Searches for Supersymmetry with the CMS detector at the LHC

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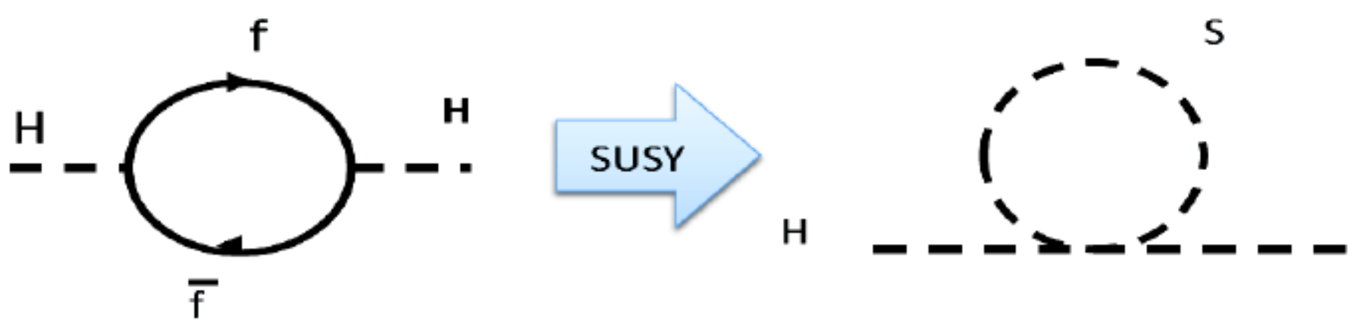
12-7-2012

The truth is out there:

- We think that there is something beyond the Standard Model.
- But there are plenty of theories that augment the Standard Model. Why SUSY?

Why SUSY?

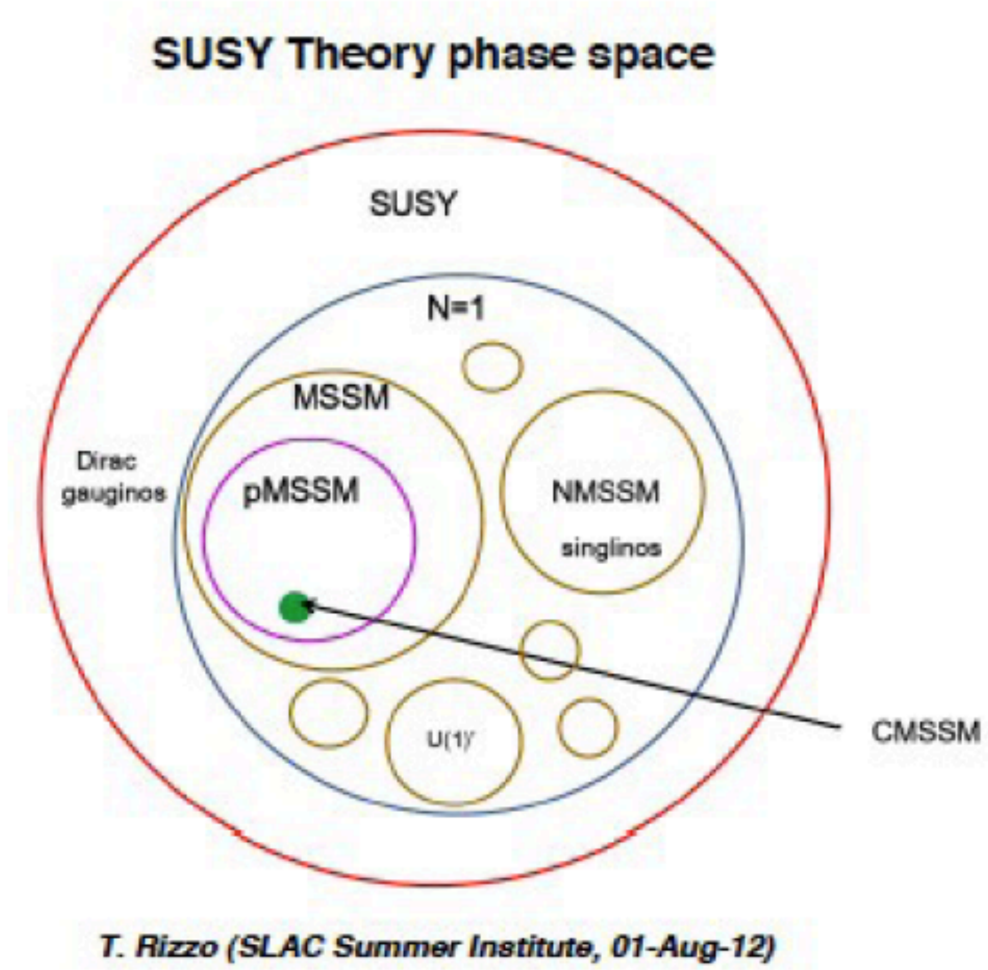
- Even if we've observed the Higgs, we need something to stabilize it's mass. Otherwise we end up with a model tuned to 1 part in 10^{30}



- Also provides a dark matter candidate, not to mention gauge coupling unification. So it's attractive.

Problematic?

- However, searching for SUSY is a rather daunting task. There's not just A SUSY, there are many, many different SUSY varieties, all of which have their own parameters and phenomenology.
- So there's a LOT of searching to be done.
- We attempt to be inclusive, and further try to set limits in generalized models which can constrain families of SUSY.
- The results I will show will mainly be in terms of "simplified models".



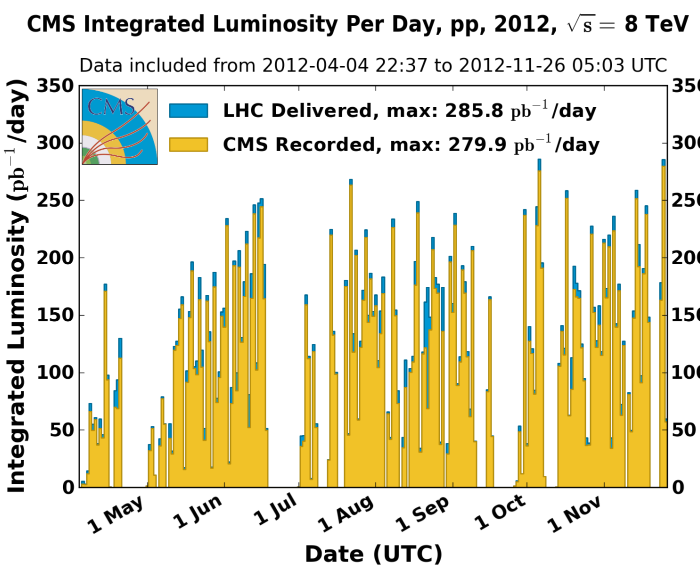
A lot more circles can be drawn here, of course.

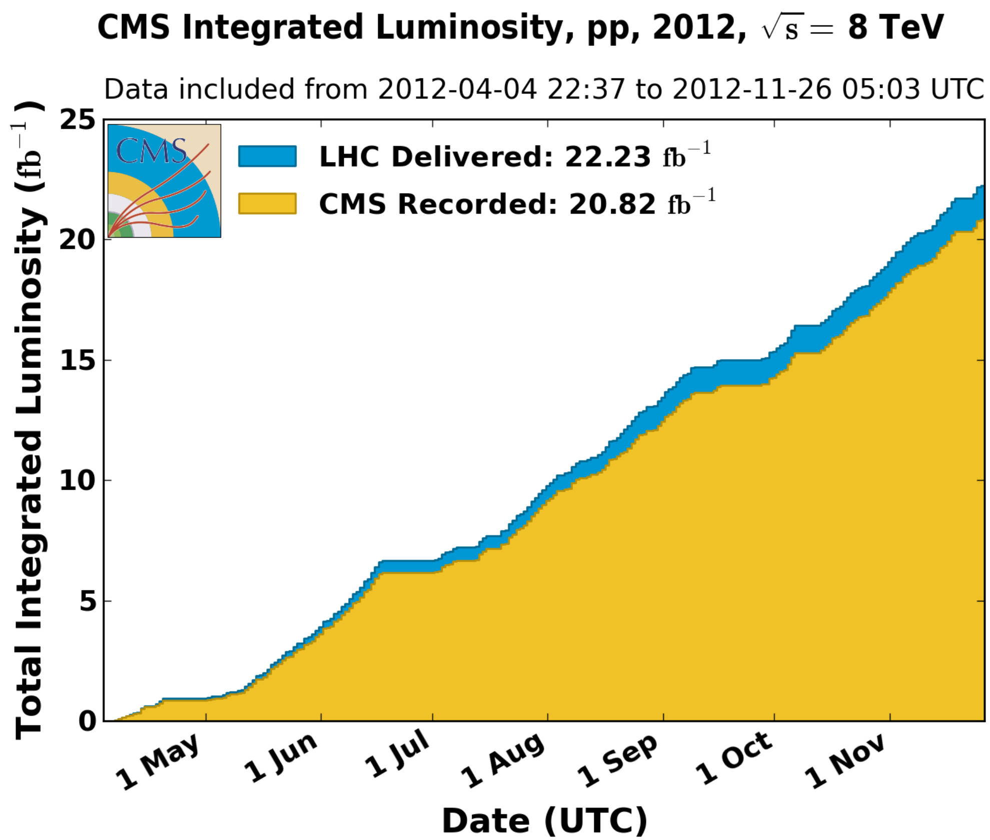
Outline:

- The CMS Detector
- SUSY Searches (by production):
  - Gluino production
    - α_T, Jets and missing E_T at 8 TeV
    - Same sign dileptons and b-tagged jets at 8 TeV
    - Inclusive multileptons at 8 TeV
  - Stop Production
    - All Hadronic with b-tags at 7 TeV
    - Single Lepton using M_T at 8 TeV
  - EWKino Production
    - Multileptons at 8 TeV
  - Stealth Susy
    - Diphoton plus small missing E_T at 7 TeV

Stand and Deliver!

A banner year!

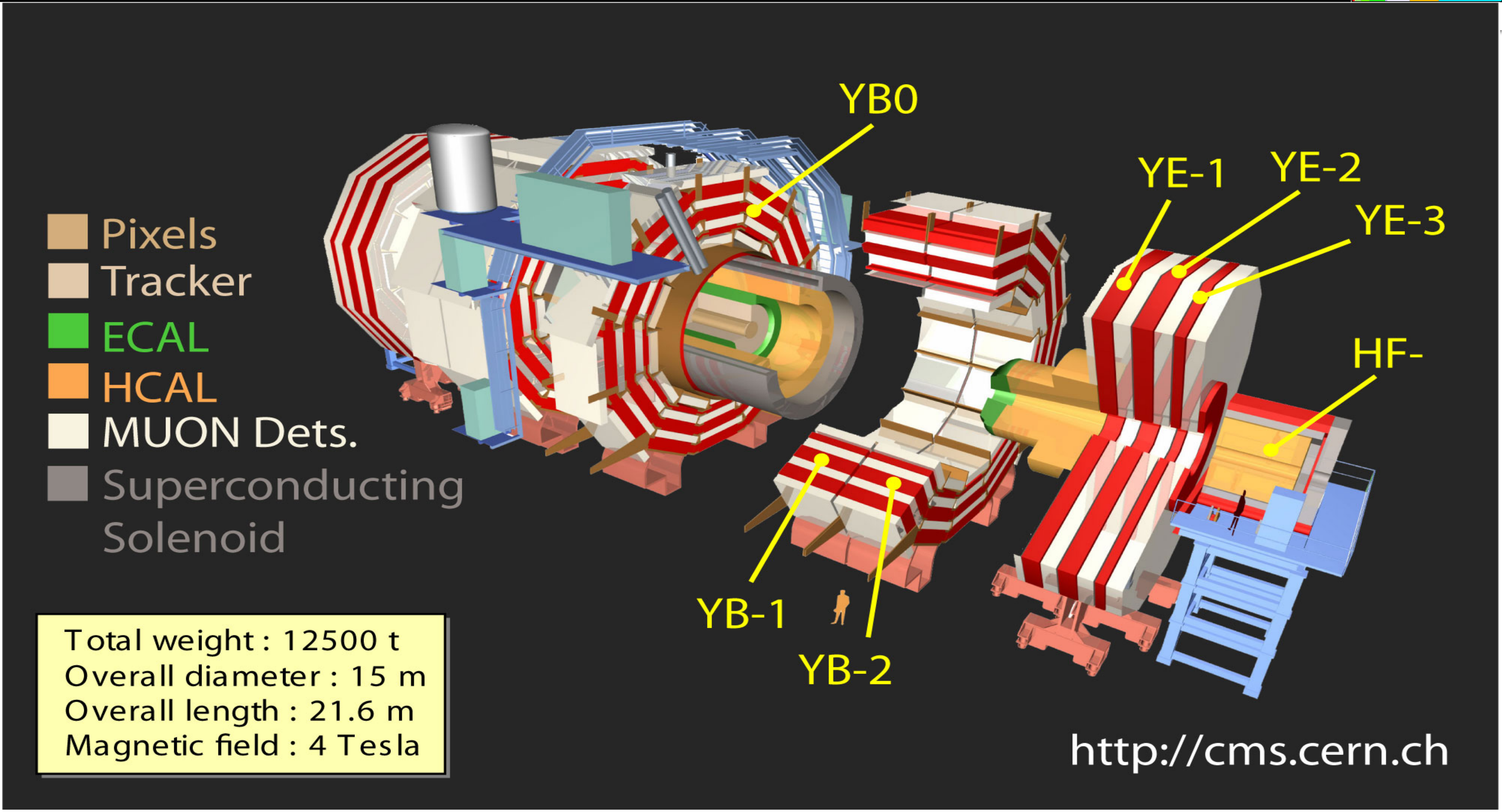




I will review analyses which have (mainly) used the much larger 2012 dataset.

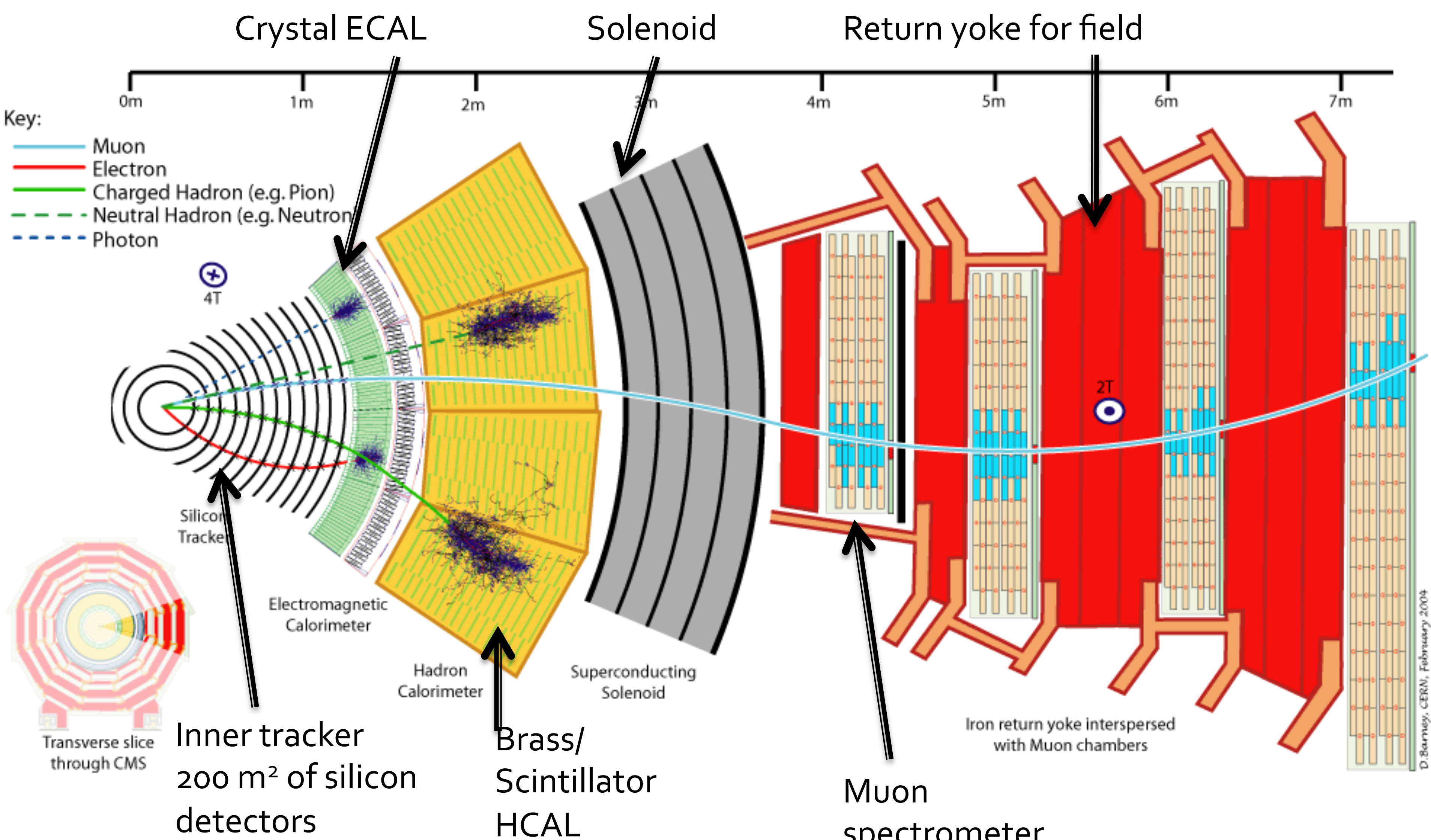
Used here: 5- 11.7 fb^{-1}

CMS Experiment:



In case you ever want to build your own.

CMS Experiment (2):

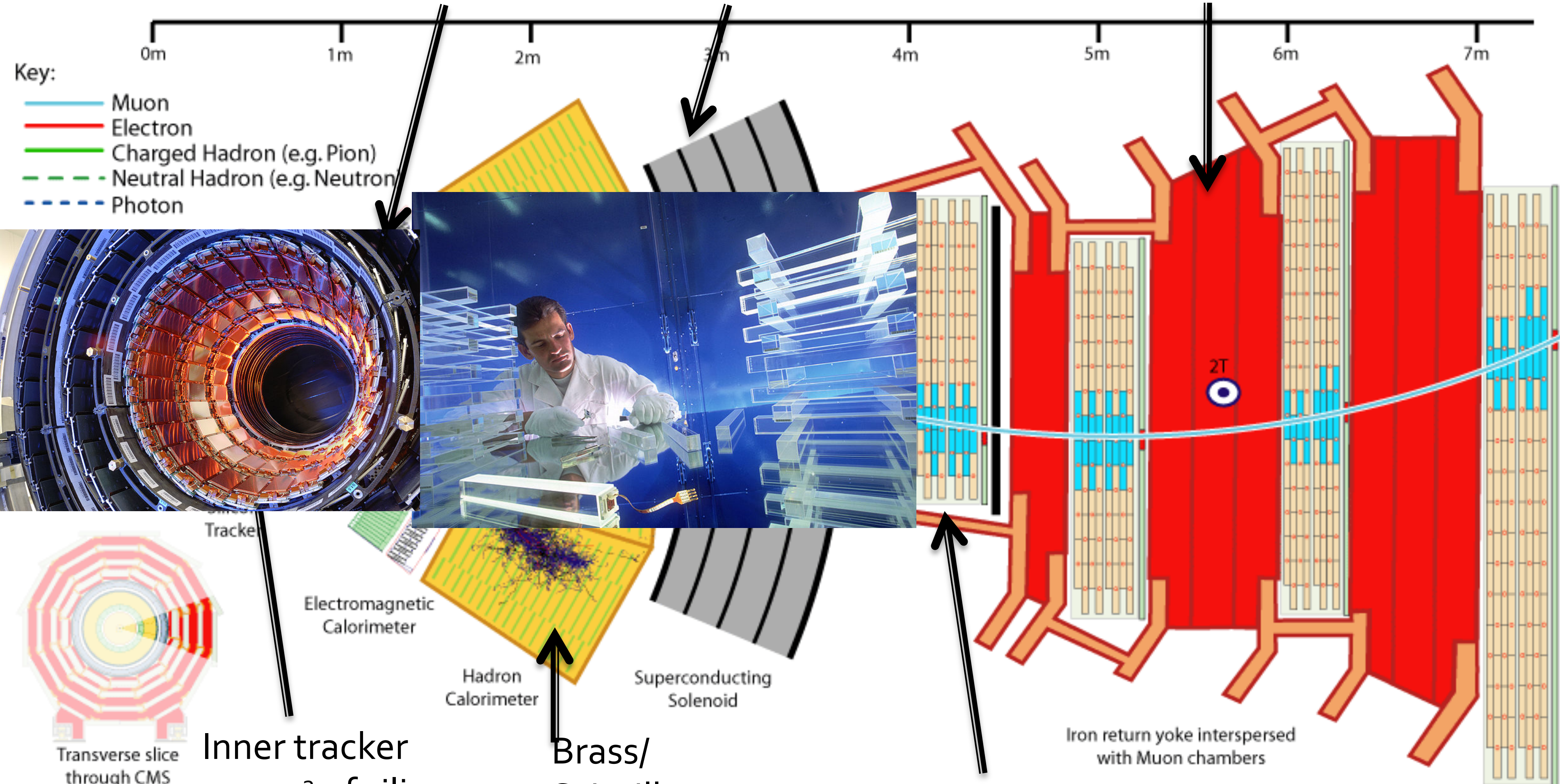


CMS Experiment: Electrons

Crystal ECAL

Solenoid

Return yoke for field

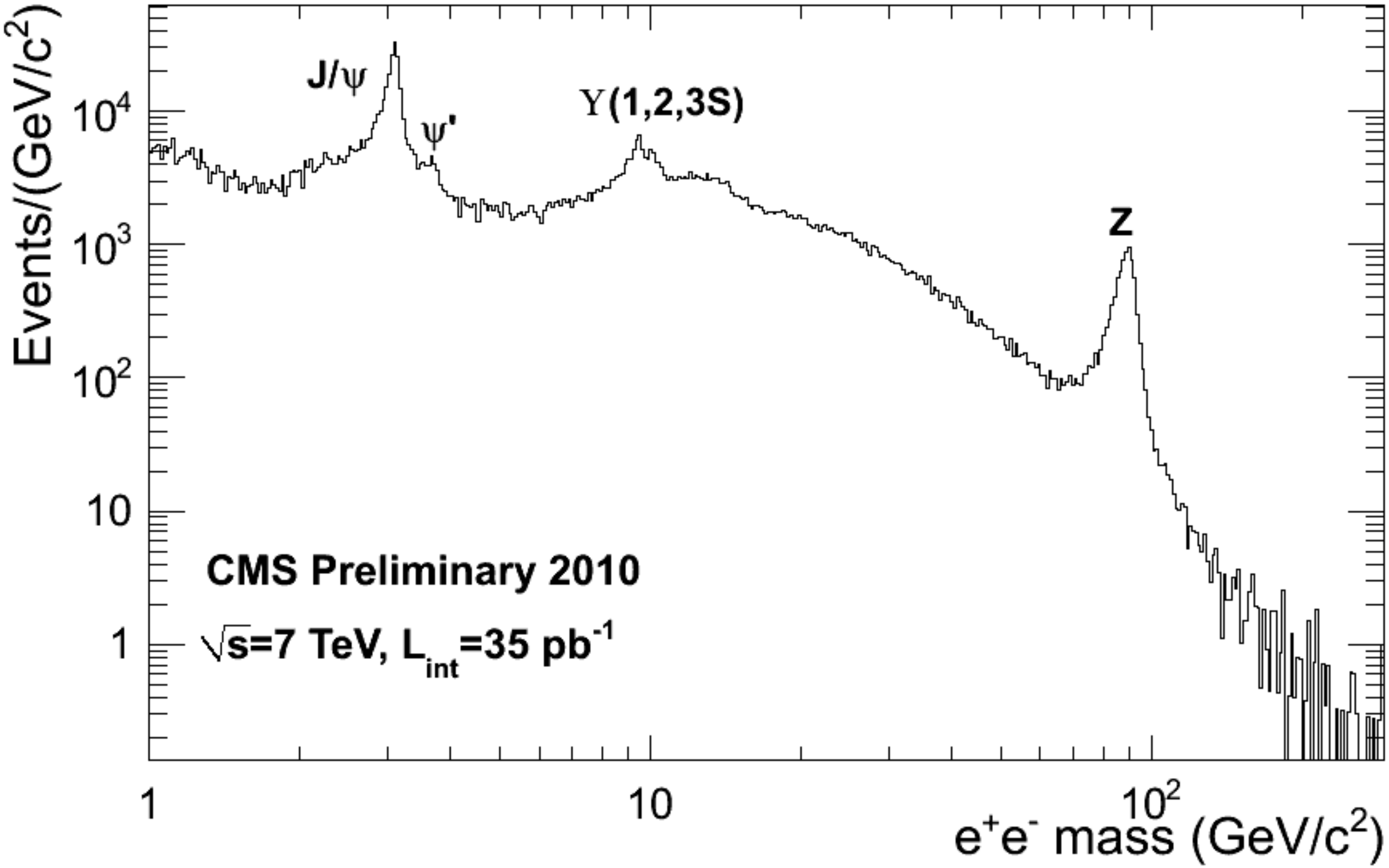


Inner tracker
200 m² of silicon detectors

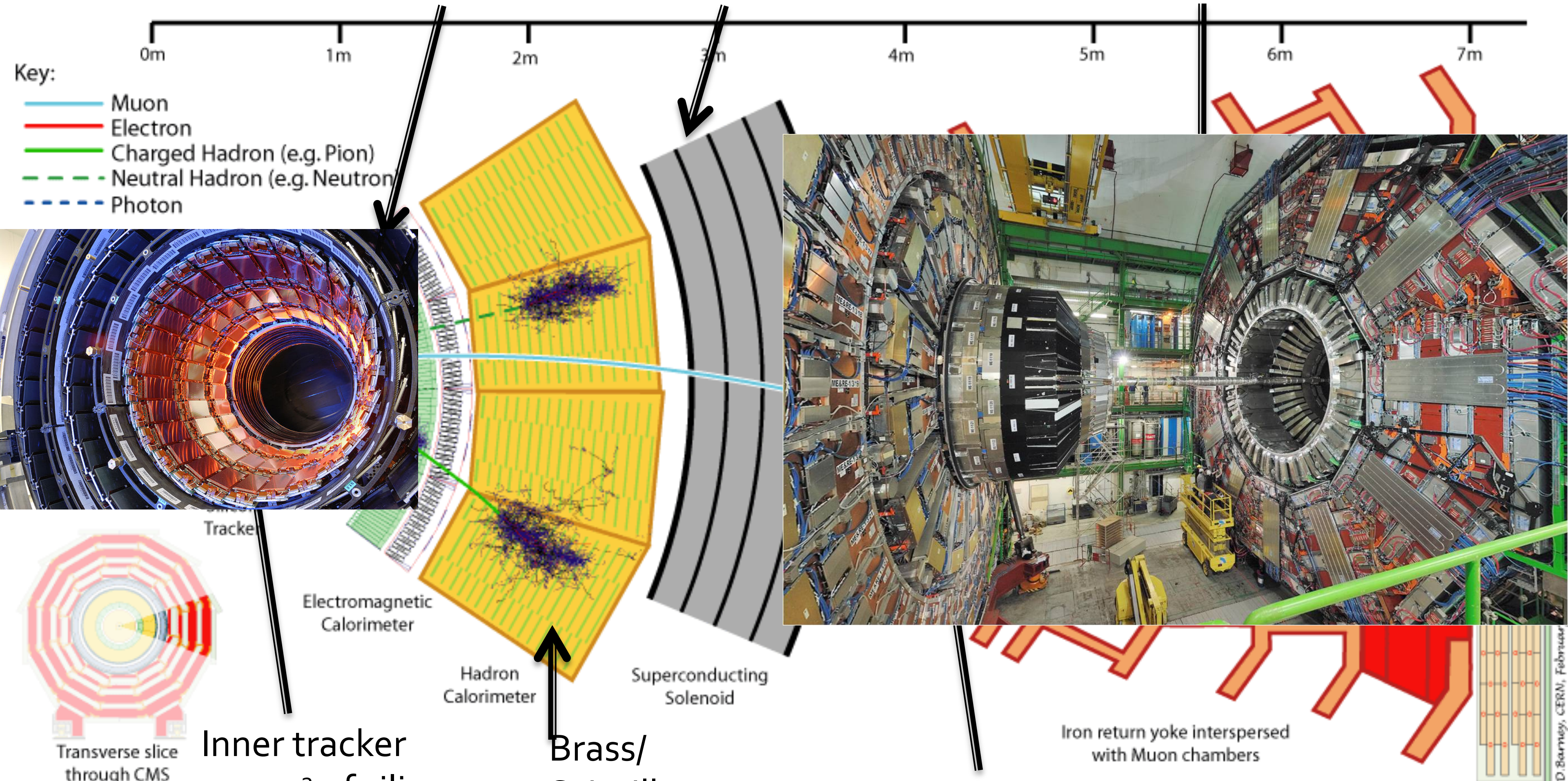
Brass/
Scintillator
HCAL

Muon
spectrometer

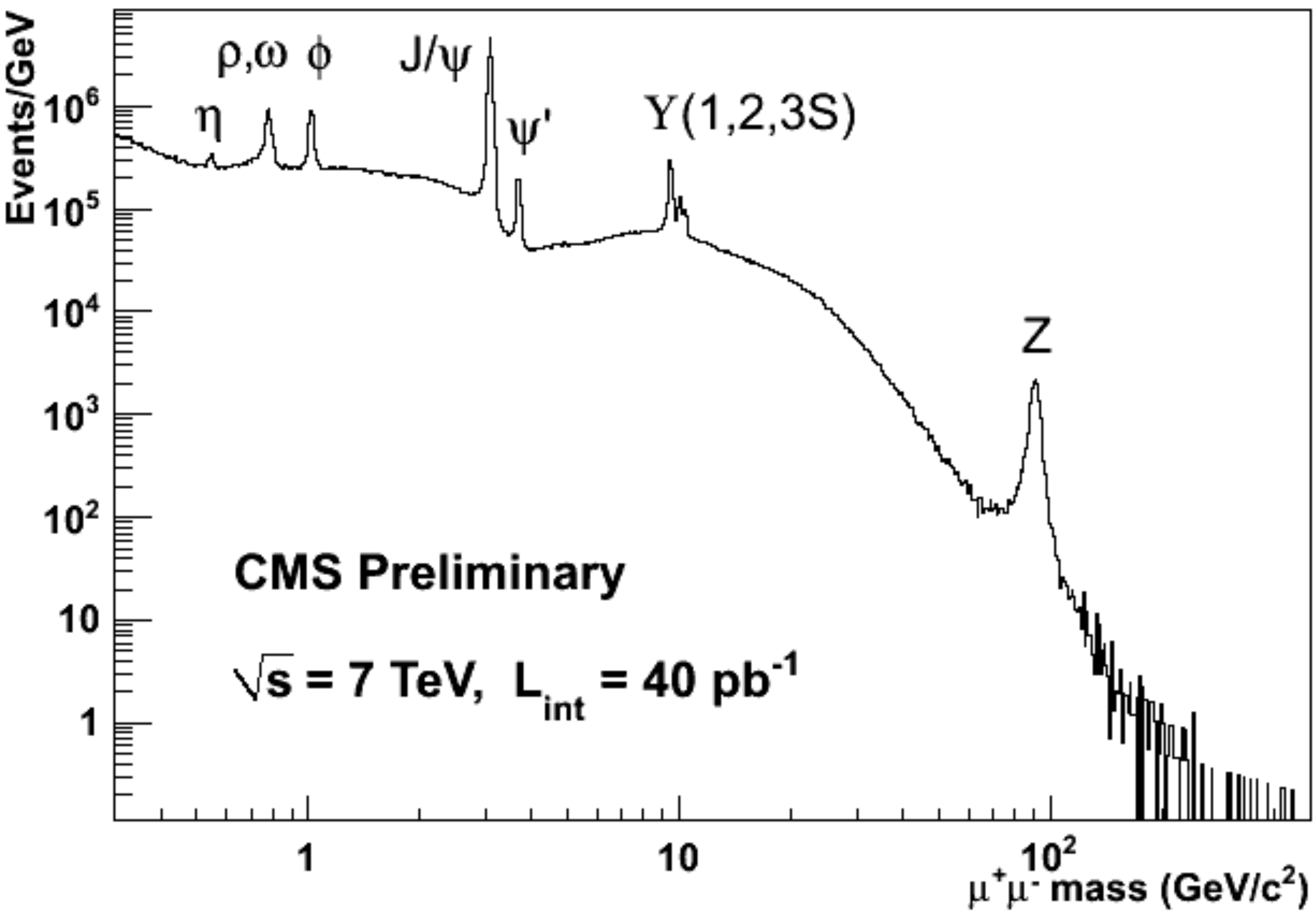
Invariant Mass:



CMS Experiment: Muons

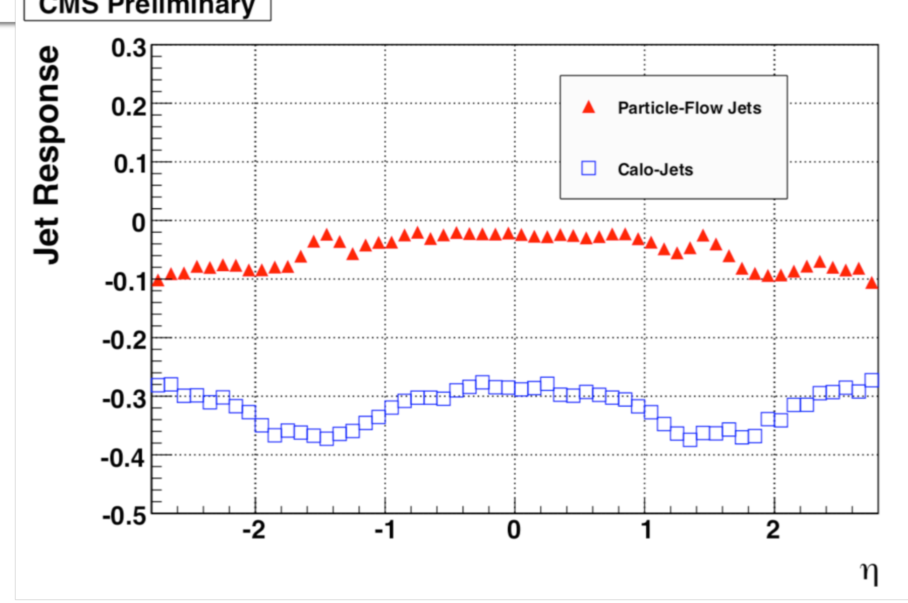


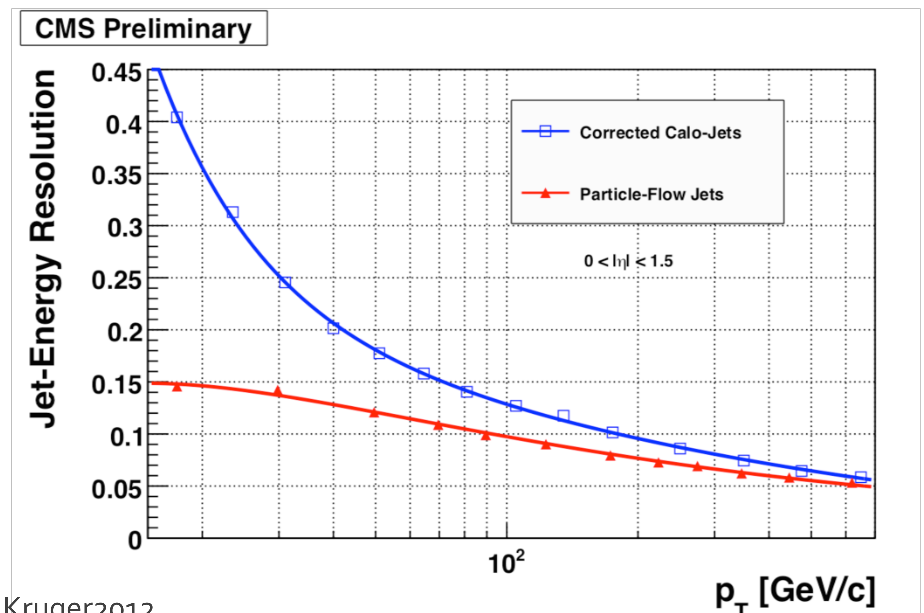
Invariant Mass:



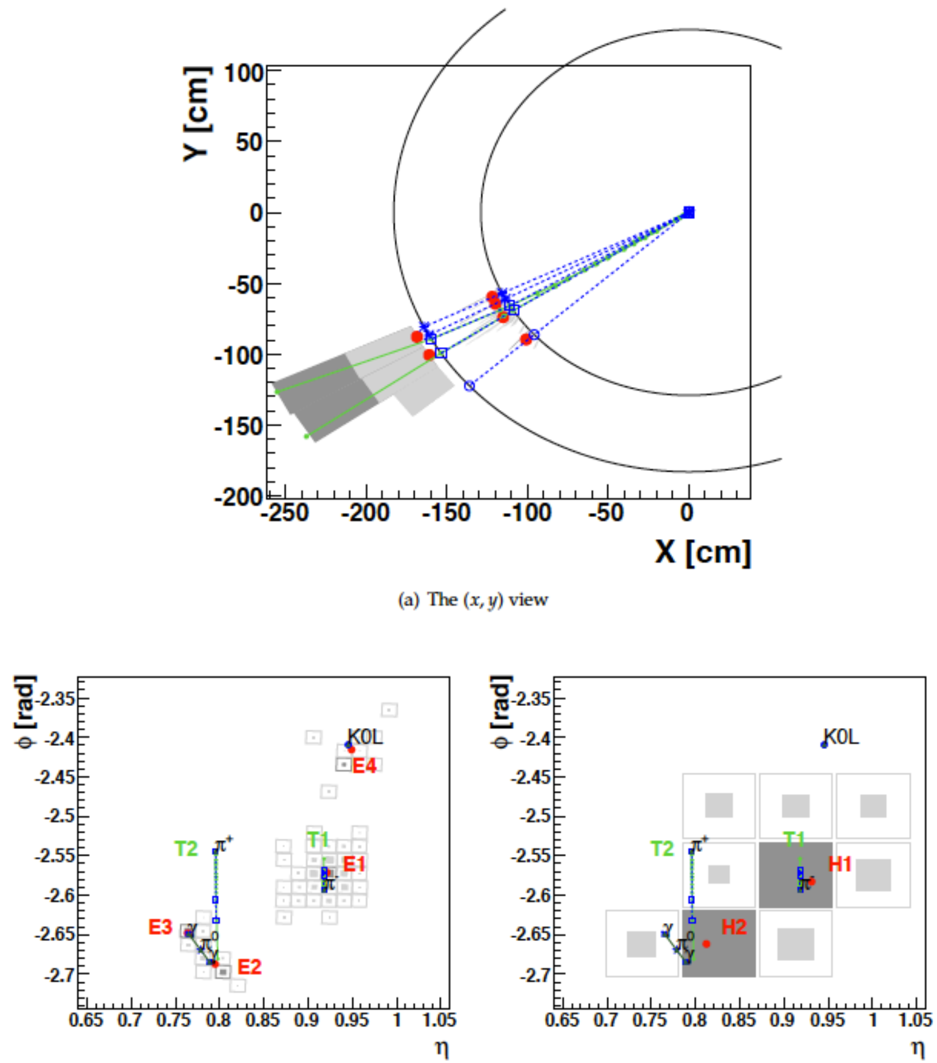
Particle Flow and Jets/MET

- As mentioned, optimizing the information from the detector as a whole can pay significant dividends.





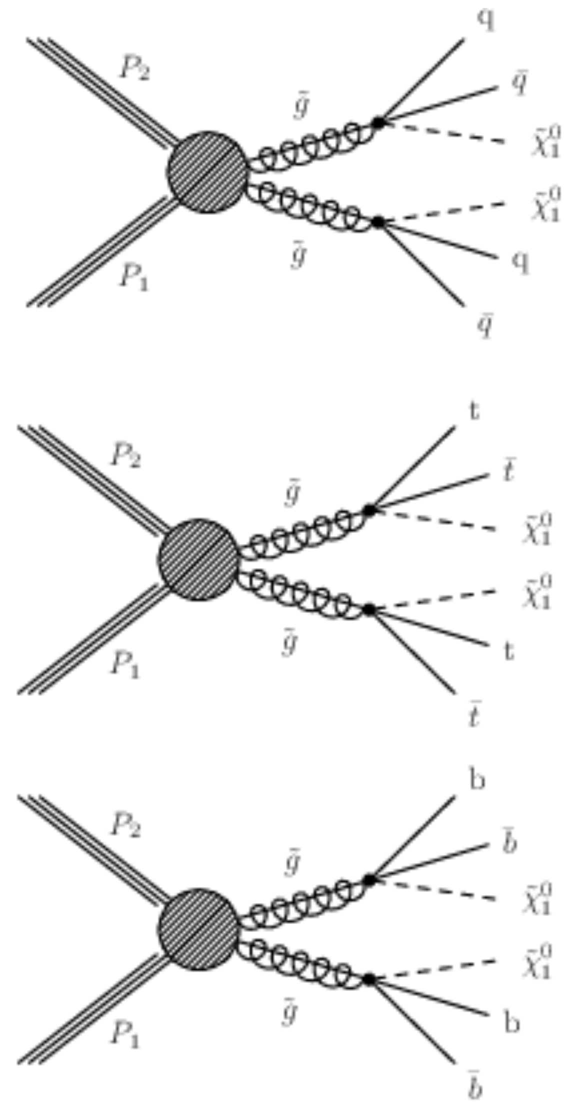
- Use the detector's best estimate of the particle energy:
  - Ex. :Charged pion →Tracker tracks
  - Ex.: Neutral pion/ photon: ECAL
- Accounting for each "particle" individually gives a much more accurate estimate for the visible energy and thus the missing E_T.



(a) The (x, y) view

Jets plus missing E_T

- Really one of the most sensitive analyses in general for SUSY searches. Can be done inclusively, but there's a sensitivity gain to examining this final state in bins of the number of jets as well as the number of b-tags.
- Shown is only an example set of the simplified models tested.



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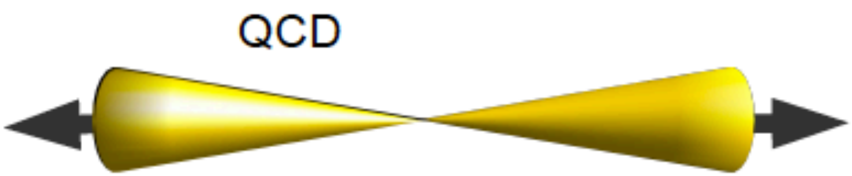
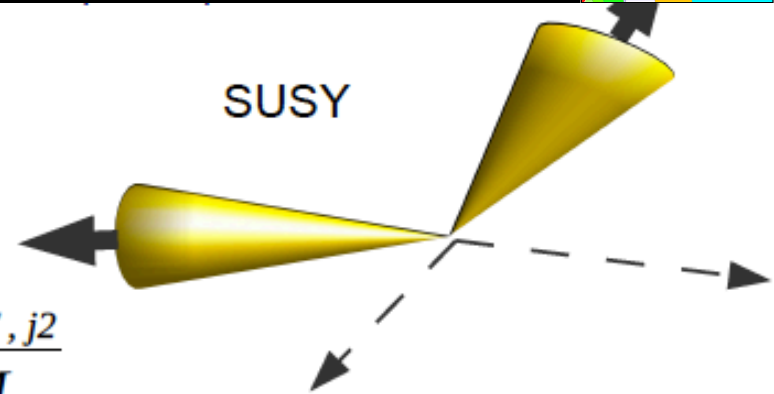
Need to measure missing transverse energy well!





- α_T defined to limit contributions from mismeasured multijet events.
- In principle only those events with true missing E_T should be at large values of α.

$$\alpha_T = \frac{p_{T,j2}}{M_T}$$

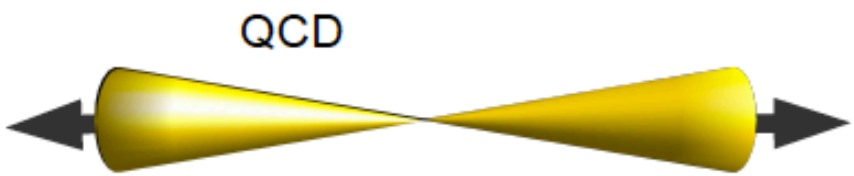
$$M_T = \sqrt{2 p_{T,j1} p_{T,j2} (1 - \cos(\Delta\phi))}$$

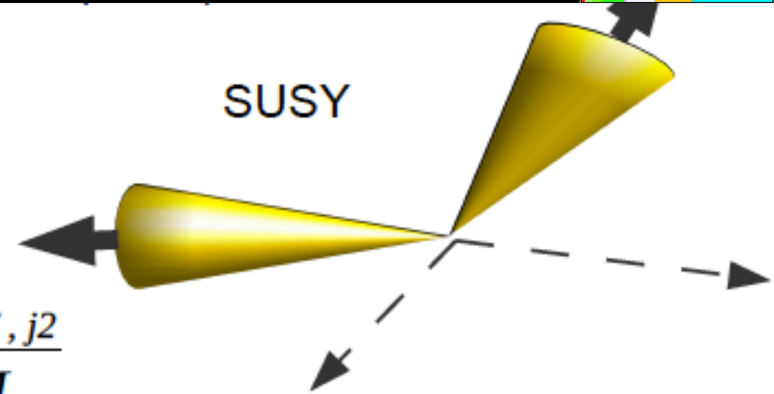
$$\rightarrow \alpha_T = \sqrt{\frac{p_{T,j2} / p_{T,j1}}{2(1 - \cos\Delta\phi)}}$$

In QCD: $\alpha_T \leq 0.5$ since $p_{T,j2}$ is by definition the lower momentum jet.
Exception: A third jet is completely lost.

For more than two jets, we group jets together to minimize the E_T difference between the groups.

Need to measure missing transverse energy well!





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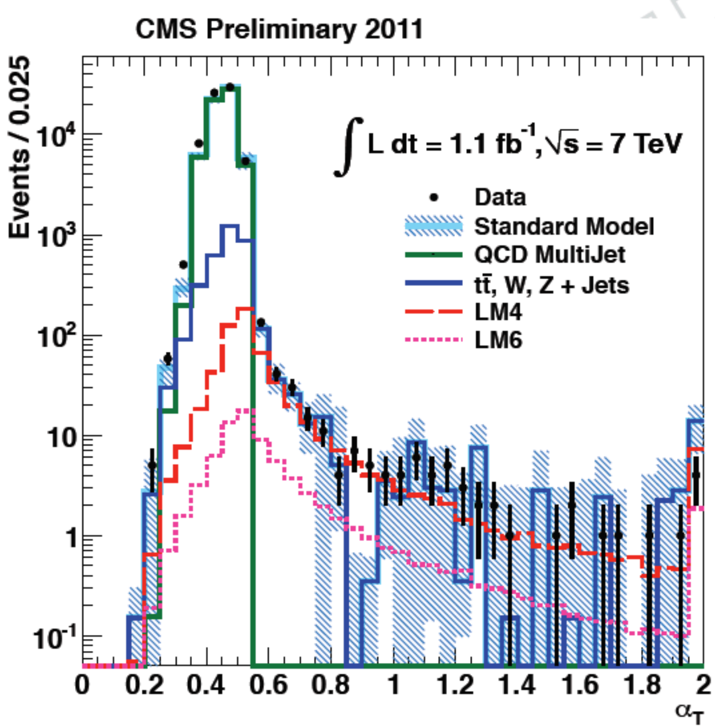
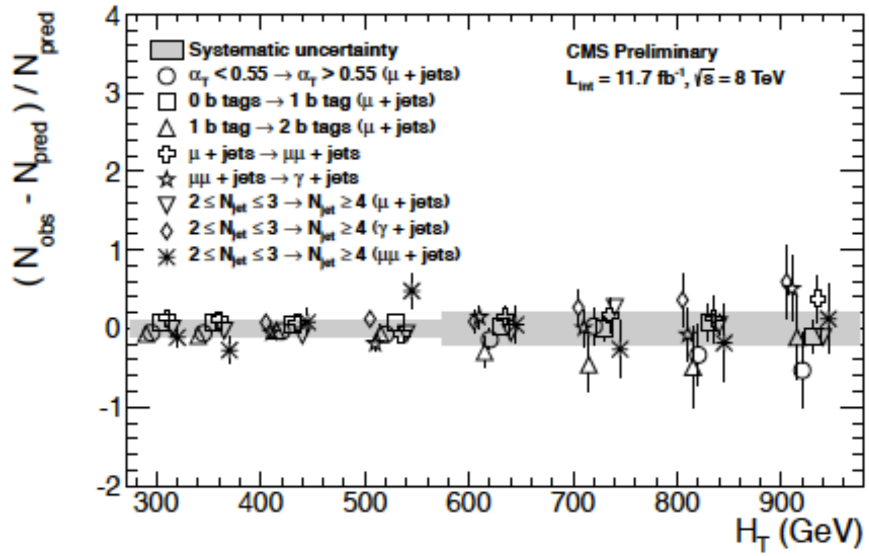


In QCD: $\alpha_T \leq 0.5$ since $p_{T,j2}$ is by definition the lower momentum jet.
Exception: A third jet is completely lost.

This is an older plot for illustration only. Non-missing E_T backgrounds are concentrated at low values of α.

Electroweak backgrounds:

- Electroweak backgrounds are estimated using a data control samples (μ+jets, μμ+jets, γ+jets) weighted by translation factors from the Monte Carlo.
- Each sample in each multiplicity bin is required to pass closure tests which model the expected number of events in the other control samples.

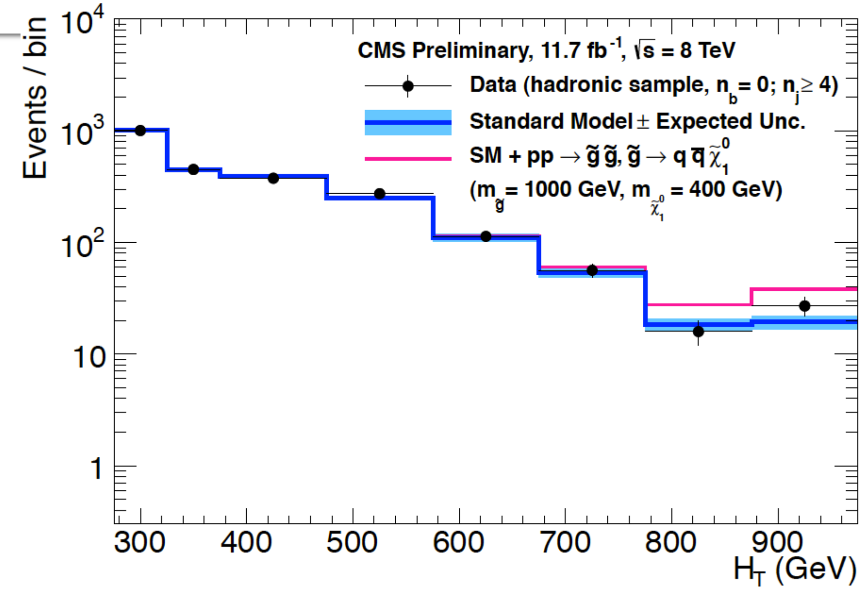


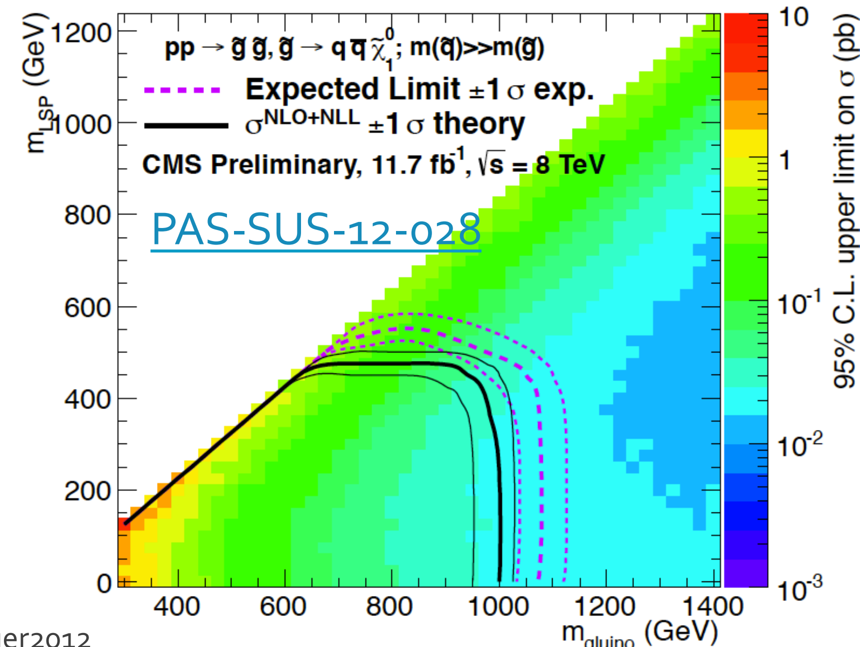
(a) $2 \le n_{\mathrm{jet}} \le 3$

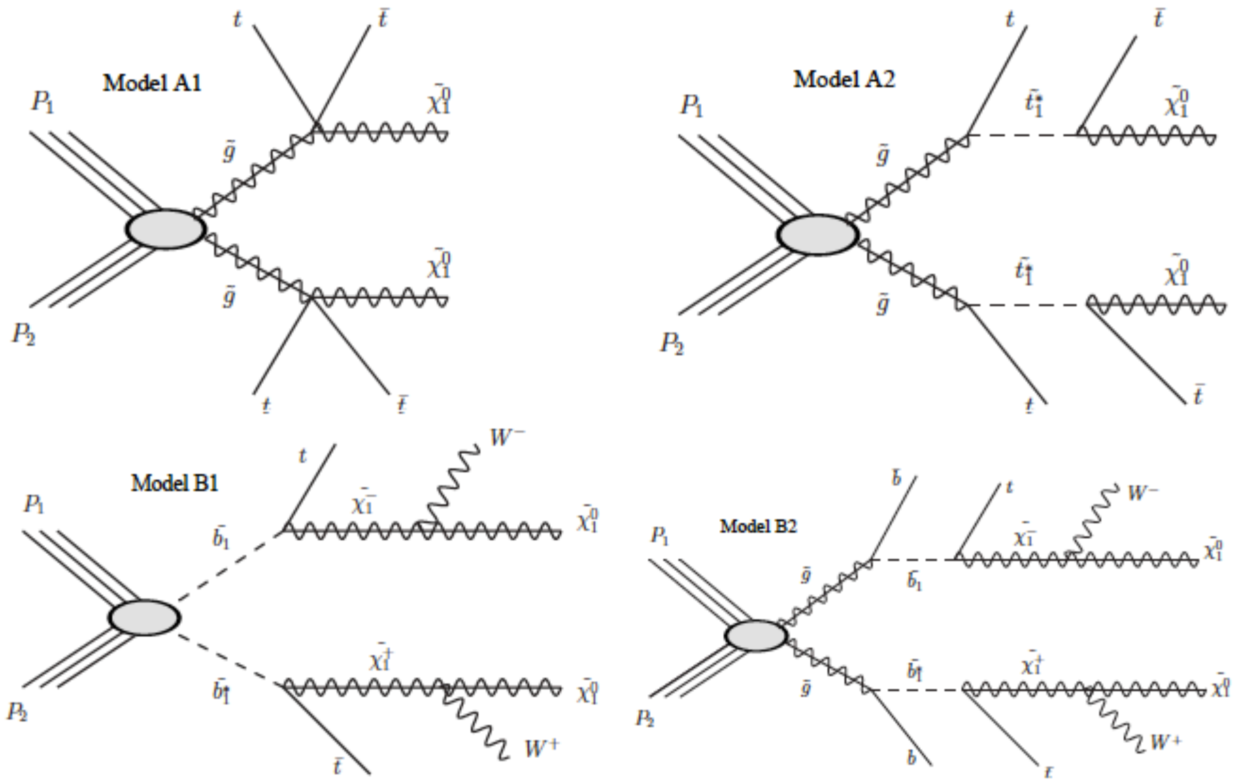
$$N^{\mathrm{signal}}_{\mathrm{pred}}(n_{\mathrm{jet}}, H_{\mathrm{T}}, n^{\mathrm{reco}}_{\mathrm{b}}) = N^{\mathrm{control}}_{\mathrm{obs}}(n_{\mathrm{jet}}, H_{\mathrm{T}}, n^{\mathrm{reco}}_{\mathrm{b}}) \times \frac{N^{\mathrm{signal}}_{\mathrm{MC}}}{N^{\mathrm{control}}_{\mathrm{MC}}}(n_{\mathrm{jet}}, H_{\mathrm{T}}, n^{\mathrm{reco}}_{\mathrm{b}})$$

Putting it all together:

- Limits are set by doing a maximum likelihood fit over all bins of H_T, N_j and N_b.
- All of the control samples are well modeled, and no excess is observed above the SM expectation.



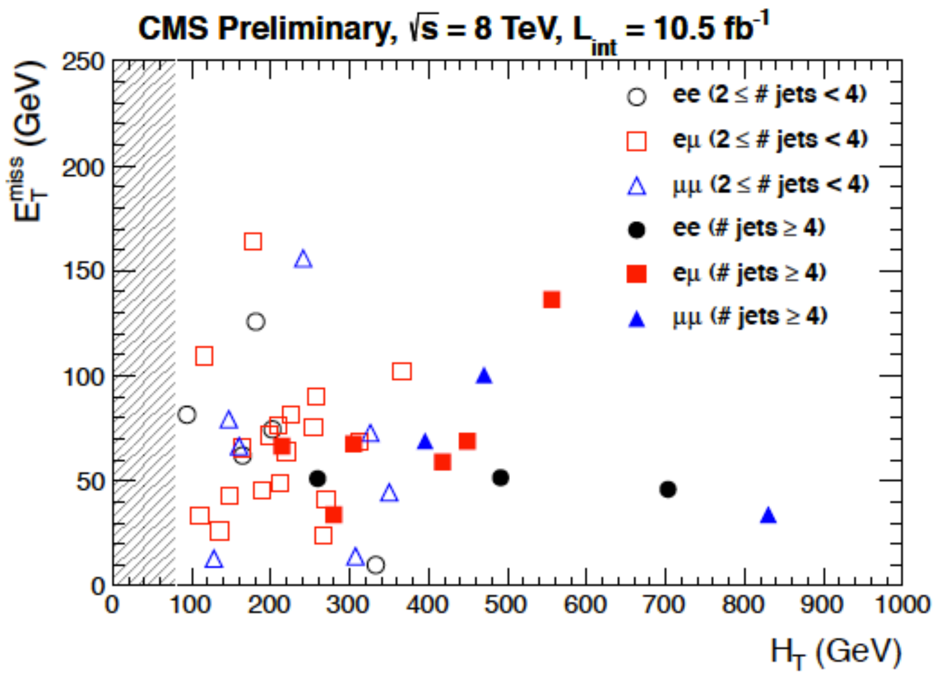




- Again, searching for gluino production, but in a more specific way, with far lower backgrounds, due to the very low rate of SM processes with same sign leptons.

Candidates:

- Events are required to have at least two leptons with $p_T > 20$, and at least two jets with $p_T > 40$ GeV.
  - Bins of number of b-tags and jets are then considered, with various missing E_T requirements
  - The greyed area corresponds to 80 GeV (since 2 jets of 40 GeV are required, this area is naturally eliminated)



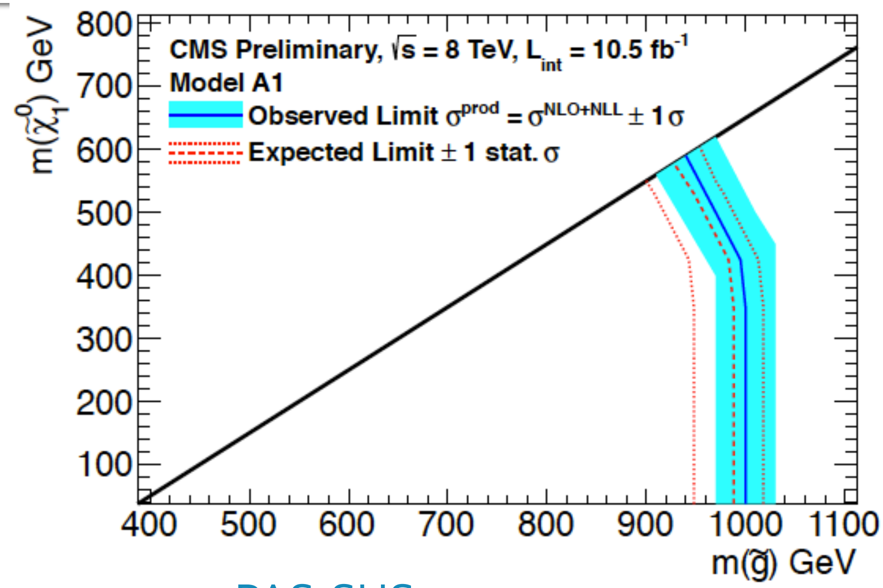
Backgrounds:

- Fake leptons: Real same sign leptons are hard to come by in the SM, but fake ones will have random signs.
- Charge misidentification: More significant a problem for electrons than muons, characterized in data cross checked in MC.
- Same sign leptons: Rare processes like ttW and ttZ.

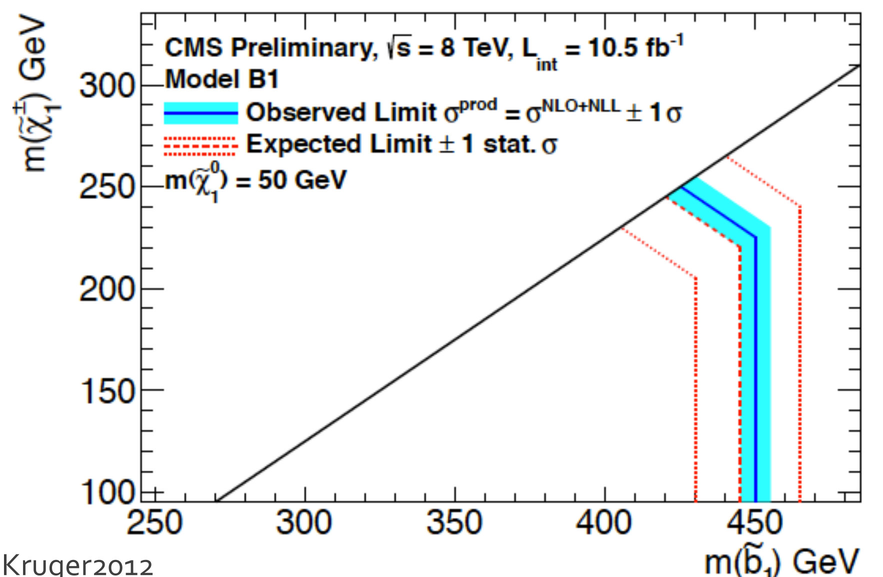
No. of jets	≥ 2	≥ 2	≥ 2	≥ 4	≥ 4	≥ 4	≥ 4	≥ 3	≥ 4
No. of btags	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 3	≥ 2
Lepton charges	$++/--$	$++/--$	$++$	$++/--$	$++/--$	$++/--$	$++/--$	$++/--$	$++/--$
E_T^{miss}	> 0 GeV	> 30 GeV	> 30 GeV	> 120 GeV	> 50 GeV	> 50 GeV	> 120 GeV	> 50 GeV	> 0 GeV
H_T	> 80 GeV	> 80 GeV	> 80 GeV	> 200 GeV	> 200 GeV	> 320 GeV	> 320 GeV	> 200 GeV	> 320 GeV
Charge-flip BG	3.35 ± 0.67	2.70 ± 0.54	1.35 ± 0.27	0.04 ± 0.01	0.21 ± 0.05	0.14 ± 0.03	0.04 ± 0.01	0.03 ± 0.01	0.21 ± 0.05
Fake BG	24.77 ± 12.62	19.18 ± 9.83	9.59 ± 5.02	0.99 ± 0.69	4.51 ± 2.85	2.88 ± 1.69	0.67 ± 0.48	0.71 ± 0.47	4.39 ± 2.64
Rare SM BG	11.75 ± 5.89	10.46 ± 5.25	6.73 ± 3.39	1.18 ± 0.67	3.35 ± 1.84	2.66 ± 1.47	1.02 ± 0.60	0.44 ± 0.39	3.50 ± 1.92
Total BG	39.87 ± 13.94	32.34 ± 11.16	17.67 ± 6.06	2.22 ± 0.96	8.07 ± 3.39	5.67 ± 2.24	1.73 ± 0.77	1.18 ± 0.61	8.11 ± 3.26
Event yield	43	38	14	1	10	7	1	1	9
N_{UL} (13% unc.)	27.2	26.0	9.9	3.6	10.8	8.6	3.6	3.7	9.6
N_{UL} (20% unc.)	28.2	27.2	10.2	3.6	11.2	8.9	3.7	3.8	9.9
N_{UL} (30% unc.)	30.4	29.6	10.7	3.8	12.0	9.6	3.9	4.0	10.5

Limits:

- Since the observed events are well modeled by the predictions, limits are set using the most sensitive set of cuts for the particular model.
- Two are shown here, for the models A1 (disquark decays to top) and B1 (sbottom production and decay).

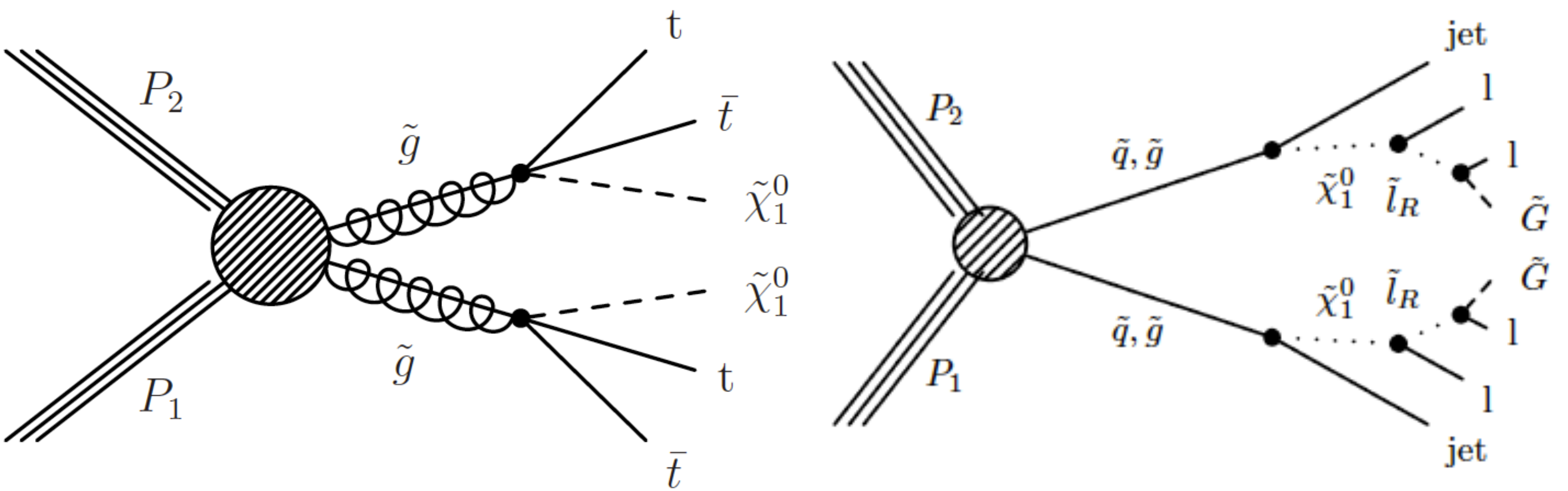


PAS-SUS-12-029



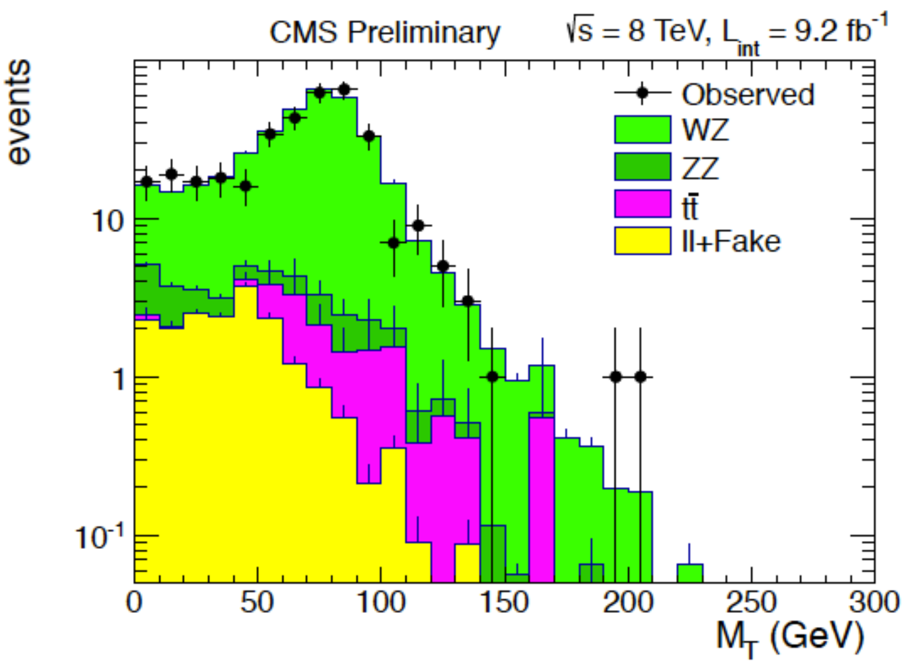
Multilepton signatures

- The first model shown here is akin to the last analysis, however a generalized approach was taken, which provides additional sensitivity to the alternative on the right.



Selection:

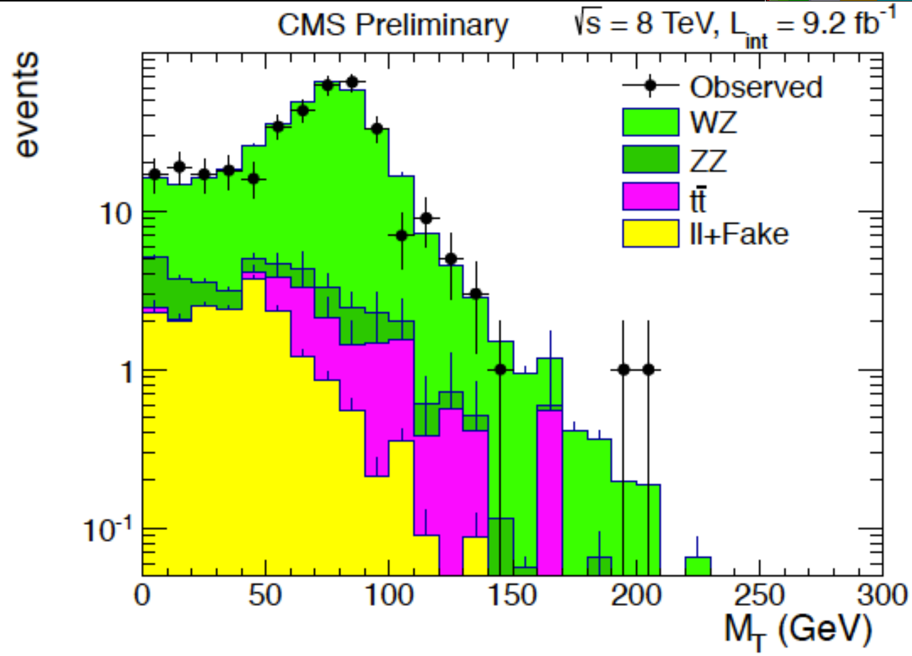
- Events are required to have at least three leptons, with at most one hadronically decaying tau. The leading muon or electron is required to have p_T > 20 , the next muon or electron is required to have p_T >10 Gev.
- Events are then classified by flavor (and presence of a tau), charge, missing transverse energy, additional leptons, H_T and b-tagged jets.

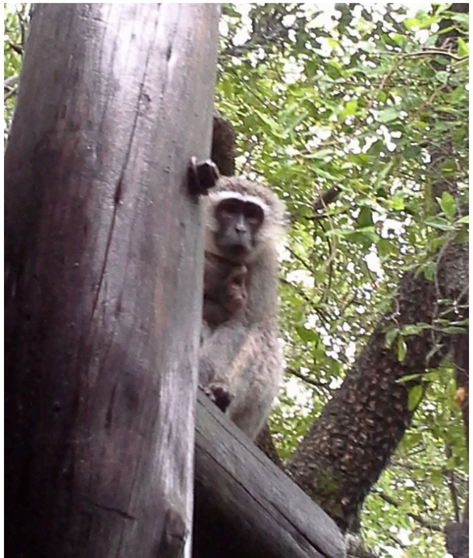


This is a control region plot in which there are three leptons, two of which are within the Z-mass range, with opposite sign, and the same flavor.

Selection:

- Events are required to have at least three leptons, with at most one hadronically decaying tau. The leading muon or electron is required to have $p_T > 20$, the next muon or electron is required to have $p_T >10$ Gev.
- Events are then classified by flavor (and presence of a tau), charge, missing transverse energy, additional leptons, H_T and b-tagged jets.





Putting it together:

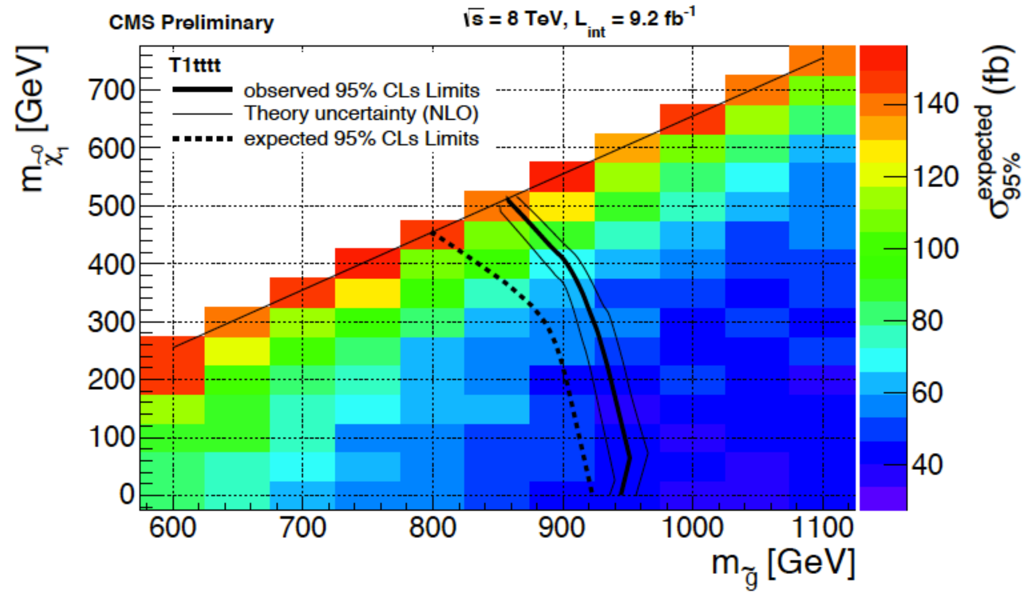
Selection		MET	N(τ)=0, Nbjet=0 obs	N(τ)=0, Nbjet=0 expect	N(τ)=1, Nbjet=0 obs	N(τ)=1, Nbjet=0 expect	N(τ)=0, Nbjet≥1 obs	N(τ)=0, Nbjet≥1 expect	N(τ)=1, Nbjet≥1 obs	N(τ)=1, Nbjet≥1 expect
3 Lepton Results $H_T > 200$										
OSSF0	NA	$(100,\infty)$	1	1.9 ± 1.2	15	7.7 ± 3.6	1	2.9 ± 1.5	27	21 ± 11
OSSF0	NA	$(50,100)$	1	1.4 ± 0.8	13	17 ± 7.4	1	4.2 ± 1.7	41	37 ± 19
OSSF0	NA	$(0,50)$	2	1 ± 0.8	13	10 ± 3.4	0	1.9 ± 0.8	32	21 ± 11
OSSF1	above-Z	$(100,\infty)$	2	2.2 ± 0.9	2	4 ± 2.4	3	2.8 ± 1.3	11	6.8 ± 3.7
OSSF1	below-Z	$(100,\infty)$	2	3.5 ± 0.8	8	7.6 ± 3.4	3	3.4 ± 1.6	12	8.3 ± 4.3
OSSF1	on-Z	$(100,\infty)$	17	30 ± 5.3	4	7.9 ± 2.2	5	6.3 ± 1.9	8	5.4 ± 2.8
OSSF1	above-Z	$(50,100)$	1	1.9 ± 0.49	10	3.7 ± 2.3	4	3.1 ± 1.2	17	12 ± 6.6
OSSF1	below-Z	$(50,100)$	4	4.5 ± 0.9	11	6.4 ± 2.4	3	5 ± 2.1	9	9.4 ± 5.3
OSSF1	on-Z	$(50,100)$	39	38 ± 6.2	34	26 ± 5.4	10	9.6 ± 2.7	12	9.5 ± 3.9
OSSF1	above-Z	$(0,50)$	3	3.2 ± 0.42	19	18 ± 4.5	0	2.7 ± 0.8	6	9.9 ± 4.6
OSSF1	below-Z	$(0,50)$	9	11 ± 1.2	57	43 ± 10	2	4.7 ± 1.4	11	13 ± 5.3
OSSF1	on-Z	$(0,50)$	58	63 ± 8.7	256	271 ± 66	12	14 ± 2.6	39	34 ± 7.9

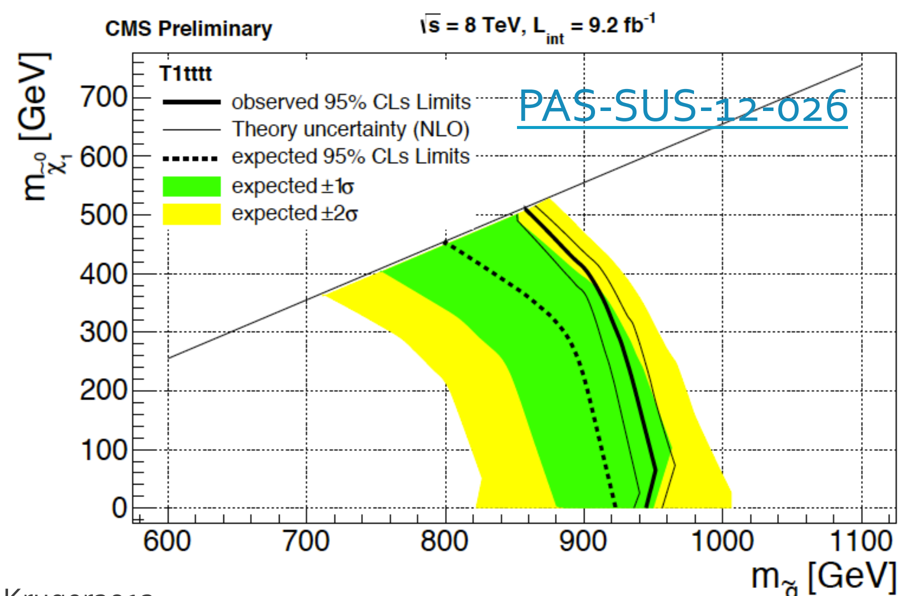
Selection		MET	N(τ)=0, Nbjet=0 obs	N(τ)=0, Nbjet=0 expect	N(τ)=1, Nbjet=0 obs	N(τ)=1, Nbjet=0 expect	N(τ)=0, Nbjet≥1 obs	N(τ)=0, Nbjet≥1 expect	N(τ)=1, Nbjet≥1 obs	N(τ)=1, Nbjet≥1 expect
3 Lepton Results $H_T < 200$										
OSSF0	NA	$(100,\infty)$	3	4.5 ± 2.3	45	44 ± 22	8	5.1 ± 2.7	41	44 ± 23
OSSF0	NA	$(50,100)$	16	17 ± 7.5	186	190 ± 63	16	11 ± 4.9	131	119 ± 67
OSSF0	NA	$(0,50)$	23	27 ± 6.7	429	457 ± 100	17	8.9 ± 3.6	109	115 ± 52
OSSF1	above-Z	$(100,\infty)$	11	5.5 ± 1.2	10	15 ± 8	4	3.1 ± 1.6	10	18 ± 8.2
OSSF1	below-Z	$(100,\infty)$	6	10 ± 3.9	20	23 ± 10	7	7.8 ± 4.1	23	21 ± 11
OSSF1	on-Z	$(100,\infty)$	65	75 ± 11	22	22 ± 5.9	7	5.2 ± 1.9	8	11 ± 5.5
OSSF1	above-Z	$(50,100)$	21	20 ± 4.2	78	53 ± 17	5	10 ± 4.8	35	39 ± 20
OSSF1	below-Z	$(50,100)$	66	56 ± 13	167	149 ± 34	26	20 ± 9.7	72	56 ± 27
OSSF1	on-Z	$(50,100)$	351∗	368 ± 57	533	457 ± 100	29	18 ± 4.6	40	37 ± 15
OSSF1	above-Z	$(0,50)$	83	101 ± 9.8	841	845 ± 204	10	10 ± 3.7	65	40 ± 15
OSSF1	below-Z	$(0,50)$	258	282 ± 29	4820	4113 ± 1018	16	21 ± 6	111	107 ± 27
OSSF1	on-Z	$(0,50)$	1888∗	2104 ± 196	24303	22663 ± 5643	65∗	69 ± 8.8	426	414 ± 99

- This is mainly a joke (I don't expect you to read these tables), just so that you get a feeling for the level of classification and characterization that has been done here. And this is merely for the case where one has only three leptons, there's more of these.

Results:

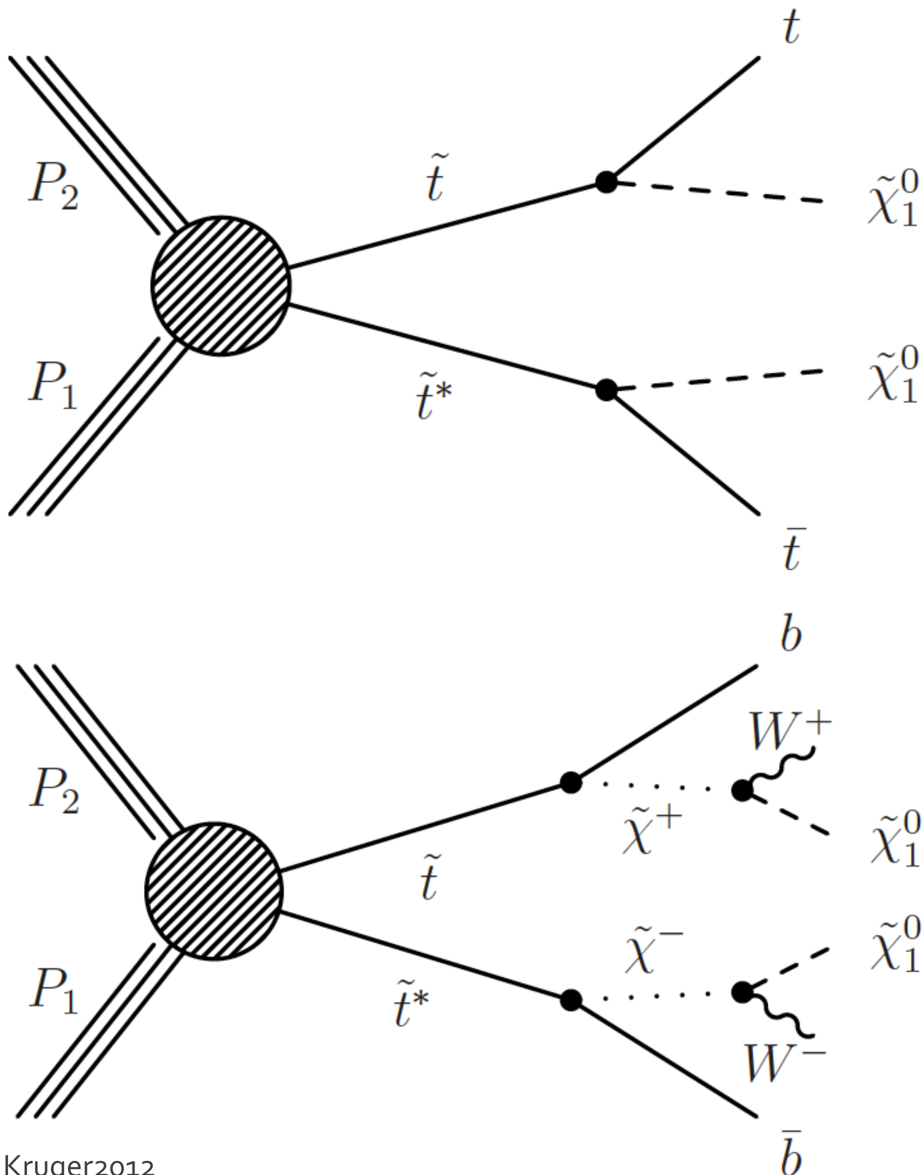
- Overall, all of the many (MANY) bins are consistent with expectations, and thus all different classifications are used to set limits in the generalized model.





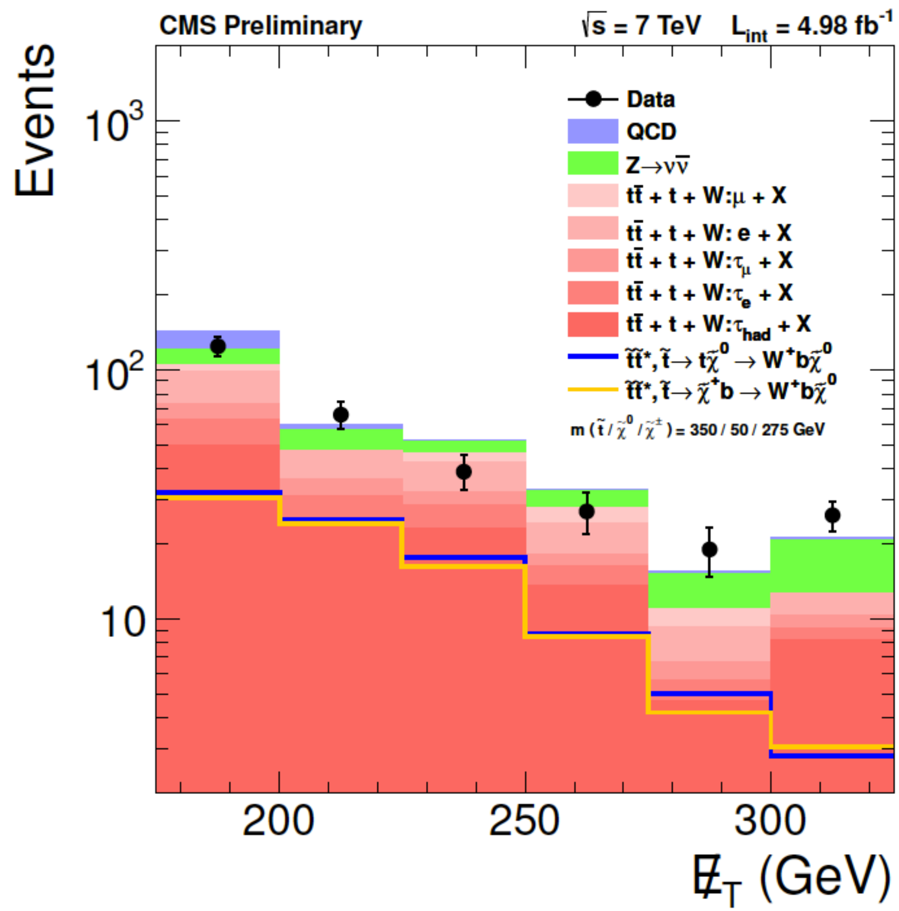
All Hadronic Stops:

- Given the large Yukawa coupling of the top to the Higgs, the stop is expected to play a dominant role in "naturalizing" the corrections to the Higgs mass.
- For the two scenarios shown here, the branching fraction should be largest searching for at least two b-jets, multiple other jets, and missing E_T.



Selection:

- Try to maintain sensitivity to both scenarios:
  - At least five jets, with at least one b-tagged.
  - Separate jets from the missing E_T, and veto on isolated leptons.
  - Use embedding of simulated leptons in data events to estimate W+jets/ditop backgrounds in realistic environment.



Optimization:

- Given that the backgrounds are still large compared to the expected signal yields, three separate kinematic ranges were defined: loose, medium and tight, besides the baseline scenario.
- The differences between them are the cuts on missing E_T and jet multiplicity.

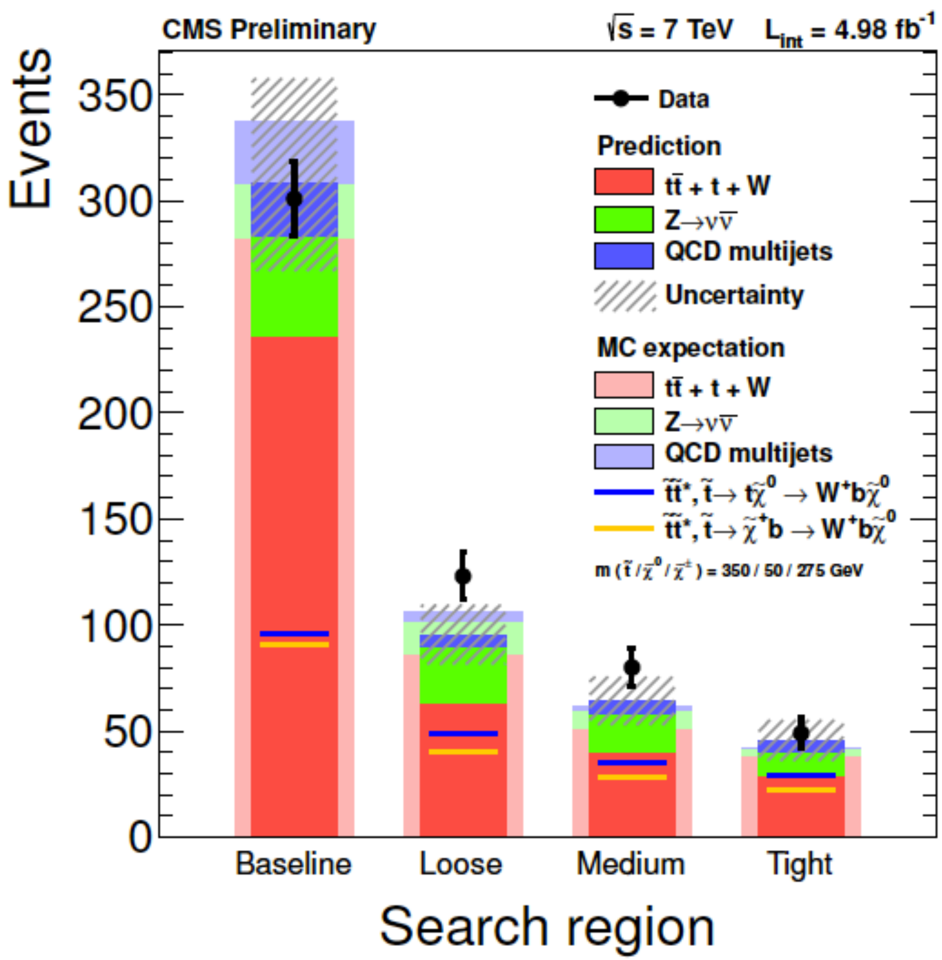
Loose: $\min|\Delta\phi(\vec{\not{E}}_T, \vec{p}_{T,b})| \geq 1.0$ and $(\not{E}_T \geq 175 \wedge n_j \geq 7) \vee (\not{E}_T \geq 200 \wedge n_j \geq 5)$

Medium: $\min|\Delta\phi(\vec{\not{E}}_T, \vec{p}_{T,b})| \geq 1.0$ and $(\not{E}_T \geq 175 \wedge n_j \geq 7) \vee (\not{E}_T \geq 200 \wedge n_j \geq 6)$ $\vee (\not{E}_T \geq 250 \wedge n_j \geq 5)$

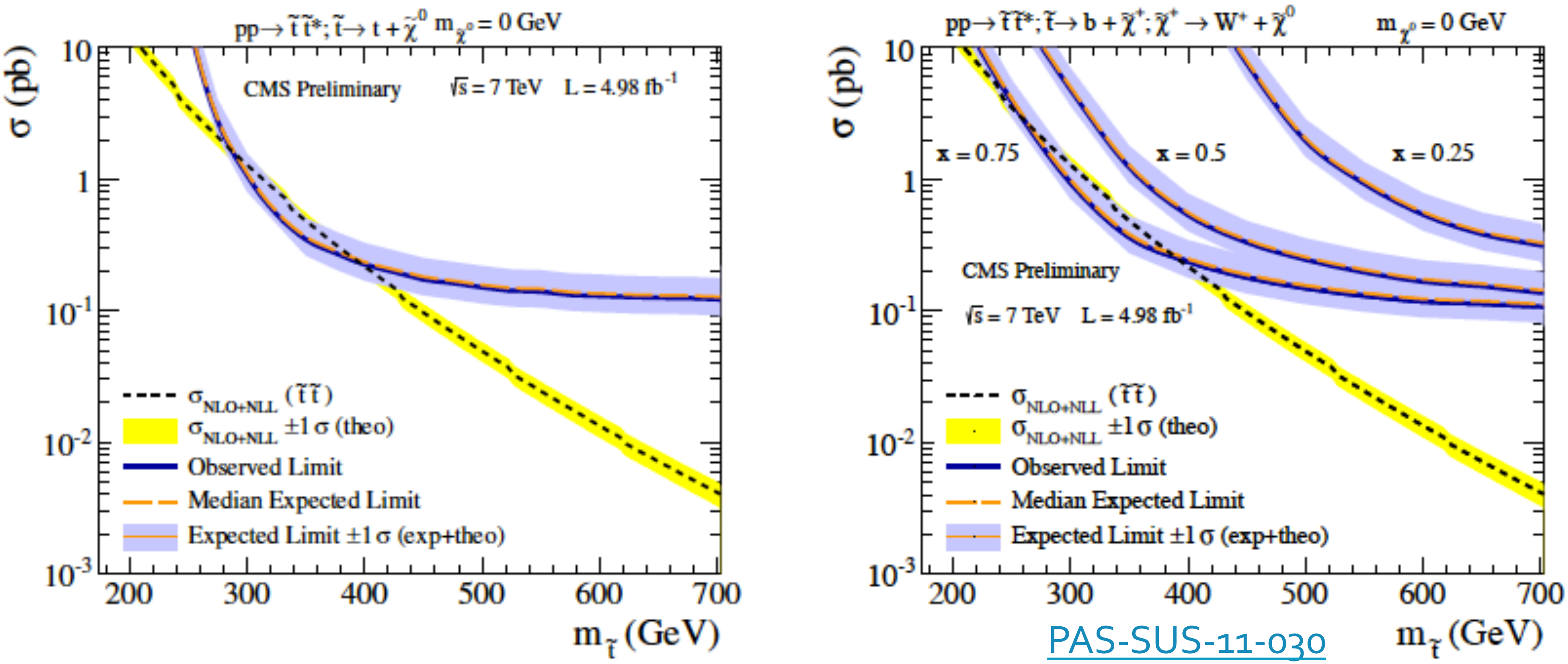
Tight: $\min|\Delta\phi(\vec{\not{E}}_T, \vec{p}_{T,b})| \geq 1.0$ and $(\not{E}_T \geq 175 \wedge n_j \geq 7) \vee (\not{E}_T \geq 200 \wedge n_j \geq 6)$

Results:

- The expected number of events corresponded quite closely with the observed number in each different category, which gives confidence in the ambitious modeling of the backgrounds.
- In the end, with all uncertainties from the background estimates taken into account, the baseline scenario gave the best expected limit, though the other selections are shown for completeness.



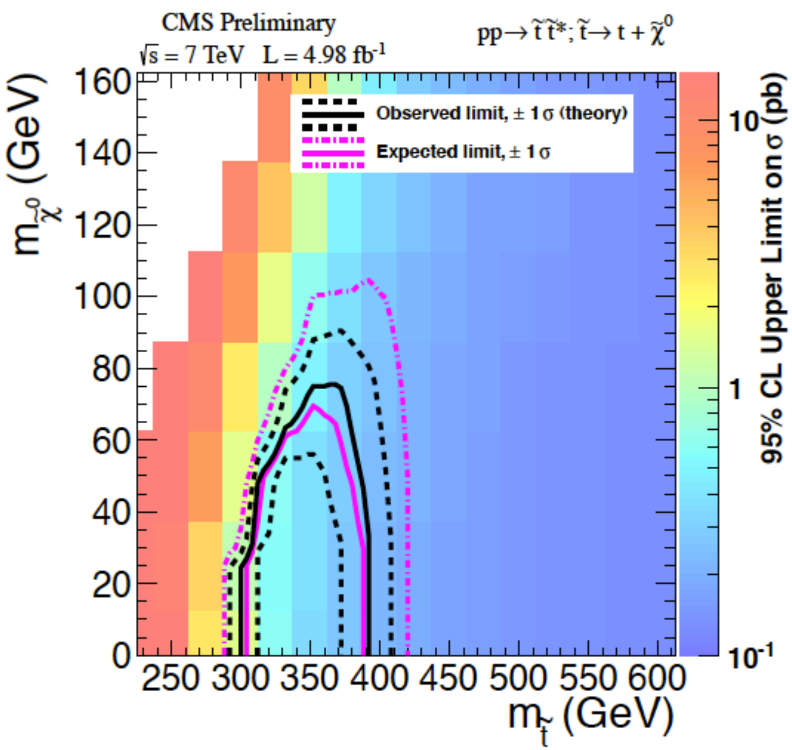
Limits:

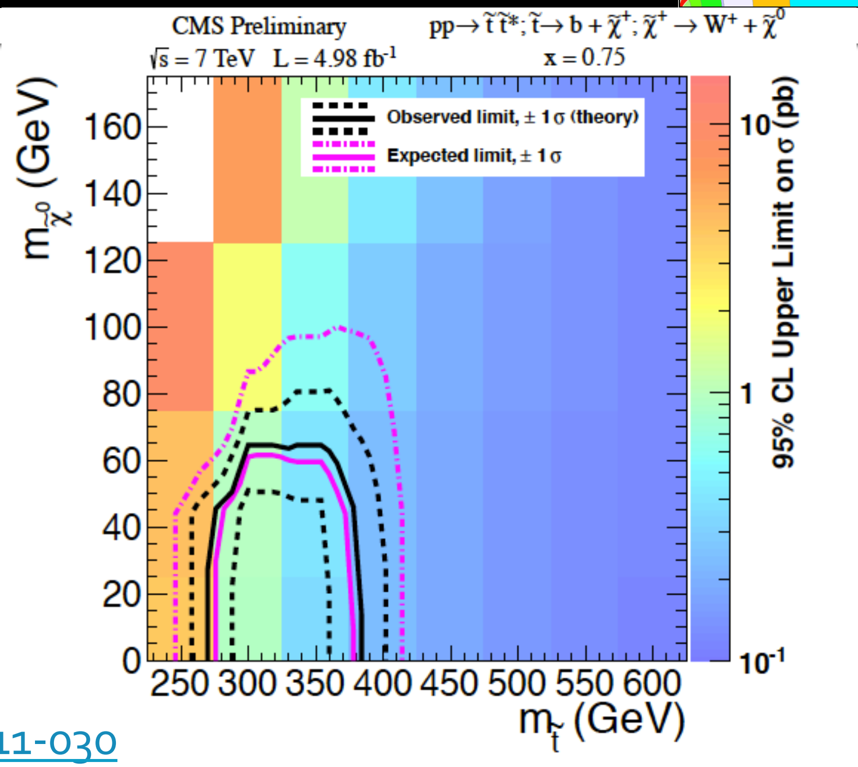


[PAS-SUS-11-030](PAS-SUS-11-030)

- The corresponding limits for the baseline selection, using the 2011 dataset.

Limits:



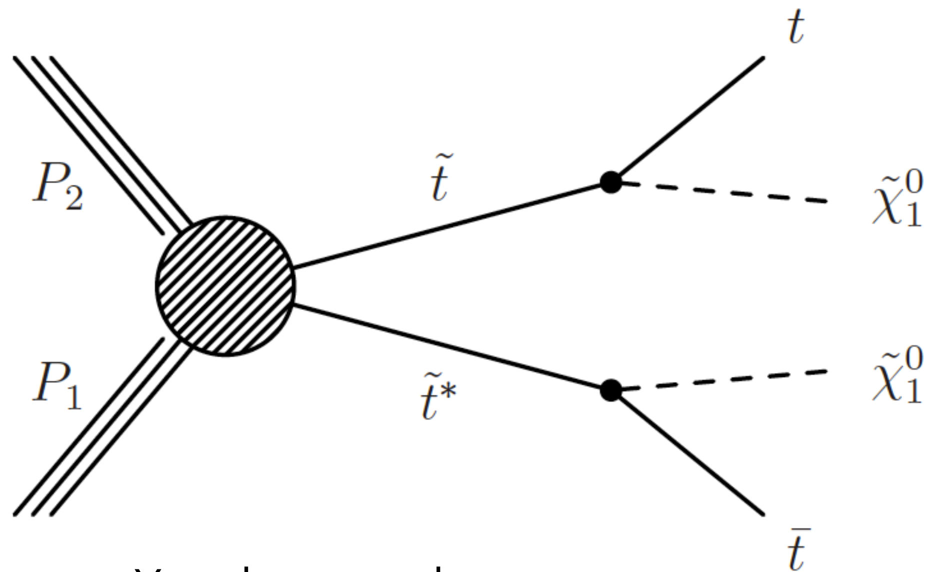


PAS-SUS-11-030

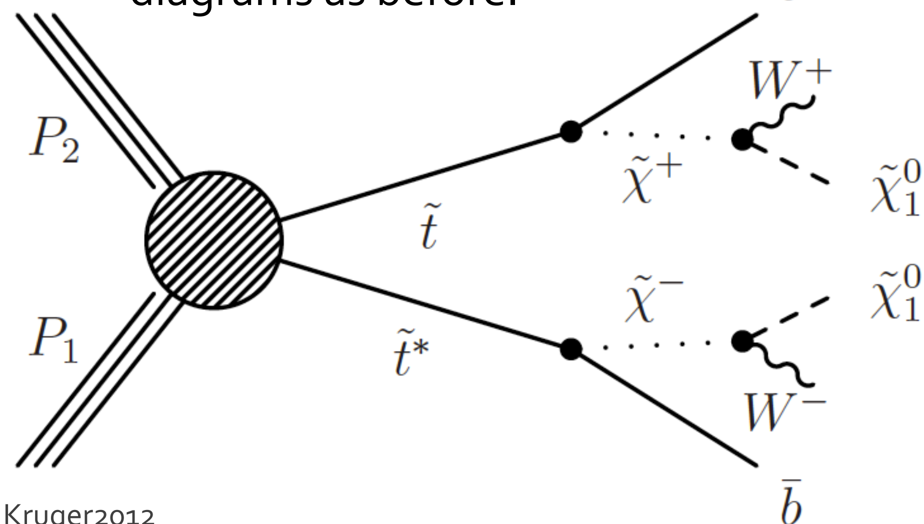
- The corresponding limits for the baseline selection, using the 2011 dataset.

Stop search using M_T

- In contrast with the all hadronic analysis, we also search for stop production by requiring leptons (as opposed to vetoing them), and using the transverse mass reduce the background from SM processes like ditop and W+jets.



Yes, these are the same diagrams as before.



Backgrounds:

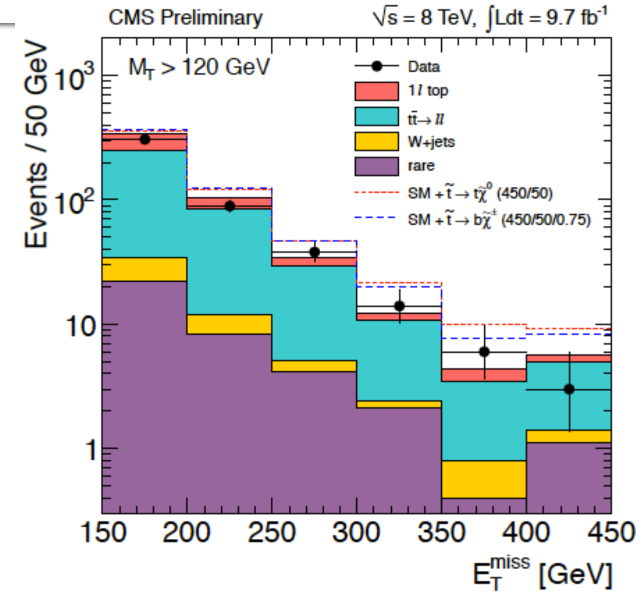
Selection Criteria	exactly 1 lepton	exactly 2 leptons	1 lepton + isolated track
0 b-tags	CR1) W+Jets dominated: Validate W+Jets M_T tail	CR2) apply Z-mass constraint $\rightarrow$ Z+Jets dominated: Validate $t\bar{t} \rightarrow \ell + \text{jets}$ M_T tail comparing data vs. MC "pseudo-M_T"	CR3) not used
≥ 1 b-tags	SIGNAL REGION	CR4) Apply Z-mass veto $\rightarrow t\bar{t} \rightarrow \ell\ell$ dominated: Validate "physics" modeling of $t\bar{t} \rightarrow \ell\ell$	CR5) $t\bar{t} \rightarrow \ell\ell$, $t\bar{t} \rightarrow \ell\tau$ and $t\bar{t} \rightarrow \ell\text{fake}$ dominated: Validate τ and fake lepton modeling/ detector effects in $t\bar{t} \rightarrow \ell\ell$

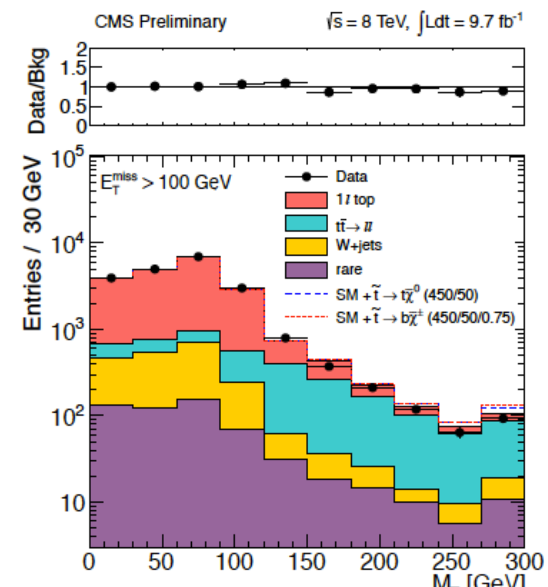
- Backgrounds are mainly found from Monte Carlo, with some normalizations set in the low transverse mass region and extrapolated into the signal area.
- Multiple control samples are used in order to verify a good description.

Signal Region:

- A number of different M_T and missing E_T cuts are considered for the final cross section limits. For each part of parameter space, the cuts that gave the best expected limits were used.

Signal Region	Minimum M_T [GeV]	Minimum E_T^{miss} [GeV]
SRA	150	100
SRB	120	150
SRC	120	200
SRD	120	250
SRE	120	300
SRF	120	350
SRG	120	400

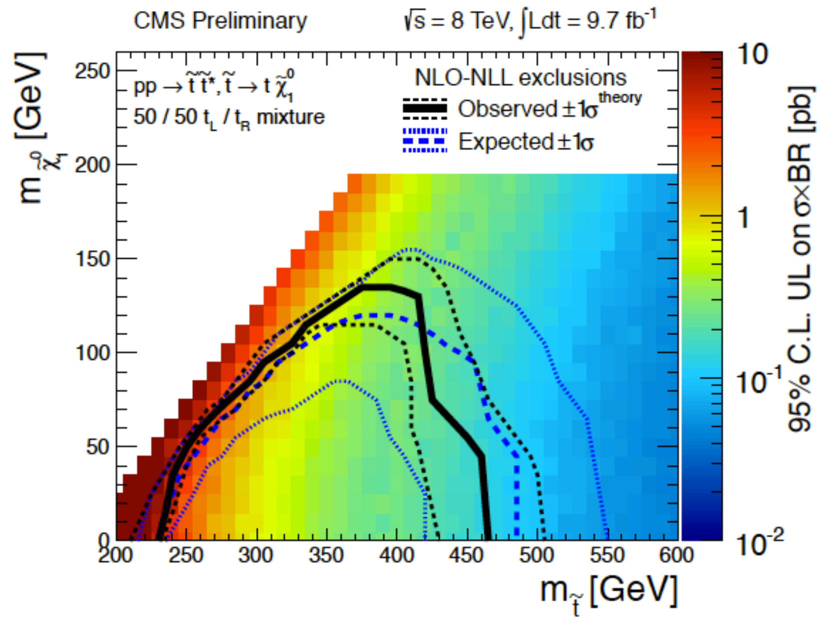


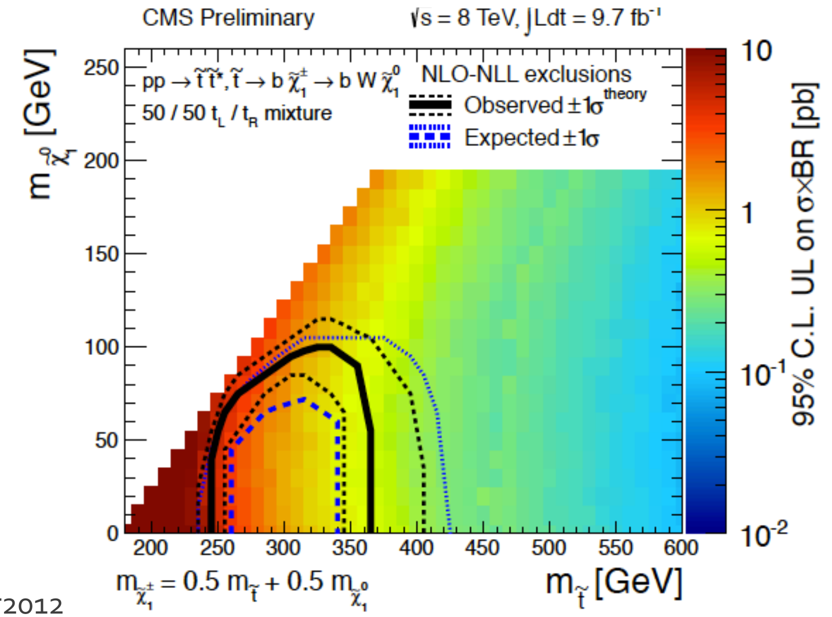


Limits:

PAS-SUS-12-023

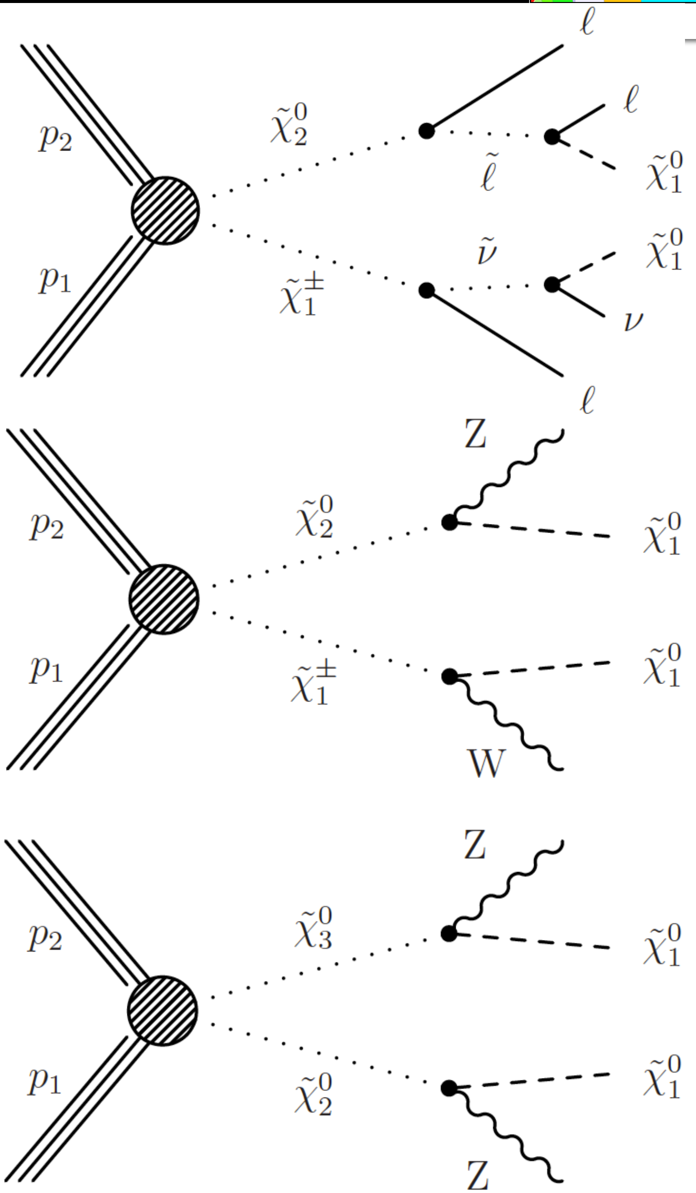
- Limits on stop production, both in the scenario stop→top, and with the intermediate chargino.
- Observed limits are in the range 275-450 GeV.



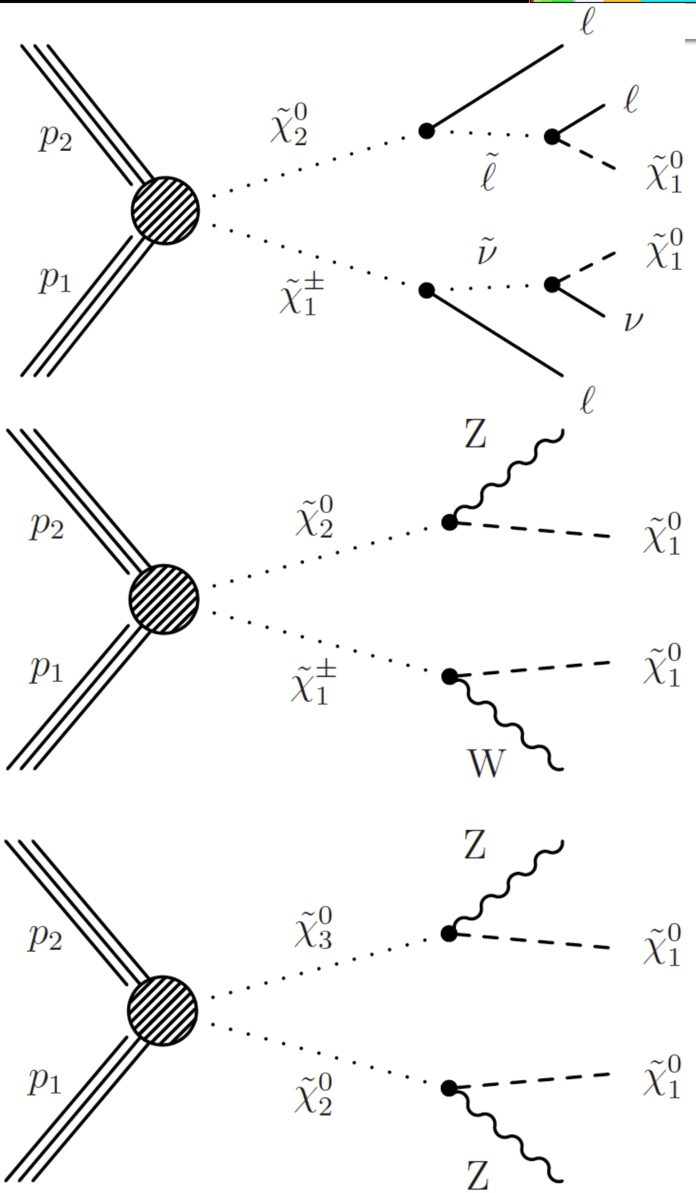


Charginos and Neutralinos (EWKino)

- This analysis is a focused searches for electroweak production of charginos and neutralinos.
- Spans multiple final states: three lepton, two same sign lptons, four lepton,two lepton+two jets, and two non-resonant leptons. The commonality is that there is very little associated hadronic activity (b-jets are explicitly vetoed).

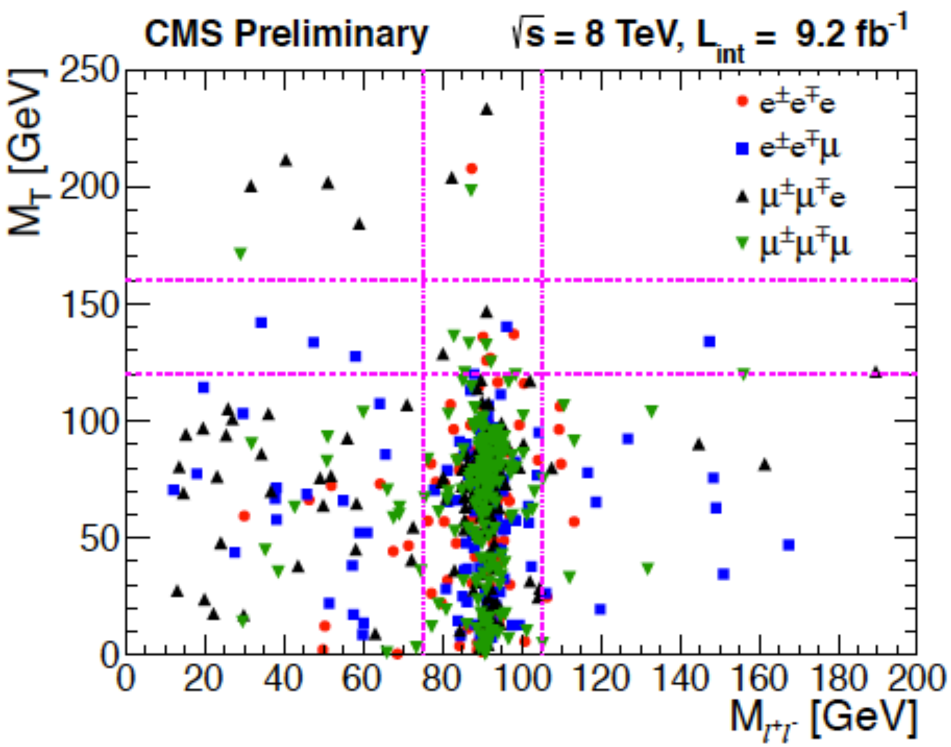


Charginos and Neutralinos (EWKino)



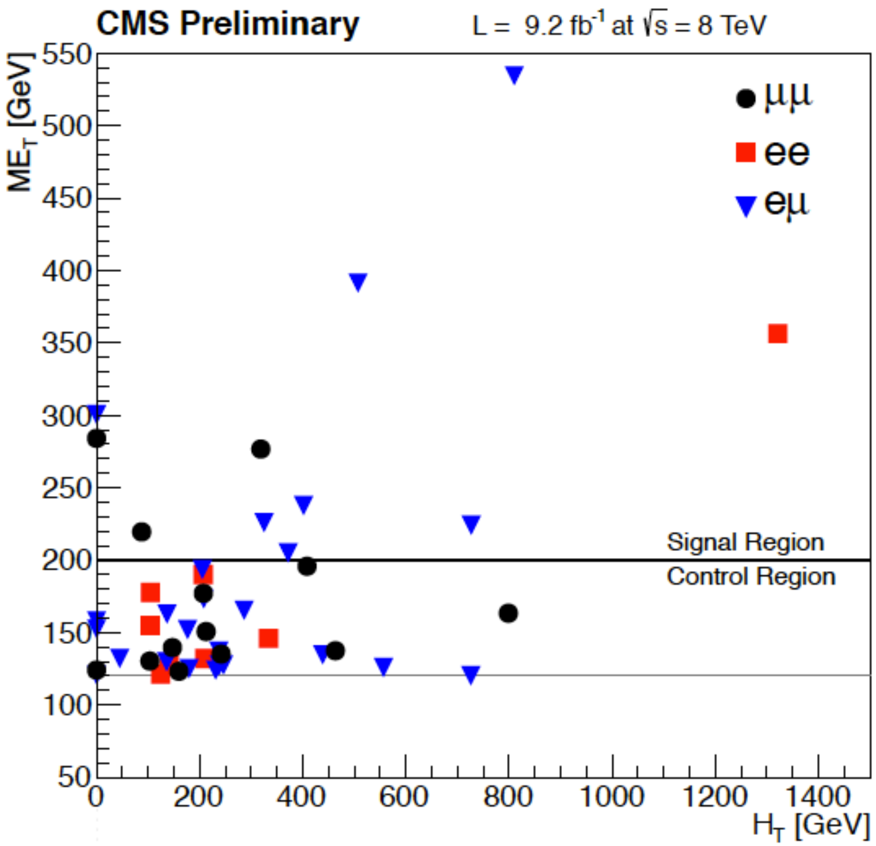
Three Lepton:

- Select events with three leptons, at least one of which must be an electron or muon with p_T>20.
  - All others e/μ must have p_T > 10
  - Allowed to have at most one hadronic τ, p_T>20. Must have exactly three leptons though.
  - Missing E_T > 50 GeV
- Major backgrounds from WZ production and ditop.



Same Sign Dilepton

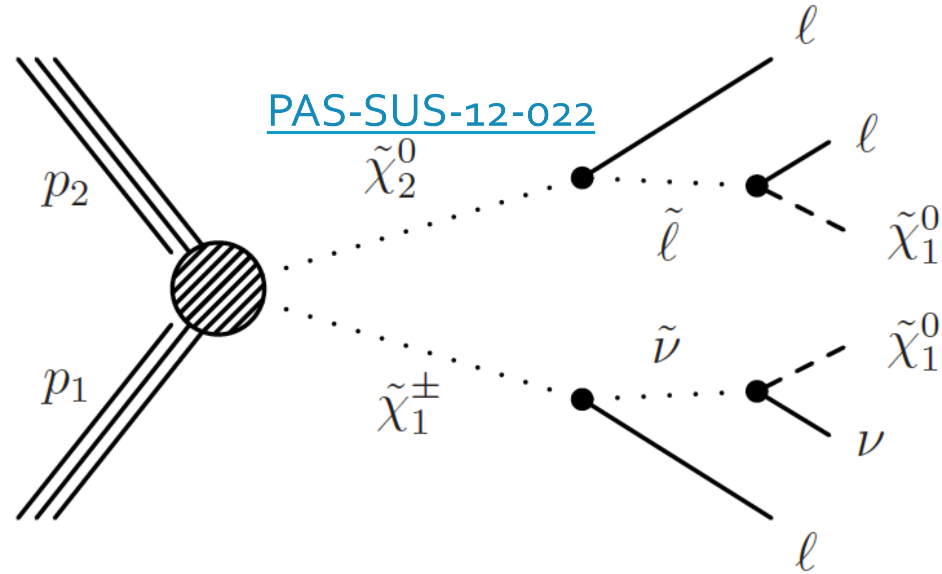
- The previous analysis required well identified fiducial leptons, but if one lepton is lost, they lose that sensitivity.
- As a complement then, events in which there are two same sign leptons are examined, though p_T and isolation cuts were tightened to reduce backgrounds.

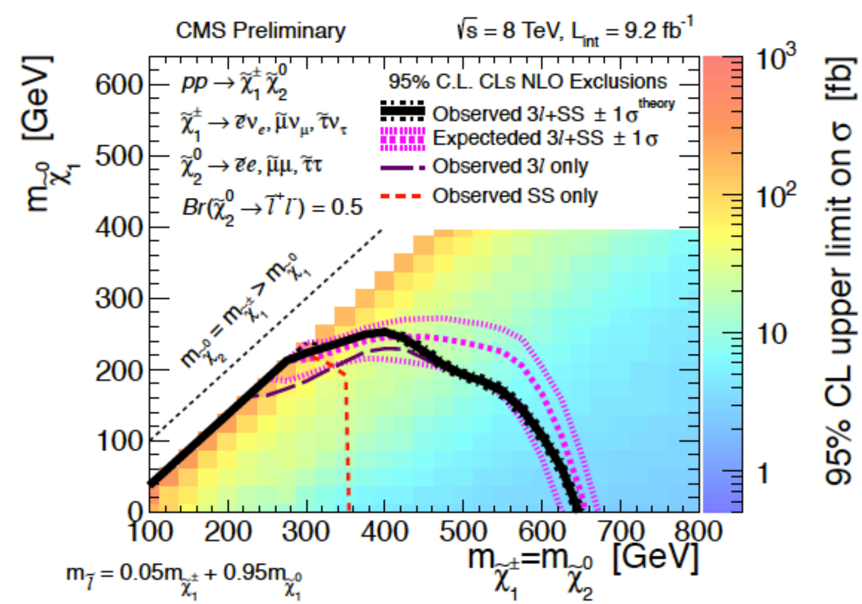


Limits:

- Since all the observed events are consistent with the expectations, limits are set, matching up the topologies which are sensitive to the particular models.
- For limits on chargino-neutralino production, this is the combination of the three lepton and same sign lepton analyses.

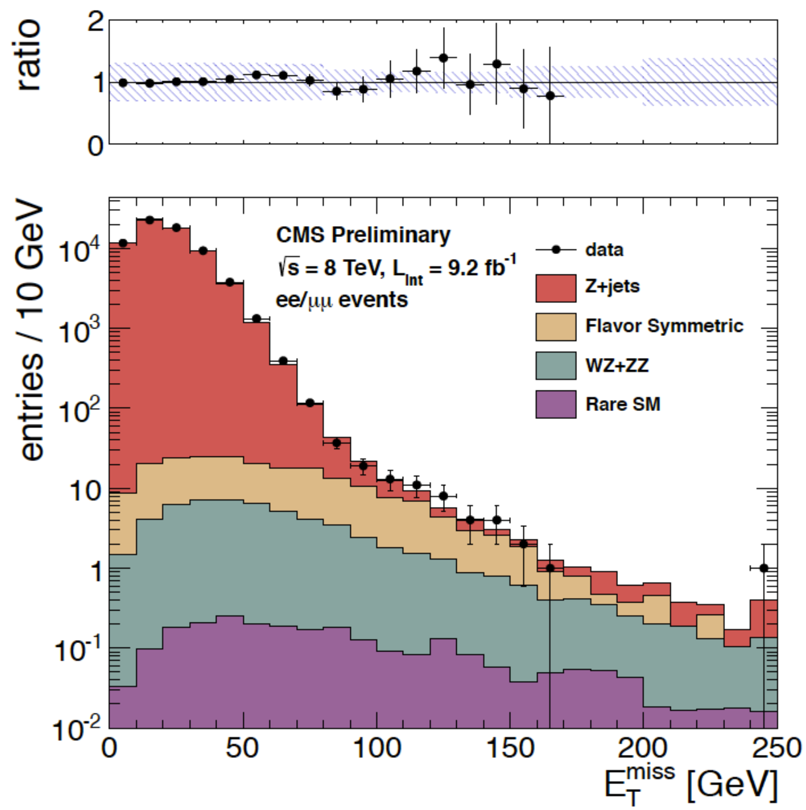
[PAS-SUS-12-022](PAS-SUS-12-022)





WZ/ZZ + missing E_T

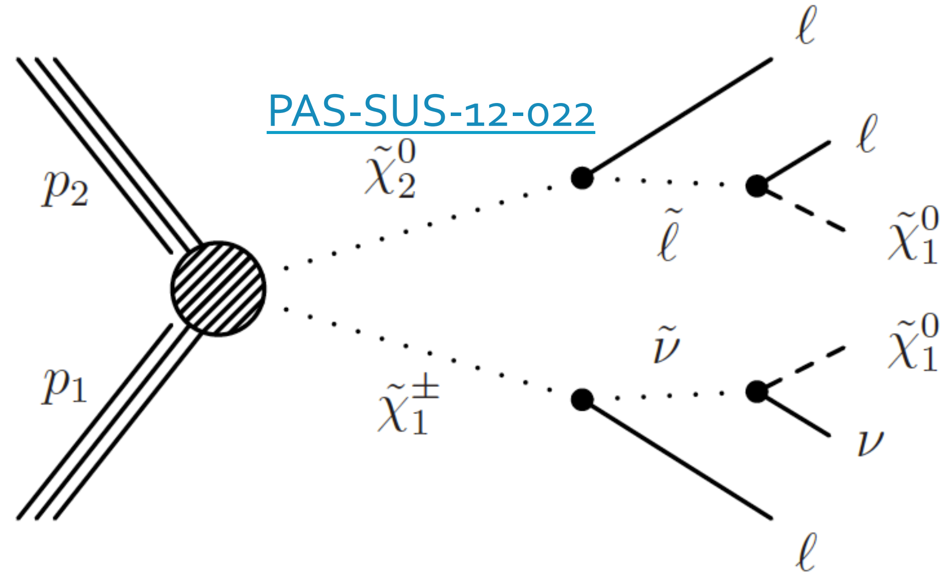
- The cost of sensitivity in requiring all lepton decays of multiple bosons is high.
- To attempt to mediate this, events with two (not more) leptons and at least two jets are selected.

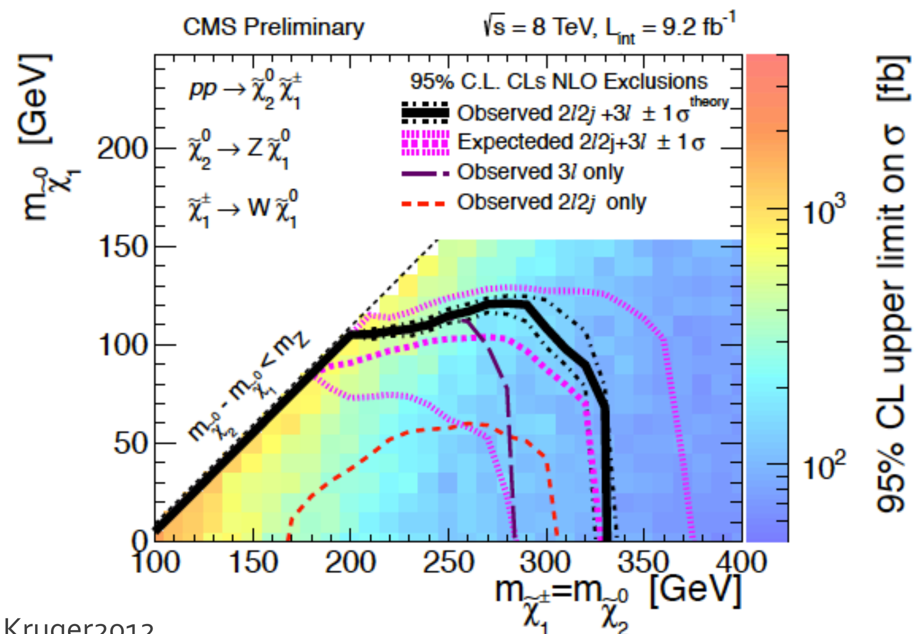


Limits:

- Since all the observed events are consistent with the expectations, limits are set, matching up the topologies which are sensitive to the particular models.
- For limits on chargino-neutralino production, this is the combination of the three lepton and dilepton plus jets analyses.

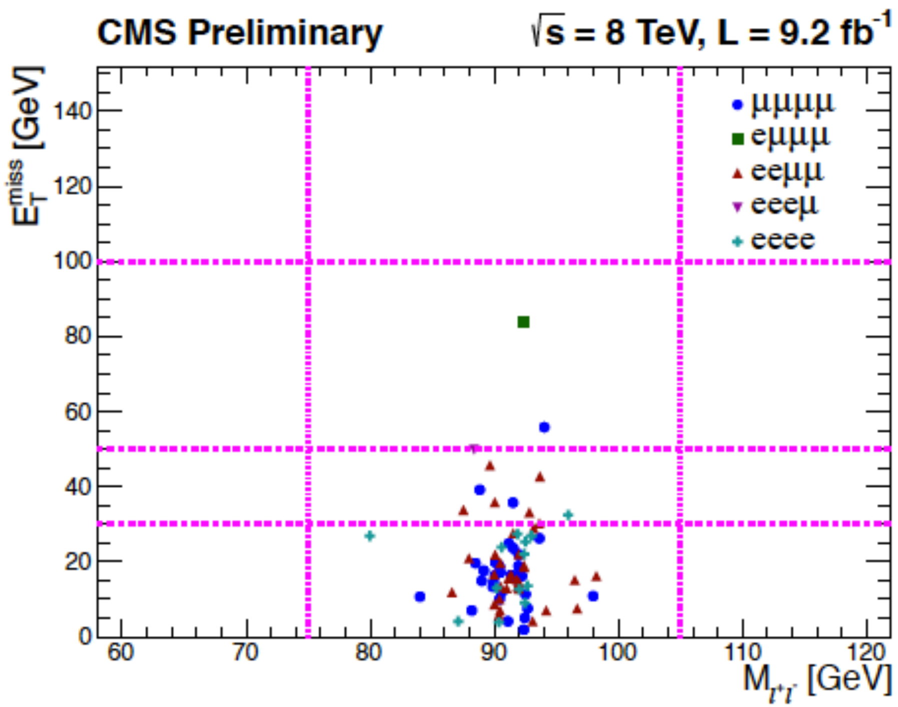
PAS-SUS-12-022





Four Lepton:

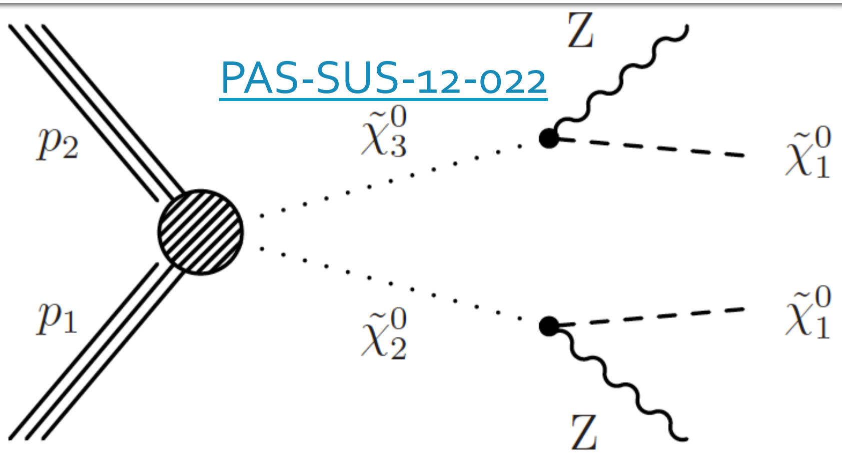
- Select events with four leptons, at least two of which must be an opposite sign electron or muon pair with p_T>20.
  - All others e/μ must have p_T > 10
  - Allowed to have at most one hadronic τ, p_T>20. Must have exactly four leptons, events binned in missing E_T.
- Major backgrounds from ZZ production.

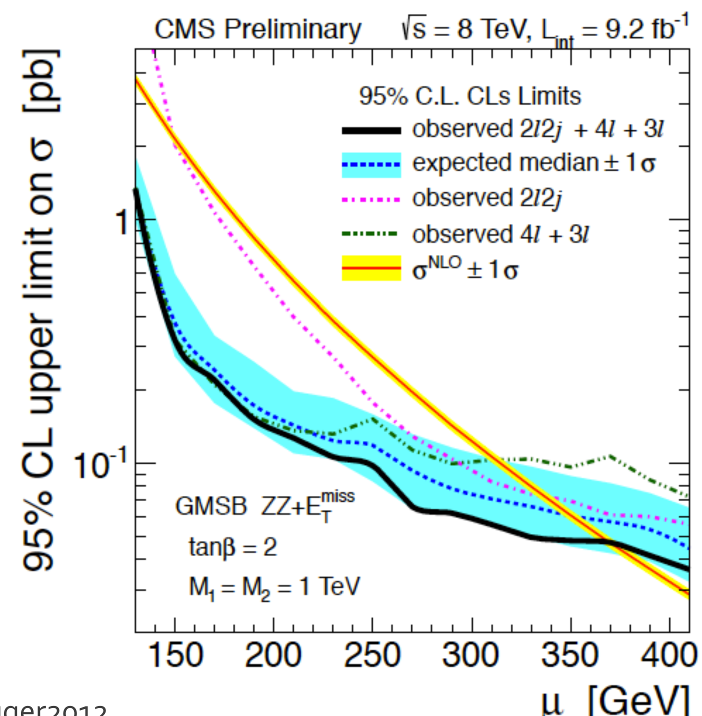


Limits:

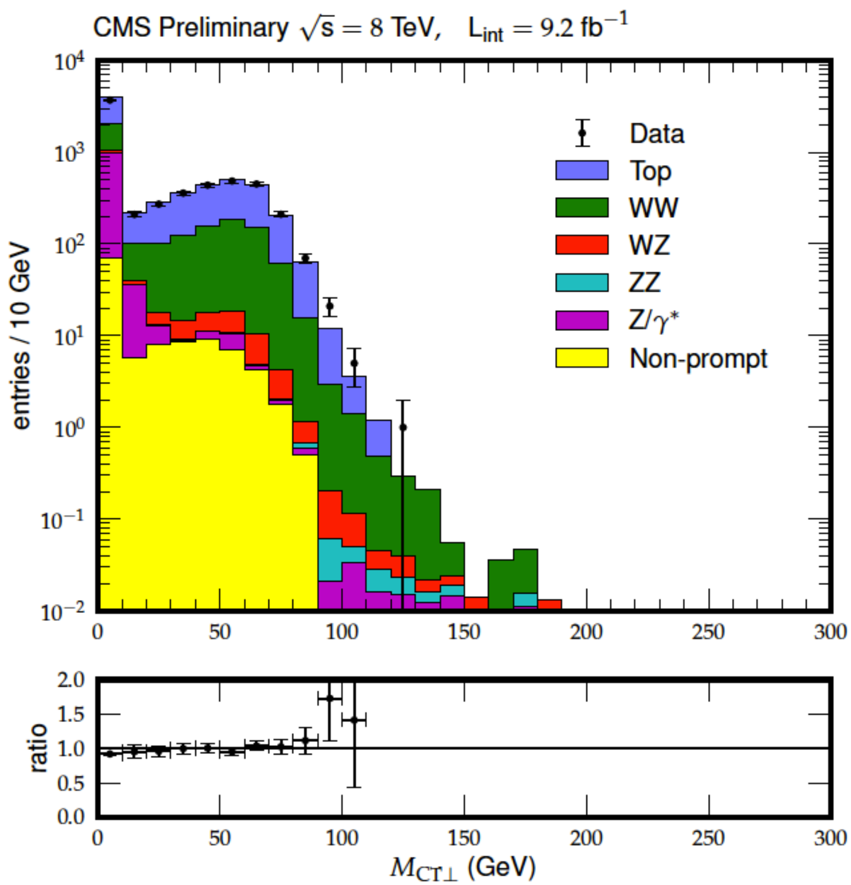
- Since all the observed events are consistent with the expectations, limits are set, matching up the topologies which are sensitive to the particular models.
- For limits on a higgsino enhanced GMSB scenario, the four lepton search limits are shown.

PAS-SUS-12-022





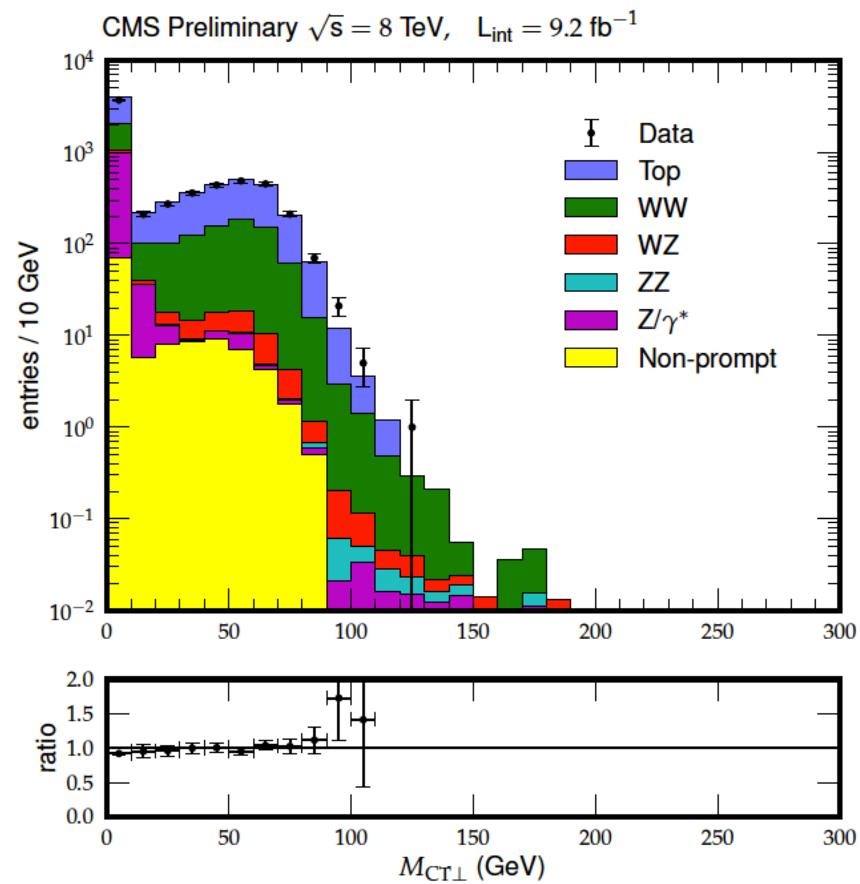
- To round out this family of analyses, the complement to the topologies with a Z candidate is considered: oppositely charged ee, eμ, μμ candidates which have invariant masses inconsistent with that of the Z, and missing E_T > 60 GeV (seeking to probe chargino production).
- In order to account for remaining backgrounds template shapes in transverse M_{CT}, a variable which is sensitive to the mass endpoint.



$$M_{CT_\perp}^{max} = \frac{M_p^2 - M_c^2}{M_p},$$ arXiv:0910.1584

Nonresonant Dileptons:

- In order to account for remaining backgrounds template shapes in transverse M_{CT}, a variable which is sensitive to the mass endpoint.
- The momentum of the system against which the visible particles recoil is calculated and then the visible particle momenta are projected onto the plane perpendicular to the recoil direction.
- As an example, if P=W and C=ν, then M_{CT} transverse is M_W.



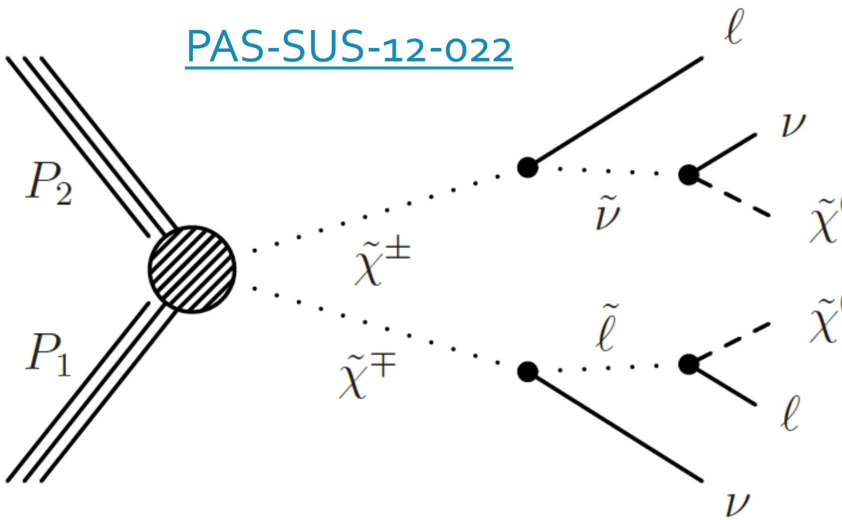
$$M_{CT_\perp}^{max} = \frac{M_p^2 - M_c^2}{M_p},$$

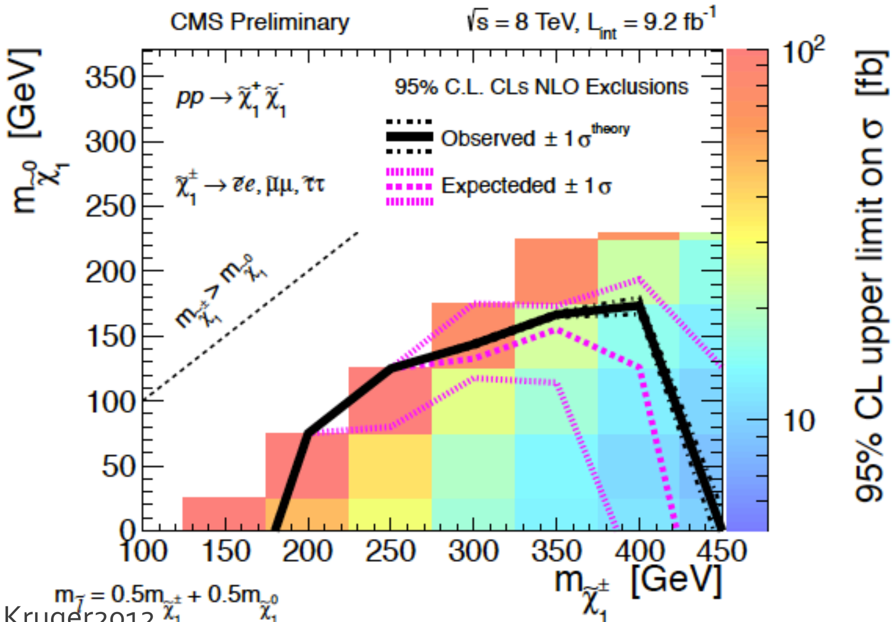
arXiv:0910.1584

Limits:

- Since all the observed events are consistent with the expectations, limits are set, matching up the topologies which are sensitive to the particular models.
- These are limits on direct chargino production using the transverse M_{CT} variable.

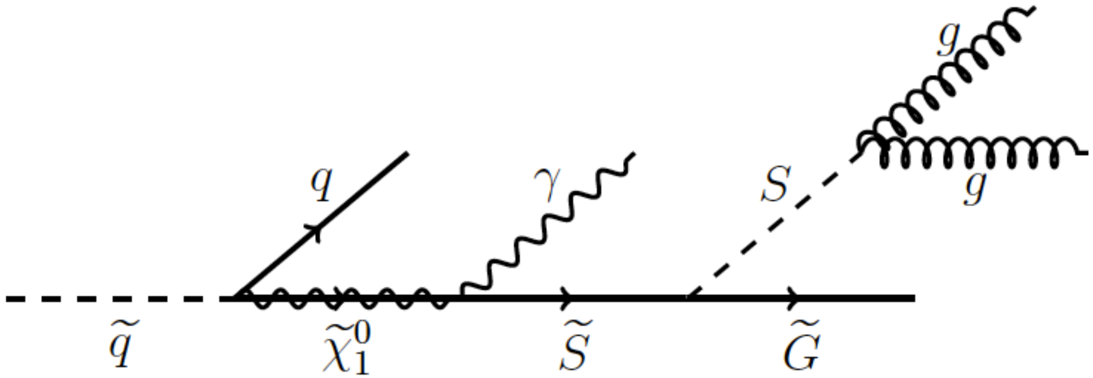
PAS-SUS-12-022





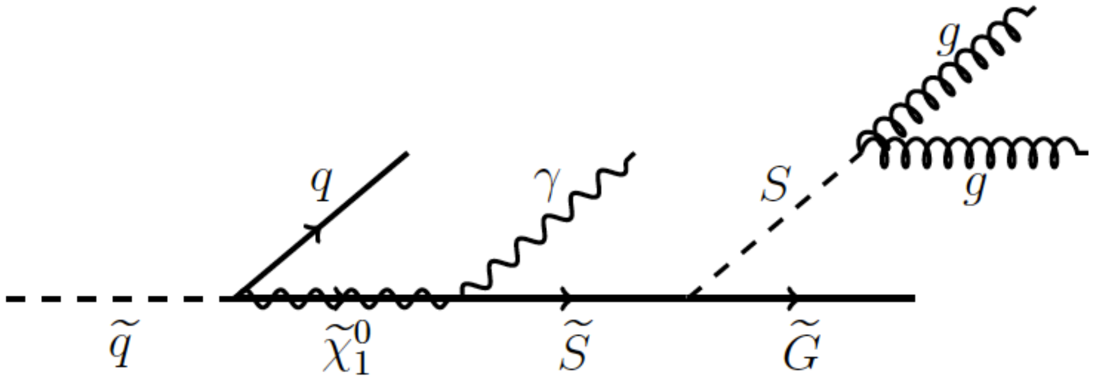
Stealth Squarks:

- The first analyses I talked about relied on both hadronic activity and missing E_T.
- The EWKino search relied on leptons and missing E_T, and little associated hadronic activity.
- This case however, sometimes called "Stealth SUSY", relies on hadronic activity, and little to no missing E_T.



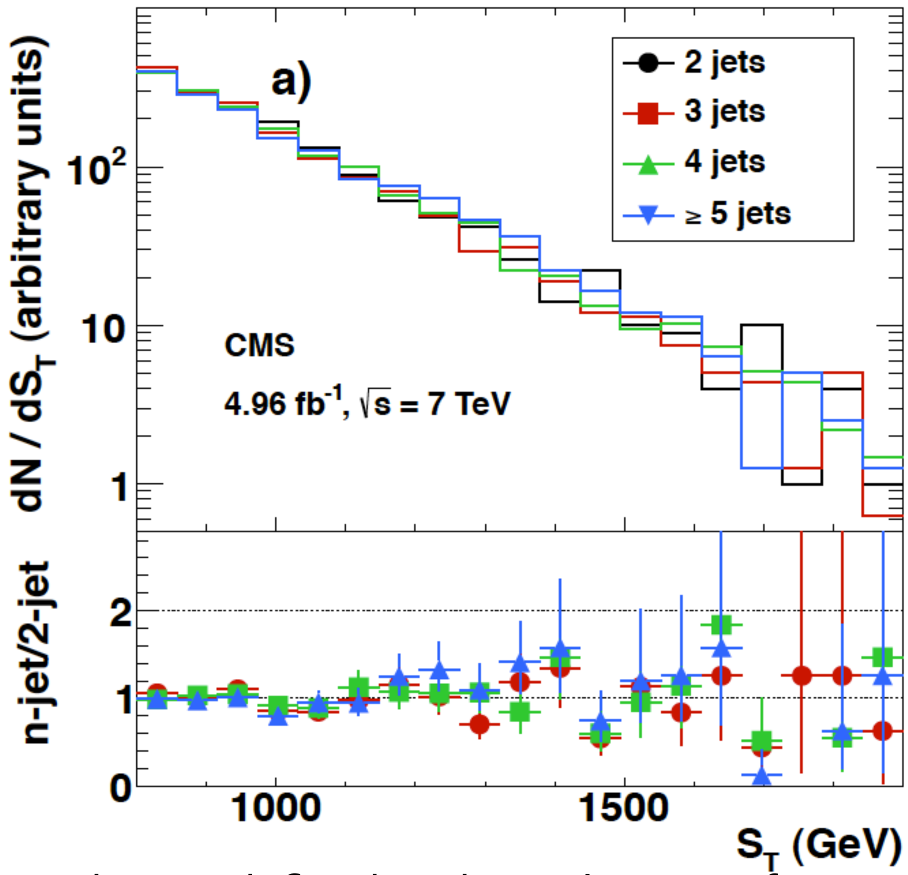
Stealth Squarks:

- This is a GMSB-like scenario in which SUSY is augmented by a hidden sector, wherein there is a singlet state that is almost mass degenerate with it's SM counterpart.
- The gravitino escapes, but doesn't carry a huge amount of transverse energy. Thus two photons, many jets, and little to no missing E_T.



Strategy:

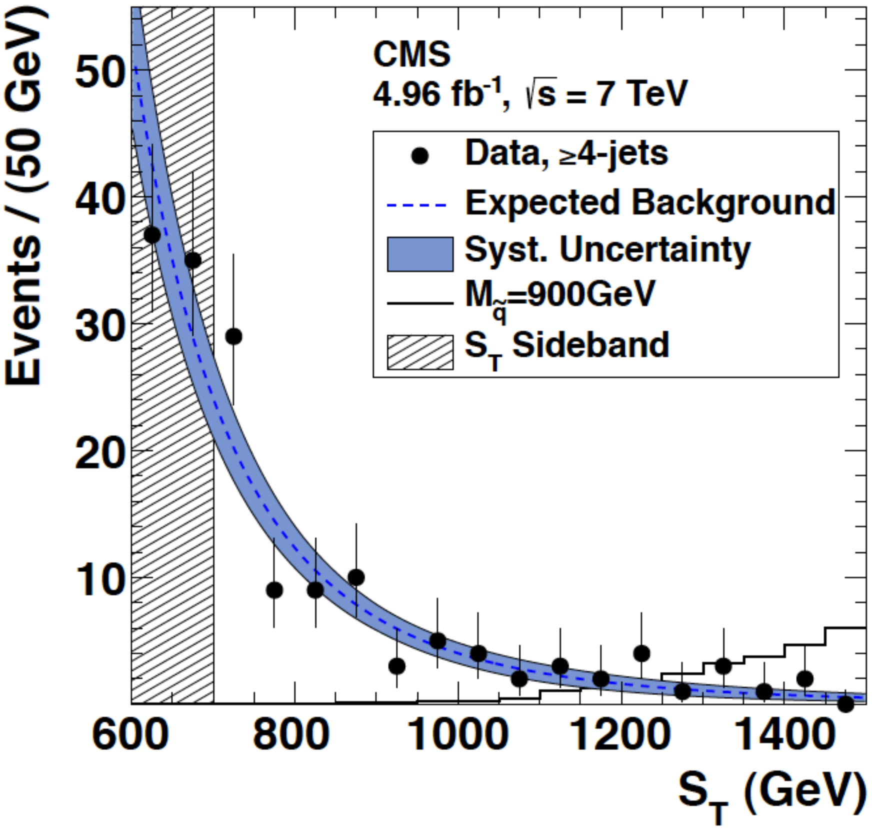
- This search mainly relies on two things:
  - That our SUSY events will mainly populate a region of high energy, and high object multiplicity
  - That the distribution of S_T from QCD is invariant with respect to the number of objects (confirmed in both data control samples and MC)



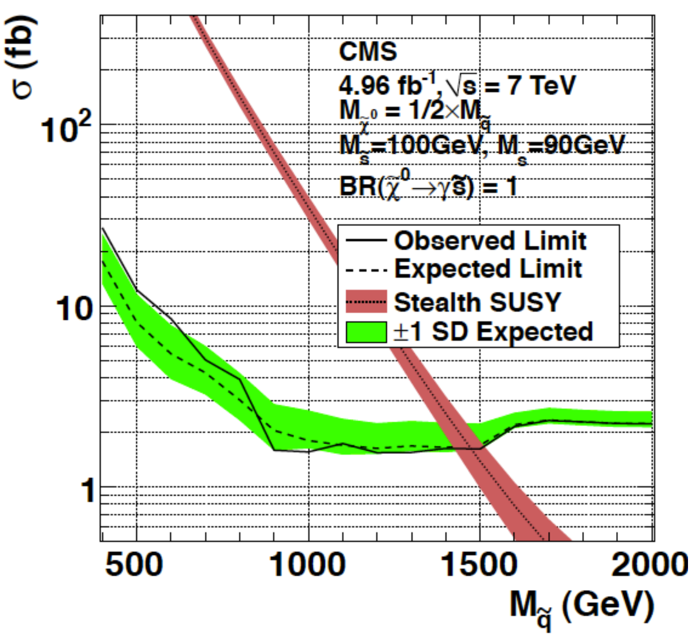
S_T here is defined as the scalar sum of jets, photons and missing E_T > 20 GeV.

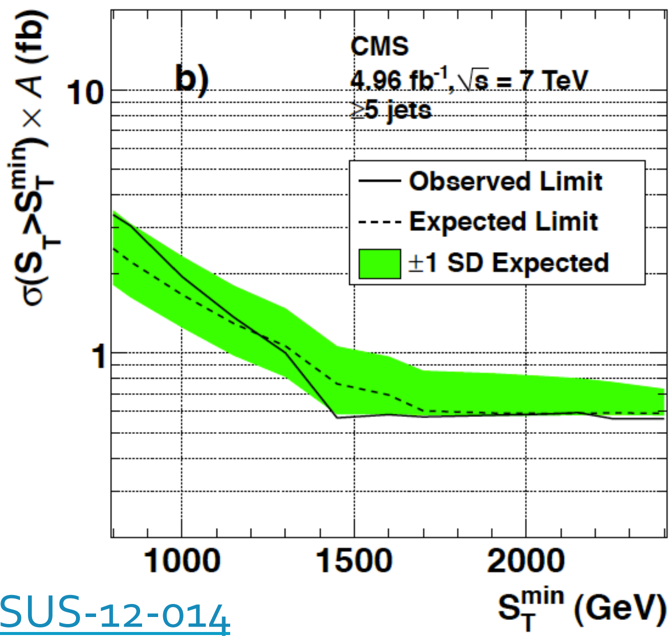
S_T shape:

- The shape of the S_T distribution in the data control samples is then fit, and normalized in the low S_T region of the signal enhanced high multiplicity bins.
- This is done not only in the 4 or more jet bin as shown, but also in the 5 or more, to optimize sensitivity.



Limits:



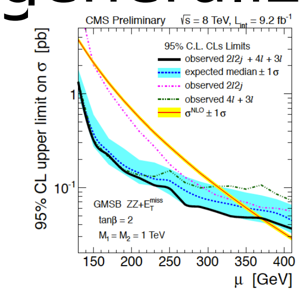


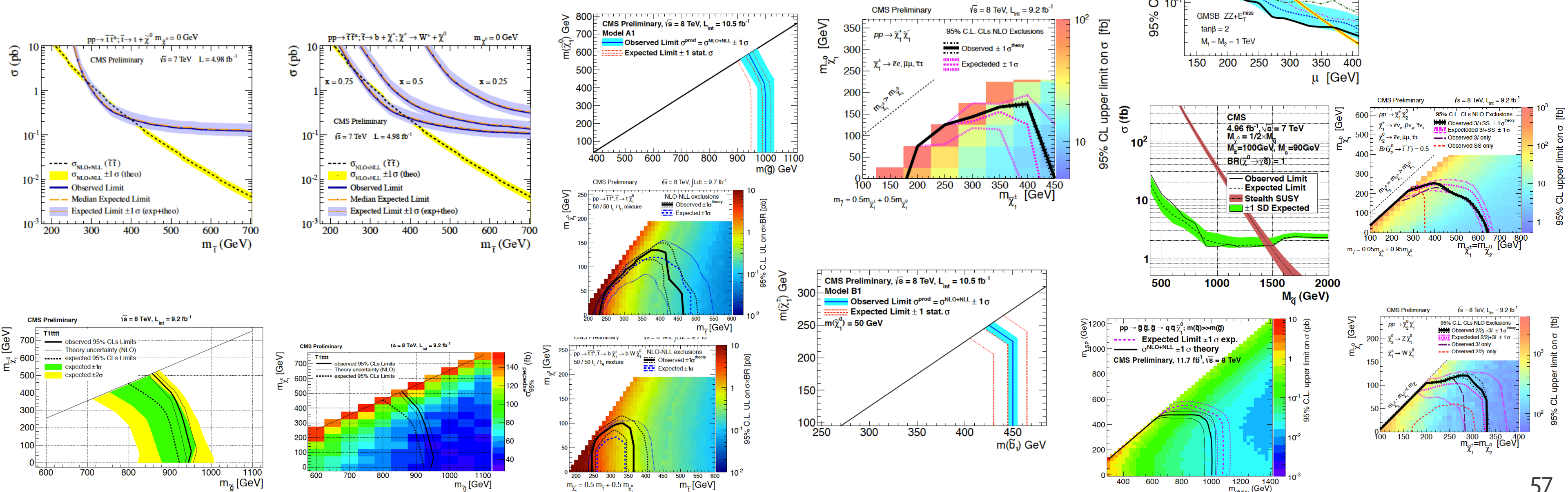
CMS-SUS-12-014

- Limits on not only the Stealth SUSY model considered, but also limits in just the S_T space (no acceptance assumption) are produced.

Conclusion

- I have concentrated on only some of the MOST recent analyses to come out of the CMS Experiment on the topic of searching for SUSY.
- We've gone from sweeping inclusive searches to targeted new scenarios, presented in generalized ways.
- A reminder of what you've seen:





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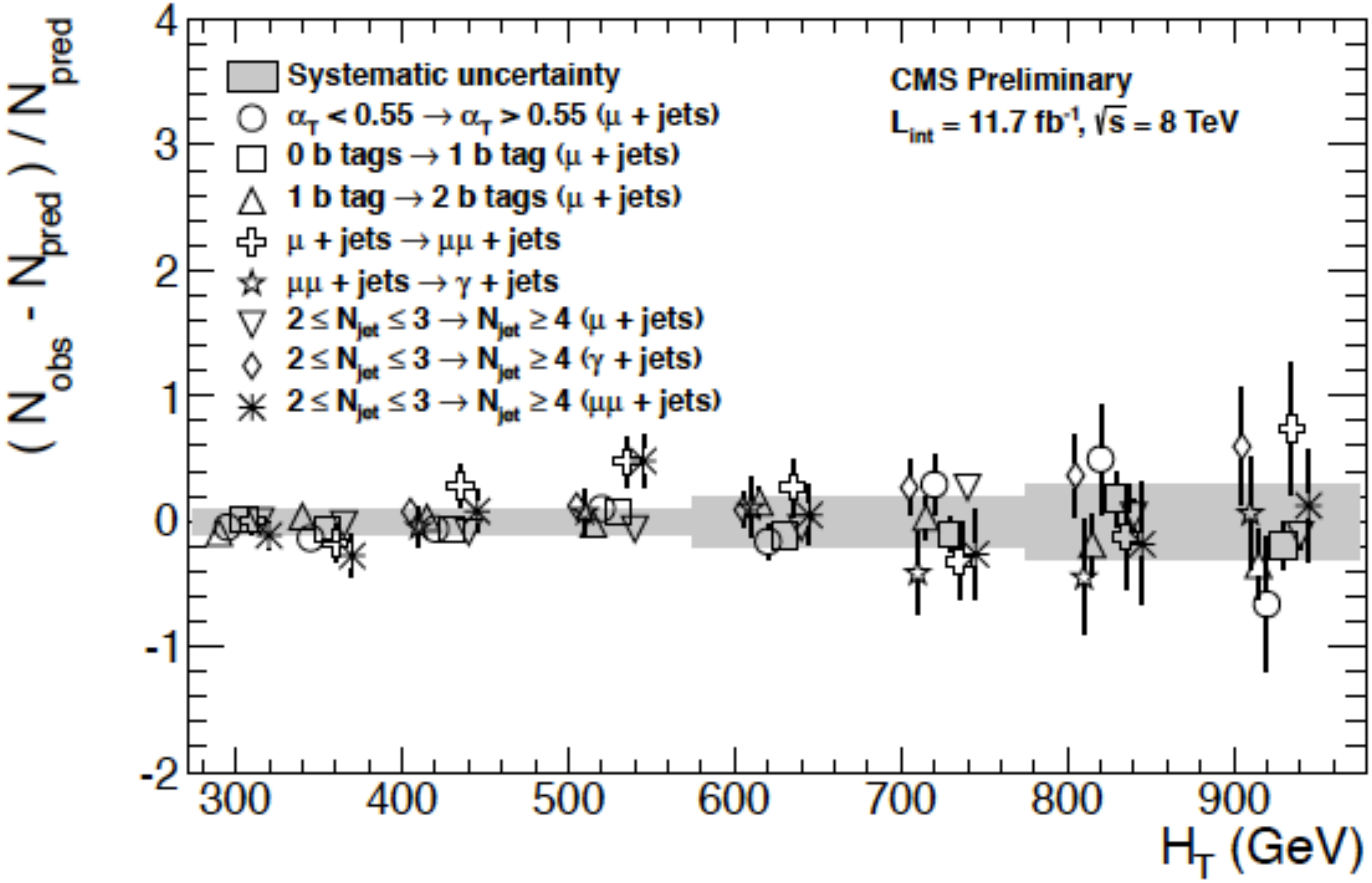
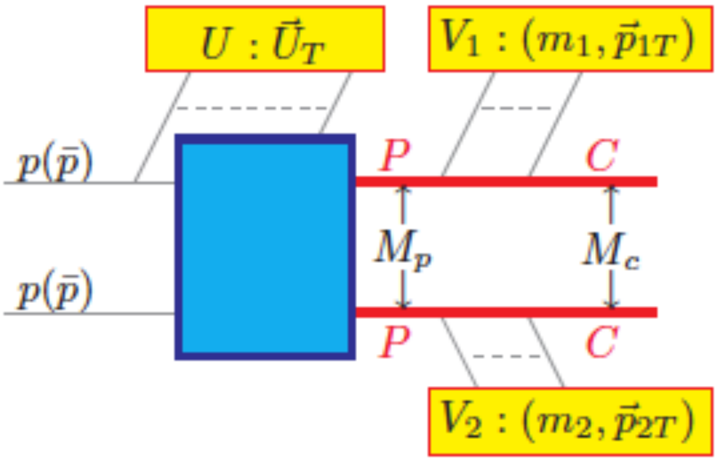
BACKUPS

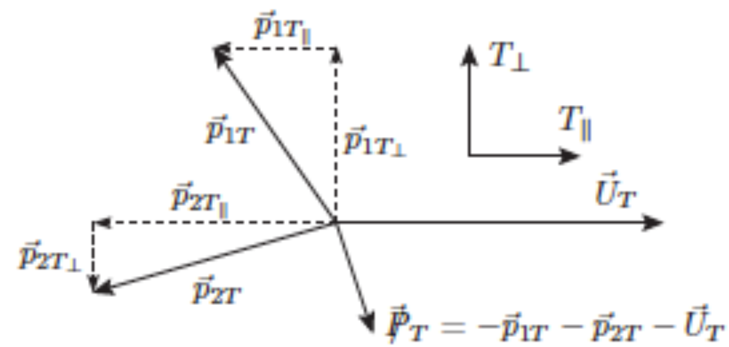
Closure plot (α_T): njet >=4



Transverse M_{CT}

- Transverse contransverse mass





$$\vec{p}_{iT_\parallel} \equiv \frac{1}{U_T^2}\left(\vec{p}_{iT} \cdot \vec{U}_T\right)\vec{U}_T,$$

$$\vec{p}_{iT_\perp} \equiv \vec{p}_{iT} - \vec{p}_{iT_\parallel} = \frac{1}{U_T^2}\vec{U}_T \times \left(\vec{p}_{iT} \times \vec{U}_T\right)$$

$$M_{CT} = \sqrt{m_1^2 + m_2^2 + 2\left(e_{1T}e_{2T} + \vec{p}_{1T} \cdot \vec{p}_{2T}\right)},$$

where e_{iT} is the "transverse energy" of V_i

$$e_{iT} = \sqrt{m_i^2 + |\vec{p}_{iT}|^2}.$$

$$M_{CT_\perp} \equiv \sqrt{m_1^2 + m_2^2 + 2\left(e_{1T_\perp}e_{2T_\perp} + \vec{p}_{1T_\perp} \cdot \vec{p}_{2T_\perp}\right)}$$

$$M_{CT_\perp}^{max} = \frac{M_p^2 - M_c^2}{M_p},$$

arXiv:0910.1584