EXOTICA AT LARGE HADRON COLLIDER

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DIPARTIMENTO DI FISICA

SAPIENZA
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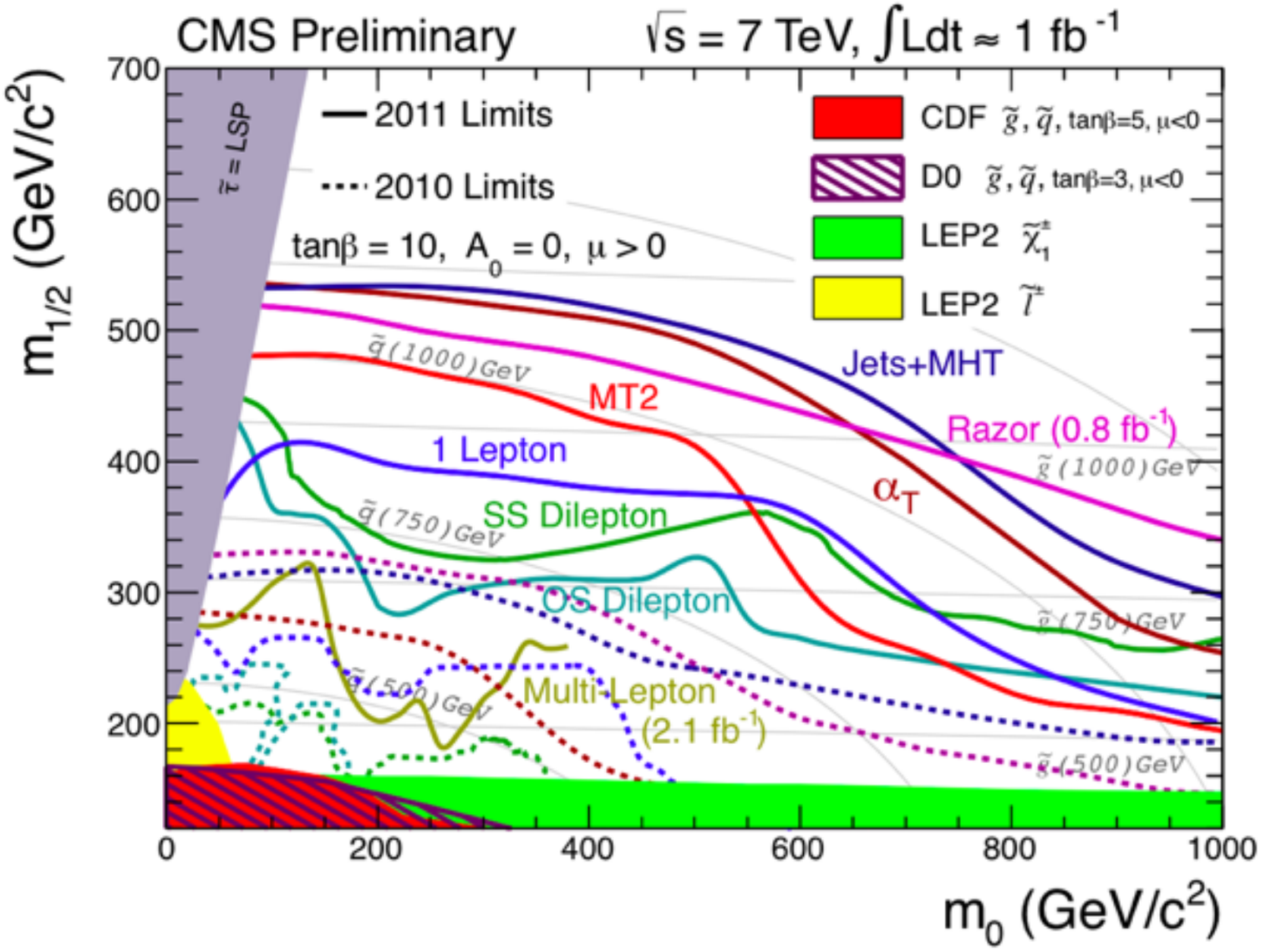
INFN
ROMA

A VERY PRODUCTIVE 2011

- About 30 results produced by CMS on 2011 data so far
  - 20 now using full 2011 data set of 5 fb^{-1}
- Comprehensive review requires a few hours hours
- This talk focused on most recent results with full statistics
- Will try to give you a taste of some exotics particles we hope to discover soon

- Focus mostly on CMS results
  - almost all searches updated to 5 fb-1
  - some ATLAS results quoted for comparison
    - many others with smaller data samples not quoted here
- Complete list of results
  - ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
  - CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO

SUSY OR EXOTICA?



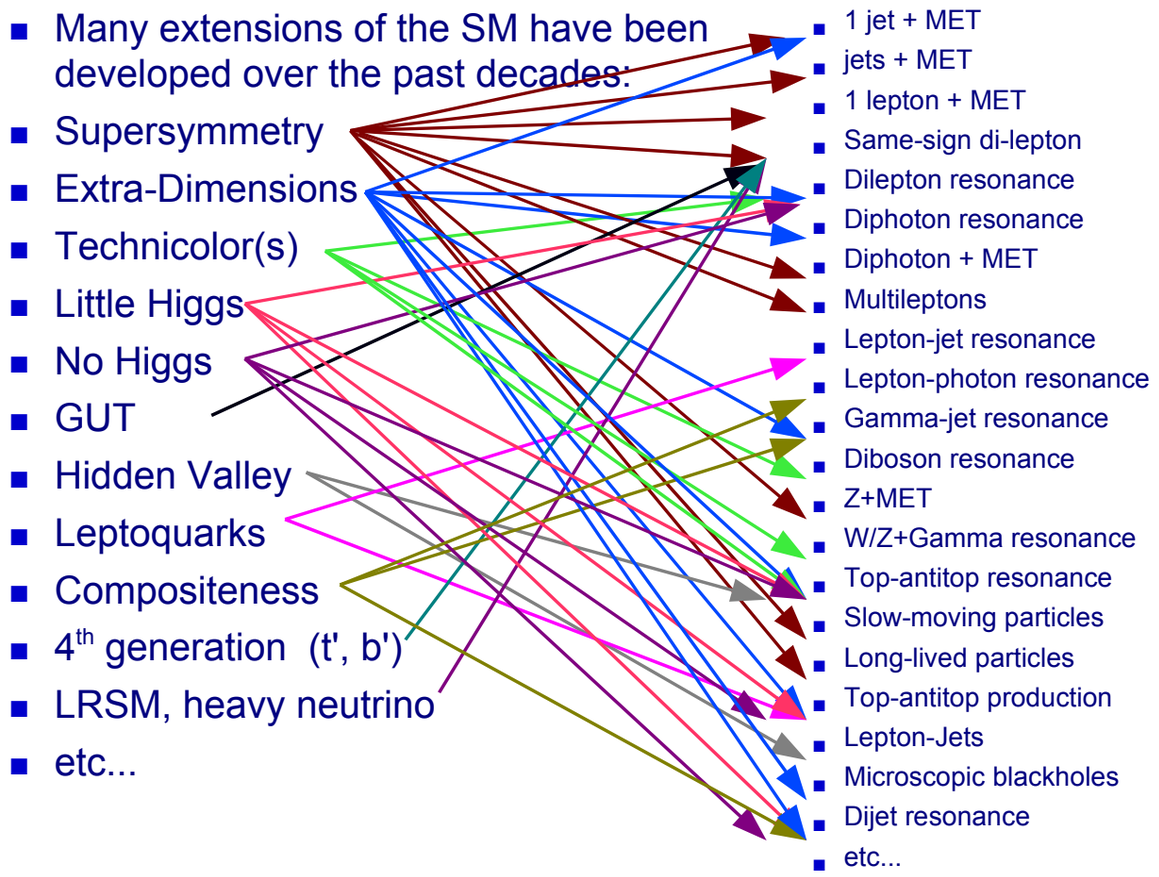
- SUSY results reported almost always in (m0,m1/2) plane
  - mass of all supersymmetric particles are related
- Large missing transverse energy is usually the primary signature
- In exotica we look for particles and resonances that are not necessarily needed or predicted in supersymmetry

SIGNATURE- OR TOPIC-BASED?

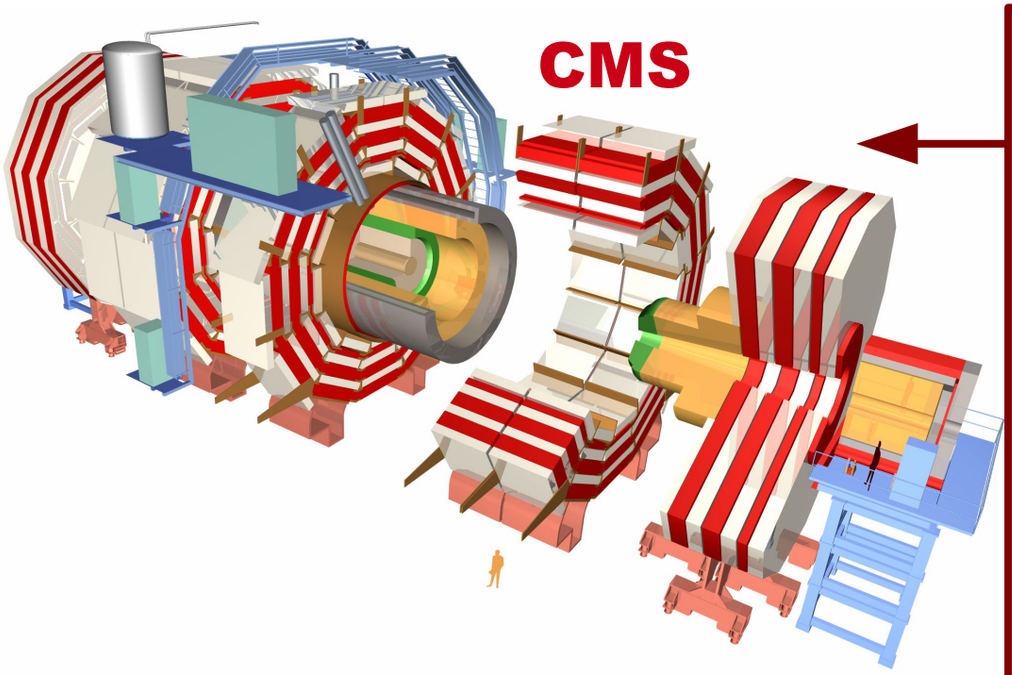
- Same final state often probing very different models or topics
  - 2 leptons, 2jets + MET, lepton+jet+MET

- Topological presentation requires jumping between very different models

- I will follow a topic-based approach
  - easier to combine constraints on model from different topologies
  - Same final state is not simple re-interpretation
    - often optimization redone to deal with different acceptance for very different models
    - different analysis strategy and signal extraction methods

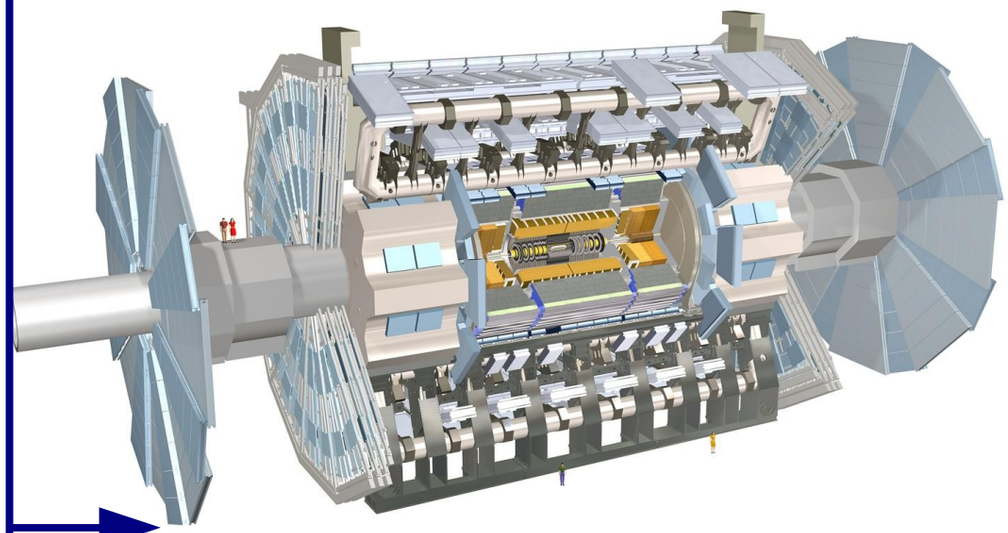


ATLAS AND CMS



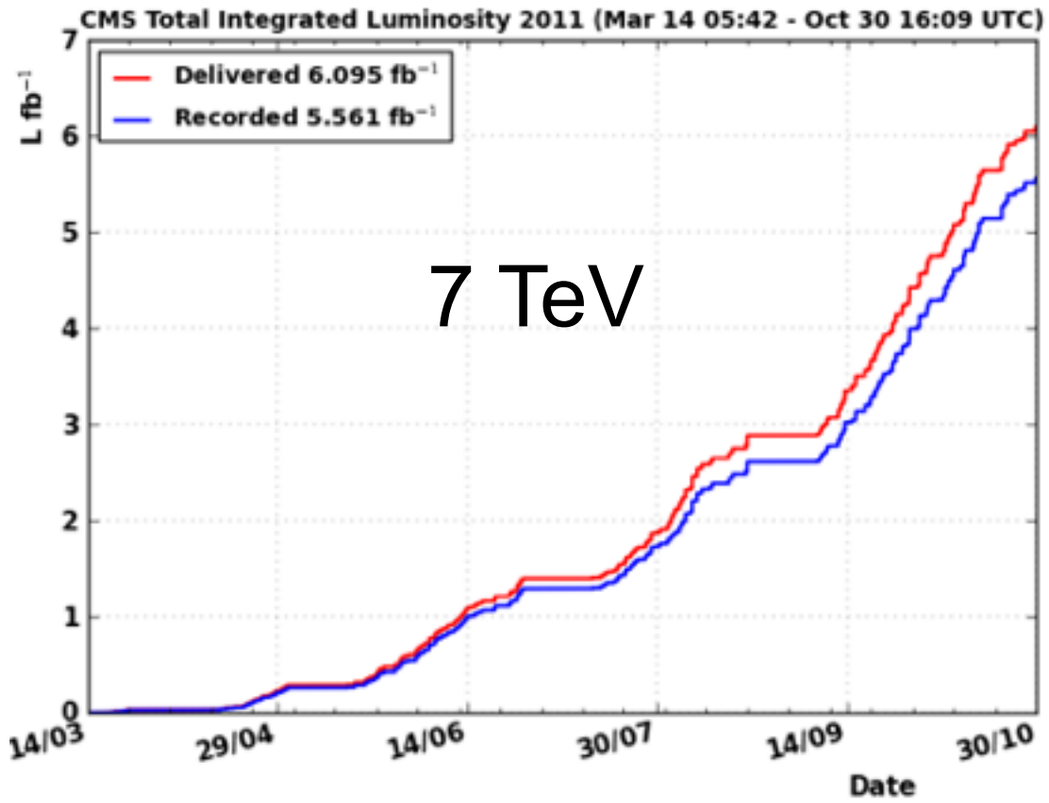
- 3.8T solenoid containing calorimeters
- Silicon tracker: $\sigma(p_T)/p_T \sim 15\%$ at 1TeV
- EM cal: homogeneous Lead-Tungstate crystal, $\sigma_E/E \sim 3\%/\sqrt{E[GeV]} \oplus 0.5\%$
- HAD cal: Brass-scint., $\geq 7\lambda_0$
  $\sigma_E/E \sim 100\%/\sqrt{E[GeV]} \oplus 5\%$
- Iron return yoke muon spectrometer

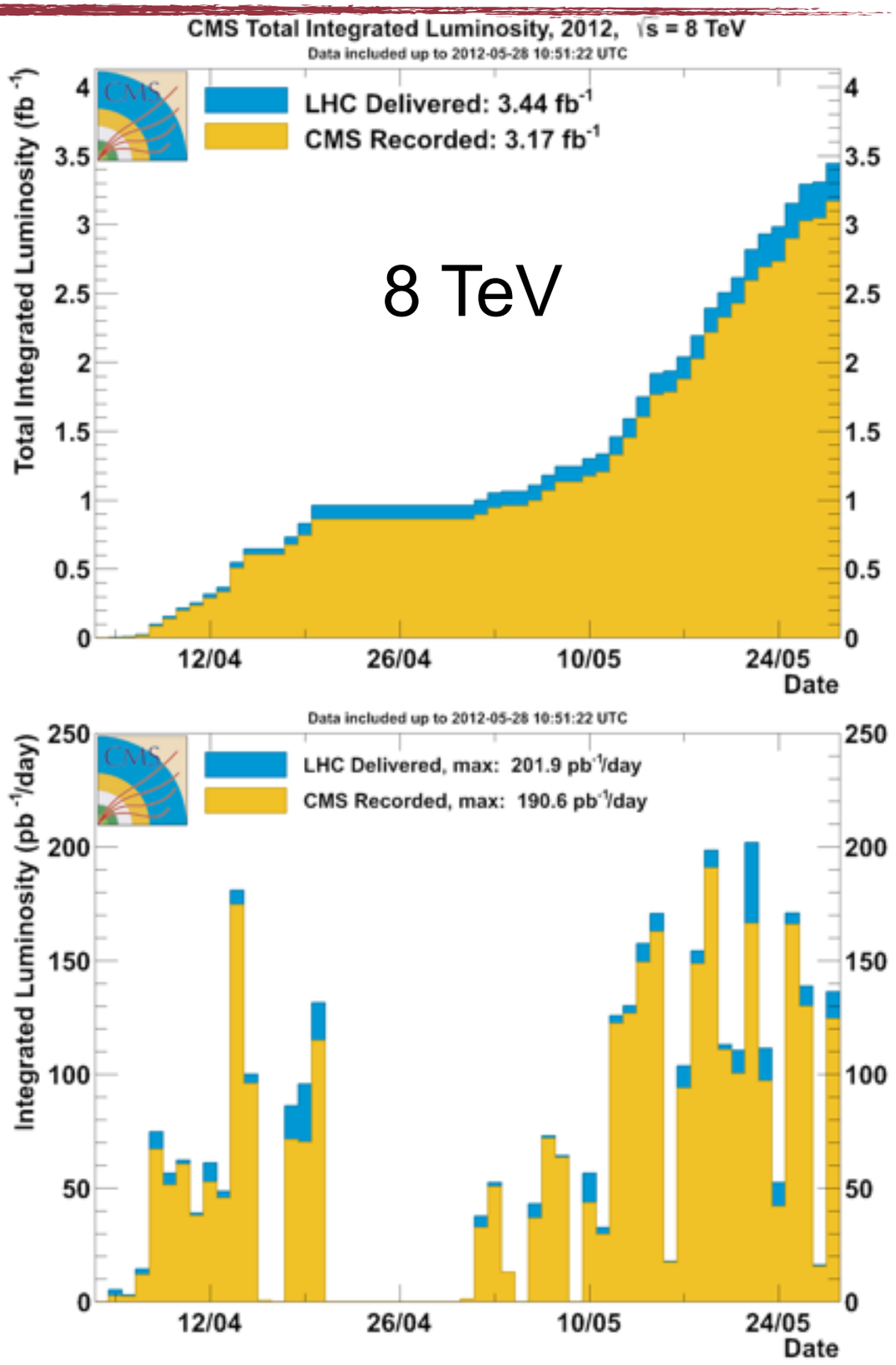
- 2T solenoid inside calorimeters
- Silicon+TRT tracker + electron ID
- EM cal: Longitudinally segmented Lead-Ar:
  $\sigma_E/E \sim 10\%/\sqrt{E[GeV]} \oplus 0.7\%$
- HAD cal: Fe-scint + Cu-Ar, $\geq 11\lambda_0$
  $\sigma_E/E \sim 50\%/\sqrt{E[GeV]} \oplus 3\%$
- Air-toroid muon sp.: $\int \sqrt{B}.dl = 1$ to 7 T.m



ATLAS

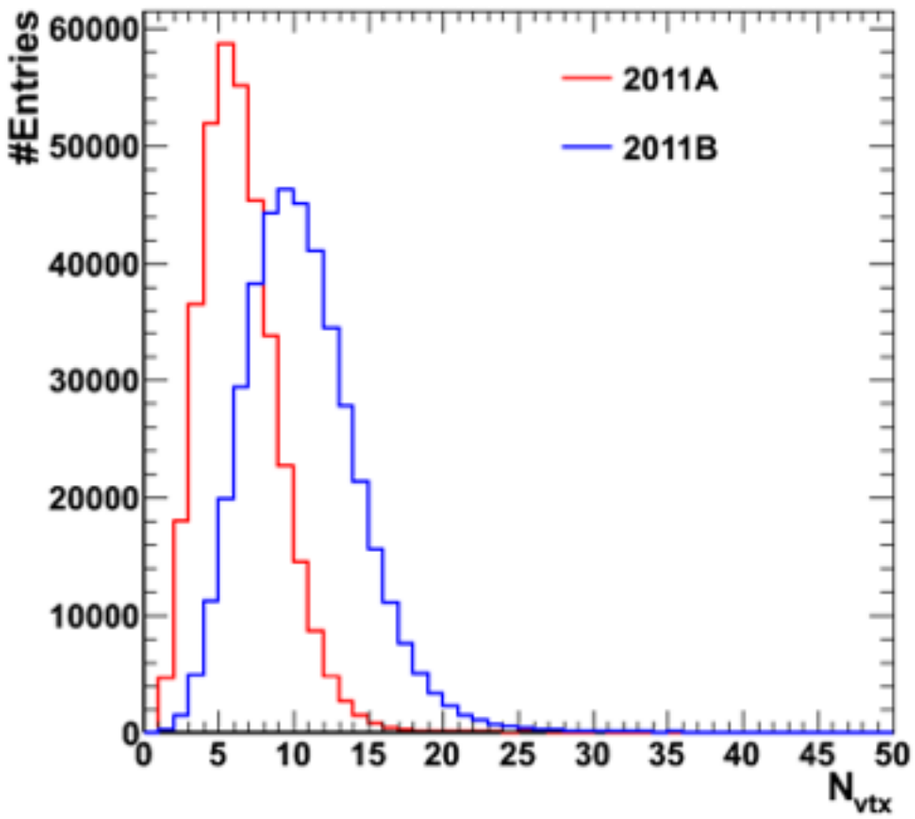
OUTSTANDING PERFORMANCE OF LHC

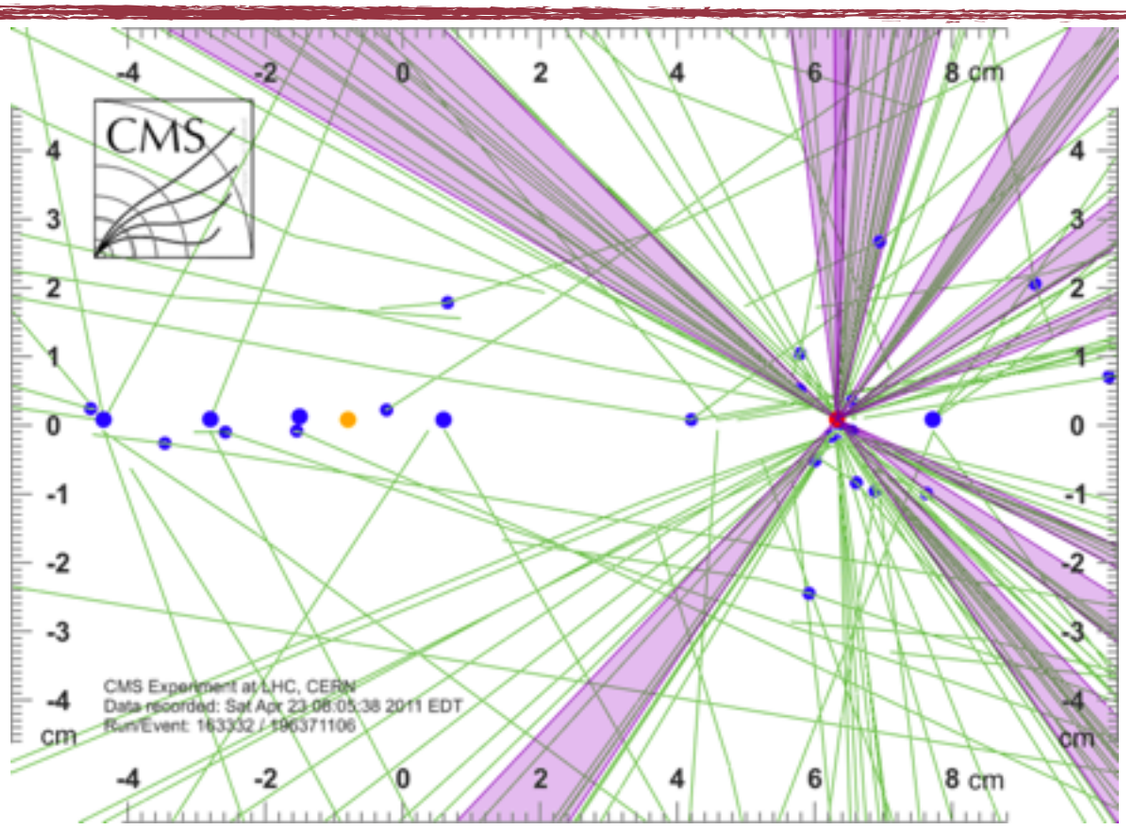




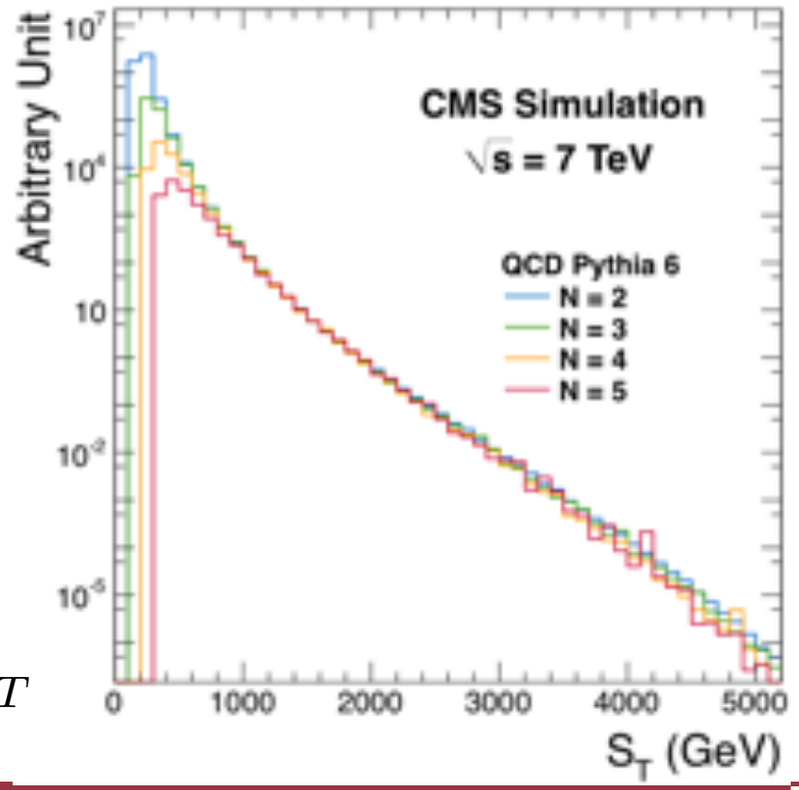
- 5 fb^{-1} of good certified data in 2011
- Almost all searches updated and being published with full 2011 data
- Expect close to 5 fb^{-1} by 8 June
  - cutoff for ICHEP 2012

Our Big Enemy: Pile-up





- Not a real problem for most of searches due to high pt objects
  - relative isolation with respect object of interest much less affected
  - average increase in event energy density not big compared to
    high pt objects from hard scattering
  - primary vertex of hard scattering not critical and identified > 80% if needed



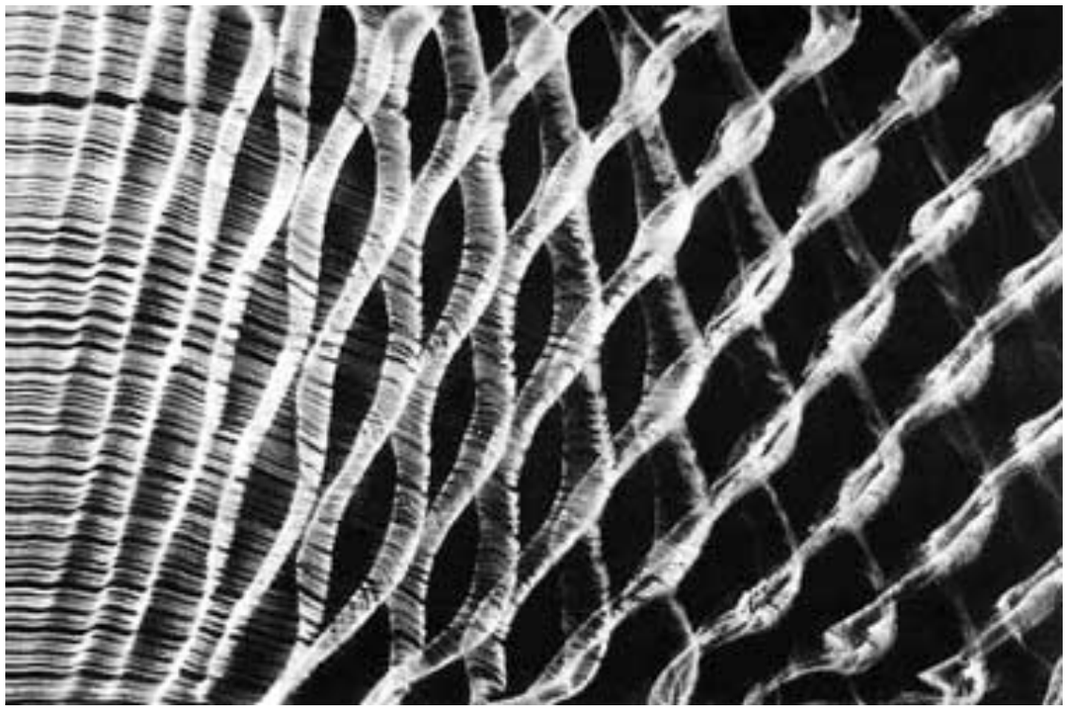
$$S_T = \sum_{i}^{jets,leptons,MET} p_T$$

OUTLINE

- Heavy Resonances
  - dileptons
  - lepton+MET
  - diphotons
  - dijets
  - heavy neutrinos
  - WZ
- Extra dimensions
  - Black Holes
- Dark Matter
  - single jet + DM candidate
  - single photon + DM candidate

- LeptoQuarks
  - 1st generation
  - 2nd generation
- 4th generation b'/t'
  - all hadronic
  - semileptonic
- Long-lived particles
  - stopped particles
  - displaced vertices

Not enough time to cover today

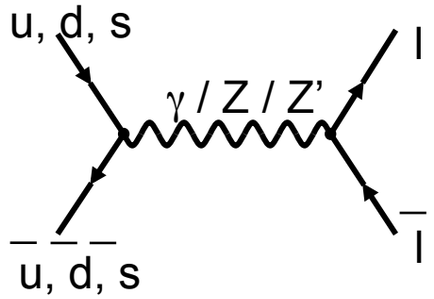


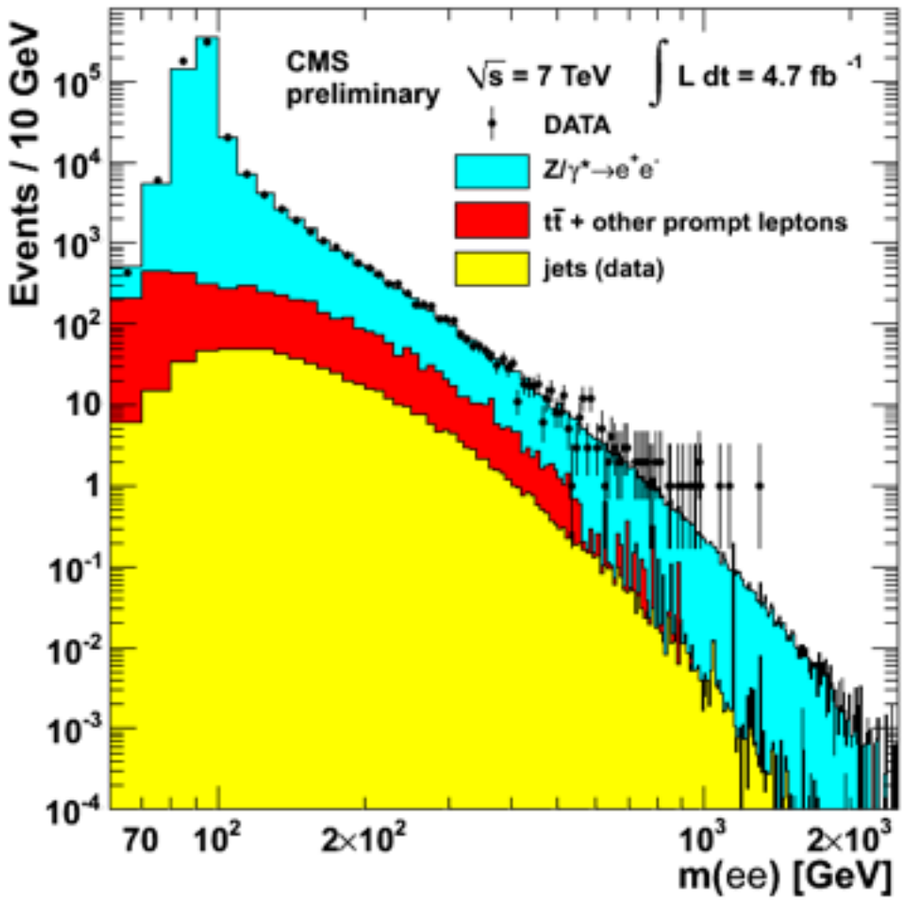
Heavy Resonances

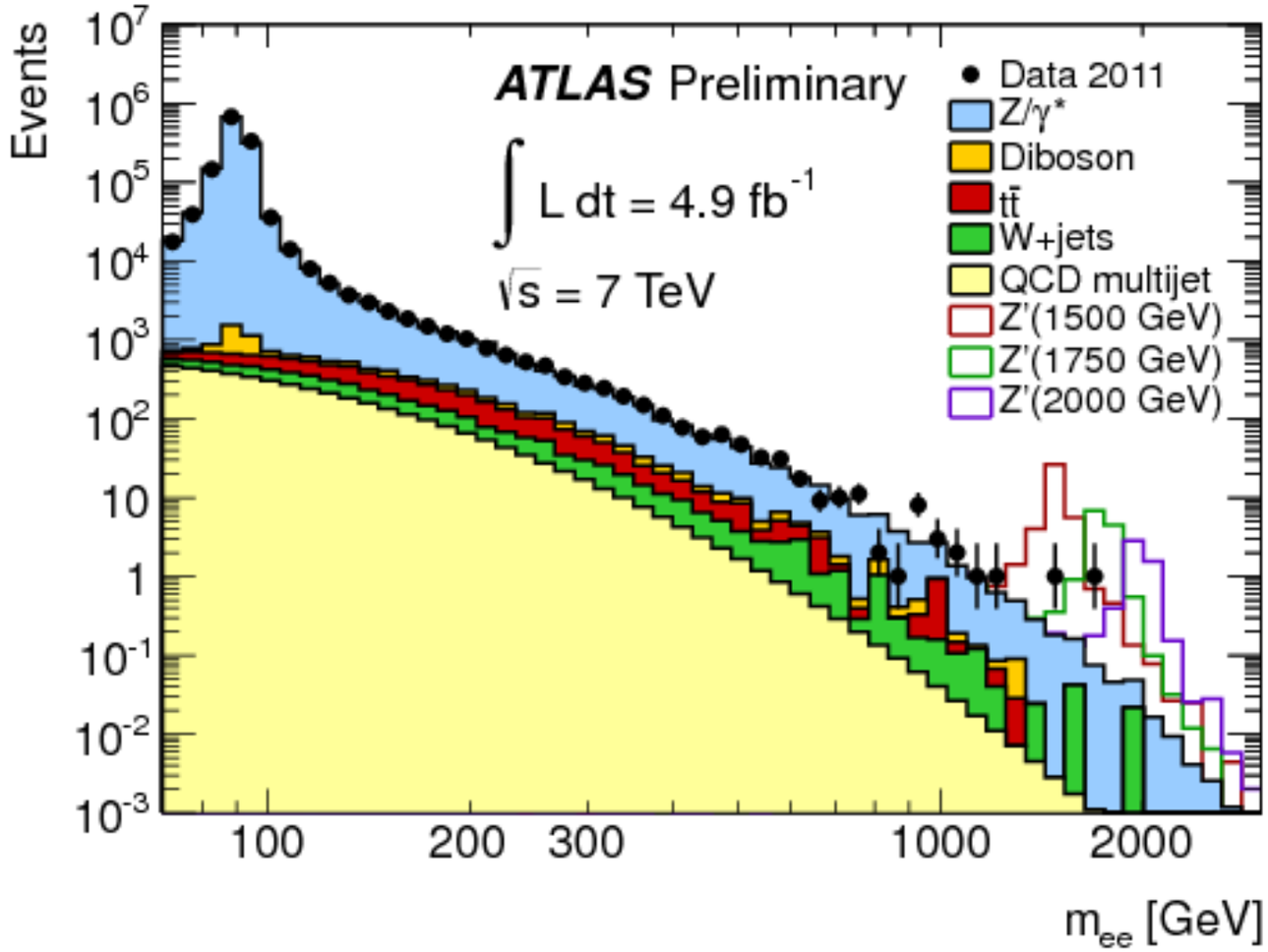
HEAVY RESONANCES

- New gauge bosons predicted by many extensions of the Standard Model with extended gauge symmetries
  - Z_{SSM} in Sequential Standard Model with same Z0 coupling as in Standard Model
  - Z' models from E6 and SO(10) GUT groups
  - The Kaluza-Klein model from Extra Dimension
  - Little, Littlest Higgs model
- No precise prediction for mass scale of gauge bosons
- Technicolor also predicts variety of narrow heavy particles
- 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-ELECTRON

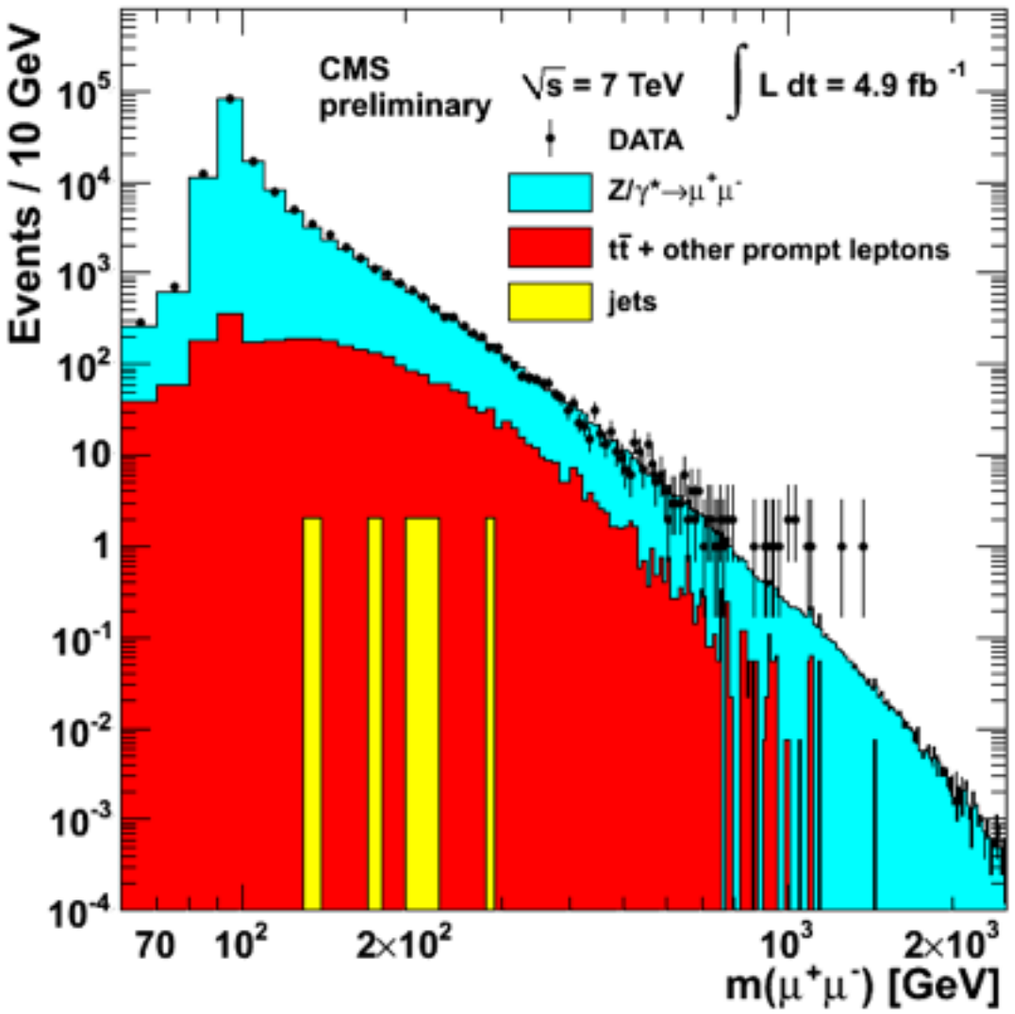


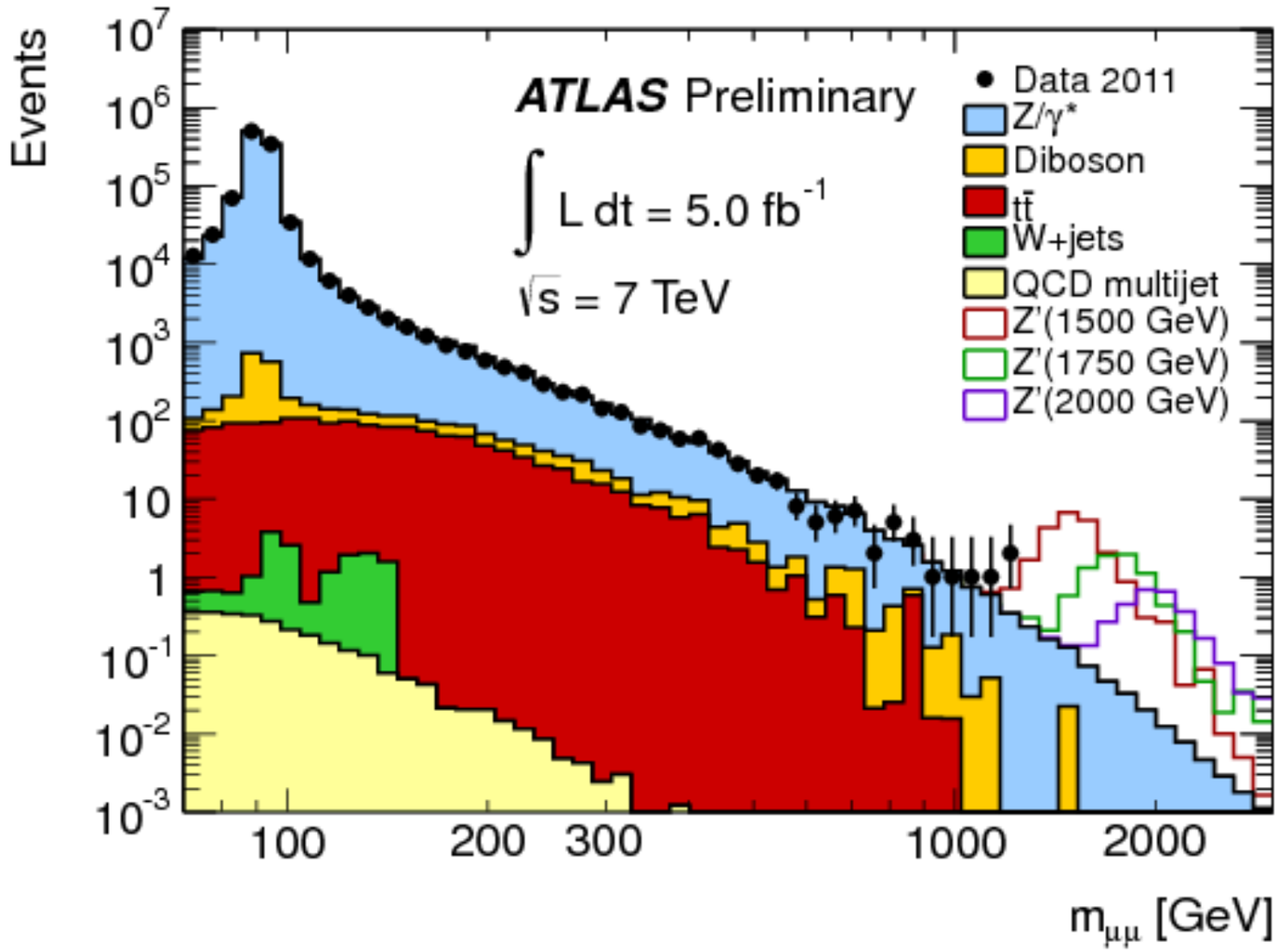




- Background estimation: QCD and ttbar from data, DY from MC

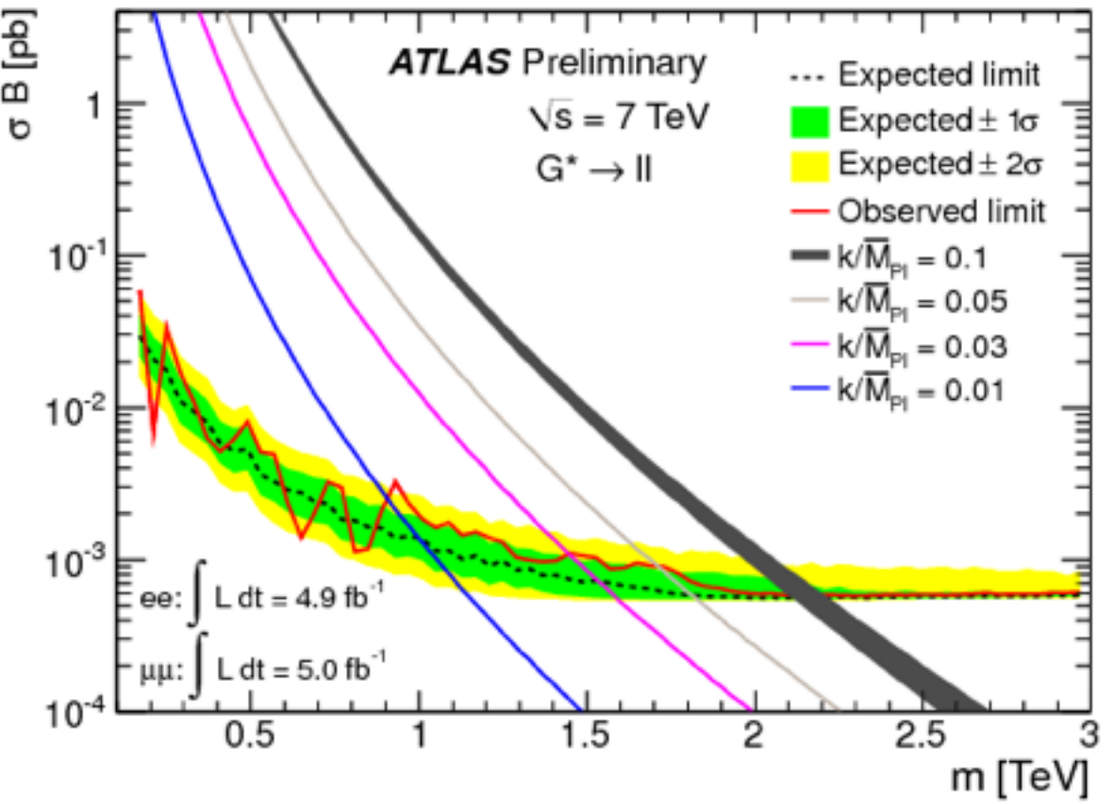
DI-MUON

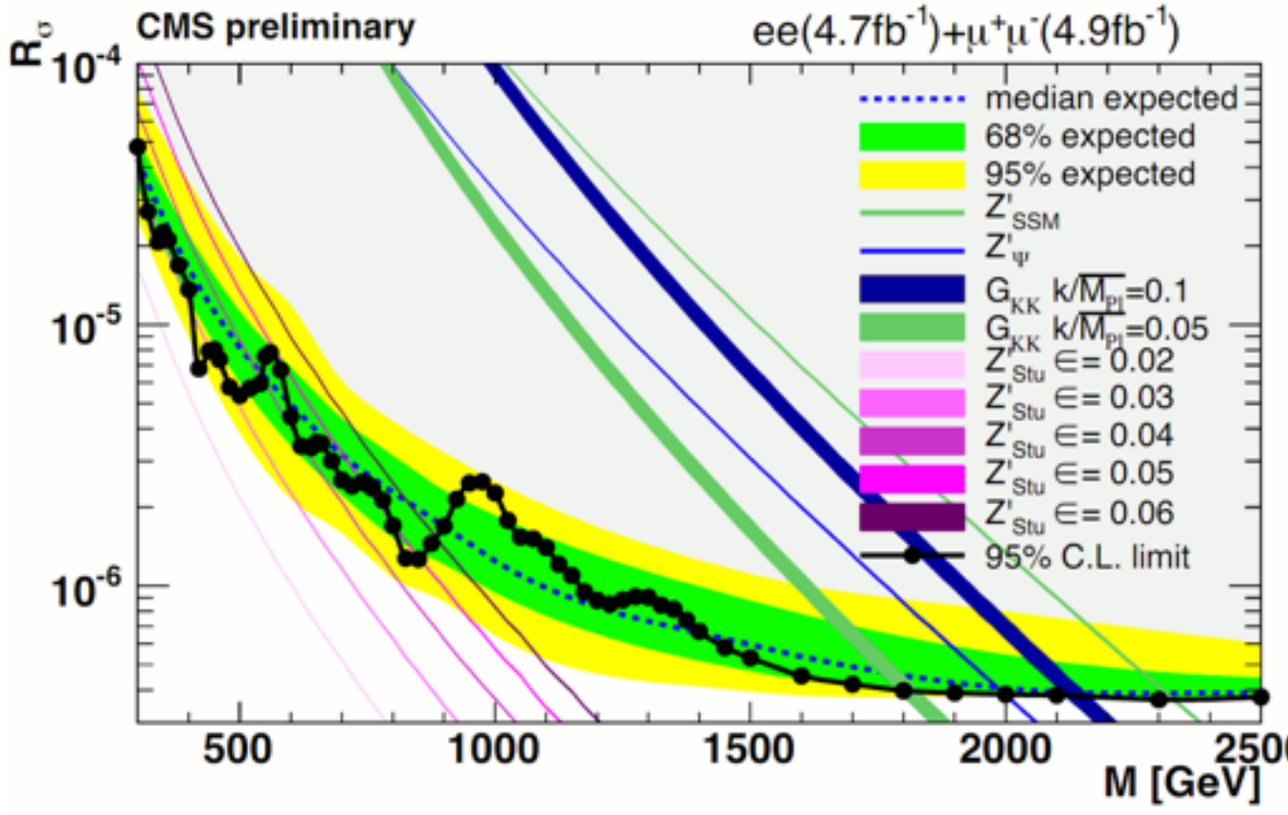




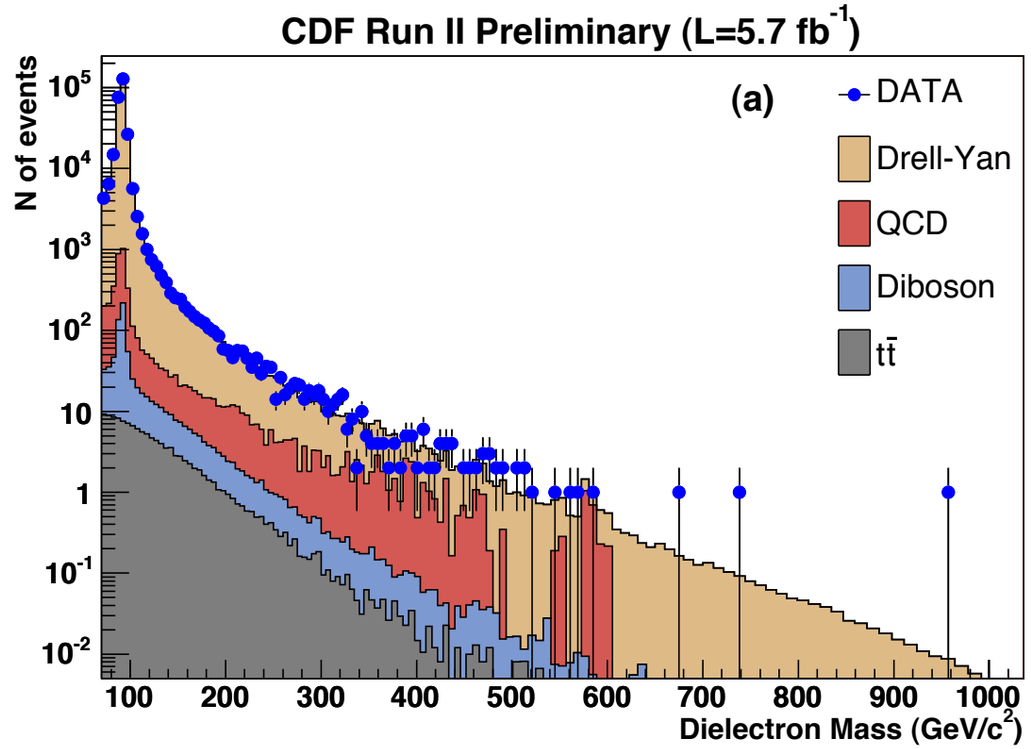
- Several events with mass of 1 TeV
- But much larger resolution with muons spreads out a possible signal a lot compared to electrons

DI-LEPTON EXCLUSIONS



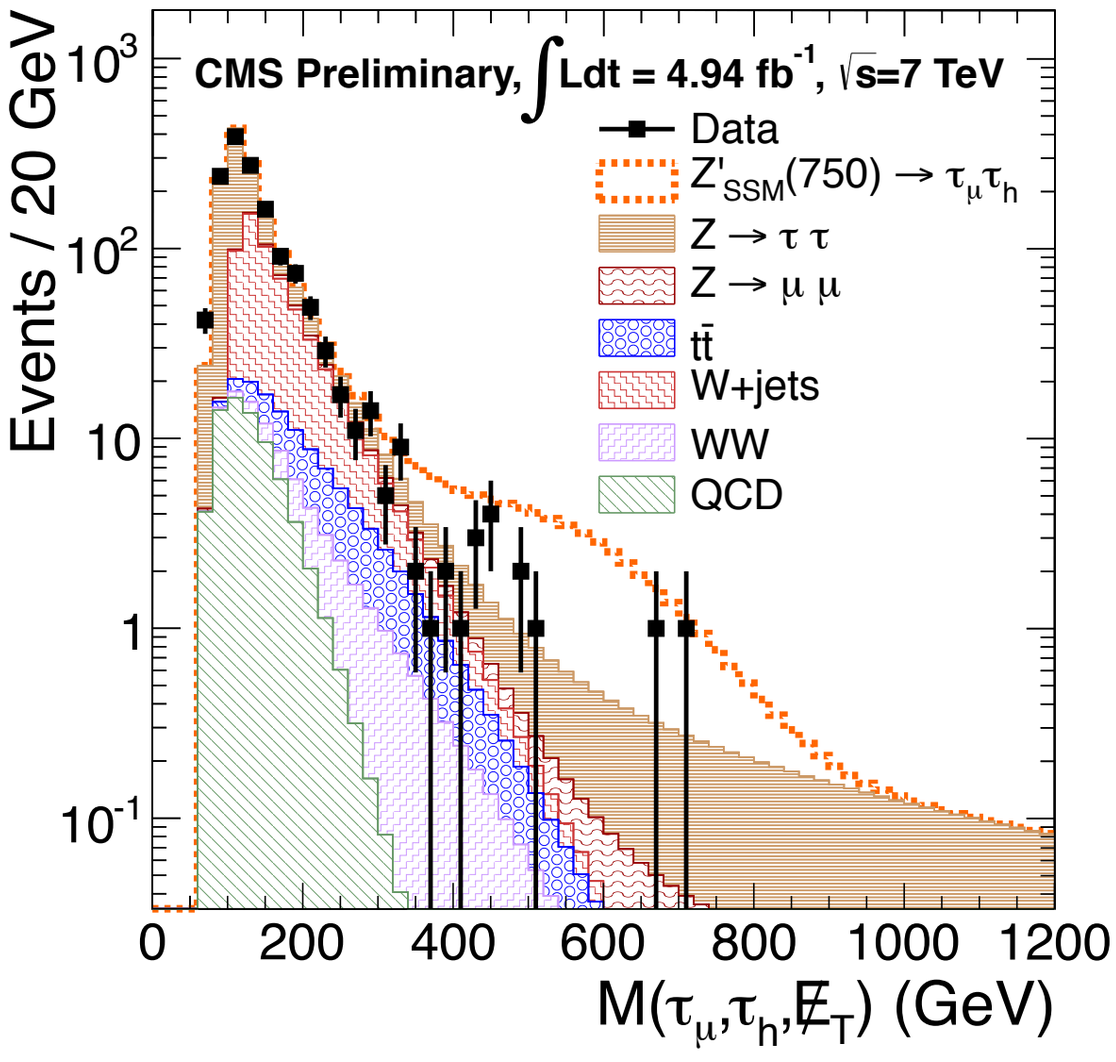


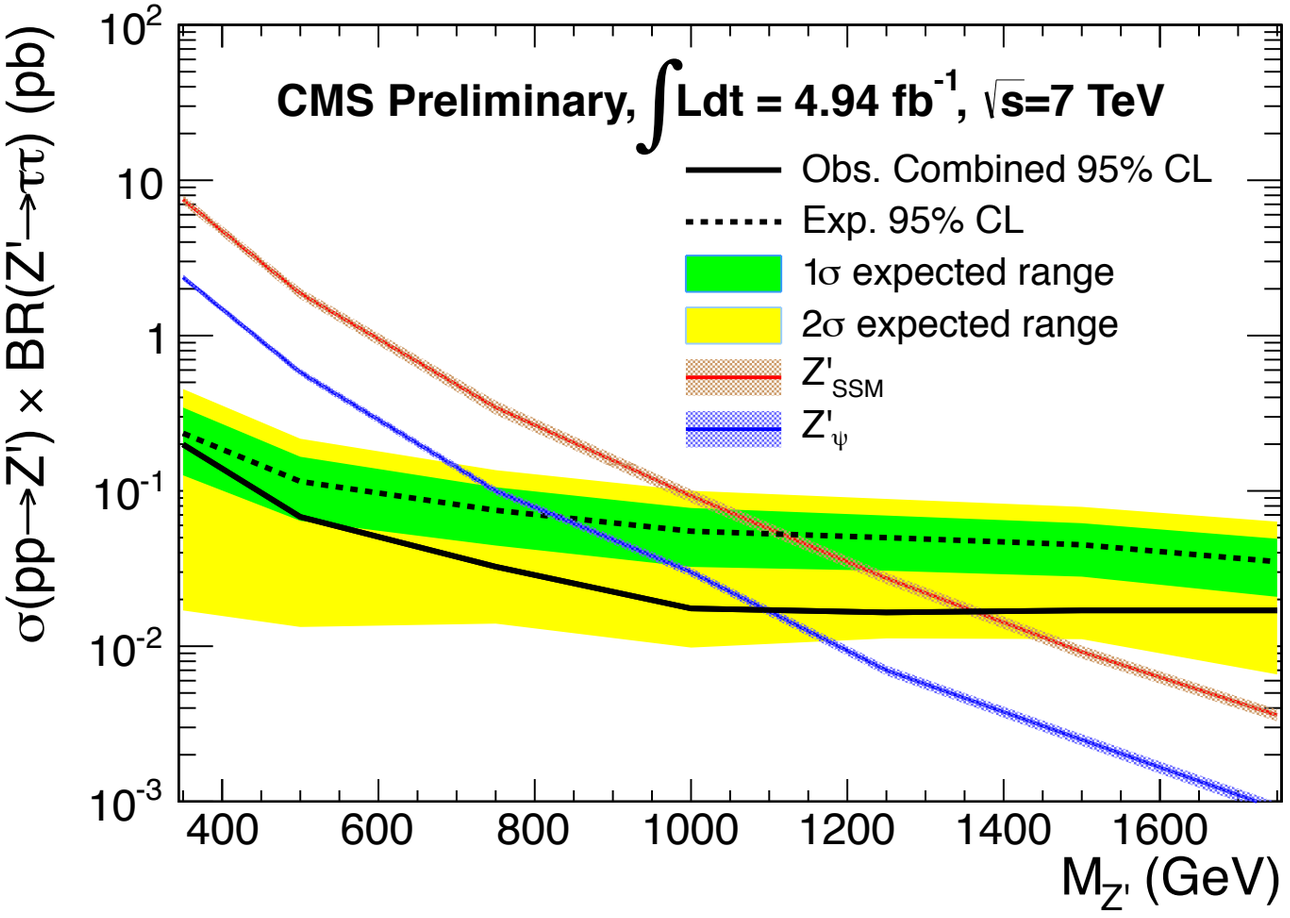
- Limits approaching 2 TeV for most models



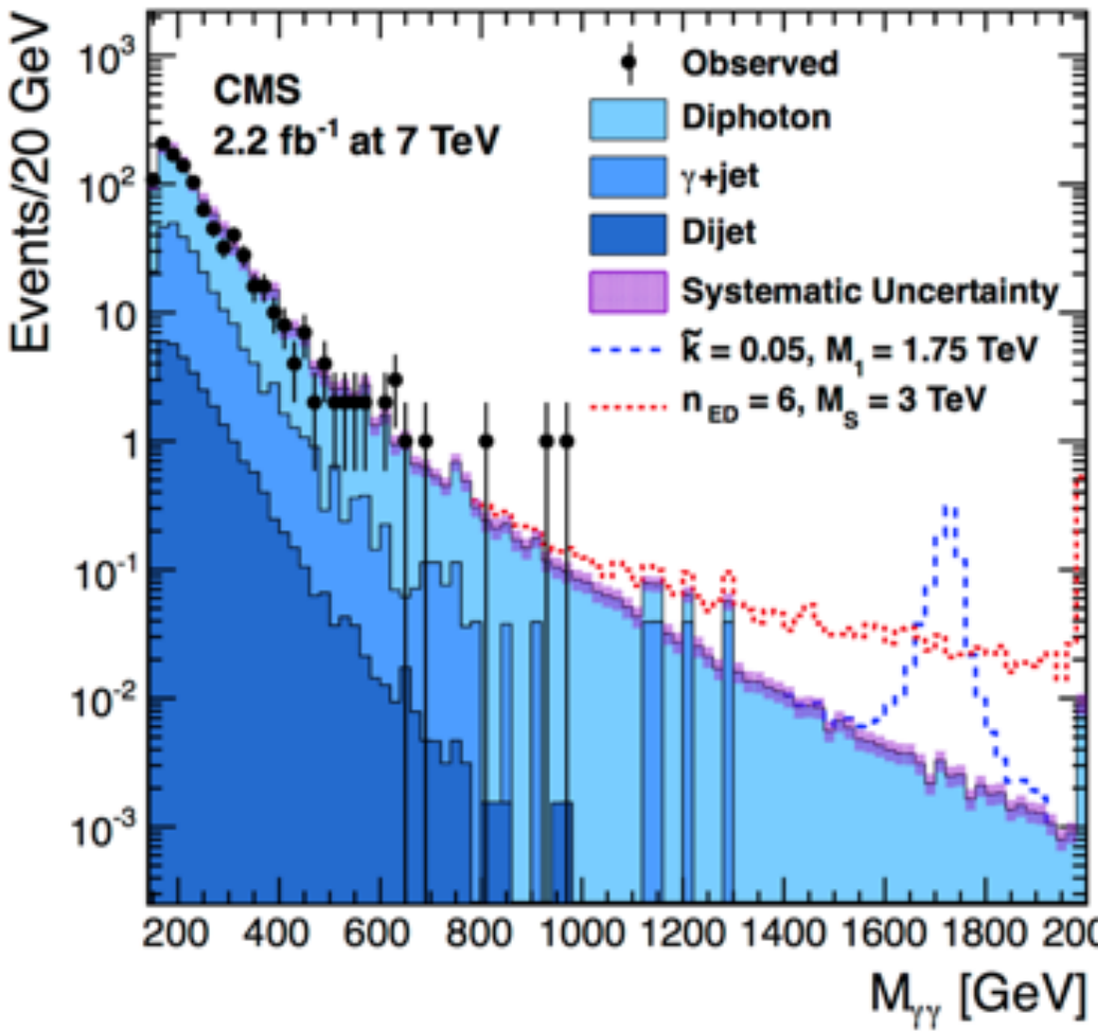
DI-TAU

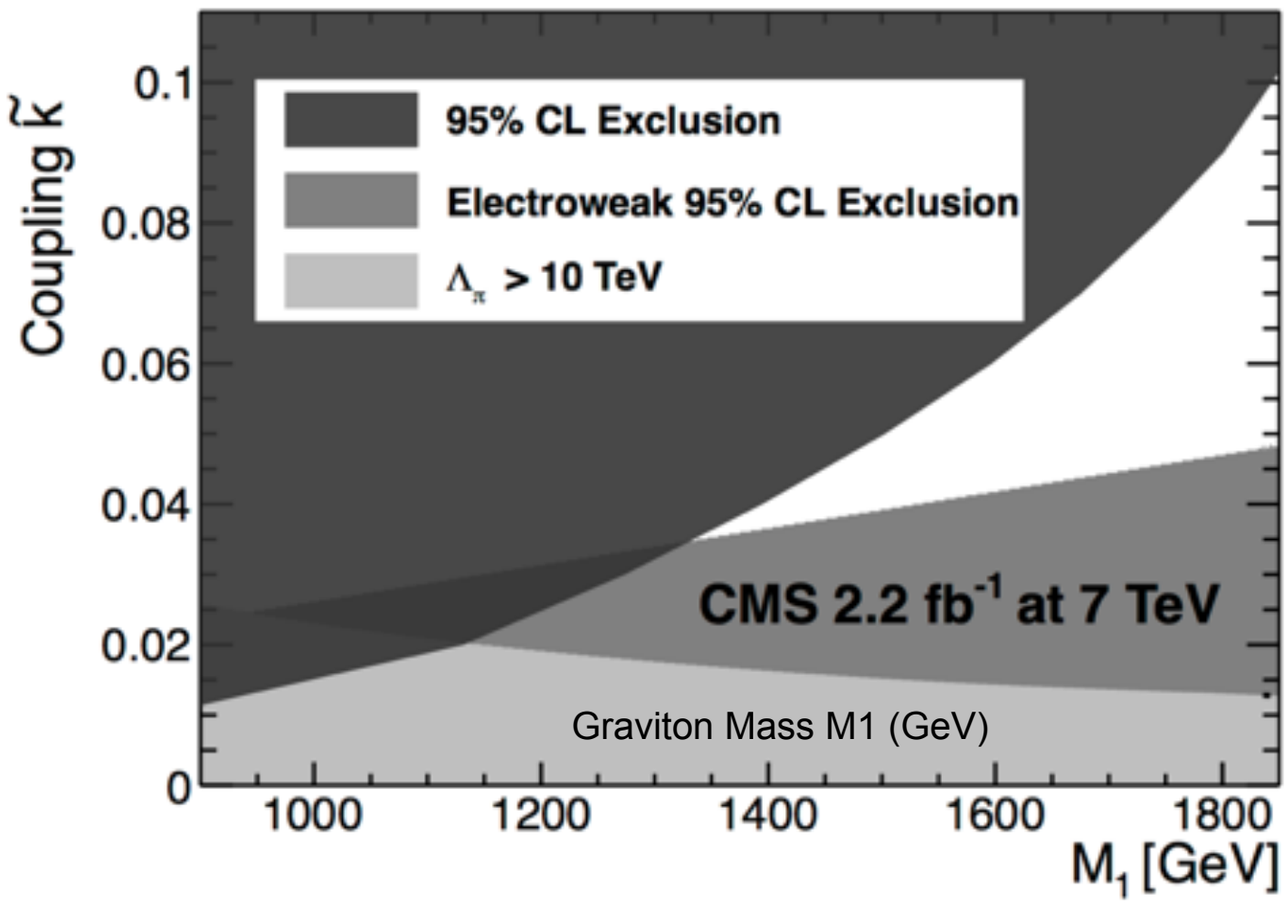
- Most challenging lepton for searches: both hadronic and leptonic tau decays
- Not competitive with di-electron and di-muon but could be sensitive for resonances with non-standard couplings or preferring 3rd generation
- Sequential standard model resonance Z'_{SSM} excluded at 95% CL below 1.36 TeV





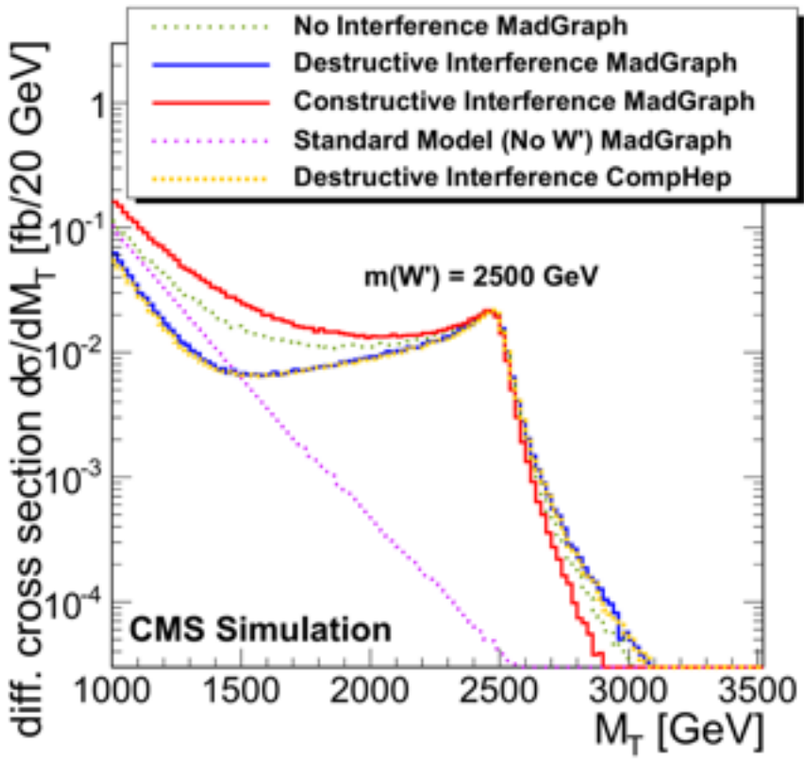
γγ

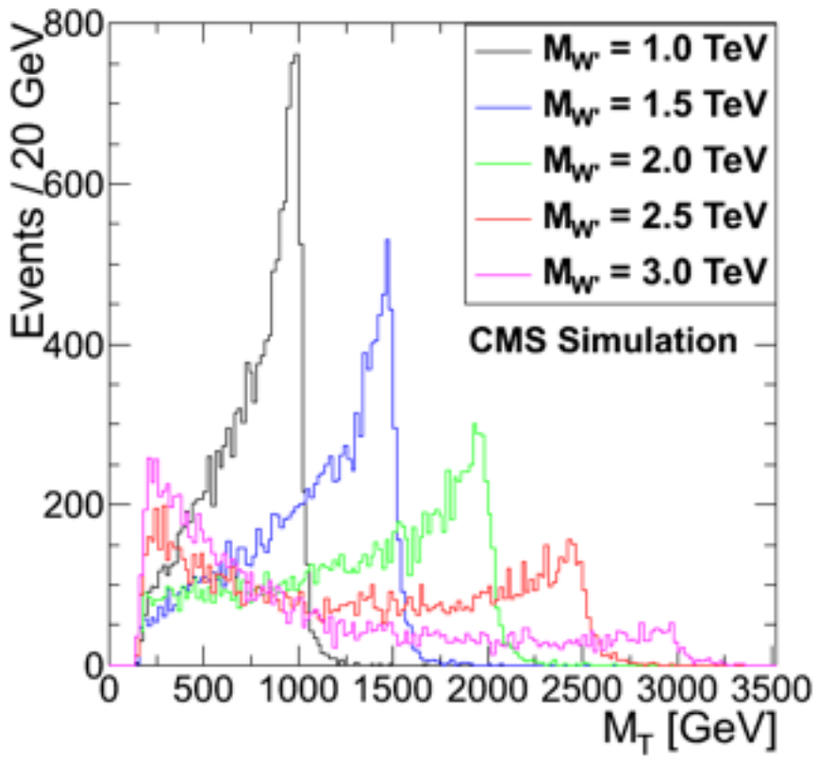


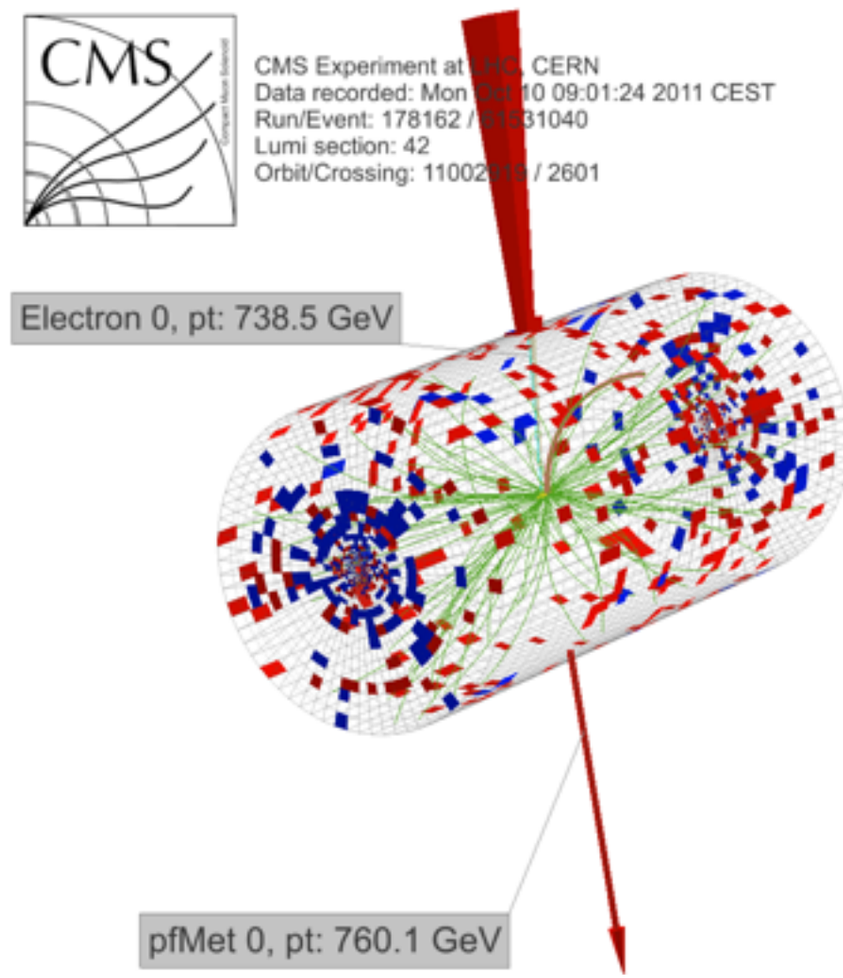


- Randall-Sundrum gravitons propagation in extra dimensions
- Background: genuine diphoton production
- Counting experiment in tails or in narrow windows for a resonance

LEPTON+MET





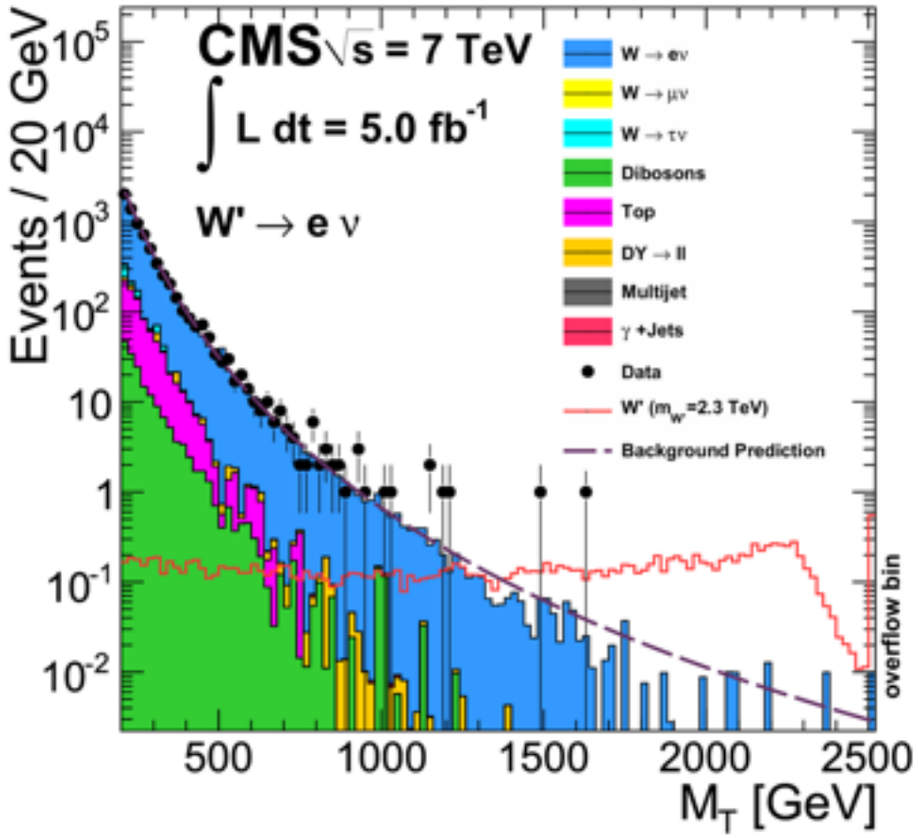


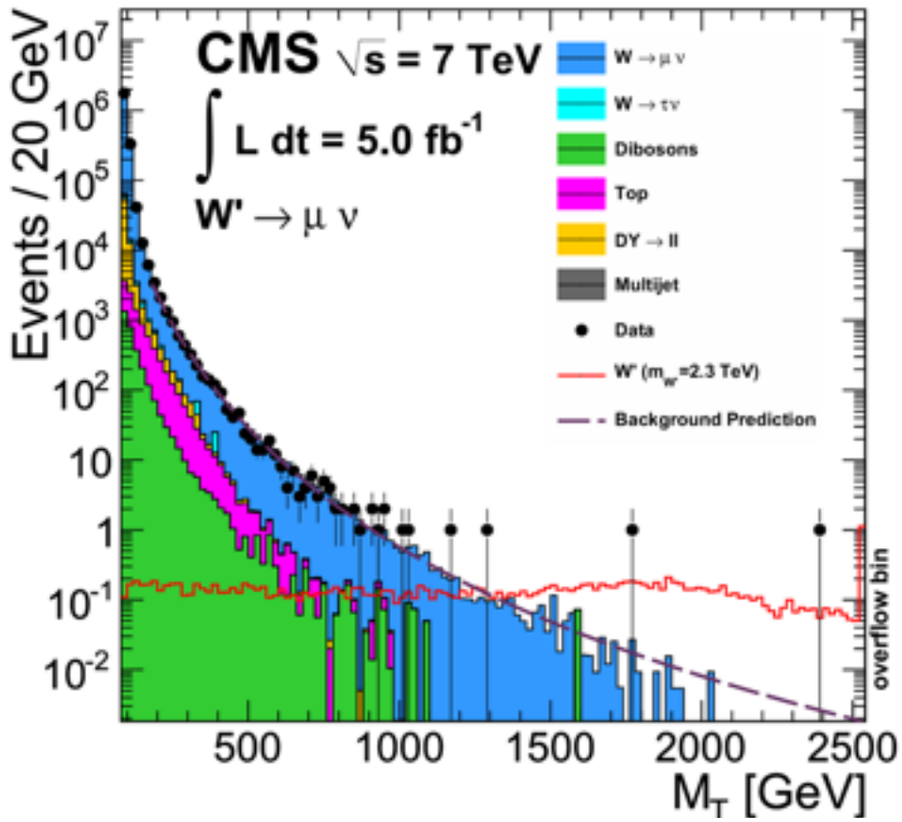
- Look for heavy W-like Jacobian peak in transverse mass

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

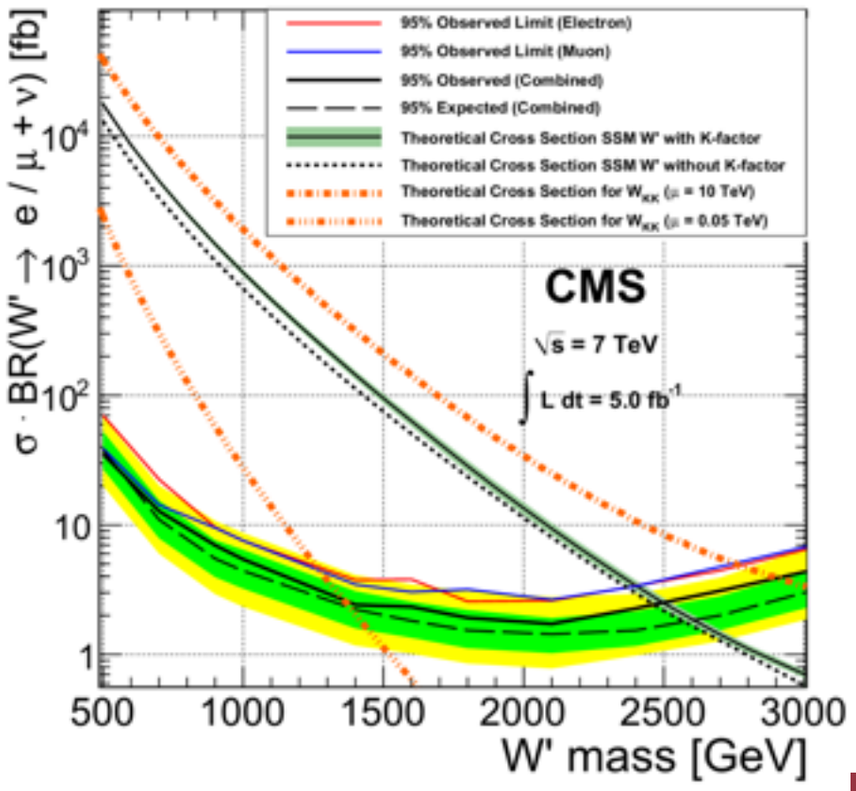
- Dominant background: W production in Standard Model
- Now also take into account interference with SM

W' → lν Exclusion Limits





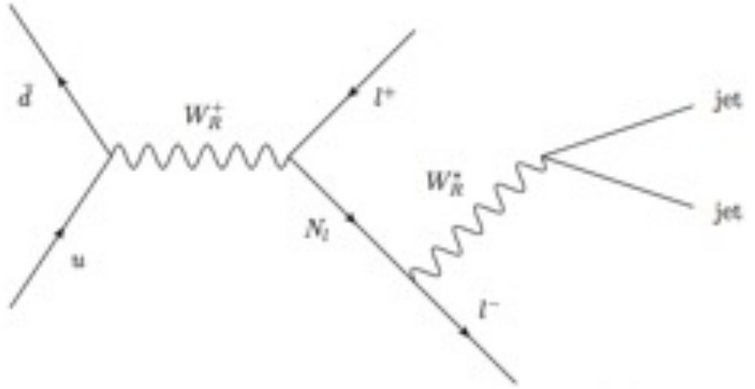
- Exclusion Limits now past 2 TeV



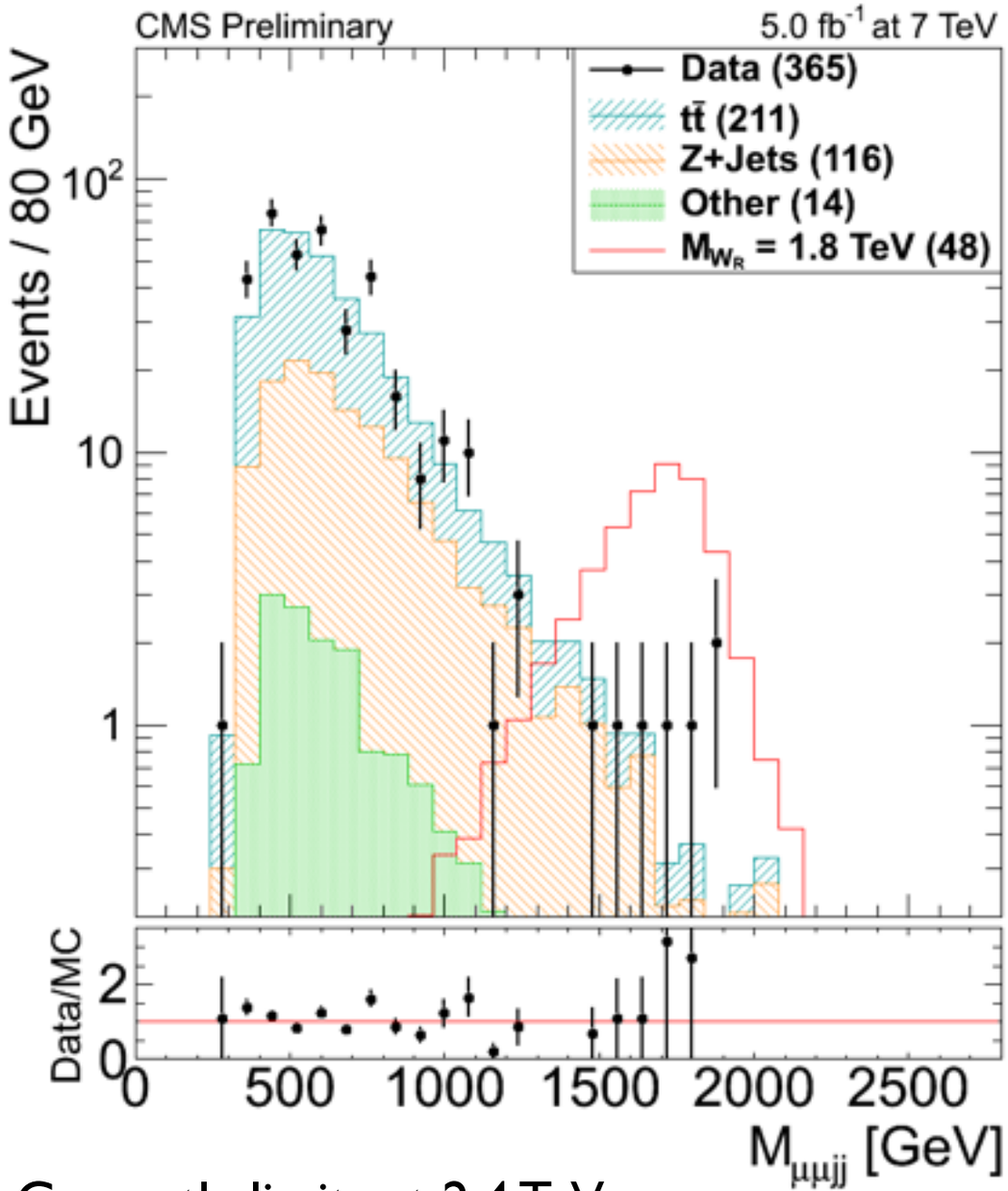
HEAVY NEUTRINO AND L-R SYMMETRY

	Standard Model	Left-Right-Symmetric Extension (LRSM)
Gauge group	$SU(2)_L$ X $U(1)_Y$	$SU(2)_L$ **X $SU(2)_R$** X $U(1)_{B-L}$
Fermions	LH doublets: $Q_L = (u^i,d^i)_L$, $L_L = (l^i,\nu^i)_L$ RH singlets: $Q_R = u^i_R$, d^i_R , $L_R = l^i_R$	LH doublets: $Q_L = (u^i,d^i)_L$, $L_L = (l^i,\nu^i)_L$ RH doublets: $Q_R = (u^i,d^i)_R$, $L_R = (l^i,N^i)_R$
Neutrinos	ν^i_R do not exist ν^i_L are massless & pure chiral	N^i_R are heavy partners to the ν^i_L N^i_R Majorana in the Minimal LRSM
Gauge bosons	$W^{\pm}_L$, Z^0, γ	$W^{\pm}_L$, **$W^{\pm}_R$**, Z^0, **Z'**, γ

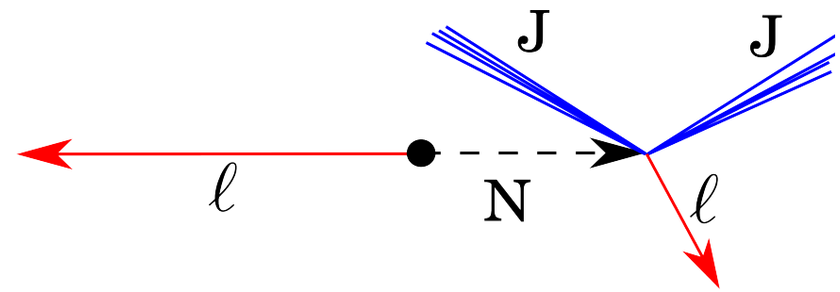
- Parity violation built-in for the Standard Model
  - Parity violation in LRSM via symmetry breaking at intermediate mass scale
- Neutrino oscillations require massive neutrinos
  - but neutrinos mass forbidden in SM
  - "See saw" mechanism in LRSM can explain small mass of neutrinos via heavy partners

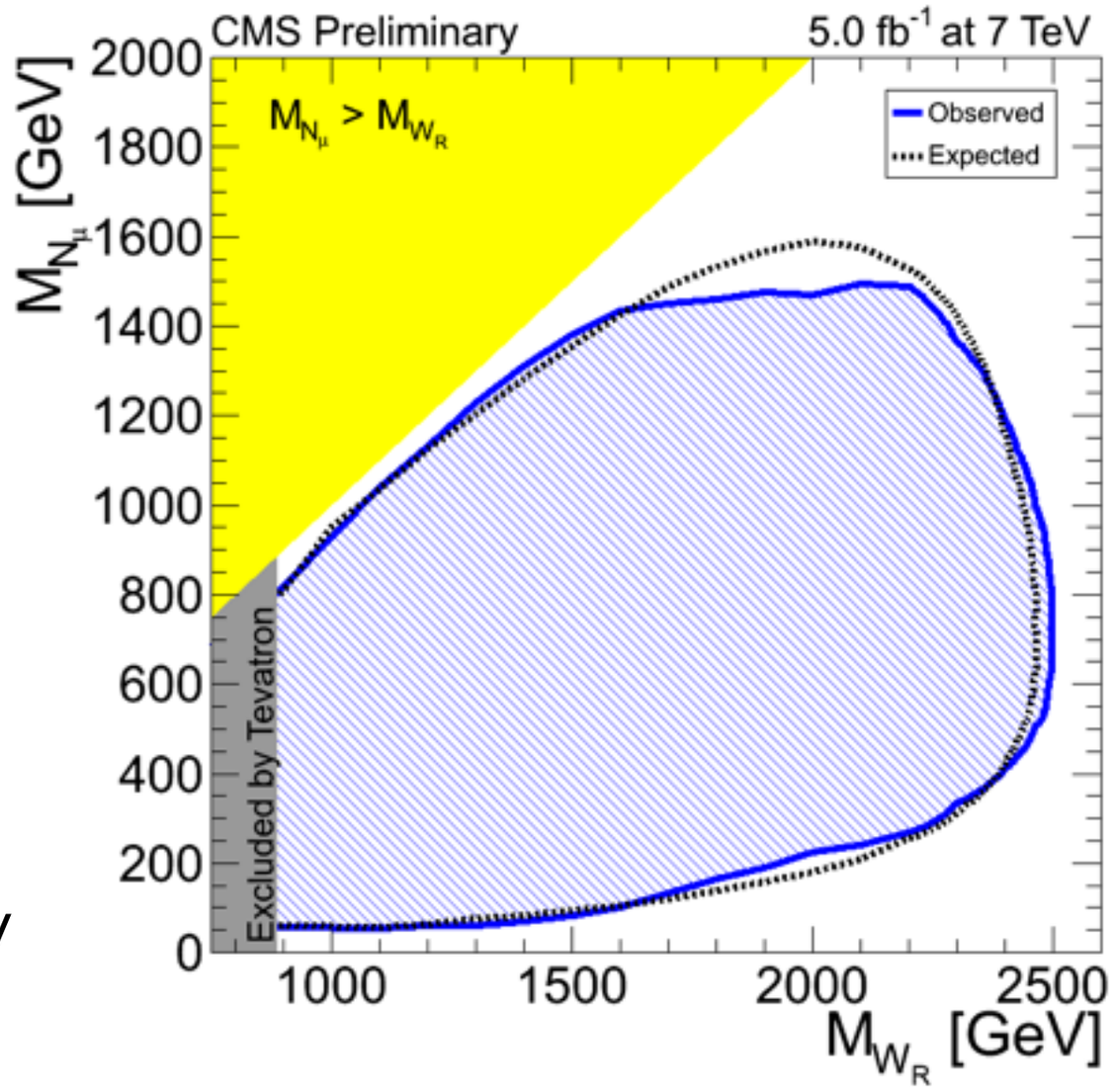


HEAVY NEUTRINO AND W_R



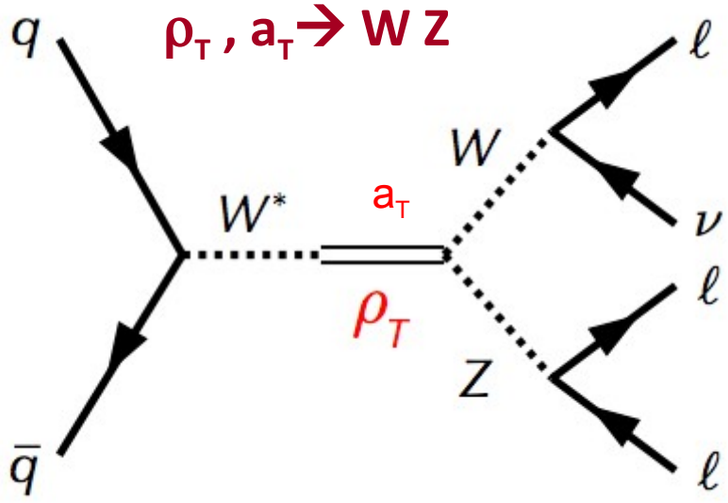
$$W_R \to \mu_1 N_\mu \to \mu_1 \mu_2 W_R^* \to \mu_1 \mu_2 jj$$





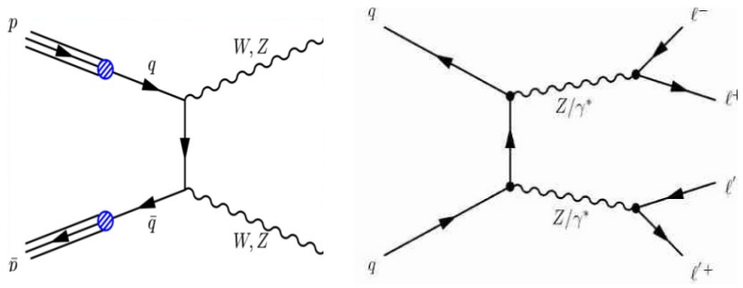
- Currently limits at 2.4 TeV
  - Most stringent limits today!
- Gets very interesting for theory once limits at 2.5 TeV
- Enhanced cross section at 8 TeV with

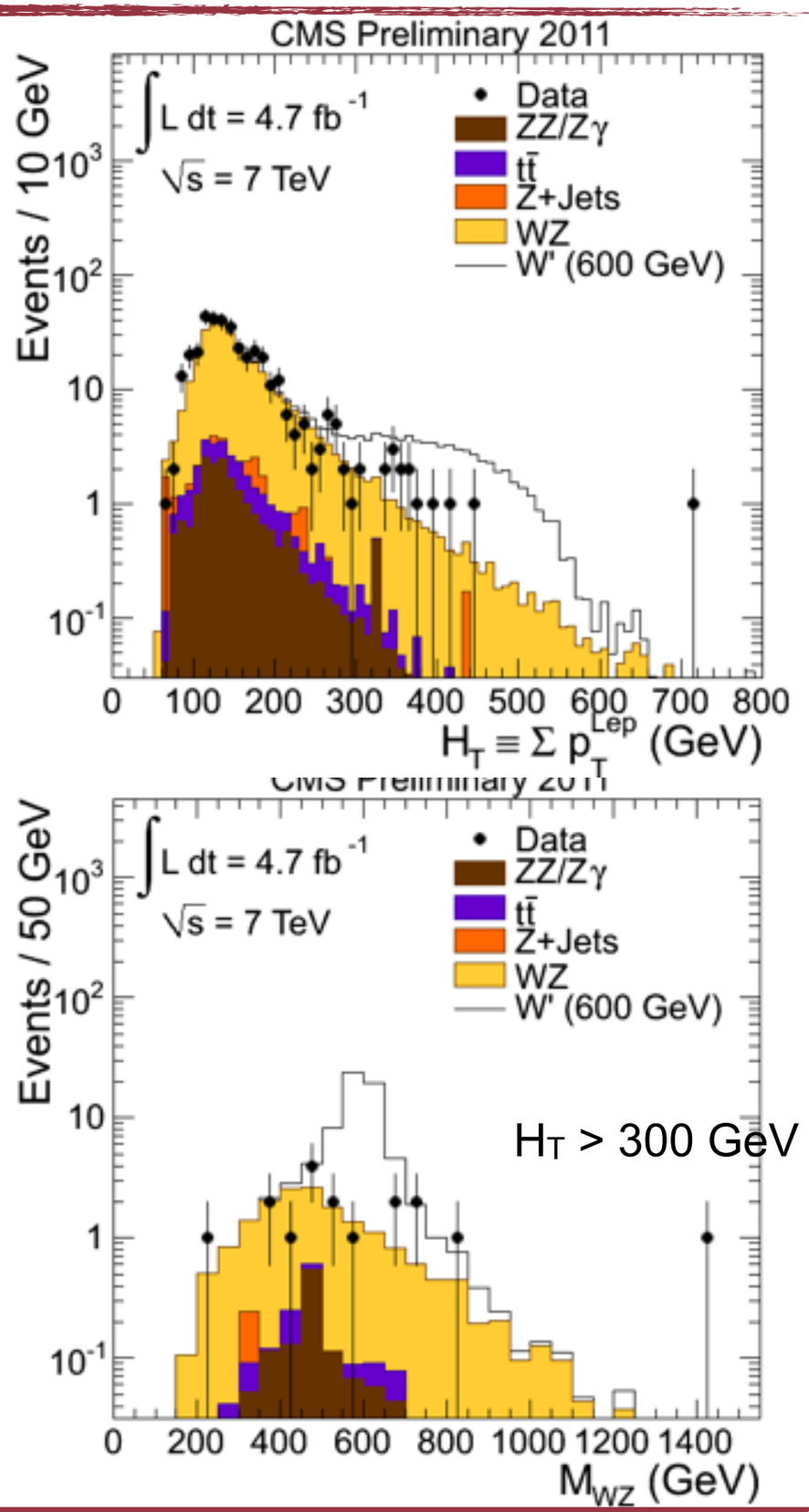
WZ Resonances



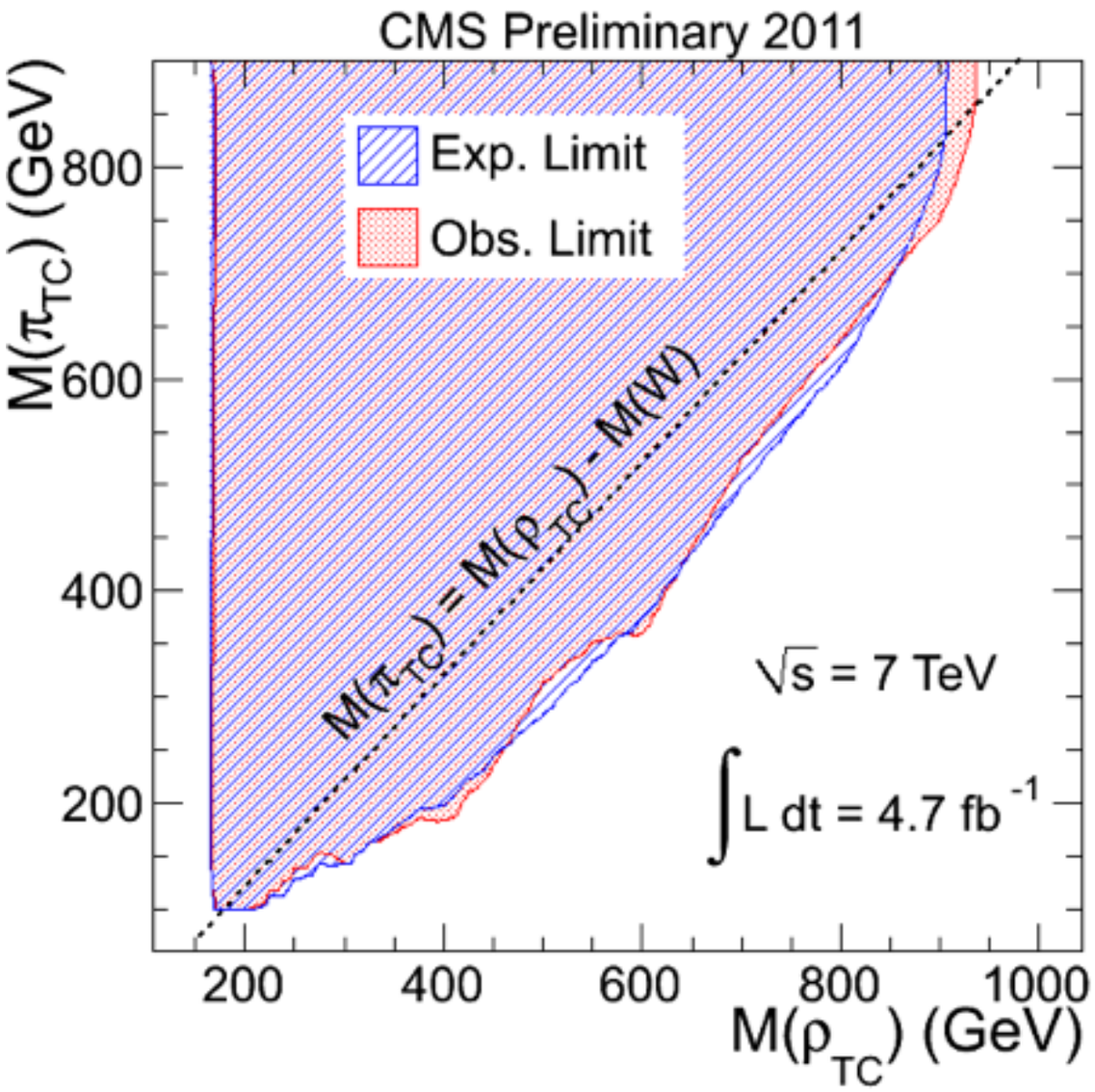
- Sensitive to sequential SM and techni-hadrons
- 3 leptons + missing energy
  - Sum of lepton Pt
  - WZ invariant mass with W mass constraint

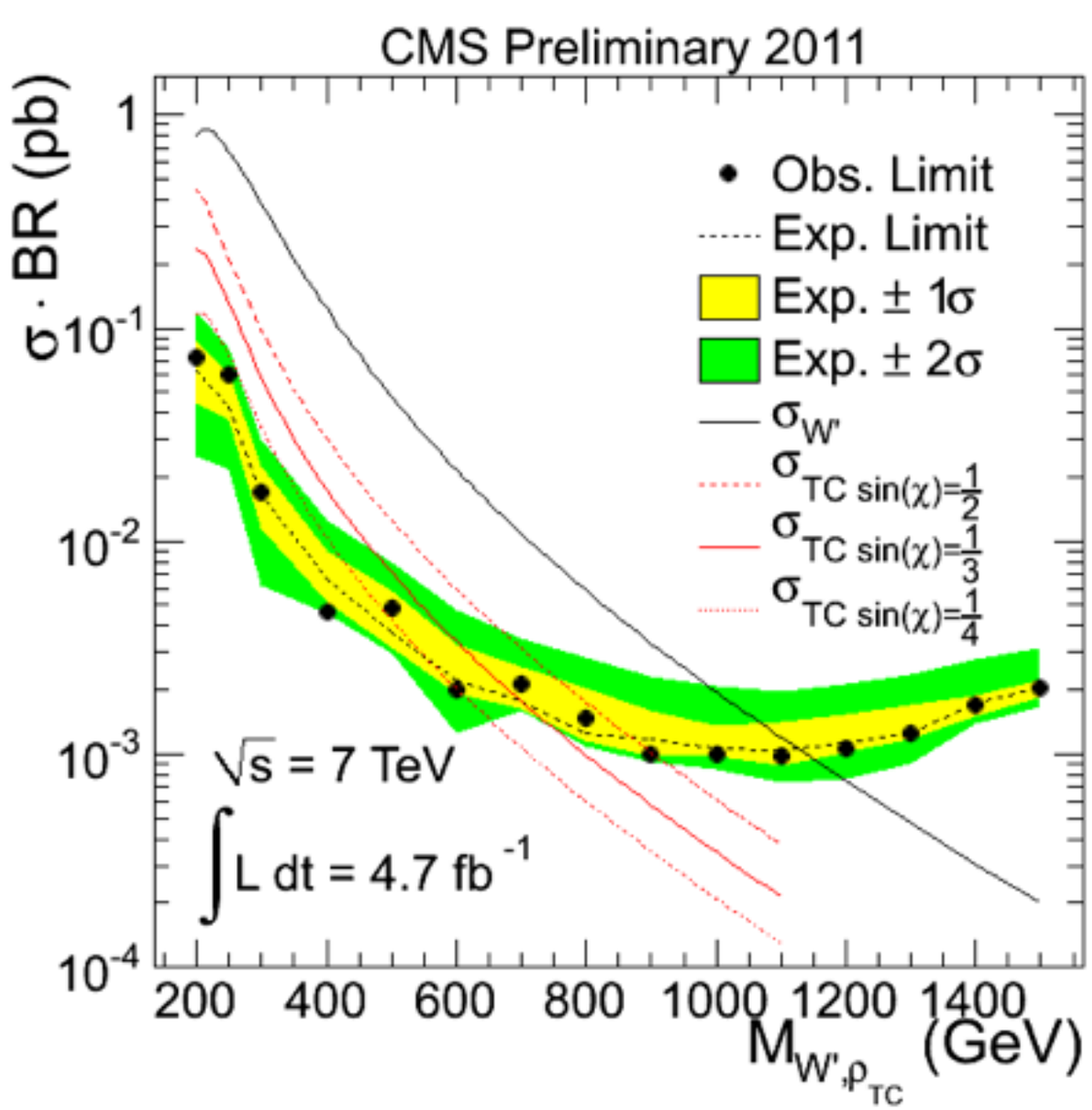
- Scalar sum of transverse momenta a key discriminator to reject SM background





WZ Exclusion Limits

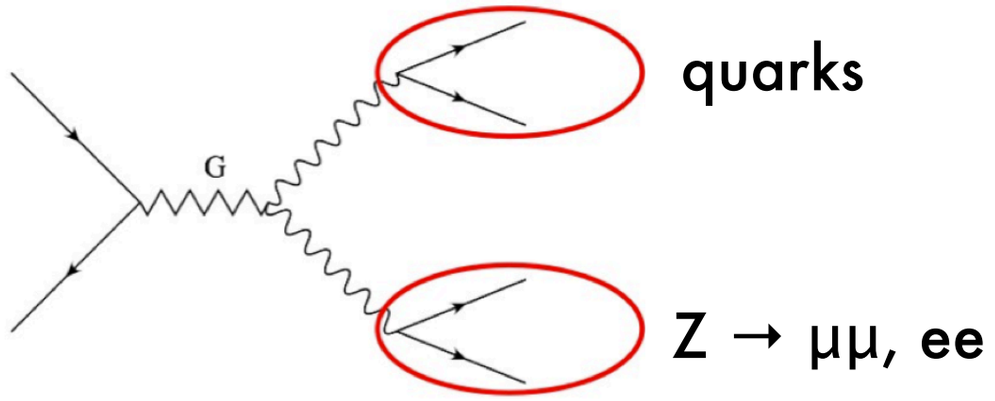


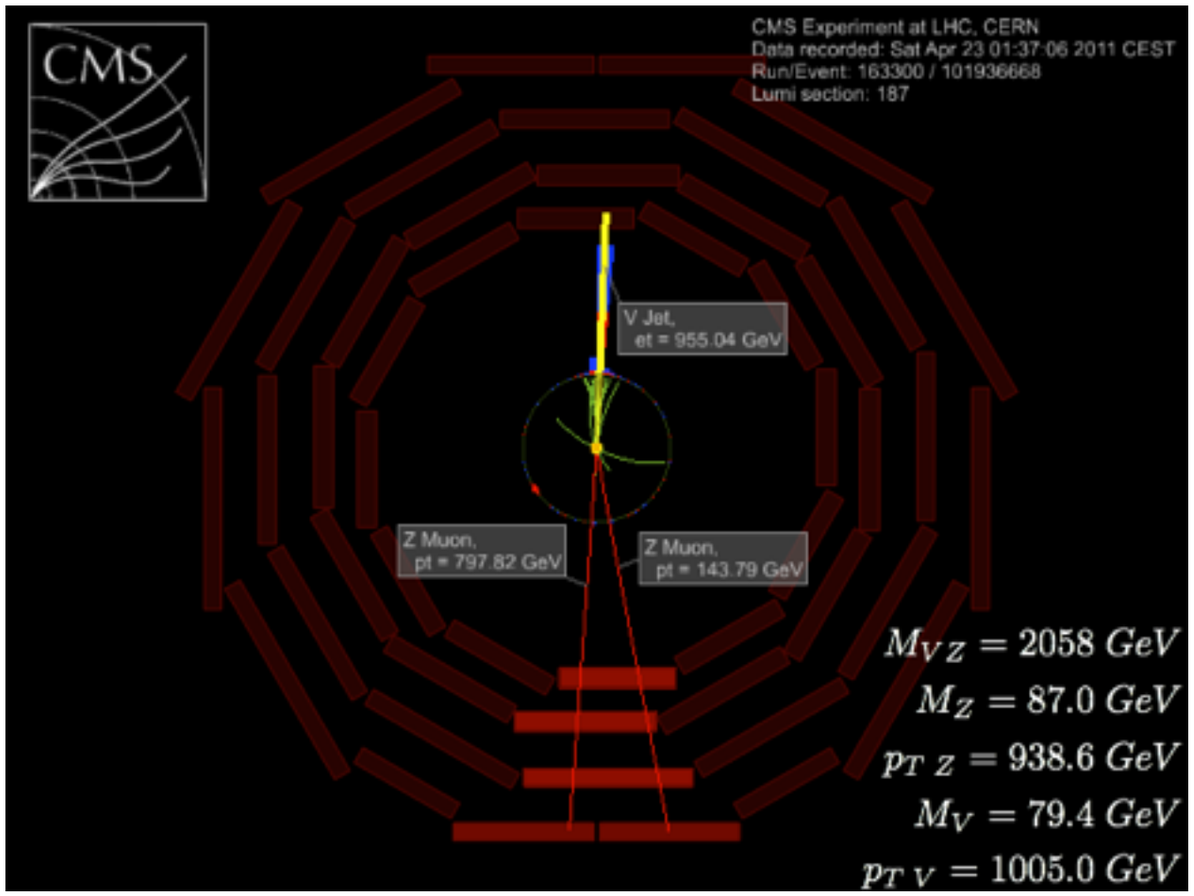


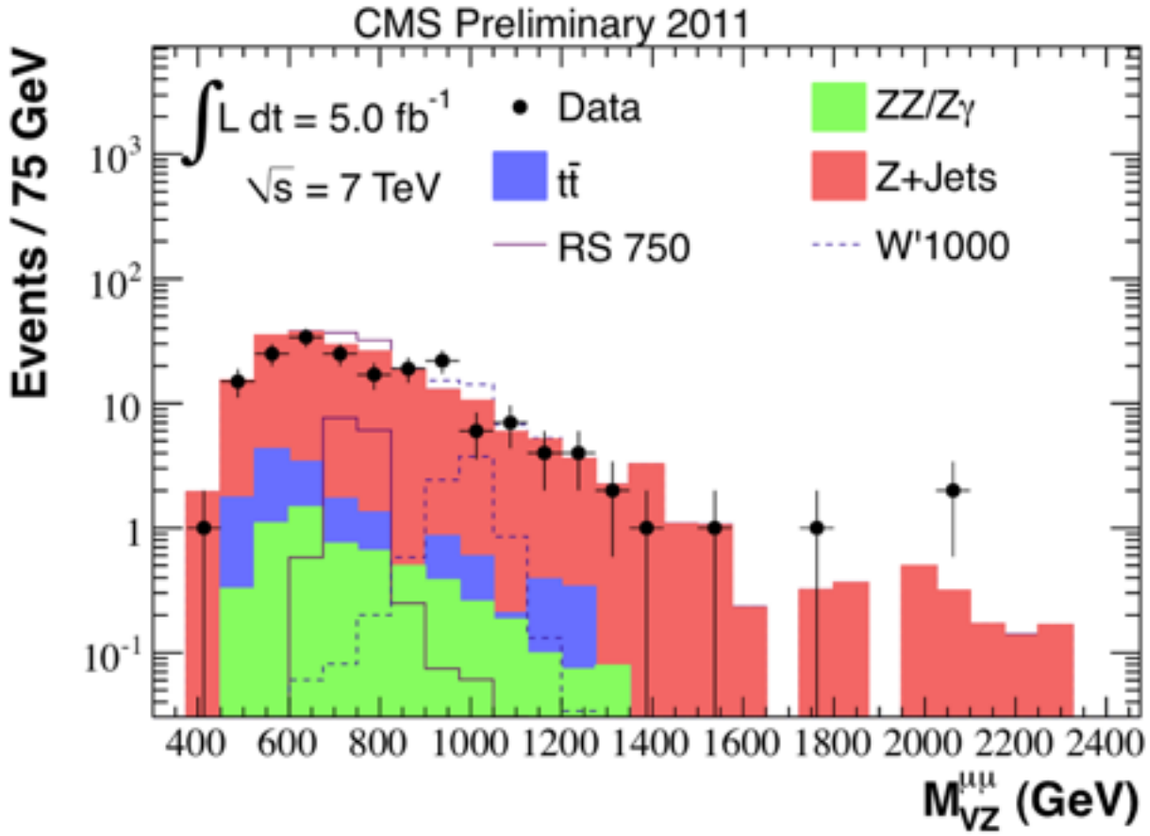
WZ AND ZZ RESONANCES

$$pp \to G^* \to ZZ \to q\bar{q}\,l^+l^-$$

$$pp \to W' \to WZ \to q\bar{q}\,l^+l^-$$



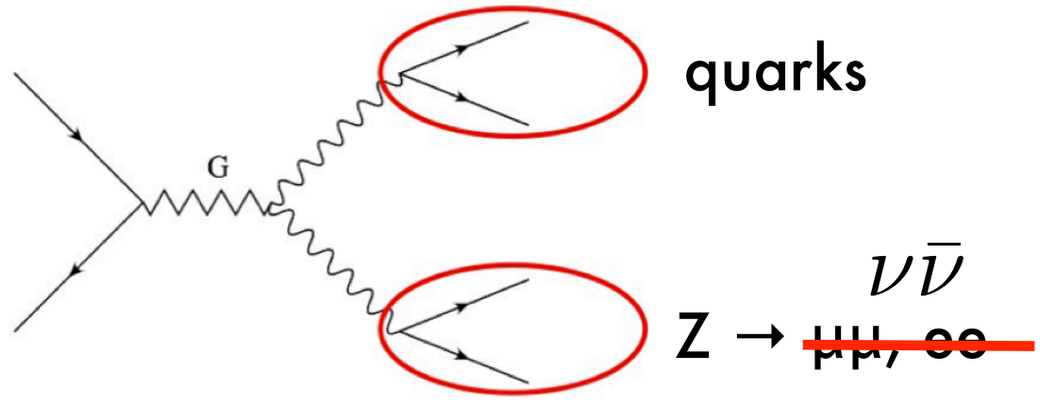


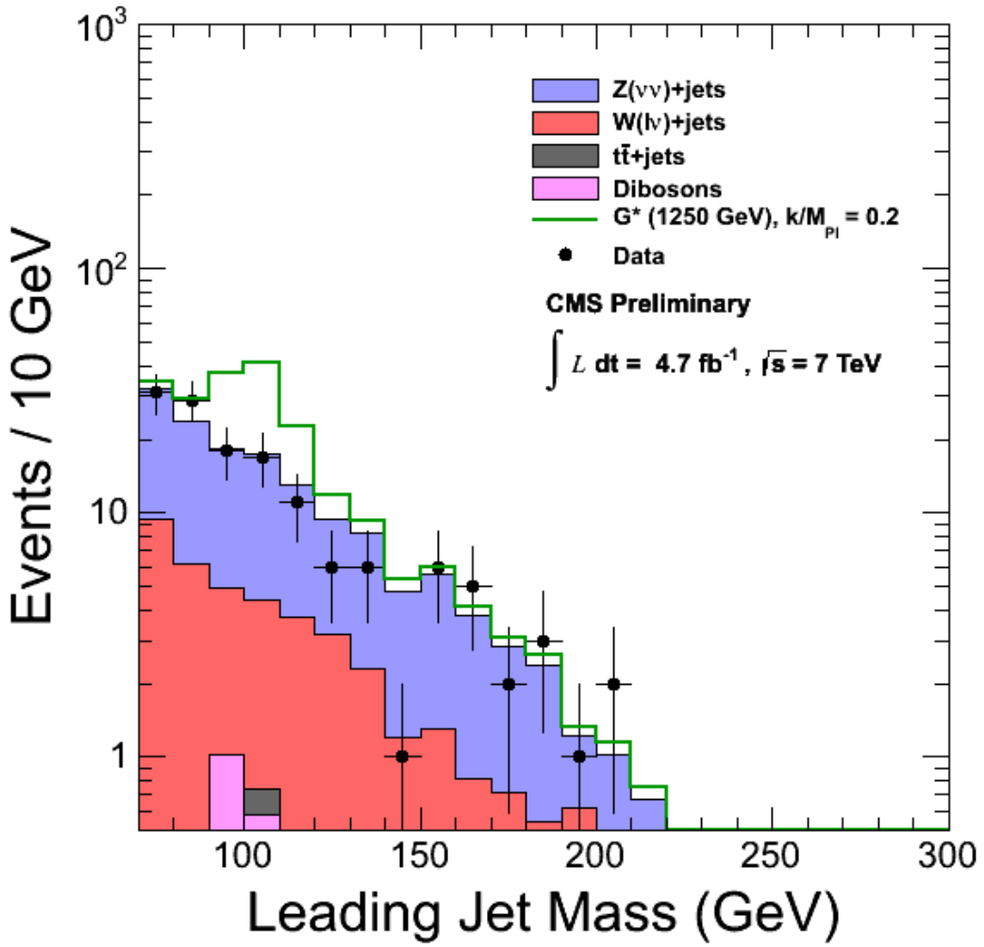


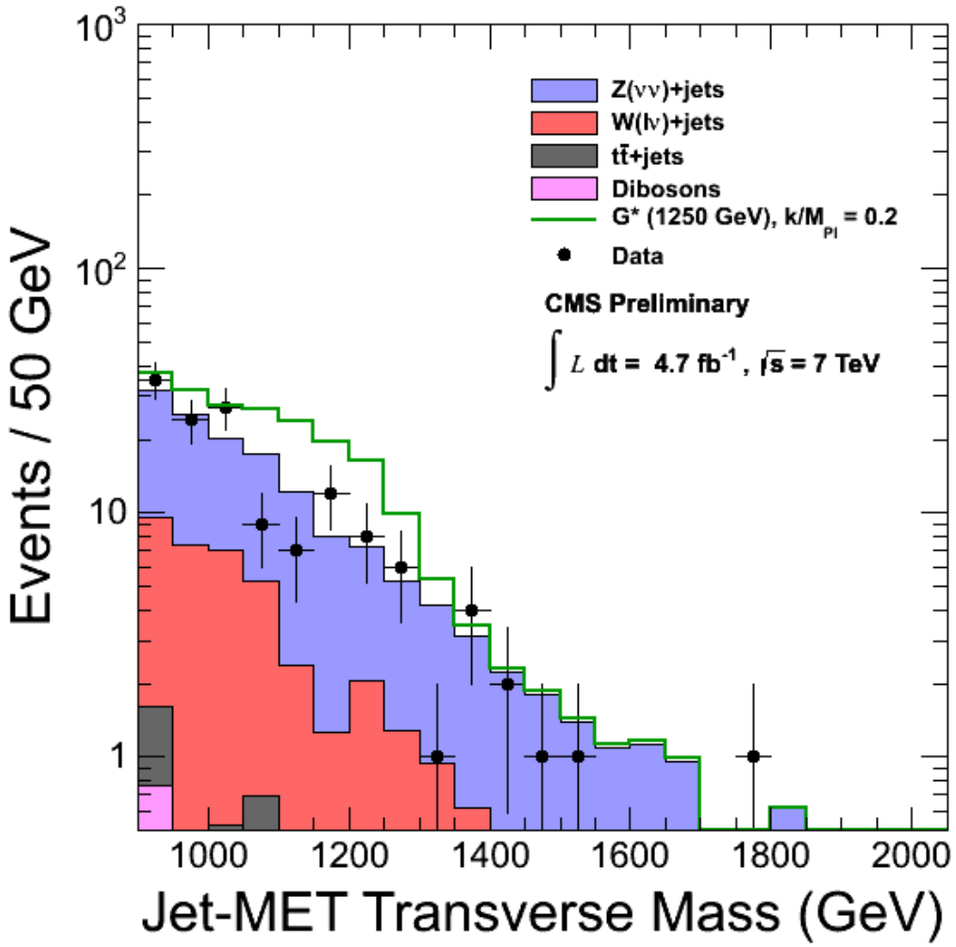
- For very heavy resonances hadronic W and Z merge into one fat jet
  - jet energy resolution

ZZ Resonance

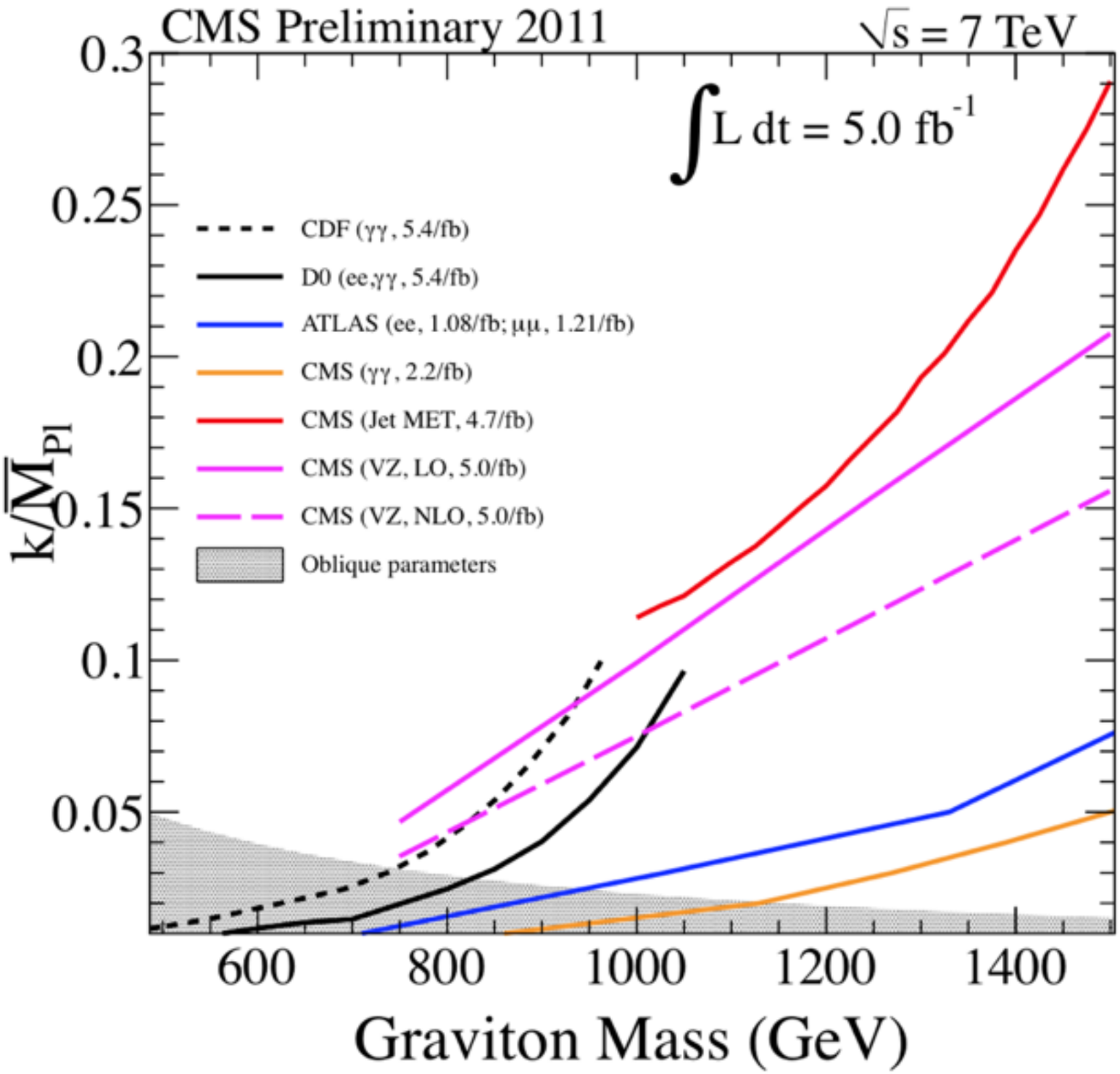
$$pp \to G^* \to ZZ \to q\bar{q}\,\nu\bar{\nu}$$



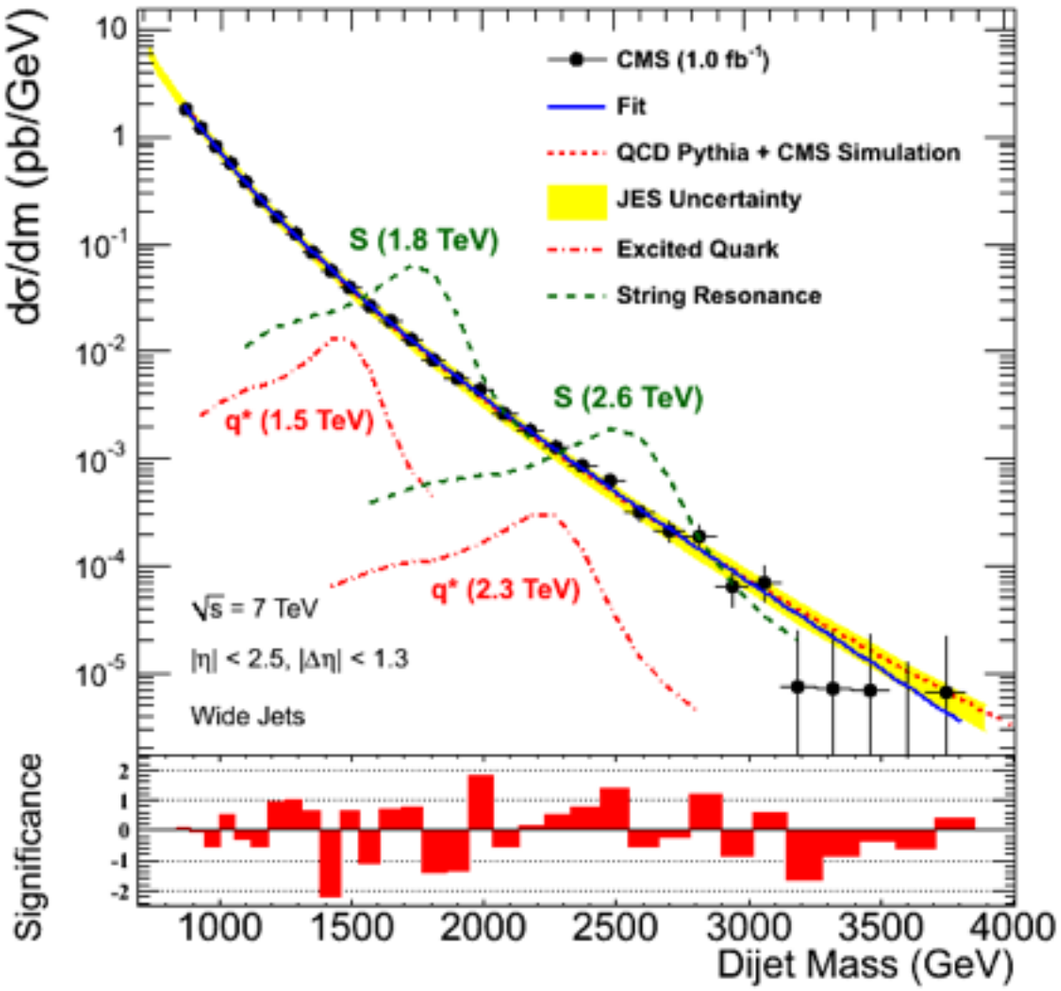


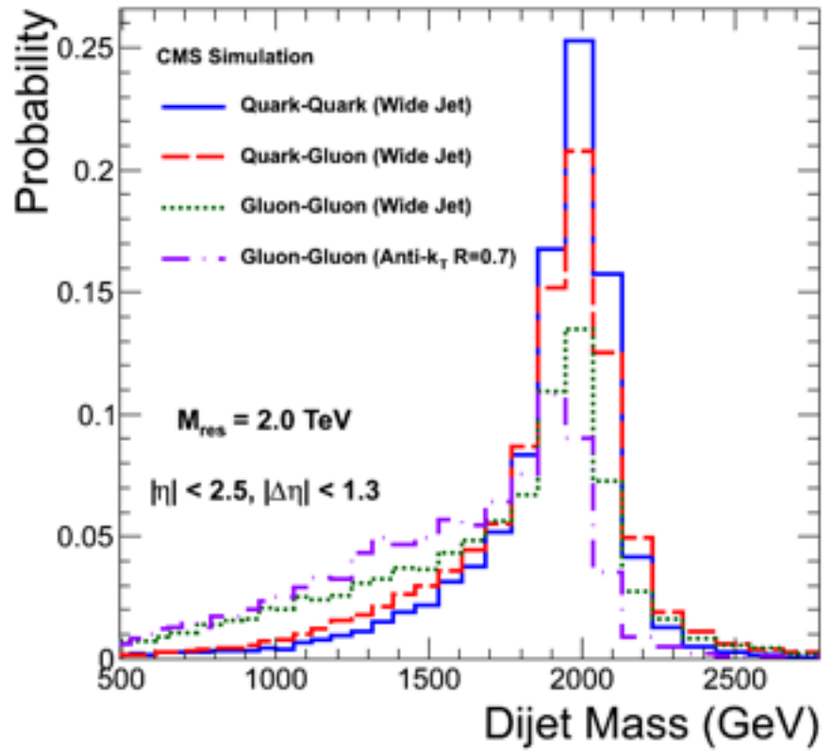


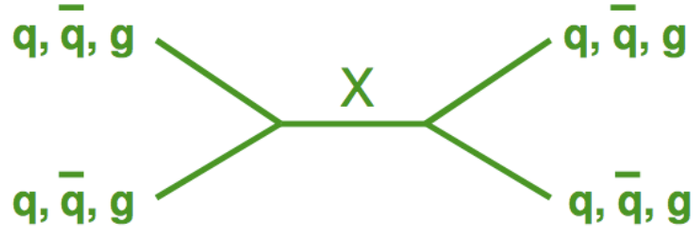
CONSTRAINTS ON GRAVITONS



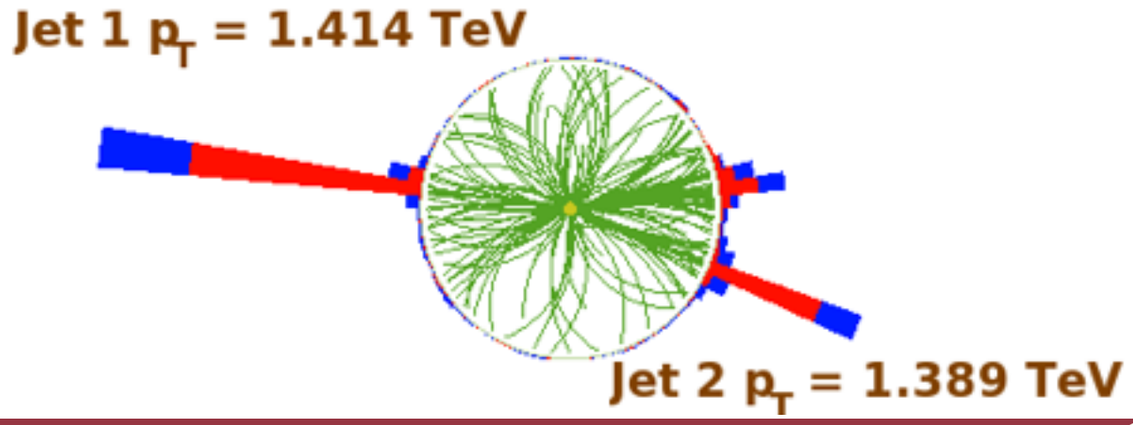
DI-JET



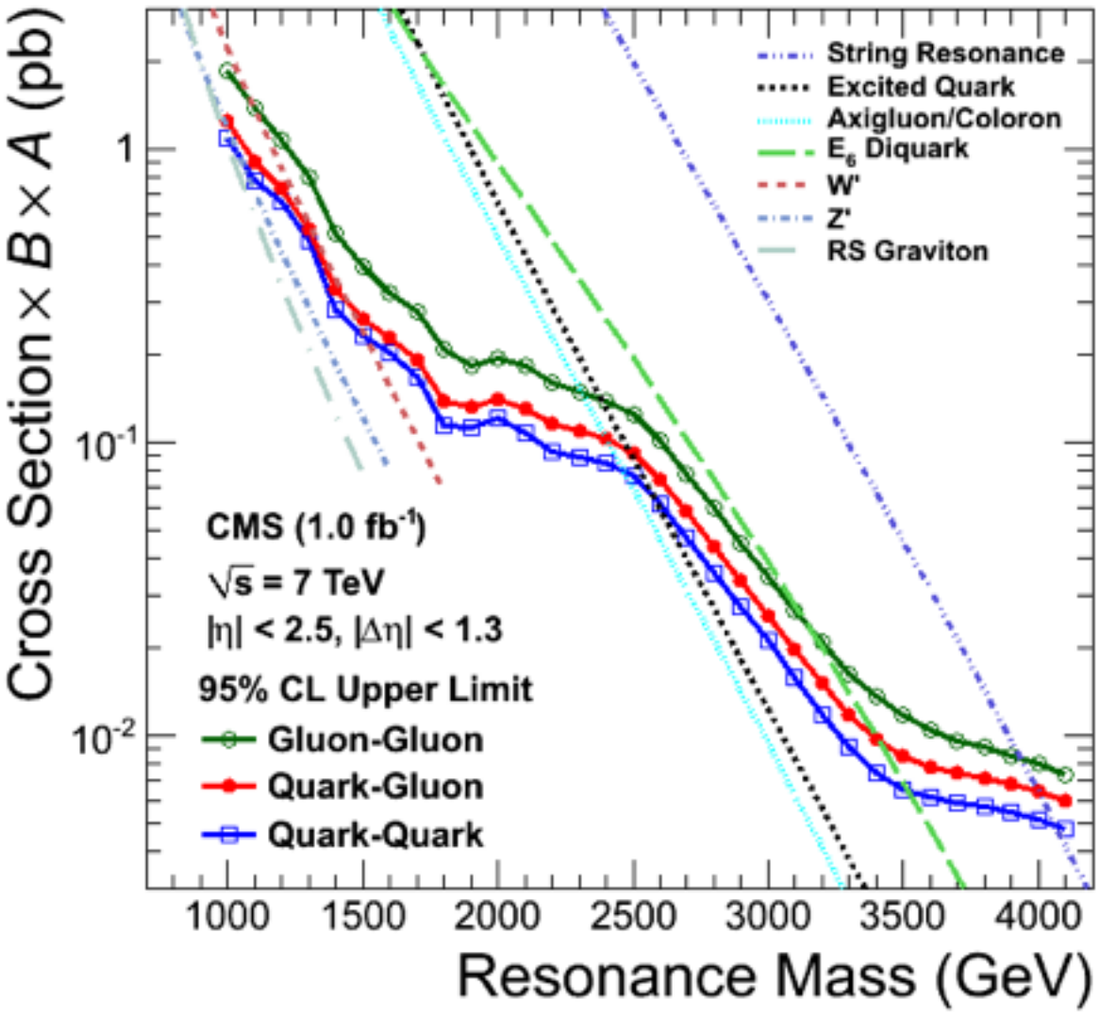


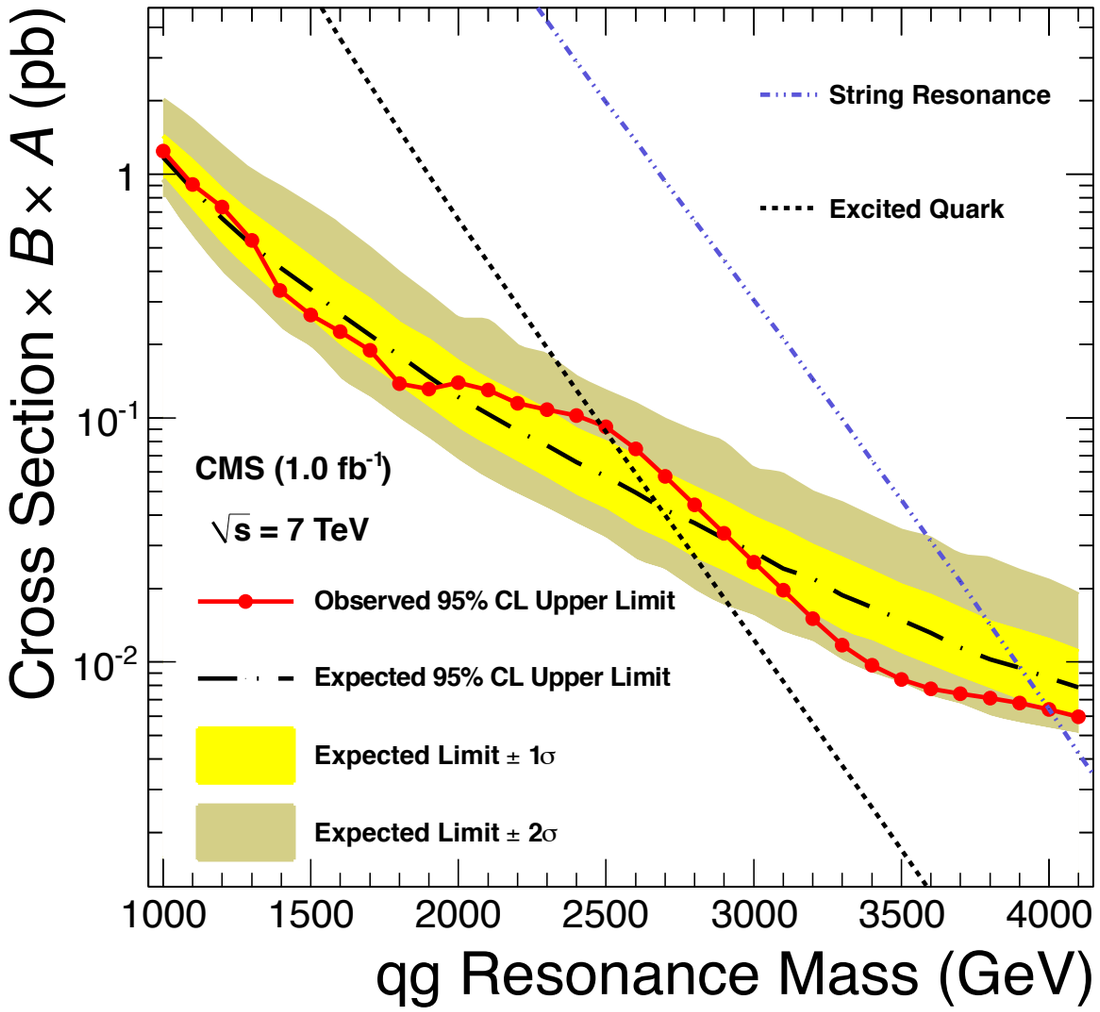


- Resonances predicted in numerous models
  - larger branching fraction compared to dileptons
  - much higher background from QCD
- Wide jets to recover radiation
  - divide event in 2 hemispheres



DI-JET EXCLUSION LIMITS



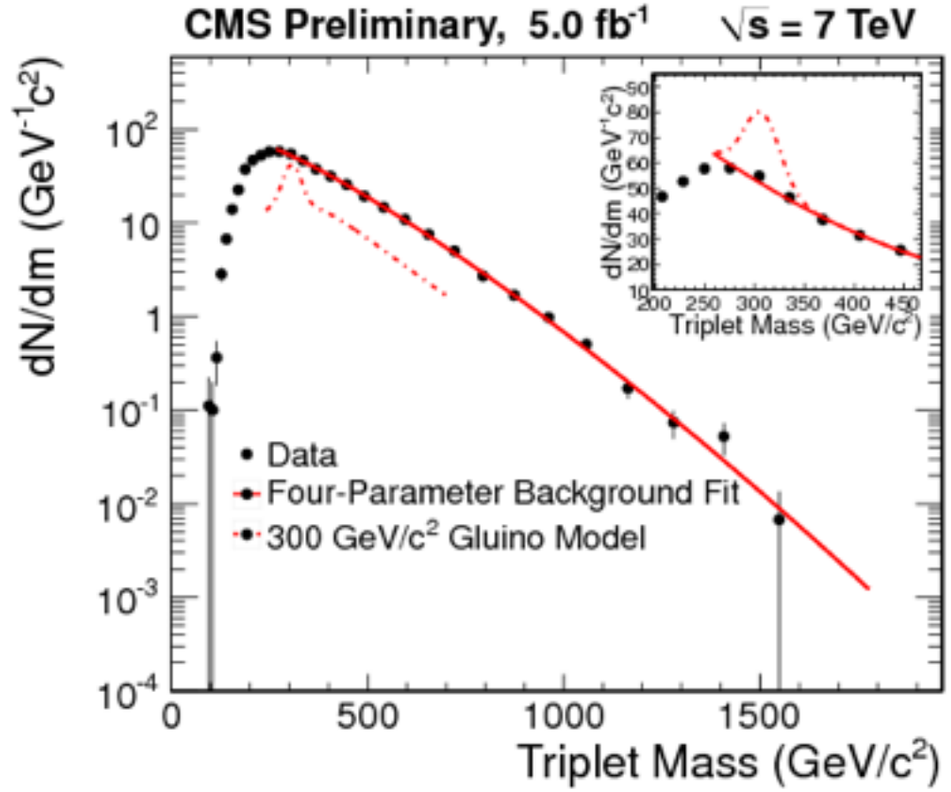


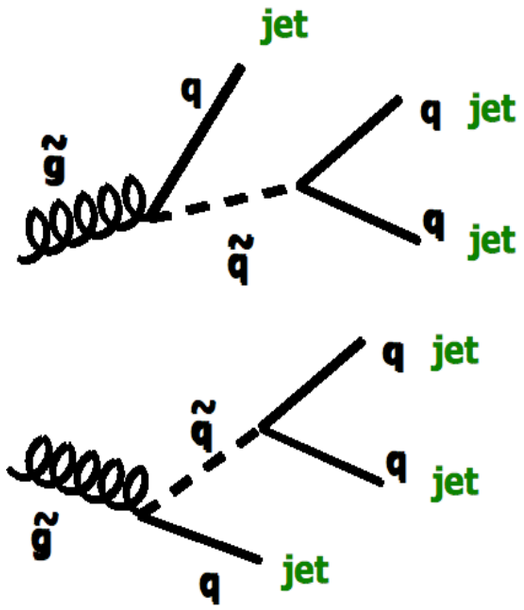
- Now excluding resonances below 2.5 TeV for variety of models

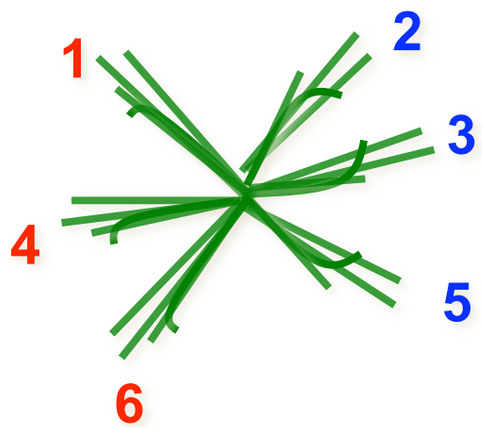
TRI-JET RESONANCE

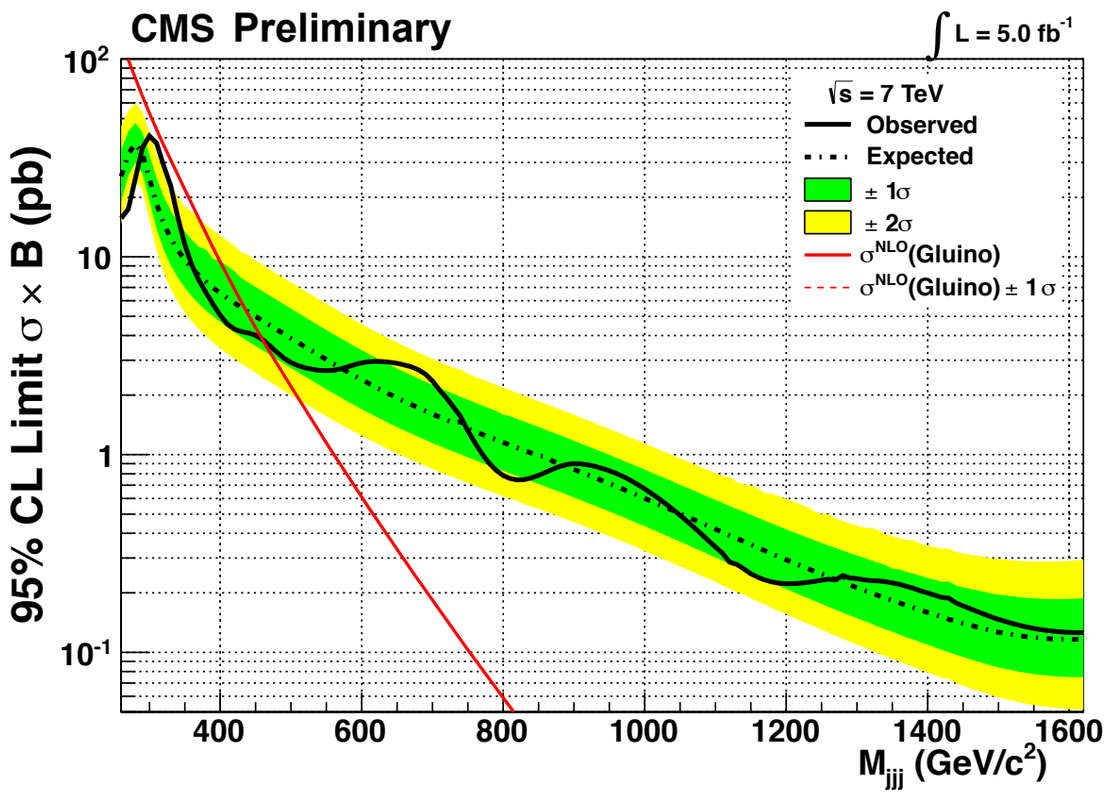
- 6 jets in several theoretical models
  - Q = g = SU(3)C Adjoint Majorana Fermion
  - R-Parity violating (No Missing ET)
- Modeled as R-parity violating gluino (negligible intrinsic width)

$$pp \rightarrow QQ \rightarrow 3j + 3j$$

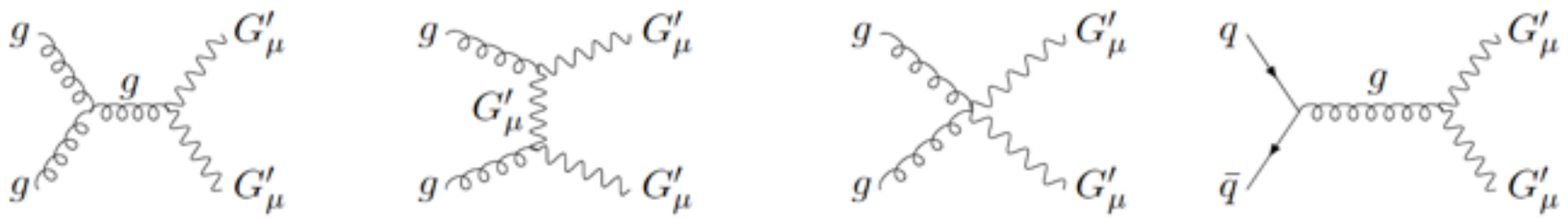


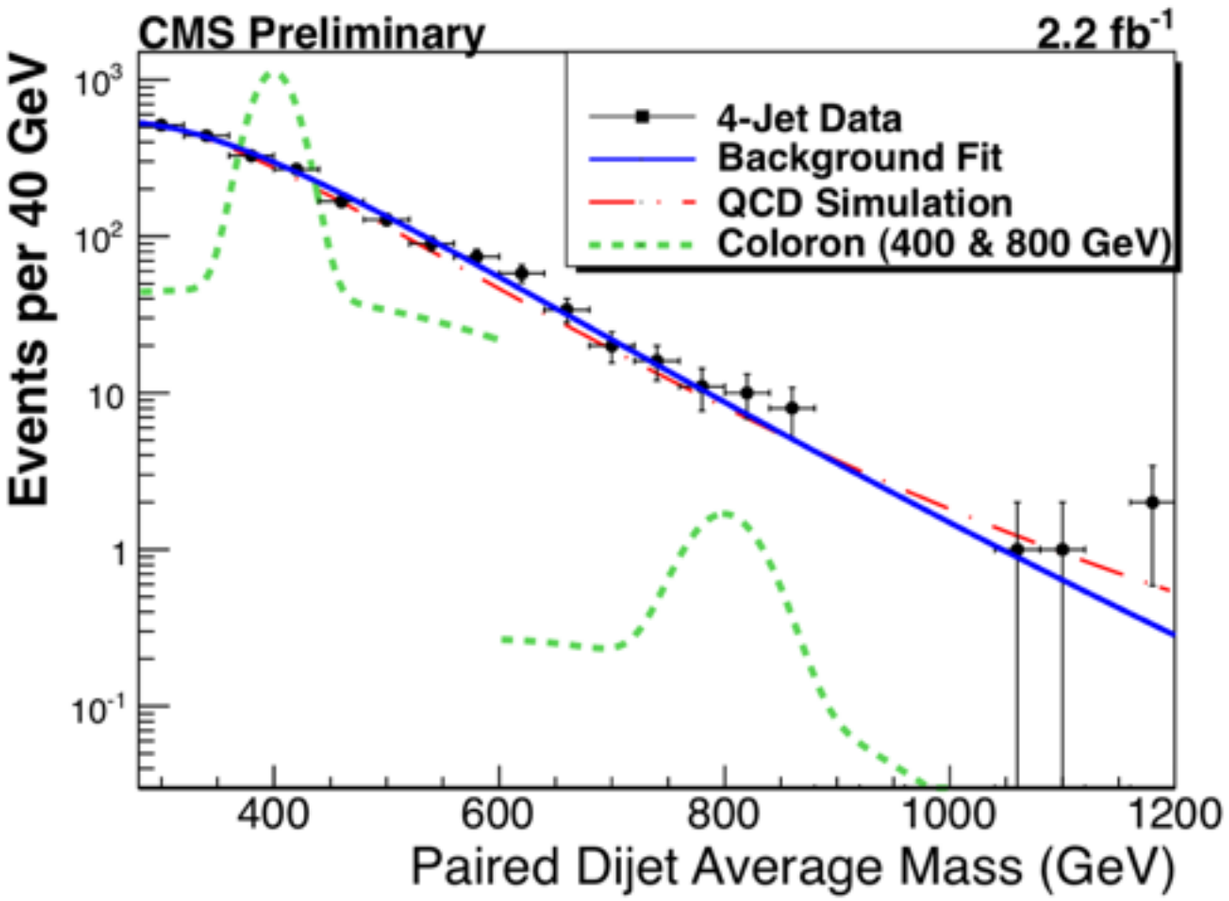


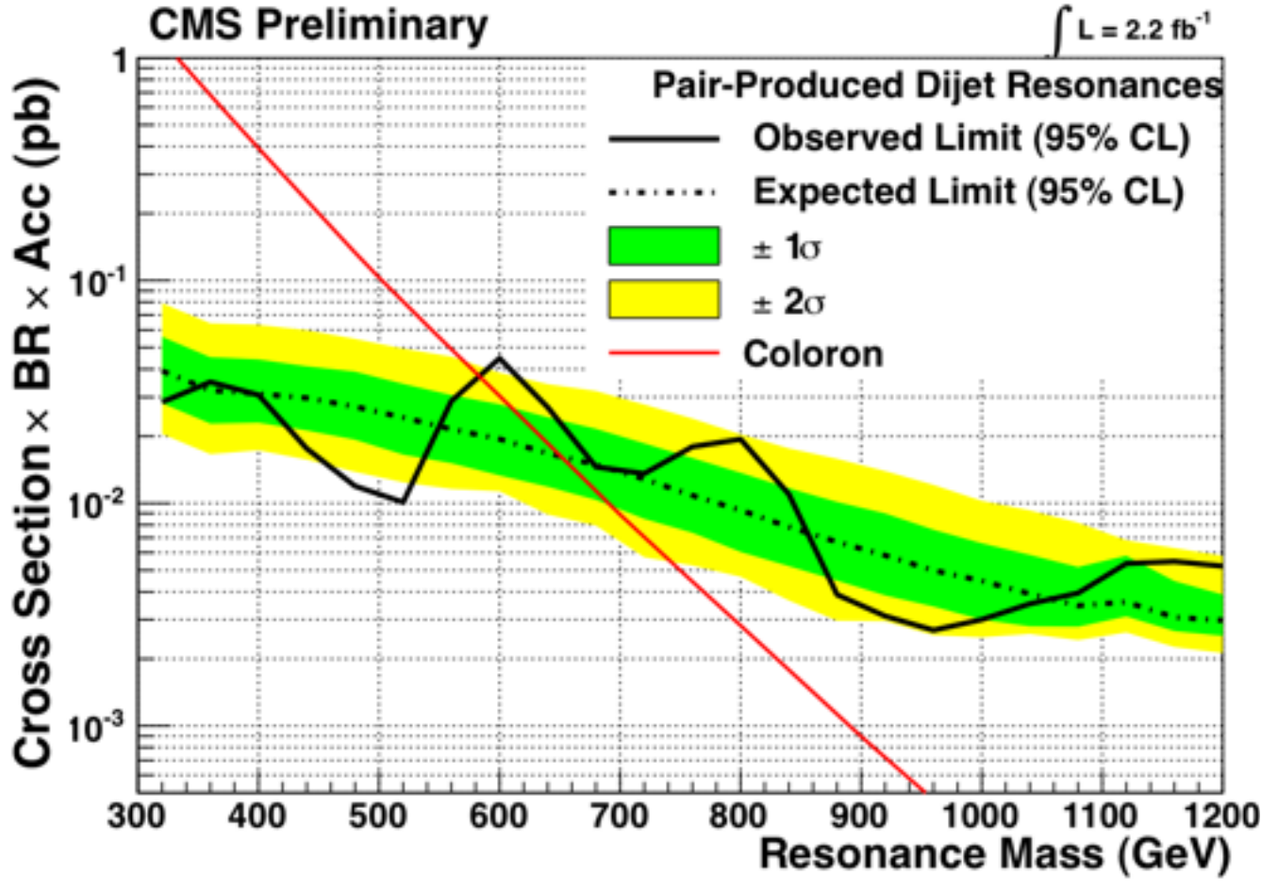


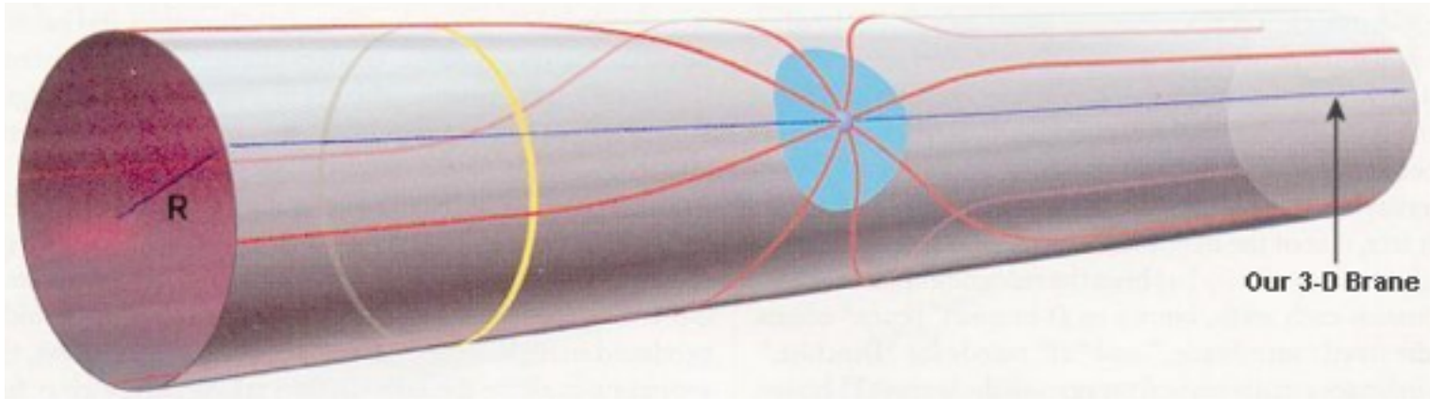


DI-JET PAIR


g
g
g
G'_μ
G'_μ
G'_μ
G'_μ
G'_μ
G'_μ
q
$\bar{q}$


CMS Preliminary
2.2 fb-1
4-Jet Data
Background Fit
QCD Simulation
Coloron (400 & 800 GeV)
Events per 40 GeV
Paired Dijet Average Mass (GeV)


CMS Preliminary
∫ L = 2.2 fb-1
Pair-Produced Dijet Resonances
Observed Limit (95% CL)
Expected Limit (95% CL)
± 1σ
± 2σ
Coloron
Cross Section × BR × Acc (pb)
Resonance Mass (GeV)



Fundamental Planck Scale

Apparent Planck Scale

# of EDs

$$M_{Pl}{}^2 \sim M_D{}^{2+n} R^n$$

Size of ED

Extra Dimensions

- Large Extra Dimension (ADD)
  - only graviton propagates in the bulk
- Warped Extra Dimension (a la Randall-Sundrum)
  - as ADD with warped geometry for extra dimension $M_{\mathrm{D}} = M_{\mathrm{Pl}} e^{-k r_c \pi}$
- Universal Extra Dimension (UED)
  - all particles propagate in the bulk

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 $M_{BH} = \sqrt{\hat{s}}$ could collide at a distance smaller than r_h
- such collisions satisfy the black hole definition but with tiny mass

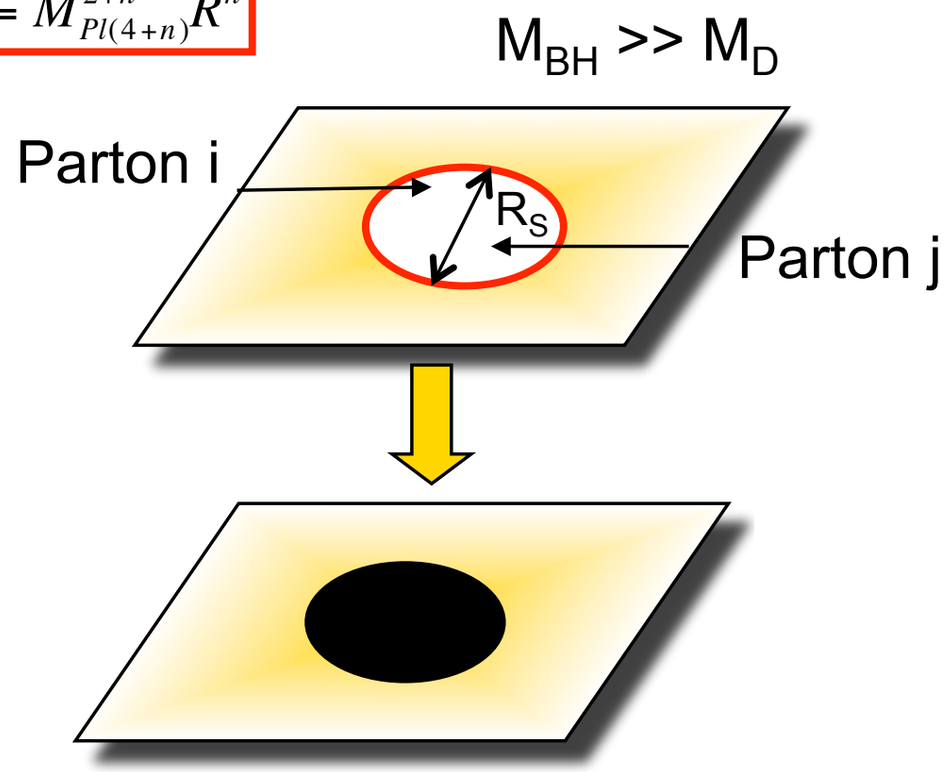
BLACK HOLES? REALLY?

PRODUCTION AND DECAY OF BLACK HOLES

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

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

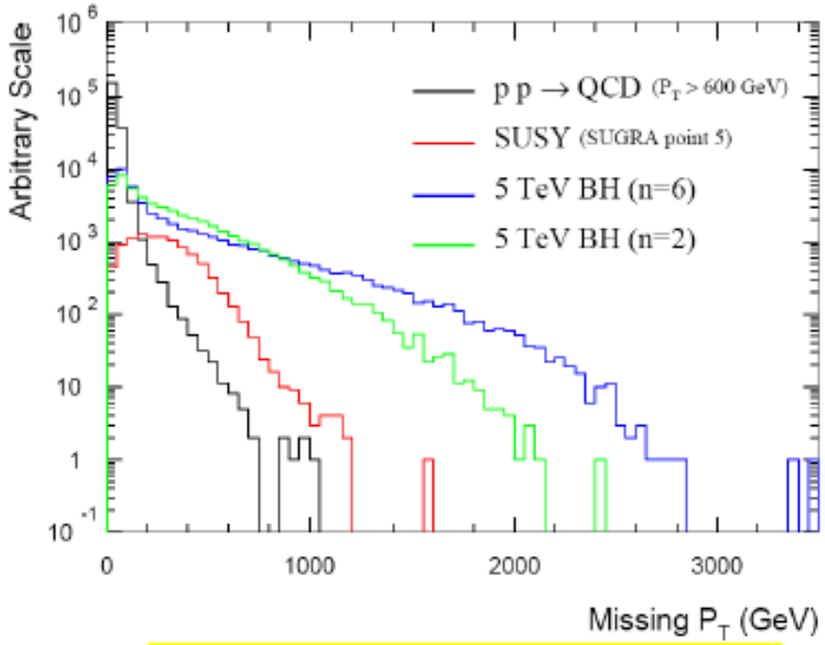
area ~ πR_S^2 ~ 1 TeV $^{-2}$ ~ 10^{-38} m^2 ~ 100 pb
Production rate of ~0.1 Hz at L = 10^{34}cm^{-2} s^{-1}



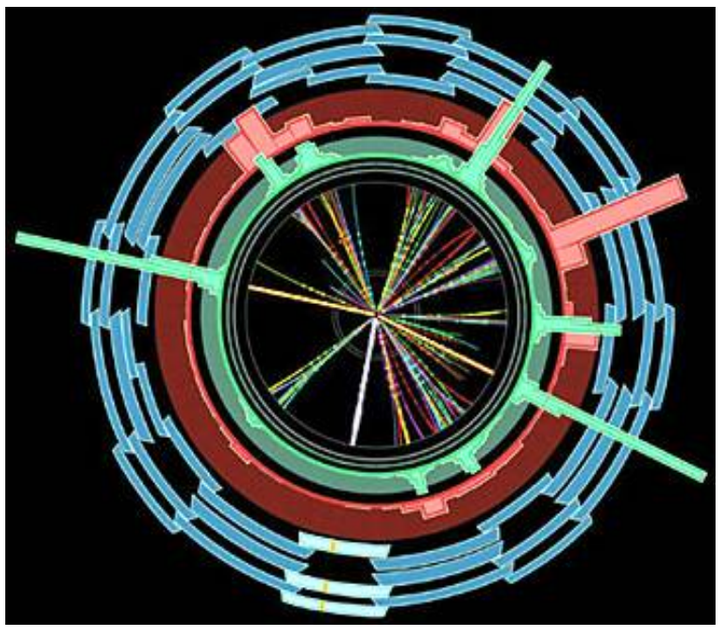
- Hawking evaporation with lifetime $\tau \sim 10^{-27}$ sec

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

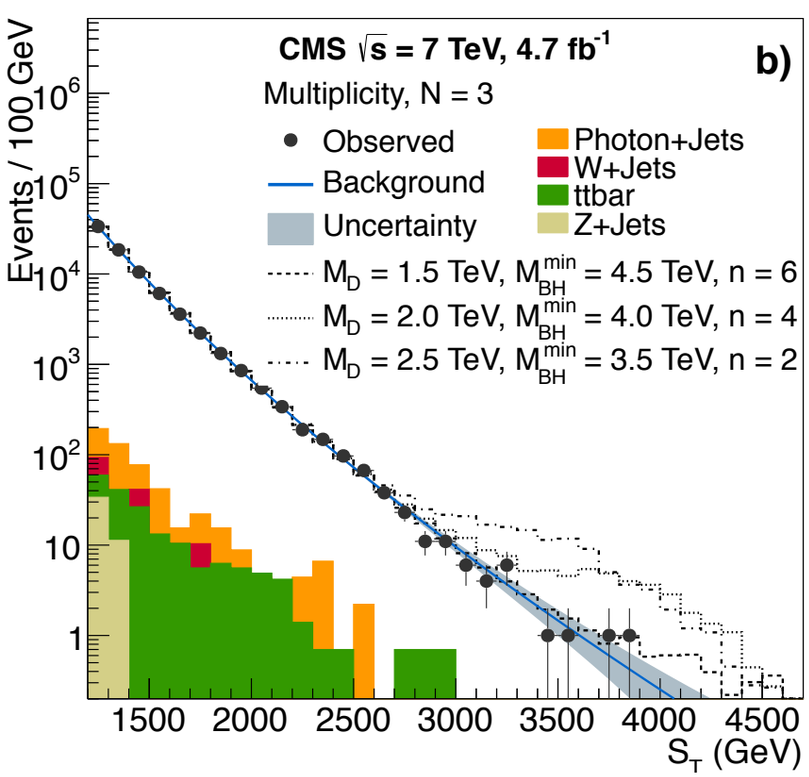


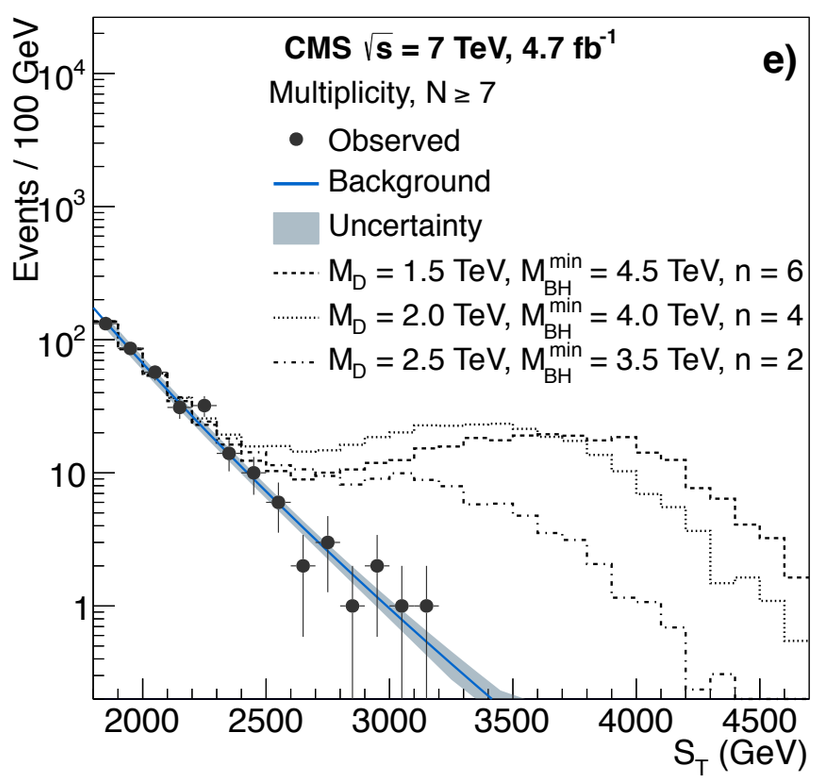
- Could be discovered with 1 fb^{-1} if M_{Pl} < 5 TeV!

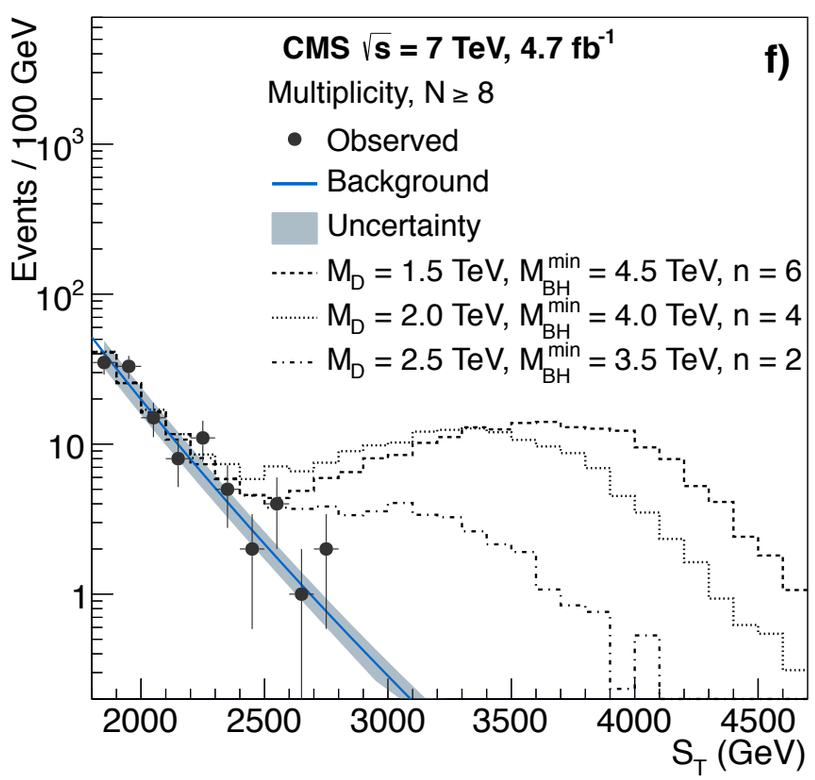


MICROSCOPIC BLACK HOLES

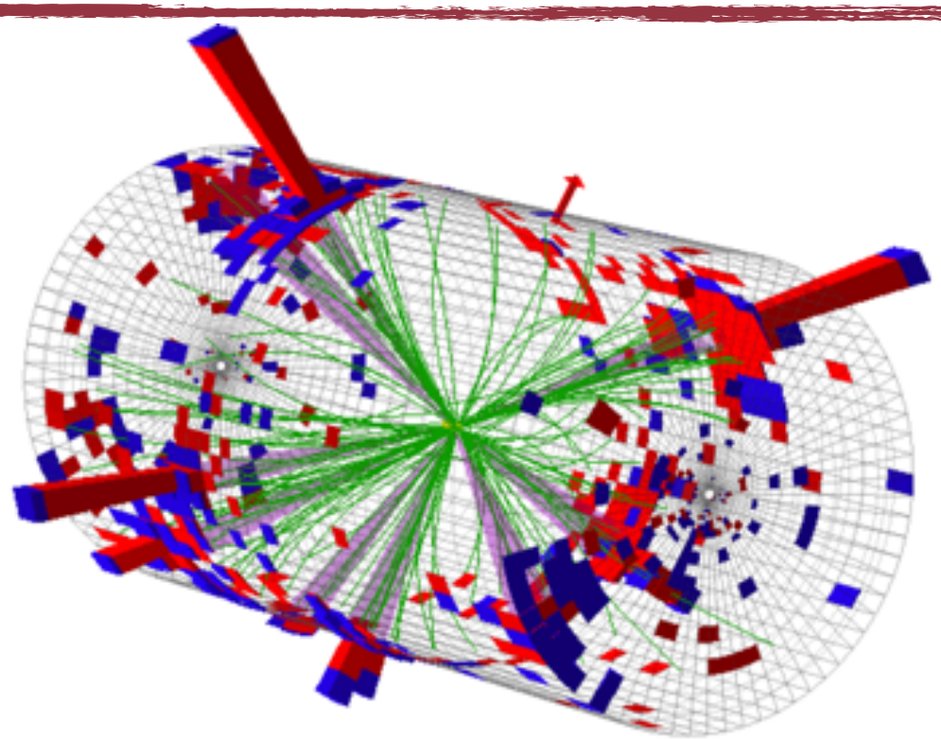
- Analysis strategy: events with large transverse energy, multiple high- energy jets, leptons, and photons
- Main Standard Model background: QCD multijet production
- Discrimination variable: visible transverse energy
  - scalar sum of ET for identified physics objects and MET
- Estimate background shape from low multiplicity events

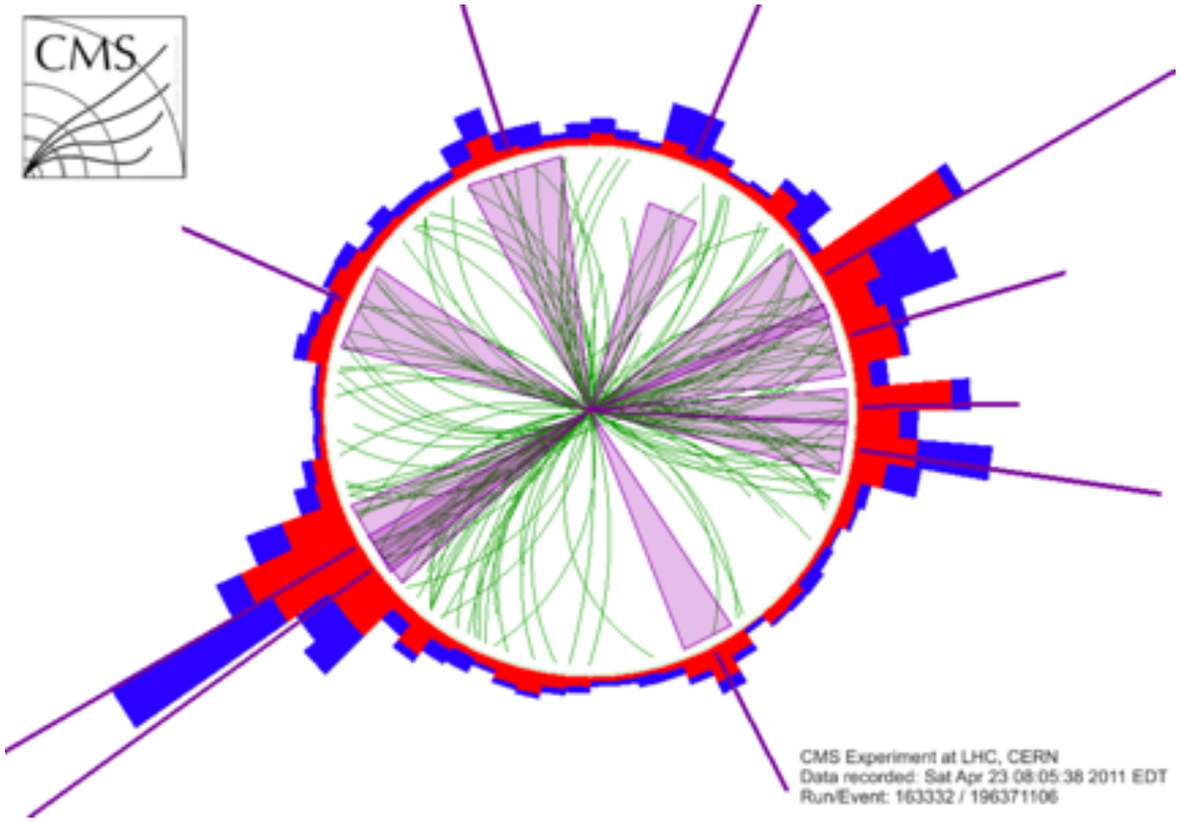




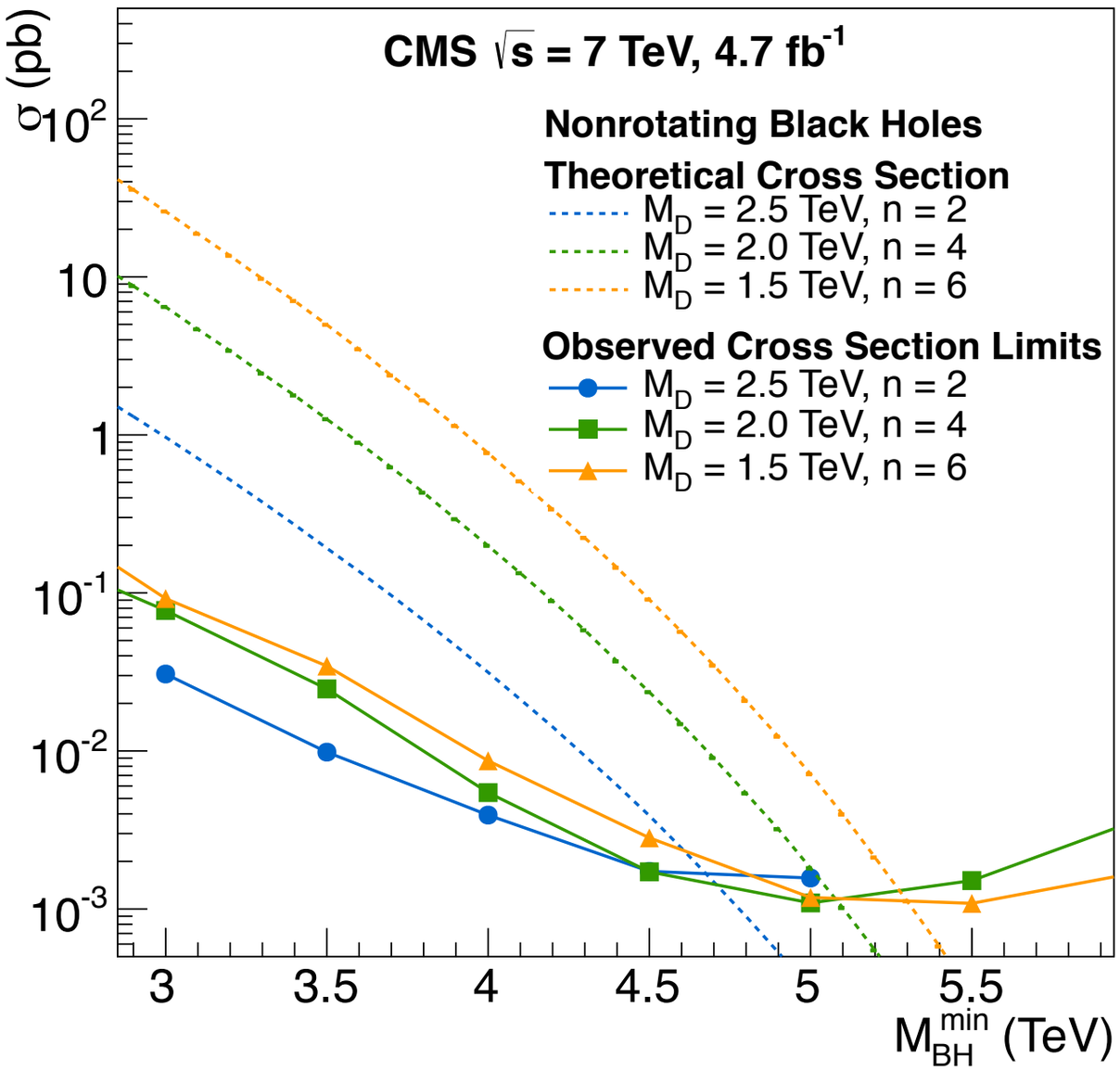


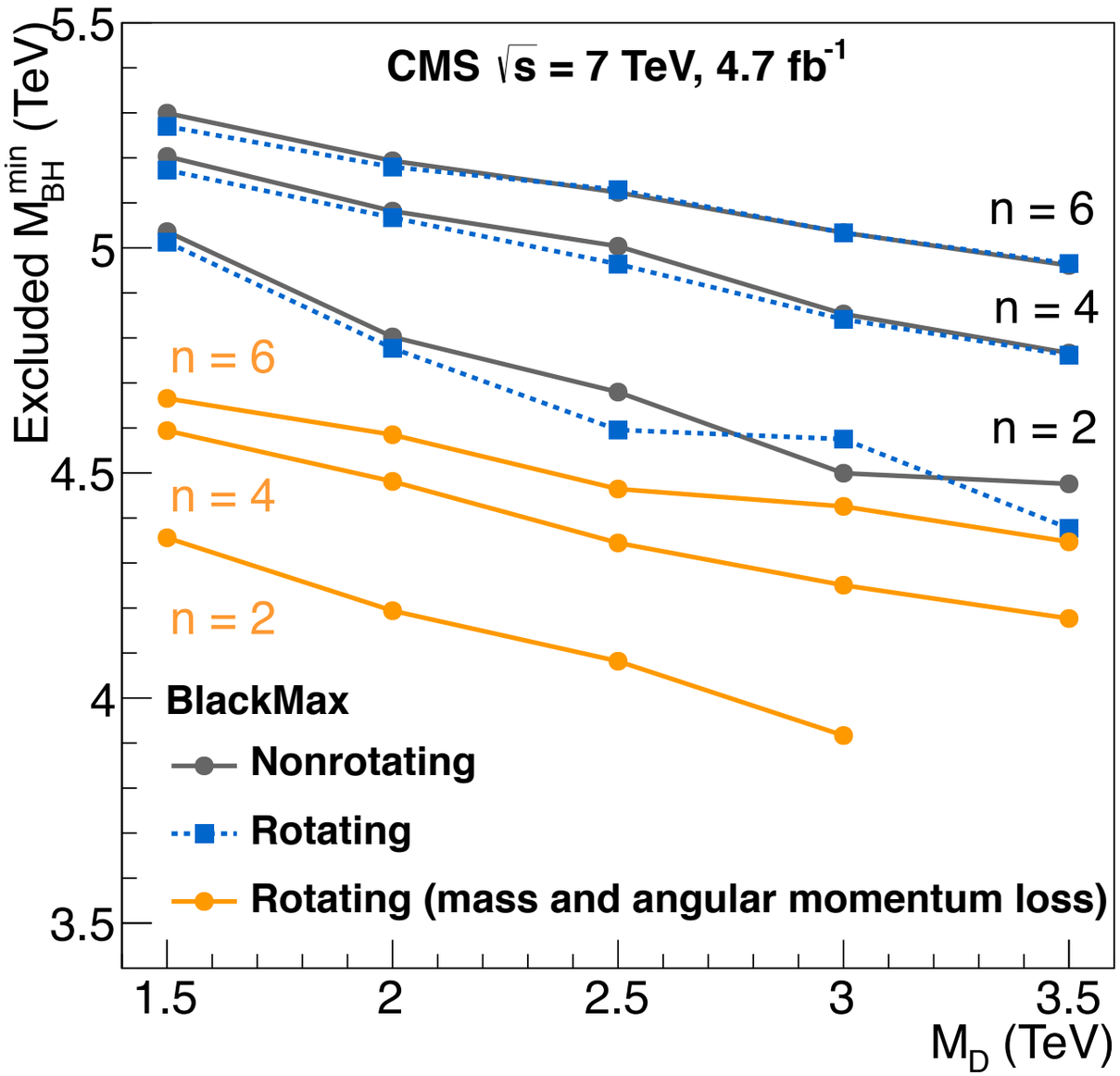
MULTIJET EVENT AS BLACK HOLE CANDIDATE



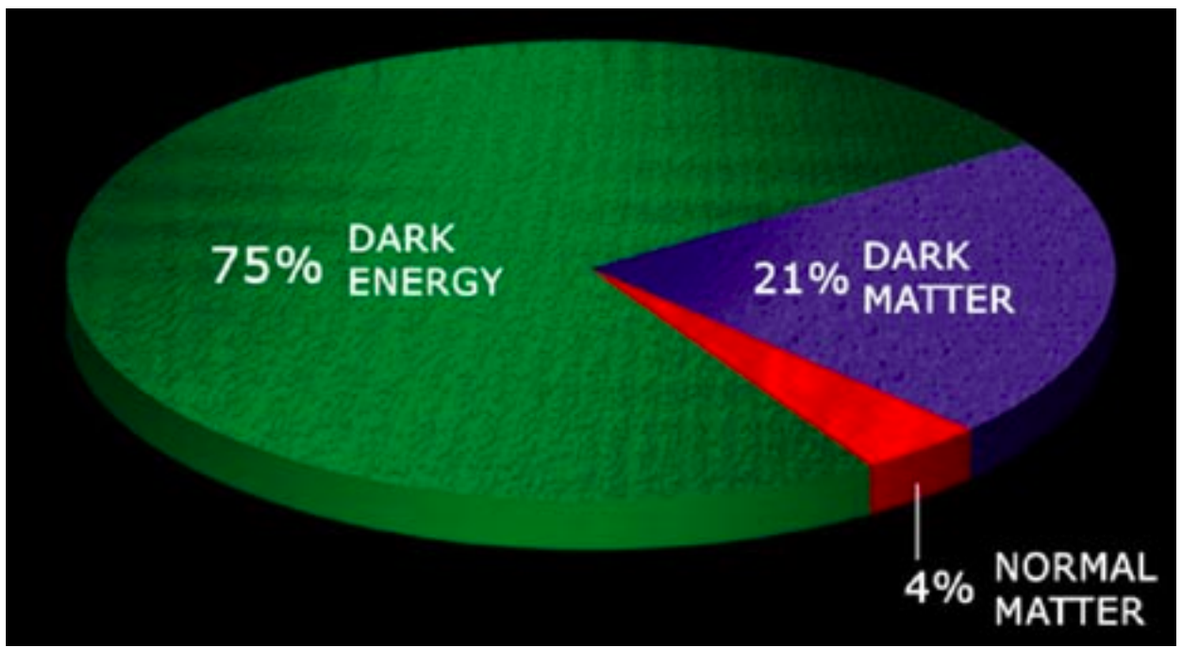


LIMITS ON BLACK HOLE PRODUCTION

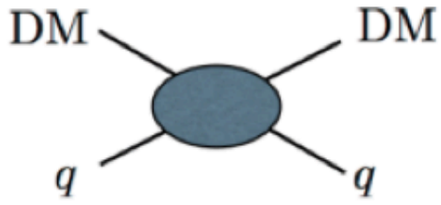




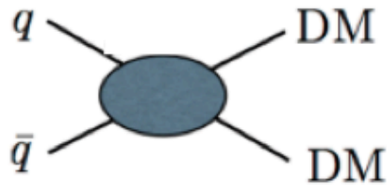
Dark Matter



DARK MATTER QUEST

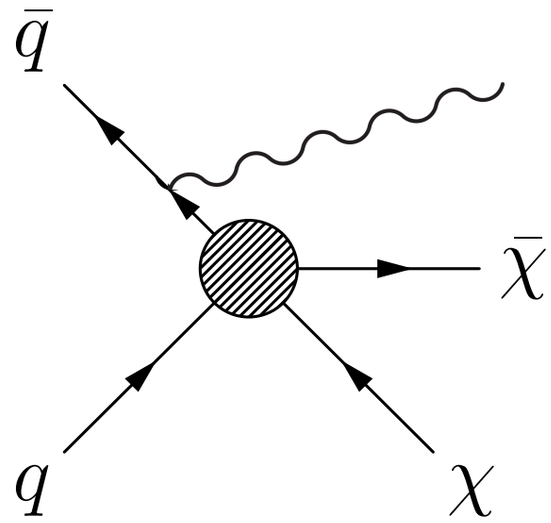


Direct Detection (t-channel)

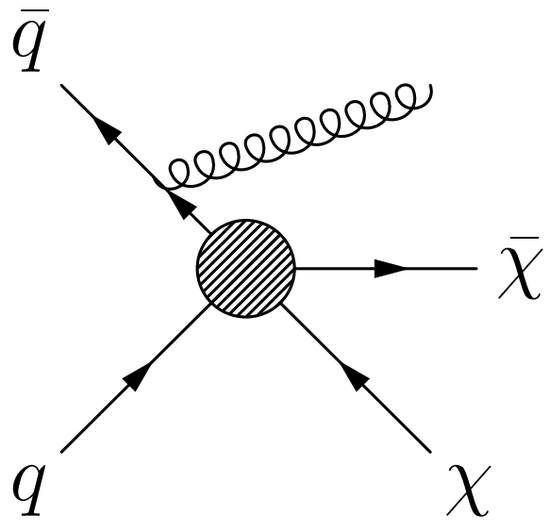


Collider Searches (s-channel)

- Pair production of Dark Matter candidates at colliders accompanied by Initial State Radiation of gluon or photon
  - More sensitive in low mass region than direct detection



Monophoton + MET

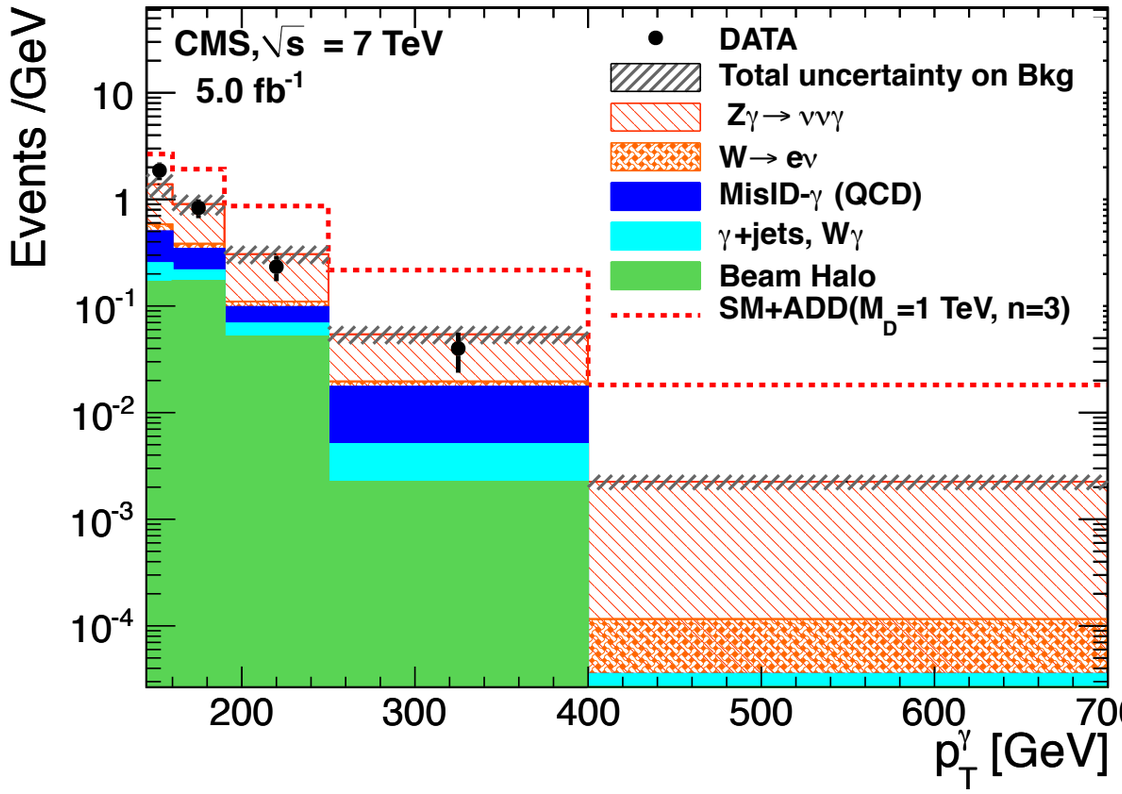


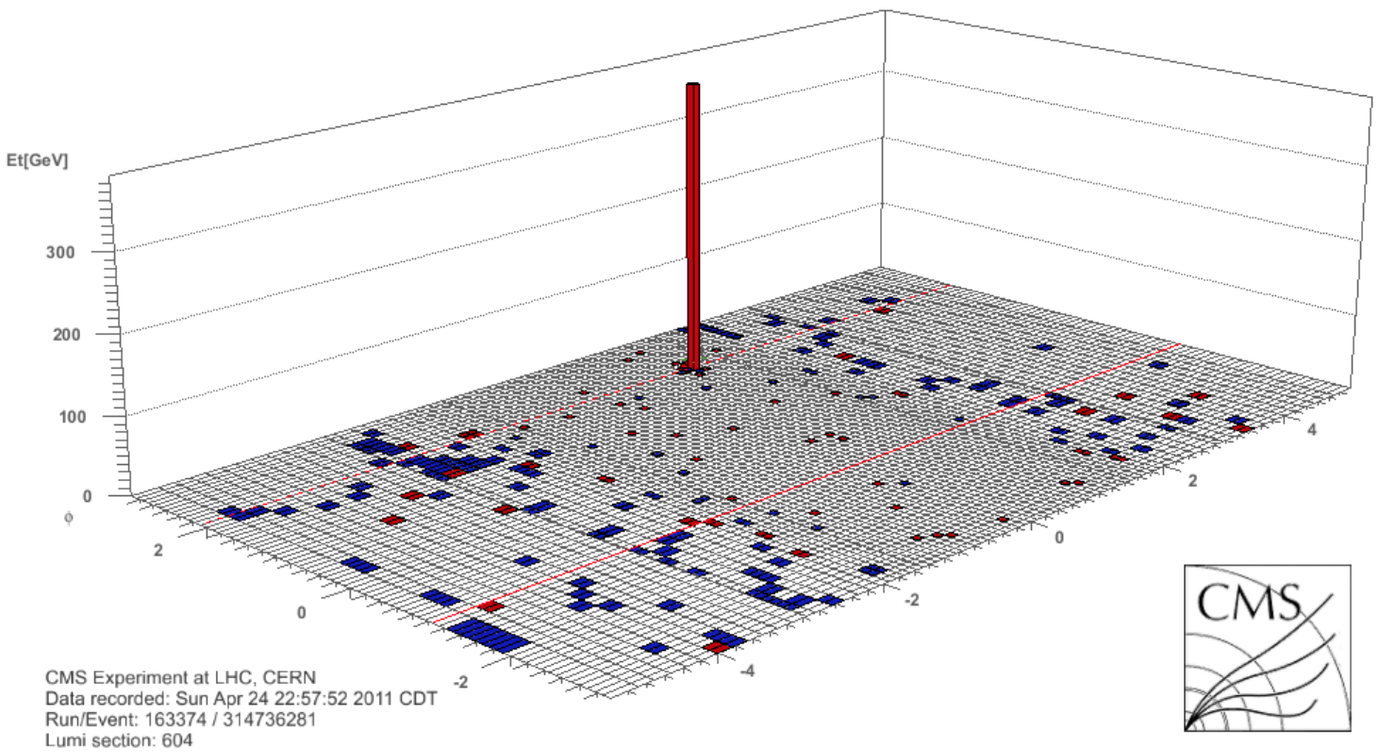
Monojet + MET

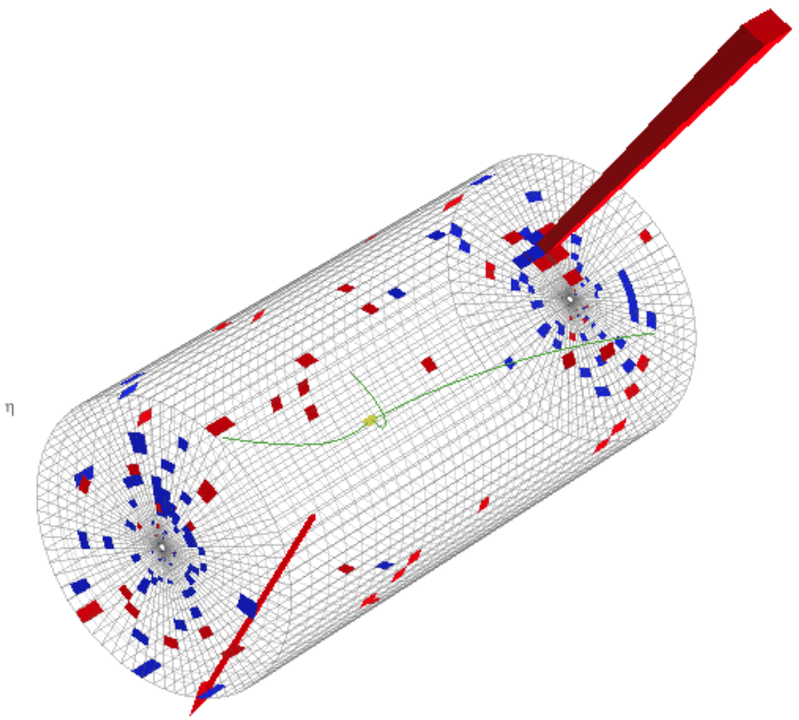
- Search for just one photon or jet and large missing transverse energy

MONO-PHOTON + MET

- Experimentally challenging
  - 1 photon, MET and no other activity
  - excellent estimate of non-beam background with ECAL time measurement
- Look for excess in photon p_T spectrum

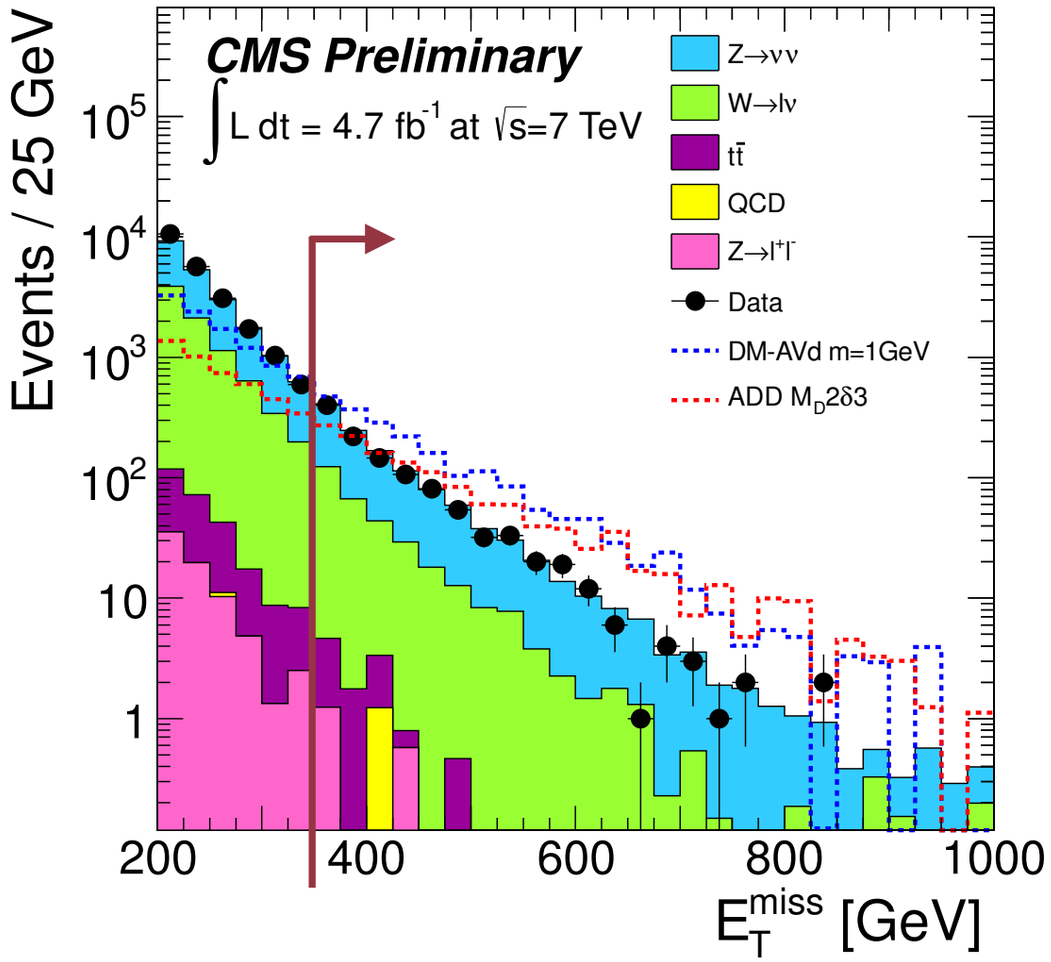


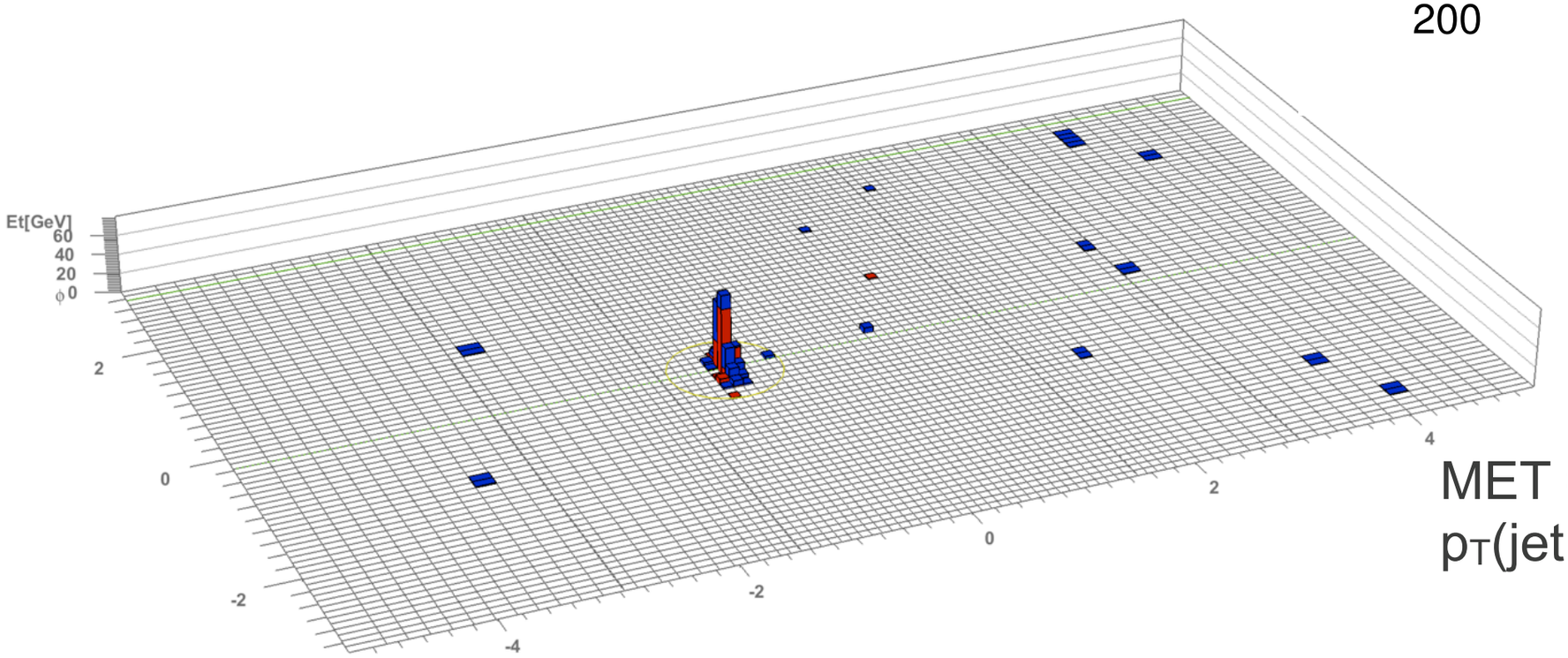




MONO-JET + MET

- Higher cross section than monophoton
  - main background from invisible Z decays in Z+jets measured with data driven method
- Require one high pt jet and possibly a second jet
  - recover radiation
  - reject events with close-by leptons





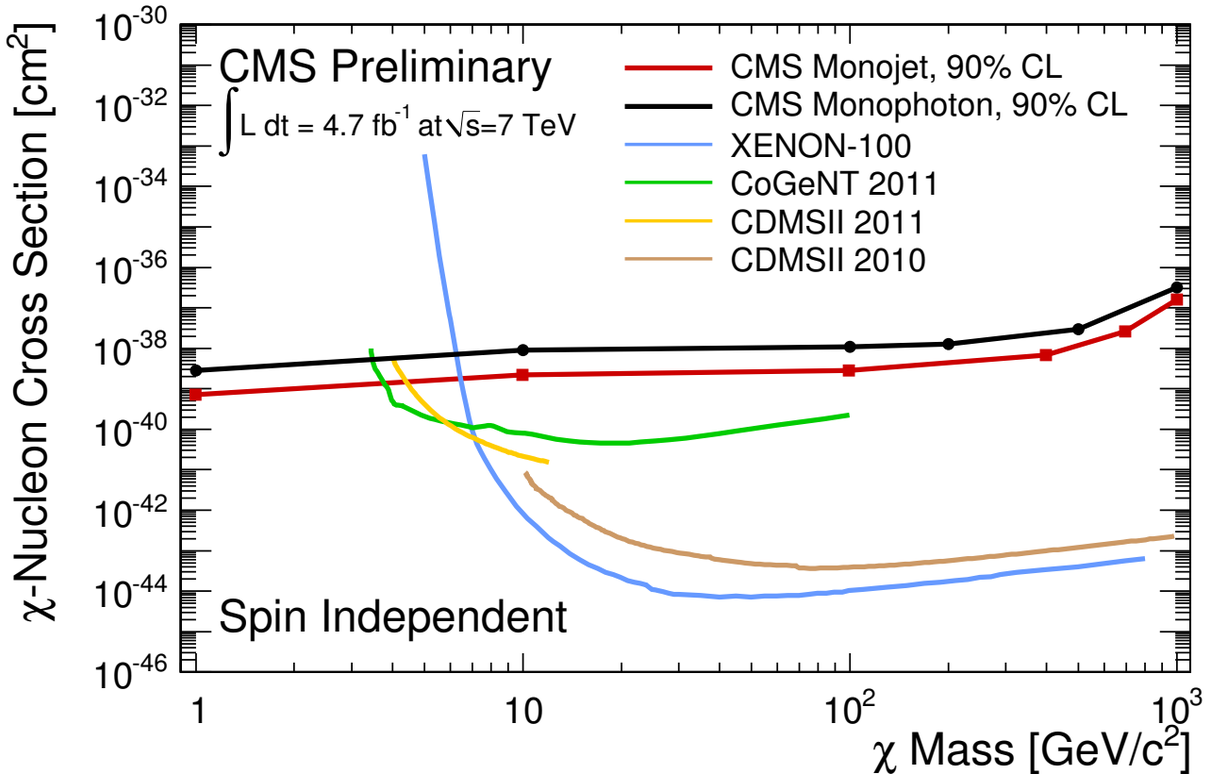
MET = 359 GeV
p_T(jet1) = 331 GeV

Dark Matter Limits

- Pair production modeled as contact interaction

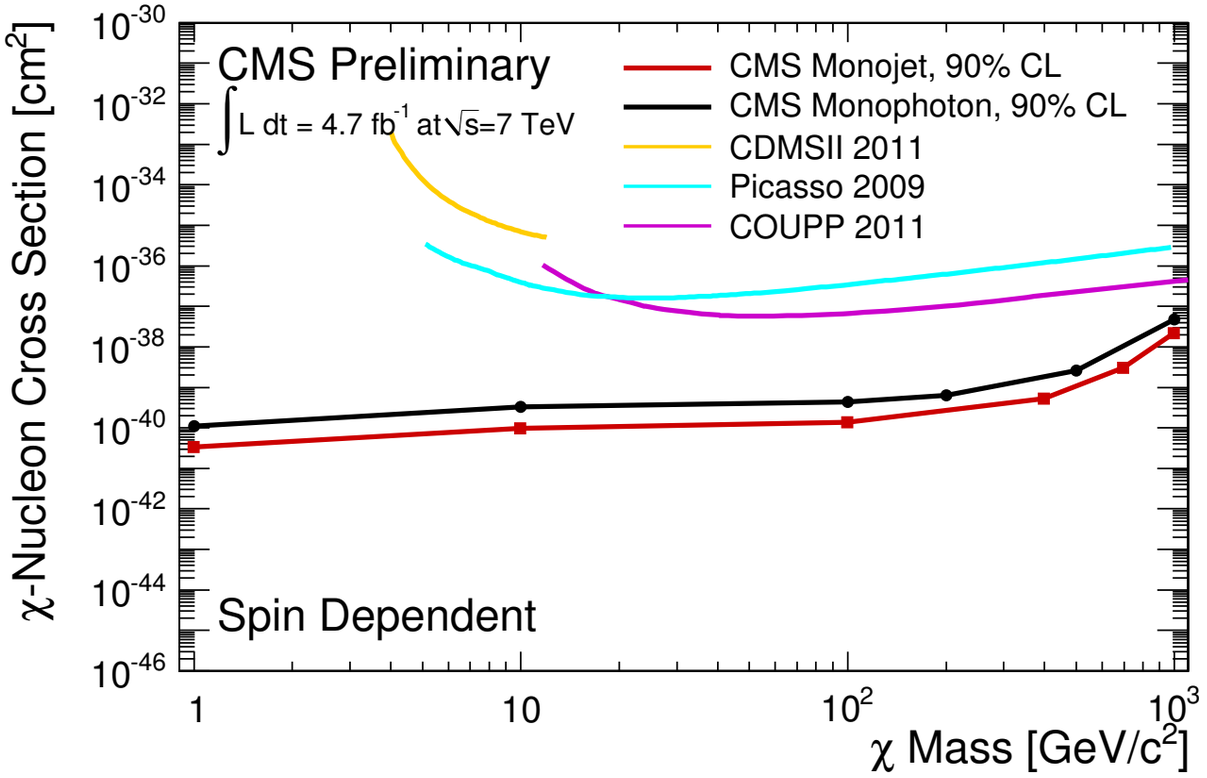
- Spin-independent

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$



- Spin-dependent

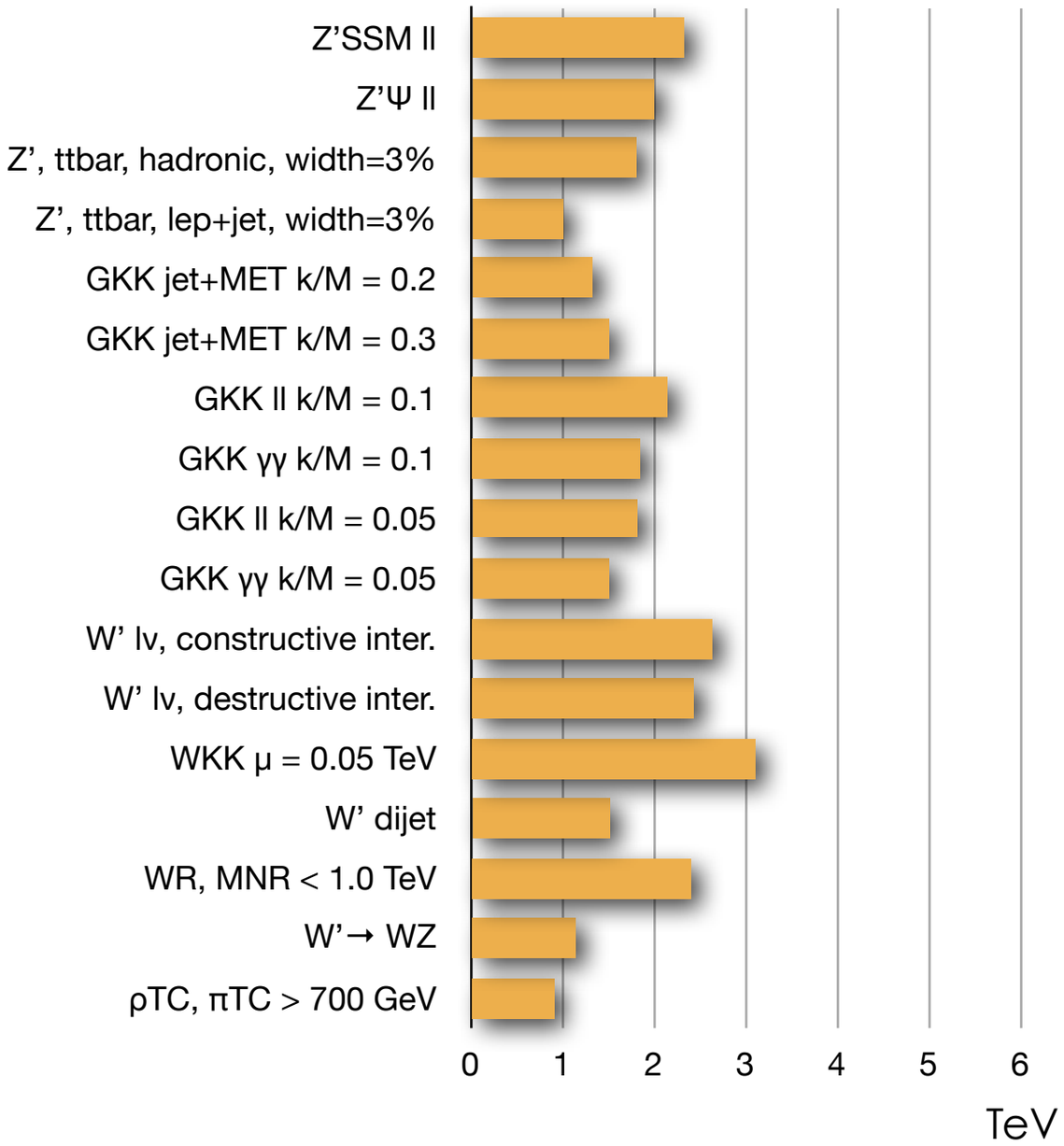
$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$



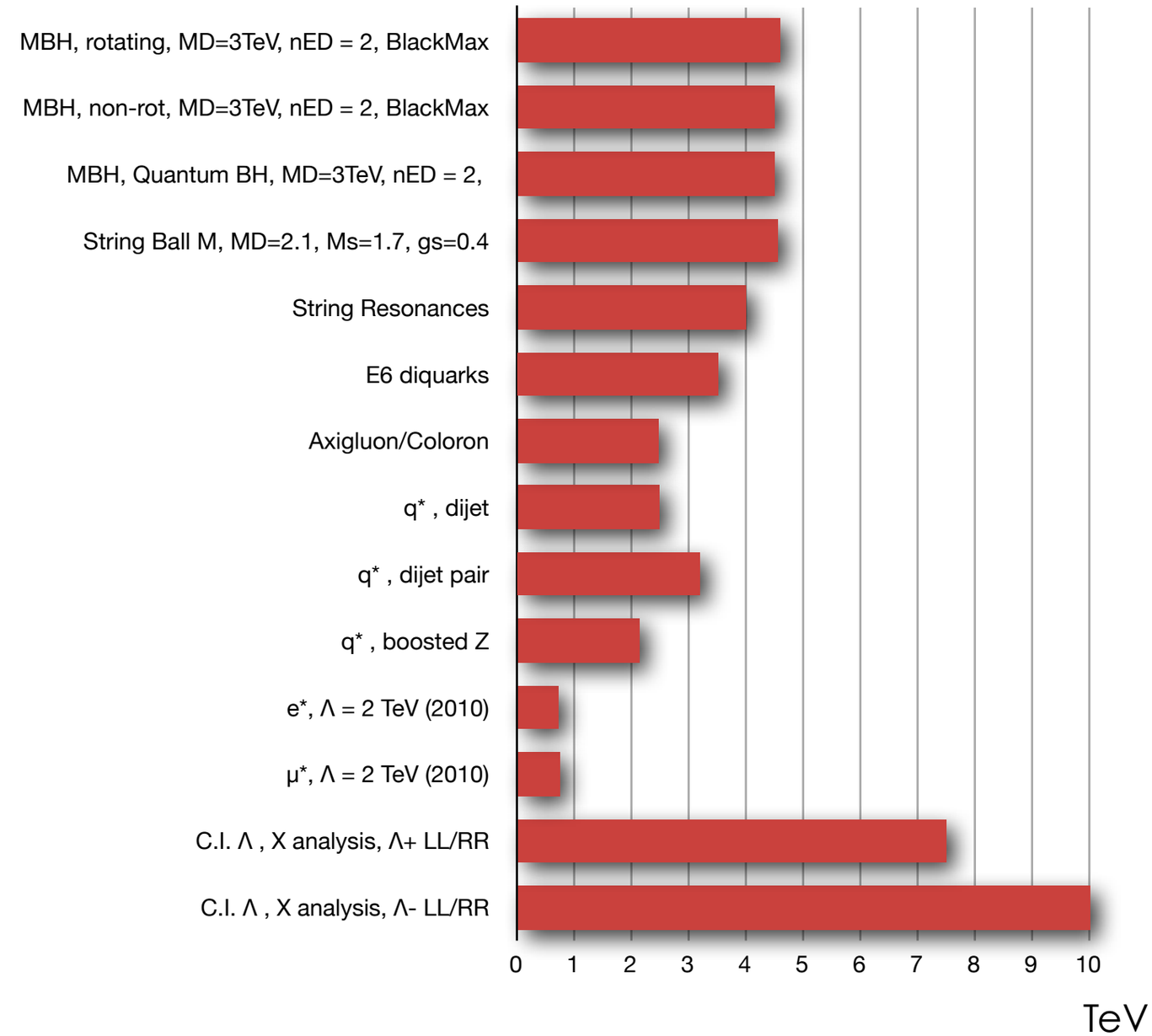
Conclusions

Mass Scale Grand Summary

Heavy Resonances

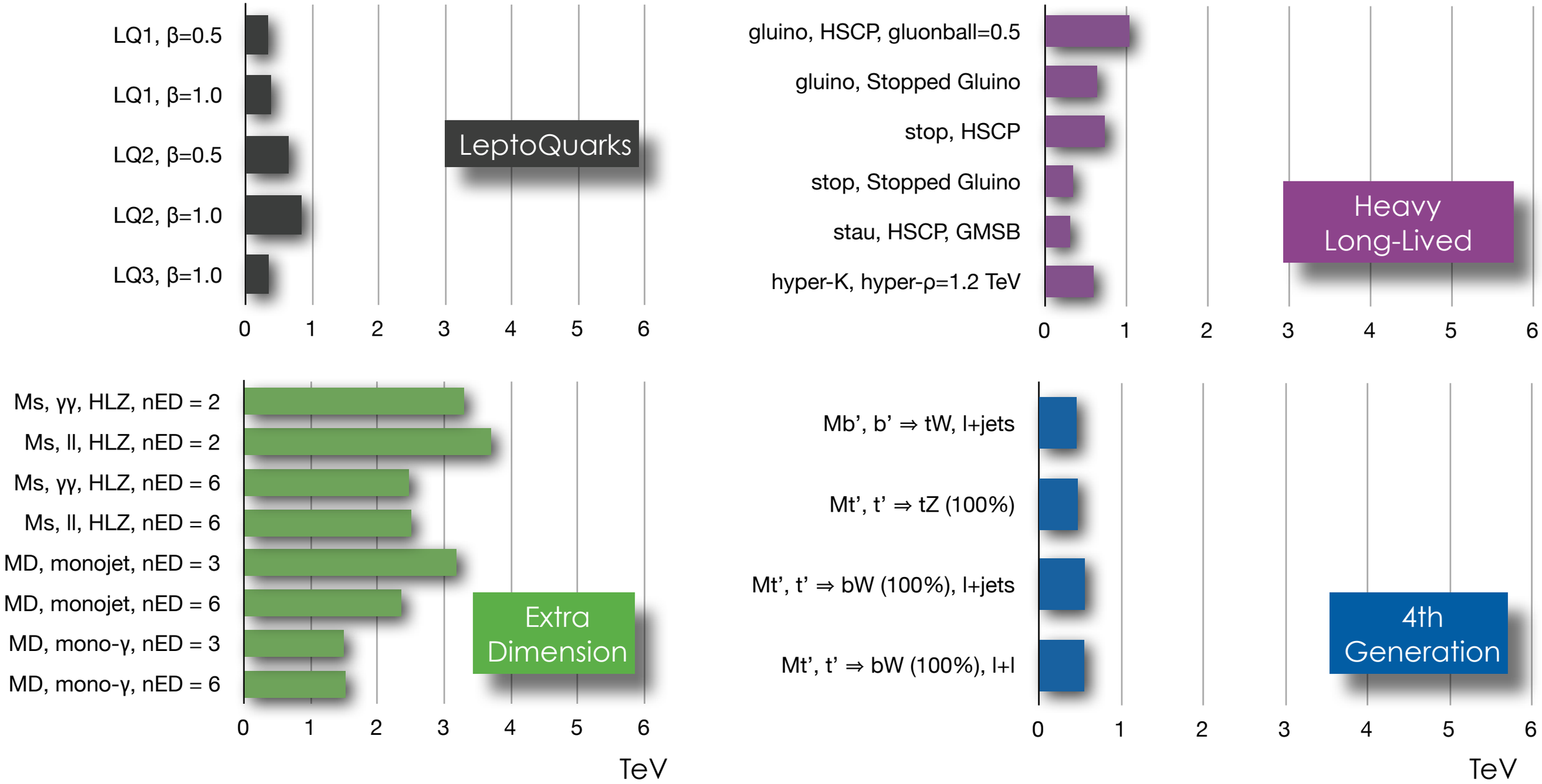


Black Holes, Compositeness



95% C.L. Exclusion Limits on Masses

Other Searches Not Discussed today



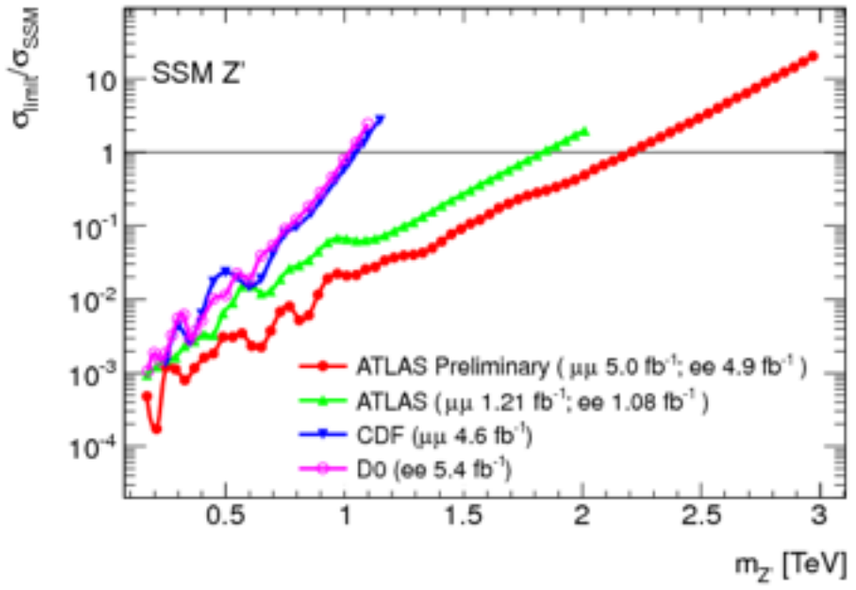
95% C.L. Exclusion Limits on Masses

FANTASTIC 2011 AT LHC

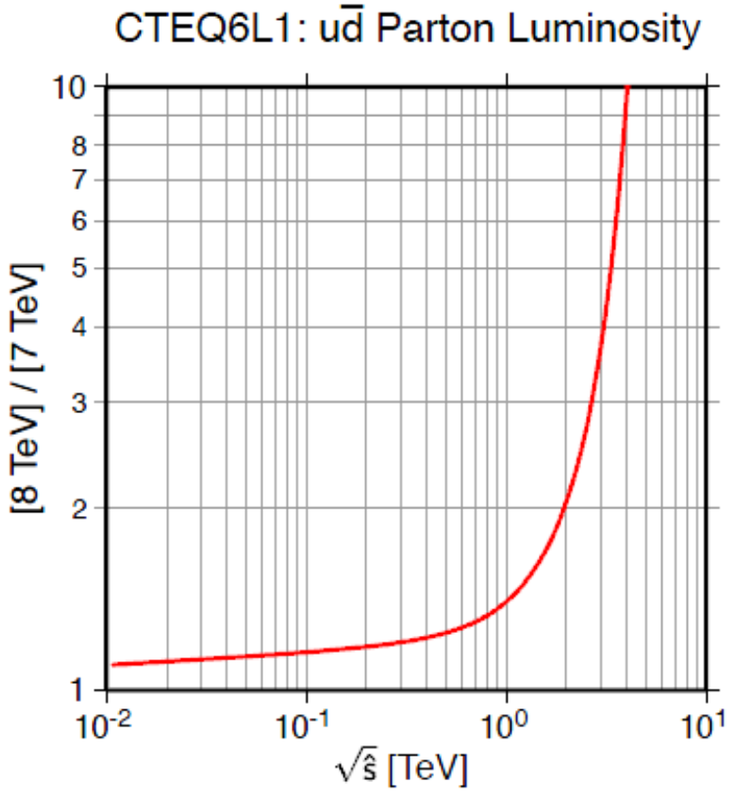
- Outstanding performance of detector, trigger, computing
  - More than 15 results using fb-1 by Summer 2011
  - Almost all searches updated to full dataset by end of year and ready for 8 TeV
- Good news
  - excellent detector performance
    - b-tagging and MET reliable and under control since day 1
  - surprisingly good data/MC agreement
- Bad news
  - So far only exclusion limits and no discovery
  - No hint of New Physics yet
- Great hope for 8 TeV data in 2012 and even more for 13 TeV after the long shutdown in 2014

OUTLOOK AND PROSPECTS

- Heavy resonances excluded past 2 TeV
- 4th generation excluded up to ~0.5 TeV
- Increase of x35 in data from 2010 to Summer 2011 improved exclusion limits sometime less than 20%
  - Increase in luminosity not a game changer in searches



- Higher center-of-mass energy opens new doors
- Higher beam energy increases cross section by x2-3
  - 1 TeV resonance: x1.5 @ 8 TeV and x2 @ 9 TeV
  - 2 TeV resonance: x2.1 @ 8 TeV and x3.6 @ 9 TeV
- 2 fb^{-1} @ 8 TeV roughly equivalent to 2011 data
- Expect LHC to deliver up to 0.9 fb^{-1} per week soon!



arxiv:1101.3201