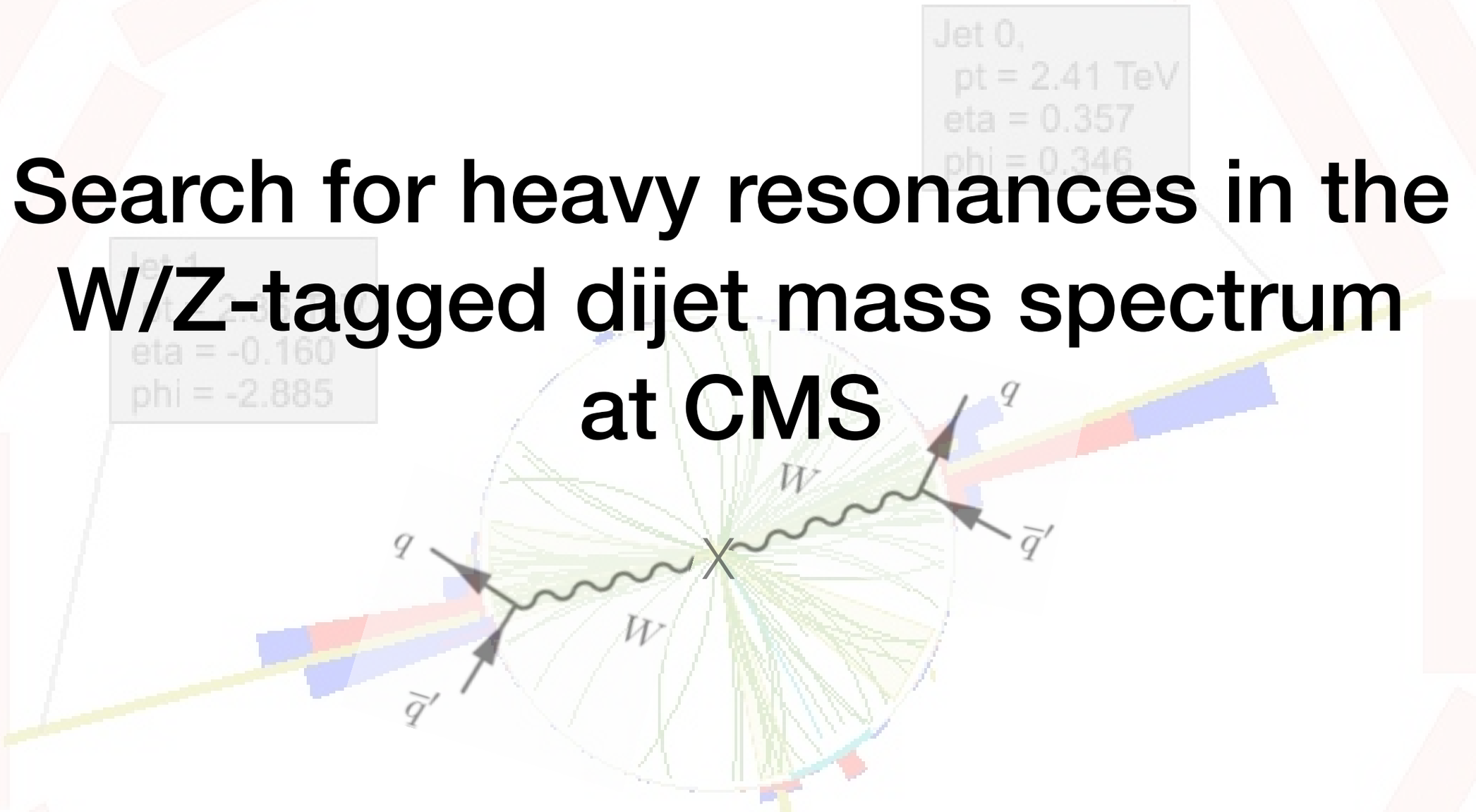
Search for heavy resonances in the W/Z-tagged dijet mass spectrum at CMS



Thea Klaeboe Aarrestad

PhD seminar, PSI 27.08.15

Physics Institute , University of Zurich

Why X→VV→jj

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THEORETICAL MOTIVATION

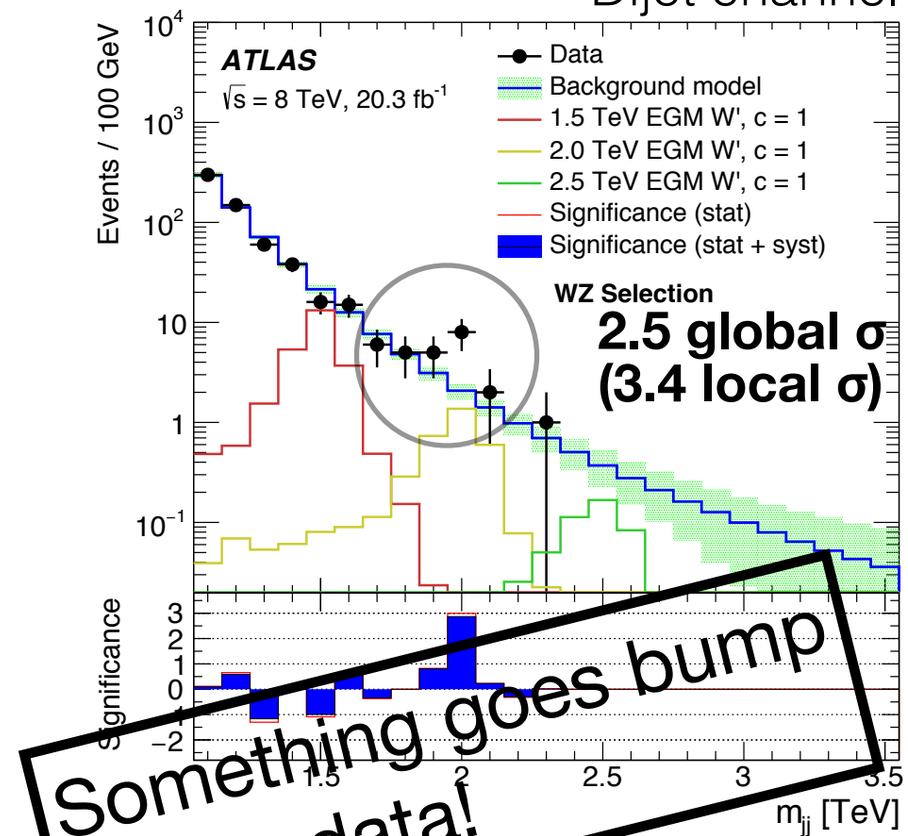
- Several BSM theories predict existence of heavy resonances with M > 1 TeV decaying to WW/ZZ/ZW
  - Extra dimension models: *Solve hierarchy problem by letting gravity propagate in extra spatial dimensions making it appear weak*
    - Bulk scenario of Randall-Sundrum (RS): *One warped extra dimension. Fermions allowed to propagate in bulk of extra dimension explaining unpredicted Higgs Yukawa couplings.*

      Signature: *Narrow resonances decaying primarily to bosons* ***(W_L, Z_L, H)***

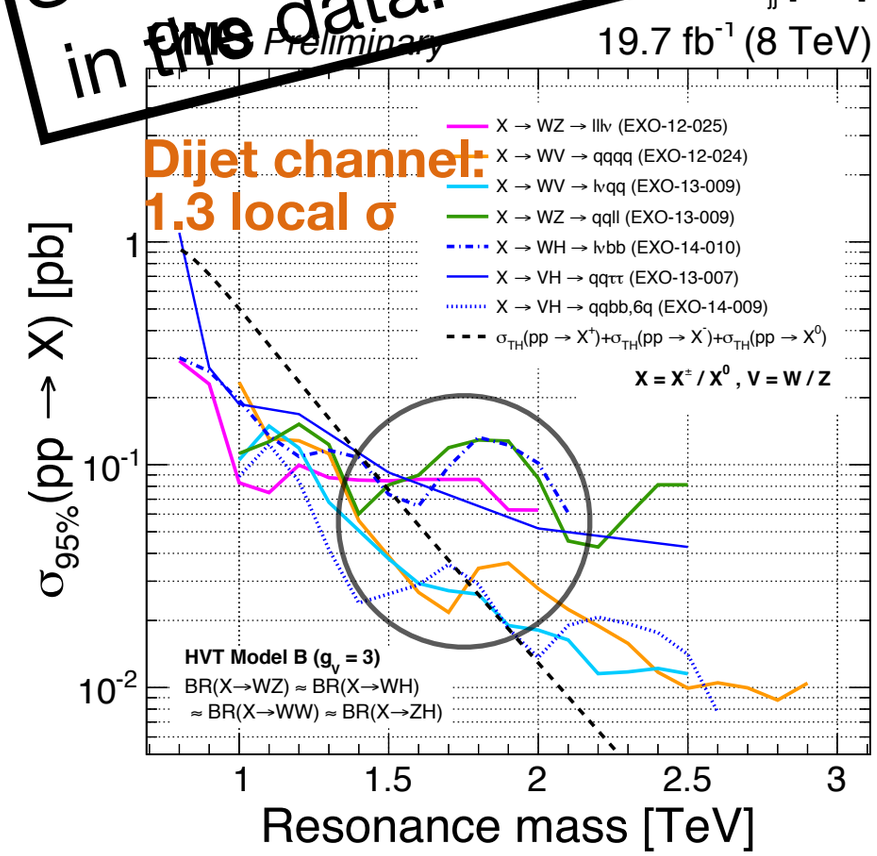
EXPERIMENTAL MOTIVATION

- 8 TeV diboson analyses see curious excess of events!
  → All-hadronic channel amongst most sensitive
- 13 TeV LHC data taking has begun
  → time to explore new energy domain!

Dijet channel



Something goes bump in the data!



Boosted topologies

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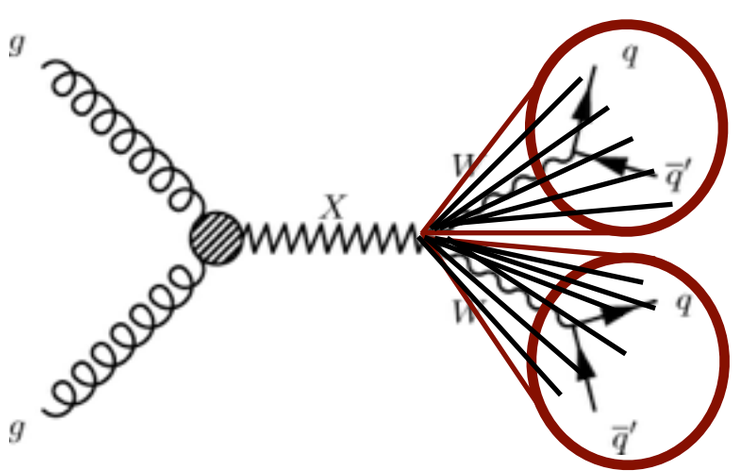
MAIN CHALLENGE

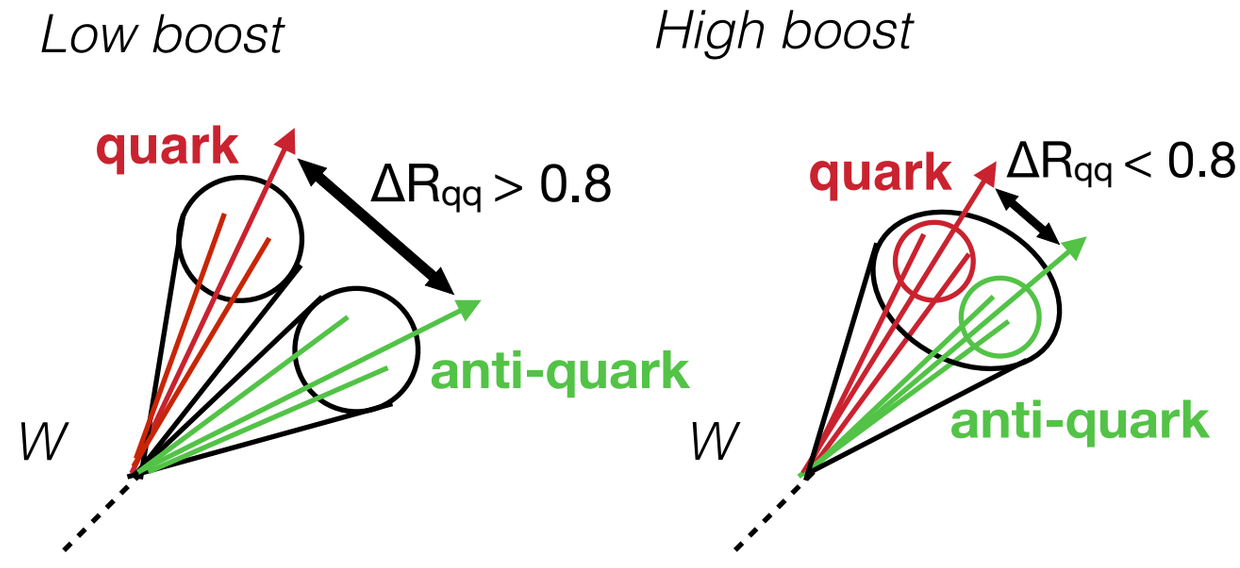
- Vector bosons emerging from decay of > 1 TeV resonances usually highly energetic:

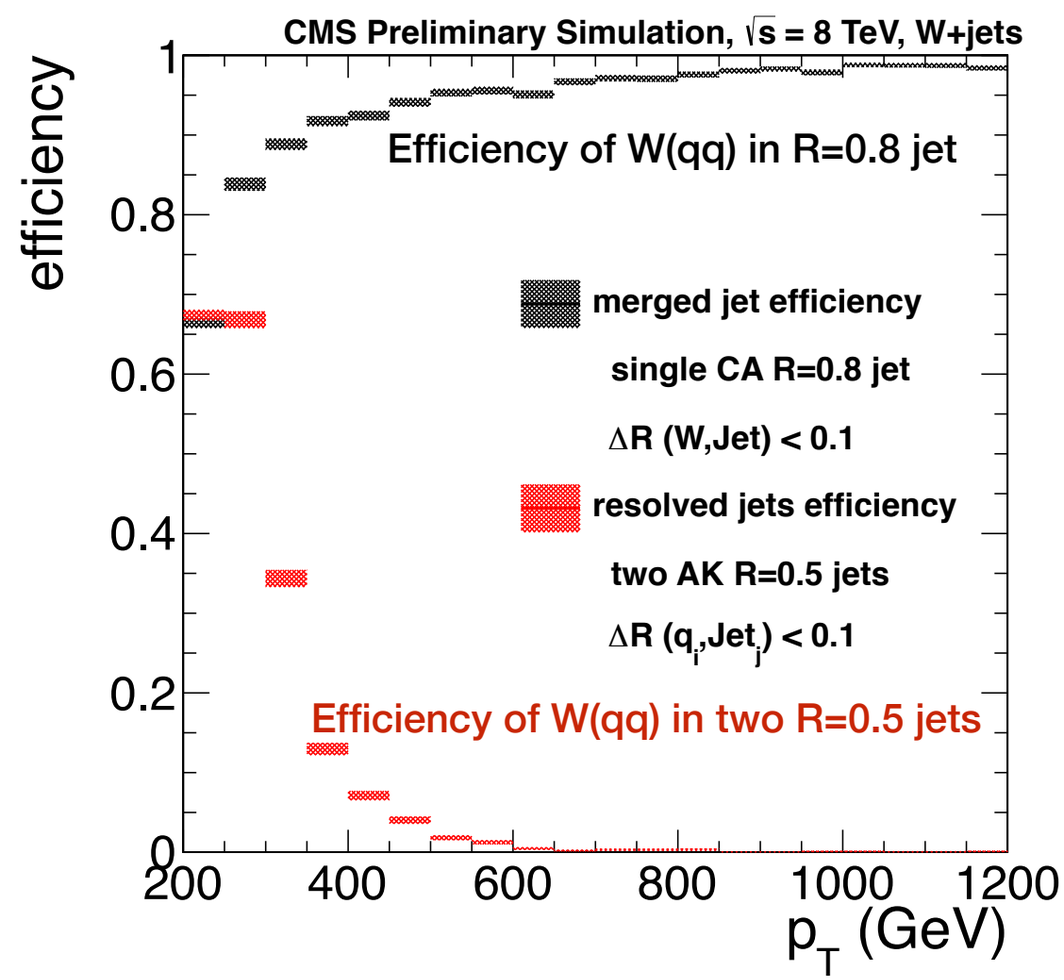
$$\Delta R_{qq}^{\min} \approx \Delta\theta_{qq}^{\min} \approx 2\frac{M_V}{p_{T,V}}$$

  - *Above W/Z p_T > 200 GeV decay products merged into single massive R = 0.8 jet!*

- Search for **X→VV→2 jets**, where V=W/Z







Analysis strategy

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DEALING WITH THE BACKGROUND

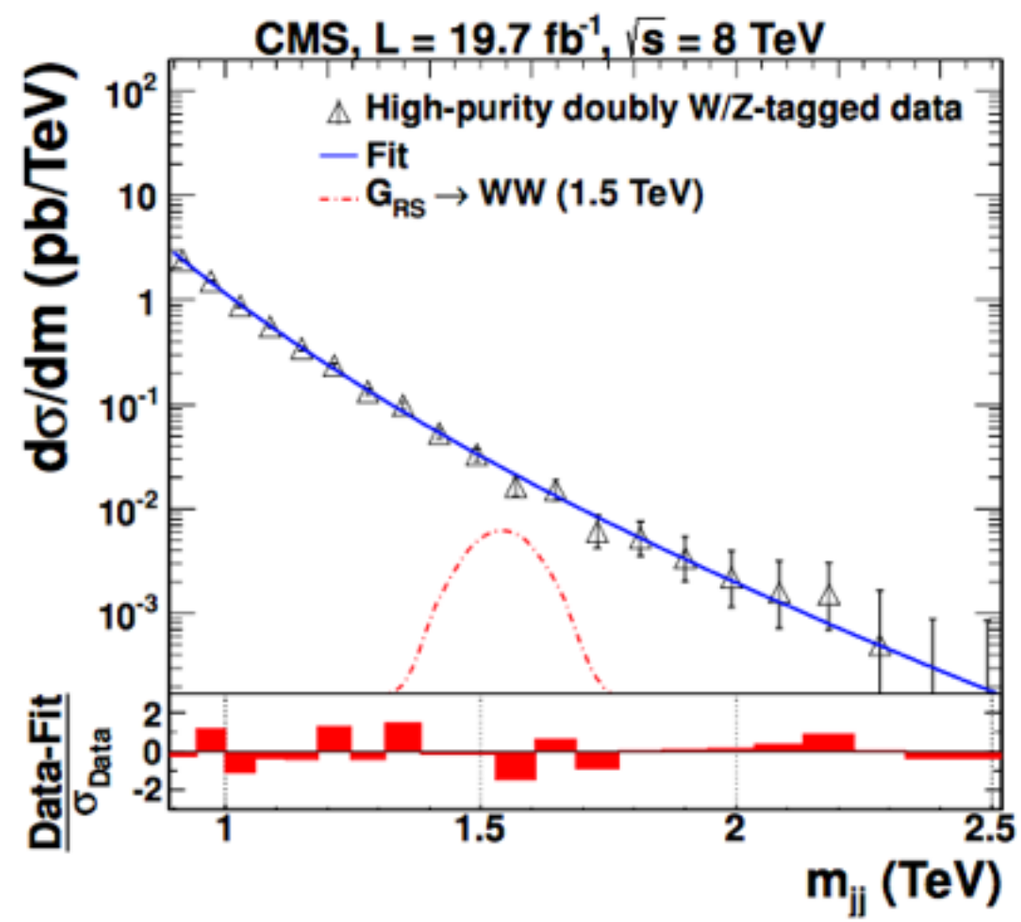
- Main background:
  QCD multijet production
- Reject by
  - *W/Z-tagging methods (grooming, n-subjetiness) taking advantage of:*

2-prong signal jet
- *Massive 4-vector sum of daughters*] Jet mass
- *1-2 wide-angle splittings*
- *Symmetric splittings*] Jet substructure

Quark/gluon jets
- *Low-mass 4-vector sum of daughters*
- *Many low-angle splittings*
- *Asymmetric splittings*

STRATEGY

- Reconstruct two bosons and VV invariant mass
- Estimate background from smooth fit to data
  - *no need for background Monte Carlo*
- Bump hunt in dijet inv. mass spectrum!



W/Z-tagging

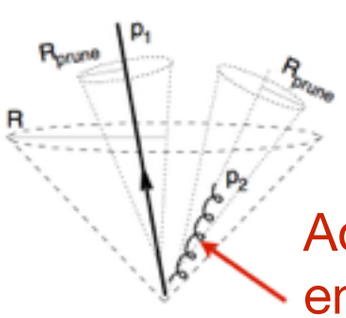
JET MASS: PRUNING

- Improve jet mass resolution by removing soft, large angle particles from the jet
- Procedure:
  - *Recluster jet using Cambridge-Achen algorithm with R=0.8, requiring that each recombination satisfies*

$$\frac{\min(p_{T1}, p_{T2})}{p_{Tp}} > 0.1 \qquad \Delta R_{12} < 0.5 \times \frac{m_{\text{jet}}}{p_T}$$

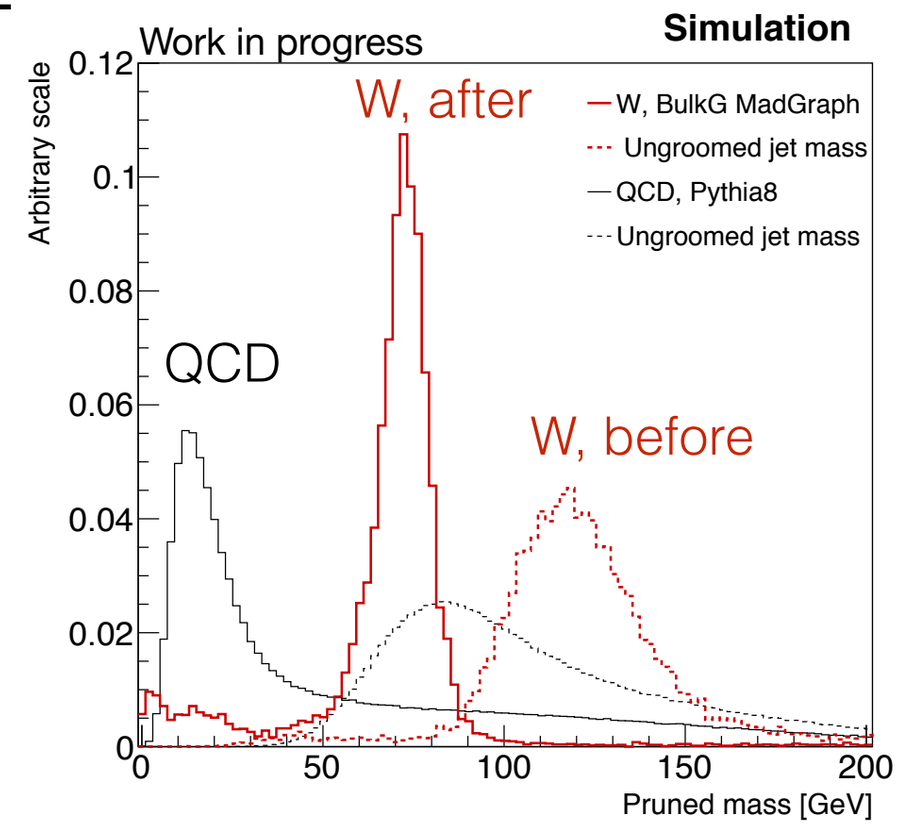
Removes soft particles

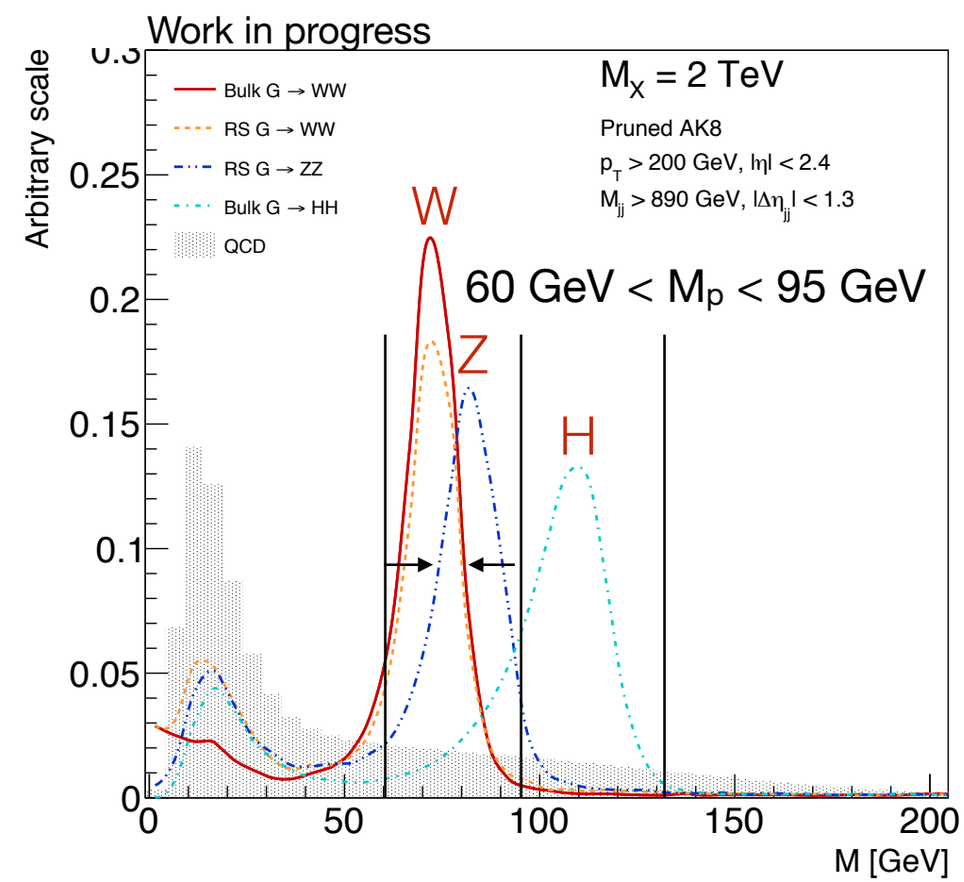
Removes wide angle particles



Additional prong hard enough to end up in different hard subjet

  - *Quark/gluon jet mass pushed to zero!*





W/Z-tagging

JET SUBSTUCTURE: N-SUBJETTINESS

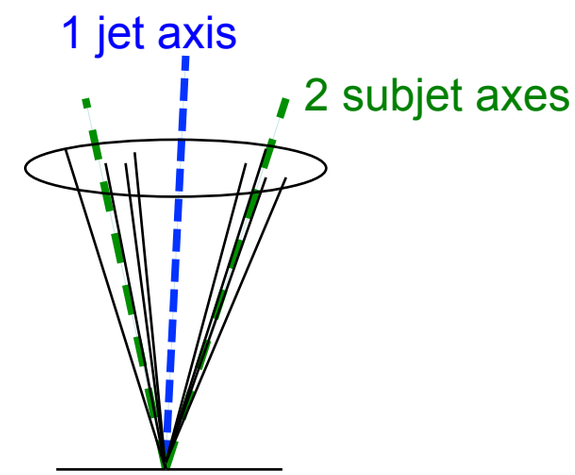
- p_T-weighted sum over all jet constituents of the distance w.r.t the closest of N axes in a jet

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min\left((\Delta R_{1,k}), (\Delta R_{2,k}) ... (\Delta R_{N,k})\right)$$

Distance between momentum of constituent k w.r.t momentum of rest-frame subjet N

Each constituent assigned to nearest subjet!

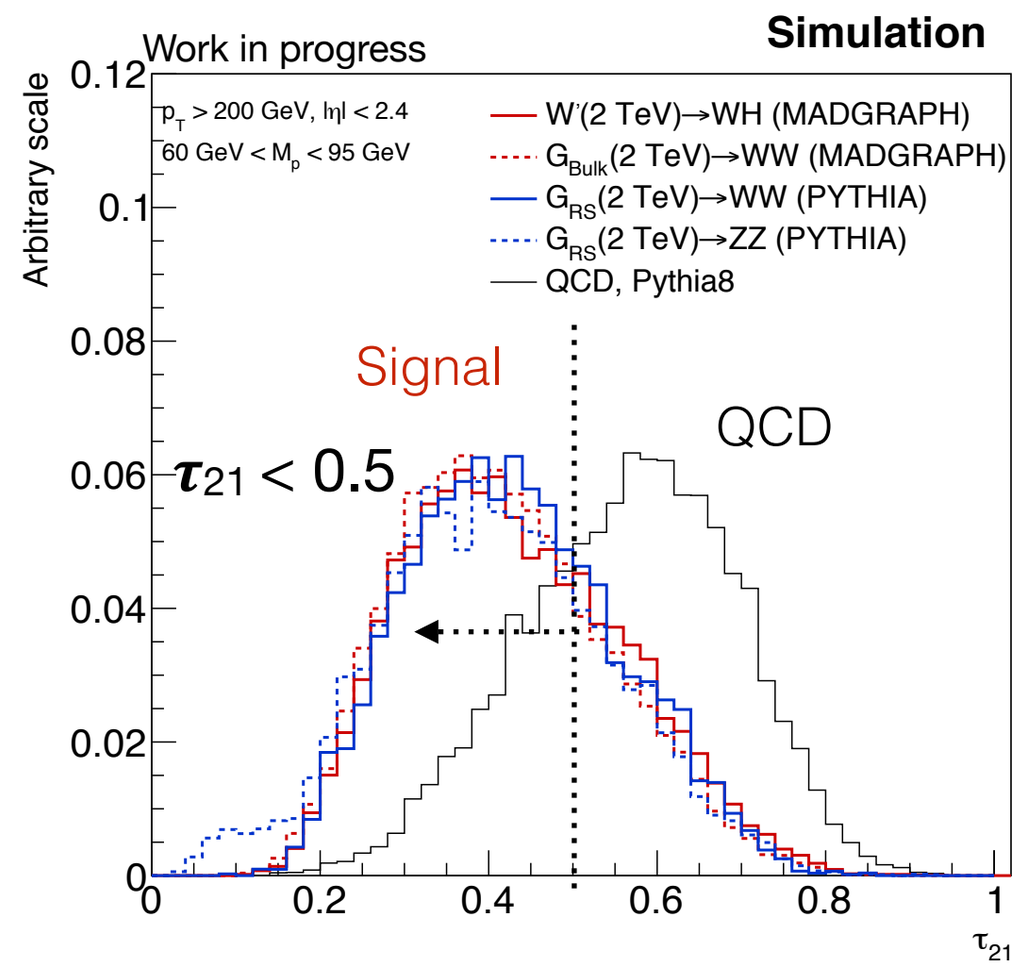
  - *Axis are obtained by undoing last (N-1) steps of jet clustering algorithm*



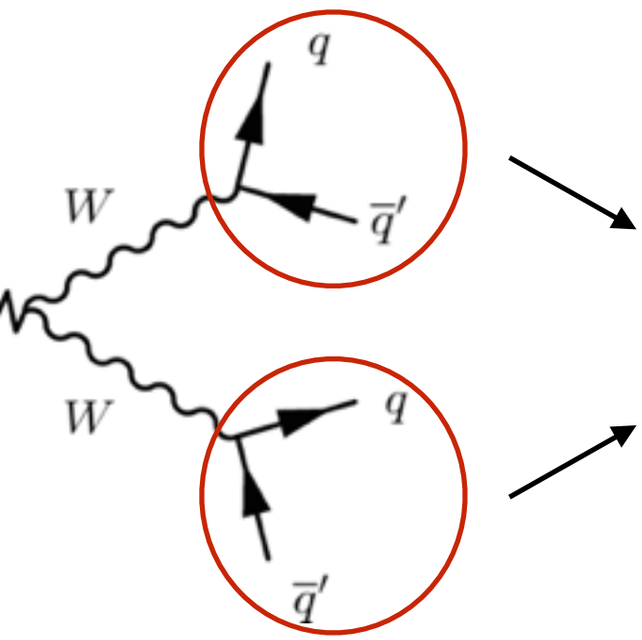
  - *Small τ_N indicates compatibility with N axes hypothesis*

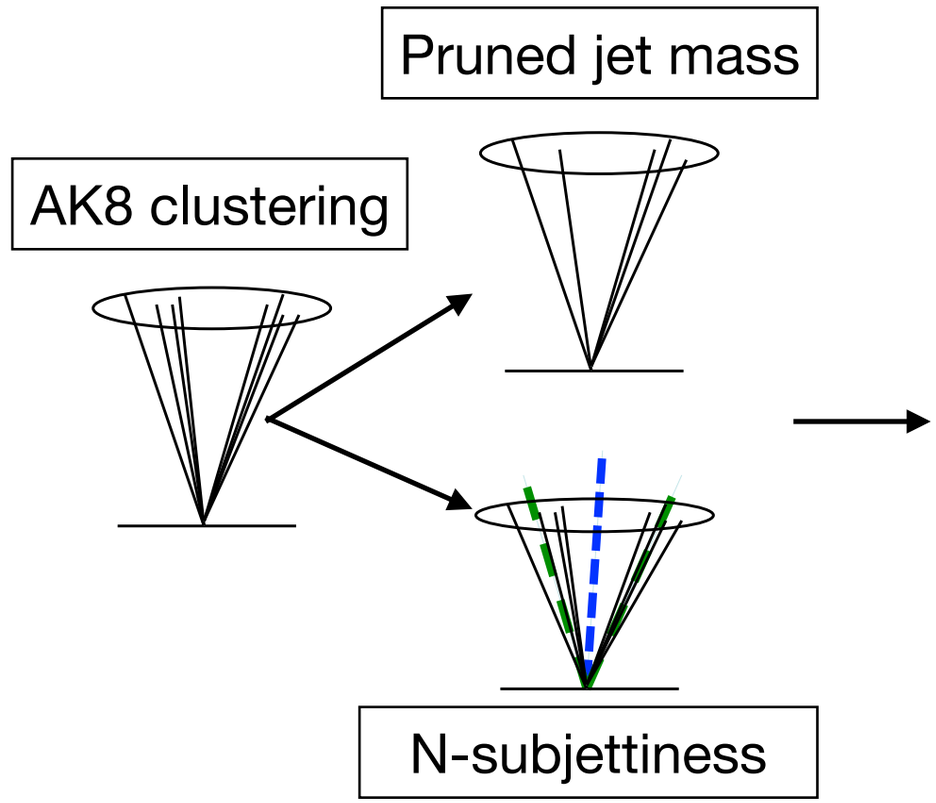
- To discriminate 2-prong W/Z jets from 1-prong q/g jets, use ratio:
  - τ_2/τ_1 (τ_{21})

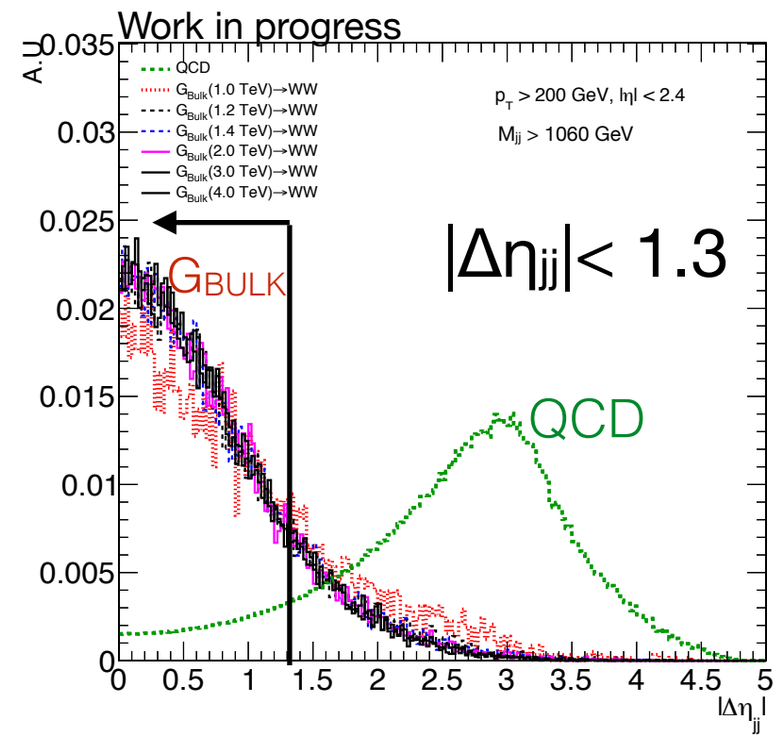
- Typical W/Z-tagger (pruning+n-subjettiness):
  - *3 % mistag rate*
  - *55 % efficiency*



Object reconstruction and selection







JETS

- Require ≥ 2 massive (anti-k_T, R=0.8) jets with:
  - p_T > 200 GeV
  - $|\eta| < 2.4$

W/Z-TAGGING

- 60 GeV < Pruned mass < 95 GeV
- N-subjetiness $\tau_{21} < 0.5$

ANGULAR SEPARATION

- To get rid of QCD t-channel processes
- $|\Delta\eta_{jj}|$< 1.3

$$\Delta\eta = |\eta(j_1) - \eta(j_2)| = \ln\left(\frac{1 + |\cos(\theta^*)|}{1 - |\cos(\theta^*)|}\right)$$

The fitting procedure

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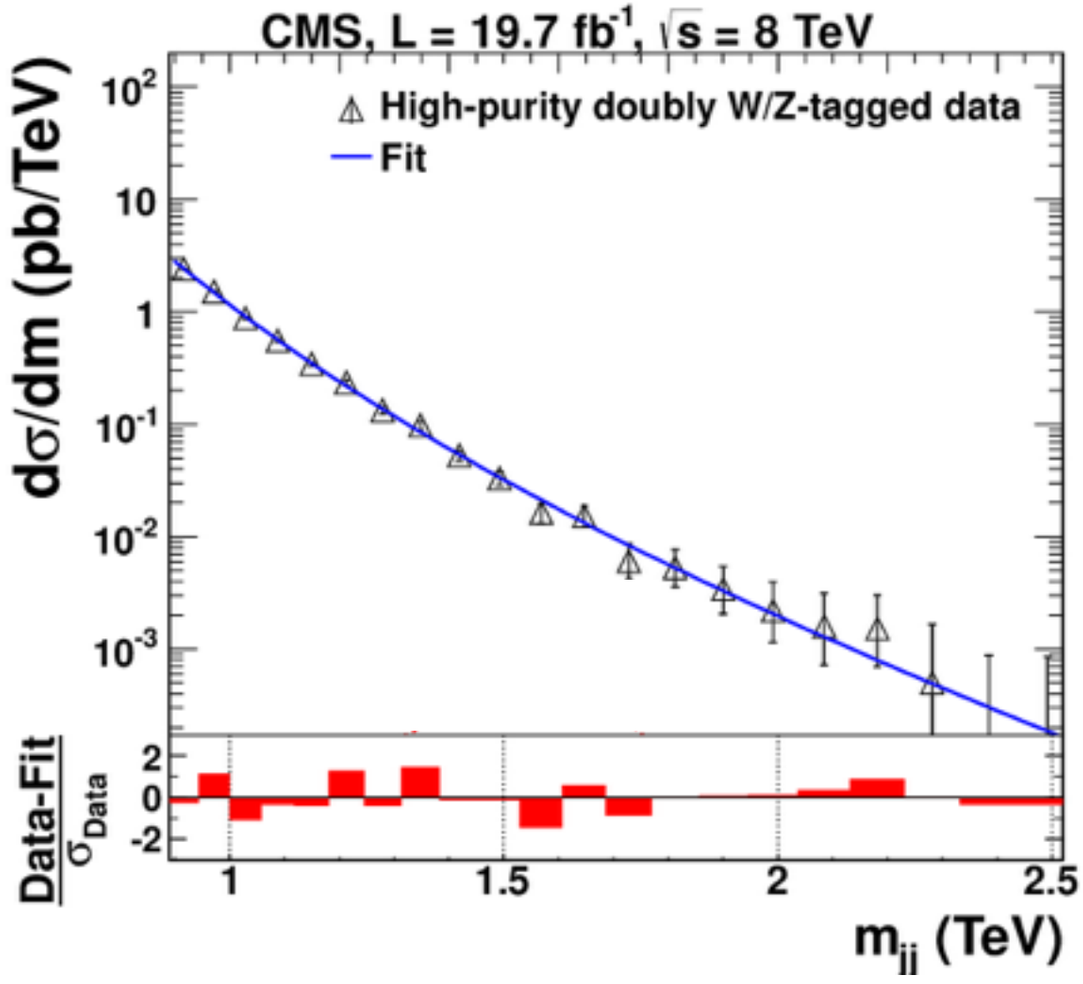
THE BACKGROUND FIT

- The QCD dijet background shape is assumed to be described by the a smoothly falling function of the form

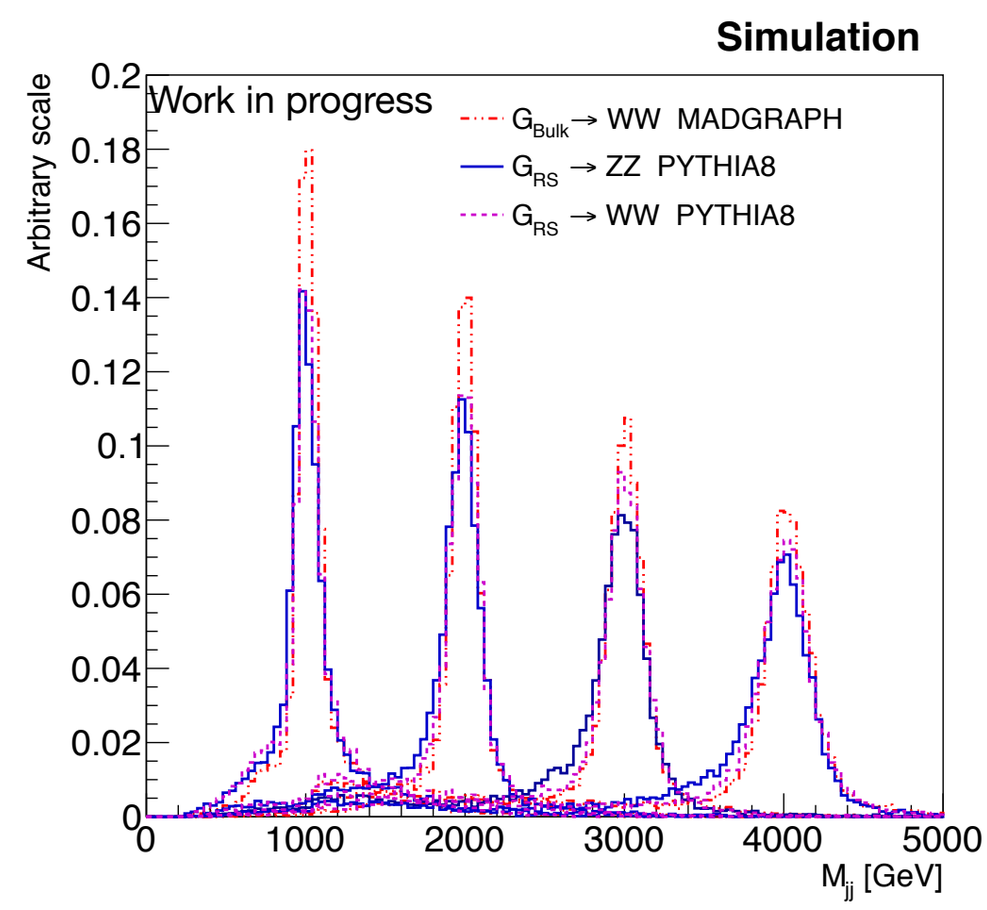
$$\frac{dN}{dm} = \frac{P_0(1 - m/\sqrt{s})^{P_1}}{(m/\sqrt{s})^{P_2}}$$

  - *Smoothness test of observed data*



THE SIGNAL FIT

- Shape extracted from signal MC
  - *P.D.F models constructed as composite models with Gaussian core and an exponential tail.*
  - *Parametric shape uncertainties due to jet energy scale and resolution uncertainties inserted by variations of Gaussian peak position and width.*



Parton luminosity distributions

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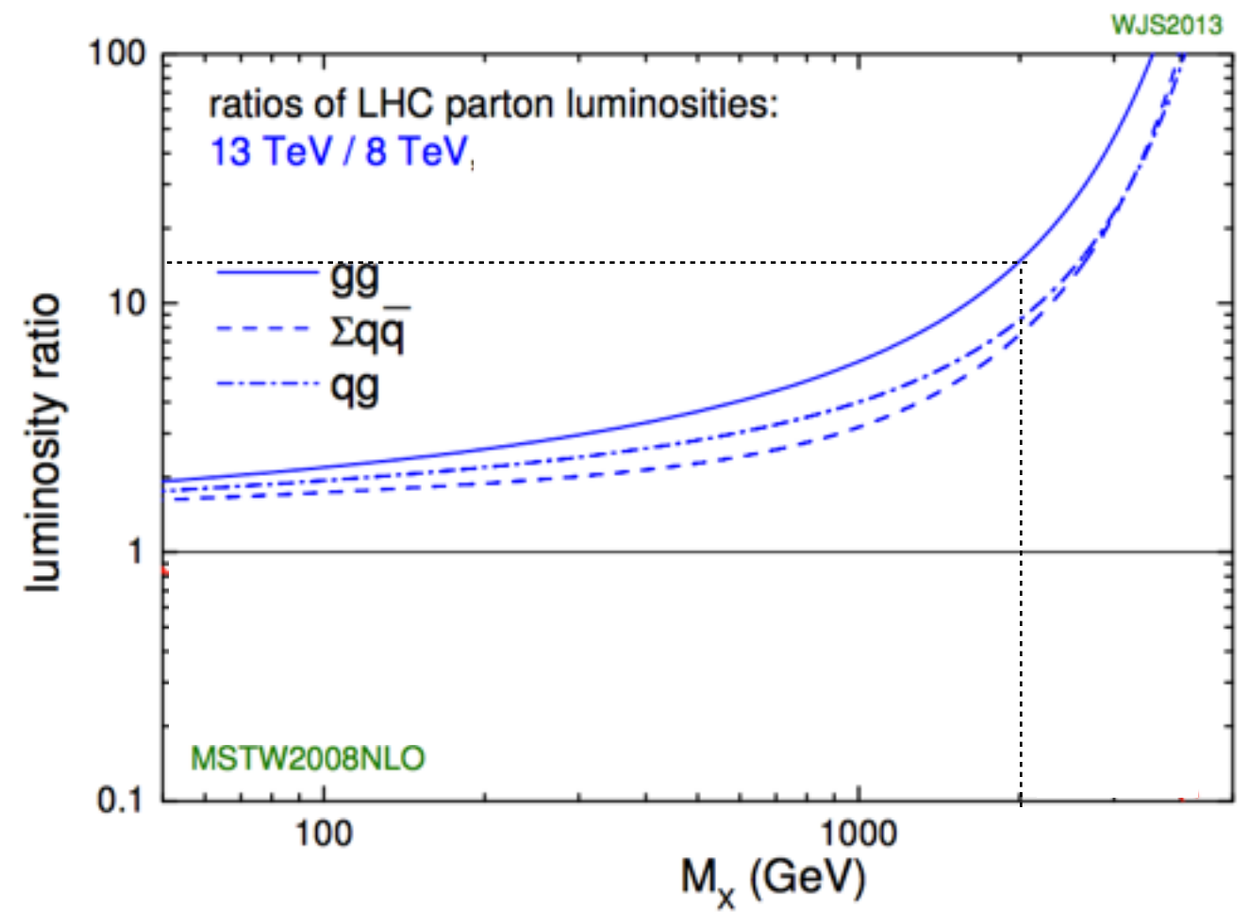
LUMINOSITY SCALING

- Scaling of parton luminosity with collision energy gives huge increase in discovery potential for the energy increase
  - *For 2 TeV Bulk Graviton, increasing energy by factor less than 2 increase parton luminosity by 15!*

    → *20 fb^{-1} at 8 TeV is the equivalent of 1.3 fb^{-1} at 13 TeV!*

- In the first few months of running at 13 TeV, huge amount of data will be available!



FIRST 13 TEV DATA EVER NOW AVAILABLE!

- 42 pb^{-1} of data recorded with CMS after first 50 ns run of LHC!

- 200k events passing analysis triggers, 30 events in signal region!

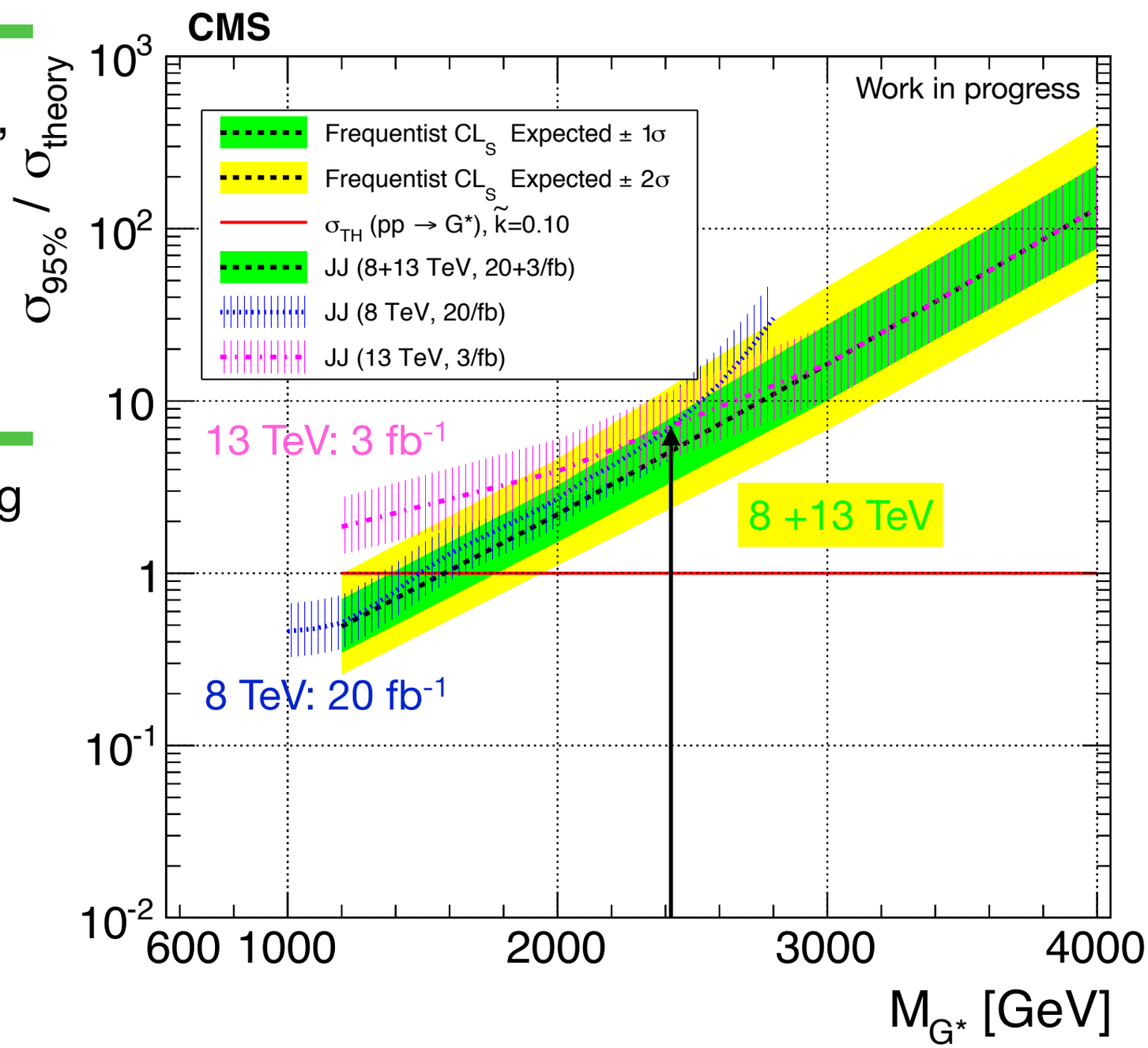
Expected limits

HYPOTHESIS TESTING

- Hypothesis test by comparing fits of observed data with “background-only” function and “background + signal" function.

8+13 TEV EXPECTED LIMITS

- Combination of the dijet analyses using 19.7 fb^{-1} of 8 TeV data and 3 fb^{-1} of 13 TeV MC:
  - *For resonance masses above 2.4 TeV, 13 TeV results more sensitive with 3 fb^{-1} of data!*
  - *8+13 TeV combination improves sensitivity over whole mass range*



Summary

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CONCLUSION

- Use of novel W/Z tagging techniques allows great discrimination between signal and background in boosted topologies
  - *Very useful tool at 13 TeV LHC!*
- Due to parton luminosity scaling, at high resonance masses 13 TeV results can be more sensitive than 8 TeV analysis with 3 fb^{-1} of data already

OUTLOOK

- Excess of events seen by both CMS and ATLAS in the diboson channel. Is bump new physics or not?
  → to be confirmed or excluded 13 TeV data!
- Very exciting to see whether the bump matures into sharp peak or dissolves into the background

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BACKUP

Jets in the CMS detector

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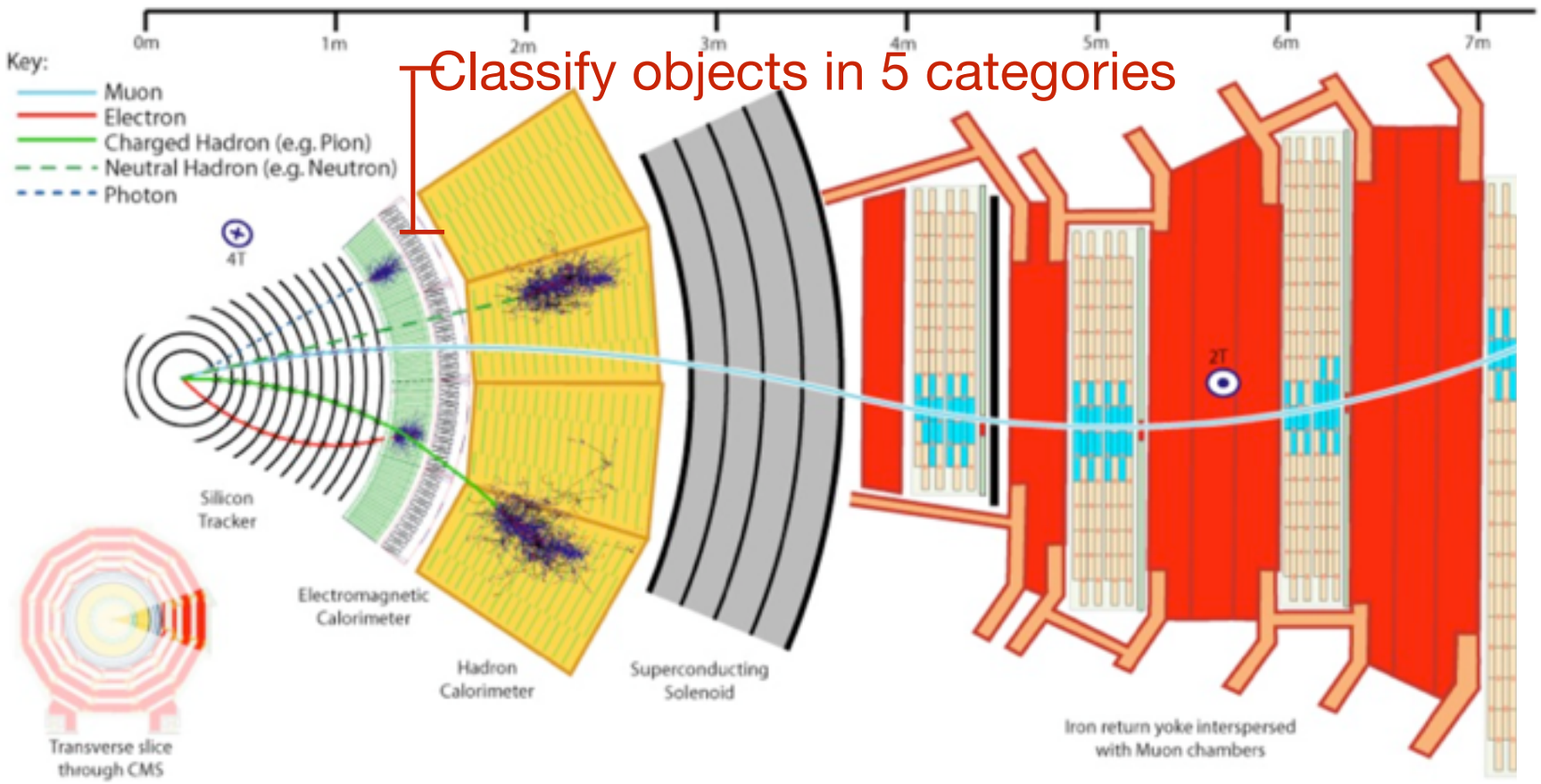
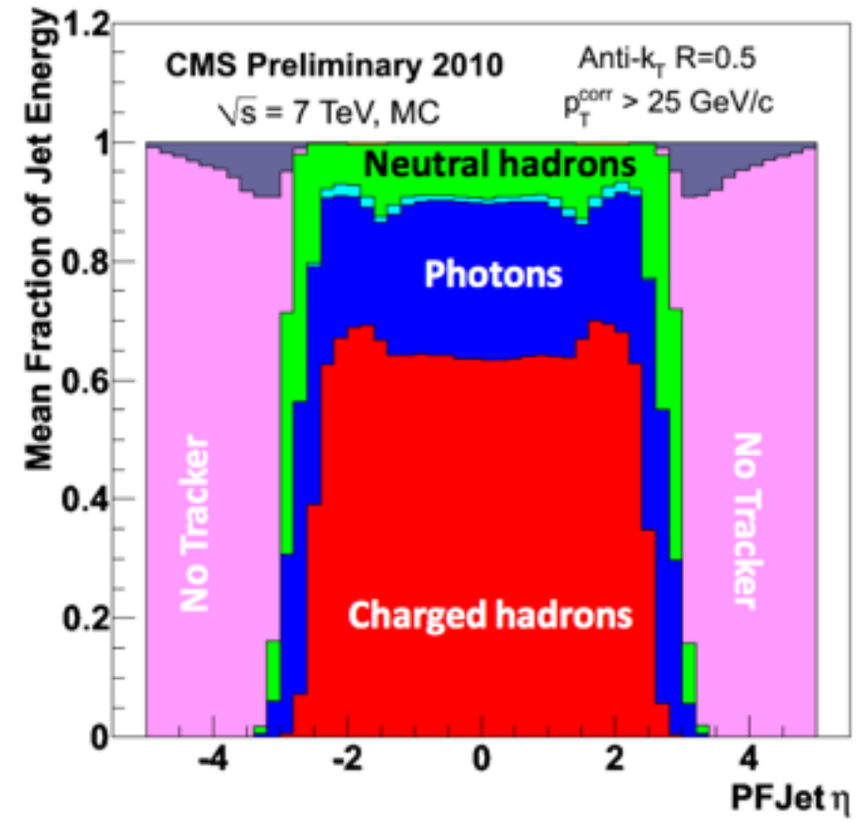
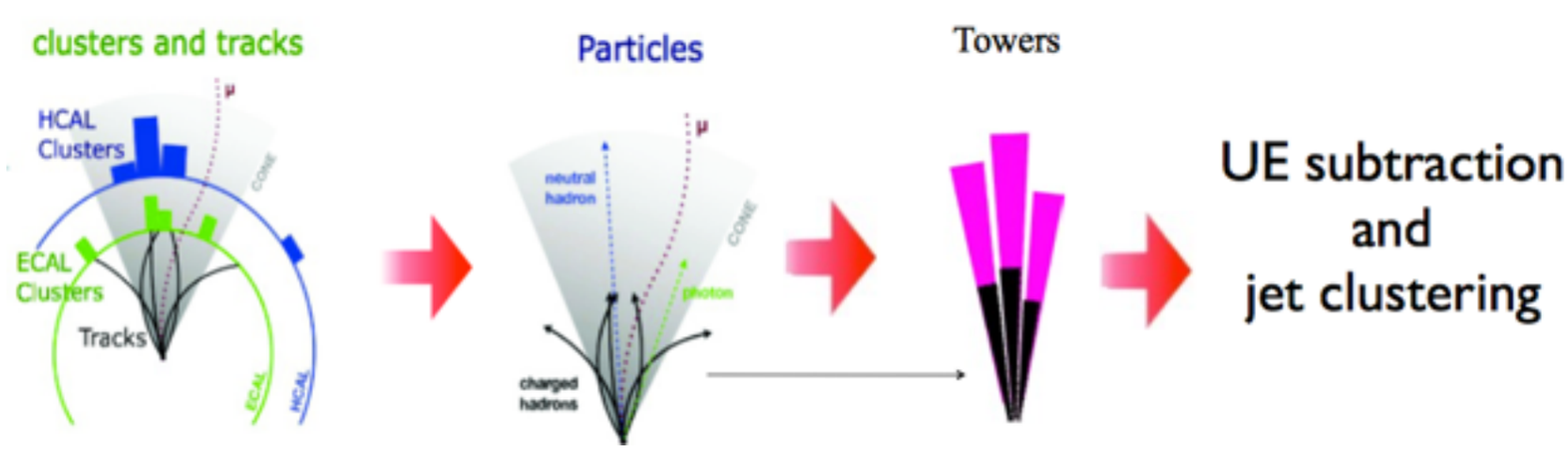
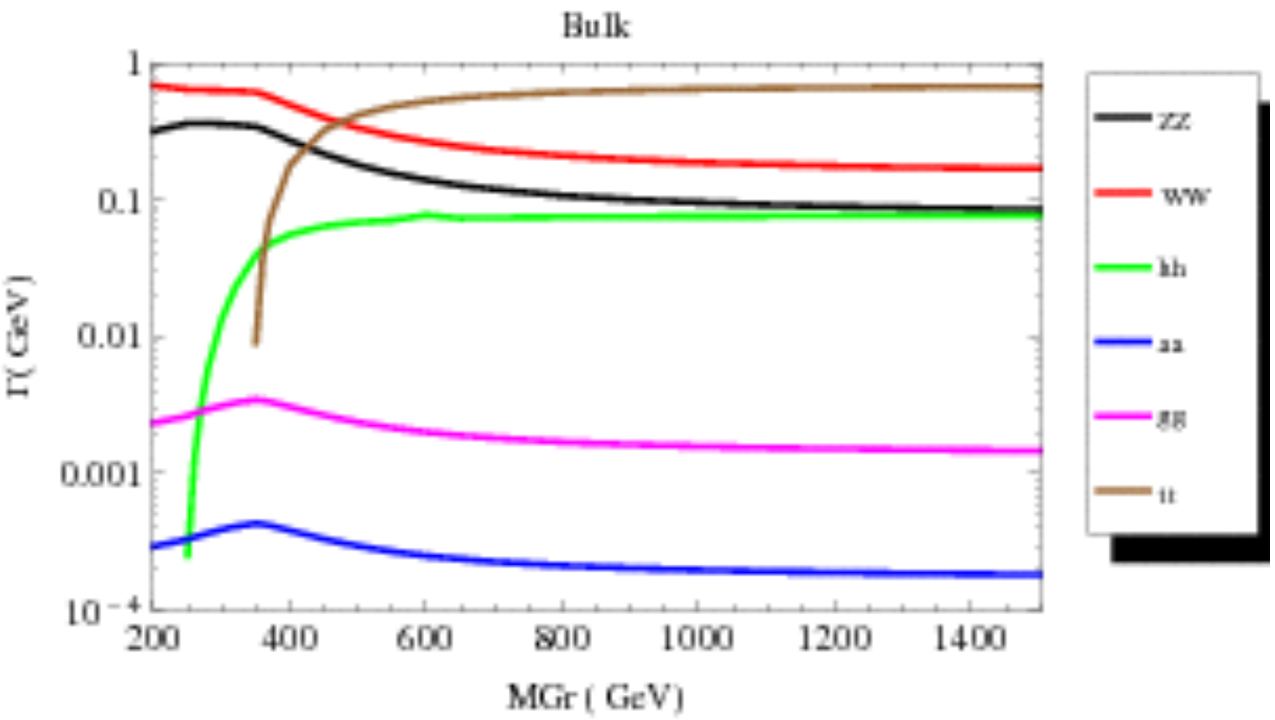


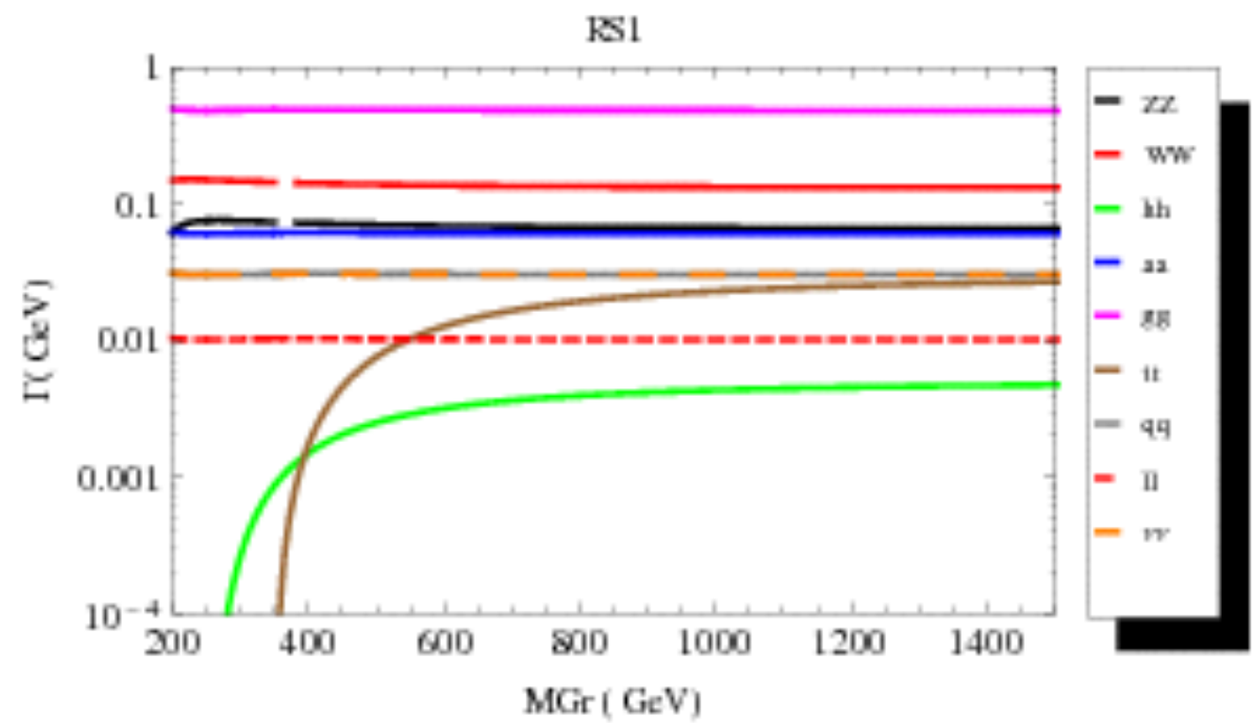


- Holistic approach to reconstruction: Particle Flow
  - *Use information from all sub-detectors and combine for excellent angular and energy resolution*



RS1 Graviton





KK-graviton branching fractions. Left: Bulk scenario, assuming elementary top quark. Right: RS1 scenario. The dashed line represents the individual RS1 kk-graviton decay rates to a pair of light fermions $f\bar{f}$, where f represents both light quarks (u,d,s,c,b) or leptons (e,μ,τ). -- Branchin ratios are independent of *k* parameter.

8+13 TeV combination

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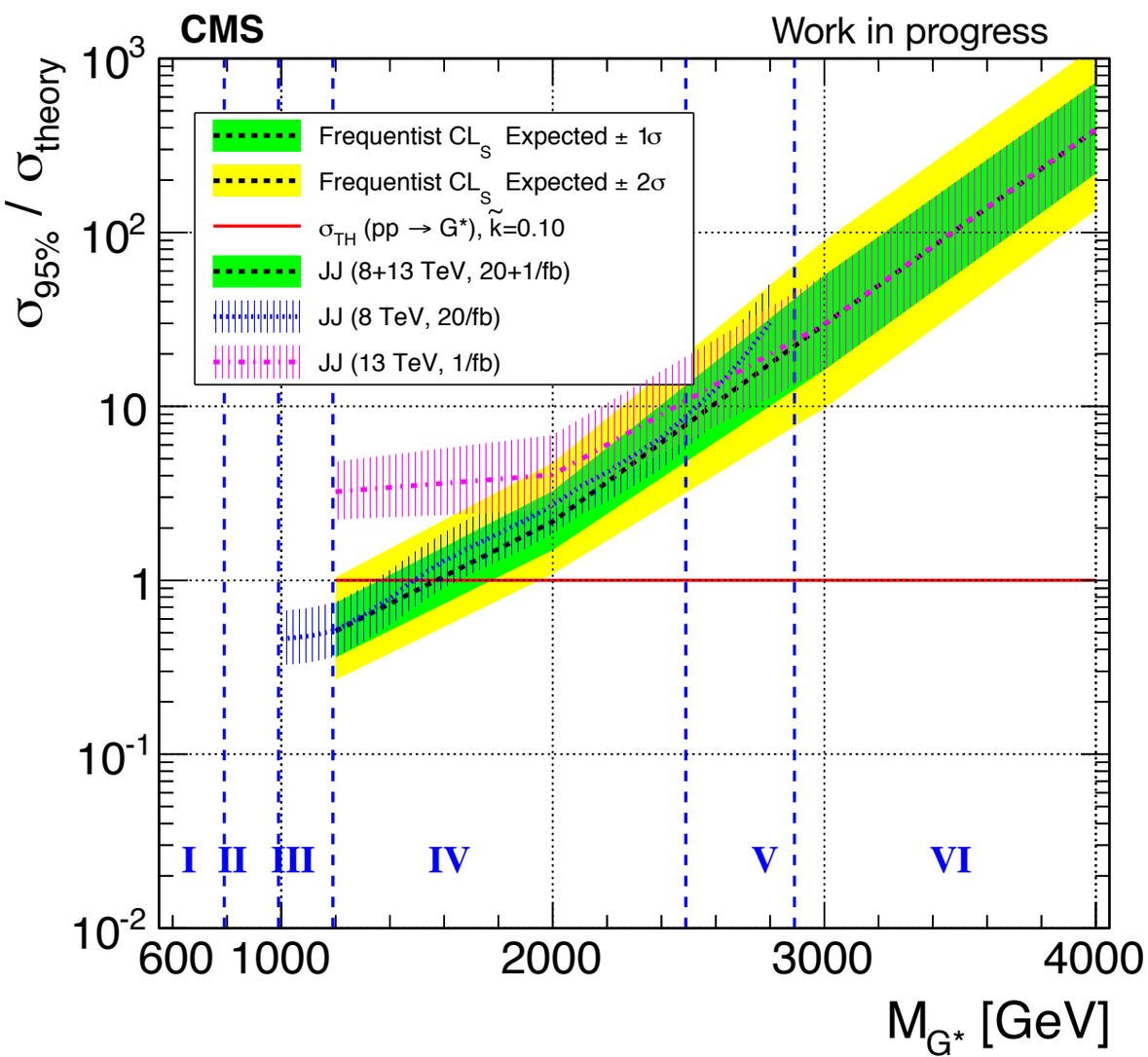
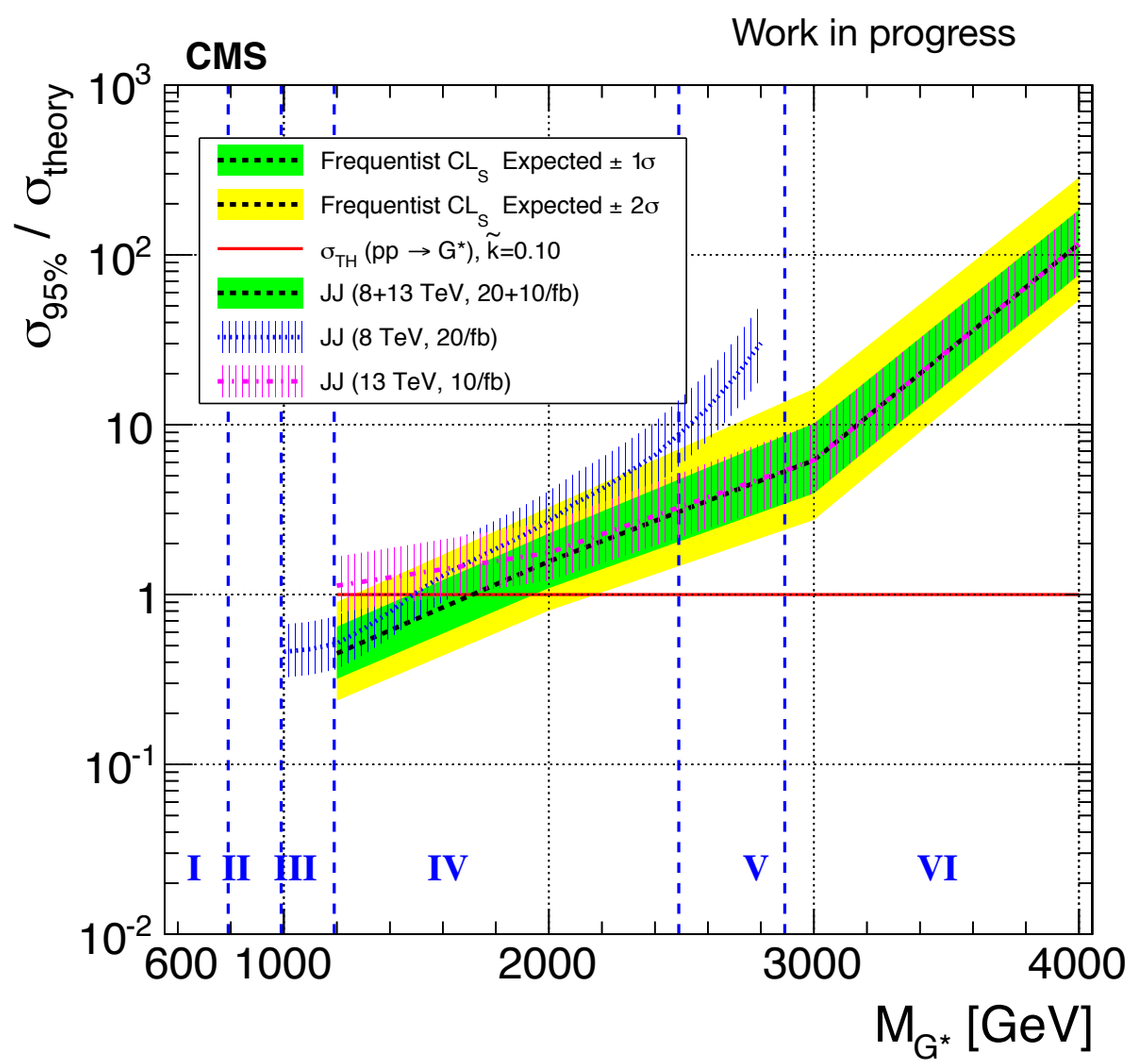
1/fb

- Combination of the dijet analyses using 19.7fb^{-1} of 8 TeV data and 1fb^{-1} of 13 TeV pseudo-data

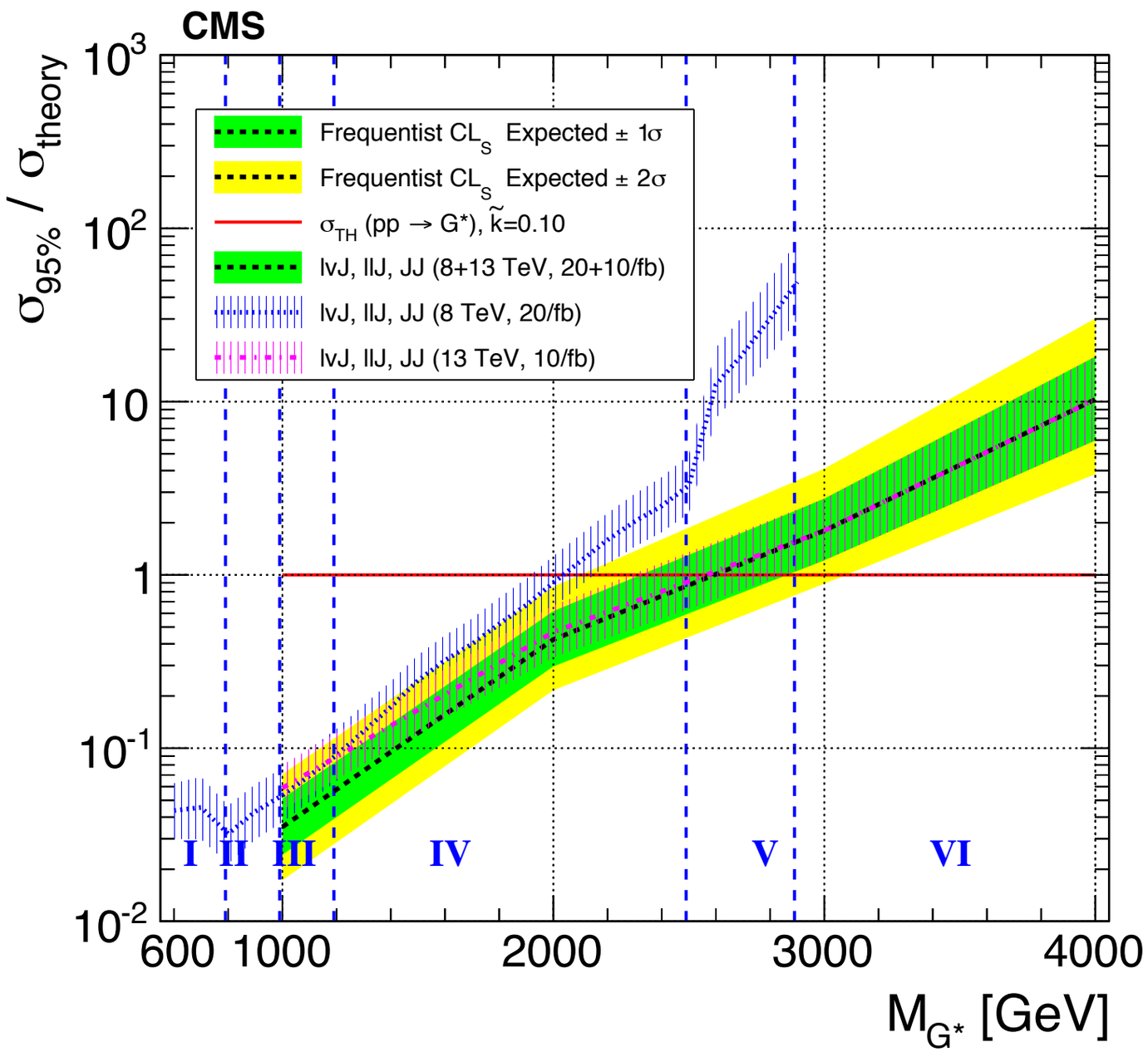


10/fb

- Combination of the dijet analyses using 19.7fb^{-1} of 8 TeV data and 1fb^{-1} of 13 TeV pseudo-data



8+13 TeV combination



Tau21 before mass cut