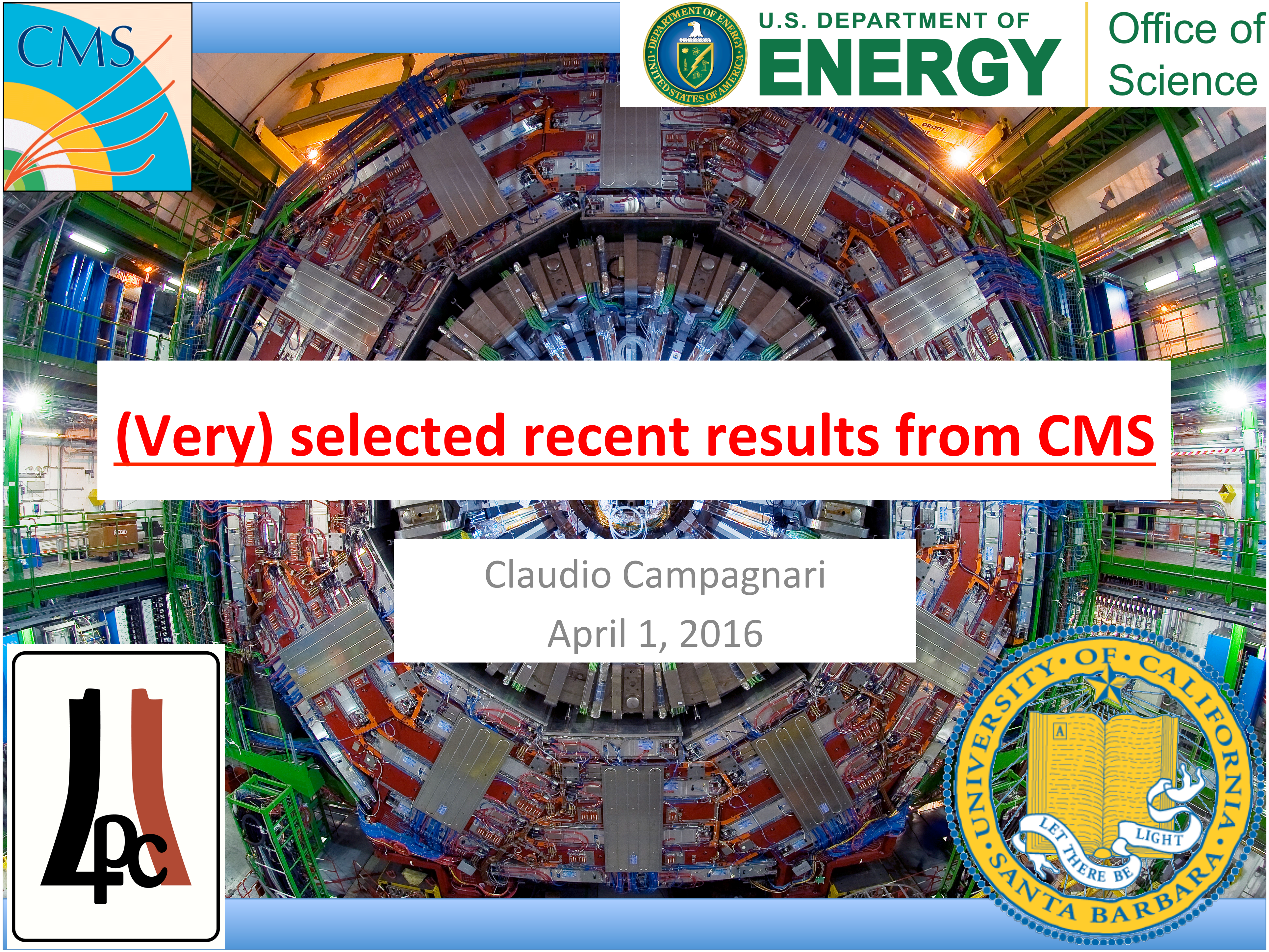


(Very) selected recent results from CMS

Claudio Campagnari

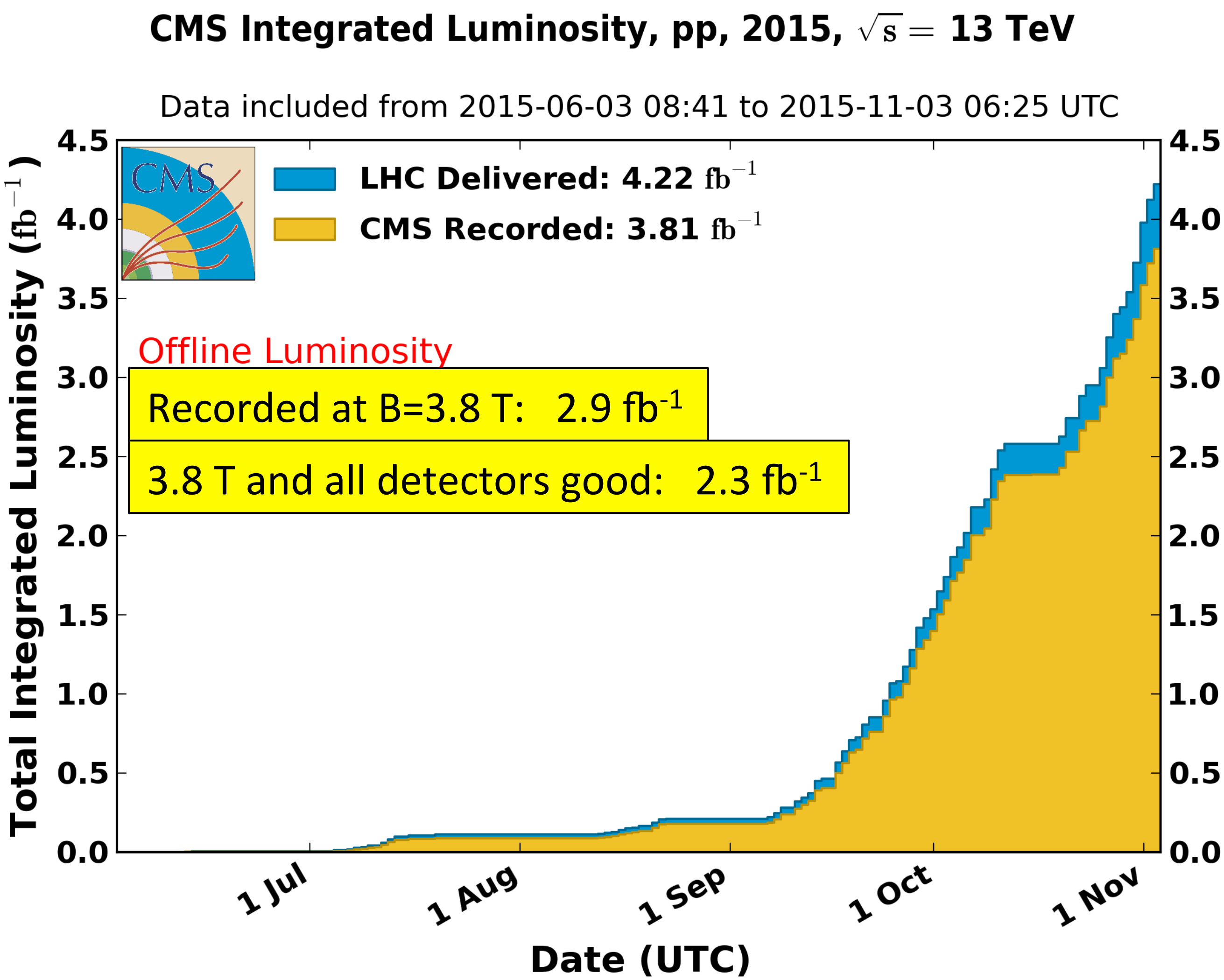
April 1, 2016

Outline

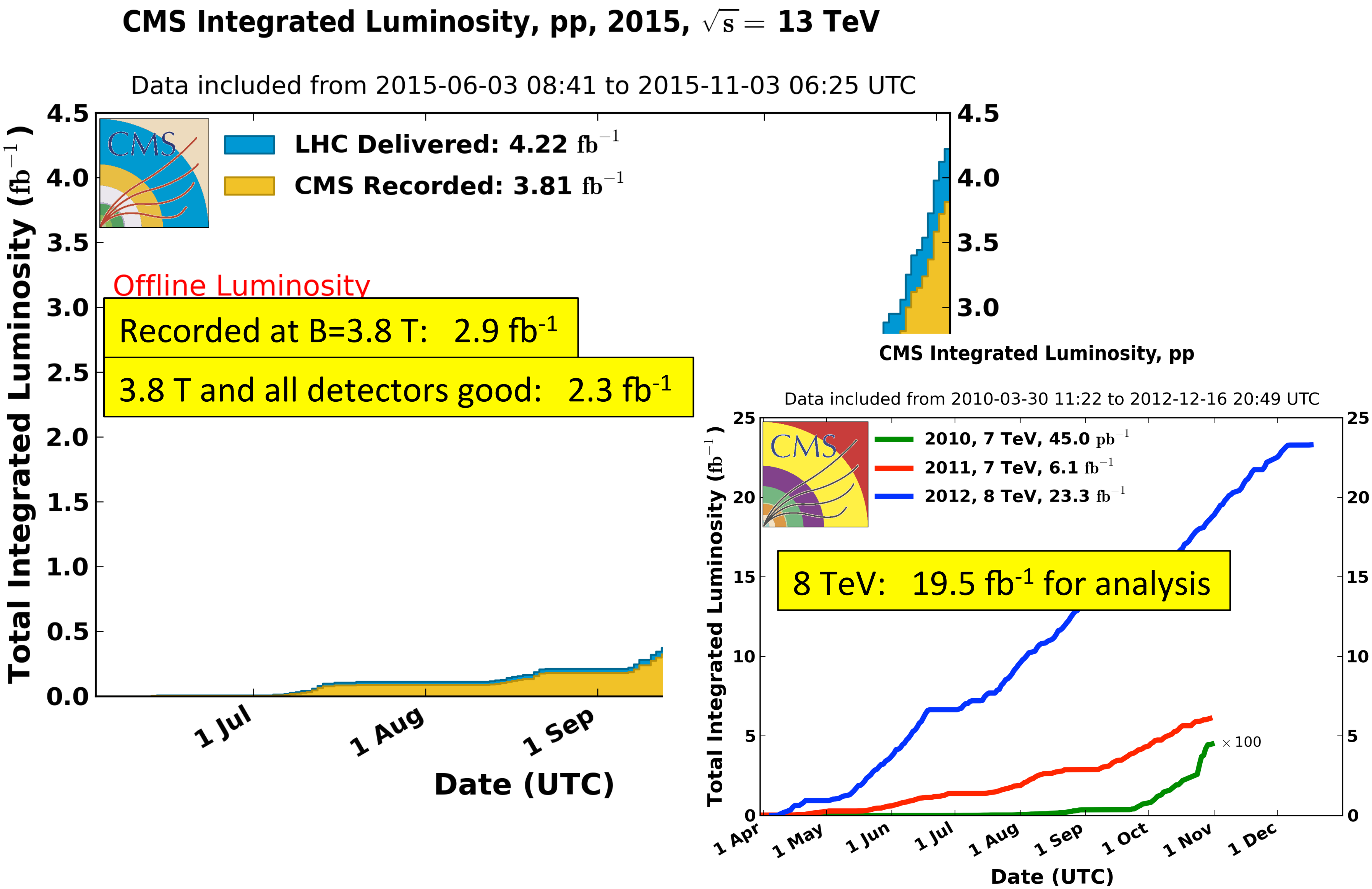
- The 2015 run of the LHC. What can we expect

- A selection of results of searches
  - Hadronic jets + MET search
  - A disappearing hint of NP: opposite sign-same flavor dileptons
  - An appearing hint (hope?) of NP: diphotons at 750 GeV

The 2015 LHC Run



The 2015 LHC Run

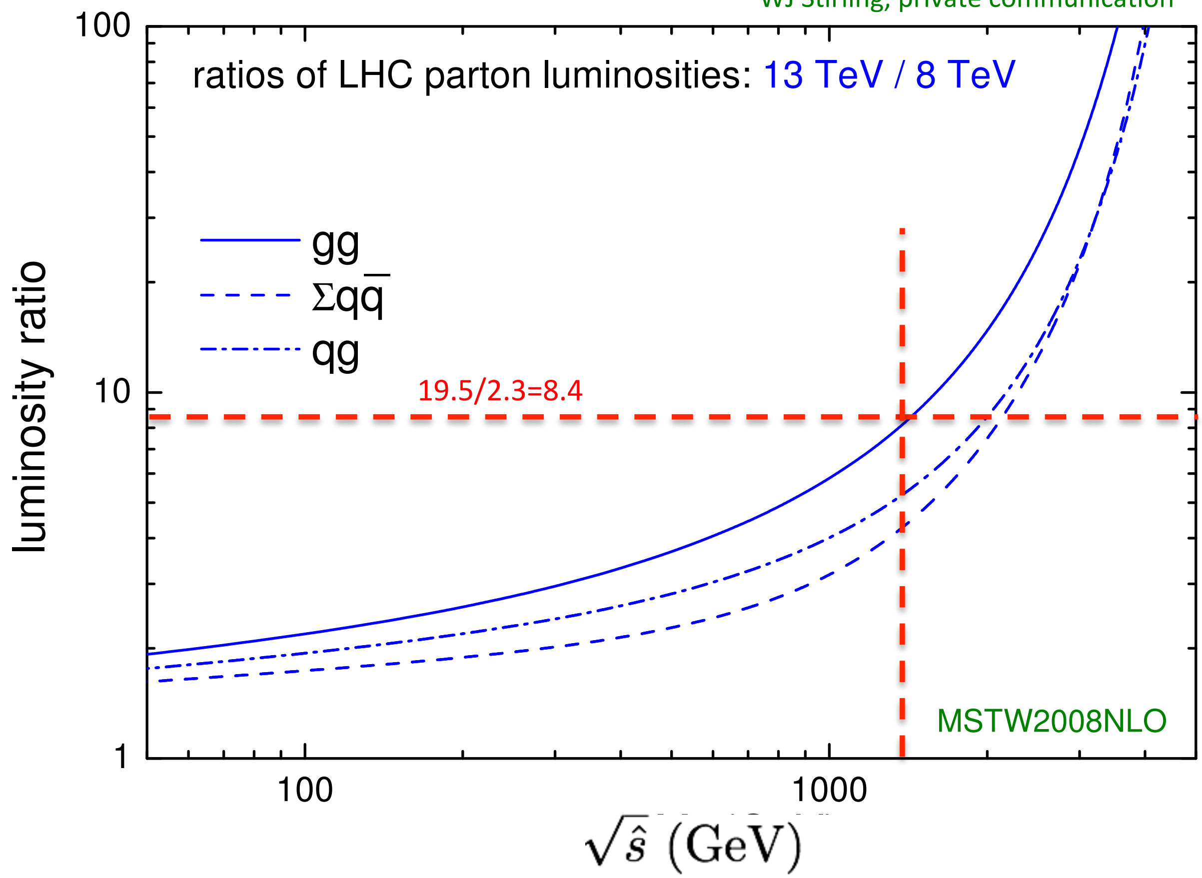


2.3 fb^{-1} @ 13 TeV vs. 19.4 @ 8 TeV

$$\frac{d\sigma(pp \to X)}{d\hat{s}} = \sum \frac{dL_{ij}}{d\hat{s}} \hat{\sigma}(ij \to X)$$

$$\frac{dL_{ij}}{d\hat{s}} = \frac{1}{1+\delta_{ij}} \frac{1}{\hat{s}} \int_{\tau}^{1} \frac{dx}{x} [f_i(x) f_j(\frac{\tau}{x}) + f_i(\frac{\tau}{x}) f_j(x)] \qquad \tau \equiv \frac{\hat{s}}{s}$$

WJ Stirling, private communication



$2.3\ fb^{-1}$ @ 13 TeV vs. 19.4 @ 8 TeV

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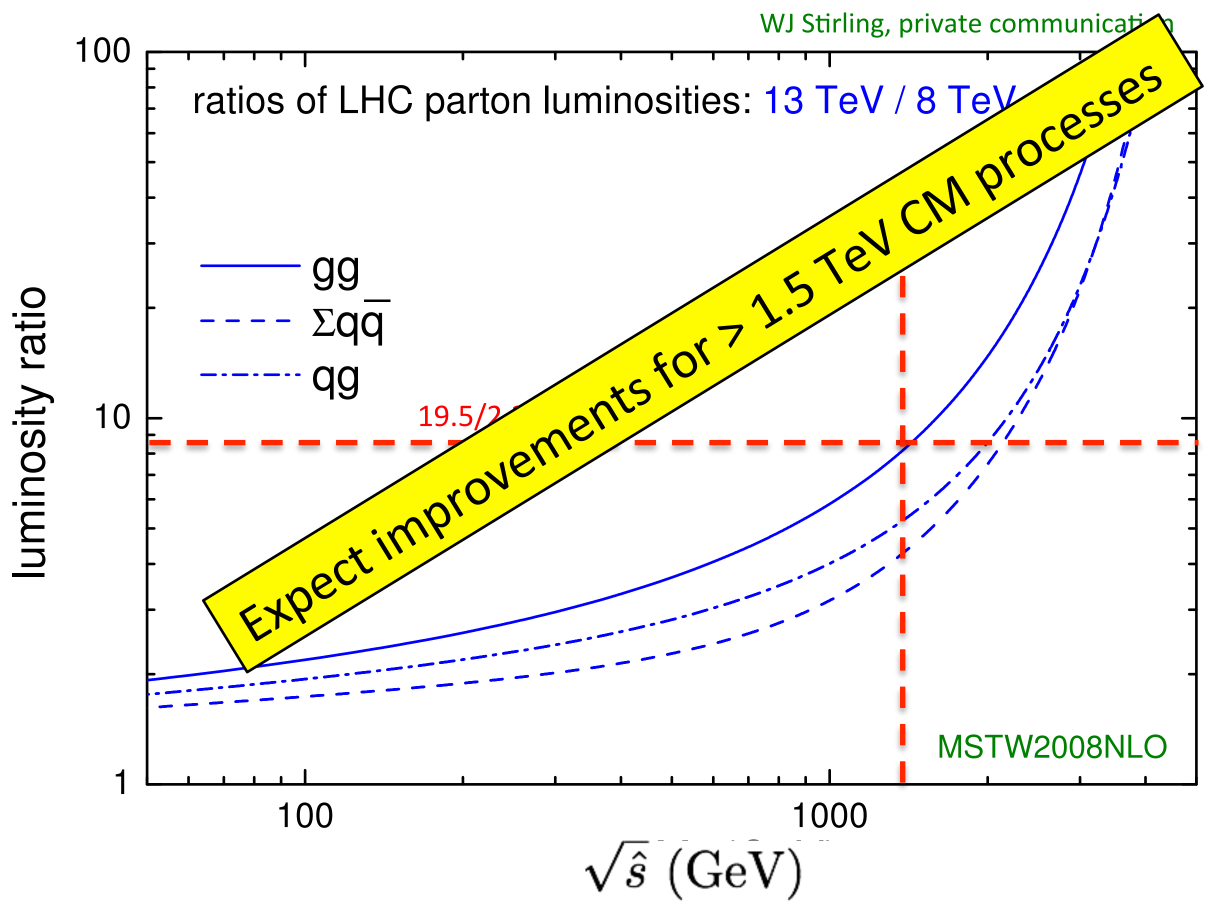
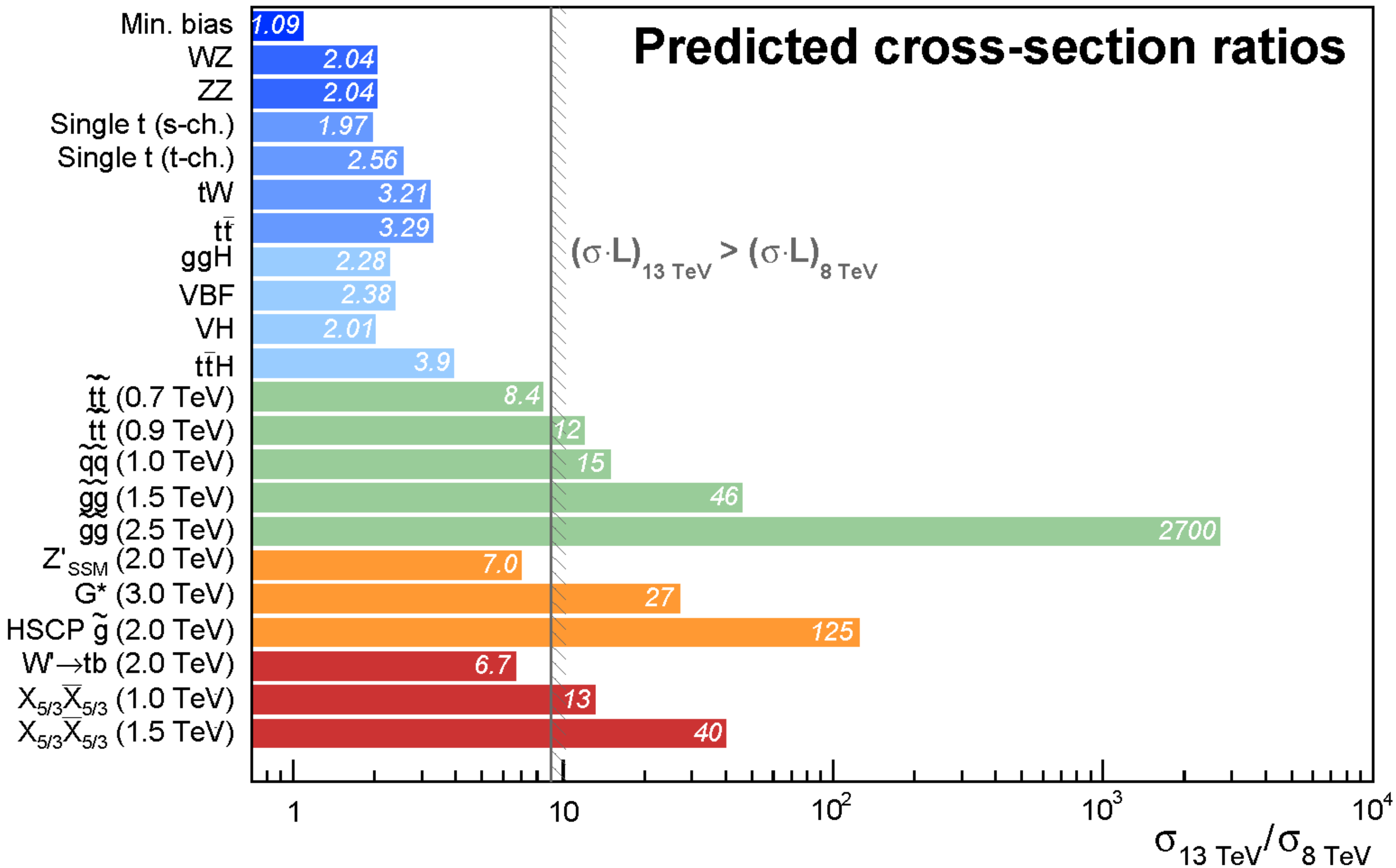
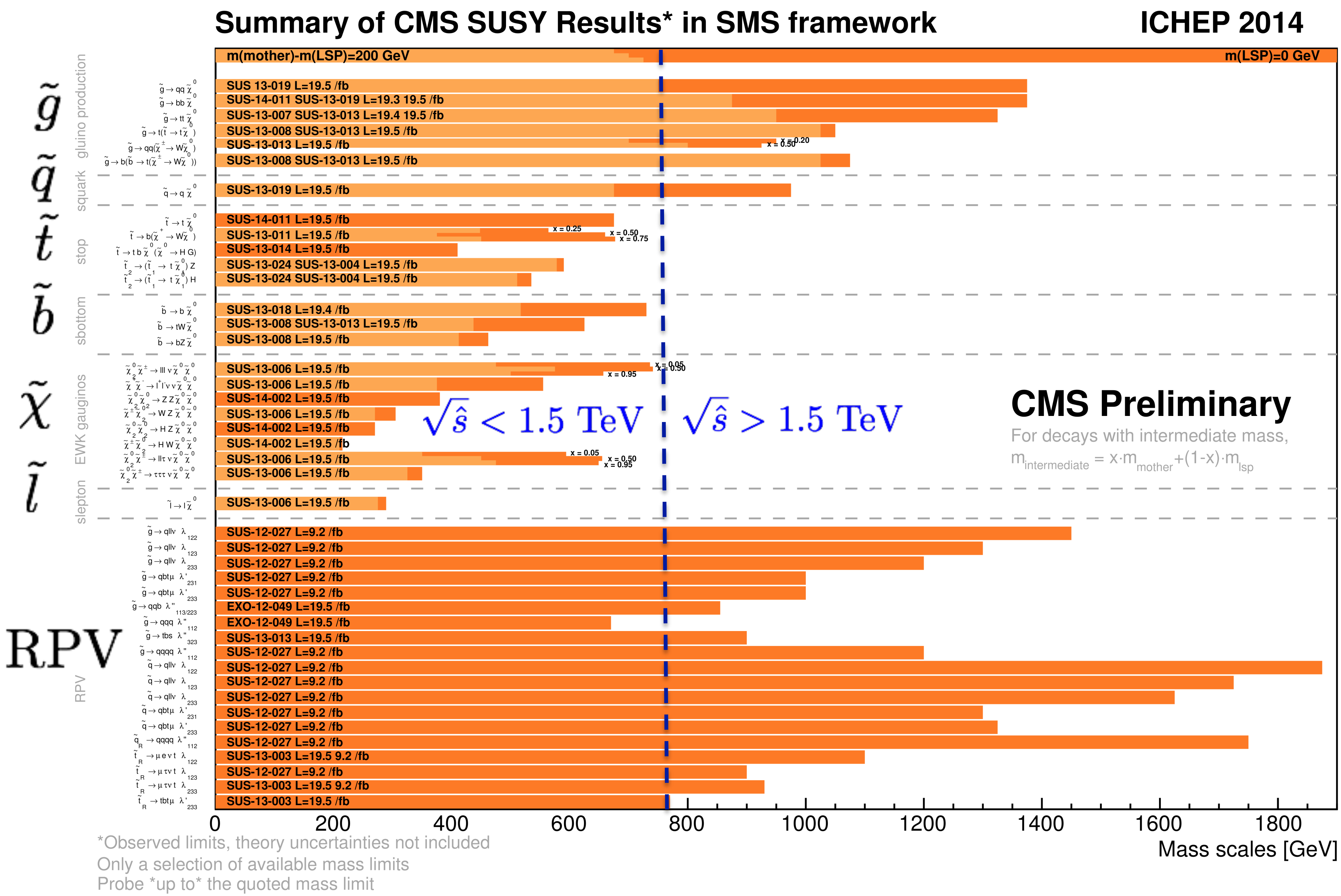



Predicted cross-section ratios
Min. bias
WZ
ZZ
Single t (s-ch.)
Single t (t-ch.)
tW
$t\bar{t}$
ggH
VBF
VH
$t\bar{t}H$
$\tilde{t}\tilde{t}$ (0.7 TeV)
$\tilde{t}\tilde{t}$ (0.9 TeV)
$\tilde{q}\tilde{q}$ (1.0 TeV)
$\tilde{g}\tilde{g}$ (1.5 TeV)
$\tilde{g}\tilde{g}$ (2.5 TeV)
Z'_{SSM} (2.0 TeV)
G* (3.0 TeV)
HSCP $\tilde{g}$ (2.0 TeV)
$W' \to tb$ (2.0 TeV)
$X_{5/3}\bar{X}_{5/3}$ (1.0 TeV)
$X_{5/3}\bar{X}_{5/3}$ (1.5 TeV)
1.09
2.04
2.04
1.97
2.56
3.21
3.29
2.28
2.38
2.01
3.9
8.4
12
15
46
2700
7.0
27
125
6.7
13
40
$(\sigma \cdot L)_{13\text{ TeV}} > (\sigma \cdot L)_{8\text{ TeV}}$
1
10
10^2
10^3
10^4
$\sigma_{13\text{ TeV}}/\sigma_{8\text{ TeV}}$



Summary of CMS SUSY Results* in SMS framework
ICHEP 2014
m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV
gluino production
squark
stop
sbottom
EWK gauginos
slepton
RPV
SUS 13-019 L=19.5 /fb
SUS-14-011 SUS-13-019 L=19.3 19.5 /fb
SUS-13-007 SUS-13-013 L=19.4 19.5 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
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SUS-14-011 L=19.5 /fb
SUS-13-011 L=19.5 /fb
SUS-13-014 L=19.5 /fb
SUS-13-024 SUS-13-004 L=19.5 /fb
SUS-13-024 SUS-13-004 L=19.5 /fb
SUS-13-018 L=19.4 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-13-008 L=19.5 /fb
SUS-13-006 L=19.5 /fb
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SUS-14-002 L=19.5 /fb
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SUS-13-006 L=19.5 /fb
SUS-12-027 L=9.2 /fb
SUS-12-027 L=9.2 /fb
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SUS-12-027 L=9.2 /fb
EXO-12-049 L=19.5 /fb
EXO-12-049 L=19.5 /fb
SUS-13-013 L=19.5 /fb
SUS-12-027 L=9.2 /fb
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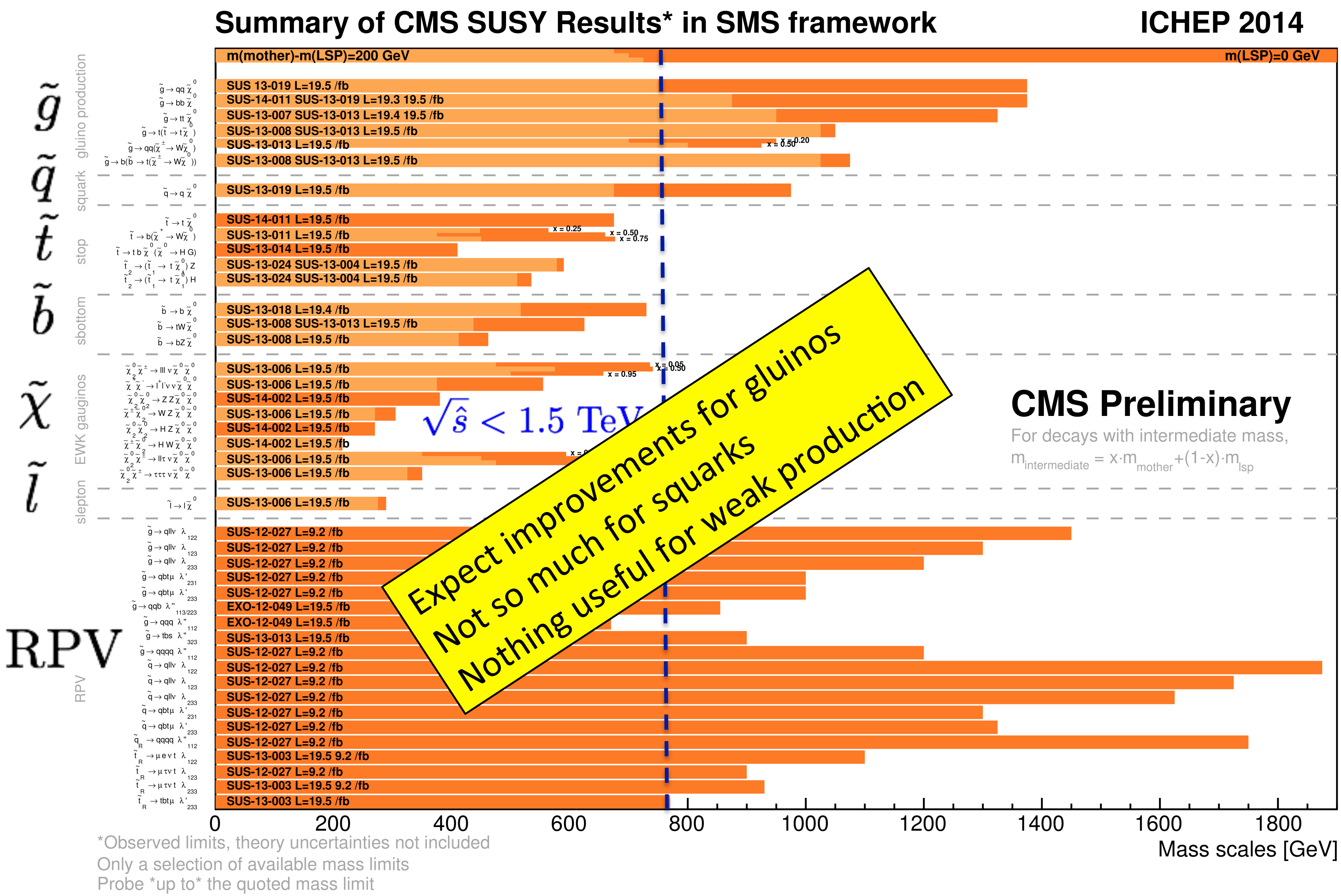
SUS-12-027 L=9.2 /fb
SUS-13-003 L=19.5 9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-13-003 L=19.5 9.2 /fb
SUS-13-003 L=19.5 /fb
$\sqrt{\hat{s}} < 1.5$ TeV
$\sqrt{\hat{s}} > 1.5$ TeV
CMS Preliminary
For decays with intermediate mass,
$m_{intermediate} = x \cdot m_{mother} + (1-x) \cdot m_{lsp}$
0
200
400
600
800
1000
1200
1400
1600
1800
Mass scales [GeV]
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit



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SUS-13-014 L=19.5 /fb
SUS-13-024 SUS-13-004 L=19.5 /fb
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SUS-13-003 L=19.5 9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-13-003 L=19.5 9.2 /fb
SUS-13-003 L=19.5 /fb
$\sqrt{\hat{s}} < 1.5$ TeV
Expect improvements for gluinos
Not so much for squarks
Nothing useful for weak production
CMS Preliminary
For decays with intermediate mass,
$m_{intermediate} = x \cdot m_{mother} + (1-x) \cdot m_{lsp}$
0
200
400
600
800
1000
1200
1400
1600
1800
Mass scales [GeV]
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

CMS generic searches for NP in jet + MET

- Four separate but similar searches. Why?
  - historical
  - redundancy
  - practicalities
- They differ mostly in how they use the MET information
  1. MHT = MET constructed from jets only
  2. MT2
  3. α_T
  4. razor

arxiv:1602.06531
arxiv:1603.04053
CMS-PAS-SUS-15-004
CMS-PAS-SUS-15-005

- Also on details of background treatment

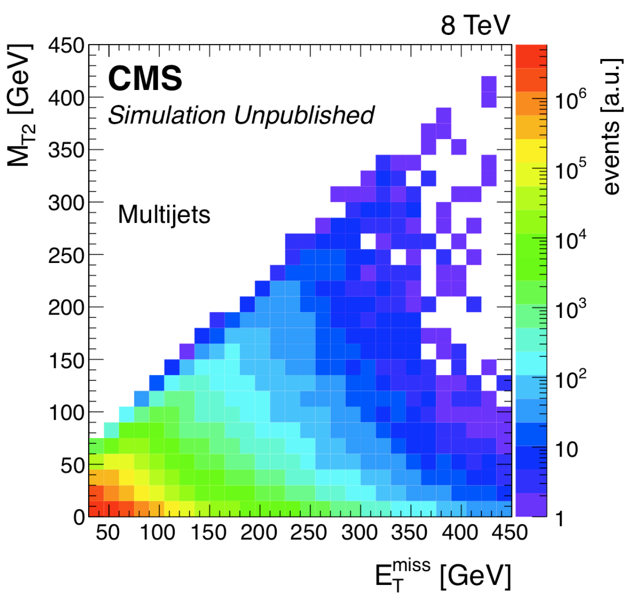
MT2

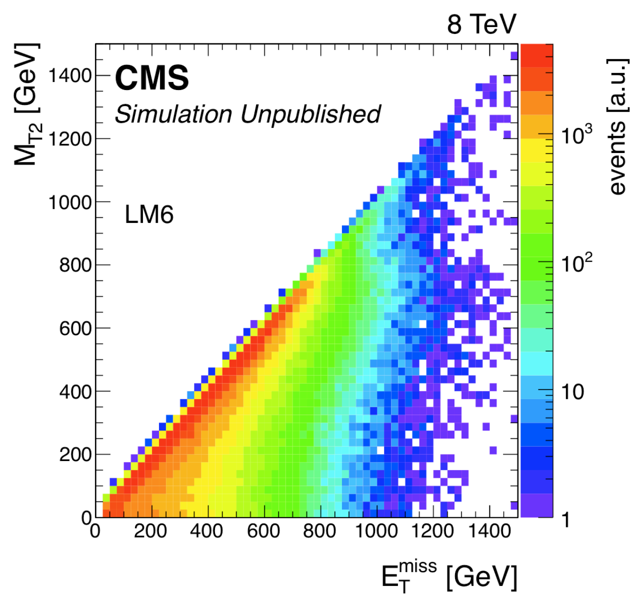
- Uses MET and jets clustered into two hemispheres

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

where the two transverse masses are calculated from the two jets and the two components of the MET, and reduces approximately to $M_{T2} \approx \sqrt{2 p_T^{J1} p_T^{J2} (1 + \cos\Delta\phi_{1,2})}$

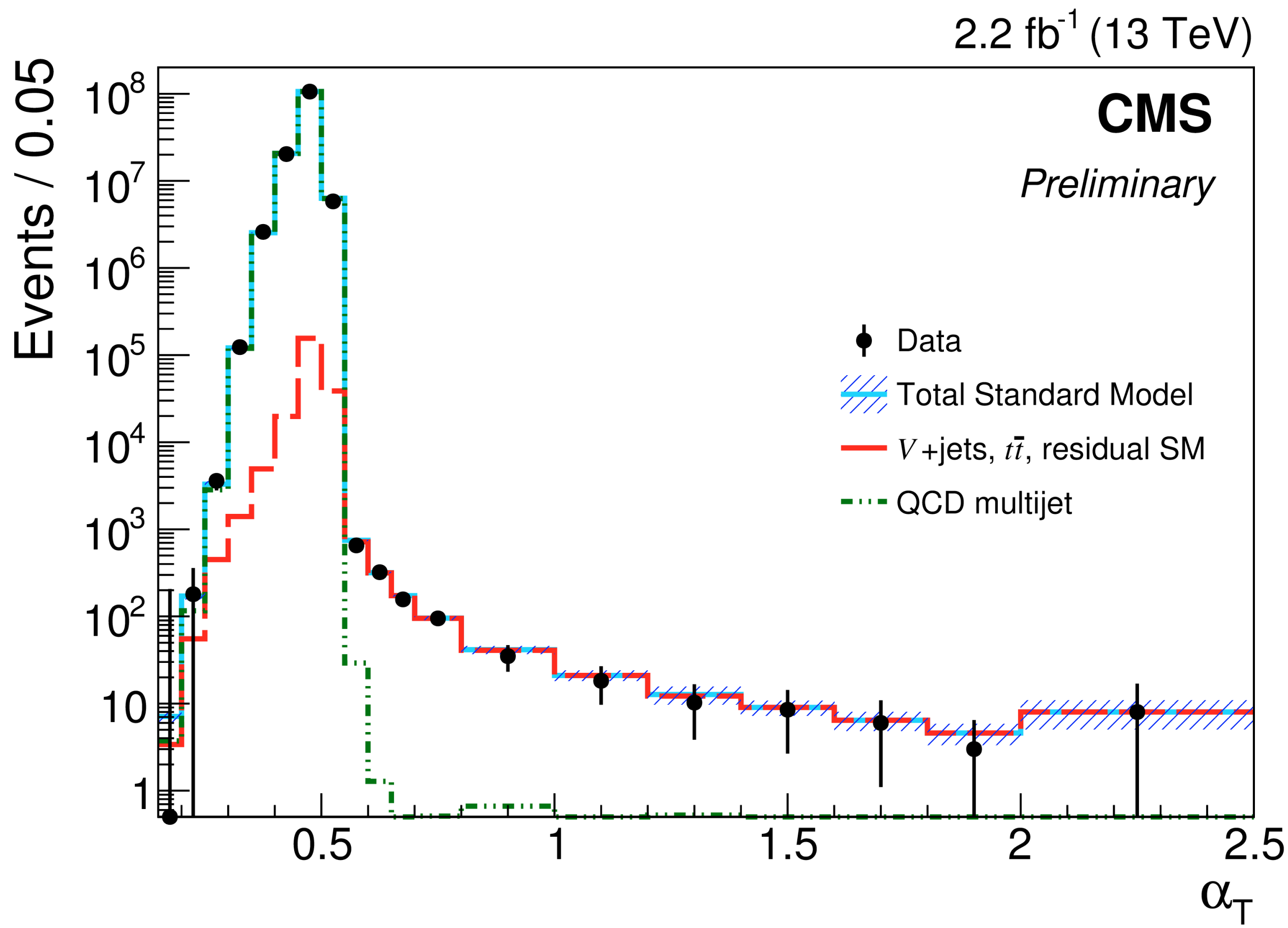
- Provides additional rejection against QCD





α_T

- Also clusters jets into two hemispheres
- A cut in the dimensionless variable α_T reduces QCD



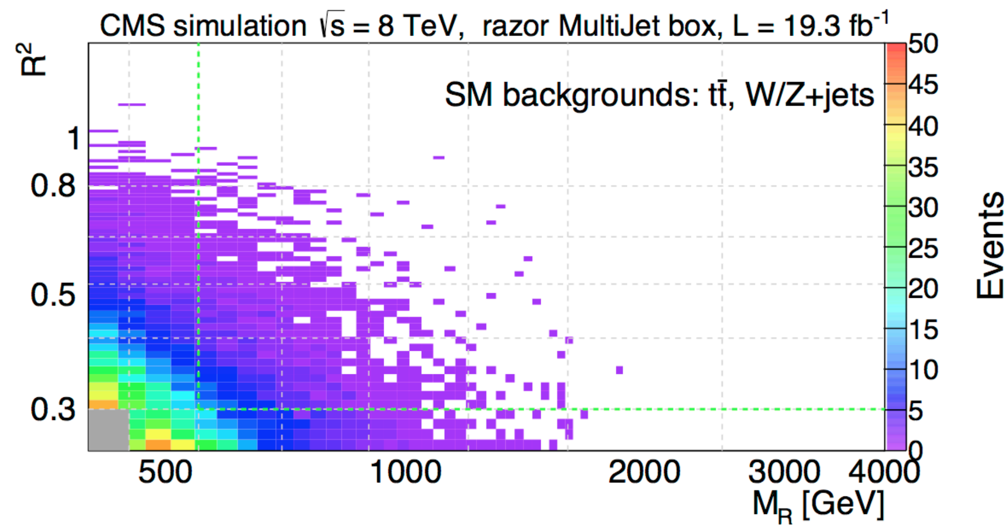
$$\alpha_T \approx \sqrt{\frac{P_T^{J2}}{2P_T^{J1}} \frac{1}{(1-\cos\Delta\phi_{1,2})}}$$

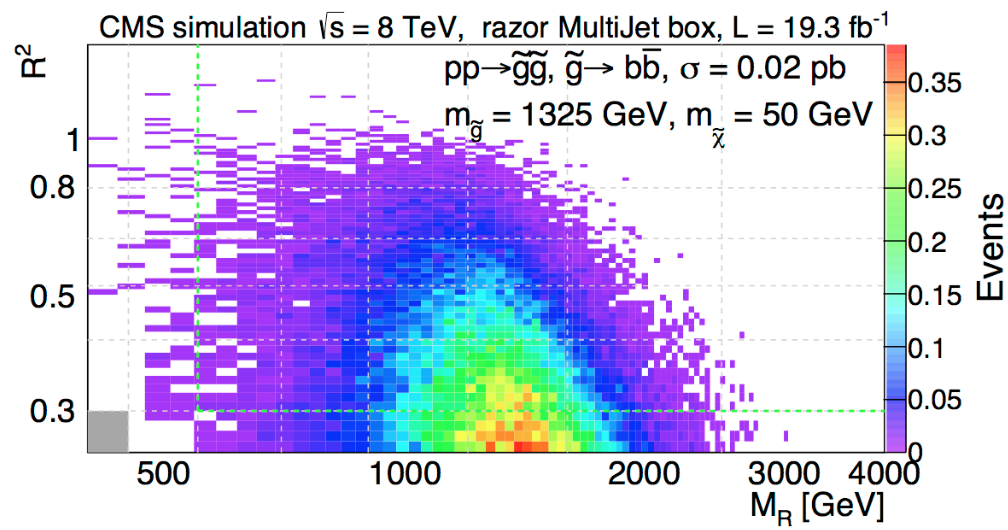
Razor

- Also clusters jets in two hemispheres
- Two variables R and M_R. M_R broadly peaks in the right place for SUSY

$$R^2 \approx \frac{E_T^{\text{miss}}(p_T^{J1}+p_T^{J2}+E_T^{\text{miss}})}{2M_R^2}$$

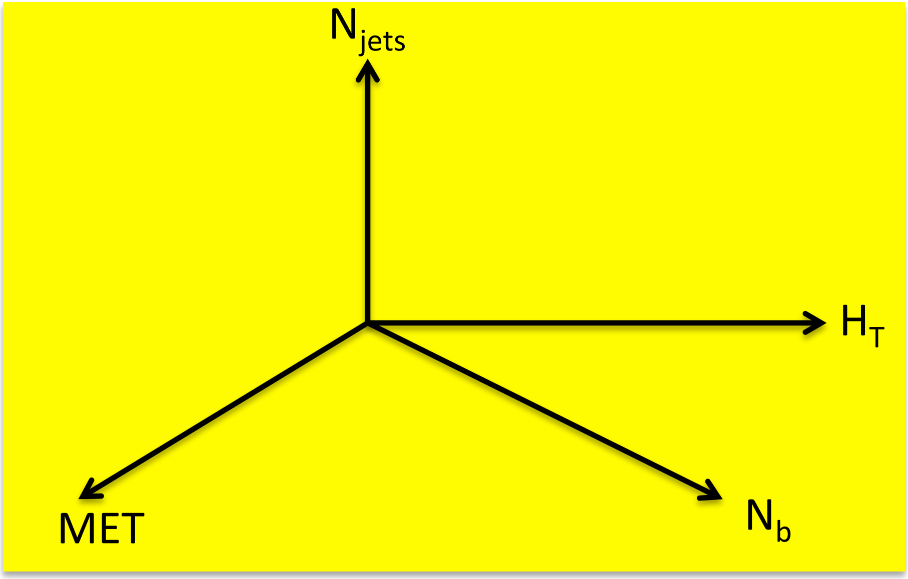
$$M_R^2 = M_{J1,J2}^2 + (E_T^{\text{miss}})^2$$



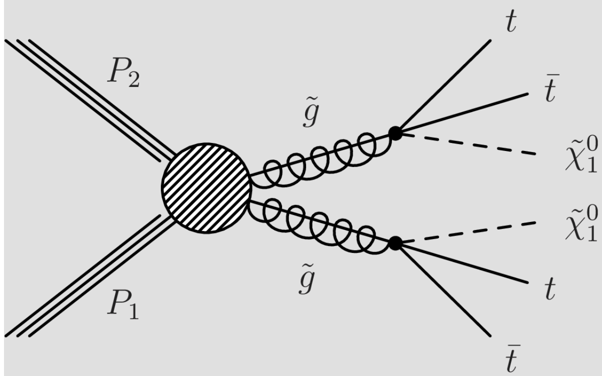


Generic searches

- The searches are "generic"
- Sensitive to NP in jets + MET
- To cover as much ground as possible, "slice and dice" the phase space into many signal regions
- e.g.: 172 signal regions in MT2 search

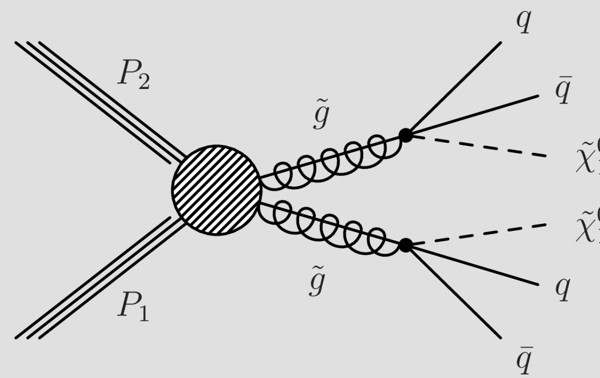


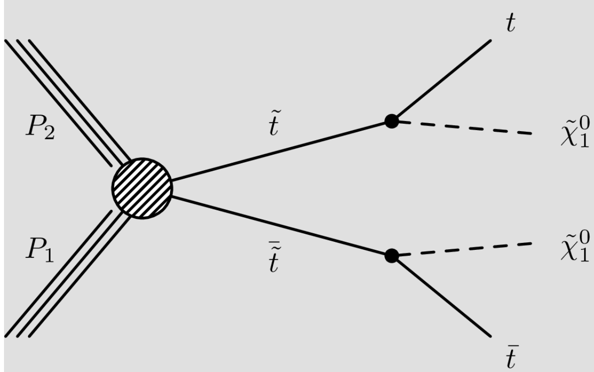
N_{jet} and N_b multiplicities



N_{jet} = 12
N_b = 4

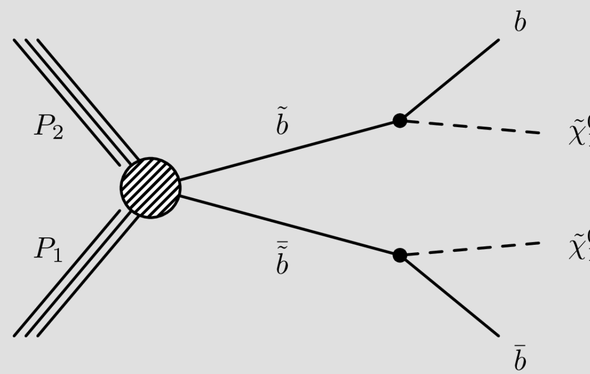
N_{jet} = 4
N_b = 0

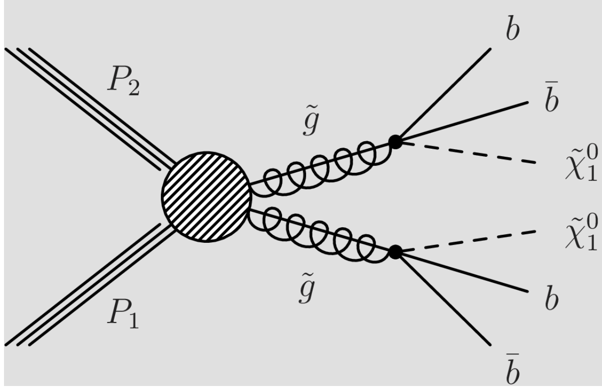




N_{jet} = 6
N_b = 2

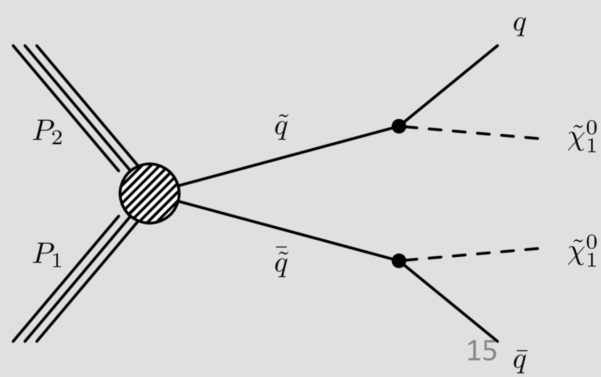
N_{jet} = 2
N_b = 2



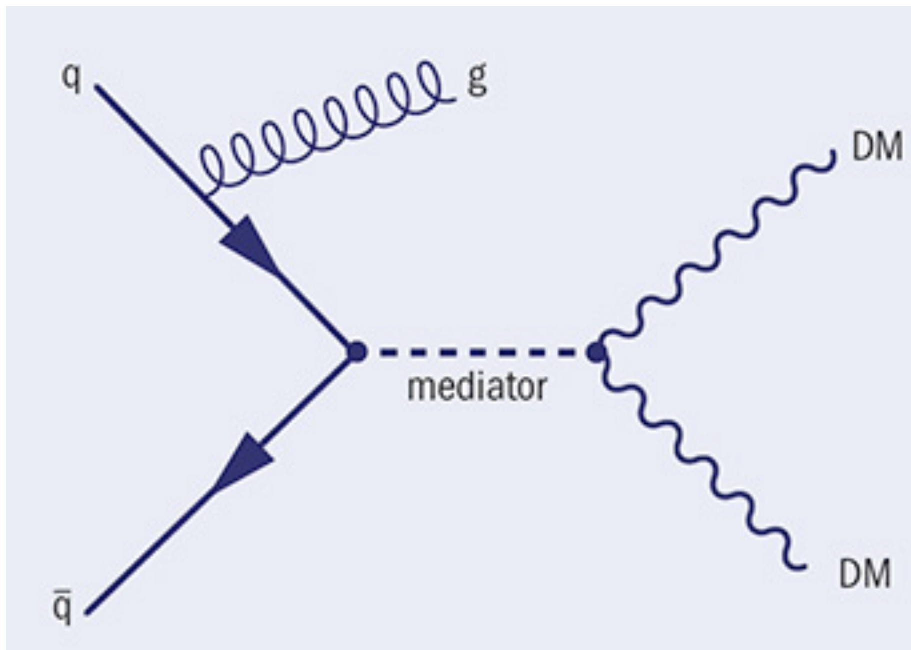


N_{jet} = 4
N_b = 4

N_{jet} = 2
N_b = 0

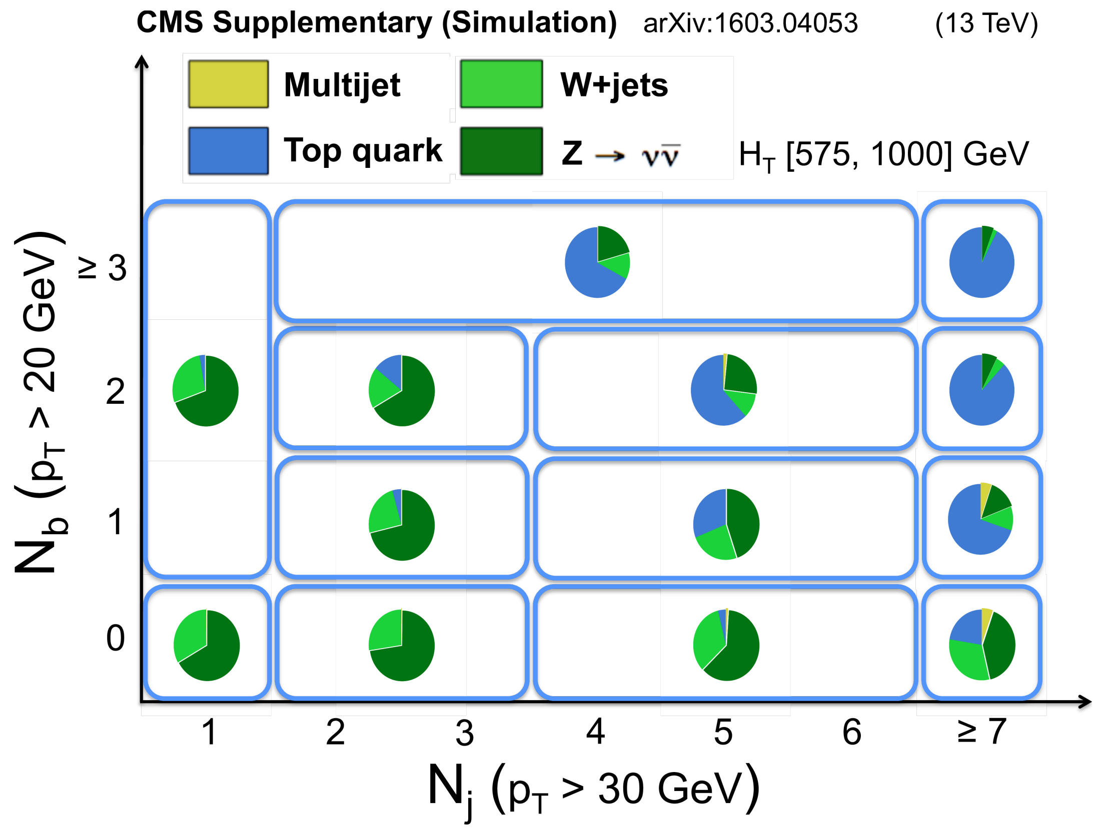


...and even monojets



It's all about the backgrounds

- ttbar and W + jets
  - with leptonic decay where the lepton is lost and the ν gives MET
- Z→νν + jets
- QCD Multijet



General ideas

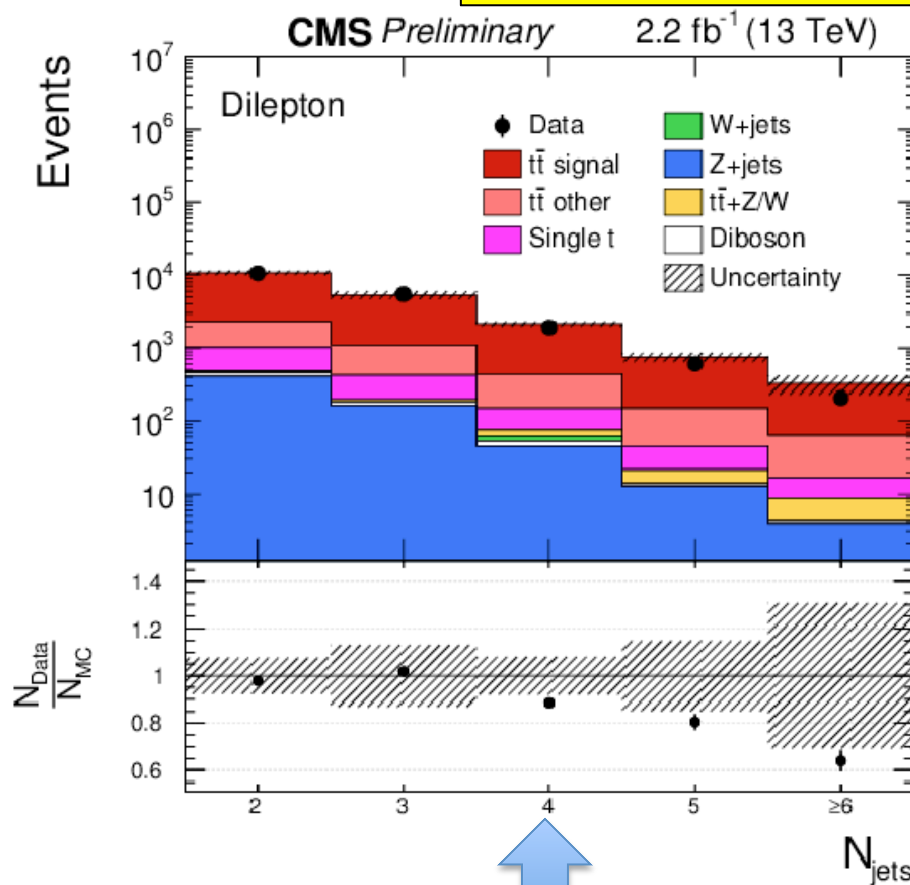
Define control regions (CR) orthogonal but kinematically similar to signal regions (SR), eg

$$N^{SR}_{1\ell-\mathrm{lost}}(H_T, N_j, N_b, MET) = k \times N^{CR}_{1\ell-\mathrm{found}}(H_T, N_j, N_b, MET)$$

where k is a CR→SR "transfer factor" from MC (mostly).

In some cases the "transfer factor" includes an extrapolation in one of the four variables.

CMS-PAS-TOP-16-011

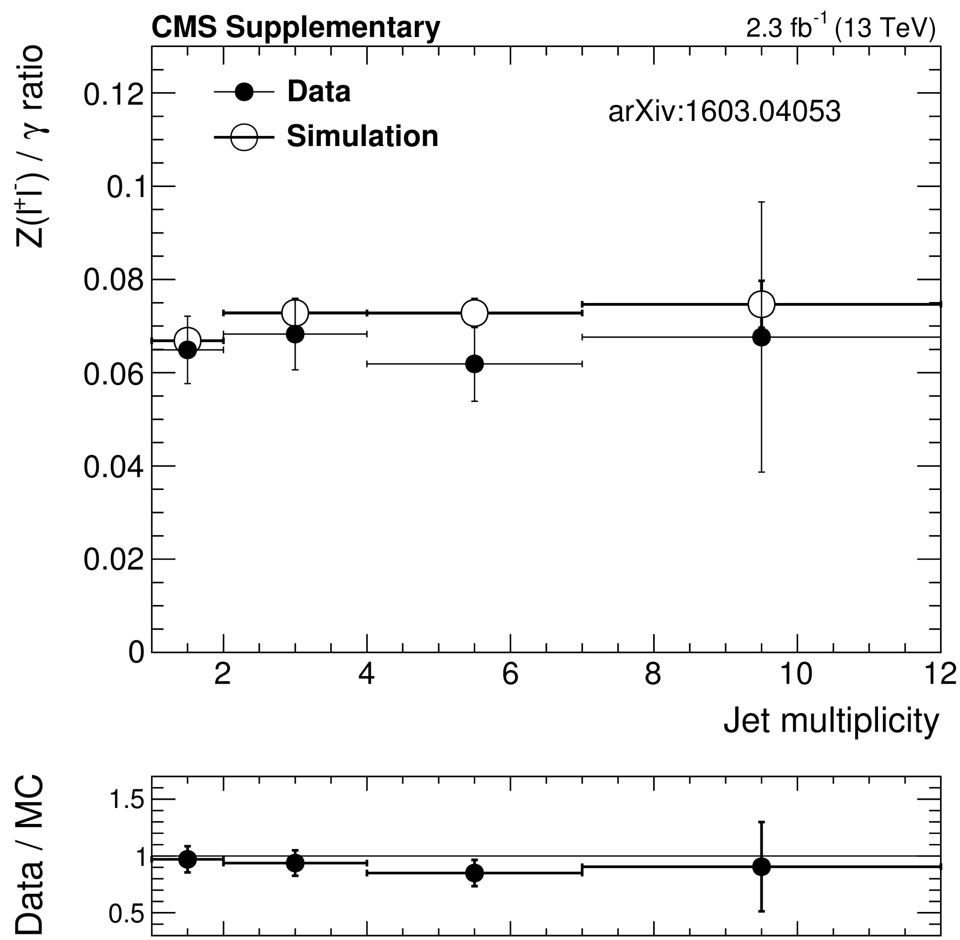


Minimize reliance on MC, which is good but not perfect

$Z \rightarrow \nu\nu$

Similar CR idea for $Z \rightarrow \nu\nu$ but using γ+jets, since at high P_T Z's and γ's are the same (sort of)

Checked with statistically limited $Z \rightarrow \mu\mu$ and $Z \rightarrow ee$ samples



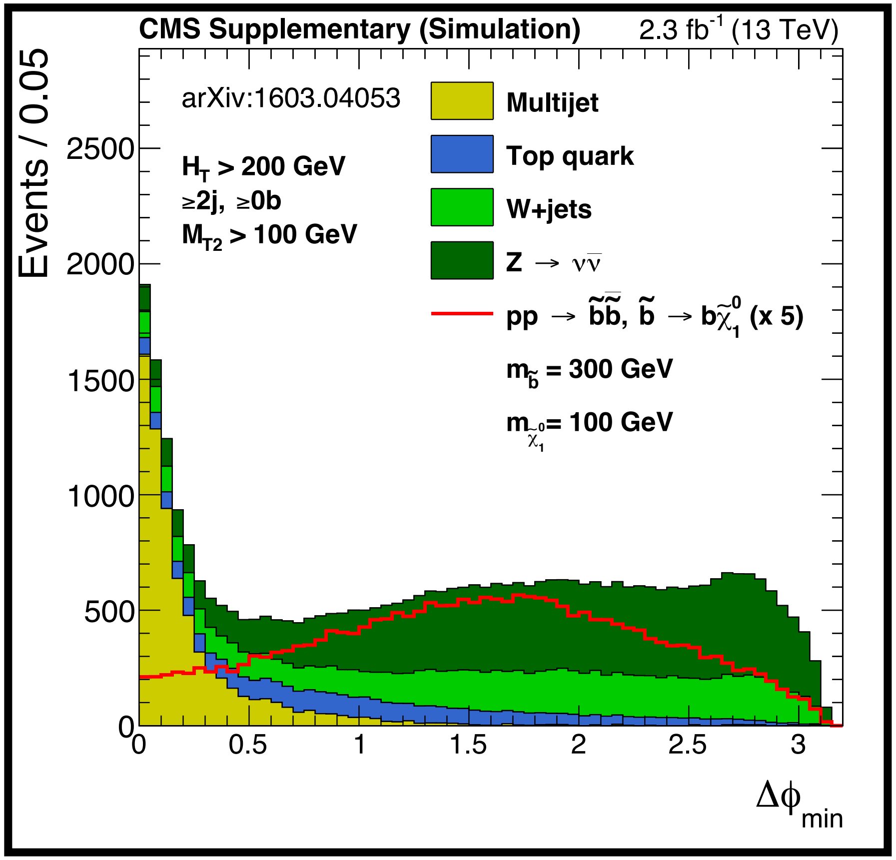
QCD BG estimate

The shakiest part of the chain.

Fortunately it is "small".

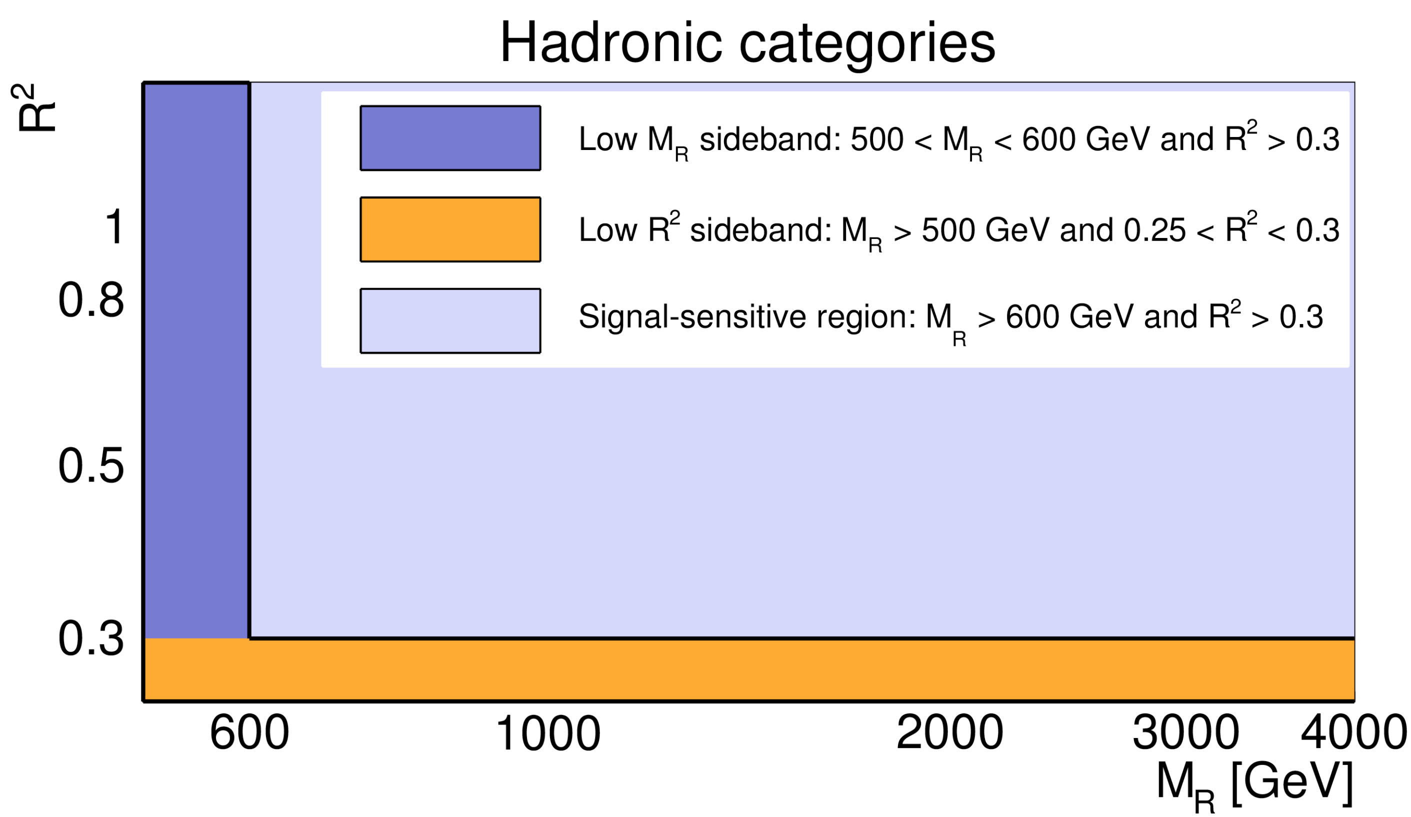
Estimated by extrapolating from the rate of events with MET aligned with one of the jets

This is a variable that we always cut on. The α_T analysis cuts particularly tight.

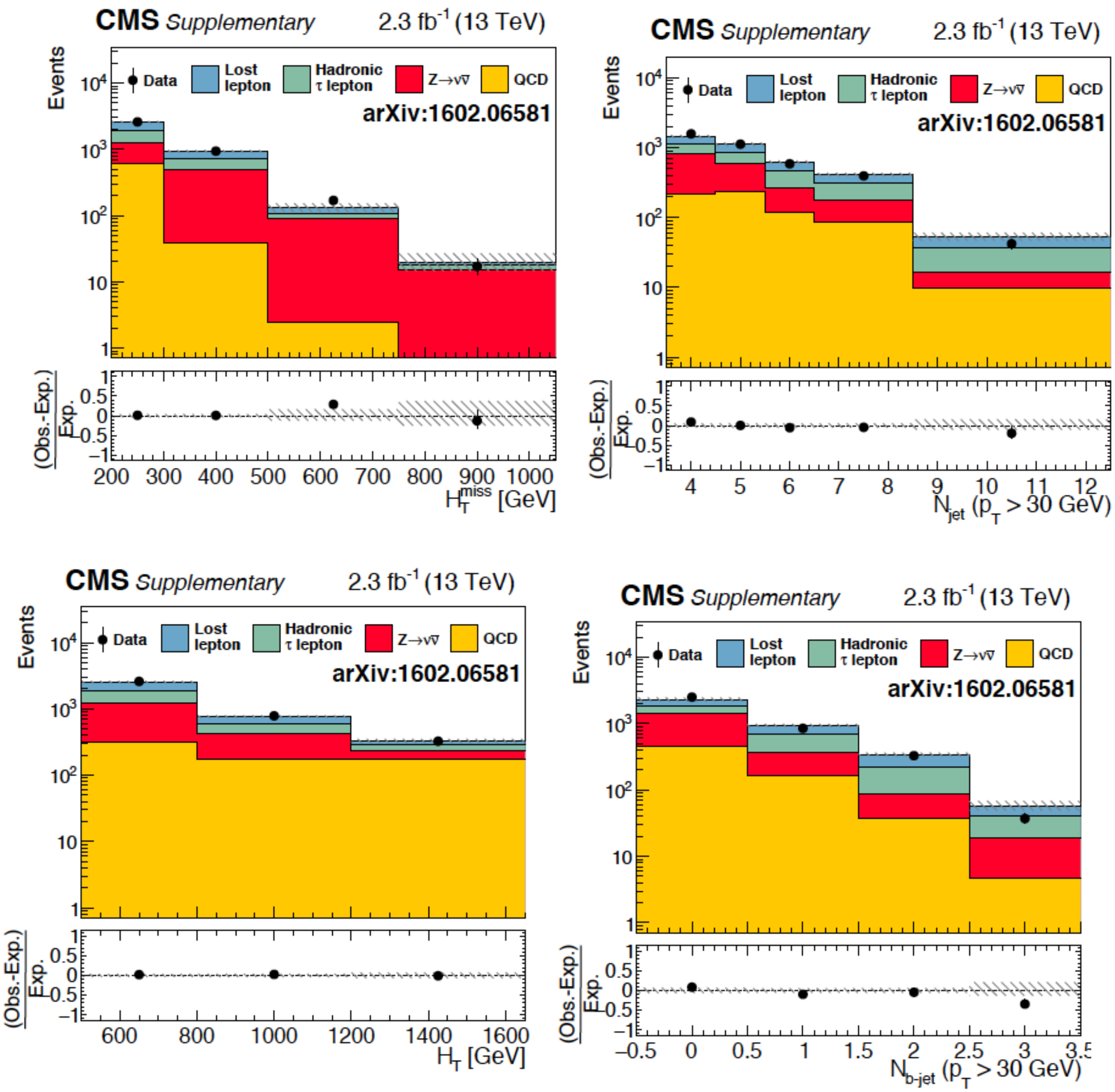


Razor is a little different

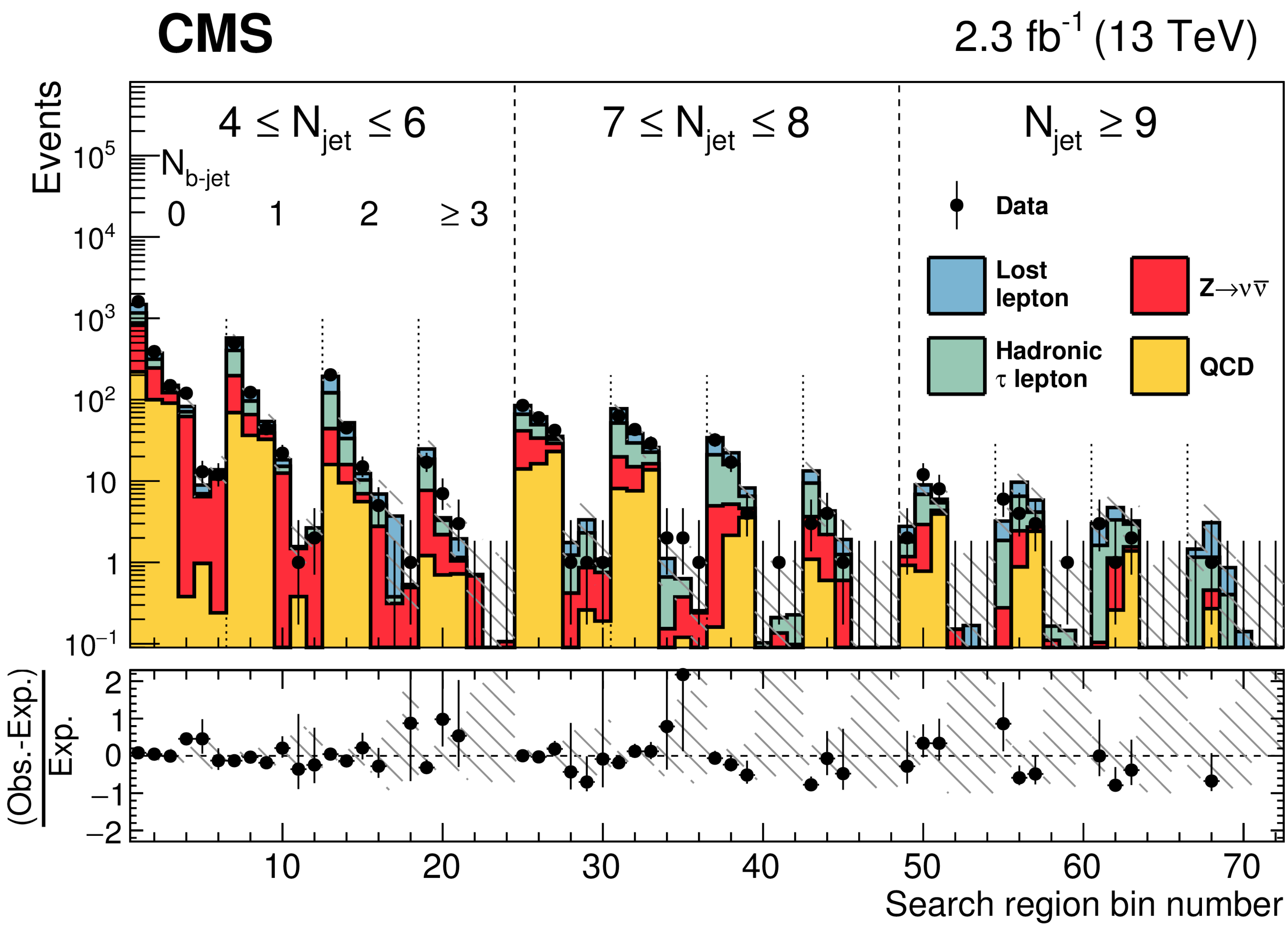
- BG predicted from 2D fit in R^2 vs. M_R plane
  - effectively ~ sideband extrapolation
- Fitting function has enough freedom to absorb background



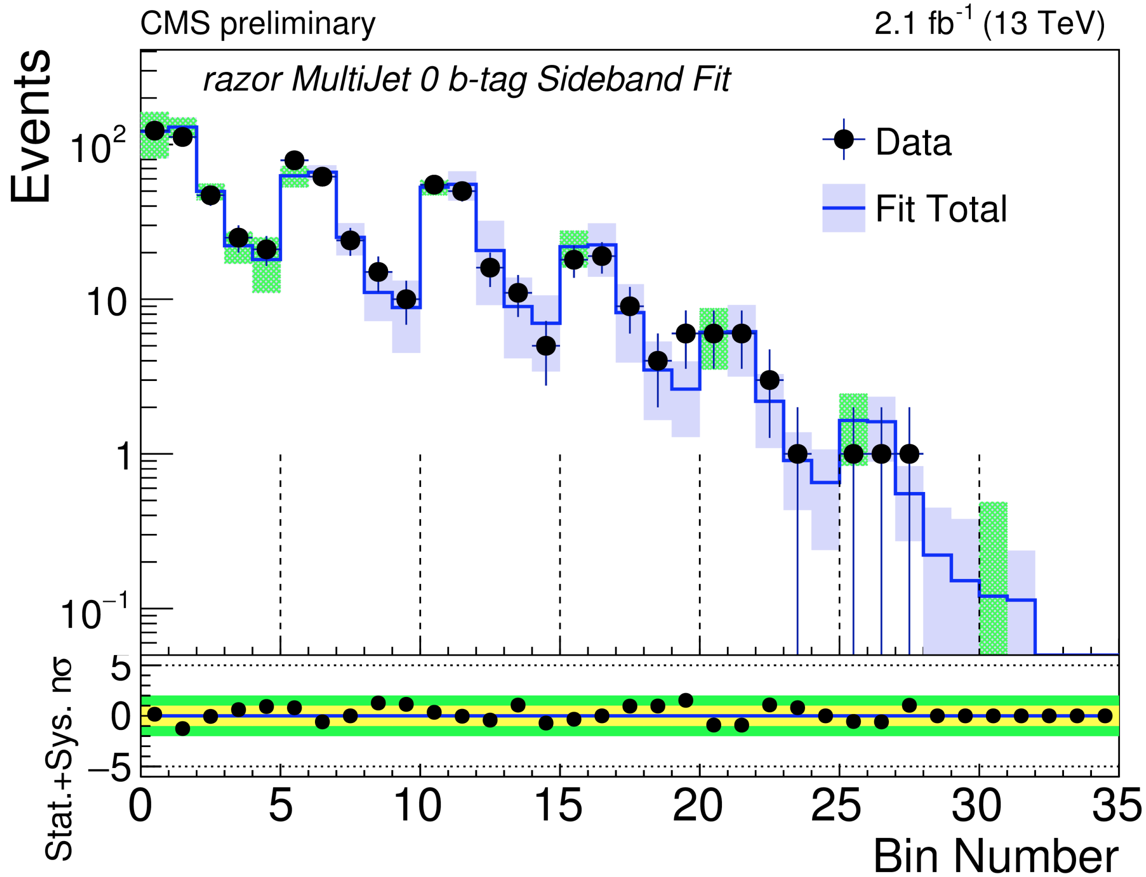
For one of the four analyses, compare data vs. SM for the 4 search variables

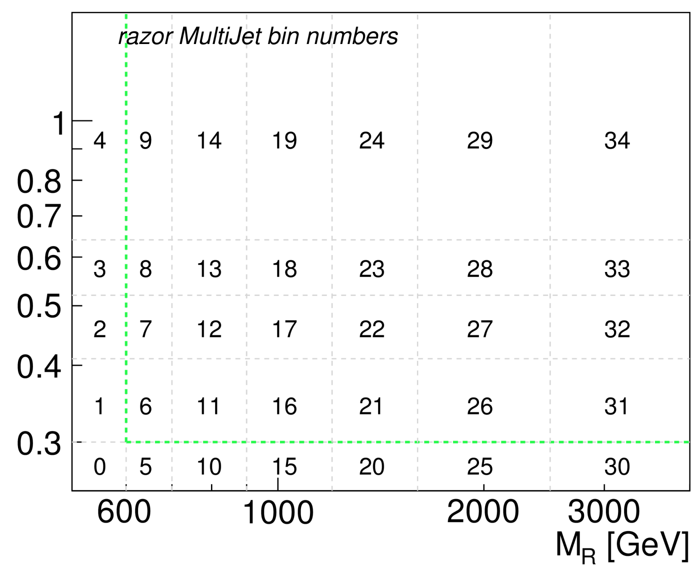


The 72 signal regions of arxiv:1602.06581: data vs. prediction

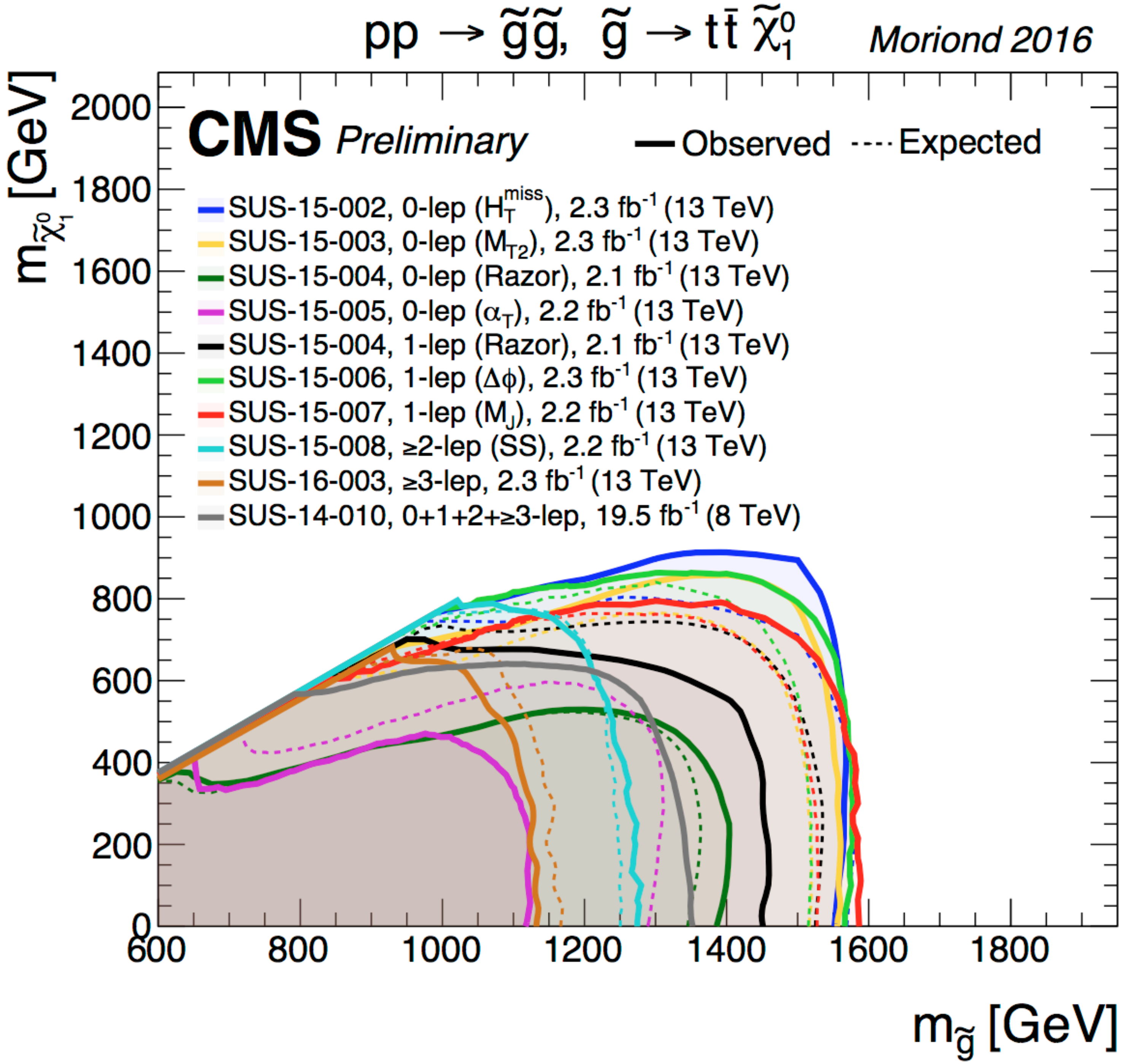


An example from the razor: data vs. BG-only fit for the 0-btag category

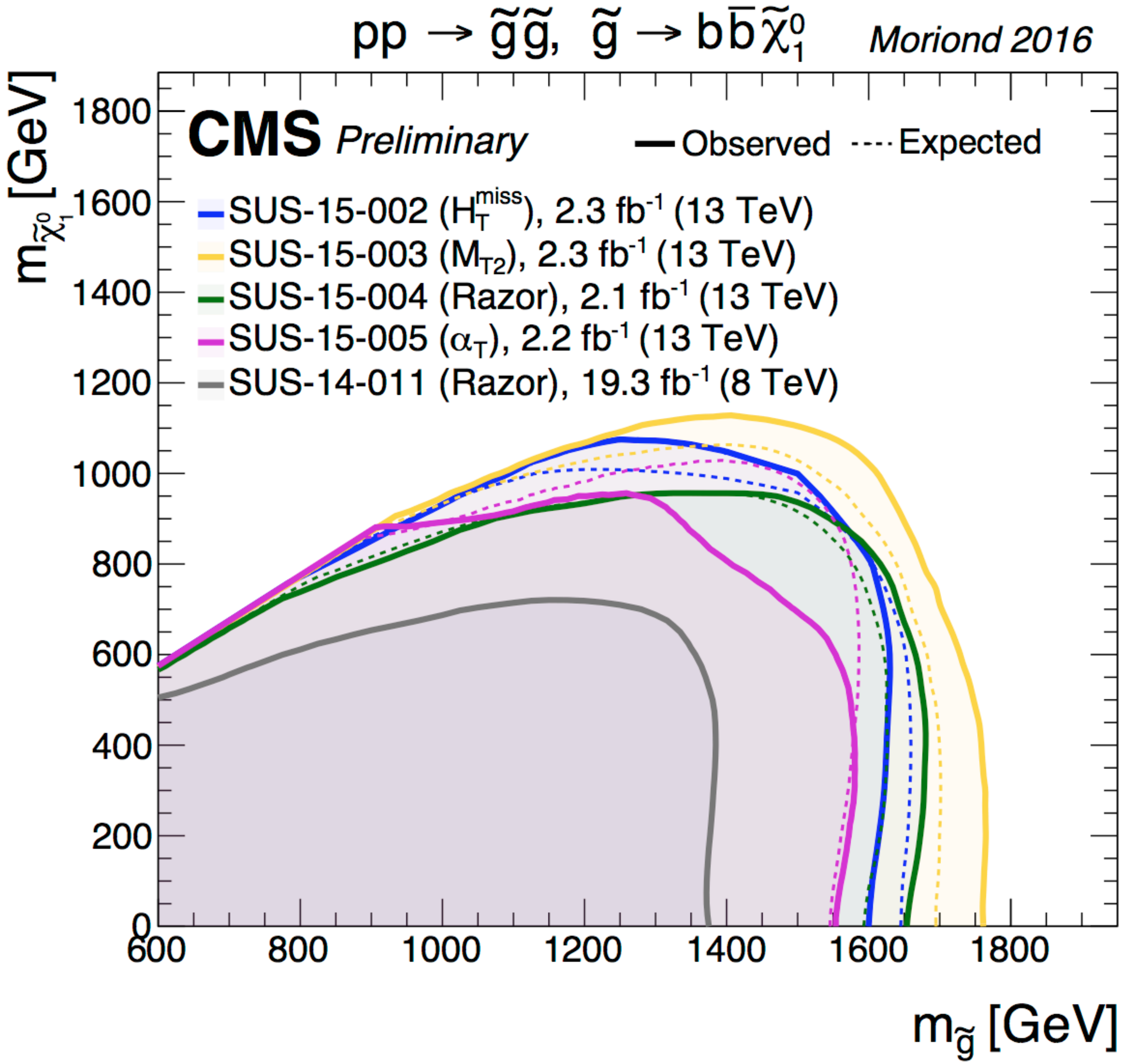




Some simplified model interpretations



$pp \to \tilde{g}\tilde{g}, \ \tilde{g} \to t\bar{t}\,\tilde{\chi}^0_1$
Moriond 2016
CMS Preliminary
Observed
Expected
SUS-15-002, 0-lep (H_T^{miss}), 2.3 fb^{-1} (13 TeV)
SUS-15-003, 0-lep (M_{T2}), 2.3 fb^{-1} (13 TeV)
SUS-15-004, 0-lep (Razor), 2.1 fb^{-1} (13 TeV)
SUS-15-005, 0-lep (α_T), 2.2 fb^{-1} (13 TeV)
SUS-15-004, 1-lep (Razor), 2.1 fb^{-1} (13 TeV)
SUS-15-006, 1-lep ($\Delta\phi$), 2.3 fb^{-1} (13 TeV)
SUS-15-007, 1-lep (M_J), 2.2 fb^{-1} (13 TeV)
SUS-15-008, ≥2-lep (SS), 2.2 fb^{-1} (13 TeV)
SUS-16-003, ≥3-lep, 2.3 fb^{-1} (13 TeV)
SUS-14-010, 0+1+2+≥3-lep, 19.5 fb^{-1} (8 TeV)
$m_{\tilde{\chi}^0_1}$ [GeV]
$m_{\tilde{g}}$ [GeV]
0
200
400
600
800
1000
1200
1400
1600
1800
2000



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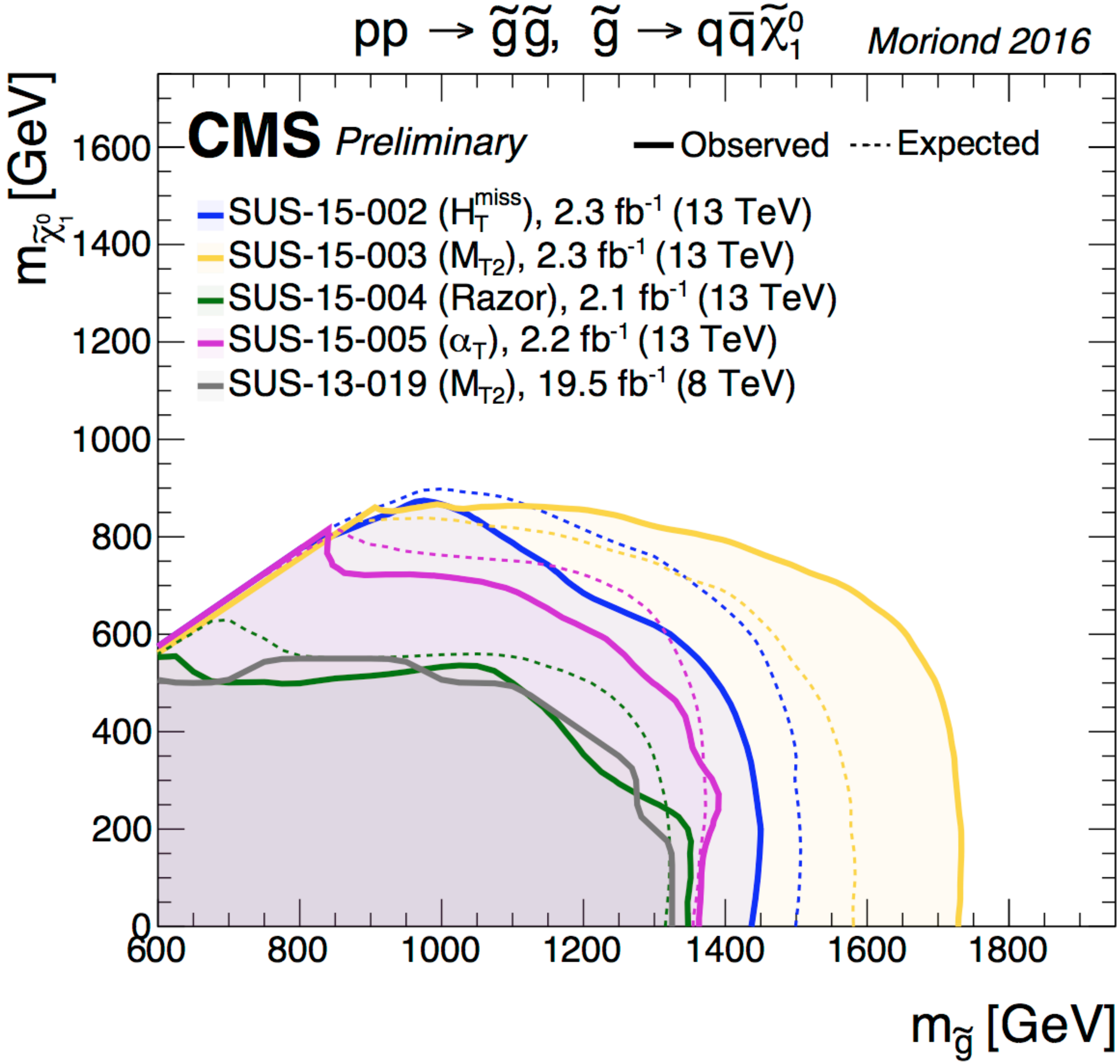
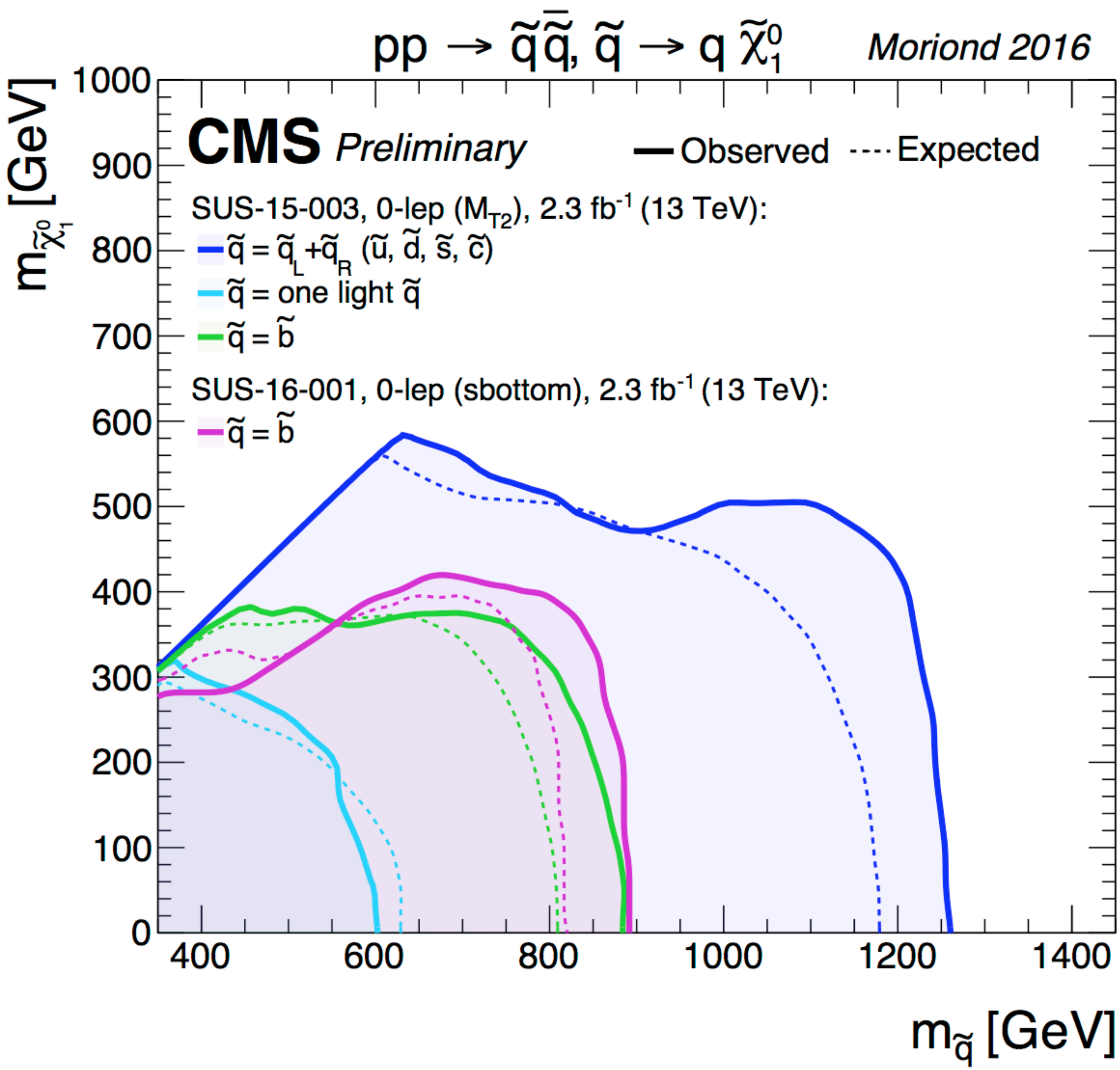
$m_{\tilde{\chi}^0_1}$ [GeV]
$m_{\tilde{g}}$ [GeV]
0
200
400
600
800
1000
1200
1400
1600
1800
600
800
1000
1200
1400
1600
1800



pp → g̃g̃, g̃ → qq̄χ̃⁰₁
Moriond 2016
CMS Preliminary
Observed
Expected
SUS-15-002 (H_T^miss), 2.3 fb-1 (13 TeV)
SUS-15-003 (M_T2), 2.3 fb-1 (13 TeV)
SUS-15-004 (Razor), 2.1 fb-1 (13 TeV)
SUS-15-005 (α_T), 2.2 fb-1 (13 TeV)
SUS-13-019 (M_T2), 19.5 fb-1 (8 TeV)
m_χ̃⁰₁ [GeV]
m_g̃ [GeV]
0
200
400
600
800
1000
1200
1400
1600
600
800
1000
1200
1400
1600
1800



pp → q̃q̃̄, q̃ → q χ̃⁰₁
Moriond 2016
CMS Preliminary
Observed
Expected
SUS-15-003, 0-lep (M_T2), 2.3 fb⁻¹ (13 TeV):
q̃ = q̃_L+q̃_R (ũ, d̃, s̃, c̃)
q̃ = one light q̃
q̃ = b̃
SUS-16-001, 0-lep (sbottom), 2.3 fb⁻¹ (13 TeV):
q̃ = b̃
m_χ̃⁰₁ [GeV]
m_q̃ [GeV]
0
100
200
300
400
500
600
700
800
900
1000
400
600
800
1000
1200
1400

Simplified models of gluino and squarks

- We have extended the exclusion limits on gluino masses in typical simplified models from ~ 1350 GeV to ~ 1600 GeV
- For degenerate light squarks from ~ 900 GeV to ~ 1200 GeV
- For bottom squarks from ~ 750 GeV to ~ 900 GeV

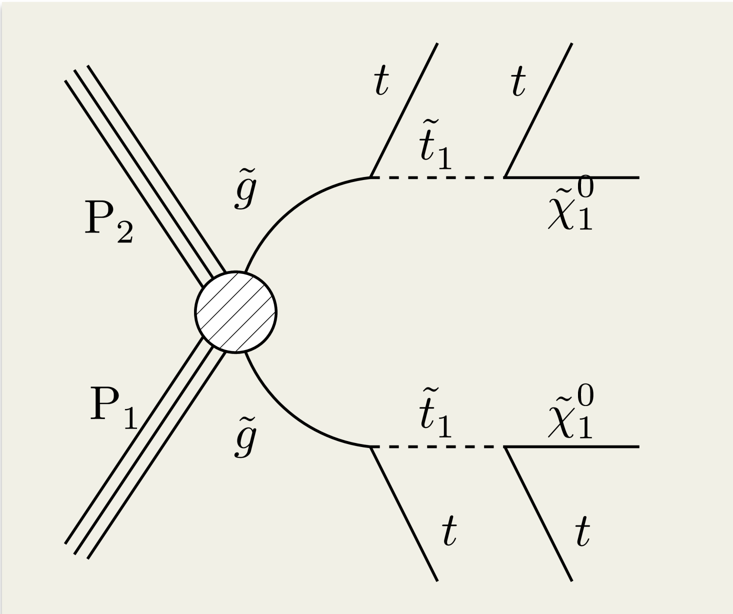
Caveats

- These are simplified models
- 100% branching ratios
- Simplified decay distributions (phase space)

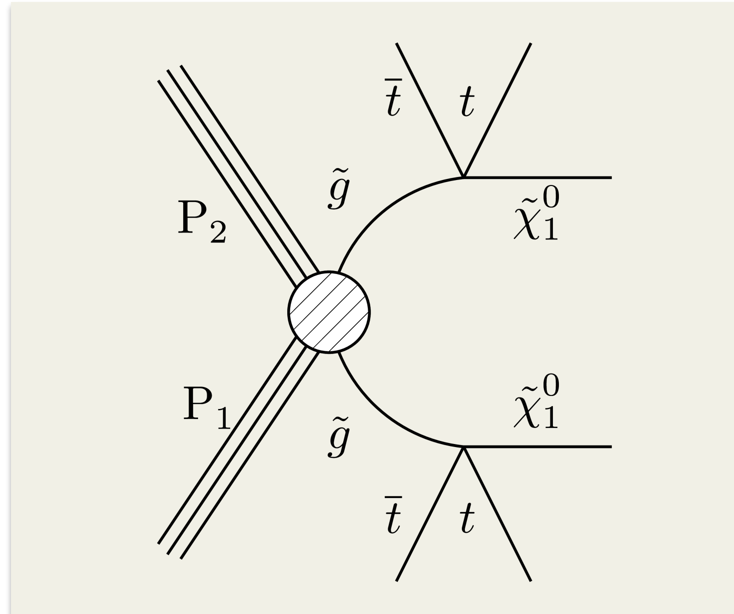
- There are plenty of "nooks and crannies" where SUSY can be hiding below our limits

- We explore some of those. We are doing more and more of this.

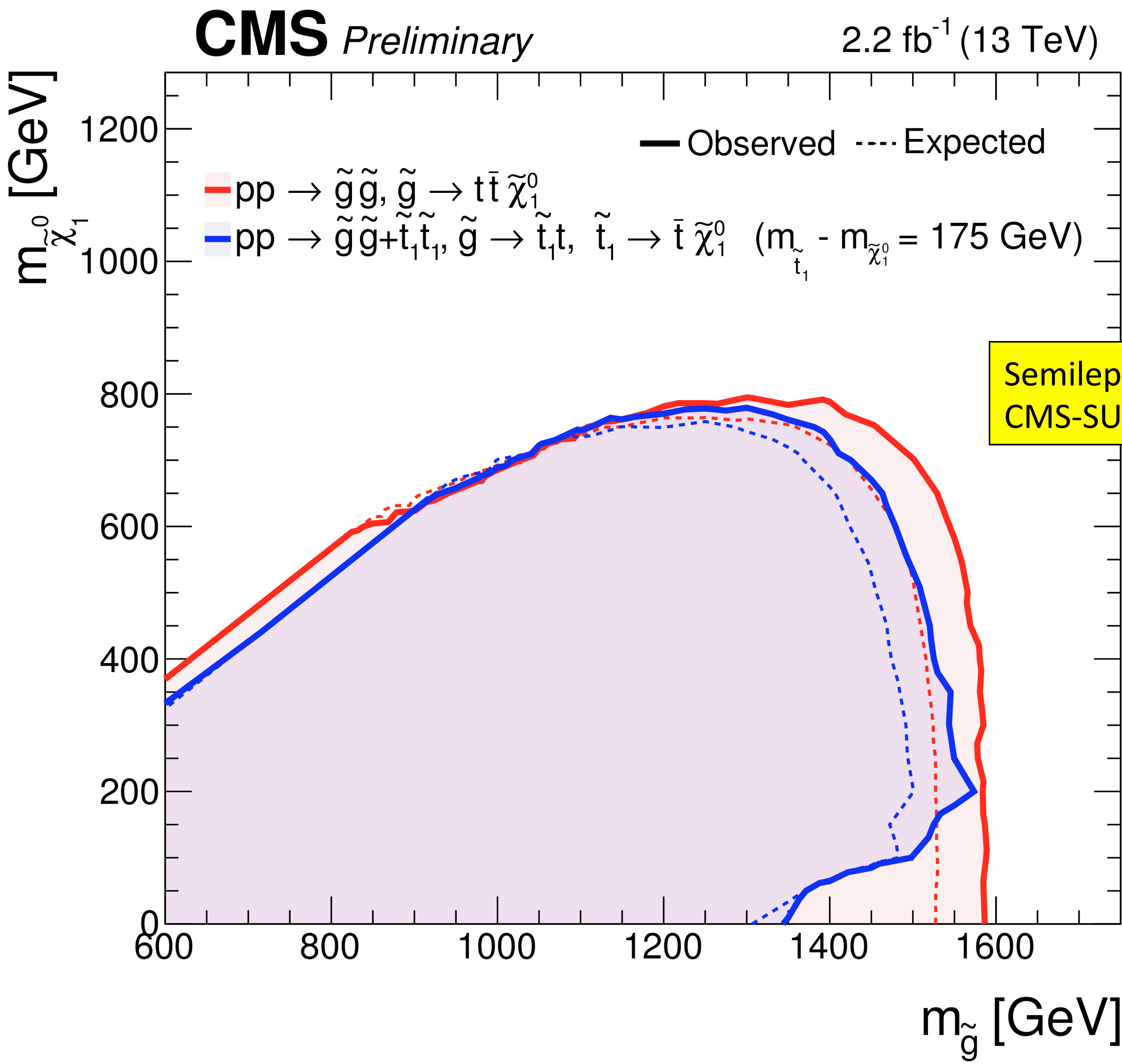
An example



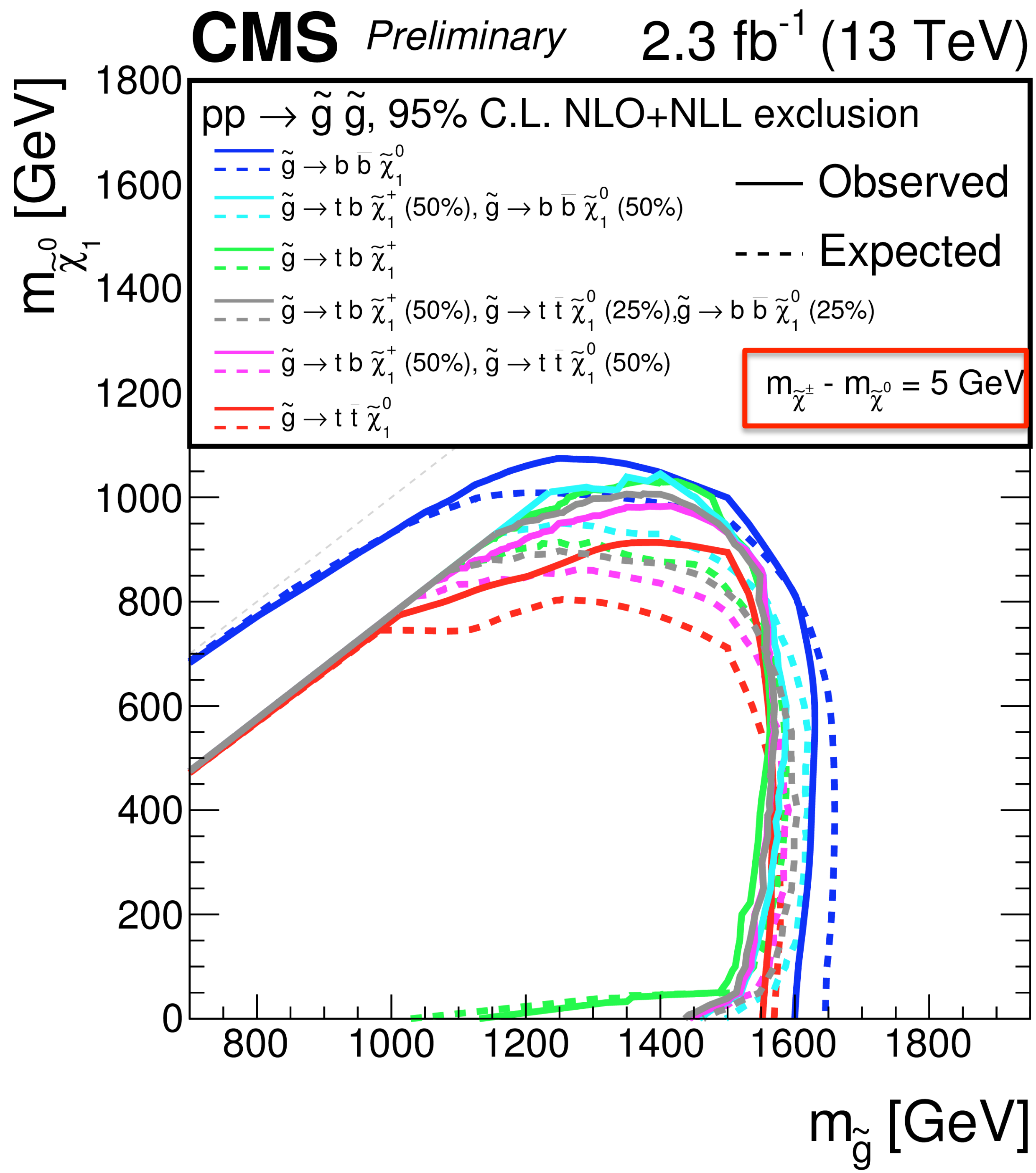
vs.



- When the stop is very heavy (virtual) they are the same
- When M(stop) >> M(top) + M(χ^0) the sensitivity is very similar
- When M(stop)~M(top) + M(χ^0) reduced sensitivity



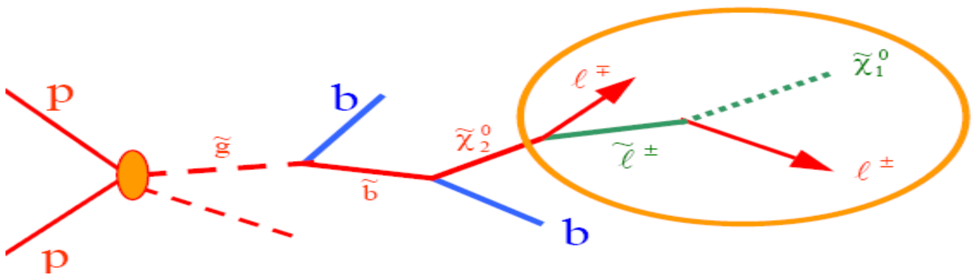
Semileptonic Search
CMS-SUS-PAS-16-004



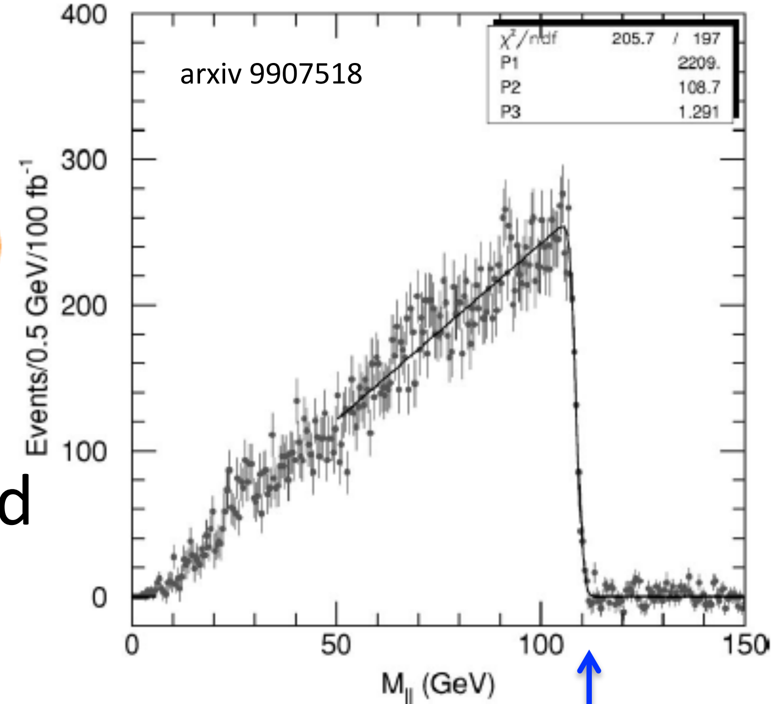
Hadronic Search
CMS-SUS-PAS-16-004

A partly disappearing excess: opposite sign-same flavor leptons + MET

- A "classic" SUSY signature



- Two leptons of opposite sign and same flavor
- The invariant mass of the pair has a kinematical edge and a triangular shape from phase space



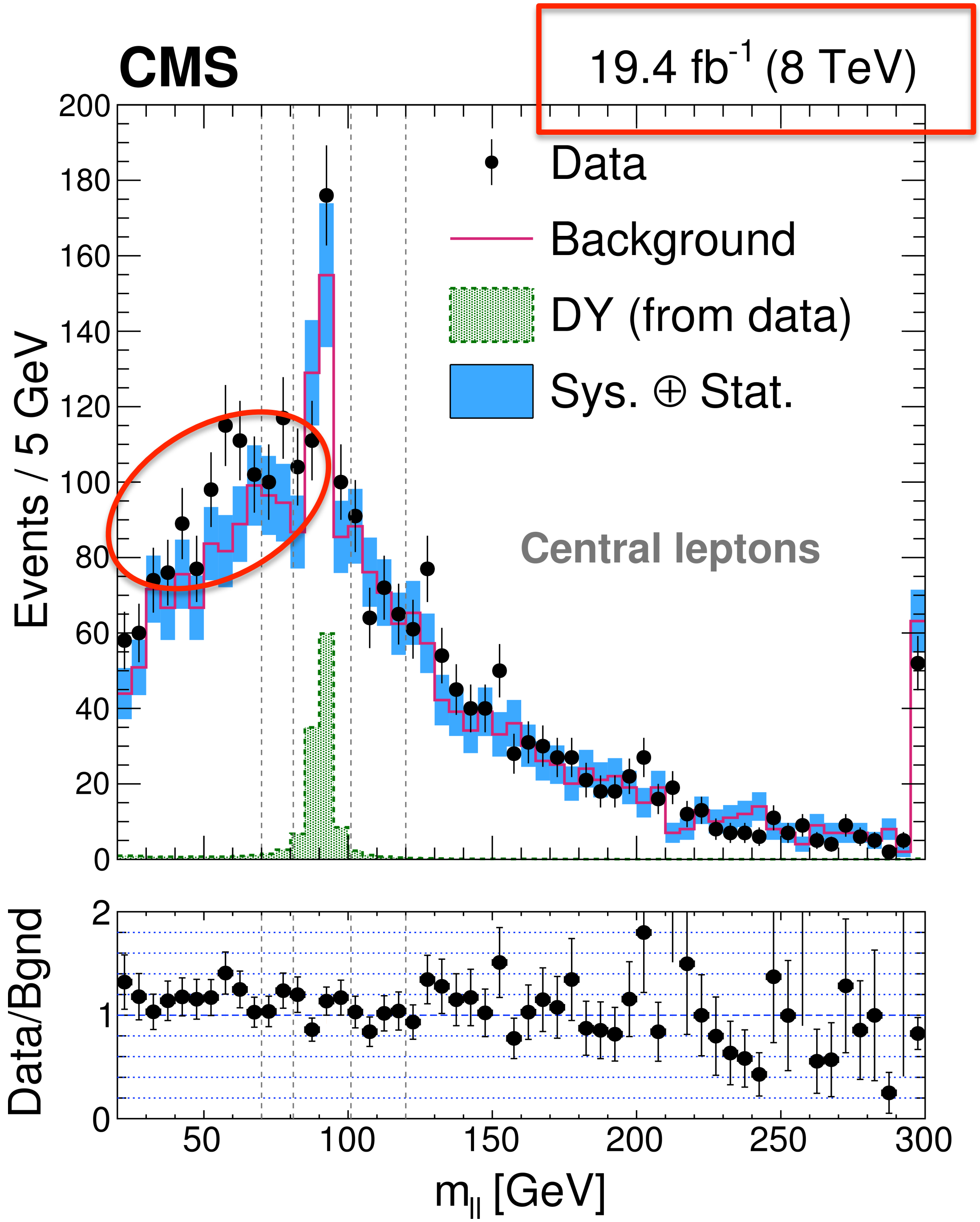
$$M(\chi_2)\sqrt{1-\frac{M(\tilde{\ell})}{M(\chi_2)}}\sqrt{1-\frac{M(\chi_1)}{M(\tilde{\ell})}}$$

- Look for e^+e^- and $\mu^+\mu^-$ + jets + MET
- You find many such events, mostly from ttbar, so look for an excess
- The BG estimate is the most robust of all the SUSY searches at the LHC
  - MC
  - Data $e\mu$ events
    - ttbar → $e\mu$, μe, ee, and $\mu\mu$ democratically
  - Differences in e vs. μ efficiencies partially cancel

$$N(ee+\mu\mu) = \frac{1}{2}N(e\mu)(r+\frac{1}{r}) \qquad r = \frac{\epsilon(e)}{\epsilon(\mu)}$$

  - BG does not have an edge

Uncertainty in BG estimate ~ 5% (trigger mostly)

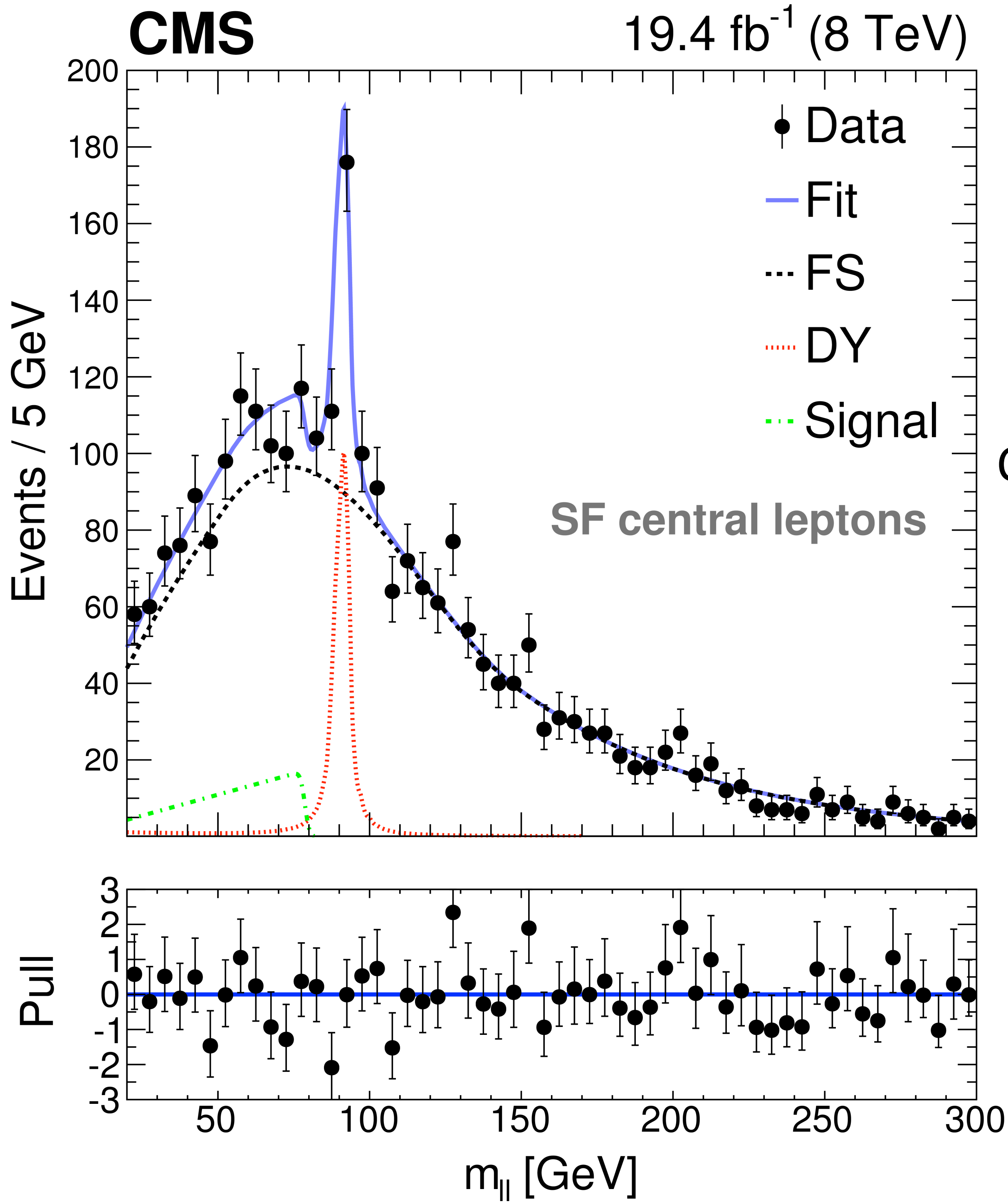


JHEP04(2015)124

$N_{jet} \geq 2$ MET>150 GeV
or
$N_{jet} \geq 3$ MET>100 GeV

$|\eta(lep)| < 1.4$

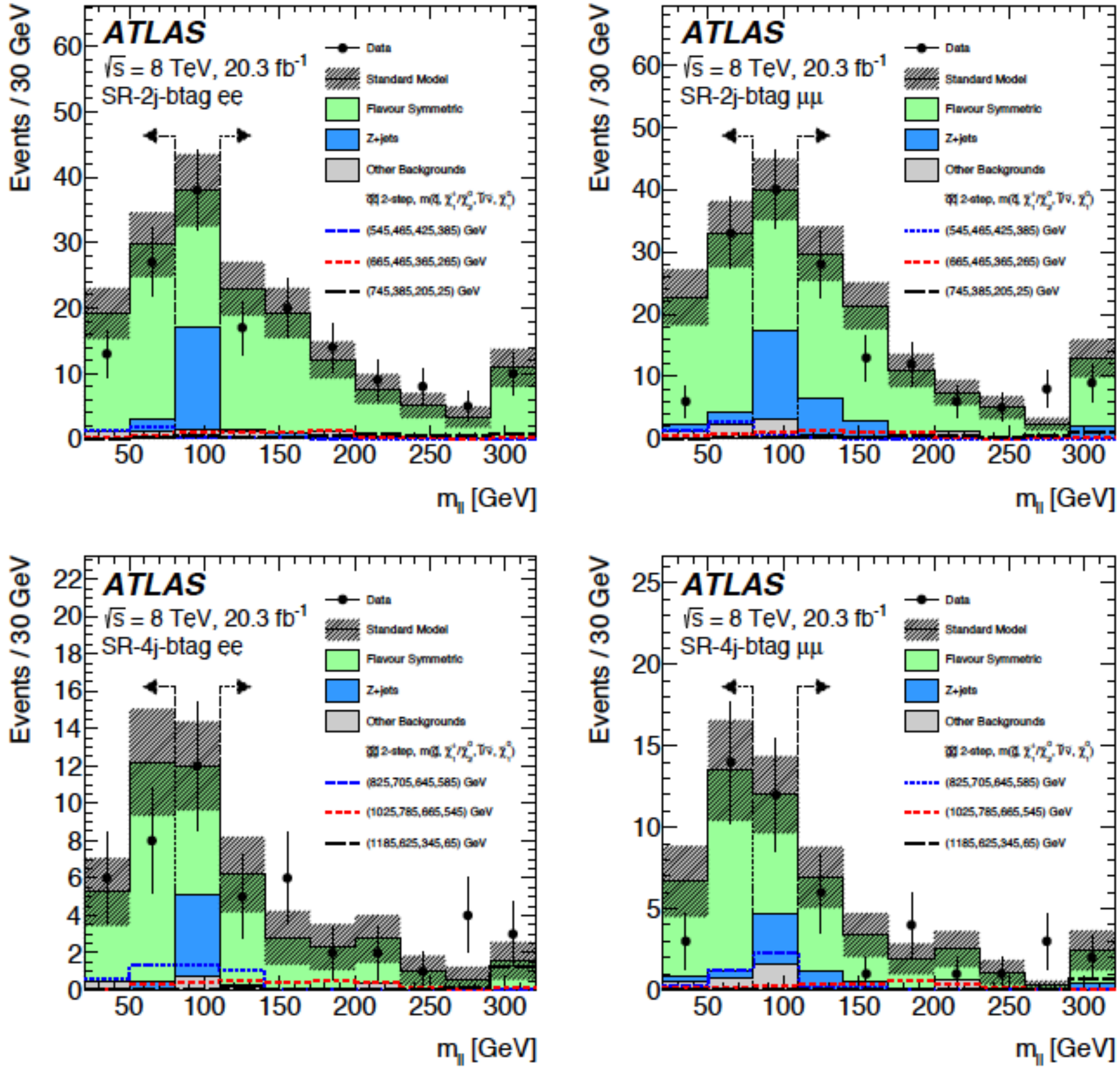
20 < M < 70 GeV	
Data	860
Predicted	730 ± 40
Excess	~ 2.6 σ



JHEP04(2015)124

Can you see a triangle?

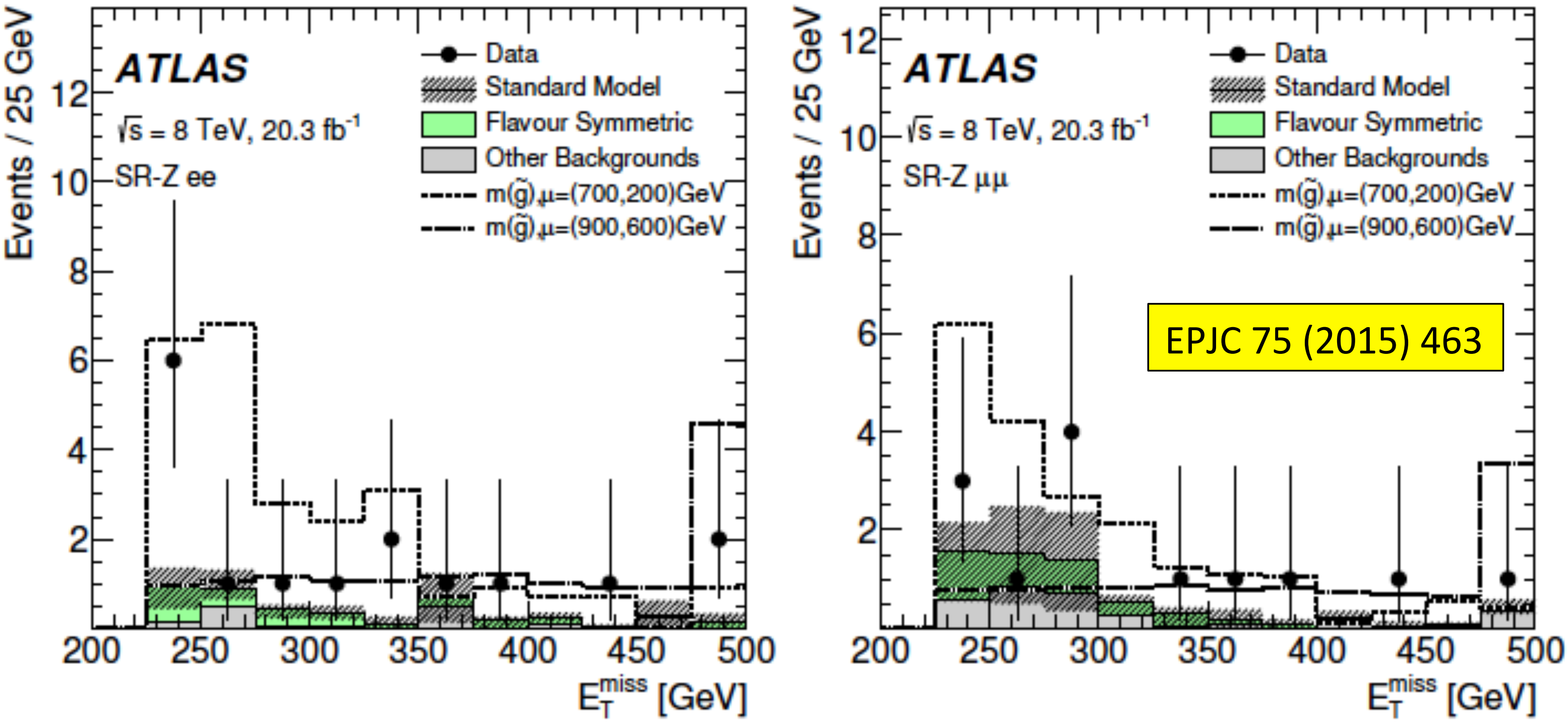
EPJC 75 (2015) 463



Atlas saw no excess (tighter selection in MET)

On-Z version of the search

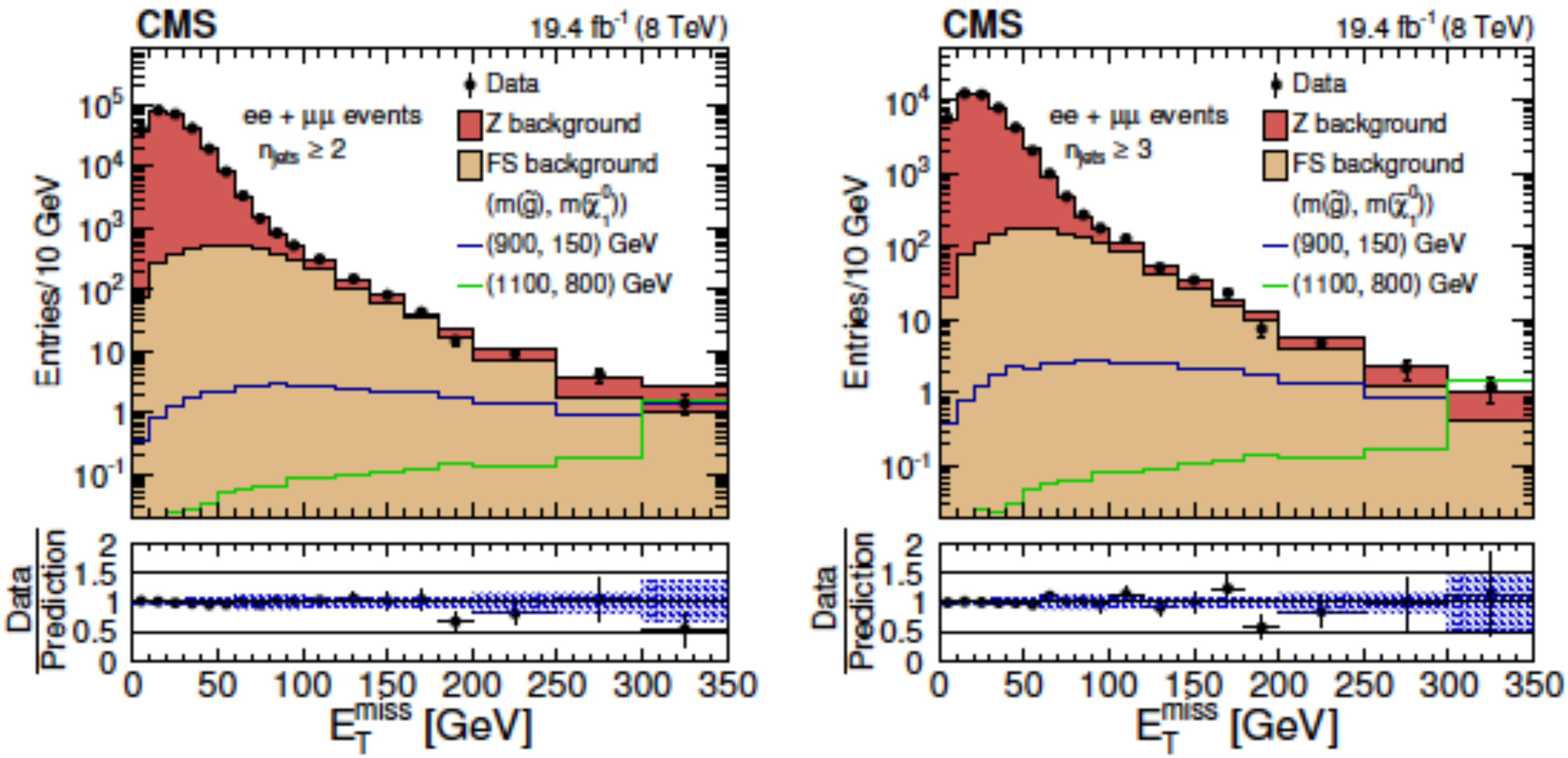
- One can also look generically for Z+MET+jets
- Same backgrounds from ttbar, estimated in the same way (opposite flavor rate)
- Also MET tail in Z events
- Some rare processes, eg, ttZ etc
- Can "slice and dice" in terms of N_{jet}, N_b, HT, MET



On-Z Region	E_T^{miss} [GeV]	H_T [GeV]	n_{jets}	$m_{\ell\ell}$ [GeV]	SF/DF	E_T^{miss} sig. [$\sqrt{\text{GeV}}$]	f_{ST}	$\Delta\phi(\text{jet}_{12}, E_T^{miss})$
Signal regions								
SR-Z	> 225	> 600	≥ 2	$81 < m_{\ell\ell} < 101$	SF	-	-	> 0.4

Atlas saw an excess in the tail of Z+MET
29 events with an estimated BG of 10.6 ± 3.2 (~ 3σ)

JHEP04(2015)124

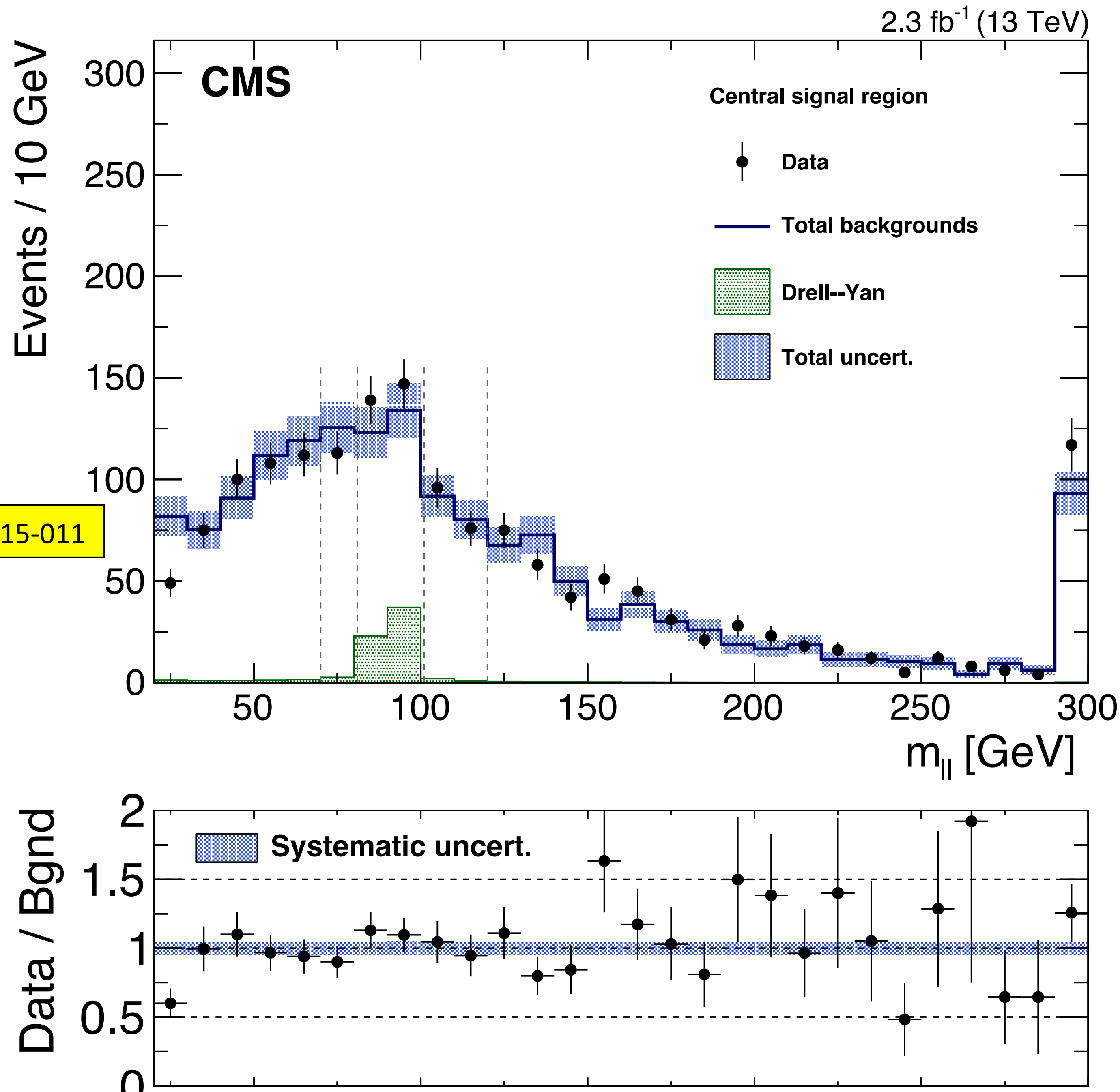


CMS saw no excess (but with looser requirements on HT)

CMS Run 2 opposite sign, same flavor search

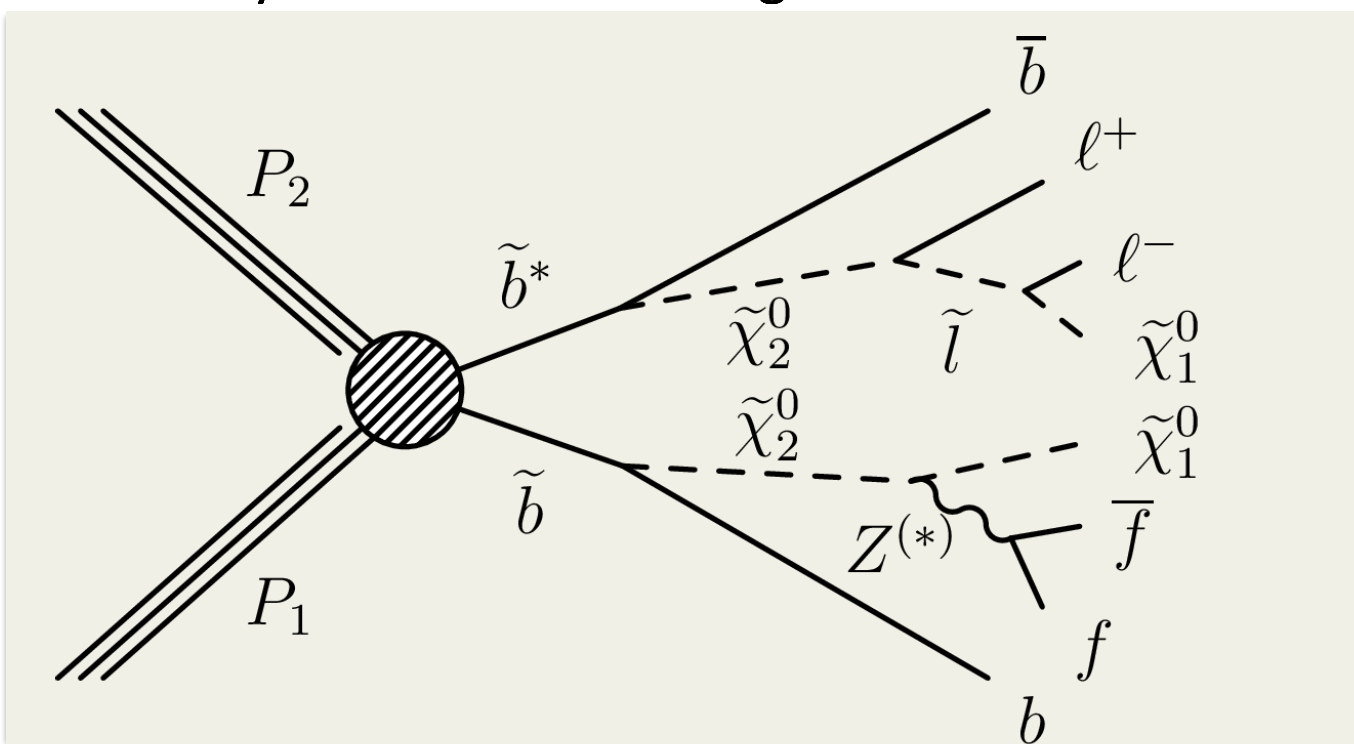
- Off-Z edge search
  - More signal regions (slicing-and-dicing) to explore more thoroughly
  - Keep one signal region identical to Run 1 (no LEE)

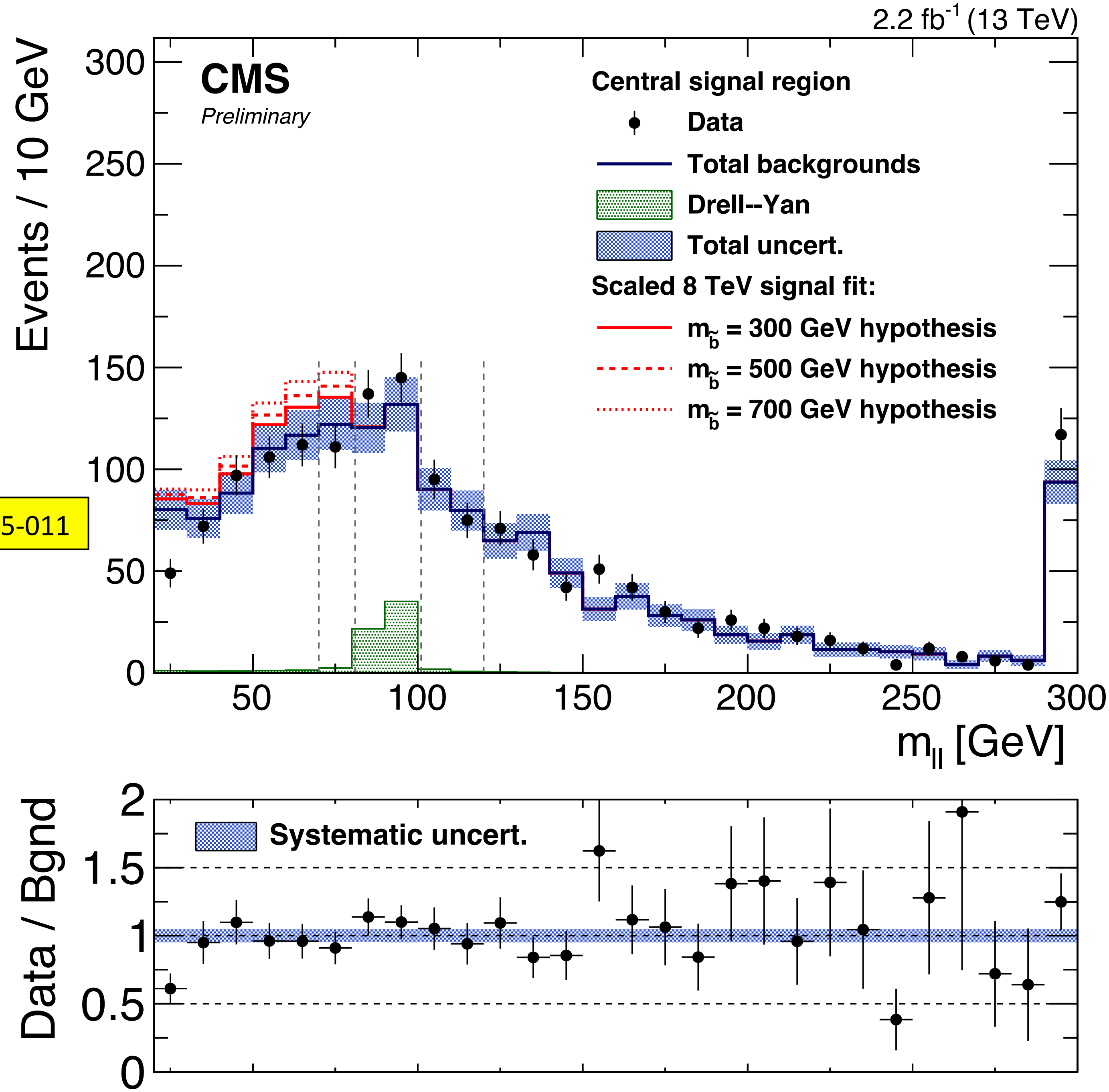
- On-Z search
  - More signal regions (slicing-and-dicing) to explore more thoroughly
  - Define one signal region "like Atlas Run 1" (no LEE)



CMS-PAS-SUS-15-011

- Can the 8 TeV excess (19.4 fb^{-1}) still be consistent with the lack of signal at 13 TeV (2.3 fb^{-1})?
- Hard to say because one needs a signal model to properly scale cross-sections vs. CM energy
- Suppose that the excess came from sbottom pair production
  - Because there are b's in these events
  - There are b's in the BG also (ttbar) so let's not get excited
- Scale 8 TeV excess yield to 13 TeV using sbottom cross-section scaling



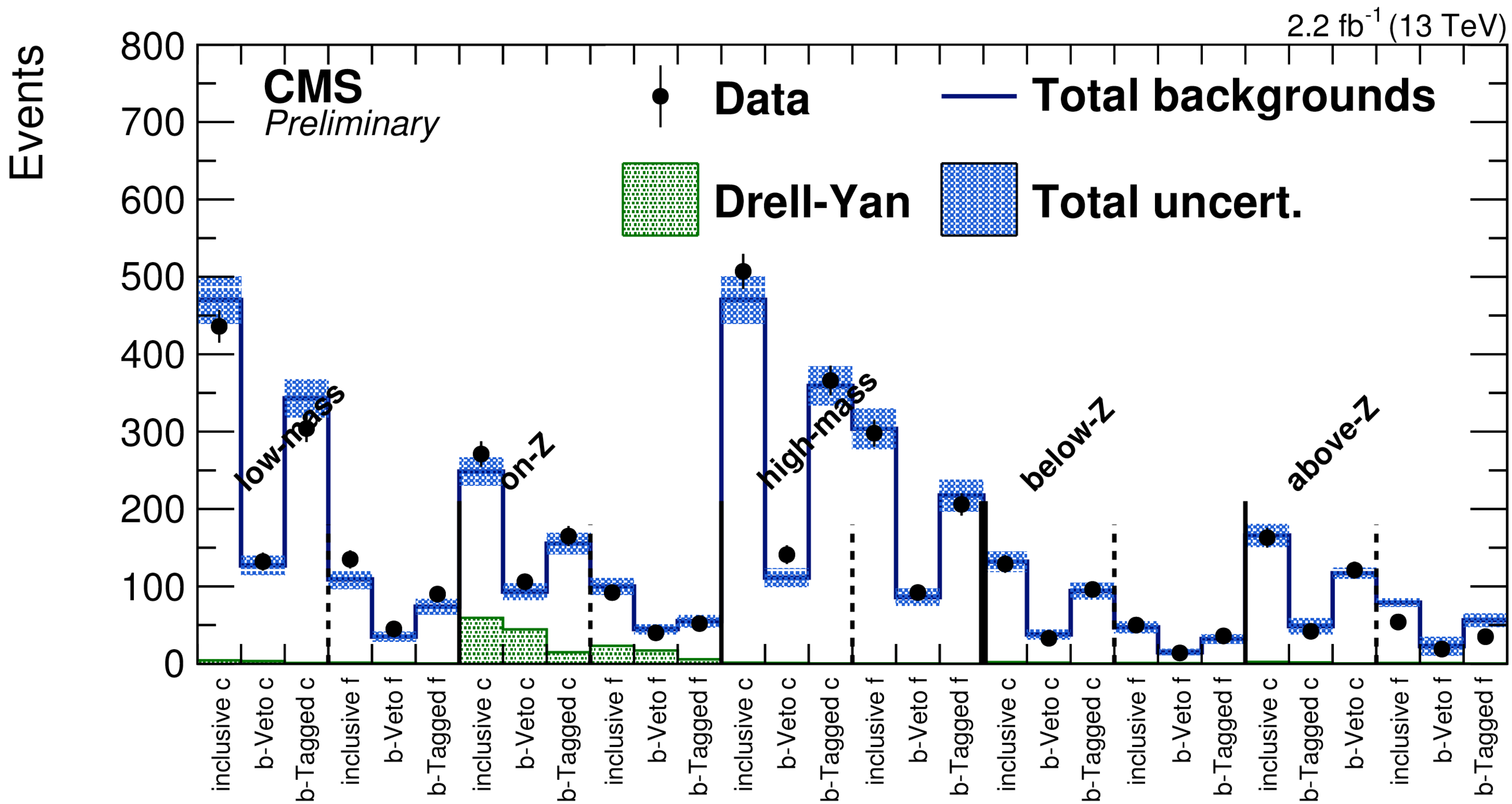


CMS-PAS-SUS-15-011

Sliced in

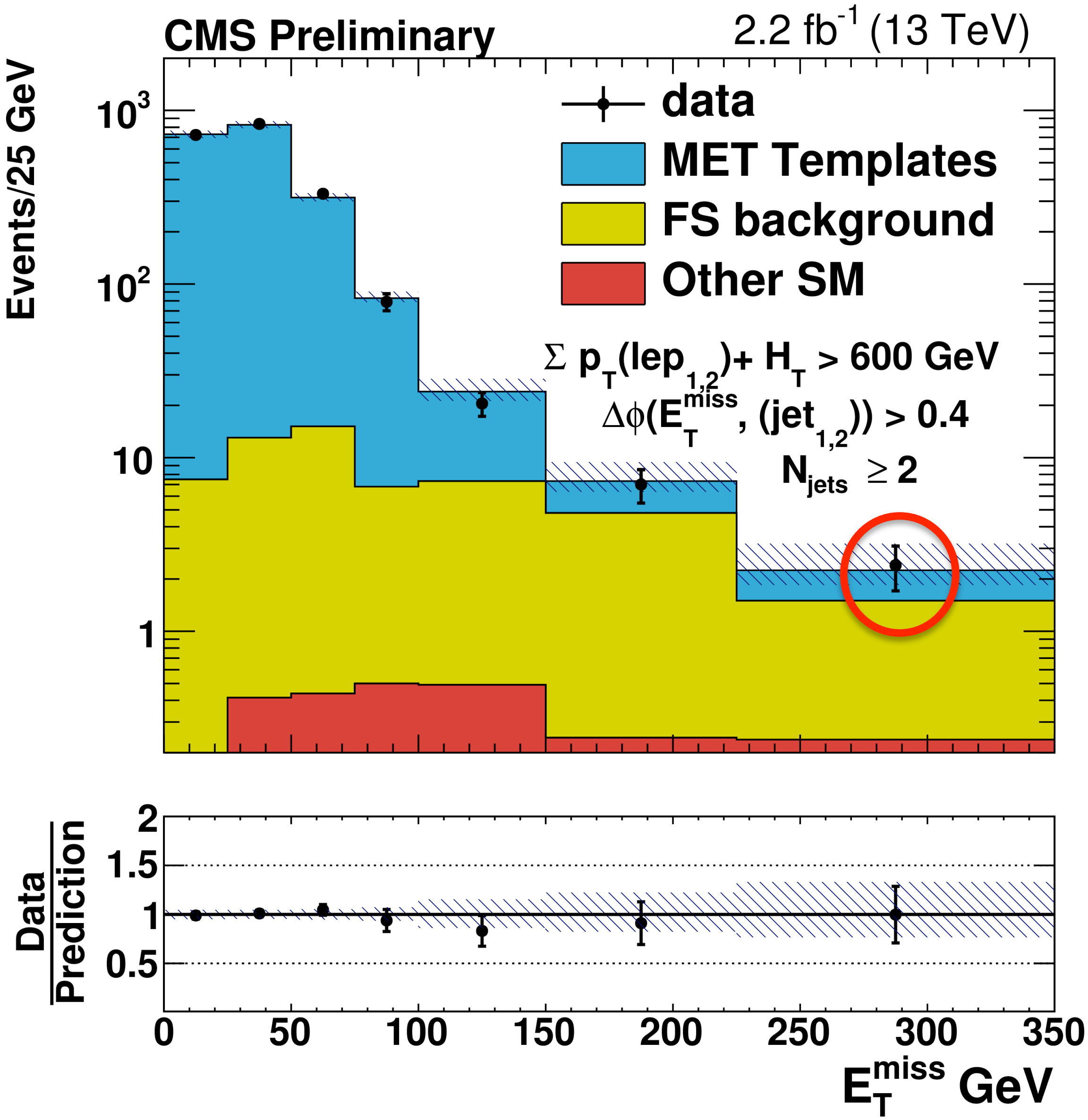
- Mass ranges: (20-70) (70-81) (81-101) (101-120) (>120)
- central vs. forward leptons
- b tagged or not

$N_{jet} \geq 2$ MET>150 GeV
or
$N_{jet} \geq 3$ MET>100 GeV



CMS-PAS-SUS-15-011

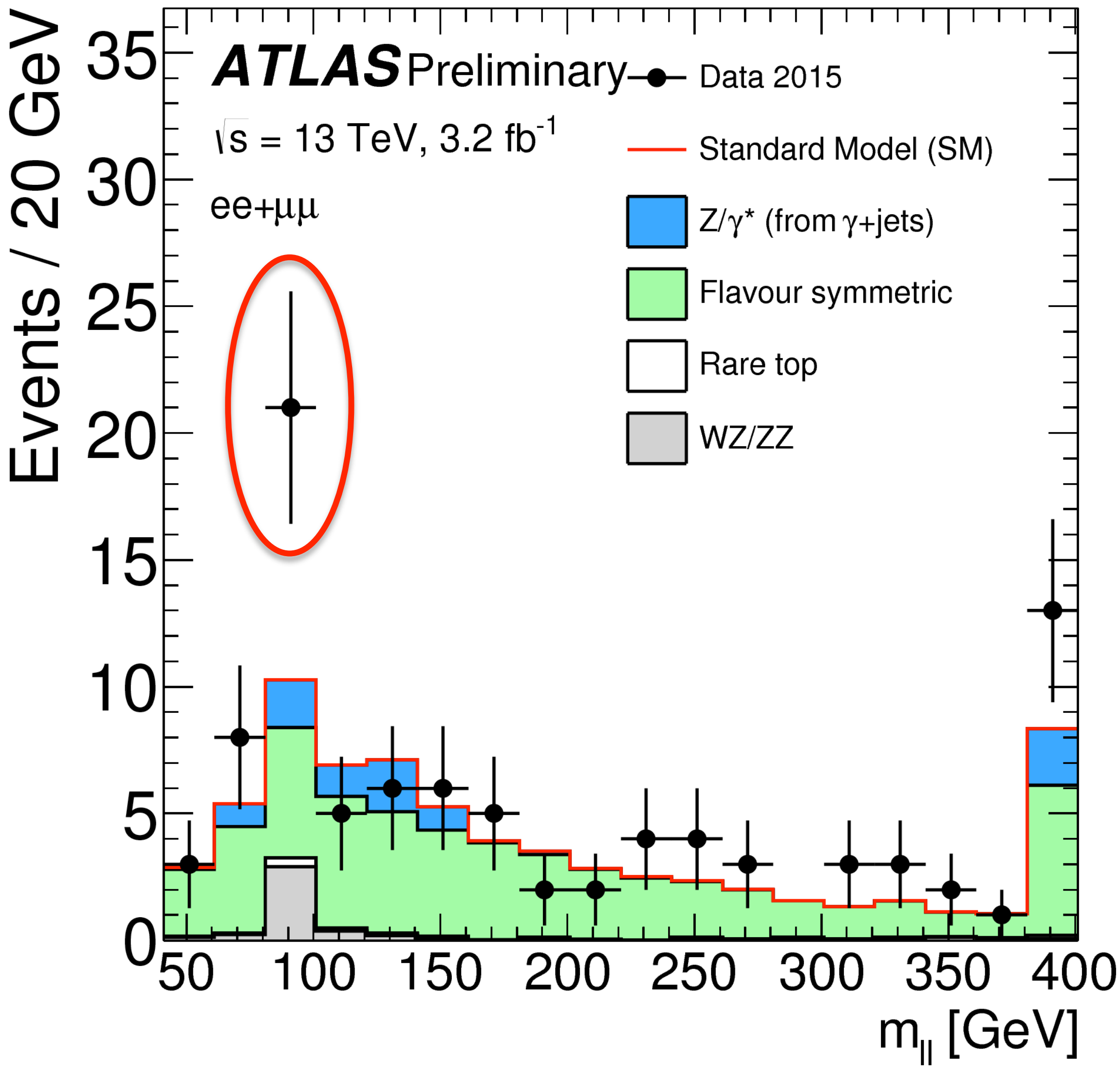
Z + MET: Signal Region like Atlas



CMS-PAS-SUS-15-011

MET>225 GeV, on-Z	
Data	12
Predicted	12 ± 3

But ATLAS does not give up so easily



ATLAS-CONF-2015-082

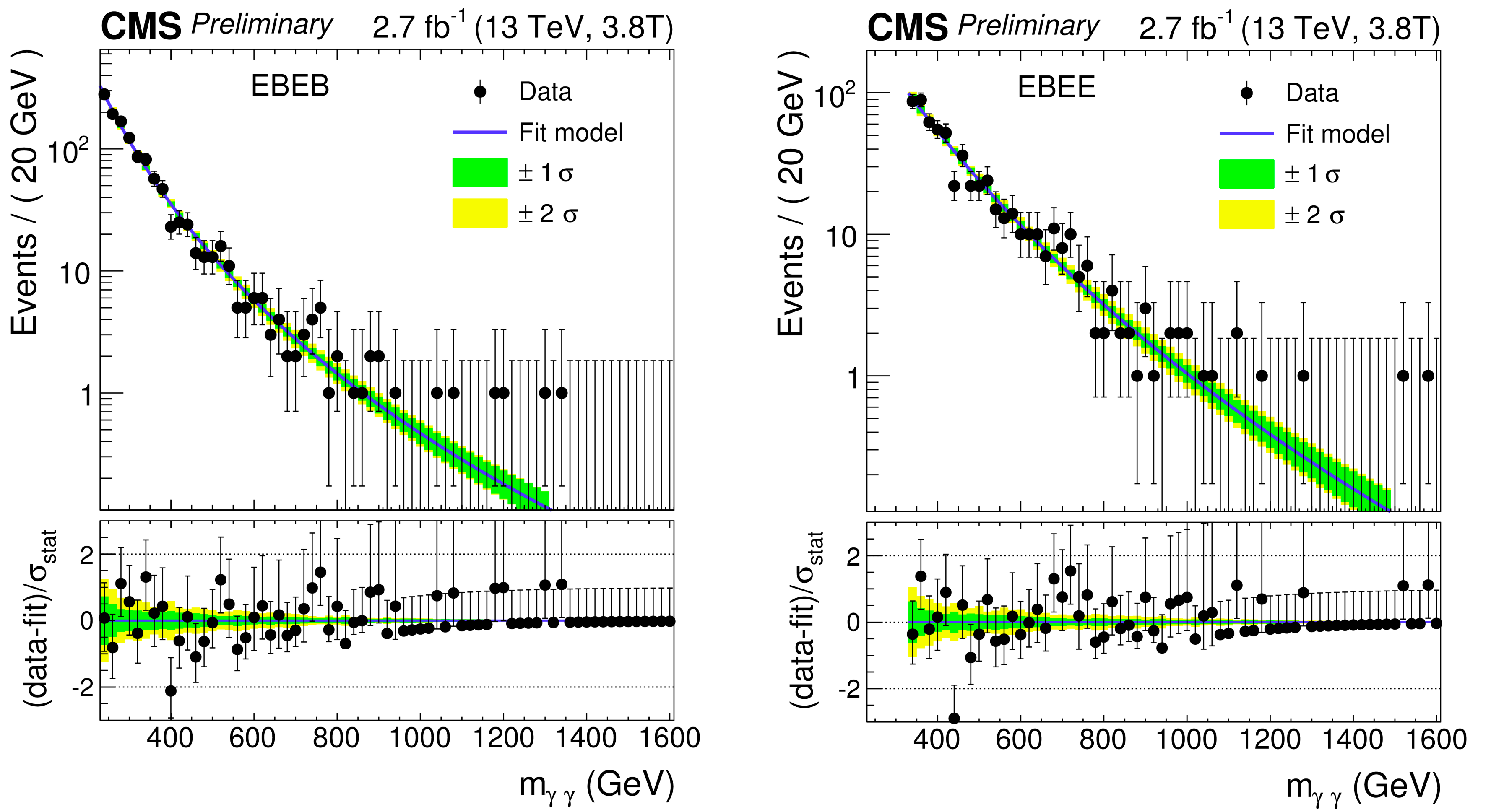
MET>225 GeV, on-Z	
Data	21
Predicted	10.3 ± 2.1
Excess	~ 2.2 σ

Comments

- The excess in the CMS edge analysis was likely a statistical fluctuation
- The Z + MET channel
  - statistical fluctuation?
  - Atlas does not know how to predict the MET tails in Z events
  - CMS has a non-understood inefficiency for Z events with lots of MET

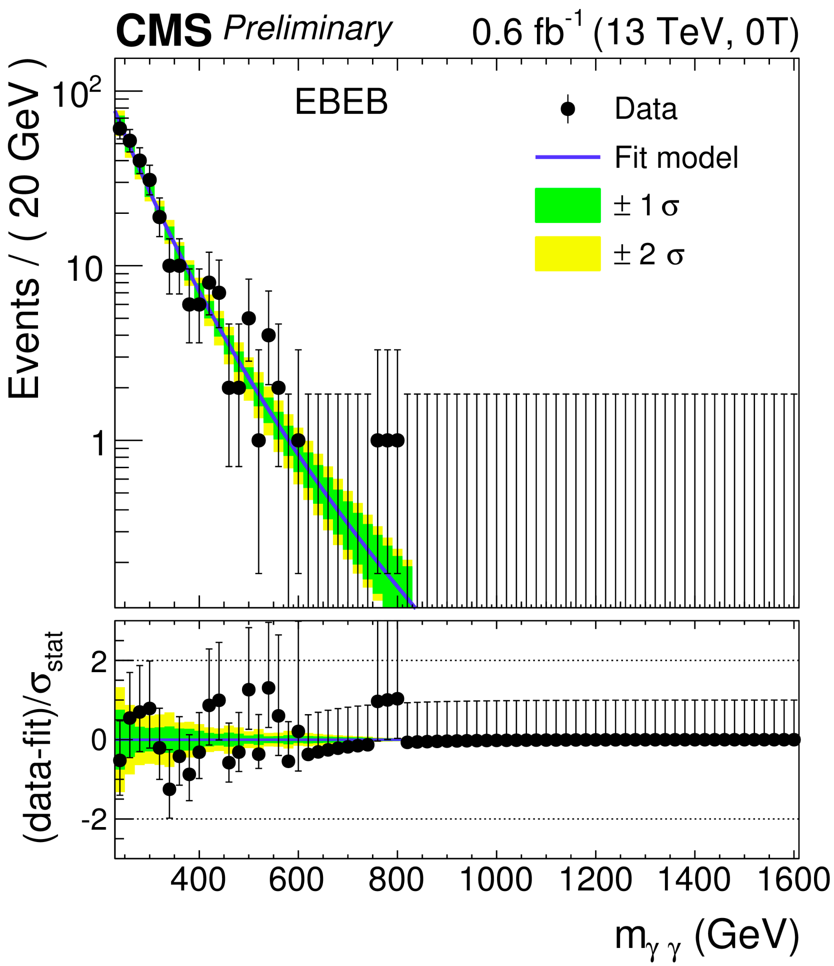
CMS-PAS-EXO-16-018

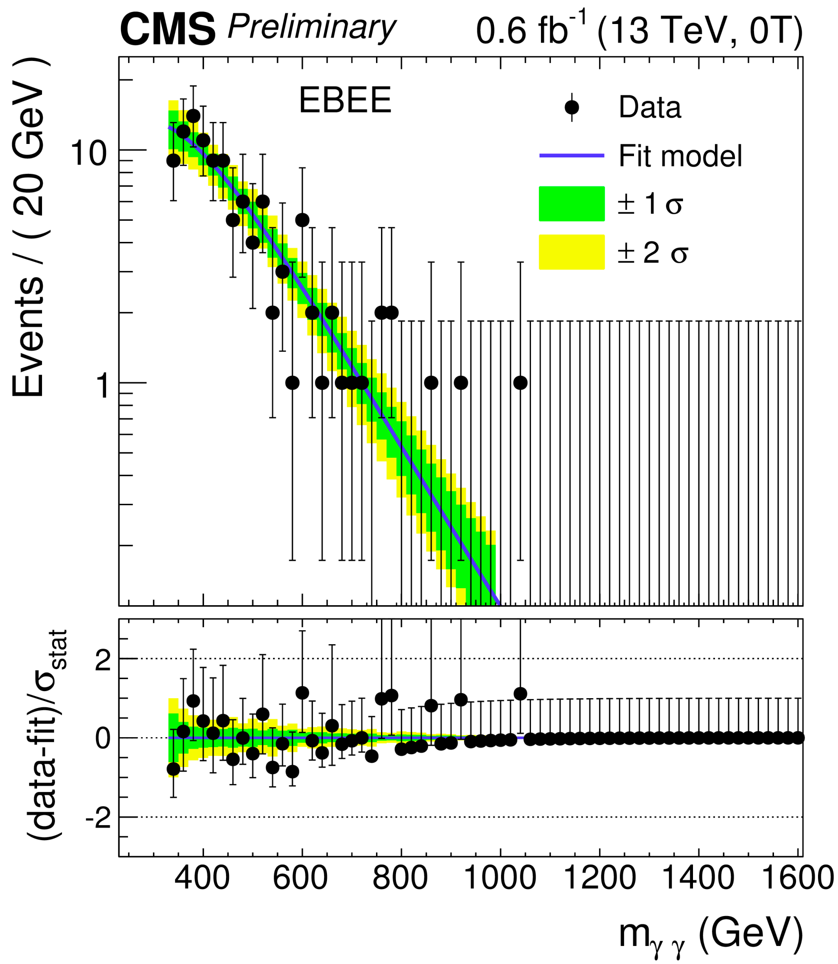
Diphotons



CMS-PAS-EXO-16-018

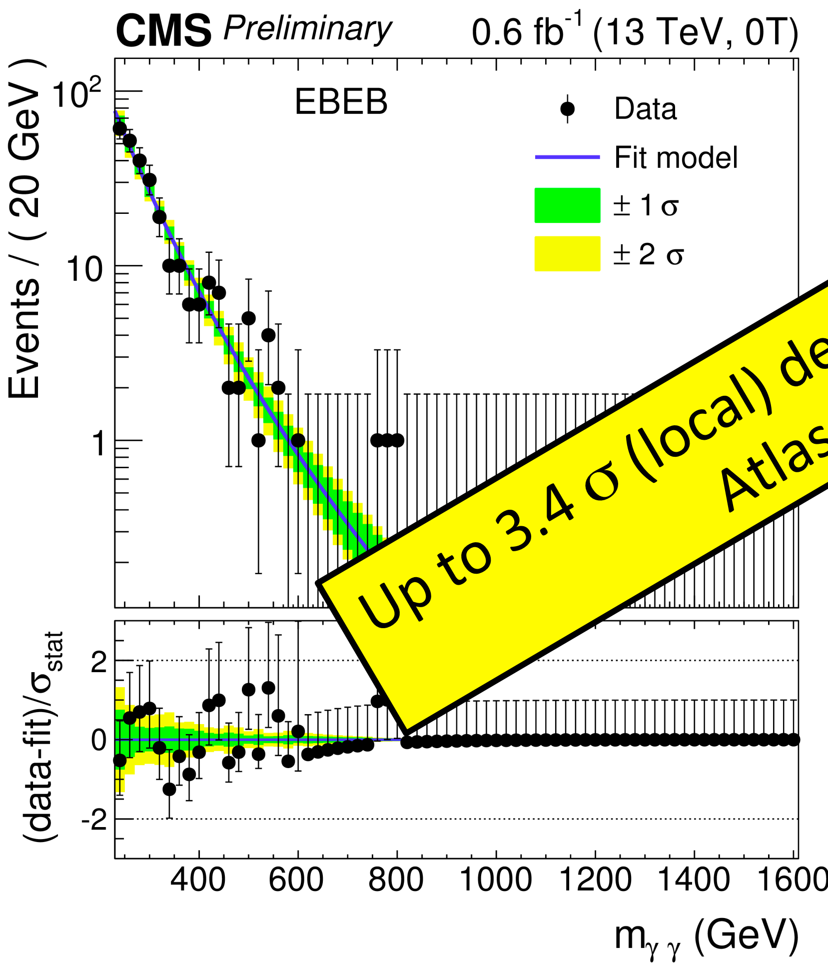
0 TeV data

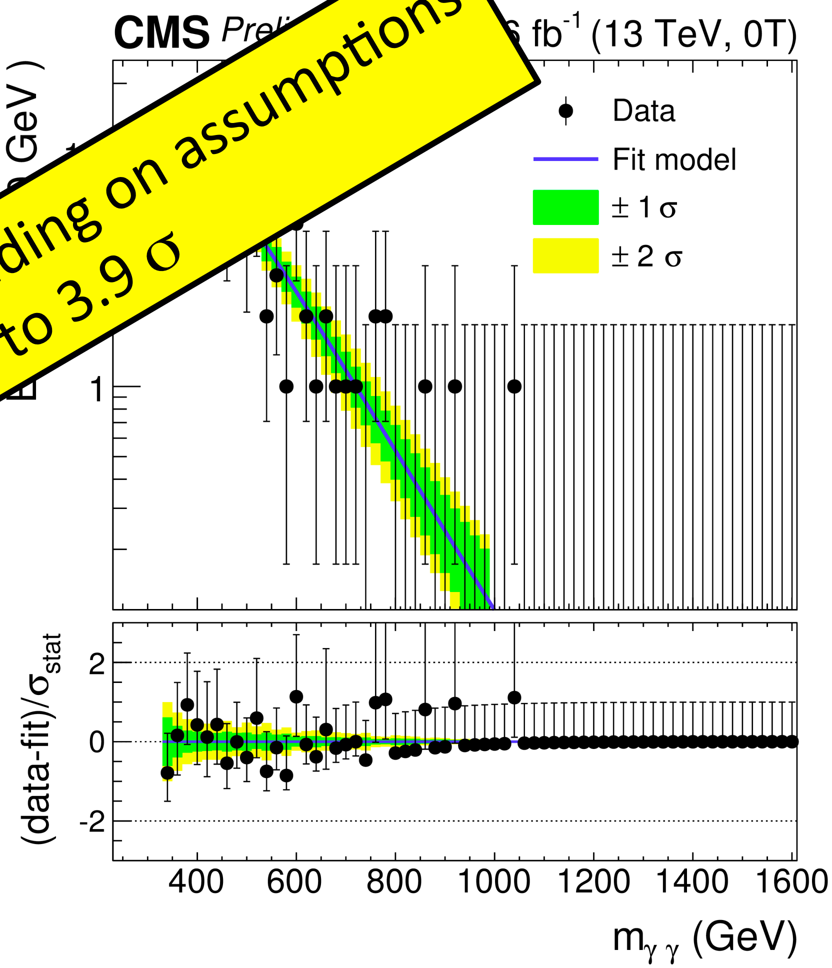




CMS-PAS-EXO-16-018

0 TeV data





Up to 3.4 σ (local) depending on assumptions

Atlas: up to 3.9 σ

Compatibility betweem Atlas and CMS and between 8 TeV and 13 TeV?

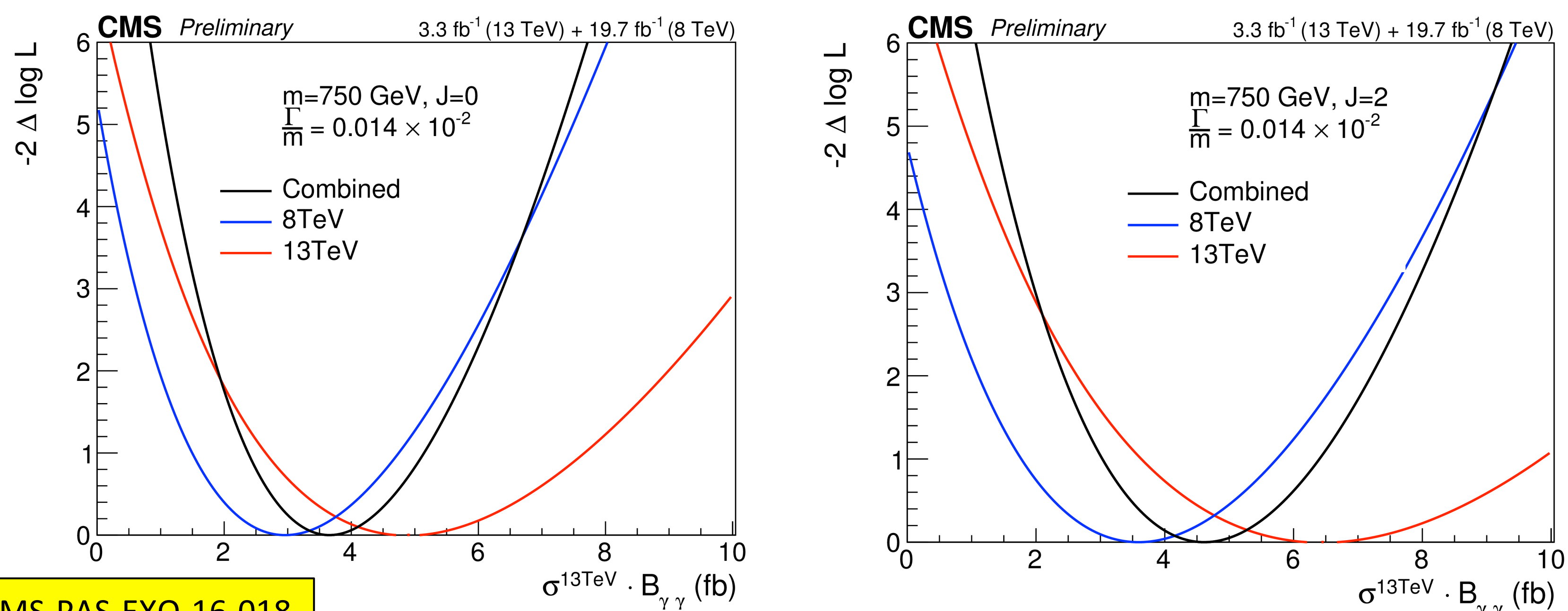
$\sigma(pp \to \gamma\gamma)$	CMS	ATLAS
8 TeV	(0.5 ± 0.6) fb	(0.4 ± 0.8) fb
13 TeV	(6 ± 3) fb	(10 ± 3) fb

Strumia
Moriond EWK

The background $q\bar{q} \to \gamma\gamma$ at 750 GeV grows by 2.3.

The signal grows by ≈ 5 if produced from gg, $b\bar{b}$, $c\bar{c}$, $s\bar{s}$: ok.

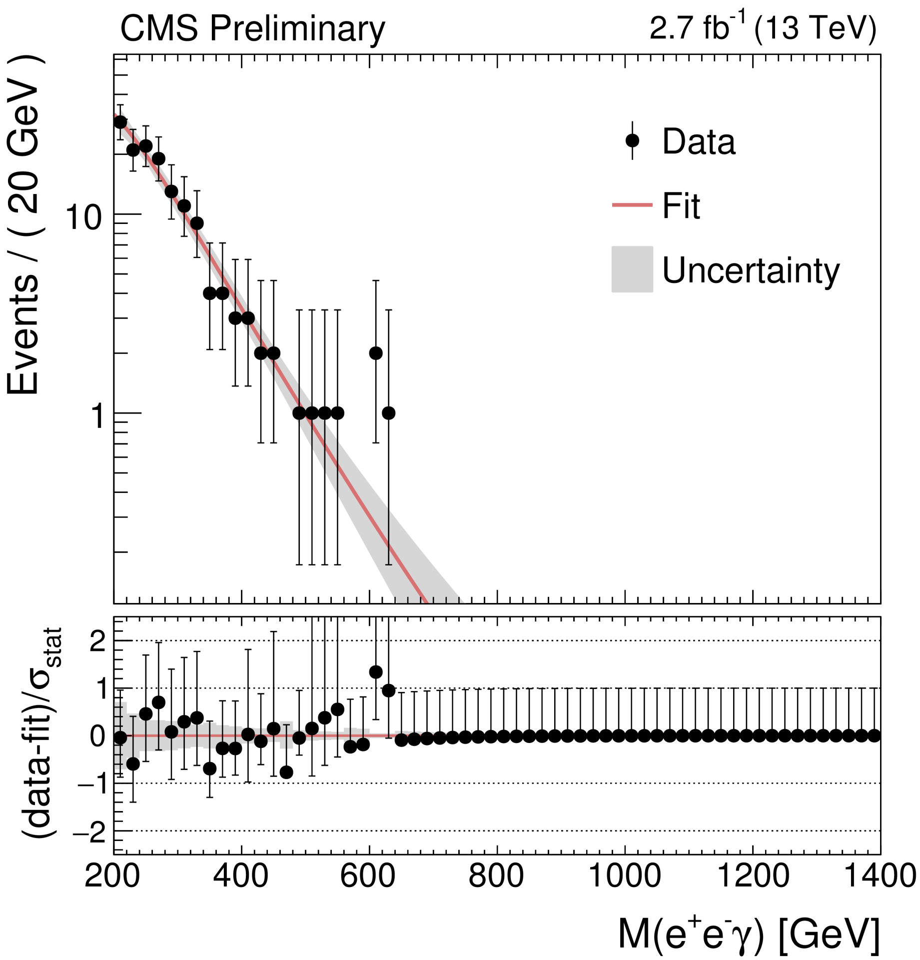
The signal grows by ≈ 2.5 if produced from $\gamma\gamma$, $u\bar{u}$, $d\bar{d}$: disfavored.

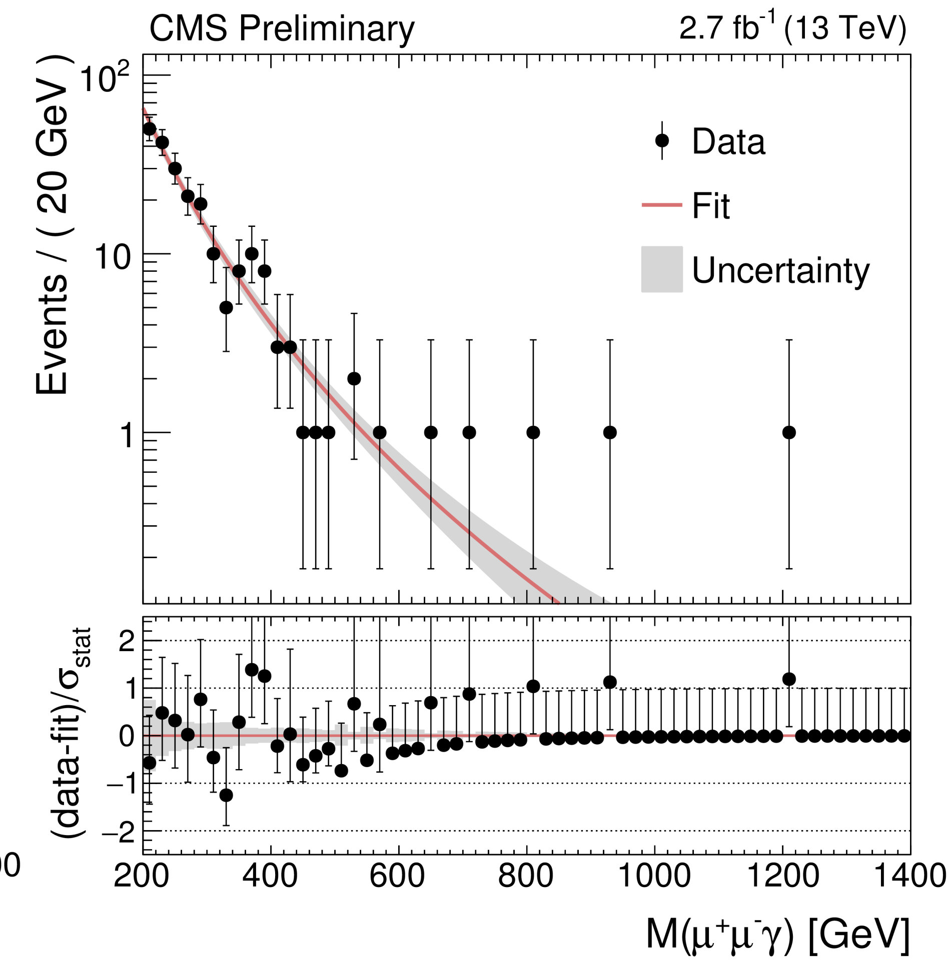


CMS-PAS-EXO-16-018

CMS-PAS-EXO-16-019

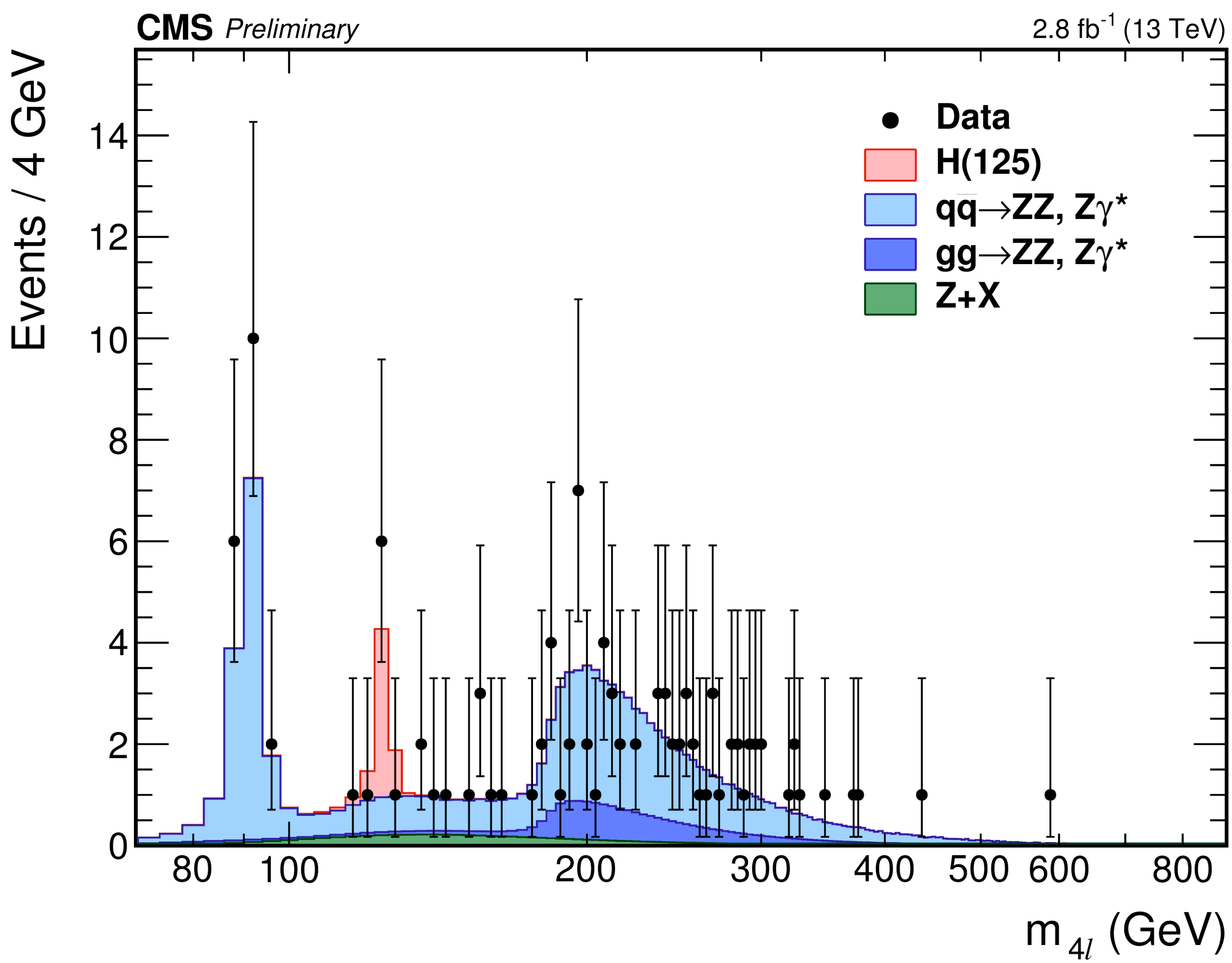
Other channels? Zγ?





CMS-PAS-HIG-15-004

Other channels? ZZ→4l



Conclusion

- Run 2 of the LHC is off to a good start
- By ICHEP this summer we will know if the 750 GeV object is real or a fluke