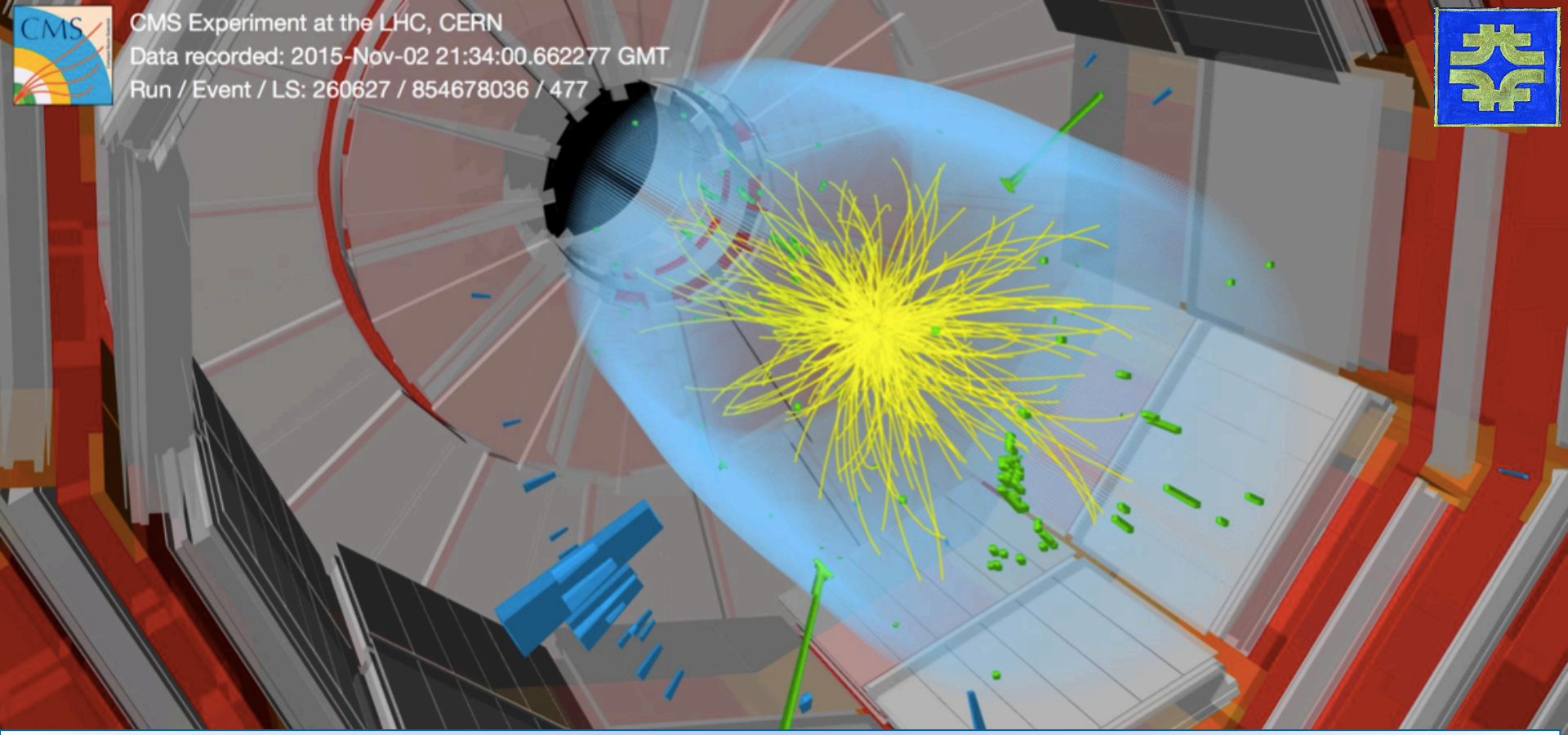


Exploring the unknown: CMS searches for new physics in 13 TeV data

Sergo Jindariani (Fermilab)
on behalf of the CMS collaboration

Fermilab Joint Experimental-Theoretical Seminar, January 15th 2016

Things evolve quickly in particle physics

2009: Joint CDF+Dzero W&C seminar on first Higgs exclusions since LEP era
Back then Higgs was sort of "new" physics we were looking for

6 years later

Last SM particle discovered

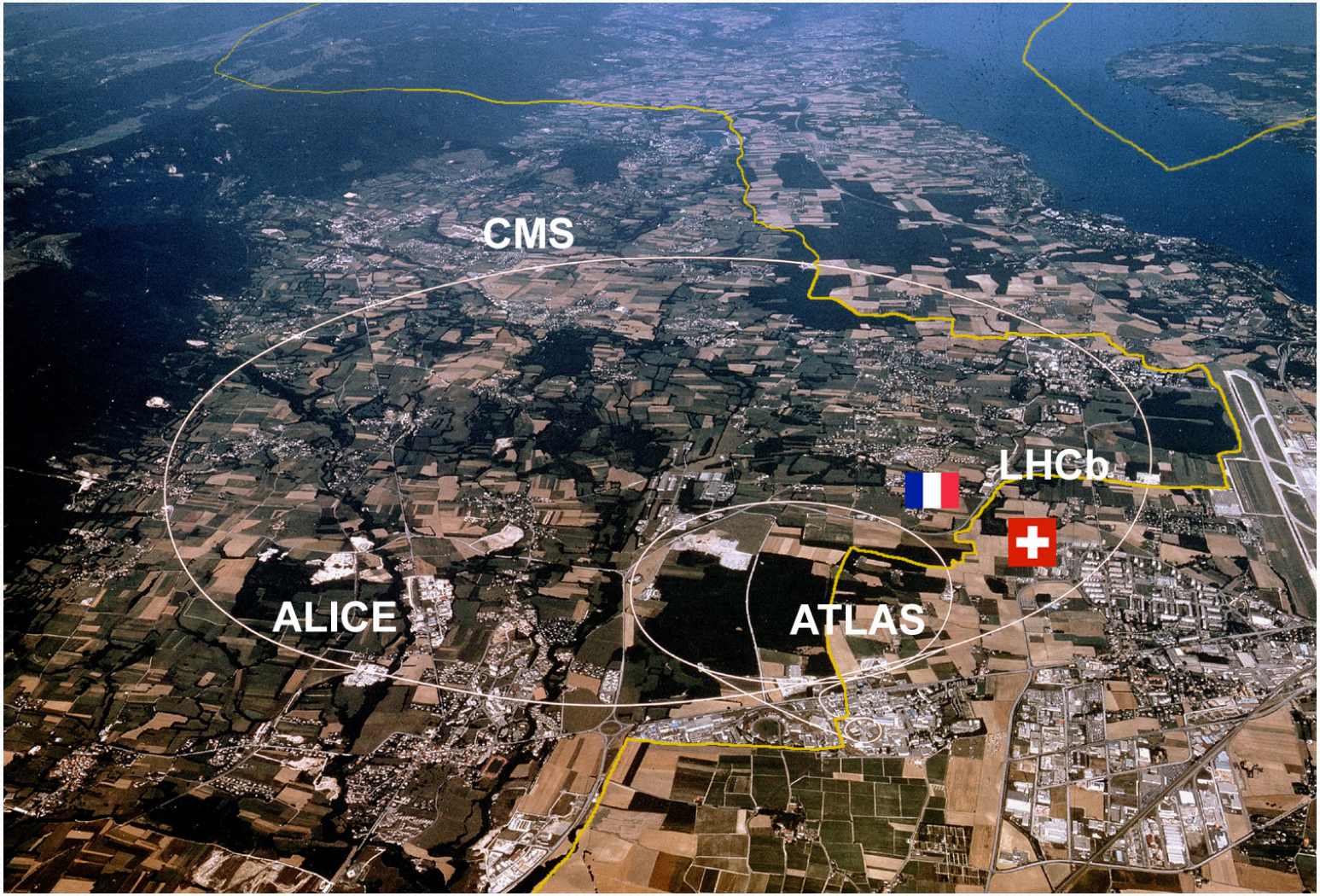
Collider based hunt for new physics continues at the LHC

But LHC Physics Center (LPC) at FNAL is a special place for CMS

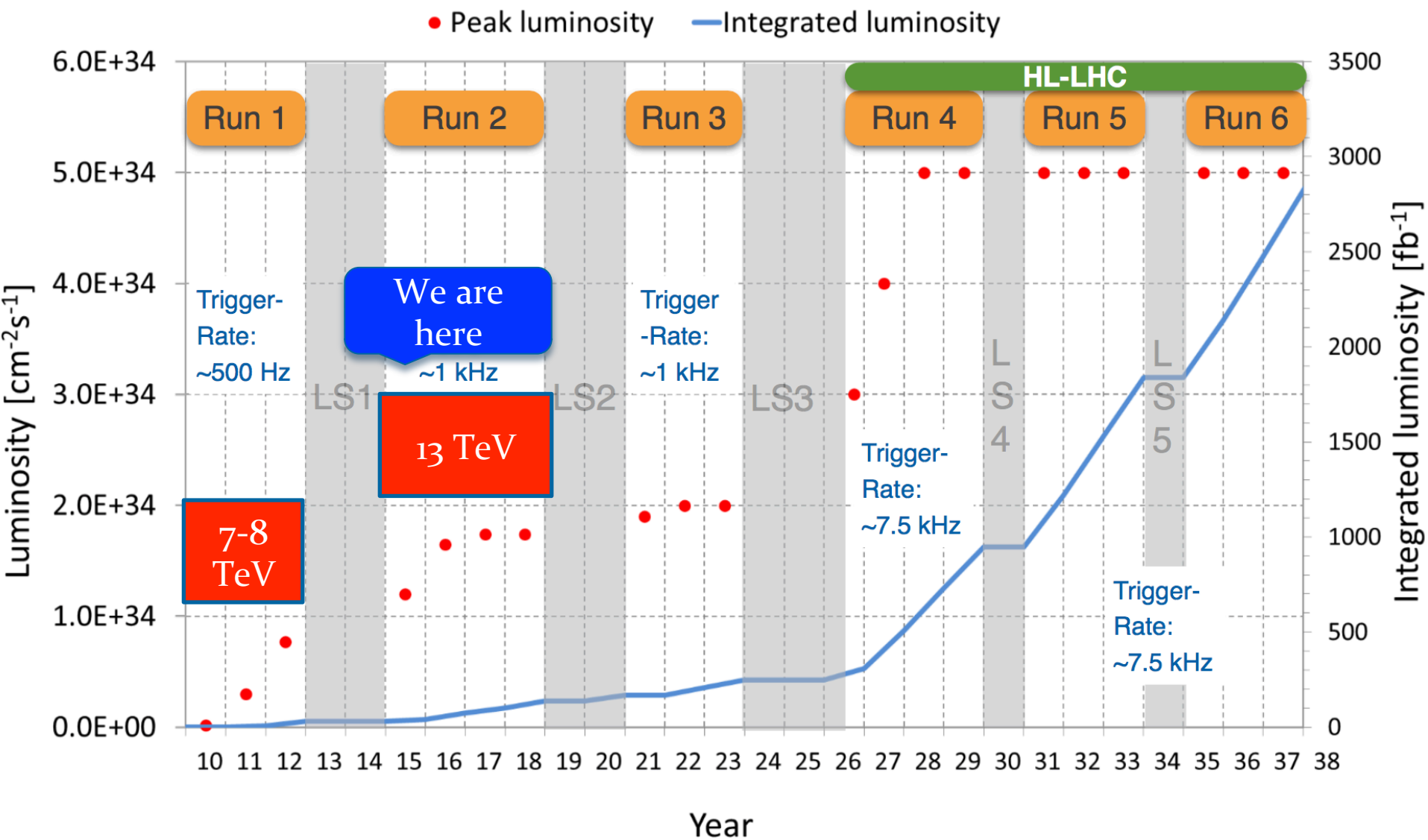
And W&C remains a special seminar

LPC CMS Data Analysis School'2016

Large Hadron Collider

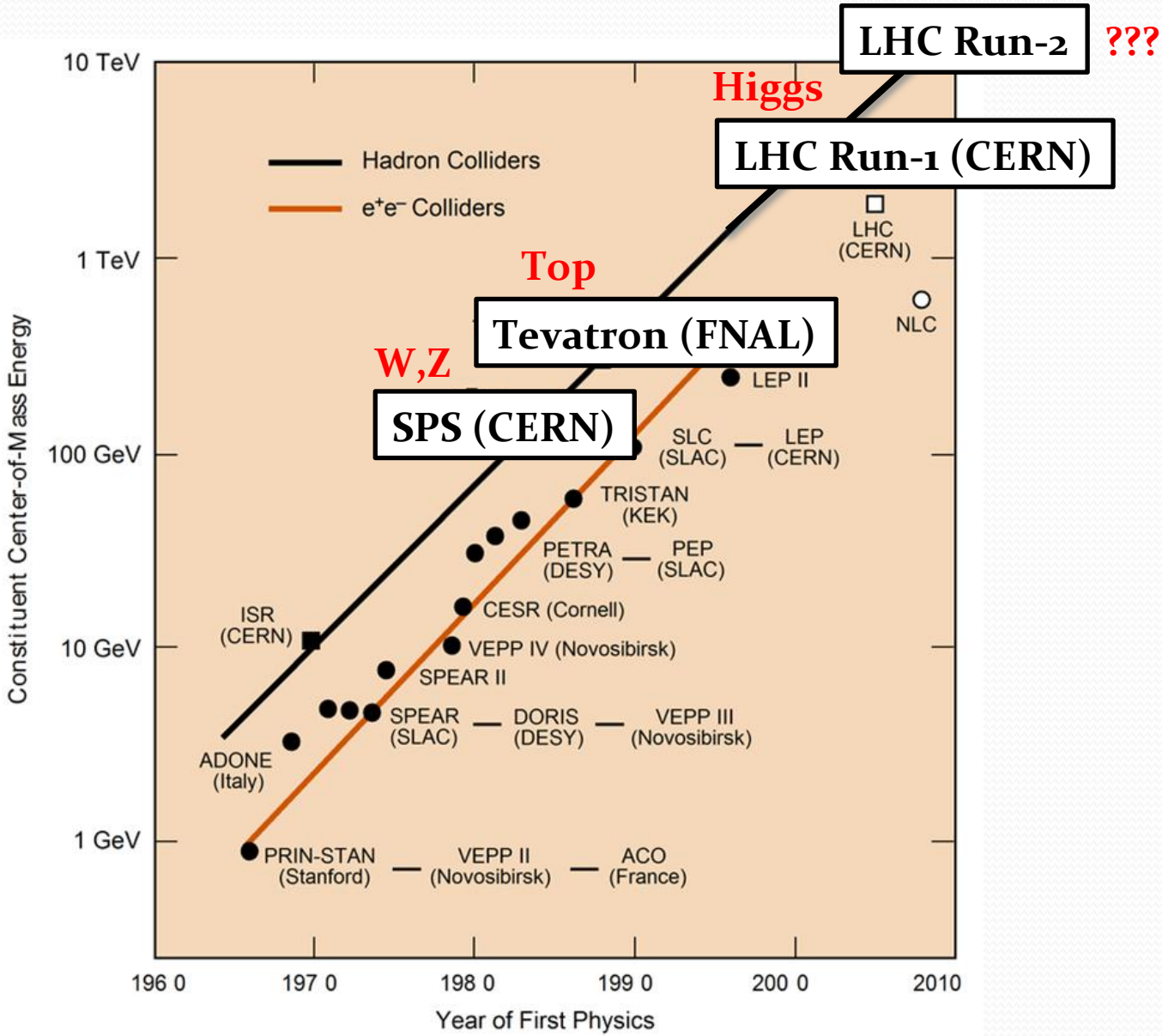


Large Hadron Collider

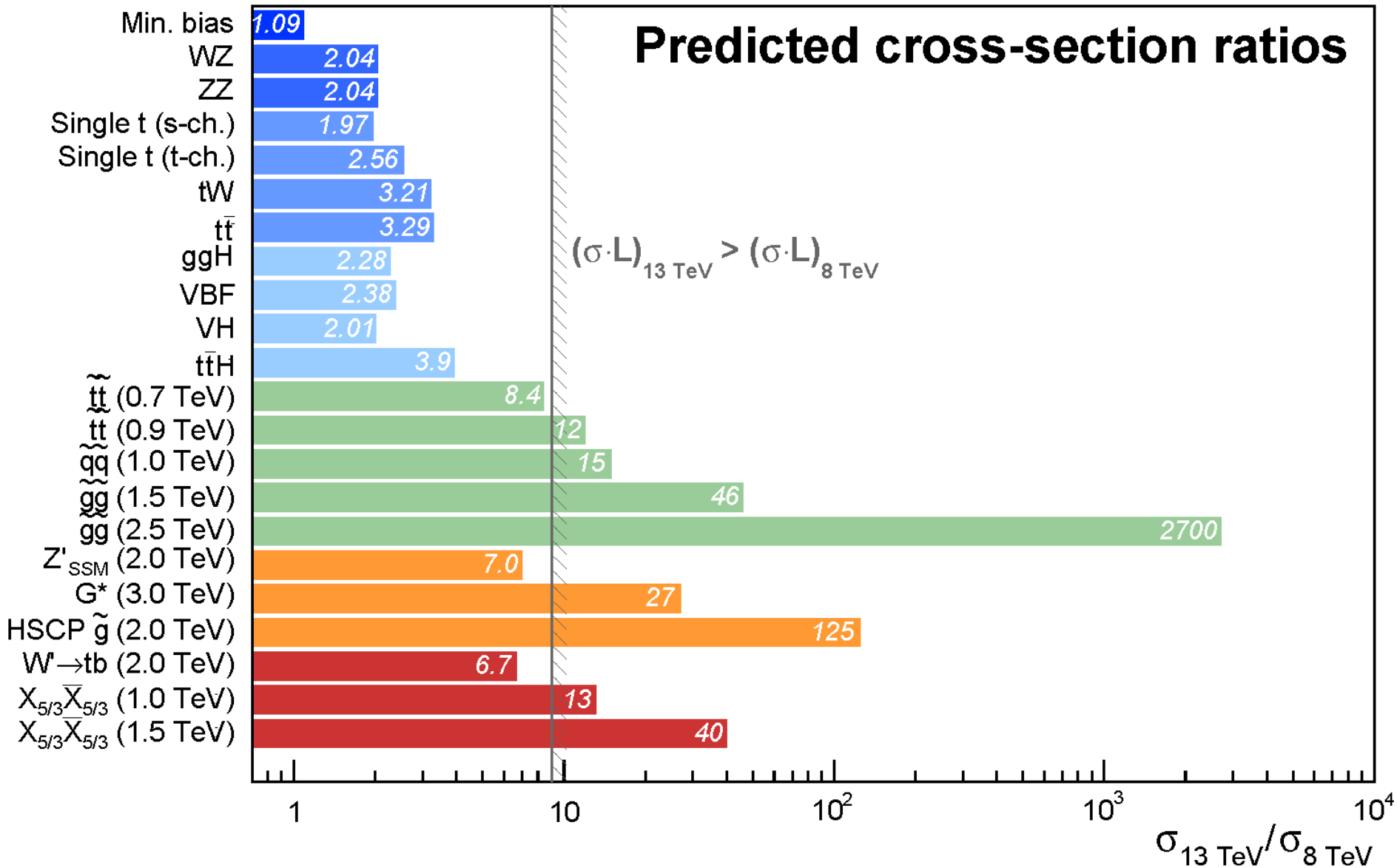


Large Hadron Collider

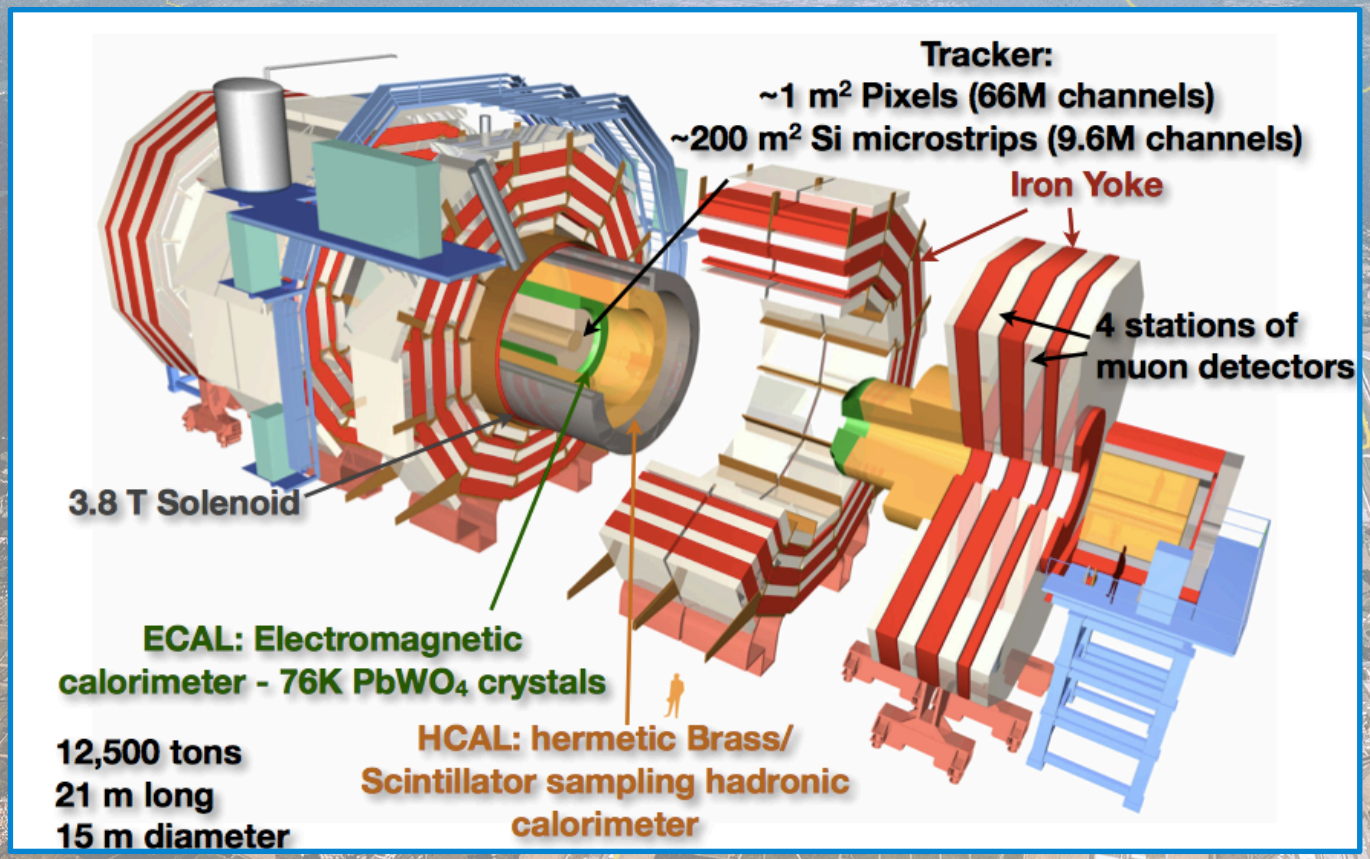
Higher Energy = discovery ?



What does more energy mean?



CMS Detector

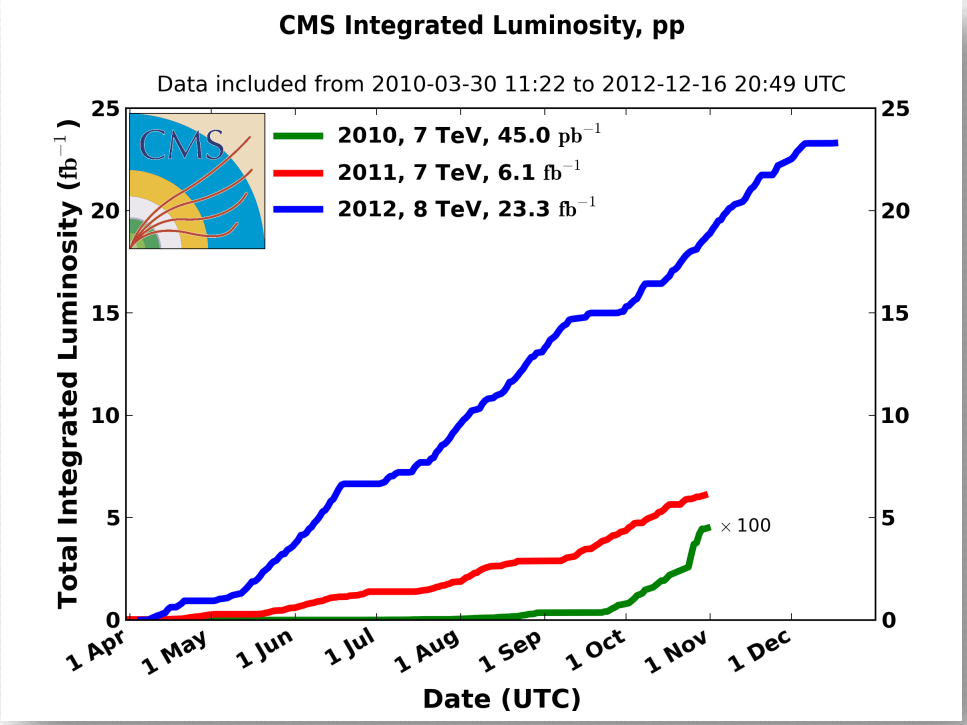


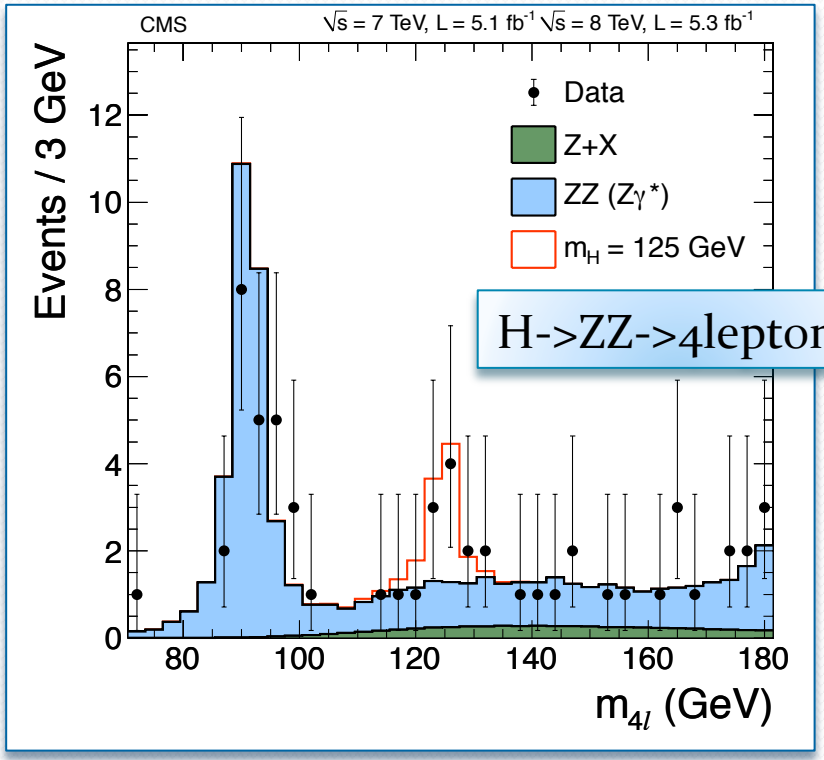
CMS Collaboration

2700 physicists, **180** institutions from **43** countries

Higgs Discovery

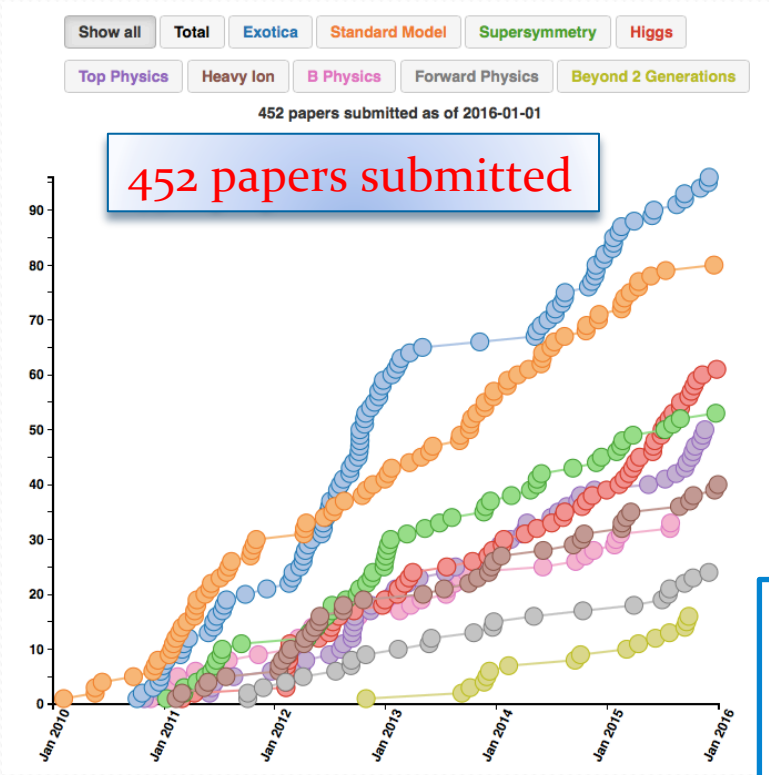
From commissioning in 2010 to Higgs discovery in 2012

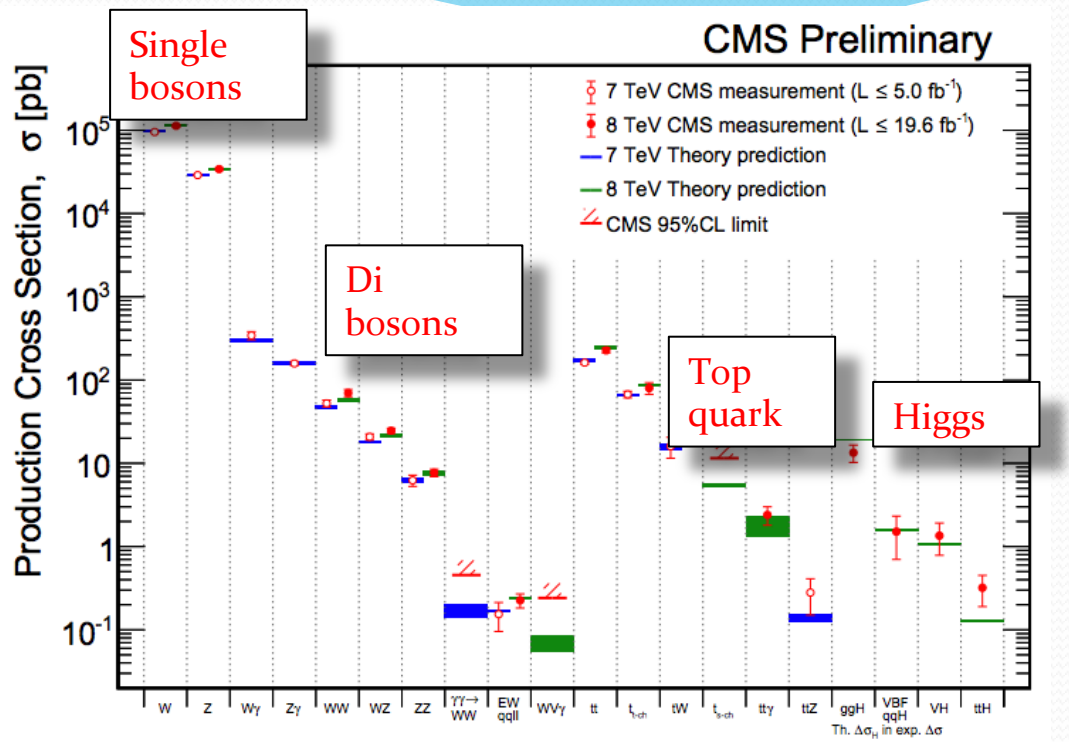




H->ZZ->4leptons

More than "just" Higgs



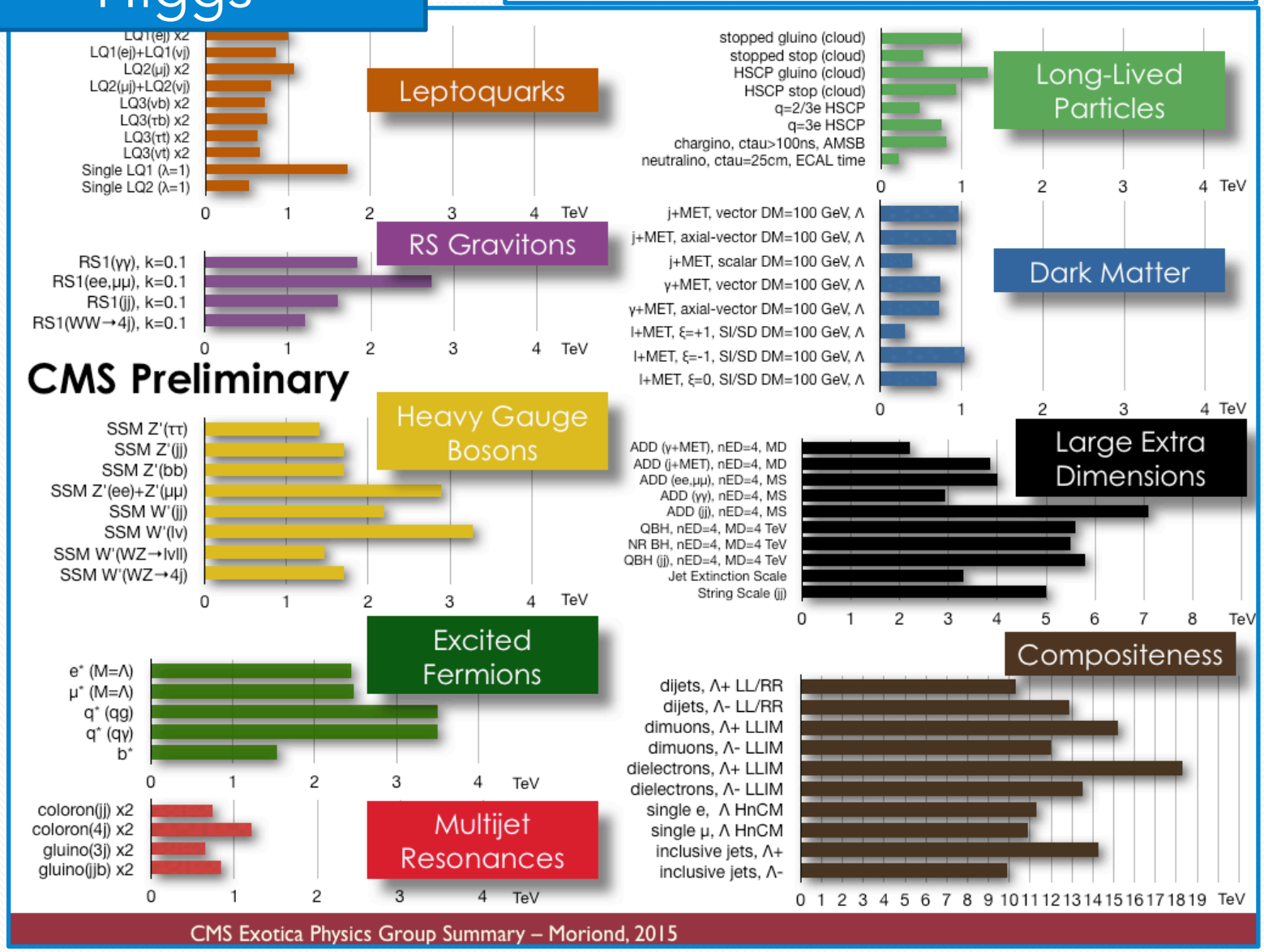


Detailed exploration of the Standard Model

- Rare processes
- Top quark mass and other properties
- Bs->μμ observation
- many others

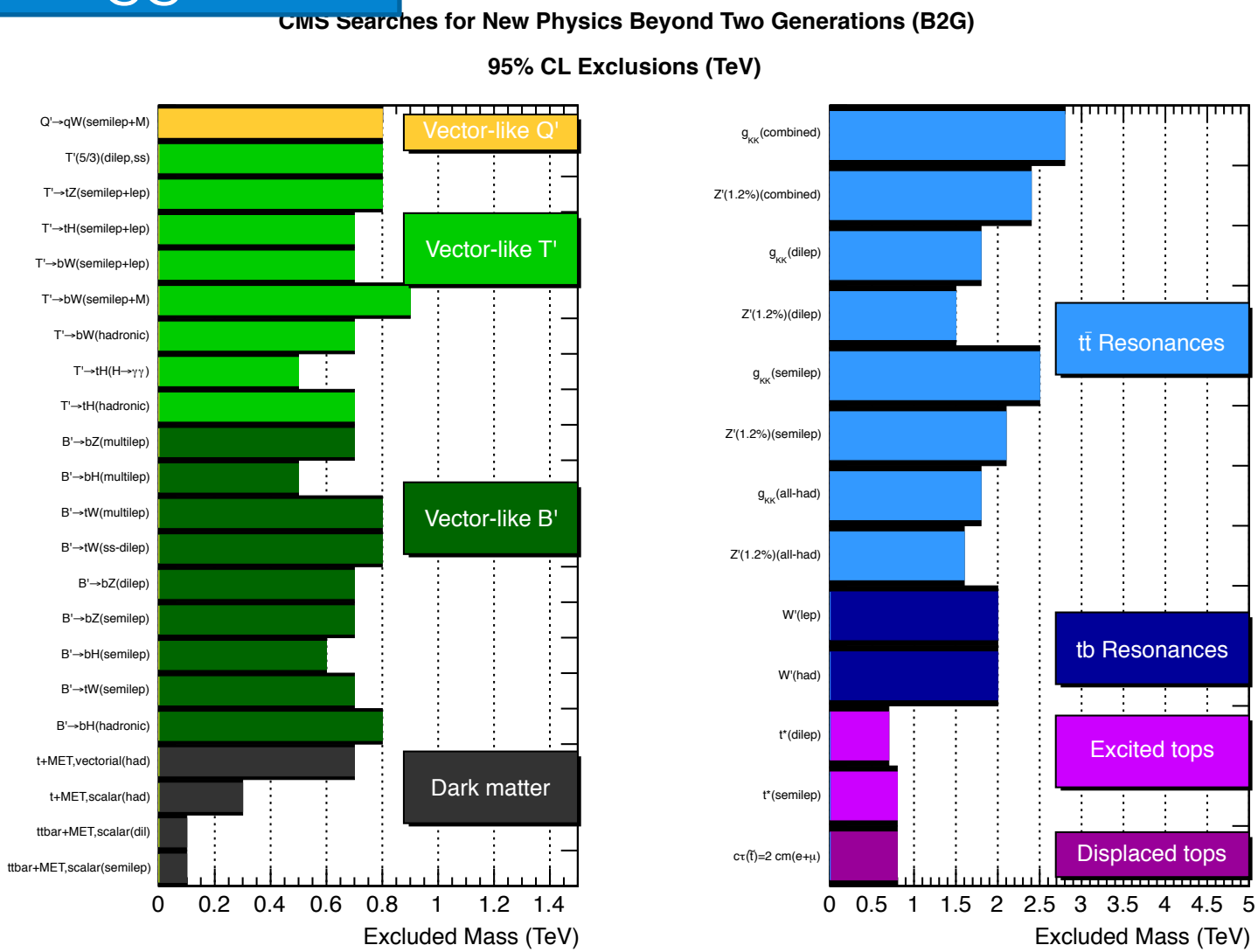
More than "just" Higgs

Broad program of Exotica searches



More than "just" Higgs

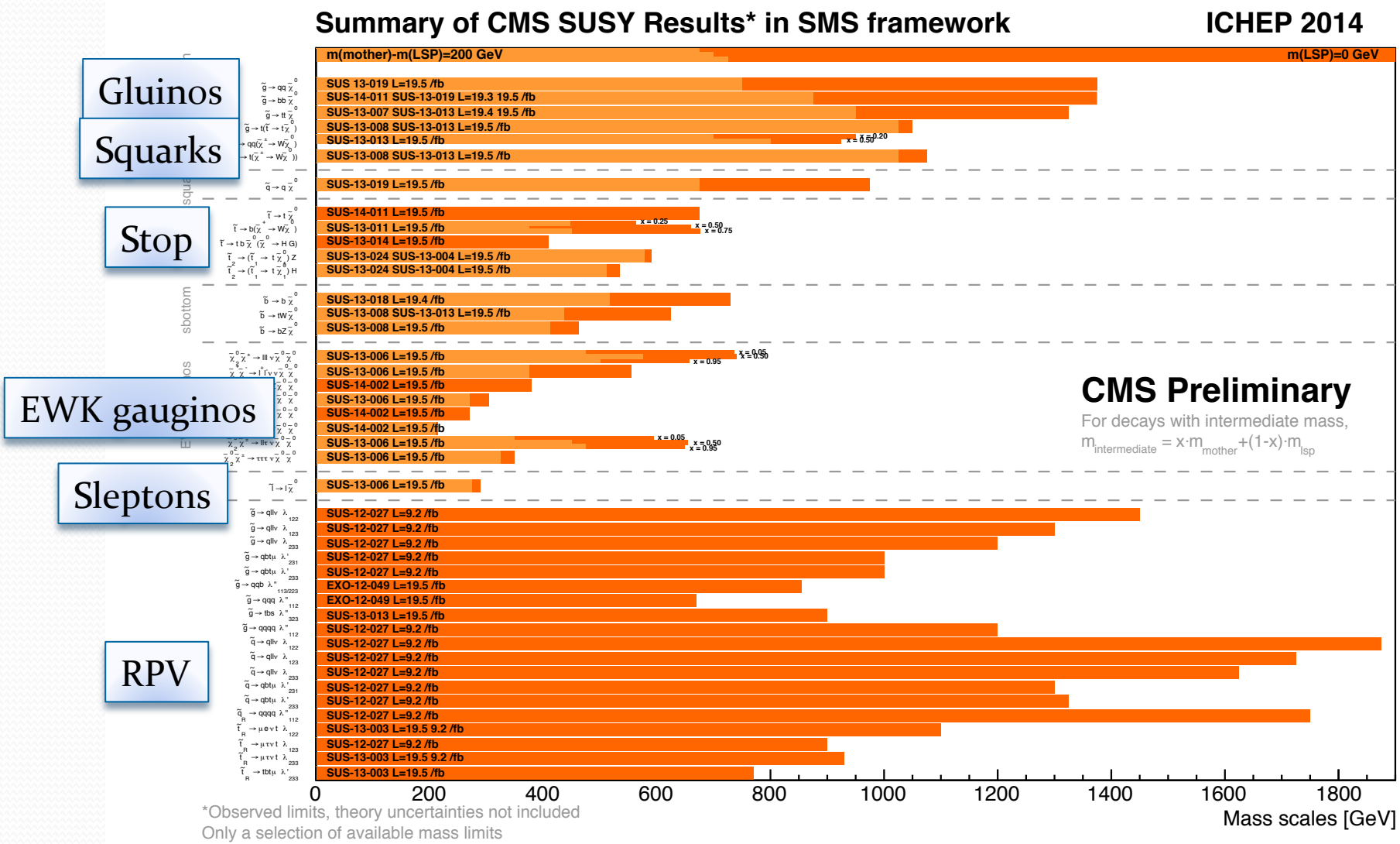
And B2G searches



More than "just" Higgs

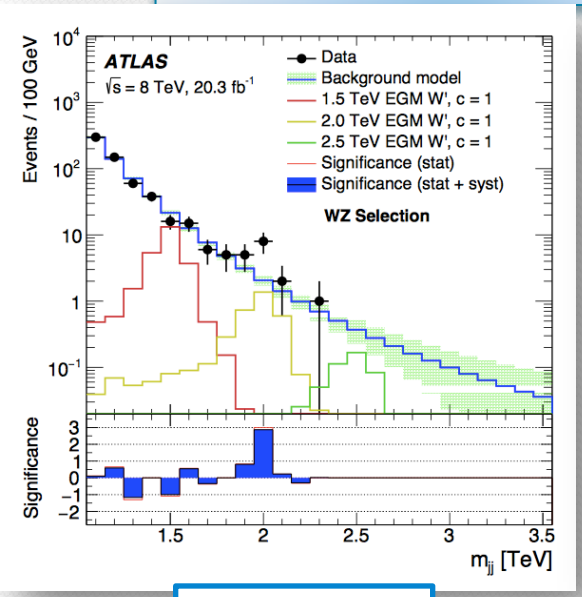
SUSY: not "around the corner"

- gluino exclusions up to **~1.4 TeV**
- Stop exclusions ~ **700 GeV**
- EWK gauginos up to **~300 GeV**

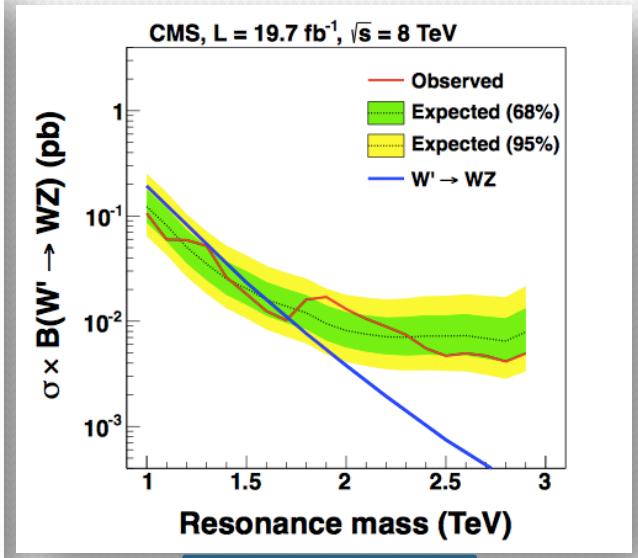


Intriguing features of Run-1data

Diboson resonances

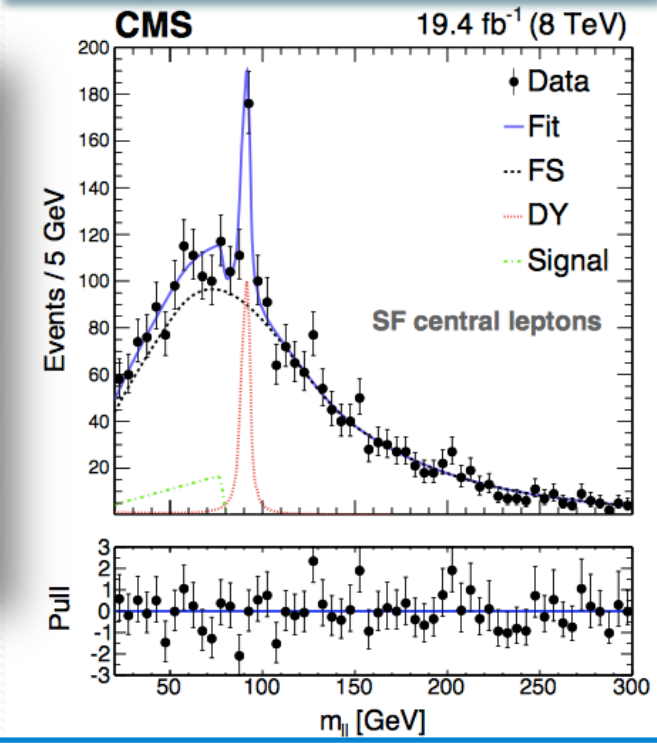


~ 3 sigma



~ 1.5 sigma

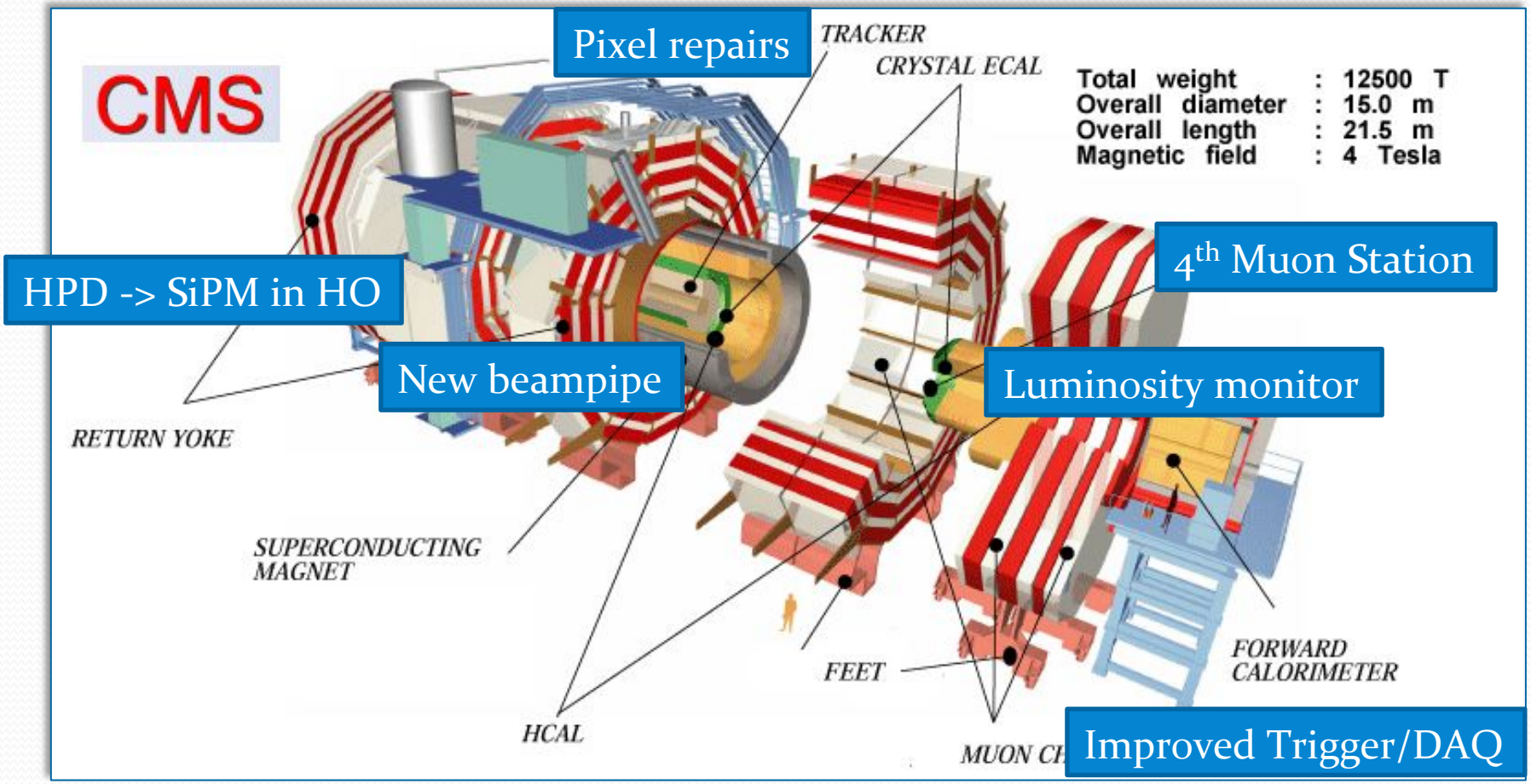
Dilepton + jets + MET



CMS excess ~ 2.6 sigma below the Z mass
ATLAS reports 3.0 sigma excess but in the Z-peak region

JP Chou's W&C seminar:
http://theory.fnal.gov/jetp/talks/JPWineAndCheese.pdf

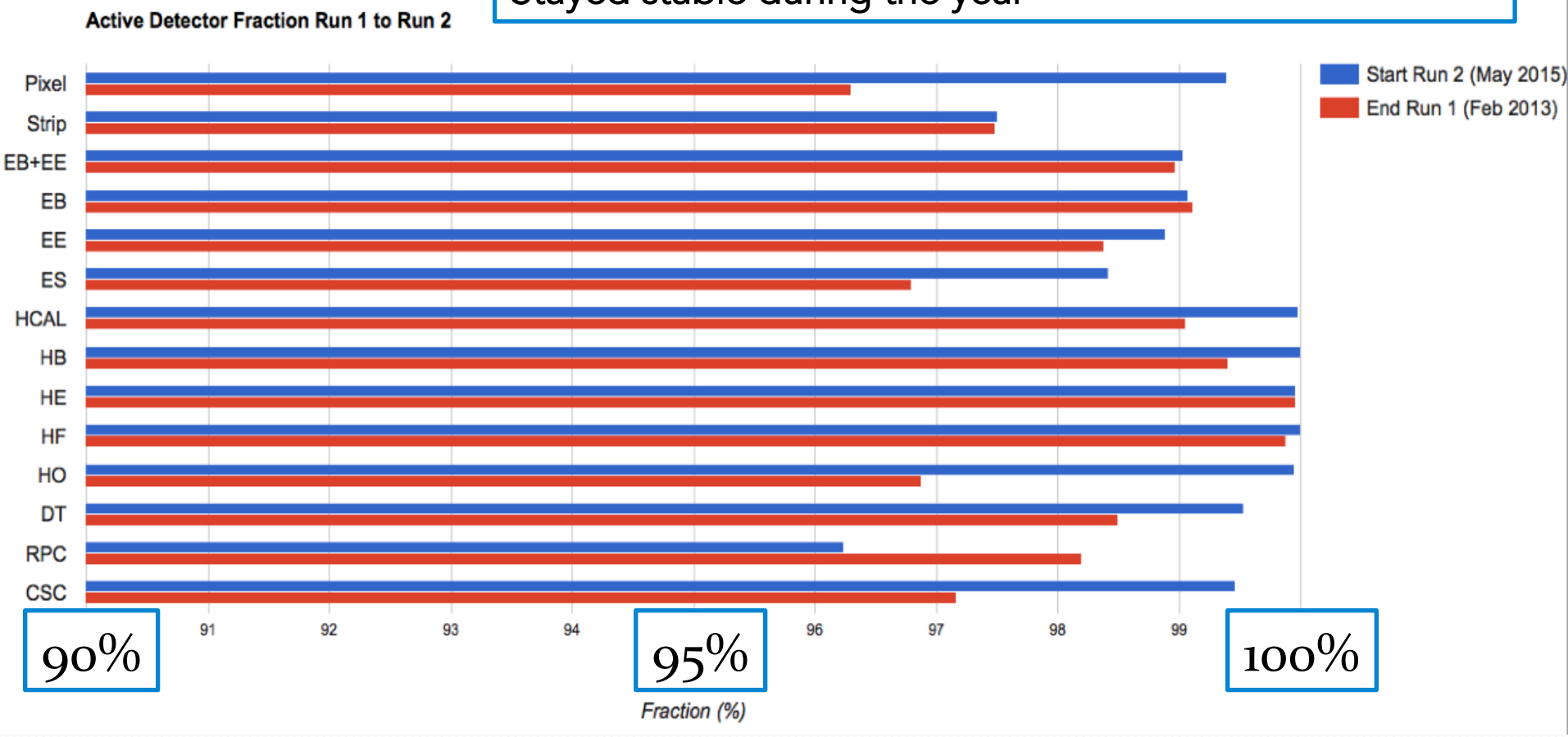
CMS detector for Run-2



CMS detector for Run-2

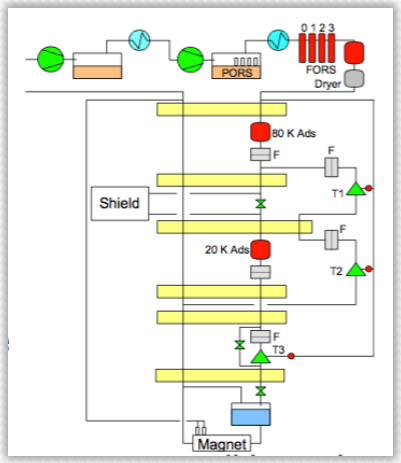
Fraction of active channels in Run-1 vs Run-2

Stayed stable during the year

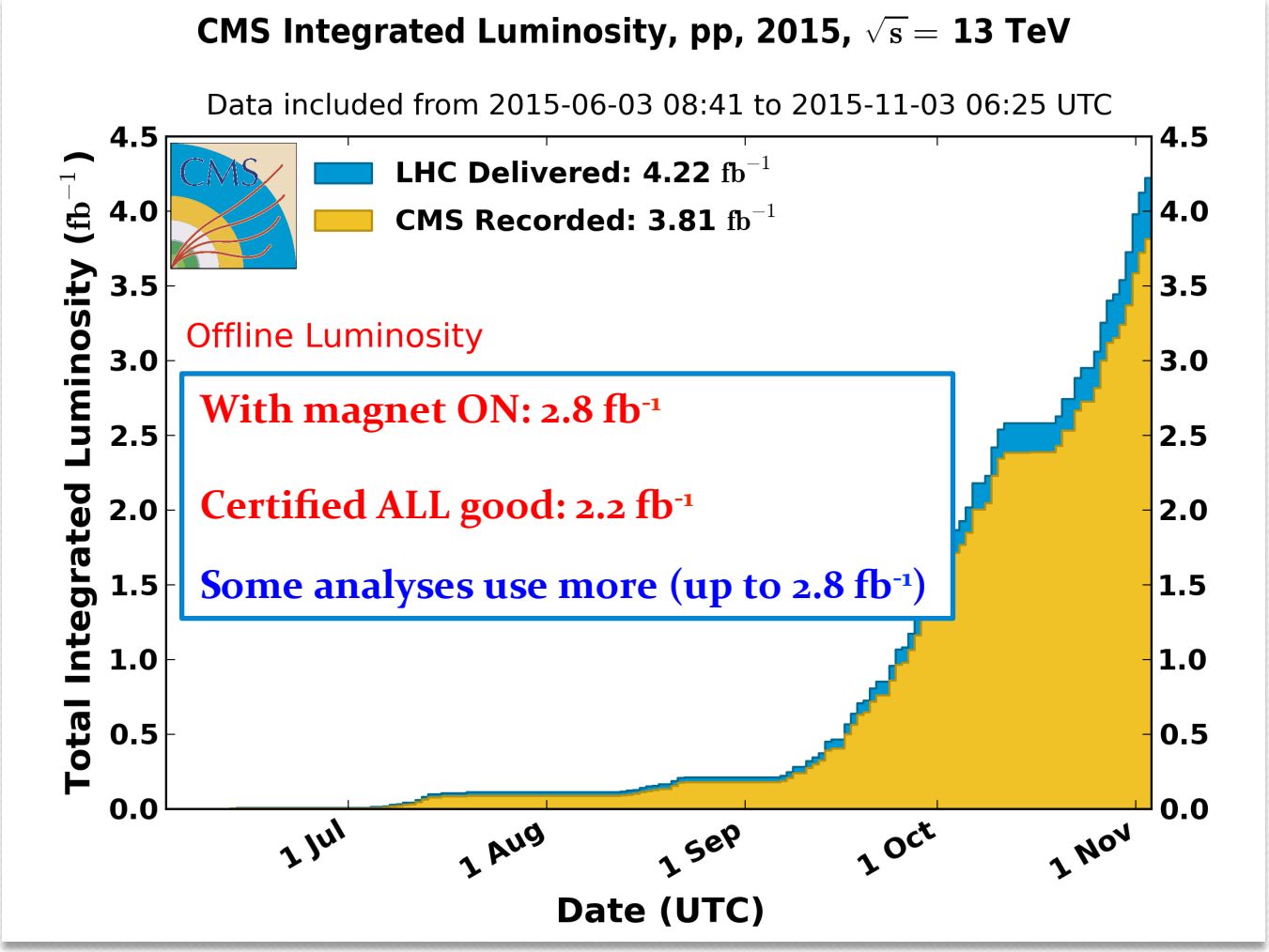


CMS magnet

- Impaired performance of the cryogenic system
- Maximize "Up-Time" of the magnet
- ¾ of 13 TeV luminosity recorded with magnetic field ON
- Repair and cleaning of the cryo system during the Year End Technical Stop
- We foresee the system to be ready by April
  - well ahead of the start of physics production of LHC in 2016



Integrated Luminosity



Commissioning results in Artur Apresyan's talk:
http://theory.fnal.gov/jetp/talks/Apresyan_W&C.pdf

CMS Run-2 results

- 33 public results based on 13 TeV data
- http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/LHC-Jamboree-2015.html

SUSY searches

Forward Physics and Small-x QCD
- Pseudorapidity Distributions of Charged Hadrons
- Two-Particle Correlations (the ``Ridge'')
- Underlying Event

QCD and EWK

Standard Model
- Inclusive Jet Production
- Inclusive W and Z Production
- Z+jets Differential Cross Section
- WZ Production Cross Section
- ZZ Production Cross Section

TOP

Heavy Flavours
- B Production Cross Section

Top Quark
- Inclusive $t\bar{t}$ Cross Section in Dileptons
- Inclusive and Differential $t\bar{t}$ Cross Sections in ℓ+jets
- Differential $t\bar{t}$ Cross Sections in Dileptons
- Differential $t\bar{t}$ Distributions as a Function of Event Variables
- Underlying Event Measurements in $t\bar{t}$+X Events
- Single Top-Quark Cross Section

Higgs signal regions remain blinded

125-GeV Higgs Boson
- Performance Studies

Search for Supersymmetry
- Supersymmetry in Multijet + Missing E_T
- Supersymmetry in All-Hadronic Using M_{T2}
- Supersymmetry in All-Hadronic Using α_T
- Supersymmetry in All-Hadronic Using Razor Variables
- Supersymmetry in One-Lepton Events Using Large Radius Jets
- Supersymmetry in Same-Sign Dilepton Events
- Supersymmetry in Opposite-Sign Dilepton Events

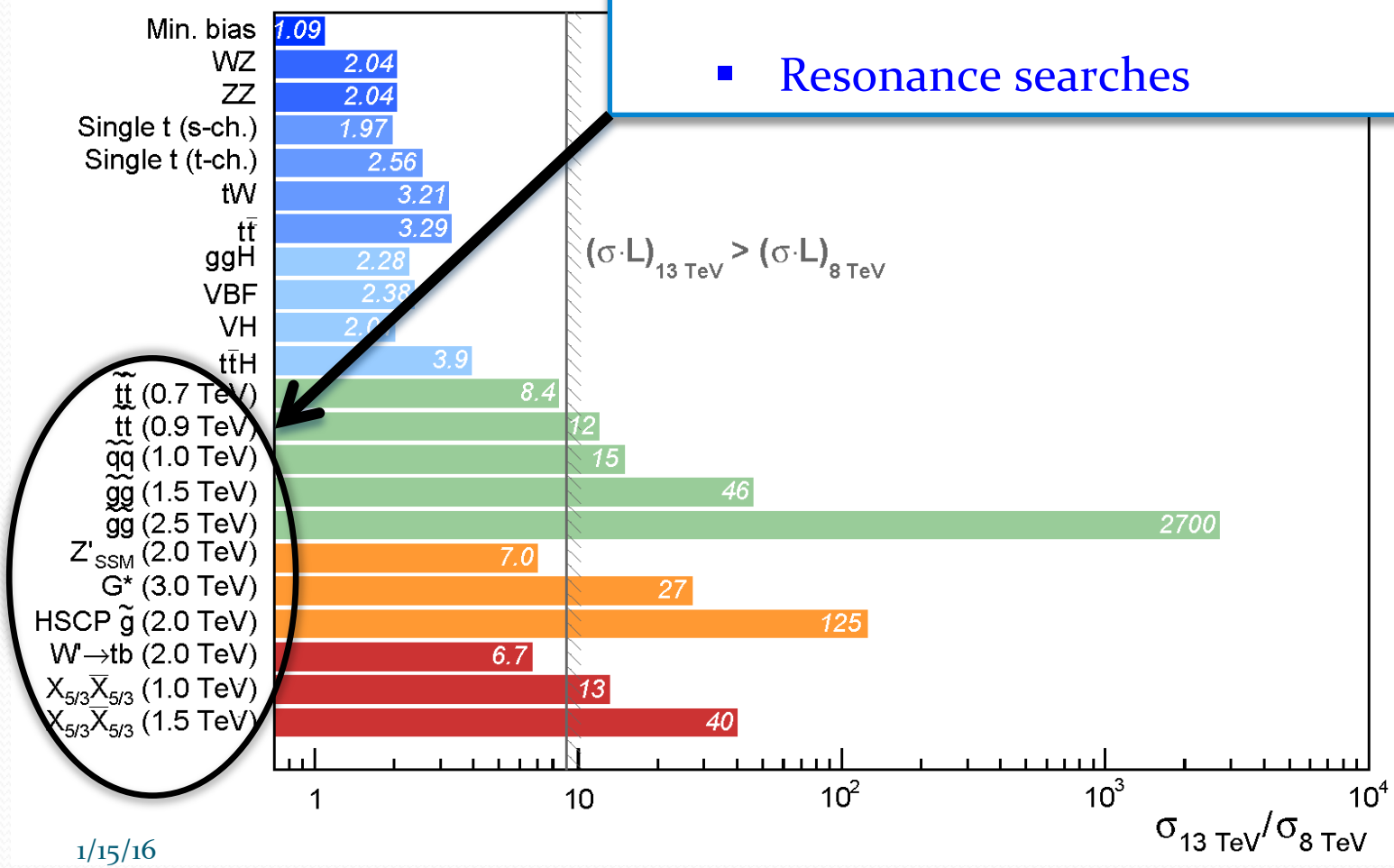
Exotica searches

Search for Exotic Pheno
- Search for Resonan
- Search for Quark Compositness in Dijet Events
- Search for Z' in Dilepton Events
- Search for W' in Lepton+E_T^{miss} Events
- Search for Resonances in Diphoton Events
- Search for Resonances in Diboson Events
- Search for Dark Matter in Monojet Events
- Search for Quantum Black Holes
- Search for Heavy Stable Charged Particles

Search for Exotic Phenomena (Topologies with Heavy Quarks)
- Search for W' in tb Events
- Search for $X_{5/3}$ in SS Dilepton and Lepton+Jets Events

What am I going to show:

- Standard Model "candles"
- Strong SUSY
- Resonance searches

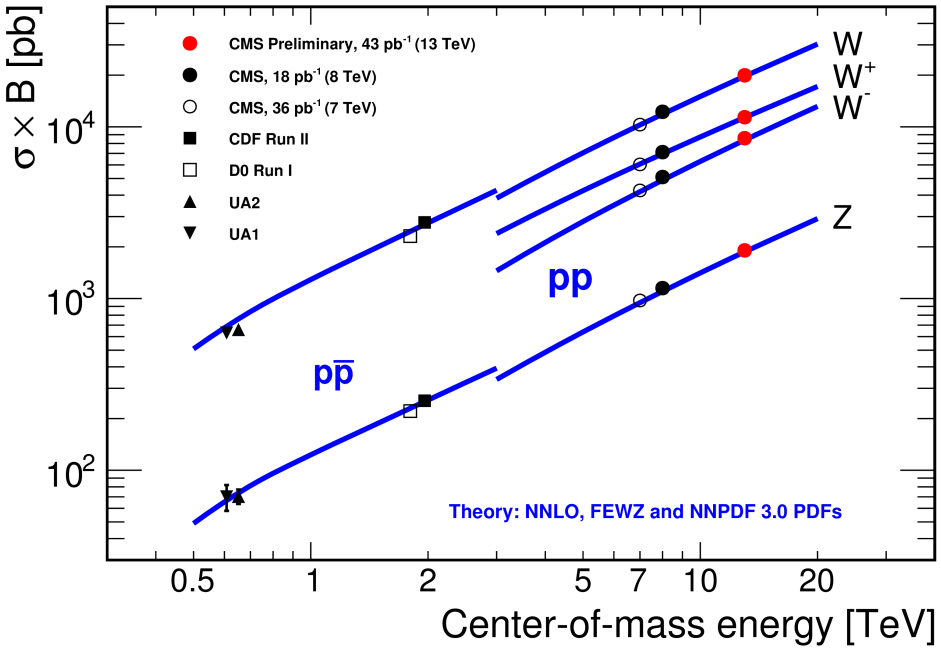


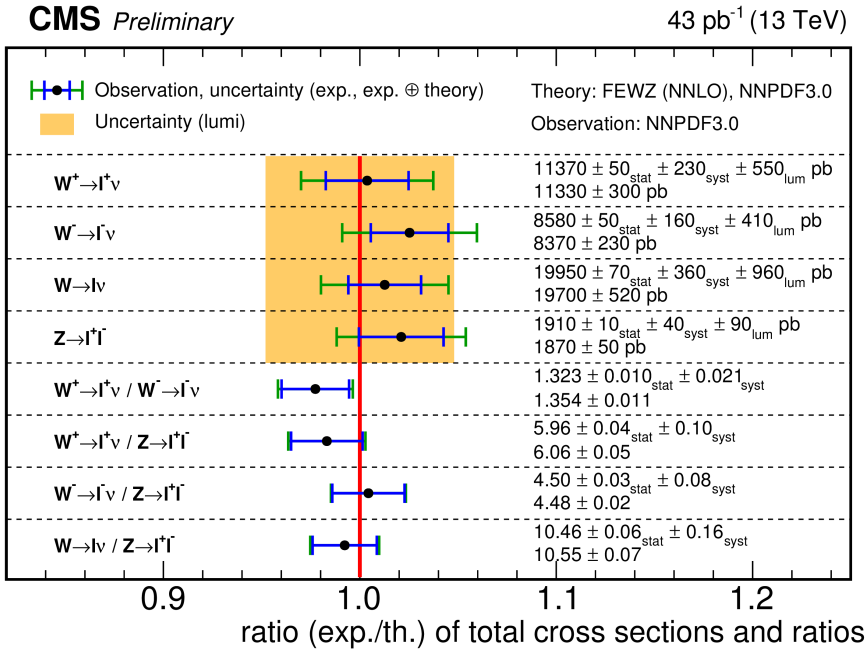
Light the candles

W and Z production cross-section

Also measure ratios (removes lumi and theory uncertainties)

Single Bosons



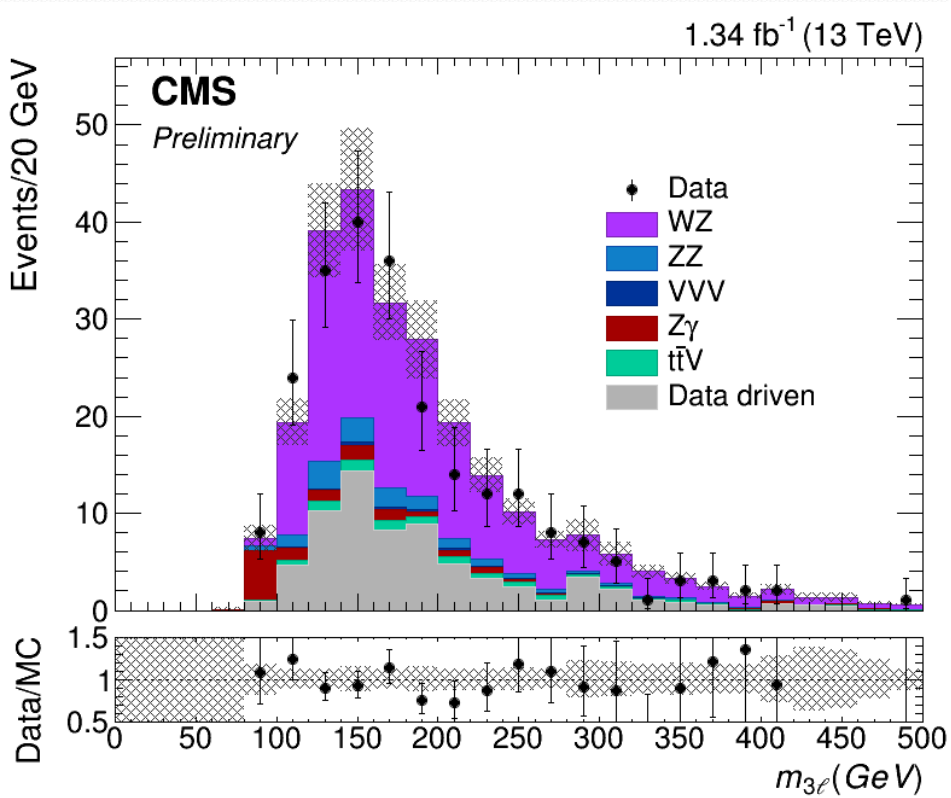


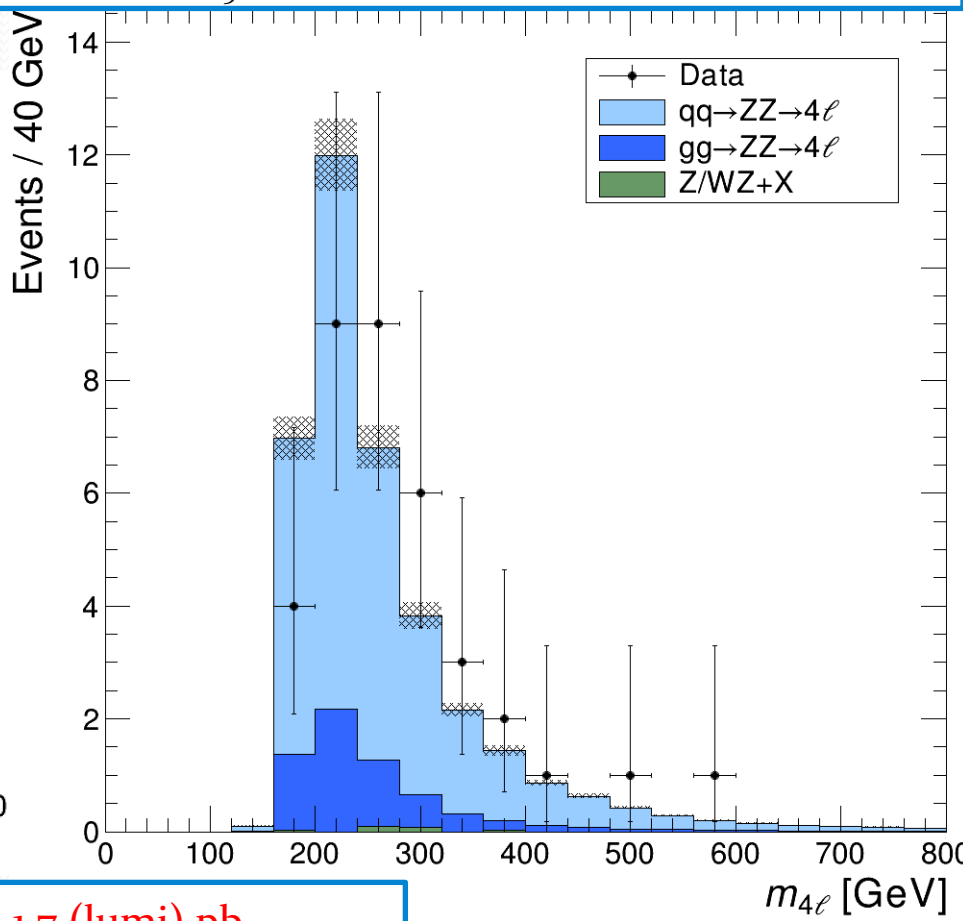
Light the candles

$\sigma(ZZ)=16.7 \pm {}^{+2.9}_{-2.6}$ (stat) ${}^{+0.7}_{-0.5}$(syst) ± 0.3(theory) ± 0.8 (lumi) pb

Theory prediction: $16.5^{+0.7}_{-0.5}$ pb

Heavy Dibosons:





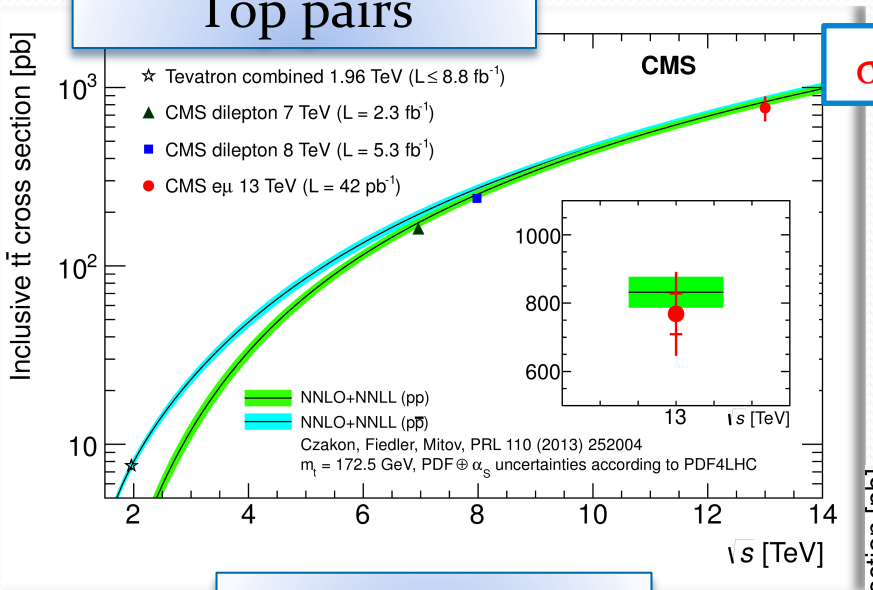
$\sigma(WZ)=36.8\pm 4.6$ (stat) ${}^{+8.1}_{-6.2}$ (syst) ± 0.6(theory) ± 1.7 (lumi) pb

Theory prediction: $42.7^{+1.6}_{-0.8}$ pb

Light the candles

Top – one of the major backgrounds in many searches

Top pairs

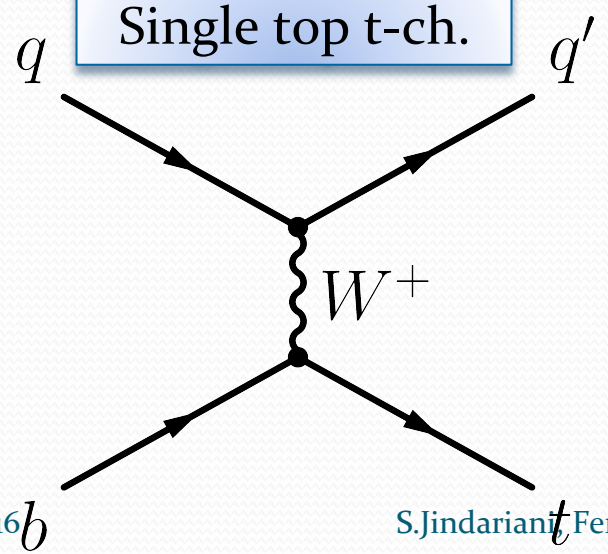


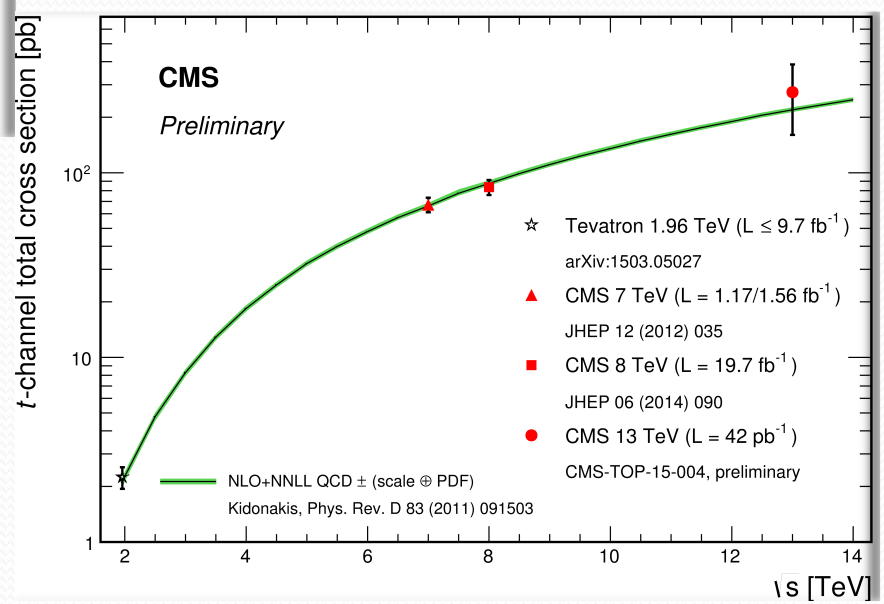
σ=769 ± 60 (stat) ± 55 (syst) ±92 (lumi) pb

Also measure cross-section in lepton+jets channel (inclusively and differentially).

σ(theory) = 832+40 pb

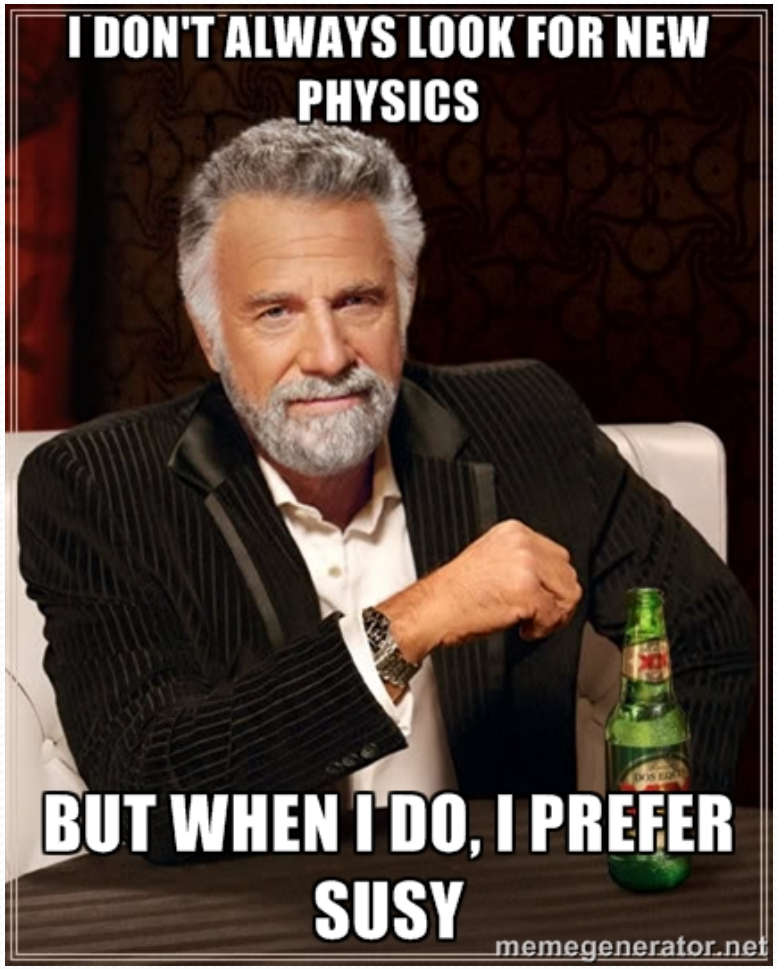
Single top t-ch.





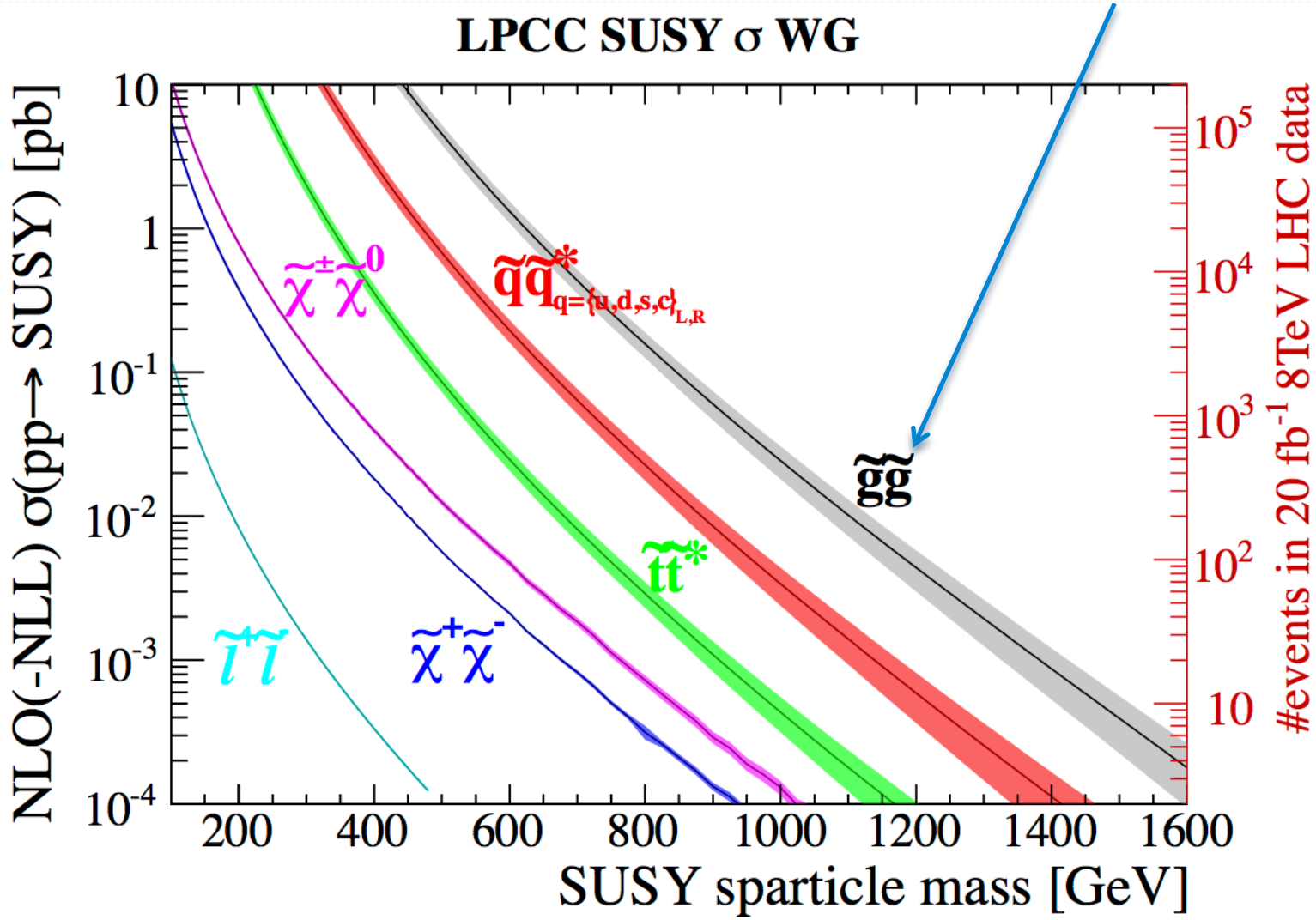
σ_{t-ch} = 274 ± 98 (stat.) ± 52 (syst.) ± 33 (lumi.)

SUSY-driven searches



SUSY

Strong gluino pair production has largest cross-section



SUSY

0-leptons	1-lepton	OSDL	SSDL	≥3 leptons
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton

Large SM backgrounds Low

sensitivity to strongly produced SUSY

SUSY

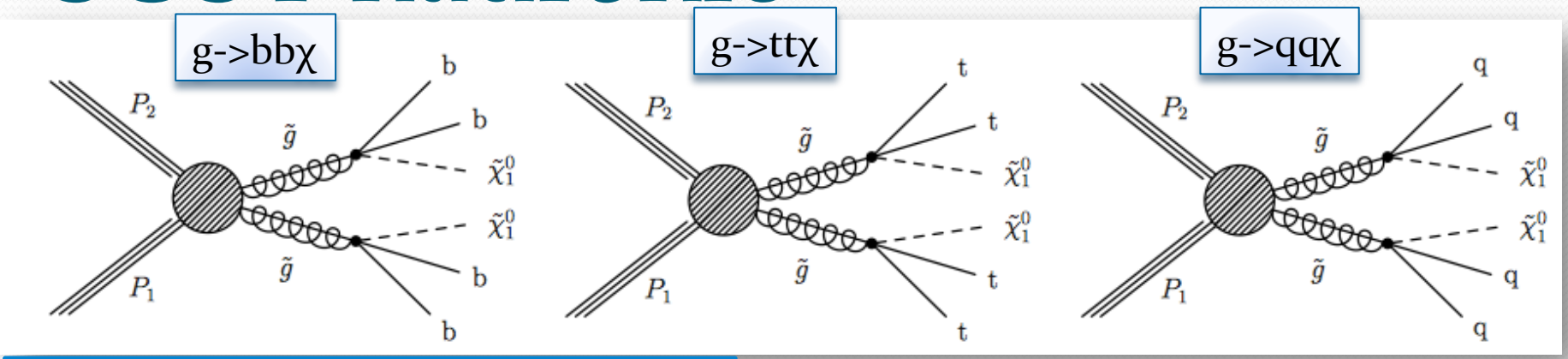
0-leptons	1-lepton	OSDL	SSDL	≥3 leptons
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton

Large SM backgrounds Low

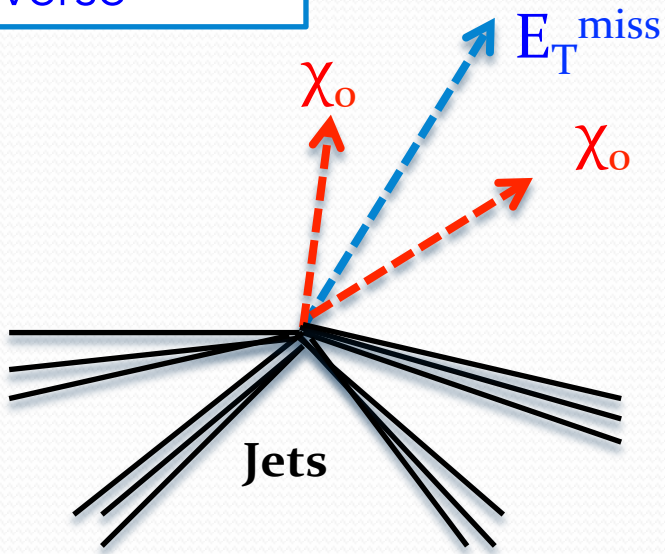
sensitivity to strongly produced SUSY

- Sensitive to broad range of models. Main focus with early dataset.
- Four analyses. Three with strong connection to the LPC.
- Use different topological variable to discriminate data from BGs.
- Use different background prediction techniques (data driven!)
- Cross-check! Cross-check! Cross-check!

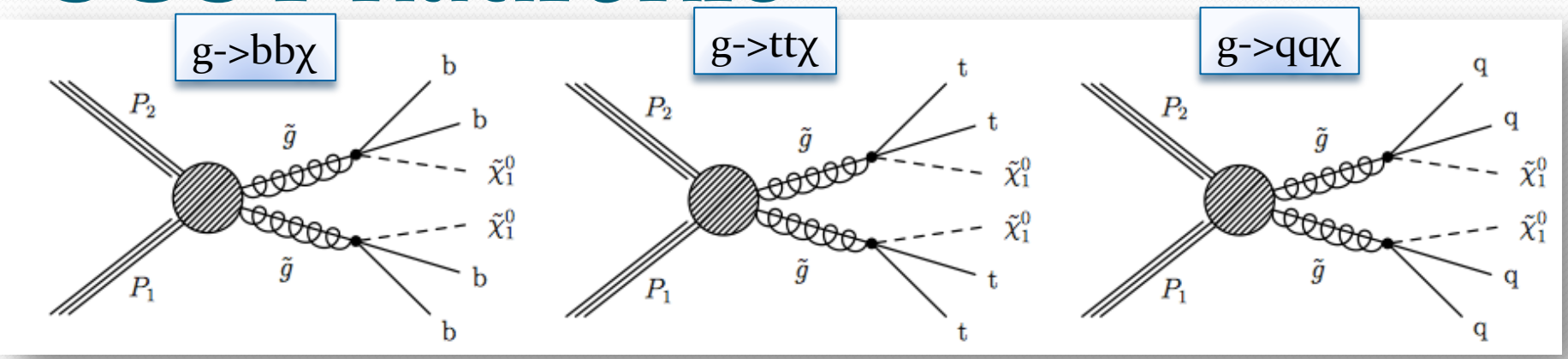
SUSY hadronic



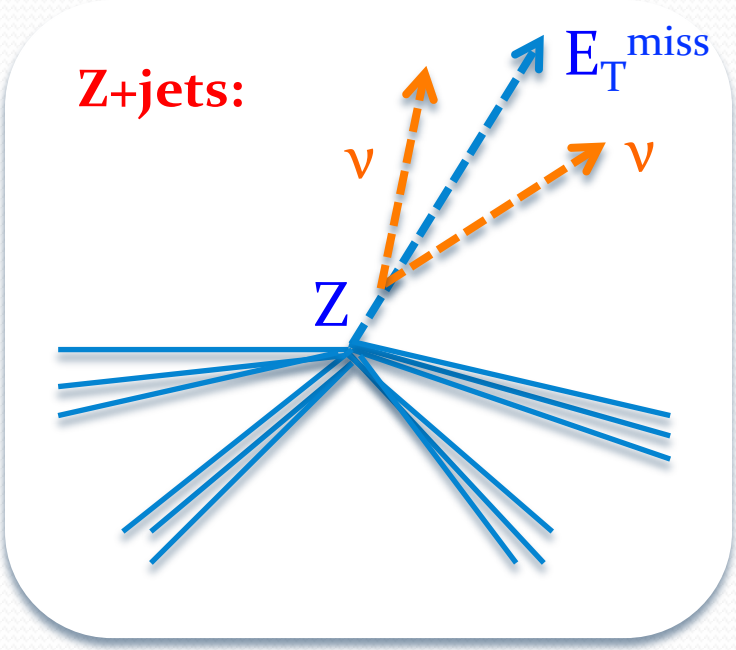
- Large number of jets
- Large missing transverse



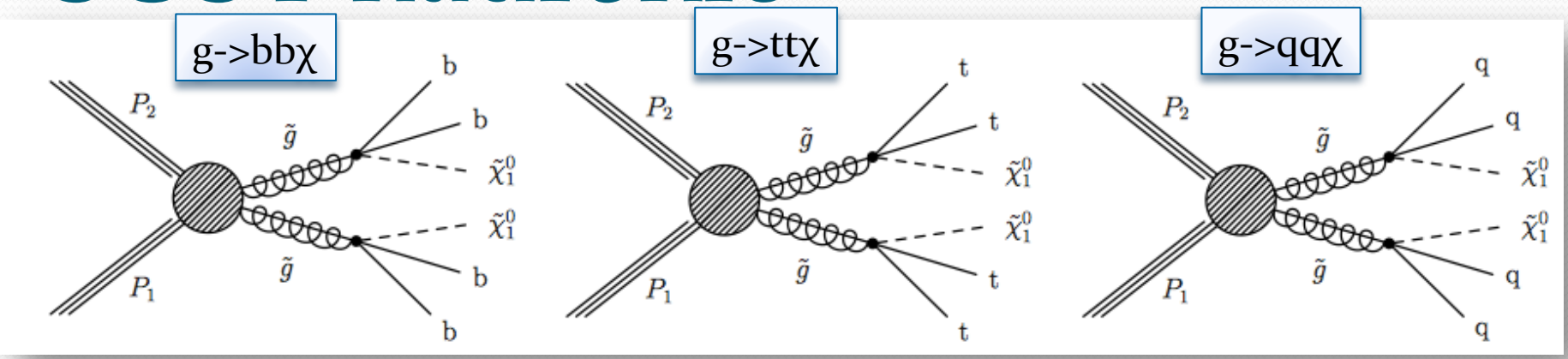
SUSY hadronic



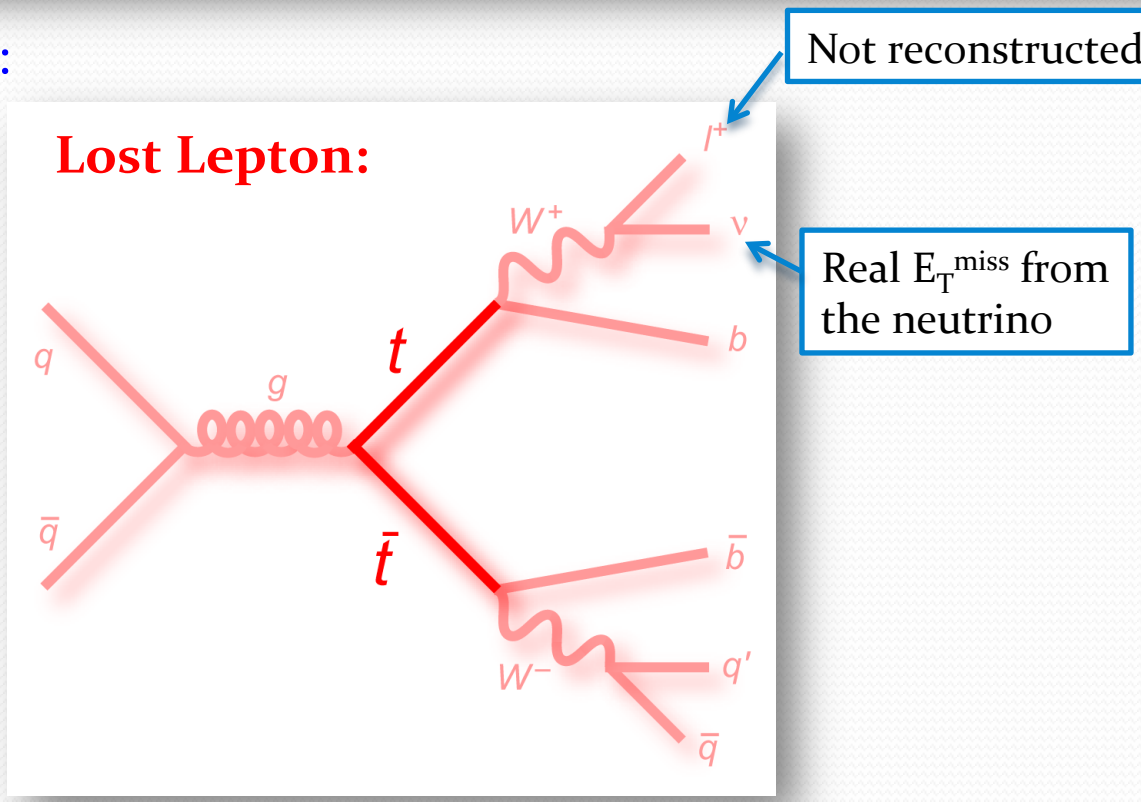
Typical backgrounds:



SUSY hadronic



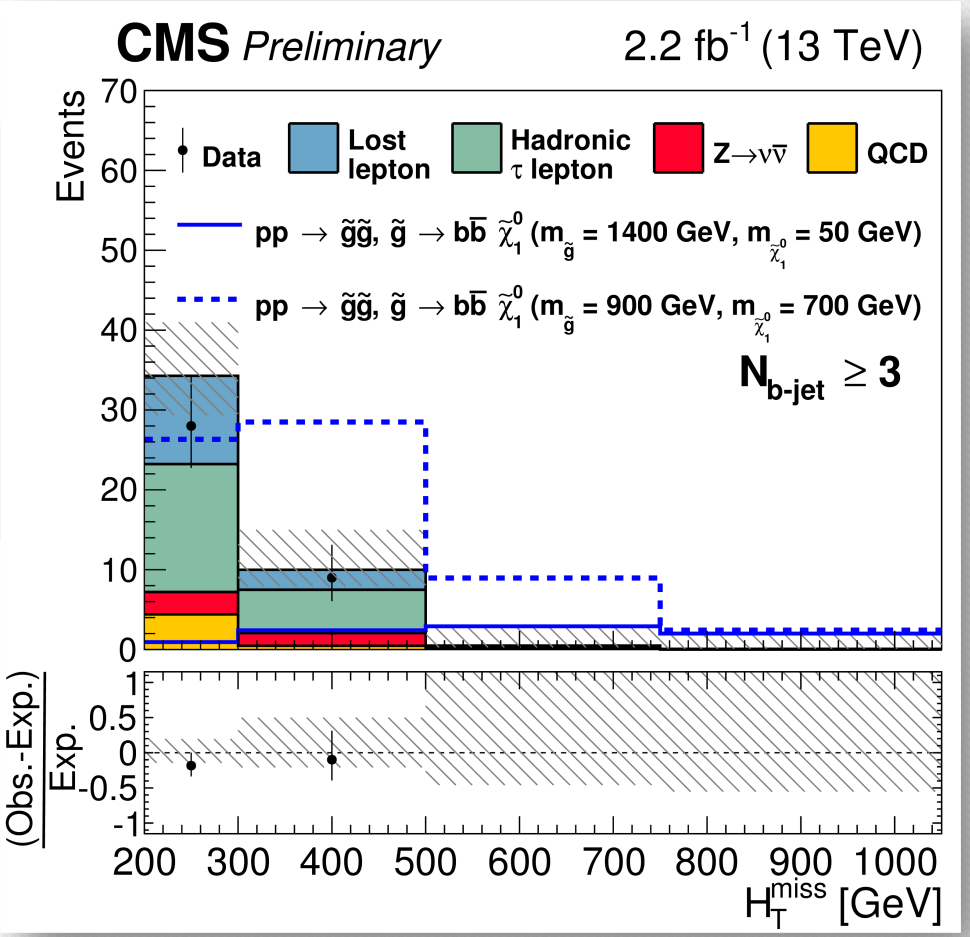
Typical backgrounds:



SUSY hadronic

Classic case $H_T + H_T^{miss}$:

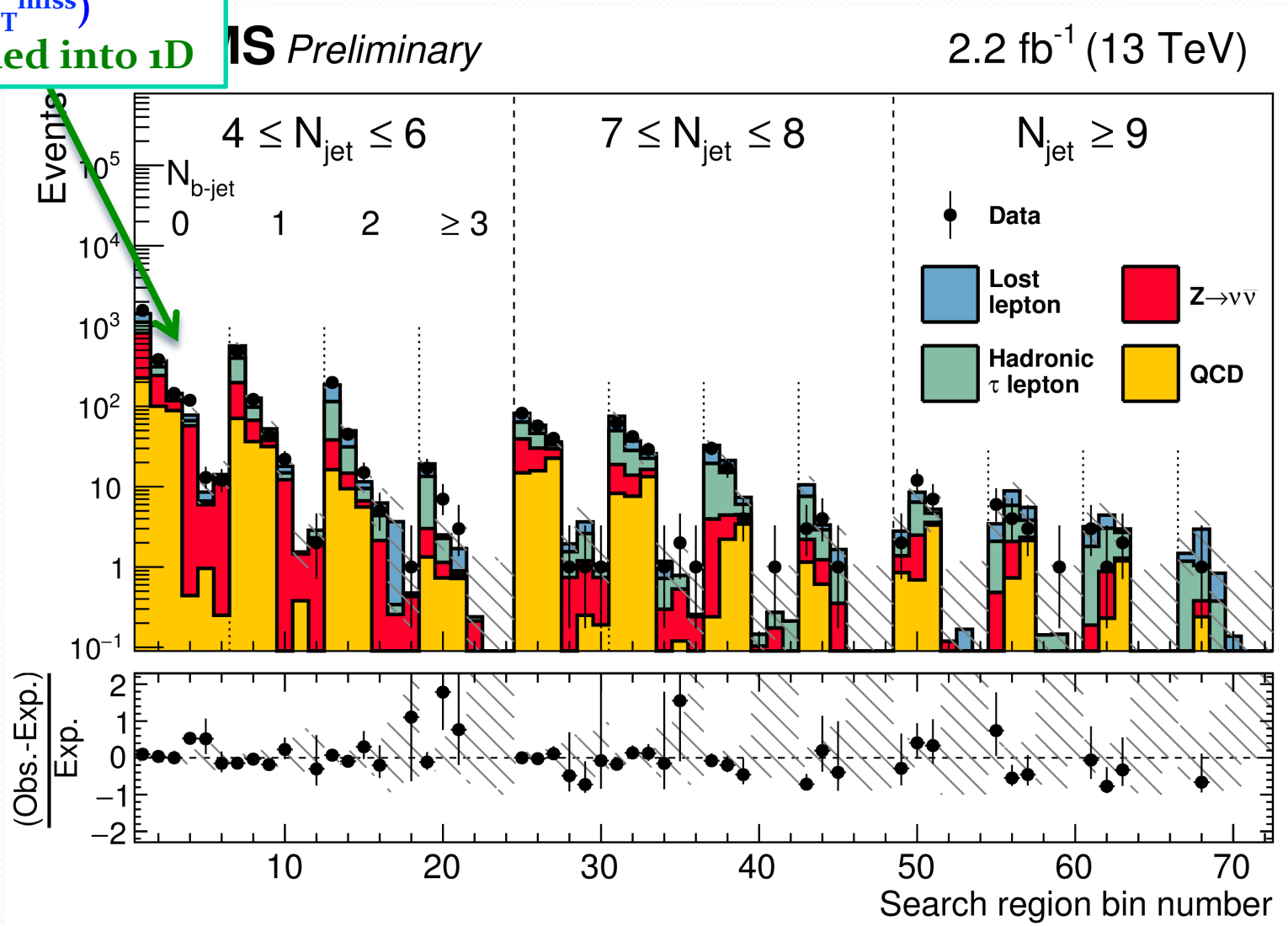
- $H_T = \Sigma E_T^{jets}$
- H_T^{miss}: ~ E_T^{miss} from jets



Other analysis use different variables: M_{T2}, αT, "Razor"

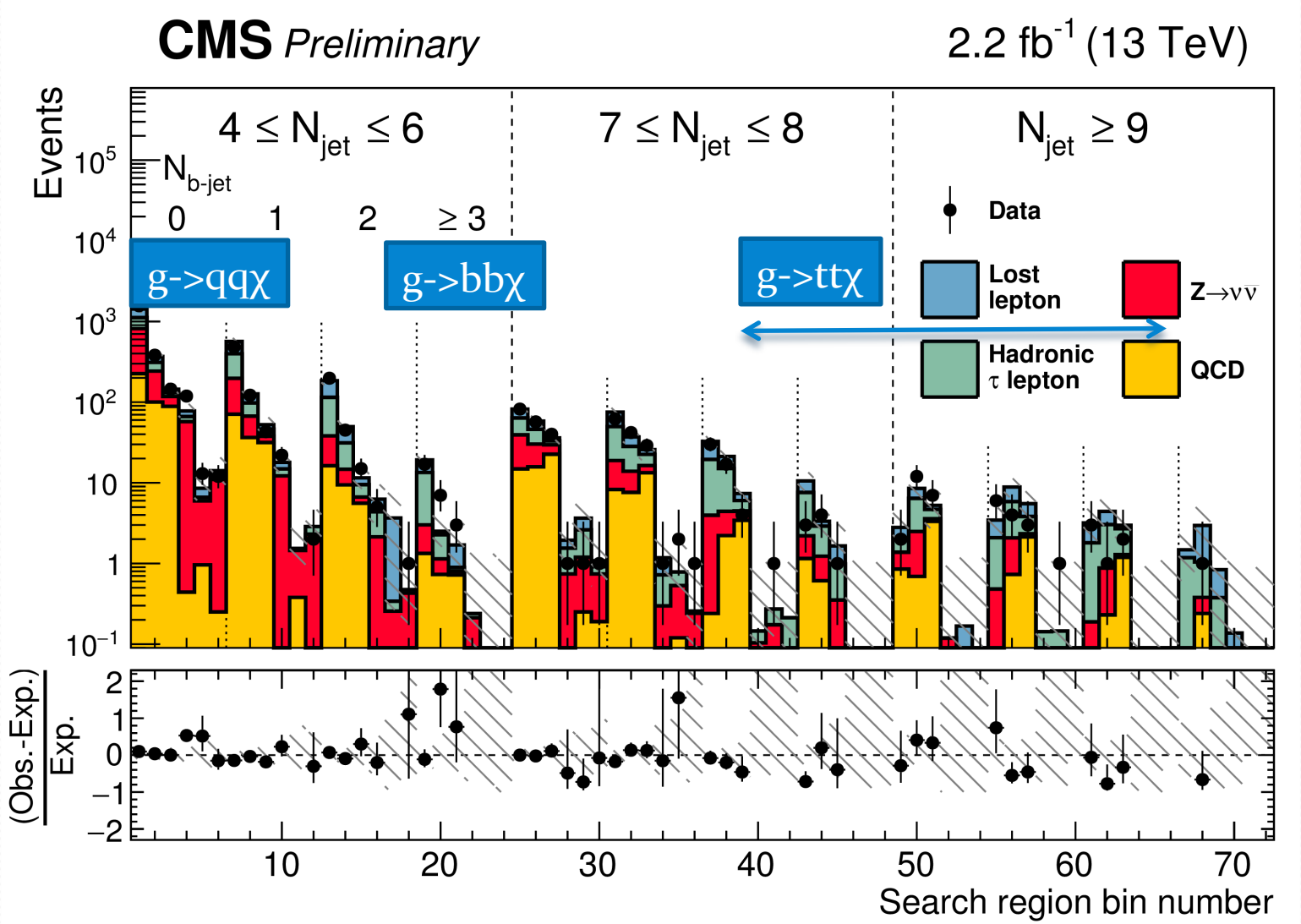
SUSY hadronic

(H_T, H_T^{miss}) unrolled into 1D



Data consistent with SM expectation

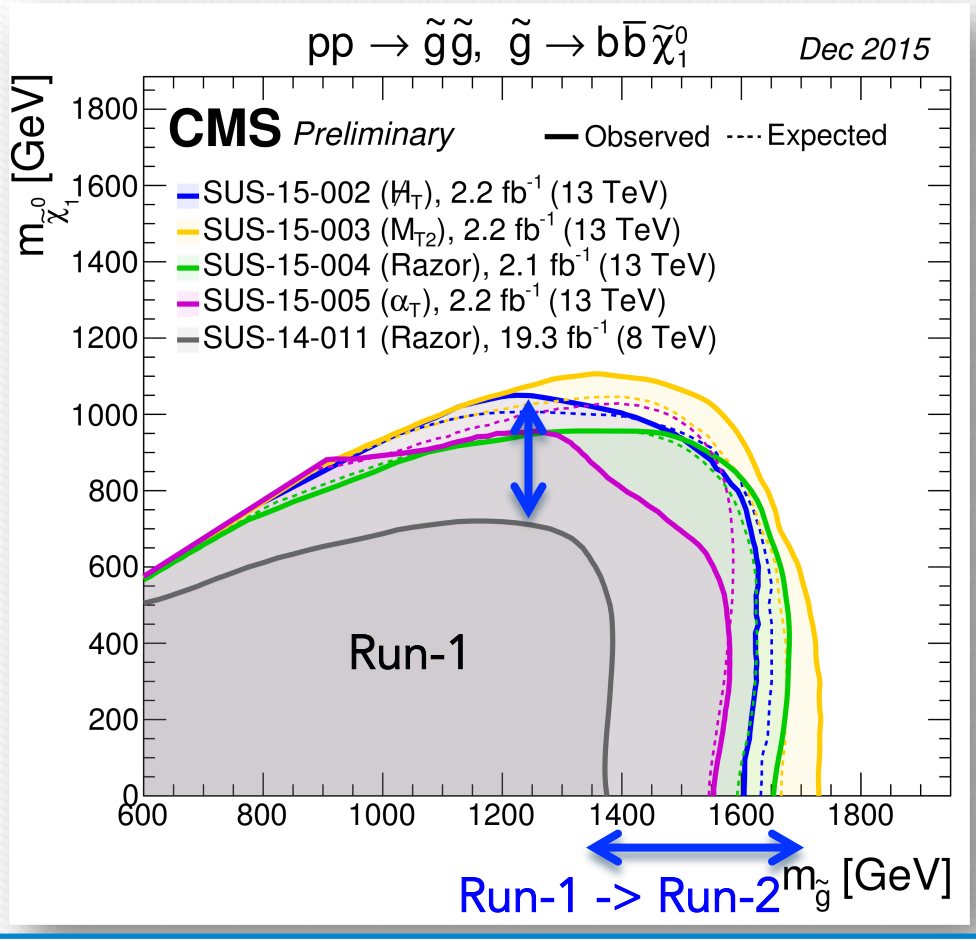
SUSY hadronic



Data consistent with SM expectation

SUSY hadronic

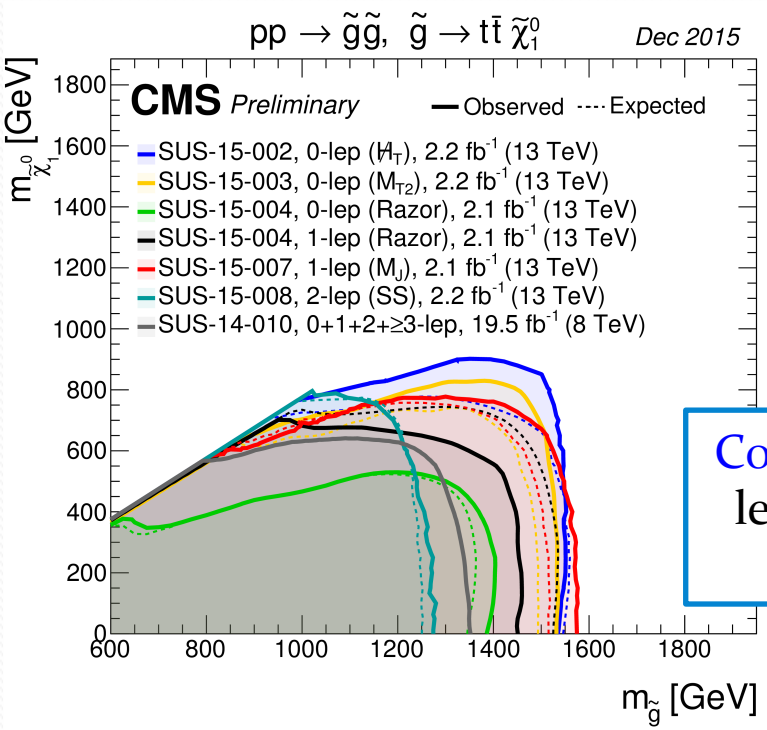
Set limits in (gluino, neutralino) mass plane



Exclude gluino masses up to 1.7 TeV within this model

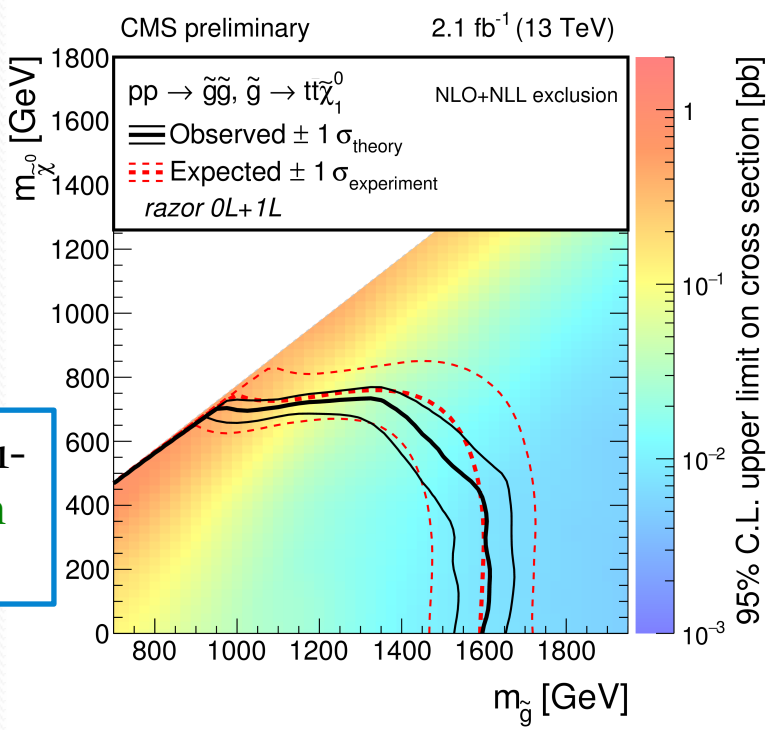
SUSY hadronic

- For some signal models leptonic channels contribute significantly
- Some analyses combine:



"Razor" analysis example

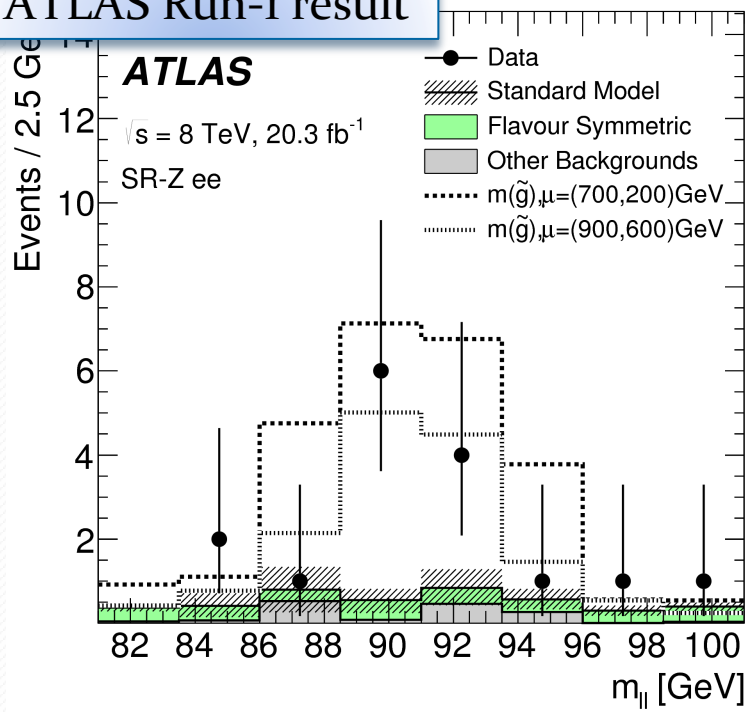
Combining Black (1-lepton) and Green (0-lepton)



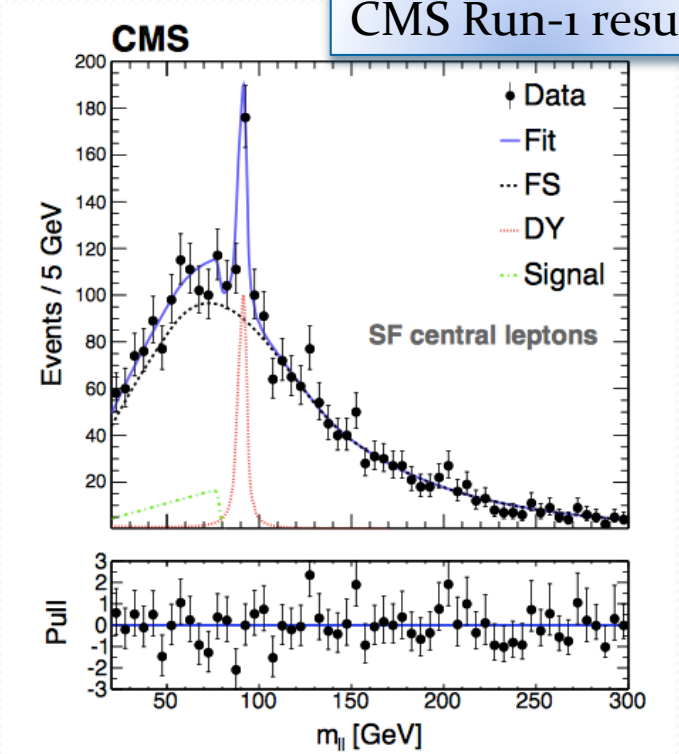
Dilepton + MET

Two leptons (same flavor, opposite charge), jets and MET

ATLAS Run-1 result



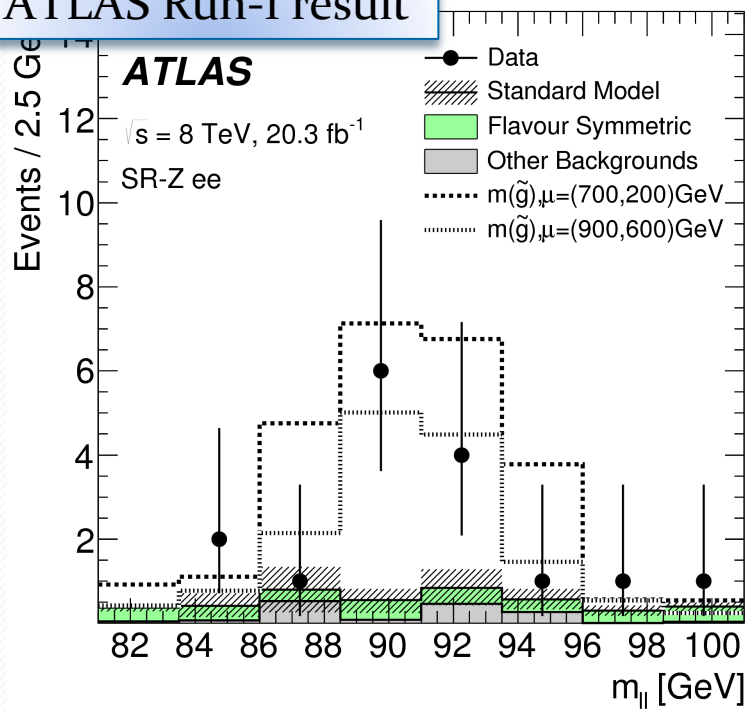
CMS Run-1 result



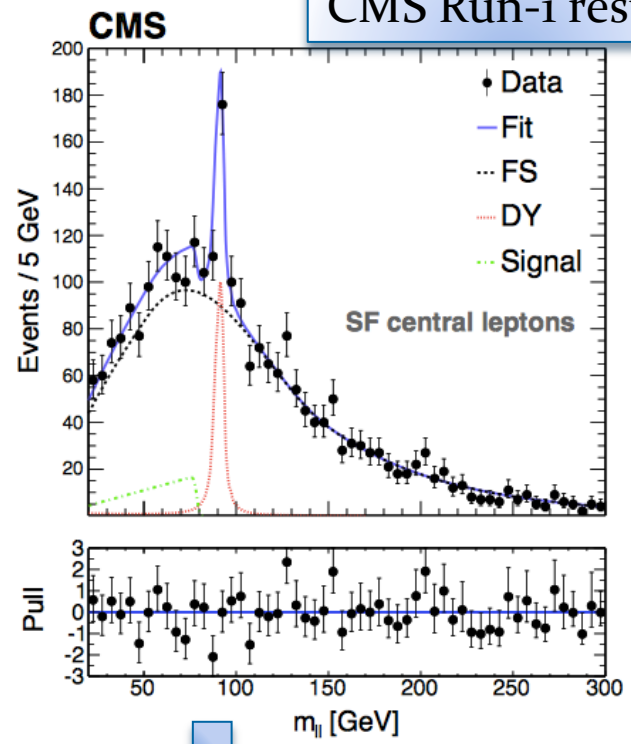
Dilepton + MET

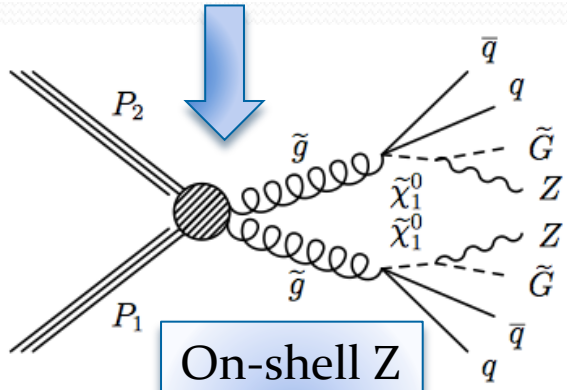
Two leptons (e+e- or μ+μ-), jets and E_T^{miss}

ATLAS Run-1 result

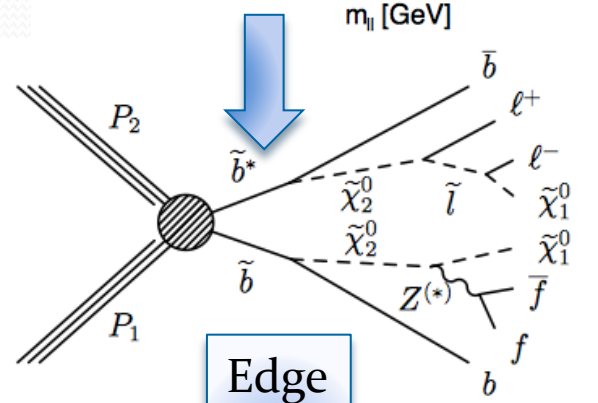


CMS Run-1 result





On-shell Z



Edge

Dilepton + MET

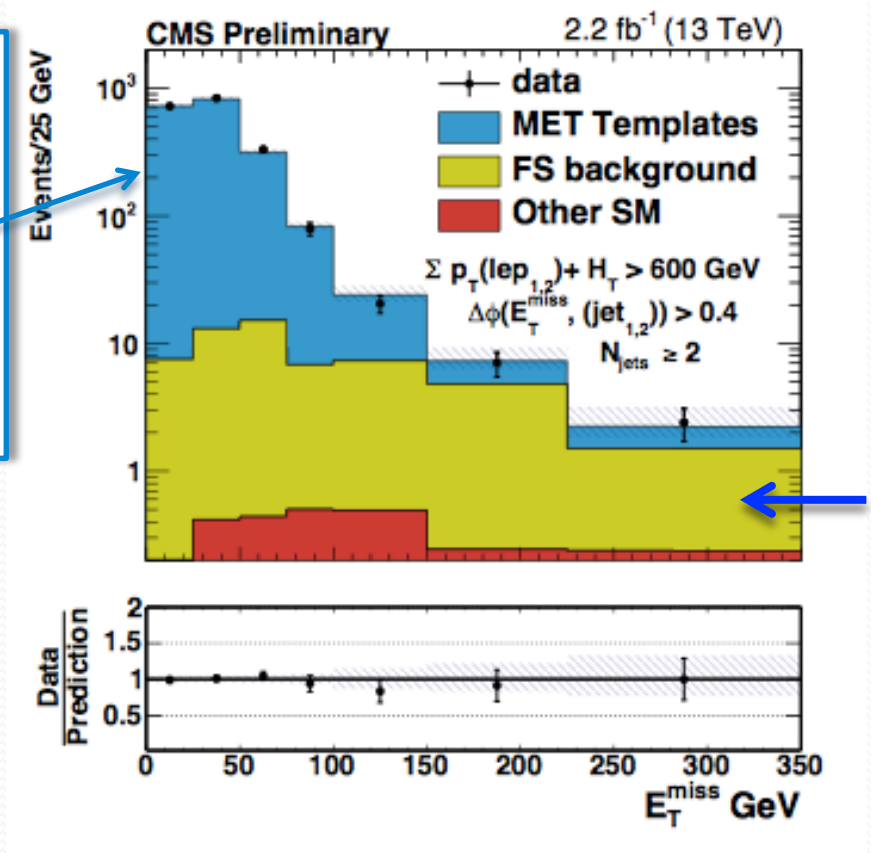
More signal regions than in Run-1:

- Bin in N_{jets}, N_{bjets}, E^{T}_{miss} and M_{ll}

Special signal region following ATLAS recipe

Drell-Yan like background

Enters through limited detector resolution of the hadronic recoil

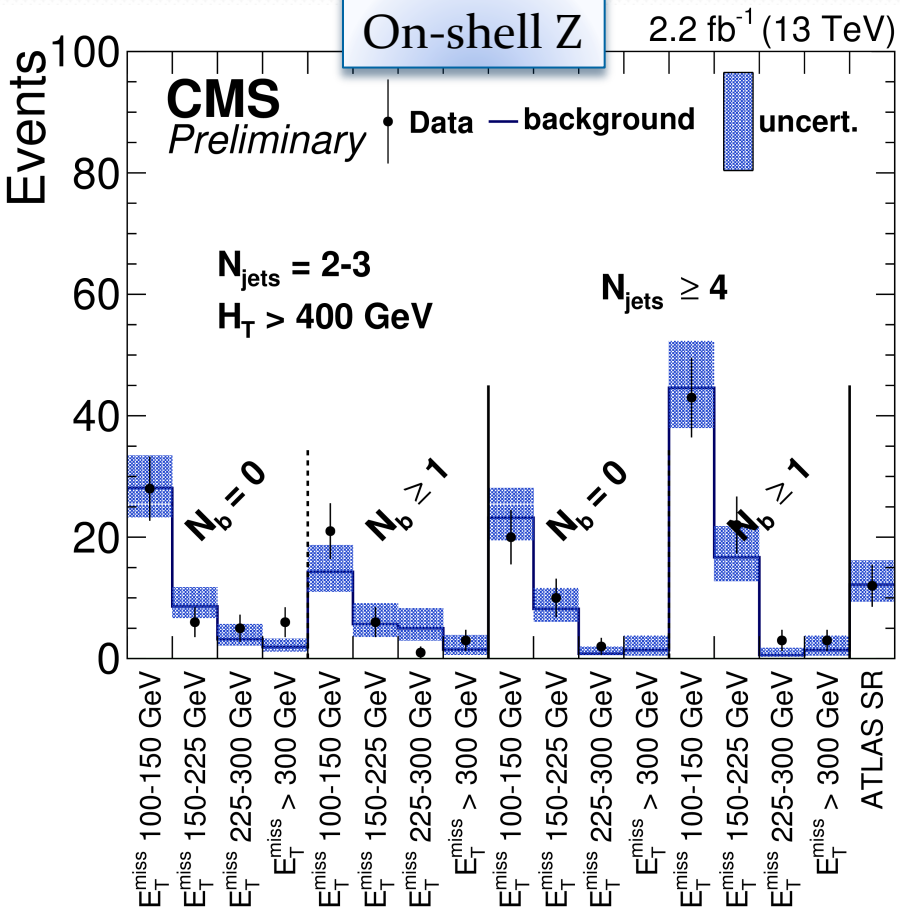


Flavor symmetric background:

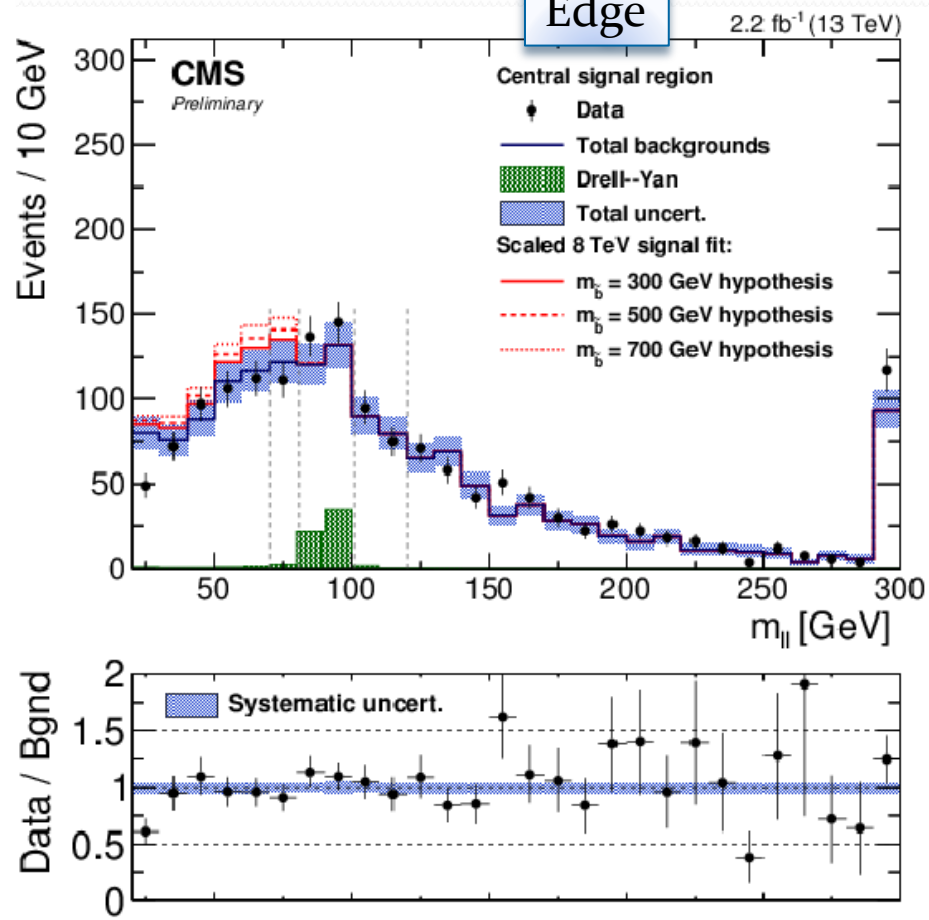
Top, W+W-, Z->ττ others

Dilepton + MET

On-shell Z



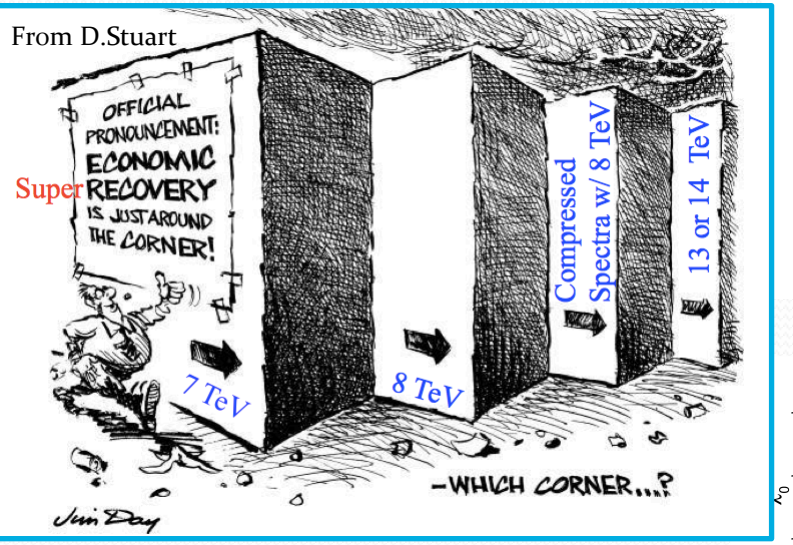
Edge



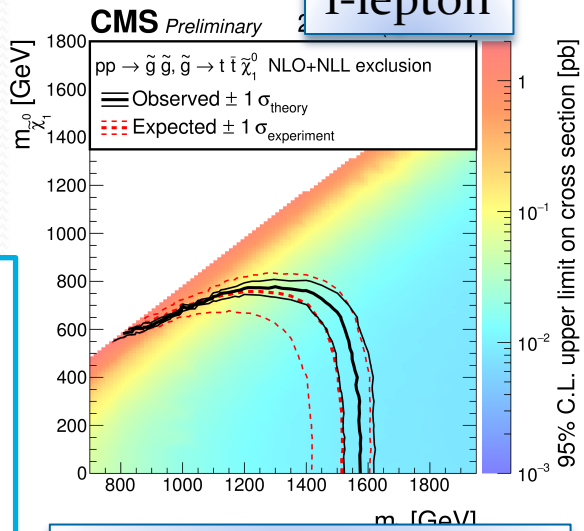
Data consistent with expectations

SUSY interpretation of the Run-1 excess is strongly disfavored

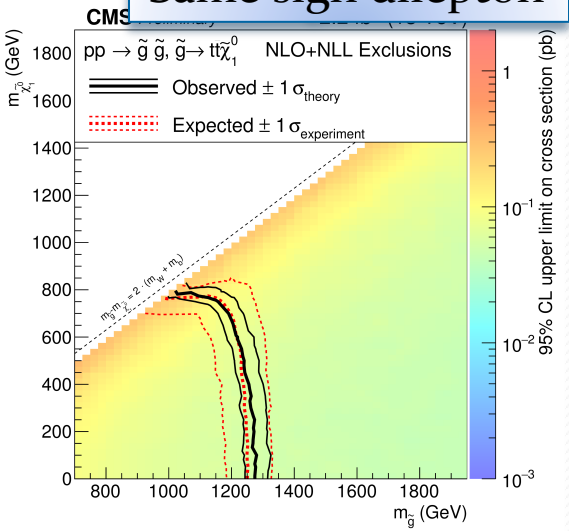
SUSY summary



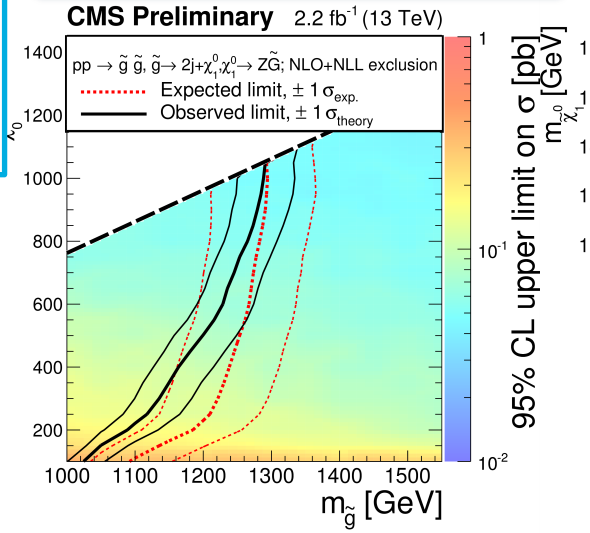
1-lepton



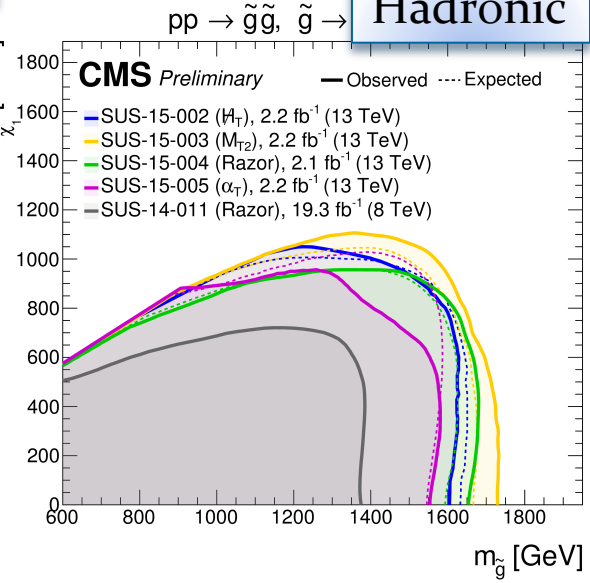
Same sign dilepton



Opposite sign dilepton



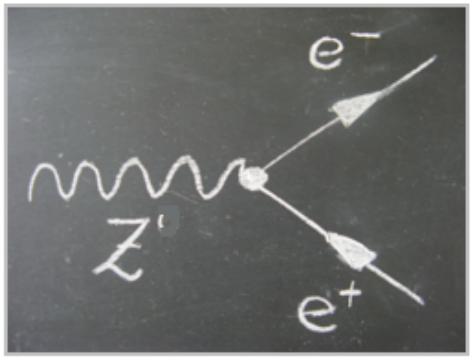
Hadronic

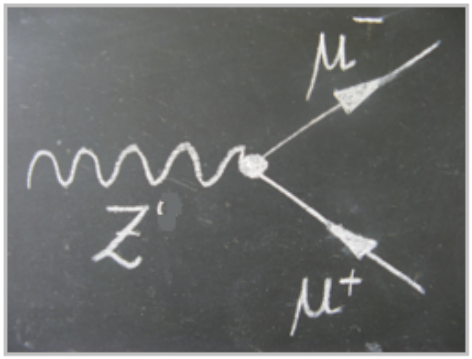


Resonance searches

Dilepton resonances

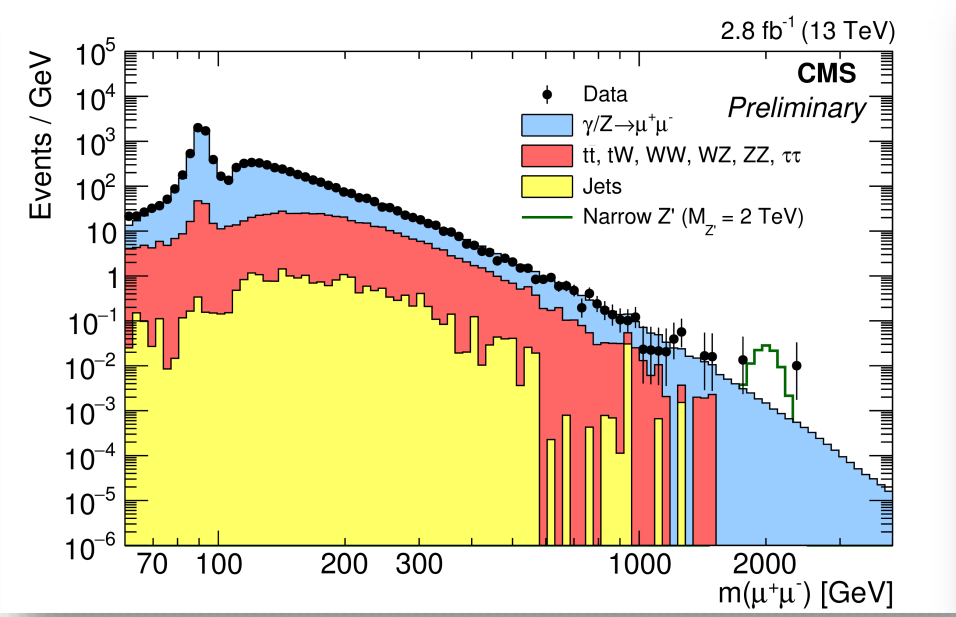
Bread and butter search

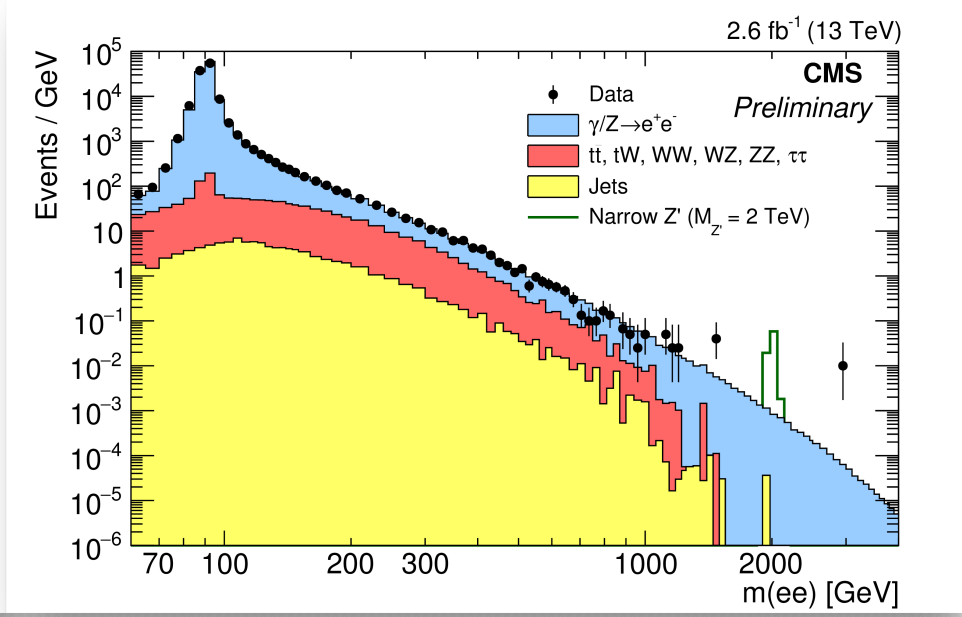




Backgrounds:

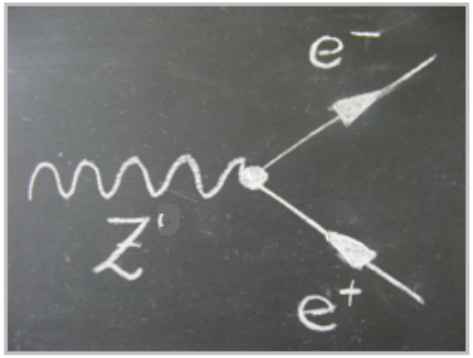
- Z->ll
- Top, Dibosons…
- Fake leptons

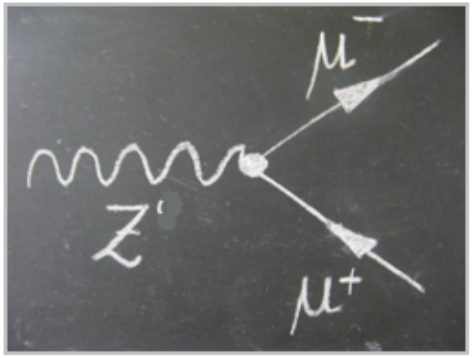




Dilepton resonances

Bread and butter search





Backgrounds:

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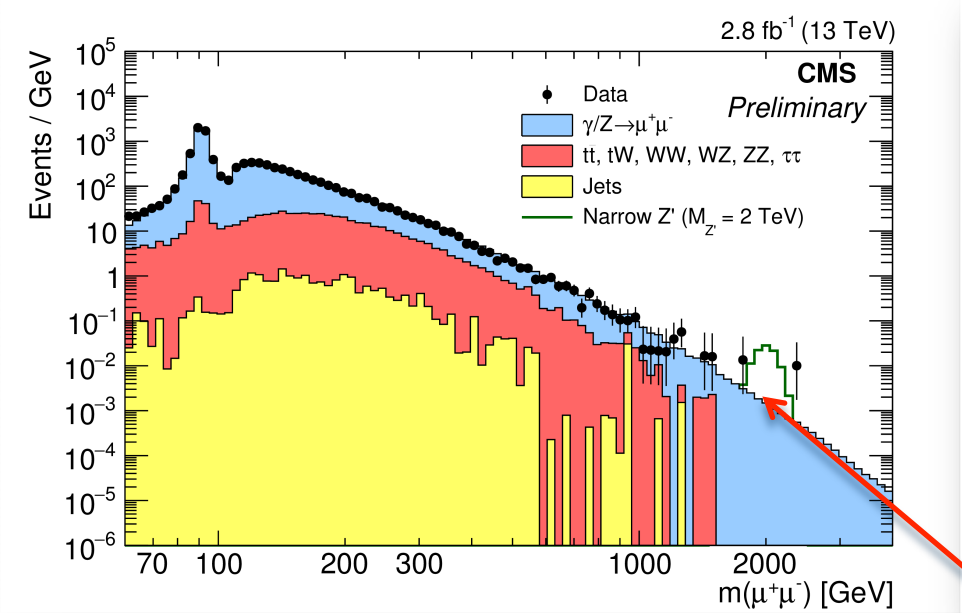
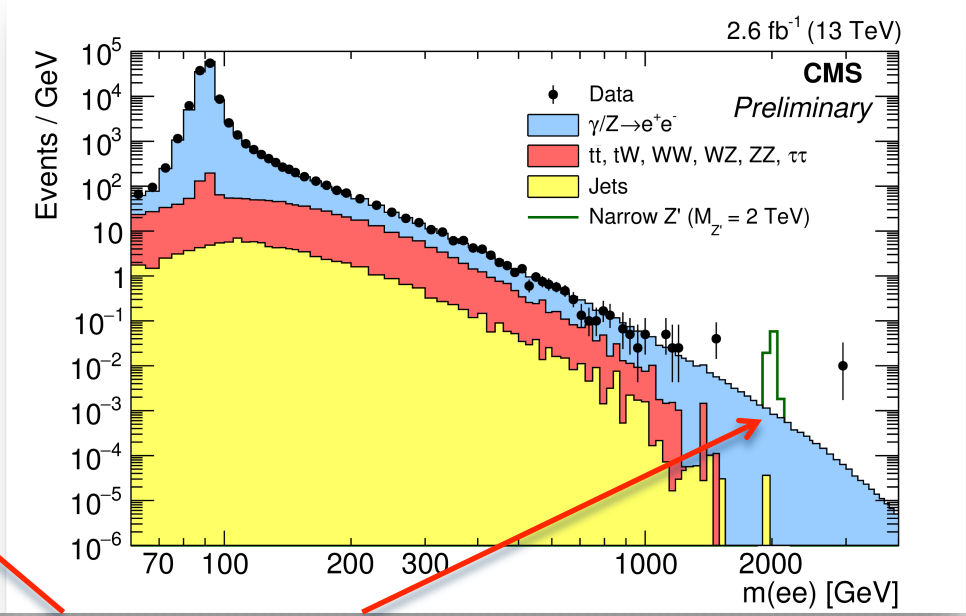
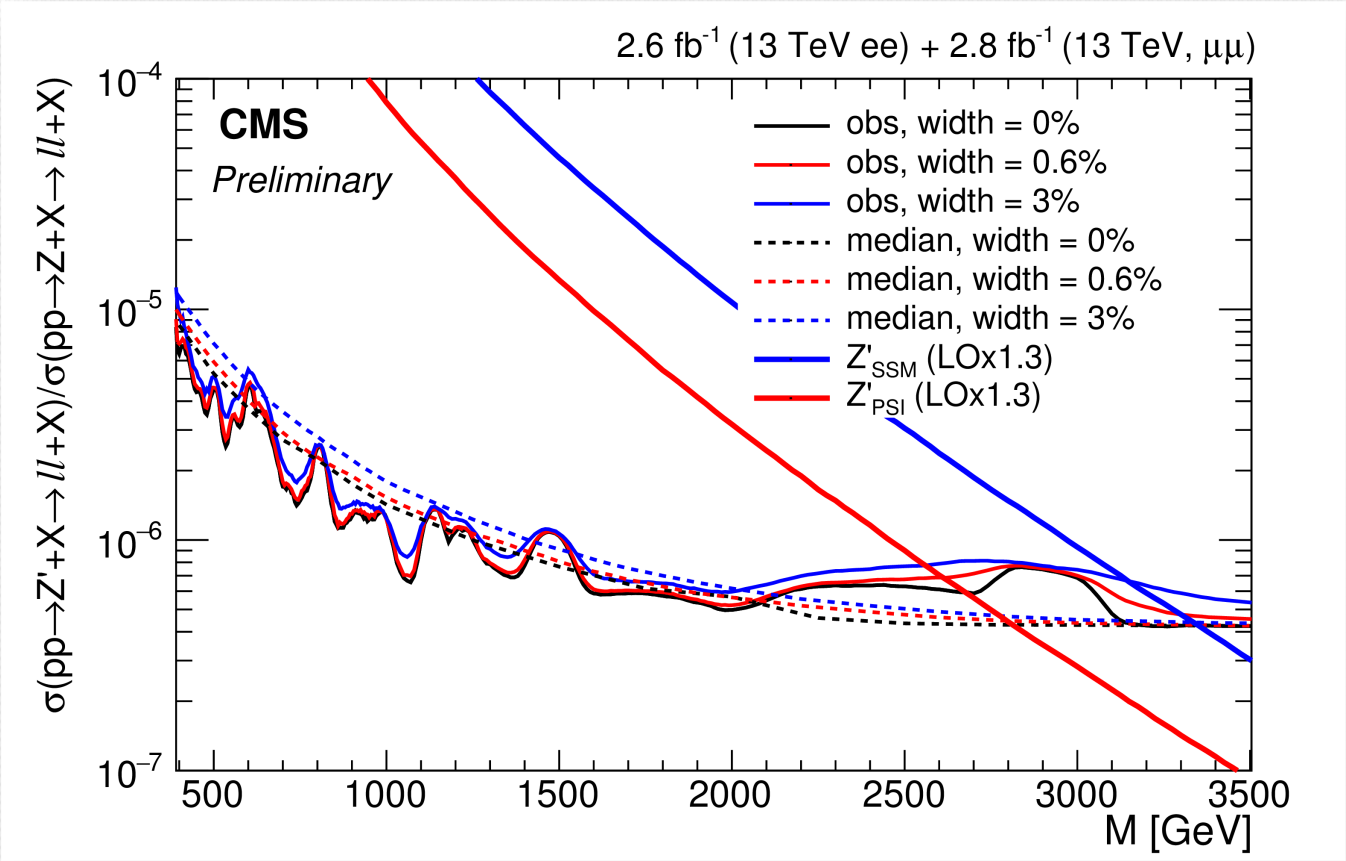




At high mass resolution in ee channel is better

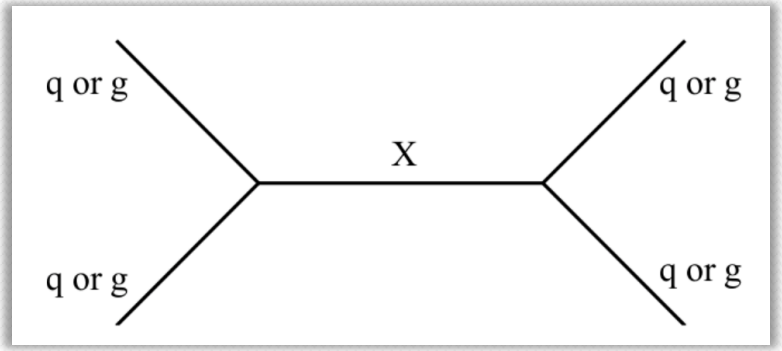
Dilepton resonances

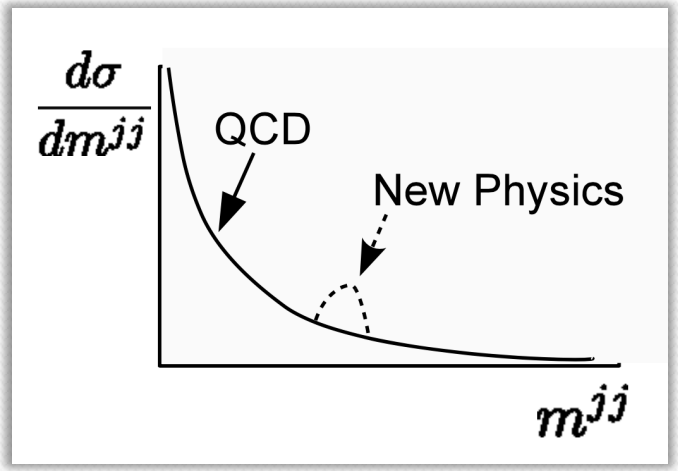


Excluding at 95% C.L. Z′(SM)<3.15 TeV and Z′(ψ) <2.6 TeV

Exceeds corresponding Run-1 20^{-fb} limits of 2.9 and 2.5 TeV

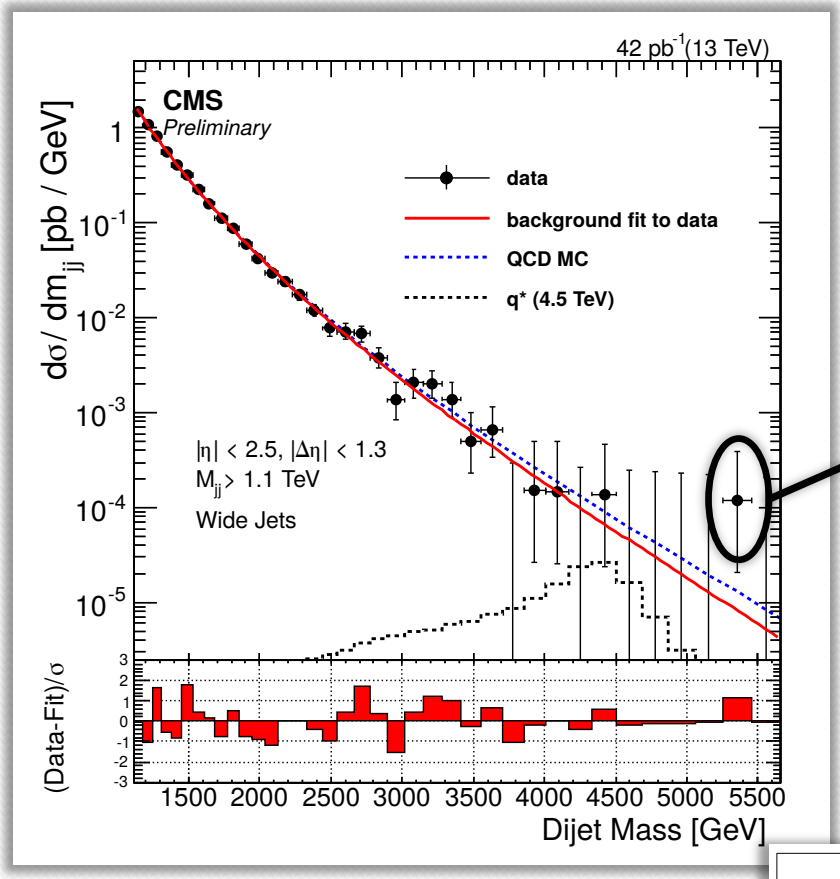
Dijet resonances

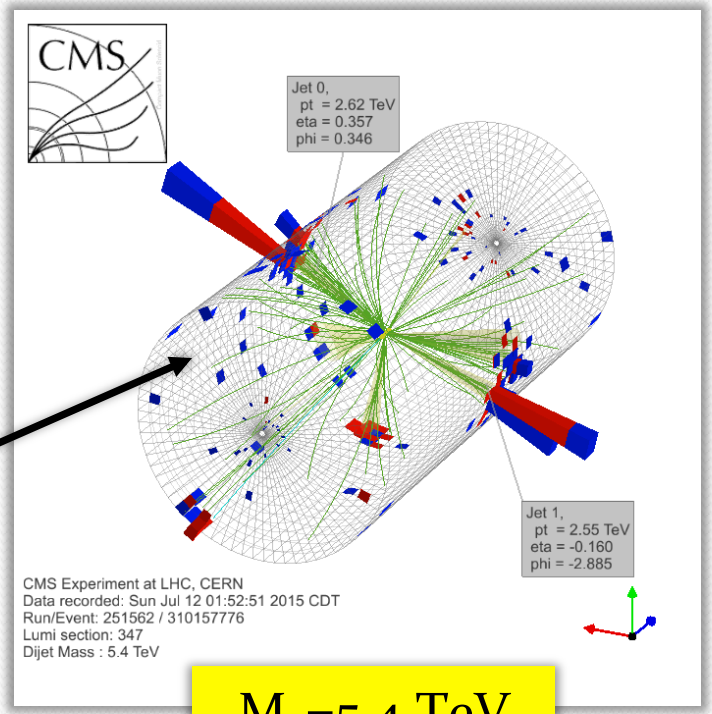




Strong production: dijets provide an early discovery potential

Early Run-2 Analysis



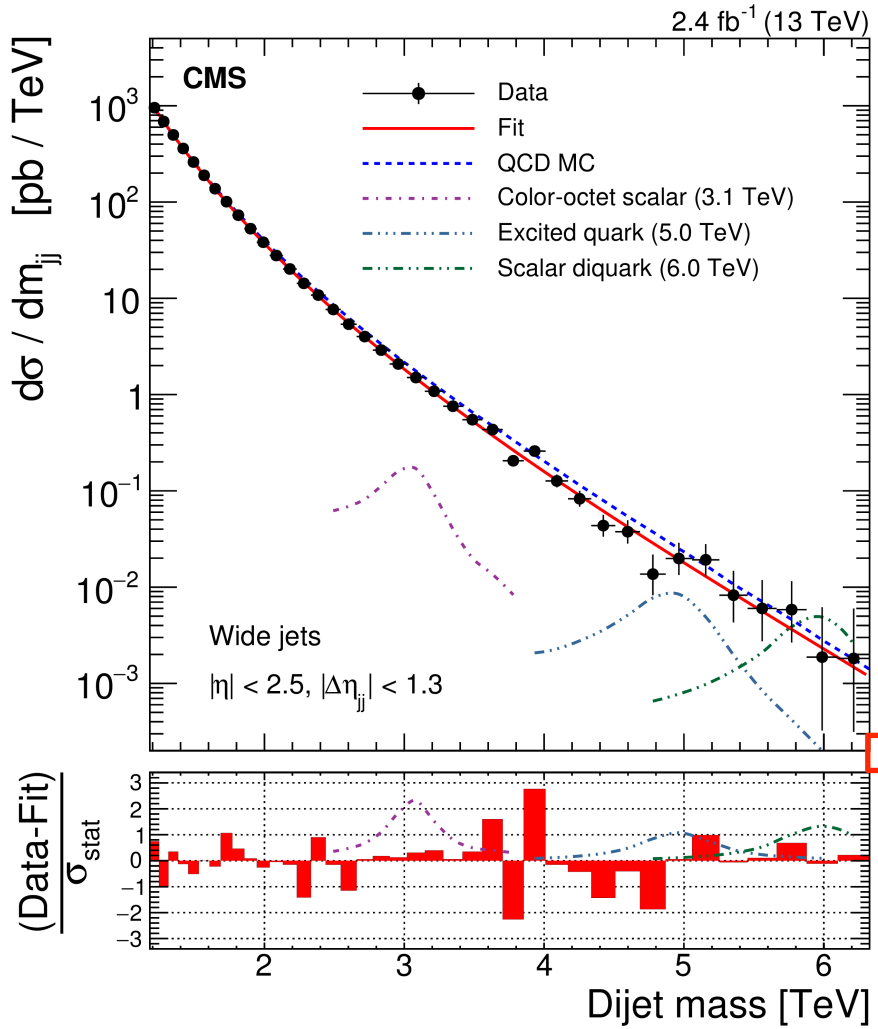


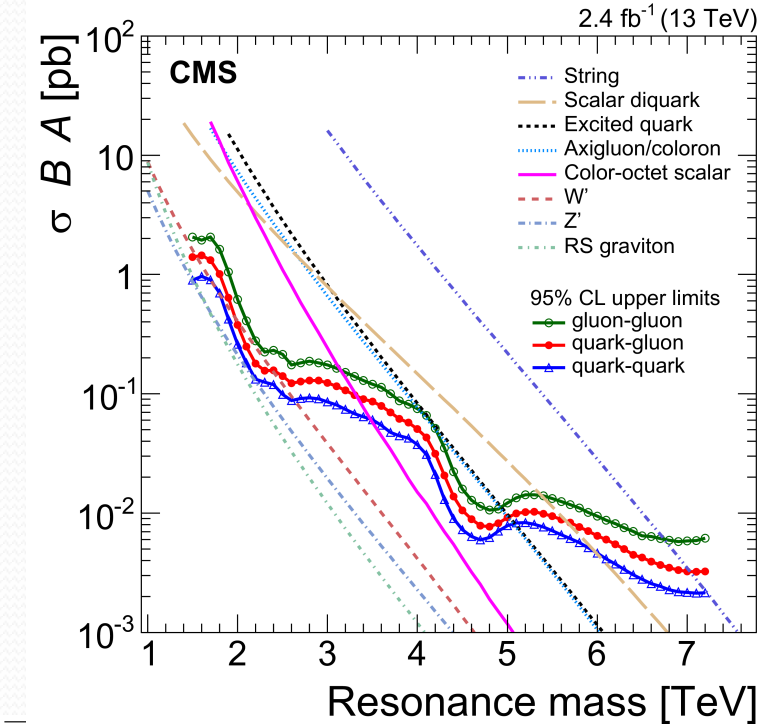
M_{jj}=5.4 TeV

Best Run 1 limit was 5.0 TeV

Model	Final State	Obs. Mass Limit [TeV]	Exp. Mass Limit [TeV]
String Resonance (S)	qg	5.1	5.2
Excited Quark (q*)	qg	2.7	2.9
Scalar Diquark (D)	qq	2.7	3.3
Axigluon (A)/Coloron (C)	$q\bar{q}$	2.7	2.9
Color Octet Scalar (s8)	gg	2.3	2.0

New Dijet Analysis

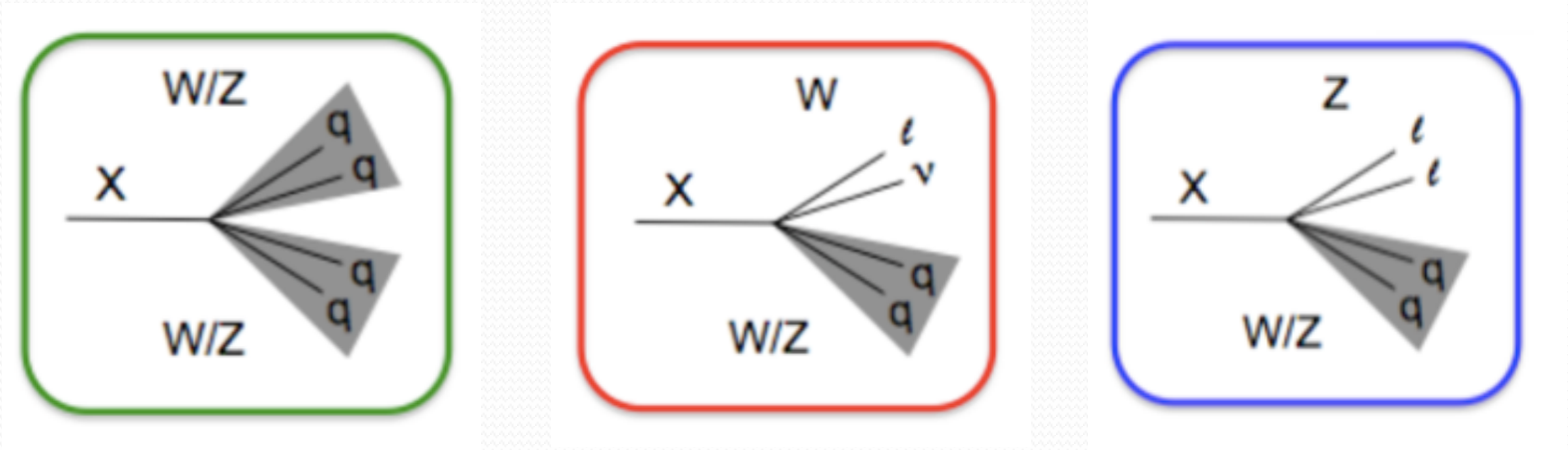


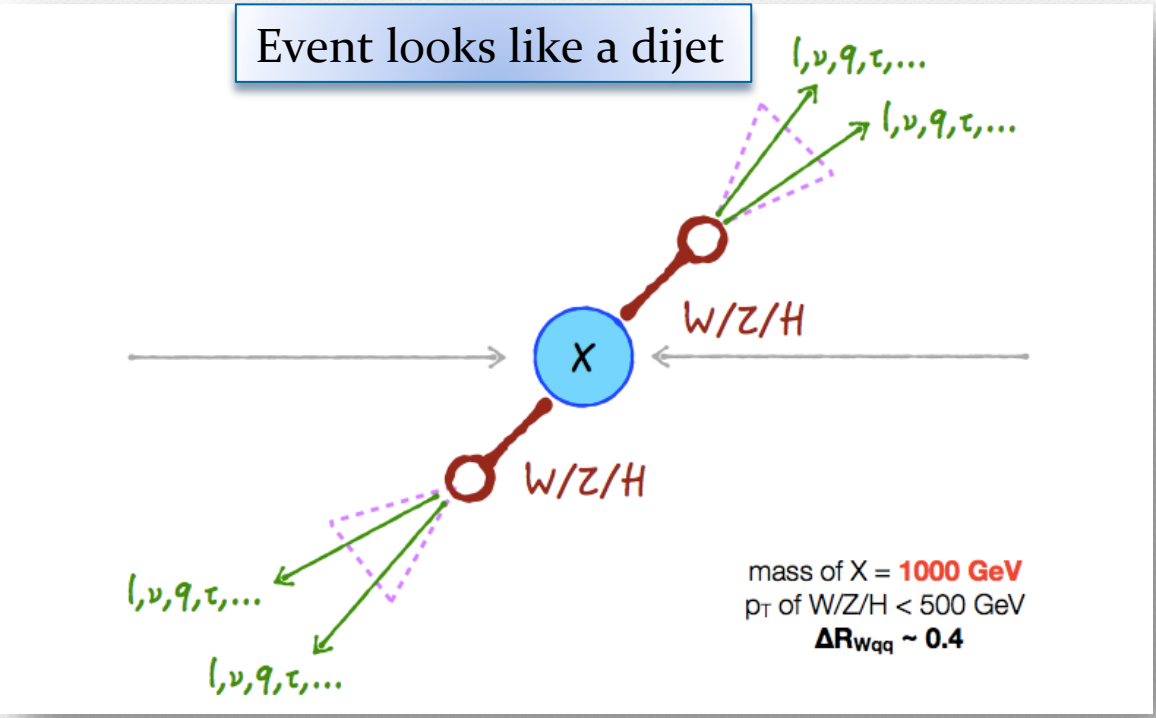


Model	Final State	Obs. Mass Limit [TeV]	Exp. Mass Limit [TeV]
String	qg	7.0	6.9
Scalar diquark	qq	6.0	6.1
Axigluon/coloron	$q\bar{q}$	5.1	5.1
Excited quark (q*)	qg	5.0	4.8
Color-octet scalar	gg	3.1	3.3
Heavy *PW* (W′)	$q\bar{q}$	2.6	2.3

Limits extended up to 7 TeV

Diboson resonances



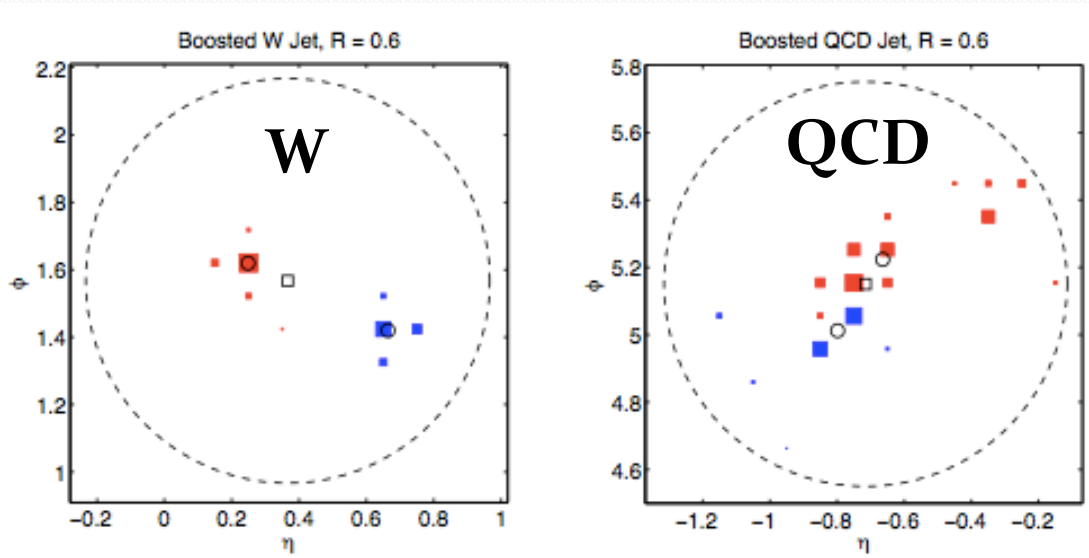


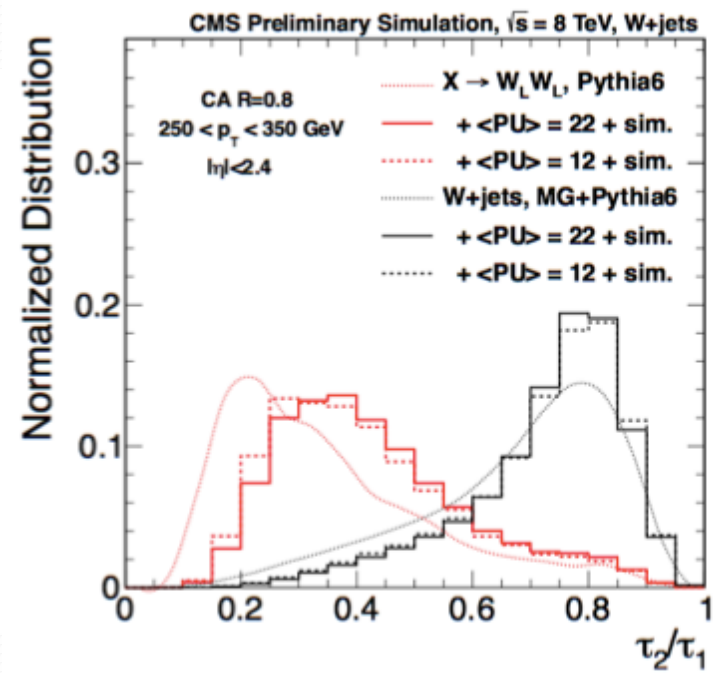
Above $M_X \approx 1$ TeV hadronic decay products of W/Z are reconstructed as a single jet object

W-tagging

N-subjettiness: a measure of how consistent a jet is with having N sub-jets

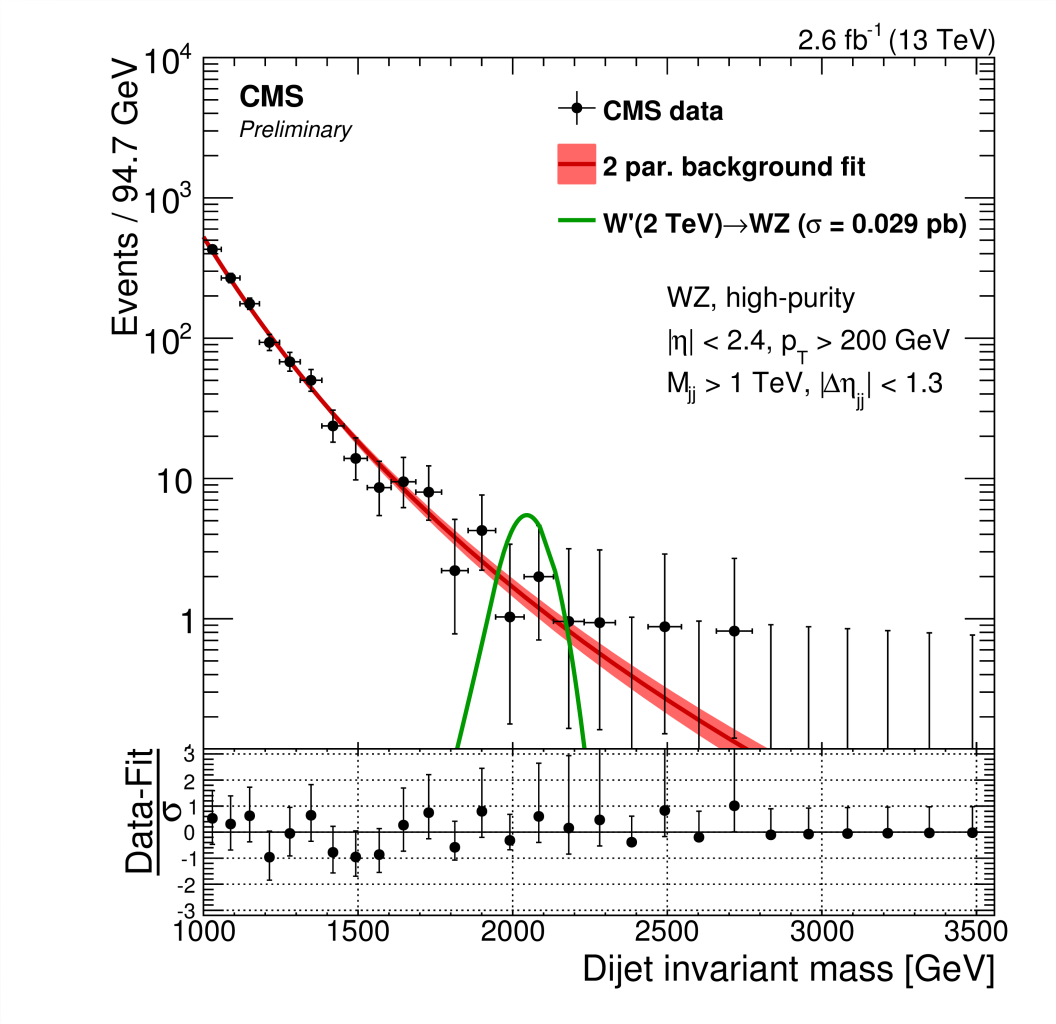
$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min\{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\}$$



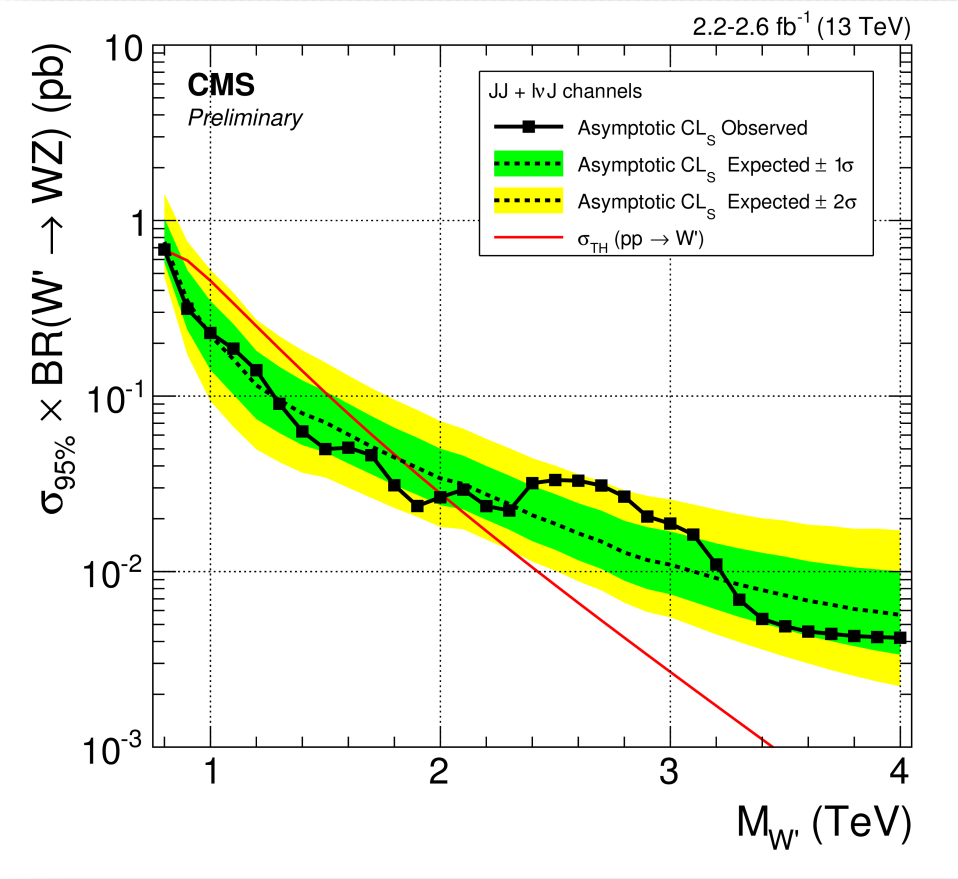


Used with M_{jet} to maximize S/B

Diboson resonances

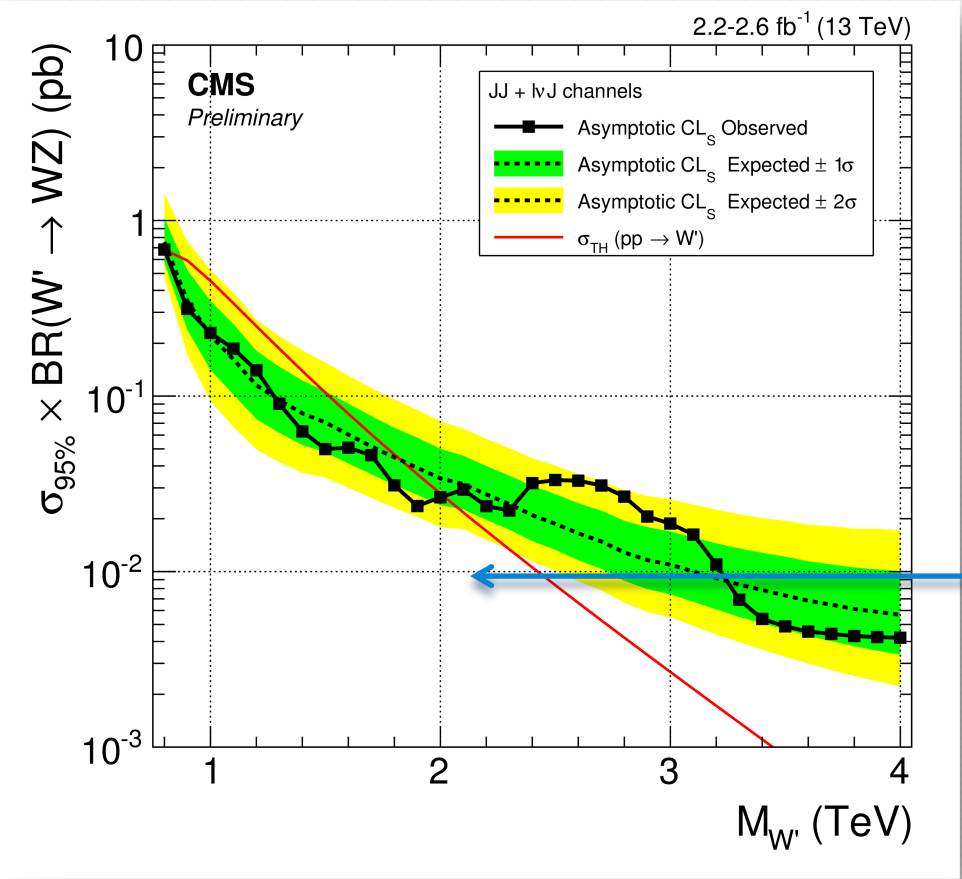


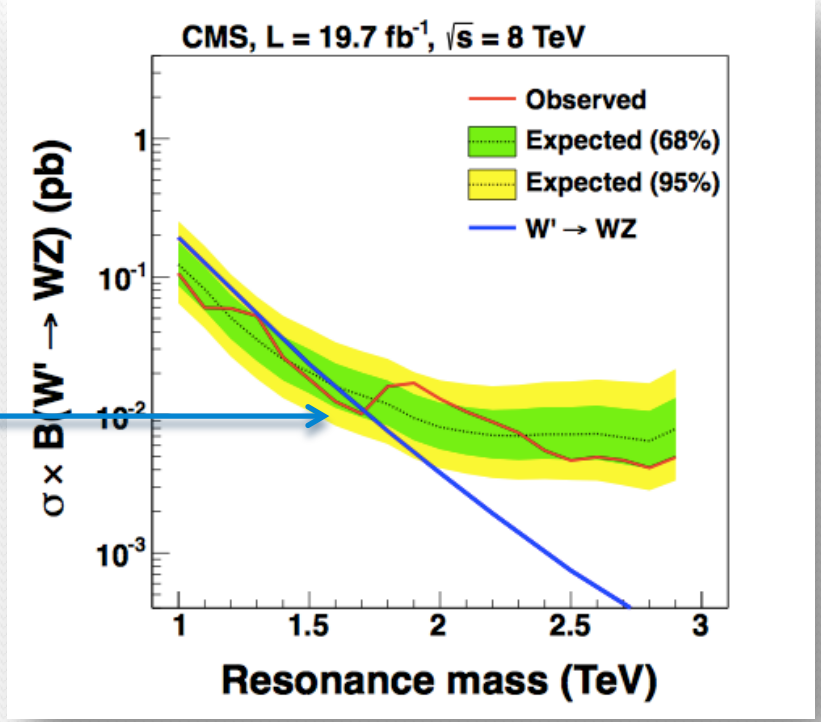
Diboson resonances



- No excess at 2 TeV
- Modest excess in 2.5-3.0 TeV range

Diboson resonances





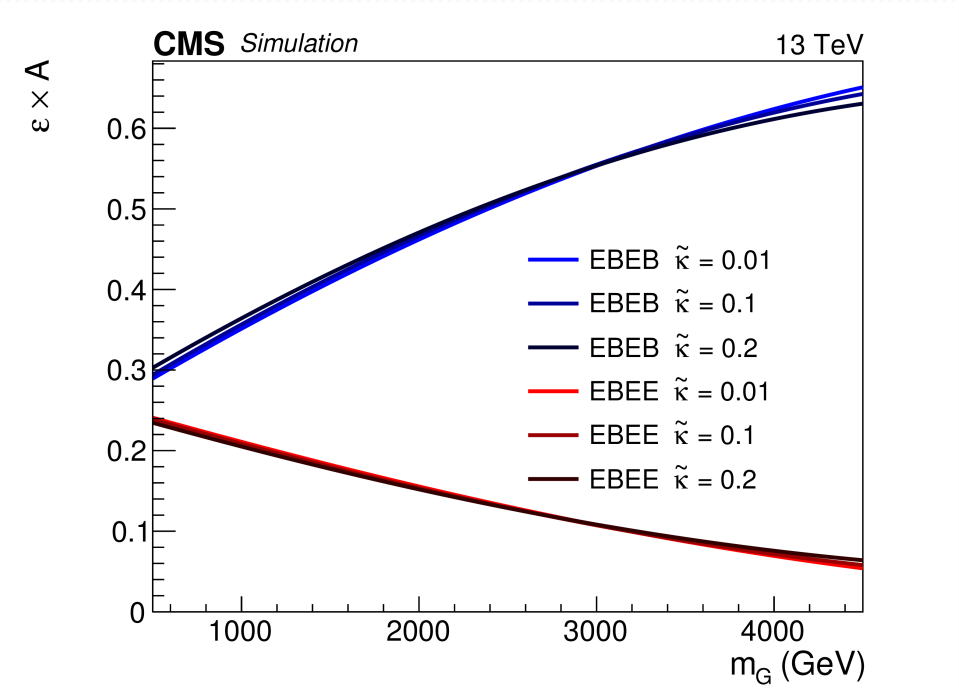
Have not yet achieved Run-1 sensitivity
Need more data for conclusive answer

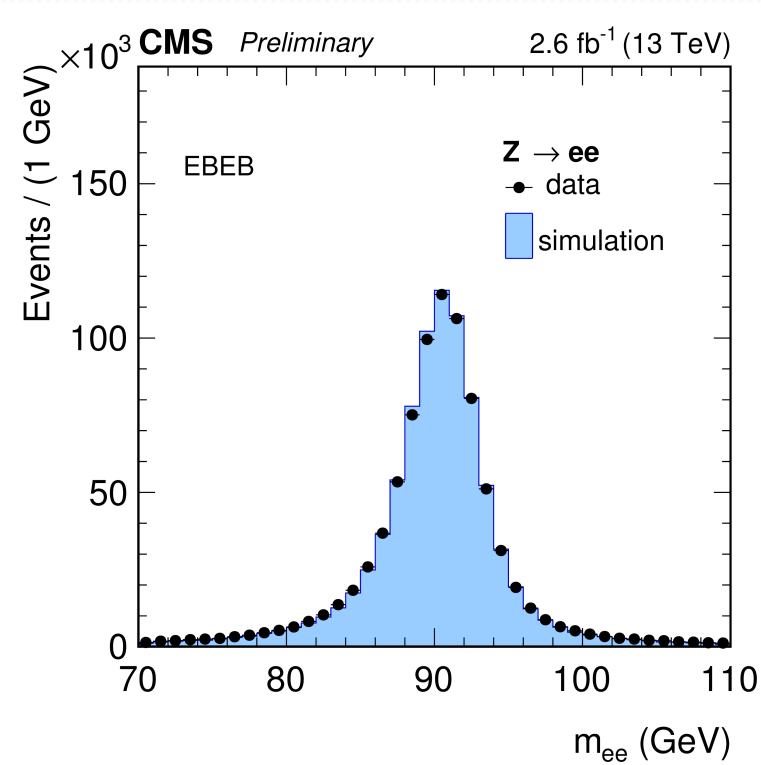
We also set limits on Graviton production

Diphoton resonances

- Two isolated photons (pT>75 GeV and |η|<2.5)
- Search range 500<Mγγ<4500 GeV
- RS graviton model as signal

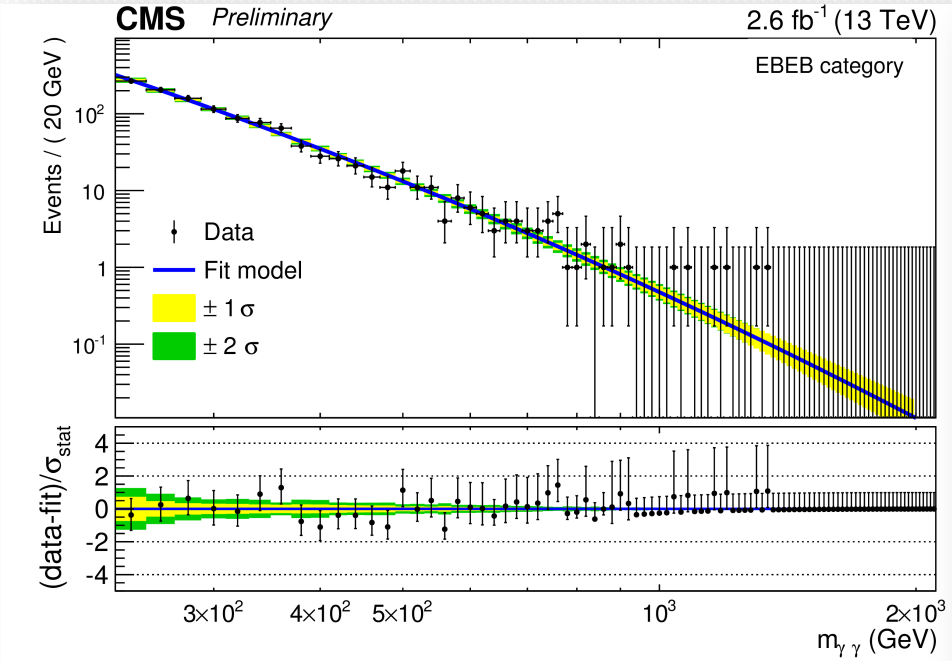
Events with both photons in the endcap (|η|>1.44) are rejected

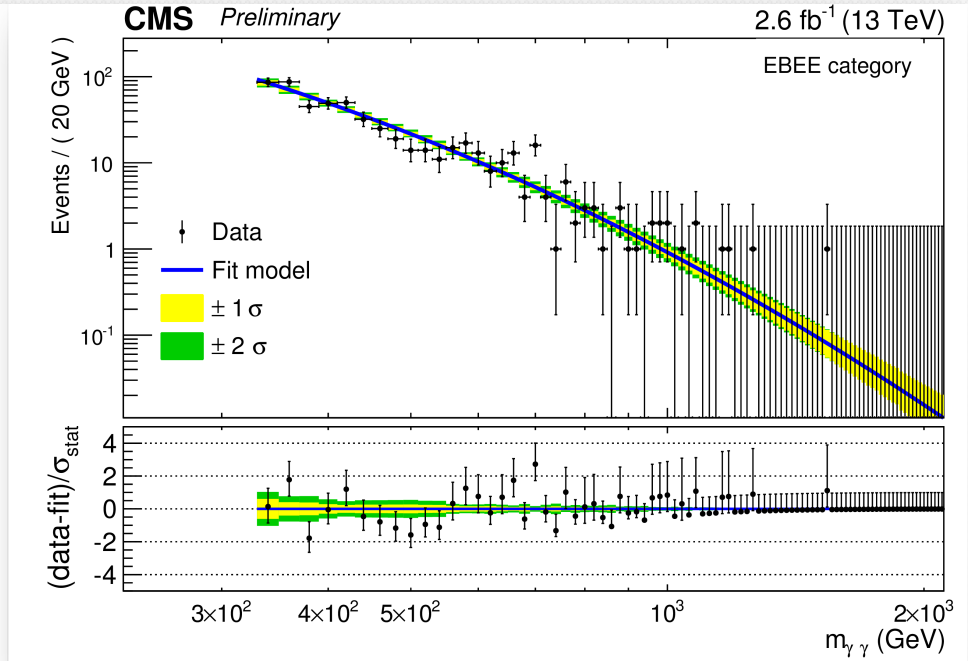




Diphoton resonances

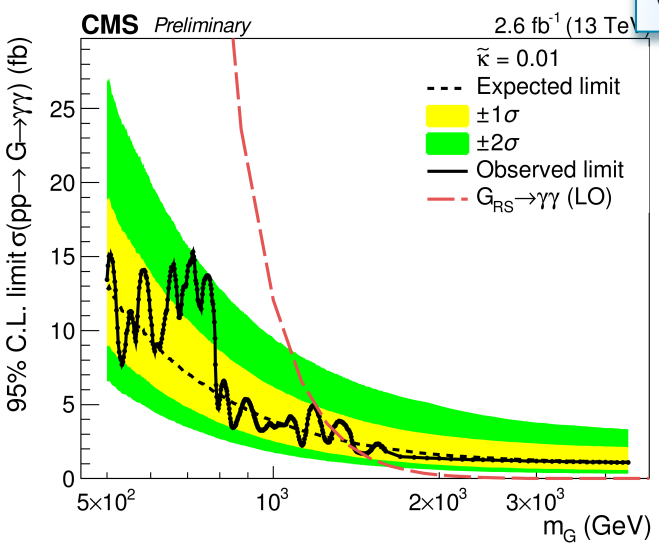
- Total of 1218 (596) diphoton pairs are selected in the EBEB (EBEE) category.
- 97 (163) diphoton pairs with an invariant mass above 500 GeV

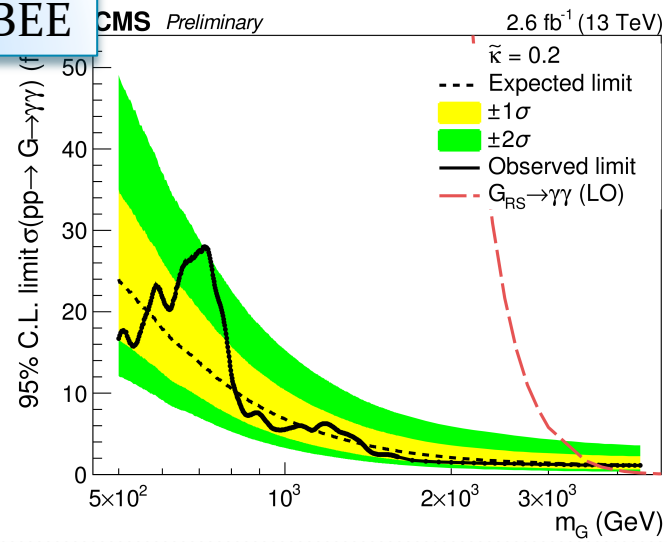




Diphoton resonances

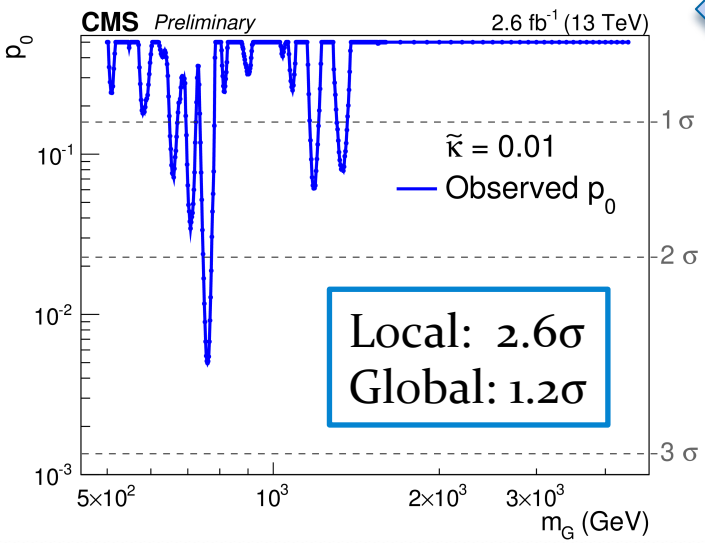
Combined EBEB and EBEE



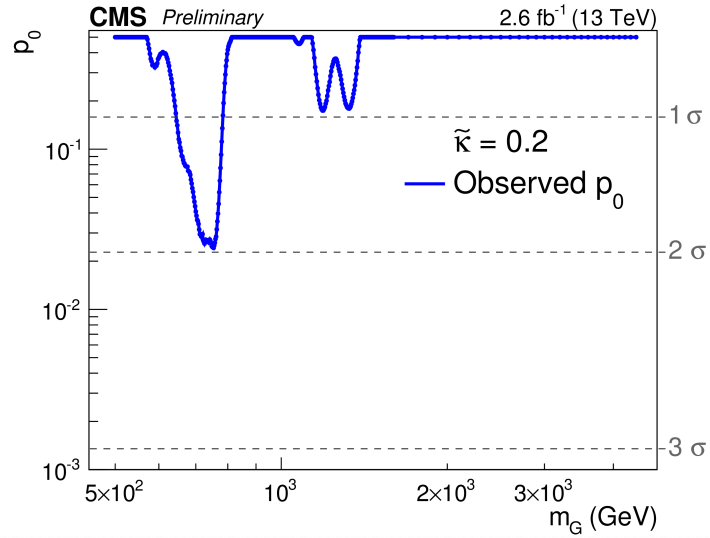


Narrower

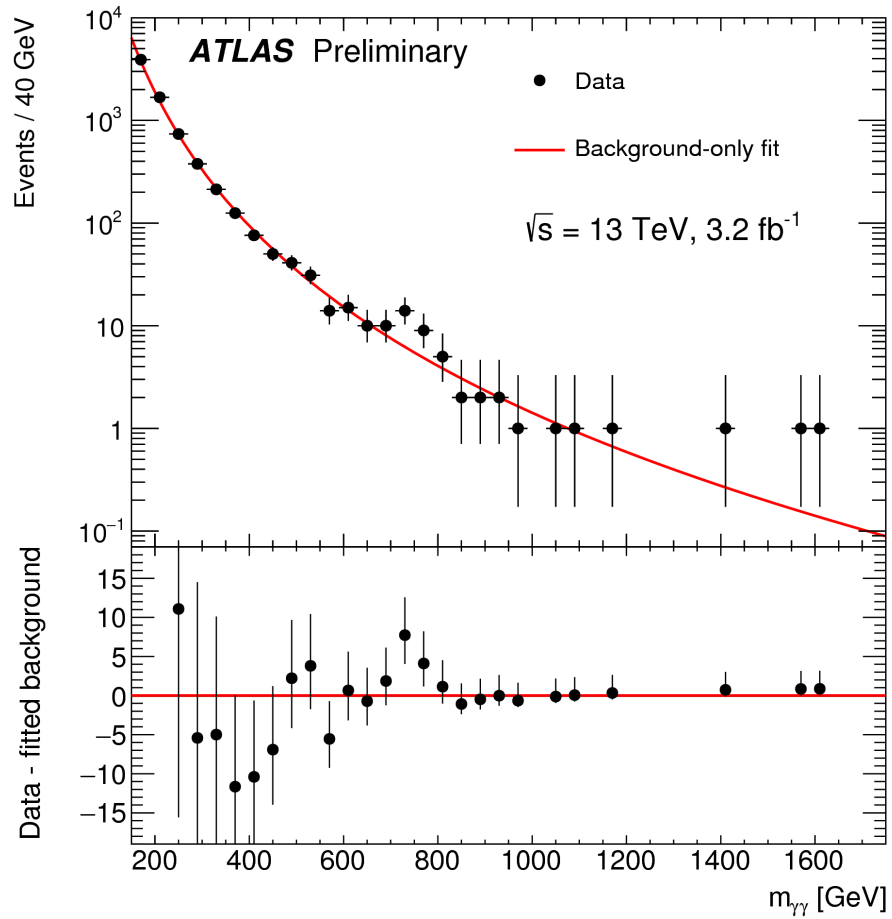
Wider



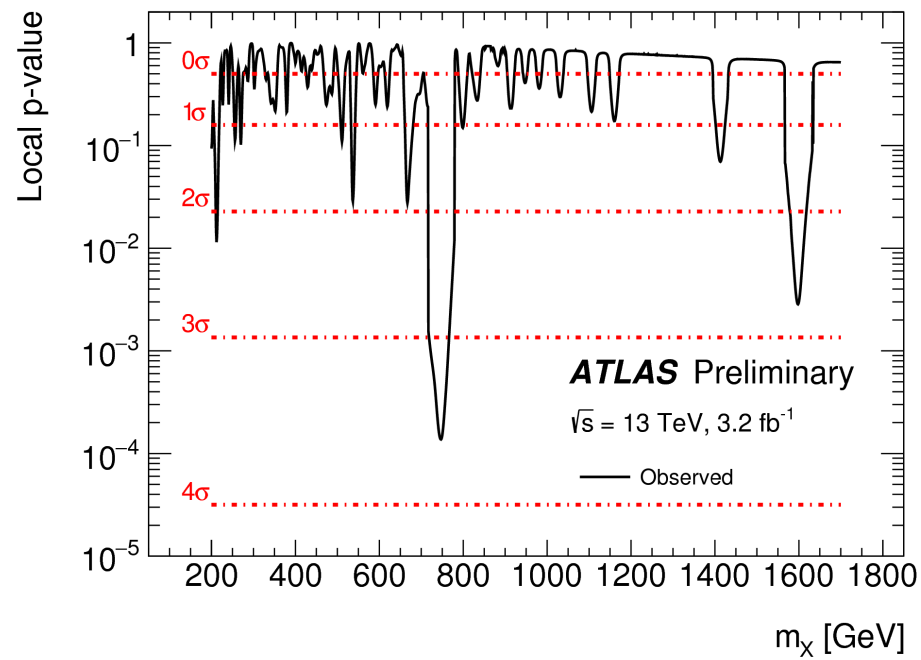
Local: 2.6σ
Global: 1.2σ



ATLAS diphotons



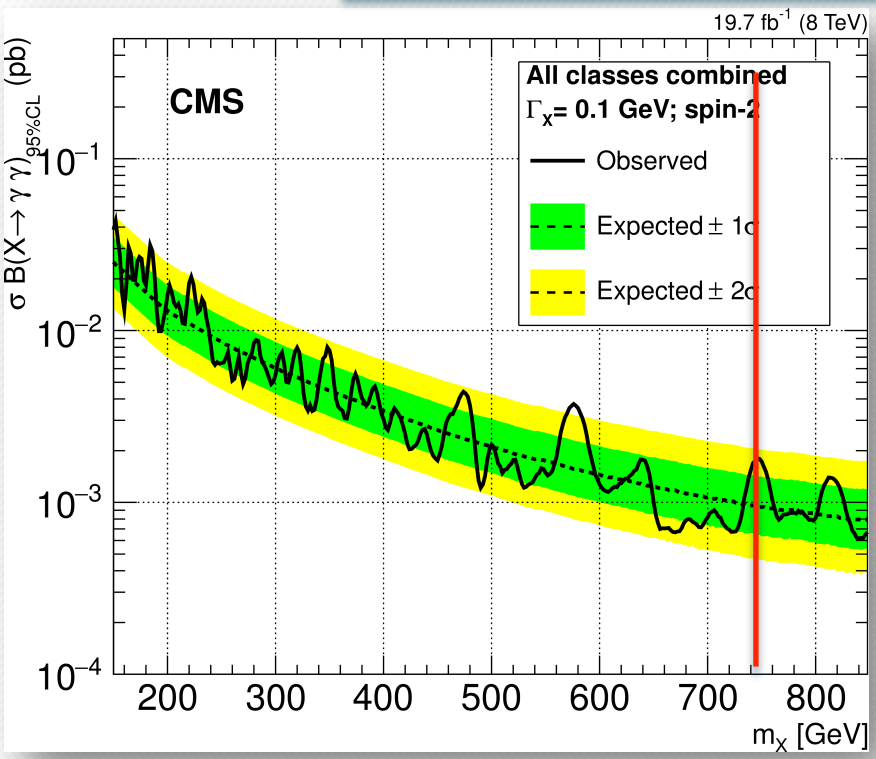
Narrow Width Approximation



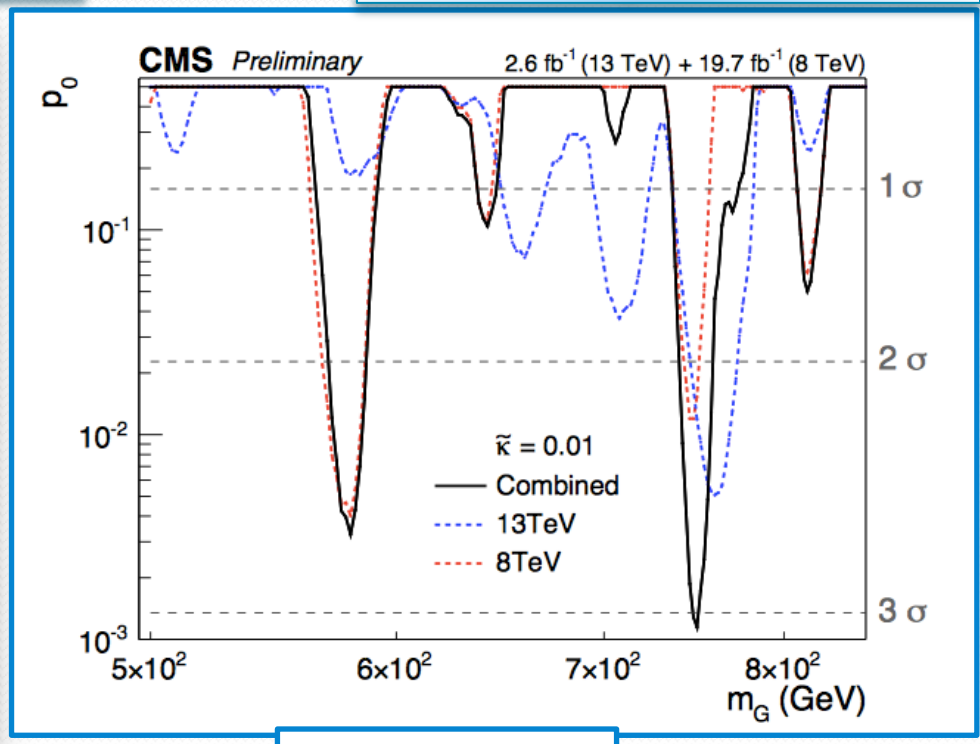
Local: 3.6σ
Global: 2.0σ

Diphoton resonances

8 TeV analysis (HIG-14-006)



Combined 13TeV and 8 TeV



Local: 3.0σ
Global: 1.7σ

On Inspire:

1. **Search for new physics in high mass diphoton events in proton-proton collisions at 13TeV**
   CMS Collaboration. 2015.
   CMS-PAS-EXO-15-004
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   CERN Document Server ; Link to Fulltext
   Detailed record - Cited by 125 records 100+

Since the submission on Dec 16th

- The 750 GeV diphoton resonance in the light of a 2HDM with S3 flavour symmetry
- Interpreting 750 GeV Diphoton Resonance in the NMSSM with Vector-like Particles
- Interpreting the 750 GeV diphoton excess in minimal extensions of Two-Higgs-Doublet models
- Implications of Gauge Invariance on a Heavy Diphoton Resonance
- Interpreting 750 GeV diphoton excess in SU(5) grand unified theory
- Interpreting the 750 GeV Di-photon Resonance using photon-jets in Hidden-Valley-like models
- The Minimal Scalar-Stealth Top Interpretation of the Diphoton Excess
- Higgs-radion interpretation of 750 GeV di-photon excess at the LHC
- Running after diphoton
- and many many others

On Inspire:

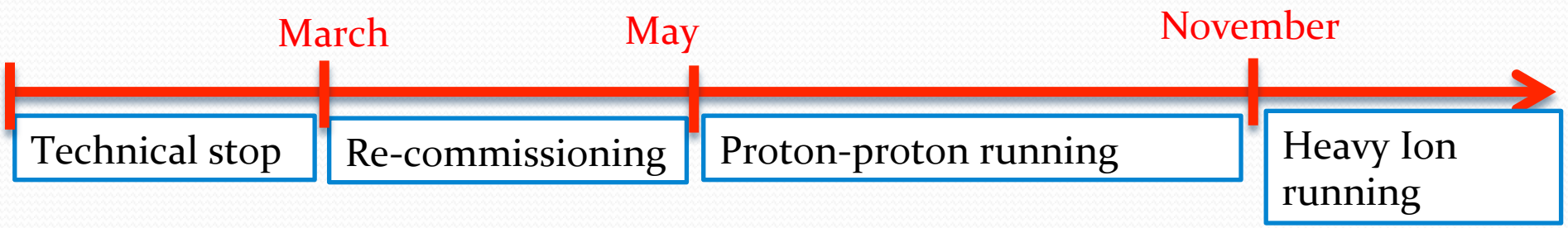
1. **Search for new physics in high mass diphoton events in proton-proton collisions at 13TeV**
CMS Collaboration. 2015.
CMS-PAS-EXO-15-004
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server ; Link to Fulltext
Detailed record - Cited by 125 records

- What is the origin of this excess?
- Is this a new particle? Couplings? Spin?
- How does it fit into bigger scheme of new physics?
- Are there more resonances? At what mass?
- Time and more data will tell!

Happy New Year 2016

From M.Lamont's talk at Evian'15 workshop

- In a new place – end of first year of operations after a long stop after Run 1.
- Having got over the hangover…



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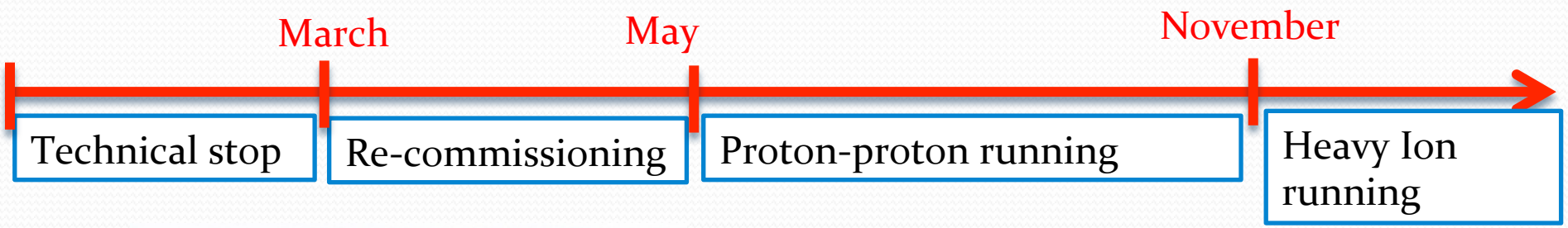


Expect:

- ~ 20 fb^{-1} in 2016
- ~100 fb^{-1} by end of 2018

What to expect in 2016?

More data helps:

- Improves statistics
- Better handle on systematics

What to expect in 2016?

More data helps:

- Improves statistics
- Better handle on systematics

- Differential X-Sections (BGs, PDFs)
- W/Z plus Heavy Flavor
- Multibosons, ttV
- Anomalous Couplings
- ....

Standard Model

What to expect in 2016?

More data helps:

- Improves statistics
- Better handle on systematics

- Differential X-Sections (BGs, PDFs)
- W/Z plus Heavy Flavor
- Multibosons, ttV

Higgs

- Interesting after ~5 fb^{-1}
- (Anomalous) Couplings, Mass, Width
- H->bb after ~10 fb^{-1}
- ttH after ~20 fb^{-1}

W&C by Si Xie:
http://theory.fnal.gov/jetp/talks/Si-FNALWineAndCheese20150515.pdf

What to expect in 2016?

More data helps:

- Improves statistics
- Better handle on systematics

- Differential X-Sections (BGs, PDFs)
- W/Z plus Heavy Flavor
- Multibosons, ttV

- Interesting after ~5 fb^{-1}
- (Anomalous) Couplings, Mass, Width
- H->bb after ~10 fb^{-1}
- ttH after ~20 fb^{-1}

W&C by Si Xie:
http://theory.fnal.gov/jetp/talks/Si-FNALWineAndCheese20150515.pdf

- Watch early excesses

New Physics

- Extend the reach. Need to ~double the dataset.
- 3rd gen SUSY with 5-10 fb^{-1}.
- Electroweak ~20-30 fb^{-1}

Conclusions

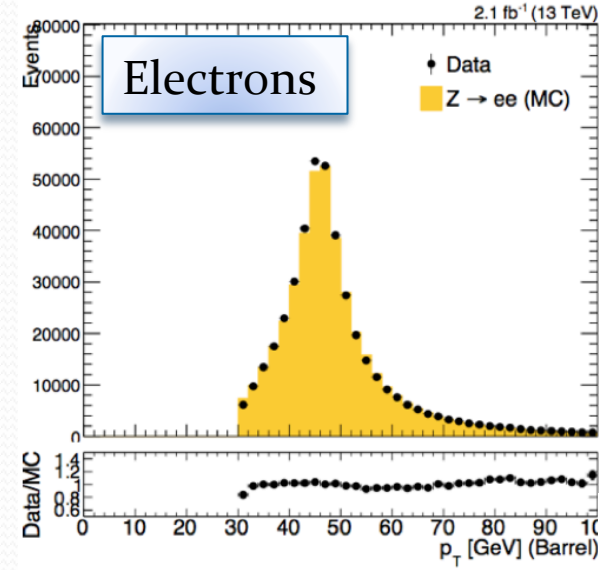
- CMS had great year coming out of shutdown. Feels great to be running again!!!
- With 2.8 fb^{-1} of data we are in the uncharted waters
- Expect new/updated results based on 2015 dataset by Moriond. More by ICHEP and end of the year 2016.
- Next year promises to be exciting, with rich physics program ahead. Stay tuned for updates

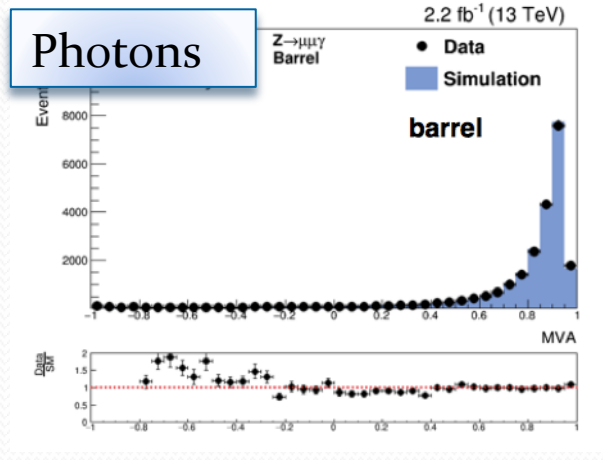
Fireworks in
Geneva, Switzerland
on New Years Eve

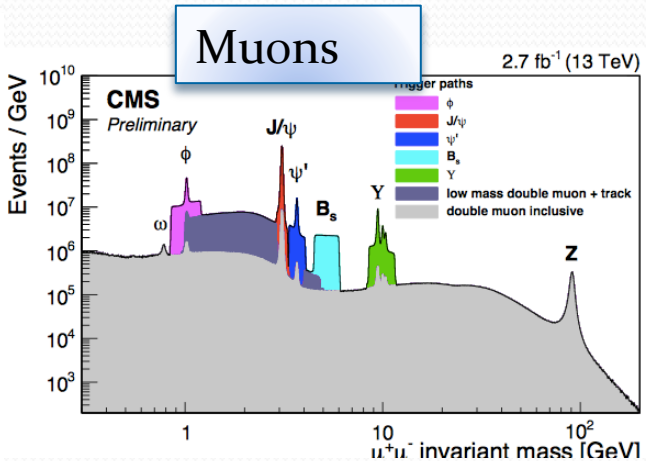
Backup

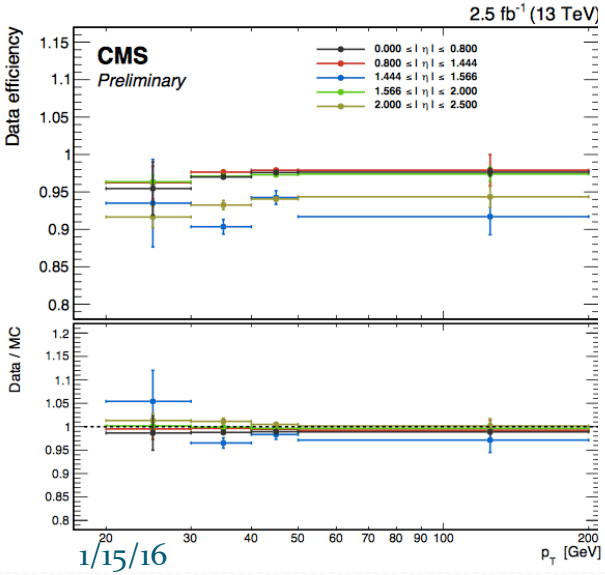
Physics objects

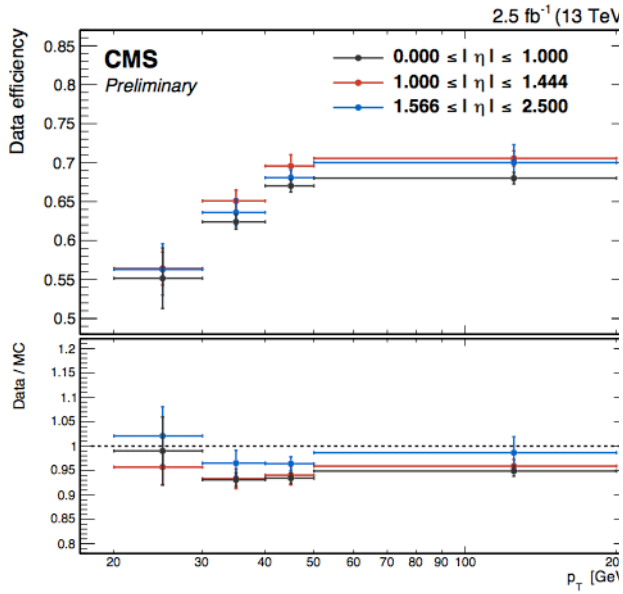
Lepton identification and energy scale

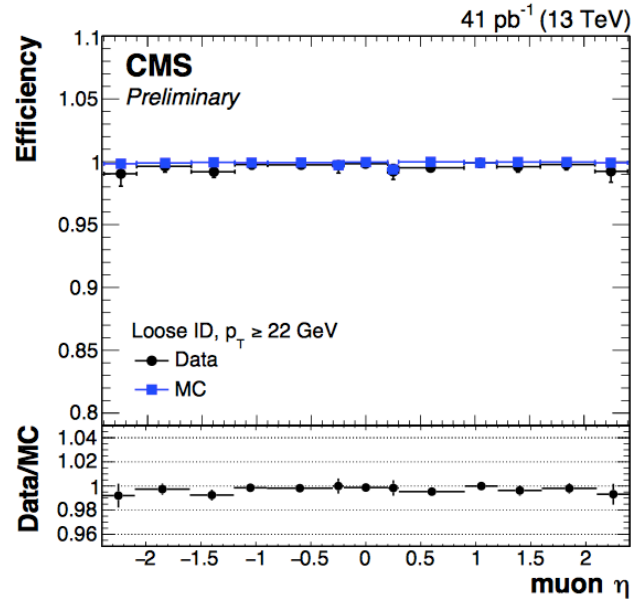








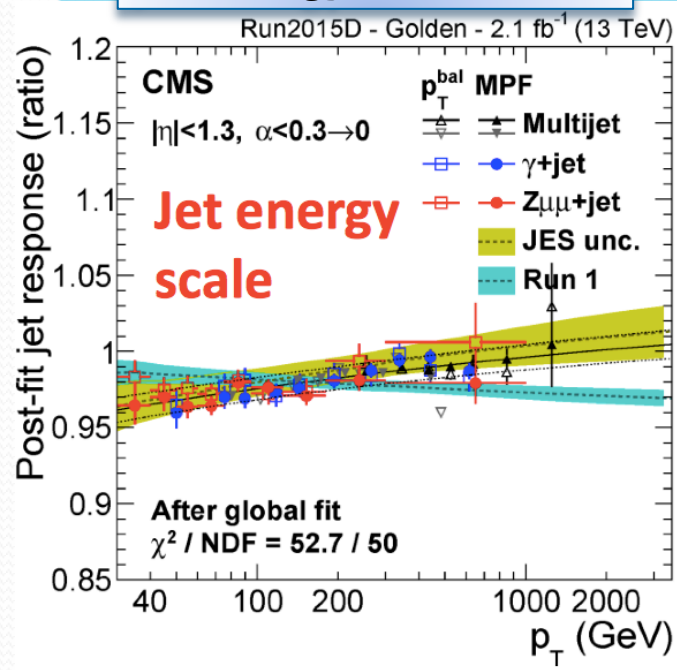




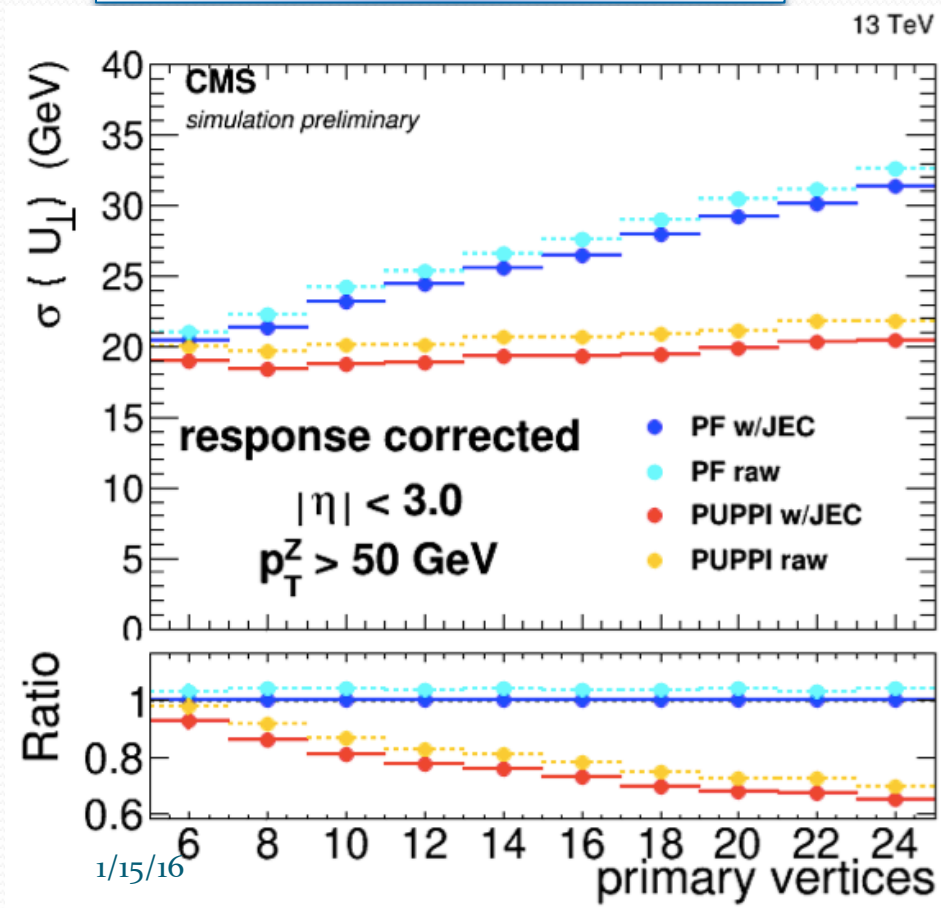
Physics objects

Jet/MET energy scale and resolution, b-tagging

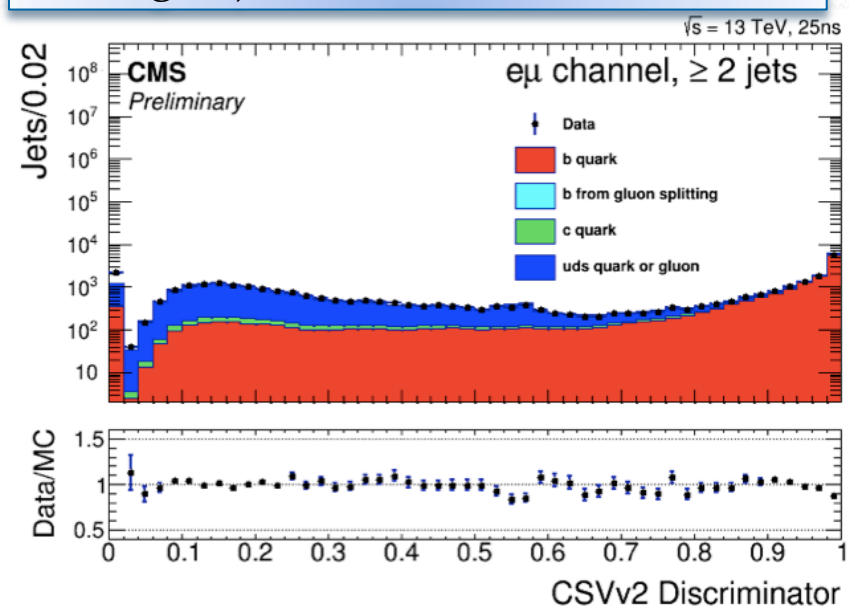
Jet Energy Scale



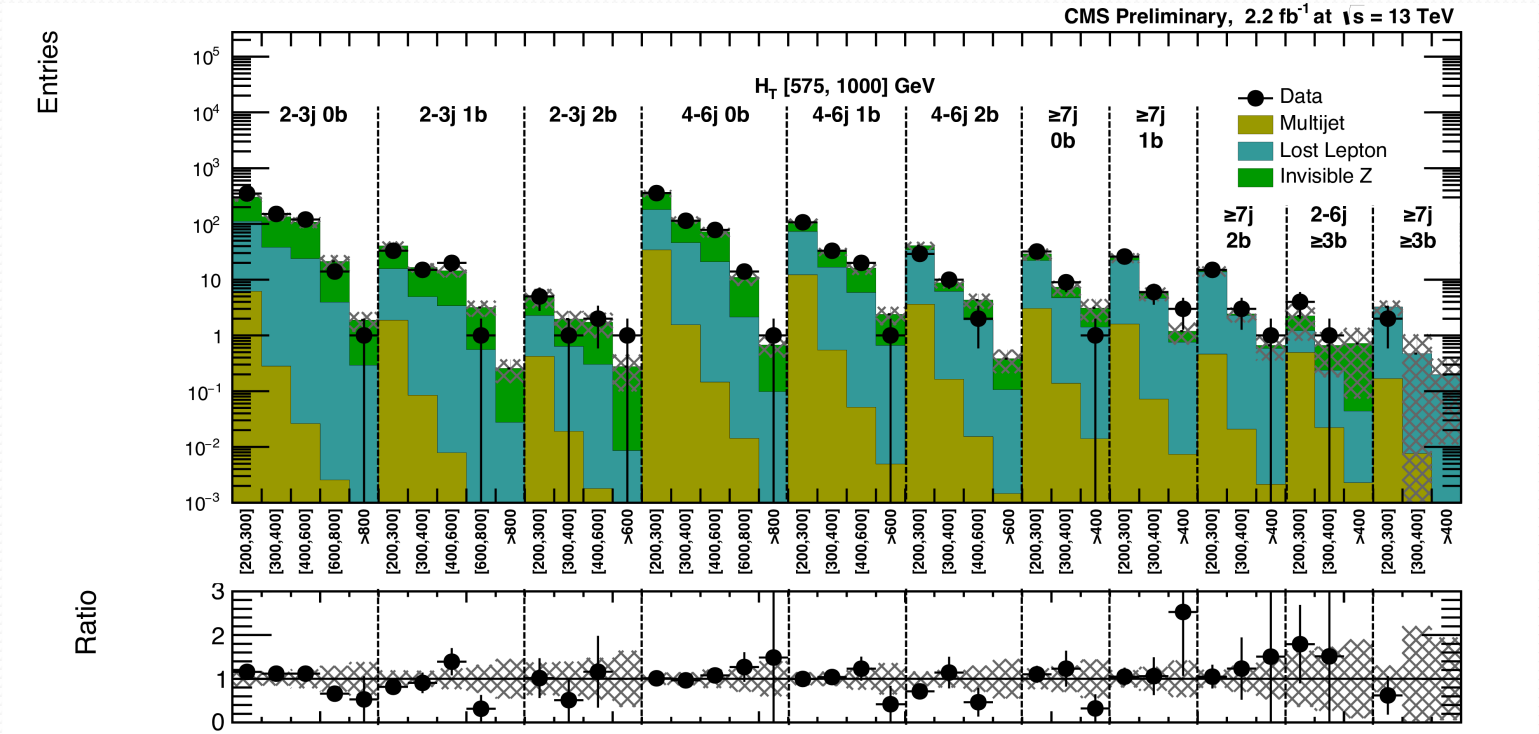
MET resolution from Z events



B vs light-jet discriminator



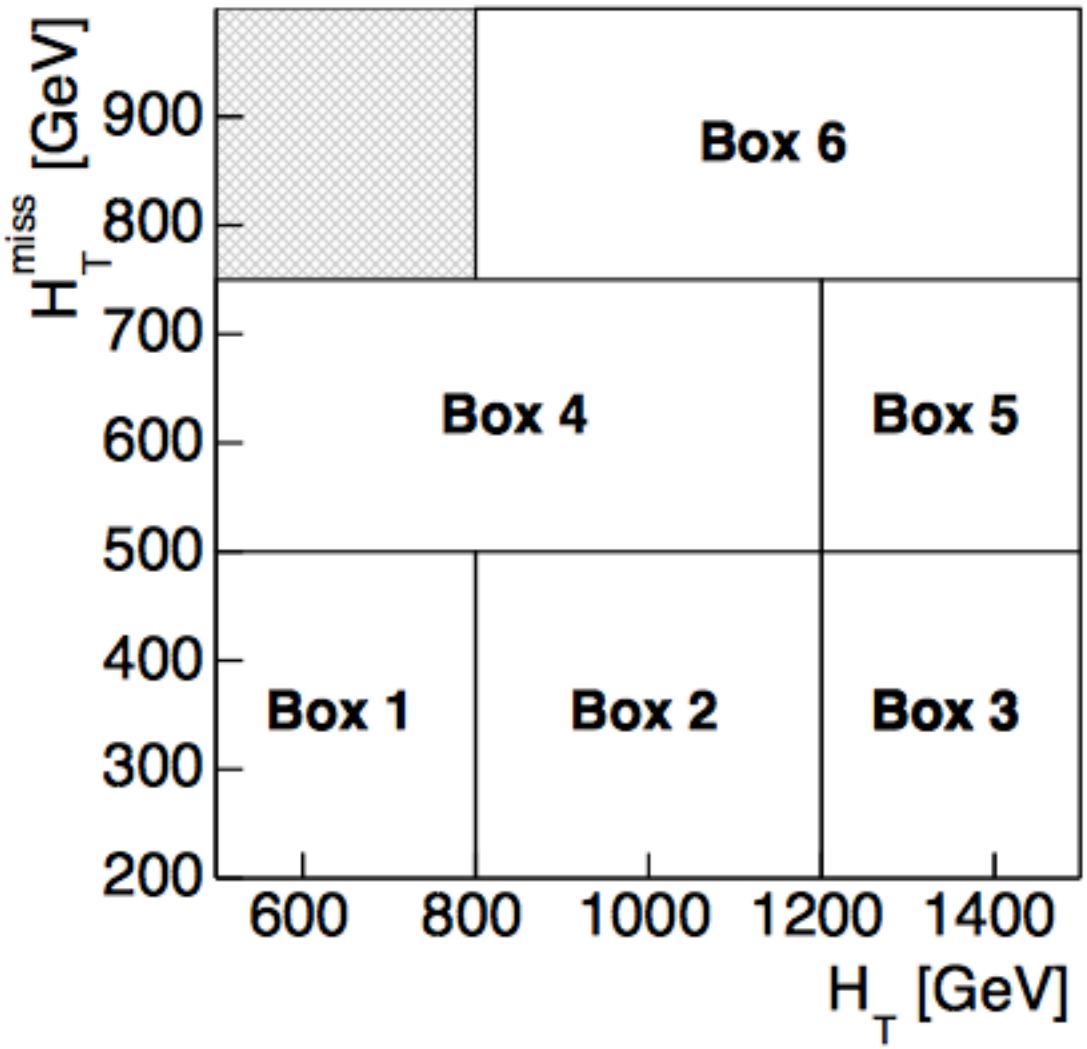
SUSY hadronic



Backgrounds:

- QCD – can be strongly suppressed with MET and topological cuts
- Z+jets -> νν + jets
- Lost lepton (W+jets, top, dibosons) with lepton not reconstructed in the detector

SUSY hadronic RA2

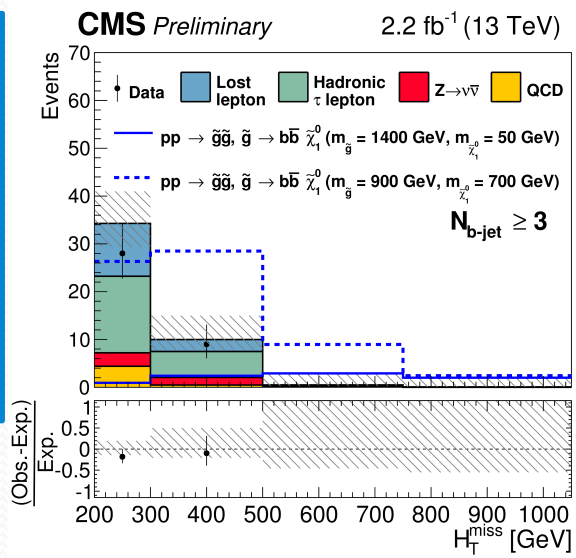


SUSY hadronic

HT+MHT, M_{T2}, αT, "Razor"

Classic case HT +MHT:

- HT: scalar sum of the jet pT's
- MHT: negative vectorial sum of jet PT's



Razor:

$$M_T^R = \sqrt{\frac{E_T^{miss}(p_T^{j_1} + p_T^{j_2}) - \vec{E}_T^{miss} \cdot (\vec{p}_T^{j_1} + \vec{p}_T^{j_2})}{2}}$$

$$M_R = \sqrt{(|\vec{p}_{j_1}| + |\vec{p}_{j_2}|)^2 - (p_z^{j_1} + p_z^{j_2})^2}$$

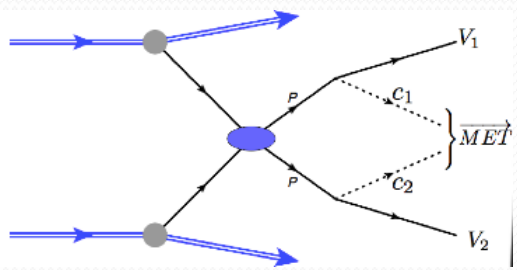
$$R = \frac{M_T^R}{M_R}$$

- Bin in M_R and R
- Large R for signal, small for QCD

M_{T2} (Stranverse mass):

$$M_{T2}(m_c) = \min_{p_T^{c(1)} + p_T^{c(2)} = p_T^{miss}} \left[\max\left(m_T^{(1)}, m_T^{(2)}\right)\right]$$

- in case the mass of the unobserved child m_c were known, the endpoint of M_{T2} would correspond to the parent mass m_p.



AlphaT:

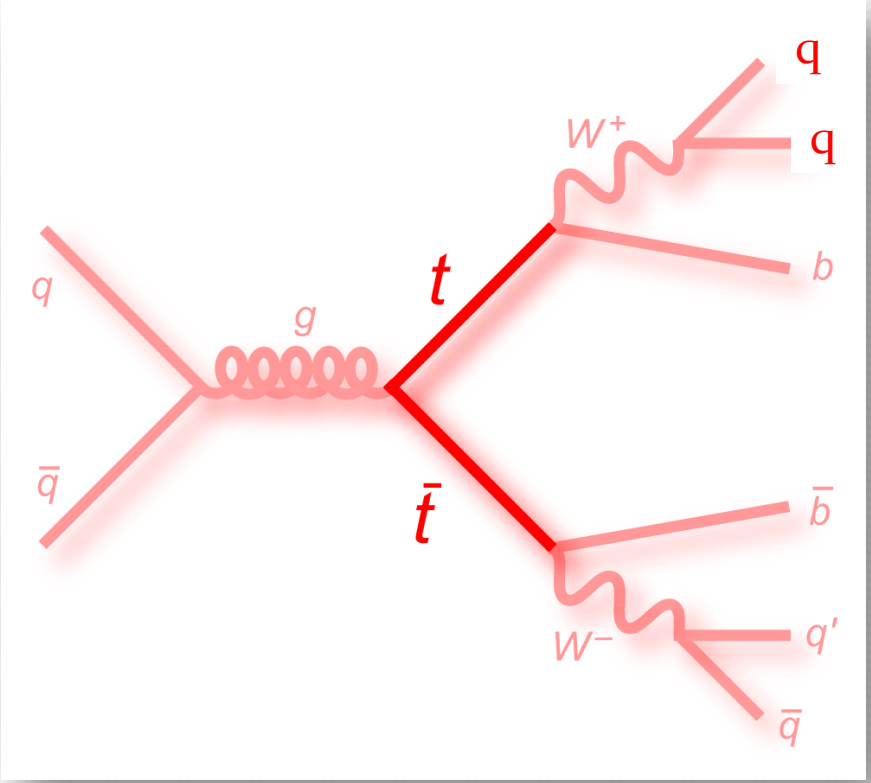
$$\alpha_T = \frac{E_T^{j_2}}{M_T}$$

peaks at 0.5 for QCD!

$$M_T = \sqrt{\left(\sum_{i=1}^{2} E_T^{j_i}\right)^2 - \left(\sum_{i=1}^{2} p_x^{j_i}\right)^2 - \left(\sum_{i=1}^{2} p_y^{j_i}\right)^2}.$$

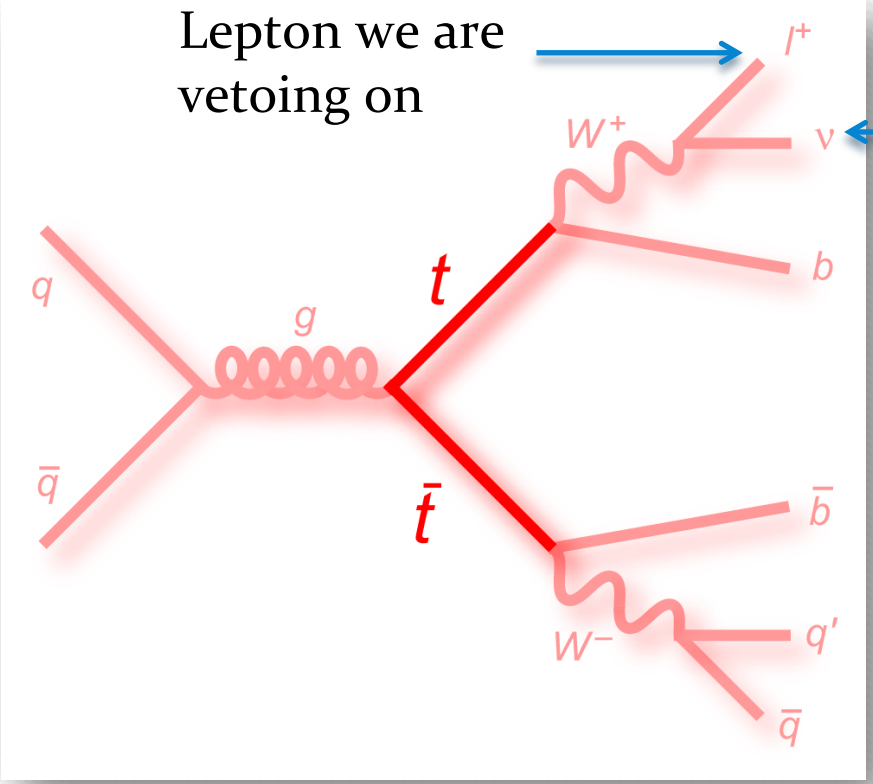
For SUSY MT2~MET, for QCD MT2<<MET

SUSY hadronic



- No real E_T^{miss}
- Removed by large E_T^{miss} requirements

SUSY hadronic

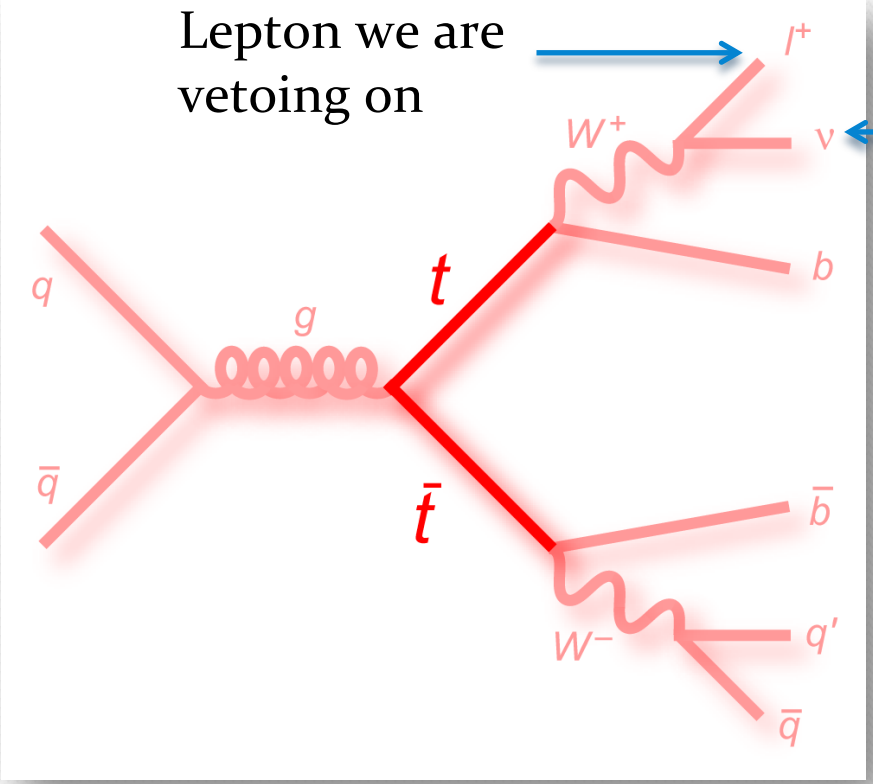


Real E_T^{miss} from the neutrino

Probability of top event to pass lepton veto:

- Electrons ~30%
- Muons ~20%
- Taus ~50%

SUSY hadronic



Real E_T^{miss} from the neutrino

Primarily interested in modeling of hadronic recoil

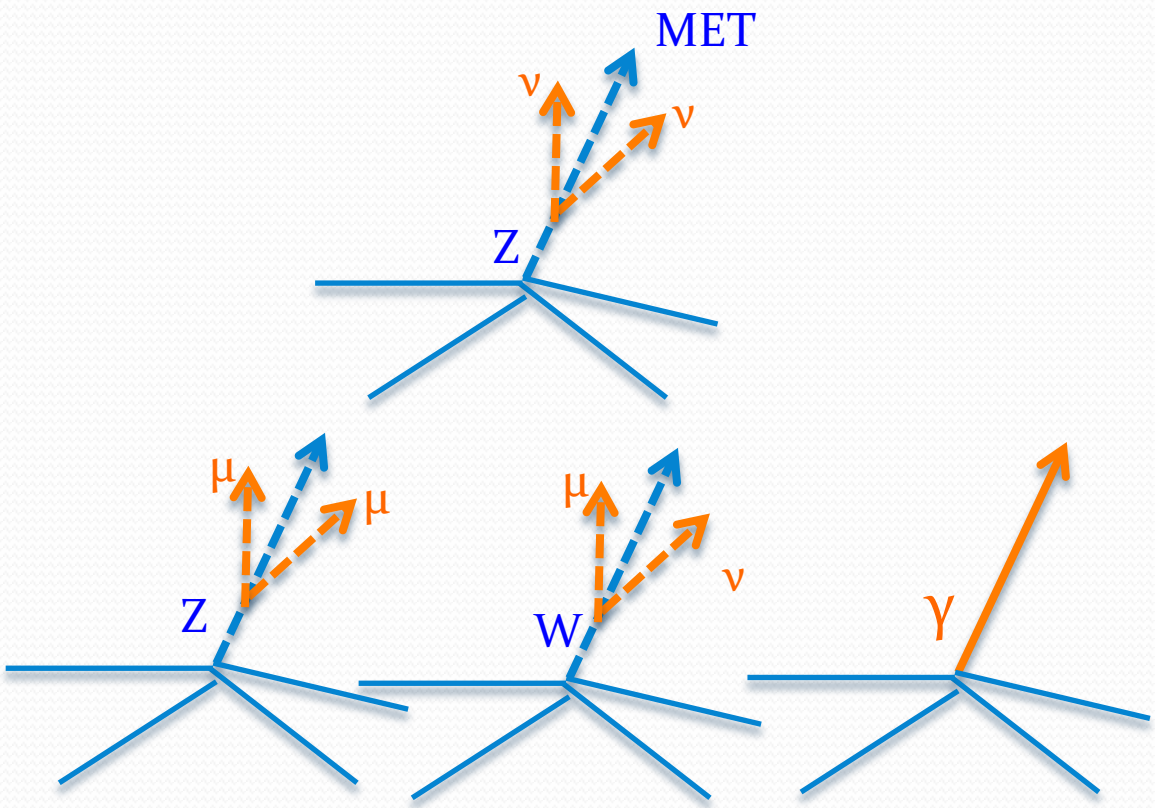
Control Region: 1- lepton → Signal Region: 0- leptons

Extrapolate using MC corrected for lepton id/reco effects

SUSY hadronic

Irreducible Z+jets ->νν+jets background

- Use similar signatures in data
- Project into search region



Clean and direct, But low stats.

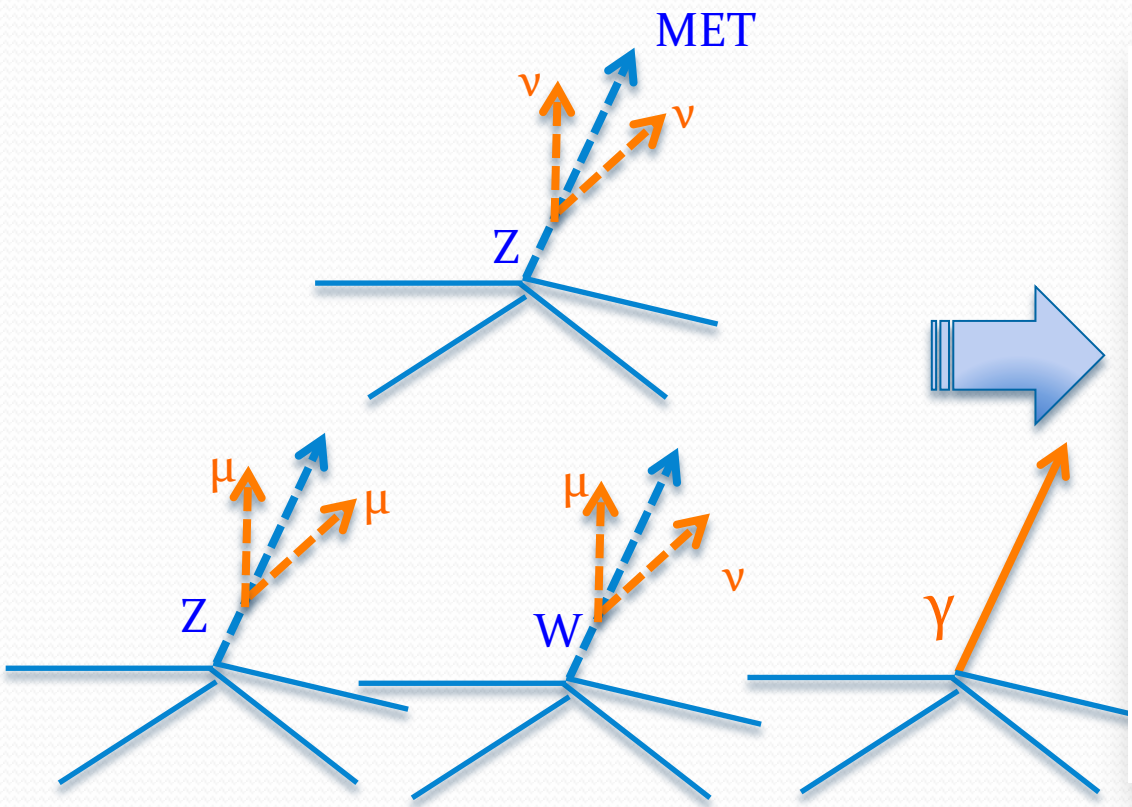
Large stats, but has BG and theory uncertainties

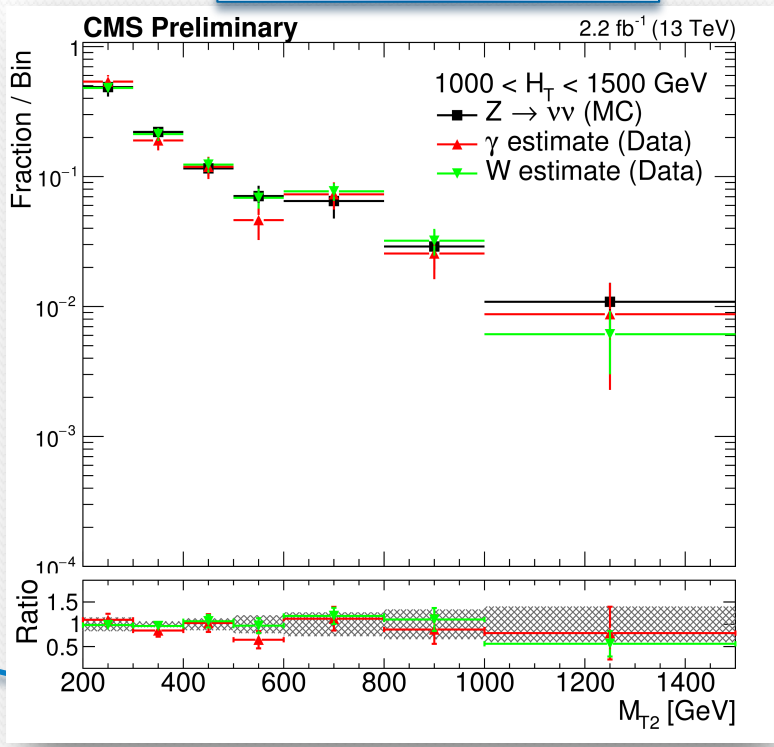
SUSY hadronic

Irreducible Z+jets ->νν+jets background

- Use similar signatures in data
- Project into search region

We use all of them



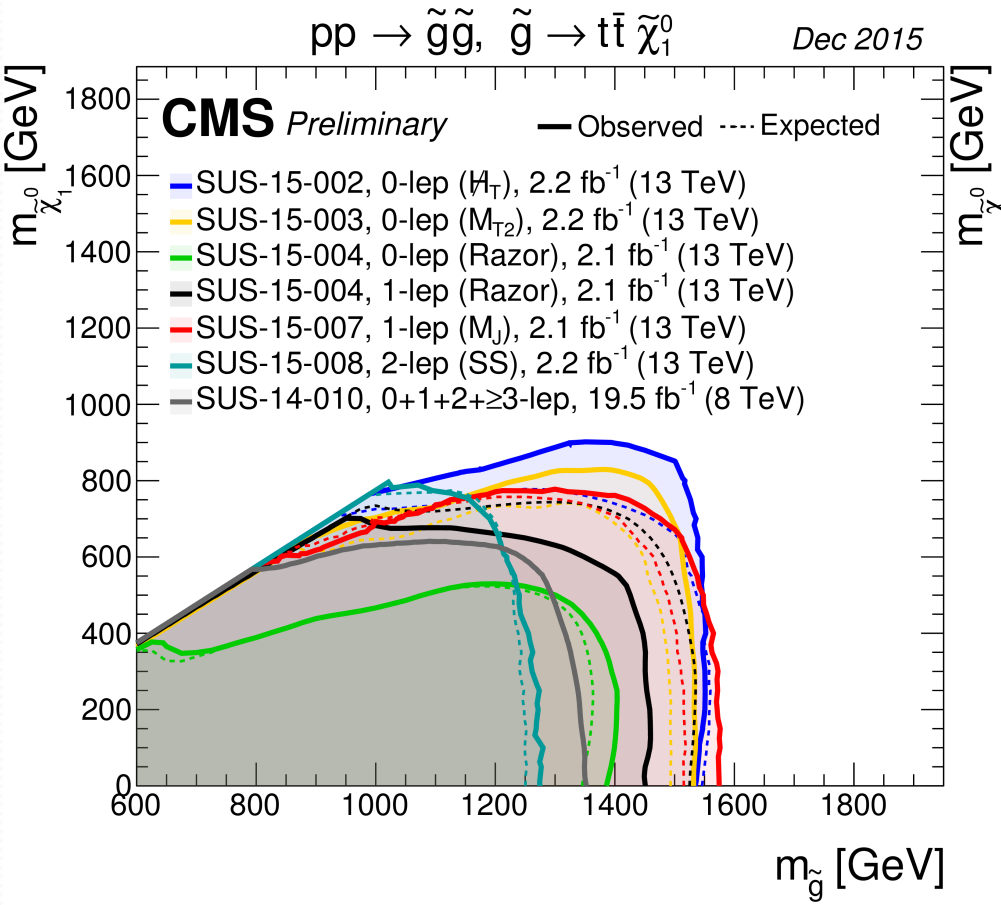


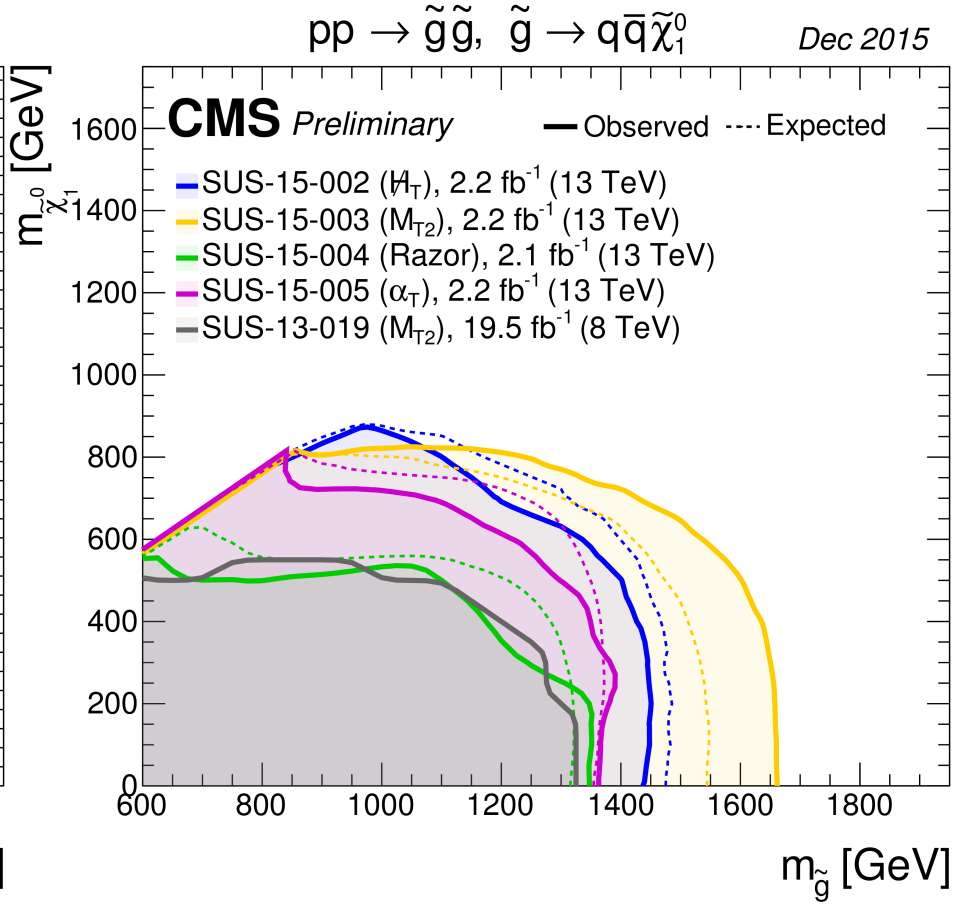
Clean and direct, But low stats.

Large stats, but has BG and theory uncertainties

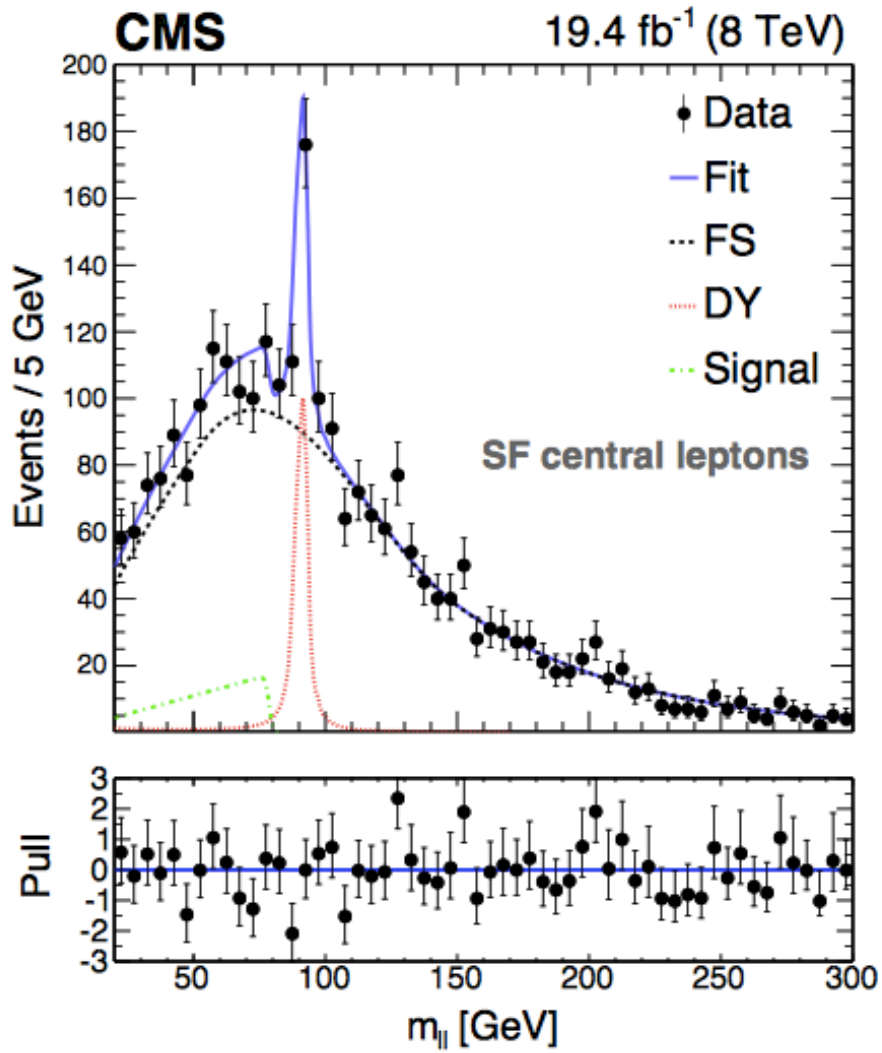
SUSY hadronic

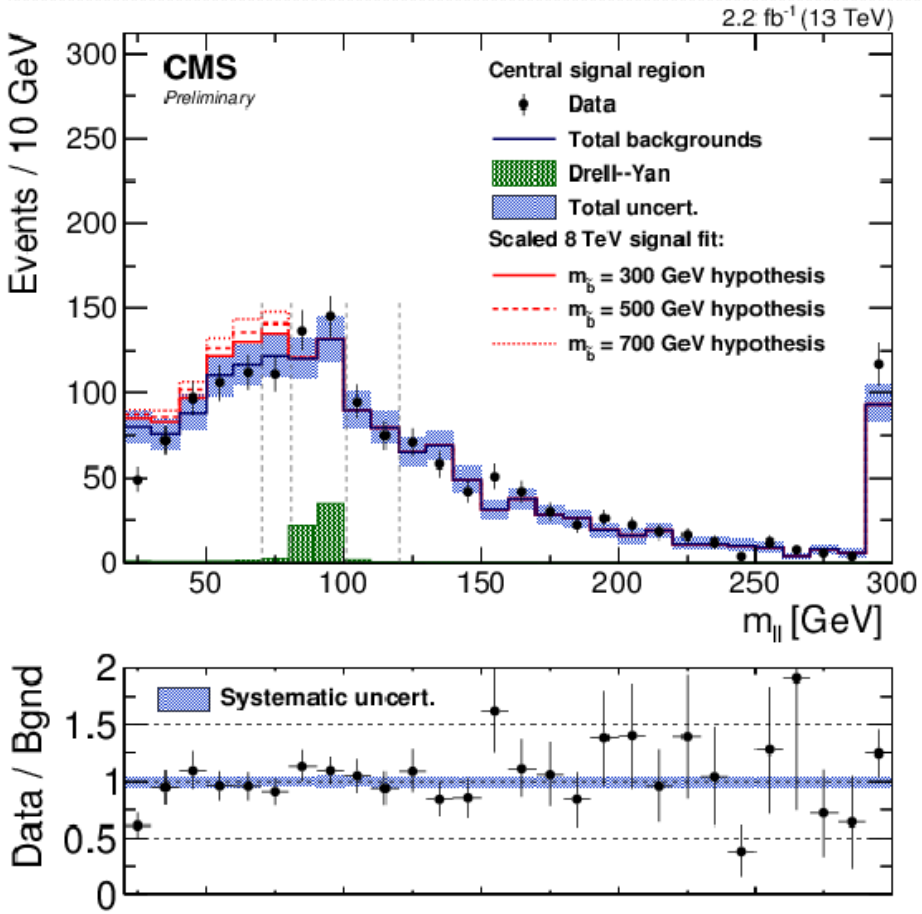
- Set limits in (gluino, LSP) mass plane



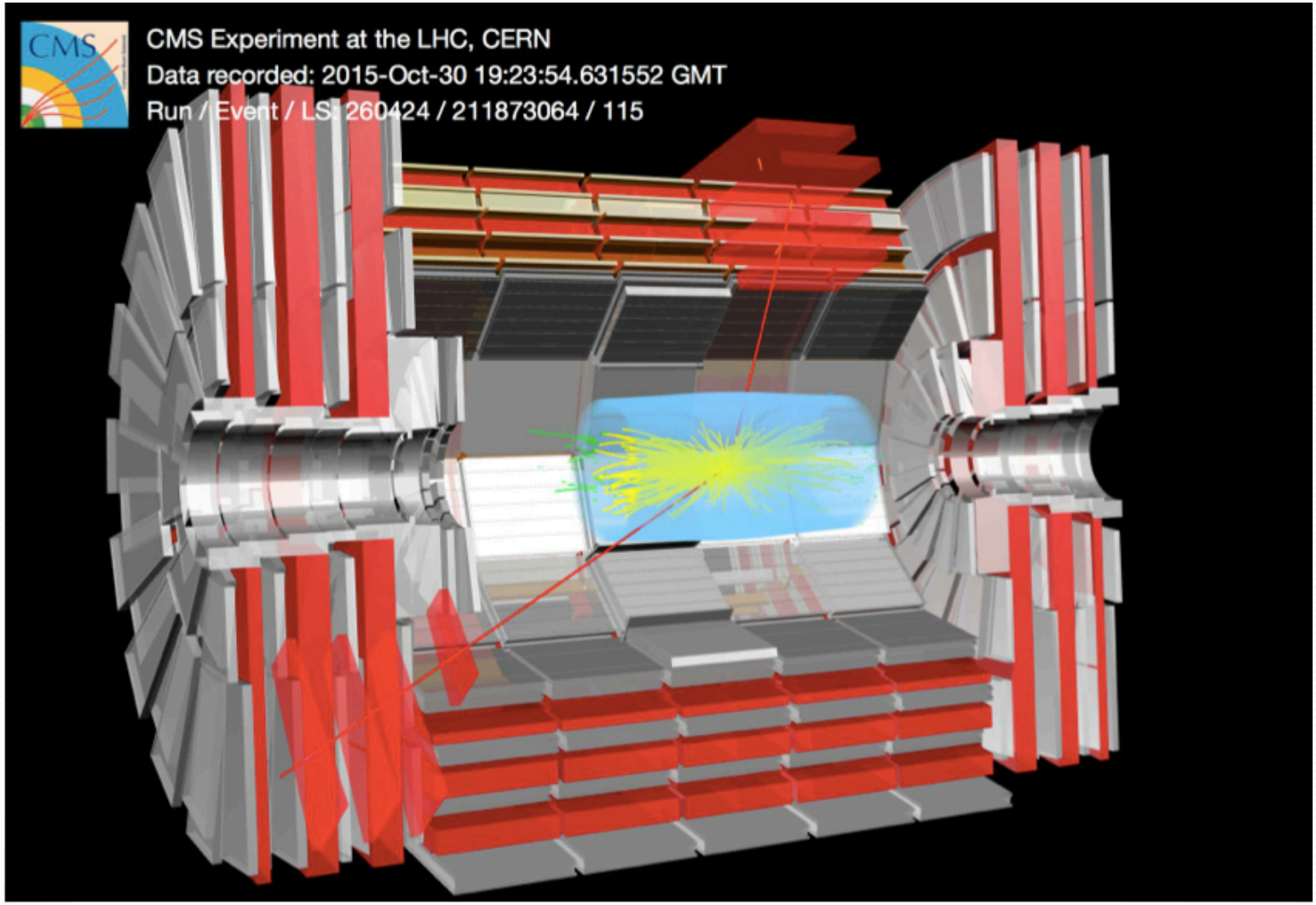


Dilepton + MET

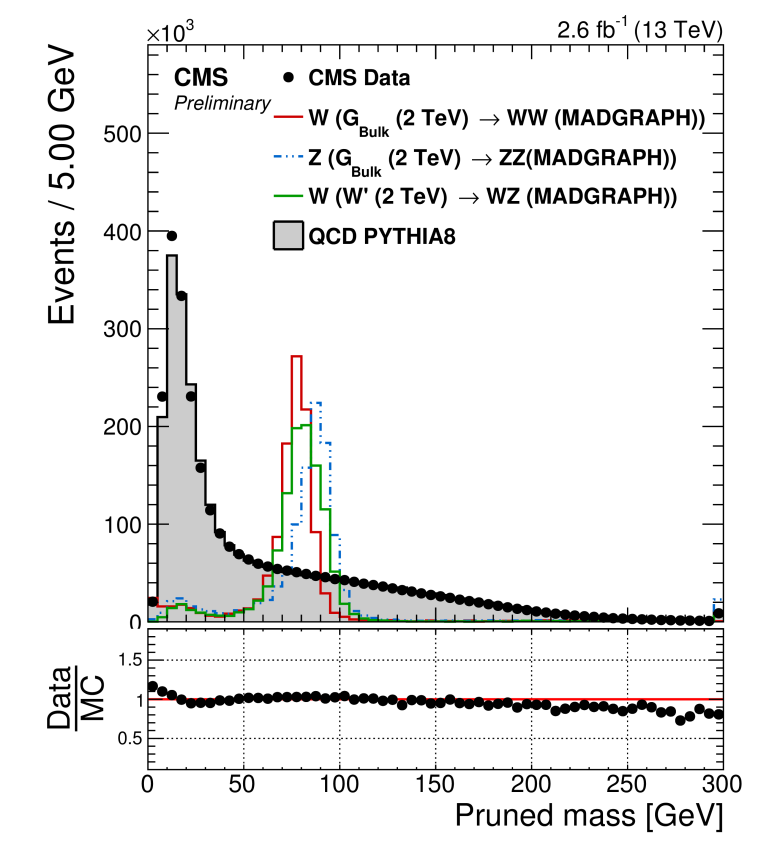




Dilepton resonances

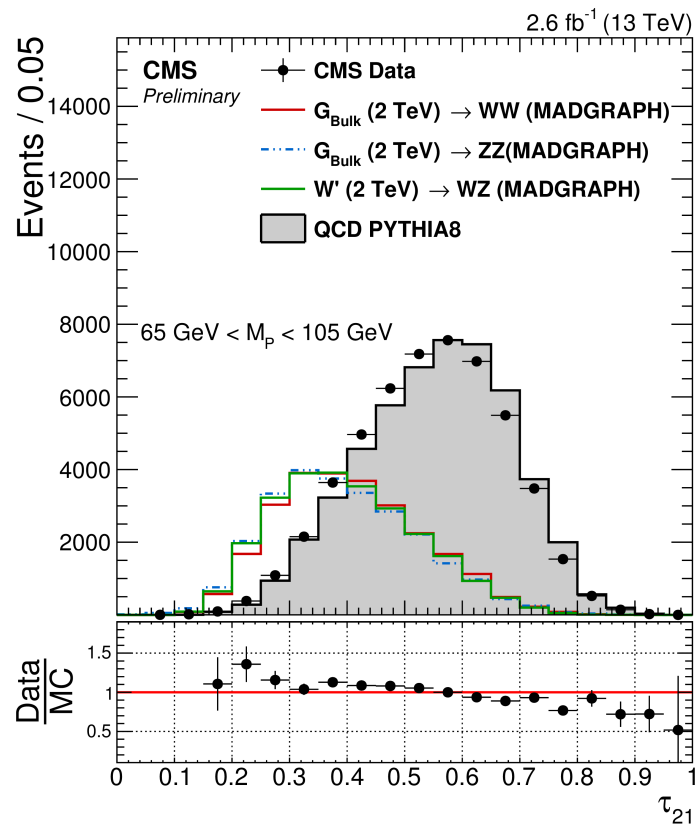


Diboson resonances



Define categories (W-like or Z-like) based on jet mass:

- 3 catgories for hadronic channel (WW, WZ, ZZ)
- 2 categories for semi-leptonic channel (WW, WZ)



Different Background prediction techniques

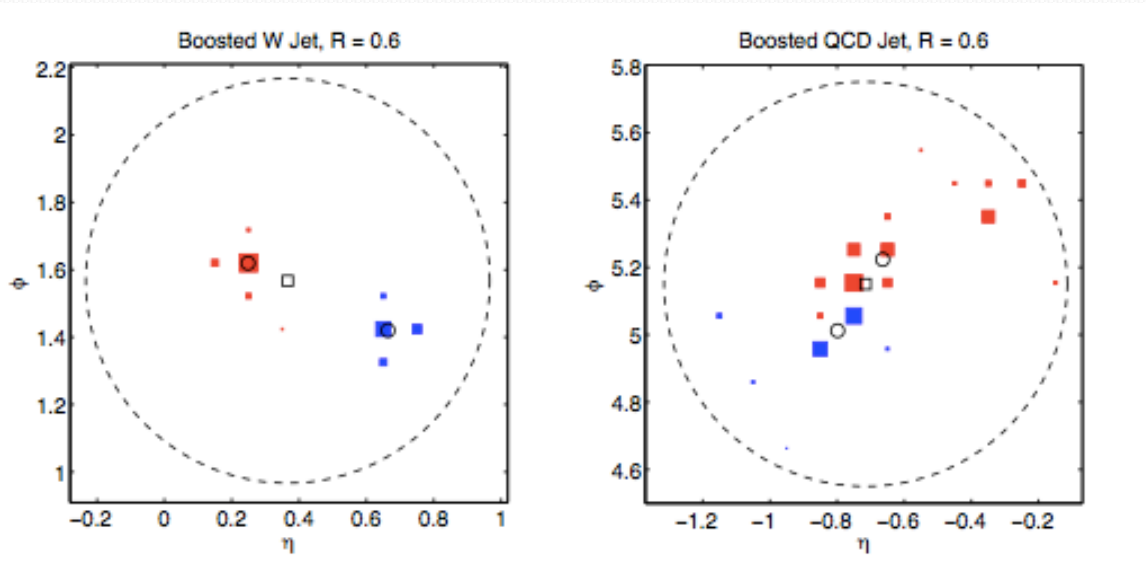
-> fit using parametric function (dijet)

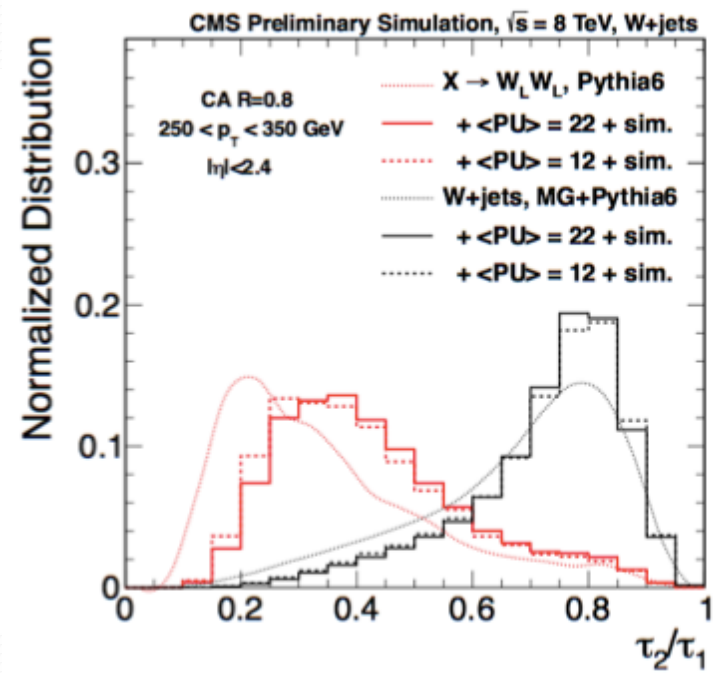
-> from sidebands in jet mass (l+jet)

W-tagging

N-subjettiness: a measure of how consistent a jet is with having N sub-jets

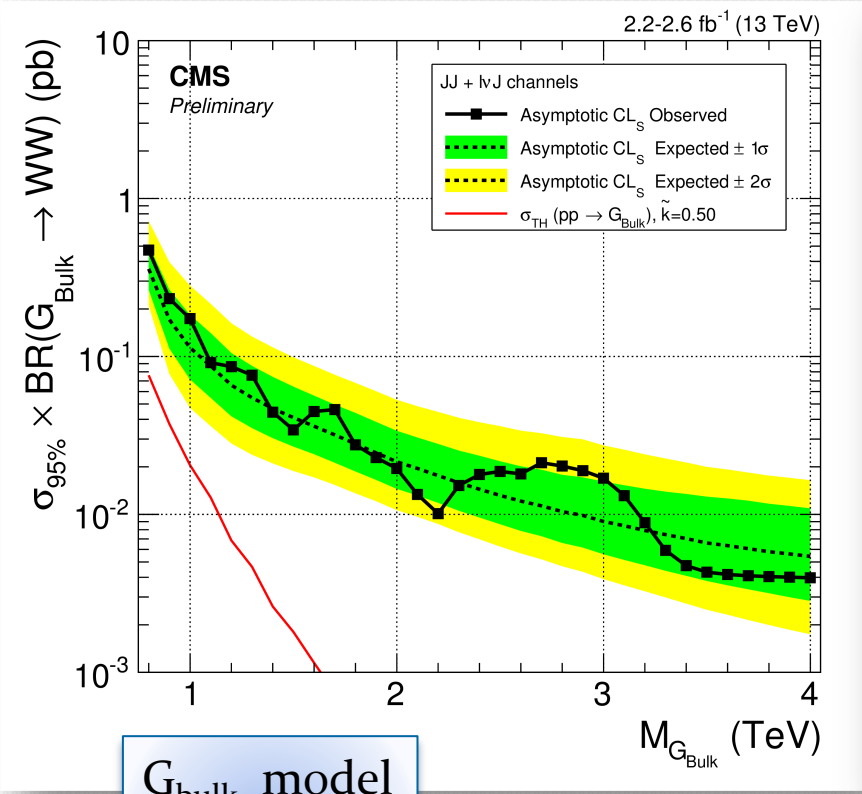
$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min\{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\}$$



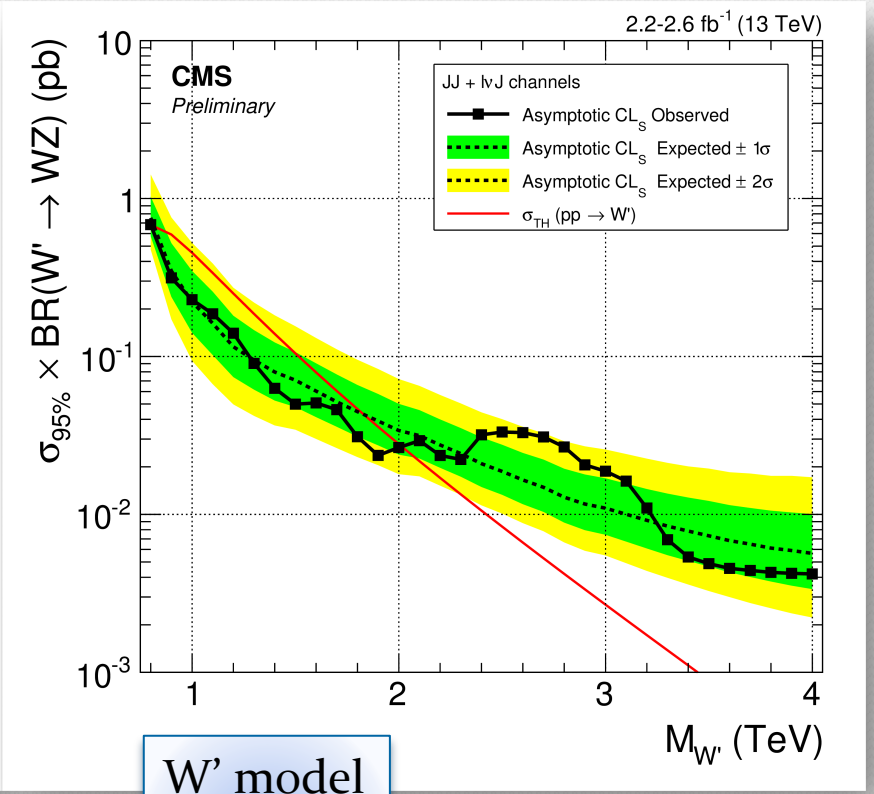


Used together with M_{jet} to maximize S/B

Diboson resonances

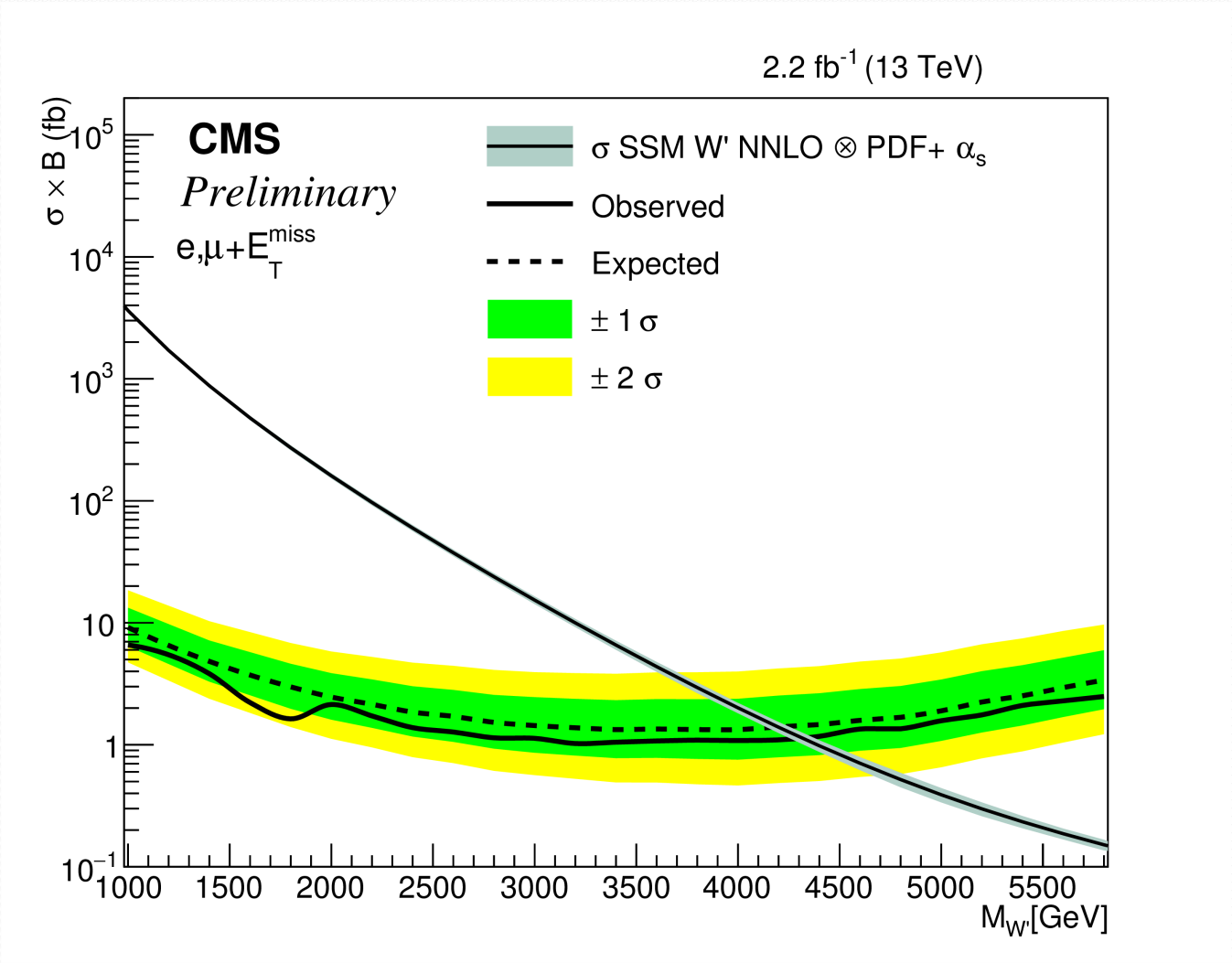


G_{bulk} model

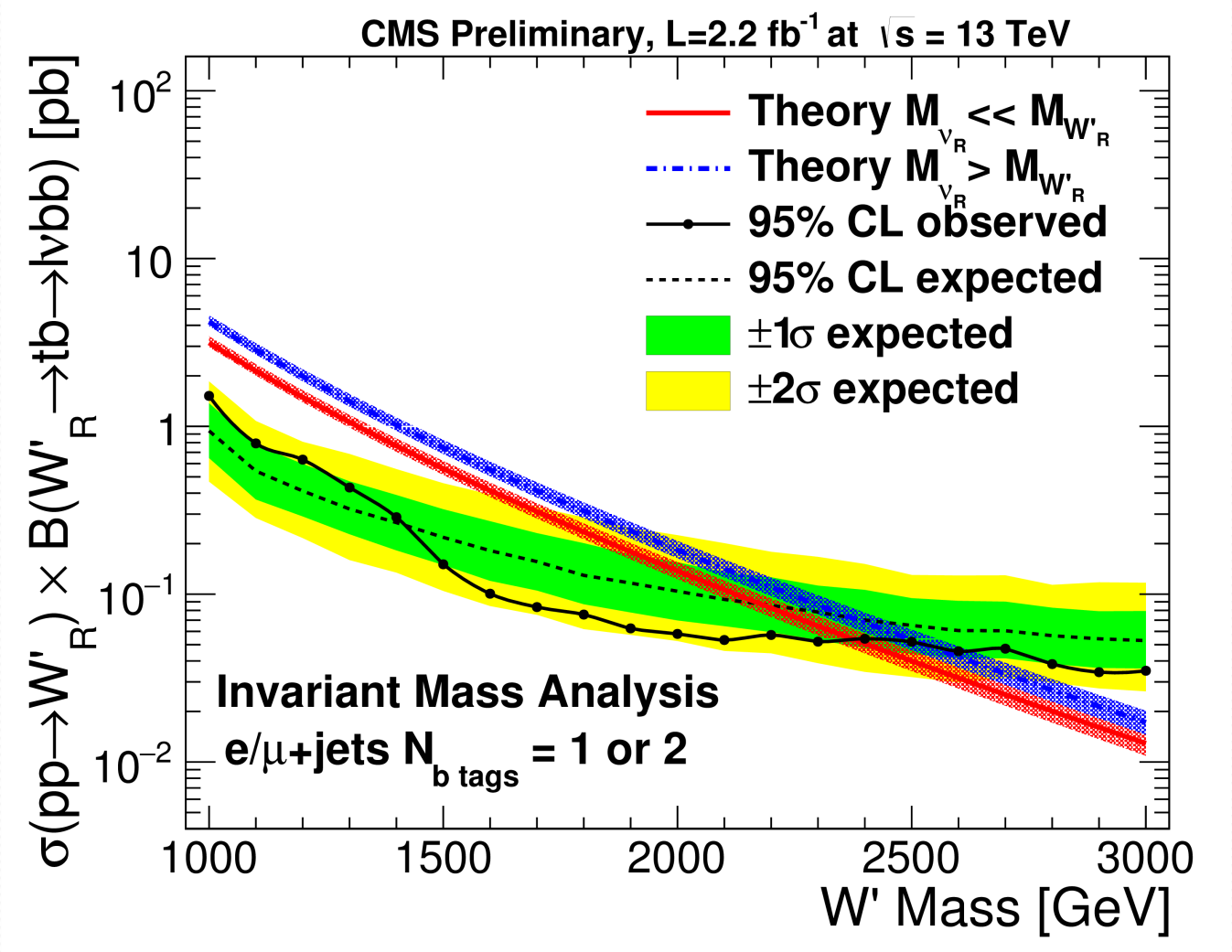


W' model

W'-> lnu

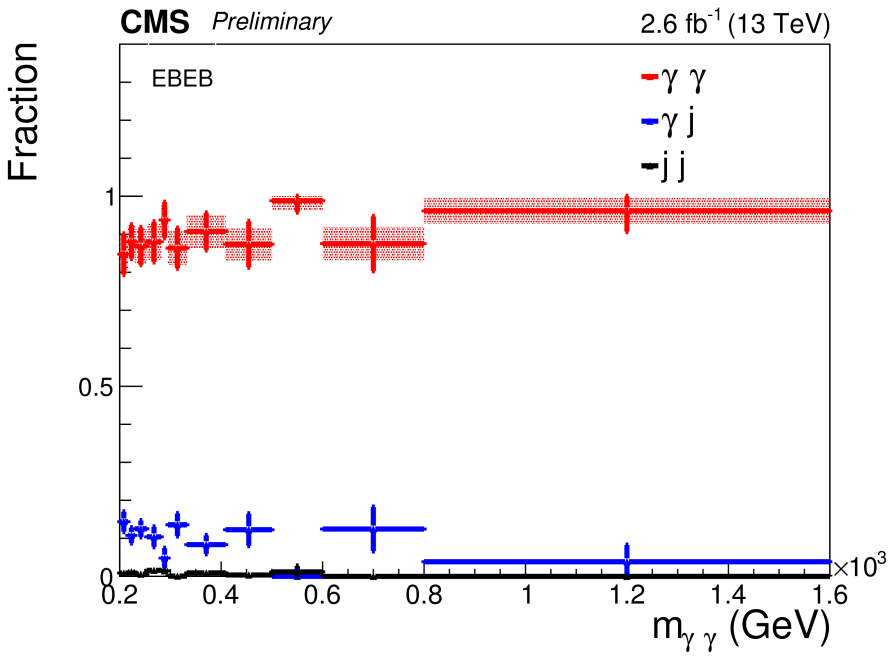

2.2 fb^{-1} (13 TeV)
CMS
Preliminary
e,μ+E$_T^{miss}$
σ SSM W' NNLO ⊗ PDF+ α$_s$
Observed
Expected
± 1 σ
± 2 σ
σ × B (fb)
10^5
10^4
10^3
10^2
10
1
10^{-1}
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
M$_{W'}$[GeV]

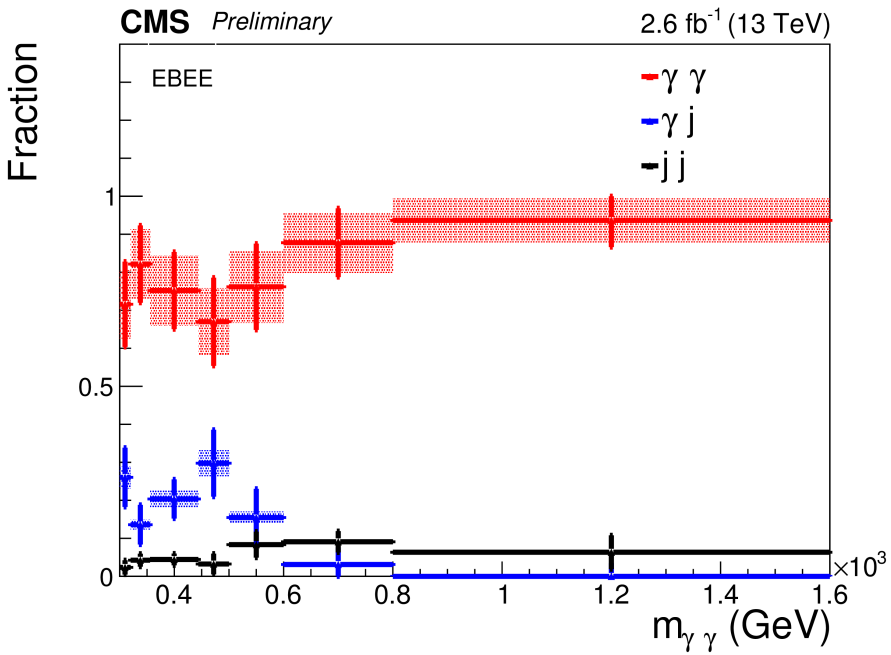
W'-> tb


CMS Preliminary, L=2.2 fb^{-1} at $\sqrt{s}$ = 13 TeV
Theory $M_{\nu_R} << M_{W'_R}$
Theory $M_{\nu_R} > M_{W'_R}$
95% CL observed
95% CL expected
±1σ expected
±2σ expected
Invariant Mass Analysis
e/μ+jets $N_{b\ tags}$ = 1 or 2
$\sigma(pp \to W'_R) \times B(W'_R \to tb \to l\nu bb)$ [pb]
W' Mass [GeV]

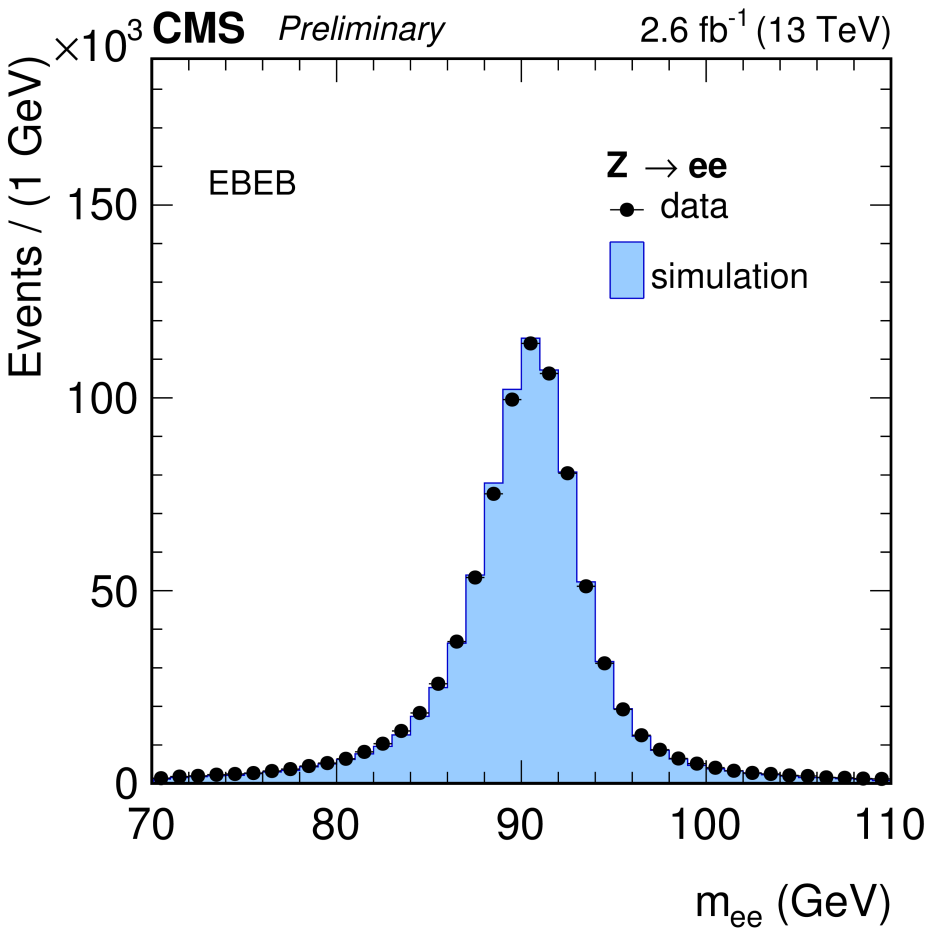
Diphoton resonances

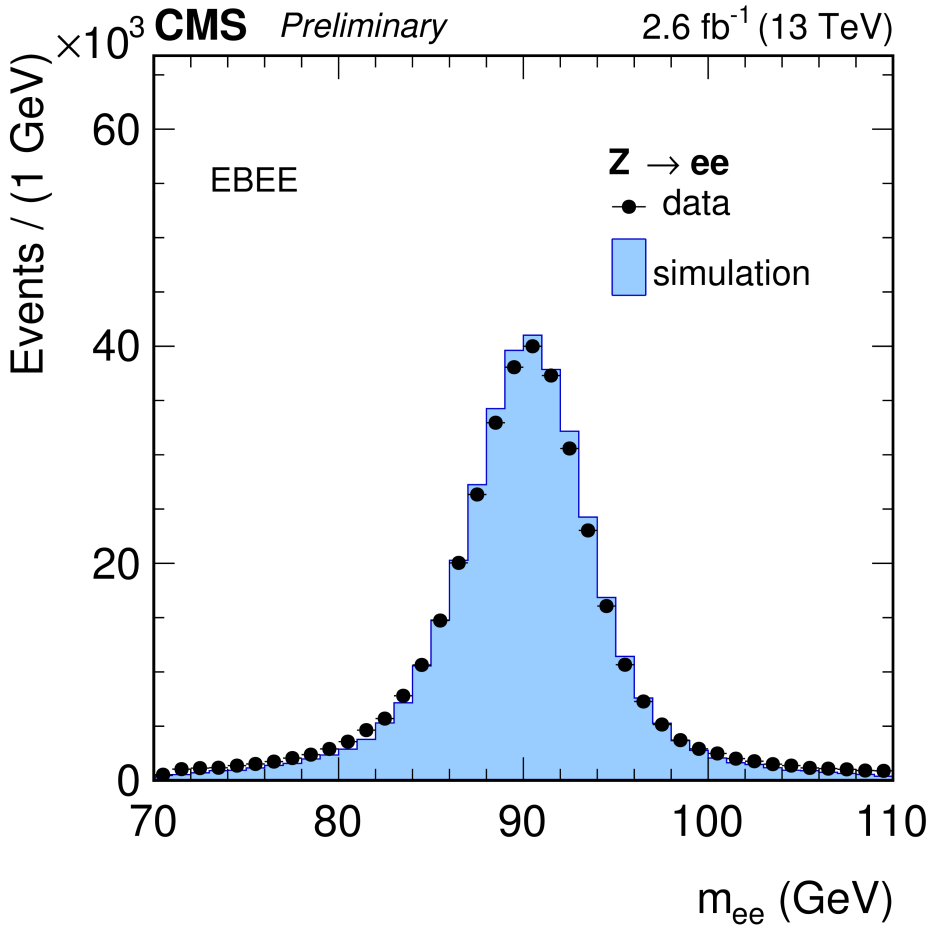
- Three main backgrounds:
  - Prompt diphotons
  - Photon+jet
  - Dijets
- Background comparison using 2 methods (template fit in the isolation distribution and simulation)





Diphoton resonances





Diphoton resonances

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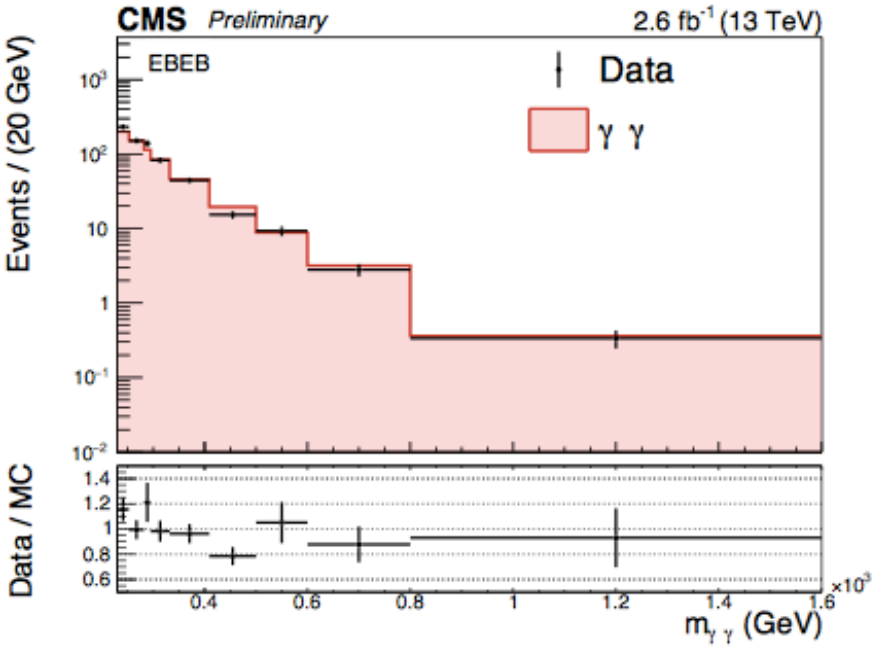
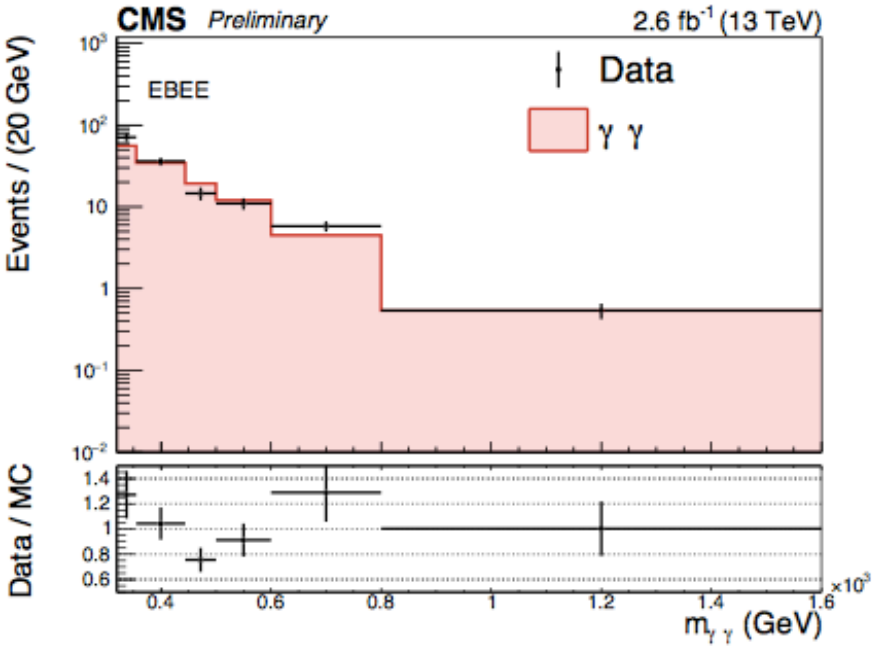
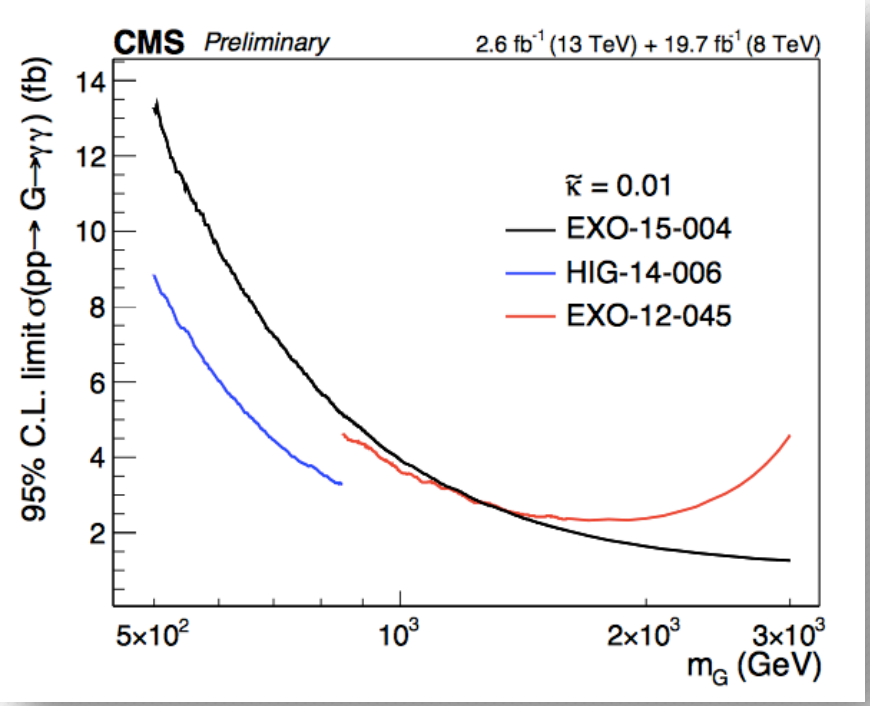
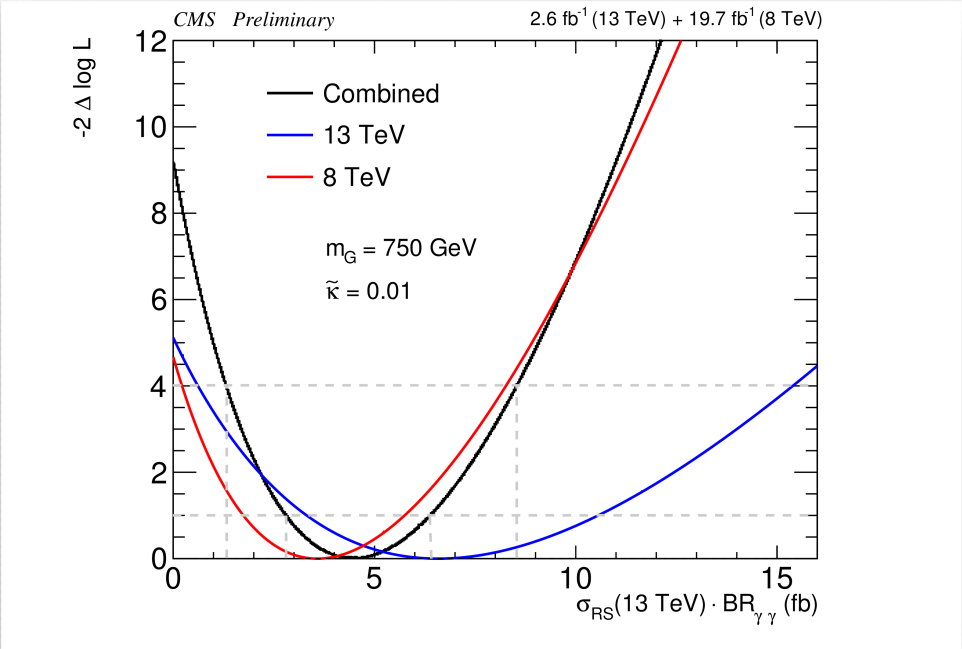




Diphoton resonances

- Background: $f(m_{\gamma\gamma}) = m_{\gamma\gamma}^{a+b\cdot\log(m_{\gamma\gamma})}$
- Signal: intrinsic RS width, corrected for the additional Gaussian smearing

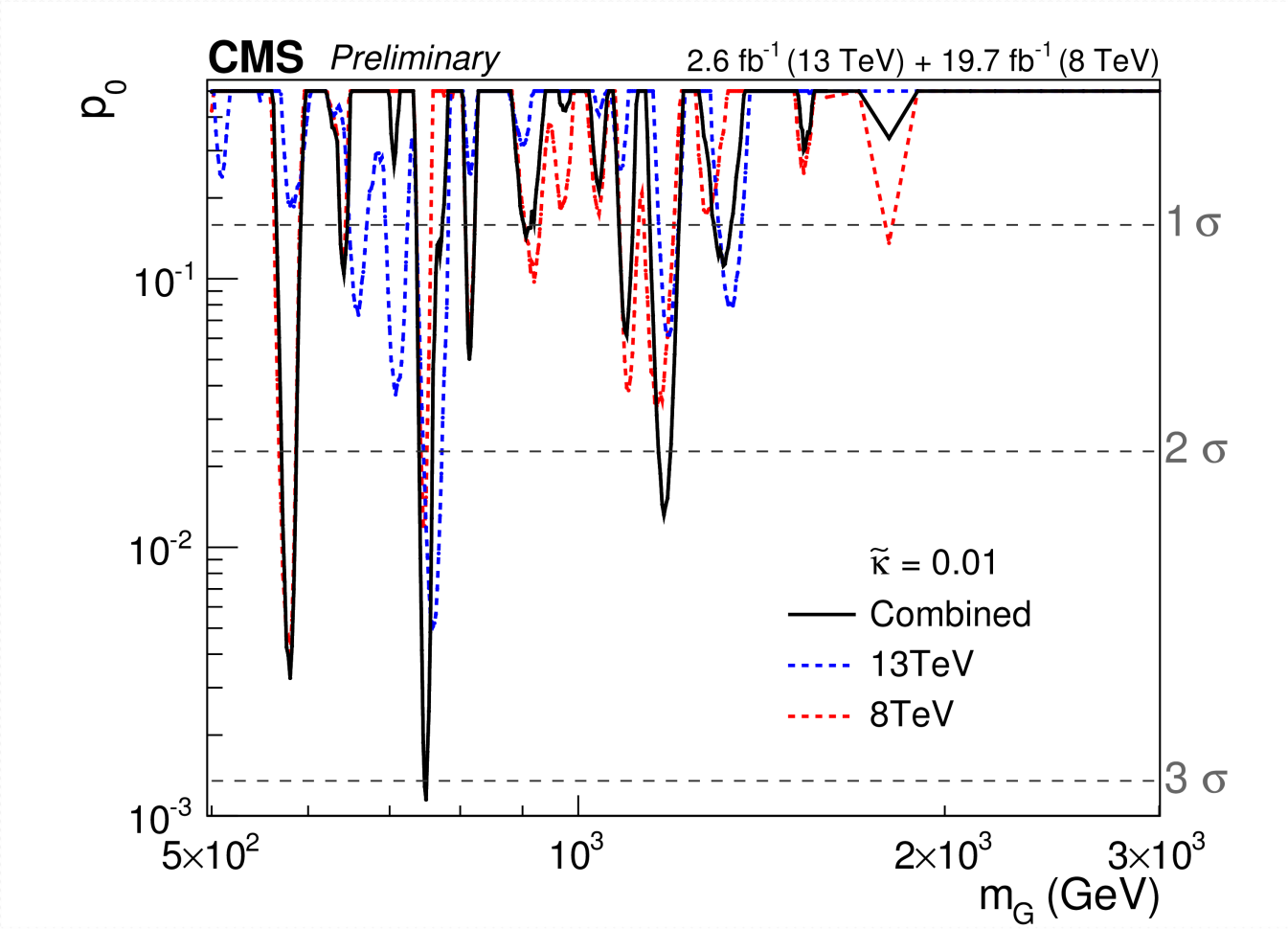




Diphoton resonances

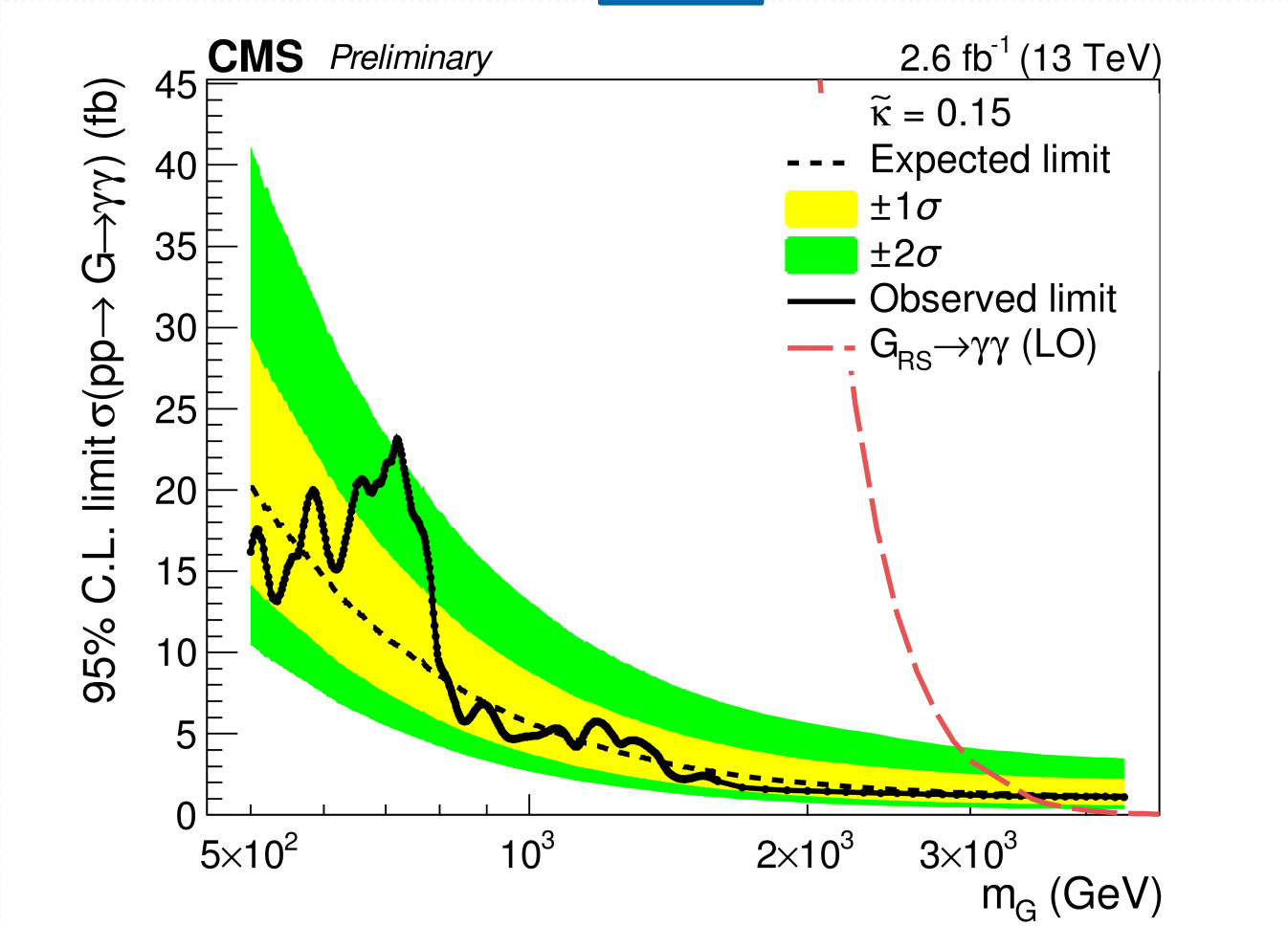
m_G (GeV)	category	$\tilde{\kappa}$	FWHM (GeV)	$\tilde{\kappa}$	FWHM (GeV)
500	EBEB	0.01	14	0.2	36
500	EBEE	0.01	22	0.2	42
1000	EBEB	0.01	27	0.2	74
1000	EBEE	0.01	43	0.2	85
2000	EBEB	0.01	54	0.2	147
2000	EBEE	0.01	76	0.2	163
3000	EBEB	0.01	96	0.2	225
3000	EBEE	0.01	110	0.2	254
4000	EBEB	0.01	121	0.2	320
4000	EBEE	0.01	150	0.2	326

Diphoton resonances



Diphoton resonances

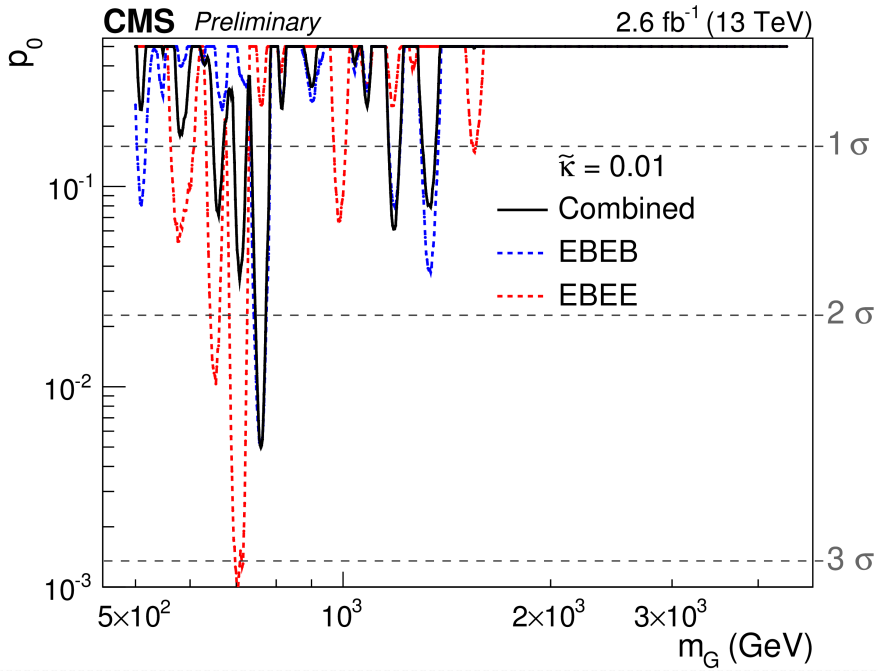
k=0.15



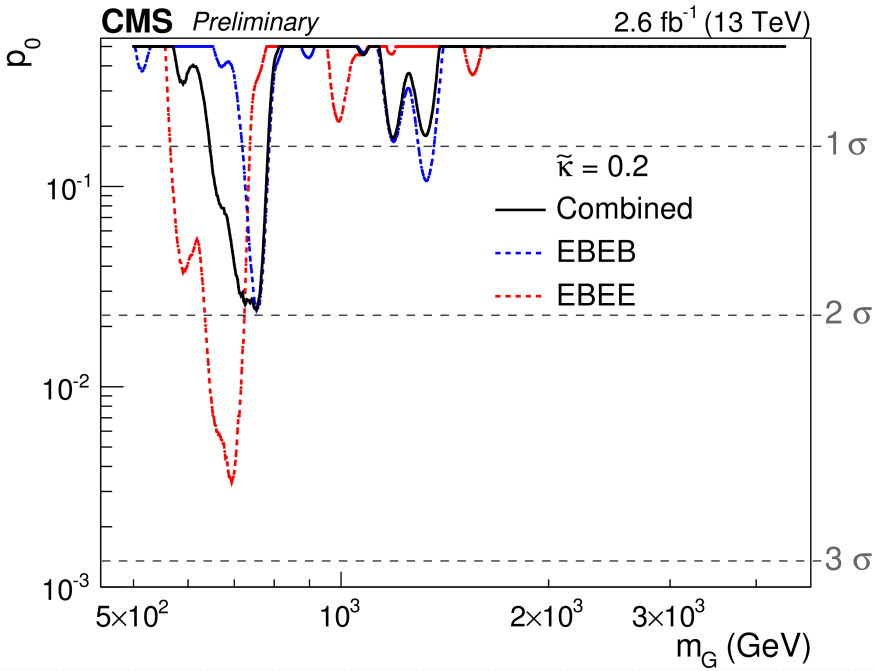
Diphoton resonances

EB vs EE breakdown

k=0.01

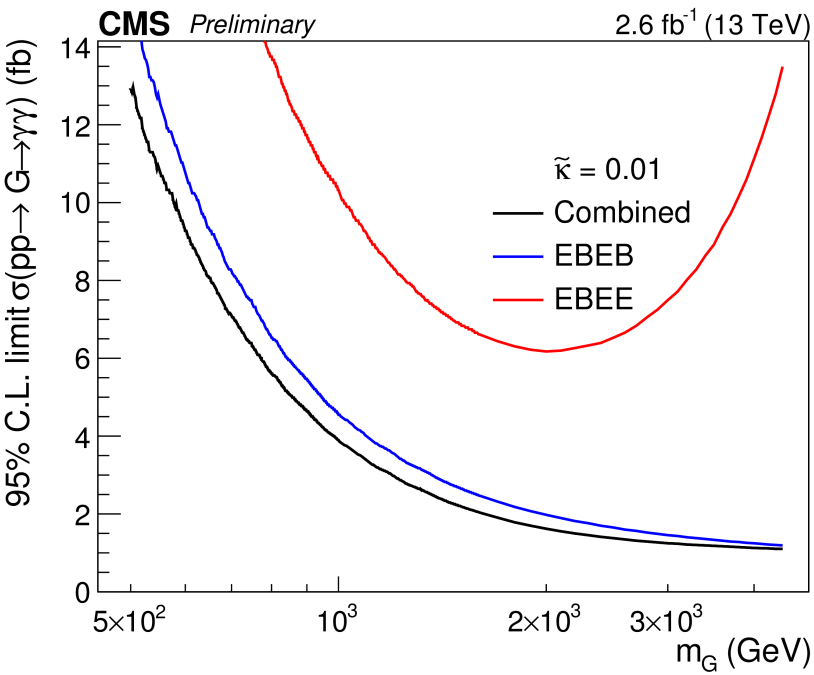


k=0.2

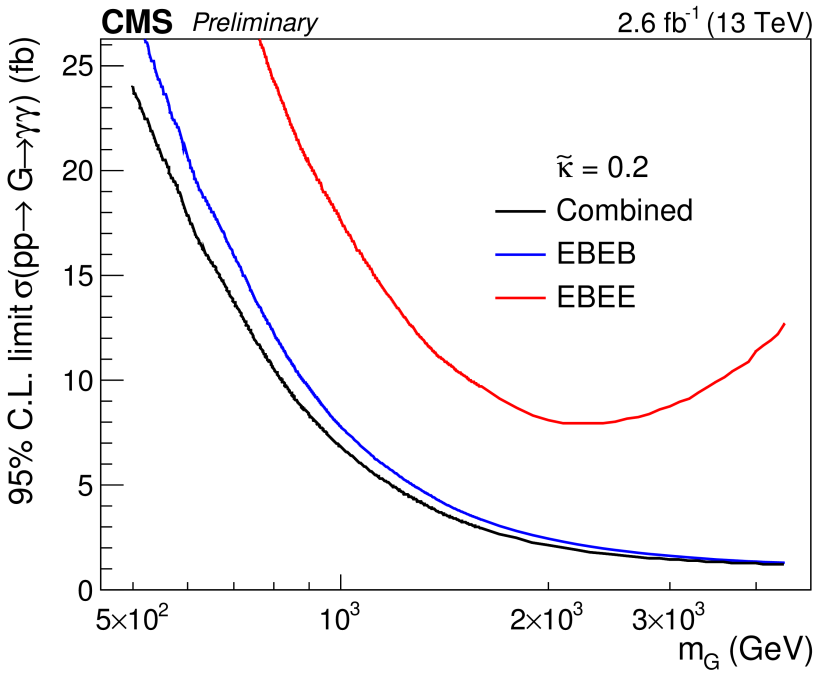


Diphoton resonances

k=0.01

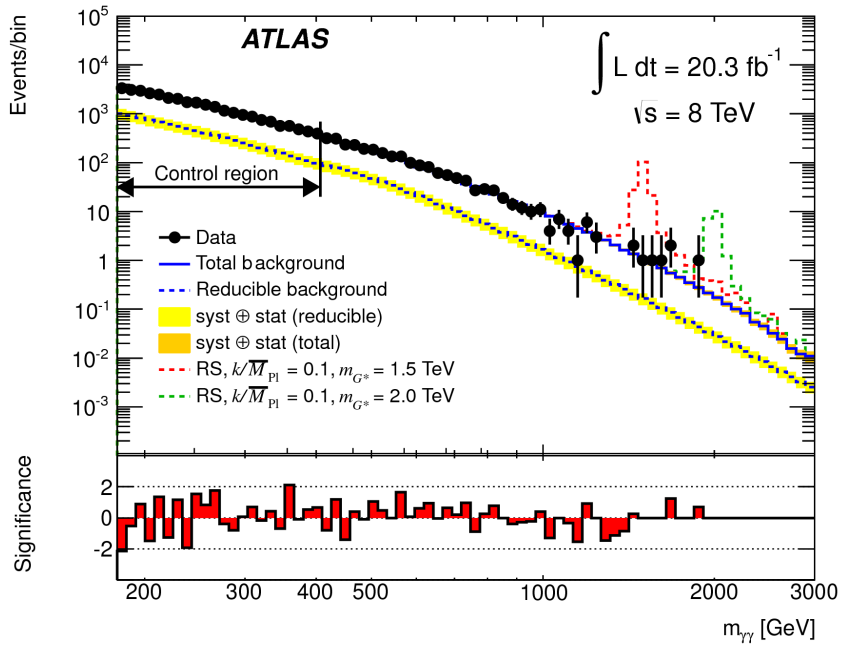


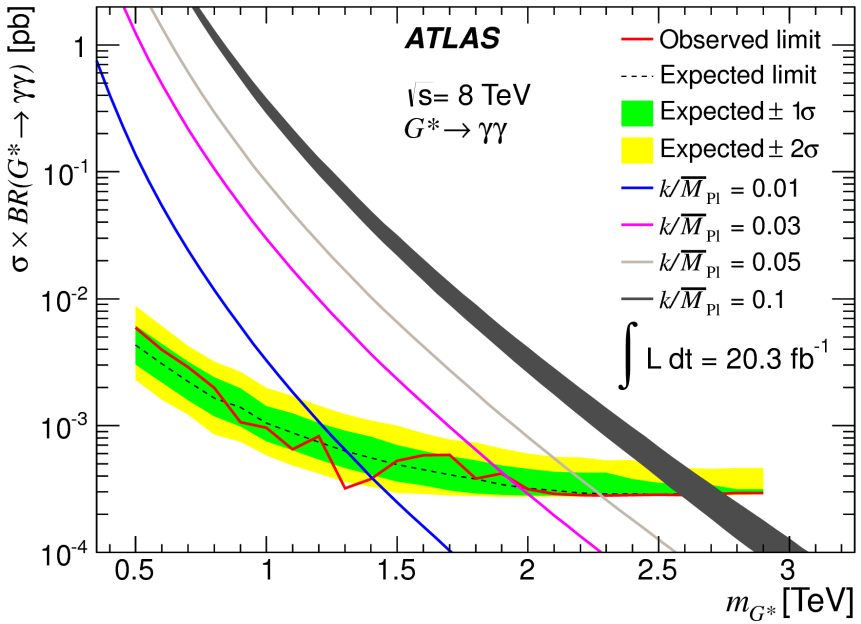
k=0.2



Diphoton resonances

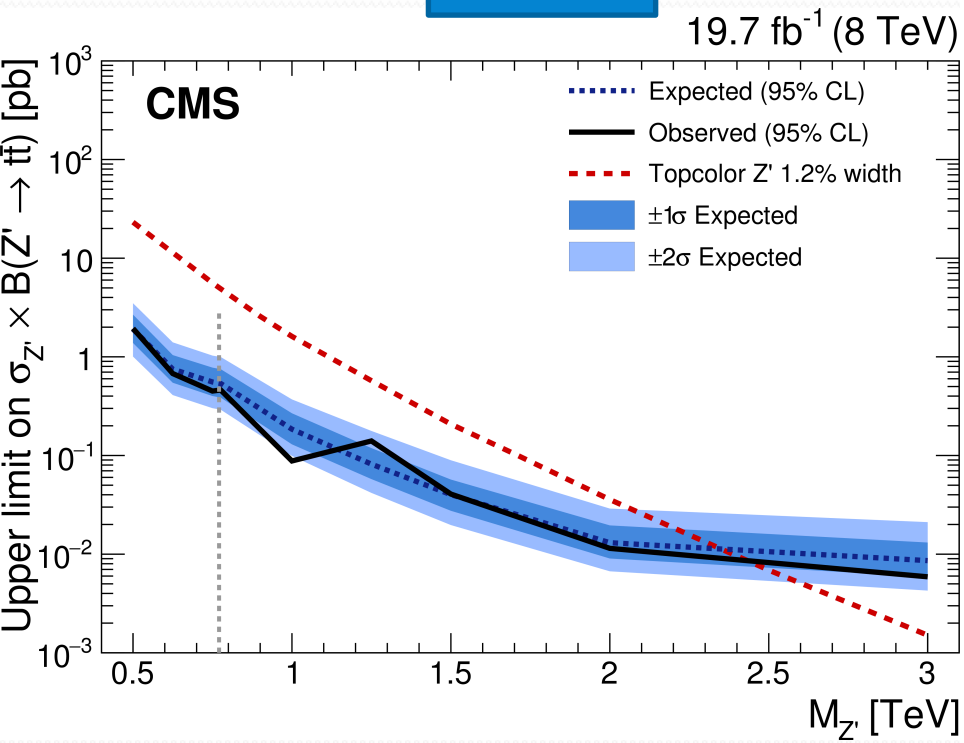
ATLAS 8 TEV



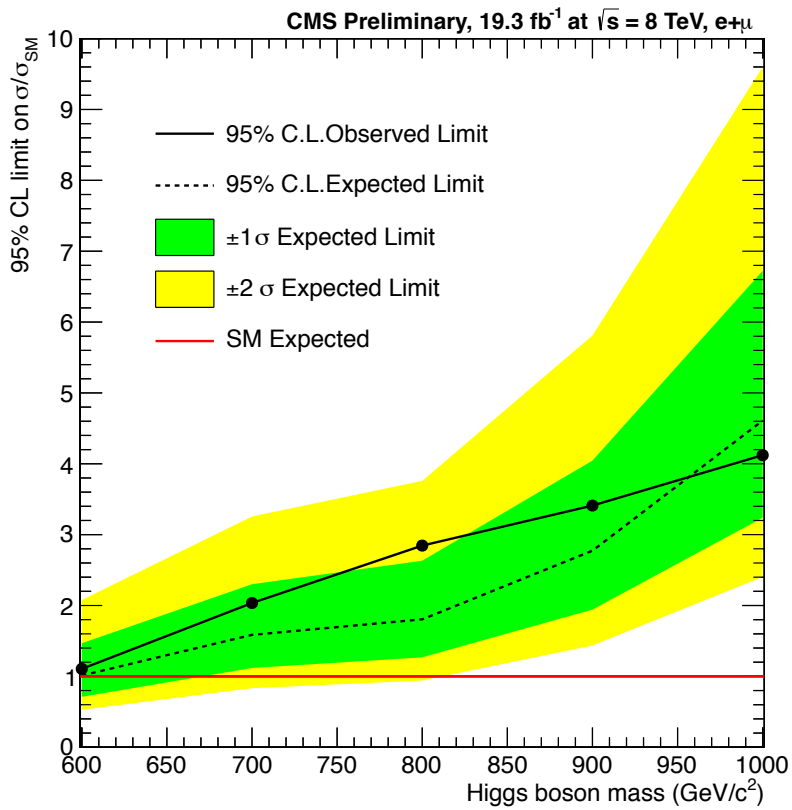


Resonances

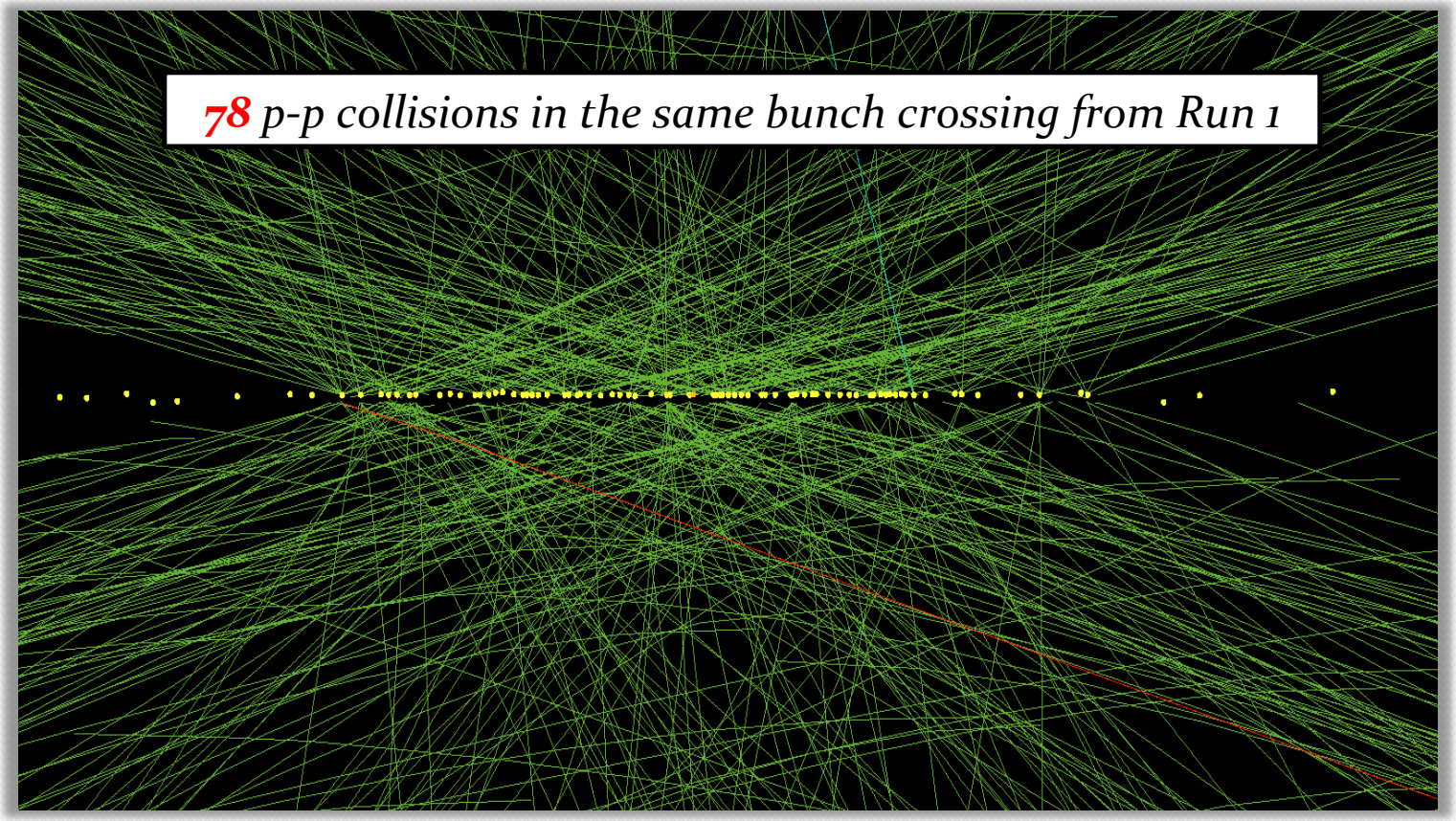
Z'->ttbar



SM-like heavy H->WW



Pileup

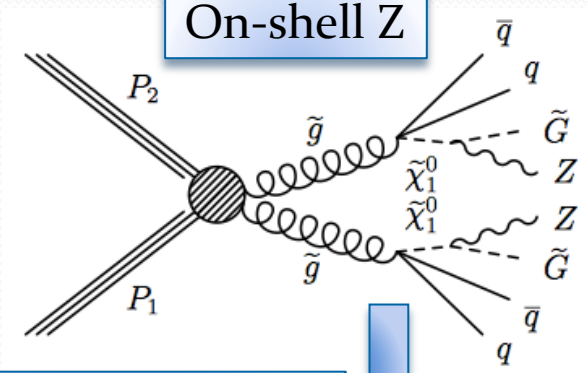


Maximize the integrated luminosity ➔ large pileup

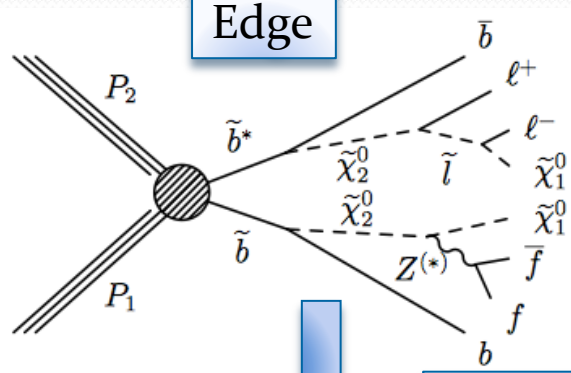
Dilepton + MET

Two leptons (same flavor, opposite charge), jets and MET

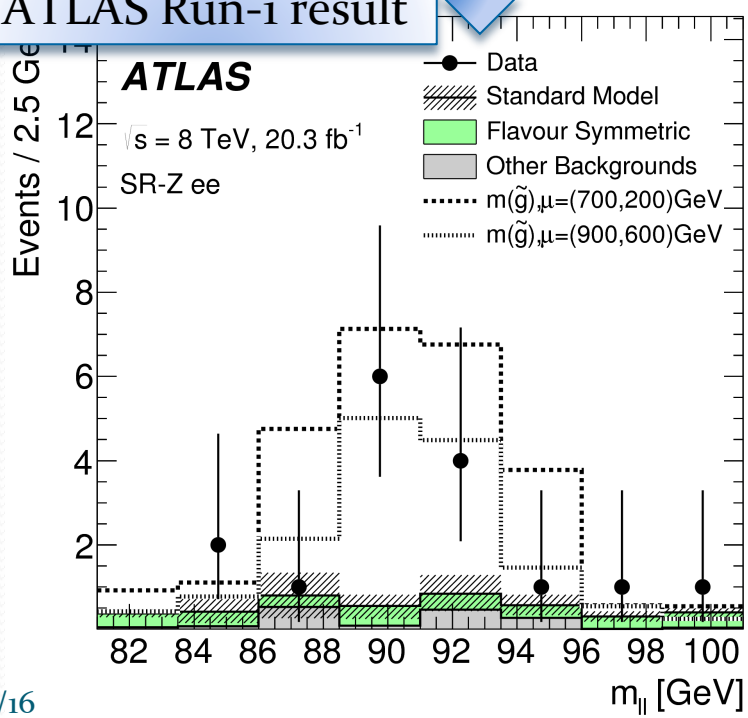
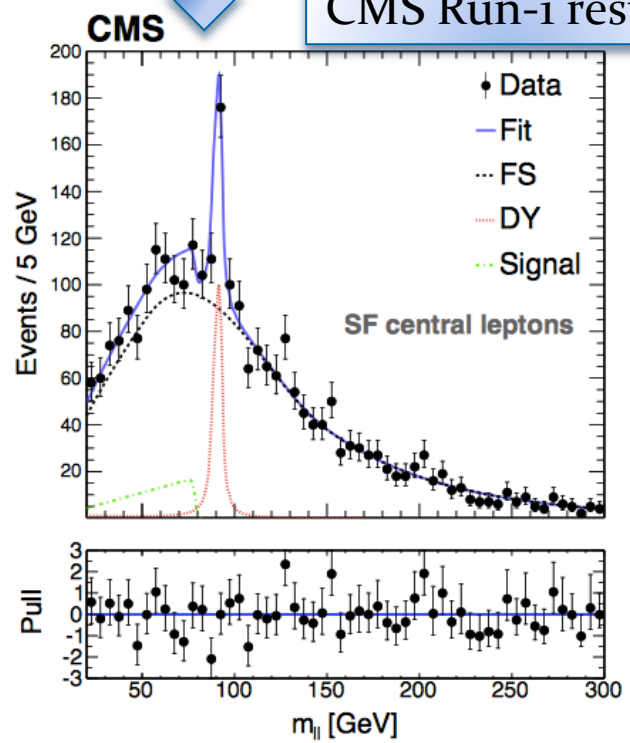
On-shell Z



Edge



ATLAS Run-1 result



CMS Run-1 result