The high-pT pp physics in the first LHC Run

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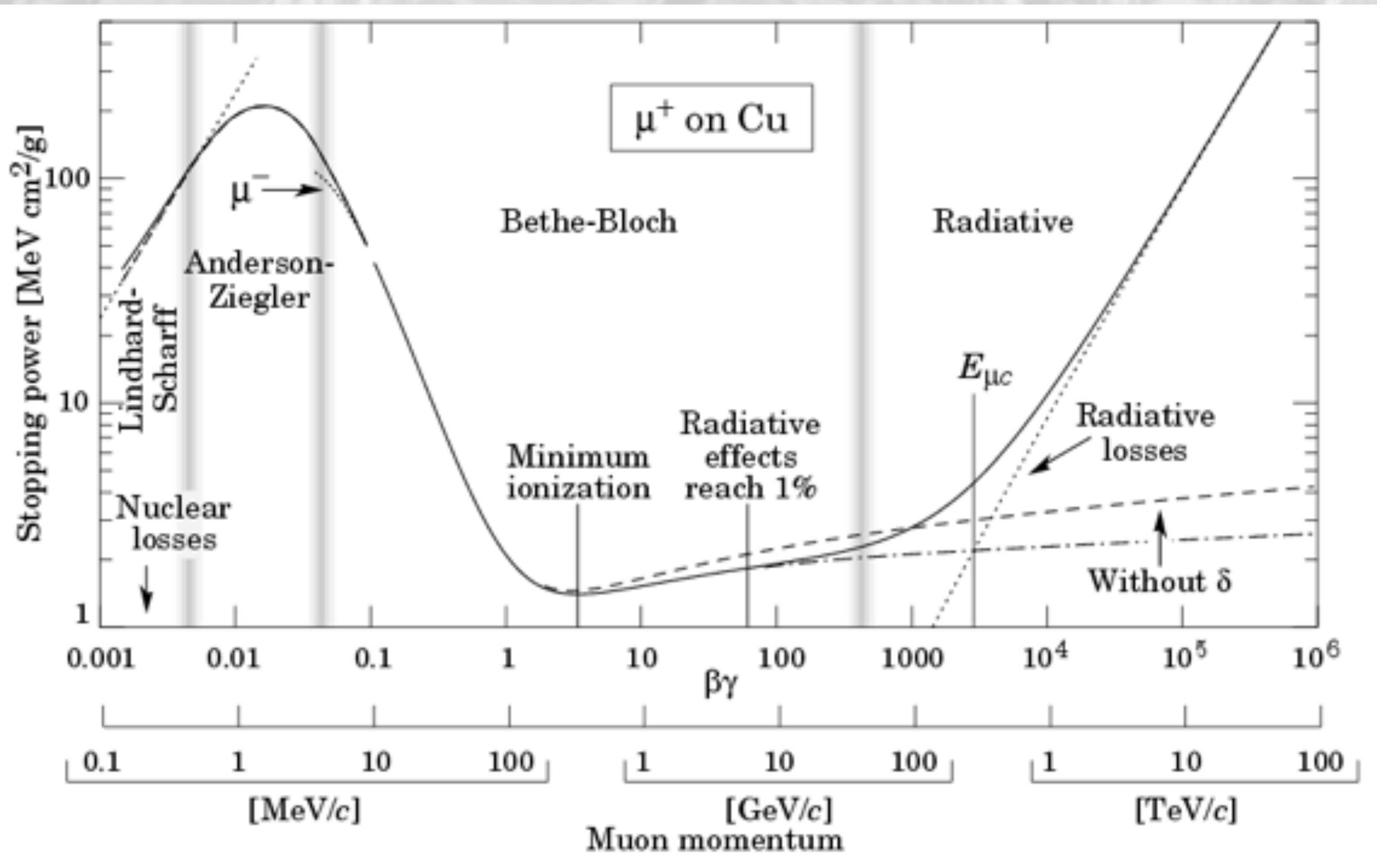
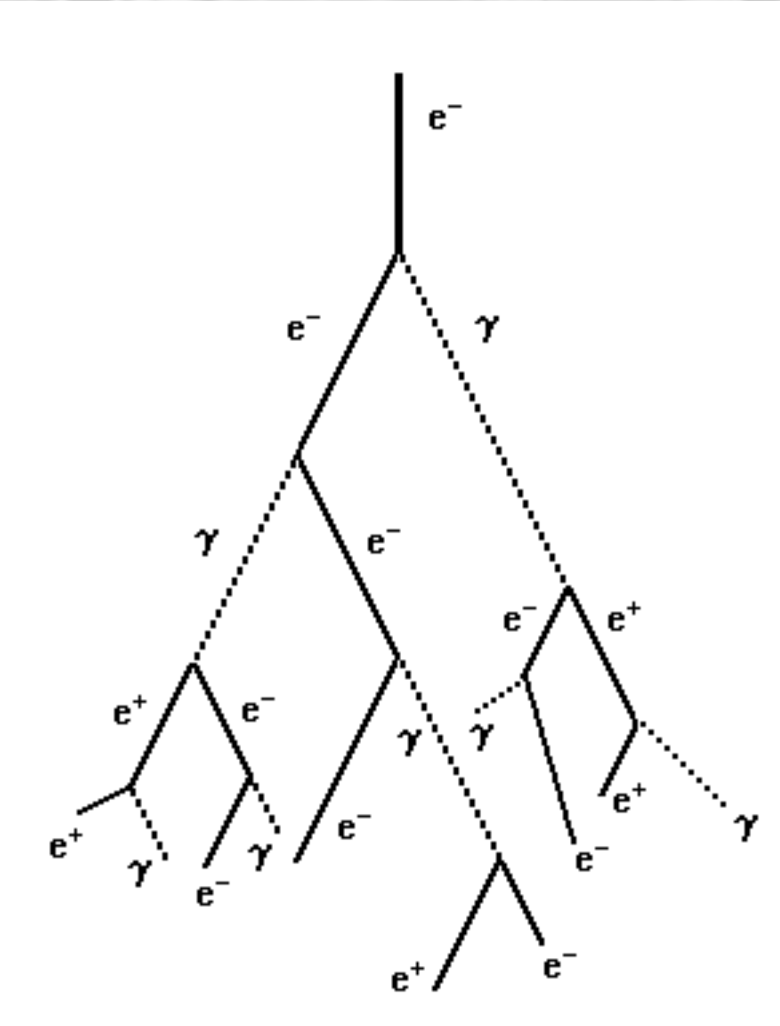
The Bethe-Bloch Formula

$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right]$$



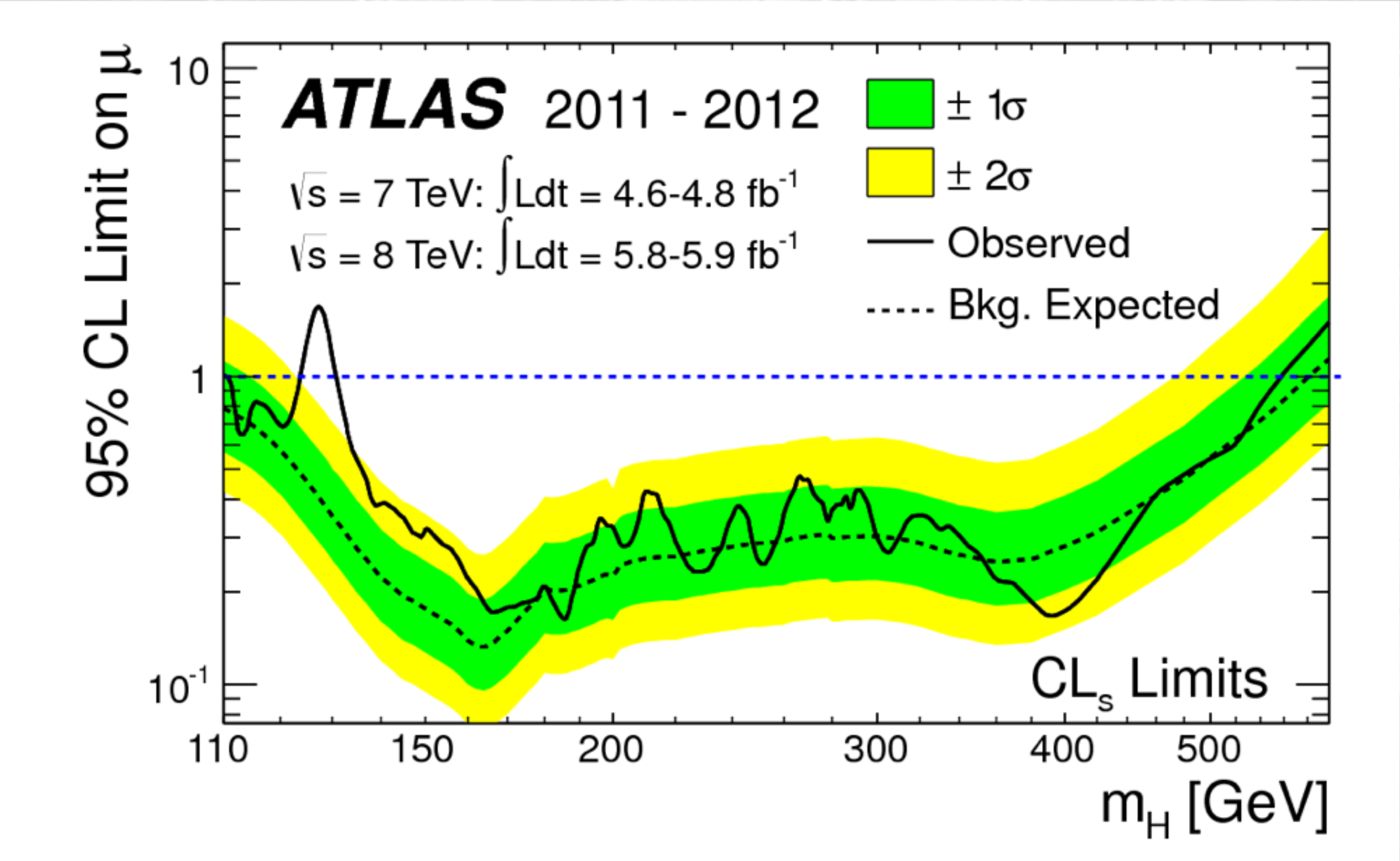
Muon as a MIP



Electron shower

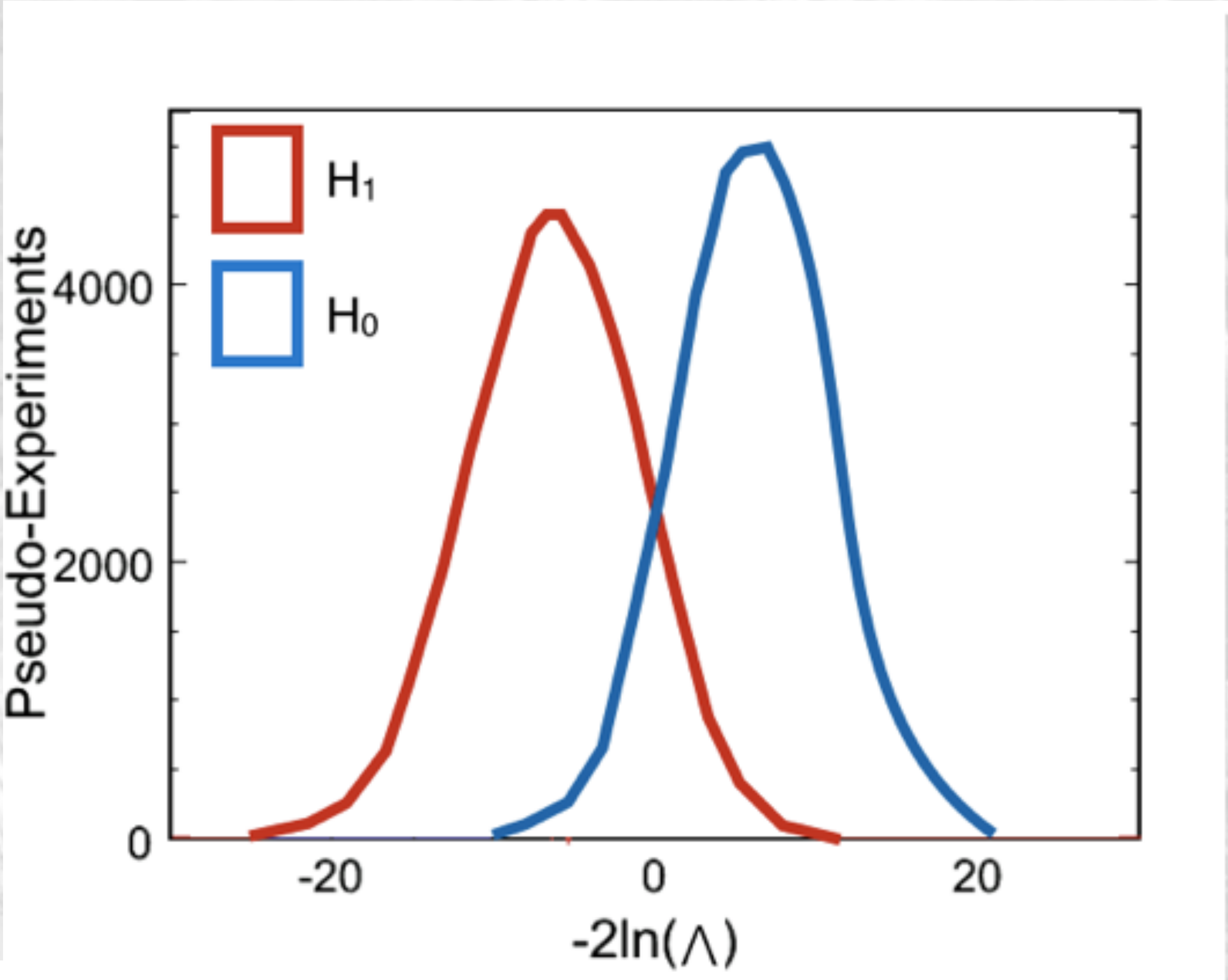
Establishing a discovery

Trying to exclude a signal

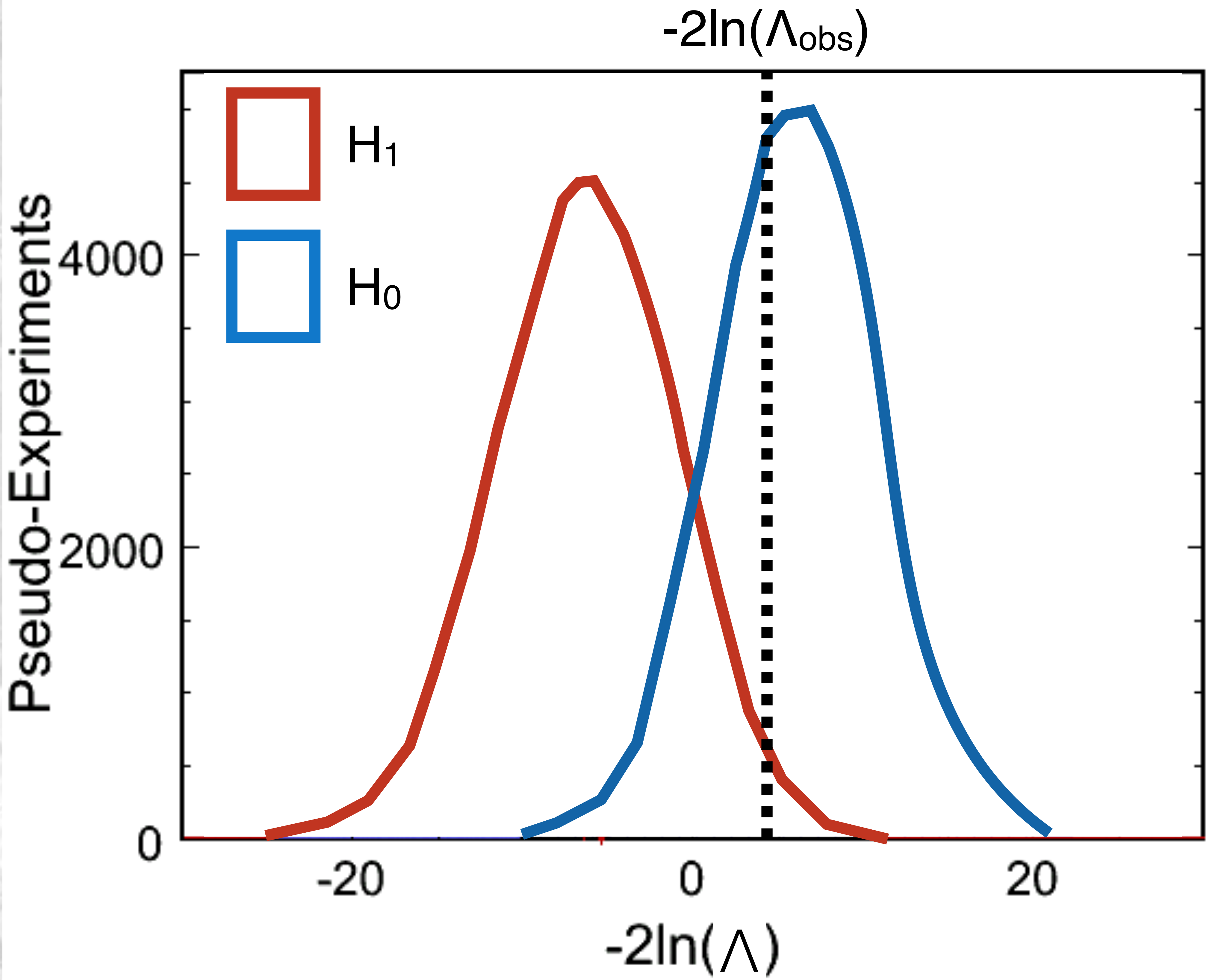


Trying to exclude a signal

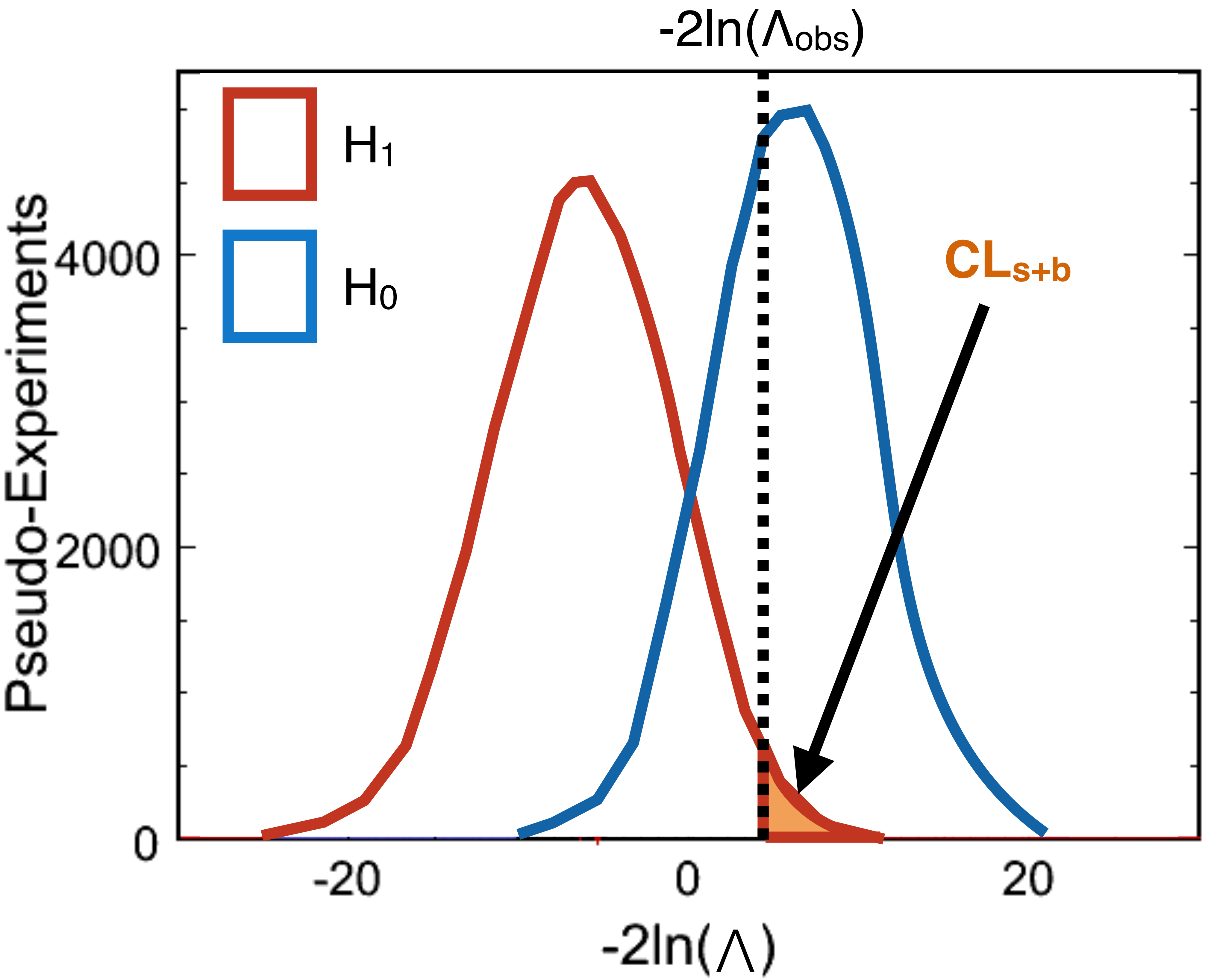
- Assume a mass value
- For each mass value, assume a cross section and construct the two distributions for Λ under H_0 and H_1
  - generate toy MC with σ=0 (H0)
  - generate toy MC with σ=σ* (H1)



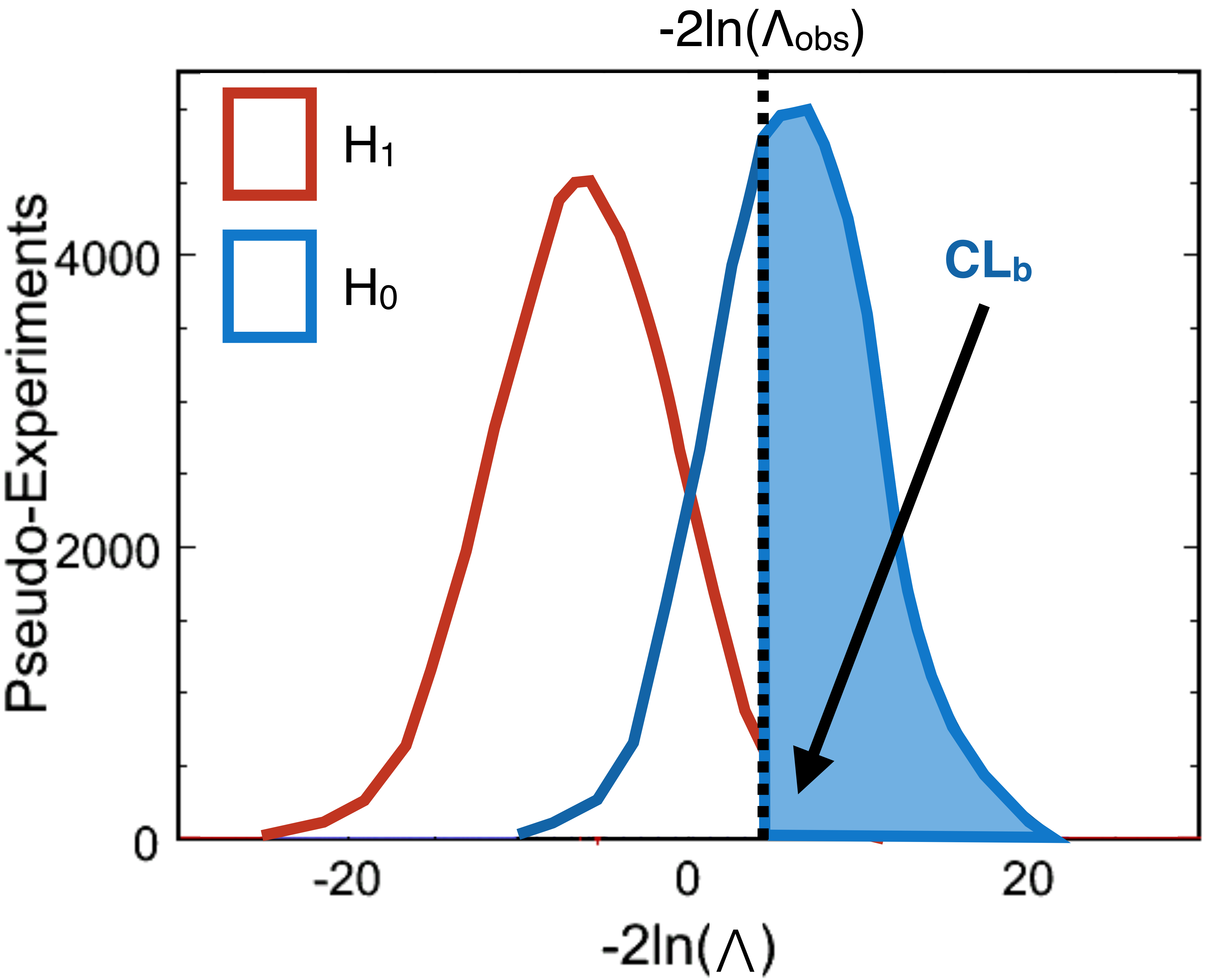
Your observation



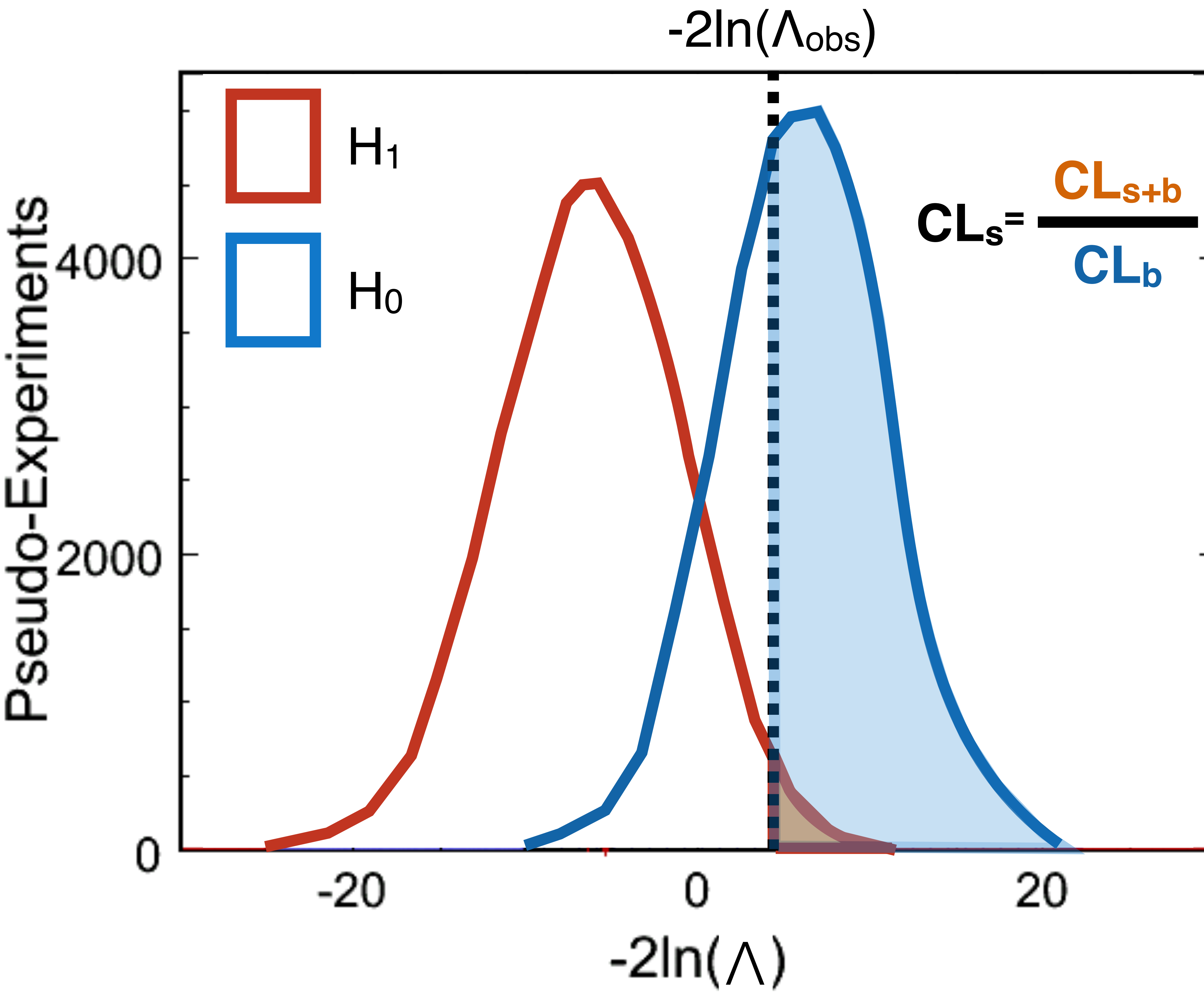
Observed CLs+b



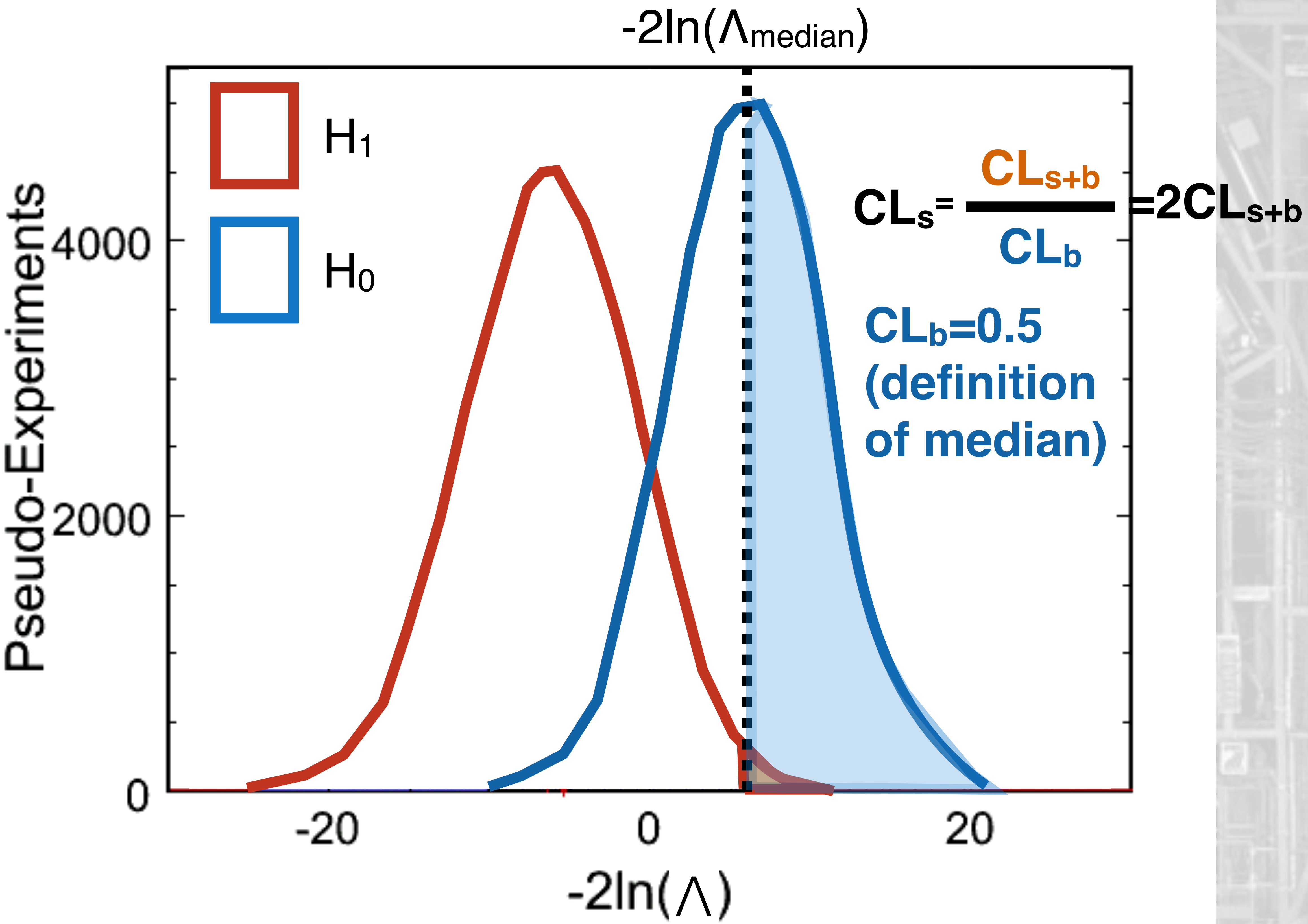
Observed CLb



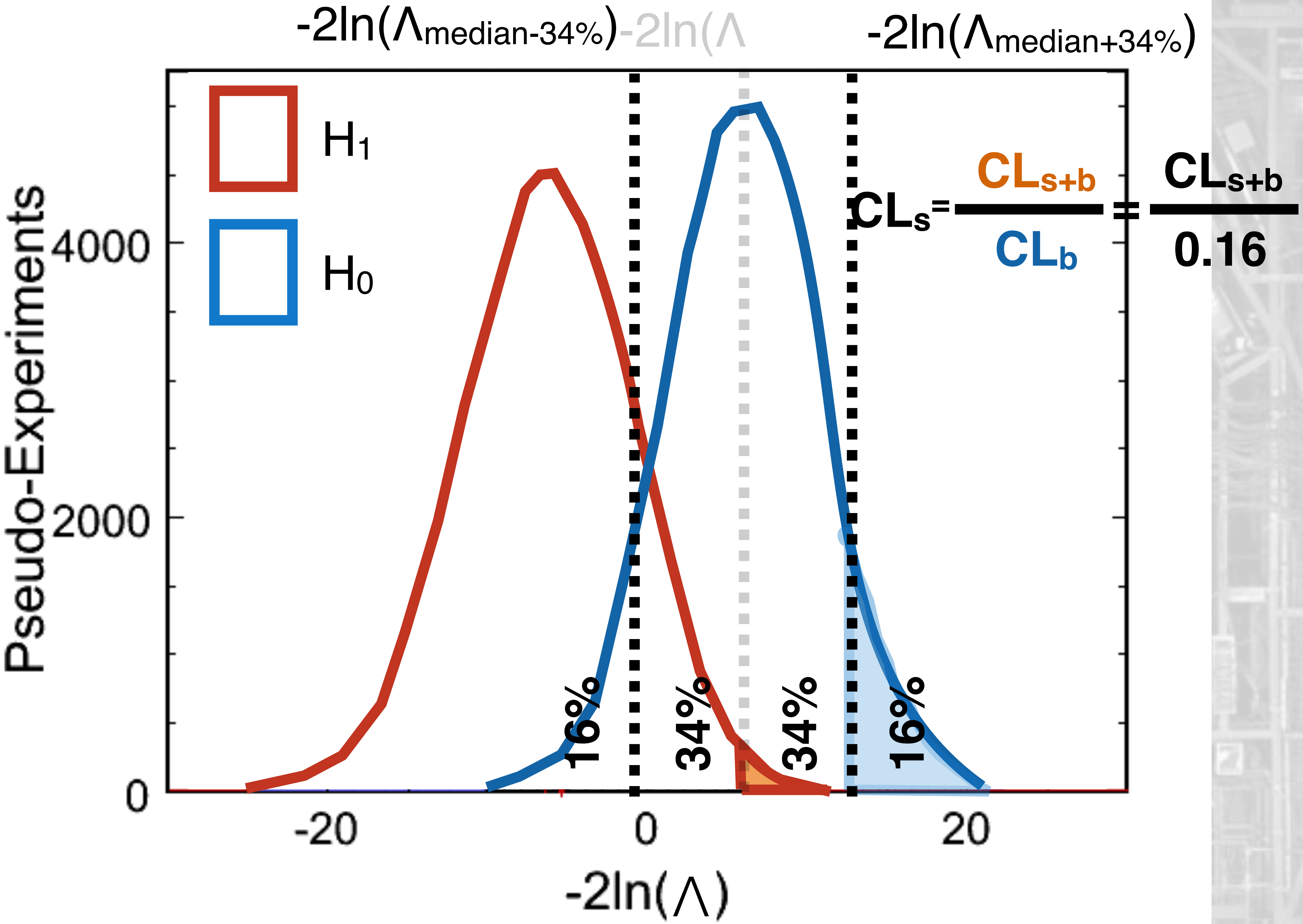
Observed CLs



Expected CLs



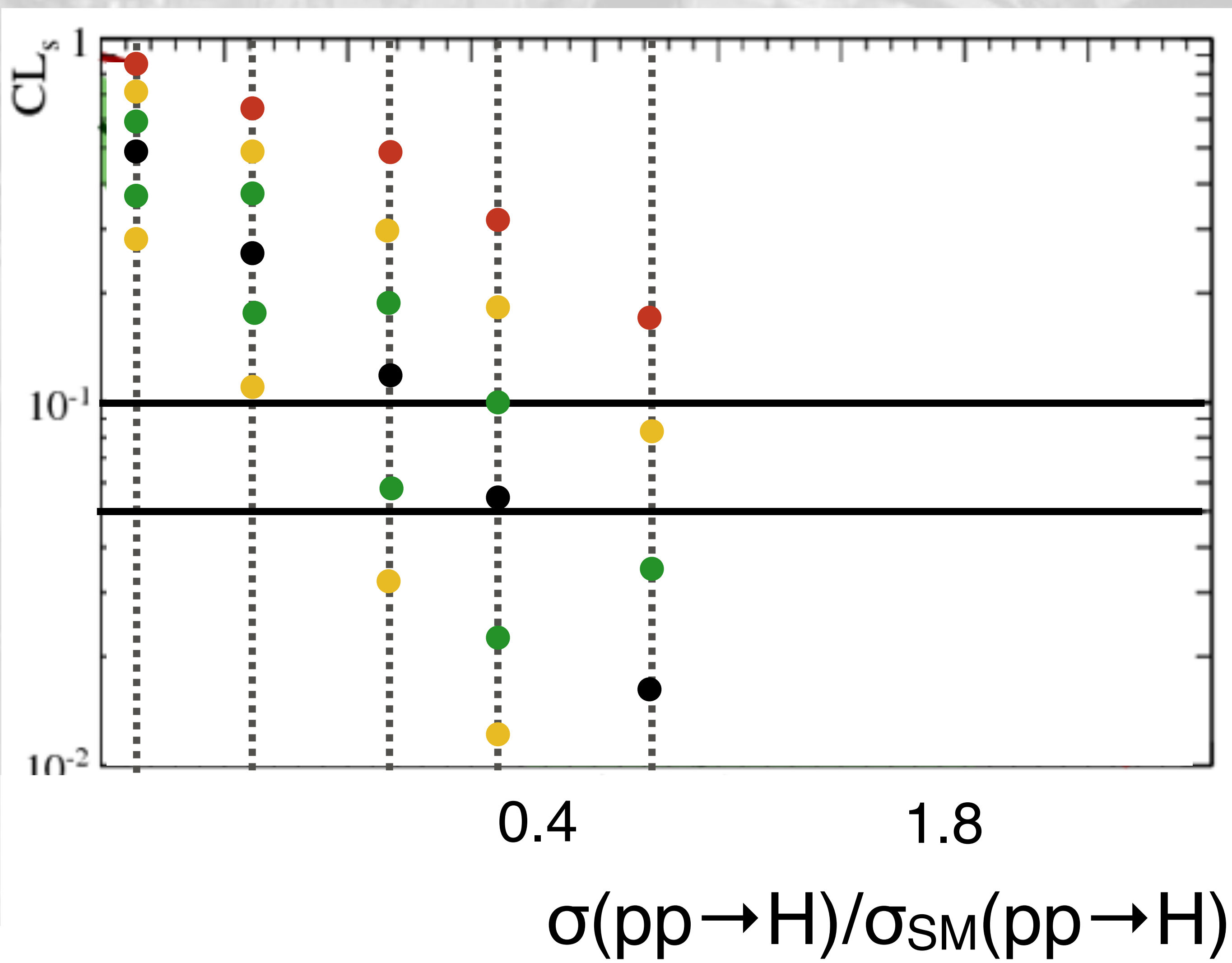
Expected CLs



$$CL_s = \frac{CL_{s+b}}{CL_b} = \frac{CL_{s+b}}{0.16}$$

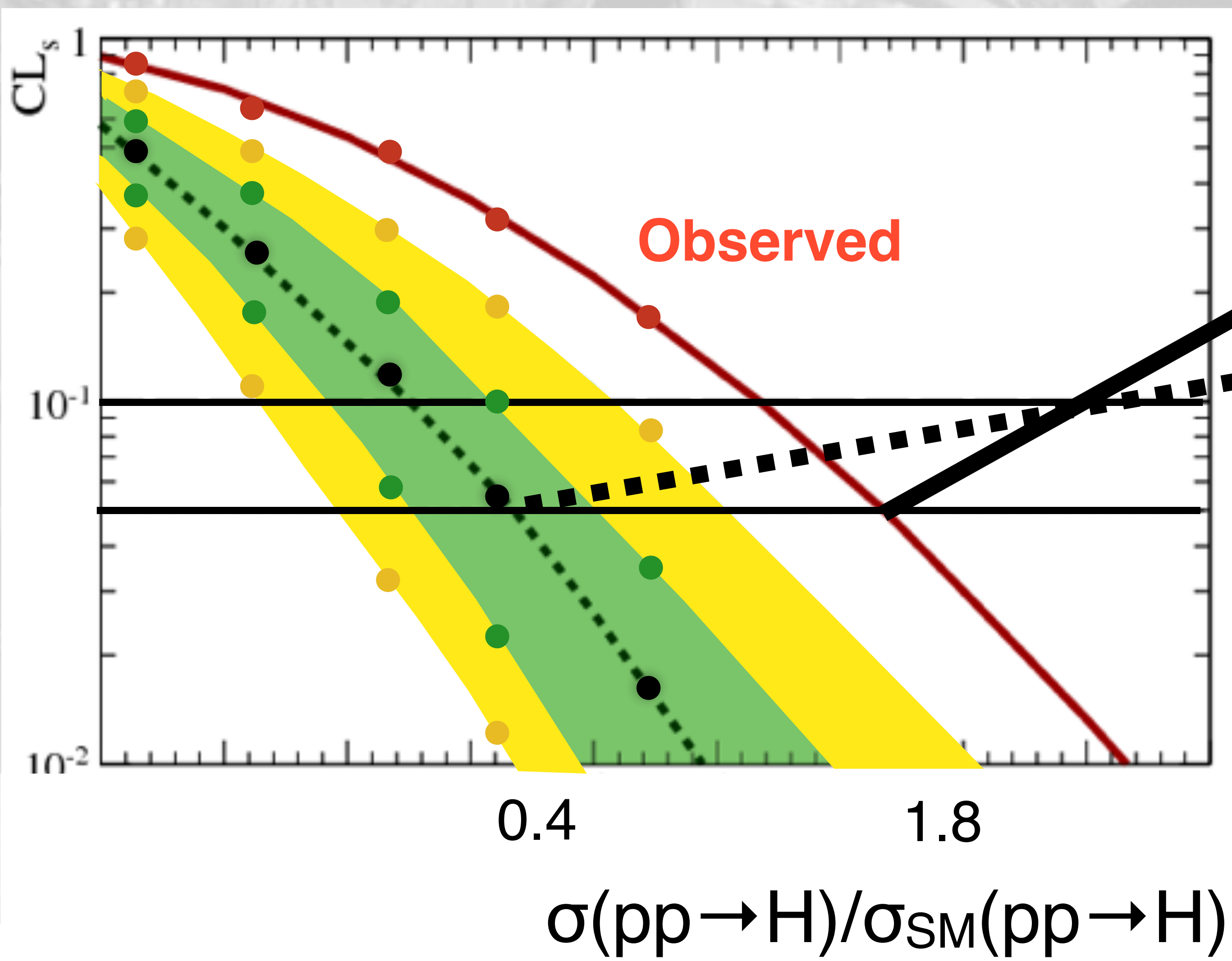
Trying to exclude a signal

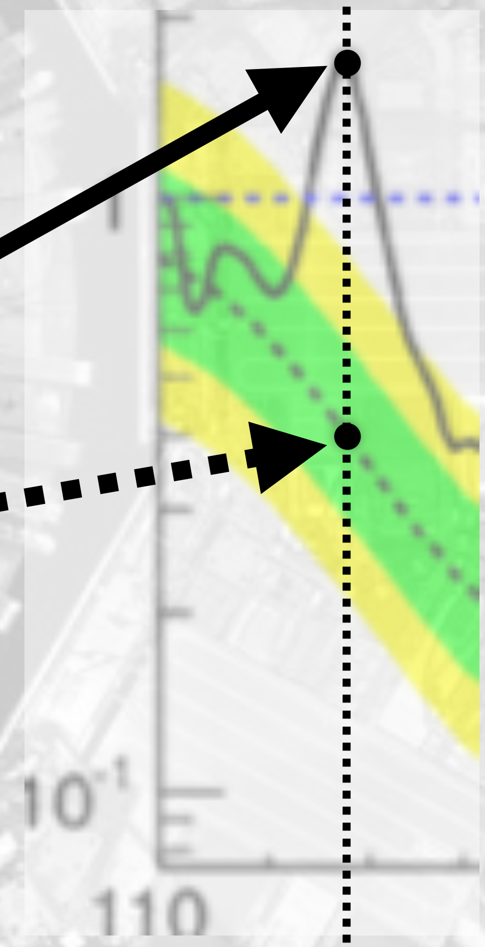
- Repeat the procedure above for several values of s/sSM



Trying to exclude a signal

- Each line intercept $CL_s = 0.05$. The intersection gives you
  - The expected and observed limit
  - The 68% and 95% range





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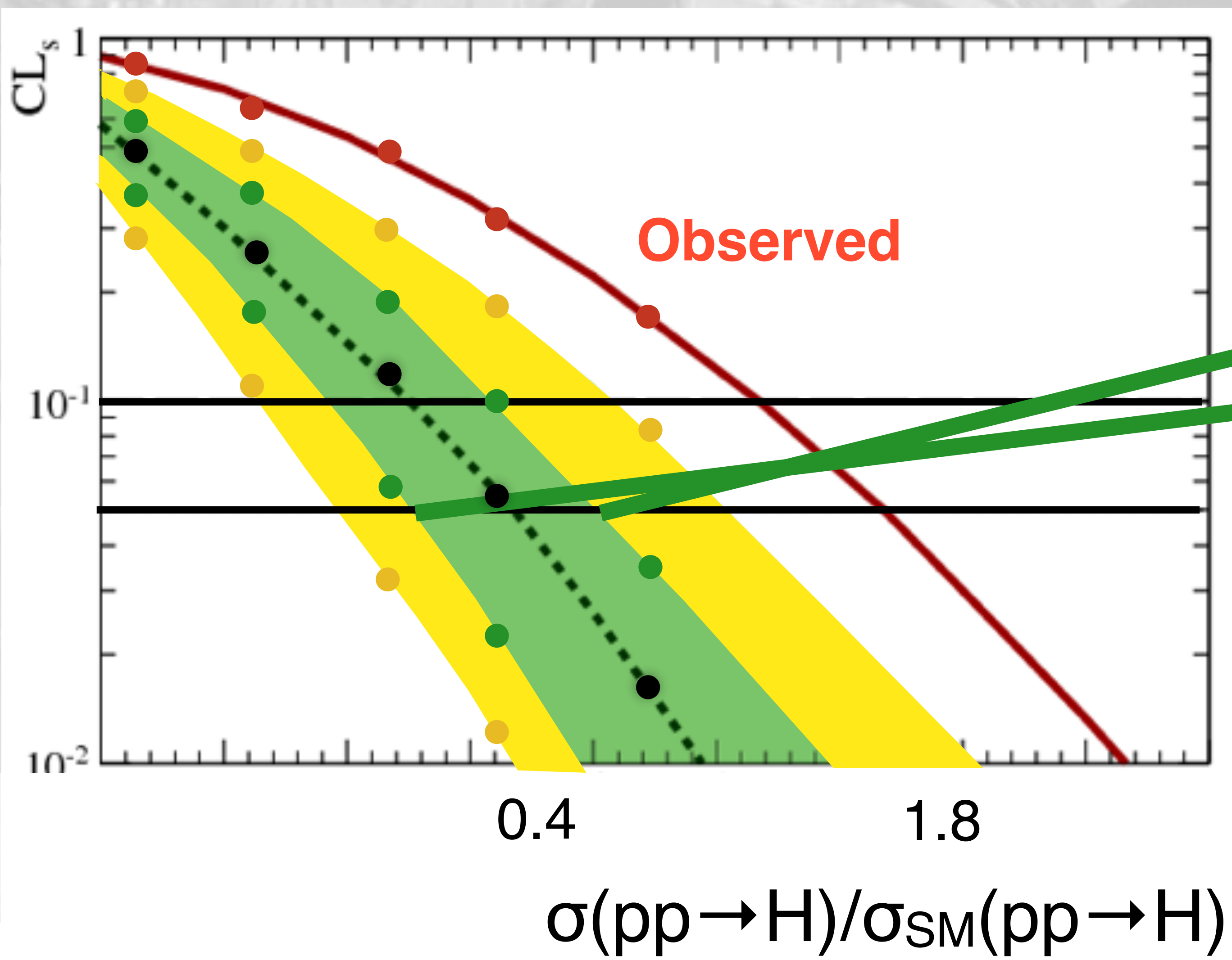

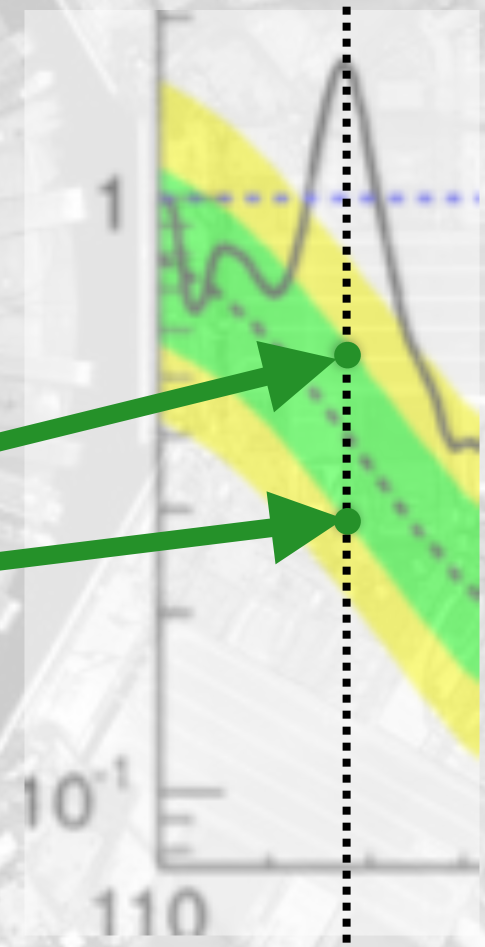

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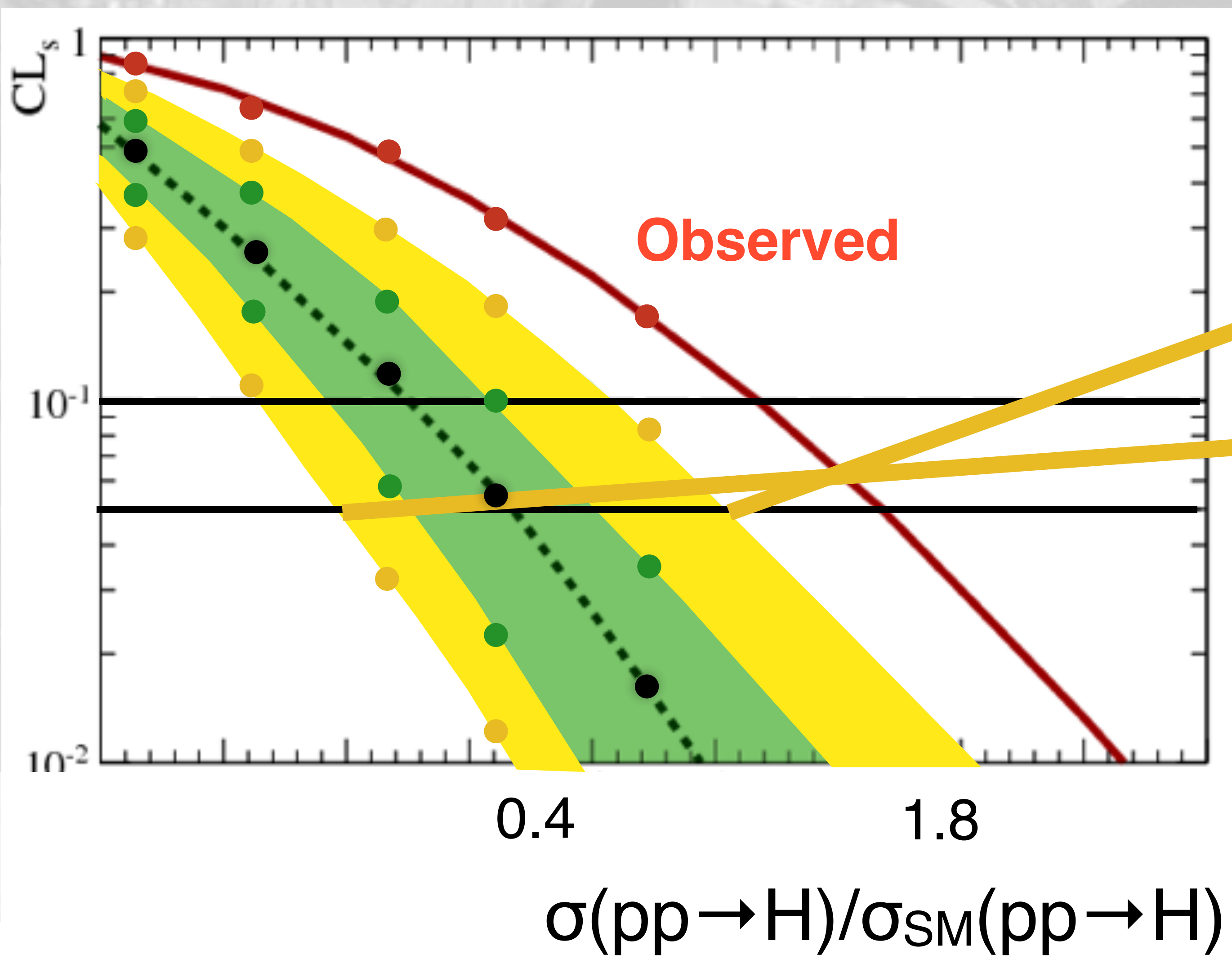
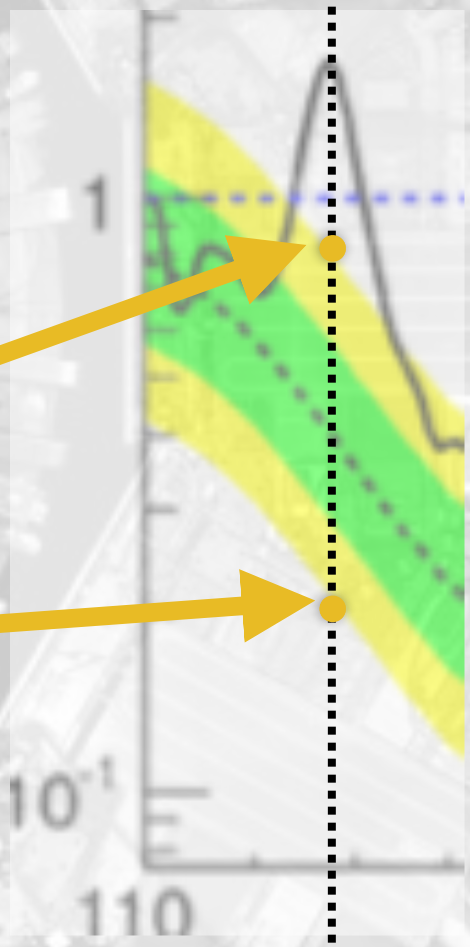
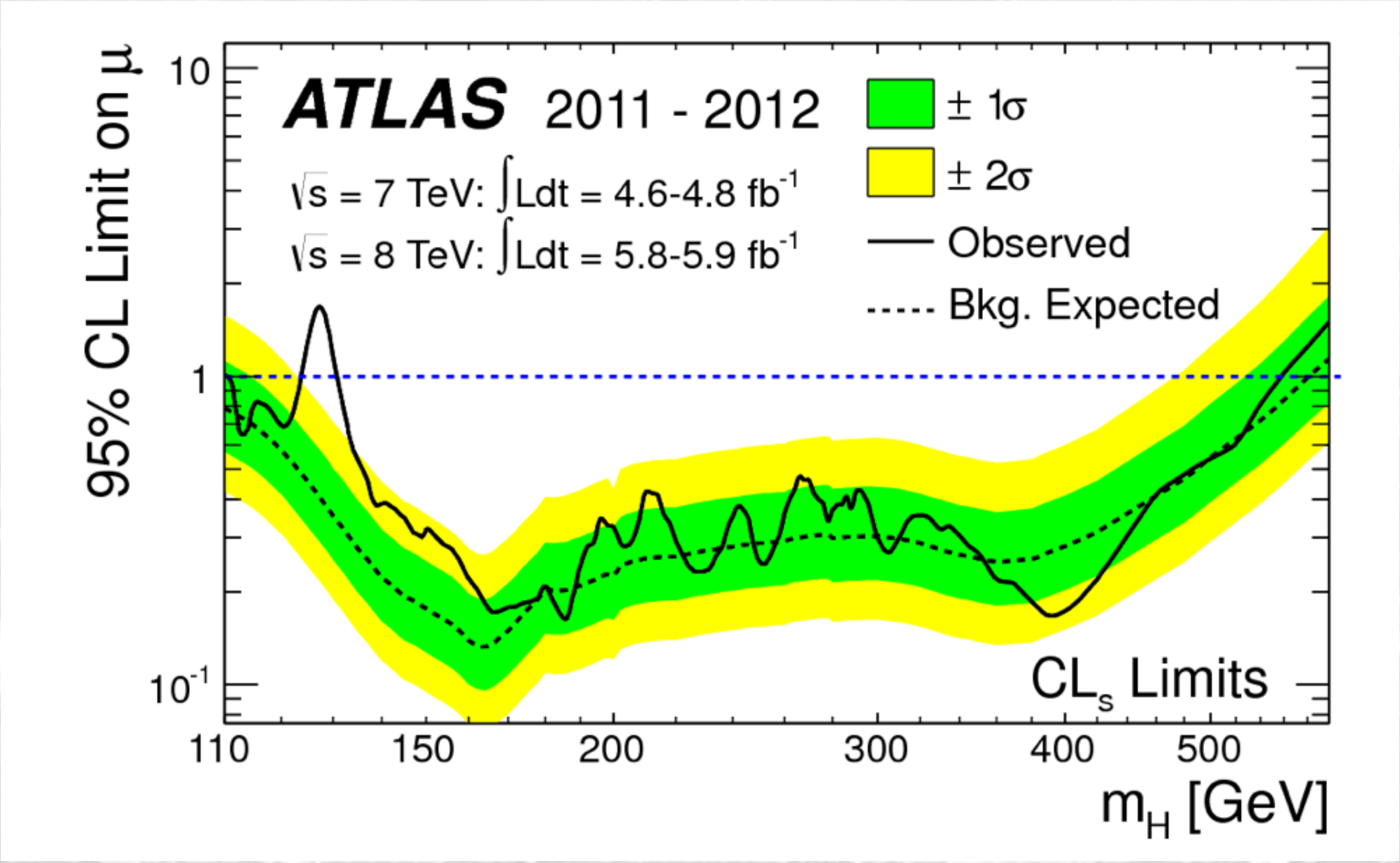




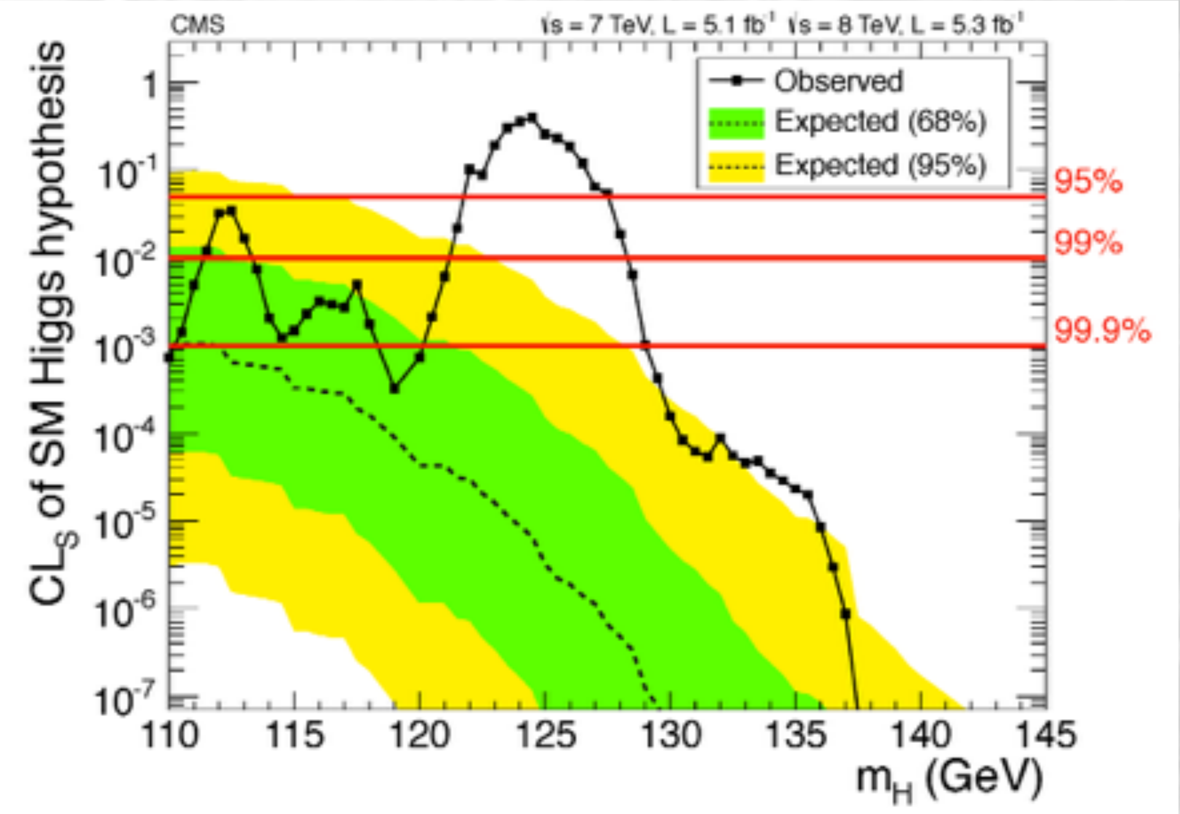
Trying to exclude a signal

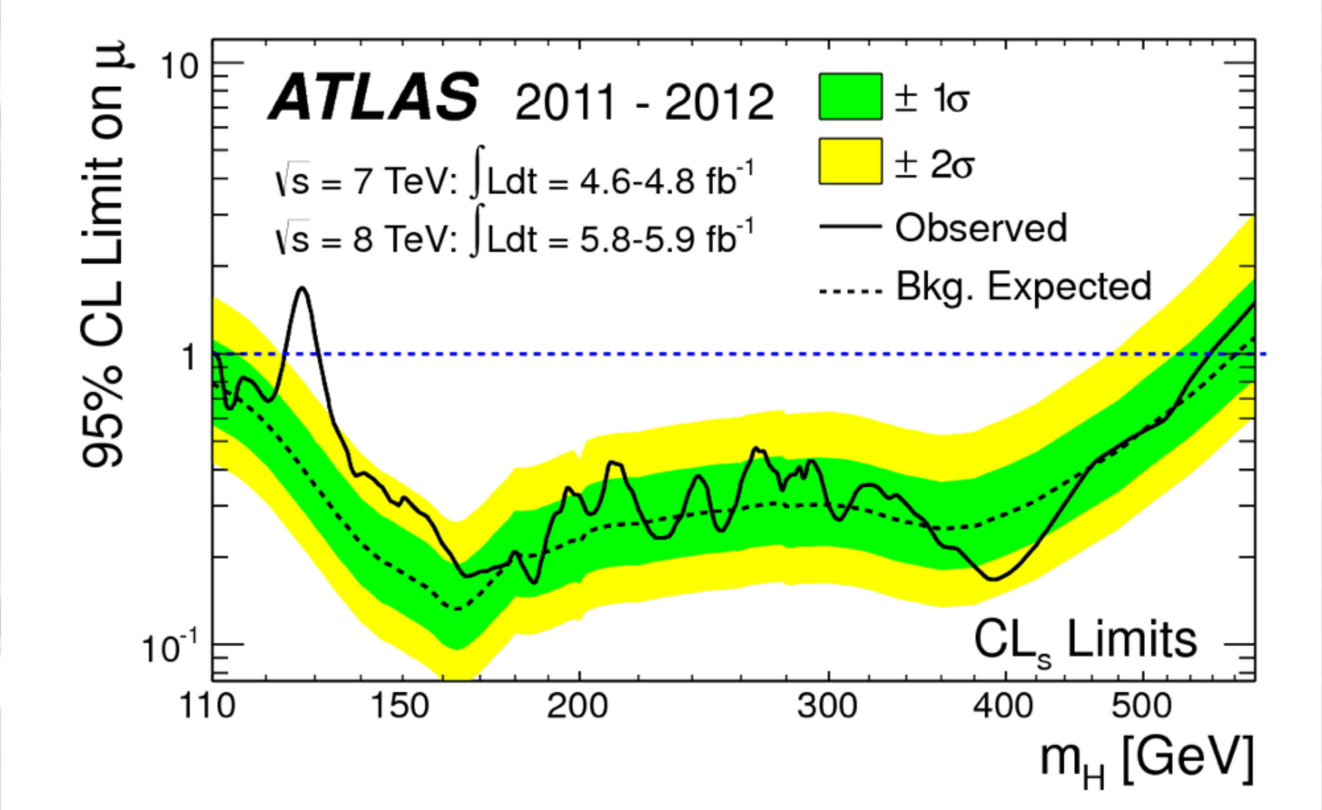
- Now repeat the procedure for any value of mH and connect the dots



Trying to exclude a signal

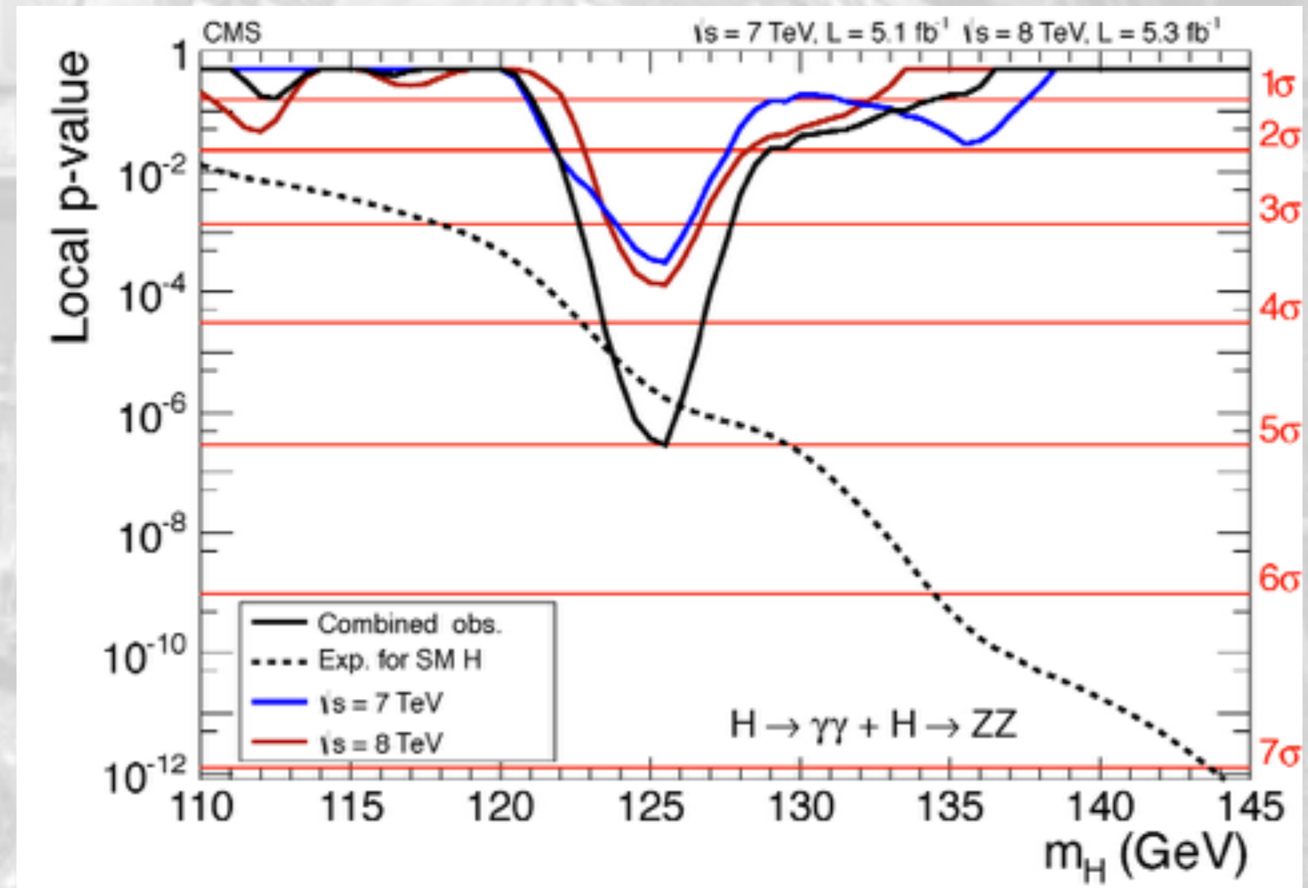
- When you don't know if you have a signal, you first try to exclude it
- If the signal is there, your limit will be poor (and worse than expectation)
- If it is much worse, you might have discovered a signal…
- … or you might have discovered that your analysis is terrible
- these plots are not the right plots to establish the presence of a signal

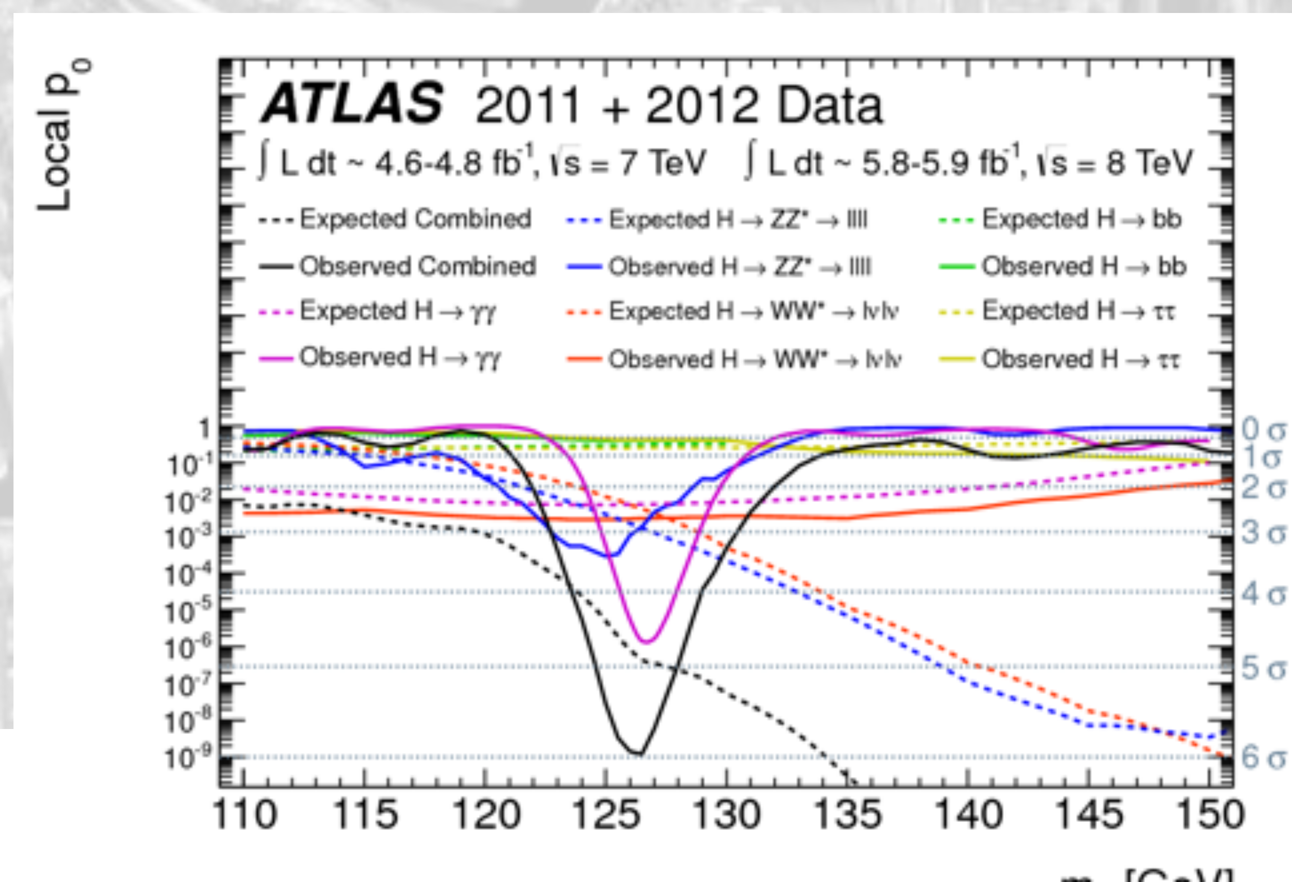




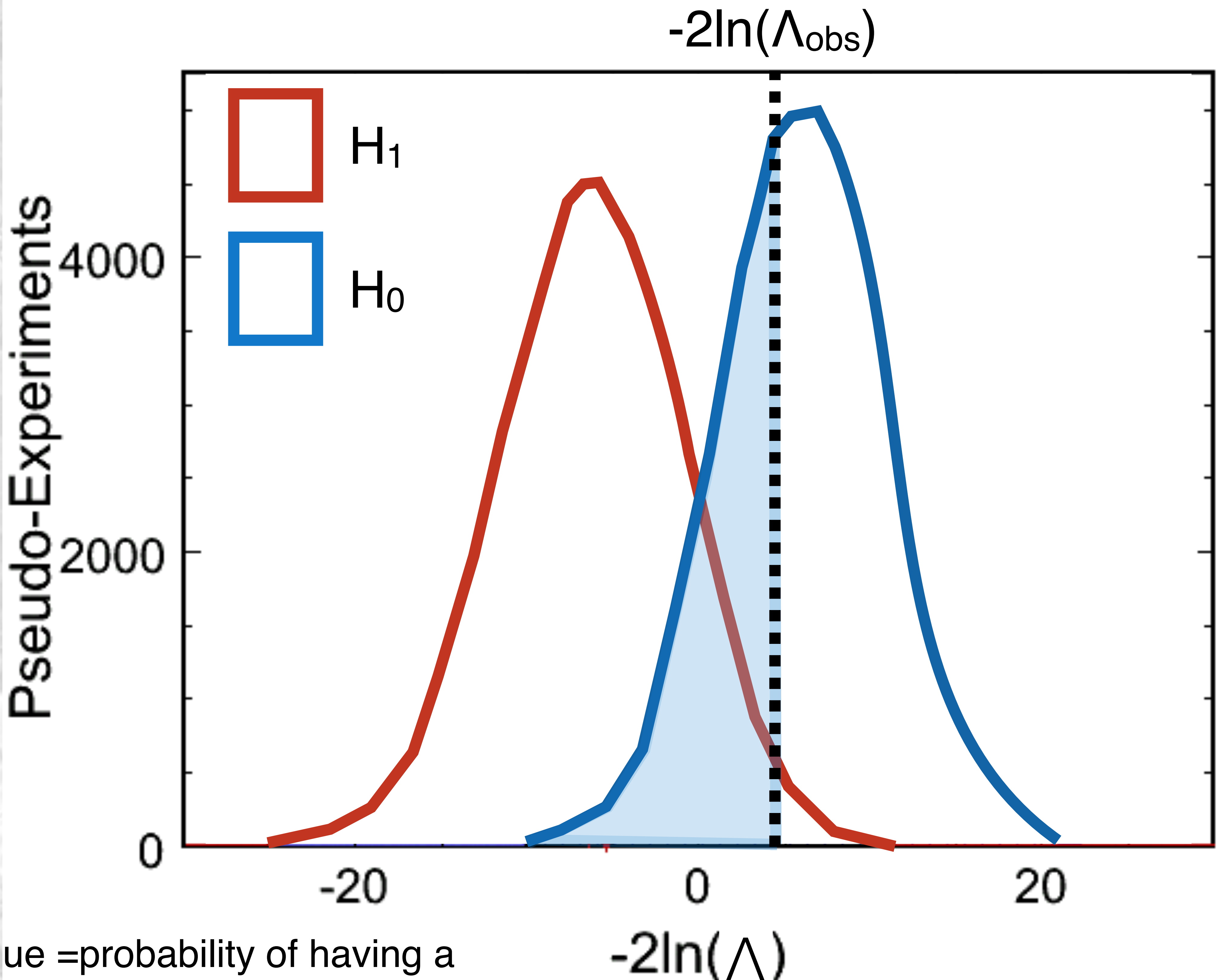
The Number of Sigmas

- To claim a discovery, you need to exclude the possibility that your background could mimic a signal
- To do so, you measure (with toy experiments) the probability that a bkg-only sample gives a result as signal-like as what you see on data
- The signal is stringer than the conventional 5σ threshold so...



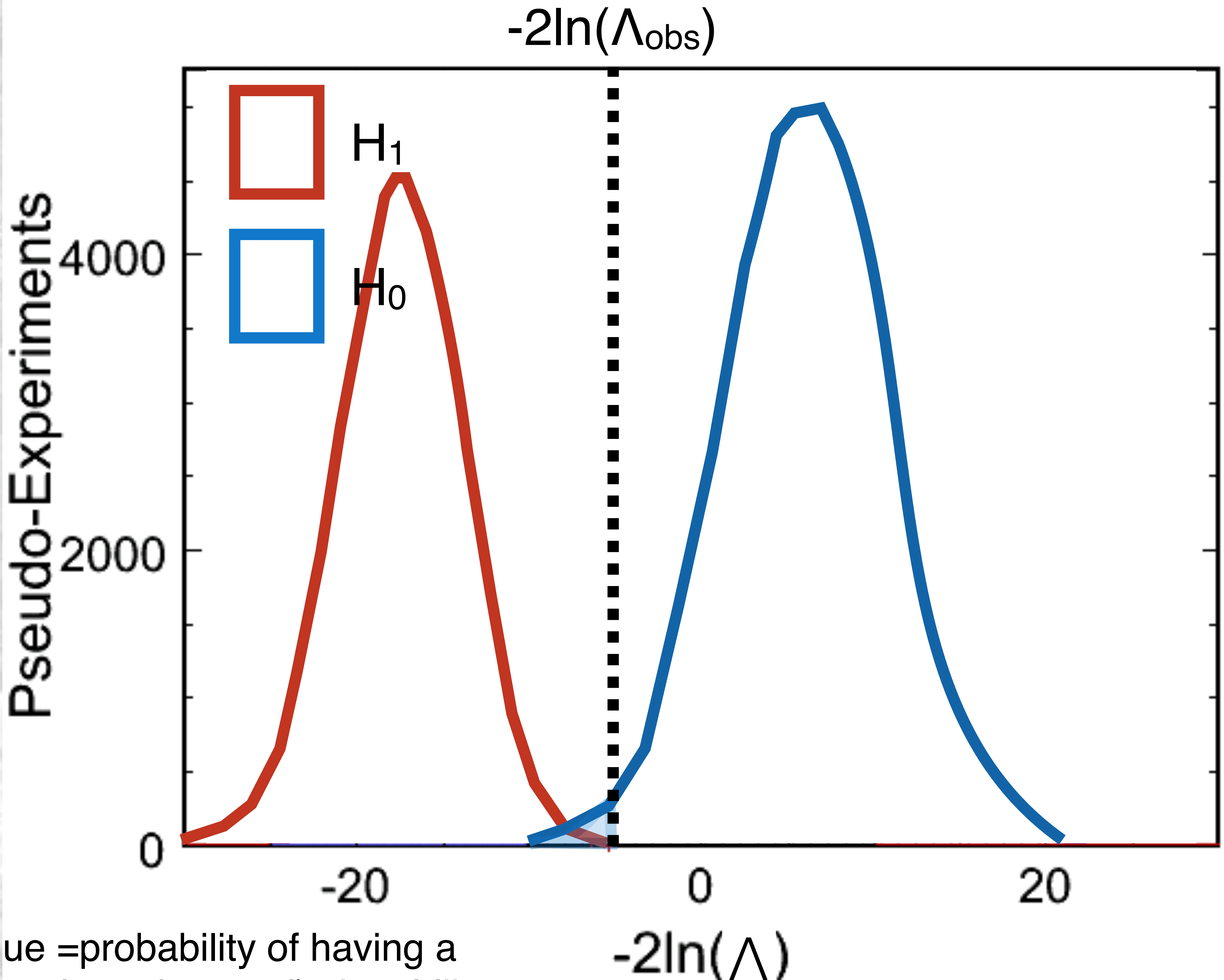


Background p-value



p-value =probability of having a (stronger than observed) signal-like fluctuation in the background

Background p-value



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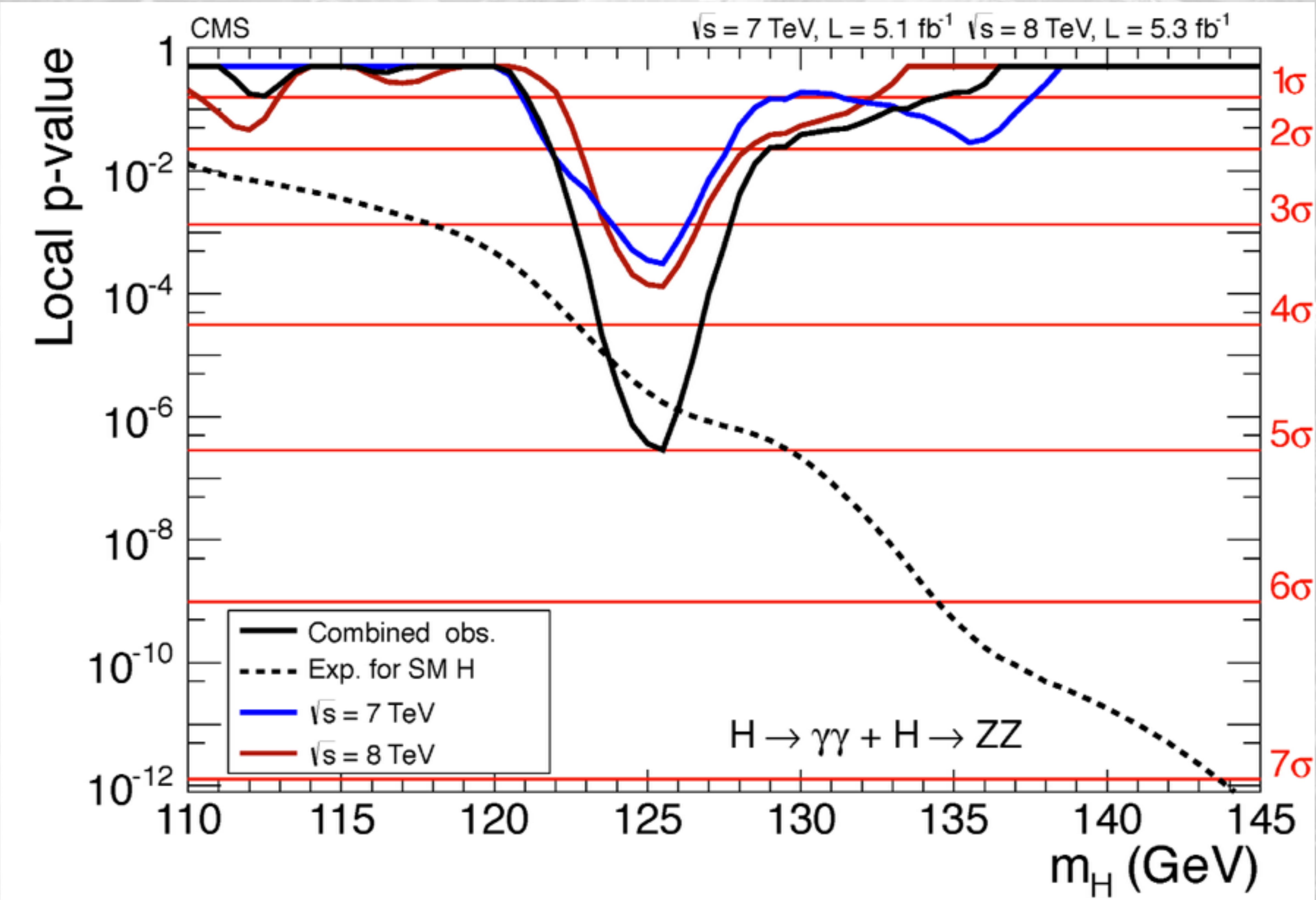
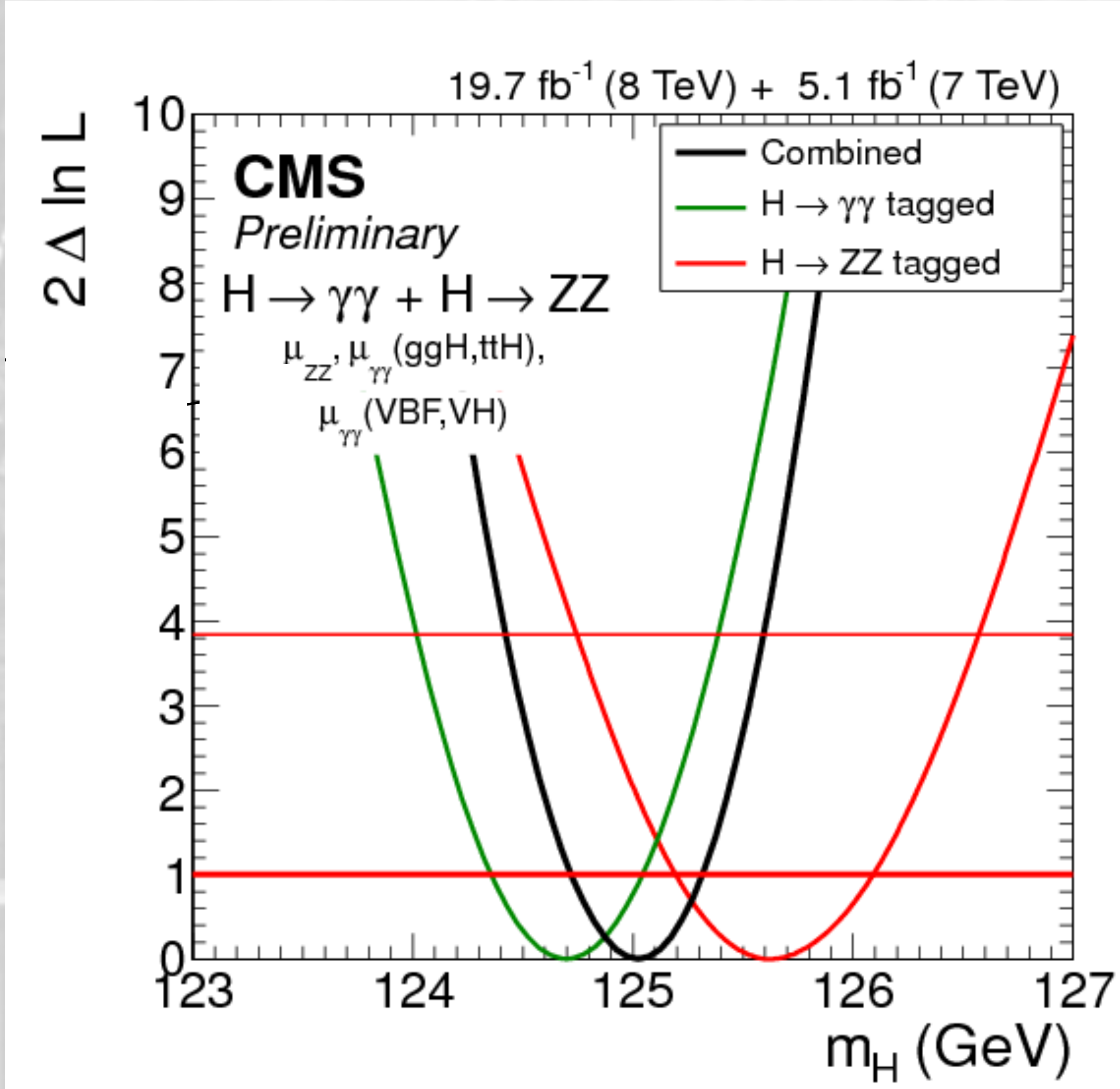
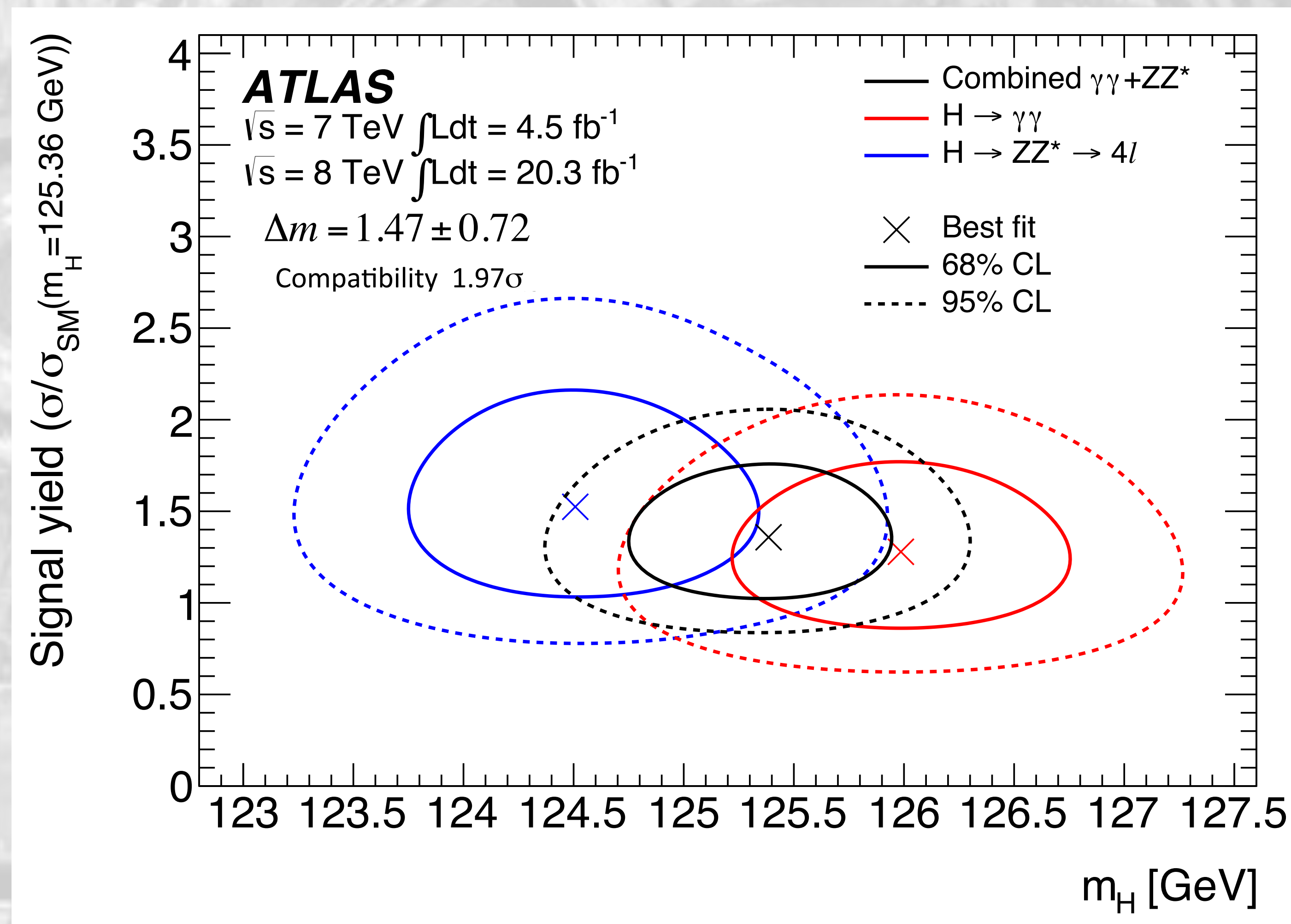
The Number of Sigmas



The Higgs boson mass

$$m_H = 125.03 \pm 0.30 \left[{}^{+0.26}_{-0.27}(\text{stat.}) {}^{+0.13}_{-0.15}(\text{syst.}) \right] \text{ GeV}$$





$$125.36 \pm 0.37 \text{ (stat)} \pm 0.18 \text{ (syst) GeV}$$

The Higgs boson width

- The Higgs width (~4 MeV) was considered too small for the LHC to measure it (expected precision ~ 5 GeV)
- It was pointed out how to exploit interference effects with ZZ events

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}$$

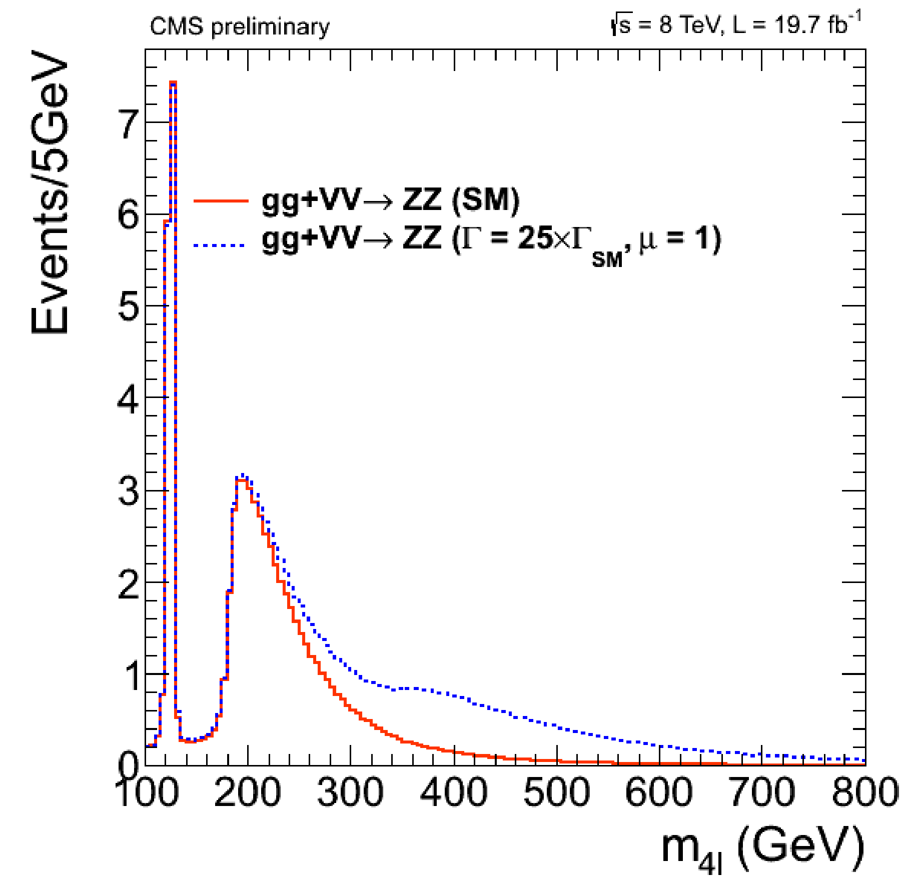
$$\sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}$$

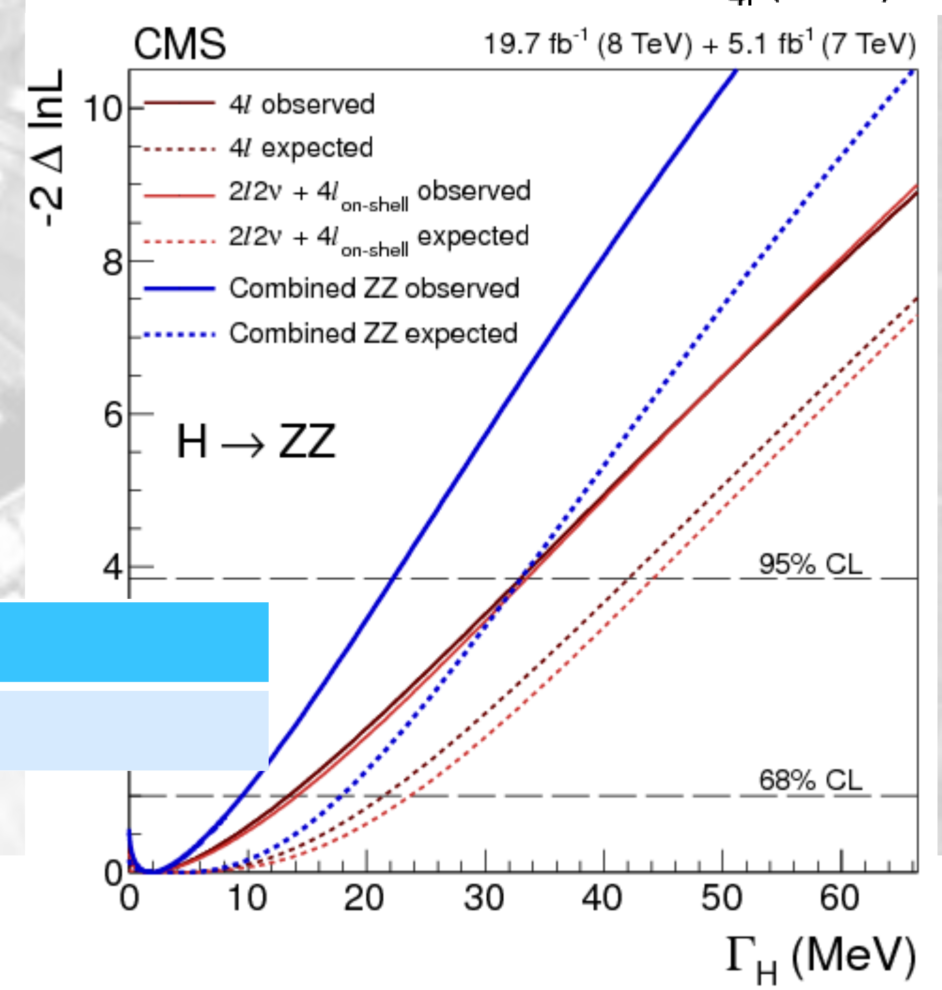
Caola & Melnikov

http://arxiv.org/abs/1307.4935

- Limit obtained ~ 20 MeV (not there yet, but not that far)

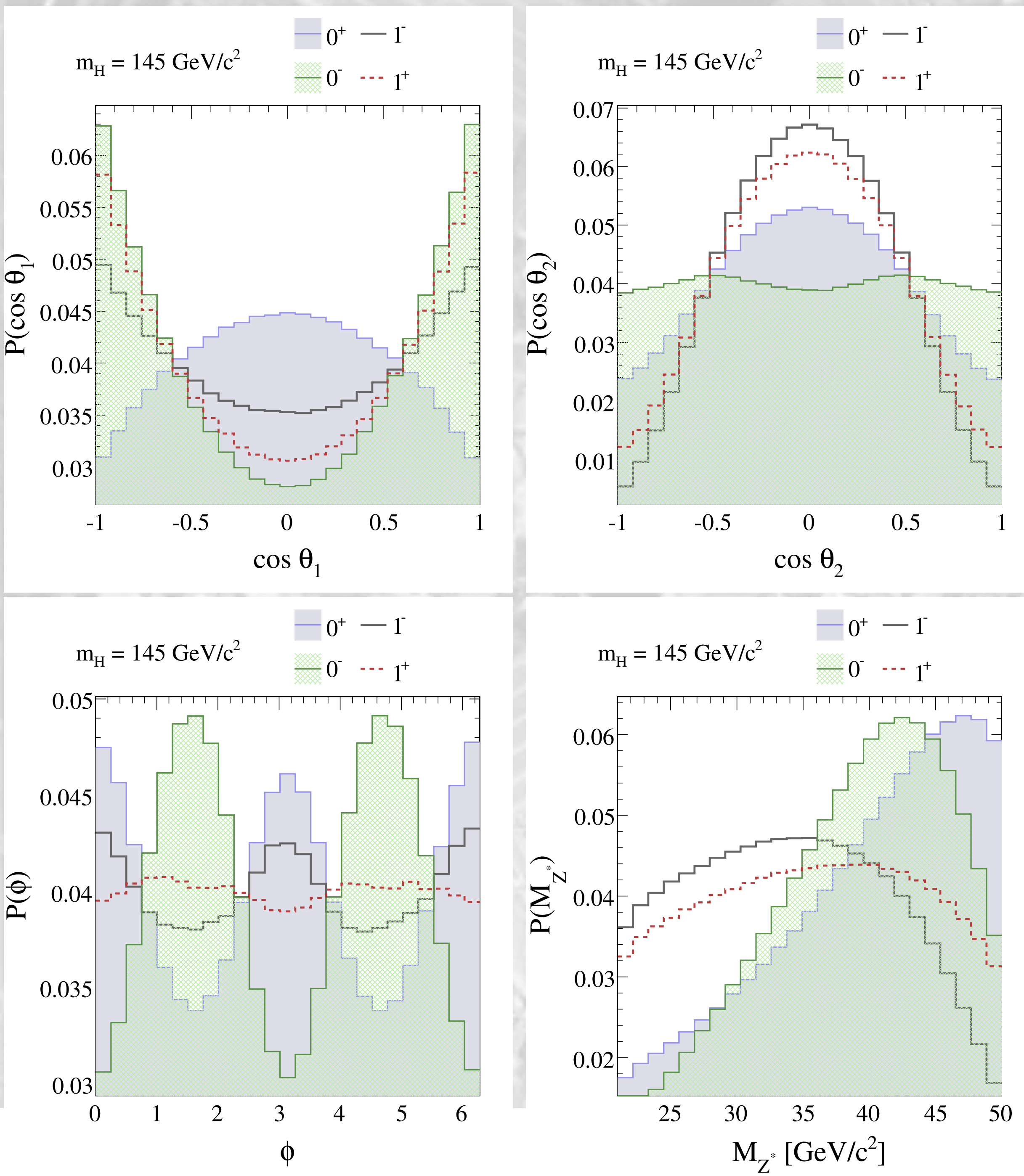
Obs. (exp.)	4ℓ	2ℓ2ν	Combined
Γ_H/Γ_H^{SM} (95% CL)	< 8.0 (10.1)	< 8.1 (10.6)	< 5.4 (8.0)

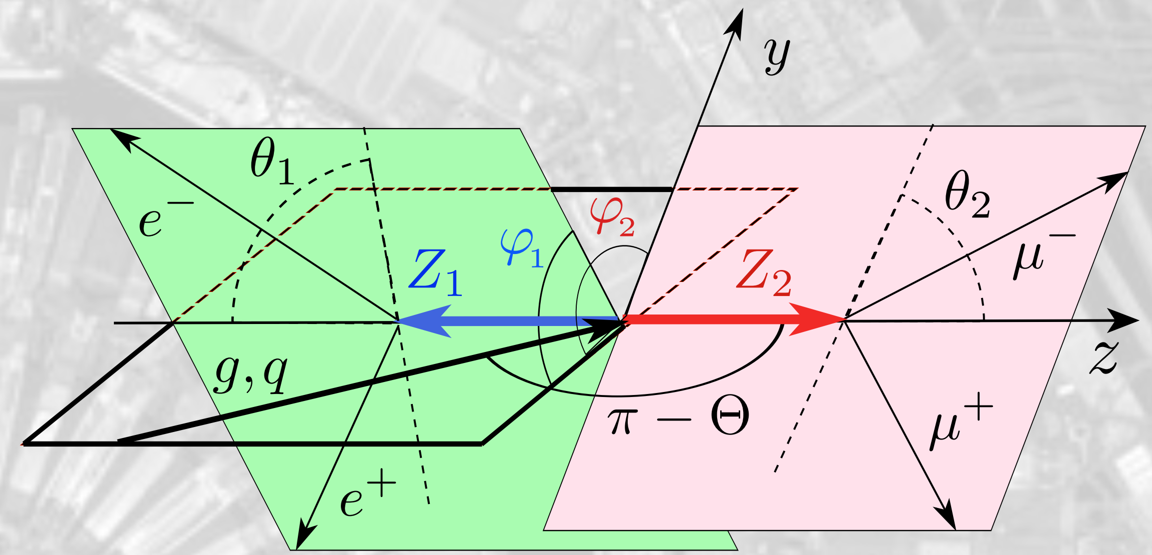




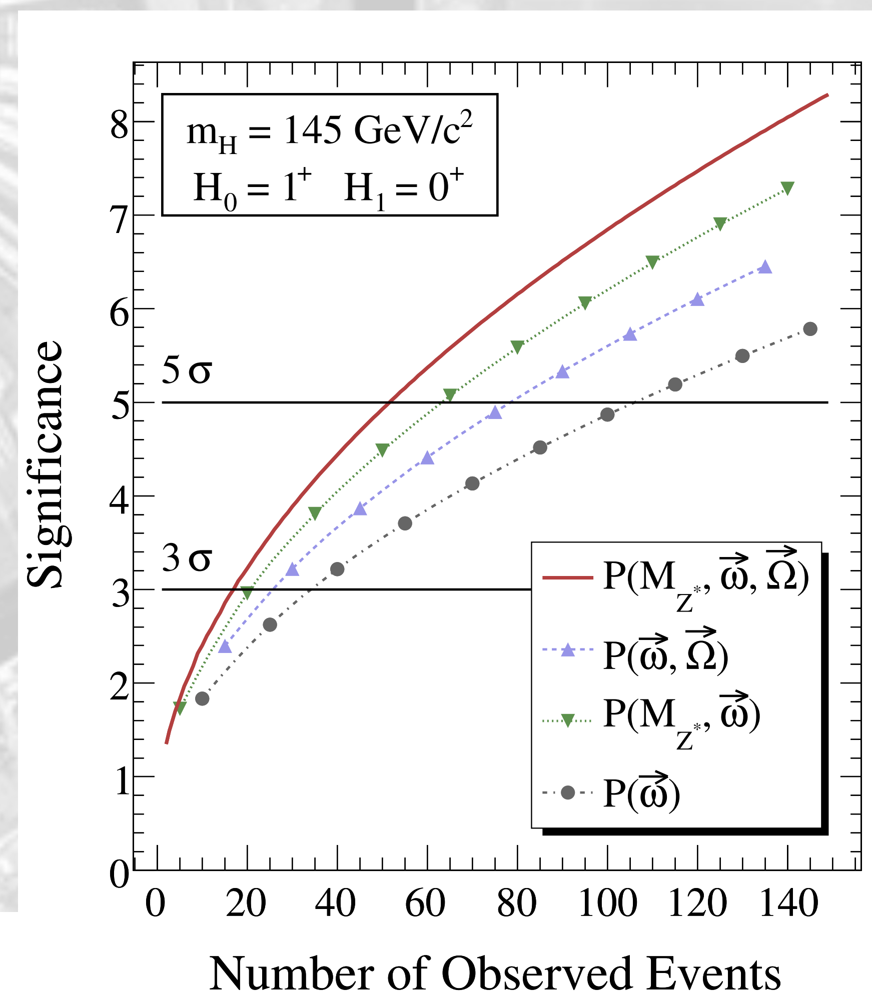
Higgs properties

- Quantum numbers can be measured from angular distribution of the H decay products
- Correlation is crucial
- The mass of the Z* helps a lot





N. Cabibbo and A. Maksymowicz, Phys. Rev. **137**, B438 (1965) [Erratum-ibid. **168**, 1926 (1968)].

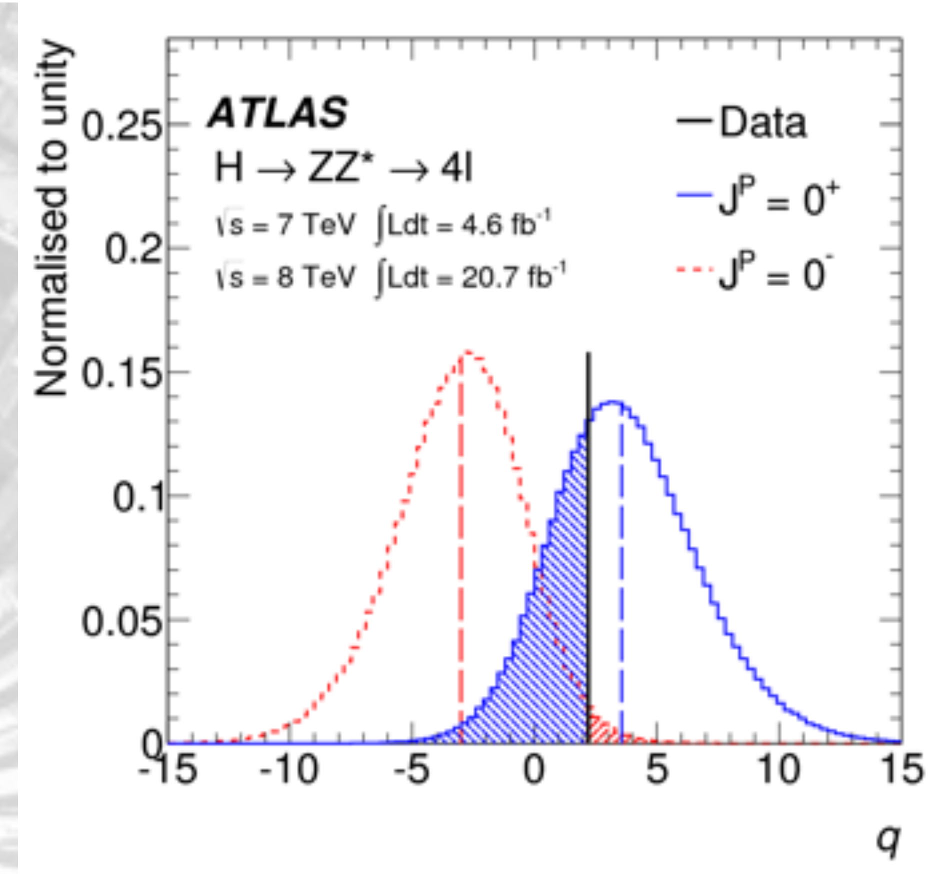


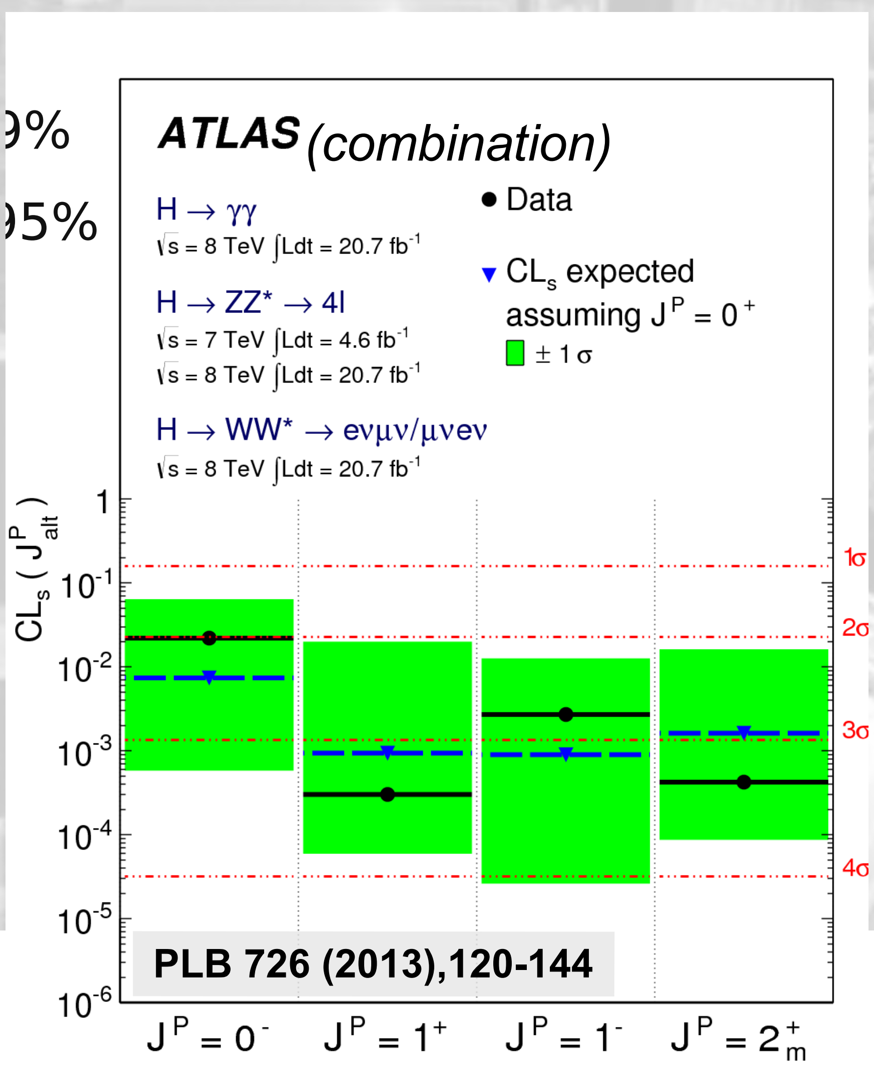
http://arxiv.org/abs/1001.5300

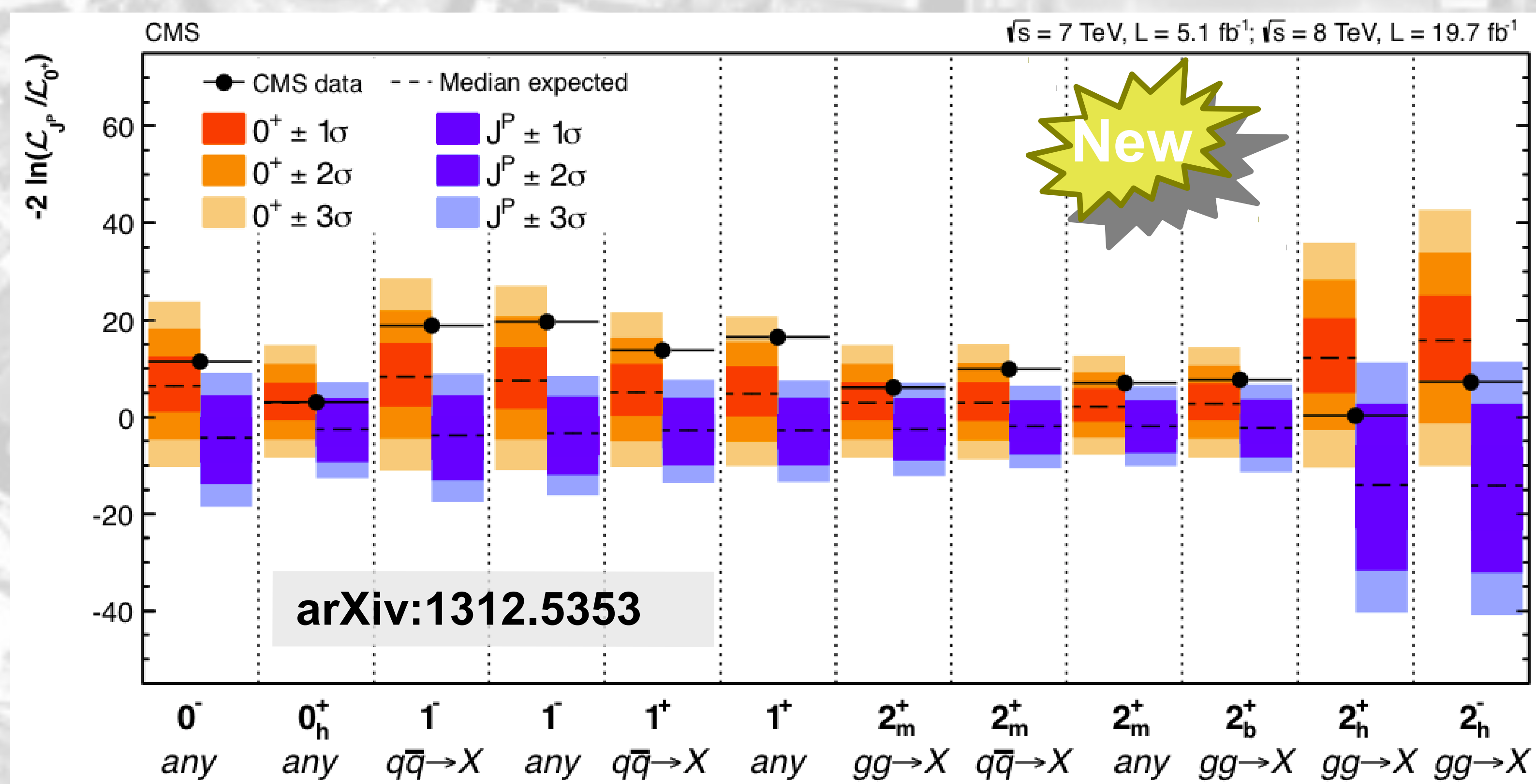
Higgs properties

- One can build a Likelihood function for the N-dim distribution of these variables under different Quantum Numbers hypotheses

- A hypothesis test allows to exclude a BSM hypothesis in favour of the SM hypothesis at a given CL

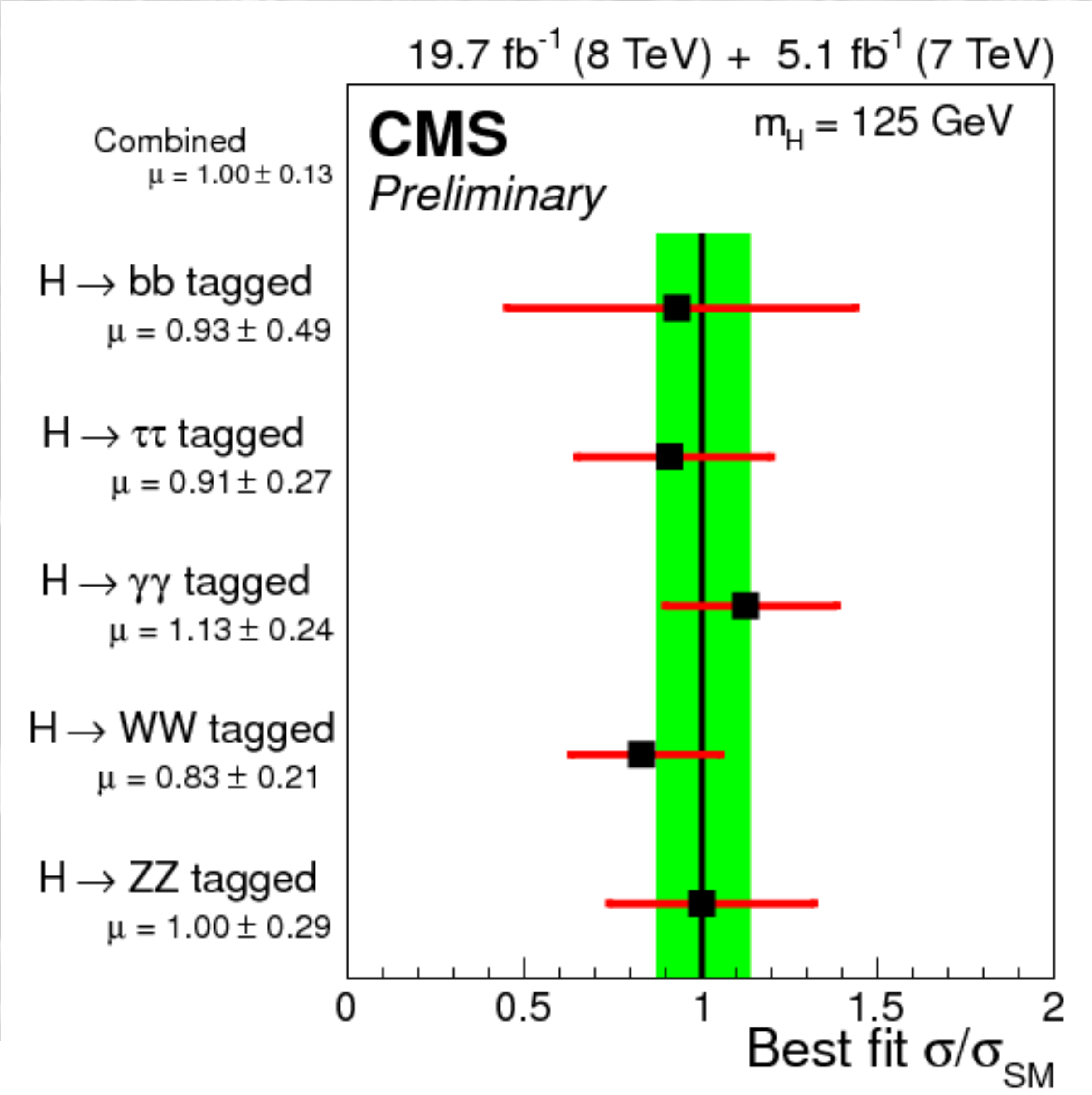


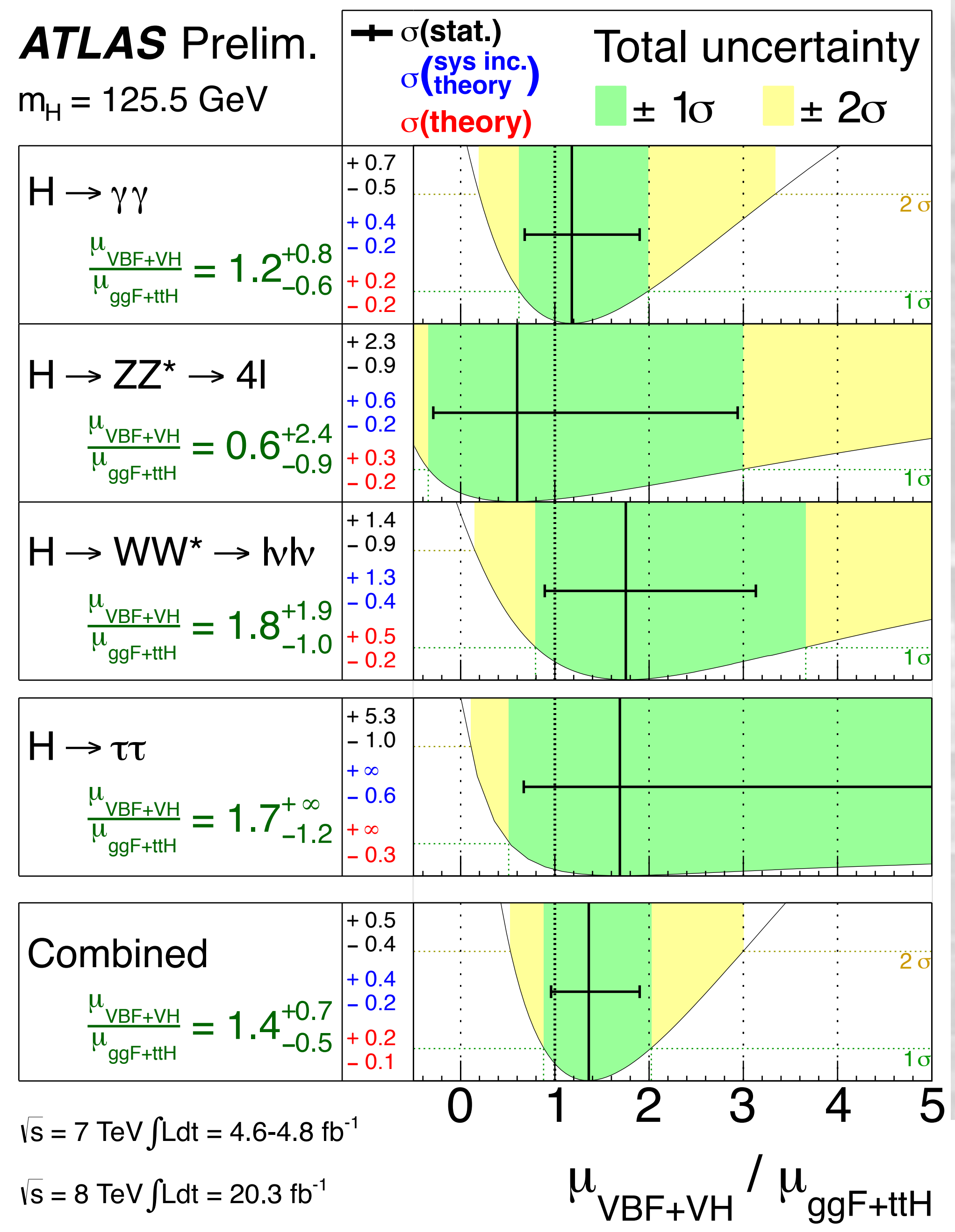




Signal Strength

- Established coupling to fermions and vector bosons
- Couplings scale as expected in the SM
- Deviations are possible (within errors) but cannot be of O(1) w/o introducing tension between different channels





COUPLING FIT

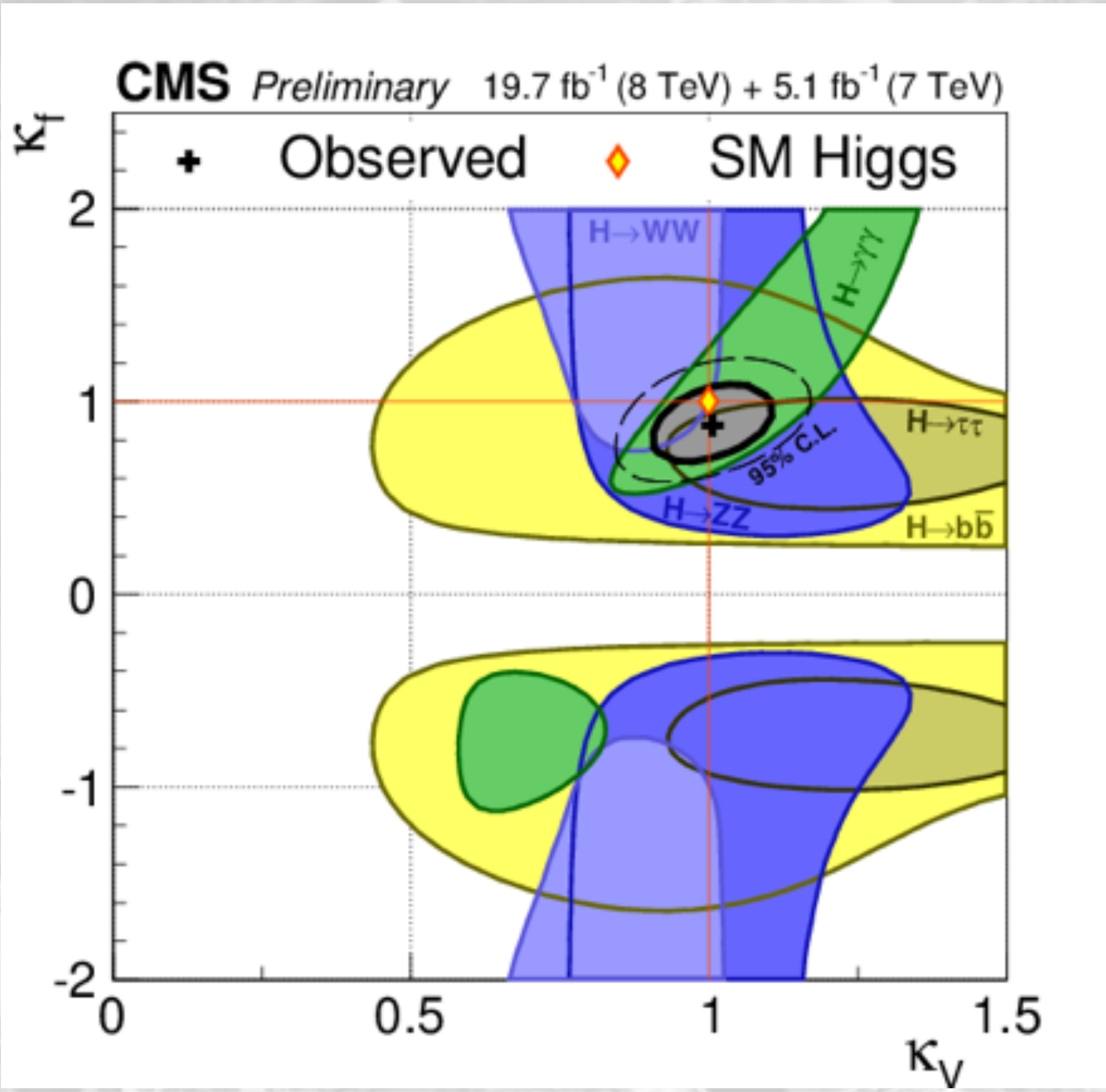
- Generalize couplings introducing multiplicative factors
- One channel can be function of more than one parameter

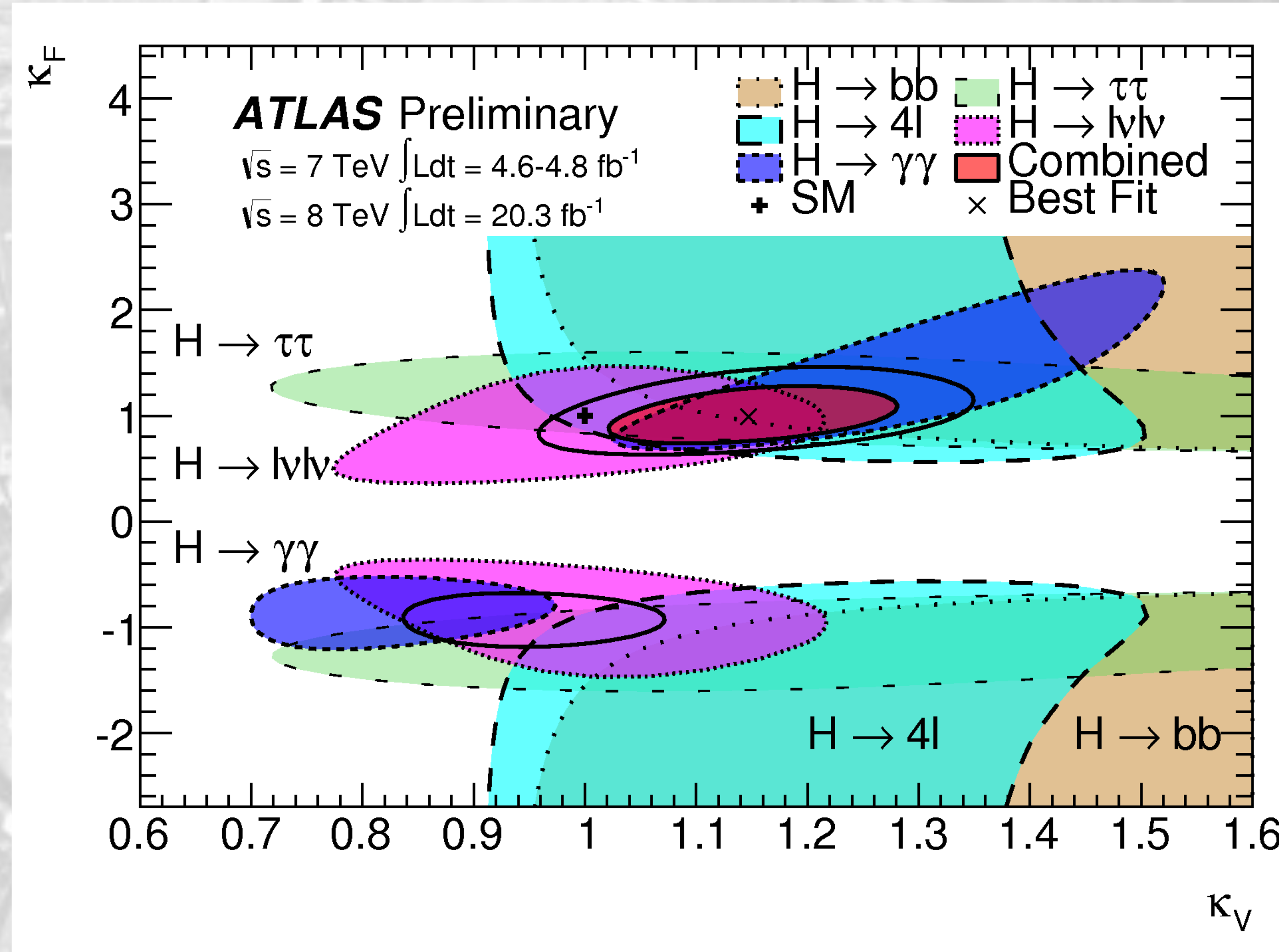
$$\kappa_g^2(\kappa_b, \kappa_t) = \frac{\kappa_t^2 \cdot \sigma_{ggH}^{tt} + \kappa_b^2 \cdot \sigma_{ggH}^{bb} + \kappa_t \kappa_b \cdot \sigma_{ggH}^{tb}}{\sigma_{ggH}^{tt} + \sigma_{ggH}^{bb} + \sigma_{ggH}^{tb}}$$

- Simplified analysis assuming universal fermion (κ_f) and vector (κ_V) deviations

Analysis	Prod.	Decay	Analysis	Prod.	Decay
H	κ	κ	H inclusive	κ	κ
H	κ	κ	H inclusive	κ	κ
H	κ	κ	H	κ	κ
H	κ	κ			
H	κ	κ			

COUPLING FIT

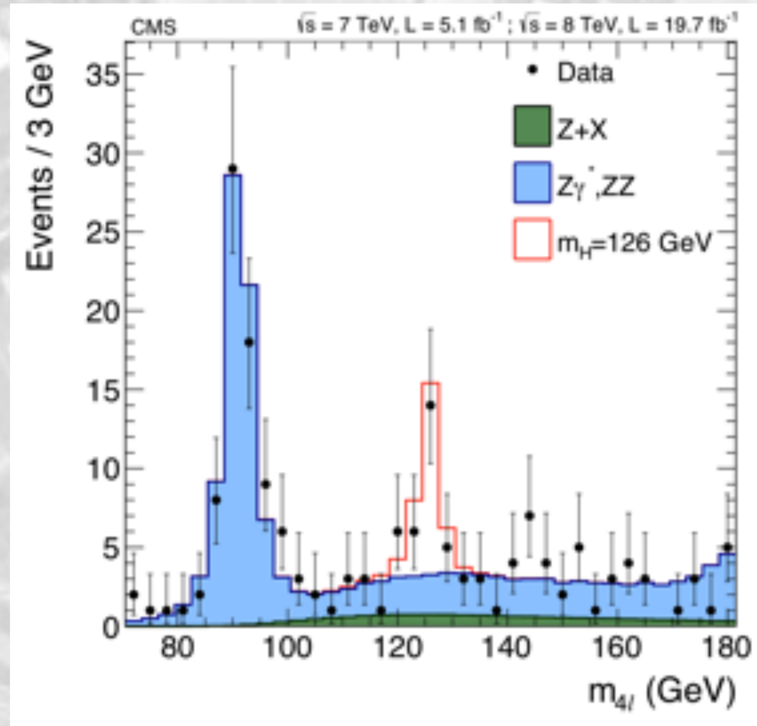


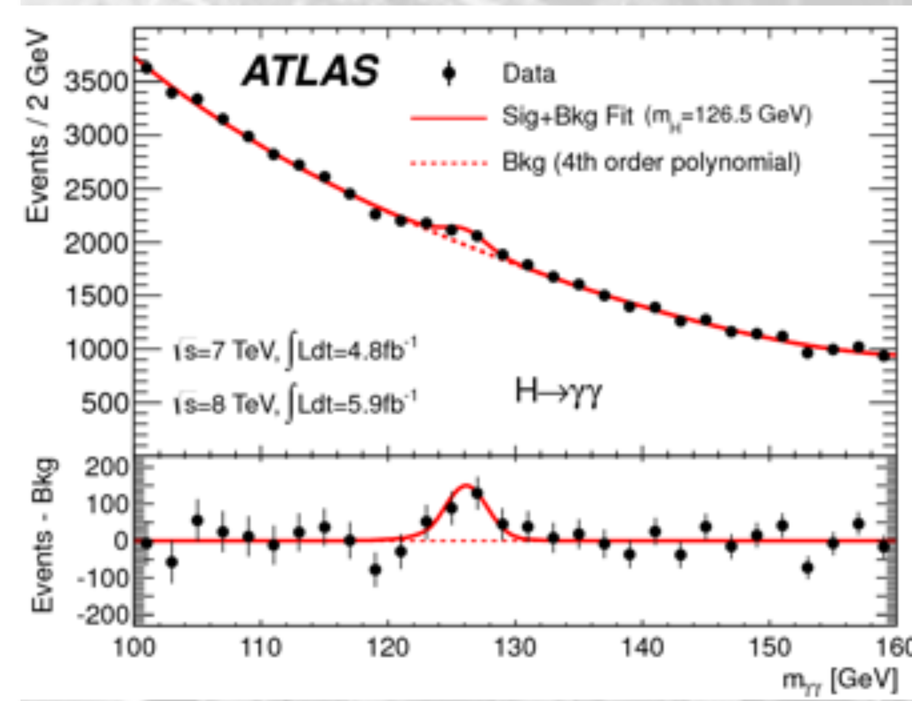


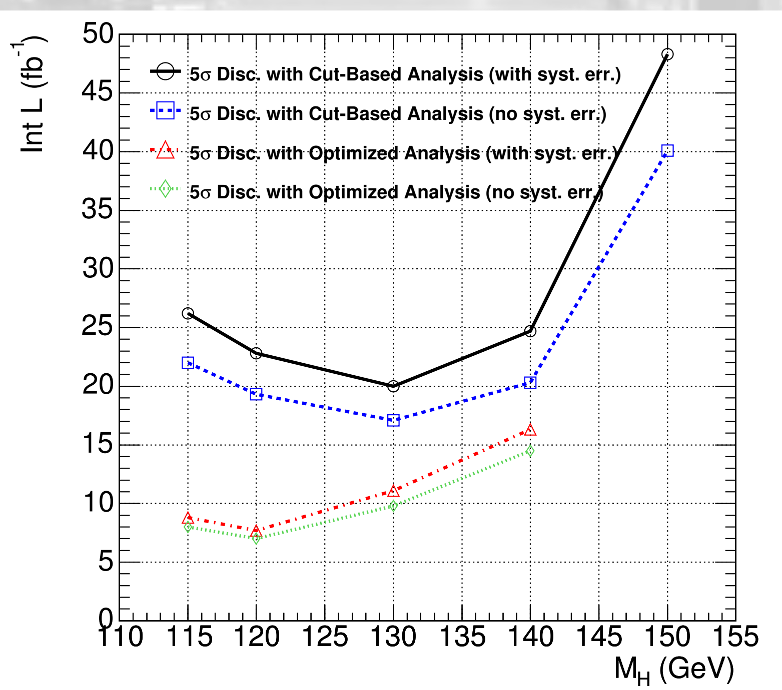
- This is the starting point for many phono studies
  - first reproduce these plots
  - then run an actual fit with a realising model/Lagrangian in mind

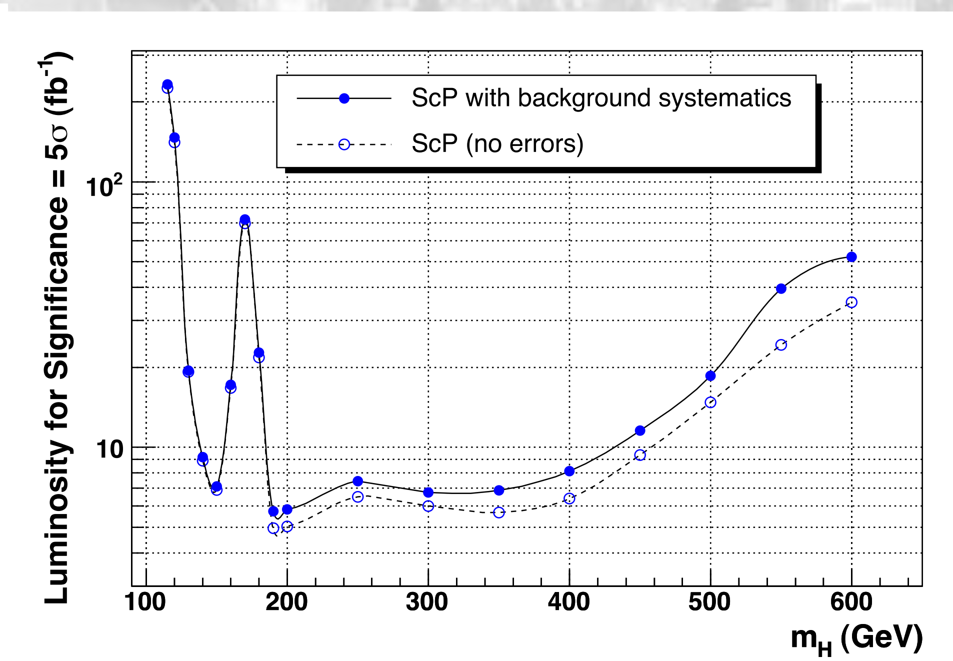
This was fast!!!

- Run I marked the first success of the LHC program
    - the Higgs boson was indeed found









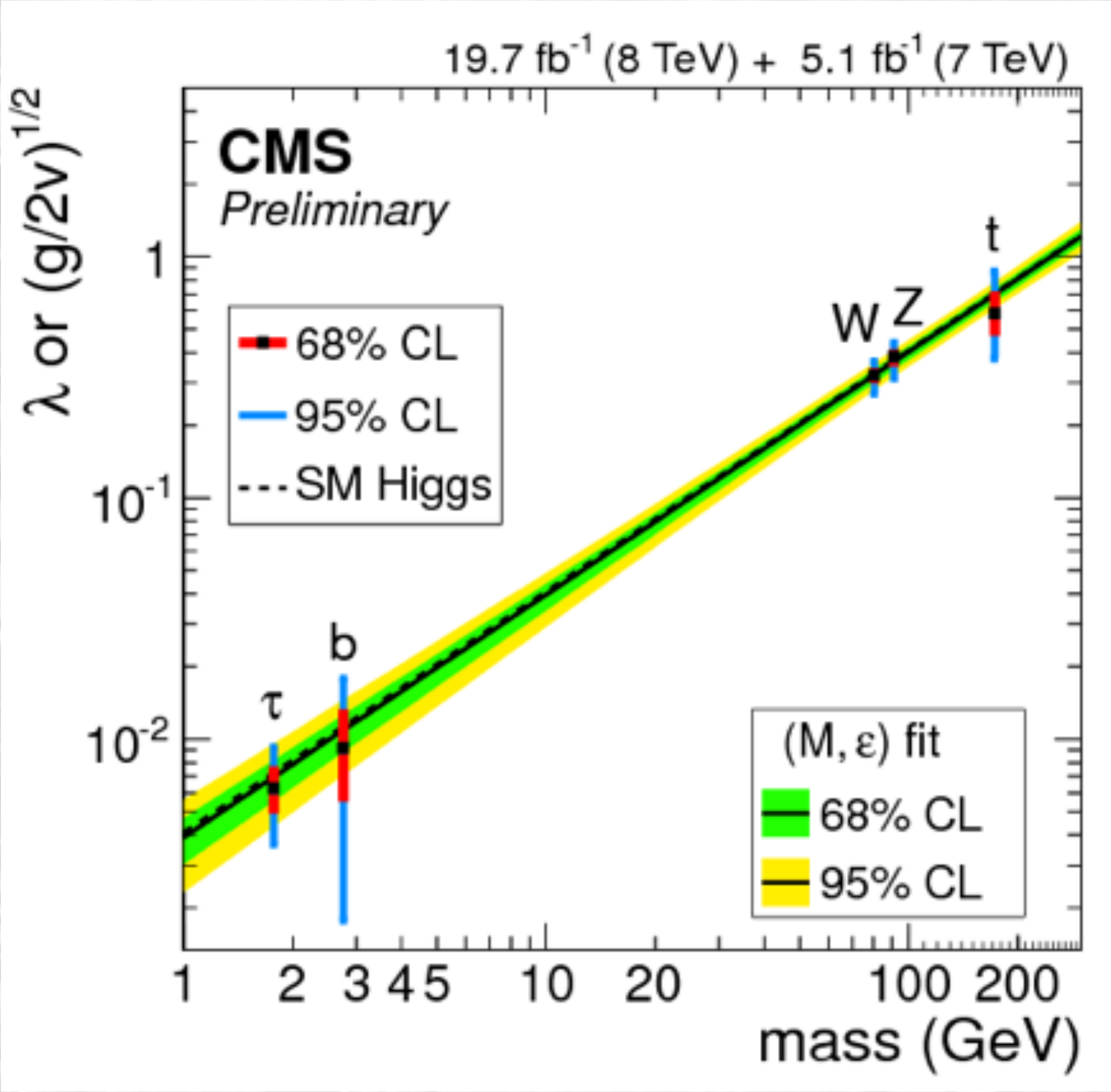
Discovery Lumi for 14 TeV collisions (where S/B is more favorable)

Two things to keep in mind

- **It arrived earlier than expected**
- **we knew what to search for, and this helped A LOT**

What I did not Cover

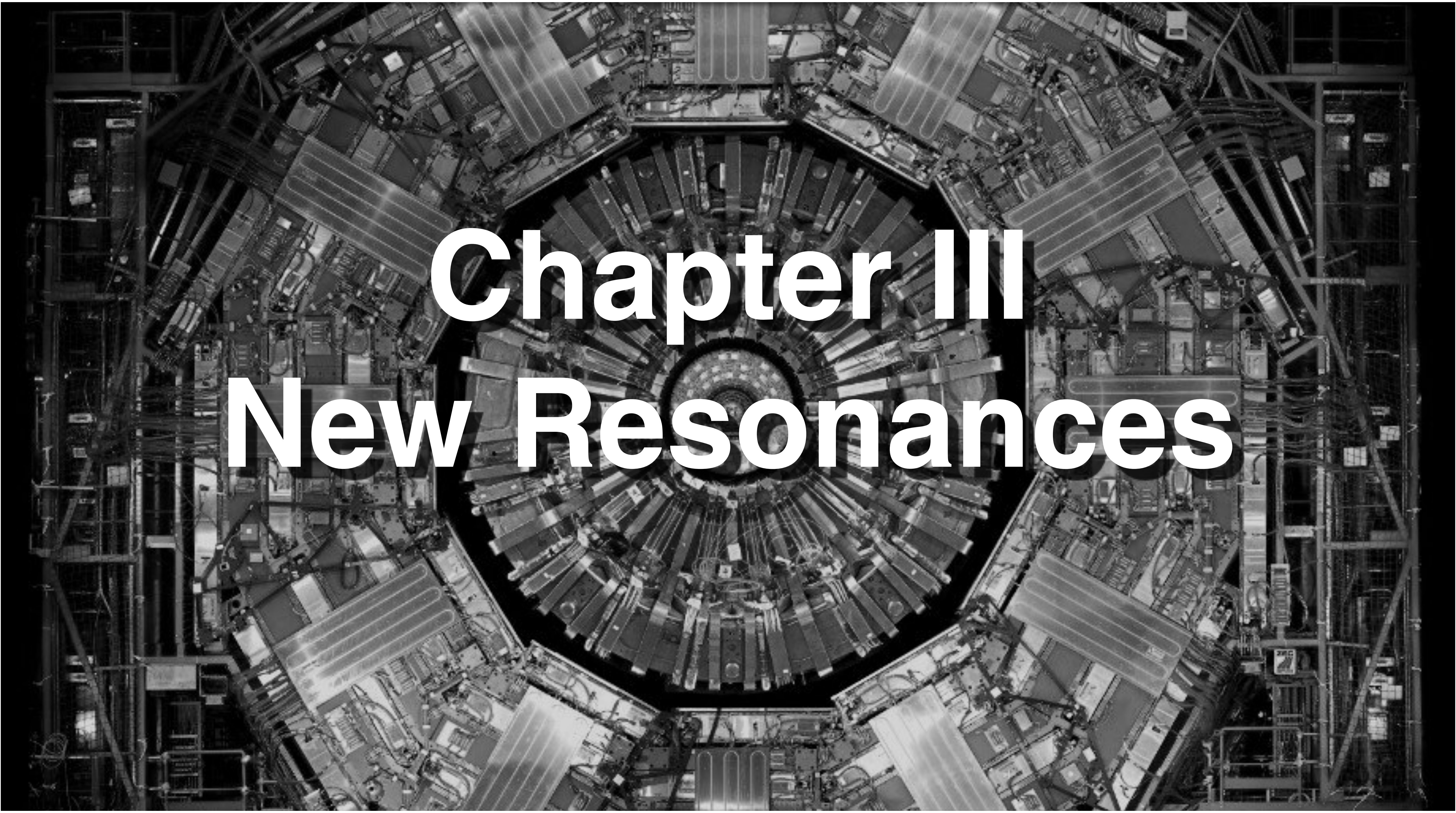
- H fermion decays
  - bb, τ τ
  - Important to characterize the new particle as the Higgs boson
- H produced in association with top pairs
  - very small cross section
  - direct access to top Yukawa coupling
  - hot topic for next run
- Rare Higgs decays



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

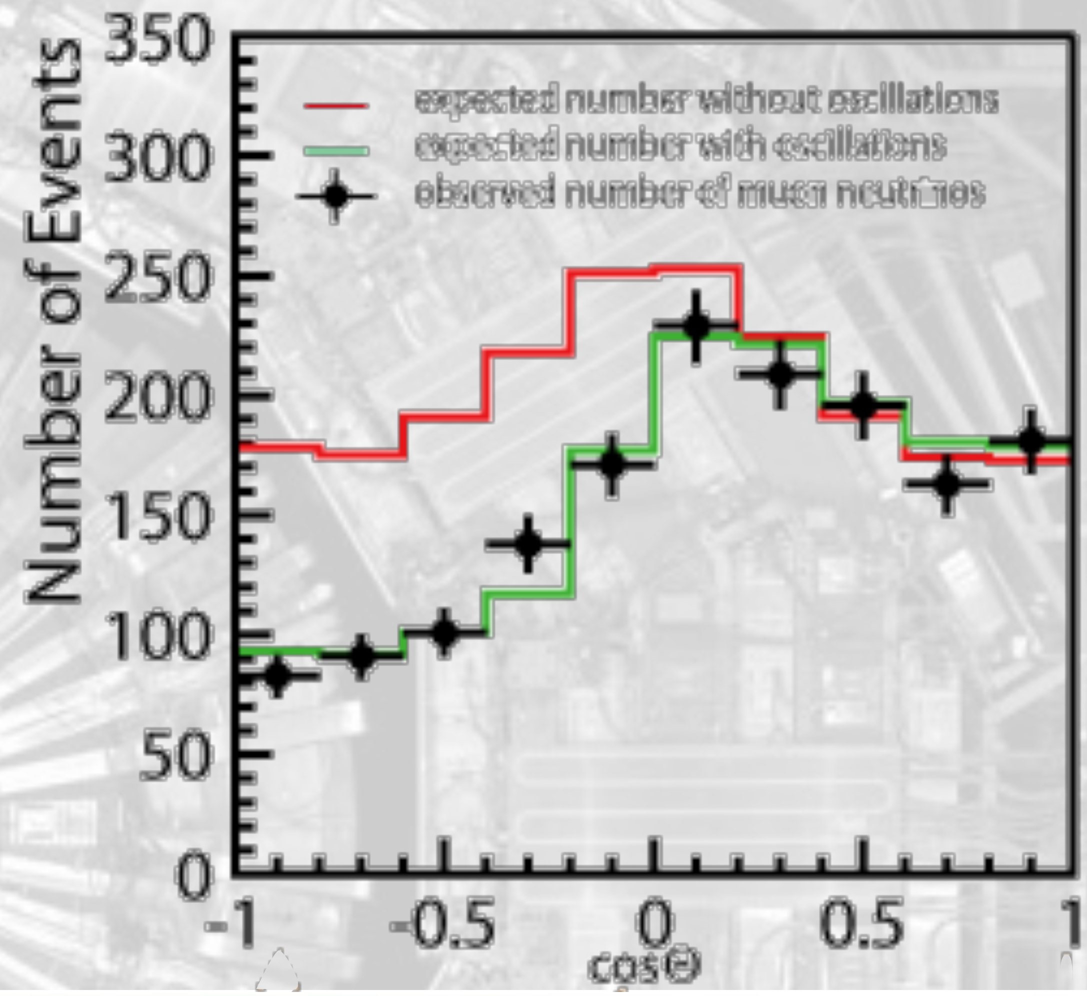
Chapter III
New Resonances

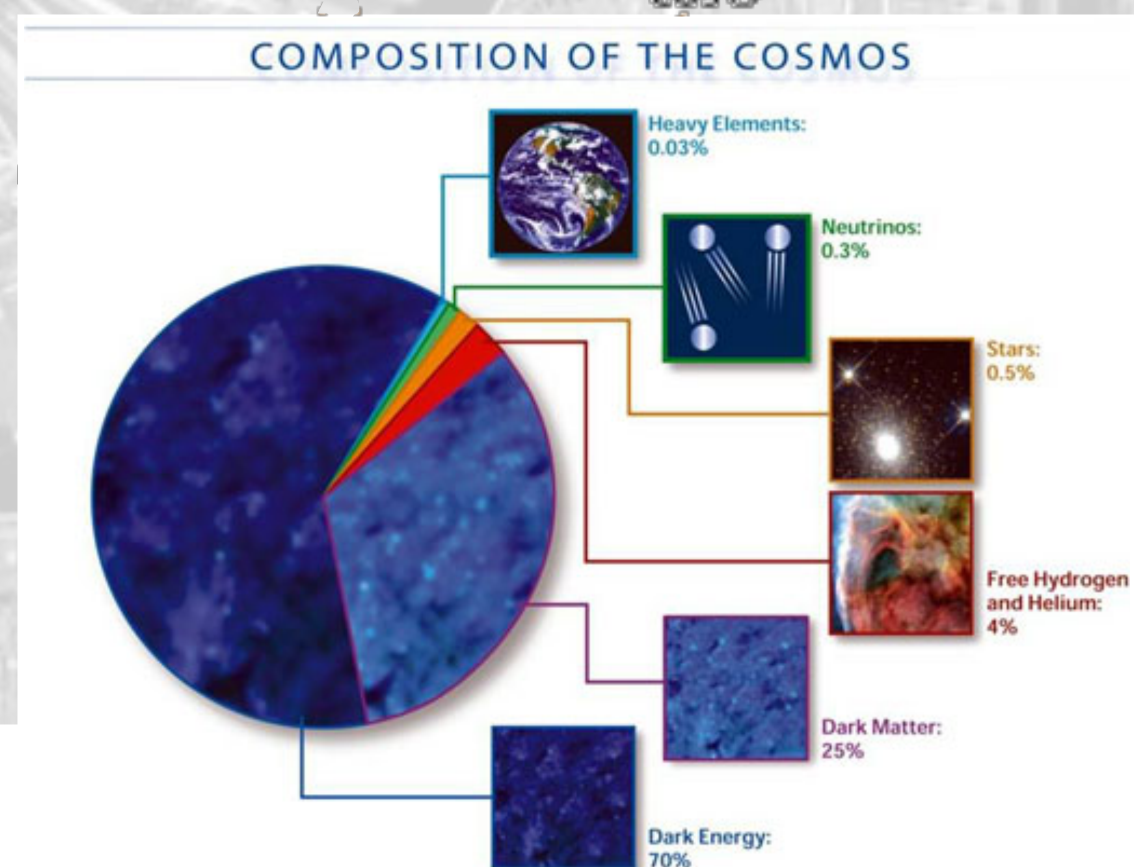


Why Going Beyond?

Because we Have some hint

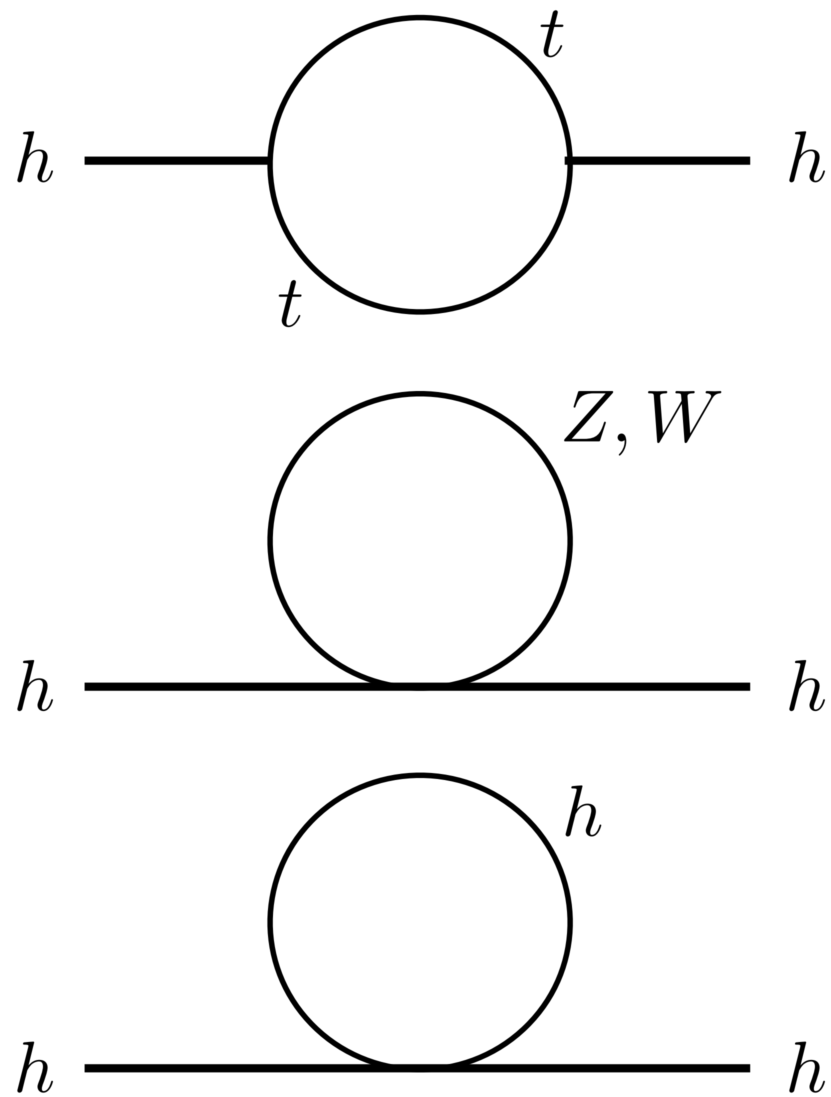
- Neutrinos have masses (as deduced by their oscillations)
  - explanation of the small values BSM (e.g. seesaw)
- Cosmology observations point to the existence of Dark Matter
  - neutrinos are too light to explain the observation
  - no other viable candidate in the SM





Hierarchy Problem

- Quantum corrections to the Higgs propagator are quadratic functions of the SM cutoff scale (e.g., the Planck scale, in absence of New Physics)
  - The Higgs mass is an indicator of where the Standard Model validity stops
  - a cancellation of these contributions happens by a new mechanism (e.g., SUSY) or by chance (fine tuning)

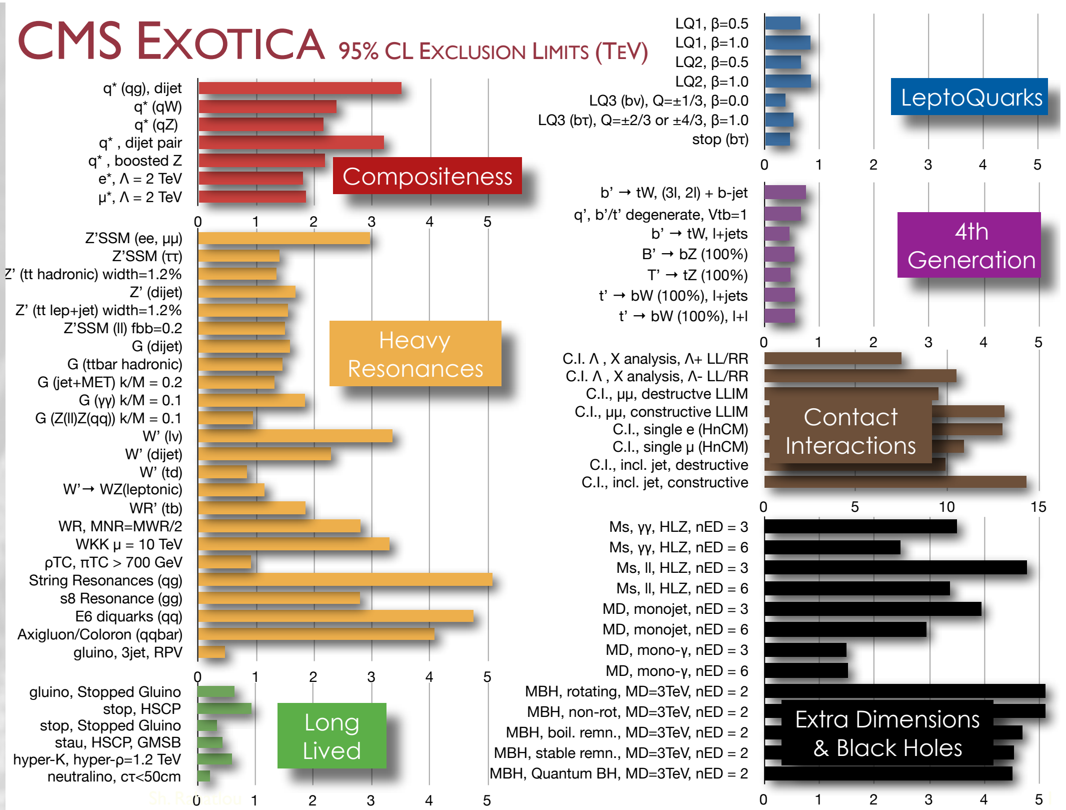


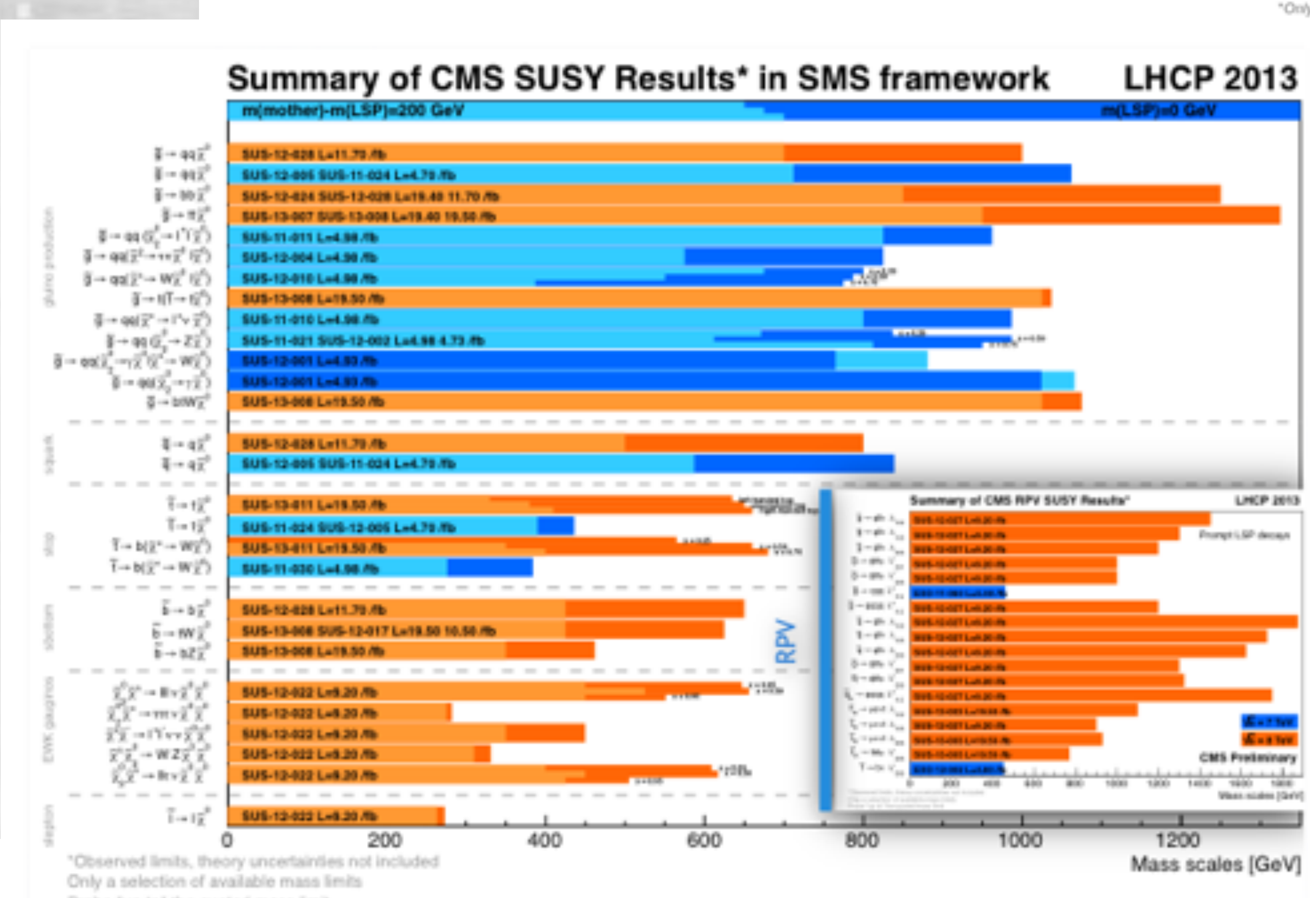
$$\delta m_h^2 \sim -\frac{3}{8\pi^2}\lambda_t^2\Lambda^2$$

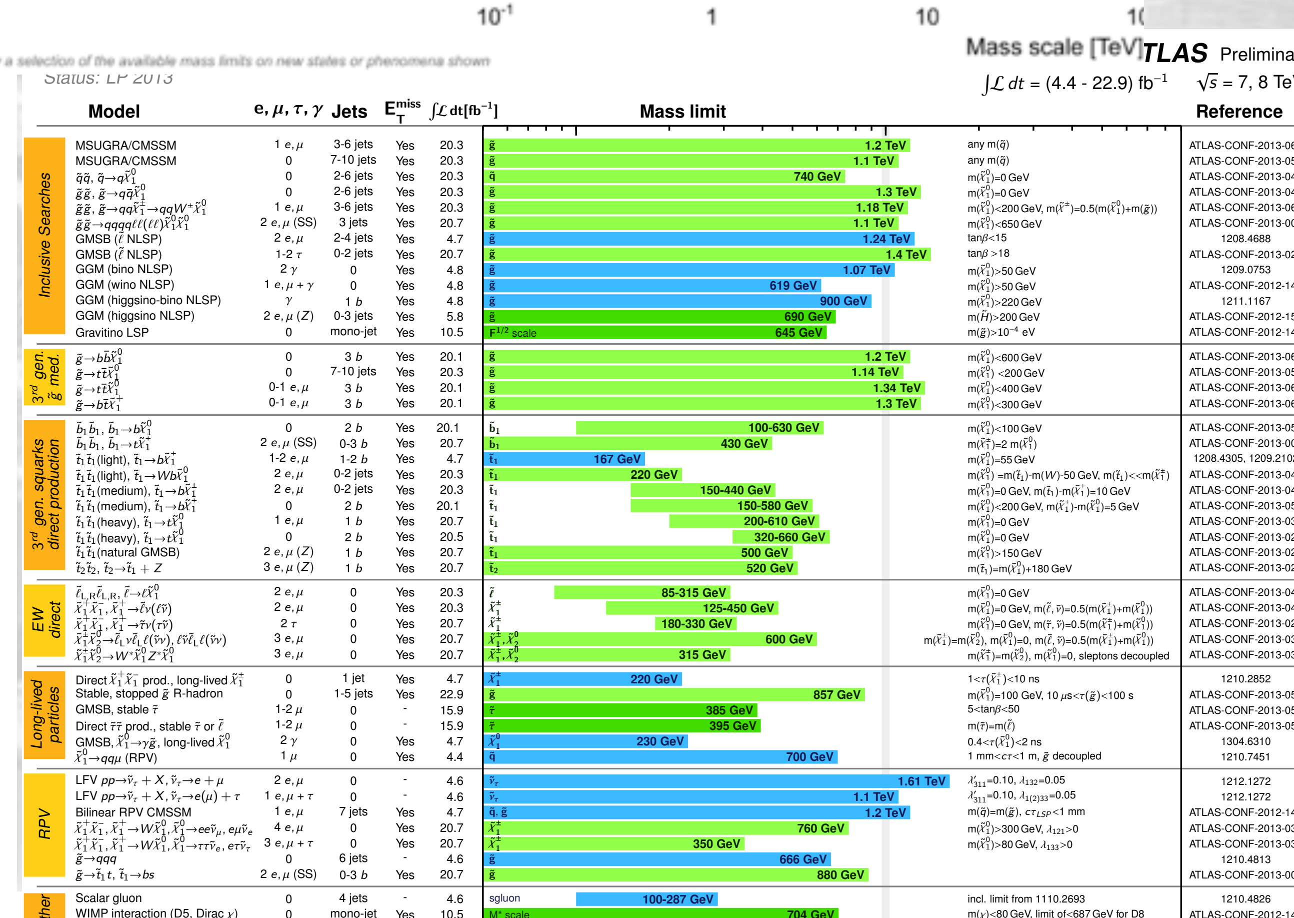
$$\delta m_h^2 \sim \frac{9}{64\pi^2}g^2\Lambda^2$$

$$\delta m_h^2 \sim \frac{1}{16\pi^2}\lambda^2\Lambda^2$$

What To Look For?







What To Look For?

- Basically everything, as we have many possibilities and not a clear path in front of us

- Several possible models of New Physics at the EW scale

  - SUSY

  - Extra Dimensions

  - Compositeness

  - ....

- The main problem is that we found nothing so far

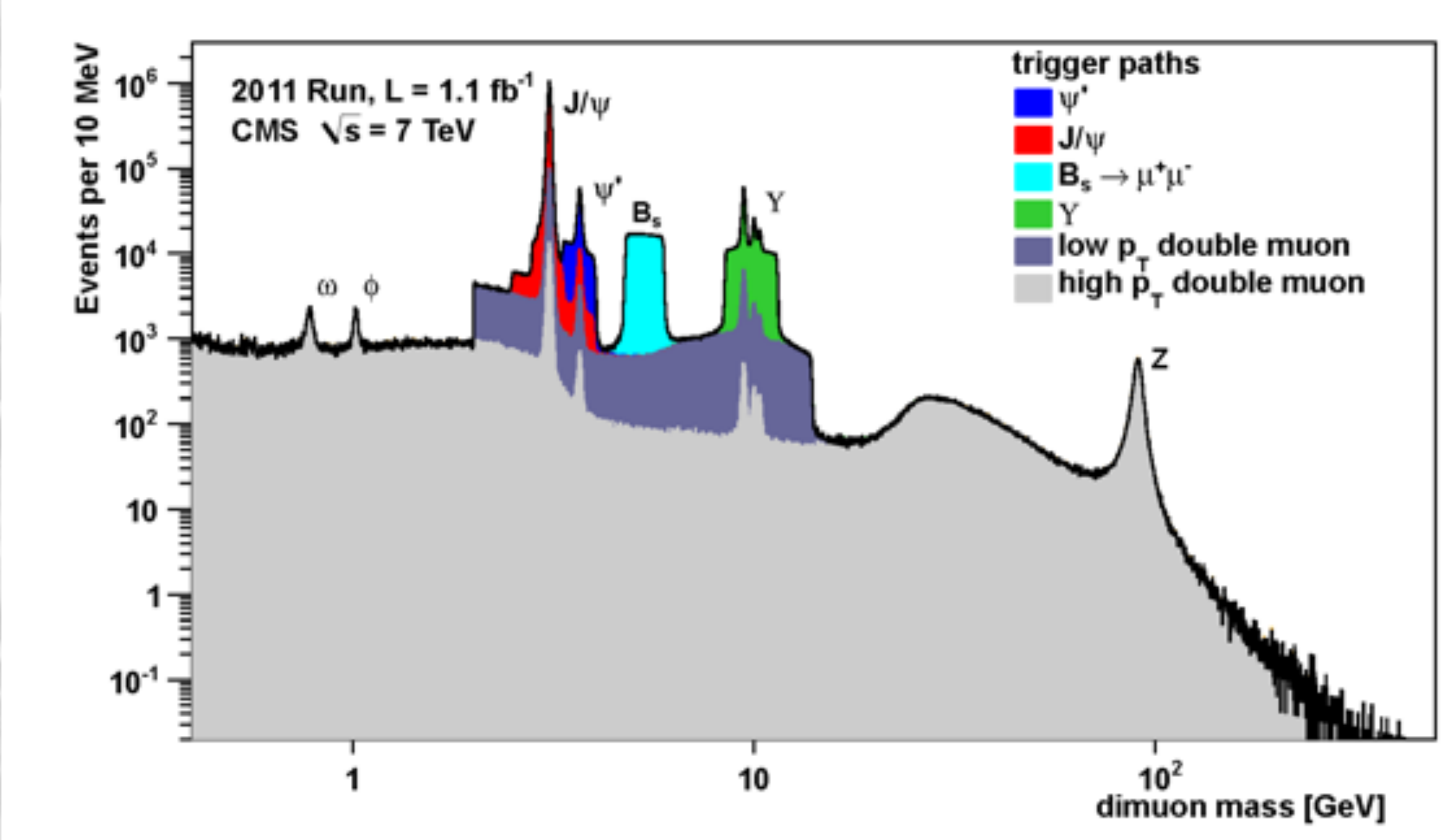
  - The fine-tuning-solving new physics to be fine-tuned

  - The hierarchy is not a problem but New Physics is still there (e.g., for Dark Matter)

New heavy Resonances

New Heavy States

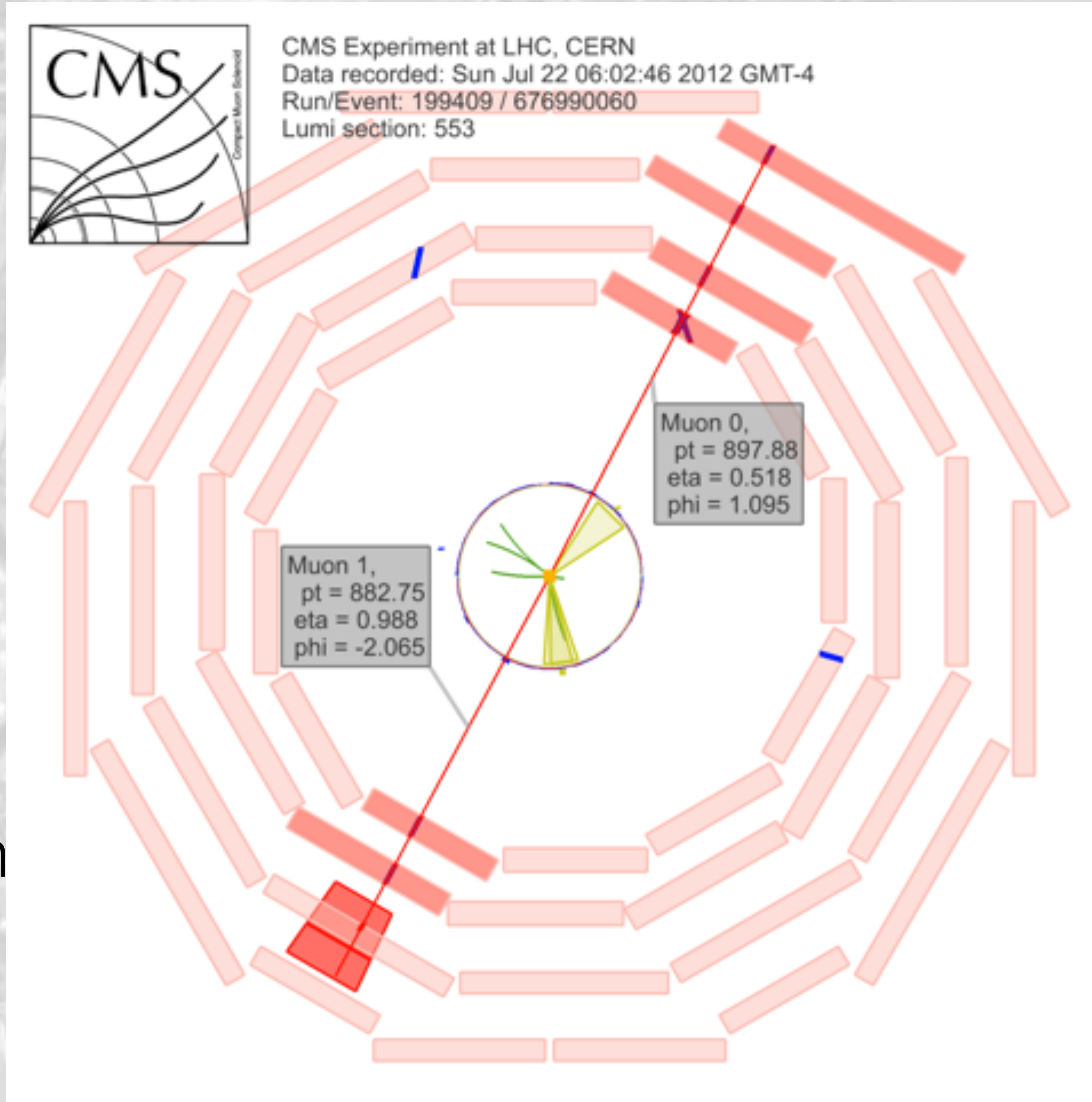
- For masses above 1 TeV, new resonances would decay to high-pT particles
- These particles are intrinsically different than the corresponding low-pT ones
  - Electrons mainly measured by calorimeter (not tracker)
  - Muons are less clean than electrons
  - Jets not necessarily come from QCD (quarks and gluons)



- Dedicated reconstruction techniques in place, optimized to keep good performances at large-pT
- **The peculiarity of ATLAS in CMS is in keeping excellent performances at 1 GeV and 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 the case of measurements with W/Z/top/H, muon final states are not the golden channel for this physics
- Despite the resolution, high-pT muons are an excellent discovery tool



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

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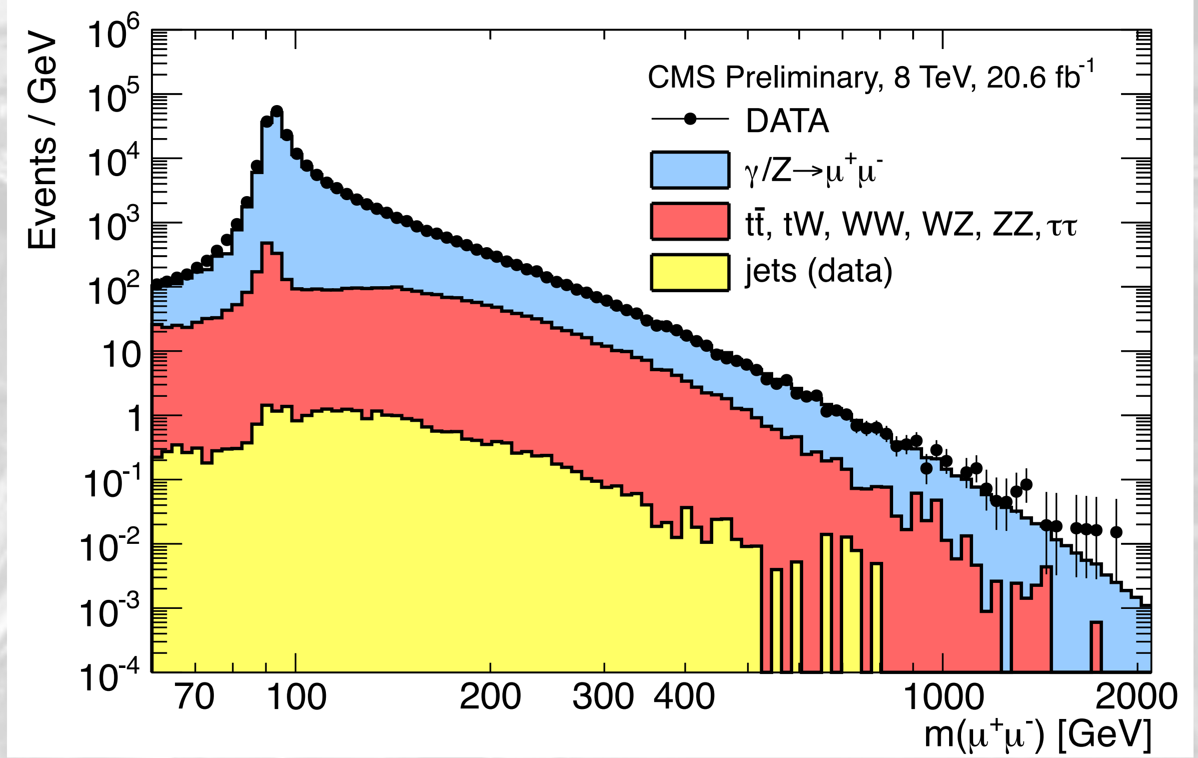
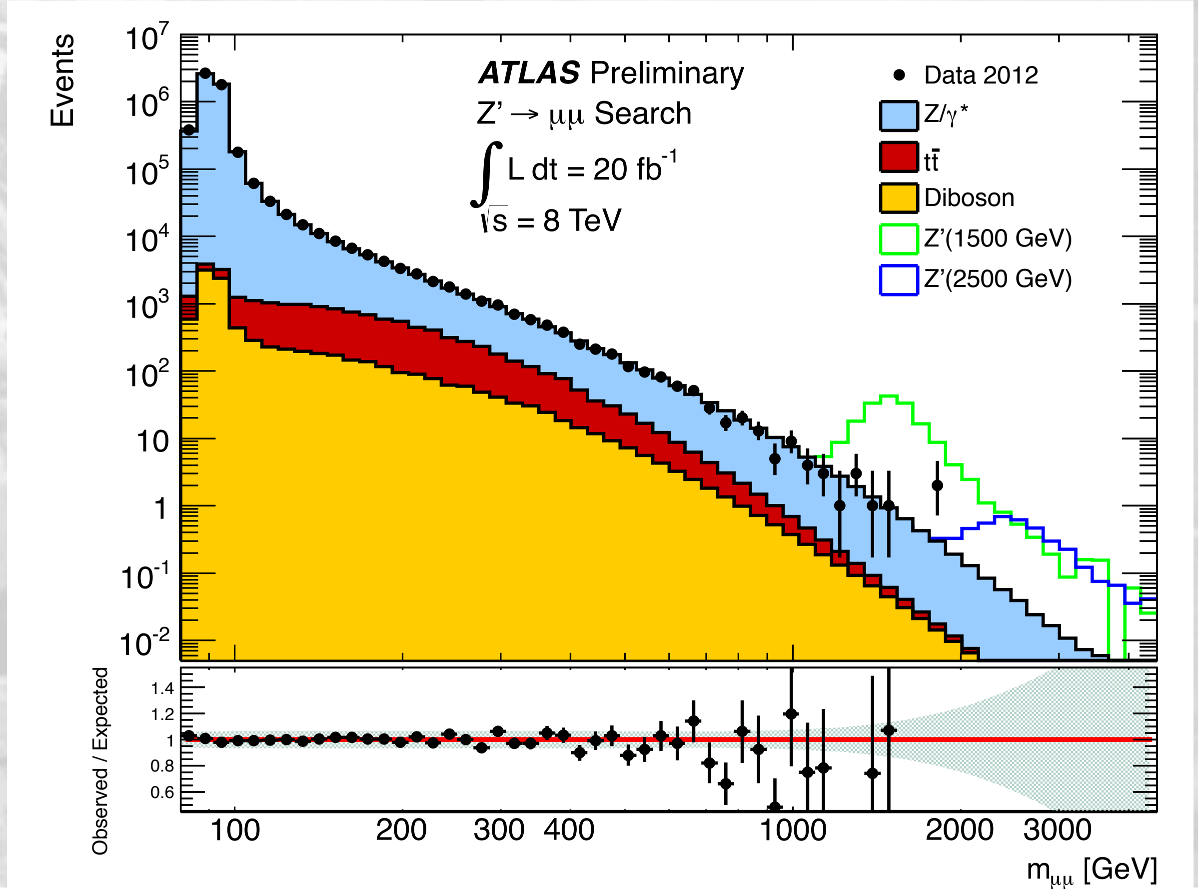
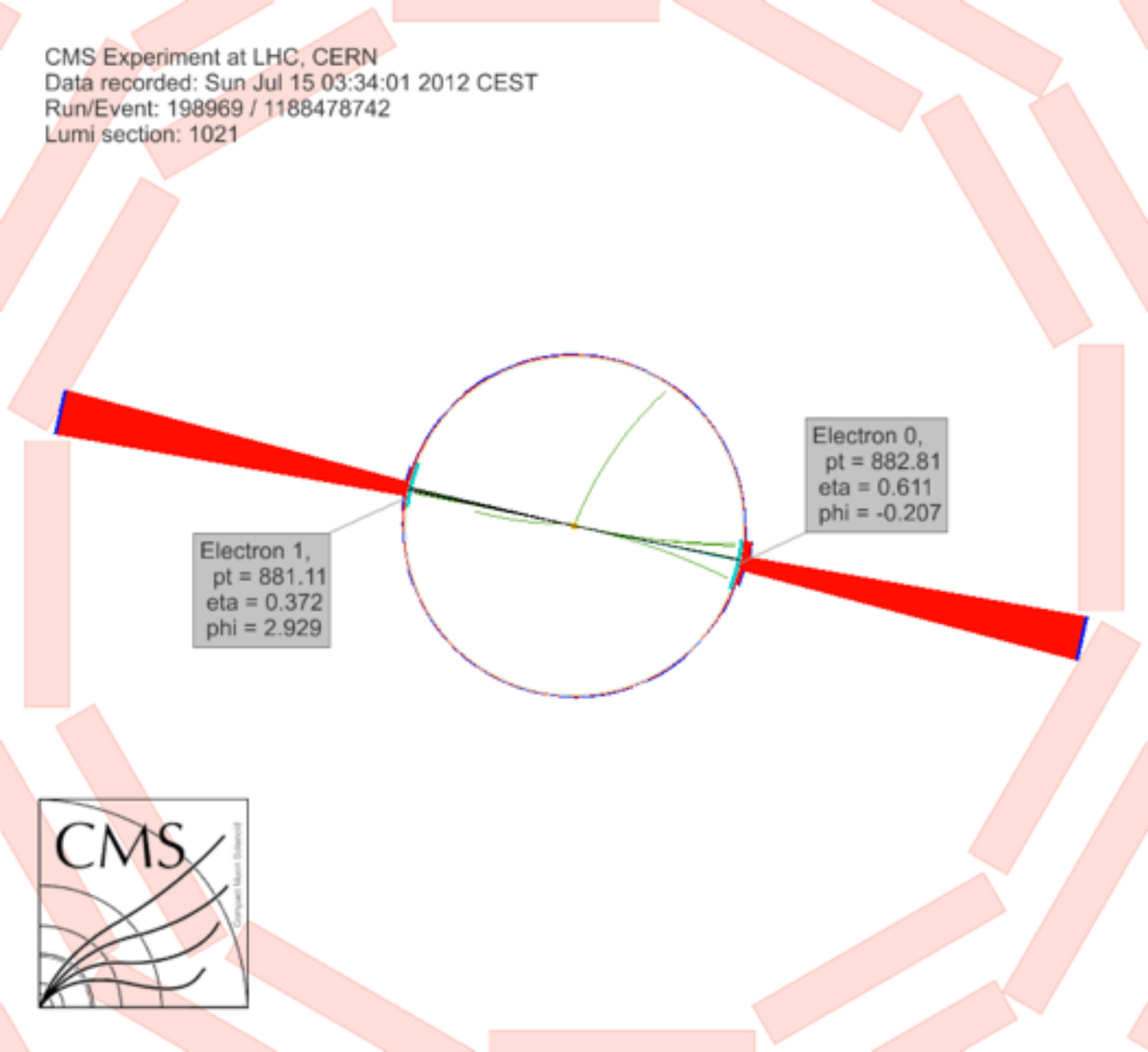




High-Pt Electrons

- 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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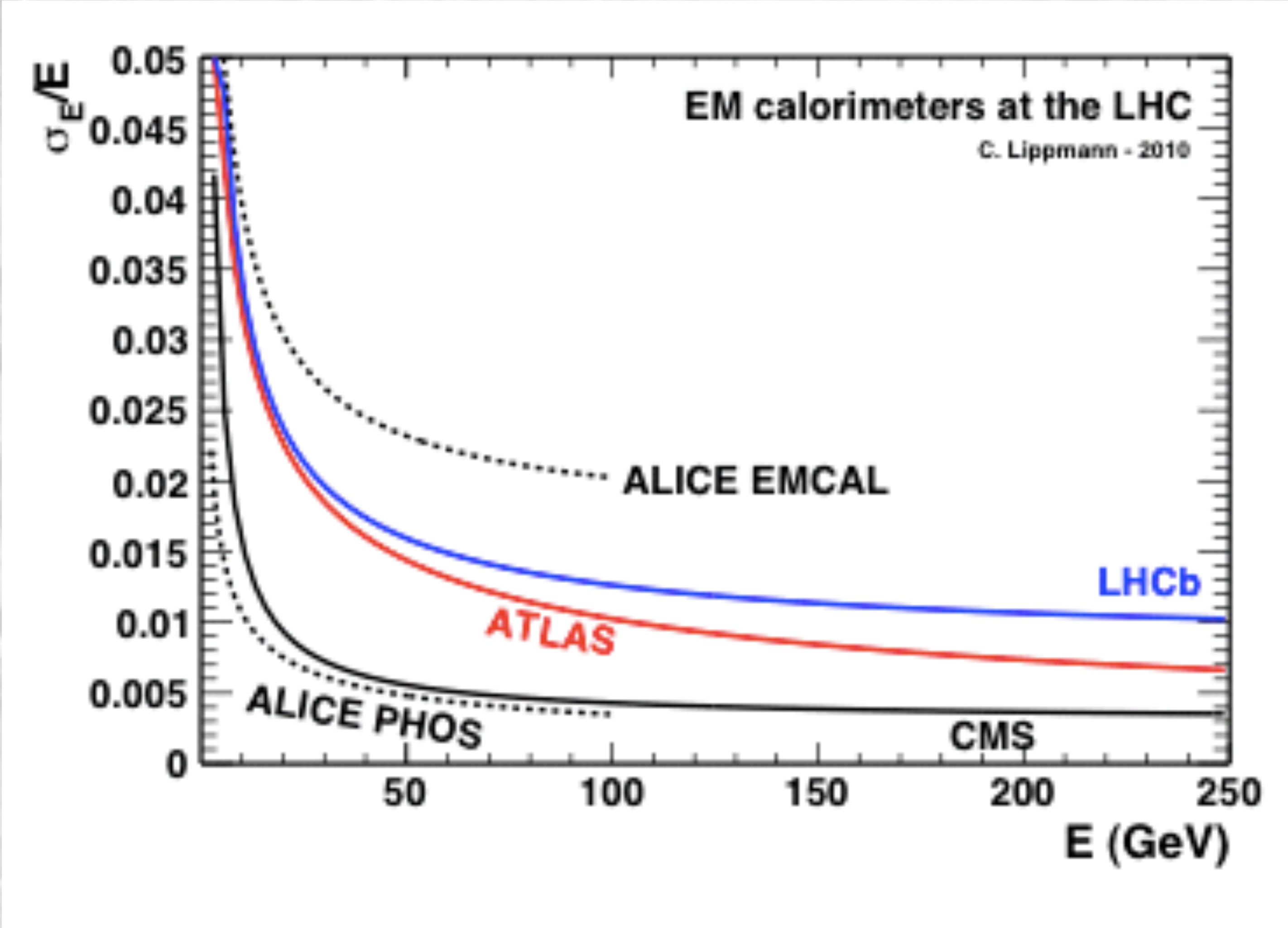

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

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

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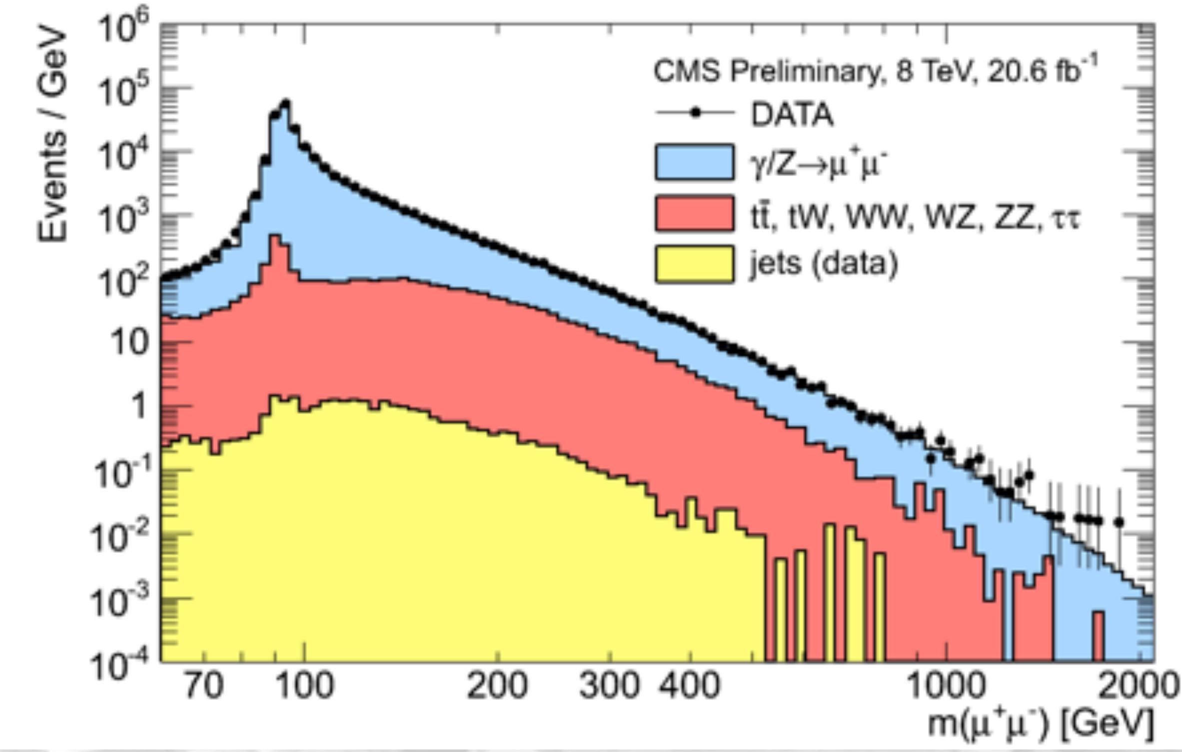
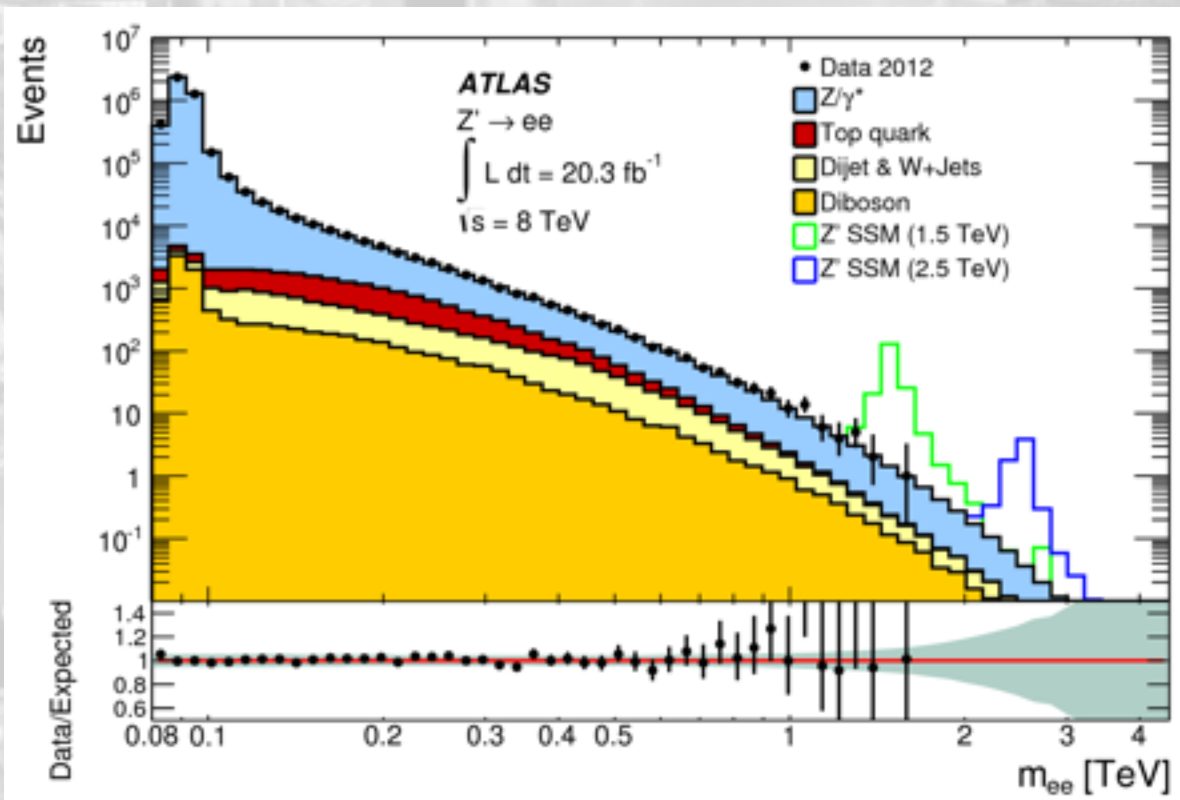
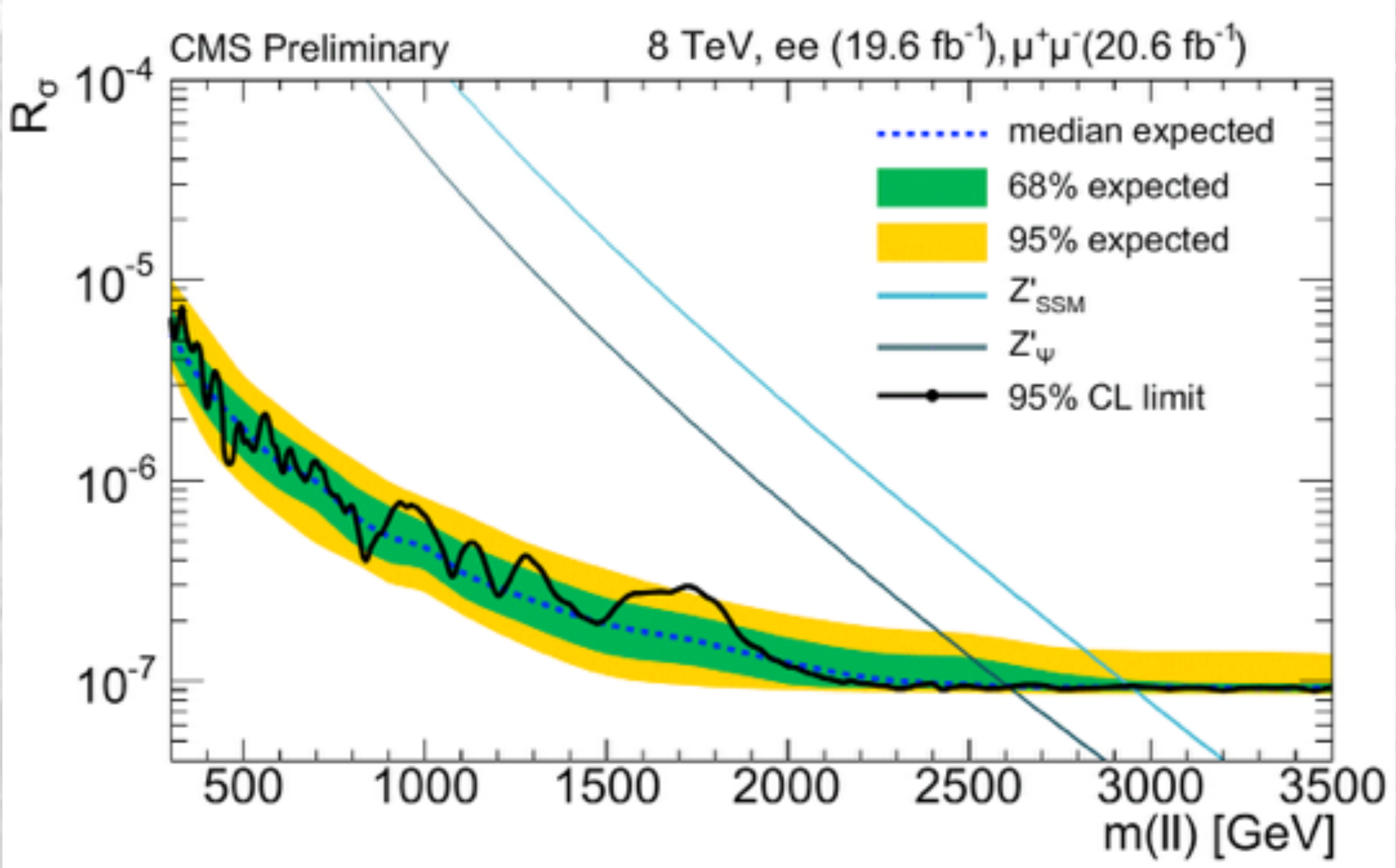
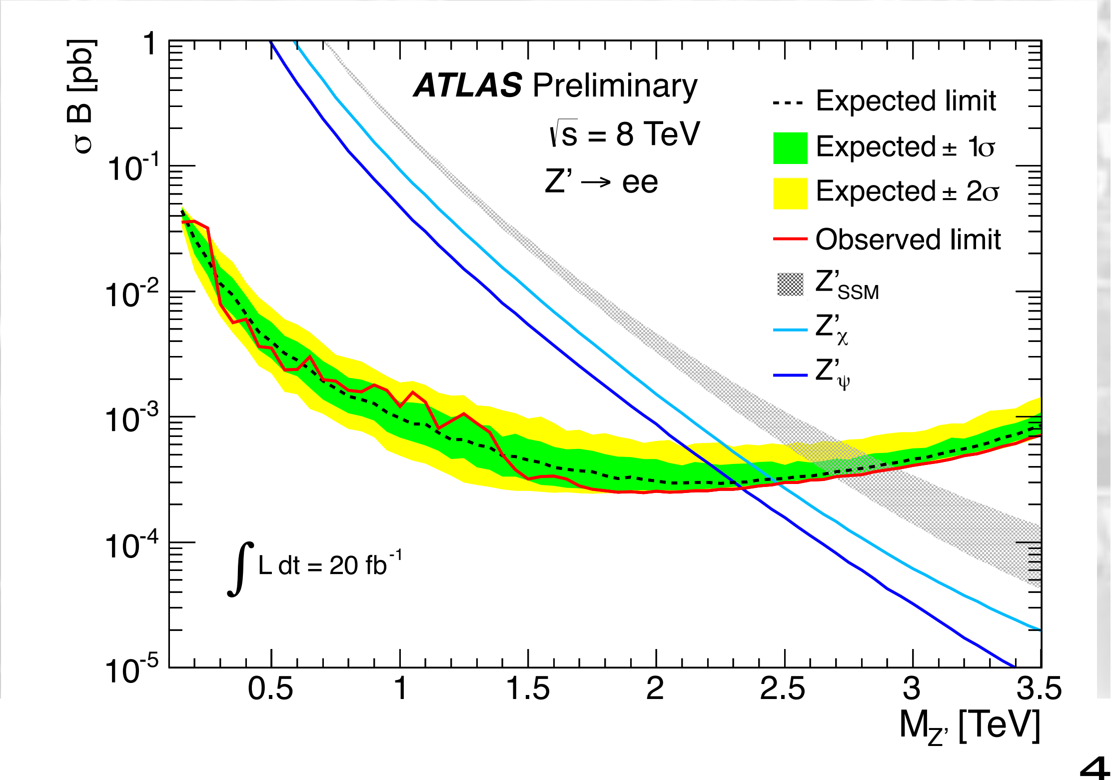
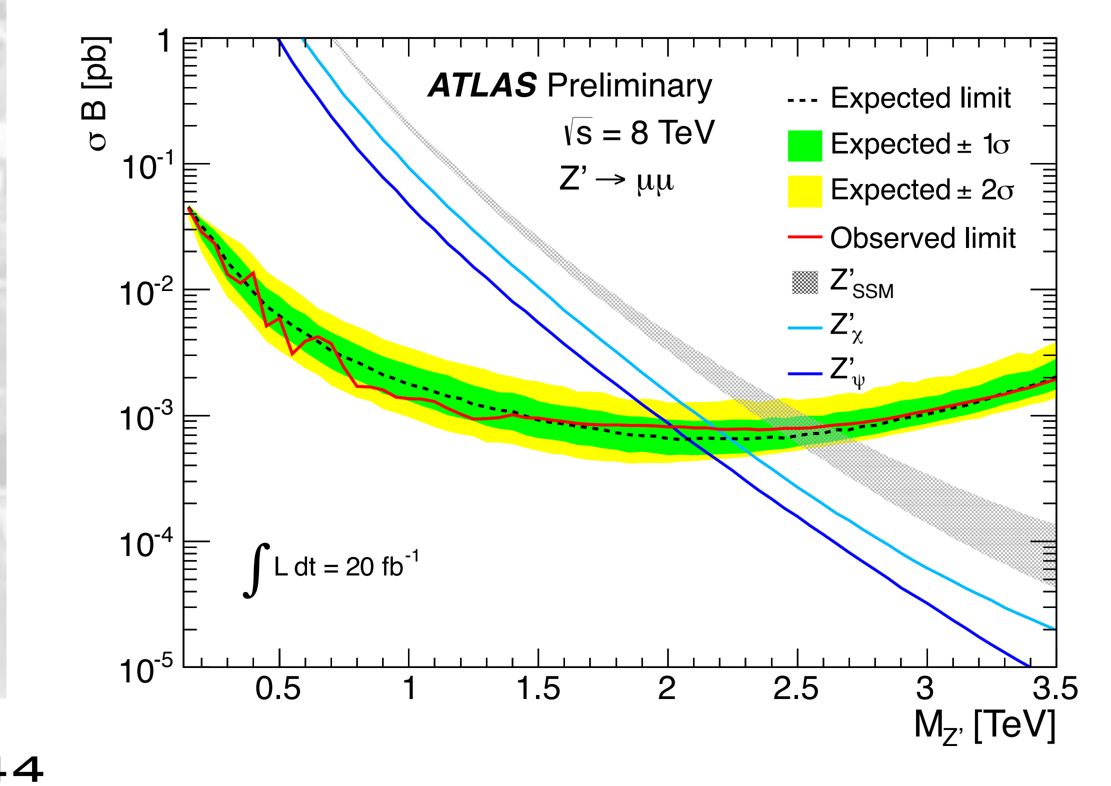




Dilepton Search



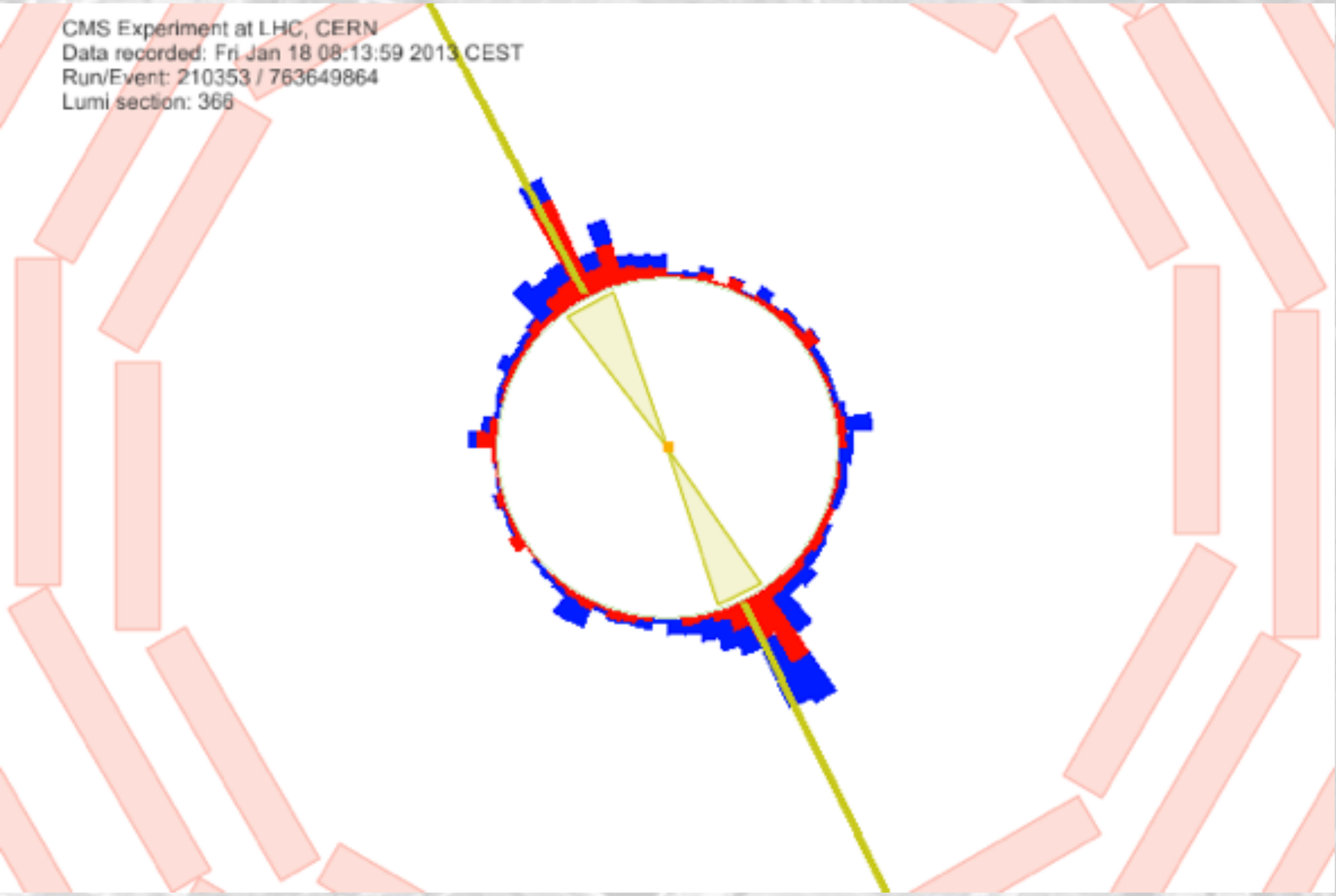




Resonances to Jets

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



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- But QCD is not geometry
  - **How many jets do you see?**

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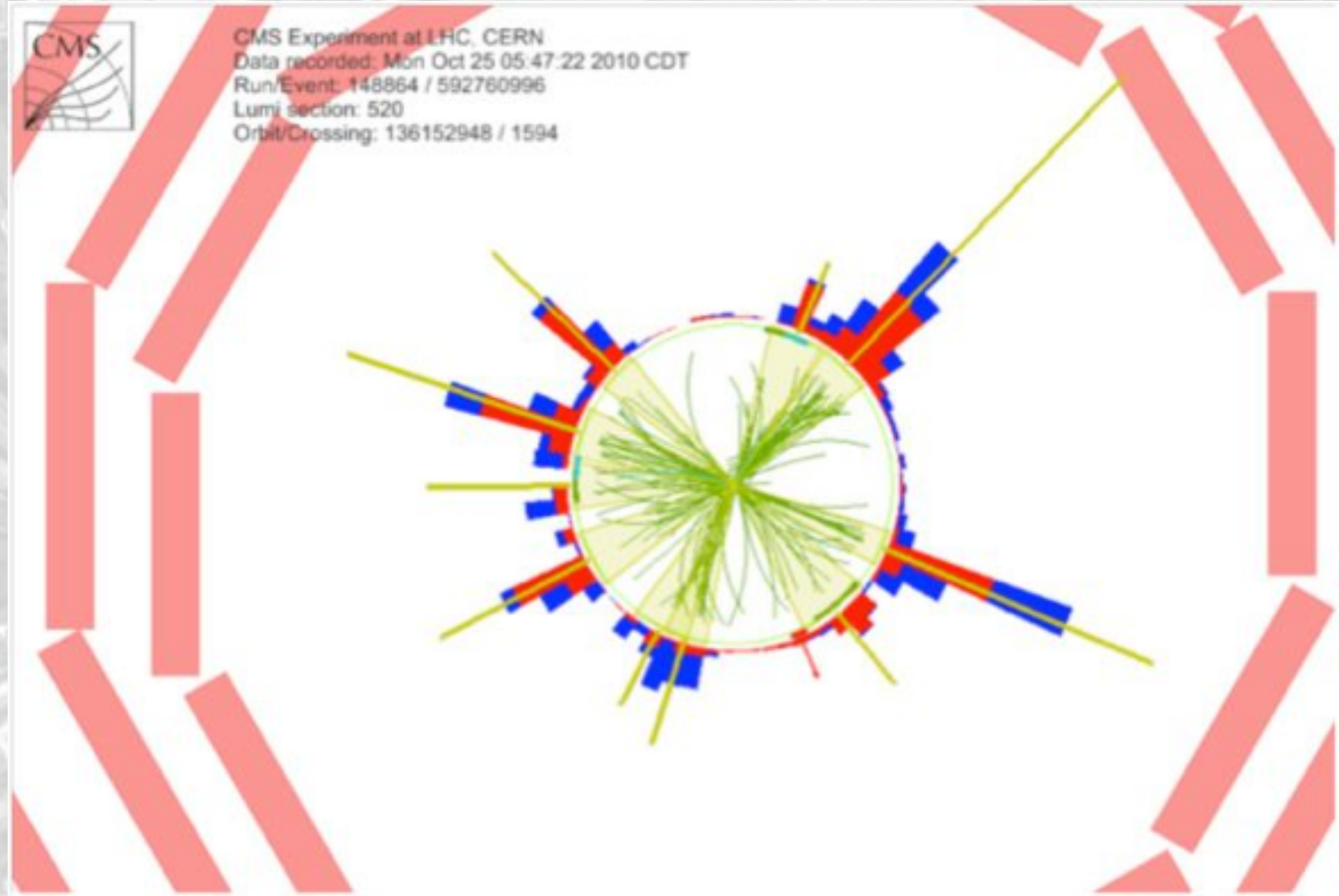

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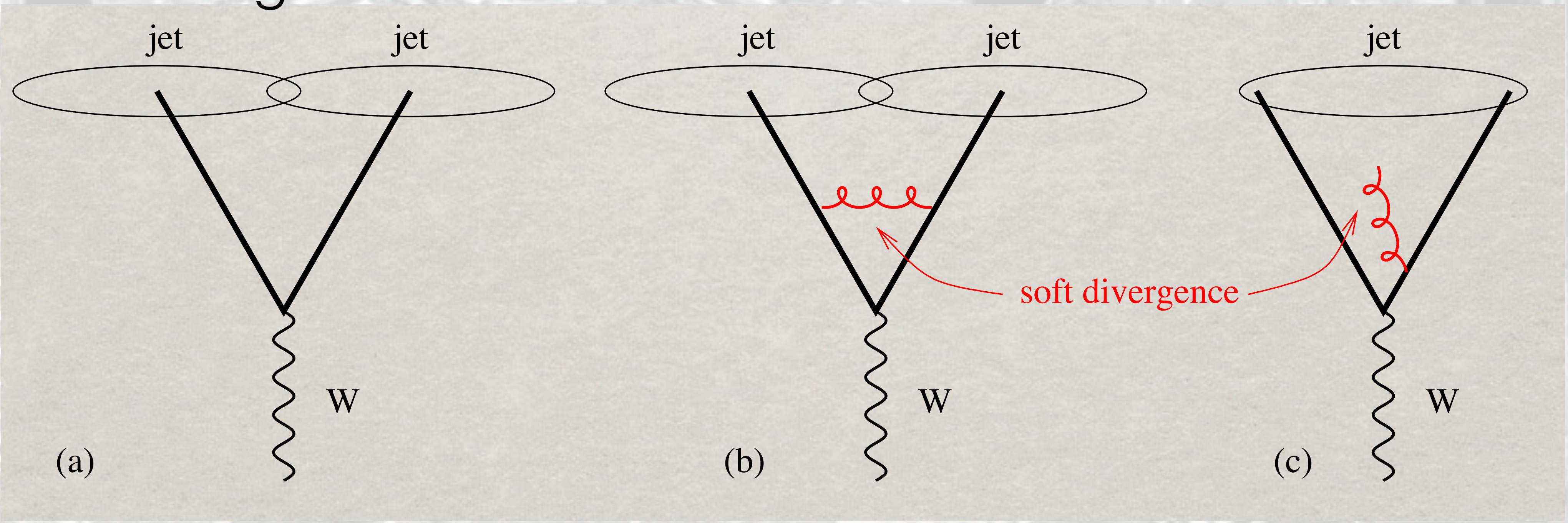
  - **How many jets do you see?**

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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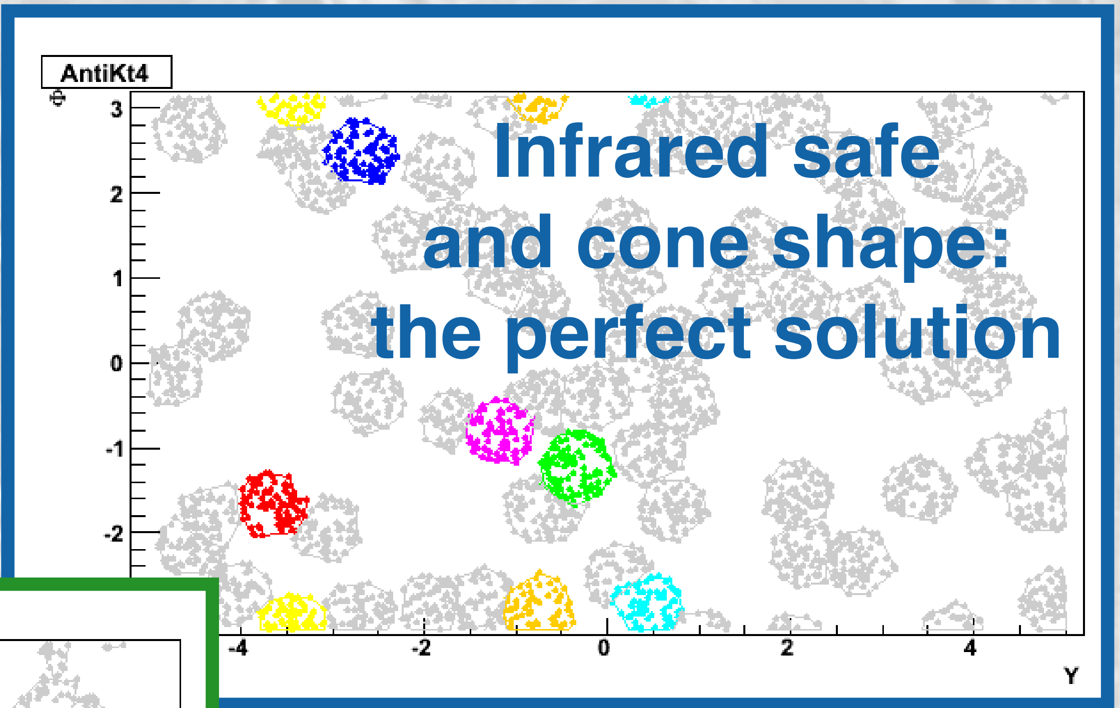
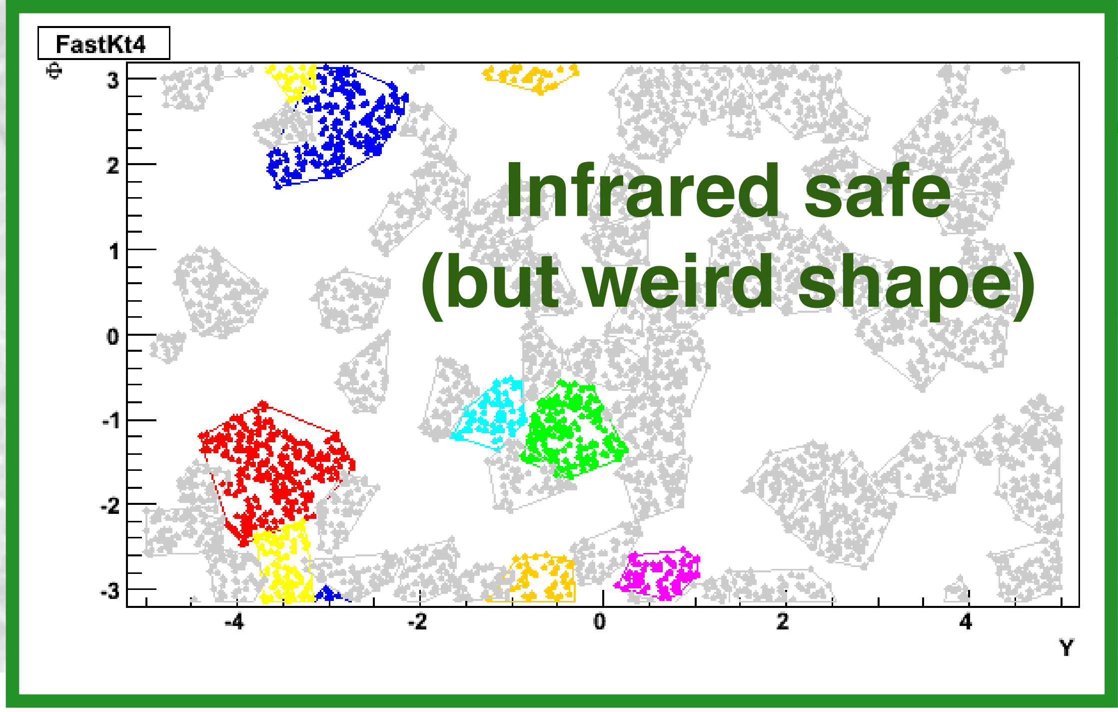
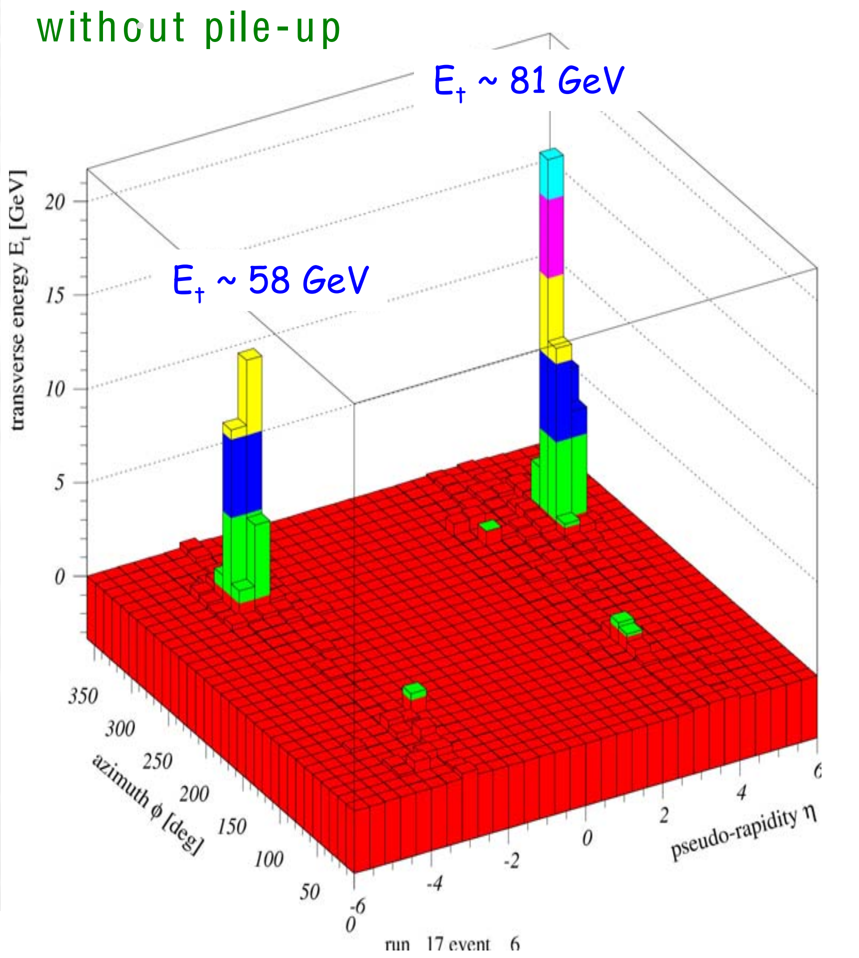
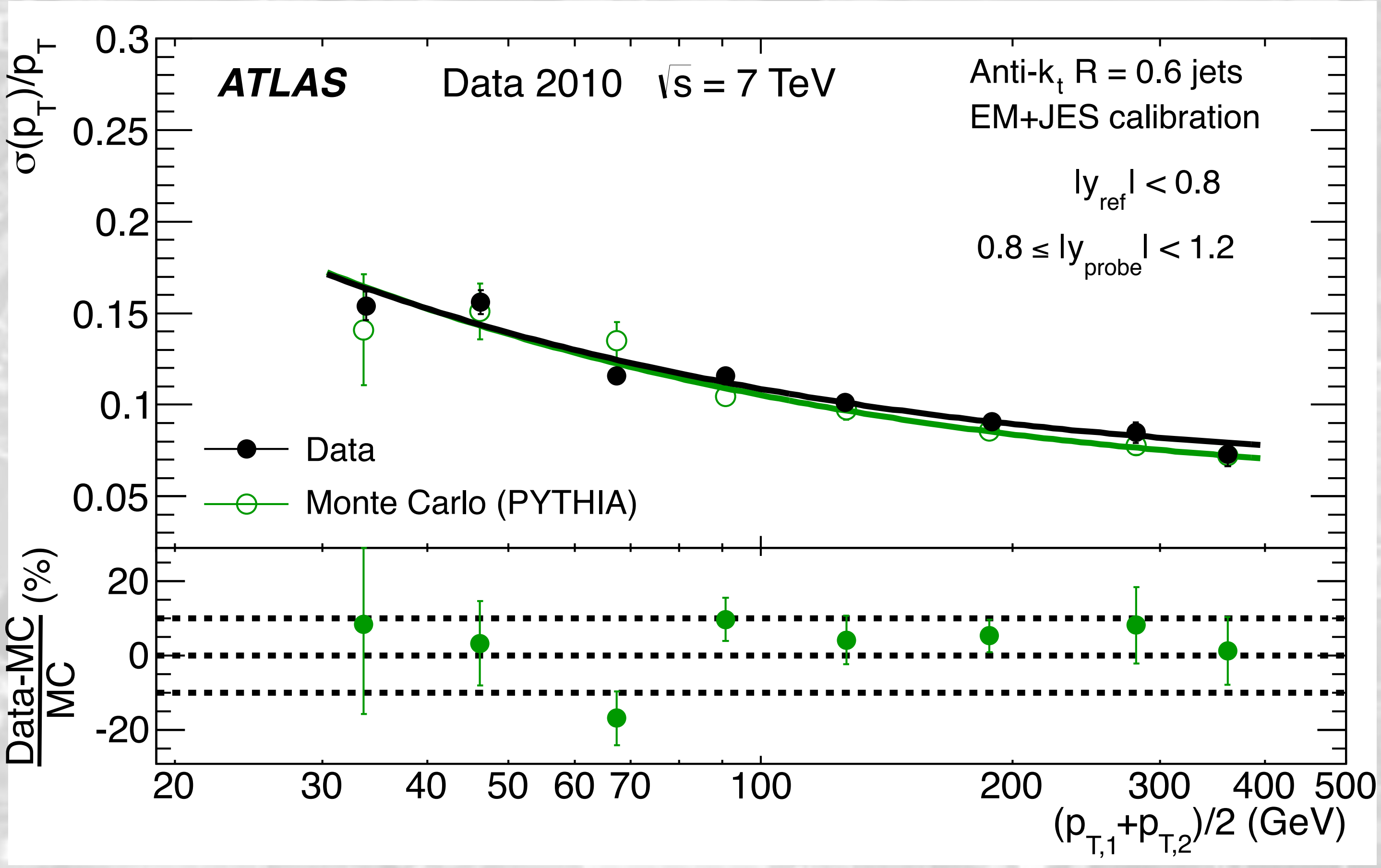




Jets of What?

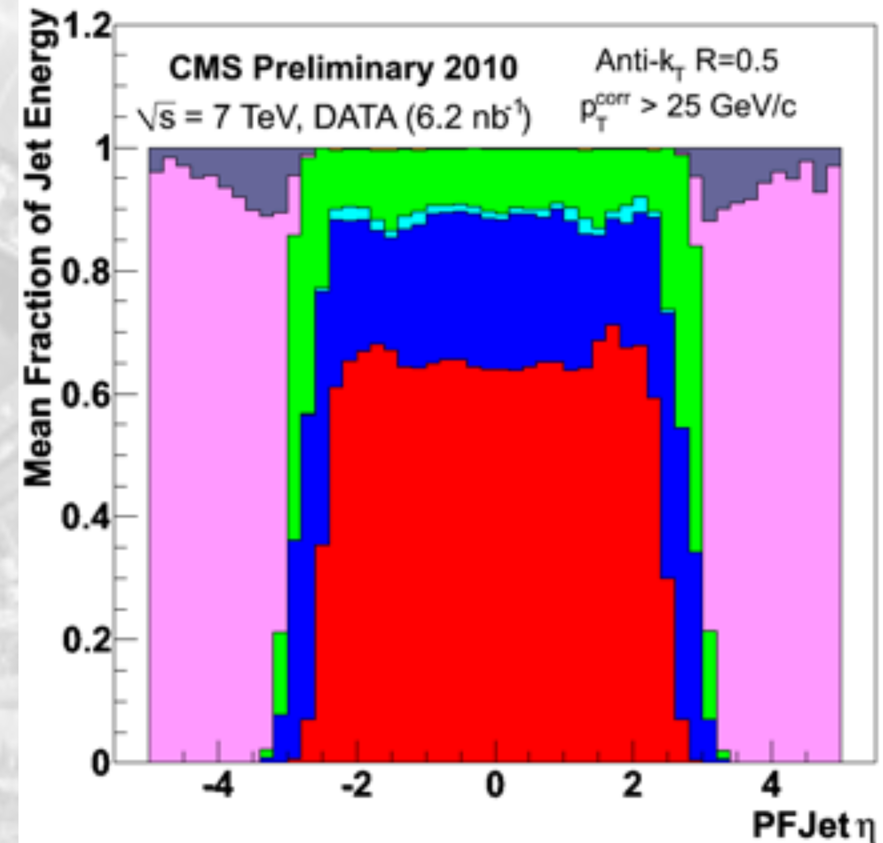
- Historically, jets are made putting together energy deposits in the calorimeter
  - Deposits in ECAL and HCAL are put together into clusters
  - clusters are made into jets using a jet algorithm
- Good technique, as long as
  - the calorimeter has the dept to contain the shower
  - the energy resolution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

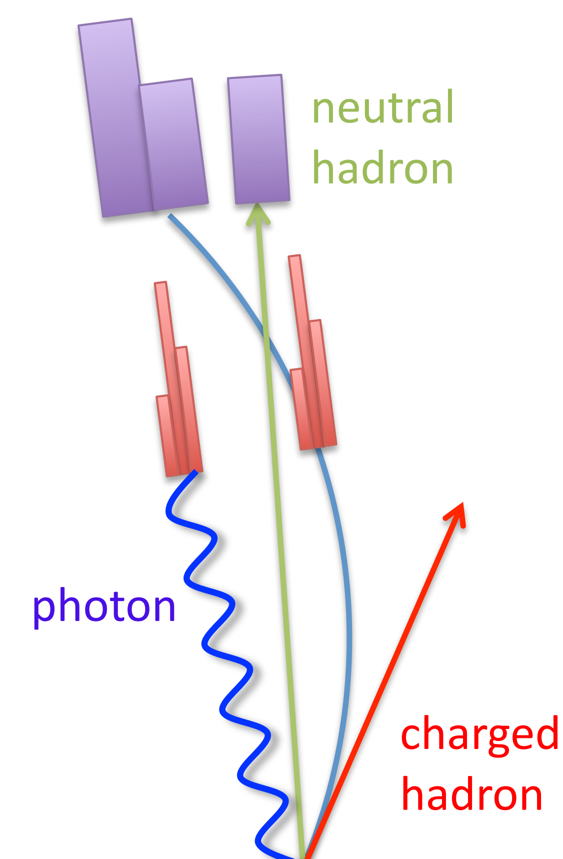




Jets of What?

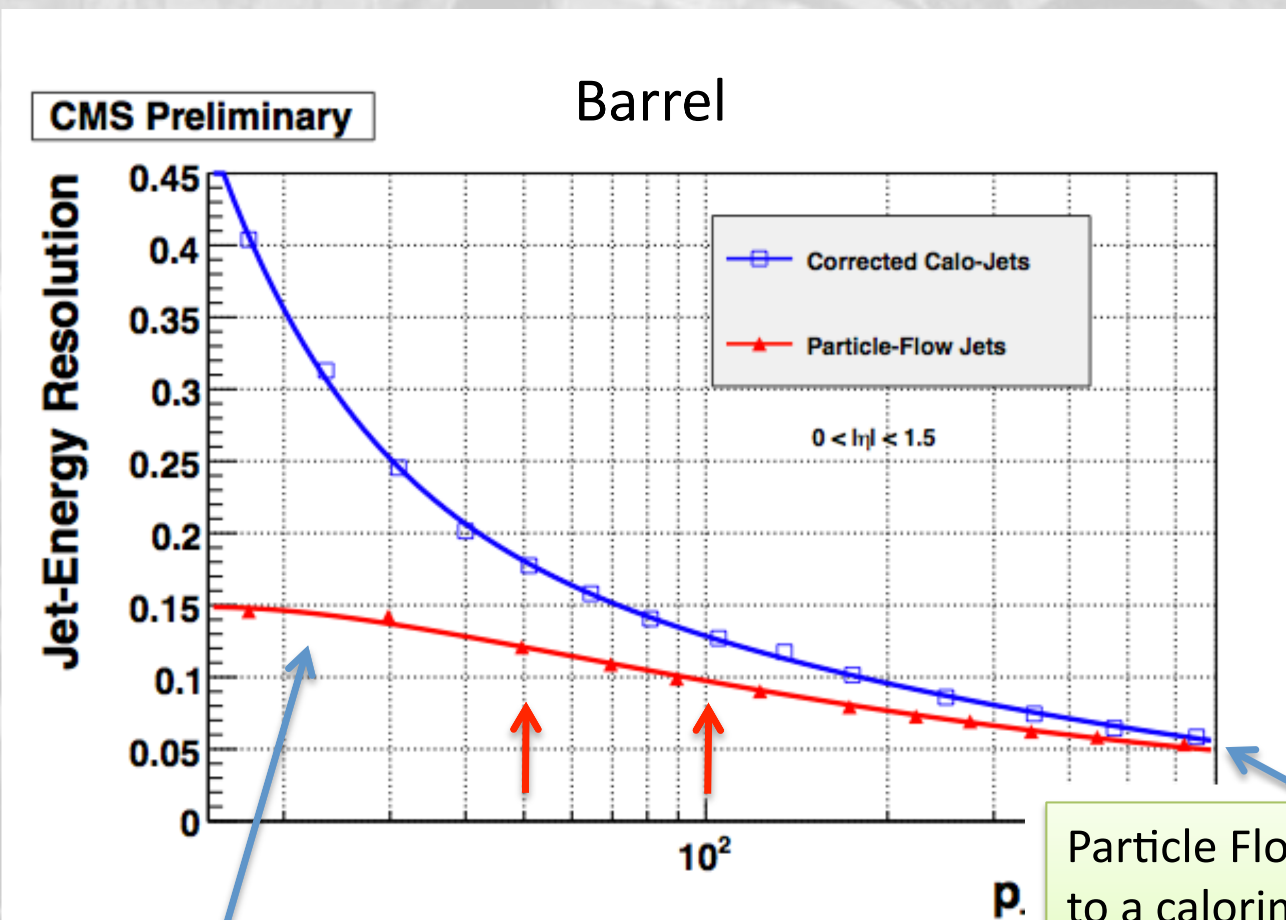
- But what if your HCAL is not good enough? Physics at rescue
  - 60% of the jet is made of **charged hadrons**
  - a largely fraction of the neutral hadrons is pions, which decay to **photon** pairs before your HCAL
- One can then
  - reconstruct individual hadrons, matching tracks to their energy deposit (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,m,g, charged and neutral hadrons)
- Improves HCAL resolution with tracker



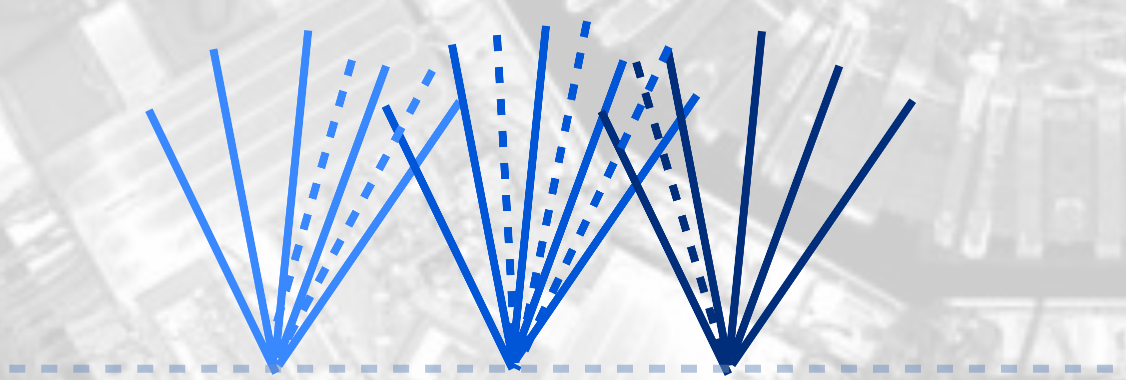
Factor 2 improvement at low pT

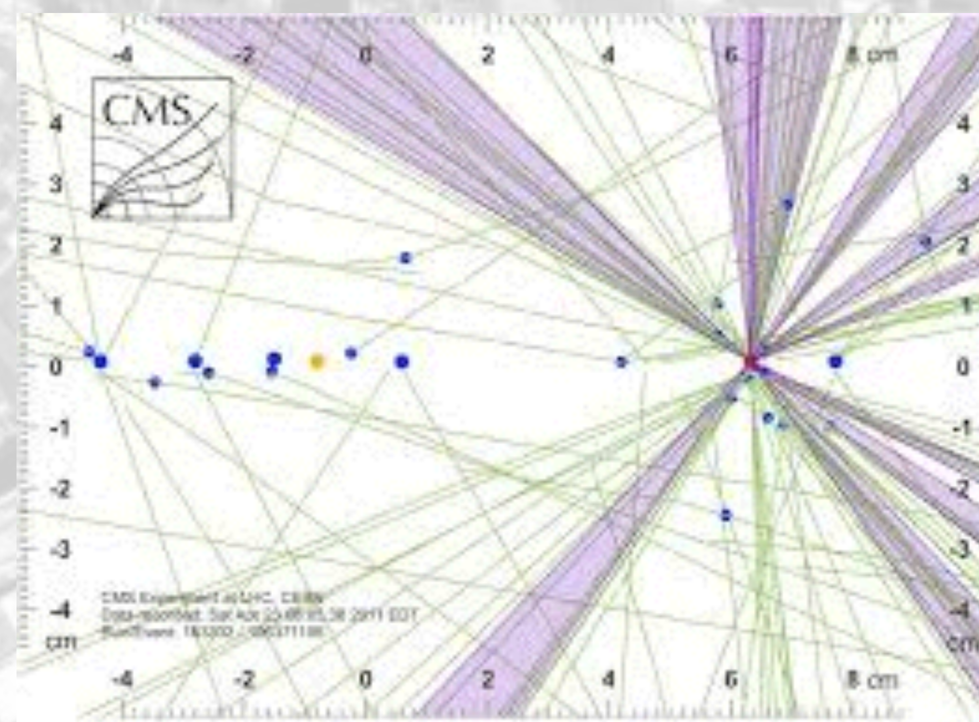
Particle Flow converges to a calorimetric measurement at high pT

- 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 Problem of PileUp

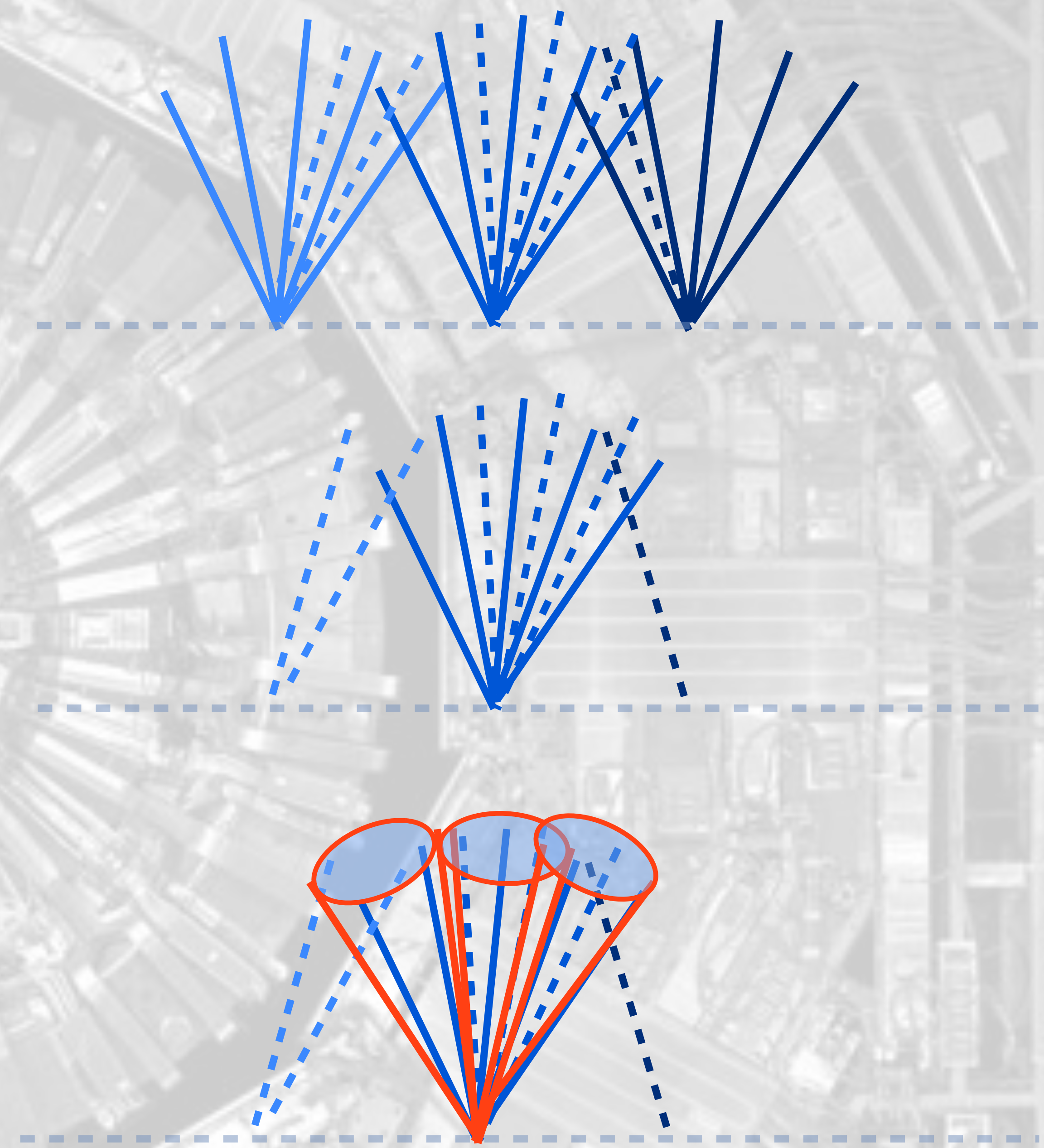
- Pileup is particularly problematic for jets
  - particles from different vertices overlap in the calorimeter area
  - the jest are then to be found on top of a diffuse noise from additional collisions
  - These collisions are typically soft (a high-pT collision is a rare event)
- Several methods put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





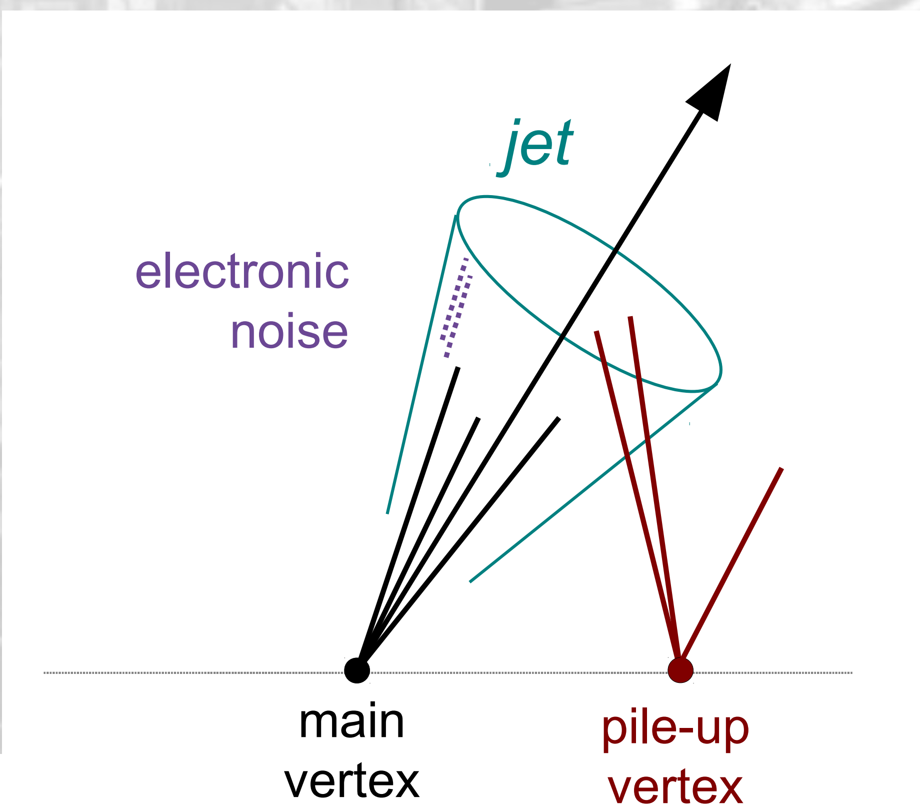
Charge Hadron Subtraction

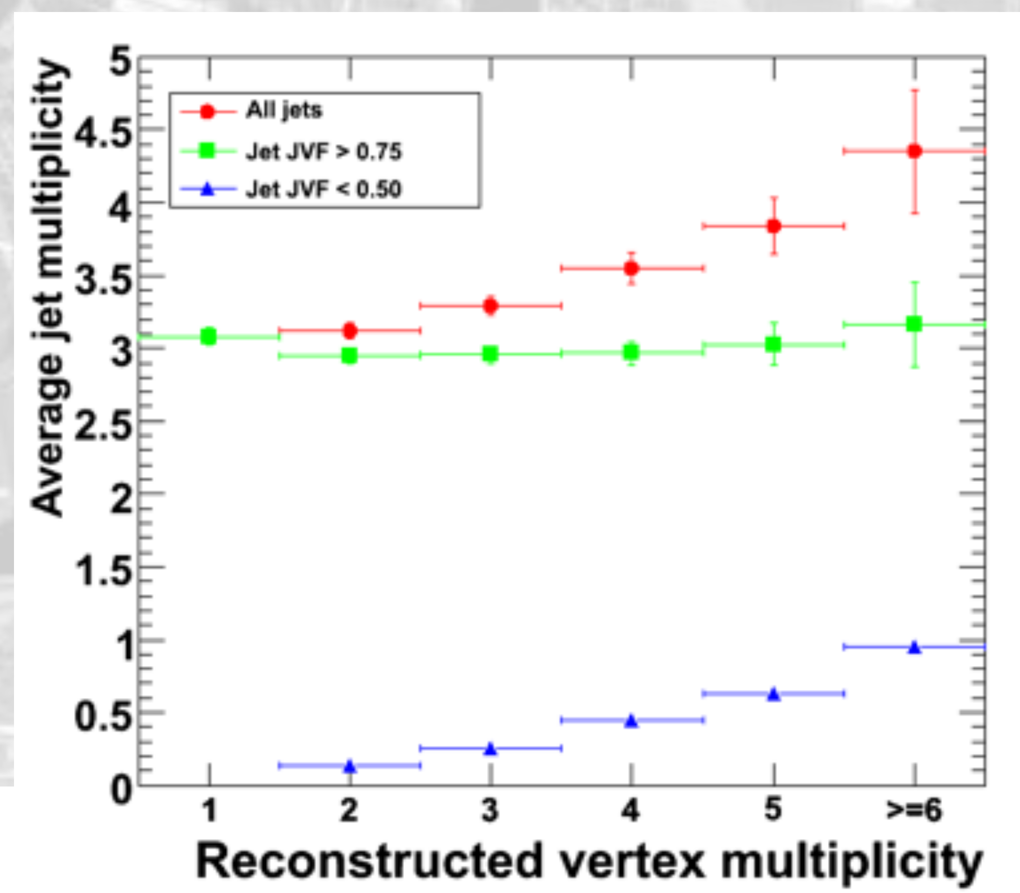
- We know where charged particles come from
  - we can reconstruct vertices from tracks
  - for each track, we know the vertex it comes from
  - For an event, we know (usually) which is the “interesting” vertex (highest associated energy) which triggered the event
- It is then easier to remove the charged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





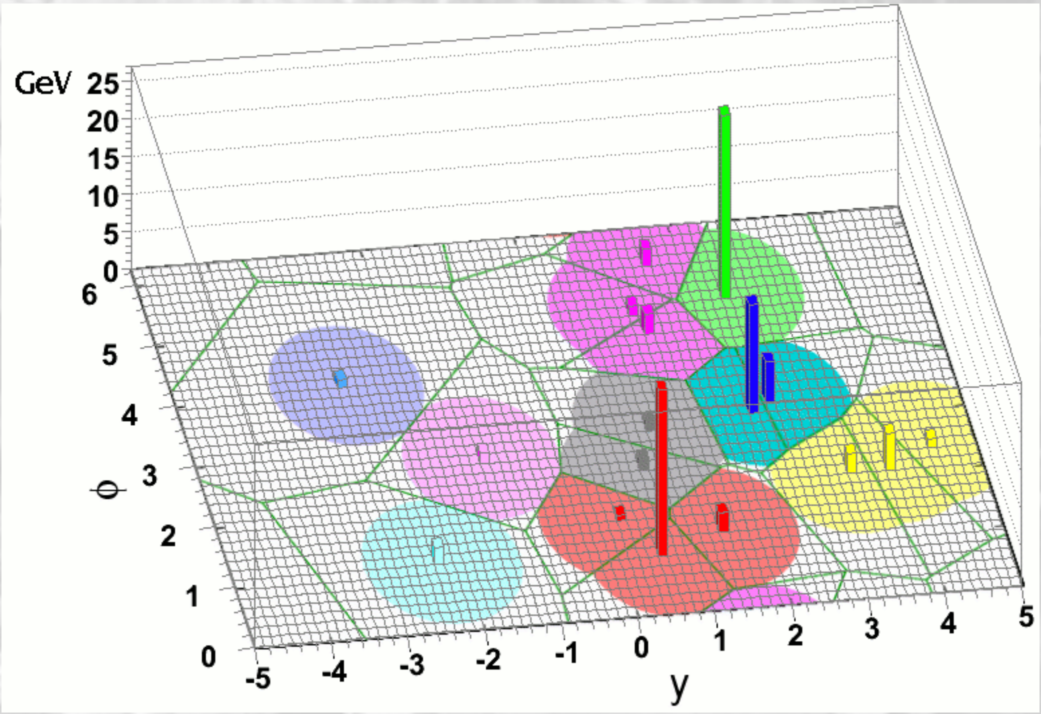
Jet Area Subtraction

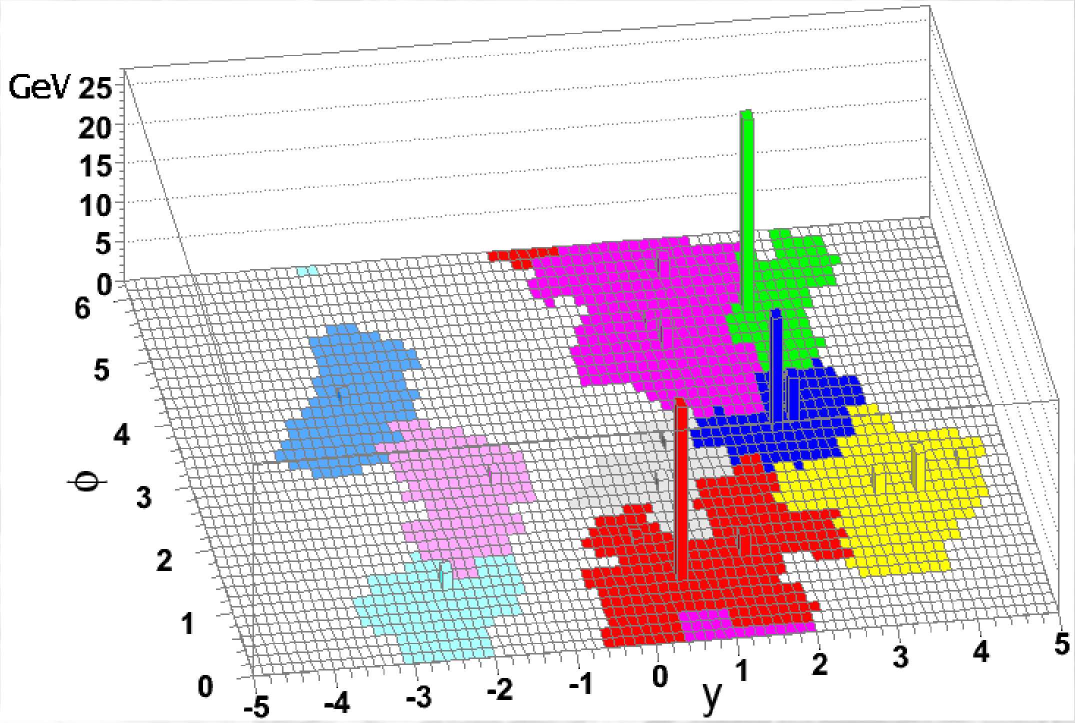
- When an exact subtraction of PU contamination is not possible, one can correct this in average
  - measure the average energy deposit per unit of area ρ
  - measure the jet area A
  - determine the jet pT by subtraction

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

- The concept of a jet area is subject to definition

arxiv.org/abs/0802.1188





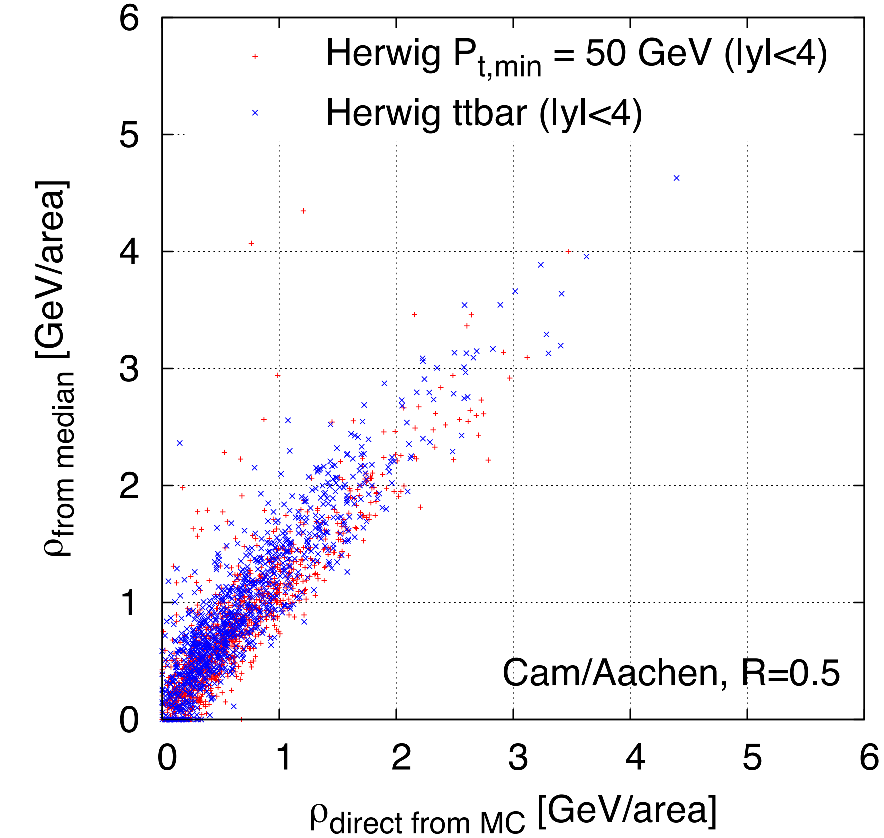
Jet Area Subtraction

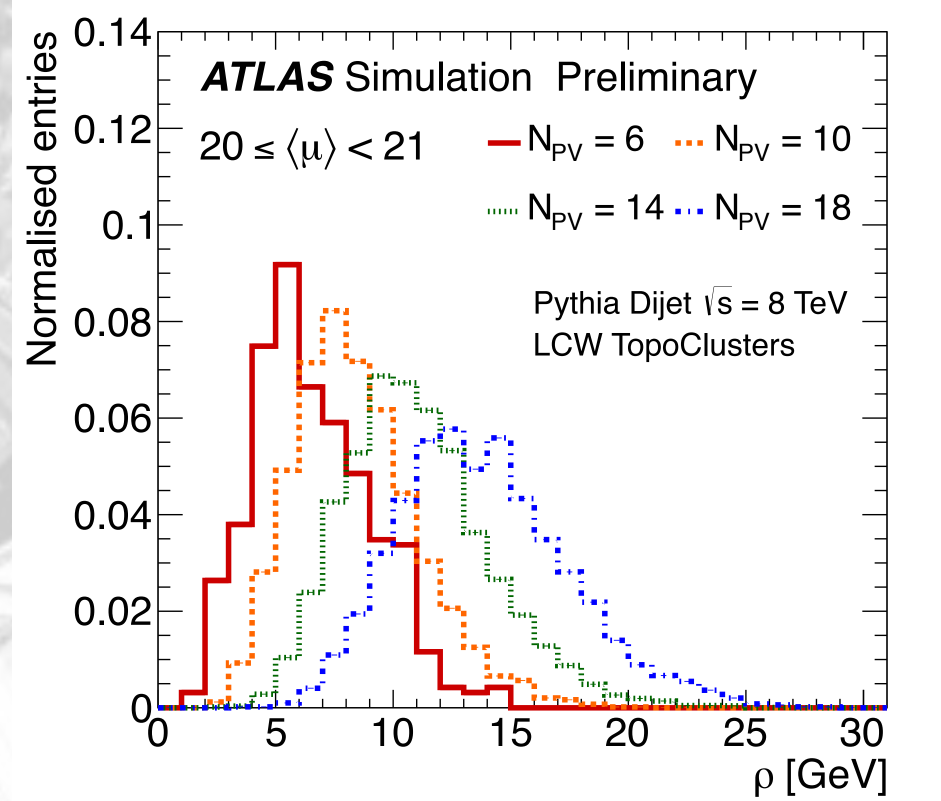
- Once the area is determined, one needs to estimate the energy density

- 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

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

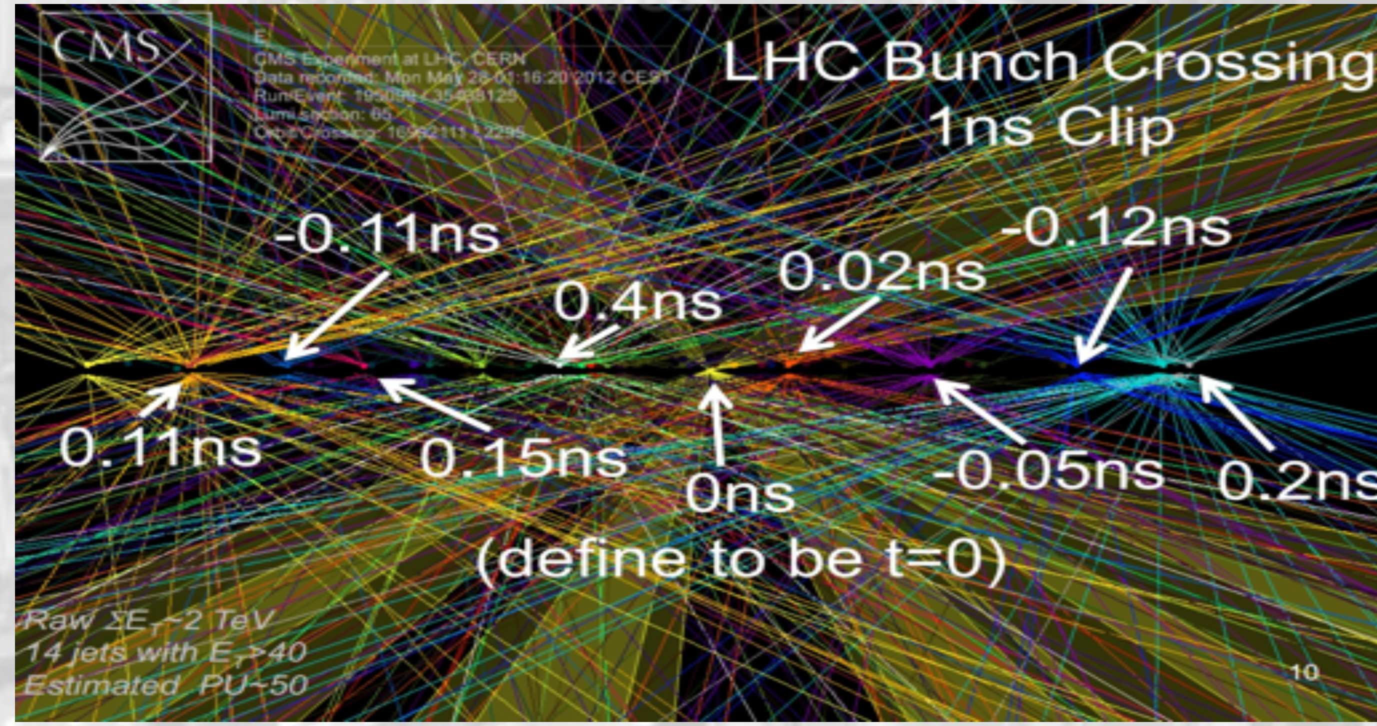


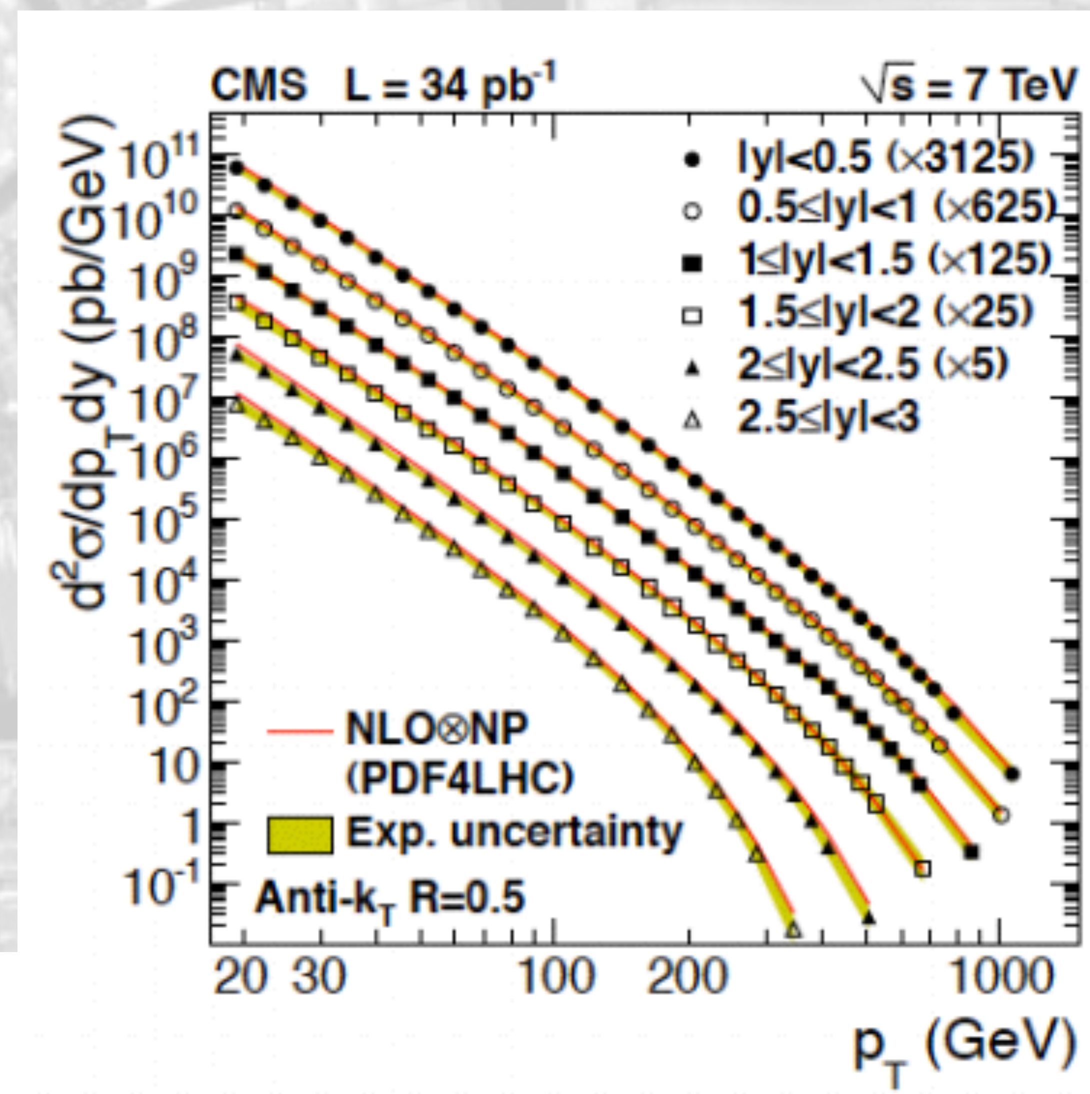


http://arxiv.org/abs/0707.1378

Precision Physics with jets

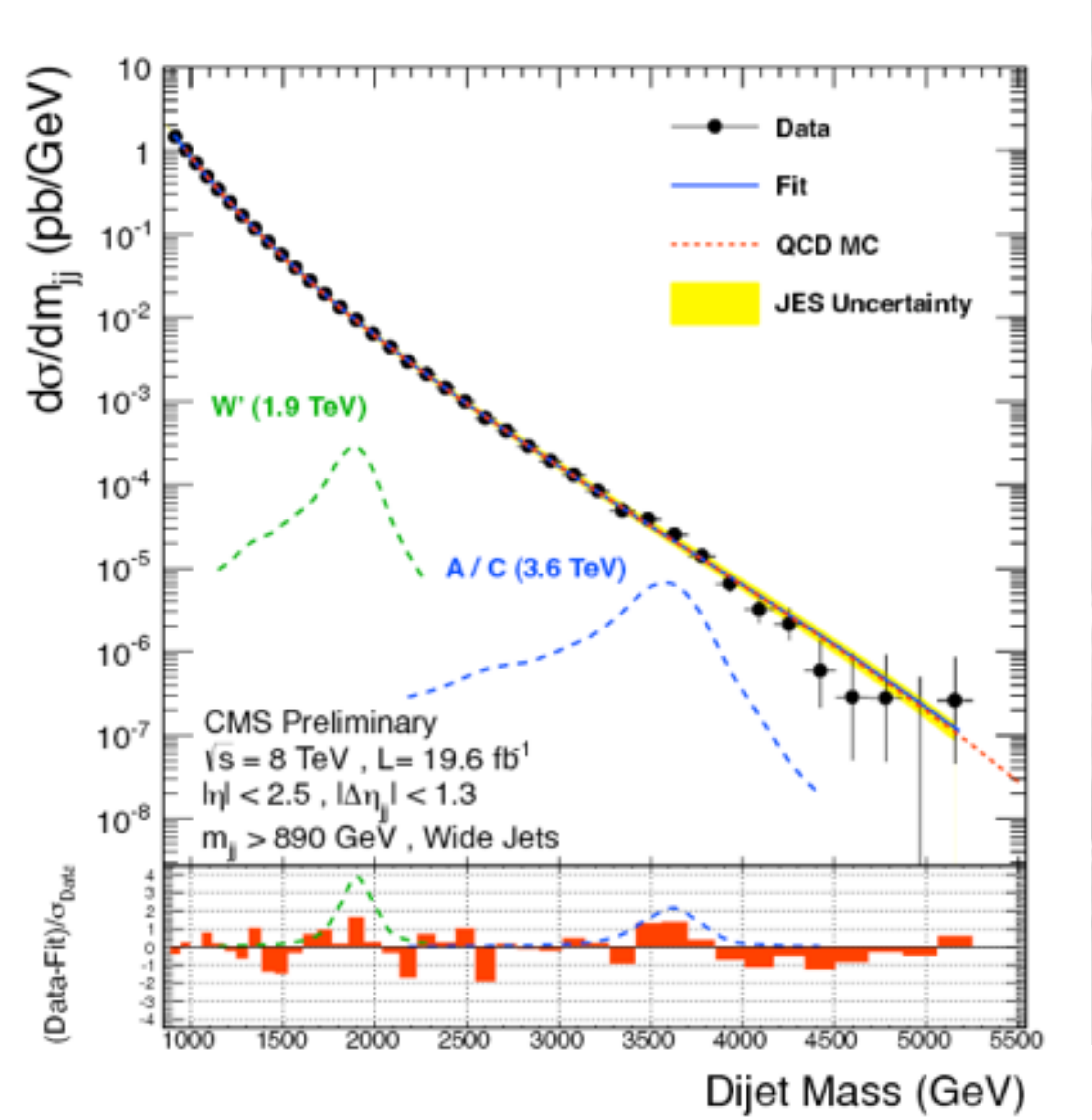
- QCD physics at the LHC is precision physics
    - Multijet NLO calculations in event generators
    - Solid jet definition
    - Handling of pileup
- During LHC run I, intense program of measurements
    - "Validated" the tools describing jet physics (e.g., event generators and detector simulation)
    - Set the basis to search for New Physics with jets

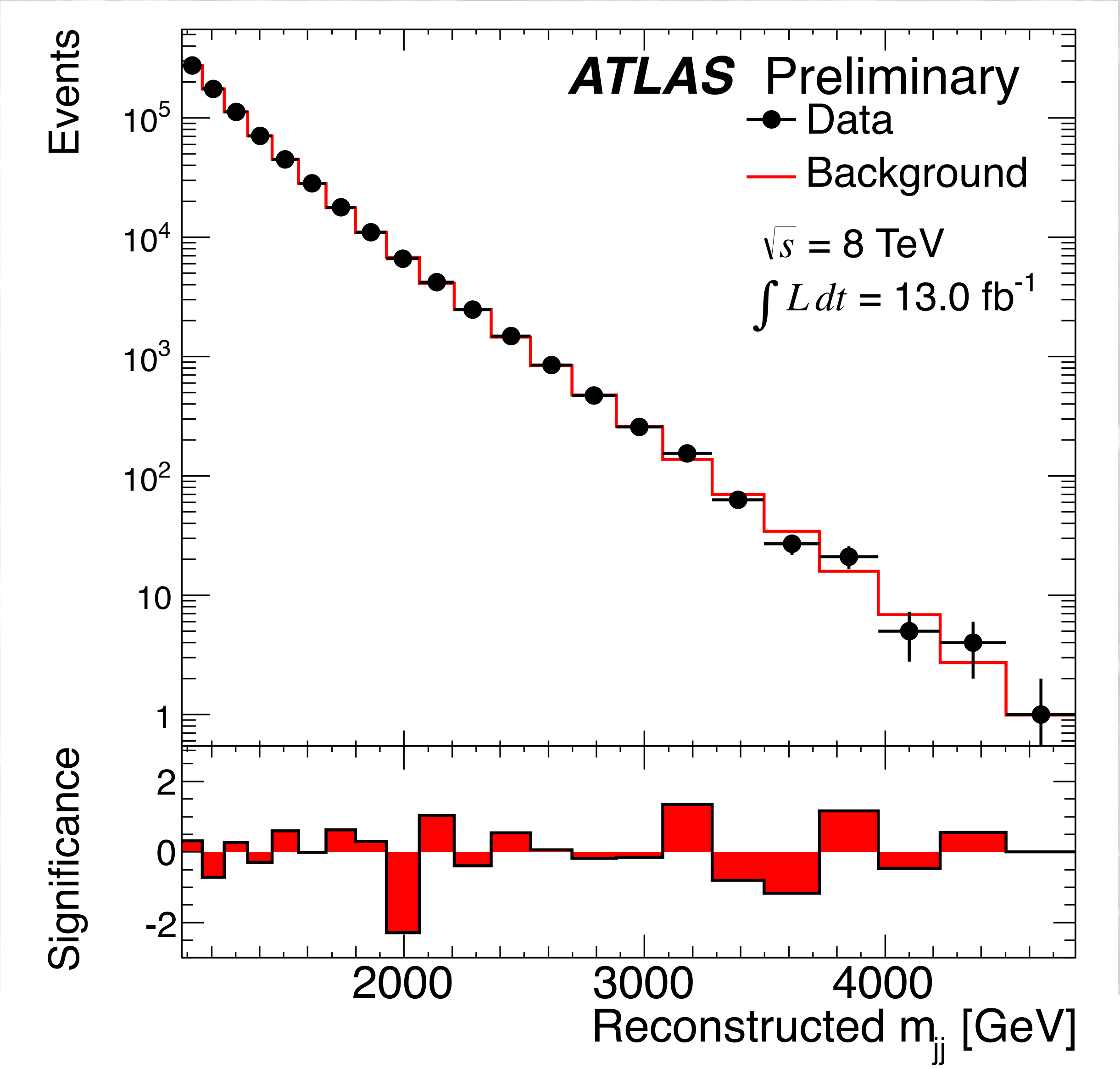




Dijet Search

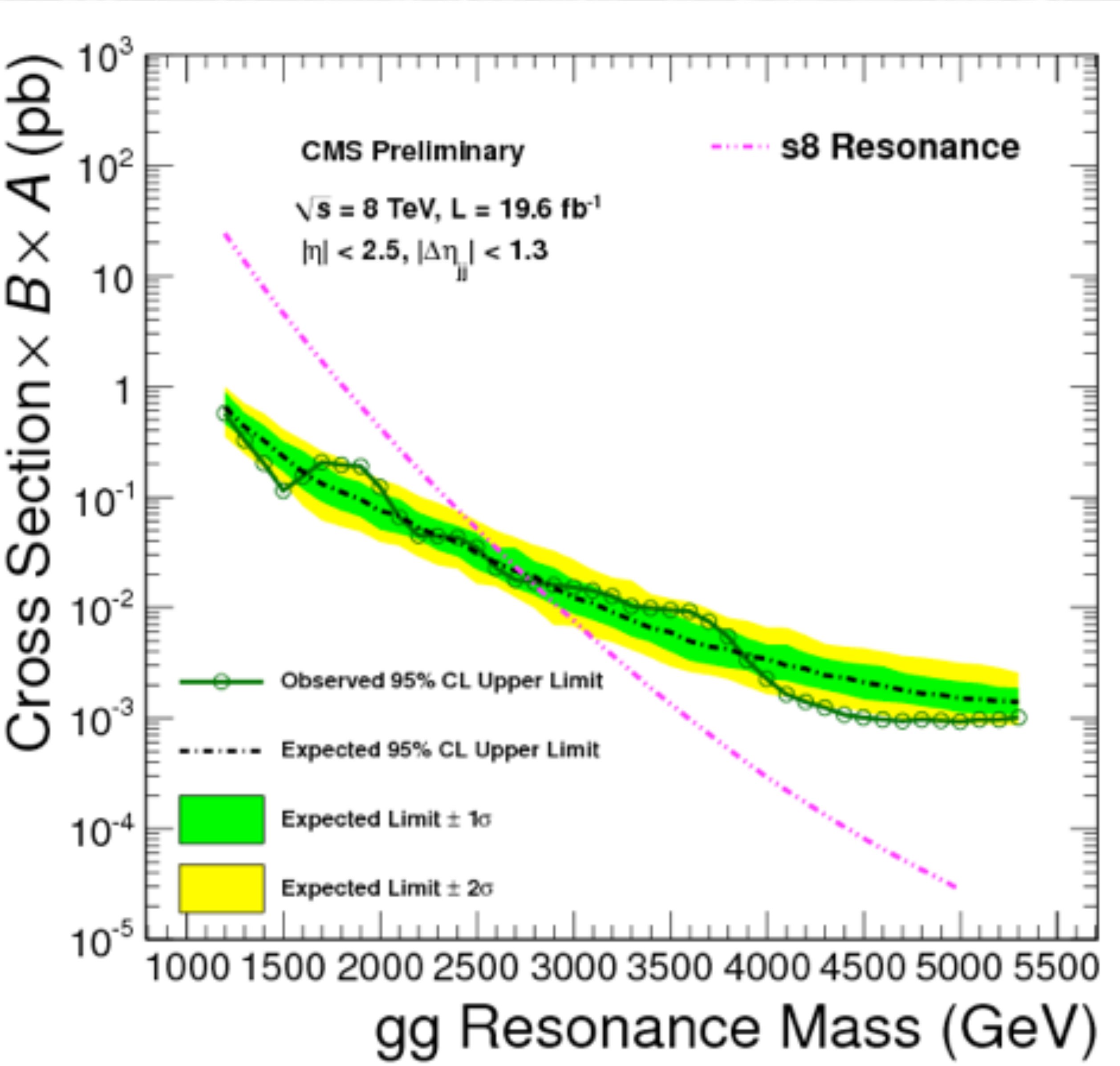
- The first application is a search for resonances to dijet
  - Parameterize the QCD dijet mass spectrum
  - Look for a bump on the falling spectrum
  - Main challenge from trigger
  - High-pT jets in the final state

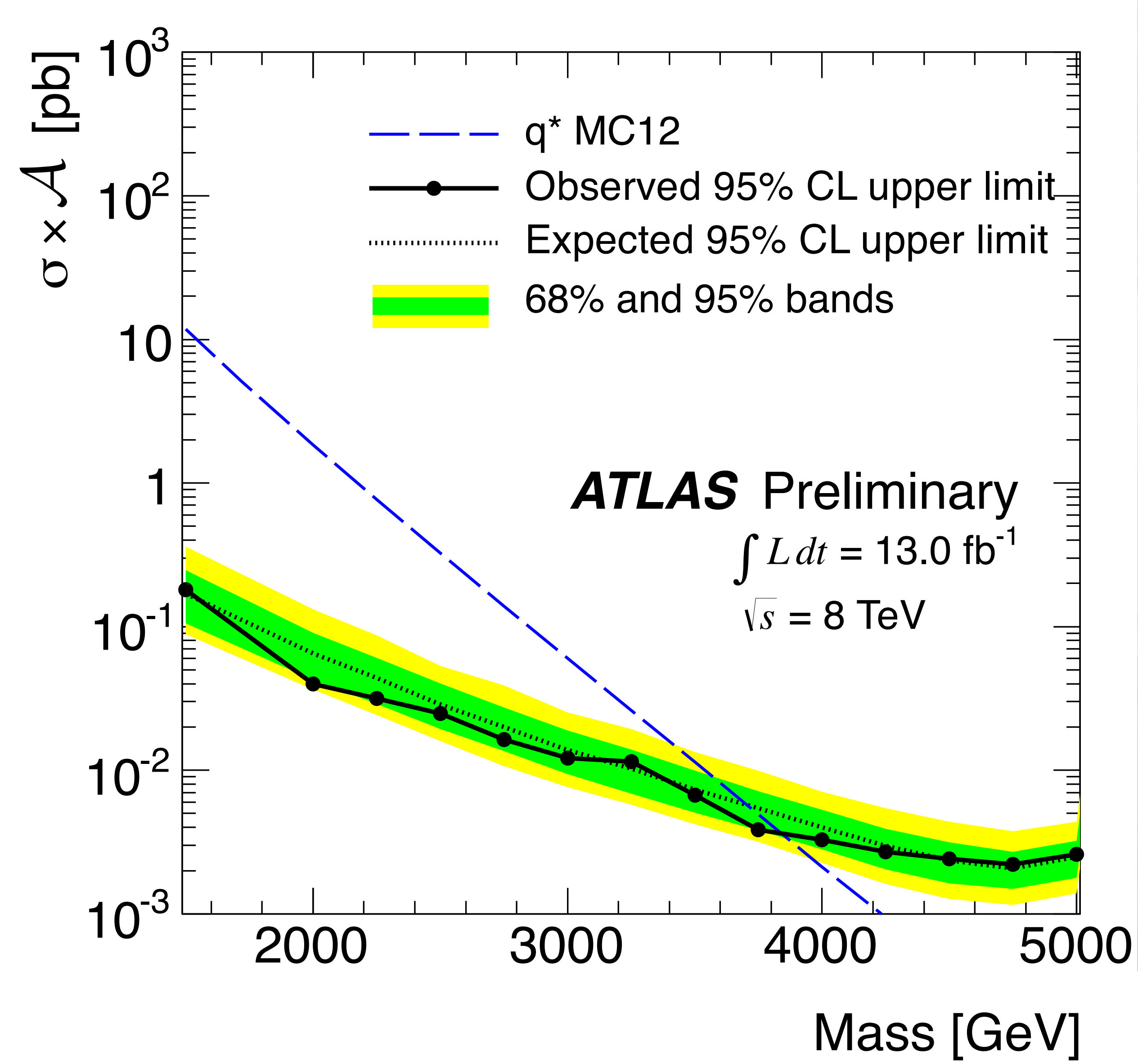




Dijet Search

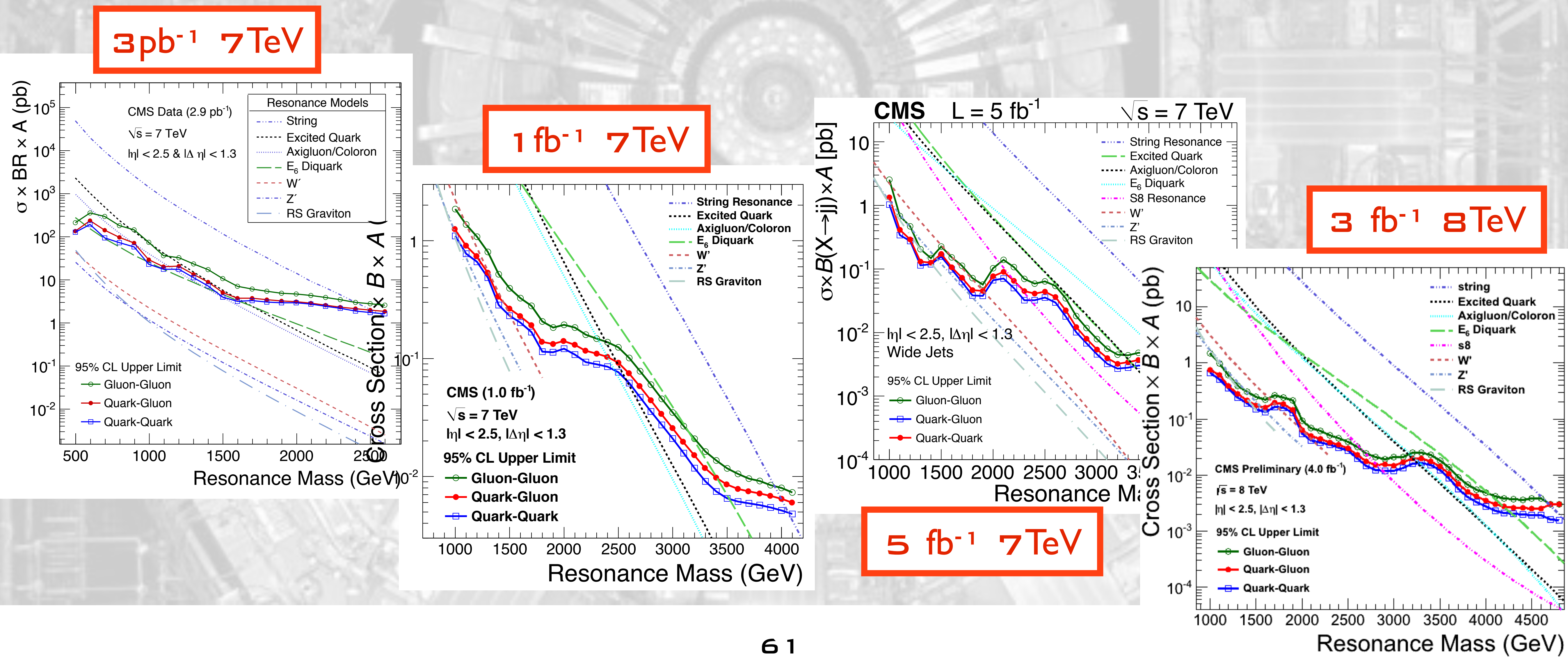
- The first application is a search for resonances to dijet
  - No excess observe
  - Result interpreted as 95% exclusion on narrow resonances
  - Result depends on the final state (qq/qg/gg)
  - Also interpretation for broad resonance (available or coming soon)





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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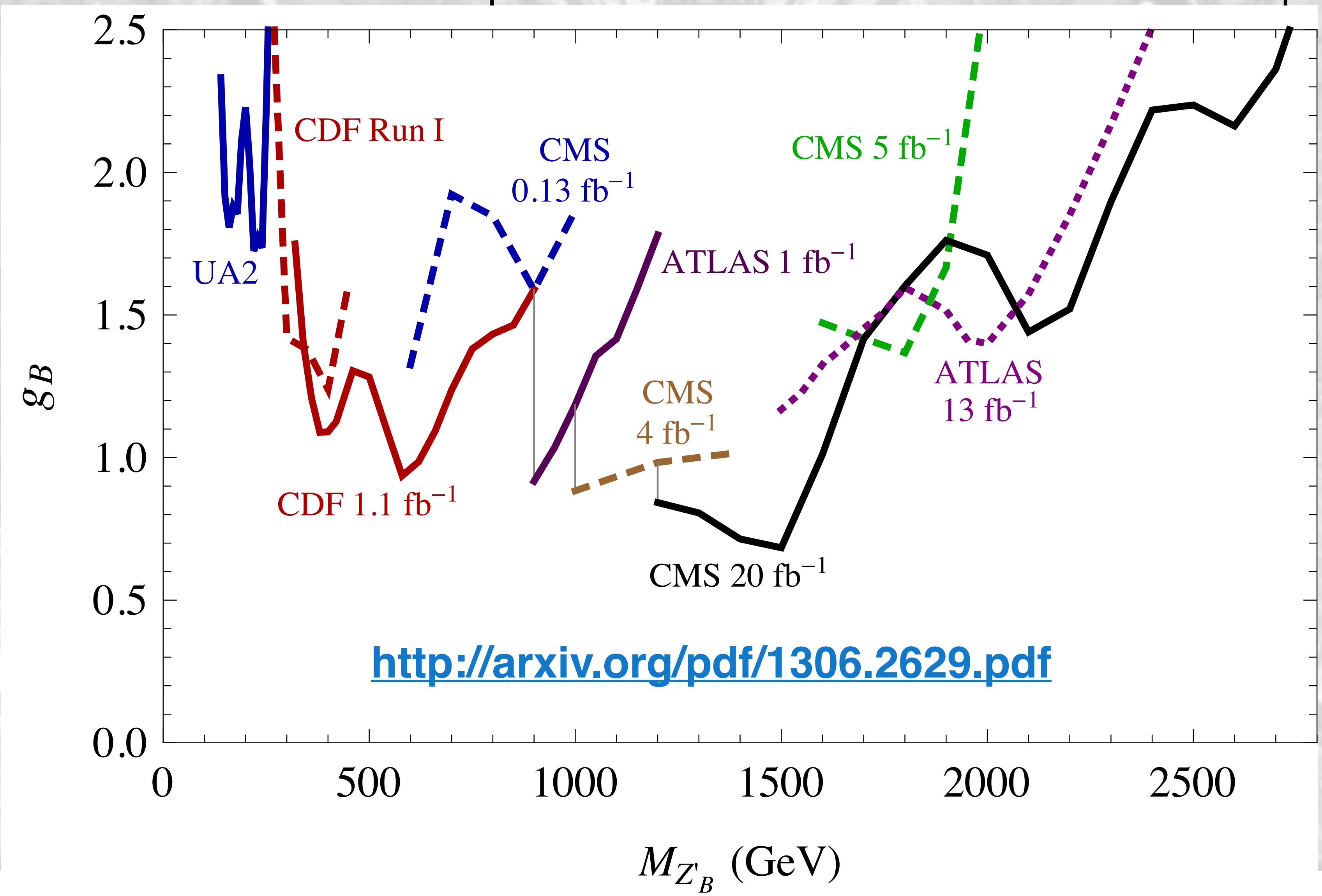

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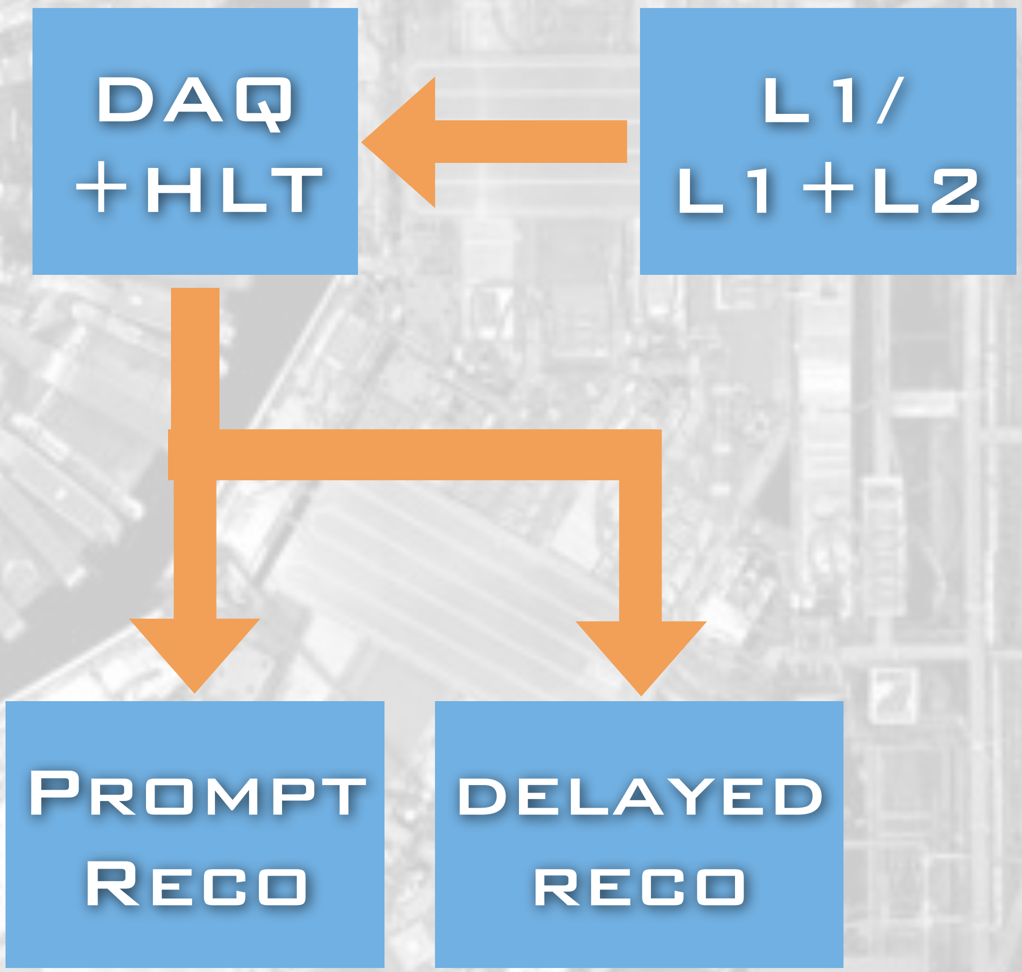
E [	L [	minMass [	σ minMass
7	0.003	400	~ 200
7	1	900	~ 1
7	5	1000	~ 1
8	3	1000	~ 0.6

Unexplored territory left behind with increasing luminosity

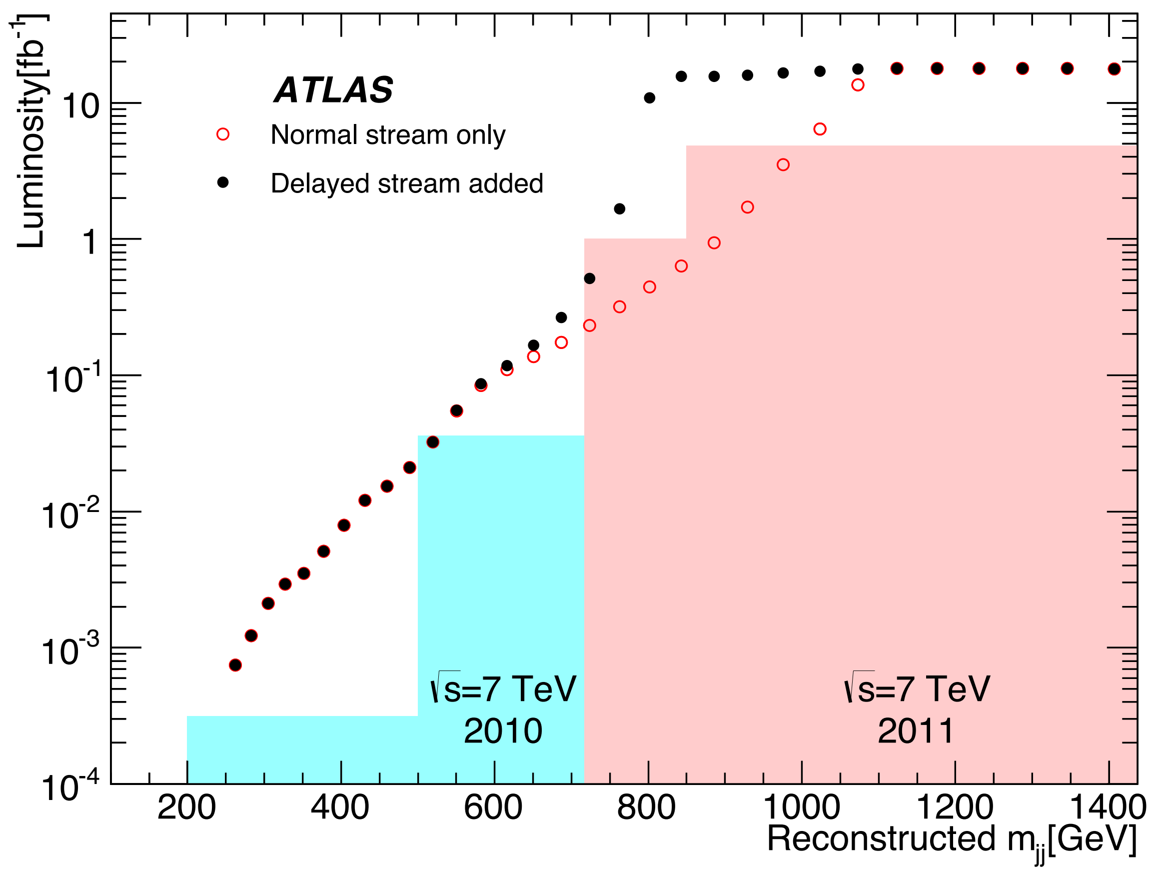
Rate vs Disk I/O

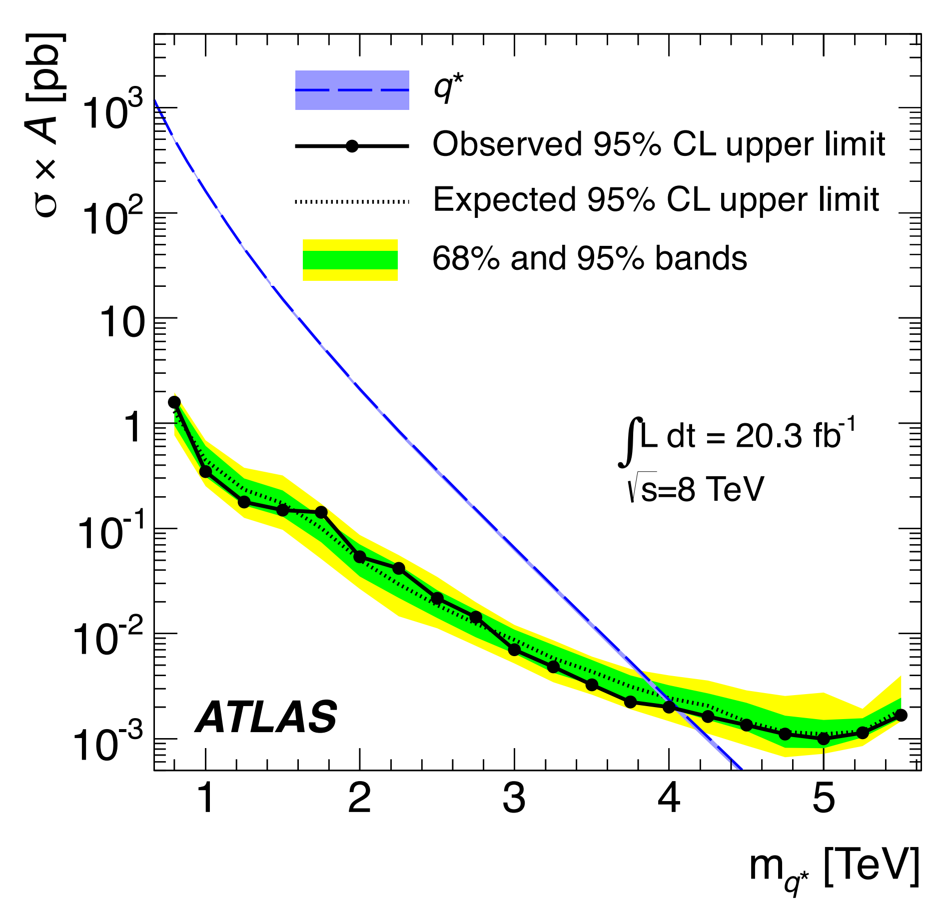
- At the beginning of the run, we considered 300 events/sec the maximum we could get out of the trigger
- It was suddenly realised that the trigger can handle much more
- The real problem was after
  - enough disk to write the data to? Set the limit to 1 kHz, considering the available disk, and the event 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

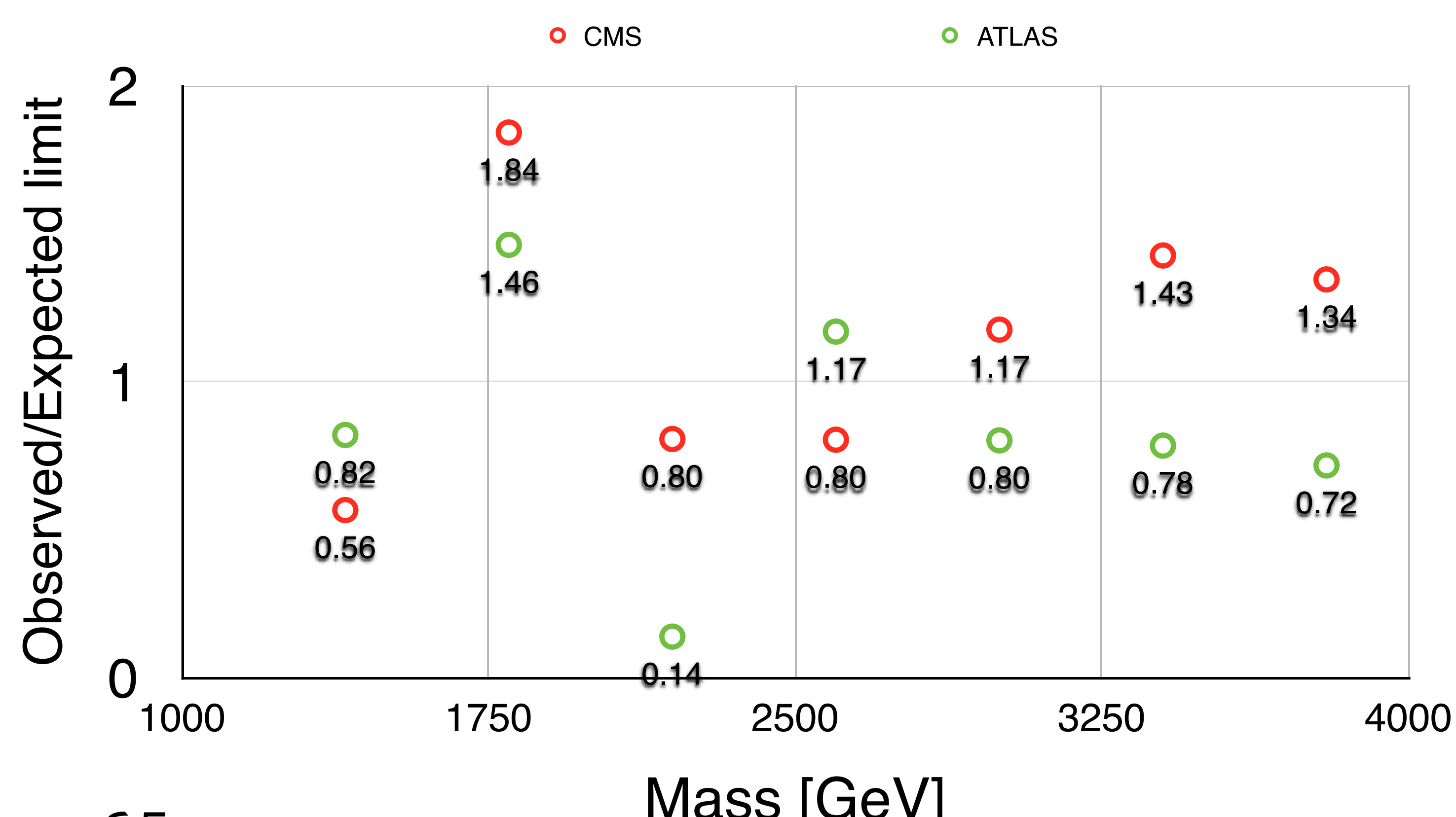


Dijet on Parked Data

- 40 Hz of data collected & processed normally
- This allows to run the dijet search for resonances above 1 TeV
- Added 100 Hz of data from the delayed stream
- This allows to extend the search down to 750 GeV

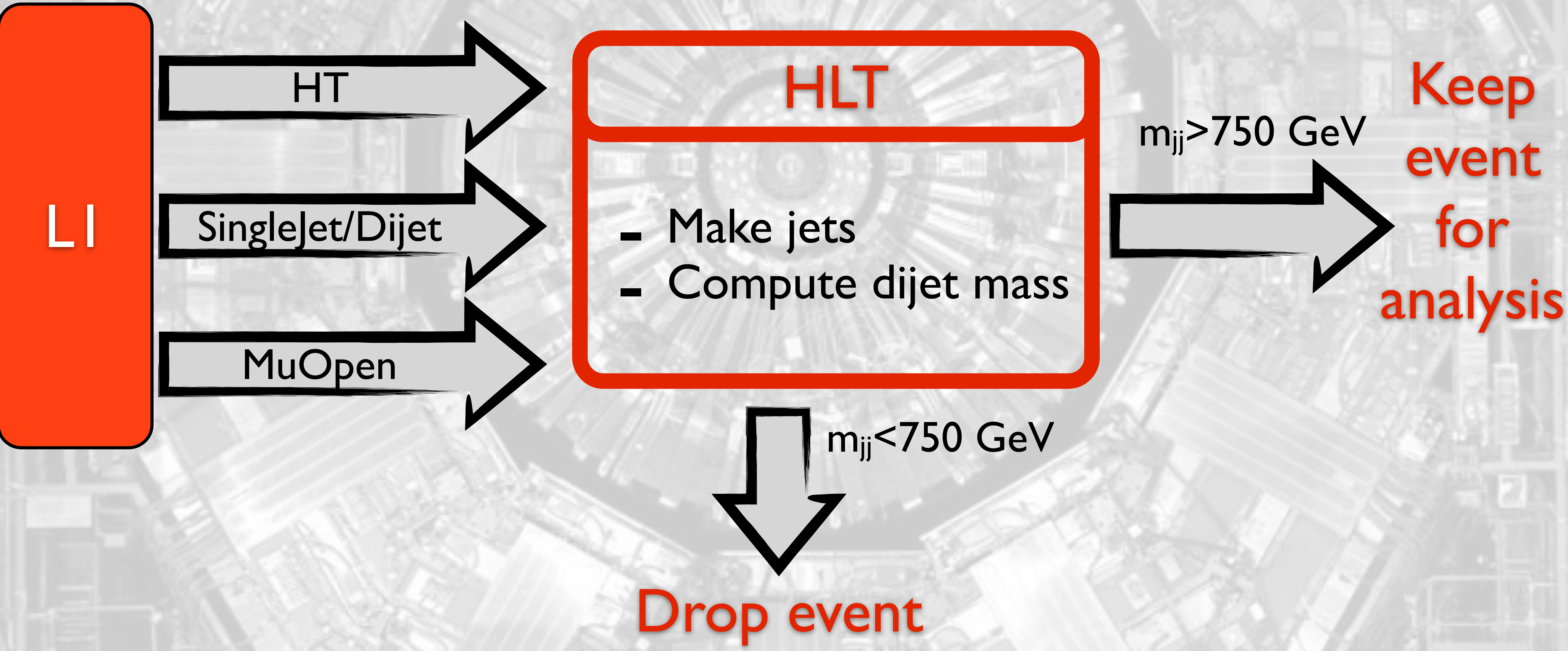






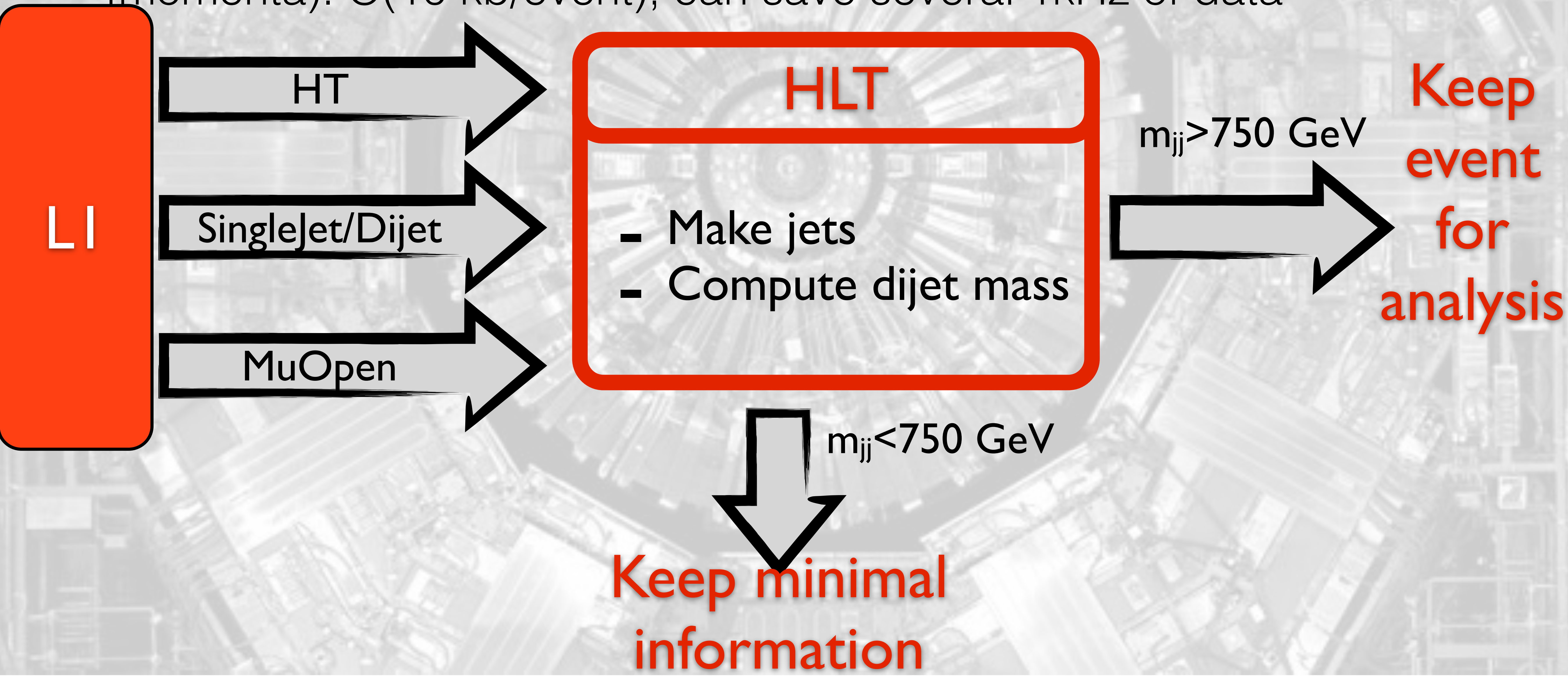
Beyond Data Parking

- 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)



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



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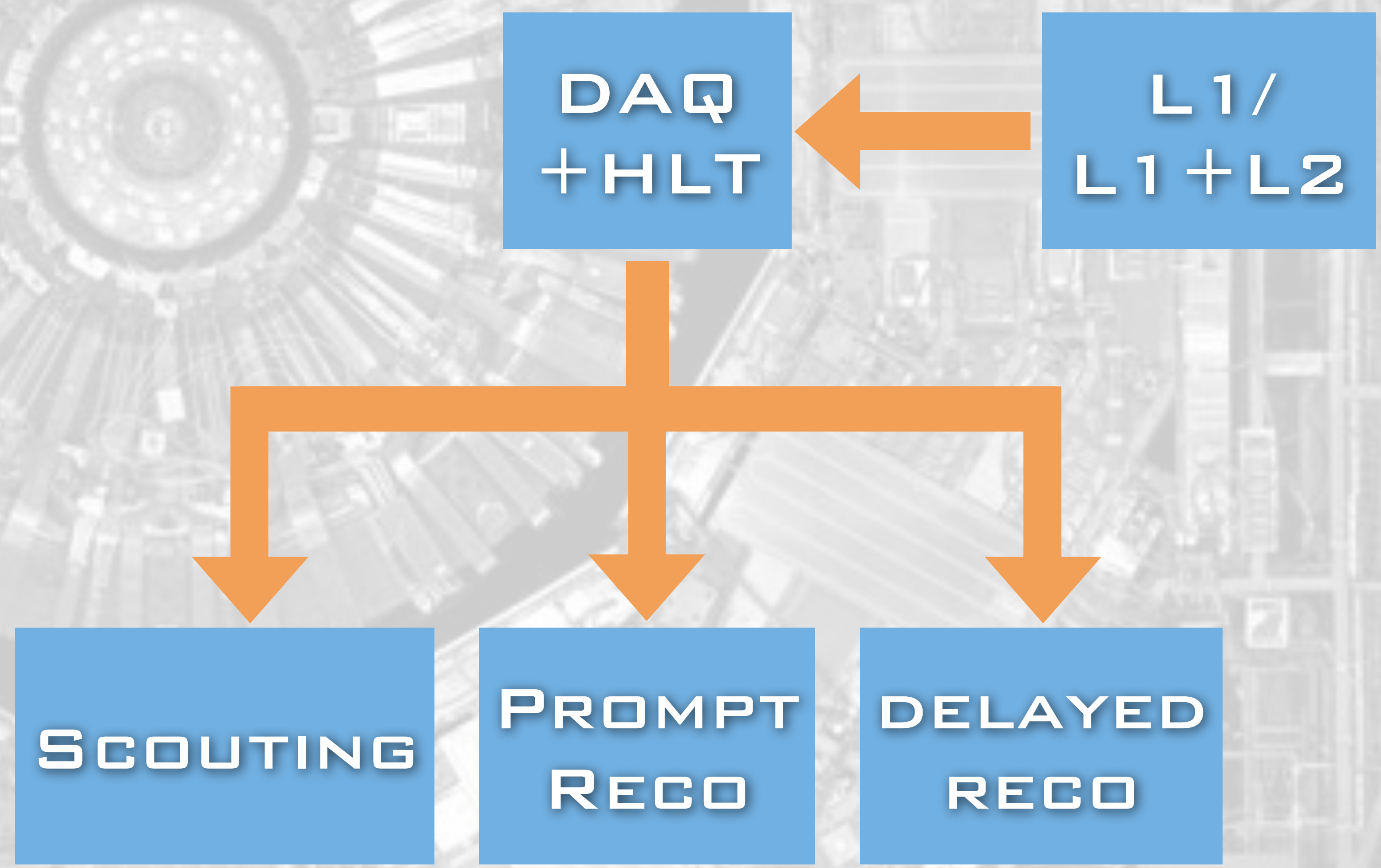
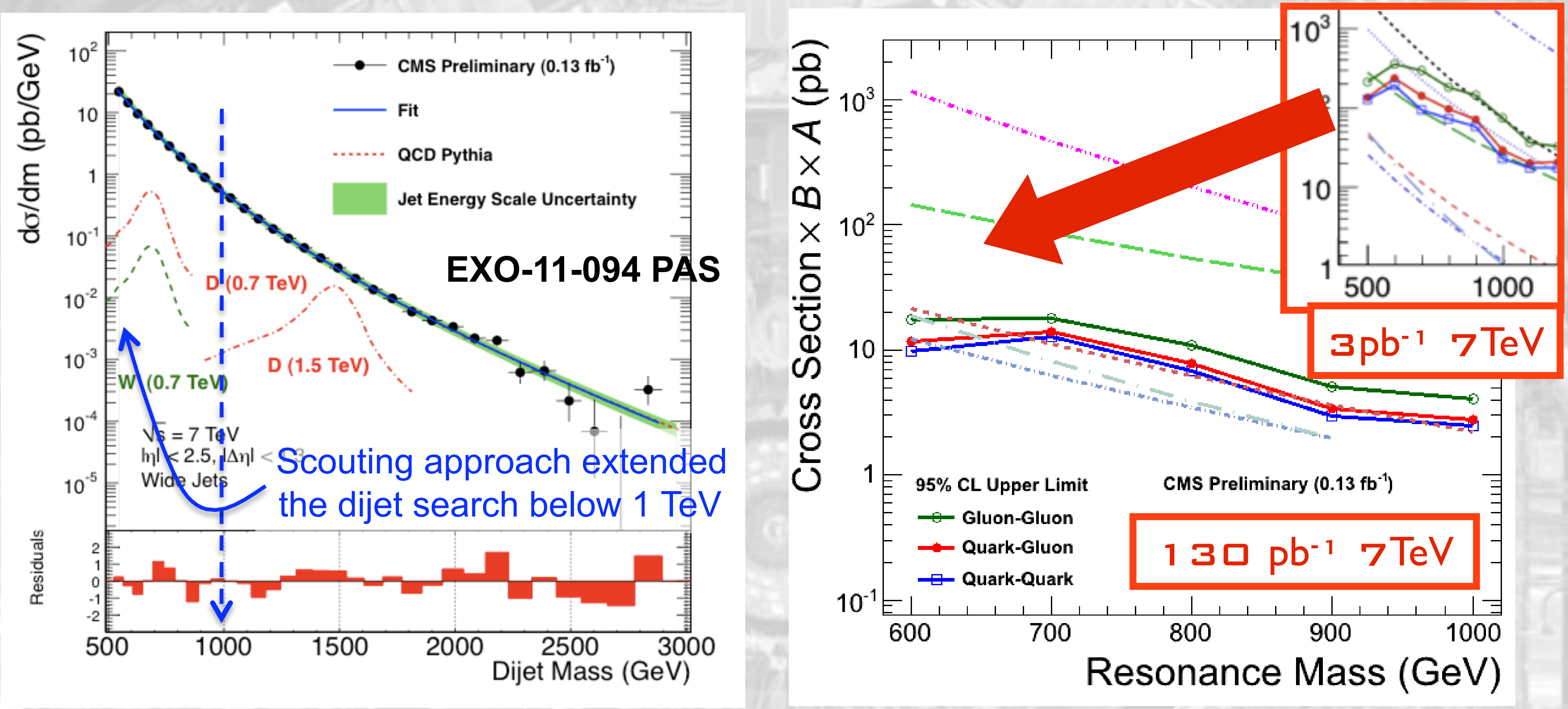
- We write on disk more event information that we (sometimes) need
- Keep ALL the events, with a small customised data format (only jet 4momenta). O(10 kb/event), can save several 1kHz of data
- Event reco not as good as normal
  - not all the analyses cannot be done this way
  - when resolution is not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



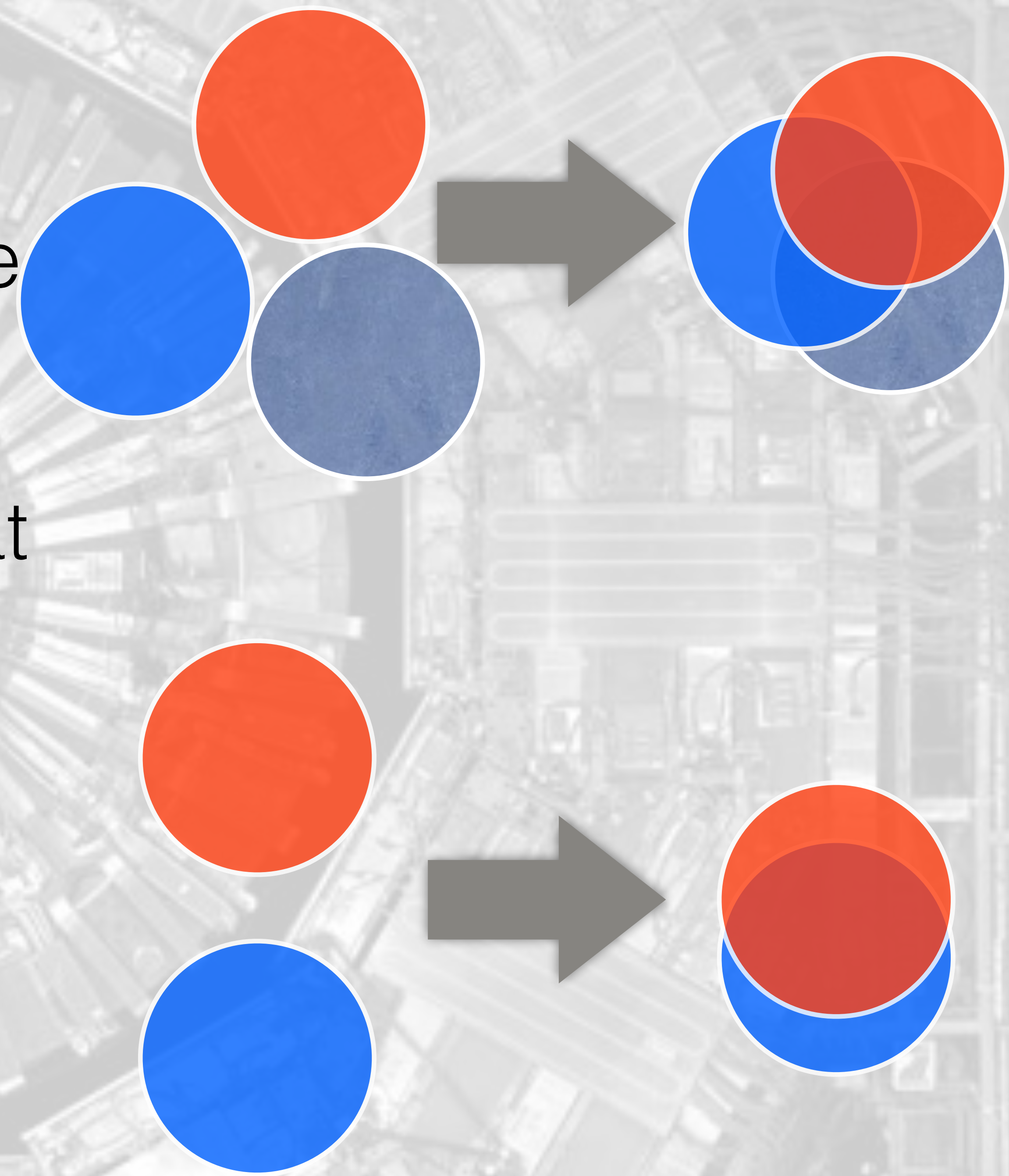
The Dijet Data Scouting



- 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

Jets beyond quarks&gluons

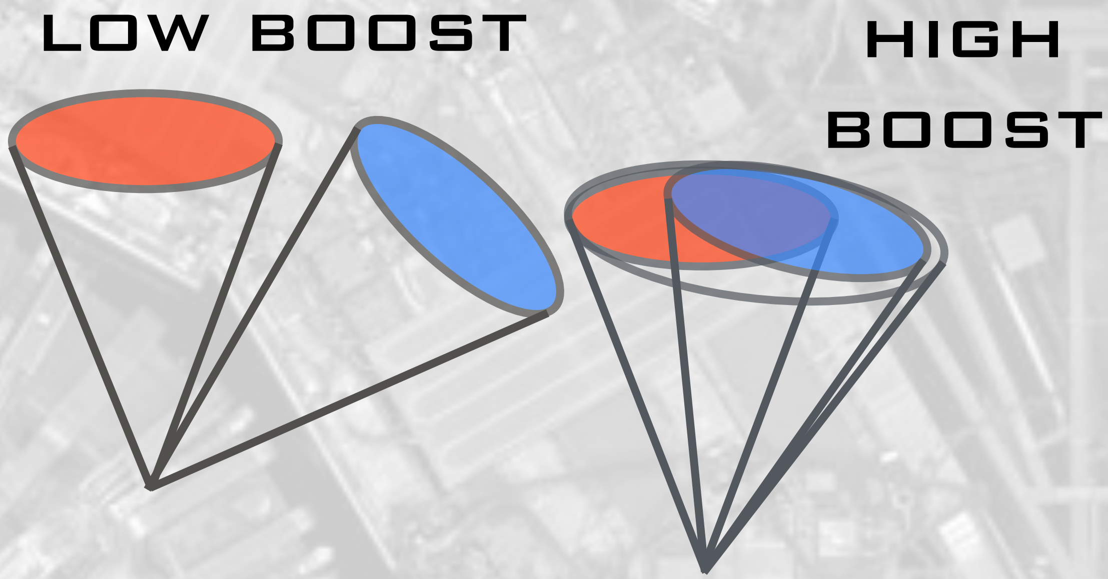
- The more we exclude, the more we push the NP scale to large masses
- For large pT of visible objects (top/W/H/Z) we push the searches in the large-boost domain
- Eventually, the boost is so large that everything looks like a jet
- QCD background is then a limiting factor for more than hadronic searches
- Jet reconstruction to be pushed to the next level

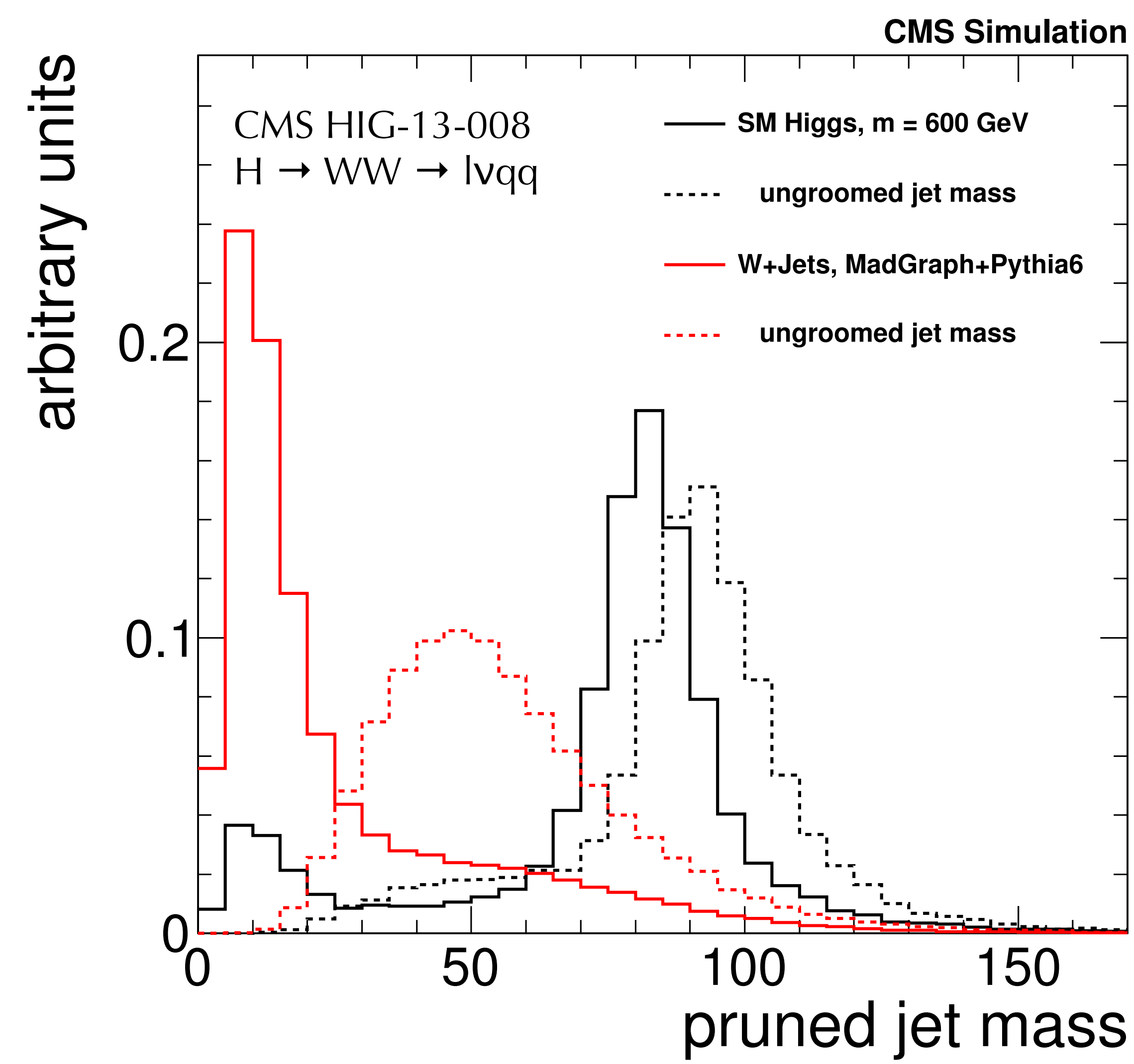



The Jet Revolution

From Jets to boosted objects

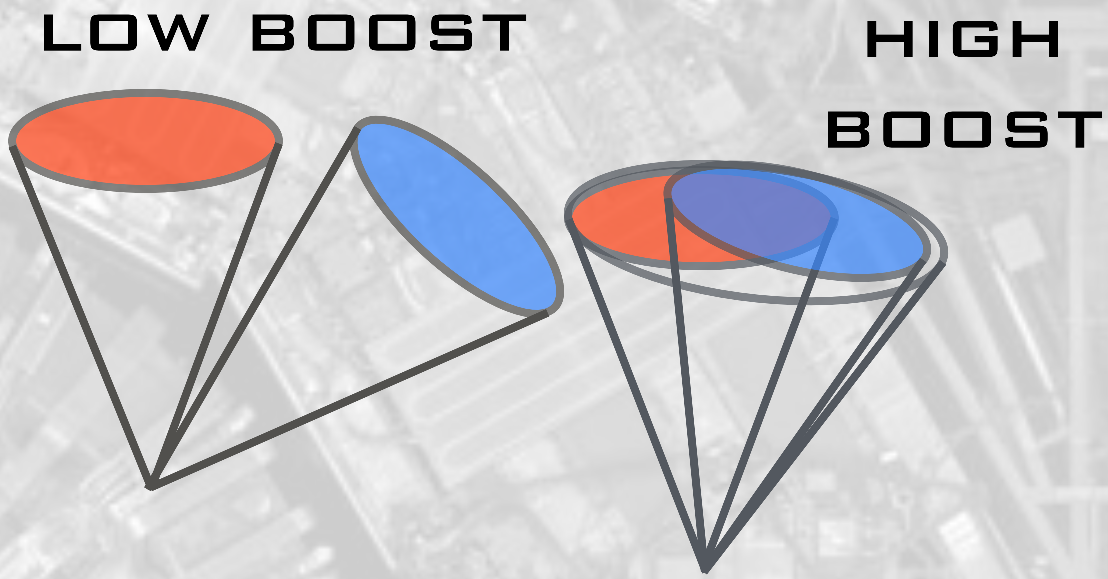
- W/Z/H/top can decay to fully hadronic final states
- For large enough pT, the decay products might merge into a single jet
- These jets are special, as their properties (e.g., the mass) are not those of a QCD jet
- On the other hand, there has to be some care in defining the "right" mass
  - the plain mass for a jet from a colourless object (W/Z/H) is the mass of the original particle
  - for a QCD jet, the mass depends on the jet pT (i.e. it is NOT the right mass)

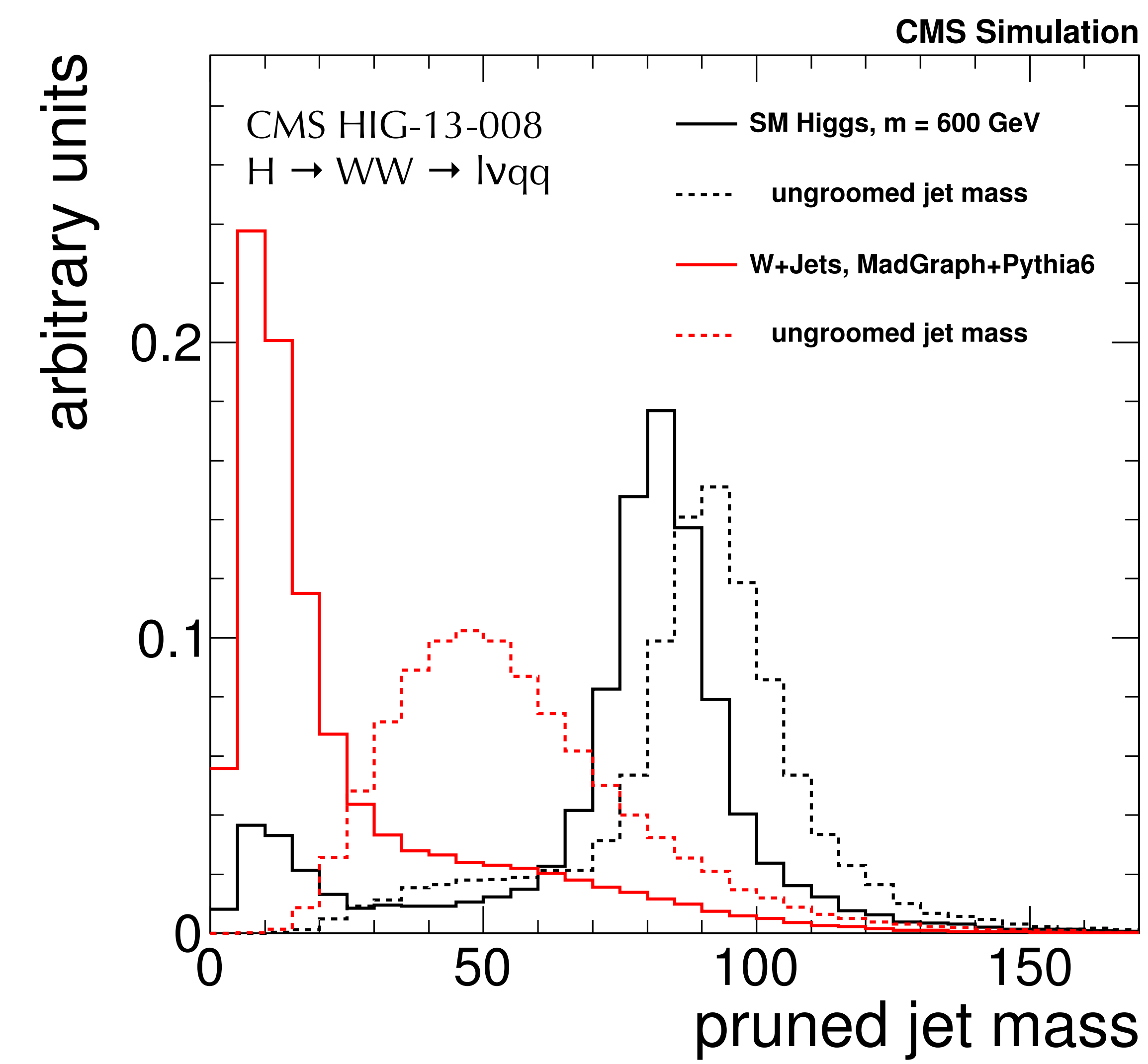




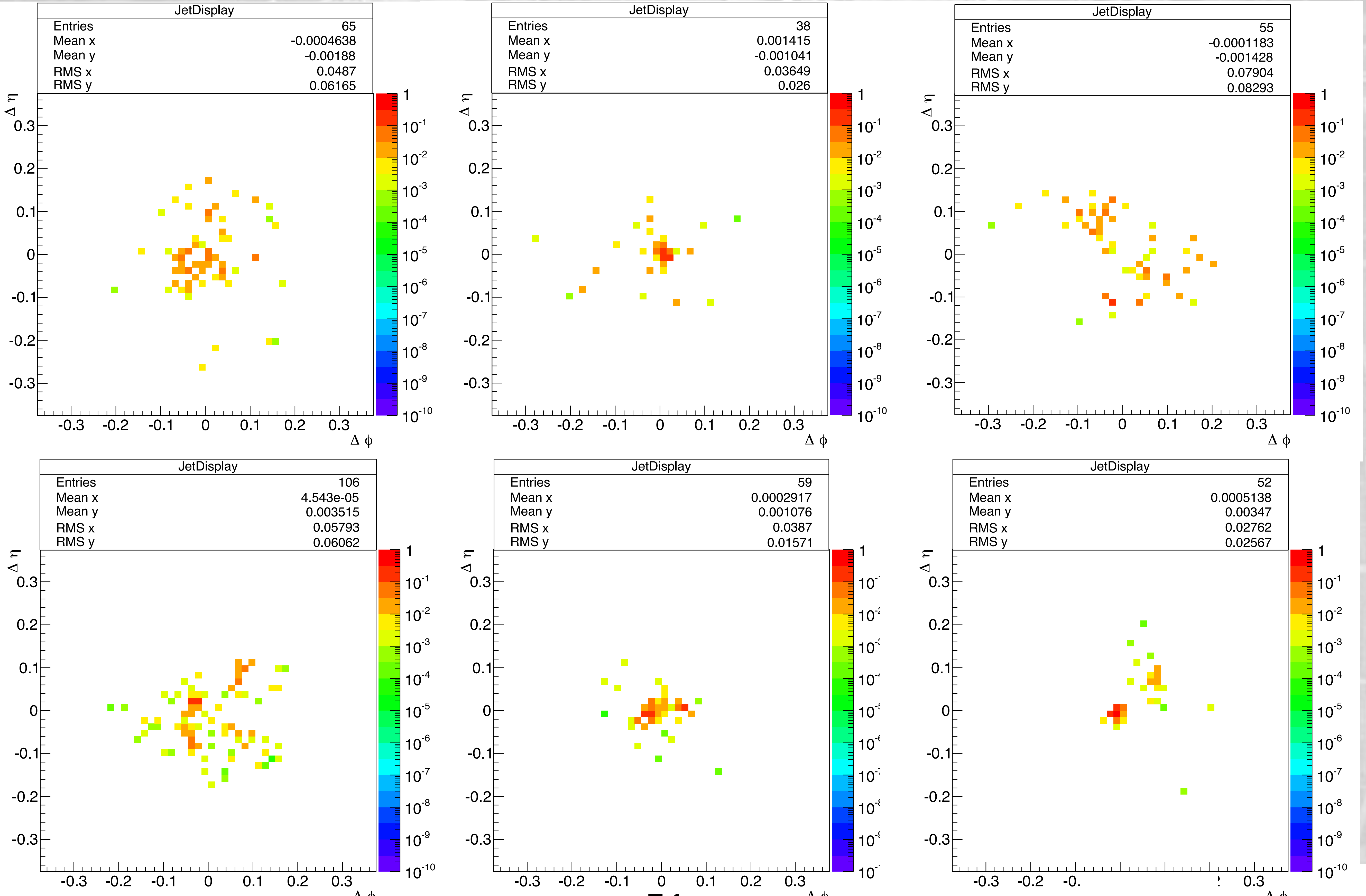
Jet Grooming

- 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)





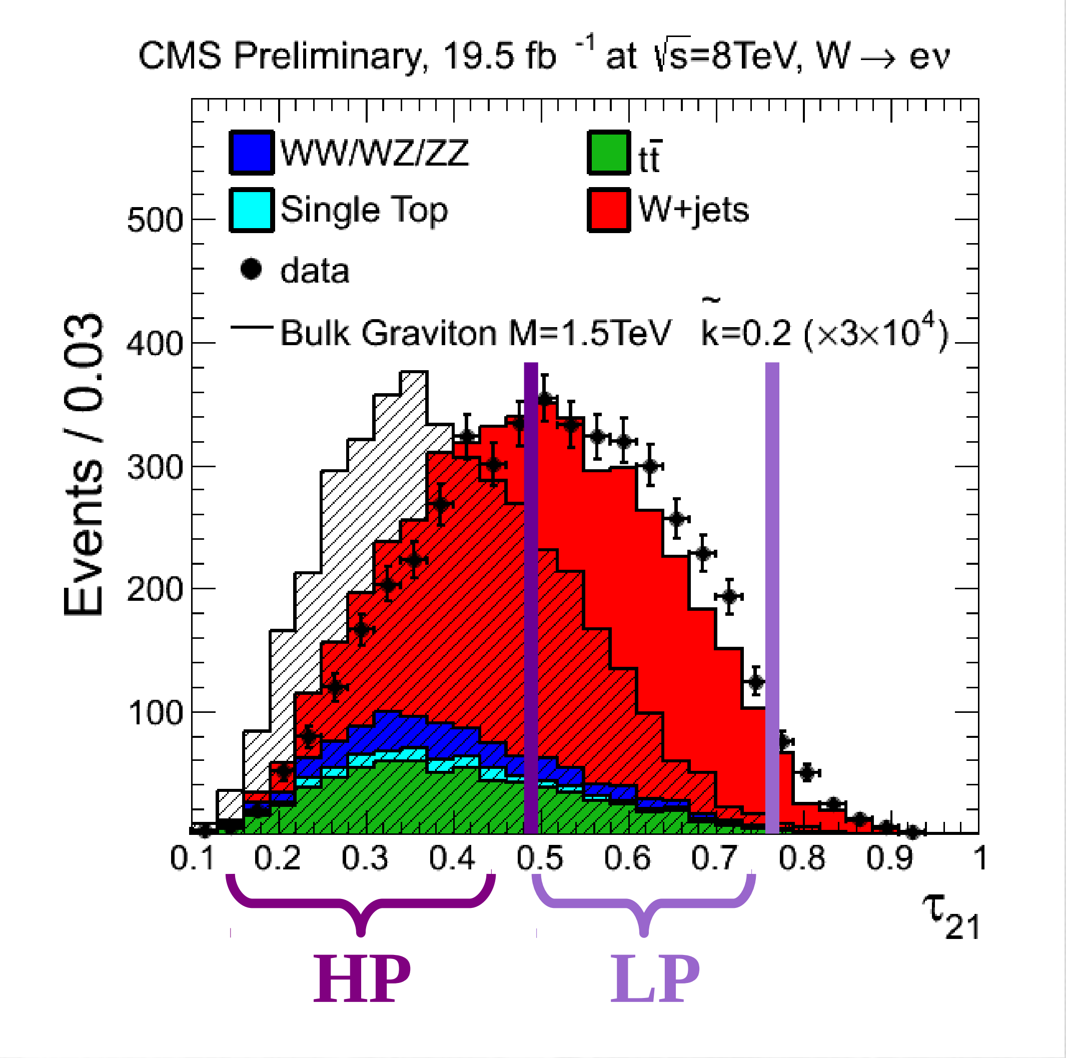
Jet Substructure



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)

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



http://arxiv.org/abs/1011.2268

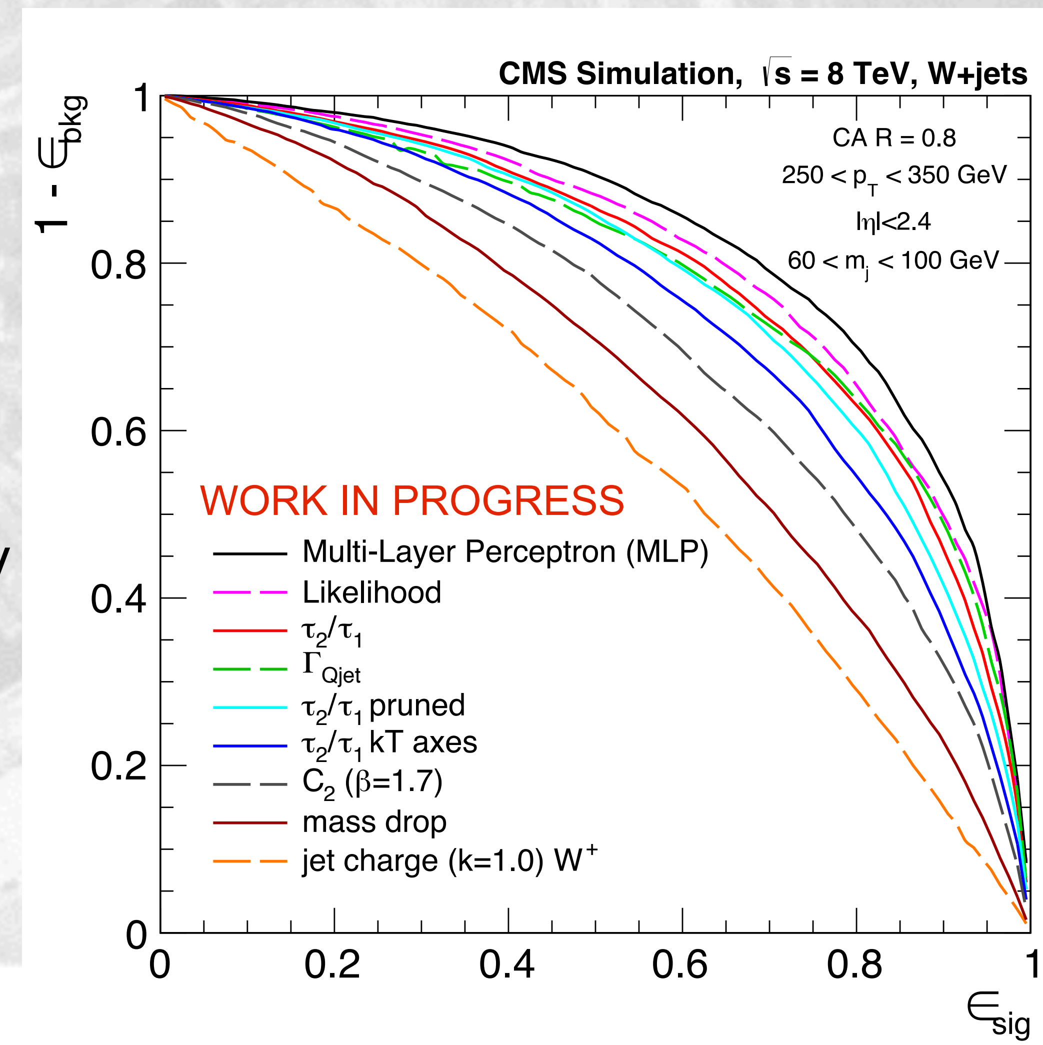
A Boosted W/Z Tagger

- 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

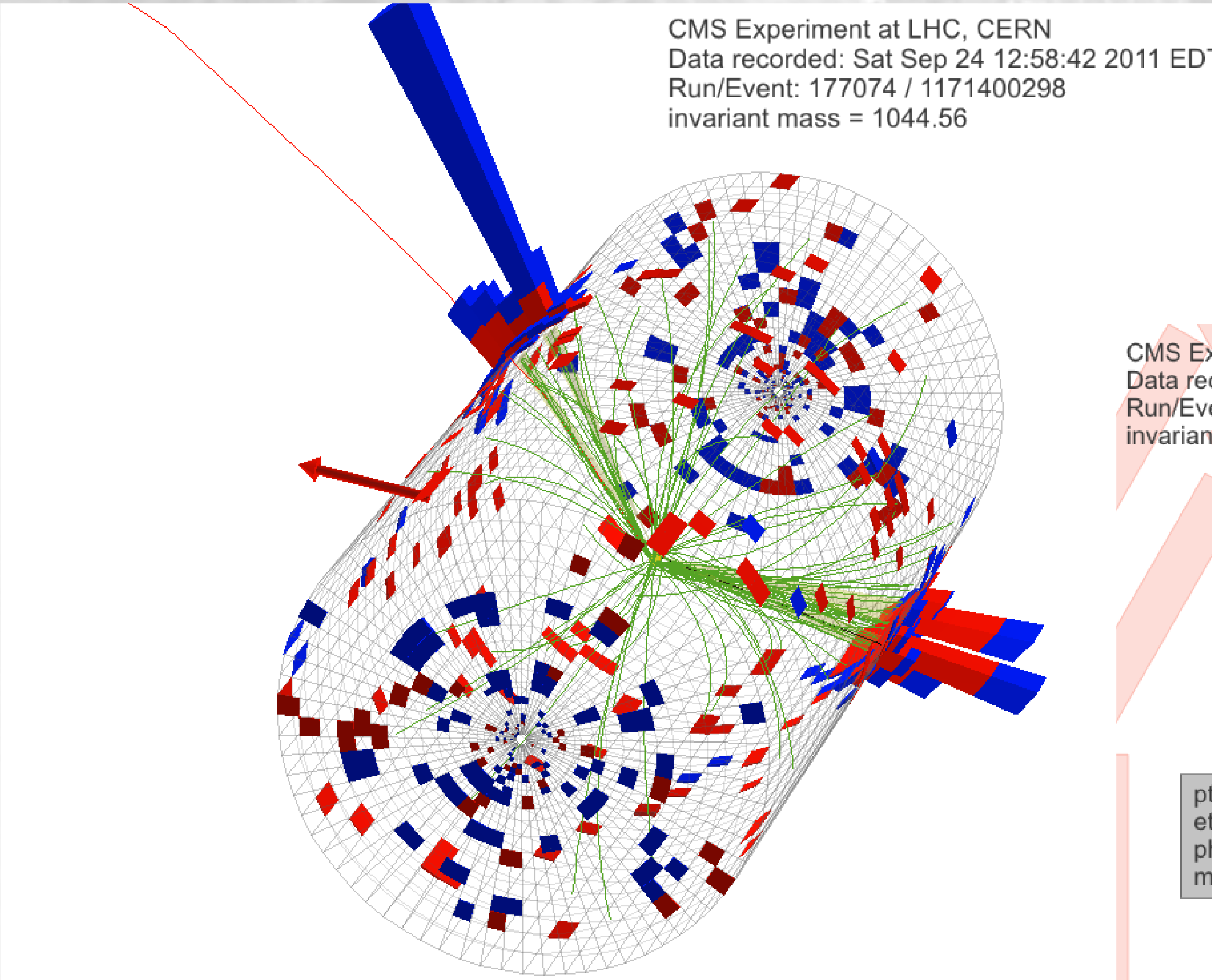
- CMS studies them and compared performances (also with MVA techniques). An obvious winner in performance vs simplicity compromise

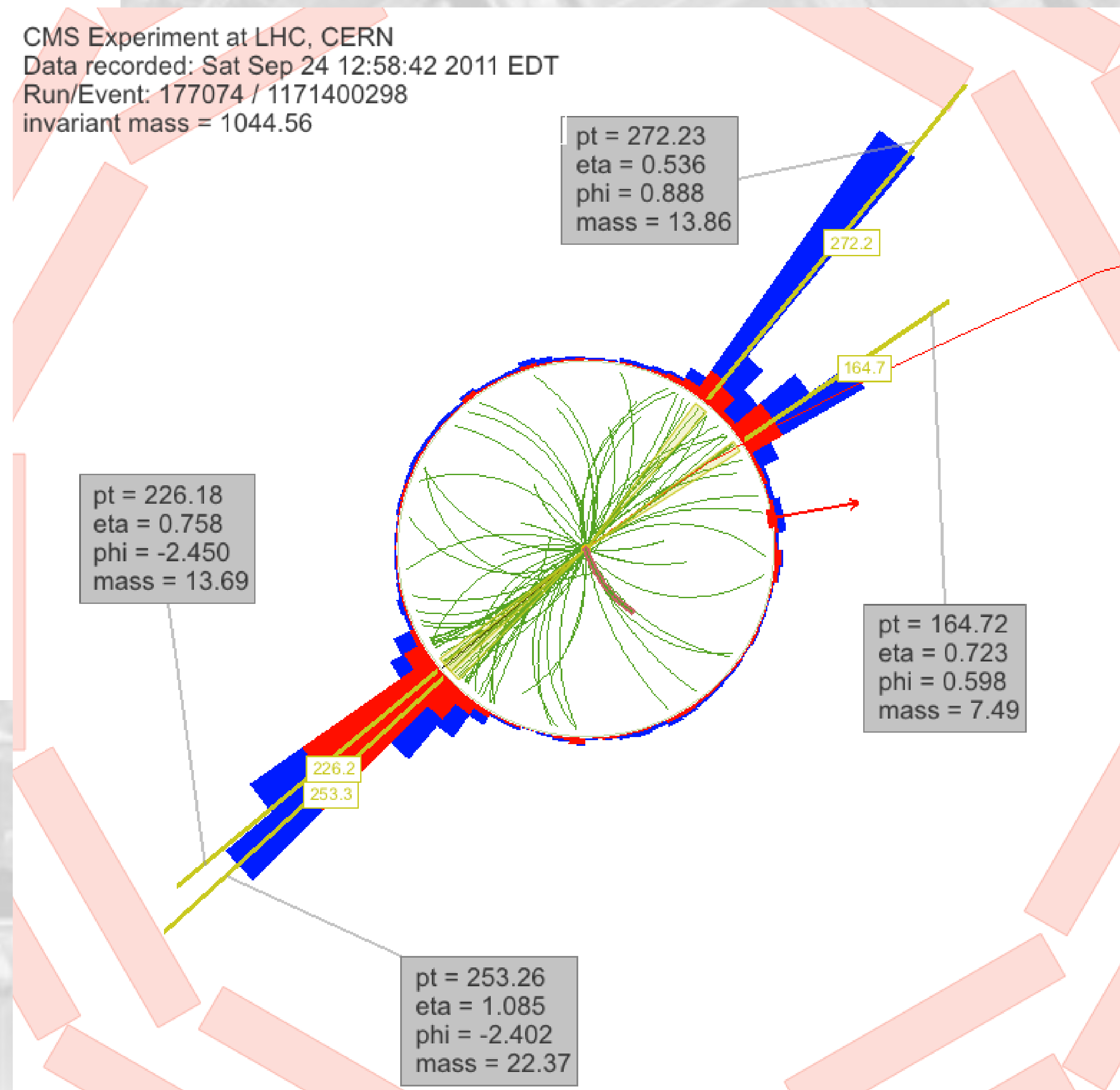
- A fundamental ingredient here is PF: not only the energy resolution but also the angular resolution and the detector granularity at play. The integration of the tracker with the calorimeters provides this at optimal



CMS-PAS-JME-13-006

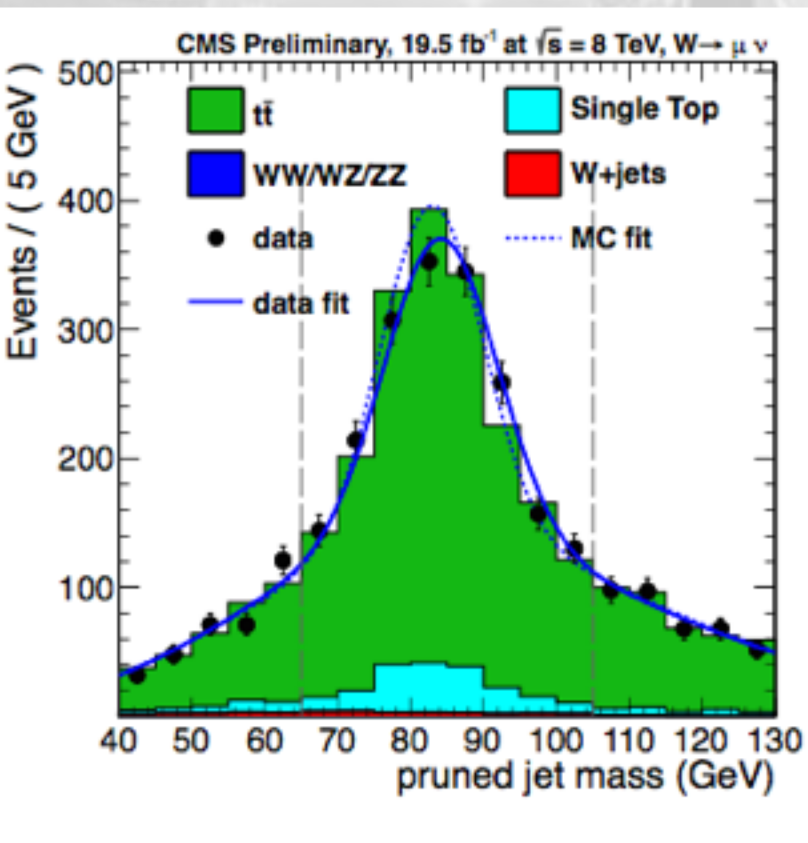
A DOUBLE-TAG EVENT

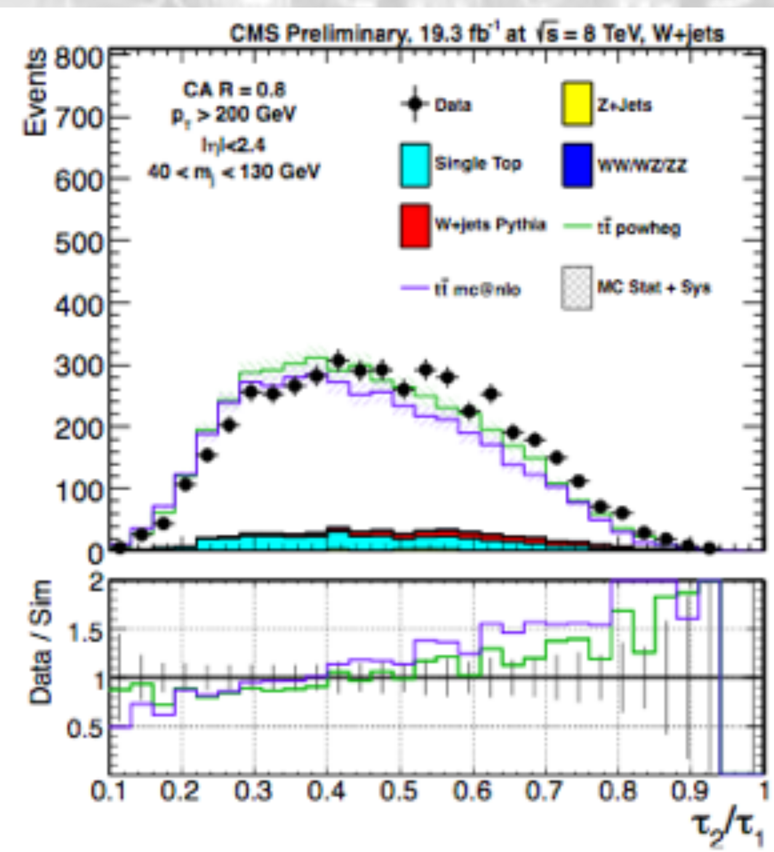


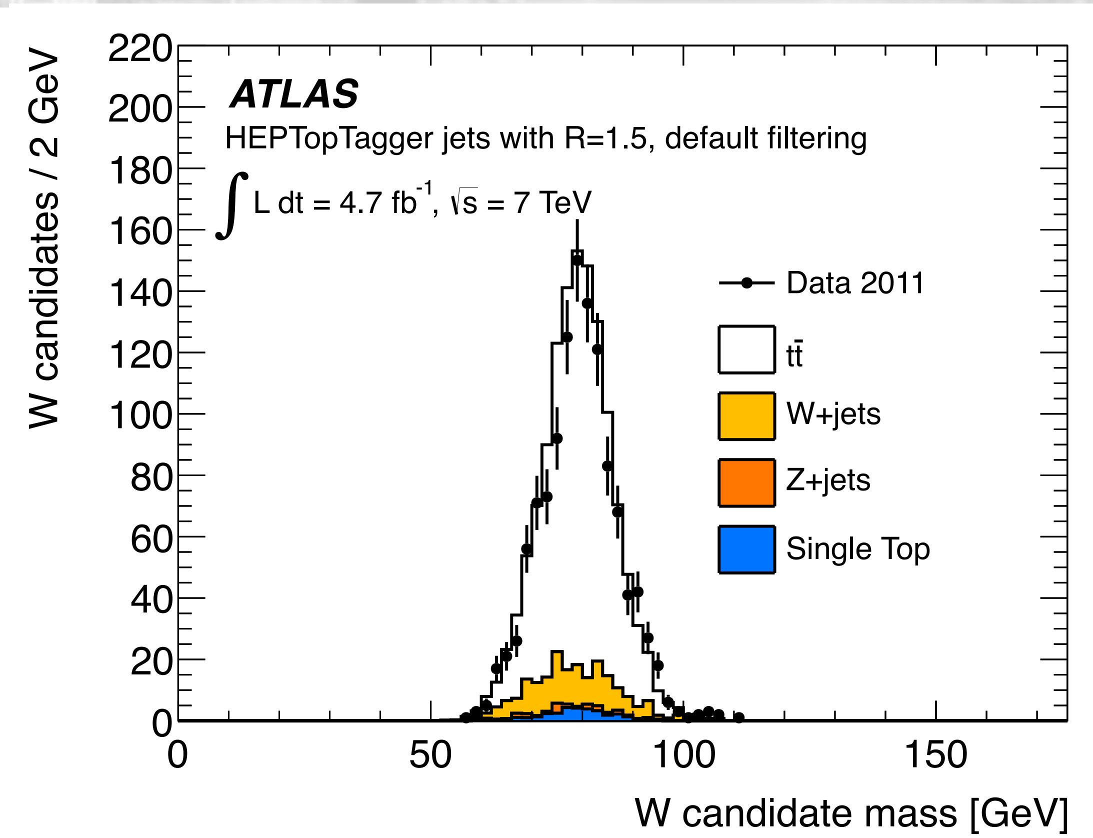


Validation With Data

- 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)

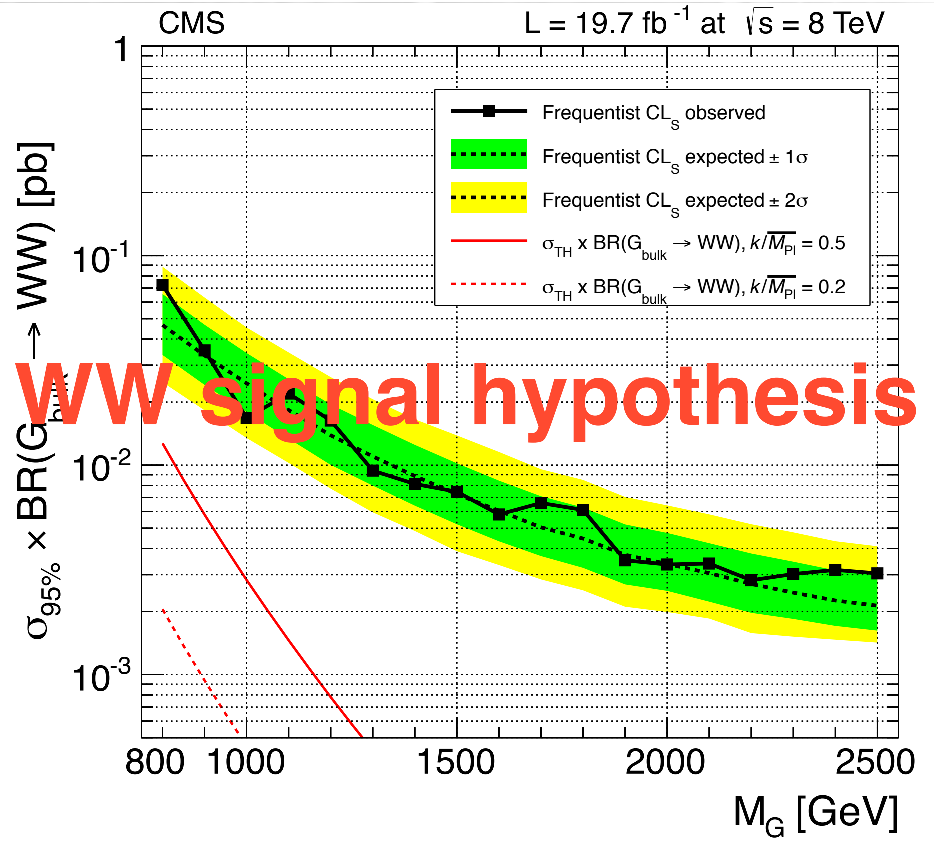


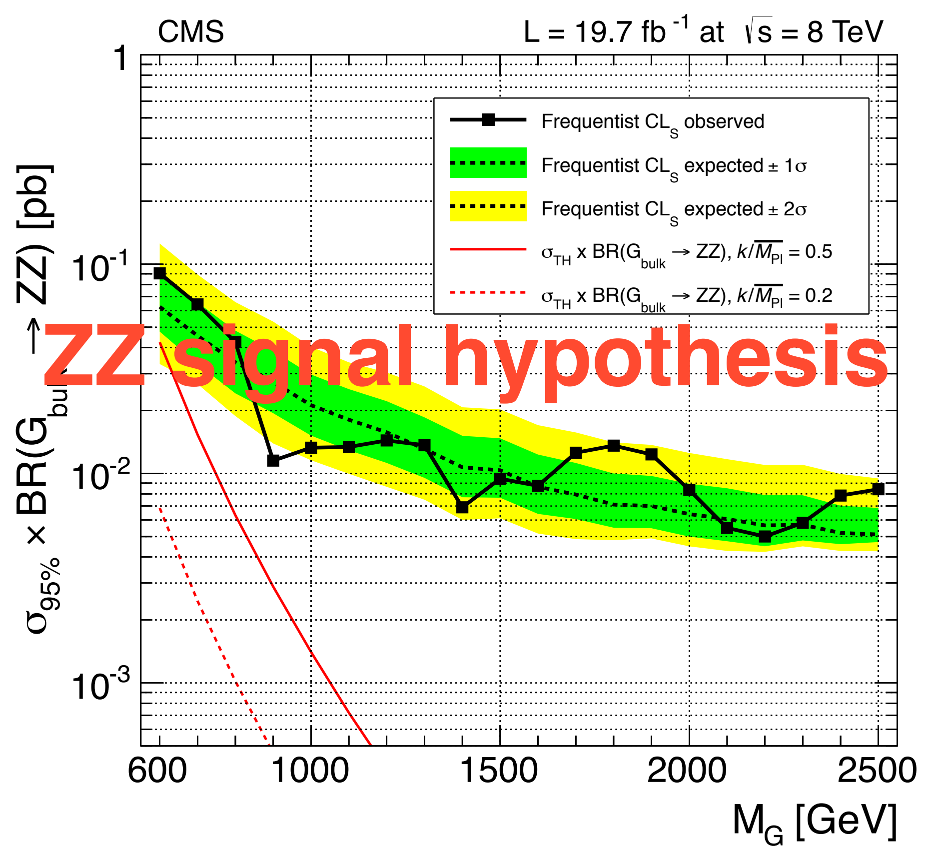


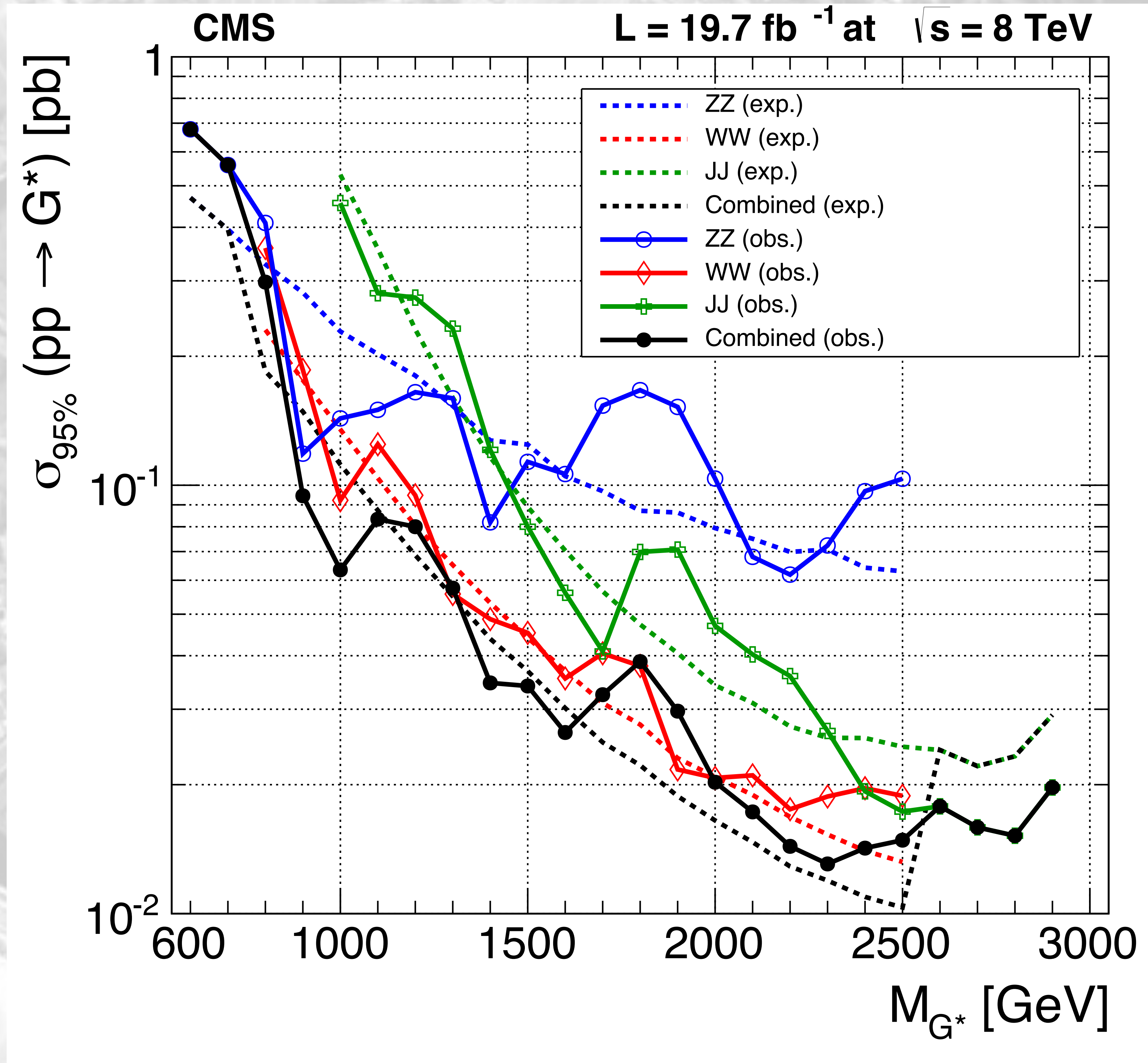


CMS-PAS-JME-13-006 ATLAS arXiv 1306.4945

Results with 8TeV data







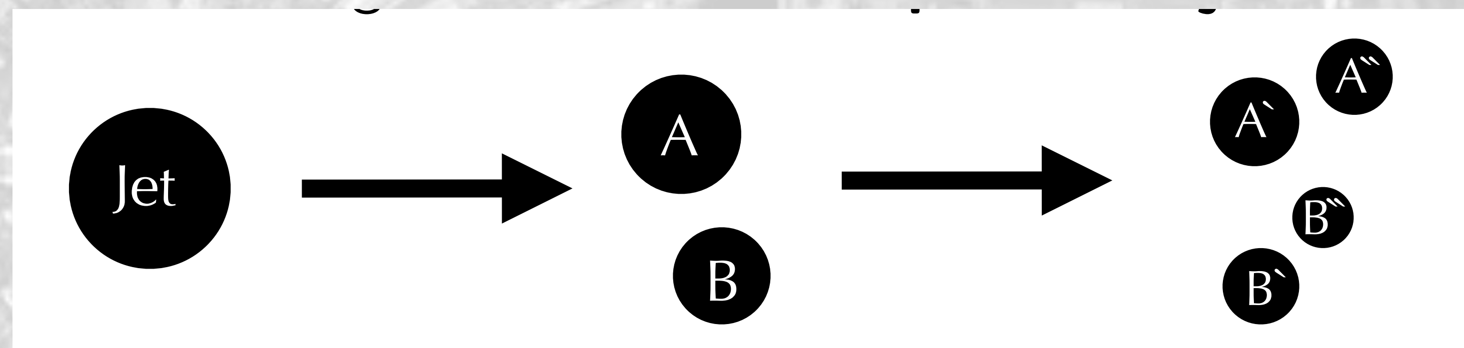
Top Tagger: TypeI top

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



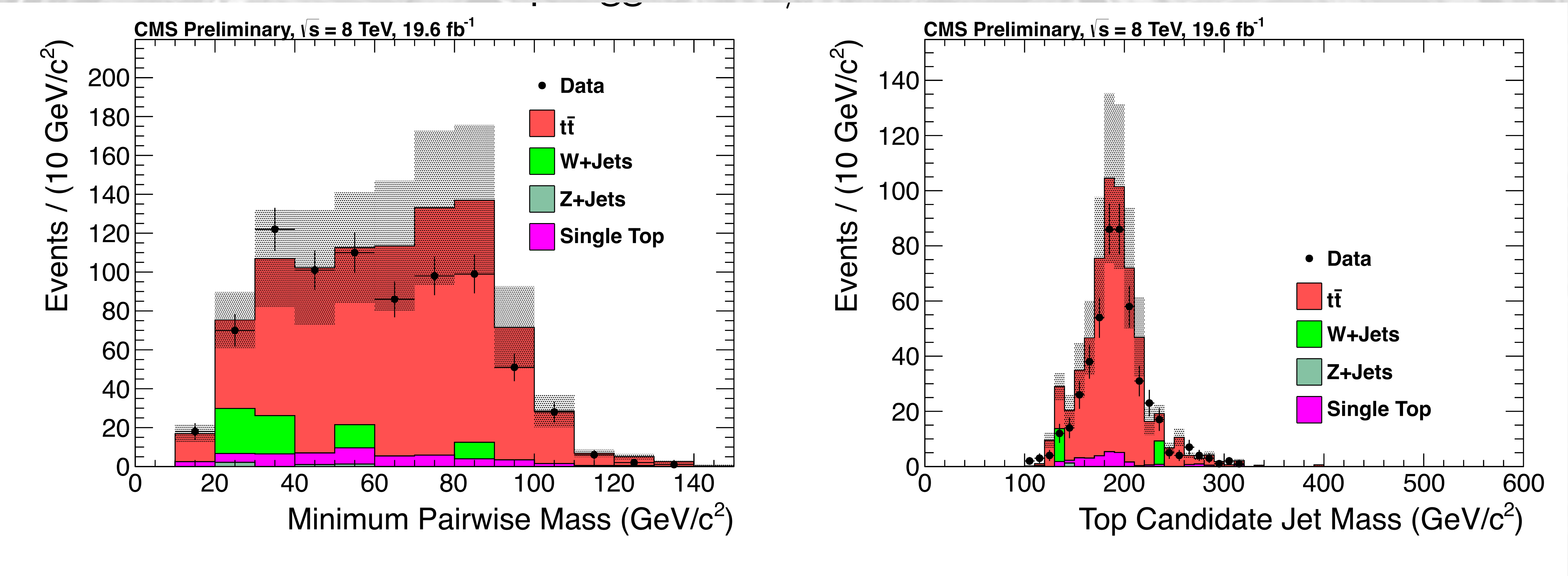
- Remove jets failing requirements and iterate

$$\begin{cases} \text{subjet } p_T > 5\% \text{ jet } p_T \\ \text{Adjacency: } \Delta R(C1,C2) > 0.4 - 0.0004\, p_T(C) \end{cases}$$

- 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)

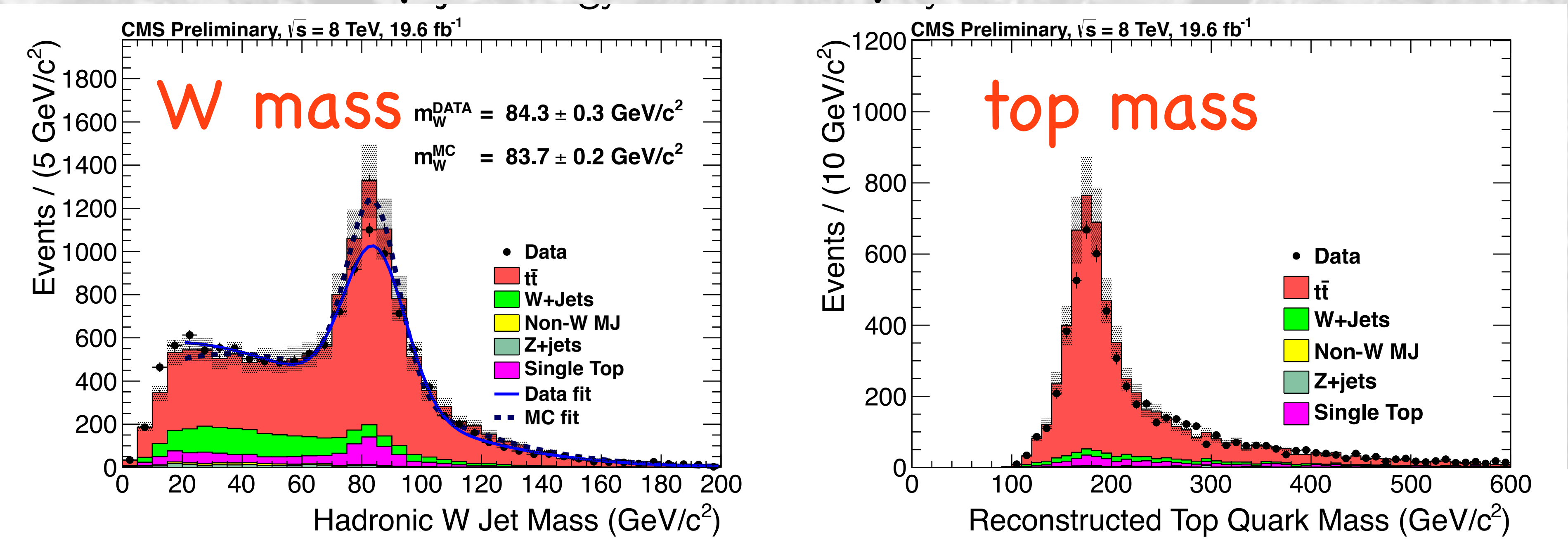
- Data / MC = 0.94±0.03 (Gray area shows the normalization uncertainty)

Top Tagger: TypeII top

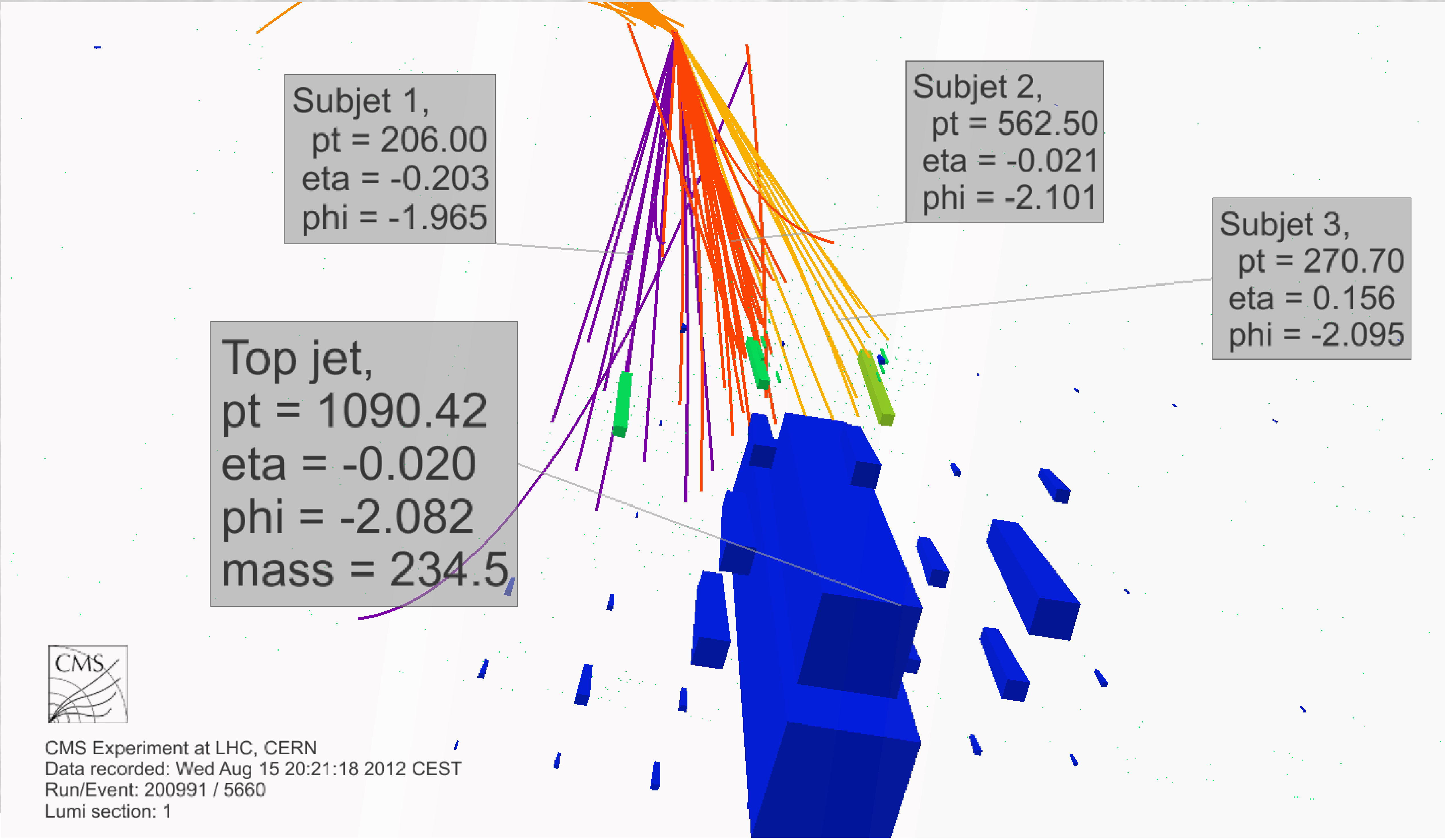
CMS-PAS-B2G-12-005

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

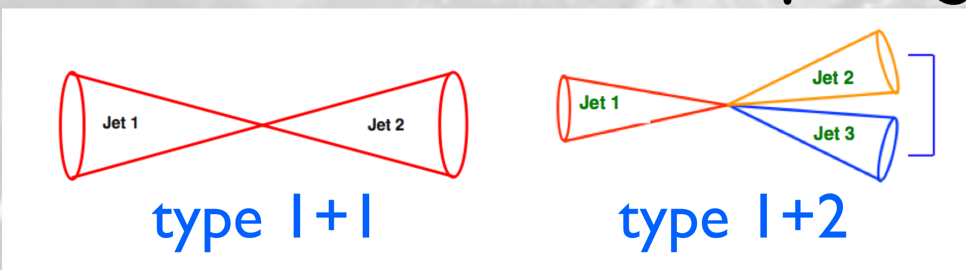


What We top-Tag

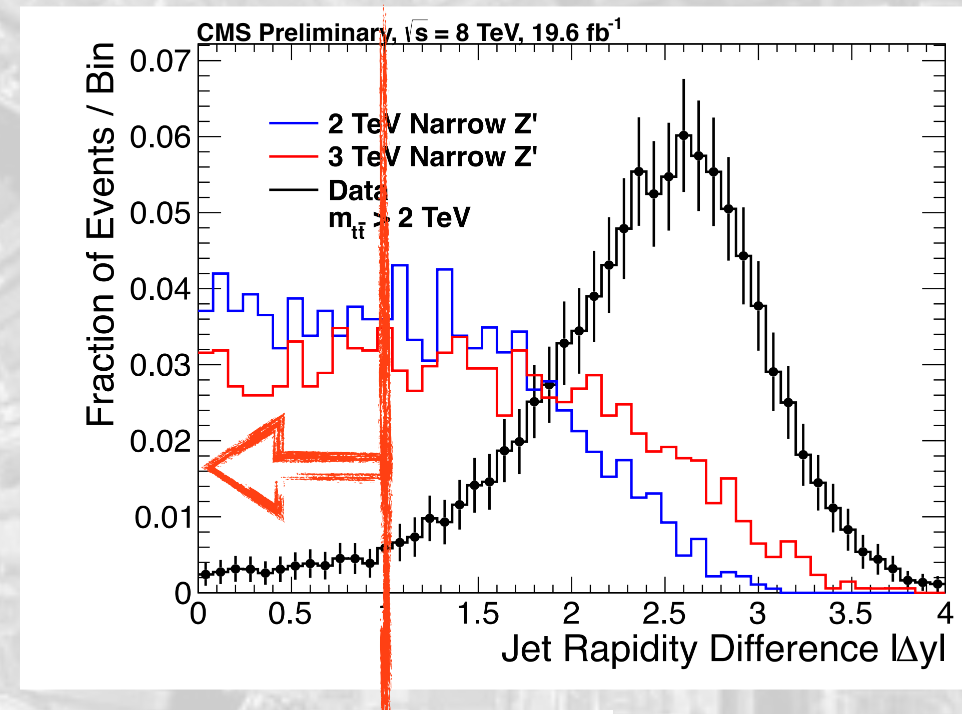


Fully Hadronic Z'→tt

- 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