Heavy Resonances in Hadronic Final States

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VI LHCpp workshop – Genova, 08-10/05/2013

Goals and outline

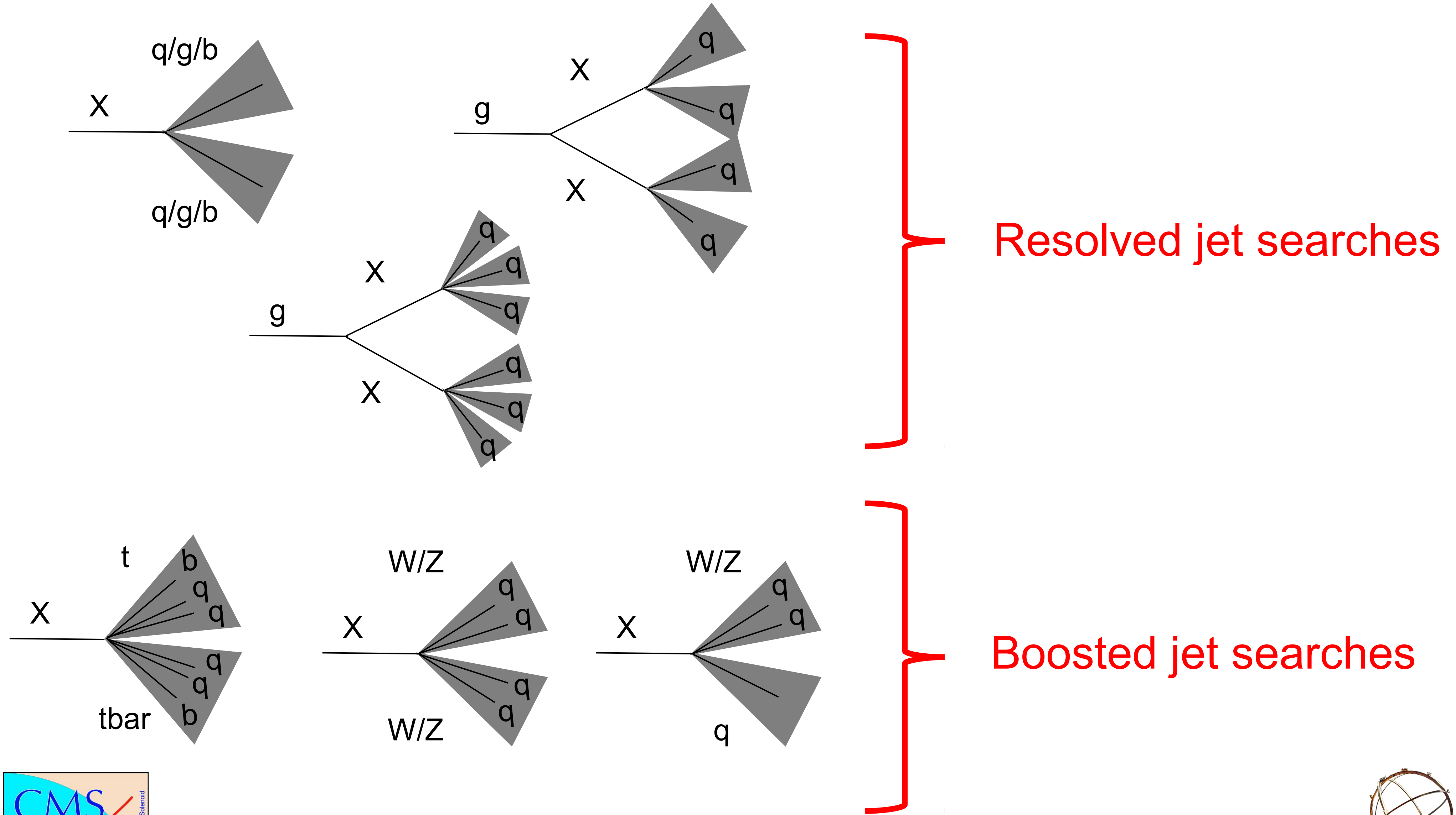
Hadronic resonances at ATLAS and CMS

Review of selected 7 and 8 TeV measurements
Discussion of present and future searches

Outline:

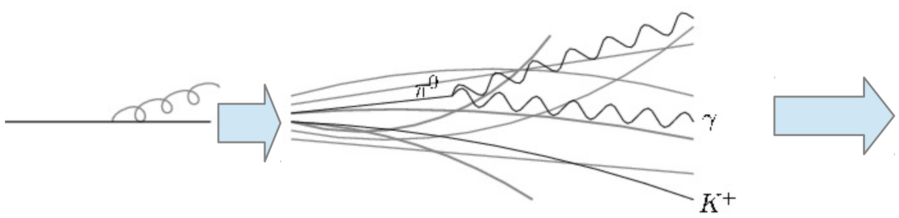
- Introduction
- Resolved jet searches
  - From 2 to 6 jets in ATLAS and CMS
- Boosted jet searches
  - Boosted top searches
  - Diboson searches
- Discussion

Heavy resonance searches : signatures



Heavy resonance searches : physics objects and their uncertainties

Hadronic jets key physics objects :
performance **well understood**
after only one year of data
in both experiments

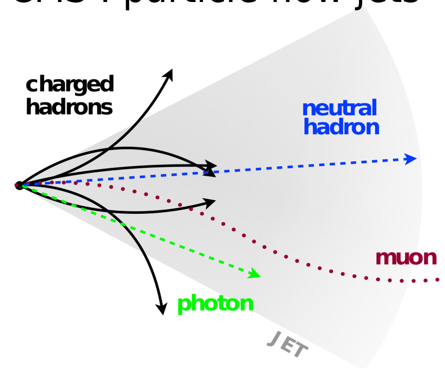


parton level jet particle level jet

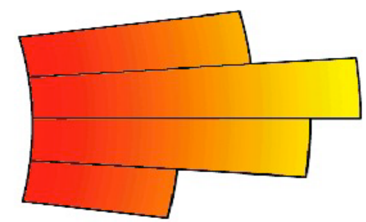
Images by D. Gillberg, H. Kirschemann

ATLAS-CONF-2013-004
JINST 6 P11002 (2011)
arXiv 1112.6426

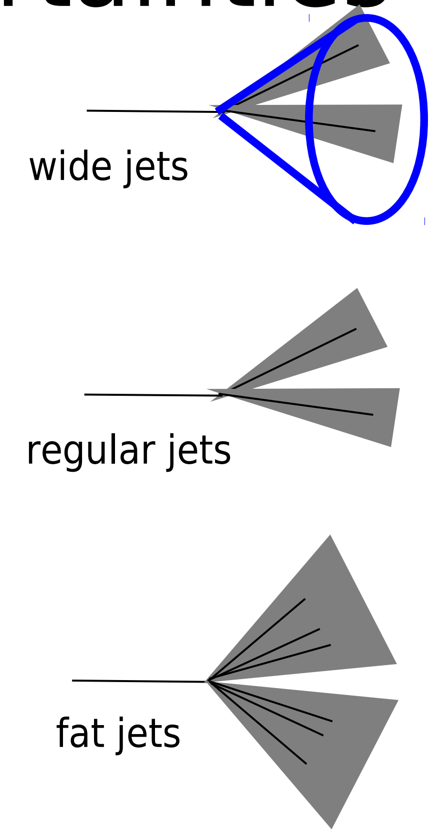
CMS : particle flow jets



ATLAS : calorimeter jets



calorimeter level jet



Factorized calibration
based on MC truth jet energy scale (JES) and in-situ techniques

JES uncertainties : **1 - 2 %** @ 100 GeV, **2 %** @ 1 TeV, **3-4 %** @ 2 TeV
Differences in high-pT calibration and uncertainties

Resonances with resolved jets

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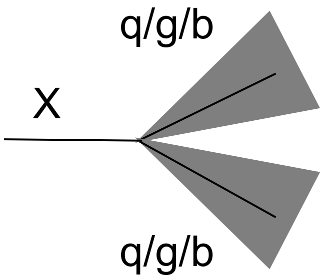
Dijet searches

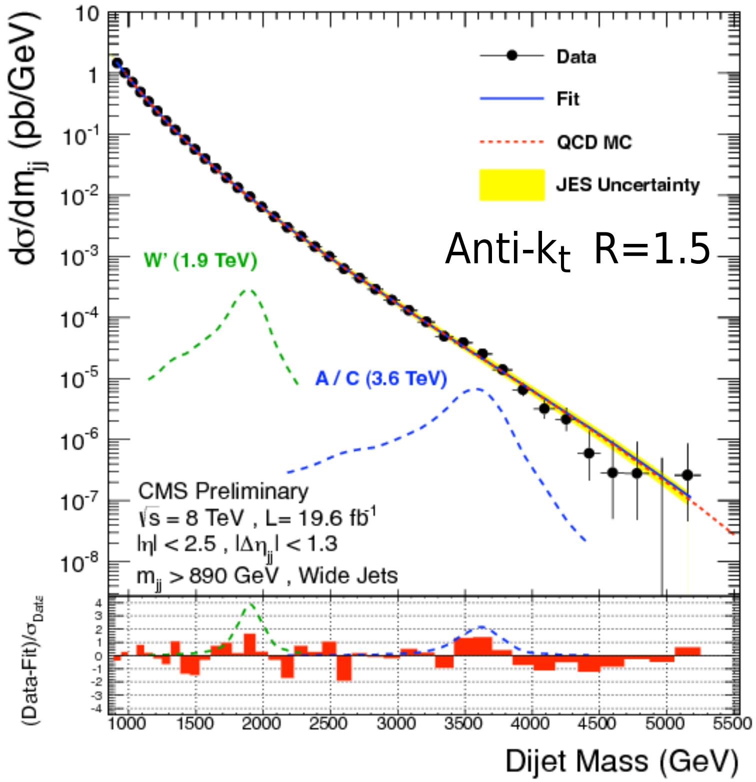
Select **central dijets** with **high dijet mass**

Search for deviations from smooth fit to background. If **no deviation**
Set limits on benchmark models using Bayesian techniques

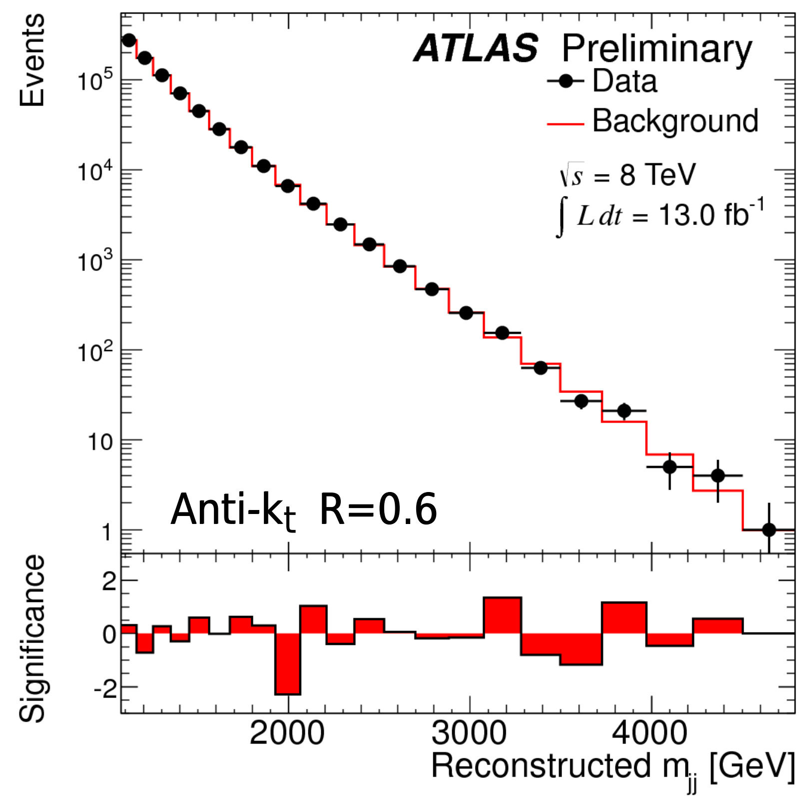
Dominant uncertainties : JES, luminosity, fitting procedure



CMS-PAS-EXO-12-059



ATLAS-CONF-2012-148

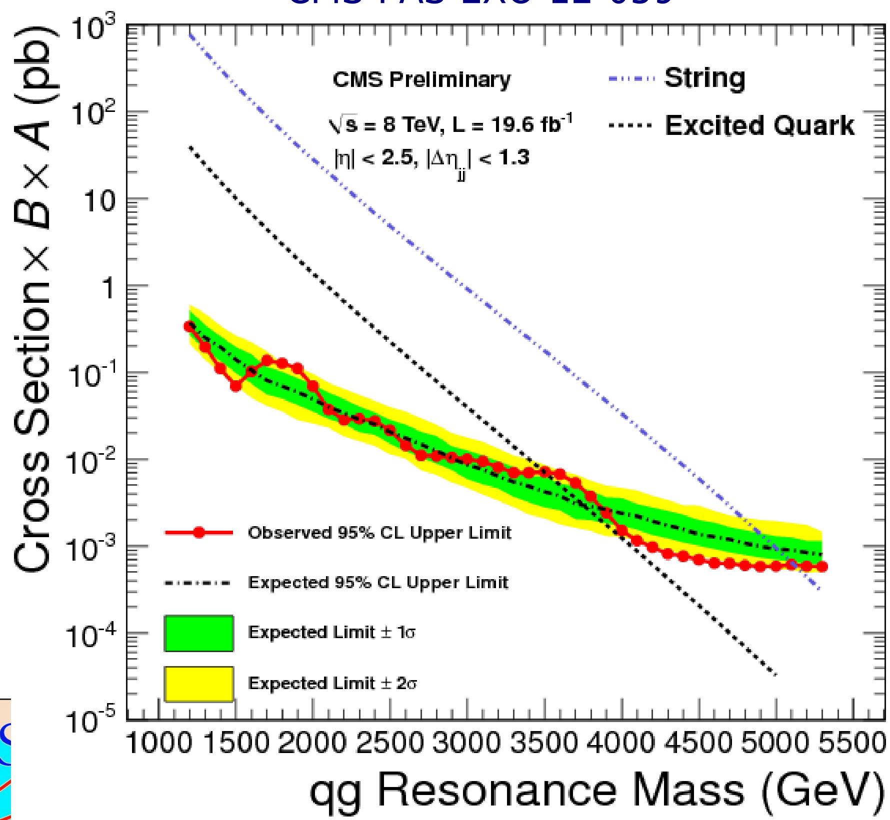


Dijet searches : 8 TeV limits

CMS benchmark models:

String resonance / excited quark → **qg**
Scalar octet / RS graviton / → **gg**
Heavy vector boson / axigluon /
E6 diquark → **qq**

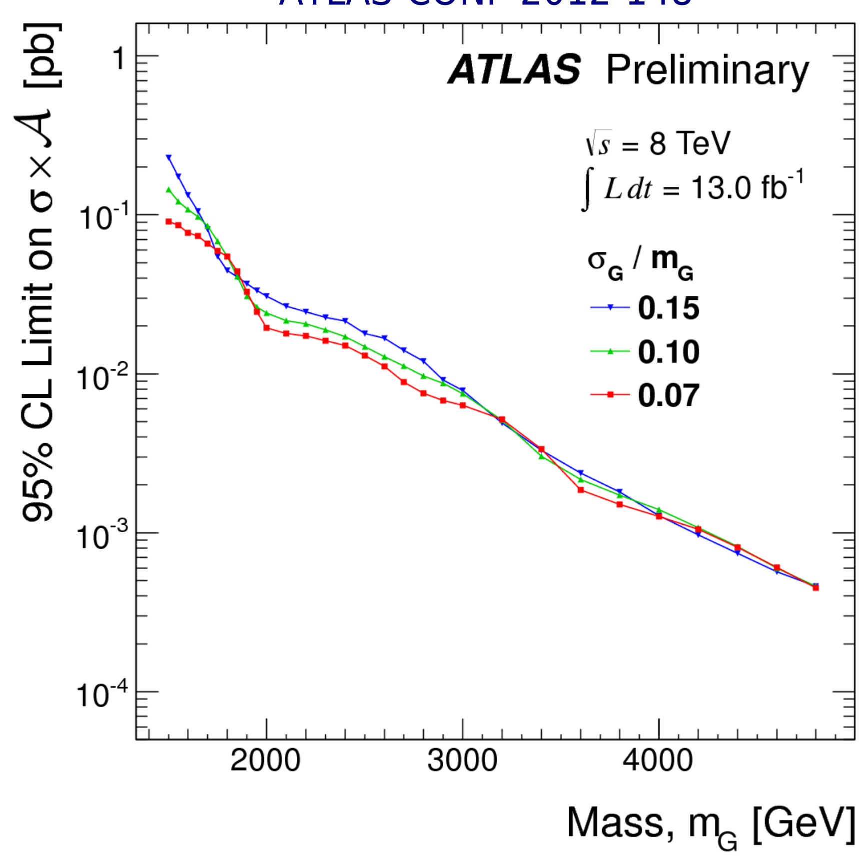
CMS-PAS-EXO-12-059



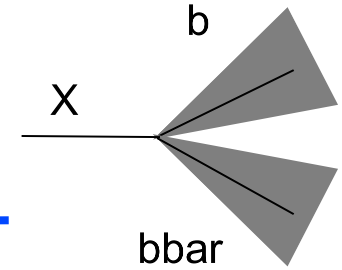
ATLAS benchmark models:

Excited quark (q*) → **qg**
Generic Gaussian resonances
of **different widths**

ATLAS-CONF-2012-148



Di-b-jet and bg searches



NEW

Similar technique to **dijet mass search**
Add 1 or 2 **b-tag requirements**

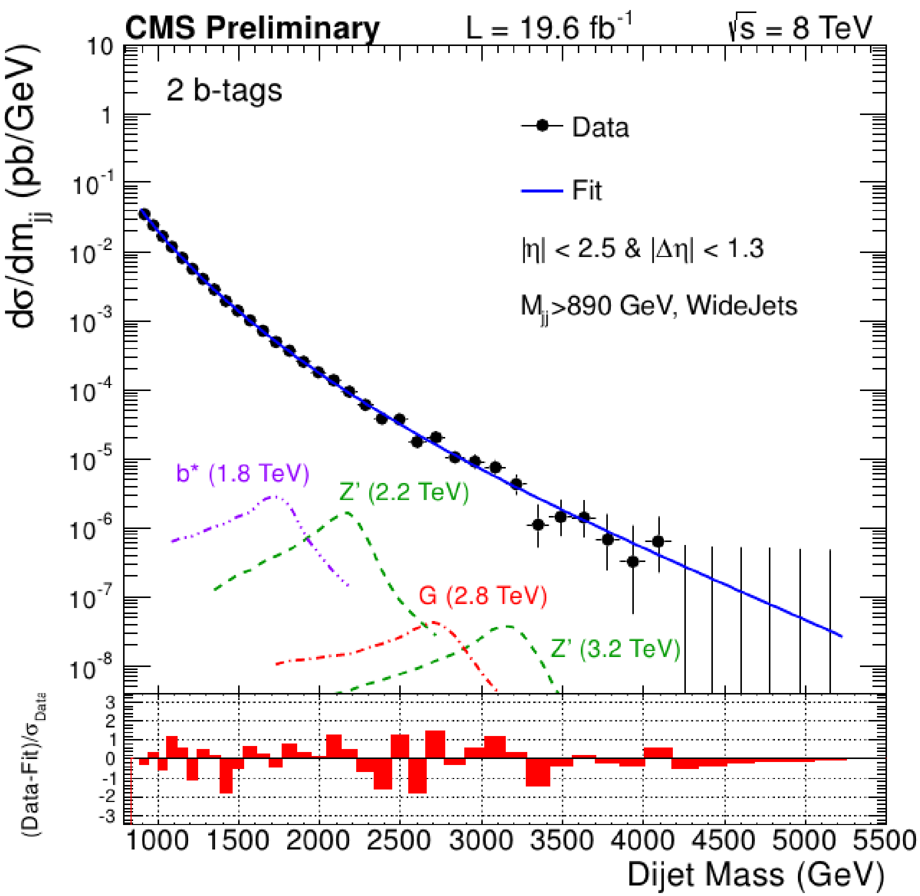
No deviations observed
from smooth fit to background → limits

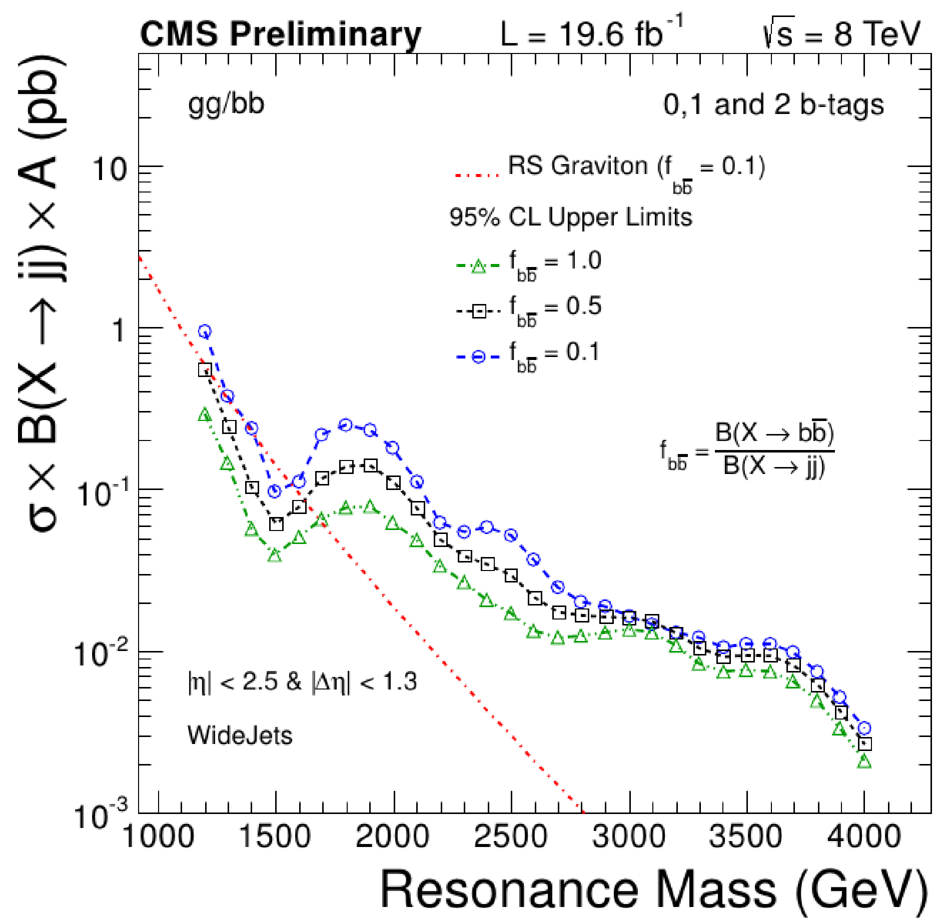
Dominant uncertainties : JER, b-tagging

Benchmark models:

SSM heavy vector boson Z' → **qq/bb**
RS graviton → **gg/bb**
Excited b quark → **bg**

CMS-PAS-EXO-12-023

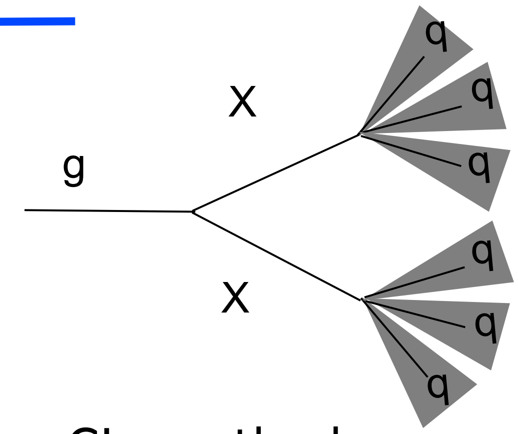




6-jet searches

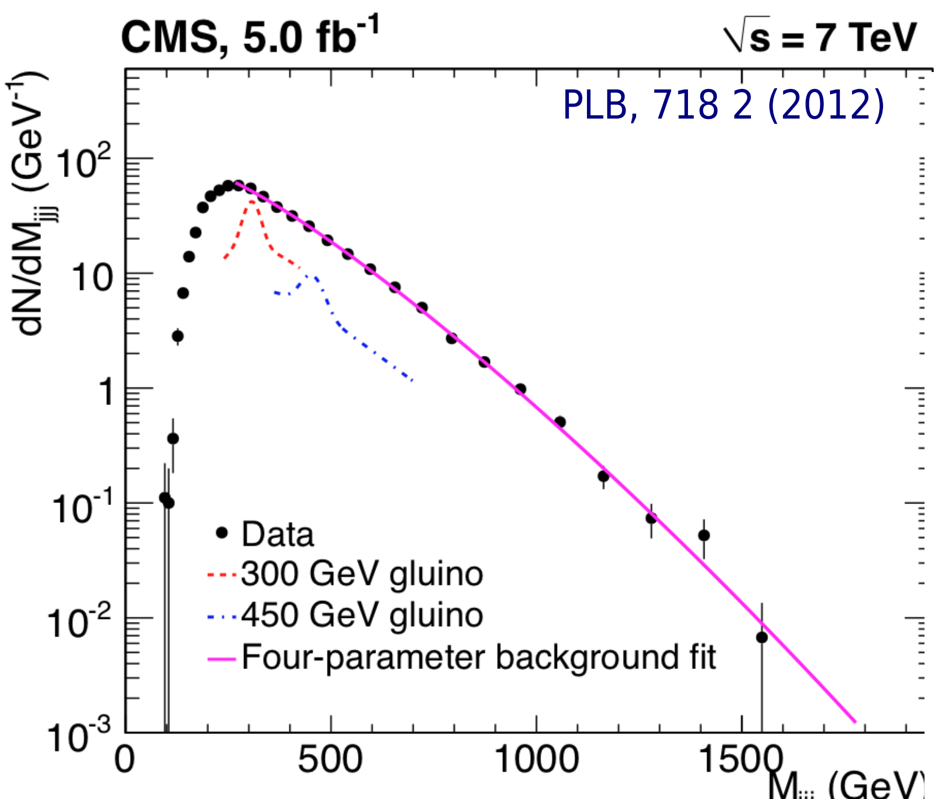
Select **high-jet-multiplicity** events (towards N=6)

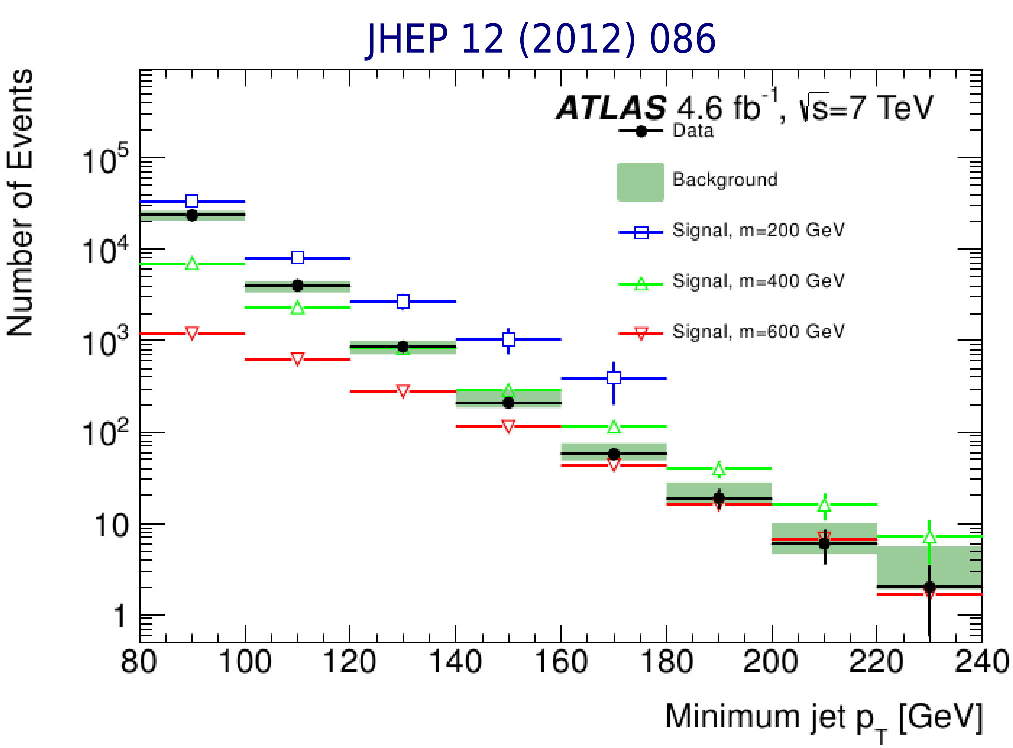
Search for:
deviations from smooth fit to Mjjj distribution (CMS)
excess in data-driven background estimation based on jet multiplicity (ATLAS)



If **no deviation, set limits on benchmark models** using CL_s method

Main uncertainties : JES, JER, ISR/FSR and pile-up (CMS), PDF, bkg estimate



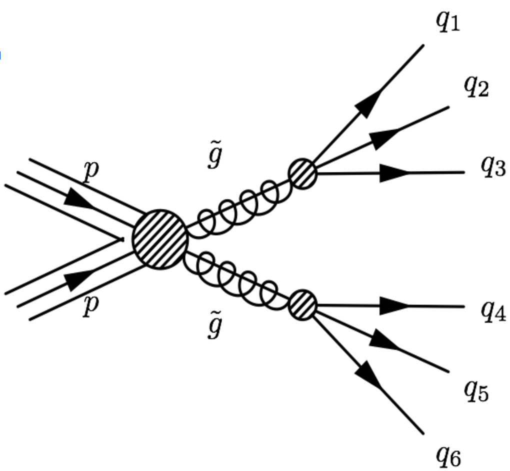


6-jet searches : limits

CMS amd ATLAS benchmark models:

Pair-produced **R-Parity Violating gluino** decaying in **three quarks** via off-shell squark

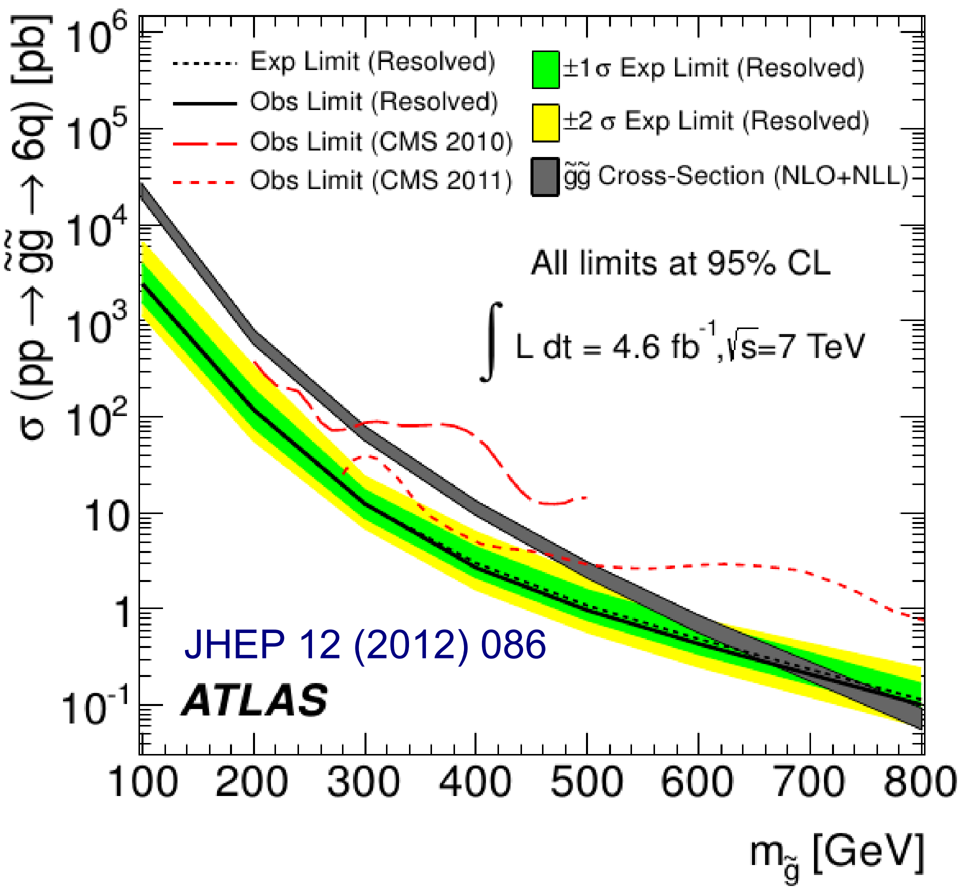
$$\tilde{g} \rightarrow q\tilde{q} \rightarrow qqq \text{ with } m_{\tilde{q}} >> m_{\tilde{g}}$$



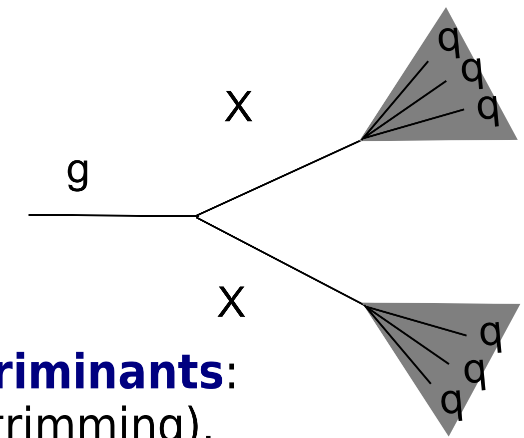
ATLAS analysis extends limit **below 200 GeV**

·**Boosted approach** available (next slide)

Limits improve when using minimum jet p_T discriminant (ATLAS) wrt fit to three-jet mass spectrum (CMS)



Boosted 6-jet searches

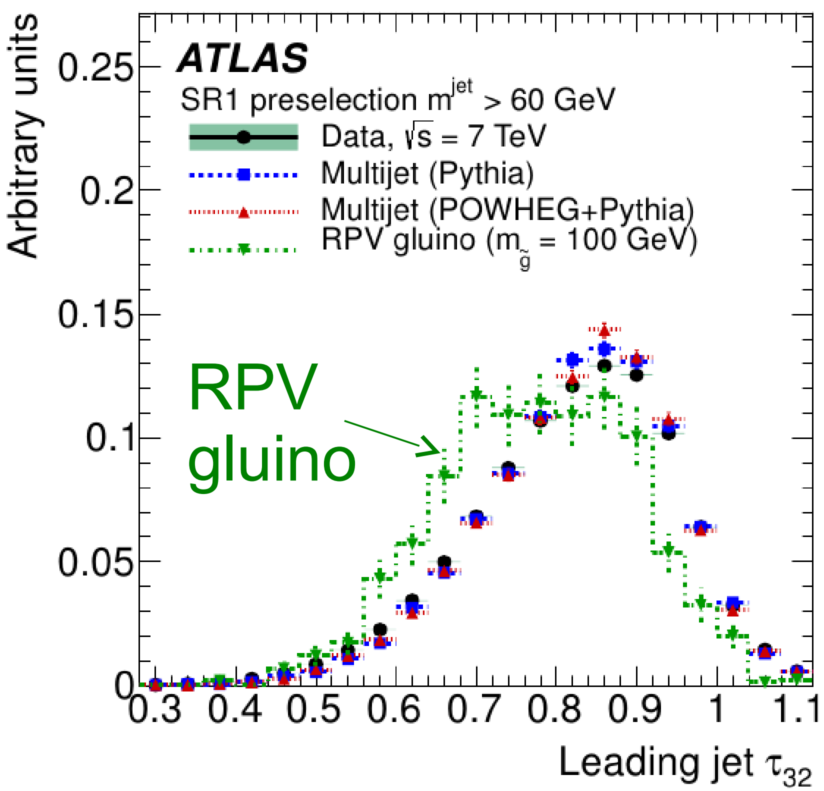


Light gluino with **large boost** $p_{\mathrm{T}} \gtrsim 2 \times m_{\tilde{g}}$

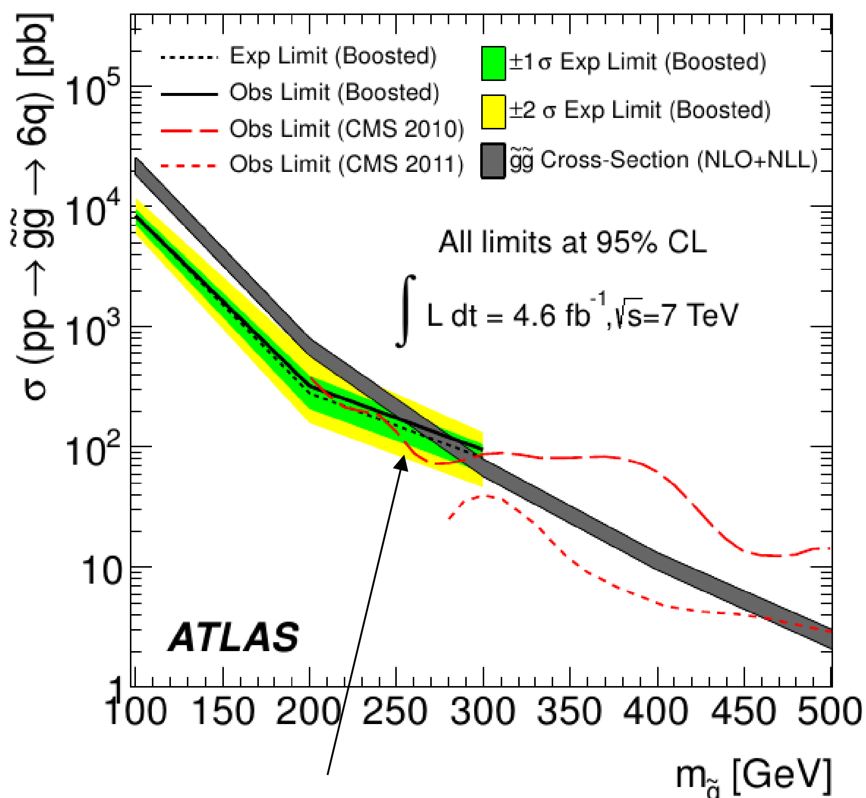
→ merging of decay products

JHEP 12 (2012) 086

Reconstruct 'fat jets' and use **jet substructure discriminants**:
jet mass after selection of harder jet components (trimming),
n-subjettiness (τ_{32}) in high jet multiplicity events



← 3 sub-jets **2 sub-jets →**



Cross-check to resolved analysis, first application of n-subjettiness in LHC physics analysis

Resonances with boosted jets

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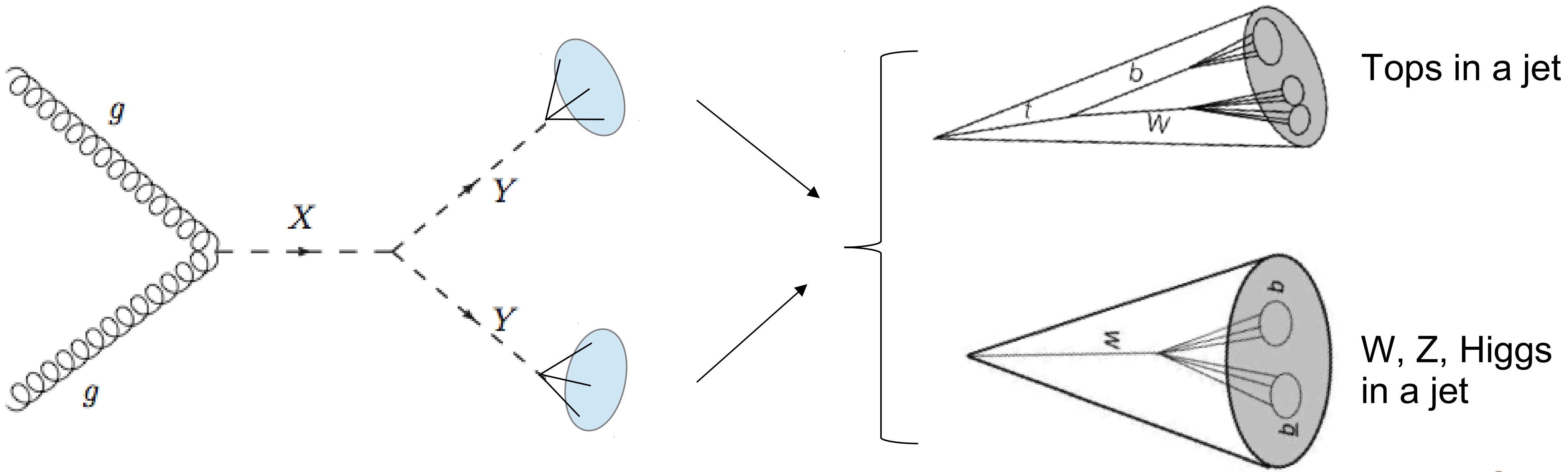
Searches with Boosted Topologies

X = BSM heavy resonance , Y = SM heavy particle (t,W,Z,H)

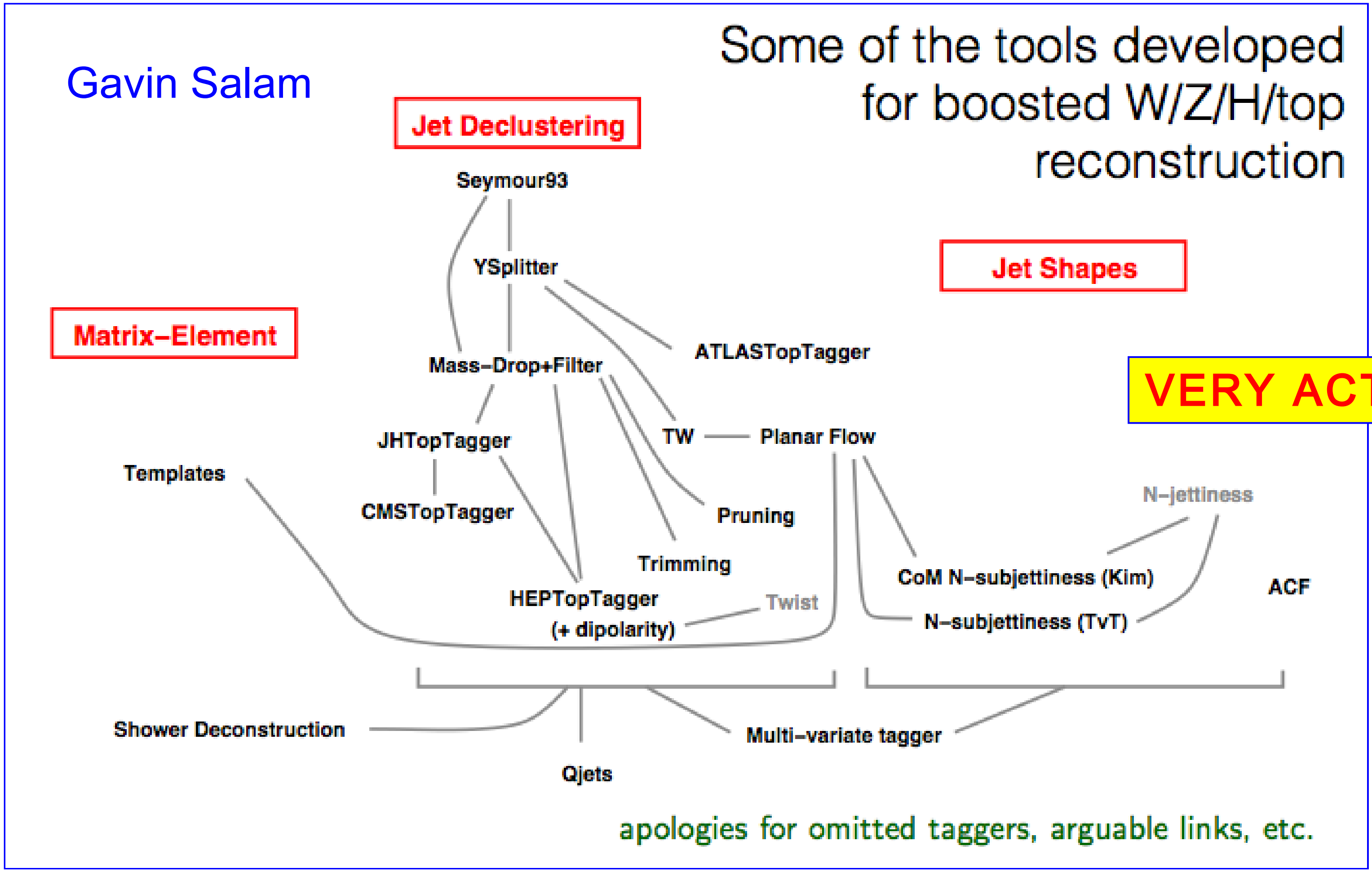
Hadronic decay products of Y merge into single "fat-jets" at high $r_M = M_X/2M_Y$ (~γ, lorentz boost) → depends on jet cone size

Use jet-substructure techniques to tag boosted hadronic decays of top, W, Z, and Higgs



Jet substructure techniques

The reconstructed mass of the boosted particle (M_Y^{reco}) is the most effective discriminant.... in addition...



VERY ACTIVE FIELD

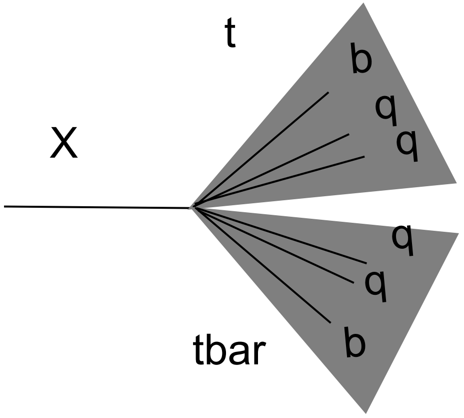
Boosted Top Searches (X→ttbar)

Fully hadronic final state (4 light quarks + 2 b quarks)

Bump hunt in m(ttbar) spectrum

Performed by both ATLAS and CMS with 7 TeV data

JHEP(2013) 116 arXiv 1204.2488



Jet triggers (SingleJet + MultiJet)

Top-tagging algorithms (jet substructure)

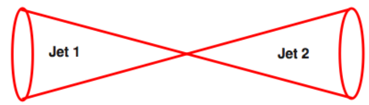
B-tagging selection (ATLAS only)

Data-driven estimates for multijet (MJ) background

Top Tagging in CMS

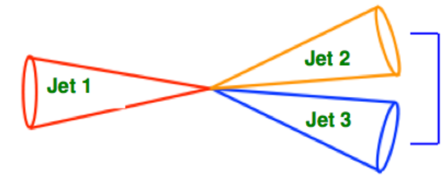
Cambridge-Aachen (CA) jet algorithm with R=0.8

Type-1 Top :
fully merged in 1 jet



- CMSTopTagger
- Finding 3 sub-jets by reversing last steps of CA clustering
- Grooming: in reclustering, reject particles with large angle and low pT

Type-2 Top
(fails Type-1 tag):

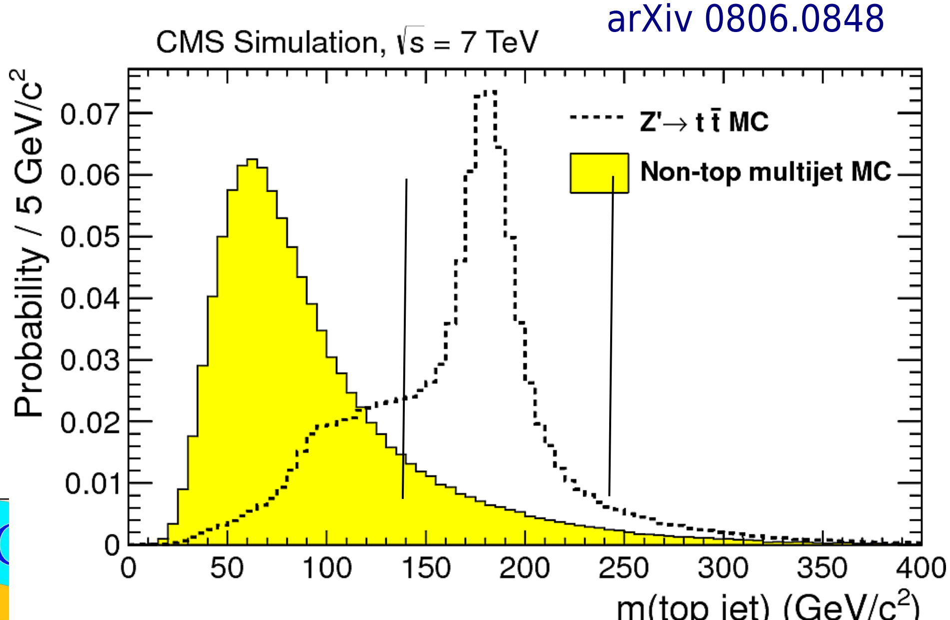


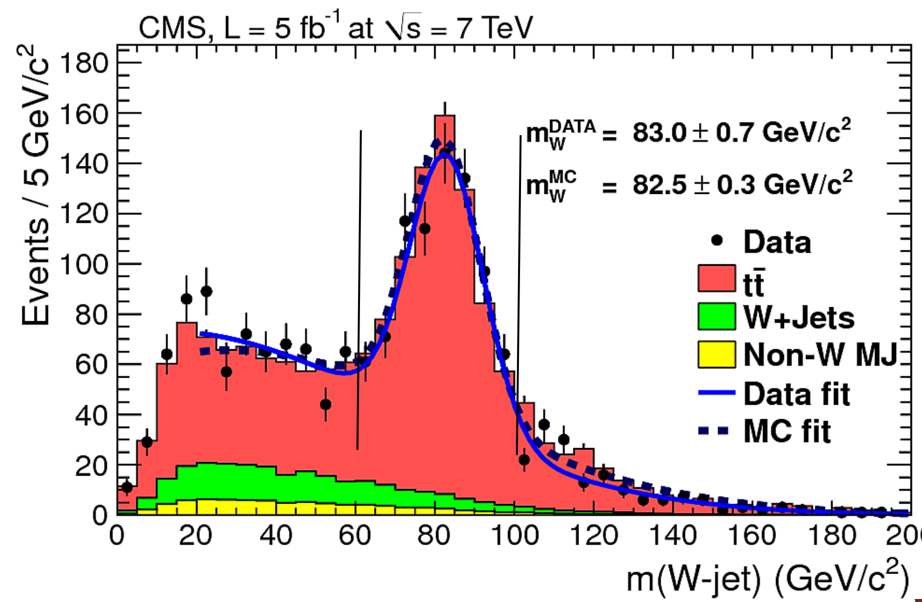
1 jet from boosted W→jj +

1 jet from b quark

- Jet pruning to reject soft particles
- Mass drop cut (m1/m<0.4) to identify boosted W, no explicit b-tag

arXiv 0806.0848





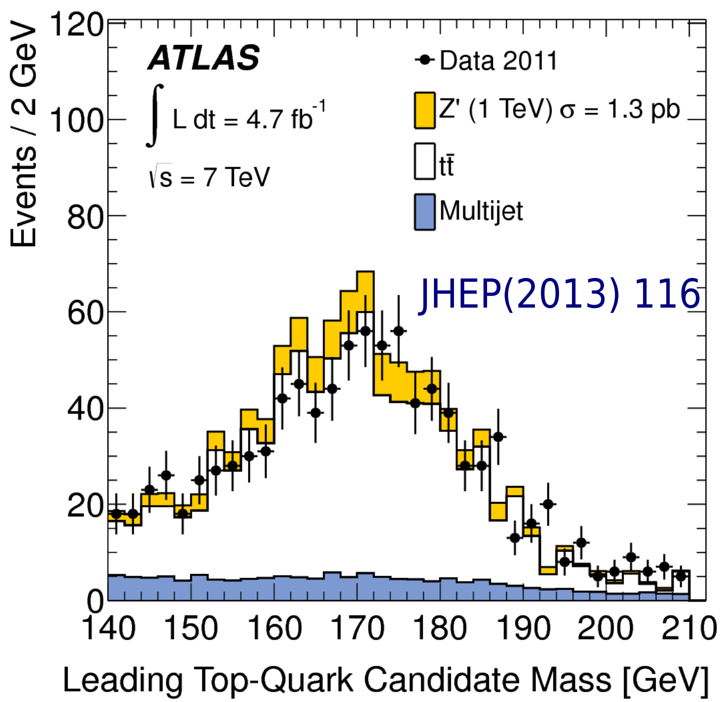
C. Doglioni, F. Santanastasio

Top Tagging in ATLAS

HEPTopTagger

arXiv 1006.2833
ATLAS-CONF-2012-065

- CA with R=1.5 ("fat-jets")
- Identify 3 sub-jets + grooming
- Effective for pT(t)>200 GeV



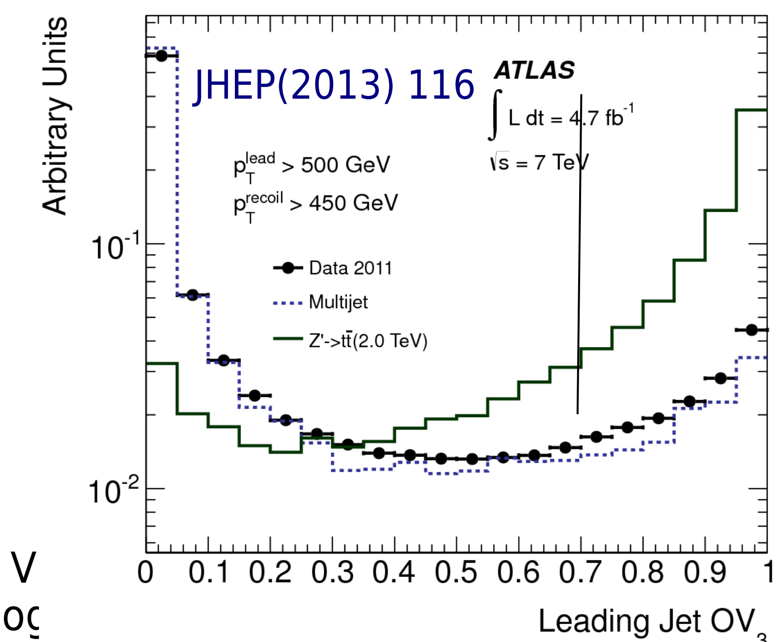
TopTemplateTagger

arXiv 1006.2035

- Anti-kT (AK) with R=1.0
- Compare energy flow in jet between given top-quark decay hyp. and obs.

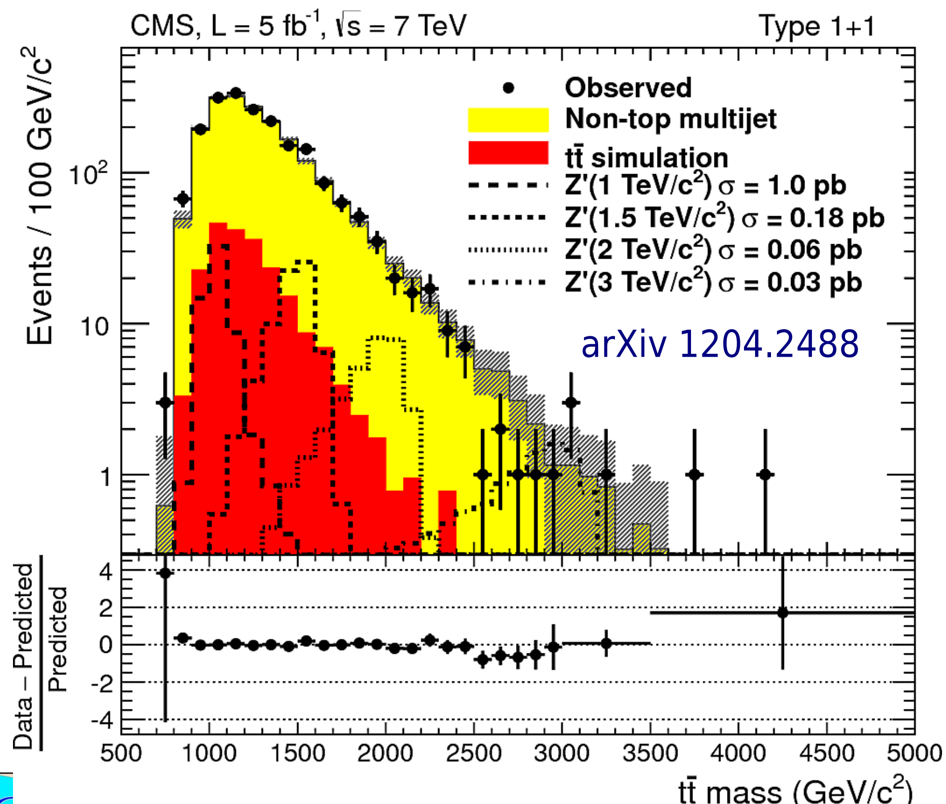
$$OV_3 = \max_{\{\tau_n\}} \exp\left[- \sum_{i=1}^{3} \frac{1}{2\sigma_i^2} \Big(E_i - \sum_{\substack{\Delta R(\text{topo},i) \\ <0.2}} E_{\text{topo}} \Big)^2 \right]$$

- Jet mass requirement: m_{top} +/-50 GeV

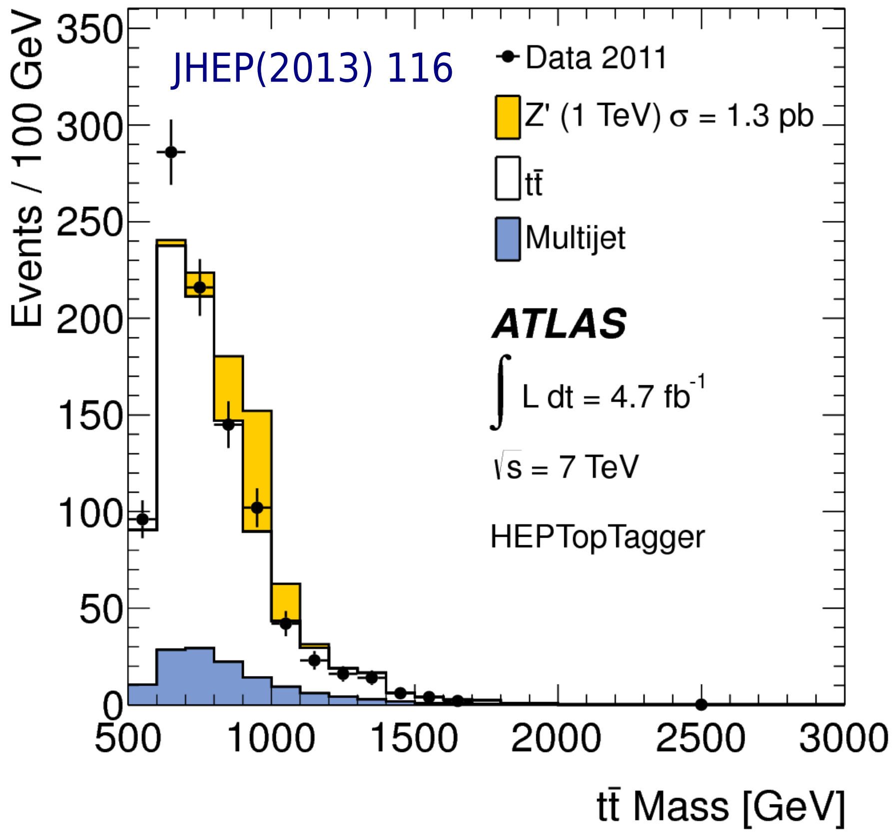


Backgrounds to boosted tops

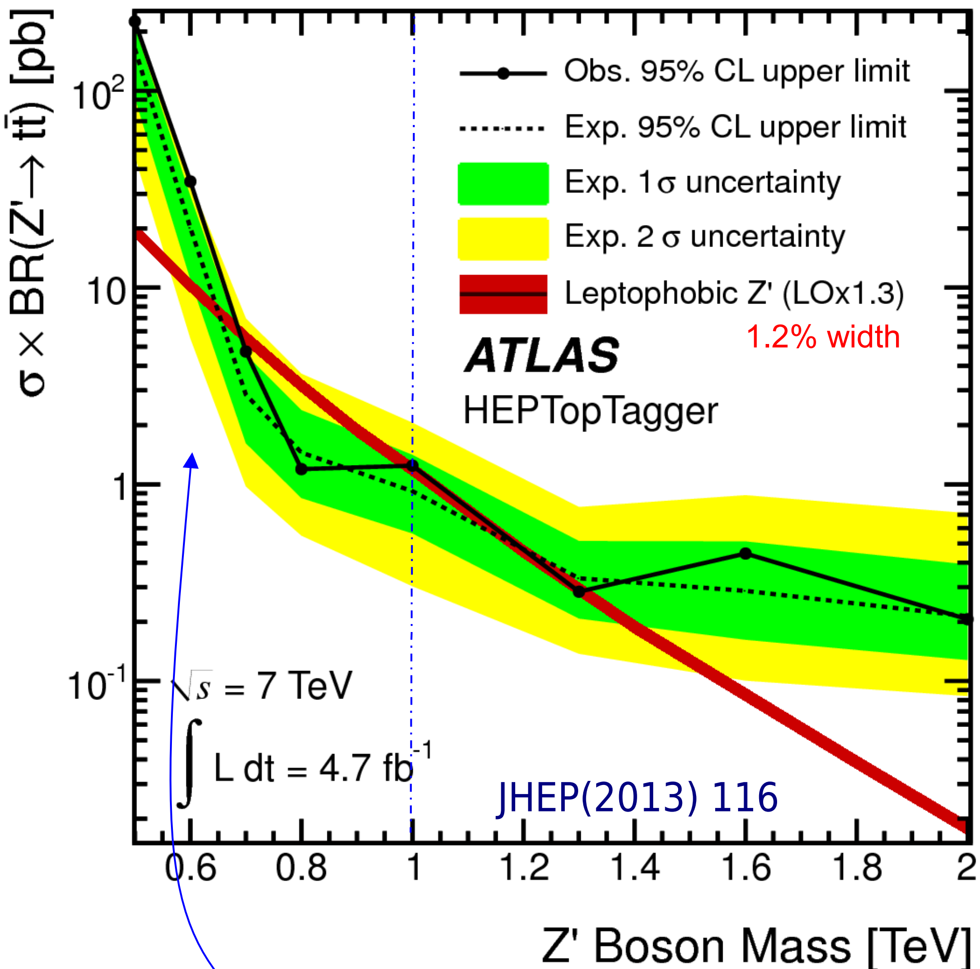
- CMS: dominated by MJ background (no b-tag)
  - Data-driven estimate using fake rates derived in control regions

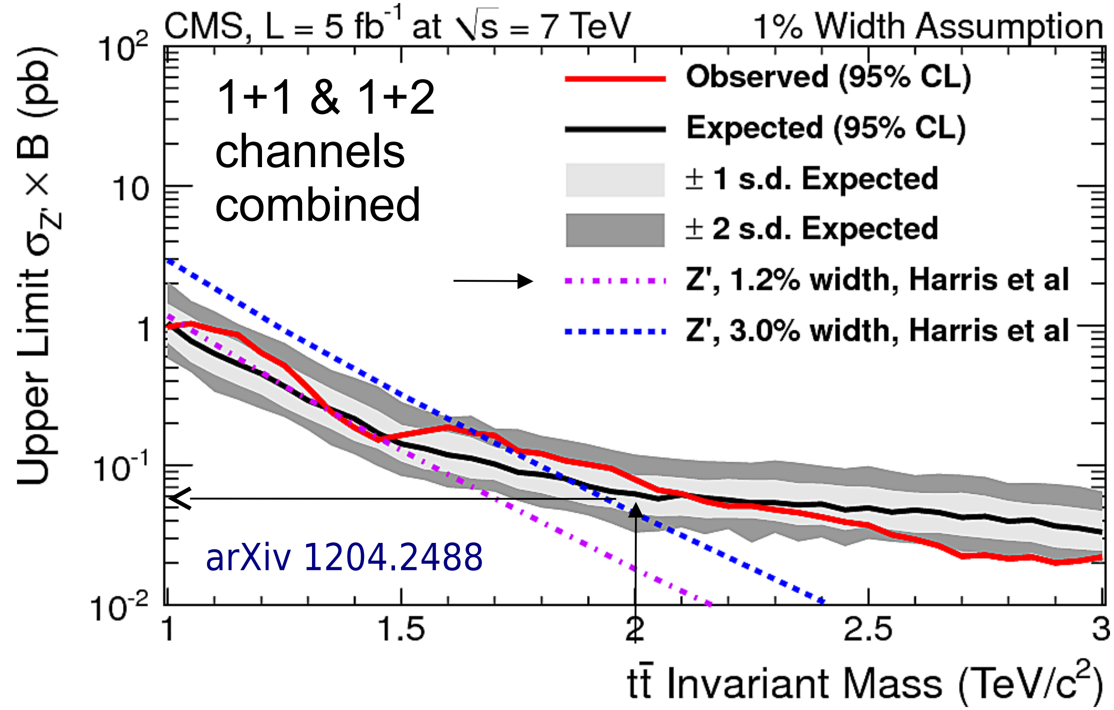


- ATLAS: dominated by ttbar events (b-tag applied)
  - ABCD method for MJ using b-tag info



Limits (Z'→ttbar) @ 7 TeV





Multijet triggers allow to extend ATLAS analysis below 1 TeV

- Expected Z'(1.2%) mass limits comparable
- ATLAS starts the search below 1 TeV
- CMS more sensitive above 1.5 TeV
- Room for improvements at high and low mass for both experiments

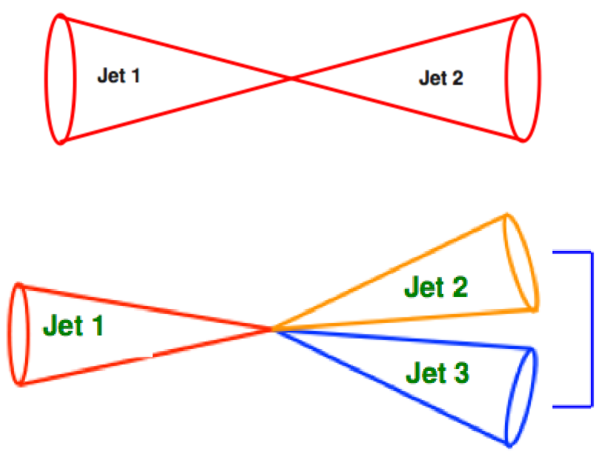
X→ttbar CMS @ 8 TeV

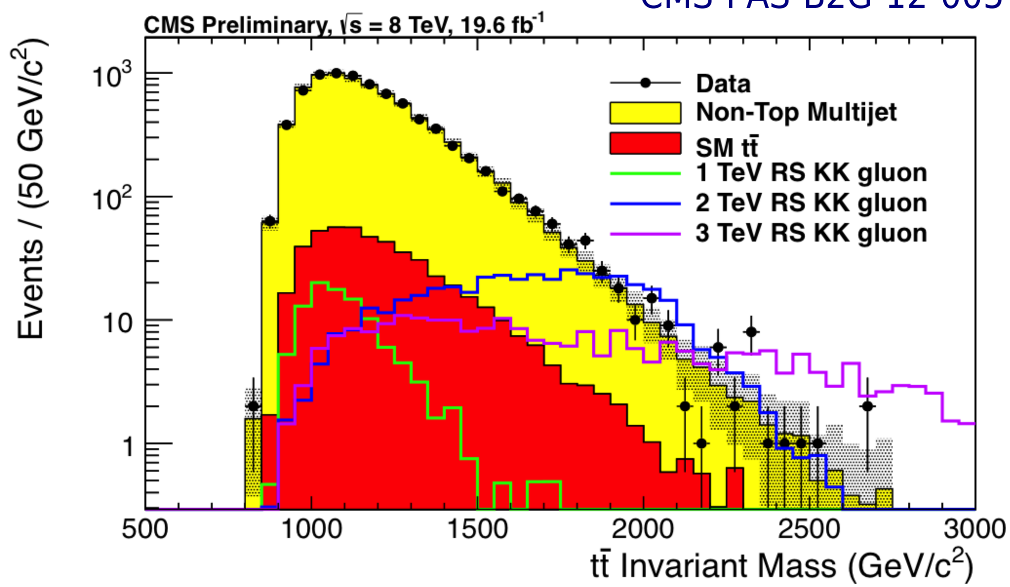
NEW

CMS-PAS-B2G-12-005

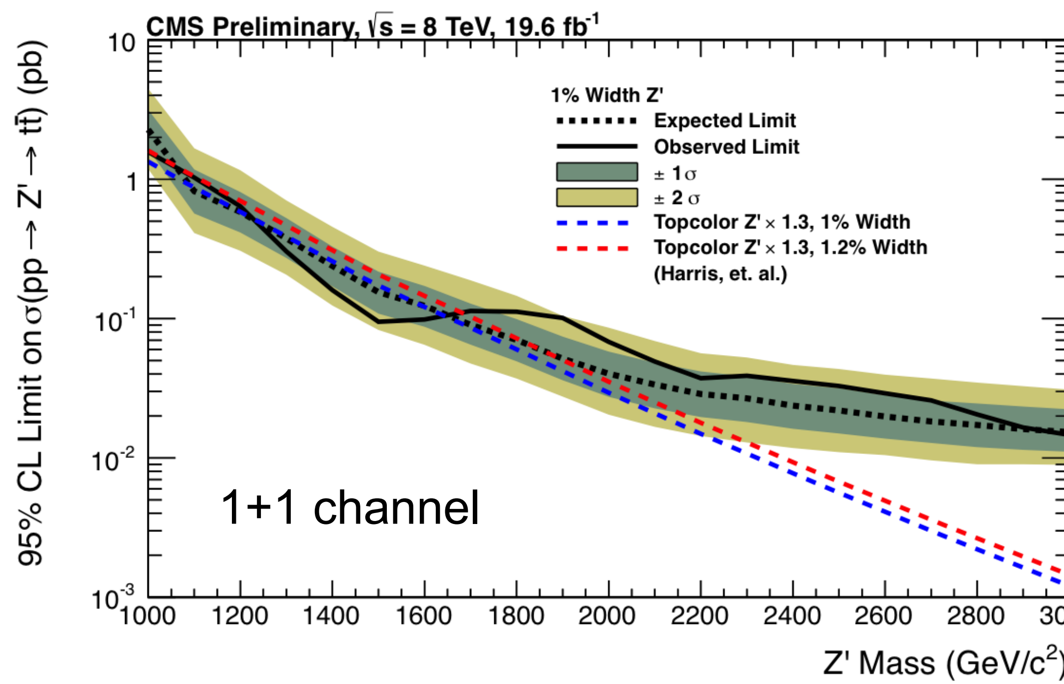
1+1

1+2



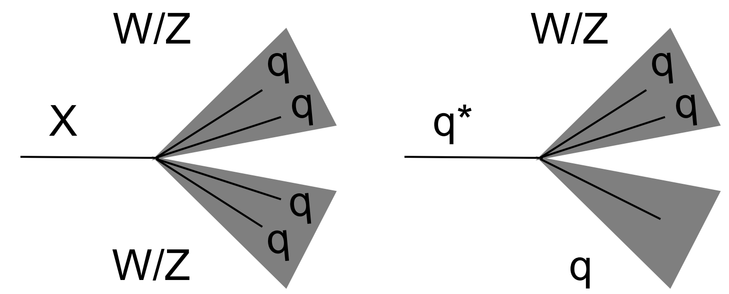


- Type1 + Type1 topology for search
- Type1 + Type 2 topology for validation of subjet energy scale
- Limits on σ x BR improved by factor of ~2 for M>2 TeV, compared to 7 TeV analysis
- Set limits on RS KK gluon (wide), Z' (narrow&wide), models predicting enhancement of ttbar cross section



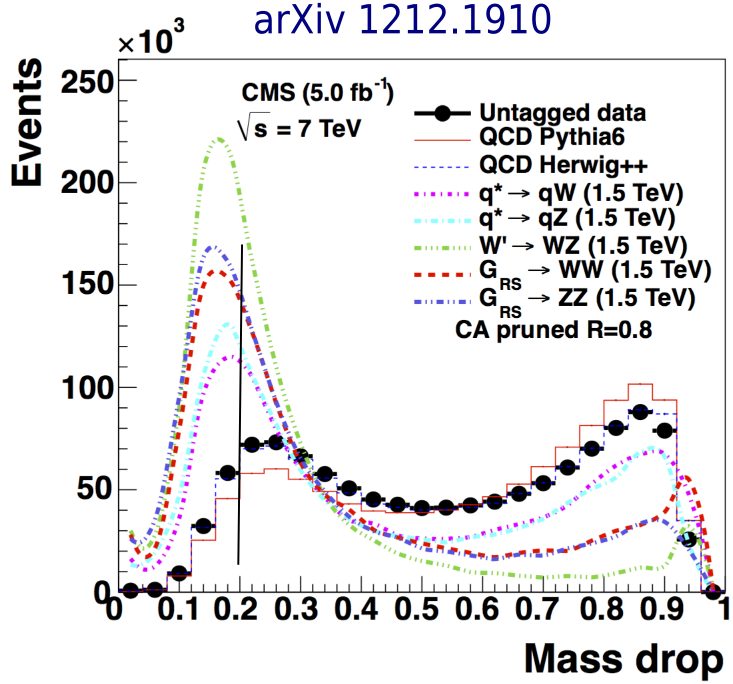
Boosted W/Z Searches (X→VV/Vq)

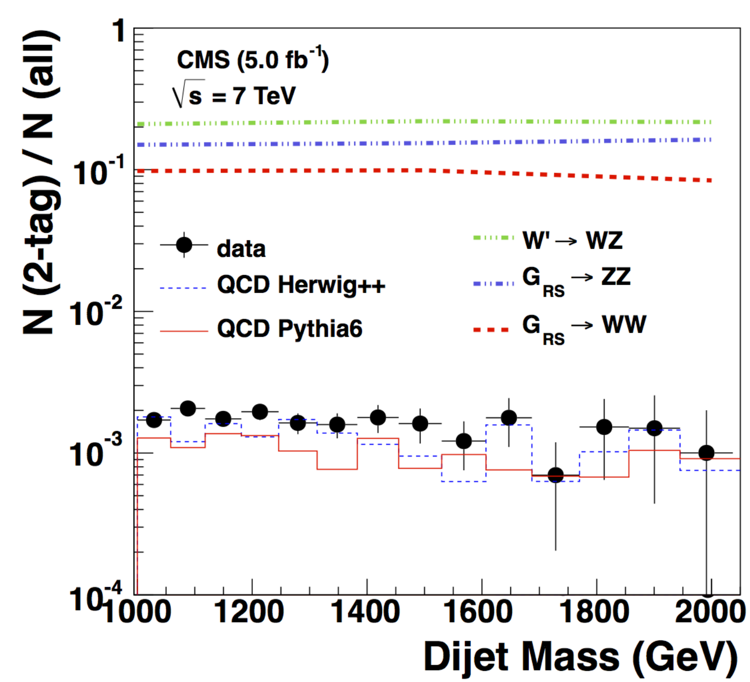
- Dijet selection (AK R=0.5 jets)
  - Mjj>890 GeV, η(jets)<2.5, |Δη(jets)|<1.3
- W/Z tagging (CA R=0.8 jets)
  - 70 < pruned jet mass < 100 GeV
  - Mass drop (m_{jet1}/m_{jet}) < 0.2 (after pruning)



BR(W/Z→qq)~70%

arXiv 1212.1910





N(all) after angular cuts

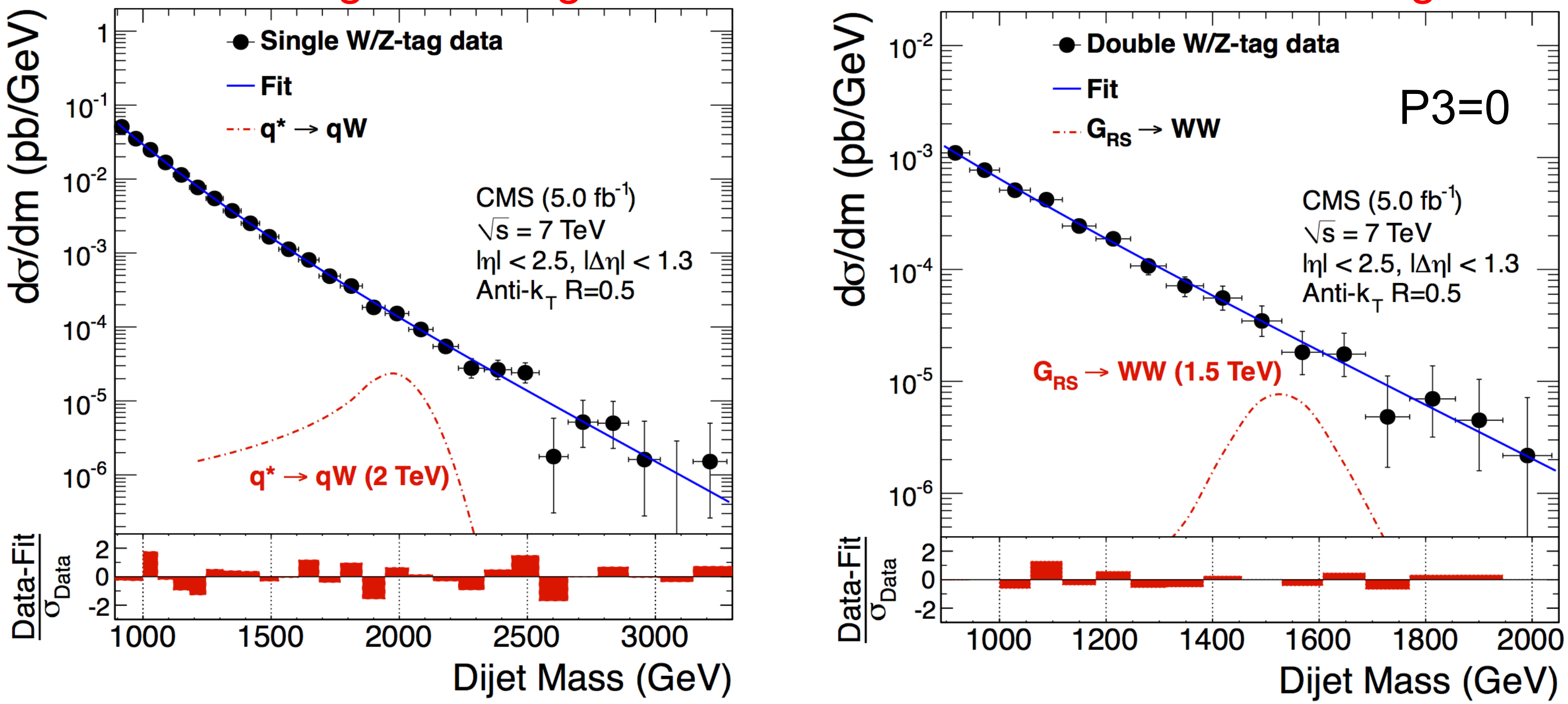
1/100

Boosted W/Z Searches (X→VV/Vq)

- Dominated by QCD background
- Fit data spectrum with smooth function (same used in dijet search)

$$\frac{d\sigma}{dm} = \frac{P_0(1-m/\sqrt{s})^{P_1}}{(m/\sqrt{s})^{P_2+P_3\ln(m/\sqrt{s})}}$$

Single W/Z-tag arXiv 1212.1910 Double W/Z-tag



Most stringent limits to date on qW and qZ final states (see backup)

Competitive limits for VV at high masses thanks to larger BR to dijet

Conclusions

→ At LHC, new heavy resonances (RS gravitons, q*, axigluons, ...) produced via strong interaction → jet decays abundant

→ RPV SUSY also predicts new particles decaying to 2 or more jets

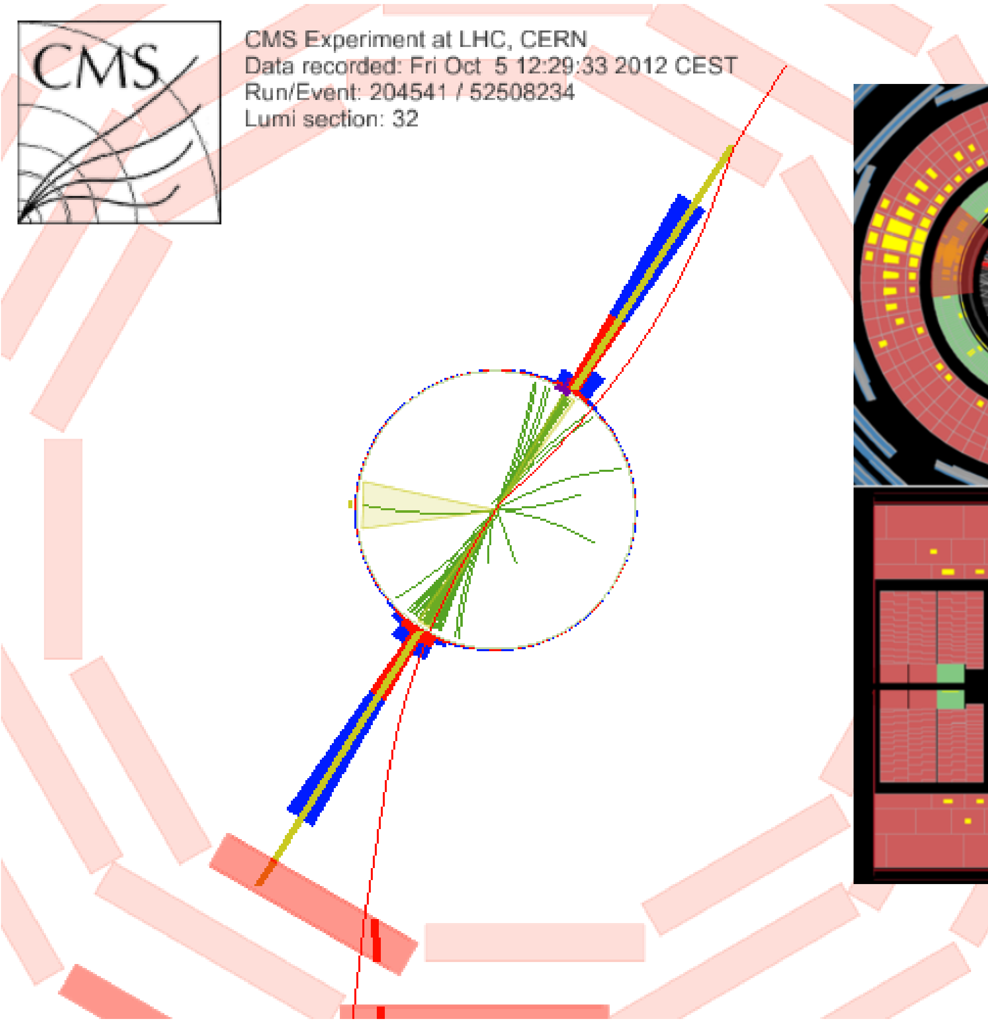
→ No evidence for new resonances in 7 TeV and 8 TeV data so far
- 8 TeV analyses still ongoing...

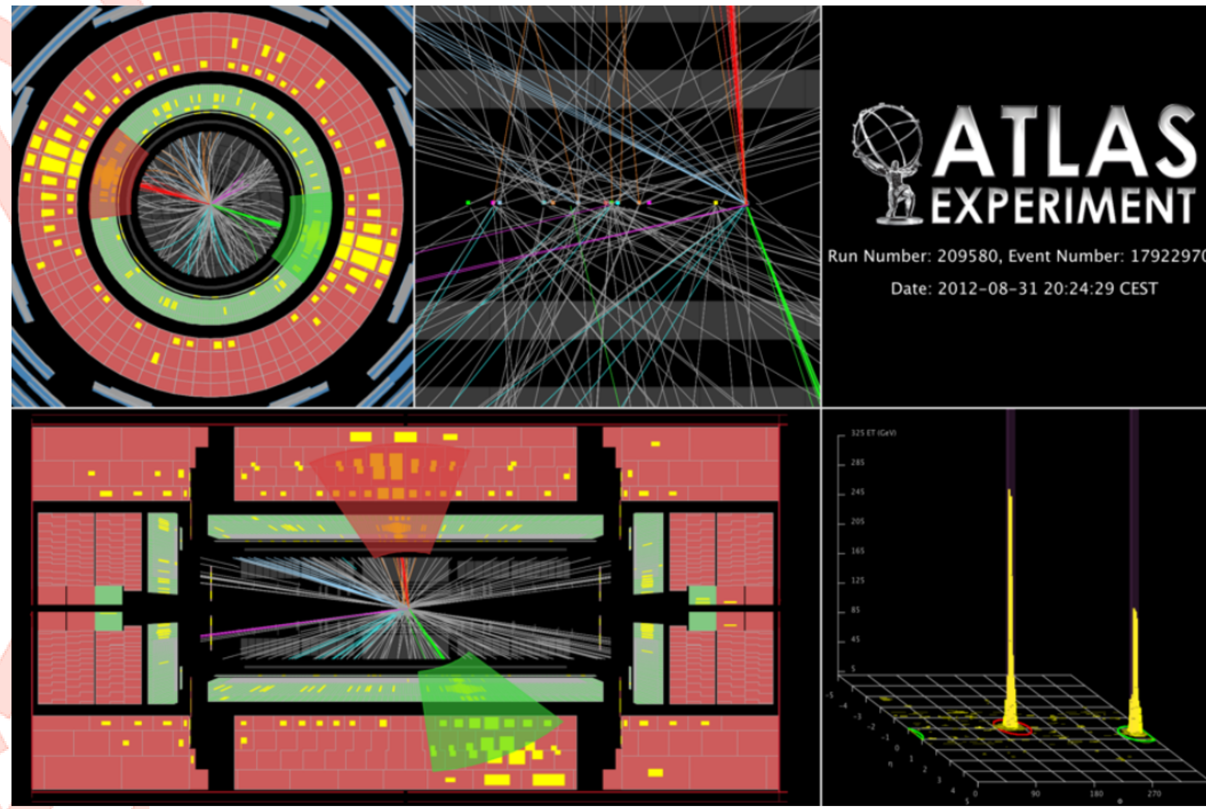
→ Dijet analysis will be crucial at the startup in 2015 at sqrt(s)=13-14 TeV
- Preparation should start soon
- Further coordination among experiments desirable?

→ Searches in boosted regime (X → ttbar, X → VV, ..) necessary at high p_T/M_X
- More prominent in 13-14 TeV searches

→ Jet substructure is an extremely active field
- We have ~2 years to learn from the 7-8 TeV experience and keep preparing the ground for this type of searches

Dijet mass ~ 5 TeV!





M(di-jet) = 4.69 TeV

M(di-widejet) = 5.15 TeV

Inclusive di-jet searches

Heavy Resonances in Hadronic Final States

Discussion

Caterina Doglioni – ATLAS, University of Geneva
Francesco Santanastasio – CMS, CERN

VI LHCpp workshop – Genova, 08-10/05/2013

Discussion points

13/14 TeV will happen **soon** for both established and new searches !

Jet energy scale uncertainties

- Jet calibration and uncertainties at high pT

Searches and reinterpretation

- How to get the most info from CMS and ATLAS searches

Coherence of experiments for future measurements

Data collection in hadronic final states

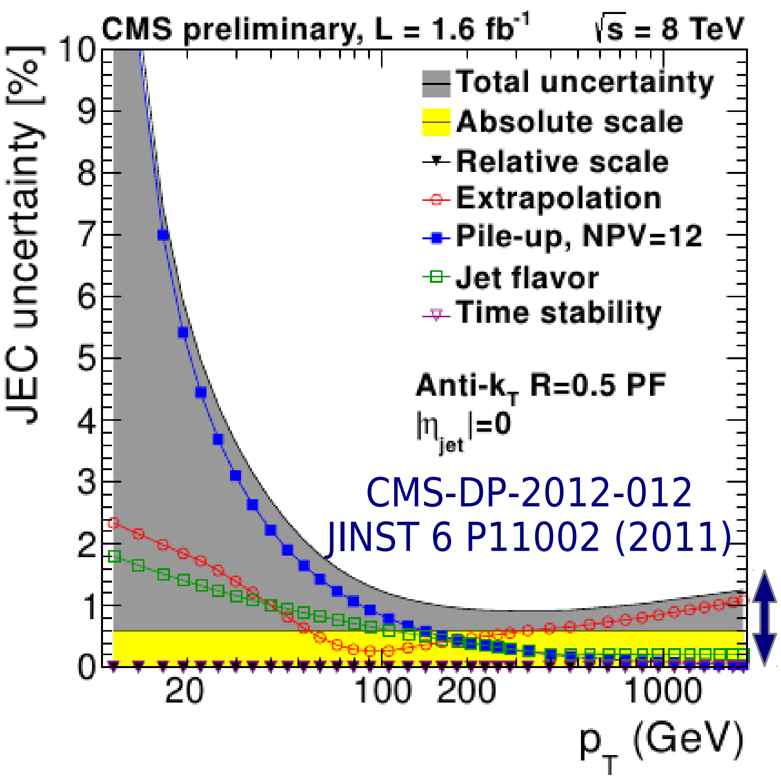
- Data parking / delayed streams
- Data scouting

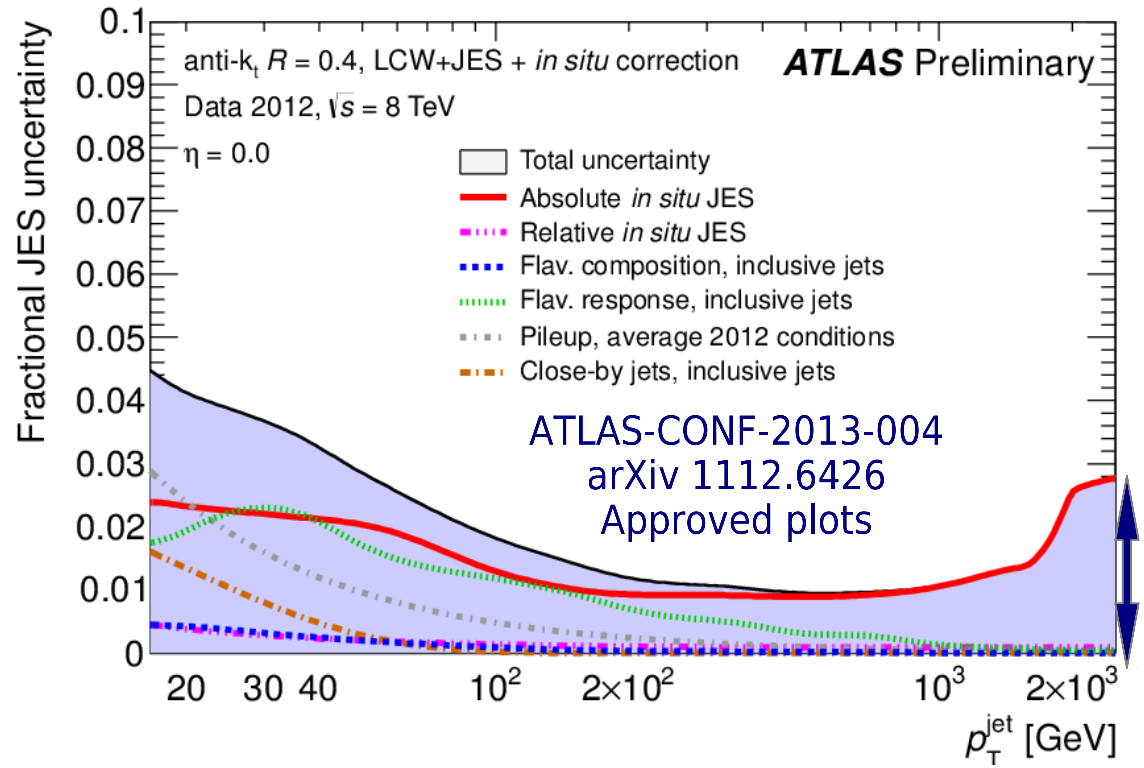
Future measurements : jet substructure

- Choice of algorithm / techniques
- Use of experimental data in MC tuning
- New directions : trigger, angular info, q/g tagging, charge

Improvements and future directions

JES uncertainties for ATLAS and CMS





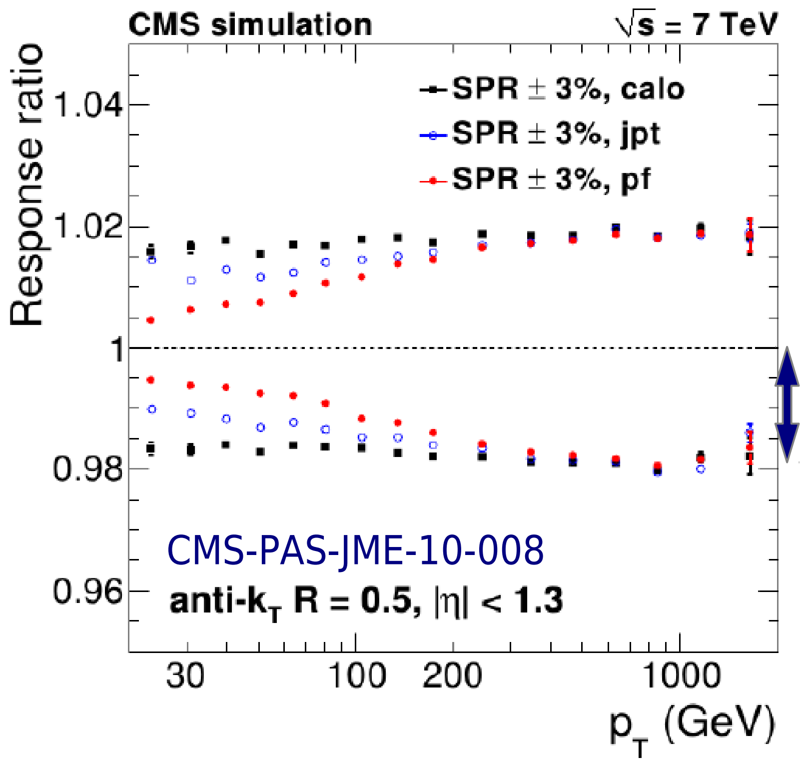
Differences between methods, **similar** uncertainty sources:
ongoing discussion on
correlation and coherence of ATLAS & CMS JES uncertainties
precision measurement, still interesting for searches

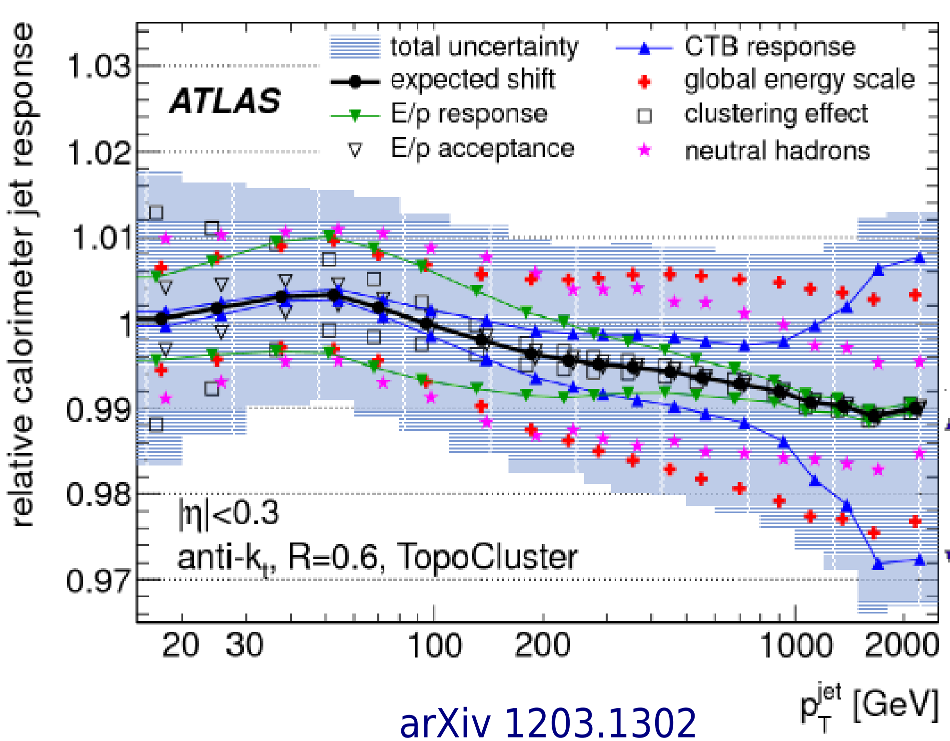
JES uncertainty coherence: high-pT

Both experiments employ propagation of single particle uncertainties to jets

CMS:
Assume flat 3 % shift for particles of all pT, from E/p and CTB (up to 2-300 GeV)

ATLAS:
· Increase uncertainties for particles beyond TB range (conservative estimates of calorimeter non-linearities)





arXiv 1203.1302

Q : Homogenize approach by using **similar assumptions** and **more motivated uncertainties ?**

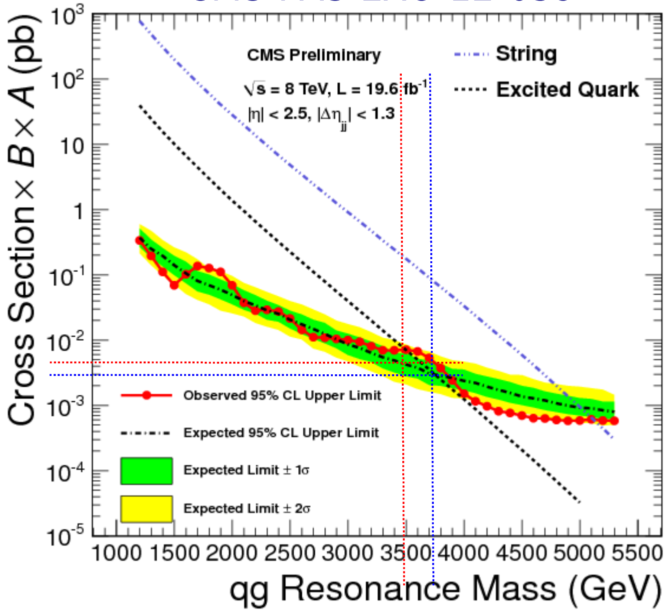
Definition of limits on resonances

New resonances could be around the corner with 13/14 TeV
→ first search, as exciting as LHC startup!
Q: coordinate resonance definition/limit presentation?

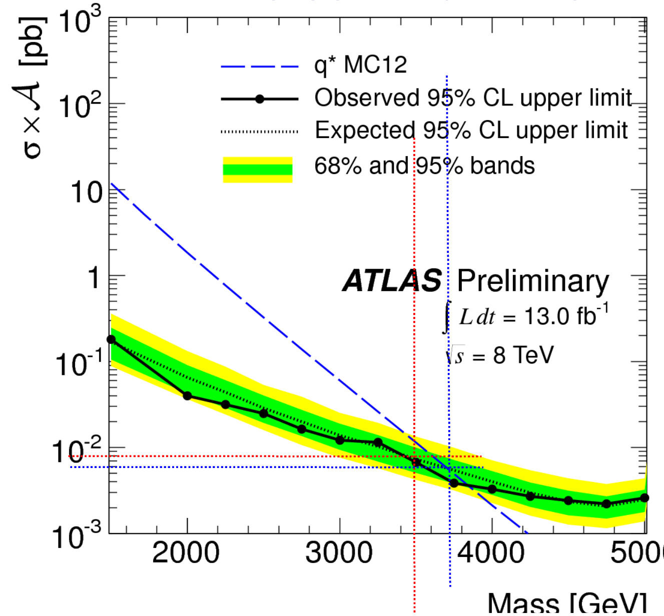
CMS:
· **narrow width** approximation used for cross section calculation
· only **core of template** used in limit setting
· Limit expressed as **σ x BR** ('dijets only')

ATLAS:
· **full** generator-level cross section
· Use of **full template** in limit setting
· **Inclusive** limit (W/Z/gamma q* decays included)

CMS-PAS-EXO-12-059



ATLAS-CONF-2012-148

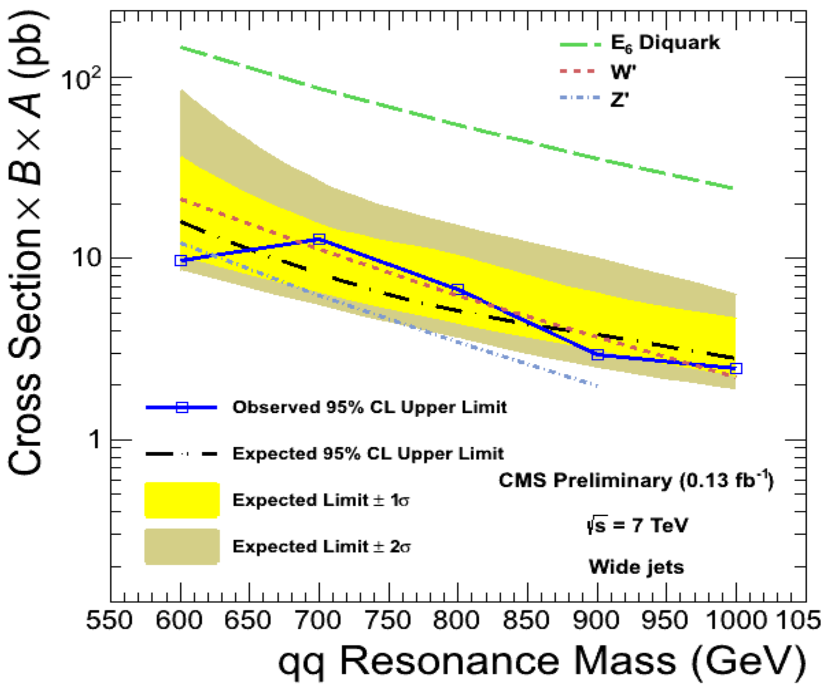


Small effect seen on 'comparable' search (q* with 8 TeV data),
'narrow width' effect noticeable for wider resonances (see backup)
reinterpretation and Gaussian templates could be more difficult near kinematic limit
Q: is there a preference for theorists? How to quantify errors?

Dijet searches : 7 TeV lower mass limits

Rare low-mass resonances can **still** be excluded in dijet mass spectrum
Problem : increased luminosity → cannot record all data online
store reduced format (*data scouting*) or analyse data later (*delayed/parked data*)
Reduced data storage also useful to **collect more of the unexpected** 'at runtime'

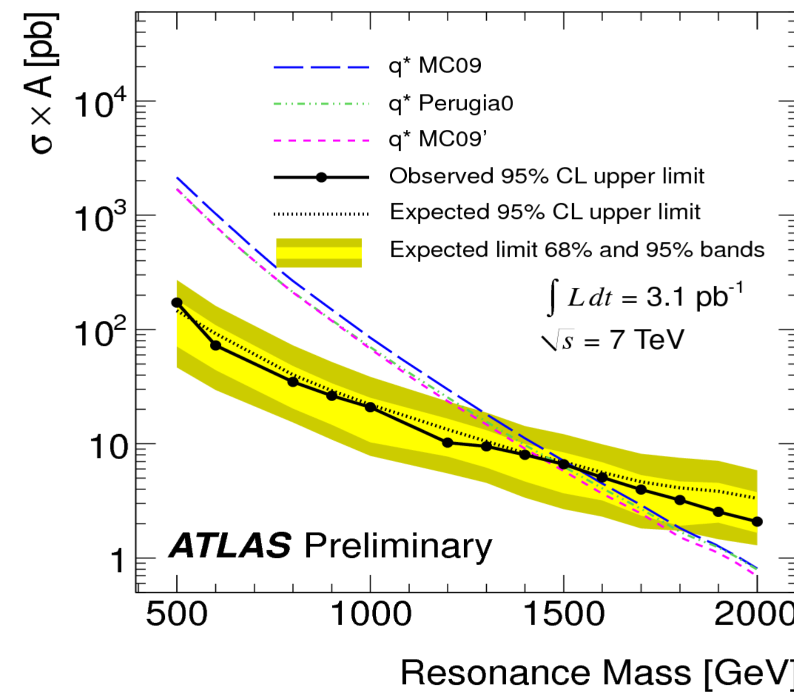
CMS : data parking (from 2012)
data scouting (from end of 2011)



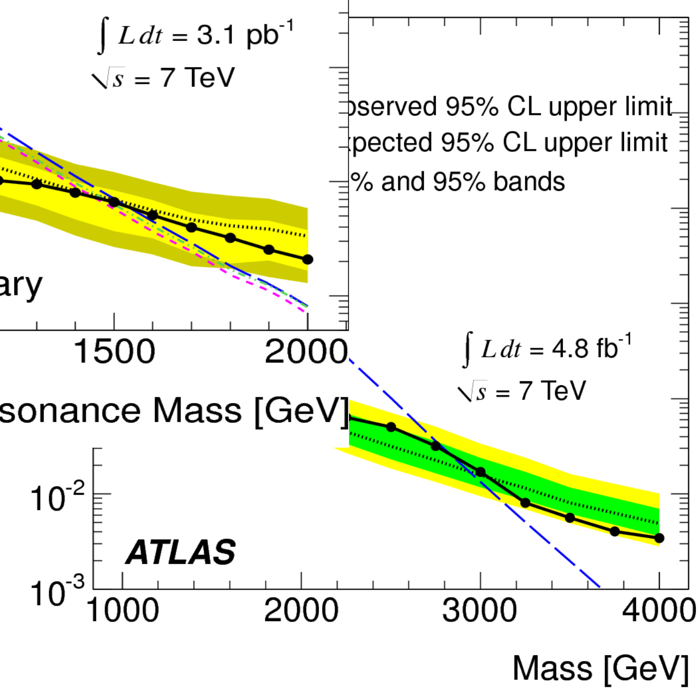
CMS-PAS-EXO-11-094
last two days of 2011 data
using **data scouting**

ATLAS : delayed triggers commissioned
starting from 2012

ATLAS-CONF-2010-093



arXiv 1210.1718



ATLAS 2011 data:
Initial data (low-mass)
Full dataset (high-mass)
no special triggers

Jet substructure tools

- Jet substructure will be **a necessary tool** for heavy resonances at 13/14 TeV (high p_T/M_X)

- Many techniques already available, **overlap** among them

- **Different approaches** in use by ATLAS/CMS
  - in some cases historical reasons / availability of calibrations

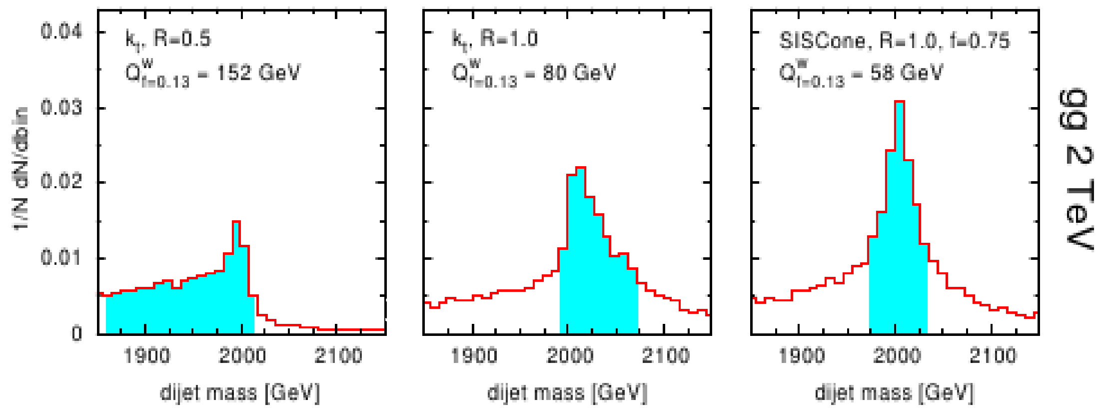
- During LHC shutdown, time to study/understand optimized approaches and implement them in time for the start-up

→ more theory/experiment interaction and groundwork needed
→ strategy will help with improvements in MC modelling

Q: Try to agree upon benchmark techniques among two experiments (starting e.g. from jet algorithms)?

arXiv : 0810.1304

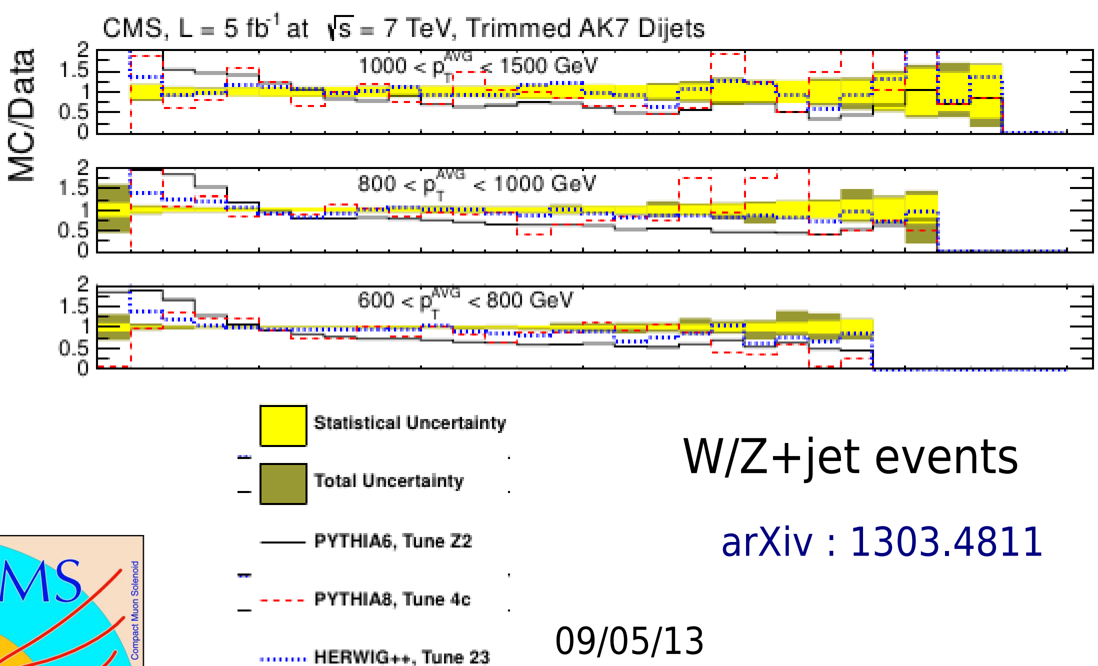
CMS: AK5, AK7, CA8, ...
ATLAS: AK4, AK6, AK10, CA12, ...

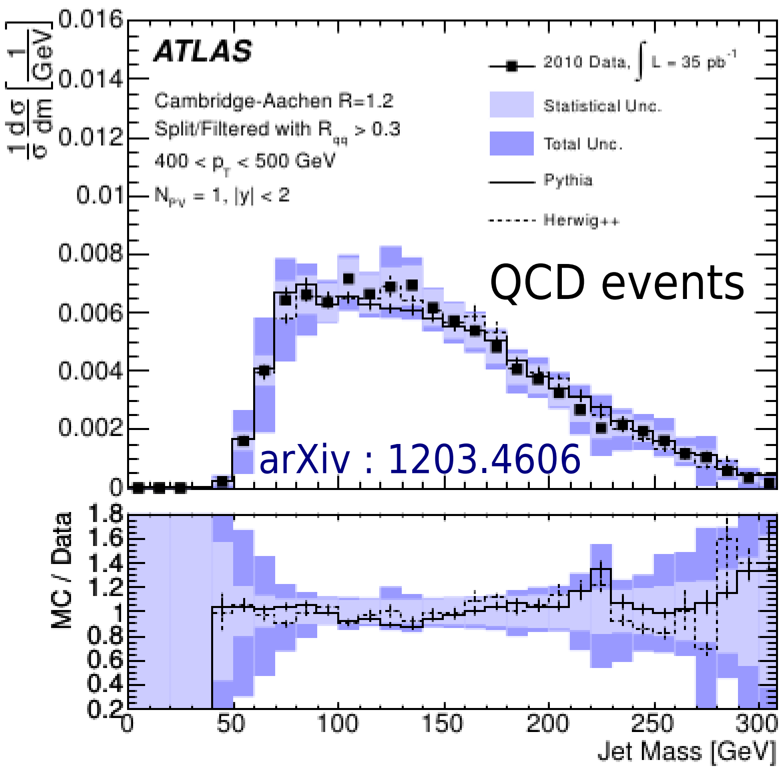


Substructure and MC tuning

- MC description of jet substructure needs improvements
  - Example: jet mass description by Herwig/Pythia

- **Q:** Tune MC parton shower parameters using the same unfolded distributions provided by both experiments? Agreement?





New directions for searches with substructure

Only a few ideas out of many...

Deploy **substructure-aware triggers**

- If tagger performance known offline, can use specific triggers online → performance studies should start now

Use internal jet properties in **'plain' resonance search**:

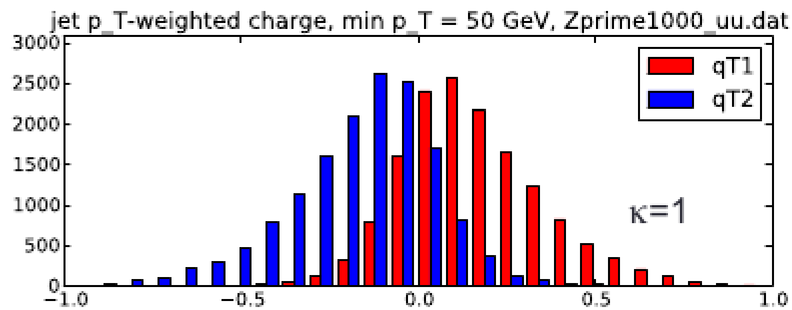
- **Quark/gluon tagging** for lower-mass resonances
  - Need to carefully avoid shaping backgrounds
  - Discrimination from data templates, but still sensitive to non-perturbative effects

Search for (and **discriminate**) resonances with substructure

- **Angular resolution** within jets
  - What is the angular resolution of subjets within a fat jet?
  - Can we measure W polarization in boosted topology (e.g. for Bulk gravitons)?
    - Useful for WW scattering at very high √s, to separate transverse and longitudinal polarizations in semi-leptonic final states
- **Jet charge** as example of new observable
  - recent theoretical studies for heavy boson resonances

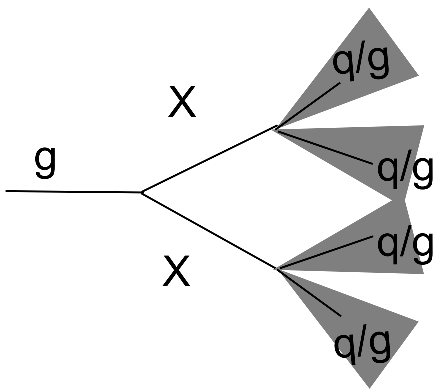
$Z' \to \bar{u}u$

M. Schwartz, BOOST 2012



Backup slides

4-jet searches

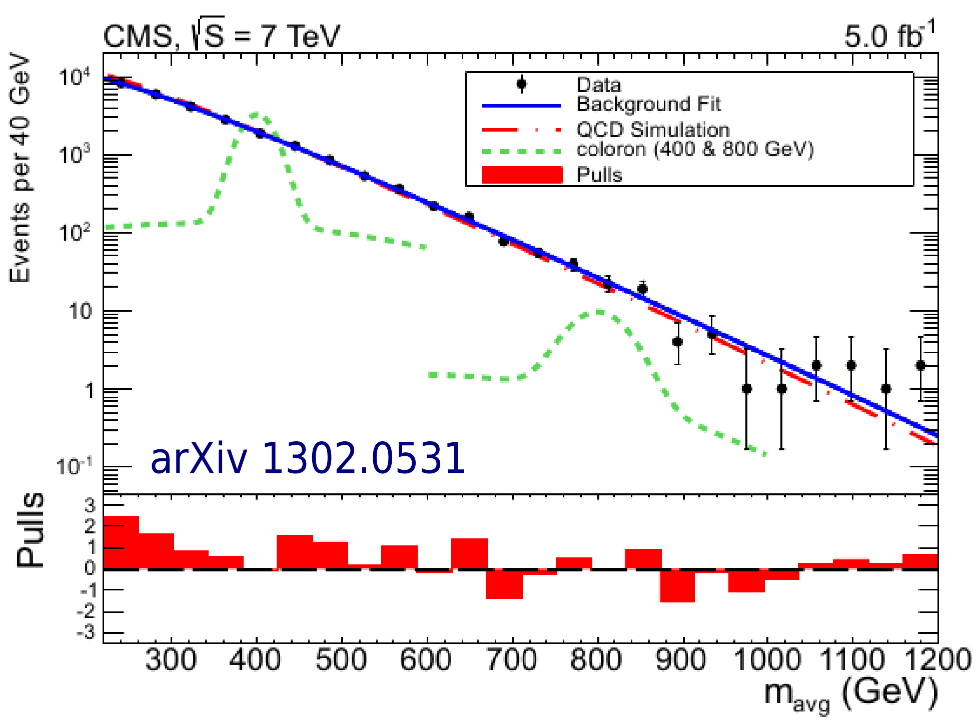


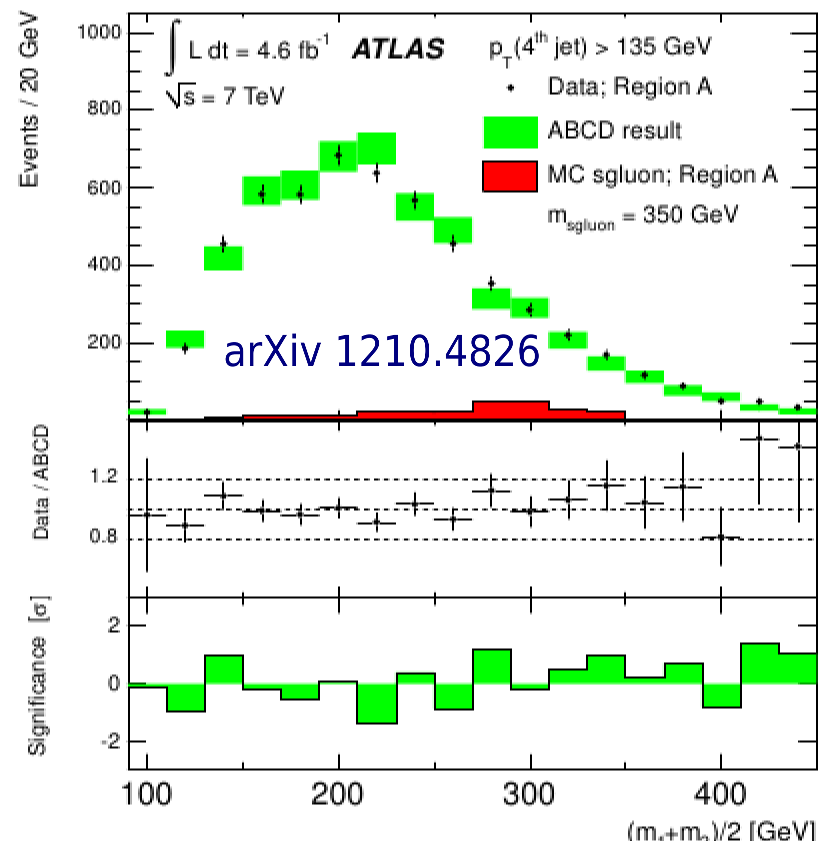
Select events with $\mathbf{N_{jet} > 4}$, **close** values of **paired dijet masses**

Search for deviations from fit to paired dijet mass distribution

If **no deviation, set limits** on **benchmark models** using CL_s method

Main uncertainties : JES, JER, luminosity, background fit





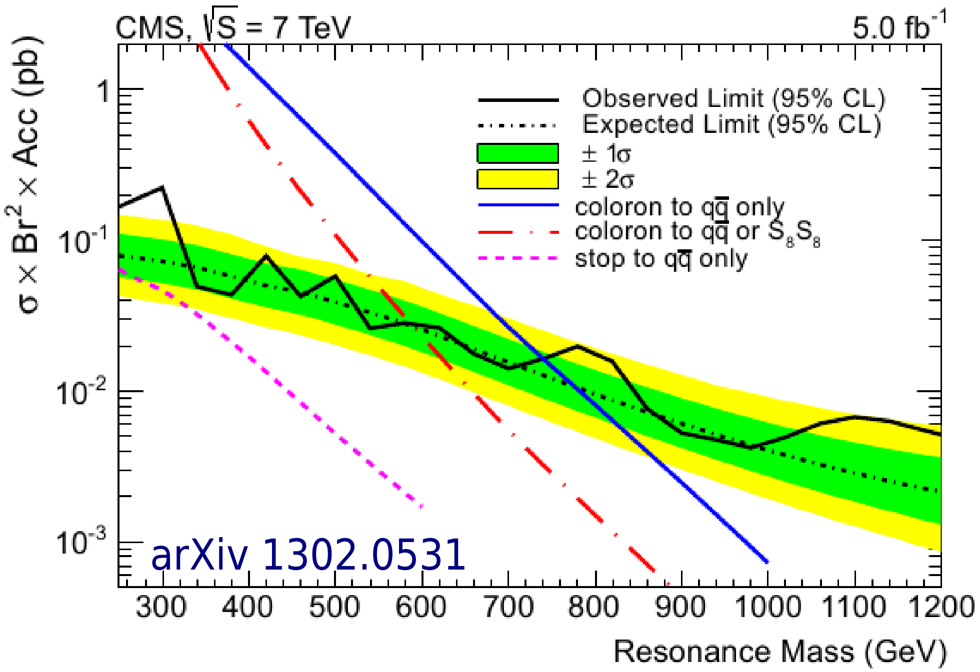
4-jet searches : limits

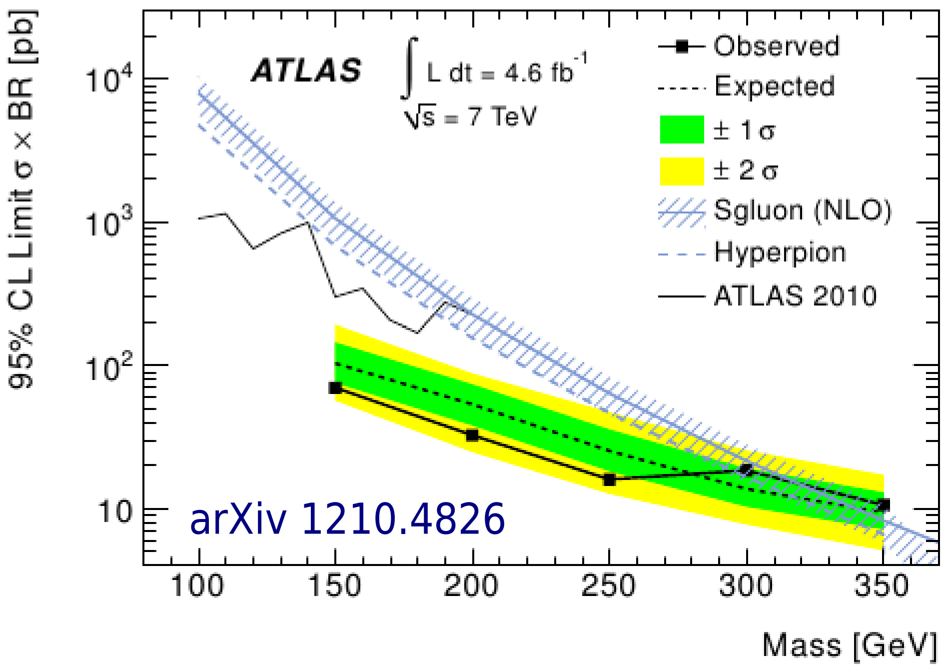
CMS benchmark models:

stop pairs → **qqbar pairs**
coloron → **qqbar / gg pairs** (through S8)

ATLAS benchmark models:

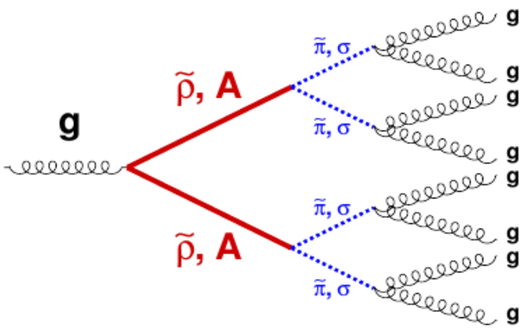
scalar gluon (SUSY) → **gg**
hyperpion → **gg**





Eight-jet searches (CMS)

Select **high-jet-multiplicity** events (N=8)
looking for vector bosons decaying in gluons

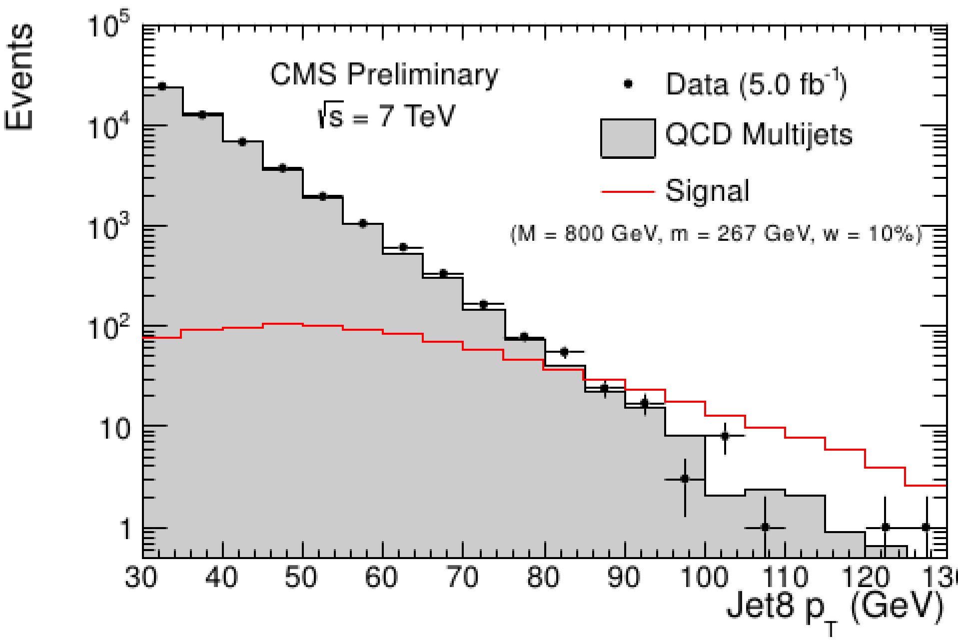


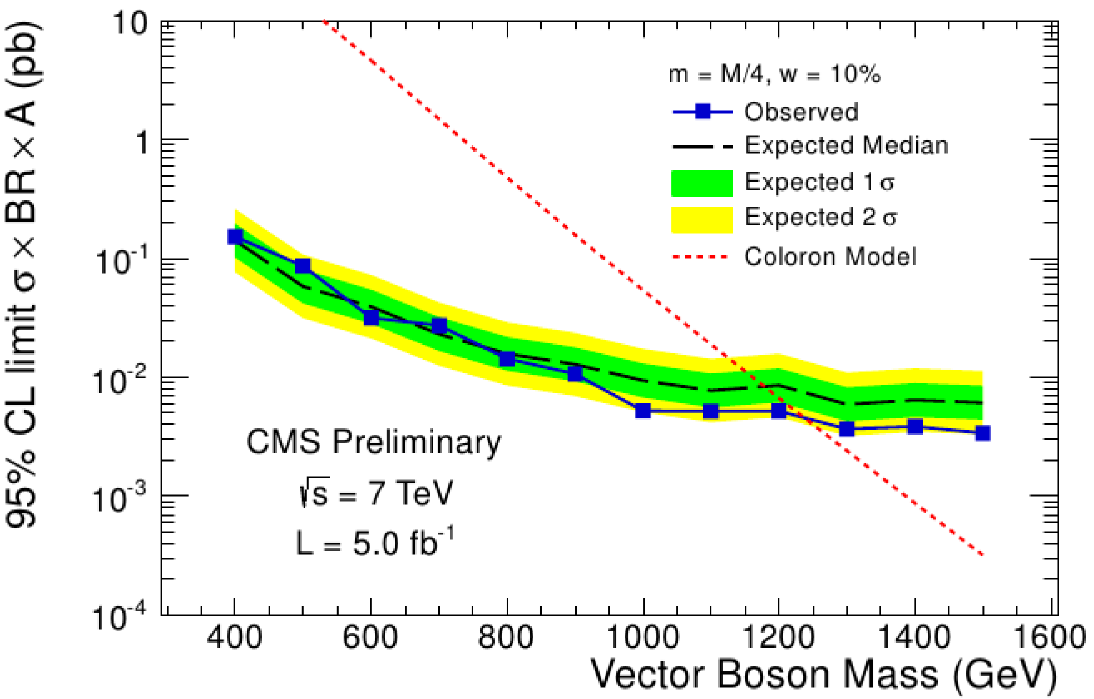
Employ neural network
to exploit correlations between kinematic variables
of signal producing jets with similar pT

If **no deviation, set limits on benchmark models** (colorons) using CL_s method

Main uncertainties : JES, simulation, PDF, bkg estimate, JER, lumi, modelling

CMS-PAS-EXO-11-075





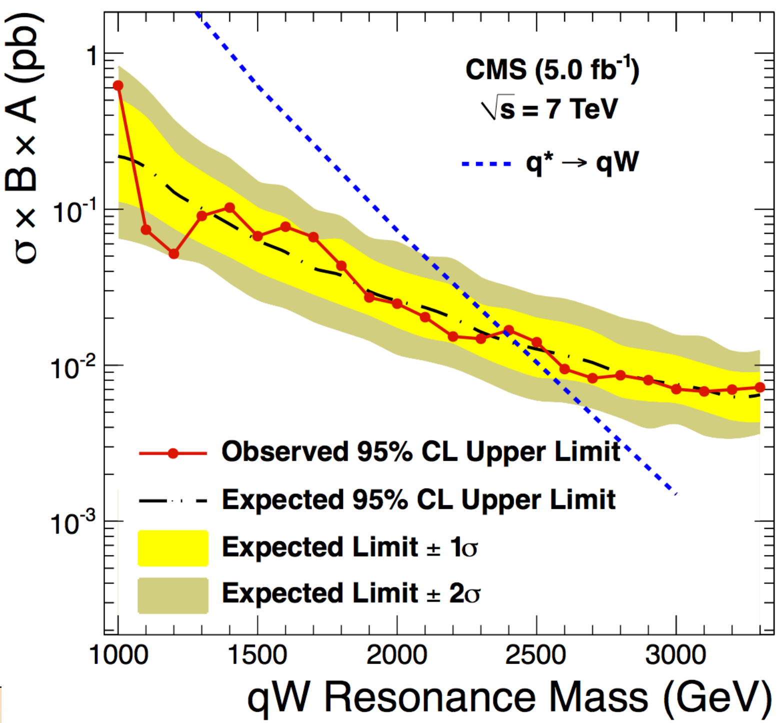
Limits (X→VV/Vq) @ 7 TeV

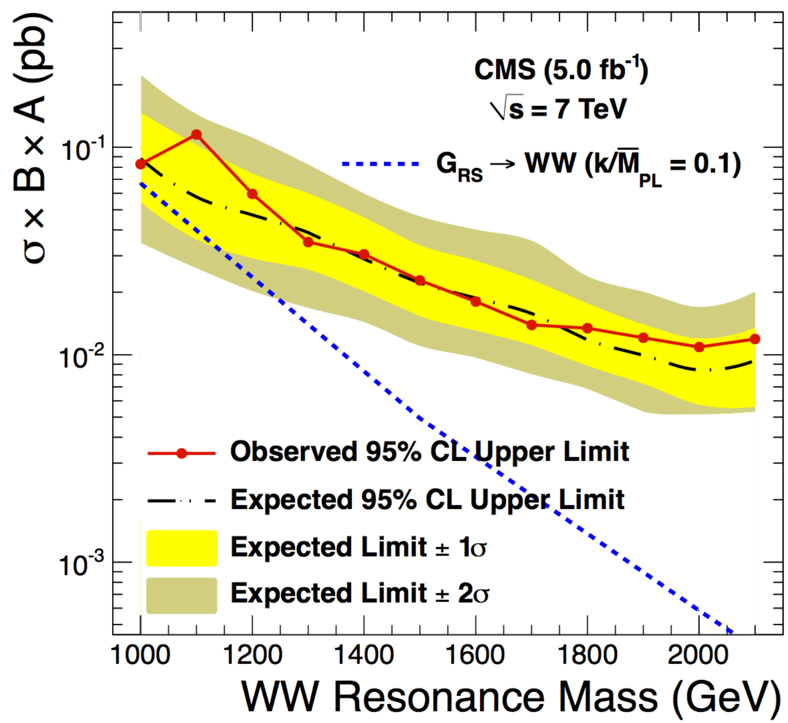
- Most stringent limits to date on qW and qZ final states
- VV limits competitive with (or better than) correspondent semi-leptonic searches at very high mass (thanks to higher BR to jets)

Single W/Z-tag

arXiv 1212.1910

Double W/Z-tag





N-subjettiness

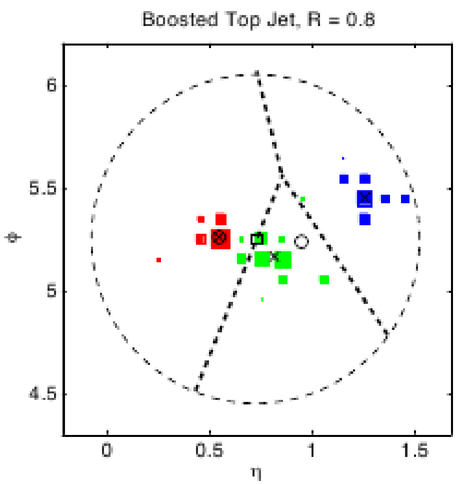
First identify k subjets in the event by forcing e.g. kT algorithm to return k subjets only

J. Thaler, BOOST 2012

Distance between subjet and constituents

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min \{\Delta R_{k,1}, \Delta R_{k,2}, \ldots, \Delta R_{k,N}\}$$

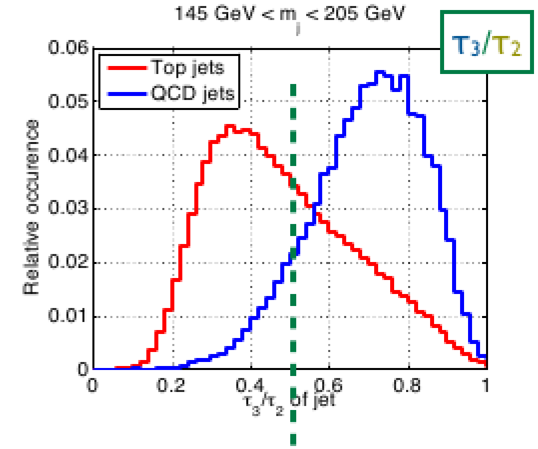
Normalisation factor, sum_k (pT_k * R)



Axes from exclusive k_T

Generalization of jet width to multiple (sub)jets!

Jet shape "counts" number of subjets!



Flexible cut to adjust signal acceptance vs. background rejection

# subjets:	$\leq N$	$> N$
τ_N:	0	1

Radiation aligned with subjet direction

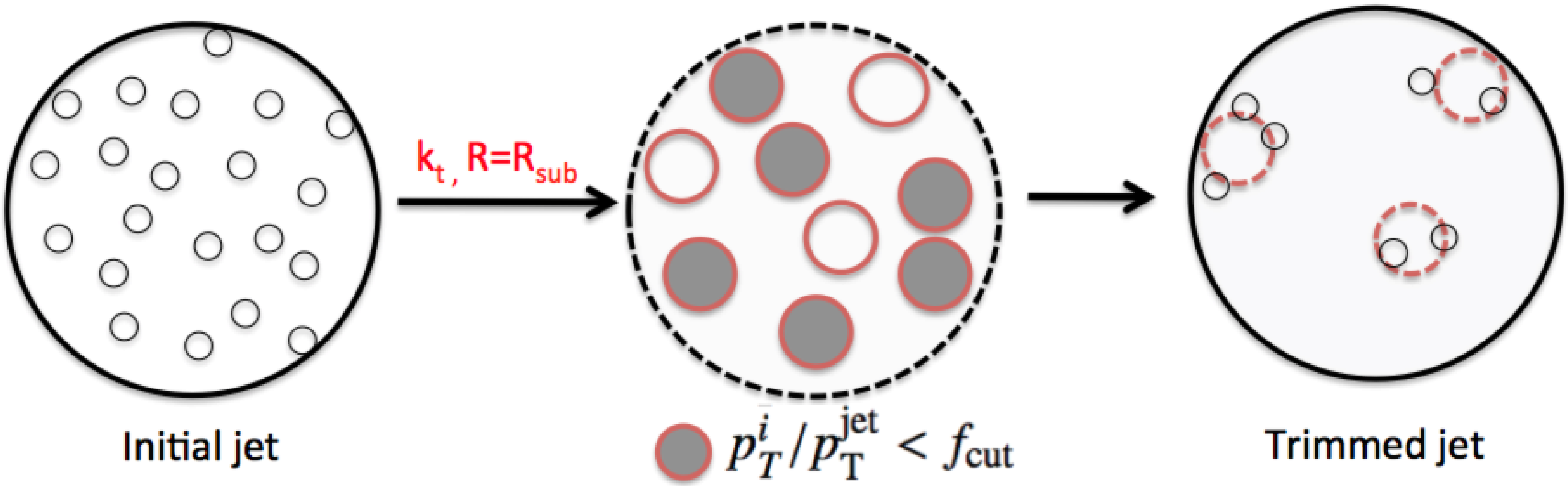
Radiation away from subjet

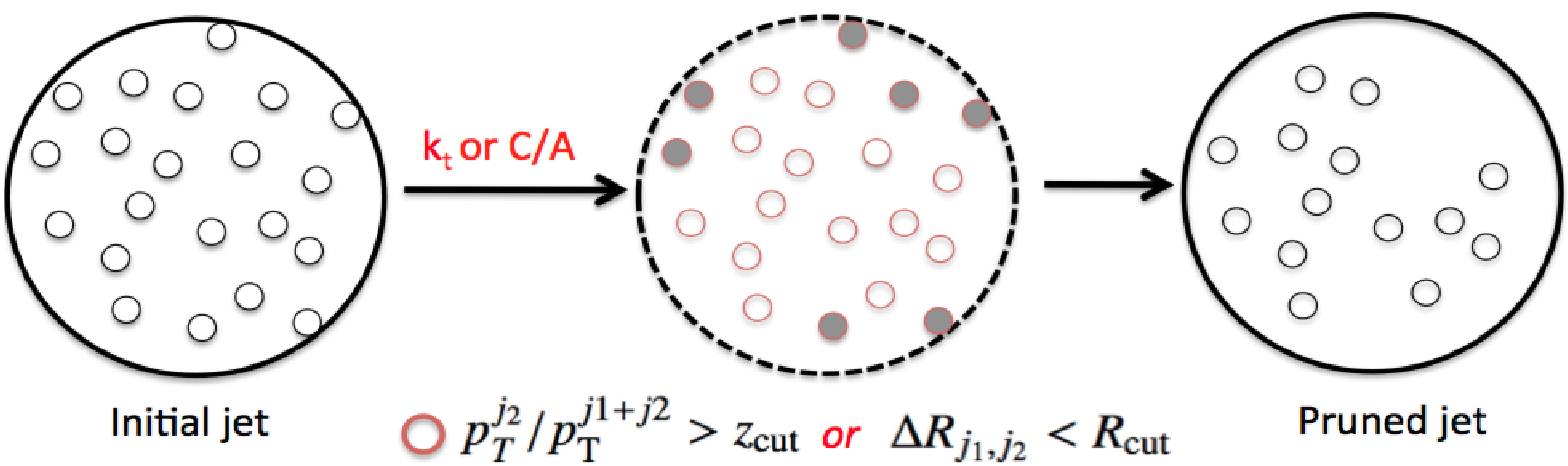
τ_3/τ_2: Boosted Tops
τ_2/τ_1: Boosted W/Z/H

Adapted from "N-jettiness", used to define exclusive jet bins
[Stewart, Tackmann, Waalewijn: 1004.2489; see Iain Stewart's Talk]

Jet trimming and pruning

ATLAS-CONF-2012-065

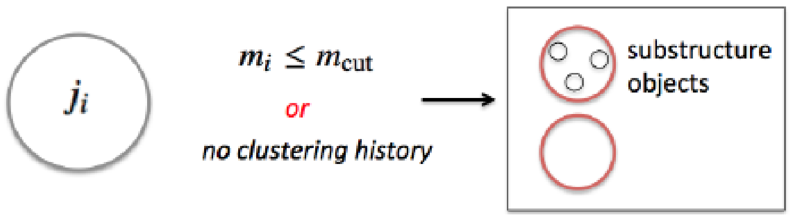




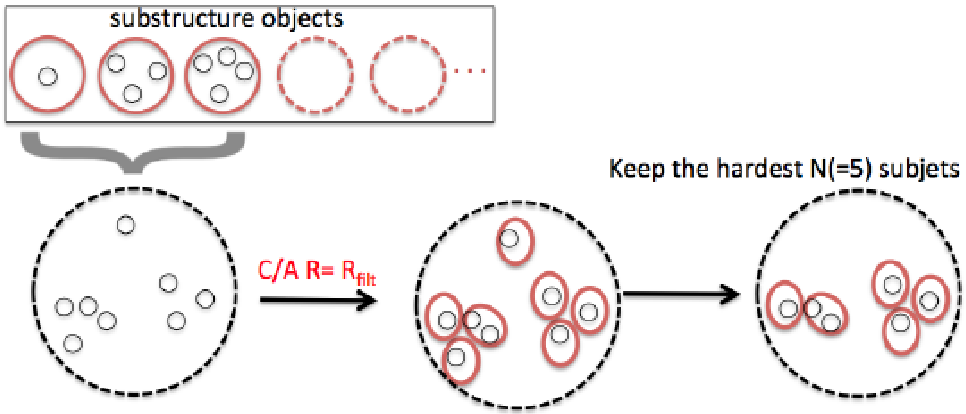
Veto large-angle radiation

HEPTopTagger

ATLAS-CONF-2012-065

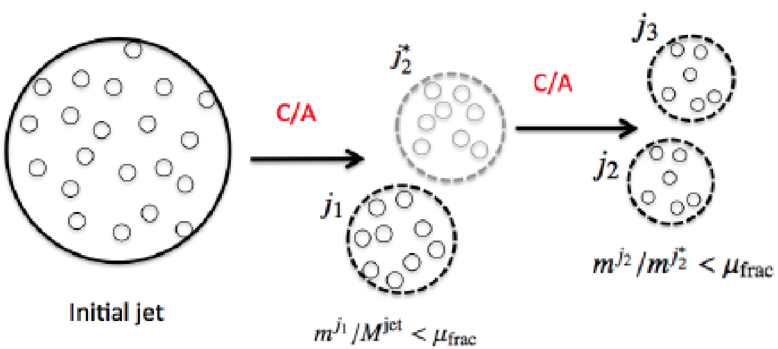


(a) Every object encountered in the de-clustering process is considered a 'substructure object' if it is of sufficiently low mass or has no clustering history.

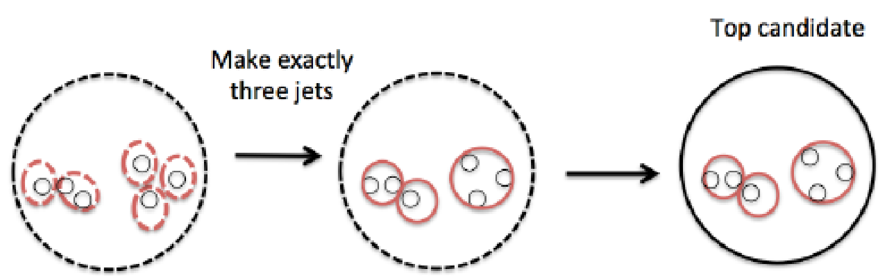


$$R_{\text{filt}} = \min[0.3, \frac{\Delta R_{j_1,j_2}}{2}, \frac{\Delta R_{j_1,j_3}}{2}, \frac{\Delta R_{j_2,j_3}}{2}]$$

(c) For every triplet-wise combination of the substructure objects, recluster into subjets and select the N_{subjet} leading-p_{T} subjets, with $3 \leq N_{\text{subjet}} \leq N_i$ (here, $N_{\text{subjet}} = 5$).



(b) The mass-drop criterion is applied iteratively, following the highest subjet-mass line through the clustering history, resulting in N_i substructure objects.



$$m_{ab} = M_{\text{W}}(1 \pm 0.15) \quad (a, b = j_1, j_2, j_3)$$

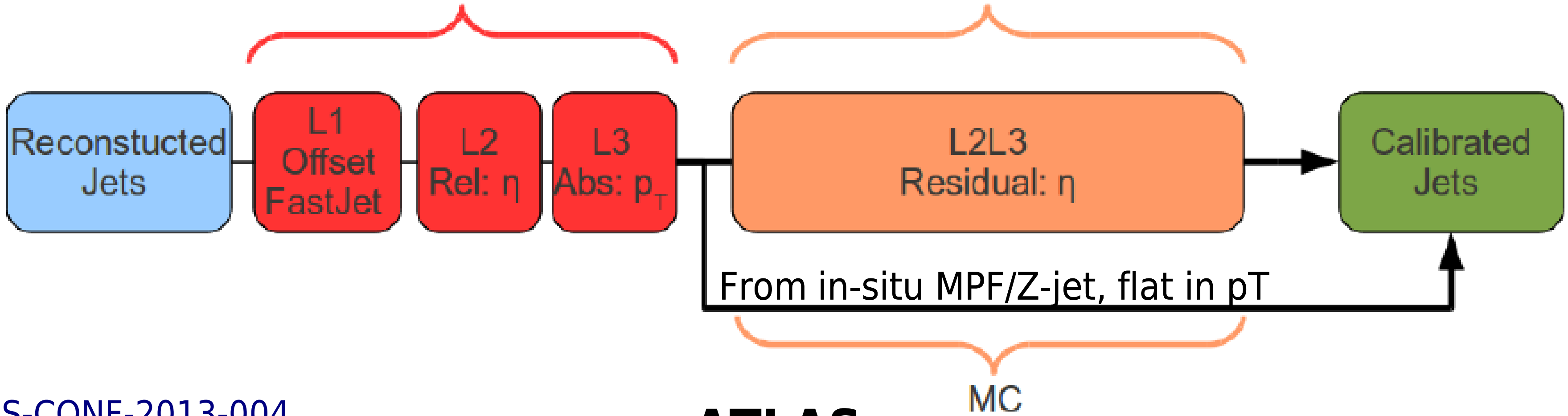
(d) Recluster the constituents of the N_{subjet} subjets into exactly three subjets to make the top candidate for this triplet-wise combination of substructure objects.

Backup slides for discussion

Absolute, relative and residual JES

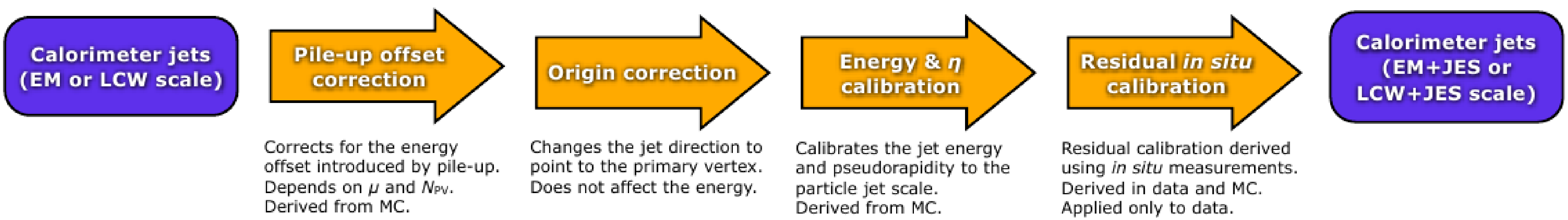
CMS-DP-2012-006
JINST 6 P11002 (2011)

CMS:



ATLAS-CONF-2013-004
arXiv 1112.6426

ATLAS:

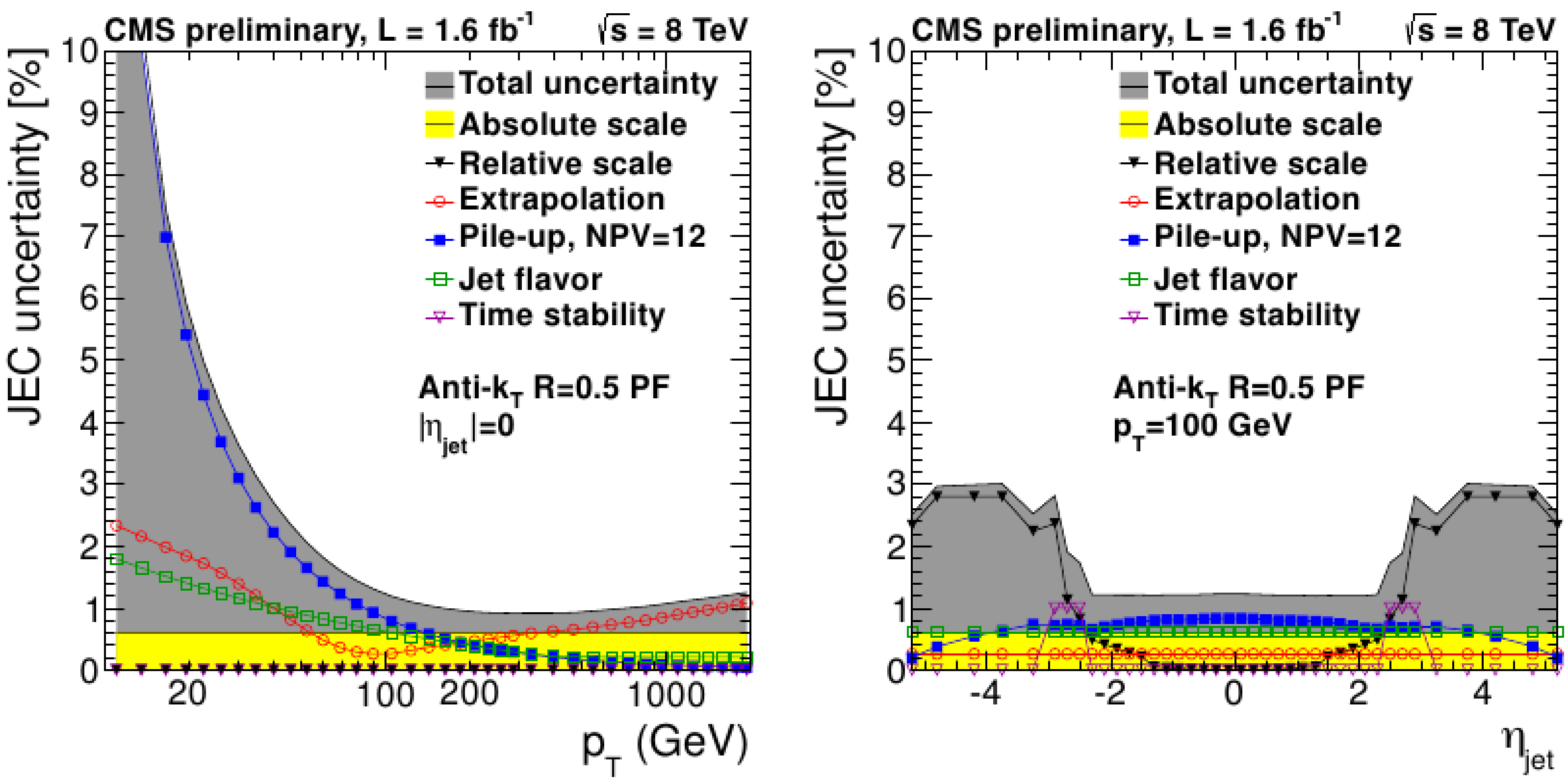


From in-situ MPF/Z-jet/Multijet balance combination

Note: reference scale for both experiments is **truth jet** (stable particles) **energy scale**
Difference: muons included in truth jets for CMS (particle flow) and not for ATLAS (calo jets)

JES uncertainties for CMS

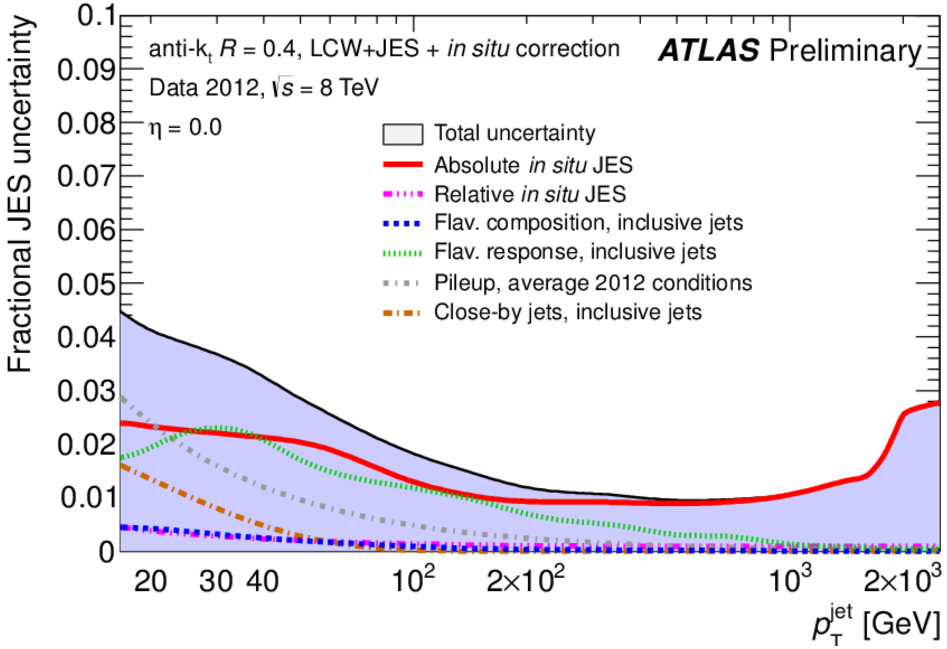
CMS:
JINST 6 P11002
CMS-DP-2012-012

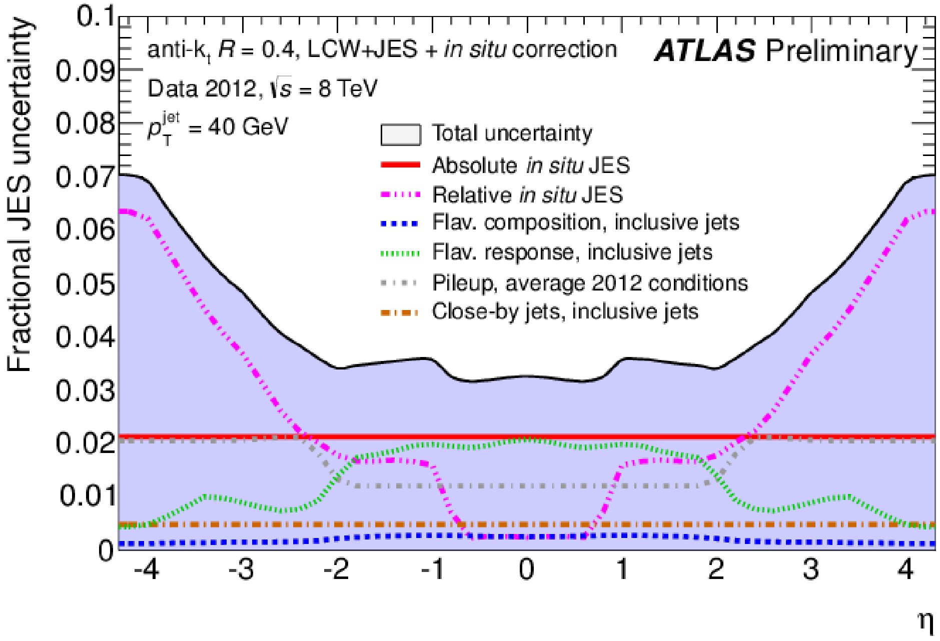


JEC uncertainties dominated by Pile-up uncertainties at low pt, relative scale in endcap/forward

JES uncertainties for ATLAS

ATLAS:
arXiv 1112.6426
ATLAS-CONF-2013-004
Approved plots



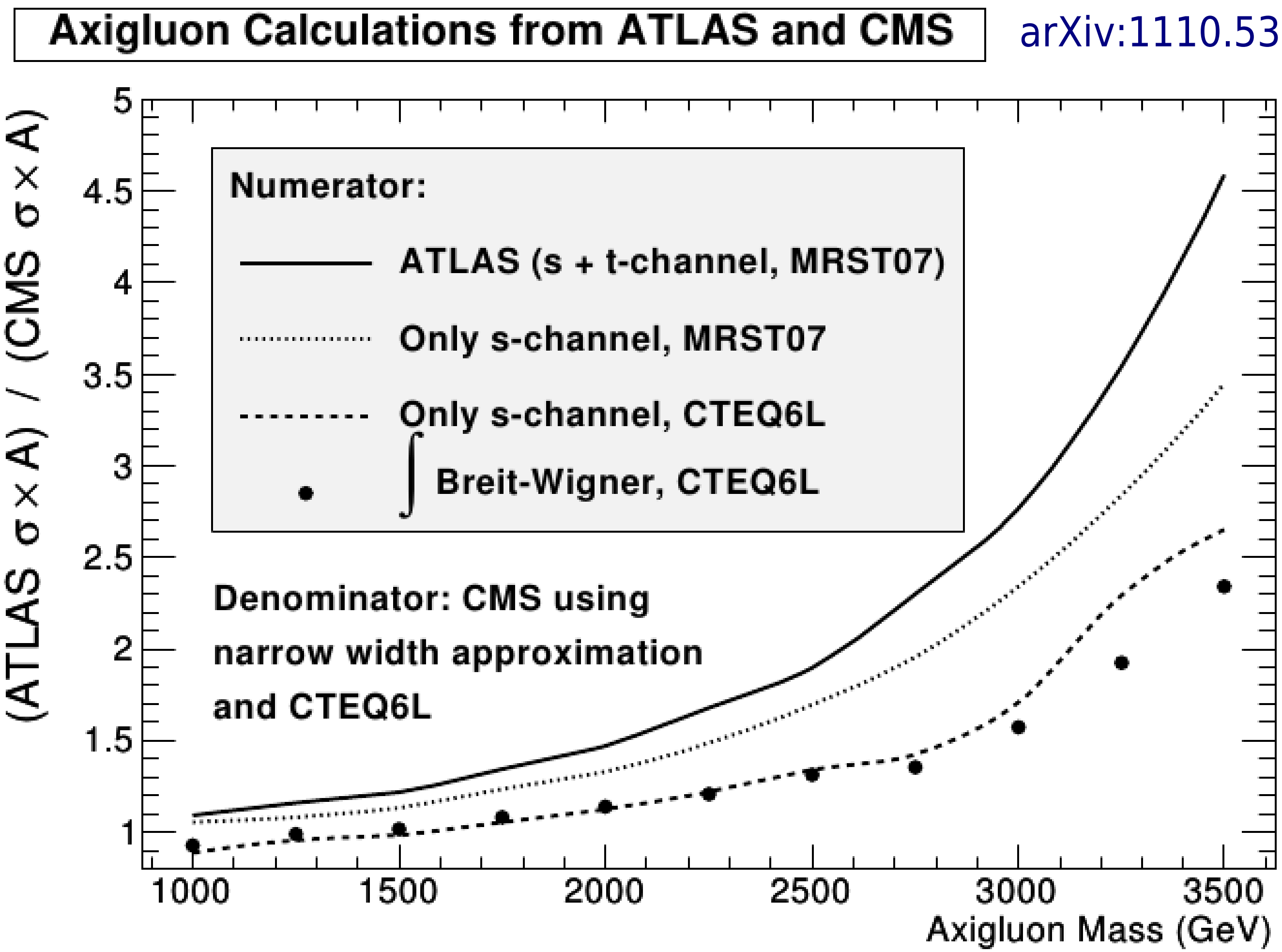


JES uncertainties dominated by baseline/PU-uncertainties at low pt,
eta intercalibration modelling at high eta

Differences between methods **similar** uncertainty sources:
ongoing discussion on
correlation and coherence of ATLAS & CMS JES uncertainties
precision measurement, still interesting for searches

Definition of resonance

- Narrow width approximation (CMS) vs using full / chopped template (ATLAS) for cross section definition in 'bump searches '



arXiv:1110.5302

Case of axigluon (2010)

ATLAS:
· calculate cross section by integrating the signal In window under the pole $0.7*M < m < 1.3*M$
· use 'chopped' template

CMS:
· use narrow width approximation
· use 'chopped' template

The narrow-width approximation

arXiv:1110.5302

width, even for resonances normally considered narrow. The extreme end of this tail due to the PDFs is sometimes suppressed in the searches by requiring the partons to be have mass close to the pole mass, within a few standard deviations on the dijet mass resolution. This is generally a reasonable solution for the shapes, as the QCD background overwhelms the signal at low dijet mass. However, the way that this tail from PDFs is handled can significantly affect the total resonance cross section quoted for specific models, as we discuss in Appendix A

Narrow width approximation:

Approximate the true resonance shape with a delta function
This avoids low-mass tails as PDFs will act only in the surrounding of the peak

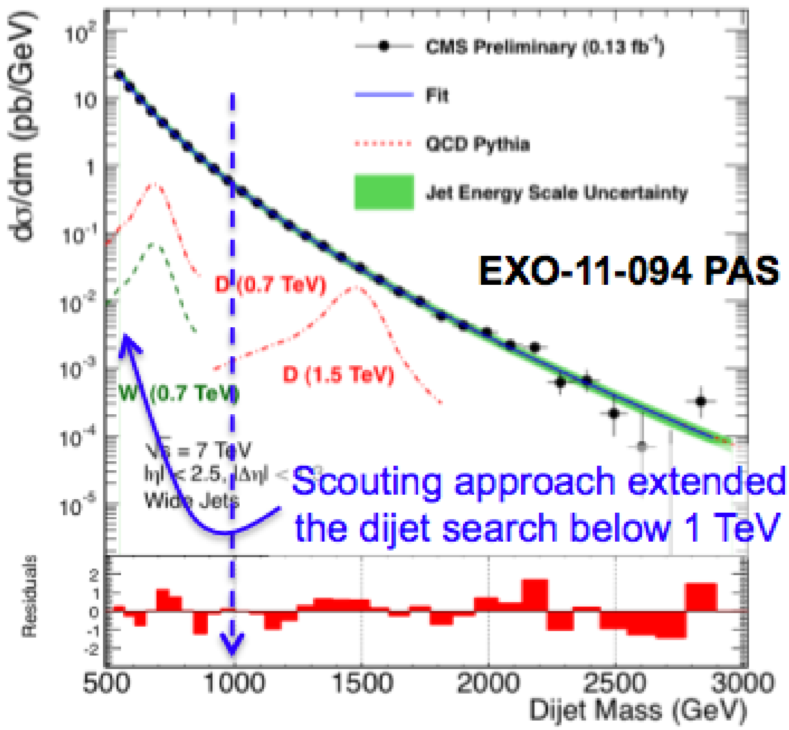
$$\sigma_{had}(m_R) = 16\pi^2 \times \mathcal{N} \times \mathcal{A}_{\cos\theta^*} \times BR \times \left[\frac{1}{s}\frac{dL(\bar{y}_{min}, \bar{y}_{max})}{d\tau}\right]_{\tau=m_R^2/s} \times \frac{\Gamma_R}{m_R}, \quad (44)$$

where the parton luminosity $\frac{dL}{d\tau}$ is calculated at $\tau = m_R^2/s$, and constrained in the kinematic range $[\bar{y}_{min}, \bar{y}_{max}]$.

Data Scouting CMS-DP-2012-022

- Special strategy to look at the data that CMS cannot normally record on tape due to trigger rate constrains
  - explore new physics channels that need very low trigger thresholds
  - possibility to extend the standard trigger setup for core physics or data parking in case something interesting shows up in the data scouting analyses
- First implementation: **new physics searches in hadronic final states at "low jet p_T / H_T"**
- **Novel** trigger and data acquisition strategy applied to physics analysis
  - Trigger: H_T>250 GeV , high event rate (~10^3 Hz)
  - Reduced event content (i.e. store calo jets reconstructed during High Level Trigger online processing, no raw data from CMS detector, no offline reconstruction of data possible)
  - Bandwidth (rate x event size) under control

Test Feasibility of Data Scouting in 2011: Dijet Resonance Search (0.13 fb^{-1})



In 2012, we can benefit from almost the full integrated luminosity (>15 fb^{-1})

Data Parking (CMS) Delayed Streams (ATLAS)

CMS-DP-2012-022

• "Core" physics program of ATLAS and CMS at 8 TeV is realized using data collected at average event rate of few hundred Hz (average lumi~4E33 $cm^{-2}s^{-1}$)

• The "core" data is promptly reconstructed (few days) and available during data taking

• "Extra" data (~ factor of 2) has been collected by both experiments to extend physics program (SM measurements and BSM searches)

• These new triggers are a looser version of the "core" triggers or brand new triggers with small-overlap with the rest

• This extra data started to be reconstructed after the end of 8 TeV data taking (i.e. delayed reconstruction) when computing resources became available