Beyond Standard Model

Direct searches

Lecture 20

Dipartimento di Fisica

Sapienza
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Fisica delle Particelle Elementari, Anno Accademico 2015-16

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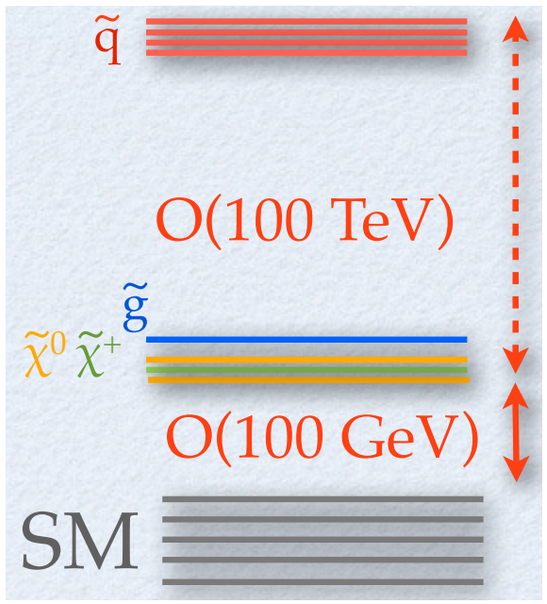
Direct Searches After *The Boson* Discovery

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



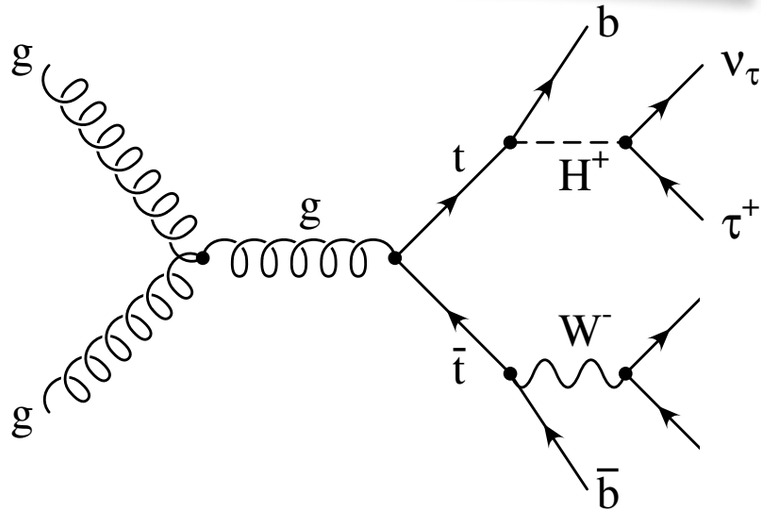
Other Higgses

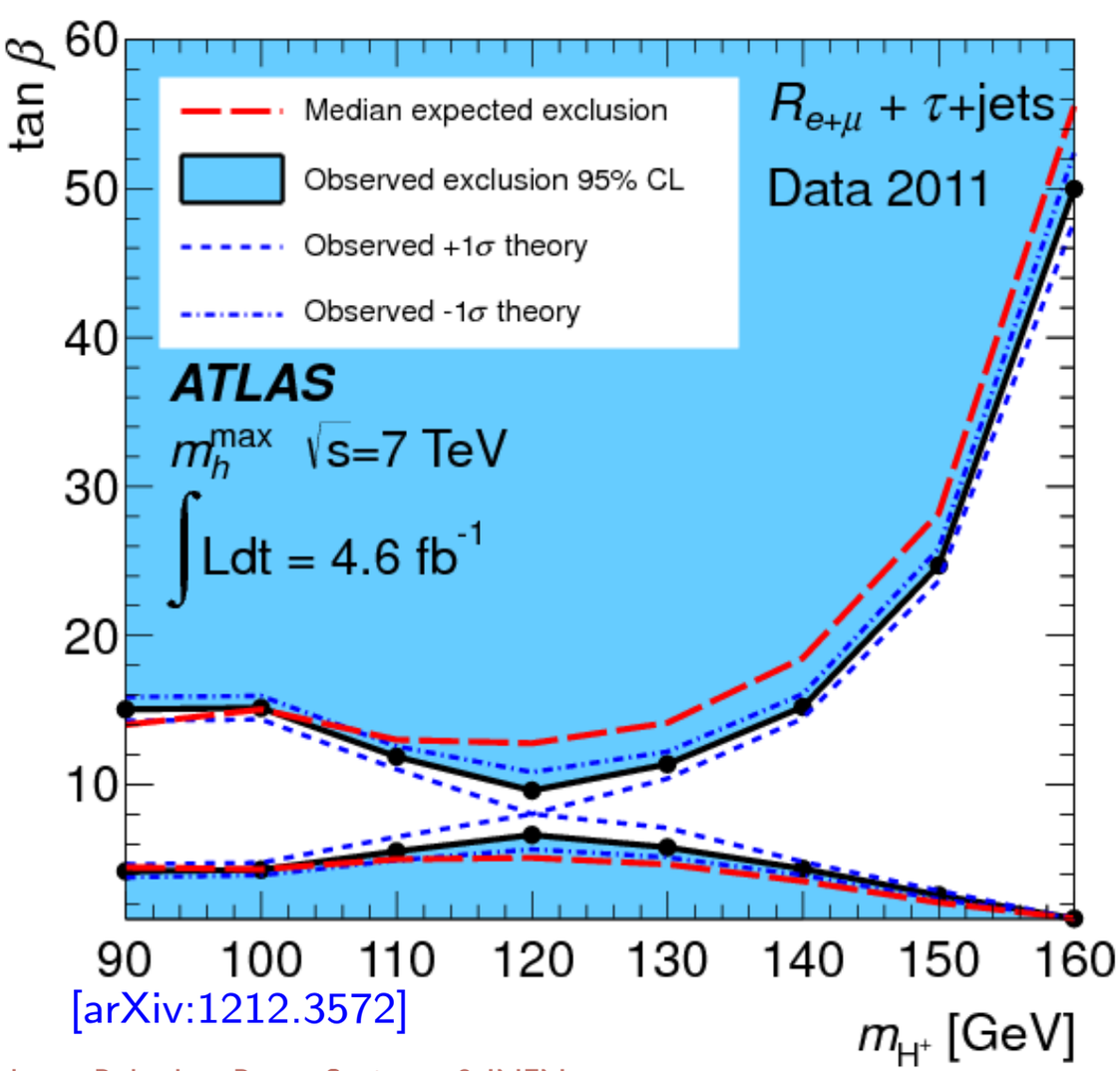
More Higgs Bosons

- Minimal supersymmetric models (MSSM)
  - 5 additional bosons: CP-even: h,H; CP-odd: A; two charged $H^{\pm}$
    - $H^{\pm}$ could have mass between top and bottom quarks
  - well defined mass hierarchy; lightest behaves like SM
  - *Search for additional charged and neutral bosons*
- Next to minimal SUSY (nMSSM) predicts more light Higgs bosons
  - Additional light singlet to MSSM
    - 3 CP-even: h_1, h_2, h_3, 2 CP-odd: a_1, a_2, and $H^{\pm}$
    - a_1 can be very light $m_{a1} \lesssim 2 \times m_b$
- Seesaw II models to address neutrino mass
  - Predicts 3 additional scalars Φ^{++}, Φ^{+}, Φ^{0}
    - Yukawa couplings proportional to neutrino mass
  - Rare resonant same-sign signature

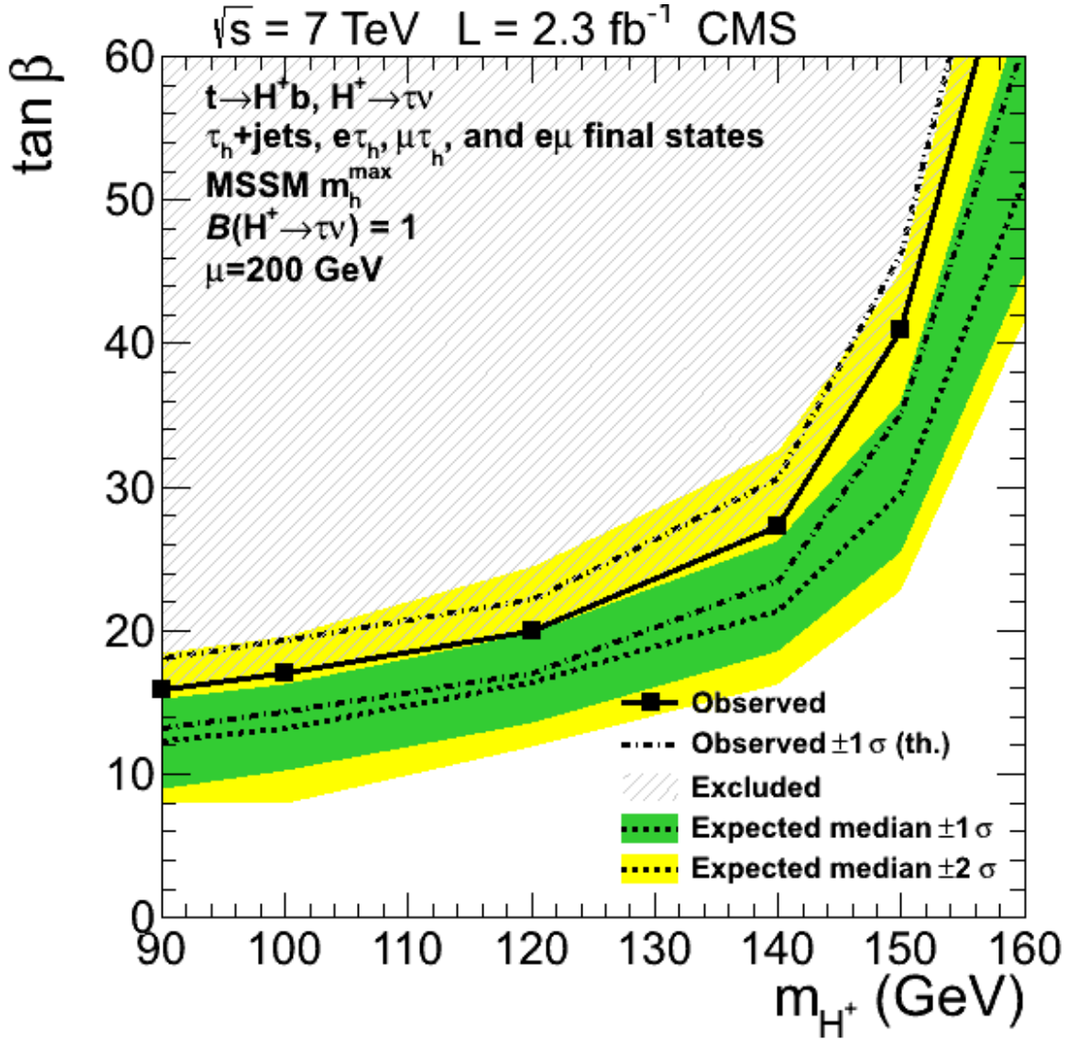
CHARGED HIGGS SEARCHES

- Both hadronic and leptonic W decays
- Strong constraints in low mass region but still room for improvement with more data



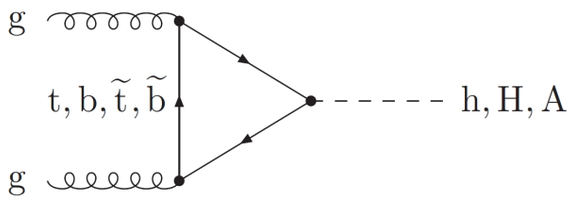


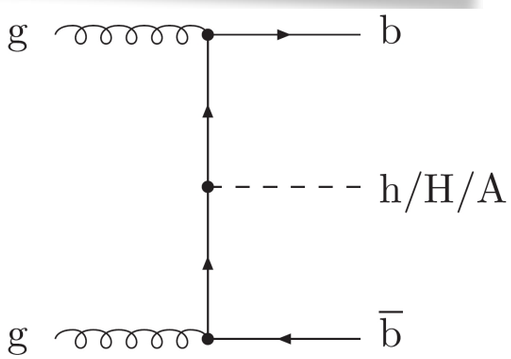
[arXiv:1212.3572]



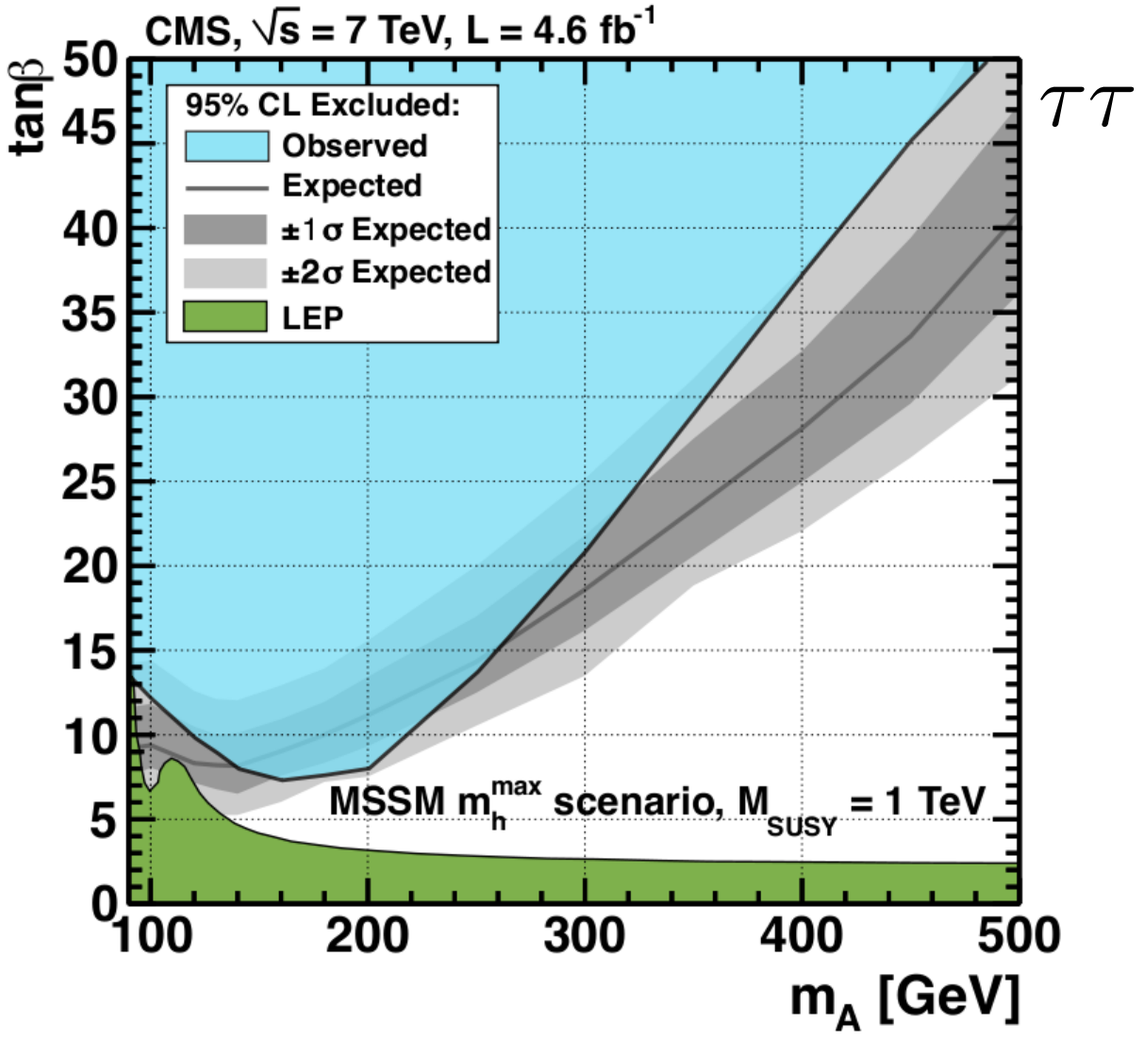
NEUTRAL MSSM HIGGS

- Important role played by b jets
  - enhanced couplings for b and tau
  - also production in association with b quarks

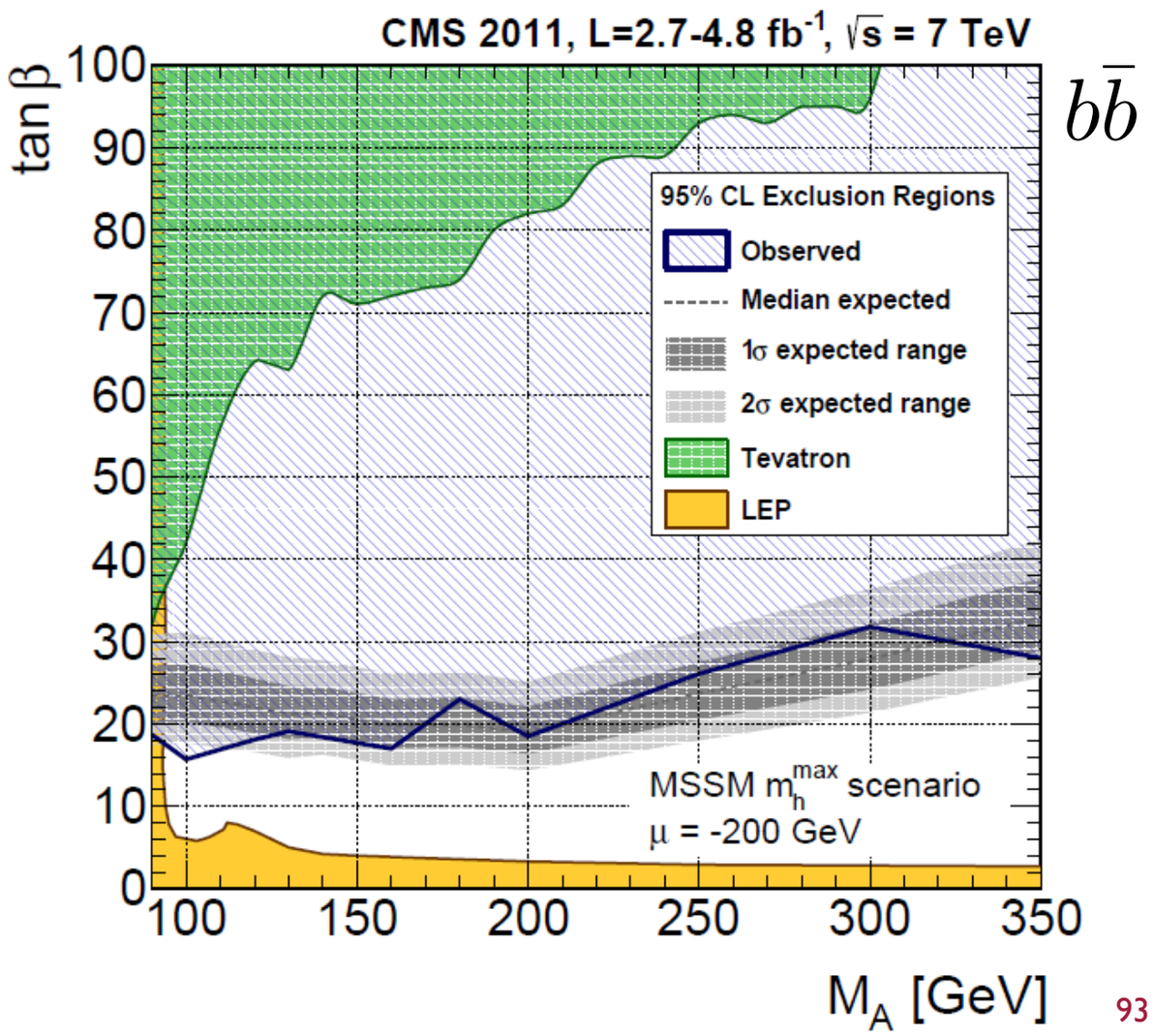




- LHC bounds approaching LEP limits to rule out light candidates



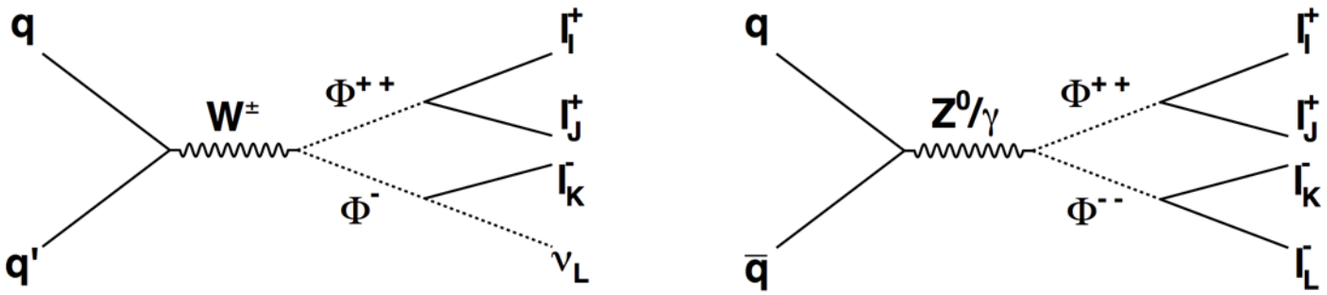
$\tau\tau$

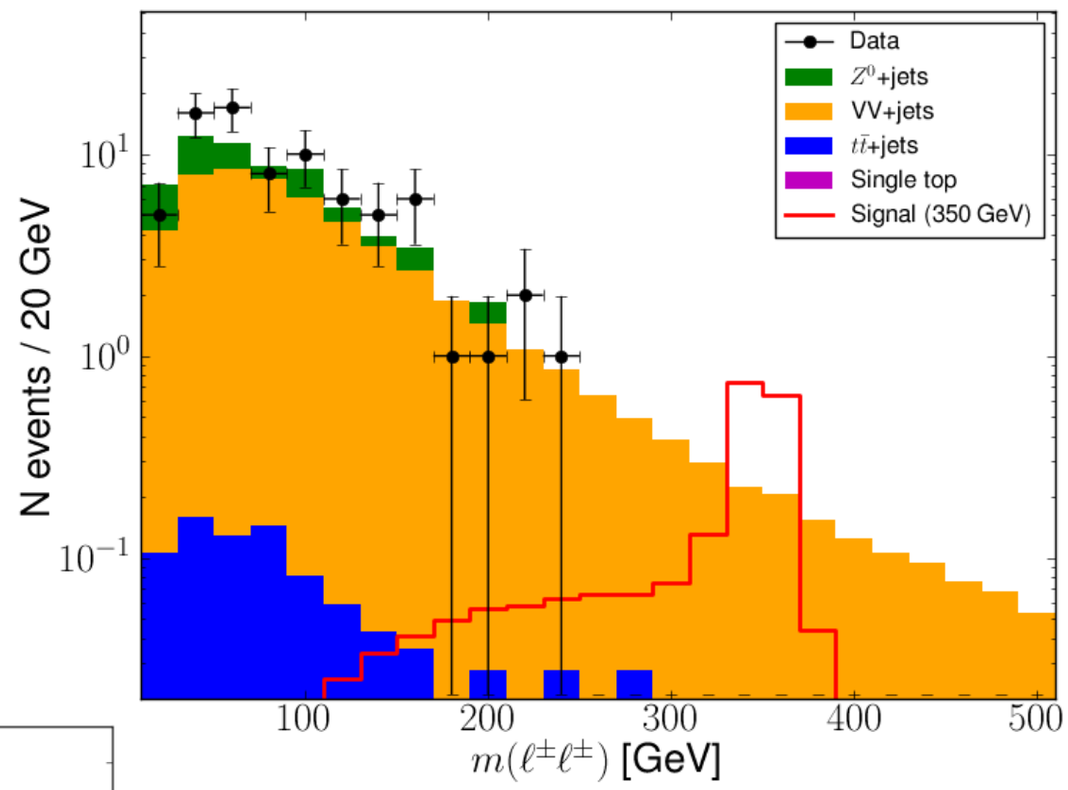


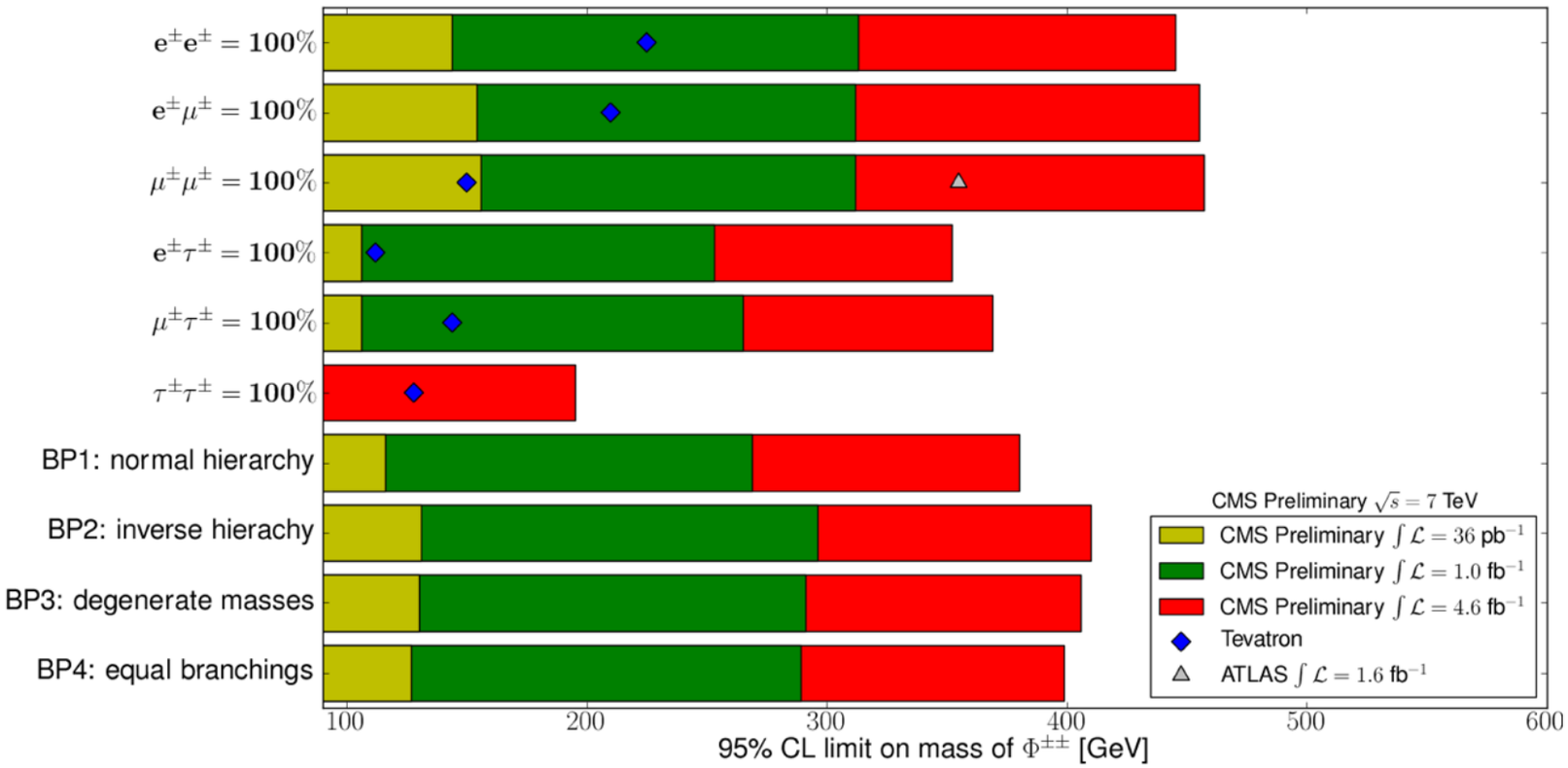
$b\bar{b}$

DOUBLY CHARGED HIGGS

- Rare signature with 3/4 isolated leptons
  - peak in same sign invariant mass

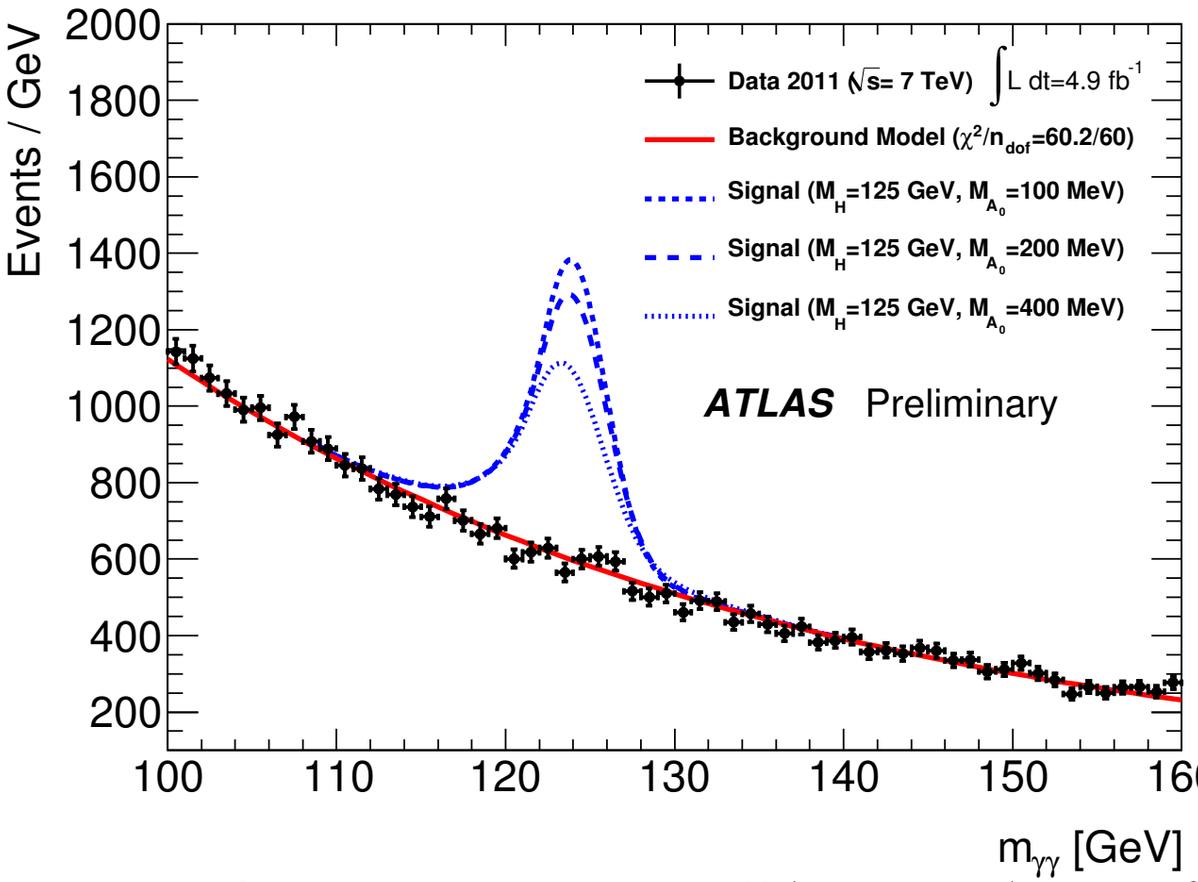






Exotic Light Higgs

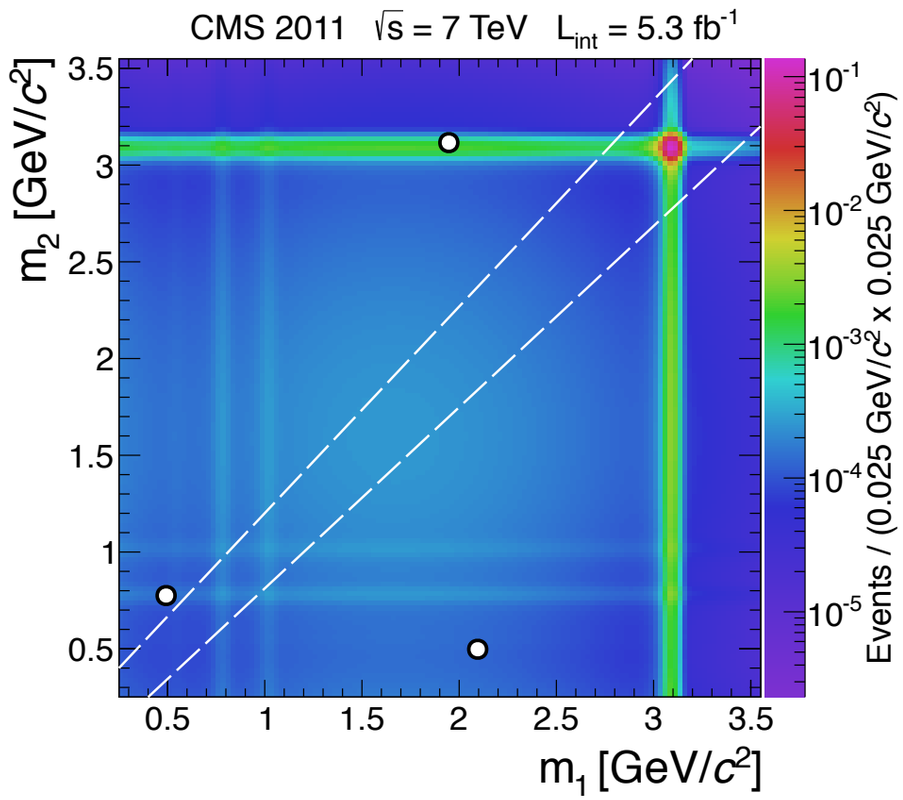
$$h \to aa \to \gamma\gamma + \gamma\gamma$$

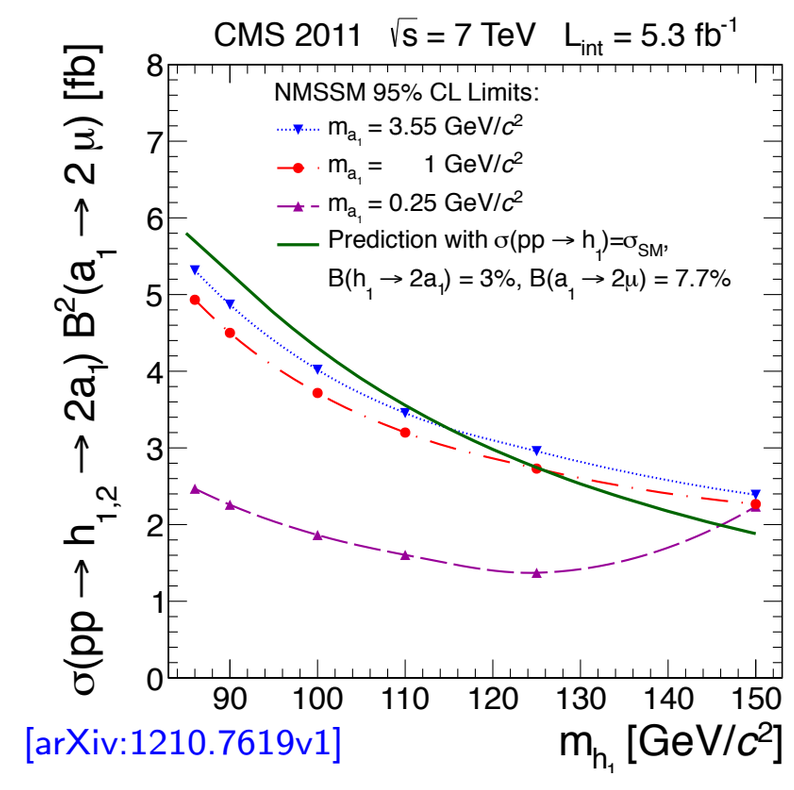


$m_{\gamma\gamma}$ after event selection; $\mathcal{B}(a \to \gamma\gamma) = 20\%$

- Re-interpretation of di-photon search assuming collimated photon pairs
- Search for clean light mass di-muon resonances

$$h \to aa \to \mu\mu + \mu\mu$$





[arXiv:1210.7619v1]

Exotic Searches

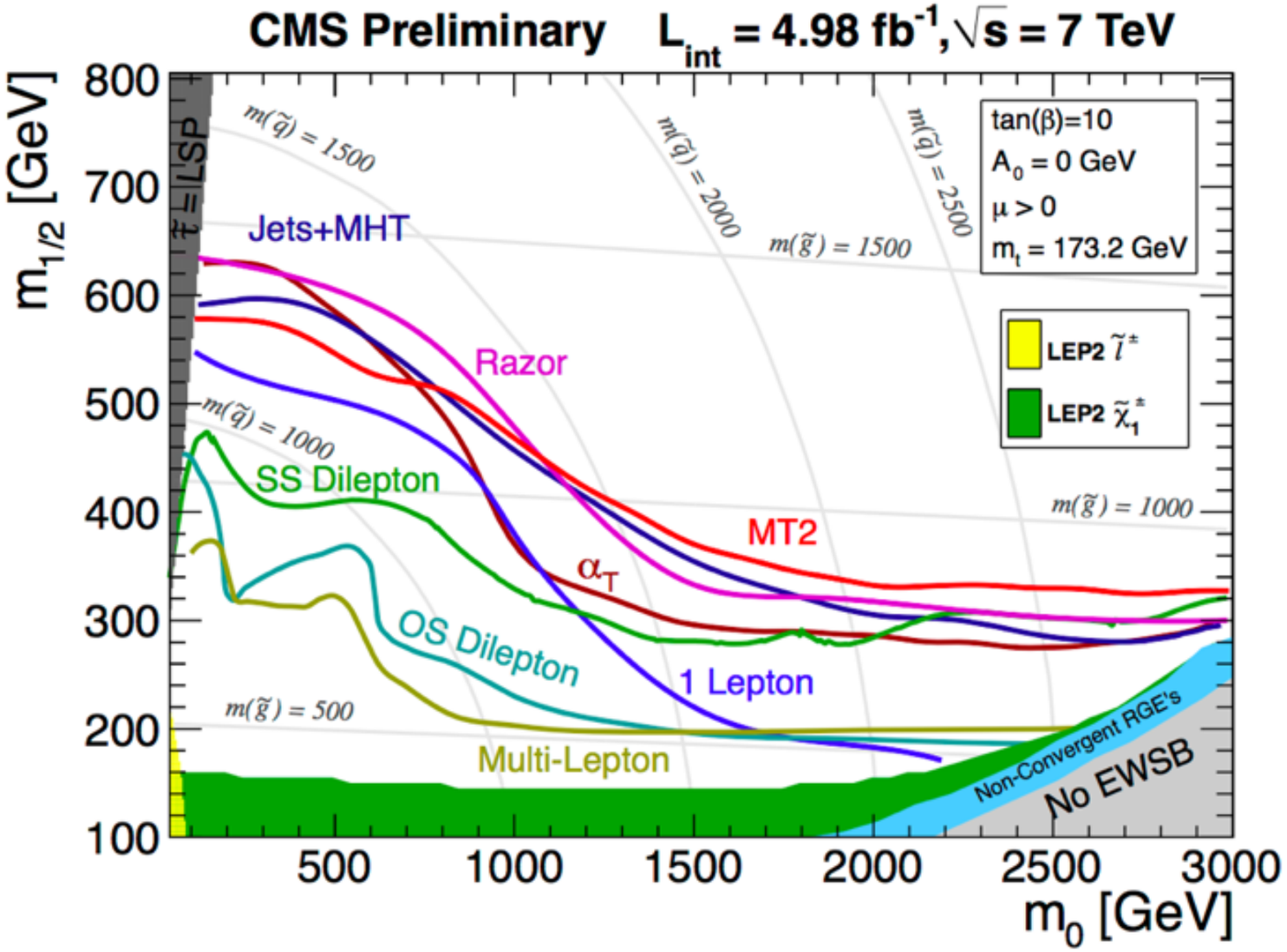
EXOTICA

- 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

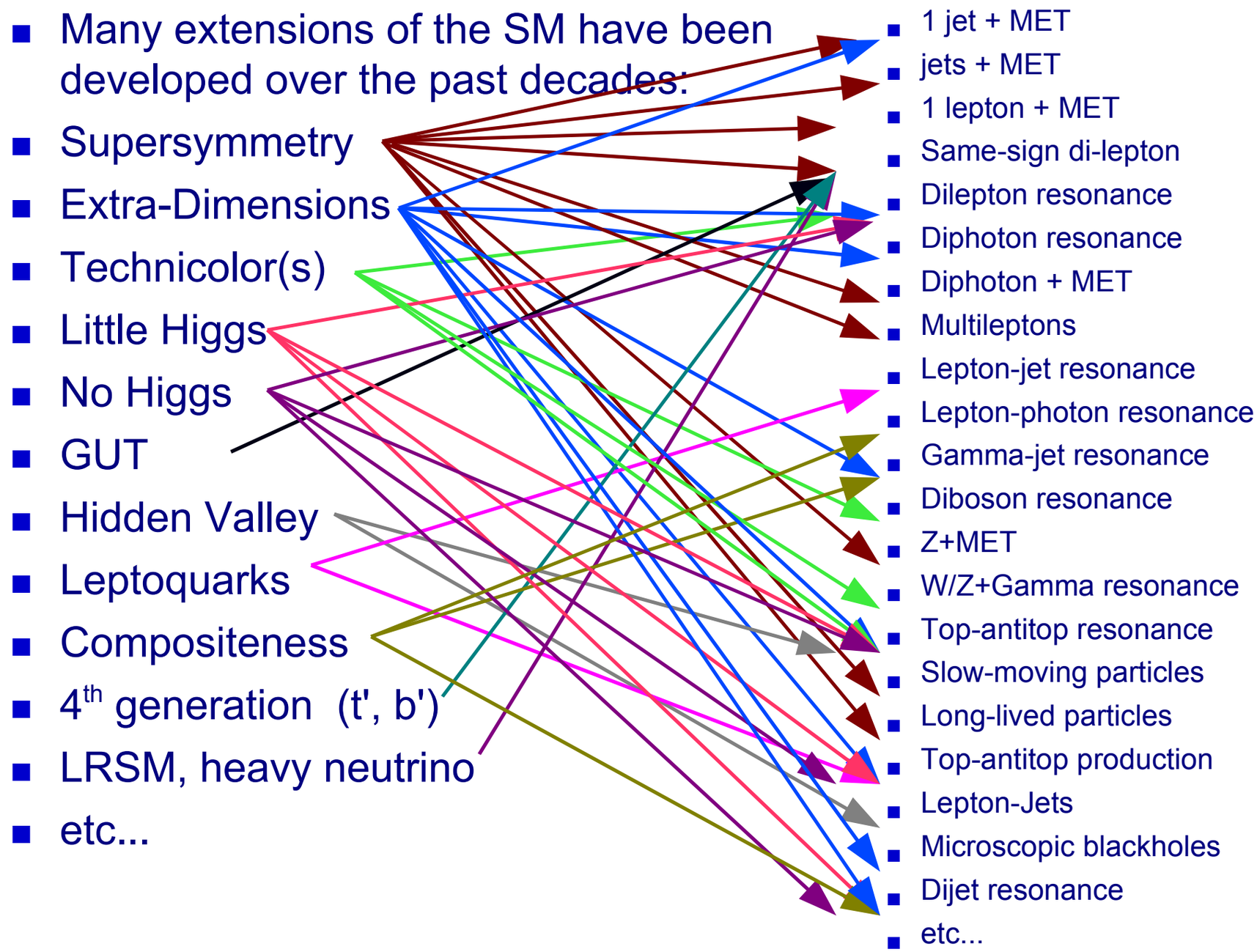
SUSY OR EXOTICA?



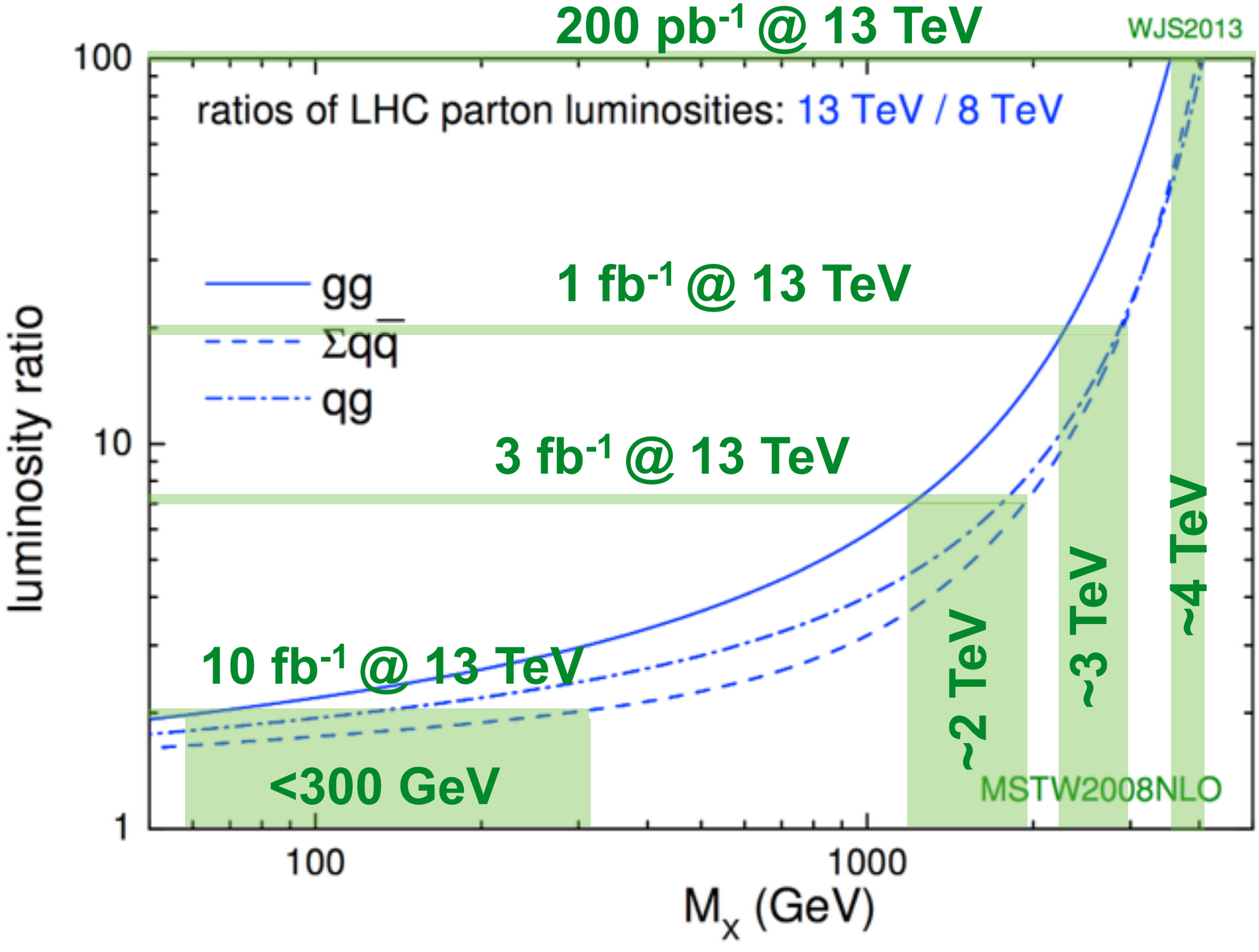
- SUSY results reported very often in (m_0,$m_{1/2}$) plane
  - Relation between mass of supersymmetric particles
- Large missing transverse energy usually the primary signature
- In exotica look for particles and resonances that are not necessarily needed or predicted in supersymmetry

SIGNATURE- OR TOPIC-BASED?

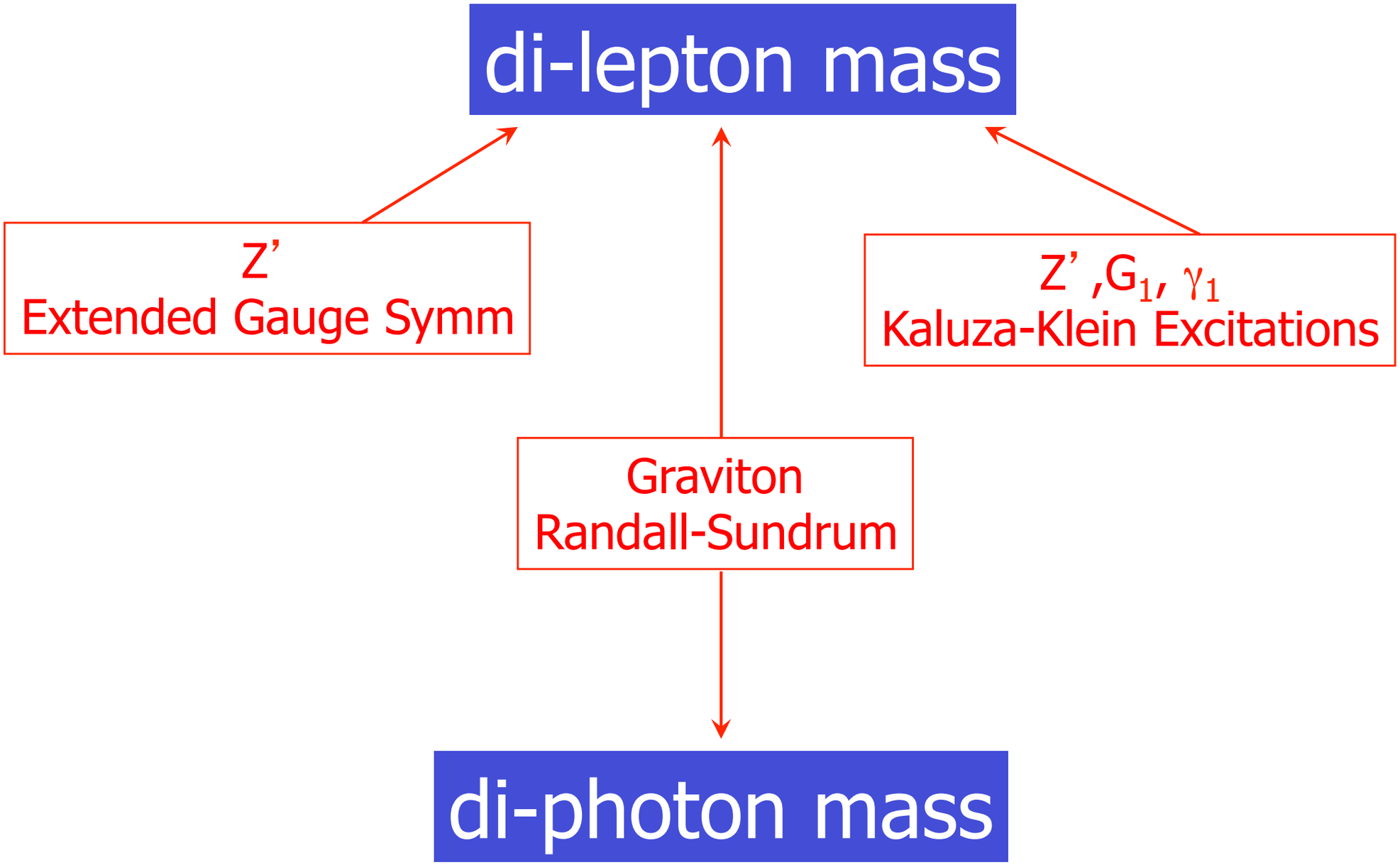
- Same final state often probing very different models or topics
  - 2 leptons, 2jets + MET, lepton+jet+MET



INCREASED SENSITIVITY @ 13 TEV



RESONANCES



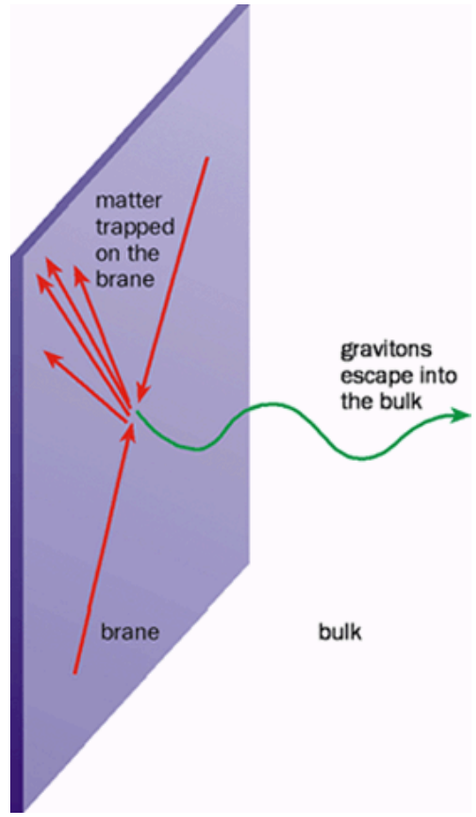
- Resonances have a good record of past Nobel-worth discoveries!
  - charm and beauty

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

Extra Dimensions

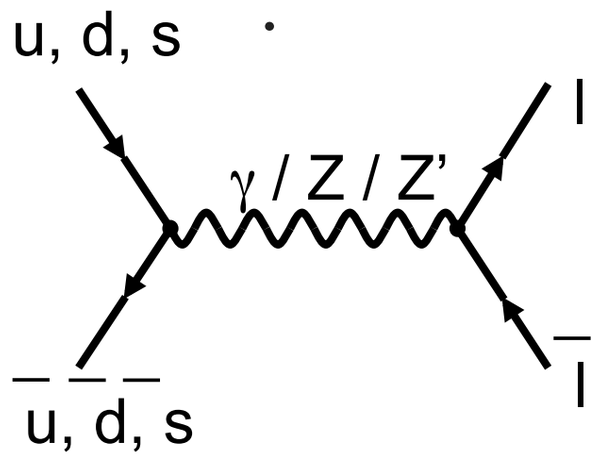
- Hierarchy problem: $M_{EW}/M_{Pl} \sim 10^{-17}$
- Gravity much weaker than other gauge fields
- Possible solution: Existence of extra dimensions!
- Gravity scale lowered to ~ 1 TeV if gravitons propagate in 4+n dimensions
  - weak in our 4D universe but strongly interacting in the extra dimensions
- If ED similar to our 3+1 dimensions Newton's law affected
  - experimentally probed down to R < 160 microns
- Tighter constraints if ED probed by elementary particles
  - M = 100 GeV corresponds to distance of 10^{-18} m
- Several models available with possible signatures to be seen at LHC
  - Graviton (and its KK modes), Black Holes



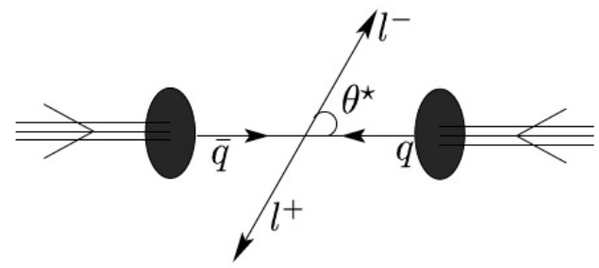
Z' Production at LHC

- Dominant Z' production process via Drell-Yan process

$$q\bar{q} \to Z'$$



- Clear experimental signature
  - 2 high pt leptons with large invariant mass
  - also decay in two jets but less sensitive than leptonic chan
    - in some models ttbar dominates over leptons. pretty exotic!

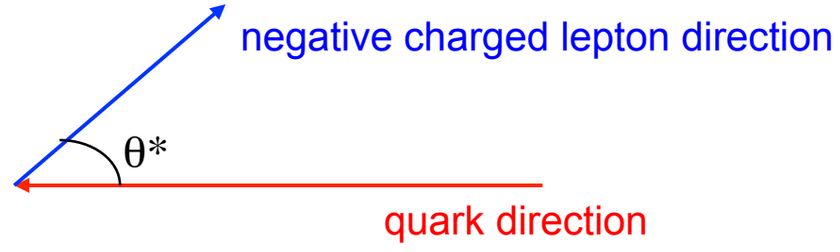


- Differential cross section

$$\frac{d\sigma}{d\sqrt{s'}dY\,d\cos\theta^\star} = \sum_{\text{quarks q}} [g_q^S(Y,\sqrt{s'})S_q(\sqrt{s'})(1+\cos^2\theta^\star) + g_q^A(Y,\sqrt{s'})A_q(\sqrt{s'})2\cos\theta^\star]$$

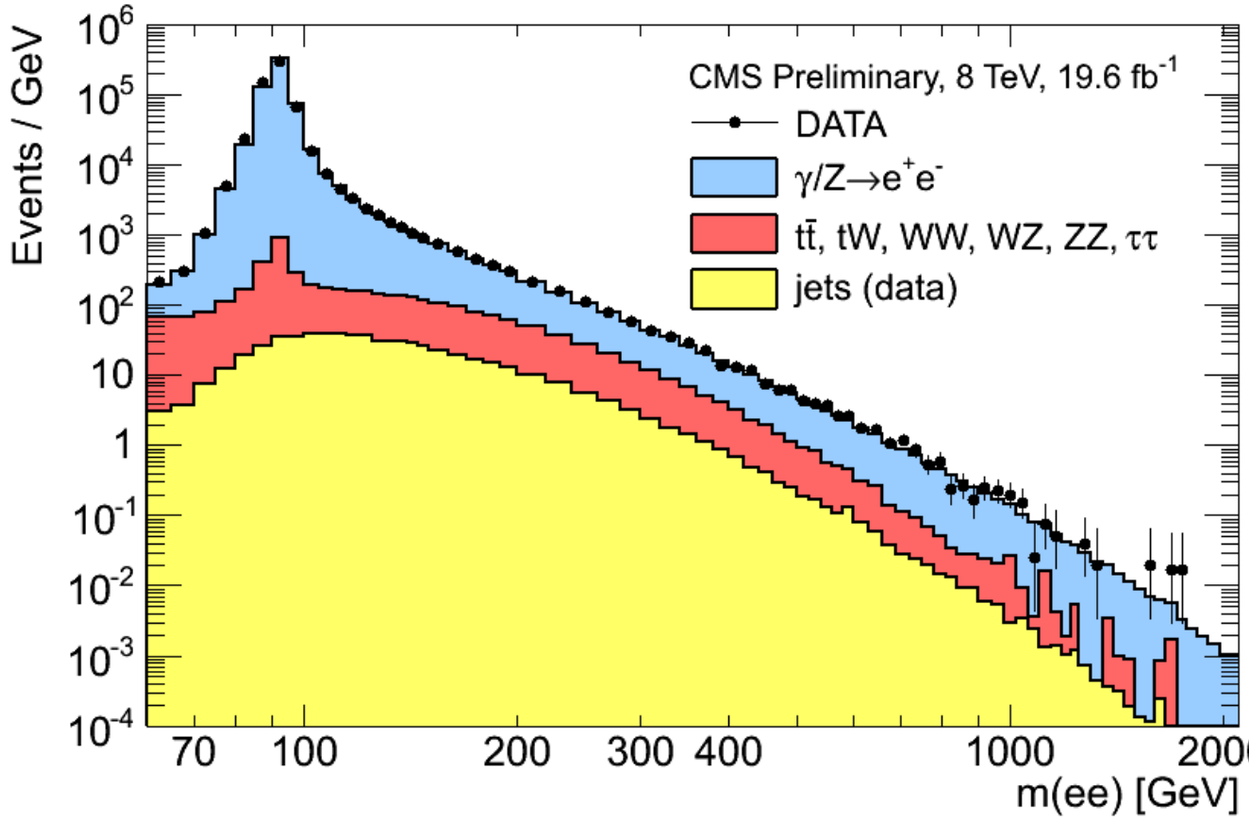
depends on

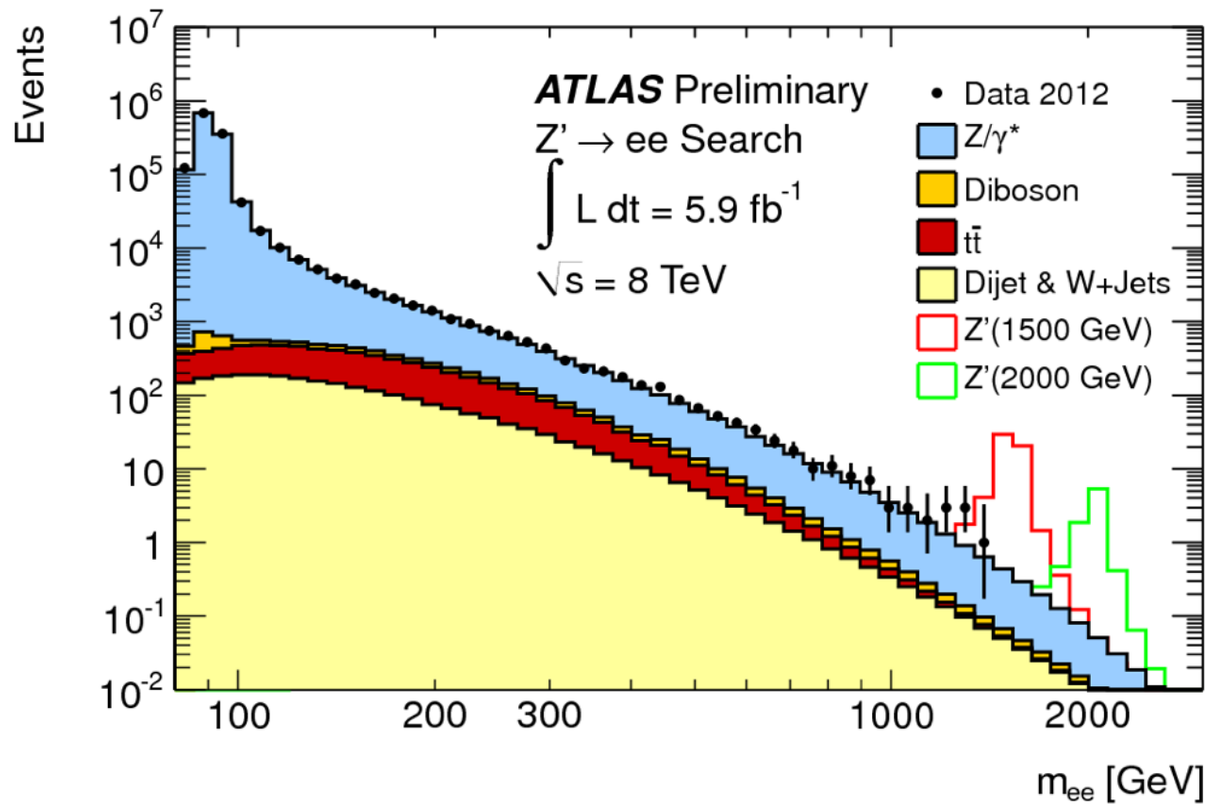
- Z' mass M=$\sqrt{s'}$
- Z' rapidity Y
- Angle θ* between l- and q in the center of mass of the colliding partons



$$\cos\theta^* > 0$$

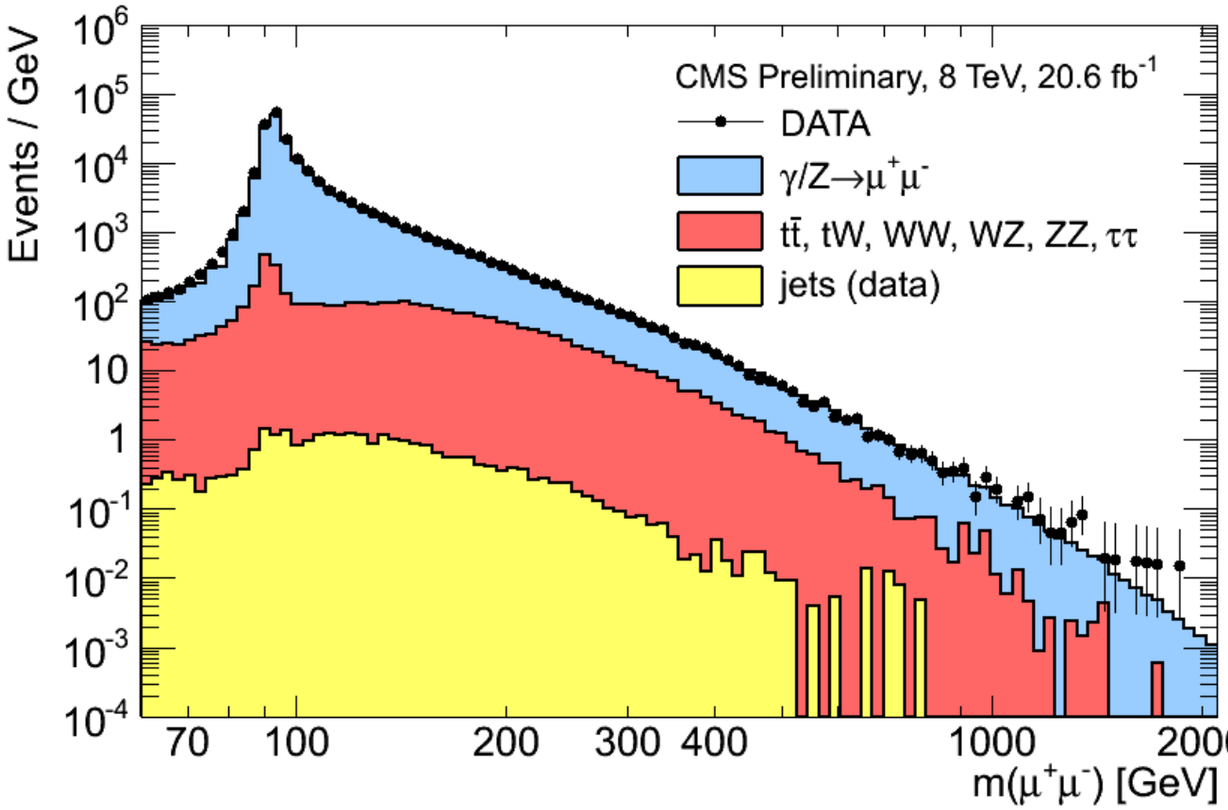
DI-ELECTRONS

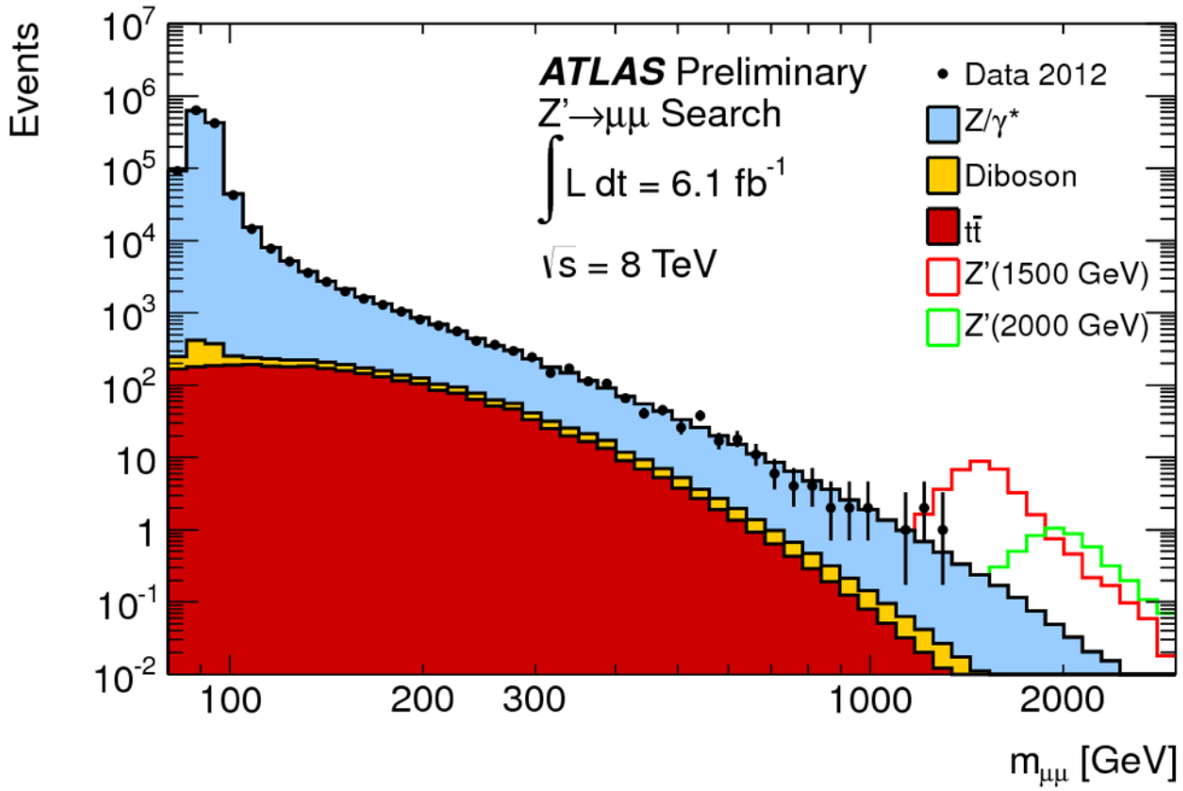




- Background mainly composed of Drell-Yan tail

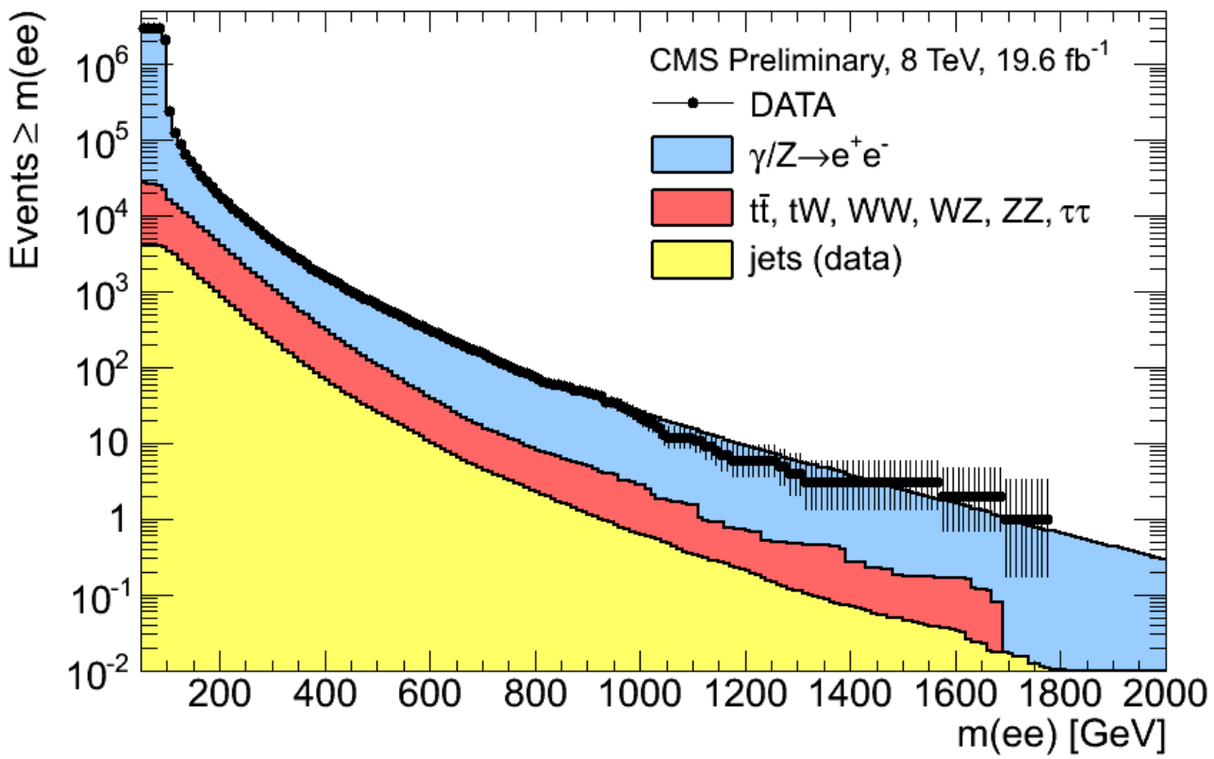
Di-Muons

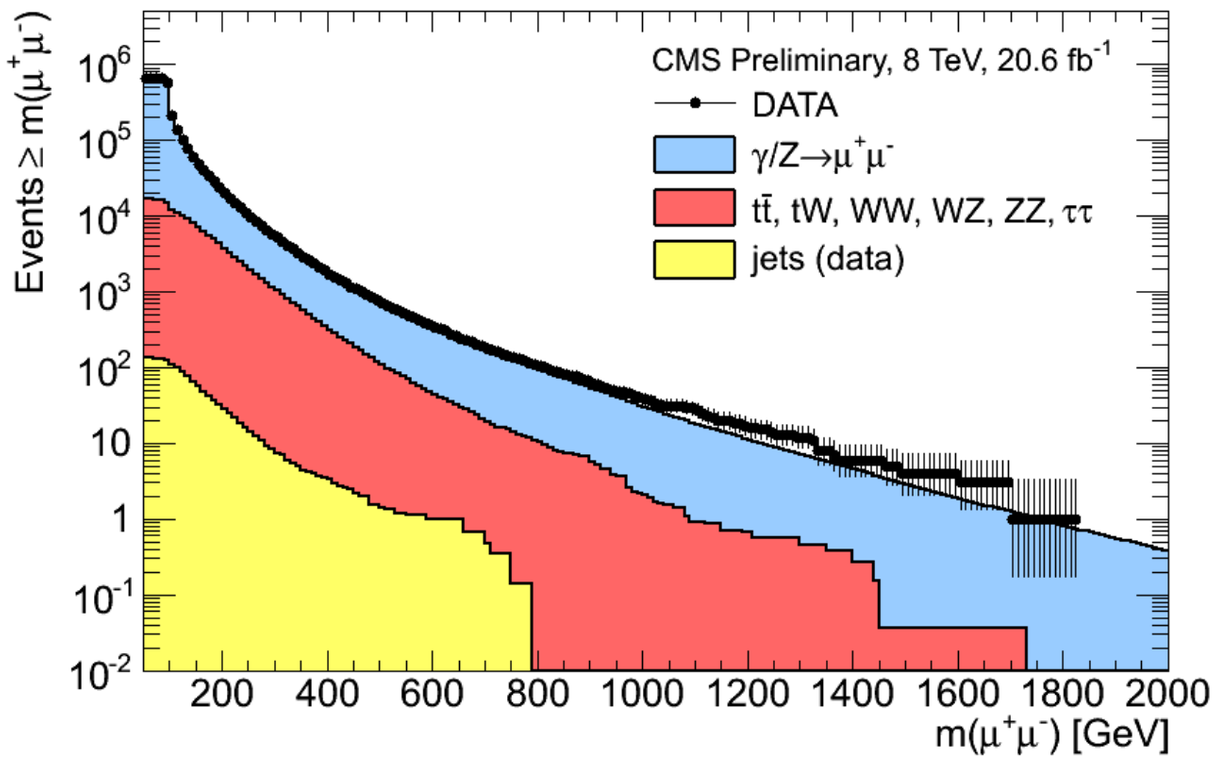


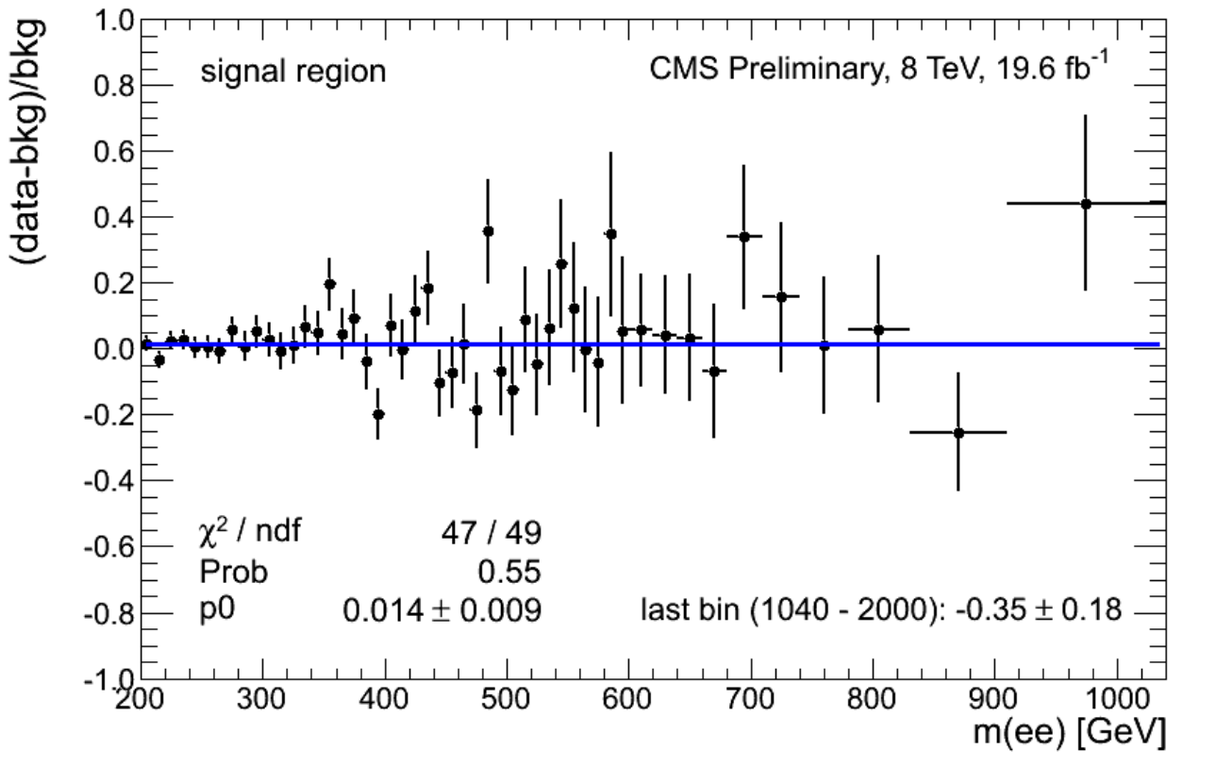


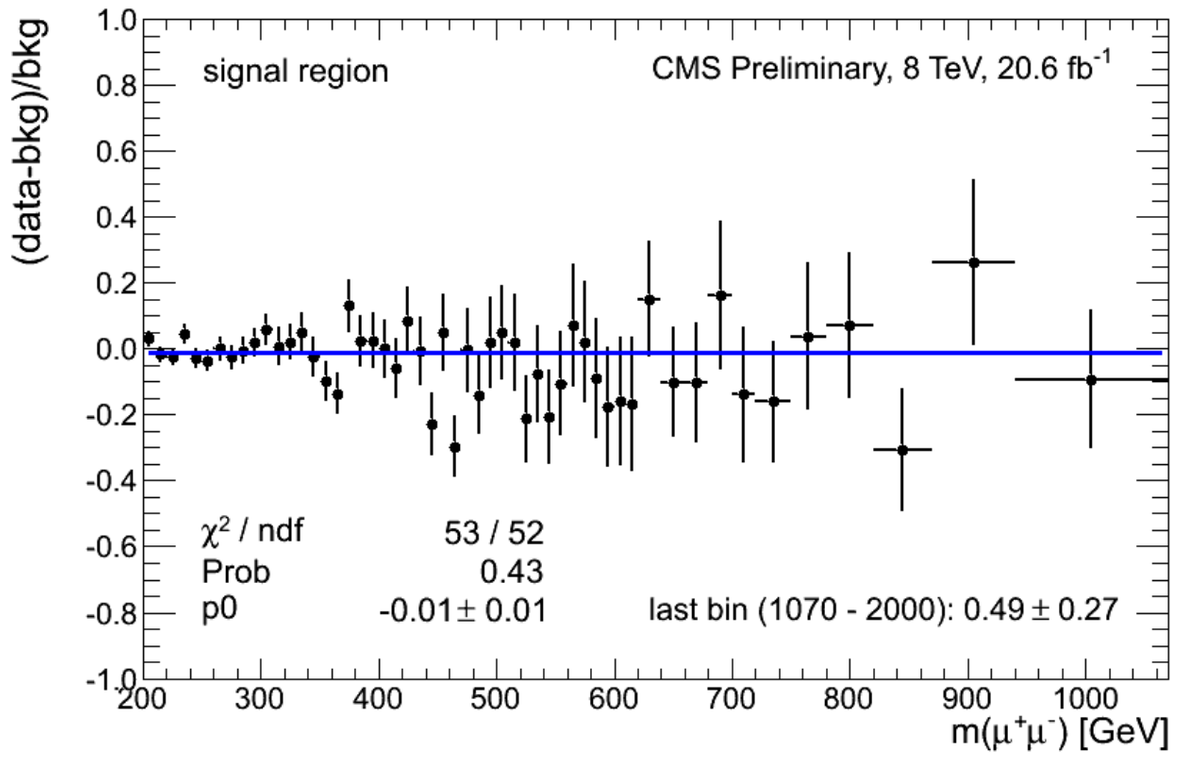
- wider peak structure
  - momentum resolution of high pt muons worse than energy resolution for high energy electrons

LOOKING FOR DEVIATIONS

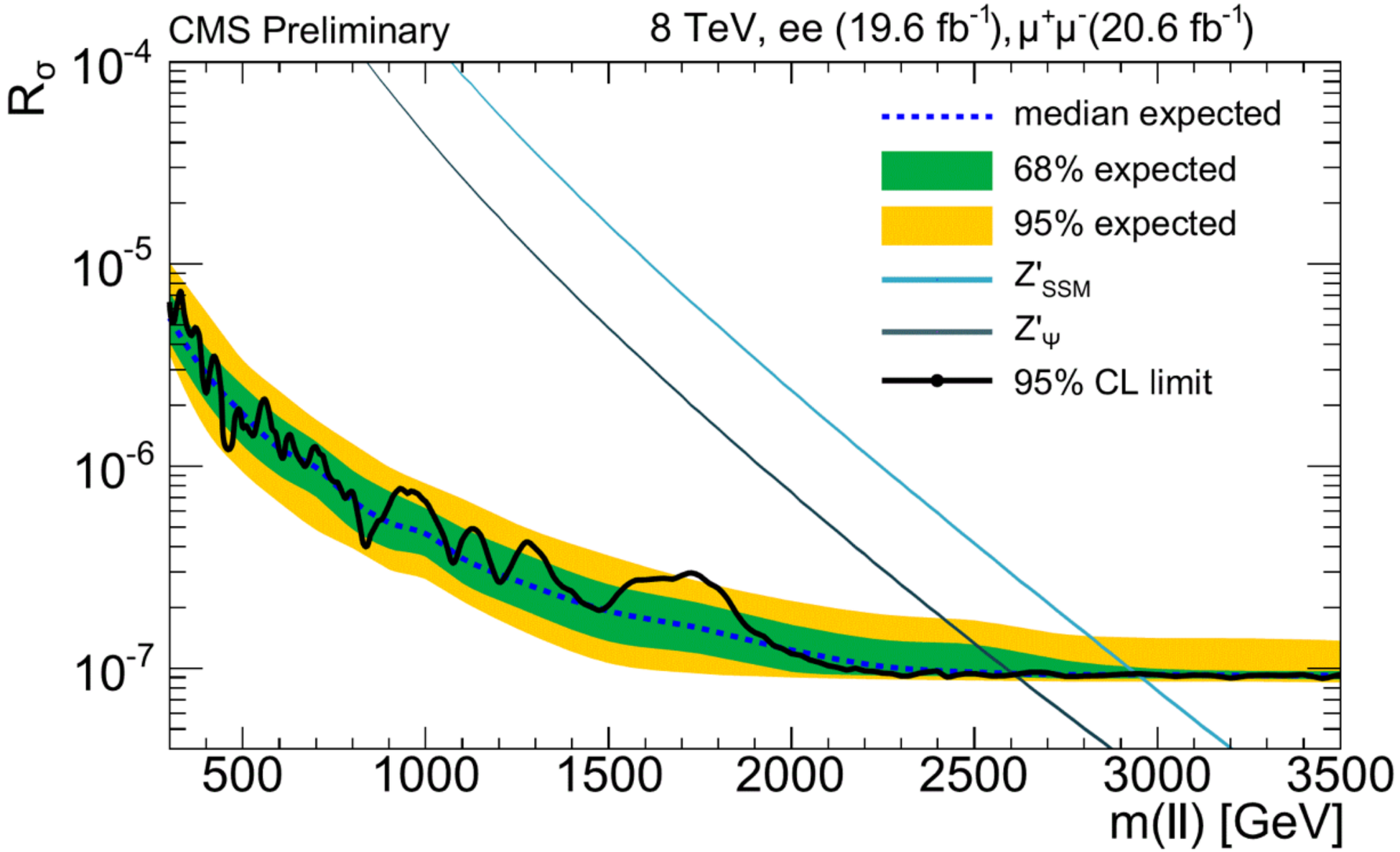




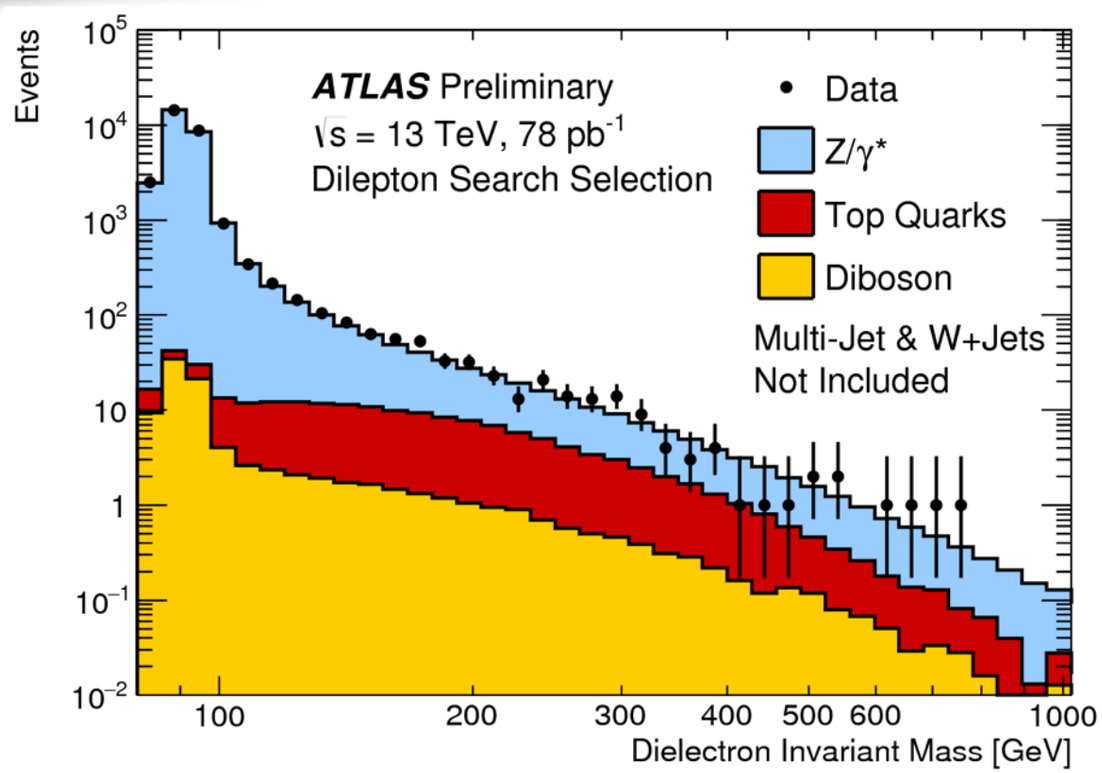


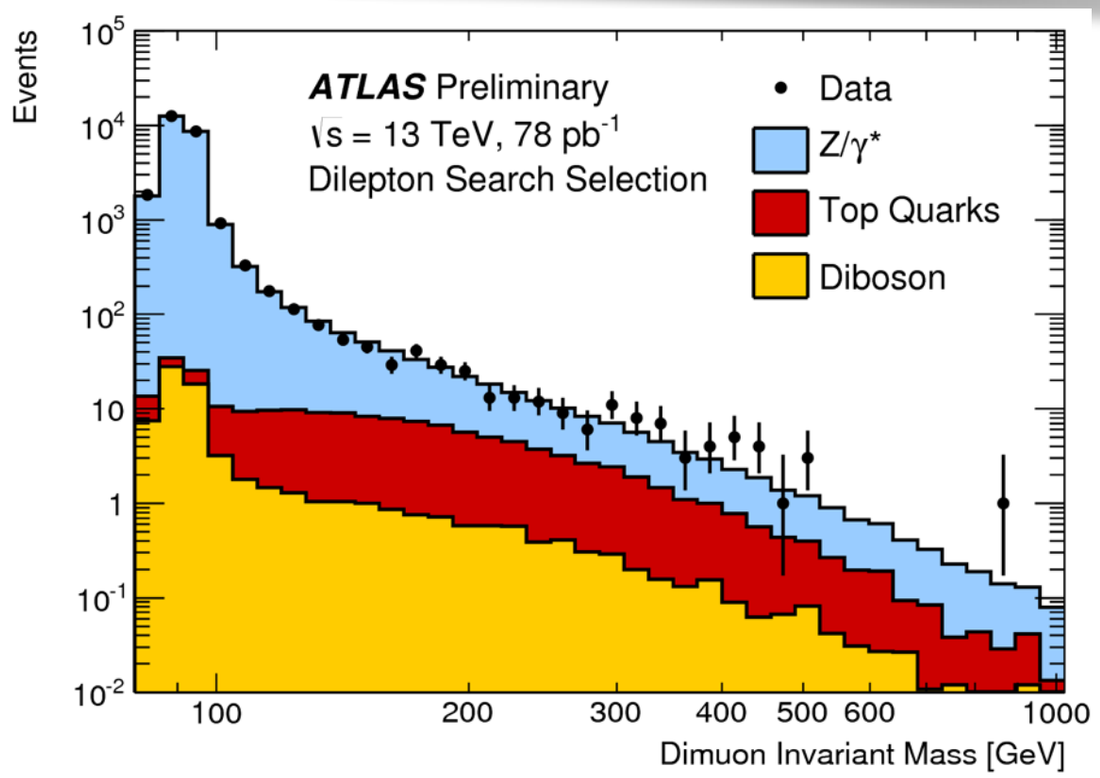


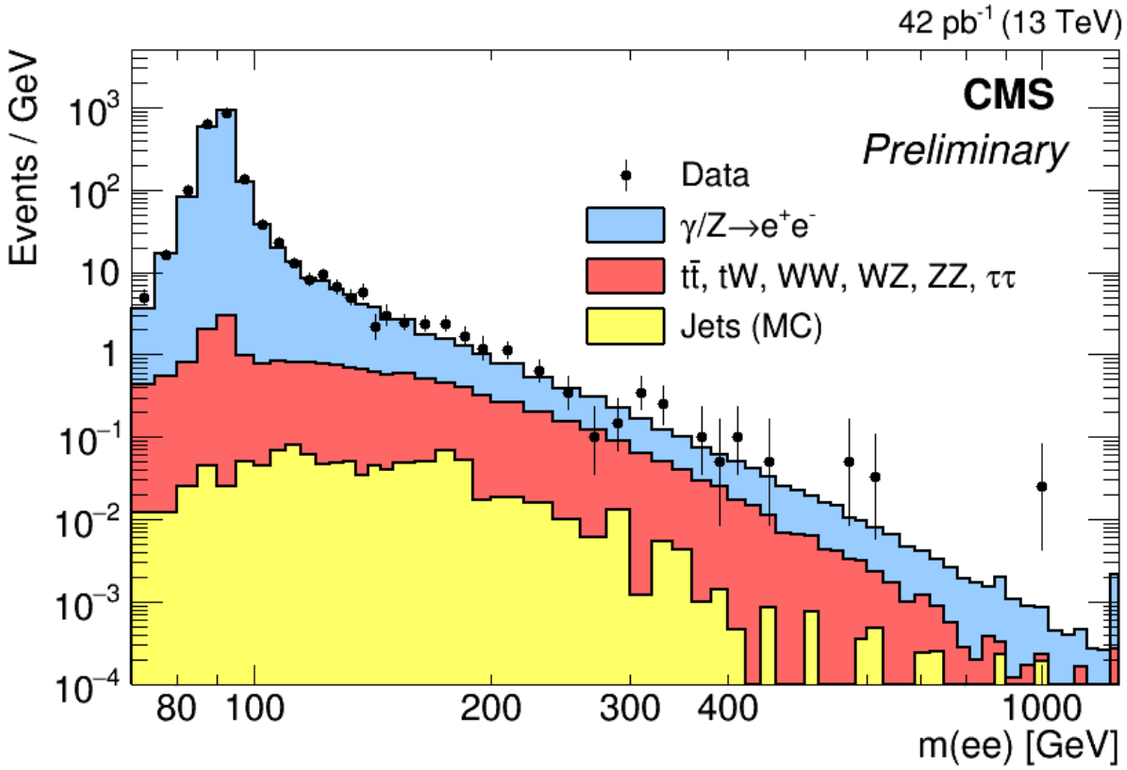
EXCLUSION LIMITS

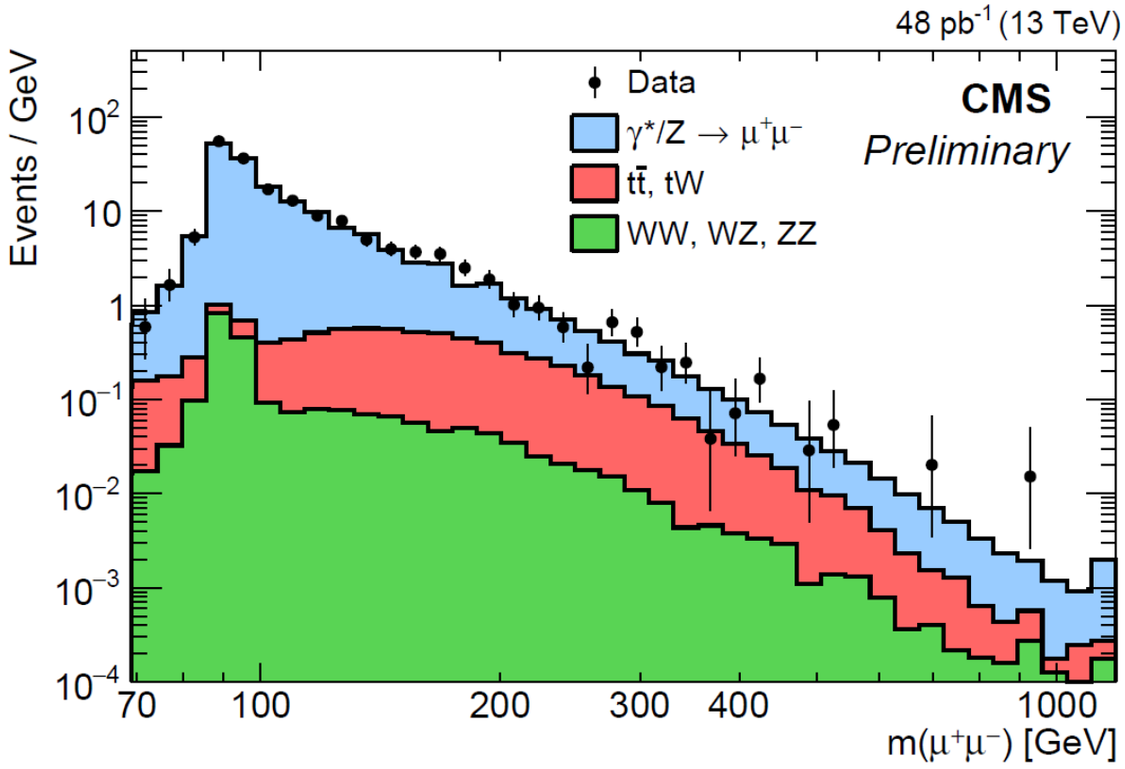


DI-LEPTON @ 13 TEV

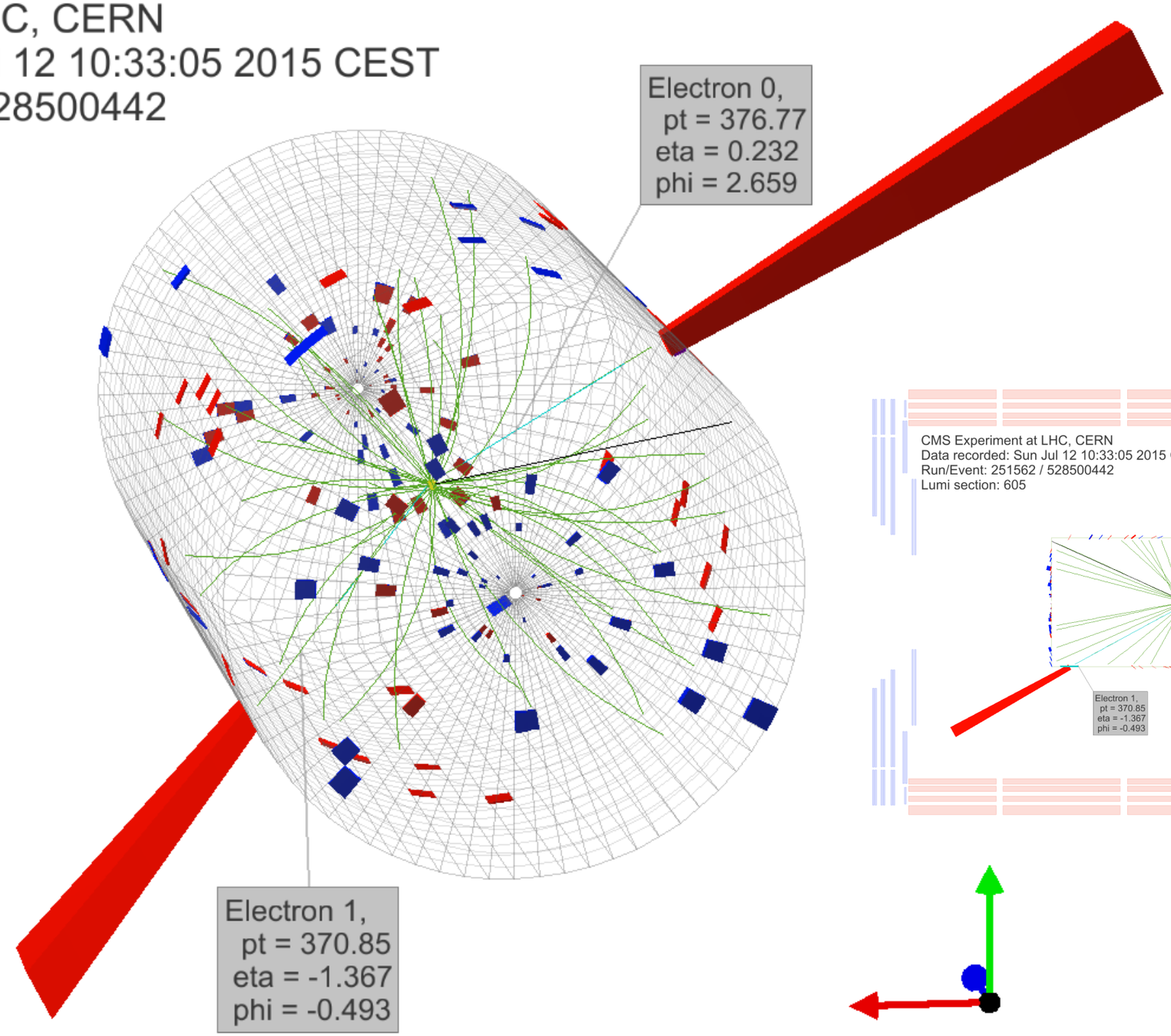


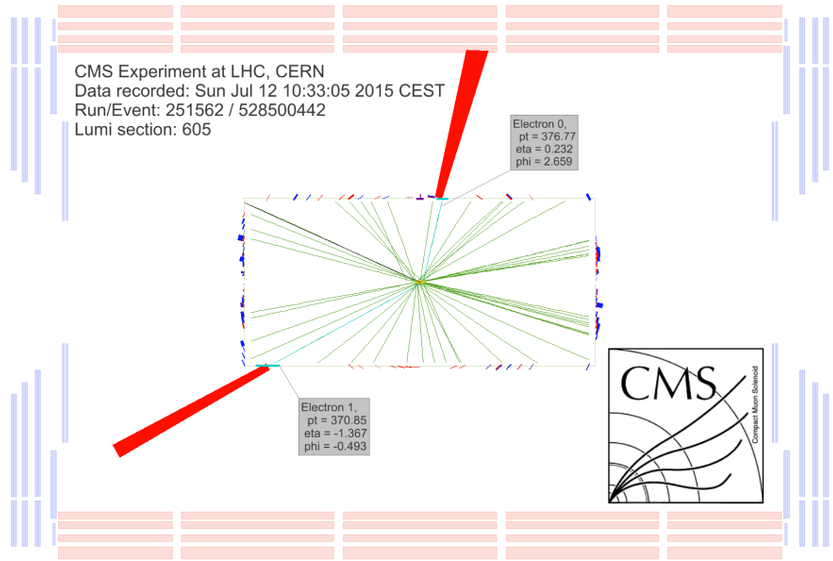


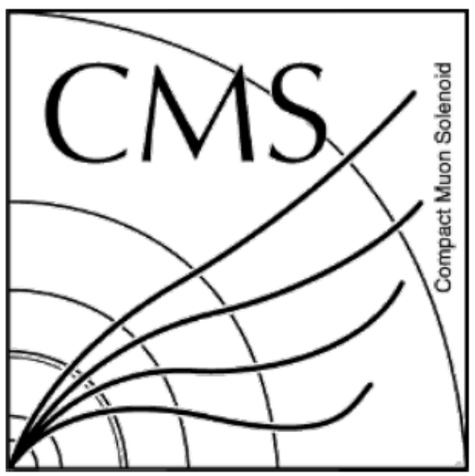




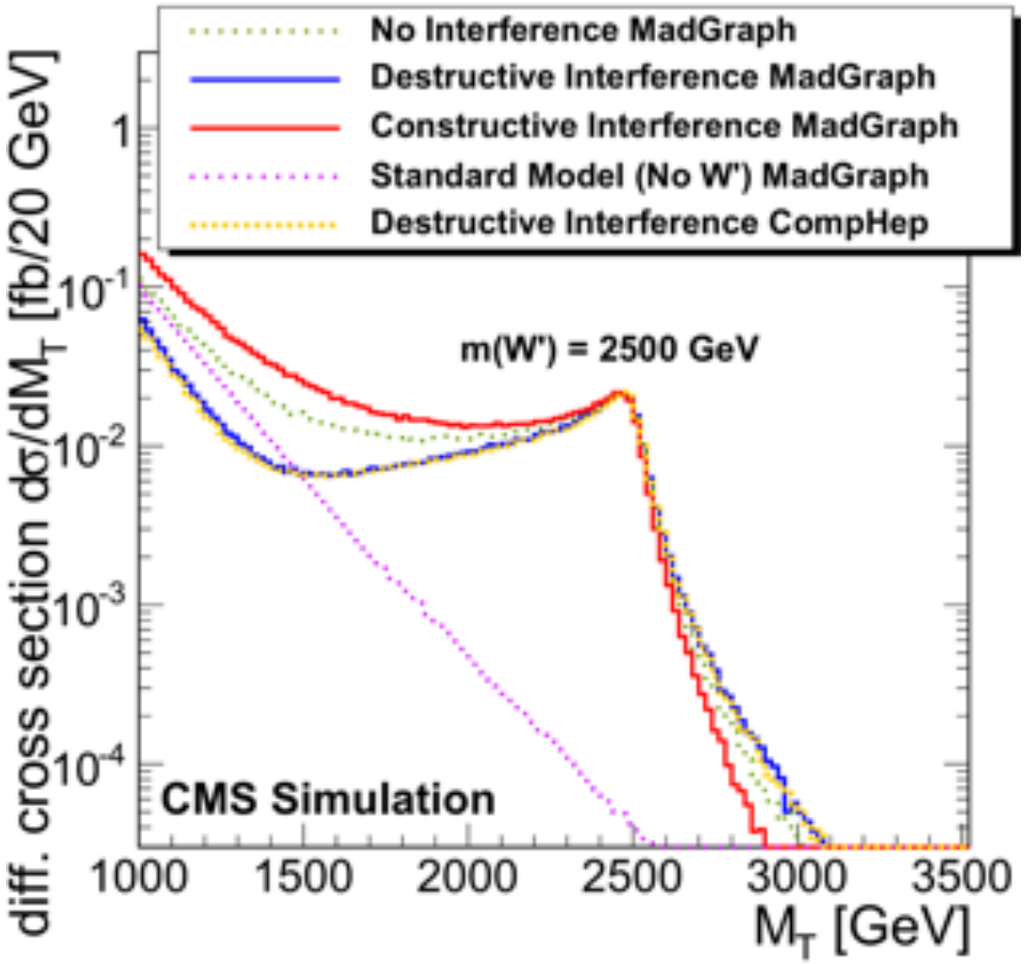
CMS Experiment at LHC, CERN
Data recorded: Sun Jul 12 10:33:05 2015 CEST
Run/Event: 251562 / 528500442
Lumi section: 605

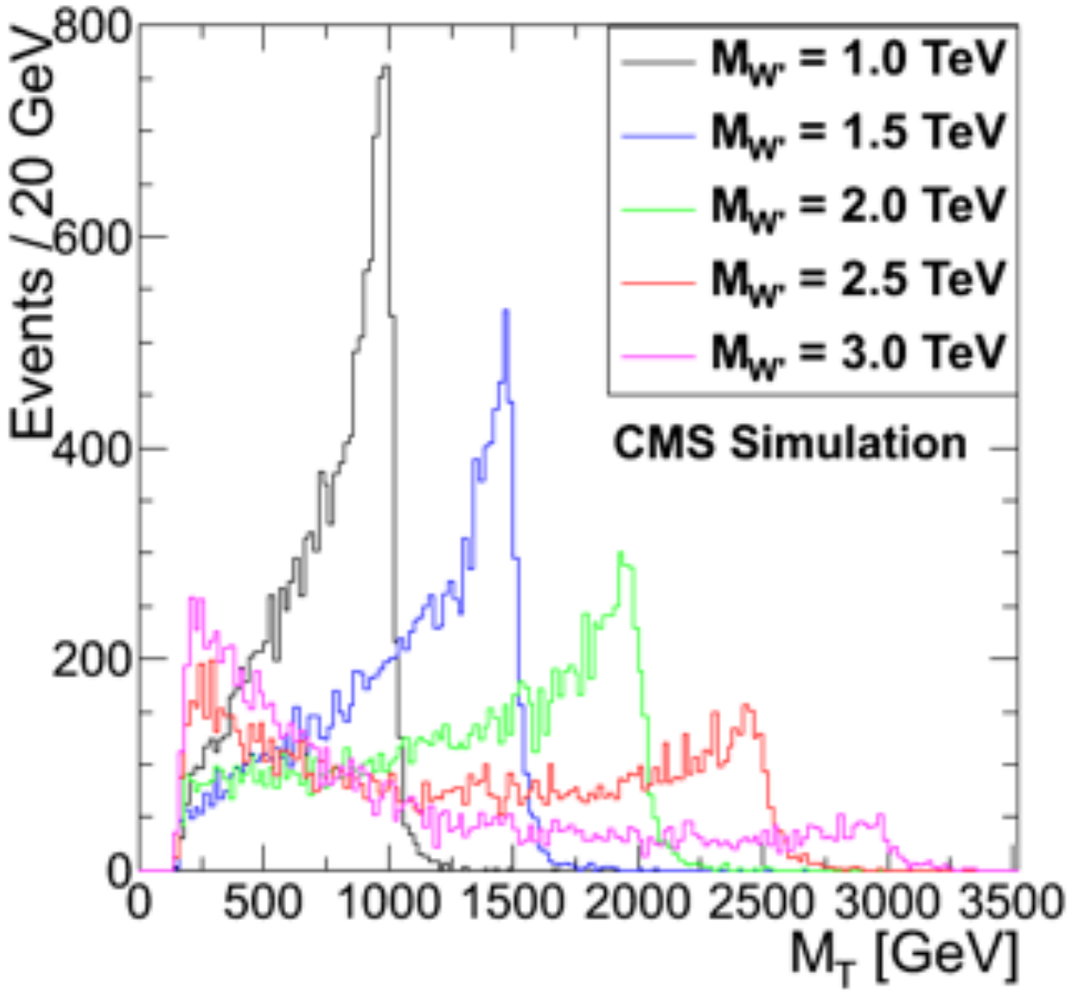






New W-like Boson



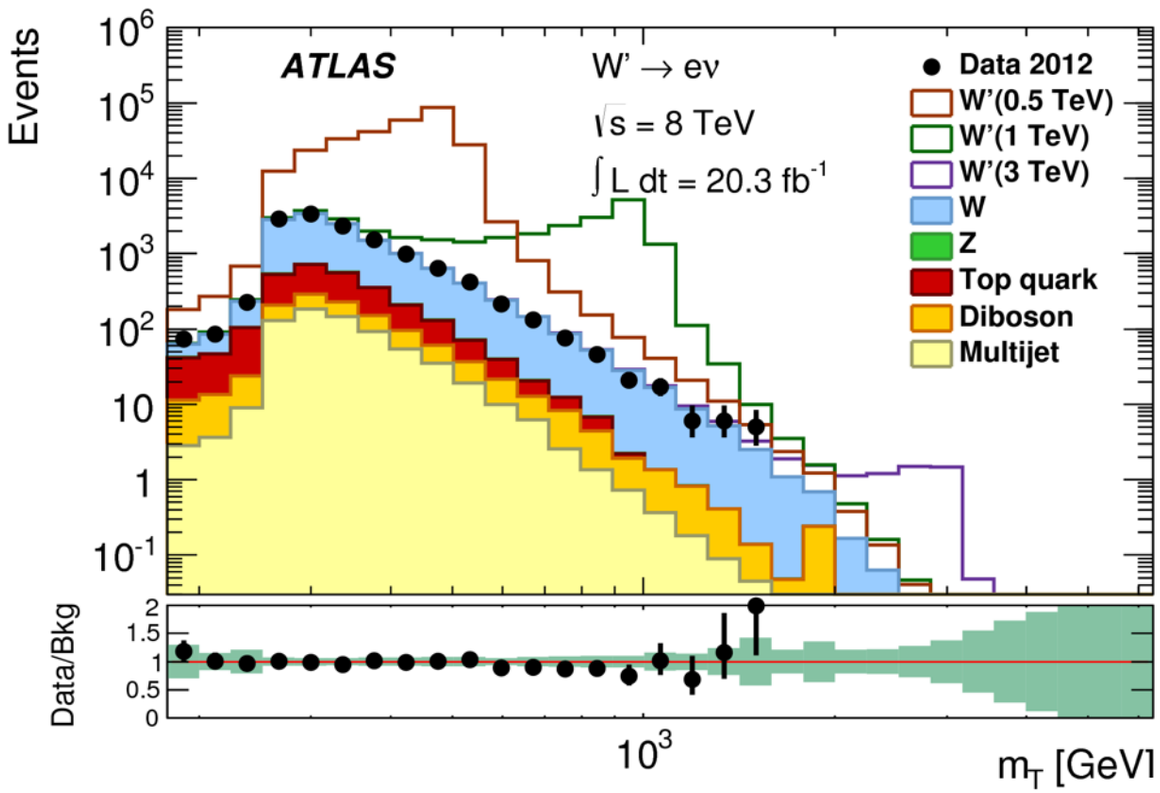


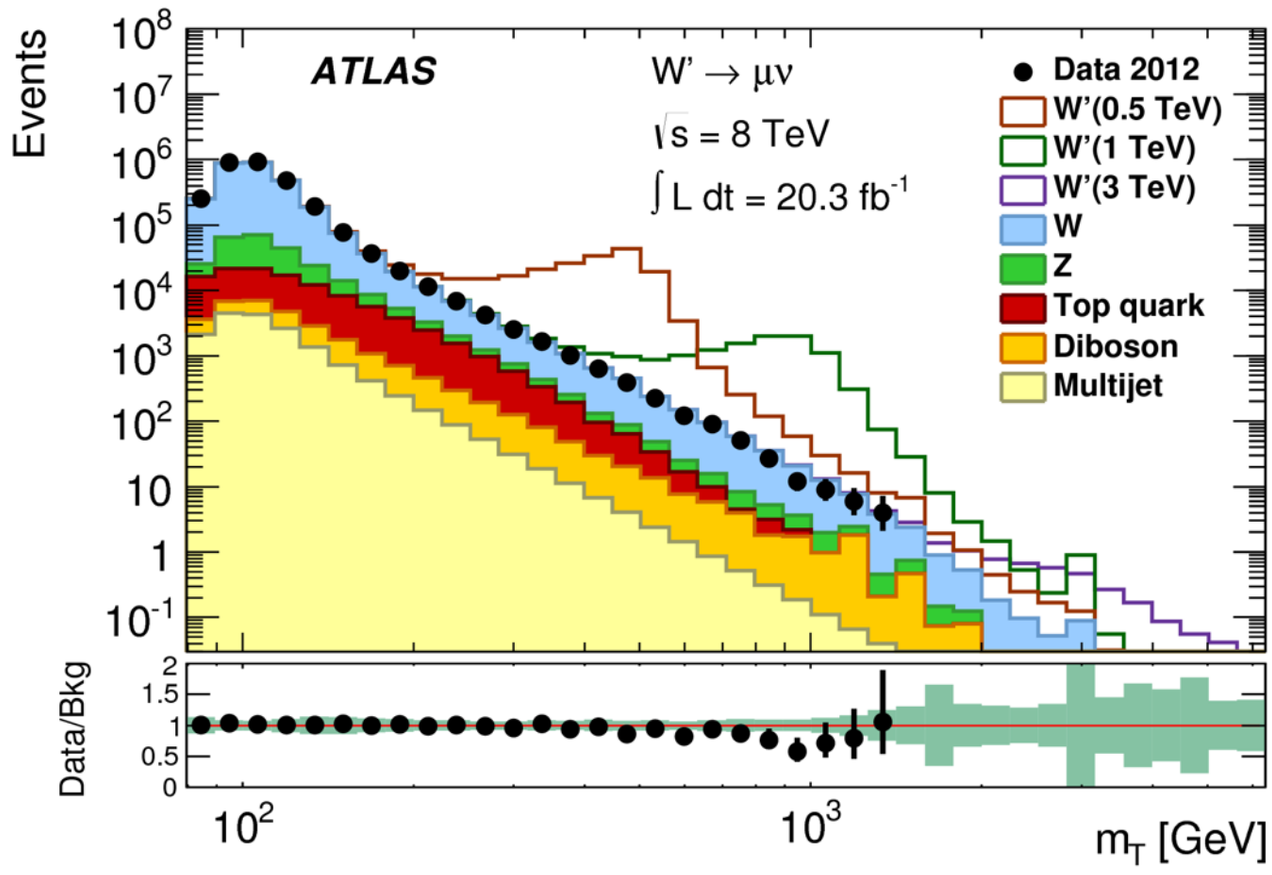
- Look for heavy W-like Jacobian peak in transverse mass

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

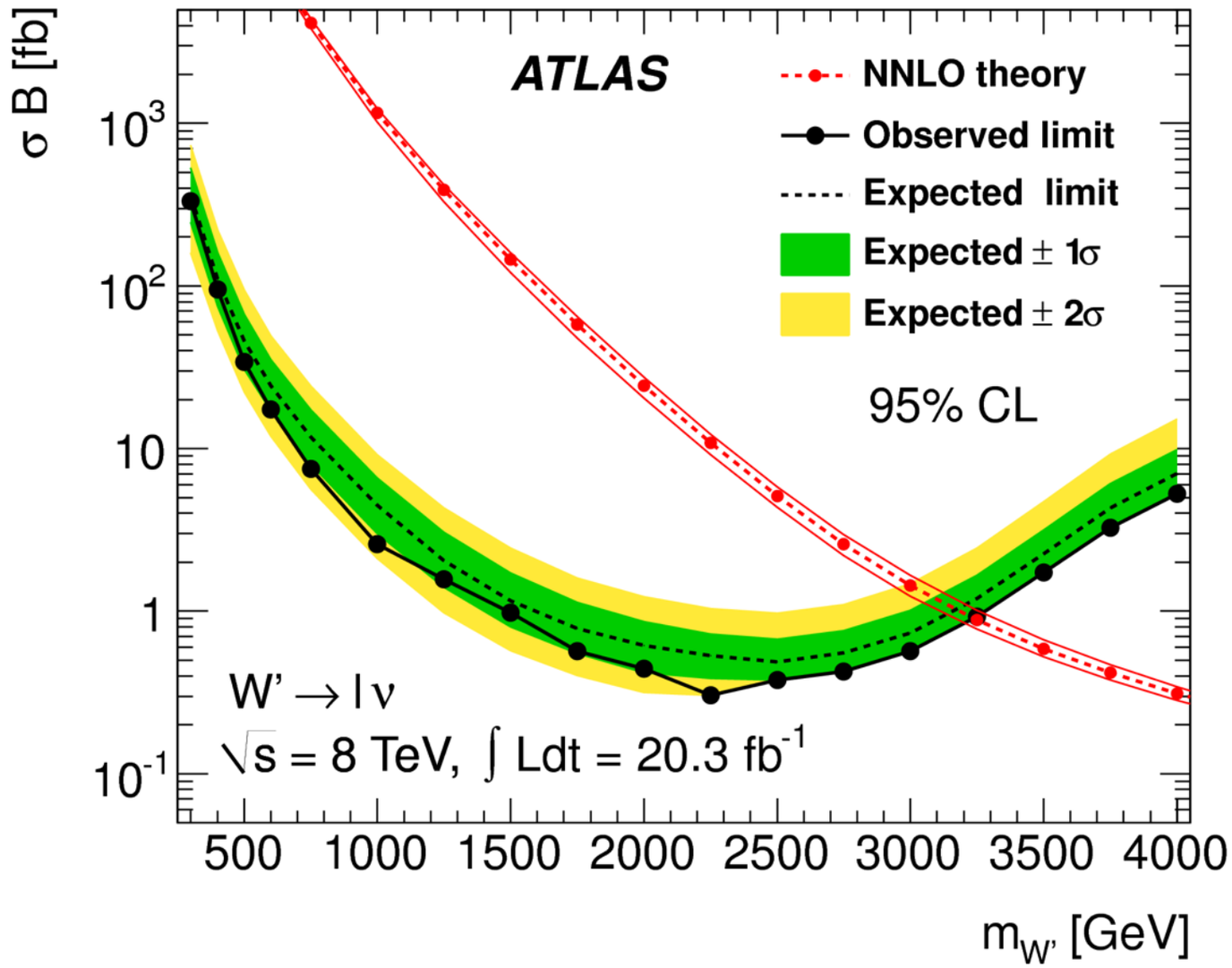
- Dominant background: W production in Standard Model
- Now also take into account interference with SM

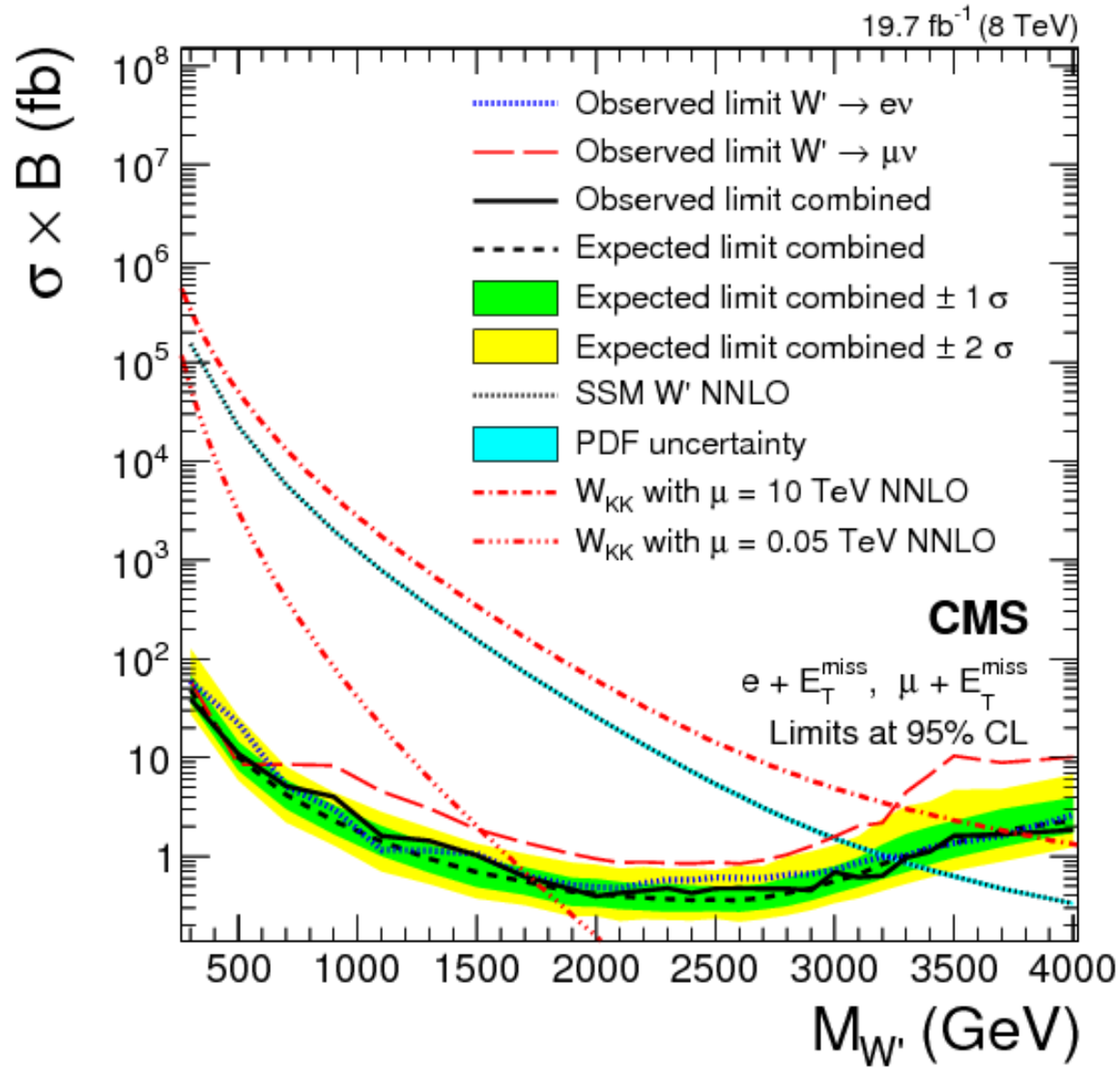
LEPTON + MET SPECTRUM



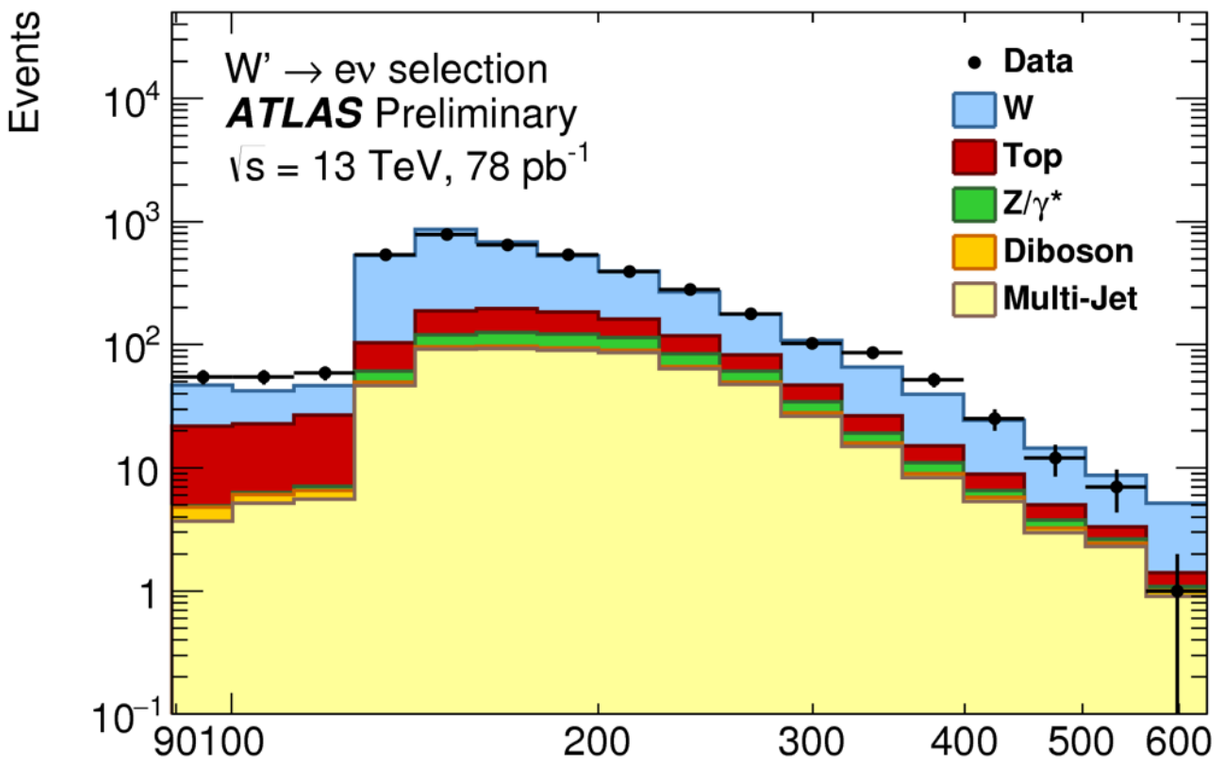


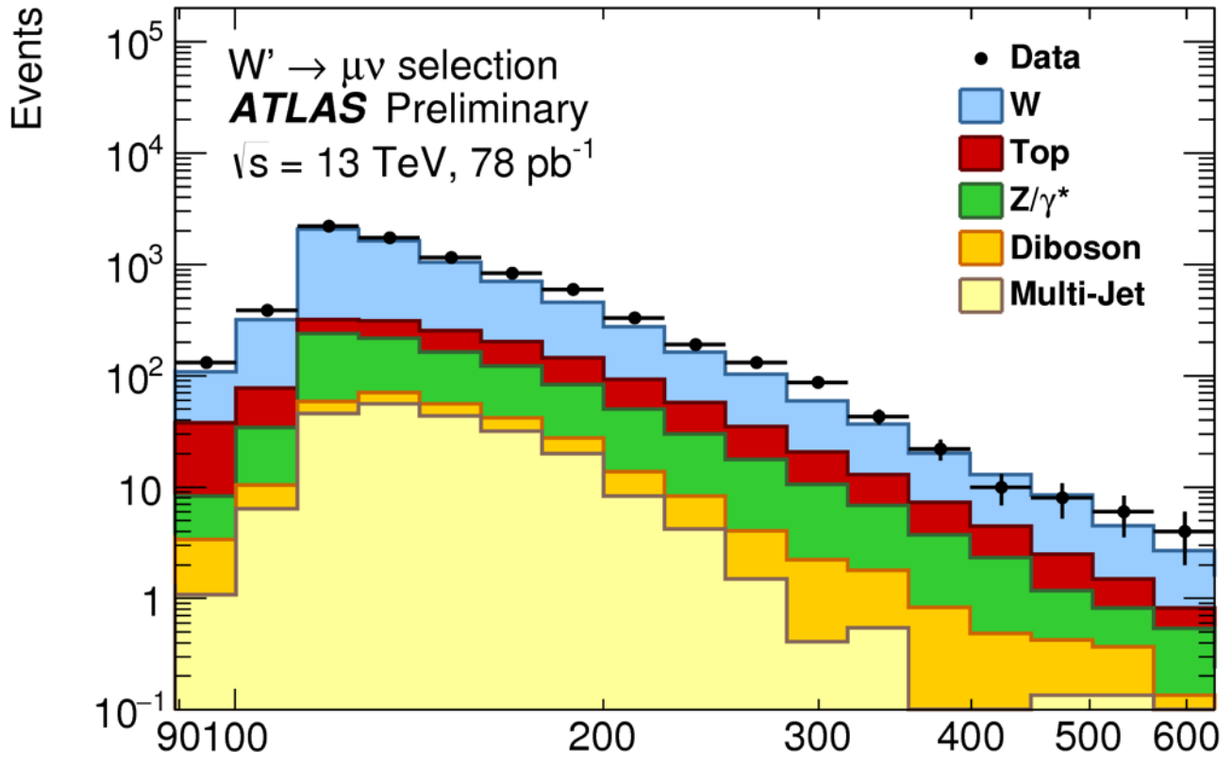
W' Exclusion Limit





W’ @ 13 TeV


W’ → eν selection
ATLAS Preliminary
√s = 13 TeV, 78 pb-1
Data
W
Top
Z/γ*
Diboson
Multi-Jet
Events
Transverse mass [GeV]


W’ → μν selection
ATLAS Preliminary
√s = 13 TeV, 78 pb-1
Data
W
Top
Z/γ*
Diboson
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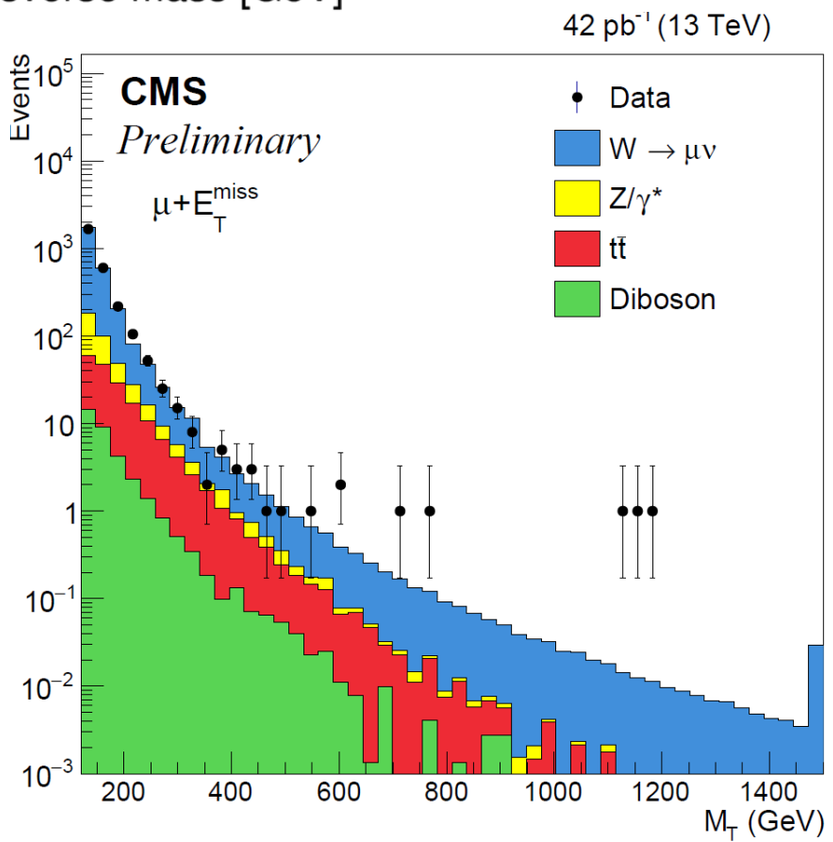
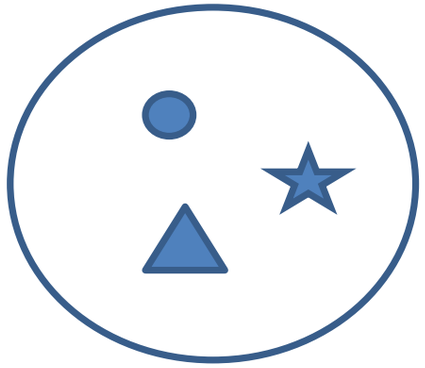
Events
Transverse mass [GeV]


42 pb-1 (13 TeV)
CMS
Preliminary
μ+E_T^miss
Data
W → μν
Z/γ*
tt̄
Diboson
Events
M_T (GeV)

COMPOSITENESS

Fermion substructure (Compositeness)

?



Quarks and leptons are probed to be elementary up to scales of 10^{-15} m or TeV

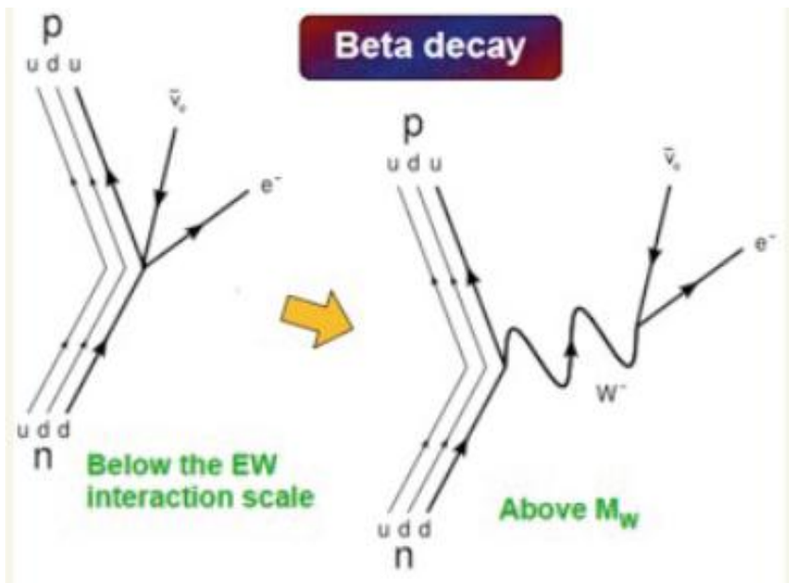
Maybe substructure? Constituents = "preons". New strong gauge (metacolor) interaction of scale Lambda Λ is introduced.

Pati & Salam, PRD 10 (1974), 2500 citations

May address open questions:

- Replication of SM families
- Their complex pattern of masses and mixing angles
- Large number of fundamental particles

Concept similar to Fermi's theory of beta decay

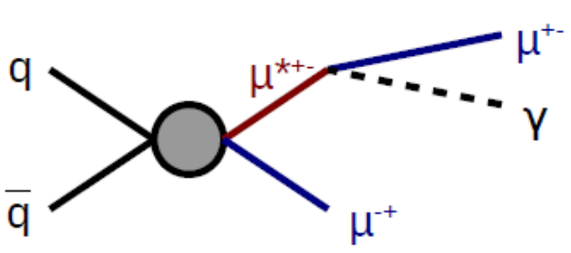


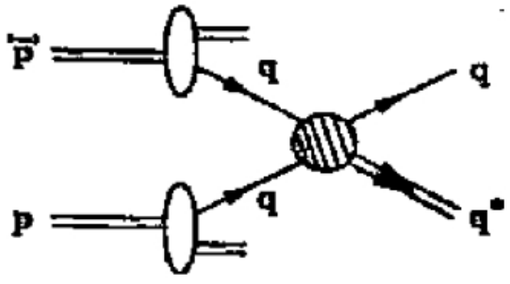
PROBING COMPOSITENESS

Excited leptons and quarks

ℓ, ℓ^*, ℓ^{**} , …. **q, q*, q****

- Sort out by mass (or spin), sharing flavor with corresponding SM particle
- Direct evidence for fermion substructure → rich spectrum of excited states
- Known ℓ,q regarded as ground states





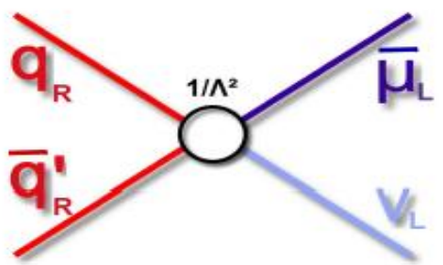
Search channels in CMS

eeγ, μμγ

q*→qg (dijet)

q*Z→Z→μμ

4-fermion contact interaction (CI) below compositeness scale Λ



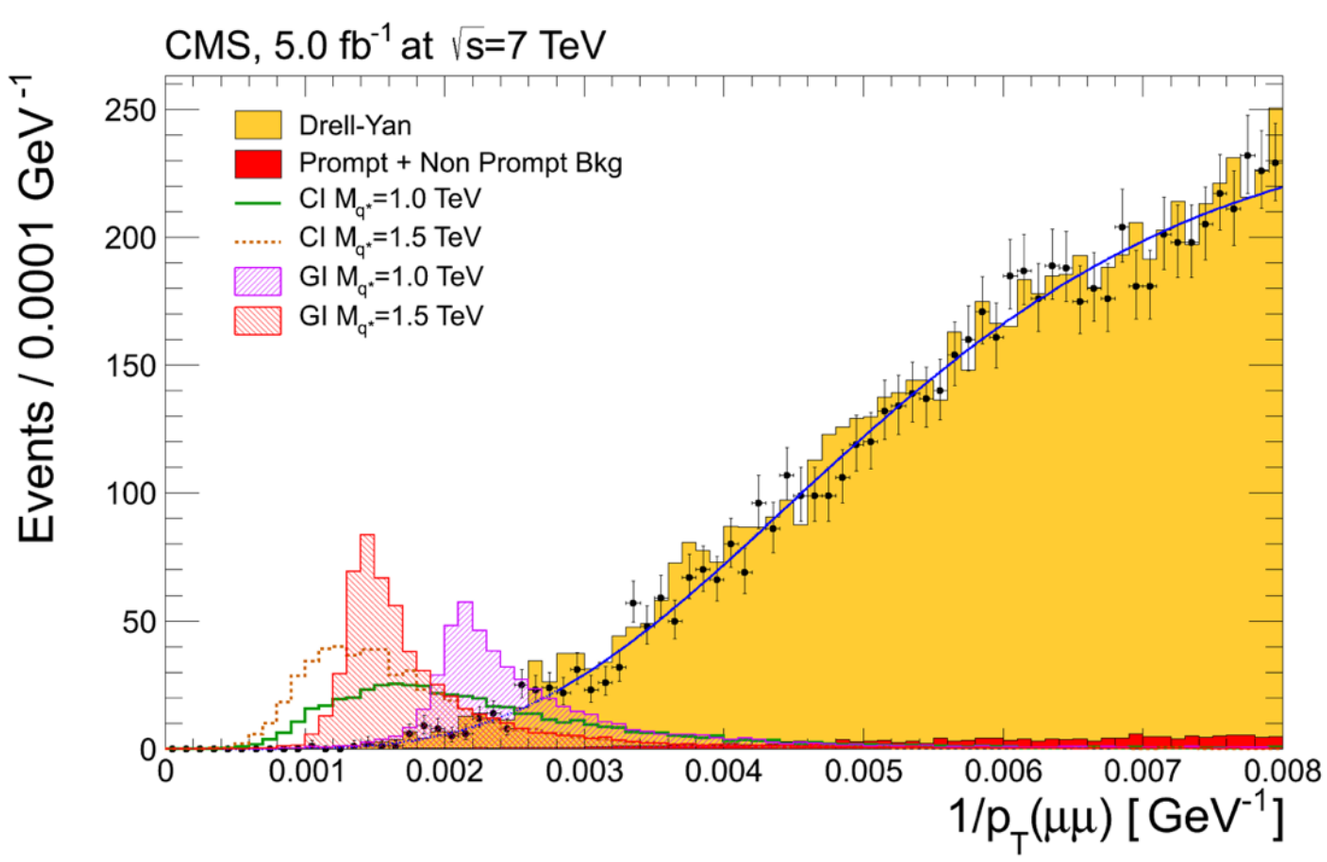
ℓ **jet**

ℓ **jet**

Search channels: μν, μμ, jj

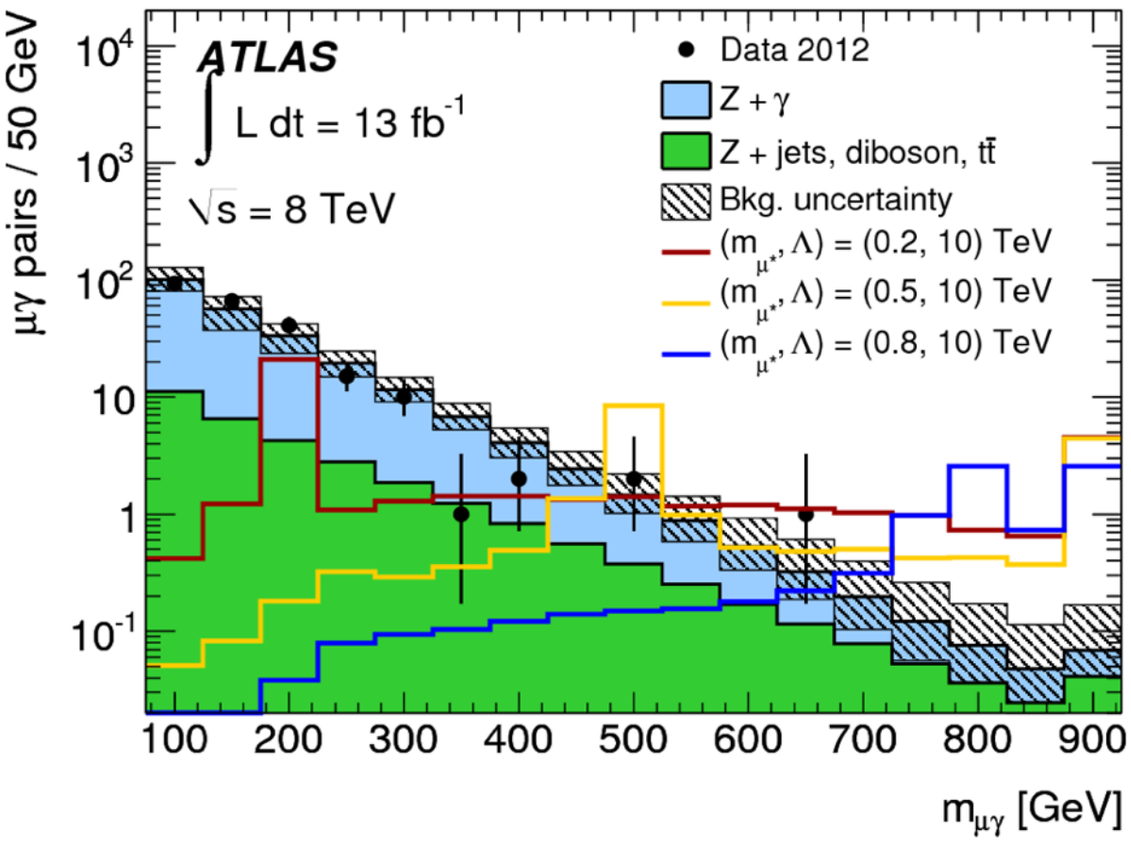
COMPOSITENESS AND CONTACT INTERACTION

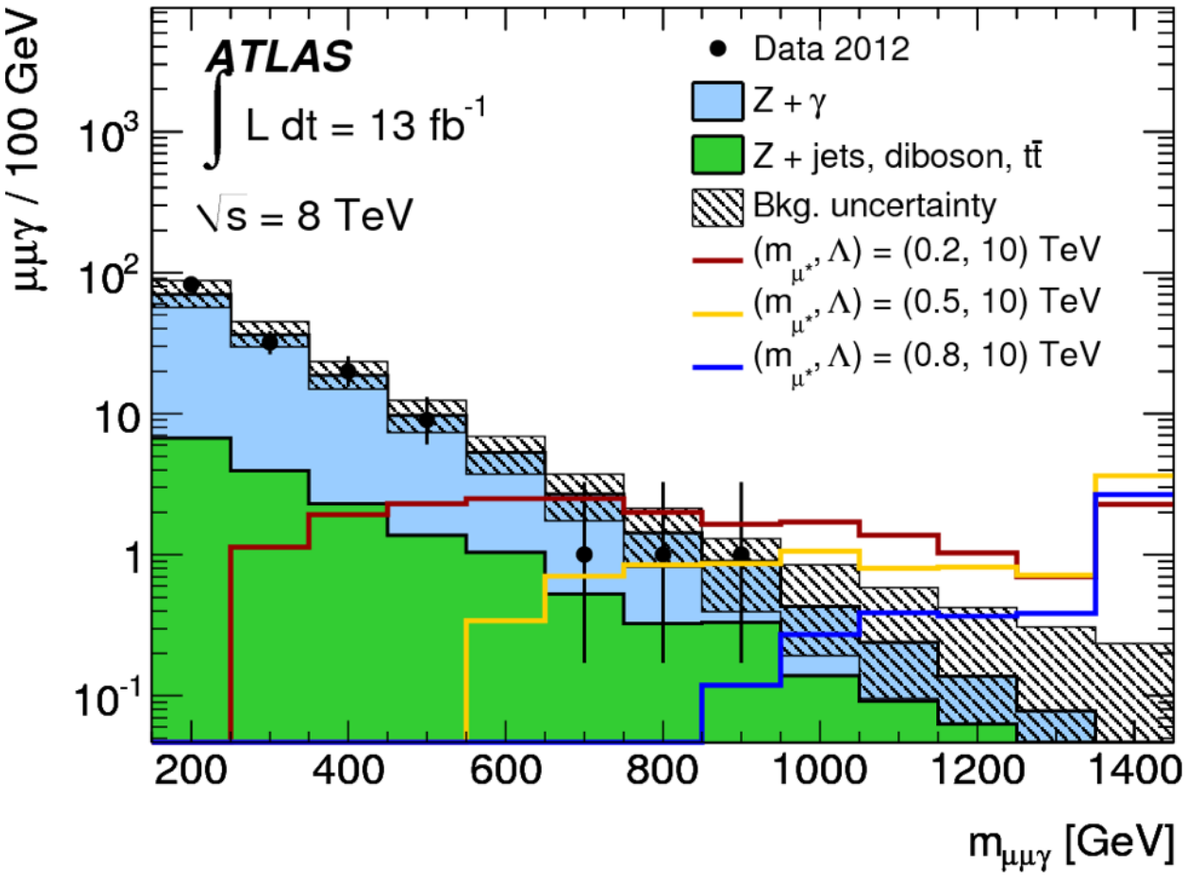
- Excited quarks and leptons
- Both leptonic and hadronic states
  - lepton + photon (l* -> l + gamma)
  - 2-jet (q* -> q glu)
  - boosted Z spectrum in q* -> q Z
- Contact interaction
  - di-jet angular analysis
  - re-interpretation of di-lepton
  - re-interpretation of W'



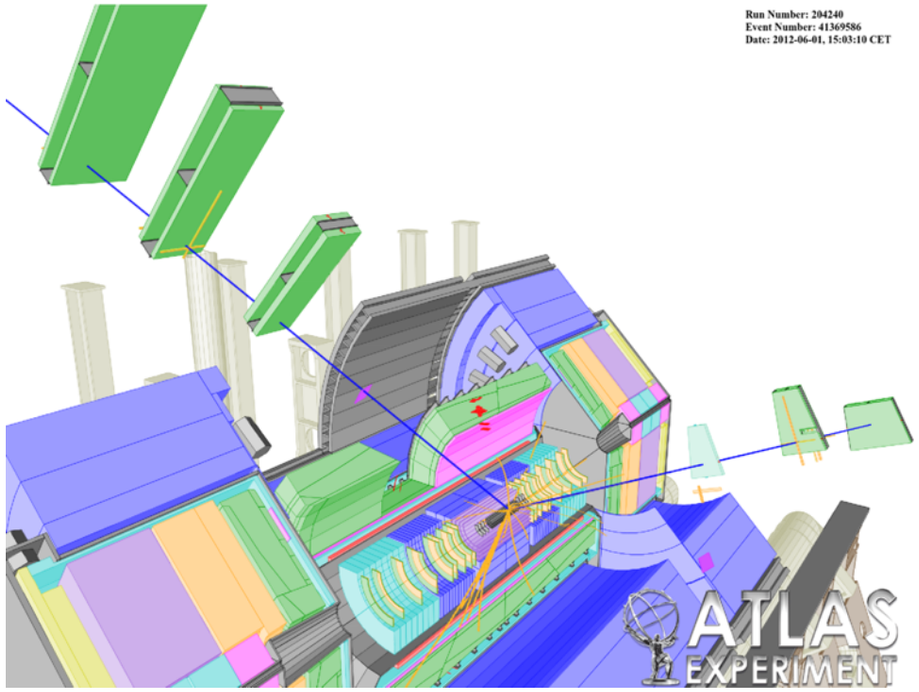
COMPOSITE LEPTONS

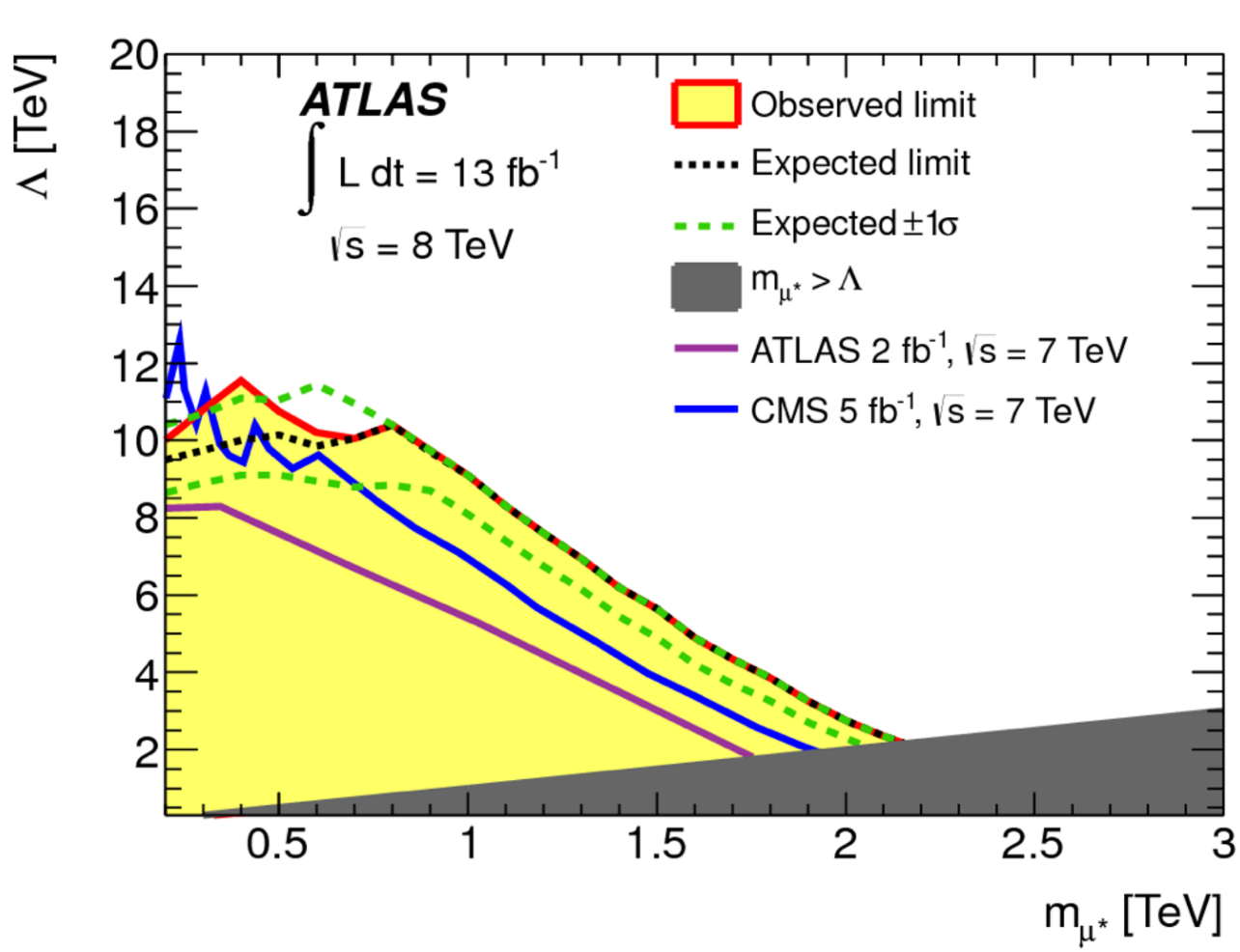
$$\mathcal{L}_{\text{contact}} = \frac{2\pi}{\Lambda^2} j^\mu j_\mu \quad , \quad j_\mu = \overline{f}_L \gamma_\mu f_L + \overline{f}^*_L \gamma_\mu f^*_L + \overline{f}^*_L \gamma_\mu f_L + h.c.$$





EXCLUSION OF COMPOSITE LEPTON

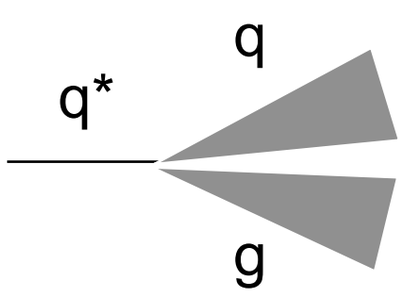




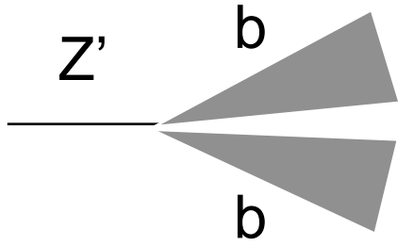
EXOTIC HADRONIC FINAL STATES

S-channel production

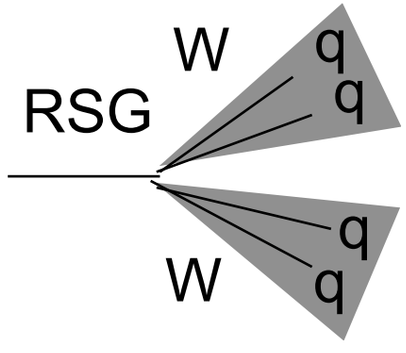
dijets



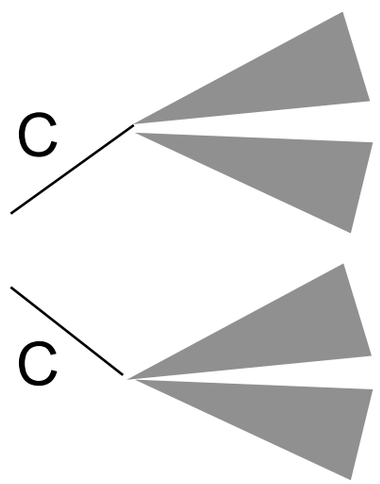
b-tagged dijets



W/Z-tagged dijets

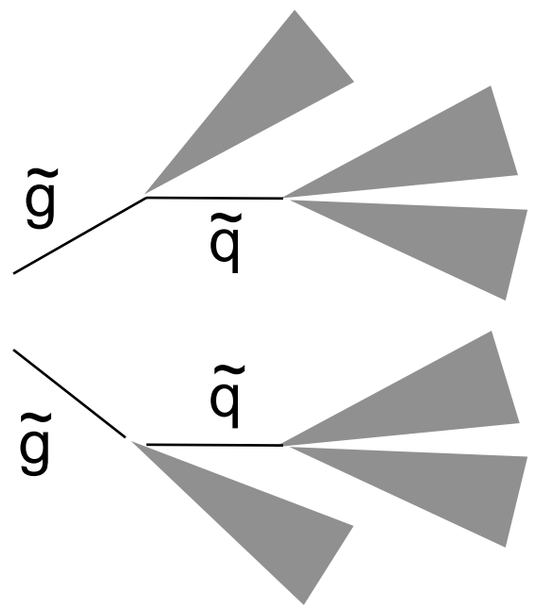


4 jets



Pair production

6 jets



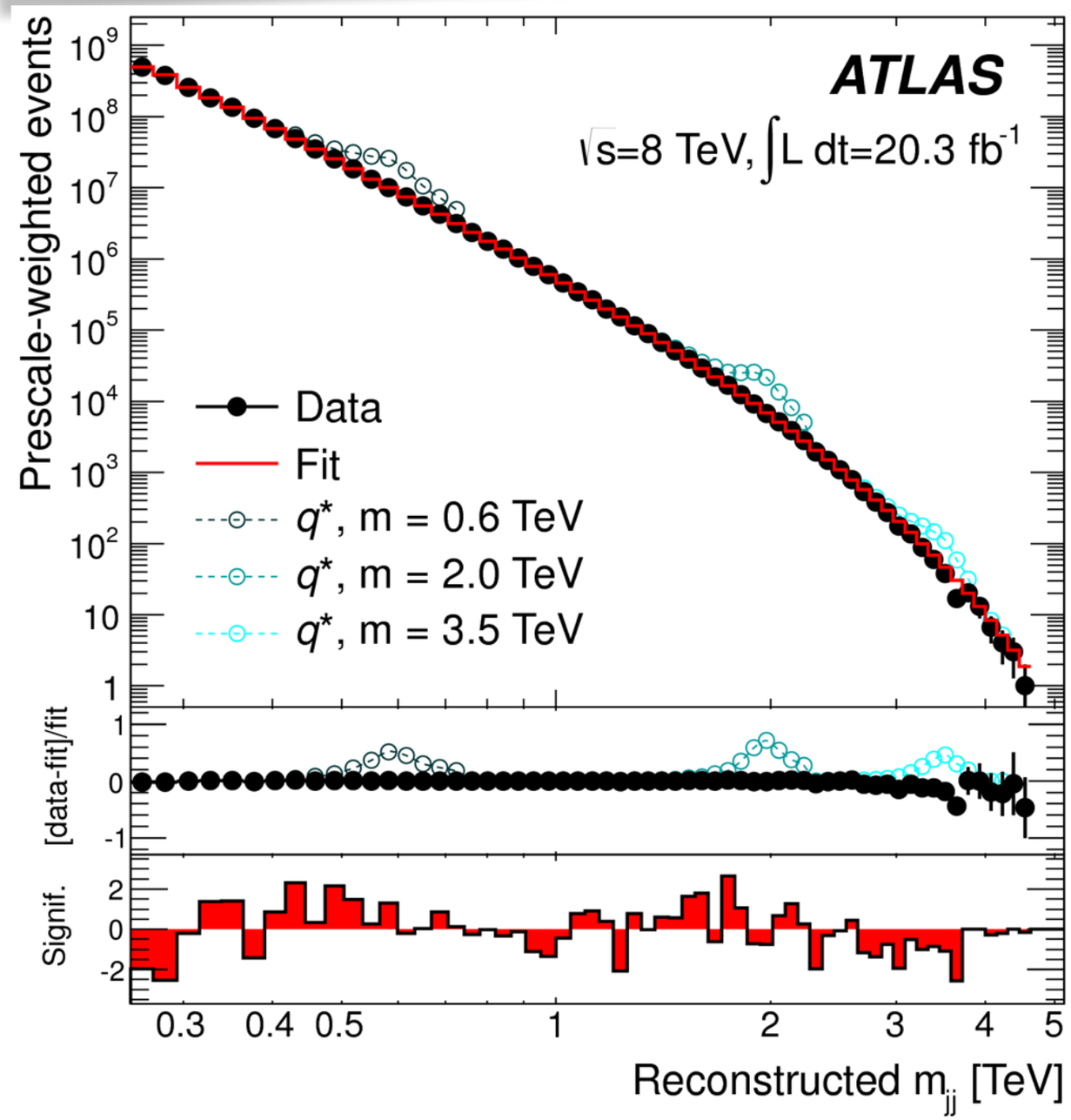
- Studied in CMS (so far)
- String resonances, S (qq,qg,gg)
- Scalar diquarks, D (qq)
- Excited quarks, q* (qg,qW,qZ)
- Axigluons, A (qq)
- Color-octet colorons, C (qq, qqqq)
- Color-octet scalar, S8 (gg,bb)
- W‘ bosons (qq,WZ)
- Z‘ bosons (qq,bb,tt)
- RPV SUSY gluinos (qqqqqq)
- RS gravitons (qq,gg,WW,ZZ)

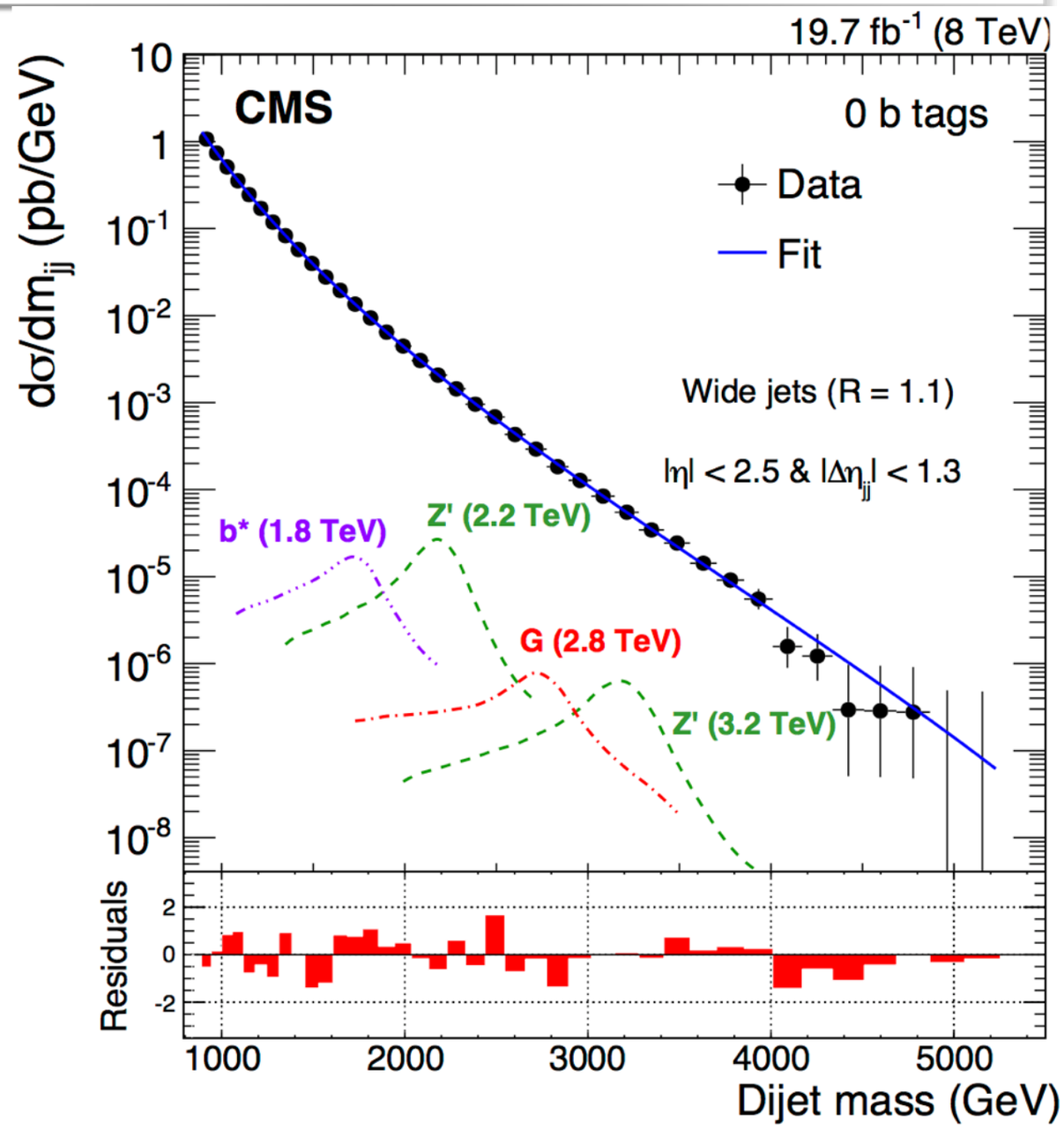
Hadronic inspired

EWK inspired

Gravitation inspired

DIJET SPECTRUM

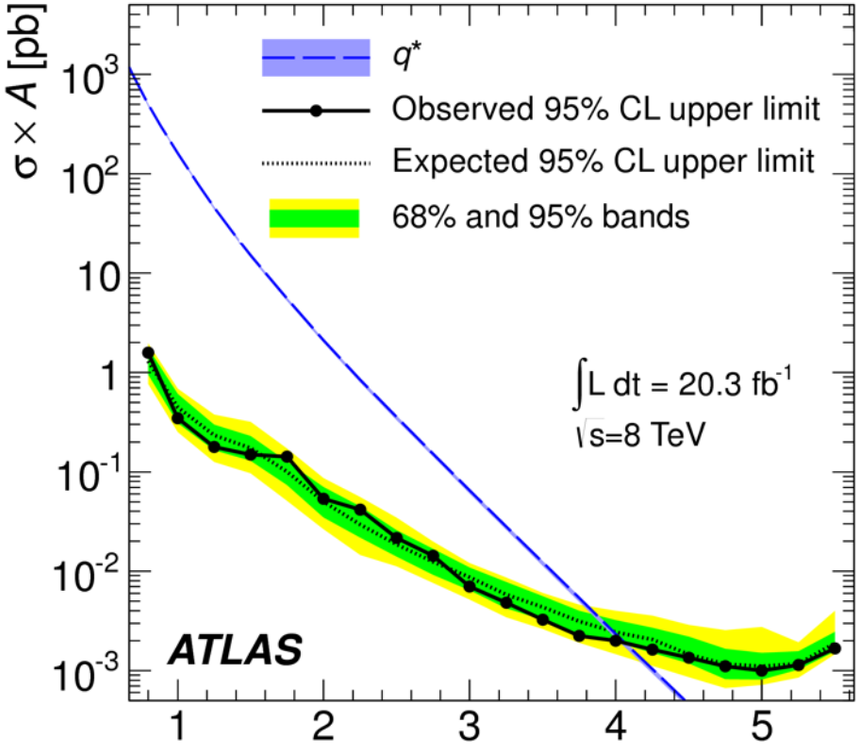


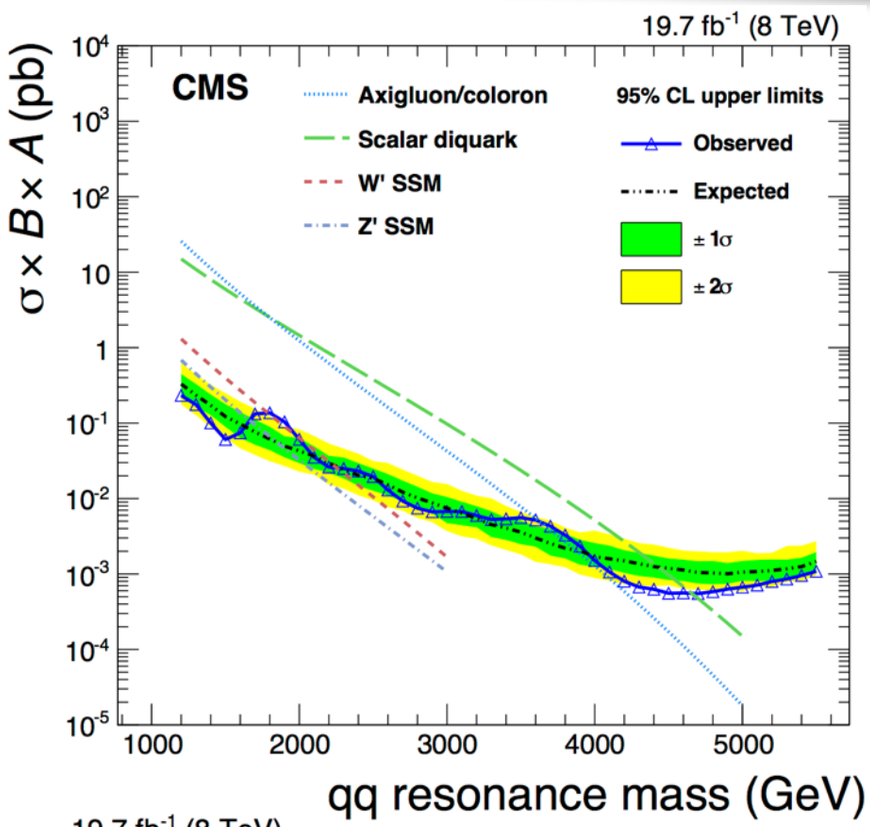


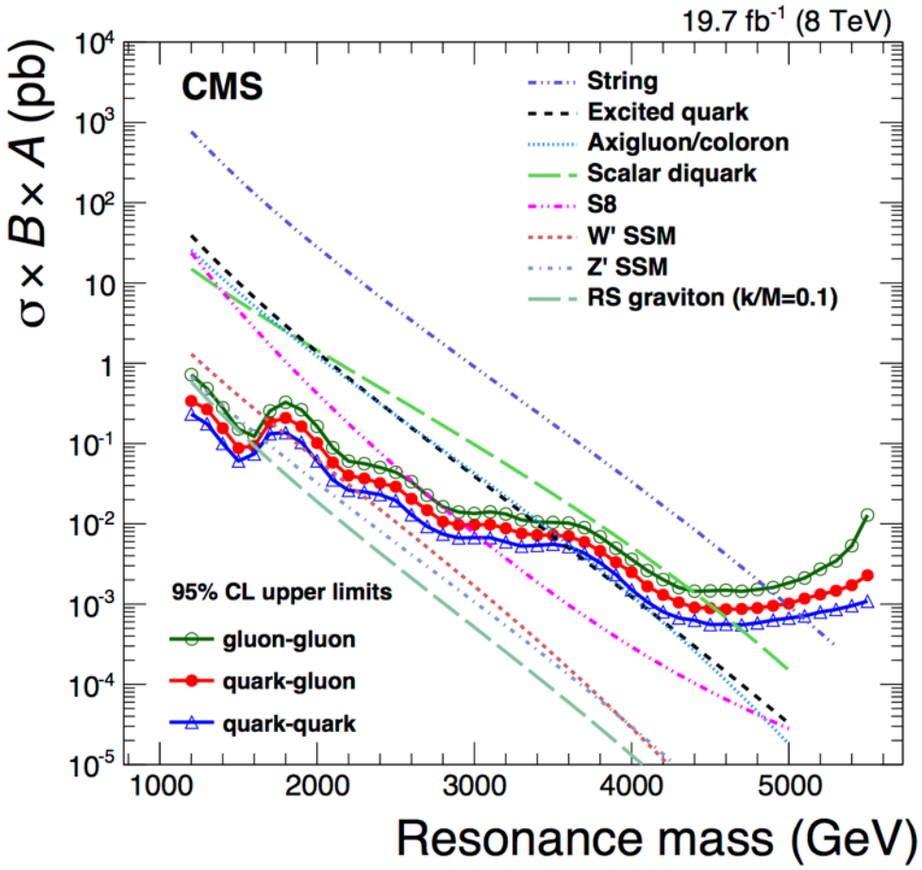
- Lower threshold fixed by trigger requirements on single jets ~500 GeV
- Fit data to define background shape
  - no dependence on MC prediction and modeling

$$\frac{\mathrm{d}\sigma}{\mathrm{d}m_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)}}$$

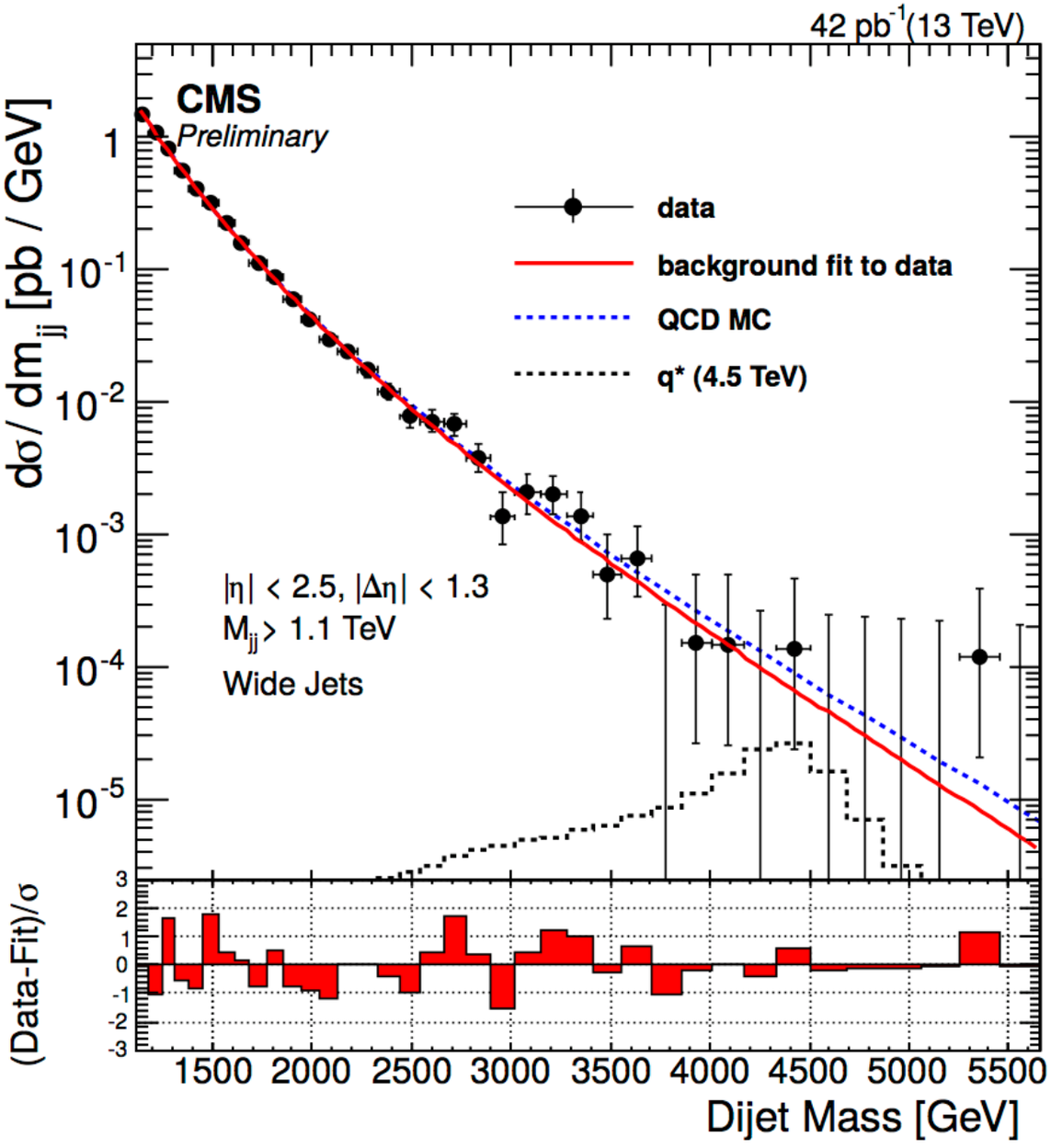
DIJET EXCLUSION LIMITS

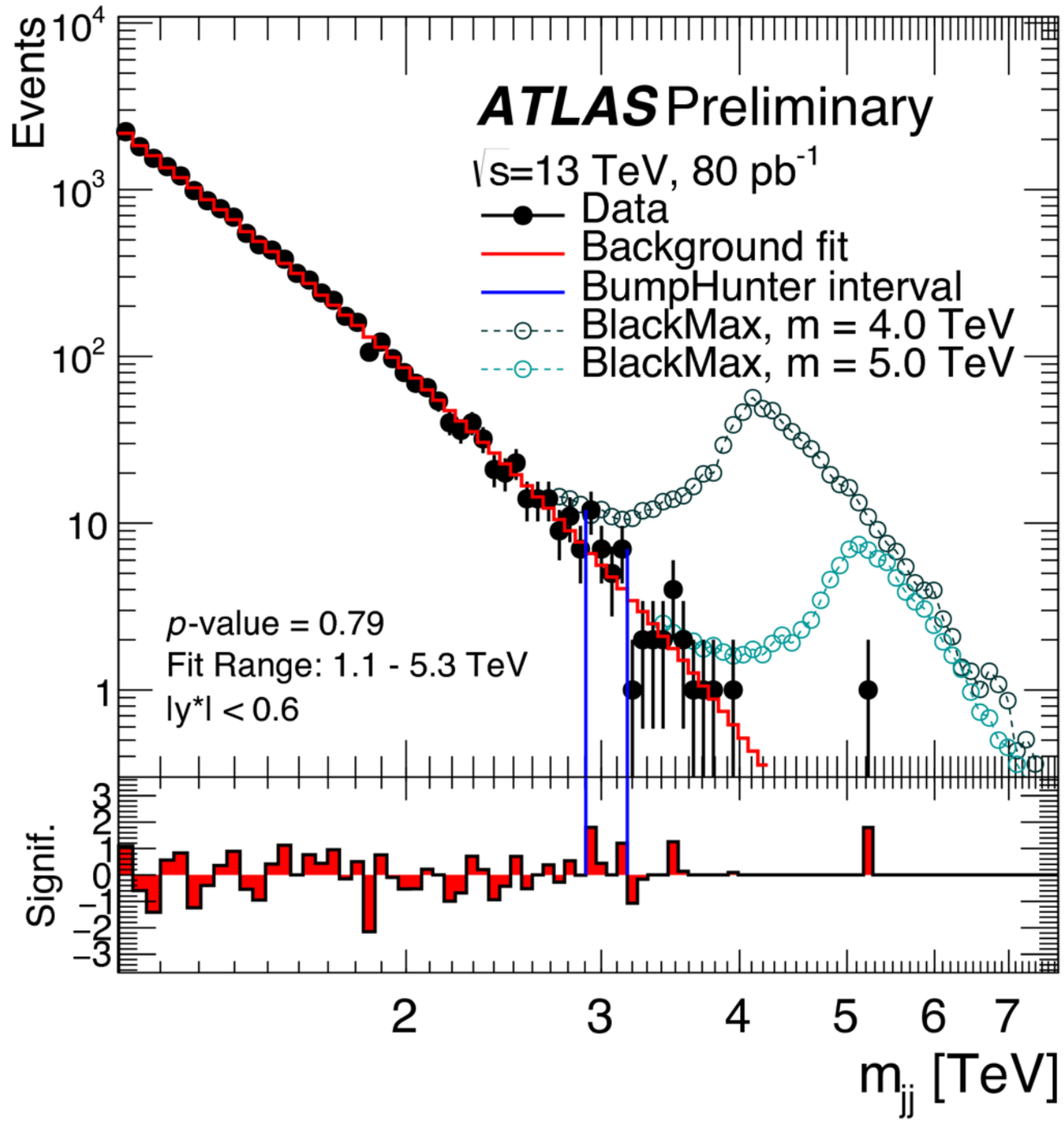




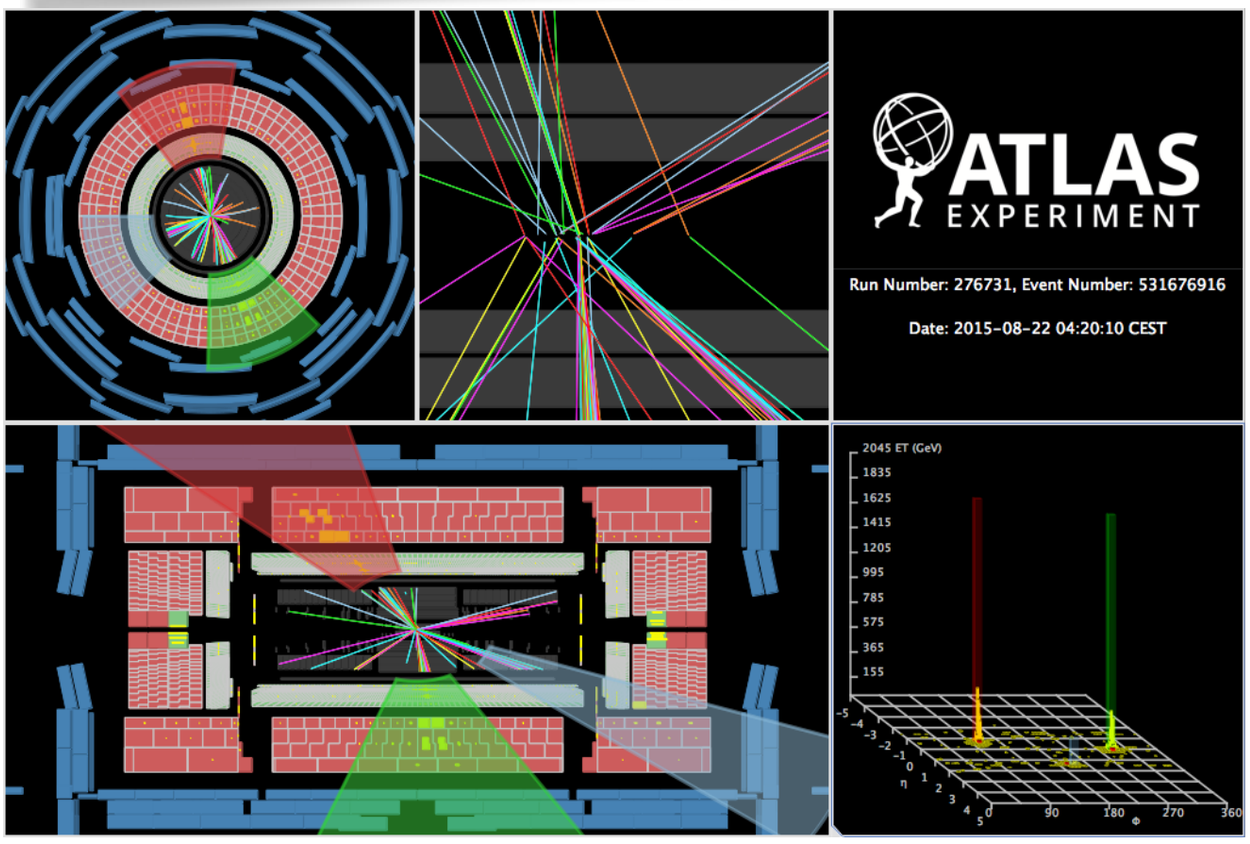


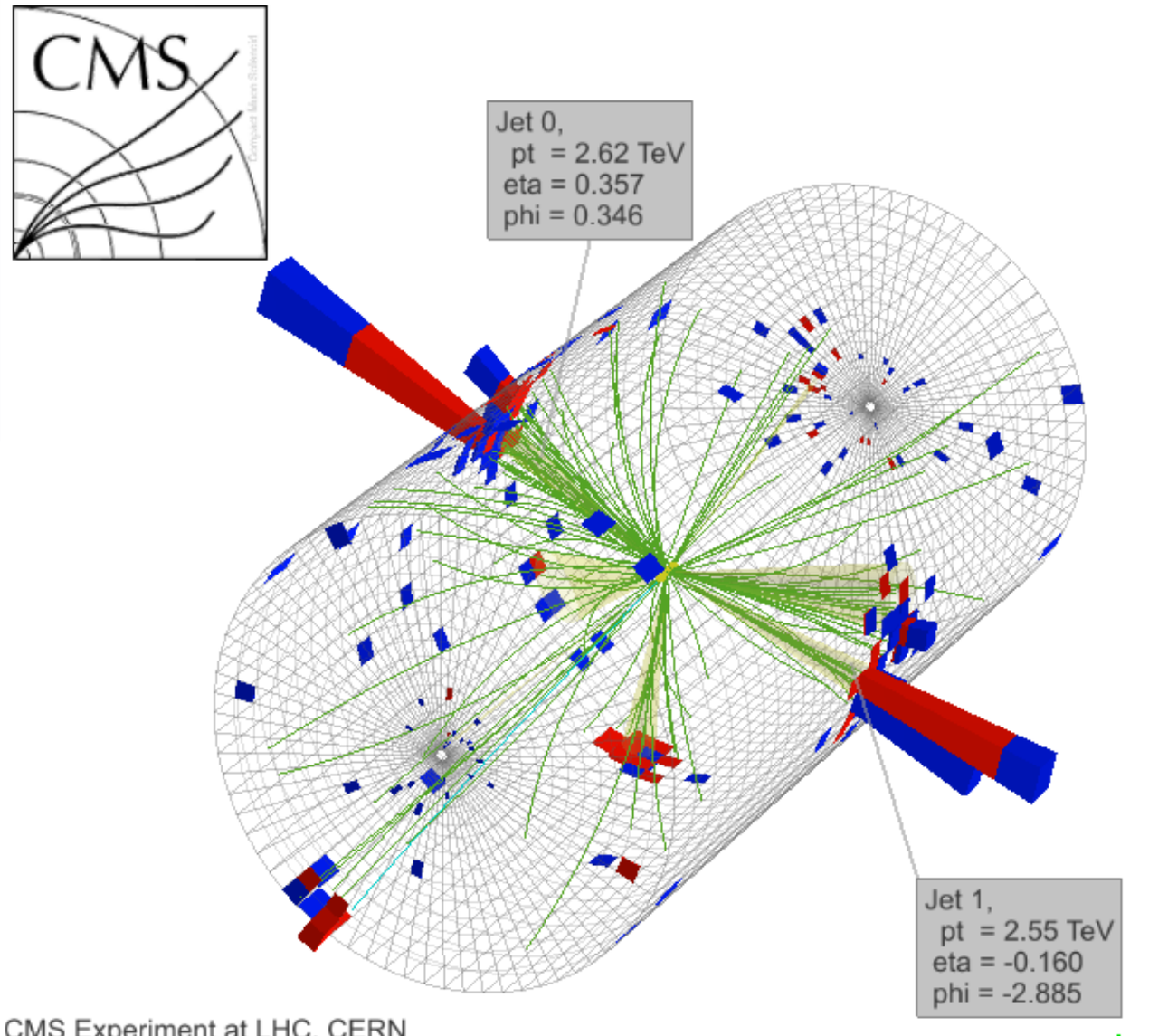
DIJET @ 13 TEV


42 pb^{-1}(13 TeV)
CMS
Preliminary
data
background fit to data
QCD MC
q* (4.5 TeV)
|η| < 2.5, |Δη| < 1.3
M$_{jj}$> 1.1 TeV
Wide Jets
dσ/ dm$_{jj}$ [pb / GeV]
(Data-Fit)/σ
Dijet Mass [GeV]

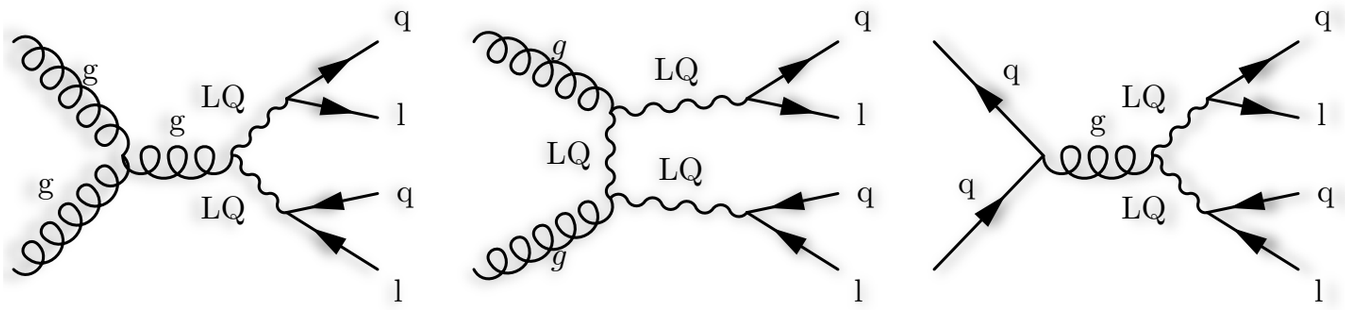

ATLAS Preliminary
√s=13 TeV, 80 pb^{-1}
Data
Background fit
BumpHunter interval
BlackMax, m = 4.0 TeV
BlackMax, m = 5.0 TeV
p-value = 0.79
Fit Range: 1.1 - 5.3 TeV
|y*| < 0.6
Events
Signif.
m$_{jj}$ [TeV]

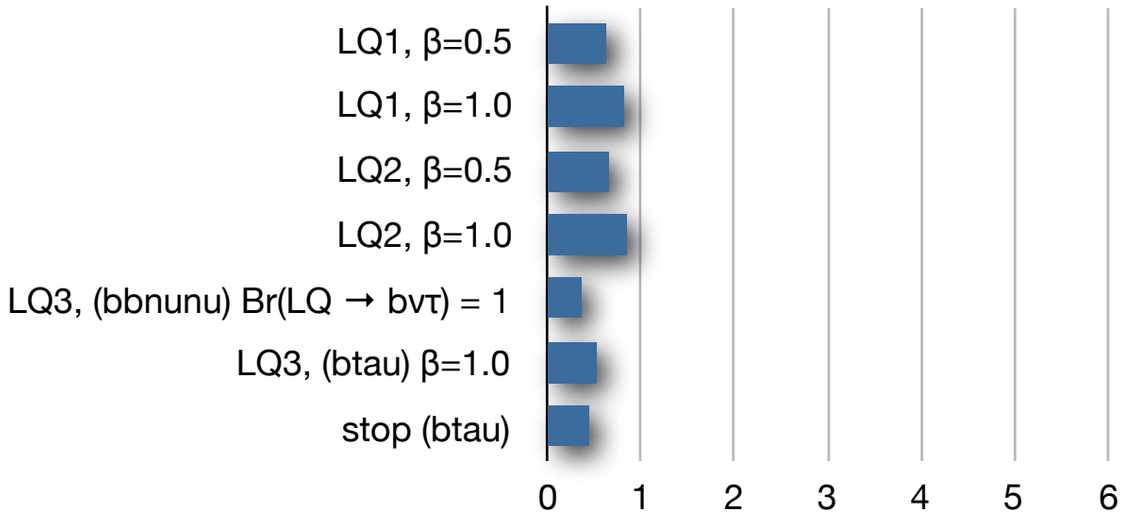
DIJET @ 13 TEV


ATLAS
EXPERIMENT
Run Number: 276731, Event Number: 531676916
Date: 2015-08-22 04:20:10 CEST
2045 ET (GeV)
1835
1625
1415
1205
995
785
575
365
155

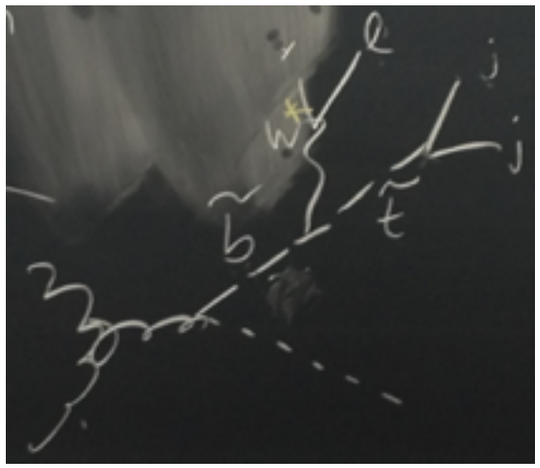

CMS
Jet 0,
pt = 2.62 TeV
eta = 0.357
phi = 0.346
Jet 1,
pt = 2.55 TeV
eta = -0.160
phi = -2.885
CMS Experiment at LHC, CERN
Data recorded: Sun Jul 12 01:52:51 2015 CDT
Run/Event: 251562 / 310157776
Lumi section: 347
Dijet Mass : 5.4 TeV

LEPTON + JETS





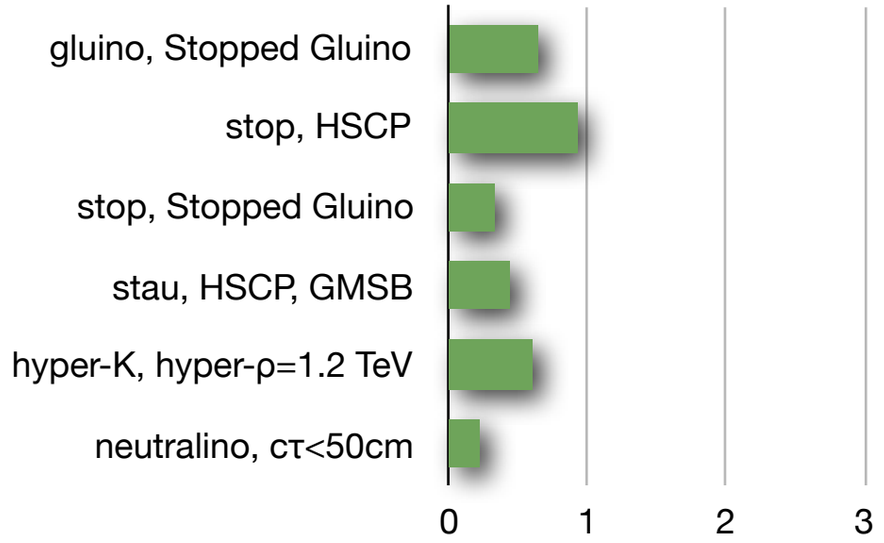
- Lepton and jets used usually for leptoquark searches
  - now also first 3rd generation searches
- Same final state sensitive also to RPV SUSY

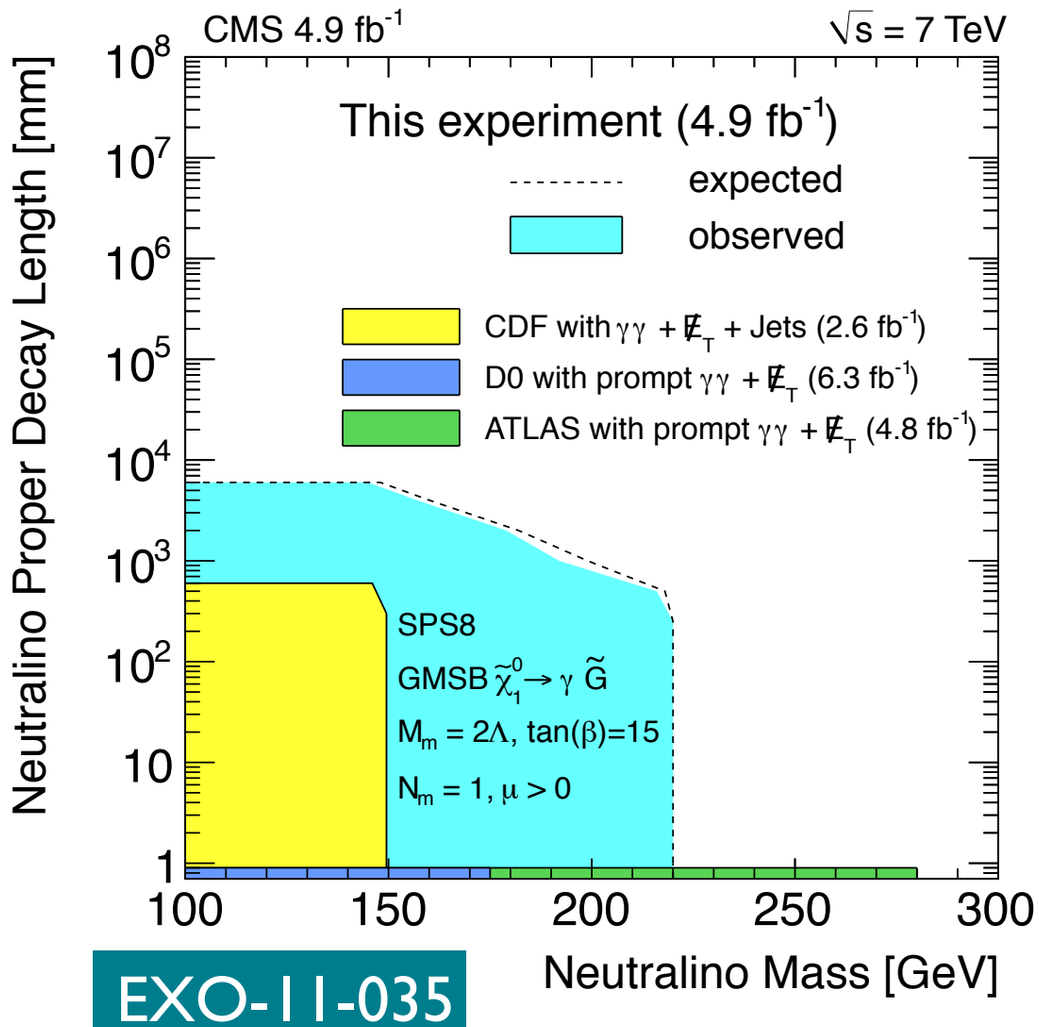


- Extending program to single LQ production and top+tau final states

LONG-LIVED PARTICLES

- Most exotic part of exotica
  - requires dedicated reconstruction, trigger, and detailed detector level understanding unlike other searches
- Heavy stable charge particles
  - slow muon-like objects
    - dE/dx, TOF, proper reco
  - also q > 1
- Stopped gluino
  - dedicated data taking conditions and understanding of beam conditions
- Fractionally charged particles
  - dE/dx in tracker
- Displaced leptons and vertices
- Displaced photons
  - first analysis using time measurement in ECAL






BLACK HOLES? REALLY?
ARE YOU KIDDING ME?

Much Ado About Nothing

- Perhaps the worst case of misleading and wrong scientific information in history prior to start of LHC
- Too much noise about non-existent dangers based on wrong assumptions by non-scientists
- No way to create an black holes in the lab
- Black hole is a term used both for astrophysical objects and solution to a pure mathematical problem
- Dedicated safety assessment group has studied and release a detailed summary
  - Review of the Safety of LHC Collisions: http://arxiv.org/abs/0806.3414
- Of course there is no danger
- if course nothing crazy has happened
- Unfortunately none of the newspaper has reported that idiots claiming catastrophes were unreliable idiots with no scientific knowledge looking for 1-day fame

MICRO/QUANTUM BLACK HOLES

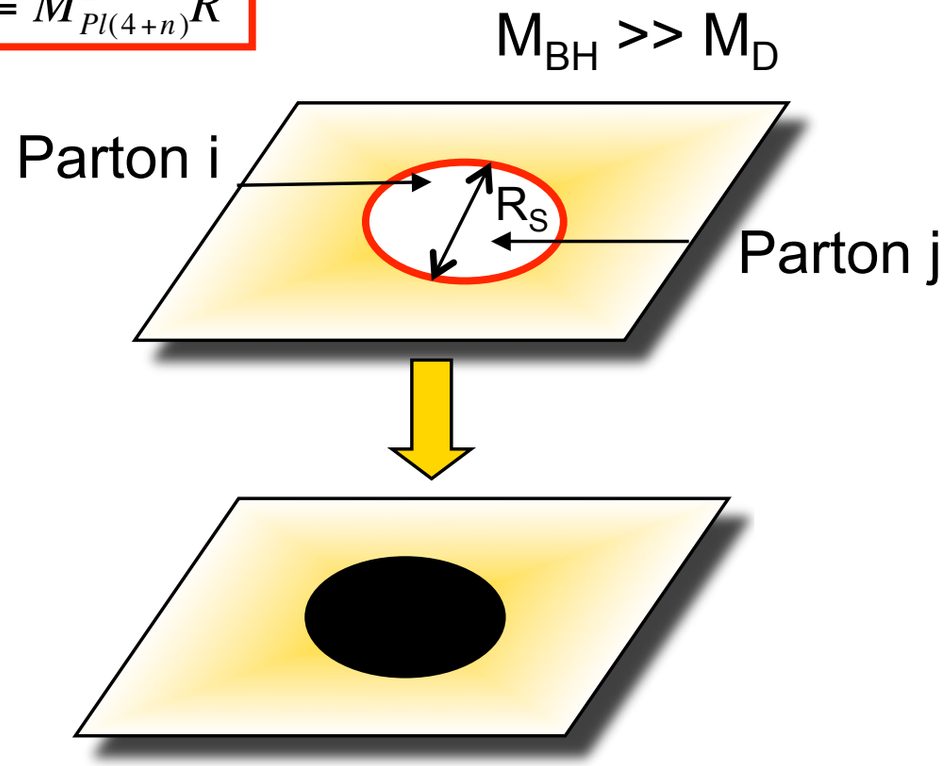
- Black Holes are a direct prediction of Einstein's general theory on relativity
- If Planck scale ~TeV region, expect Quantum Black Hole production
- Using Gauss's law with n extra dimensions $V(r) \sim \frac{M}{M_p^{n+2}} \frac{1}{r^{n+1}}$
- For small extra dimension of size R $V(r) \sim \frac{M}{M_p^{n+2} R^n} \frac{1}{r}$

- Relation between planck scale in 4D and 4+nD $M_{p(4)}^2 \sim M_p^{n+2} R^n$
- Schwarzschild radius is the radius in which a confined mass would become a black hole $r_h = \frac{1}{\sqrt{\pi} M_p} \left(\frac{M_{BH}}{M_p} \right)^{\frac{1}{n+1}} \left(\frac{8\Gamma\left(\frac{n+3}{2}\right)}{n+2} \right)^{\frac{1}{n+1}}$
  - $M_{pl} = 10^{19}$ GeV in 4D implies $r_h << 10^{-35}$ m
  - M_{pl} = TeV in 4+n D implies $r_h \sim 10^{-17}$ m
- Occasionally protons with parton center of mass energy could collide at a distance smaller than rh $M_{BH} = \sqrt{\hat{s}}$
- such collisions satisfy the black hole definition but with tiny mass

PRODUCTION AND DECAY OF BLACK HOLES

- Formation: semi-classical argument
  - Partons with impact parameter less than Schwarzchild radius $R_s(\sqrt{s})$

$$M_D^2 = M_{Pl(4+n)}^{2+n} R^n$$

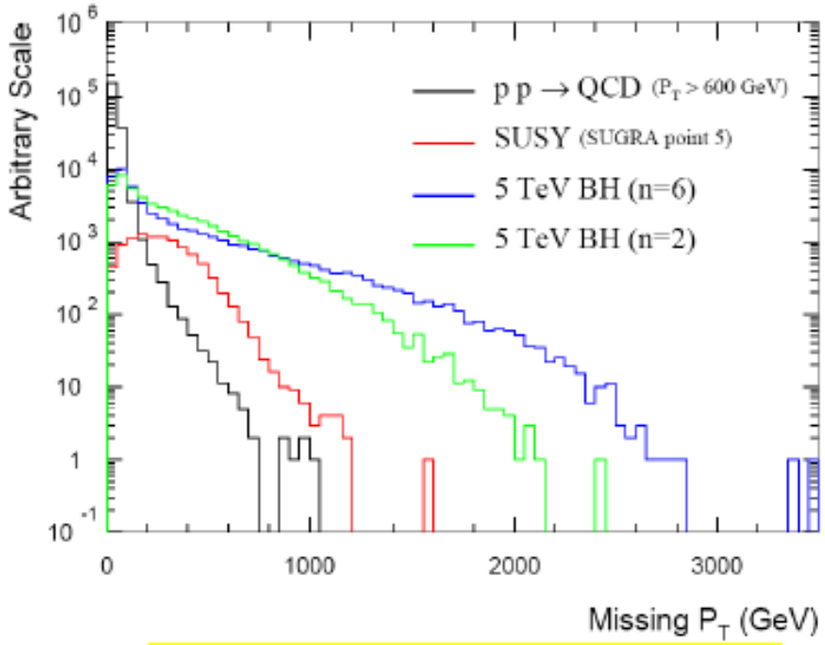


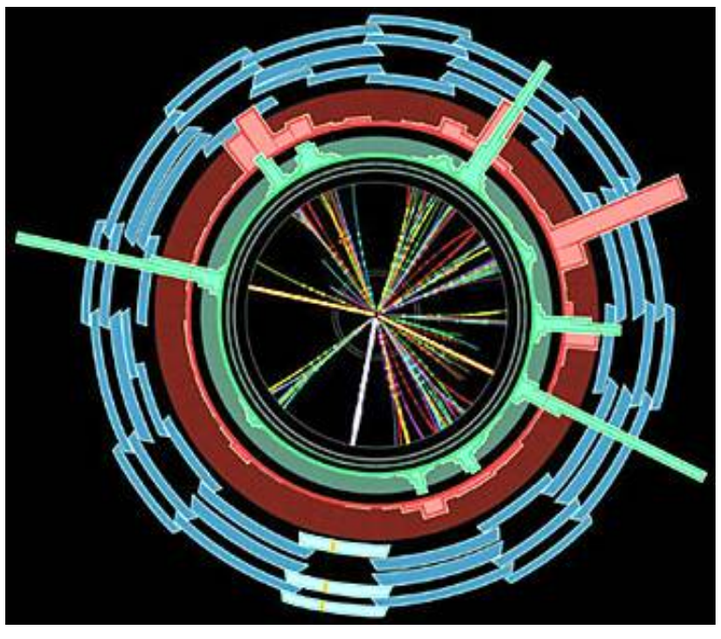
area ~ πR_S^2 ~ 1 TeV $^{-2}$ ~ 10^{-38} m^2 ~ 100 pb
Production rate of ~0.1 Hz at L = $10^{34} cm^{-2} s^{-1}$

- Hawking evaporation with lifetime $\tau \sim 10^{-27}$ sec

BH → (q and g : leptons : Z and W : ν and G : H : γ)
= (72% : 11% : 8% : 6% : 2% : 1%)

- Experimental signatures
  - High multiplicity events
  - Hadrons:Leptons ~ 5:1
  - Spherical events
  - Large missing PT

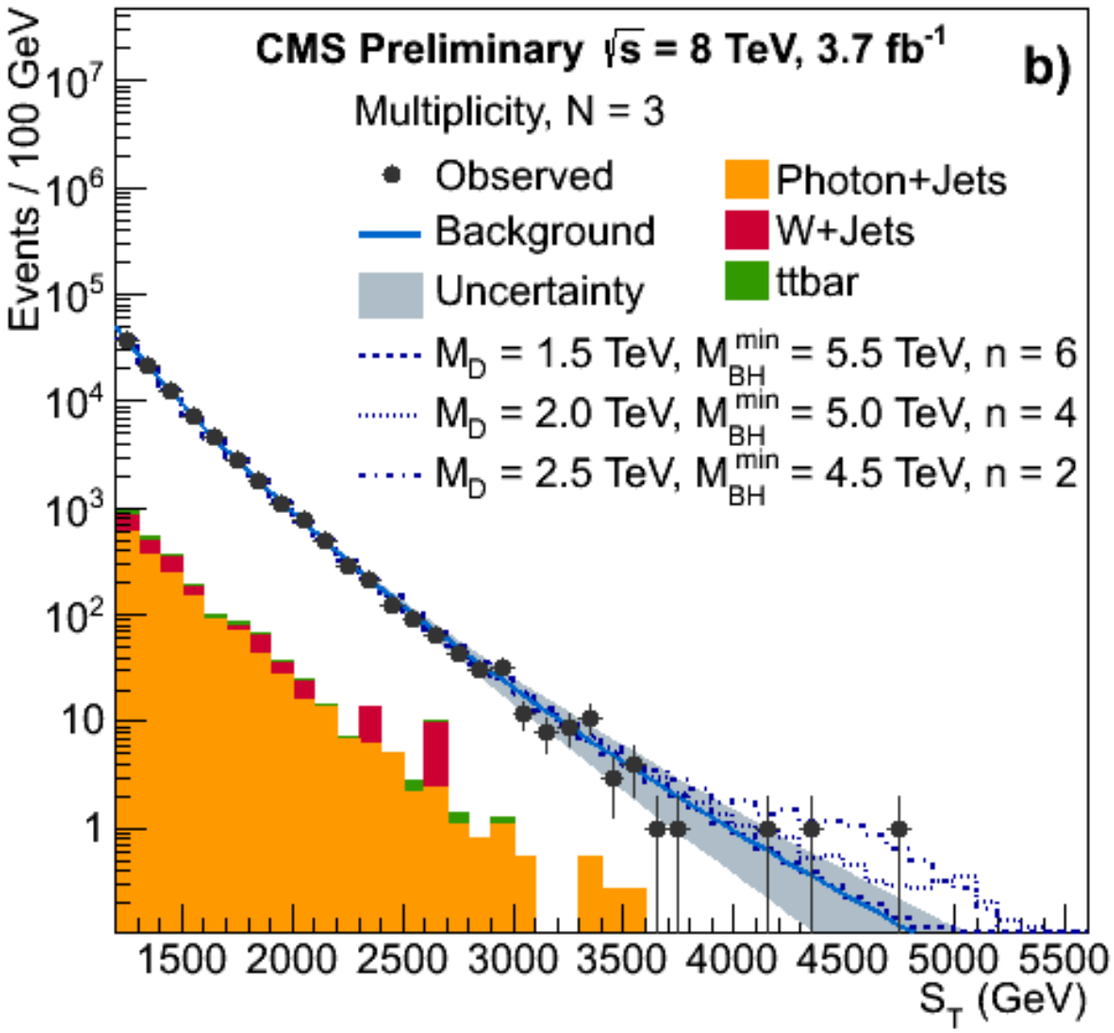


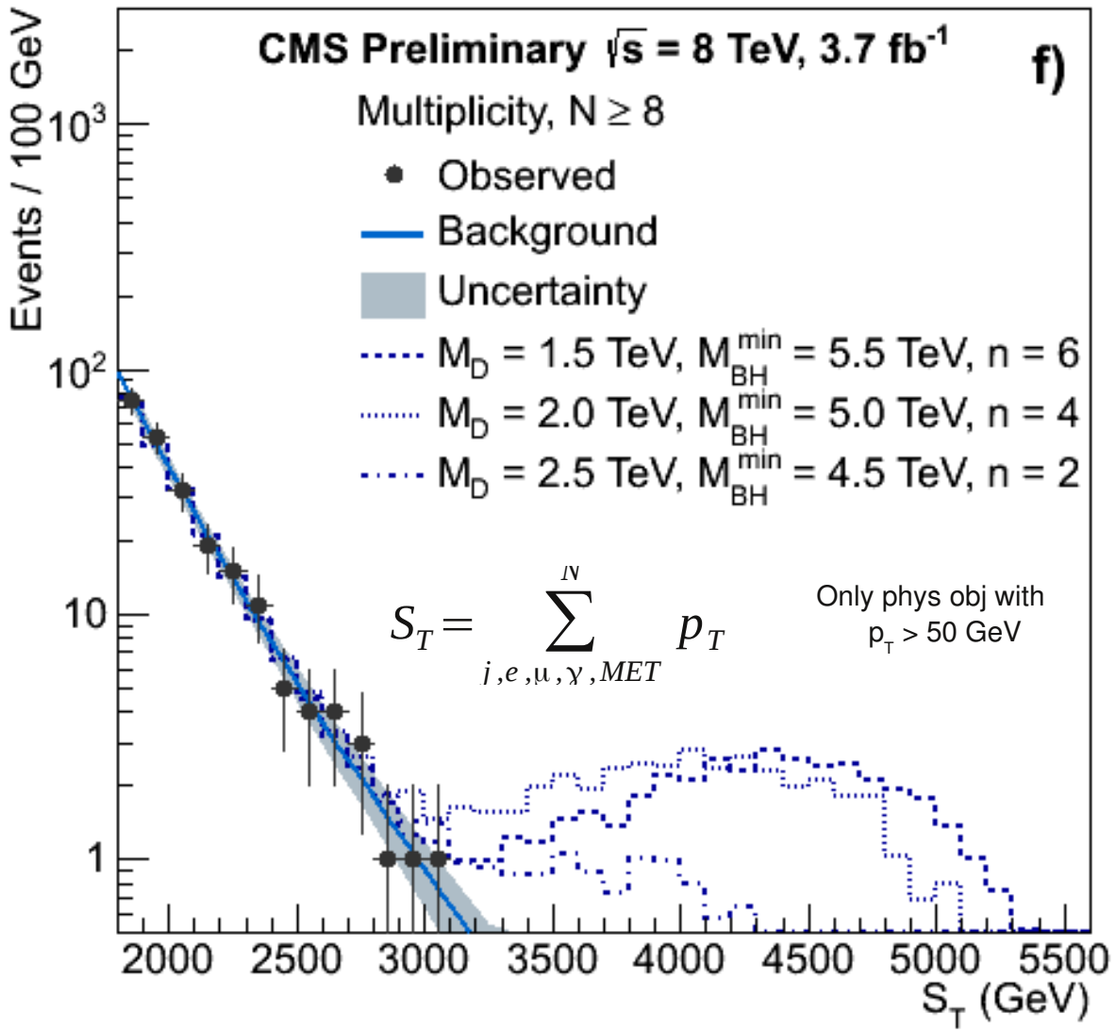


- Could be discovered with 1 fb^{-1} if M_{Pl} < 5 TeV!

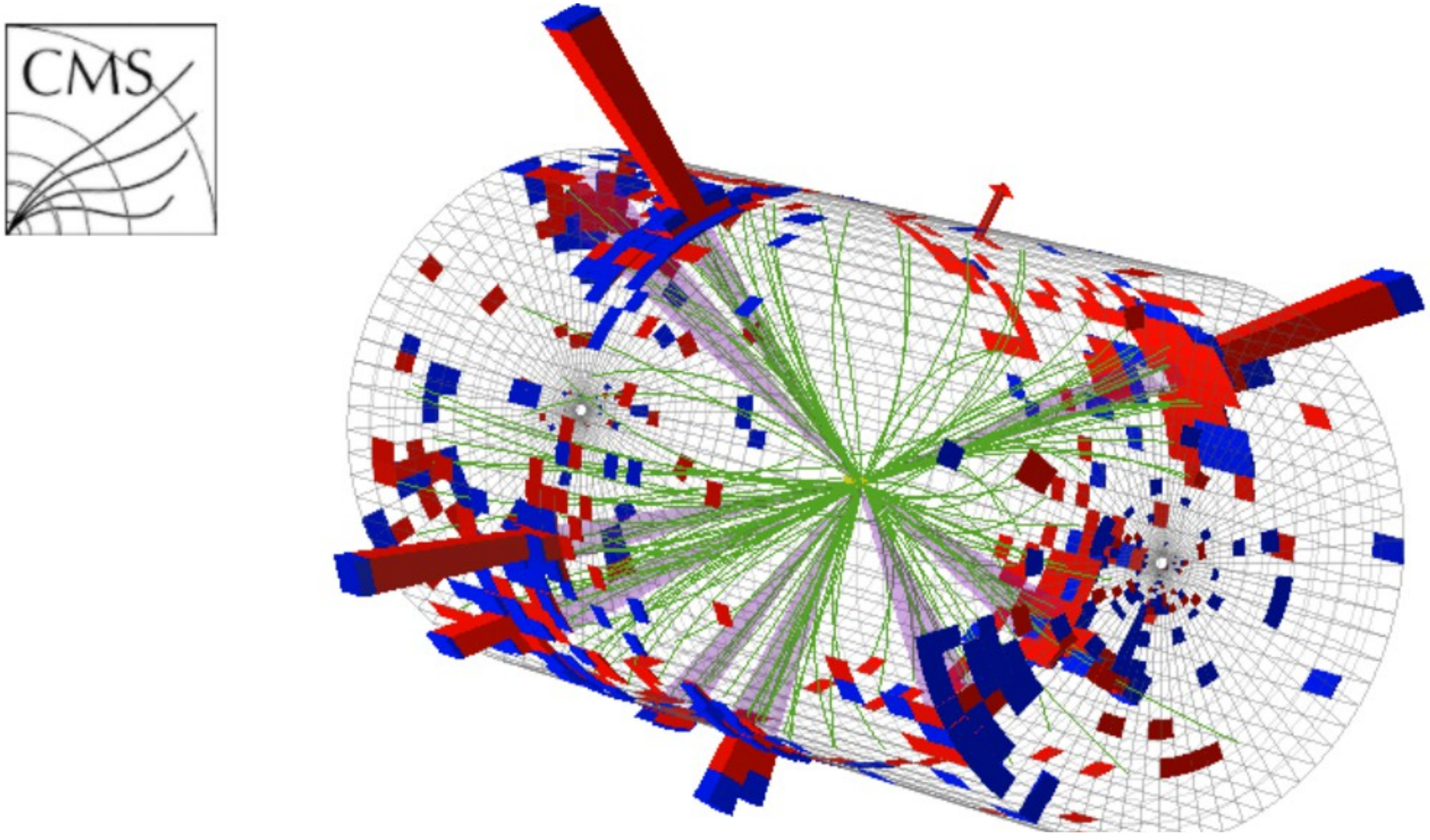
SEARCHES AT LHC

- Analysis strategy: events with large transverse energy, multiple high- energy jets, leptons, and photons
- Main Standard Model background: QCD multijet production
- Discrimination variable: visible transverse energy
  - scalar sum of ET for identified physics objects and MET
- data-driven background estimate from low S_T region and lower multiplicity as control sample

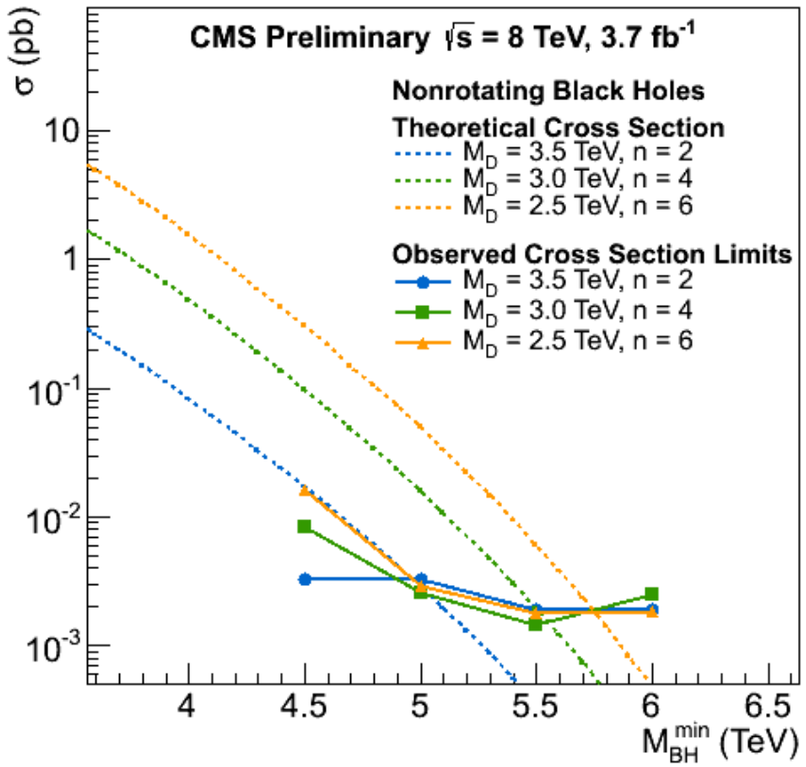


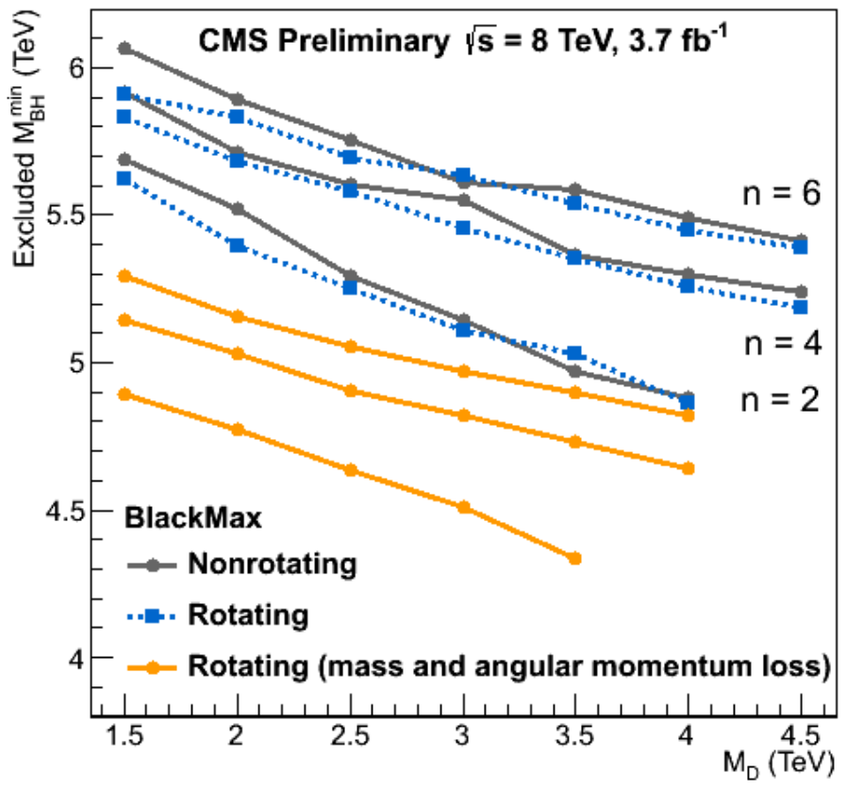


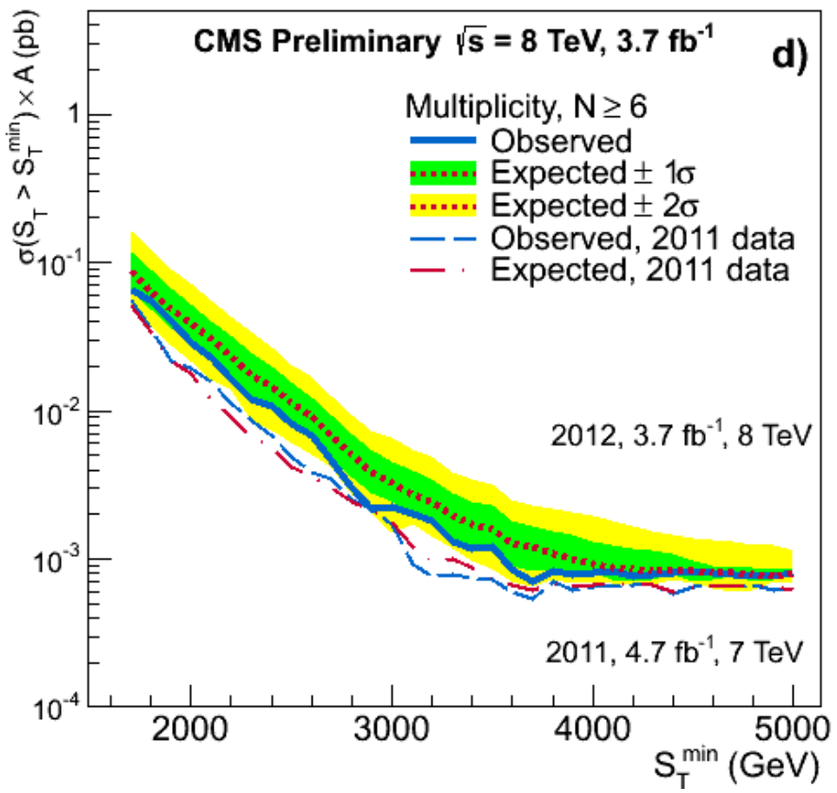
CANDIDATE MULTIJET EVENT



EXCLUSION LIMITS







- No quantum black holes observed yet!

SUMMARY

- Excellent search program at 7 and 8 TeV
- One discovery down and many more to go
  - More discoveries at 8 TeV would have been nice, but recall
    - Studies until 2006 projected discovery of Higgs with ~100 fb^{-1} of data at 14 TeV
- Heavy resonances excluded up to ~3 TeV
- 4th generation excluded up to ~0.5 TeV
- Third generation SUSY actively pursued
  - Next challenge: compressed spectra with small mass gaps between sparticle and LSP
- Machine was built to operate at 14 TeV for a reason
  - Energy needed to produce heavy states
  - Statistics needed to observed weakly coupled states