EXOTIC SEARCHES

PSI Summer School Exothiggs
Lyceum Alpinum Zuoz, 15-19 August 2016

Lecture 1: resonances

DIPARTIMENTO DI FISICA

SAPIENZA
UNIVERSITÀ DI ROMA

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OUTLINE

- Motivation for New Physics
- Exotic searches
- Dark Matter at Colliders
- Long-Lived Particles
- Supersymmetry (maybe)
- Prospects at 13 TeV and beyond

LHC: A Discovery Machine

- Higgs discovery the best known objective of LHC
  - Solve the mass puzzle
  - explain generation of mass for ALL particles in Standard Model

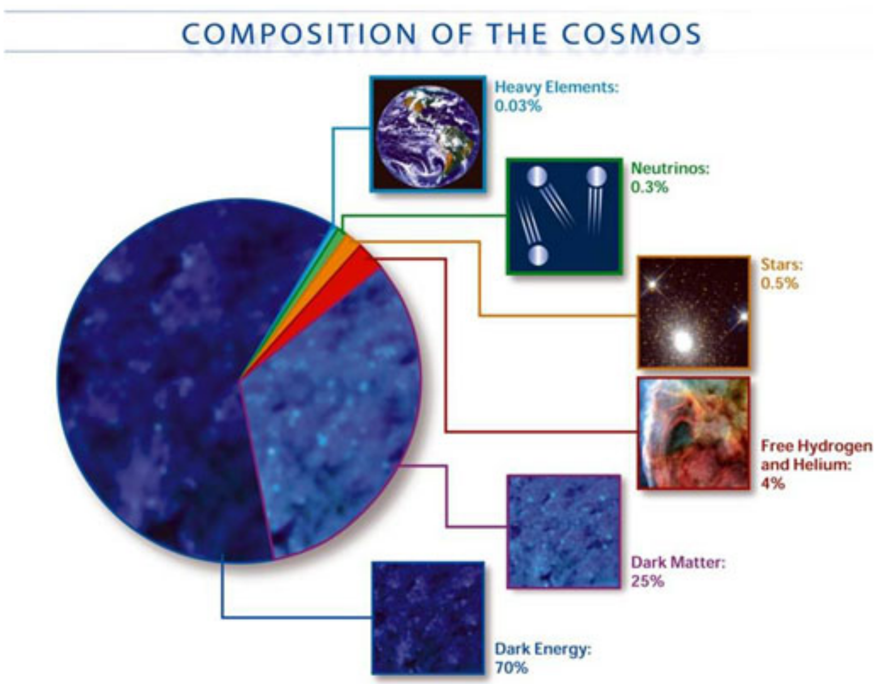
- But new particles might be right around the corner

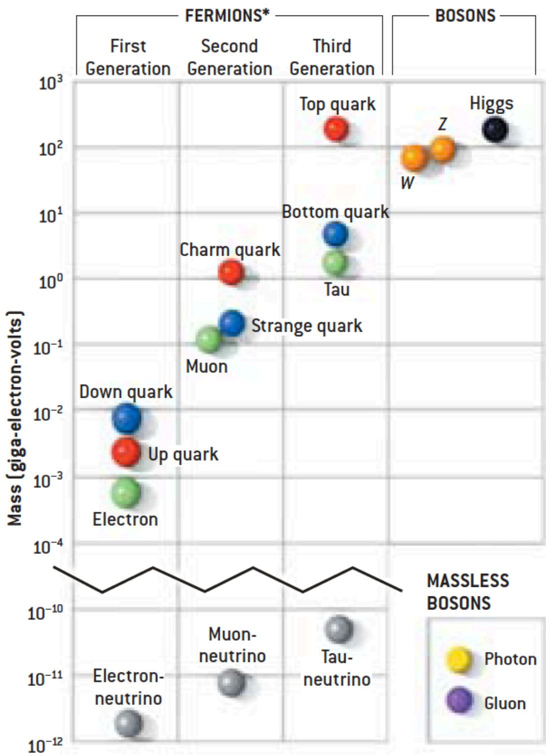
- Center of mass energy highest ever achieved in laboratory
  - Einstein equation tells us: $E = m_X c^2$
  - New heavy particles can be produced

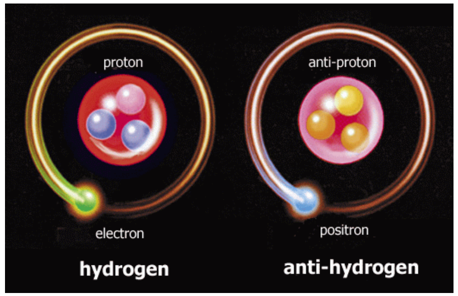
- What do we expect to see and why?

Hints of New Physics

- Neutrinos have very small but non-zero mass
- Astrophysical proof of existence of cold dark matter and we also need a large amount of yet-to-be-understood dark energy
- Mass hierarchy and mixing structure
- Almost complete absence of anti-matter in the universe







Planck Scale

- Mass with same Compton wavelength and Schwarzschild radius
- Compton wavelength: defines length scale where quantum mechanics must be used
  - decreases with for lager mass
  - e.g. for a photon the corpuscular nature of light becomes relevant

$$E = mc^2 = \hbar\nu \to mc^2 = \frac{\hbar c}{\lambda_c} \to \lambda_c = \frac{\hbar}{mc^2}$$

- Schwarzschild radius is the radius in which a confined mass object becomes a black hole
  - classically radius such that escape velocity equal to speed of light
  - increases for larger mass

$$\frac{1}{2}Mv^2 = \frac{GMm}{r} \to r_S = \frac{2Gm}{c^2}$$

- Planck mass or scale defines the scale at which quantum and gravitational effects are both relevant and comparable

$$m_P = \sqrt{\frac{c\hbar}{G}} = 1.2 \cdot 10^{19}\,\mathrm{GeV/c^2}$$

$$\ell_P = \frac{\hbar}{m_P c} = \sqrt{\frac{\hbar G}{c^3}} = 1.6 \cdot 10^{-35}\,\mathrm{m}$$

$$t_P = \ell_P / c = \sqrt{G\hbar / c^5} = 5.4 \cdot 10^{-44}\,\mathrm{s}$$

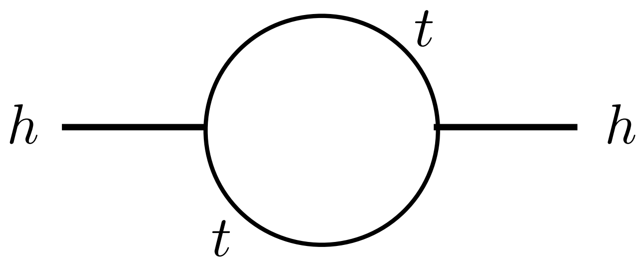
Higgs Mass

$$m_h^2 \sim m_{h0}^2 + \delta m_h^2$$

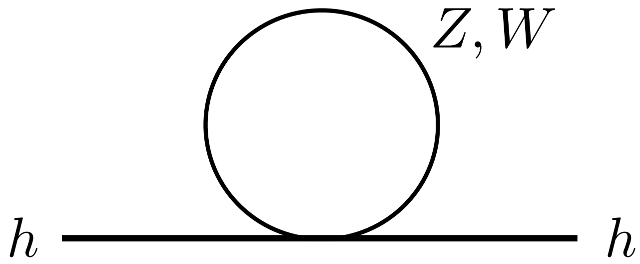
- We know that m_h ~ 100 GeV for consistency of Standard Model
  - Precision EW tests at LEP and direct measurement at 125 GeV
- Nature sets m_{h0} at Planck scale and we observe the physical mass after all higher order correction terms
- For Higgs mass to be finite at EW scale, corrections must balance the bare mass over 16 order of magnitude
- This is *not a consistency problem for the theory* but ***requires incredible fine-tuning of parameters*** to achieve such precise cancellation
- Such accidental features although possible are extremely unlikely
- Nature generally prefers rules and symmetries to accidents

Corrections To Higgs Mass

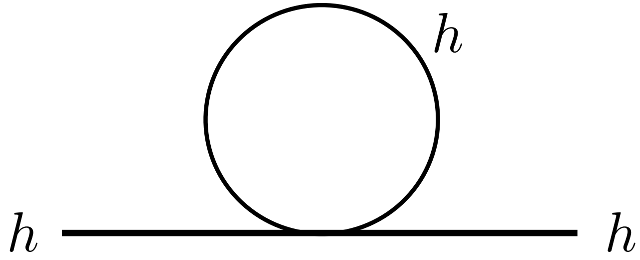
- Propagator of Higgs mass affected by higher order corrections



$$\delta m_h^2 \sim -\frac{3}{8\pi^2}\lambda_t^2\Lambda^2$$



$$\delta m_h^2 \sim \frac{9}{64\pi^2}g^2\Lambda^2$$



$$\delta m_h^2 \sim \frac{1}{16\pi^2}\lambda^2\Lambda^2$$

- Such terms change the bare Higgs mass. Regularization is needed to keep corrections finite

What is a Natural Scale?

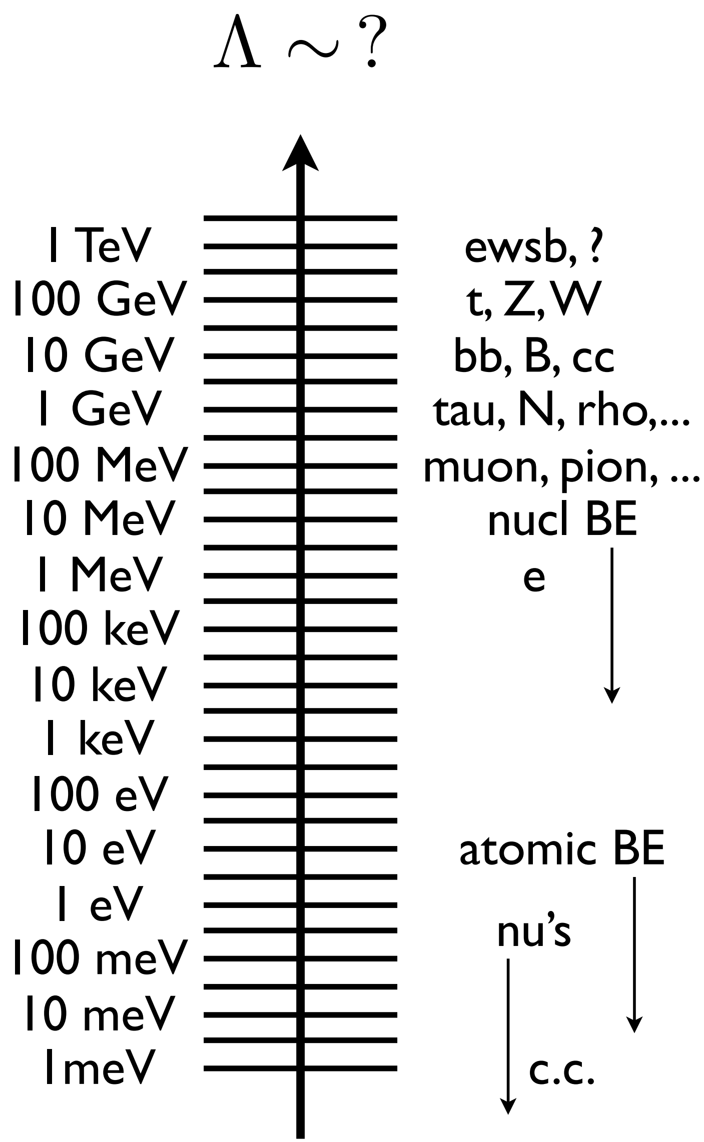
- We could afford corrections of the order of the Higgs mass
  - fermion mass corrections are proportional to their mass
    - approximate chiral symmetry

- If Λ = 1 TeV the Higgs mass fine tuning would be natural

- This implies that new particles and processes to be discovered at LHC!

Scale of New Physics?

- Since birth of particle physics experiments have explored many orders of magnitude in energy
- Different phenomena have appeared at different scales
- Standard Model and EW breaking occurs up to TeV scale
- How to determine scale of new physics beyond Standard Model?



DIRECT SEARCHES AFTER *THE BOSON* DISCOVERY

Direct Searches After *The Boson* Discovery

- At a cross road with relatively light new boson
- Higgs is light *because of* new physics
  - Higgs couplings different from Standard Model
  - Observable phenomena at ~TeV
    - SUSY: light third generation squarks
    - New Gauge bosons and resonances
    - Compositeness: top partners with odd charge
  - Searches at 8 TeV and underway at 13 TeV

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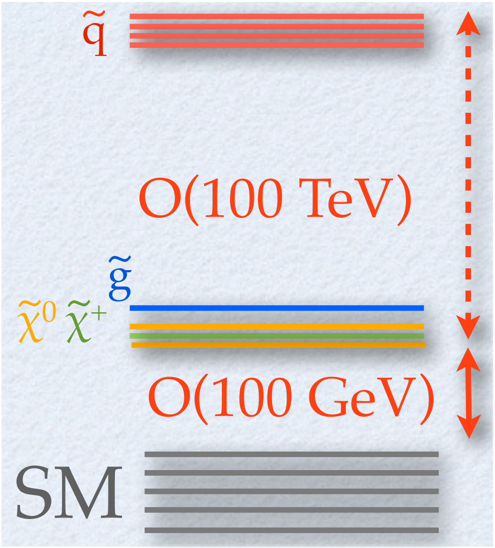
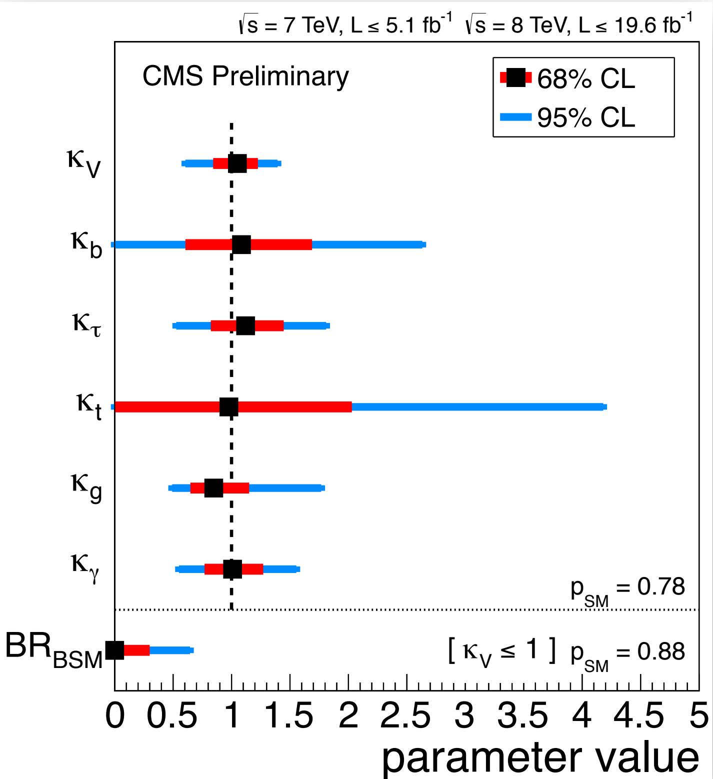
  - Searches at 8 TeV and underway at 13 TeV
- Higgs is light *regardless* of new physics
  - Higgs couplings annoyingly predicted by Standard Model
  - Best scenario
    - Split SUSY: new long-lived particles
    - Possible dark matter candidate
  - Worst (and somewhat boring) scenario
    - Standard Model for a long time

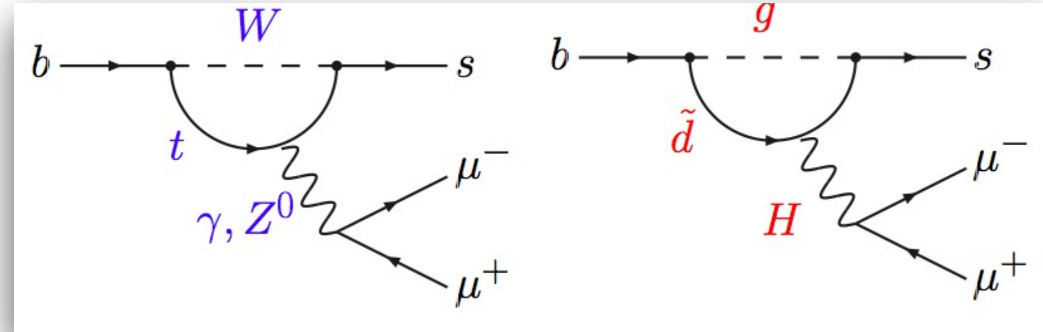


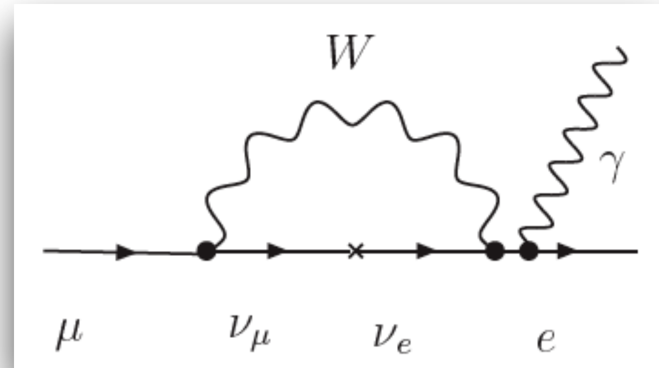
BEYOND STANDARD MODEL

BEYOND STANDARD MODEL

- Indirect searches and precision measurements
  - Measure deviations in precise predictions
    - Higgs couplings constants: needs precision of 1%
  - Enhanced decay and production rates for rare processes
    - Bs →μμ branching ratio: prediction of 10^{-9}
  - Rare or extremely suppressed processes
    - Lepton flavor violation in μ→eγ: predicted rate of 10^{-55}







Beyond Standard Model

- Indirect searches and precision measurements
  - Measure deviations in precise predictions
    - Higgs couplings constants: needs precision of 1%
  - Enhanced decay and production rates for rare processes
    - Bs $\rightarrow \mu\mu$ branching ratio: prediction of 10^{-9}
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    - Lepton flavor violation in $\mu \rightarrow e\gamma$: predicted rate of 10^{-55}
- Supersymmetry
  - complete theory with few free parameters
  - Rich and well defined phenomenology with new particles
    - Possibly new long-lived particles
  - Primary background from rare Standard Model processes

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  - Rich and well defined phenomenology with new particles
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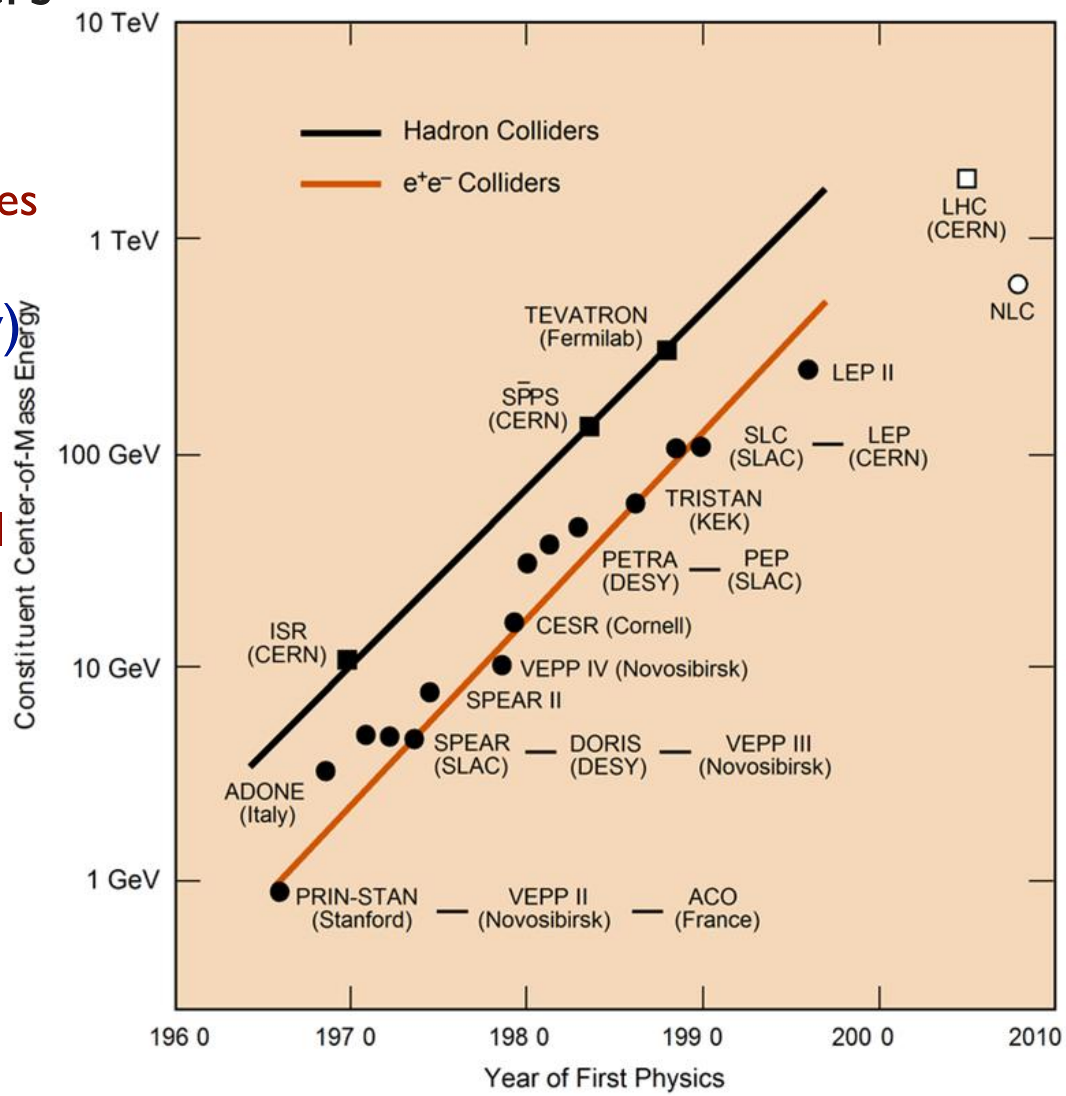
  - Primary background from rare Standard Model processes
- New particles and forces (exotica)
  - Clean experimental signature in mass of new particles
  - Many models and many signatures but no comprehensive theory
  - Typically very good signal to noise

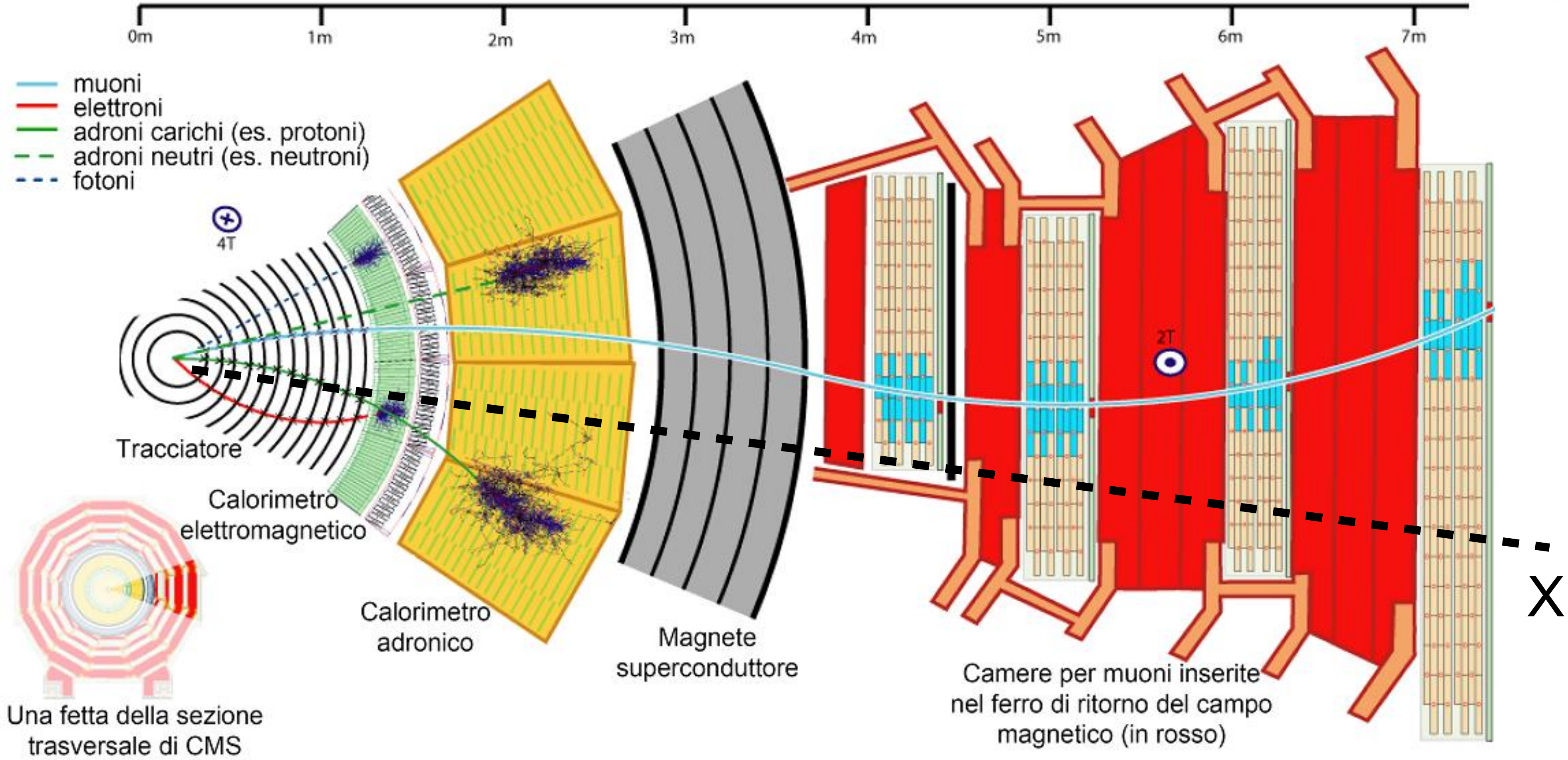
Evolution of Particle Colliders

- Direct production of new particles typically searched at hadron colliders
  - Increase of energy to access new production channels
    - Lack of discovery implies new particles are heavier
  - Accumulating data (high luminosity) to probe weakly interacting particles
    - Particles are produced but have small cross section to be detected
- Alternatives
  - Lepton colliders if we know *where* to look for
  - Fixed target if we know *what* to look for



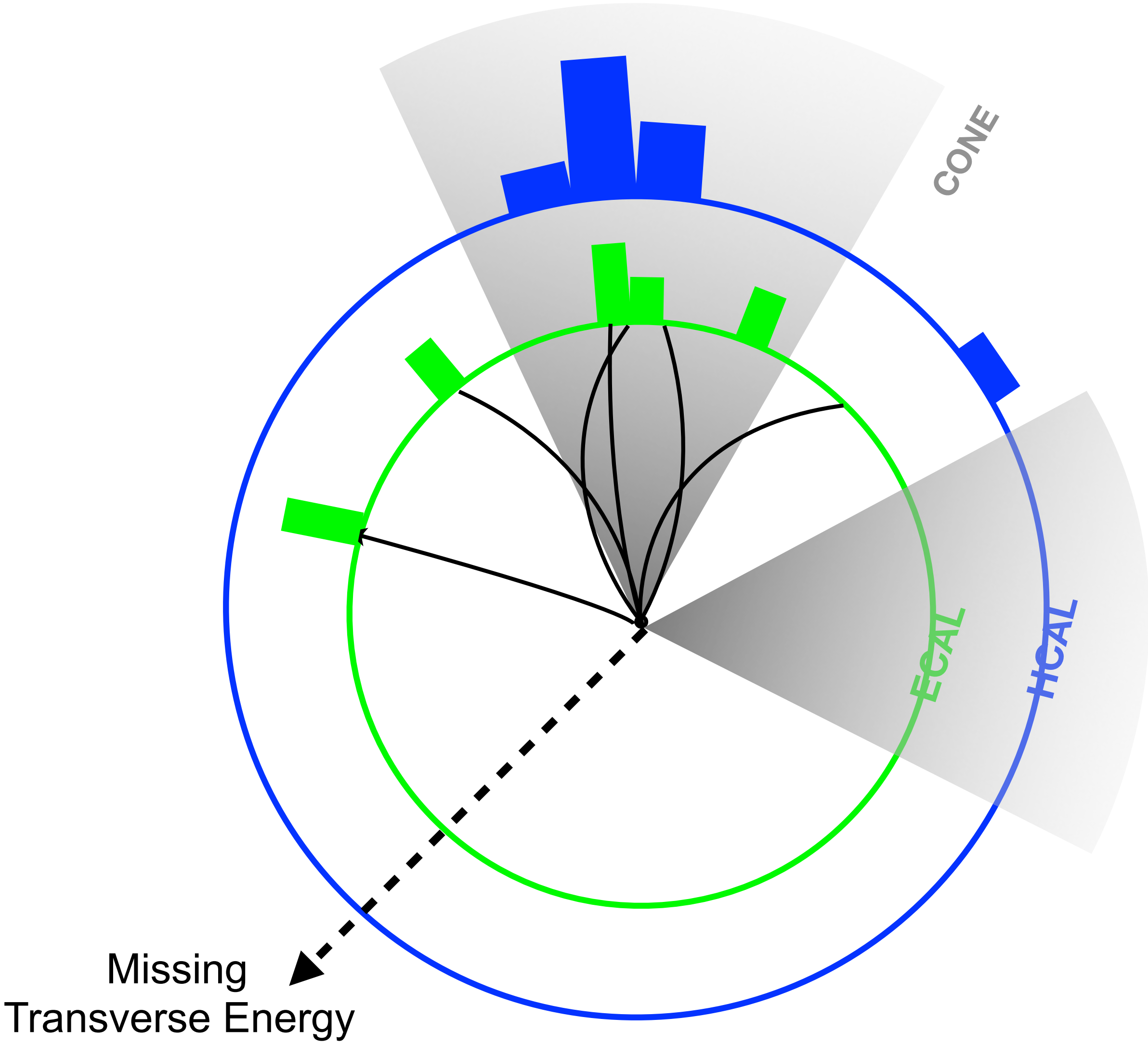
Experimental Ingredients

PARTICLE IDENTIFICATION



- Detectors record signals from hadrons, charged leptons, and photons
- Simple kinematics with momentum and energy
- Energy and momentum conservation used to discriminate signal and background

JETS AND MISSING TRANSVERSE ENERGY

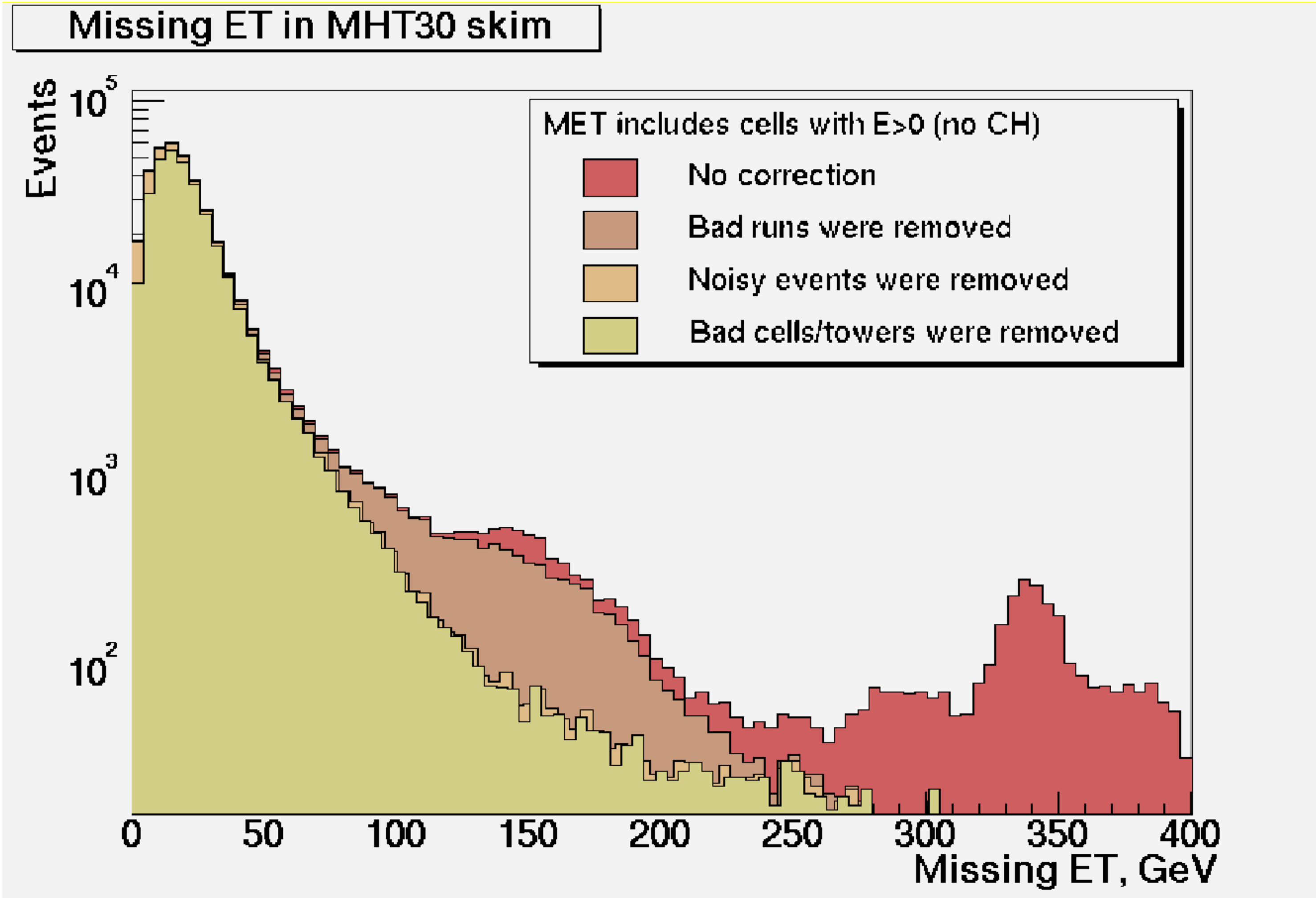


- Conservation of Energy in transverse plane to estimate missing energy from measured visible energy deposits

Experimental Challenges

- Missing transverse energy (MET) measurement
  - correct for instrumental effects and reduce tails
  - verify correct MET resolution and tail description with known control samples
    - Electroweak events: small missing energy
    - di-jet and QCD events: no intrinsic MET only instrumental effects
- Background estimation
  - after kinematic requirements typically remain with
    - t-tbar
    - W/Z + jets
    - WW and ZZ production
    - tt + γ/W/Z/H
  - Cross sections sometimes known at 5-10% level
    - directly affects exclusion limits and discovery potential
  - background kinematics also affected by PDF uncertainties

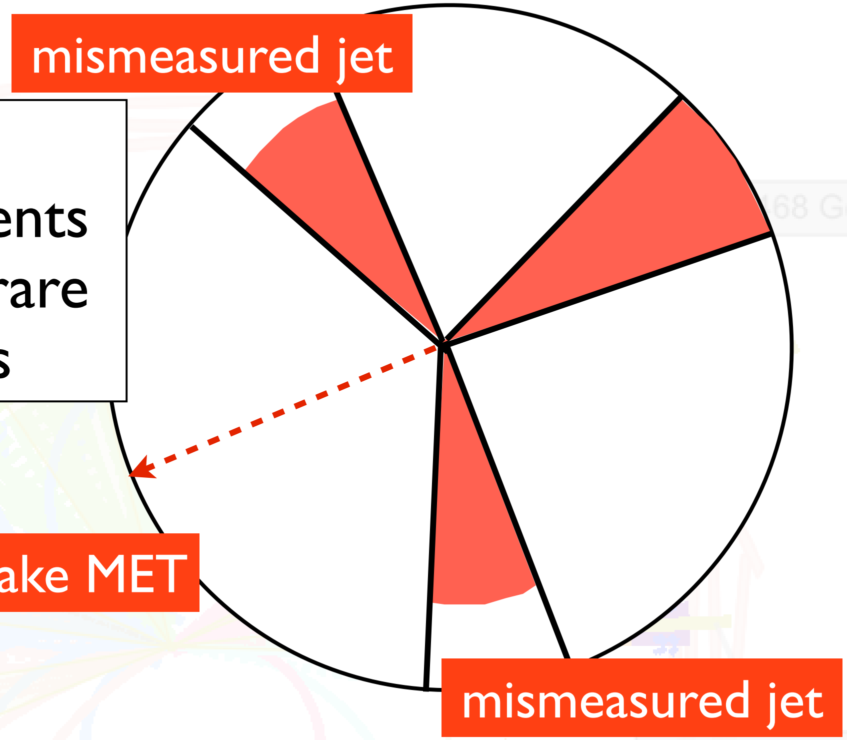
MISSING TRANSVERSE ENERGY

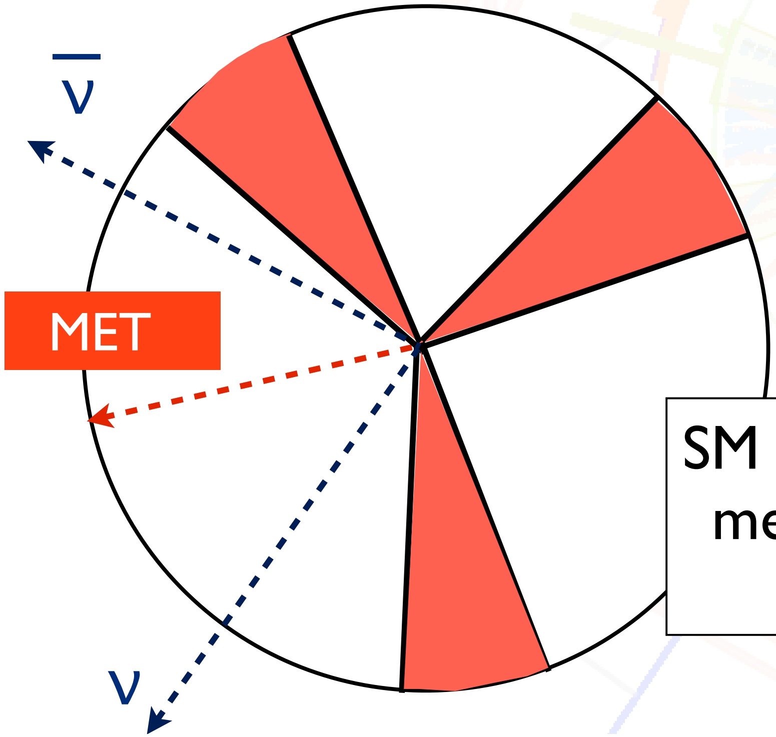


- D0 experiments in early part of Run II
  - Lots of new physics caused by instrumental effects!

Real and Fake MET Background

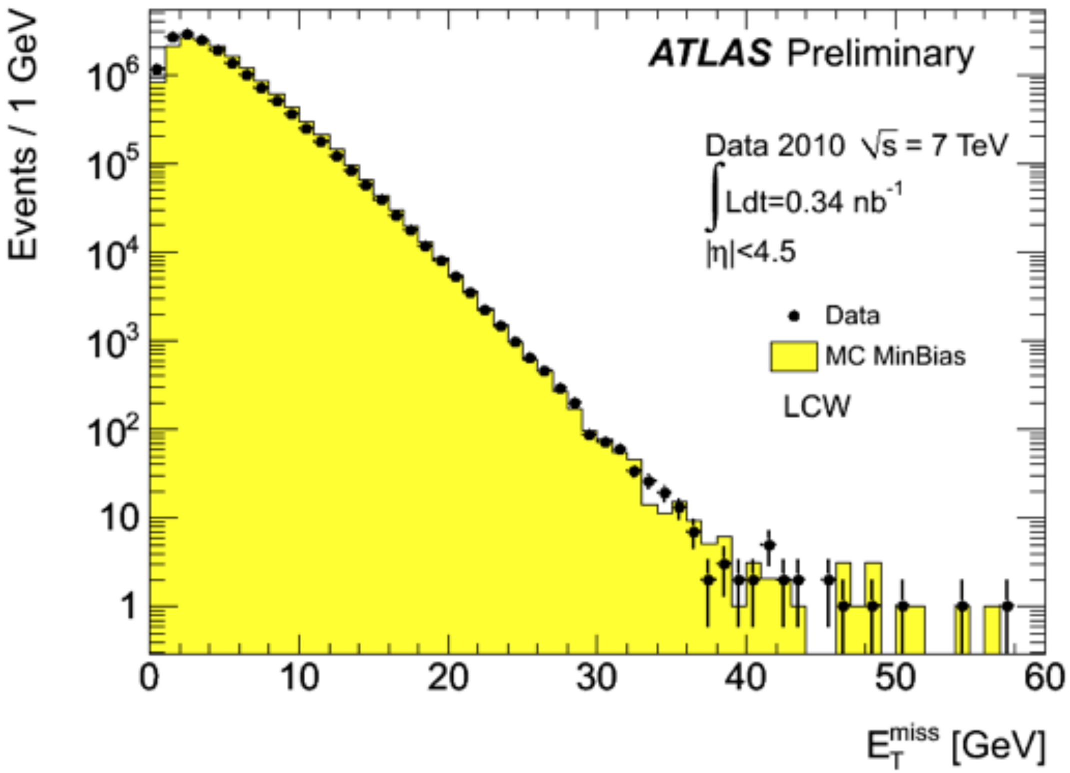
QCD with fake MET
related to pathological events require understanding of rare detector-related effects

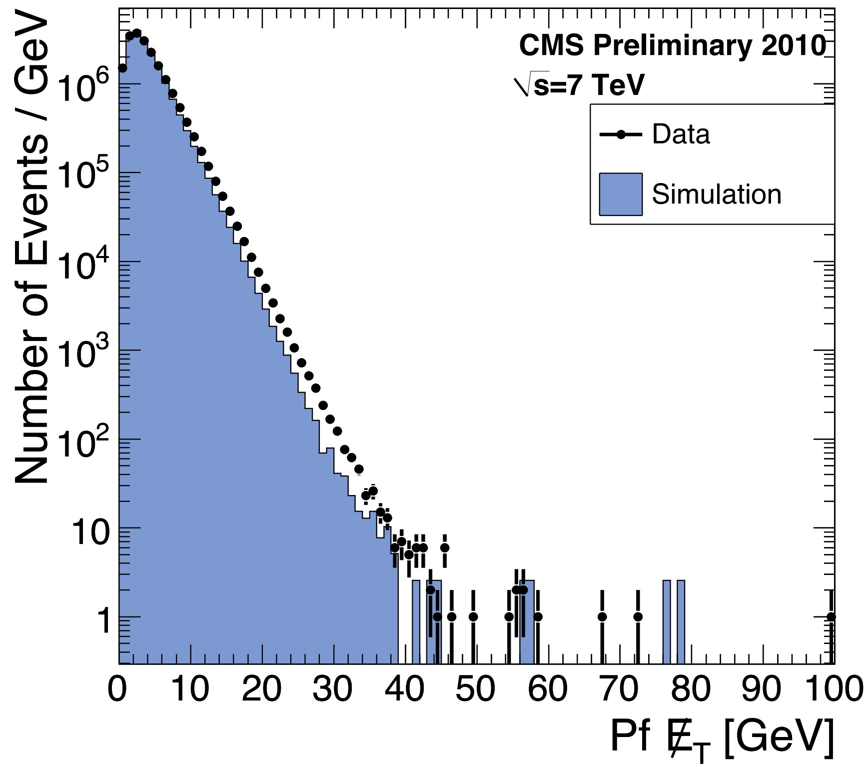




SM processes with real MET, e.g. Z(νν)+jets measurable from control samples defined on data

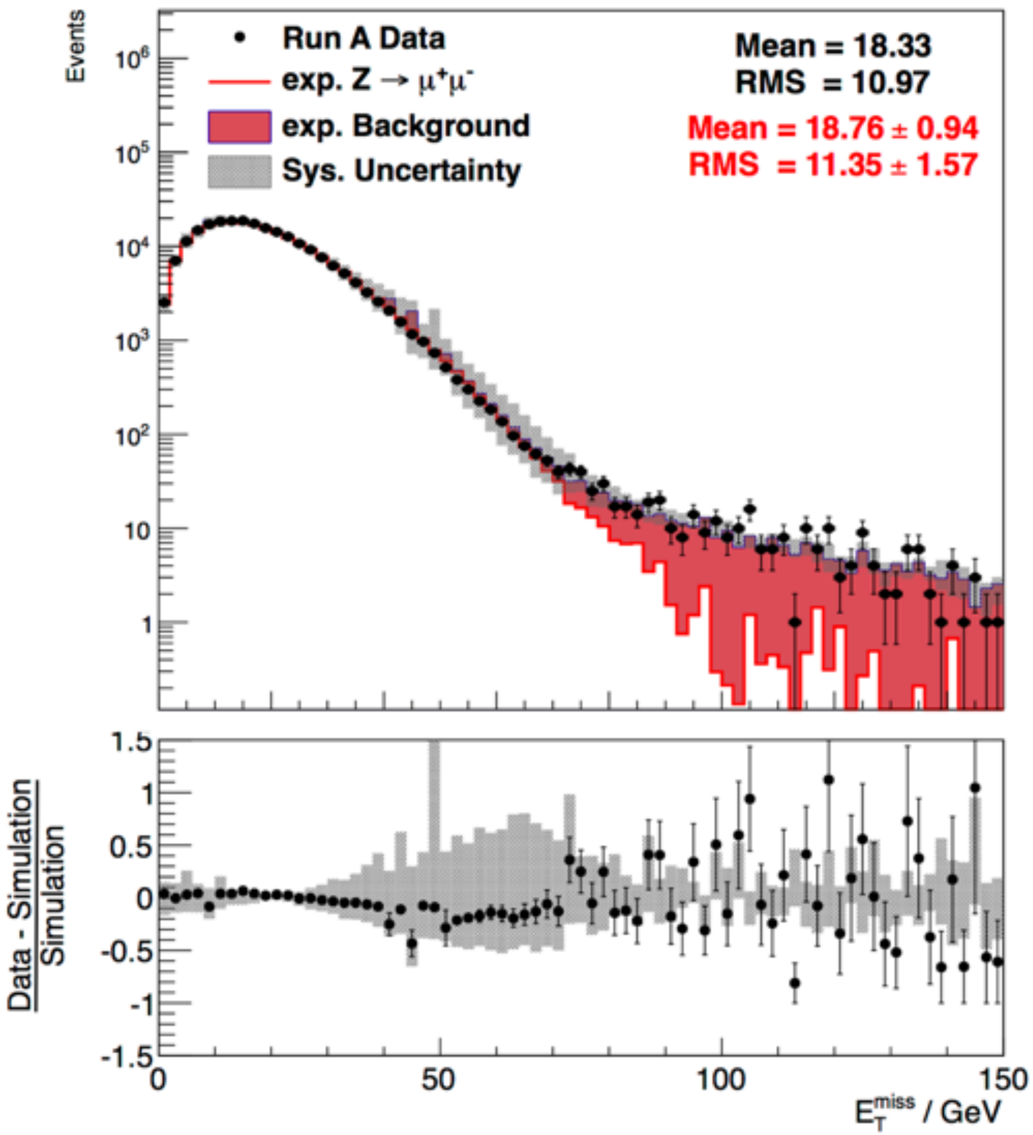
MET at LHC after 3 Months!

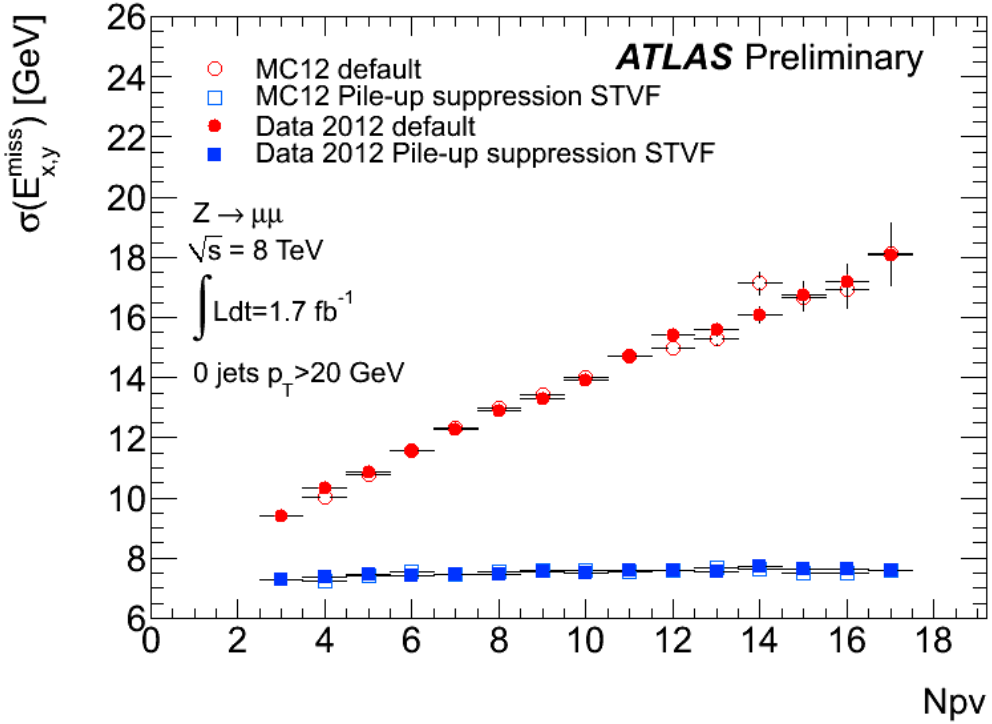




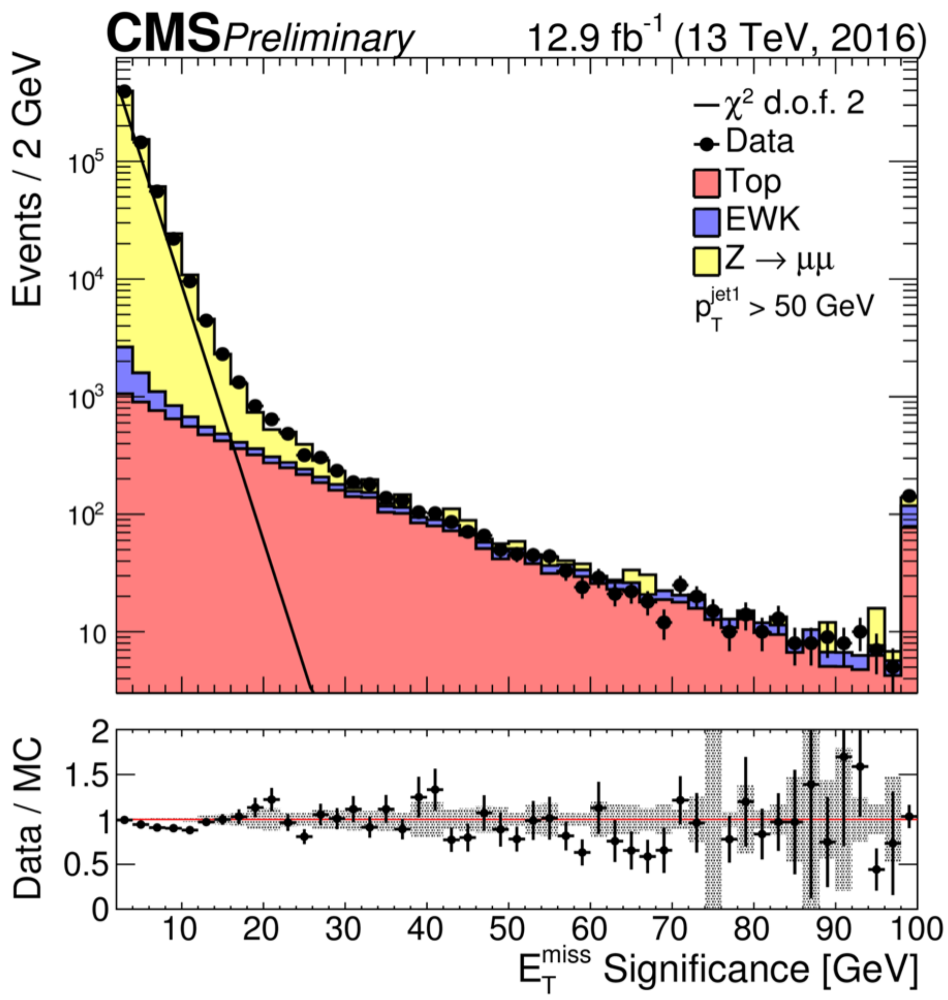
- Excellent understanding of bulk and tails after few weeks of operation
- Very promising for SUSY and New Physics searches already with 50 pb^{-1}

MET AT LHC IN 2012

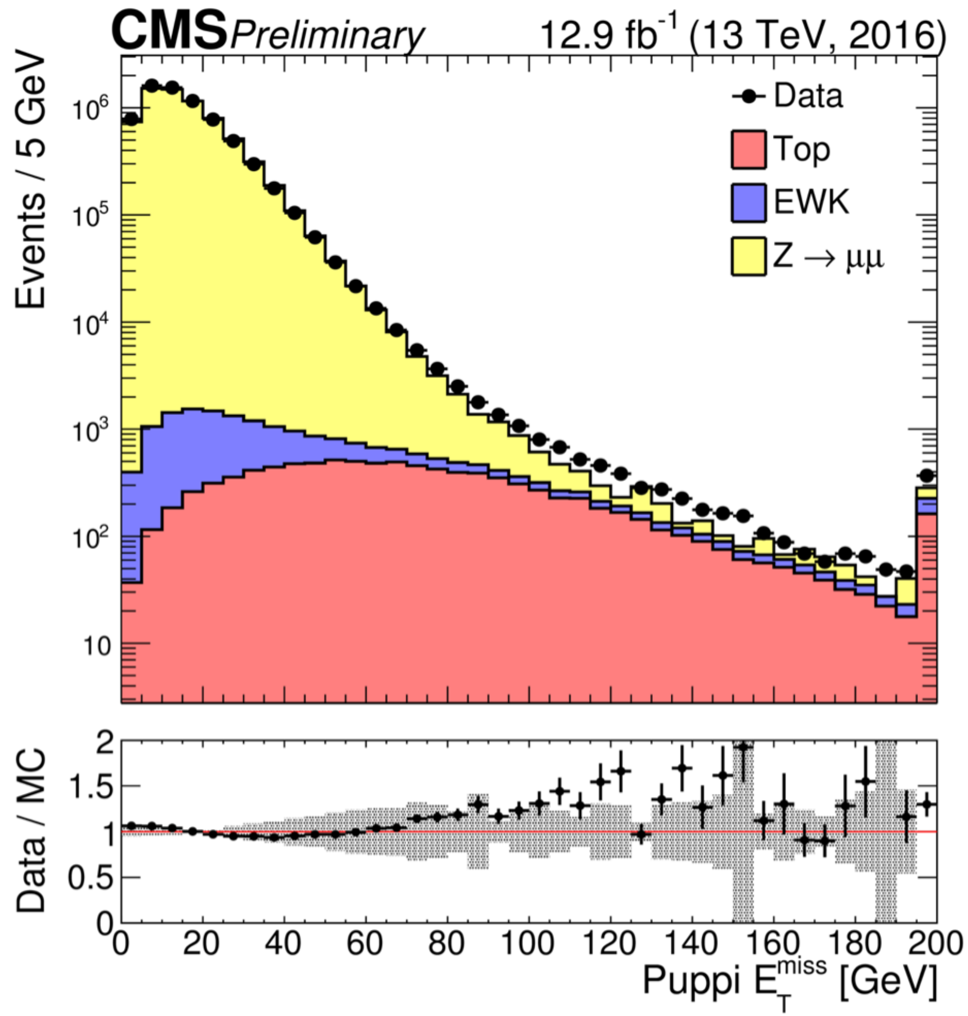




MET @ 13 TeV



CMS Preliminary
12.9 fb-1 (13 TeV, 2016)
χ2 d.o.f. 2
Data
Top
EWK
Z → μμ
p_T^jet1 > 50 GeV
Events / 2 GeV
Data / MC
E_T^miss Significance [GeV]



CMS Preliminary
12.9 fb-1 (13 TeV, 2016)
Data
Top
EWK
Z → μμ
Events / 5 GeV
Data / MC
Puppi E_T^miss [GeV]

Exotica

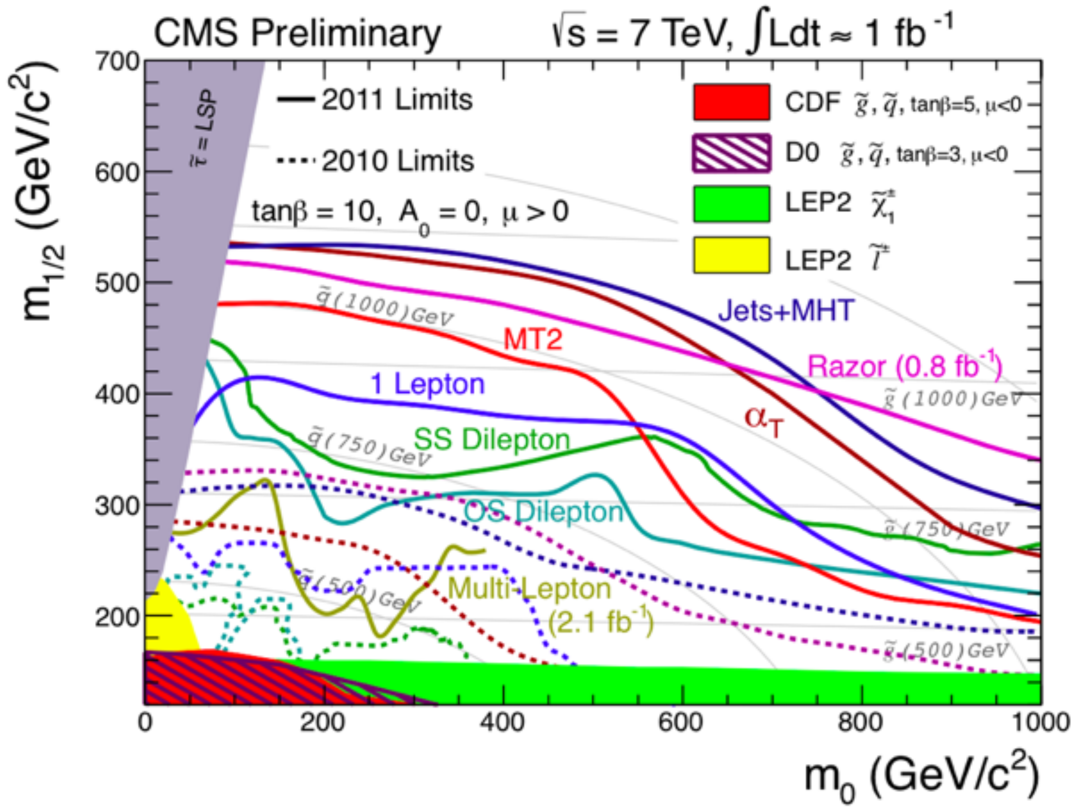
DIFFERENCE BETWEEN EXOTICA AND SUSY

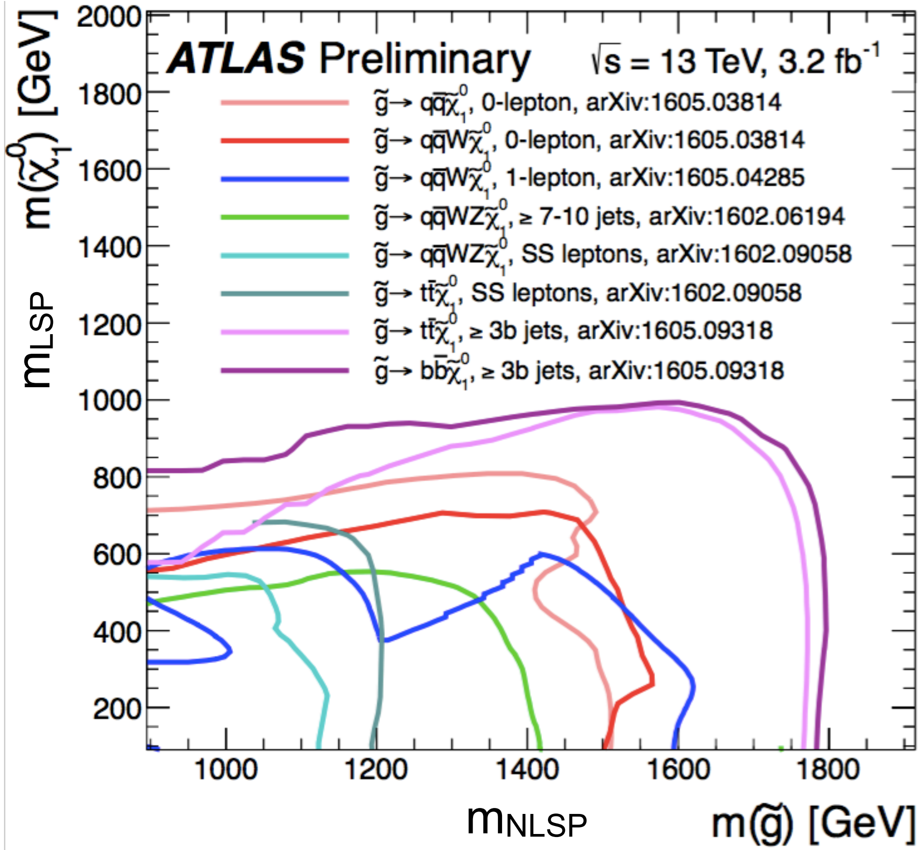
- Fine line between SUSY and Exotic searches

- Historically searches with large missing energy classified as SUSY searches
  - fully hadronic
  - lepton + jets + MET
  - dilpeton + MET
  - trilepton

- Signatures of resonances and new particles commonly go under exotic searches
  - very high pt spectrum for leptons and jets

SUSY vs Exotica

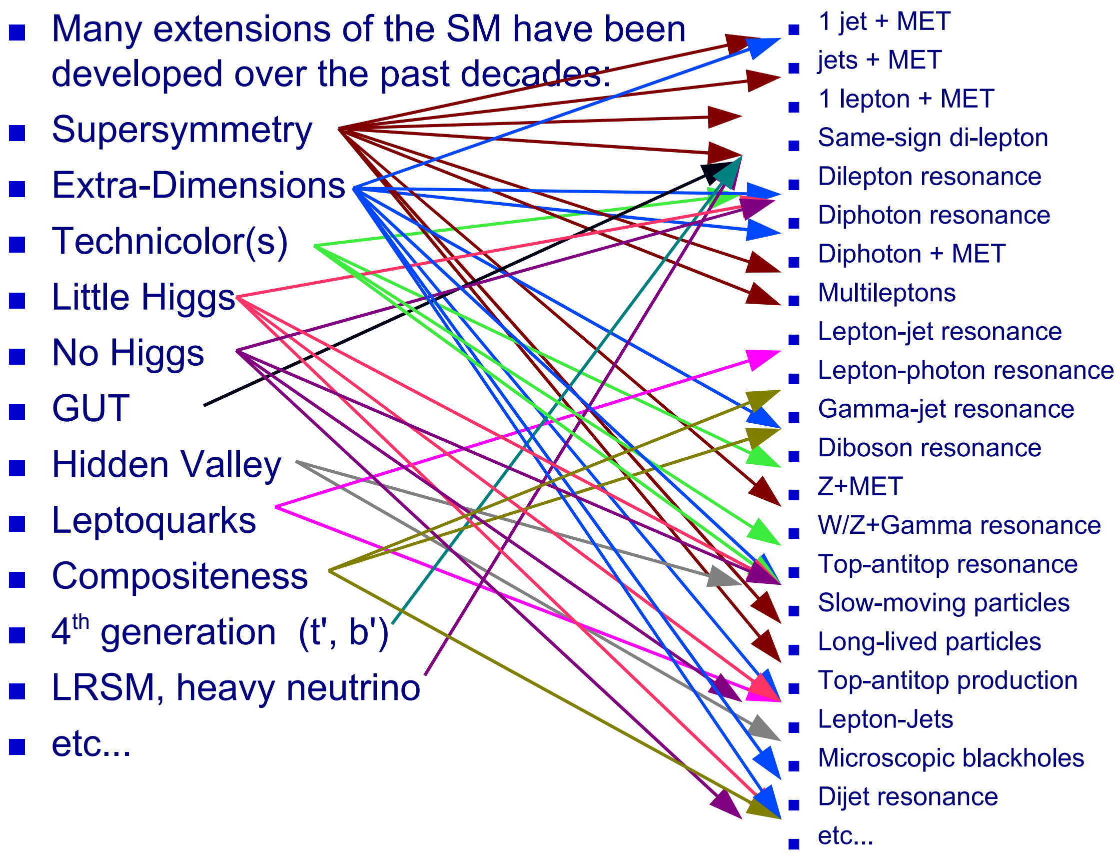




- SUSY results often reported in $(m_0, m_{1/2})$ or (m_X, m_{LSP}) plane
  - Relation between mass of supersymmetric particles
- Large missing transverse energy usually the primary signature
- In exotica look for particles and resonances that are not necessarily needed or predicted in supersymmetry

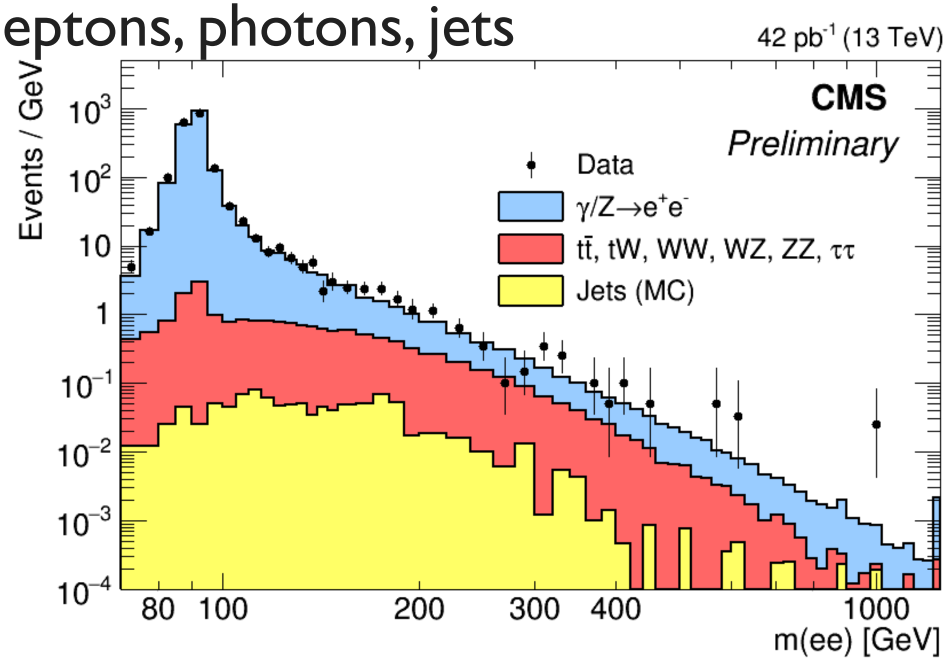
SIGNATURE- VS TOPIC-BASED

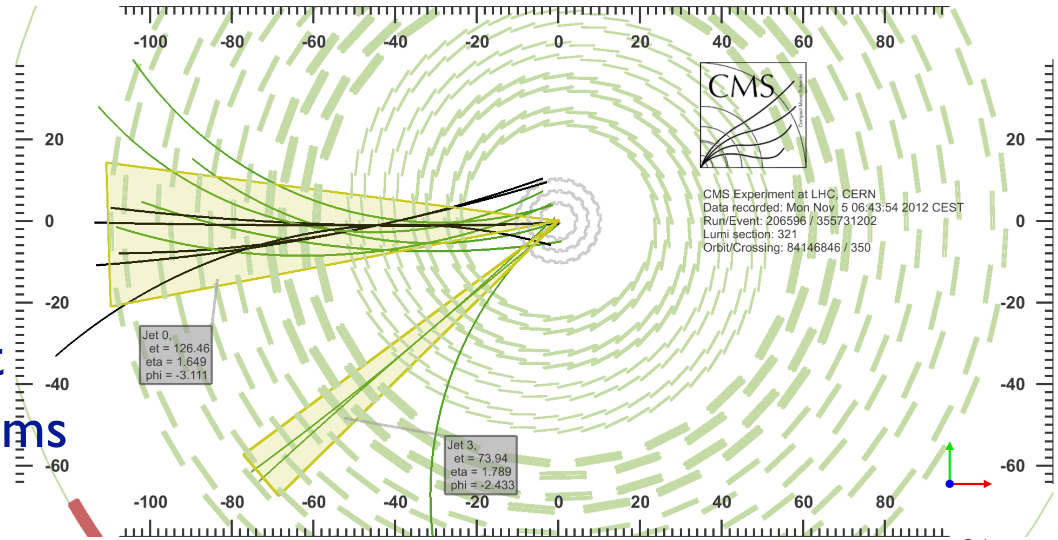
- Same final state often probing very different models or topics
  - 2 leptons, 2jets + MET, lepton+jet+MET
- Topological presentation requires jumping between very different models
- Mostly a topic-based approach in this talk
  - easier to combine constraints on model from different topologies
  - Same final state is not simple re-interpretation
    - often optimization redone to deal with acceptance for very different models
    - different analysis strategy and signal extraction methods



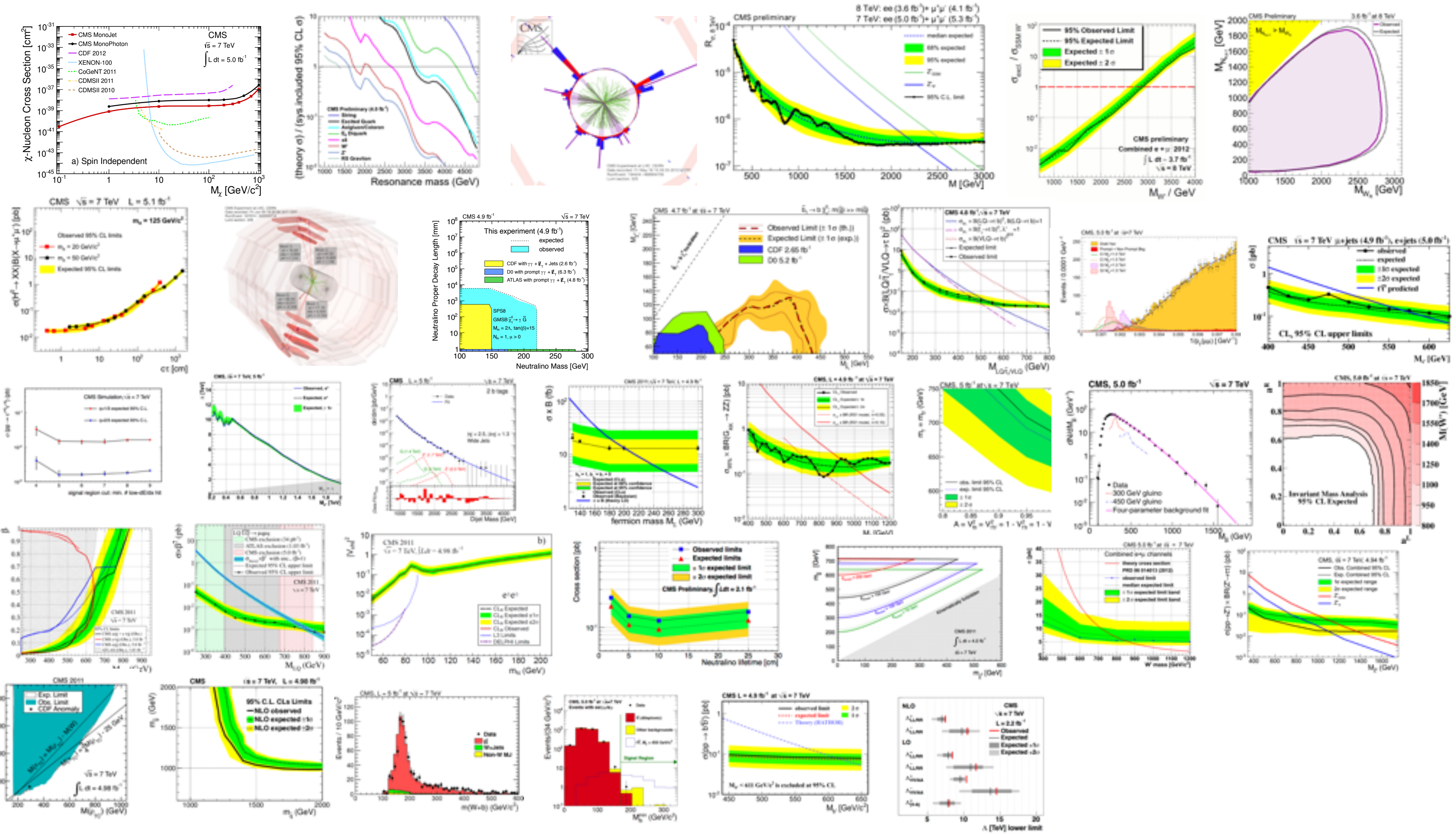
Exotica Timeline

- Rich variety of theoretical models and new particles
- Two-body resonances from day one: leptons, photons, jets
  - detector effects usually not critical
  - sensitive to bumps right away
- increase complexity and multiplicity of final state
  - better understanding and calibration of detector
- Final states with MET + X
- Really exotic signatures such as long-lived particles
  - control of detector conditions over longer period
  - ultimate calibration and alignment
  - optimisation of dedicated algorithms





EXOTICA IN ONE PAGE



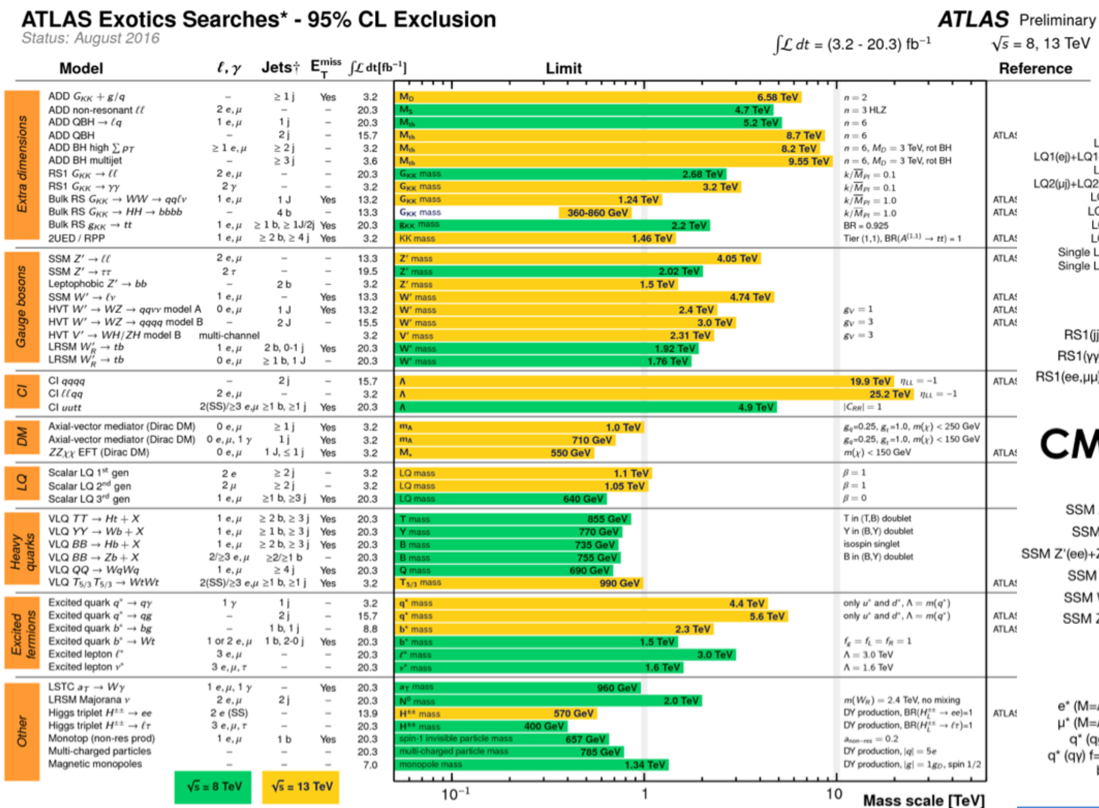
REFERENCES

- Exotica
  - ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
  - CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
    http://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G

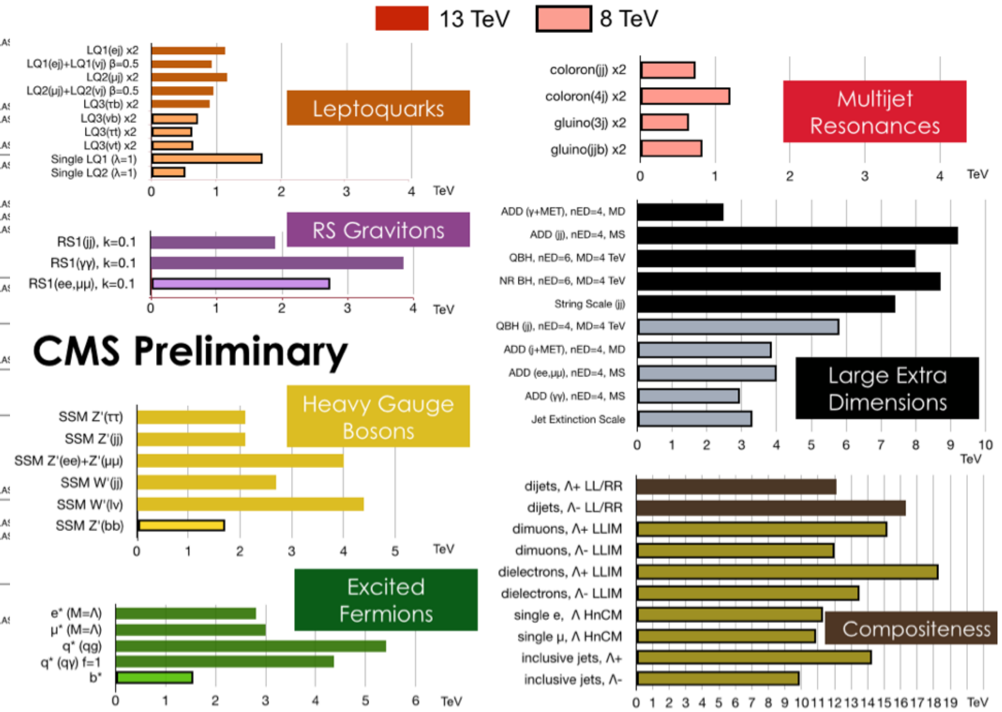
- SUSY results
  - ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
  - CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

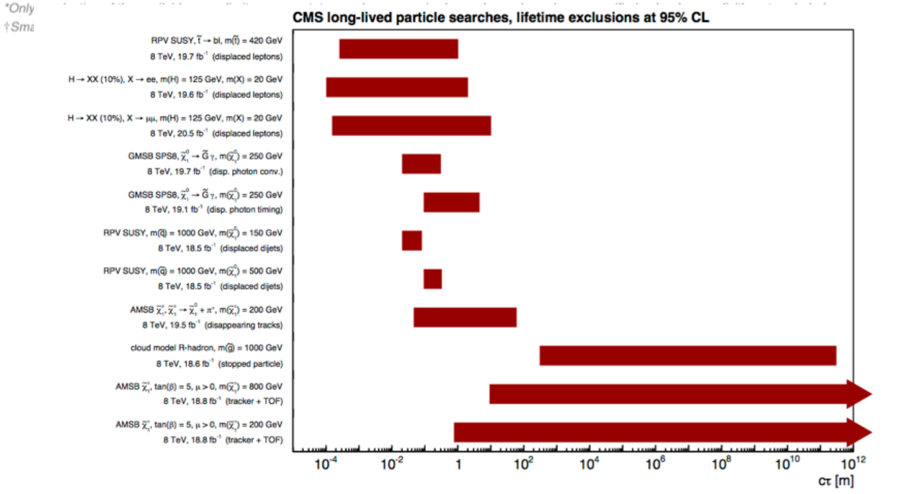
EXOTICA SUMMARIES…

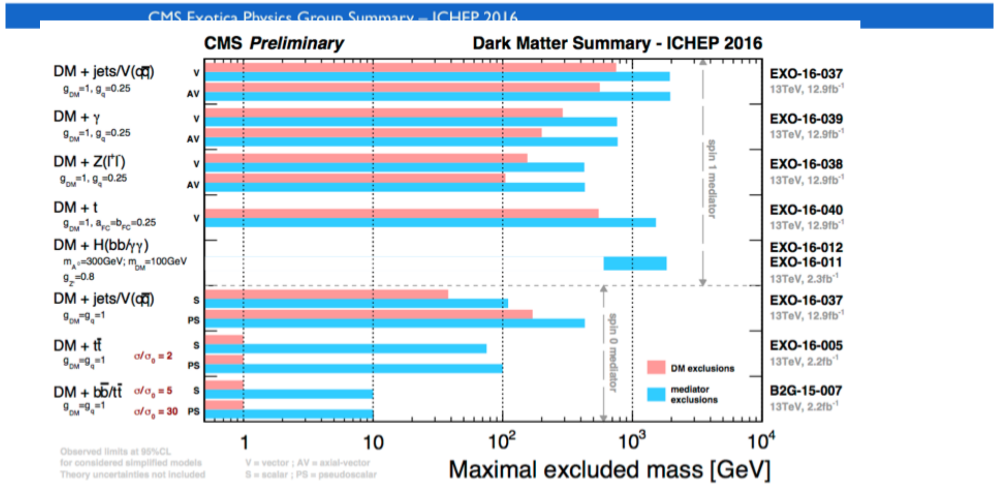
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/ATLAS_Exotics_Summary/ATLAS_Exotics_Summary.png



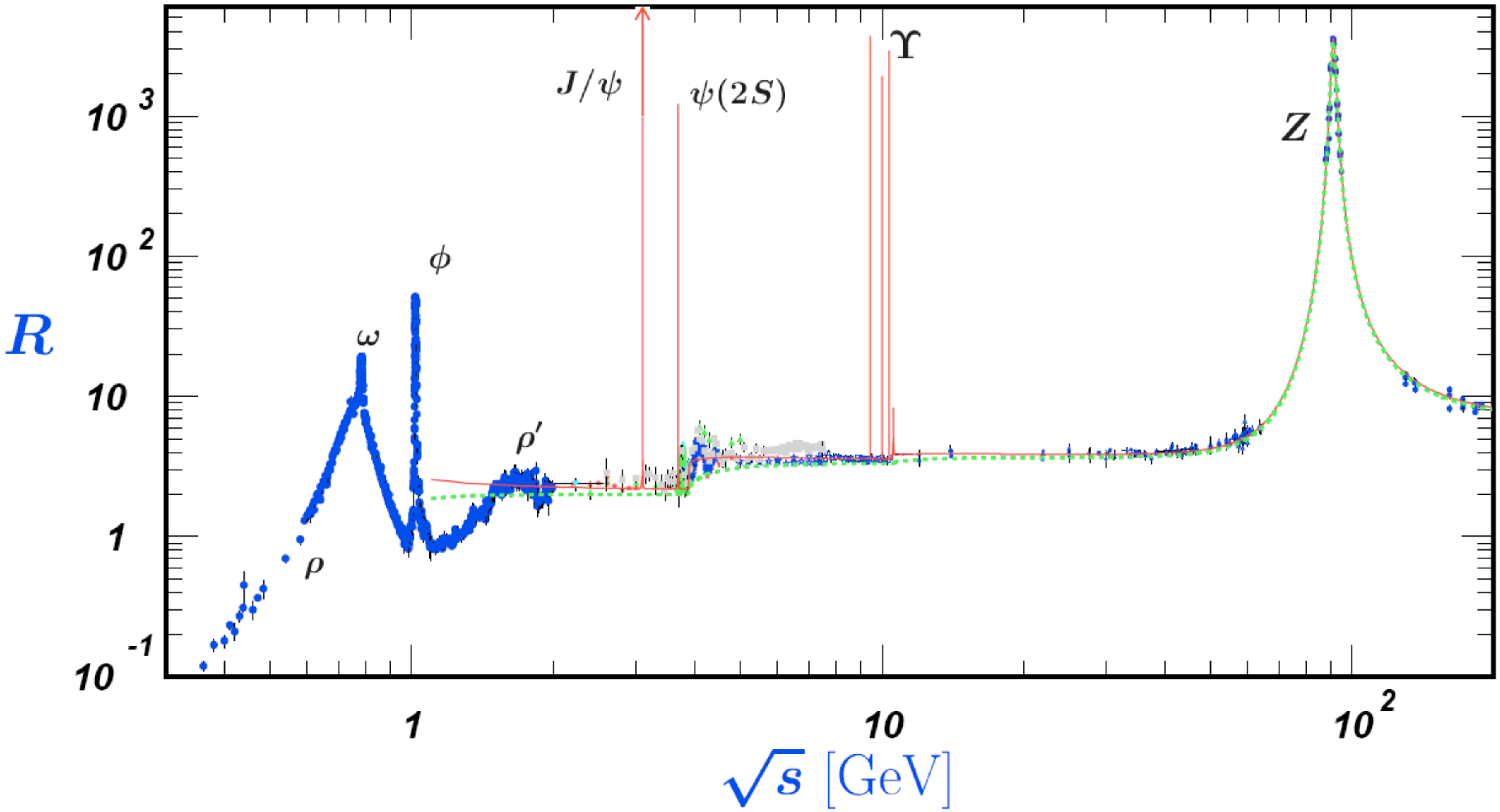
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO







RESONANCES



R
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10^2
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10^2
$\sqrt{s}$ [GeV]
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$\psi(2S)$
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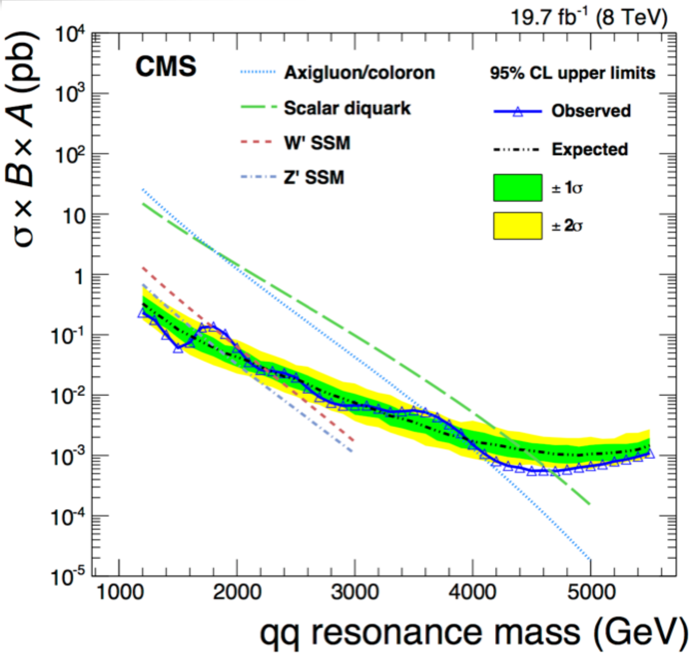
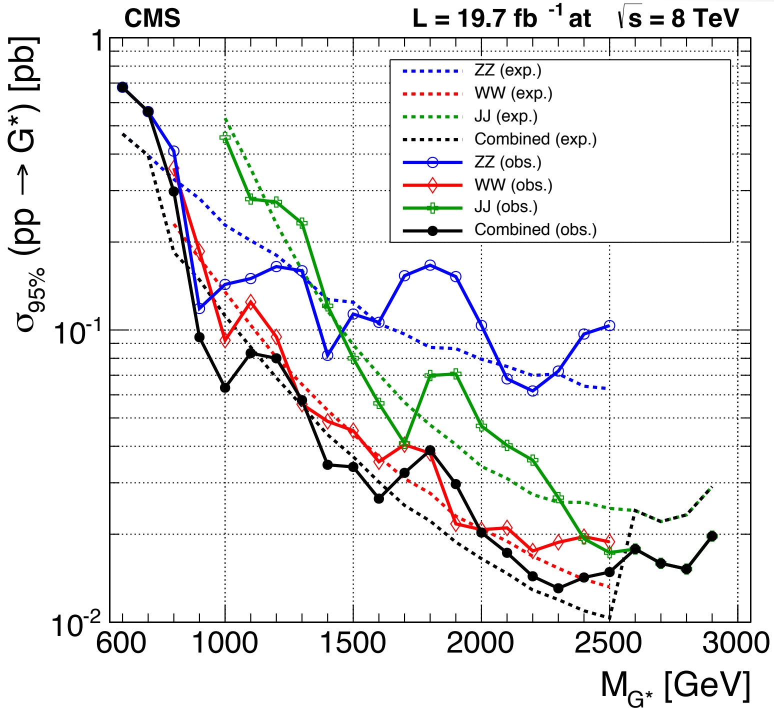
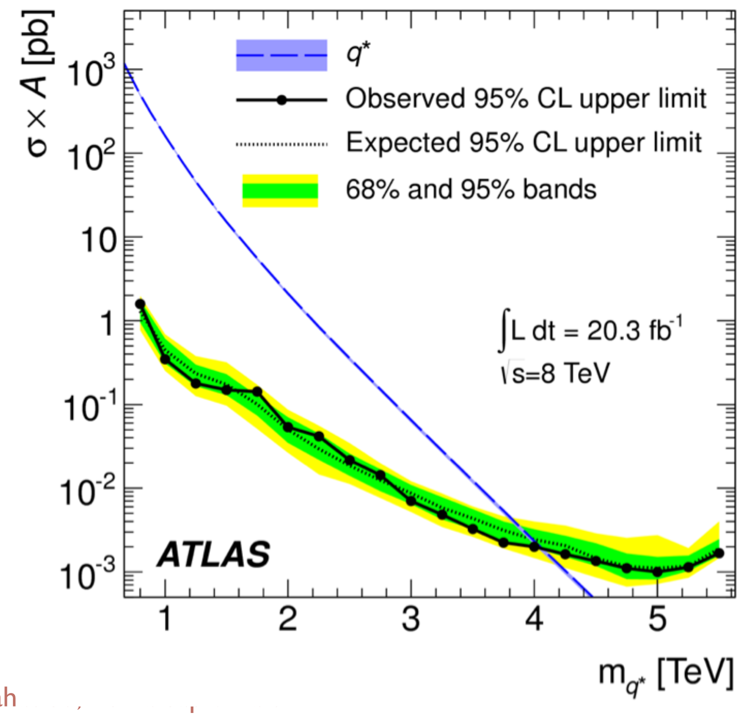
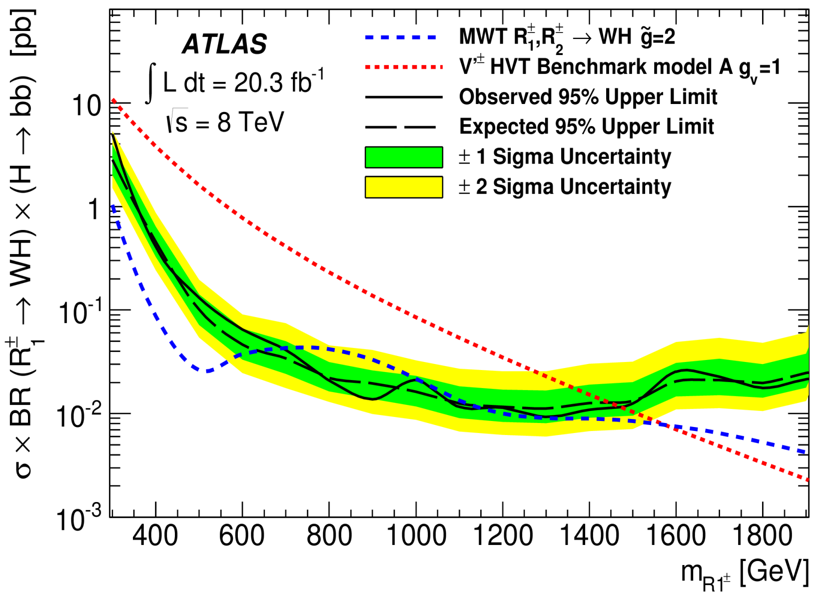
?

RESONANCES AT 8 TEV

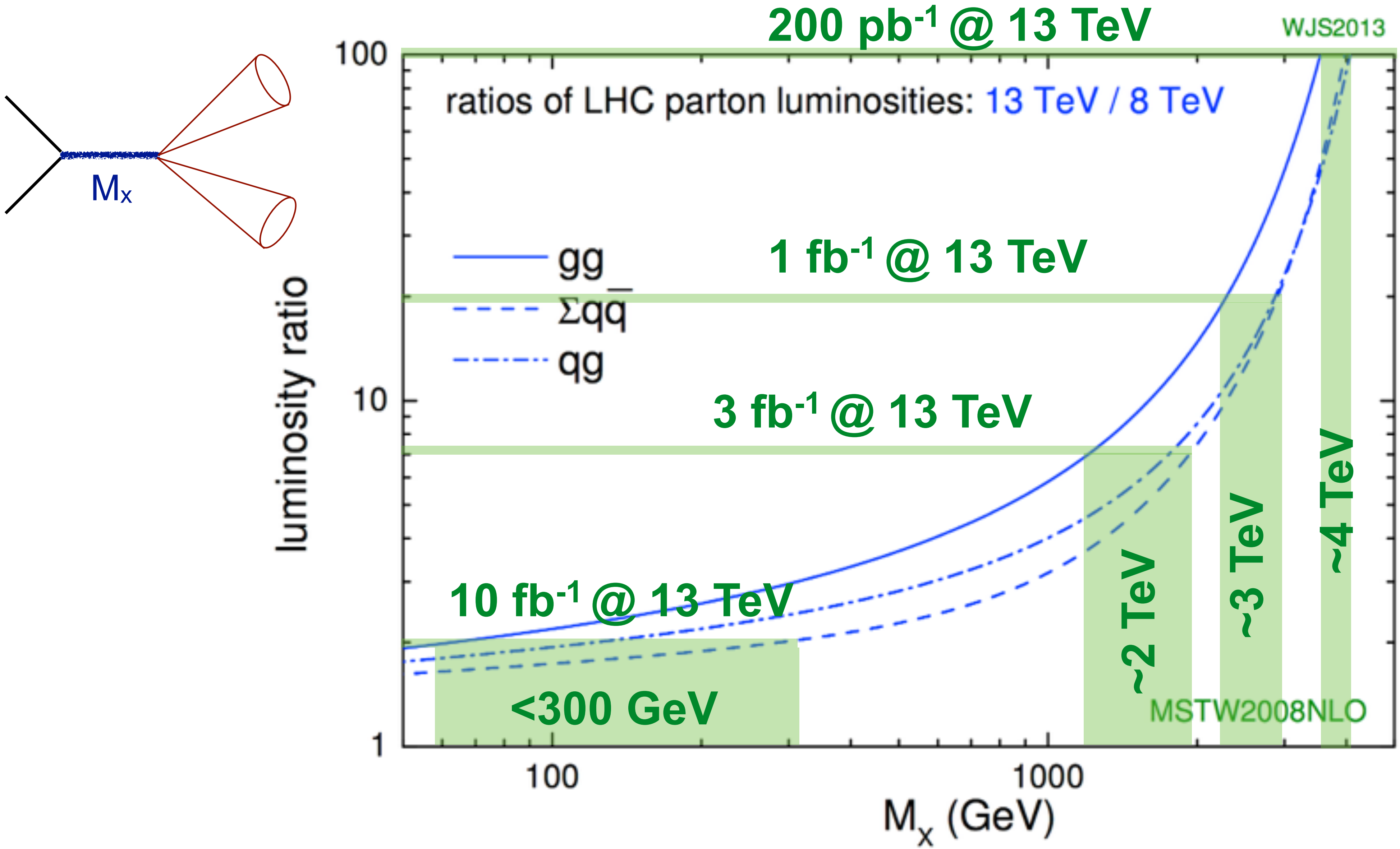






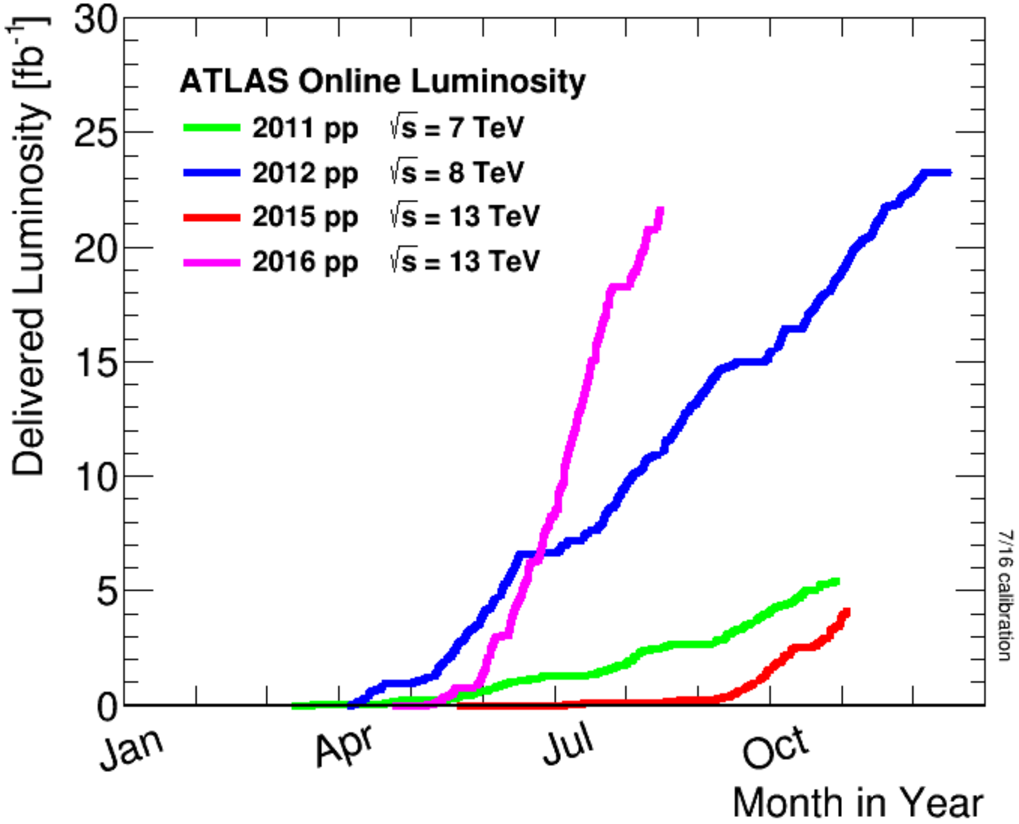


Importance of Energy Increase



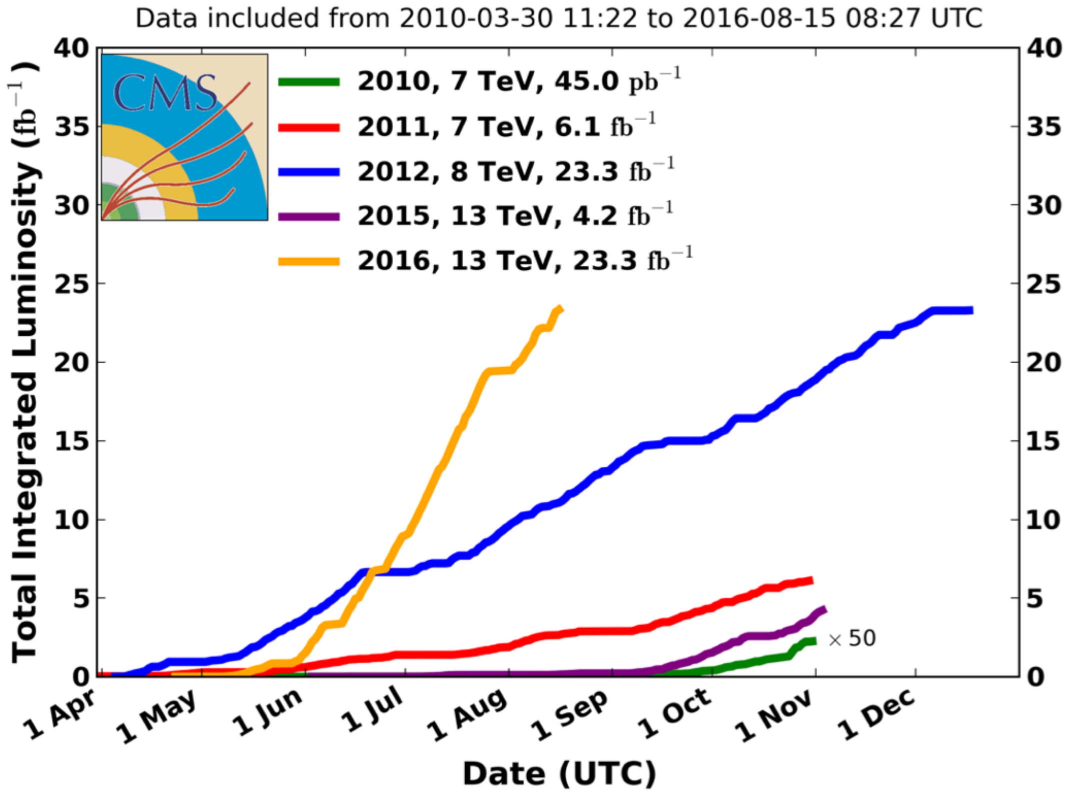
- 2015 data collected equivalent to 2012 dataset for Mx ~ 2-3 TeV

Spectacular Performance of LHC in 2016



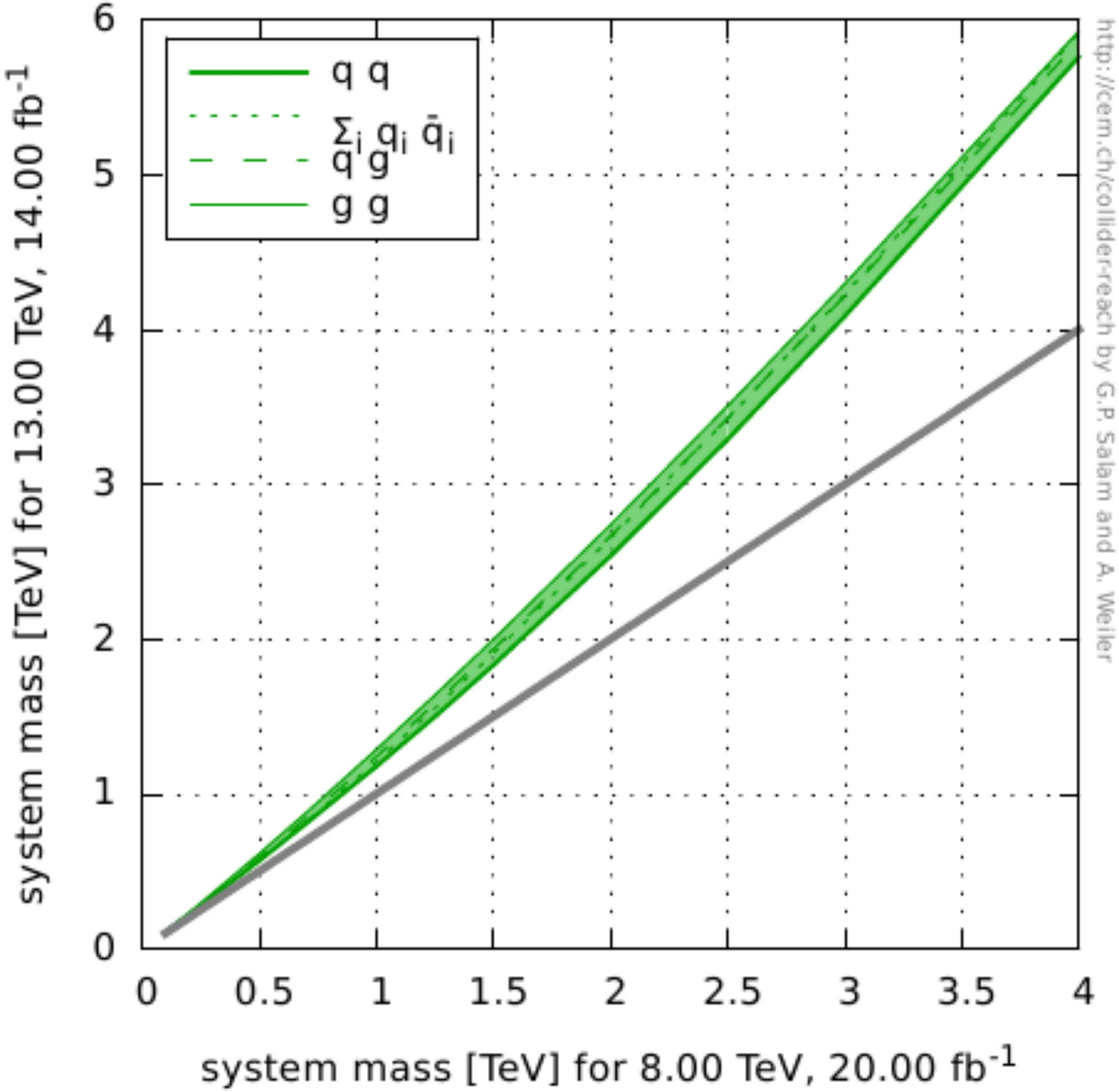
ATLAS online luminosity

CMS online luminosity



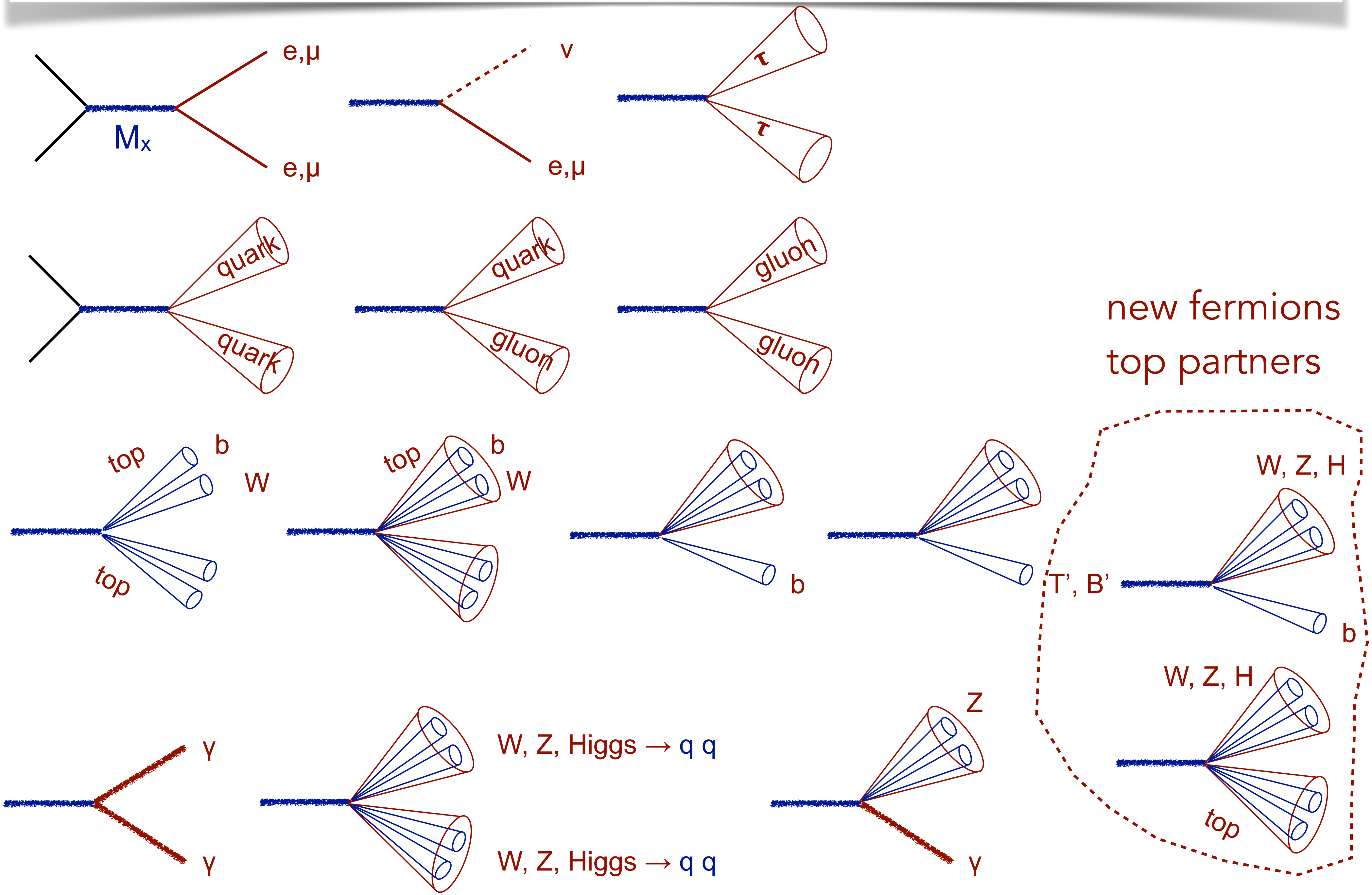
- Kudos to
  - LHC for outstanding delivery
  - ATLAS and CMS detector teams for extremely quick availability for analysis

SENSITIVITY WITH 2016 DATA SO FAR



http://cern.ch/collider-reach

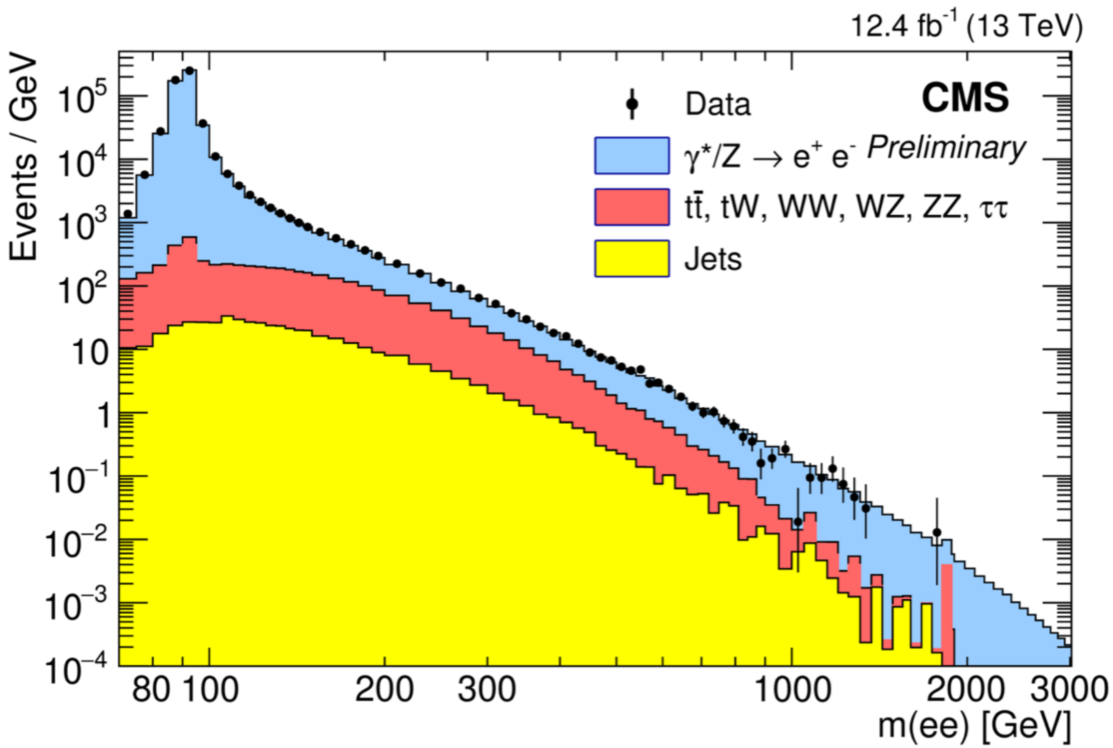
HEAVY RESONANCES

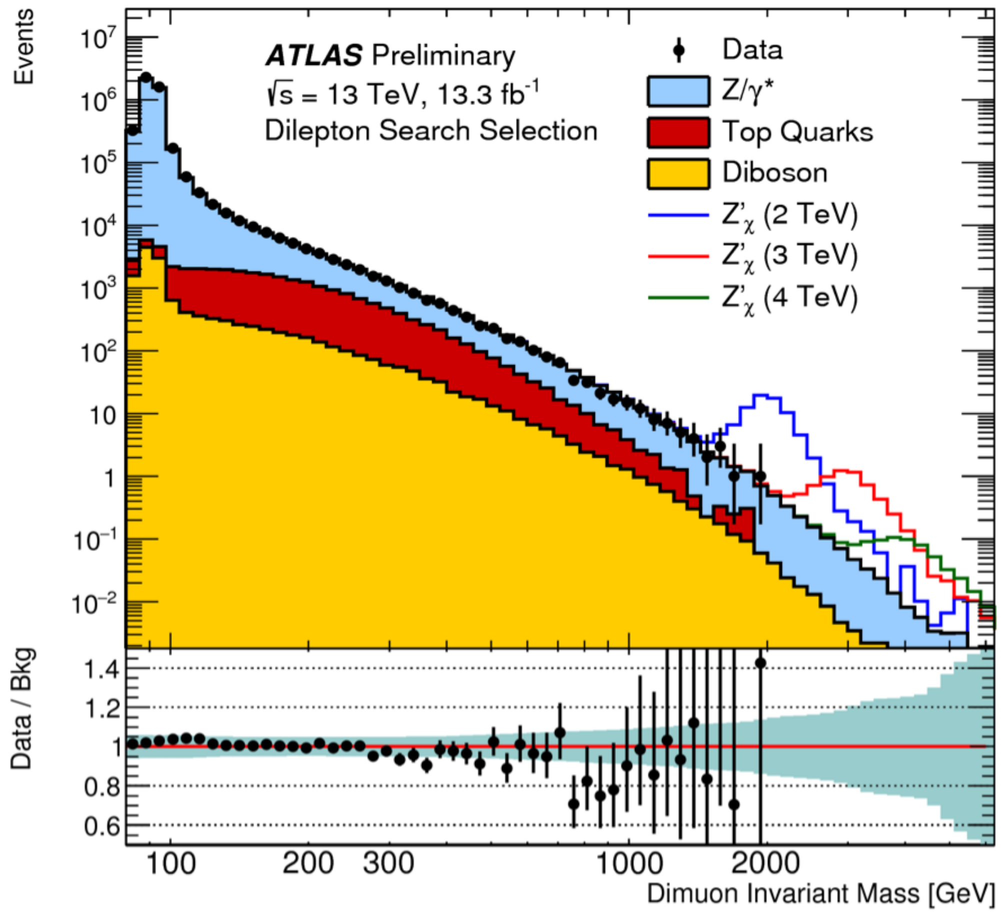


EXTENDED GAUGE SYMMETRIES

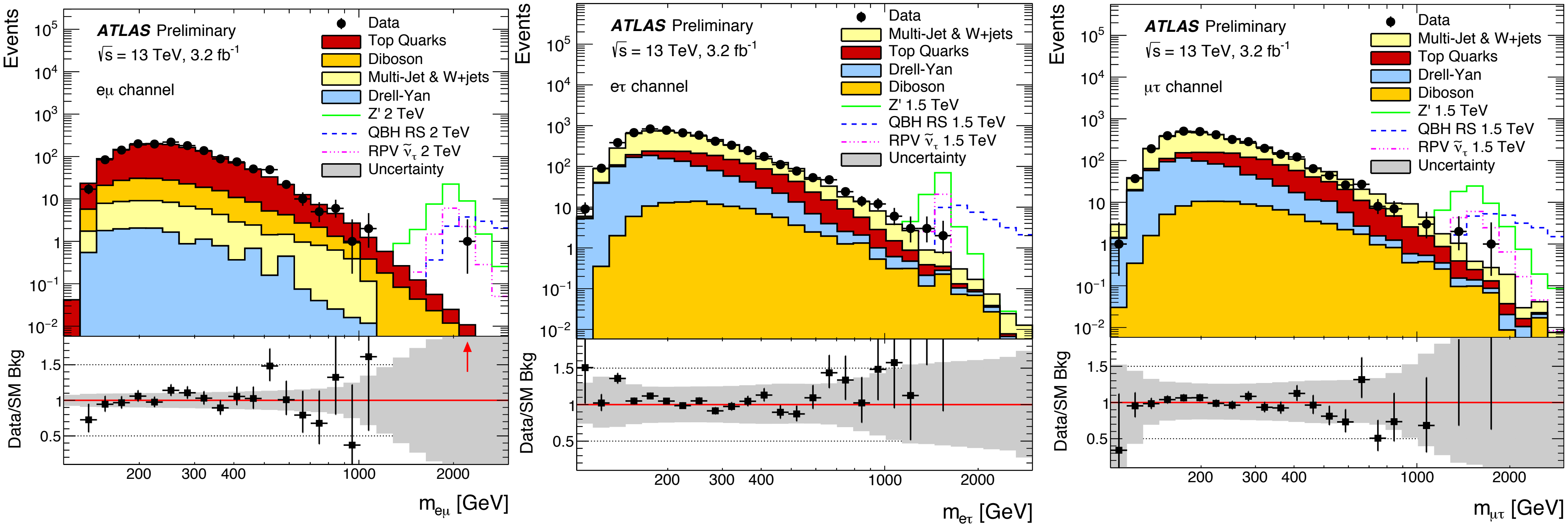
- New gauge bosons predicted by many extensions of the Standard Model with extended gauge symmetries
  - ZSSM in Sequential Standard Model with same Z0 coupling as in Standard Model
  - Z'_ψ , Z'_χ , Z'_η models from E6 and SO(10) GUT groups
  - Left-Right symmetry model (LRM) and Alternative LRM (ALRM)
  - The Kaluza-Klein model (KK) from Extra Dimension
  - Little, Littlest Higgs model
- *No precise prediction for mass scale of gauge bosons*
- Discrimination of different models requires measurement of
  - cross section: limits with very little data
  - mass: exact value requires a visible peak
  - width: about same amount of data as for for mass
  - backward-forward asymmetry: requires high statistics in order to divide events in categories
- Backgrounds
  - relatively clean with good S/B
  - mostly tails of SM processes
- Experimental challenges
  - detector resolution can be a key player
  - 1.3% - 2.4% for electrons and 7% for muons at 1 TeV mass
- extra care for energy/momentum reconstruction above 1 TeV

DI-LEPTONS

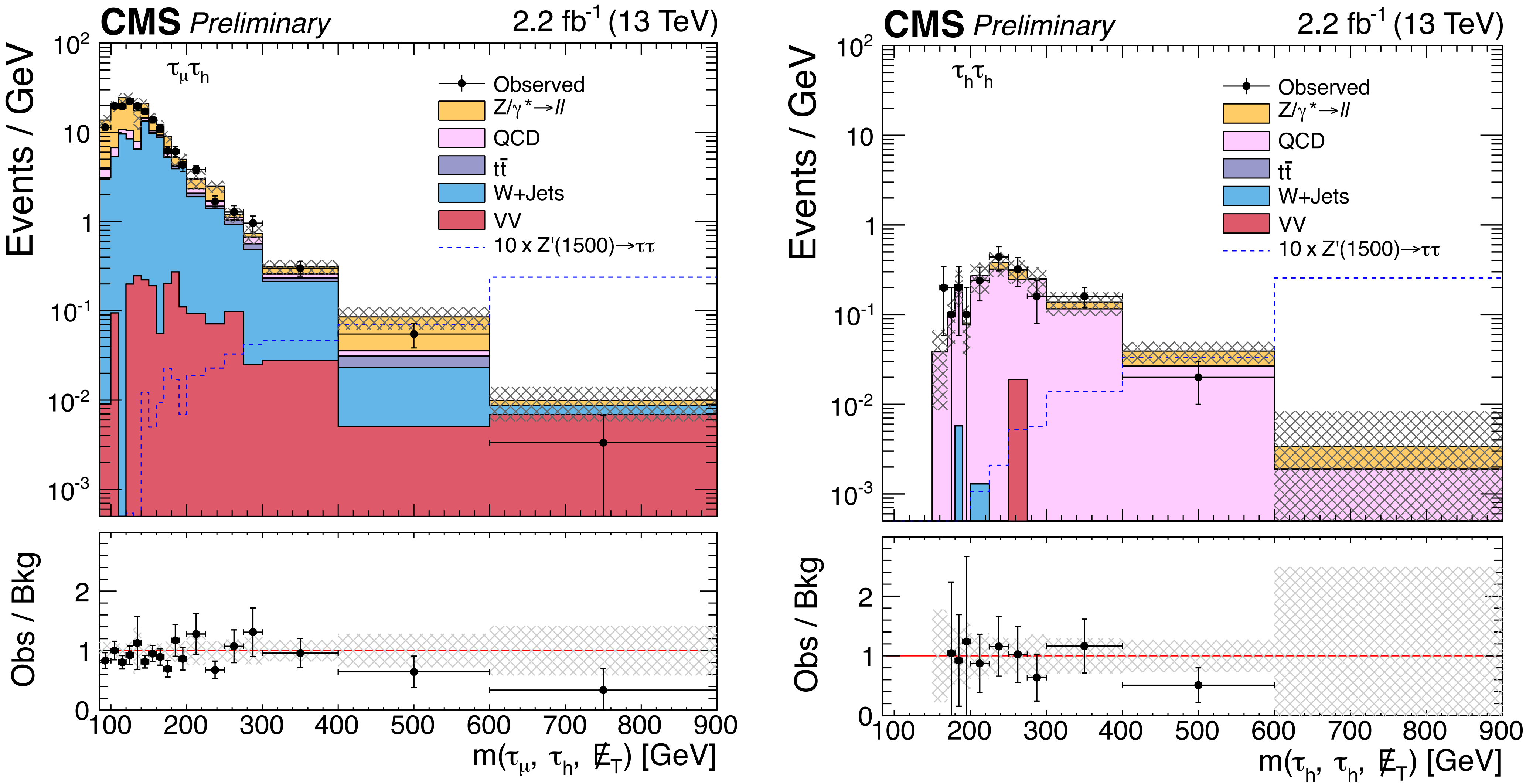

12.4 fb^{-1} (13 TeV)
CMS
Preliminary
Data
$\gamma^*/Z \to e^+ e^-$
$t\bar{t}$, tW, WW, WZ, ZZ, $\tau\tau$
Jets
Events / GeV
m(ee) [GeV]


ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 13.3 fb^{-1}
Dilepton Search Selection
Data
Z/γ^*
Top Quarks
Diboson
Z'_χ (2 TeV)
Z'_χ (3 TeV)
Z'_χ (4 TeV)
Events
Data / Bkg
Dimuon Invariant Mass [GeV]

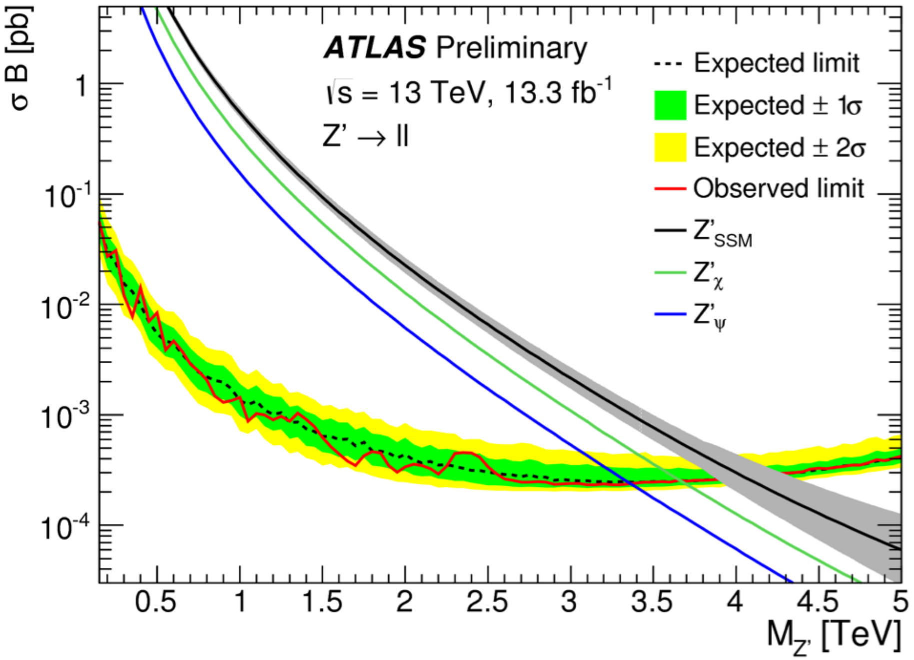
Lepton Flavor Violation

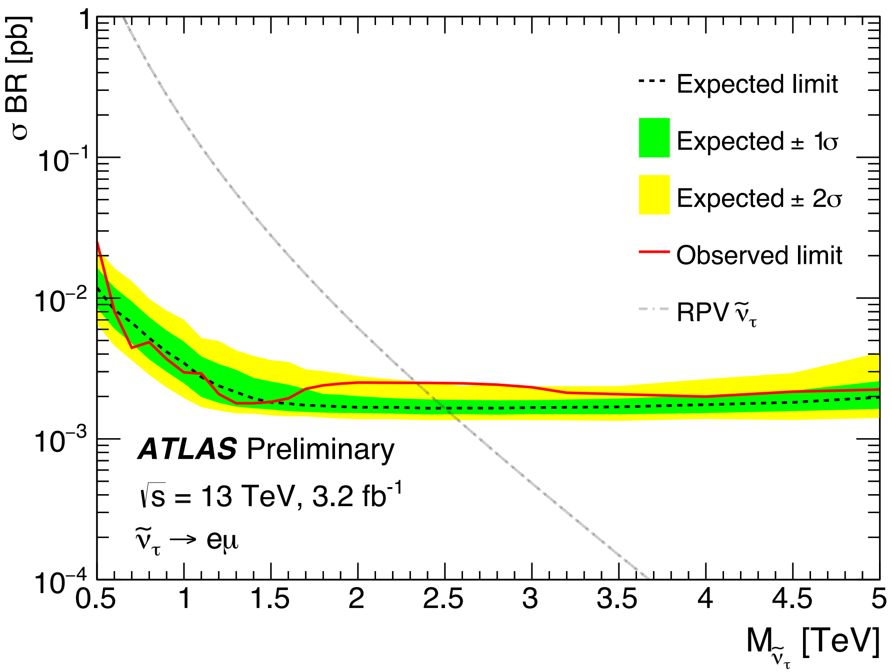


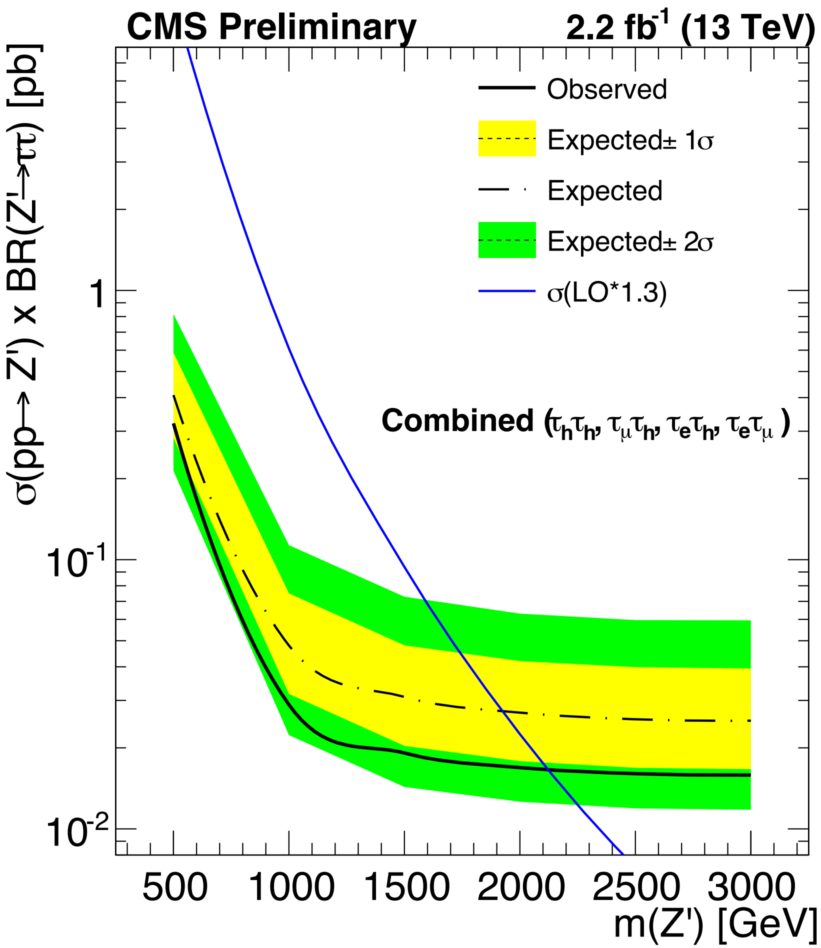
TAU-TAU


CMS Preliminary
2.2 fb^{-1} (13 TeV)
$\tau_\mu\tau_h$
Observed
$Z/\gamma^* \to ll$
QCD
$t\bar{t}$
W+Jets
VV
10 x Z'(1500)→ττ
Events / GeV
Obs / Bkg
$m(\tau_\mu, \tau_h, \not{E}_T)$ [GeV]
CMS Preliminary
2.2 fb^{-1} (13 TeV)
$\tau_h\tau_h$
Observed
$Z/\gamma^* \to ll$
QCD
$t\bar{t}$
W+Jets
VV
10 x Z'(1500)→ττ
Events / GeV
Obs / Bkg
$m(\tau_h, \tau_h, \not{E}_T)$ [GeV]

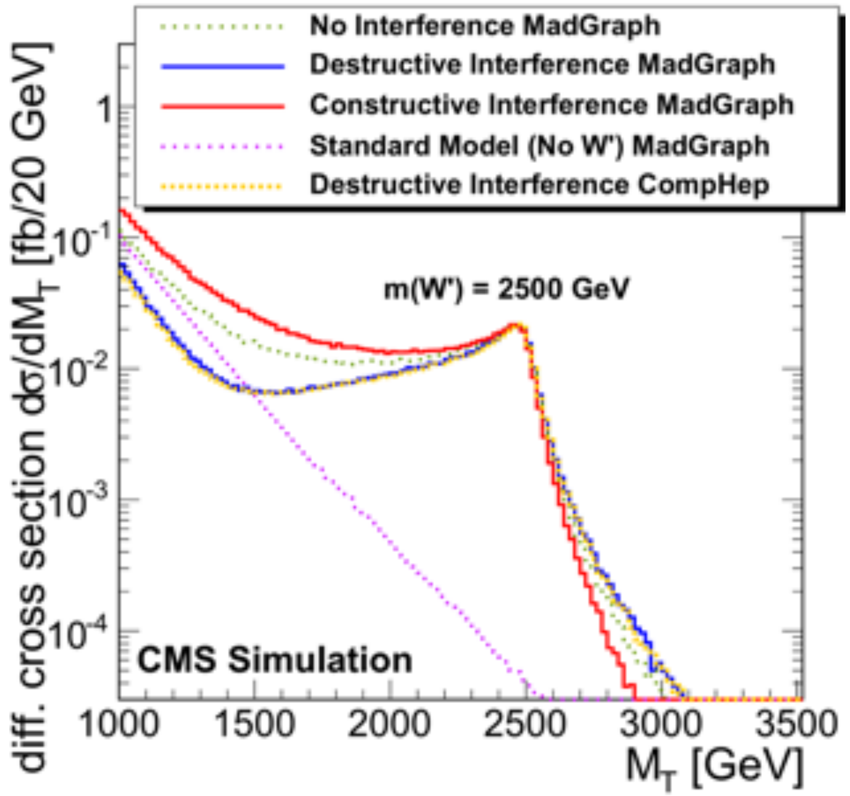
EXCLUSION LIMITS

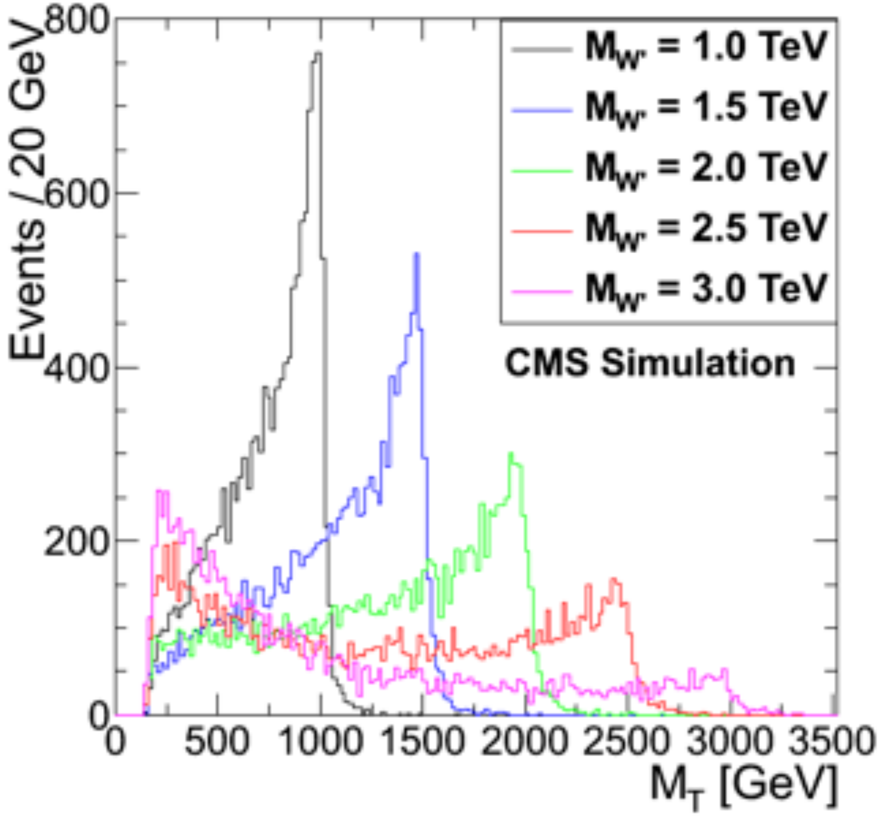






NEW W-LIKE BOSON



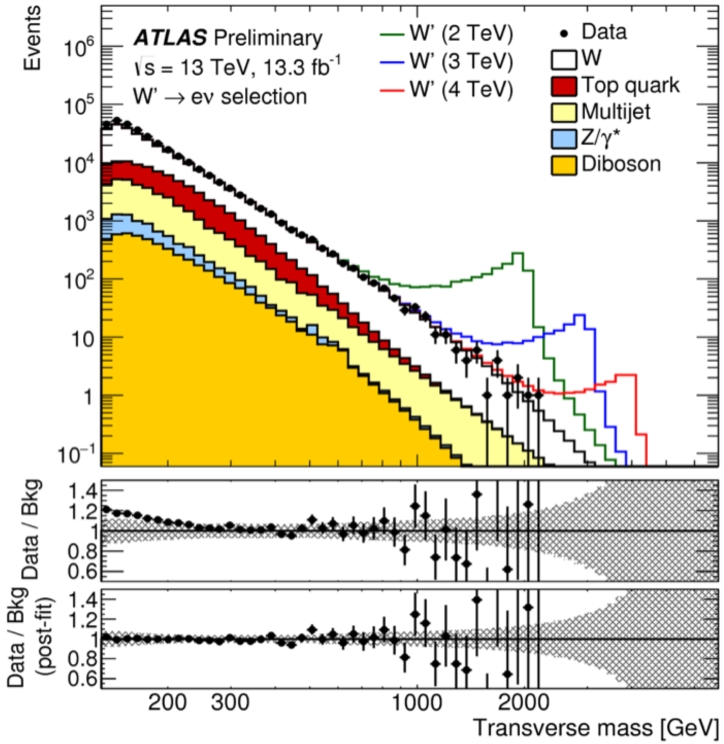


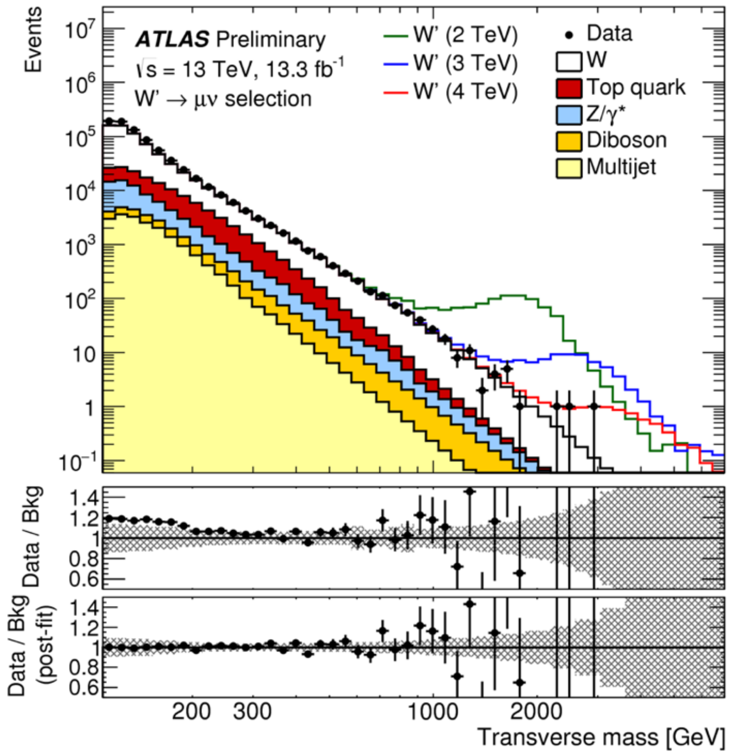
- Look for heavy W-like Jacobian peak in transverse mass

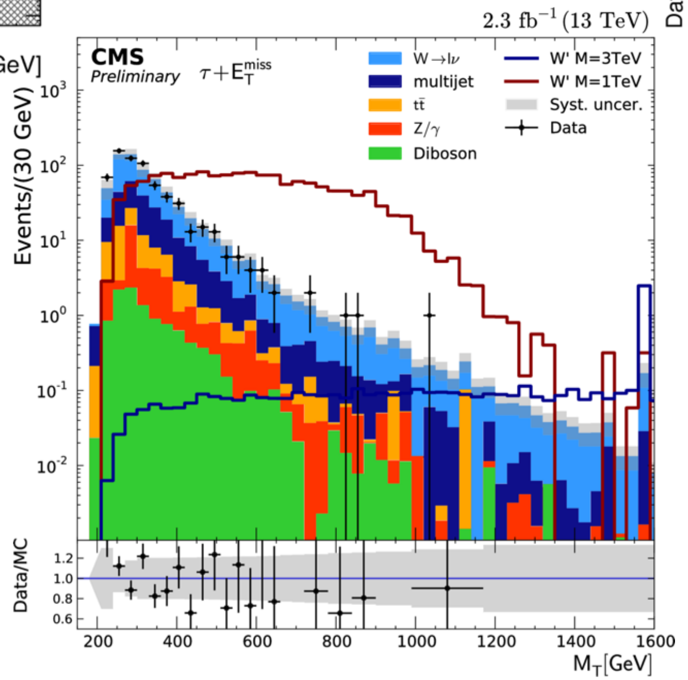
$$m_T = \sqrt{2 p_T \not{E}_T (1 - cos\Delta\phi_{\ell,\not{E}_T})}$$

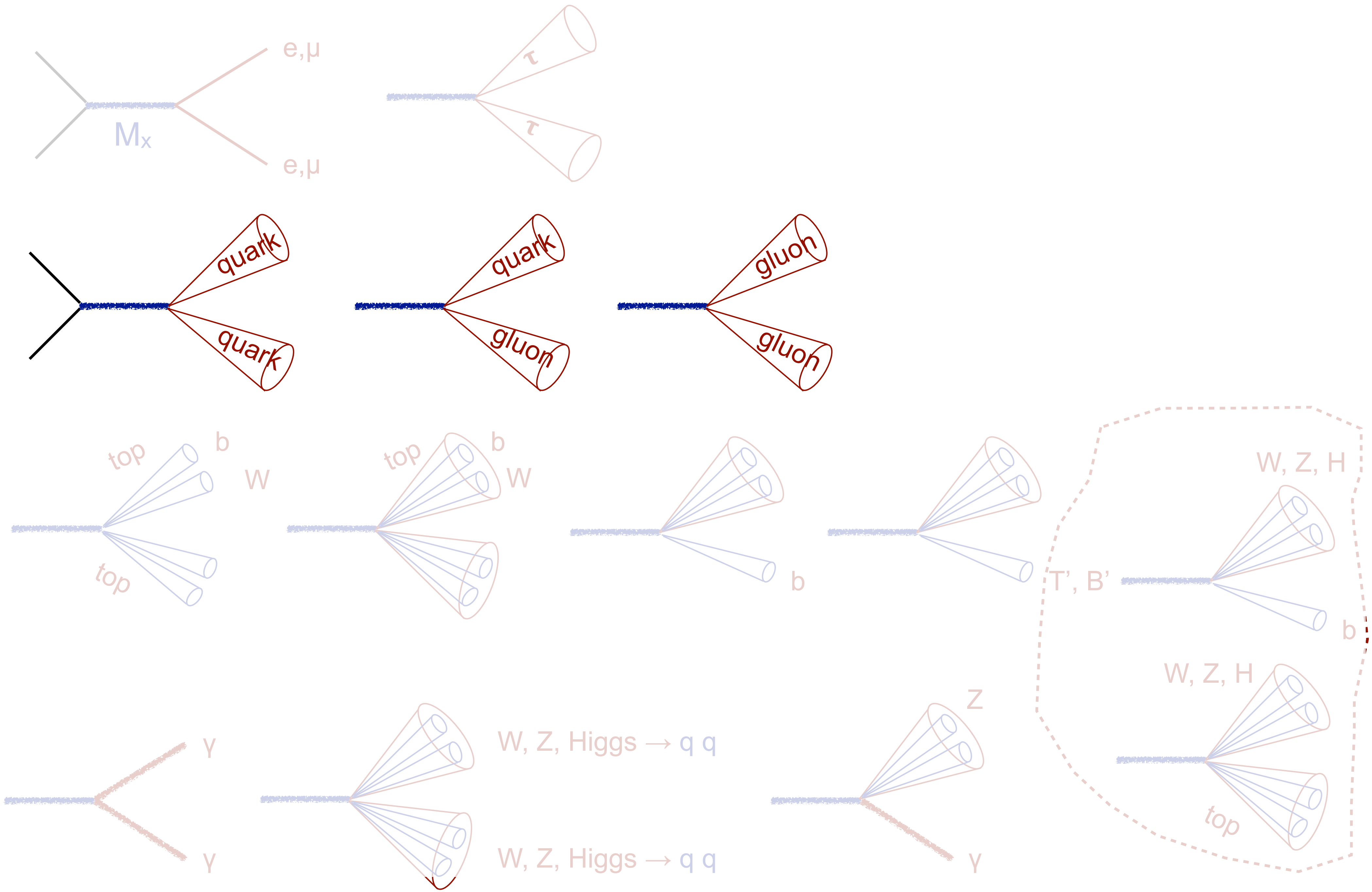
- Dominant background: W production in Standard Model
- Take into account interference with SM

LEPTON + MET SPECTRUM

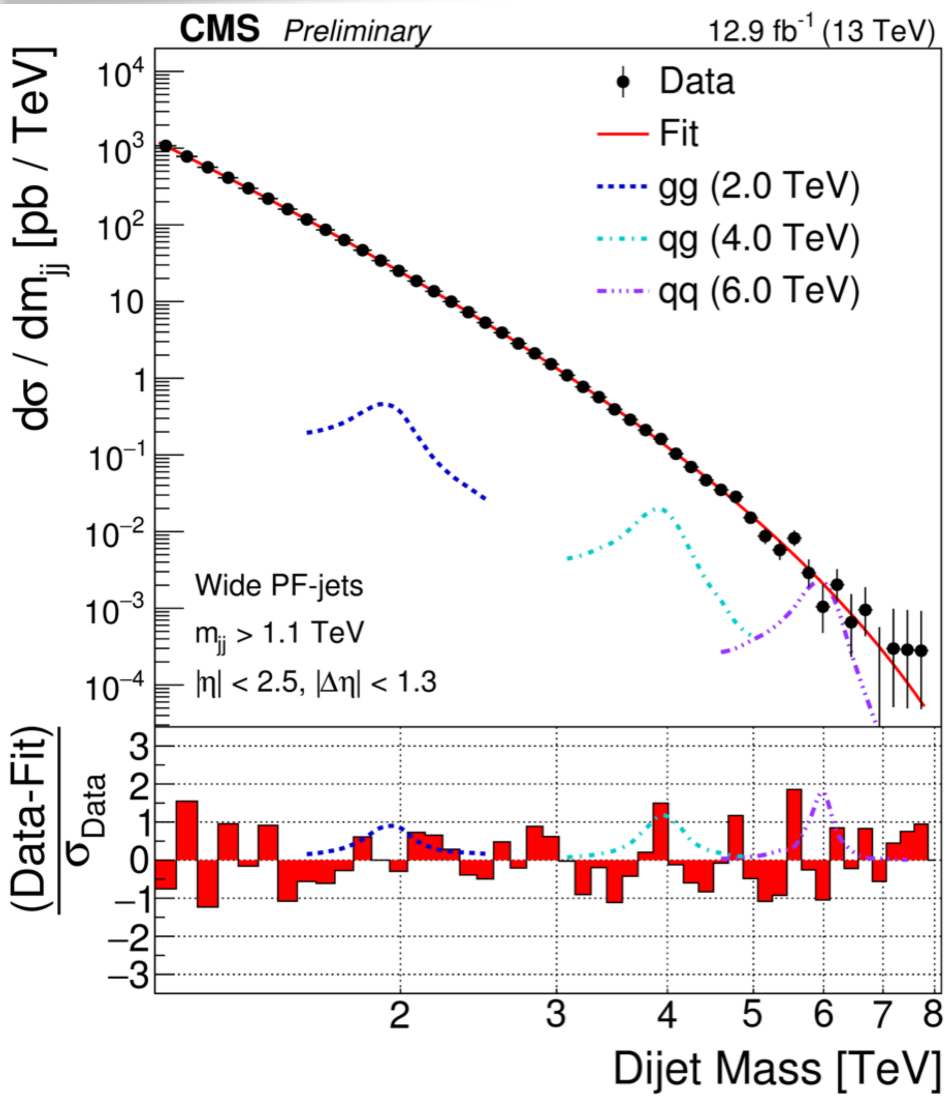


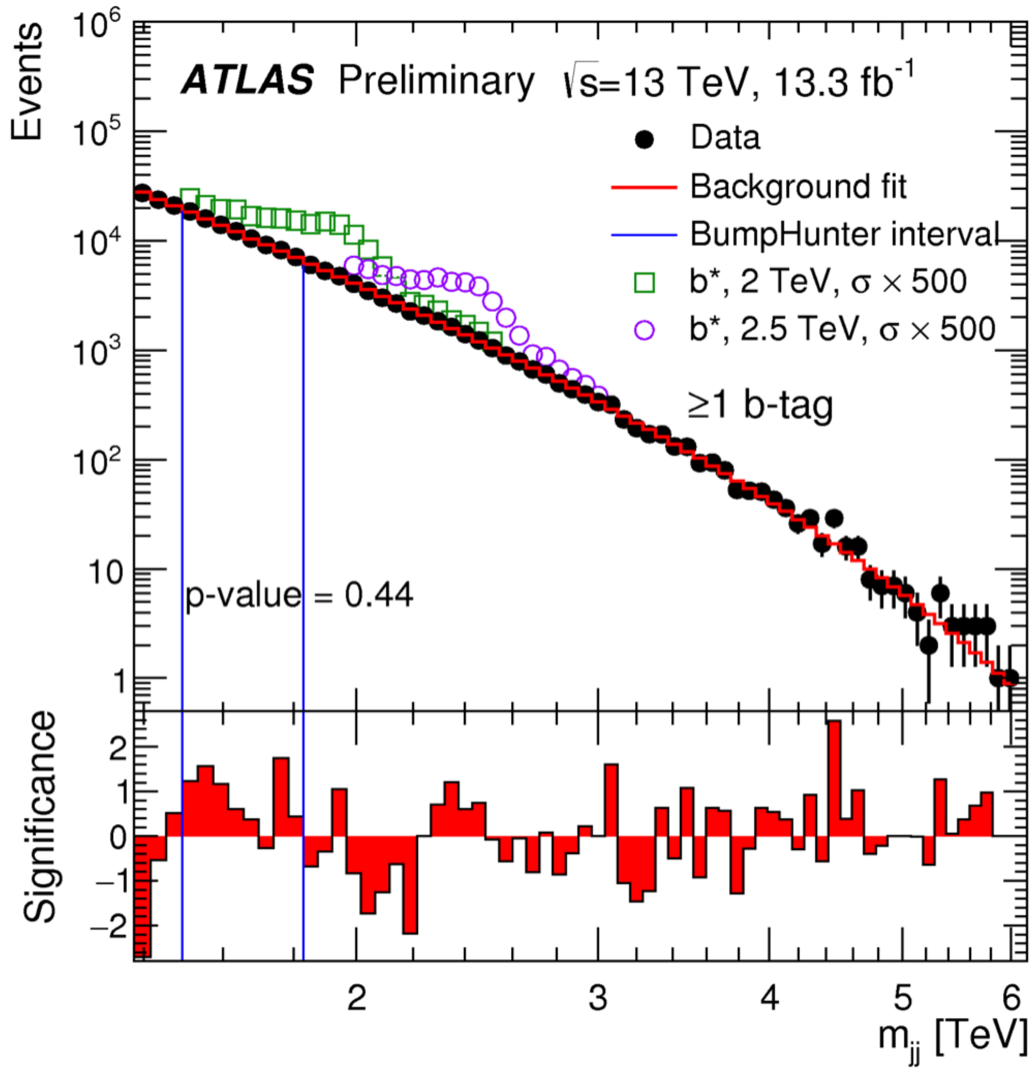





e,μ
Mx
e,μ
τ
τ
quark
quark
quark
gluon
gluon
gluon
top
b
W
top
top
b
W
b
T', B'
W, Z, H
b
W, Z, H
top
γ
γ
W, Z, Higgs → q q
W, Z, Higgs → q q
Z
γ

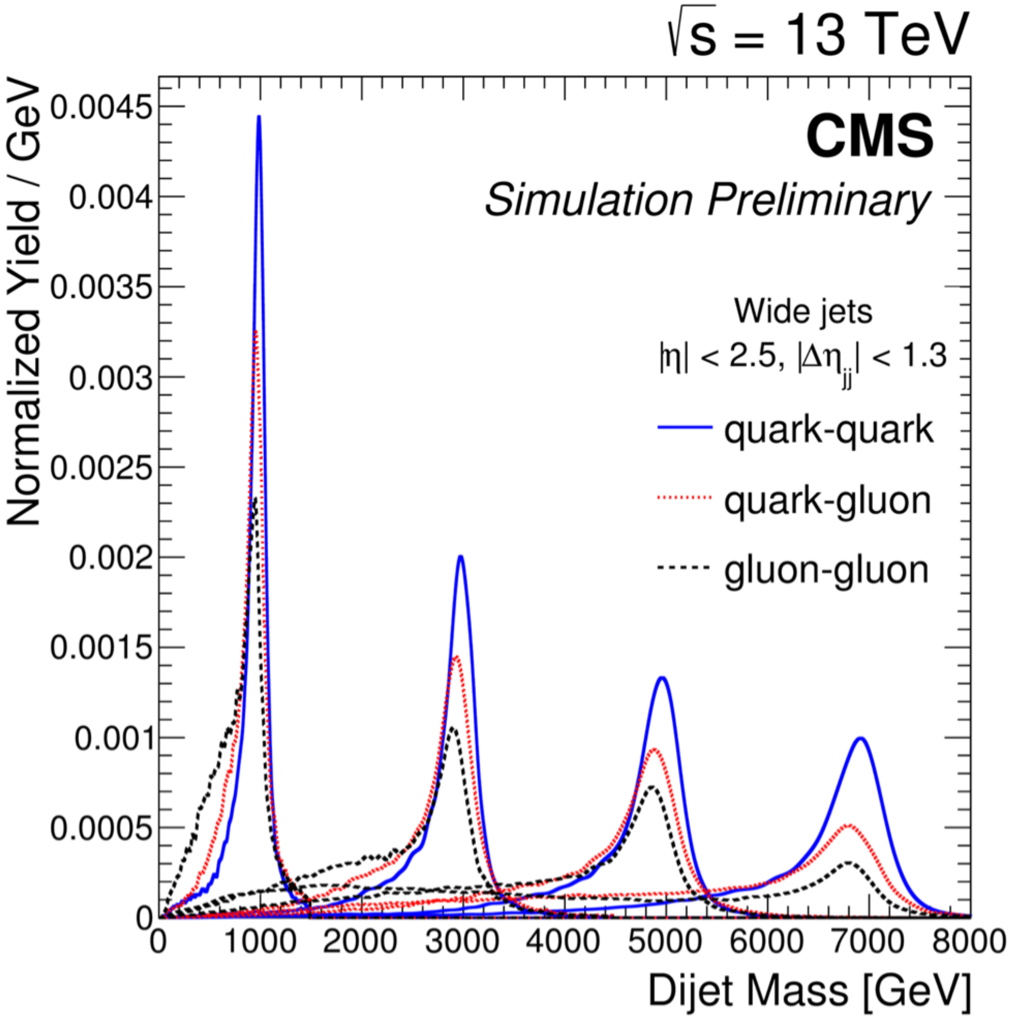
DI-JET AT 13 TEV

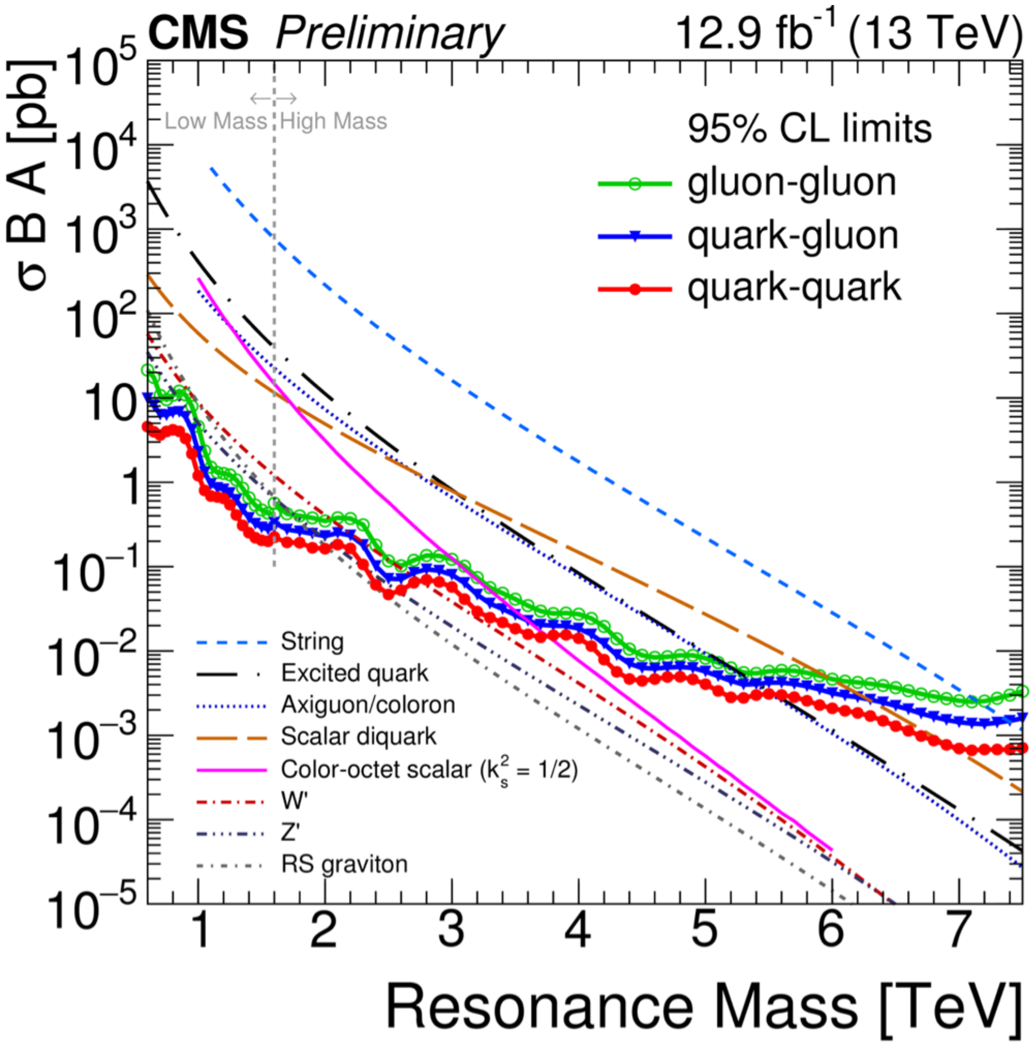




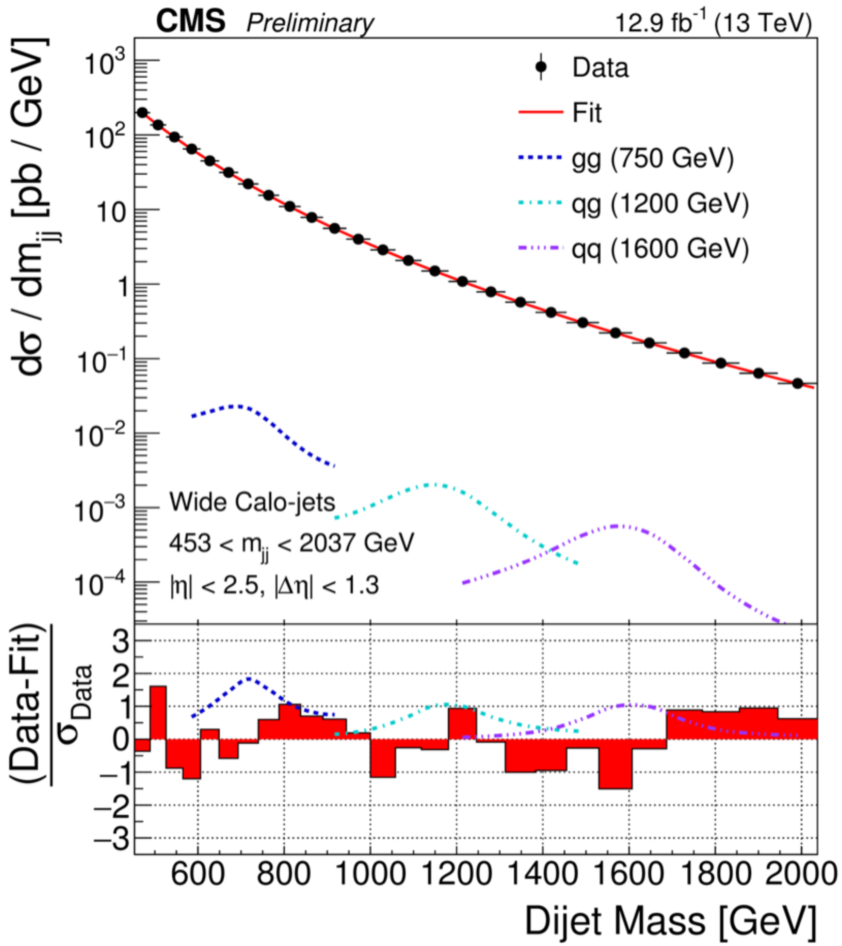
- High p_T trigger thresholds to cope with enormous cross section

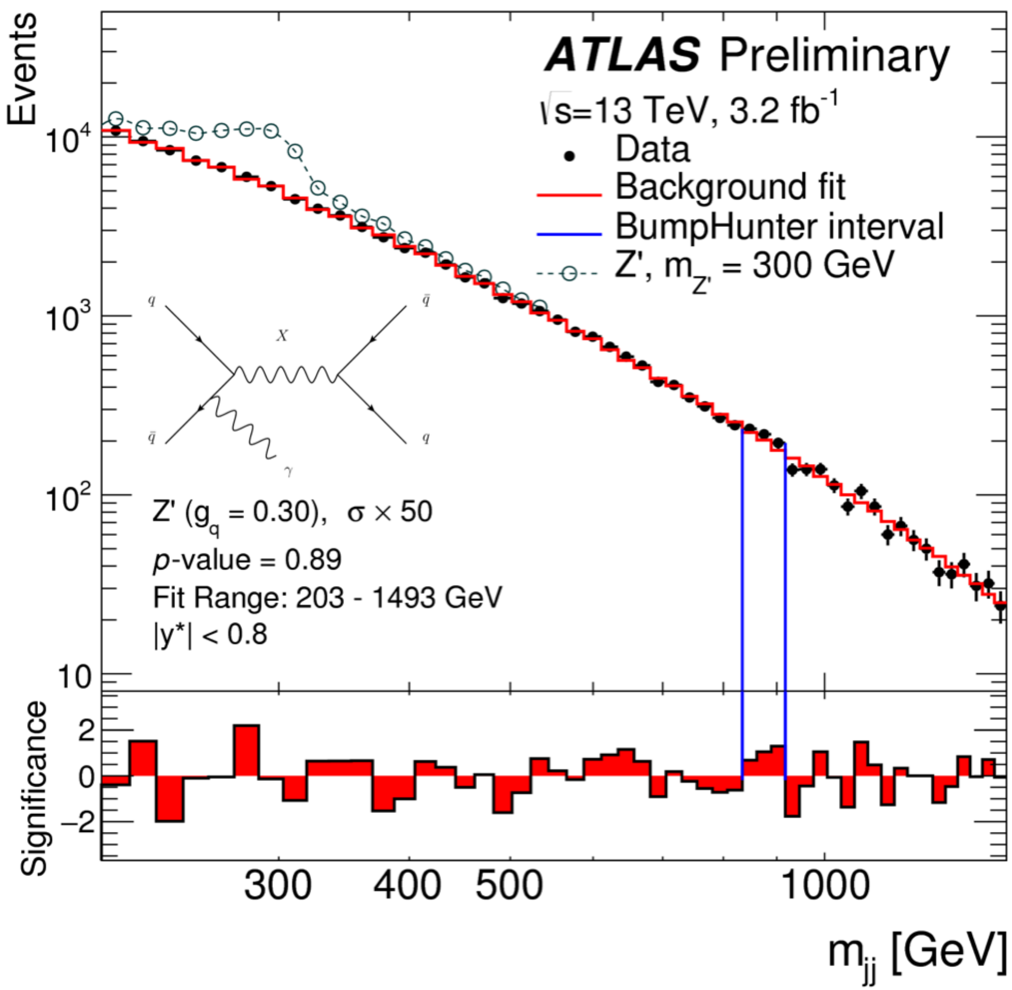
QUARK VS GLUON



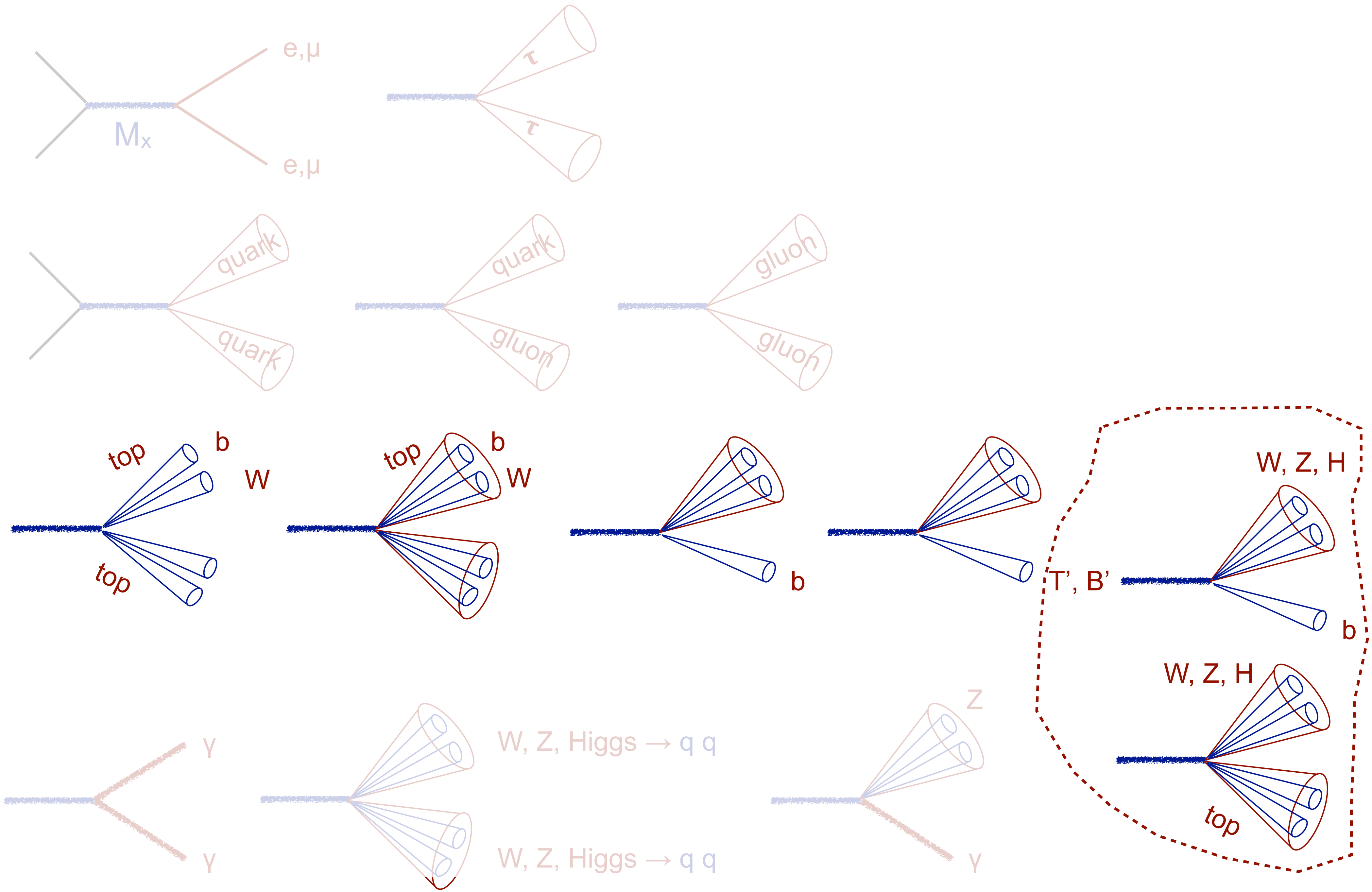


LOW-MASS DI-JET



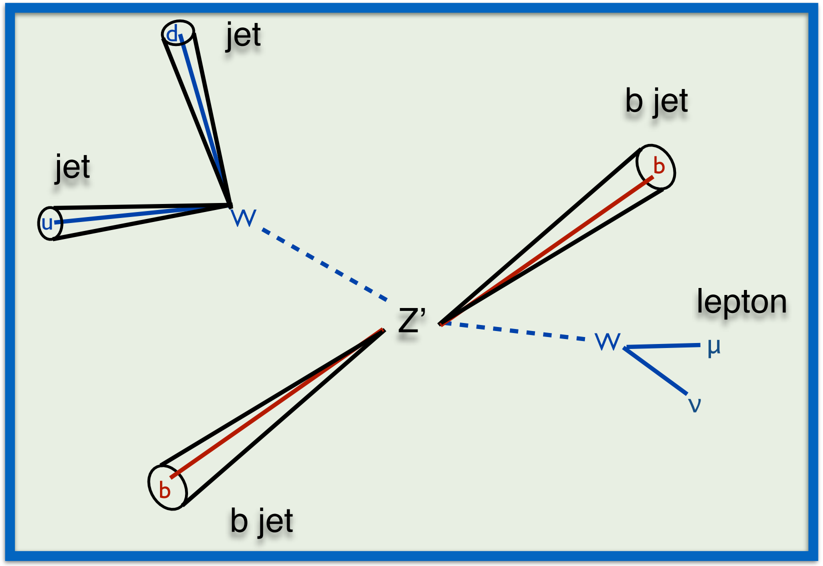


- Dedicated triggers and data parking techniques to explore low-mass dijet
  - use trigger-level jet objects
  - dedicated jet calibration and corrections
  - *not suffering from pre-scales due to huge hadronic trigger rates*


e,μ
Mx
e,μ
τ
τ
quark
quark
quark
gluon
gluon
gluon
top
b
W
top
top
b
W
b
T', B'
W, Z, H
b
W, Z, H
top
γ
γ
W, Z, Higgs → q q
W, Z, Higgs → q q
Z
γ

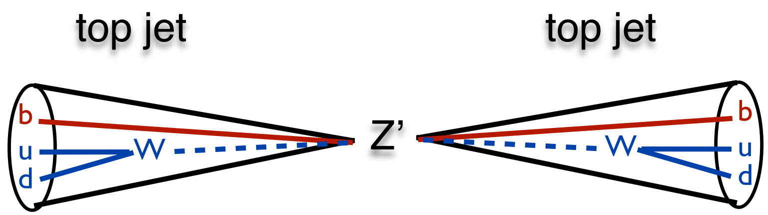
BOOSTED TOPOLOGY

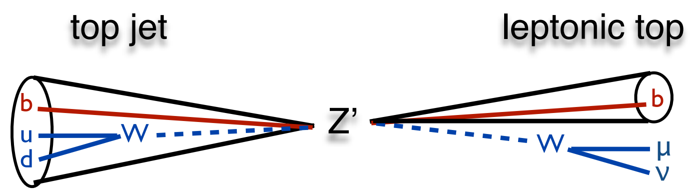
$M_X < 1$ TeV



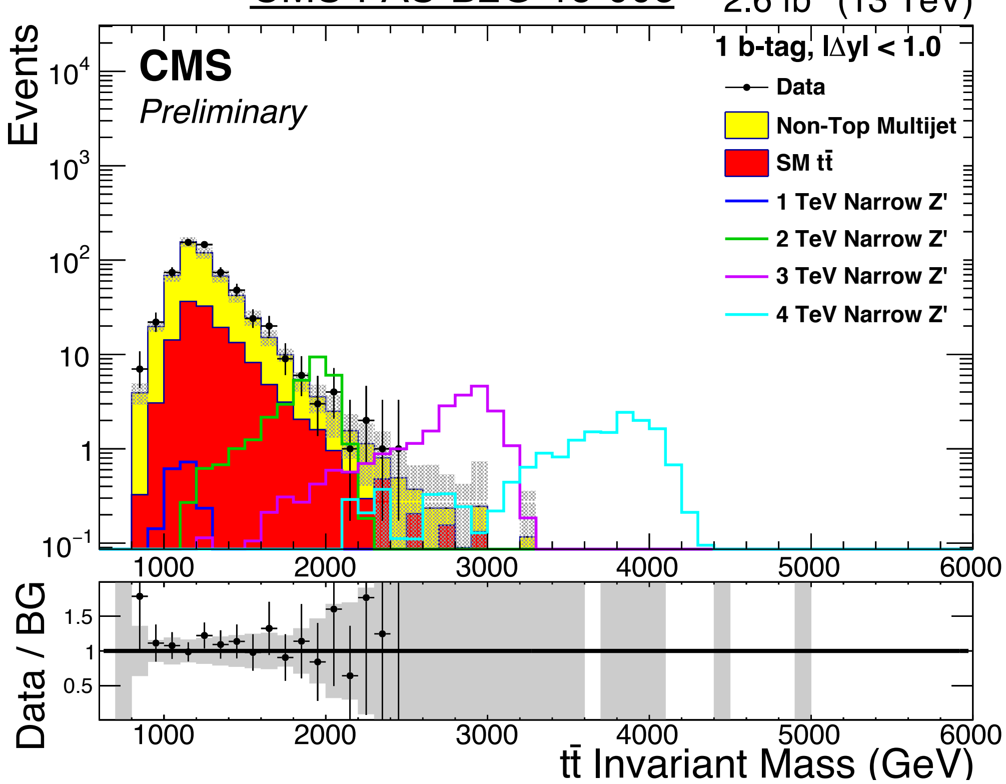
$M_X \sim 2$ TeV

T-TBAR

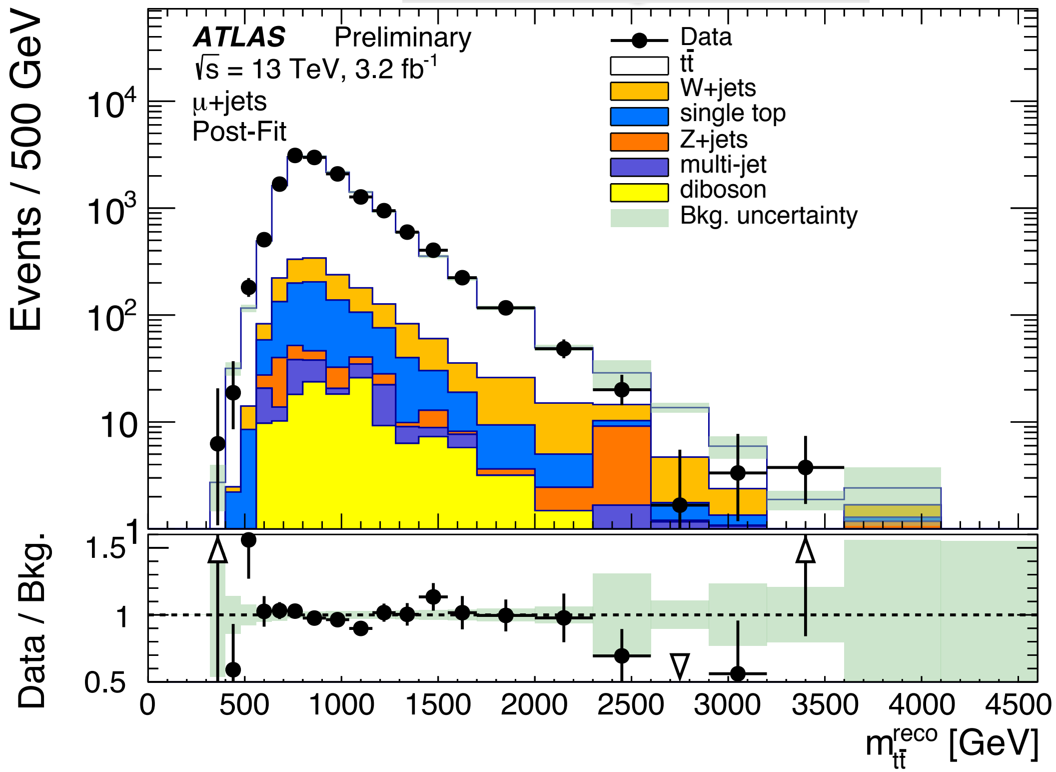




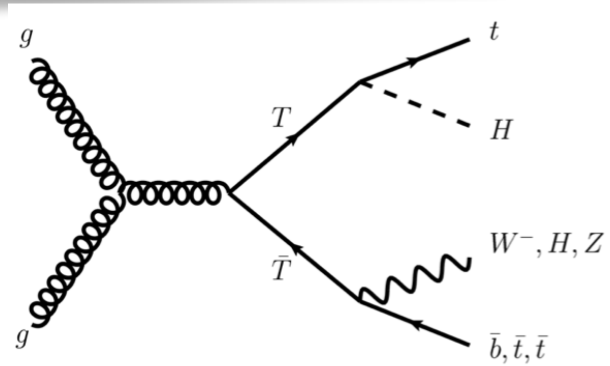
CMS-PAS-B2G-15-003

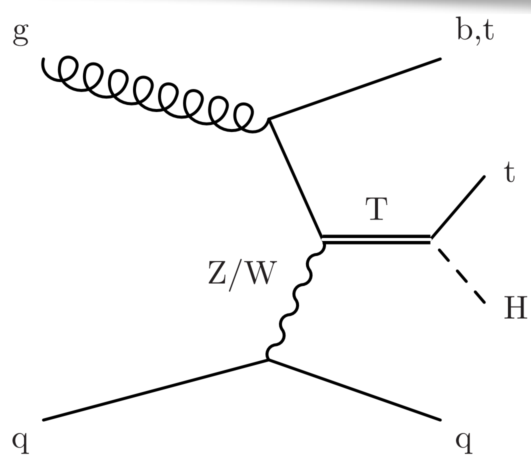


[ATLAS-CONF-2016-014]

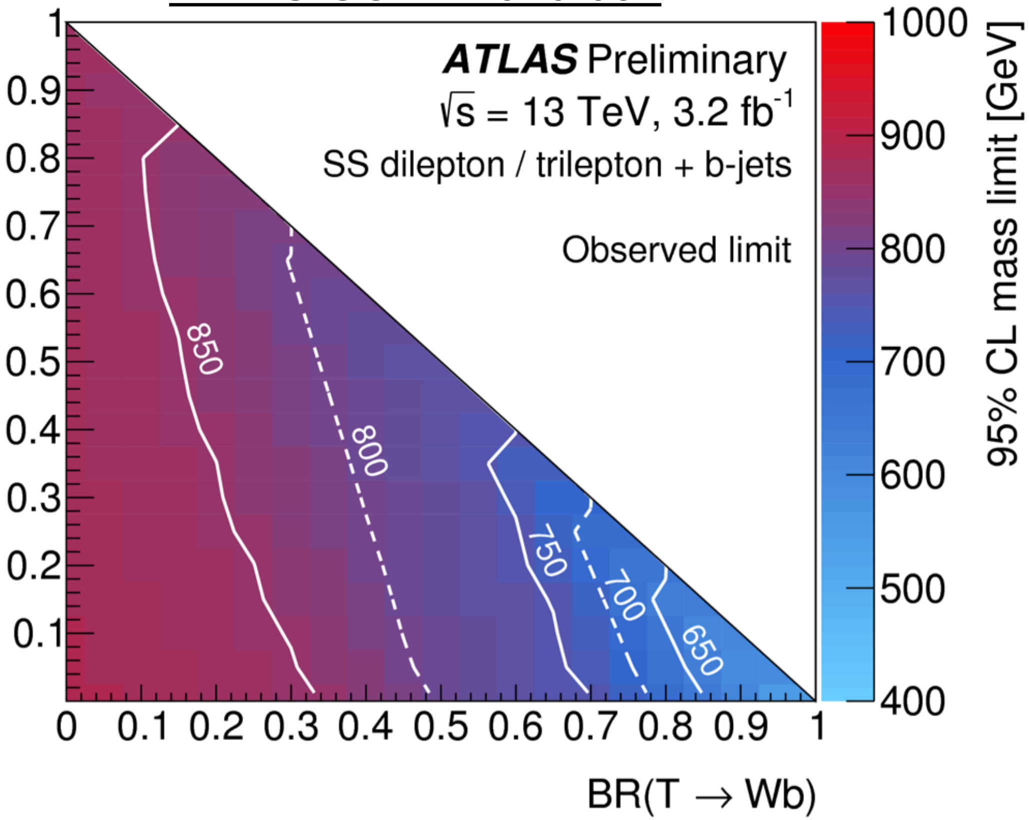


TOP PARTNERS

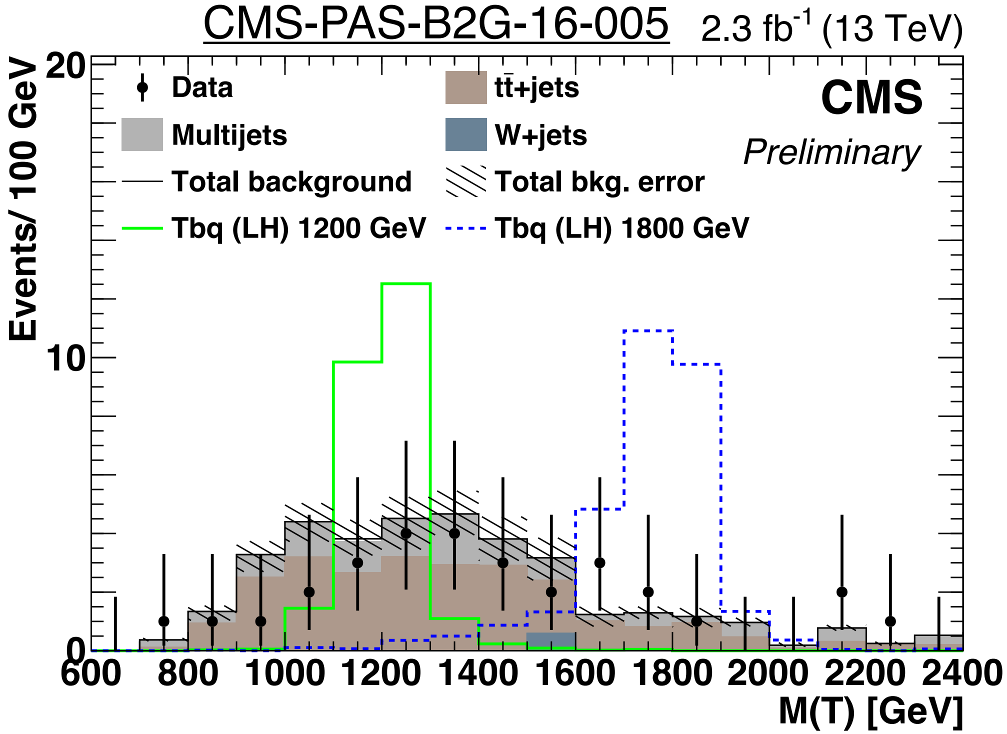




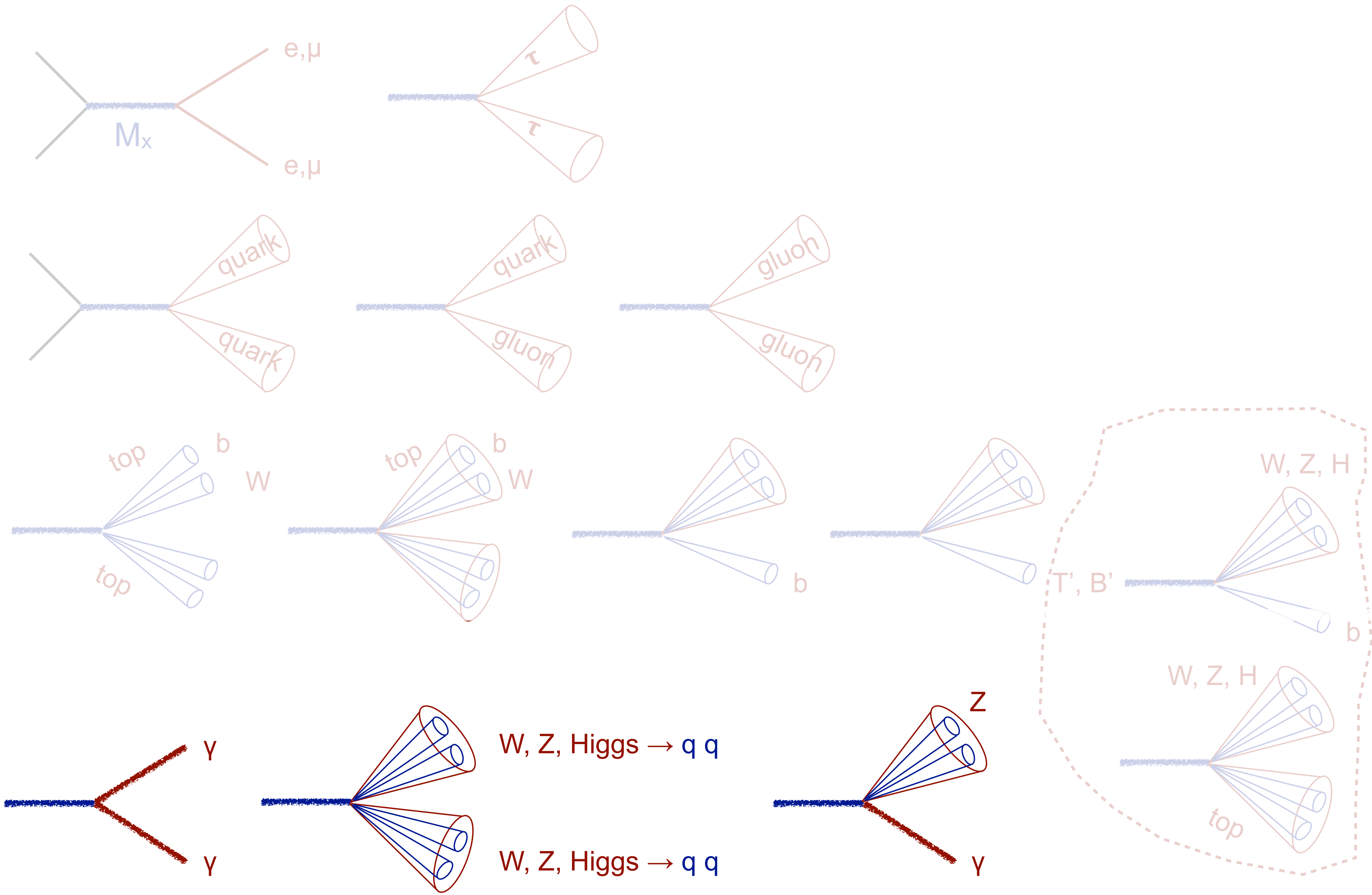
ATLAS-CONF-2016-032



CMS-PAS-B2G-16-005



- Constraints in Run2 already competitive or better than Run1


e,μ
e,μ
Mx
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quark
quark
quark
gluon
gluon
gluon
top
b
W
top
top
b
W
b
T', B'
W, Z, H
b
W, Z, H
top
γ
γ
W, Z, Higgs → q q
W, Z, Higgs → q q
Z
γ

DI-BOSON FINAL STATES

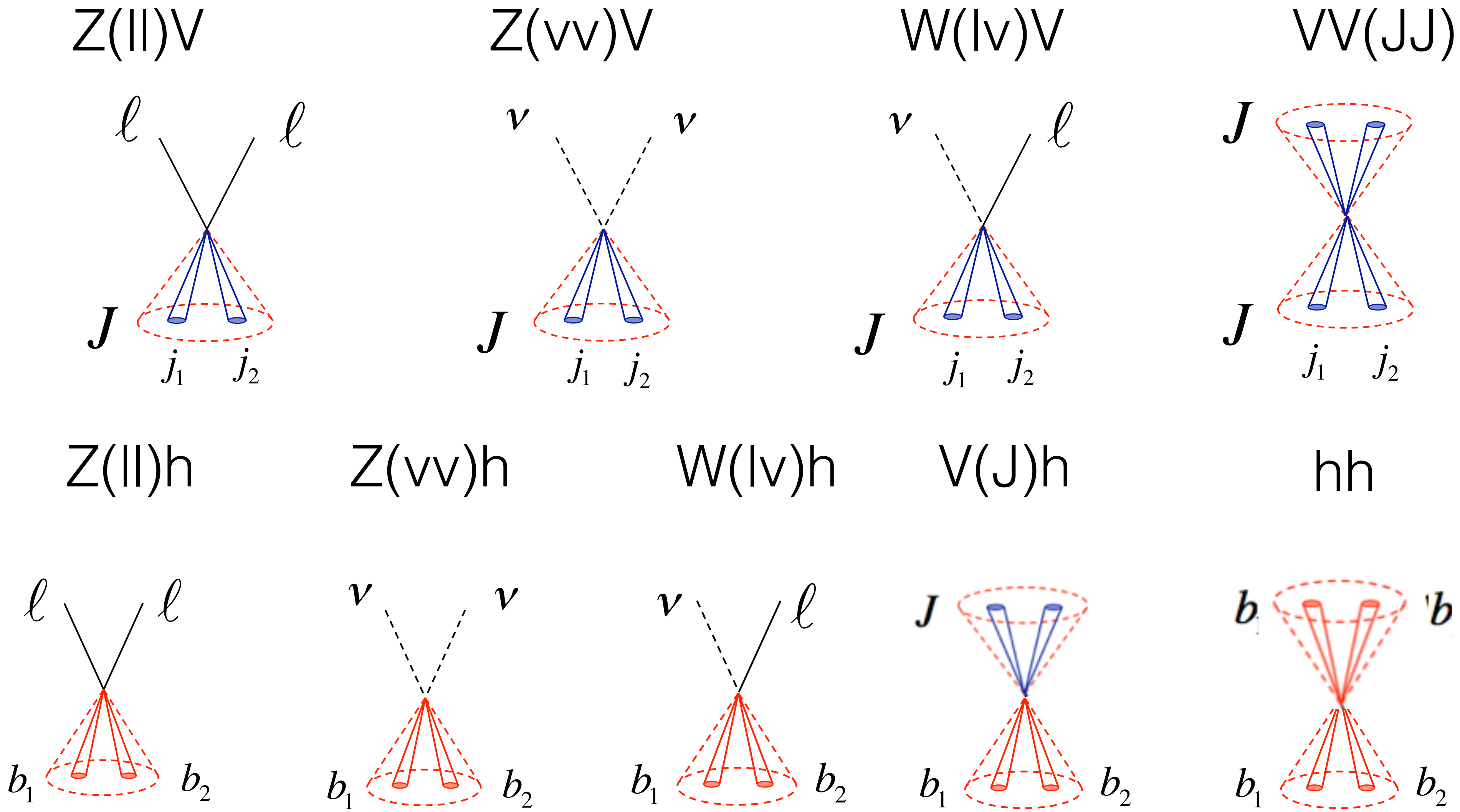
- Rich search program for both vector and scalar bosons

Signature	Final state	ATLAS	CMS
γγ	γγ	ATLAS-CONF-2015-081 *10.1103/PhysRevLett.113.171801* *10.1103/PhysRevD.92.032004*	CMS-PAS-EXO-15-004 *CMS-PAS-EXO-12-045* *10.1016/j.physletb.2015.09.062*
	combination	**arXiv:1606.03833**	**arXiv:1606.04093**
γZ	γll	ATLAS-CONF-2016-010 *10.1016/j.physletb.2014.10.002*	CMS-PAS-EXO-16-019 *CMS-PAS-HIG-16-014*
	γqq	ATLAS-CONF-2016-010	**CMS-PAS-EXO-16-020**
	combination		**CMS-PAS-EXO-16-021**
WW/WZ/ZZ	qqqq	**arXiv:1606.04833**	CMS-PAS-EXO-15-002 *10.1007/JHEP08(2014)174*
	qqll	**arXiv:1606.04833**	
	qqlν	**arXiv:1606.04833**	CMS-PAS-EXO-15-002 CMS-PAS-B2G-16-004
	qqνν	**arXiv:1606.04833**	
	combination	**arXiv:1606.04833**	CMS-PAS-EXO-15-002
WH/ZH	bbll	**ATLAS-CONF-2015-074**	CMS-PAS-B2G-16-003
	bblν	**ATLAS-CONF-2015-074**	CMS-PAS-B2G-16-003
	bbνν	**ATLAS-CONF-2015-074**	CMS-PAS-B2G-16-003
	combination	**ATLAS-CONF-2015-074**	CMS-PAS-B2G-16-003
Combination of VV/VH			**CMS-PAS-B2G-16-007**
HH	bbbb	**arXiv:1606.04782**	*CMS-PAS-EXO-12-053*

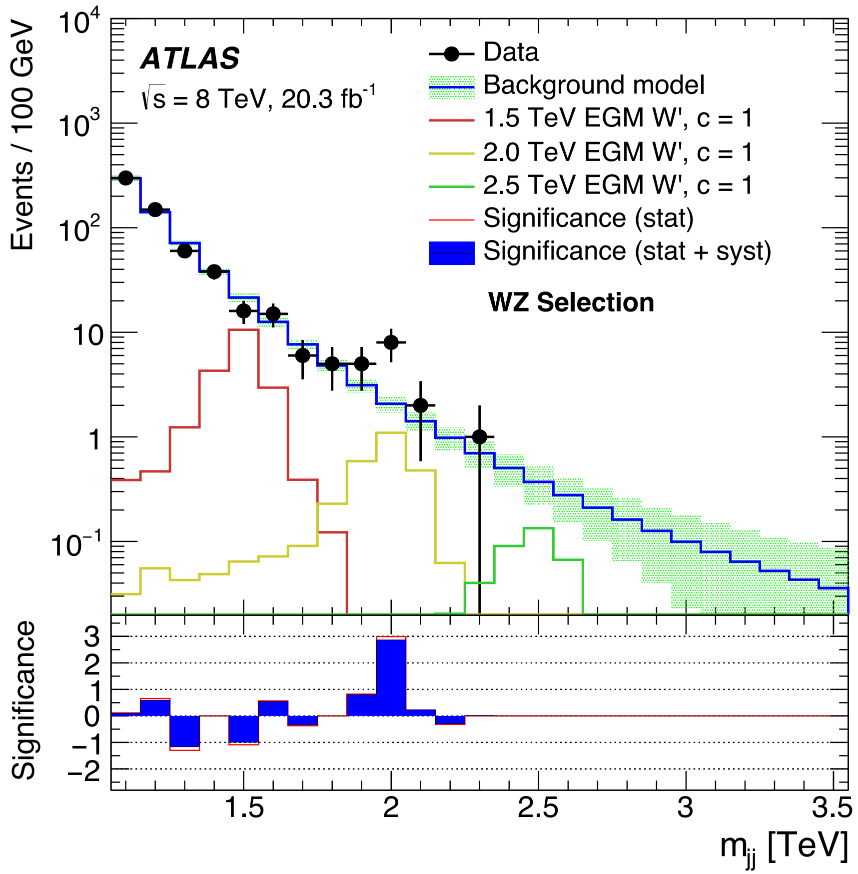
Many results updated with 2016 data
for ICHEP in early august
See references on last page

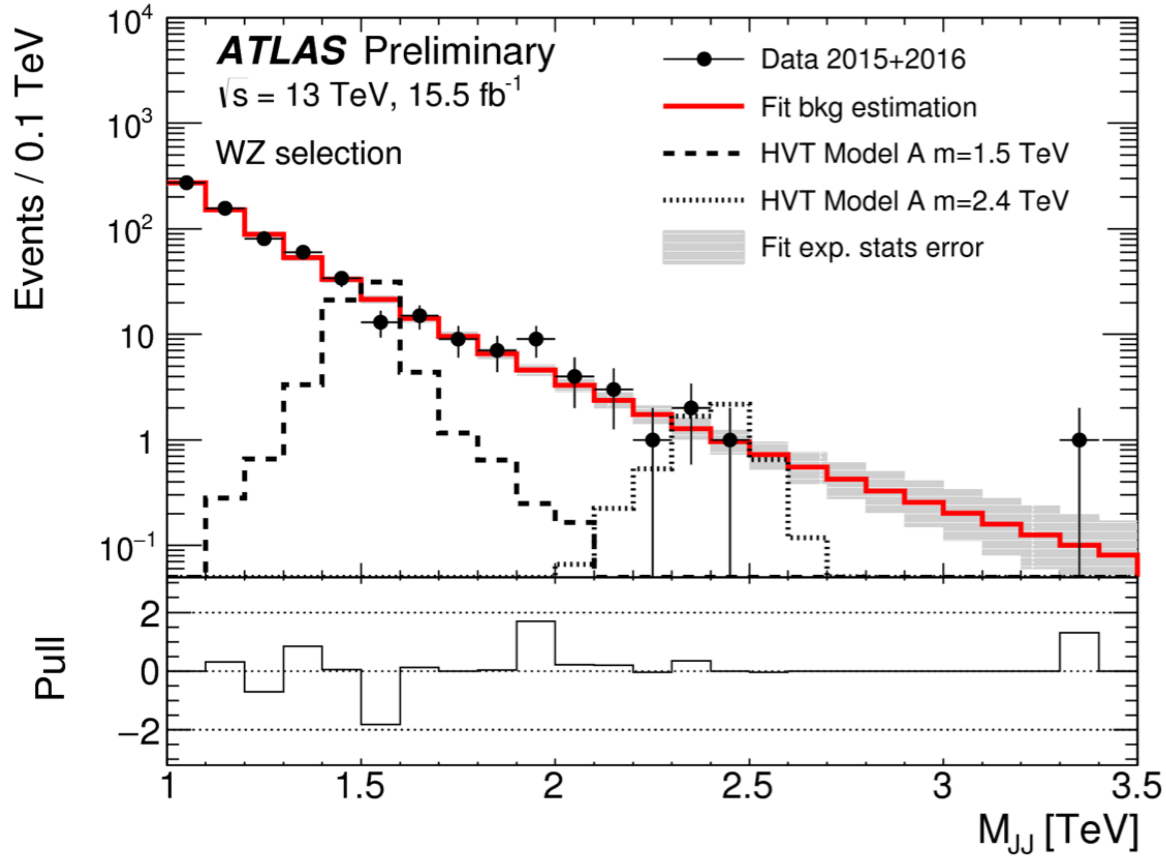
Courtesy of
Andreas Hinzmann
(U Zurich)

Z/W/H IDENTIFICATION

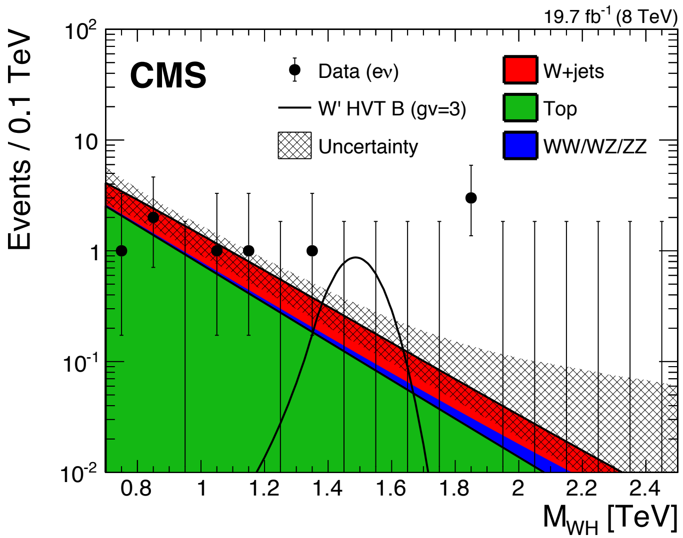


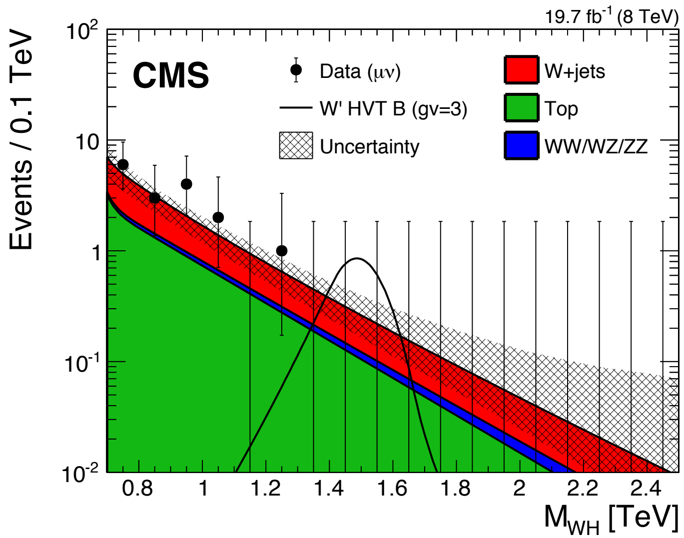
WZ EXCESS IN RUN 1

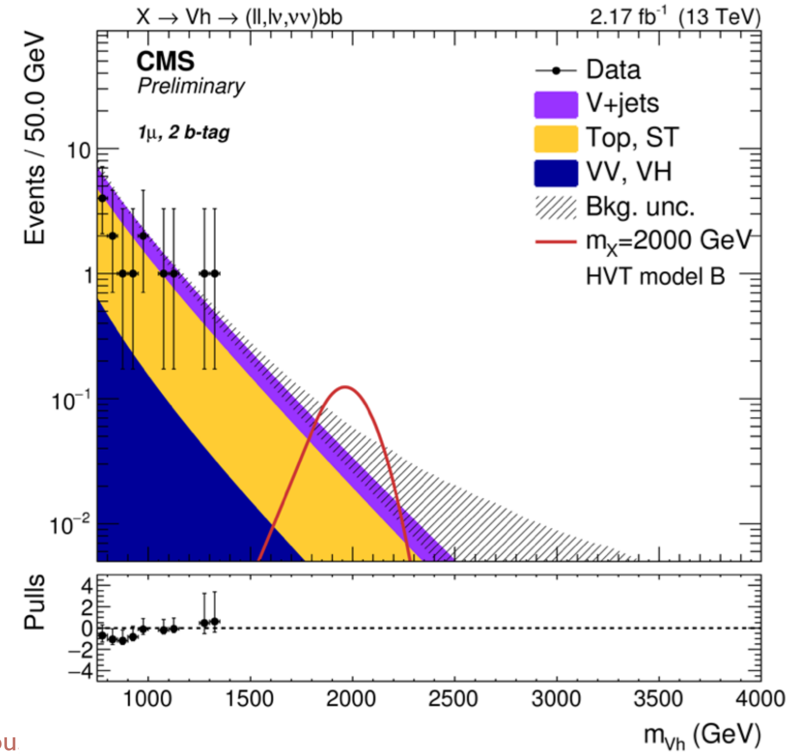


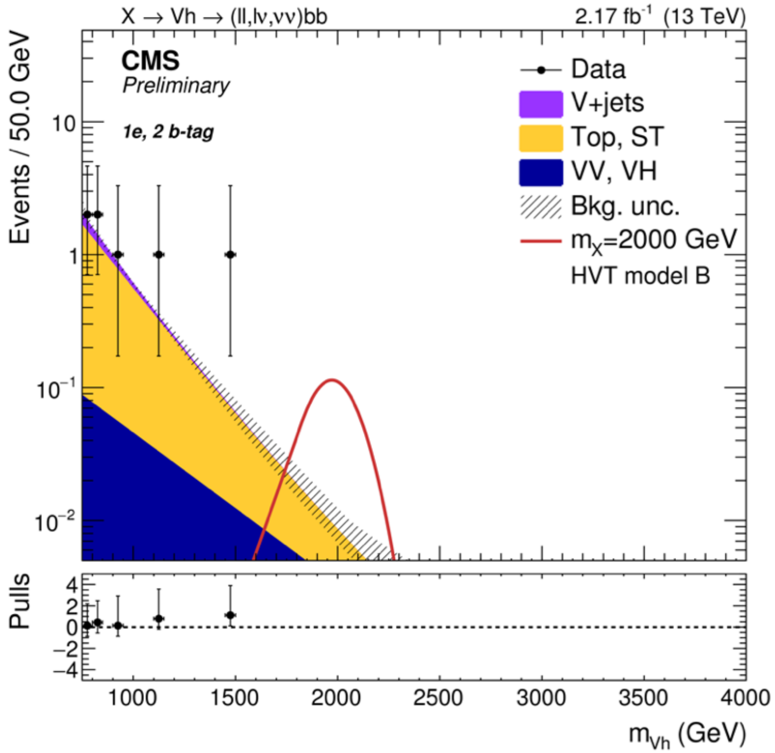


WH EXCESS IN RUN 1

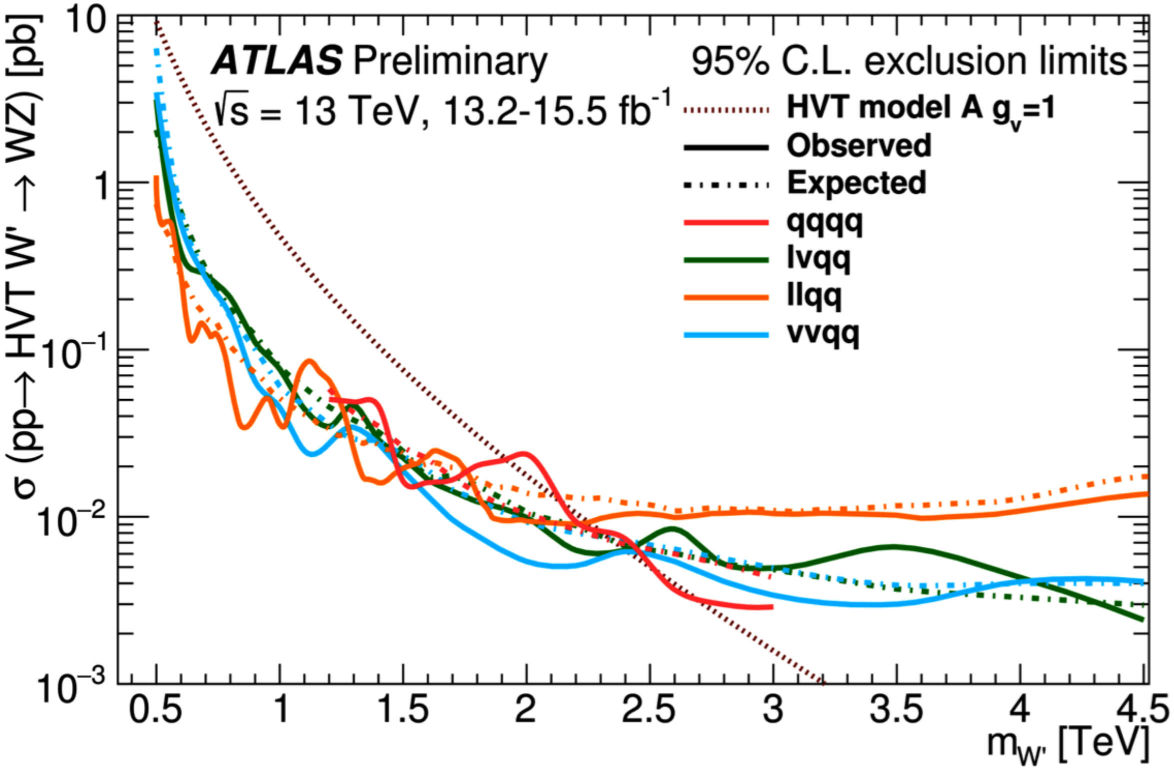


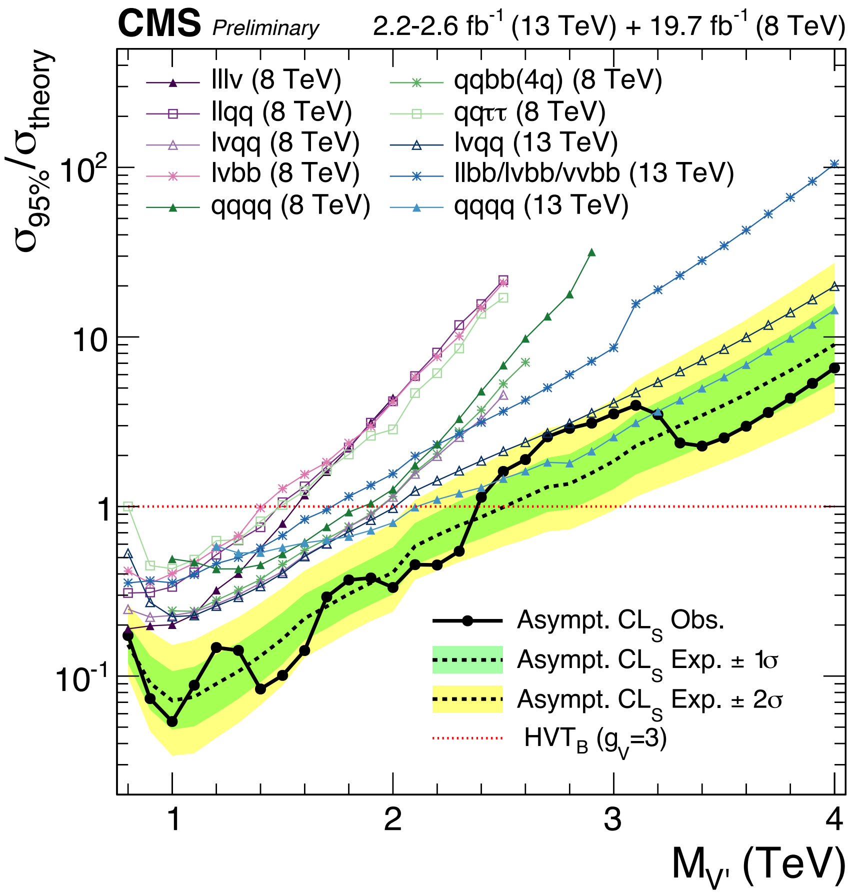






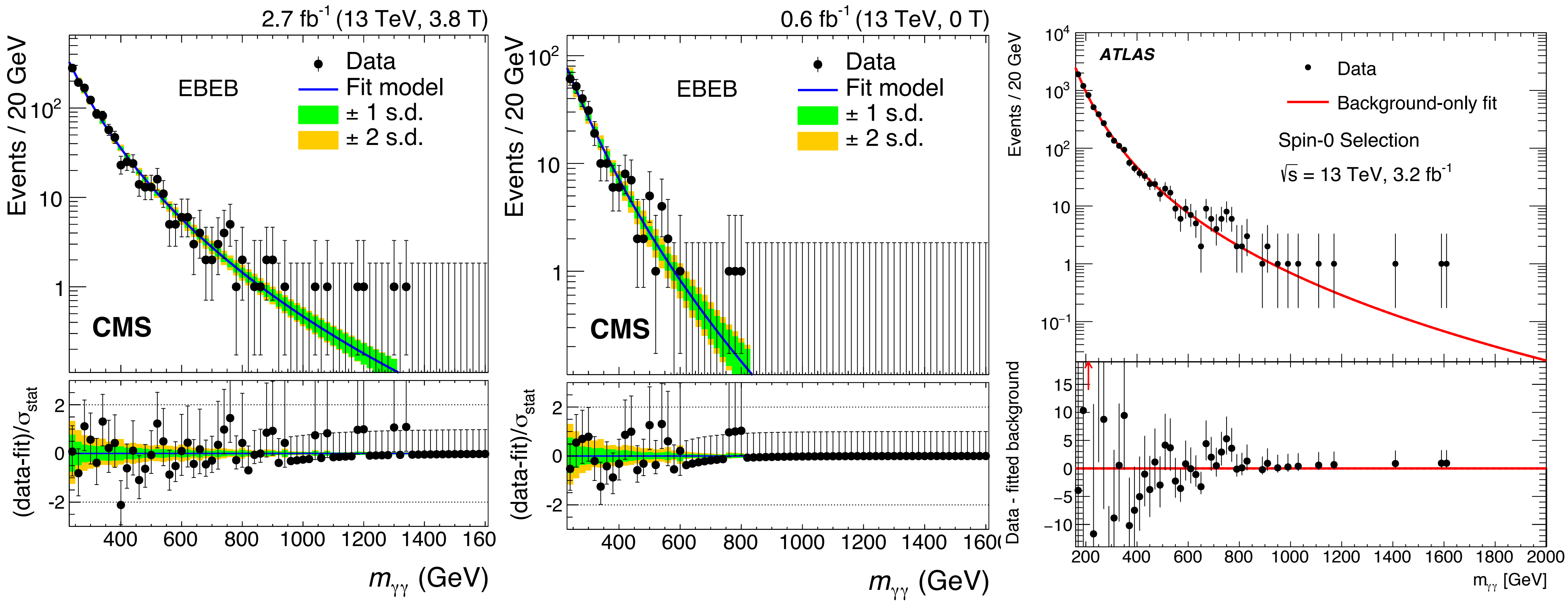
VV AND VH PICTURE





Heavy vector

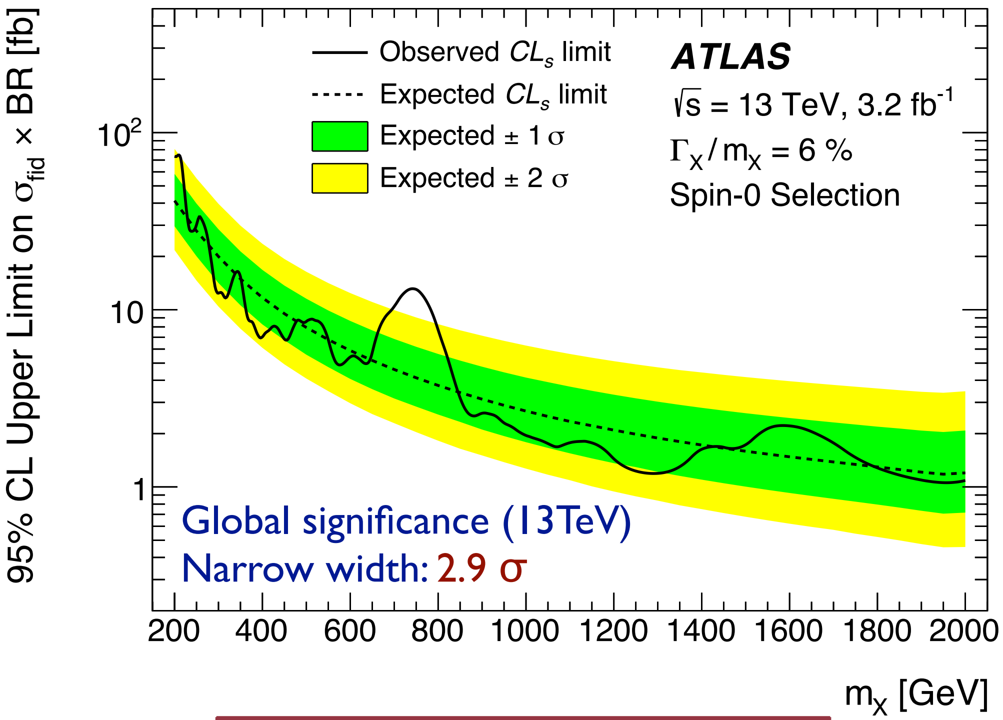
γγ SPECTRUM IN 2015



- Use of data without magnetic field in CMS added 10% sensitivity
  - outstanding detector and calibration work by ECAL team
- Spin-0 and Spin-2 hypotheses, with narrow and wide width as benchmark

THE 400-SOMETHING-THEORY-PAPER BUMP

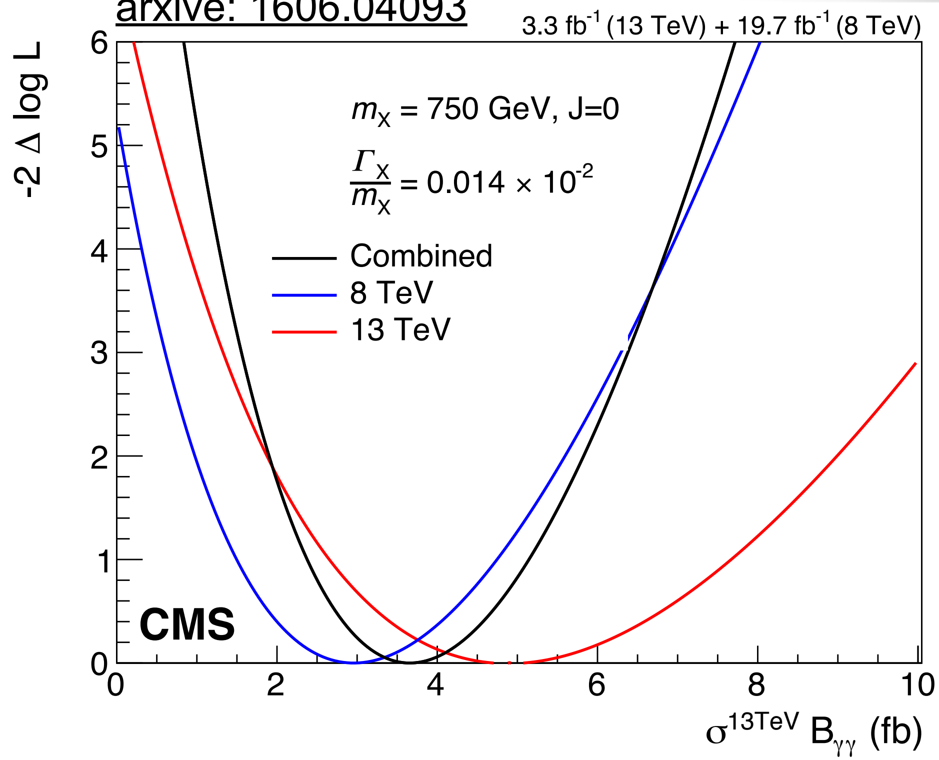
arxive: 1606.03833



	Γ = 4 MeV	Γ/m = 6%
glu-glu	1.5 σ	1.2 σ
q - q	2.0 σ	2.1 σ

ATLAS compatibility with 8 TeV

arxive: 1606.04093

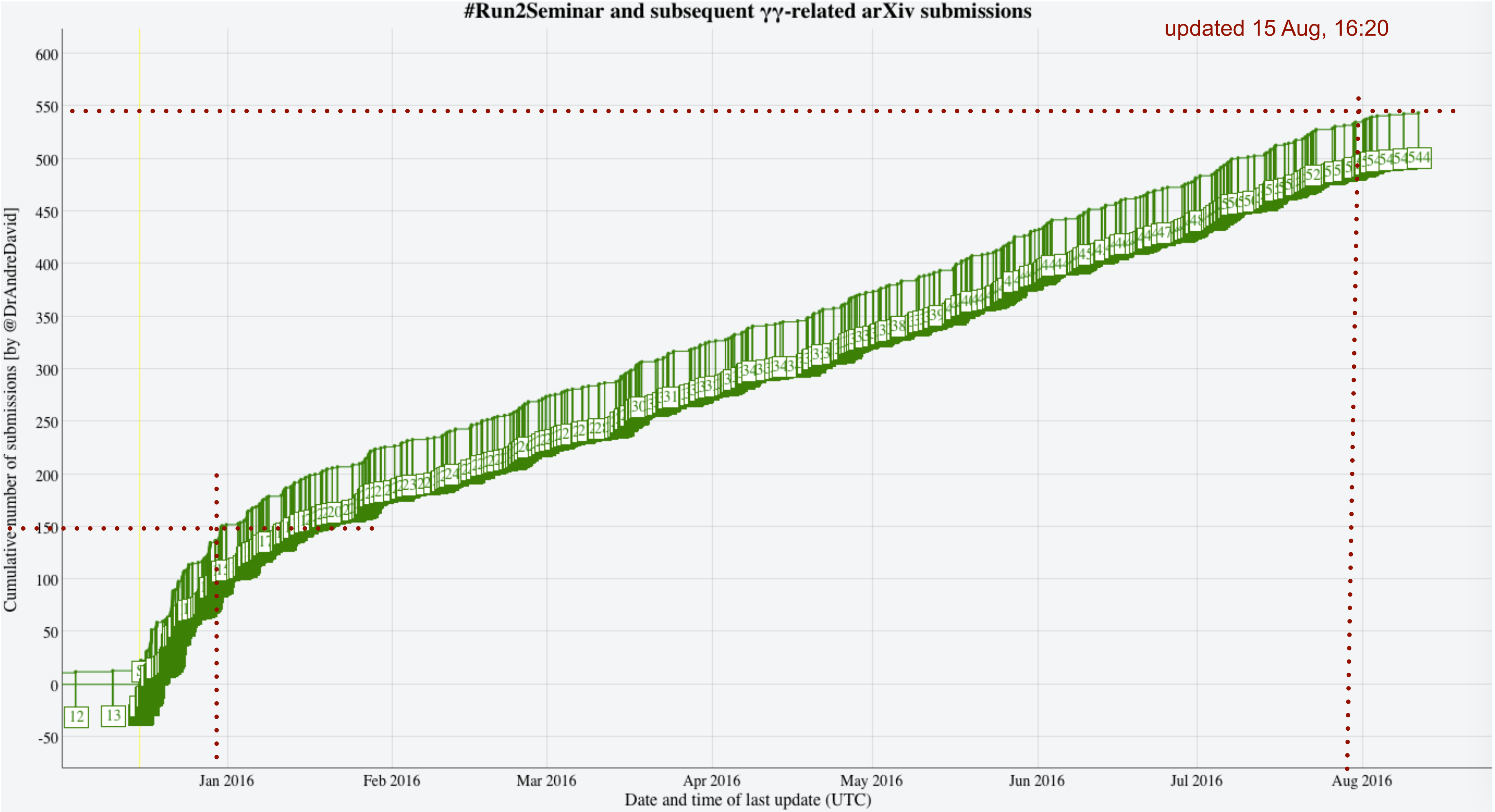


Global significance (13TeV+8TeV)
Narrow width: 1.6 σ

- Outstanding performance of LHC in 2016 to verify the 'bump'
  - each experiment with *x4 data analysed*

SIGNAL?

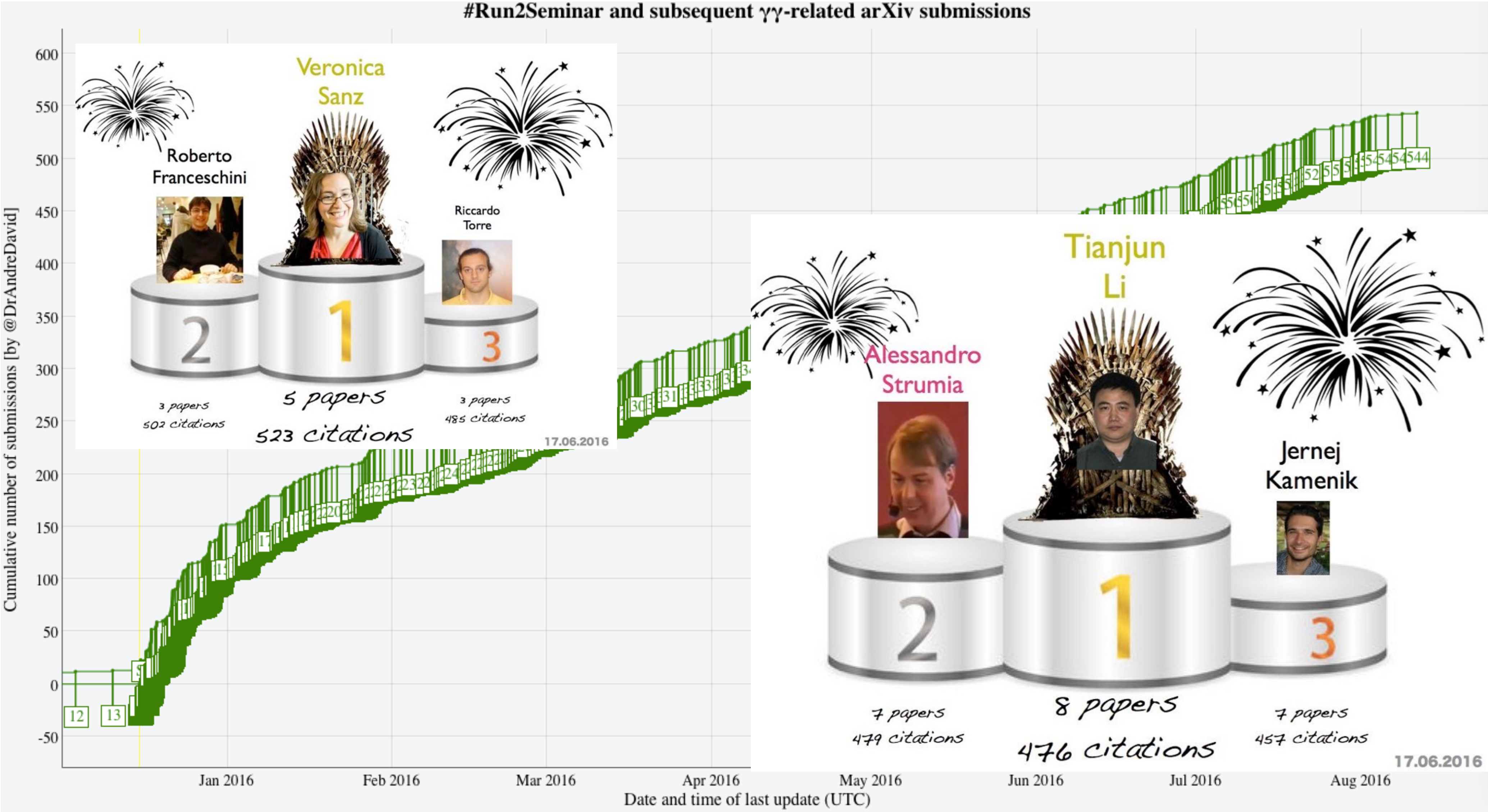
Daily diphoton theory report



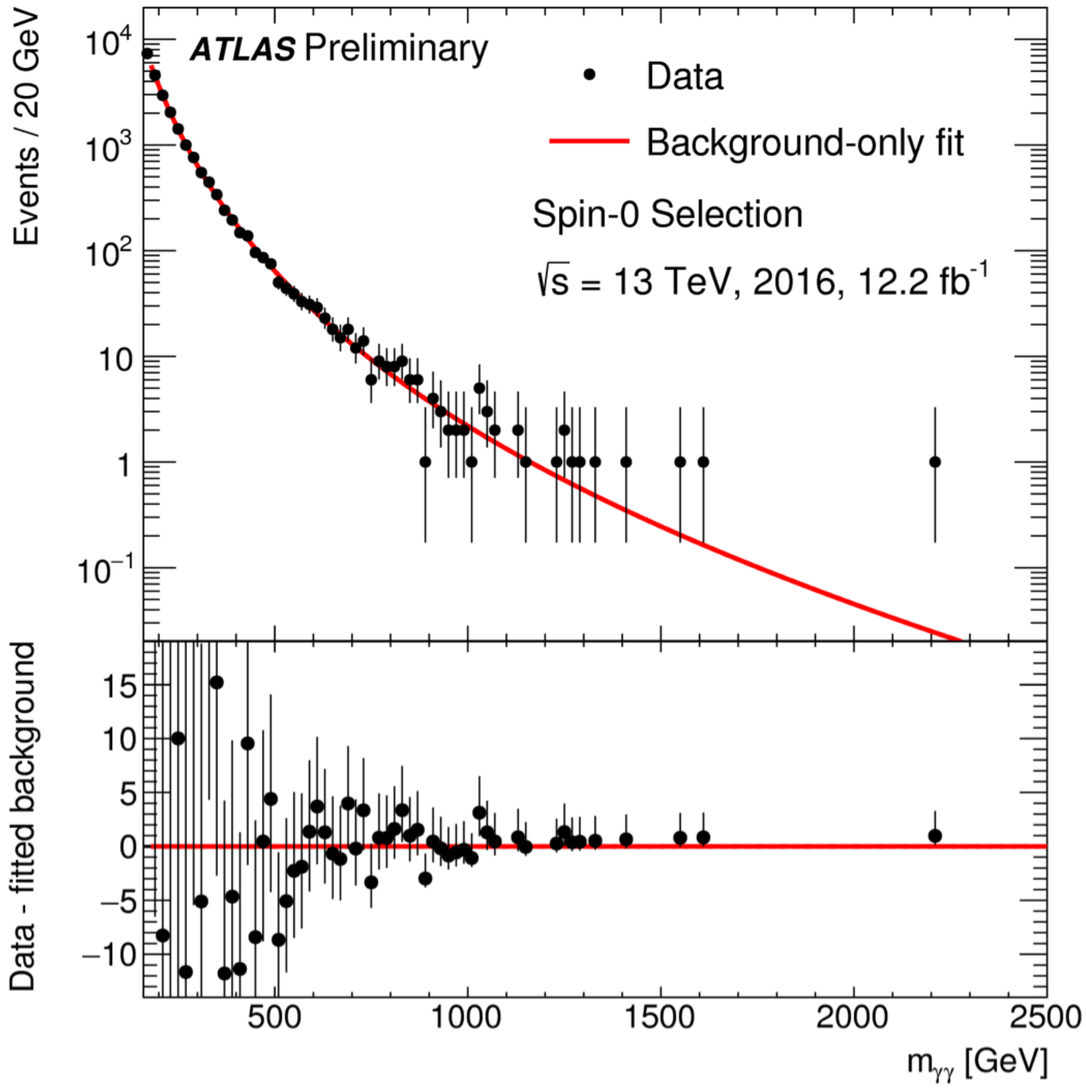
SIGNAL?

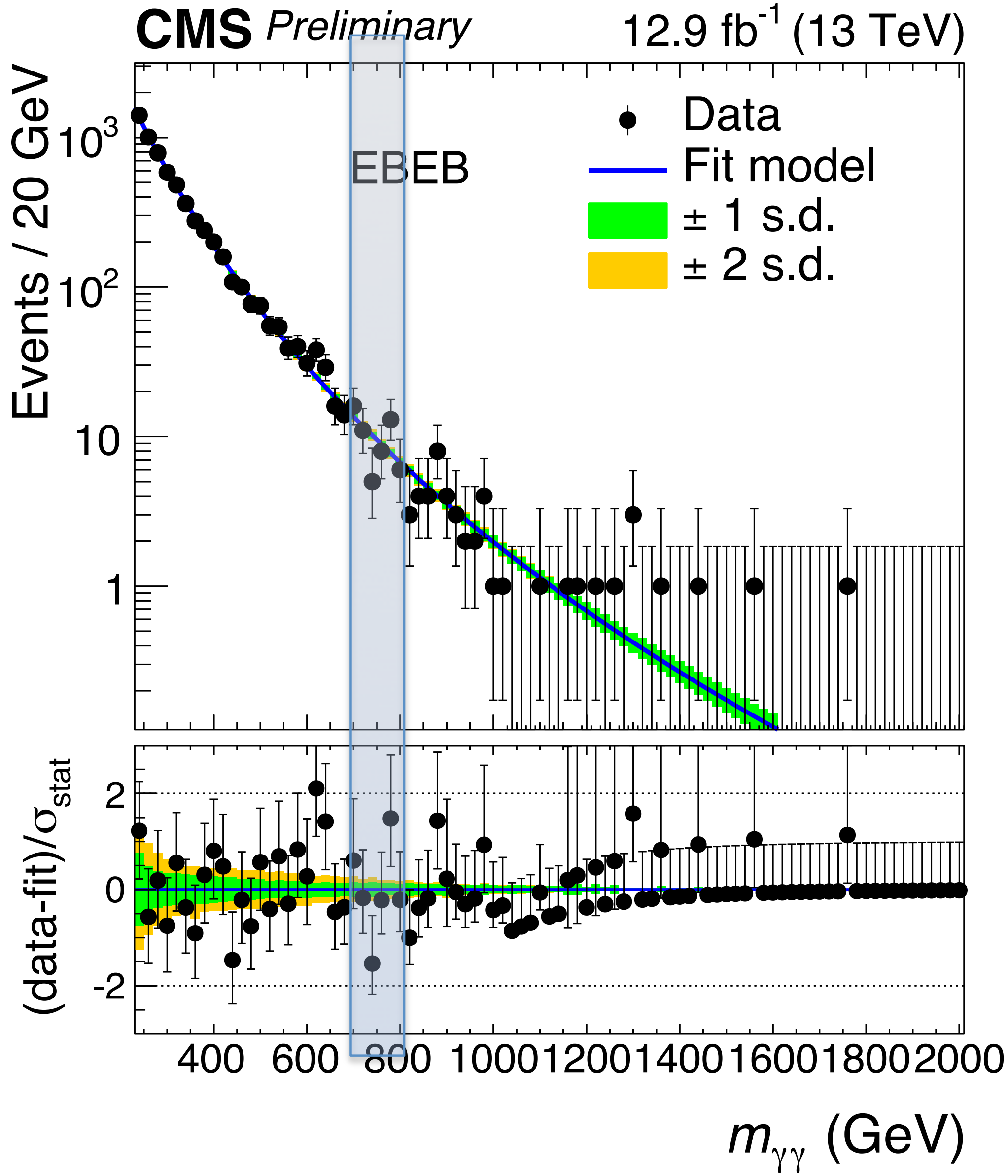
Daily diphoton theory report

Game of Thrones: 750 GeV Edition

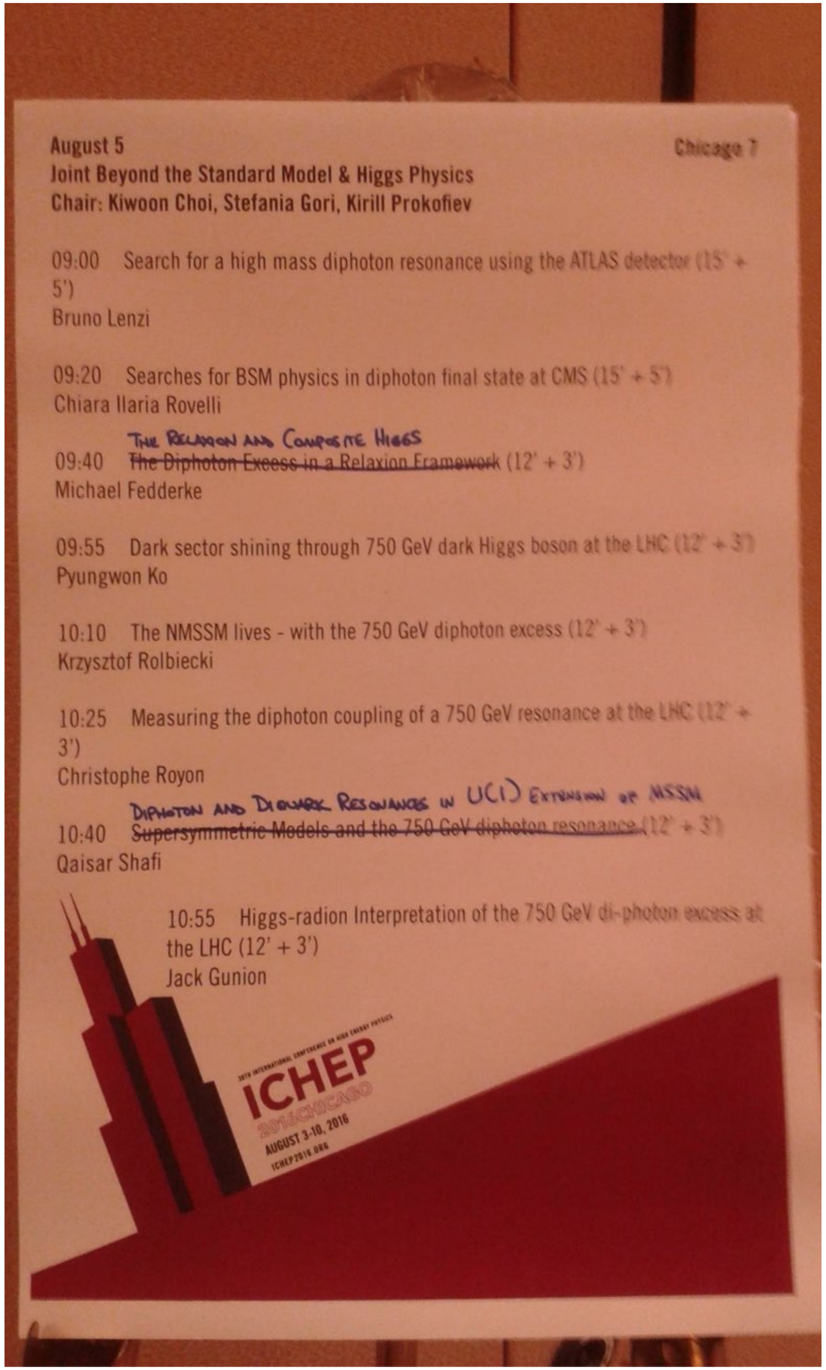


γγ SPECTRUM IN 2016

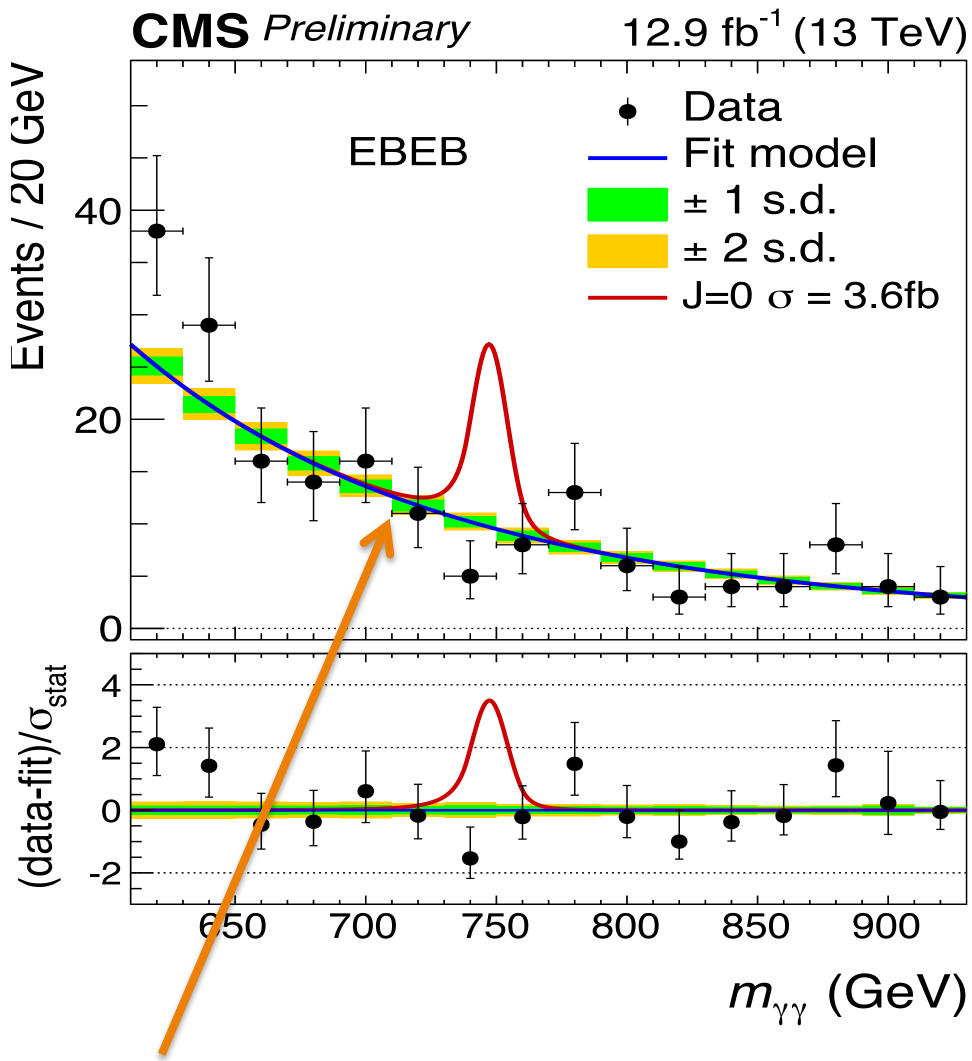


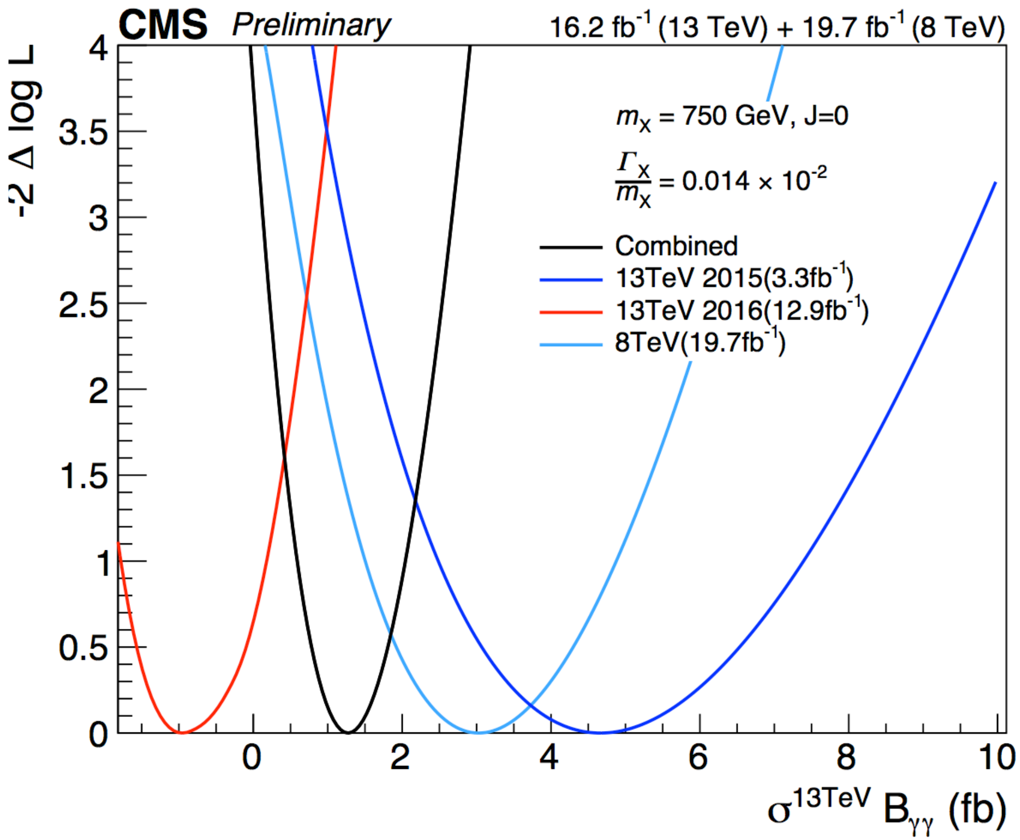


SHORT-DISTANCE INTERACTION



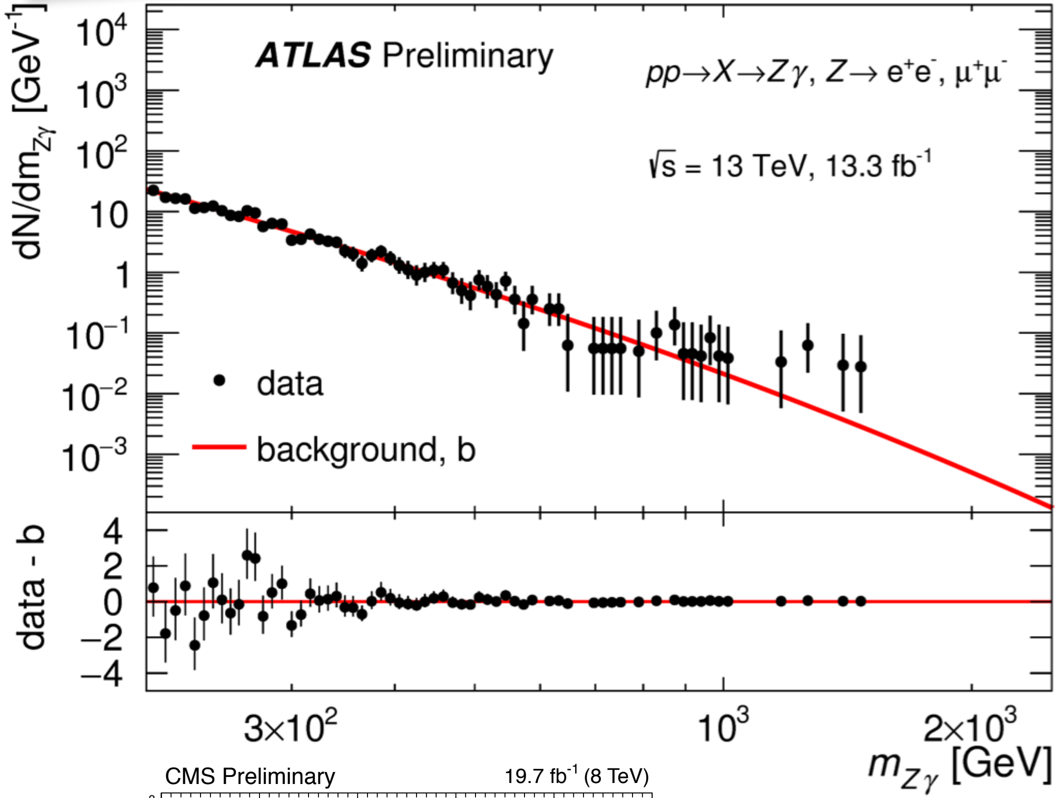
POST MORTEM

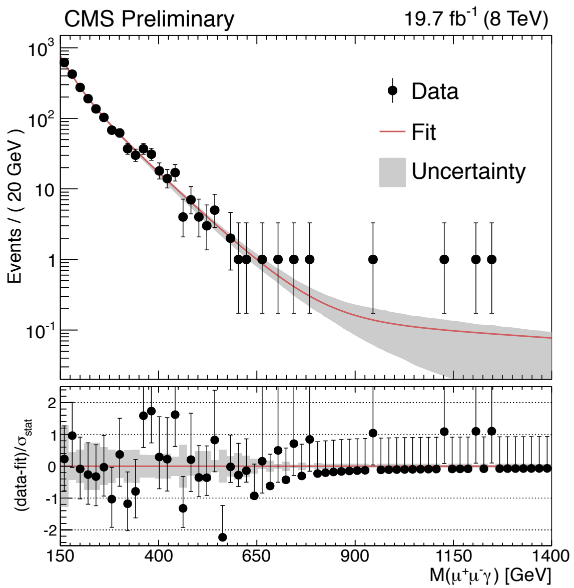


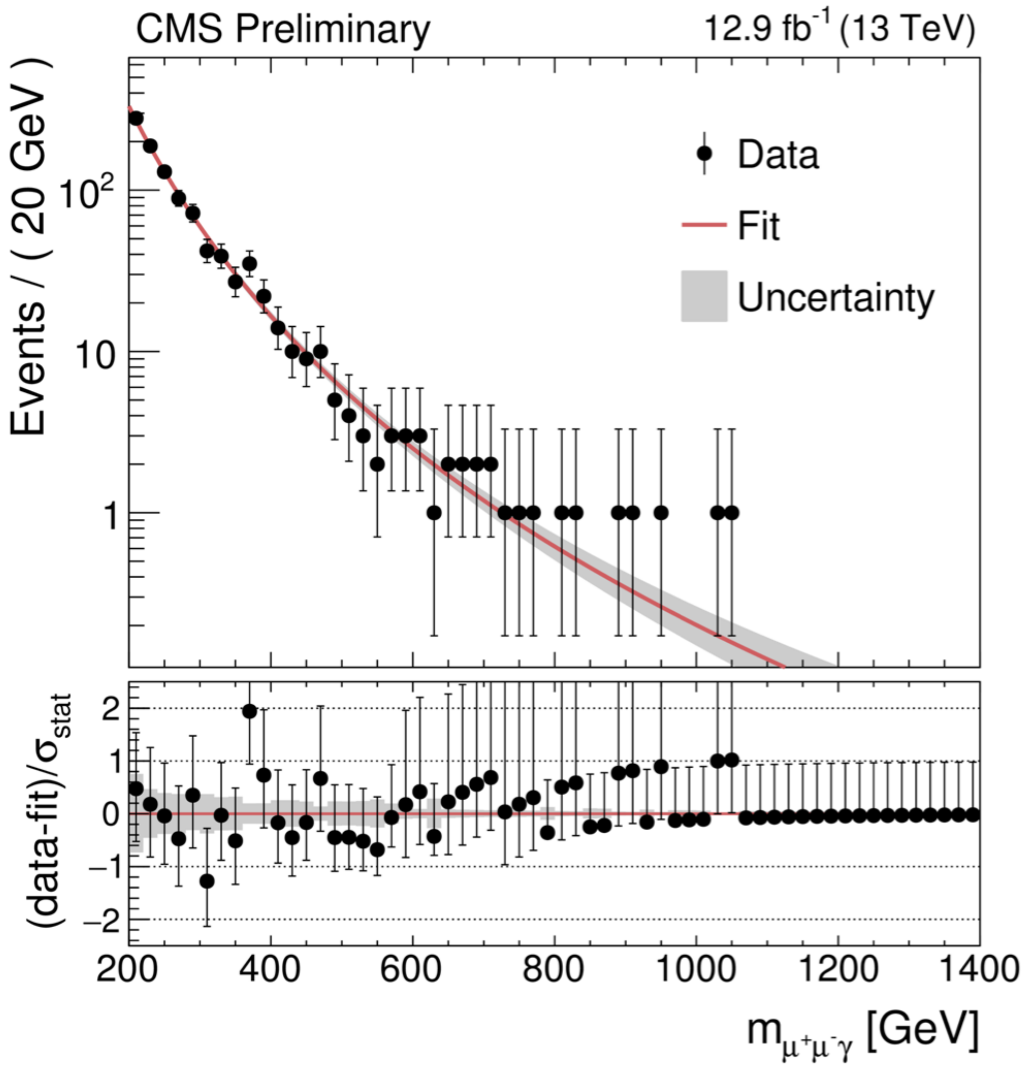


A signal with cross-section as the largest excess in 2015+8TeV would look like this

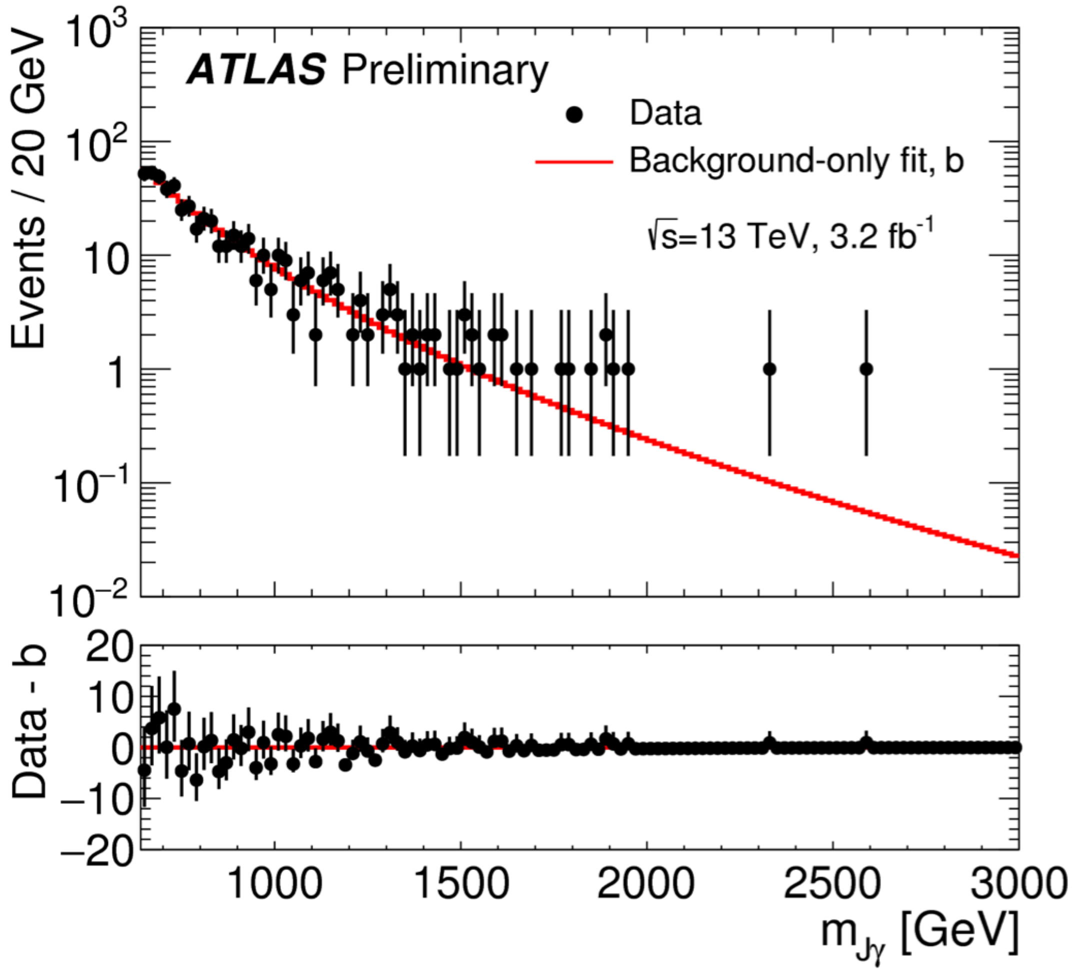
Z(ll)+γ SPECTRUM

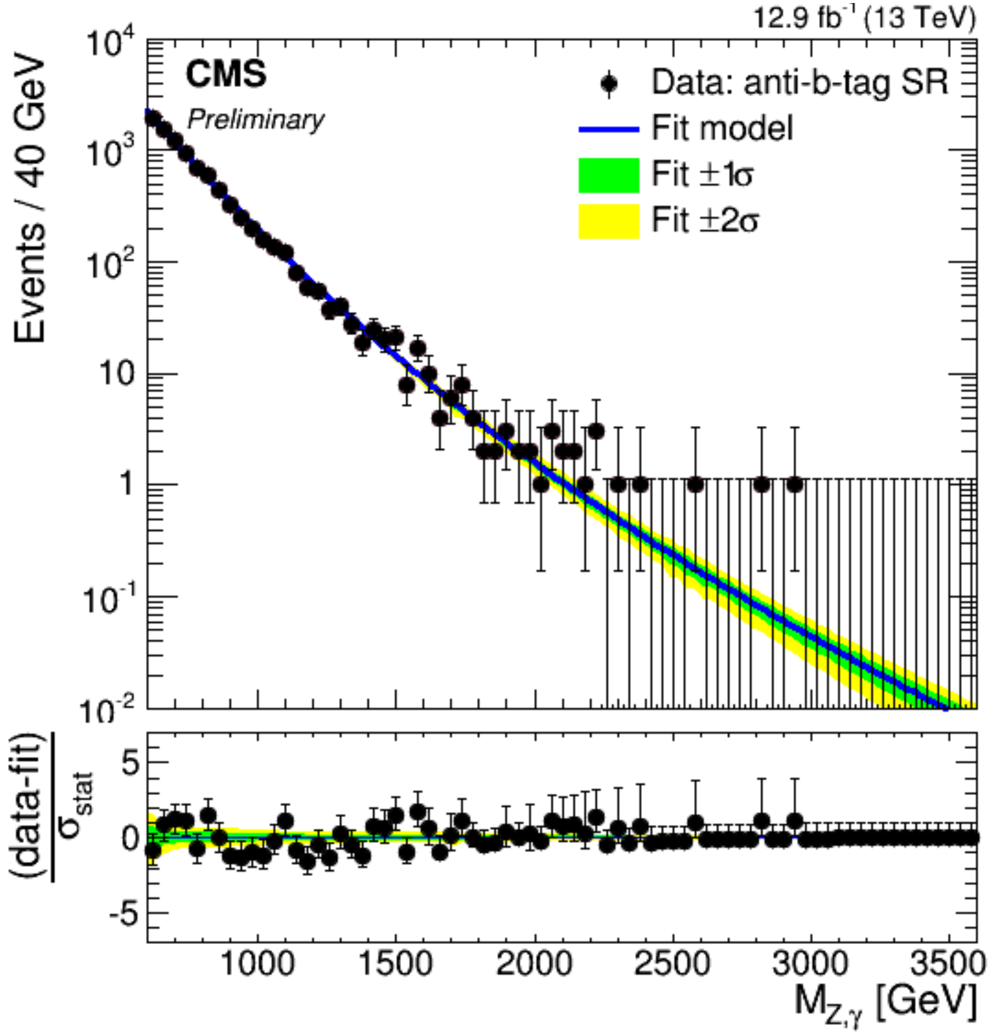






Z(qq)+γ SPECTRUM





- Merged jets and substructure analysis to reconstruct Z

MIDSUMMER NIGHT'S DREAM