Search for Exotic Physics at the LHC

Results from Atlas and CMS Experiments

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GUAYASAMIN
12/11/2012

one of the things I discovery this week here in this venue

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Oswaldo Guayasamin
(Ecuadorian Painter)
Madre y niño
(Mother and son)
1992

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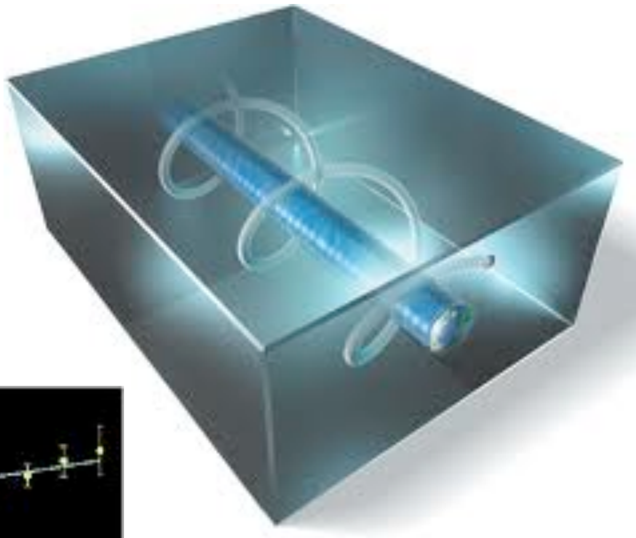
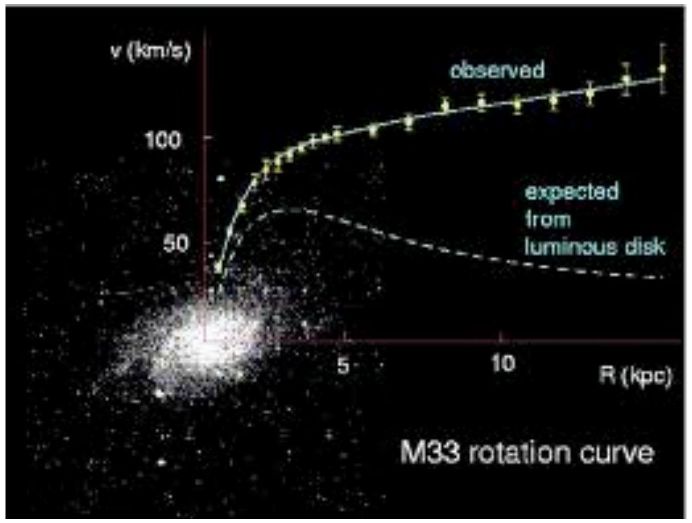
Where is the

NEW PHYSICS!

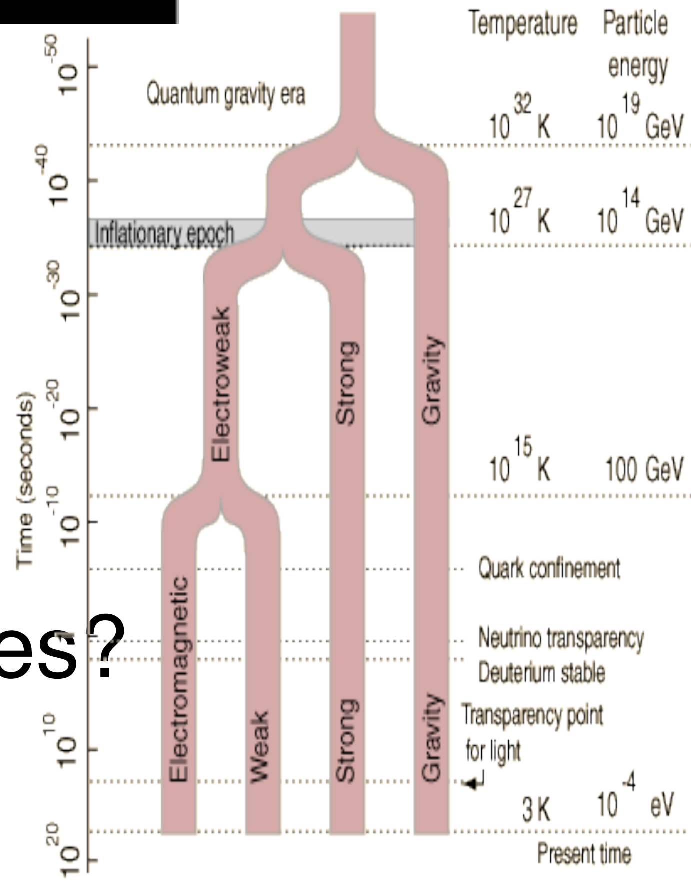
Questions Beyond the Standard Model (SM)



- Are there extra dimensions?
  - ADD (Arkani-Hamed, Dimopoulos, Dvali), RS (Randall-Sundrum), UED (Universal extra dimensions)



- Are there additional quarks?
  - Fourth generation quarks t', b', ...
- Are there right-handed neutrinos?
  - Massive neutrinos ...
- What is Dark Matter?
- Is there a Unification theory?
- Are electrons and quarks the fundamental particles?



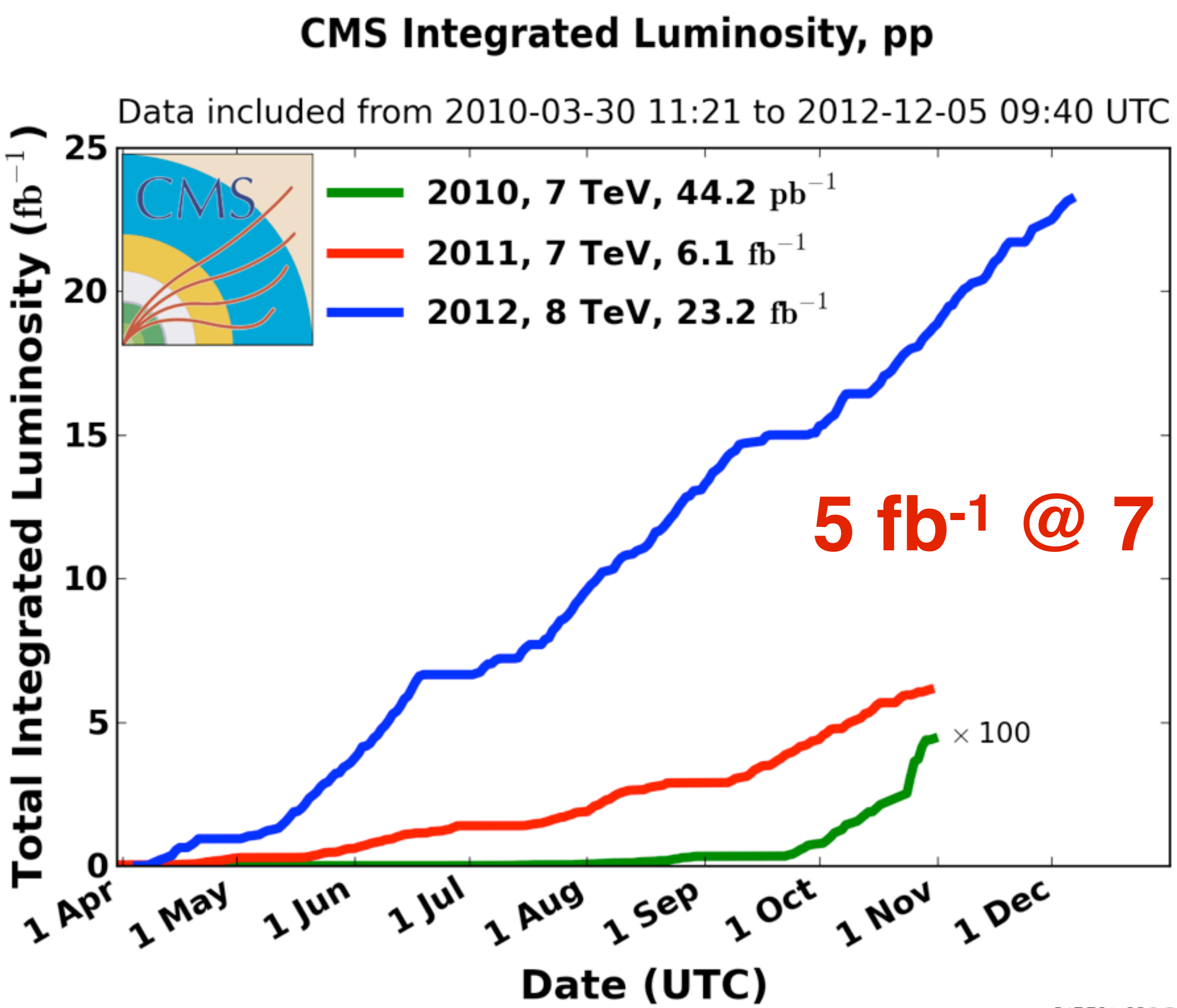
Many, Many, Many Searches

- Classical Resonance Searches:
  - Dijet, dilepton, lepton-neutrino, diphoton, multijet, photon-jet, diboson, ditau, ditop, top-bottom ... final states
  - interpret in various models, sequential SM, E6, RS gravitons, ADD, axiguons, sequential SM, technicolor
- Resonance Searches using boosted techniques.
- Black Holes
- Heavy Neutrinos
  - Right-handed WR bosons, heavy neutrinos N arise from L-R symmetric extensions of the SM
- Leptoquarks
- 4th generations (new quarks)
- Searches involving top quark
- Dark Matter
- Long-lived particle: Hidden valleys.

Outline

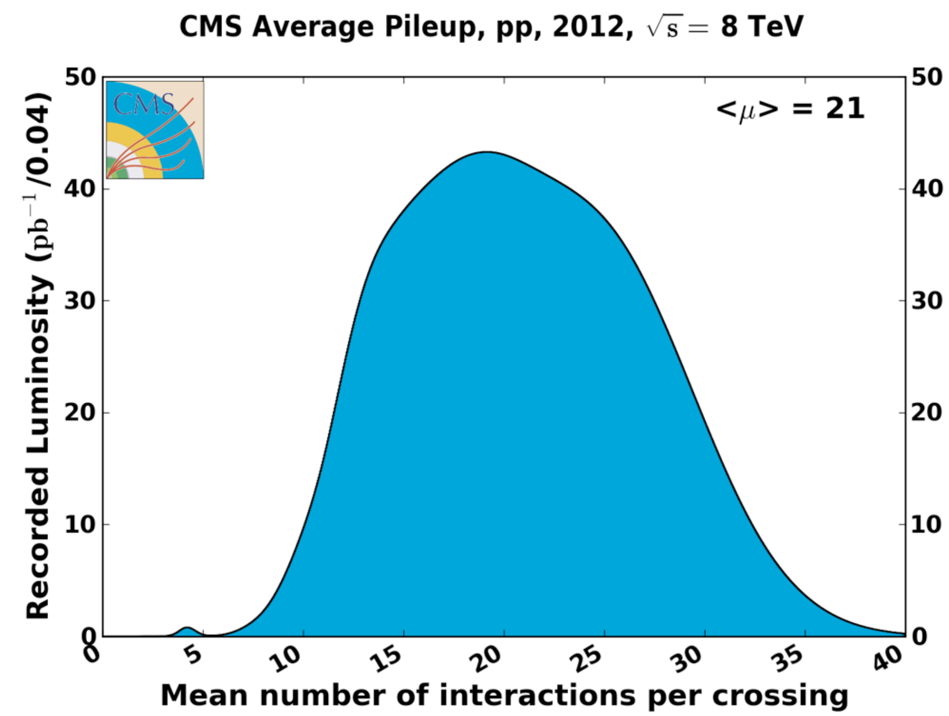
- The LHC is embarked upon the journey to discovery new physics.
  - Excellent performance of the detectors and the LHC. 
  - However, only limits for the moment. 
- Some of the latest and greatest results (~14) from CMS and Atlas will be presented here with some personal bias.
  - Too many results to fit in this talk.
- References and more detailed results can be found
  - CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
  - Atlas: https://twiki.cern.ch/twiki/bin/view/AtlasPublic

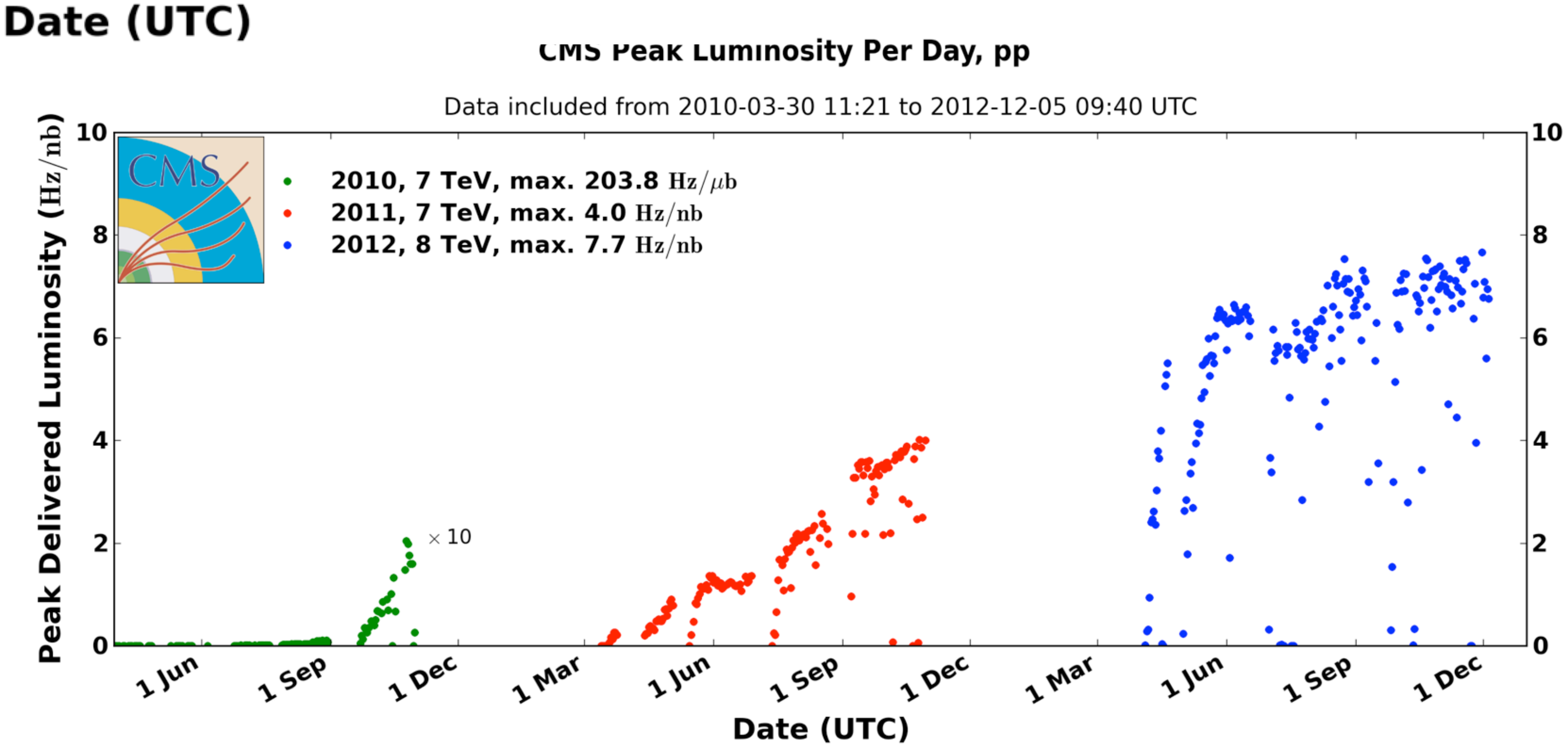
Status of CMS and ATLAS



~20 fb^{-1} @ 8 TeV (2012)

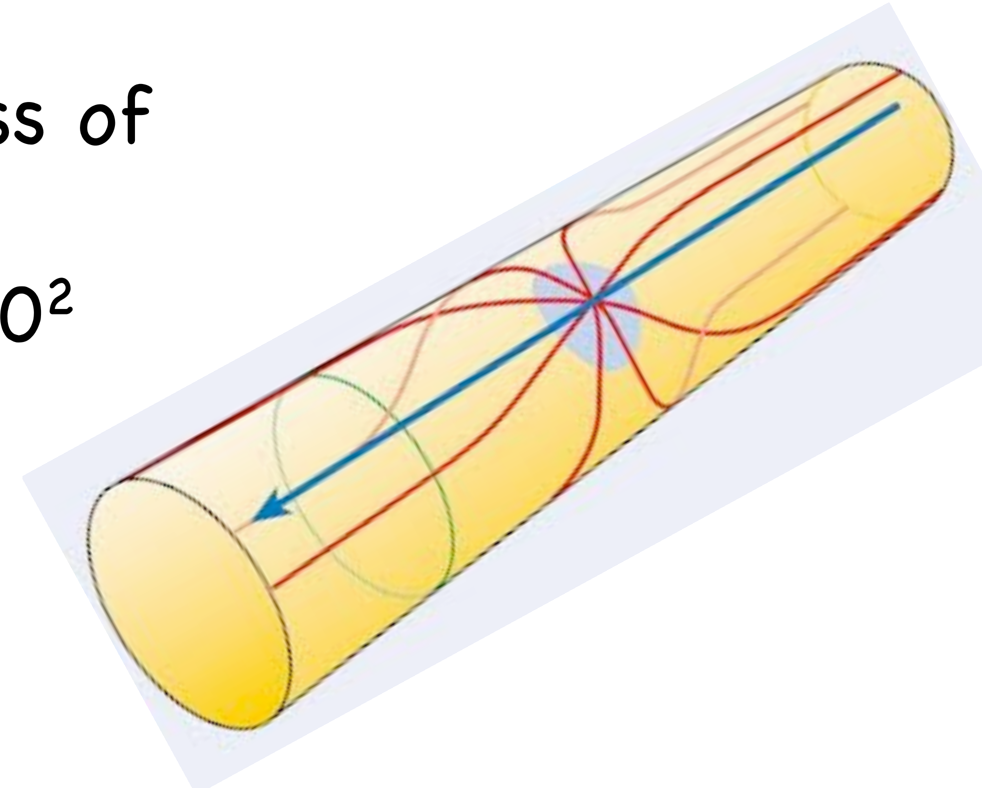
5 fb^{-1} @ 7 TeV (2011)



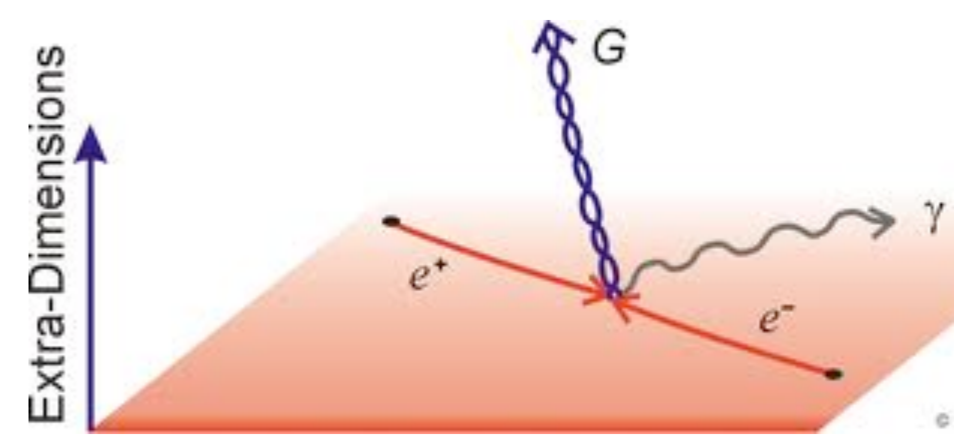


Extra Dimensions

Large Extra Dimensions: ADD model



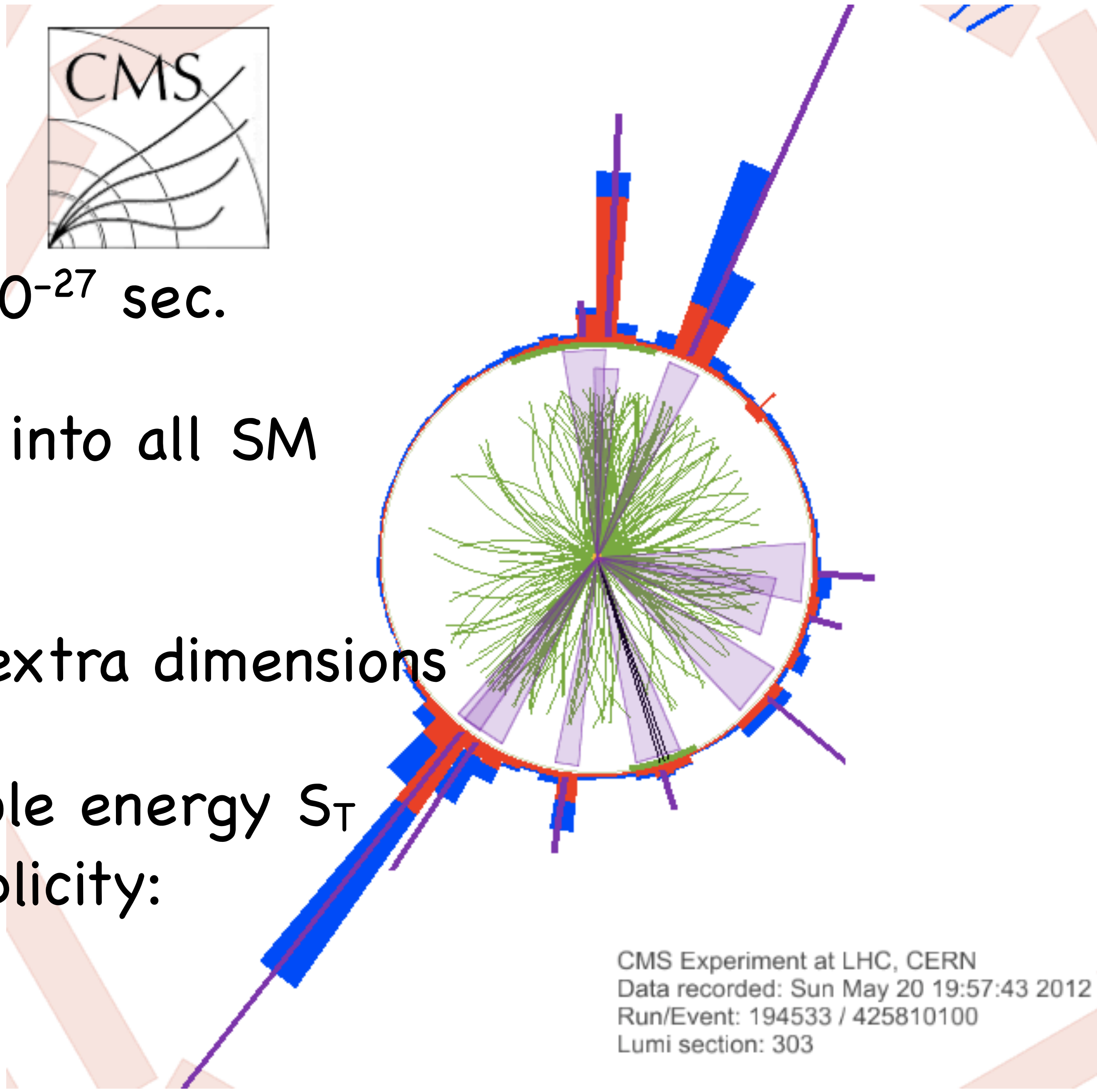
- Alternative scenario to explain the weakness of gravity relative to the other forces: the hierarchy problem: $M_{Planck} \sim 10^{19}$ GeV, $M_{EWK} \sim 10^{2}$ GeV)
- Introduces n extra dimensions in space, compactified on a n-dimensional torus or sphere with radius R
- Only gravity can propagate in extra dimensions
- Gravitation coupling enhanced at distances smaller than R
- "true" Planck scale in 4+n dimensions can be lowered to the EWK scale



Black Holes

- Microscopic Black Holes. Short-lived 10^{-27} sec.
- Thermal decay via Hawking radiation into all SM particles (75% quarks/gluons)
- Cross section up to few 10^2 pb with extra dimensions
- Search for deviation in the total visible energy S_T distribution in bins of N object multiplicity:

$$S_T = \sum_N E_T \quad \text{for jets,e,}\gamma,\mu \text{ with } p_T>50 \text{ GeV} + \text{MET}$$



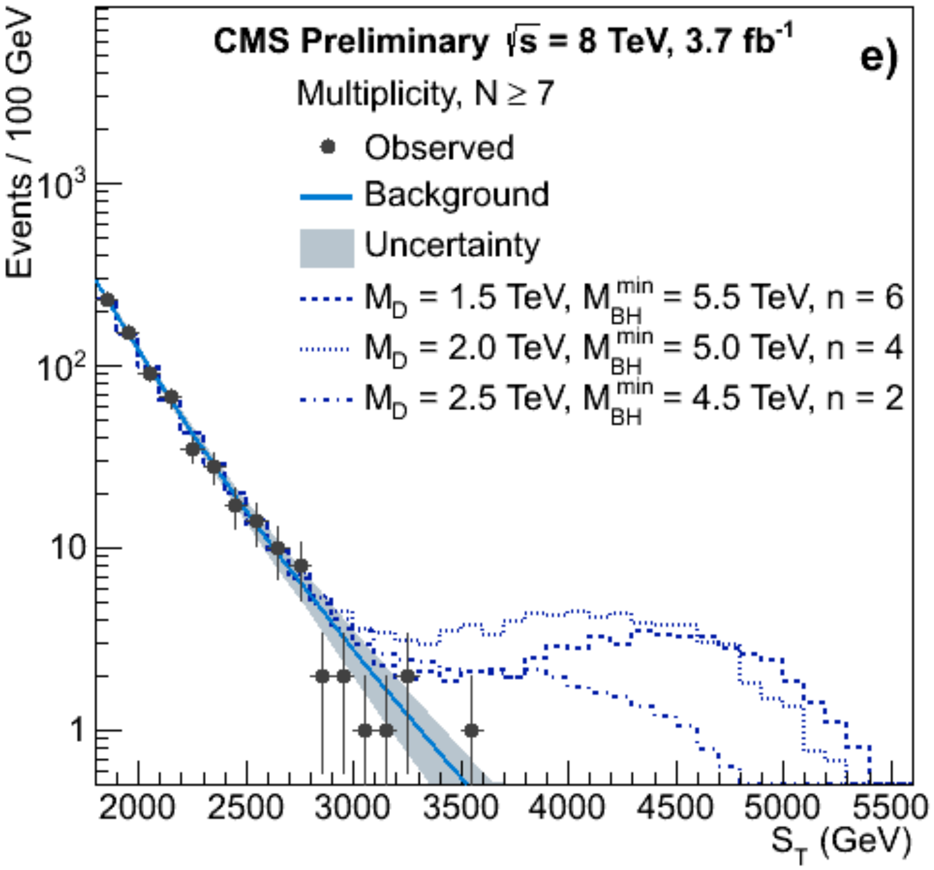
10 jets, S_T=2.7 TeV

- Sample with N=2 used to predict QCD bkg. Signal N>=3
- Set stringent model-independent limits
  - Model specific on semiclassical BH masses in the 4-6 TeV range

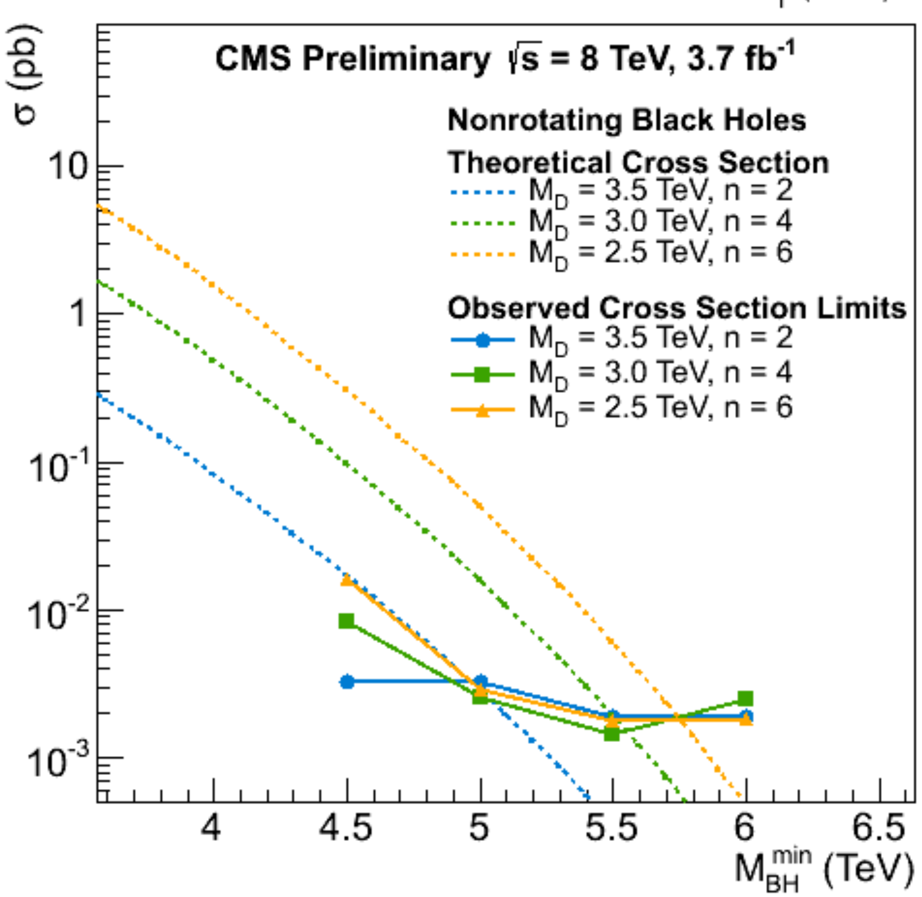
Black Holes Results

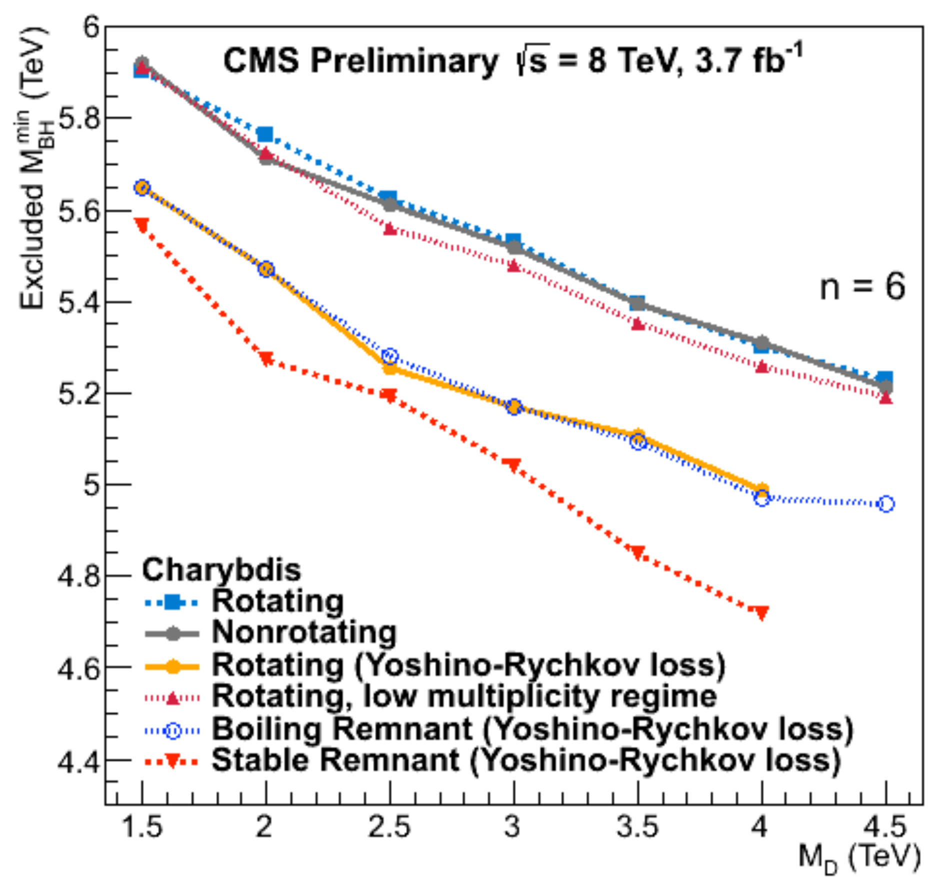
CMS-EXO-12-009

$\sqrt{s}$ = 8 TeV



- Analysis done in N object multiplicity
- Background prediction in good agreement with data
- Background dominated by multijet events is estimated from data

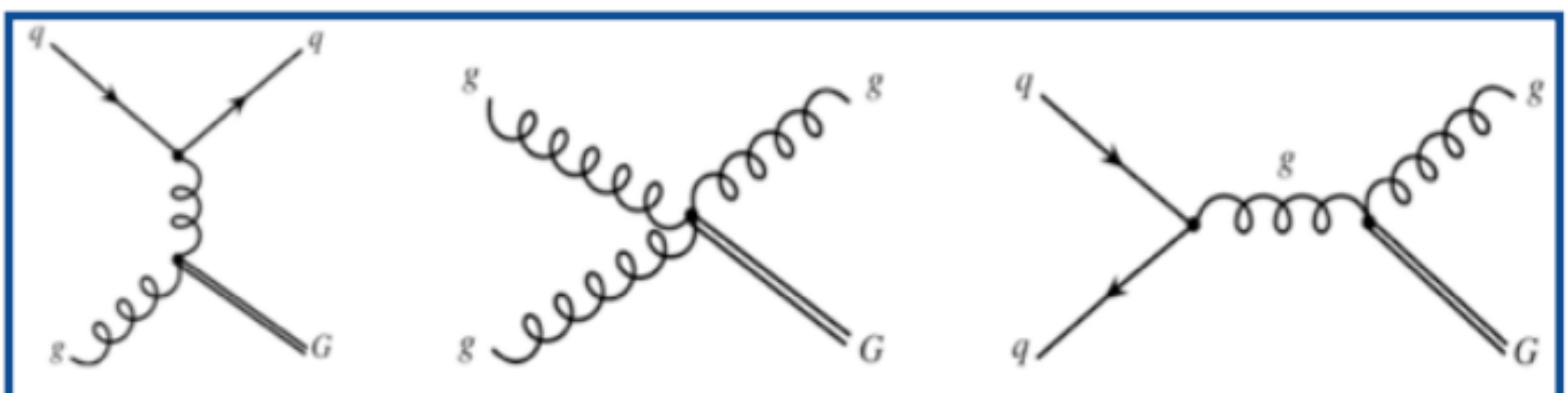




95% CL for semiclassical BH limits on M_{min}=4-6 TeV

Monojet + MET

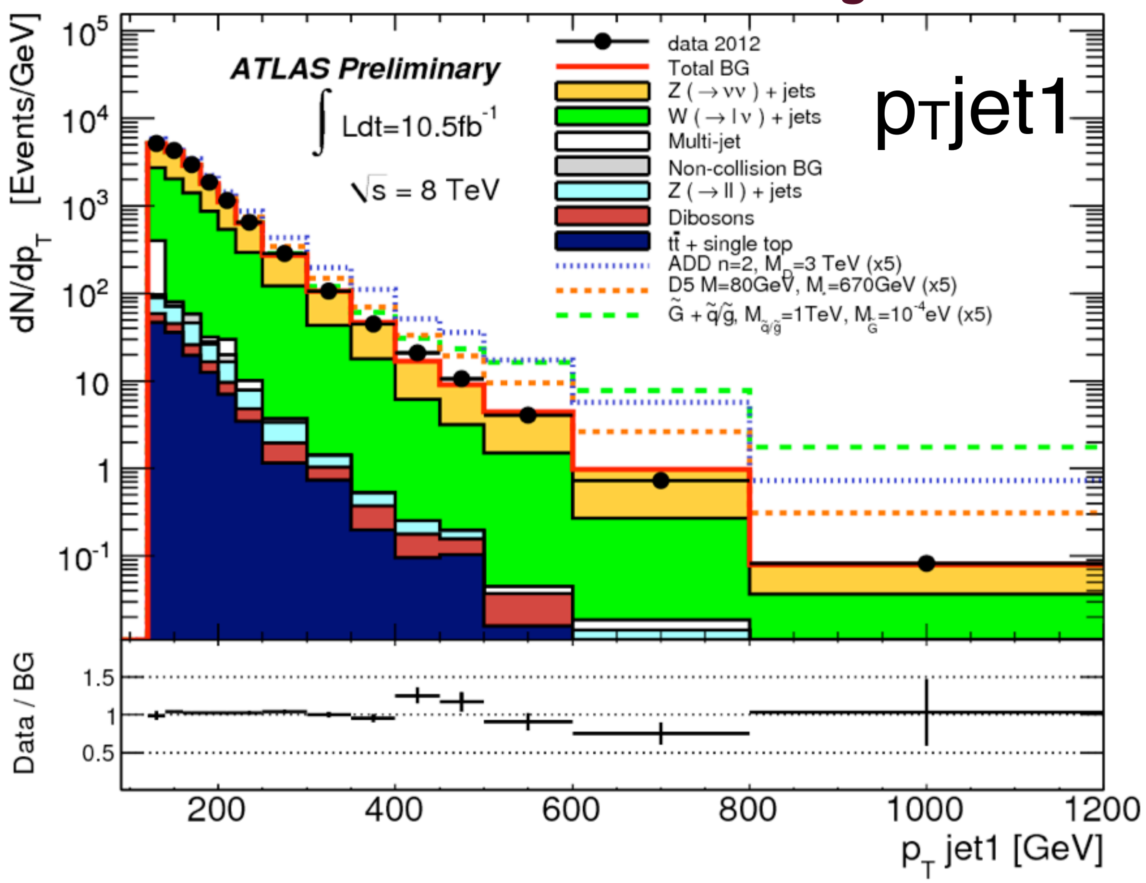
- Real and virtual production of gravitons.
  - Virtual graviton exchange, signature: diphoton, dilepton
  - Direct graviton production: $q\,\bar{q} \rightarrow gG,\ qg \rightarrow qG,\ gg \rightarrow gG,$
    - Real graviton emitted in final state
    - Signature: jet + MET



Monojet+MET Results

$\sqrt{s}$ = 8 TeV

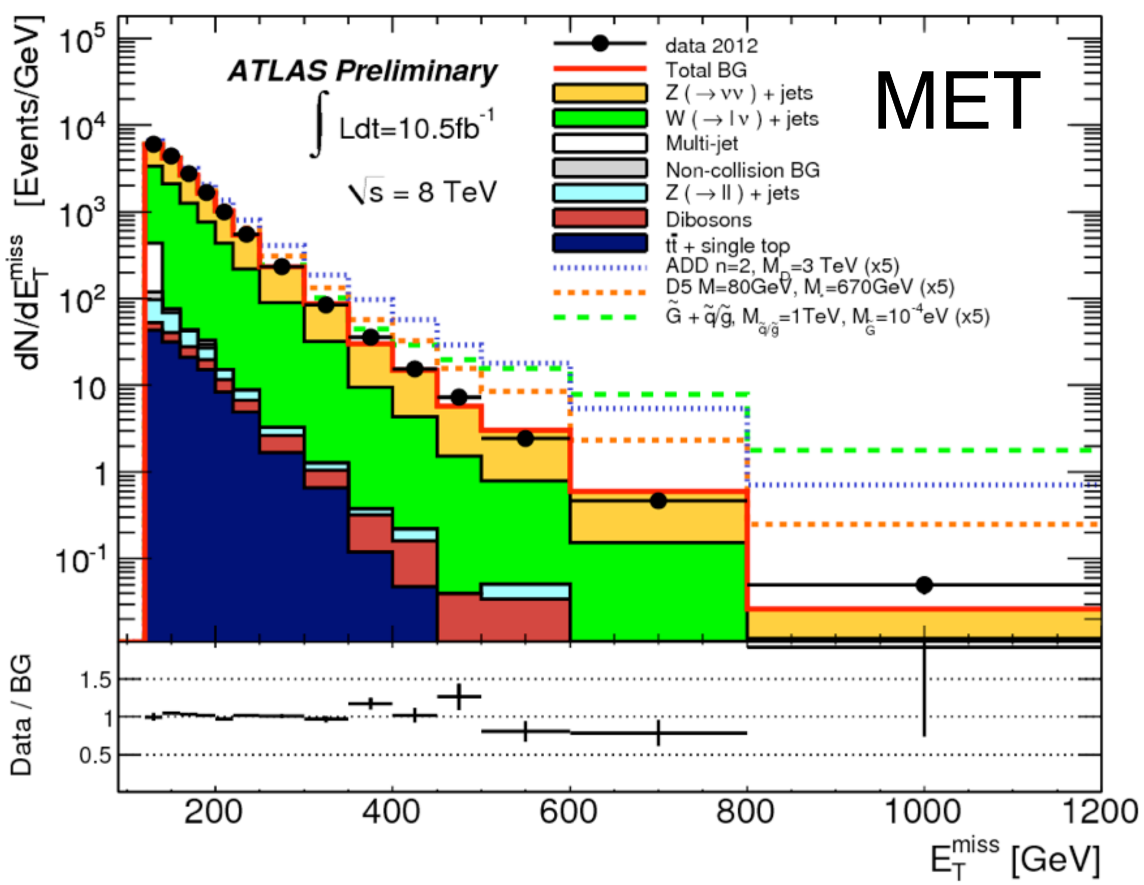
Atlas-2012-147

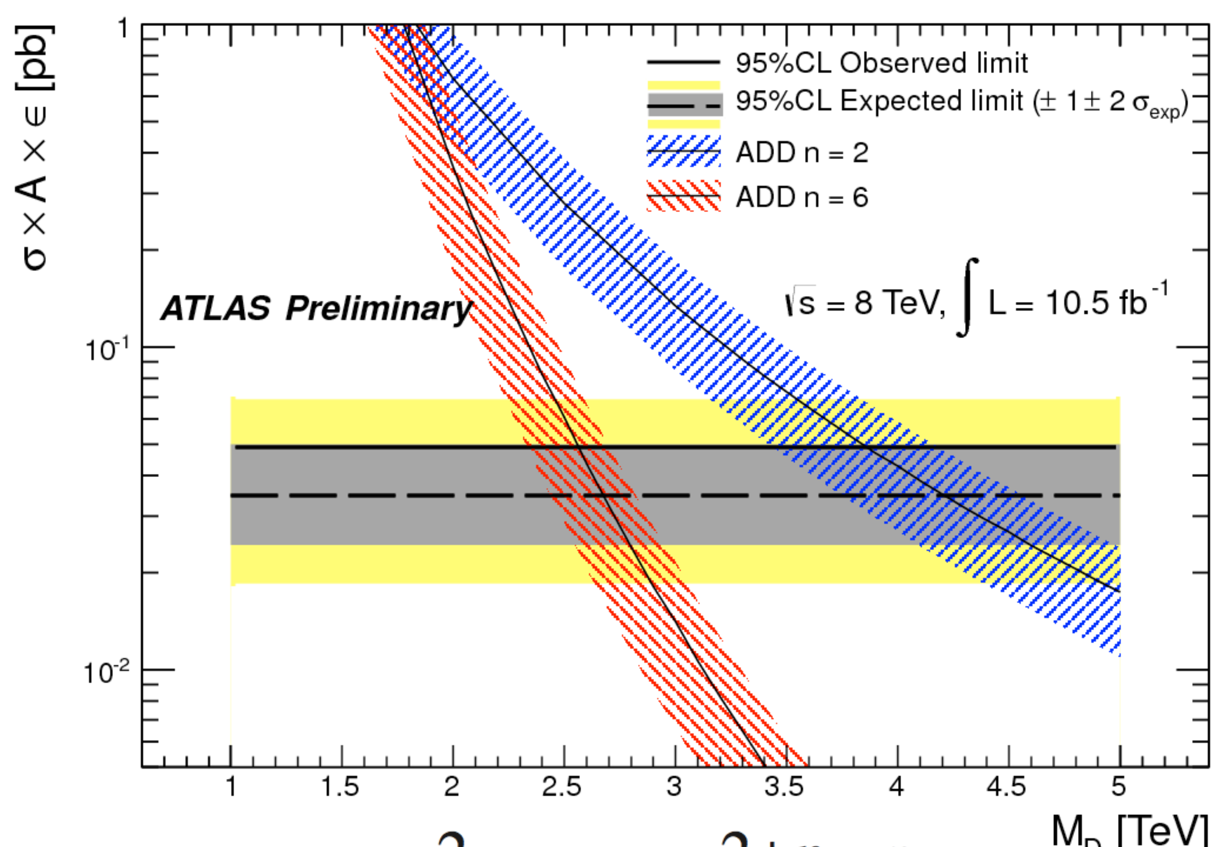


MET > 120 GeV,
leading jet p_T > 120 GeV
veto events with 2 jets p_T>30 GeV
or with muons or electrons

$$\Delta\phi(\mathrm{jet}, E_T^{\mathrm{miss}}) > 0.5$$

EWK background estimate from
data control sample with muons



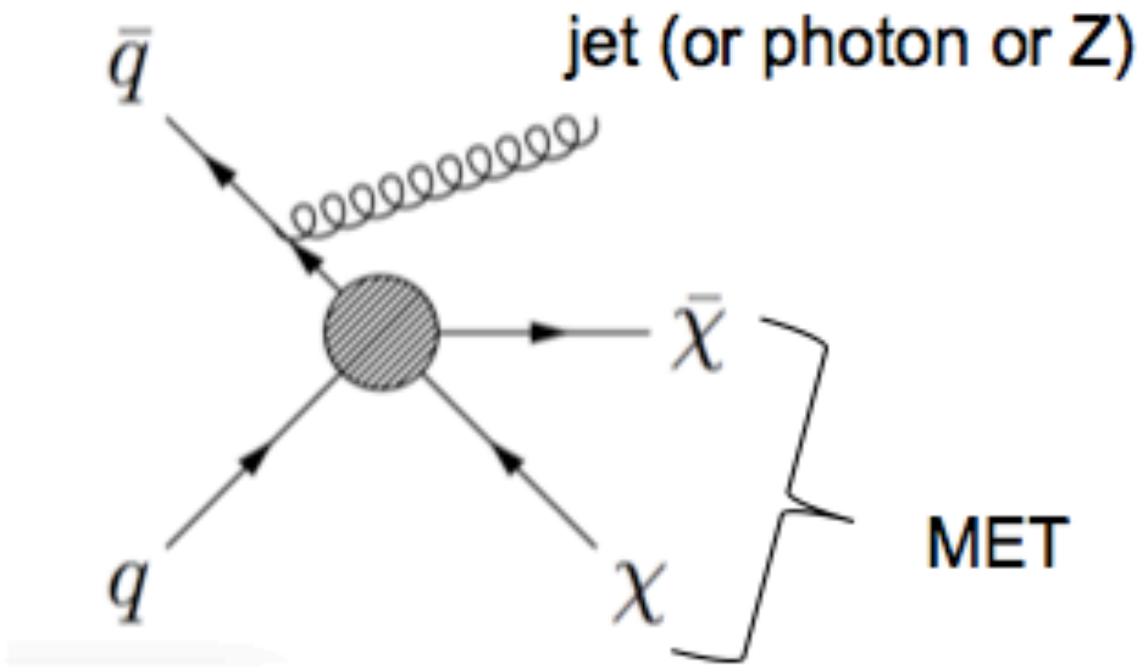


$$M_{Pl}^{\ 2} \sim M_D^{\ 2+n} R^n$$

Dark Matter

Dark Matter Search with monojet + MET

Pair production of DM (χ) particles in association with a jet (or photon or Z)



- Effective field theory with a contact interaction scale Λ:

$$\Lambda = M / \sqrt{g_\chi g_q}$$

  - M = mass of the heavy "s-channel" mediator
  - g_χ, g_q = coupling of mediator to DM / quarks

- This model provides a way to connect the s-channel χ pair-production mechanism to the t-channel χ-nucleon elastic scattering.

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

(vector s-channel) → *Spin-independent* χ-nucleon interactions

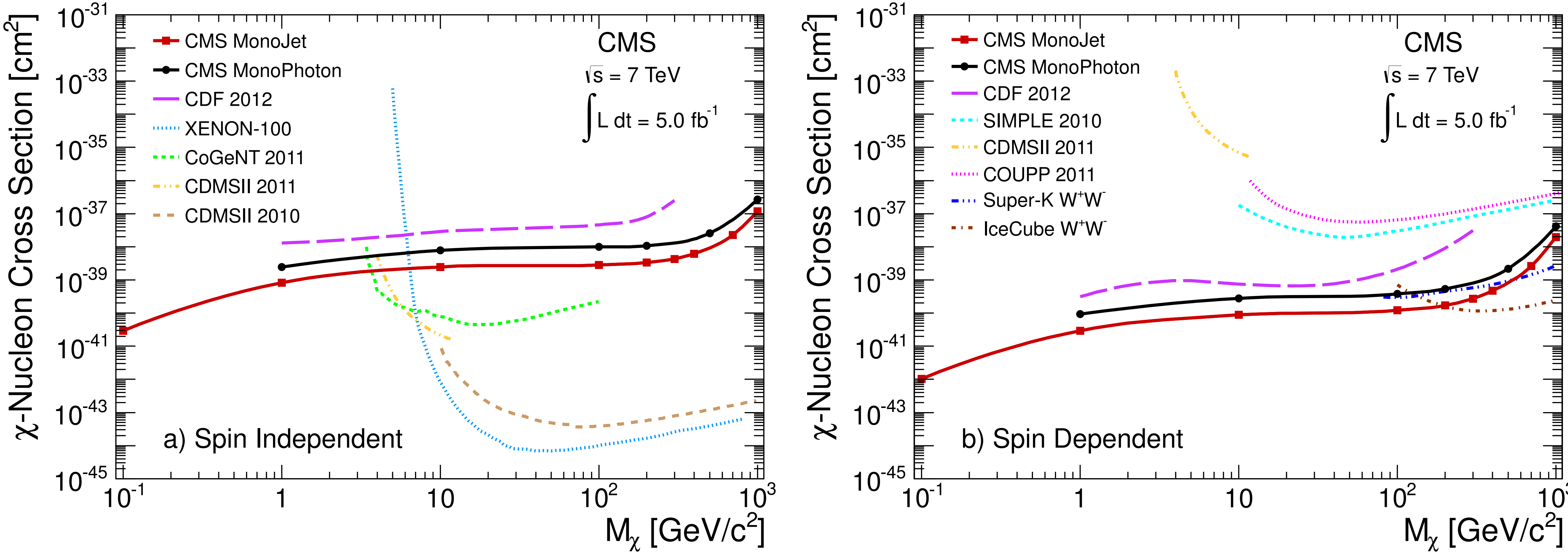
$$\mathcal{O}_A = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$

(axial vector s-channel) → *Spin-dependent* χ-nucleon interactions

Can compare collider limits from mono-X + MET searches with limits on χ-nucleon interaction from direct detection experiments (next slide →)

Dark Matter Results

CMS-EXO-11-059



- Most stringent collider limits from mono-jet searches
  - spin-independent model: limits for Mx < 3.5 GeV
  - spin-dependent model: limits for 0.1 < Mx < 200 GeV

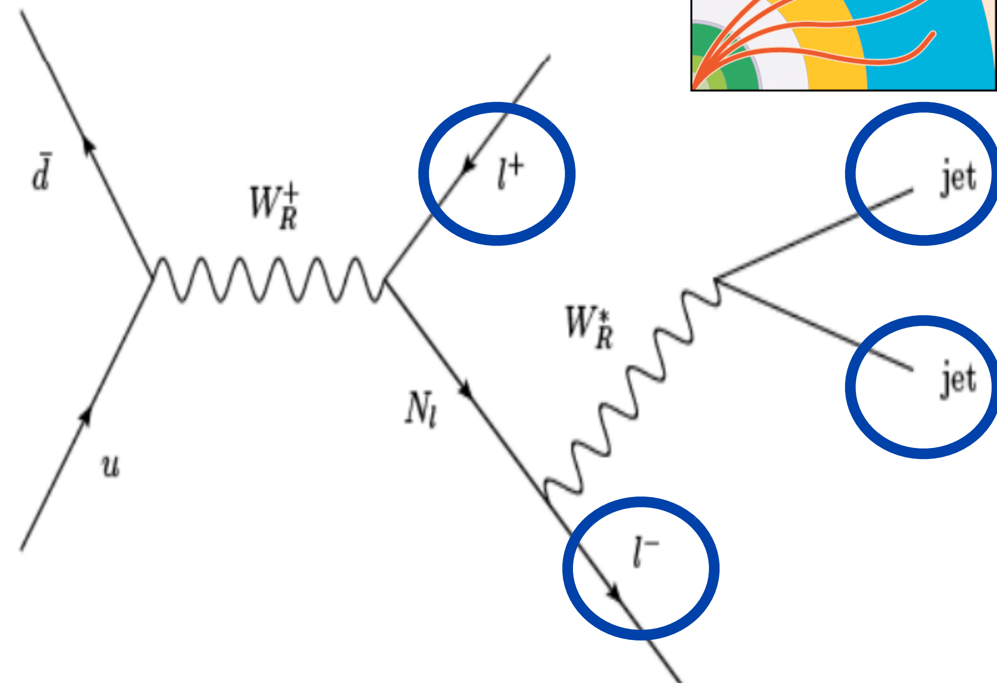
Heavy Neutrinos

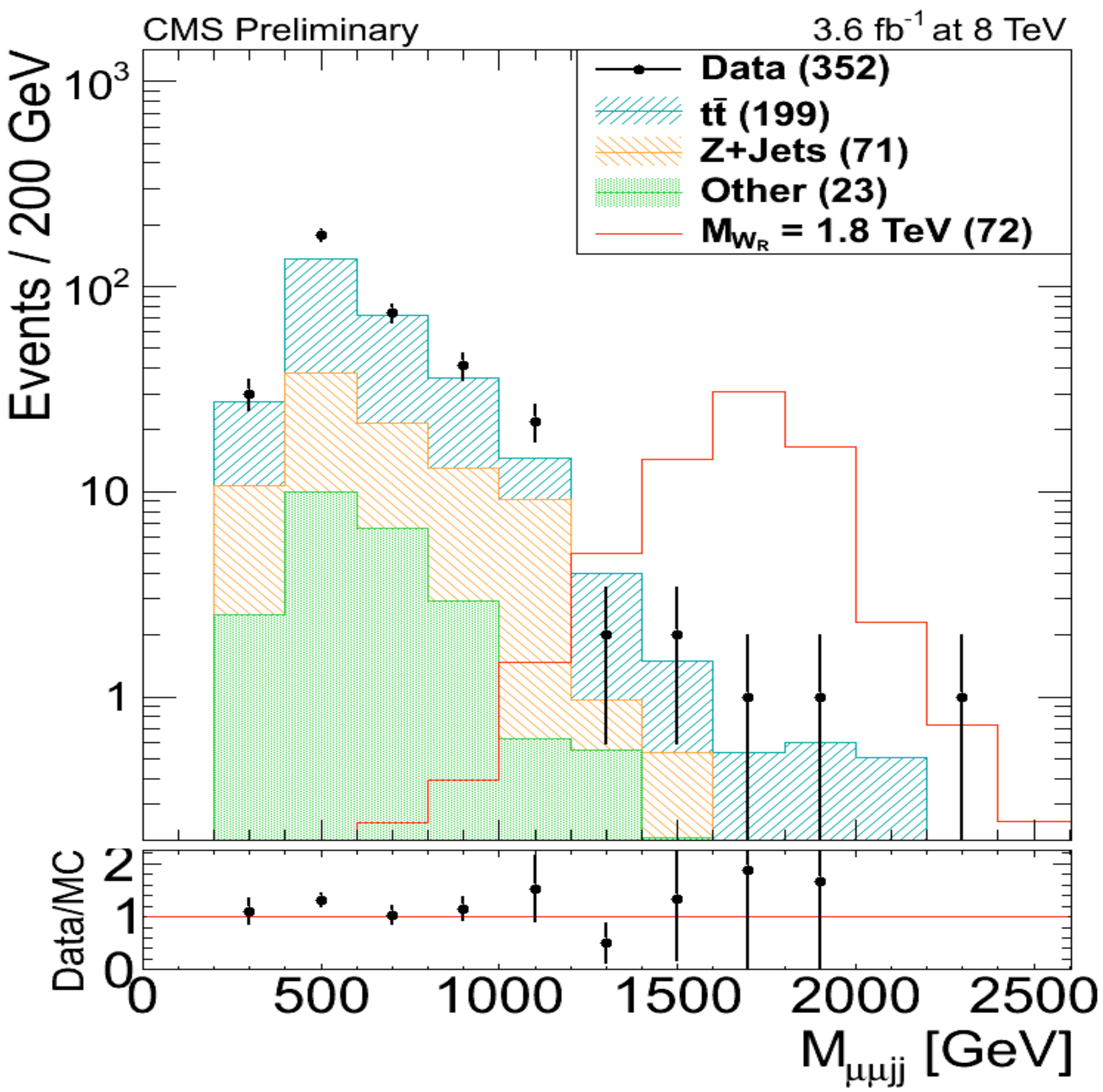
Heavy Neutrinos

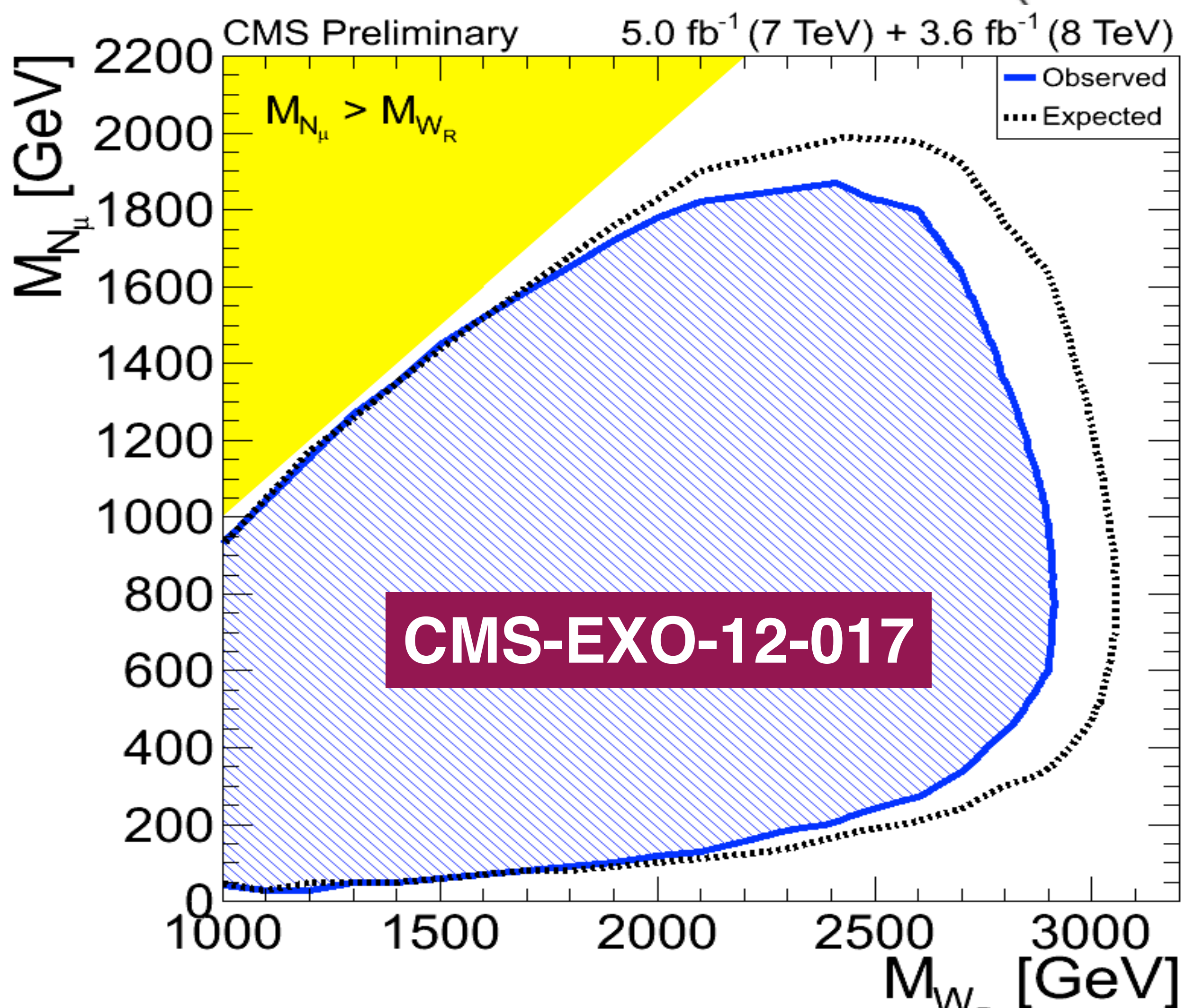
- Right-handed W_R bosons and heavy neutrinos N arise in left-right symmetric extensions of the SM.

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \qquad W^{\pm}_L, W^{\pm}_R, Z^0, Z', \gamma$$

- Final states with electrons and muons. Leptons may be same-sign (Majorana)







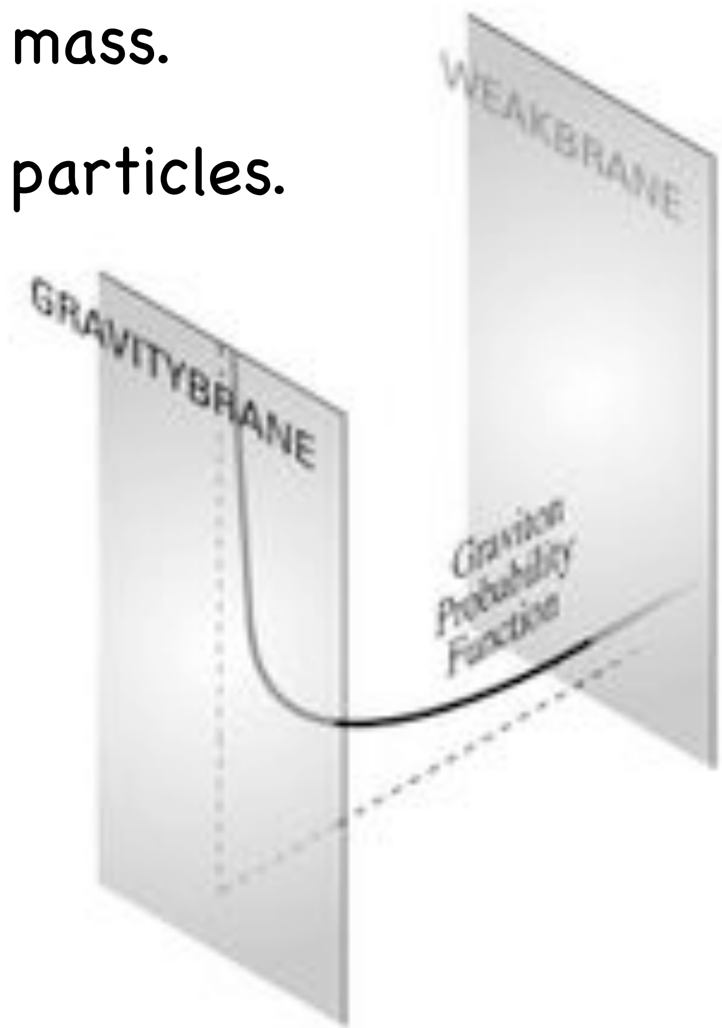
Resonance Searches

in the context of several models:
axigluons, sequential SM, technicolor,
RS gravitons, ADD

Several searches in this model: Randall-Sundrum (RS) graviton
Warped Extra Dimensions (RS Model)

RS1 model

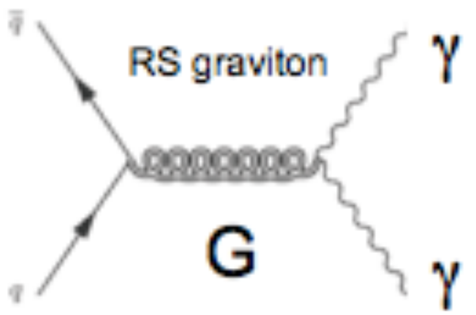
- RS1 postulates a warped 5-dimensional universe.
- SM particles on the TeV brane, graviton on the Planck brane.
- Prediction of massive spin-2 resonances, well separated in mass.
- RS graviton, the lightest resonance, couples to all the SM particles.



"Bulk RS model"

- Extension of the RS1 model.
- SM fields allowed to propagate in the extra dimension.
- 1st and 2nd generation fermions close to Planck brane.
- Explain hierarchy of fermion Yukawa coupling to Higgs.
- Coupling to ll, qq, and $\gamma\gamma$ suppressed.
- Sizable decays to top pairs and diboson final states.

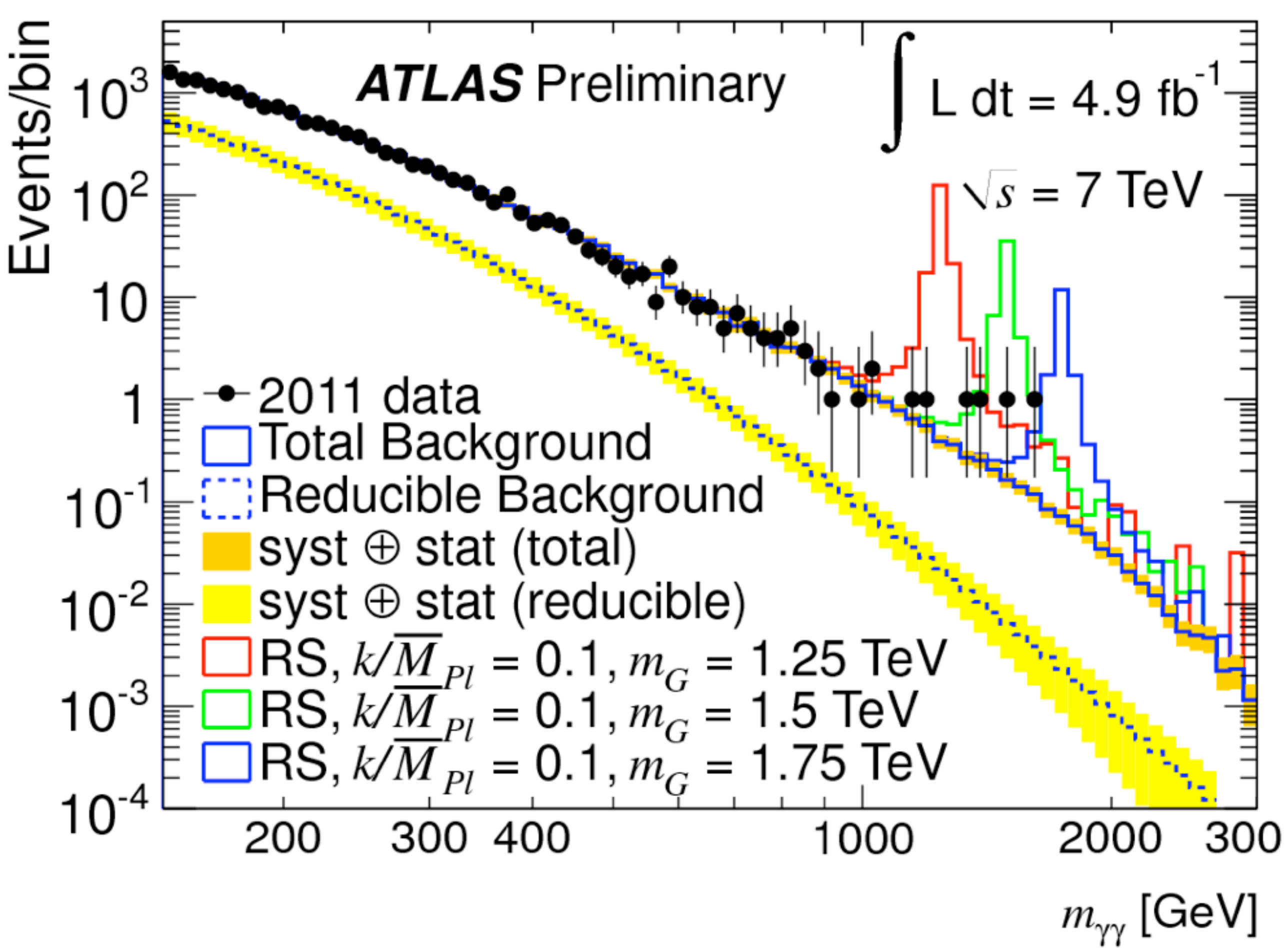
Diphoton Events

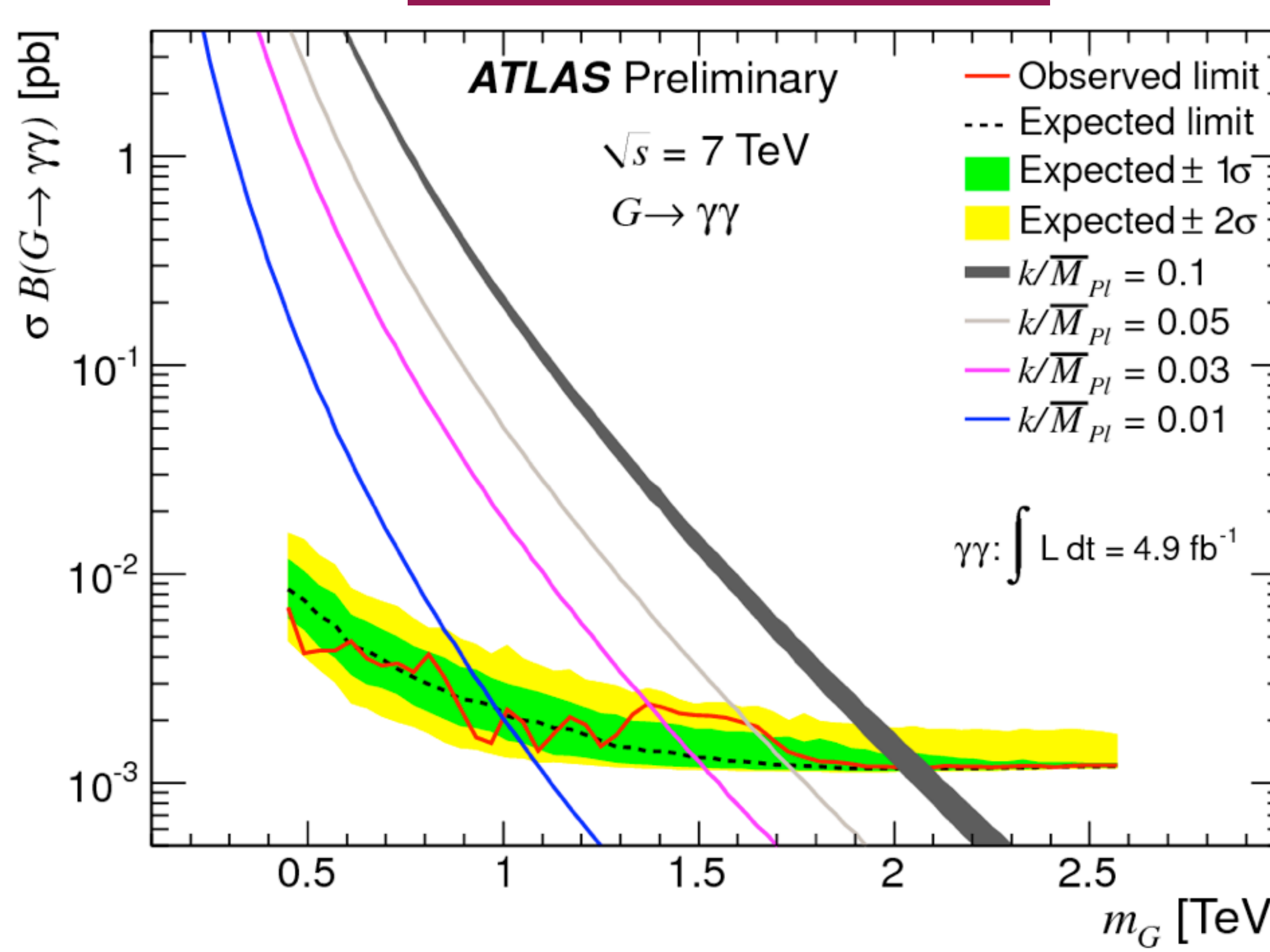


RS model parameters:
m_G = graviton mass
k/M_{Pl} = coupling

- Observable is the diphoton invariant mass. Look for excess in the high tail.
- Irreducible diphoton bkg shapes from MC (reweighted by NLO factor)
- Reducible photon+jet, dijet bkg shapes from data.
- Low-mass region (<400 GeV) for bkg normalization.
- No significant excess in data.

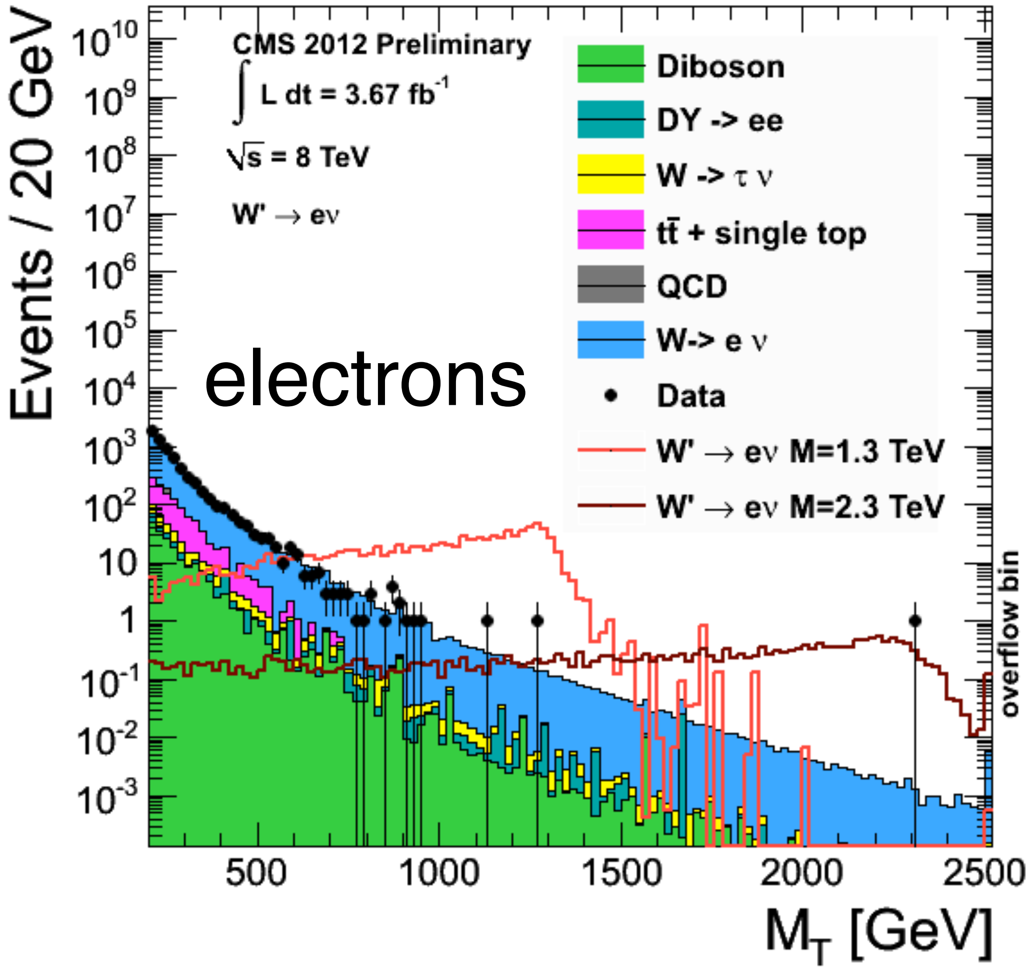
Atlas-2012-087

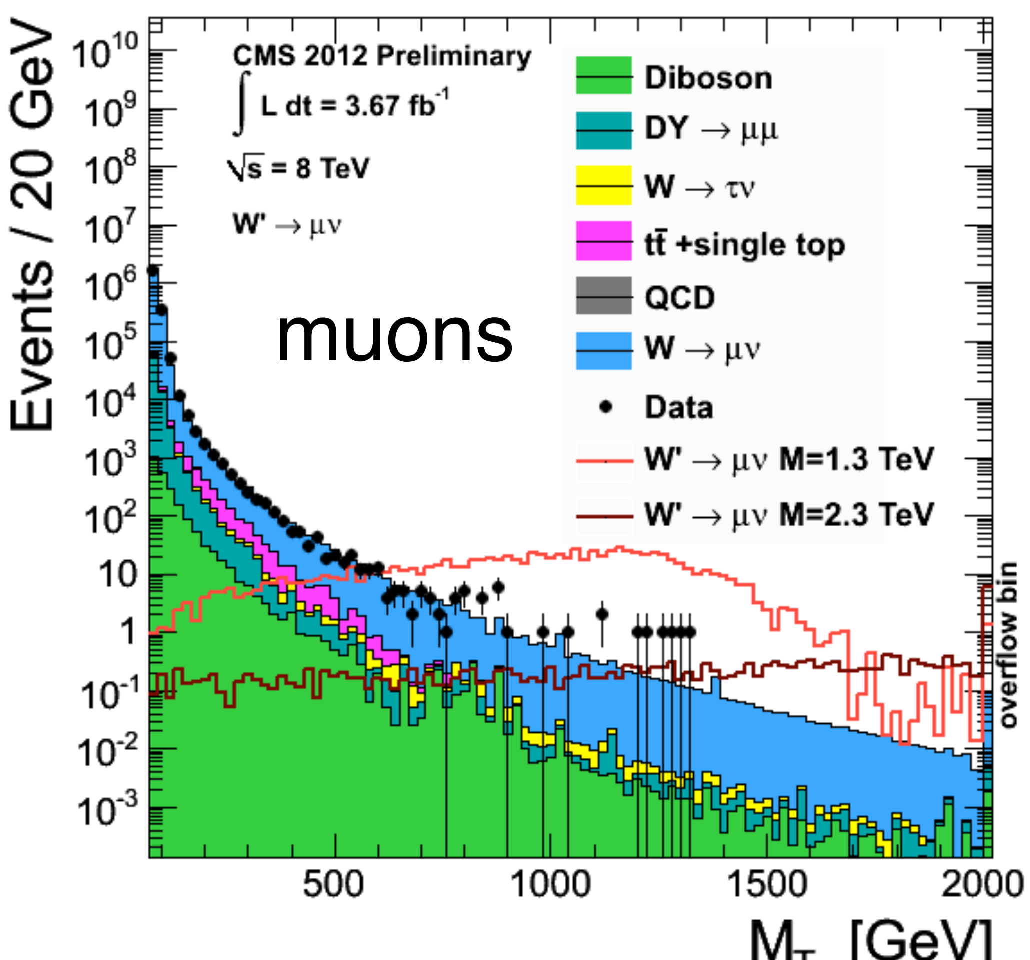




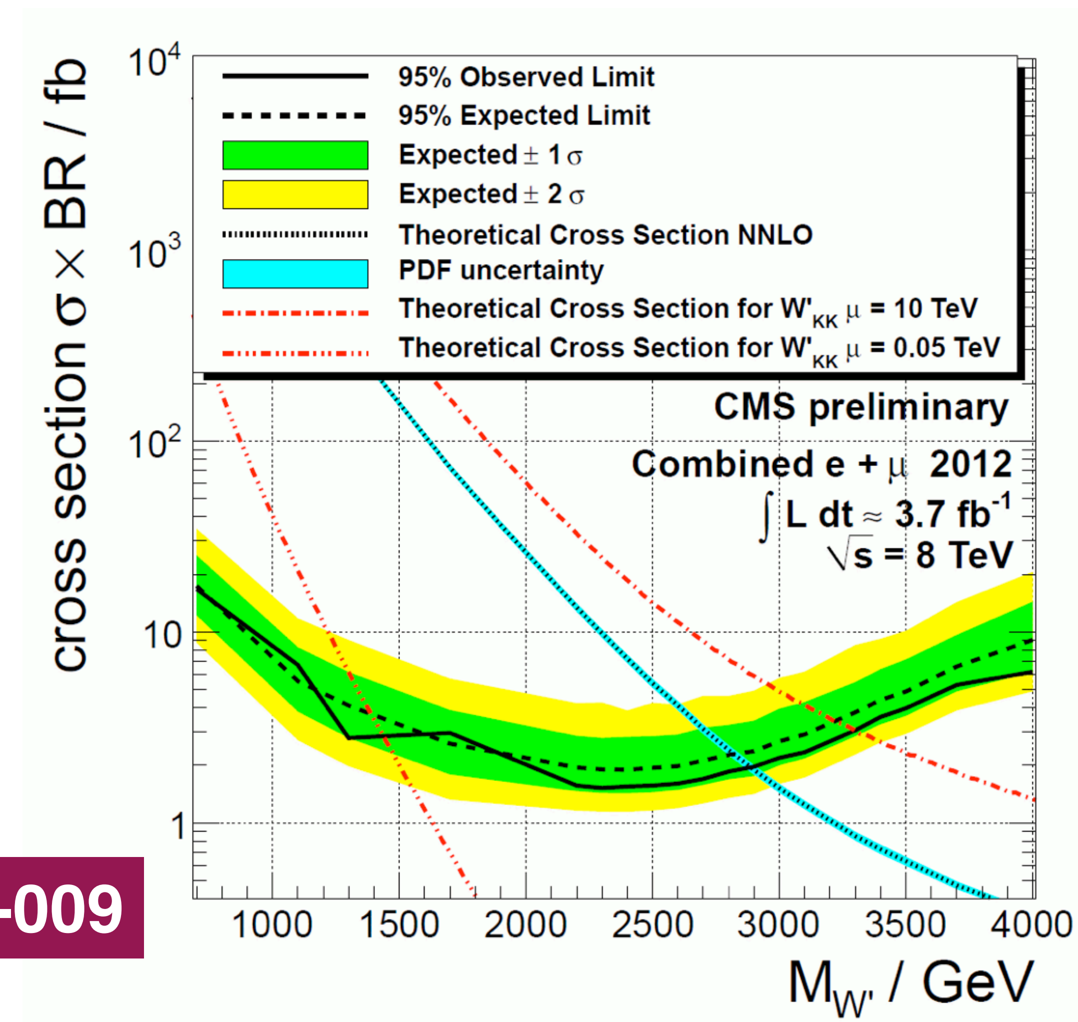
W’ → lν

√s = 8 TeV



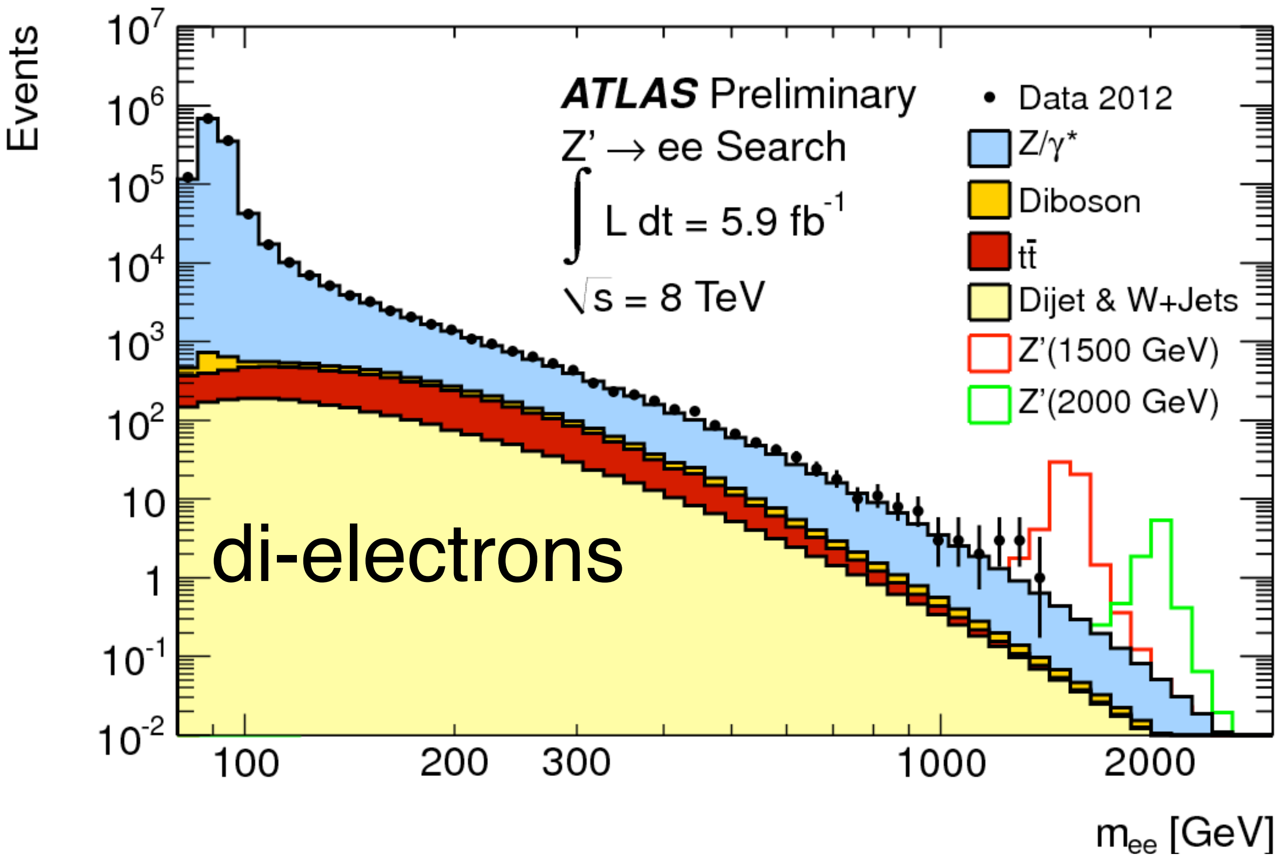


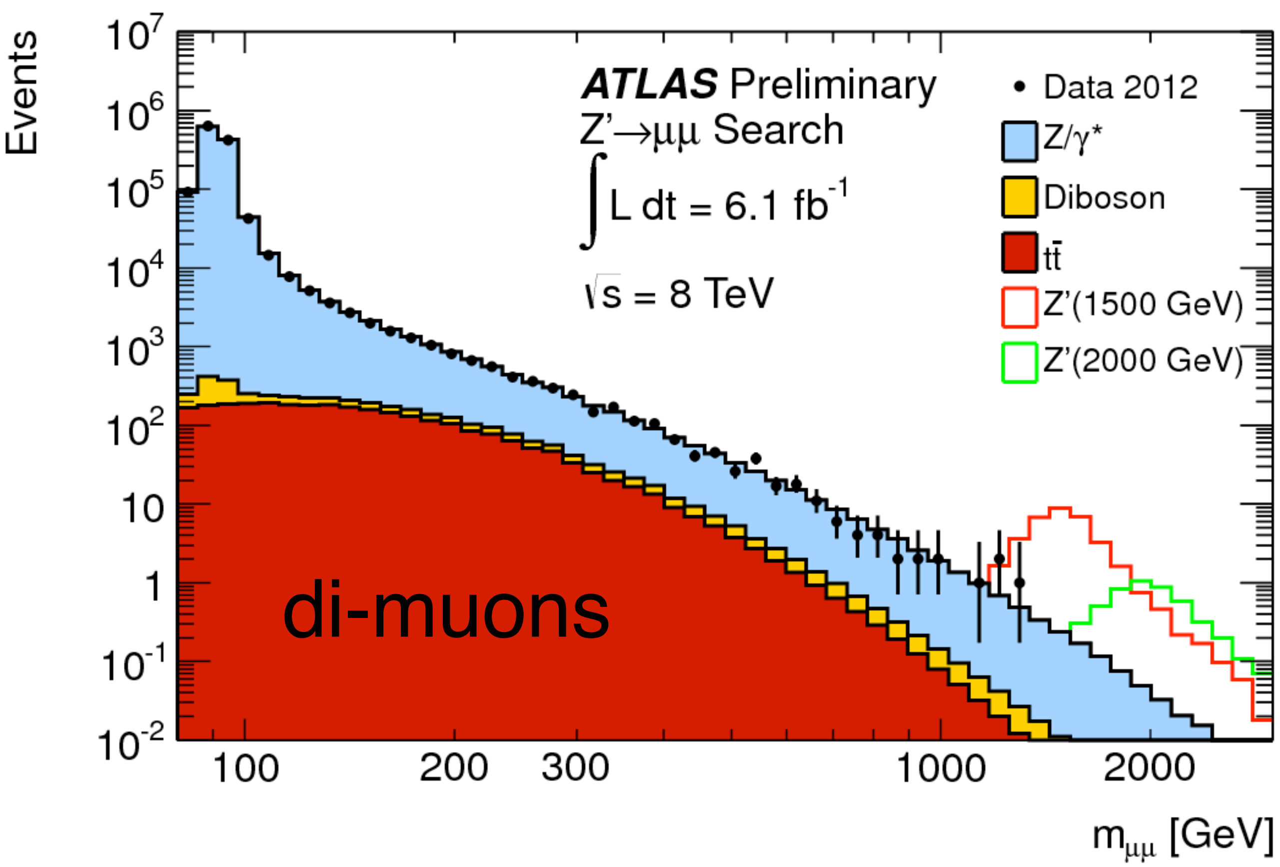
- EWK background estimate using side bands.
- SSM W’ limit is 2.85 TeV
- Second KK excluded below 1.4 TeV (3.3 TeV) assuming a bulk parameter of 0.05 TeV (10 TeV)



CMS-EXO-12-009

Dileptons

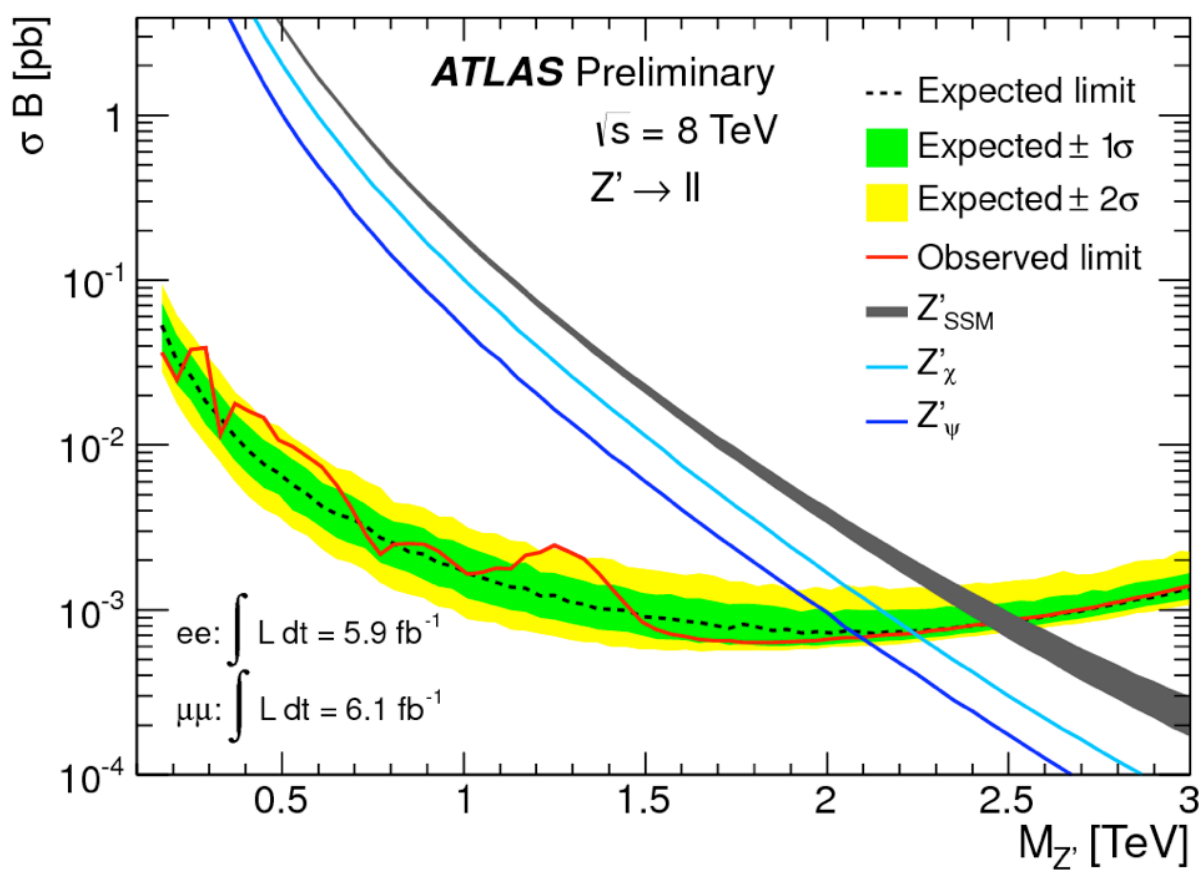




Atlas-2012-129

$\sqrt{s}$ = 8 TeV

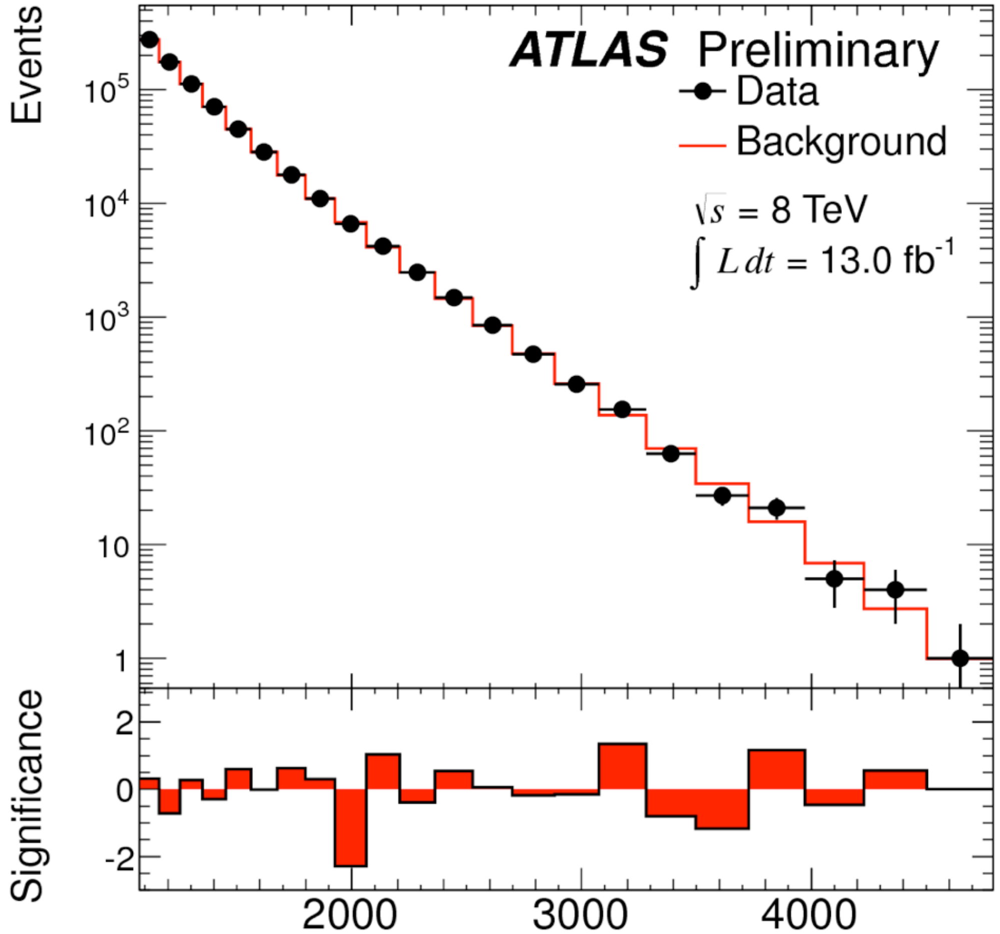
- Z' Benchmark model is based on the Sequential SM.
- Also limits for the Grand Unification E_6 model
- Bkg estimated using side bands.
- Z' masses excluded below 2.49 TeV
- CMS results is 2.59 TeV

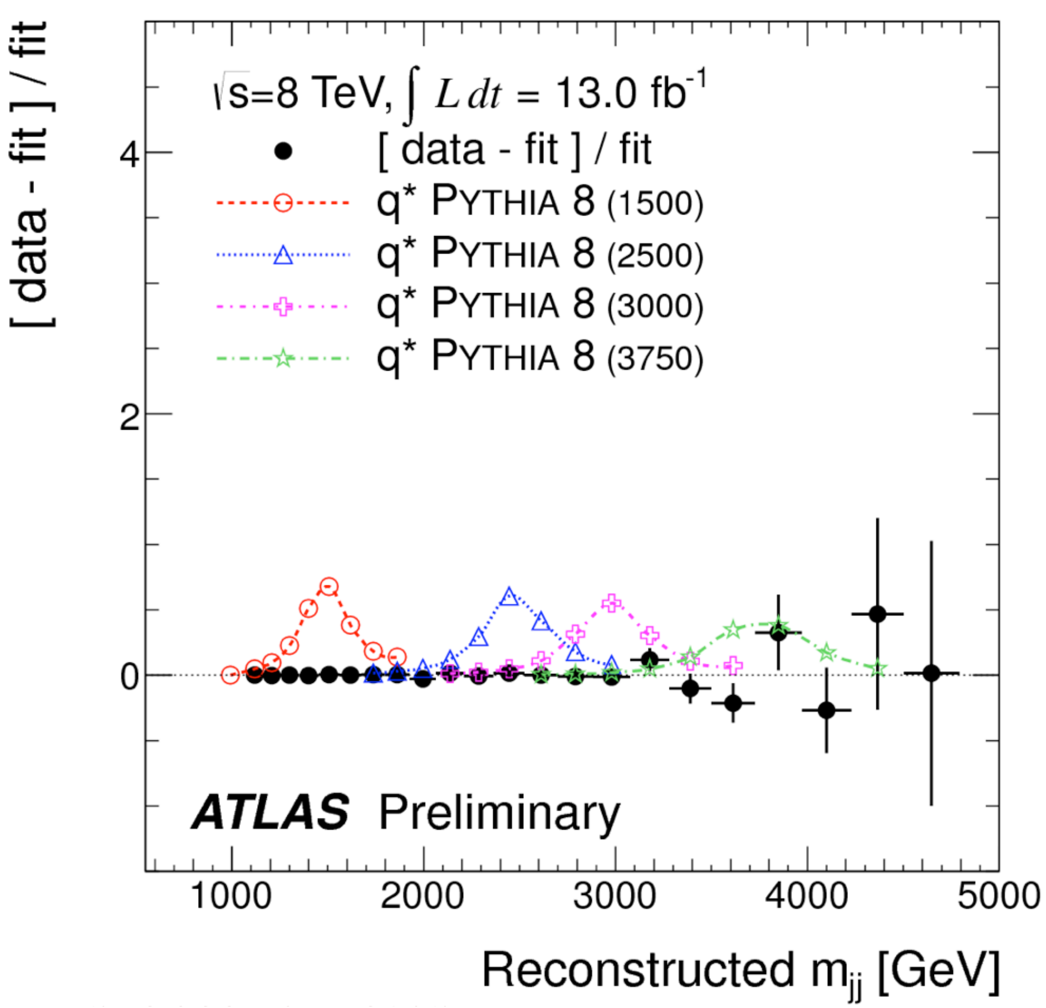


Dijets

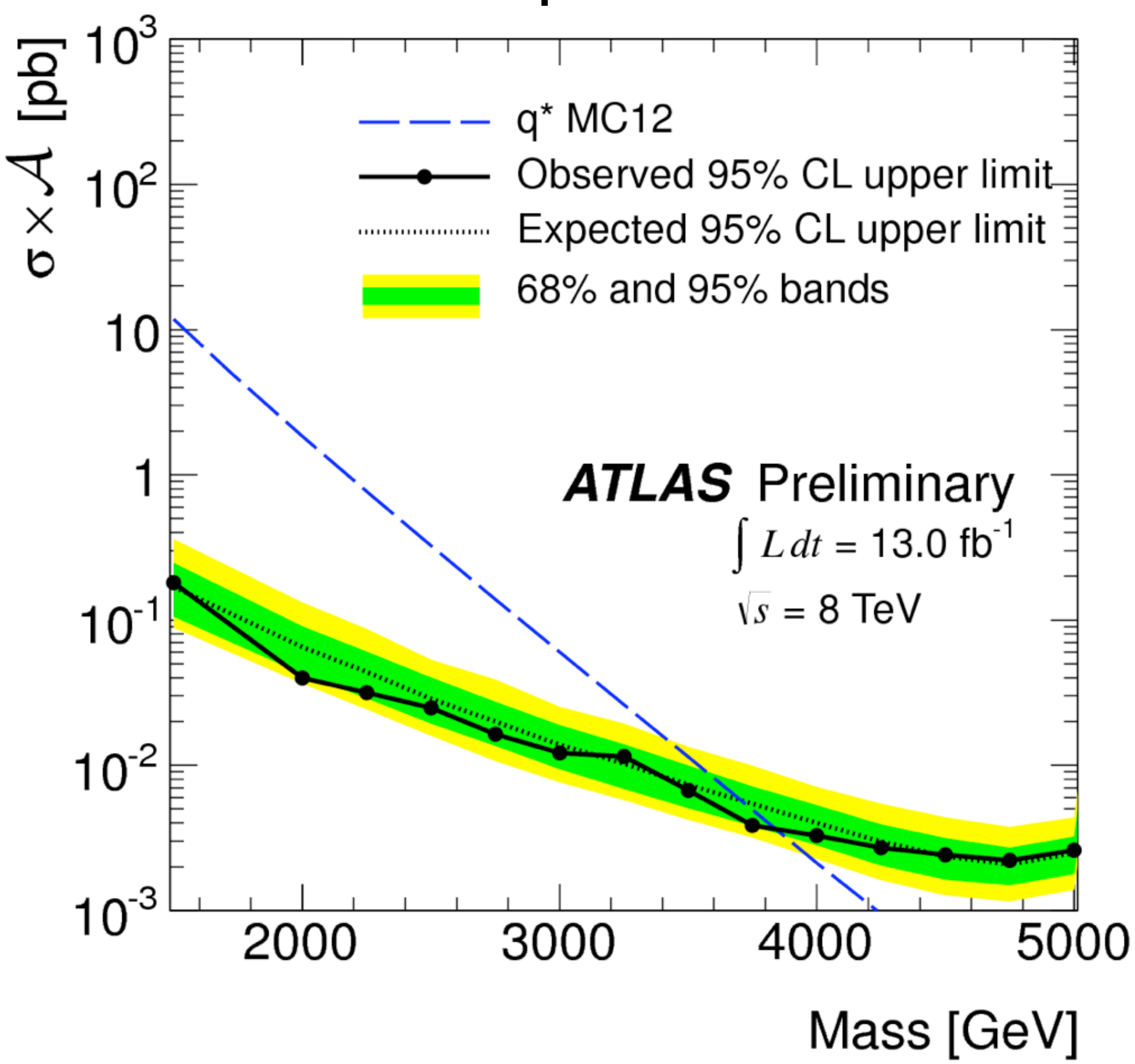
√s = 8 TeV

Atlas-2012-129





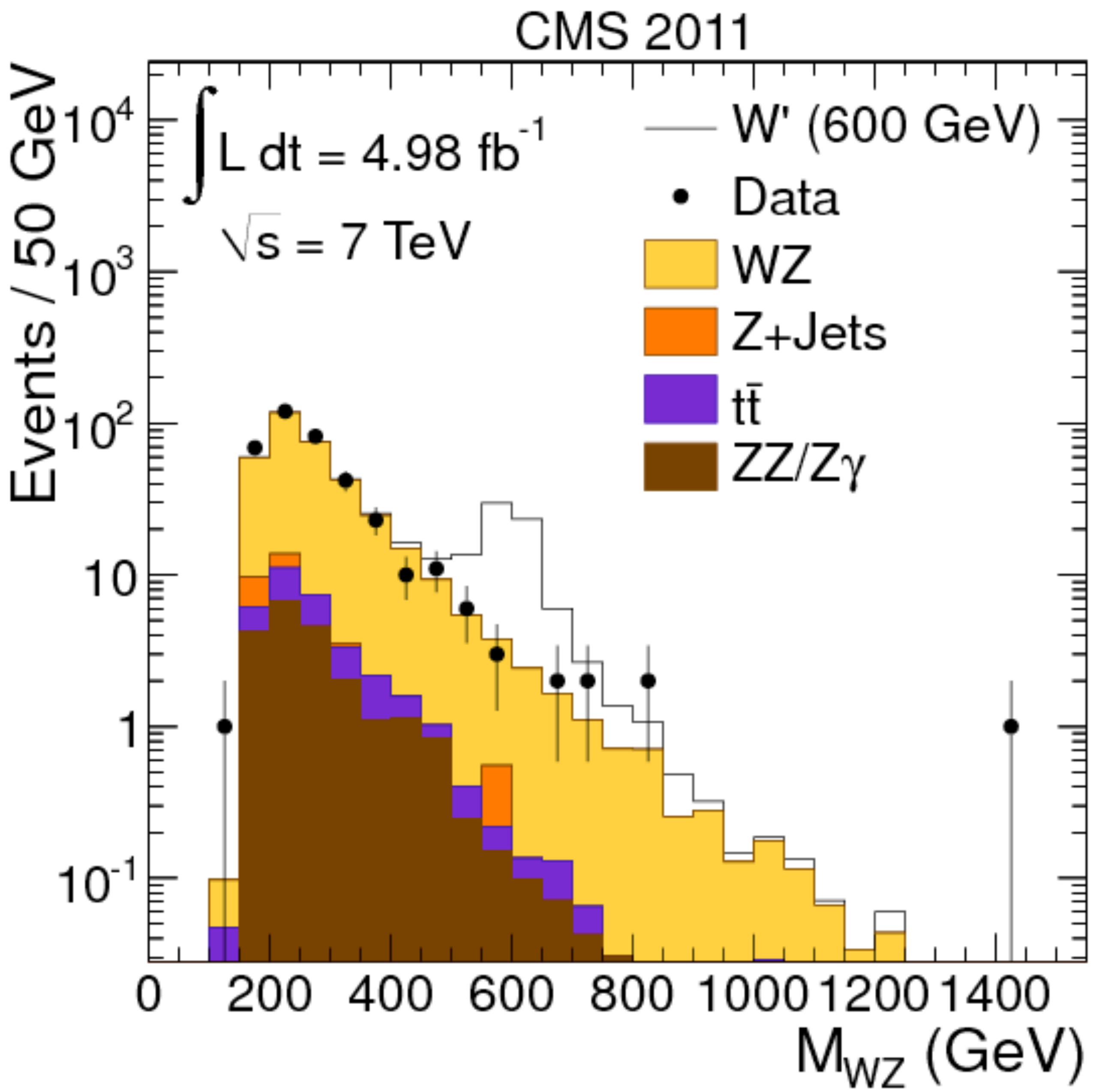
- Jets reconstructed with anti-kT R =0.6
- Fit side band with 4 parameter function
- Highest invariant mass has a dijet mass of 4.69 TeV.
- Exclusion of excited quarks set at 3.84 TeV

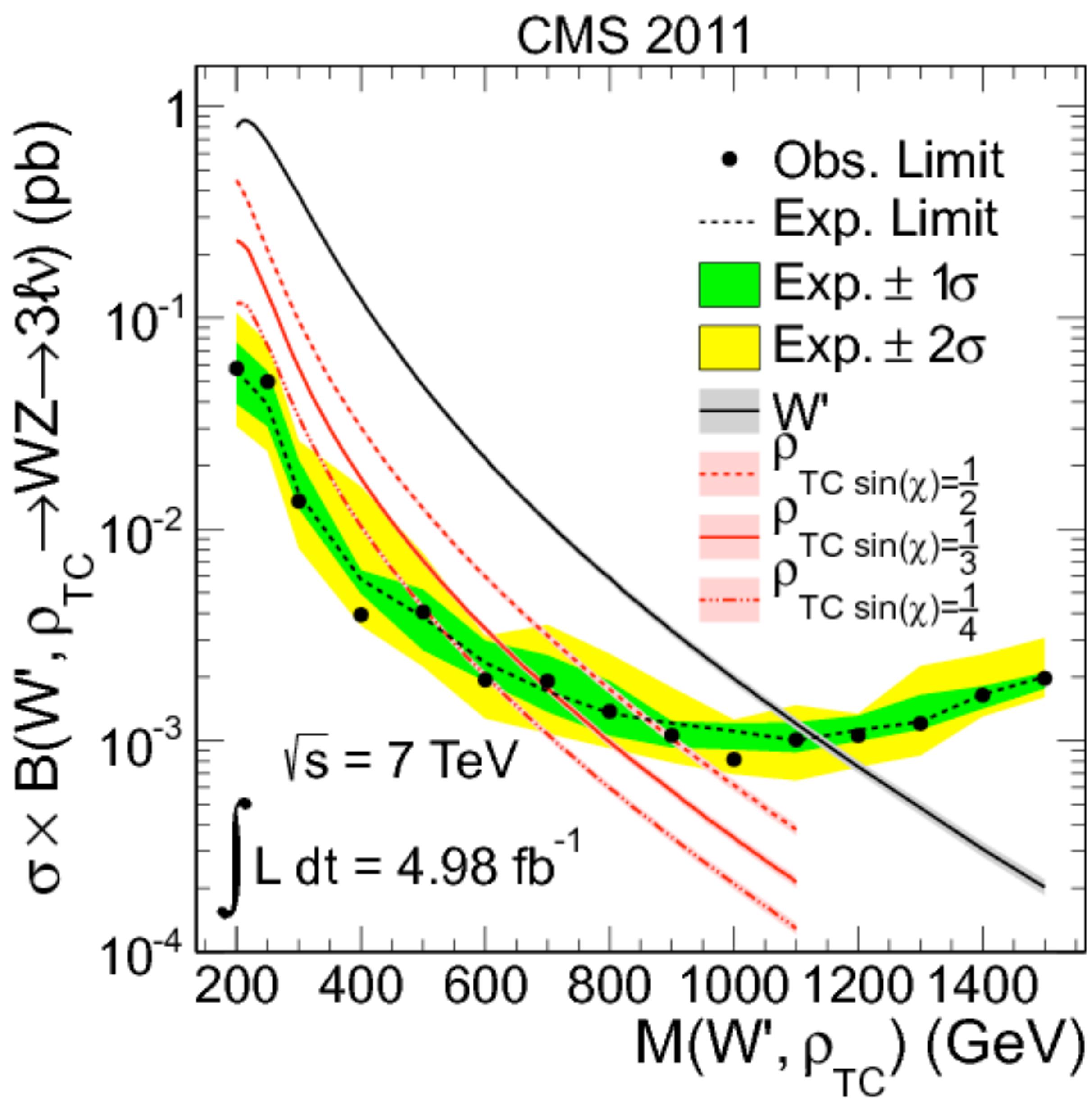


W' (techni-rho)→ WZ

CMS arxiv:1206.0433

- Electron and muons final states.
- Sequential SM W' bosons excluded with mass < 1.14 TeV.
- Low-scale technicolor models excluded to mass between 167 and 687 GeV.

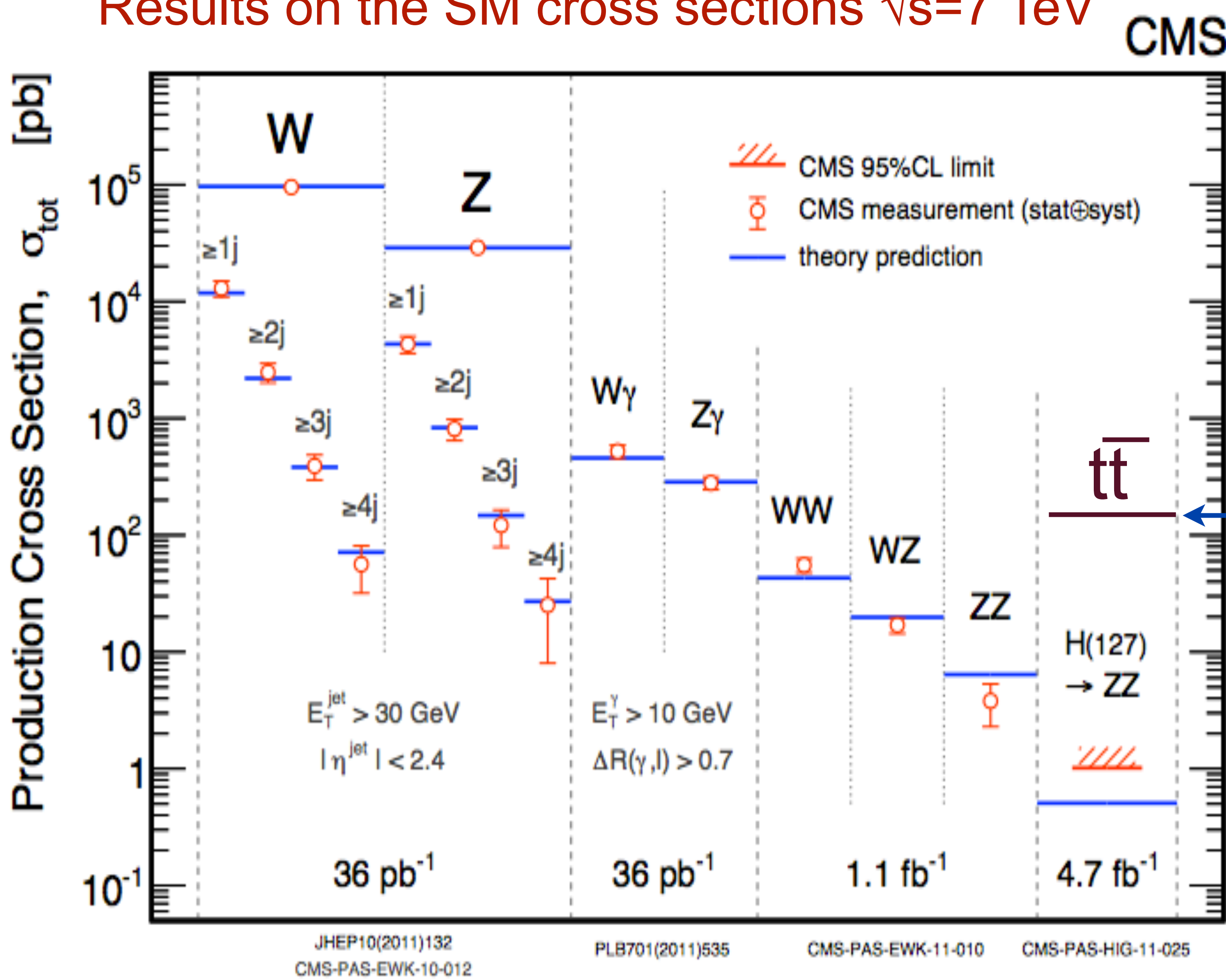




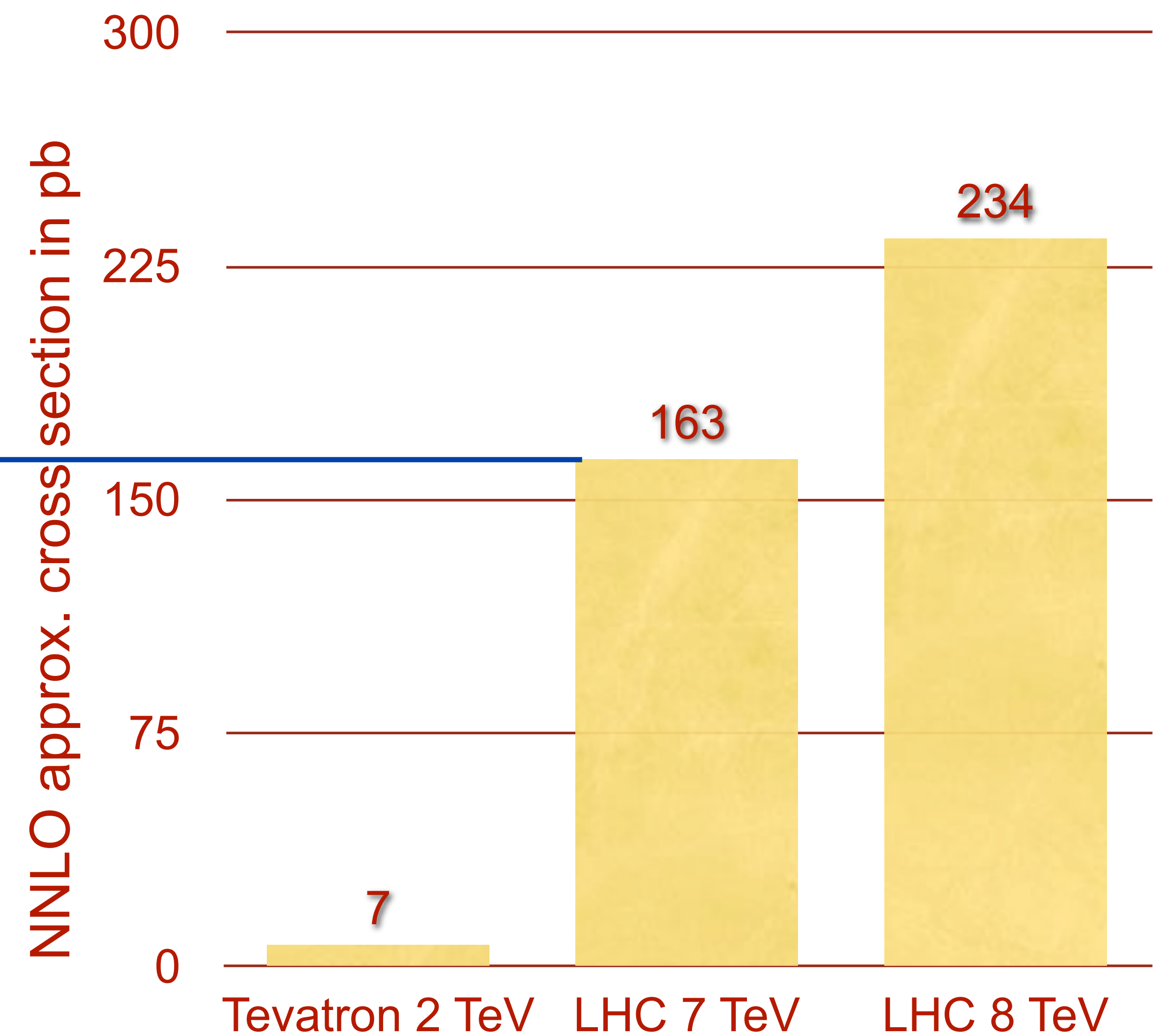
Searches with top quarks

Why Search with Top Quarks?

Results on the SM cross sections √s=7 TeV



top pair production cross section as a function of center of mass energy



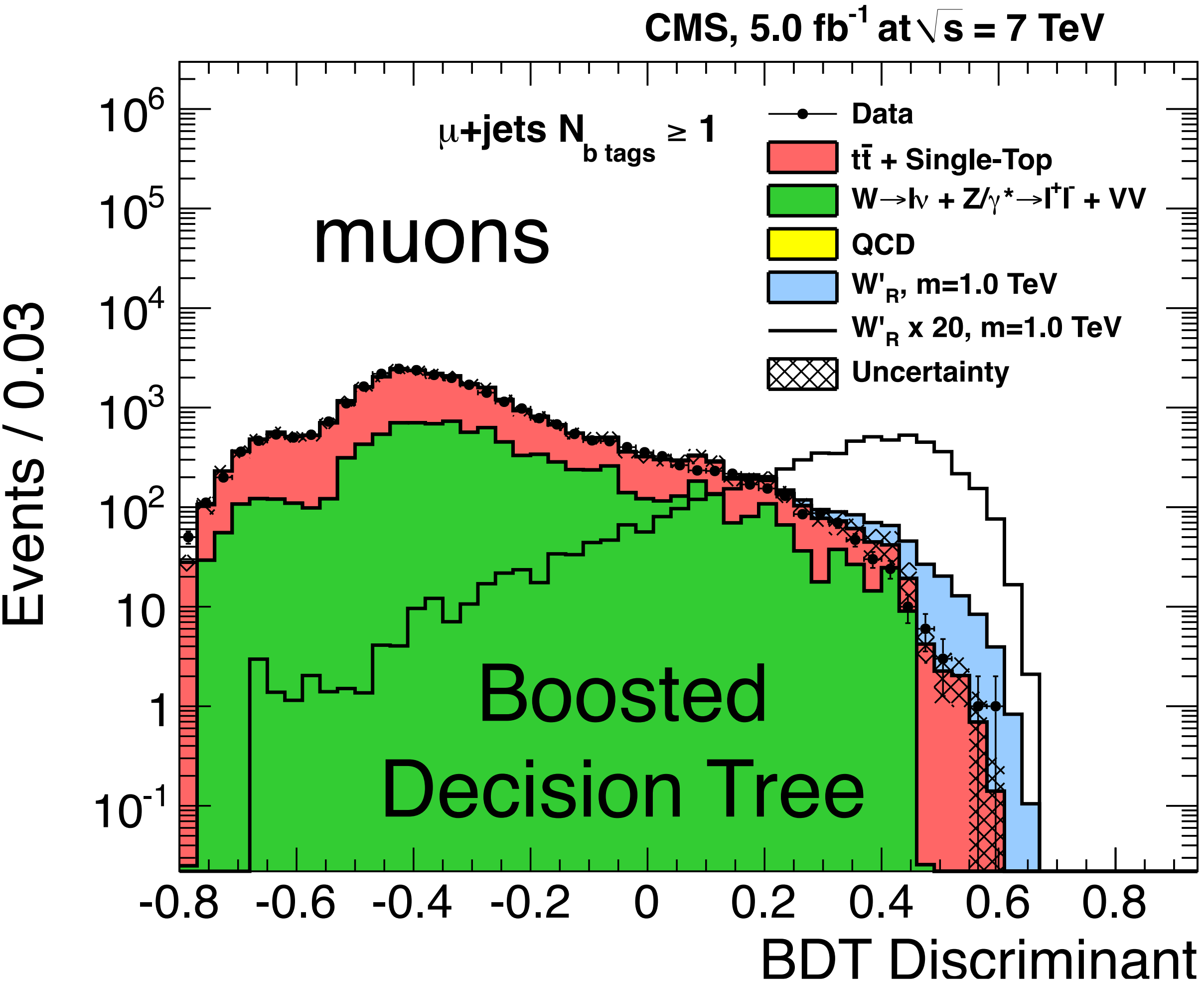
The largest dataset of top quarks = ideal lab to search for new physics

The heaviest of all quarks, the top quark likes to couple with Higgs boson

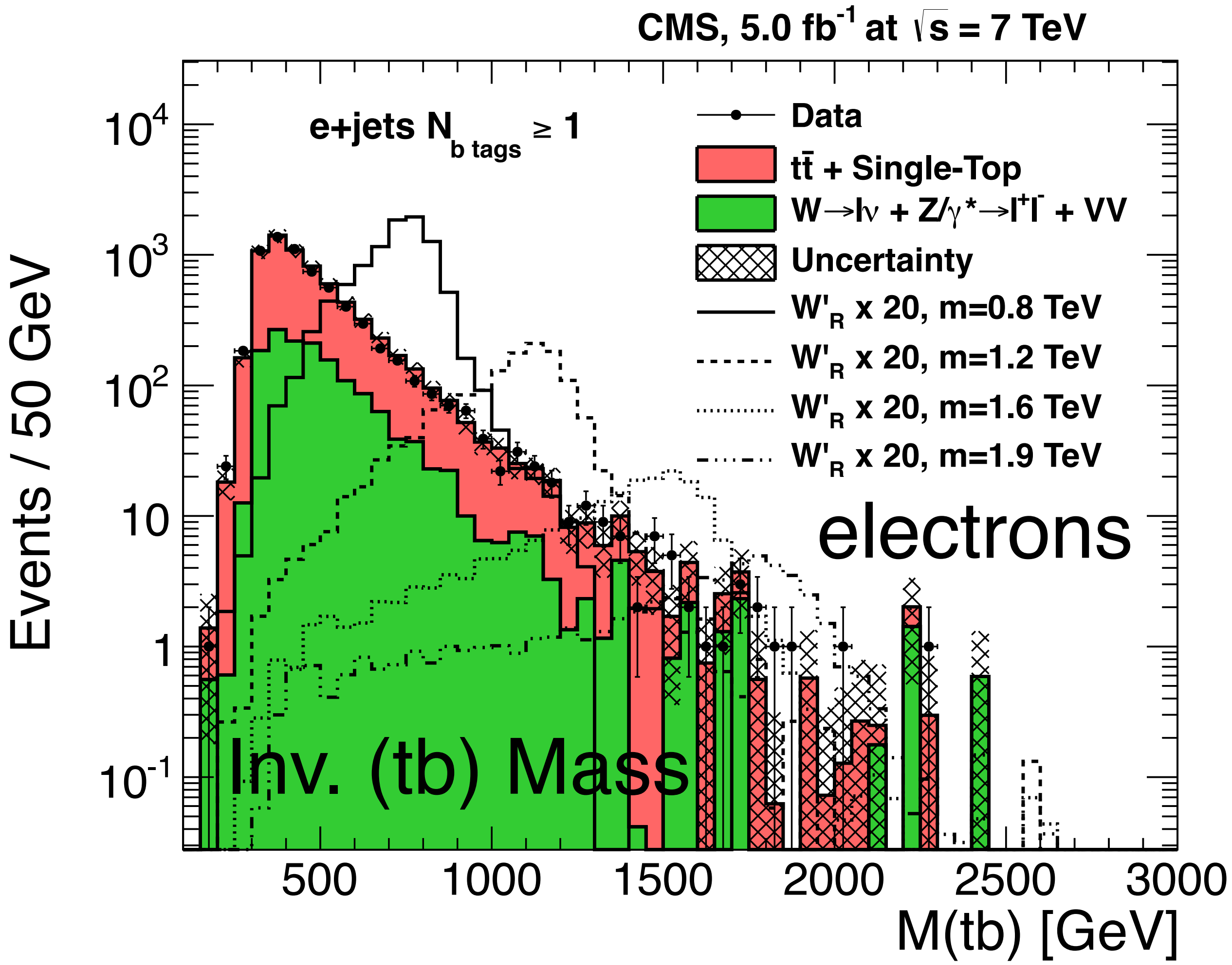
The top quark plays an important role in many BSM

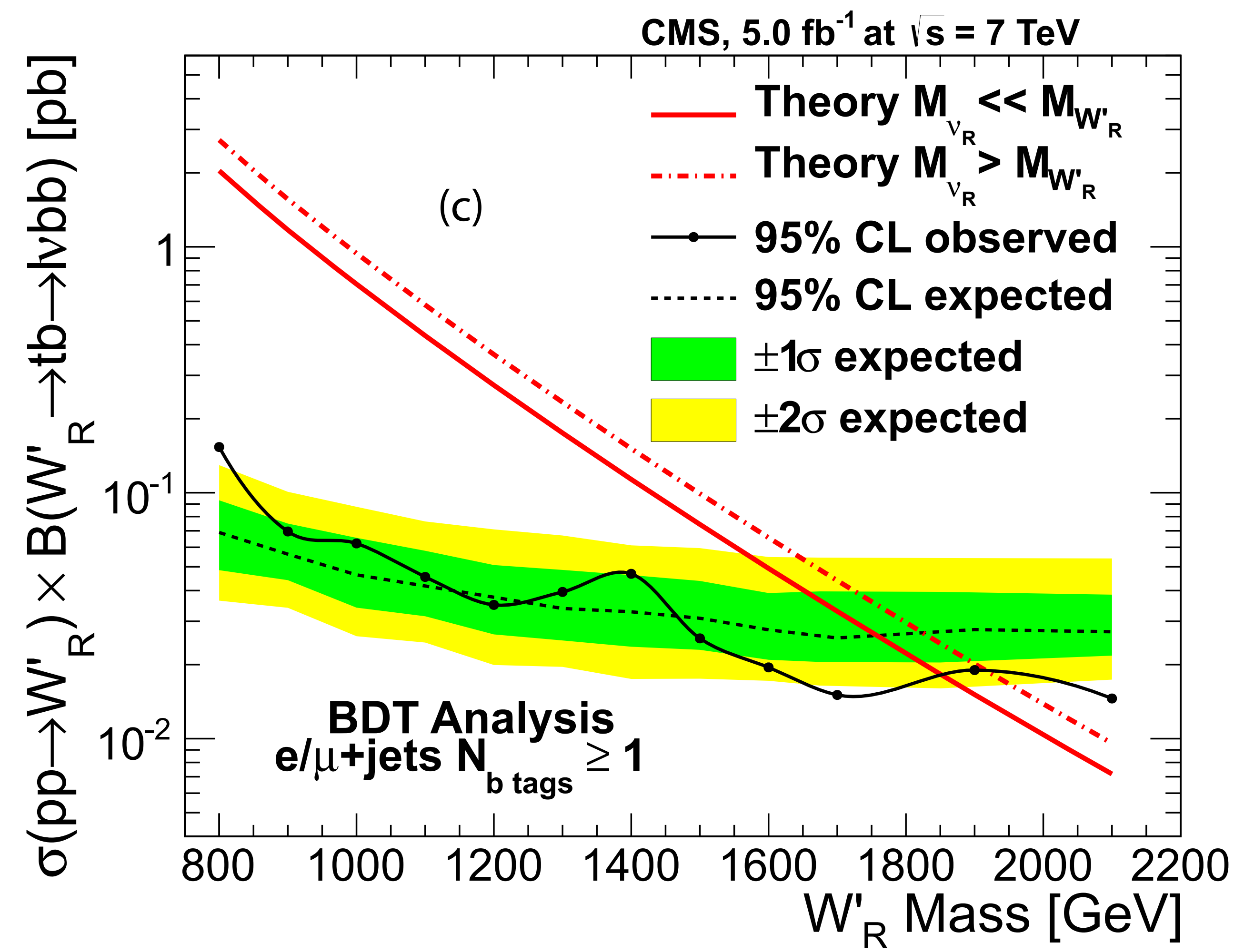
Search for W'→tb

CMS arXiv:1208.0956



- New massive W' bosons are predicted by various extensions of the SM.
- W' boson may be purely right-handed, purely left handed, or a mixture of the two.
- Some models the W' couples more strongly to the third generation.
- Fully reconstructible (up to a quadratic ambiguity) (tb) invariant mass.
- W' boson RH (LH) is excluded < 1.85 (1.51) TeV





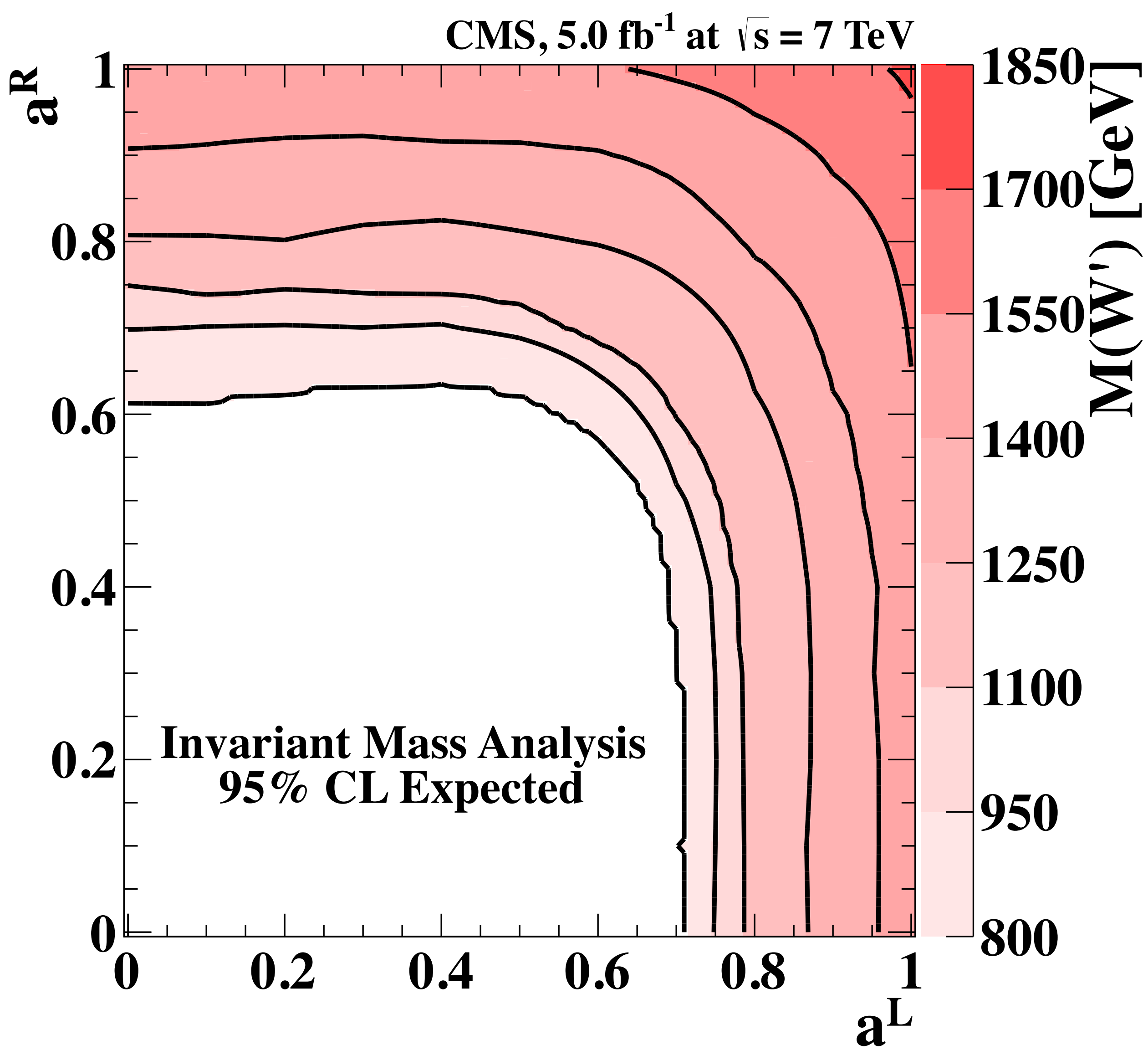
W’→ tb Limits on Coupling Strength

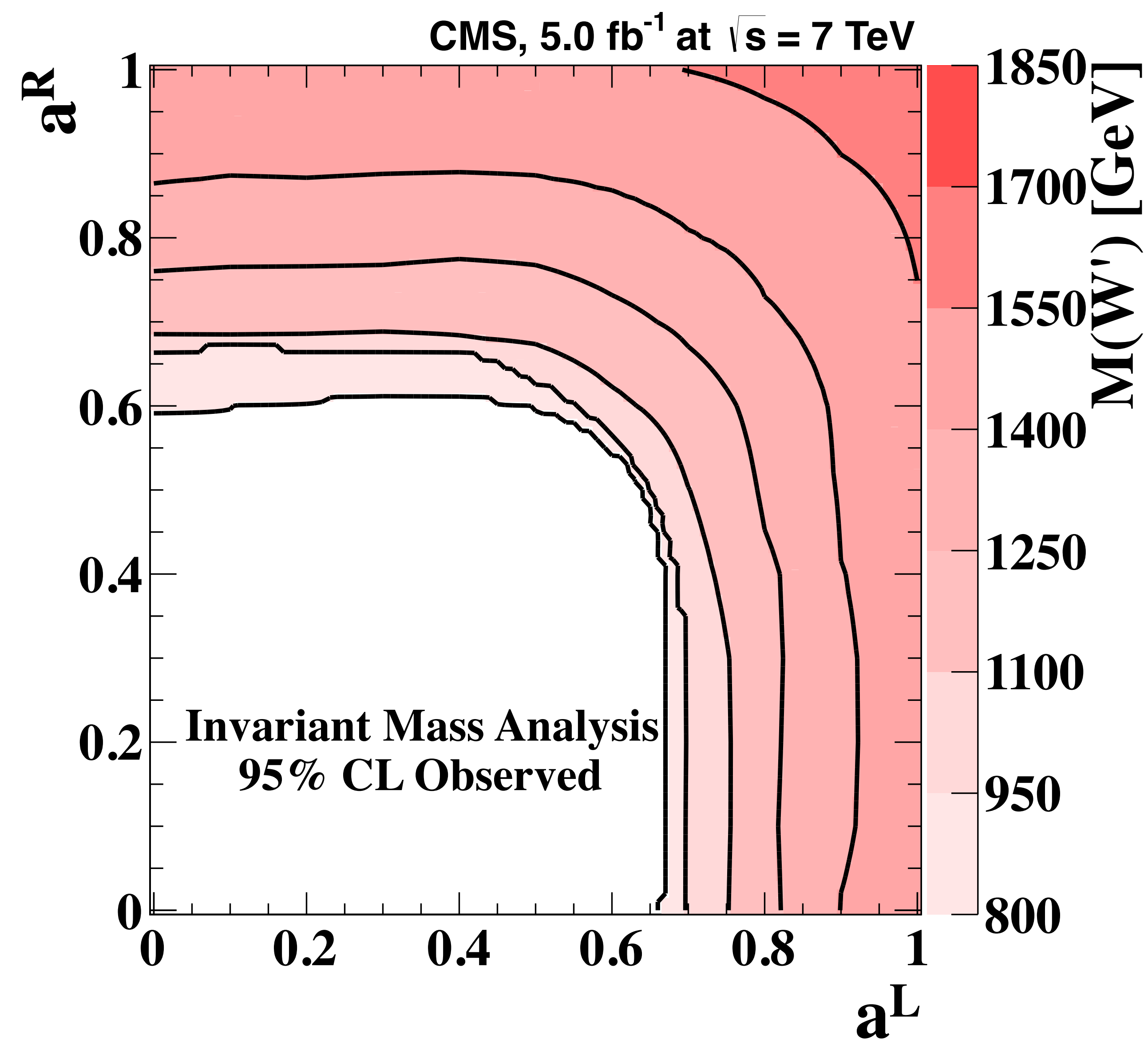
CMS arXiv:1208.0956

- The effective Lagrangian can be expressed as a function of RH, LH, Mixing (LR) and SM cross sections.
- Vary aL and aR in steps of 0.1 for a series of values of the mass of the W’ boson.

$$\mathcal{L} = \frac{V_{f_i f_j}}{2\sqrt{2}} g_w \bar{f}_i \gamma_\mu \left[a^{\mathrm{R}}_{f_i f_j}(1+\gamma^5) + a^{\mathrm{L}}_{f_i f_j}(1-\gamma^5) \right] \mathrm{W}'^{\mu} f_j + \mathrm{h.c.}$$

$$\sigma = \sigma_{\mathrm{SM}} + a^{\mathrm{L}}_{ud} a^{\mathrm{L}}_{tb} (\sigma_{\mathrm{L}} - \sigma_{\mathrm{R}} - \sigma_{\mathrm{SM}}) + \left((a^{\mathrm{L}}_{ud} a^{\mathrm{L}}_{tb})^2 + (a^{\mathrm{R}}_{ud} a^{\mathrm{R}}_{tb})^2 \right) \sigma_{\mathrm{R}} + \frac{1}{2} \left((a^{\mathrm{L}}_{ud} a^{\mathrm{R}}_{tb})^2 + (a^{\mathrm{R}}_{ud} a^{\mathrm{L}}_{tb})^2 \right) (\sigma_{\mathrm{LR}} - \sigma_{\mathrm{L}} - \sigma_{\mathrm{R}}).$$





Highly Boosted Jets

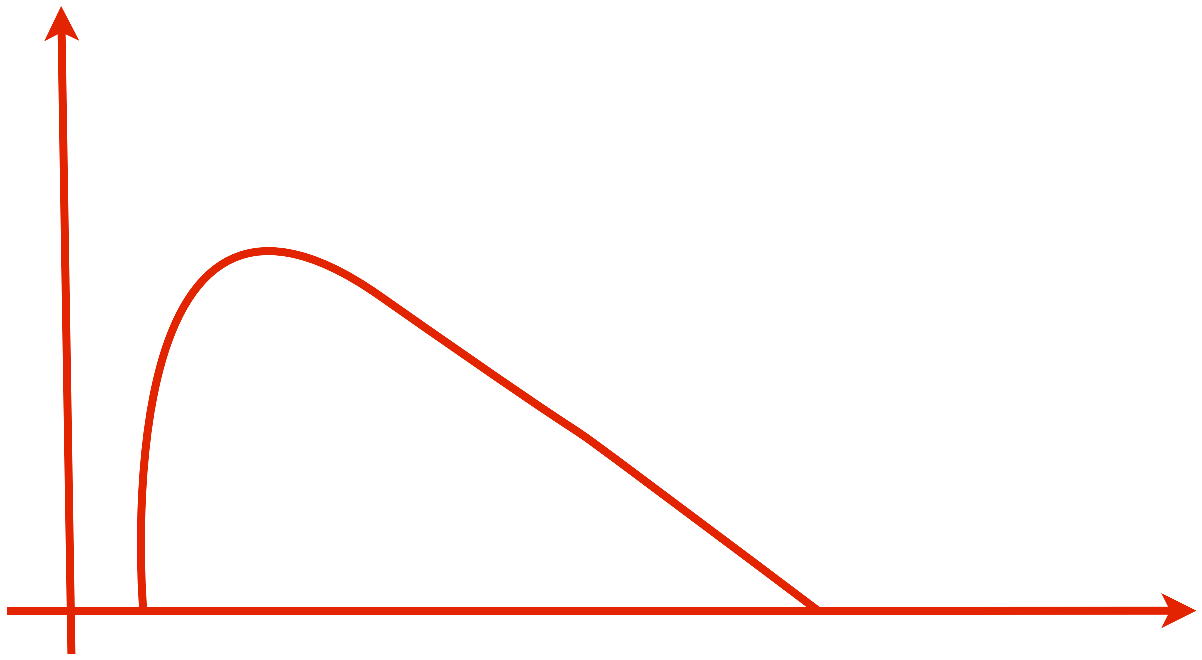
W/Z- and top- Tagging

Where to look for New Physics?

e.g. ttbar$\rightarrow$(Wb)(Wb)$\rightarrow$(jjb)(lνb)

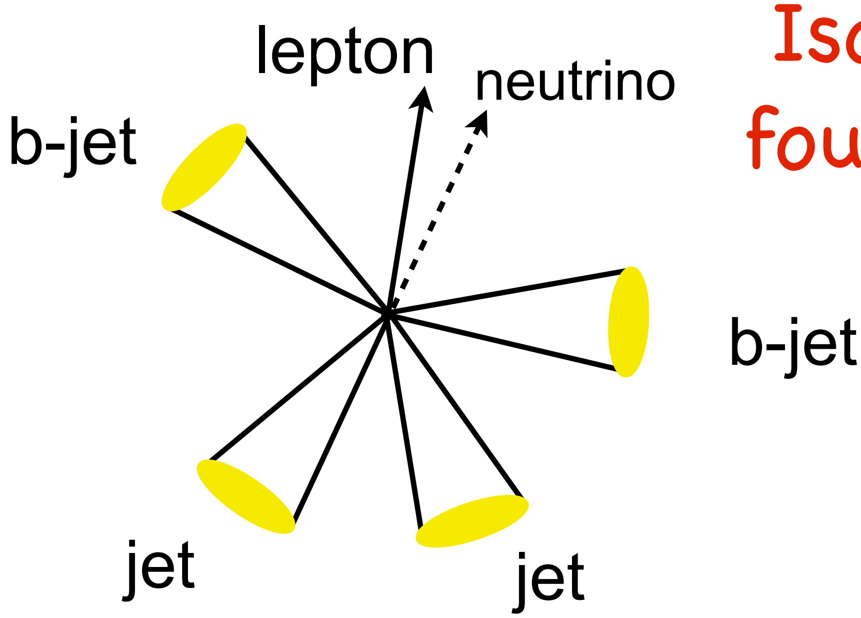
neutrino

neutrino

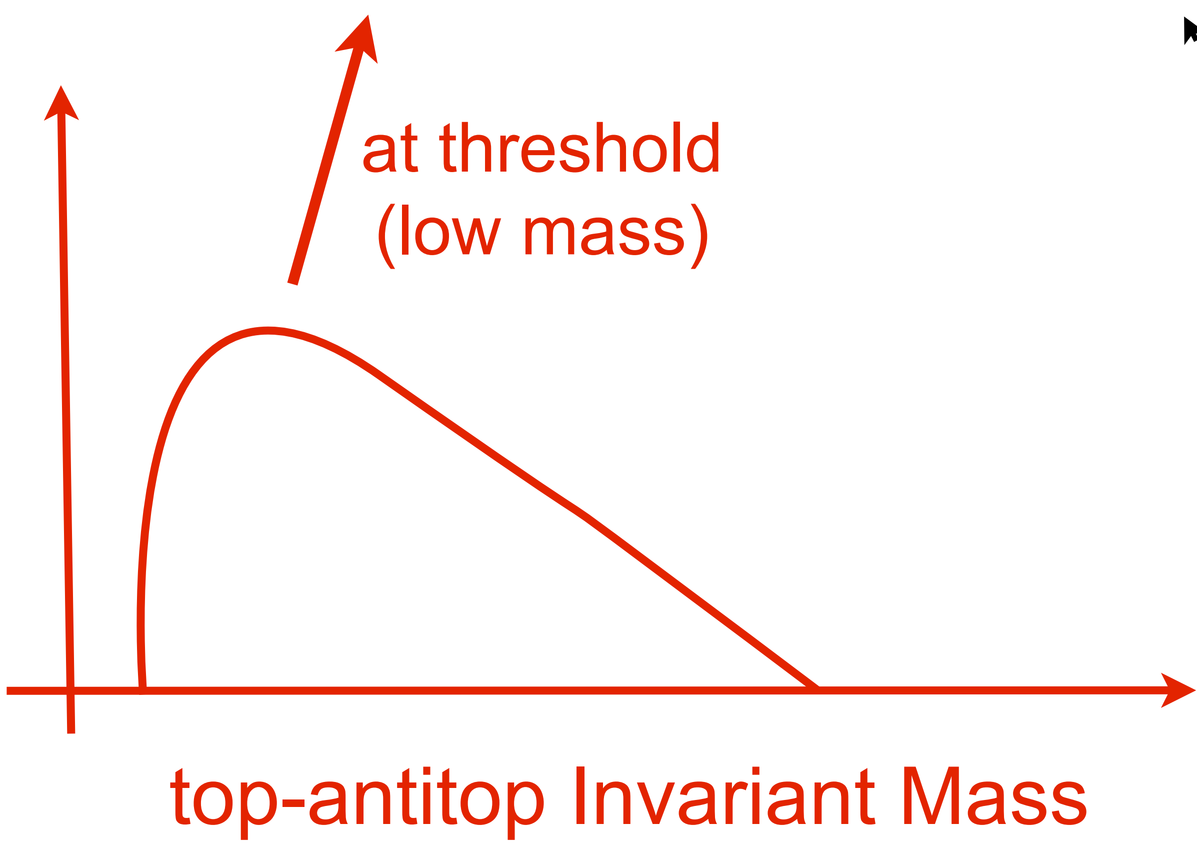


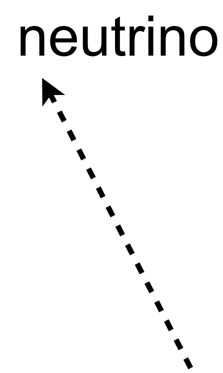
top-antitop Invariant Mass

Where to look for New Physics?
e.g. ttbar→(Wb)(Wb)→(jjb)(lνb)



Isolated lepton +
four separate jets





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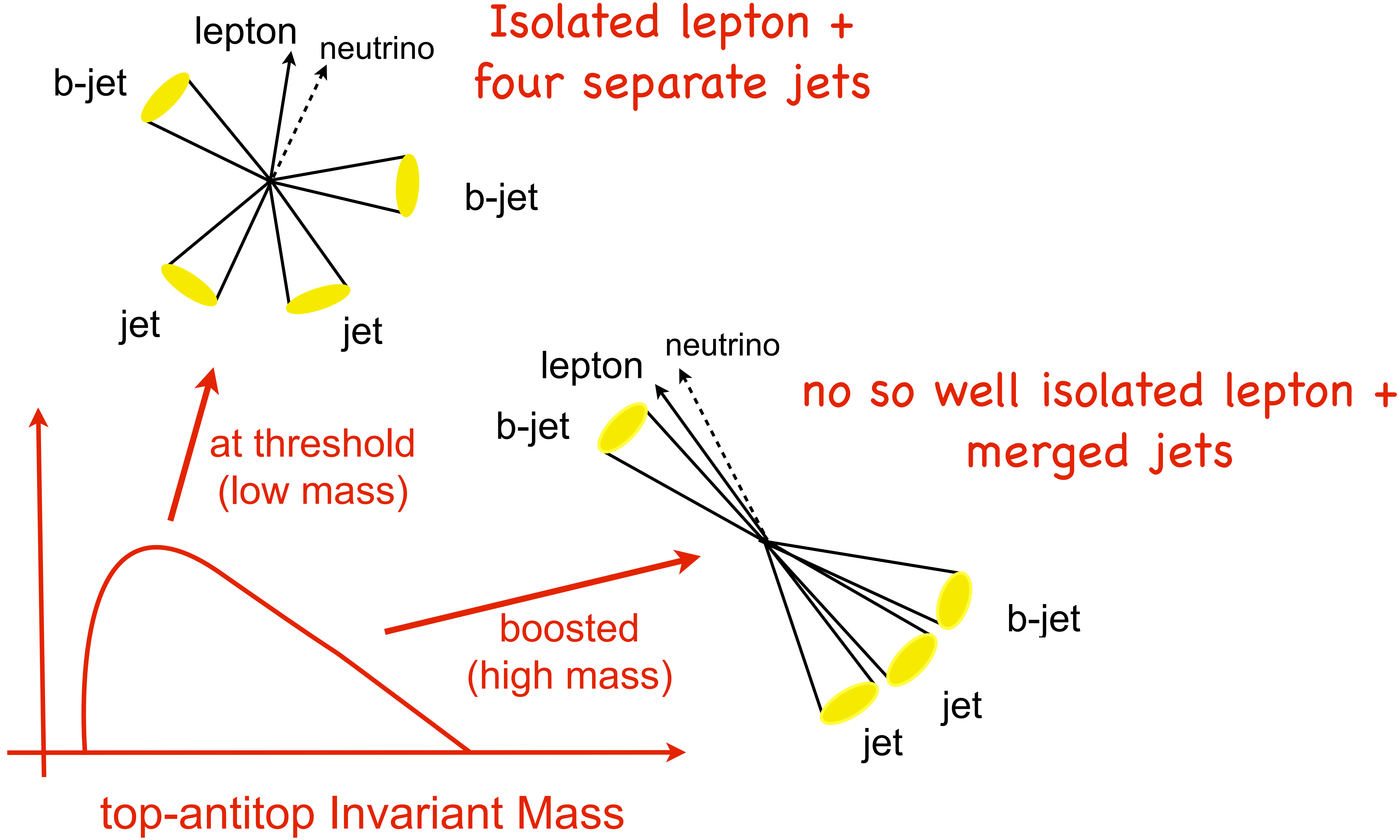
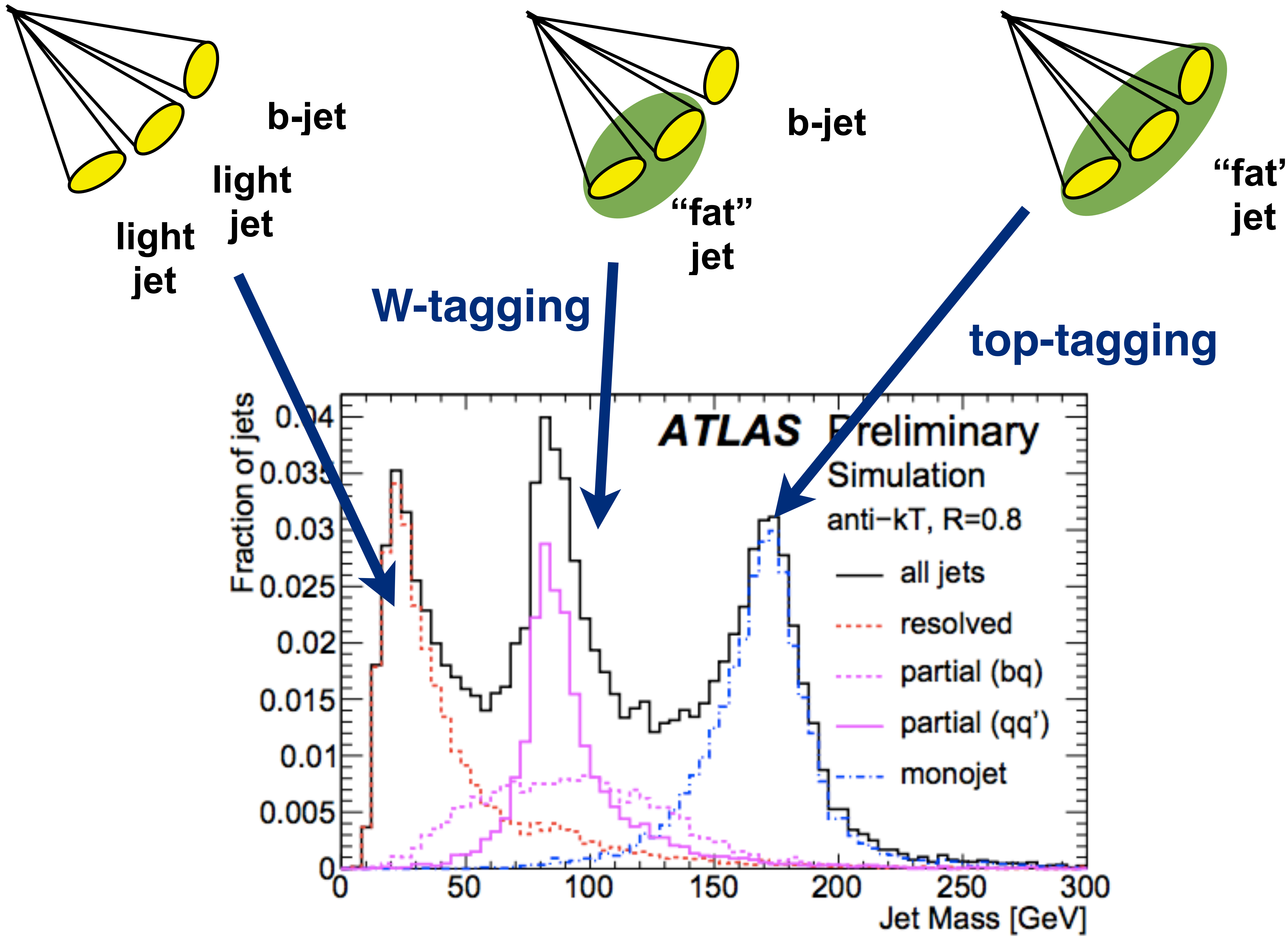
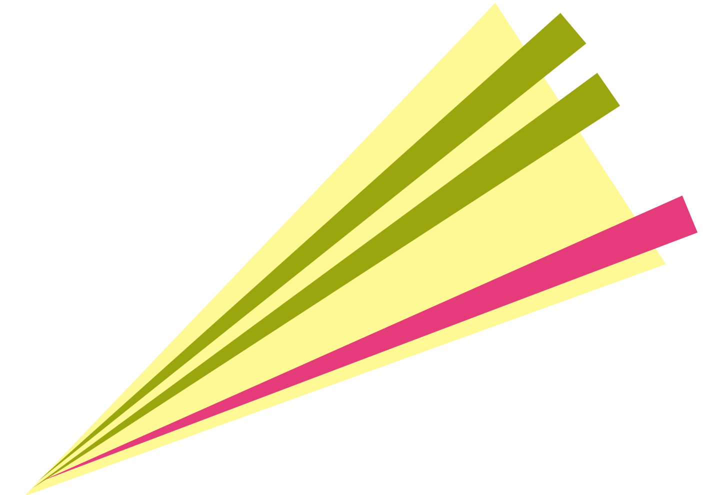


Objects merge as boost increases



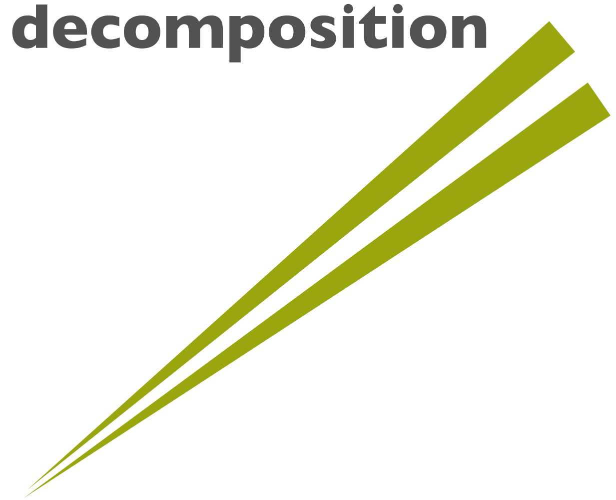
Top-tagging

- Cluster PF candidates using Cambridge-Aagen Algo. (CA) R = 0.8.
- Reverse the clustering sequence in order to find substructure (arXiv: 0806.0848).
- Subjets must satisfy two requirements:
  - Momentum fraction criterion:
  - Adjacency criterion
- Iterative process - throw out objects that fail momentum fraction cut and try to decluster again.



Primary decomposition

Secondary decomposition



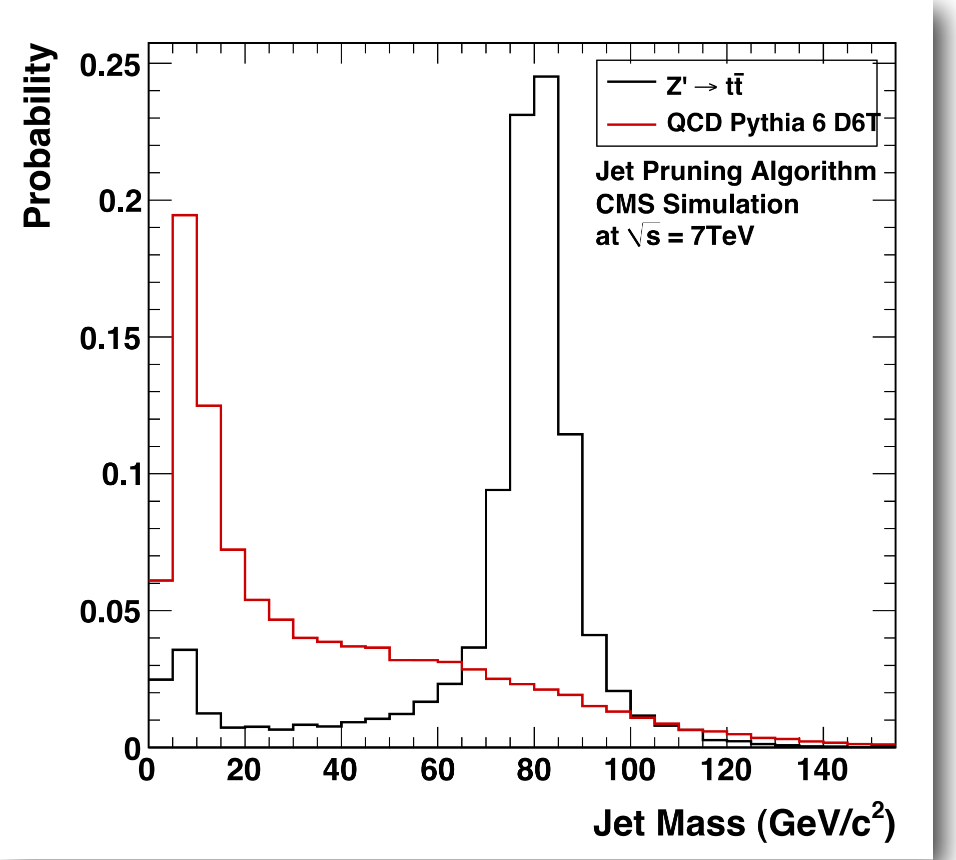
W-tagging: jet pruning

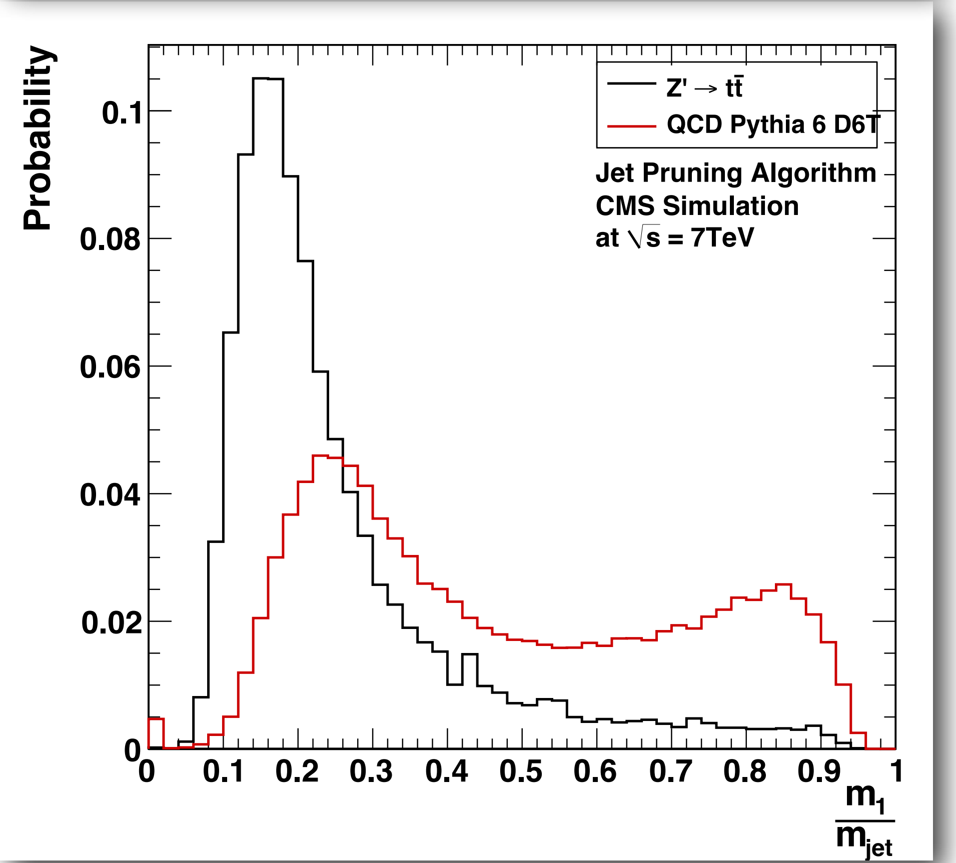
- Improves mass resolution by removing soft, large angle particles from the jet (arXiv:0903.5081).
- Recluster each jet, requiring that each recombination satisfies the following:

$$\frac{min\{p_{T,i}, p_{T,j}\}}{p_{T,p}} > 0.1$$

$$\Delta R_{ij} < 0.5 \times \frac{m_{jet}}{p_T}$$

- If recombination fails the softer of the two jets is removed.
- W-tagging requires:
  - Two subjets
  - Pruned jet mass $60 < m_{\mathrm{wjet}} < 100\mathrm{GeV}$
  - Mass ratio between hardest subject and the original jets (mass drop) μ < 0.4.

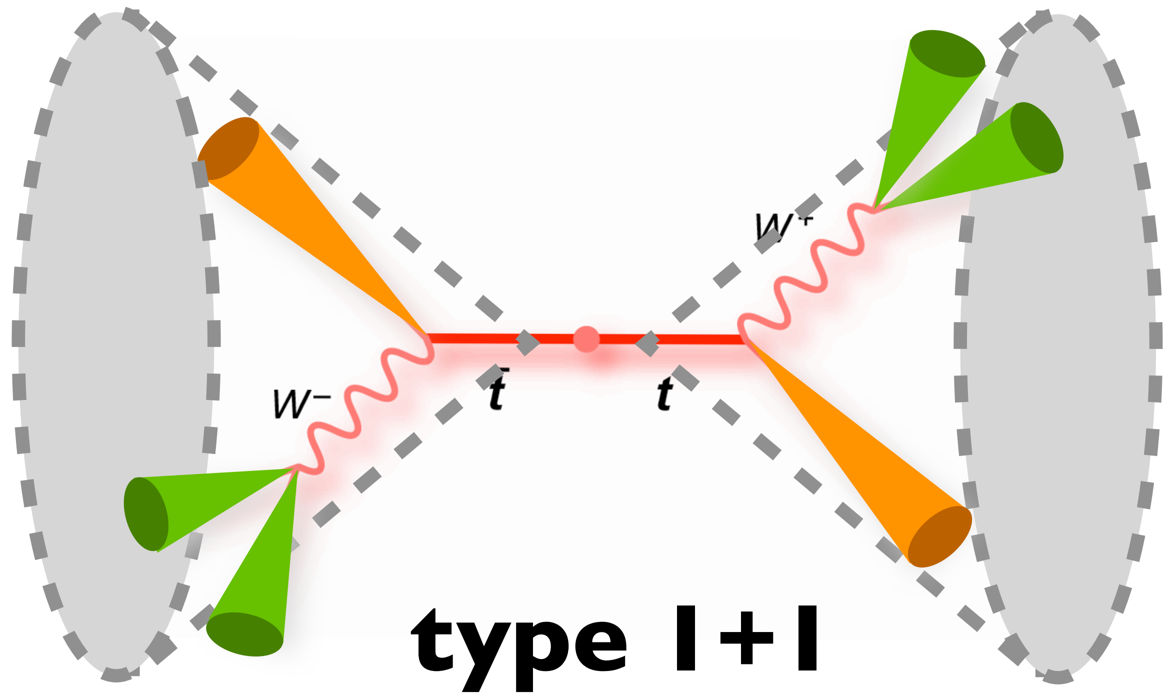




Top pair resonances IN HIGHLY-BOOSTED all-hadronic

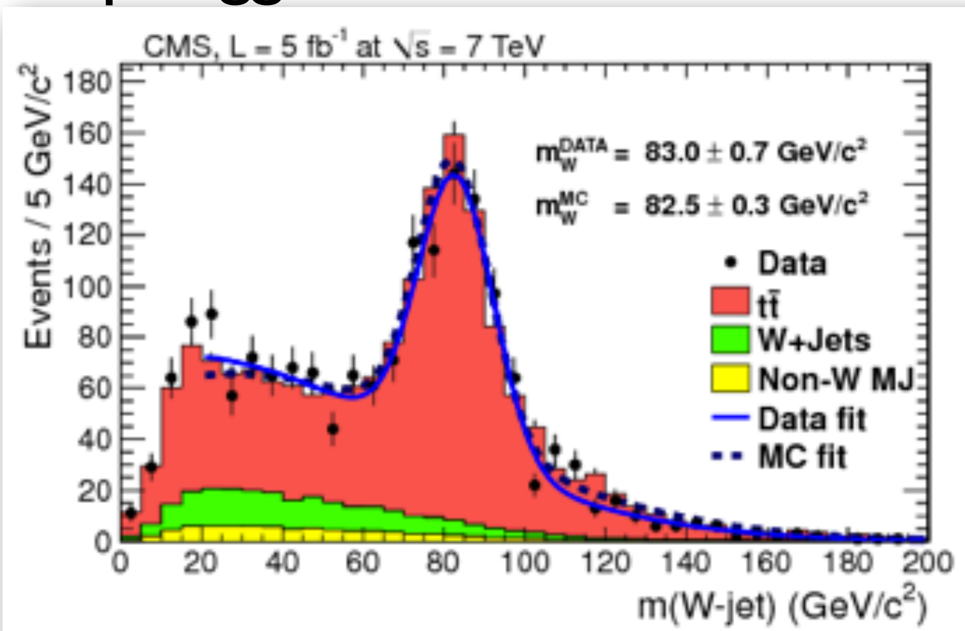
CMS arXiv:1204.2488 (5 fb^{-1})

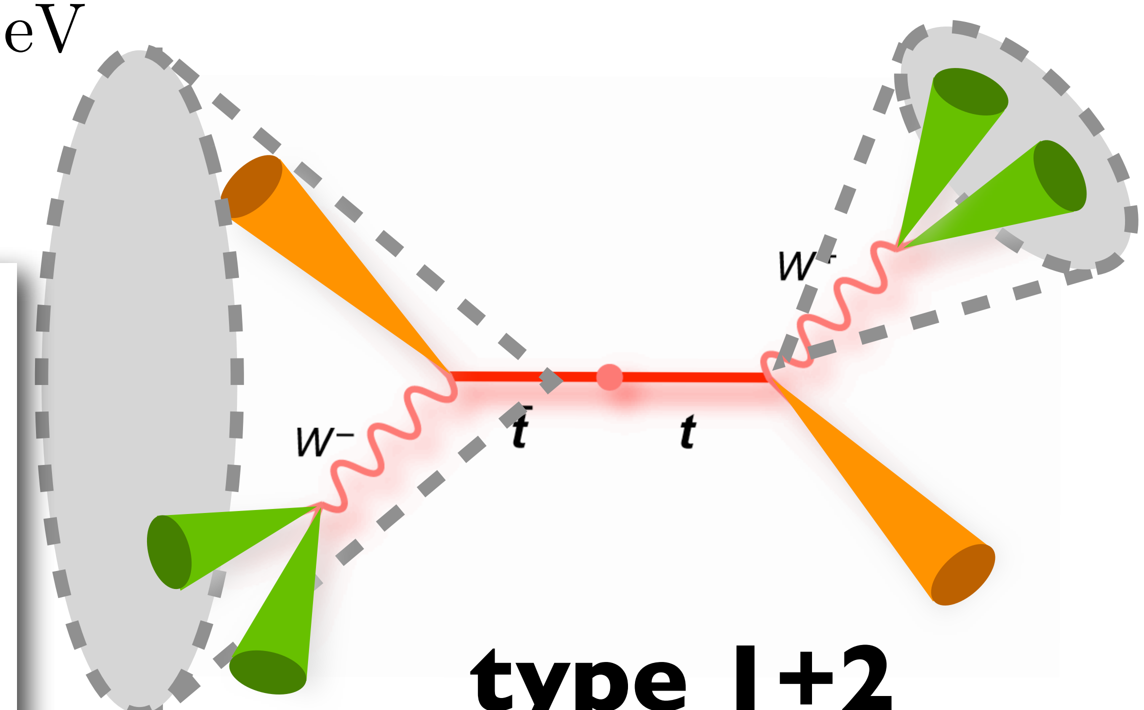
- Type 1+1 (high mass search)
  - Two jets pt > 350 GeV
  - Two top-tagged jets: $140 < m_{\text{jet}} < 250$ GeV, $N_{\text{subjets}} \geq 3$, $m_{\text{min}} > 50$ GeV



- Type 1+2 (medium mass search)
  - Veto 1 + 1 (<1% overlap)
  - Jet p$_T$ > 350, 200, 30 GeV
  - Top jet must be top-tagged
  - W jet must be W-tagged

$60 < m_{\text{jet}} < 100$ GeV
$N_{\text{subjets}} = 2$
$m_1/m_{\text{jet}} < 0.4$

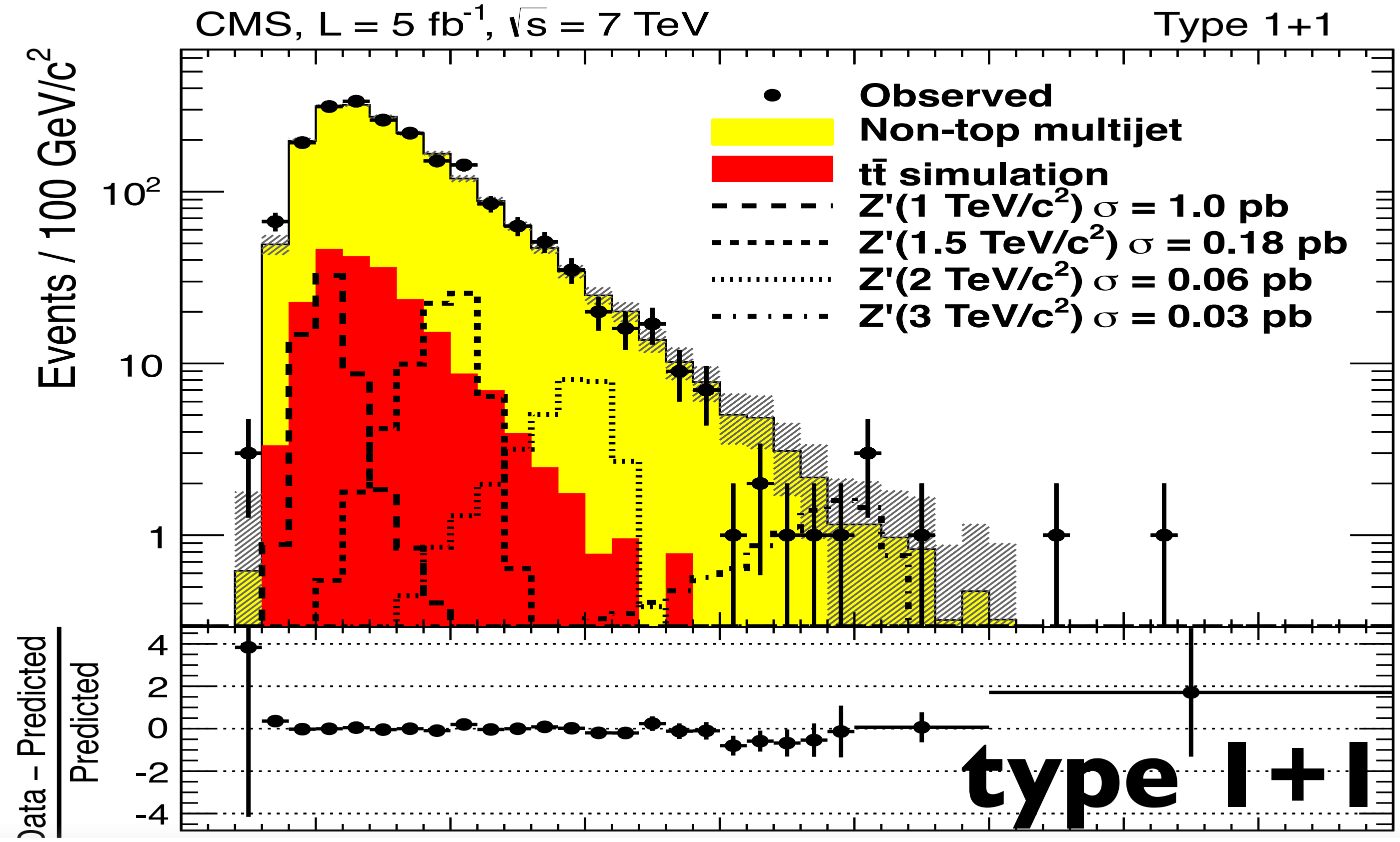


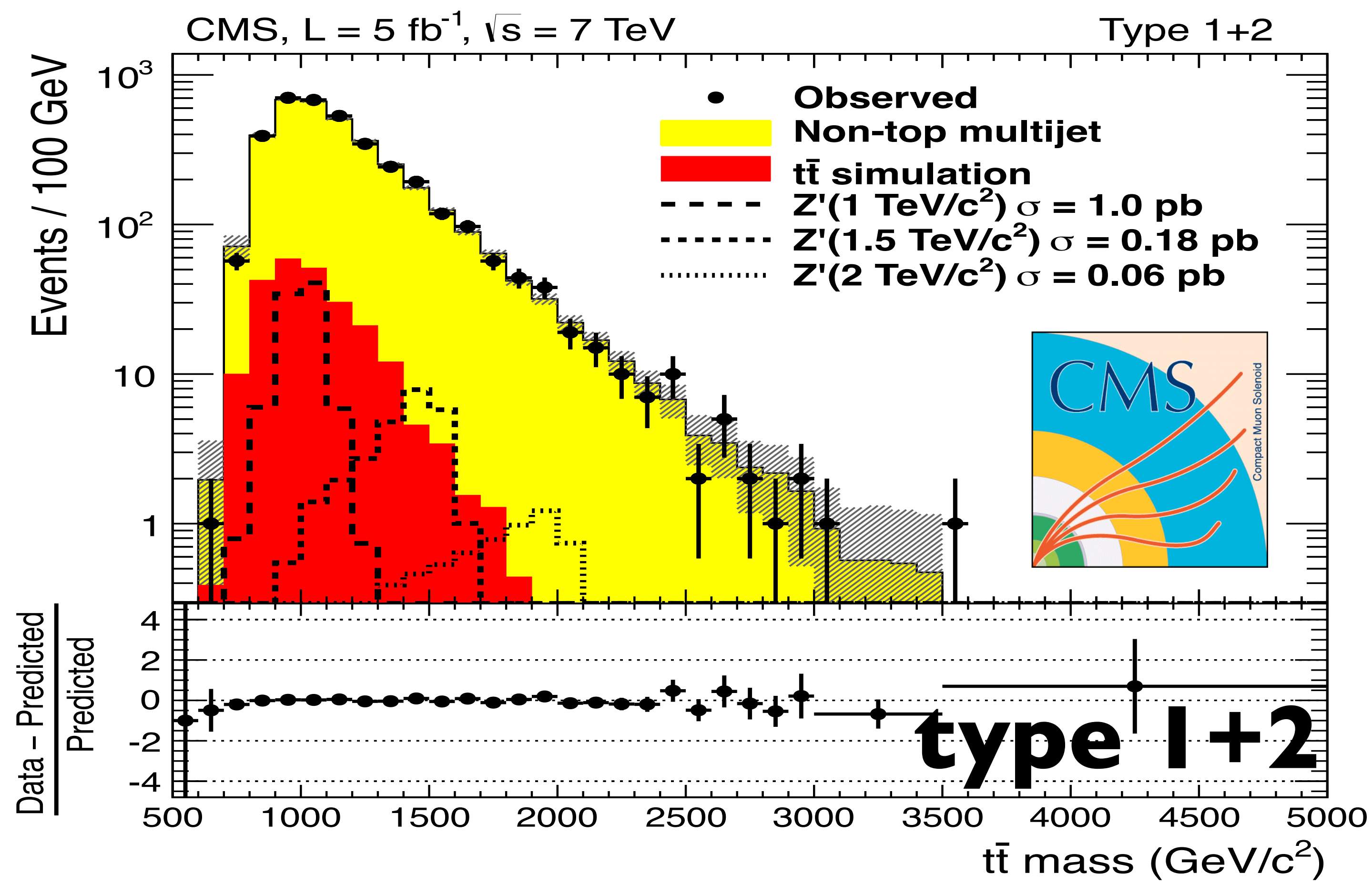


Background modeling for all-hadronic boosted channel

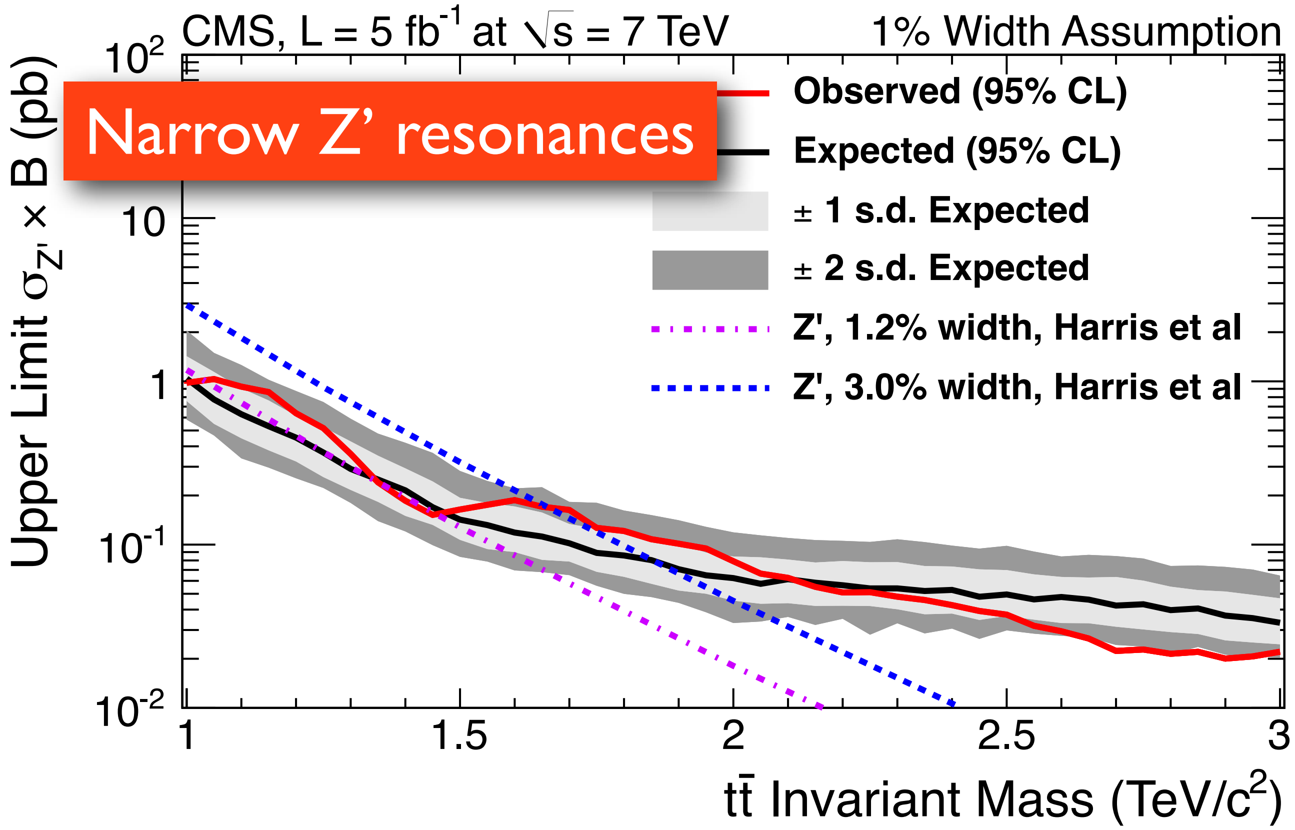
CMS arXiv:1204.2488 (5 fb^{-1})

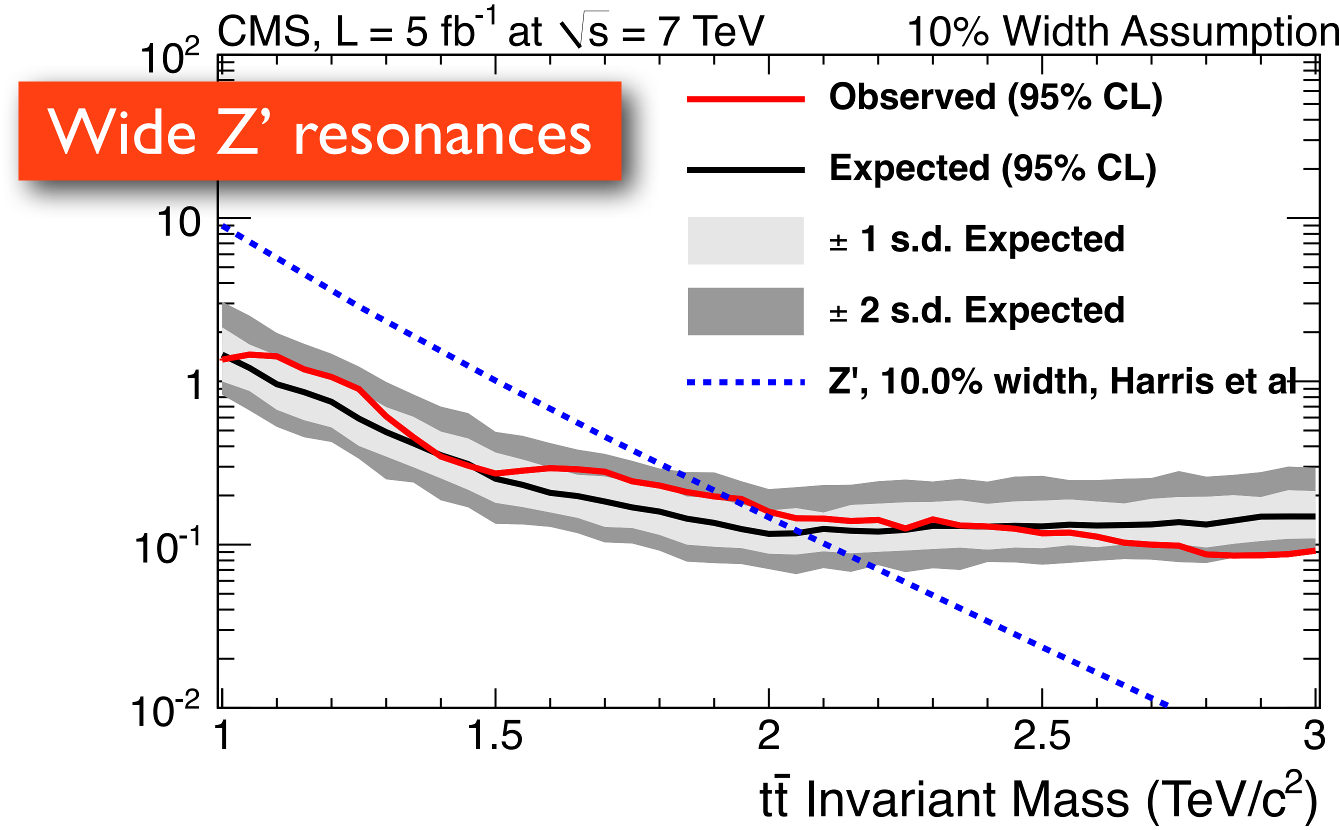
- Distribution for SM top pair production is obtained from simulation and normalized to theory.
- For type 1+1, QCD multijet events are modeled from data using dijet sample with only one top-tagged jet.
- For type 1+2, QCD multijet events are modeled from data using a sample with a W jet candidate and no top-tagged jet.
- Both samples are weighted by top-tagging mistag rate efficiency.
- Top-tagging efficiency measured in top pairs with muon+jets final state.
- Mistag rate is measured by inverting some of the top and W tagged jet selection.





Highly-boosted all-hadronic Results





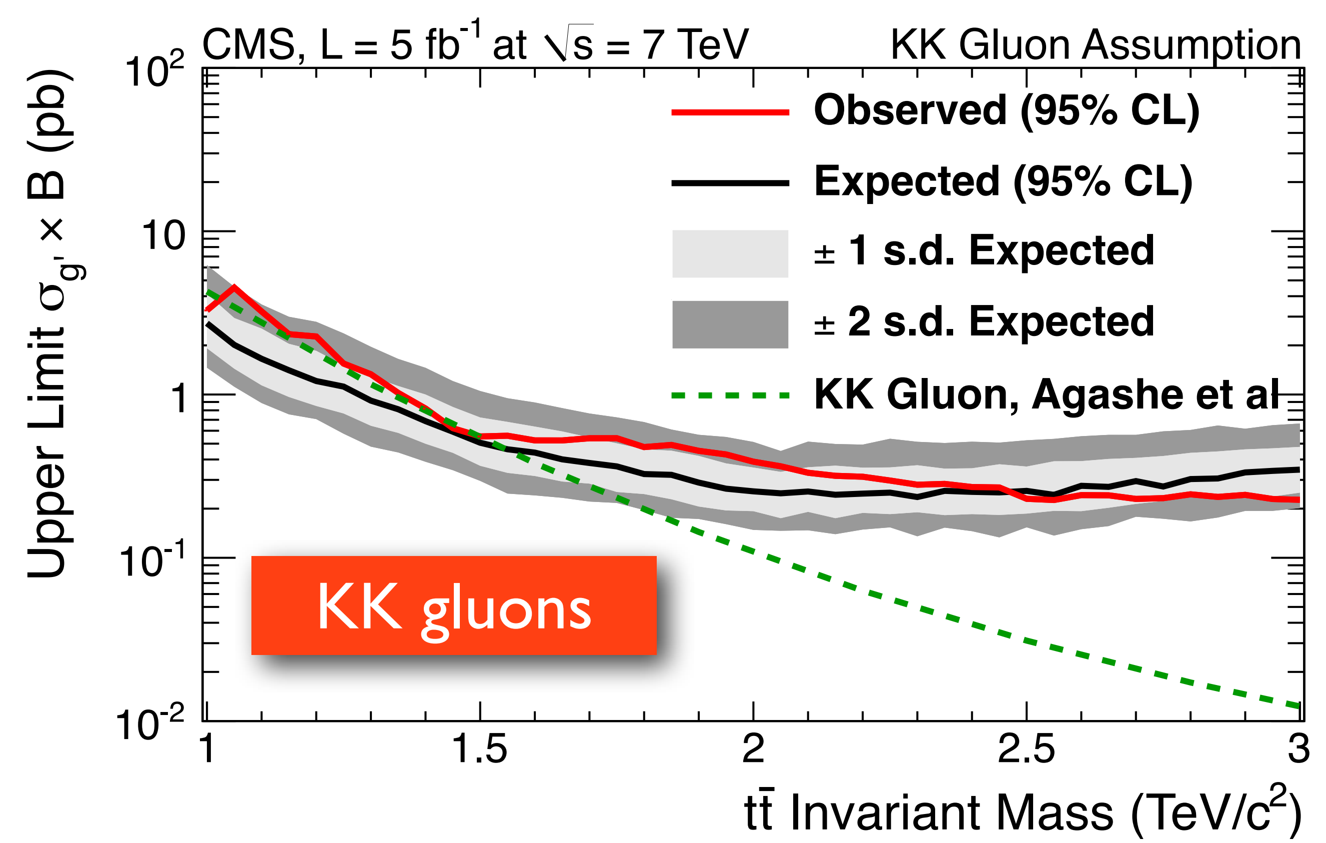
CMS arXiv:1204.2488 (5 fb^{-1})

95% CL upper limits on the production cross section:

narrow Z' mass < 1.55 TeV

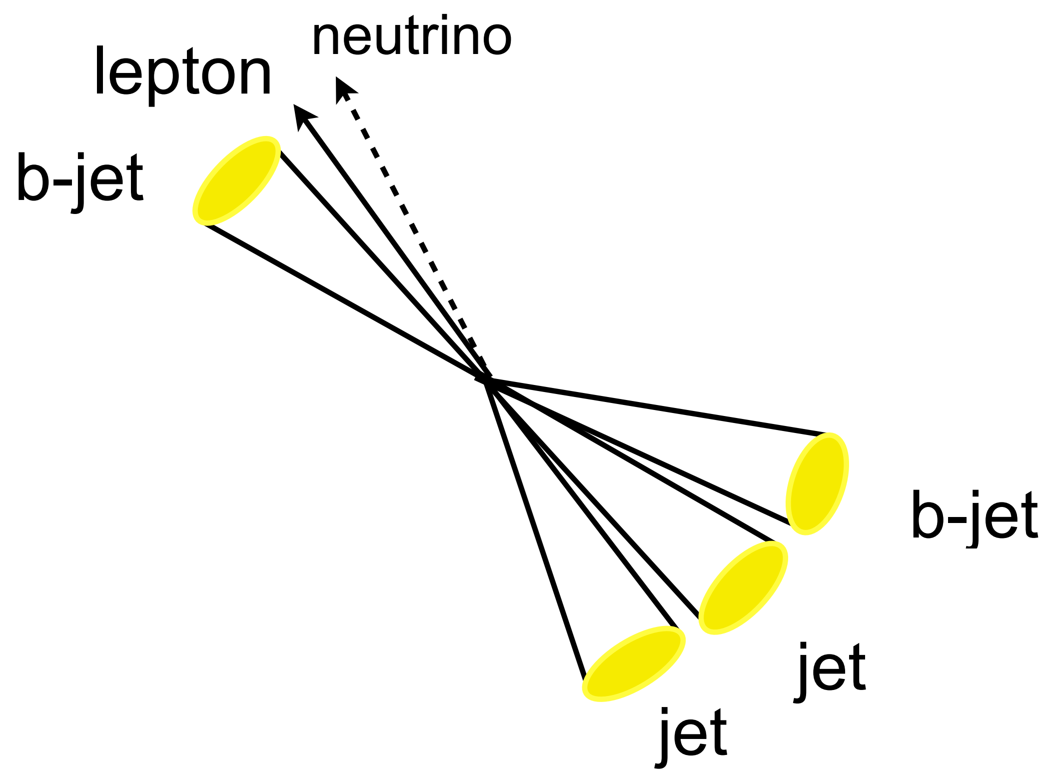
wide Z' mass < 2.0 TeV

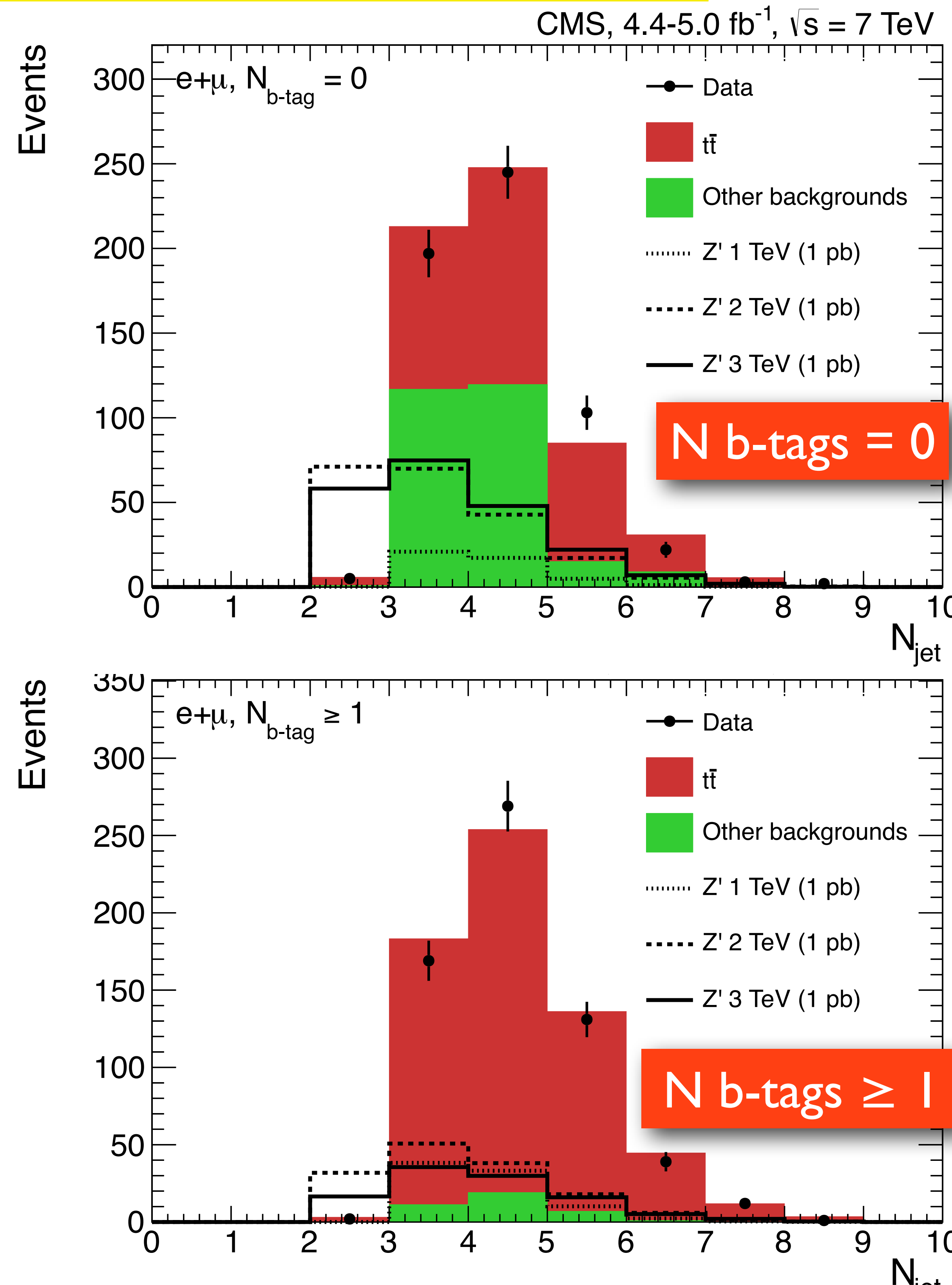
1.4 < KK gluon mass < 1.5 TeV



Top pair resonances IN HIGHLY-BOOSTED lepton+jets

CMS TOP-11-017 (arXiv:1209.4397)



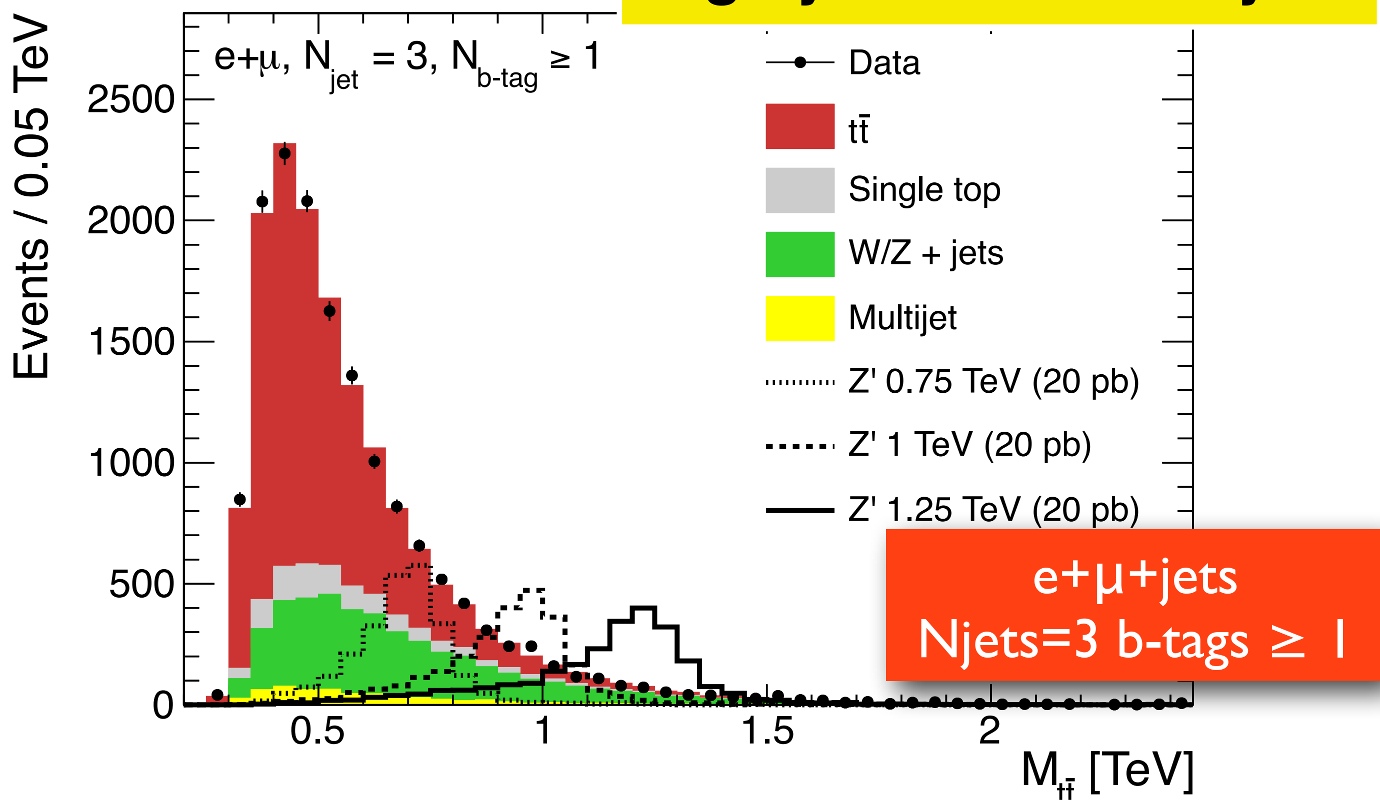


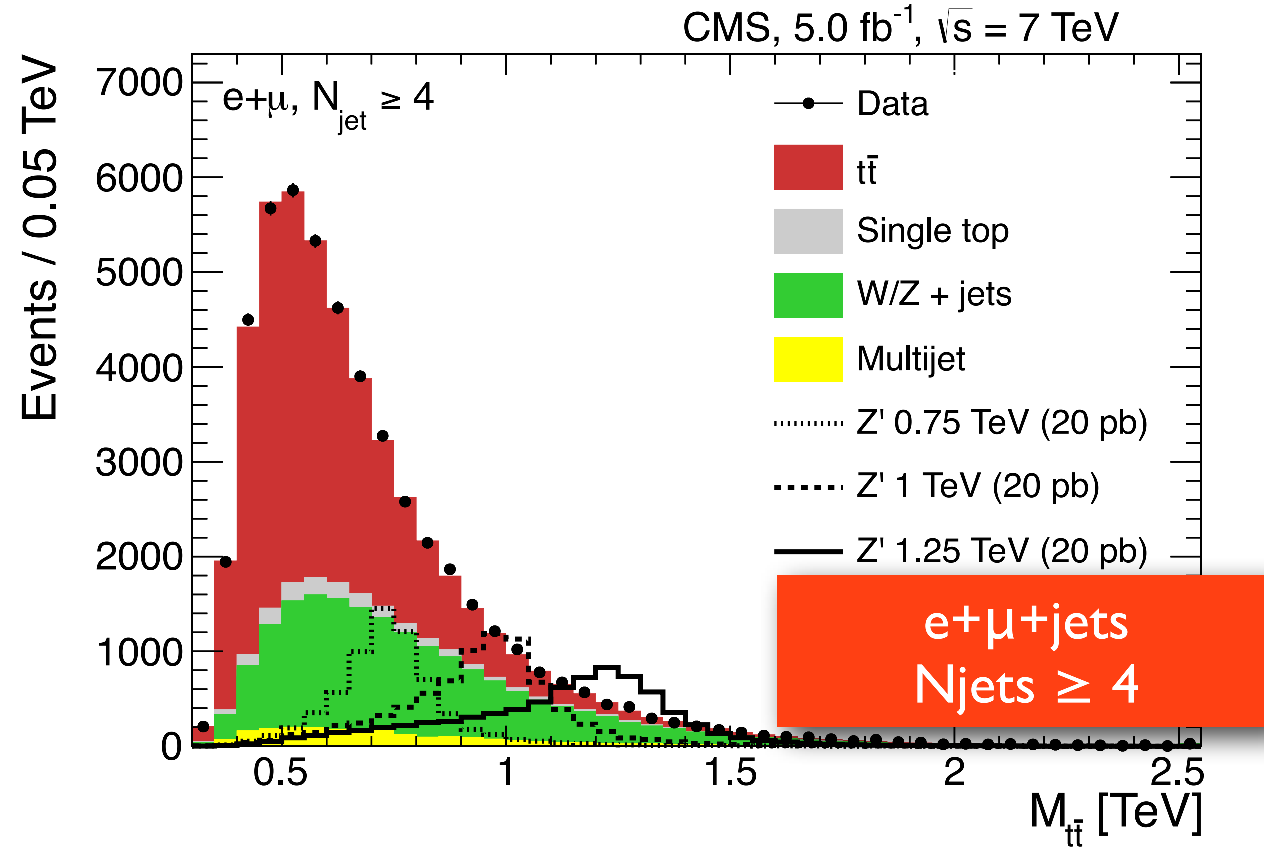
- Back-to-back dijet topology at boosted regime
  - ✓ Include 2 jet events
- Isolation requirement is inefficient for events with boosted jets.
  - ✓ Replace isolation with lepton-close-to-jet identification

Invariant mass of Top pairs in lepton+jets

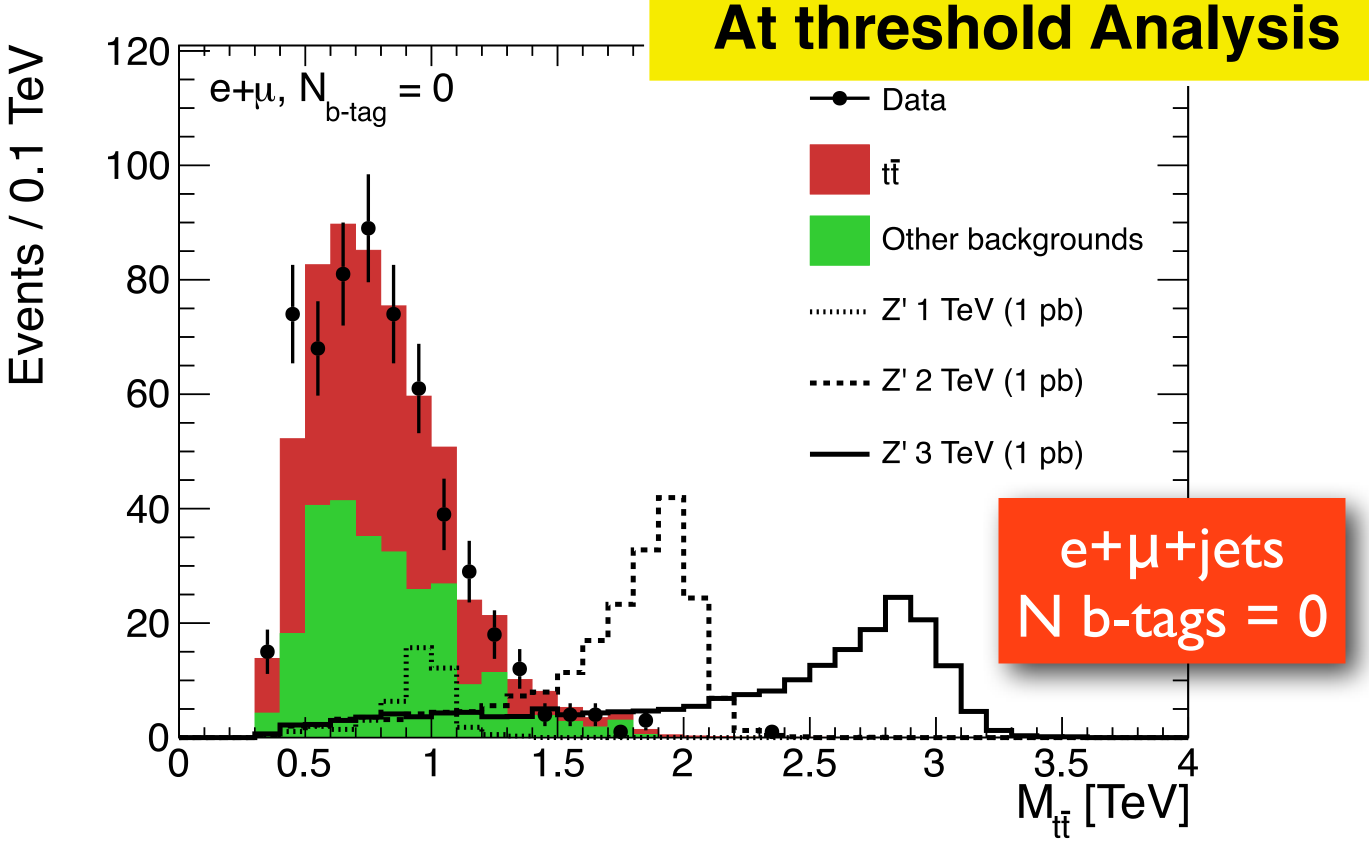
CMS TOP-12-017

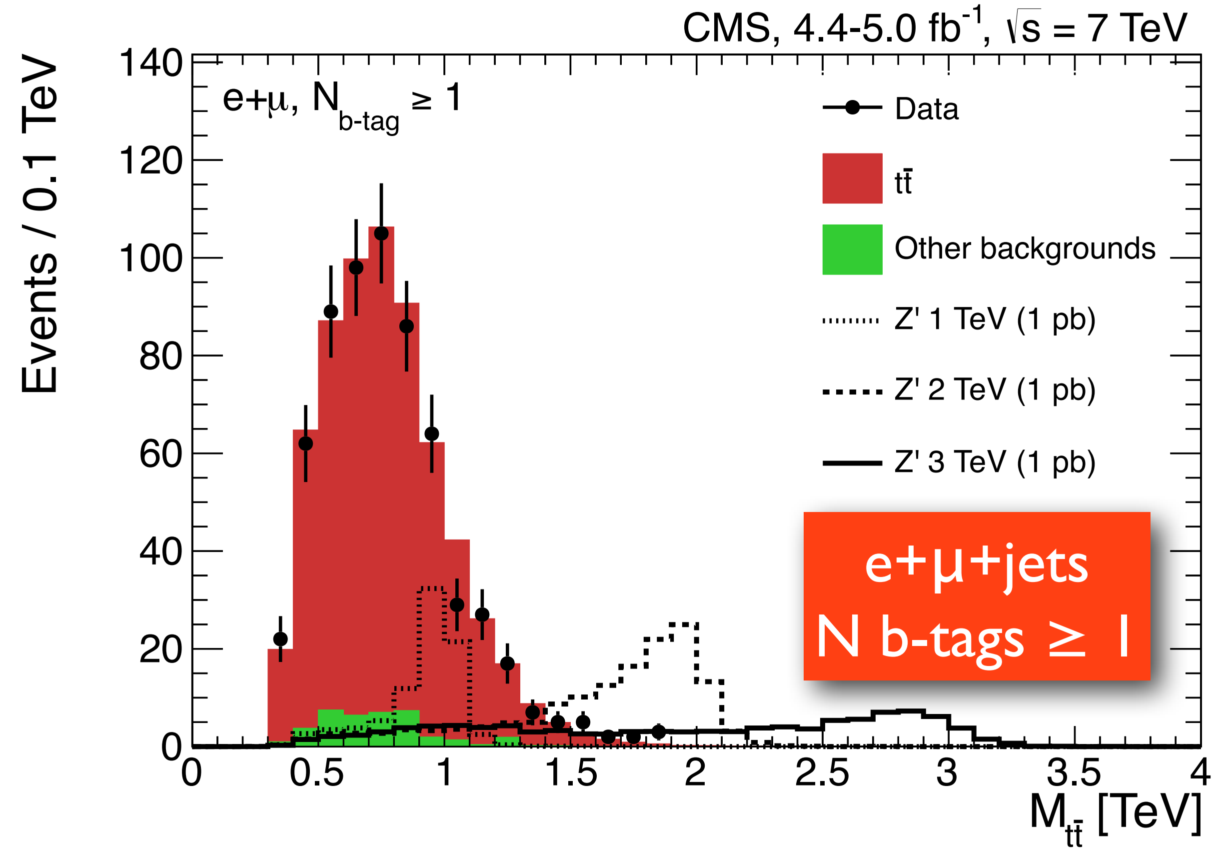
Highly-boosted Analysis





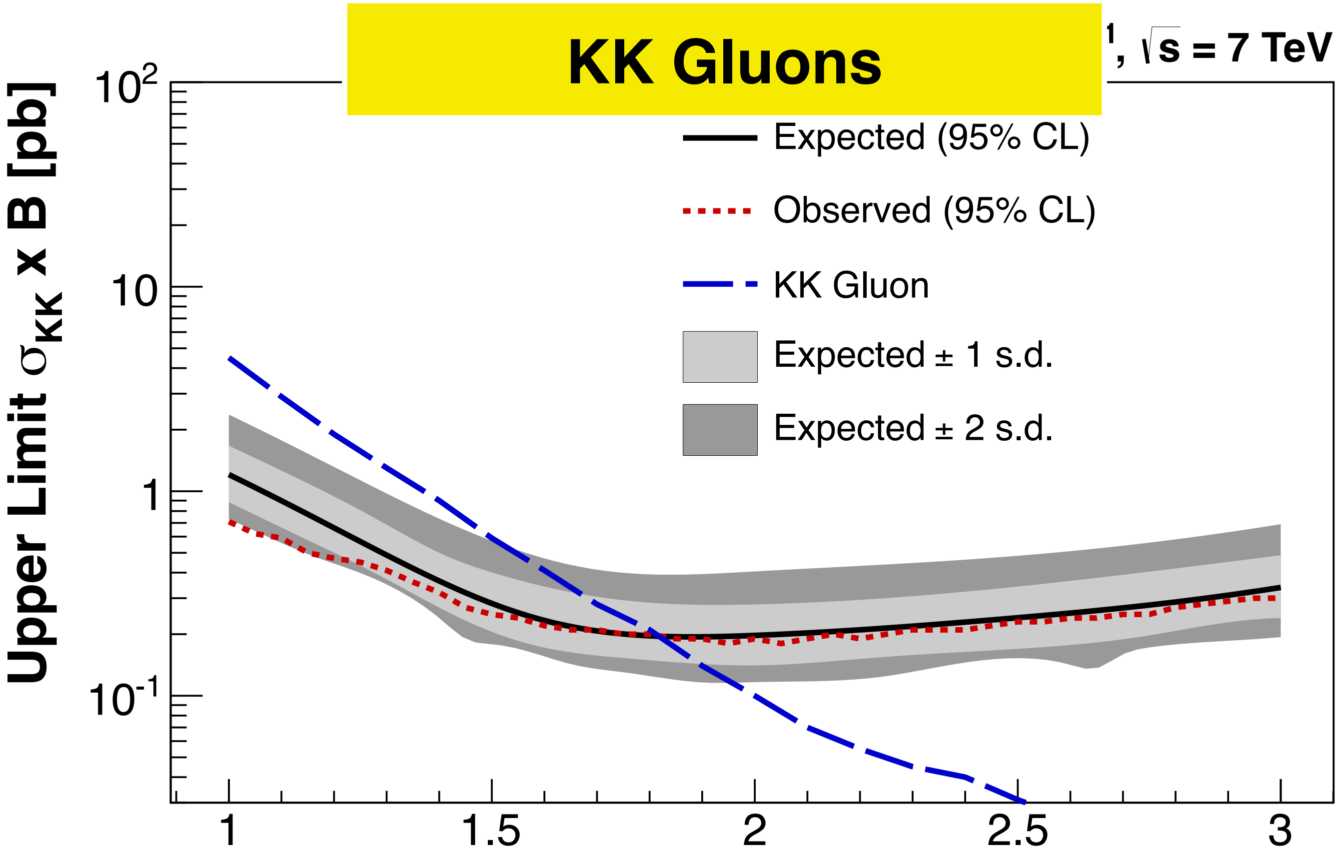
At threshold Analysis



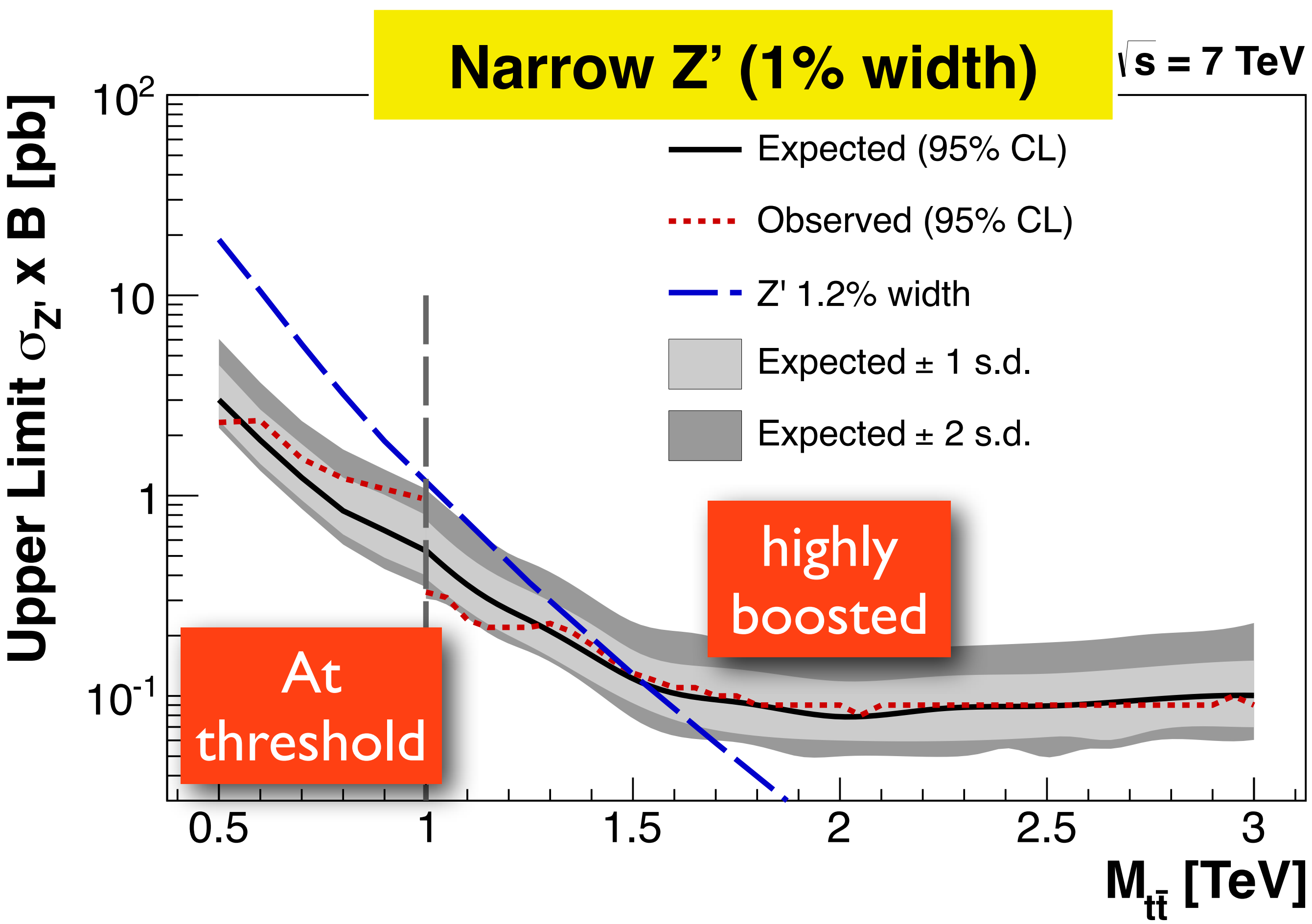


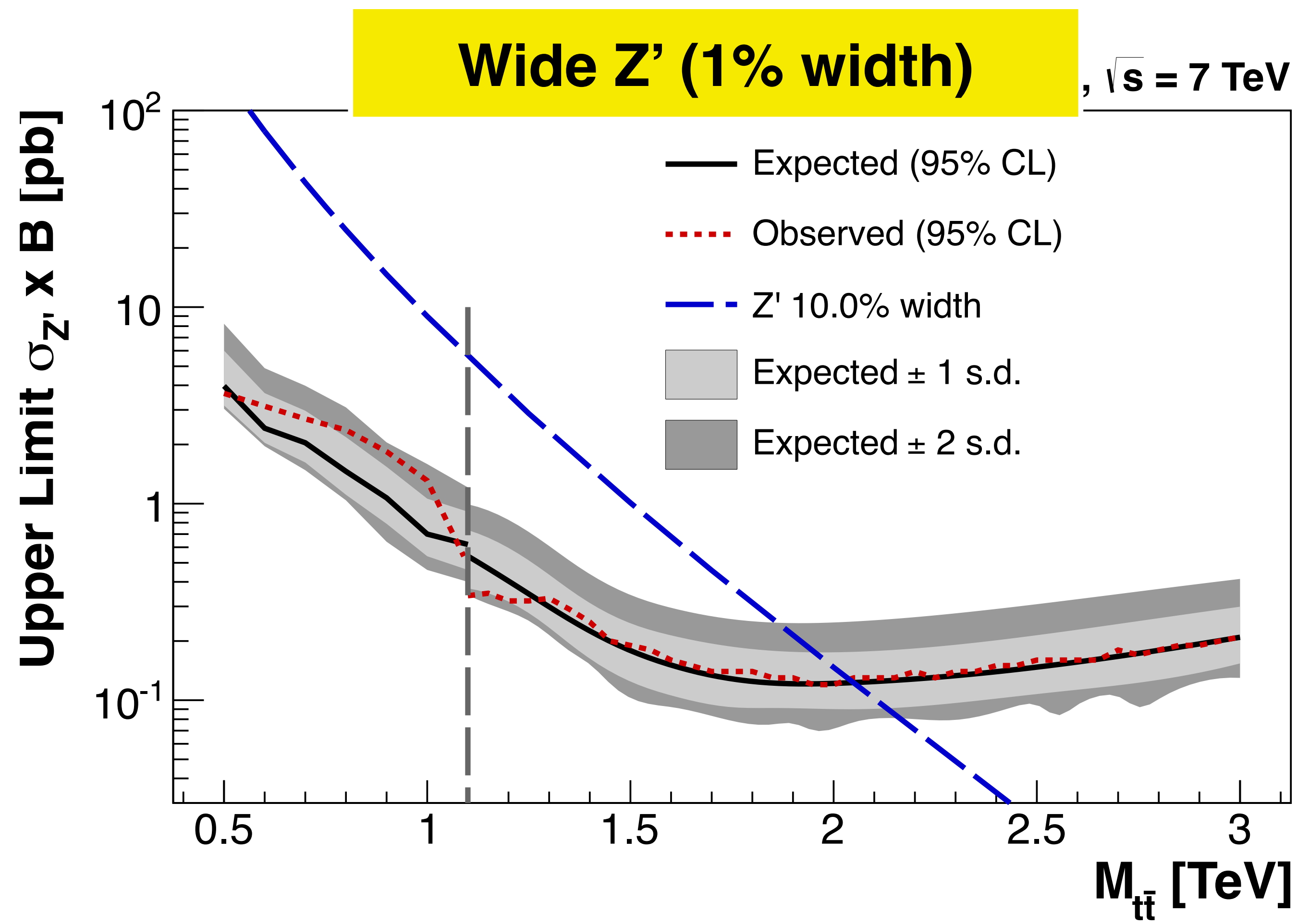
Results for Top pair Resonances in lepton+jets

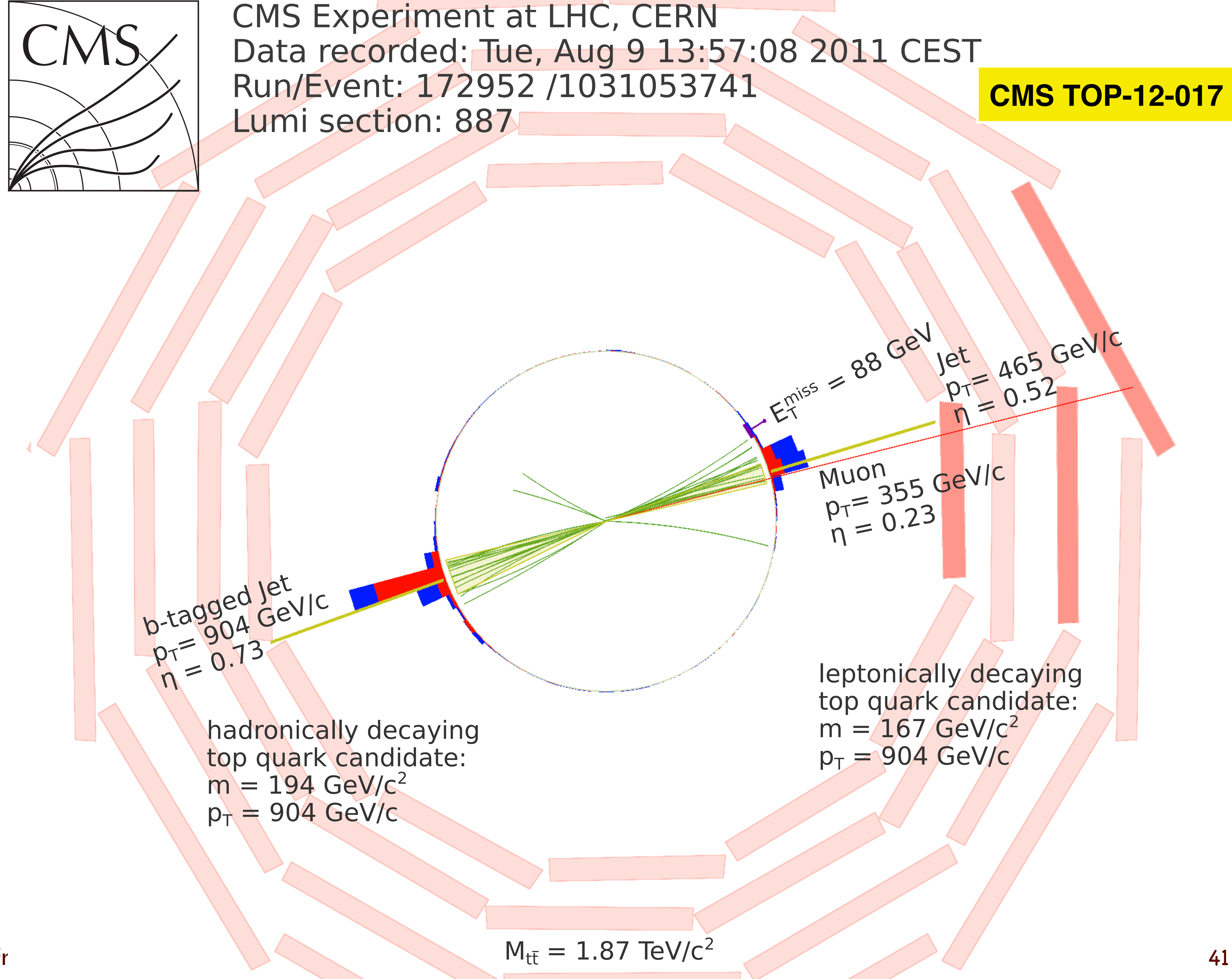
CMS TOP-12-017



- Topcolor Z’ bosons with narrow (wide) width are excluded for masses below 1.49 (2.04) TeV.
- KK gluons in the RS model excluded for masses below 1.82 TeV.



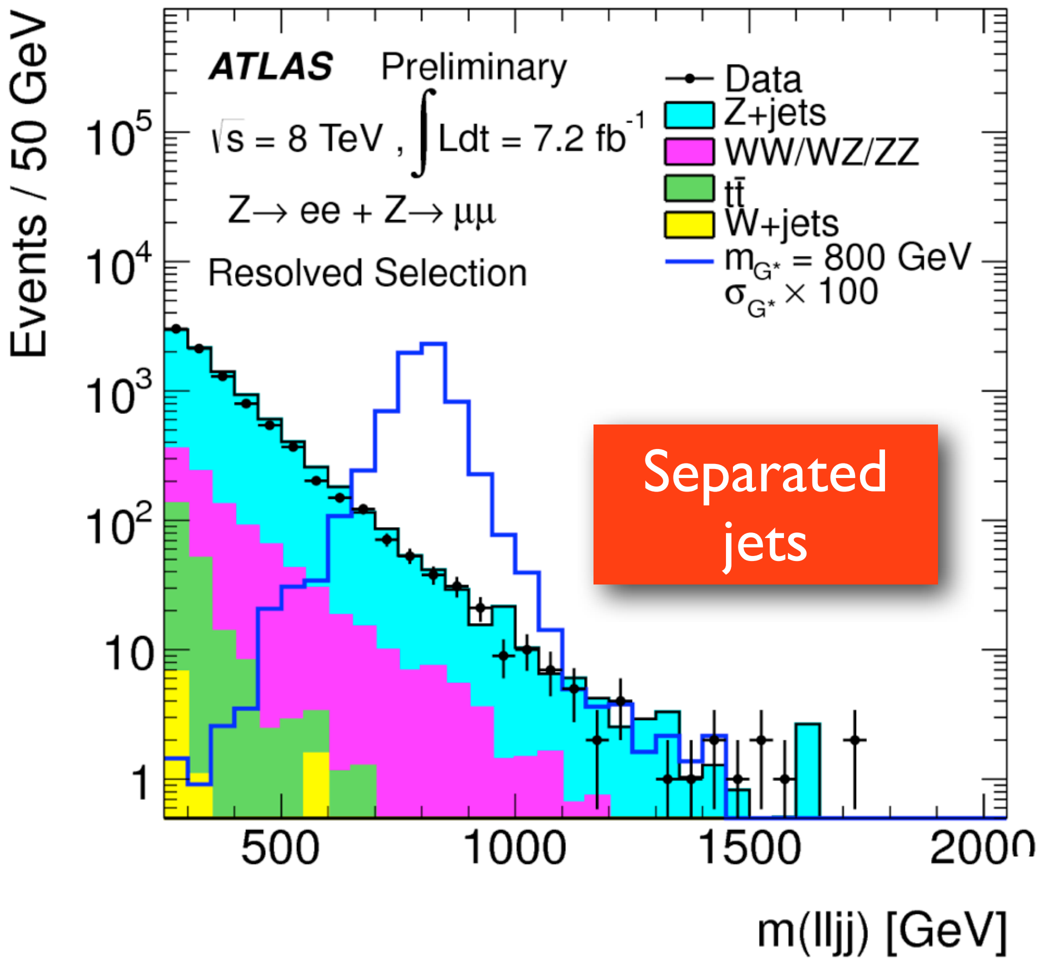


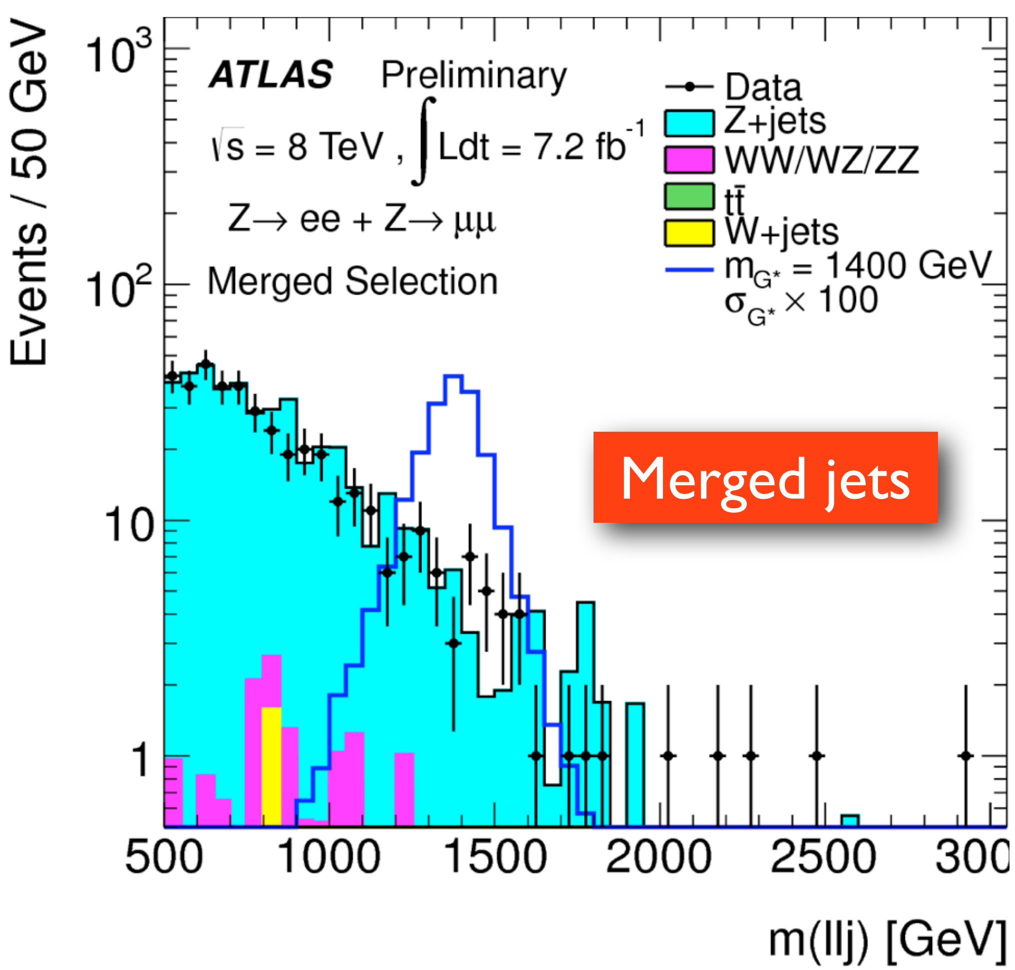

CMS
CMS Experiment at LHC, CERN
Data recorded: Tue, Aug 9 13:57:08 2011 CEST
Run/Event: 172952 /1031053741
Lumi section: 887
CMS TOP-12-017
E_T^{miss} = 88 GeV
Jet
p_T= 465 GeV/c
η = 0.52
Muon
p_T= 355 GeV/c
η = 0.23
b-tagged Jet
p_T= 904 GeV/c
η = 0.73
leptonically decaying
top quark candidate:
m = 167 GeV/c^2
p_T = 904 GeV/c
hadronically decaying
top quark candidate:
m = 194 GeV/c^2
p_T = 904 GeV/c
$M_{t\bar{t}}$ = 1.87 TeV/c^2

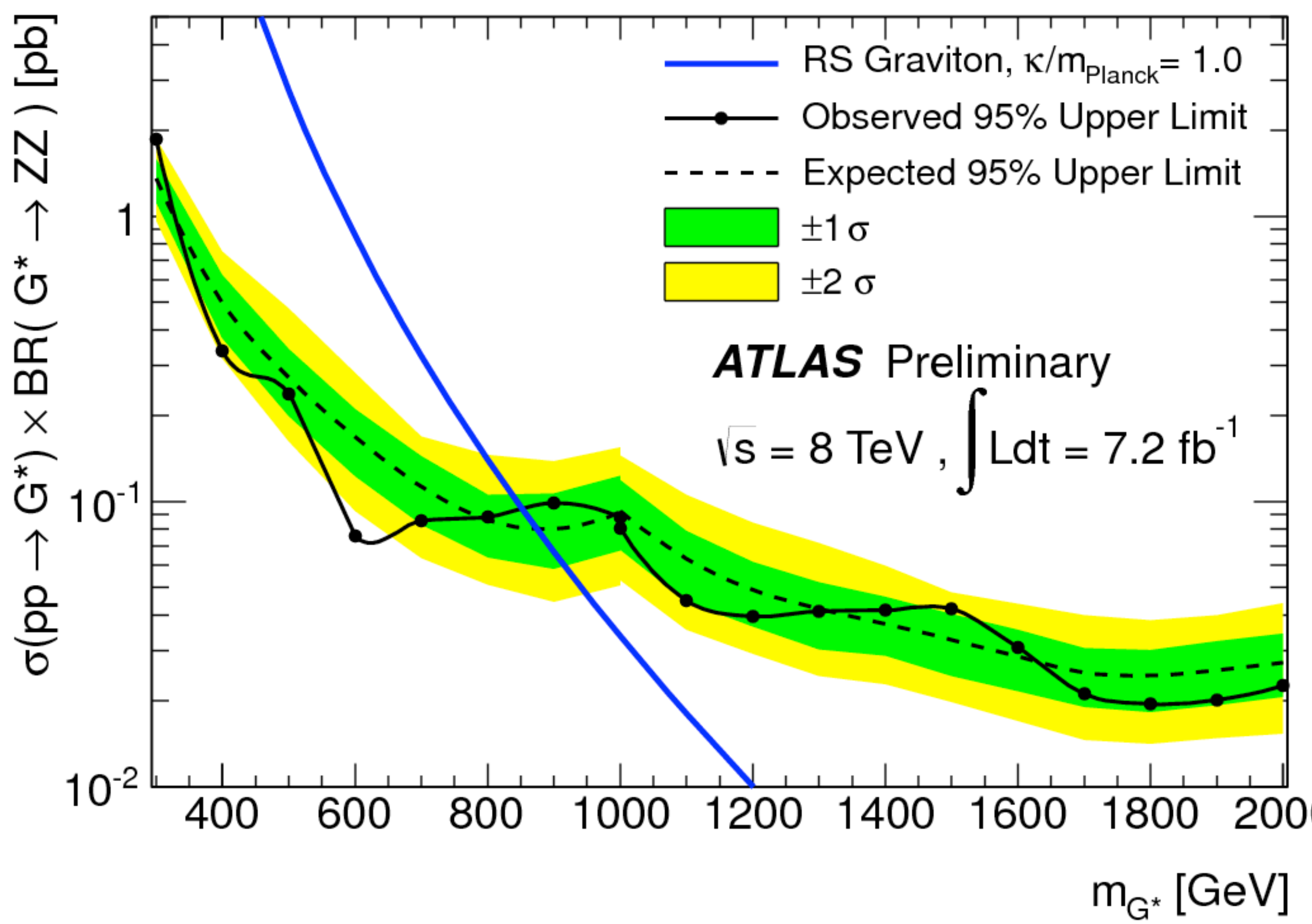
Resonant ZZ →llqq

Atlas-2012-150

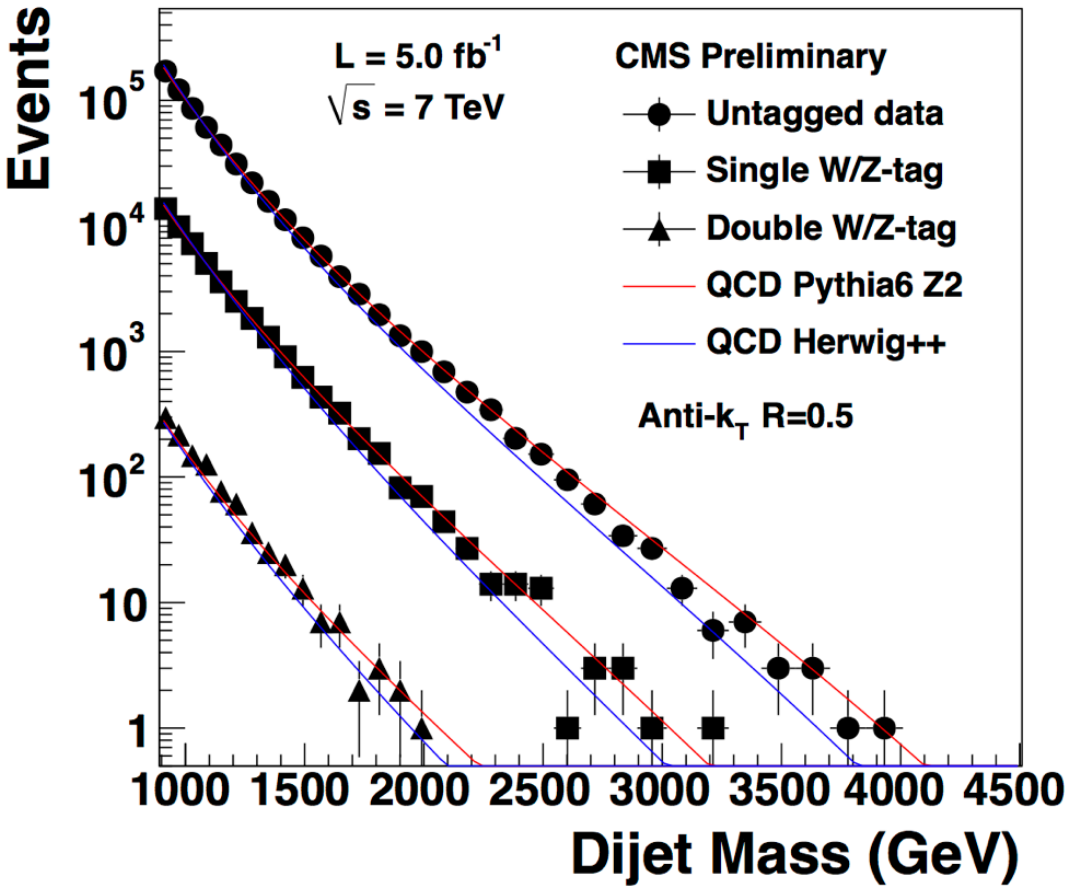
- Hadronic Z boson reconstructed using 1 jet (merged) or two jets.
- KK gluons in the bulk RS model are excluded below mass 850 GeV.



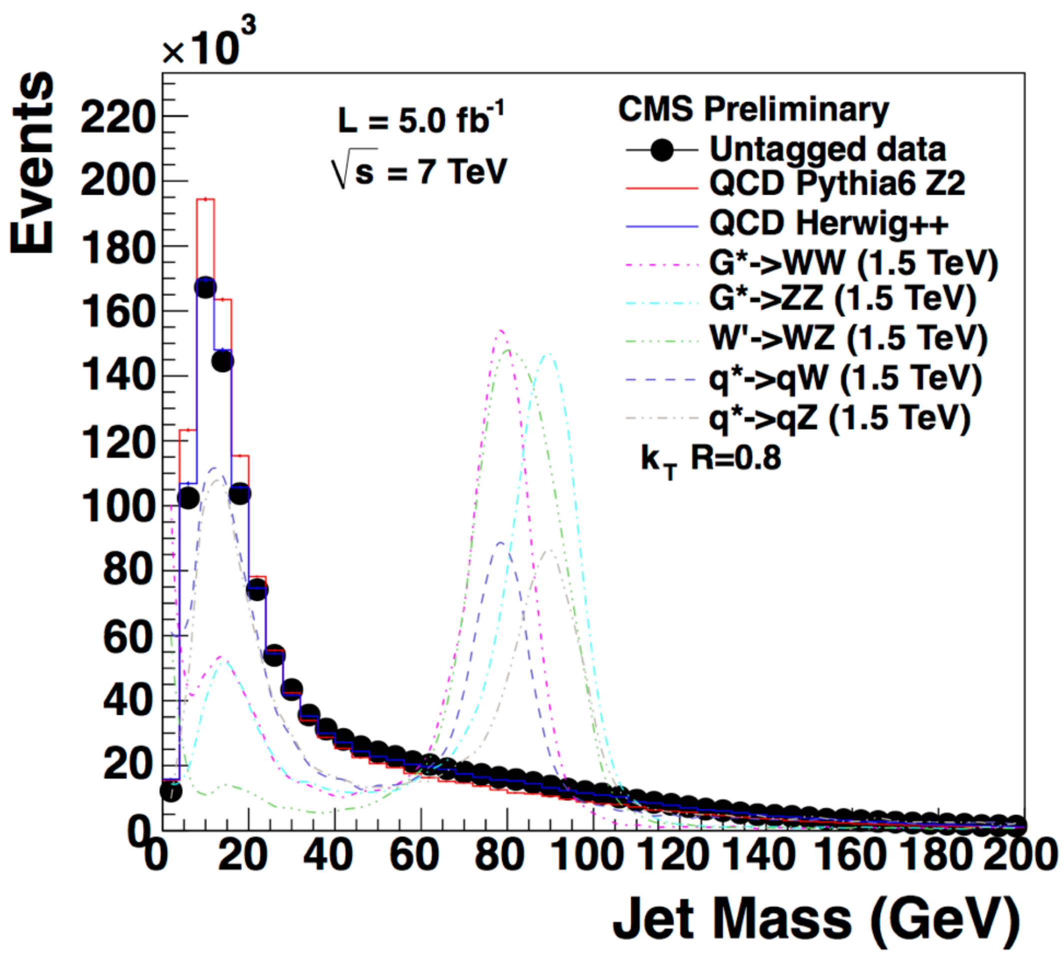


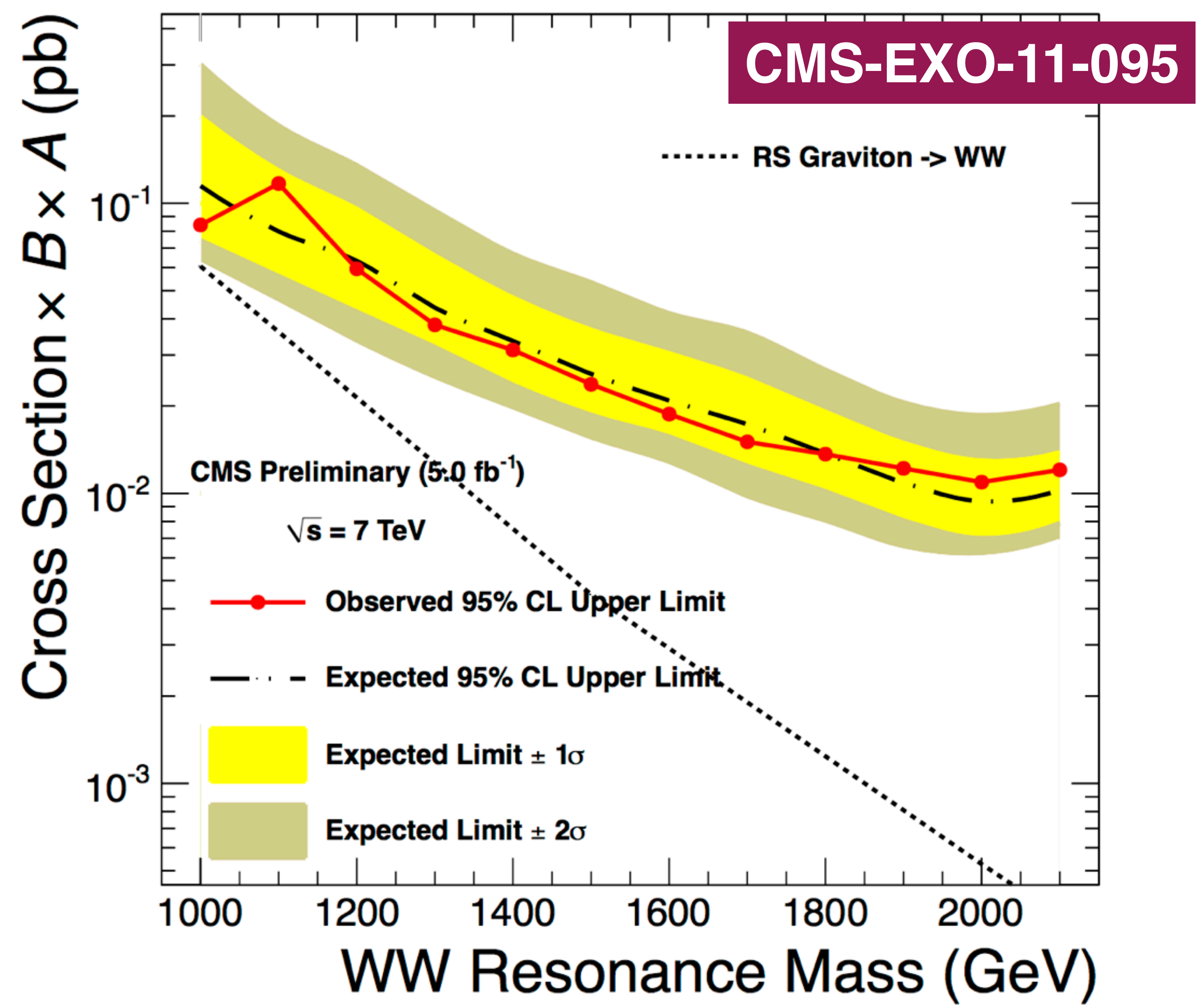


WW Resonances in the W-tagged Dijet Spectrum



- Jets reconstructed using Cambridge-Aachen CA algo. with R =0.8 Subjets are identified.
- At least one W-tagged jet with mass drop < 0.25
- Upper limits on RS graviton at 1 TeV WZ mass





Searching for New Physics

Searching for New Physics

Searching over
a large amount of data
and phase space

Searching for New Physics

Searching for New Physics

For the moment, only some illusions have appeared

Searching for New Physics

Searching for New Physics

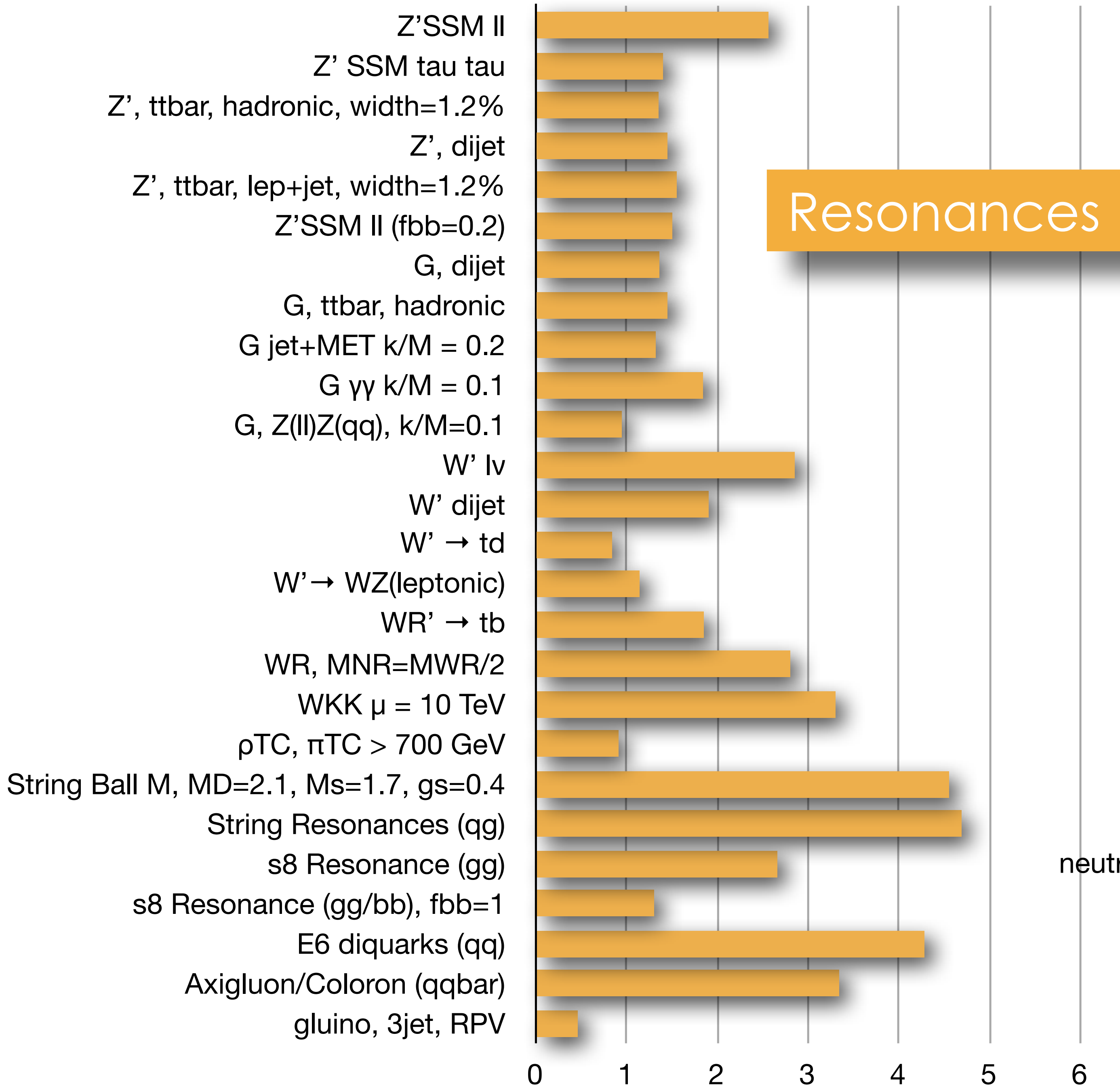
Still looking for the
real oasis ... it could be
just hiding behind the
next hill

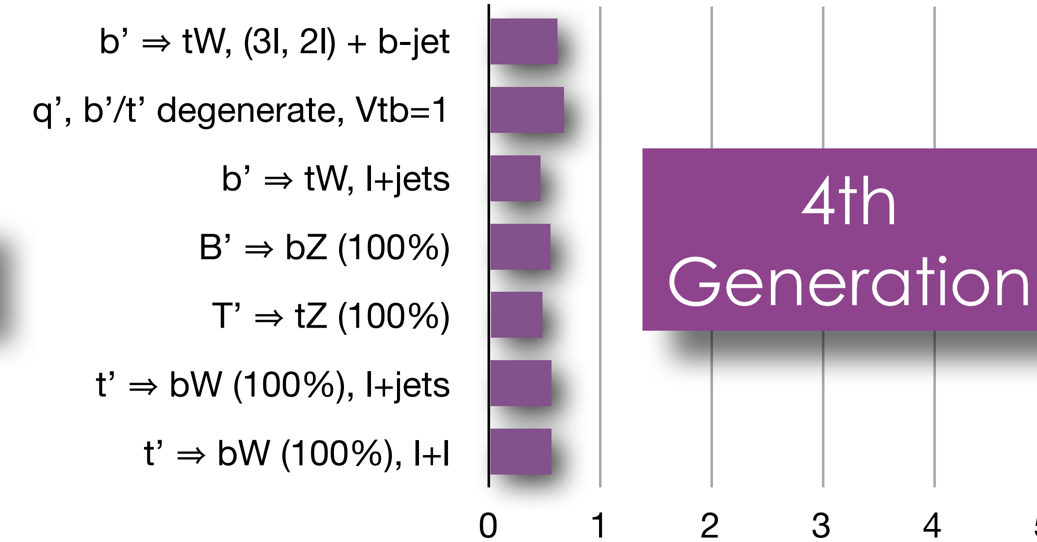
Searching for New Physics

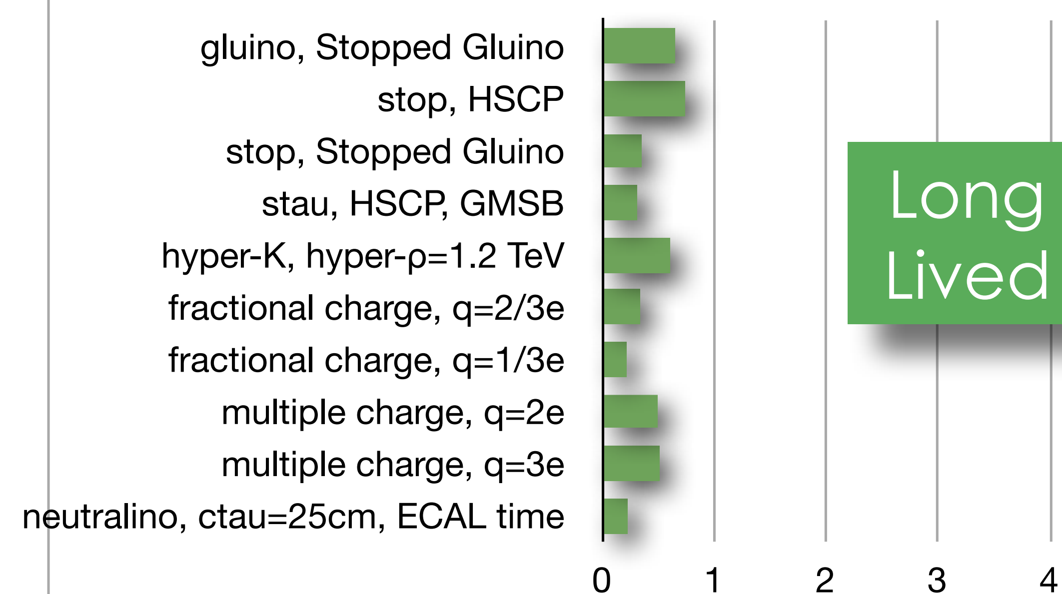
Searching for New Physics

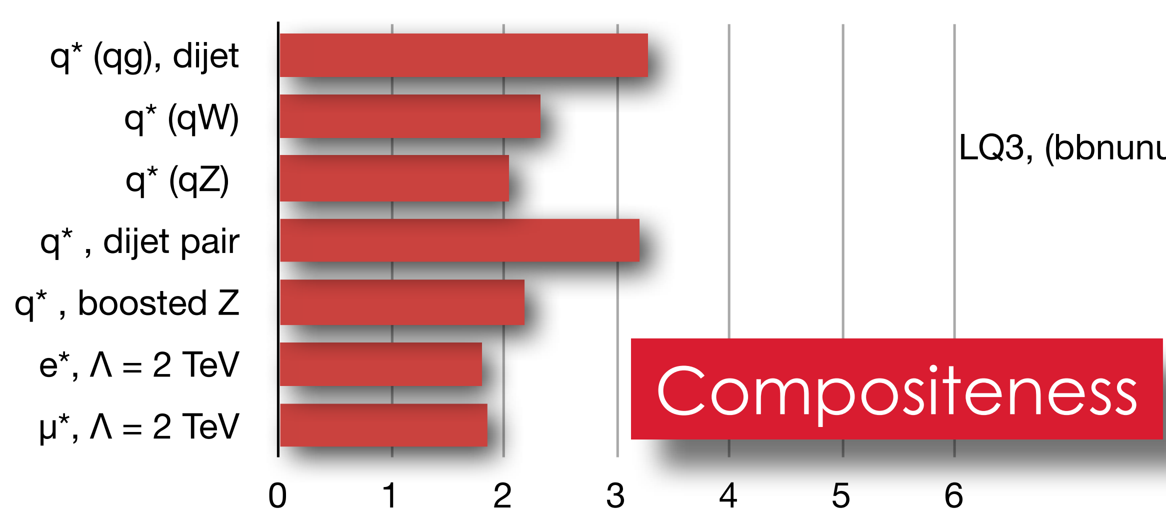
we continue combing
the dessert ....

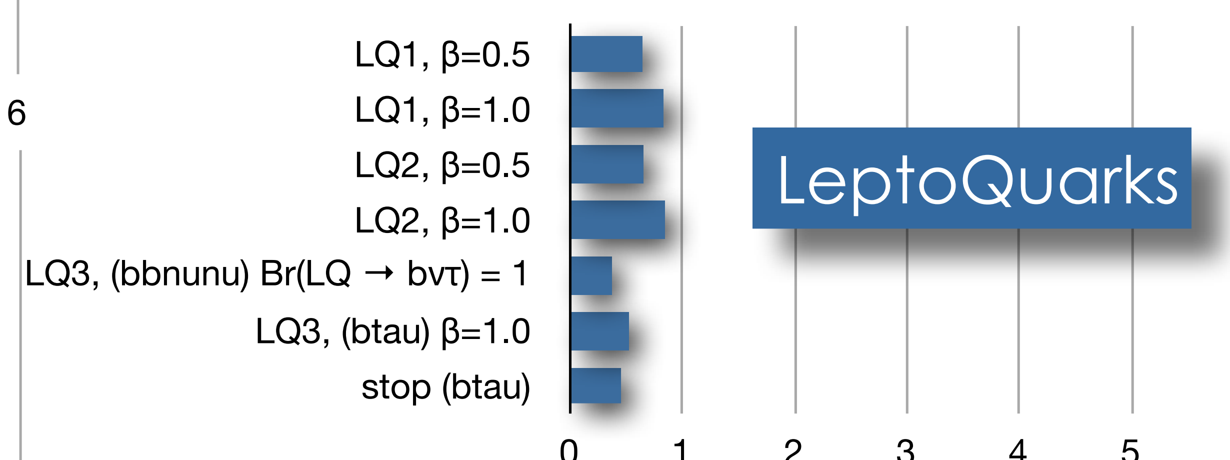
Summary from CMS



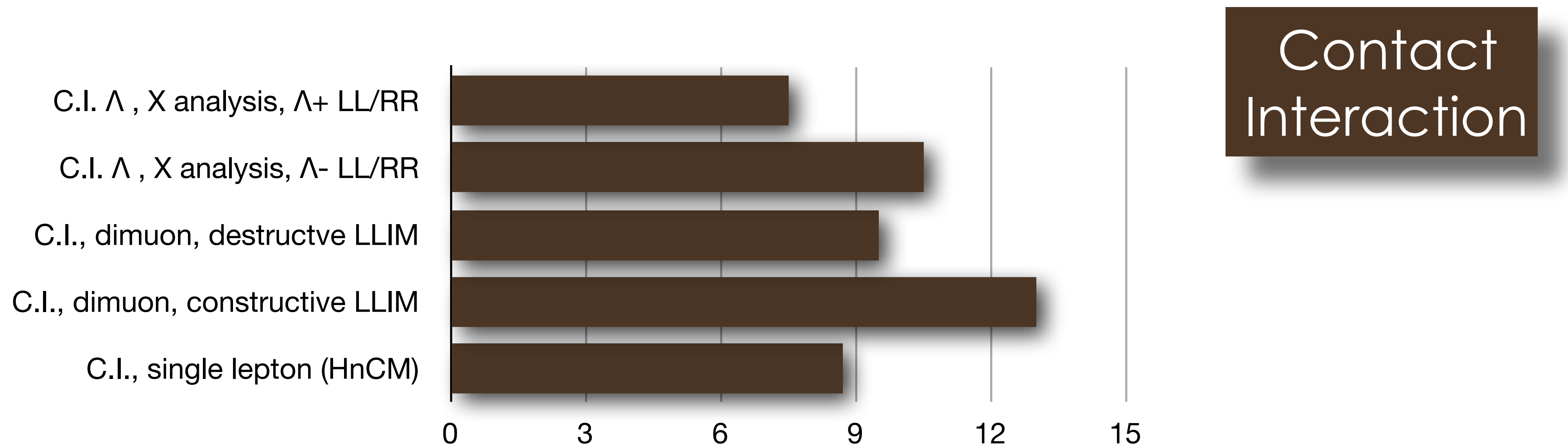


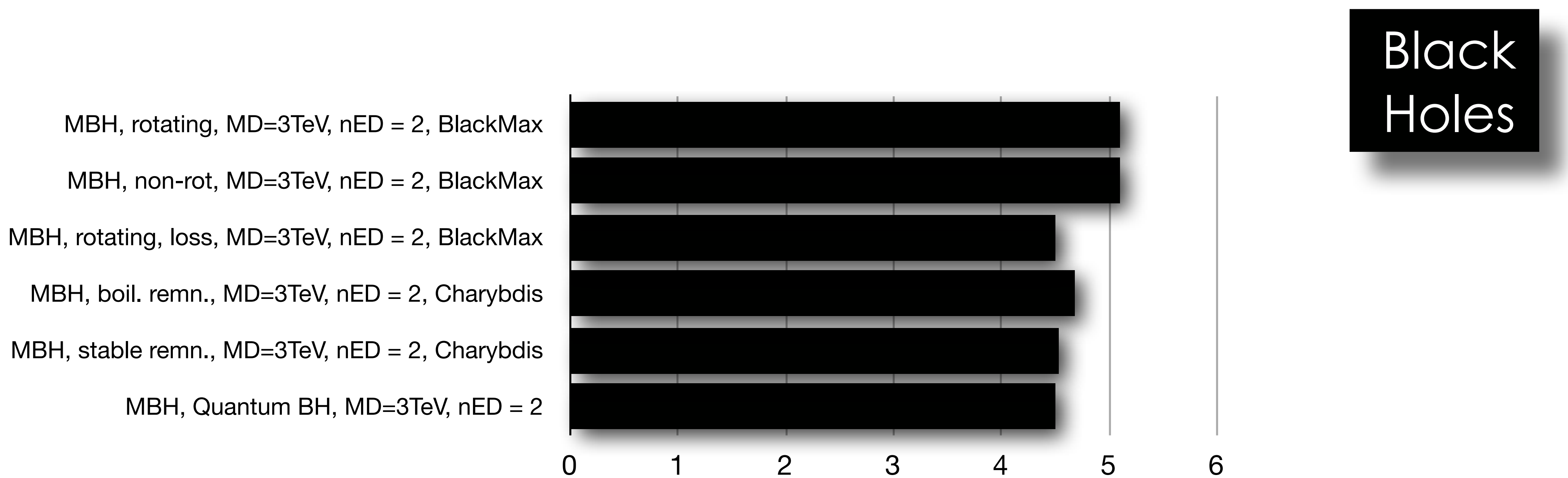




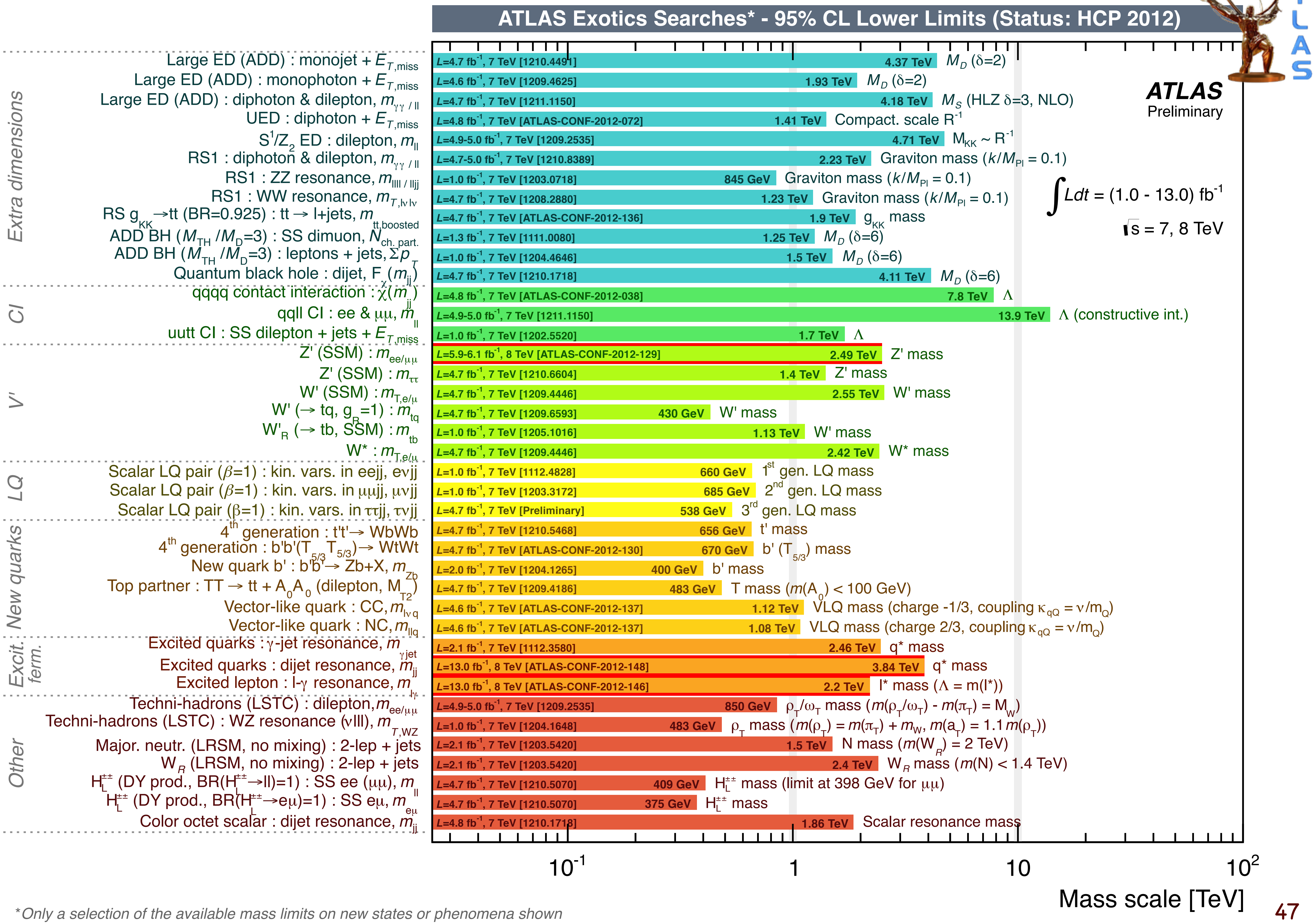


Summary from CMS





Summary from Atlas



Summary

- Outstanding performance by the LHC and the experiments.
- Many exotic searches are being updated with the larger $\sqrt{s}$= 8 TeV data from 2012:
  - A small snapshot of these analyses has been showed in this talk.
- With larger samples, expect new innovative searches.
  - Need to comb the whole dessert.
  - New physics could by hiding around the corner (in your face)
- Entering a new territory at higher energies and large statistics
  - We can try new analysis techniques

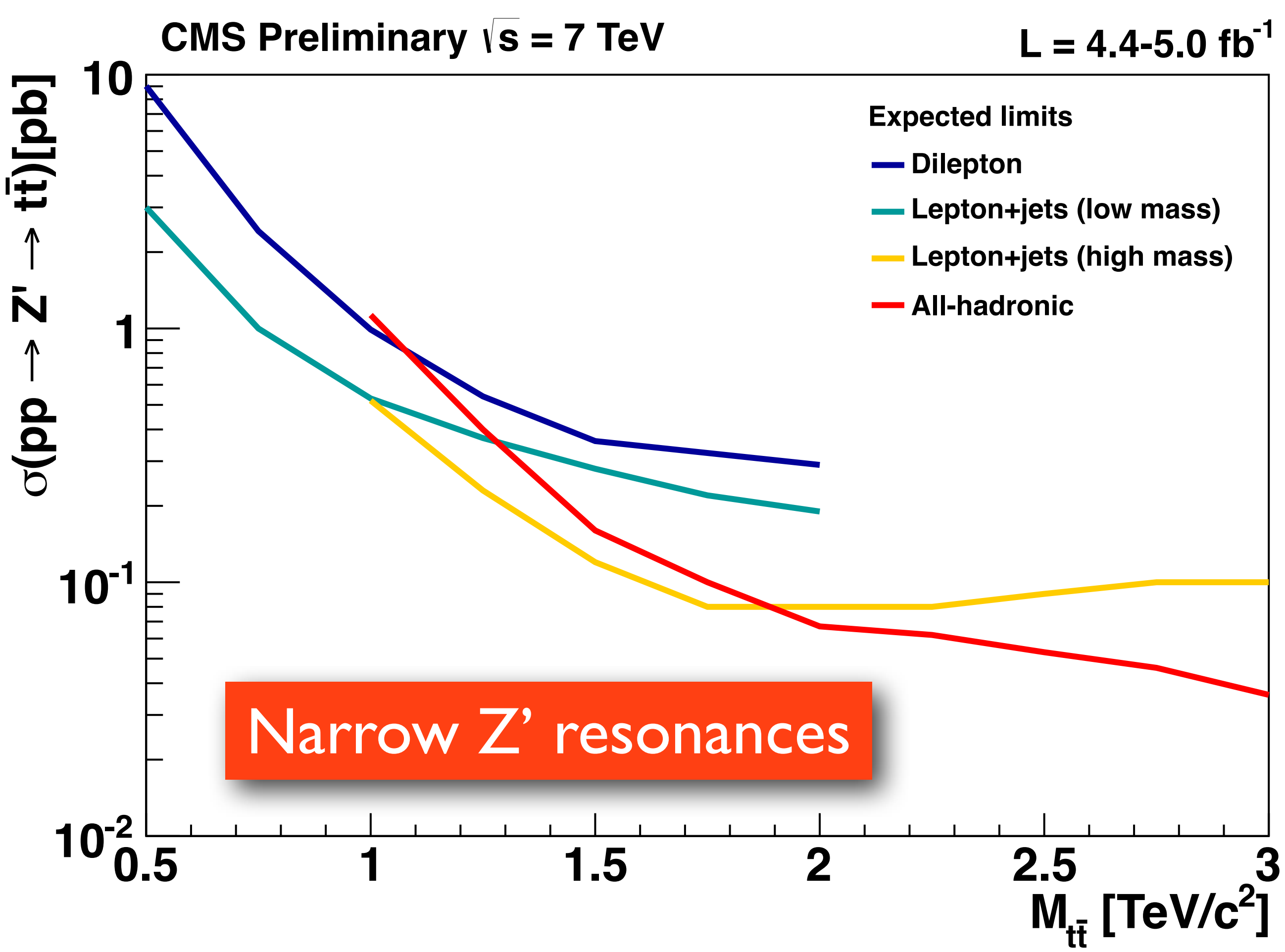
Valladro Keating

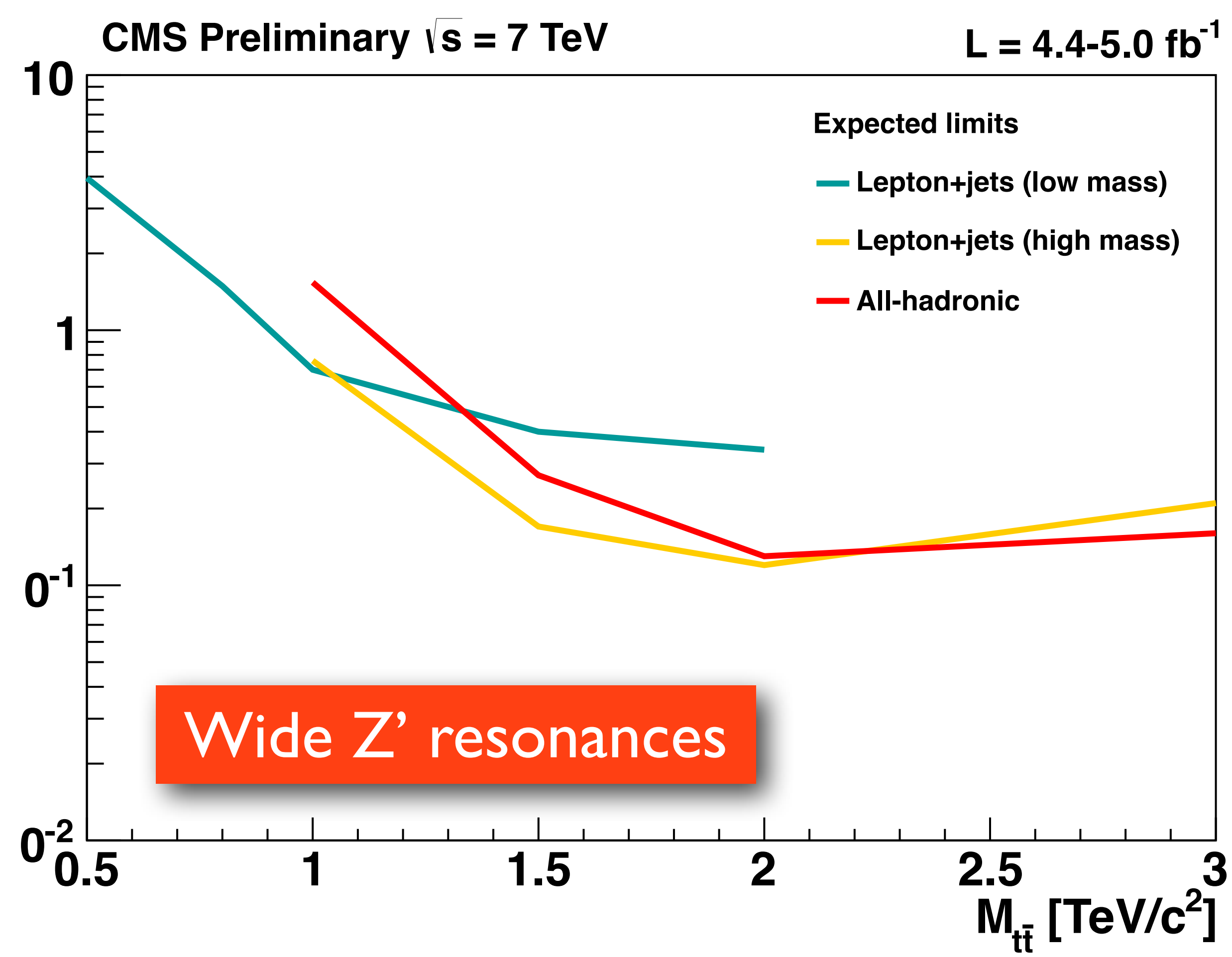
“This land is very pleasant, so much that I thought to be close to Paradise” Americo Vespucio

Obrigado
Feliz Natal

additional slides

Comparison of search sensitivity between Z'(ttbar) analyses





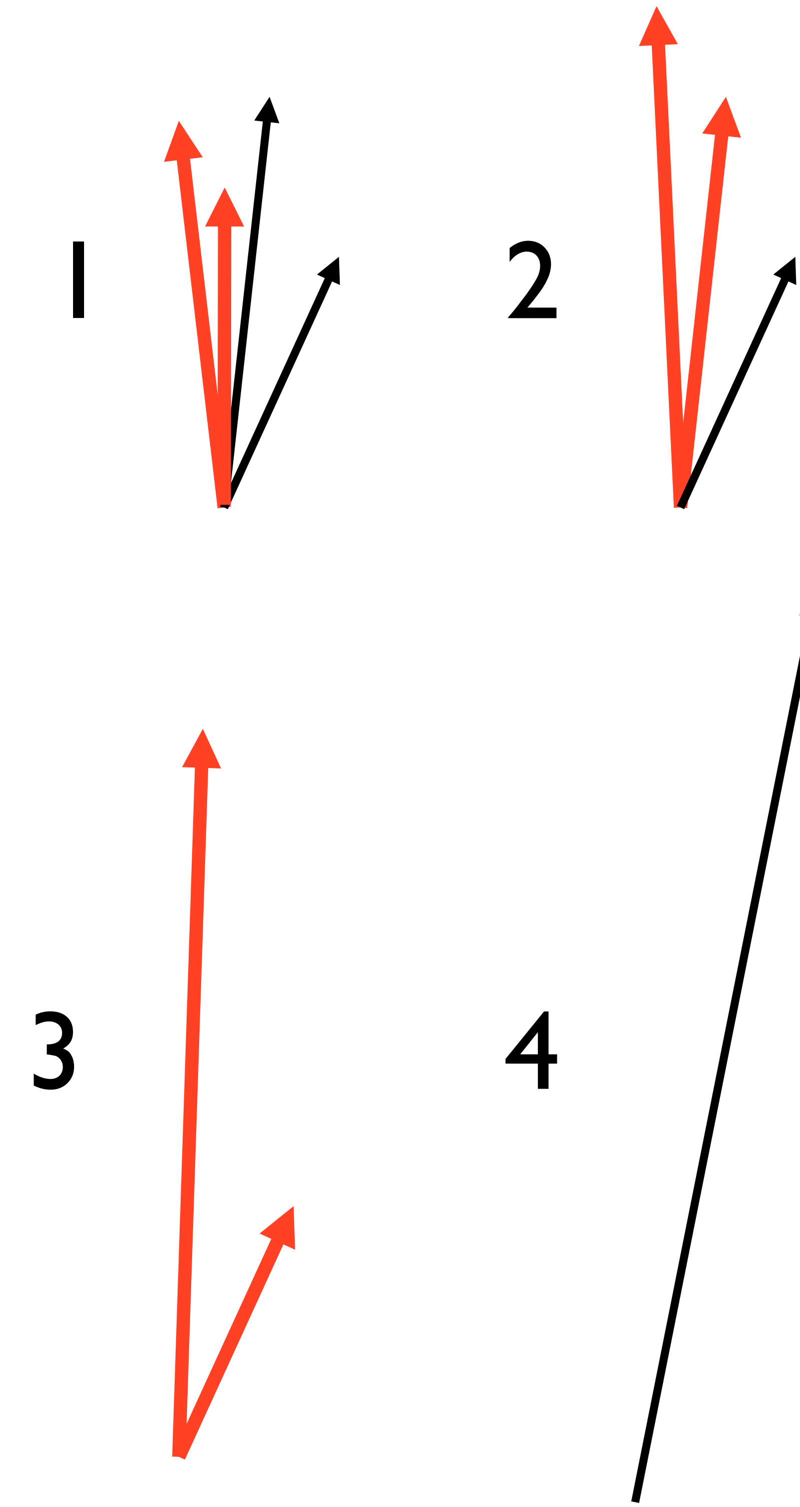
Sequential Clustering Algorithm

- Pairwise examination of input 4-vectors of particle flow (PF) candidates.
- Calculate d_{ij}, d_{iB}

$$d_{ij} = min\{k_{ti}^n, k_{tj}^n\} \frac{\Delta R_{ij}}{R}$$

$$d_{iB} = k_{ti}^n$$

  - k_T (n = 2)
  - **Cambridge Aachen CA (n=0)**
  - Anti-k_T (n = -2)
- Find min of all dij and diB
  - If min is a dij, merge and iterate
  - If min is a diB, classify as a final jet
- Continue until list is exhausted



arXiv:0802.1189

top-tagging kinematic requirements

- Jet mass: the mass of the four-vector of the hard jet constituents.

$$140 < m_{\text{tjet}} \leq 250 \text{ GeV}$$

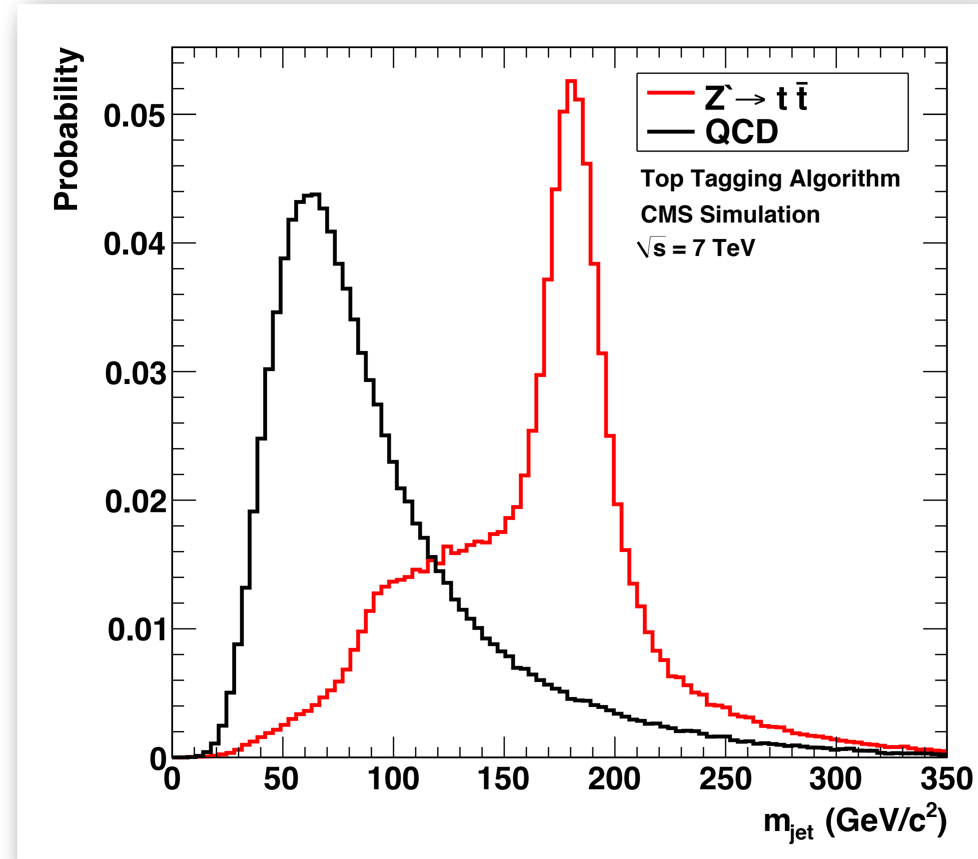
- Number of subjets: the number of jets found by the algorithm.

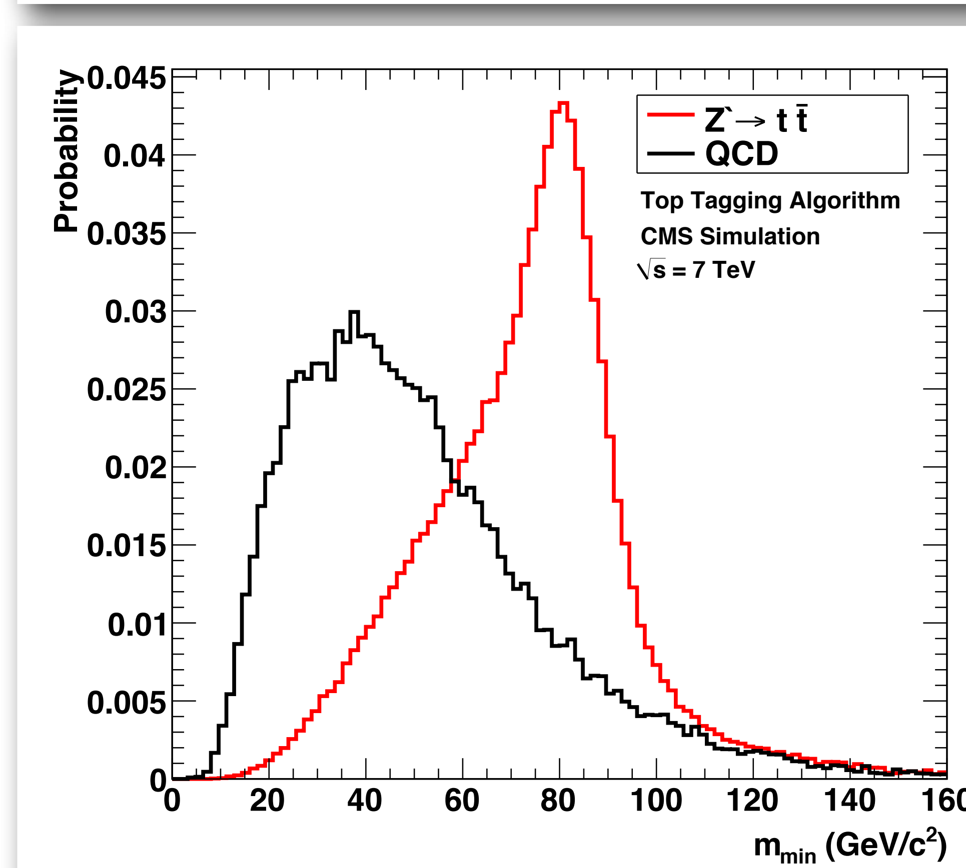
$$N_{\text{subjets}} \geq 3$$

- Minimum pairwise mass:

$$m_{ij} = \sqrt{(E_i + E_j)^2 - (\mathbf{p}_i + \mathbf{p}_j)}$$

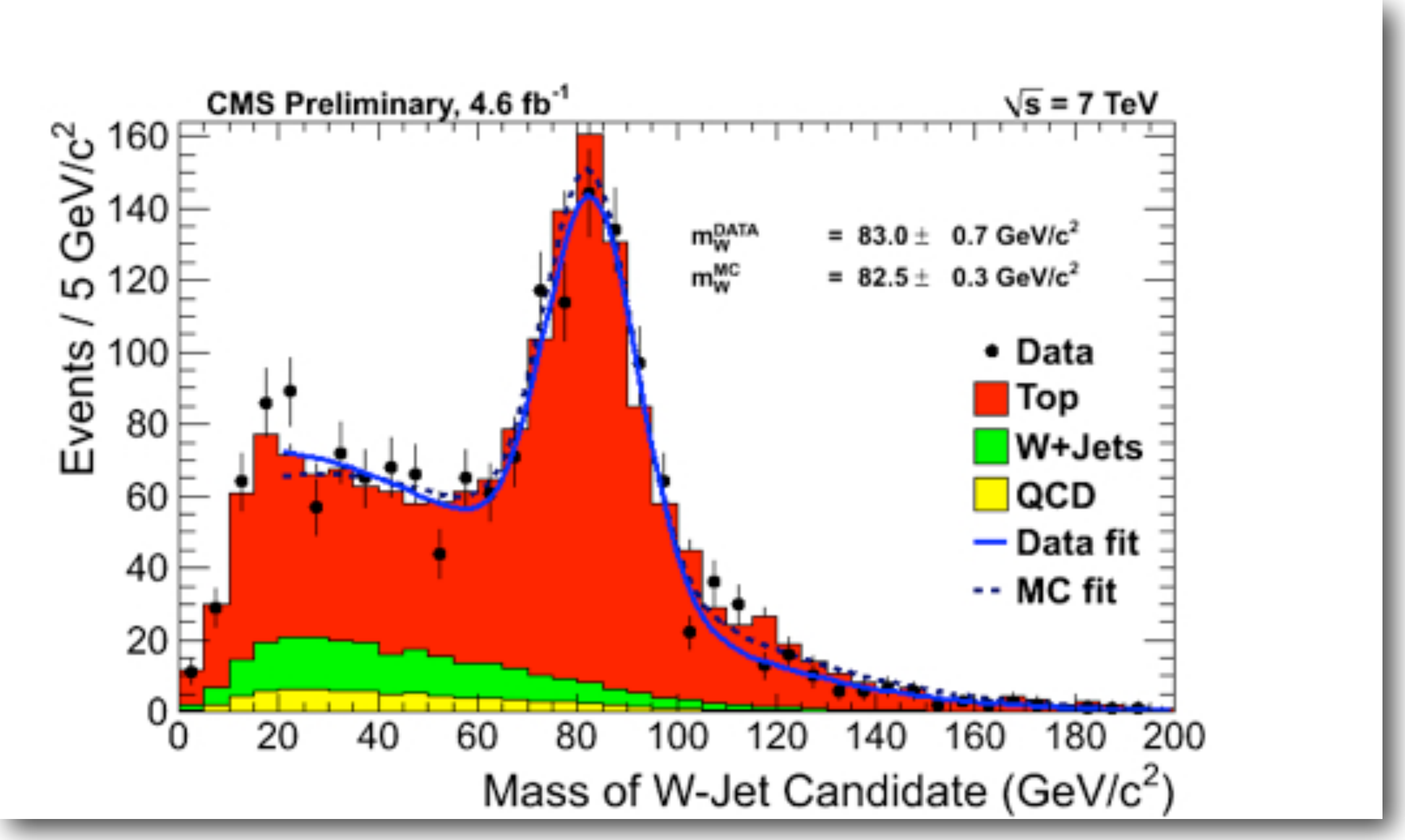
$$m_{\min} = \min\{m_{ij}\} > 50 \text{ GeV}$$





Subjet energy scale

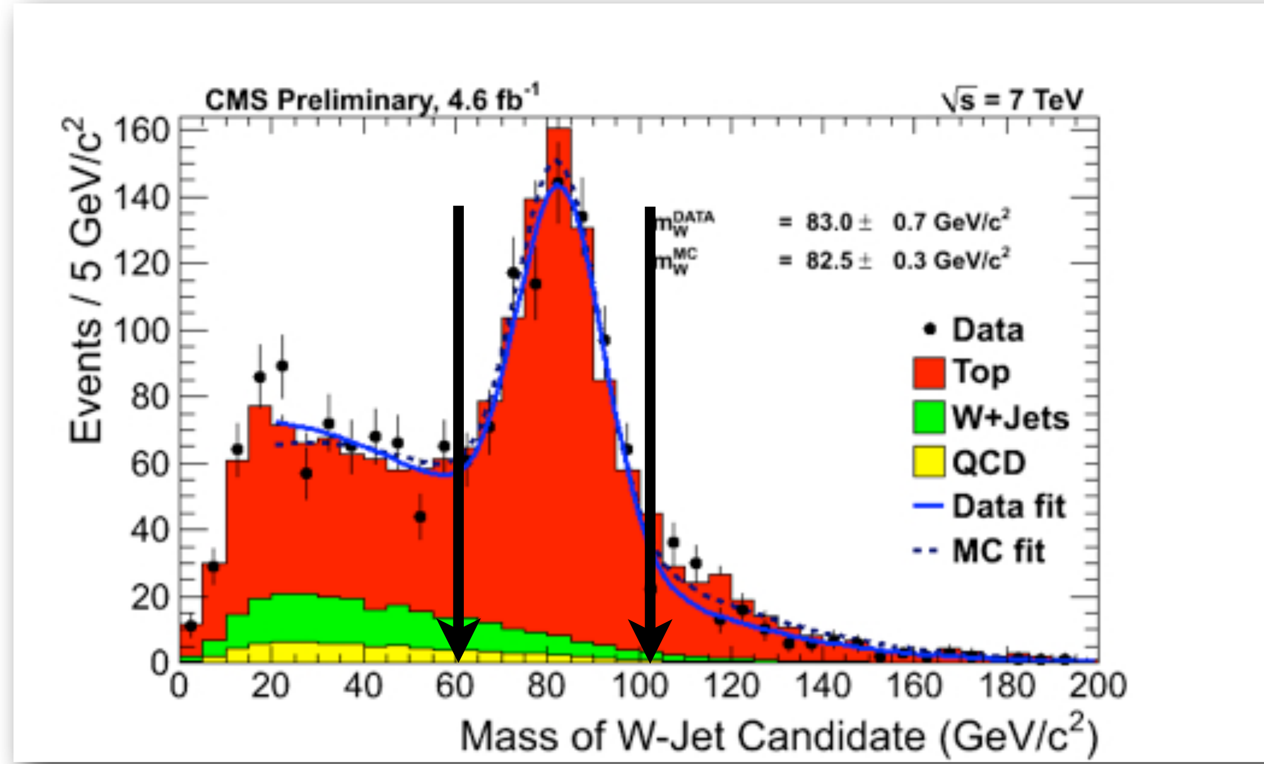
- The energy scale for subjets might be different to the one for the total jet.
- Tested using hadronic top in semilep. tt events:
  - One high-pT isolated muon from PV.
  - At least two jets pt > 30 GeV with a leading jet pt > 200 GeV and at least one b-tagged jet.

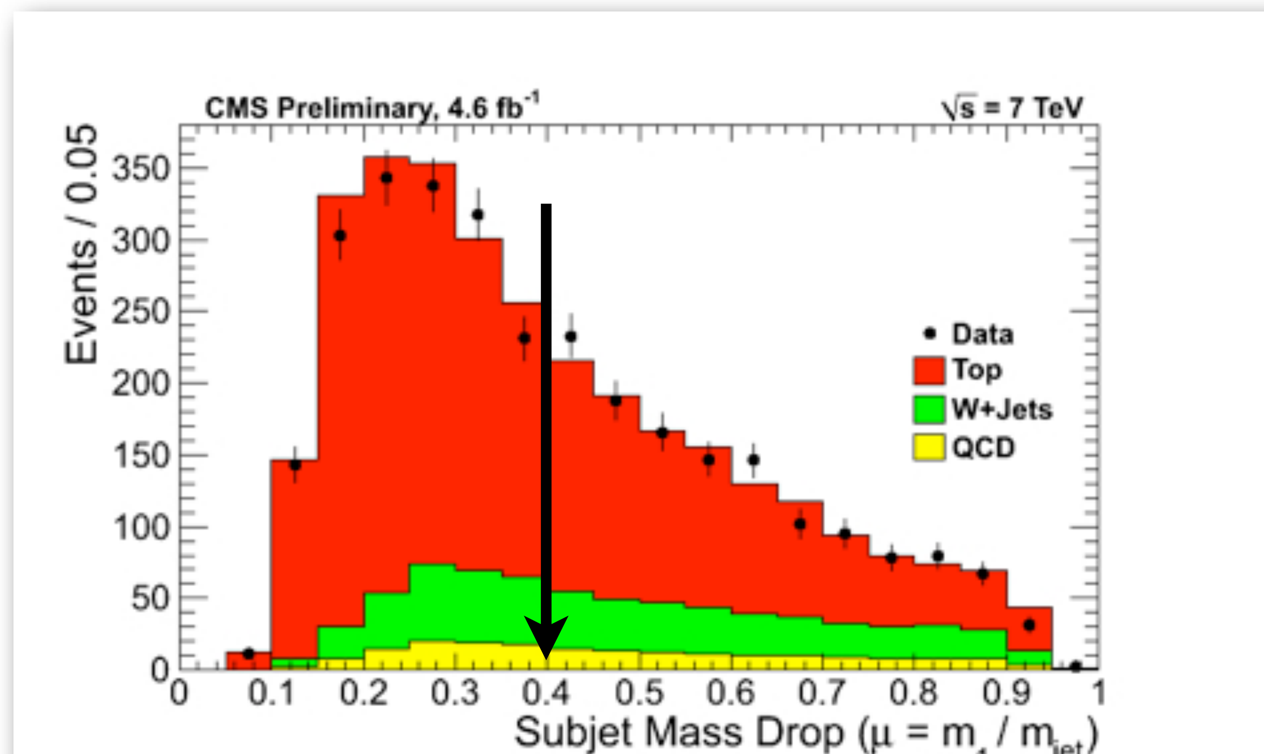


- Events with W tagged jets are used to reconstruct the W and the top mass of the hadronic side.
- Subjet energy scale is the same than for the total jet within 5%.

Subjet selection efficiency

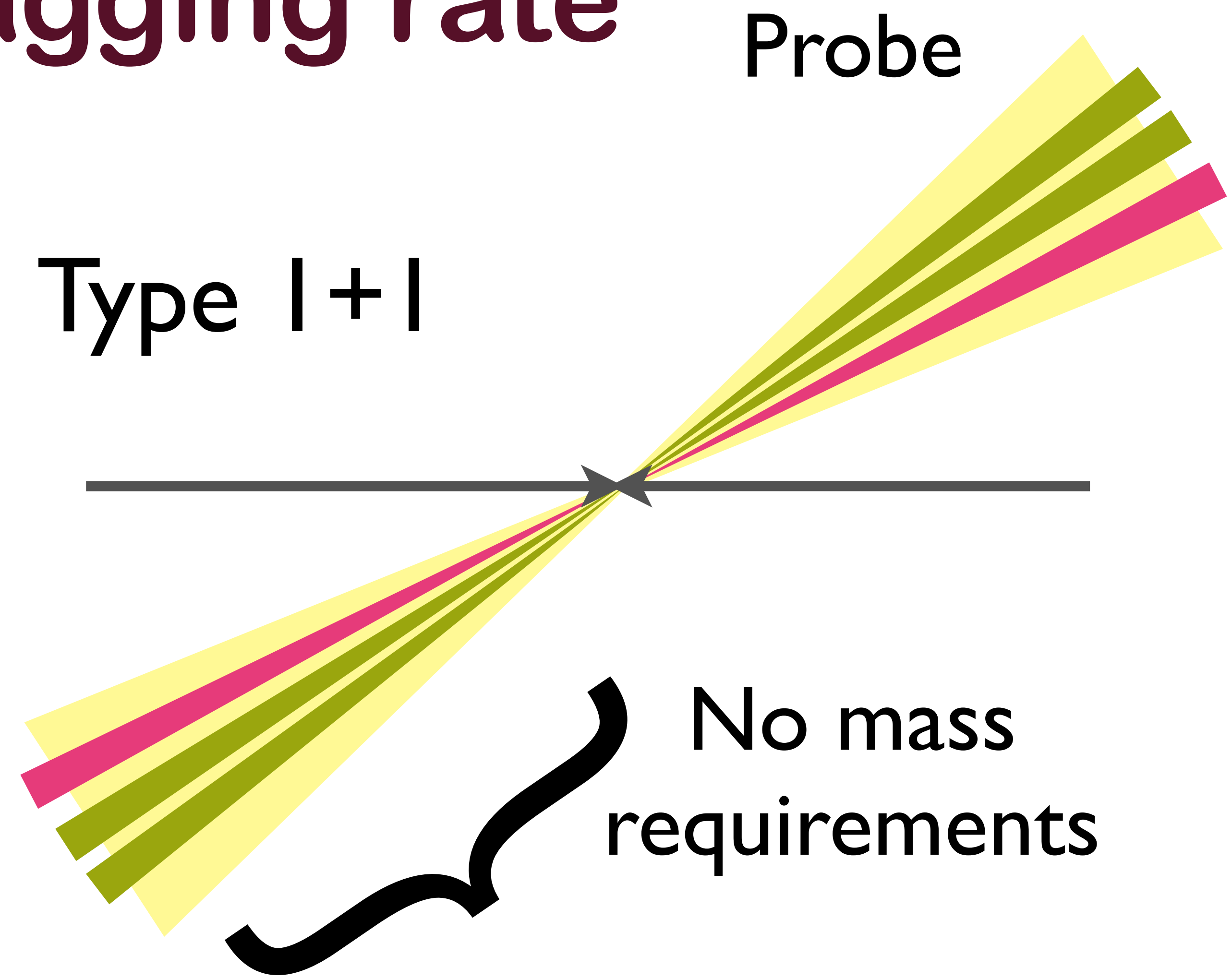
- Using the same semileptonic ttbar sample as described before.
- Combined efficiencies after applying m_{wjet} and μ cuts in W tagging we get:
  - Data: 49%
  - MC: 50%
- Data-to-MC scale factor:
  - SF = 0.97 ± 0.03
- **It is assumed the same SF for top tagging.**

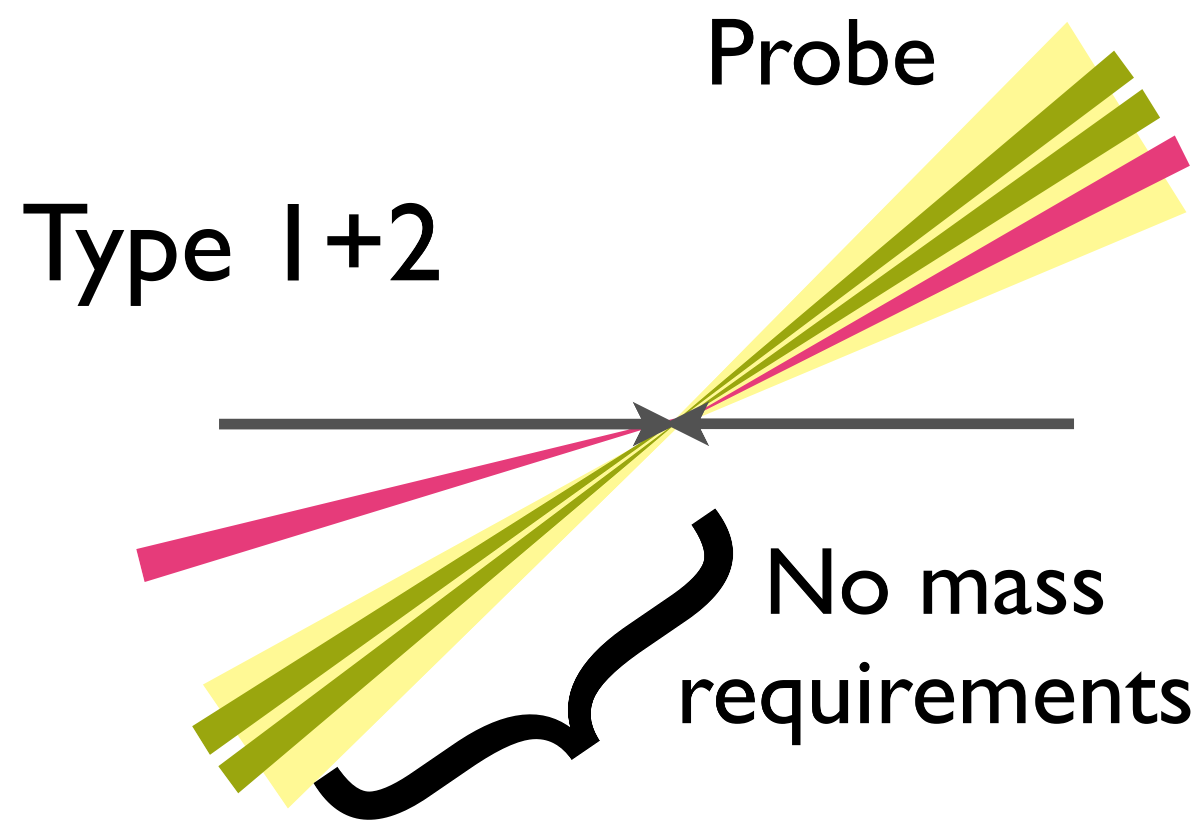




Subjet mistagging rate

- Type 1 + 1:
  - Select dijet events
  - Randomly pick one jet
  - Reverse requirements $N_{subjets}$ and m_{min} maintaining m_{tjet} (anti-tag).
  - Measure efficiency probe jet.
- Type 1 + 2:
  - Select trijet events
  - No mass requirement for m_{tjet}, m_{min}, m_{wjet} and m_{wb} candidates.
  - Use the top jet candidate as probe.
  - Systematic uncertainty is half-difference between the two estimates.





Top pair resonances IN HIGHLY-BOOSTED lepton+jets Selection

CMS EXO-11-093 (5 fb^{-1})

- High-p_T lepton (non isolated triggers):
  - muon p_T > 35 GeV, electron p_T > 70 GeV.
- Replace isolation by $\Delta R > 0.5$ or $p_T^{\mathrm{rel}} > 25$ GeV
- At least two anti-k_T (R=0.5) jets p_T > 50 GeV.
- Leading jet p_T > 250 (150) GeV for muons (electrons).
- QCD suppress by $H_T = p_T^{\mathrm{lep}} + E_T^{\mathrm{miss}} > 150$ GeV
- Top candidates reconstructed using:

$$\chi^2 = \left[\frac{M_{lep} - \bar{M}_{lep}}{\sigma_{M_{lep}}}\right]^2 + \left[\frac{M_{had} - \bar{M}_{had}}{\sigma_{M_{had}}}\right]^2$$

- W+jets background is reduced with $\chi^2 < 8$.
- Secondary vertex b-tagging algorithm used to split data with 0 and ≥ 1 b-tagged jets.