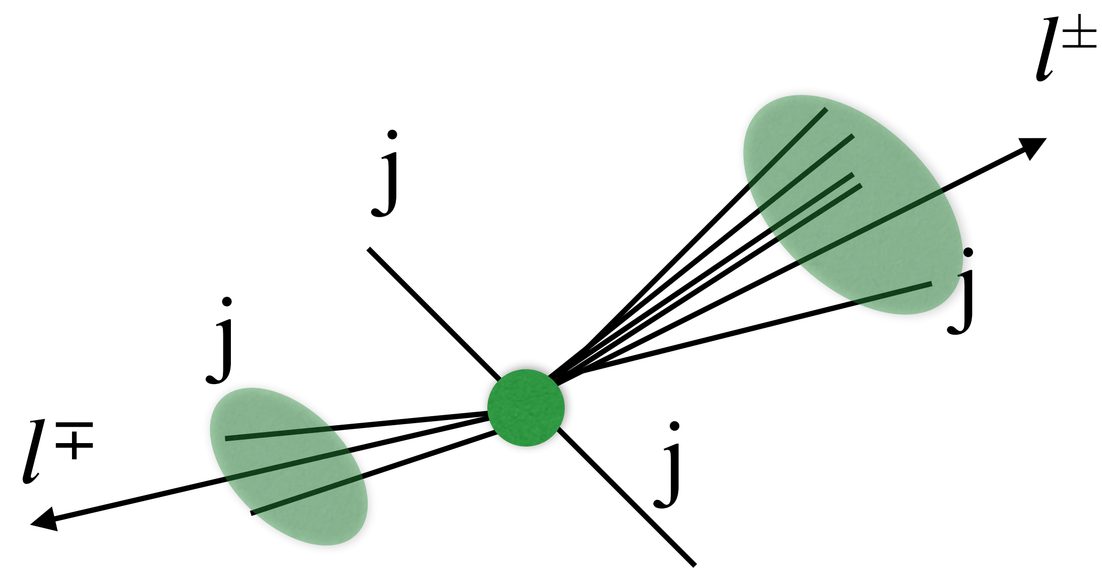
Drell-Yan background

- 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

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 [%]
$N_{\text{jets}} \geq 4$, $S_{\text{T}} \geq 300$	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

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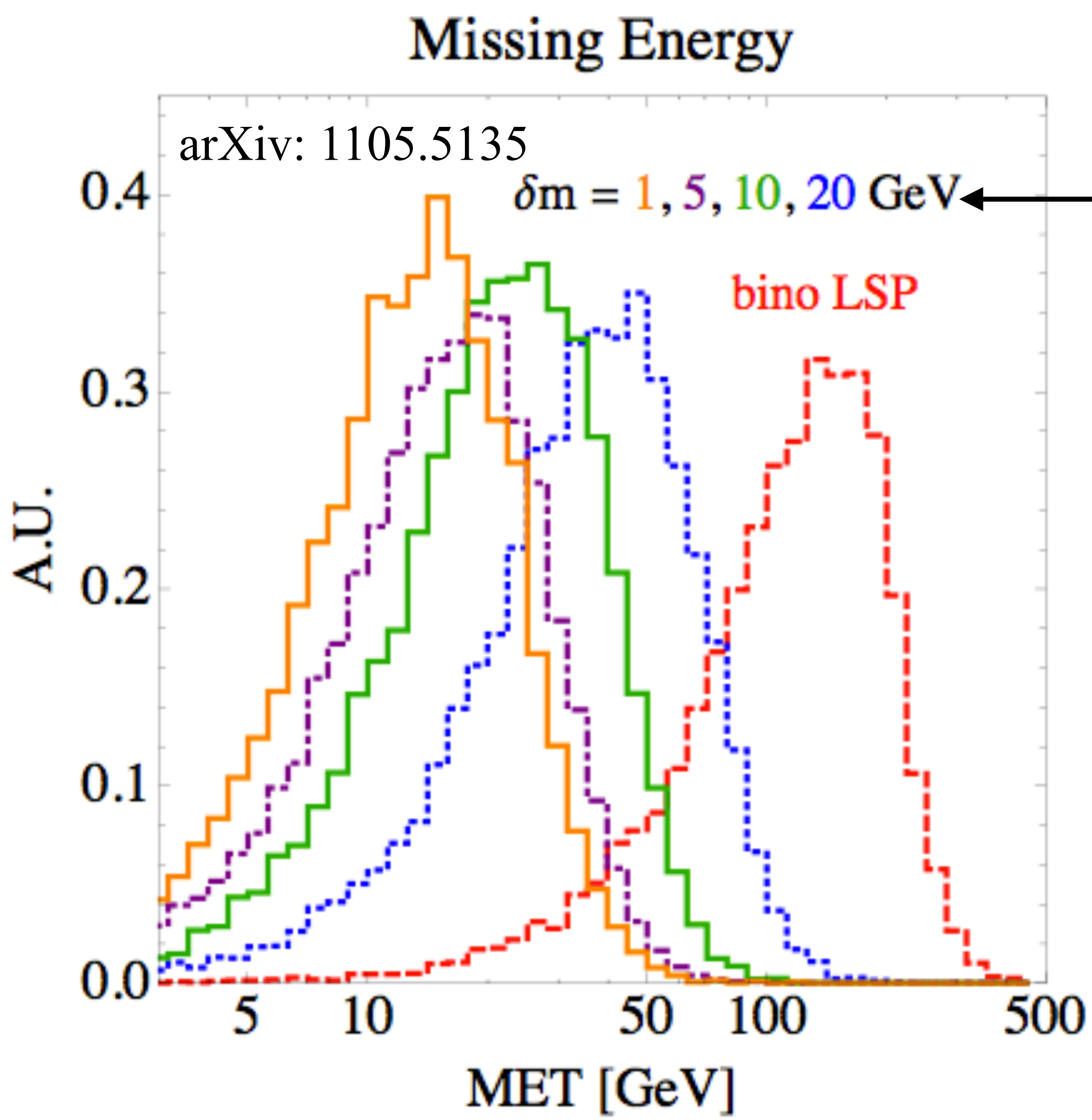
No MET handle on stealth



- 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!

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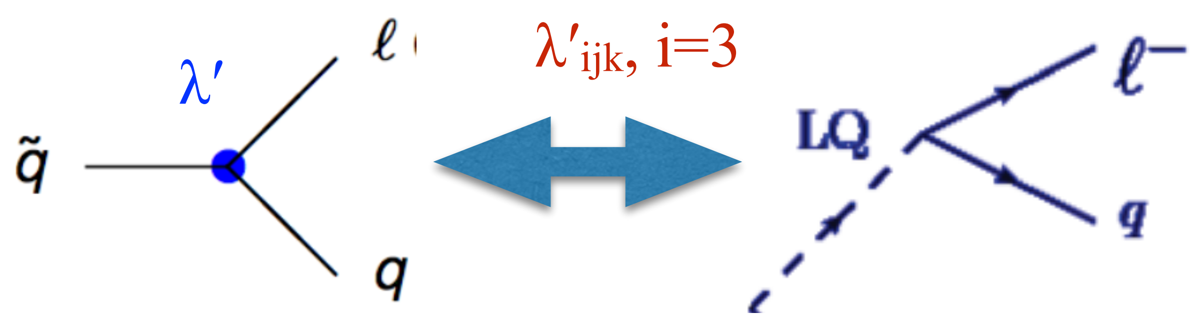
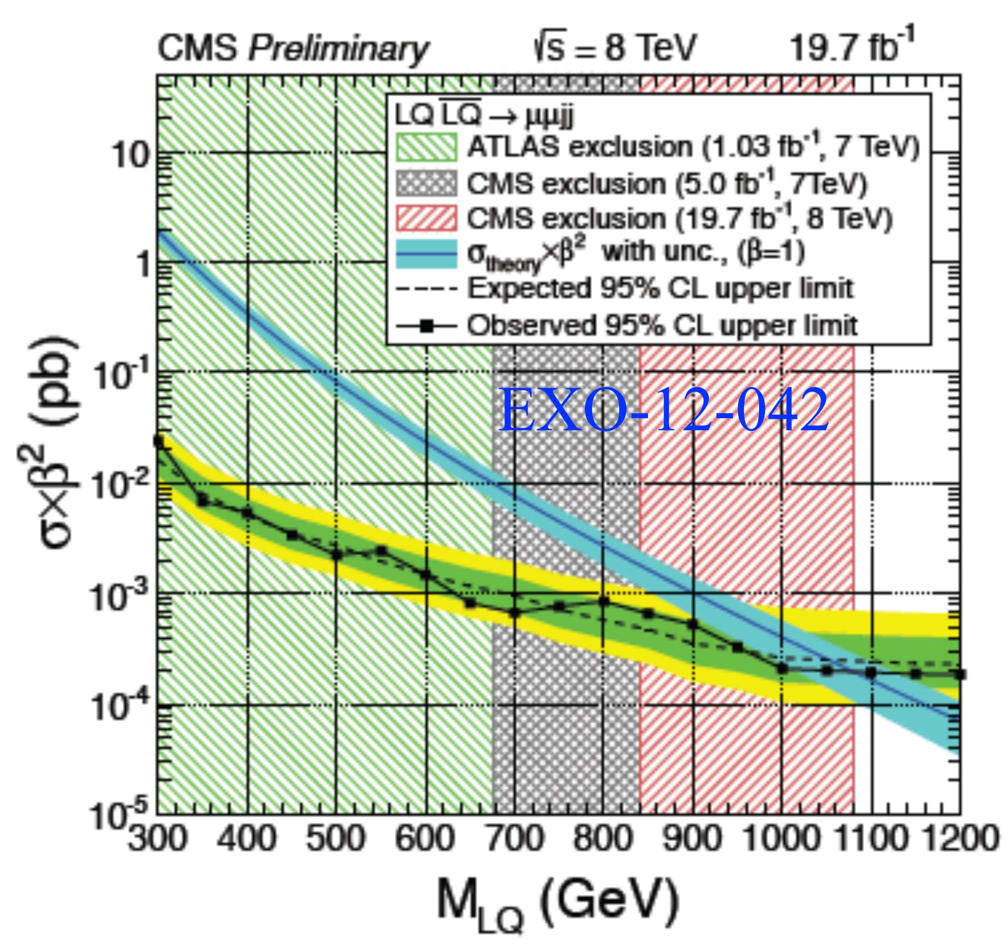
RPV top squark decays

- 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

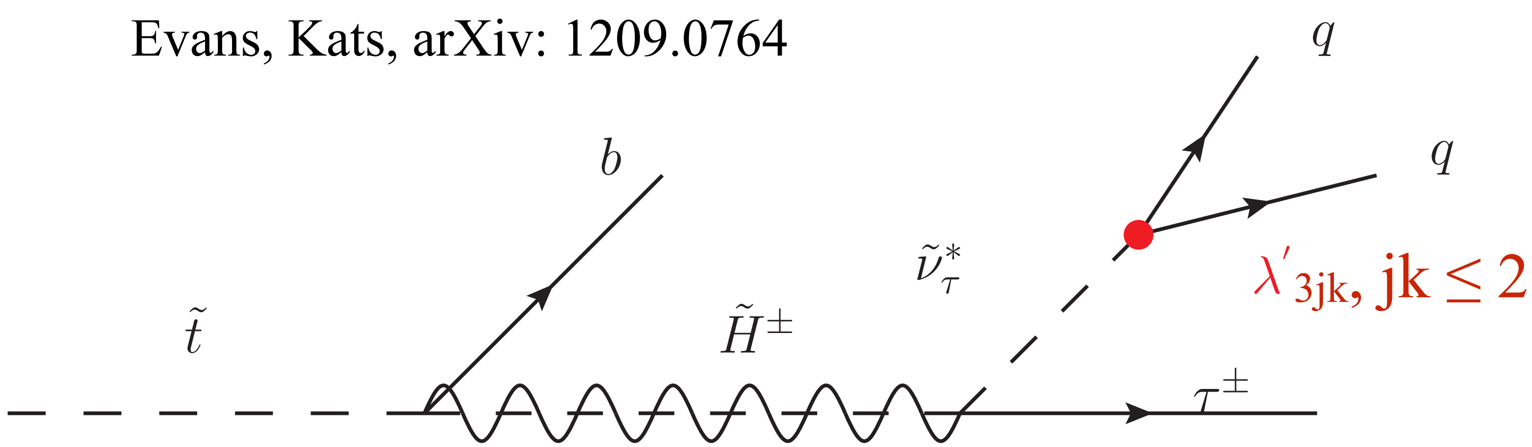




M_{LQ} equivalent to M(top squark)

Higgsino mediated top squark decay

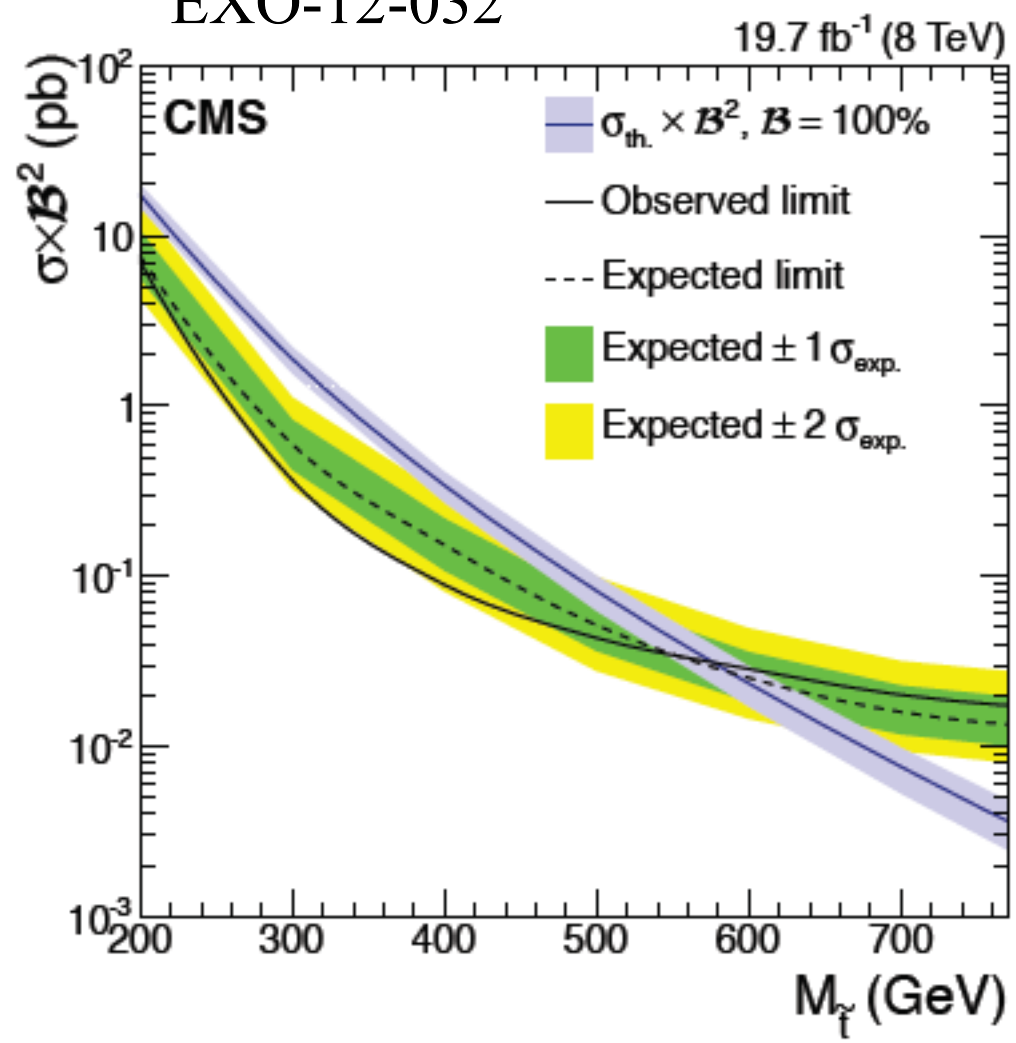
Evans, Kats, arXiv: 1209.0764



- 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



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.

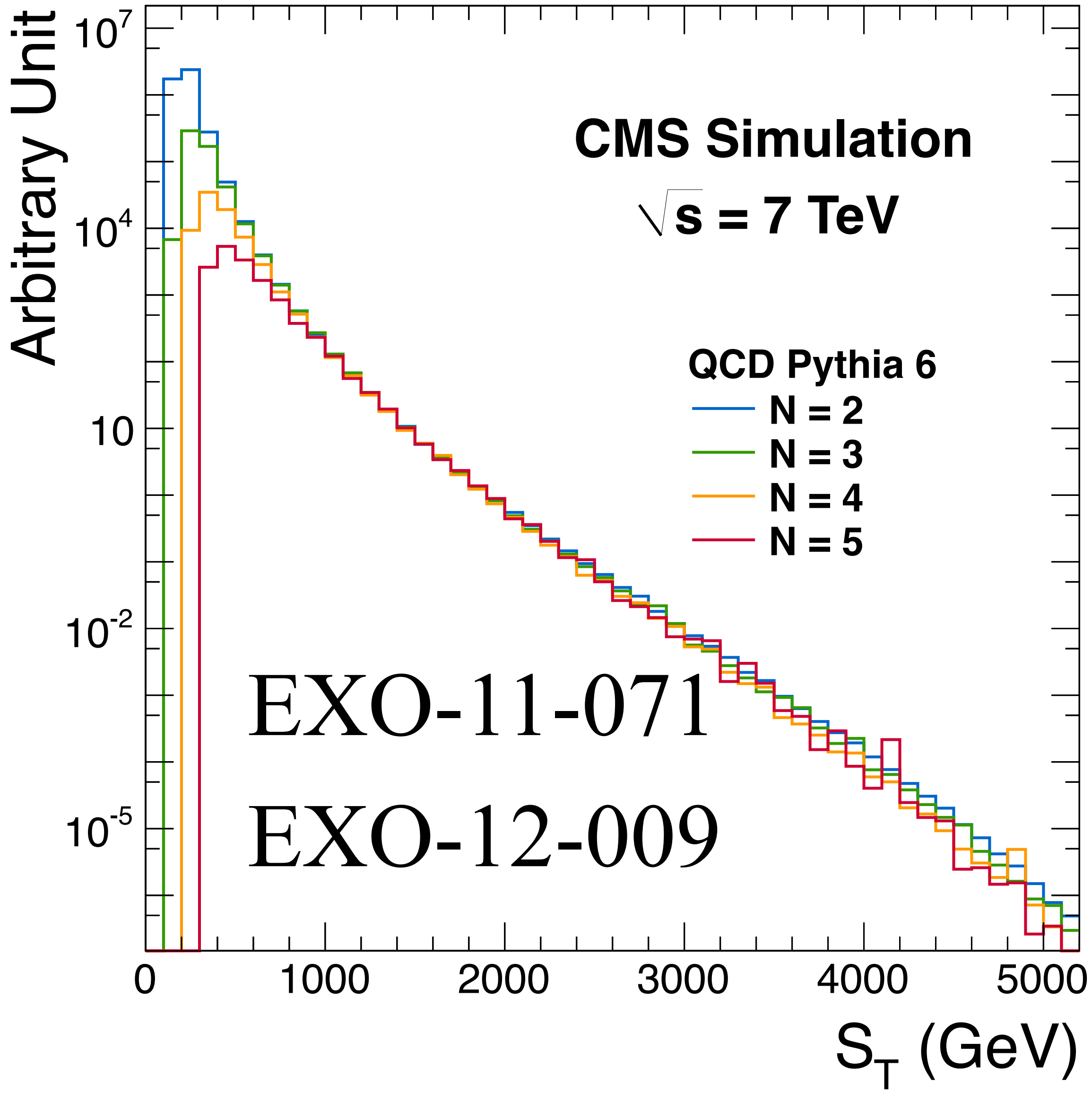
$^{a-h}$ sources of constraint: charged current universality, τ BRs, ν_e mass ν-less double β decay, $D^0-\bar{D}^0$ mixing, Z, pion, D^+ BRs, etc.

* 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)

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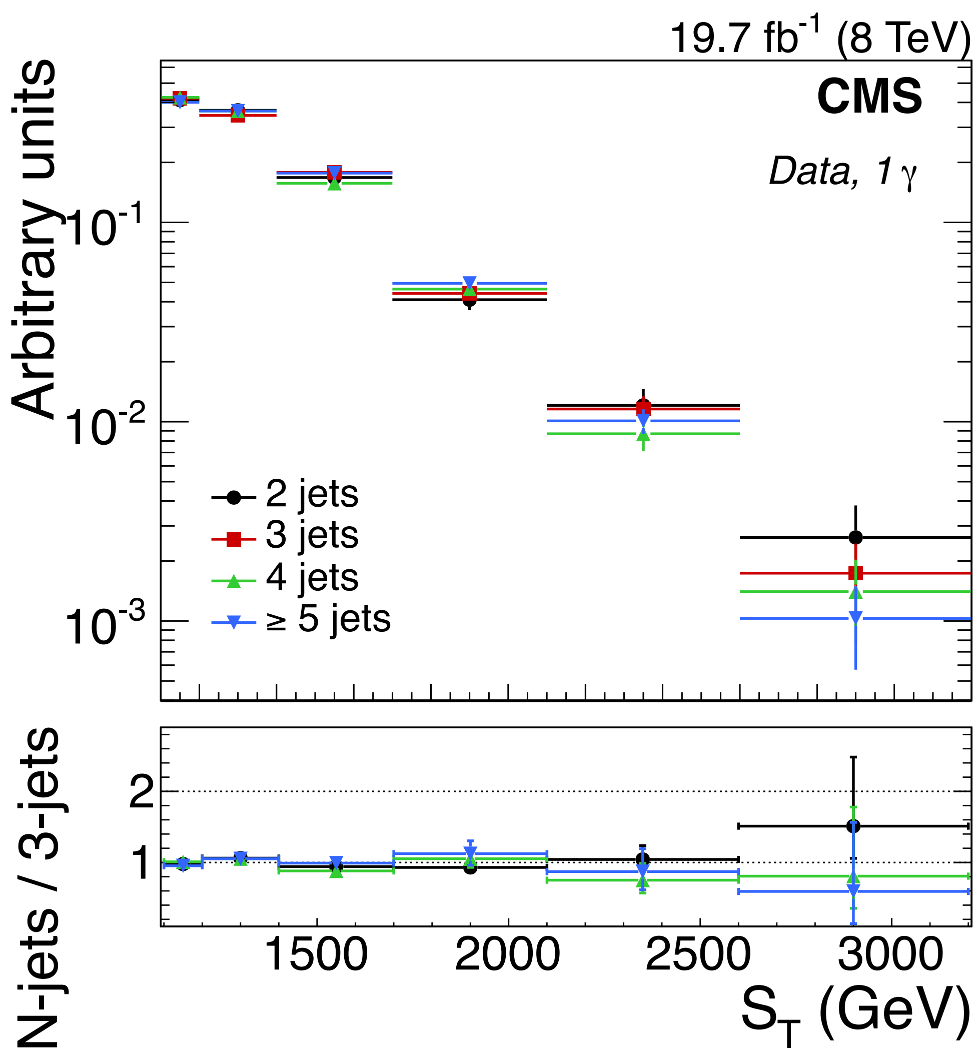
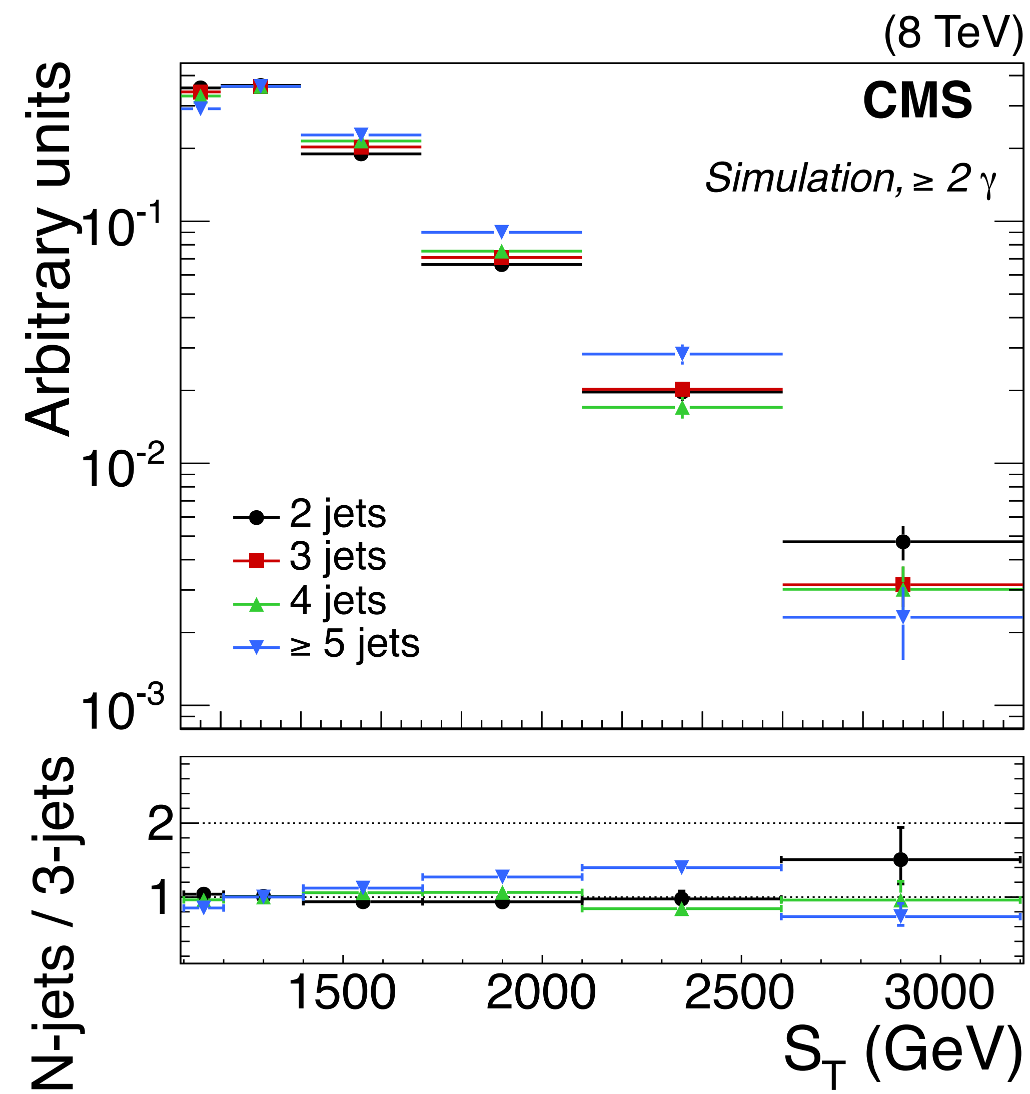
S_T invariance with γ or $\gamma\gamma$





- 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

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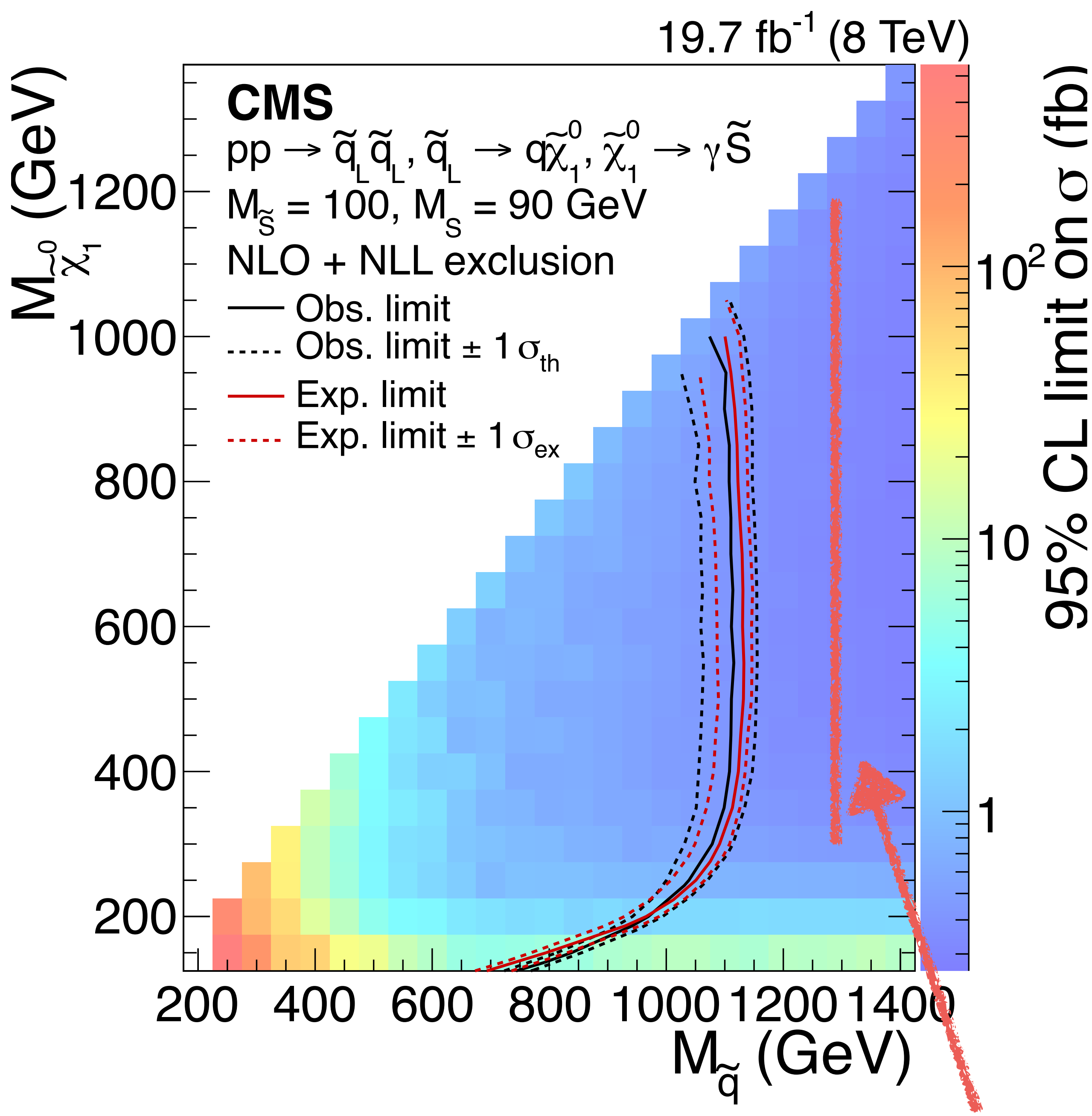
Stealth SUSY limits: 13 TeV projections

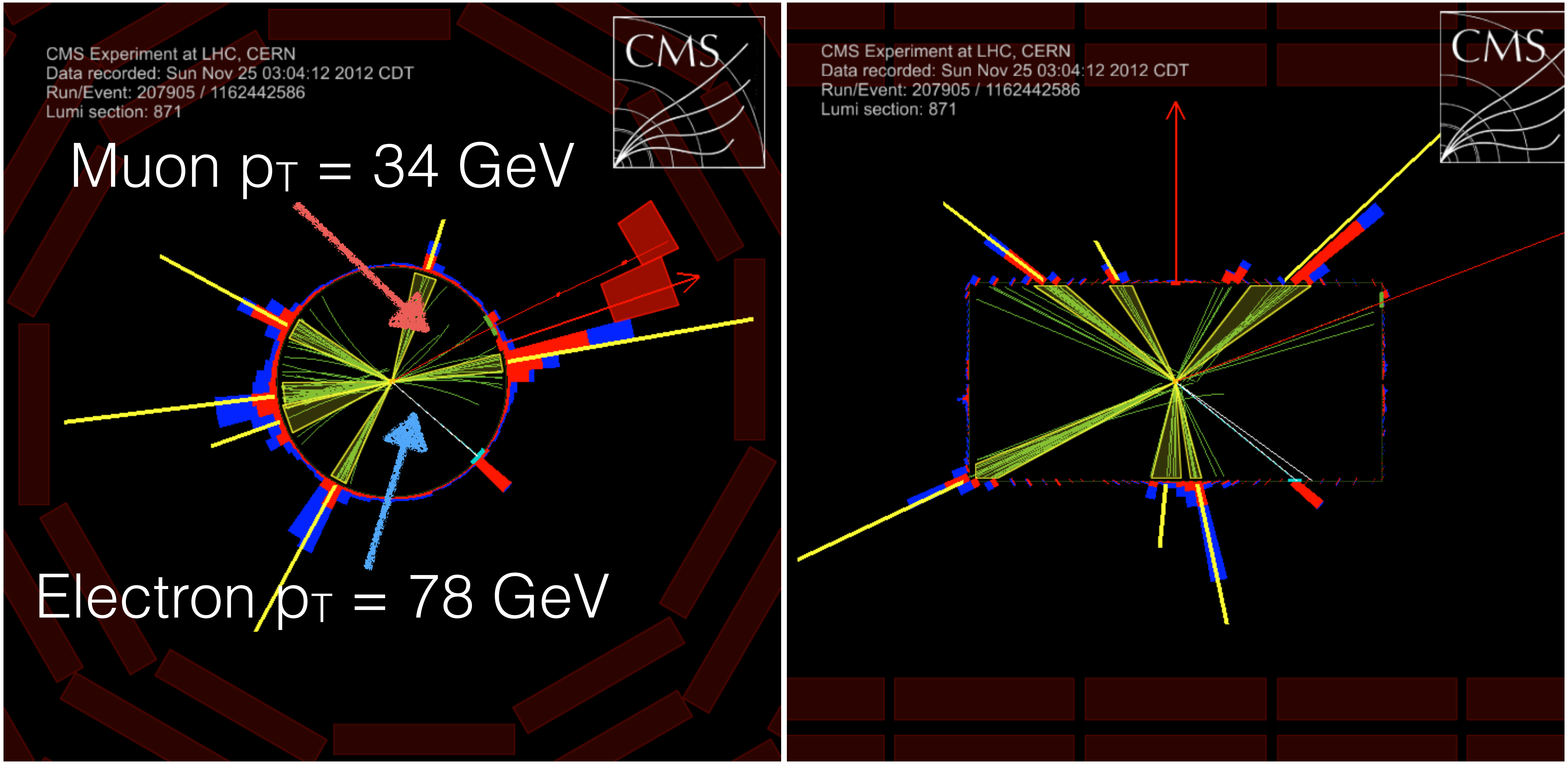
- Backgrounds increase by a factor of two
- Limits based on 10 fb^{-1}
- Photons:
  - Signal efficiency ~30%
  - Exclusion improved to ~1300 GeV
- Leptons:
  - Signal efficiency 2%
  - Exclusion limit improved to ~900 GeV



- Projection for 13 TeV

Event display

- S_T = 2200 GeV, 6 jets



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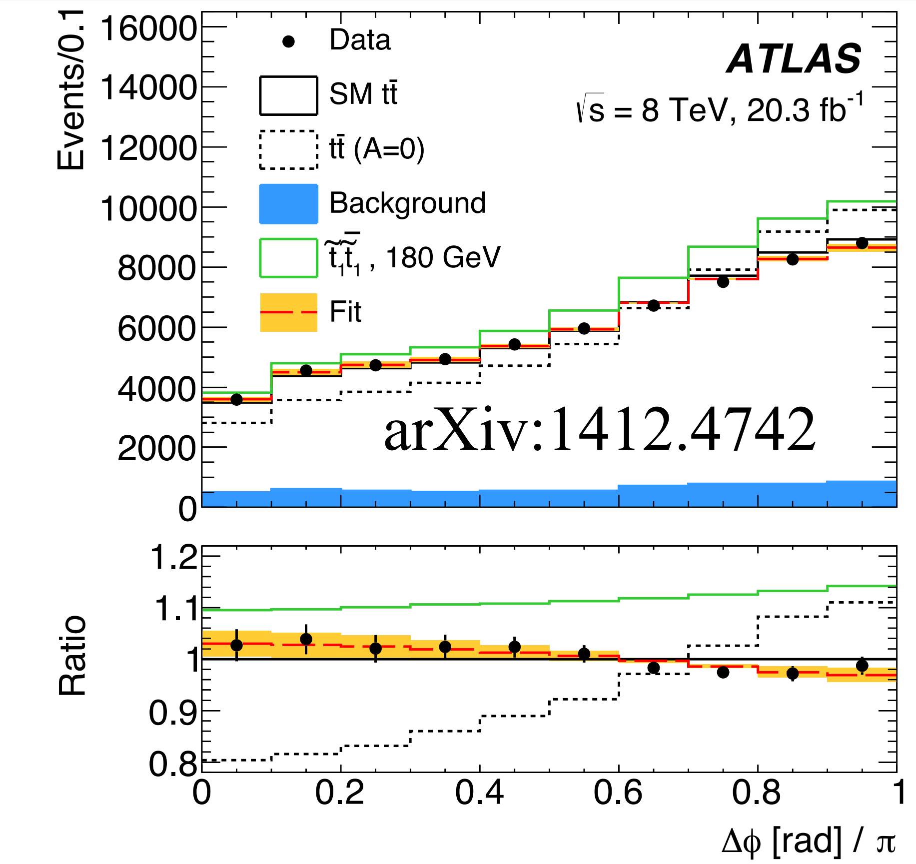
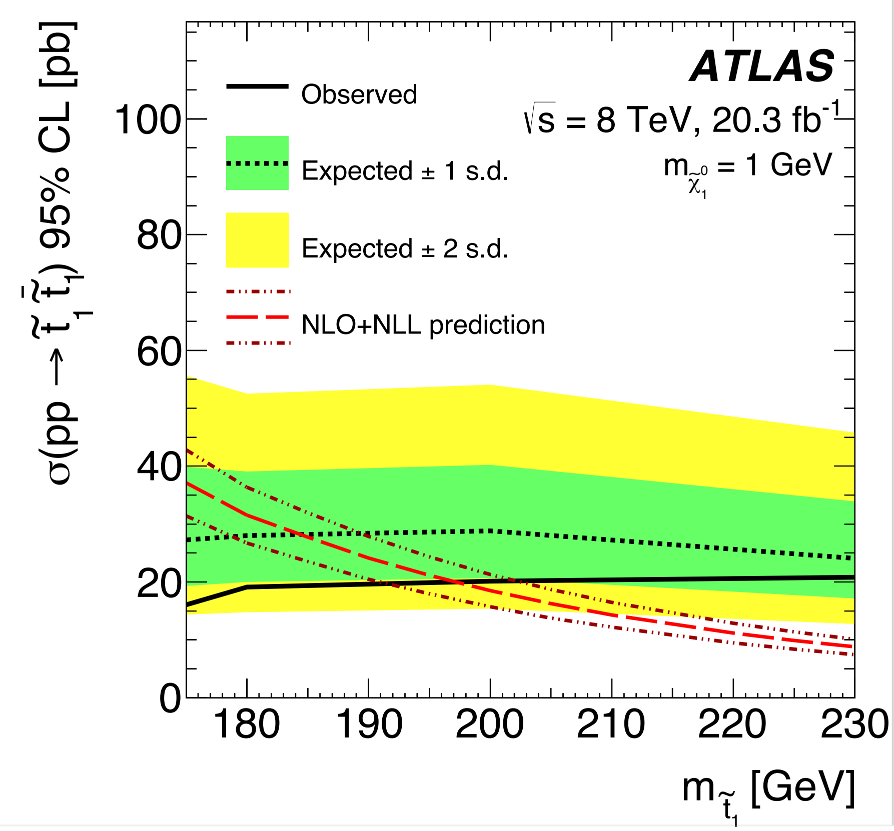
Compressed spectra example

- 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

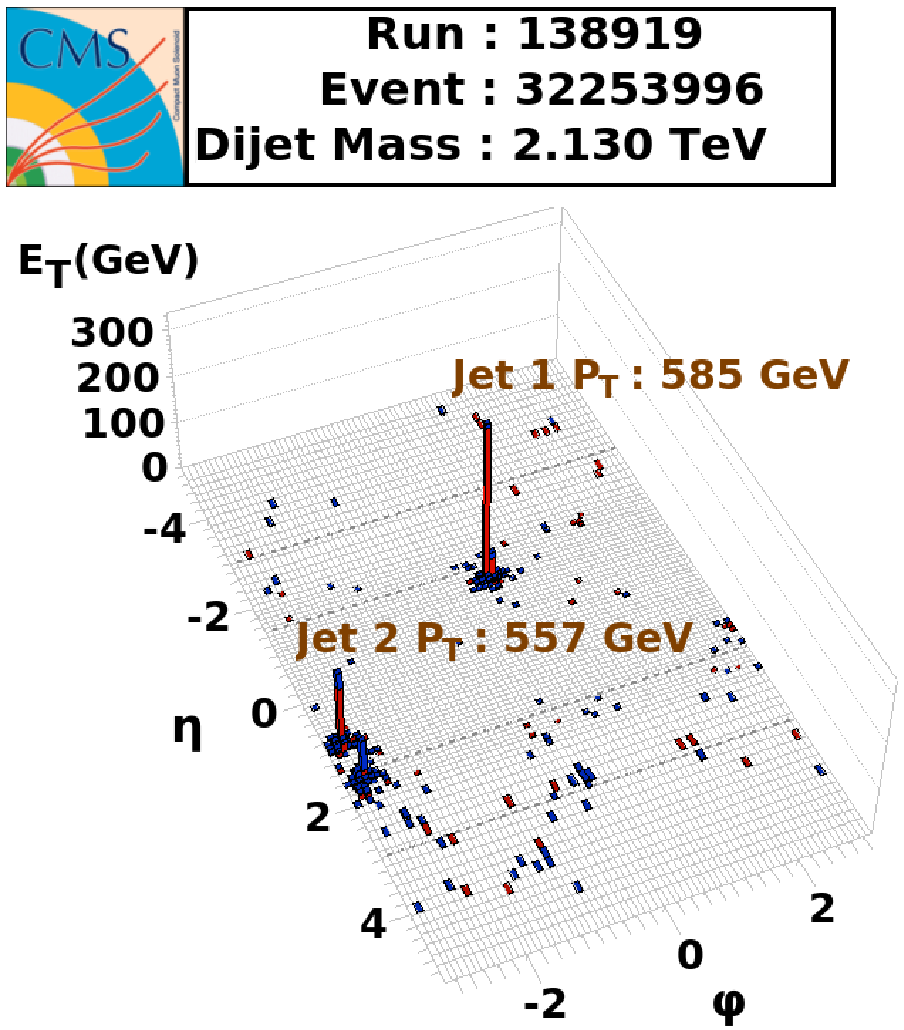
Theory paper, arXiv:1205:5808

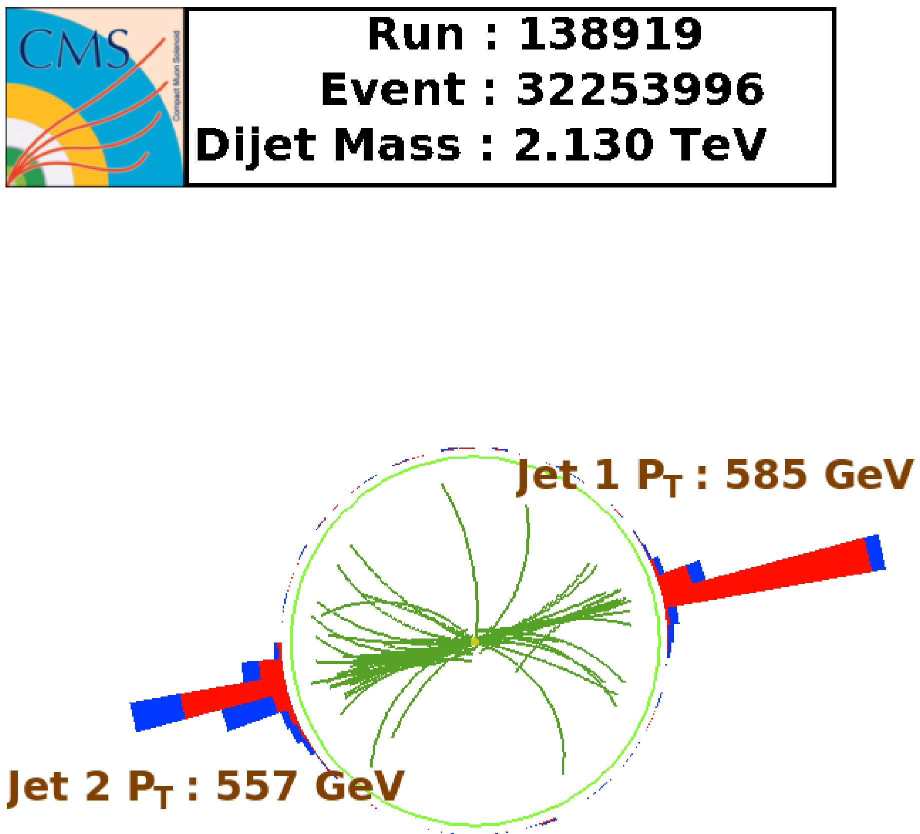




Jets

- Reconstructed jets from quark (gluon) events



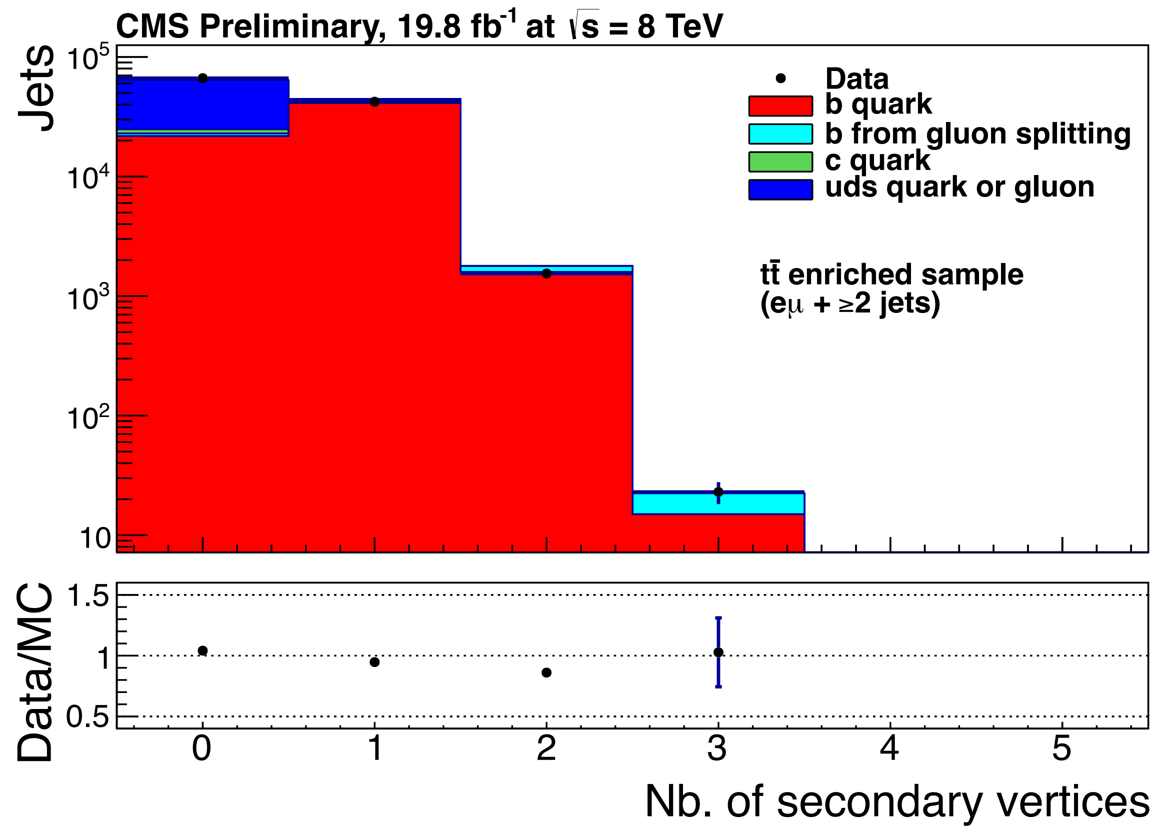


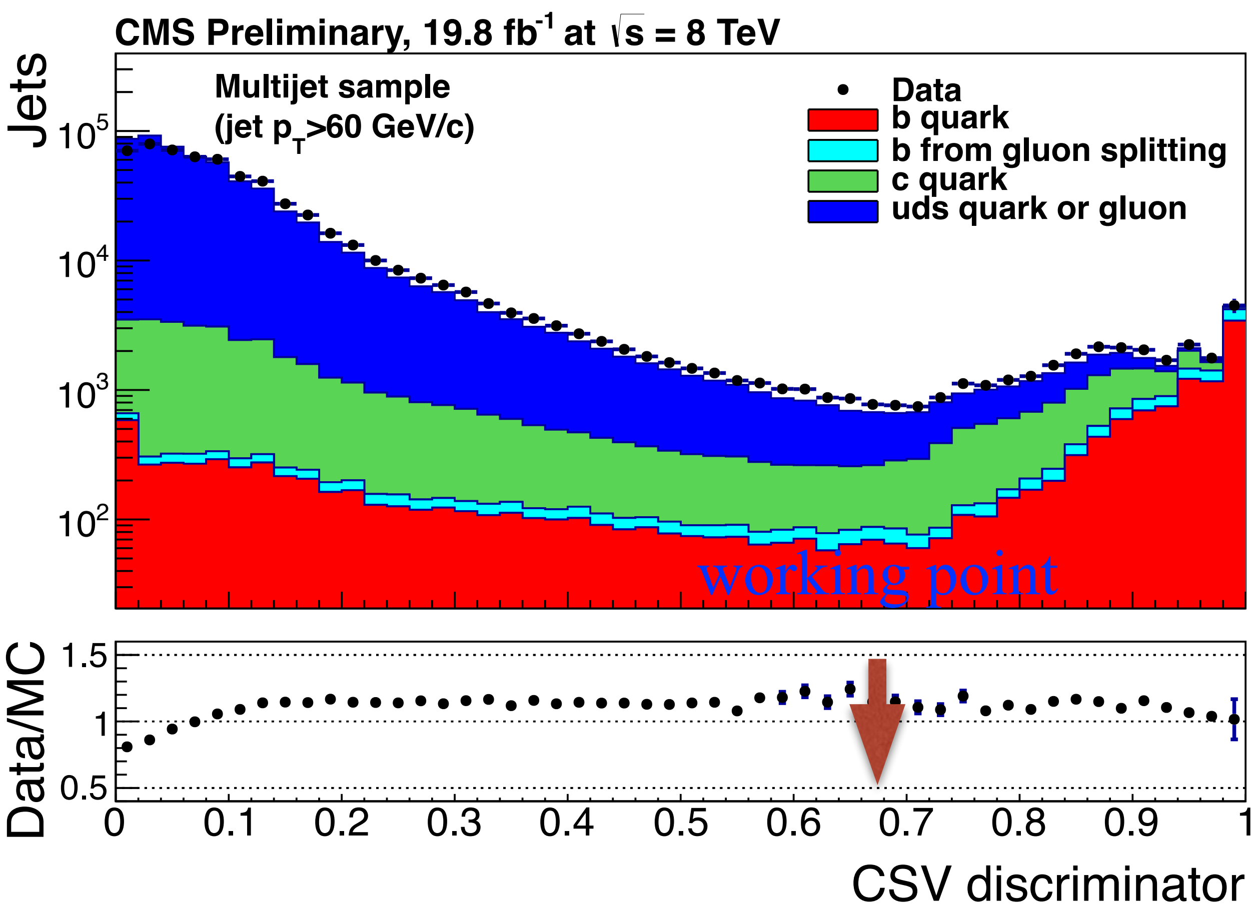
- Jets reconstructed from particle flow objects
- Anti-k_T clustering, radius parameter R=0.5

b jets

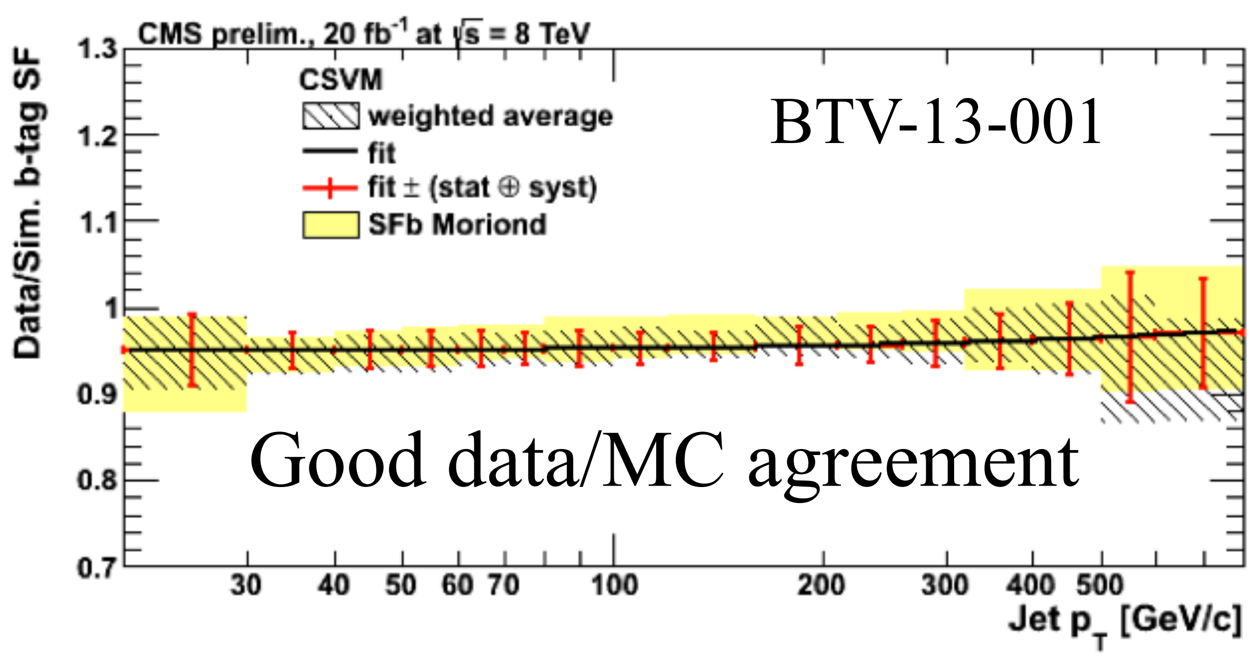
arXiv: 1211.4462

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





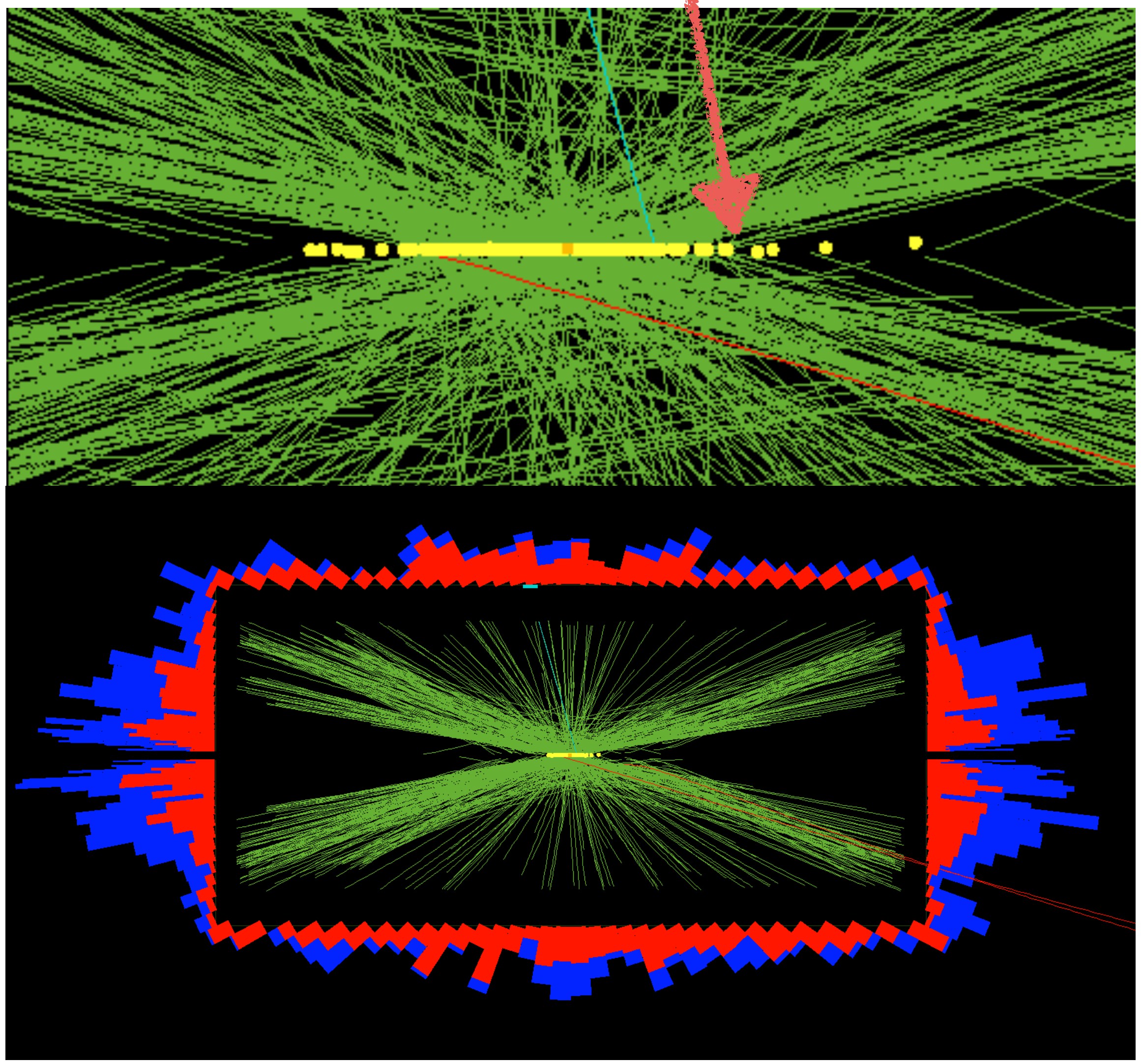
- Efficiency: 70% (b quarks), 20% (c), 1% udsg



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

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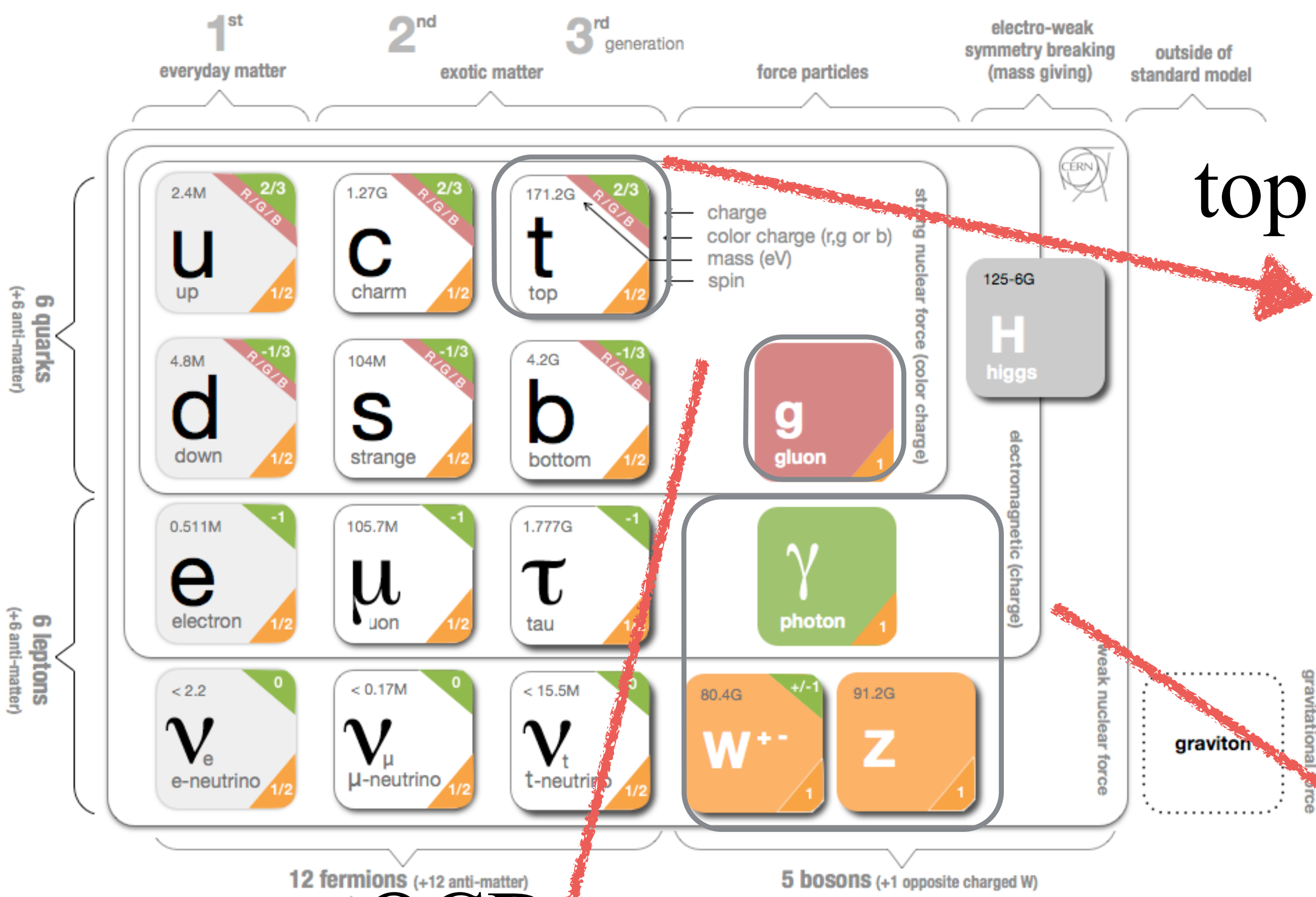
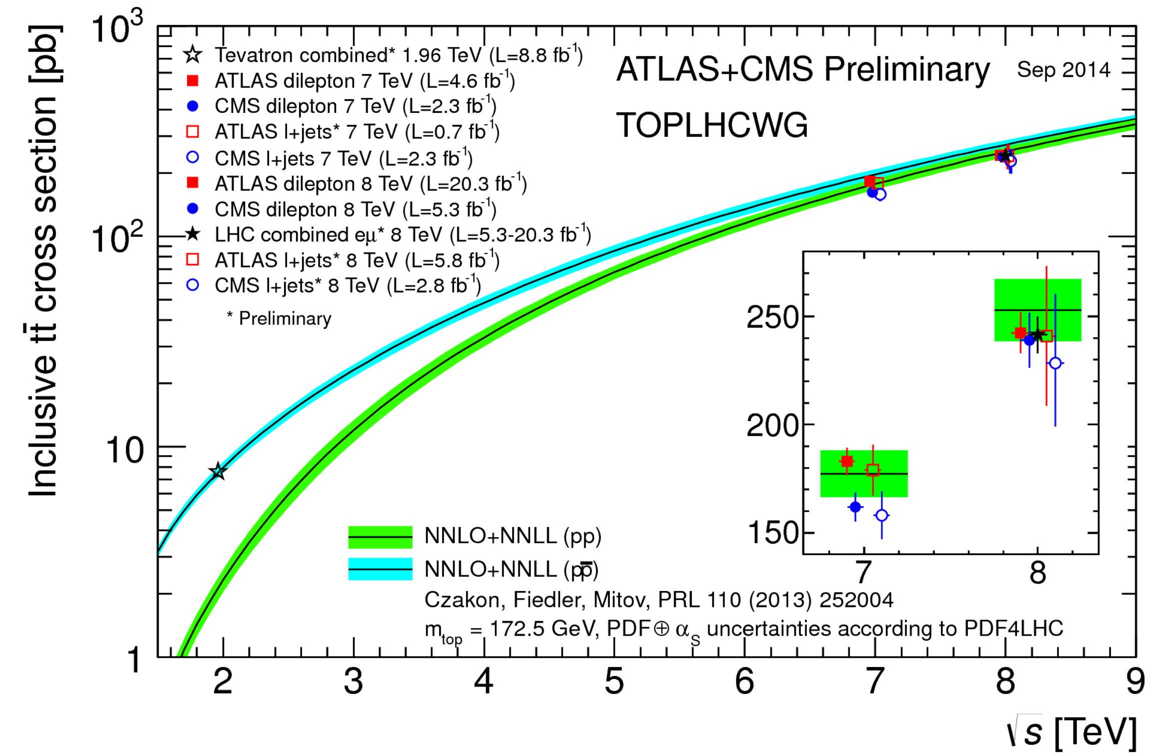
Success of the SM at the LHC

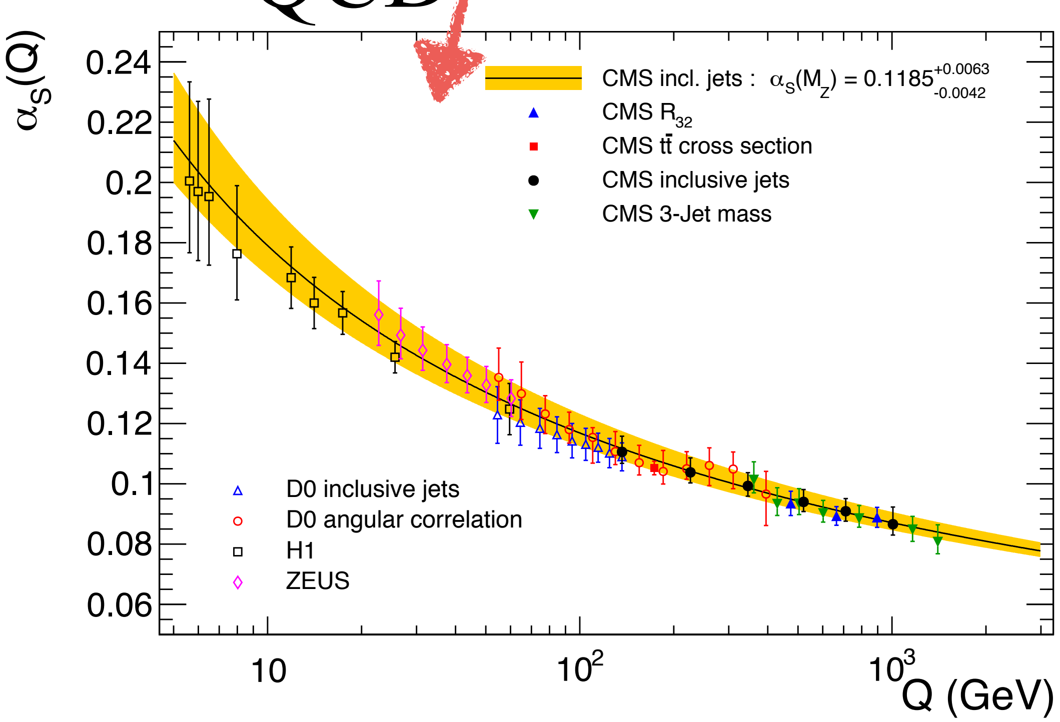


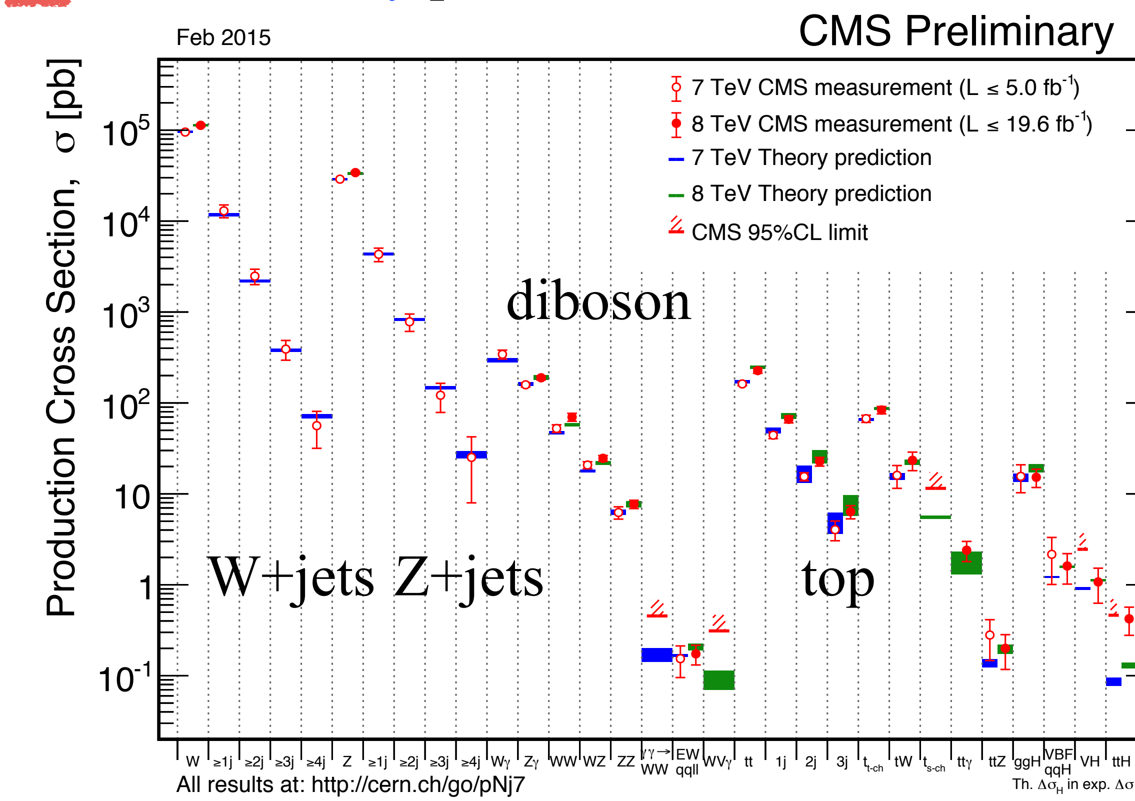
top



Comparison of measurements and theory predictions

QCD

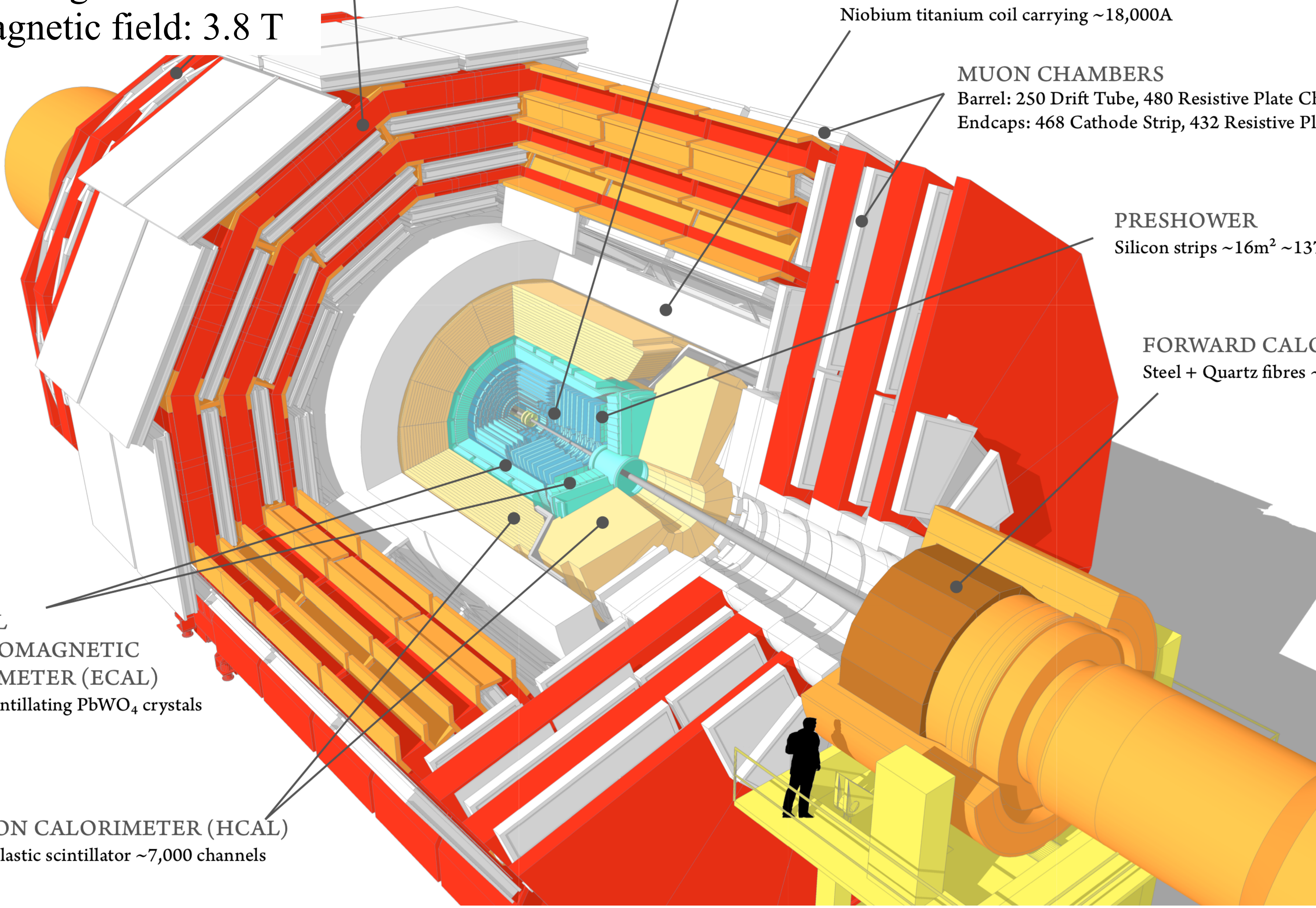




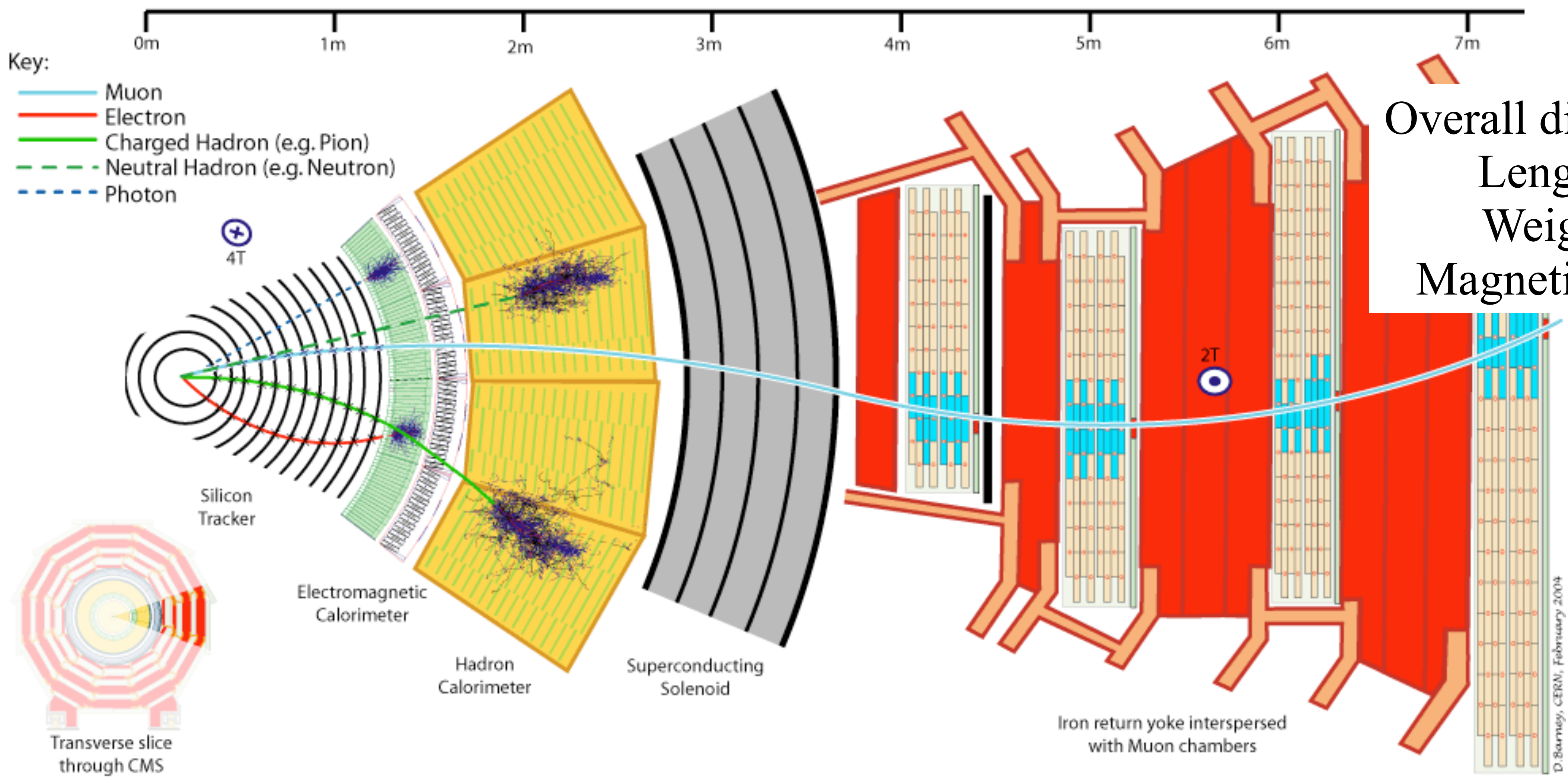
The Compact Muon Solenoid

CMS DETECTOR

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



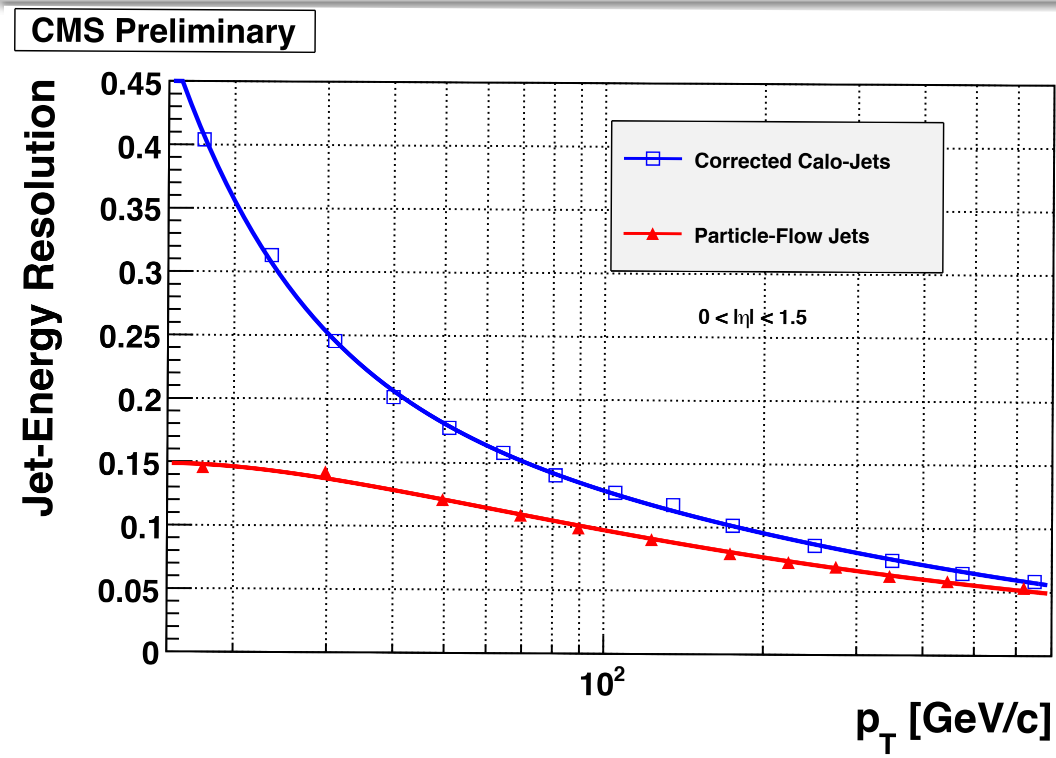
The Compact Muon Solenoid

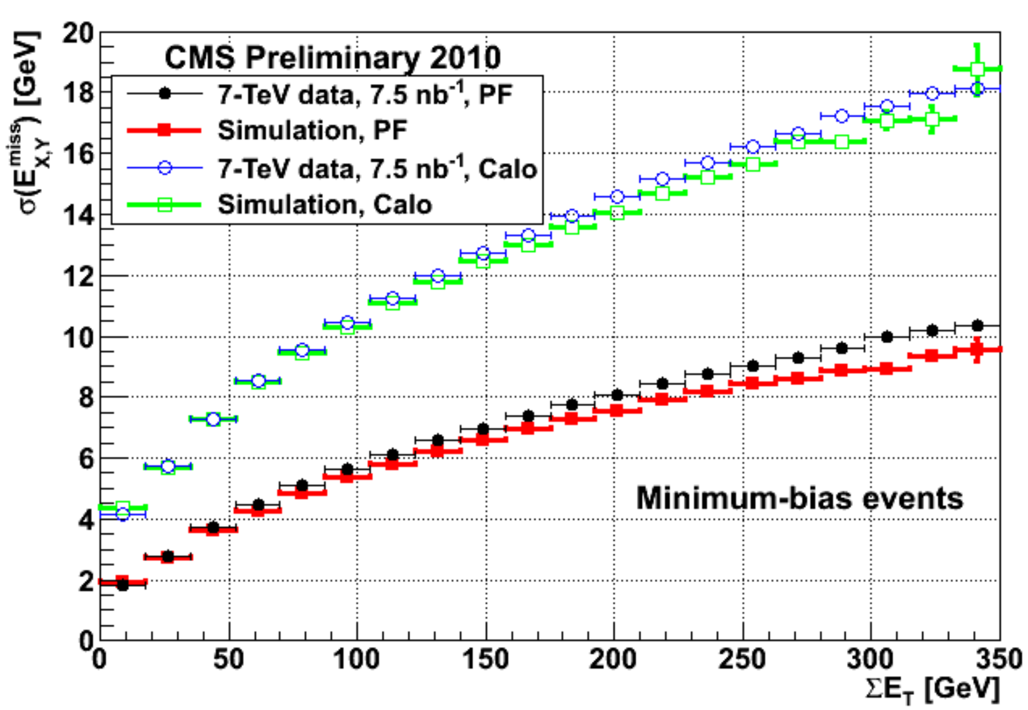


Overall diameter: 15.0 m
Length: 28.7m
Weight: 14 kT
Magnetic field: 3.8 T

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

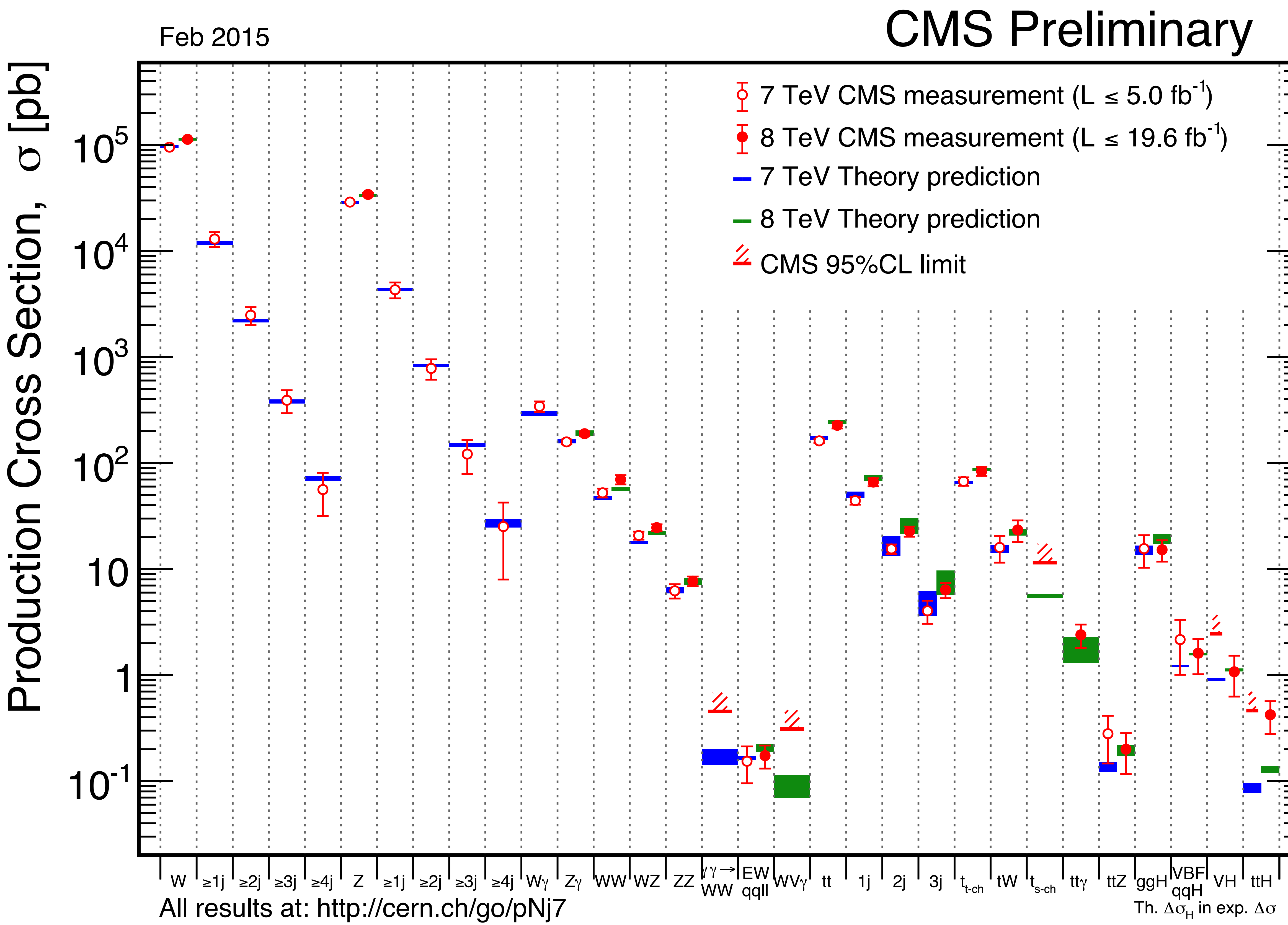
Detector performance with particle flow



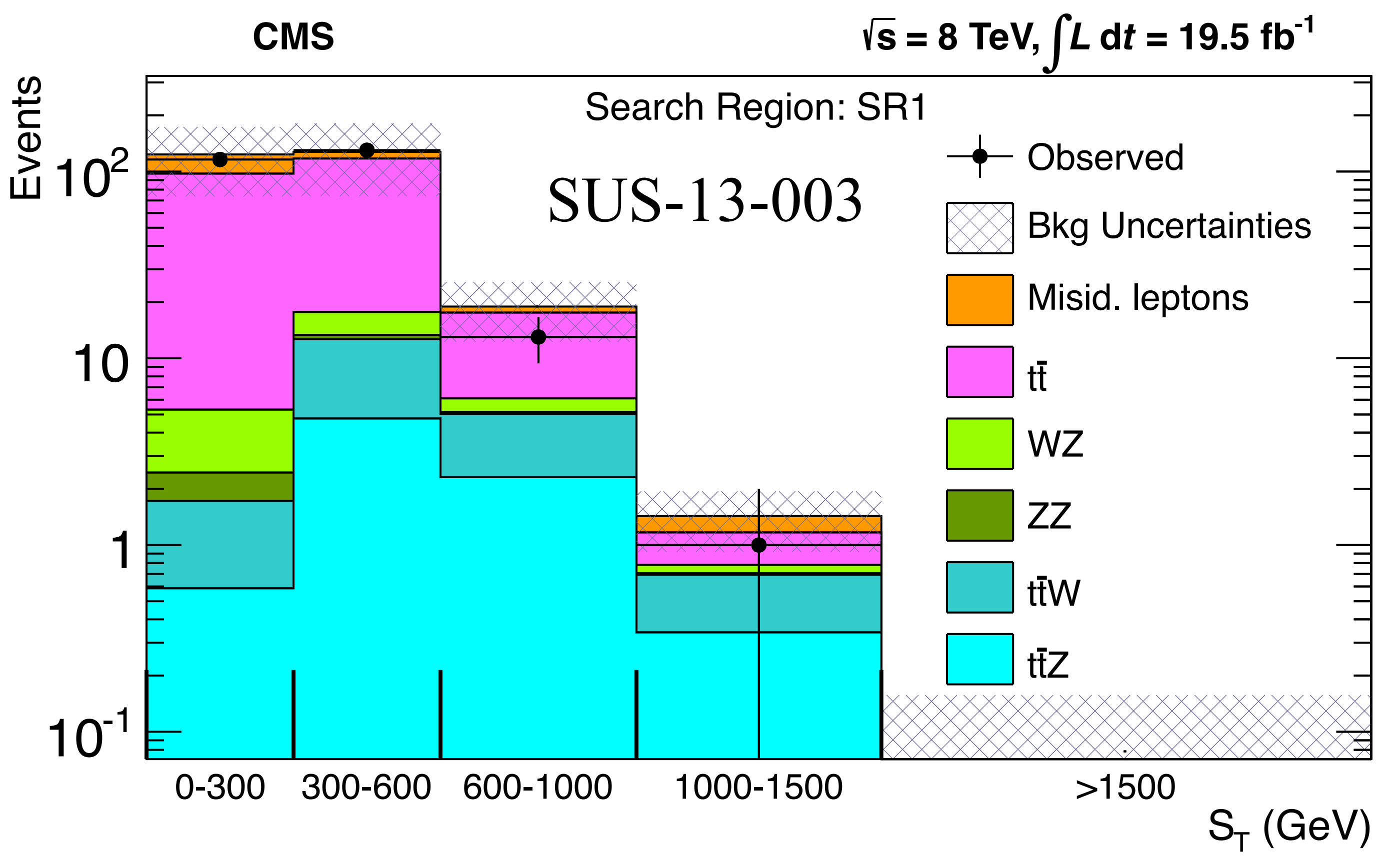


- Improved performance for particle flow objects
- Particularly relevant for jets and MET

SM measurement summary



Multileptons (N_ℓ=3, ≥4)



- $N_\ell = 3$, 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

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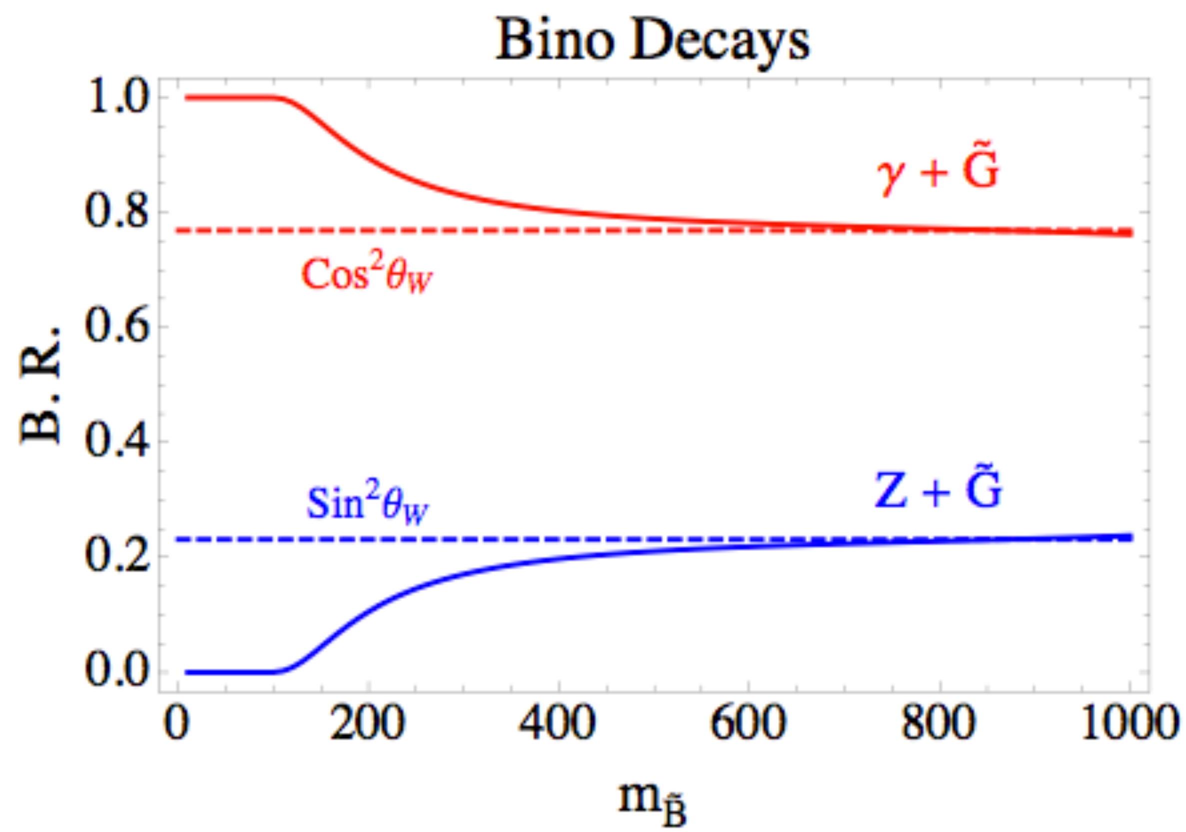
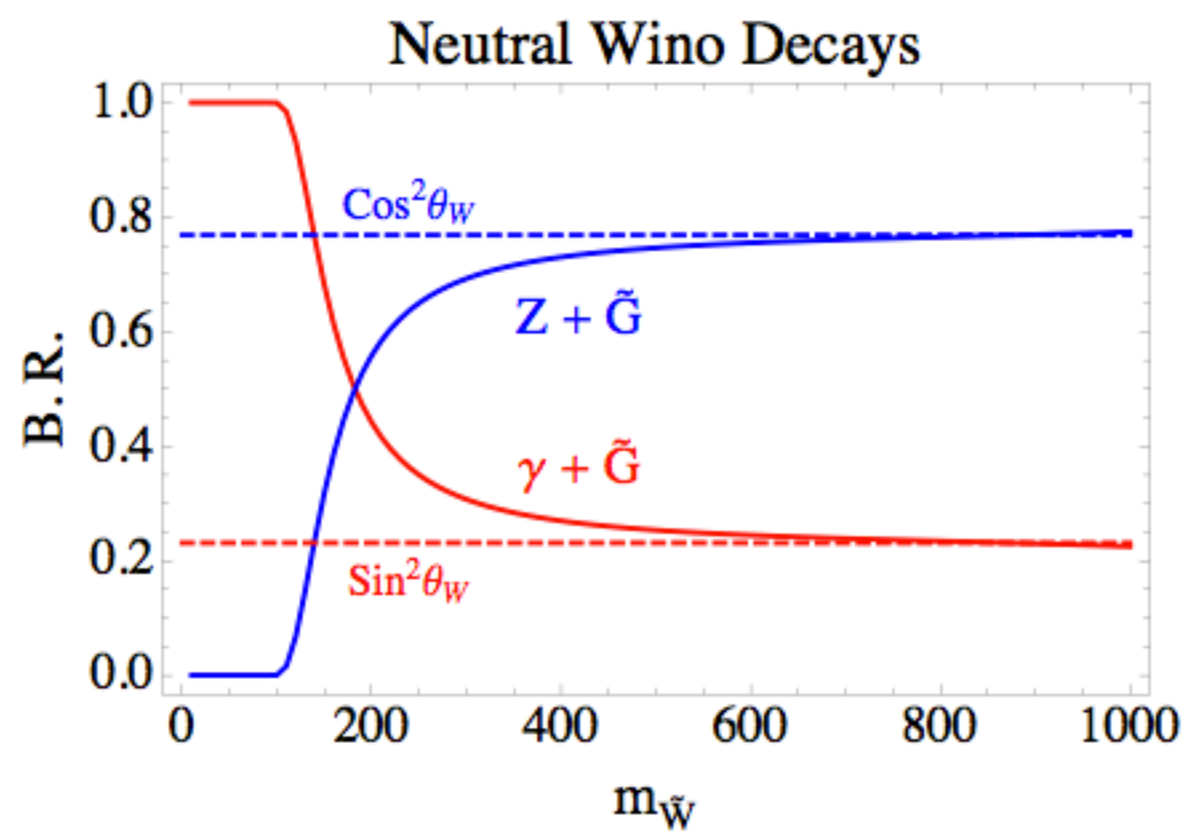
Gaugino branching fractions

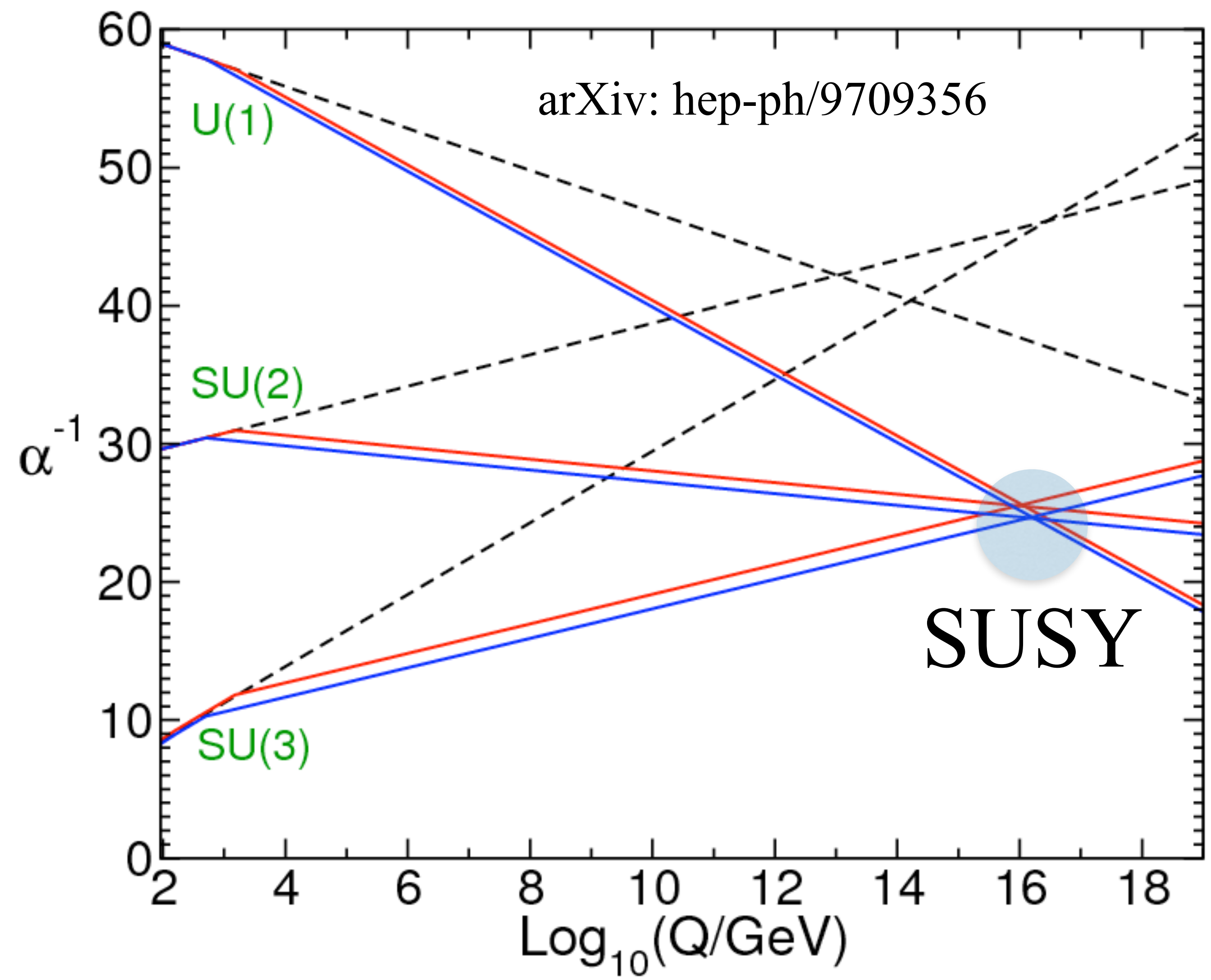
arXiv: 1103.6083





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



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