BEYOND STANDARD MODEL

Search for Supersymmetry

Lecture 19

DIPARTIMENTO DI FISICA

SAPIENZA
UNIVERSITÀ DI ROMA

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Fisica delle Particelle Elementari, Anno Accademico 2015-16

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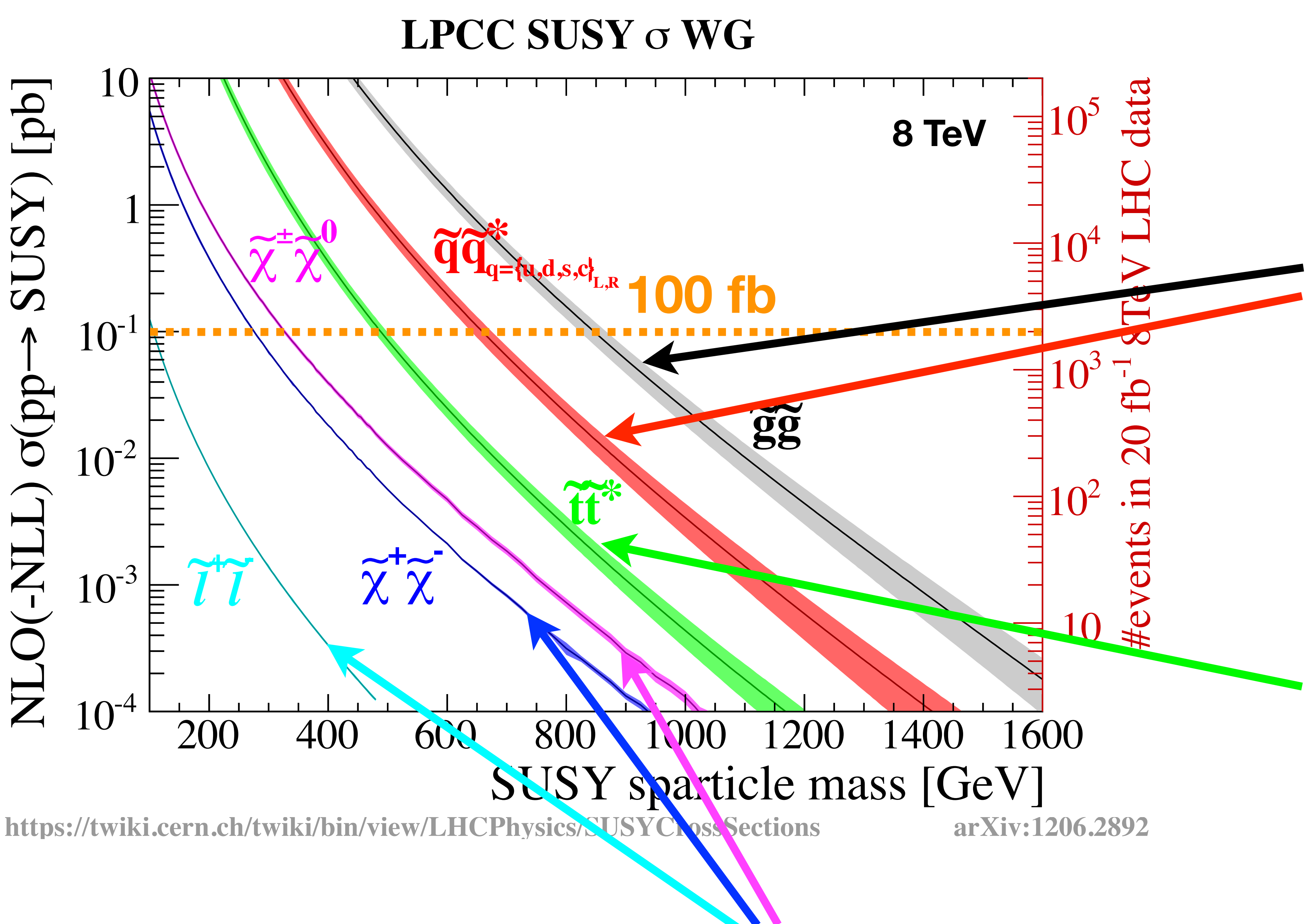
SUSY at LHC Run1



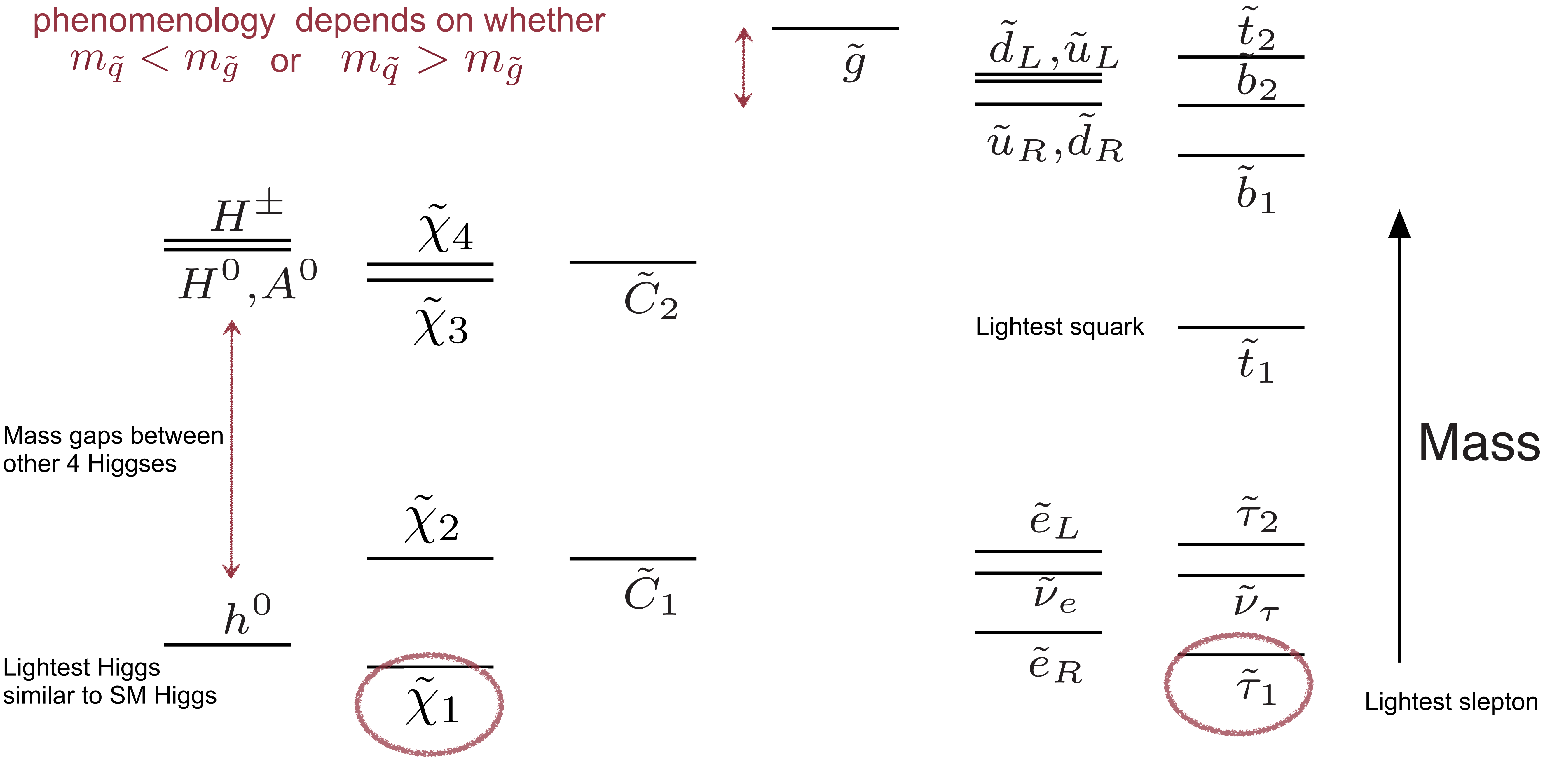
Gluinos and squarks
Largest cross-section
Probing up to ~1TeV

3rd generation squarks
Mid cross-section
Probing up to ~500 GeV

Charginos, neutralinos, sleptons
Smaller cross-section
Probing up to ~100-200 GeV

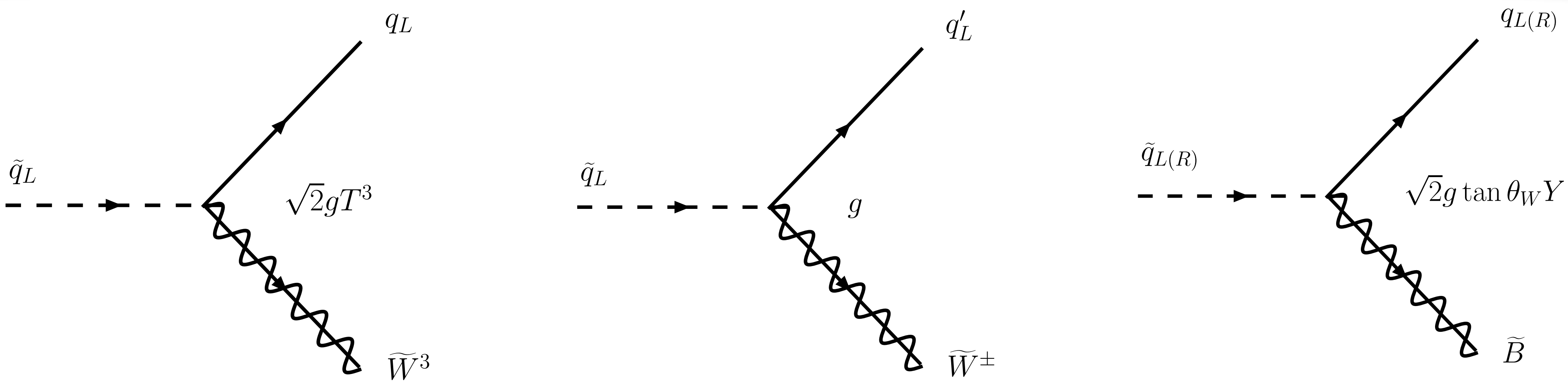
SUSY Mass Spectrum

phenomenology depends on whether
$m_{\tilde{q}} < m_{\tilde{g}}$ or $m_{\tilde{q}} > m_{\tilde{g}}$



Typical LSP candidates in several SUSY models

Sparticle Couplings



- Feynman rules: take any SM diagram and change R-parity of two lines
  - Must conserve R-parity!
- Coupling constant strength: typically similar to SM to make sure hierarchy problem is cured
- Yukawa interaction: coupling proportional to m^2 of corresponding fermion
  - significant only for third generation
- Gauge interaction: same coupling as in SM

$BR(\tilde{q}_L \to \tilde{\chi}_2^0 q) = 30\%$ $BR(\tilde{q}_L \to \tilde{\chi}_1^\pm q') = 60\%$ $BR(\tilde{q}_R \to \tilde{\chi}^0 q) = 100\%$

SPARTICLE DECAYS

- mass difference between squarks and gluinos determines kinematically allowed decays

Gluino decays: always to $q\,\tilde{q}$.

If $M_{\widetilde{g}} < M_{\widetilde{q}}$, then gluino will decay via an off-shell squark:
3-body decays, $\widetilde{g} \to q\widetilde{q}^* \to q\bar{q}\,\tilde{\chi}^0$ or $q\bar{q}'\,\tilde{\chi}^{\pm}$

Squark decays:
To $q\,\tilde{g}$ (strong coupling) if kinematically allowed.
Otherwise $q\,\tilde{\chi}^0$ or $q\,\tilde{\chi}^{\pm}$ or (for 3rd gen.) $q\,\widetilde{H}$.
Decay branching fractions controlled by squark and -ino compositions.

Slepton decays: to $\ell\,\tilde{\chi}^0$ or $\ell\,\tilde{\chi}^{\pm}$ ($\ell = \ell^{\pm}$ or ν as appropriate)

Neutralino and chargino decays: to $\ell\,\tilde{\ell}$ or $q\,\tilde{q}$,
or to gauge or Higgs boson + lighter neutral-/charg-ino

SUSY DECAY CASCADE

- cascade decays through intermediate states because of heavy mass of SUSY particles $m_{\tilde{g}} > m_{\tilde{q}} > m_{\tilde{\chi}_4^0} > m_{\tilde{\ell}_L} > m_{\tilde{\chi}_2^0} > m_{\tilde{\ell}_R}$:

$\tilde{g}$

$\hookrightarrow \tilde{q}_L \quad q$

$\hookrightarrow \tilde{\chi}_4^0 \quad q$

$\hookrightarrow \tilde{\ell}_L^{\pm} \quad \ell^{\mp}$

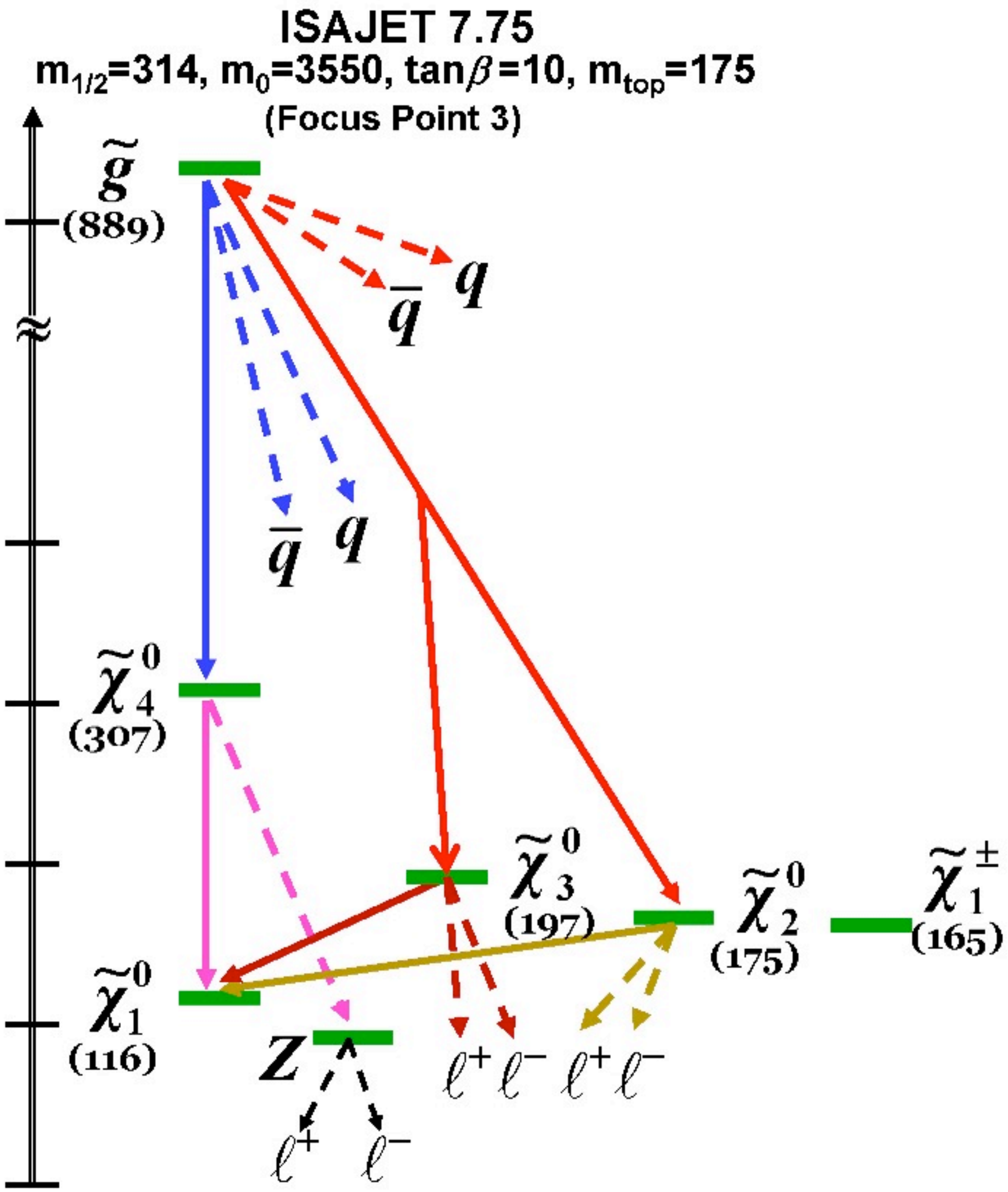
$\hookrightarrow \tilde{\chi}_2^0 \quad \ell^{\pm}$

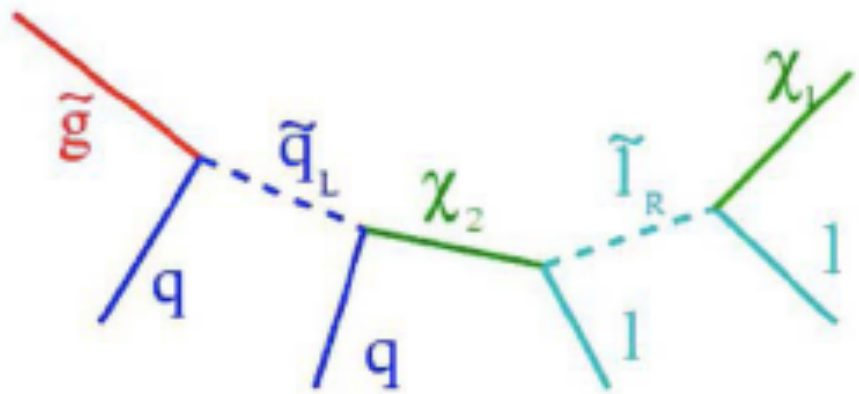
$\hookrightarrow \tilde{\ell}_R^{\pm} \quad \ell^{\mp}$

$\hookrightarrow \tilde{\chi}_1^0 \quad \ell^{\pm}$

- mass spectrum changes for different breaking mechanism
- Exact chains must be determined from measurements
- Often final states with at least 2 jets and 2 or more leptons
  - such final states suppressed in Standard Model
    - reconstruction effects can fake leptons but unlikely to have many real leptons produced in decay chains

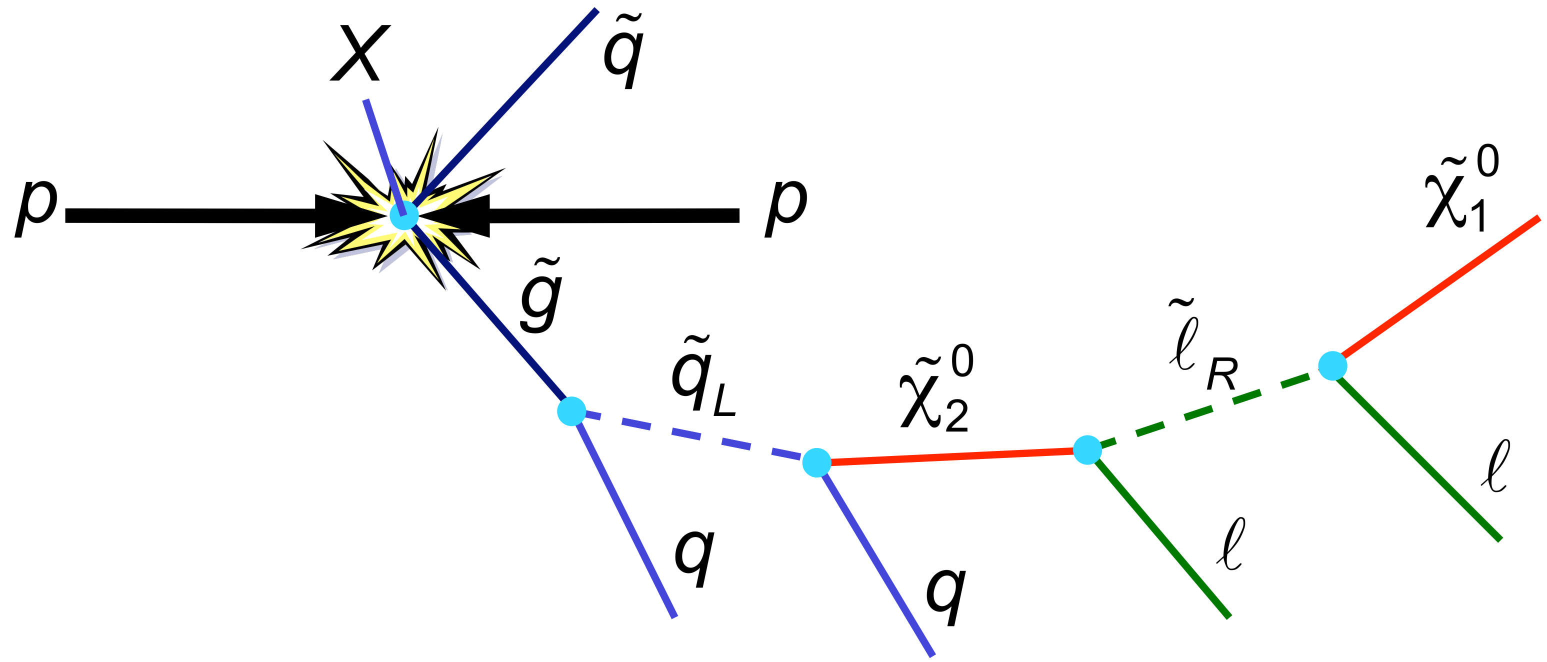
GLUINO DECAY CHAIN



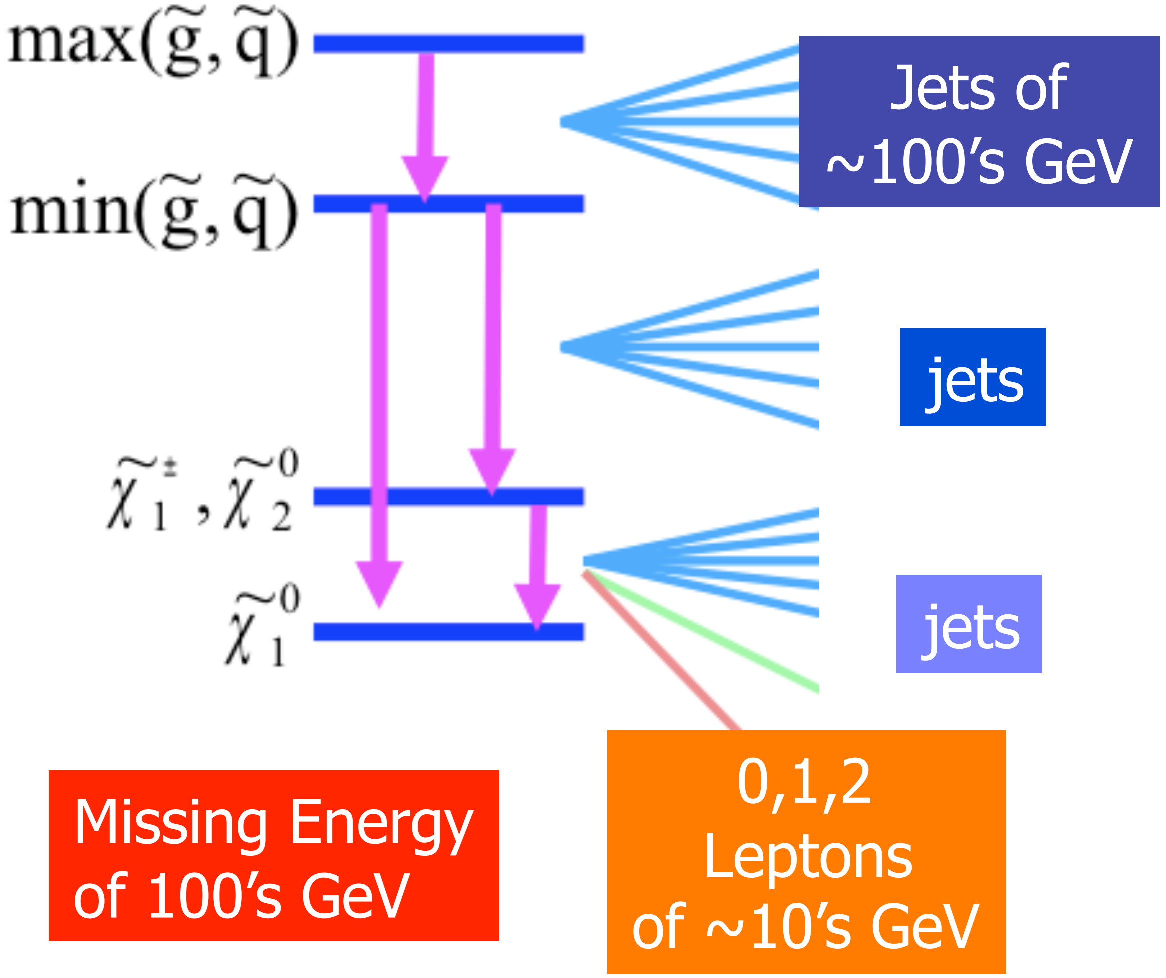


- Multiple decay paths leading to several leptons in final state
  - peaks in invariant mass + multiple jets + large missing energy

EXPERIMENTAL SIGNATURE OF SUSY



$$
\begin{aligned}
\tilde{\chi}_2^0 &\to \tilde{l}l, \\
\tilde{\chi}_2^0 &\to \tilde{\nu}\nu, \\
\tilde{\chi}_2^0 &\to h^0\tilde{\chi}_1^0, \\
\tilde{\chi}_2^0 &\to Z^0\tilde{\chi}_1^0, \\
\tilde{\chi}_2^0 &\to l^+l^-\tilde{\chi}_1^0
\end{aligned}
$$



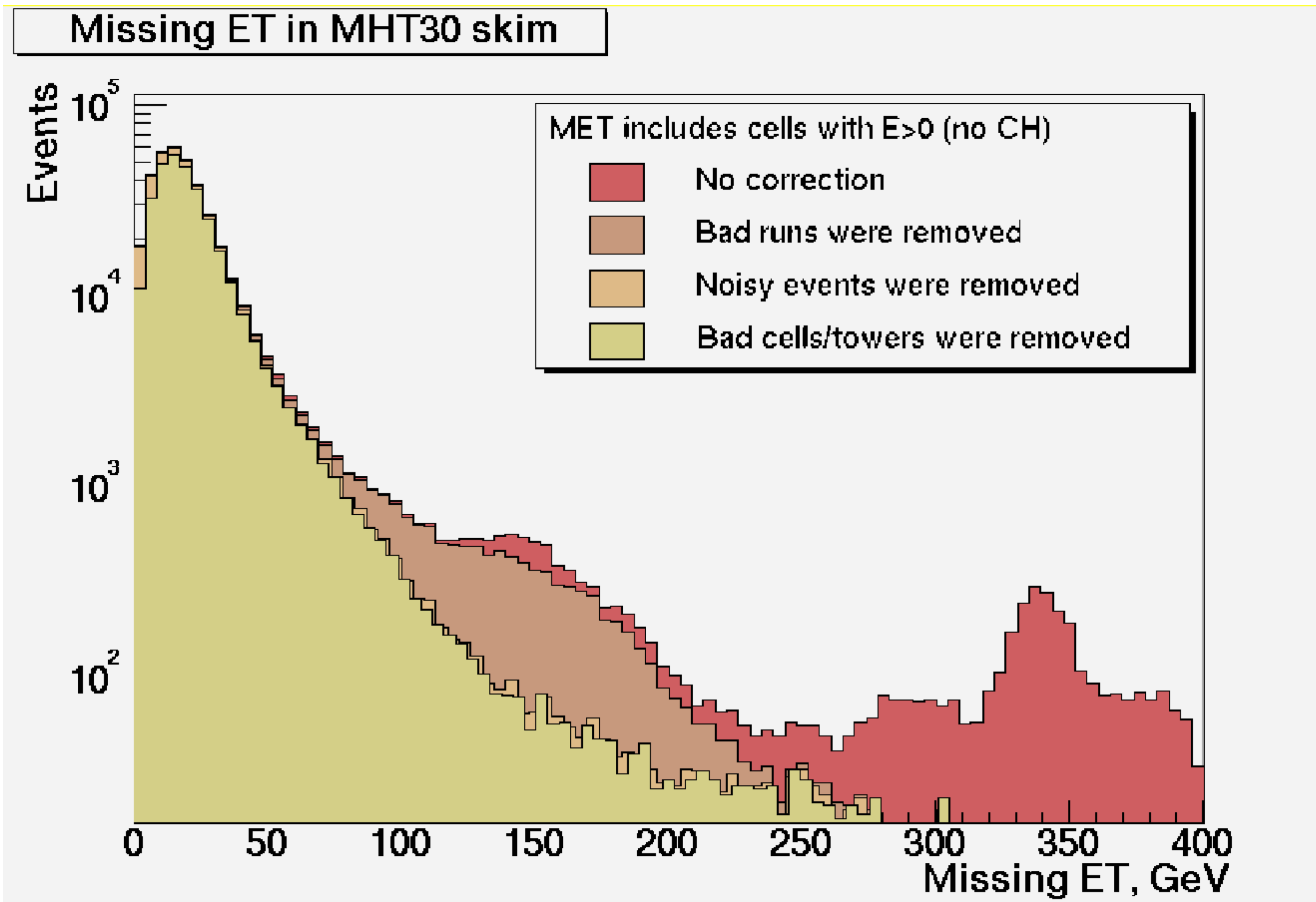
Main Backgrounds:
ttbar
Z/W+jets
Z(νν)+jets
QCD

Experimental Challenges

- Missing transverse energy (MET) measurement
  - correct for instrumental effects and reduce tails
  - verify correct MET resolution and tail description with known control samples
    - Electroweak events: small missing energy
    - di-jet and QCD events: no intrinsic MET only instrumental effects

- Background estimation
  - after kinematic requirements typically remain with
    - t-tbar
    - W/Z + jets
    - WW and ZZ production
  - Cross sections sometimes known at 5-10% level
    - directly affects exclusion limits and discovery potential
  - background kinematics also affected by PDF uncertainties

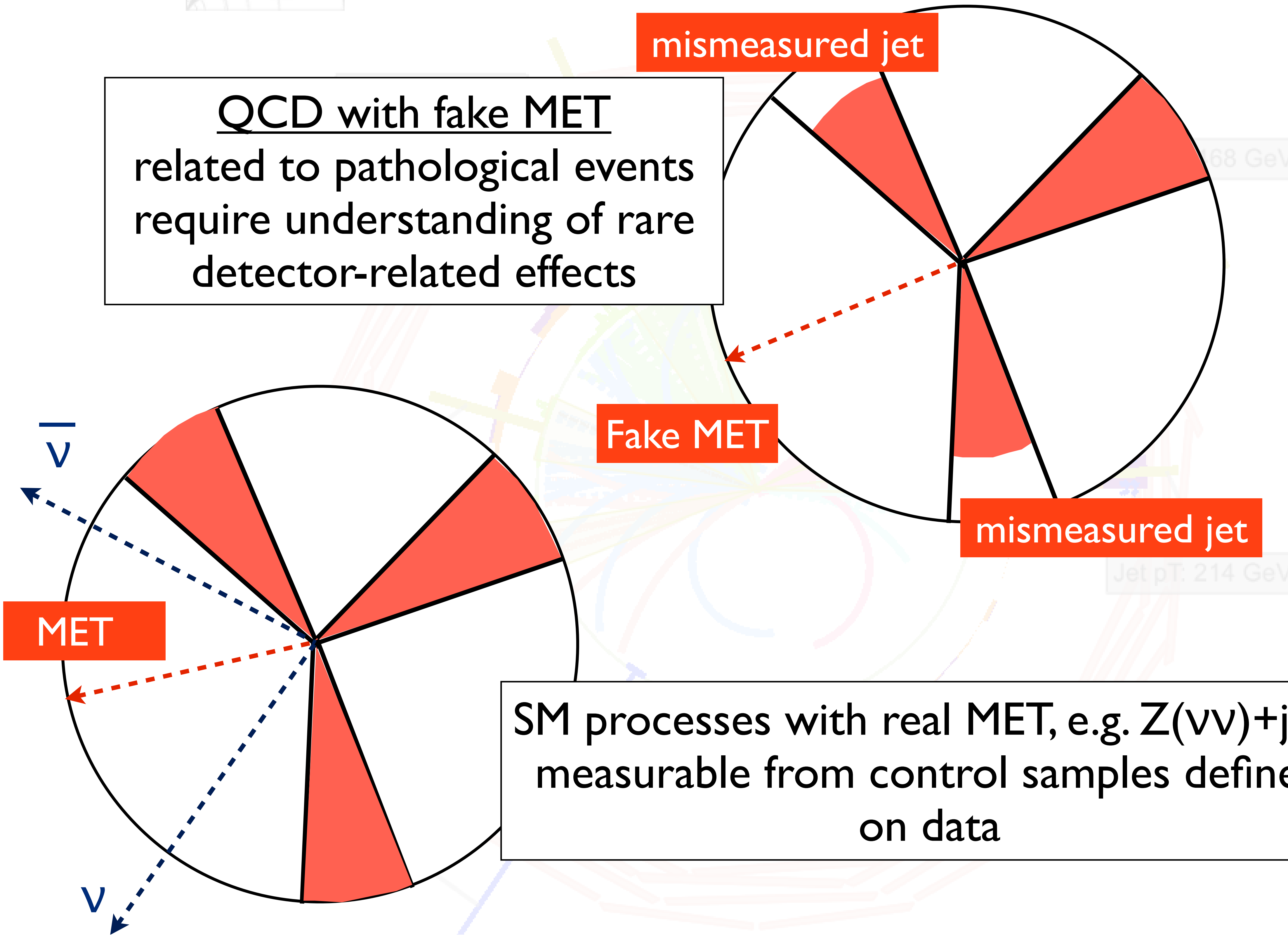
MISSING TRANSVERSE ENERGY



- D0 experiments in early part of Run II
  - Lots of new physics caused by instrumental effects!

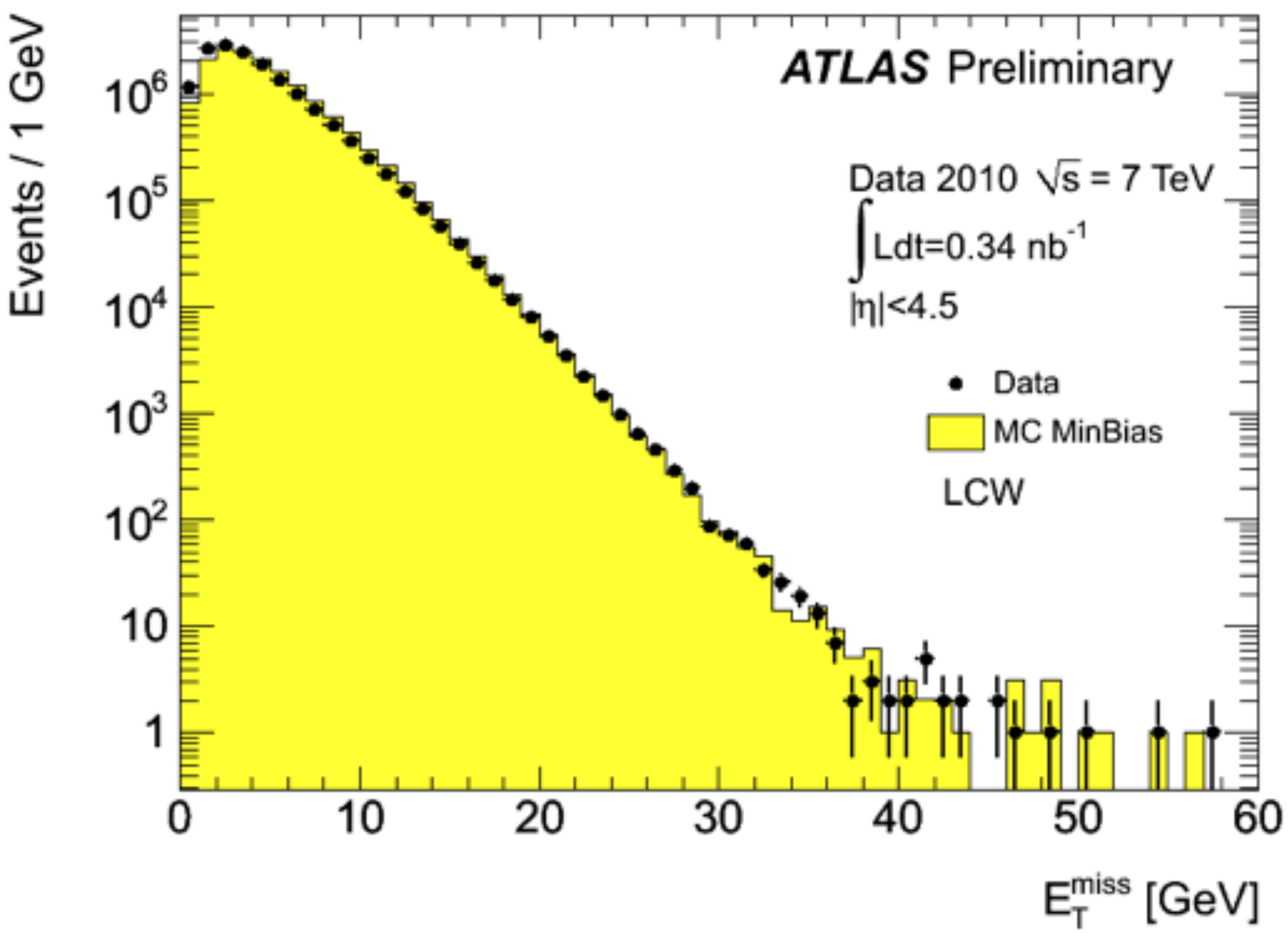
REAL AND FAKE MET BACKGROUND

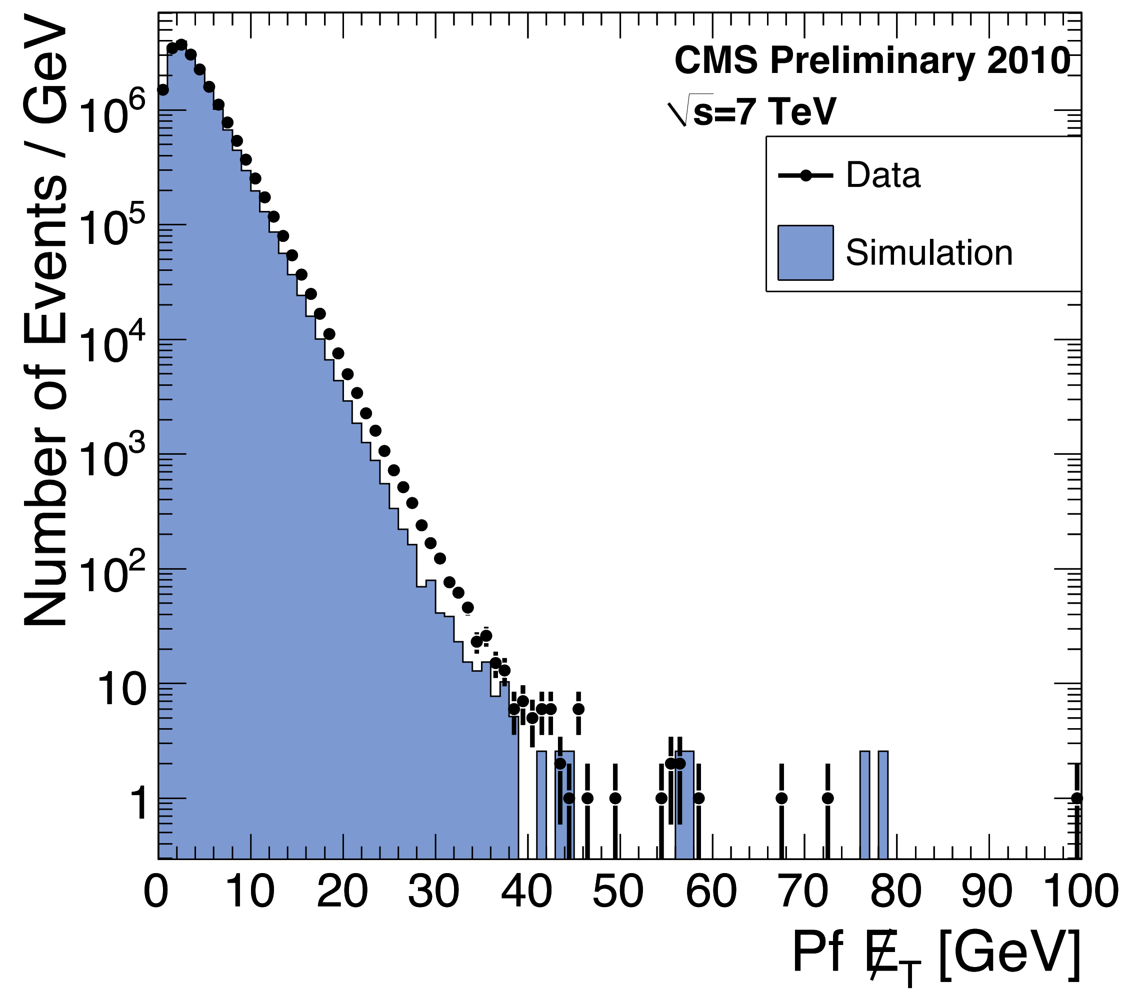
<u>QCD with fake MET</u>
related to pathological events require understanding of rare detector-related effects



SM processes with real MET, e.g. Z(νν)+jets measurable from control samples defined on data

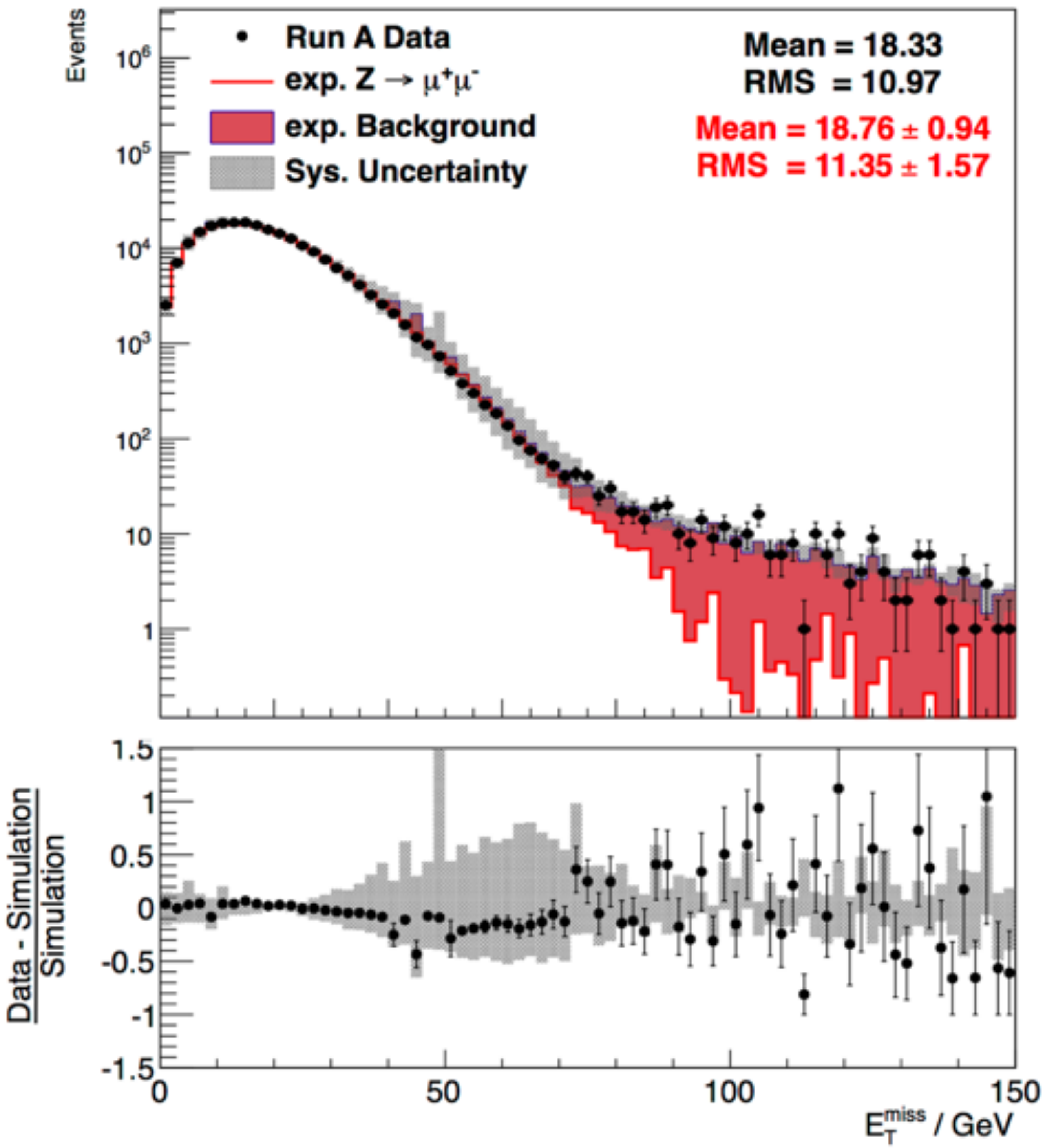
MET AT LHC AFTER 3 MONTHS!

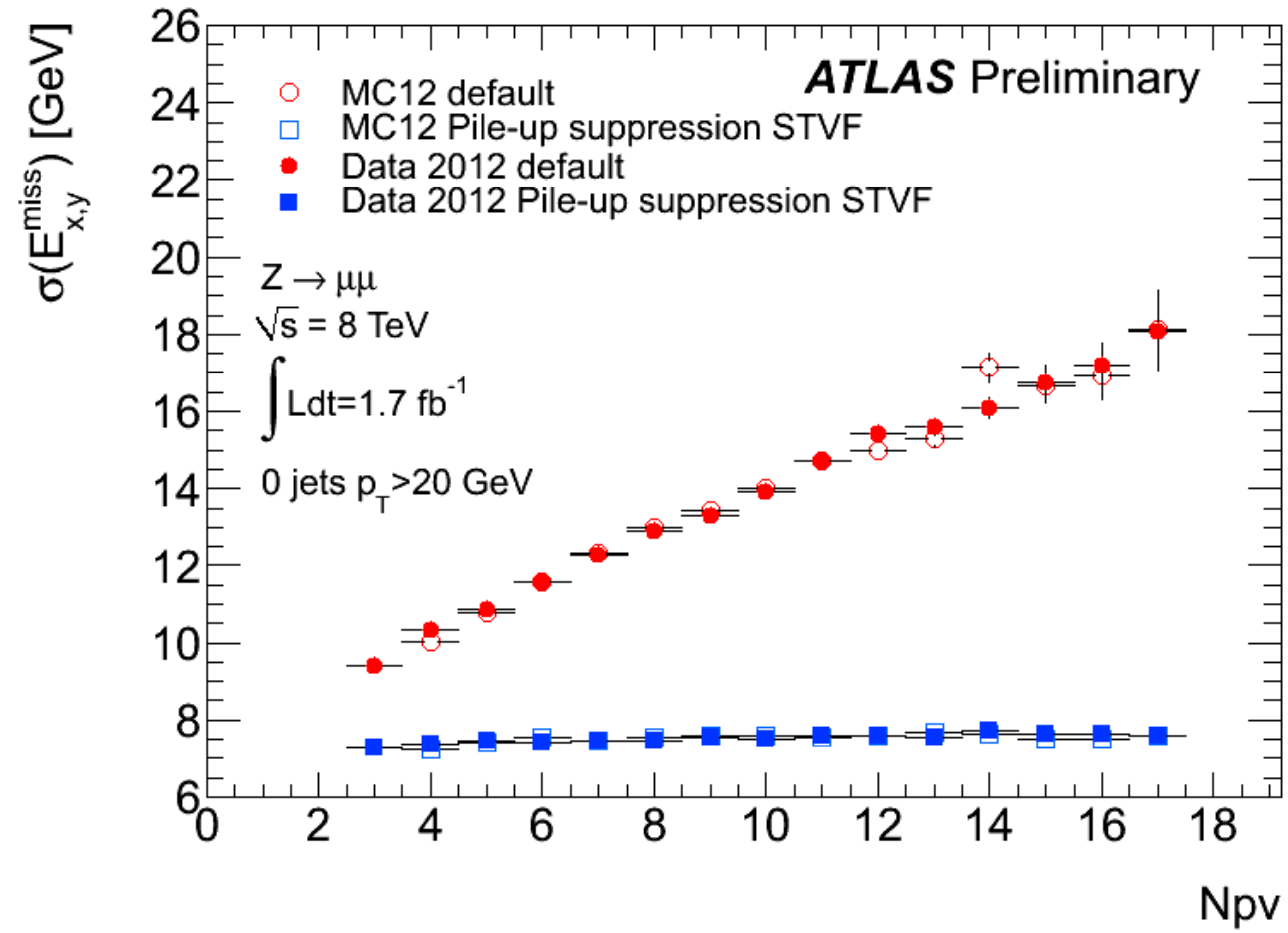




- Excellent understanding of bulk and tails after few weeks of operation
- Very promising for SUSY and New Physics searches already with 50 pb^{-1}

MET AT LHC IN 2012





mSUGRA (MSSM WITH SUPERGRAVITY)

- Minimal model with gravity as messenger of SUSY breaking at GUT scale
- Gravity becomes relevant only near the Planck scale
- mSUGRA can generate MSSM soft breaking term with only 5 free parameters
  - common gaugino mass
  - common scalar squared mass
  - scalar trilinear term
  - tanβ
  - sign(μ) (in the Higgs potential)

$$m_{1/2} = f\frac{\langle F\rangle}{M_P}$$

$$m_0^2 = k\frac{|\langle F\rangle|^2}{M_P^2}$$

$$A_0 = \alpha\frac{\langle F\rangle}{M_P}$$

Sparticle Masses in mSUGRA

- Highly predictive for squark and gluino masses in terms of m_0 and $m_{1/2}$

$$
\begin{aligned}
m^2_{\tilde{u}_L} &\simeq m_0^2 + 5.0 m^2_{1/2} + 0.35 cos2\beta M_Z^2 \\
m^2_{\tilde{d}_L} &\simeq m_0^2 + 5.0 m^2_{1/2} - 0.42 cos2\beta M_Z^2 \\
m^2_{\tilde{u}_R} &\simeq m_0^2 + 4.5 m^2_{1/2} + 0.15 cos2\beta M_Z^2 \\
m^2_{\tilde{d}_R} &\simeq m_0^2 + 4.4 m^2_{1/2} - 0.07 cos2\beta M_Z^2 \\
m^2_{\tilde{e}_L} &\simeq m_0^2 + 0.49 m^2_{1/2} - 0.27 cos2\beta M_Z^2 \\
m^2_{\tilde{\nu}} &\simeq m_0^2 + 0.49 m^2_{1/2} + 0.50 cos2\beta M_Z^2 \\
m^2_{\tilde{e}_R} &\simeq m_0^2 + 0.15 m^2_{1/2} - 0.23 cos2\beta M_Z^2
\end{aligned}
$$

$$M_{\tilde{g}} \lesssim 1.2 m_{\tilde{q}}$$

mSUGRA Mass Spectrum

- Region 1: gluinos heavier than any squark

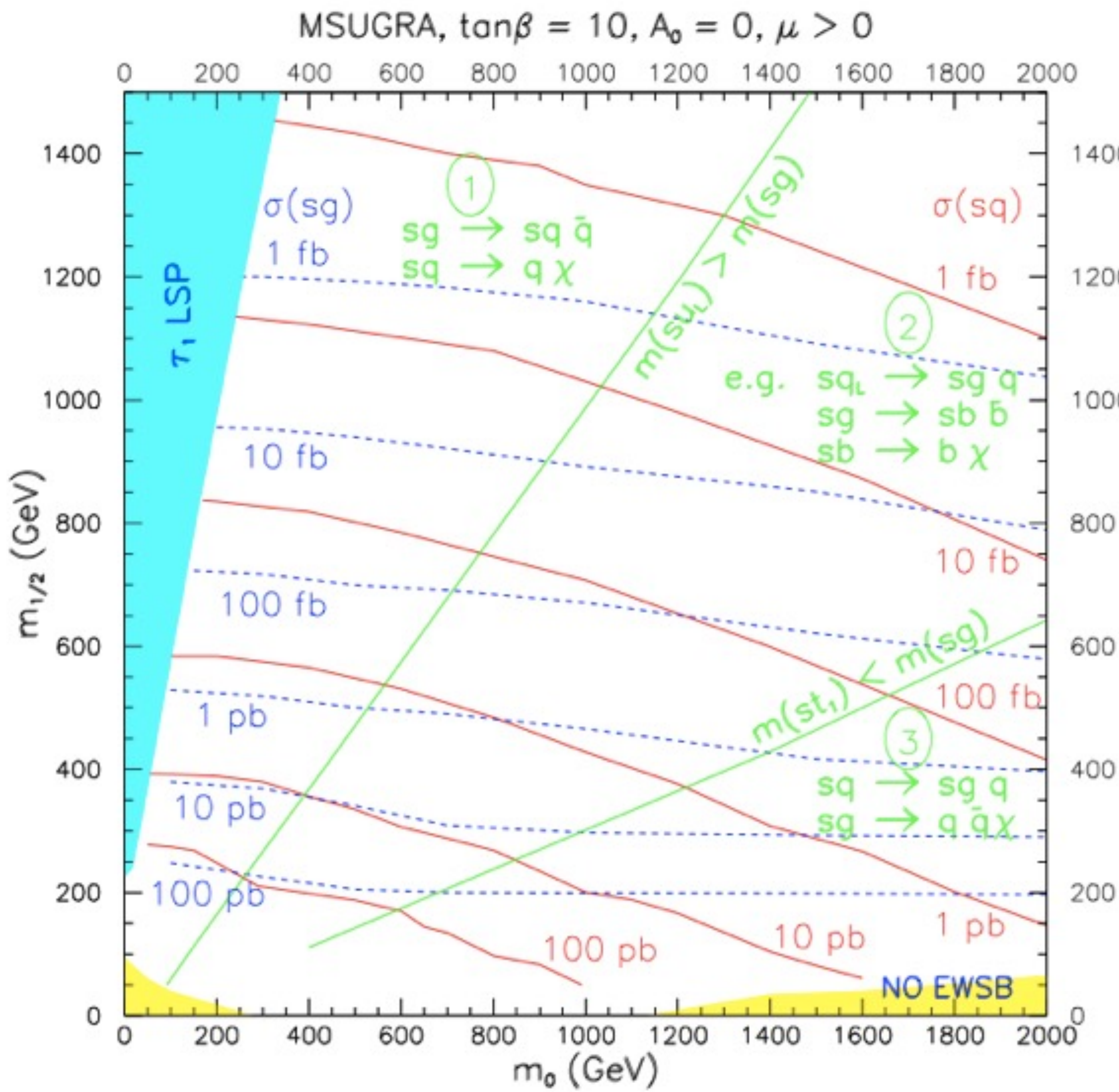
$$\tilde{g} \to \tilde{q}\bar{q}\ ,\ \tilde{q} \to q\chi$$

- Region 2: some squarks are heavier and some are lighter than gluinos

$$\tilde{q}_L \to \tilde{g}q\ ,\ \tilde{g} \to \tilde{b}\bar{b}\ ,\ \tilde{b} \to b\chi$$

- Region 3: gluinos are lighter than any squark

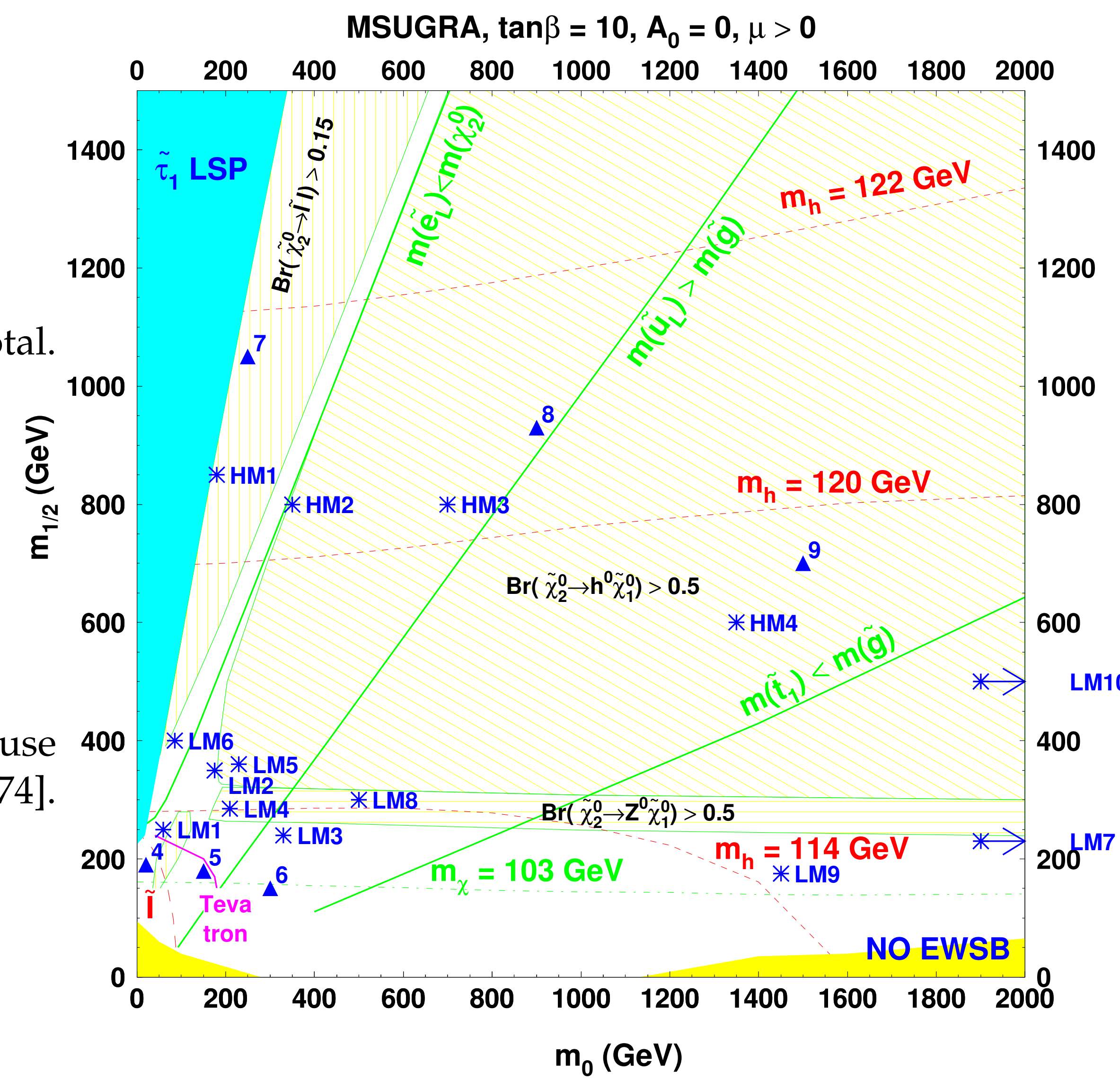
$$\tilde{q} \to \tilde{g}q\ ,\ \tilde{g} \to q\bar{q}\chi$$



TESTING mSUGRA

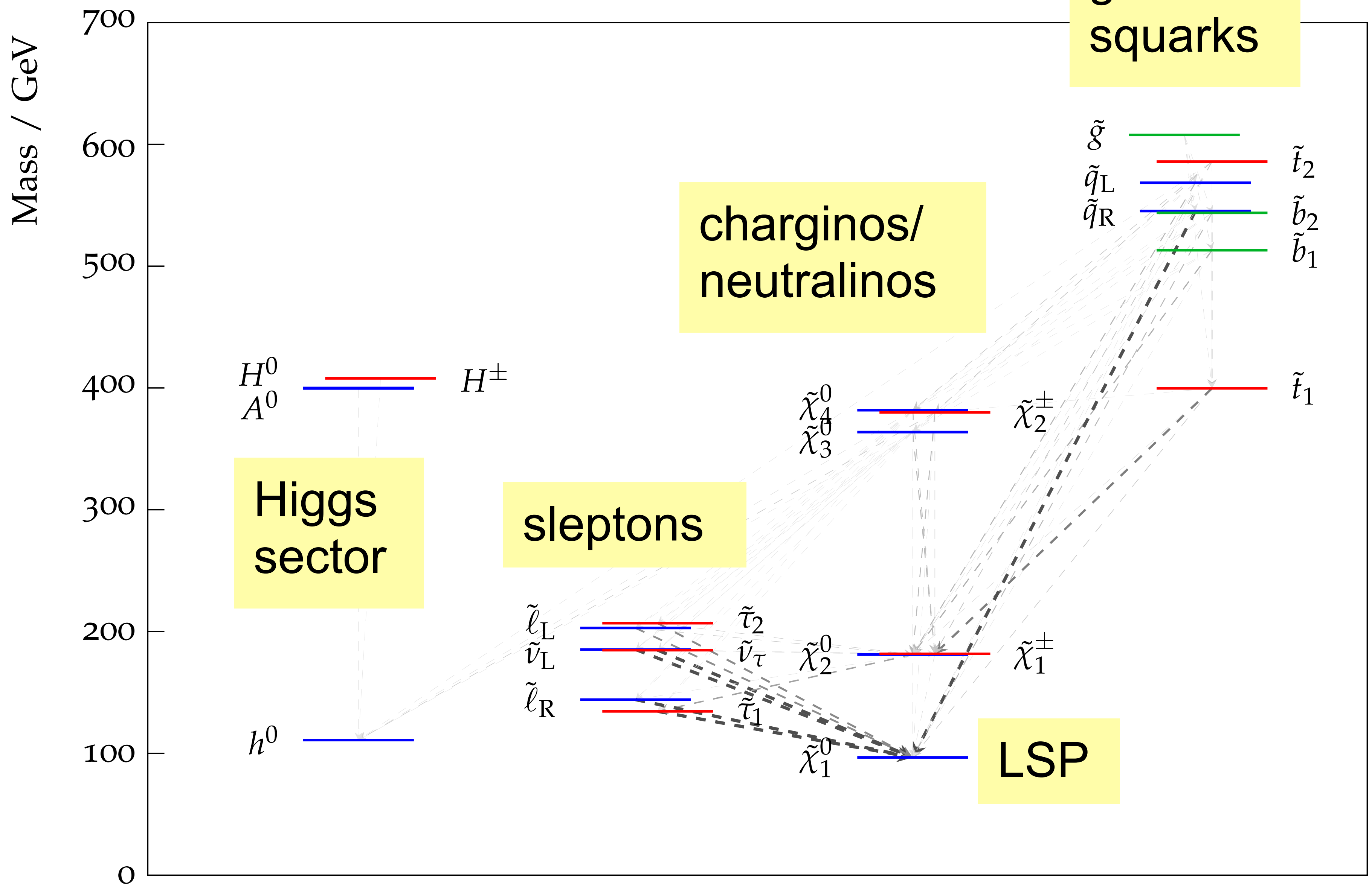
- Given continuous nature of free parameters and dramatic change of experimental signatures for specific values of m_0 and $m_{1/2}$ one cannot explore entire parameter space
- Practical solution: choose benchmark points with very different phenomenology for event generation and feasibility studies with different detectors

- **Point LM7** :
  - Very heavy squarks, outside reach, but light gluino.
  - $m(\tilde{g})$ = 678 GeV/c^2, hence $\tilde{g} \to$ 3-body is dominant
  - $B(\tilde{\chi}_2^0 \to ll\tilde{\chi}_1^0) = 10\%$, $B(\tilde{\chi}_1^\pm \to \nu l\tilde{\chi}_1^0) = 33\%$
  - EW chargino-neutralino production cross-section is about 73% of total.
- **Point LM8** :
  - Gluino lighter than squarks, except $\tilde{b}_1$ and $\tilde{t}_1$
  - $m(\tilde{g})$ = 745 GeV/c^2, $M(\tilde{t}_1)$ = 548 GeV/c^2, $\tilde{g} \to \tilde{t}_1 t$ is dominant
  - $B(\tilde{g} \to \tilde{t}_1 t) = 81\%$, $B(\tilde{g} \to \tilde{b}_1 b) = 14\%$, $B(\tilde{q}_L \to q\tilde{\chi}_2^0) = 26-27\%$,
  - $B(\tilde{\chi}_2^0 \to Z^0\tilde{\chi}_1^0) = 100\%$, $B(\tilde{\chi}_1^\pm \to W^\pm\tilde{\chi}_1^0) = 100\%$
- **Point LM9** :
  - Heavy squarks, light gluino. Consistent with EGRET data on diffuse gamma ray spectrum, WMAP results on CDM and mSUGRA [674]. Similar to LM7.
  - $m(\tilde{g})$ = 507 GeV/c^2, hence $\tilde{g} \to$ 3-body is dominant
  - $B(\tilde{\chi}_2^0 \to ll\tilde{\chi}_1^0) = 6.5\%$, $B(\tilde{\chi}_1^\pm \to \nu l\tilde{\chi}_1^0) = 22\%$



SUSY SPECTRUM (SPS1A)

Use the famous SPS1a benchmark point for illustration [m_0=100, m_{12}=250, tanβ=10, A_0=-100, μ>0]



CMSSM

$m_0, m_{1/2}, \tan\beta, A_0, sign(\mu)$

Advantage:

- Only four free parameters (when sign(μ) fixed)
- One of the most studied incarnations of the MSSM

Disadvantage:

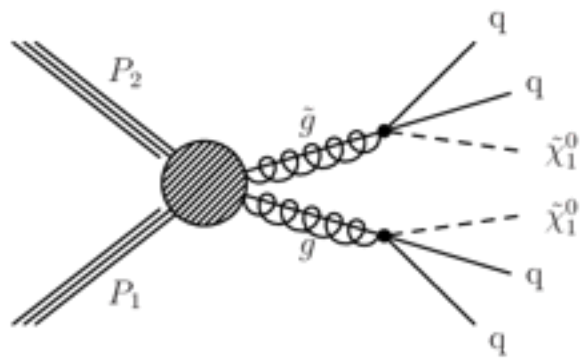
- Not generally representative of SUSY (e.g. fixed mass relation between M_{gluion} and M_{LSP})

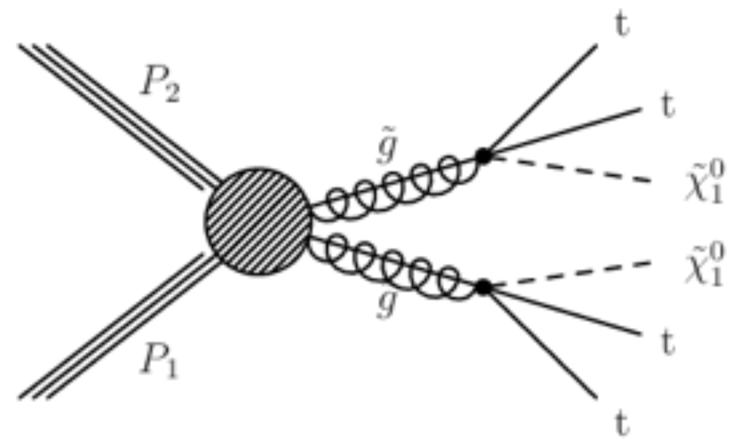
Signature-based Search Strategy

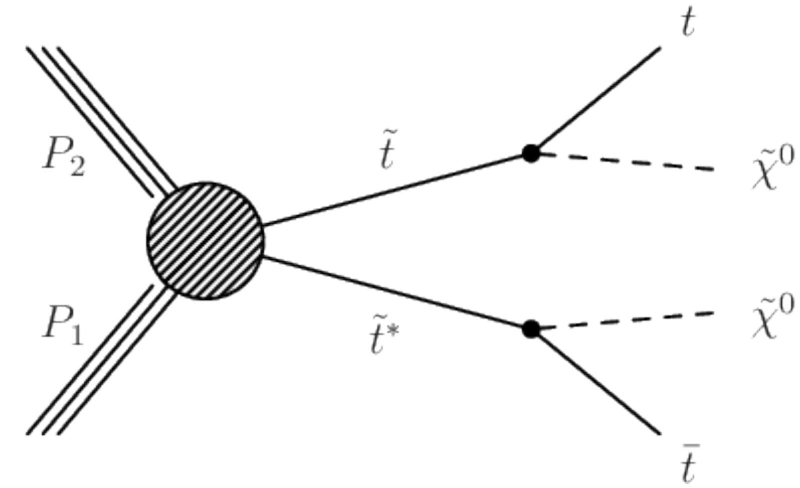
- Do not relay on your best theory friend to define signatures
  - Variety of creative models sometimes with very specific predictions
  - Fine tuning of search strategy for model A dangerous and counterproductive
    - If model A is incorrect you will see nothing
    - If model A prediction very different from models B and C, you might not be even sensitive to B and C predictions. Waste of time!
- Experimental approach: define categories of events that could be predicted by different models for different corners of phase space
  - MET + 1 jet
  - MET + n jet
  - MET + 1 lepton
  - MET + dilepton (same sign and opposite sign treated differently)
  - MET + multi-leptons
  - MET + high pt photon
- Model-independent strategy potential rules out some or even classes of models with individual measurement

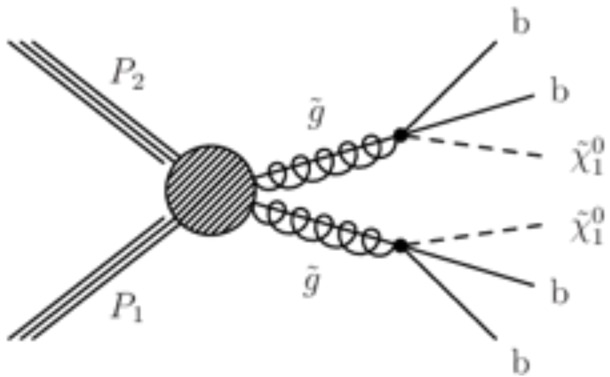
Simplified Models (SMS)

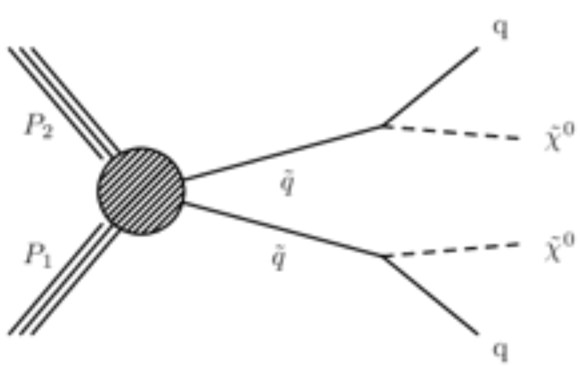
Simplified Models for LHC New Physics Searches, arxiv:1105.2838

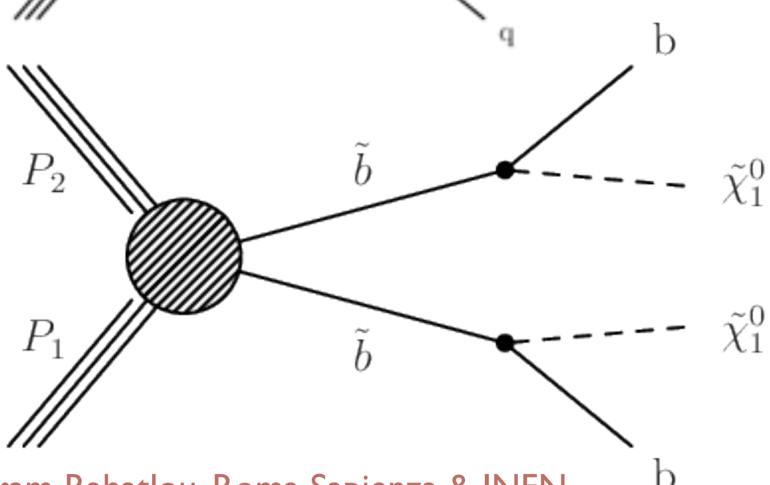


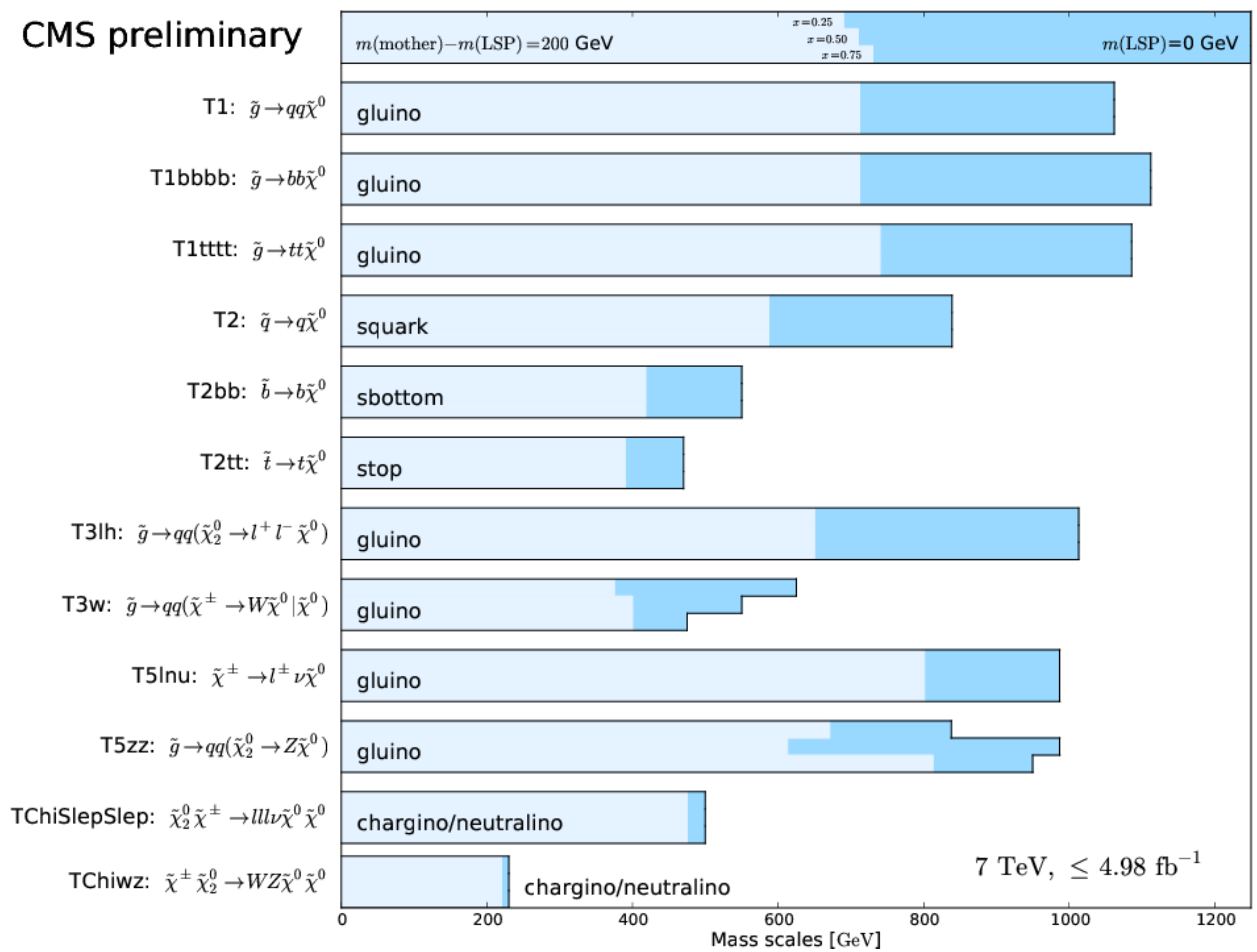






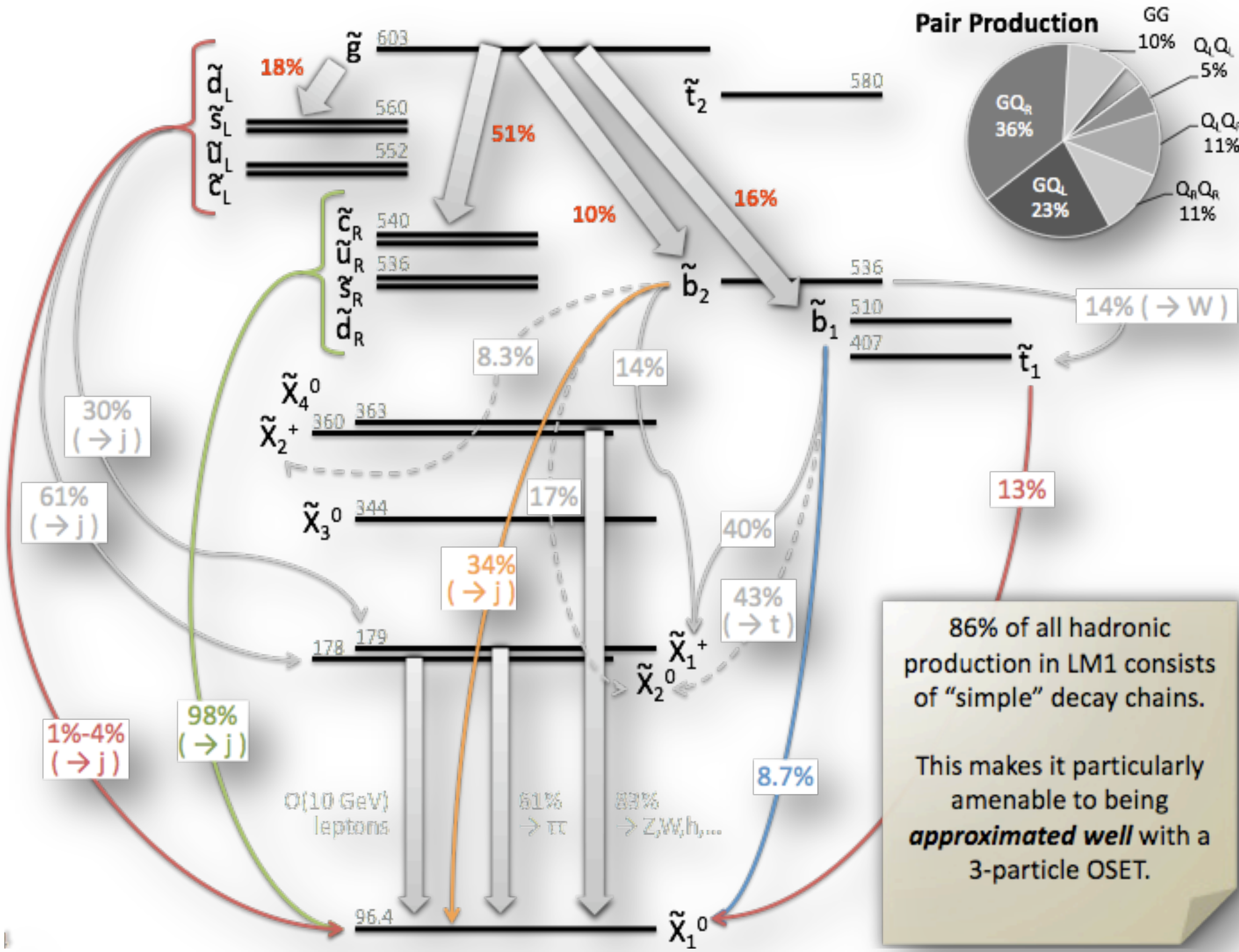




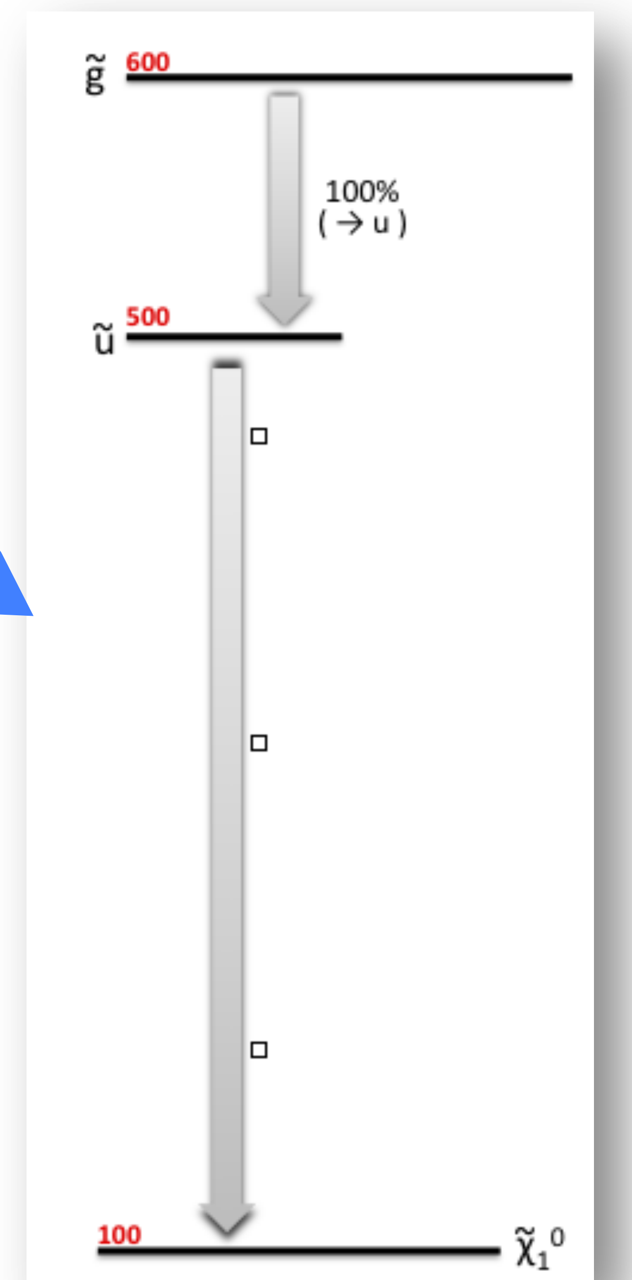


INTERPRETATION OF SMS

CMSSM

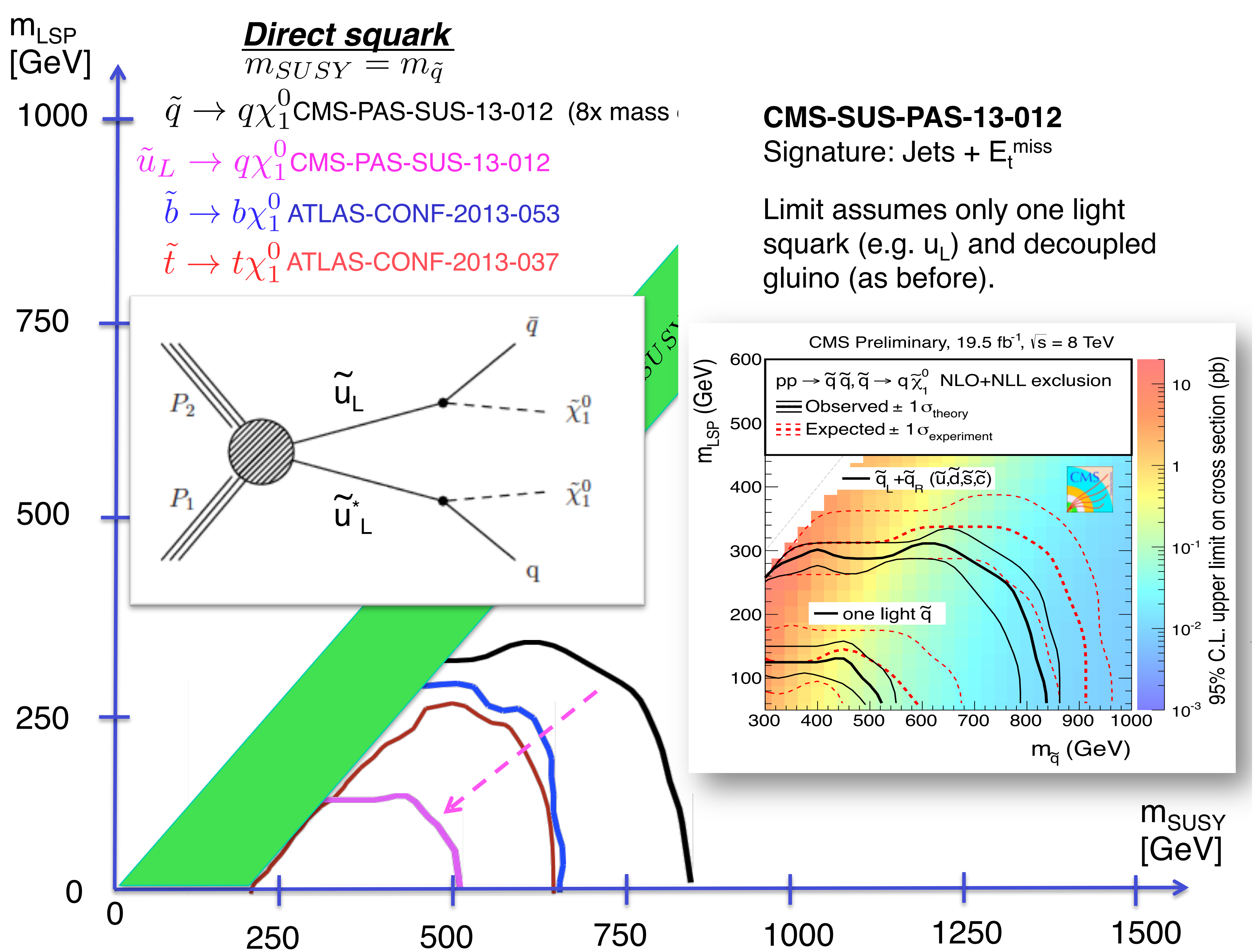


What the individual searches are sensitive to is much more simple…



Simplified model spectrum (SMS)
with 3 particles, 2 decay modes

DIRECT SQUARK PRODUCTION

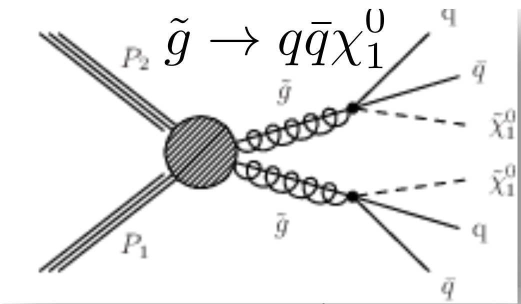


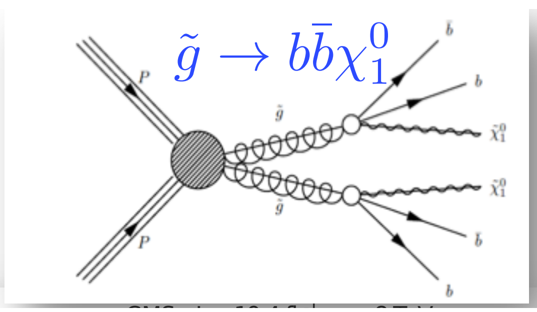
CMS-SUS-PAS-13-012

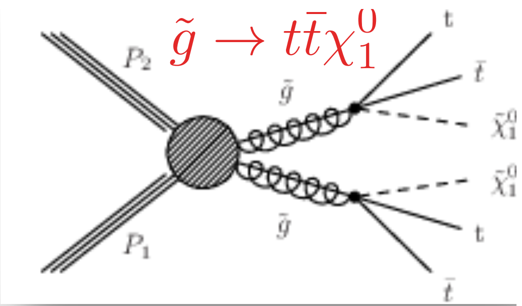
Signature: Jets + E_t^{miss}

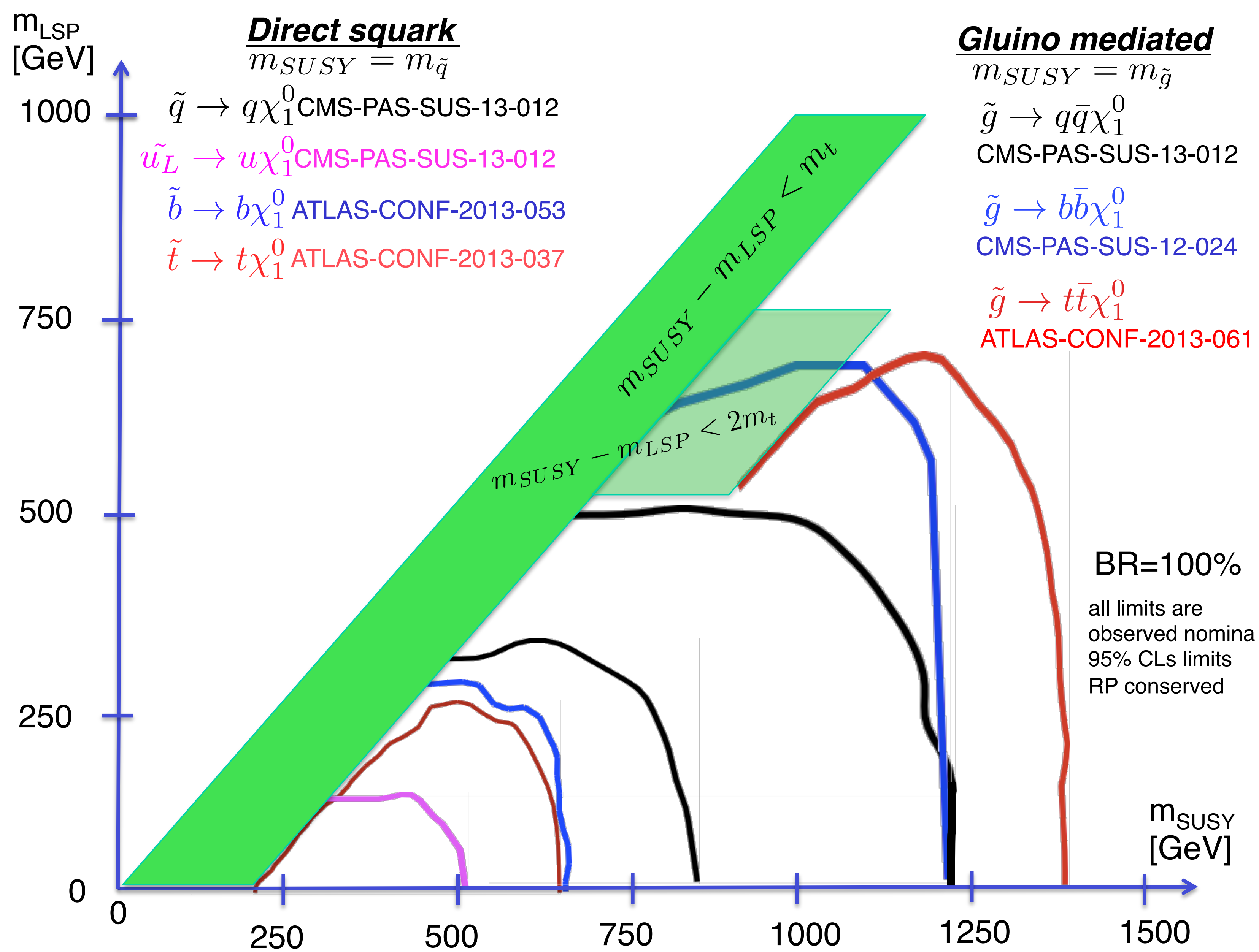
Limit assumes only one light squark (e.g. u_L) and decoupled gluino (as before).

GLUINO-MEDIATED PRODUCTION

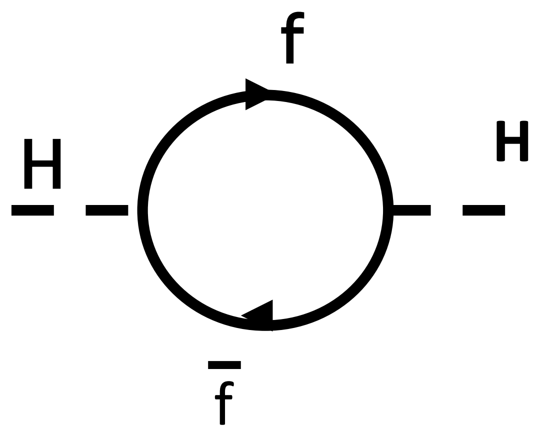






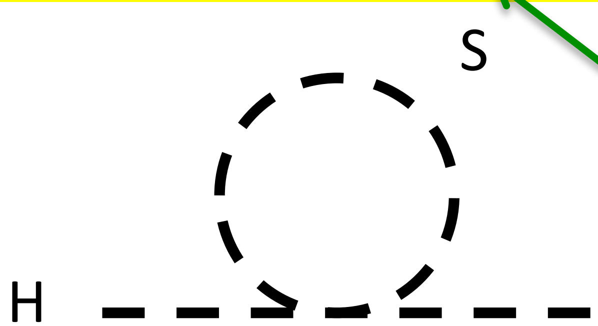


THIRD GENERATION

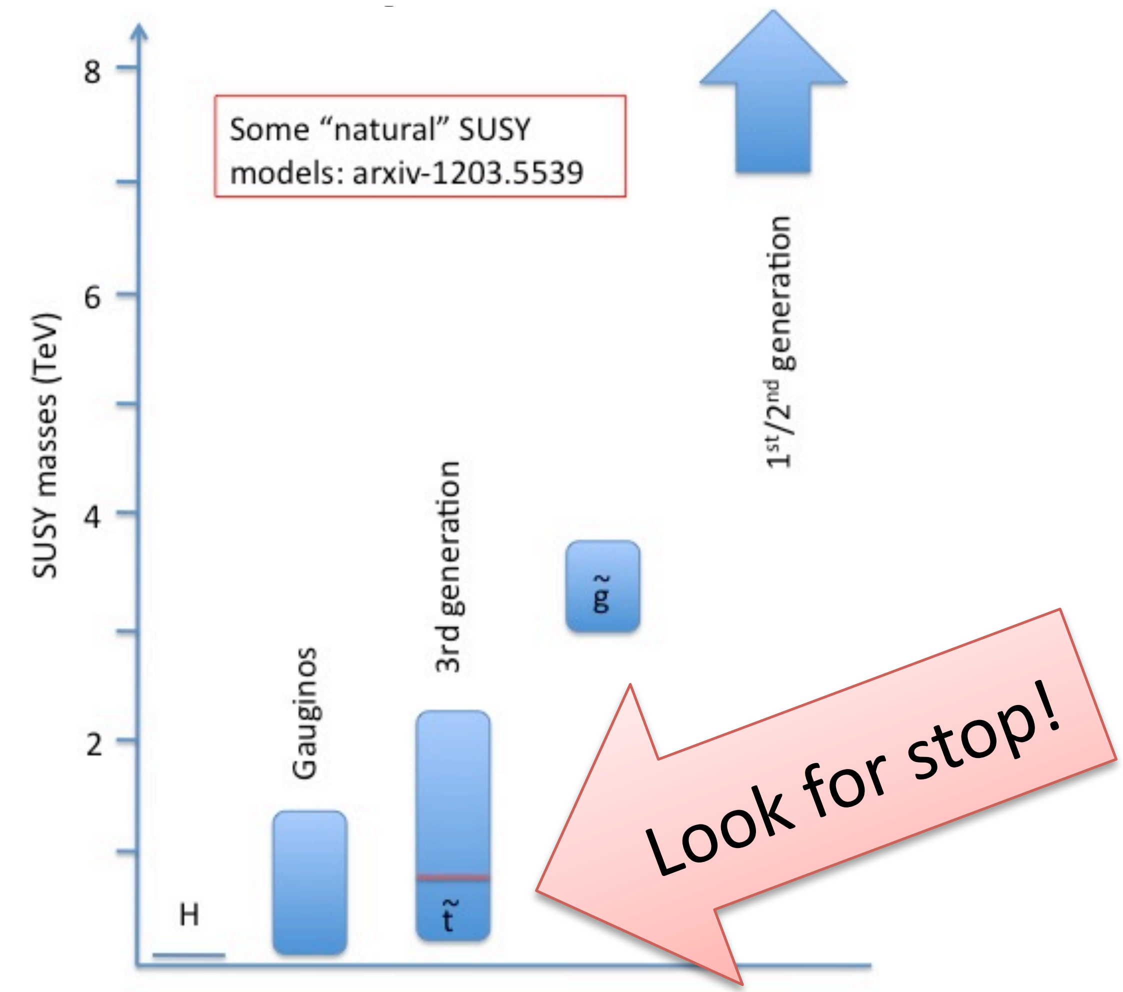


$$\Delta m_H^2 = \frac{|\lambda_f|^2}{16\pi^2}\left[-2\Lambda_{UV}^2 + 6m_f^2 \ln(\Lambda_{UV}/m_f) + \ldots\right]$$

m_f^2



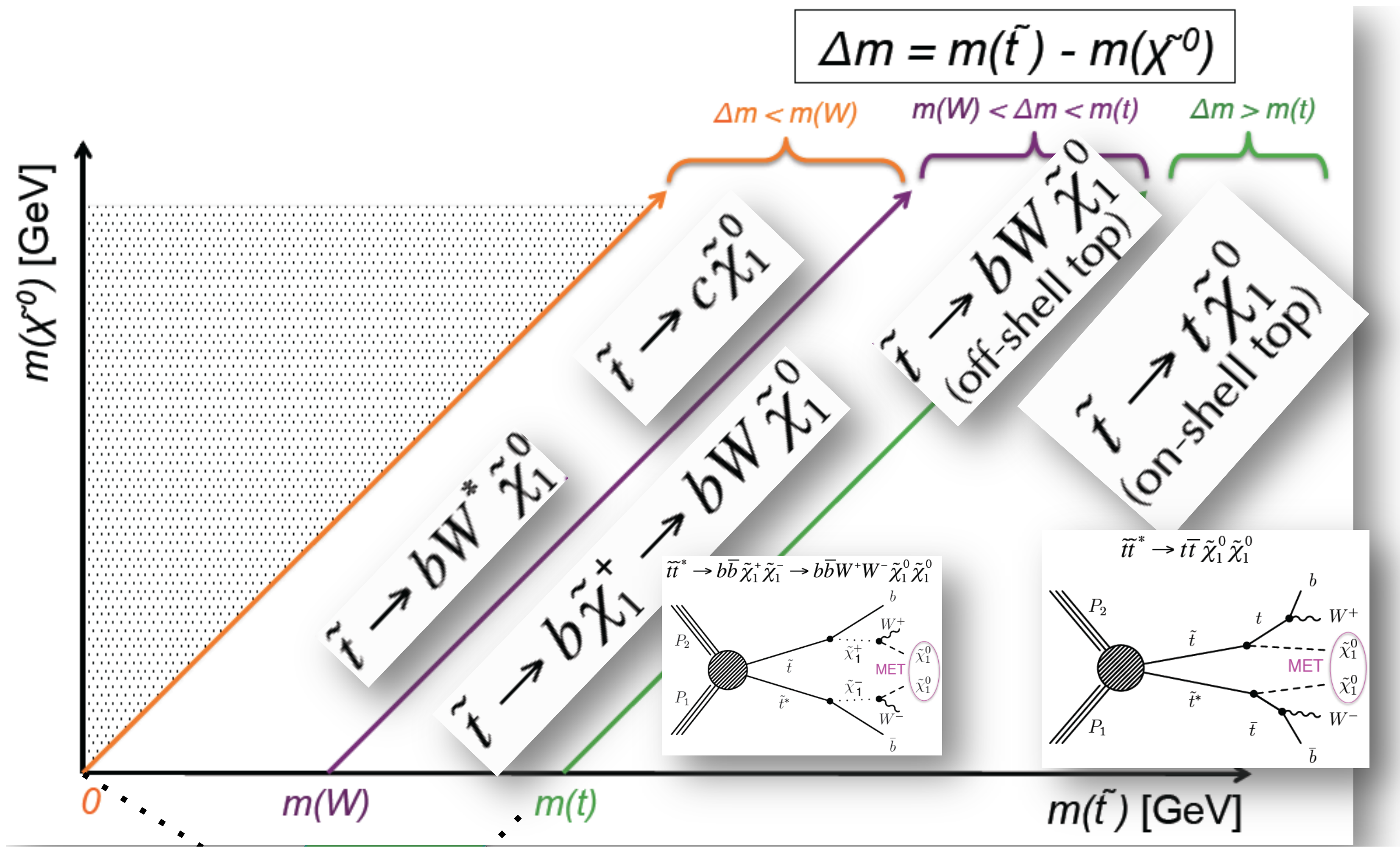
$$\Delta m_H^2 = \frac{\lambda_s}{16\pi^2}\left[\Lambda_{UV}^2 - 2m_s^2 \ln(\Lambda_{UV}/m_s) + \ldots\right]$$

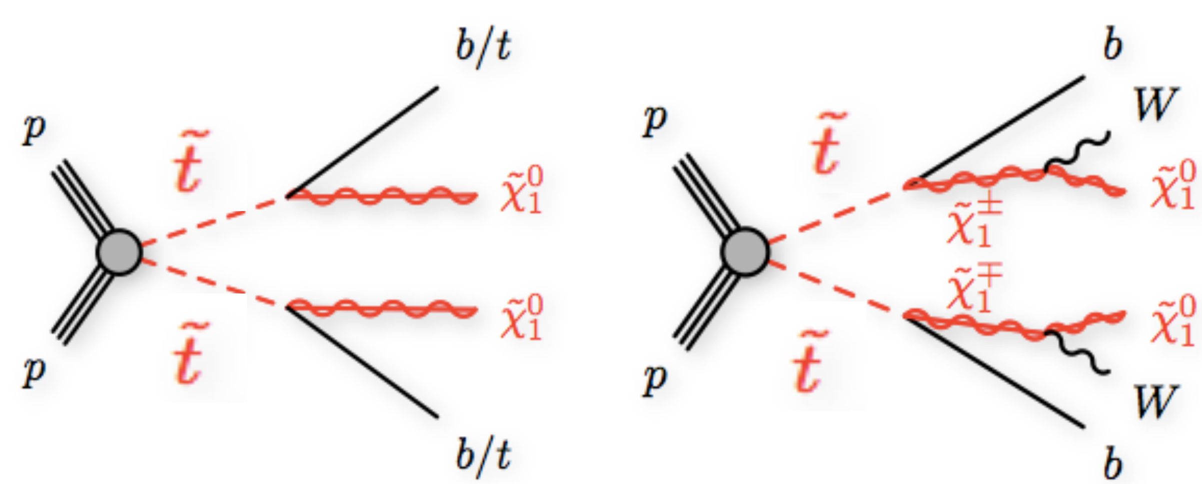


Dominant loop is from top: only need third generation squarks to be really light.

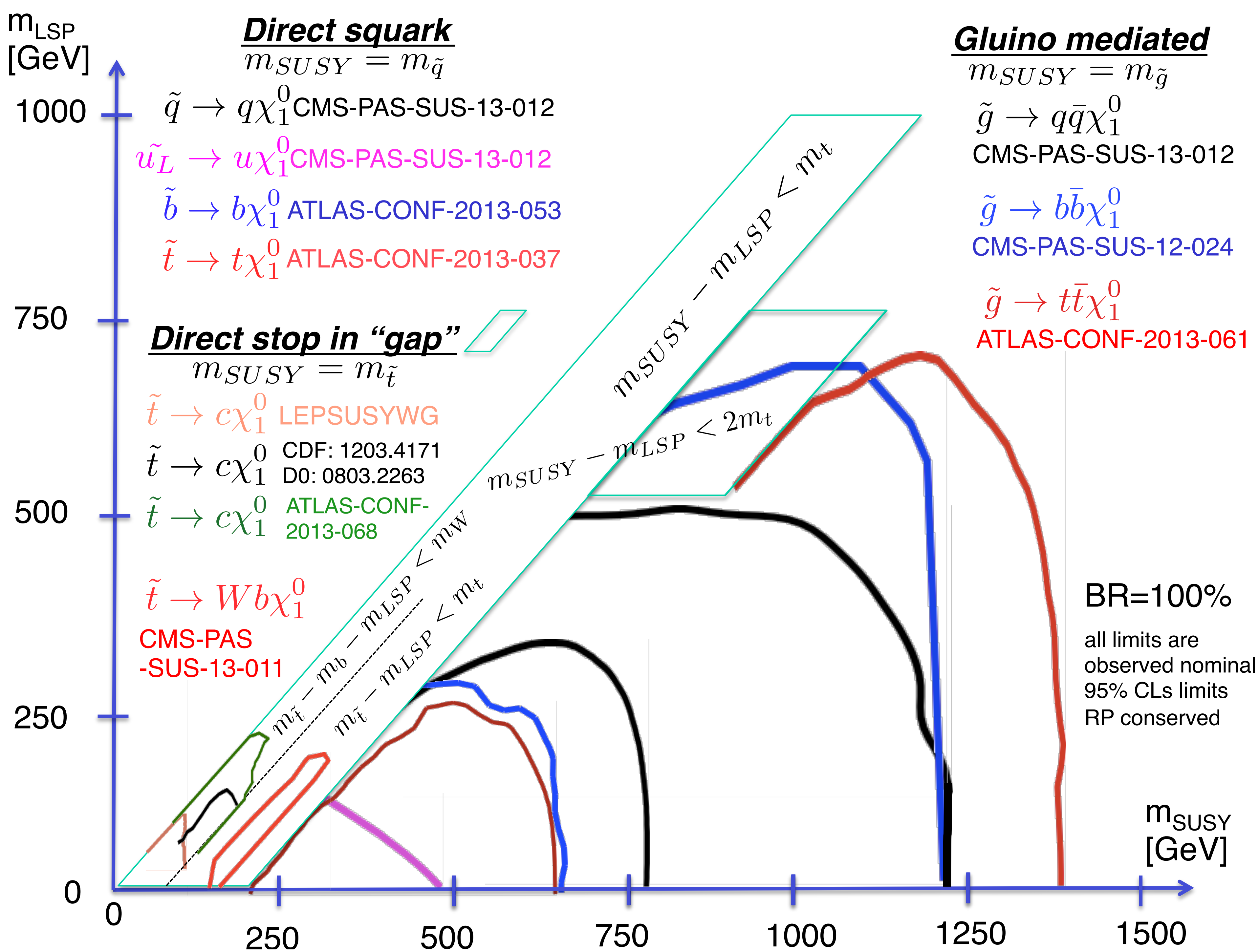
3rd generation cross section is reduced (no t/b content in proton): existing limits don't apply!

Search for Stop





CONSTRAINTS FROM STOP



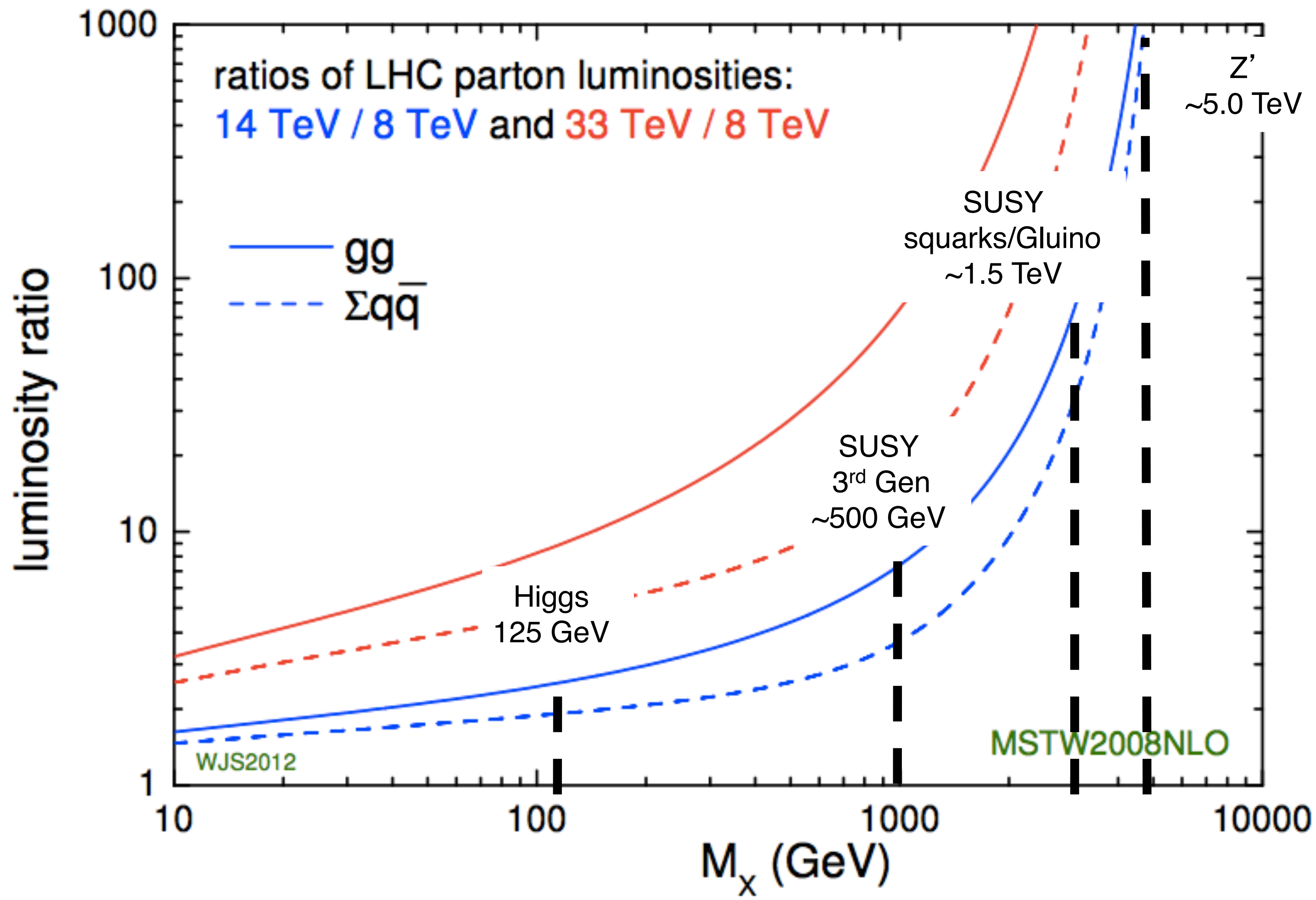
Benefits of Higher Energy

Higgs:
pp → H, H→WW, ZZ and γγ
mainly gg: factor ~2

SUSY – 3rd Generation:
Mass scale ~ 500 GeV
qq and gg: factor ~3 to 6

SUSY – Squarks/Gluino:
Mass scale ~ 1.5 TeV
qq,gg,qg: factor ~40 to 80

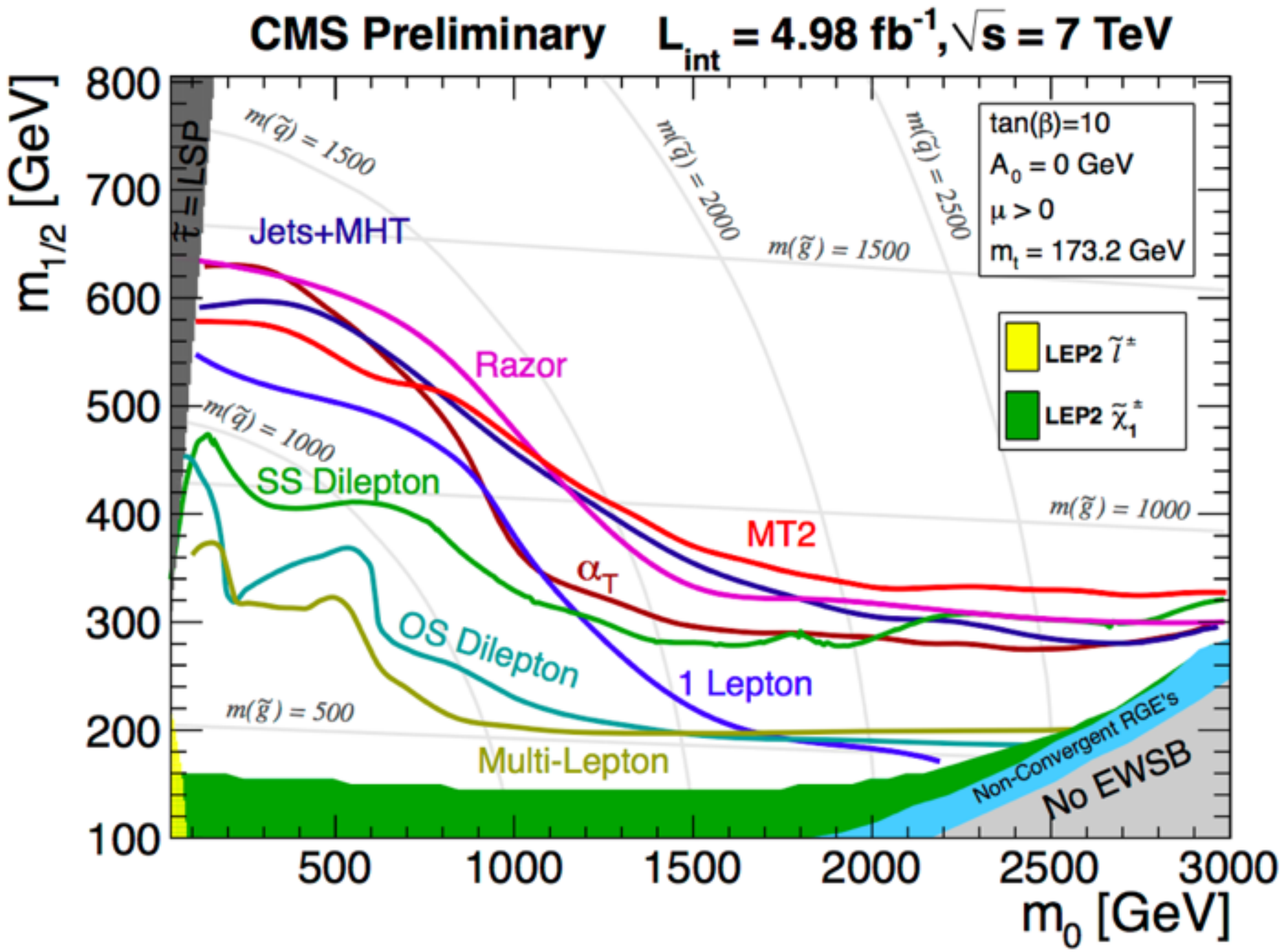
Z' :
Mass scale ~ 5 TeV
qq: factor ~1000



Increase in energy will help a lot!
Not just for SUSY...

CONSTRAINTS ON CMSSM

Constrained Minimal Supersymmetry: unification of superpartner masses and Gauge couplings at GUT scale

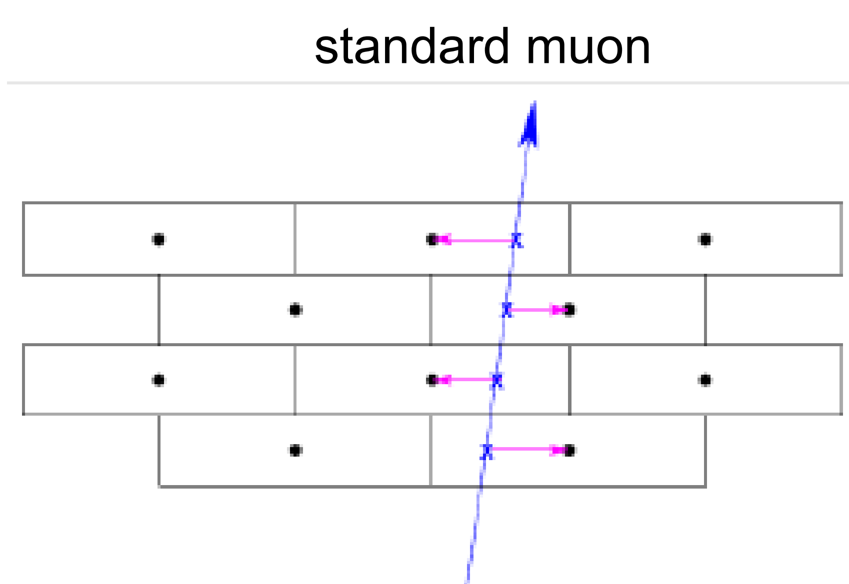


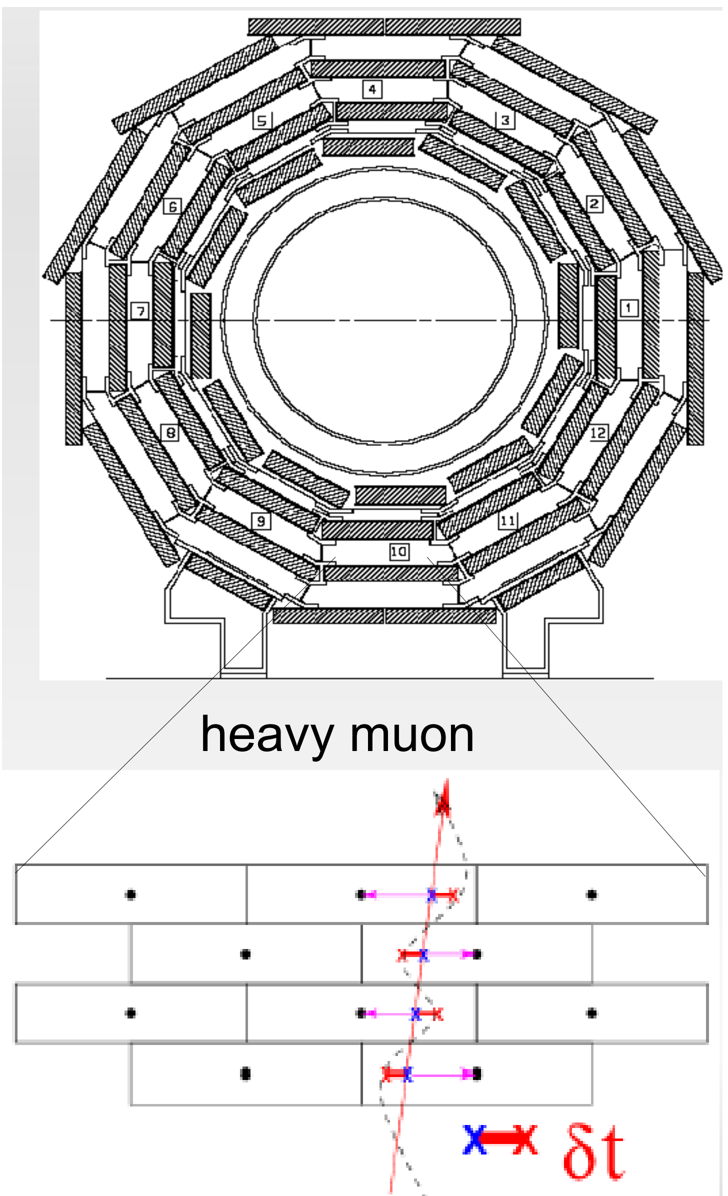
- G. Kane et al., "Study of constrained minimal supersymmetry", http://arxiv.org/abs/hep-ph/9312272

Heavy Stable Particles

HEAVY STABLE CHARGED PARTICLES

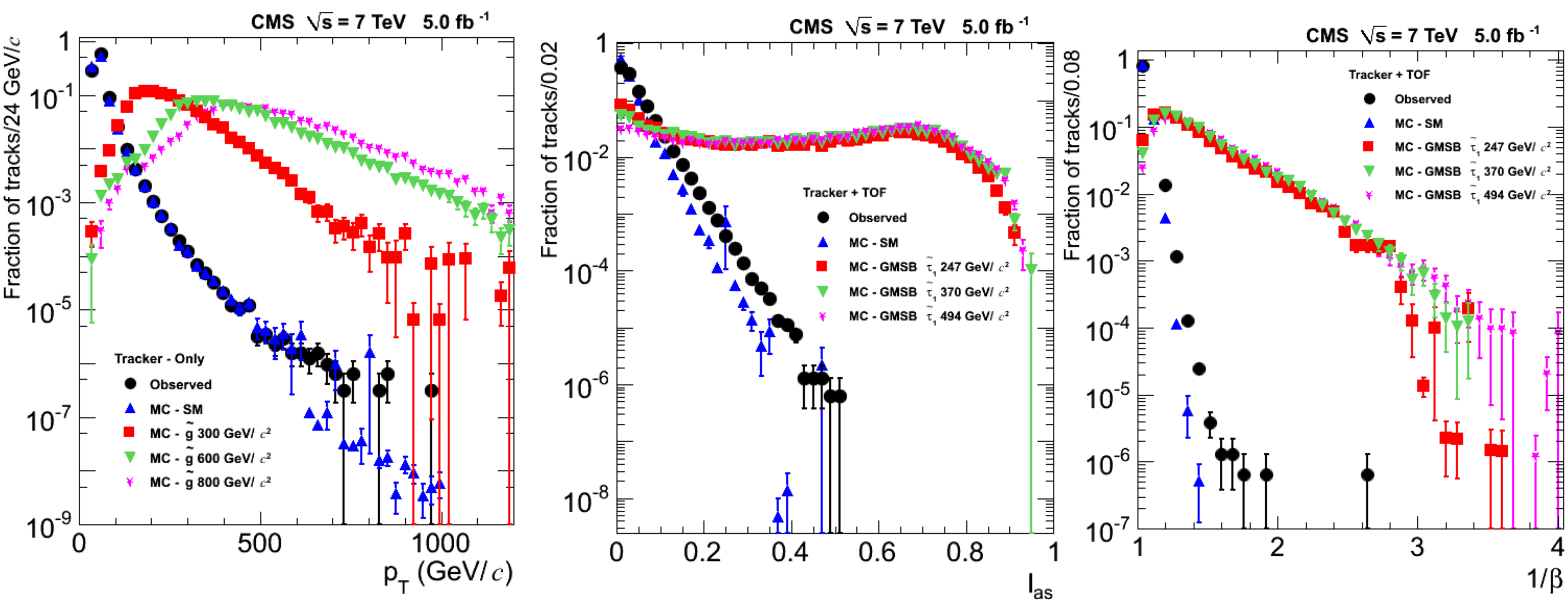
- In many flavors of SUSY, LSP is a heavy charged particle, stau, stop, gluino
  - split SUSY, GMSB, KK tau from some universal extra dimension models
- Behave like very heavy muon through tracking and muons detectors
  - β<1 so later time of arrival in detectors compared to common relativistic particles from collisions
  - Smaller velocity implies larger ionization energy loss
- Search for muon like particles and measure dE/dx energy loss
- Dedicated muon reconstruction because of late arrival compared to standard muon



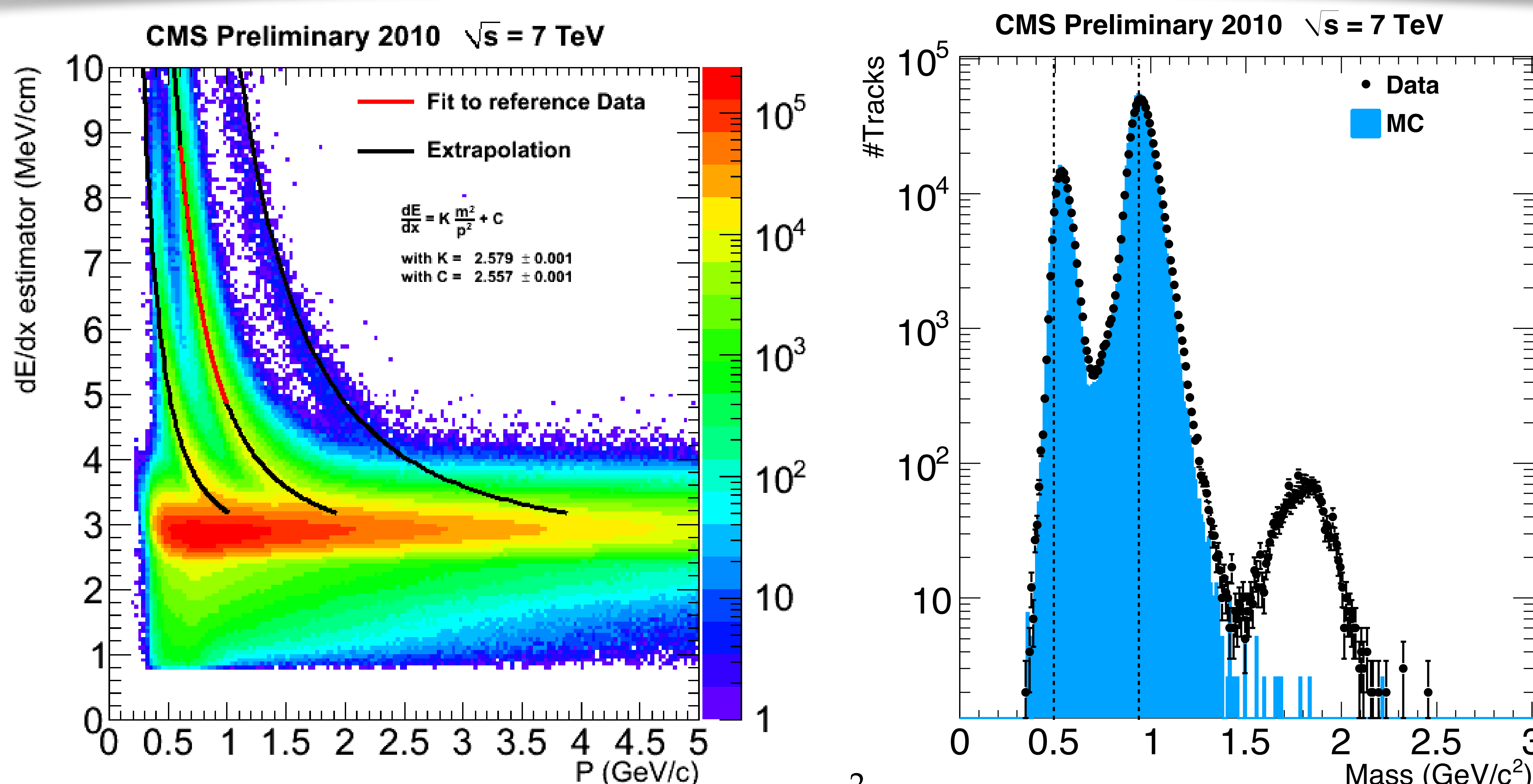


Analysis Method

- Discriminating variables
  - –High pt tracks
  - –ionization energy loss
  - –time of flight



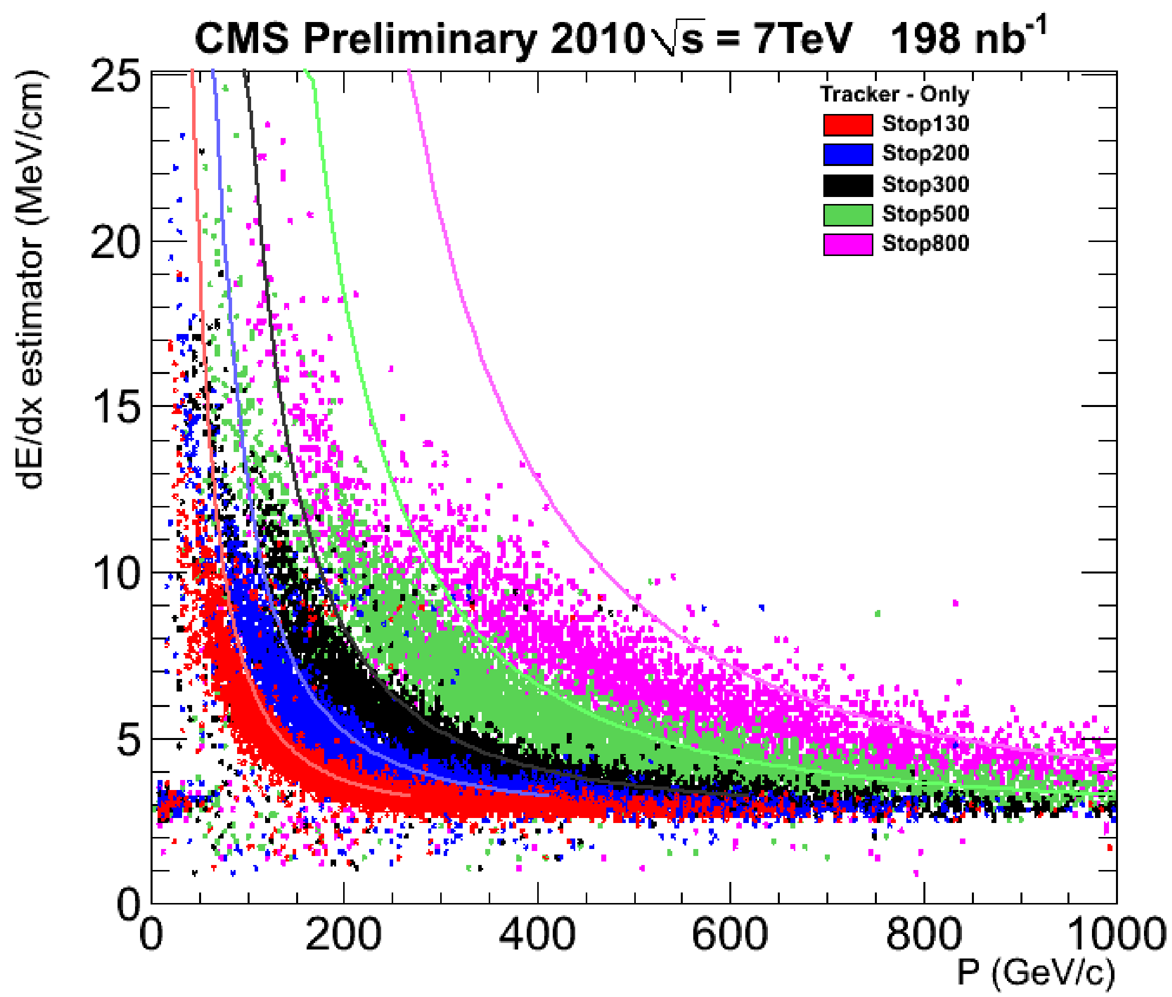
Mass Measurement from dE/dx

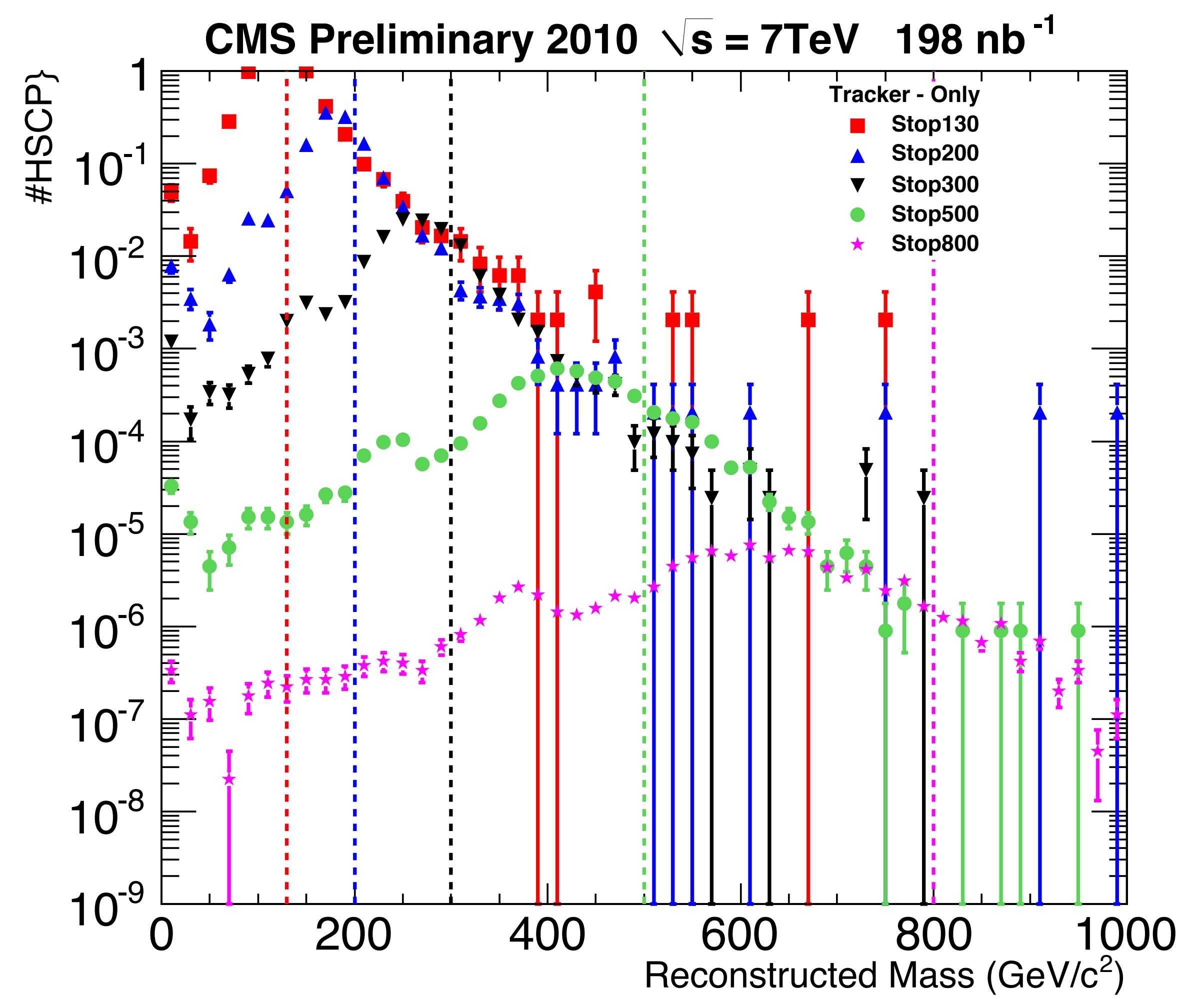


$$I_h = K\frac{m^2}{p^2} + C$$

- Quadratic relation between measured energy loss I_h and mass
- Determine K and C from fit to known particles (pions, kaons, protons)
- Determine mass of heavy particles based on measured I_h and momentum p

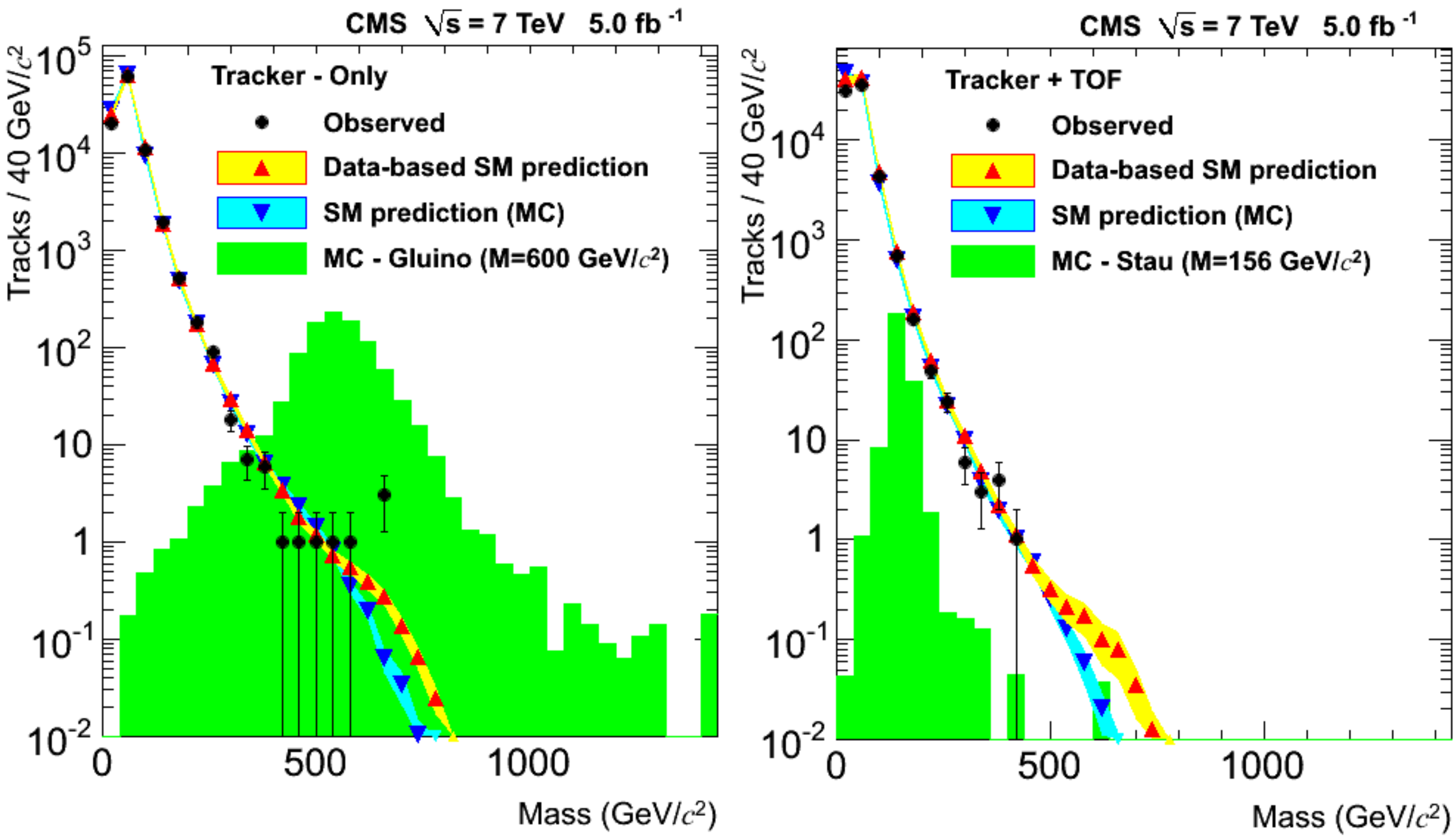
Mass of heavy Particles





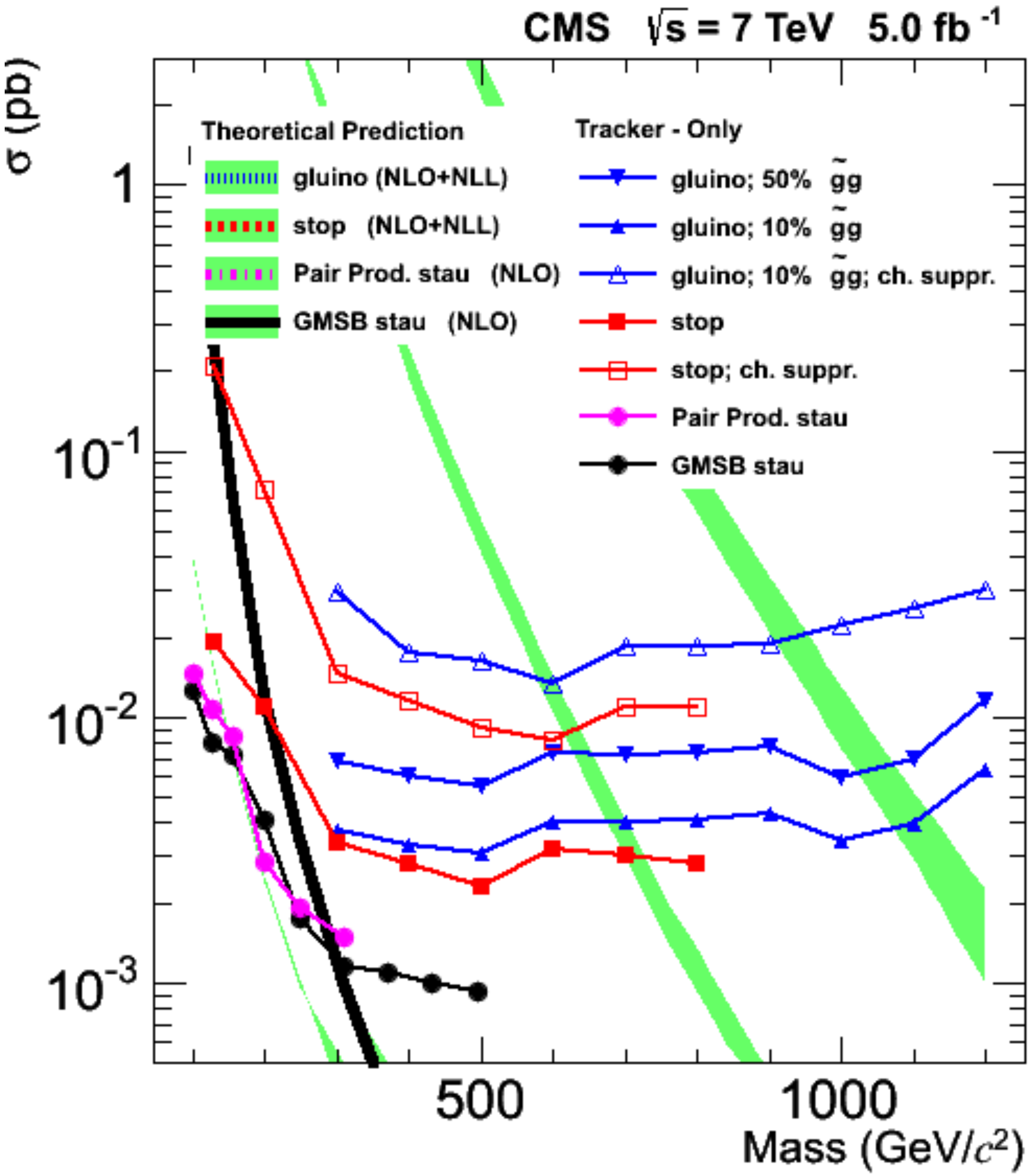
- Not enough data yet to measure precisely the mass of the heavy particle

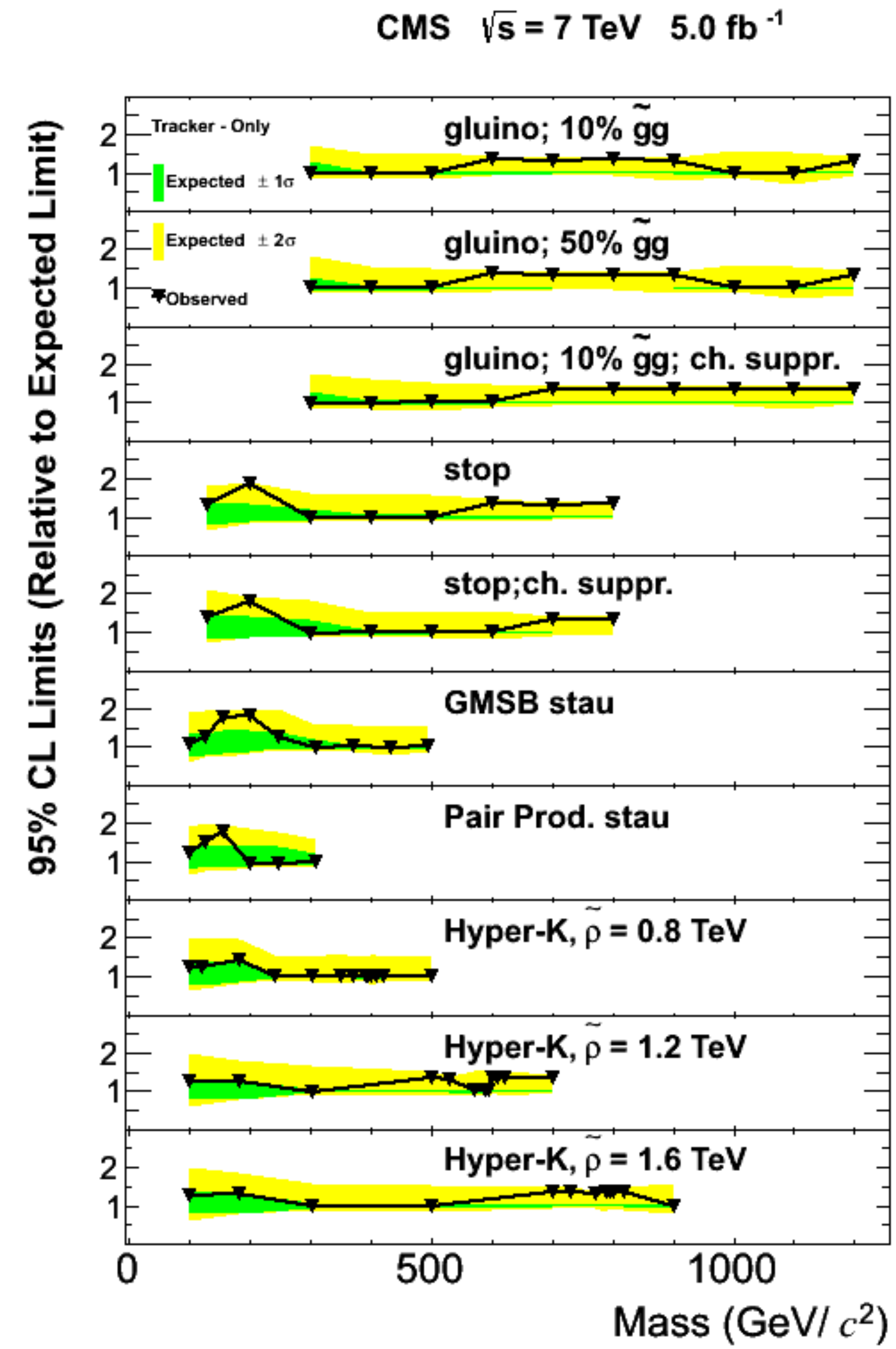
HSCP MASS



CMS √s = 7 TeV 5.0 fb -1
Tracker - Only
Observed
Data-based SM prediction
SM prediction (MC)
MC - Gluino (M=600 GeV/c²)
Tracks / 40 GeV/c²
Mass (GeV/c²)
CMS √s = 7 TeV 5.0 fb -1
Tracker + TOF
Observed
Data-based SM prediction
SM prediction (MC)
MC - Stau (M=156 GeV/c²)
Tracks / 40 GeV/c²
Mass (GeV/c²)

Exclusion Limits





Long-Lived Searches

Gauge Mediated SUSY Breaking (GMSB)

- SUSY breaking transmitted via ordinary $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge interactions
- New fields F with non-zero VEV <F> in hidden sector
- New heavy messengers of mass M_{mess} mediate between hidden sector and gauge and gaugino particles in visible sector
- soft SUSY breaking scale $m_{\text{soft}} \sim \frac{\alpha_a}{4\pi} \frac{\langle F \rangle}{M_{\text{mess}}}$
- If $M_{mess} \sim 10^4$ GeV then comparable VEV of <F> $\sim 10^4$ GeV
  - SUSY breaking at much lower energy scale compared to mSUGRA and other models
- Important feature of GMSB: gravitino as LSP and lightest neutralino as NLSP

$$m_{3/2} \sim \frac{\langle F \rangle}{M_P} \quad \ll \quad m_{\text{soft}} \sim \frac{\alpha_a}{4\pi} \frac{\langle F \rangle}{M_{\text{mess}}}$$

- Enhanced decay mode: $\tilde{\chi}_1^0 \to \tilde{G} + \gamma$

GMSB PARAMETERS

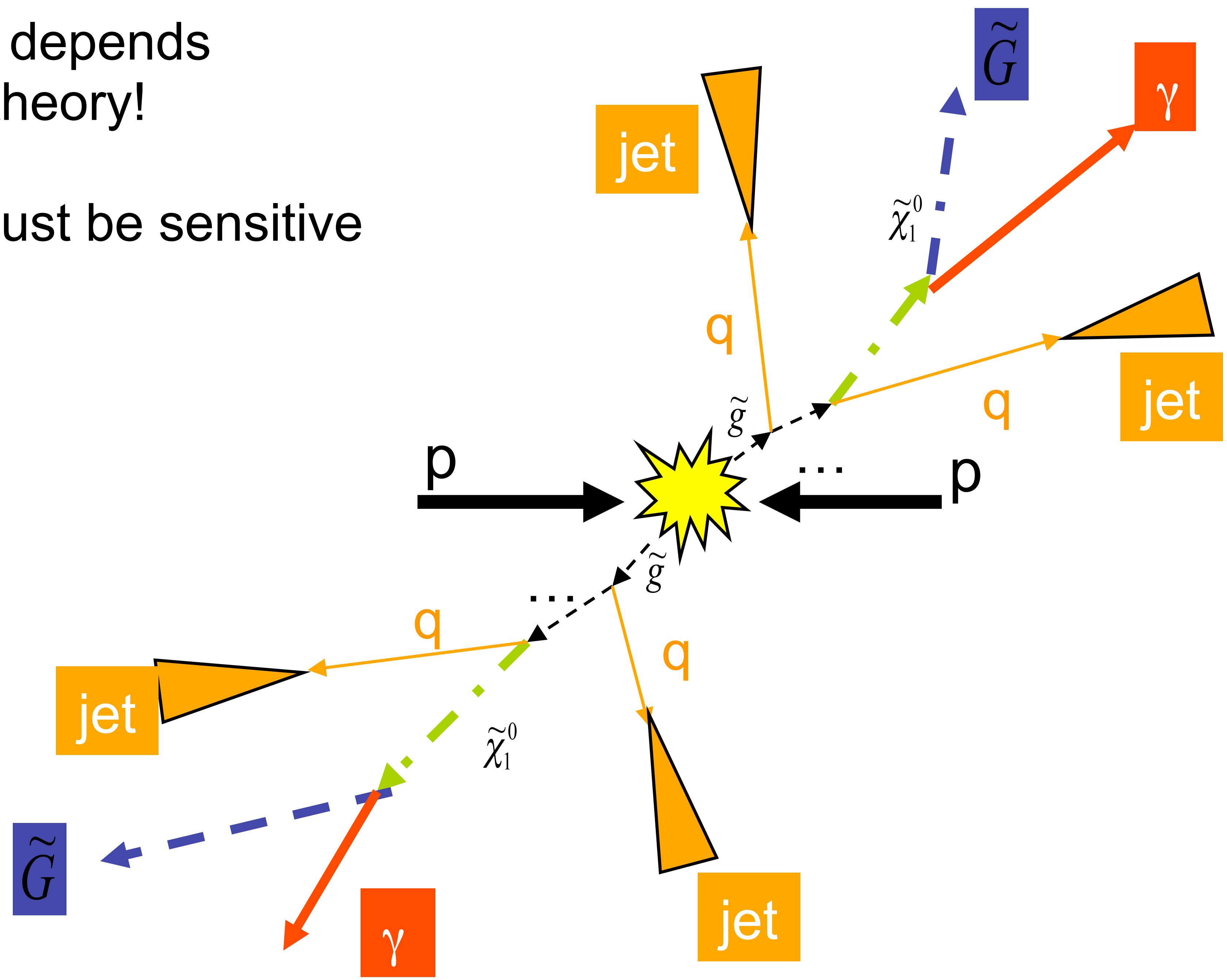
- Only 6 free parameters to provide SUSY breaking
  - N: number of messengers
  - messenger mass scale M_{mess}
  - SUSY breaking scale $\Lambda = \frac{\langle F \rangle}{M_{mess}}$
  - $\tan\beta$
  - sign(μ) (in the Higgs potential)
  - C_{grav}: determines lifetime of neutralino

- For N > 1 stau becomes the NLSP

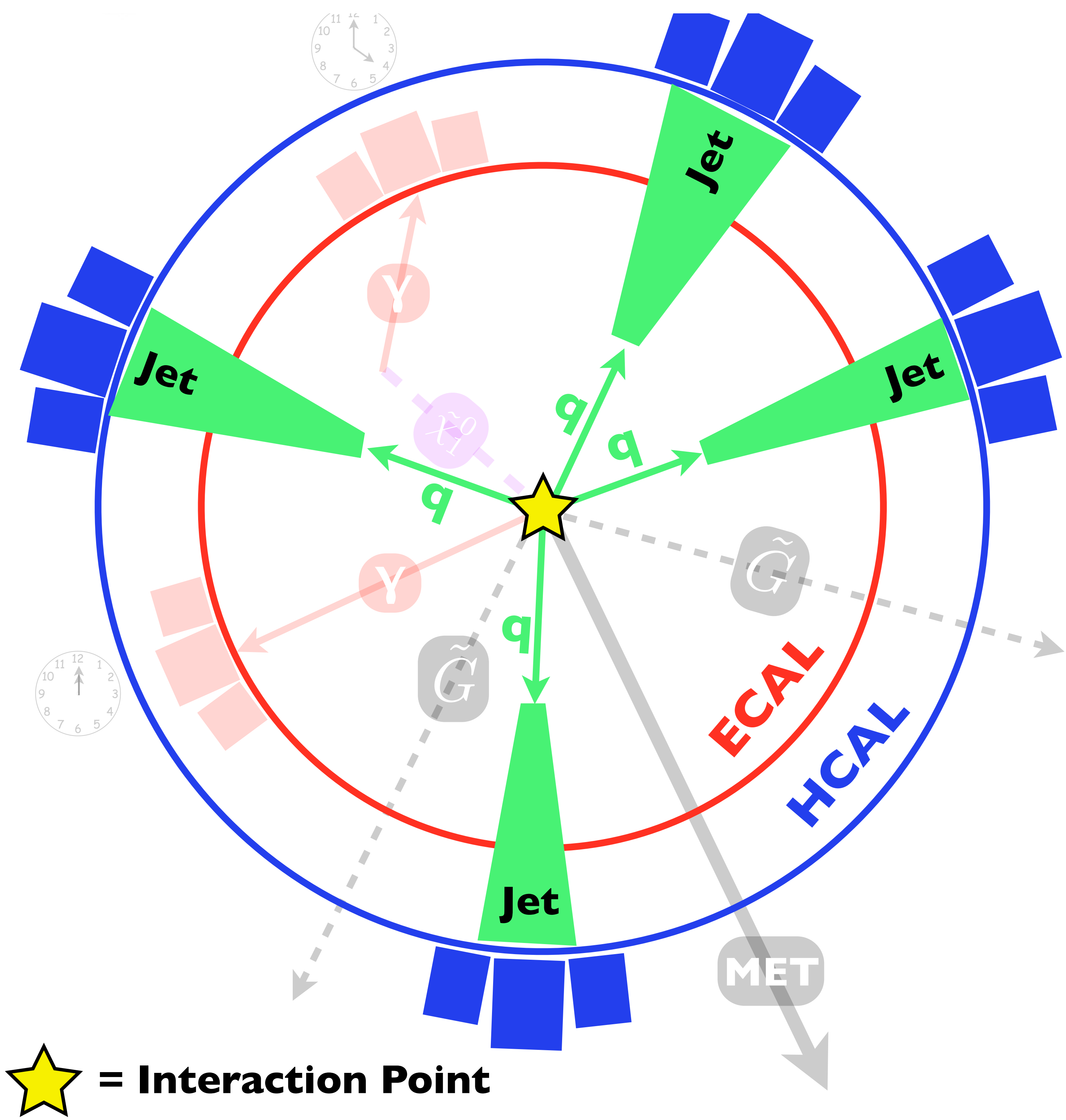
High P_T Photon(s) + MET + Jets

Neutralino lifetime depends on parameters of theory!

Search strategy must be sensitive to both scenarios



Experimental Signature



Two high-P_T γ
- ✓ $c\tau \sim 0 \Rightarrow$ in-time γ
- ✓ $c\tau > 0 \Rightarrow$ off-time γ

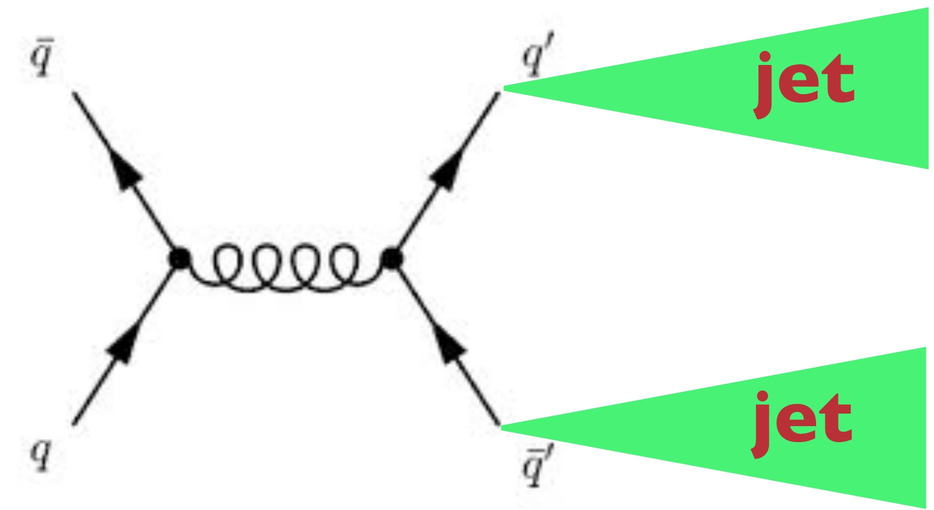
Two undetectable $\tilde{G}$
- ✓ Energy imbalance
- ✓ Missing E_T

Many high-P_T quarks
- ✓ High jet multiplicity

STANDARD MODEL BACKGROUND

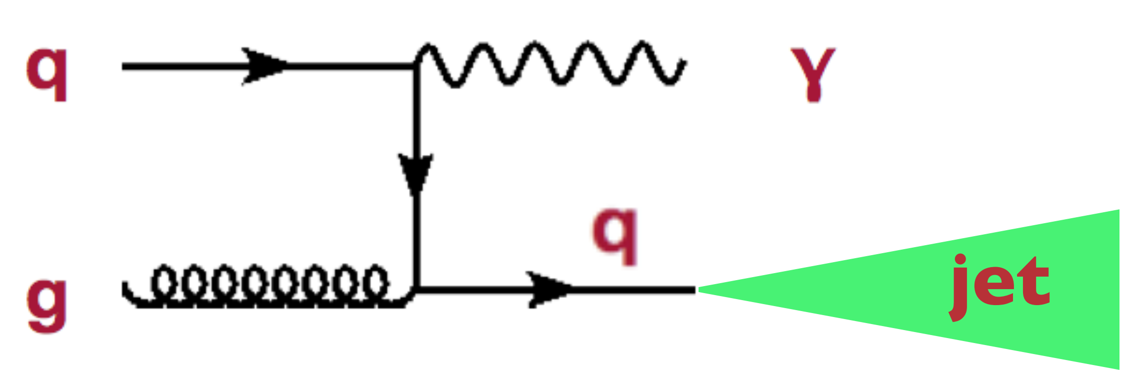
QCD events:
- ➡Large cross section
- ➡Fake photons from jets
- ➡Mis-identified MET

Rejected by γ isolation and MET



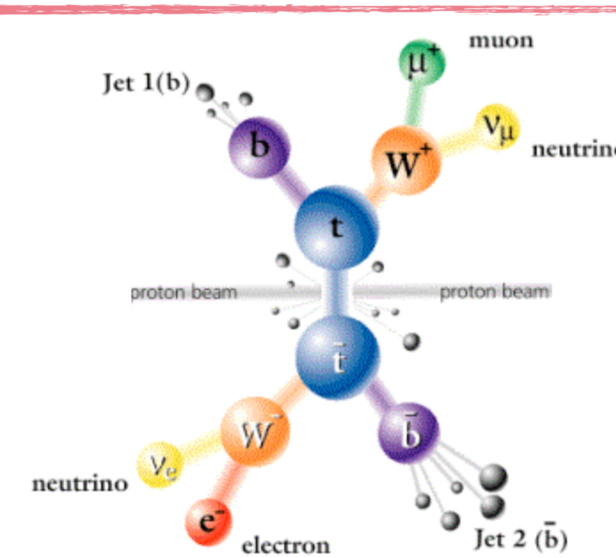
Photon+Jet:
- ➡Real photon in the final state
- ➡Mis-identified MET
- ➡Low jet multiplicity

Rejected by jet multiplicity



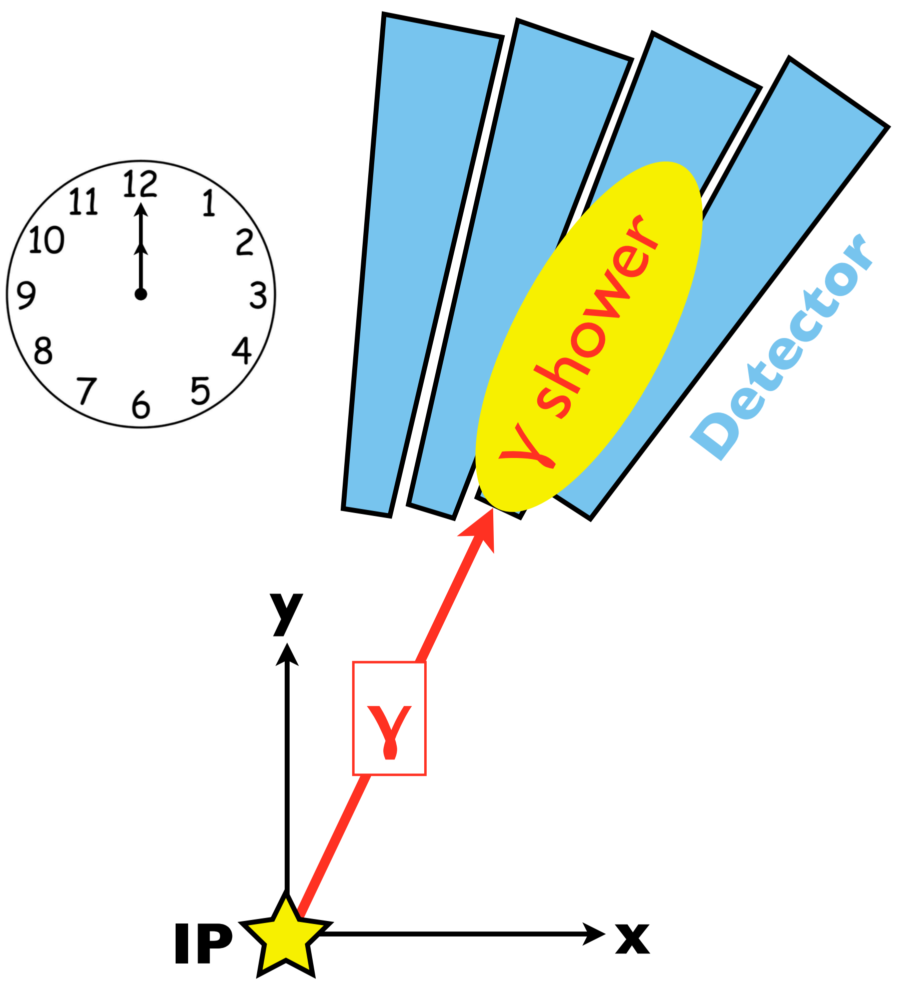
$t\,\bar{t}$ events:
- ➡Fake photons from electrons
- ➡Real MET from neutrinos
- ➡High jet multiplicity

Rejected by γ isolation



Impact of Neutralino Lifetime

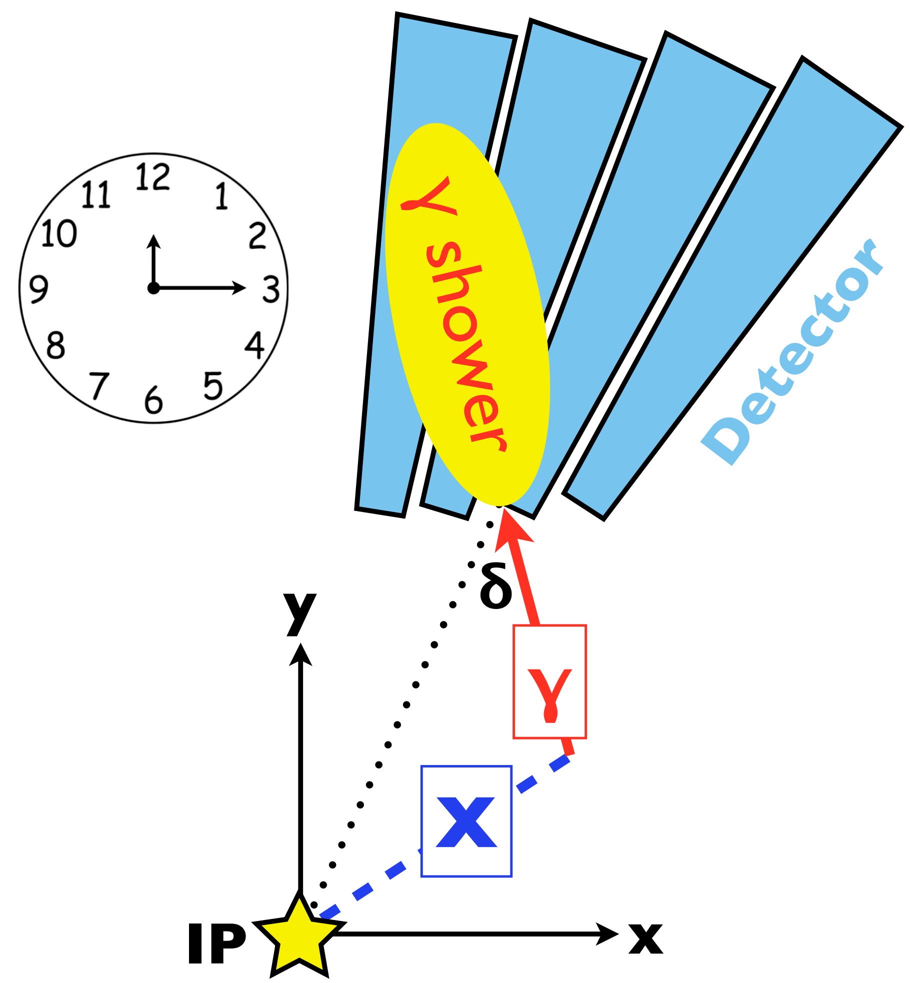
Zero lifetime



In-time photon

➡Arrival time compatible with that of a relativistic particle from the IP

Non-zero lifetime

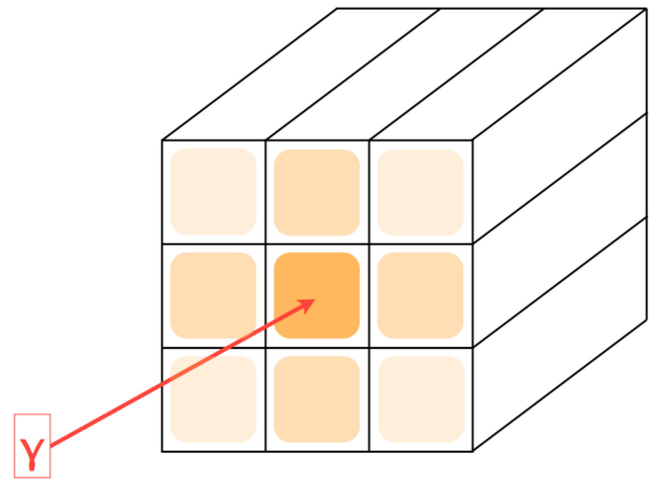


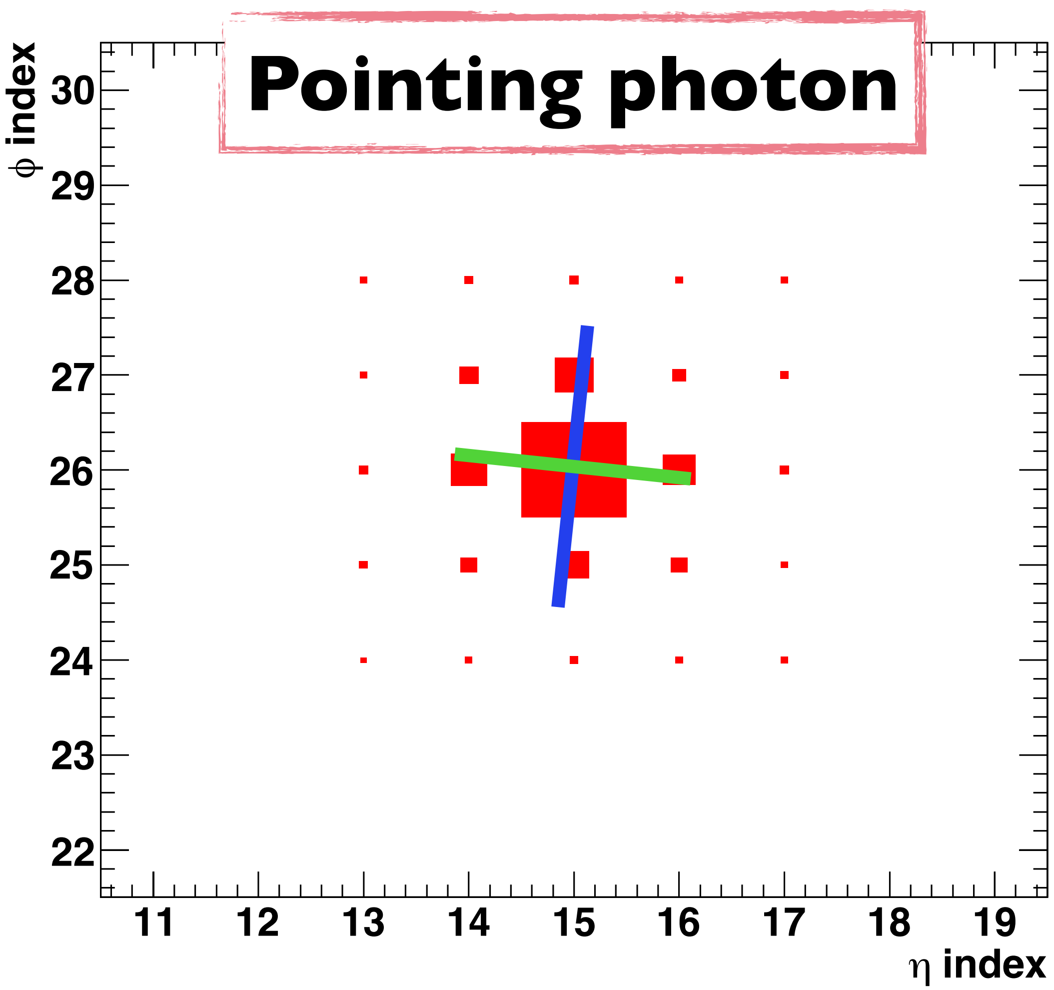
Off-time photon

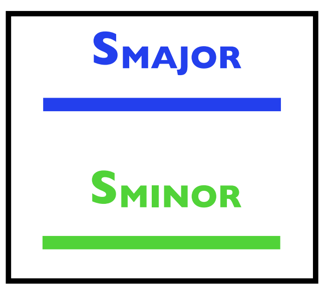
➡Arrival time sensibly increases with parent particle lifetime

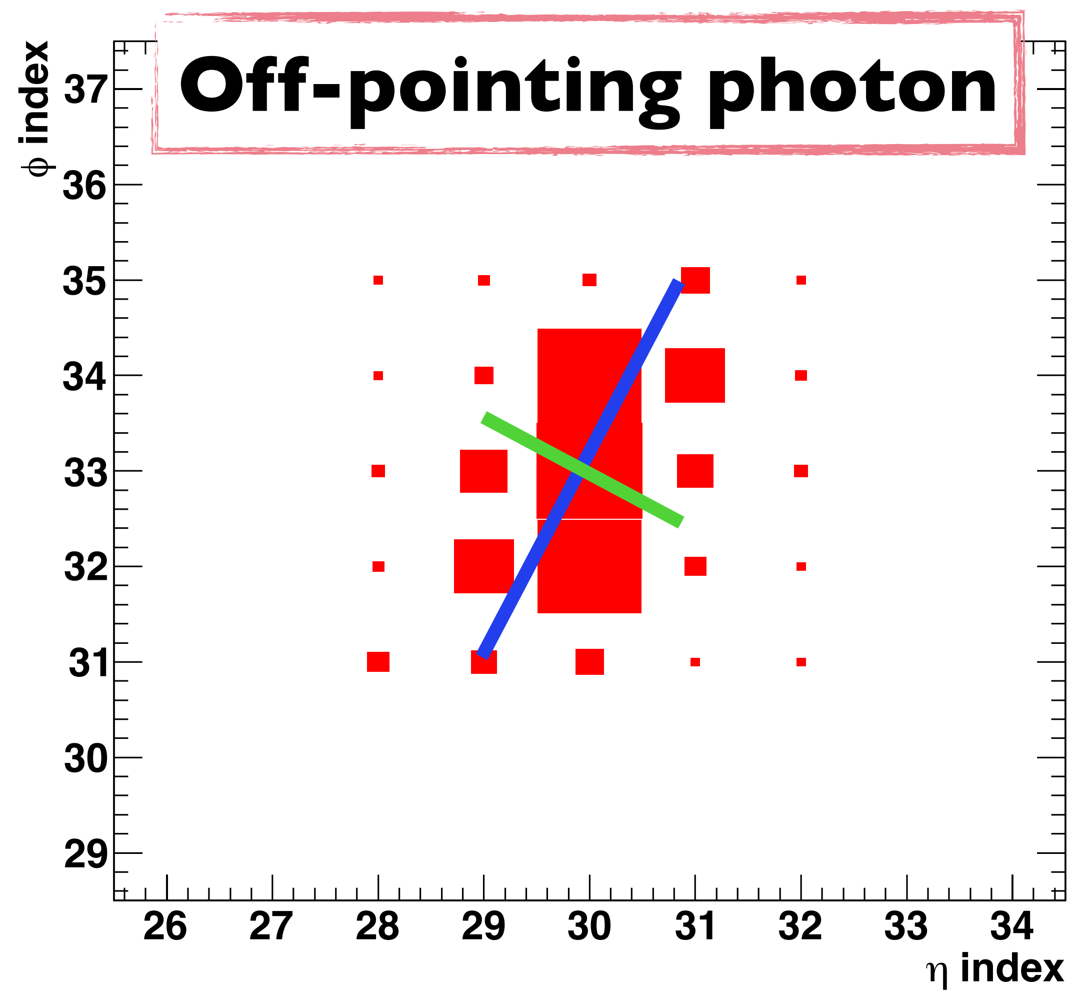
➡$\Delta T \sim O(ns)$

Shape of Photons in Calorimeter

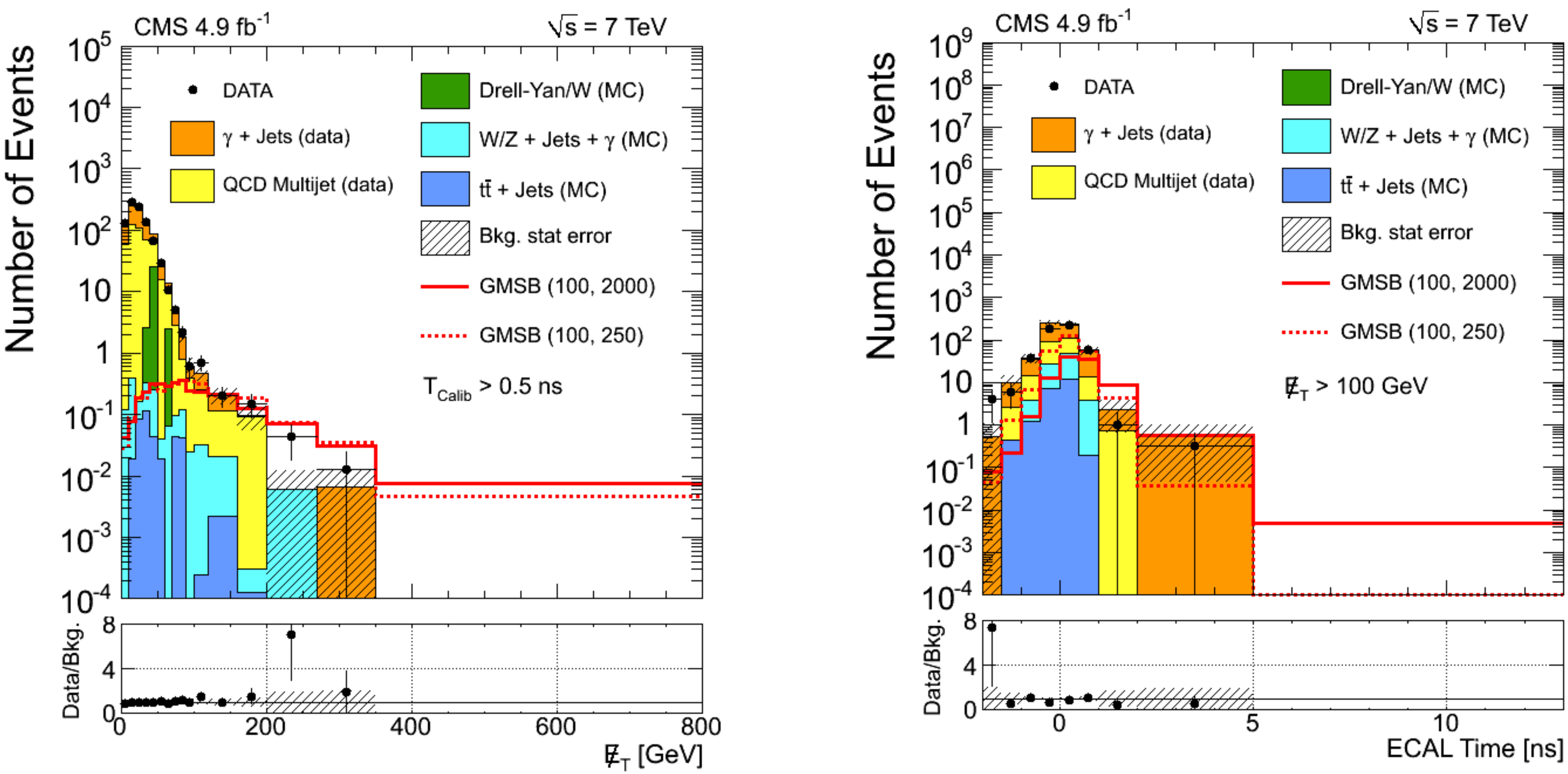






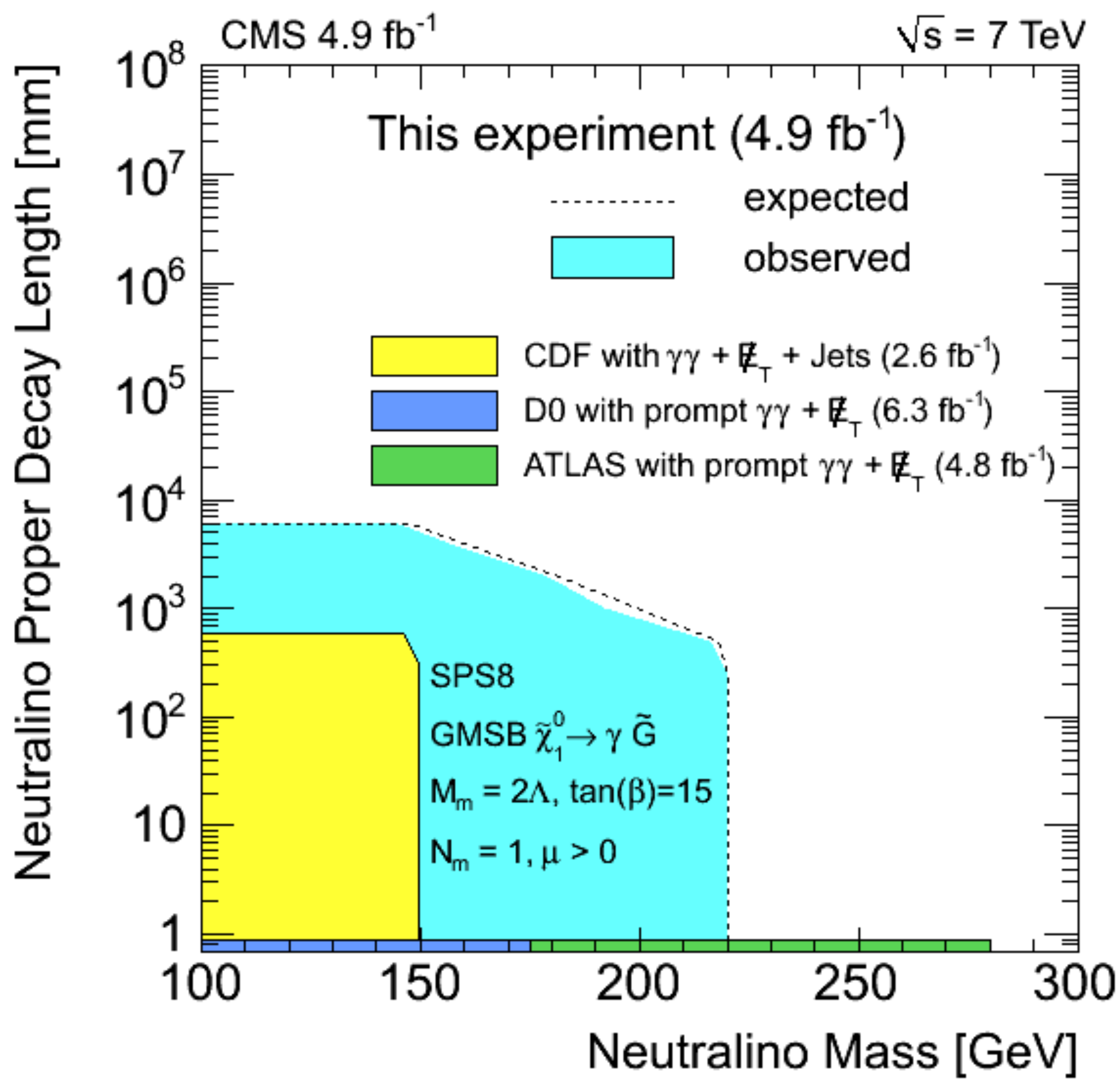


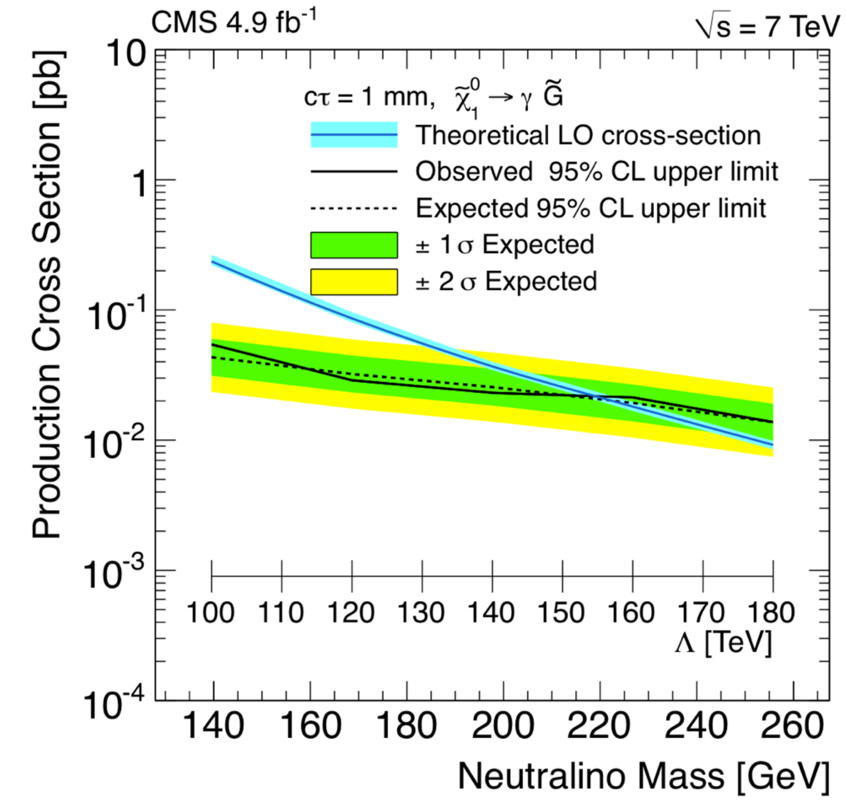
MISSING TRANSVERSE ENERGY

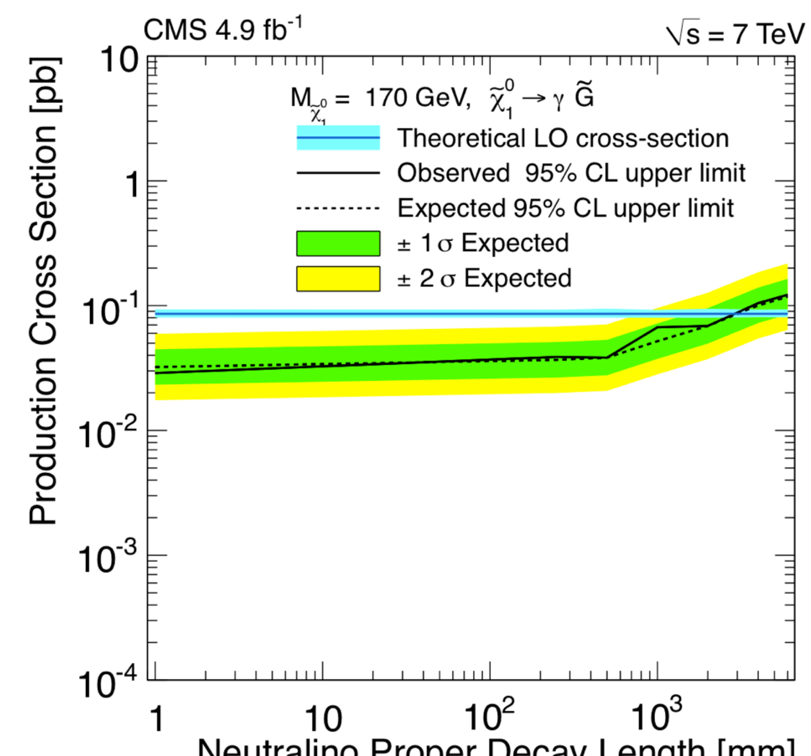


- Select events with at least 3 jets and isolated high p_T photon
- Low MET populated by SM while signal dominates at high MET

Exclusion Limits







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