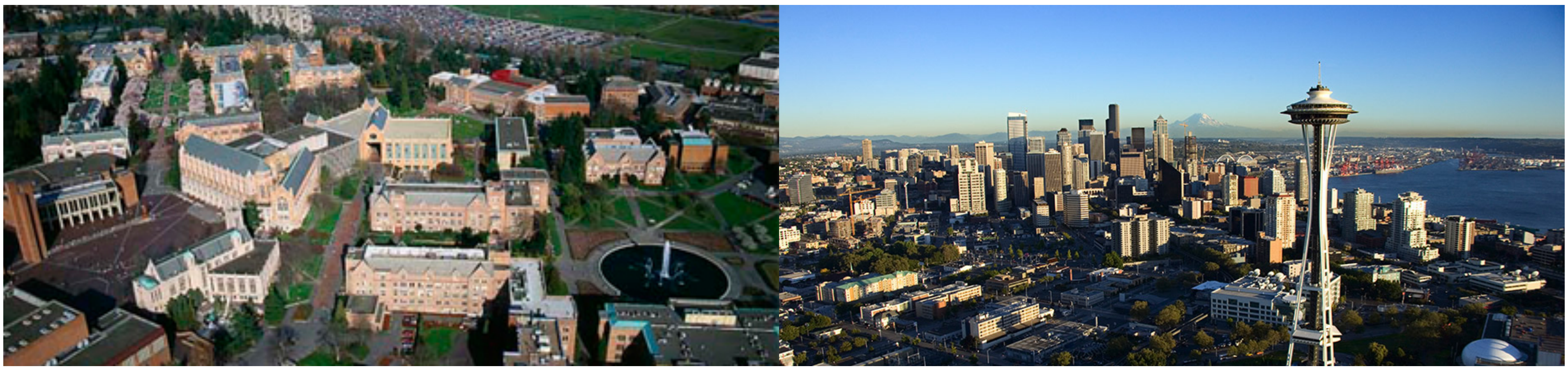
Preparing for Discovery
- A SUSY inspired perspective -



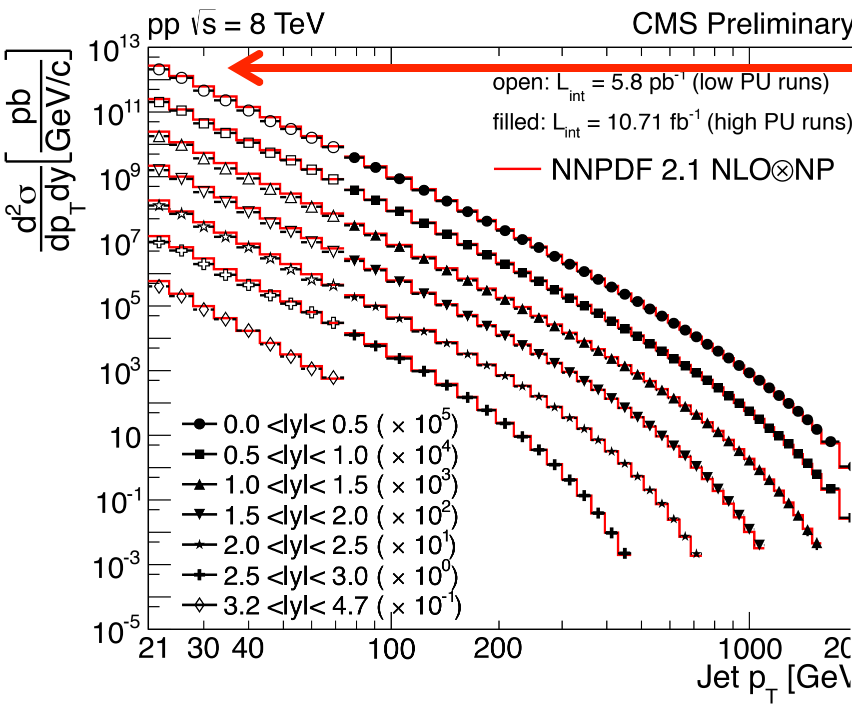
Frank Würthwein
UCSD

UCSD

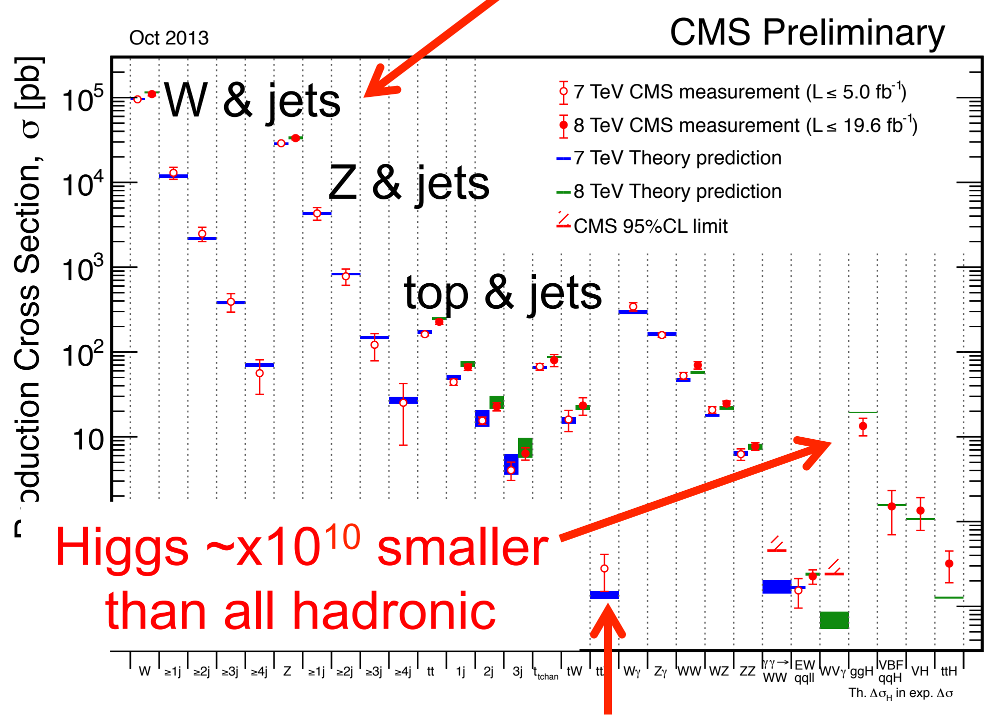
Without any loss of generality, this talk uses CMS results whenever possible to make my point.

(Most of you are from ATLAS. Why would you invite me to present to you your own results ?)

Standard Model Backgrounds



1-lepton & MET cross section
~ x10^6 smaller than all hadronic

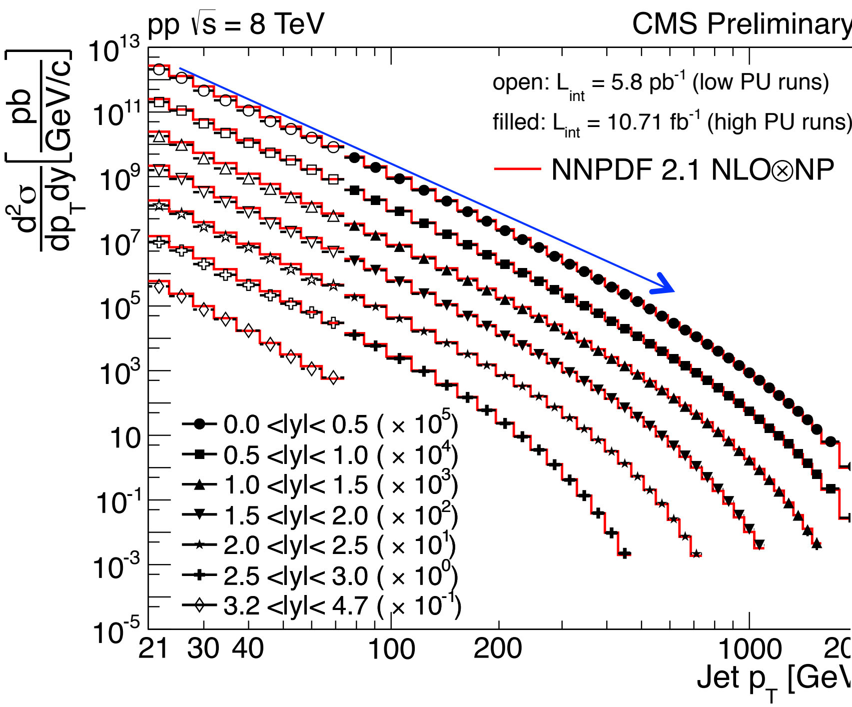


Higgs ~x10^{10} smaller
than all hadronic

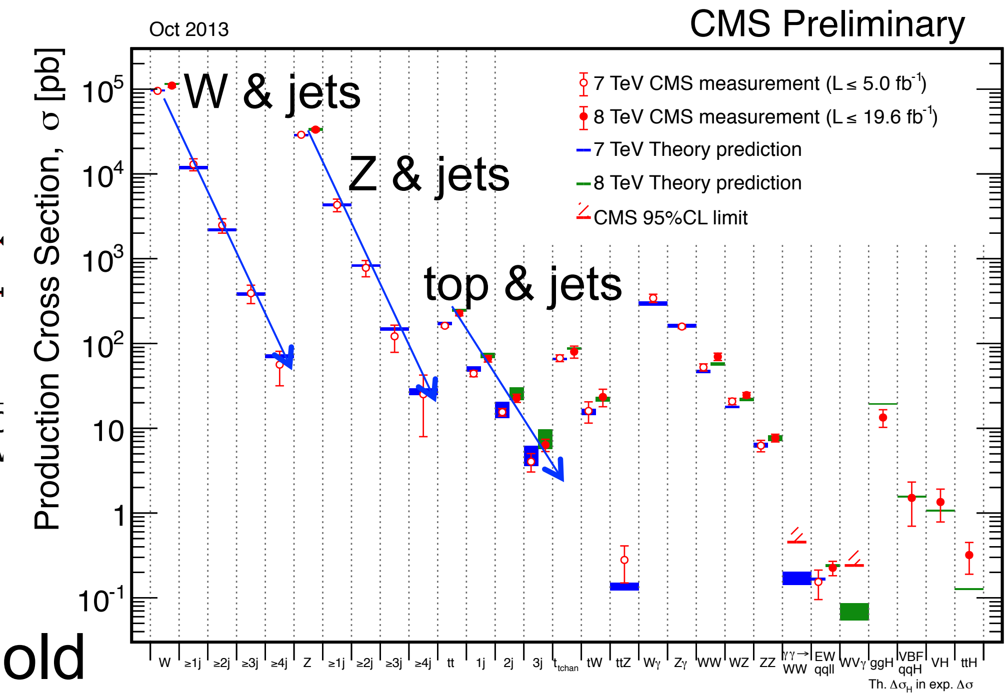
Dilepton same-sign & MET
~ x10^{12} smaller than all hadronic.

**Leptons, MET, Z, h, …
are excellent probes in
search for BSM physics**

Standard Model Backgrounds



Cross sections decrease exponentially with jet pT and # of jets.



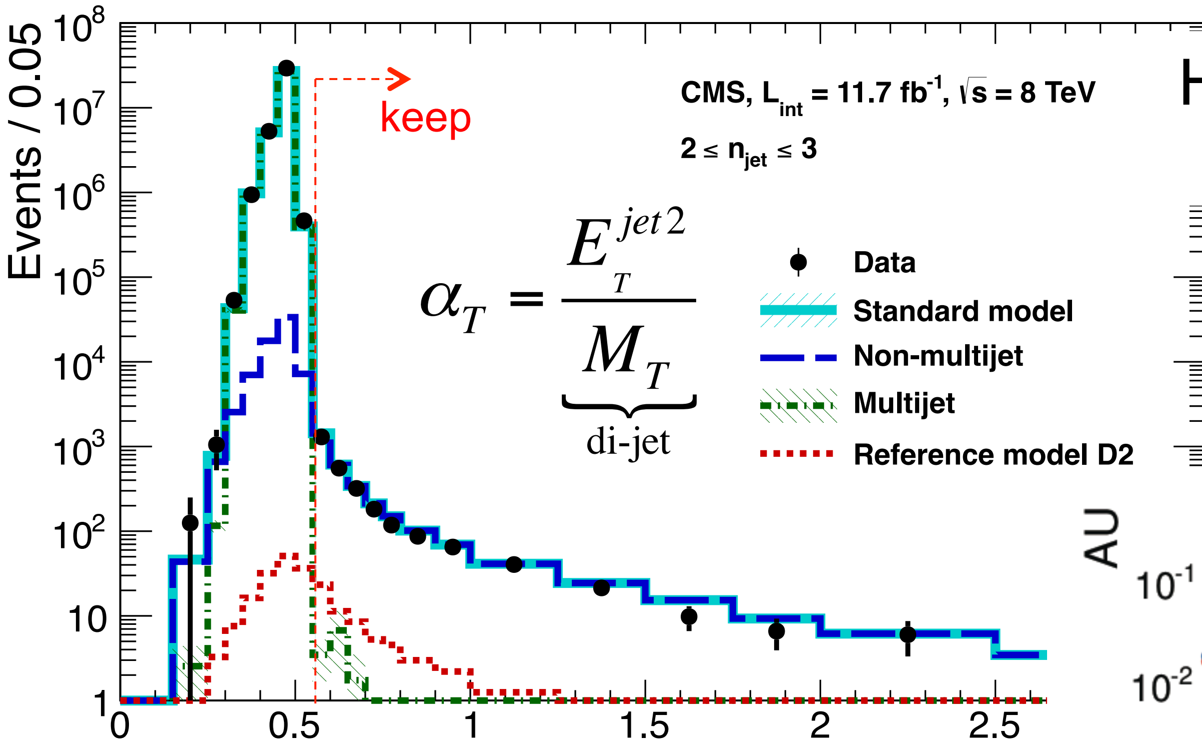
Define:

$H_T = \Sigma\, p_T$ of jets above threshold

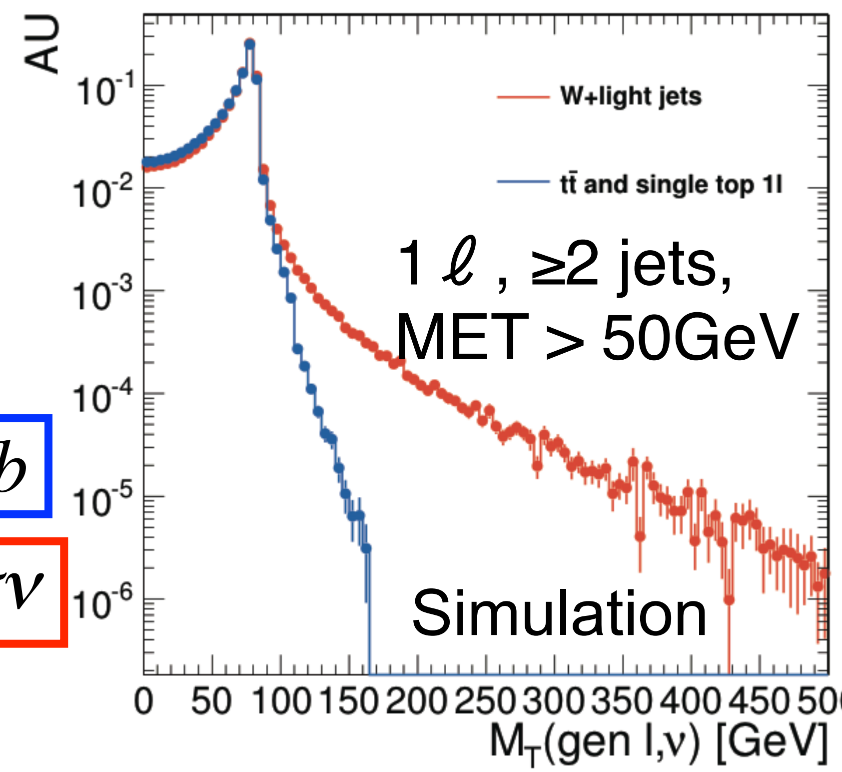
meff = H_T + MET

S_T = meff + $\Sigma\, p_T$ of leptons above threshold

Kinematic Endpoints



Hadronic event clustered into 2 megajets



Transverse mass for:

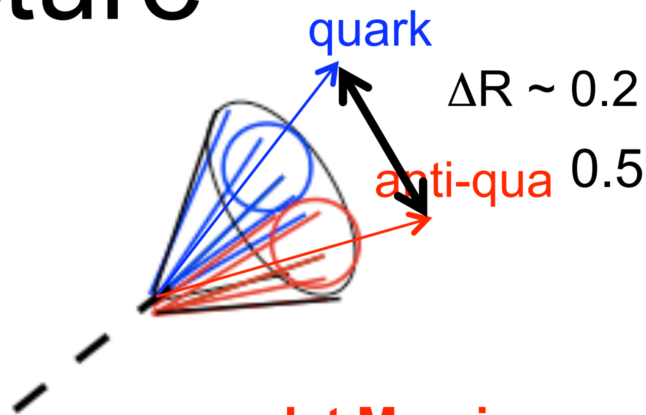
$$t \rightarrow Wb \rightarrow l\nu b$$

$$W \rightarrow \mu\nu, e\nu, \tau\nu$$

Jet Substructure

CMS-JME-13-006

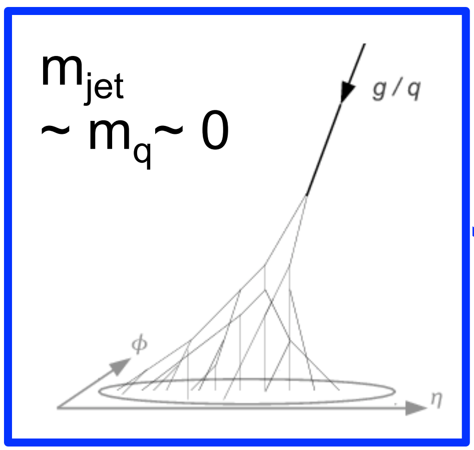
$$\Delta R_{qq}^{\min} \approx \Delta\theta_{qq}^{\min} \approx 2\frac{M_V}{p_{T,V}}$$

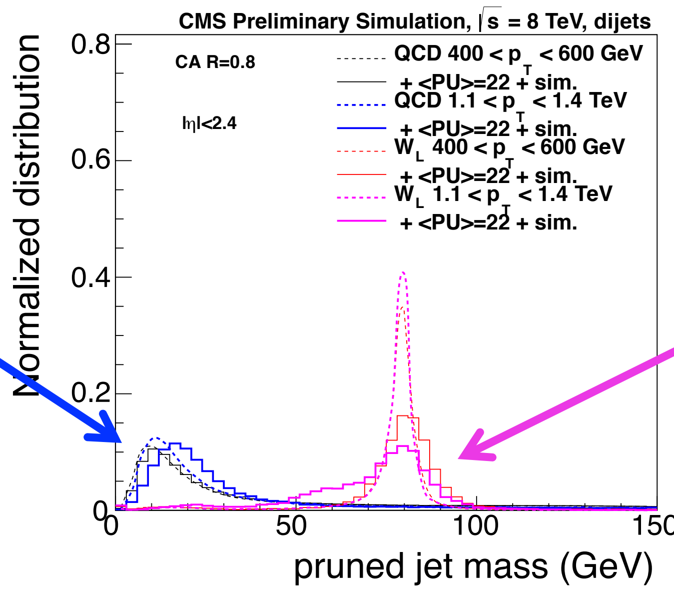


Jet Merging

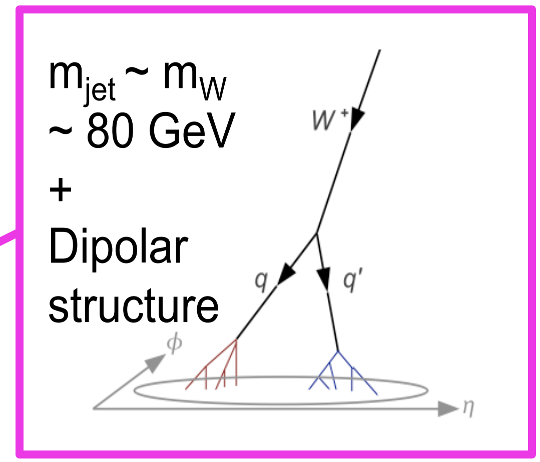
For W,Z,h Bosons of M ~ 100GeV
and jet cones of ΔR < 0.5
=> cones start merging at p > ~ 200GeV

Background





Signal



Typical Search Strategy

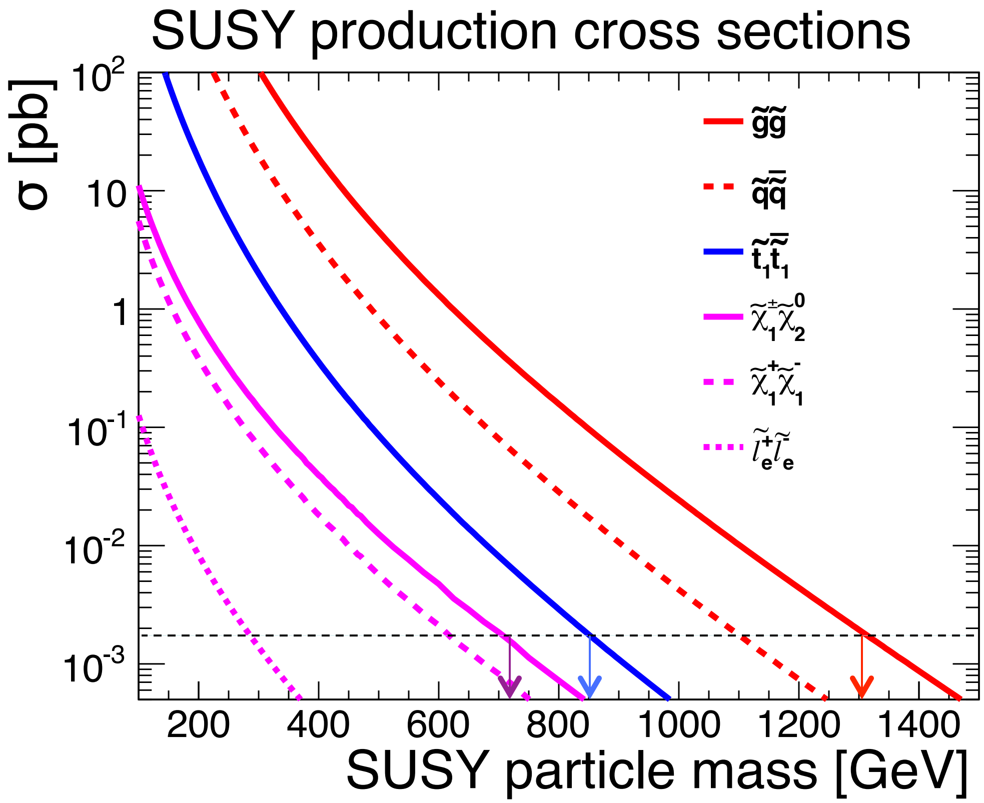
- Define "low bkg" signal regions using the ingredients from previous slides.
- Extrapolate expected bkg yields from carefully chosen bkg rich samples.
  - Derive extrapolation factors from mix of data and simulation.
- Measure accuracy of extrapolation in independent control regions in data and simulation.

Brains (Strategy) + Brawn (Execution) => Success

Three guiding principles

- Broadly search where noone has searched before.
- Detailed but narrowly focused searches when there is excellent theoretical motivation.
- Be mindful of any “gaps” in sensitivity

To set the scale @ 8TeV



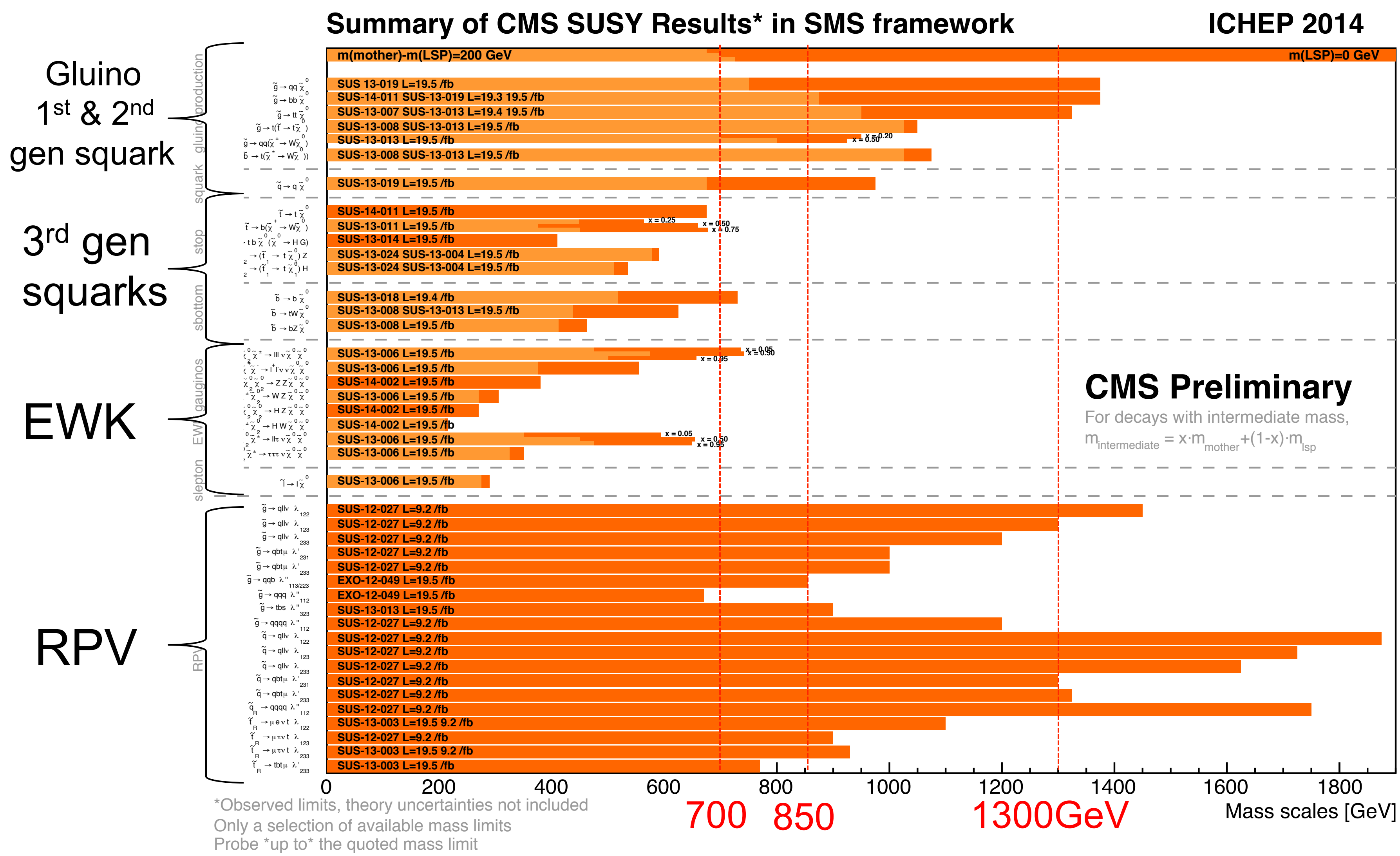
Kramer et. al.
arXiv:1206.2892
"Decoupling limit"

events in 20 fb^{-1}
8 TeV data sample

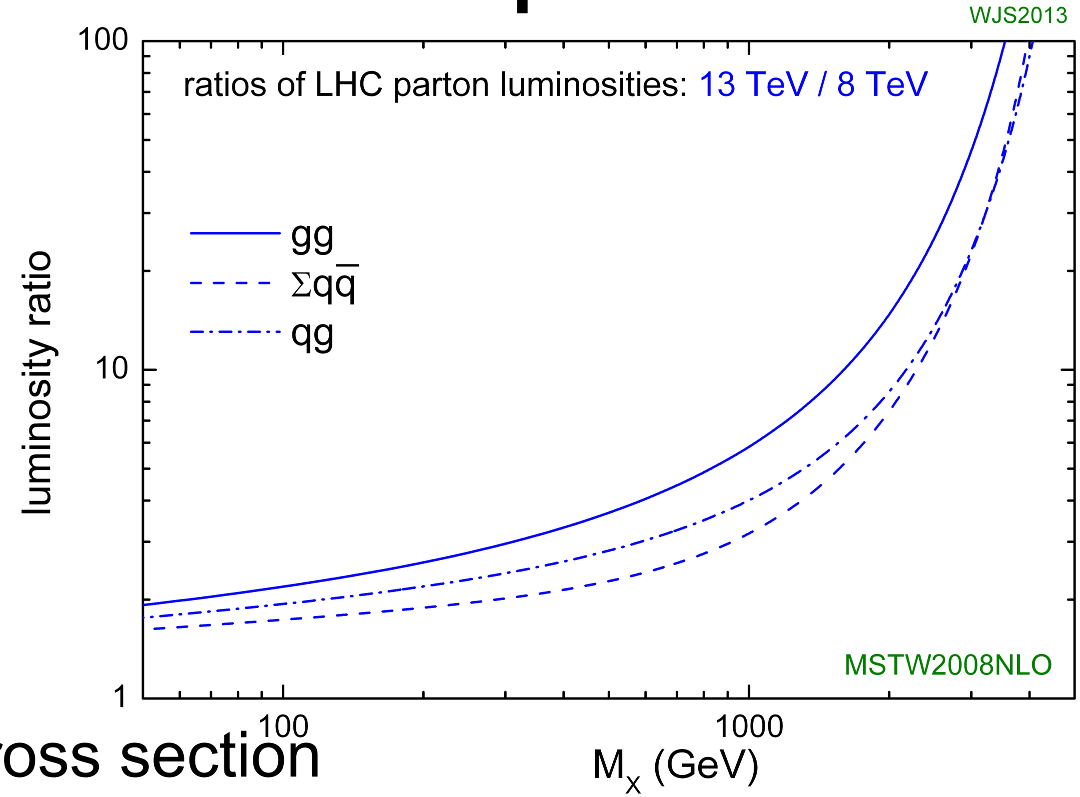
1000
100
10

- "threshold" for producing ~ 40 events
  - Gluinos @ ~ 1300 GeV
  - Stop/sbottom @ ~ 850 GeV
  - Chargino/neutralino @ ~ 700GeV

No New Physics Found !!!



What to expect in 2015



increase in cross section

1350GeV gluinos: x30

1000GeV gluinos: x20

750GeV squarks: x9

350GeV $X^{+-}X^{0}$: x3

top pairs: x4

Reach new territory with 1-6/fb of 13TeV luminosity

Signal grow much faster than SM bkg.

To set the scale

- “threshold” for producing ~ 40 evts in 20/fb @ 8TeV
  - Gluinos @ ~ 1300 GeV
  - Stop/sbottom @ ~ 850 GeV
  - Chargino/neutralino @ ~ 700GeV

- “threshold” for producing ~ 40 evts in 10/fb @ 13TeV
  - Gluinos @ ~ 1700 GeV
  - Stop/sbottom @ ~ 1050 GeV
  - Chargino/neutralino @ ~ 850GeV

Lesson 1

If SUSY was right around the corner then we might see some evidence for it already early in Run 2.

Broadly Search where noone has searched before.

2 Example inclusive SUSY Analyses

All Hadronic M_{T2}

Count jets with pT > 40GeV
Leading 2 jets pT > 100GeV
MET Δϕ > 0.3 with 4 leading jets
| H_T^{miss} – MET | < 70GeV
Veto events with e,μ (τ) with pT > 10(20)GeV
Minimum M_{T2} cut of 100-200GeV

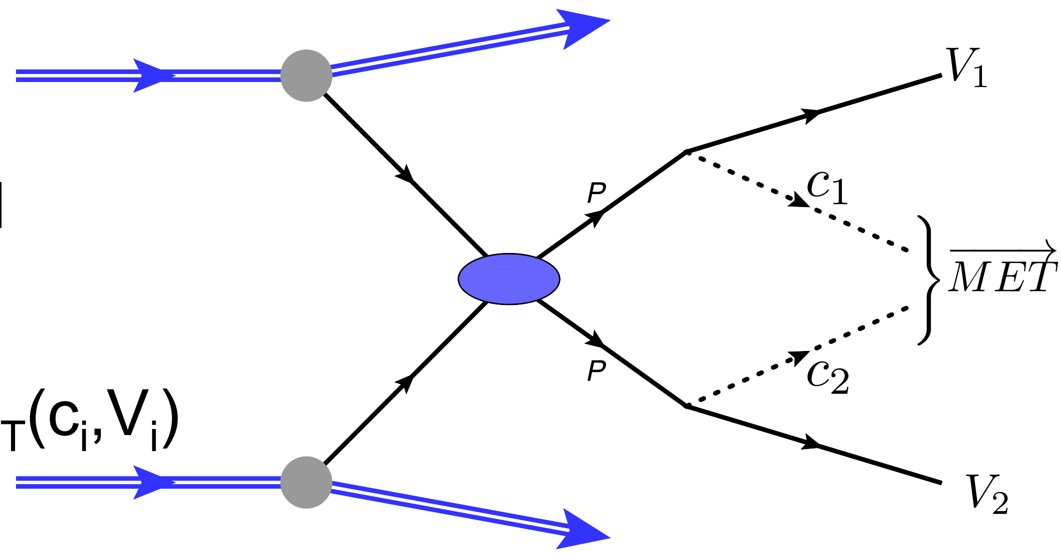
SUS-13-019

M_{T2} = *stransverse* mass

Cluster visible particles into two megajets V_1 and V_2

Partition MET vector into all possible combinations c_1, c_2

Form transverse masses $M_T(c_i, V_i)$



$$M_{T2}(m_c) = \min_{\vec{p}_T^{c(1)} + \vec{p}_T^{c(2)} = \vec{p}_T^{miss}} \left[\max \left(M_T^{(1)}, M_T^{(2)} \right) \right]$$

Signal Regions in M_{T2} are chosen to make QCD multijet bkg subdominant.

How M_{T2} suppresses QCD

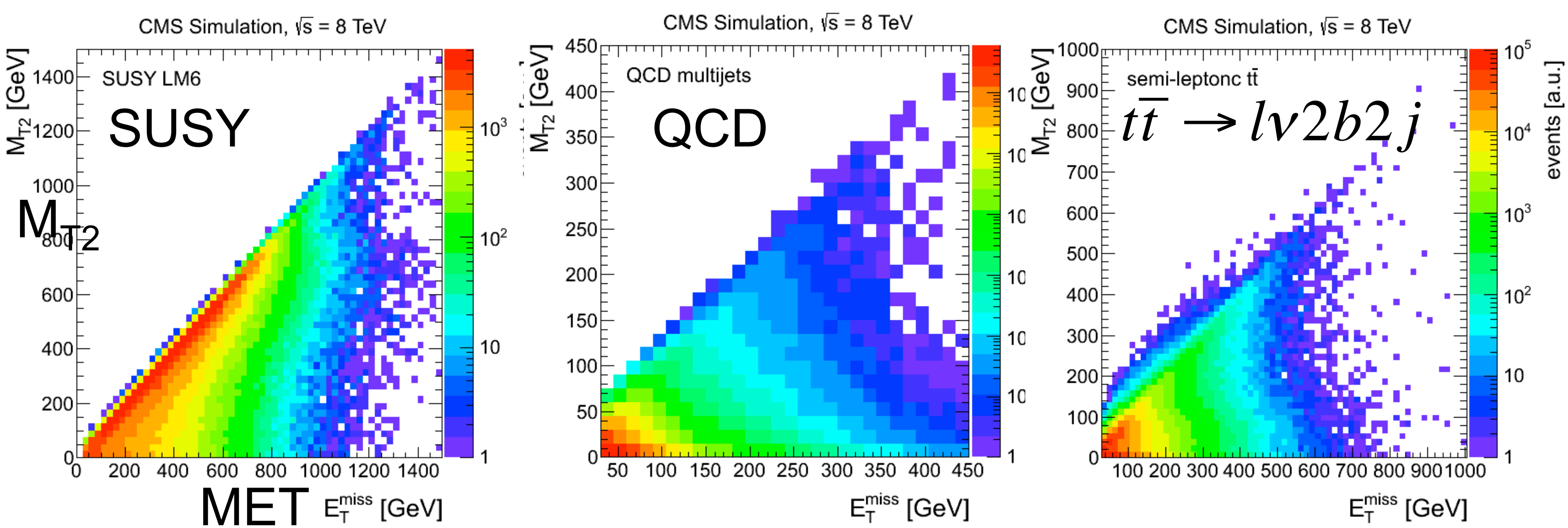
M_{T2} for dijet events:

$$M_{T2}^2 = 2 p_T^{V(1)} p_T^{V(2)} (1 + \cos\phi_{1,2})$$

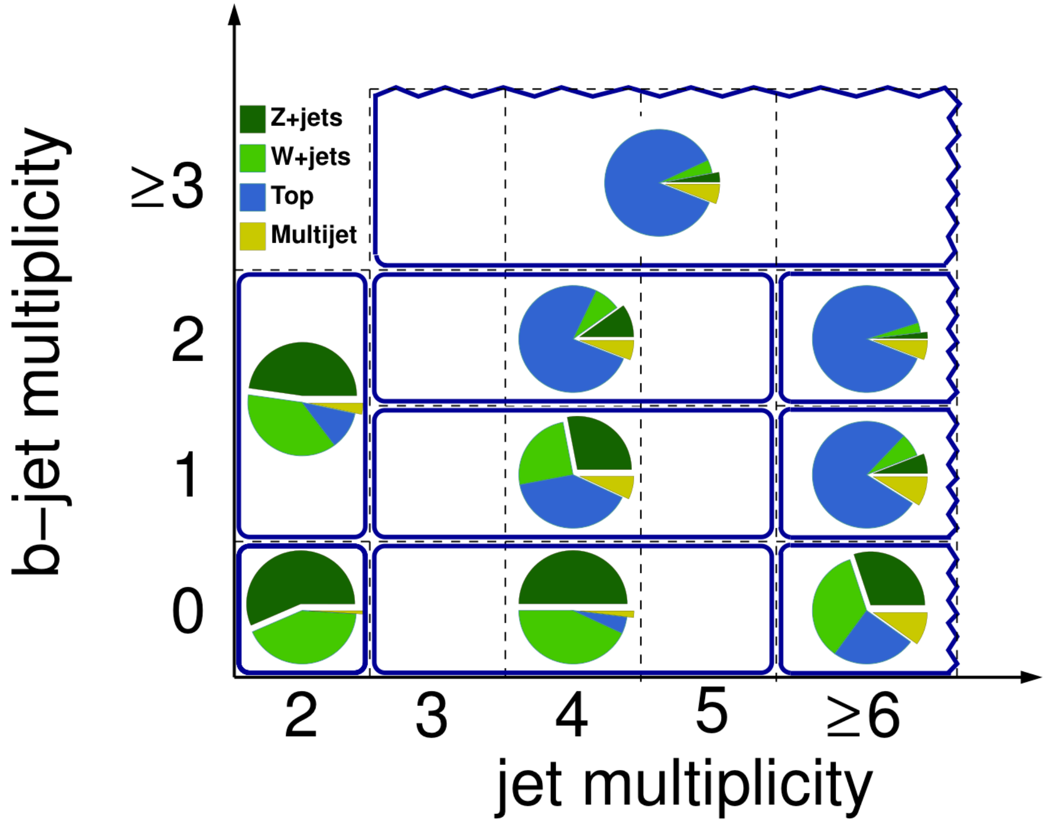
$M_{T2} \approx$ MET for X to Y + LSP pair production.

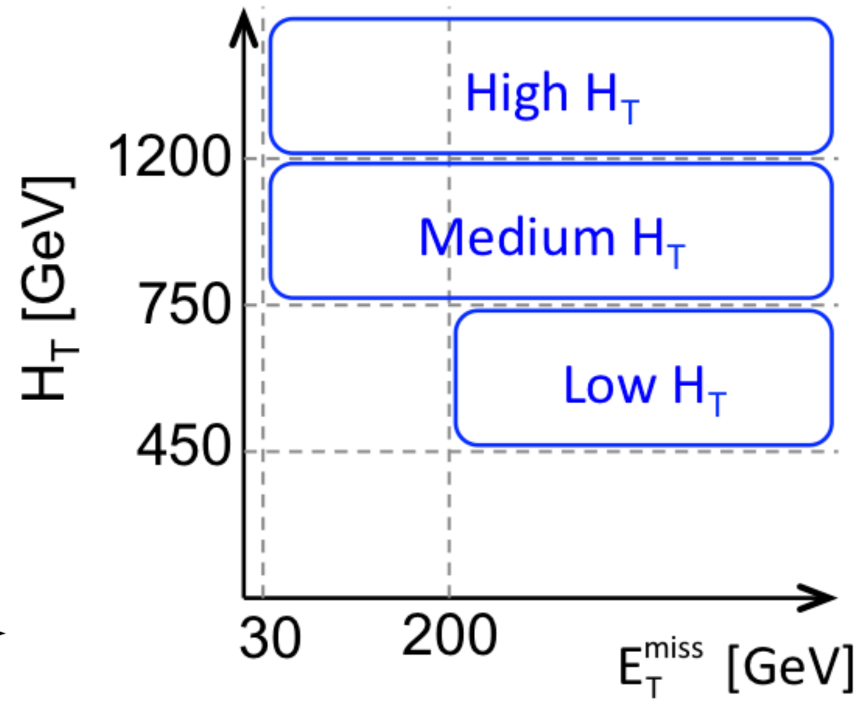
M_{T2} << MET for near back-to-back topologies.

M_{T2} is a robust QCD killer



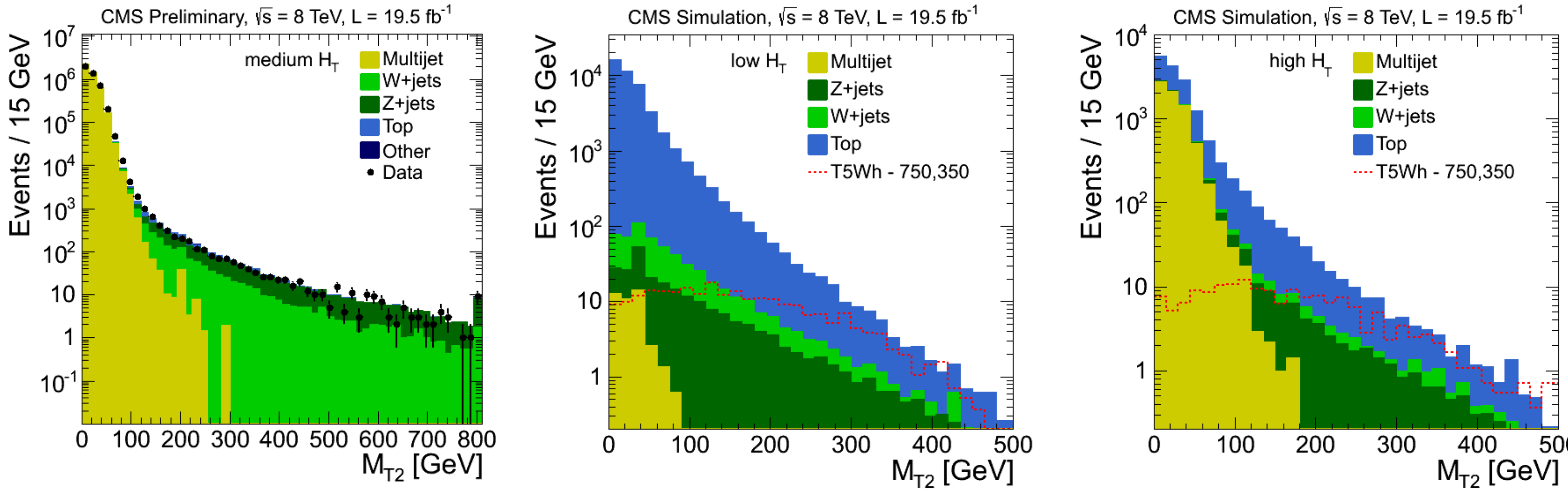
Search Strategy





Bin the data in bins of #jets, #b-tags, and MET, H_T, and M_{T2}.
Search for excess yield above data driven bkg predictions.

Example M_{T2} distributions



Medium H_T integrated over all jet, b-tag bins

Low H_T for Njet ≥ 4 b-tags ≥ 2

High H_T for Njet ≥ 4 b-tags ≥ 2

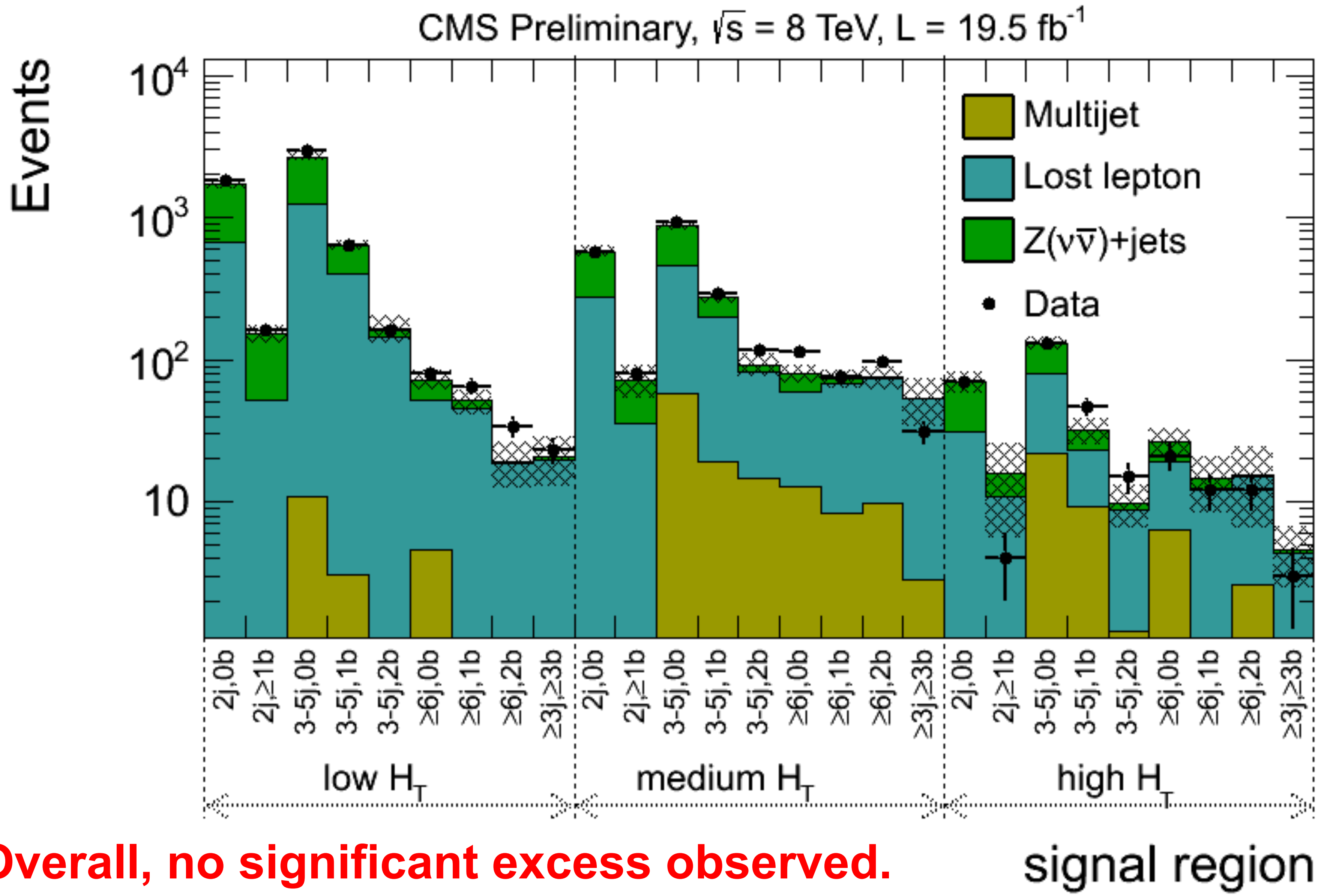
Background sources differ considerably!

However, bkg without MET from neutrinos are negligible at large M_{T2}.

Data driven bkg estimation

- Classify 3 categories of bkg as follows:
  - "Lost lepton" background
    - W jets & top where W decays to lepton neutrino
    - Lepton is not found, and event thus passes lepton veto.
    - Estimate bkg from lepton found sample & eff. measured.
  - Irreducible Z to neutrinos background
    - Estimate from photon sample with Z/γ from MC.
  - Background from QCD multijet production
    - Entirely instrumental. Estimate from data control sample with mismeasured jets.

Observed & Predicted Yields



Overall, no significant excess observed.

≥3 leptons Analysis (I)

- 20/10 pT ee/eμ/μμ dilepton trigger
- Additional e/μ (tau) with pT>10 (20)GeV
- At most one hadronic tau out of 3(4) leptons
- All leptons are prompt and isolated
- Distinguish 3 (4) leptons with/without tau
  - Allow at most 1 tau
- Distinguish DY to dilepton events
  - Distinguish below Z, on-Z, and above Z
- Distinguish ≥ 1 b-tag events

=> 36 different multilepton categories

≥3 leptons Analysis (II)

- Now take these 36 different lepton categories and use them to search for either:
- RP Conserving SUSY SUS-13-002
  - Bin in 2x3 bins of H_T and MET
    - H_T > or < than 200GeV
    - MET ranges of [0,50[, [50,100[, [100,infty[
- RP Violating SUSY SUS-13-003
  - Distinguish up to 5 different S_T ranges
    - [0,300[, [300,600[, [600,1000[, [1000,1500[, [1500,infty[

=> Very broad Multilepton Search Strategy

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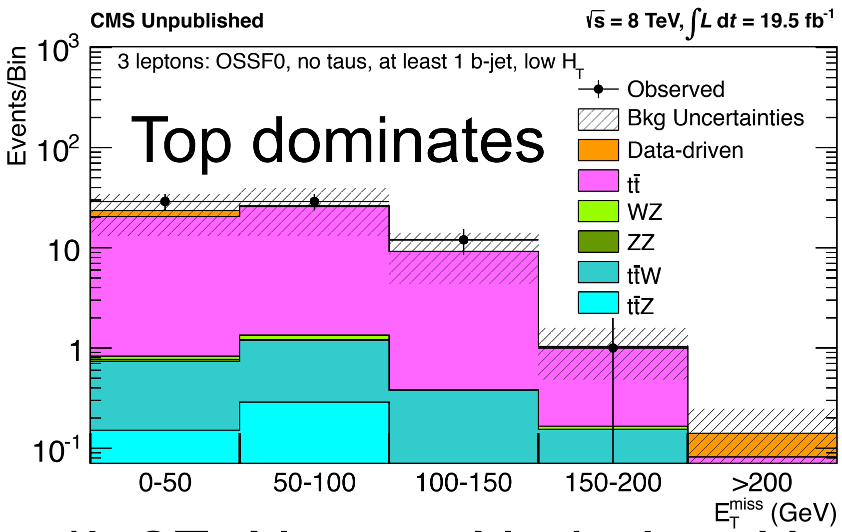
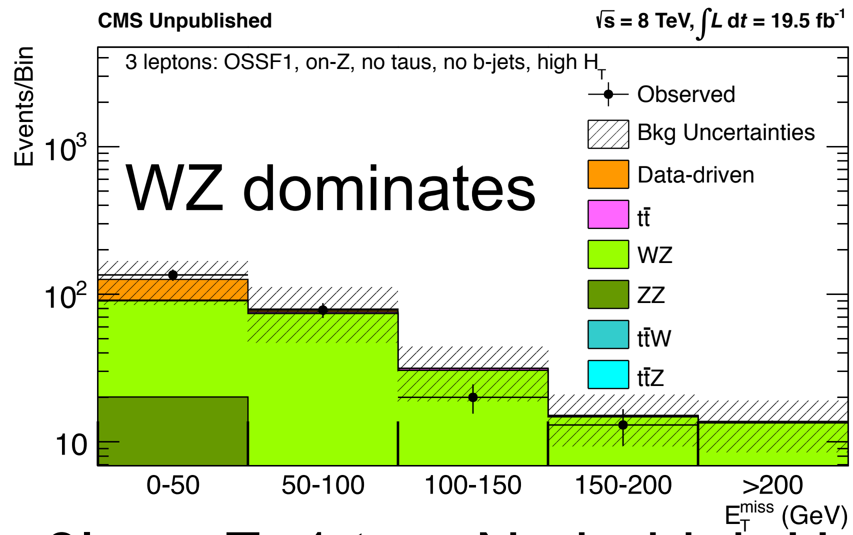
Different Bins Probe Different Bkg's

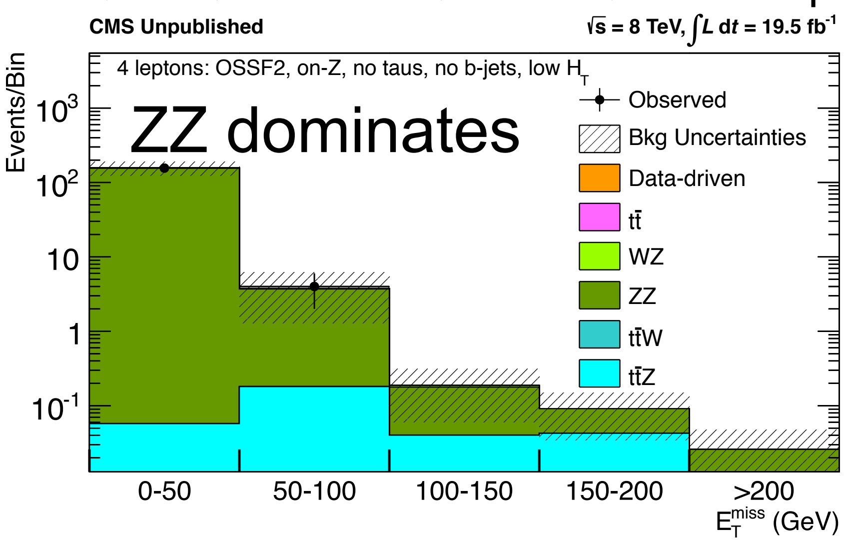
3l, No DY, No tau, 1b, low H_T



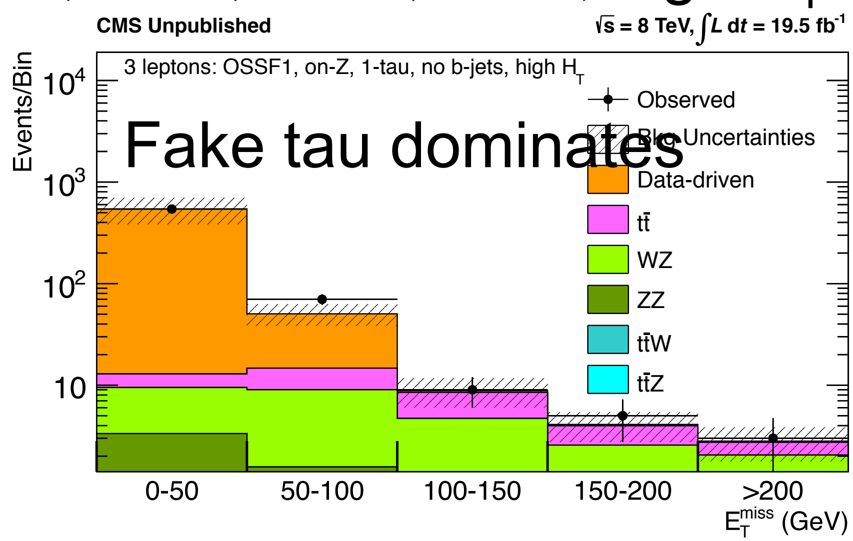
3l, on-Z, No tau, No b, high H_T



4l, 2Z, No tau, No b, low H_T



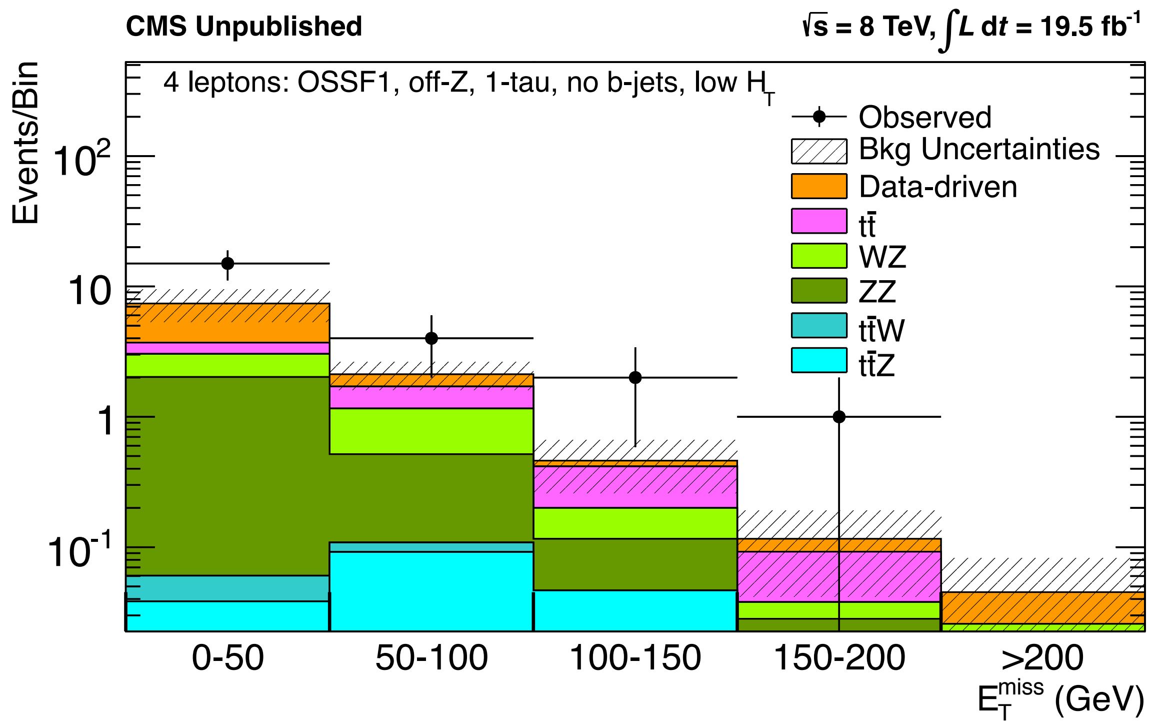
3l, on-Z, 1 tau, No b, high H_T



One of 64 MET distributions has a sizable excess

4l, 1 off-Z, 1 tau, No b, low H_T

Observe 22
Expect 10.1 +- 2.4
=> ~1% probability



However, to find at least 1 out of 64 with such a low prob. should happen in about half of all experiments.

General Problem of SUSY Searches

- SUSY can be anywhere.

$\Rightarrow$ We don't know where to look!

$\Rightarrow$ So we look everywhere.

$\Rightarrow$ We must see some large fluctuations somewhere.

$\Rightarrow$ How do we reasonably quantify LEE ??

(LEE = Look Elsewhere Effect)

- When does "excess" become "evidence" ?

Lesson 2

Even 3σ excesses are useful only when we use them to define a LEE free selection for data not yet analyzed.

Corollary:
Use excesses seen in 2015 to refine searches for potential discoveries with 2016 data?

Be mindful of any gaps in sensitivity

2 Examples from “Natural SUSY” with Dark Matter

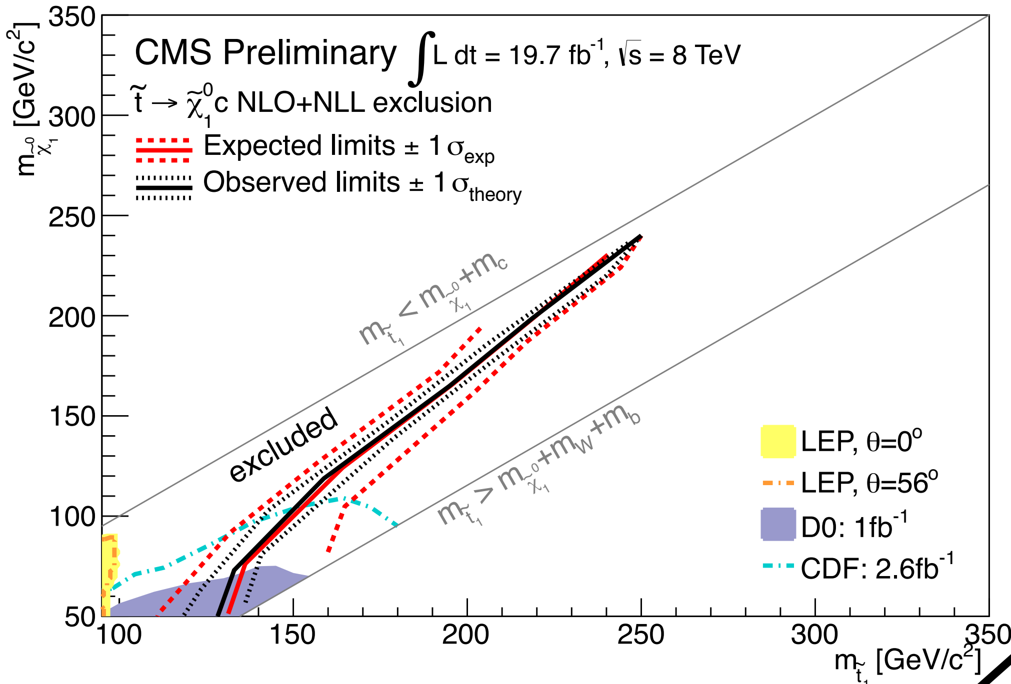
Dark Matter

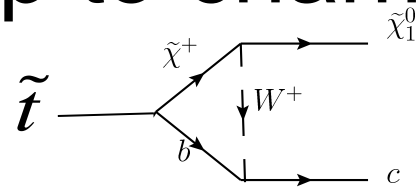
- Anti-social: pp -> nothing
- Semi-social: compressed spectra, …
- Social: DM at the end of cascades

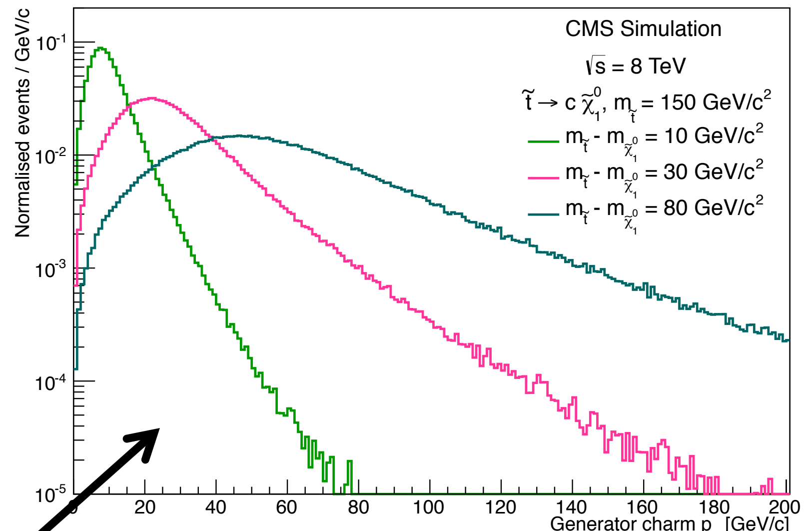
Our Program of searches MUST seamlessly interpolate between these three scenarios!

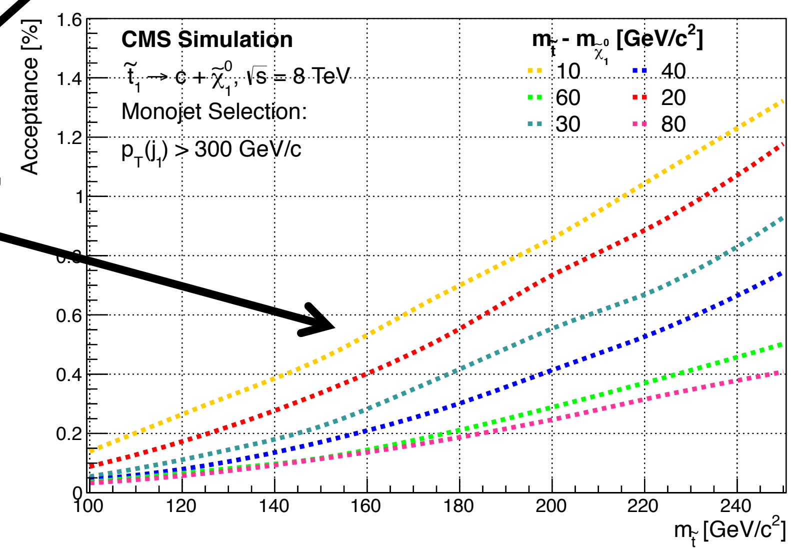
Monojet search for stop to charm X^0

CMS-PAS-SUS-13-009





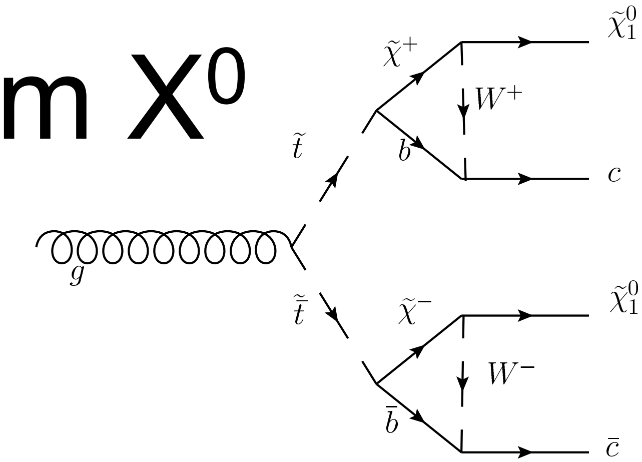




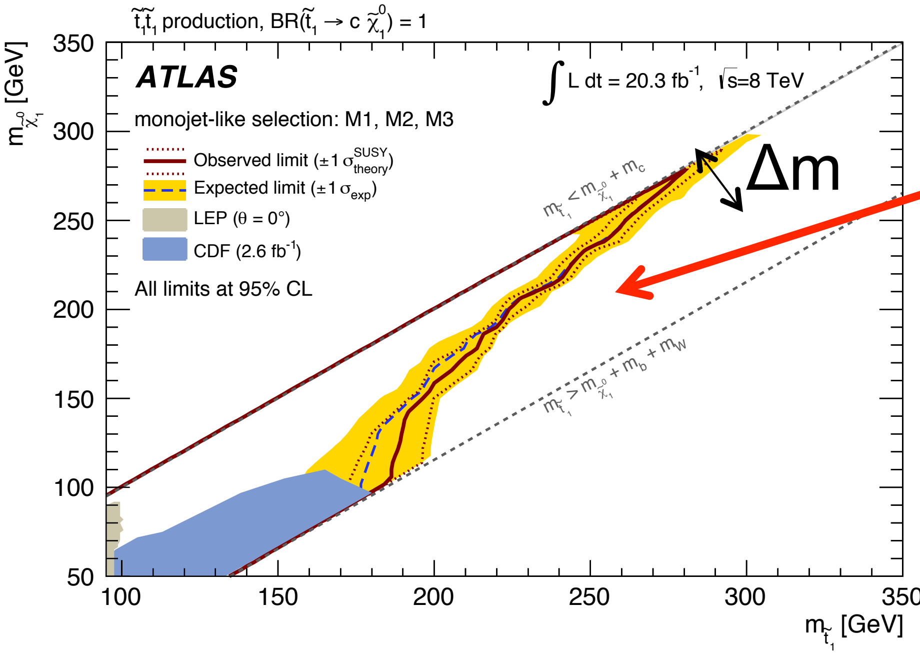
Δm increases -> charm quark pT increases,
-> efficiency decreases due to 3rd jet veto.
=> Sensitivity decreases with Δm

E.g. stop to charm X^0

arXive: 1407.0608

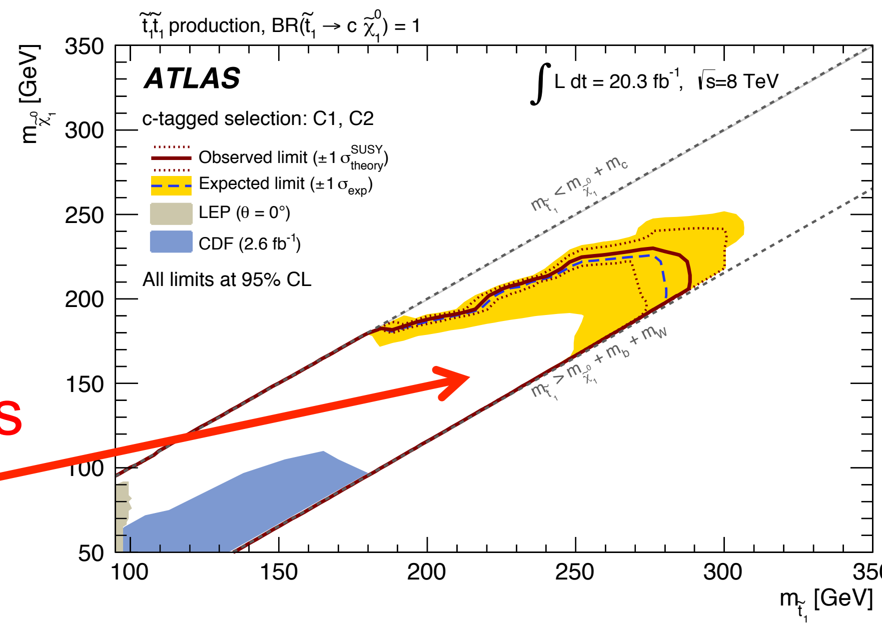


Mono jet analysis



As Δm increases, mono-jet search becomes insensitive.

Charm Tag Analysis



Dedicated Search w. charm tags required to fill the gap

… but that's not enough …

The relative BR of:

$$\tilde{t} \rightarrow b\chi_1^0 W^{+(*)} \qquad \tilde{t} \rightarrow c\chi_1^0$$

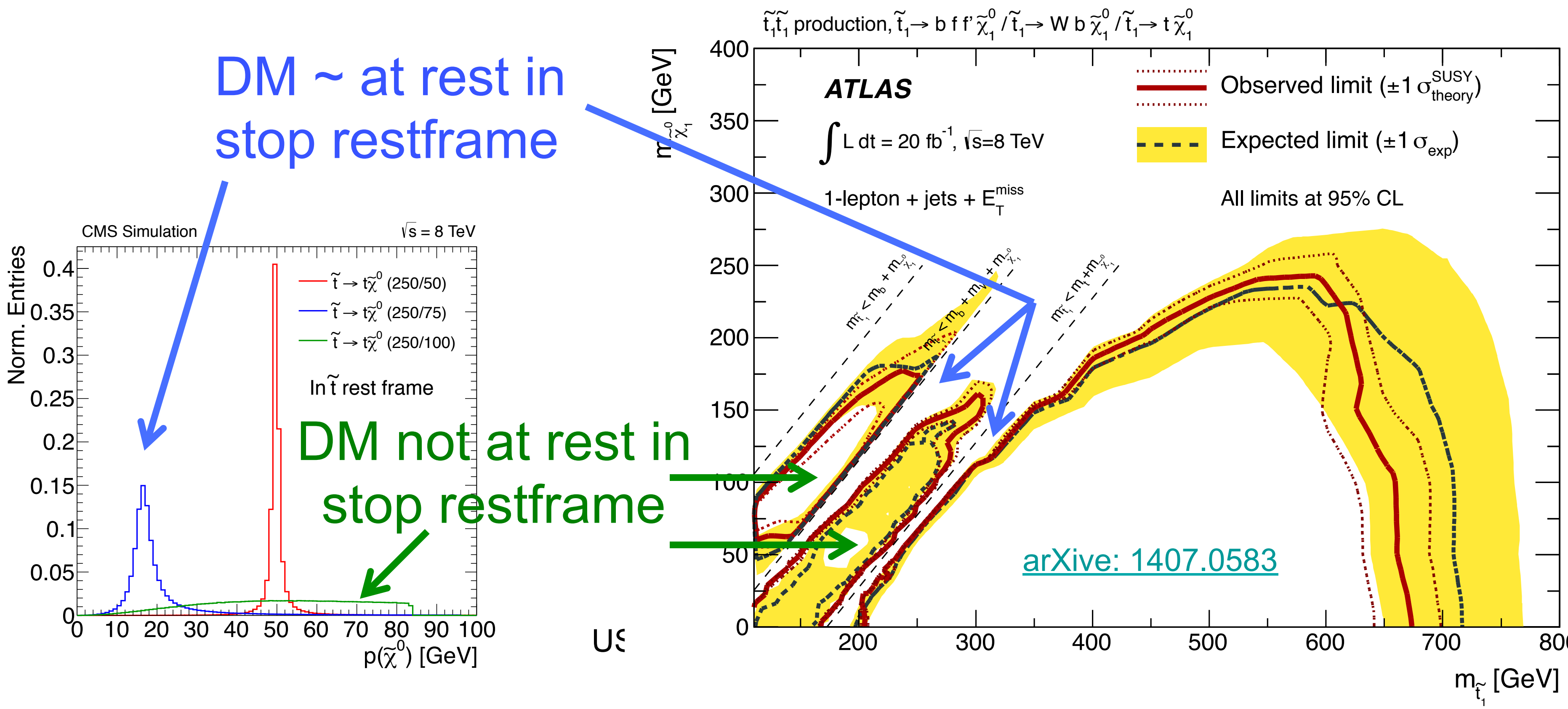
is completely model dependent.

Any relative BR is possible for most of the relevant Δm

We must prepare a combined search strategy for these two final states!

“The stop gaps”

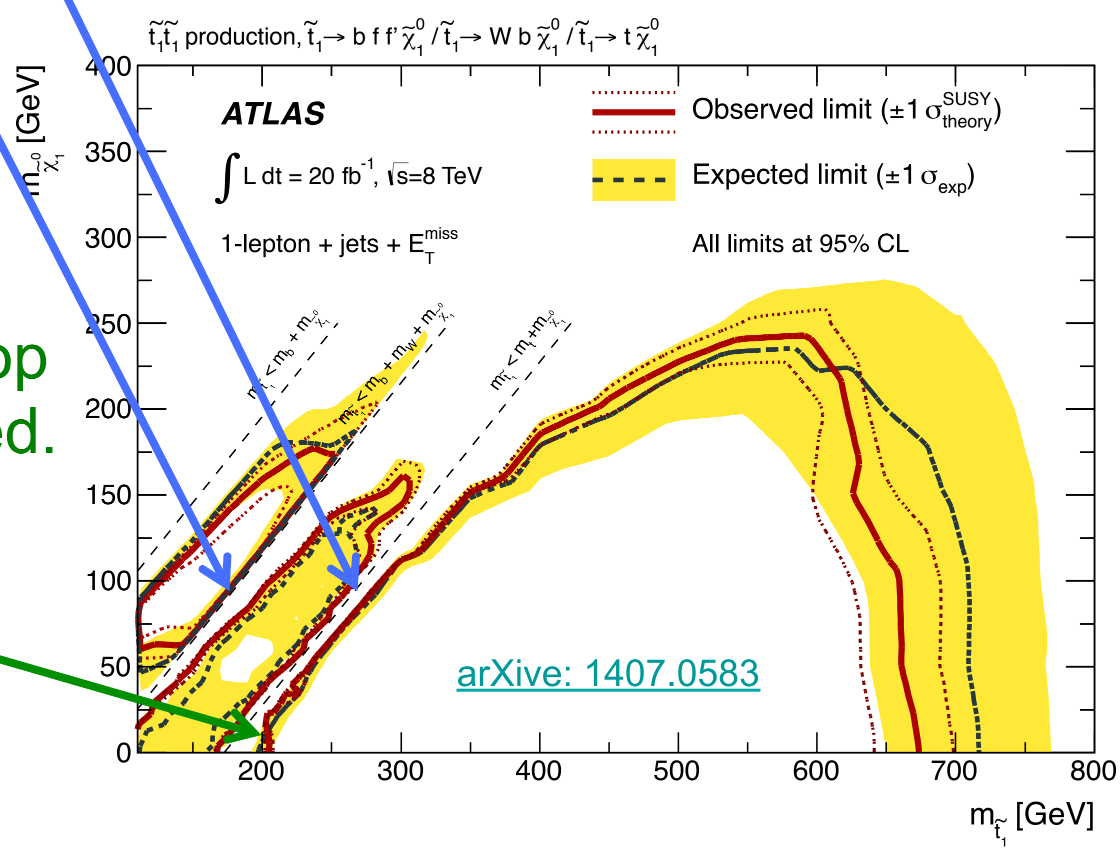
On-shell W,top leads to DM ~ at rest in stop restframe
=> No MET when $m_{stop} - m_{DM} \approx m_W$ or m_{top}



“Closing the gaps”

At larger m_{DM} ,
ISR boost and increased luminosity will close the gap.

Near m_{DM} ~ 0 precision top measurements are needed.
(e.g. arXive: 1406.5375)



Lesson 3

ISR boost is a powerful tool that we should exploit more consciously beyond just the monojet search.

What else are we missing ?

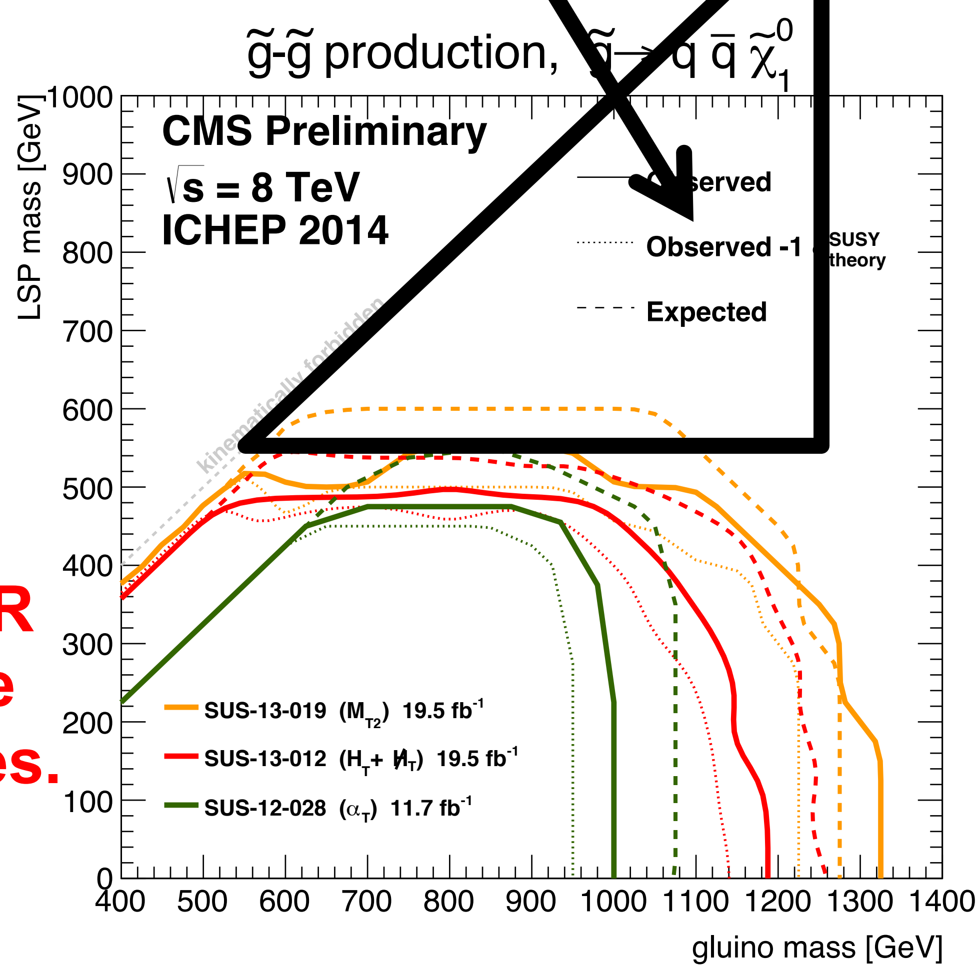
A Case Study

Hundreds of GeV of unexplored territory between gluino mass and LSP mass.

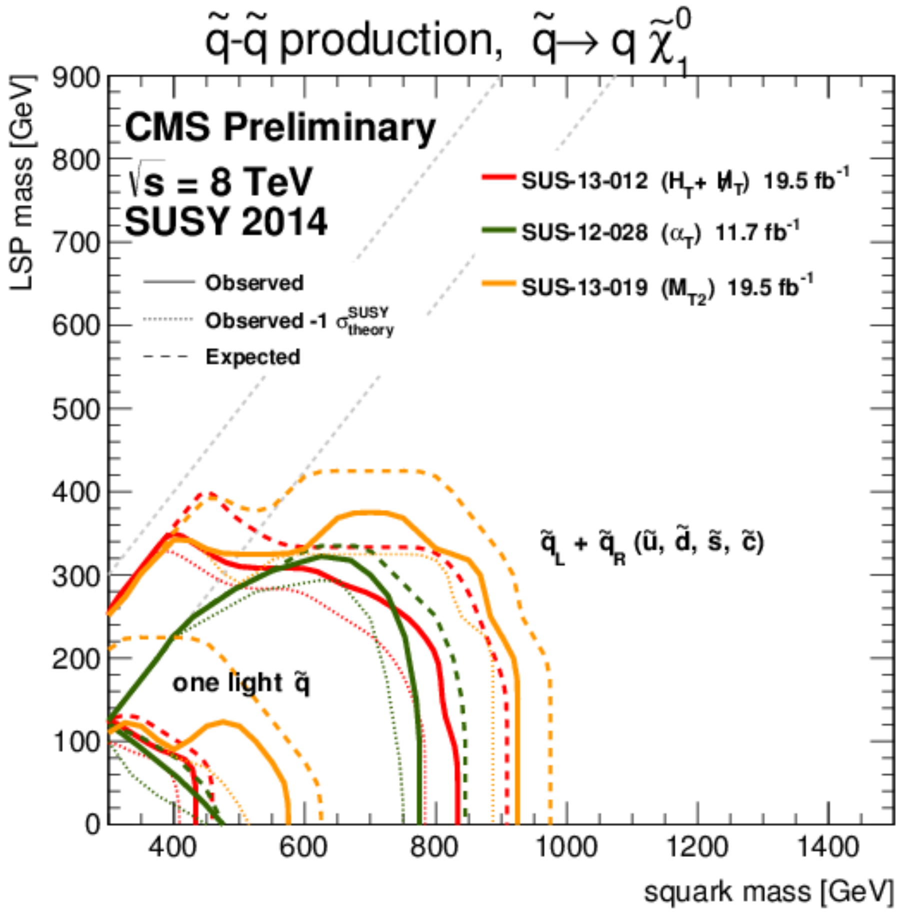
Much of it comes with Xsections of 10fb to 1pb.

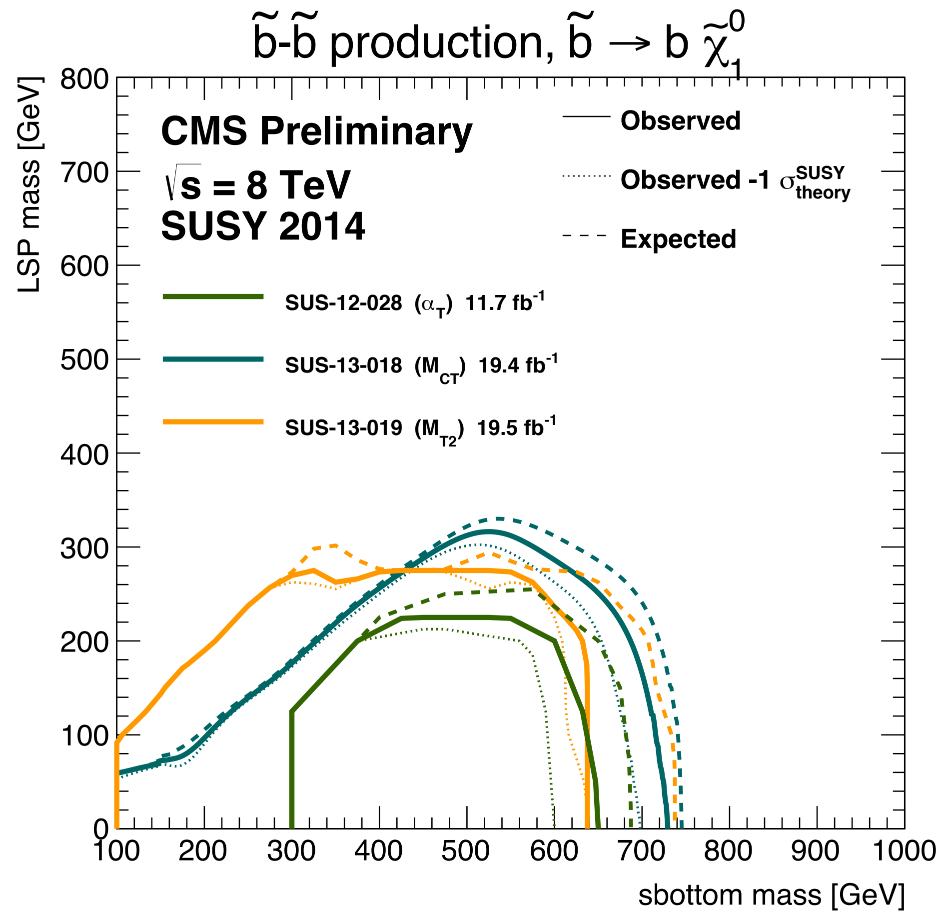
Some simple math:
100fb * 20/fb * 1% * 2 = 40

We are sensitive to O(1%) BR decay chains if they provide sufficiently striking signatures.



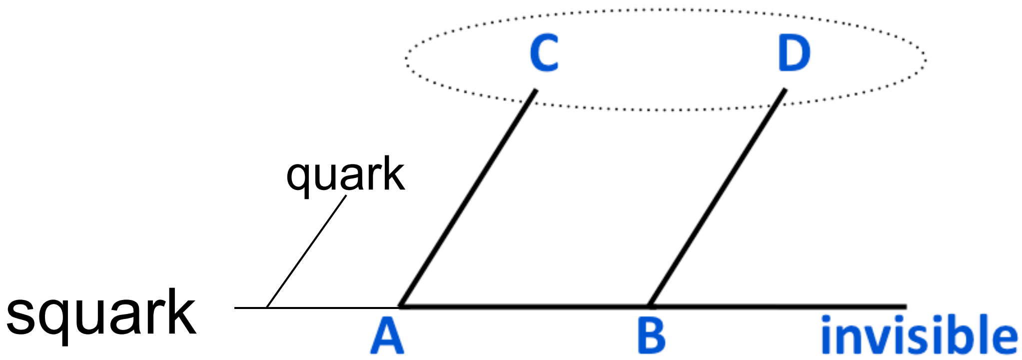
Consider squark pair production

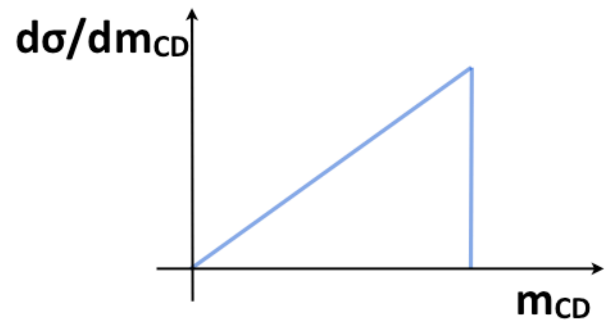




A squark mass of 400-600 GeV can not be ruled out if LSP mass is large enough and/or not all squarks are degenerate.

Can we get an "edge" on squarks?





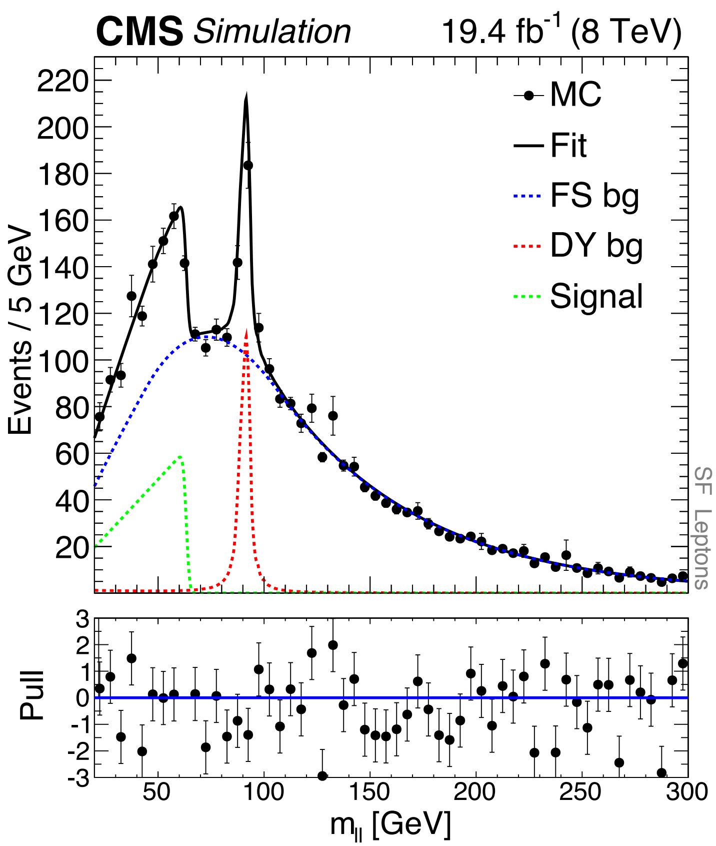
If C,D are leptons, then we may be able to probe squark pair production that would otherwise be invisible, even for squarks that predominantly decay into all hadronic final states.

E.g. m=4-6e2 GeV => σ ~ O(pb) => 20,000 squark pairs in 20/fb

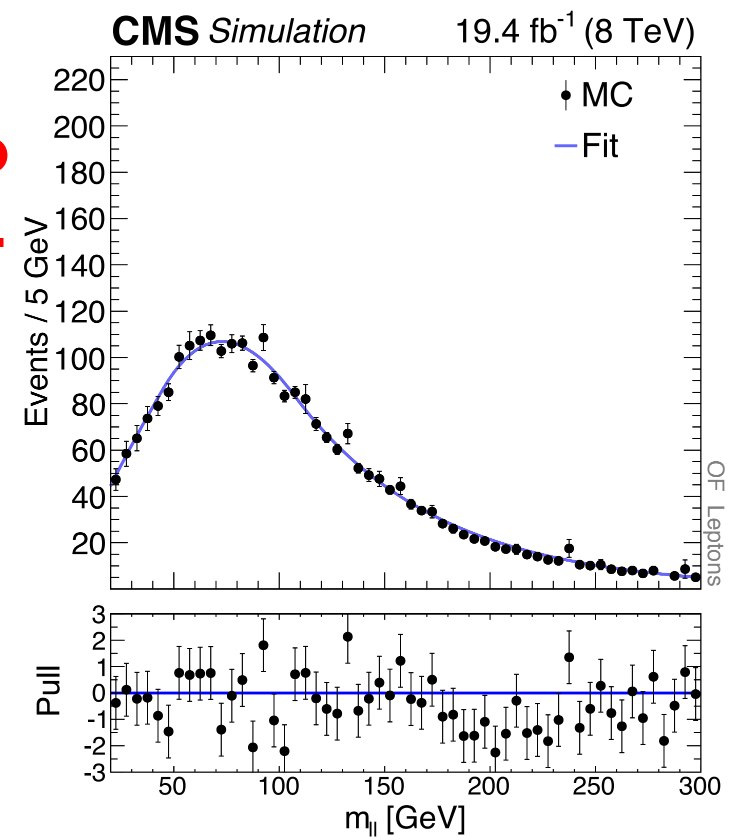
Sweetspot: BR of O(%) into dileptons is too small to see with 4 leptons but still large enough for dilepton edge.

The Idea

Search for excess in same-flavor opposite sign dileptons.
Do so for modest H_T and MET requirements,
targetting unexplored region in squark/gluino production.

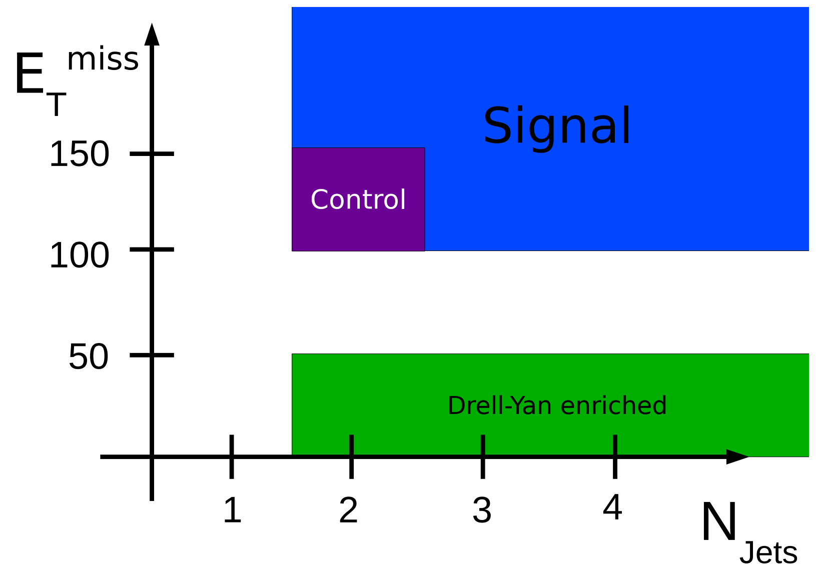


Use eμ data to predict ee+μμ.



The Selection

- Lepton (e,μ) p_T > 20GeV
- Jet p_T > 40GeV
- Signal region:
  - (N_{jets} > 1 .AND. MET > 150 GeV)
    .OR.
  - (N_{jets} > 2 .AND. MET > 100 GeV)
- Control region:
  - 100GeV < MET < 150GeV .AND. N_{jets} = 2



Background Estimation (I)

- Top, WW, …, flavor symmetric bkg
  - Use eμ data with corrections measured via either control region or reco & trigger eff. measurements in data.

- DY bkg:
  - Predict Z peak bkg via MET-templates and JZB.
  - Predict off peak from in peak via $R_{in/out}$

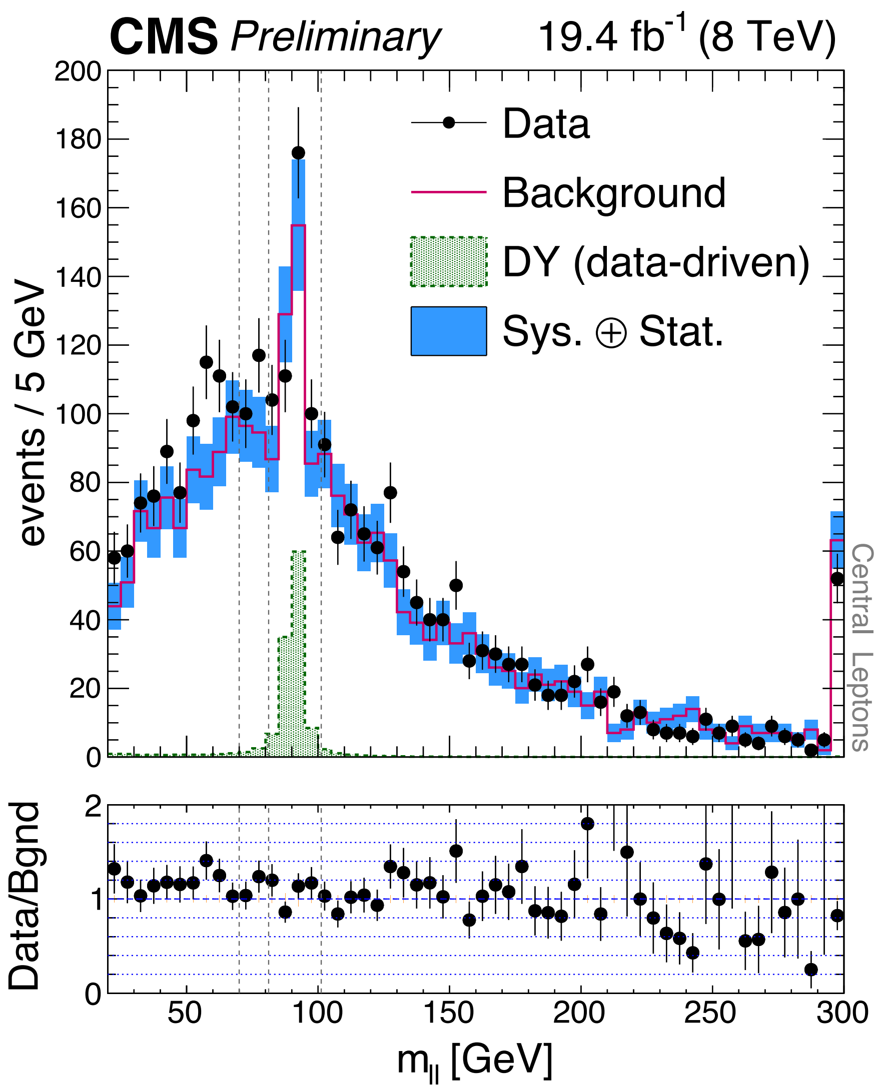
Background Estimation (II)

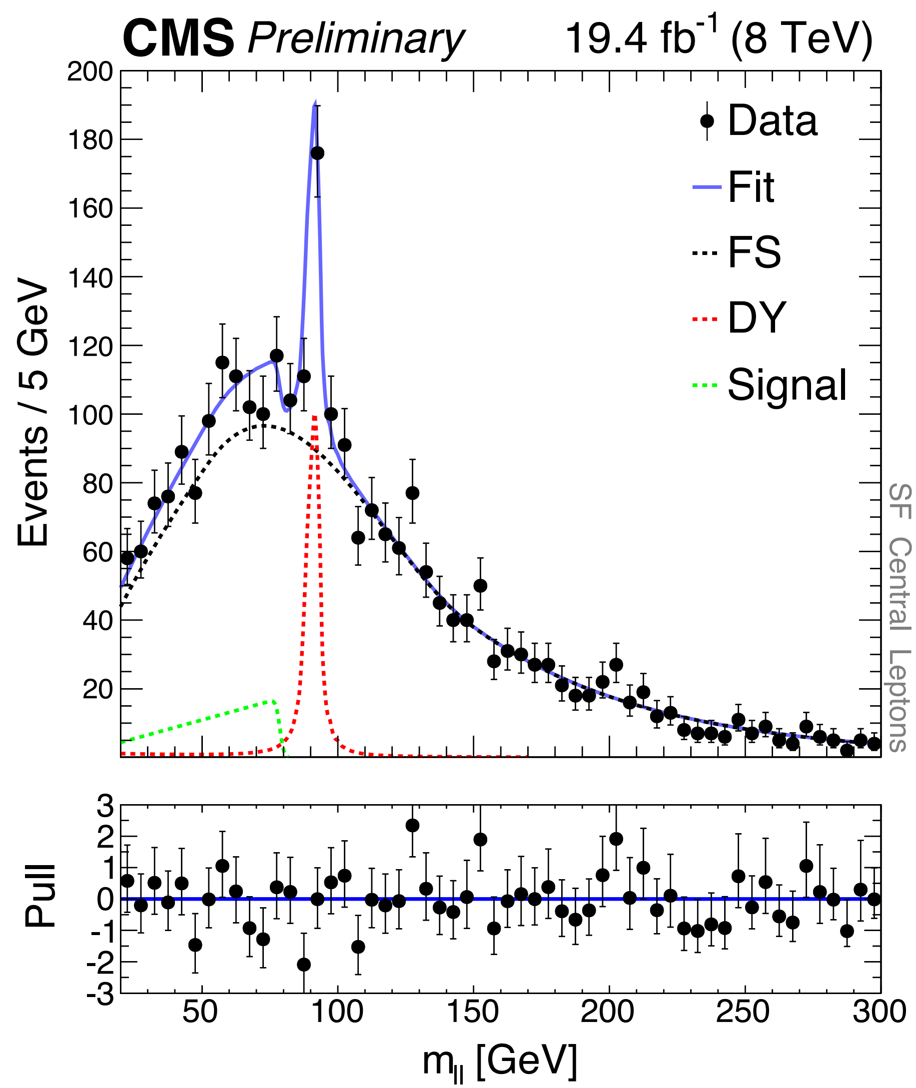
	central	forward
Factorized method		
$R_{SF/OF}$	$1.03 \pm 0.01 \pm 0.06$	$1.11 \pm 0.04 \pm 0.08$
$R_{ee/OF}$	$0.47 \pm 0.01 \pm 0.061$	$0.46 \pm 0.02 \pm 0.102$
$R_{\mu\mu/OF}$	$0.56 \pm 0.01 \pm 0.07$	$0.65 \pm 0.03 \pm 0.14$
$r_{\mu e}$	$1.09 \pm 0.00 \pm 0.11$	$1.18 \pm 0.00 \pm 0.24$
R_T	$1.03 \pm 0.01 \pm 0.062$	$1.10 \pm 0.04 \pm 0.07$
Control region method		
$R_{SF/OF}$	$0.99 \pm 0.05 \pm 0.02$	$1.11 \pm 0.11 \pm 0.03$
$R_{ee/OF}$	$0.44 \pm 0.03 \pm 0.01$	$0.49 \pm 0.06 \pm 0.02$
$R_{\mu\mu/OF}$	$0.55 \pm 0.03 \pm 0.01$	$0.62 \pm 0.07 \pm 0.02$
$r_{\mu e}$	1.12 ± 0.04 (stat.)	1.12 ± 0.08 (stat.)
R_T	0.98 ± 0.05 (stat.)	1.11 ± 0.11 (stat.)
Combined		
$R_{SF/OF}$	1.00 ± 0.04	1.11 ± 0.07
$R_{ee/OF}$	0.45 ± 0.03	0.48 ± 0.05
$R_{\mu\mu/OF}$	0.55 ± 0.03	0.63 ± 0.07

Distinguish central & forward.
Central has smaller systematics,
and larger expected signal yield.

**4% systematics for
eμ based bkg prediction**

Results (I)


CMS Preliminary
19.4 fb^{-1} (8 TeV)
Data
Background
DY (data-driven)
Sys. ⊕ Stat.
events / 5 GeV
Central Leptons
Data/Bgnd
m_{ll} [GeV]


CMS Preliminary
19.4 fb^{-1} (8 TeV)
Data
Fit
FS
DY
Signal
Events / 5 GeV
SF Central Leptons
Pull
m_{ll} [GeV]

Results (II)

Yield in 20GeV < m_{ll} < 70GeV signal region.

	Central	Forward
Observed [SF]	860	163
Flav. Sym. [OF]	$722 \pm 27 \pm 29$	$155 \pm 13 \pm 10$
Drell–Yan	8.2 ± 2.6	1.7 ± 1.4
Total estimates	730 ± 40	157 ± 16
Observed – Estimated	130^{+48}_{-49}	6^{+20}_{-21}
Significance [σ]	2.6	0.3

Results (III)

Fitted Edge across 20GeV < m_{ll} < 300GeV region.

	Central	Forward
Drell–Yan	158 ± 23	71 ± 15
Flav. Sym. [OF]	2270 ± 44	745 ± 25
$R_{SF/OF}$	1.03	1.02
Signal events	126 ± 41	22 ± 20
$m_{\ell\ell}^{edge}$ [GeV]	78.7 ± 1.4	

Lesson 4

We have enough luminosity accumulated to make searches for rare signatures in decay chains worthwhile.

Summary & Conclusion

Rather than summarizing let me conclude with my personal opinion on what I will want to see to believe a discovery.

Requirements for Discovery

- A LEE free 5σ excess.
- Background predictions from both MC and data driven.
  - Our MCs are good enough that we can't ignore them.
  - At the same time, there are discrepancies between data and MC, and we are likely to see more of them with more luminosity.
- Kinematic distributions of the excess events that show a clear distinction from bkg and are not yet already used in the search strategy.

Backup

Are our Searches too much influenced by Simplified Models?

We have searched for WW, WZ, Wh, Zh, ZZ, and hh plus MET.
When we do so, we search for one final state at a time.

Are we prepare for something like this:

```
DECAY    1000037     5.33993931E+00   # chargino2+ decays
#           BR          NDA       ID1        ID2
     2.58630618E-01     2      1000024        23    # BR(~chi_2+ -> ~chi_1+  Z )
     2.49797977E-01     2      1000022        24    # BR(~chi_2+ -> ~chi_10  W+)
     2.59870362E-01     2      1000023        24    # BR(~chi_2+ -> ~chi_20  W+)
     2.31701044E-01     2      1000024        25    # BR(~chi_2+ -> ~chi_1+  h )
```

26% X+ to Z X+
50% X+ to W X0
23% X+ to h X+

```
DECAY    1000025     5.33171141E+00   # neutralino3 decays
#           BR          NDA       ID1        ID2
     3.88604156E-02     2      1000022        23    # BR(~chi_30 -> ~chi_10  Z )
     2.11792763E-01     2      1000023        23    # BR(~chi_30 -> ~chi_20  Z )
     2.68240565E-01     2      1000024       -24    # BR(~chi_30 -> ~chi_1+  W-)
     2.68240565E-01     2     -1000024        24    # BR(~chi_30 -> ~chi_1-  W+)
     1.80468356E-01     2      1000022        25    # BR(~chi_30 -> ~chi_10  h )
     3.23973361E-02     2      1000023        25    # BR(~chi_30 -> ~chi_20  h )
```

25% X0 to Z X0
53% X0 to W X+
21% X0 to h X0

Di-boson + MET present at large rate, but none dominates.

Lost lepton bkg

Dominates for large jet and b-jet multiplicity.

Estimated from 1-lepton sample plus lepton finding efficiency

$$N_l^{lost} = (N_l^{reco} - N_l^{bg})\frac{1-\varepsilon_l}{\varepsilon_l \varepsilon_{M_T}}, \quad l = e, \mu, \tau_h$$

ε_l: Lepton reconstruction efficiency (incl. acceptance).

ε_{MT}: M_T cut efficiency.

Estimated separately for each lepton flavor.

For 1-lepton sample, require $M_T < 100$GeV to limit possible signal contamination.

Z to neutrinos background

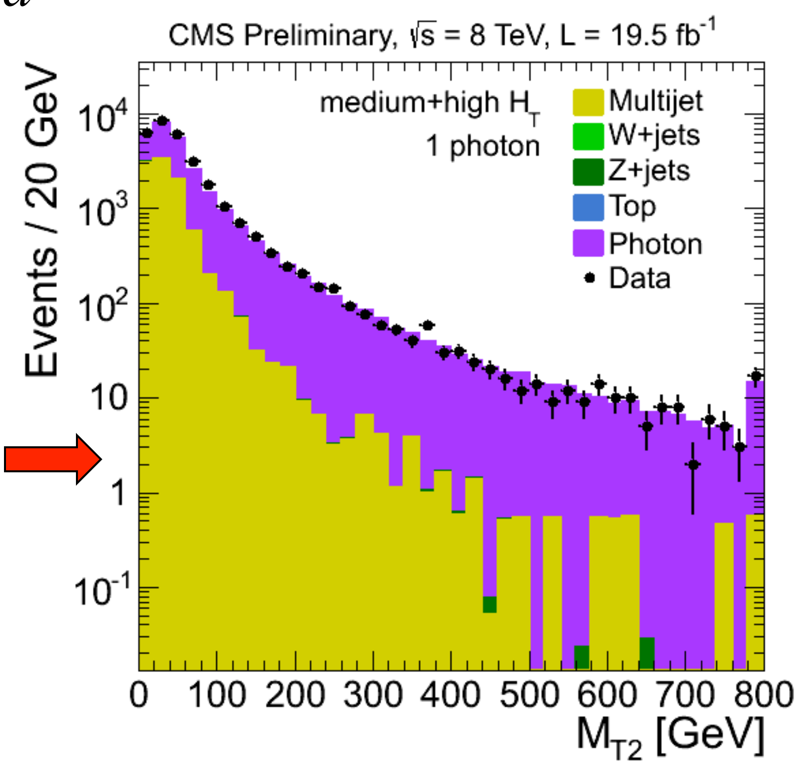
Dominates for small jet and b-jet multiplicity.

γ + jets events used to predict this background.
Physics difference between γ and Z plus jets taken from MC.

$$R^{MC}(Z(\nu\nu)/\gamma)\cdot Purity\cdot N_{\gamma}^{Data}$$

Purity obtained via fit to
Shower shapes in data.

Data and MC agree in photon sample

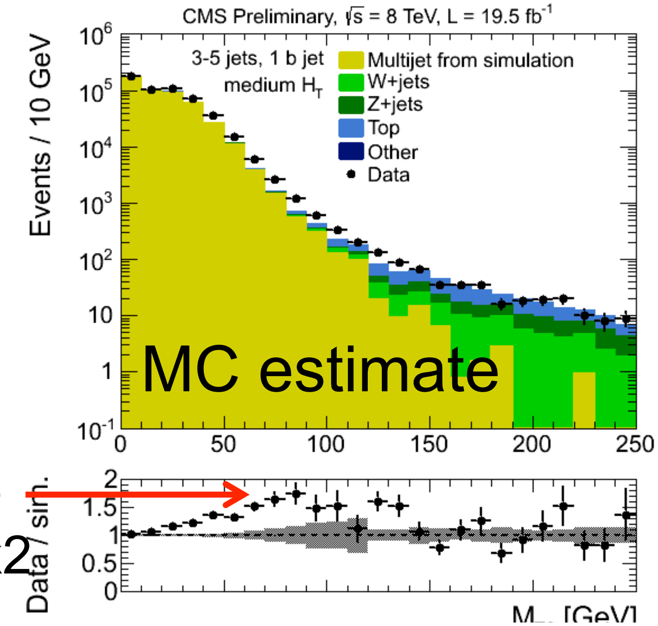


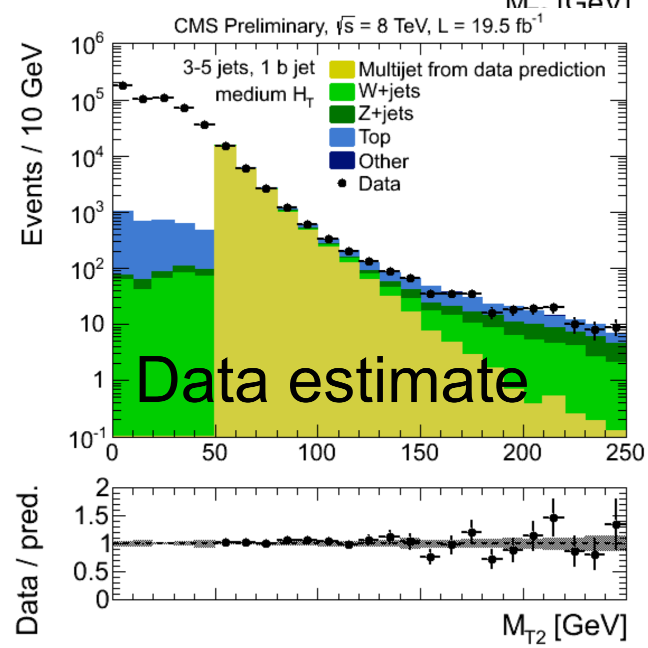
QCD Multijet background

Only consider M_{T2} regions for which QCD Multijets bkg is < 10% of total bkg.

Extrapolate bkg from data regions for which MET points in direction of one of 4 leading jets.

MC estimate low by up to x2





Systematics depends on signal region:

10-50% for M_{T2} < 200GeV

50-100% for M_{T2} > 200GeV

Higher M_{T2} have less stats in data control regions, thus larger syst on projections.

M_{T2} Signal Region Definitions

Table 1: Signal bin definitions of the inclusive M_{T2} analysis.

	low H_T region M_{T2} bin [GeV]			medium H_T region M_{T2} bin [GeV]			high H_T region M_{T2} bin [GeV]	
2 jets, 0 b jets	200-240 240-290 290-350	350-420 420-490 490-570	570-650 $\geq$ 650	125-150 150-180 180-220	220-270 270-325 325-425	425-580 580-780 $\geq$ 780	120-150 150-200 200-260	260-350 350-550 $\geq$ 550
2 jets, $\geq$ 1 b jets	200-250 250-310	310-380 380-450	450-550 $\geq$ 550	100-135 135-170	170-260 260-450	$\geq$ 450	100-180 $\geq$ 180	
3-5 jets, 0 b jets	200-240 240-290 290-350 350-420	420-490 490-570 570-650 $\geq$ 650		160-185 185-215 215-250 250-300	300-370 370-480 480-640 640-800	$\geq$ 800	160-185 185-220 220-270 270-350	350-450 450-650 $\geq$ 650
3-5 jets, 1 b jets	200-250 250-310	310-380 380-450	450-550 $\geq$ 550	150-175 175-210	210-270 270-380	380-600 $\geq$ 600	150-180 180-230	230-350 $\geq$ 350
3-5 jets, 2 b jets	200-250 250-325	325-425 $\geq$ 425		130-160 160-200	200-270 270-370	$\geq$ 370	130-200 $\geq$ 200	
$\geq$ 6 jets, 0 b jets	200-280 280-380	$\geq$ 380		160-200 200-250	250-325 325-425	$\geq$ 425	160-200 200-300	$\geq$ 300
$\geq$ 6 jets, 1 b jets	200-250 250-325	$\geq$ 325		150-190 190-250	250-350 $\geq$ 350		150-200 200-300	$\geq$ 300
$\geq$ 6 jets, 2 b jets	200-250 250-300	$\geq$ 300		130-170 170-220	220-300 $\geq$ 300		120-200 $\geq$ 200	
$\geq$ 3 jets, $\geq$ 3 b jets	200-280	$\geq$ 280		125-175	175-275	$\geq$ 275	1$\geq$ 125	