SUSY searches with b-jets at CMS

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UC Davis HEP seminar

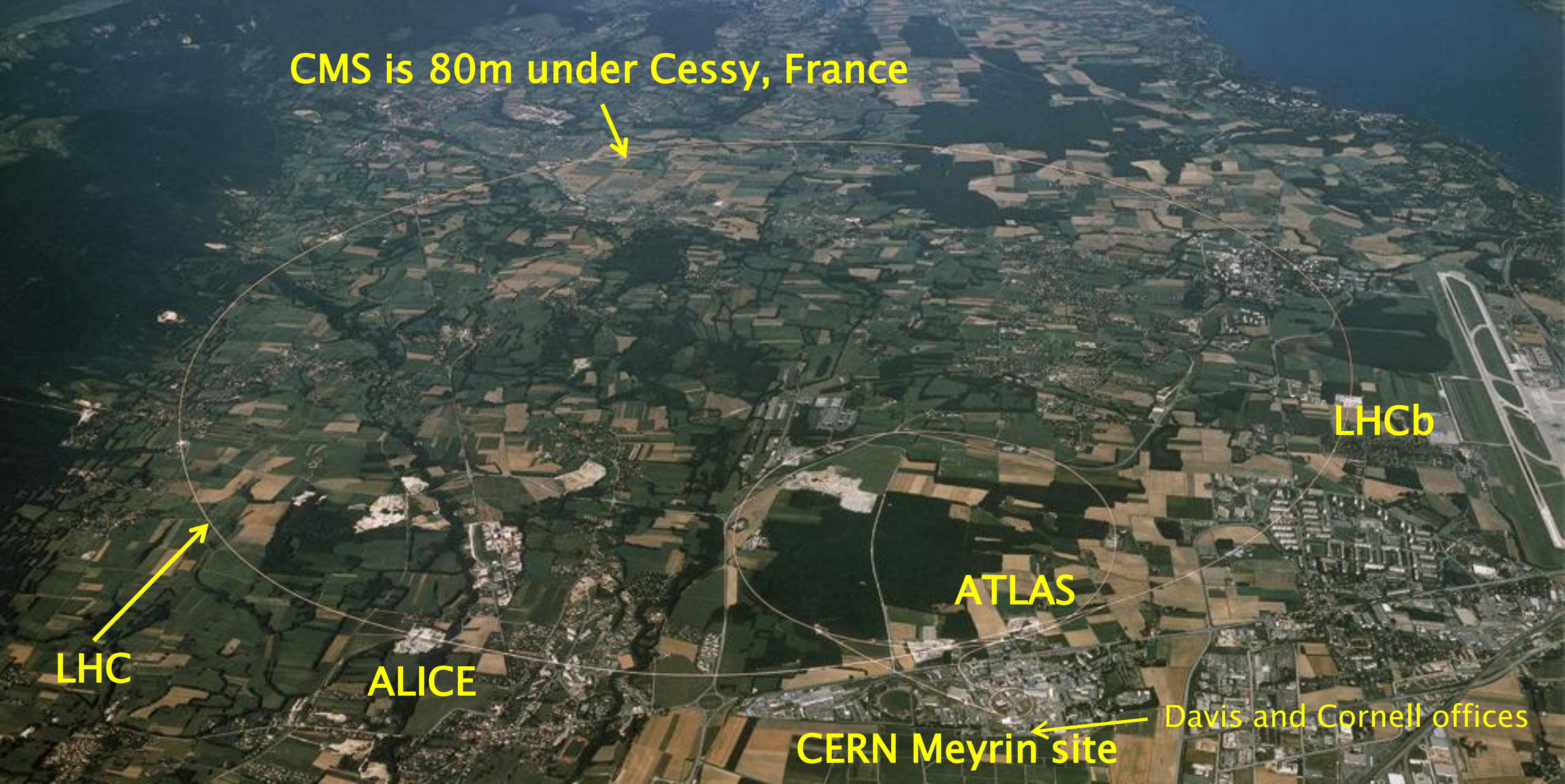
I don't usually have to travel so far to talk to people from Davis!

Outline

- Introduction
  - The LHC and CMS
  - SUSY and b-jets
- Analyses
  - CMS has two 2011 b-tagged SUSY searches
    - MT2+b, MET+b
  - I will cover both but give more detail on MET+b
    - Event selection
    - Background estimation methods
- Results and interpretation

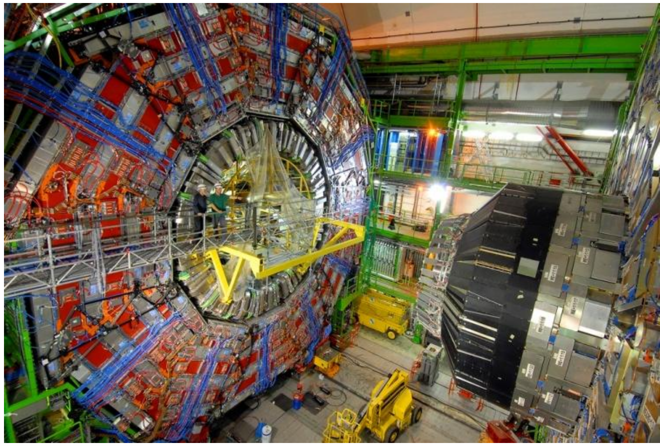
CMS at the LHC

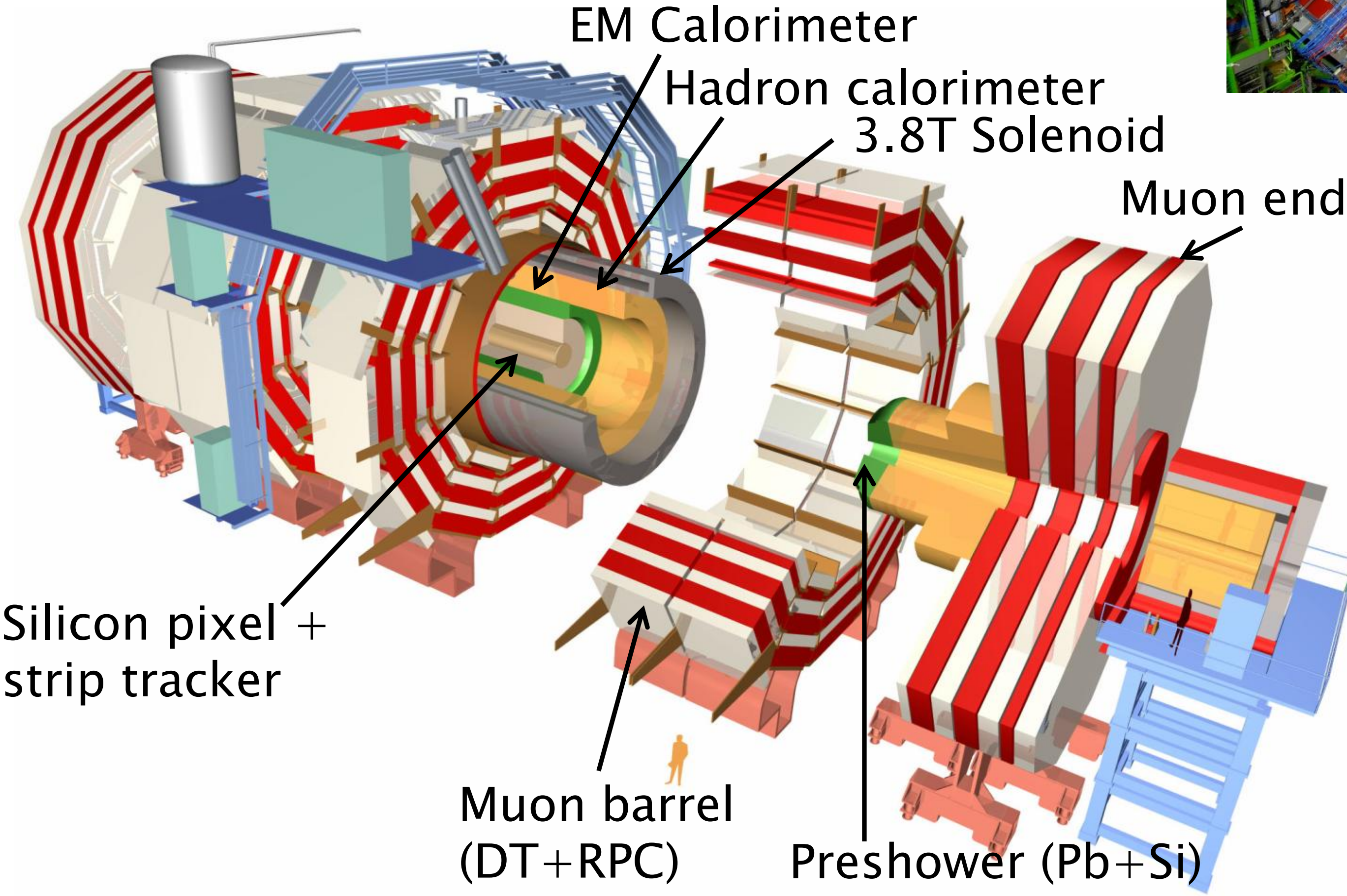
- proton-proton collider currently at 3.5 TeV per beam (designed for 7 TeV per beam)
- 9300 superconducting magnets (1232 dipoles) in a 27 km ring



The CMS Detector

- 21m long, 15m in diameter
- 14000 tons





CMS Collaboration:

- *~2500 scientists + engineers*
- *~850 students*
- *173 institutes*
- *40 countries*

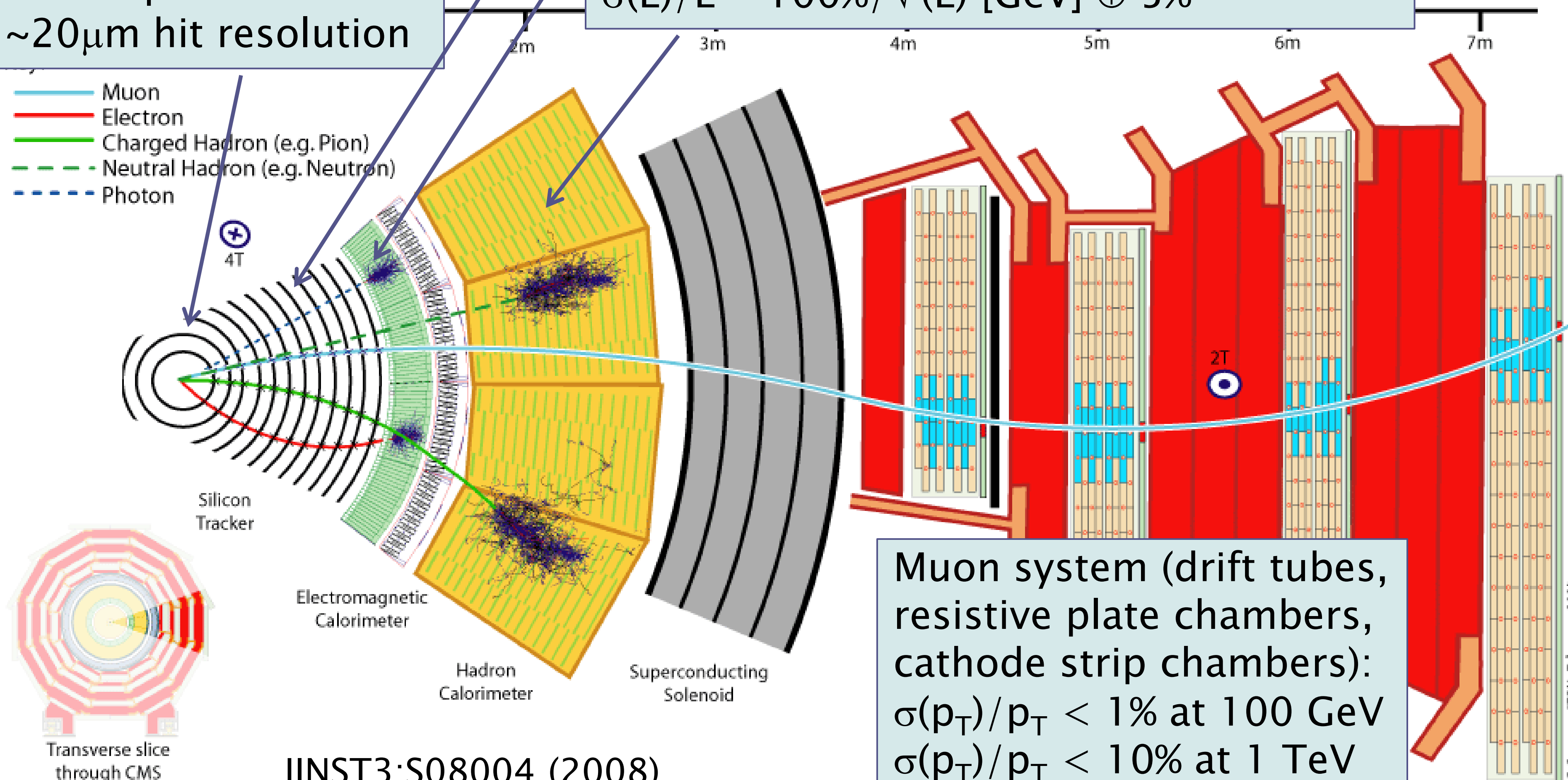
A slice of CMS

Electromagnetic Calorimeter (lead tungstate crystals):
$\sigma(E)/E \sim 3\%/\sqrt{(E)}$ [GeV] $\oplus$ 0.3%

Silicon tracker:
$\sigma(p_T)/p_T \sim 15\%$ at 1 TeV

Hadron calorimeter (brass + scintillator):
$\sigma(E)/E \sim 100\%/\sqrt{(E)}$ [GeV] $\oplus$ 5%

Silicon pixel detector:
~20μm hit resolution



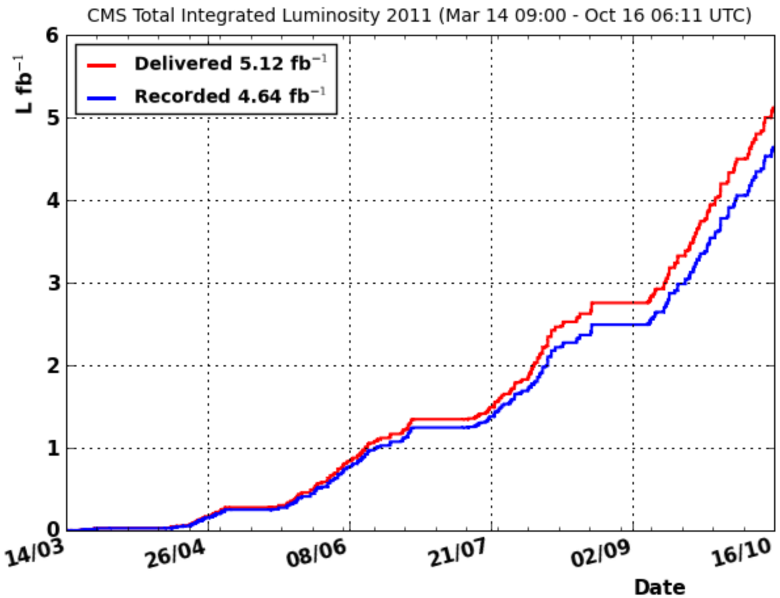
Muon system (drift tubes, resistive plate chambers, cathode strip chambers):
$\sigma(p_T)/p_T < 1\%$ at 100 GeV
$\sigma(p_T)/p_T < 10\%$ at 1 TeV

JINST3:S08004 (2008)

2011 data–taking at CMS

- >5 fb^{-1} delivered so far
  - 2010 dataset now delivered in a few hours
- 1318 bunches colliding in CMS with 50 ns spacing
  - (design is twice as many bunches at 25 ns)
  - Very good emittance (smaller transverse beam size) and bunch intensity
  - Since Sep., β* lowered to 1.0m (smaller transverse beam size)
    - Very high pileup
      - At L ~ $3x10^{33}$ cm^{-2} s^{-1}, ~15 interactions/bunch crossing

- Recorded/delivered ~ 90%
- Good / recorded ~ 90%
- ~98% of the detector is working and in the readout



Current lumi uncertainty = 4.5%

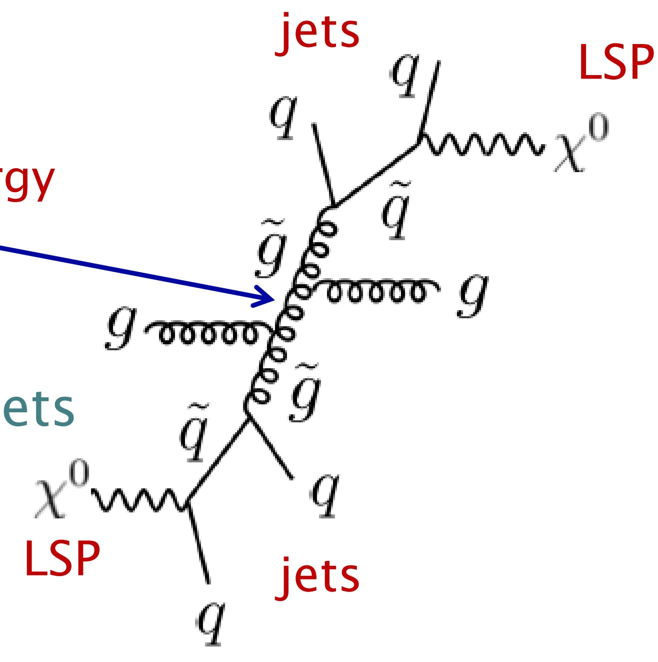
Why Supersymmetry?

- The Standard Model has never* failed to describe our data, despite our best efforts
- But the observed SM + SM Higgs is not the whole story….
  - e.g. "Hierarchy problem"
    - Higgs mass receives radiative corrections due to quantum loops, proportional to the largest scale in the theory (Planck Mass, 10^{19} GeV)
- SUSY adds a partner particle for each SM particle, with the same quantum numbers, except differing by ½ unit of spin; e.g.:
  - Spin ½ quarks → spin 0 squarks (q~)
  - Spin 1 gluons → spin ½ gluinos (g~)
    - This new symmetry neatly cancels the dangerous contributions to the Higgs mass

** disregarding neutrino mass and mixing*

Signatures of SUSY

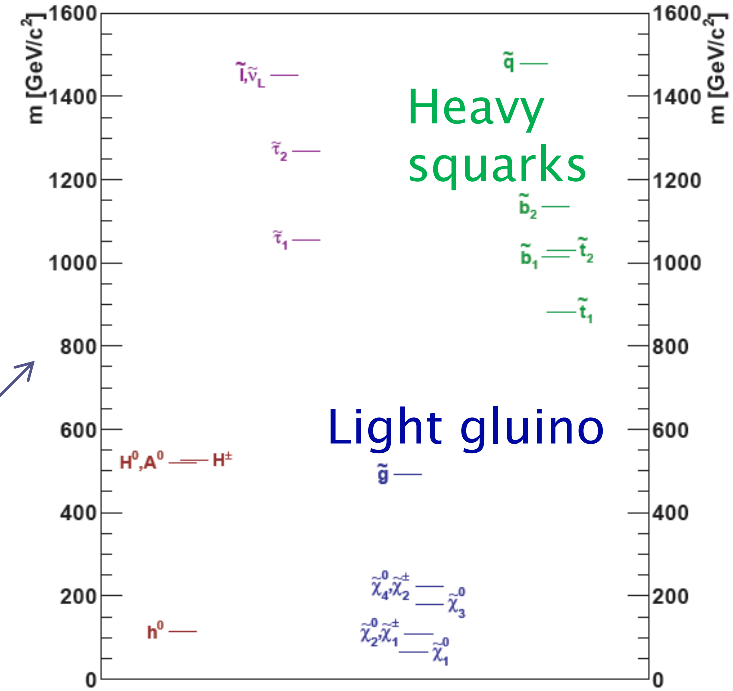
- Common to assume *R-parity conservation*
  - i.e. SUSY particles produced in pairs and always decay into another SUSY particle
    - Lightest SUSY particle (LSP) is stable
      - Good dark matter candidate
      - Escapes our detectors unseen→missing energy
- At the LHC, production dominated by gluino-gluino, squark-squark, gluino-squark
  - These are colored objects and so a lot of jets are produced when they decay
- Classic LHC SUSY signature:
  - Jets + Missing transverse energy (MET)
    - Why *transverse*?
      - remember that we don't know the initial momentum along the beamline, so we can only talk about the momentum balance in the transverse direction



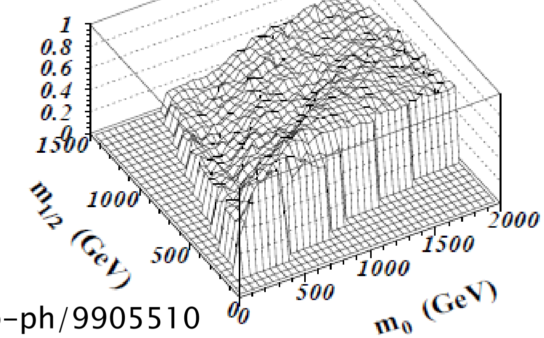
b jets and SUSY

- Example signals:
  - Models with a light 3rd generation of sparticles (b~, t~), with the other squarks heavier
    - e.g. g~ → ttX~
  - Models with all squarks heavy, but gluinos light
    - e.g. high tan β, high m_0, low $m_{1/2}$ in the CMSSM (like “LM9”)
    - g~ → qqX~ with q=b,t
- Adding b-tagging also provides an experimentally complementary approach
  - Different mix of backgrounds, different systematics, etc

Mass spectrum of CMSSM test point “LM9”



Fraction of events with a b (tan β=35)



hep-ph/9905510

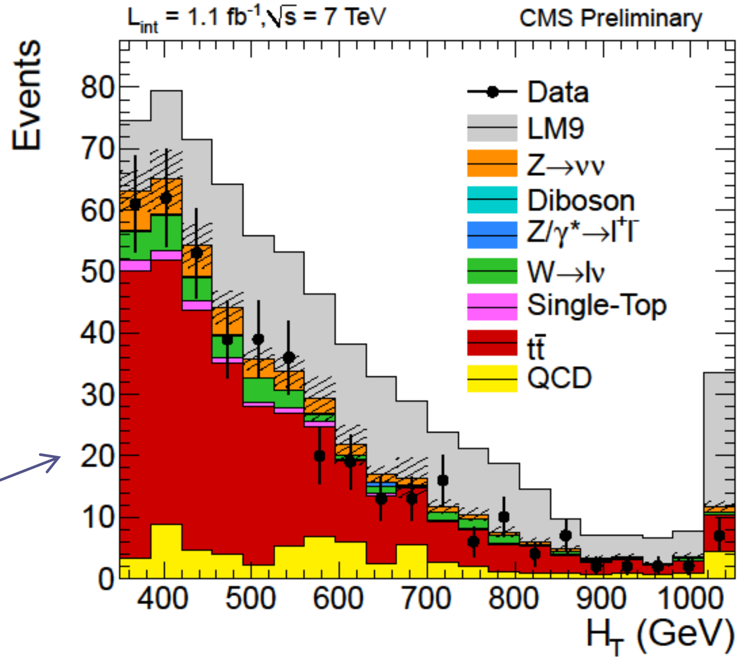
Overview of backgrounds

- Signature: jets+MET+b tag
- Main background:
  - ttbar → Wb Wb
    - One W decays to hadrons
    - Other W decays to lν, where l=τ→hadrons or l=e,μ,τ→e,μ and e,μ slips through veto
      - Neutrino provides a source of real MET
- Other backgrounds:
  - QCD
  - W+Jets
  - Z+Jets, with Z→$\nu\nu$

Event selection: jets

- Expect lots of jet production from SUSY
  - Multiple hard jets
    - ≥4 for MT2 analysis
      - p_T>20 GeV, $|\eta|$<2.4
    - ≥3 for MET analysis
      - p_T>50 GeV, $|\eta|$<2.4
  - Large $H_T=\Sigma_{jets}\ |p_T|$
    - >650 GeV for MT2 analysis
    - >350 (500) GeV for Loose (Tight) branch of MET analysis

HT>350 GeV
MET>150 GeV
>=1 b tag



Event selection: lepton veto

- ttbar is the largest background
- Reduce it by vetoing events with an isolated e or μ, passing the following criteria:
  - $p_T > 10$ GeV
  - $|\eta| < 2.4$ (plus veto of barrel/endcap transition for electrons)
  - Various quality and isolation requirements
- Remaining ttbar events either have lepton that is outside of the selection above (~2/3), or have $W \rightarrow \tau \rightarrow$hadrons (~1/3)

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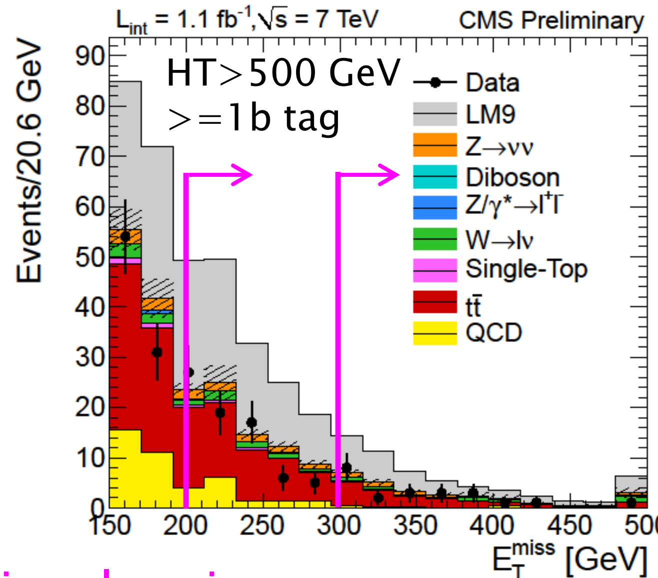
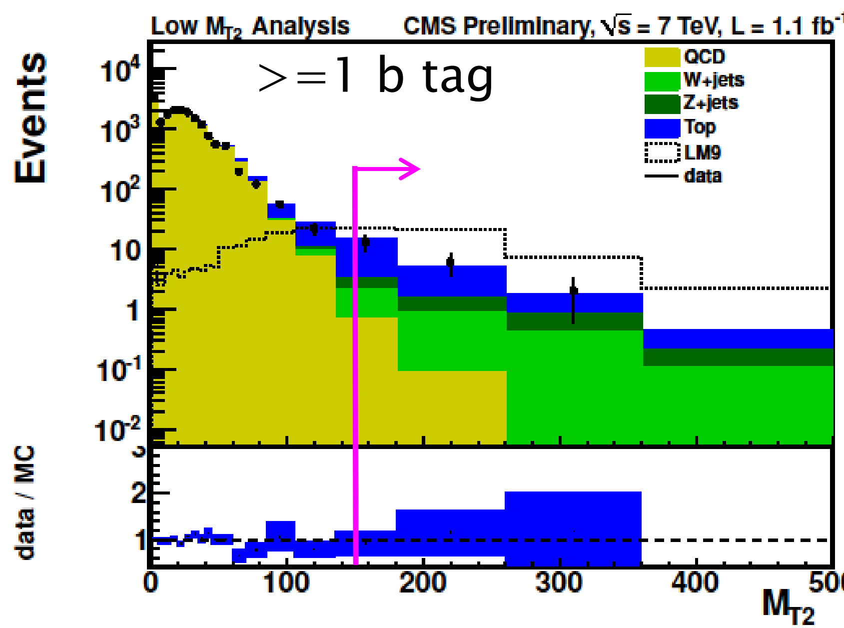
Event selection: missing energy

- Weakly interacting particles in SUSY final state → missing transverse energy
  - MET analysis uses MET directly
    - MET > 200 (300) for GeV for Loose (Tight)
  - MT2 analysis uses MT2
    - An extension of the transverse mass concept (commonly used for W→lν decays) to decay chains with 2 unobserved particles.
    - Largely correlated with MET, but gives better rejection of non-SUSY events

$$(M_{T2})^2 = 2A_T = 2p_T^{vis(1)} p_T^{vis(2)} (1 + cos\phi_{12})$$



Signal regions



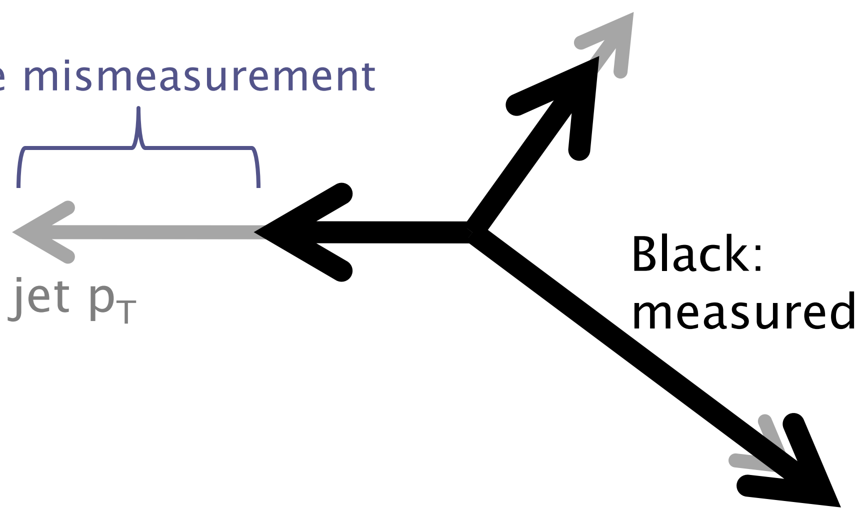
Triggers

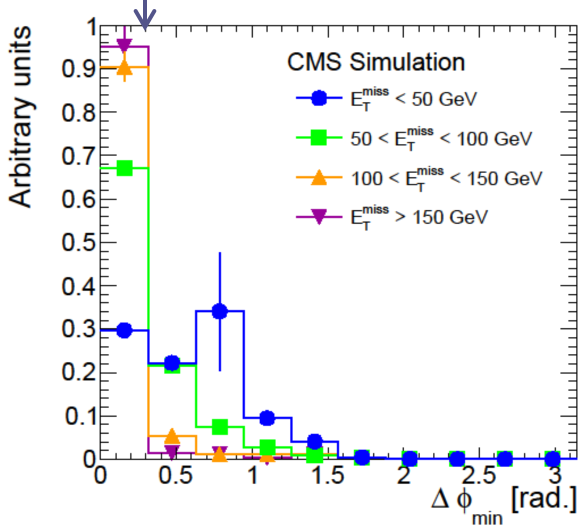
- How to select this signature online?
  - Use online versions of HT, missing energy
    - These calculations use calorimeter-only quantities (no "particle flow" reconstruction)
    - The missing energy calculation uses only jets ("MHT")
- MT2+b analysis uses HT trigger
  - HT > 550 GeV (computed online)
    - Fully efficient for offline analysis HT cut
- MET+b analysis uses HT+MHT cross-trigger
  - Online thresholds: HT > 300 GeV, MHT > 80 GeV
    - Fully efficient offline HT > 400 GeV
      - Below plateau, correct MC for small inefficiency
    - 99 ± 1% efficient for (PF) MET > 200 GeV

NB: I'm giving the tightest thresholds used. Earlier in the run, thesholds were lower

Event selection: Δϕ(jet, MET)

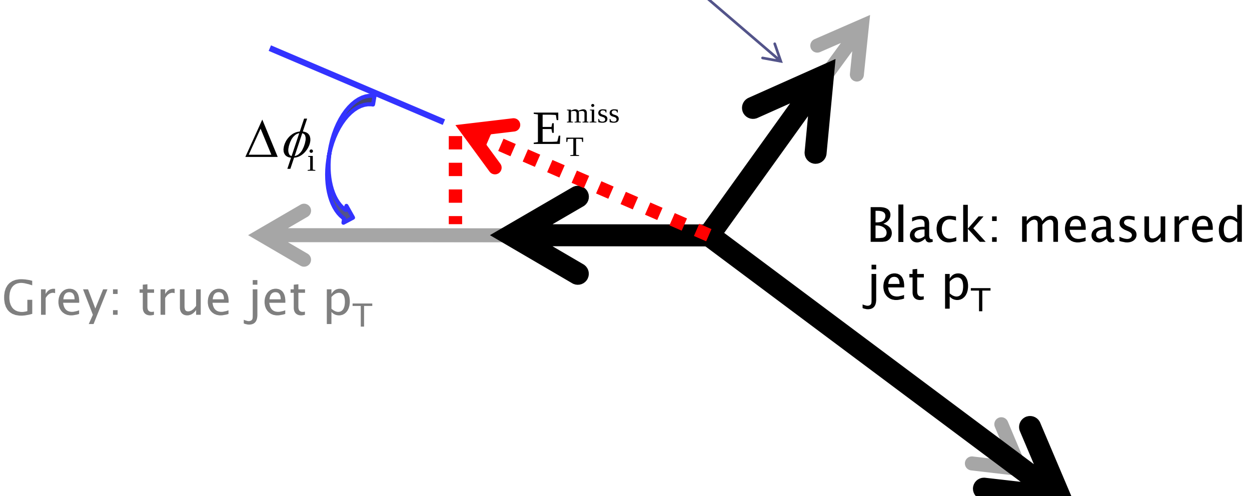
- QCD events can sneak into high MET region when a jet is severely mismeasured
  - Creates fake MET aligned with the jet
- Reject this background with angle Δϕ(jet, MET)
  - In MT2+b, require $\Delta\phi_{min}$(all jets, MET) > 0.3
  - In MET+b, use a slightly different variable
    - (more on the following slides)





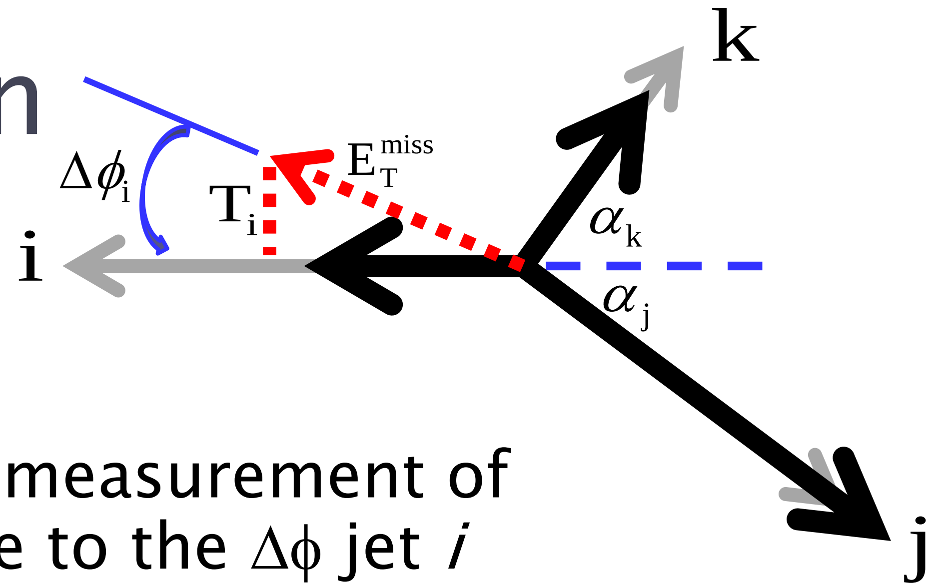
Motivation for $\Delta\phi_N$(jet, MET)

- The standard $\Delta\phi$(jet, MET) variable is great for rejecting QCD at high MET
  - But it is also highly correlated with MET (and MT2)
- For an event with a very badly measured jet, why is the angle $\Delta\phi$(jet, MET) non-zero?
  - The MET direction is smeared by the small mismeasurements of the p_T of the other jets in the event



- This smearing becomes less important as the big mismeasurement (hence MET) increases →MET and $\Delta\phi$(jet,MET) are correlated
- we try to model this and construct an uncorrelated variable

$\Delta\phi_N$ construction

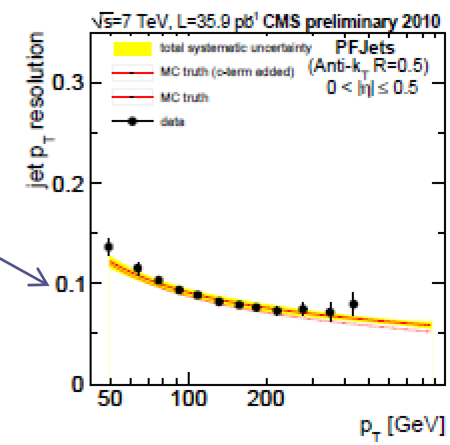


- T_i is the component of mismeasurement of other jets that is transverse to the $\Delta\phi$ jet *i*

$$T_i^2 \approx \sum_n \left(\sigma_{pT,n} \sin\alpha_n\right)^2$$

- Use 10% for jet p_T resolution $\sigma_{pT,n}$
  - Cross-checks done to show we are not sensitive to this choice
- $\Delta\phi_{N,i} = \Delta\phi_i \,/\, \tan^{-1}(T_i \,/\, \text{MET})$
- This new variable is $\Delta\phi_i$ normalized by its resolution

PAS JME-10-014



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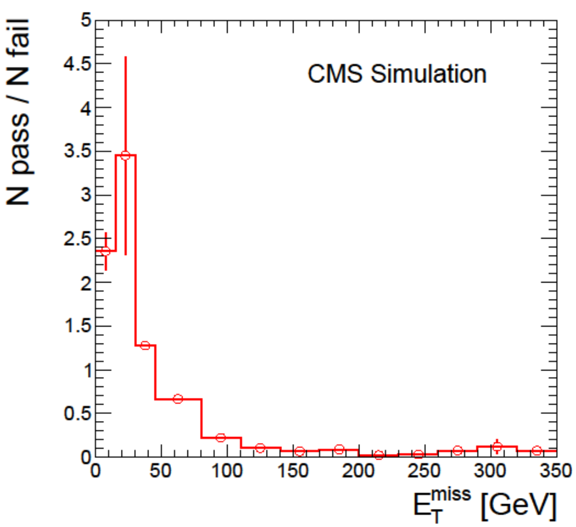
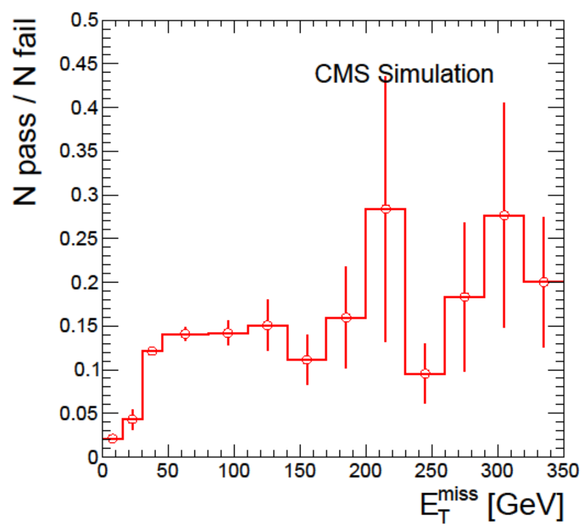
$\Delta\phi$ versus $\Delta\phi_N$

- Plot the ratio of events passing the $\Delta\phi$ cut to the ratio failing it, as a function of MET
  - This is a good way to judge the correlation
    - (flat means uncorrelated)

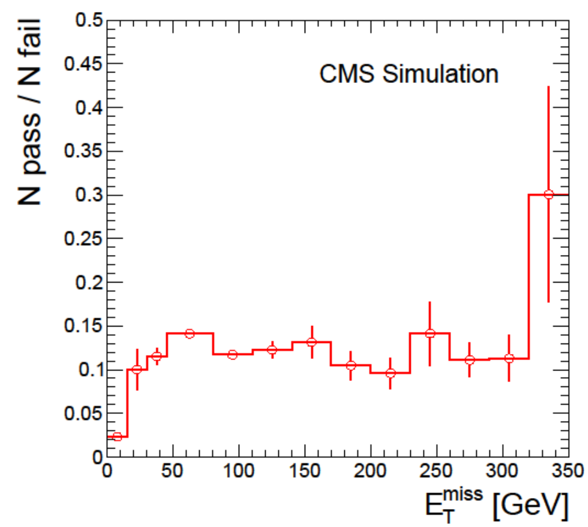
$\Delta\phi^{min}$, >=1b



$\Delta\phi_N^{min}$, >=1b



$\Delta\phi_N^{min}$, =0b



→pass/fail ratio for $\Delta\phi_N^{min}$ is ~constant for MET>~30GeV and independent of b tagging.

Lends itself to a simple background estimate (discussed later)

Event selection: b tagging

- Both of these analyses use the Simple Secondary Vertex High Purity algorithm
  - Find a secondary vertex in a jet with at least 3 tracks
    - Make a tight selection on the discriminator value with ~50% efficiency and ~0.1% mistag for light jets (higher for charm)
- For signal efficiency evaluation, use data-driven scale factors to correct MC b-tag efficiency
  - $p_T < 240$ GeV: centrally provided by the CMS b-tag group
  - $240 < p_T < 350$ GeV: the MET+b analysis performed an evaluation using the ratio of double b-tagged events to single b-tagged events using a 1 lepton (~ttbar) control sample
    - Found scale factors to be the same, with a larger uncertainty
  - $p_T > 350$ GeV: MET+b analysis uses a scale factor of 0 for signal efficiency (conservative for a limit)
    - Not enough statistics (yet) for a proper evaluation of the scale factor in data
- Both analyses use ≥ 1 b tag selections
  - MET+b also uses selections with ≥ 2 b tags

MC expectations in 1.1 fb^{-1}

- After the event selection:
  - Jet multiplicity, HT
    - Lead jet p_T in MT2 analysis
  - Lepton vetoes (e, μ)
  - $\Delta\phi_{(N)}$ requirement
  - MT2/MET requirement

	ttbar	QCD	W+jets	Z(νν)+jets	Total SM	LM9
MT2+b	10.8	0.2	2.2	1.8	15.0	42.9
MET ≥1b Tight	14.7	1.3	4.2	4.3	25.1	27.7
MET ≥2b Loose	28.9	2.5	1.2	2.2	35.7	60.0

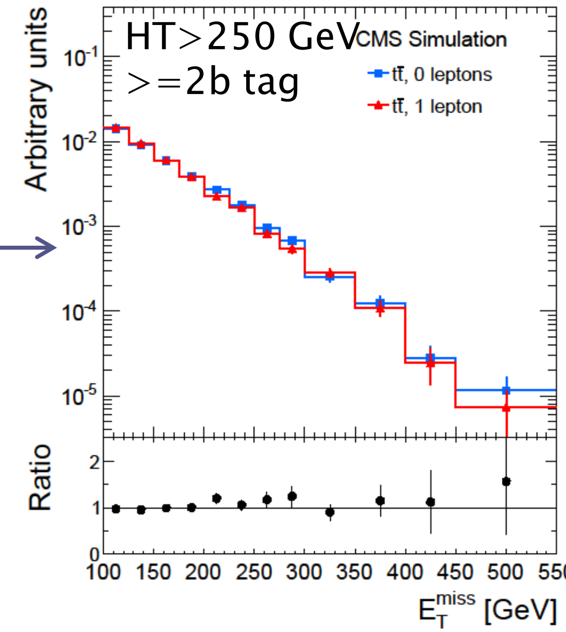
Note that MET analysis has 4 selections: (Loose, Tight) x (≥1b, ≥2b)
The ones shown here are the most powerful for setting limits.

MT2+b: background methods

- ttbar
  - Use control sample with 1 electron or 1 muon
    - Use MC efficiency numbers to move from 1 lepton → 0 lepton sample
      - Perform this method in control region 100<MT2<150 GeV
        - Compare prediction for 0 lepton sample to MC for 0 lepton sample; level of agreement quantified in the uncertainty
    - Scale from control region to signal region using MC, propagating uncertainties
- QCD
  - Extracted using a ratio of events that pass/fail $\Delta\phi_{min}$ selection
    - Extrapolated using a exp+c function to model this ratio
  - Find 0.8 ± 0.8 QCD events

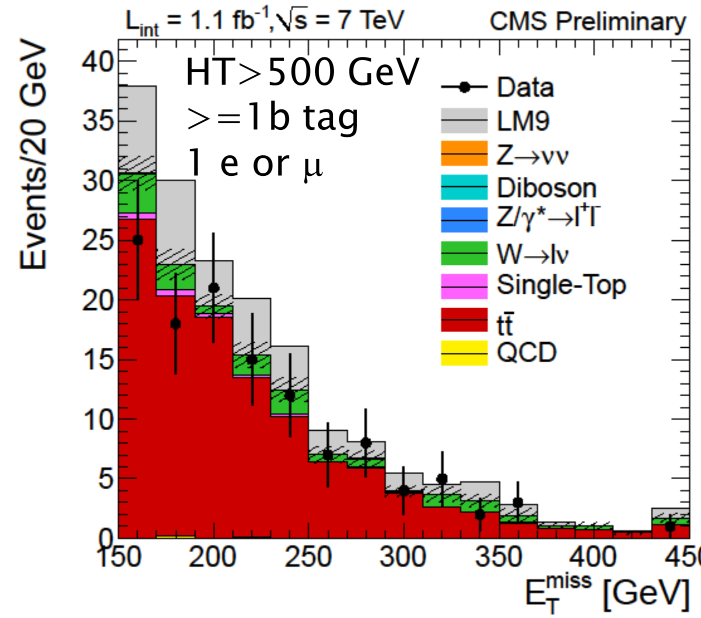
MET+b: ttbar+W+t method

- MET shapes in 1 lepton sample are compatible with 0 lepton sample
- Find MET shape in 1 lepton control sample, then normalize to ttbar-dominated region at medium MET (150<MET<200 GeV)



$$N_{SIG}^{top+W} = \frac{N_{SIG-SL}}{N_{SB-SL}} \times \left(N_{SB} - N_{SB}^{Z\to\nu\bar{\nu}} - N_{SB}^{QCD} - N_{SB}^{other,MC}\right)$$

Subtraction of contamination from other backgrounds (mostly data-driven)



Not discussed here: independent method used as a cross-check

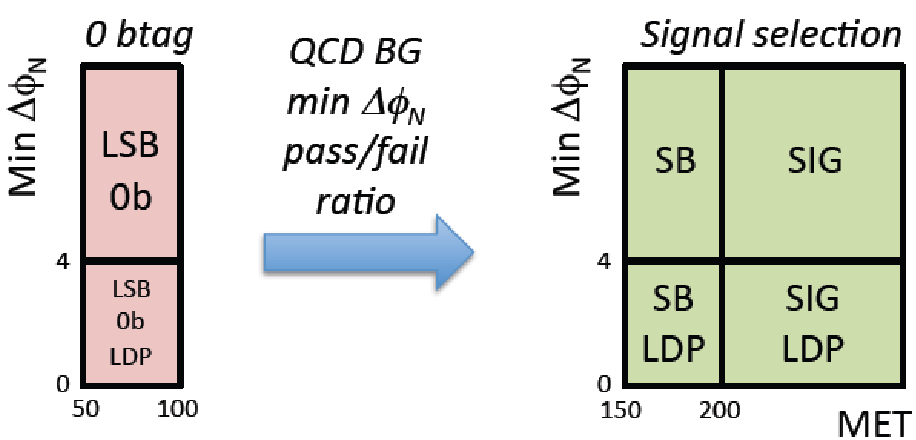
MET+b: QCD

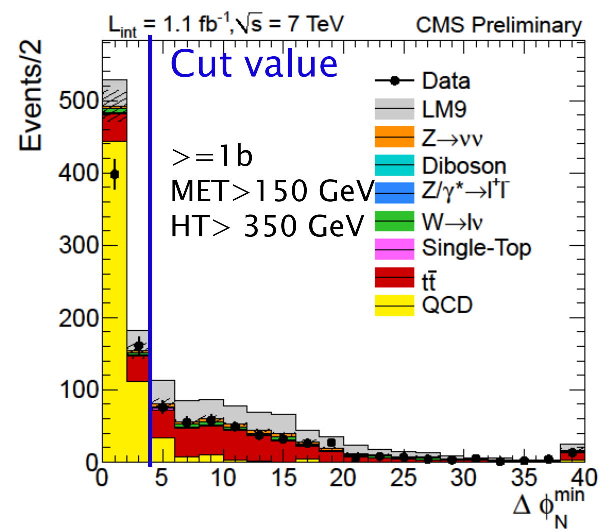
- $\Delta\phi_N$(j,MET) variable and MET are ~uncorrelated
  - Therefore an extrapolation can be made from low MET to high MET of the fraction of events that pass the $\Delta\phi_N$(j,MET) selection

$$(N_{pass})^{\text{high MET}} = (N_{pass}/N_{fail})^{\text{low MET}}\{(N_{fail})^{\text{high MET}} - N_{contamination}\}$$

ttbar and EW contamination taken from MC

We make this estimate in 2 different "high MET" regions:
→150<MET<200 GeV (used in ttbar estimate)
→Signal Region





MET+b: Z→νν method

- Use Z→ll, l=e,μ control samples
  - Treat the event as though you didn't see the leptons and you have a pseudo Z→νν event
  - Correct for:
    - Branching ratio Z→νν / Z→ll = 5.95
    - efficiency to detect the leptons ε

$$\epsilon = \mathcal{A} \cdot \epsilon^2_{\ell\,\mathrm{reco}} \cdot \epsilon_{\mathrm{trig}} \cdot \epsilon^2_{\ell\,\mathrm{sel}}$$

Efficiency factors for the leptons

Acceptance $\mathcal{A}$: sufficient p_T, in $|\eta|$ range (MC)

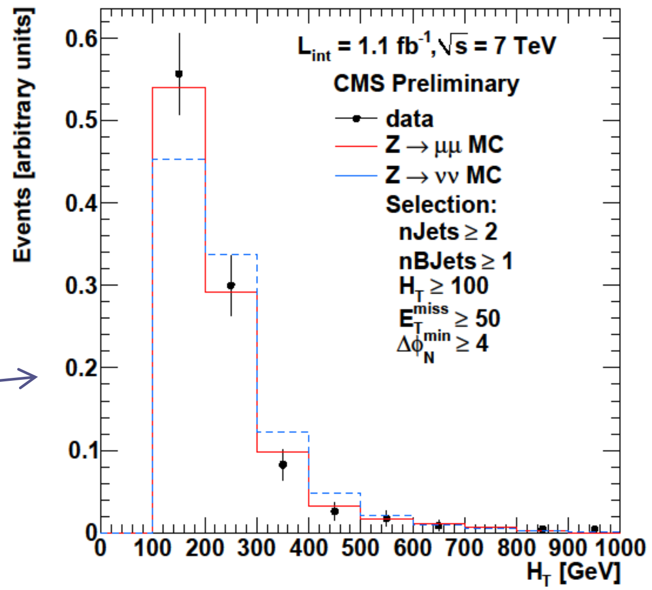
$\varepsilon_{l,reco}$: reconstruction eff for leptons in the acceptance (from CMS e/γ group)

ε_{trig}: trigger efficiency for dilepton control samples (orthogonal trigger in data)

$\varepsilon_{l,sel}$: efficiency for various quality criteria added for our analysis (tag and probe in data)

MET+b: Z→νν details

- Must determine the purity of the Z→ll samples
  - done by fitting a Z mass peak to samples obtained with somewhat looser selection criteria
- Dilepton control samples usually have no events after the nominal MET, HT selections
  - Do estimates for looser selections, extrapolate using MC
    - MC seems to be reliable
    - Cross-check this procedure several ways, including a method that loosens the b-tagging instead of the kinematic selections
      - measure (loose b tag)/(nominal b tag) in a data control sample



MET+b: Main systematics on backgrounds

- QCD
  - closure in MC
    - often driven by high-weight events in MC
    - closure was done in several ways, including a test with the MC reweighted based on the jet multiplicity distribution in data
- ttbar
  - QCD subtraction
  - closure in MC
- Z→$\nu\nu$
  - MC-based scaling to HT, MET tails

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Results in 1.1 fb^{-1} of data

- Observed events consistent with SM background predictions

Data-driven background estimates

	">=2b Loose" HT>350 GeV MET>200 GeV	">=1b Tight" HT>500 GeV MET>300 GeV	MT2+b HT>650 GeV MT2>150 GeV $\geq$1 b
	≥ 2 b	≥ 1 b	
QCD	$0.0 \pm 0.4^{+5.8}_{-0.0}$	$0.2 \pm 0.2^{+0.5}_{-0.2}$	
top and W+jets	$24 \pm 7 \pm 5$	$13 \pm 5 \pm 4$	
top and W+jets cross-check	—	$17.0 \pm 5.7 \pm 2.1$	
$Z \rightarrow \nu\bar{\nu}$	$2.6 \pm 2.9 \pm 2.0$	$5.0 \pm 1.6 \pm 2.0$	
Total SM	$25.8 \pm 7.4^{+7.8}_{-5.2}$	$18.2 \pm 5.3 \pm 4.5$	$10.6 \pm 1.9 \pm 4.8$
Data	30	20	19
SM MC prediction	35.7 ±1.3	25.1 ± 1.6	15.0
LM9 signal	60.0 ±2.5	27.7 ± 2.2	42.9

LM9 is eliminated by both analyses

Signal efficiency systematics

MET+b values shown; MT2+b results similar

Table 17: Systematic uncertainties, in percent, on the efficiency of the LM9 signal. The "Other" category includes the trigger efficiency, the lepton veto, and the anomalous $E_{\mathrm{T}}^{\mathrm{miss}}$ terms.

	Loose search region		Tight search region	
Source	≥ 1 b	≥ 2 b	≥ 1 b	≥ 2 b
Jet energy scale	7.7	8.6	12.1	13.7
Jet energy resolution	0.1	0.3	3.0	4.2
Unclustered energy	2.0	1.6	5.7	7.5
Pileup	3.4	3.1	4.3	4.2
b-tagging efficiency	6.5	15.8	7.1	17.2
Parton distribution functions	11.1	11.2	11.8	12.1
Other	3.5	3.5	3.5	3.5
Luminosity	4.5	4.5	4.5	4.5
Total uncertainty	16.5	22.2	20.7	27.5

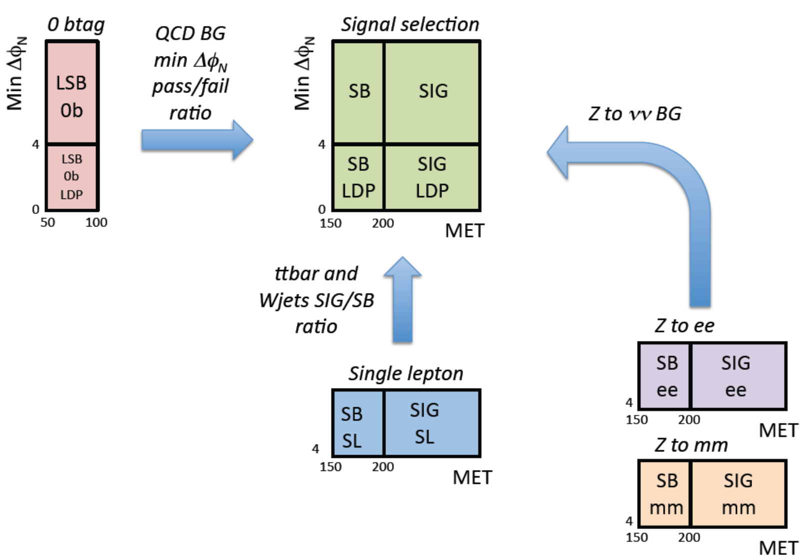
→JES, unclustered energy, b-tag eff, PDF are evaluated point-by-point across the CMSSM and simplified model planes
→Other uncertainties are fixed to LM9 values.

MET+b analysis

Likelihood treatment (for limits)

- Combine background estimates into a RooStats framework that incorporates uncertainties and SUSY contamination
  - Event counts in data get Poisson uncertainties
    - 12 numbers total (11 control regions + signal box)
    - Note that the 5 of the control boxes can be "contaminated" by SUSY and this is treated in a consistent way in the likelihood
  - Other parameters get log normal uncertainties
  - 95% CL upper limits are evaluated using CLs tools built into RooStats

Data observables

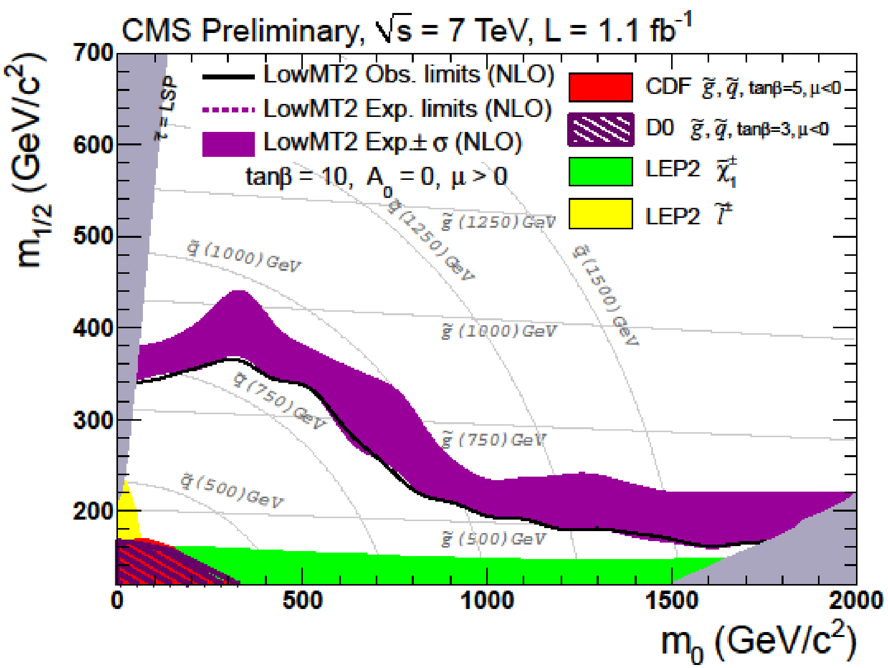


Other Parameters

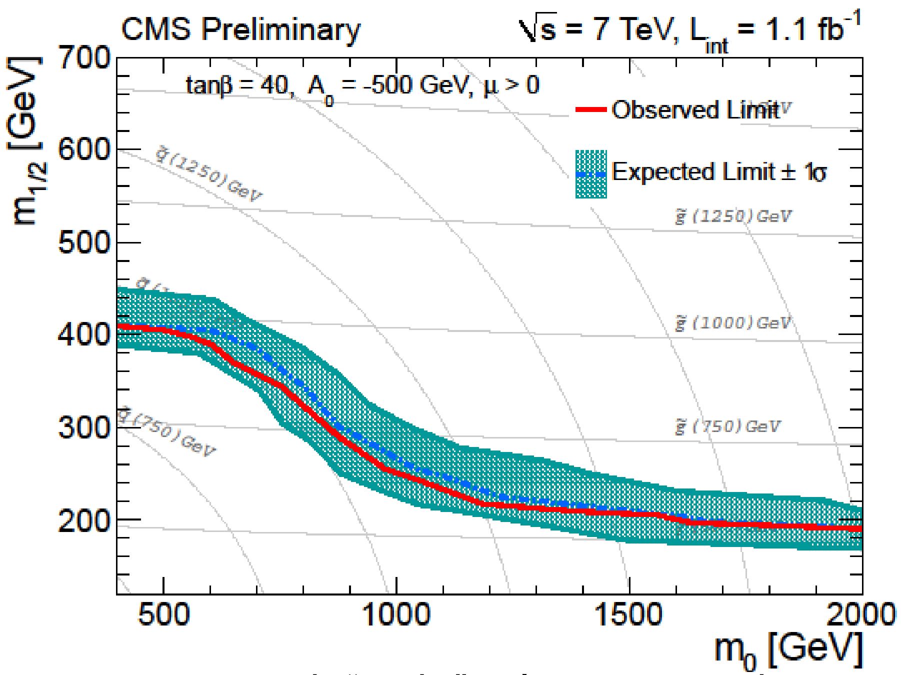
- systematics on the background estimation methods
  - e.g. closure test results, Z→νν efficiency factors, …
- statistical and systematic uncertainty on signal efficiency

Interpretation in the CMSSM

MT2+b



MET+b



Note: ≥ 1b "Tight" selection gives best *expected* limit everywhere in CMSSM, so we focus on that result

Note: MT2+b is tanβ=10 while MET+b is tanβ=40

→ignoring this difference, limits are similar

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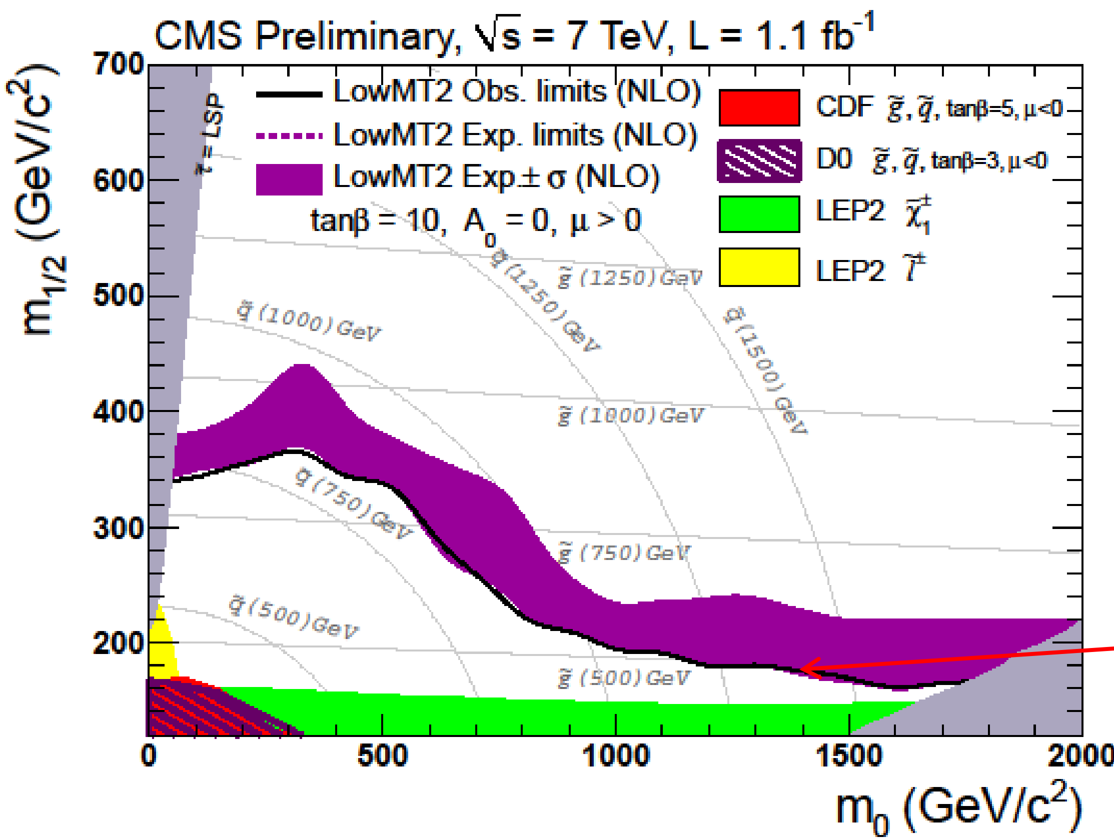
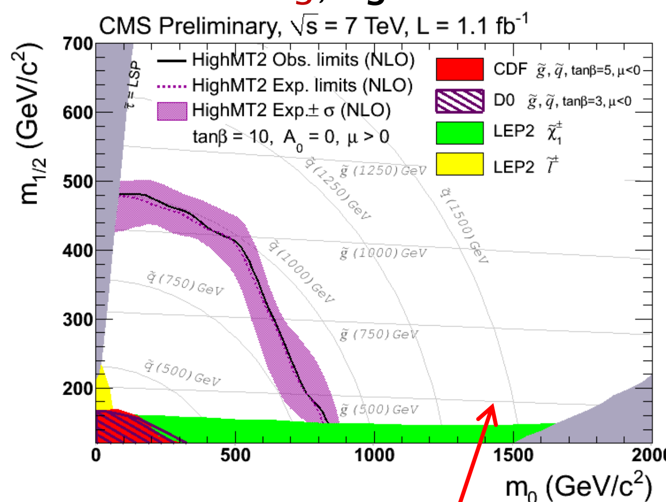
More on MT2+b results in CMSSM

With b tag, **looser** MT2 cut



No b tag, **tighter** MT2 cut



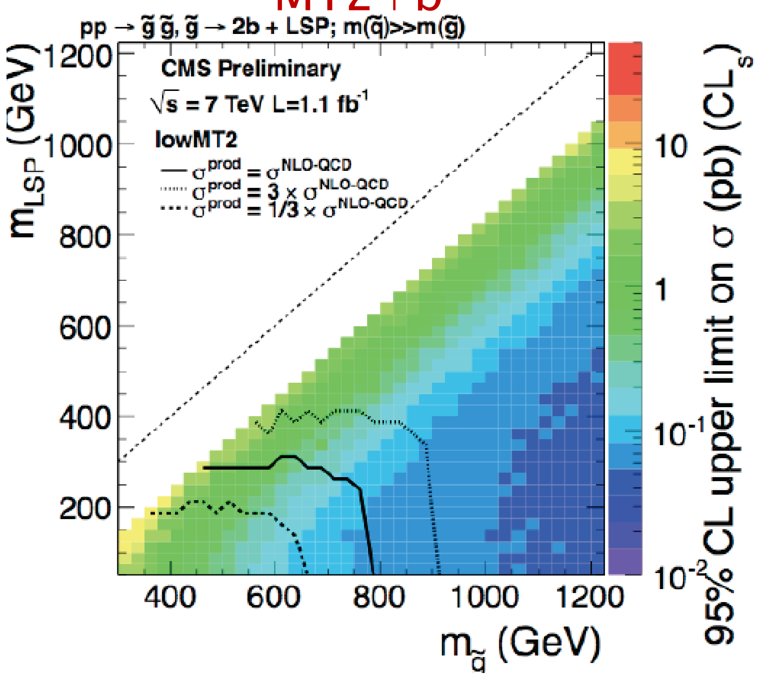
b-tagged analysis does better at high m_0

→a key advantage of b-tagged SUSY searches is that they can have looser kinematic selections while maintaining low levels of background

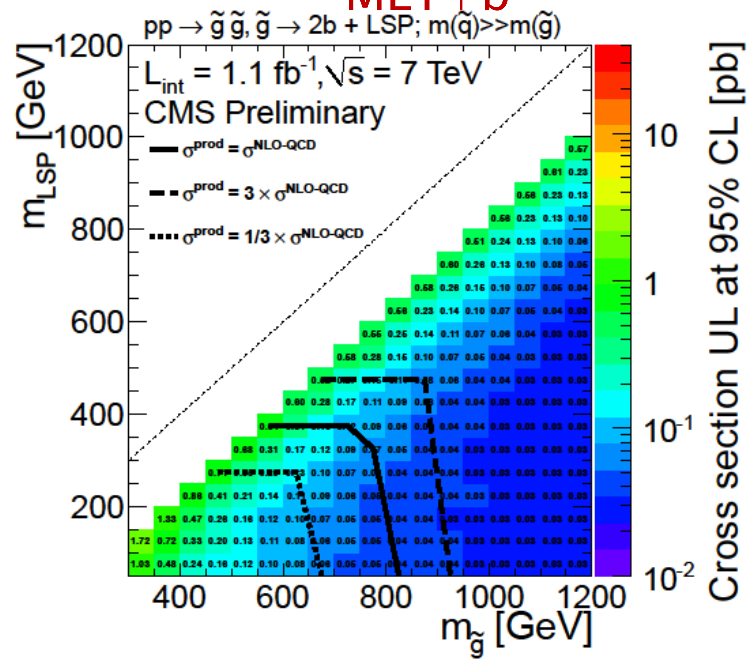
Interpretation in Simplified Models

- Hard to generalize results in full models like CMSSM
  - Instead look at a simplified model, which is easier for a theorist to use when building new models
  - In our case: g~g~ → bbX~ bbX~
    - Exclusive production and decay
  - Set an upper limit on the cross section as function of mg~, mX~
    - (Also get excluded region based on NLO cross section)

MT2+b



MET+b



→**Similar sensitivity**; MET+b does better in regions closer to the diagonal

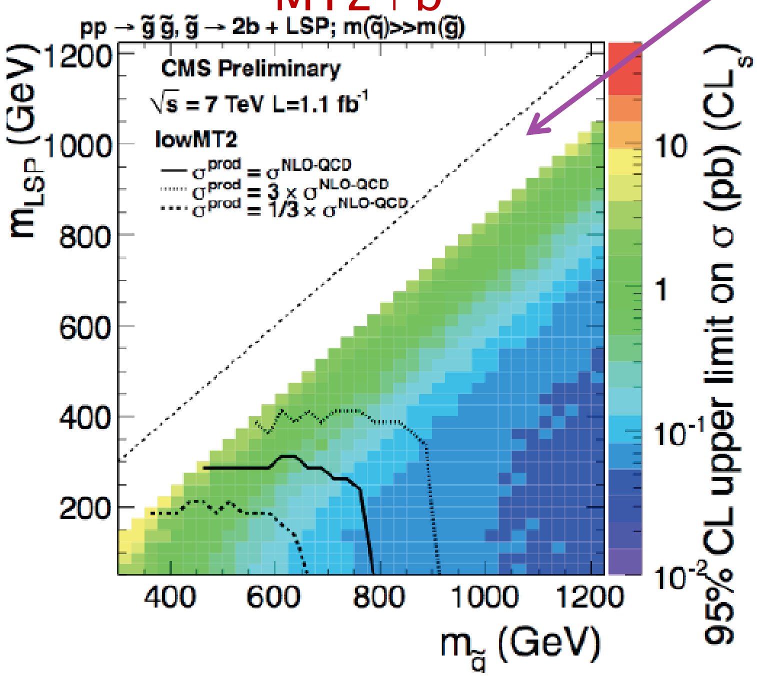
Interpretation in Simplified Models

- Note: Region very near the diagonal is very sensitive to initial state radiation (ISR).

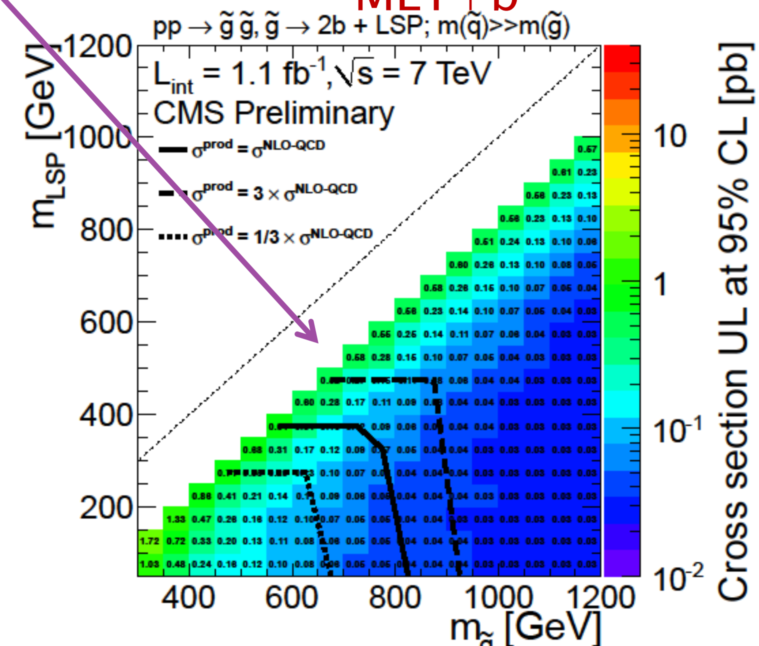
  At the moment we do not consider a systematic uncertainty due to ISR in these analyses, so we do not show results in this region.

  - (Also get excluded region based on NLO cross section)

MT2+b



MET+b

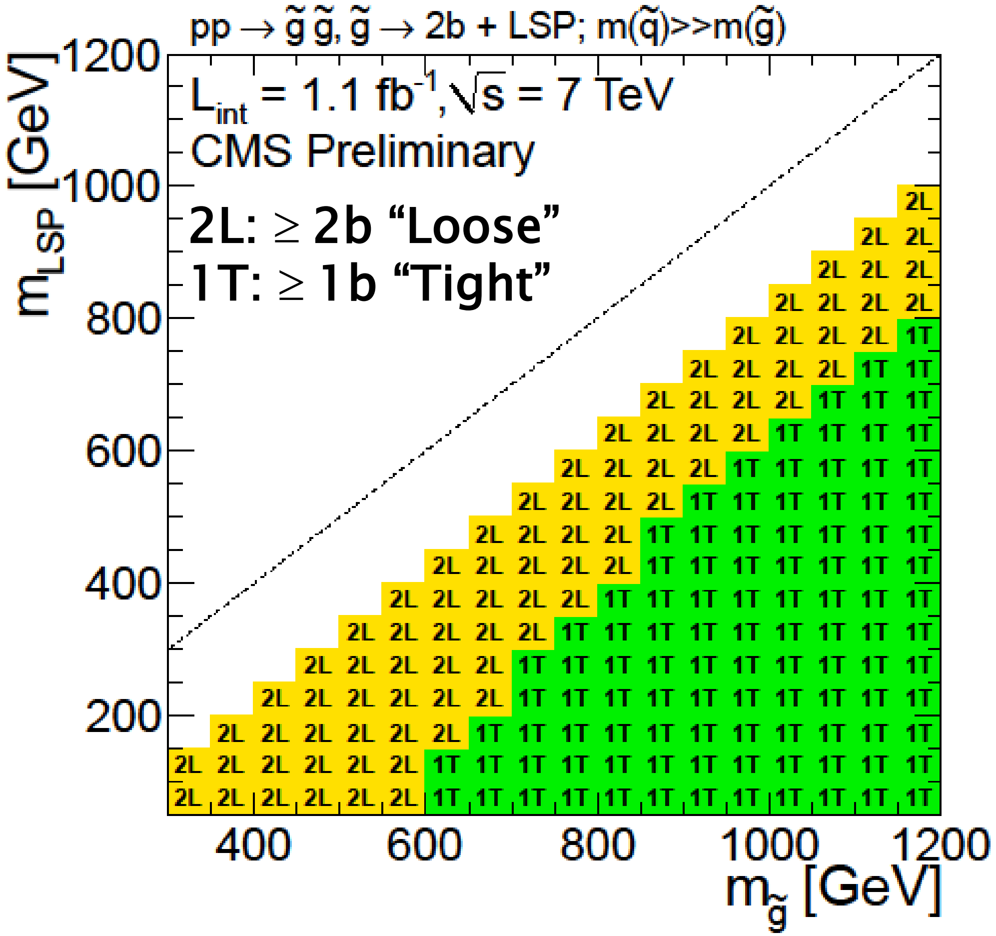


→**Similar sensitivity**; MET+b does better in regions closer to the diagonal

Note on kinematics and selections

- Simplified models have widely varying kinematics by construction
  - Heavy gluino, light LSP gives high p_T daughters → hard jets and lots of MET
  - Nearly degenerate gluino, LSP → soft jets and little MET
    - Challenging! Favors looser selections
- In MET+b, choose to show the limit at each point as determined by the best **expected** limit
  - "expected" limit is derived from data-driven background estimates, but without using the observed data counts in the signal region
  - The limit you would expect if your observed data exactly matched your background estimate

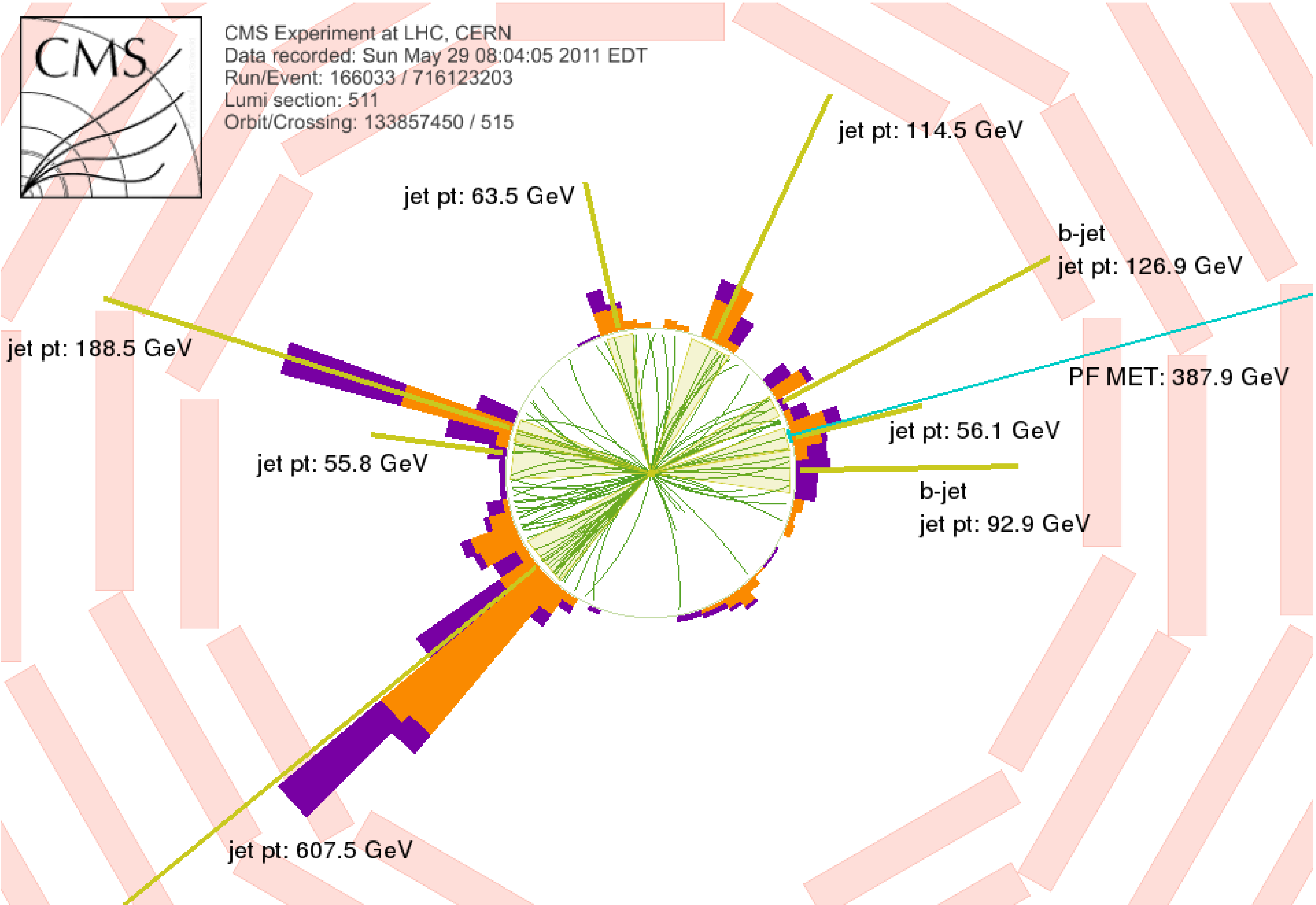
MET+b: which selection is best



Conclusion

- CMS has two b-tagged SUSY searches with 1.1 fb^{-1} of data
  - Expect publications with the full 2011 dataset
- Observed data consistent with background
  - Limits placed in CMSSM, 4b simplified model
    - Watch for more simplified models in the future
      - Limits on stop mass are particularly interesting…
- Further information
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS
    - MT2+b: CMS PAS SUS-11-005
      - http://cms-physics.web.cern.ch/cms-physics/public/SUS-11-005-pas.pdf
    - MET+b: CMS PAS SUS-11-006
      - http://cms-physics.web.cern.ch/cms-physics/public/SUS-11-006-pas.pdf

Highest HT event in MET+b signal region

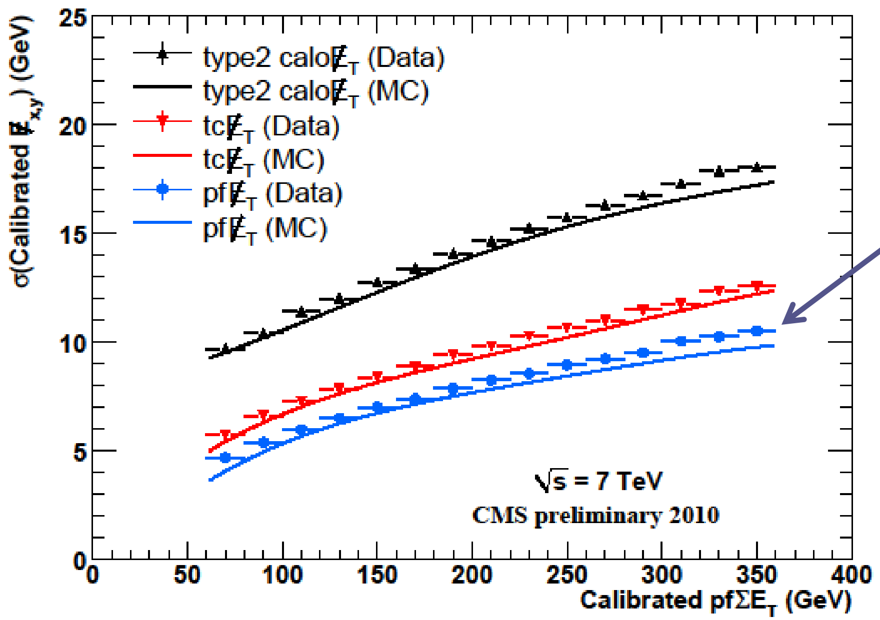


Extra slides

Particle flow reconstruction

- CMS makes heavy use of "particle flow" reconstruction, which combines information from the tracker, calorimeters, and muon systems to reconstruct jets, leptons, MET, etc

CMS PAS JME-10-005



MET resolution enhanced using PF reconstruction

What is the CMSSM?

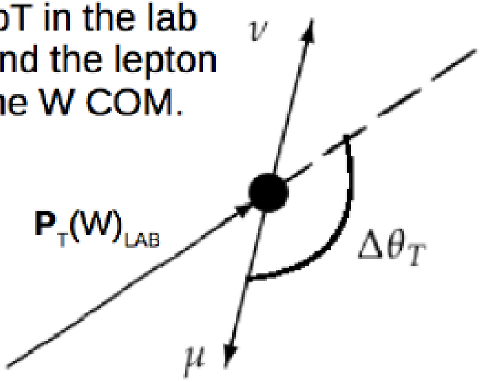
- SUSY, even in its "Minimal" MSSM variant, is rather unwieldy
  - Constrained Minimal Supersymmetric Standard Model (CMSSM) is a minimal supergravity (mSUGRA)-inspired model of soft supersymmetry breaking
    - Only 5 parameters!
      - m_0: scalar mass
      - $m_{1/2}$: universal gaugino mass
      - A_0: trilinear coupling
      - tan β: ratio of Higgs VEVs
      - sign(μ): sign of the Higgs mixing parameter
    - "It is a matter of some controversy whether the assumptions going into this parameterization are well-motivated on purely theoretical grounds, but from a phenomenological perspective they are clearly very nice." – S.Martin [hep-ph/9709356v6]
      - In practice, even a 2d parameter space is tough to simulate!

MET+b analysis

Cross-check of ttbar+W+t with $\Delta\theta_T$

- For W→e,μ,τ (τ→e,μ) decays
  - Angular distribution of lepton w.r.t. W, $\Delta\theta_T$, depends on W polarization, which is well understood
    - $\Delta\theta_T$ low → lepton is boosted forward, neutrino goes backward→lower MET
    - $\Delta\theta_T$ high→lepton softer and neutrino boosted forward→higher MET
- For W→τ (τ→had) decays
  - Single muon control sample from $\mu+H_T$ trigger
  - Transform muon into a τ jet using a response template taken from MC
- For dileptonic decays
  - Dilepton control sample, scaled by an efficiency ratio taken from MC

The angle between the W pT in the lab frame, and the lepton pT in the W COM.



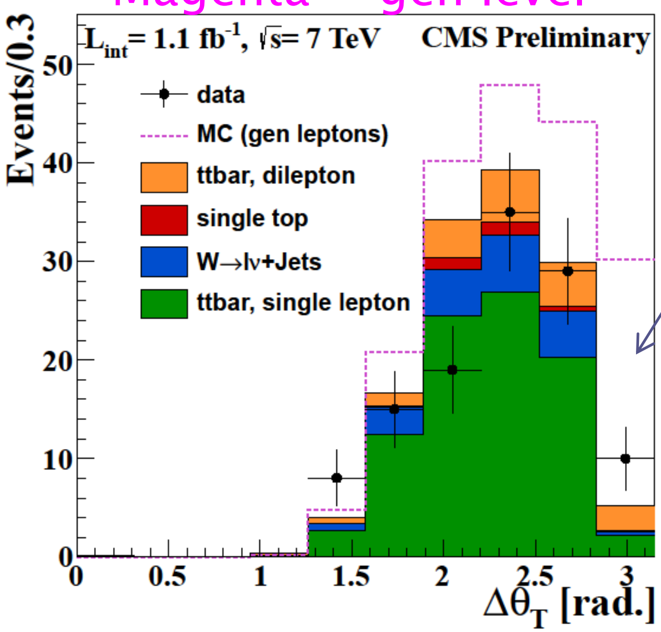
ttbar+W+t cross-check:

Method for decays with e or μ

- Start with single lepton control sample
- Rescale the MET distributions of the SL sample in bins of $\Delta\theta_T$ using scale factors from MC
- Predicts both the shape and normalization of signal sample MET distribution

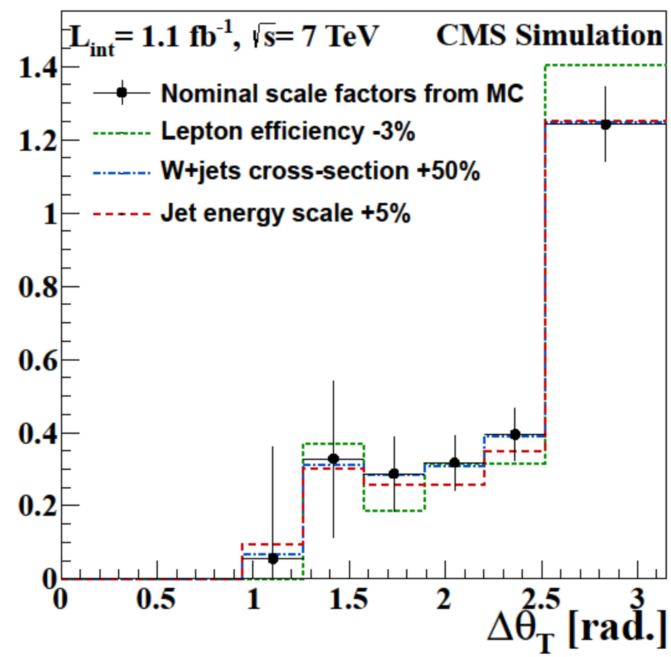
$$SF(\Delta\theta_T) = \frac{\text{N MC gen tt/W/t with 1 lost lepton}}{\text{N SM MC with 1 reco lepton}}$$

Magenta = gen level



Lost leptons

>=1b, MET>150 GeV

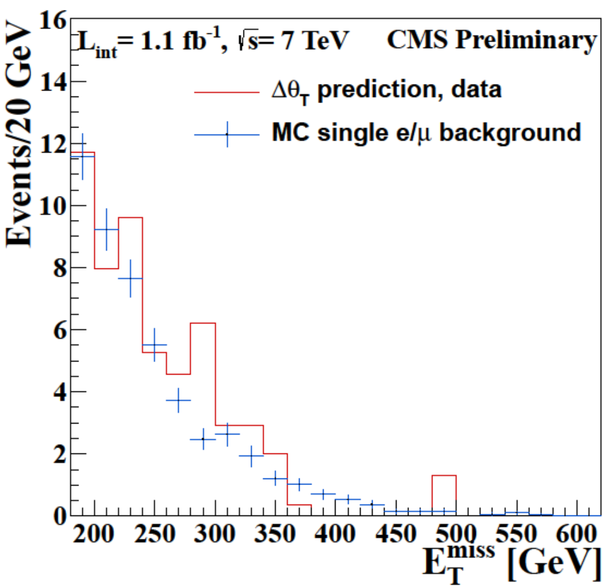


MET+b analysis

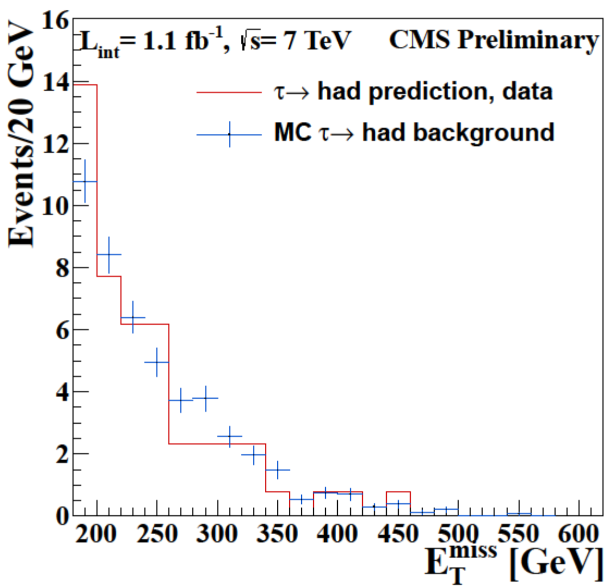
ttbar+W+t cross-check:

MET spectrum predictions

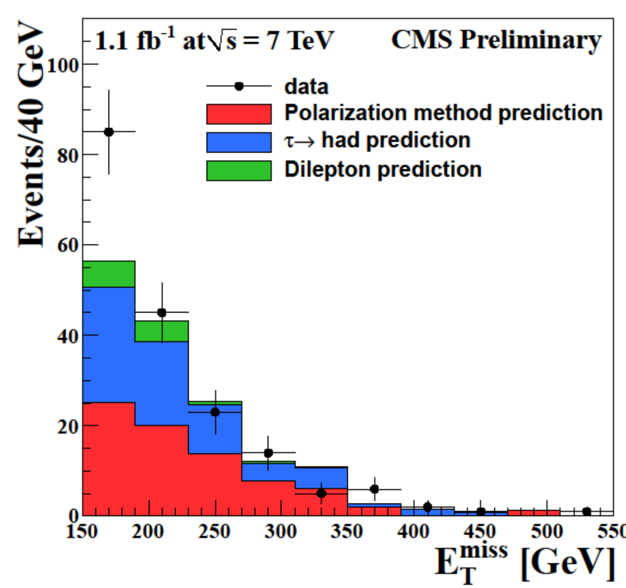
>=1b, Tight (HT>500 GeV) selection



$\Delta\theta_T$ prediction compared to MC shape



τ→had prediction compared to MC shape



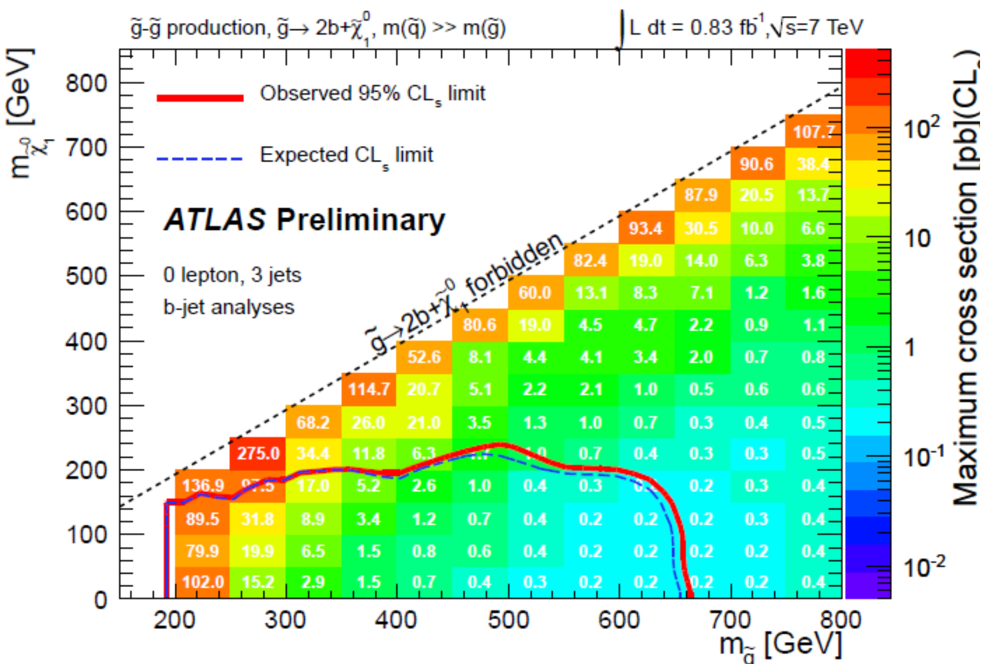
Overall prediction compared to data

NB: sizable QCD contribution in lowest bin

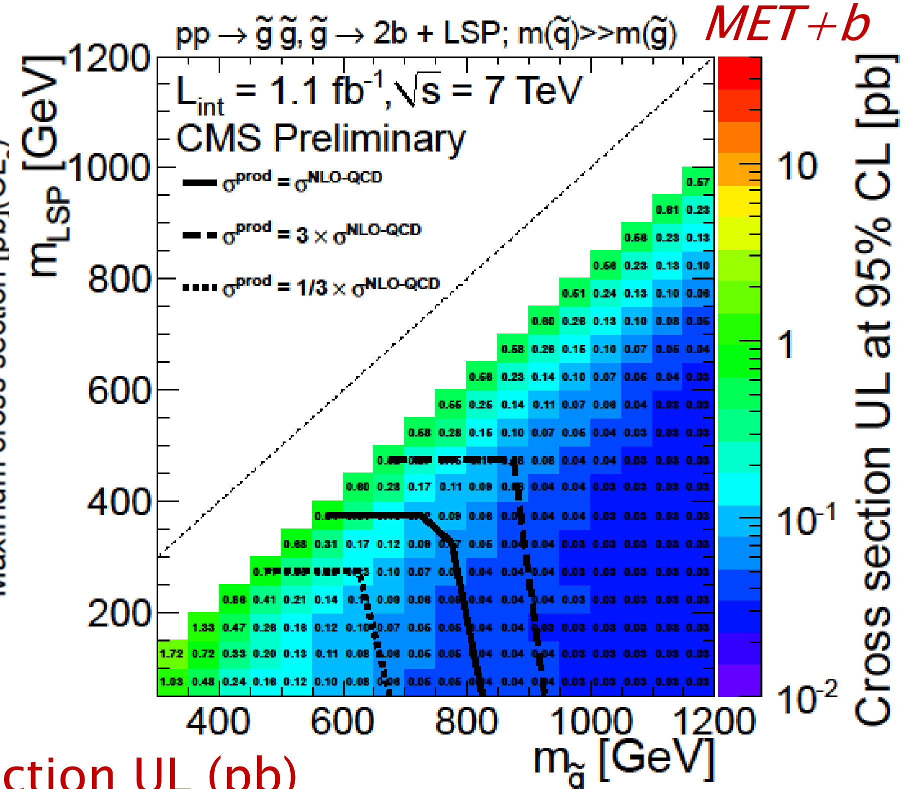
Note: cross-check done only for Tight selection because trigger requirements preclude doing Loose selection

Comparison with ATLAS

ATLAS-CONF-2011-098



MET+b



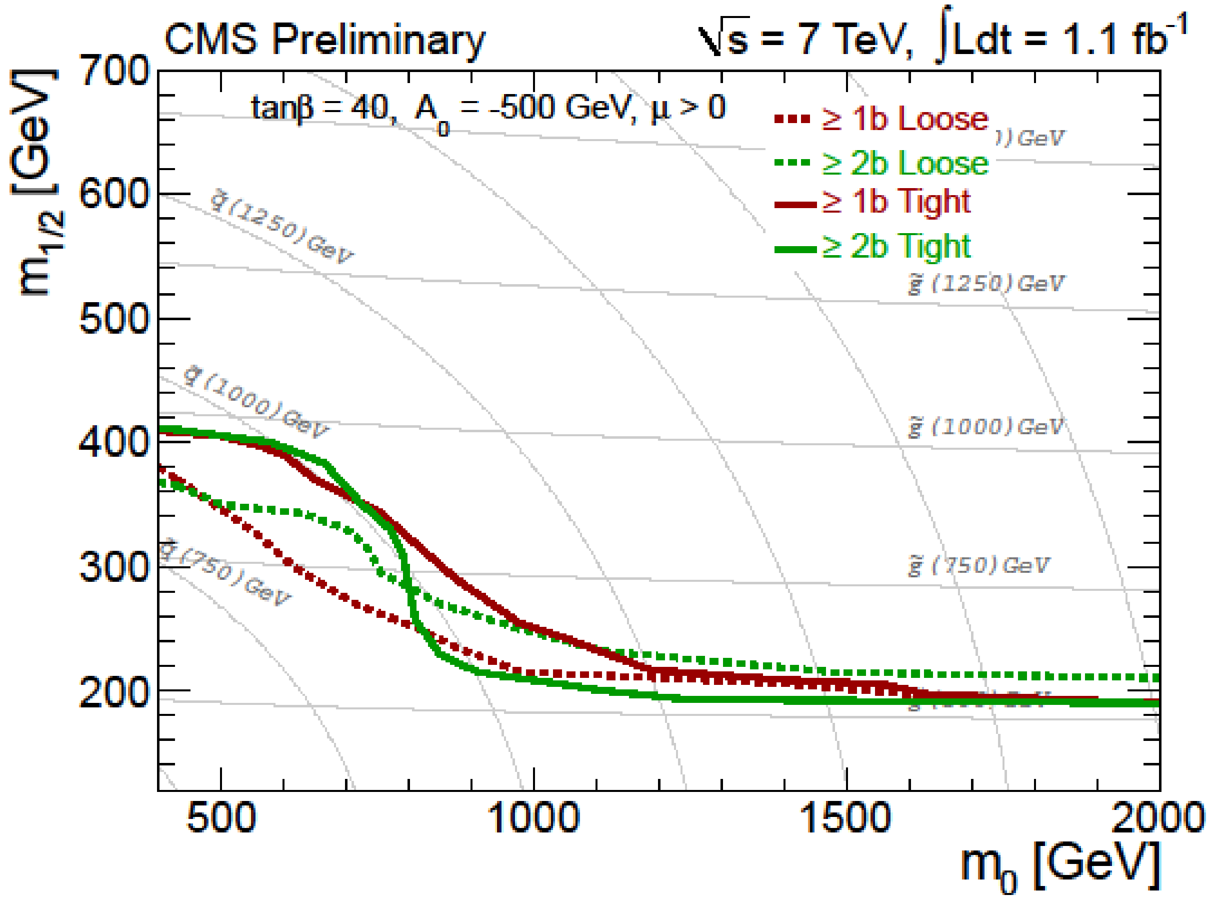
Cross section UL (pb)

$m_{g\sim}, m_{LSP}$ (GeV)	MT2b	METb	ATLAS
600, 300	0.60	0.17 (2L)	1.0
800, 200	0.08	0.04 (1T)	0.5

(Keep in mind that CMS uses slightly more luminosity)

Interpretation in CMSSM

- Observed limits for all four selections



95% CL exclusion using CLs

MET+b: QCD systematics

MC:
vary MC-based subtraction by +/-50%
[this number comes from the >=2 b Tight case. Use it for all cases to be conservative]
Closure:
$1-N_{true}/N_{predicted}$ [in quadrature with its stat error]
(use worse of raw MC and jet multiplicity-reweighted MC)
LSB range:
vary LSB range by +/-10 GeV and take the larger observed shift →
factor of >2 change in statistics with each shift

Systematic uncertainties in %

Selection	MC	Closure	LSB range	Total
$\geq$ 1 b, Loose, SB	10	28	2	30
$\geq$ 1 b, Loose, SIG	29	102	2	106
$\geq$ 1 b, Tight, SB	8	71	10	72
$\geq$ 1 b, Tight, SIG	73	213	10	225
$\geq$ 2 b,Loose, SB	21	69	2	72
$\geq$ 2 b,Loose, SIG	*	1156	*	*
$\geq$ 2 b,Tight, SB	19	199	10	200
$\geq$ 2 b,Tight, SIG	34	370	10	371

NB on >=2, Loose, SIG:
Large systematic stems from large stat error on N_{true} in MC
** reflects the fact that the nominal value is 0, so a % change is ill-defined.*

MET+b: Z→νν systematics

- Background subtraction:
  - From the stat uncertainty in the fits to the Z peak
- MC closure:
  - Full lack of closure taken as a systematic
- MC extrapolation:
  - 50% for MC scale factor >0.1; 100% for MC scale factor <0.1
    - These numbers are justified by the spread seen in the cross-checks

Table 7: Systematic uncertainties for the $Z \to \nu\bar{\nu}$ background estimate.

Contribution	size (%) $Z \to \mu^+\mu^-$	size (%) $Z \to e^+e^-$
Background subtraction	18	20
Acceptance	2	2
Trigger efficiency	3	3
Lepton selection efficiency	5	5
MC closure	19	11
MC extrapolation	$0-100$	$0-100$
Total without extrapolation	27	24
Total with 50% extrapolation uncertainty	57	55
Total with 100% extrapolation uncertainty	104	103

MET+b: ttbar systematic uncertainties

- Closure systematic taken from worse (for each selection independently) of ttbar+W+t closure test and ttbar-only closure test
- Data-driven subtractions varied by their errors
- Small MC-driven subtraction varied by ± 100%

%

Selection	Closure	Contamination subtraction QCD	$Z \to \nu\bar{\nu}$	Other	Total
≥ 1 b, Loose	6	9	6	0.4	12
≥ 1 b, Tight	17	22	7	0.2	29
≥ 2 b, Loose	16	8	7	0.1	19
≥ 2 b, Tight	28	30	7	0.1	42