Search for Heavy Resonances at the LHC

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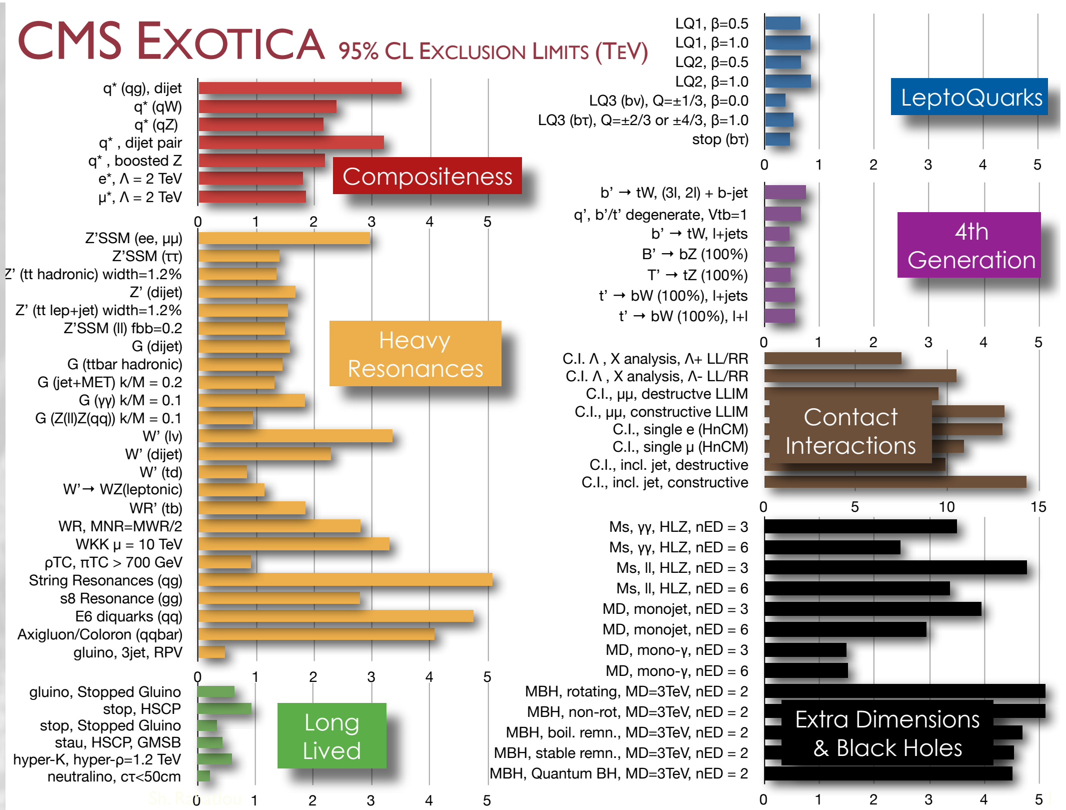
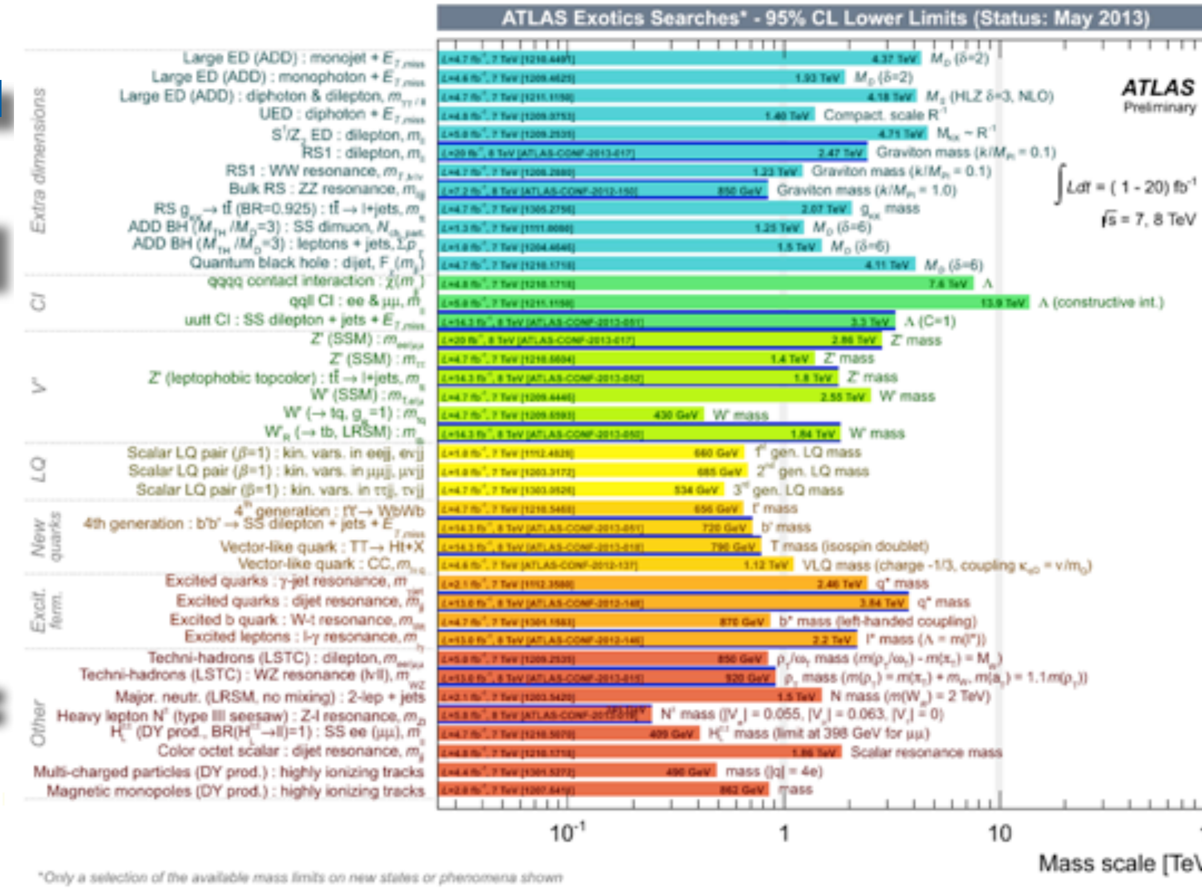
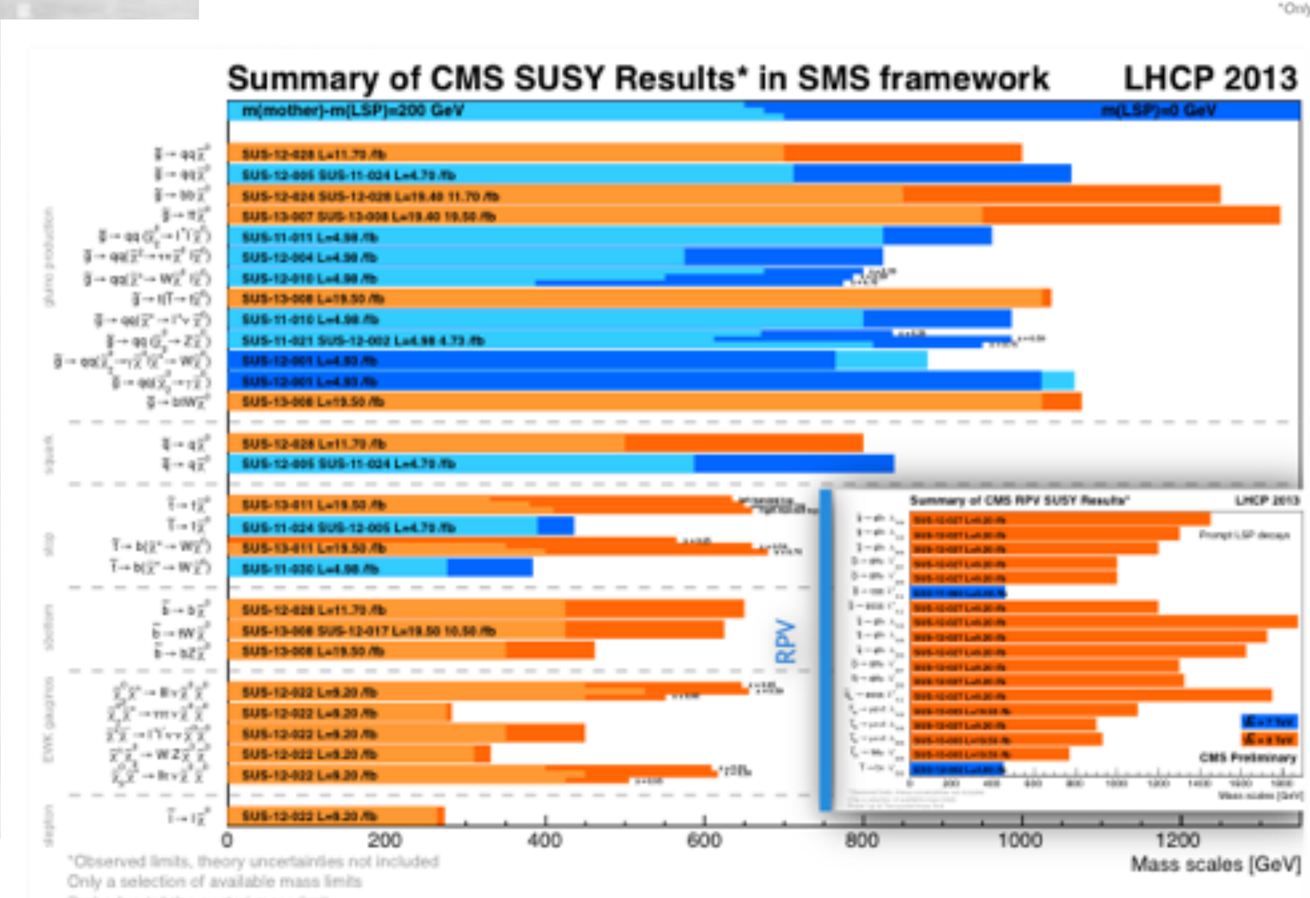
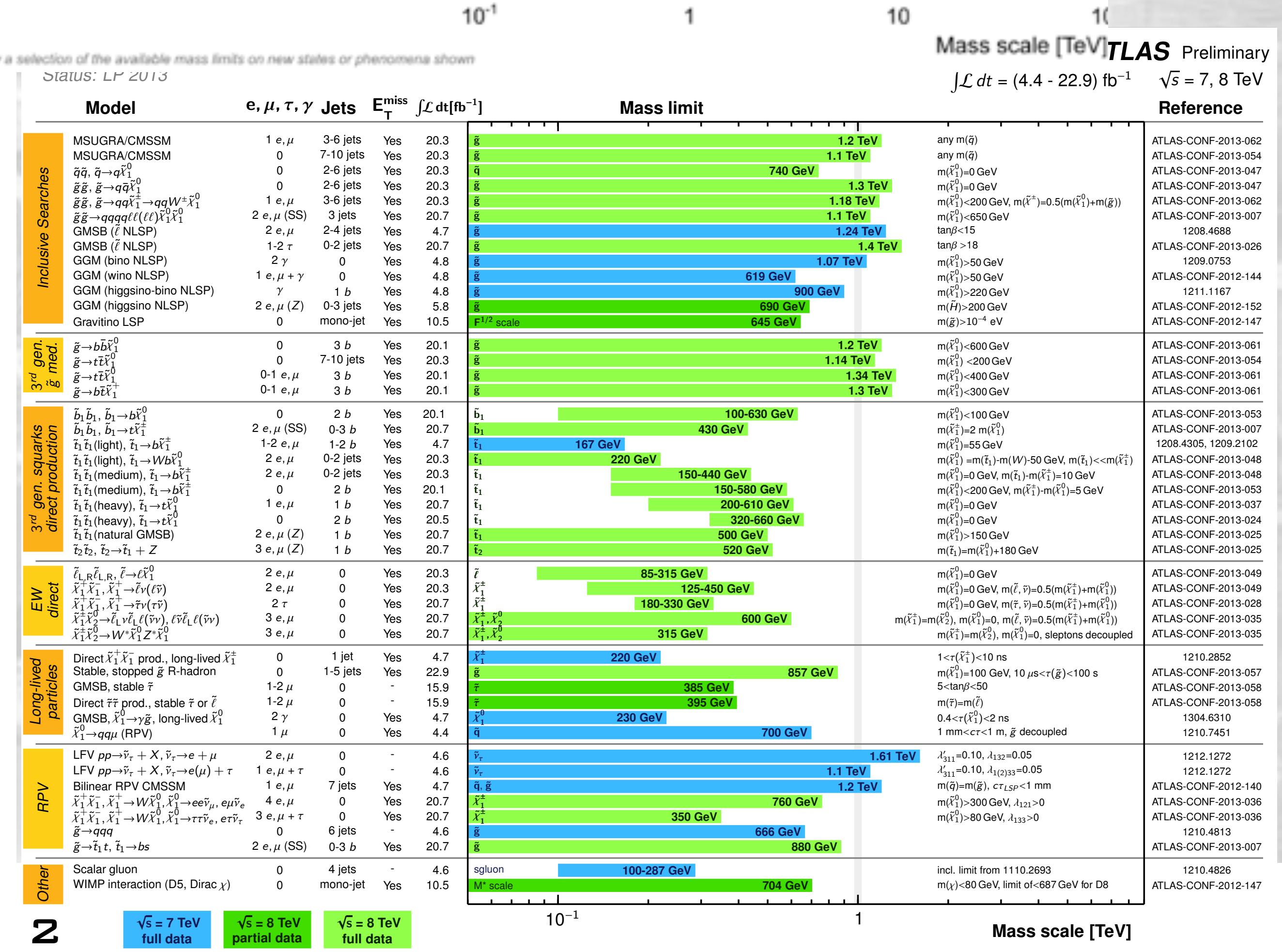
Caltech

We searched for a lot of things

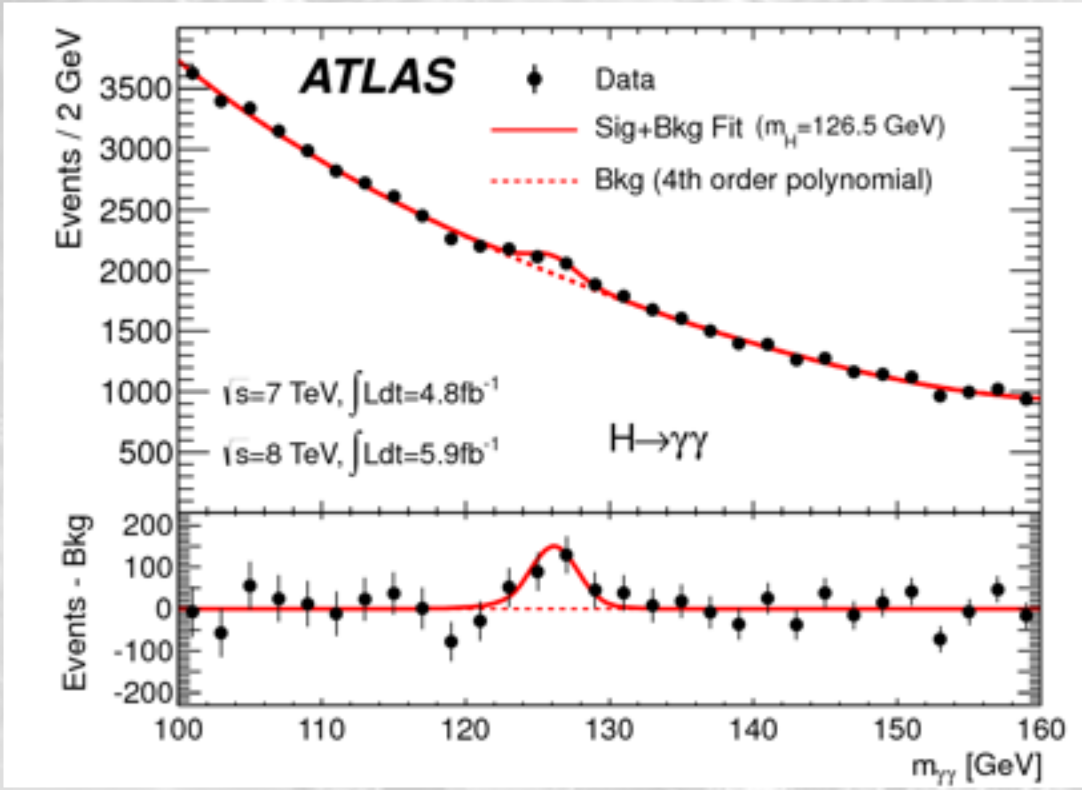


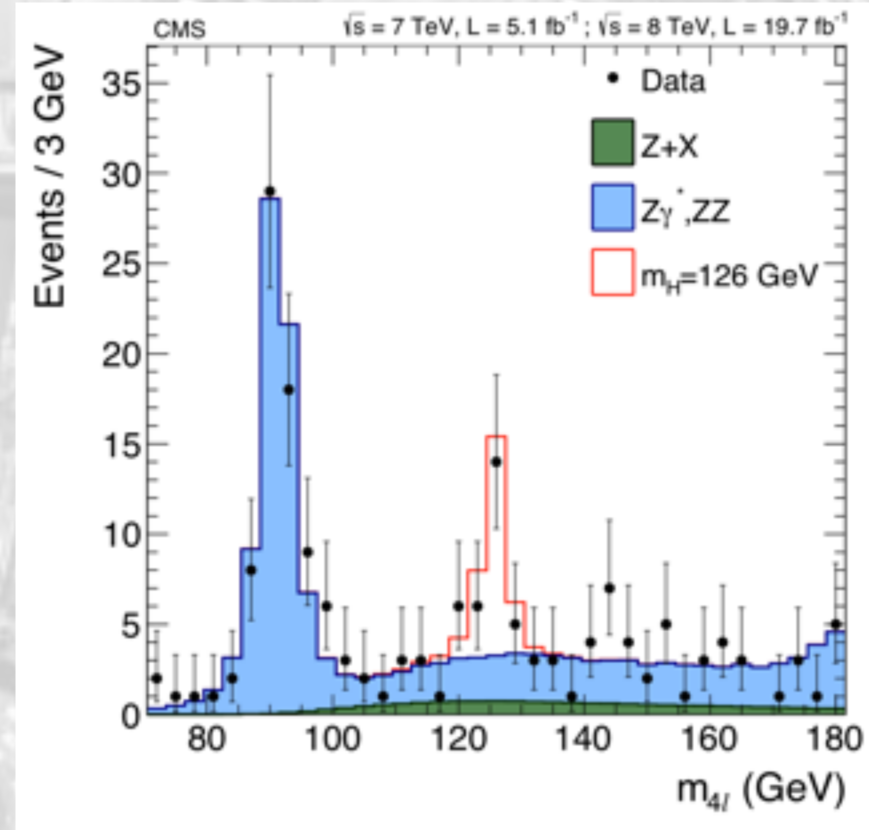






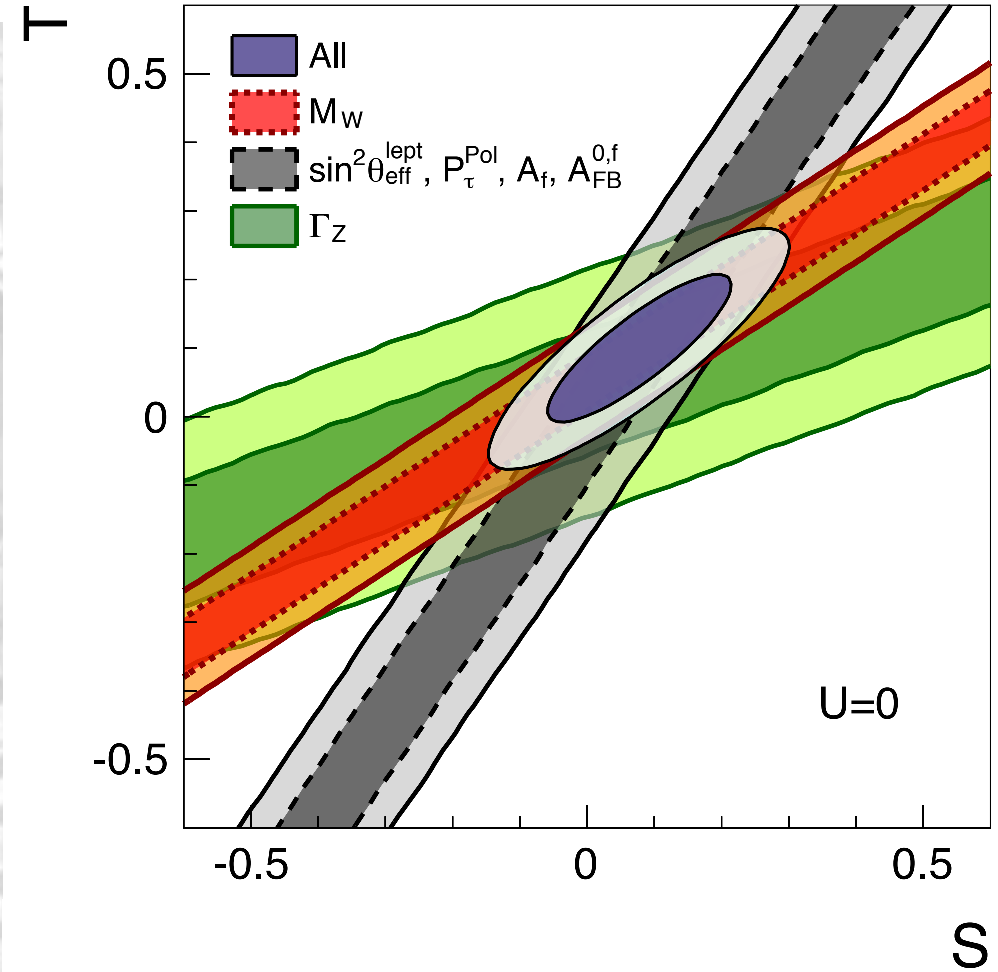
So far we found a resonance

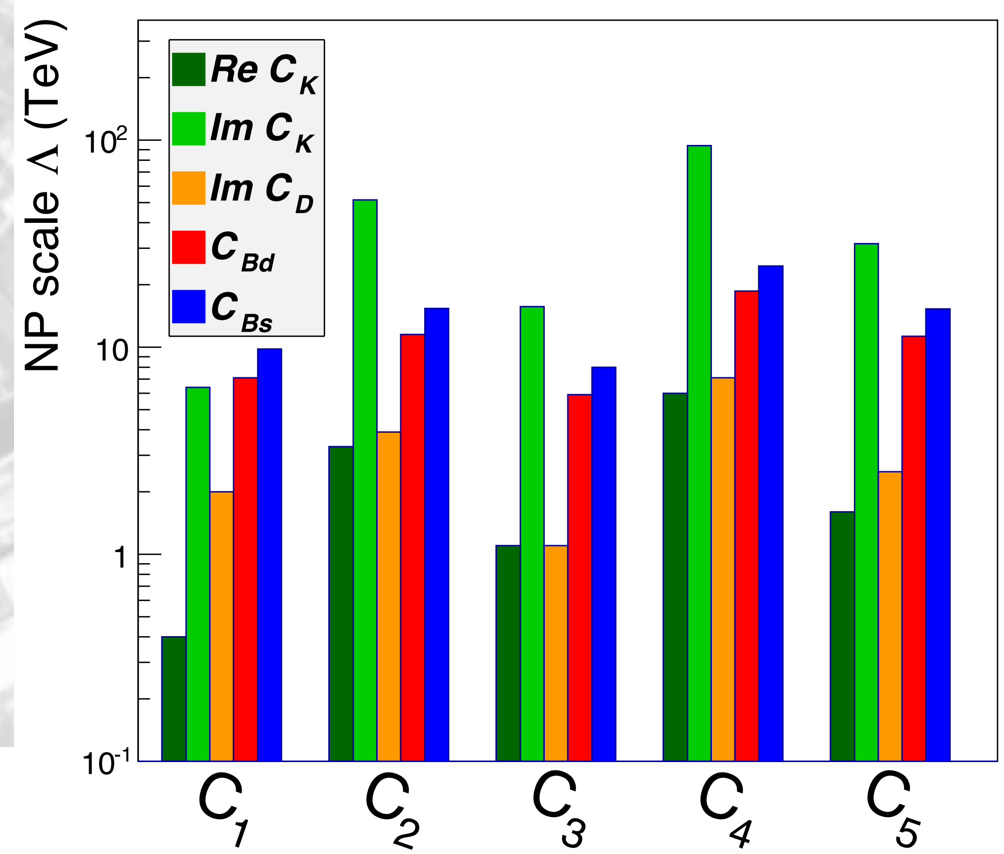




COULD THERE BE MORE?

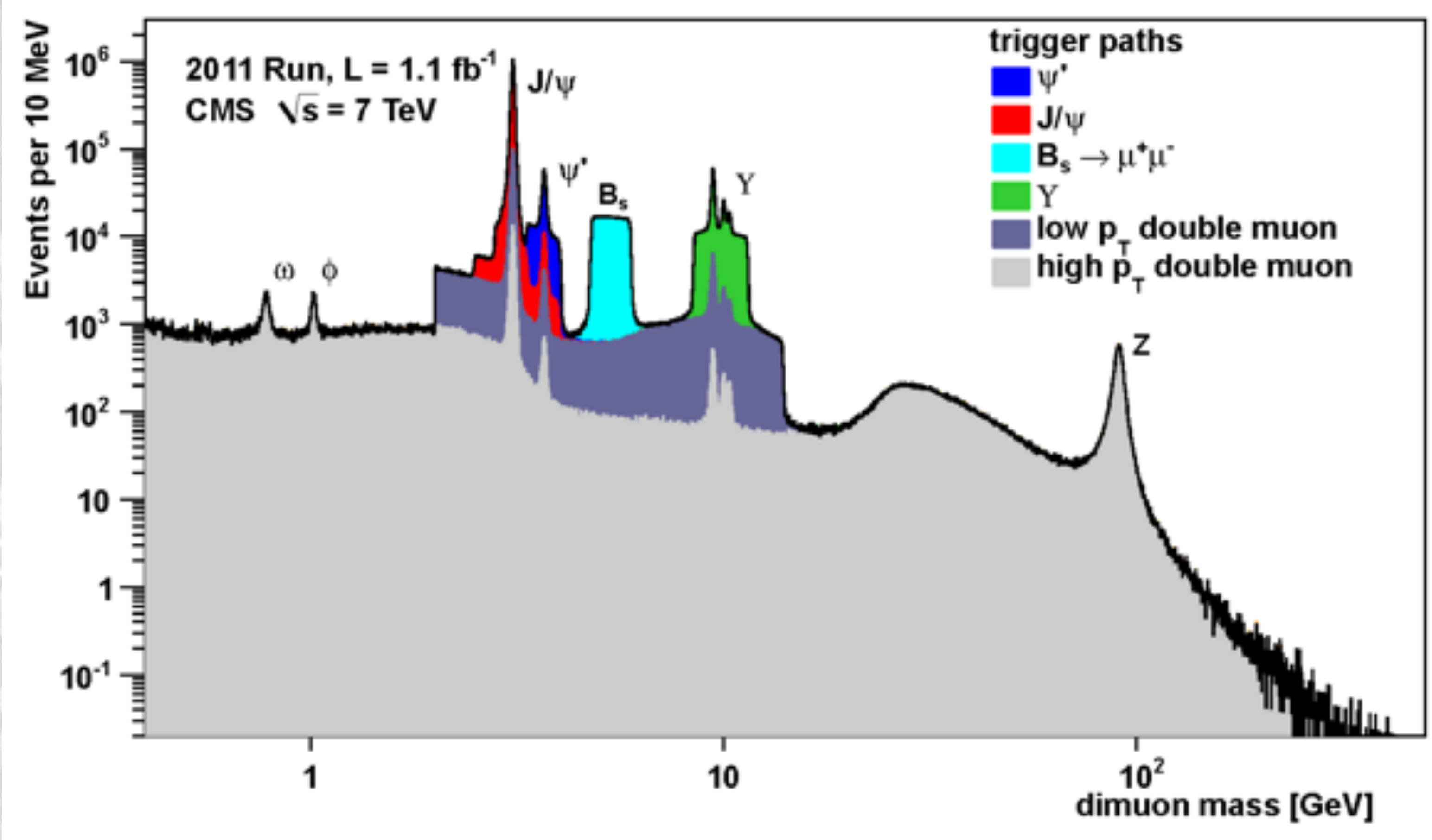
- Sure… Why not?
- But we know from pre-LHC results that they should/could to be heavier than O(1 TeV)
  - Not seen in previous experiments (e.g, Tevatron)
  - Strong bounds from EW precision physics
- … and/or have to come with SM-like features
  - no sign of NP in B/D/K physics pushed flavor-violating NP to PeV scale
  - even assuming (Nexto-to-)Minimal Flavor Violation, the bounds do not generically relax below the TeV





The Experimental Challenge

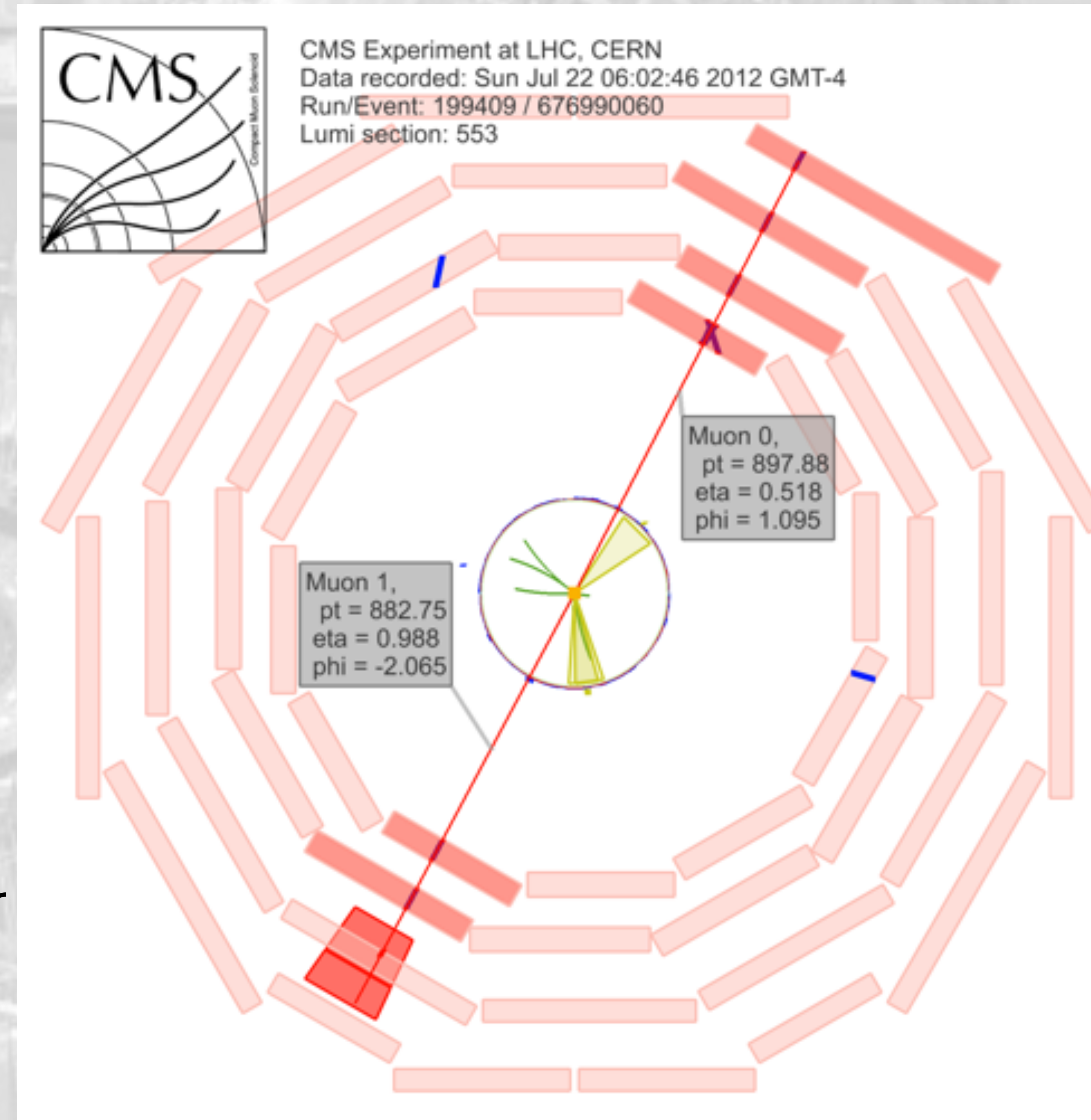
- For masses above 1 TeV, new resonances would decay to high-pT particles
- Experimentally, the high pT regime is different than what expiated for Higgs physics
  - Electrons mainly measured by calorimeter (not tracker)
  - Muons have large pT uncertainties
  - Jets not necessarily come from QCD (quarks and gluons)



- Dedicated reconstruction techniques in place, optimized to keep good performances at large-pT
- **The peculiarity of ATLAS in CMS is the excellent performances in a large range of pT (~1 GeV to ~1 TeV)**

High-Pt Muons

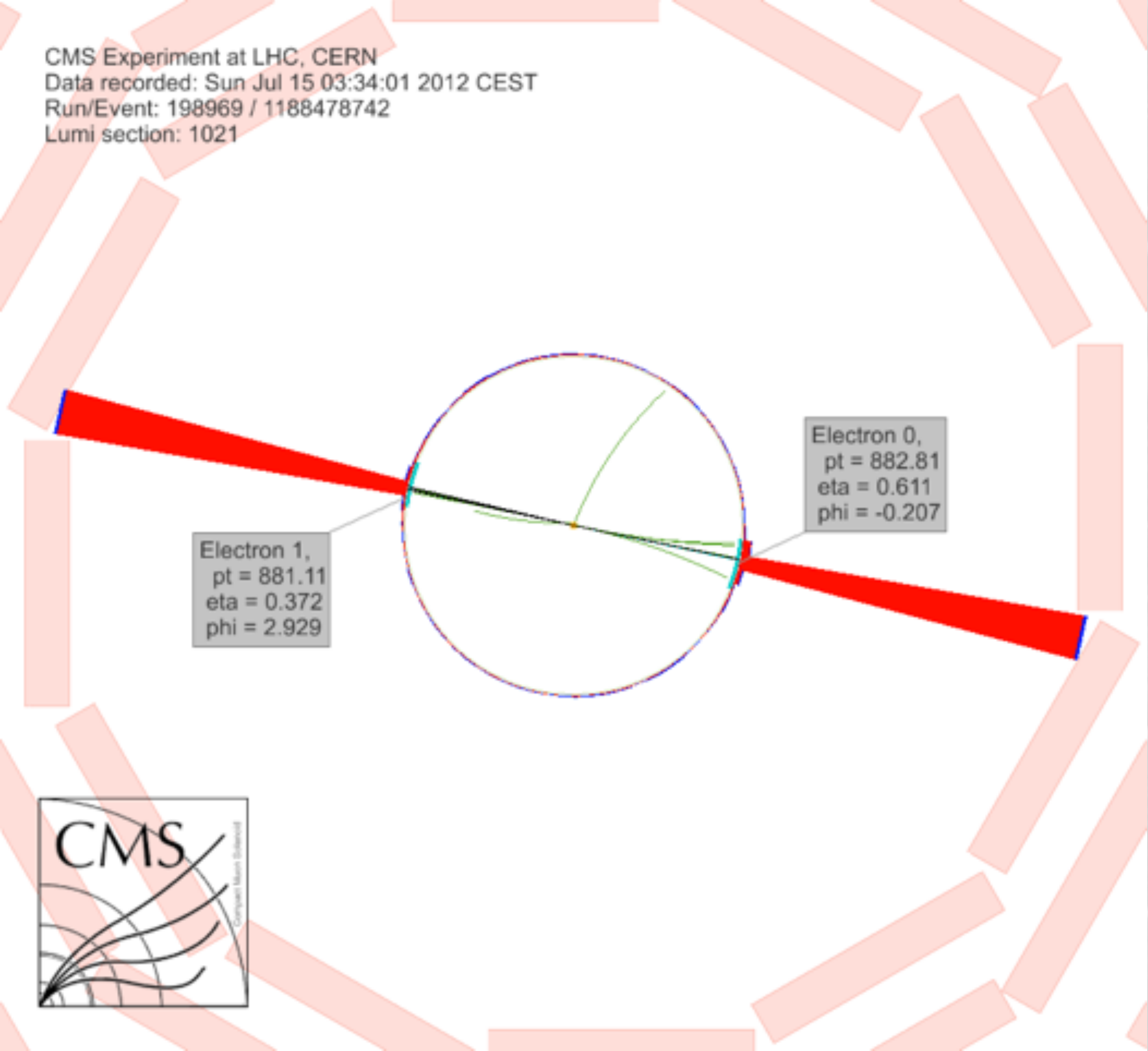
- Muon momenta are measured through the bending in the magnetic fields
- The bending is reduced at large muon momenta
- For high-pT muons, the precision deteriorates
- Unlike for W/Z/top/H, muon final states are not the golden channel for very-high-pT physics
- Despite the resolution, high-pT muons are an excellent discovery tool



$$\sigma_{p_T}/p_T \sim p_T/(qBL)$$

High-Pt Electrons

- Electron momenta are measured in the tracker and in the calorimeter
- The resolution of the calorimeter improves with energy, giving a better S vs B discrimination above 1 TeV
- Electrons (and photons) are excellent tools to search for davy resonances and measure their masses



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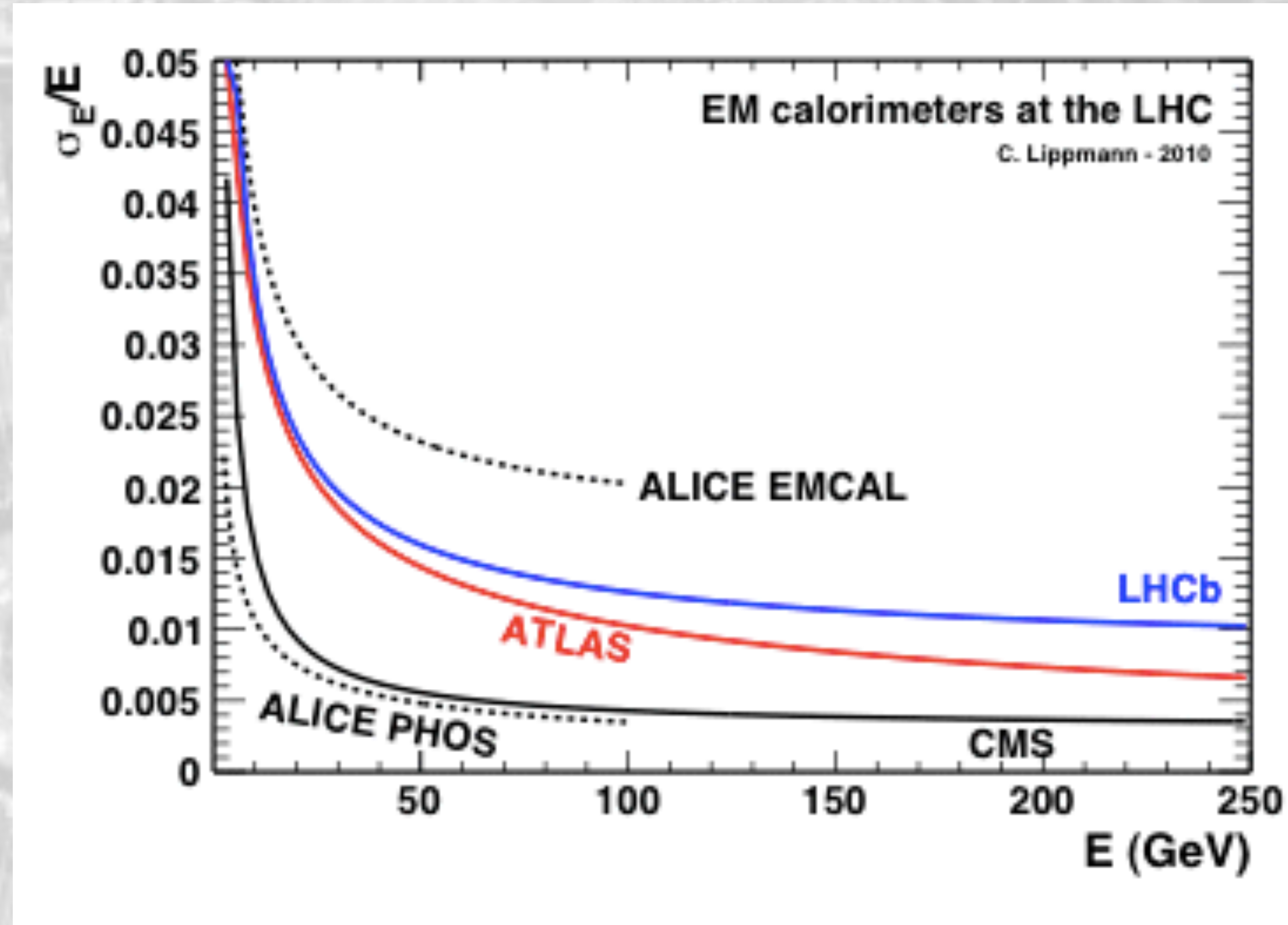
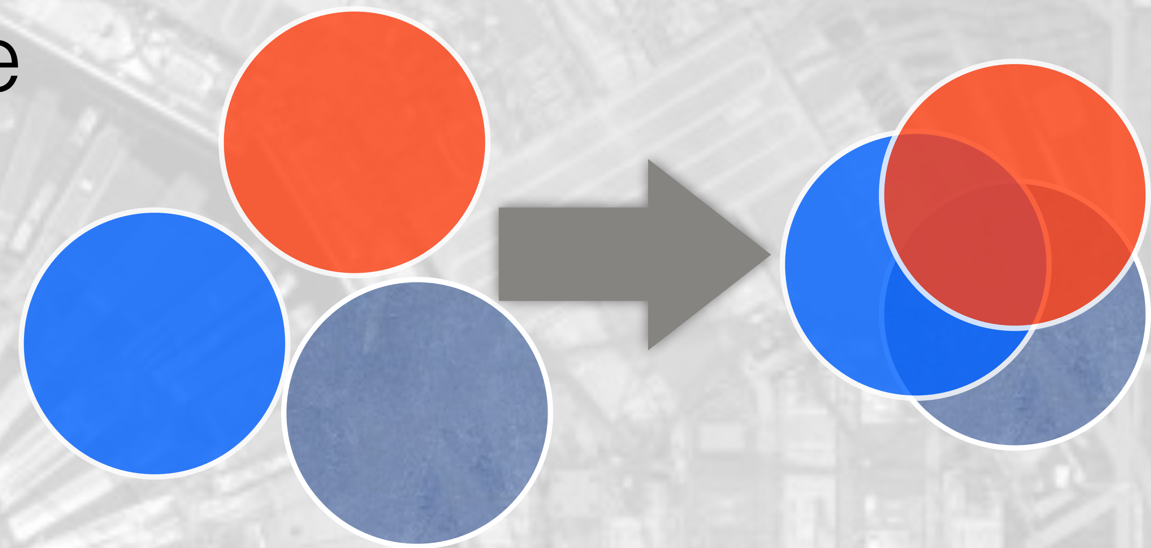


$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

a ~ 0.027 $GeV^{1/2}$
b < 200 MeV
c ~ 0.005

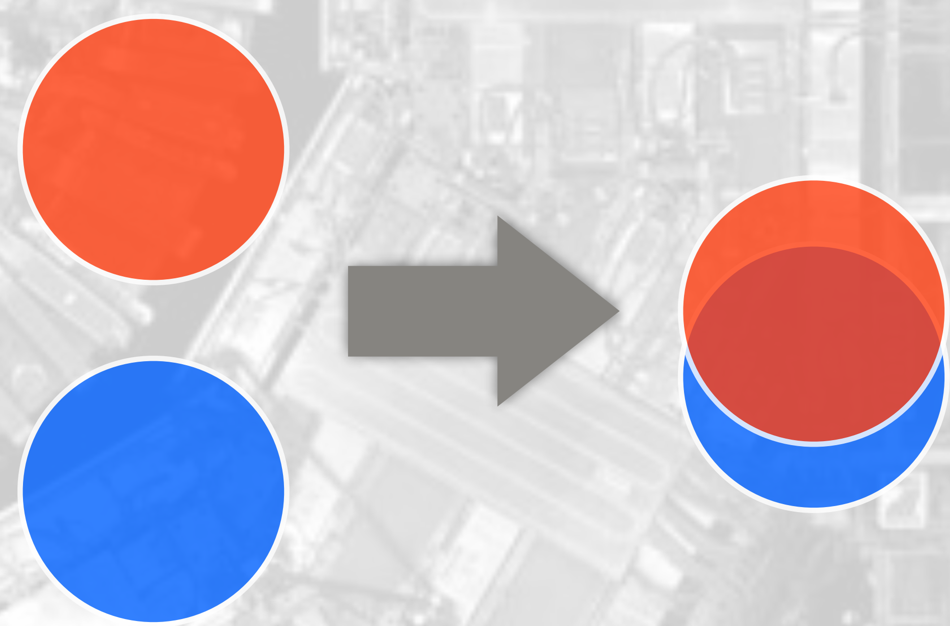
Jets beyond quarks&gluons

- High-pT top/W/H/Z can be boosted enough for the final-state jets to merge into a single jet



- These jets are special: particles cluster in multiple “poles” in (η,ϕ) → jet substructure

- Jet reconstruction to be pushed to the next level



- QCD multijet background becomes an issue for more than just hadronic searches

Examples of resonance searches

- Search for XVV resonances (V=W/Z)
  - Fully-hadronic final states and substructure
  - But also final states with leptons
- Ditop, dilepton and dijet resonance searches

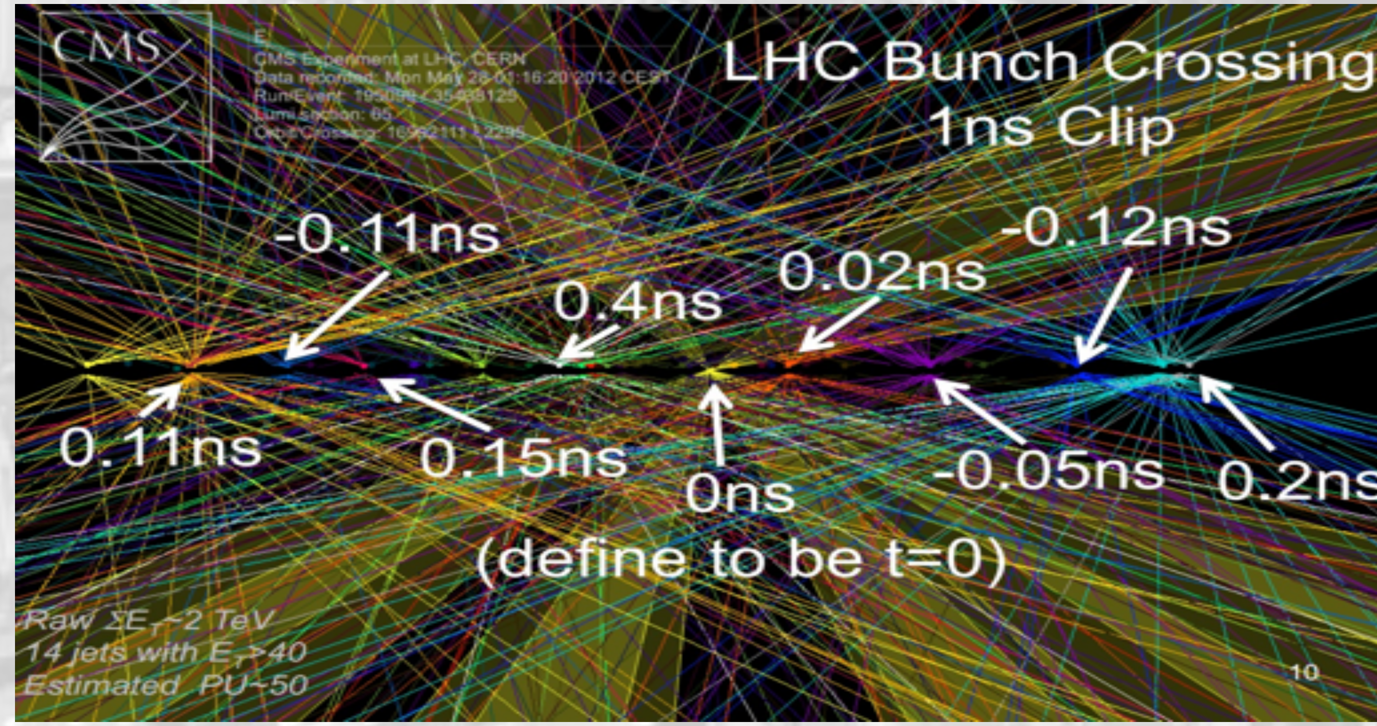
DISCLAIMER:

- I mainly show CMS results
- I also show some ATLAS result for comparison (which you saw this morning already)
- When I don't show ATLAS results, I am not implying that they don't exist. I was just lazy…

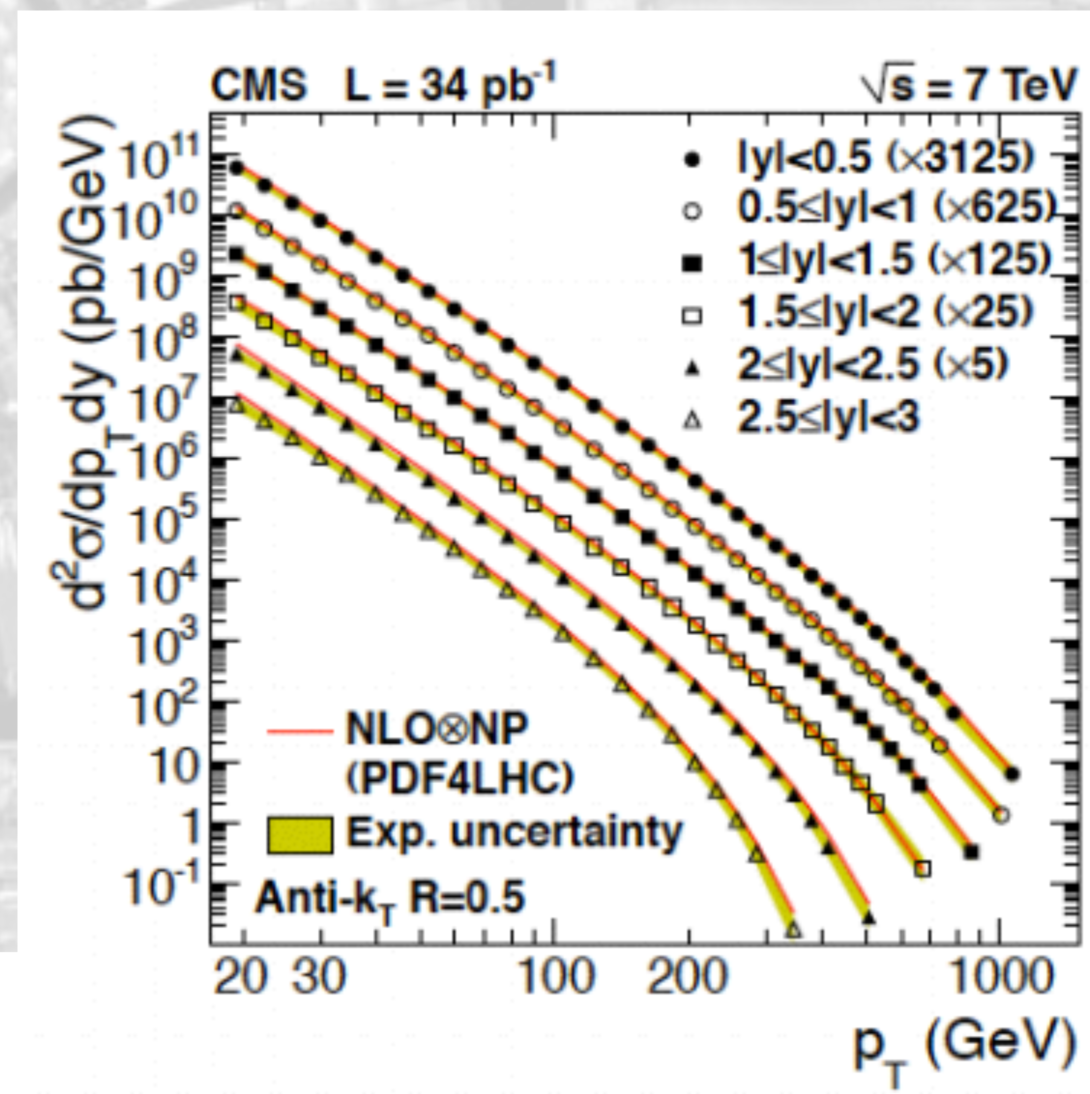
Jets, Jet substructure, and $X \to VV$ searches

Precision Physics with jets

- QCD physics at the LHC is precision physics
  - Multijet NLO calculations in event generators
  - Solid jet definition
  - Handling of pileup

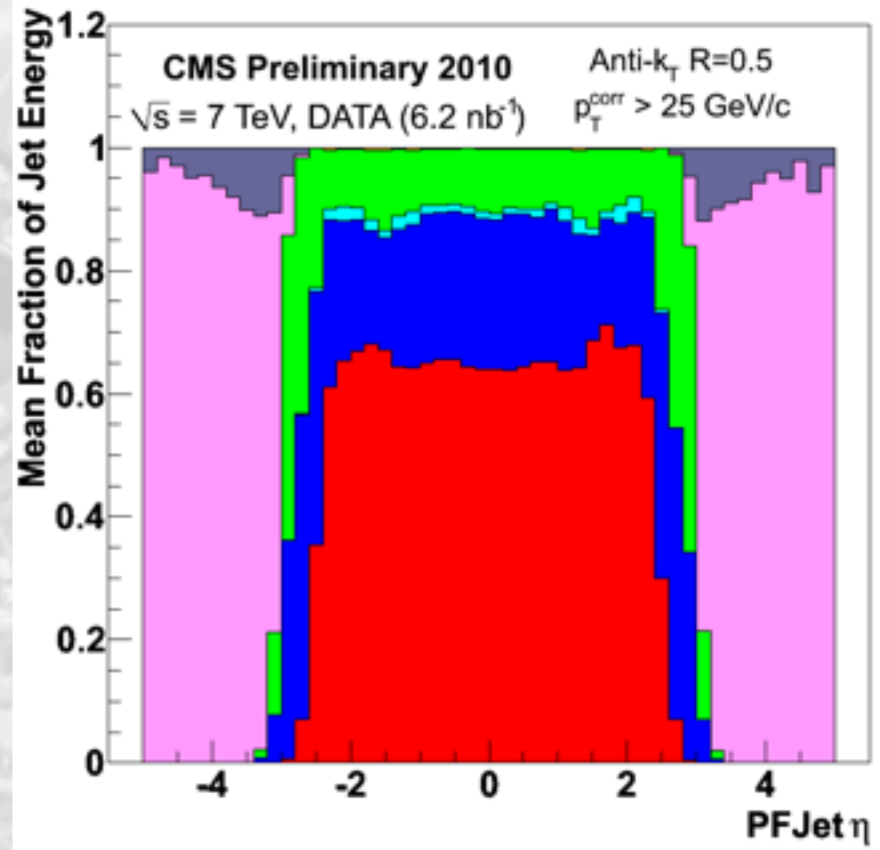


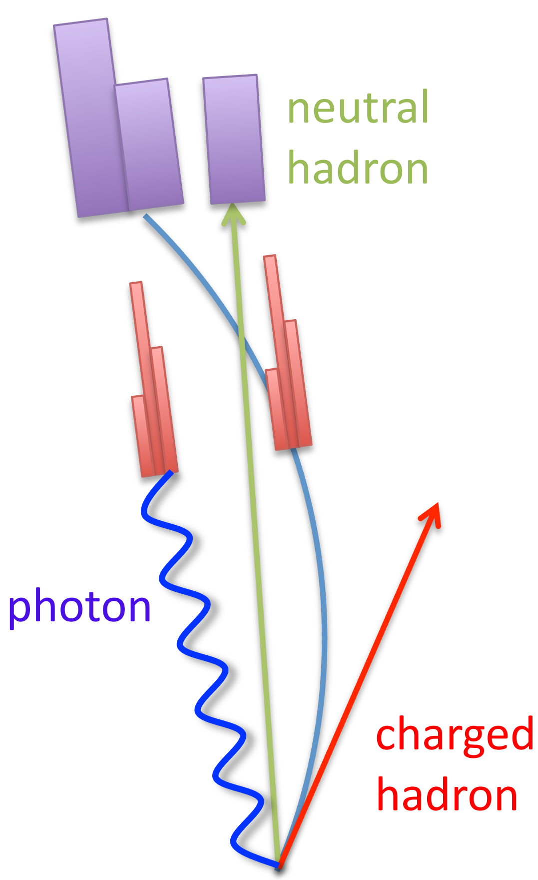
- During LHC run I, intense program of measurements
  - “Validated” the tools describing jet physics (e.g., event generators and detector simulation)
  - Set the basis to search for New Physics with jets



Jets of What?

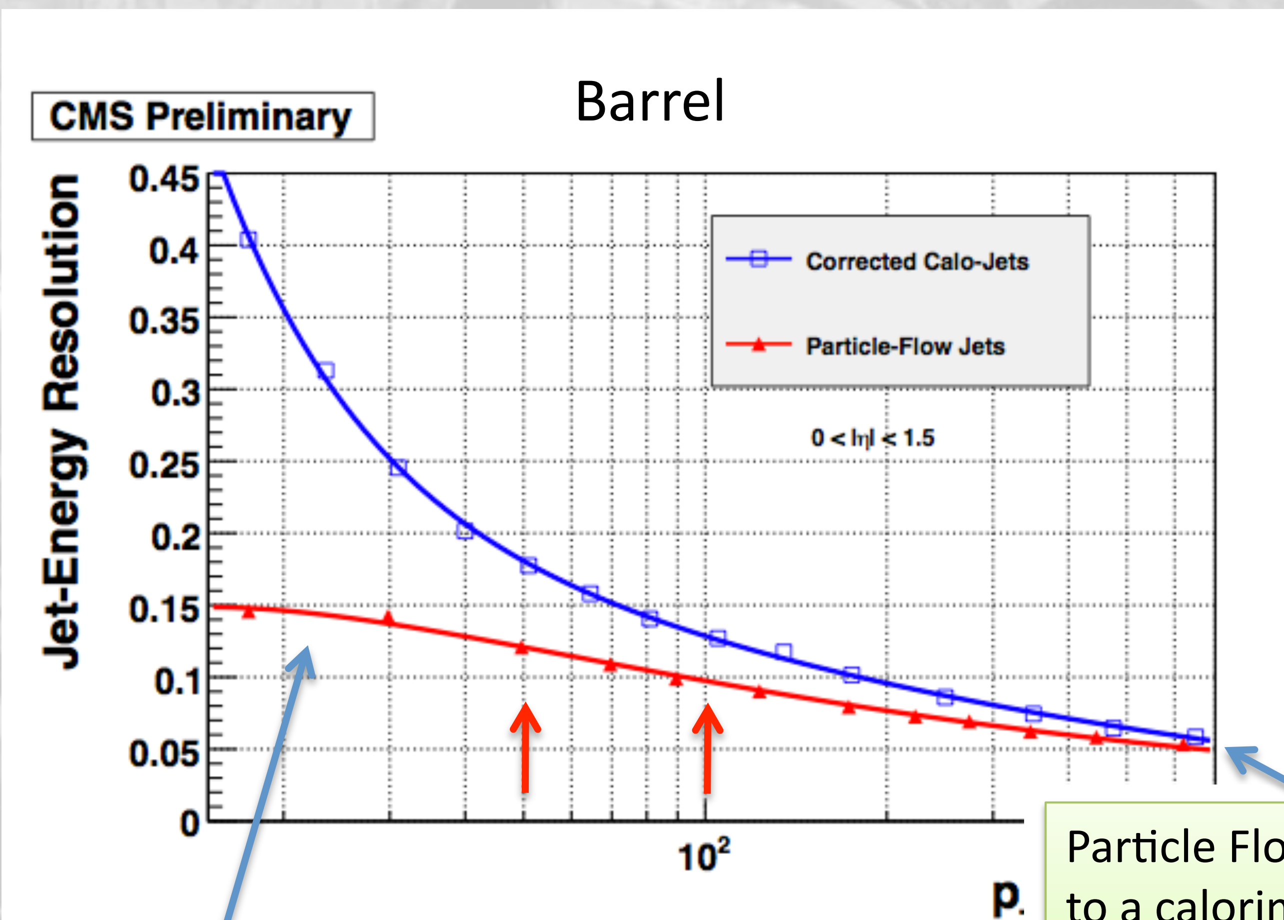
- What if your HCAL is not that great? Physics at rescue
  - 60% of the jet is made of **charged hadrons**
  - a largely fraction of the neutral hadrons is pions, which decay to **photon** pairs before your HCAL
- One can then
  - reconstruct individual hadrons, matching tracks to their energy deposit (the good pT resolution compensated for the bad energy resolution of the HCAL)
  - use the ECAL to reconstruct the energy deposit there
  - Live with the poor resolution on **neutral hadrons** (e.g., neutrons, KL, etc)





Particle Flow

- Combine the information from all detectors to reconstruct single particles
- Provides lists of particles (e,μ,γ, charged and neutral hadrons)
- Improves HCAL resolution with tracker



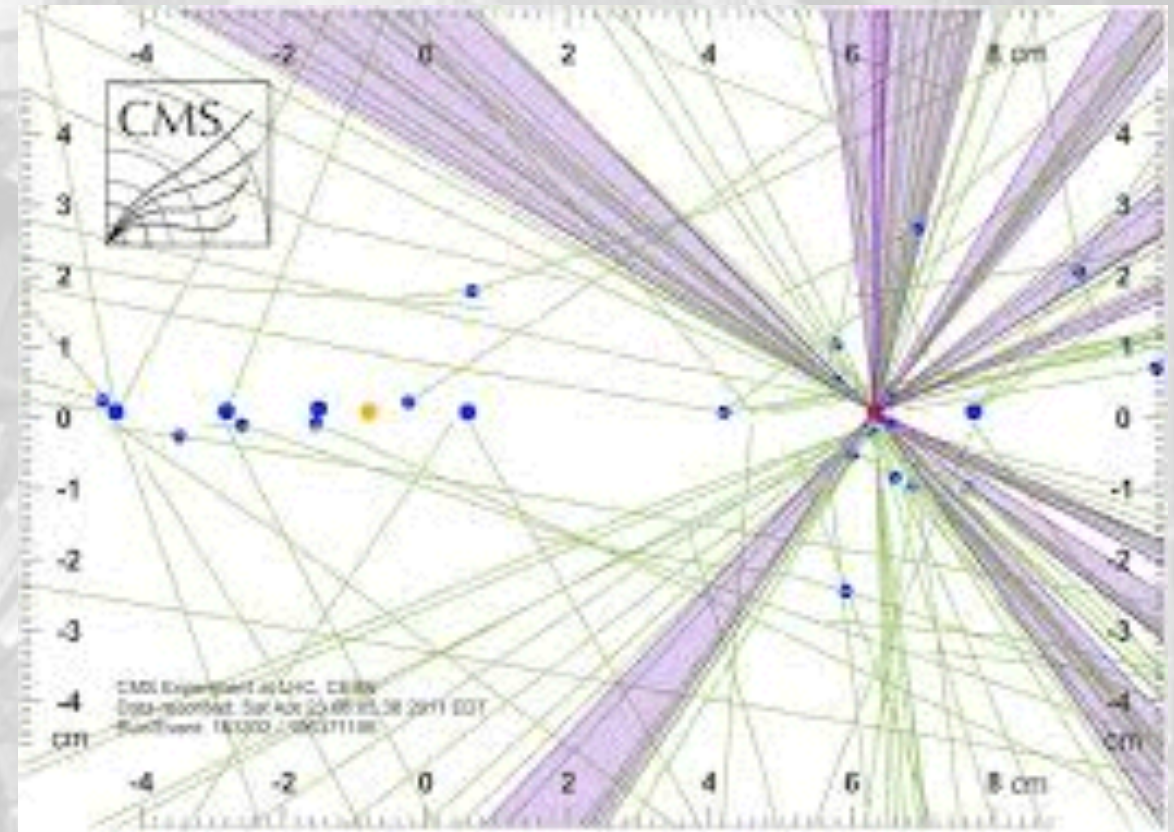
Factor 2 improvement at low pT

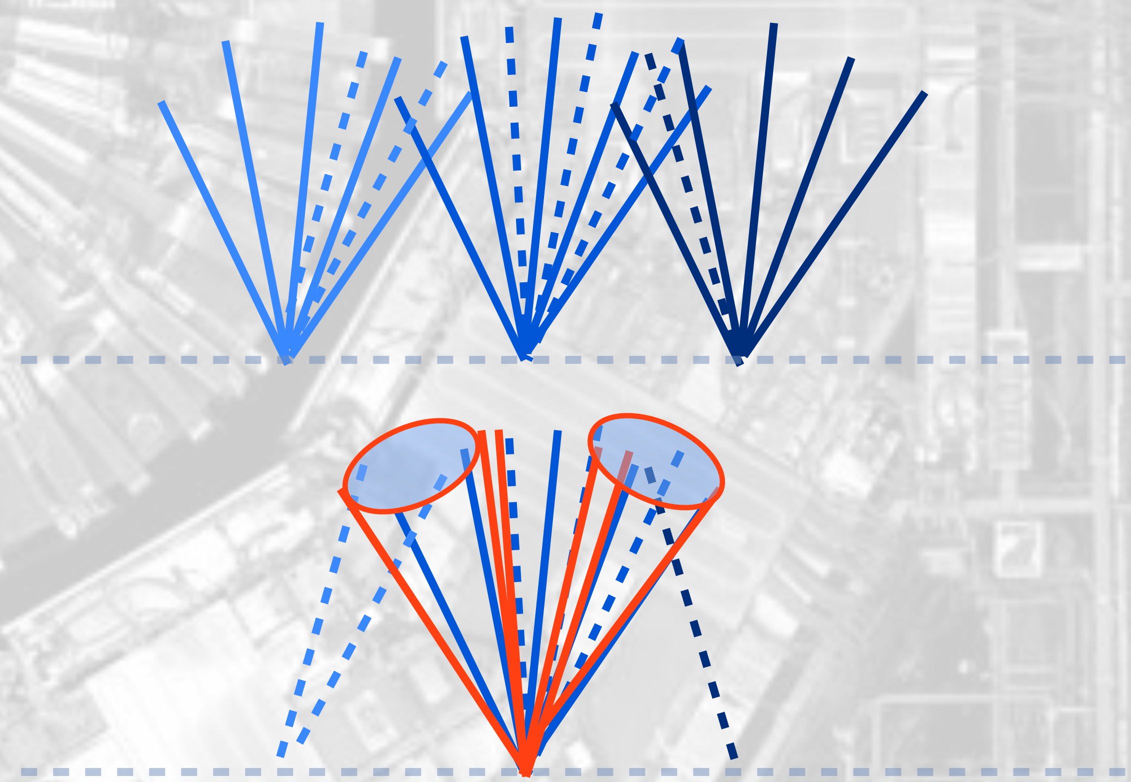
Particle Flow converges to a calorimetric measurement at high pT

- Replace the HCAL granularity with tracker granularity (important for jet substructure)
- The final result is a list of particles, similar to a generator-level study

The PileUp Problem

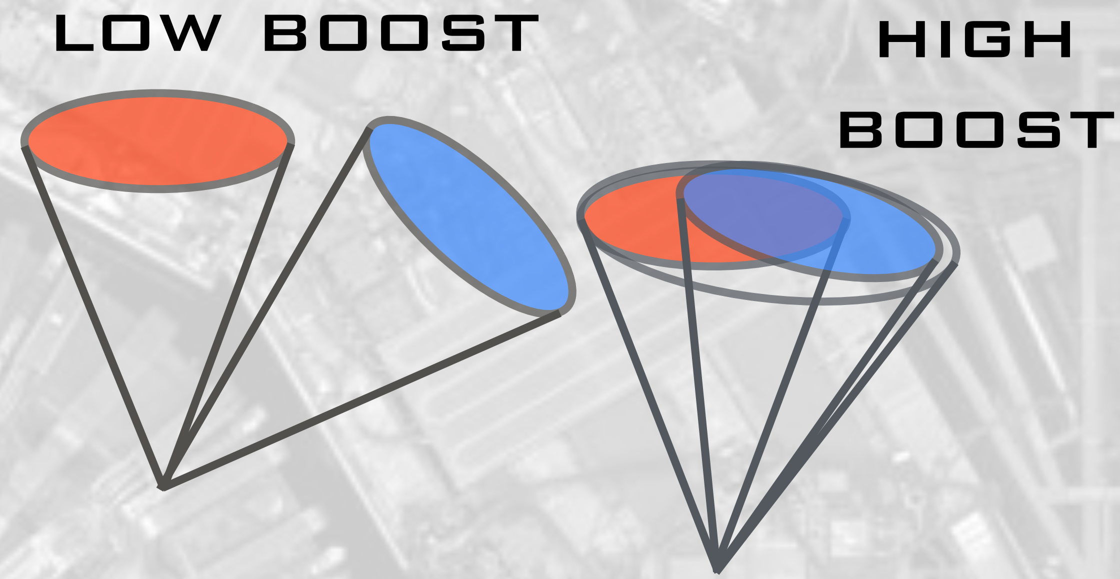
- Pileup is particularly problematic for jets
  - particles from different vertices overlap in the calorimeter area
  - the jest are then to be found on top of a diffuse noise from additional collisions
  - These collisions are typically soft (a high-p_T collision is a rare event)
- Several methods put in place to limit the impact of pileup on the jet reconstruction (charge hadron subtraction, jet vertex fraction, jet area subtraction, …)

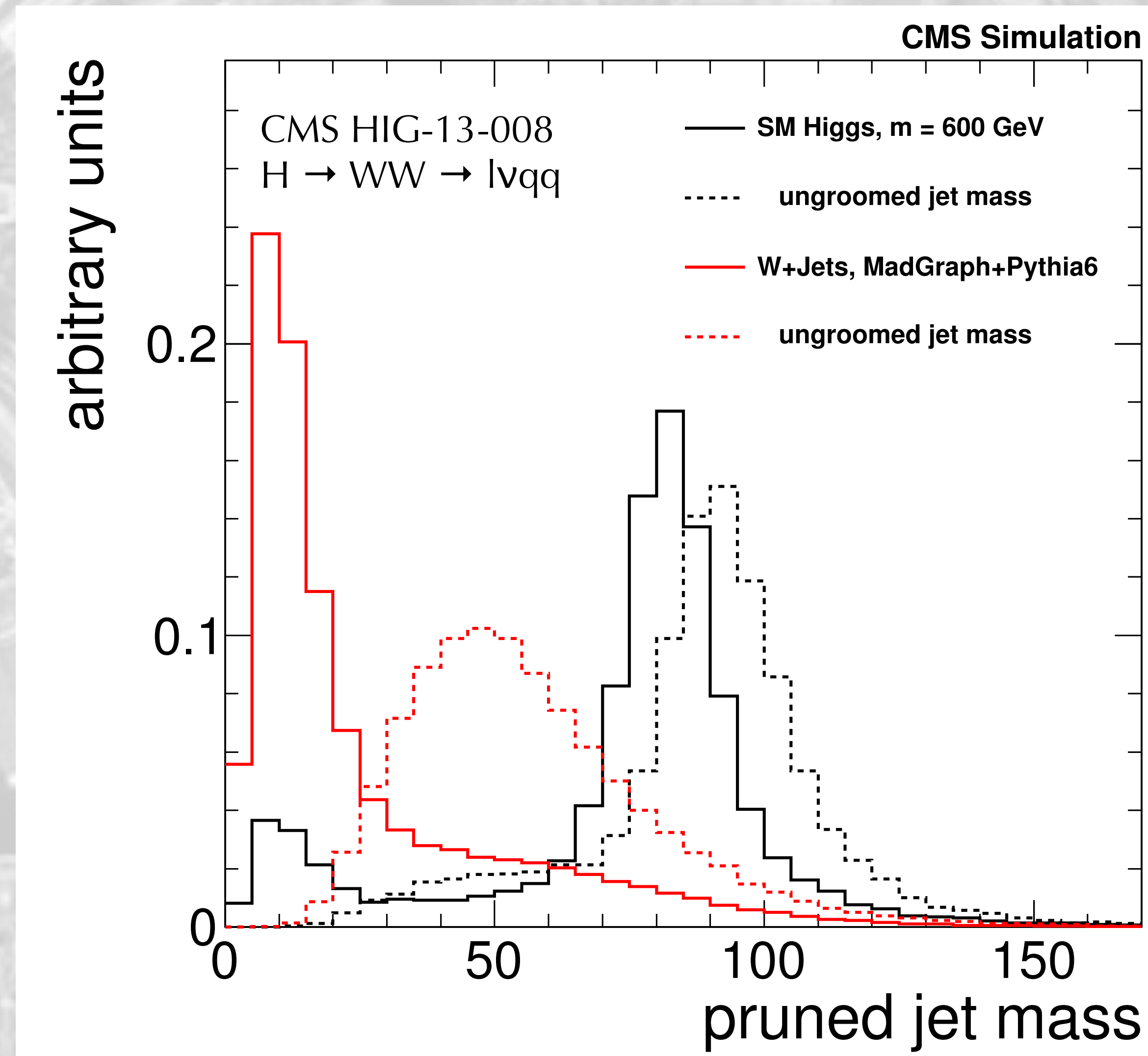




A Special Kind of Jet

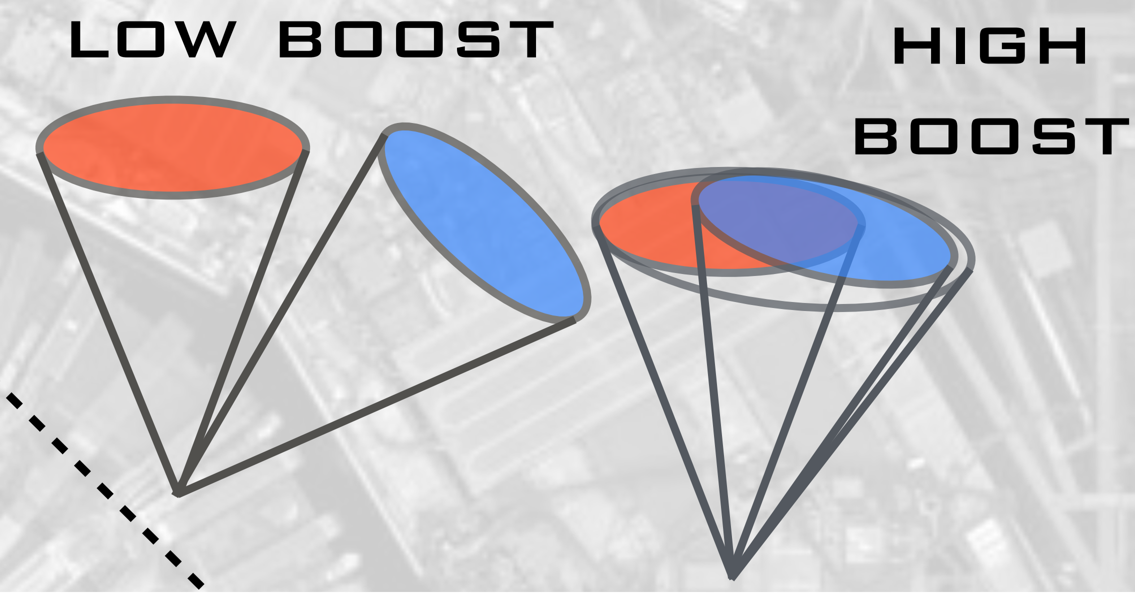
- W/Z/H/top can decay to fully hadronic final states
- For large enough p_T, the decay products might merge into a single jet
- These jets are special, as their properties (e.g., the mass) are not those of a QCD jet

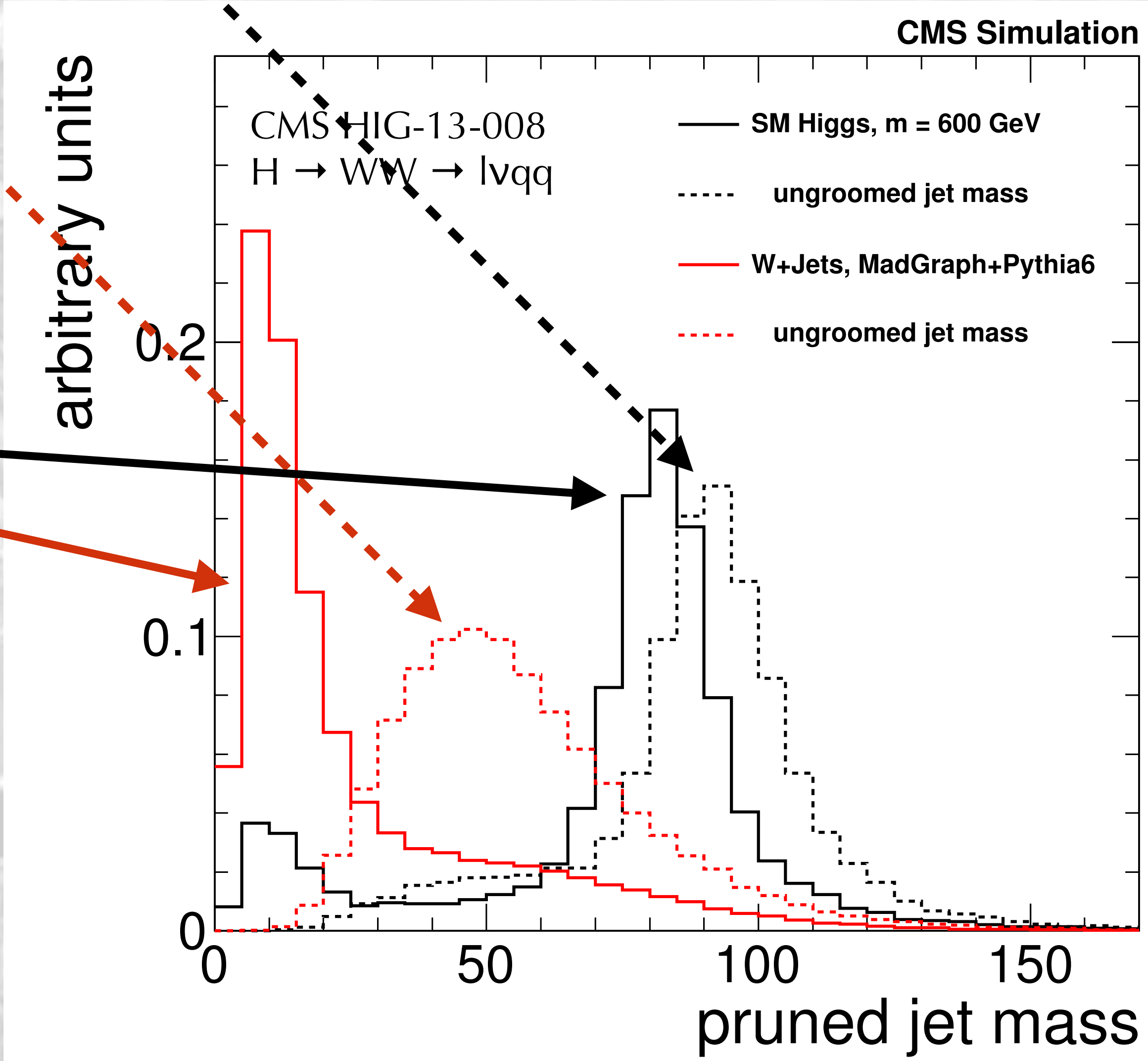




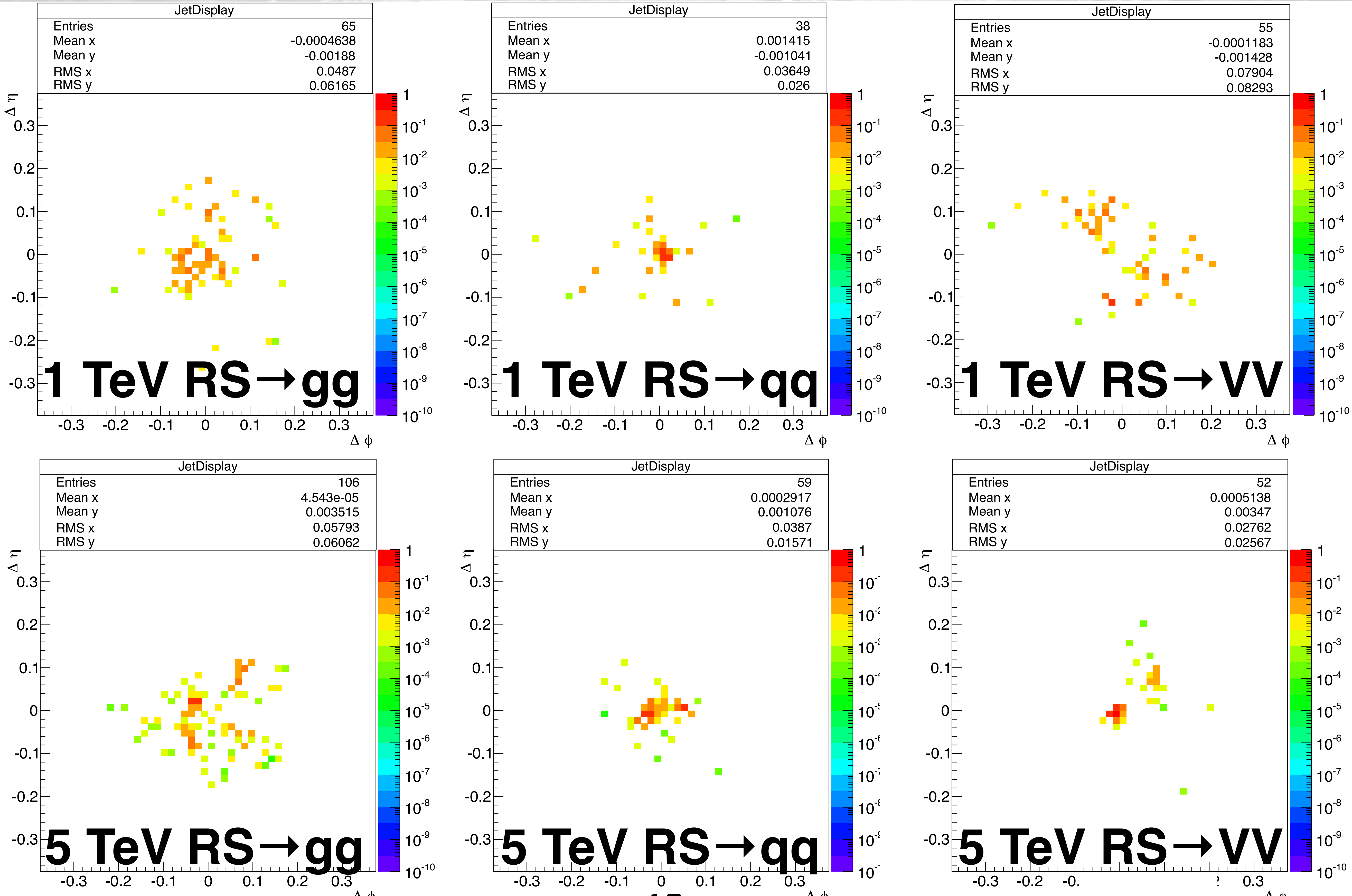
Jet Grooming

- Care is needed in defining the “right” mass
  - the plain mass for a jet from a colourless object (W/Z/H) peaks in the right spot
  - for a QCD jet, the mass depends on the jet p_T (i.e. it is NOT the right mass)
- The “right” mass comes from grooming (removal of soft and collinear radiation + pileup)
- Several techniques proposed and ad data opted for data by ATLAS & CMS
- More than the mass: the jet constituents have multipole distribution (due to the number of partons starting the showering)



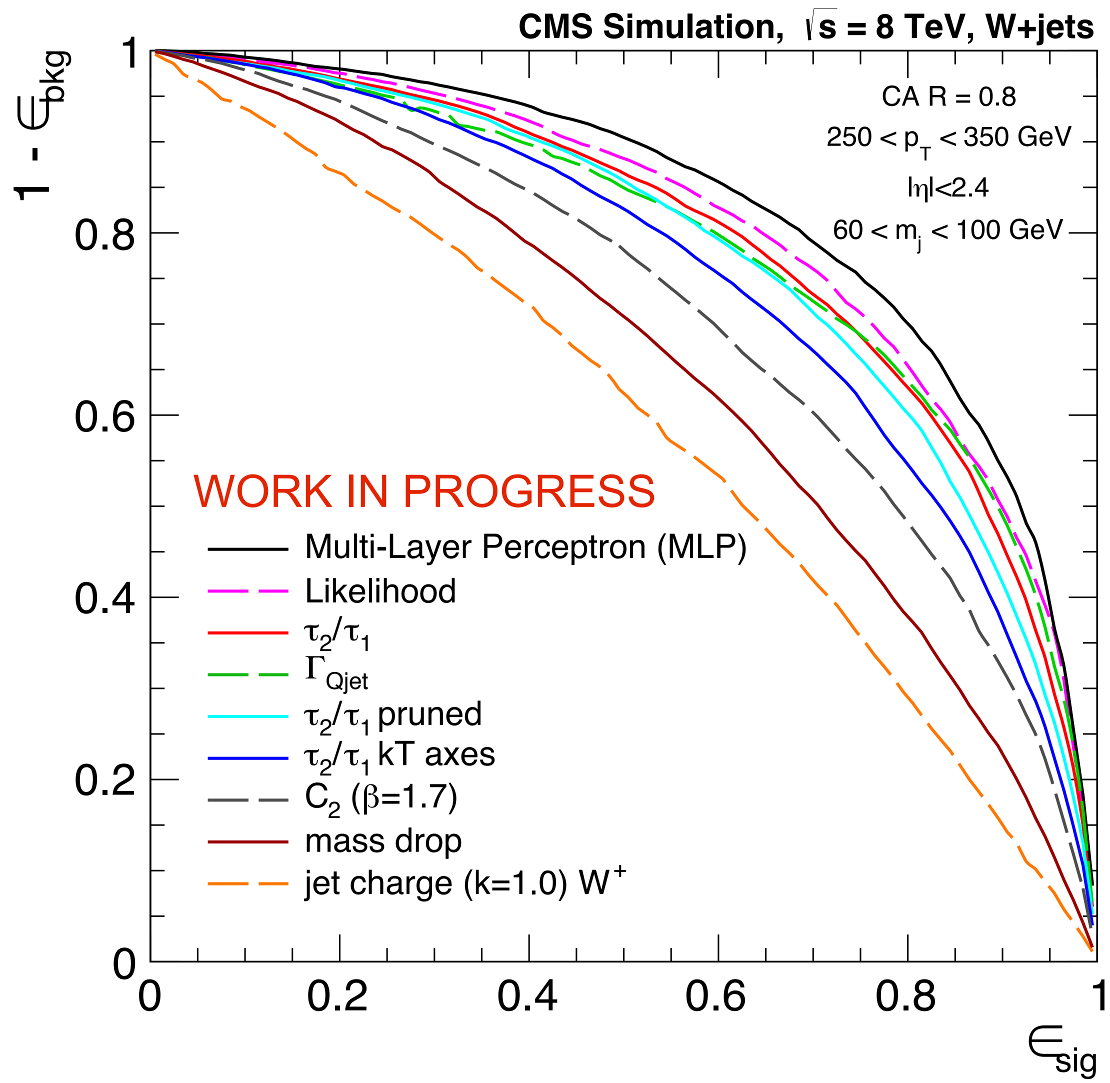


More than QCD Jets



Substructure Variables

- One wants to separate a multi-prong from a single-prong angular distribution of the decay products around the jet axis
- Several variables "on the market" to exploit this difference (see for instance CMS and ATLAS papers)
- A few lessons learned
  - the jet mass cut does much of the job
  - the higher the p_T, the smaller the QCD background. Better use substructure as an event classifier, not to loose efficiency
- In CMS, Particle Flow is important here (despite the high-p_T regime). Angular resolution matters, and tracker is better for that

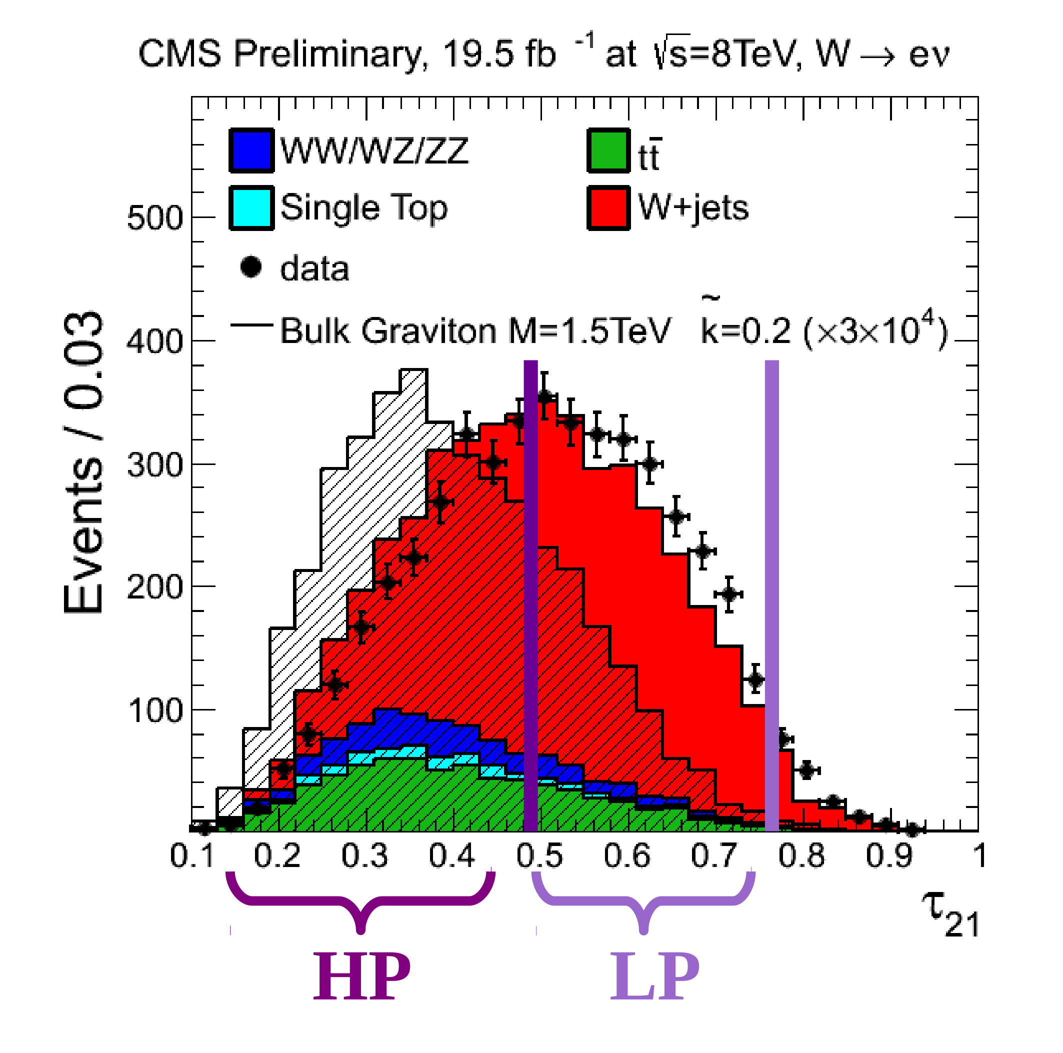


CMS-PAS-JME-13-006

Jet N-Subjettiness

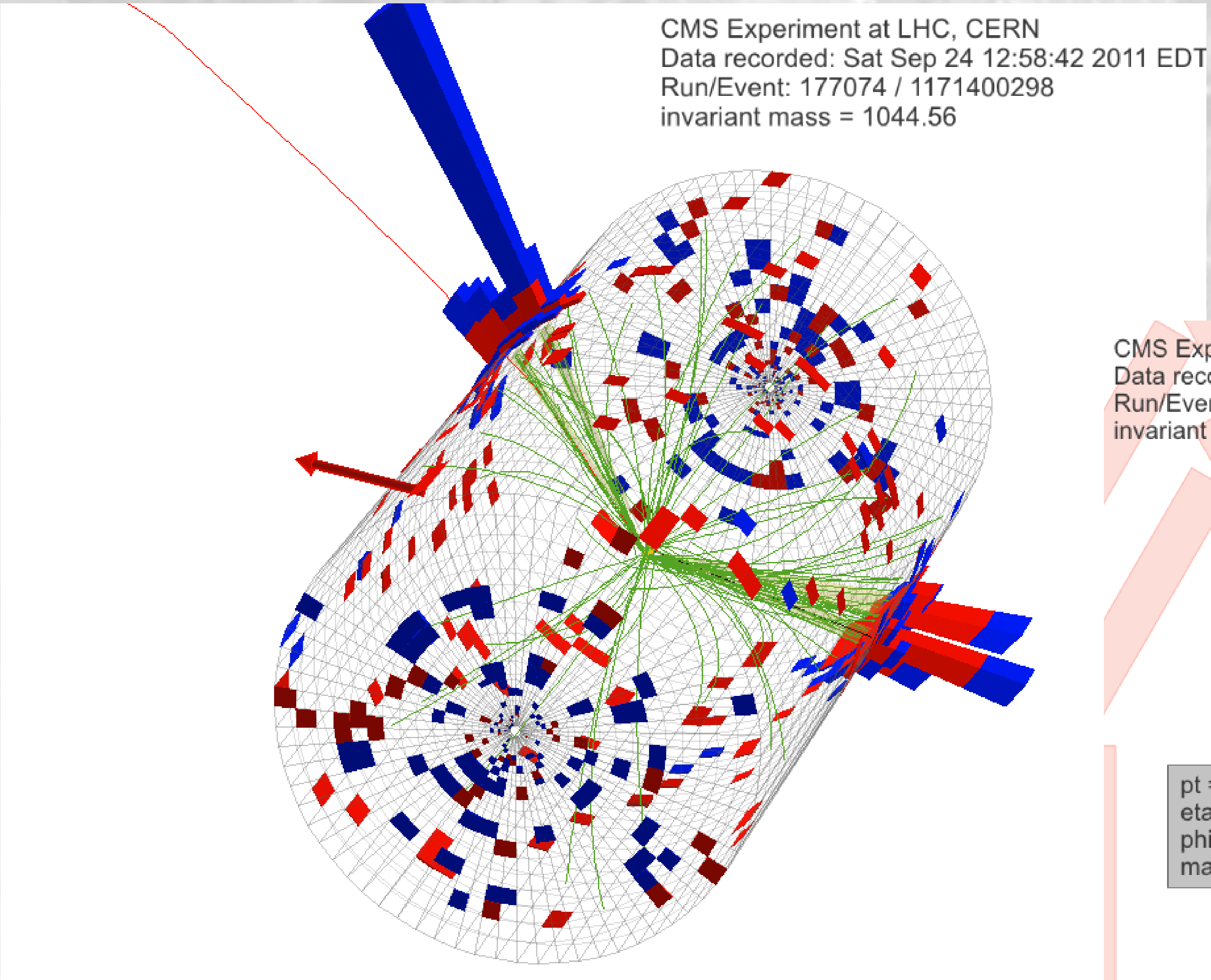
- N-subjettiness is smaller if the constituents of a jet can be arranged in N subjets
- One can use the variable to test different hypotheses (e.g. V vs top vs QCD jet)
- In real life, ratios are particularly useful to categorize events (High purity vs Low Purity) after a mass cut on the jet is applied
- Correlation with jet mass and PU effects tend to reduce the discrimination power
- Polarization also matters (e.g. separation more effective for V_L than V_T)

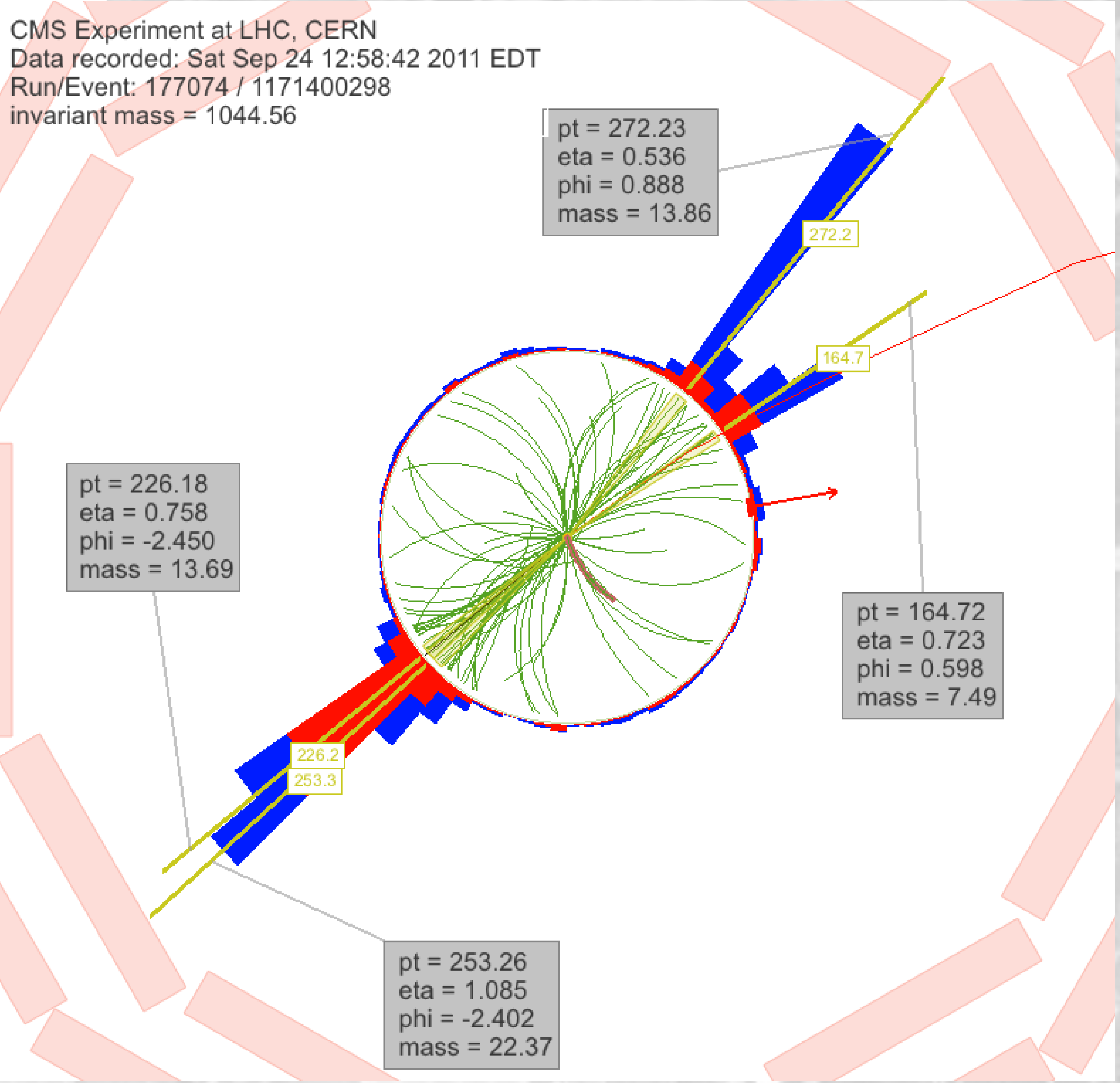
$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \, min\{\Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k}\}$$



http://arxiv.org/abs/1011.2268

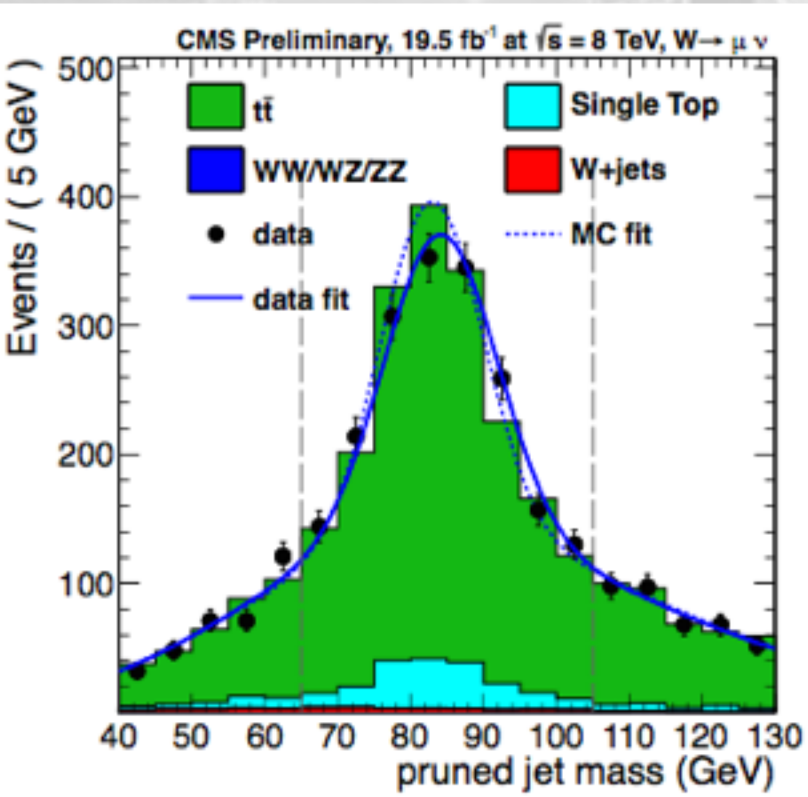
A DOUBLE-TAG EVENT

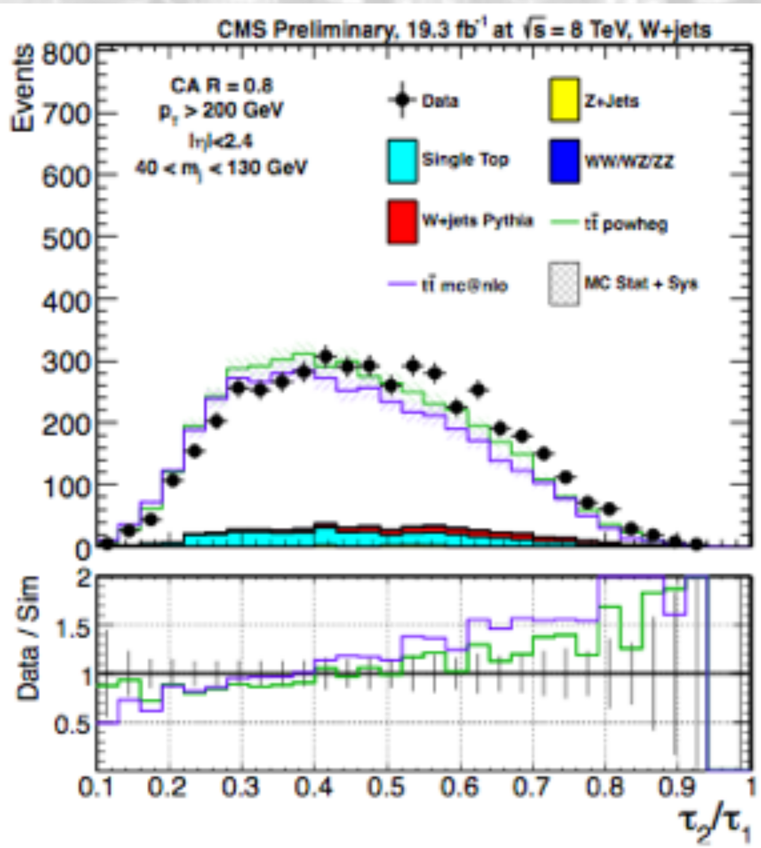


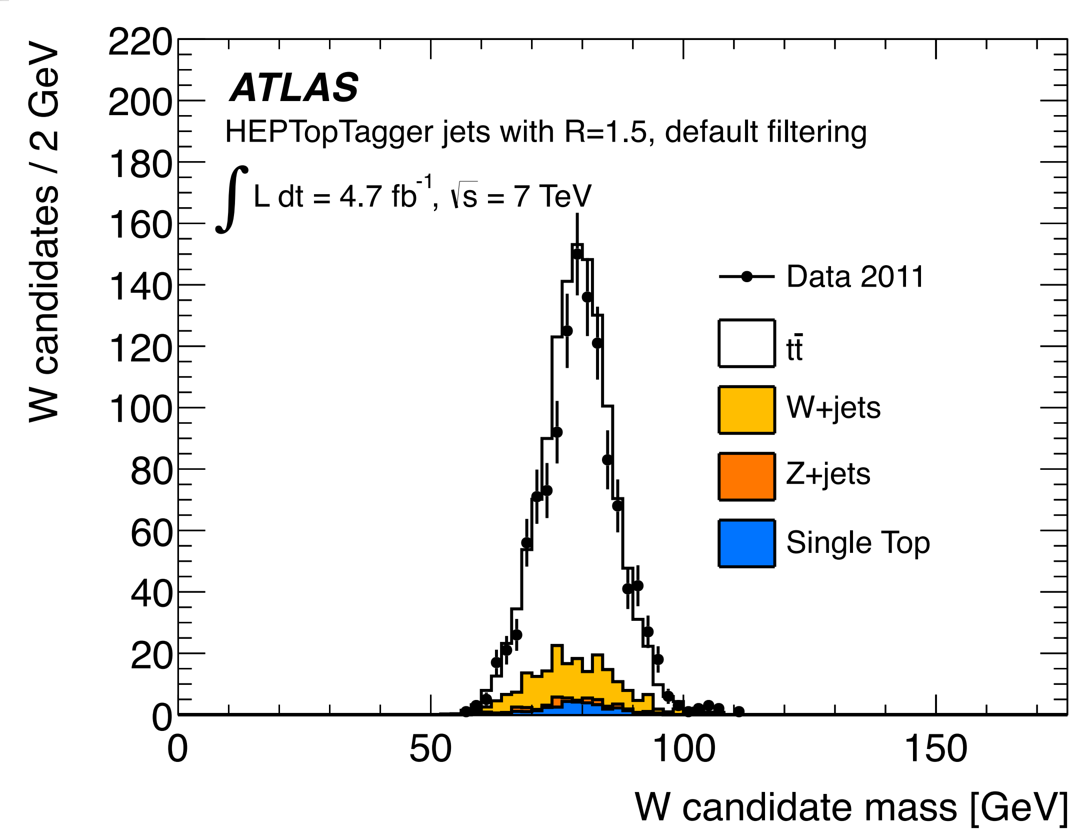


Validation With Data

- boosted tt reconstructed as one b-Jet+1lepton recoiling against one bjet and one jet (the W candidate)
- Peak in the jet mass: we are seeing boosted Ws
- Study substructure variables data vs MC
- MC get substructure quite right (~5% systematic on predicted efficiency)



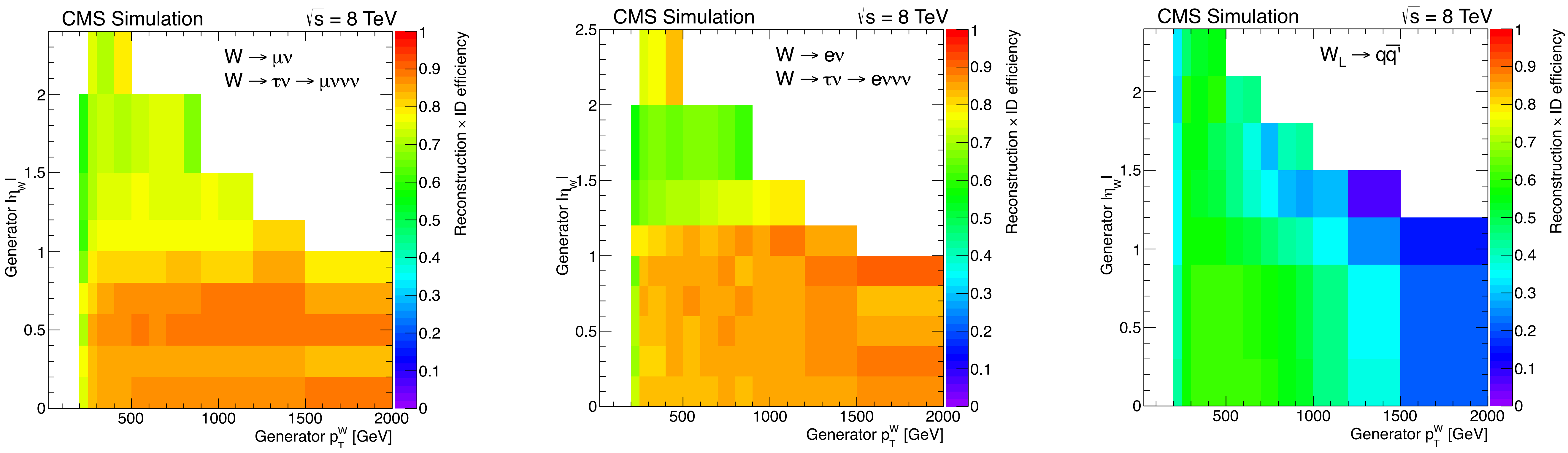




CMS-PAS-JME-13-006 **ATLAS arXiv 1306.4945**

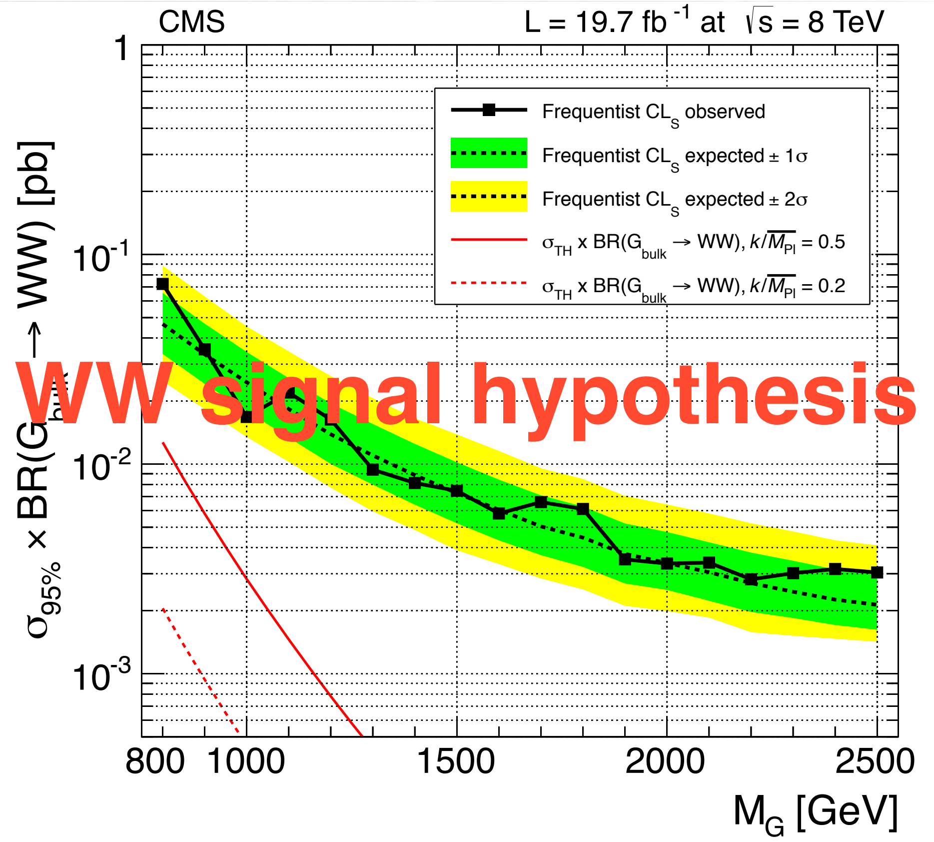
Theory "Outreach"

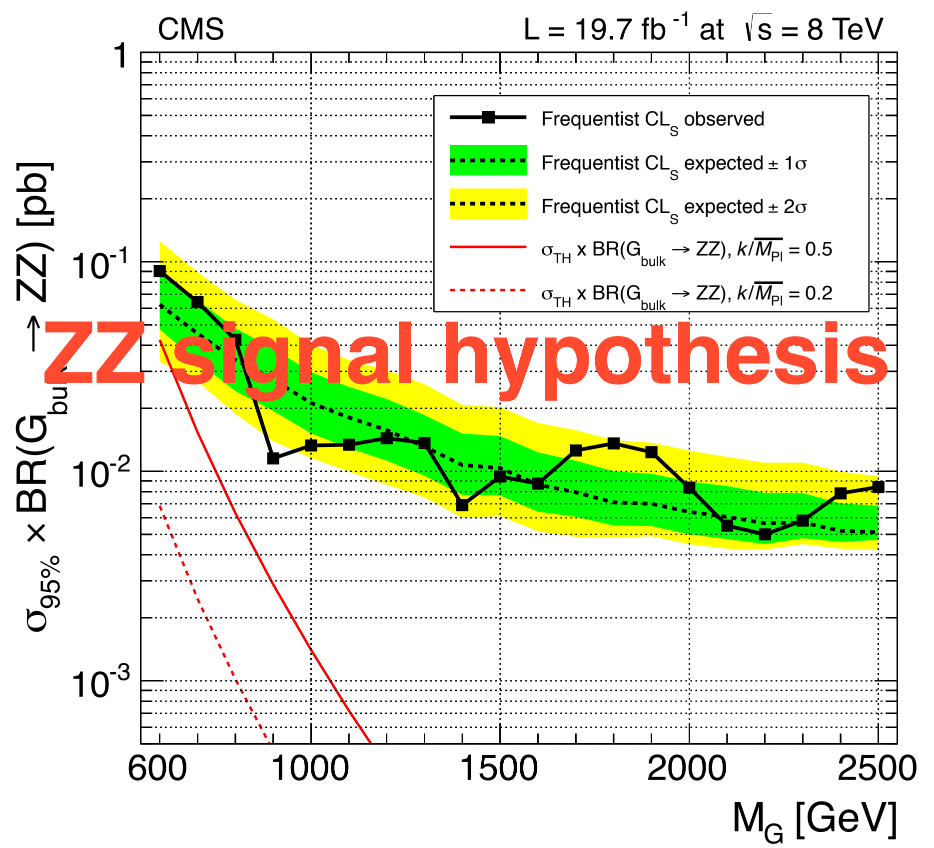
- We spent some time to provide the information to reinterpret these results in specific models
- You have to generate resonance production w/o detector effects (run Madgraph/Pythia/…) and decay to VV
- We provide the efficiency vs the boson pT and η for leptonic and hadronic final states (including the cross-feed background fot leptons from τ decays). Efficiency quoted for V_L and reduced by 15% for V_T

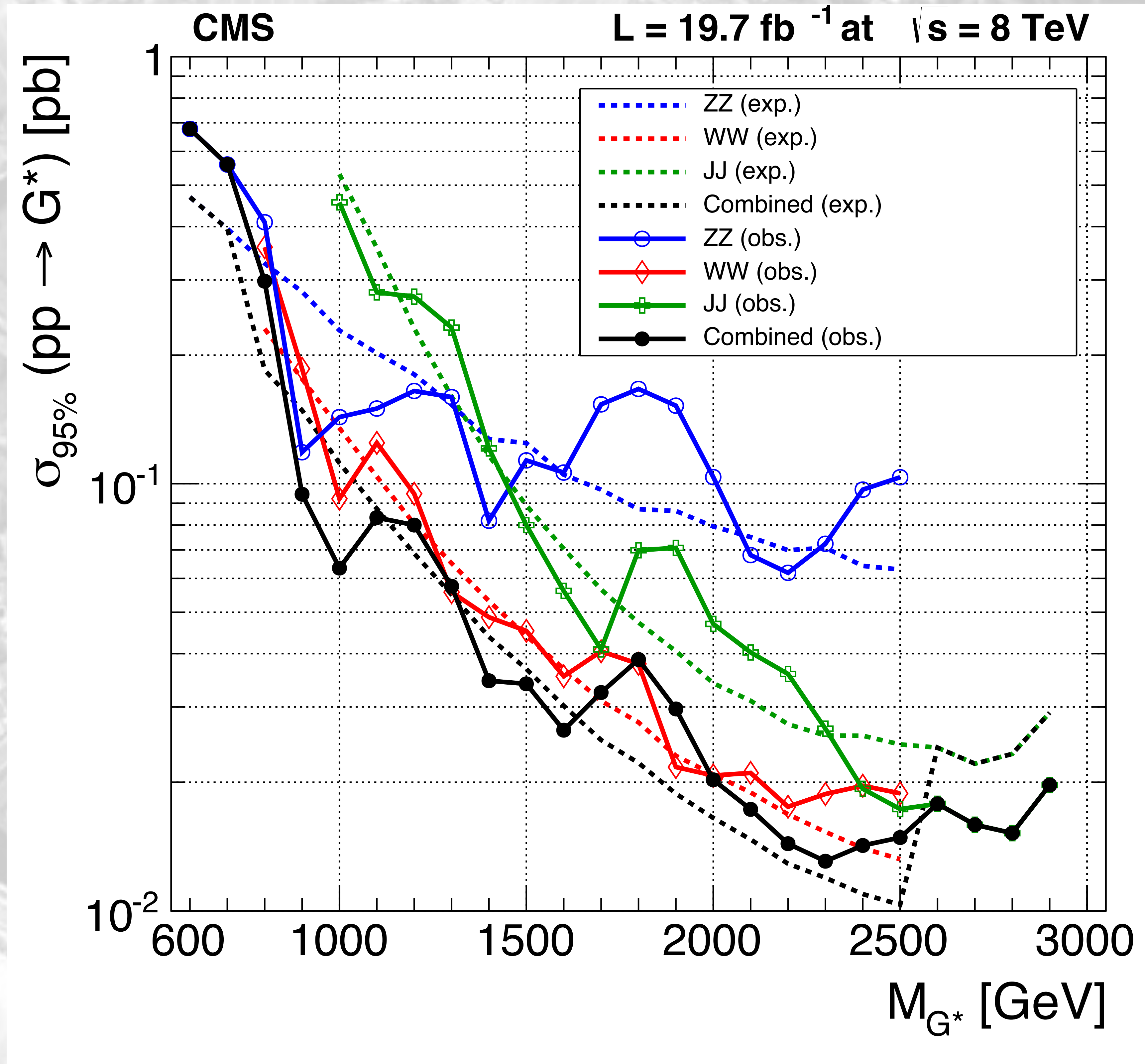


http://arxiv.org/abs/1405.3447

Results with 8TeV data







http://arxiv.org/pdf/1405.3447.pdf

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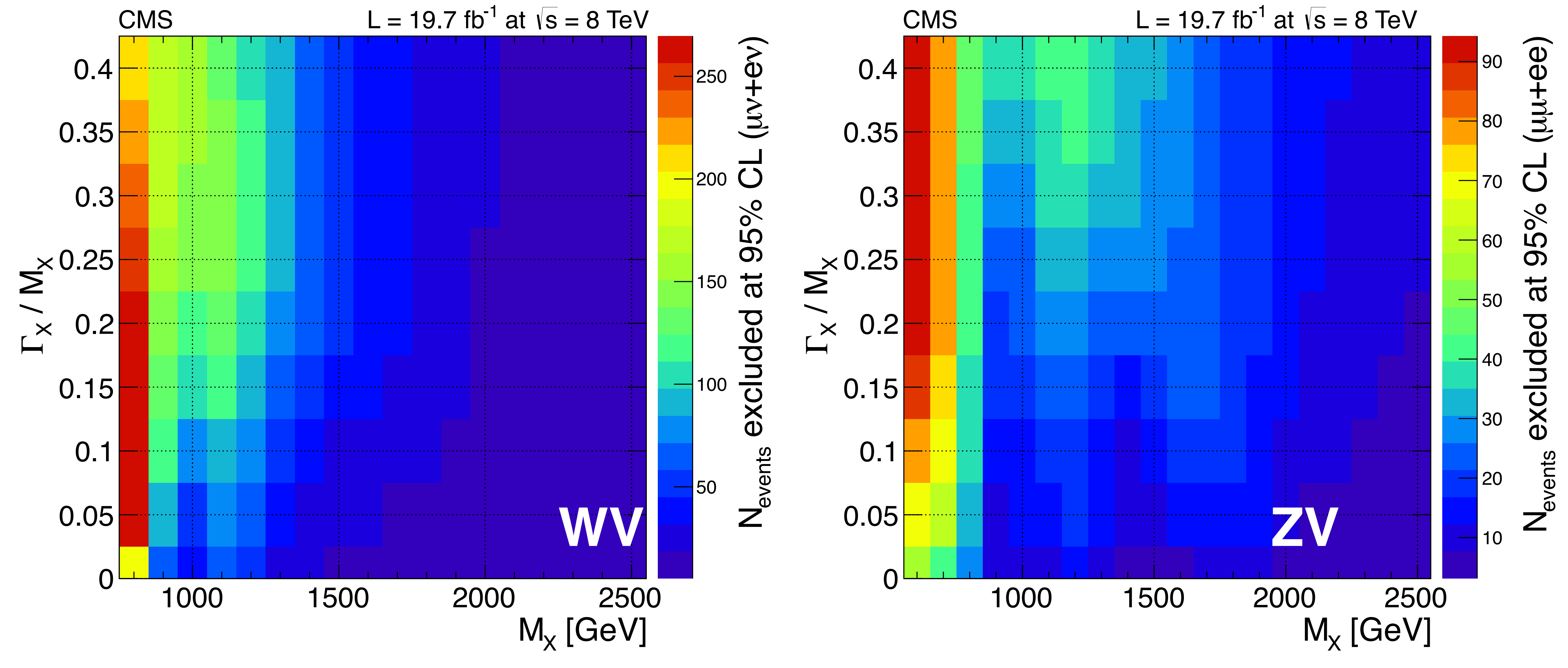
Results with 8TeV data

- Limits derived for generic masses and relative widths
- Provided (in paper Appendix) the details on how to derive these results with the provided “outreach” information (look for “Simplified limits)



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X → ll/jj Searches

High-Pt Muons

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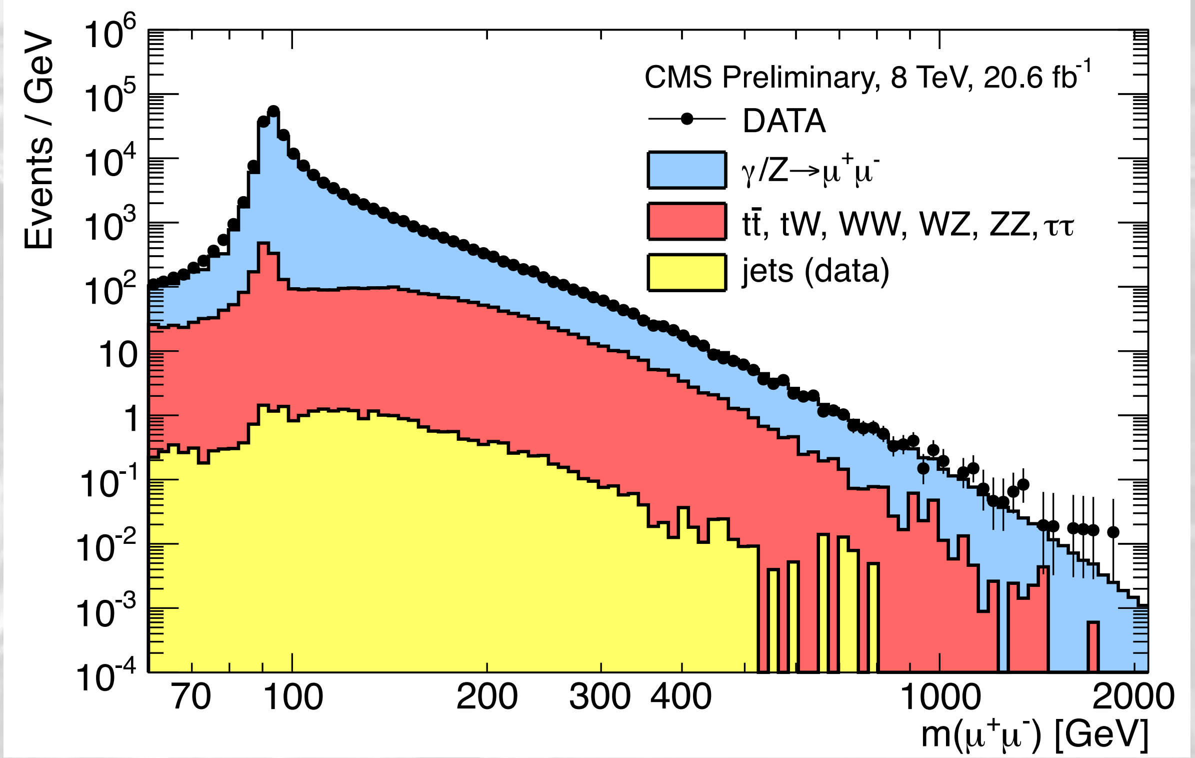

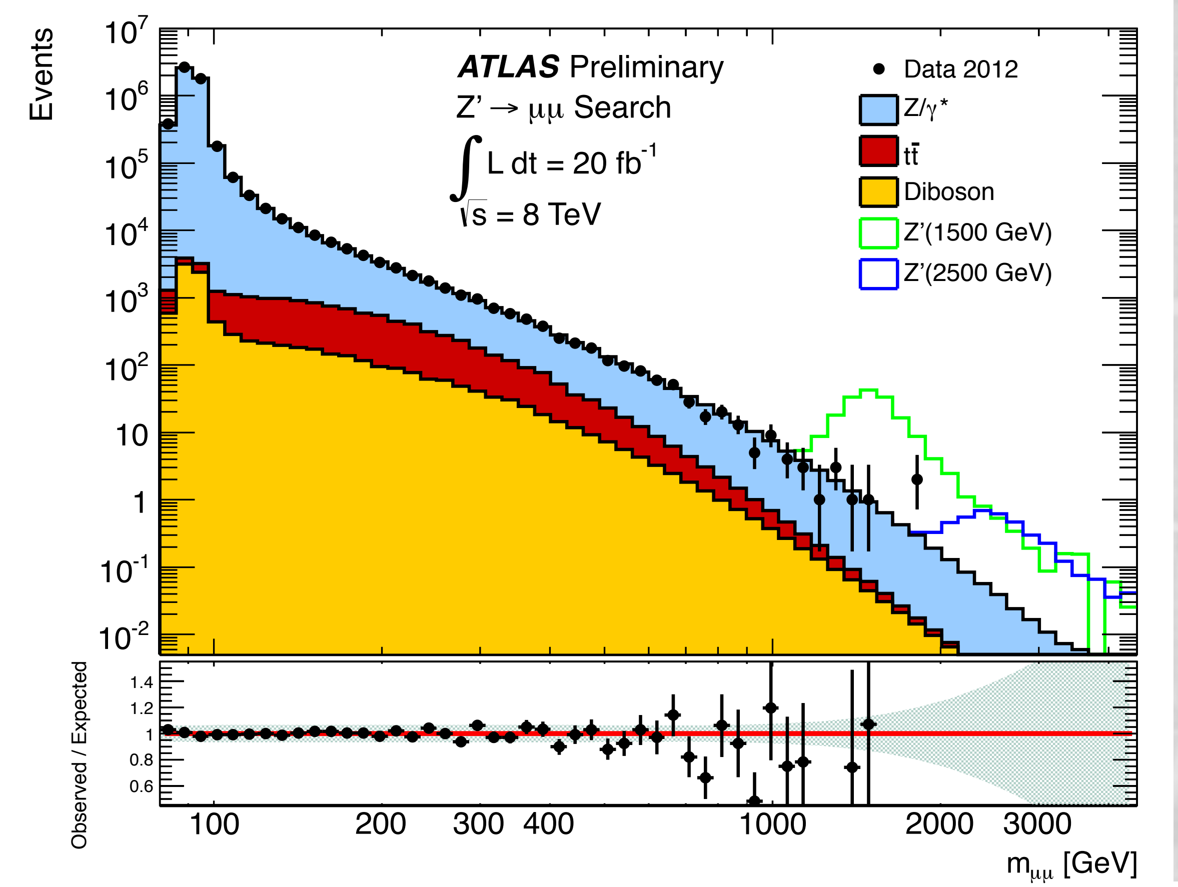

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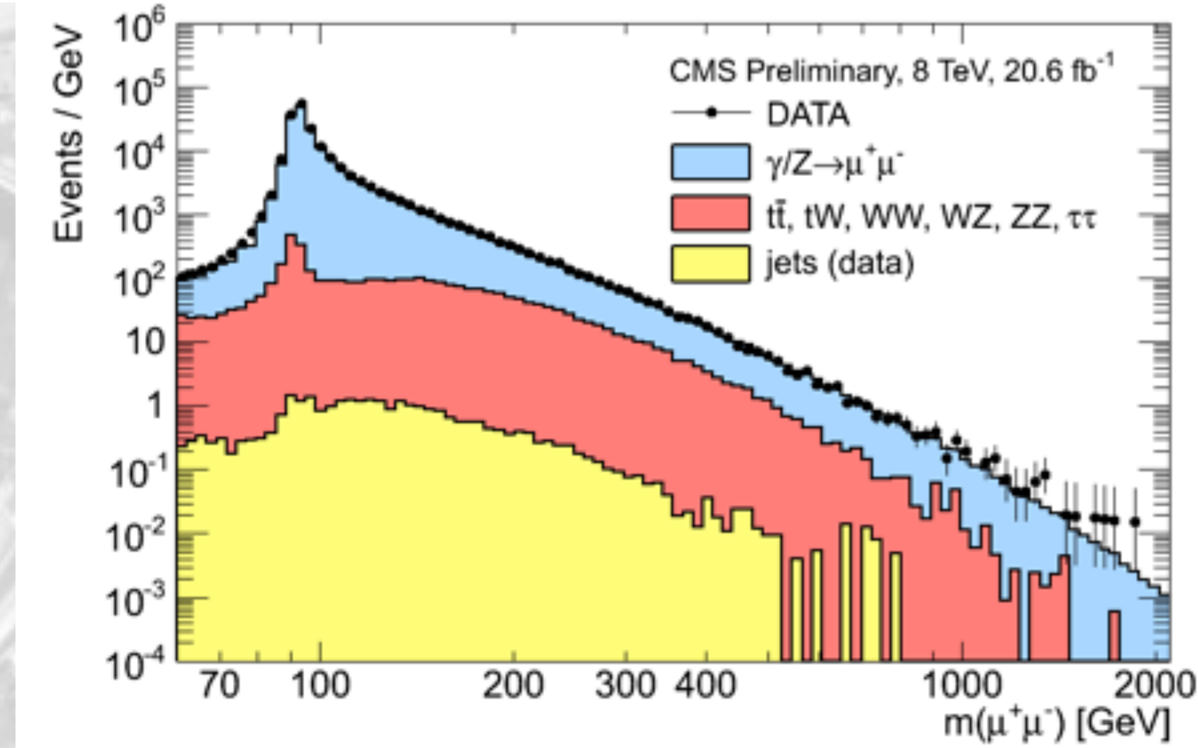
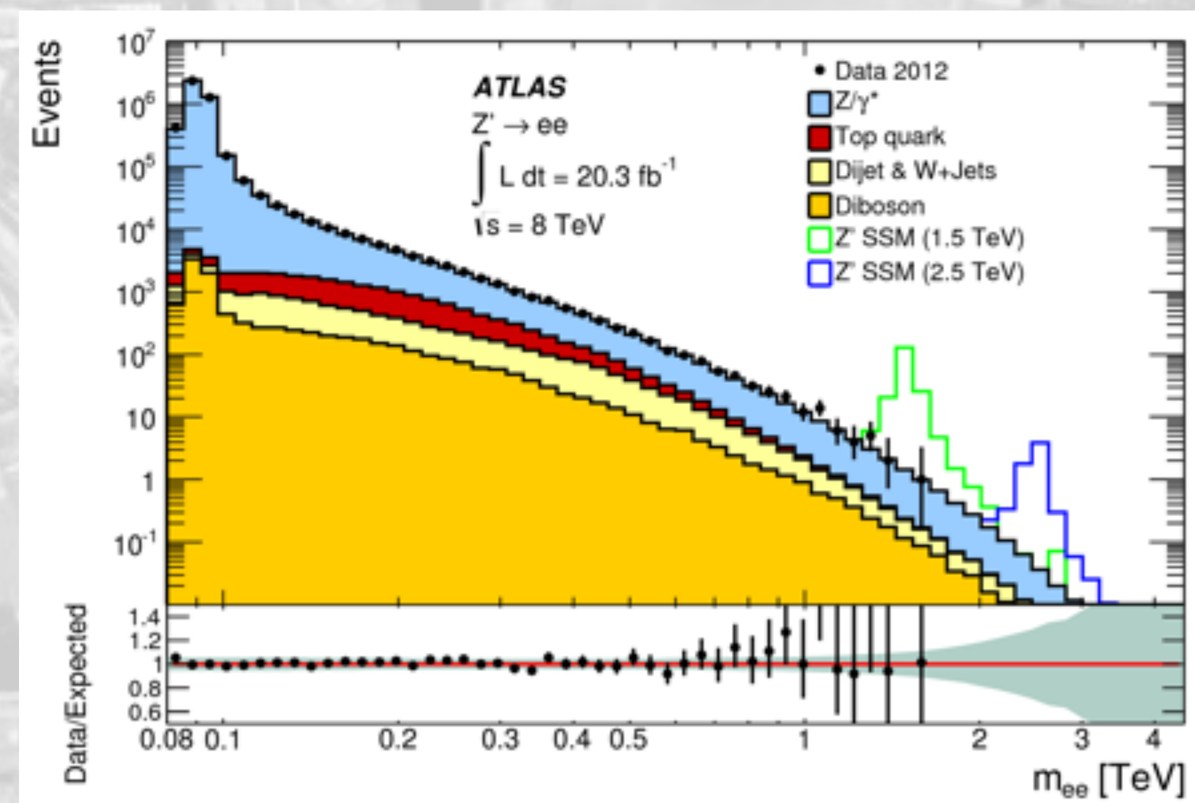
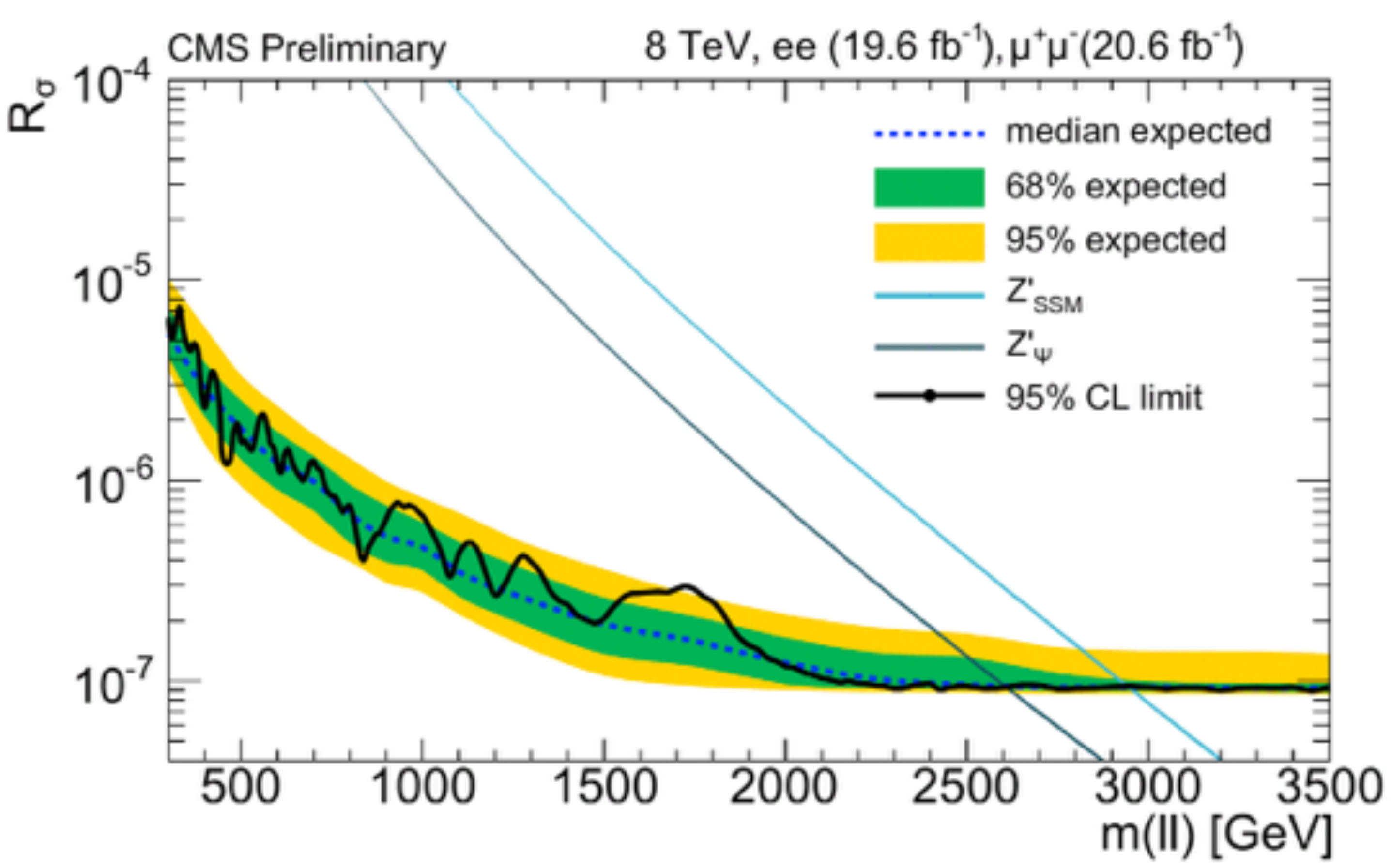
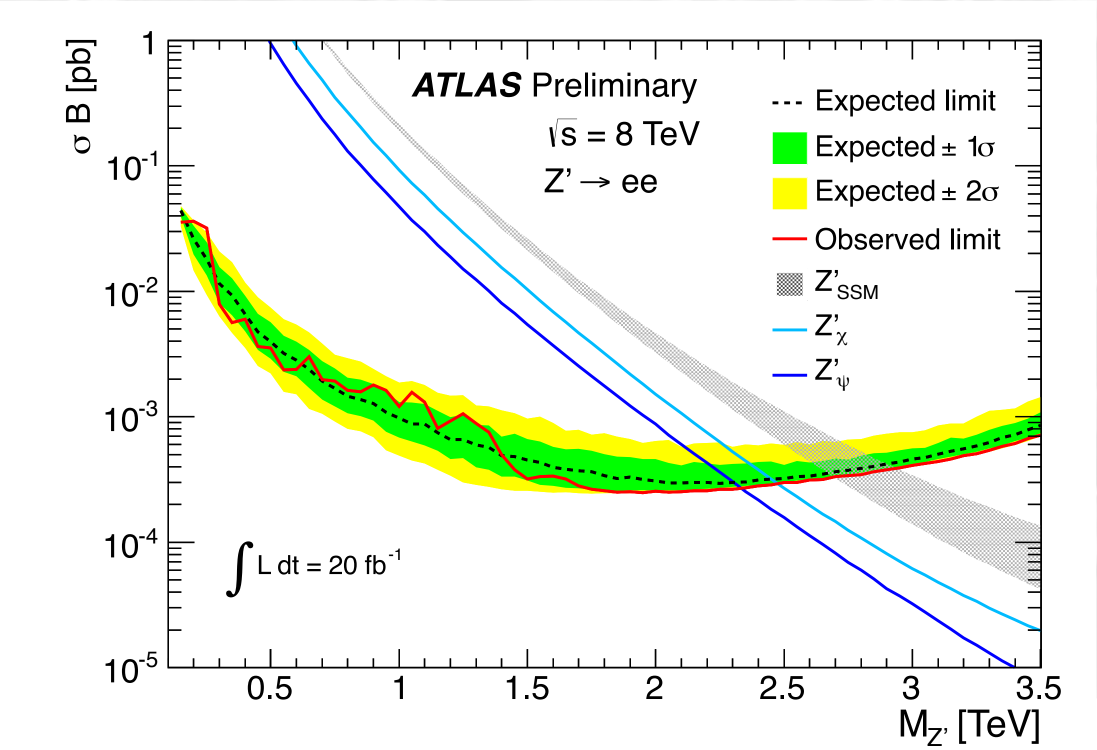
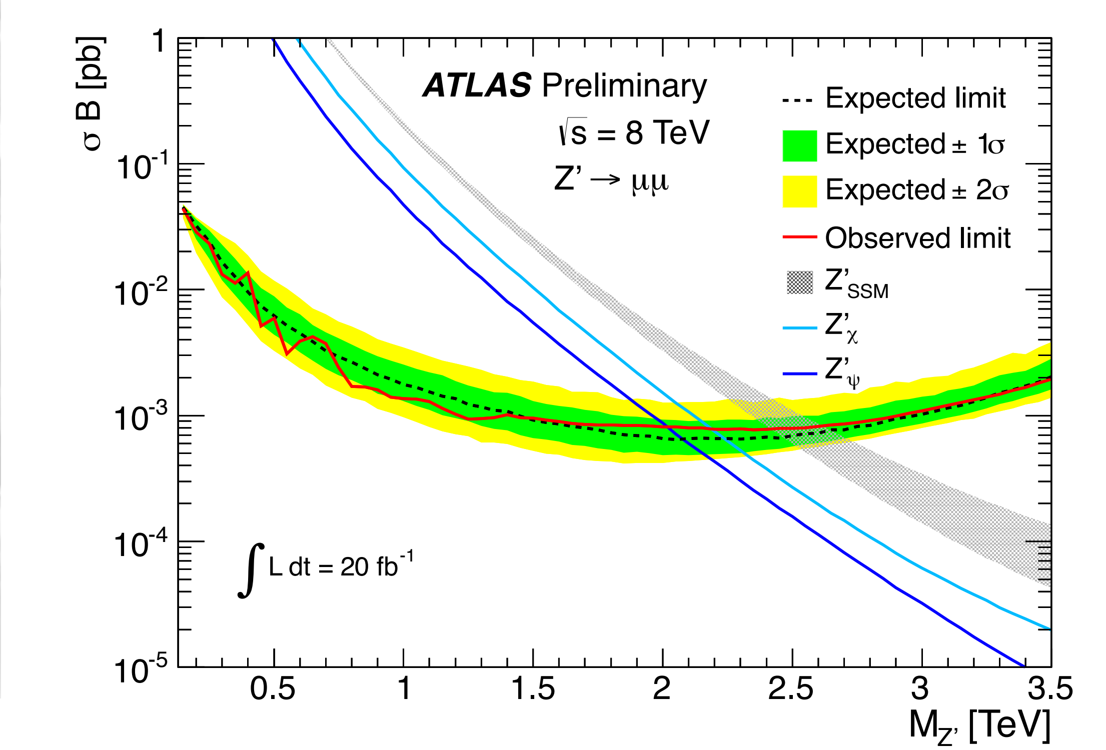




Dilepton Search

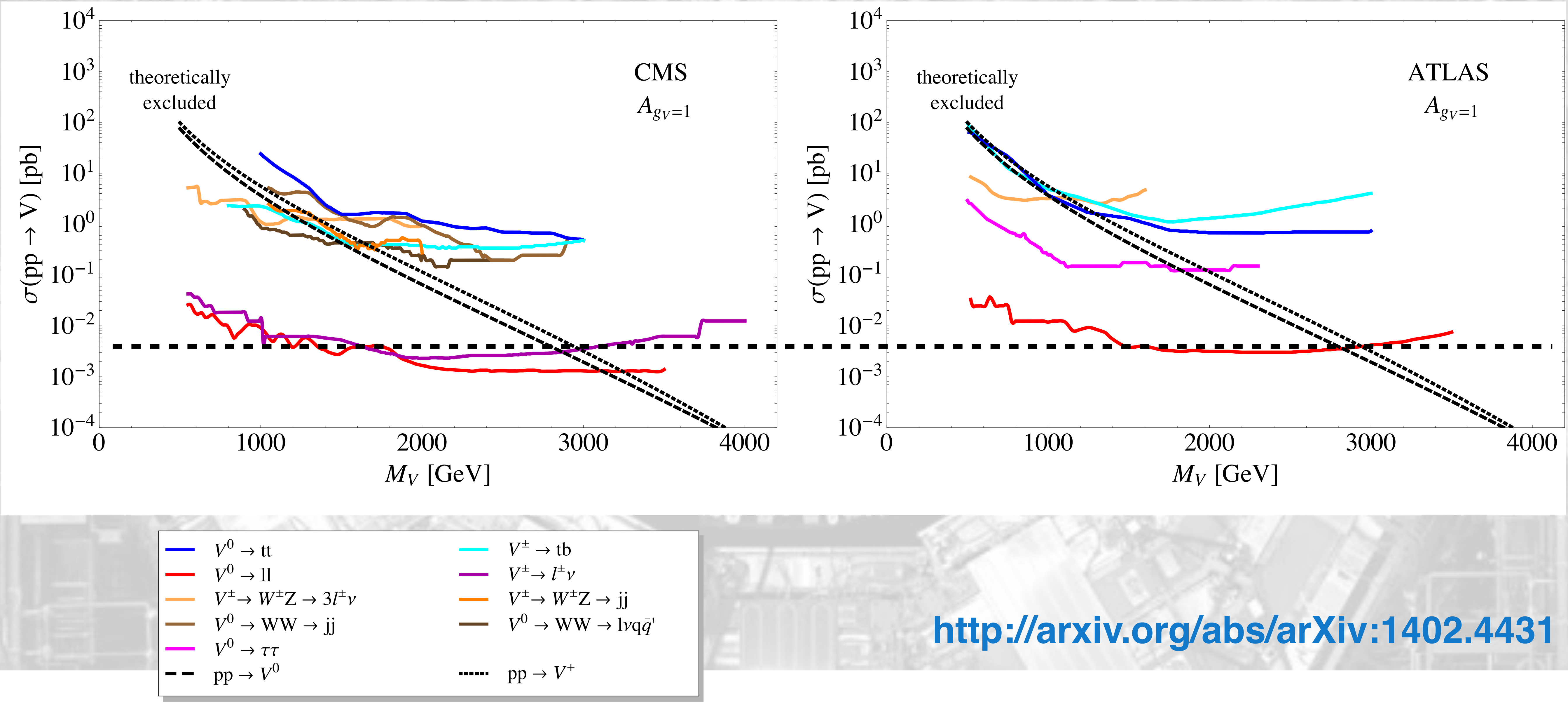






Dilepton Search

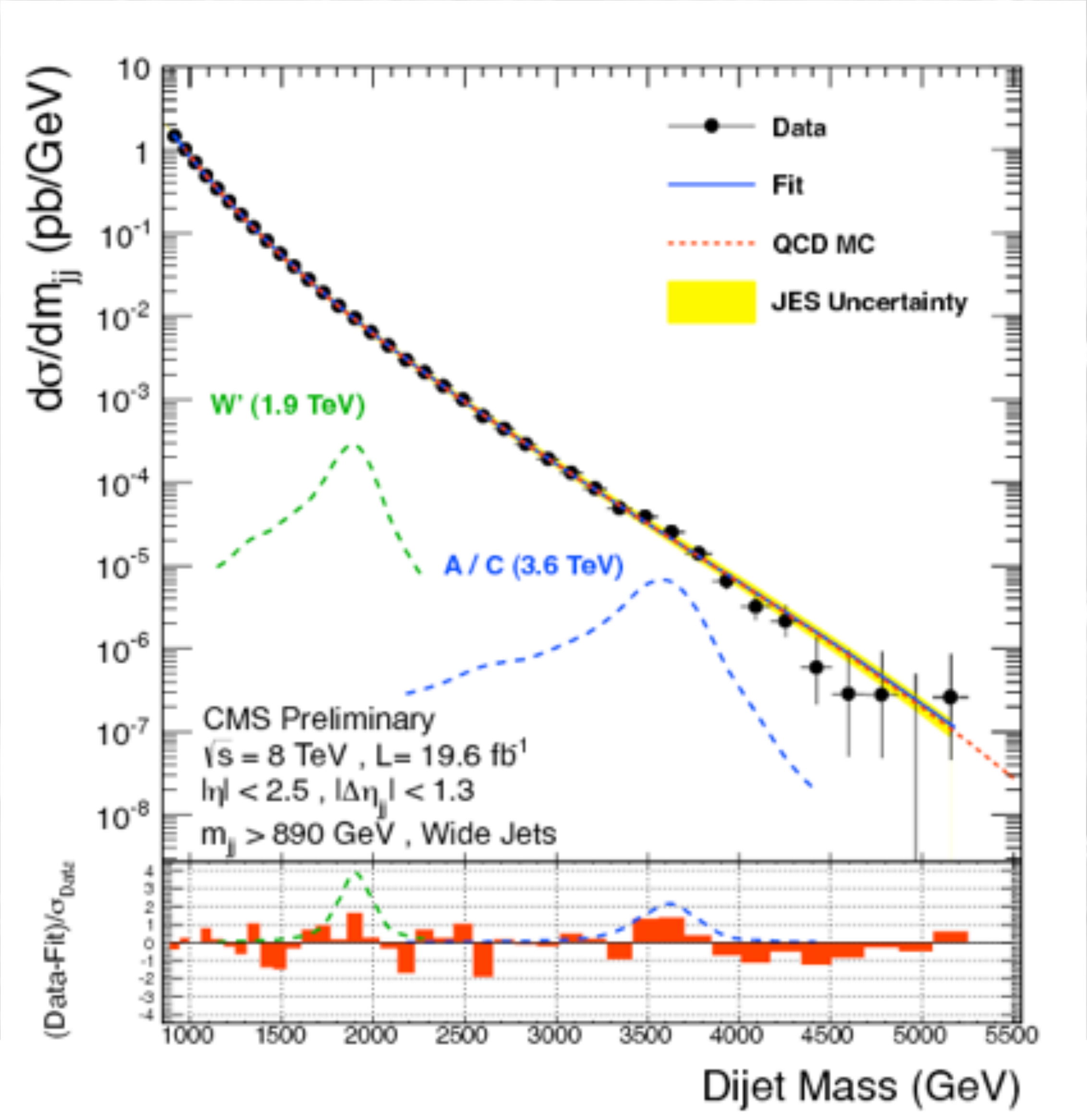
- Despite what it might look like, no contradiction here
  - Same limit at ~ 1800 GeV
  - CMS expected a better limit, but sees a ~2s excess
  - ATLAS did not expect to exclude below the observed limit

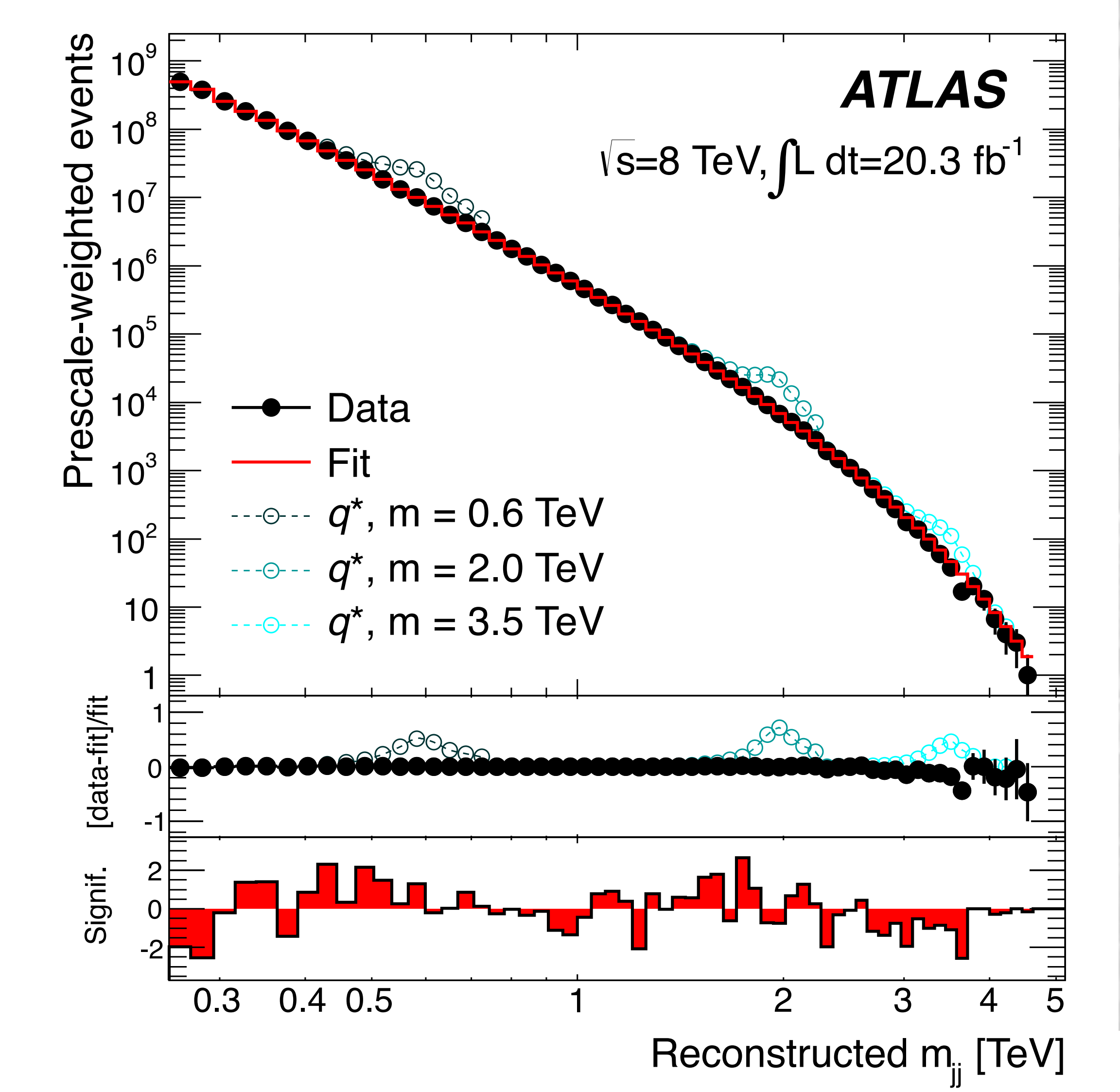


http://arxiv.org/abs/arXiv:1402.4431

Dijet Search

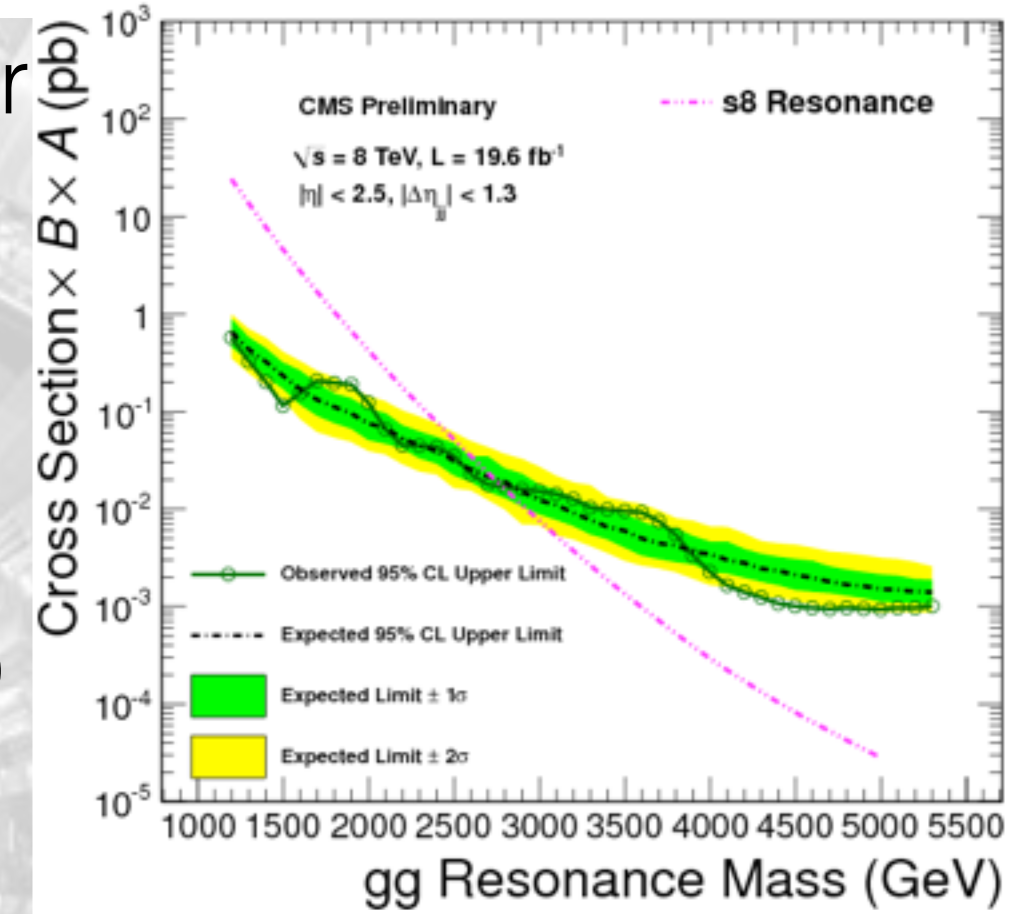
- The fastest search at a hadron collider
  - Parameterize the QCD dijet mass spectrum
  - Look for a bump on the falling spectrum
  - Main challenge from trigger
  - High-pT jets in the final state

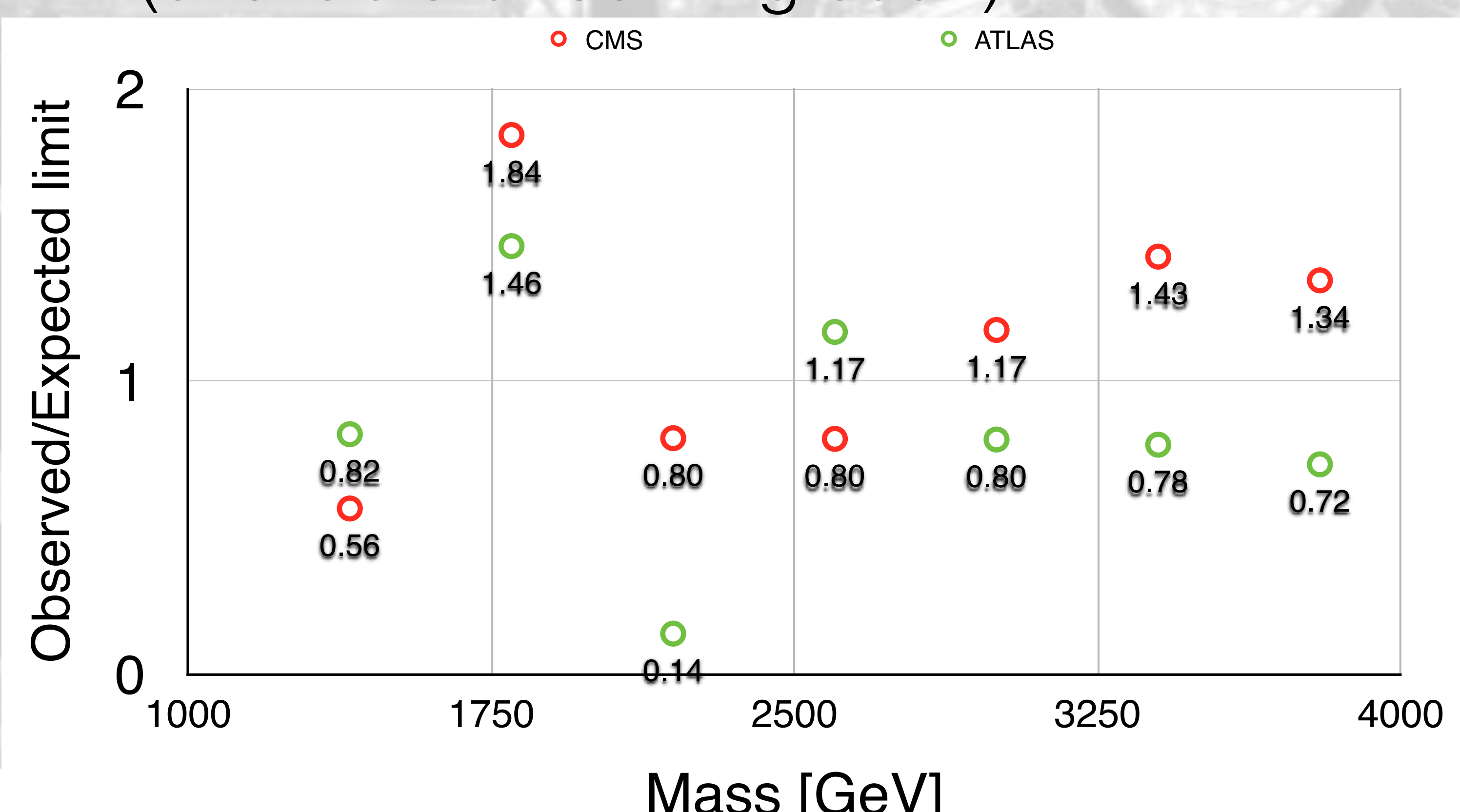


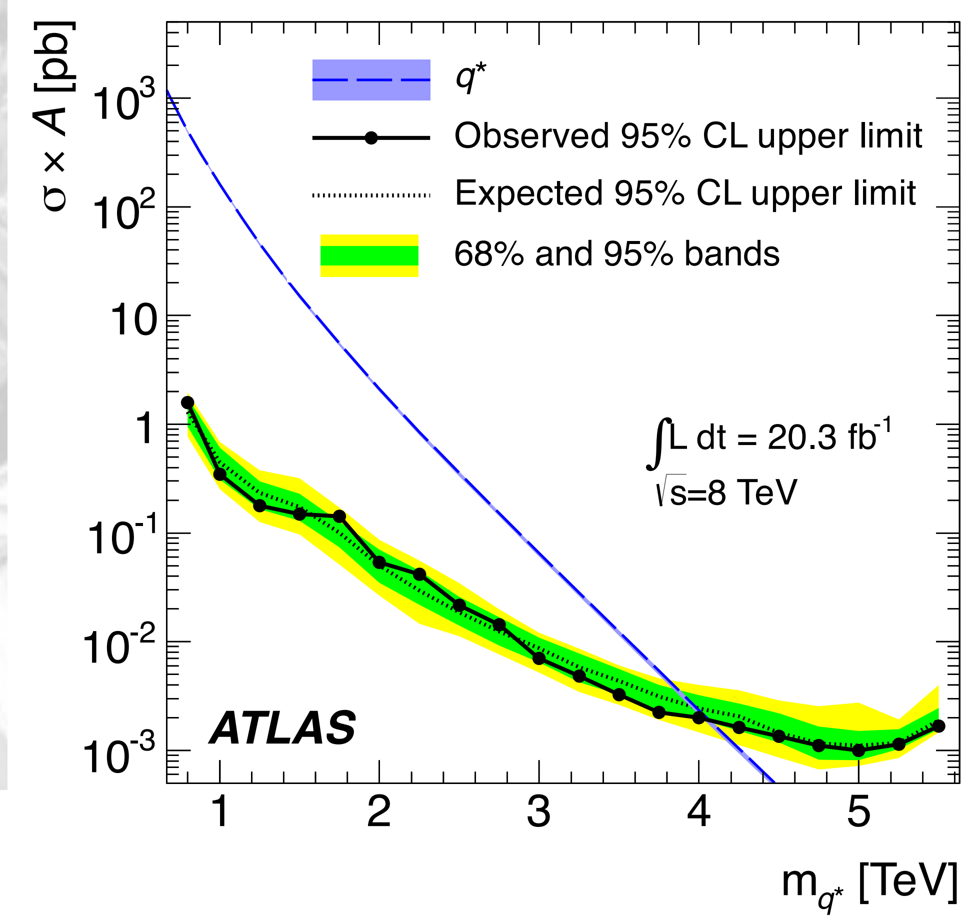


Dijet Search

- The fastest search at a hadron collider
  - No excess observe
  - Result interpreted as 95% exclusion on narrow resonances
  - Result depends on the final state (qq/qg/gg)
  - Also interpretation for broad resonance (available or coming soon)



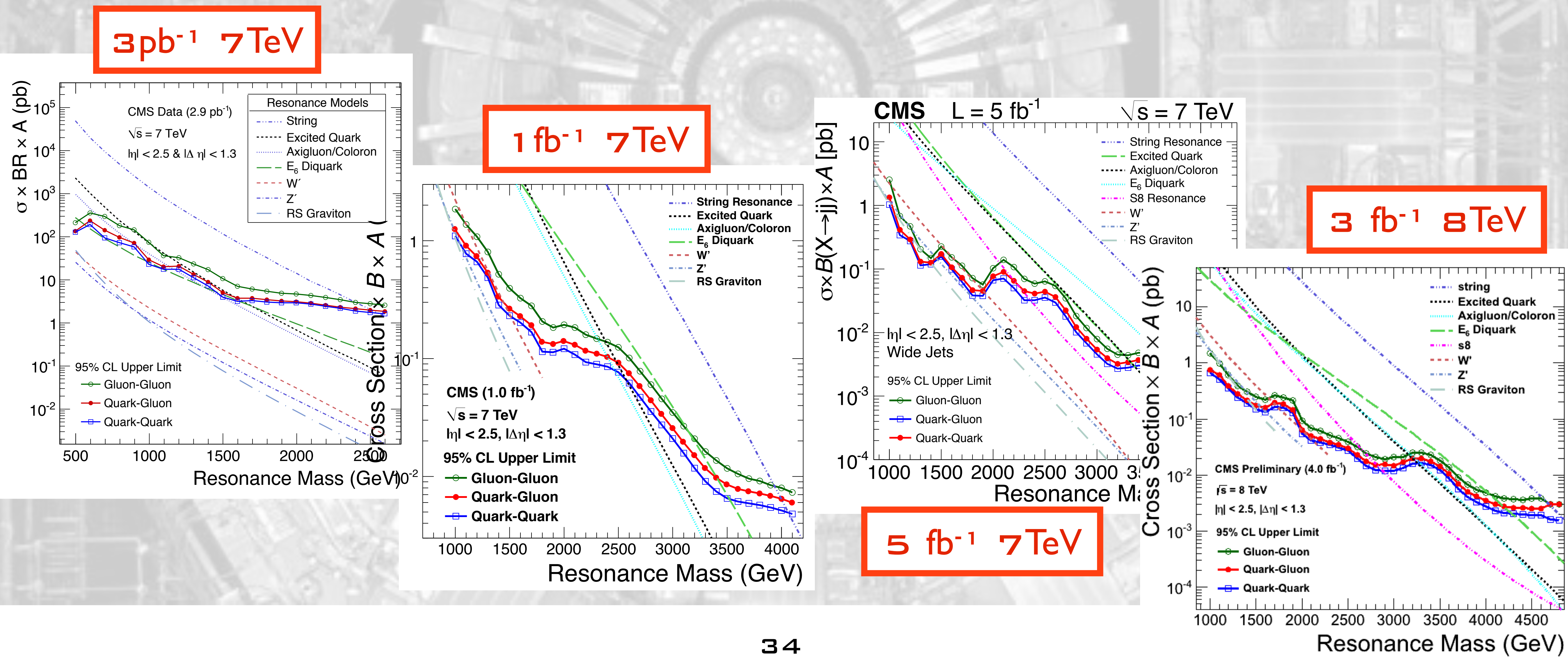




Not Only Heavy Resonances

Blind Spots

- Hadronic searches are limited by trigger & disk space
  - we cannot keep all the events with jets (as almost any event has jets)
  - Loose triggers are used at low-peak luminosity
  - When luminosity increases, the triggers become tighter
  - Combinatoric makes the peak reconstruction more complicated



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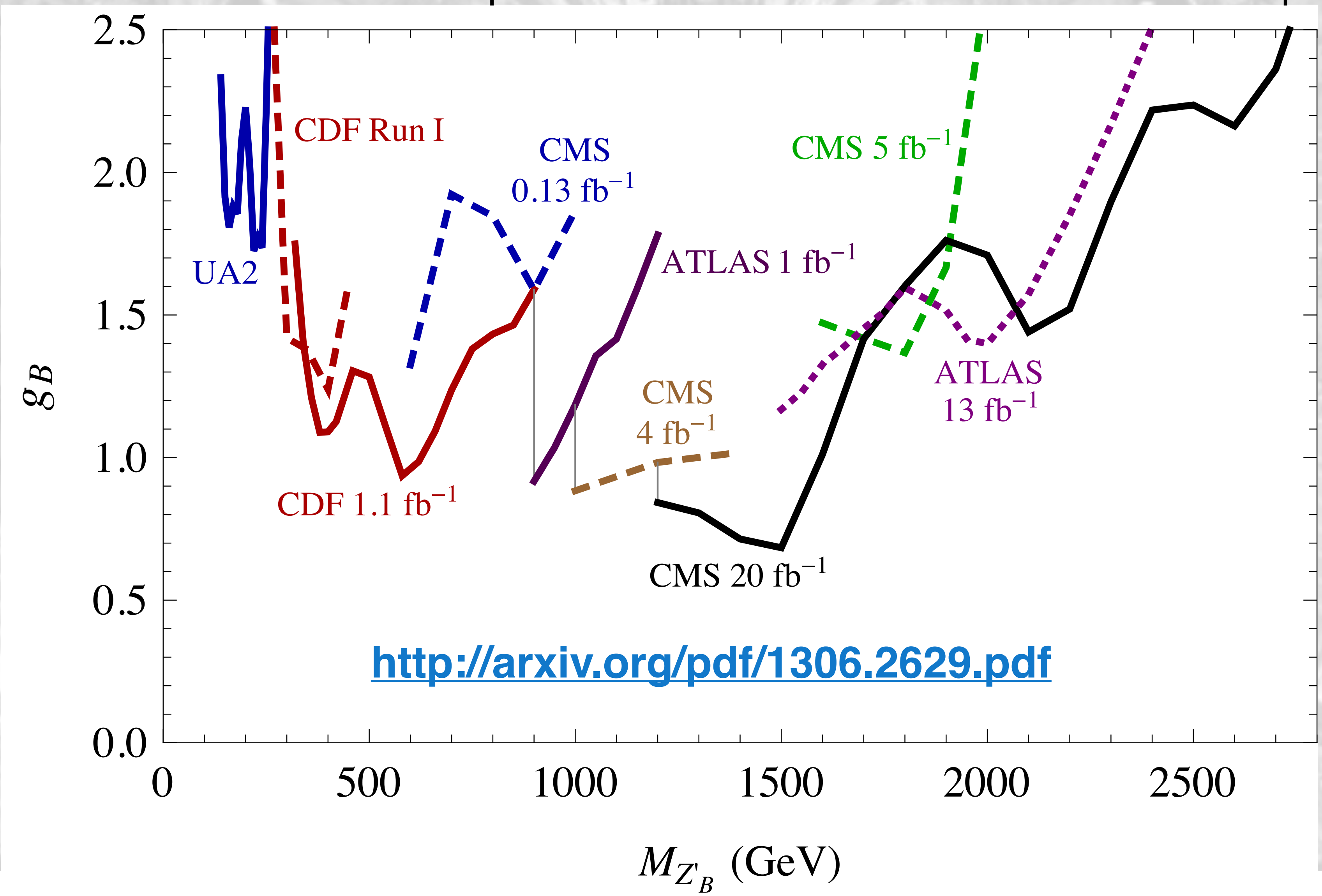
  - Combinatoric makes the peak reconstruction more complicated



Blind Spots

- Hadronic searches are limited by trigger & disk space
  - we cannot keep all the events with jets (as almost any event has jets)
  - Loose triggers are used at low-peak luminosity
  - When luminosity increases, the triggers become tighter
  - Combinatoric makes the peak reconstruction more complicated

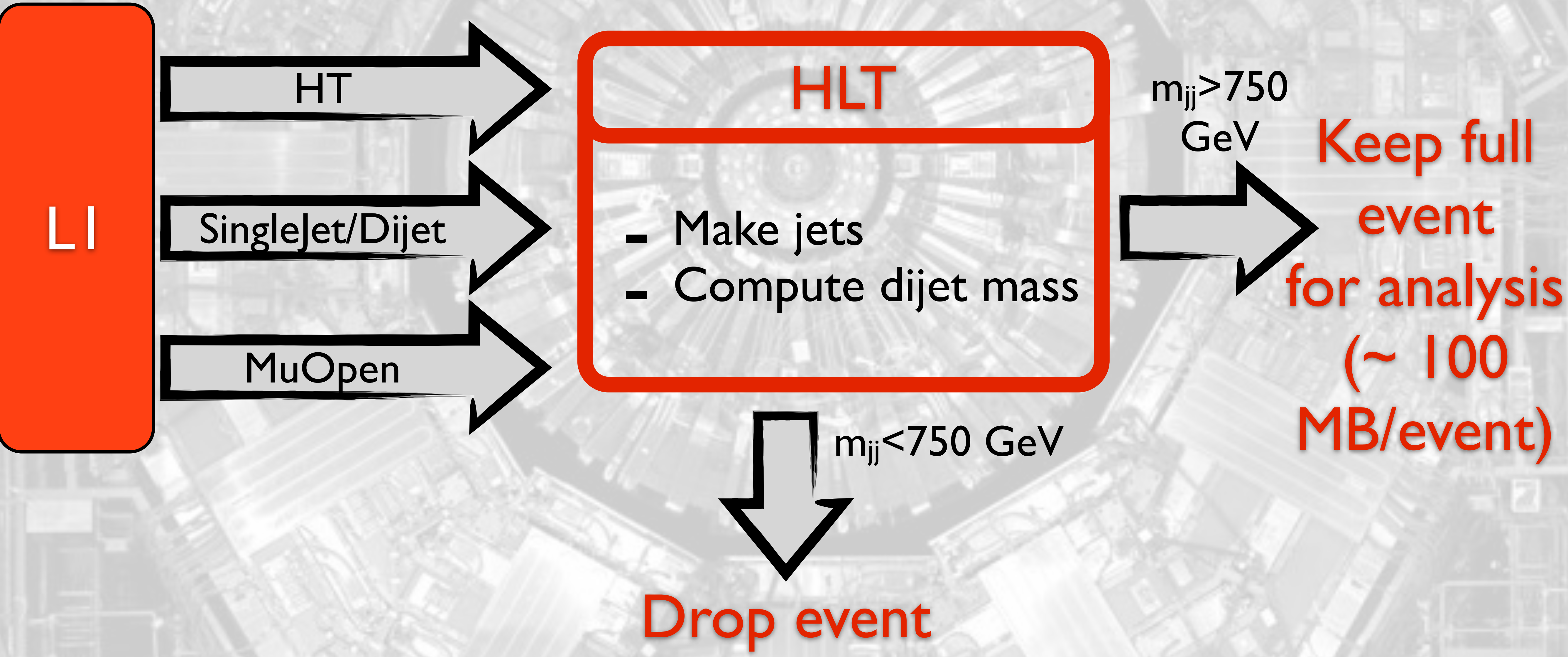
E [	L [	minMass [	σ minMass
7	0.003	400	~ 200
7	1	900	~ 1
7	5	1000	~ 1
8	3	1000	~ 0.6

Unexplored territory left behind with increasing luminosity

Standard Data Taking

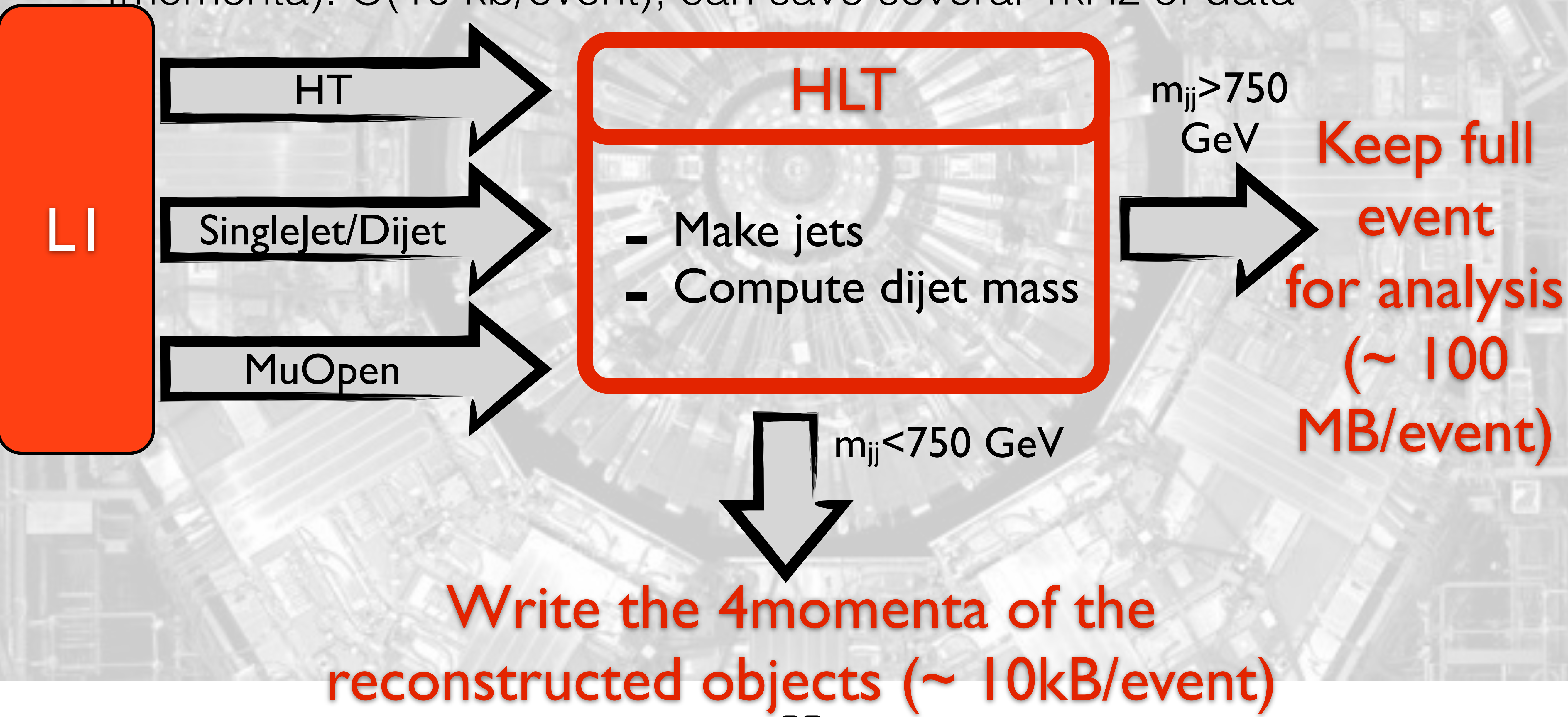
- The moment we drop the event, we know everything about it (jet momenta, MET, maybe lepton momenta) with a coarser precision than offline (faster reconstruction →less precise reconstruction)

- When we access the event for analysis, sometimes we need a small part of this information (e.g., dijet search only needs dijet 4momenta)

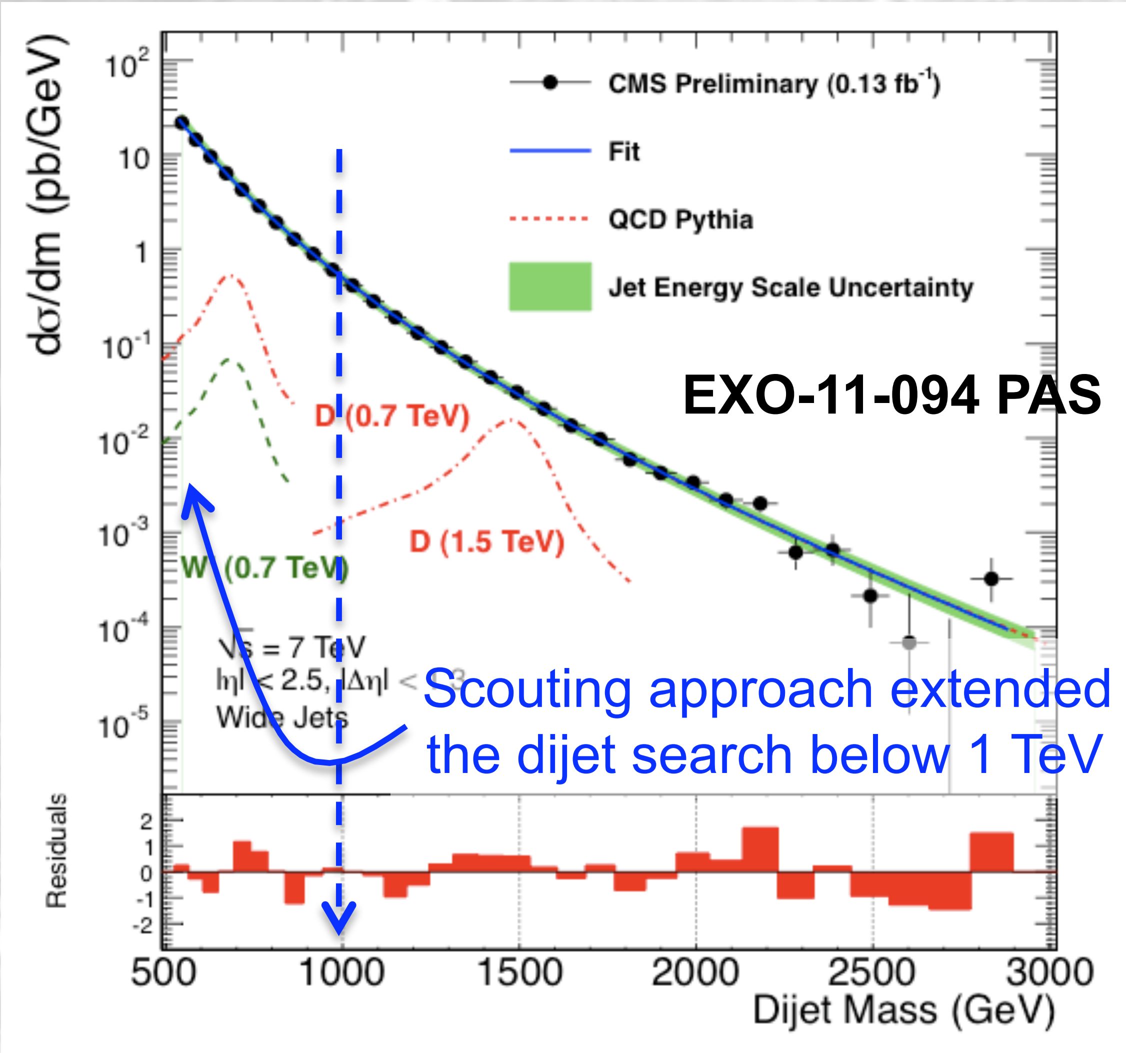


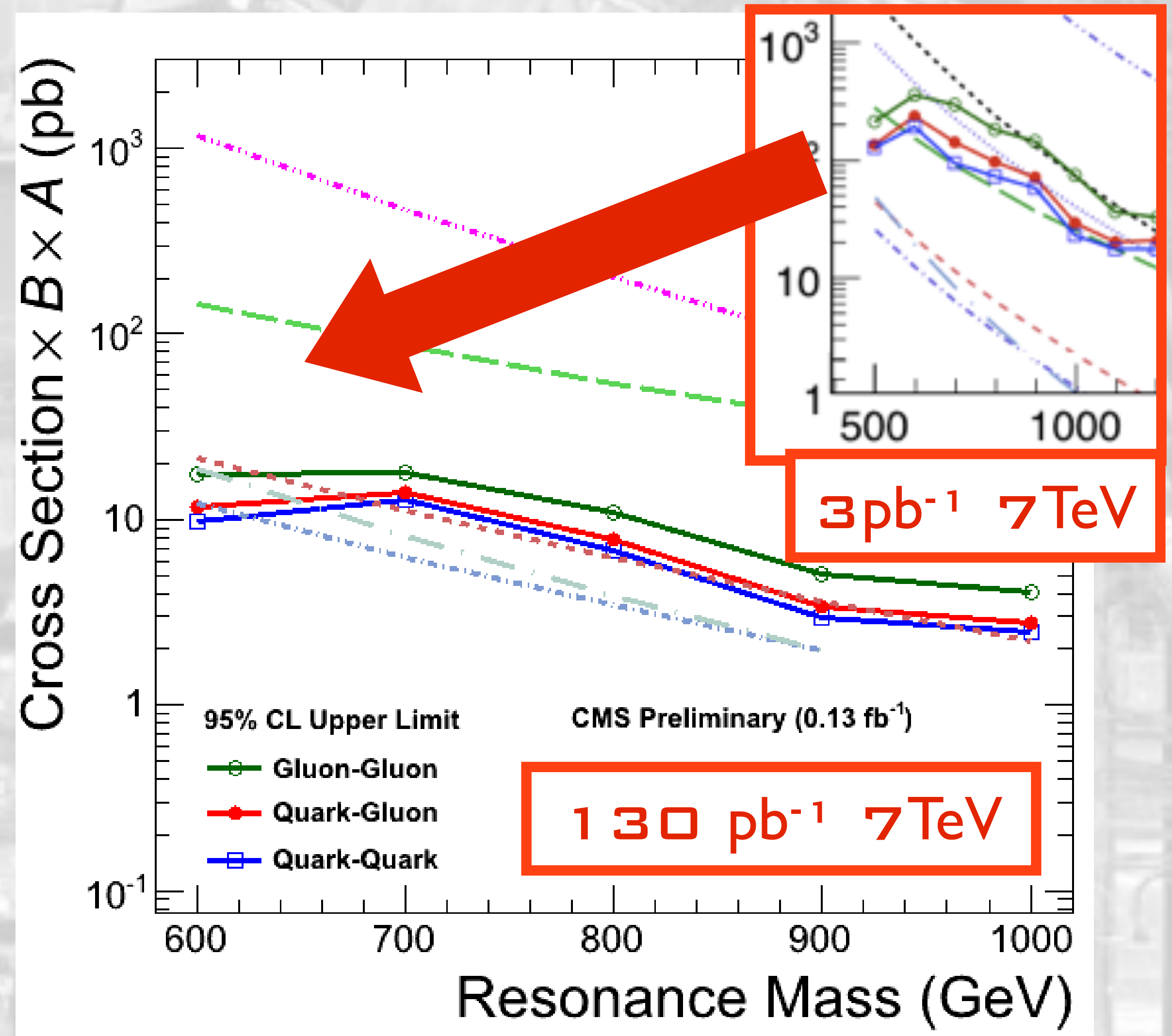
Data Scouting

- We don't save events because we cannot write them on disk
- We write on disk more event information that we (sometimes) need
- Keep ALL the events, with a small customised data format (only jet 4momenta). O(10 kb/event), can save several 1kHz of data



The Dijet Data Scouting





- 16 hour Run at the end of 2011 run (7TeV)
- Collected ~4 times the statistics we had in 2010 (35 pb^{-1}) with equivalent trigger
- Improved the limit published in 2010 by one order of magnitude
- 18 fb^{-1} results@8TeV to be released soon

Conclusions

- The search for heavy resonances has been a productive front during Run I
- Ingredients are in place for Run II
  - high-pT object reconstruction
  - Jet substructure
- Despite the large pT regime, pileup was an issue (e.g. for substructure) and this will be worse. We are getting ready for that
- Interesting to look at with first few fb^{-1} (a few 2σ excesses around m_X~1800 GeV)
- Keeping open eyes on low-mass regime too (e.g. improving data scouting)

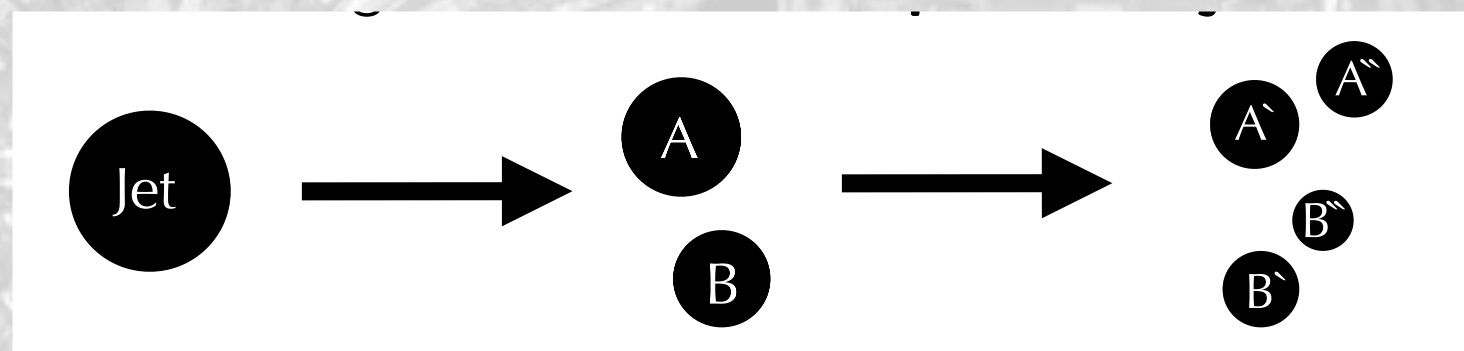

Backup Slides

Top Tagger: TypeI top

CMS-PAS-B2G-12-005

Reconstruct fully hadronic top quarks merging into one jet

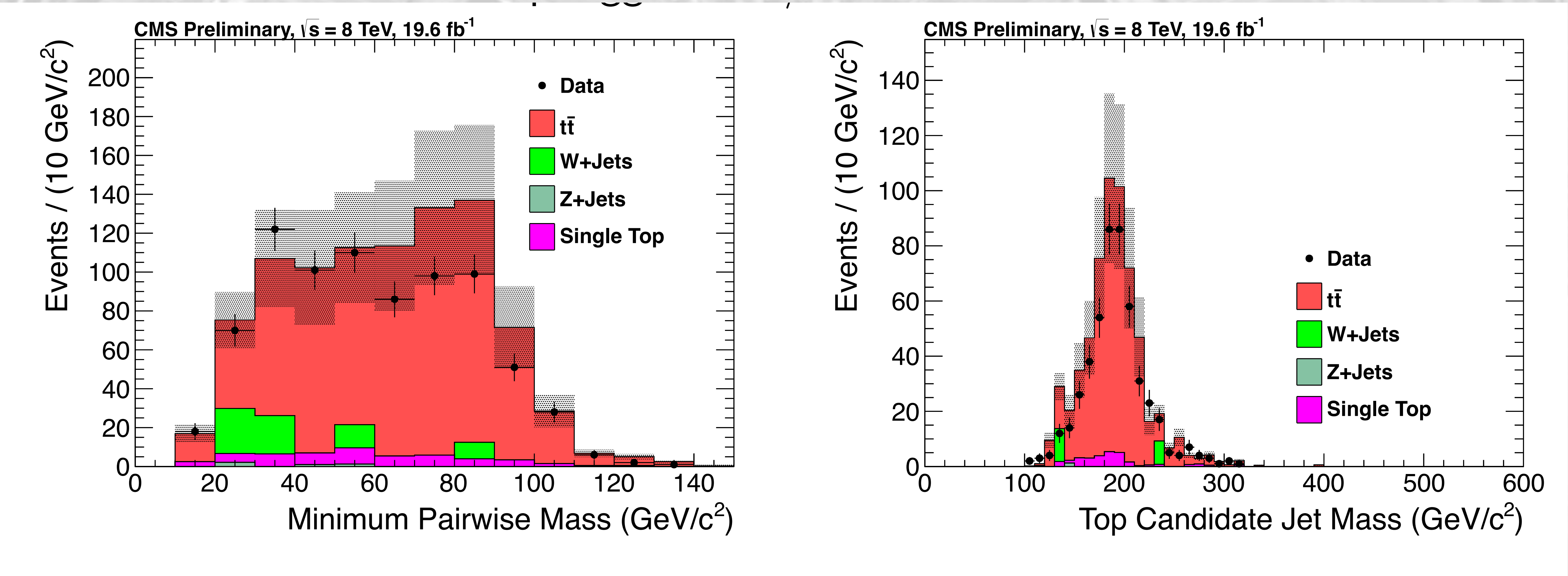
- Start from CA jet with R=0.8 and pT>400 GeV
- Decluster in two stages to identify up to 4 jets



- Remove jets failing requirements and iterate { subjet pT > 5% jet pT; Adjacency: $\Delta R(C1,C2) > 0.4 - 0.0004\ pT(C)$ }
- Apply requirements on jet mass (compatible to mtop) and minimum subjet pair mass (compatible to W)

Top Tagger: TypeI top

- Use semileptonic tt events: 1lep+1b (tag) and 1 CA jet (probe)
- Compare the tagging performances data vs MC



Mmin (W candidate in top jet) top mass (for Mmin>50 GeV)

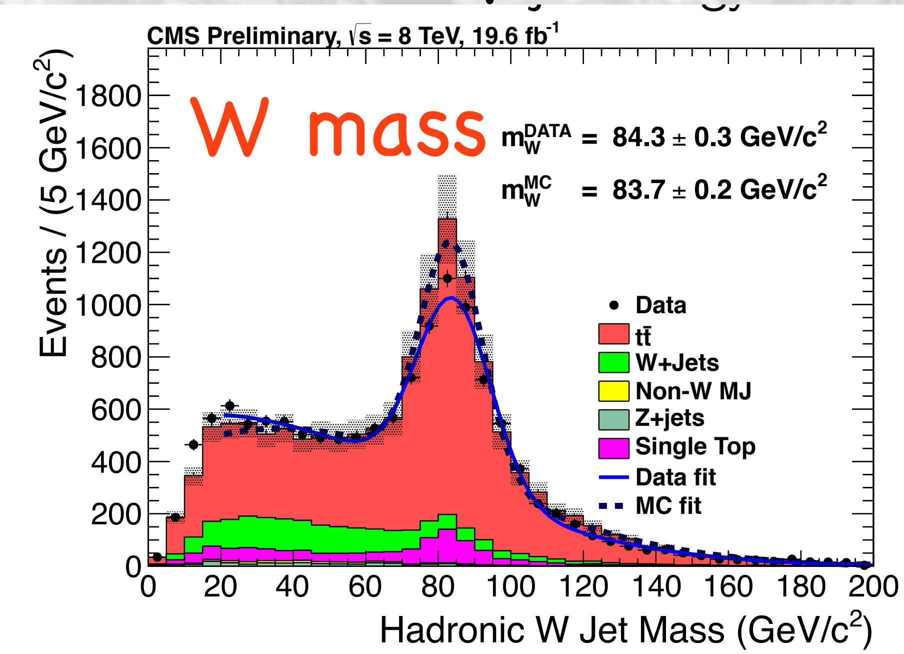
- Data / MC = 0.94±0.03 (Gray area shows the normalization uncertainty)

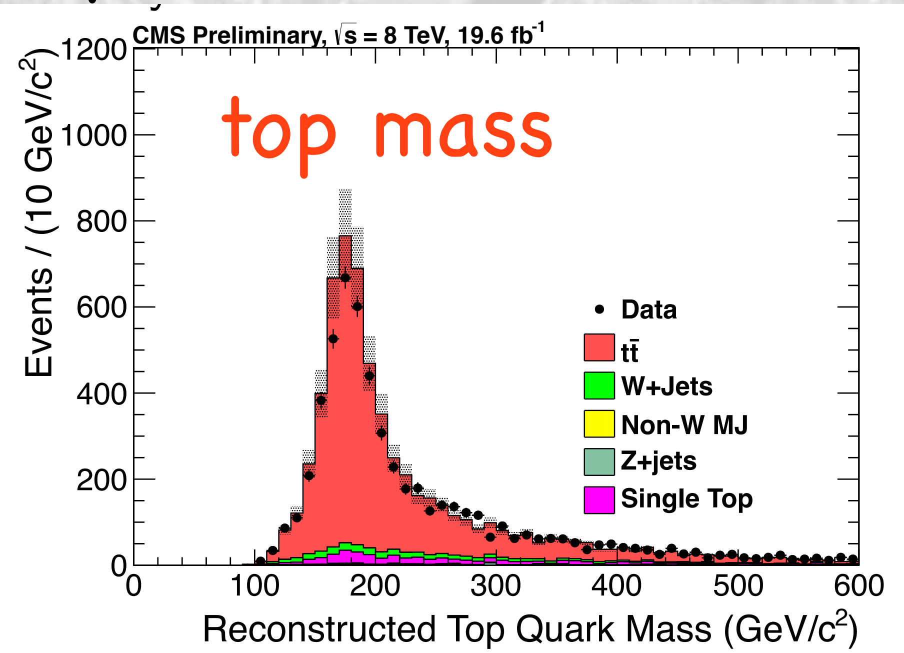
Top Tagger: TypeII top

CMS-PAS-B2G-12-005

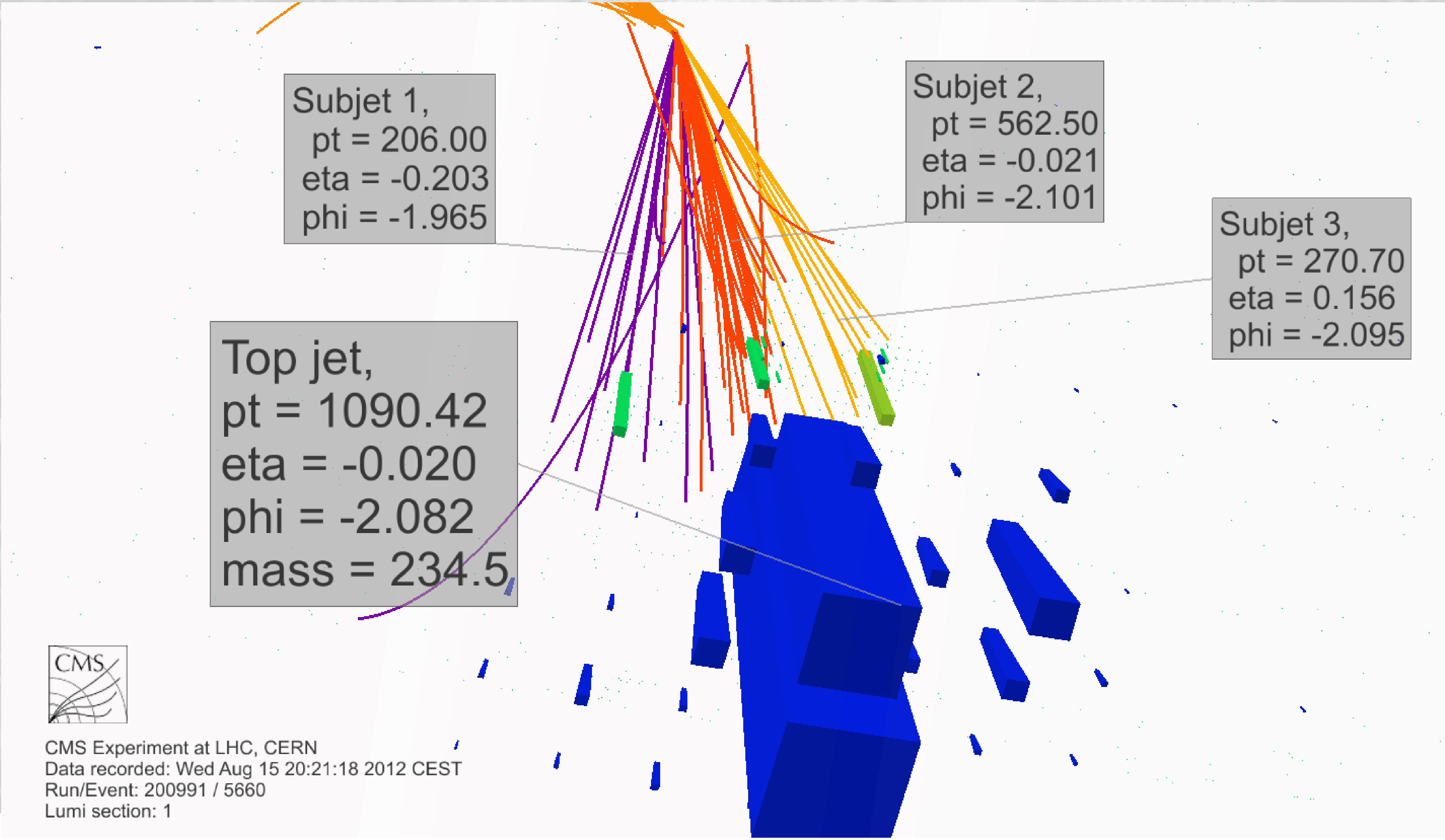
Reconstruct fully hadronic top quarks as one b jet and one merged-W jet

- Using V tagger for the W (as described before)
- Reconstruct the top adding W 4momentum to a close jet (no btag applied)
- Validate the technique with semileptonic ttbar



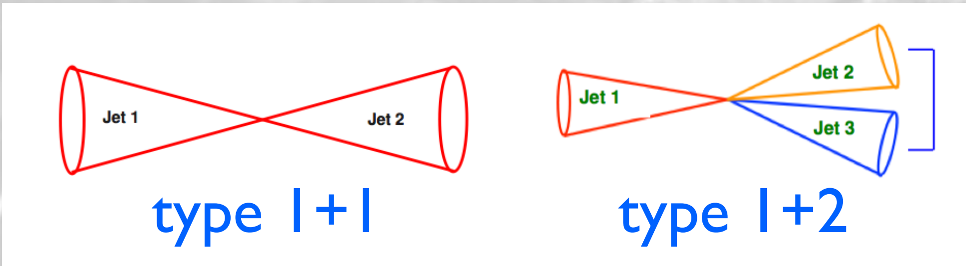


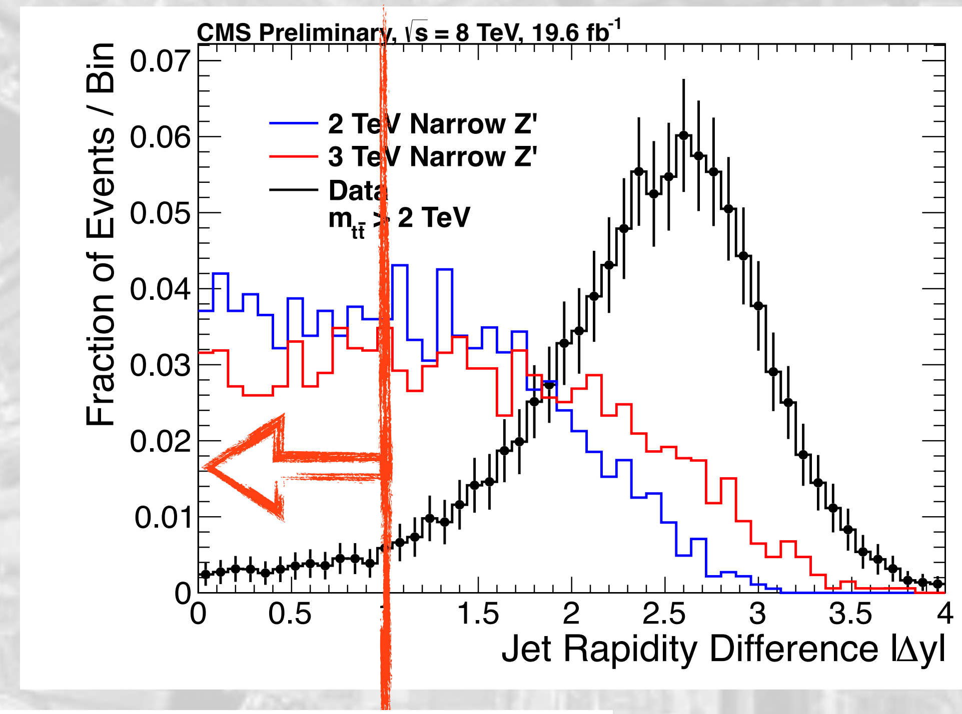
What We top-Tag



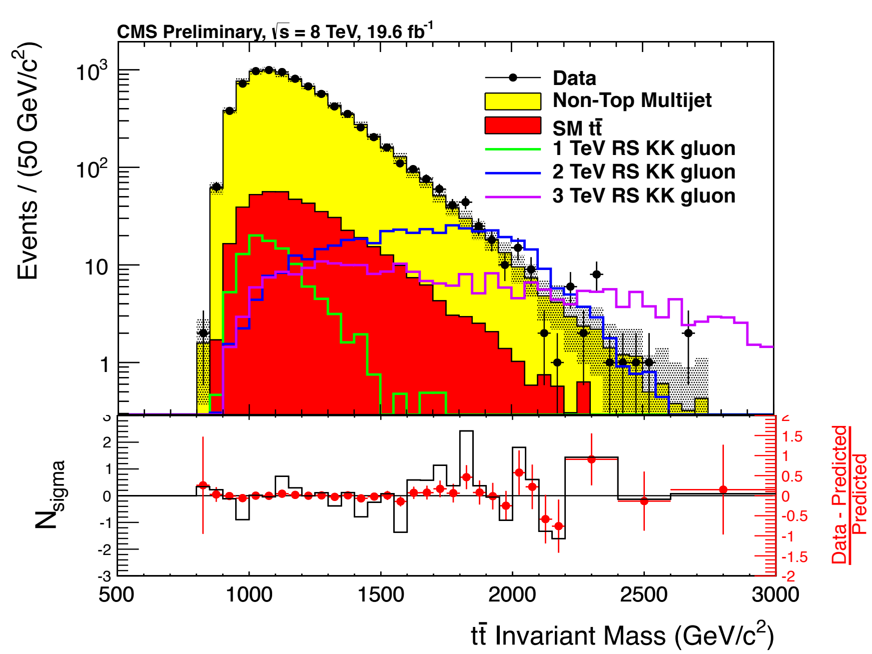
Fully Hadronic Z'→tt

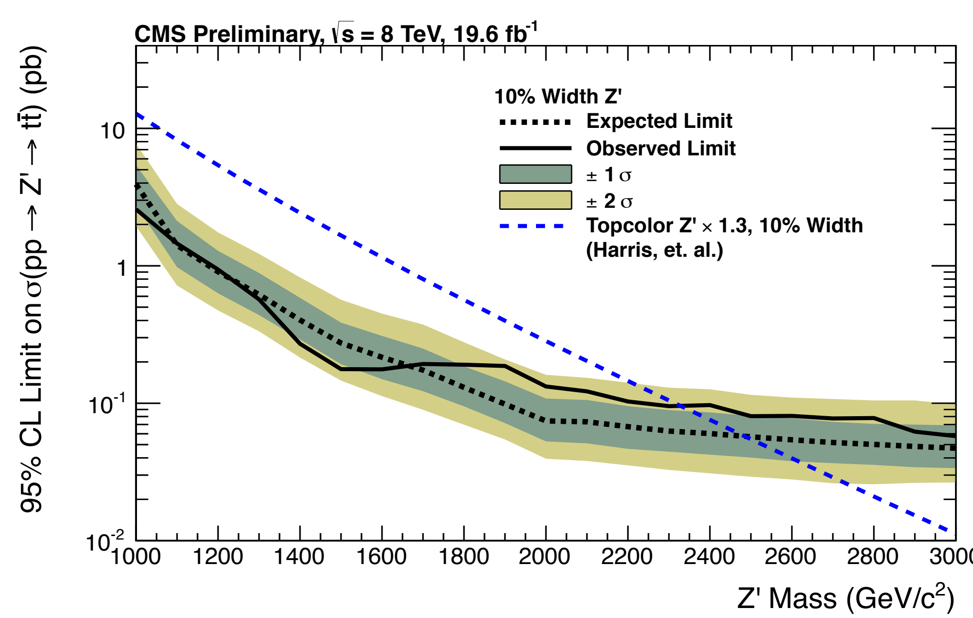
- Consider two event topologies: type-I + type I or type-I + type-II





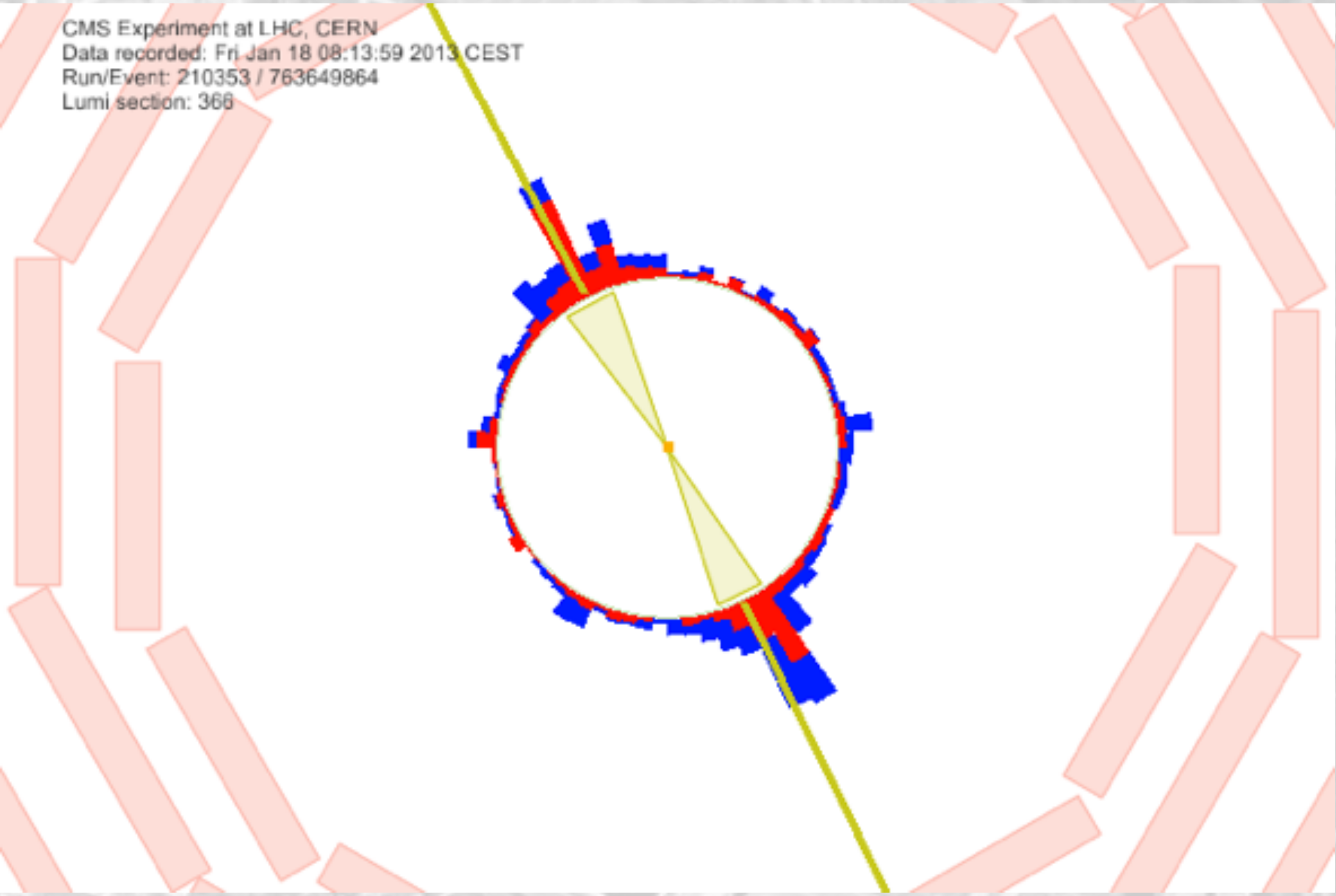
- Select events by jet-rapidity difference
- Study the ditop mass spectrum, looking for a bump on a falling spectrum





What we mean by jet

- The concept of a jet is intuitive
  - A quark or gluon is produced
  - It showers other quarks and gluons
  - The quarks hadronize to hadrons
  - Because of momentum conservation, the hadrons are close to the original parton



- We then imagine a jet as a cone around the parton
- But QCD is not geometry
  - **How many jets do you see?**

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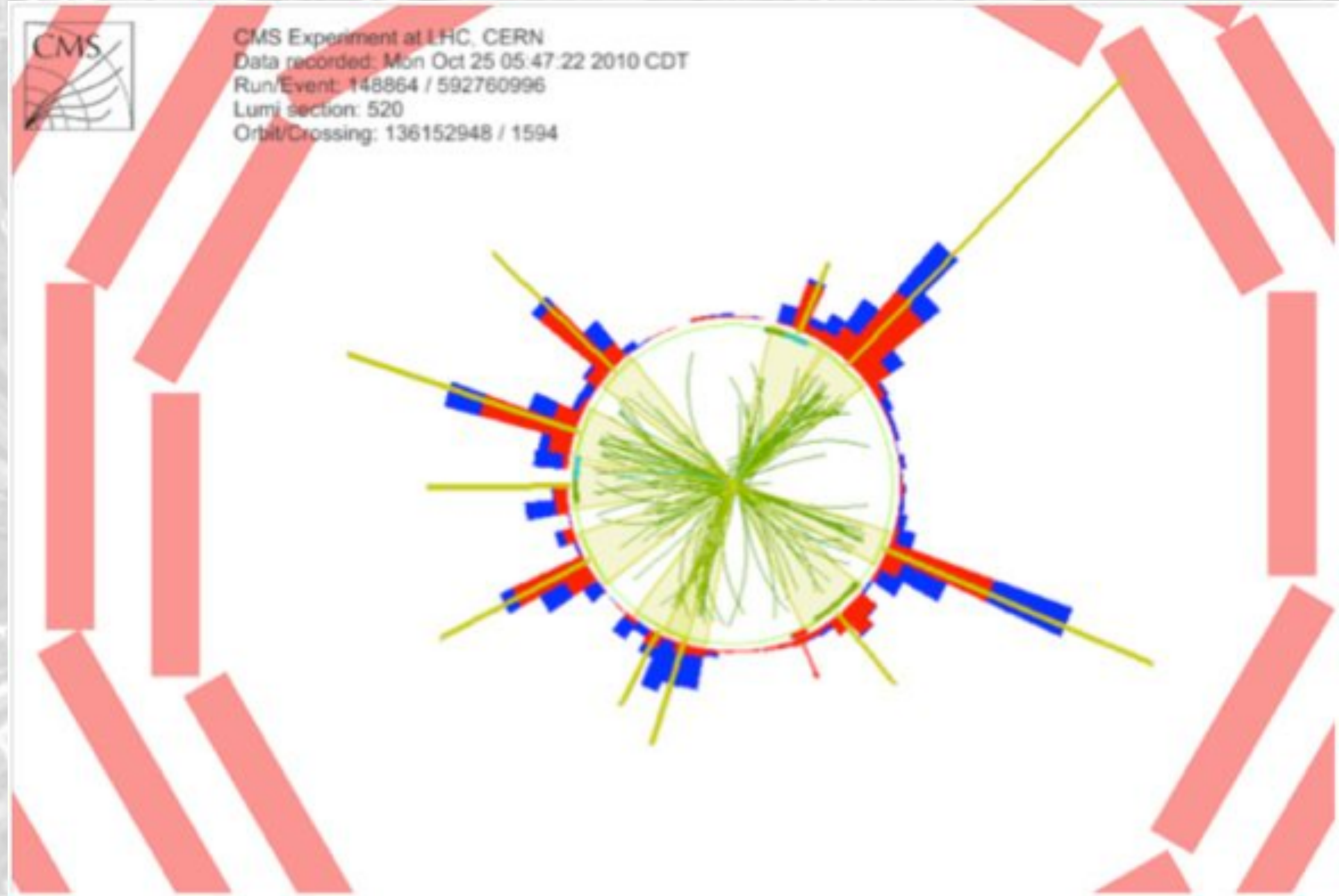

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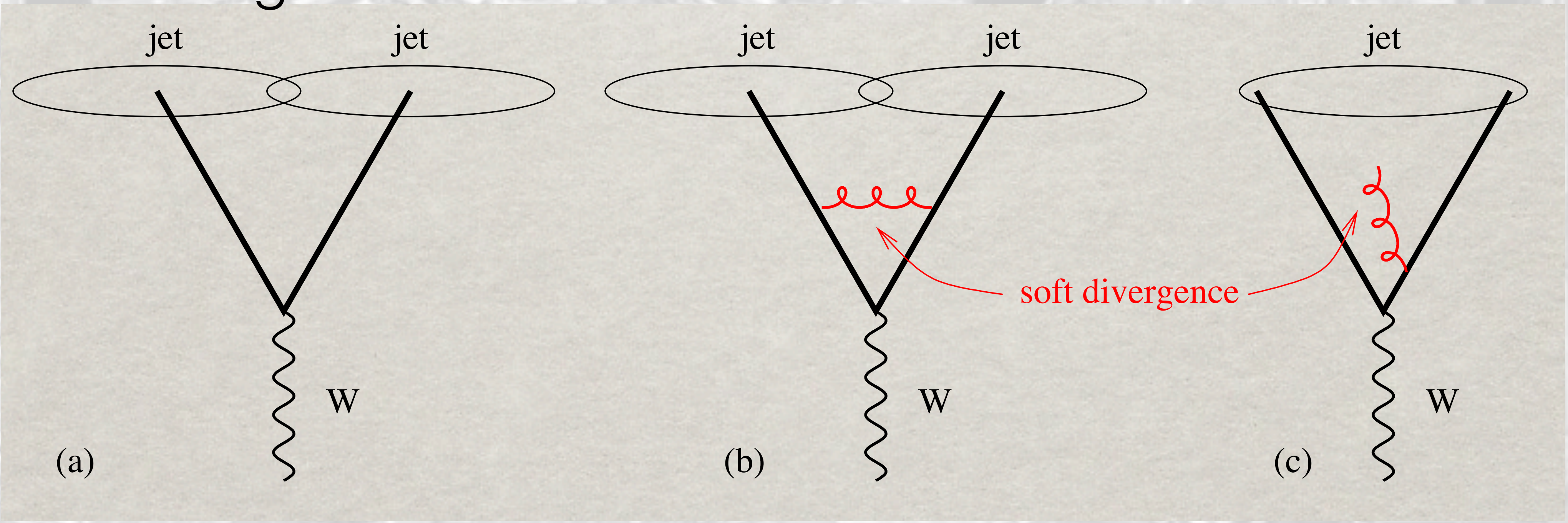
More than a cone

- For some time, cone algorithms were used to reconstruct jets
- This created problems to compute QCD processes (e.g., differential cross section vs jet pT). The number of reconstructed jets was fragile vs. soft divergences
- Several solutions proposed in literature
  - kT algorithm
  - Cambridge-Aachen algorithm
  - Siscone
  - Anti-kT



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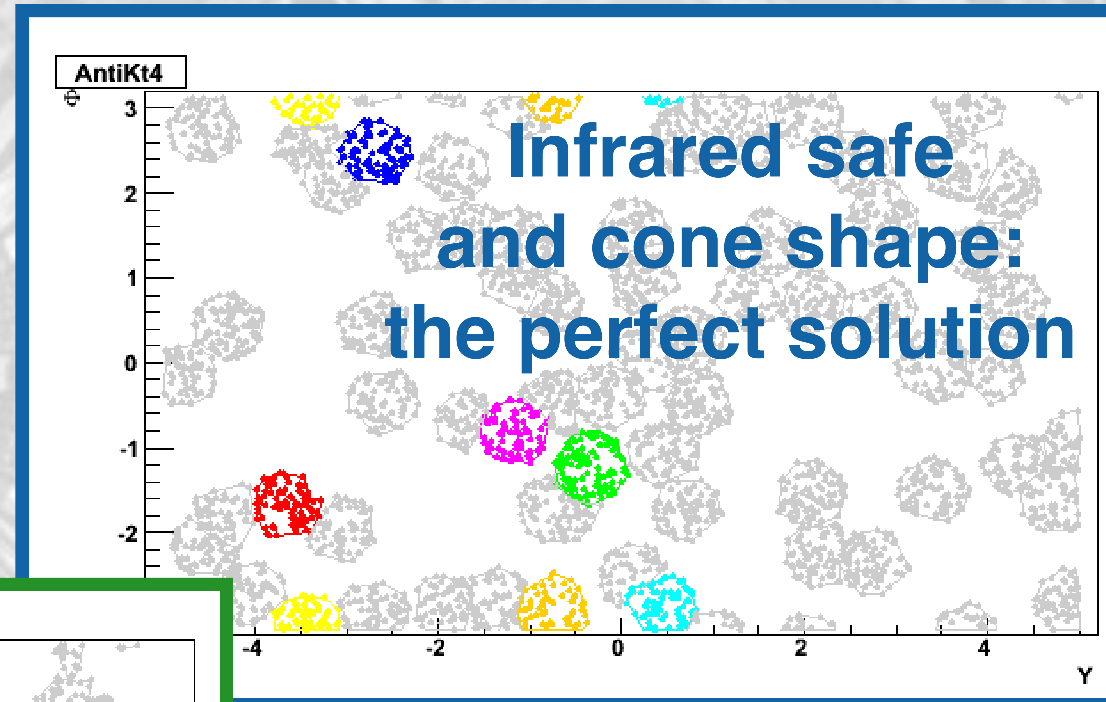
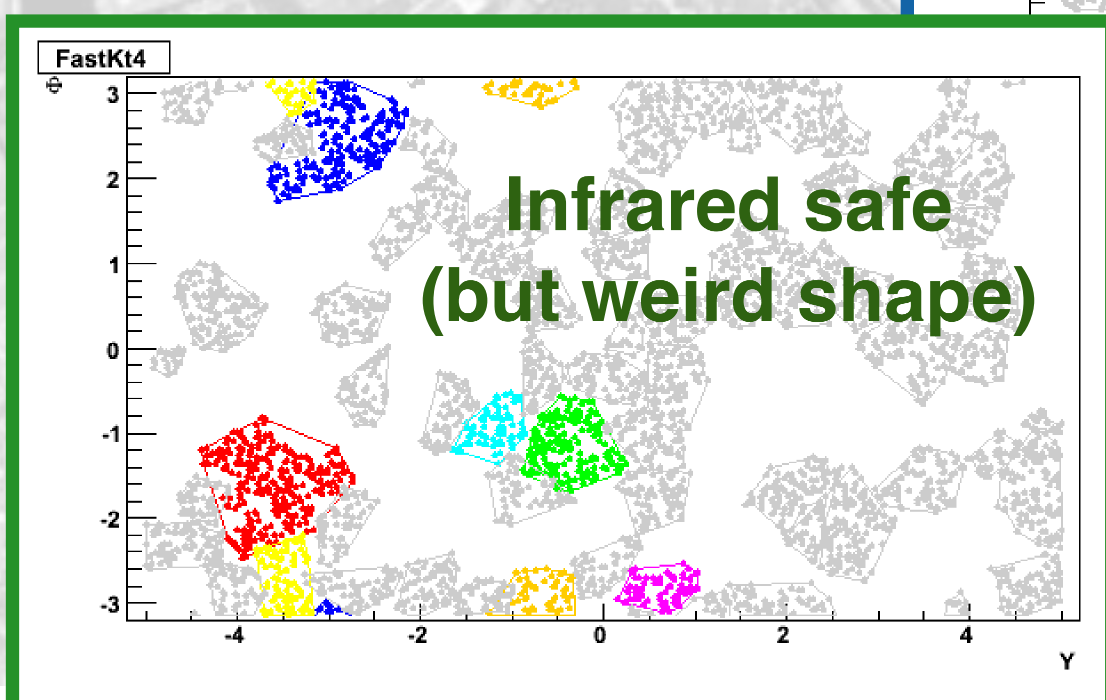
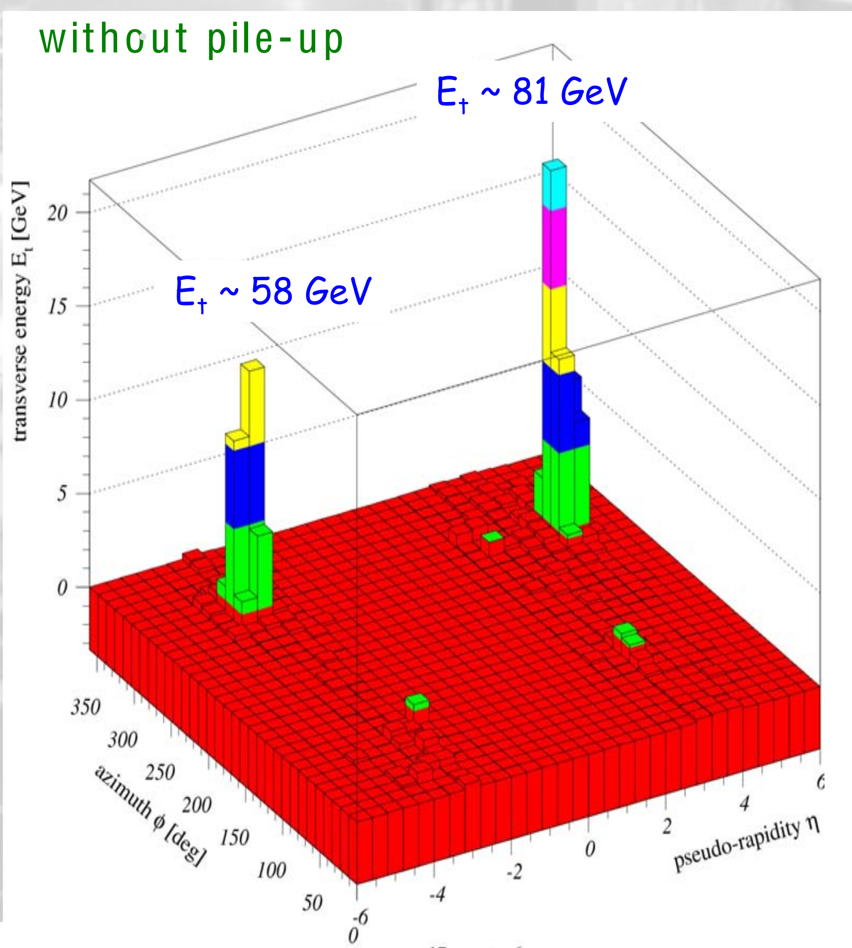
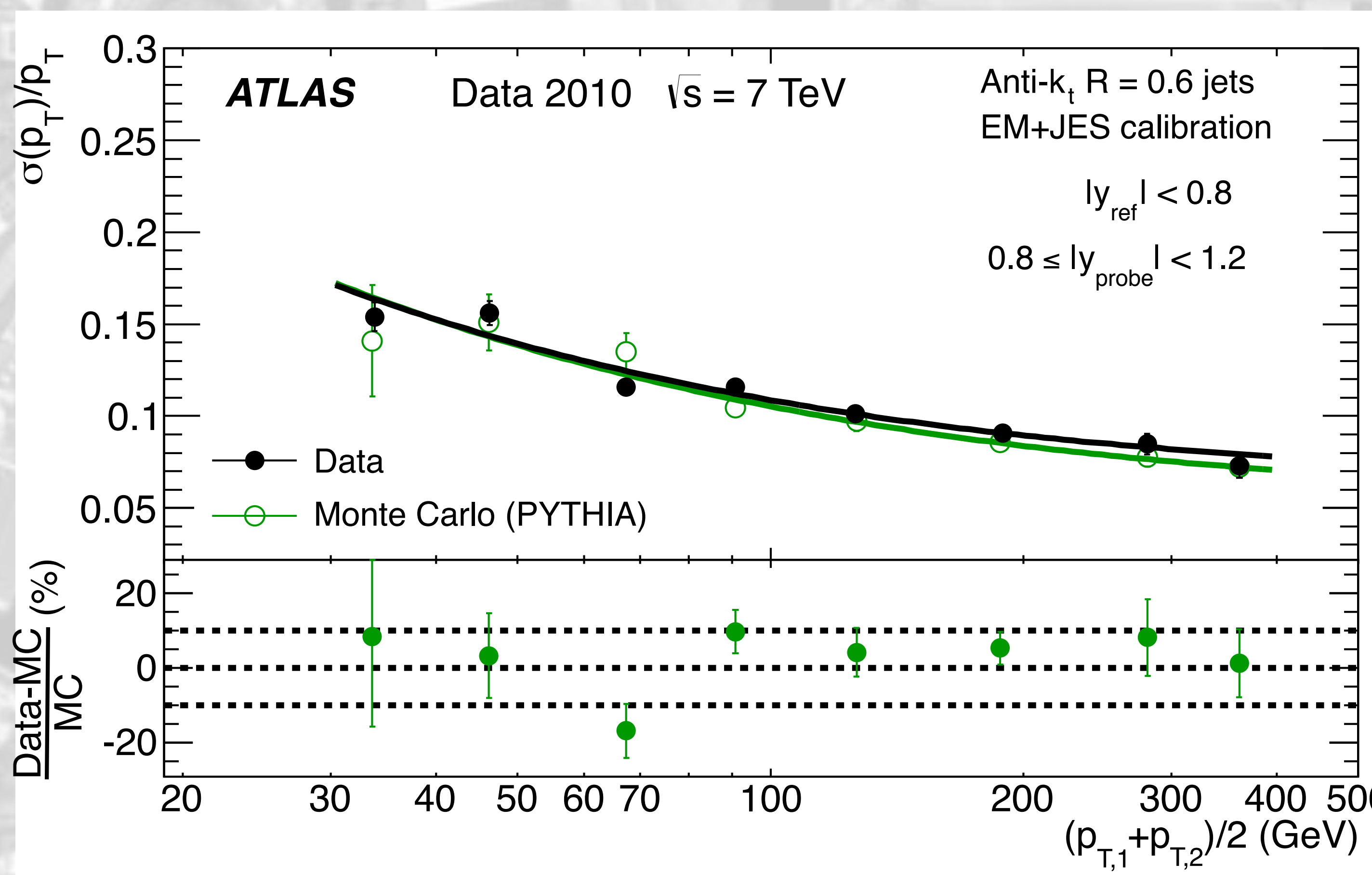




Jets of What?

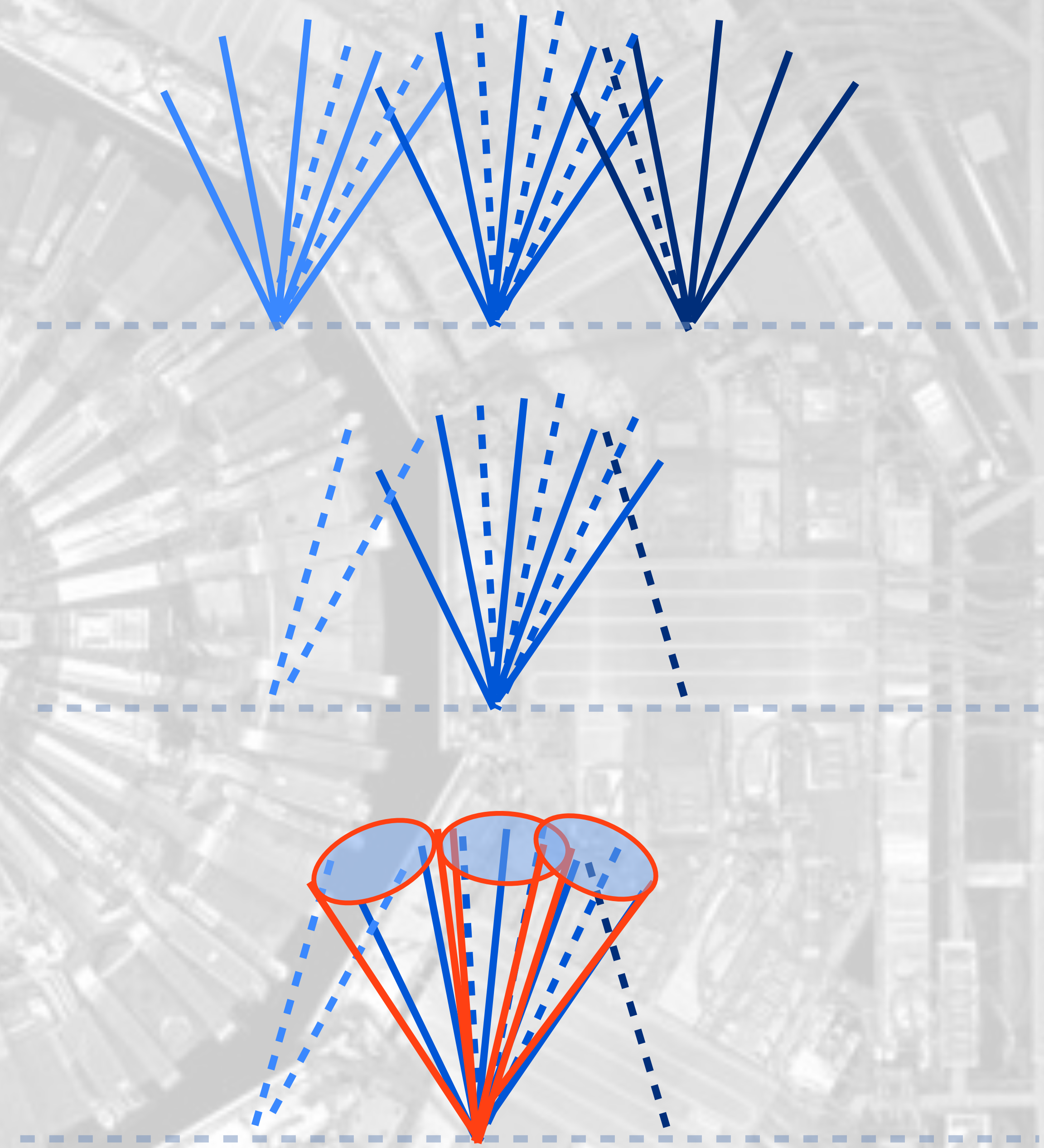
- Historically, jets are made putting together energy deposits in the calorimeter
    - Deposits in ECAL and HCAL are put together into clusters
    - clusters are made into jets using a jet algorithm
- Good technique, as long as
    - the calorimeter has the dept to contain the shower
    - the energy resolution is good for both ECAL and HCAL (as in ATLAS)





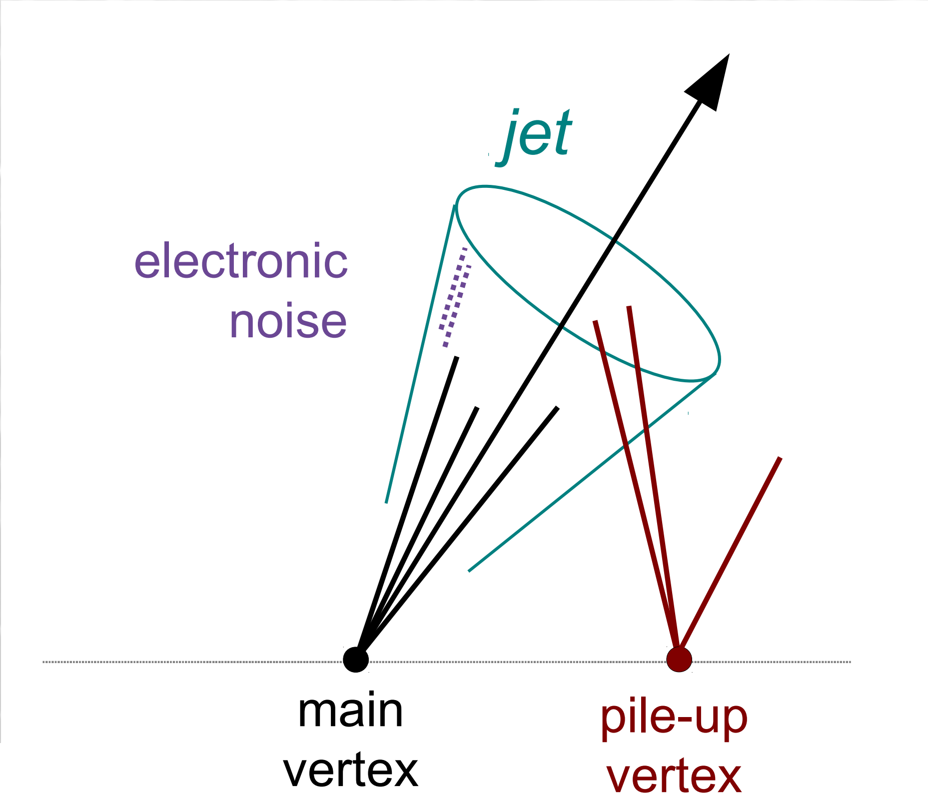
Charge Hadron Subtraction

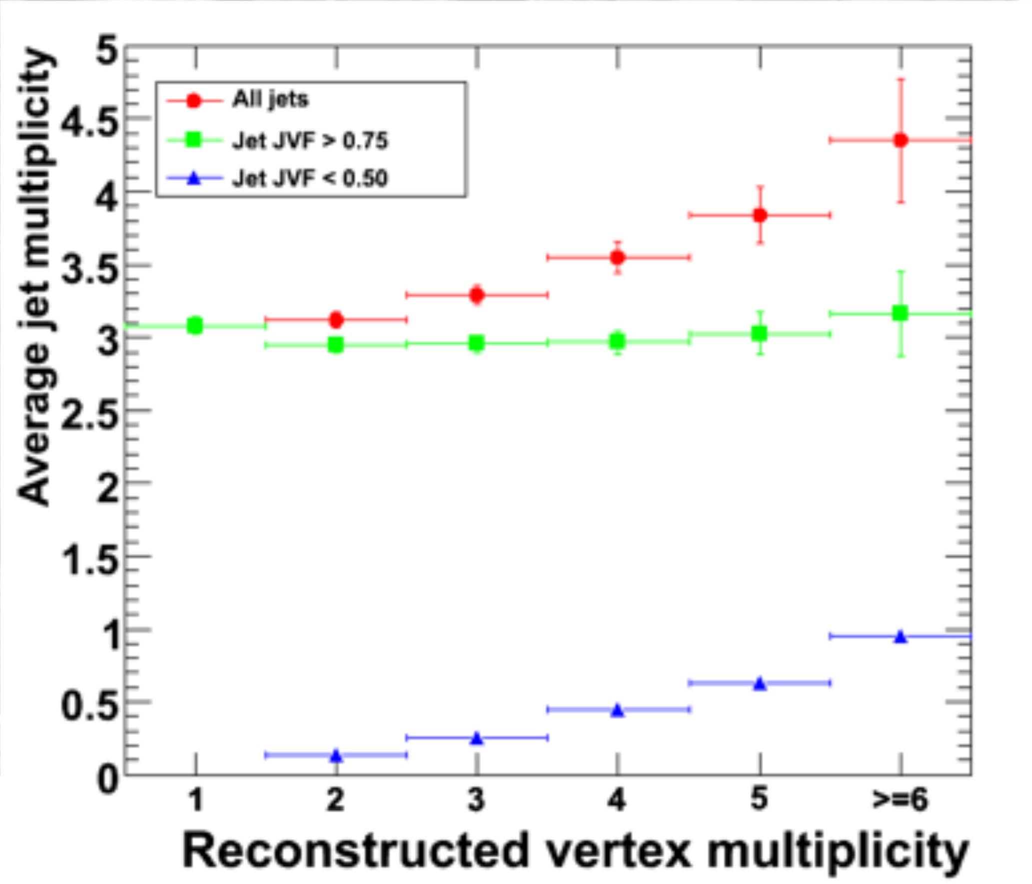
- We know where charged particles come from
  - we can reconstruct vertices from tracks
  - for each track, we know the vertex it comes from
  - For an event, we know (usually) which is the "interesting" vertex (highest associated energy) which triggered the event
- It is then easier to remove the charged hadrons from the wrong vertices, before clustering the jets



Charge Hadron Subtraction

- ATLAS does not use PFJets.
- Tracks vertexing is used to perform CHS a posteriori
  - Identify the tracks inside a jet “cone”
  - Compute the fraction of track momentum coming from the primary vertex
  - If this number is small, the jet is most likely due to pileup and it is rejected





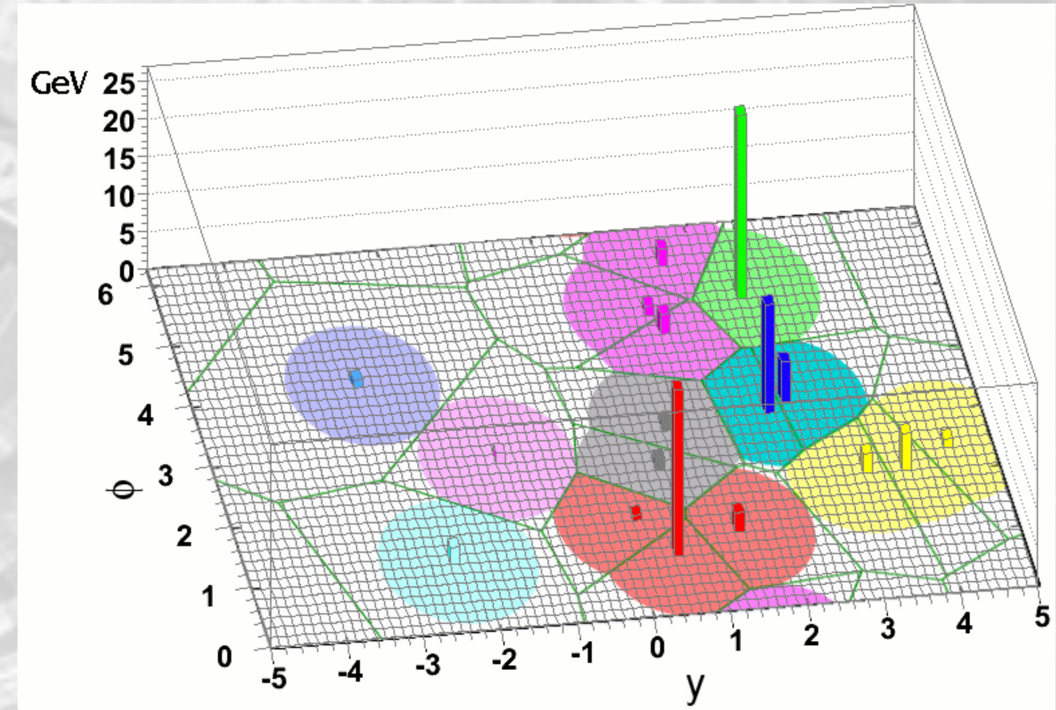
Jet Area Subtraction

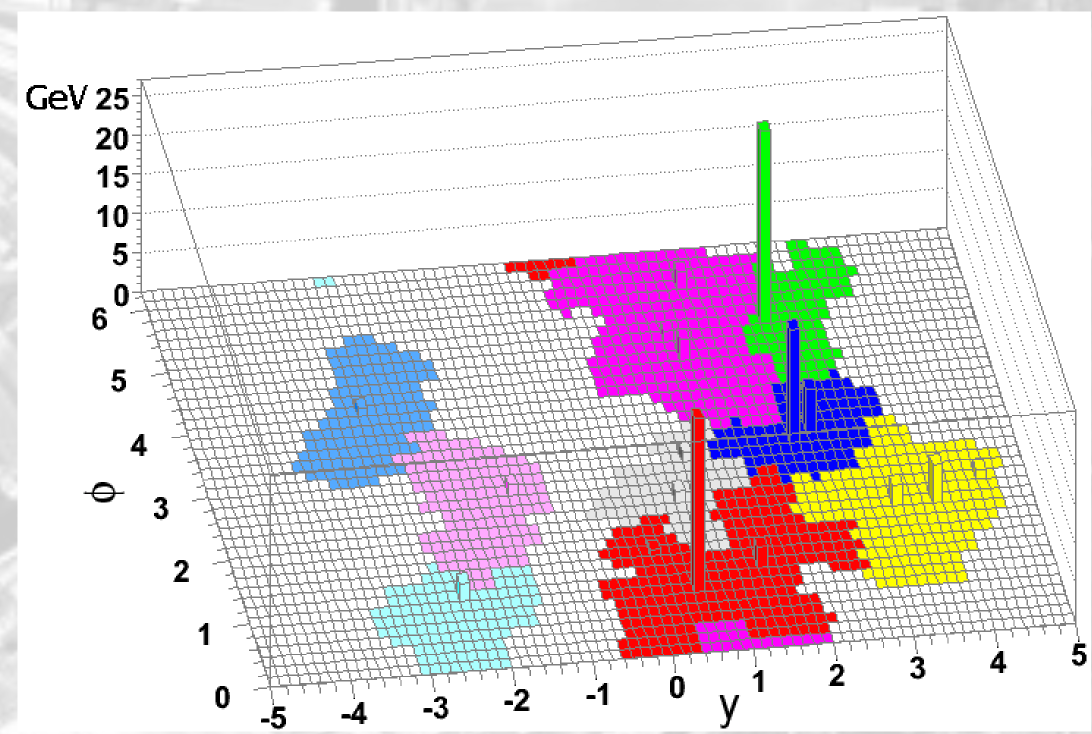
- When an exact subtraction of PU contamination is not possible, one can correct this in average
  - measure the average energy deposit per unit of area ρ
  - measure the jet area A
  - determine the jet pT by subtraction

$$p_{tj}^{(\mathrm{sub})} = p_{tj} - A_j \rho$$

- The concept of a jet area is subject to definition

arxiv.org/abs/0802.1188

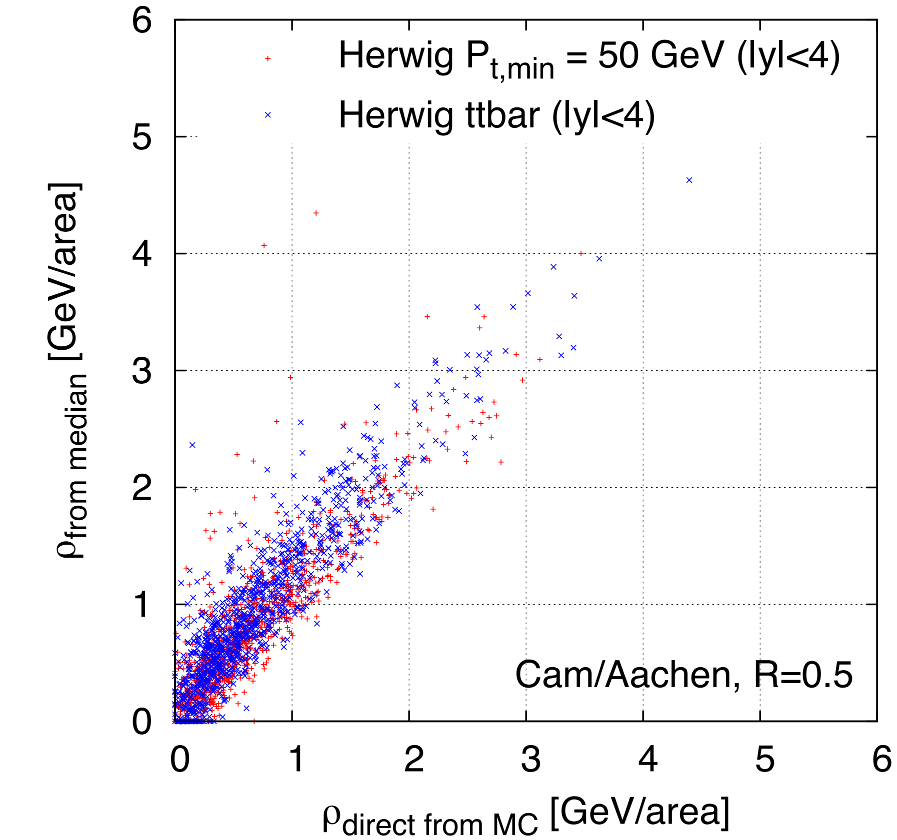


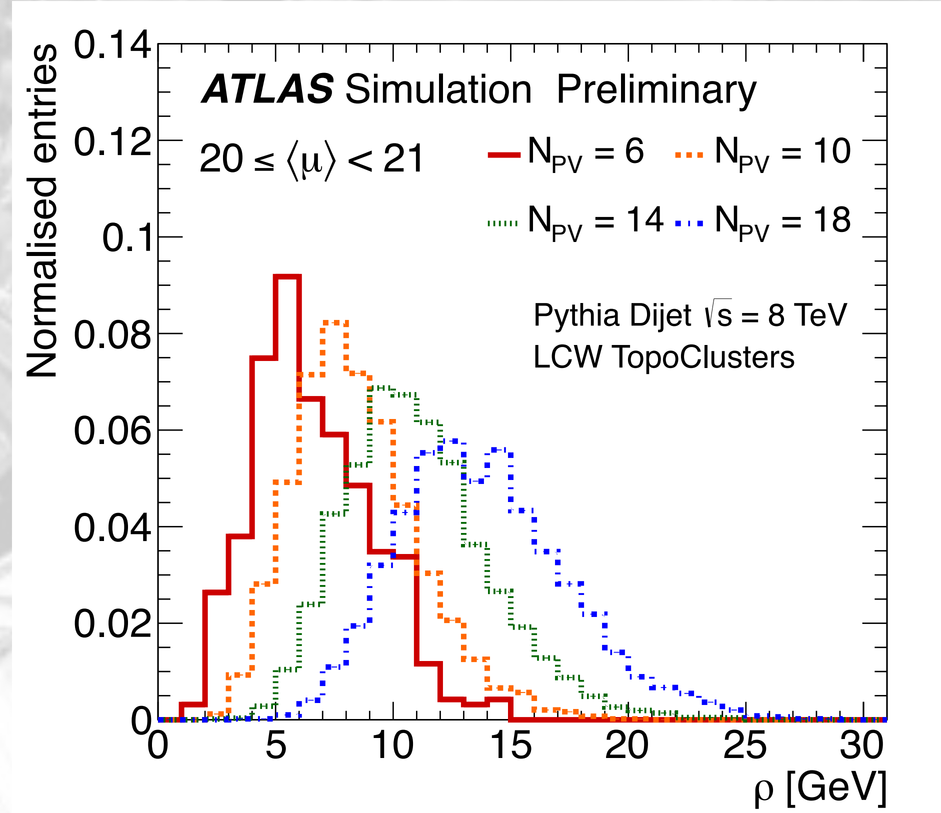


Jet Area Subtraction

- Once the area is determined, one needs to estimate the energy density
- For this, one should consider that the list of jets clustered in an event is made of
  - a few high-pT jets
  - a long list of soft jets, coming from clustering the PU particles
- Under the assumption of a uniform diffuse PU contribution
  - each soft jet has energy ρA
  - ρ can then be estimated as

$$\rho = \text{median}\left[\left\{\frac{p_{tj}}{A_j}\right\}\right]$$

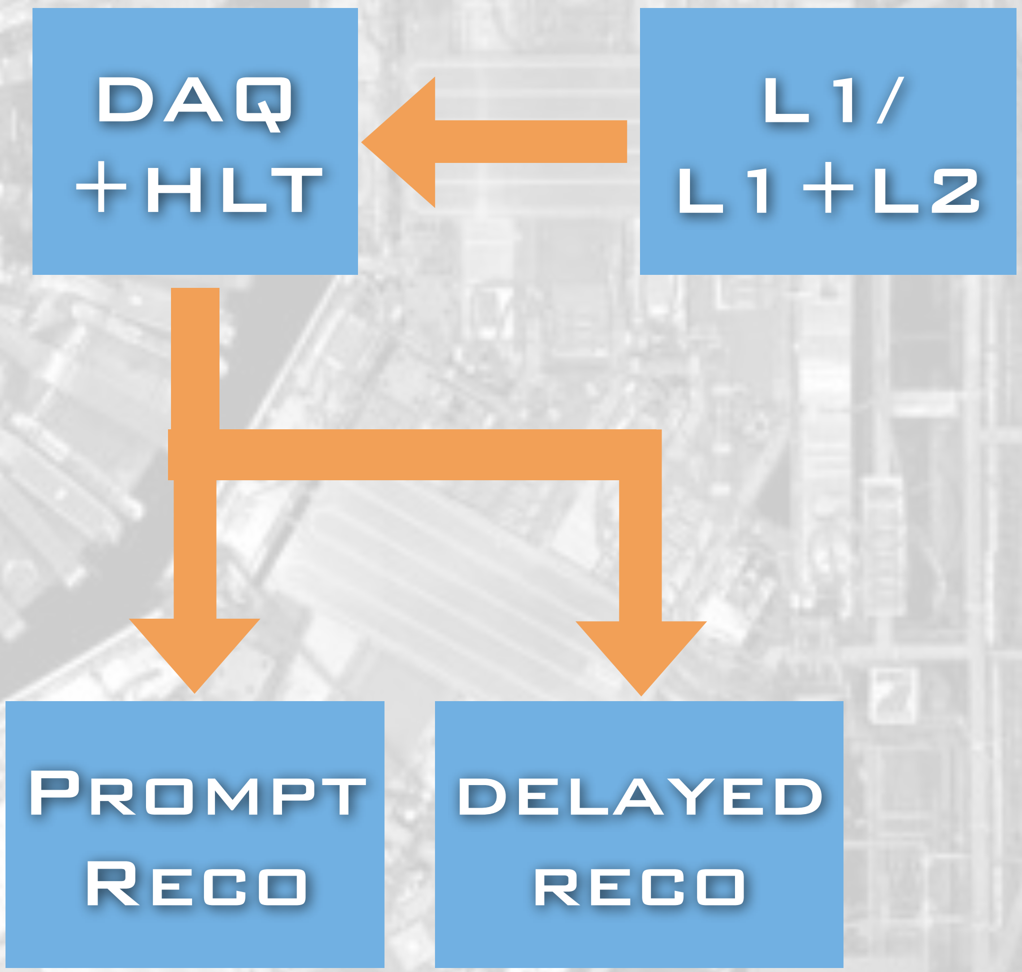




http://arxiv.org/abs/0707.1378

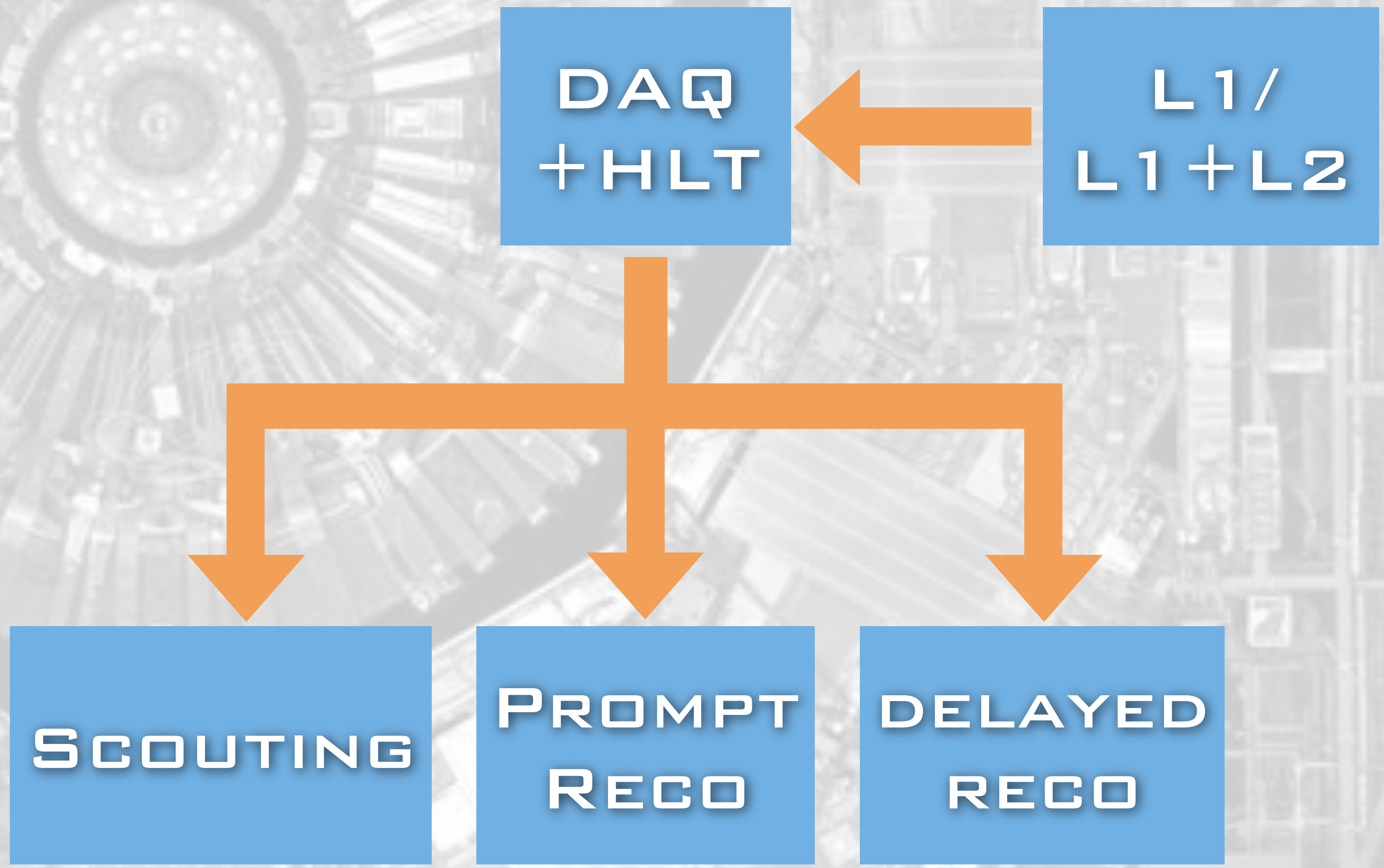
Rate vs Disk I/O

- At the beginning of the run, we considered 300 events/sec the maximum we could get out of the trigger
- It was suddenly realised that the trigger can handle much more
- The real problem was after
  - enough disk to write the data to? Set the limit to 1 kHz, considering the available disk, and the event size (O(300 Mb/event) after reconstruction)
  - enough CPU to process the data and reconstruct? OK for 2012 (full 2013/2014 shutdown)
- Data parking was introduced



Beyond Data Parking

- We don't save events because we cannot write them on disk
- We write on disk more event information that we (sometimes) need
- Keep ALL the events, with a small customised data format (only jet 4momenta). O(10 kb/event), can save several 1kHz of data
- Event reco not as good as normal
  - not all the analyses cannot be done this way
  - when resolution is not great (e.g., with jets) this is not a big issue
- Can do things we could not do otherwise (i.e., better than nothing)



More on Substructure

Before Mass cut

After Mass cut

Not Pruned

Pruned