The search for new physics (at the LHC)

Paris Sphicas
CERN & University of Athens
CERN Summer Student program
July 28 - 30, 2014

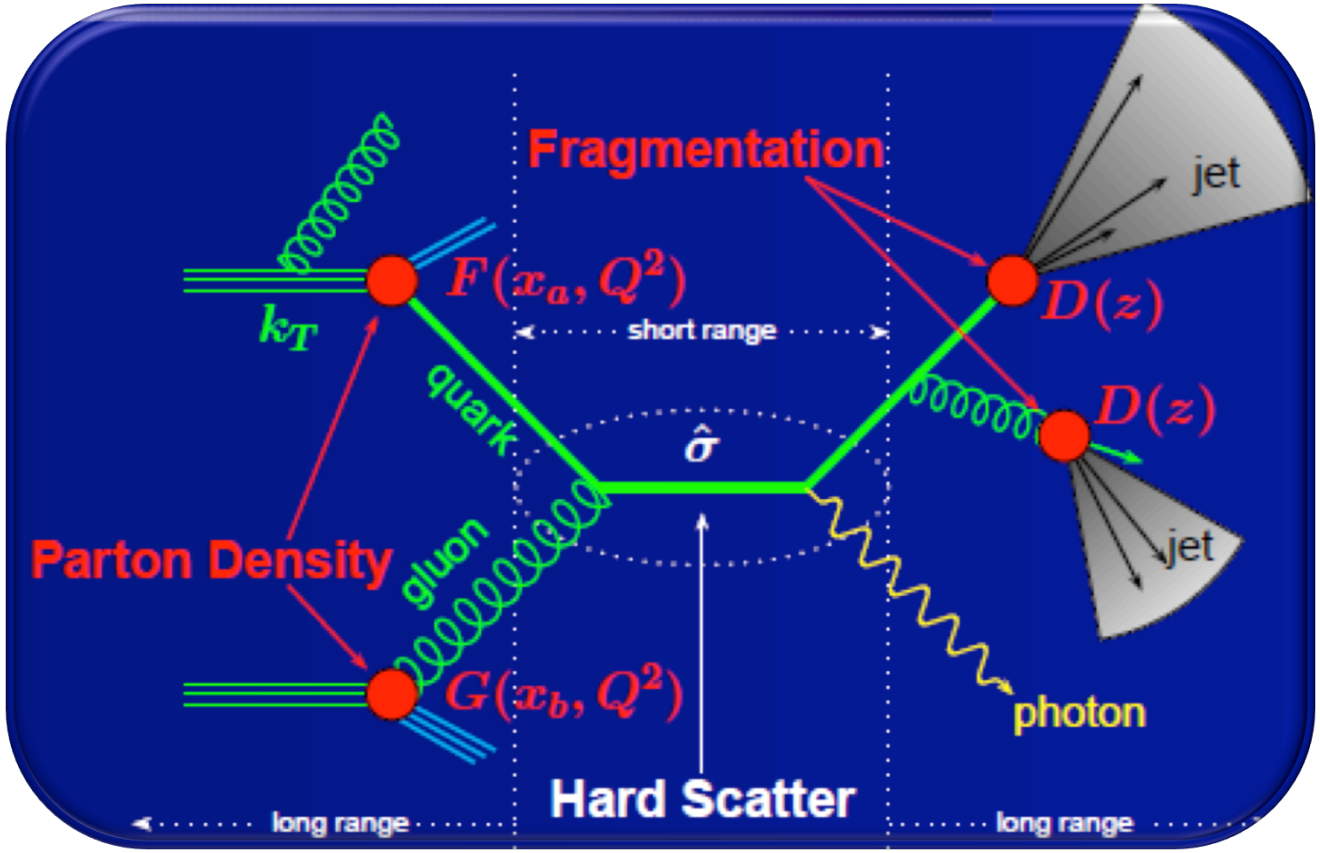
- **Prelude – reminder of the prerequisites**
  - **Why we believe there should be new physics BSM**
  - **Proving that there is "new physics"; main prerequisites: understanding the detector, understanding (measuring) Standard Model physics at 7 and 8 TeV**
  - **What happens when we do not find a new signal [limits]**
- **Searching for New Physics**
  - **Searching for substructure, new interactions**
  - **Searches for extra dimensions and other Exotica**
  - **Supersymmetry [SUSY]**
- **Summary**

So what new physics?

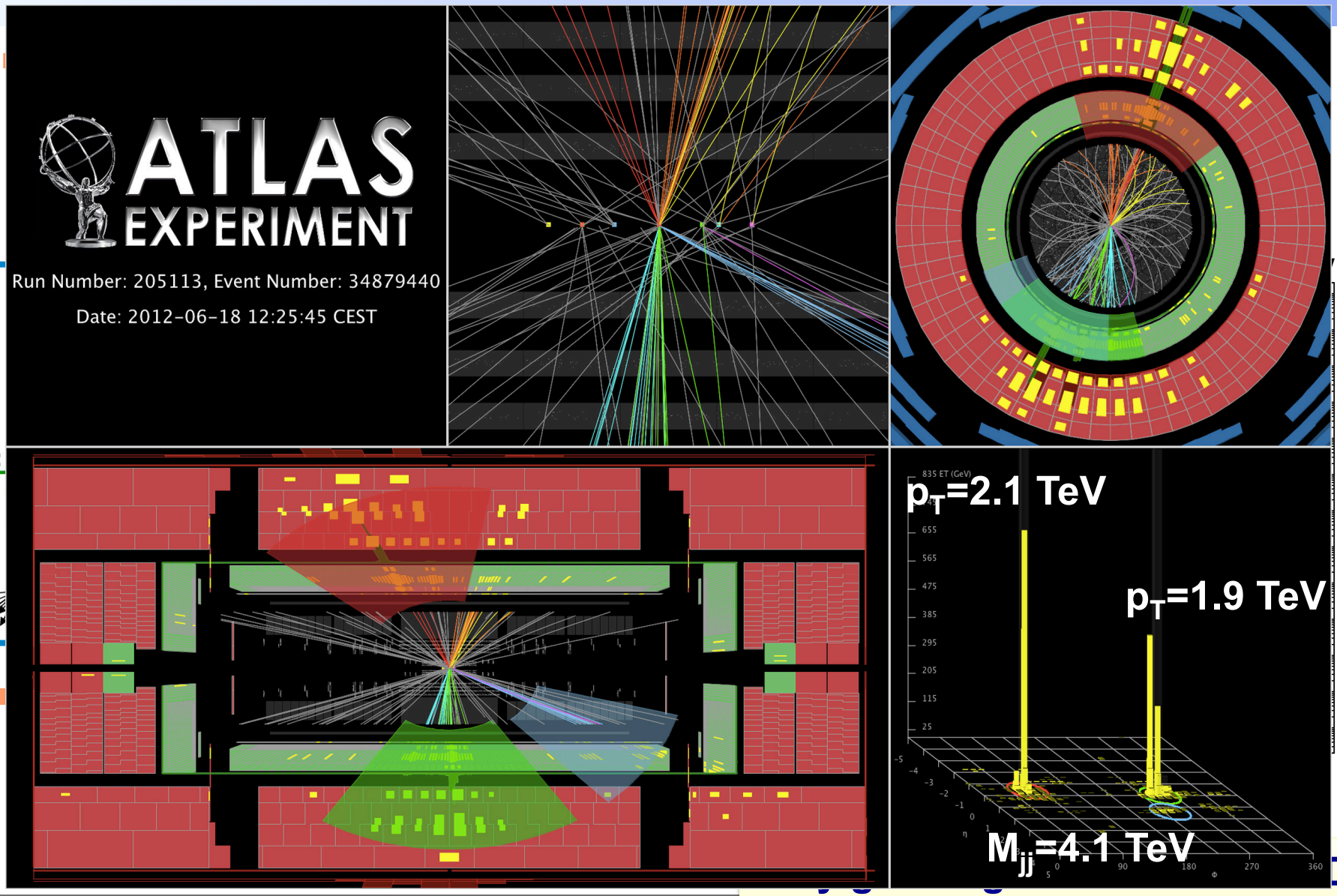
Many (many) possibilities

- New strong interections?
  - Technicolor; excited quarks; compositeness; new "contact" interactions
- Exotica:
  - Weird stuff: leptoquarks?
  - New "forces"?
    - New resonances (W-Z-like)
  - More generations?
    - Fourth generation (b')
  - Gravity descending at the TeV scale?
    - New resonances; missing stuff; black holes; SUSY-like signatures [Universal Extra dimensions]
- Supersymmetry (SUSY)
  - (super) partners to all that we have in the SM
    - production of squarks, gluinos, sleptons, gauginos,…
- SUSY-inspired exotica:
  - Long-lived massive (new) particles?
- Some true inspirations: "hidden valleys"?

parton-parton scattering and QCD



Jets


ATLAS
EXPERIMENT
Run Number: 205113, Event Number: 34879440
Date: 2012-06-18 12:25:45 CEST
p_T=2.1 TeV
p_T=1.9 TeV
M_{jj}=4.1 TeV

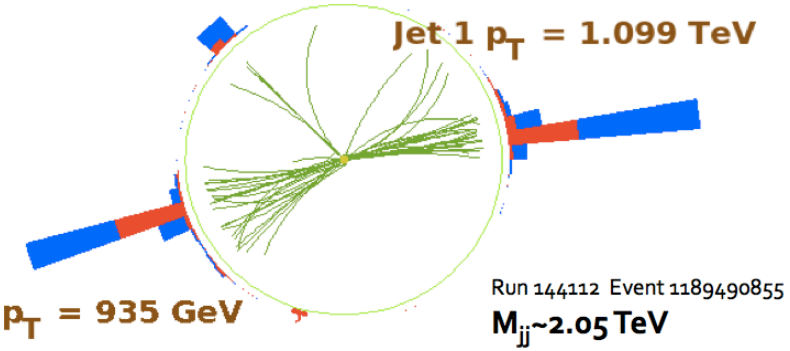
How would new structure show up?

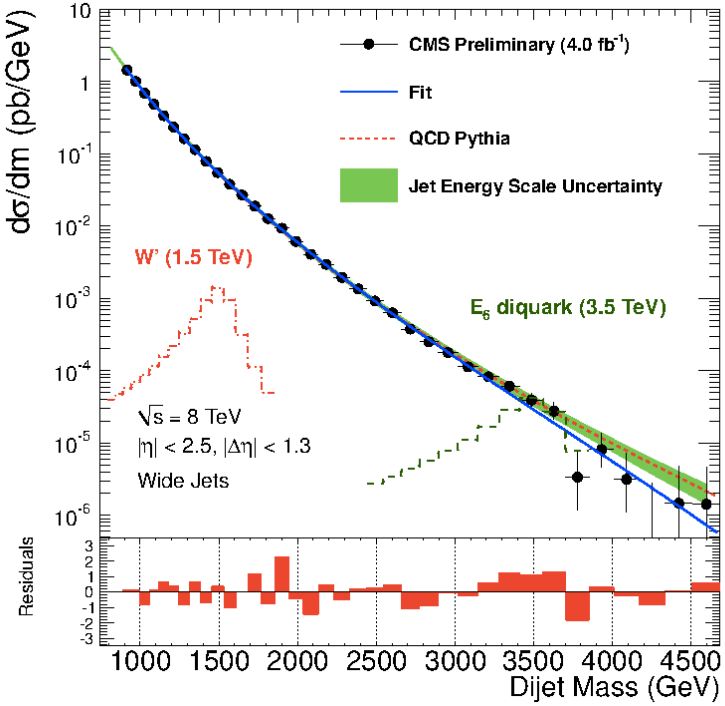
- **If quarks are composite, i.e. they are made of other "stuff", then there will be excited states, q*, which would decay to a quark and a neutral boson (gluon, photon or Z)**
  - **Look for following decays: $q^* \rightarrow qg$; $q^* \rightarrow q\gamma$, $q^* \rightarrow qZ$**
  - **Signature: resonance in di-jet, photon+jet or Z+jet mass spectrum**

- **The scattering of two quarks (and gluons, and quarks against gluons) will not follow QCD but will show deviations from the exchange of a new boson**
  - **Signature: the angular distribution of two-jet events will look different from "Rutherford scattering with scaling violations"**

Dijet mass (and search)

- **Very early search for numerous resonances BSM: string resonance, excited quarks, axi-gluons, colorons, E6 diquarks, W' & Z', RS gravitons**

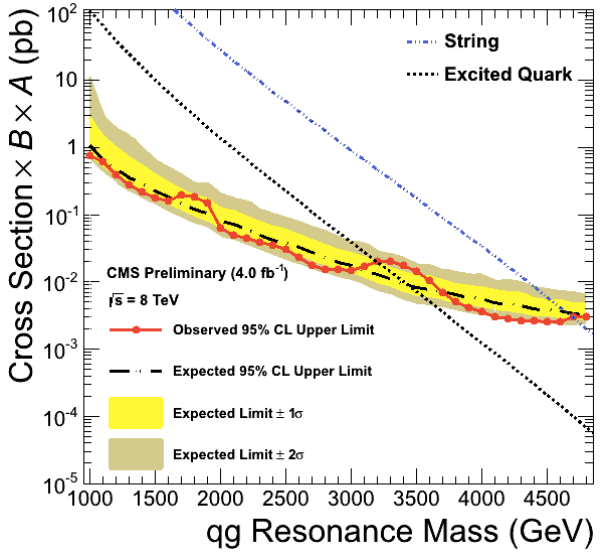




Four-parameter fit to describe QCD shape

$$\frac{d\sigma}{dm} = p_0 \frac{\left(1 - \frac{m}{\sqrt{s}}\right)^{p_1}}{\left(\frac{m}{\sqrt{s}}\right)^{B}};$$

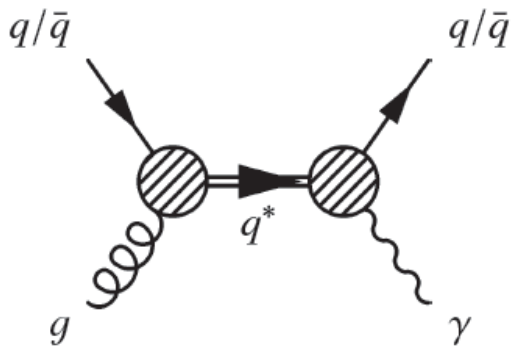
$$B = p_2 + p_3\left(m/\sqrt{s}\right)$$



M(q*)>3.1 TeV

Excited quarks (continued)

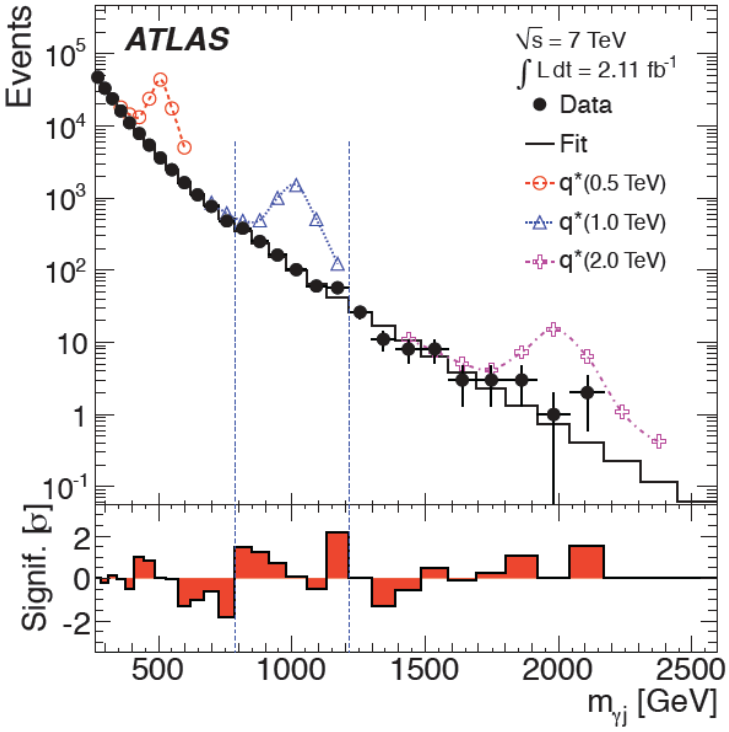
- **Decays into quark and photon?**



Kinematic selection
(acceptance)
- $p_{T\gamma} > 85$ GeV
- $p_{Tjet} > 30$ GeV
- $m_{\gamma j} > 260$ GeV
- $\Delta R(\gamma,j) > 0.4$

j is any jet w $p_T > 30$ GeV

- **Background: by fit to data across all bins (same form as for dijets)**
  - **Run "BumpHunter": most significant excess in 784< $M_{\gamma j}$ <1212 GeV (*p-value = 0.20*)**



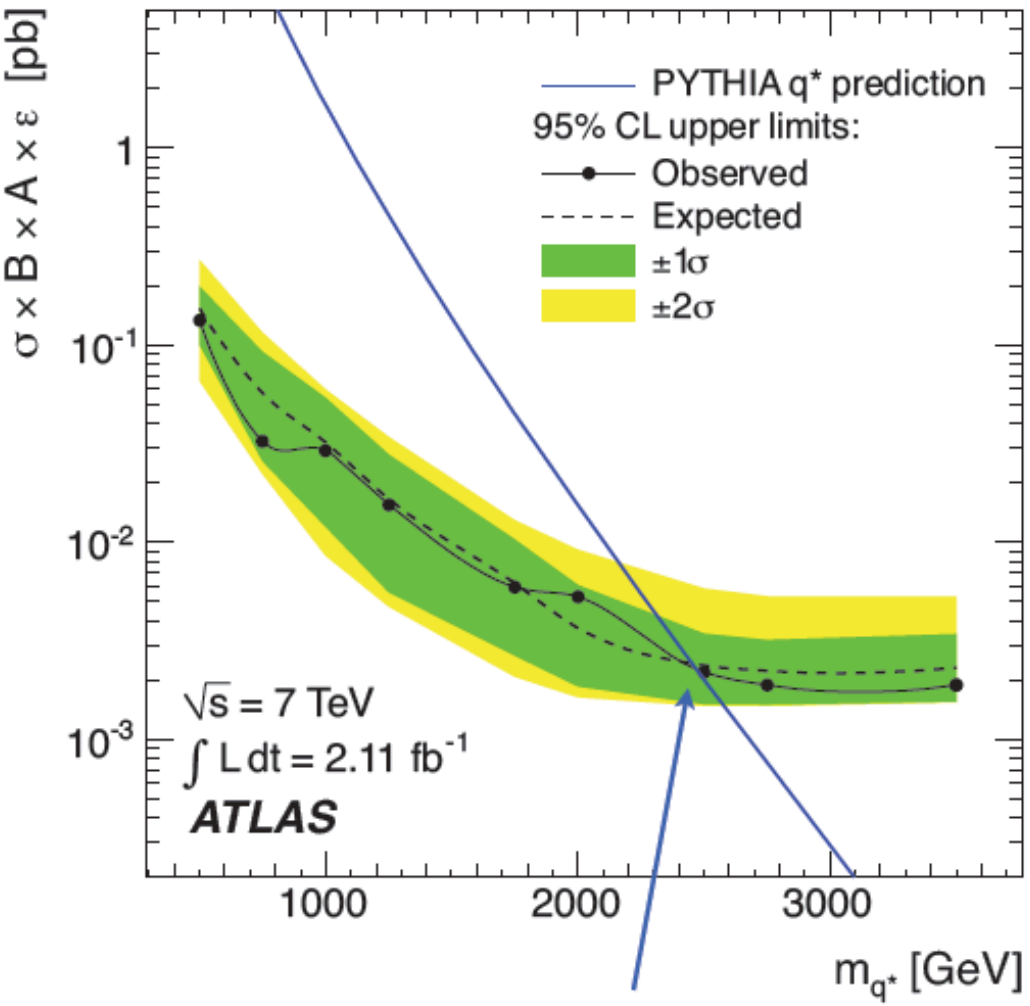
Excited quarks (continued)

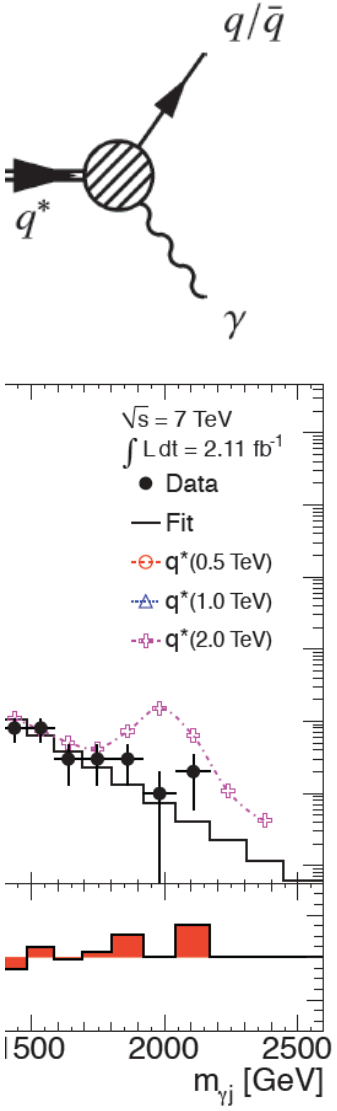
- **Decays in**

Kinem
(a
- $p_{T\gamma} > 8$
- $p_{Tjet} >$
- $m_{\gamma j} >$
- $\Delta R(\gamma, j$

j is any

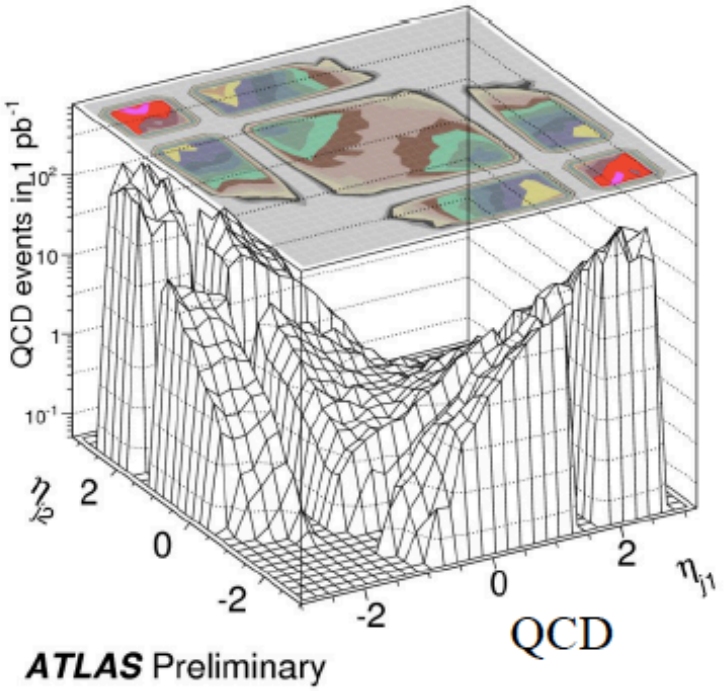
- **Backgrou across all for dijets)**
  - **Run "Bu significa <1212 G**

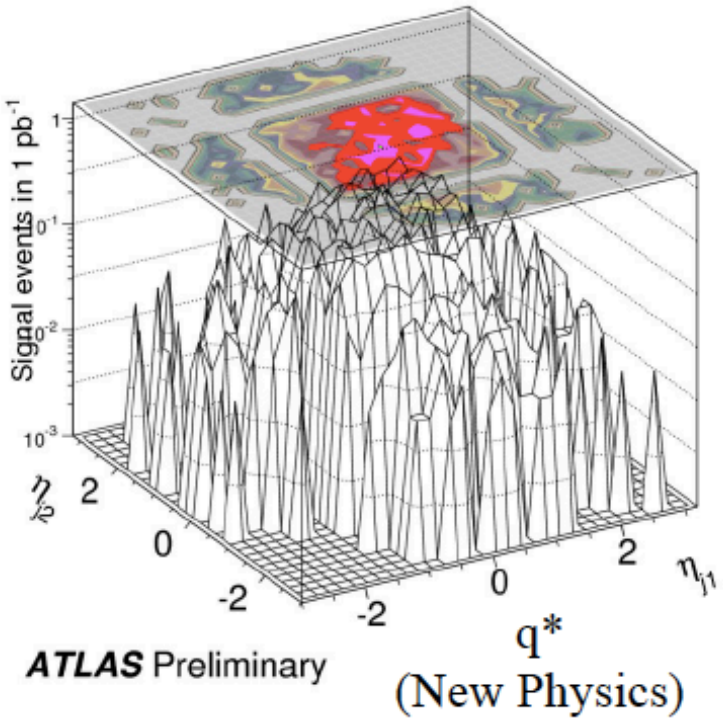




Angular distributions

- **New physics: presumably high-mass; so not boosted along z-axis; so more "central"!**
  - **Angular distribution in QCD background different than that from various signals [e.g. an excited quark, decaying to two jets; or jets from "stronger scattering"]**

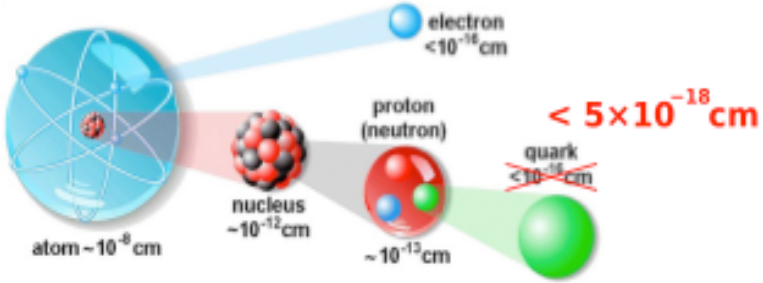




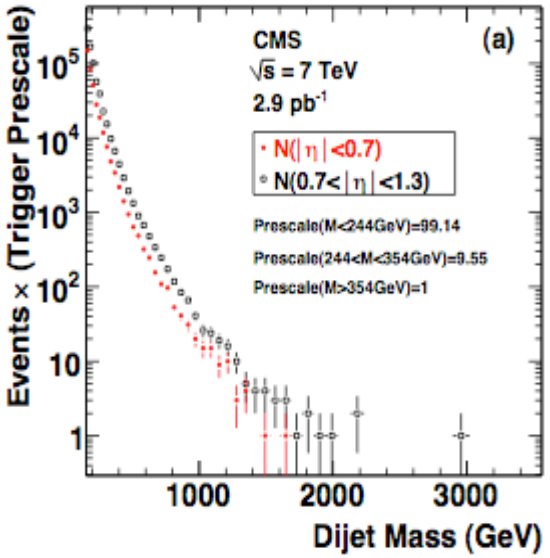
Quark compositeness

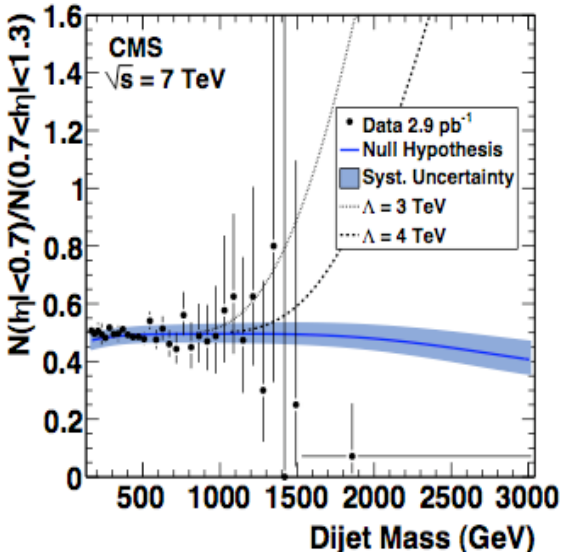
- **Centrality ratio: events with two central leading jets to events with both leading jets**
  - **Sensitive to deviations from the SM from quark sub-structure.**

$$R_\eta = \frac{\sum_{|\eta|<0.7} Dijets}{\sum_{0.7<|\eta|<1.3} Dijets}$$



arXiv:1010.4439



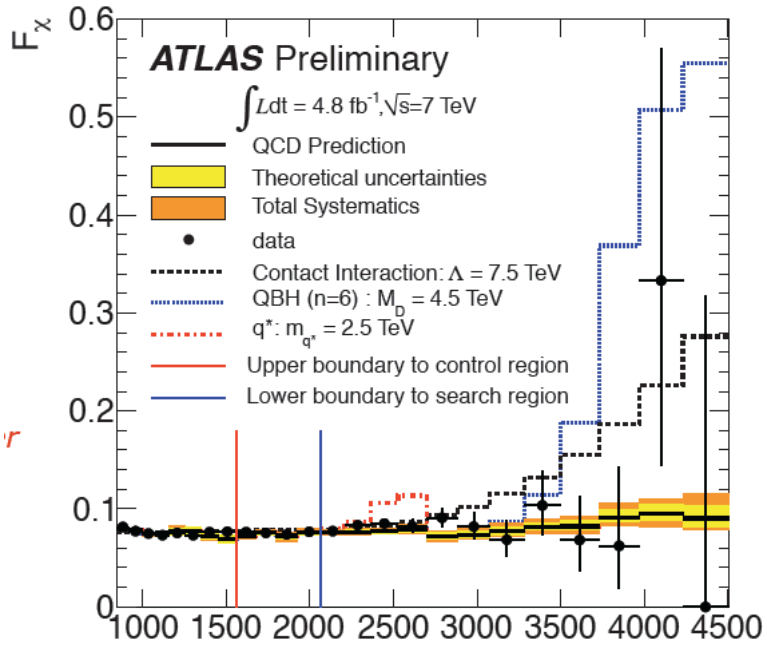


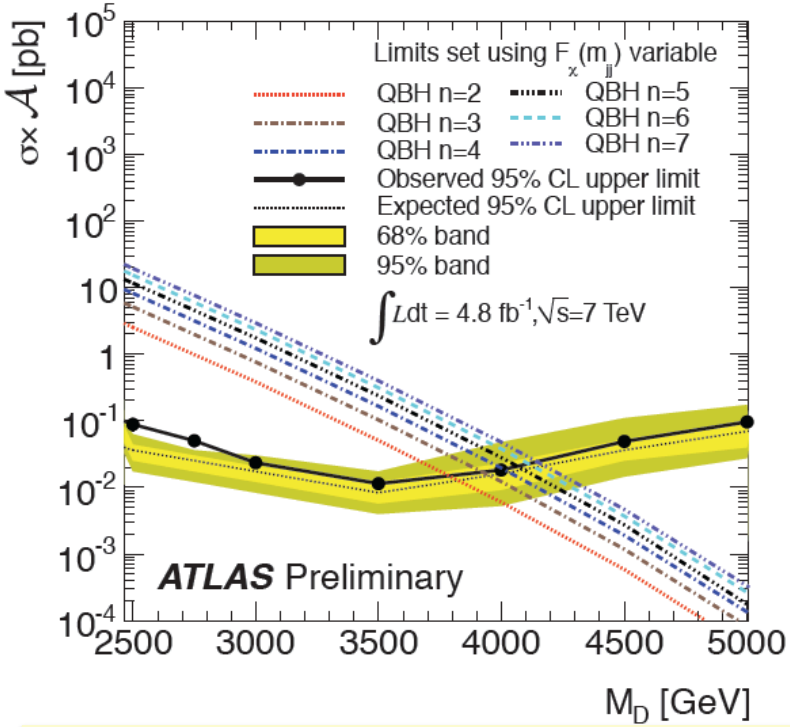
Very small dependence of ratio on m_{jj}. Agreement with QCD.
Exclude (95%CL) quark compositeness for Λ<4.0TeV.

Search for quark compositeness

- **ATLAS at 4.8 fb^{-1}, at 7 TeV**

$$F_\chi = N(|y^*|<0.6) / N(|y^*|<1.7)$$



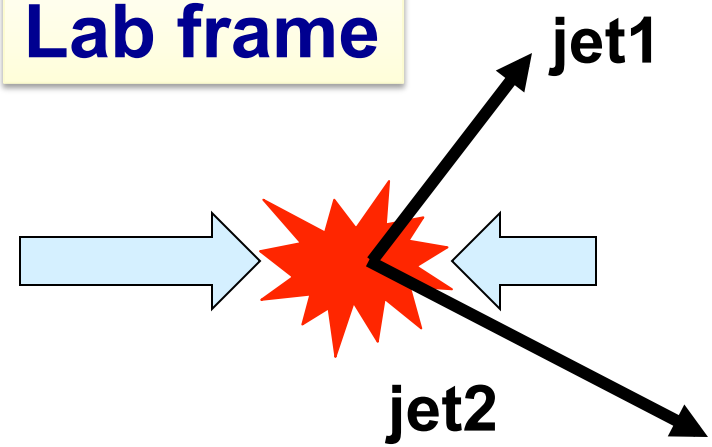


Quark Contact Interaction: Λ>8.2TeV.

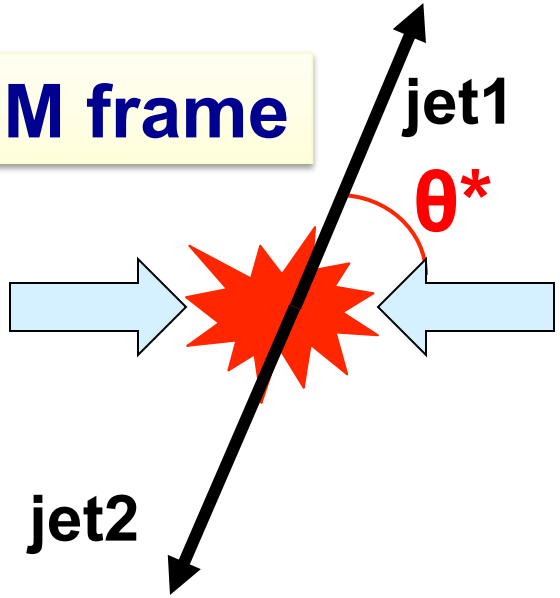
Limits in extra dimensions: (n=2) M_D>3.8 TeV; (n=6) M_D>4.1 TeV

Parton-parton scattering ("2 to 2 process")

Lab frame



CM frame



$$y_{boost} = \frac{1}{2}(y_1 + y_2) = \frac{1}{2}\ln\frac{x_1}{x_2}$$

$$x_1 = (2p_T/\sqrt{s})\, e^{y_{boost}} \cosh y^*$$

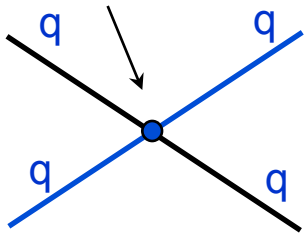
$$x_2 = (2p_T/\sqrt{s})\, e^{-y_{boost}} \cosh y^*$$

$$y^* = \frac{1}{2}(y_1 - y_2)$$

Contact interactions & Dijet Angular Distributions

$d\sigma \sim$ [QCD + Interference + Compositeness]

$$\alpha_s^2(\mu^2)\frac{1}{\hat{t}^2} \qquad \alpha_s(\mu^2)\frac{1}{\hat{t}}\cdot\frac{\hat{u}^2}{\Lambda^2} \qquad \left(\frac{\hat{u}}{\Lambda^2}\right)^2$$



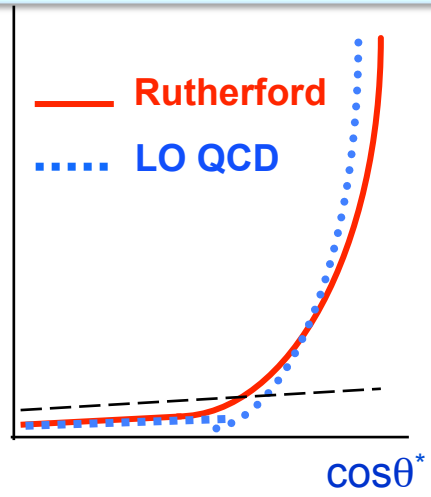
$\sqrt{\hat{s}} << \Lambda$

$d\sigma \sim 1/(1-\cos\theta^*)^2$

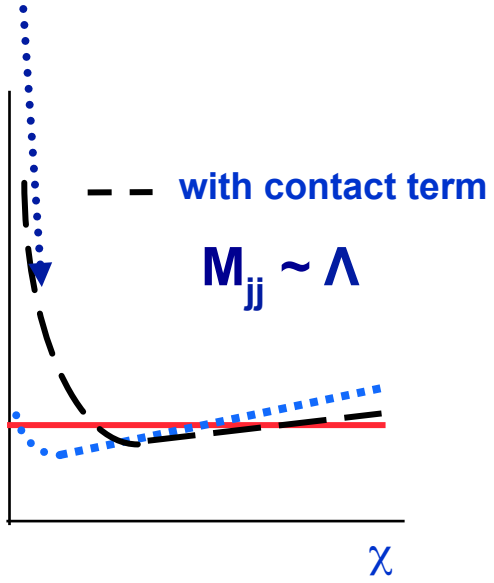
$d\sigma \sim (1+\cos\theta^*)^2$

Instead of $\cos\theta^*$, use: dN/dχ sensitive to contact interactions

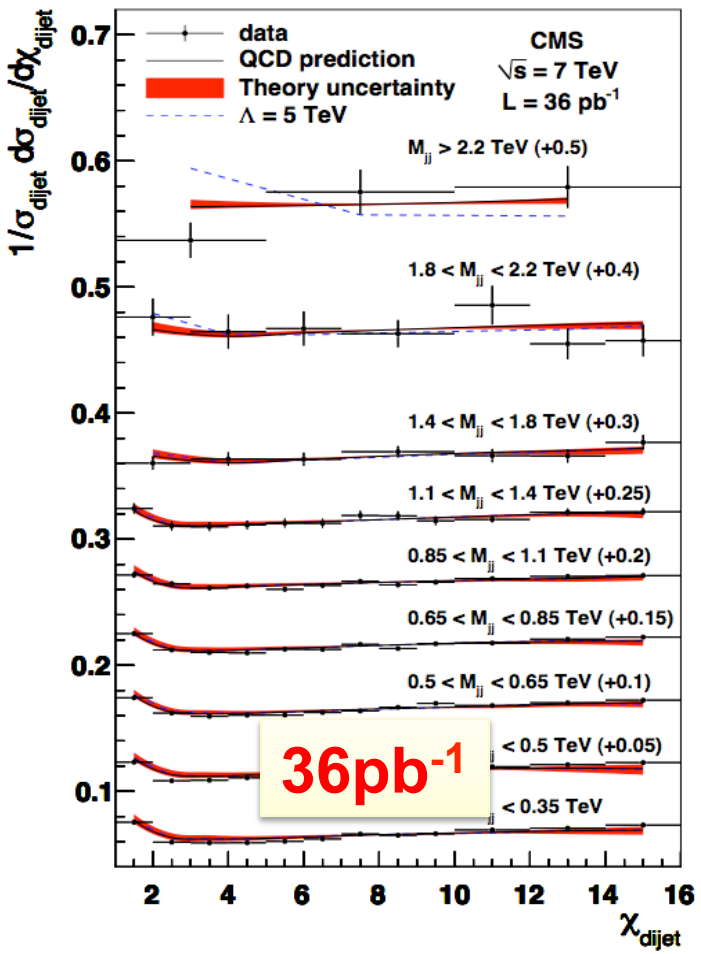
$$\chi = \frac{1+\cos\theta^*}{1-\cos\theta^*} = \exp\left(2\left|y^*\right|\right)$$



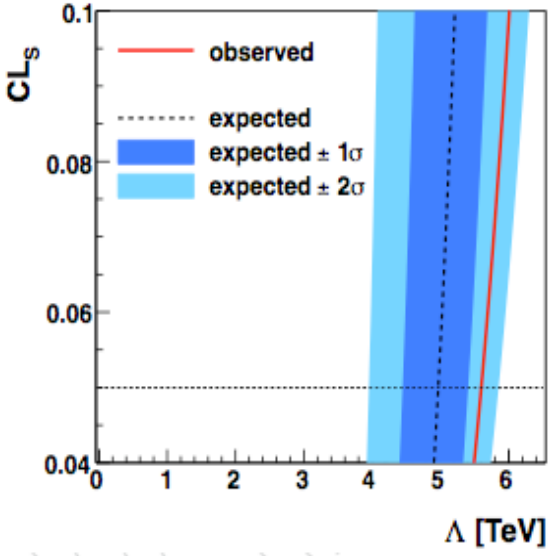
$\Longrightarrow$



Contact interactions



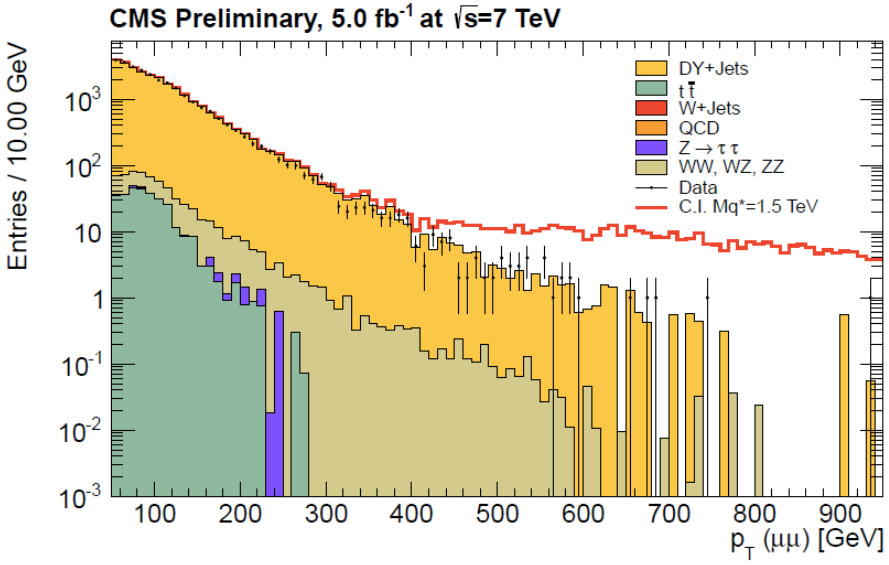
- The χ distributions do not exhibit any excess at low χ. Good description by QCD.
- Lower limit on scale of contact interaction Λ=5.6 TeV (95% CL)

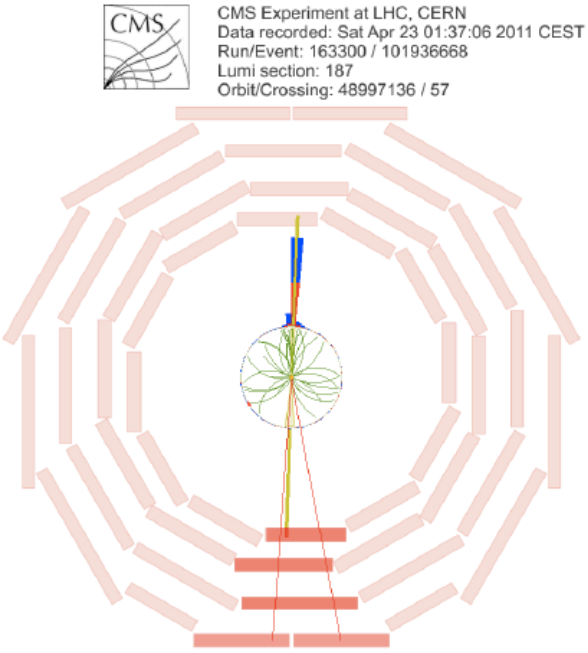


- Most recent results from 7 TeV: 7.8 TeV

Quark compositeness

- **Decay to jet + Z?**
  - **High mass q* → Z with large boost (p_T)**





Quark compositeness

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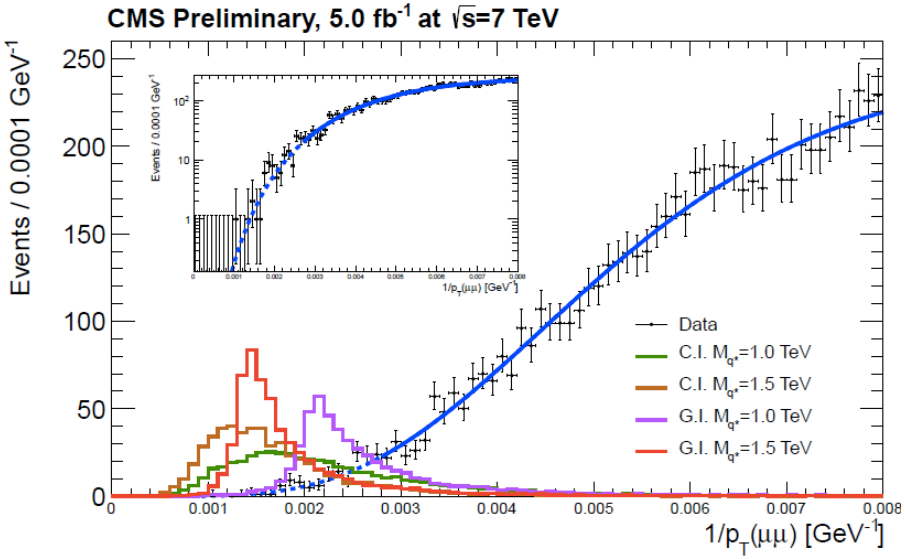
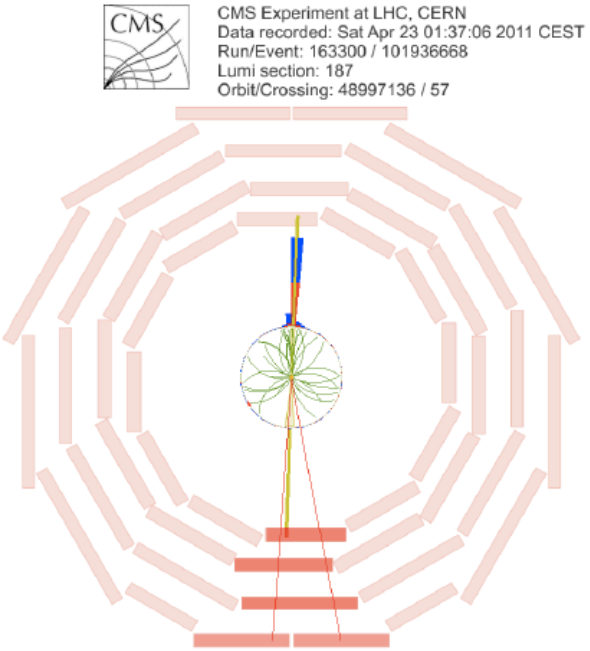




Main background: DY+jets. Bkg estimate:

(a) template fit to high stats, signal-free region in $1/p_T$: [125-360] GeV

(b) extrapolation to high p_T

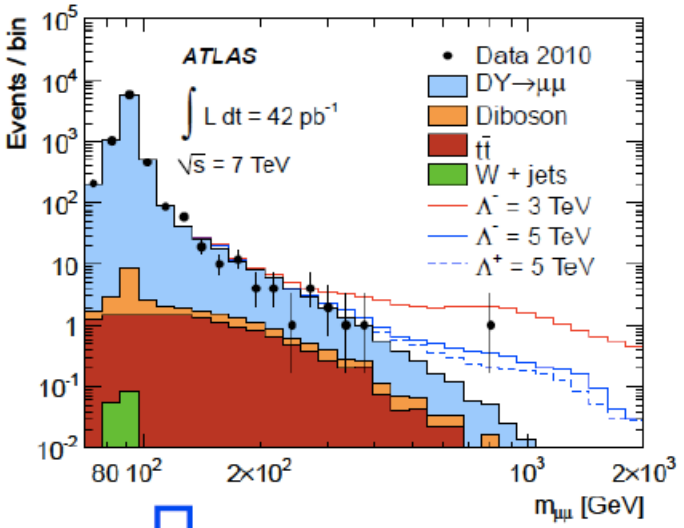
Signal efficiency X acceptance ~ 50-70% (increasing with q* mass)

Contact Interactions (CI)

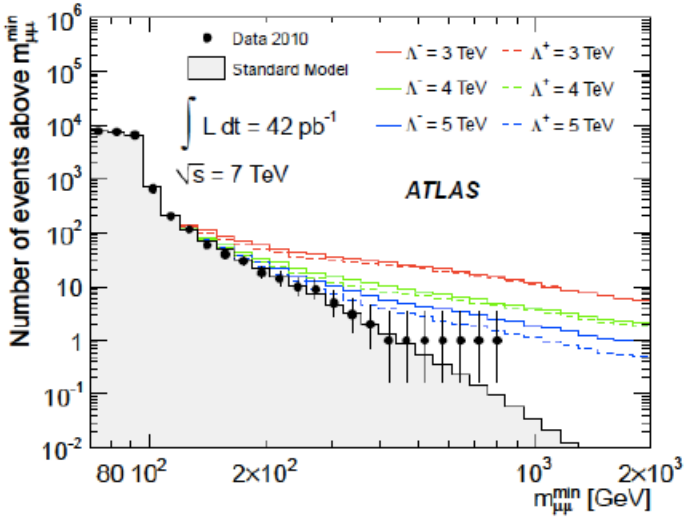
- **Cis: low-energy manifestation of "true" phenomena, e.g.**
  - **Quark-lepton compositeness**
  - **Large Extra Dimension (ADD) model**
- **Deviations in dimuon mass:**

$$\frac{d\sigma}{dm_{\mu\mu}} = \frac{d\sigma_{DY}}{dm_{\mu\mu}} - \eta_{LL}\frac{F_I(m_{\mu\mu})}{\Lambda^2} + \frac{F_C(m_{\mu\mu})}{\Lambda^4}$$

  - **F_I and F_C: interference terms**
  - **Λ: energy of "new binding"**
- **Mass spectrum agrees, so set limits instead:**
  - **For Constr Interf: Λ_C>4.9 TeV**
  - **For Destr Interf: Λ_I>4.5 TeV**



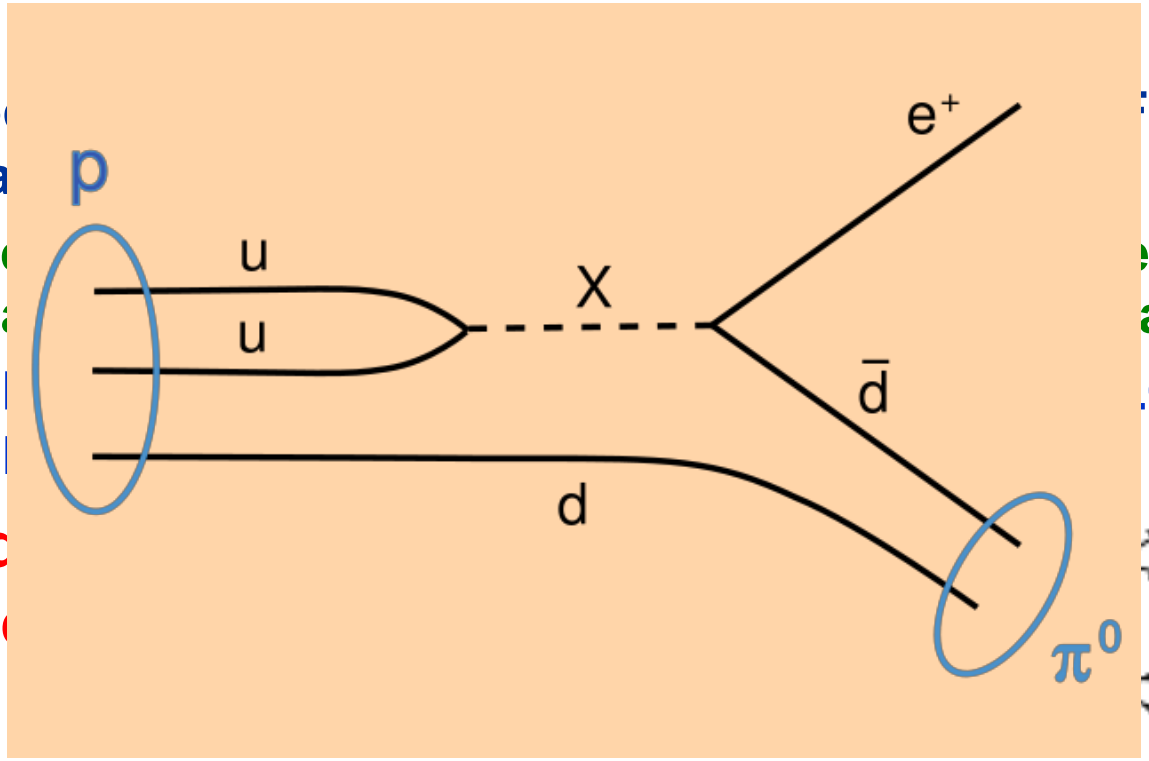
Taking an integral...



Searches for signs of exotic New Physics

Leptoquarks (I)

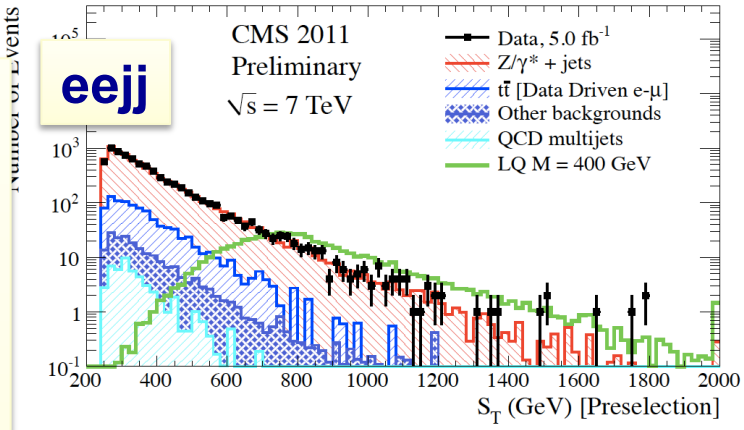
- As name implies, they are both "leptons" and "quarks": i.e. carry baryon and lepton number – & color (large σ!)
  - GUT-inspired models, with (hypothetical) proton decay acting as one of the main motivations
  - Decay:
  - A lepto… FCNC constra…
    - In g… earches usua… ation
      - ➨ … LQ1 and …
- Pair-proc… final stat… look for:

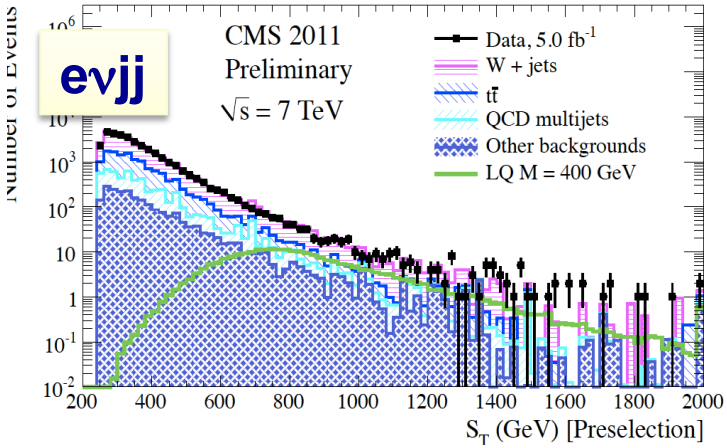


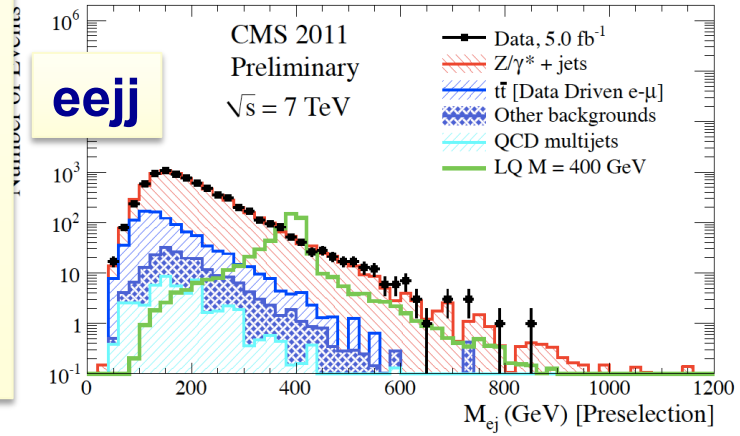
Leptoquarks (II)

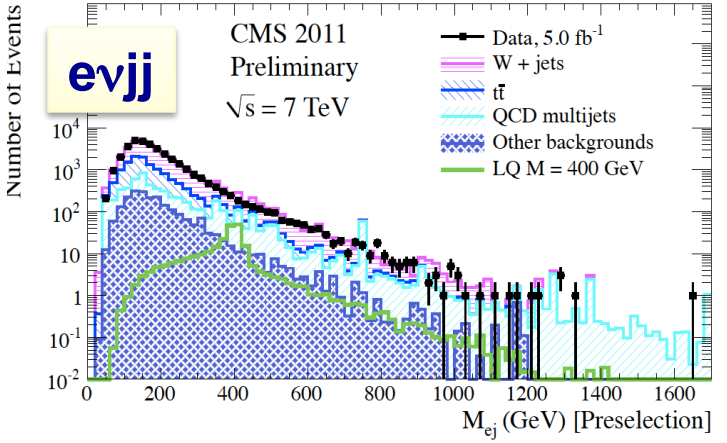
- **Main irreducible bkg: DY+jets; 2nd: top production**
  - **In situ Z+jets measurement + measured top cross section in the dilepton channel to estimate both bkgs**

- **DY+jets normalized to Z+jets (control region)**
- **anti-Z cut**
- **optimize S_T cut (mass-dependent)**



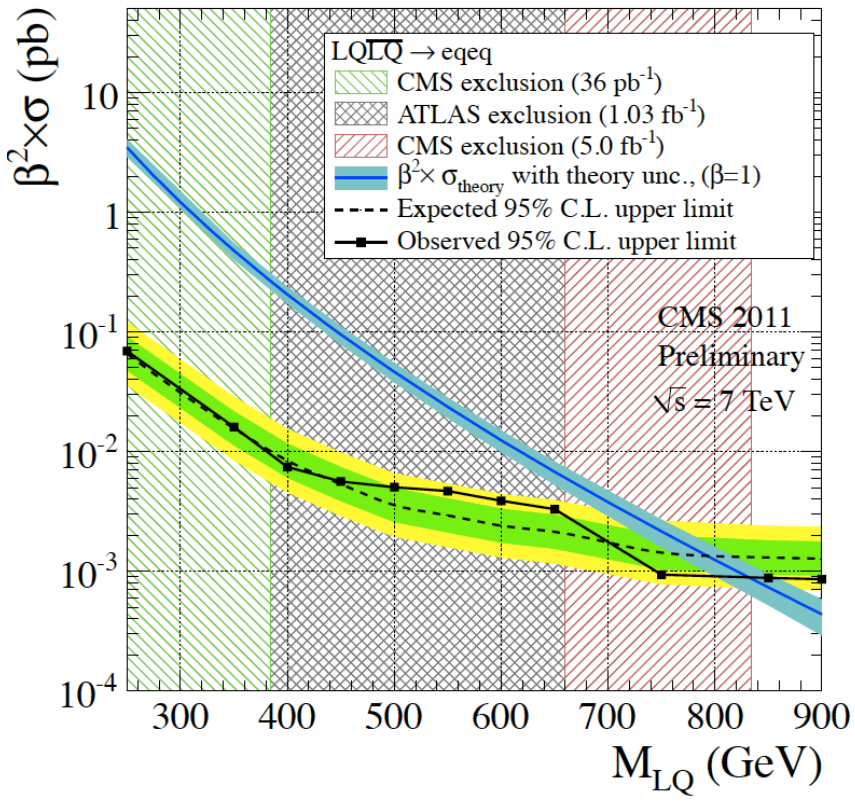




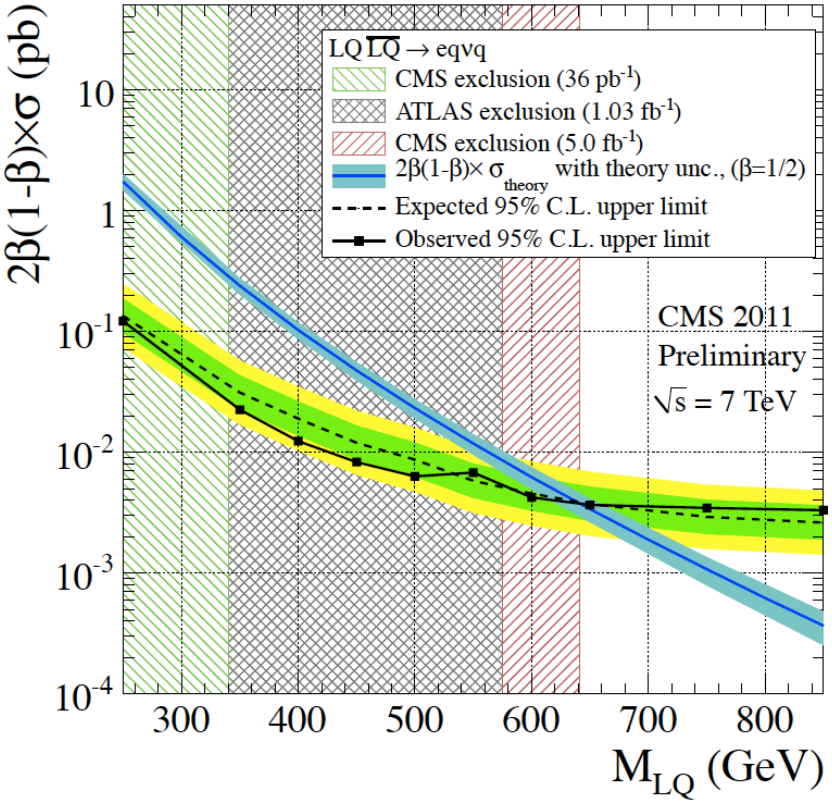


Leptoquarks: limits

- β=1

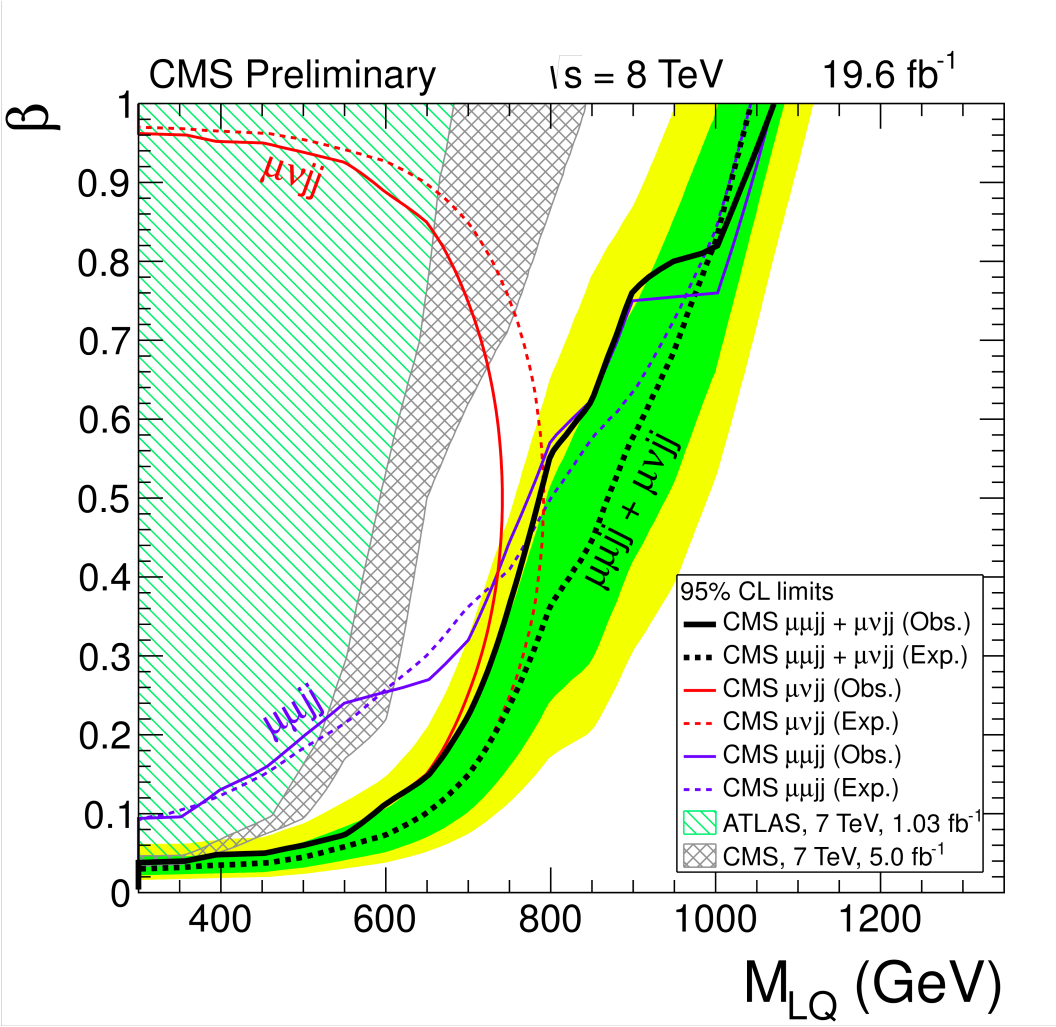


- β=0.5



Leptoquarks: limits

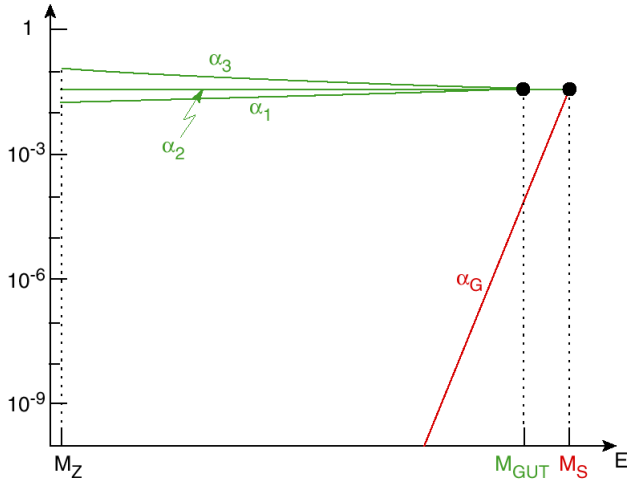
- **Combined limit**

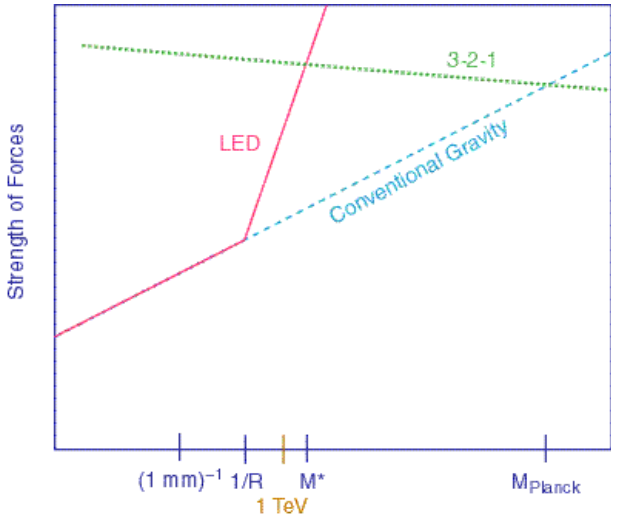


Extra Dimensions (?!?)

TeV-scale gravity

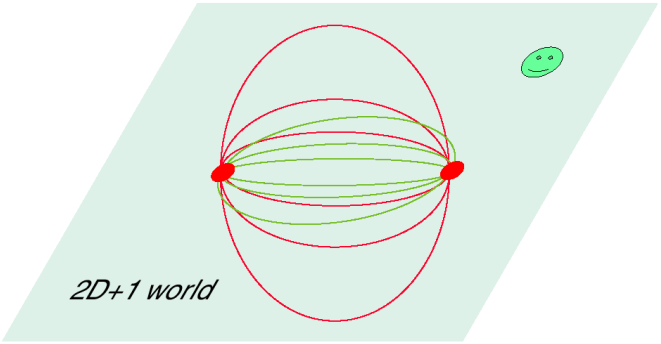
- **The idea of our times: that the scale of gravity is actually not given by M_{PL} but by M_W**
  - **Strings live in >4 dimensions. Compactification → 4D "SM". M_{PL-4} related to $M_{PL-(4+d)}$ via volume of xtra dimensions:**
    - $M_{PL-4}^2 \sim V_d\, M_{PL-(4+d)}^{2+d}$
  - **Conventional compactification: very small curled up dims, $M_{PL-4} \sim M_{PL-(4+d)}$**
    - $V_d \sim (M_{PL-4})^{-d}$
  - **Alternative: volume is large; large enough that $V_d >> (M_{PL-(4+d)})^{-d}$**
    - **Then $M_{PL-(4+d)}$ can be ~ TeV (!)**
    - **"our" Planck mass at $\log(\Lambda) \sim 19$: an artifact of the extrapolation**





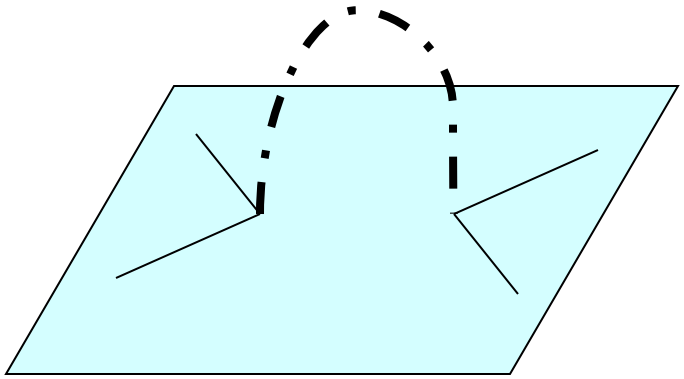
Forces and number of dimensions

- **Number (D) of space-time dimensions → form of force observed**
  - **E+M: $F \sim 1/r^2$ because D=3+1**
  - **For "ants" living in D=2+1 dimensions, E+M is actually a $F \sim 1/r$ force**

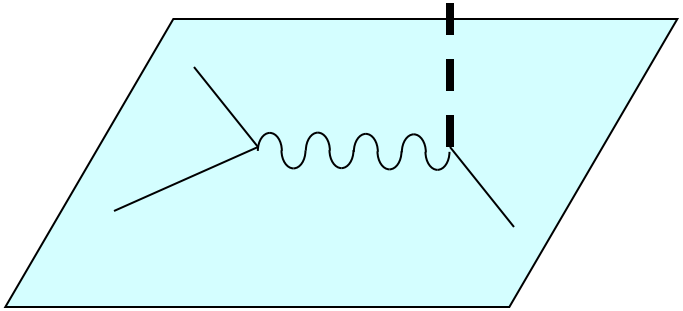


- **Tabletop experiments: look for deviations from $1/r^2$ law**

- **Propagation into the other dimensions:**
  - **Resonances!**



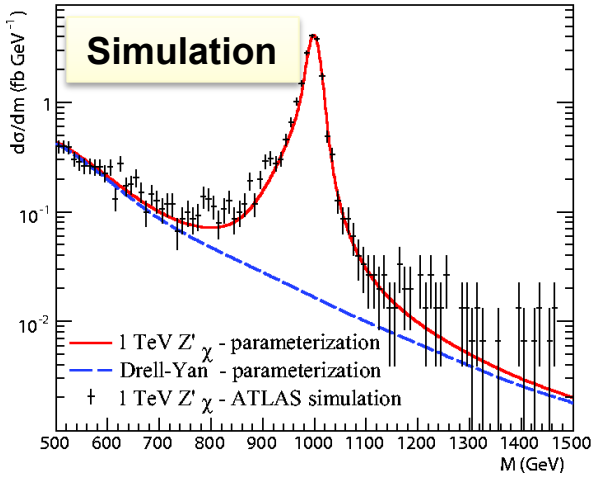
  - **Missing energy!**



Different types of extra dimensions

- **The "traditional" image of a circular extra dimension**

$$\phi(x) = \phi(x + k2\pi R)$$
$$(k = 0, 1, 2, ...)$$
$$p = k/R$$



- **Randal-Sundrum**

$ds^2 = g_{\mu\nu}\, dx^\mu\, dx^\nu + g_{mn}(y) dy^m dy^n$

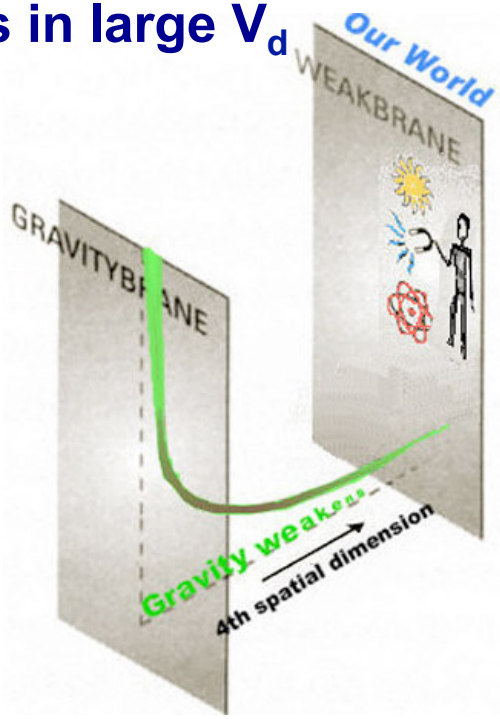
(x: SM coordinates; y: d extra ones)

Generalize: dependence on location in extra dimension

$ds^2 = e^{2A(y)}\, g_{\mu\nu}\, dx^\mu\, dx^\nu + g_{mn}(y) dy^m dy^n$

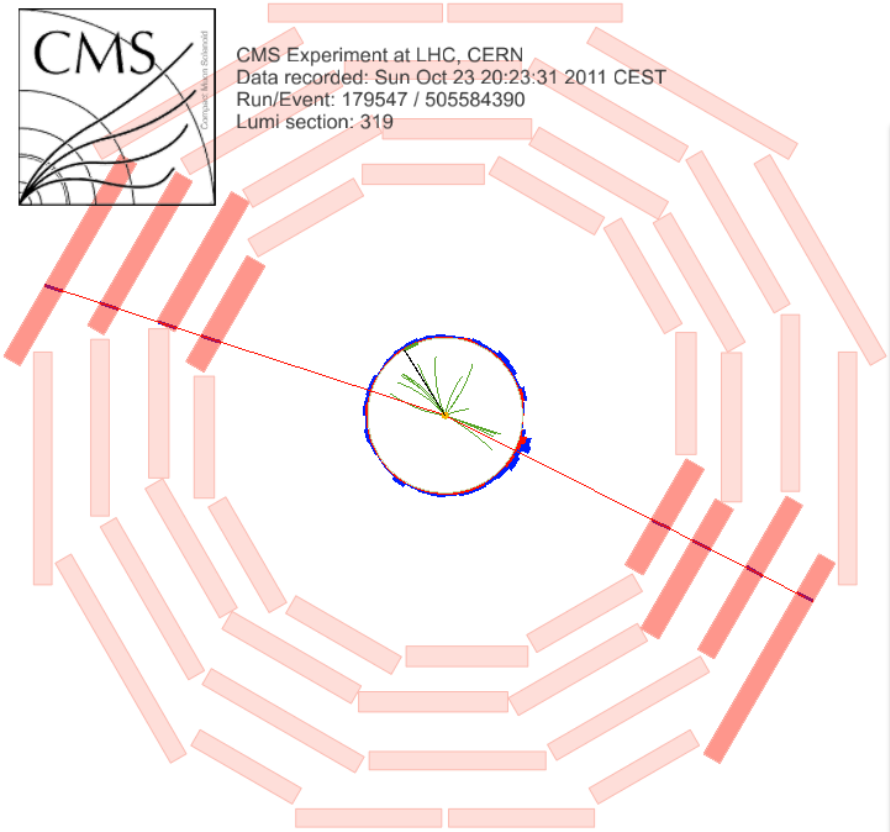
Large exp(A(y)) results in large V_d

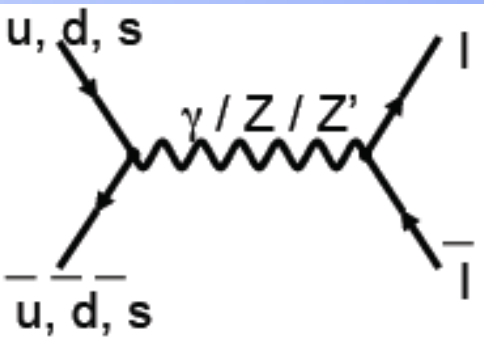
As an example (RS model), two 4-D branes, one for SM, one for gravity, "cover" a 5-D space – with an extra dimension in between



Search for Z′

- **Di-muon event, M(μμ)=1379 GeV**



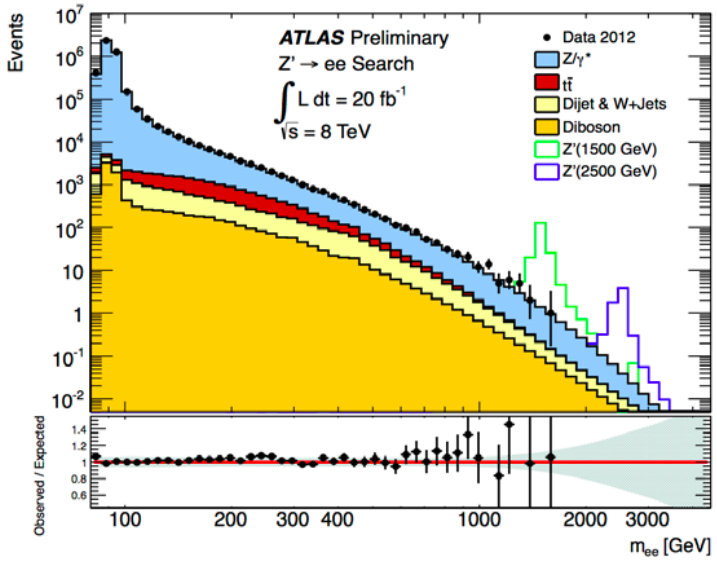


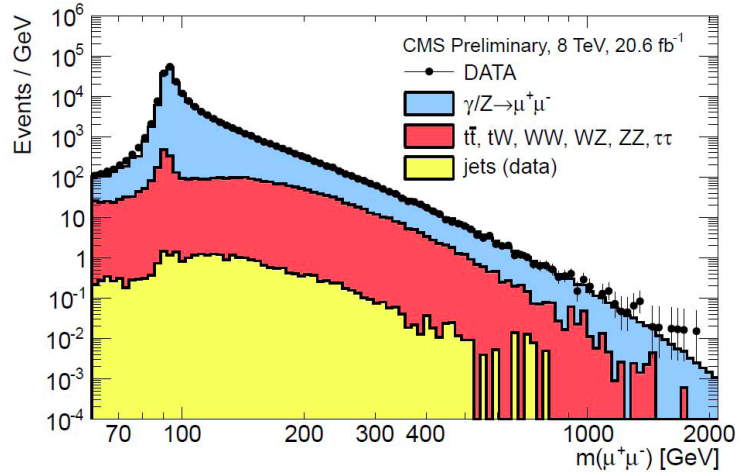
Nice, clean signature (but SM tails)

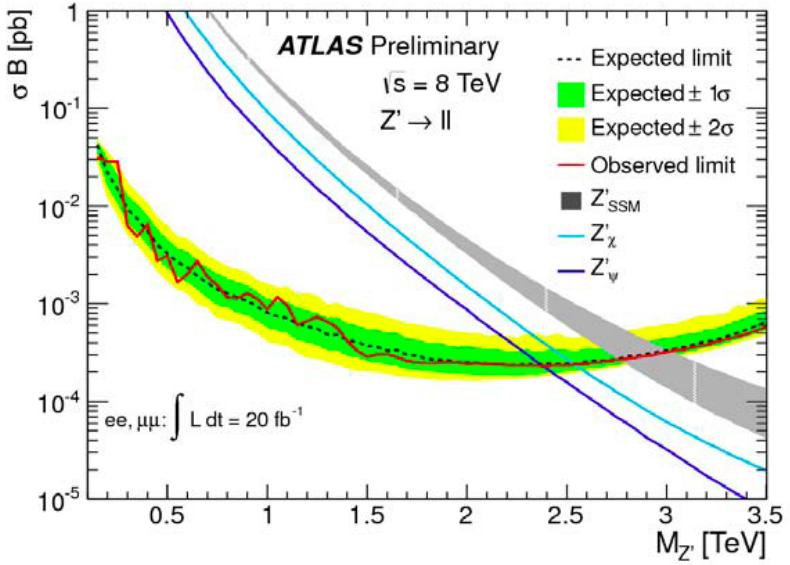
Experimental issues:

- **detector resolution: for muons deteriorates with mass; for electrons the opposite**
- **reconstruction of *E* and *p* recontruction with > 1 TeV can be tricky business…**

Search for a Z′→ee and/or μμ







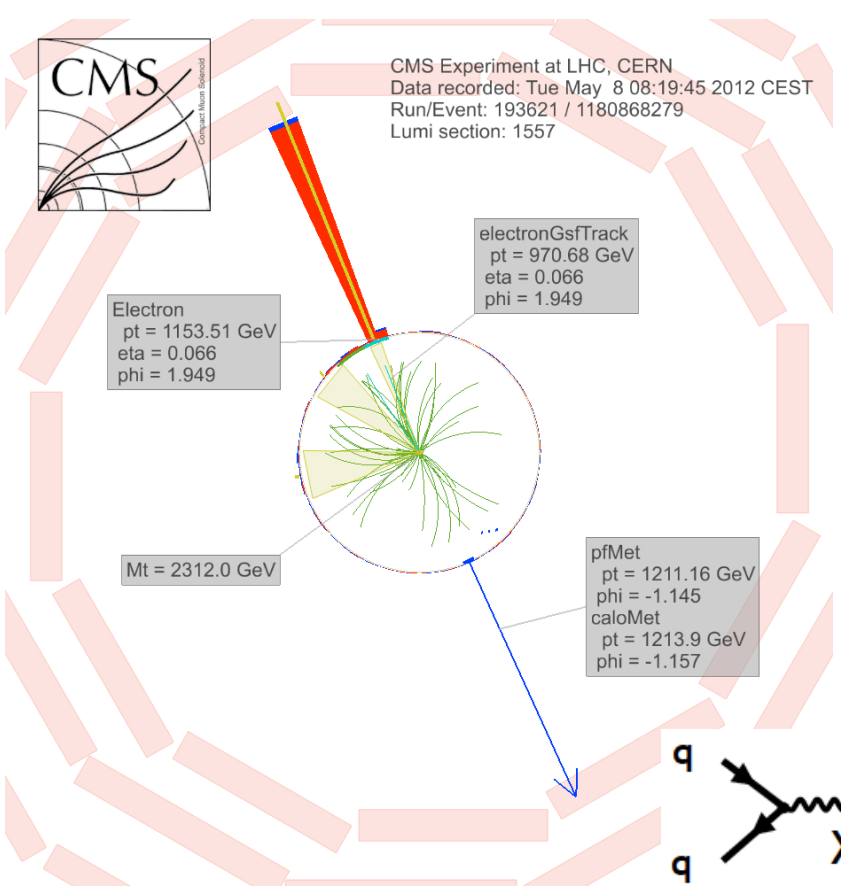
Model	ATLAS	CMS
SSM Z'	2.86	2.96
E_6 Z'$_\psi$	2.38	2.60
RS G* ($k/\bar{M}_{Pl}$=0.1)	2.47	

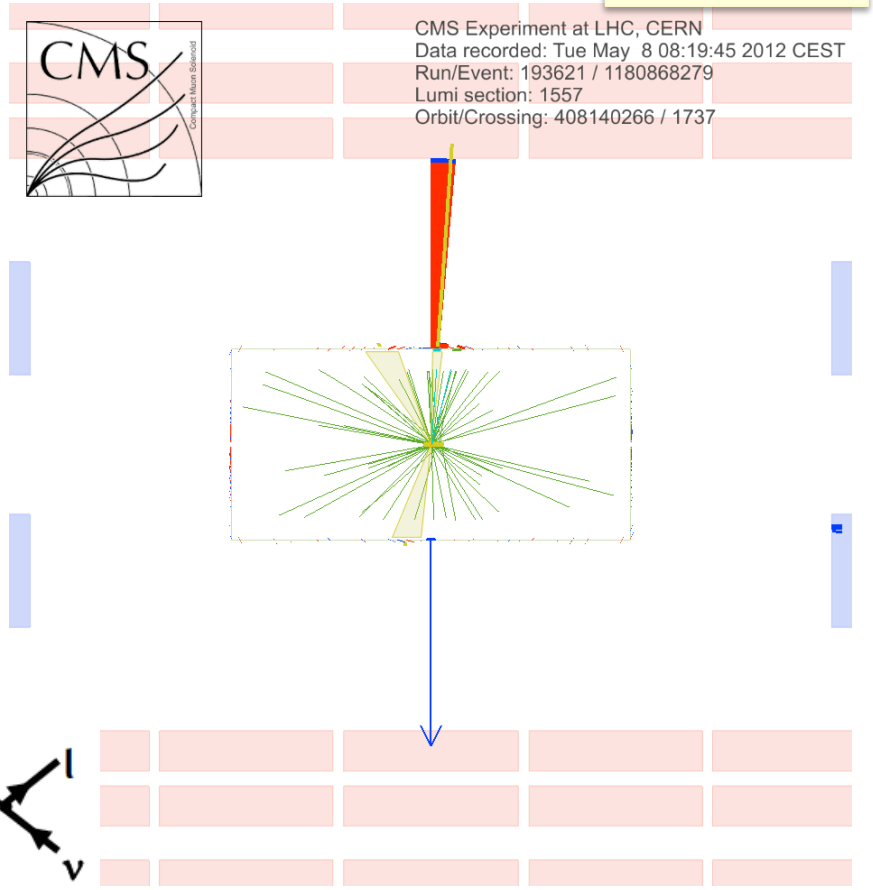
SSM: Sequential SM
RS: Randall-Sundrum

Search for W′: example from CMS

- **Events are equally spectacular; a very high-p_T lepton, and little, very little else!**

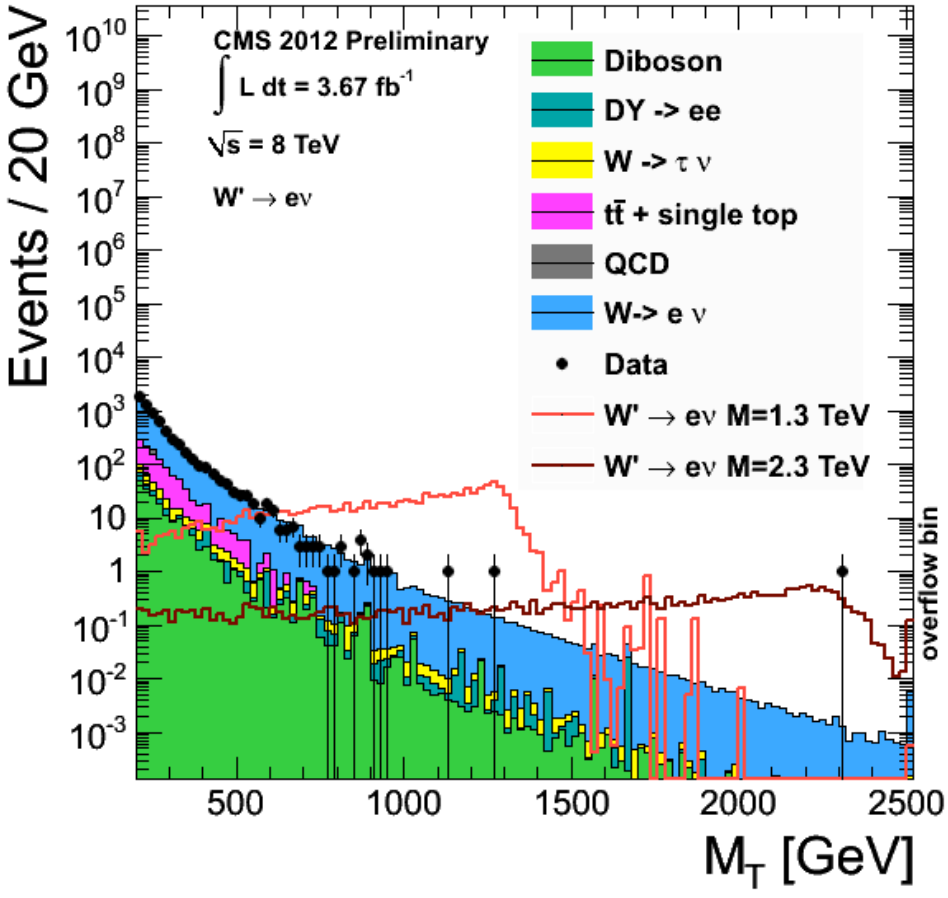
8 TeV



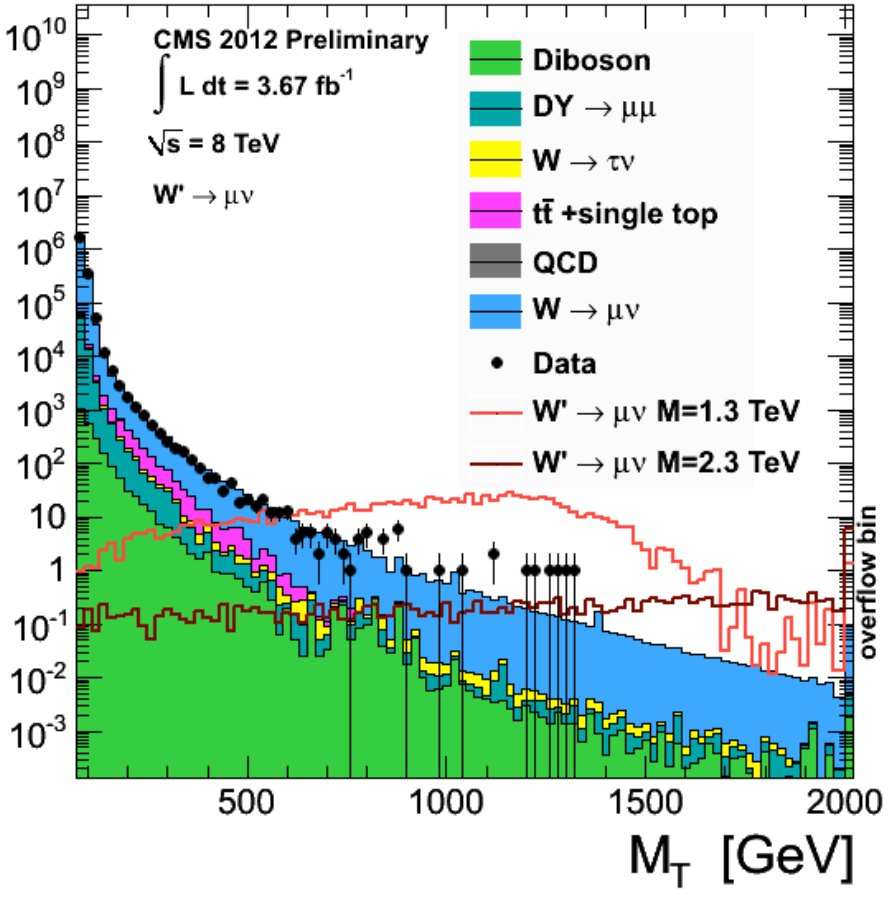


Search for W′: example from CMS

Electrons

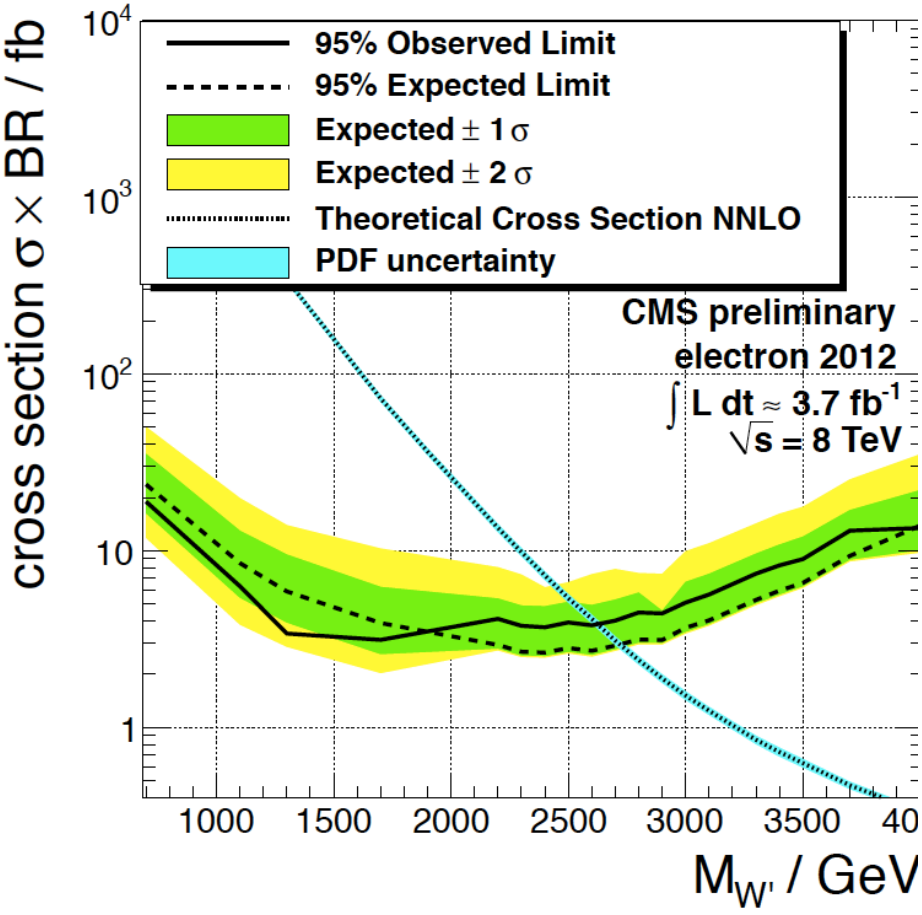


Muons

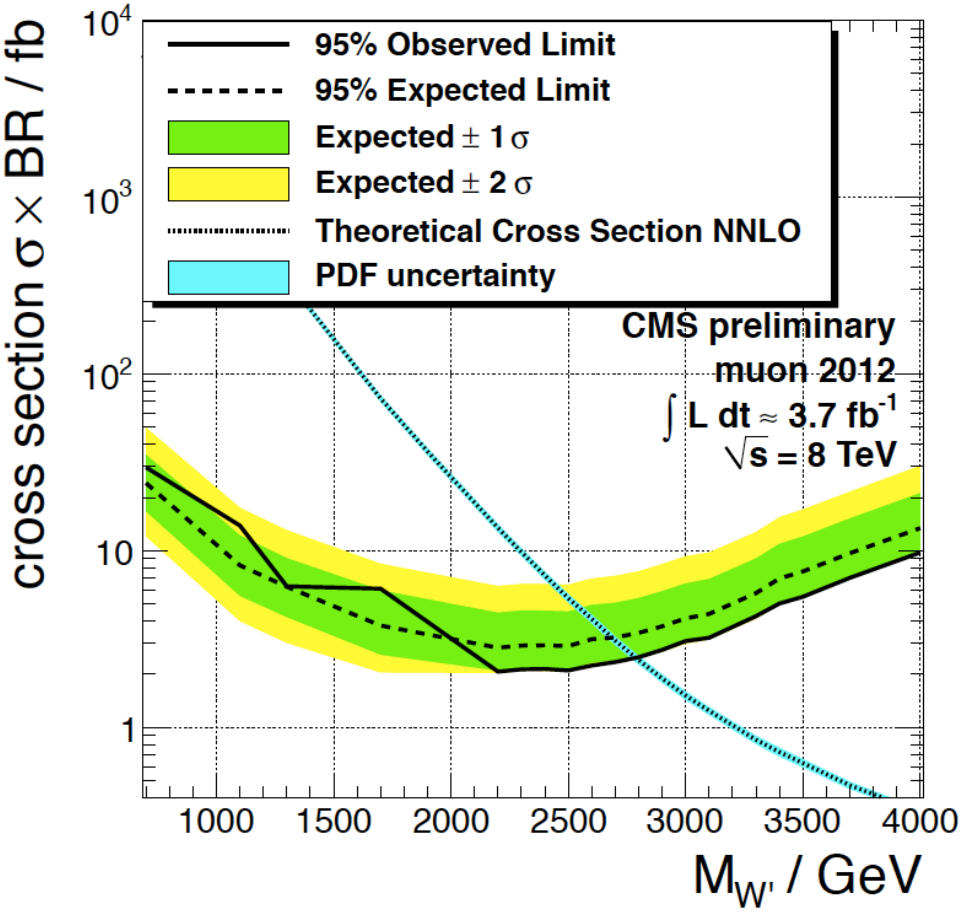


Search for W′: example from CMS

Electrons

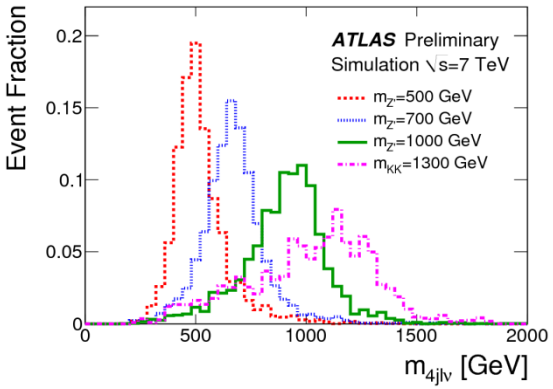


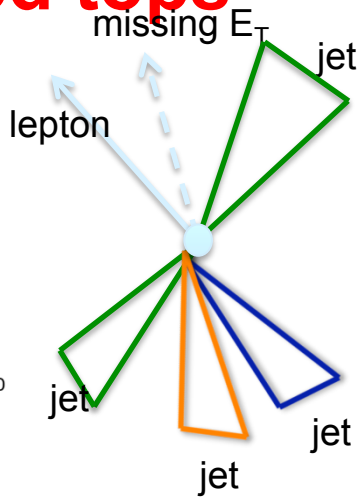
Muons

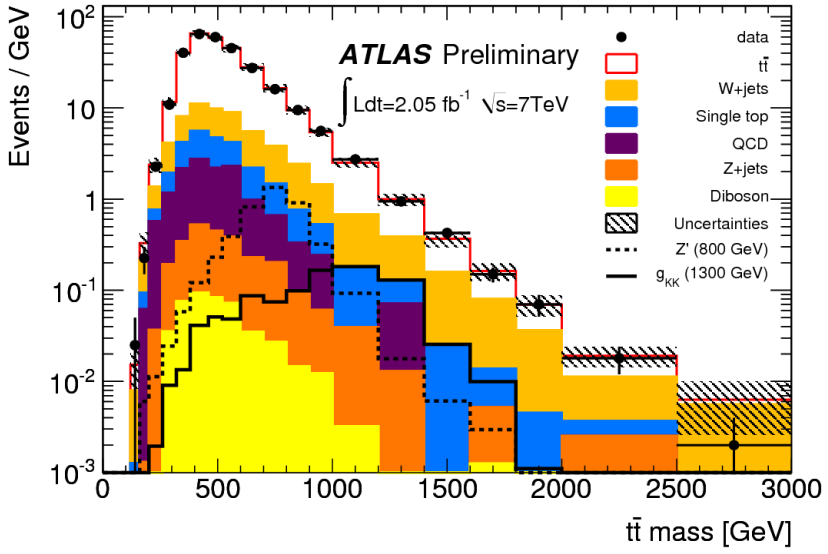


Search for a resonance decaying to t-tbar

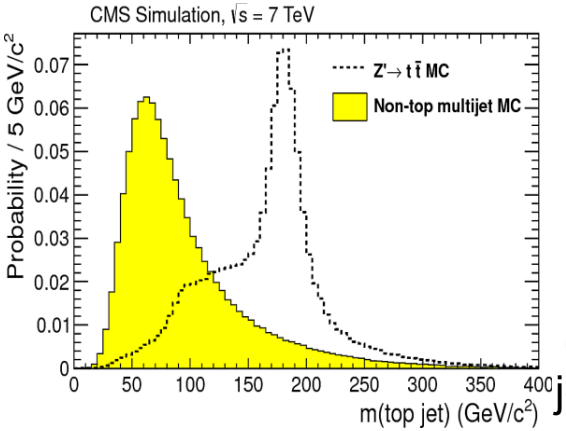
non-boosted tops

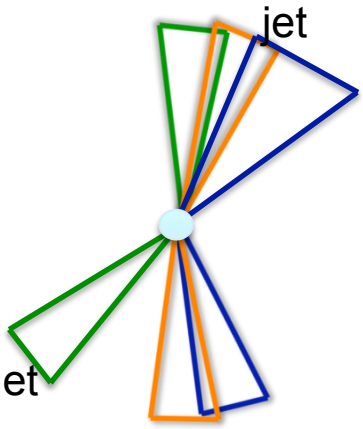


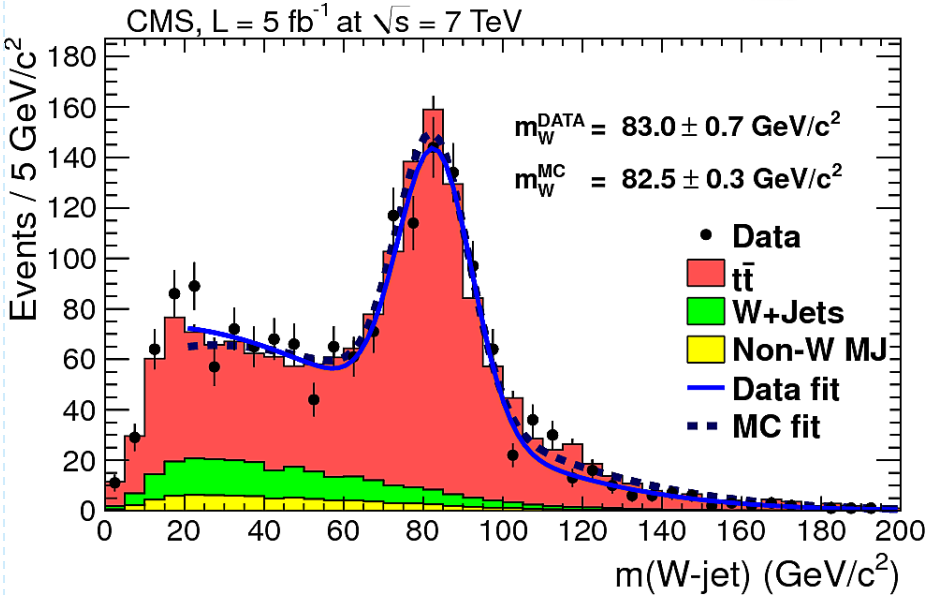




boosted tops

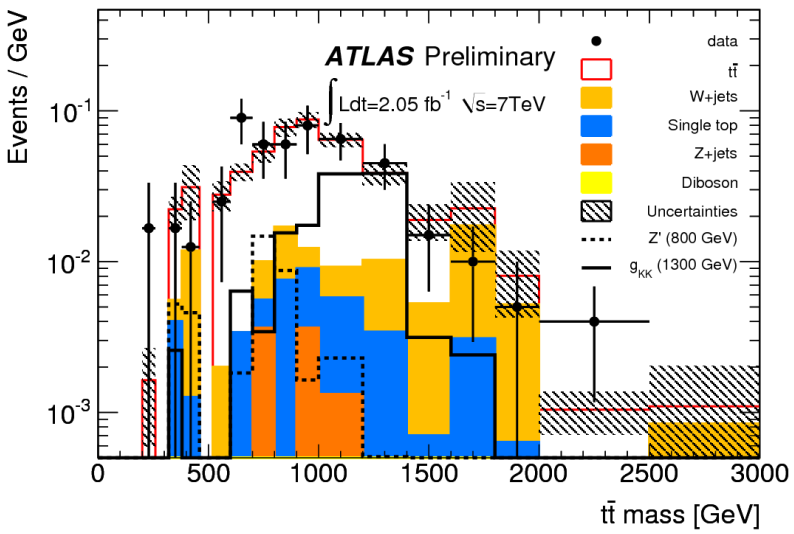


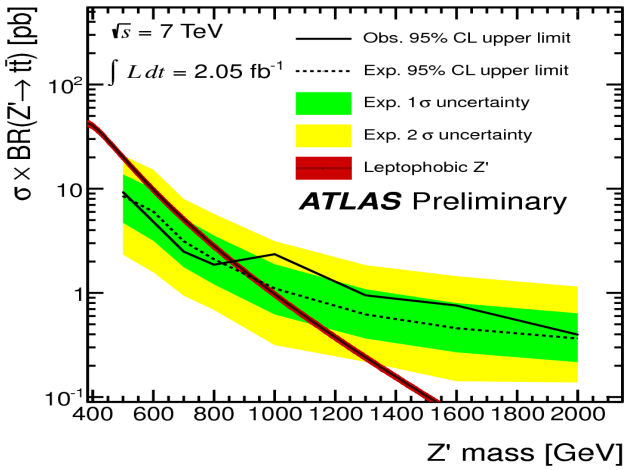




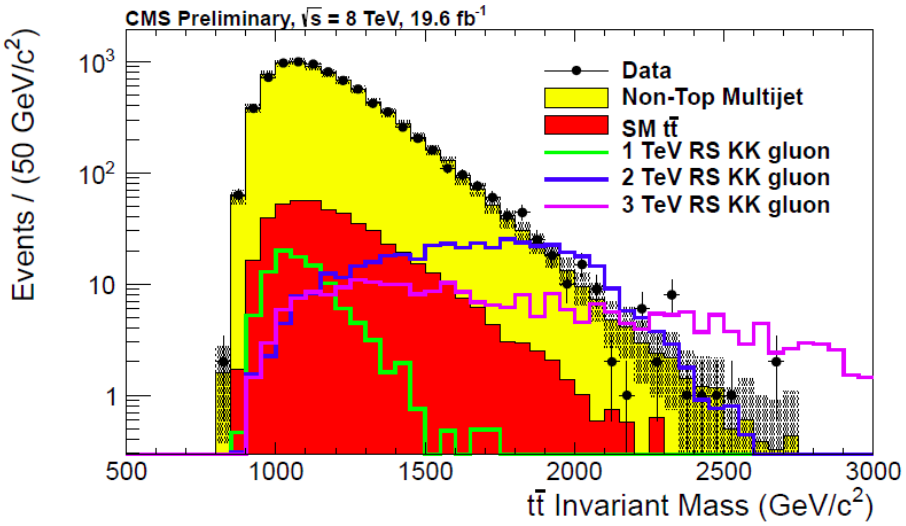
Search for a resonance decaying to t-tbar

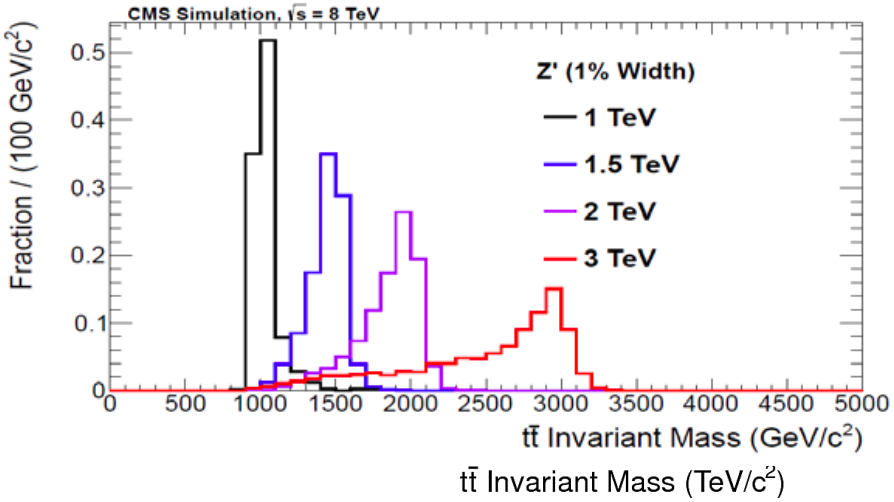
- **non-boosted tops**





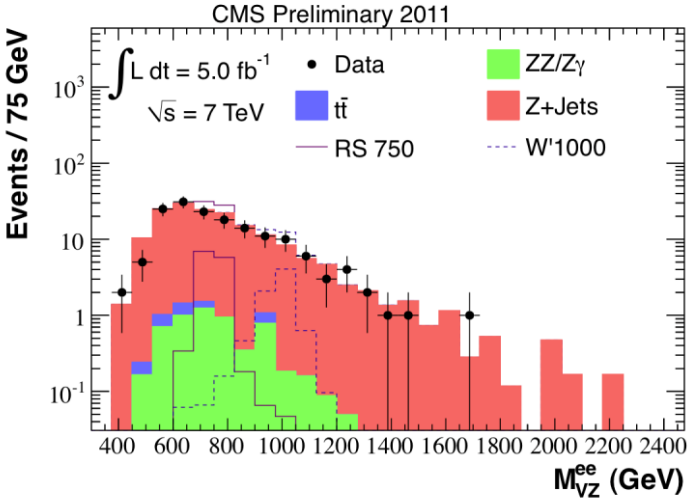
- **boosted tops**

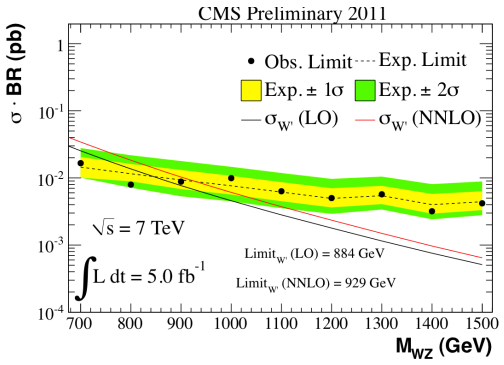


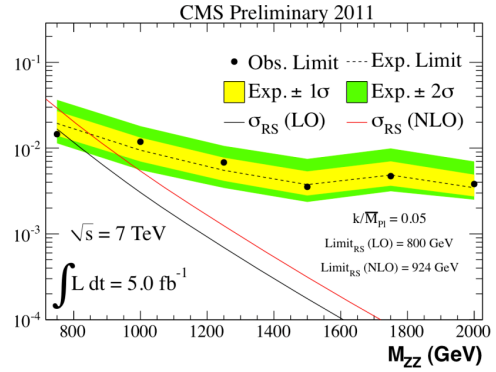


Search for diboson resonances

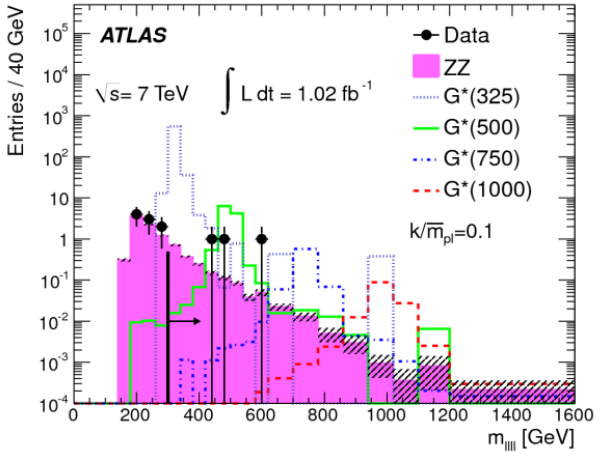
- **X→WZ**
  - **Dilepton+ jets**

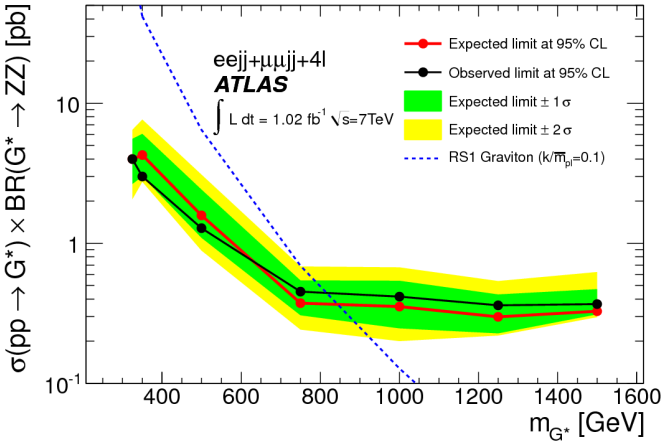




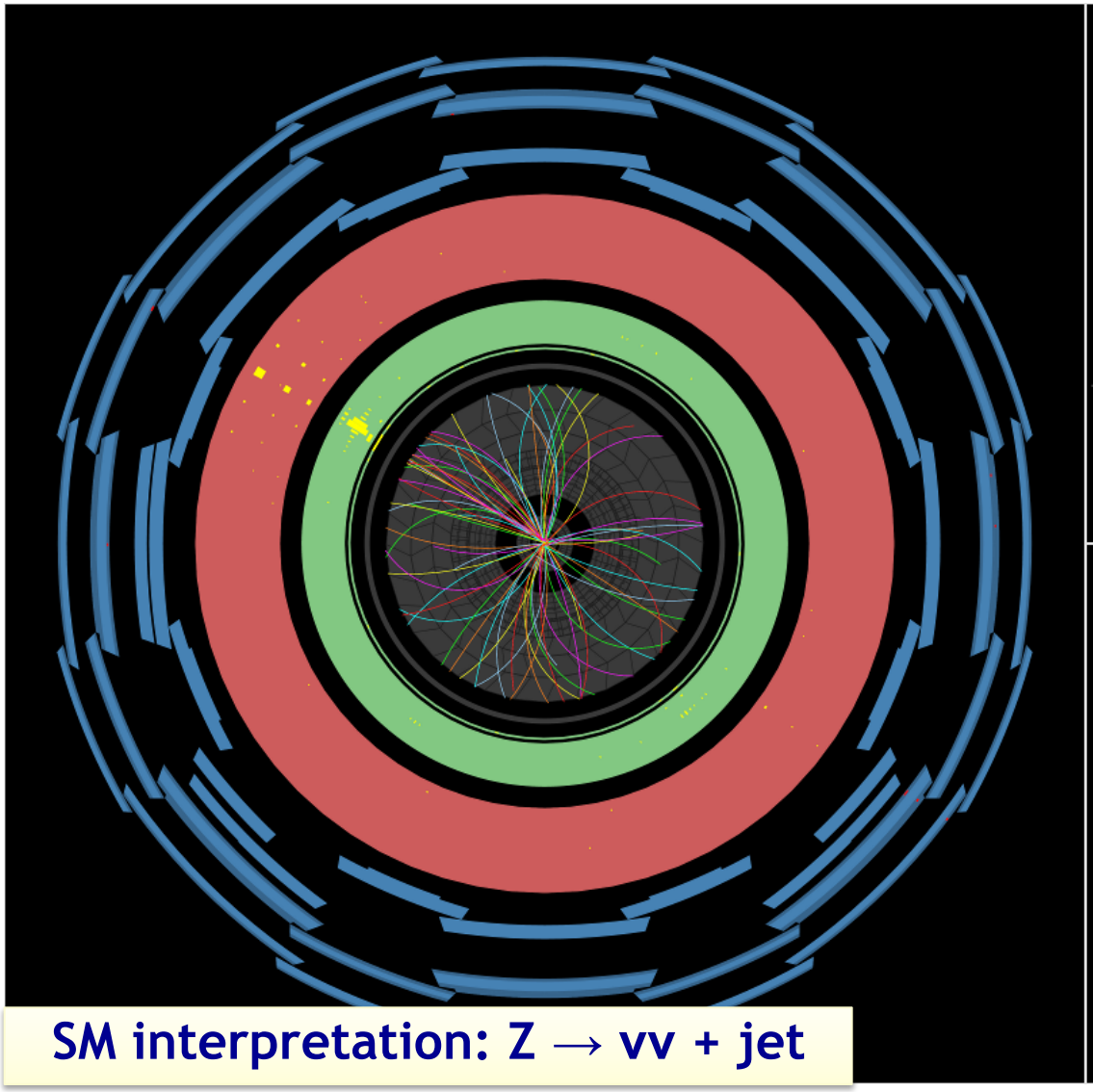


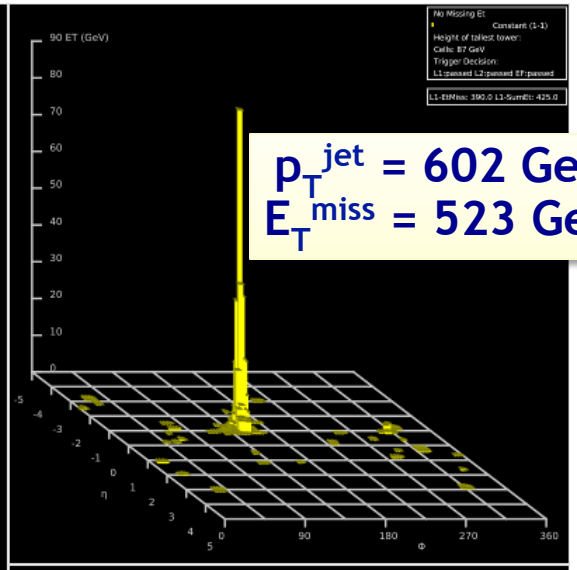
- **X→ZZ**
  - **2lep+jets; 4lep**





Monojets?



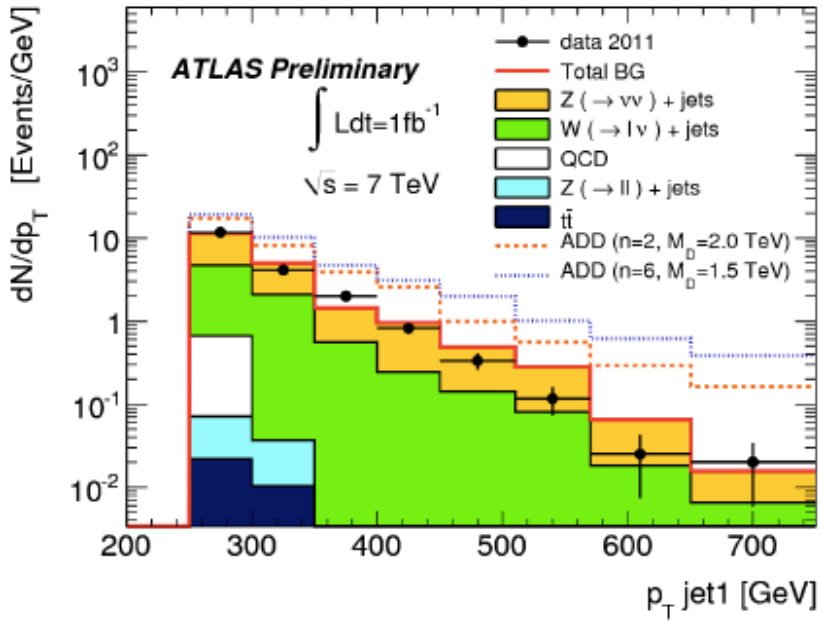


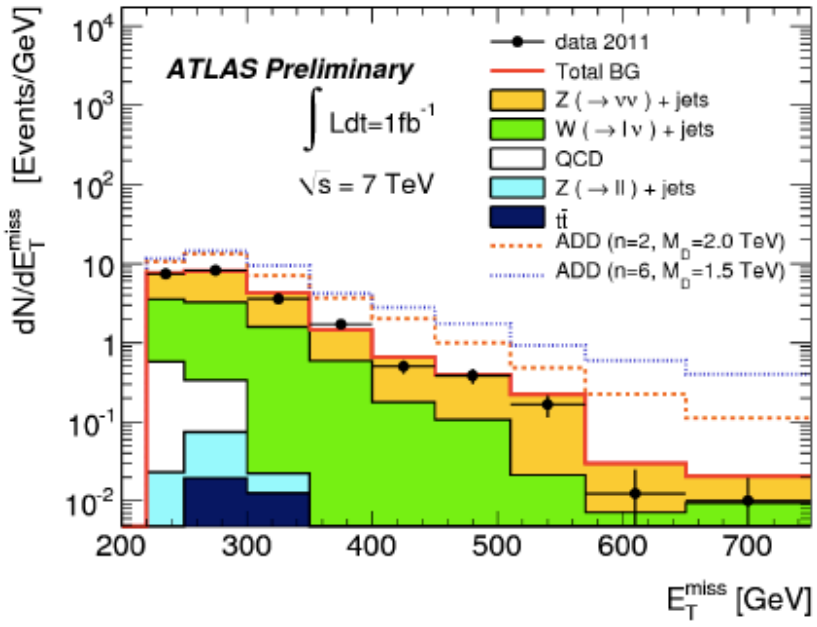
p_T^{jet} = 602 GeV
E_T^{miss} = 523 GeV

SM interpretation: Z → νν + jet

Monojets (I)

- **Extra dimensions: hard scatter leads to a jet plus an invisible particle [e.g. a graviton]; signal region:**
  - **P_T(jet1)>250 GeV, ME_T>220 GeV**
  - **P_T(jet2)<60GeV, $\Delta\phi$(jet2,ME_T)>0.5**
  - **No "reasonable" electrons or muons**



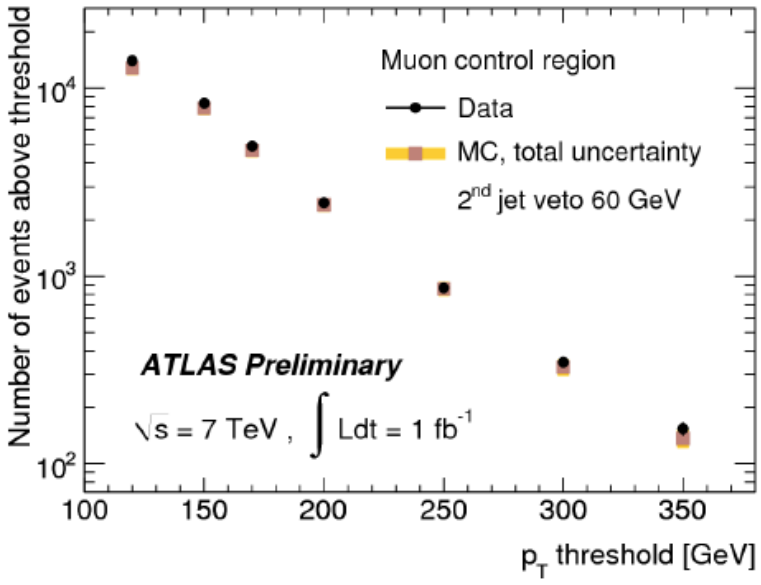


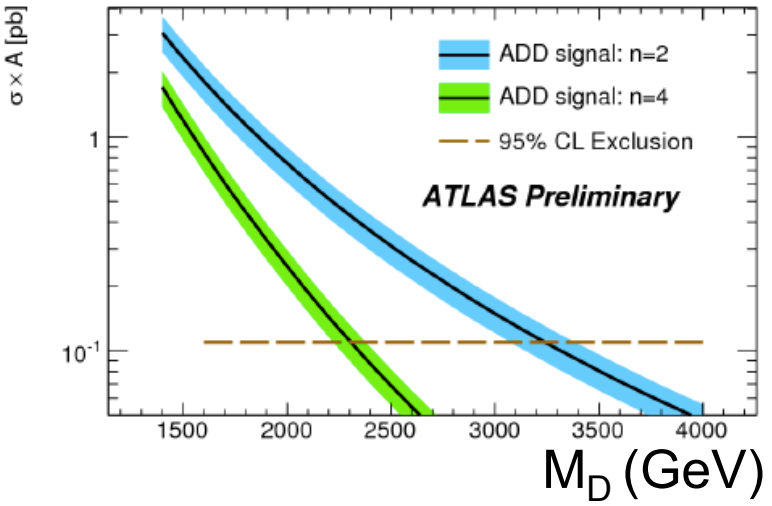
Monojets (II)

- **Main bkg: EWK**
  - **Irreducible: Z(→νν)+jets & W(→lν) +jets**
  - **Get normalization from data, then apply to Monte Carlo samples**
- **QCD (multijet) bkg: reverse Δϕ cut and allow 2nd jet!**
- **Data agree with sum of bkgs:**
  - **Bkg est: 1010±37(stat)±65(syst)**
  - **Data: 965 events**
- **Model-independent limit on cross section x acceptance: "0.11 pb at 95% CL"**

  95 out of 100 experiments [with 0.11 pb] would have observed a larger number of events

  No "magic" to "95%" – only a norm.

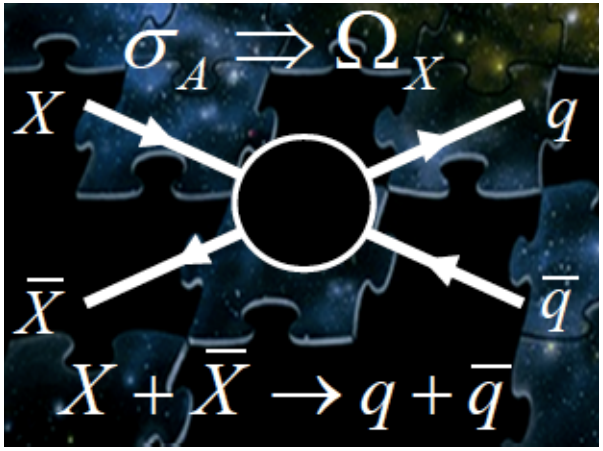


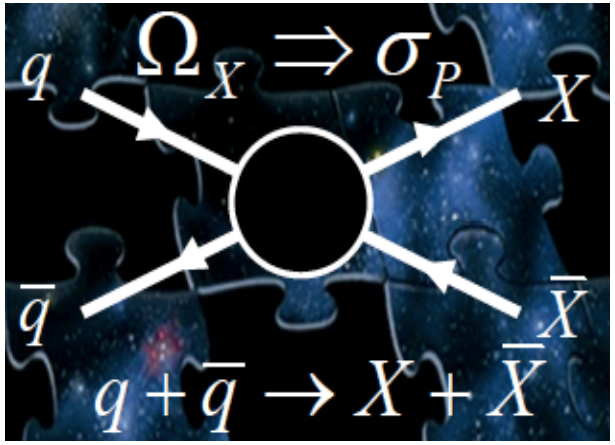


Dark Matter?

Dark matter

- **Early universe: create/destroy dark matter via:**

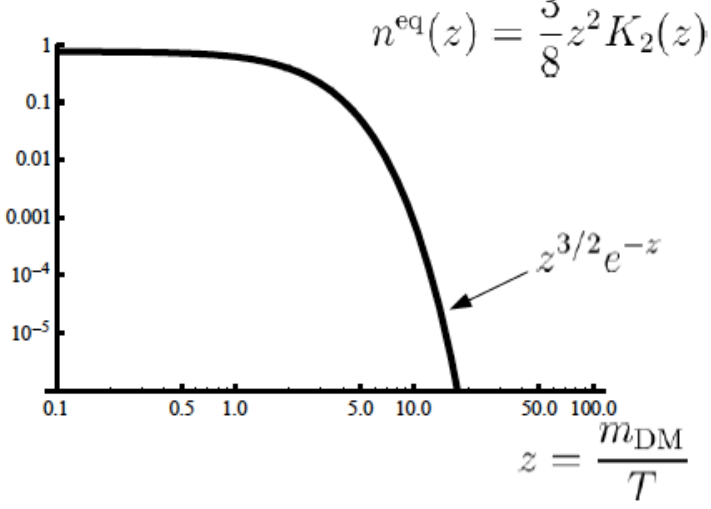




  - **If the two rates are the same → equilibrium; and then, as it cools off…**

$$\frac{dn}{dt} = -\langle \sigma_{\rm ann} v \rangle (n^2 - n_{\rm eq}^2)$$

But: universe is expanding

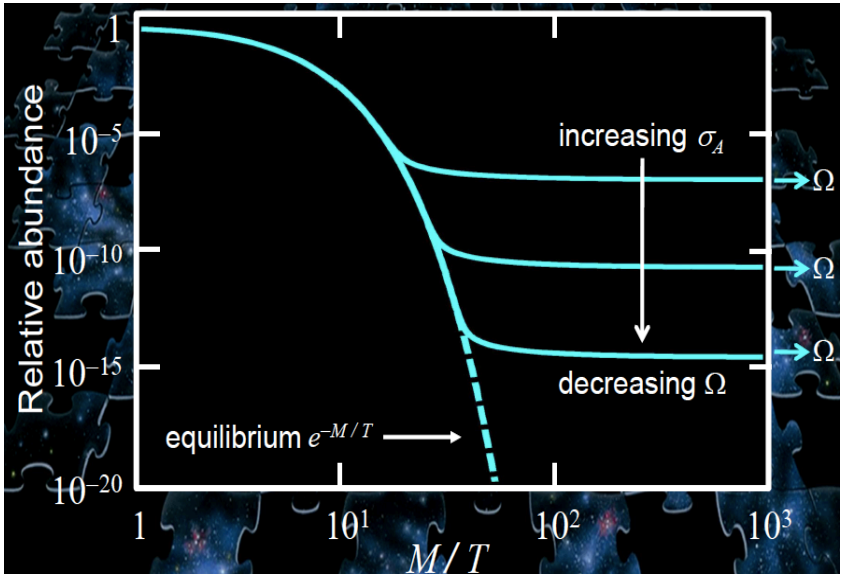


Dark matter (II)

- **If DM production rate large compared to expansion rate**
  - Essentially a static configuration
  - DM particles are in thermal equilibrium
- **If DM production rate small compared to expansion rate**
  - Few DM particles remain
  - DM particles do not bump into each other (and do not destroy themselves)
    - Density remains constant (!)

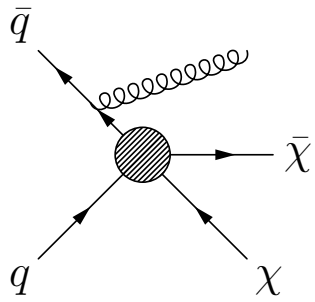
$$\Omega_{\rm DM} h^2 \simeq \frac{3 \times 10^{-27} {\rm cm}^3 {\rm s}^{-1}}{\langle \sigma v \rangle}$$

$$\Omega_{\rm DM} h^2 \simeq 0.1$$

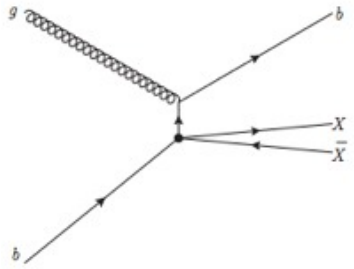


- **Thus: σ ~ 1pb!**

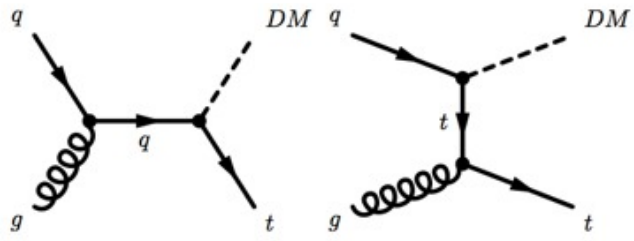
Mono-X signatures



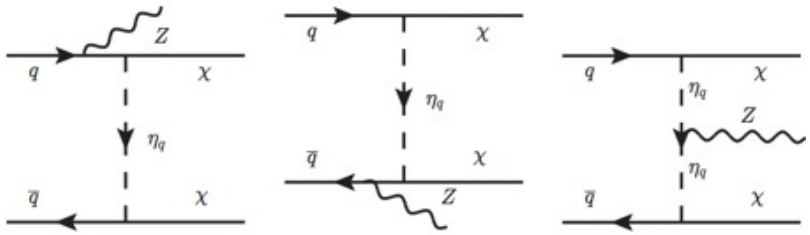
Monojet



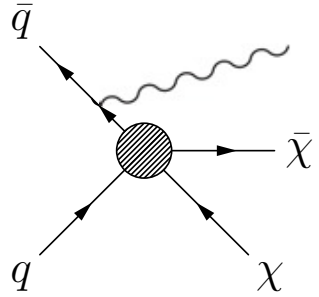
MonoB



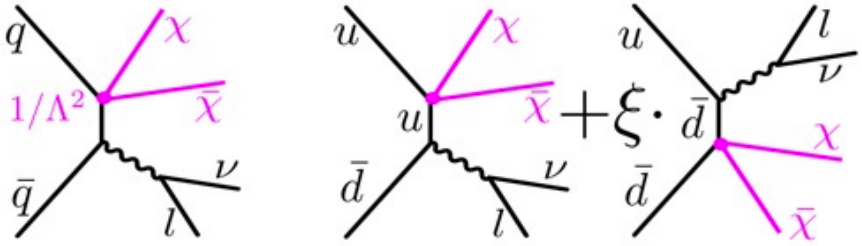
MonoTop



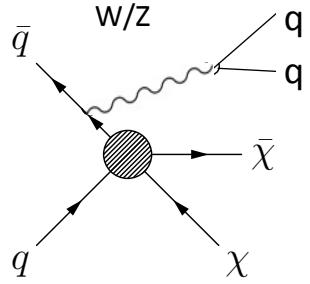
MonoZ



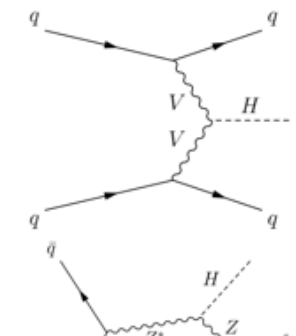
MonoPhoton



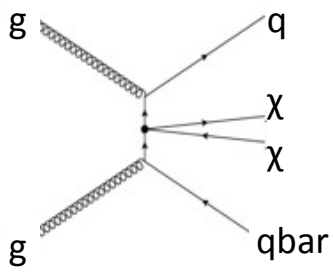
MonoW (monoLepton)



MonoW/Z (Hadronic)



Higgs Portal



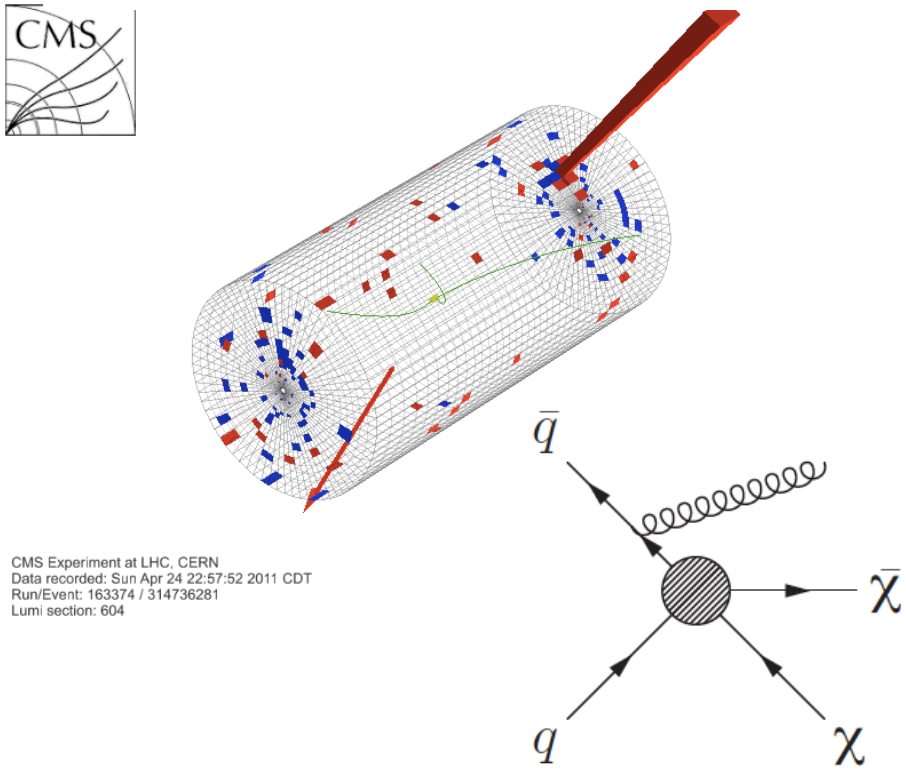
BBbar /TTbar

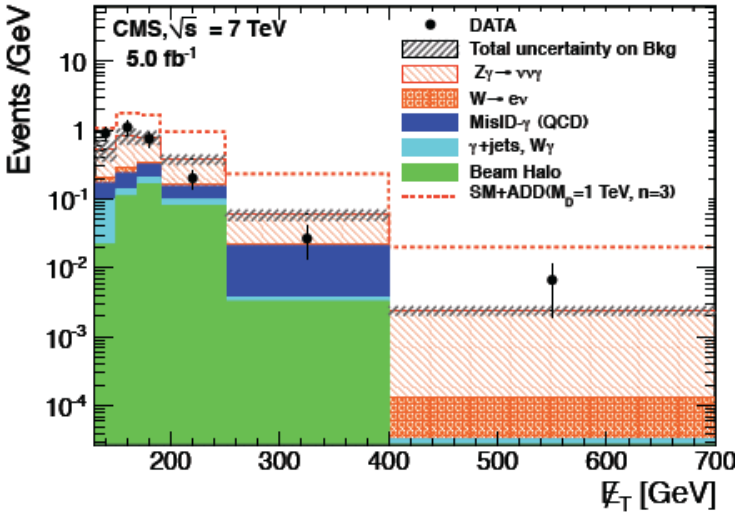
Search for dark matter: photon/jet+MET

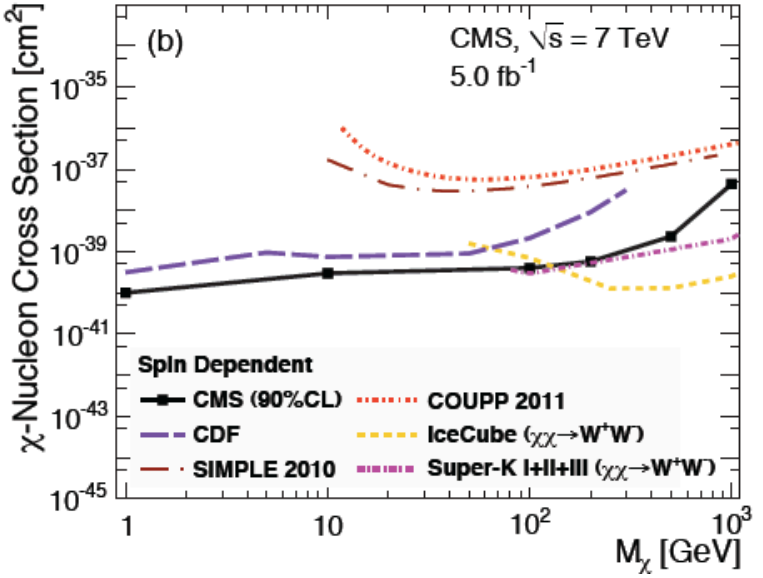
γ+MET signature from:

Extra dimensions $q\bar{q} \rightarrow \gamma G$

Dark matter $q\bar{q} \rightarrow \gamma\chi\bar{\chi}$





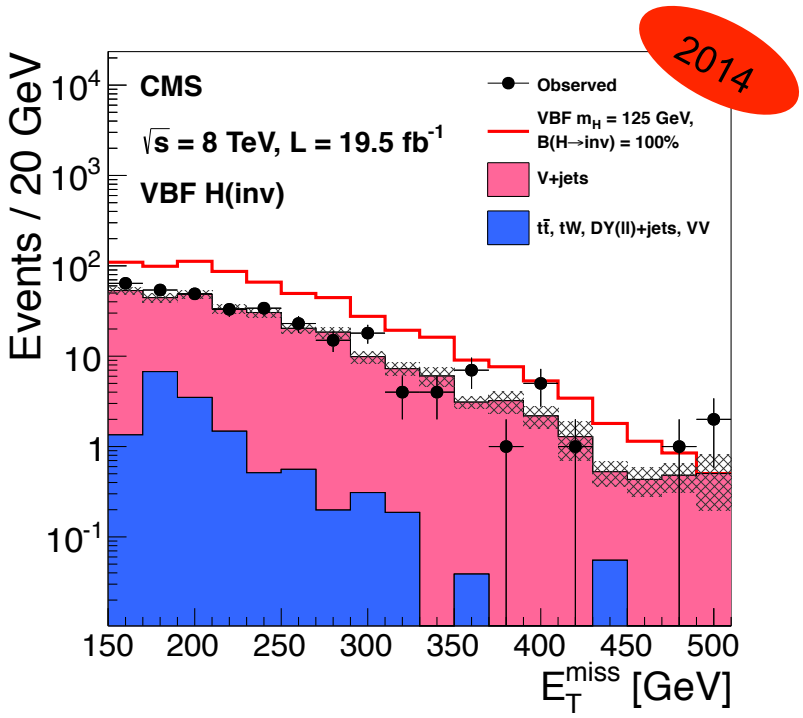


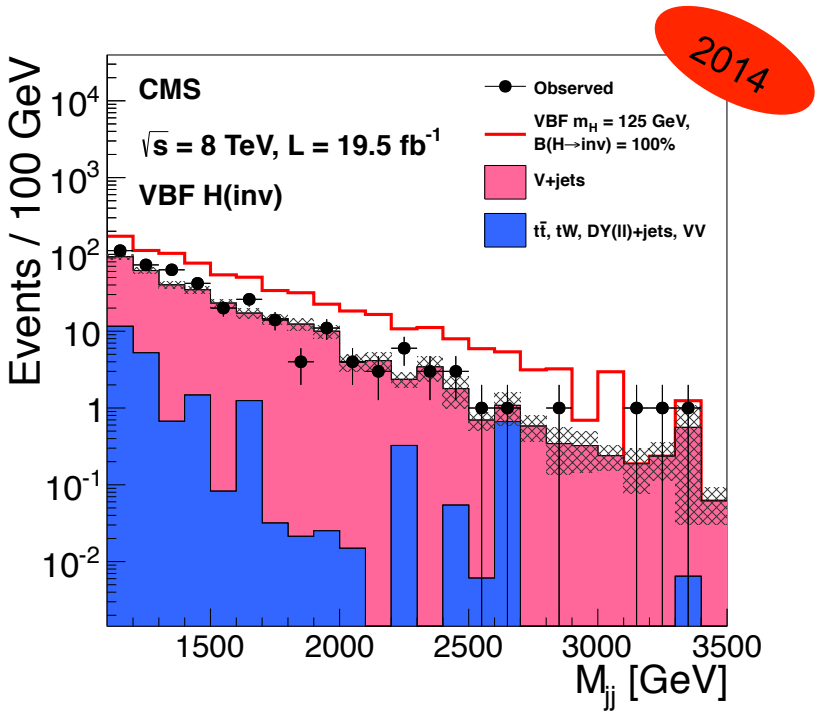
Higgs invisible decays?

M_{jj} > 1.1 TeV
$\Delta\eta_{jj}$ > 4.2
$\Delta\Phi_{jj}$ < 1
MET > 130 GeV
lepton veto pT > 10GeV
central jet veto pT > 30 GeV

Expected 210+-30 evts if BR~100%
=> Would be clearly visible above bkg

⇒ Proof of principle for VBF to nothing search strategy!

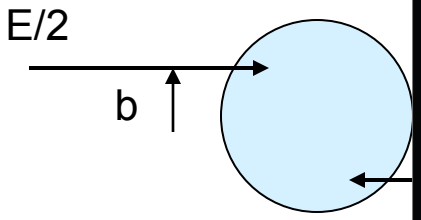




Black Holes?

Search for BHs

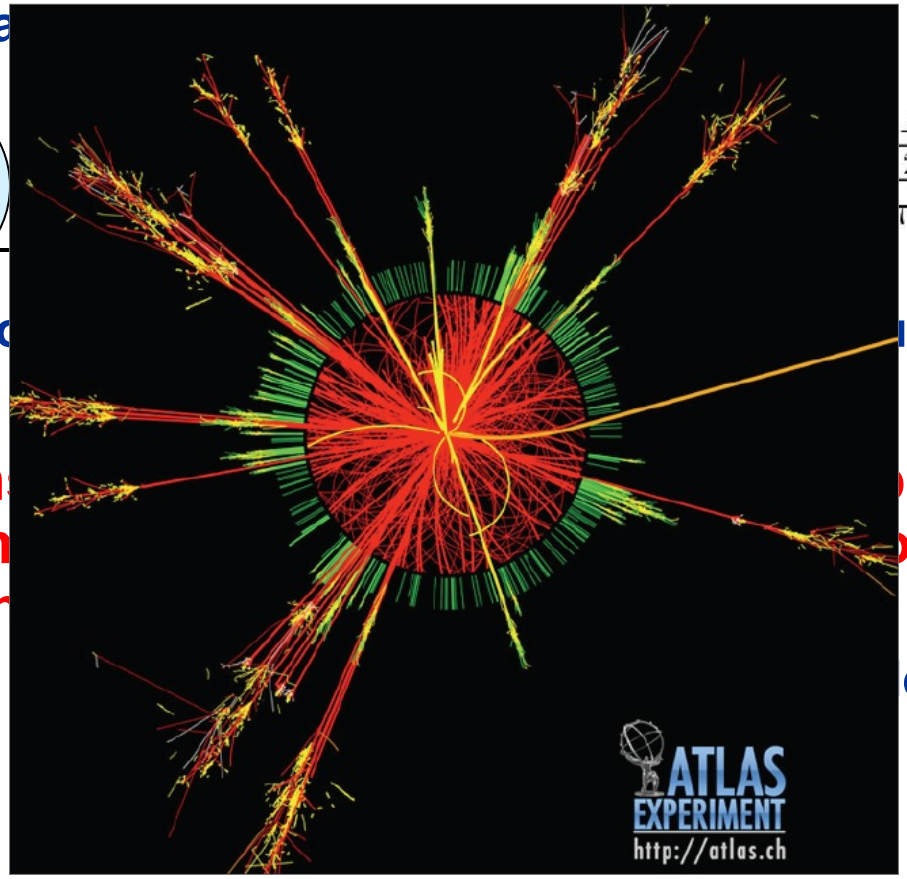
- **THE signature of low-scale quantum gravity (M_D << M_{Pl})**
  - **BH formation when the two colliding partons have distance smaller than R_s,, the Schwarzschild radius corresponding to their invariant ma**



$$\left[\frac{\frac{n+3}{2})}{\pi^{(n+3)/2}}\frac{M_{BH}}{M_*}\right]^{1/(n+1)}$$

  - **Cross sectio** **p to ~100 pb!)**

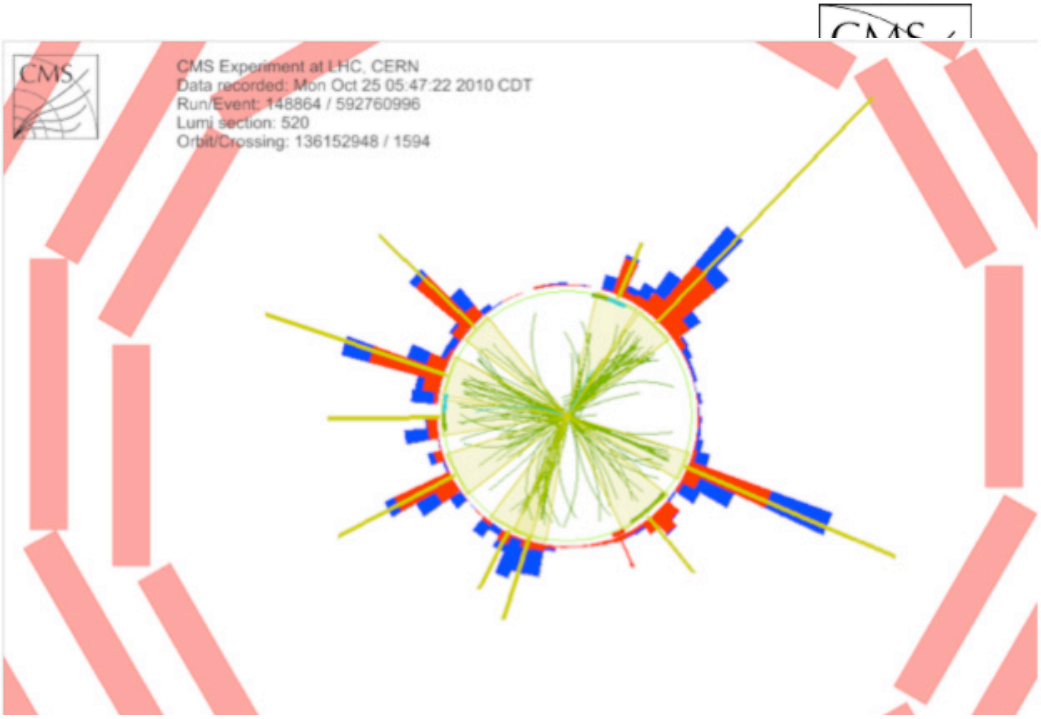
- **BHs decay in** **oration emitting "den** **f energetic quarks, gluor**
  - **Contrary to** **el-dependent)**



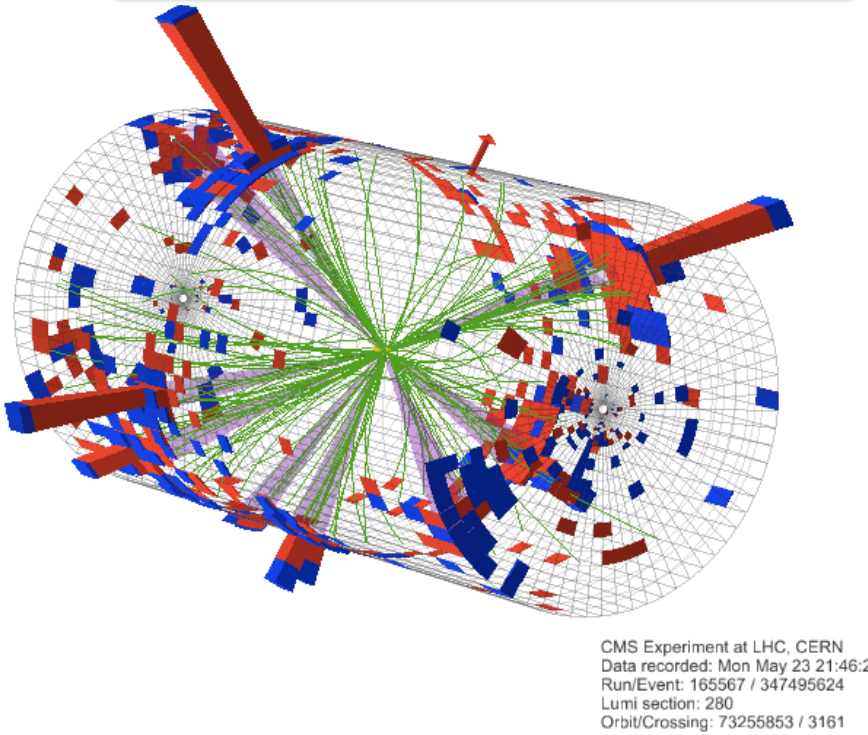
Search for micro-BH

- **Expect lots of activity in the event, so**
  - **Use S_T = Sum E_T of all objects (including ME_T) with E_T>50 GeV.**

A candidate event with 10 jets and S_T = 1.3 TeV



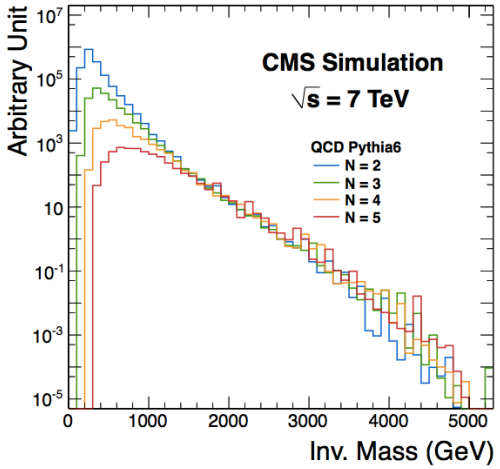
A candidate event with 9 jets and S_T = 2.6 TeV

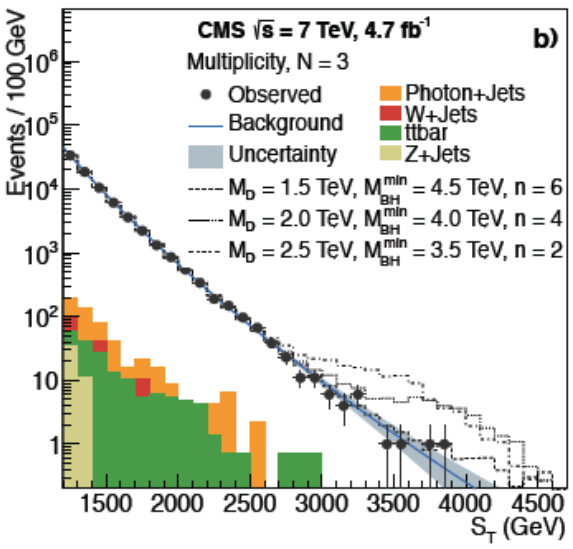


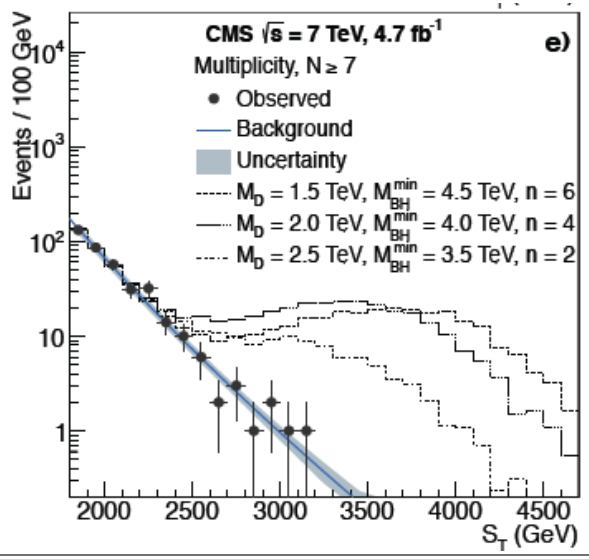
(Null) search for BHs

arXiv:1012.3375

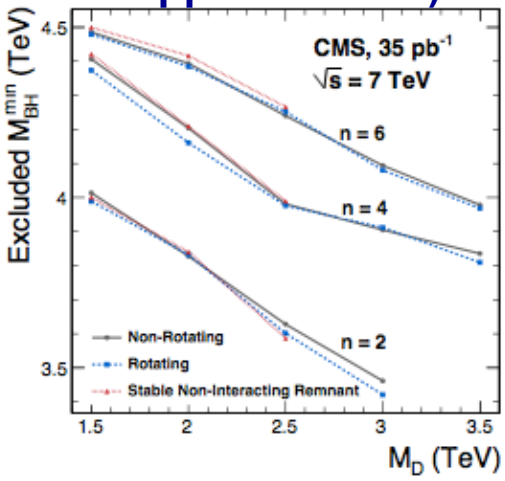
- Expect lots of activity in the event, so
  - Use S_T = Sum E_T of all objects (including ME_T) with E_T>50 GeV.
    - Great against pileup (in the future as well)
- Key for search: S_T-invariance of final state multiplicity
  - A posteriori wisdom: FSR/ISR collinear do not affect S_T a lot
- Use N=2 shape (with uncertainties) to fit higher multiplicities – where signal more prominent





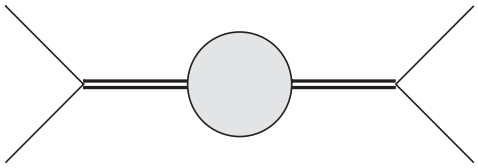


M_{BH}> 3.8-5.3 TeV (semi-classical approximation)

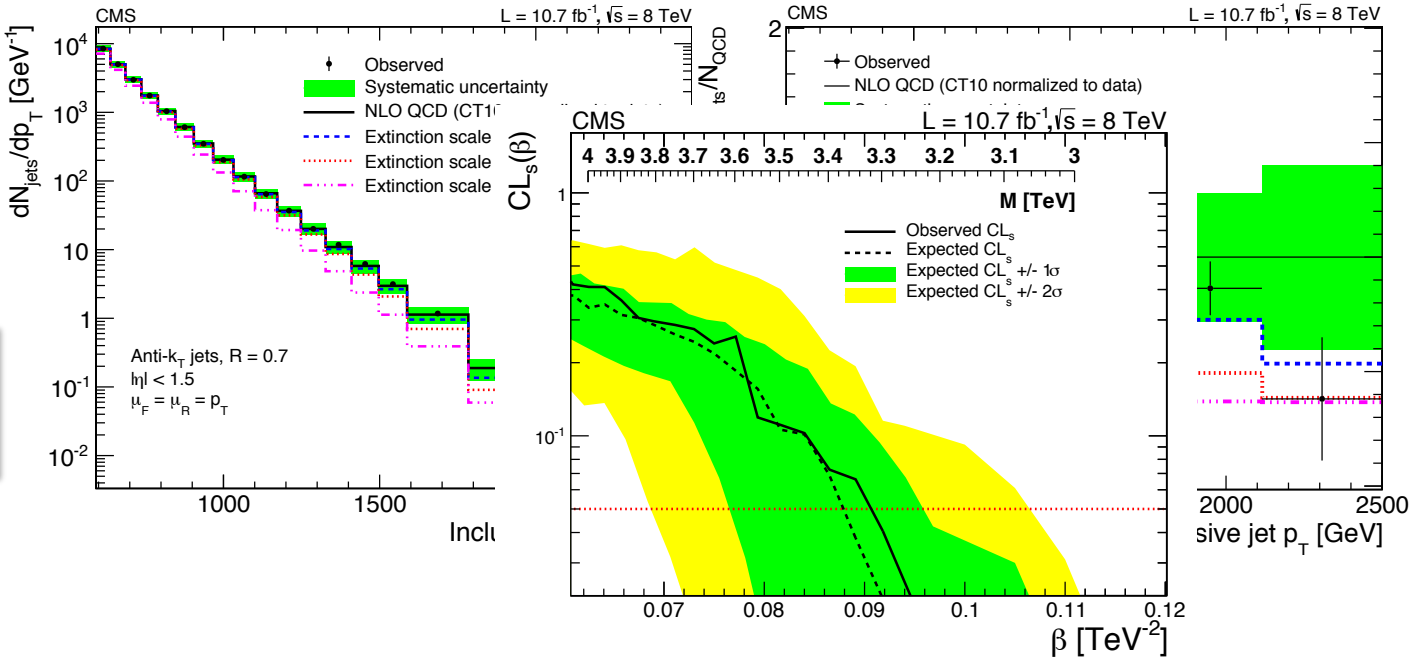


Jet extinction?

- **Production of either black holes or other non-perturbative quantum gravity effects can have rapidly increasing total cross section beyond some scale ~ Λ**
  - **Their decay to low-multiplicity final states could be thermally suppressed. Leads to effective extinction of high-pT SM scattering**

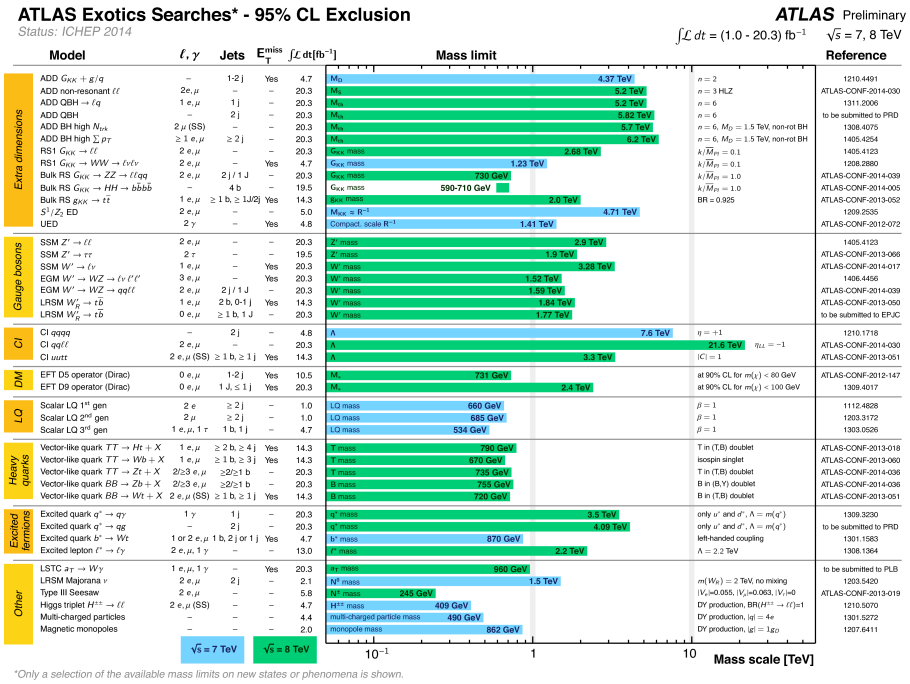


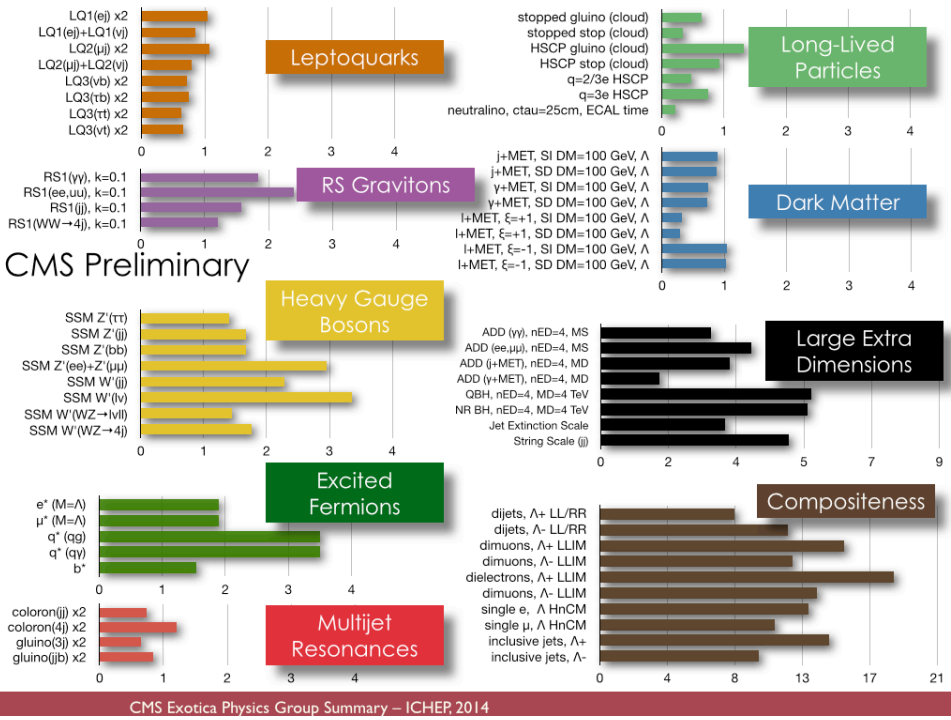
Basic QCD 2→2 process modified



Summary [2/3]

Searches for BSM physics





Summary [2/3]

- **First set of searches today: hadronic channels**
  - Jet resonances, jet angular distributions, probing compositeness [nope]
  - New contact interactions [nope]
- **Second set of searches today: "exotica" channels**
  - Searches for new gauge bosons [nope]
  - Searches for other signs of etxra dimensions [nope]
  - Searches for leptoquarks [nope]
  - Mono-objects, for a signature from "extra dimension physics" or dark matter [nope]
- **Next [and final for these lectures] stop: SUSY searches**