The Future of the CMS BSM Searches

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SiD Workshop @ SLAC

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Outline

- *Reality check: where are we?*
- *Where we looked so far?*
- *What we may have been missing?*
- *How to get there?*
- *Conclusions*

The LHC on the Run

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- We were perfectly geared for a sprint: all pumped-up and ready for a victory
- But can we survive a marathon?..

Where We Stand?

- We ripped through ~10-year long Tevatron program in less than a year and scooped the Tevatron out on the majority of searches, including searches for Higgs
- The first LHC 7 TeV paper was published just about a year ago:
  - ATLAS Collaboration, "Search for New Particles in Two-Jet Final States in 7 TeV Proton-Proton Collisions with the ATLAS Detector at the LHC," PRL **105** (2010) 161801 [submitted August 14, 2010] - 0.3 pb^{-1}
- The first full 2010 statistics paper was submitted less than a year ago:
  - CMS Collaboration, "Search for Microscopic Black Hole Signatures at the Large Hadron Collider", PL **B697** (2011) 434 [submitted December 15, 2010] - 36 pb^{-1}
- Each Collaboration has published about hundred 7 TeV papers in this one year - unprecedented success and performance!
- And yet, so far we mainly aimed for low-hanging fruit
- Unfortunately, nature does not always hang its fruits low...

Reaching for Low-Hanging Fruit

Where We Looked so Far?

- Strongly produced stuff
- Fourth generation particles
- TeV-scale EWK resonances
- mSUGRA-like SUSY
- GMSB SUSY
- Extra dimensions and strong gravity
- You heard about the Higgs...

- ... and we discovered nothing too exciting so far
- (Yet, we have had a good time and a few excitements on the way, including the latest Higgs excitement!)

- So, where are we and what have we learned?

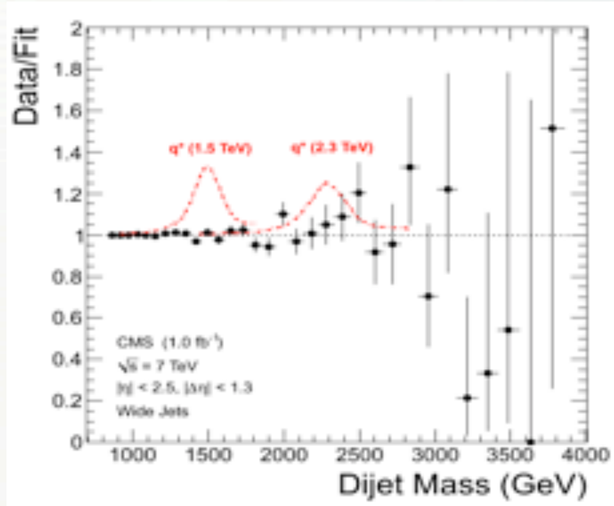
Searches for Strongly Produced Stuff

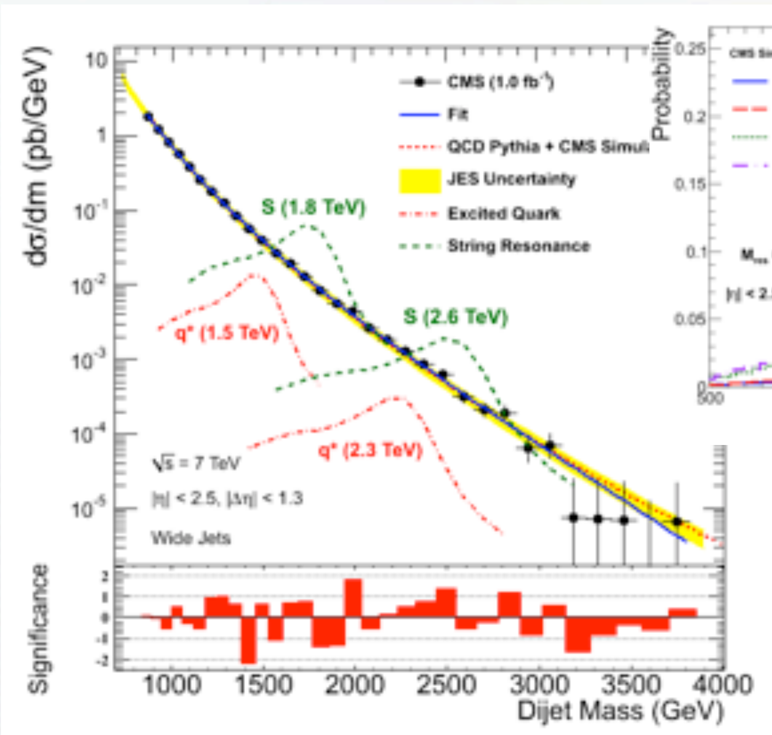
Dijet Bump Hunt

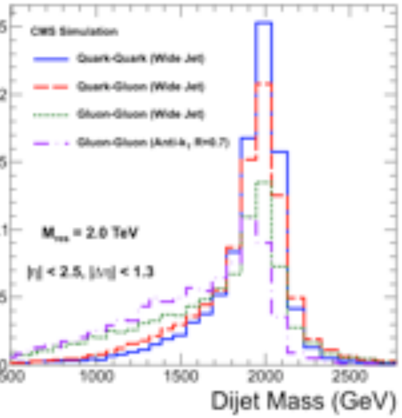
- Parameterize dijet mass spectrum with a smooth, 4-parameter fit function:
$$\frac{d\sigma}{dm} = \frac{P_0(1-m/\sqrt{s})^{P_1}}{(m/\sqrt{s})^{P_2+P_3\ln(m/\sqrt{s})}},$$
and look for bumps
- In their absence, set limits

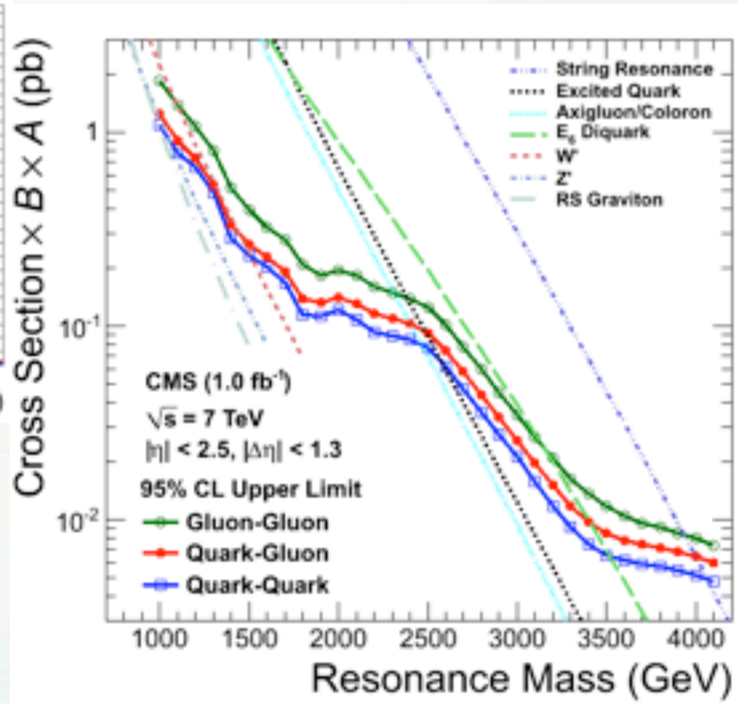
Phys. Lett. B704, 123 (2011)

$M_{q^*} > 2.49$ TeV
$M_D > 3.52$ TeV
$M_{W'} > 1.51$ TeV









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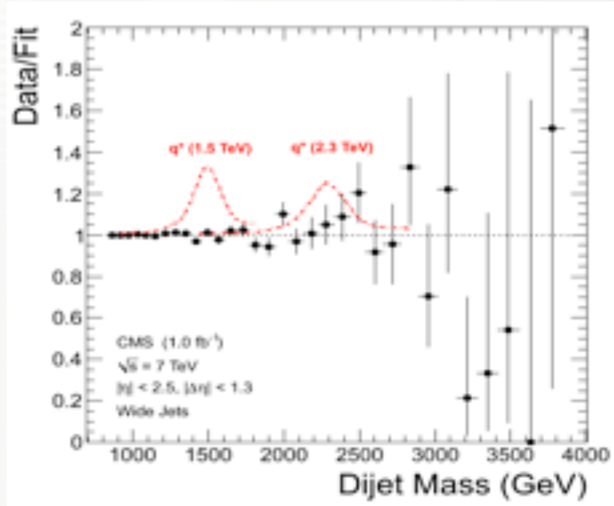

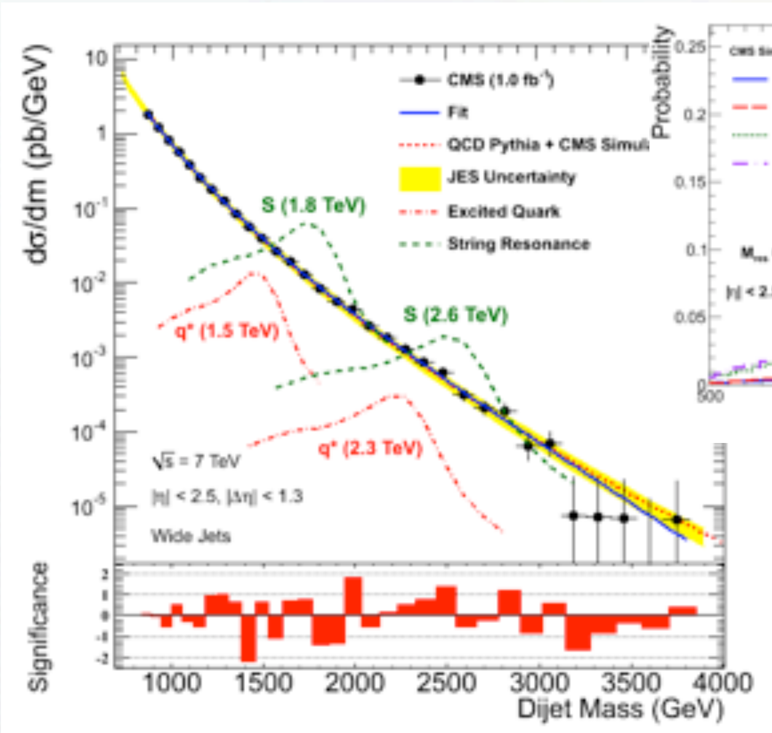

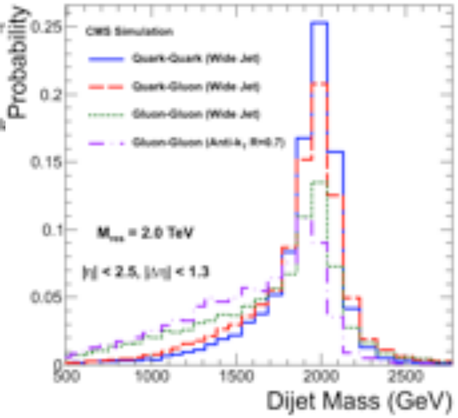

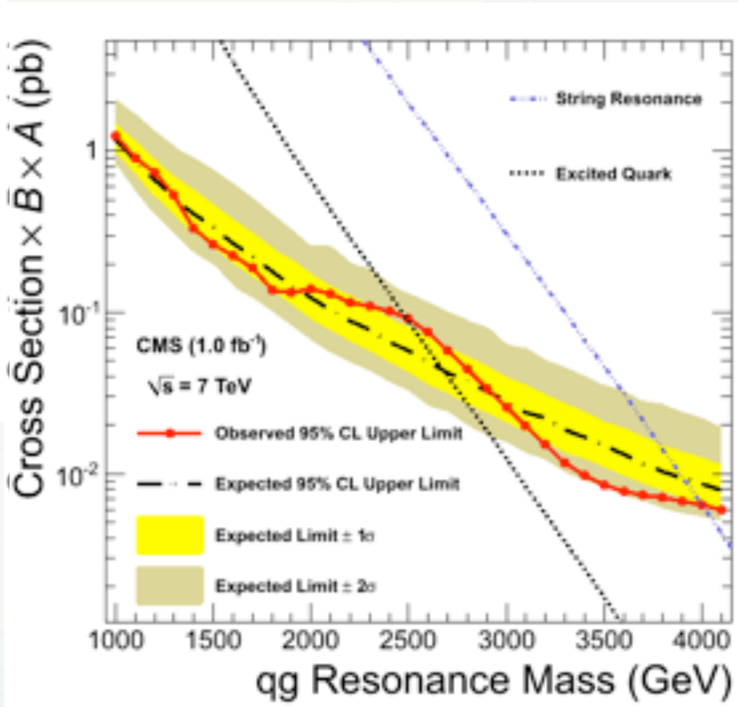

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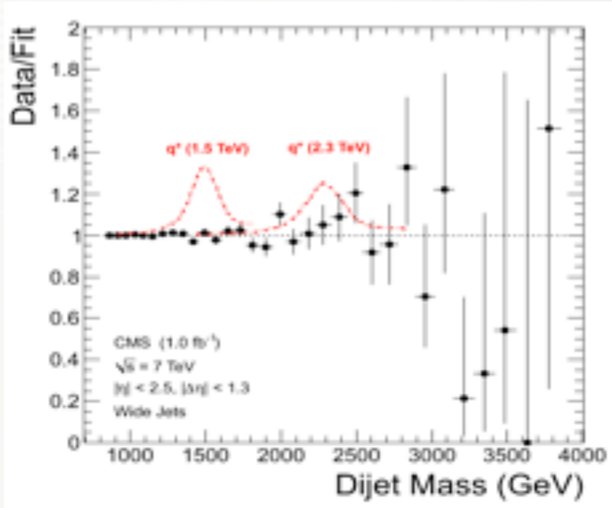
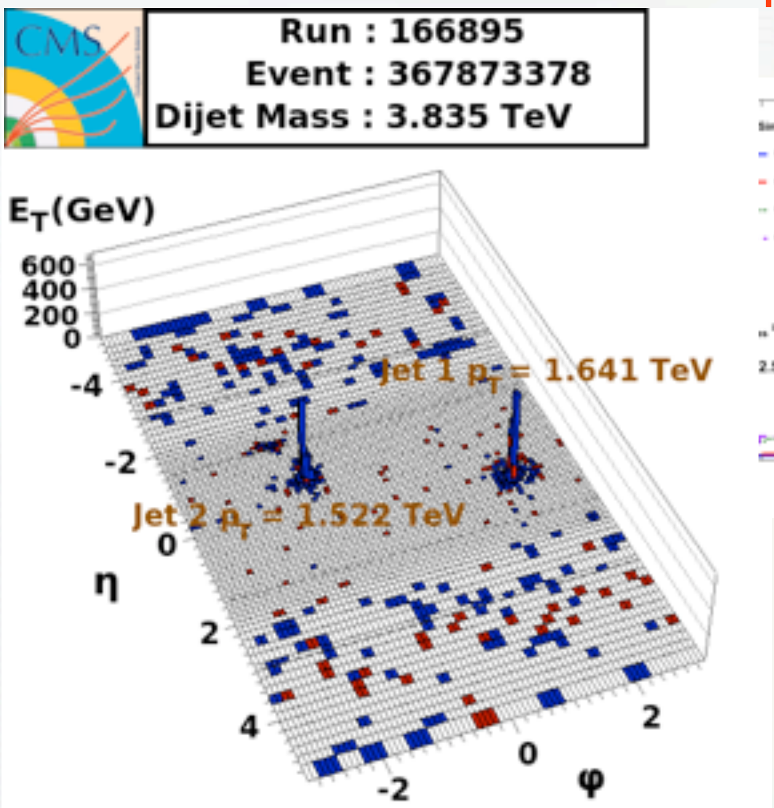
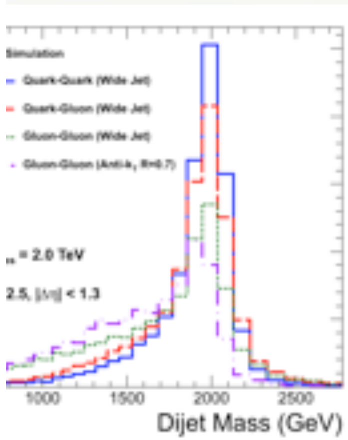
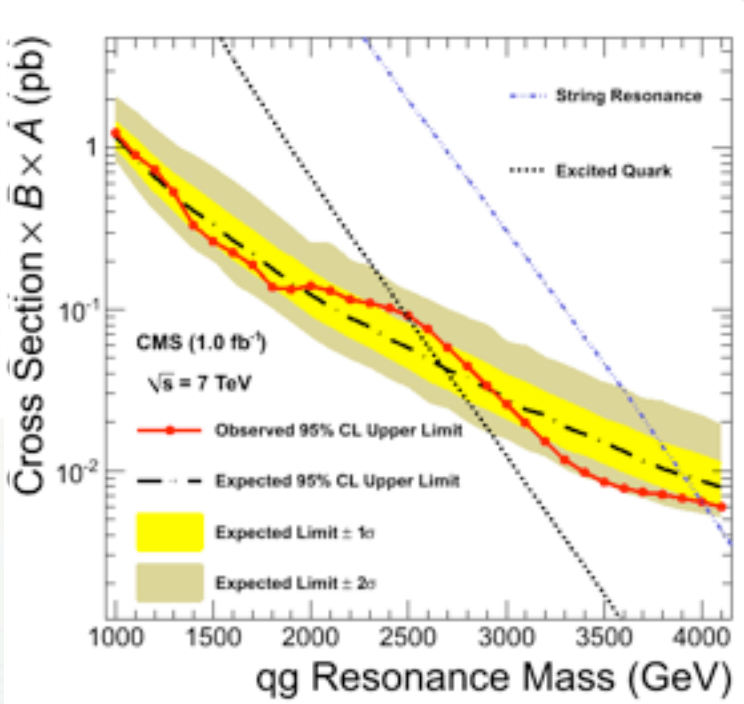




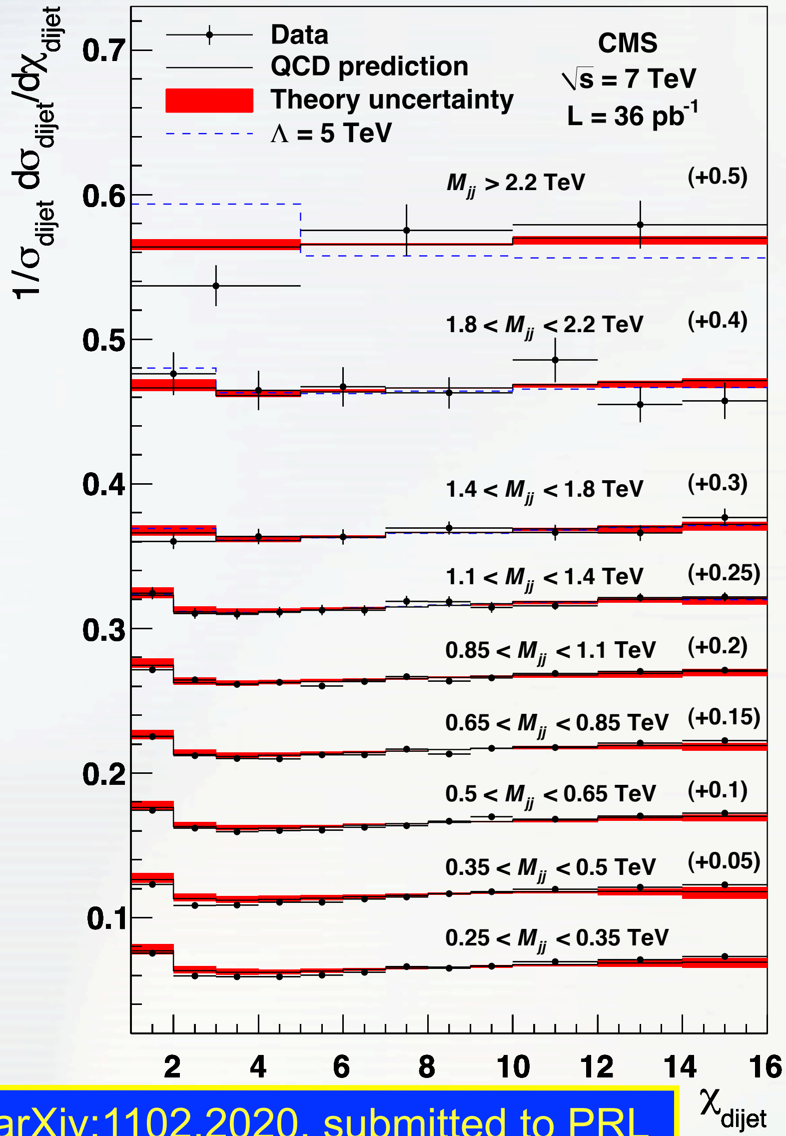




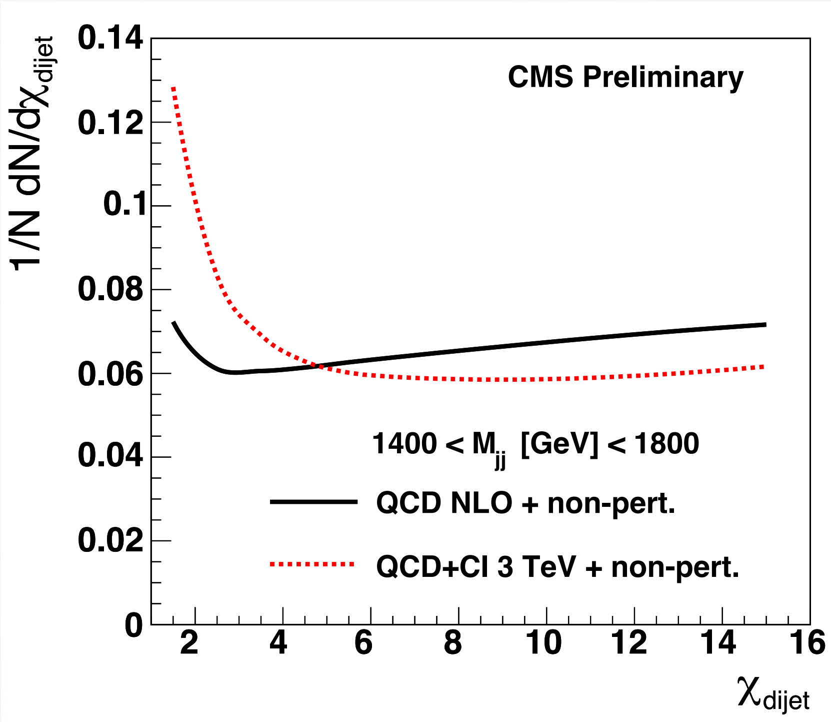
Wednesday, December 14, 11

Dijet Angular Distribution

- Use dijet c.o.m. scattering angle, via $\chi = e^{2y^*} = \dfrac{1+\cos\theta^*}{1-\cos\theta^*}$



- Complementarity of the two approaches: ratio uses coarse angular bins but fine mass bins; χ uses much finer angular info, but coarse mass bins



arXiv:1102.2020, submitted to PRL

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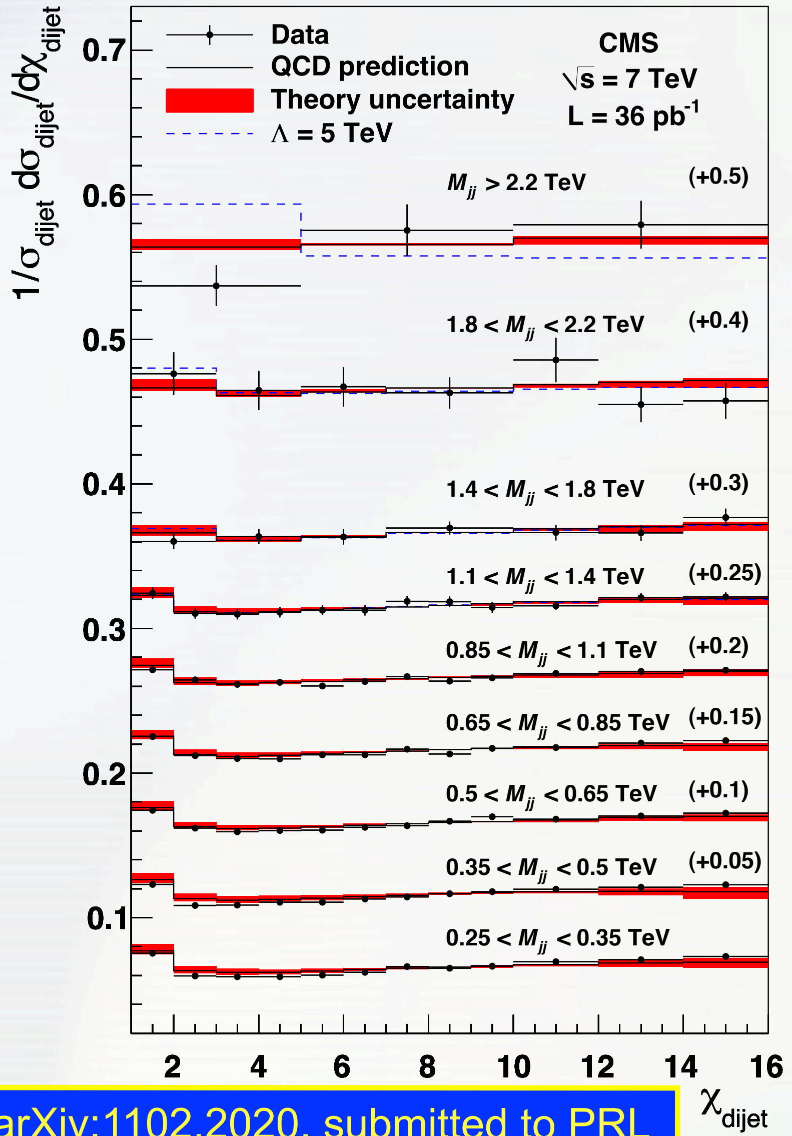

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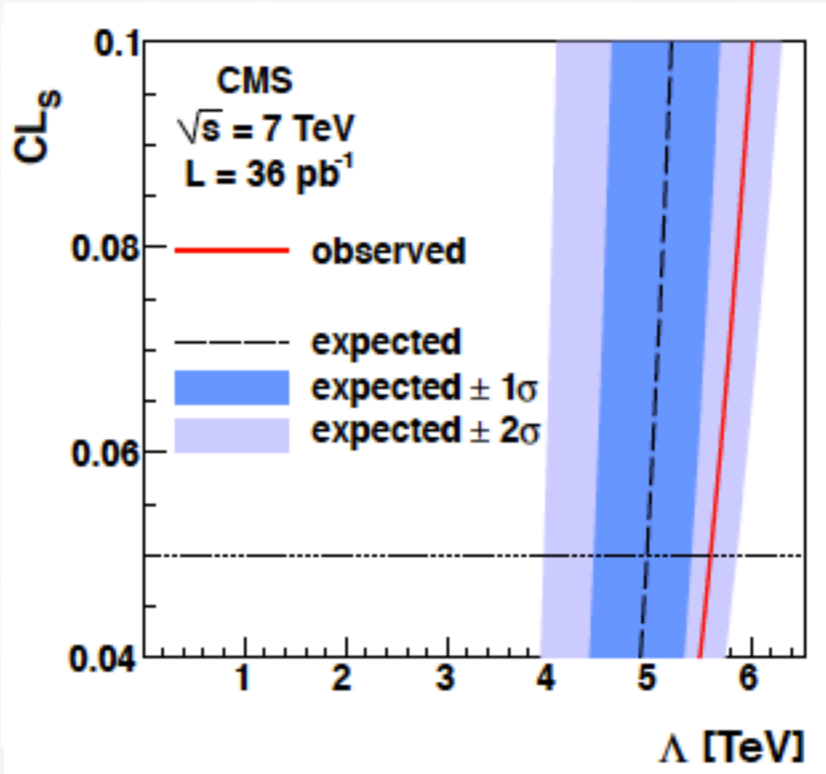

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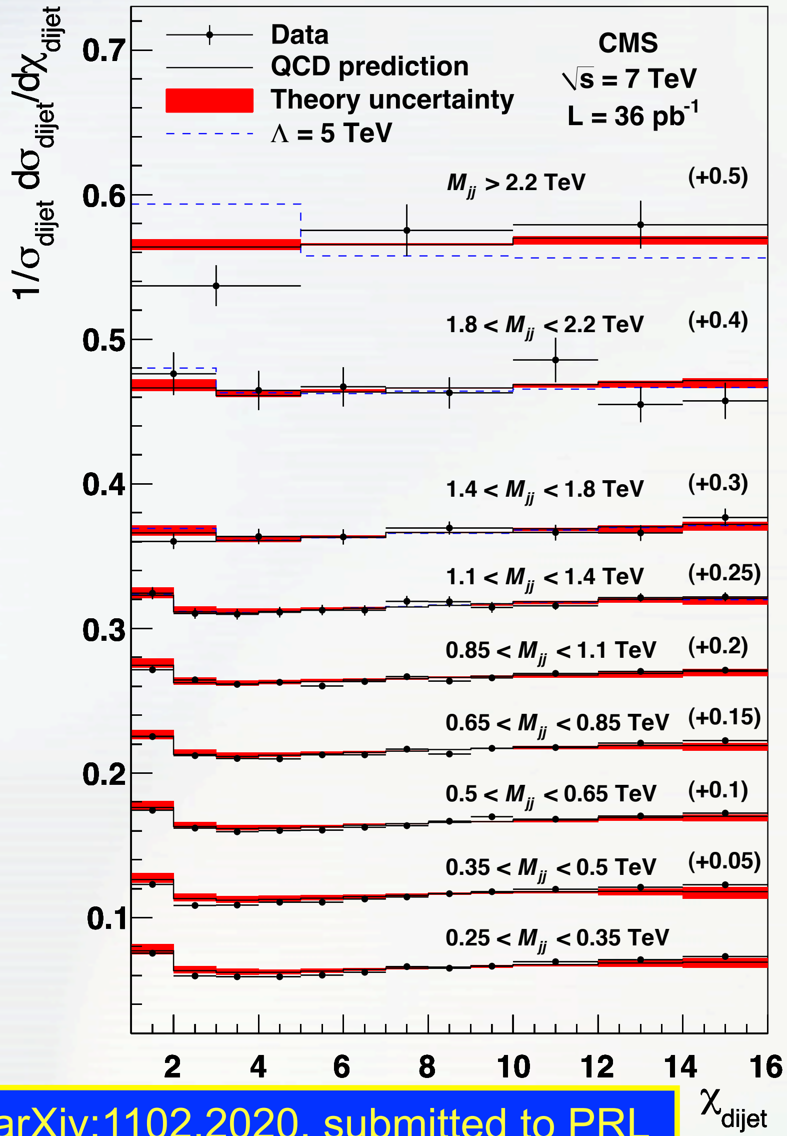

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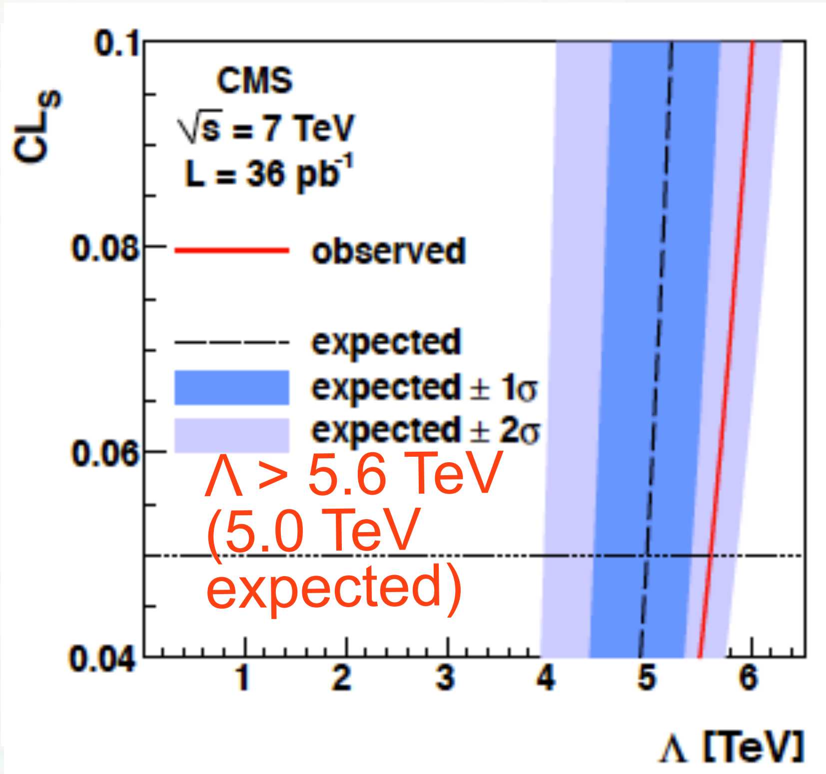
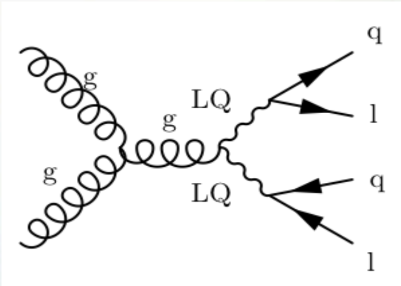


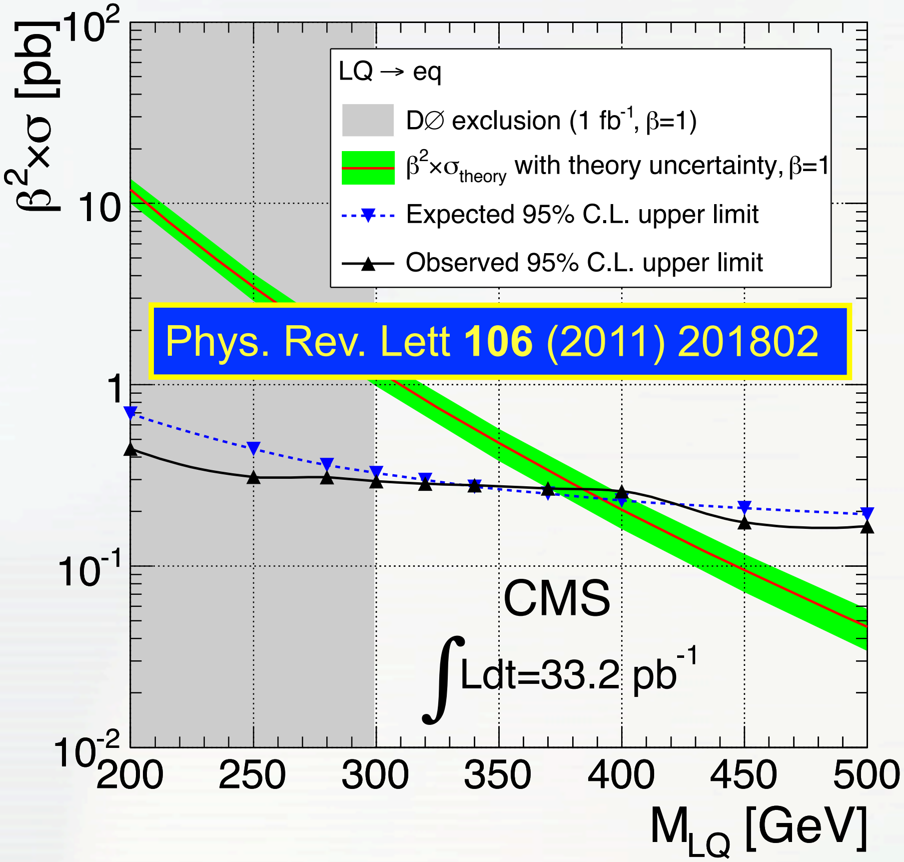
Leptoquarks

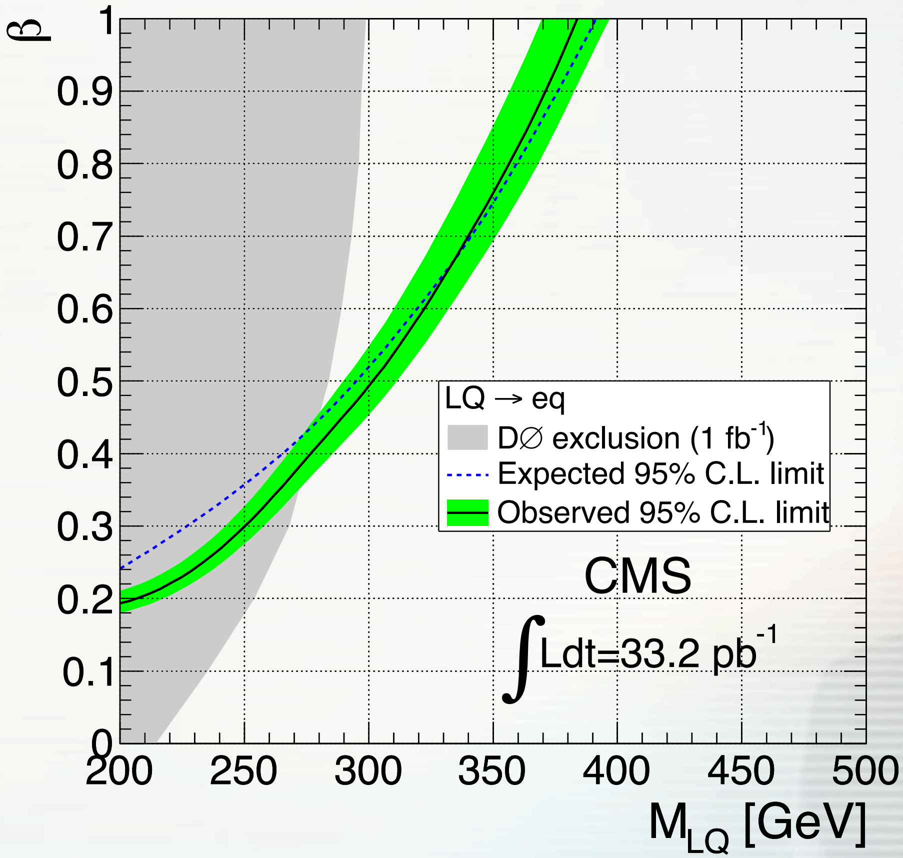
- Hypothetical bosons that carry properties of both leptons and quarks (color, baryon and lepton number)
  - Can be either scalar or vector particles (focus on scalars)
  - Often appear in GUT-inspired models to provide connection between three lepton and quark generations
- Decay into ℓq (νq) with the branching fraction β ($1-\beta$)
  - Cross-generational couplings are restricted by the FCNC constraints; assume decay into one generation only
  - In the simplest model, β is fixed to 1, 1/2, or 0; here we consider it a free parameter $0 < \beta < 1$
- Consider leptoquarks of three generations independently
  - Focus on the first two generations, LQ1 and LQ2 in this search
- Explore pair-production via gluon fusion, with subsequent decays into dileptons and jets



LQ1 Limits

- S_T > 340-660 GeV for M_{LQ1} = 200-500 GeV, 2-0 events observed, consistent with the expected background
- Significant extension of the Tevatron limits (M_{LQ1} > 299 GeV)
- Complementary eνjj analysis ongoing (improved β < 1 sensitivity)

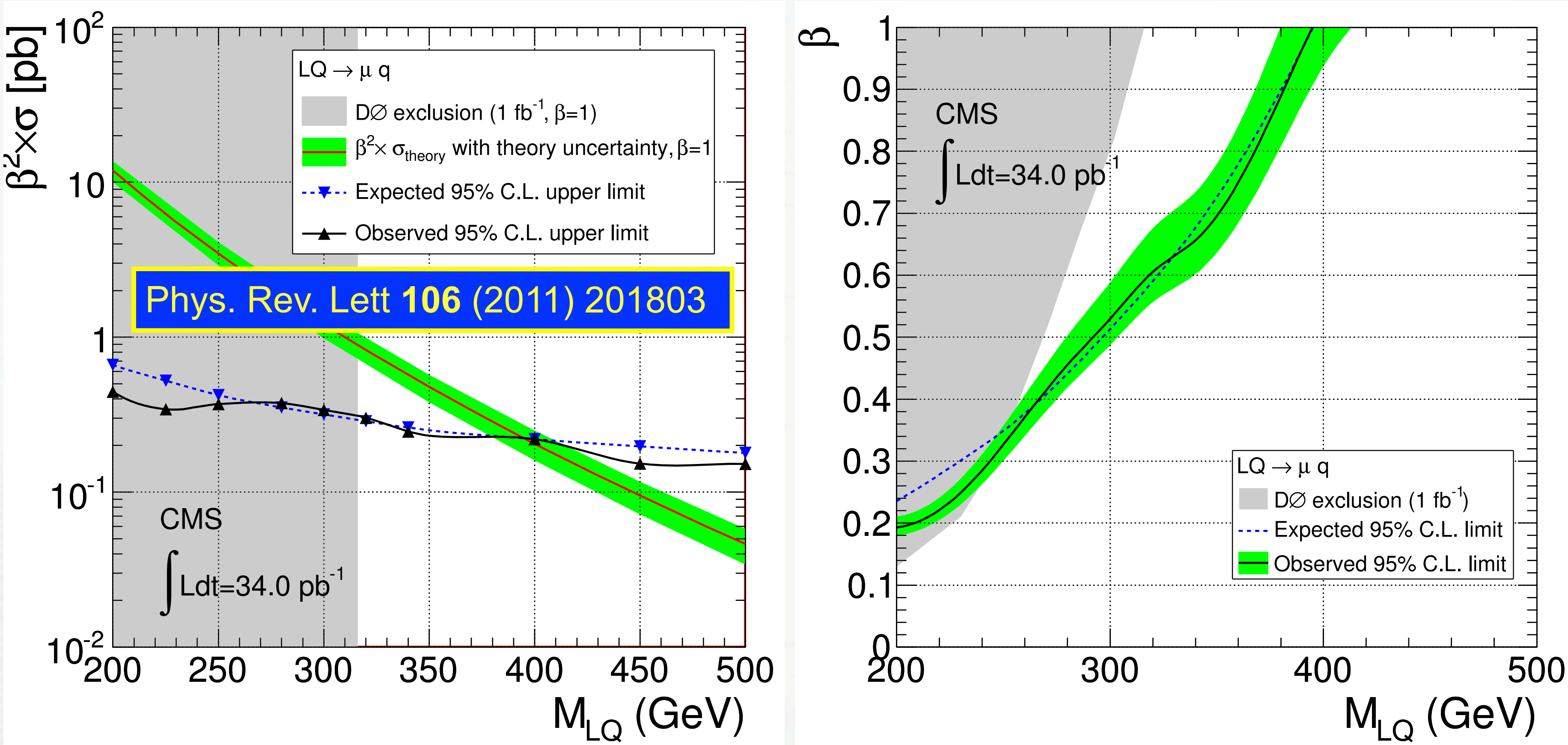




M_{LQ1} > 384 (391 expected) GeV, β = 1

LQ2 Limits

- S_T > 310-700 GeV for M_{LQ2} = 200-500 GeV, 5-0 events observed, consistent with the expected background
- Significant extension of the Tevatron limits (M_{LQ2} > 316 GeV)
- Complementary μνjj analysis ongoing (improved β < 1 sensitivity)



M_{LQ1} > 394 (394 expected) GeV, β = 1

LQ1 Search in the eνjj Channel

- Similar selections, except that ST is defined to include missing transverse energy:
  - $S_T = E_T(\ell_1) + ME_T + E_T(j_1) + E_T(j_2)$

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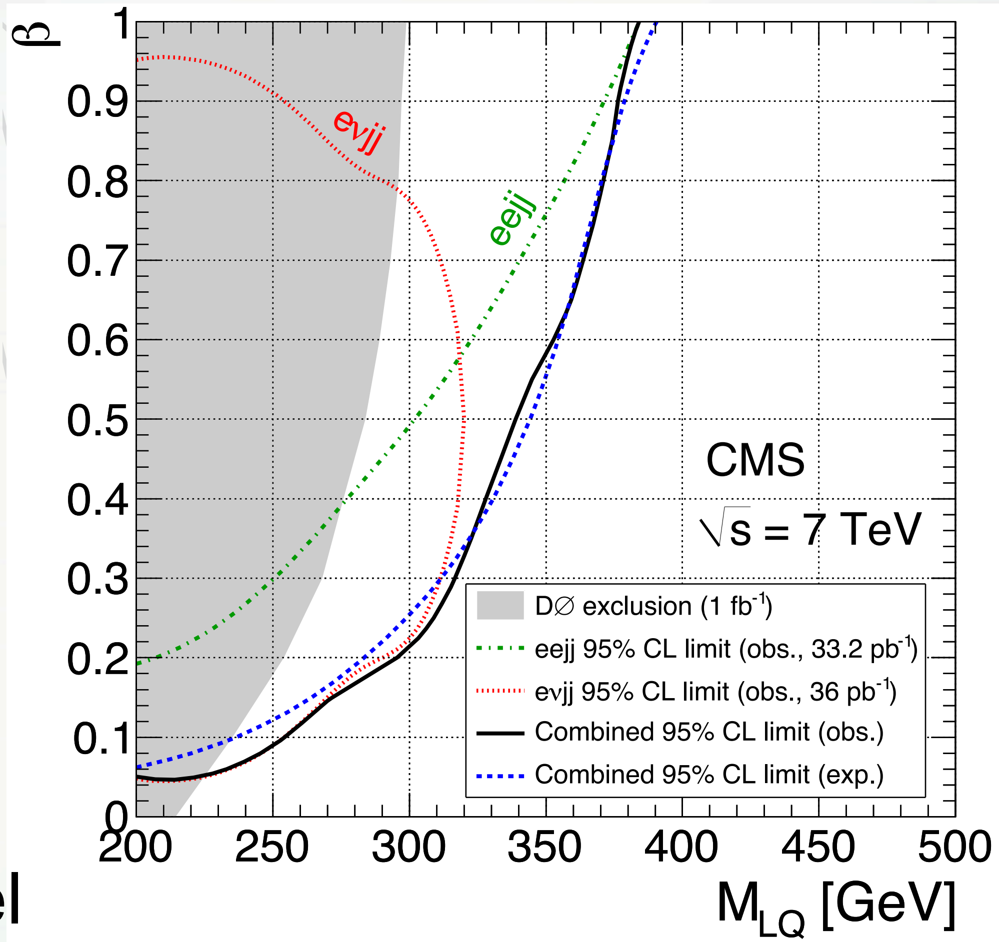
- Optimize the minimum requirement on S_T by maximizing discovery significance, defined as $S/\mathrm{sqrt}(S+B+\sigma_B^2)$
- S_T cut varies from 350 GeV to 670 GeV for the LQ1 mass between 200 and 500 GeV
- Combine w/ eejj channel



Search for Fourth Generation

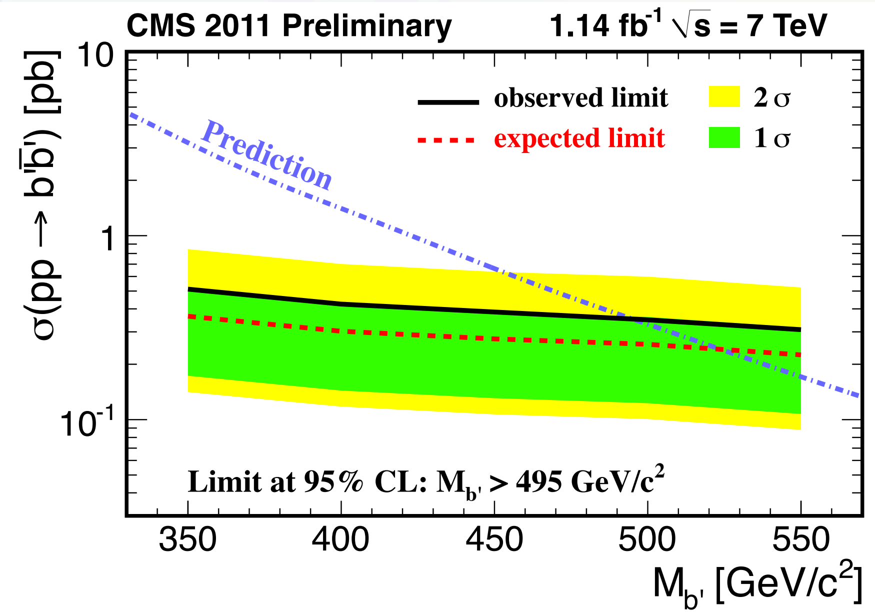
Searches for b' and t'

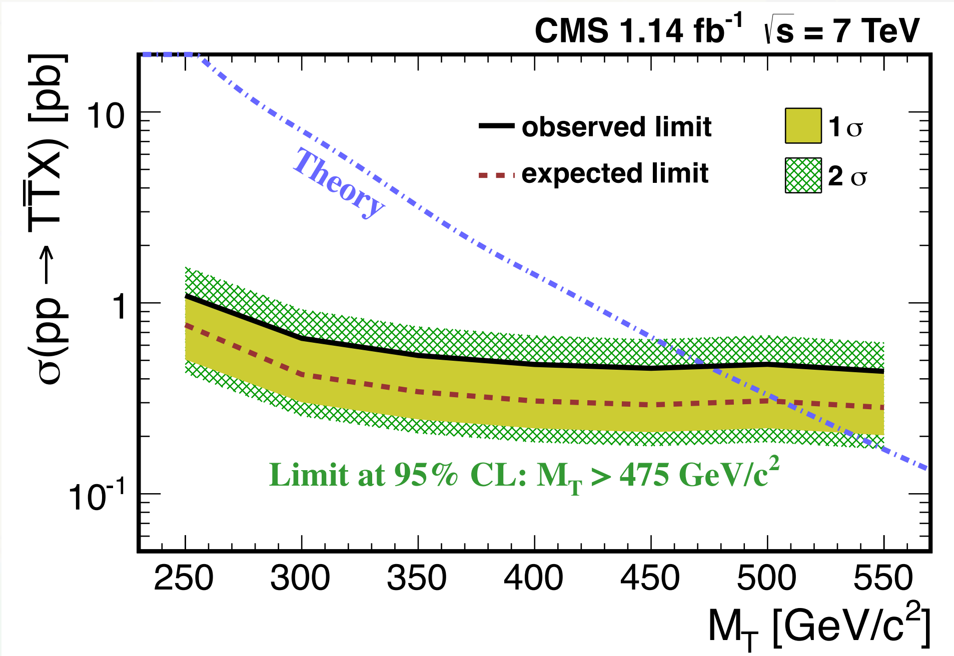
- Just a couple of examples: b'(tW) and heavy, charge +2/3, vector-like quark with tree-level FCNC couplings

CMS, arXiv:1109.4985

$pp \to T\bar{T}X$, with $T\bar{T} \to tZ\bar{t}Z \to b\bar{b}W^+W^-ZZ$

EXO PAS-11-036

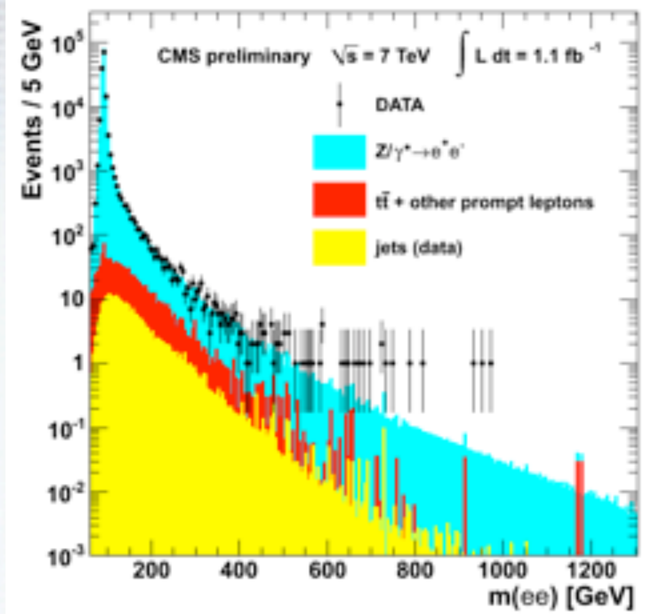


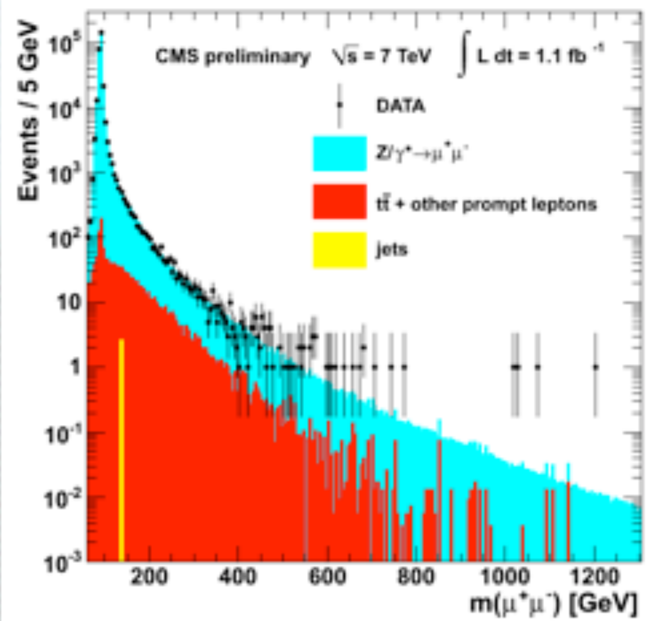


Search for Additional Gauge Bosons

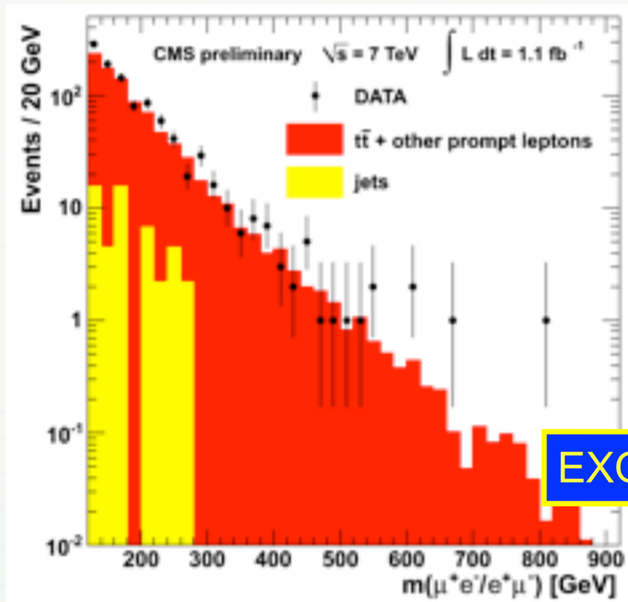
Dance of the Gauge Bosons in Vacuum, 2010

Search for Dilepton Resonances





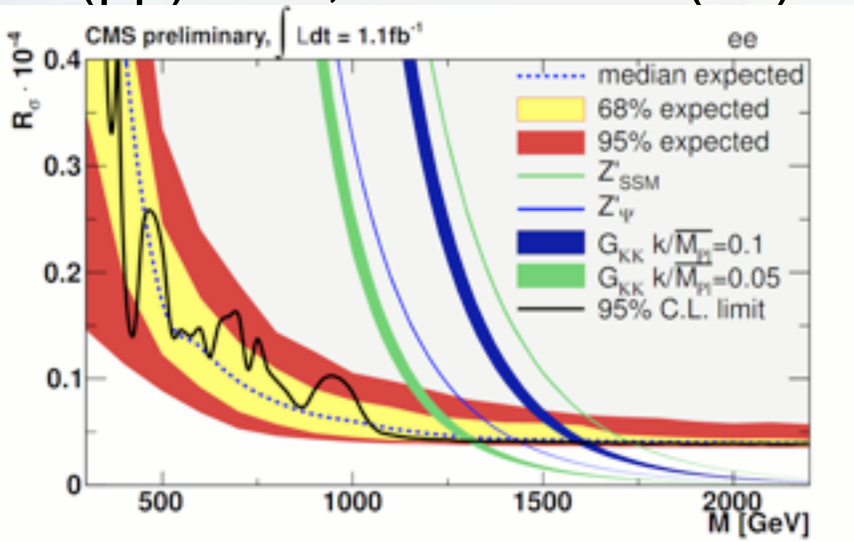
- Coherent ee and $\mu^+\mu^-$ analyses
  - Opposite-sign requirement ensures good momentum determination for dimuons; not needed for ee
- Muon momentum scale checked with cosmics
- DY is the dominant irreducible background
  - Top background from eμ data

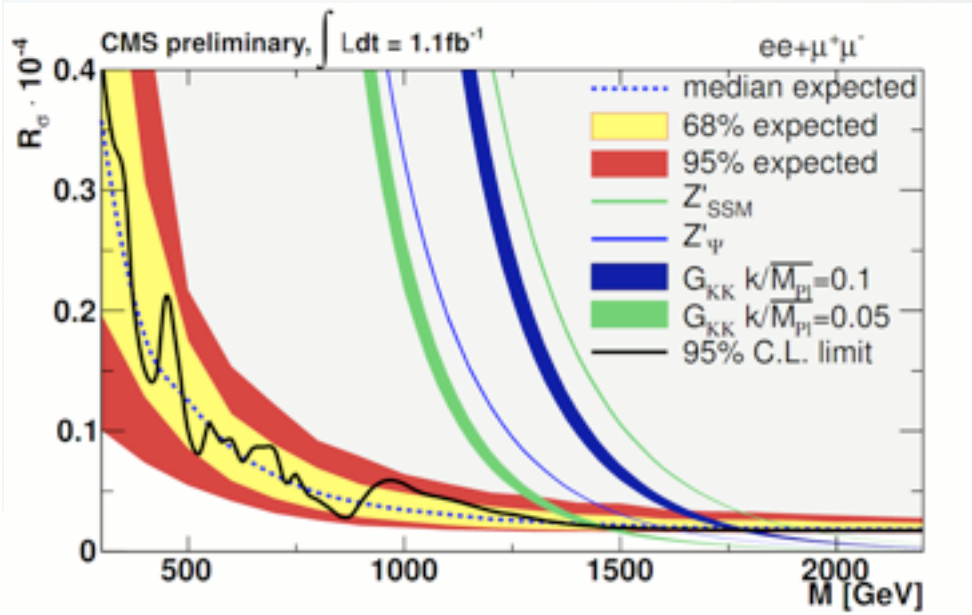


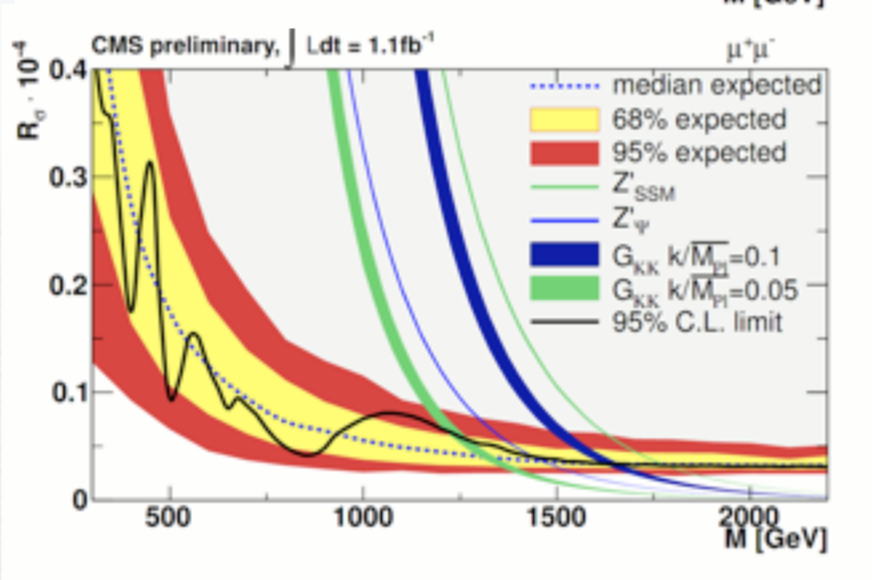
EXO PAS-11-019

Limits on the Z' and G_{KK}

- Doubles the Tevatron reach: G_{KK}, k/M_{Pl} =0.1: 1050 (ee+γγ) & 921 (μμ) GeV; Z'_{SSM}: 1023 (ee) & 1030 GeV (μμ)







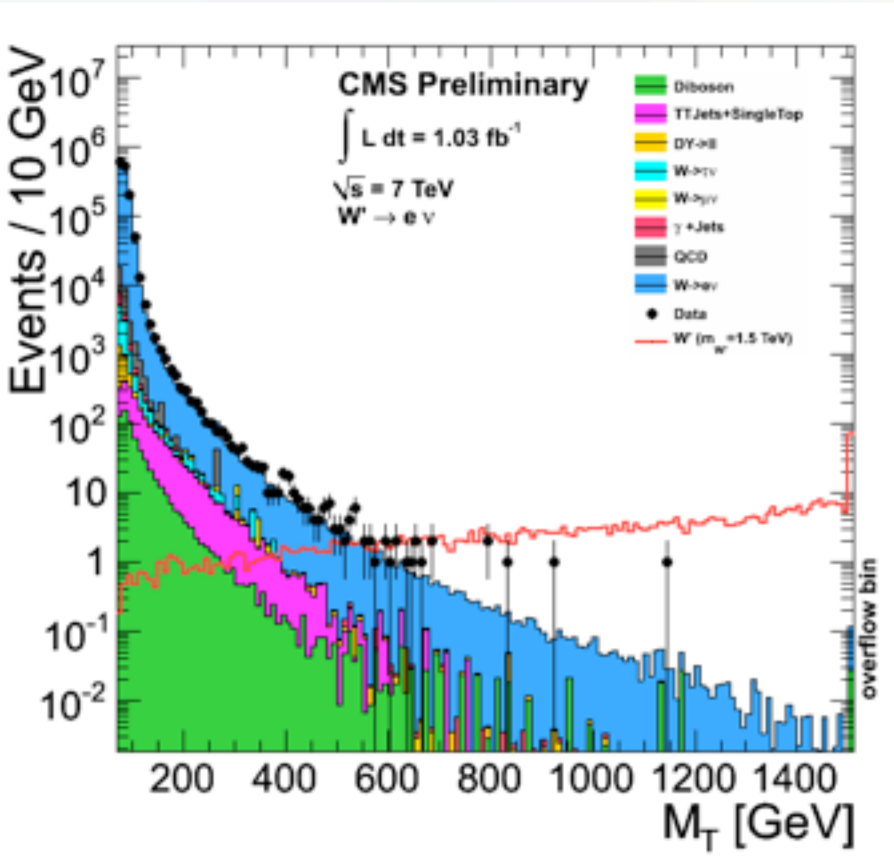
$M(Z'_{SSM}) > 1940$ GeV
$M(Z'_{\psi}) > 1620$ GeV

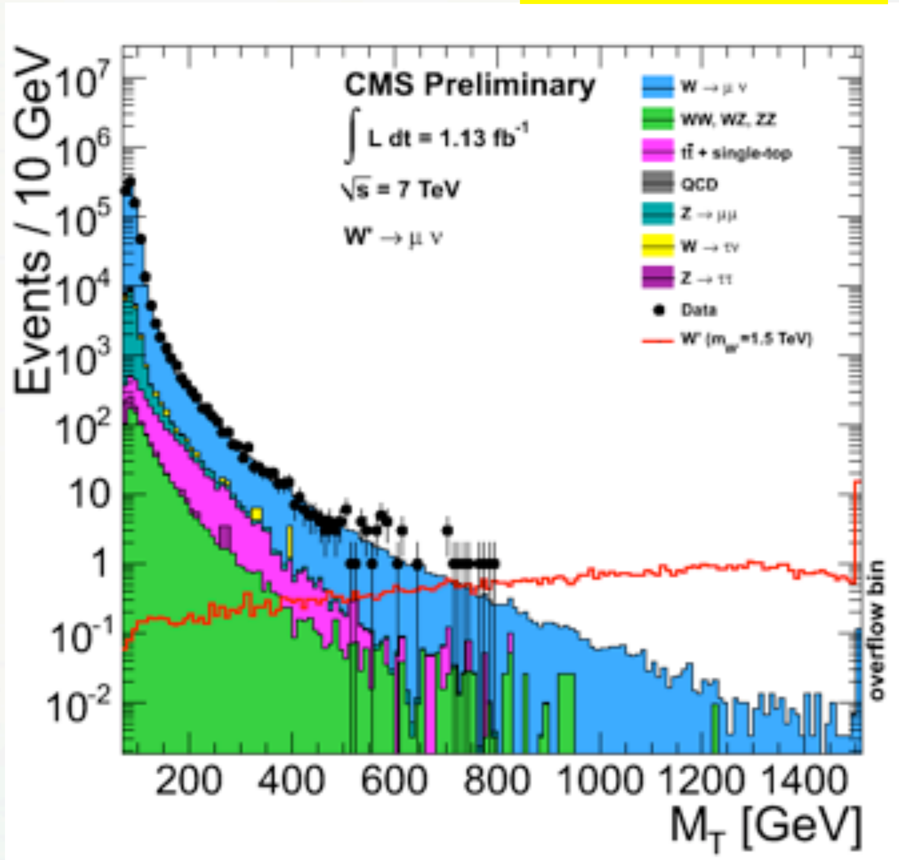
Max. significance:
Before LEE: 2.1σ
After LEE: 0.2σ

W'(eν+μν) Search

- W* and QCD backgrounds estimated via template method
- M_T > 1.0-1.1 TeV for M(W′) = 1.4-2.4 TeV; 1 eν event observed
- M(W′) > 2.27 TeV (eν+μν) - doubles the Tevatron limit of 1.12 TeV [CDF, arXiv:1012.5145, 5.3 fb^{-1}]!

EXO PAS-11-024





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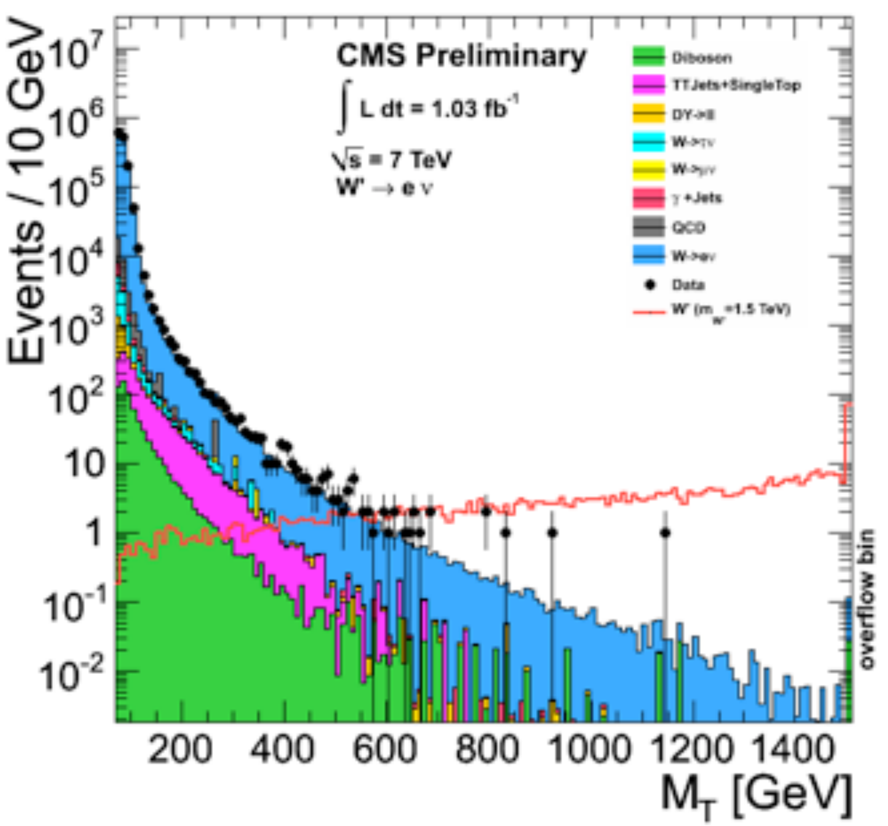
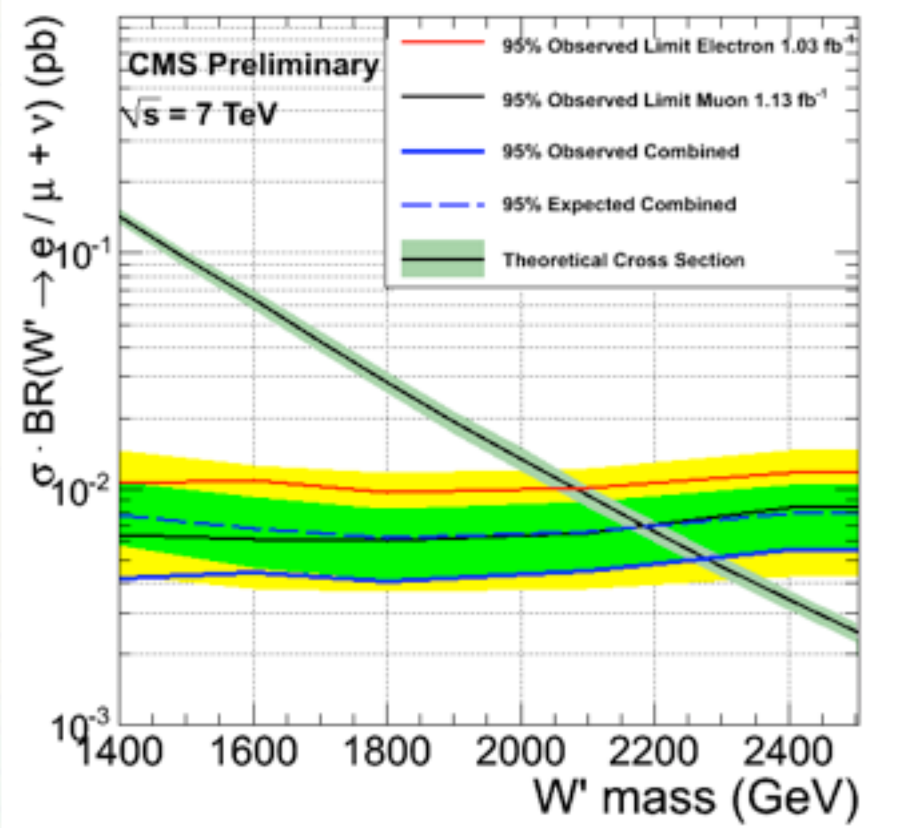
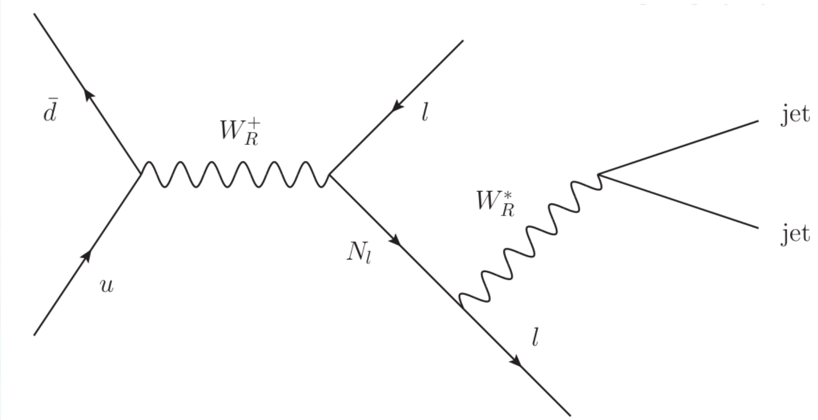




Search for a Heavy Neutrino

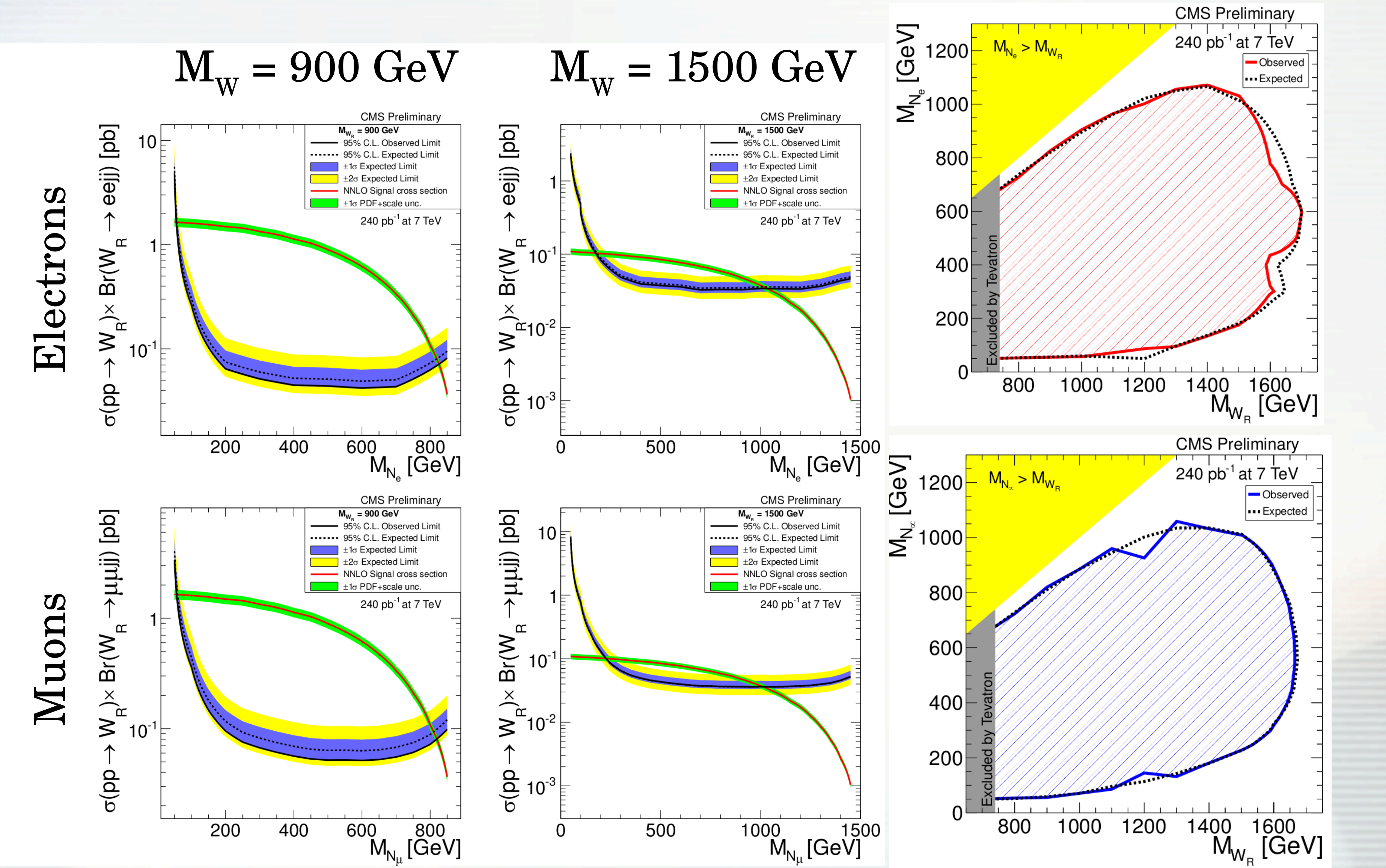
- Search for heavy right-handed neutrino
- Natural in LR-symmetric model; exist in other SM extensions
- Say final state as for LQ searches: two OS leptons and two jets
- Resonance is expected in the 4-body and 3-body invariant masses

	Left-Right Symmetric Model
Gauge Group	$SU(2)_L \times SU(2)_R \times U(1)$
Fermions	$Q_L=(u^i,d^i)_L$, $L_L=(l^i,\nu^i)_L$ $Q_R=(u^i,d^i)_R$, $L_R=(l^i,N^i)_R$
Neutrinos	ν^i_L have a heavy partner N^i_R N^i_R are Majorana
Gauge Bosons	$W^\pm_L$, $W^\pm_R$, Z^0, Z', γ

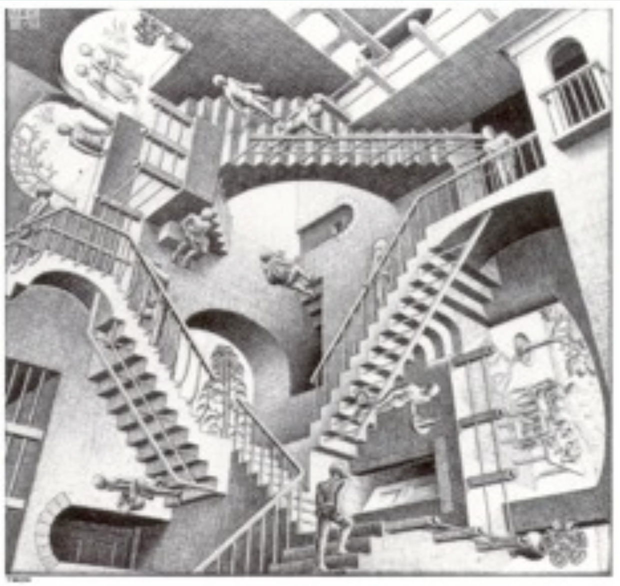


Limits on Right-Handed W

- Set limits on electron and muon heavy neutrino

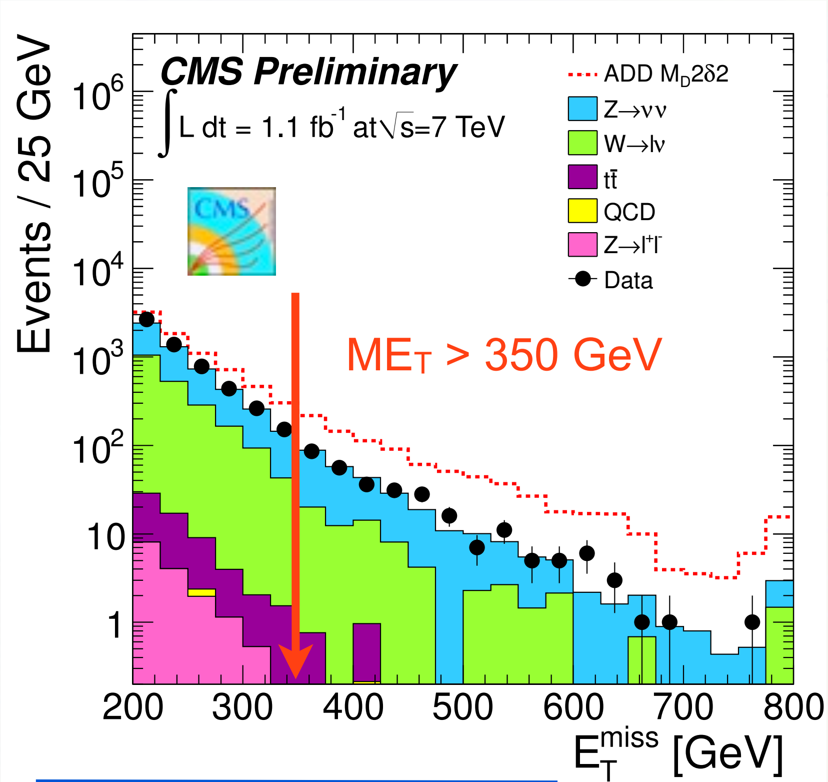


Searches for Extra Dimensions

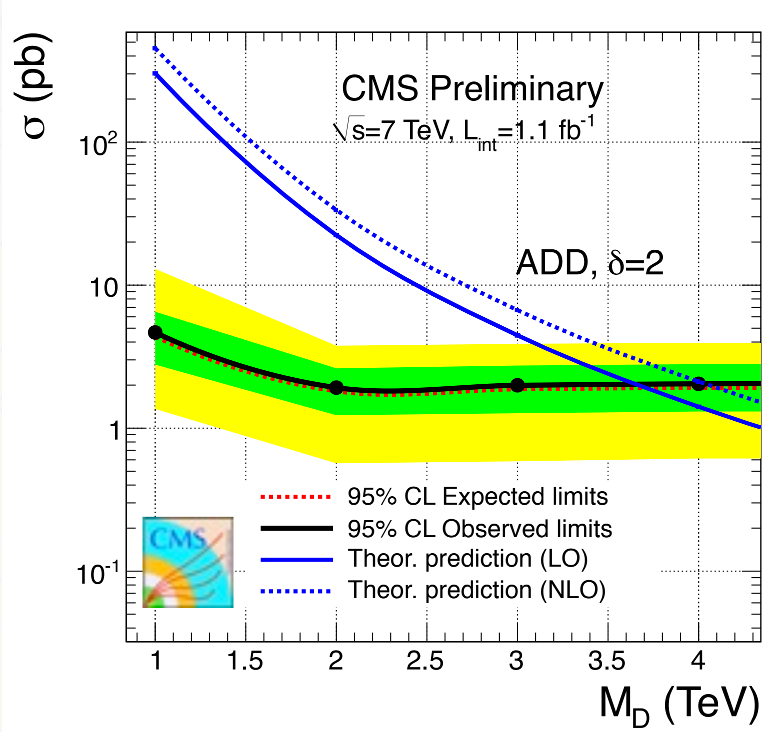


Search for Monojets

- CMS published 2010 data search (36/pb)
- CMS also presented preliminary results with 2011 data (1.1/fb)
- Dominated by irreducible Z(νν)+jets background (determined from W(eν/μν)+jets)



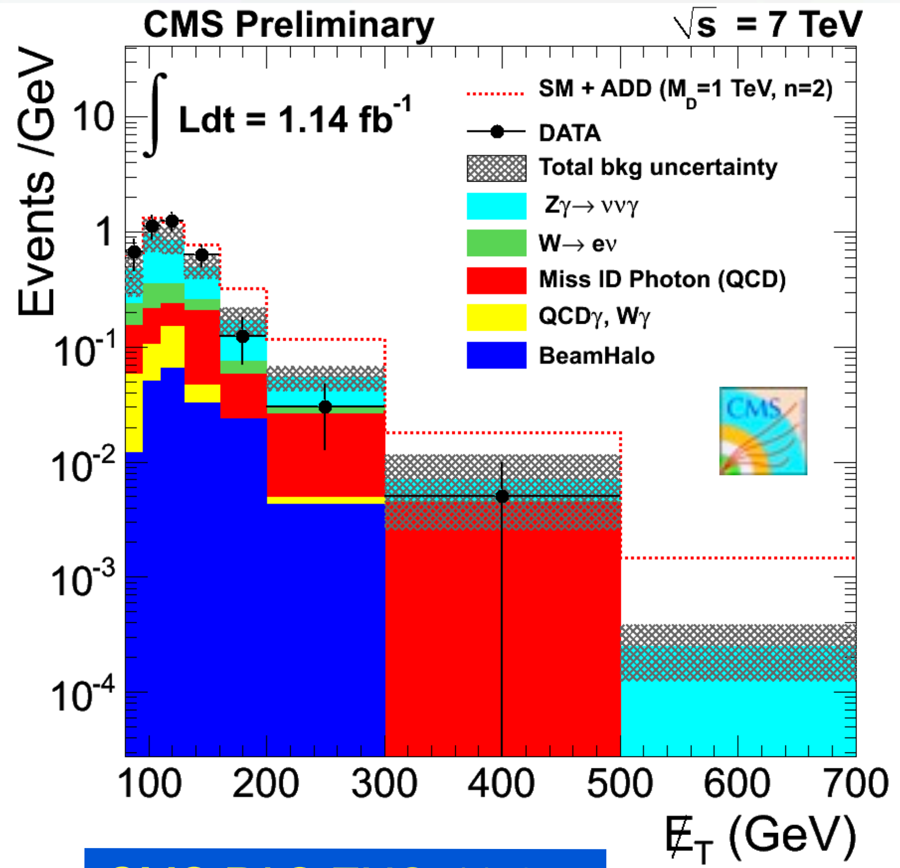
CMS PAS EXO-11-059

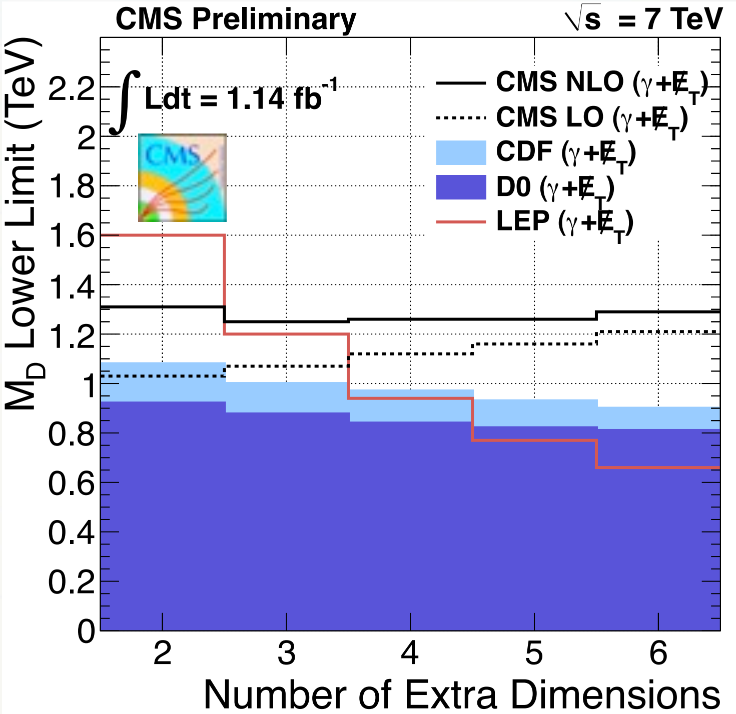


CMS limits w/ 1.1 fb^{-1} @ 95% CL
n=2: M_D > 3.7 TeV
n=6: M_D > 2.3 TeV

Search for Monophotons

- First analysis of a kind at the LHC
- Similar techniques to the monojet analysis
- Irreducible background from Z(νν)+jets





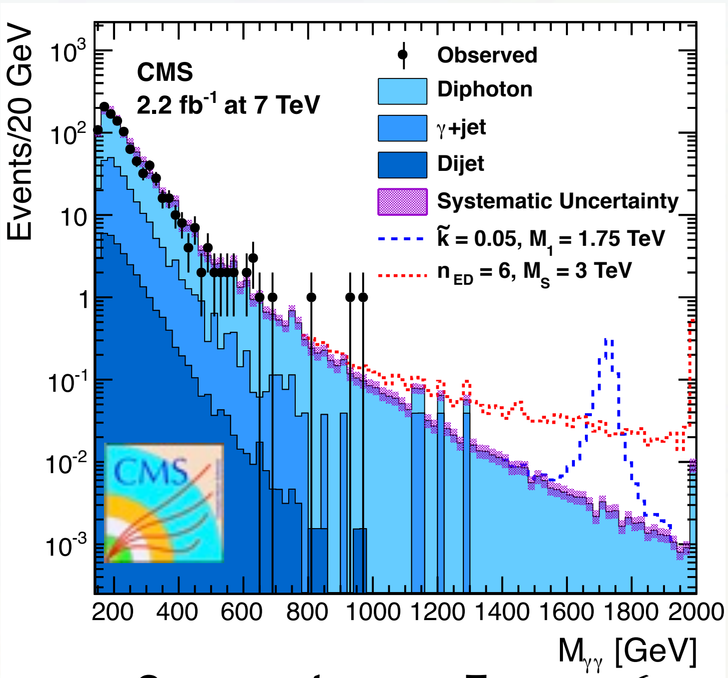
CMS PAS EXO-11-058

CMS limits w/ 1.14 fb^{-1}
95% CL
n=2: M_D > 1.0 TeV
n=6: M_D > 1.2 TeV

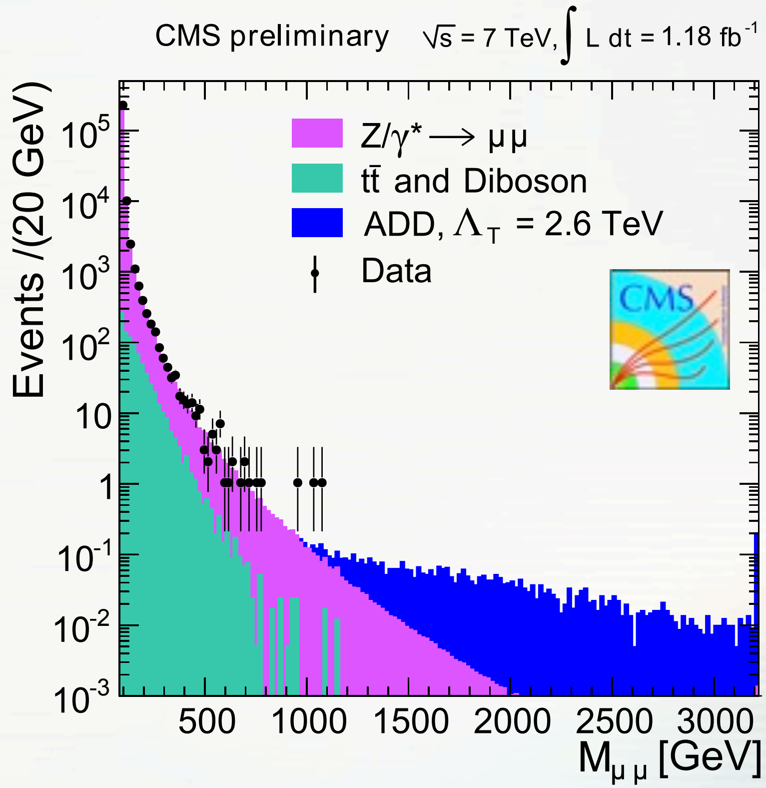
Virtual Graviton Effects at the LHC

- Clean signature, with a huge potential of a quick discovery in dimuon, dielectron, and diphoton channels
- CMS published $\gamma\gamma$ with 2010 data (36/pb) and 2011 data (2.2/fb)
- CMS preliminary 2011 $\mu\mu$ results with 1.1-1.2/fb

arXiv:hep-ex/1112.0688



2	3	4	5	6
3.29	3.50	2.94	2.66	2.47
2.58	3.12	2.62	2.36	2.20



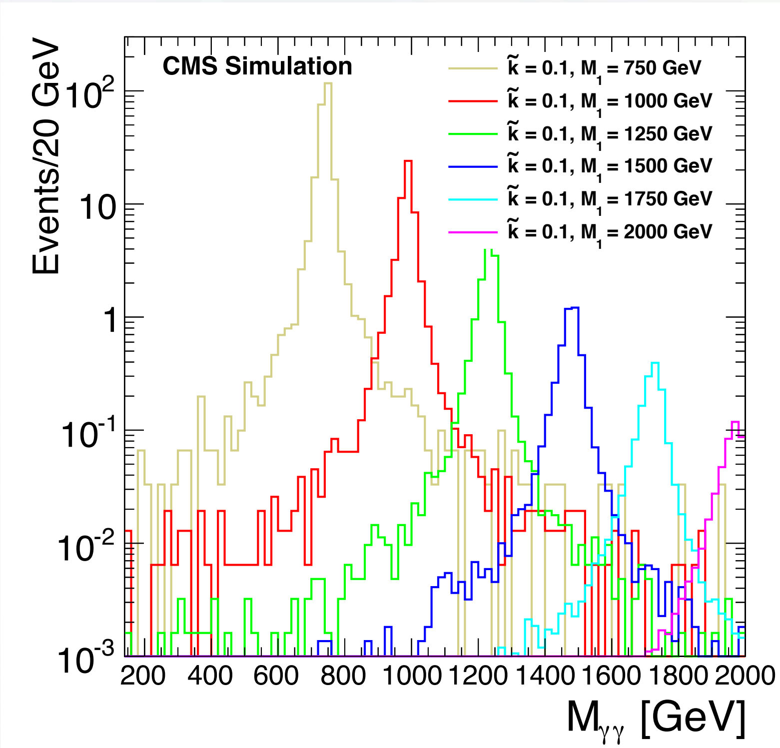
CMS PAS EXO-11-039

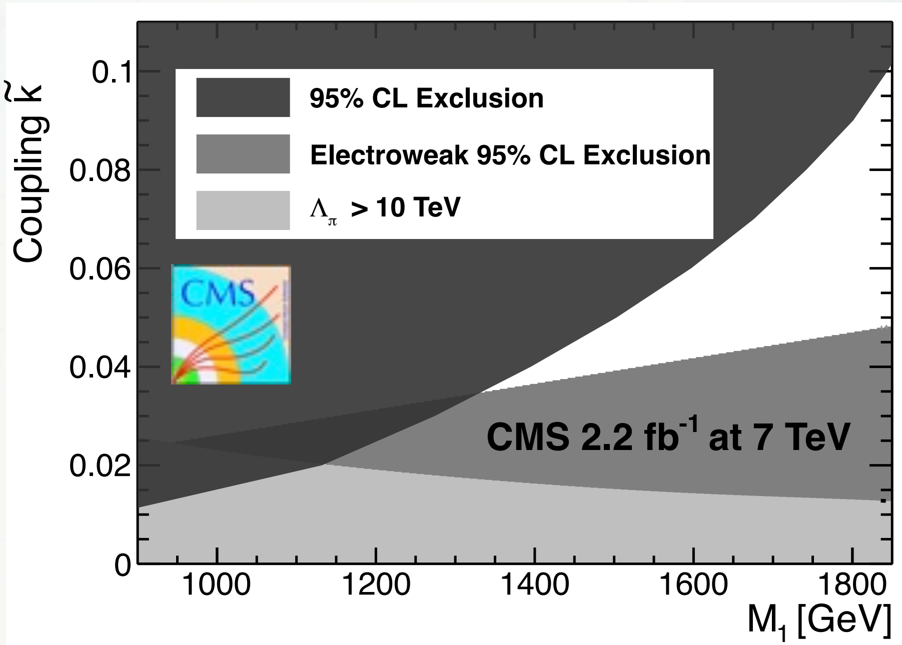
Limits in the diphoton channel

Limits in the dimuon channel

RS Gravitons at the LHC

- Same analyses can be reinterpreted as search for resonances decaying into pair of photons (e.g., G_{KK})
- Significantly exceeds the Tevatron limits with ~2/fb of LHC data





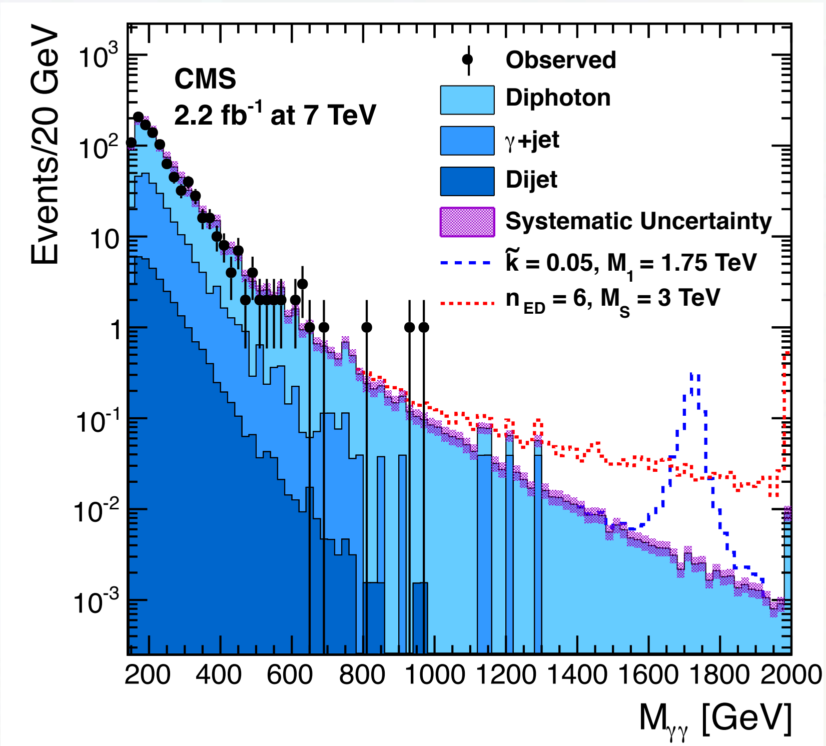
$\tilde{k}$	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11
M_1 [TeV]	0.86	1.13	1.27	1.39	1.50	1.59	1.67	1.74	1.80	1.84	1.88

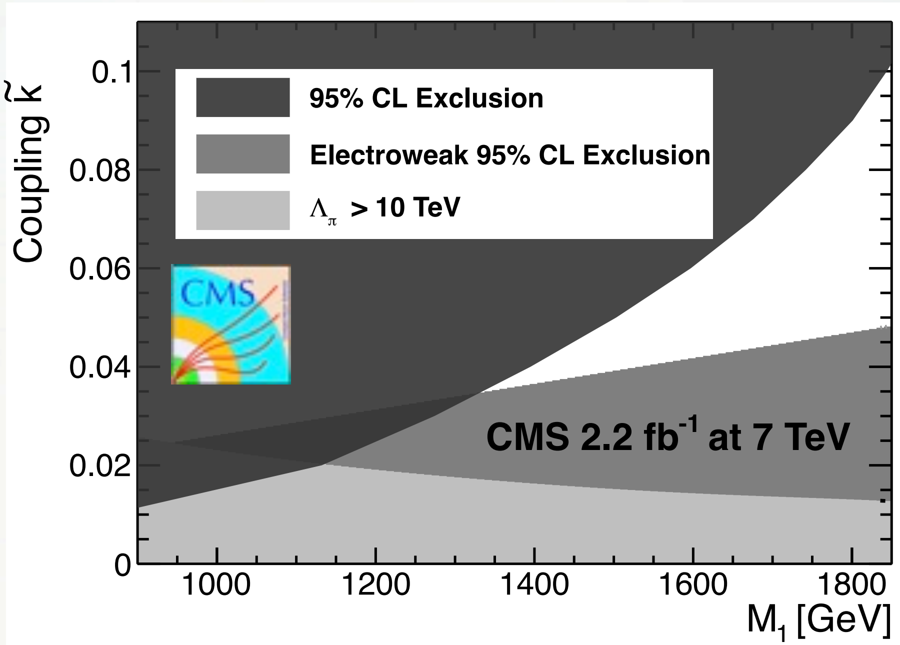
CMS: ee+μμ @1.1/fb
M > 1450-1780 GeV
for k/M_{Pl} = 0.05-0.10

CMS PAS EXO-11-038

RS Gravitons at the LHC

- Same analyses can be reinterpreted as search for resonances decaying into pair of photons (e.g., G_{KK})
- Significantly exceeds the Tevatron limits with ~2/fb of LHC data





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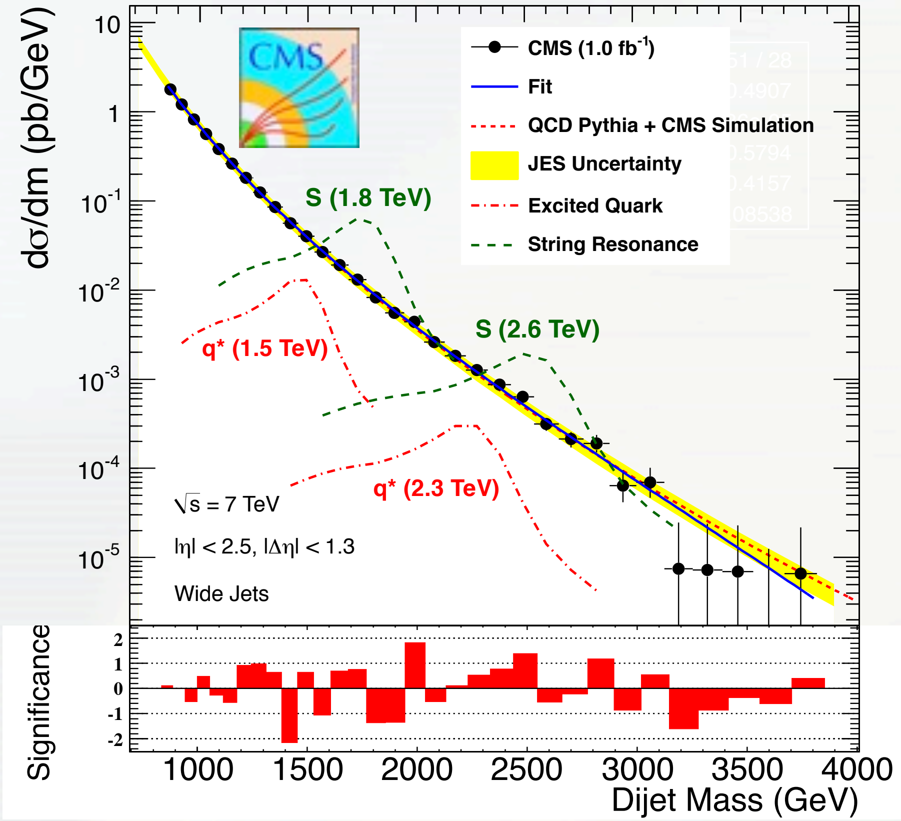
CMS PAS EXO-11-038

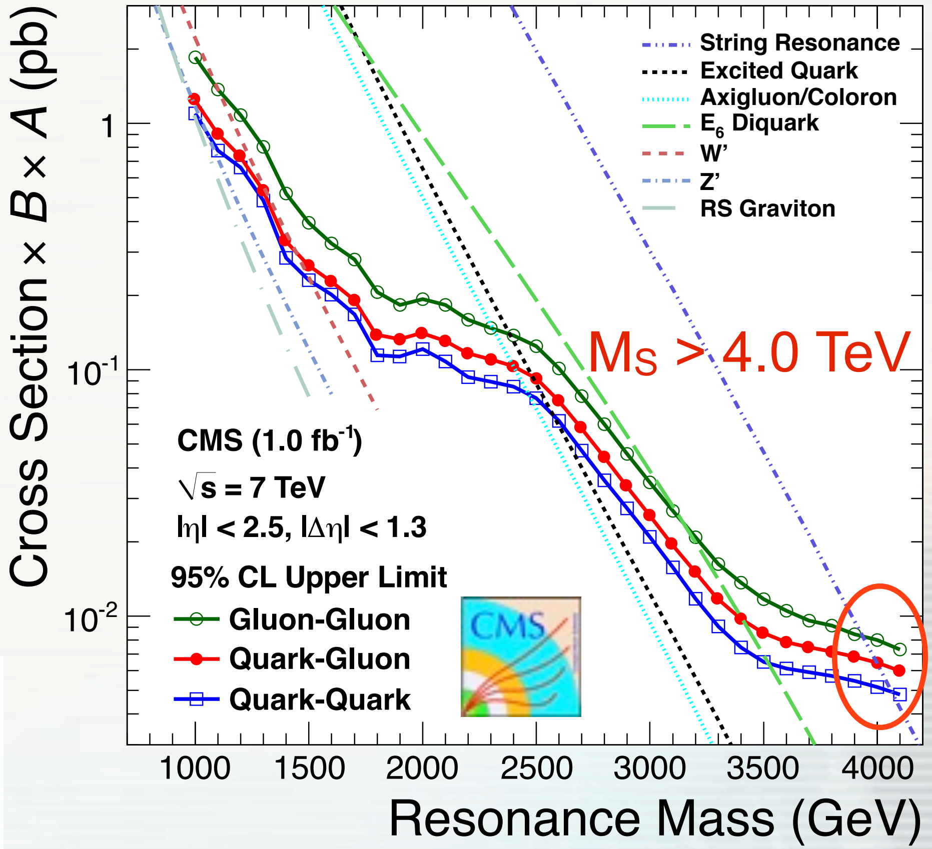
Searches for Quantum Gravity at the LHC

String Resonances at the LHC

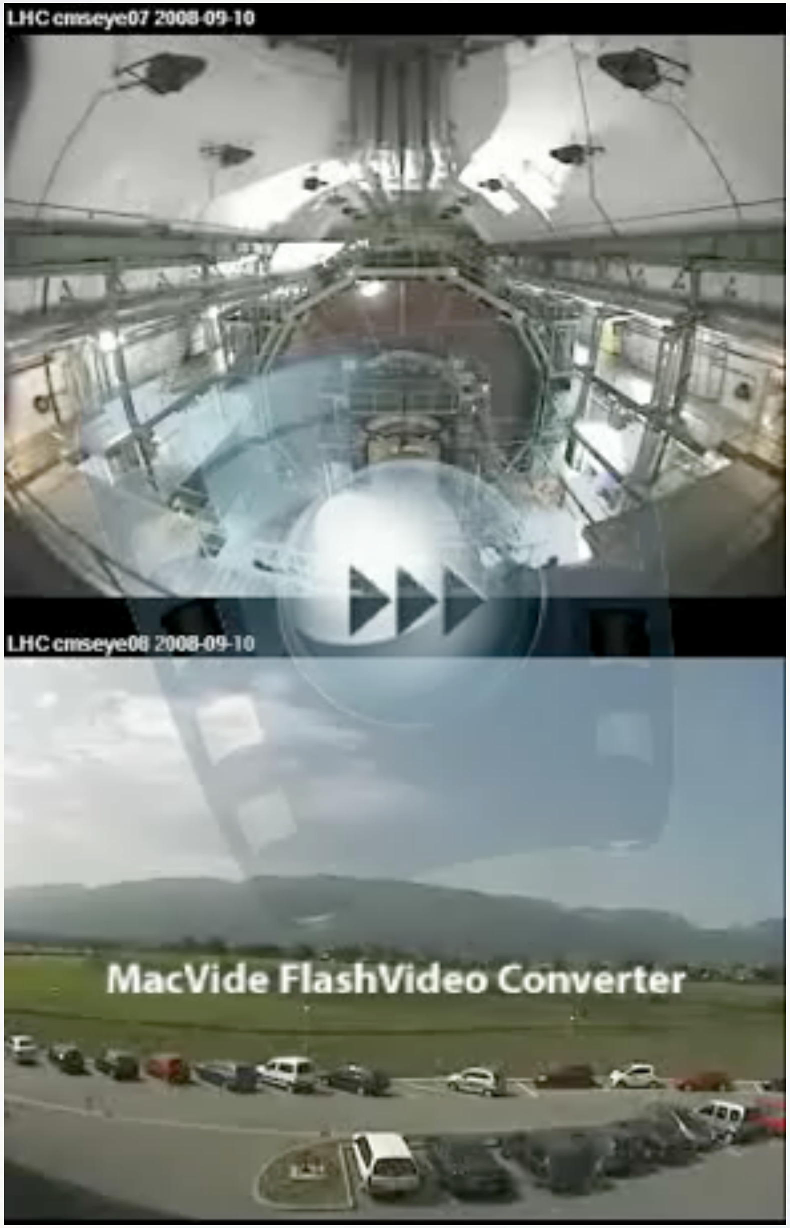
- Highly-degenerate excitations of quarks & gluons, decaying into qq, gg, qg
- Look for “bumps” on top of steeply falling QCD spectrum
- Similar limits apply to quantum BH’s, decaying into pair of initial partons

PLB **704** (2011) 123





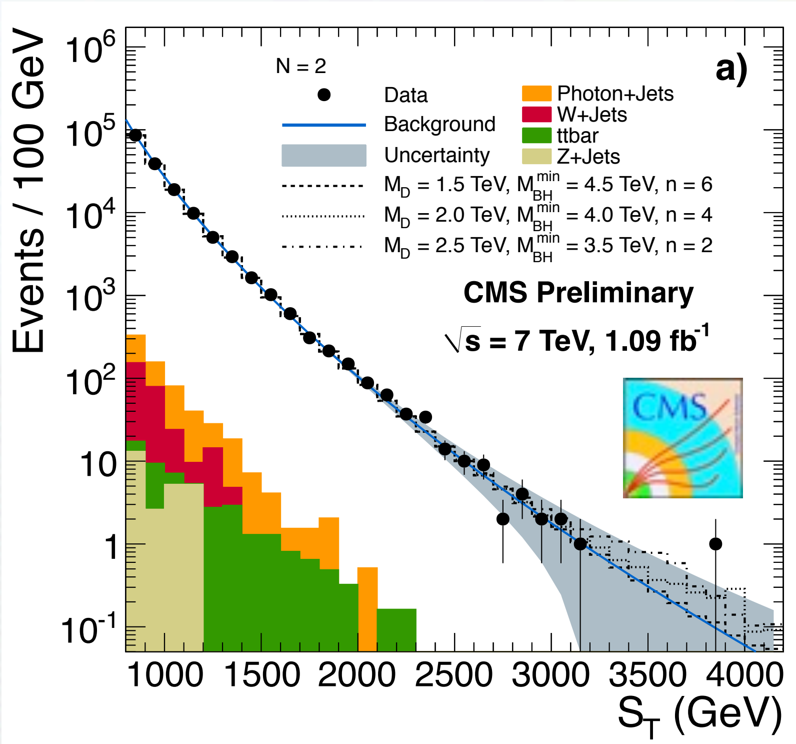
Black Holes in CMS



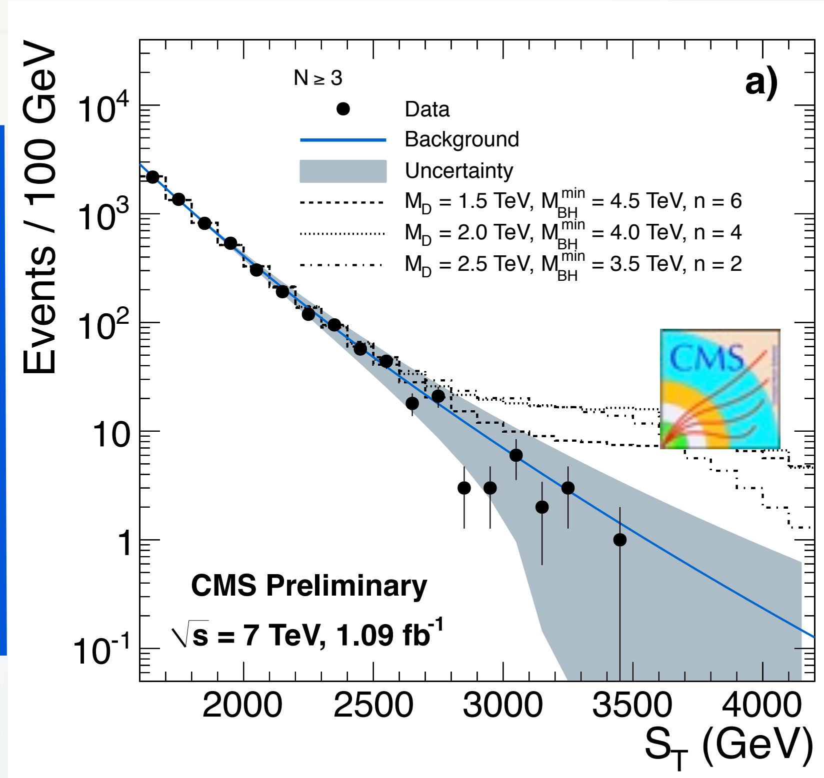
Black Holes in CMS

Analysis with 2011 Data (1/fb)

- First dedicated collider search based on the 2010 data published earlier this year [Phys. Lett. **B697** (2011) 434]; updated w/ 1.1/fb
- Use $S_T = \Sigma E_T$, where the sum is over all the N objects in the event with E_T > 50 GeV, including ME_T
- Established the empirical S_T invariance of N with the data, using exclusive N = 2 and 3 multiplicities
- Assign shape uncertainty due to fit parameter variation and template function choice



CMS PAS EXO-11-071



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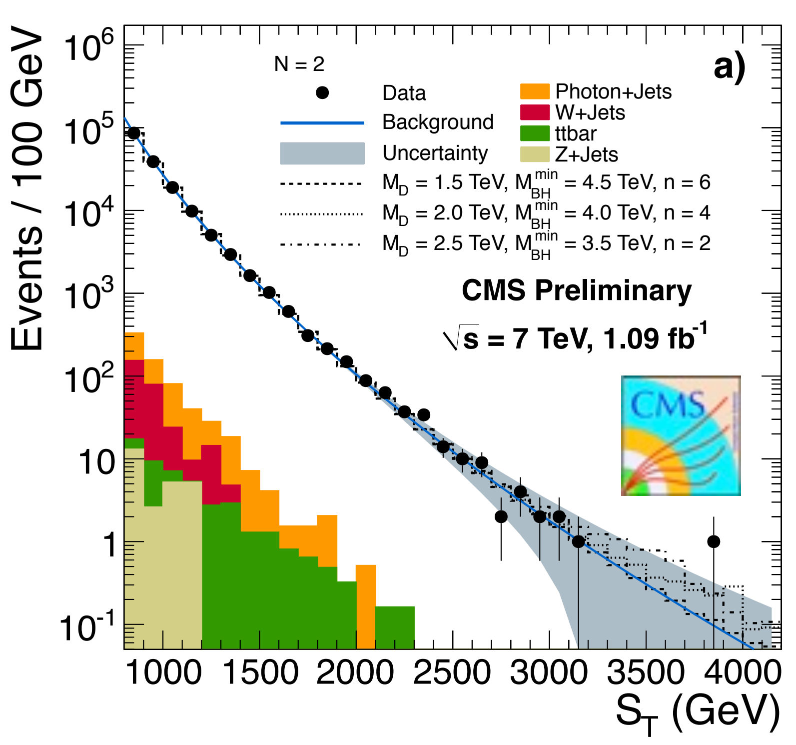
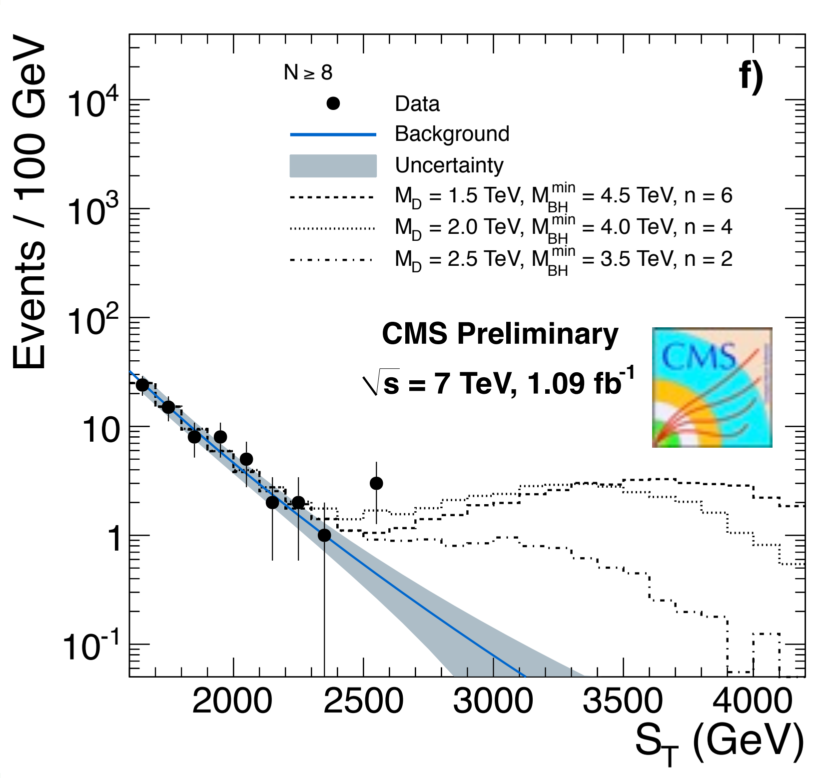
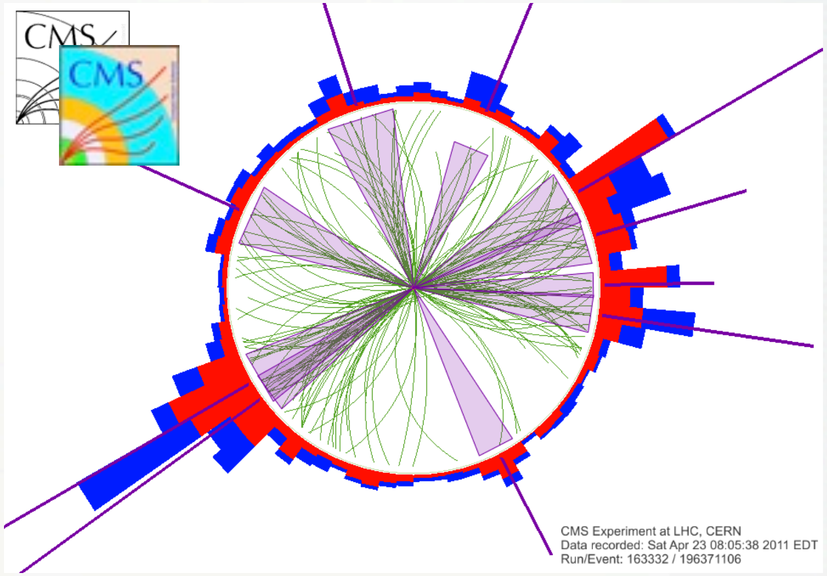


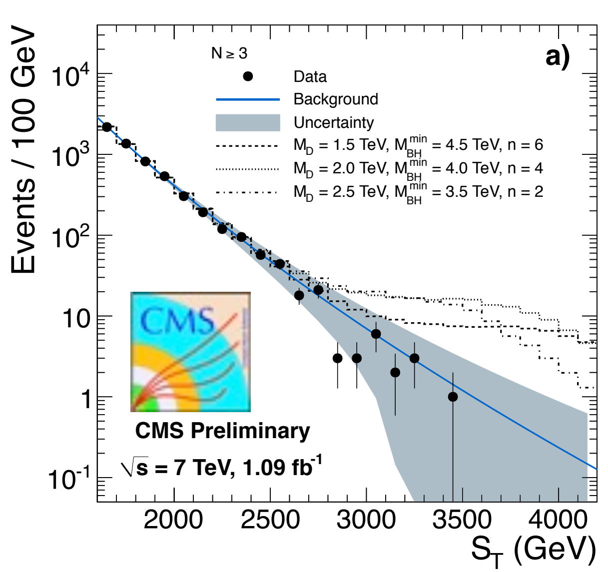
CMS PAS EXO-11-071

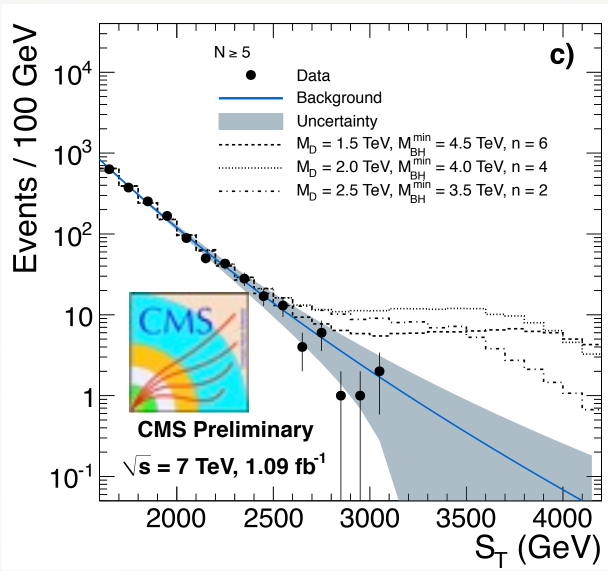


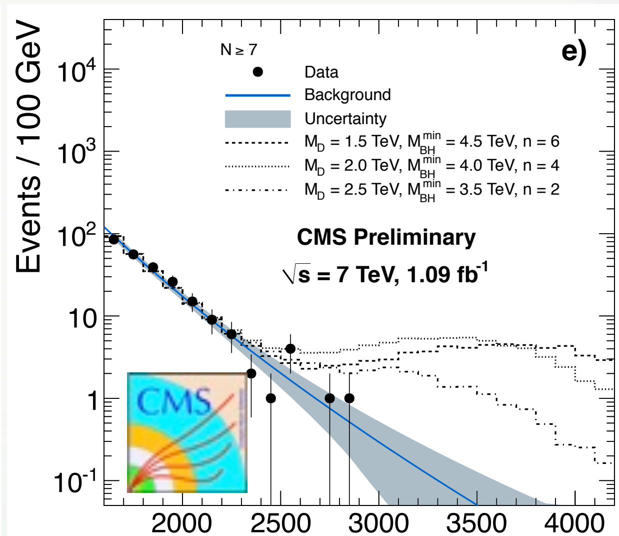
Spectra at Different Multiplicities

- Used the N=2 shape with its uncertainties, to fit higher multiplicities, where the signal is expected to be most prominent
- Given no excess, set limits on the minimum BH mass
- Despite lack of excess, see some truly spectacular events!









CMS PAS EXO-11-071

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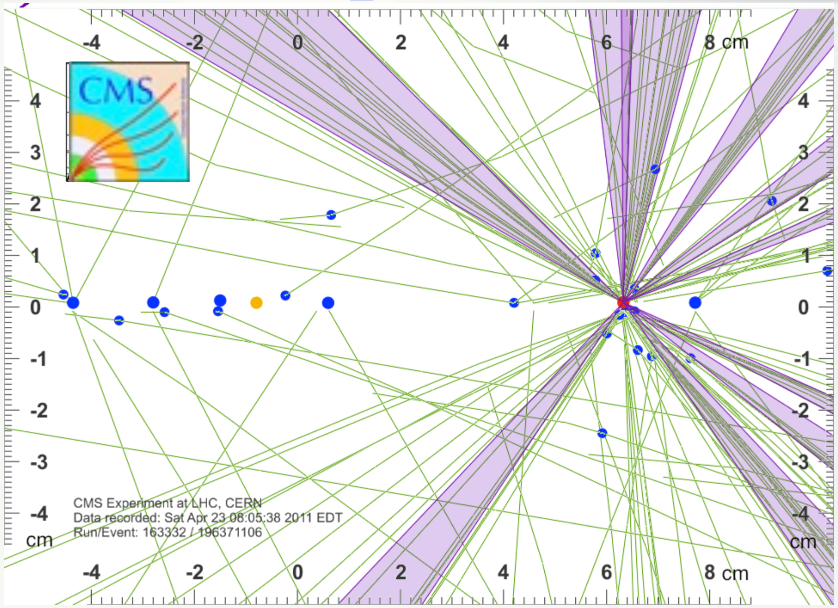

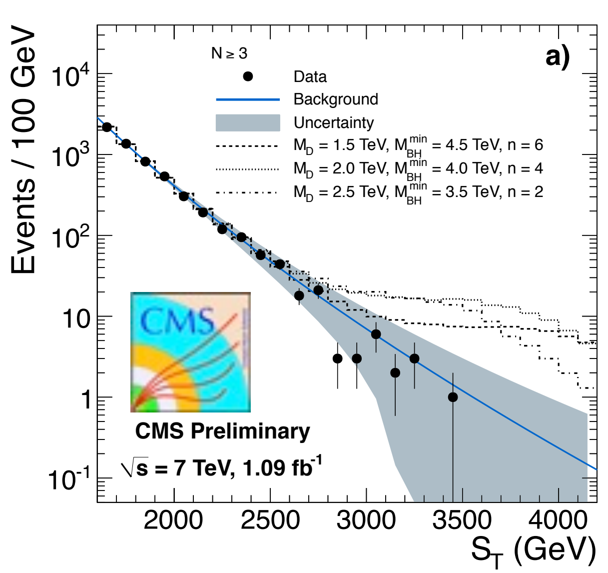

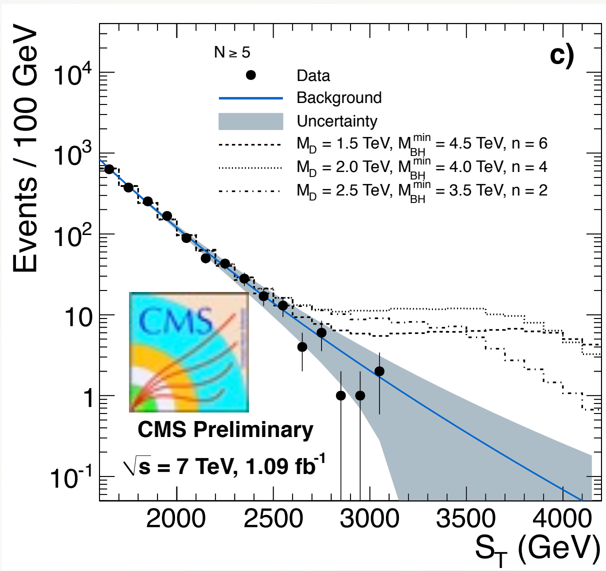

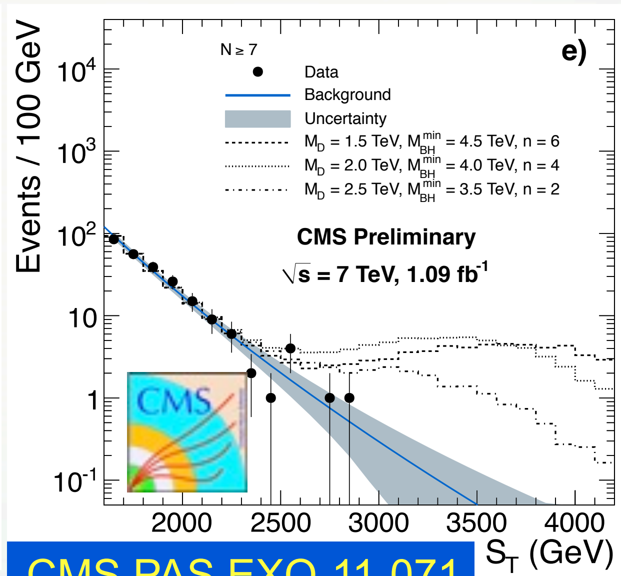

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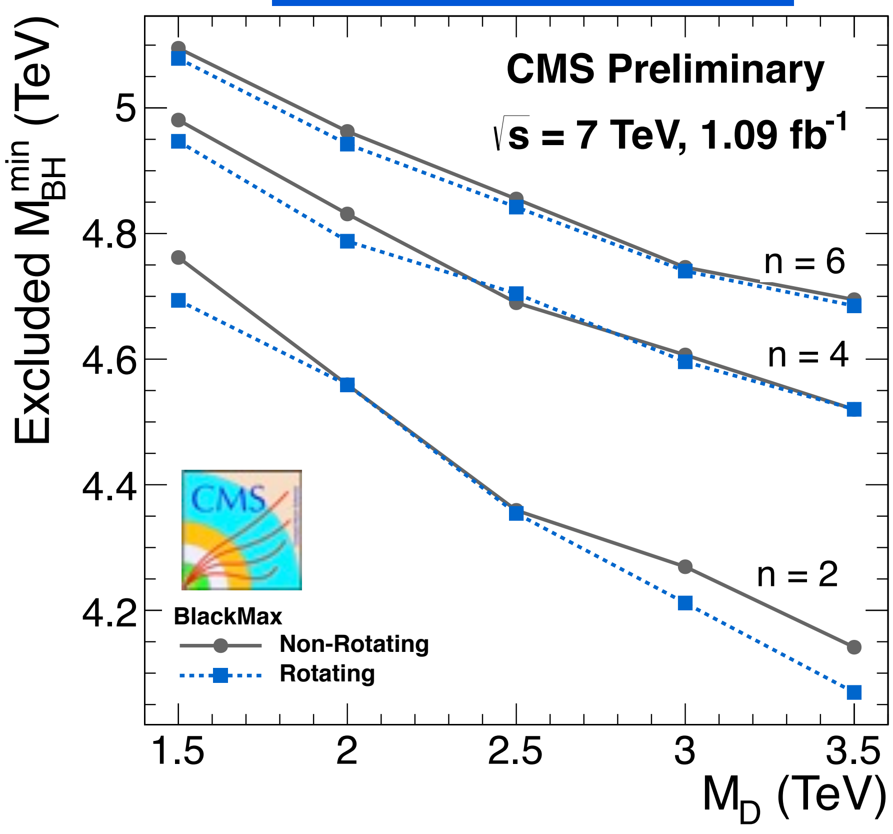
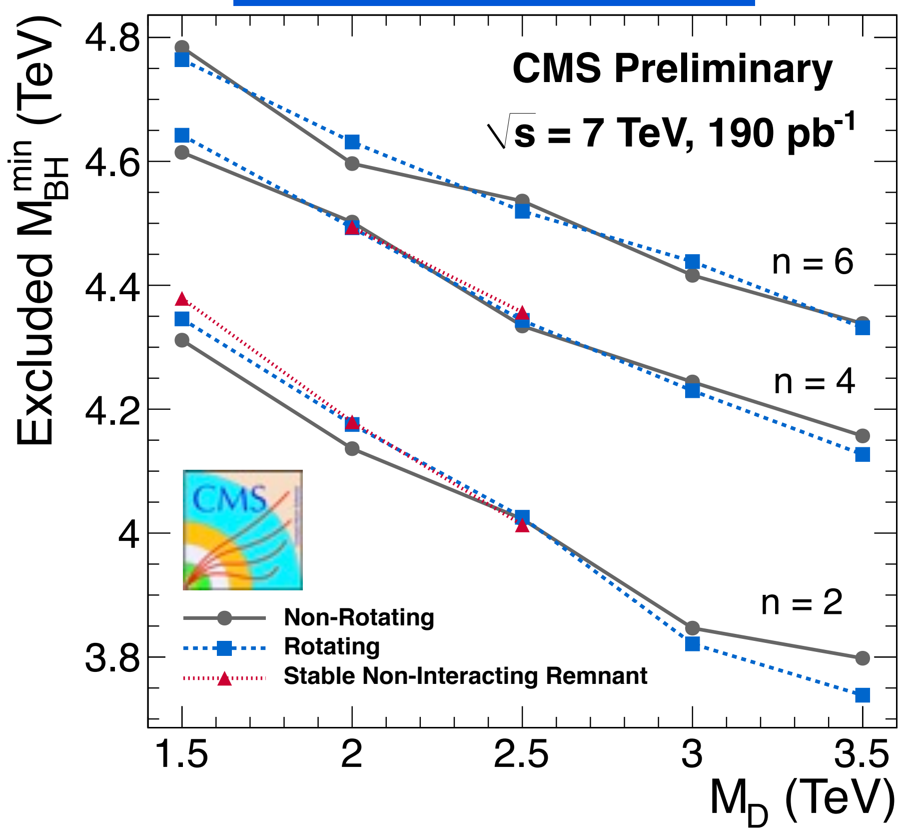
Semi-Classical Limits

- Not very useful at these relatively low masses, but give one an idea on the typical mass reach
- Important point is low sensitivity on the parameters of the production and decay model, such as remnant, rotation, etc.

CMS PAS EXO-11-071

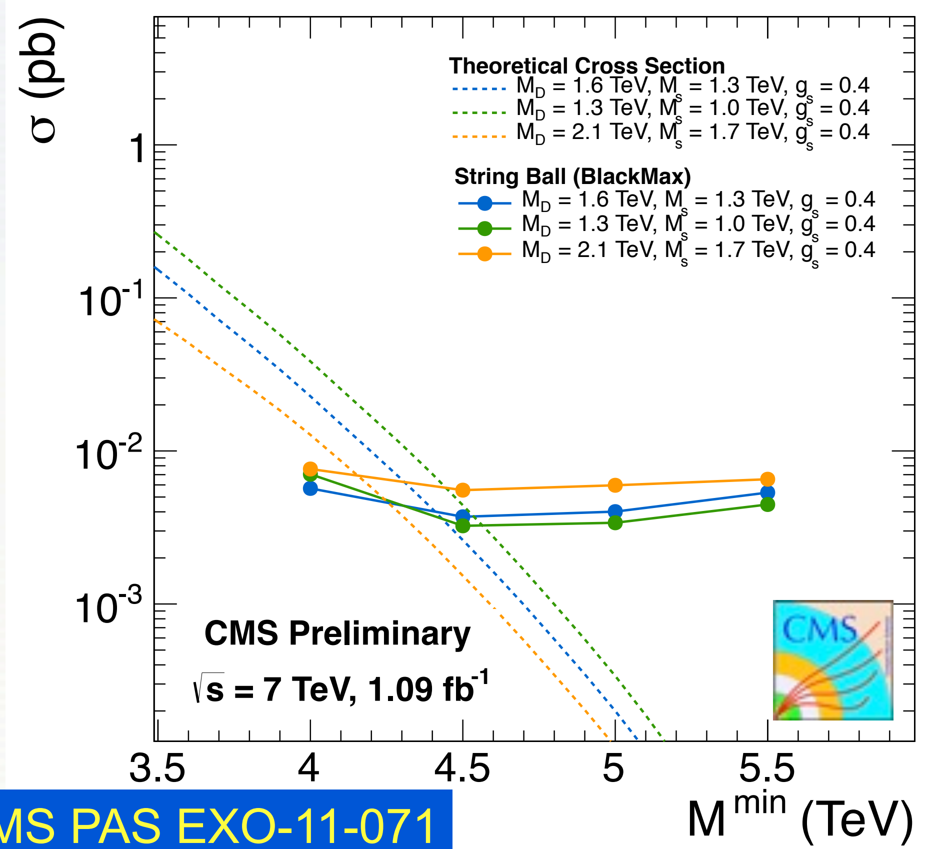


CMS PAS EXO-11-021



String Balls Limits

- An attempt to see the sensitivity of our results to quantum effects is to interpret our limits in terms of string balls - quantum precursors of black holes
- First limits on string balls from a collider experiment

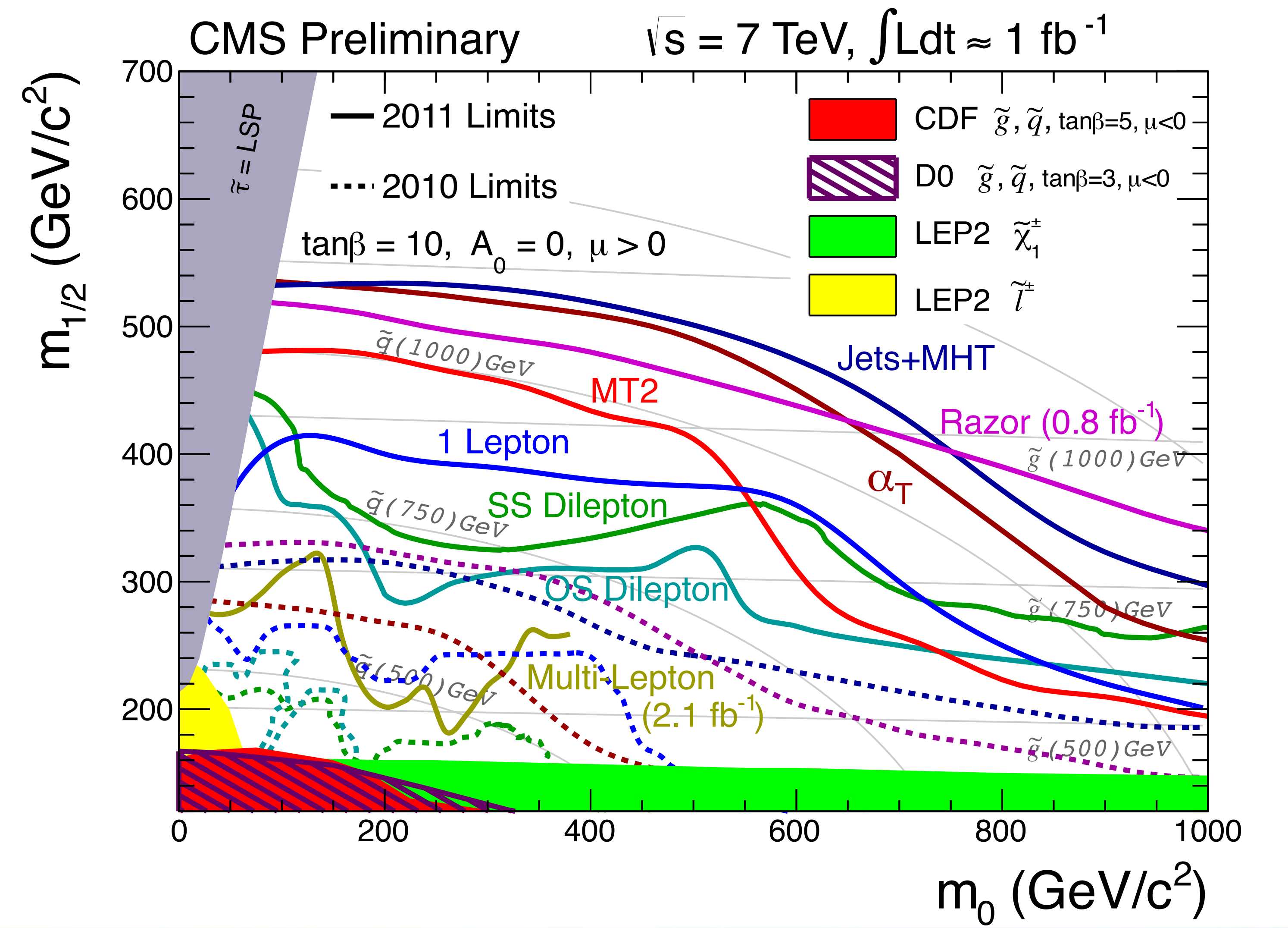


CMS PAS EXO-11-071

Searches for SUSY

SUSY @ 1/fb: The Grand Picture

- You've heard details already from other workshop speakers

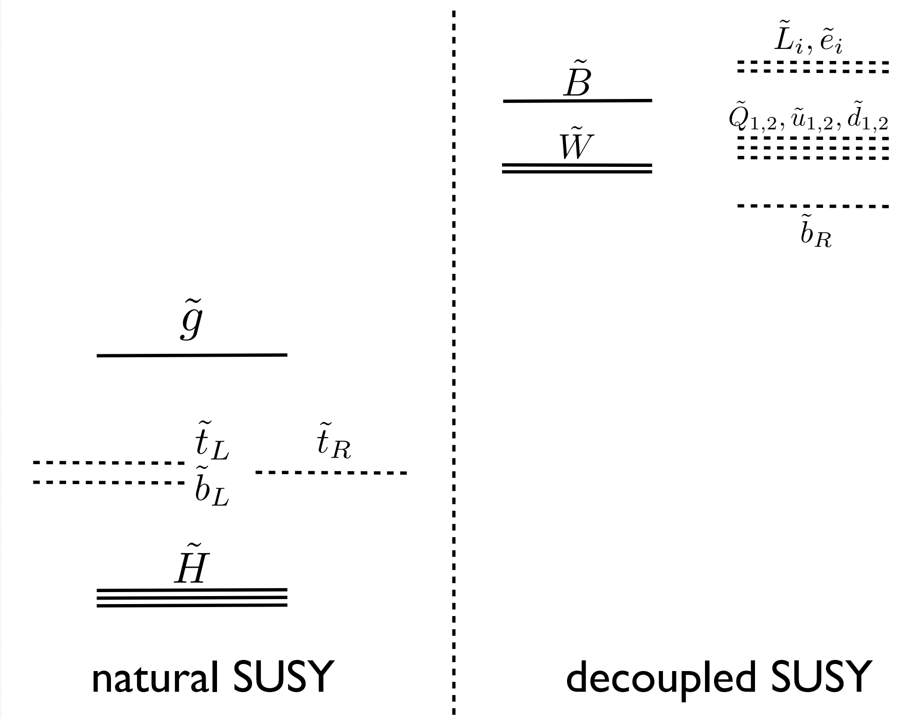


What Does this Mean

- We have excluded (in the context of CMSSM):
  - Squarks with the masses < 1.1 TeV
  - Gluinos with the masses < 850 GeV
- Does this mean that we ruled out "natural SUSY"?
  - No, as naturalness has little to do with these particles
  - The ones that must be light as stops, sbottoms, and perhaps gluinos, but not as light as 1 TeV
- Does this mean that we ruled out SUSY accessible at 7 TeV?
  - No, as we only looked under the lamppost so far!
  - Current analyses have low/vanishing efficiency for more complex signatures
  - No optimized searches for third generation squark and sleptons yet

Natural SUSY

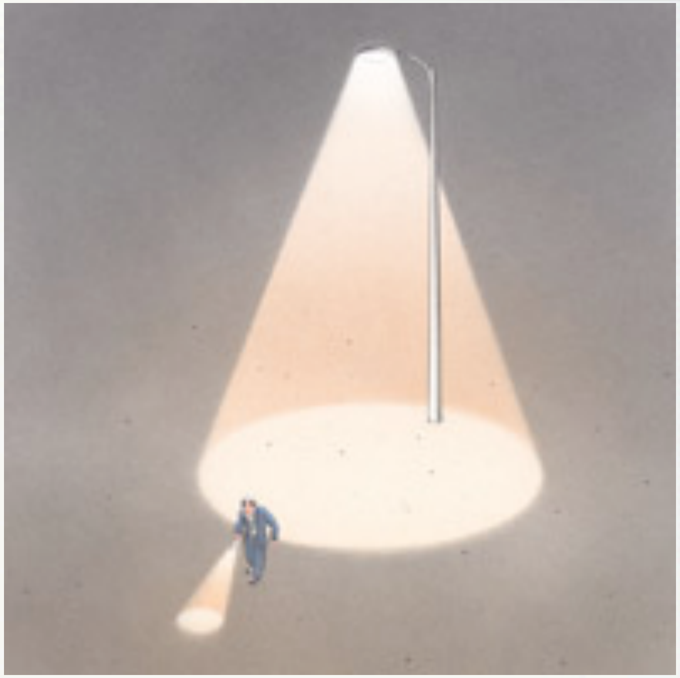
- Two stops and left-handed sbottom below 500-700 GeV
- Two neutralinos and one chargino below 200-350 GeV; the spectrum can be degenerate
- Not too heavy gluino: in the 900-1500 GeV range



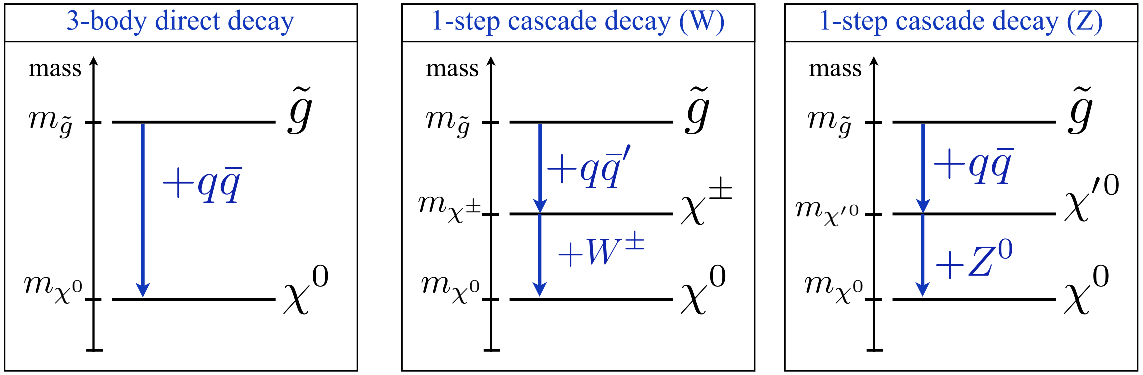
Papucci, Ruderman, Weiler, arXiv:1110.6926

Away from the Lamppost

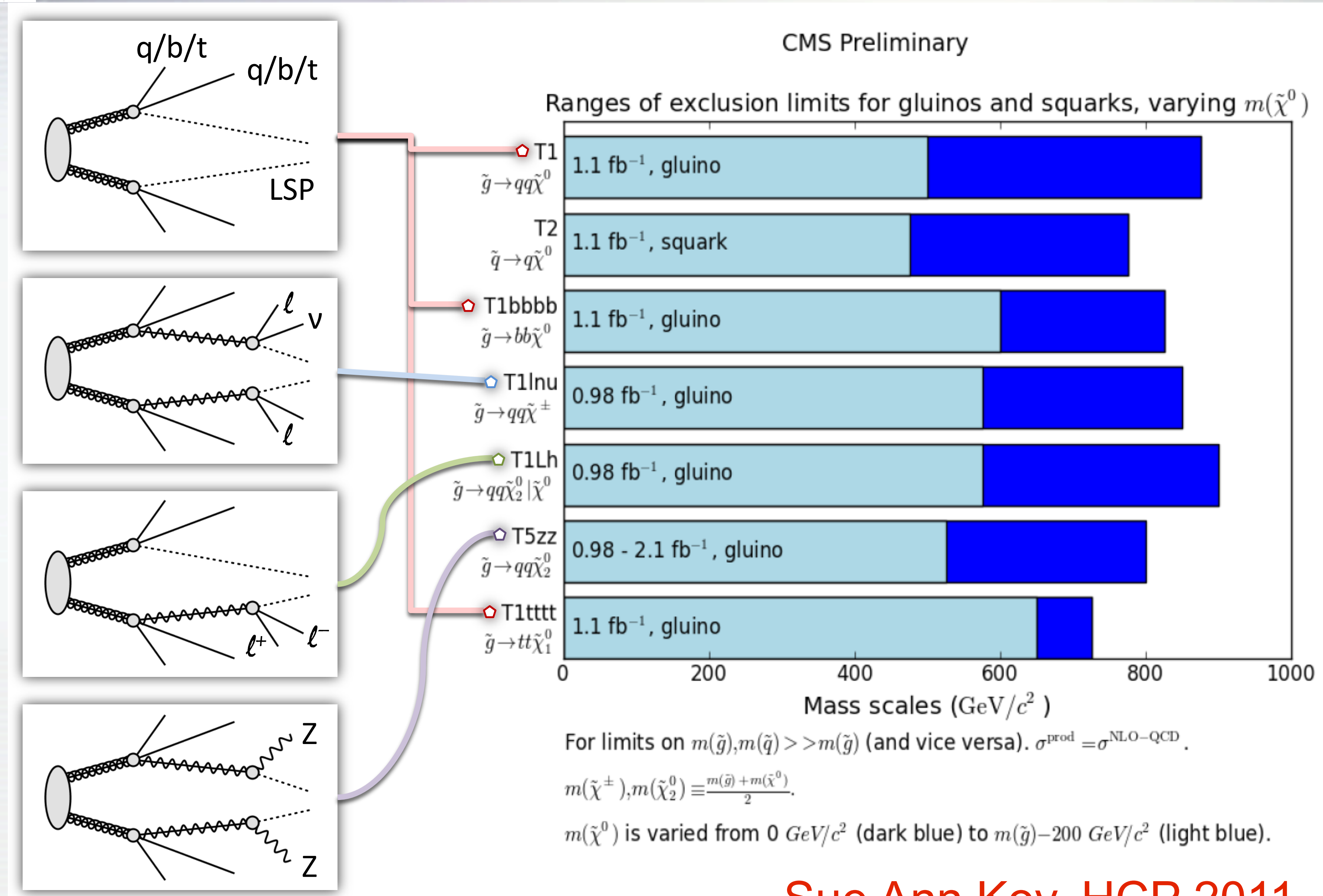
- What can be our guiding light, once we move away from the lamppost of "easy-SUSY"?
- Simplified models, focusing on the event kinematics rather than on the details of SUSY spectra, can light the way
- In these models we ignore the structure of matrix elements and focus on the kinematics of the decays
- Hence, everything is fixed by a few masses and their splittings
- While simple, this approach allows us to see clearly the limitations of current searches and design new ones



Alves et al. (LHC NP WG) arXiv:1105.2838



SSM Searches in CMS

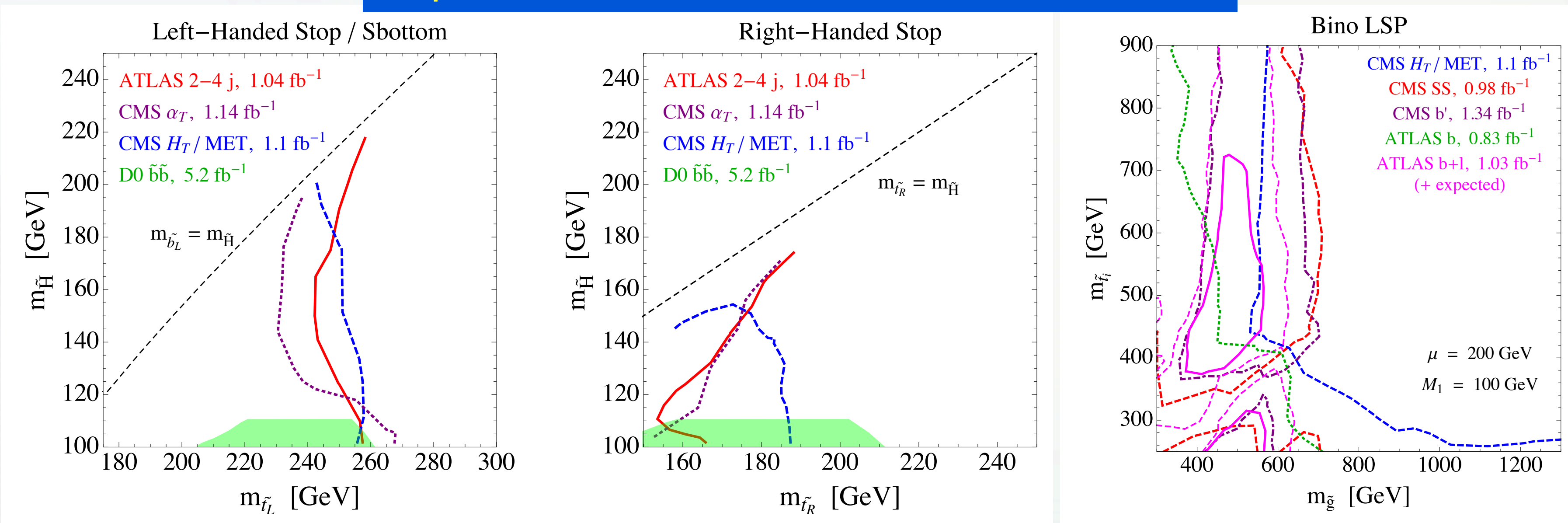


Sue Ann Koy, HCP 2011

Examples of Simplified Models Use

- The current ATLAS/CMS searches, when reinterpreted in the light sbottom/stop scenario, only extend the Tevatron limits on stop/ sbottom slightly
- Curiously, b-tagged channels mostly are not as sensitive than non-b-tagged ones
- Provides an excellent tool to reoptimize the analyses targeting light stops and sbottom in a variety of cases

Papucci, Ruderman, Weiler, arXiv:1110.6926

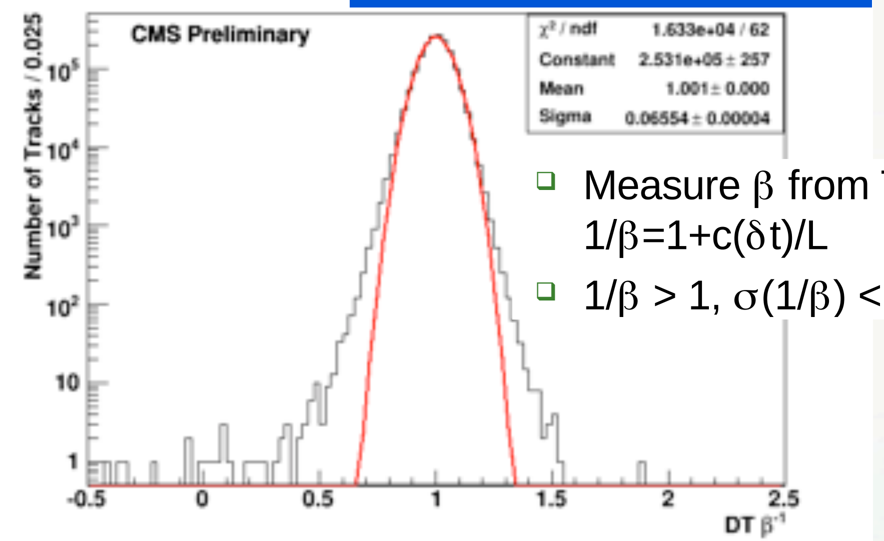


Beyond the Low-Hanging Fruit

Searches for Long-Lived Particles

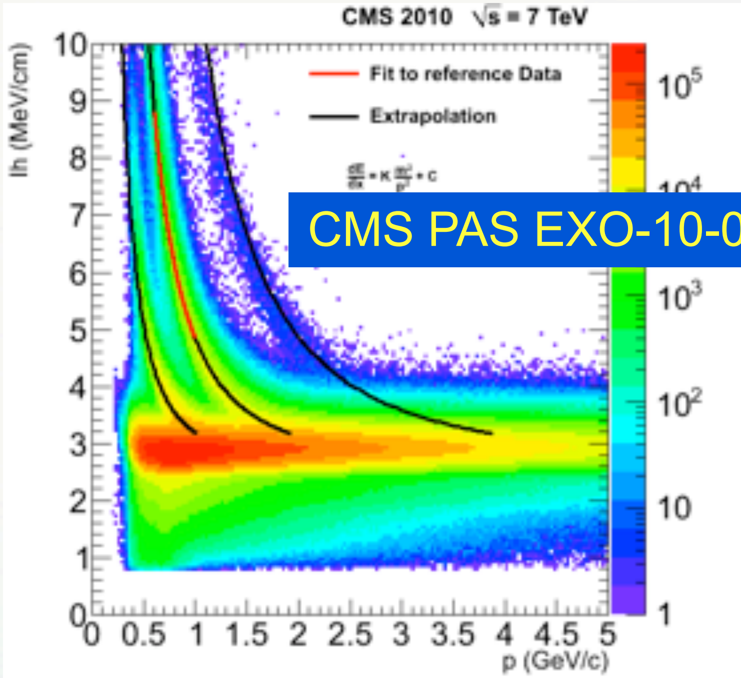
- Naturally come in models with compressed and degenerate mass spectrum, including SUSY
- Several types of searches:
  - Classical dE/dx and TOF search for charged, massive LLP
  - Search for stopped LLPs decaying later asynchronous with the beam
  - Search for non-pointing decay products in inclusive final states
- Capitalizes on excellent tracker dE/dx capabilities and the versatile muon system

CMS PAS EXO-11-020



- Measure β from TOF: $1/\beta = 1 + c(\delta t)/L$
- $1/\beta > 1$, $\sigma(1/\beta) < 0.07$

CMS PAS EXO-10-011



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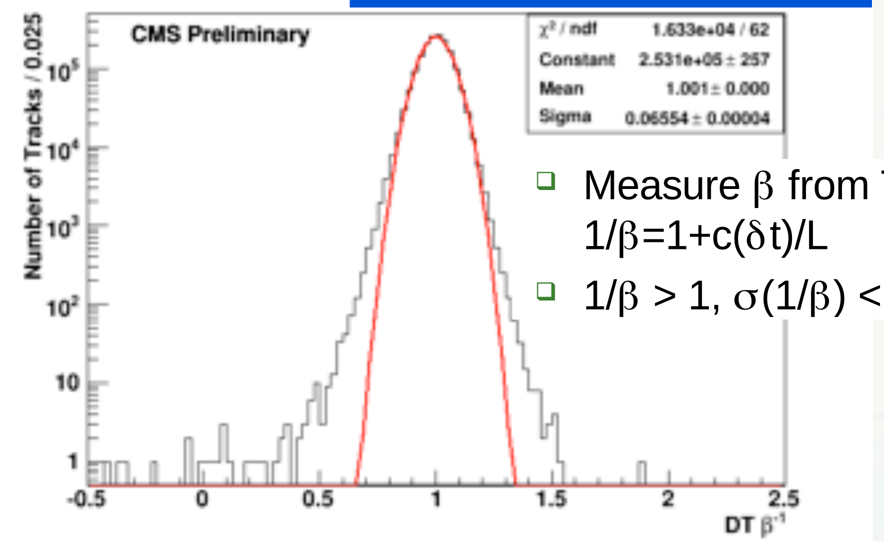
CMS PAS EXO-11-020



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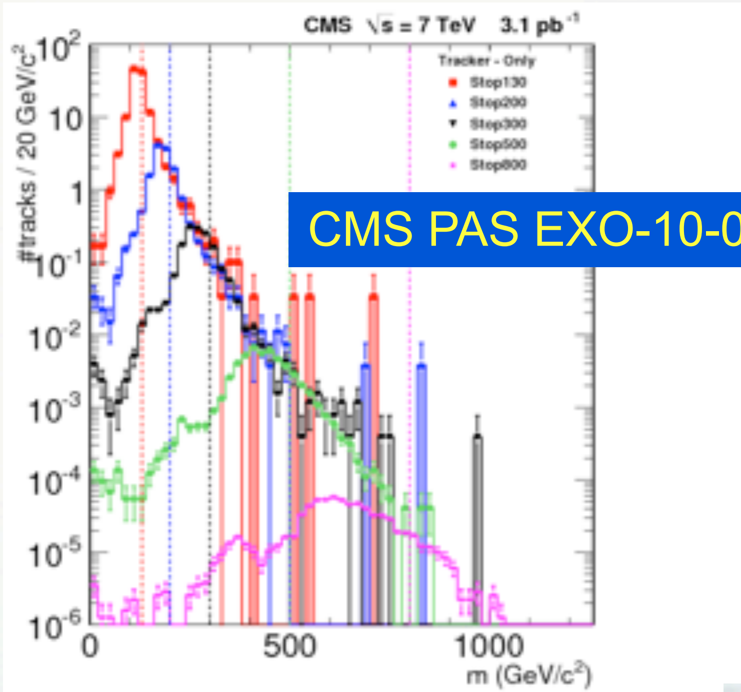
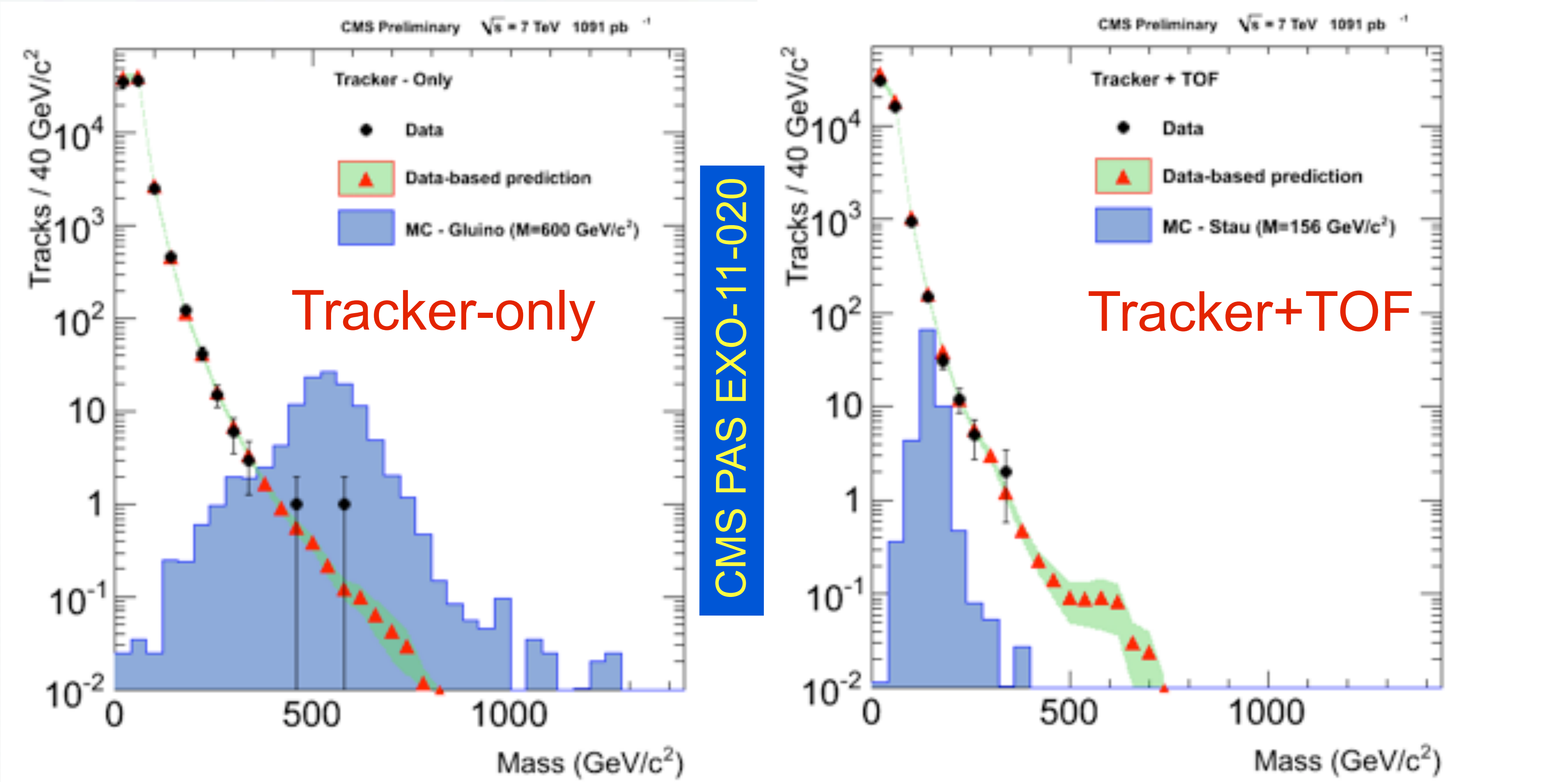


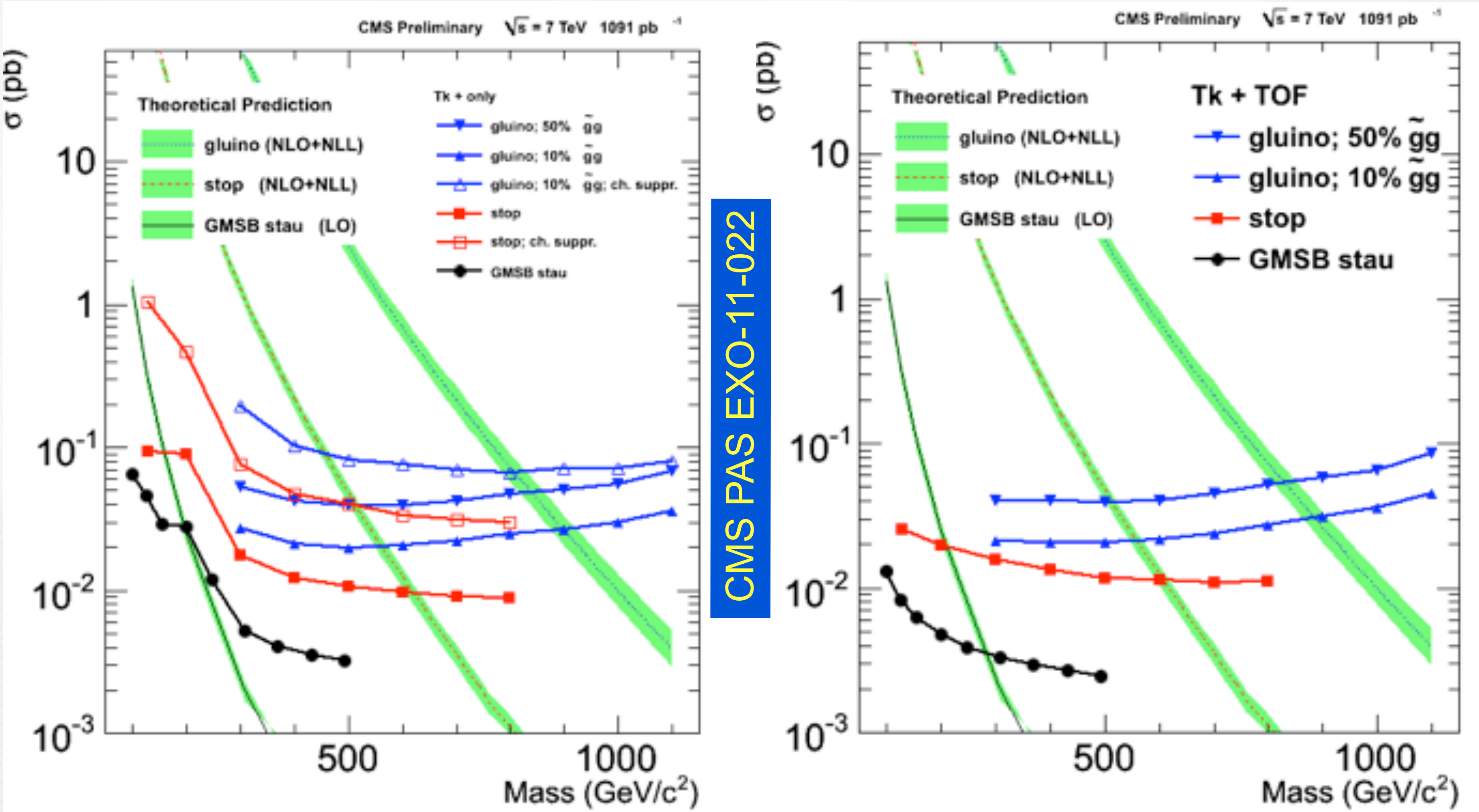
CMS Analyses

- Two analyses paths: tracker only and tracker+muon
- Sensitive to different interaction/charge exchange mechanisms
- Background derived from low-p_T data using lack of correlations between the dE/dx and p_T distributions



CMS Limits

- Gluino: M > 808-899 GeV (depending on the fraction of neutral in hadronization); 885 GeV in TOF analysis;
- Stop: 515-620 GeV; 829 GeV in TOF analysis; stau limit: 293 GeV



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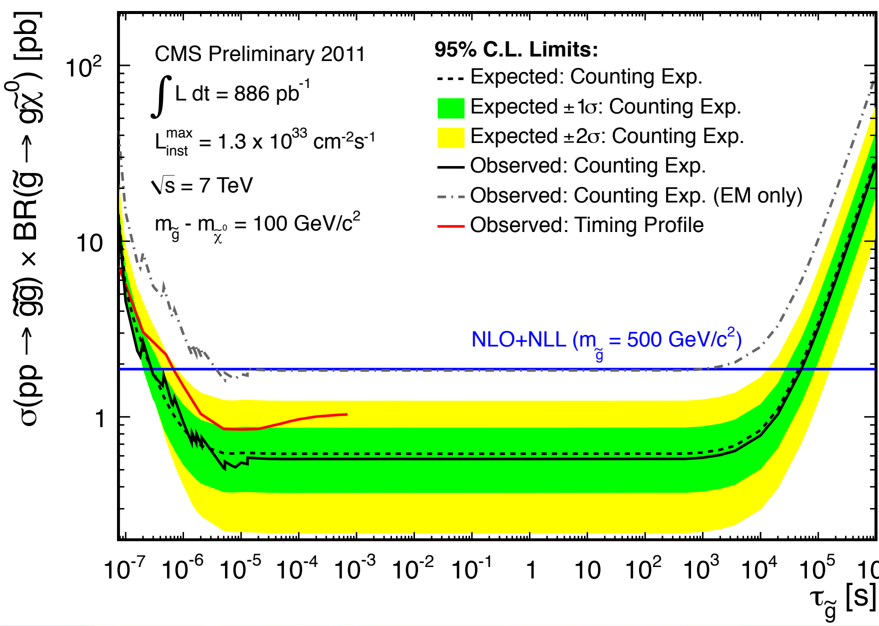
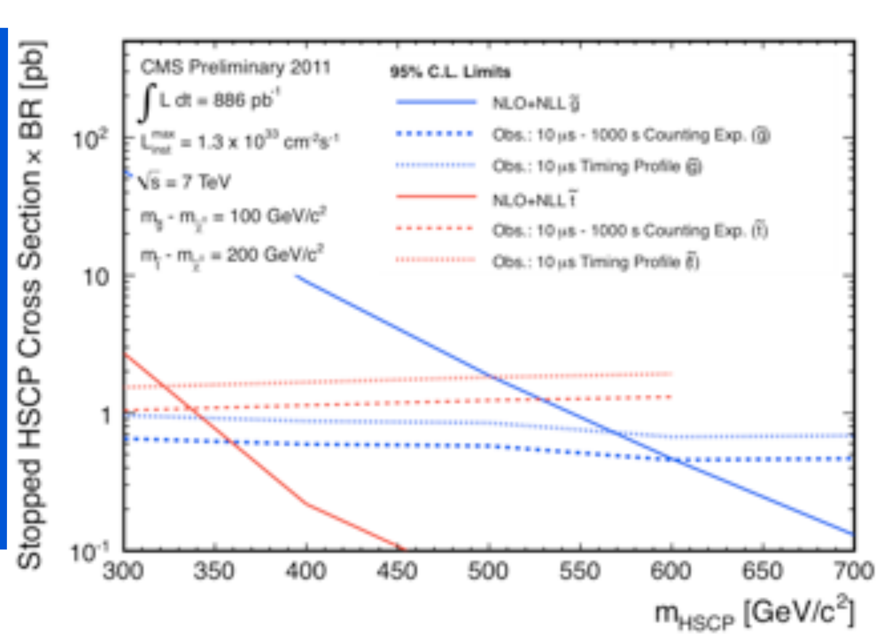
Search for Stopped LLPs

- Looking for out-of-time decays of hadronized gluinos/stops stopped in CMS HCAL
- Special trigger masking proton bunch crossings in CMS
- Sensitive to 10 orders of magnitude in lifetime; mass limits in the 350 (stop) - 600 (gluinos) LHC range
- Unique analysis at the LHC, using detector capabilities in an ultimate way



CMS PAS EXO-11-020



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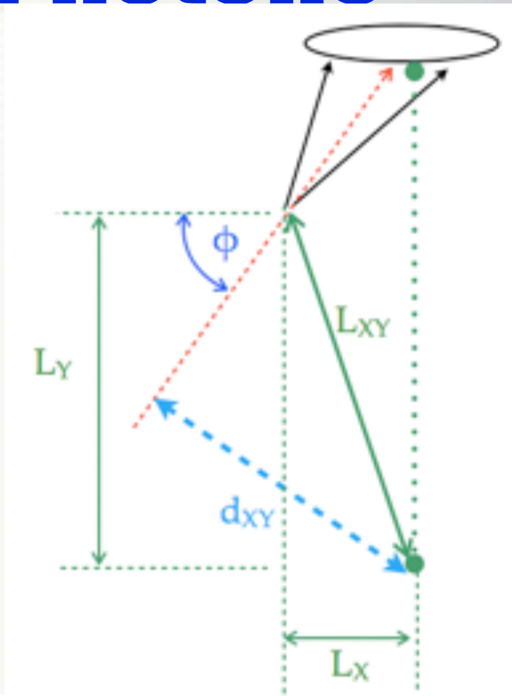
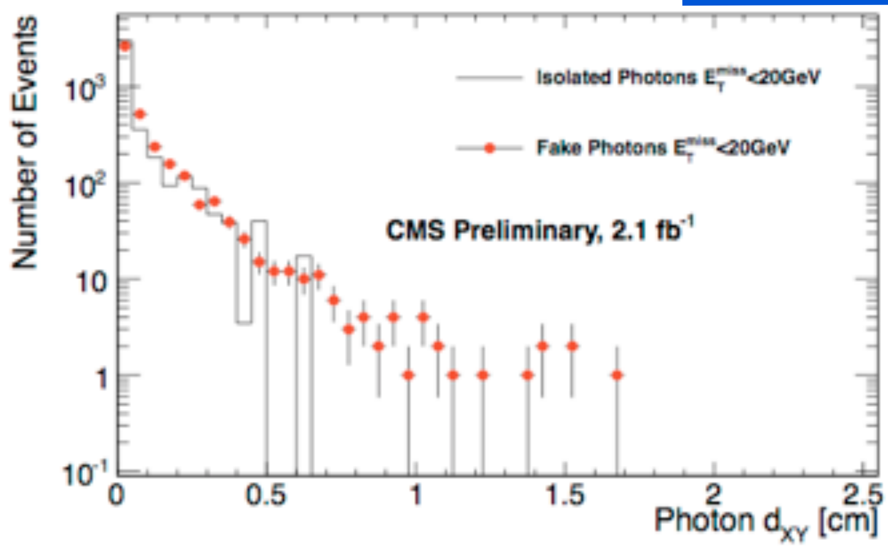
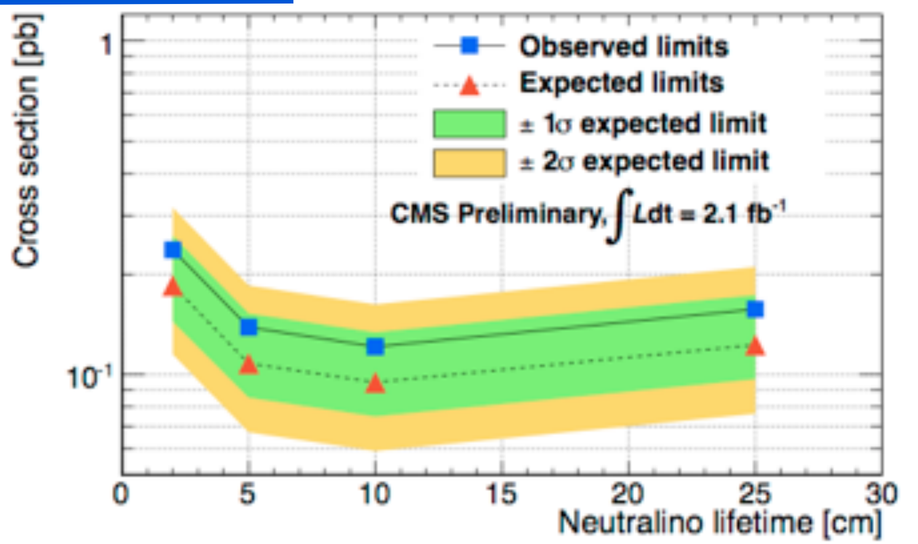
Search for non-Pointing Photons

- Use converted photons to reconstruct conversion track pointing back to the detector center (use d_{XY} as the discriminator)
- Use photons "faked" by jets to predict the shape of background and normalize it to the total at low d_{XY}



CMS PAS EXO-11-004

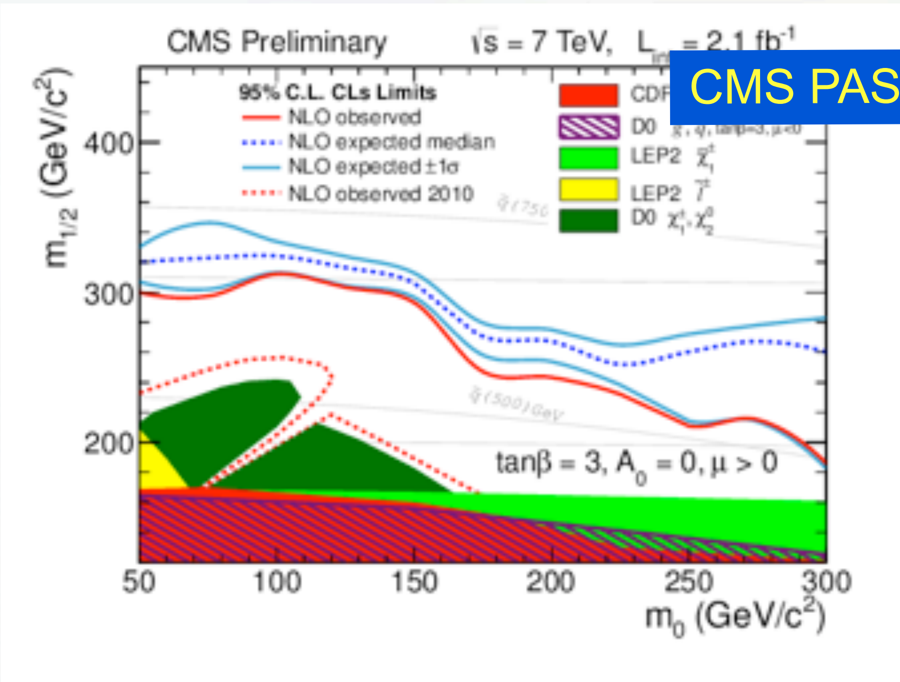




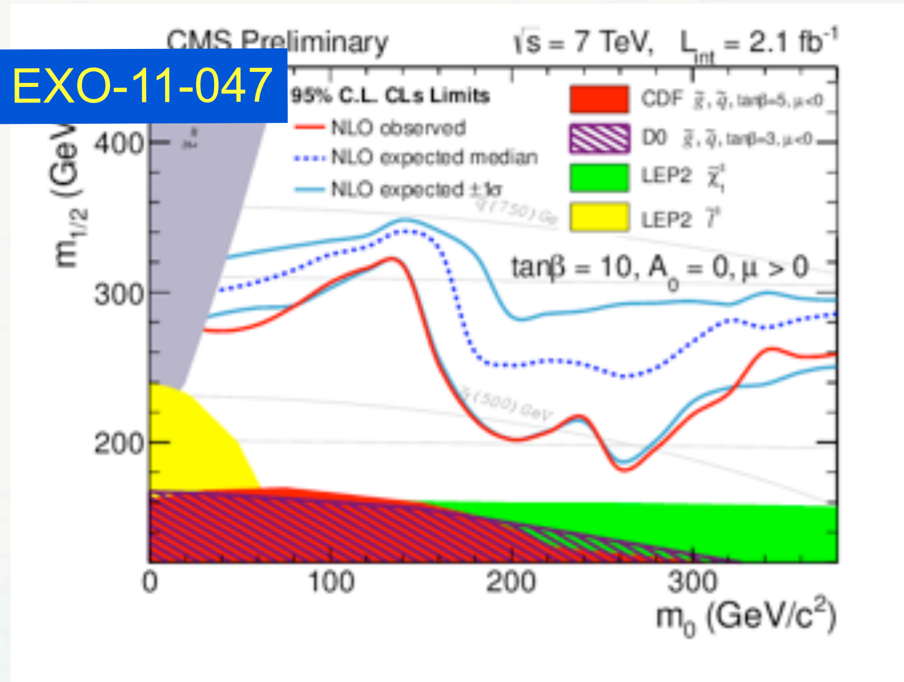
Toward Chargino-Neutralino Search

- Backgrounds mainly from MC; slight excess in 3 and 4 lepton bins

Channel	$\ell\ell + Jet$	$\ell\ell + \gamma$	$t\bar{t}$	VV	Total SM	Data	Signal
$OS(\ell\ell)e$	0.33±0.08	0.42±0.42	1.5±0.8	3.3±1.3	6.0±1.7	10	76±19
$OS(\ell\ell)\mu$	0.42±0.10	0.17±0.17	2.2±1.1	4.3±1.7	7.5±2.1	14	106±21
$OS(\ell\ell)\tau$	28.4±4.4	0.35±0.35	29±15	4.5±1.7	63±16	71	202±30
$\ell\ell'\tau$	24.6±6.0	1.7±1.7	38±19	7.5±2.9	73±20	88	29±10
$SS(\ell\ell)\ell'$	0.45±0.08	0.35±0.35	2.3±1.1	0.49±0.18	4.3±1.3	6	9.1±5.4
$SS(\ell\ell)\tau$	3.9±1.5	0.48±0.48	1.7±0.9	3.4±1.3	9.9±2.3	21	4.0±4.0
$\ell\tau\tau$	96±18	NA	12.3±6.2	1.7±0.6	110±19	88	24.0±9.1
$\sum\ell(\ell/\tau)(\ell/\tau)$	154±28	3.1±3.1	87±44	25.3±9.7	273±53	298	450±49
$\ell\ell\ell\ell$	0.0000±0.0006	<0.0002	<0.006	0.016±0.005	0.016±0.006	1	14.6±7.4
$\ell\ell\ell\tau$	0.00±0.07	<0.007	<0.07	0.14±0.04	0.23±0.11	0	14.8±7.7
$\ell\ell\tau\tau$	0.34±0.33	<0.005	0.27±0.13	0.14±0.04	0.89±0.40	0	7.8±5.6
$\sum\ell\ell(\ell/\tau)(\ell/\tau)$	0.34±0.34	0.00±0.00	0.27±0.13	0.29±0.08	1.14±0.42	1	37±12

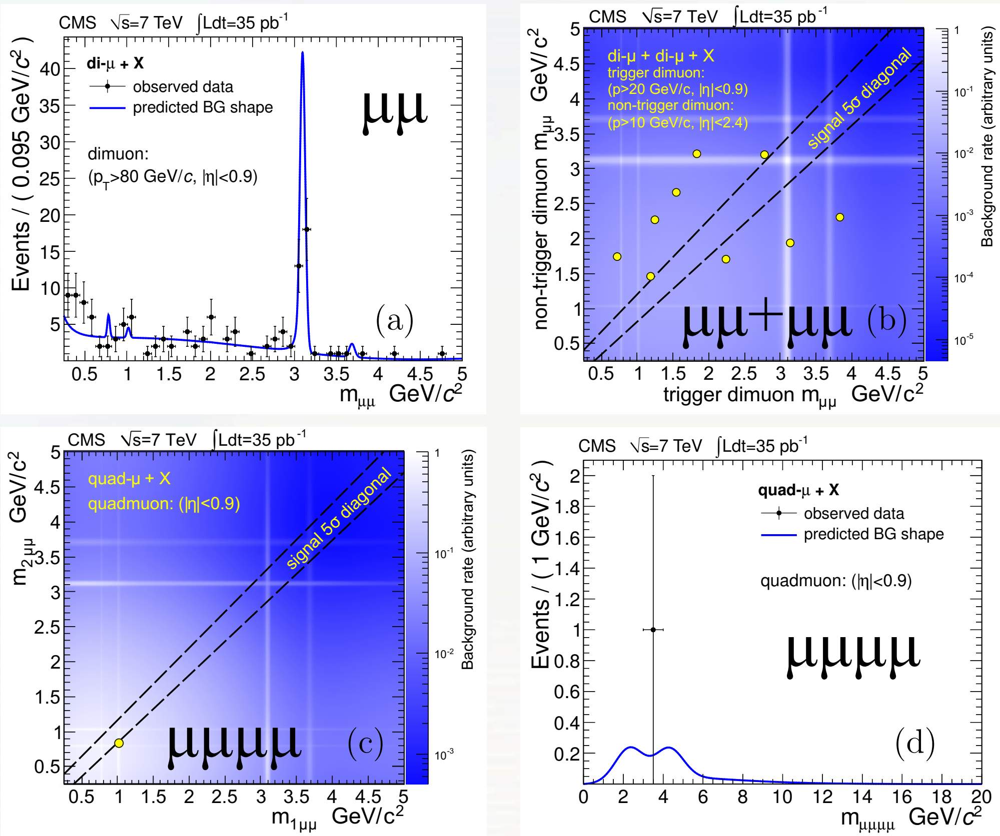


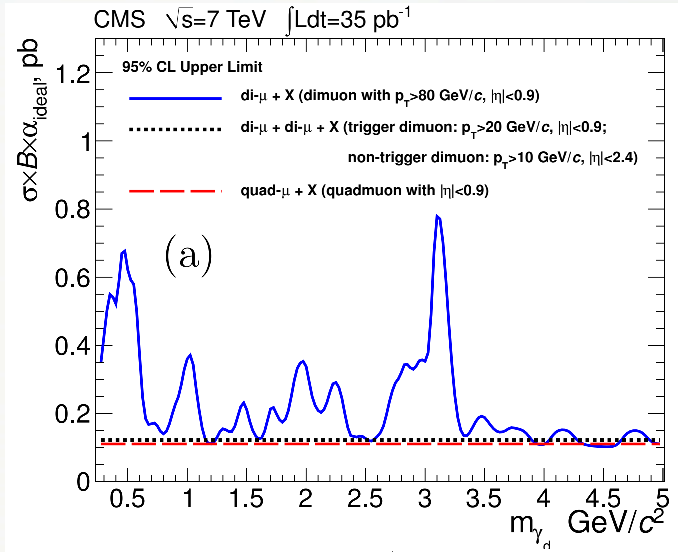
CMS PAS EXO-11-047

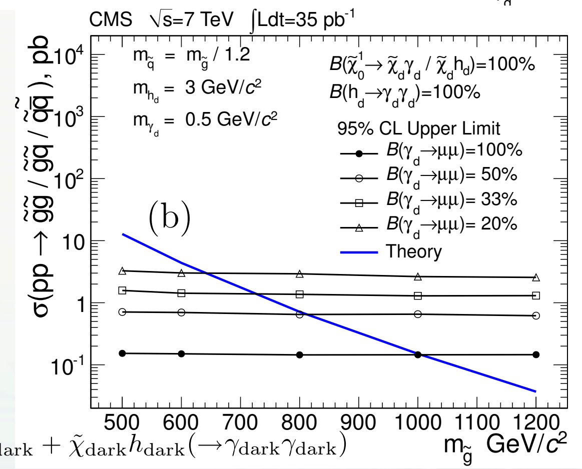


Searches for Lepton Jets

- Appear in models with light particles (e.g., dark matter ones) decaying with emission of multiple muons or electrons
- Often found in hidden valley models; could also arise from light axial Higgs decays
- First dedicated search at the LHC



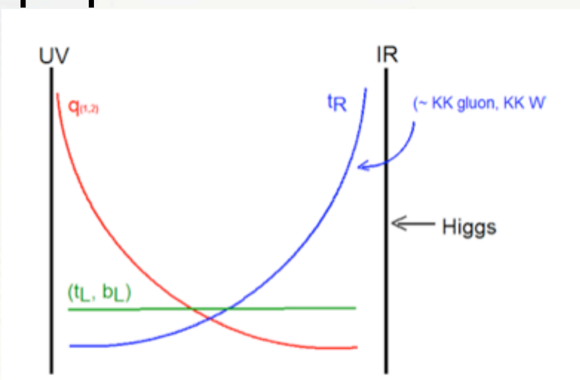




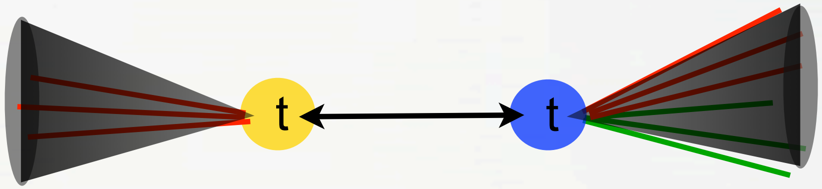
$\tilde{\chi}_1^0 \rightarrow \tilde{\chi}_{\rm dark}\gamma_{\rm dark} + \tilde{\chi}_{\rm dark}h_{\rm dark}(\rightarrow\gamma_{\rm dark}\gamma_{\rm dark})$

Searches for tt-Resonances

- Simple RS model has many potential problems: FCNC, CP-violation
  - Those can be solved by putting fermions in the bulk
- Top quark is localized near the SM brane; light fermions are near the Planck brane
- KK gravitons mainly couples to the top quark, and thus the dominant decay mode is a pair of top quarks



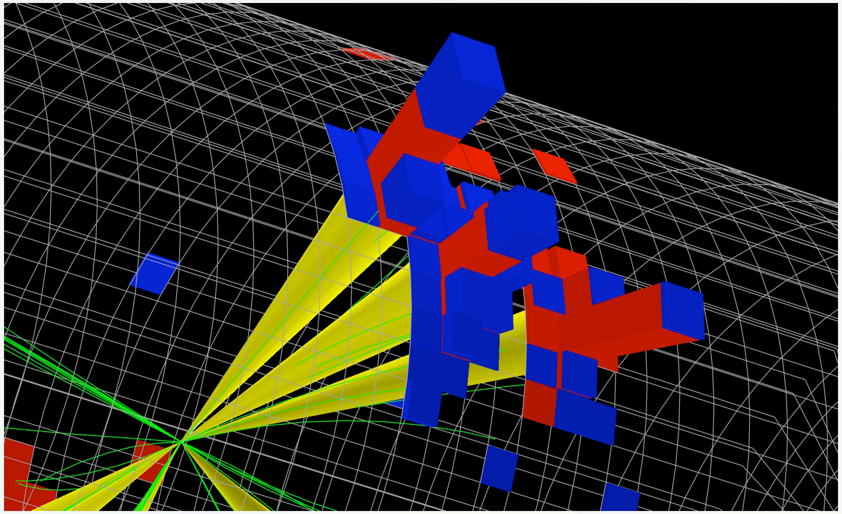
- For graviton masses ~2-3 TeV, top quarks emerge highly boosted, which makes it challenging to reconstruct them

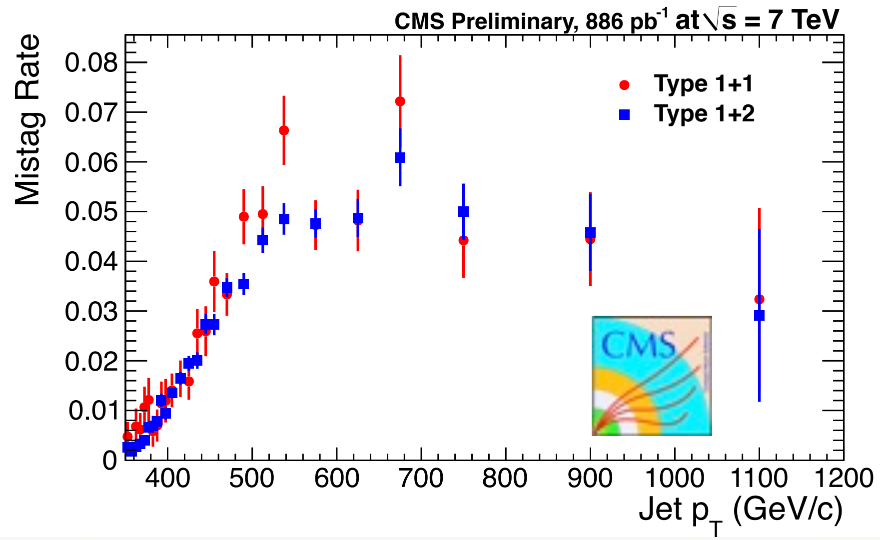


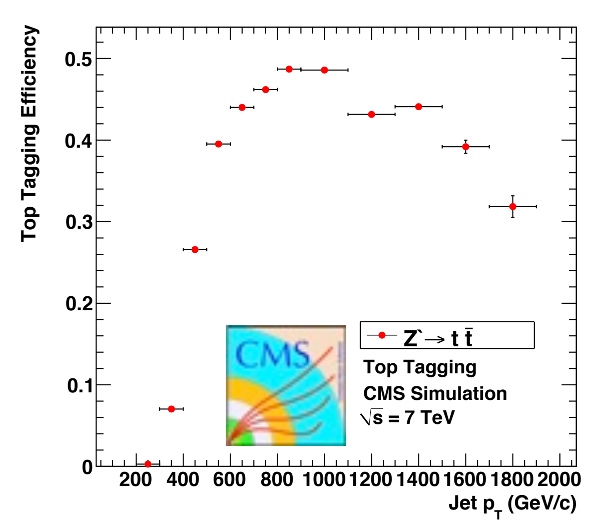
- Several challenges:
  - for 3-jet top decays jets are often merged in a single “fat” jet
  - b-tagging efficiency drops dramatically, as the opening angle between the tracks becomes small.

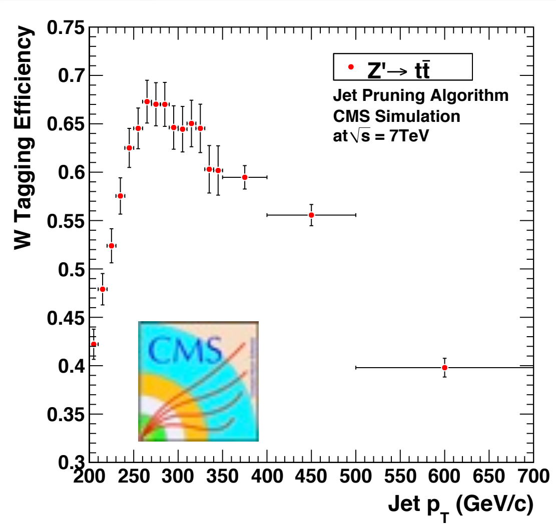
Boooooooooosted Top Searches

- New techniques in jet reconstruction and b-tagging
- E.g., Cambridge-Aachen Algorithm (CMS)









CMS PAS EXO-11-006

Booooooooosted Top Searches

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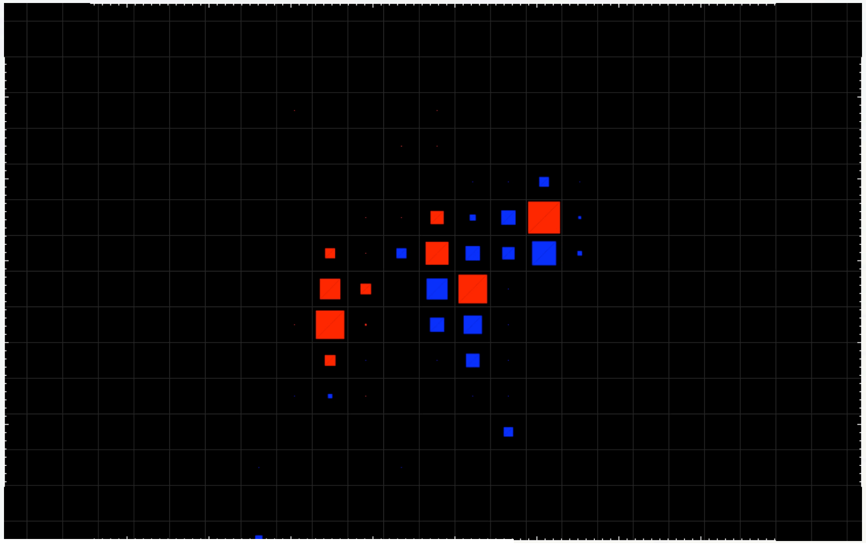

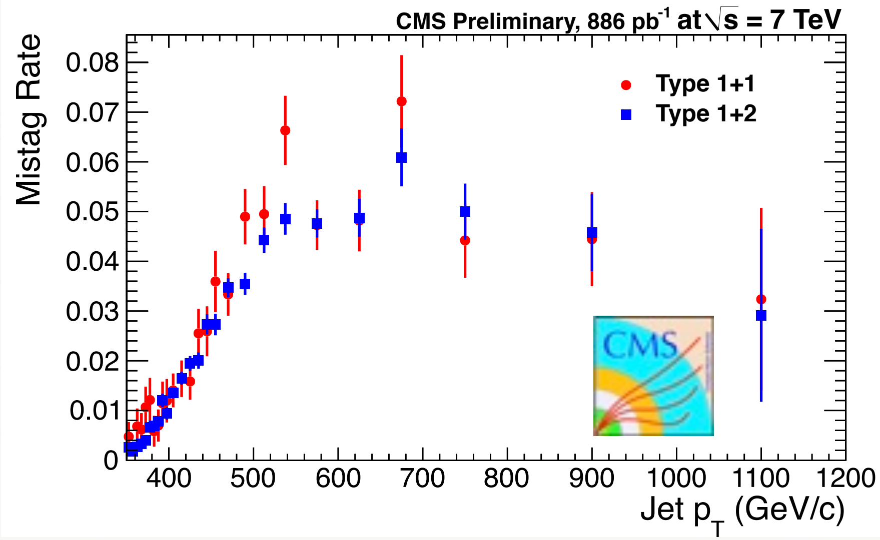

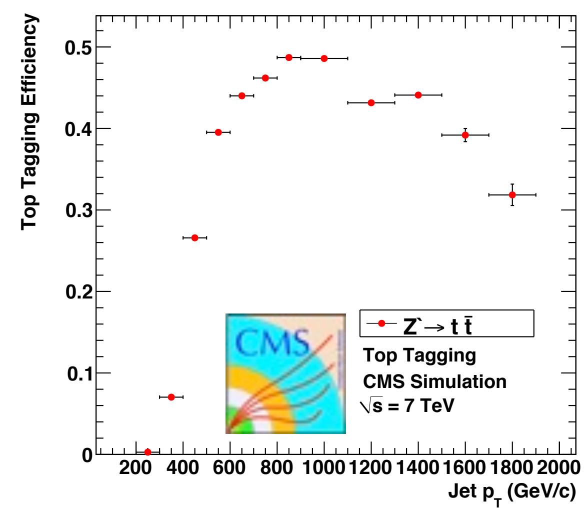

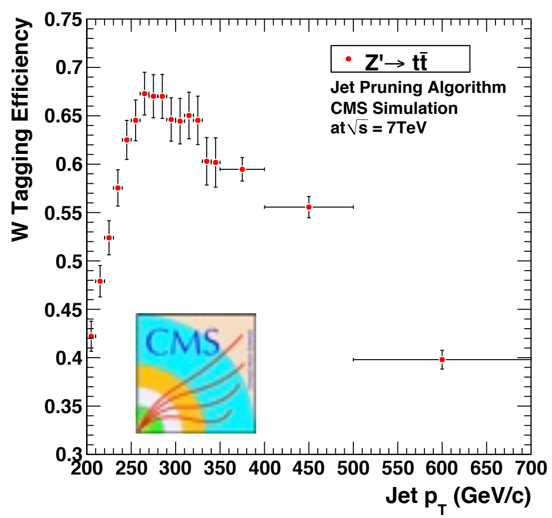

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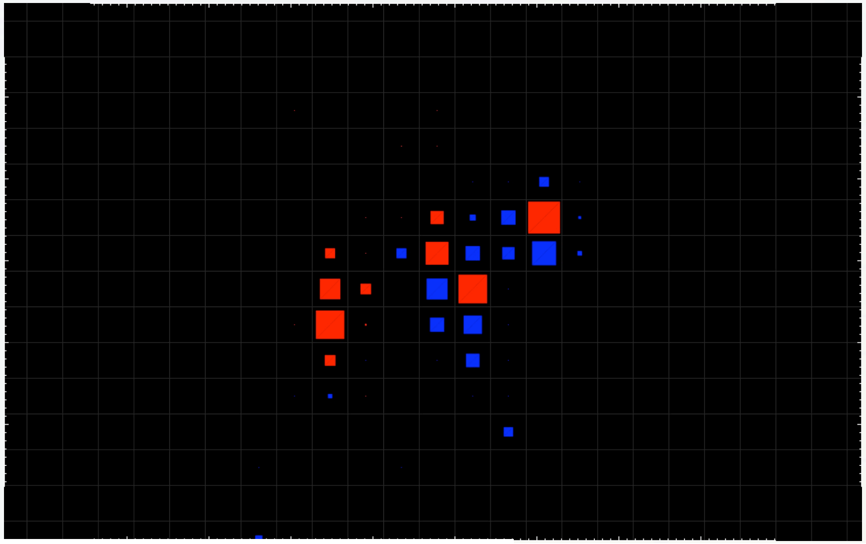

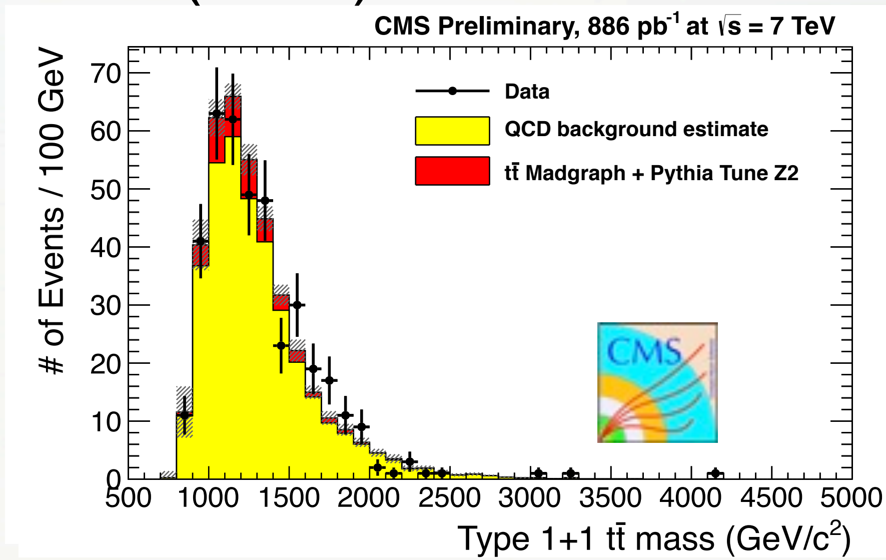

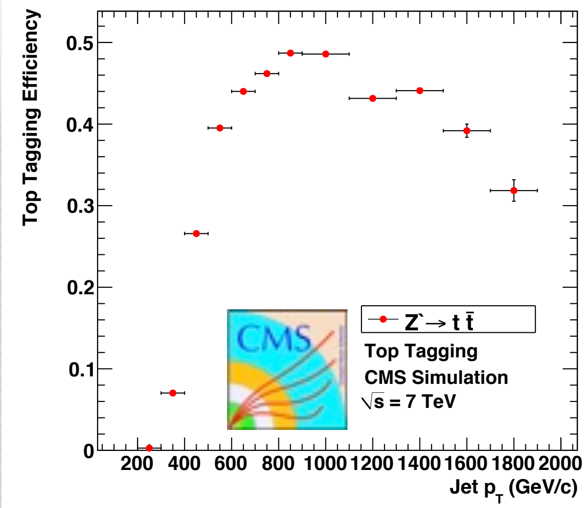

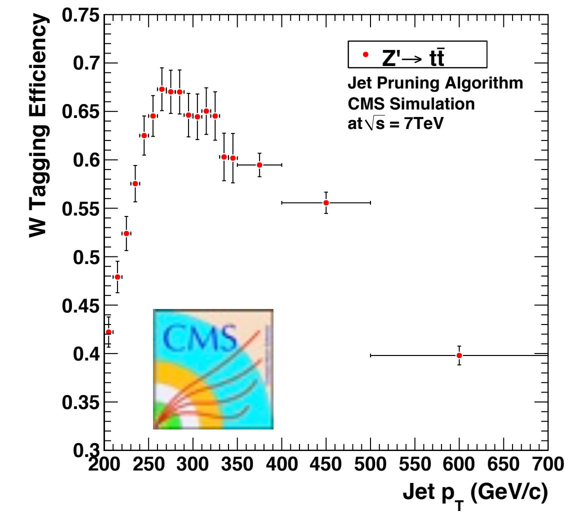

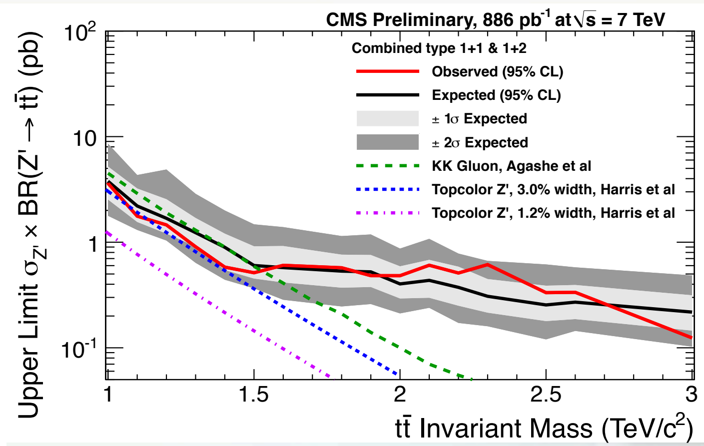

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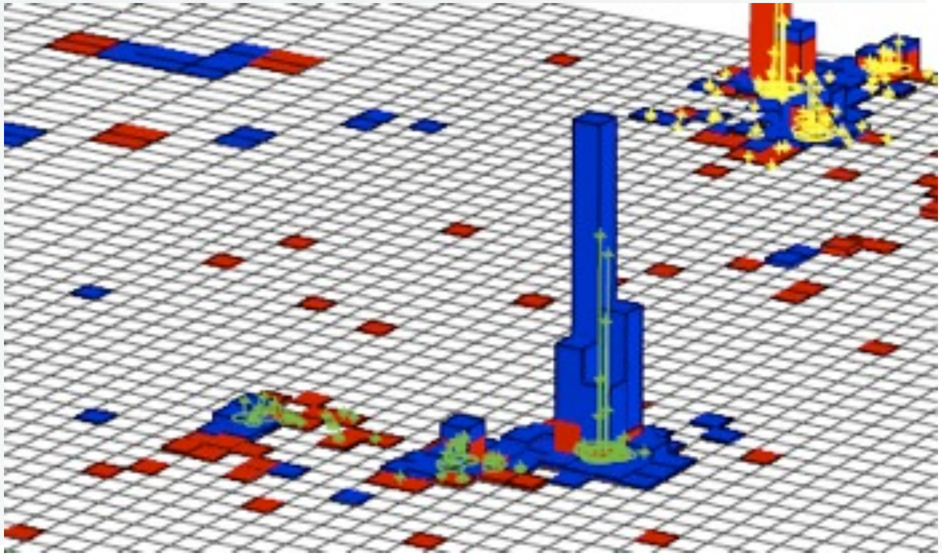

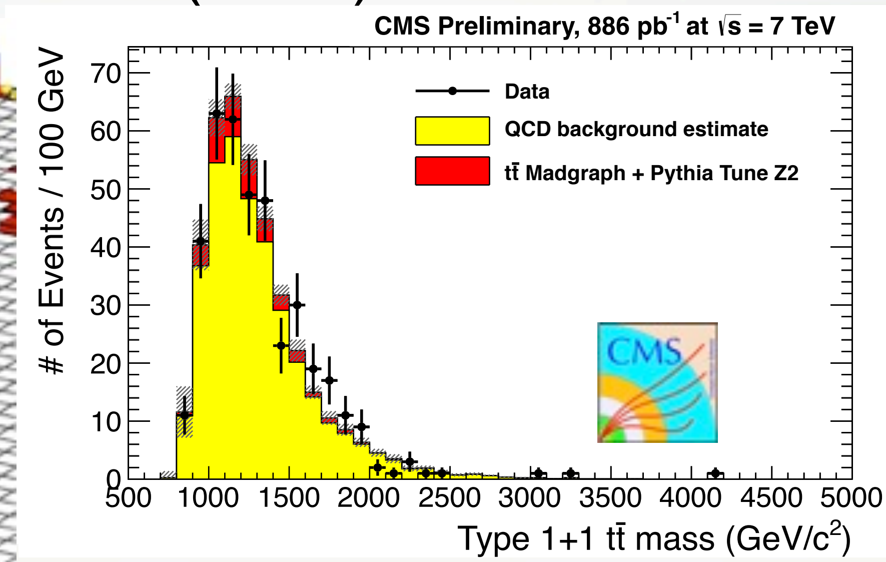

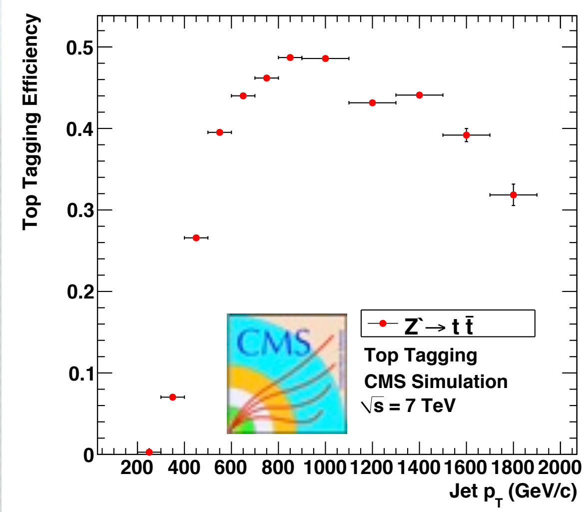

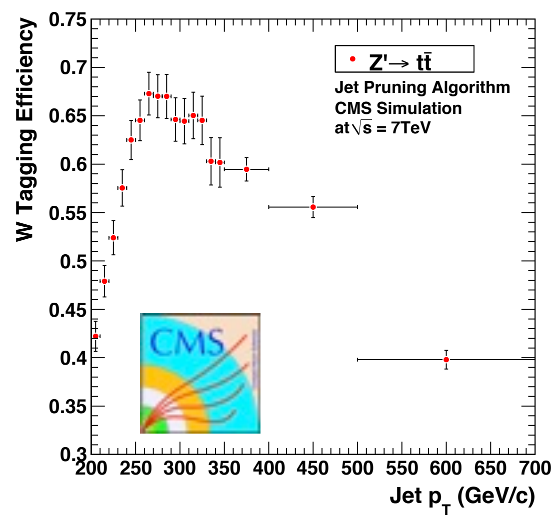

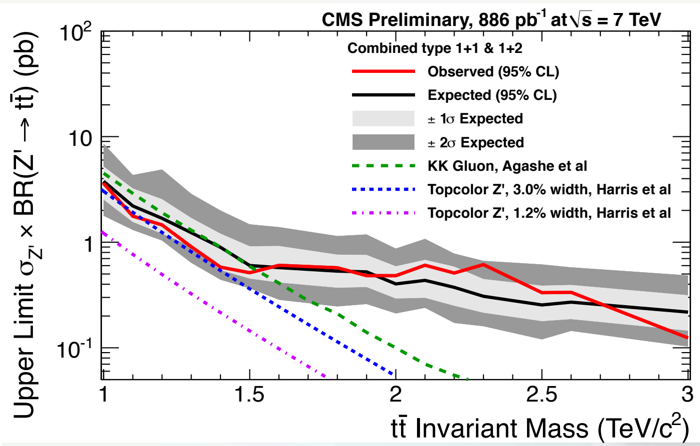

CMS PAS EXO-11-006

Other Searches

- Moving toward searches for resonances decaying into multijets
  - 6 jets: published
  - 4 jets: in progress (ATLAS published)
  - 8 jets: in progress
- tt+X
- Boosted Z's
- ...

Conclusions

- The LHC had fantastically successful, albeit so far frustratingly empty 2010-2011 runs
- We (nearly) closed several chapters in terms of accessibility at the 7 TeV machine:
  - "Easy-SUSY" (aka mSUGRA inspired scenarios)
  - Extra dimensions and low-scale quantum gravity in most of scenarios
- This required major revisiting of our searches program in the next two years:
  - Go after more complex signatures and final states:
    - Multijet resonances
    - Various long-lived particles
    - Boosted objects
  - Focus on more natural SUSY scenarios:
    - Dedicated searches for third-generation squark and sleptons
    - Searches for RPV scenarios and other SUSY models with low ME_T
    - Looking for chargino-neutralino production
  - Pushing the $B_{d,s} \to \mu\mu$ analysis to reach SM sensitivity
- All eyes are on the low-mass Higgs:
  - Whether we see it or not would tell us a lot about possible new physics at low energies
- New physics maybe already hiding in our 5/fb data samples - we are now turning every stone to make sure we find it if it is there to be found (and do not find it if it is not there! :))

Thank You!