Searches for New Physics at the Large Hadron Collider

Lecture 3: odd things

Scottish Universities Summer School in Physics, St. Andrews,
19 August – 1 September 2012

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Outline

- SUSY signatures with leptons; direct (EW) production of neutralinos & charginos
  - Charginos hiding in plain sight?
- Hiding SUSY ("exotic models")
  - Long lived particles (e.g., long-lived gluinos in split SUSY)
  - R-parity violating SUSY searches
- Large extra dimensions (monojets...)
- Black holes
- Conclusions

Exotica - from a review talk at ICHEP

Steve Worm – Searches for Physics Beyond the Standard Model, ICHEP

BSM SEARCHES @ LHC – NEW RESULTS

Heavy Resonance, Leptons

TeV-scale gravity l+j arXiv:1204.4646

Resonant WZ → lvll arXiv:1204.1648

b' to Zb ATLAS arXiv:1204.1265

Like-sign leptons ATLAS-CONF-2012-069

Z' to ττ ATLAS-CONF-2012-067

WW to lvlv ATLAS-CONF-2012-068

Monophoton ATLAS-CONF-2012-085

W' ATLAS-CONF-2012-086

Diphoton ATLAS-CONF-2012-087

μμ contact interact. CMS EXO-11-009

Boosted Z to μμ CMS EXO-11-025

e* CMS EXO-11-033

μ* CMS EXO-11-034

ADD in ee CMS EXO-12-013

Jet-based Searches

Monojet ATLAS-CONF-2012-084

b-jet resonances CMS EXO-11-008

Three-jet resonance CMS EXO-11-060

Dijet resonances CMS EXO-11-094

Boosted VV, Vjet CMS EXO-11-095

Lepton + Jets

LQ1 (eejj + evjj) CMS EXO-11-027

LQ2 (μμjj + μvjj) CMS EXO-11-028

Heavy Majorana N to ll EXO-11-076

VZ to l+jets CMS EXO-11-081

Heavy neutrino to μμjj EXO-11-091

RS Graviton in ZZ(2l2q) EXO-11-102

LQ3 -> τ+b CMS EXO-12-002

Long-Lived

Monopole ATLAS-CONF-2012-062

SUSY R-Hadron ATLAS-CONF-2012-075

Displaced μ jets ATLAS-CONF-2012-089

Non prompt lepton jets in HV decays ATLAS-CONF-2012-110

Stopped HSCP CMS EXO-11-020

Displaced photons CMS EXO-11-035

Fractionally charged CMS EXO-11-074

Multiply charged CMS EXO-11-090

Long-lived to displaced lep EXO-11-101

Top, 4th Gen and Boosted

Z' to ttbar l+j ATLAS arXiv:1205.5371

Z' to ttbar l+j boosted ATLAS-TOPQ-2011-23

t+b resonance ATLAS arXiv:1205.1016

t+j resonance ATLAS-CONF-2012-096

W' to top pair + jet CMS EXO-11-056

B to bZ CMS EXO-11-066

Z' to ttbar in l+jets CMS EXO-11-093

b'/t' inclusive CMS EXO-11-098

W' to tb CMS EXO-12-001

8 TeV Searches

Dijet 8 TeV ATLAS-CONF-2012-088

Black holes in 8 TeV CMS EXO-12-009

W' in 8 TeV CMS EXO-12-010

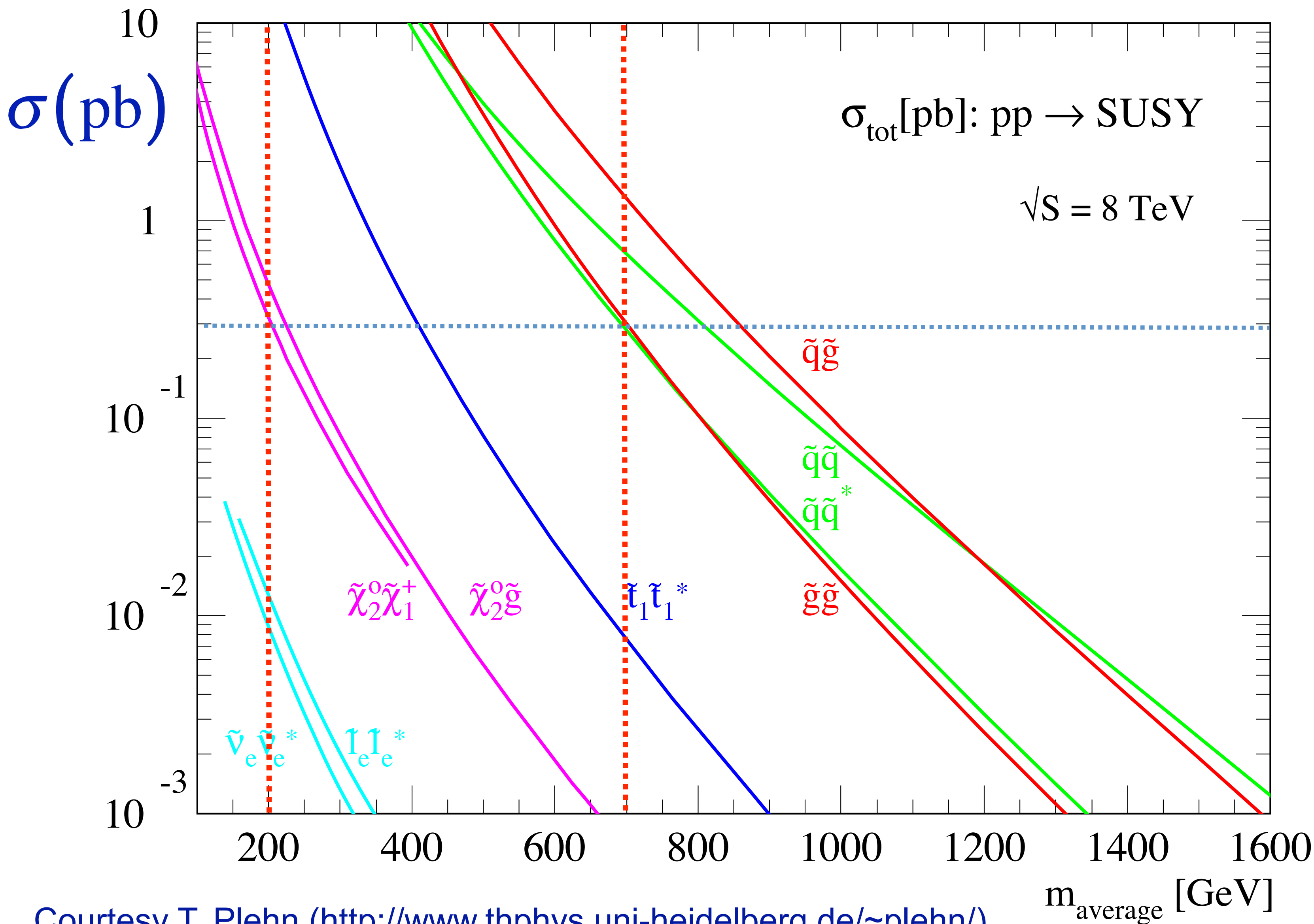
Z' in 8 TeV CMS EXO-12-015

Dijet in 8 TeV CMS EXO-12-016

Heavy neutrino 8 TeV EXO-12-017

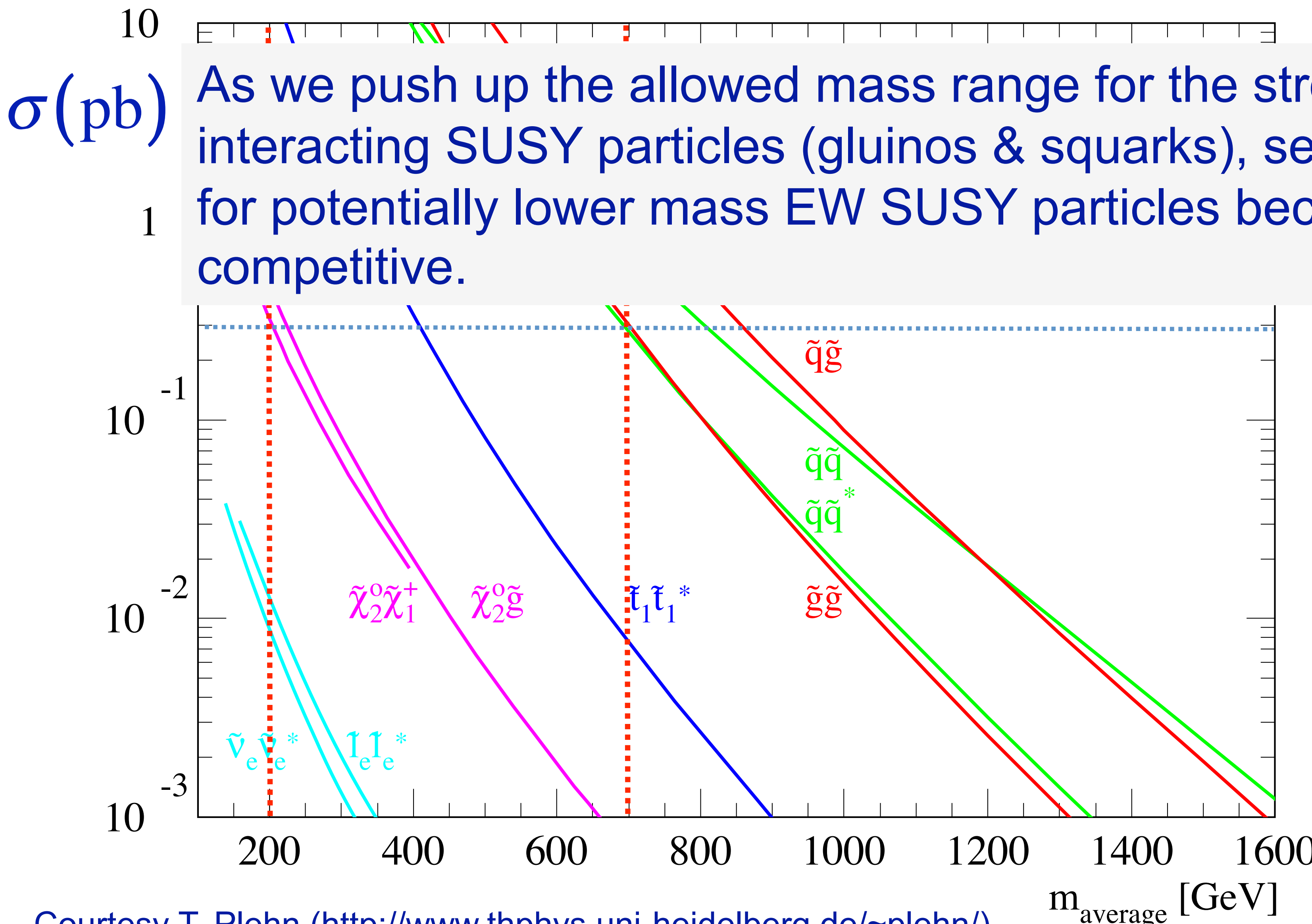
Several key topics covered in other talks at this school (e.g., SM physics): dijet mass & angular distrib, Z' → l+l-, ttbar

Thinking about EW production (√s=8 TeV)



Courtesy T. Plehn (http://www.thphys.uni-heidelberg.de/~plehn/)

Thinking about EW production (√s=8 TeV)

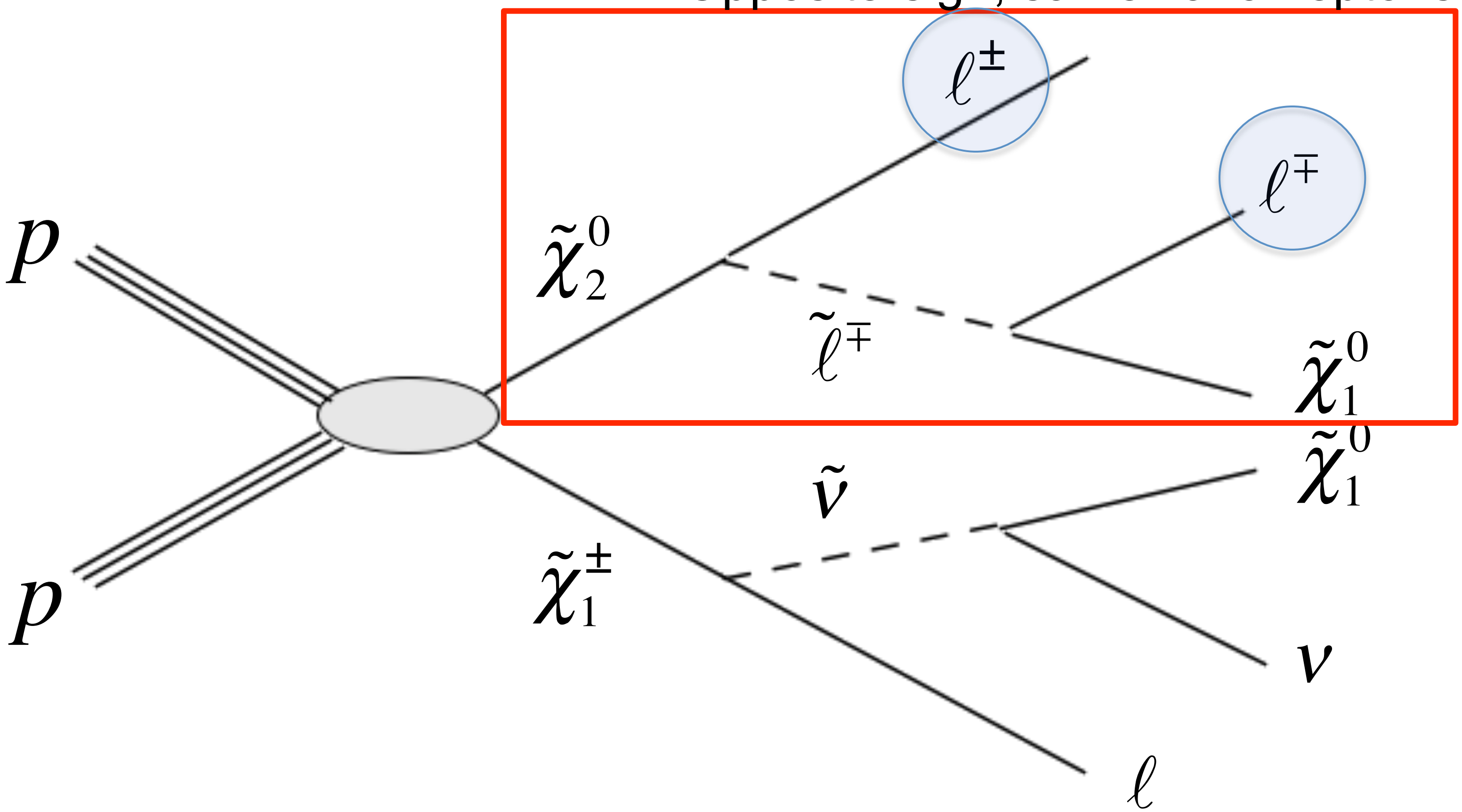


As we push up the allowed mass range for the strongly interacting SUSY particles (gluinos & squarks), searches for potentially lower mass EW SUSY particles become competitive.

Courtesy T. Plehn (http://www.thphys.uni-heidelberg.de/~plehn/)

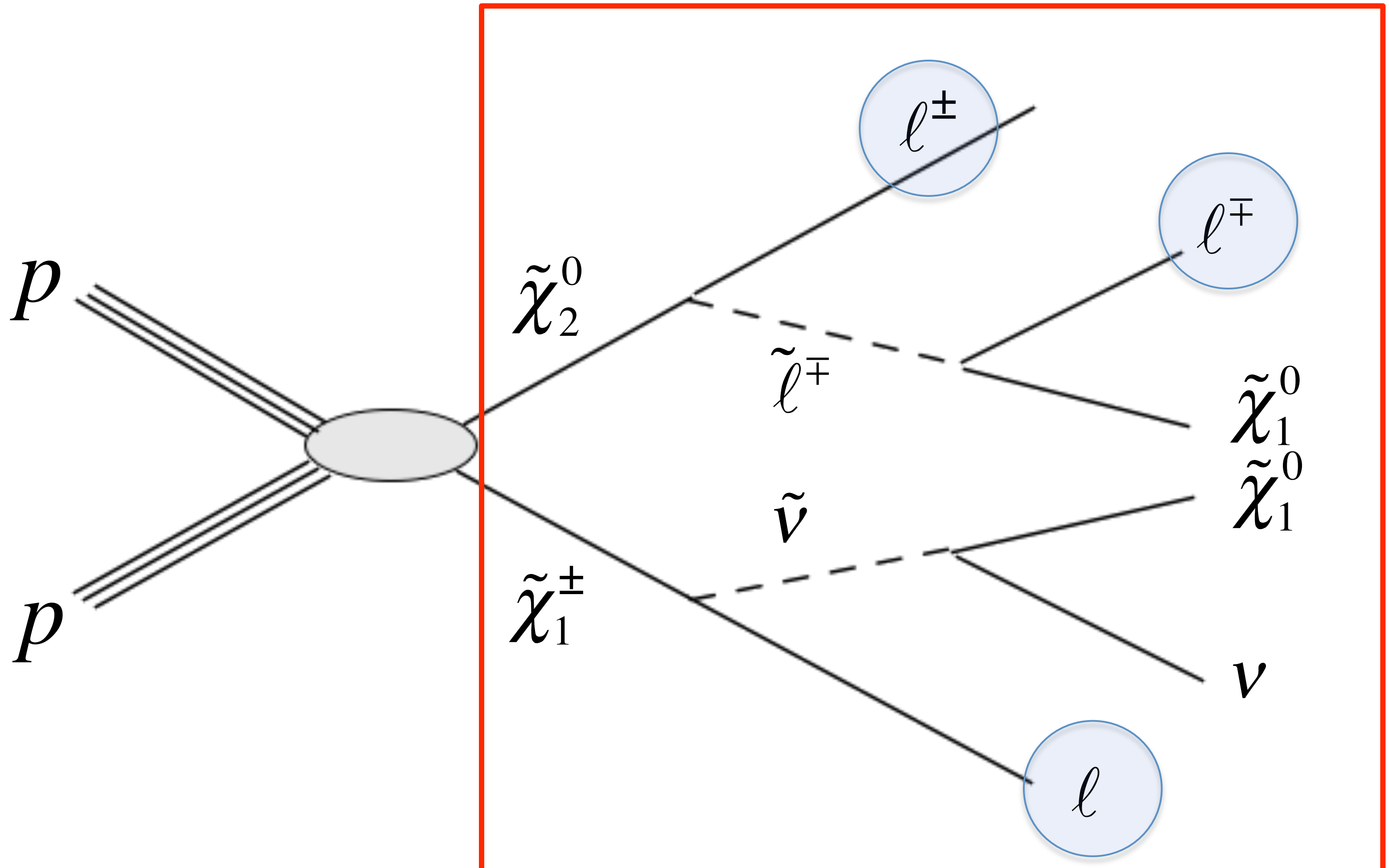
The famous neutralino dilepton cascade

Opposite-sign, same flavor leptons



The $\tilde{\chi}_2^0$ can be produced in any process, not just direct EW production.

The famous SUSY trilepton signature



The $\tilde{\chi}_2^0$ can be produced in any process, not just direct EW production. Extensive searches for trilepton signatures, including tau leptons.

For amusement...

http://arxiv.org/abs/1206.6888

Charginos Hiding In Plain Sight

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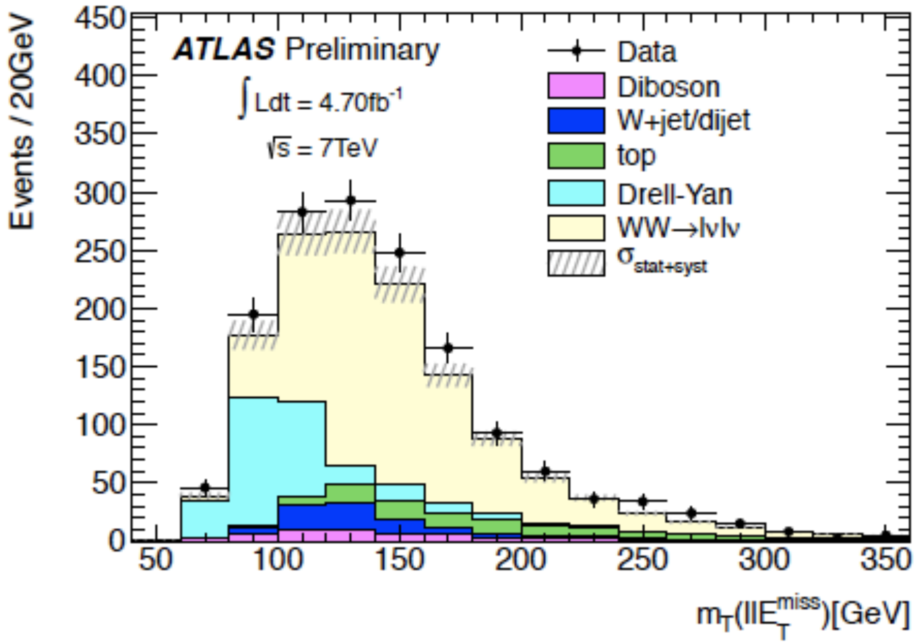
[2] *Department of Physics, Brookhaven National Laboratory, Upton, NY 11973, USA*

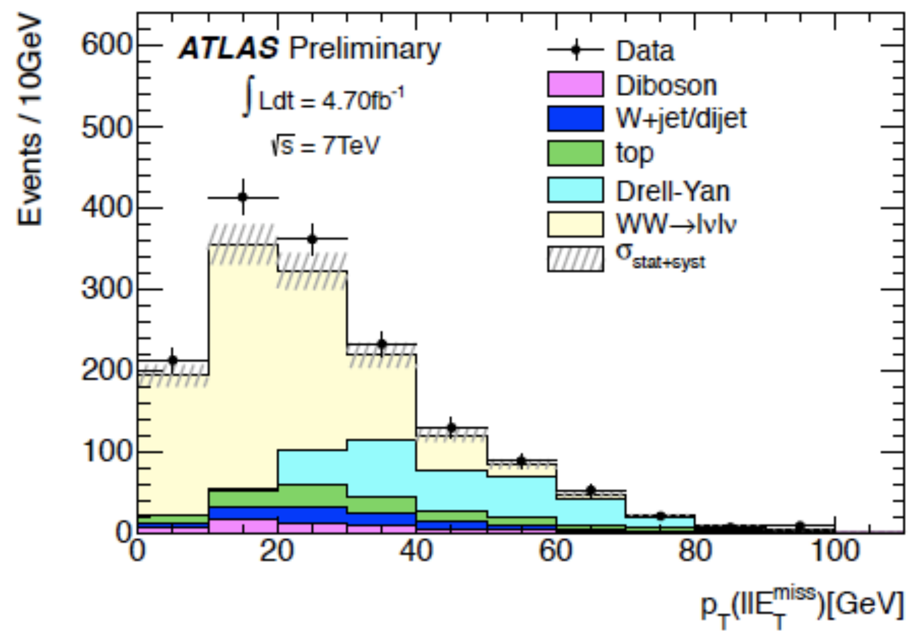
Recent 5/fb measurements by ATLAS and CMS have measured both overall and differential W^+W^- cross sections that differ from NLO SM predictions. While these measurements aren't statistically significant enough to rule out the SM, we demonstrate that the data from both experiments can be better fit with the inclusion of electroweak gauginos with masses of $\mathcal{O}(100)$ GeV. These new states can also provide a better fit for SM $W^\pm Z$ measurements. We show that these new states are consistent with other experimental searches/measurements and have ramifications for Higgs phenomenology.

	ATLAS: σ(pb)	CMS: σ(pb)
Measured cross sec.	53.4 ±2.1± 4.5± 2.1	52.4 ±2.0 ±4.5± 1.2
Theory cross sec. NLO	45.1±2.8	47.0±2.0

pp→W$^+$W$^-$ kinematic distributions

http://cdsweb.cern.ch/record/1430734/files/ATLAS-CONF-2012-025.pdf

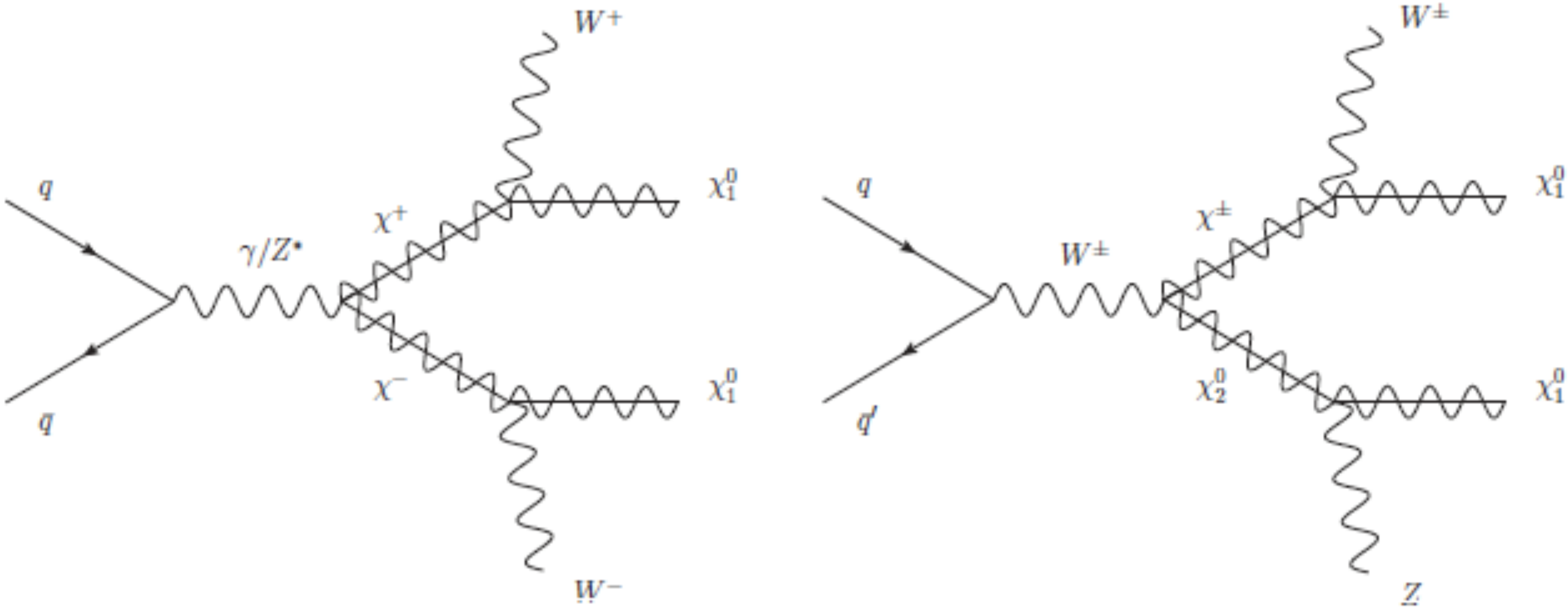




Main selection requirements

- Opposite-sign dileptons (ee, emu, mumu), leading lepton pT>25 GeV
- No additional leptons
- Exclude Z mass window (±15 GeV) for same flavor leptons
- No jets with pT > 25 GeV (suppresses ttbar); no b-jets pT>20 GeV
- ETmiss_Rel > 25 -55 GeV

EWK SUSY can contribute a "background" to pp → W^+W^-



parameters used for plots

$$m(\tilde{\chi}_1^\pm) \approx 112 \text{ GeV} \qquad \tan\beta = 10$$

$$m(\tilde{\chi}_1^0) \approx 15 \text{ GeV} \qquad \sigma(pp \to \tilde{\chi}_1^+ \tilde{\chi}_1^-) = 2.8 \text{ pb}$$

Excess in the W^+W^- cross section?

http://arxiv.org/abs/1206.6888

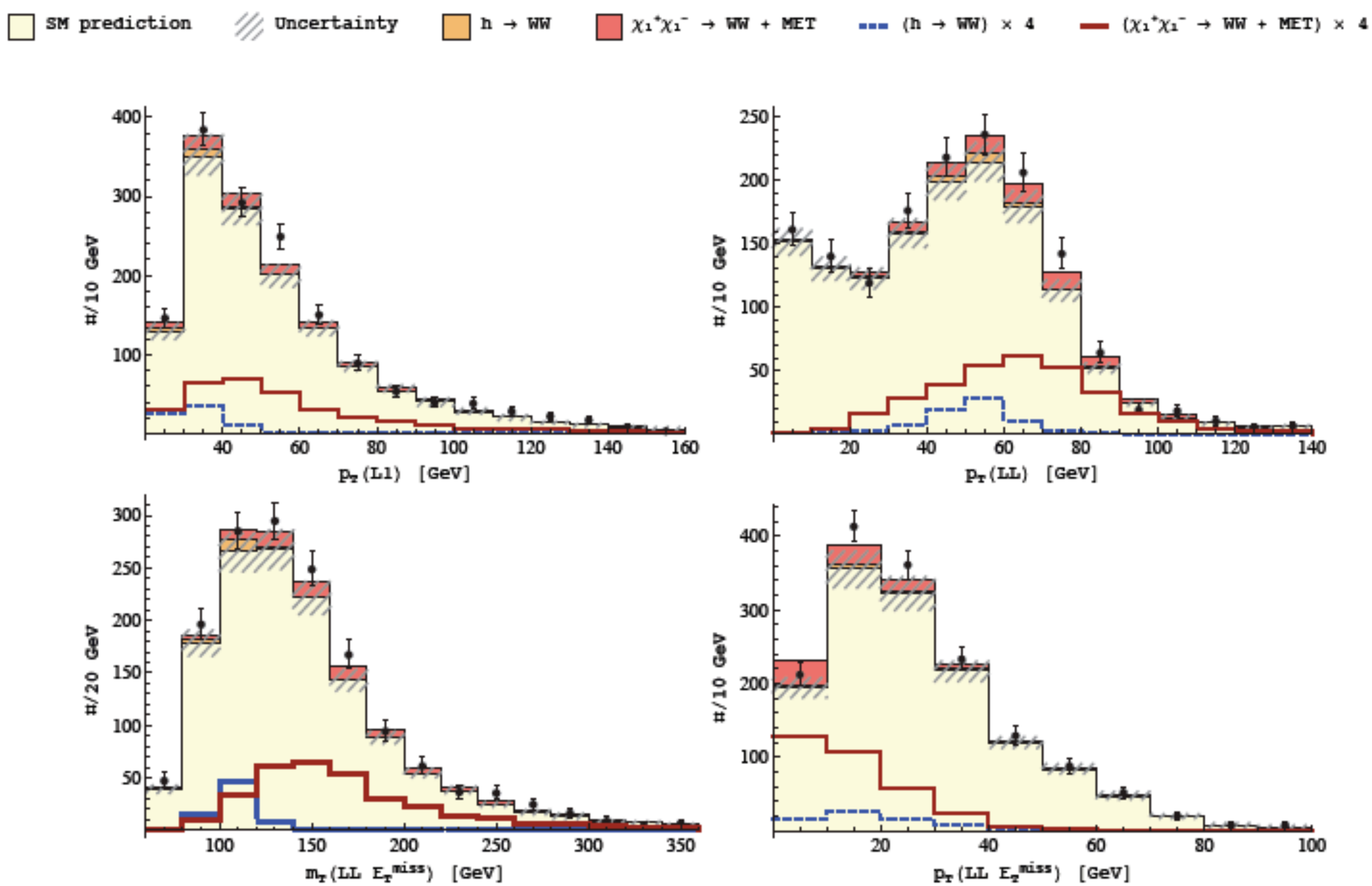


FIG. 2: The total SM prediction (signal + background) from the ATLAS W^+W^- study [1], with additional contributions from a 125 GeV SM higgs and chargino pair production in the best-fit gravity mediated scenario ($m_{\tilde{\chi}_1^+}, m_{\tilde{\chi}_1^0} = 112, 15$ GeV) shown. The gray bands represent the uncertainty of the SM prediction.

What does it mean?

I have no idea. First of all, it is a modest effect relative to the uncertainties.

Lots of reasons this could have nothing whatsoever to do with an additional physics process in the data.

But it does show that we have to be very careful about SUSY...it might appear in places that we are not expecting. We also have to be careful about our control samples.

wise there would be an obvious discrepancy. While it is quite probable that the discrepancies in the total cross section and differential distributions are due to insufficient background modeling, we demonstrate that SM NLO W^+W^- combined with the inclusion of new EW processes fits the data significantly better than the SM alone.

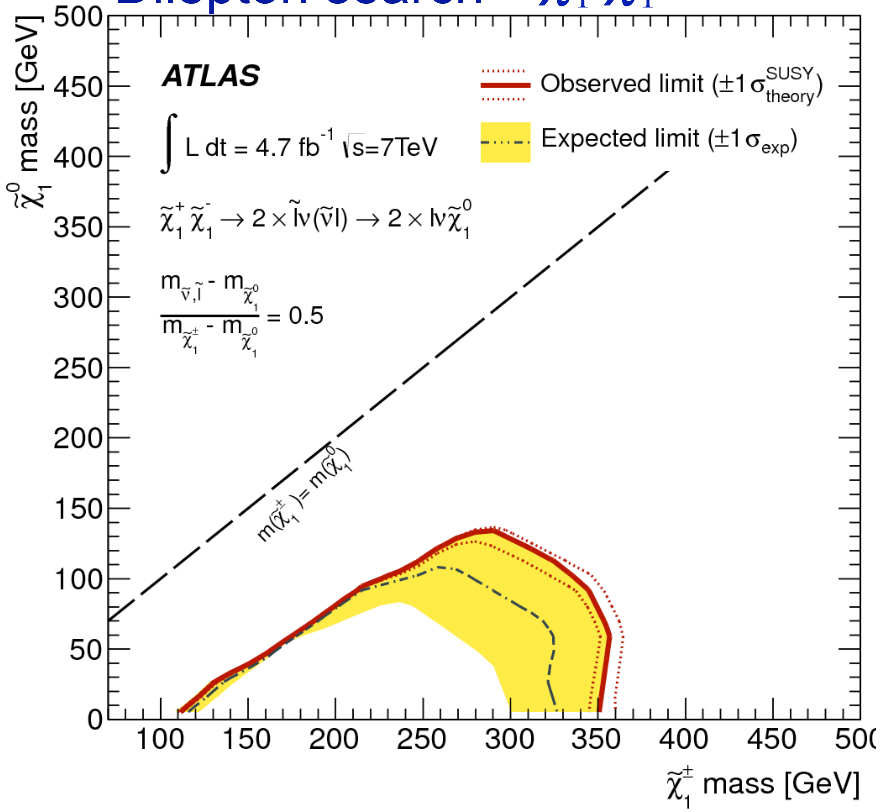
Direct gaugino searches (ATLAS, 7 TeV)

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2011-23/

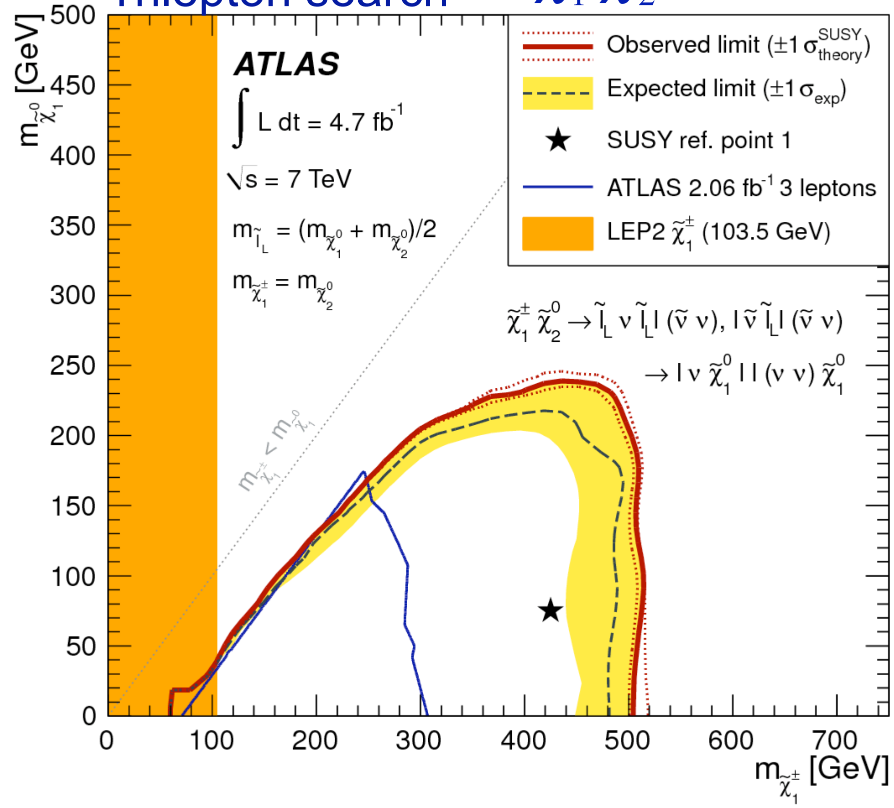
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2012-13/

- Combination of 2-lepton and 3-lepton searches for leptons produced in cascades starting from $\tilde{\chi}_1^+\tilde{\chi}_2^0$, $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\ell}^+\tilde{\ell}^-$ production.

Dilepton search $\tilde{\chi}_1^+\tilde{\chi}_1^-$



Trilepton search $\tilde{\chi}_1^+\tilde{\chi}_2^0$

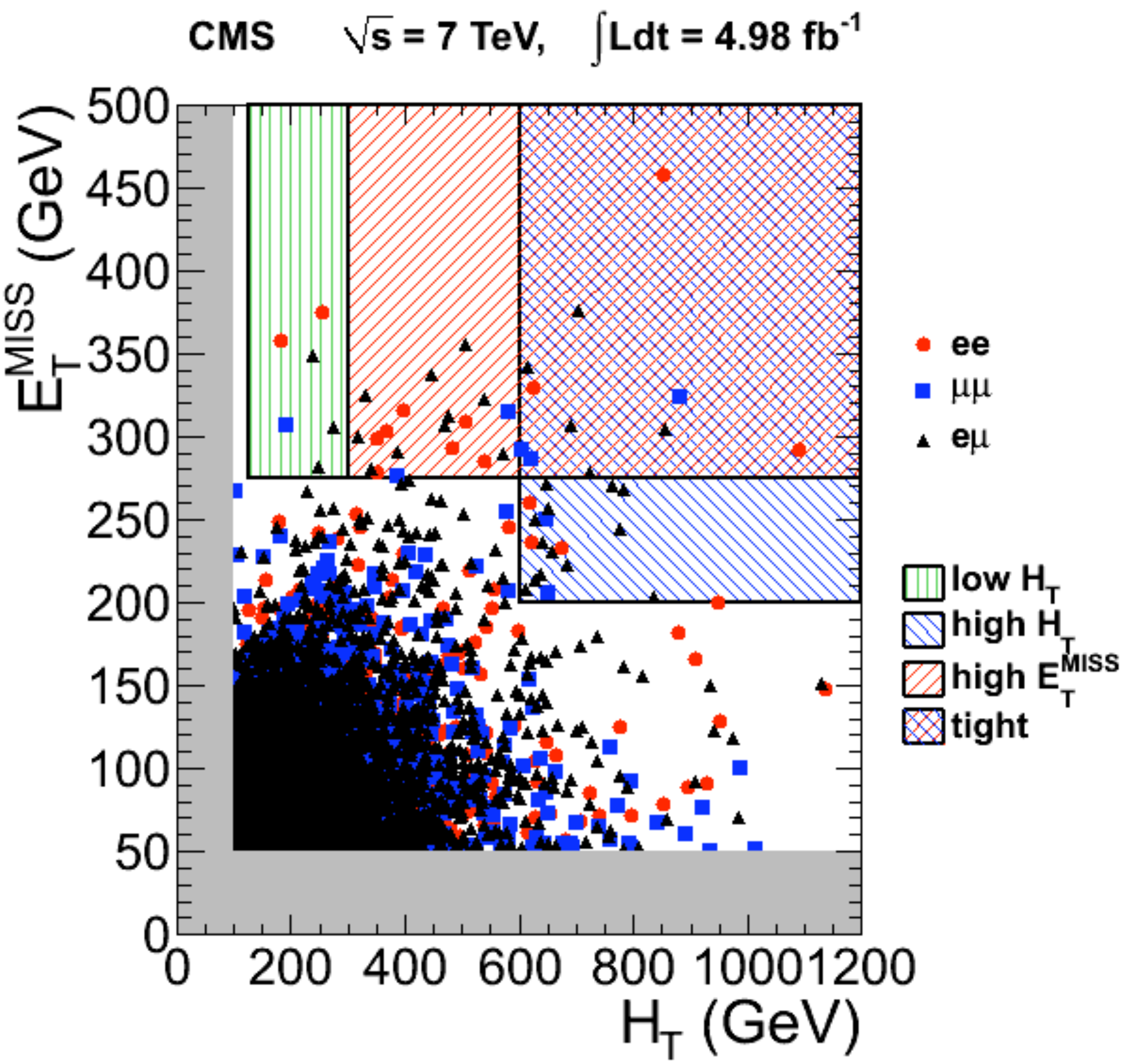


Opposite-sign dileptons + jets + MET

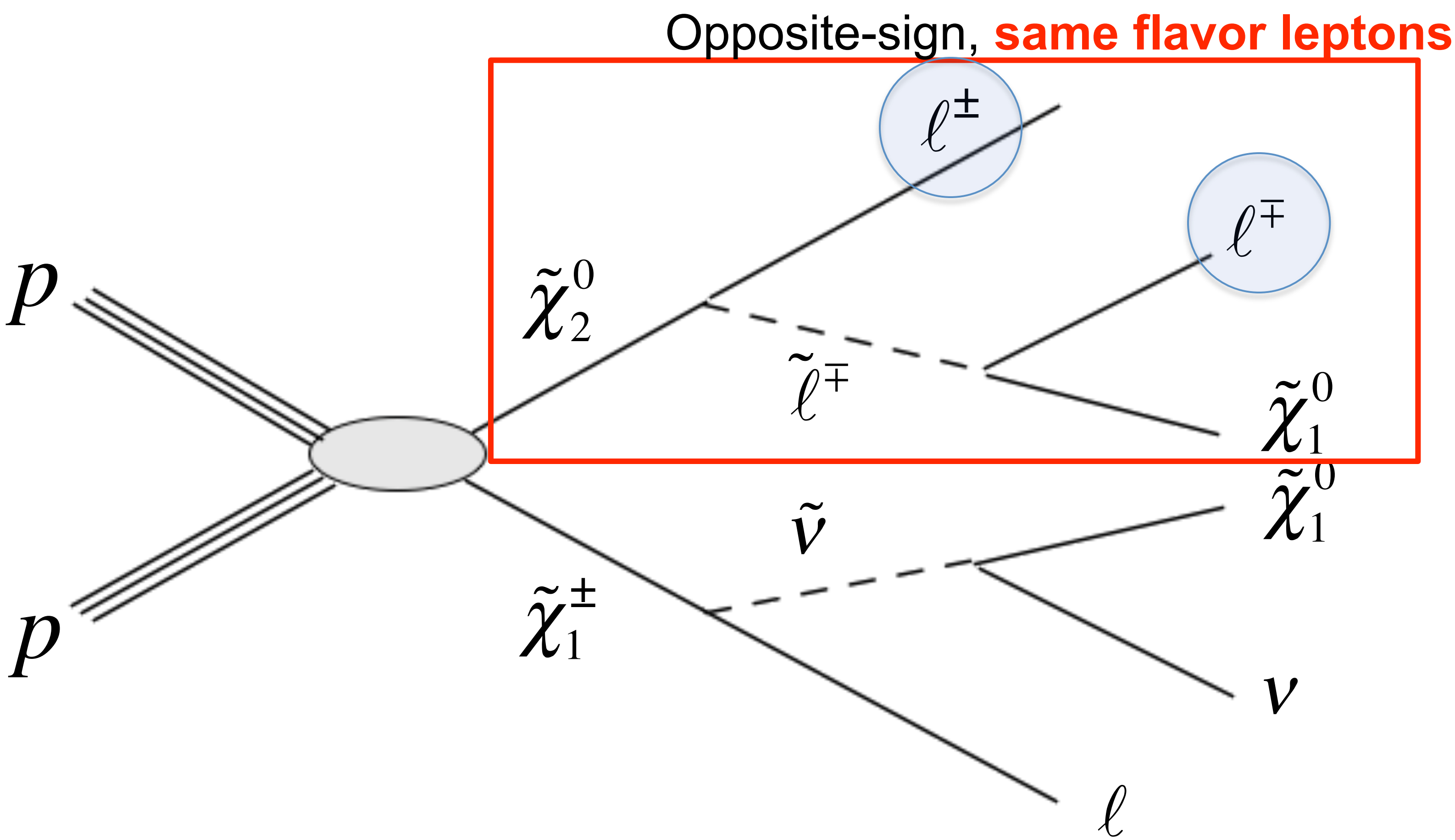
CMS SUS-11-011 http://arxiv.org/abs/arXiv:1206.3949

Event selection

- 2 opp-sign leptons
- ee, μμ, eμ (control)
- eτ, μτ (sep cuts)
- ≥2 jets, pT>30 GeV
- pT(lep 1)>20 GeV
- pT(lep 2)>10 GeV
- HT>100 GeV, MET>50 GeV
- Z veto region
-



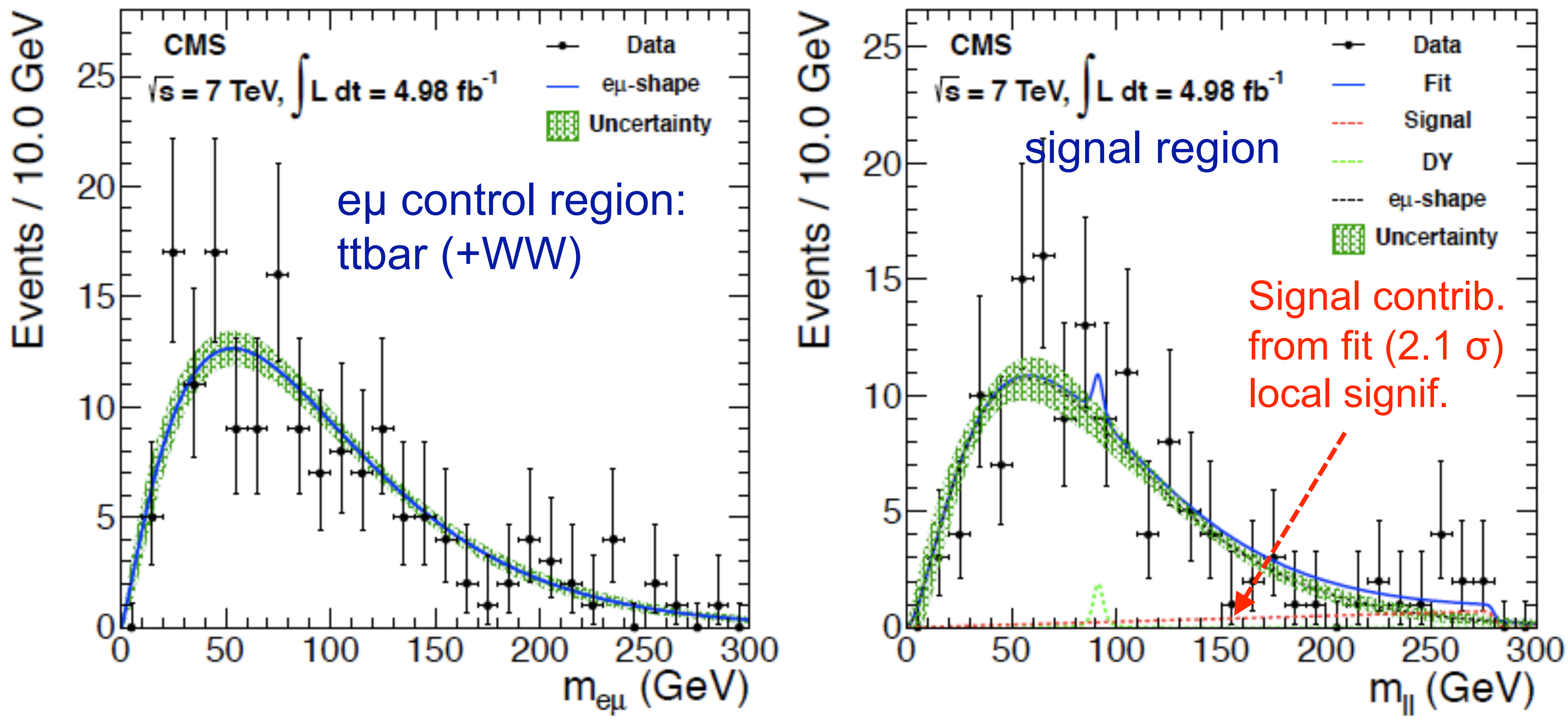
The famous neutralino dilepton cascade



The dominant background (ttbar) produces different flavor leptons as well → use eμ control sample!

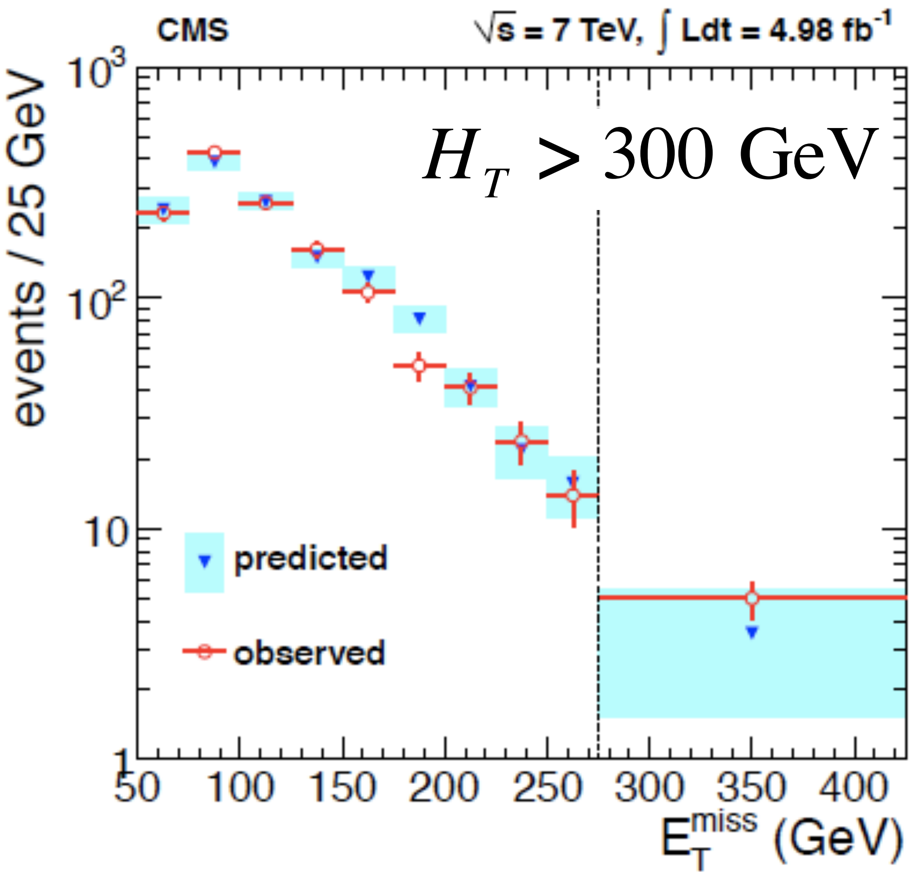
Opposite-sign dileptons: $m(l^+l^-)$

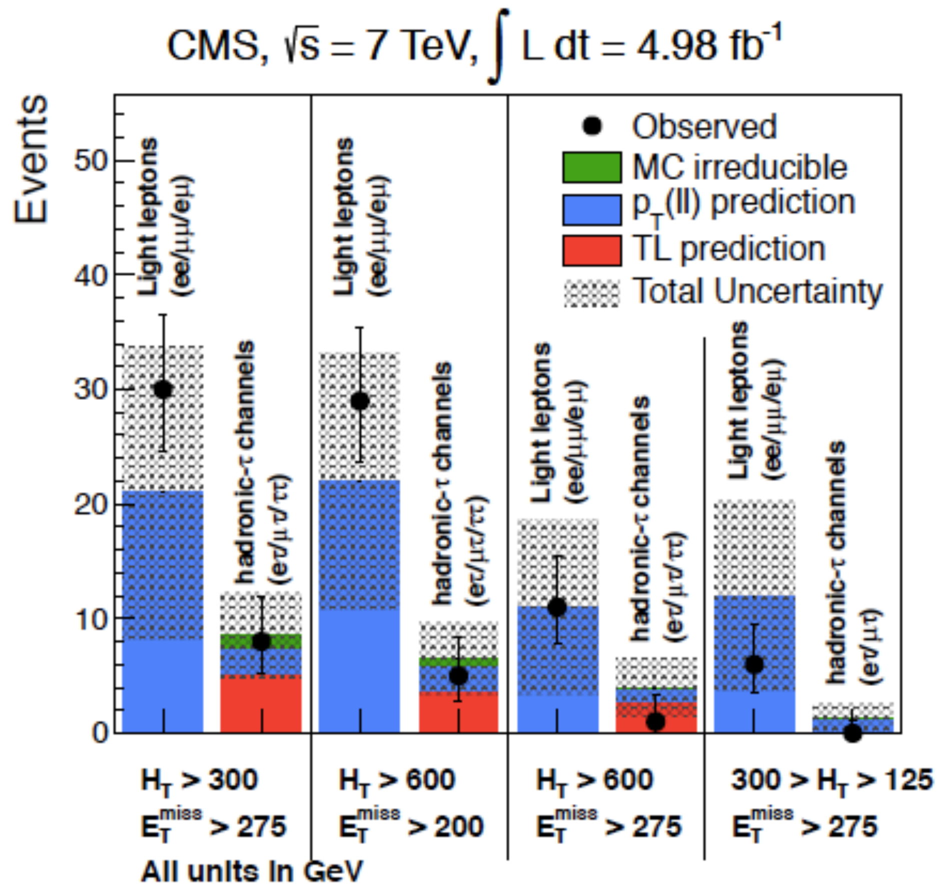
Fit signal and control regions jointly to shapes describing ttbar + DY + signal (smeared triangle).



Signal shape reflects kinematics of sequential two-body decay (m_{max}=280 GeV)

Opposite-sign dileptons: MET prediction



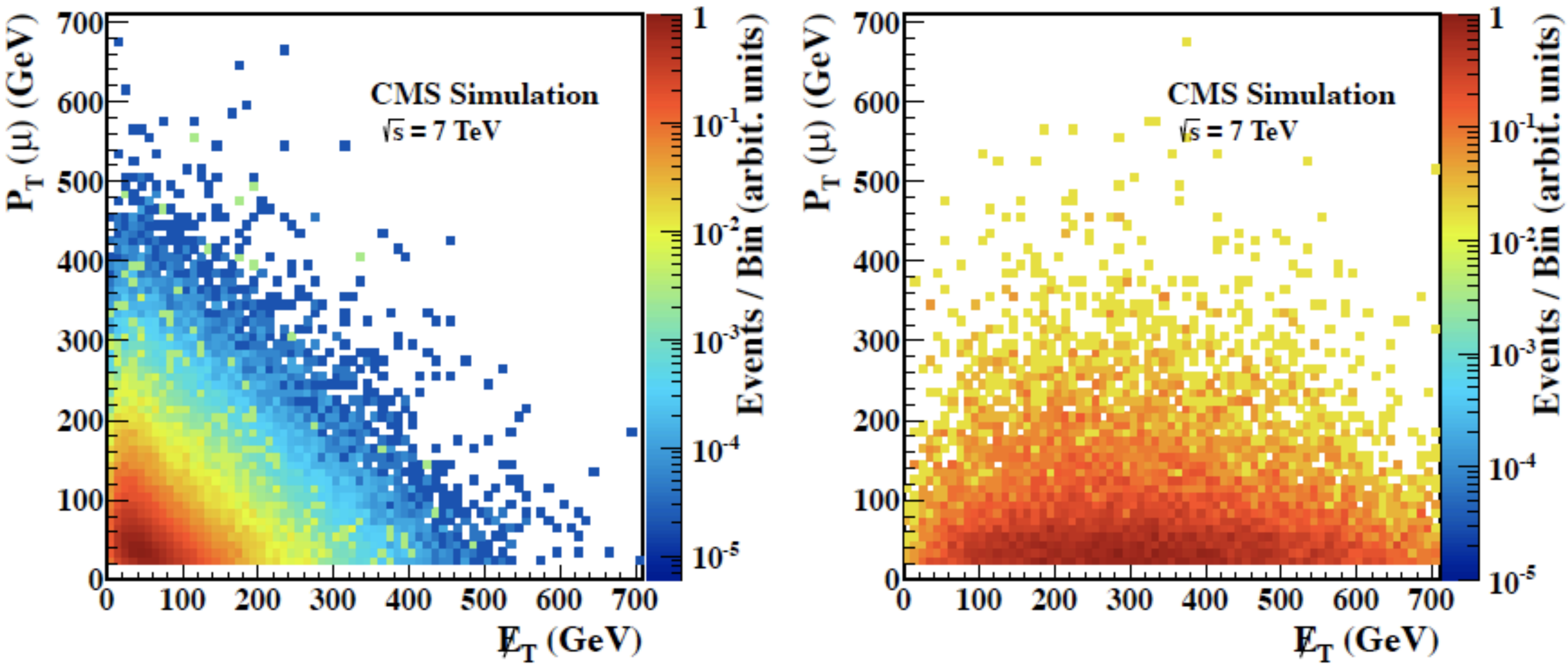


In SM events, can use lepton spectrum to predict the MET spectrum! In general need suitable corrections for W polarization in W+jets and ttbar, as well as resolution and threshold effects.

Using the lepton spectrum to predict MET in single-lepton events

CMS-PAS-SUS-12-010 http://cdsweb.cern.ch/record/1445275

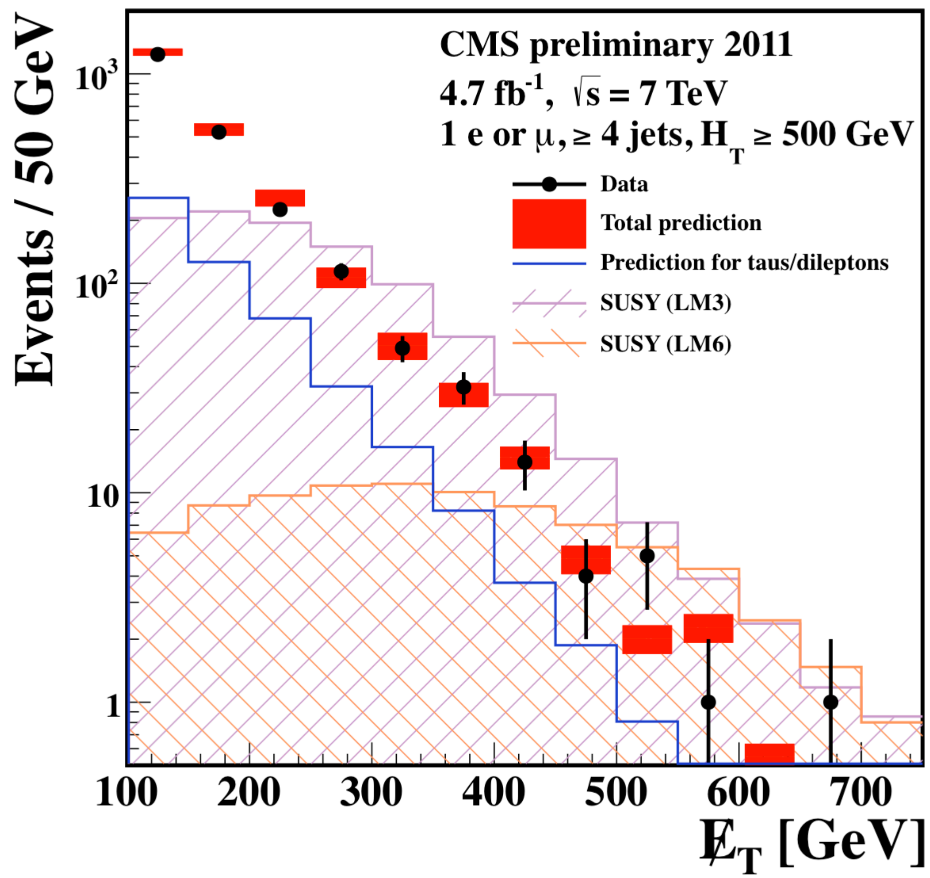
- In ttbar and W+jets events, the lepton & neutrino are produced together in W decay.
- In many SUSY models the lepton and MET are decoupled.

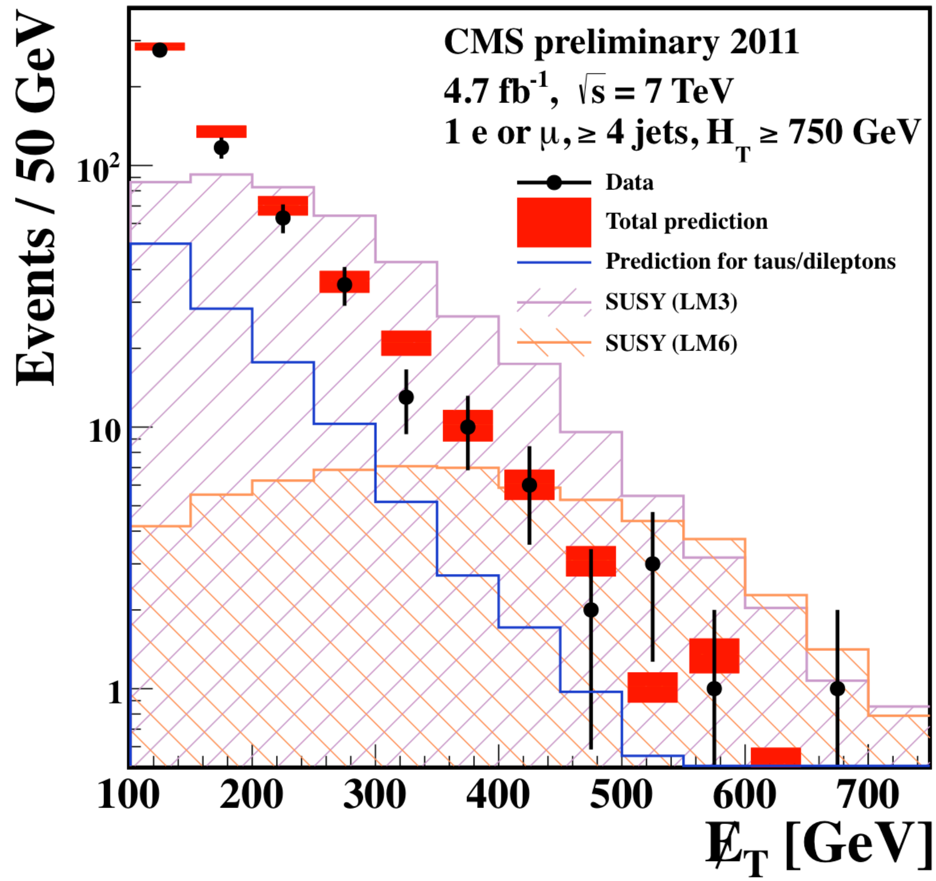


Using the lepton spectrum to predict MET in single-lepton events

CMS-PAS-SUS-12-010 http://cdsweb.cern.ch/record/1445275

- The MET distribution for SM events is dominated by ttbar and W+jets.
- The MET is dominated by the neutrino.
- The neutrino spectrum can be predicted from the lepton spectrum, taking into account W polarization in both cases! MET resolution also included.





Search for long-lived, stopping particles

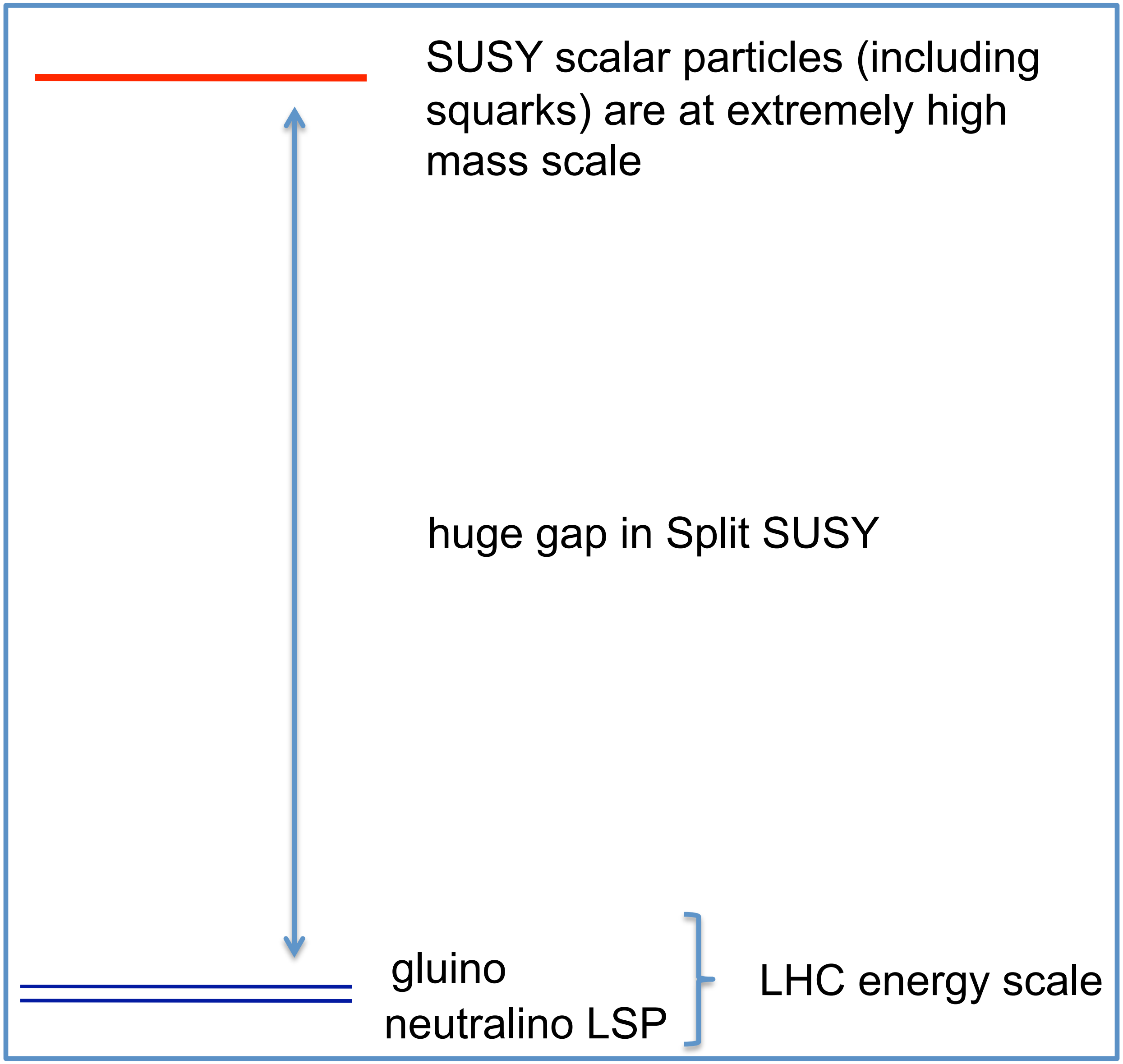
- Imagine a particle that lives long enough that it does not decay during the beam crossing interval when it was produced, but stops in the detector!
- It decays (asynchronously to beam X-ing.)
- Such particles are predicted in several models.
- Do we even trigger on events like this?
- "If it didn't trigger, it didn't happen."
  - or it might as well not have happened...

Search for long-lived, stopping particles

Some references

- M. J. Strassler and K. M. Zurek, "Echoes of a hidden valley at hadron colliders", Phys. Lett. B **651 (2007) 374,** arXiv:hep-ph/0604261.
- N. Arkani-Hamed and S. Dimopoulos, "Supersymmetric unification without low energy supersymmetry and signatures for fine-tuning at the LHC", JHEP **06 (2005) 073,** arXiv:hep-th/0405159.
- P. Gambino, G. F. Giudice, and P. Slavich, "Gluino decays in split supersymmetry", Nucl. Phys. B **726 (2005) 35,** arXiv:hep-ph/0506214.
- R. Mackeprang and A. Rizzi, "Interactions of coloured heavy stable particles in matter", Eur. Phys. J. C **50 (2007) 353,** arXiv:hep-ph/0612161.

Example scenario: split SUSY



Compare with lifetime of free neutron!

$$\tilde{g} \to g\tilde{\chi}_1^0 \text{ (via loops)}$$

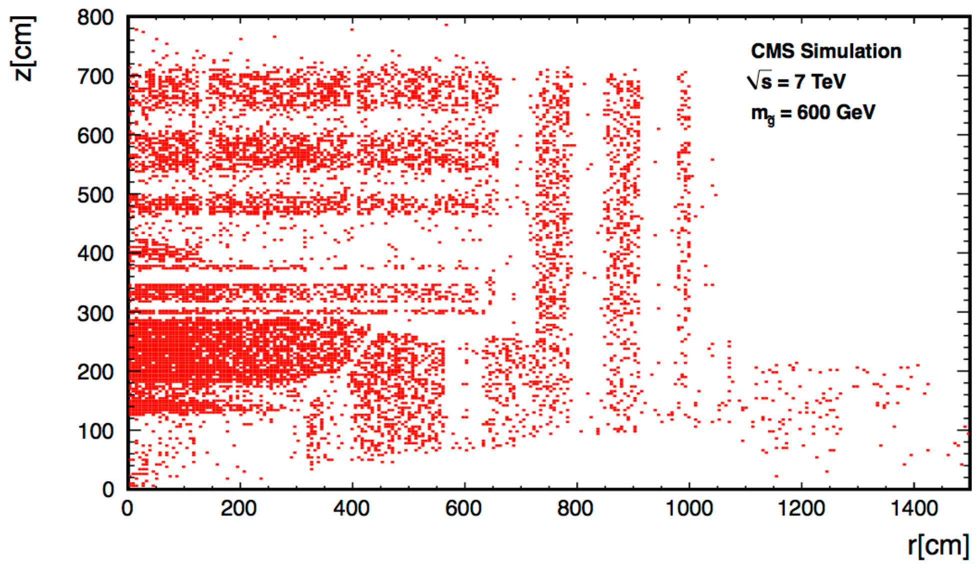
$$\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$$

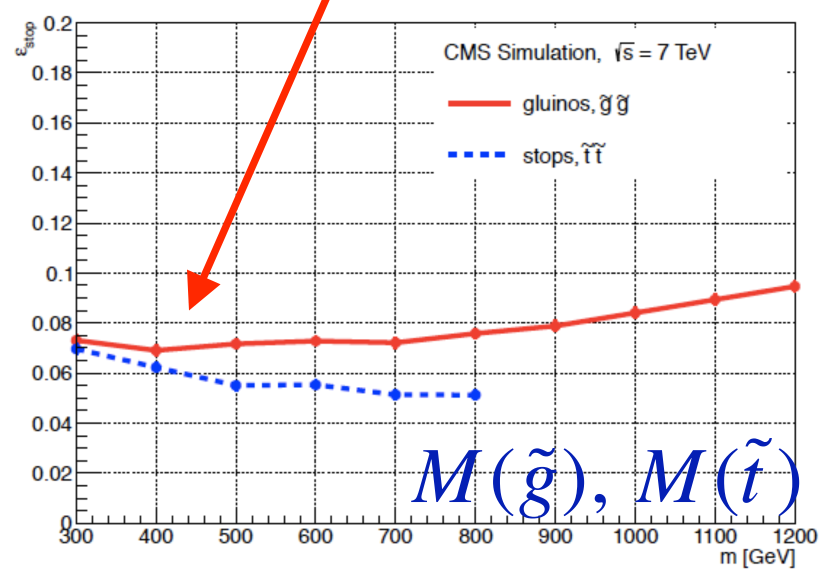
What happens to a long-lived gluino?

- Hadronization turns gluino/stop into "R-hadron"

  $\tilde{g}g \quad \tilde{g}q\bar{q} \quad \tilde{g}qqq \; ... \quad \tilde{t}\bar{q} \quad \tilde{t}qq \; ...$

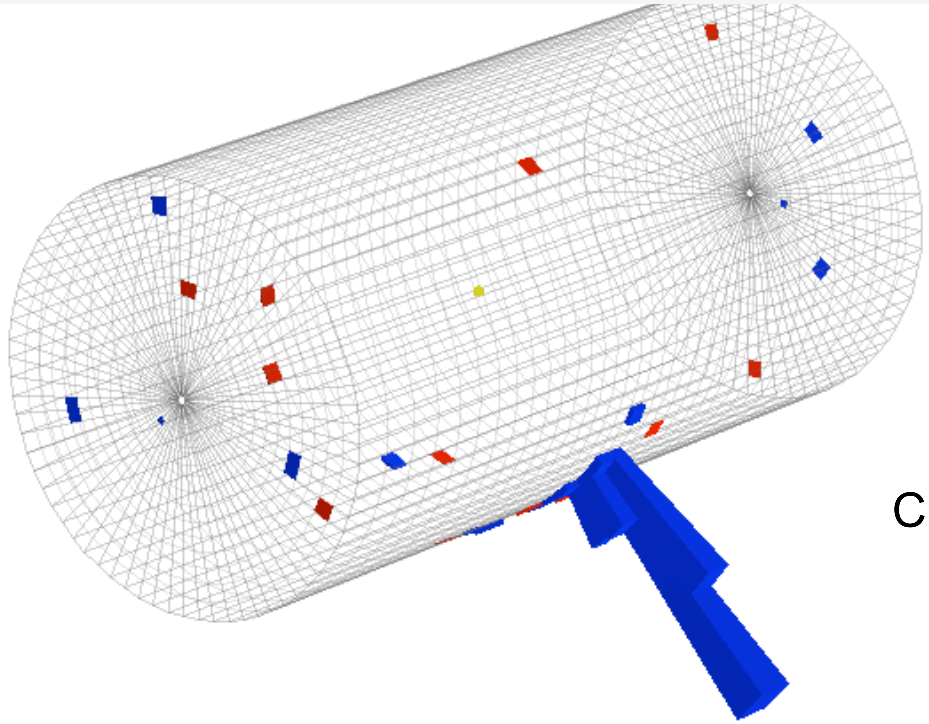
- The R-hadron interacts with the material of the detector. Some fraction will stop, typically in the densest regons in the detector. Prob to stop ~0.07.
- Eventually the gluino decays.





Gluino decay in hadronic calorimeter (MC)

Trigger = CALO cluster + no incoming p bunches + no muon segments



CMS simulation

Trigger: Calo jet ET>50 GeV + veto on signals from Beam Position and Timing Monitors (BPTX) 175 m on either side of CMS. Don't want either proton bunch present (beam gas events can be produced with just one p bunch). Also veto on beam halo forward muon trigger.

Event selection for stopping particles

- During 2011 run, number bunches/beam varied from 228 to 1380.
- Select time intervals for analysis between bunch crossings.
- Veto any event within two LHC clock cycles (BX= 25 ns) of either p bunch passing through CMS.
- Get 85% of orbit time for 228 bunch fills; 16% of orbit for 1380 bunch fills for the search → 249 hours live time. LHC orbit period is 89 μs.
- Cuts to reject beam halo muons, cosmics, HCAL noise. Final rate: $(1.5 \pm 2.5)\times 10^{-6}$ Hz.

Stopped gluino search: Background & observed yields

Estimate of background contributions over total live time.

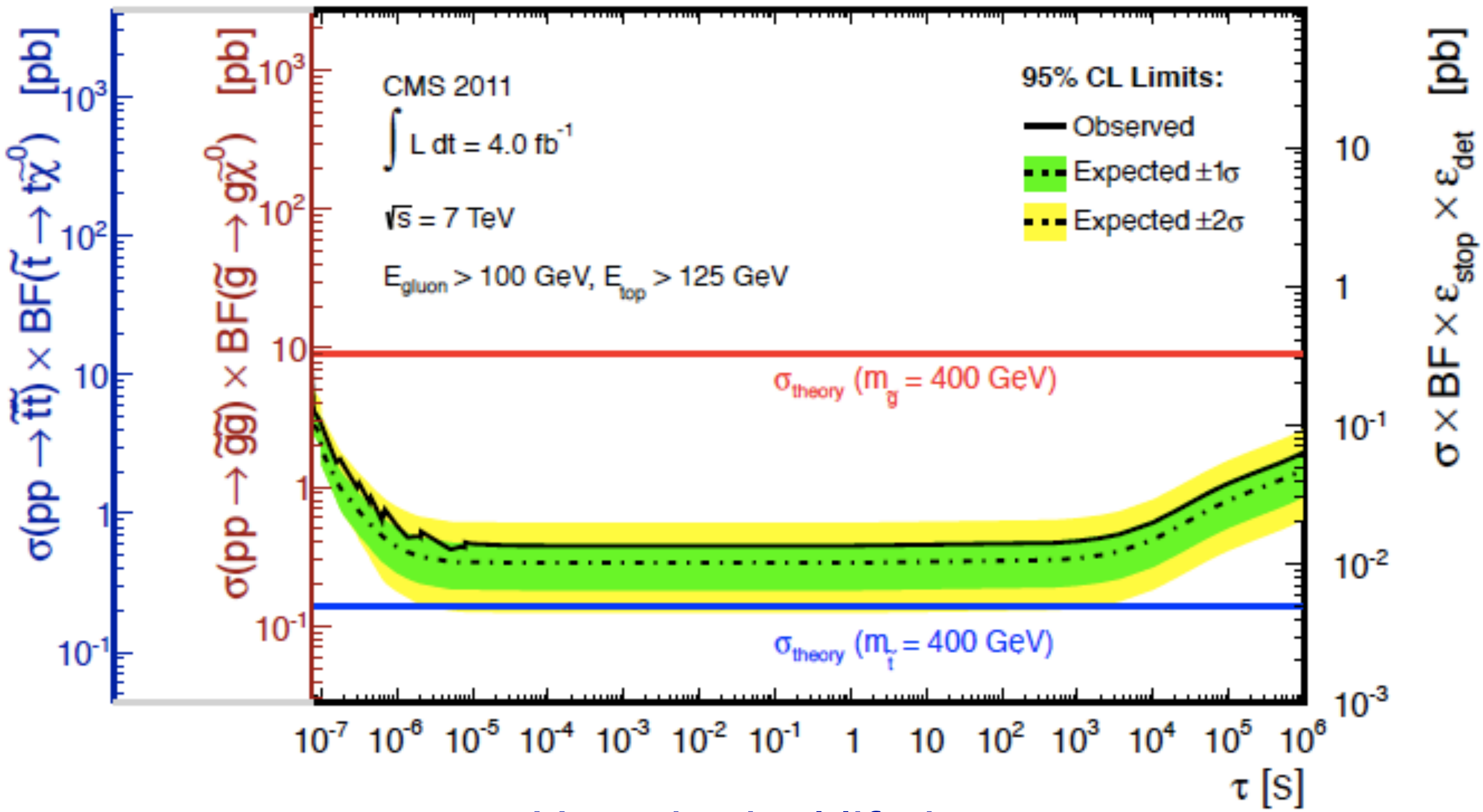
Cosmic rays	Beam-halo	Noise	Total
5.71 ± 0.62	1.50 ± 0.70	1.4 ± 2.2	8.6 ± 2.4

Estimate of background contributions for live-time intervals chosen for each lifetime hypothesis.

τ	L_{eff} (pb^{-1})	Live time (s)	N_{exp}	N_{obs}
75 ns	19.6	2.06×10^4	0.200 ± 0.056	1
100 ns	57.8	6.17×10^4	0.60 ± 0.17	2
1 μs	508	4.41×10^5	4.3 ± 1.2	7
10 μs	913	8.67×10^5	8.5 ± 2.4	12
100 μs	935	8.86×10^5	8.6 ± 2.4	12
10^3 s	866	8.86×10^5	8.6 ± 2.4	12
10^4 s	636	8.86×10^5	8.6 ± 2.4	12
10^5 s	332	8.86×10^5	8.6 ± 2.4	12
10^6 s	198	8.86×10^5	8.6 ± 2.4	12

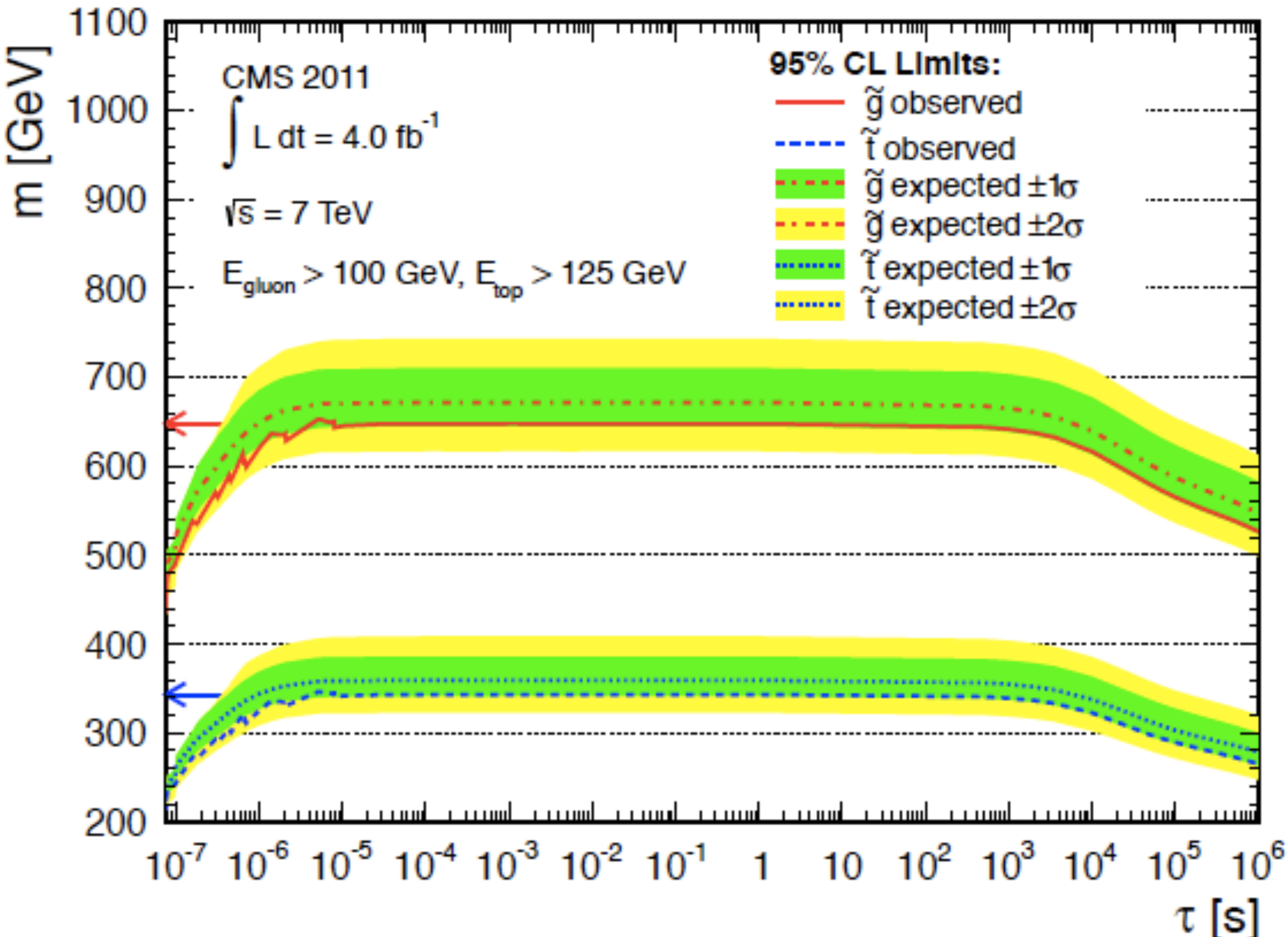
For lifetimes shorter than one LHC revolution time, search in an time window of 1.3τ after beam xing.

Cross section exclusion from stopped gluino search



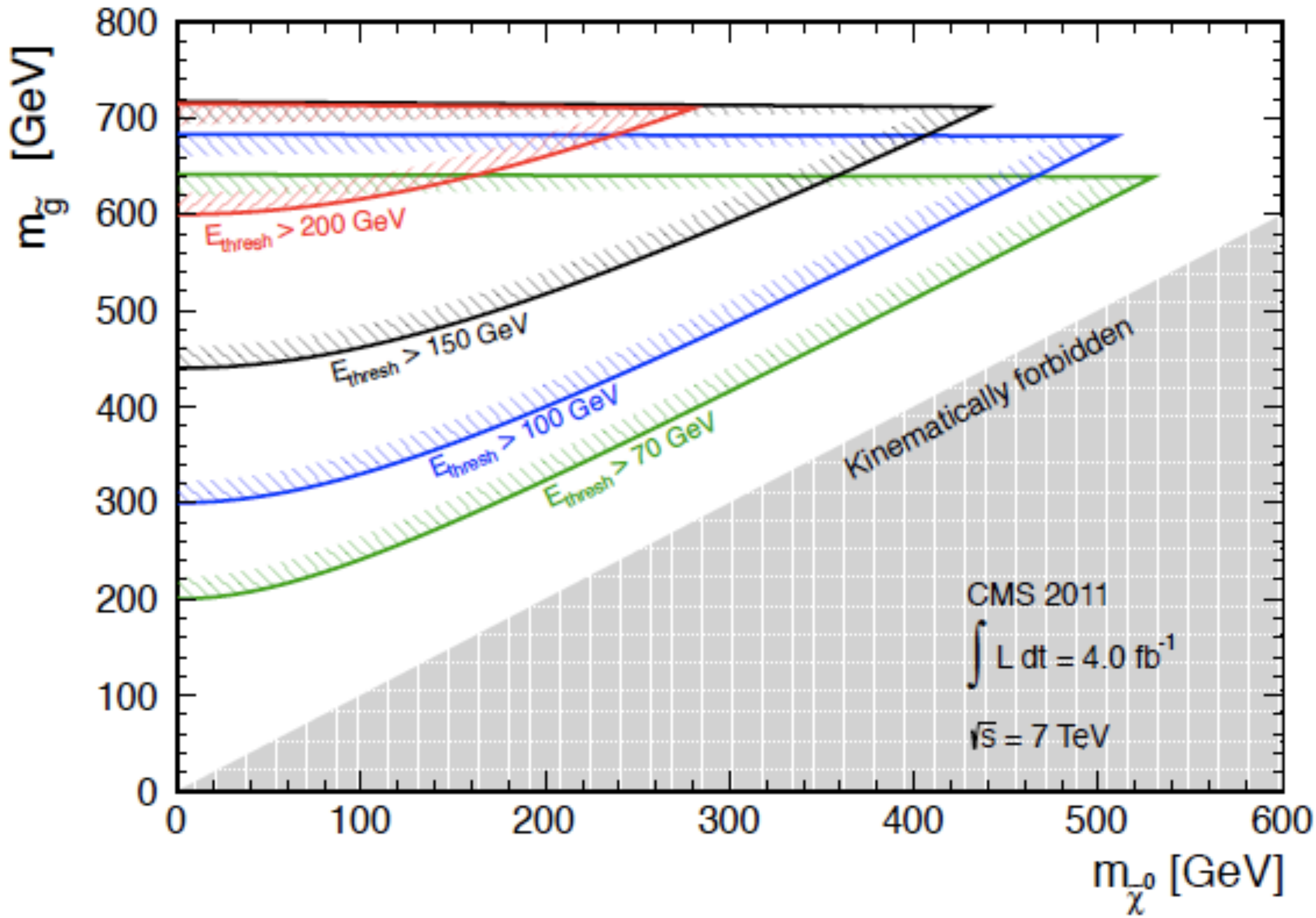
Hypothetical lifetime

Mass limits on stopping $\tilde{g}$ and $\tilde{t}$



Hypothetical lifetime

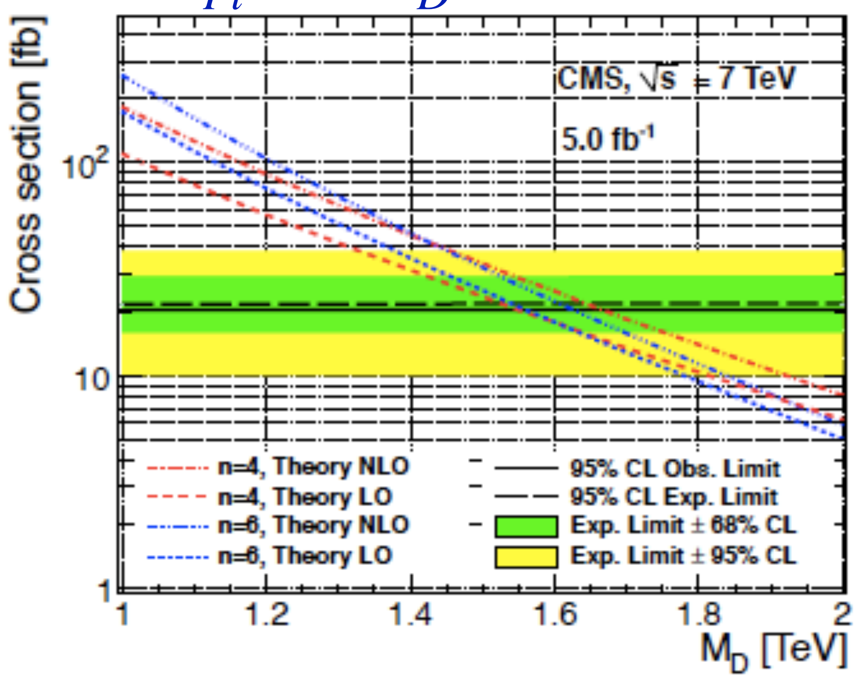
Mass exclusion from stopped gluino search

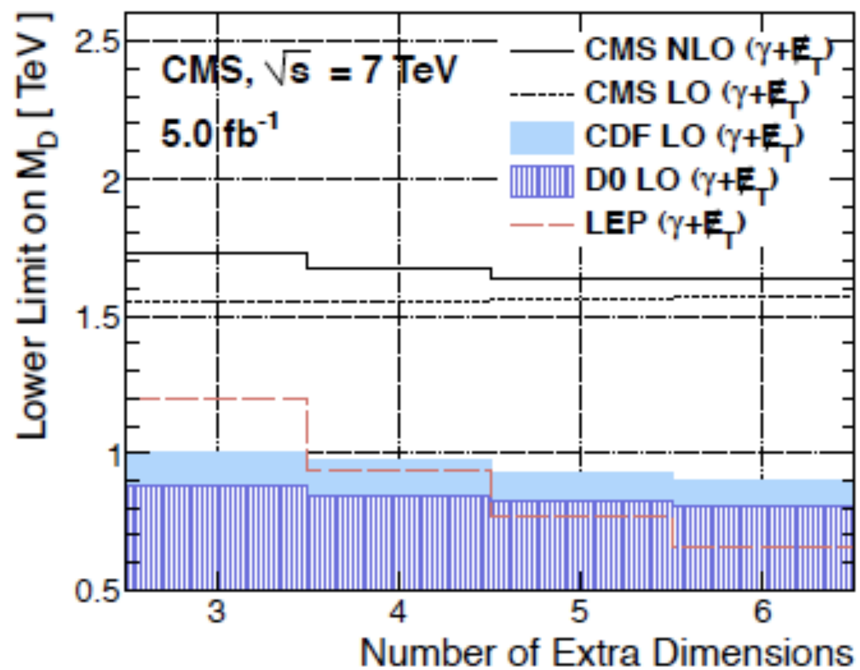


Monophoton search: interpretation in Large Extra Dimensions models

- Try to explain difference between Planck and EW scales.
- *n* extra compact spatial dimensions, characteristic scale *R*
- Gravity propagates in the (4+n) dimensional bulk of space-time; SM fields are confined to four dimensions. Graviton production seen as missing momentum. $q\bar{q} \rightarrow \gamma G \quad q\bar{q} \rightarrow gG \quad gg \rightarrow gG$

$$M_{Pl}^2 \approx M_D^{n+2} R^n$$

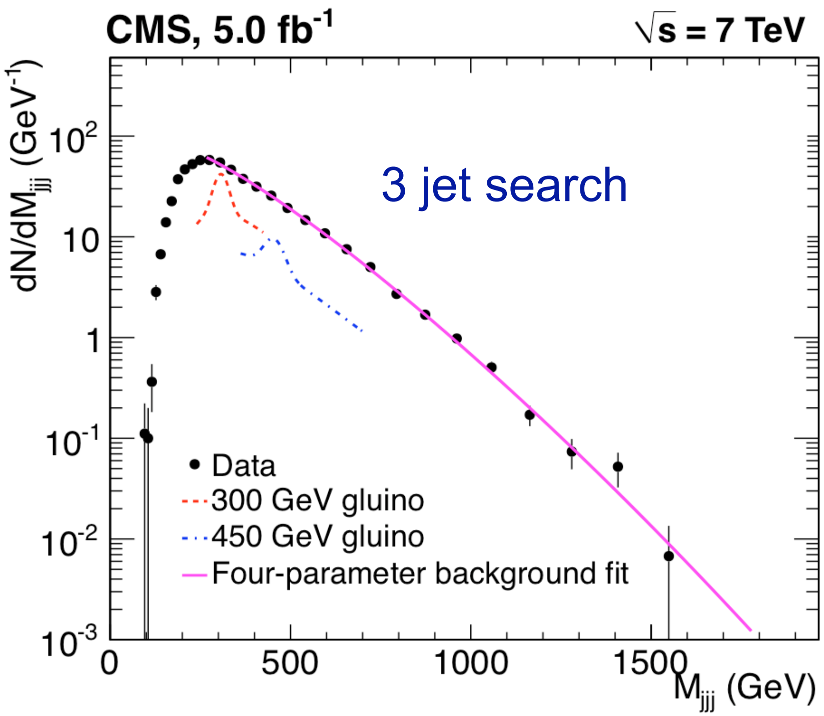


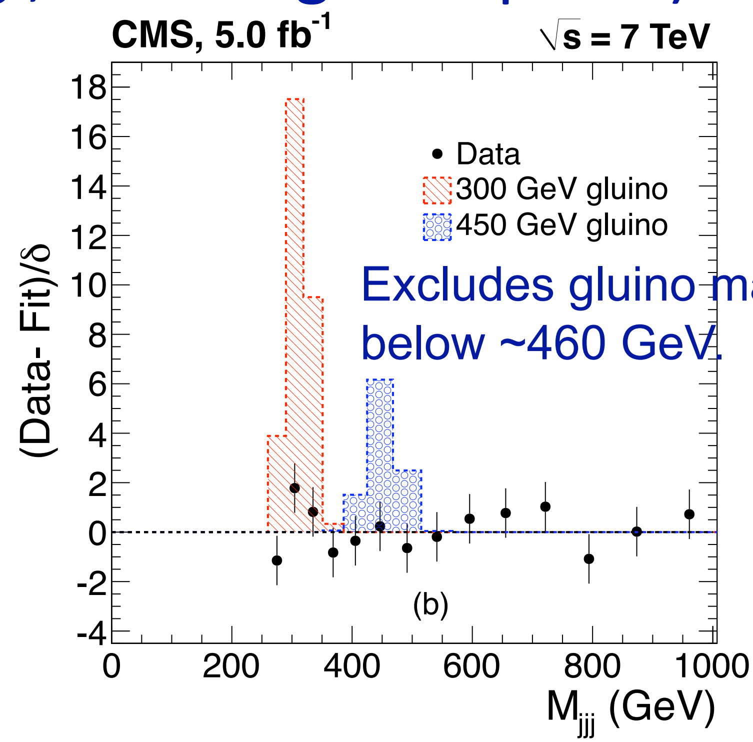


R-parity violating SUSY

CMS multilepton analysis: http://arxiv.org/abs/1204.5341
CMS three-jet search: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11060

- What if SUSY violates R-parity?
- Main issue: can have very little MET. Some existing SUSY searches with “strong” signatures can work with loose MET requirements (e.g., same-sign dileptons).





Excludes gluino masses below ~460 GeV.

Search for "microscopic" black holes

CMS black hole search: http://arxiv.org/abs/1202.6396

- Signature of low-scale quantum gravity.
- But many different scenarios – small industry of simulations/models.
- Physics of black hole formation and evaporation has several subtleties. (E.g., what fraction of the initial parton energy is trapped in the event horizon, rotating vs. non-rotating, etc.)

Table 1: Signal Monte Carlo samples and generators used in the analysis.

Sample description	BLACKMAX	CHARYBDIS
Non-rotating BH	YES	YES
Rotating BH	YES	YES
Rotating BH with M/J loss	YES (10 % loss)	YES (18-30 % loss)
Rotating BH, low multiplicity regime	NO	YES
Boiling remnant	NO	YES
Stable remnant	NO	YES

Search for microscopic black holes

- Object selection is simple
  - Leptons (e, mu): pT> 50 GeV
  - Photons (e, mu): pT> 50 GeV
  - Jets: pT>50 GeV
  - Nonoverlapping in cone ΔR=0.3.
- Compute total scalar sum of transverse momenta in the event.

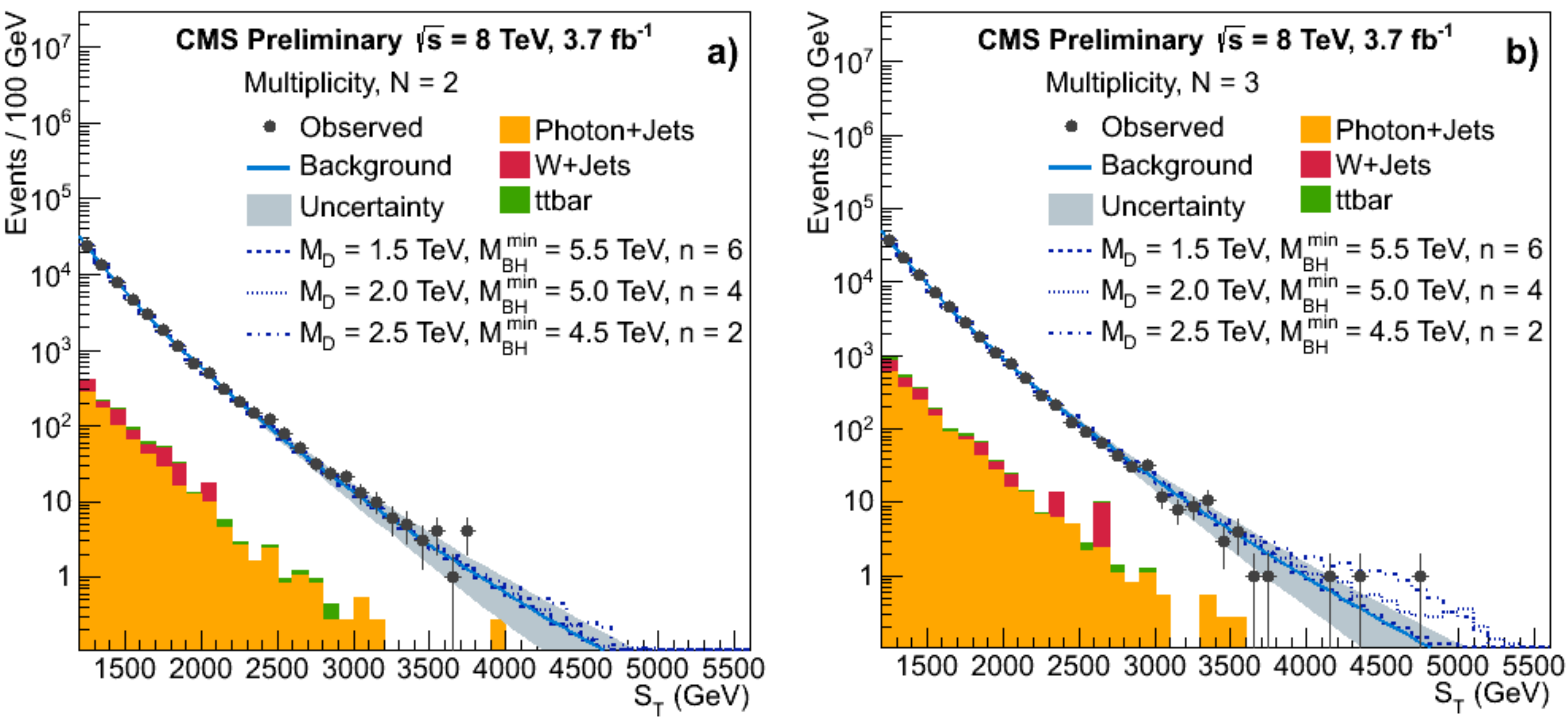
$$S_T = \sum_{j=\text{jets, leptons, photons, MET}} \left| \vec{\boldsymbol{p}}_T^{\,j} \right|$$

- Study S_T as a function of object multiplicity, which does not include MET.

Black holes: background estimation

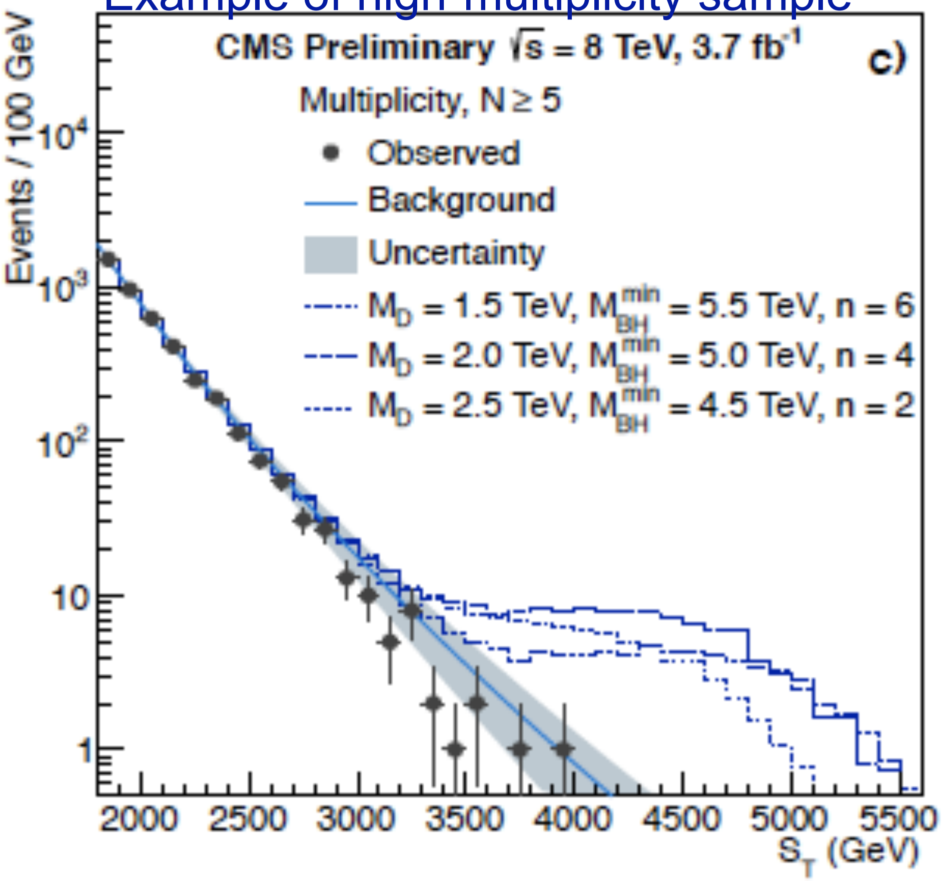
CMS black hole search: http://arxiv.org/abs/1202.6396

- Background shape is obtained from fit to low-multiplicity (N) events and restricting S_T to range 1200 < S_T < 2800 GeV.
- Shapes in N=2 and N=3 samples are very similar.
- Dedicated search for new physics in N=2 sample shows no signal.

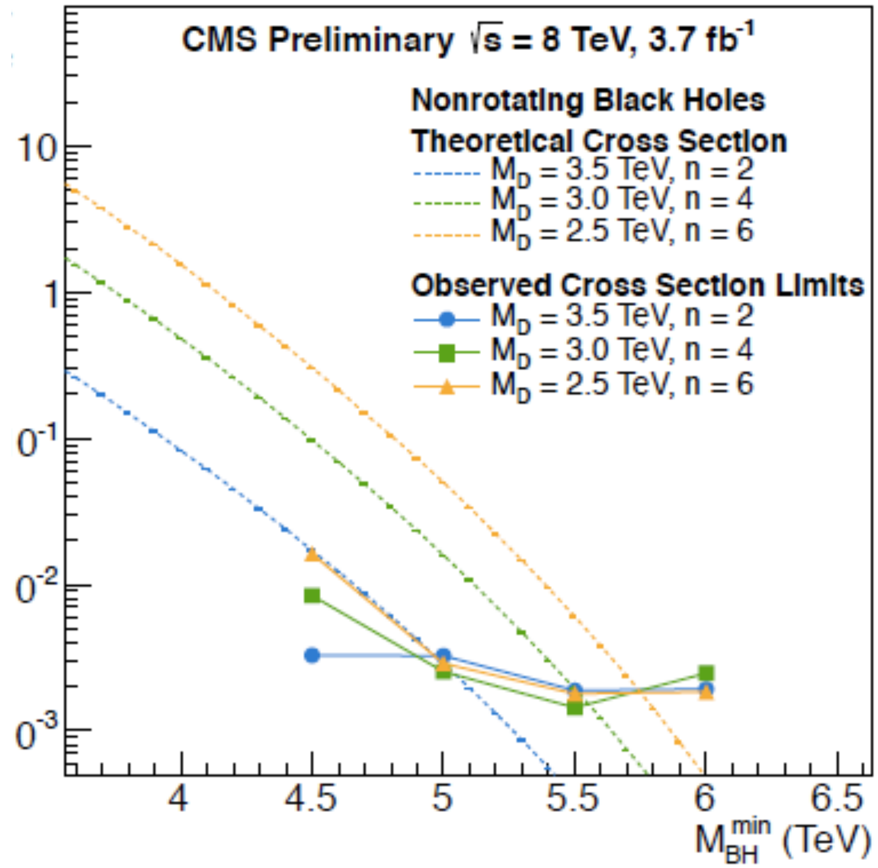


Search for microscopic black holes

Example of high-multiplicity sample

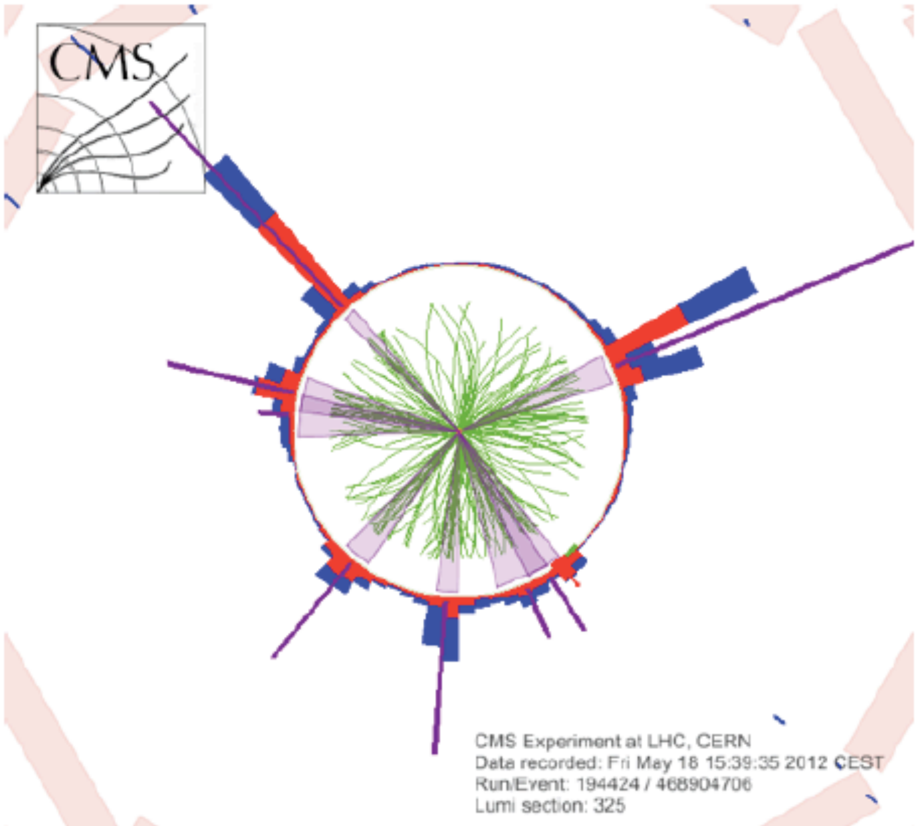


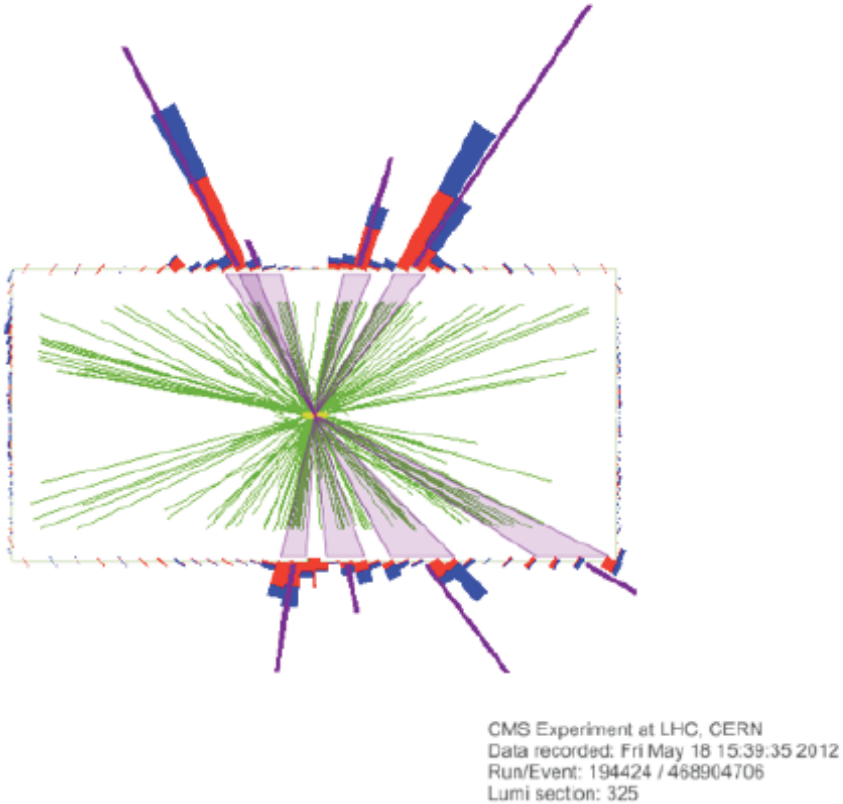
Cross sections vs. black hole mass



750 MC samples for the signal scenarios considered...
Excluding black hole masses below 4-6 TeV.

Black hole search: high ST event

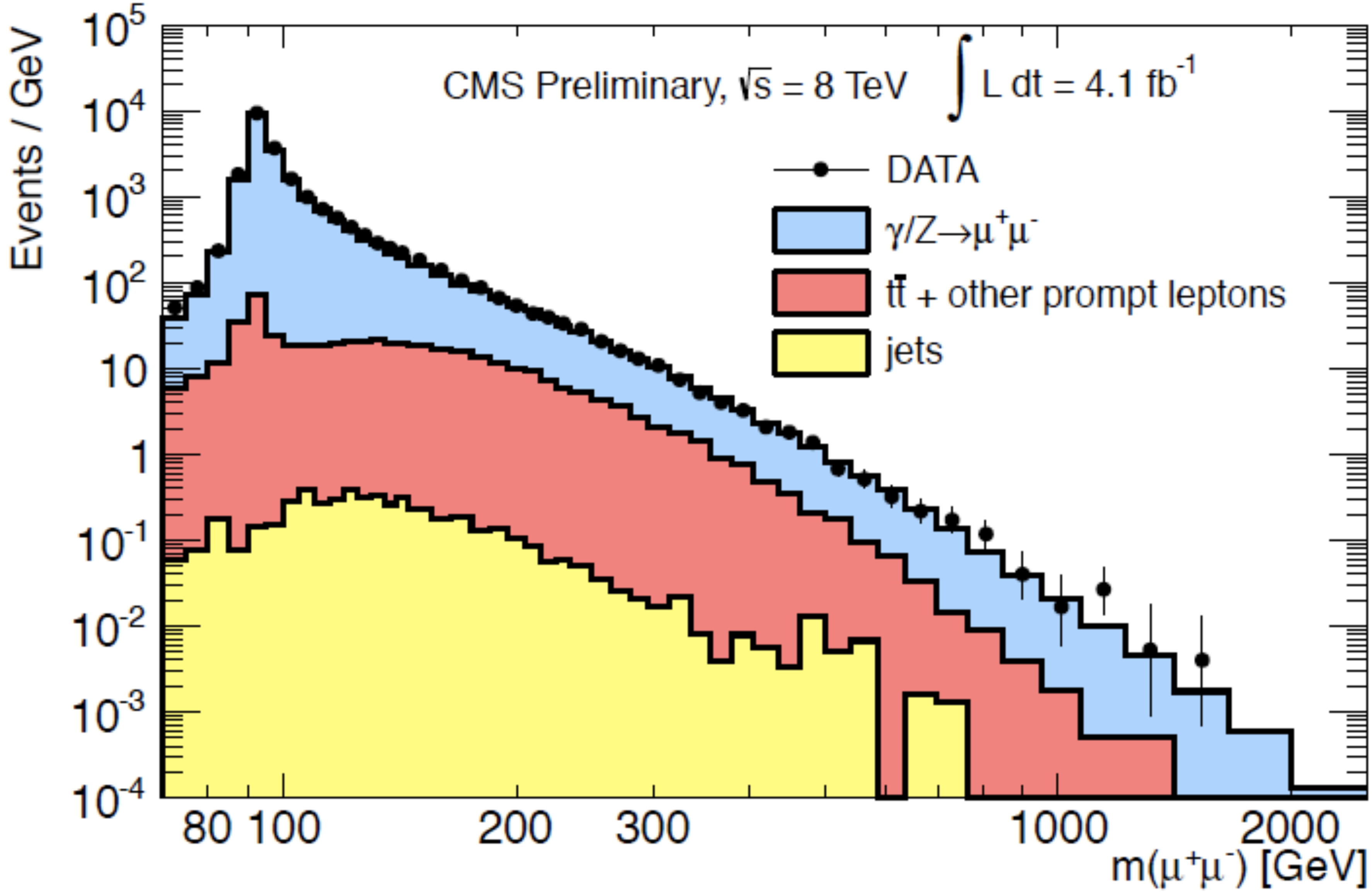




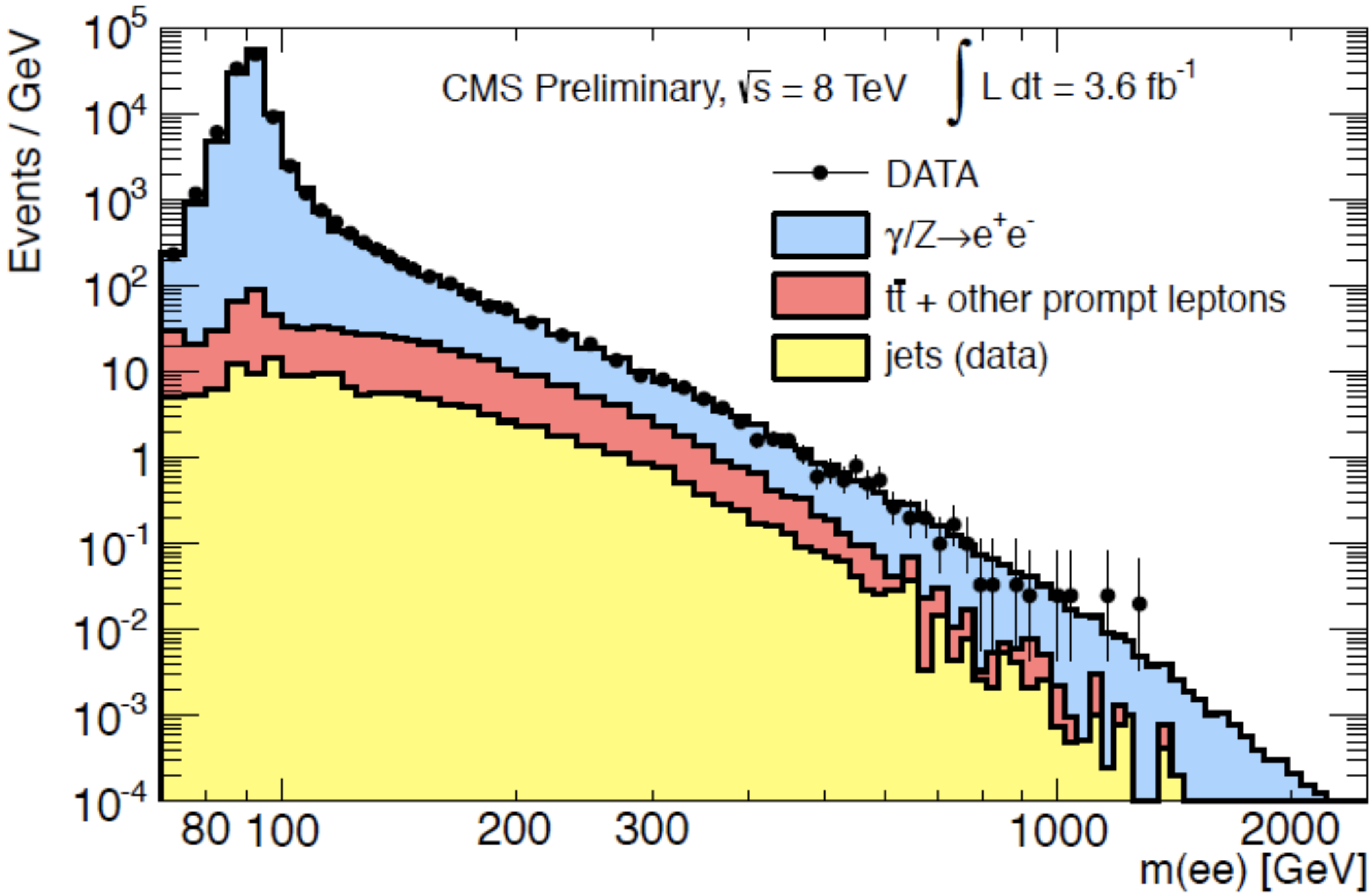
Conclusions

- This is a unique period in the history of particle physics.
- We don't know what we will discover – that is the fundamental nature of science.
- There are no guarantees, <u>but the potential for breakthroughs has never been greater.</u>
- Your work and leadership are critical to the future of high energy physics.
- Many thanks to all the organizers, staff, postdocs, and students!

Search for Z' → e^+e^-, $\mu^+\mu^-$



Search for Z' → e^+e^-, $\mu^+\mu^-$



Data with simulated ADD signal

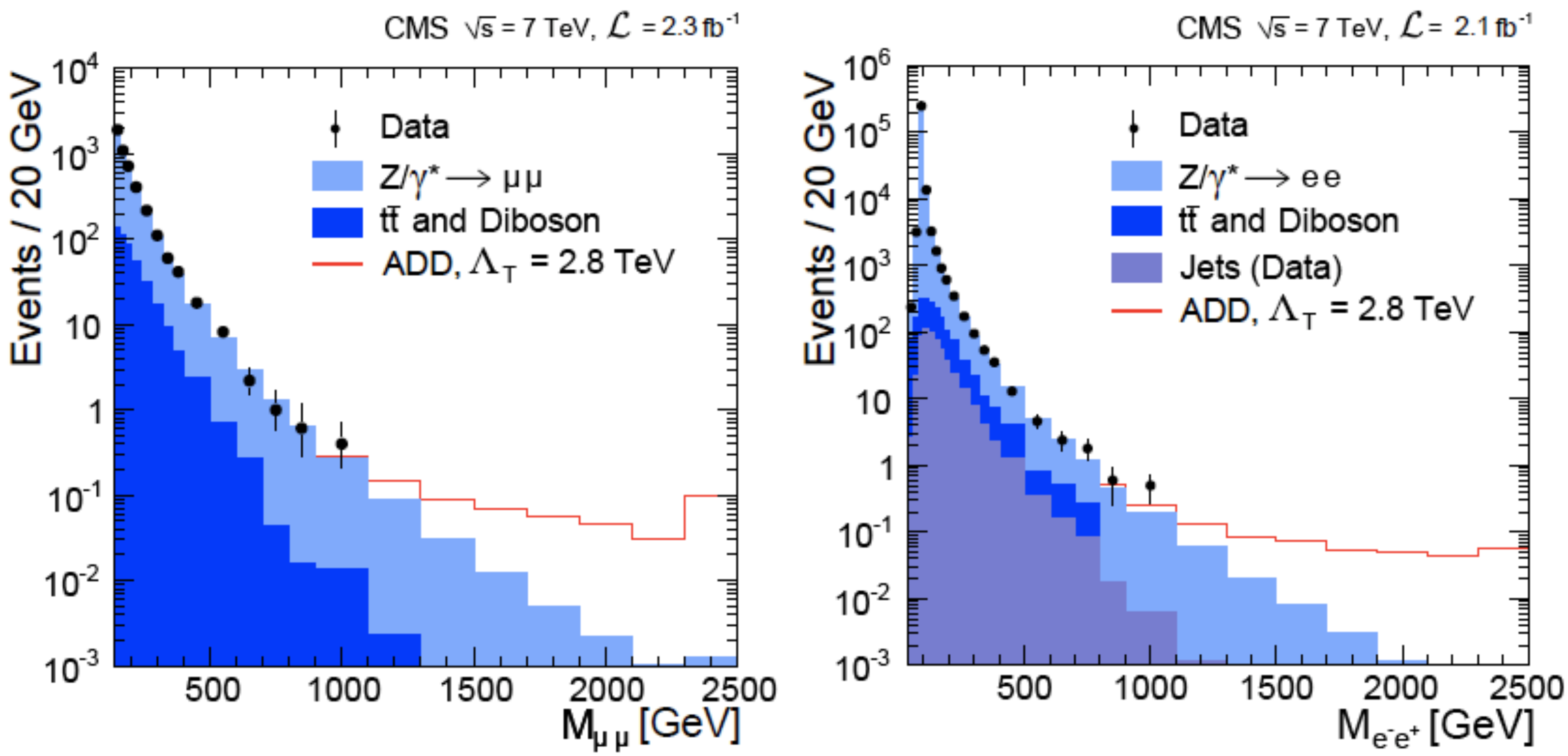


Figure 1: Dimuon (left) and dielectron (right) invariant mass spectra compared with the SM predictions and a simulated ADD signal with $\Lambda_T = 2.8$ TeV (ADD K-factor 1.0, no signal truncation). The highest-mass bins contain all contributions above 2.3 TeV. The error bars reflect the statistical uncertainty.