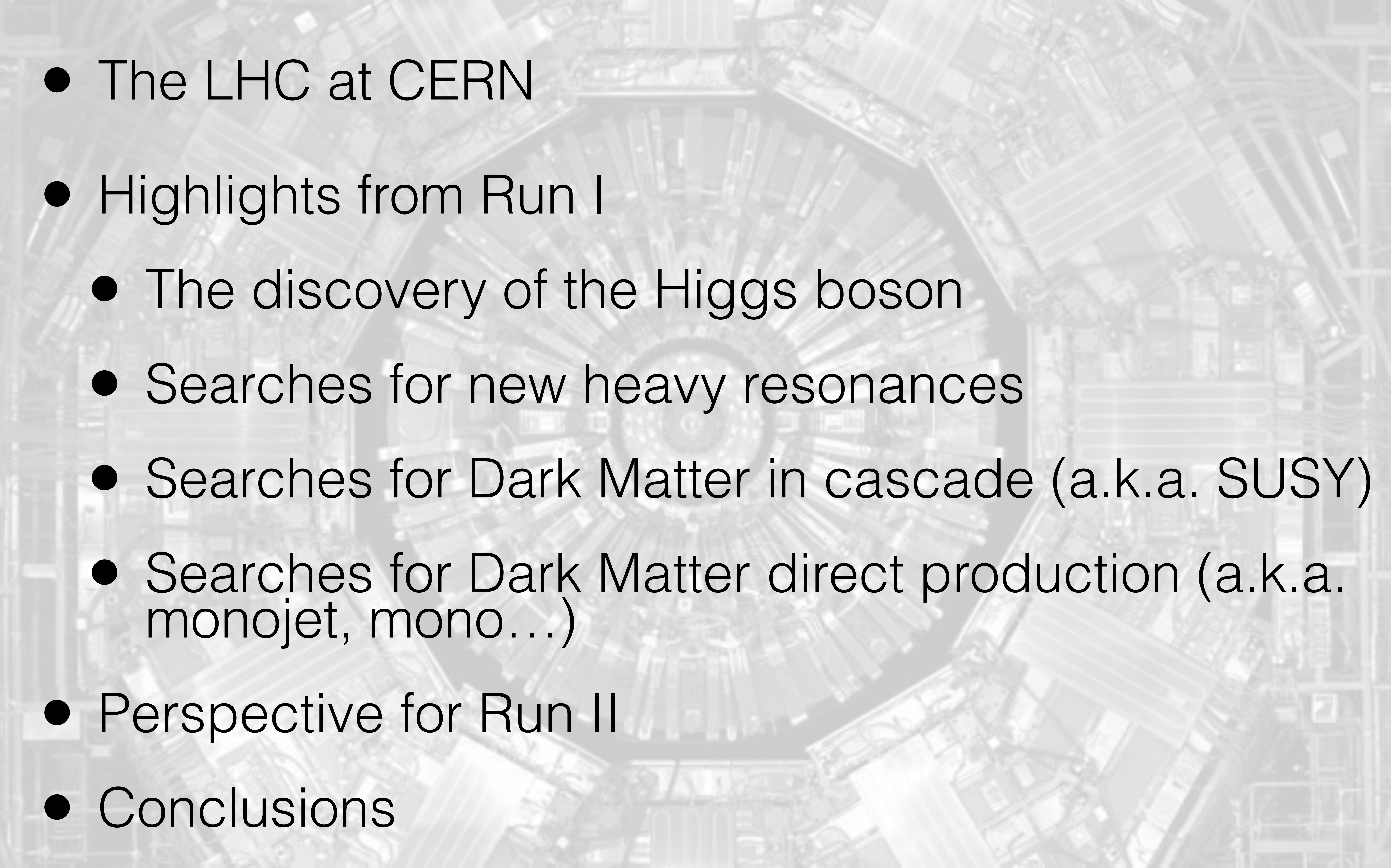
Results from the LHC Run I and perspectives for Run II

Maurizio Pierini
CERN

Outline

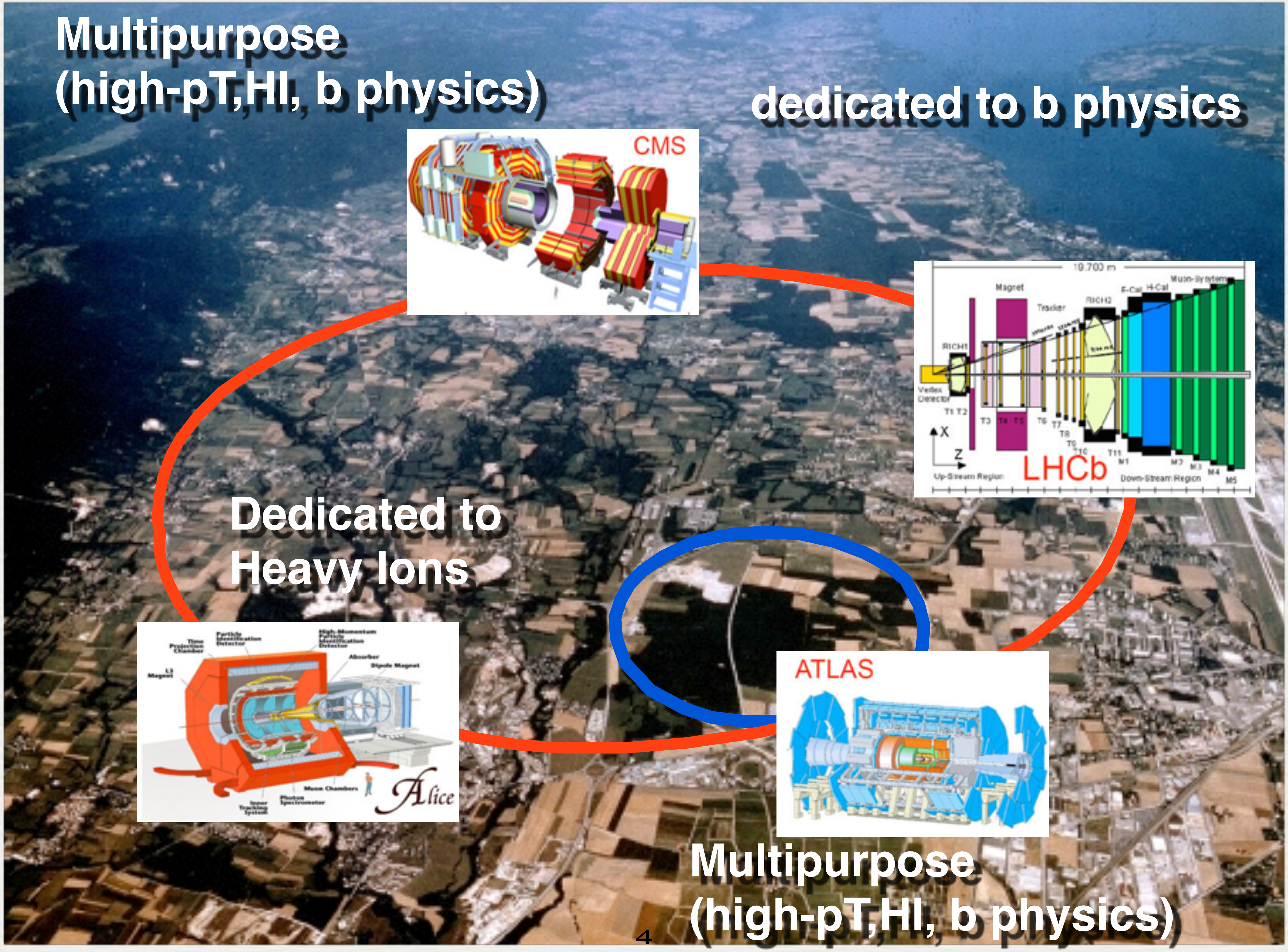


- The LHC at CERN
- Highlights from Run I
  - The discovery of the Higgs boson
  - Searches for new heavy resonances
  - Searches for Dark Matter in cascade (a.k.a. SUSY)
  - Searches for Dark Matter direct production (a.k.a. monojet, mono…)
- Perspective for Run II
- Conclusions

THE LARGE HADRON COLLIDER

27 Km tunnel
filled with
superconductive 8.3T
magnets kept @~3 K
Designed for 14 TeV
pp collisions
So far operated at
7TeV and 8 TeV

THE LHC EXPERIMENTS



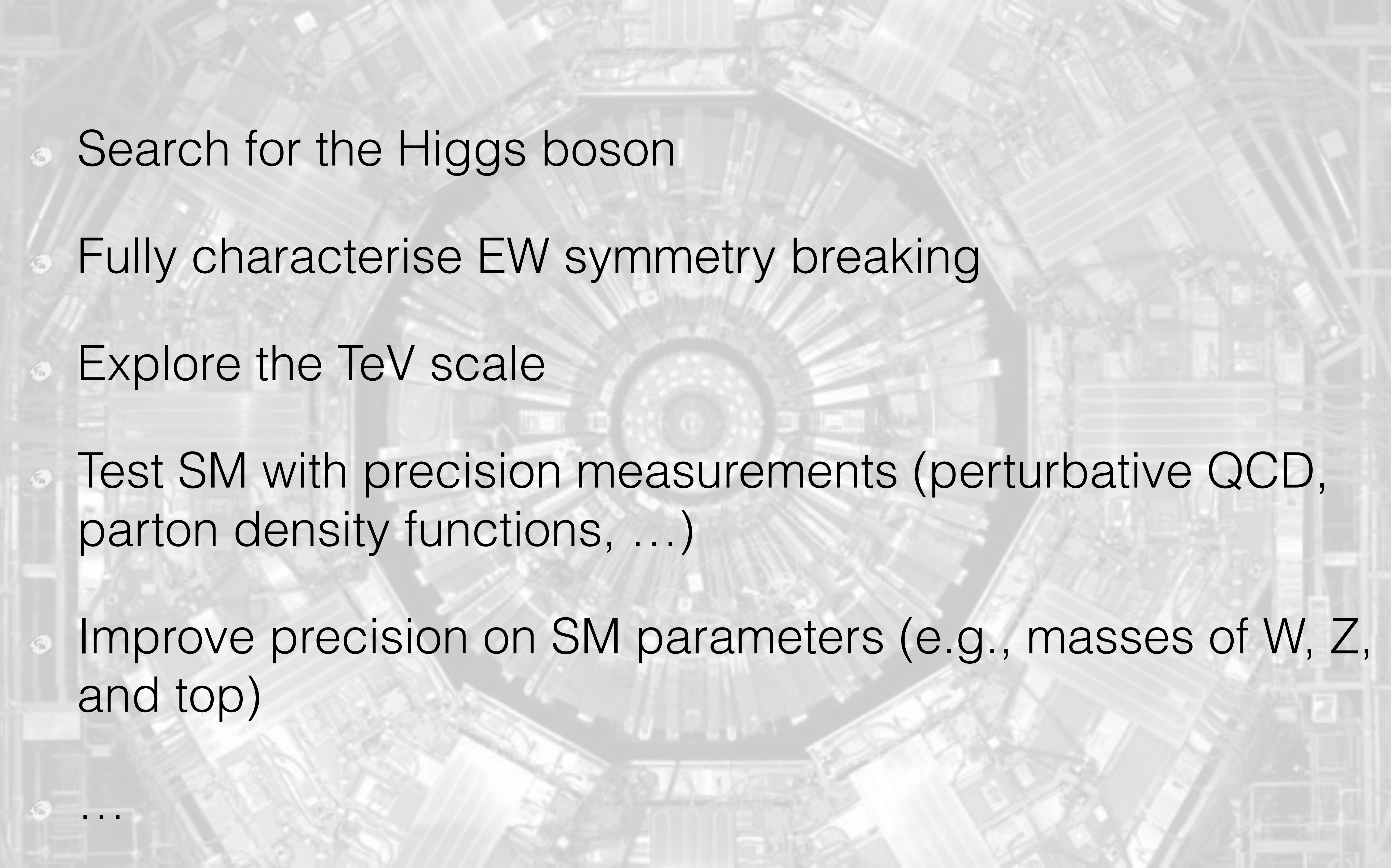
Multipurpose
(high-pT,HI, b physics)

dedicated to b physics

Dedicated to
Heavy Ions

Multipurpose
(high-pT,HI, b physics)

Atlas&CMS physics Goal

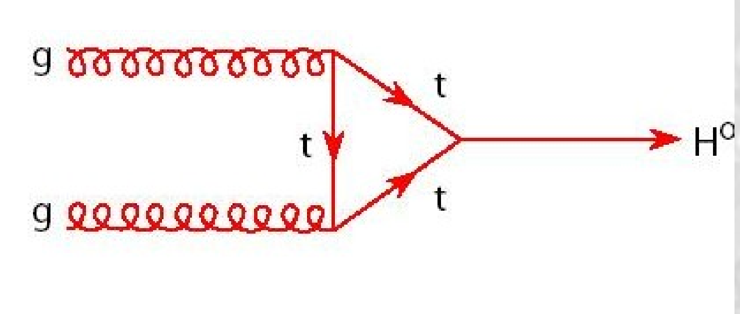


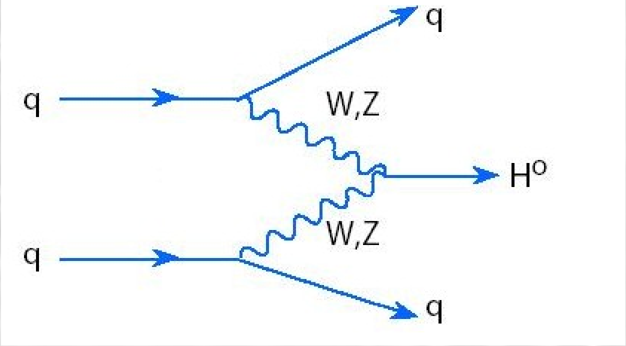
- Search for the Higgs boson
- Fully characterise EW symmetry breaking
- Explore the TeV scale
- Test SM with precision measurements (perturbative QCD, parton density functions, …)
- Improve precision on SM parameters (e.g., masses of W, Z, and top)
- …

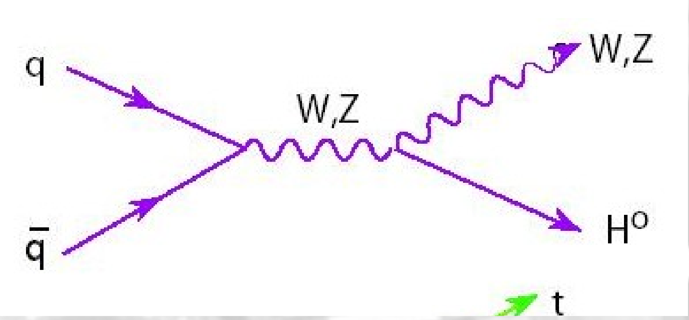
Highlights from Run I:
discovery of the Higgs boson

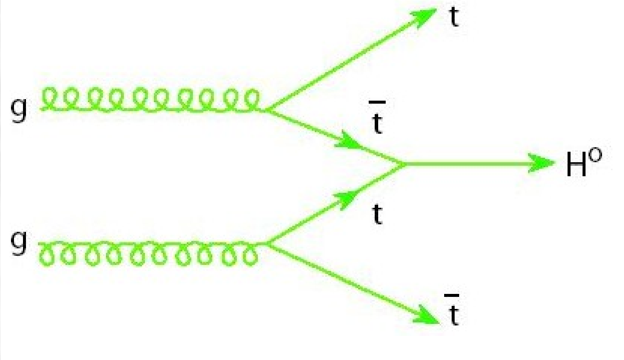
HIGGS BOSON PRODUCTION

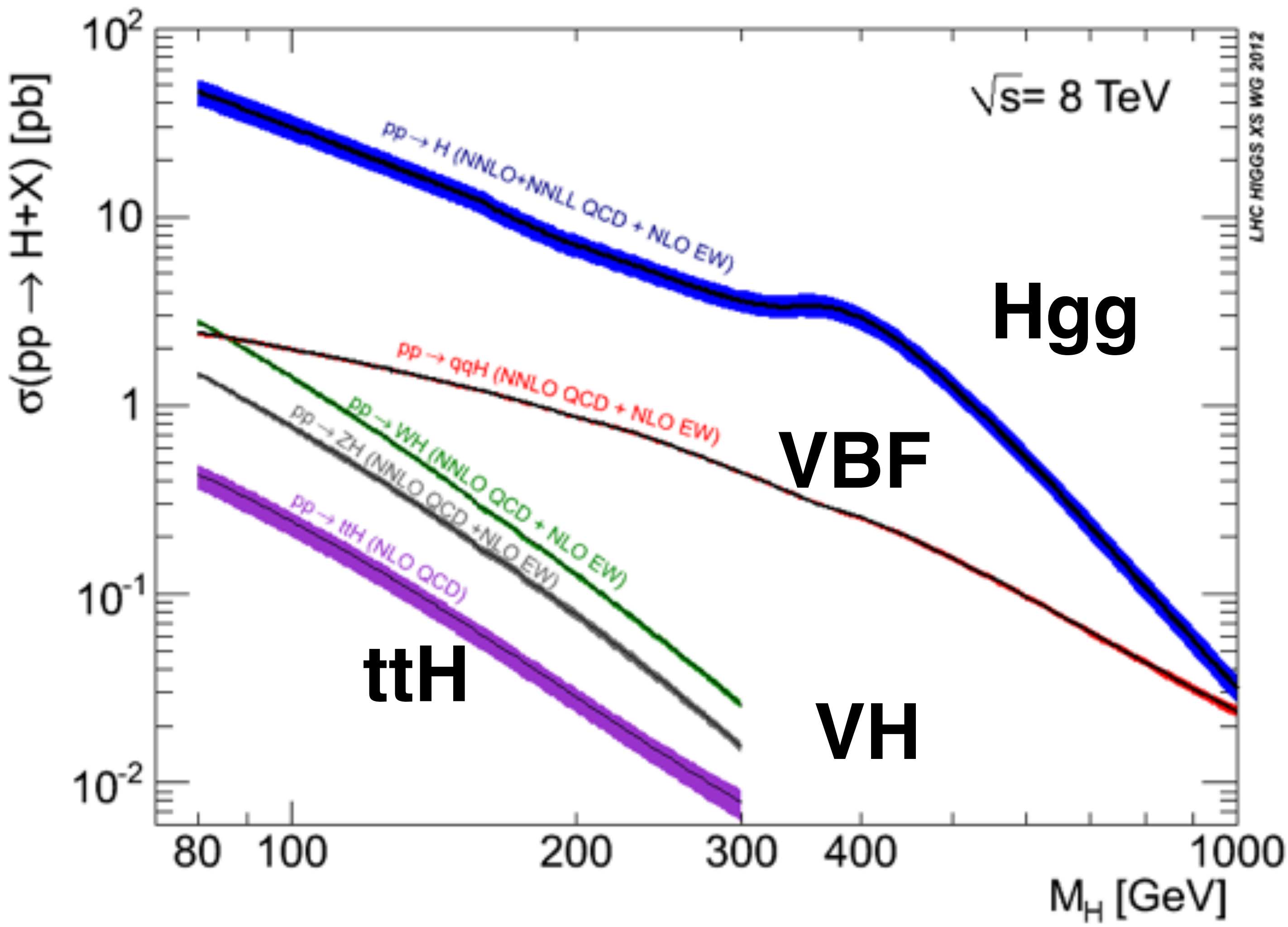
- There are mainly four production mechanisms
  - gluon-gluon fusion (Hgg)
  - vector-boson fusion (VBF)
  - in association with vector boson (VH)
  - top-top fusion (ttH)
- While gg is dominant, all the mechanisms have been considered
  - redundancy
  - favourable S vs B for problematic channels





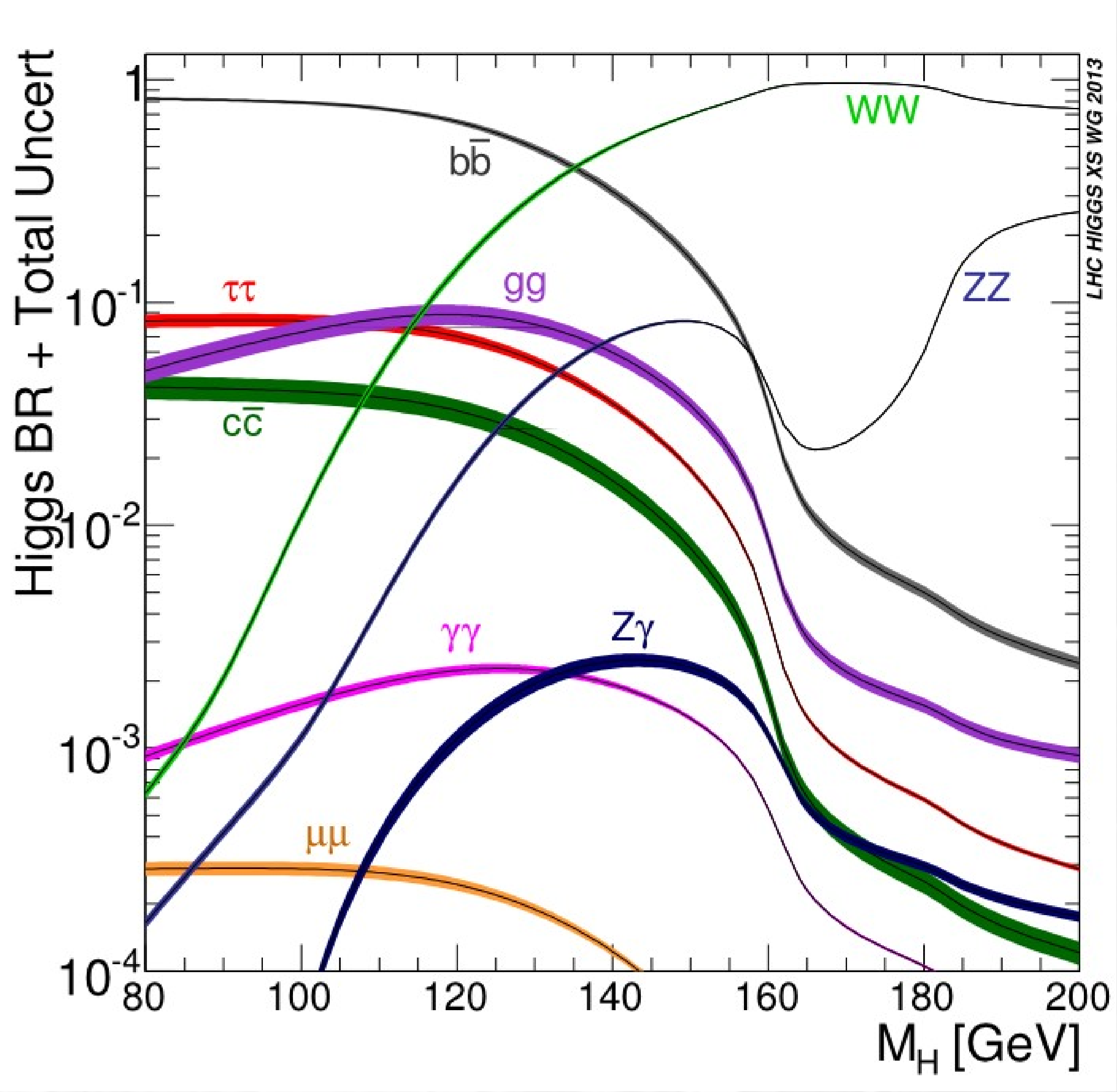




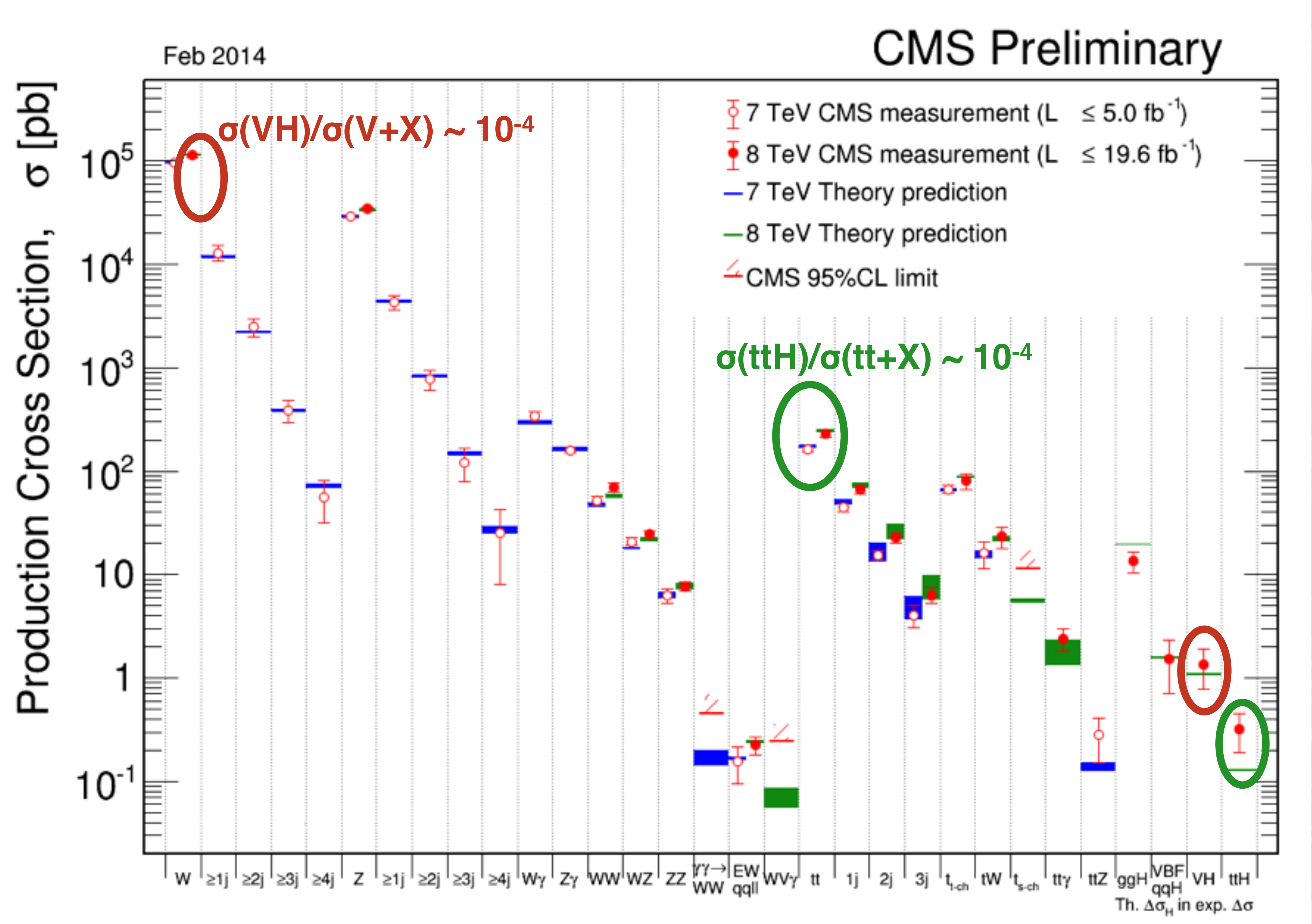


HIGGS BOSON DECAY

- The Higgs phenomenology is driven by the allowed decay modes
- Depending on the Higgs mass, this can result in a more or less rich set o possibilities
- Particularly for mH ~ 130 GeV there are several possibilities (i.e., we ended up in a lucky spot)
    - Four leptons (the golden channel)
    - Diphoton
    - WW
    - τ τ & bb: large background but needed to prove coupling to fermions



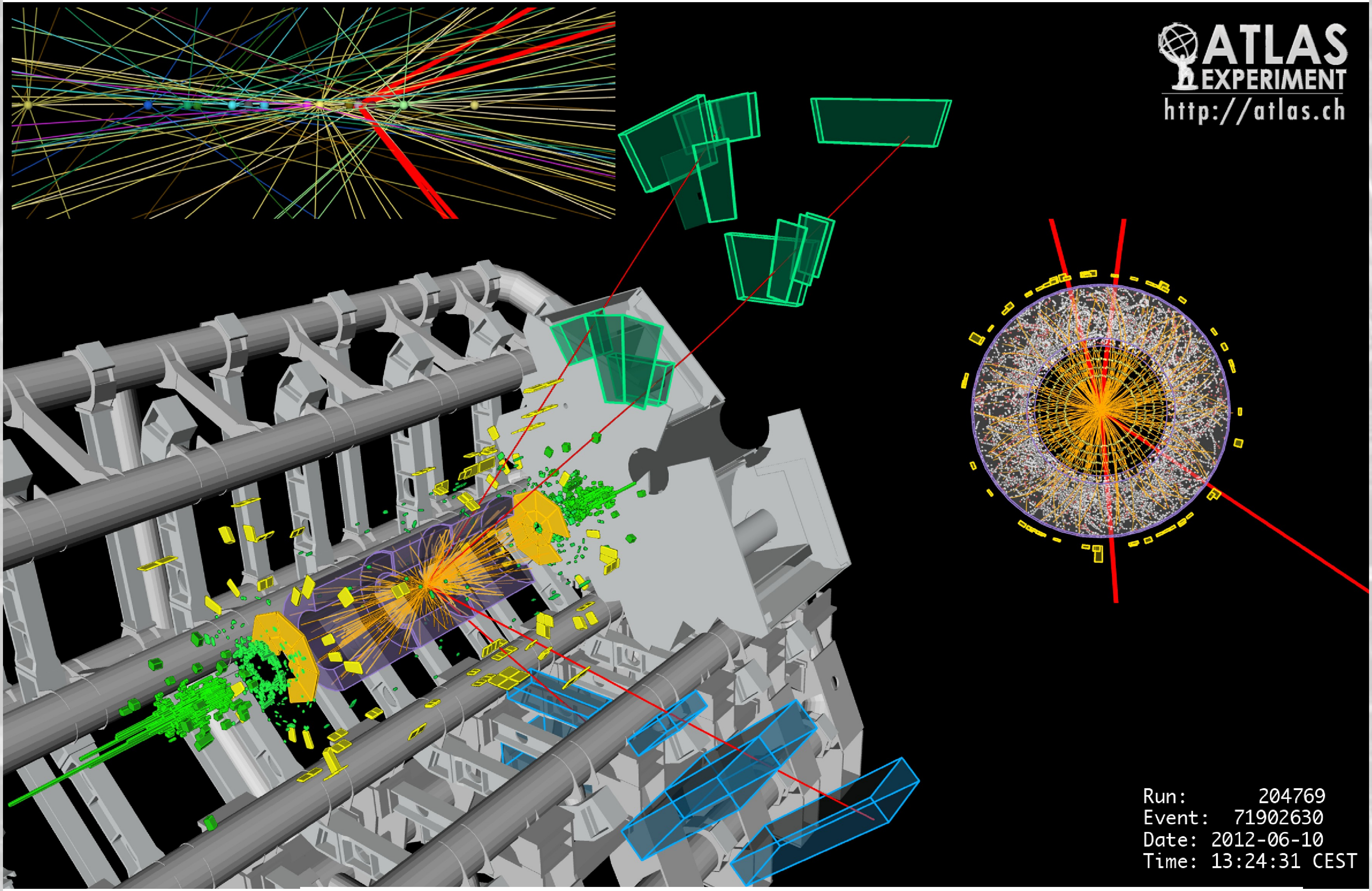
BACKGROUND IS CHALLENGING



σ(VH)/σ(V+X) ~ 10^{-4}

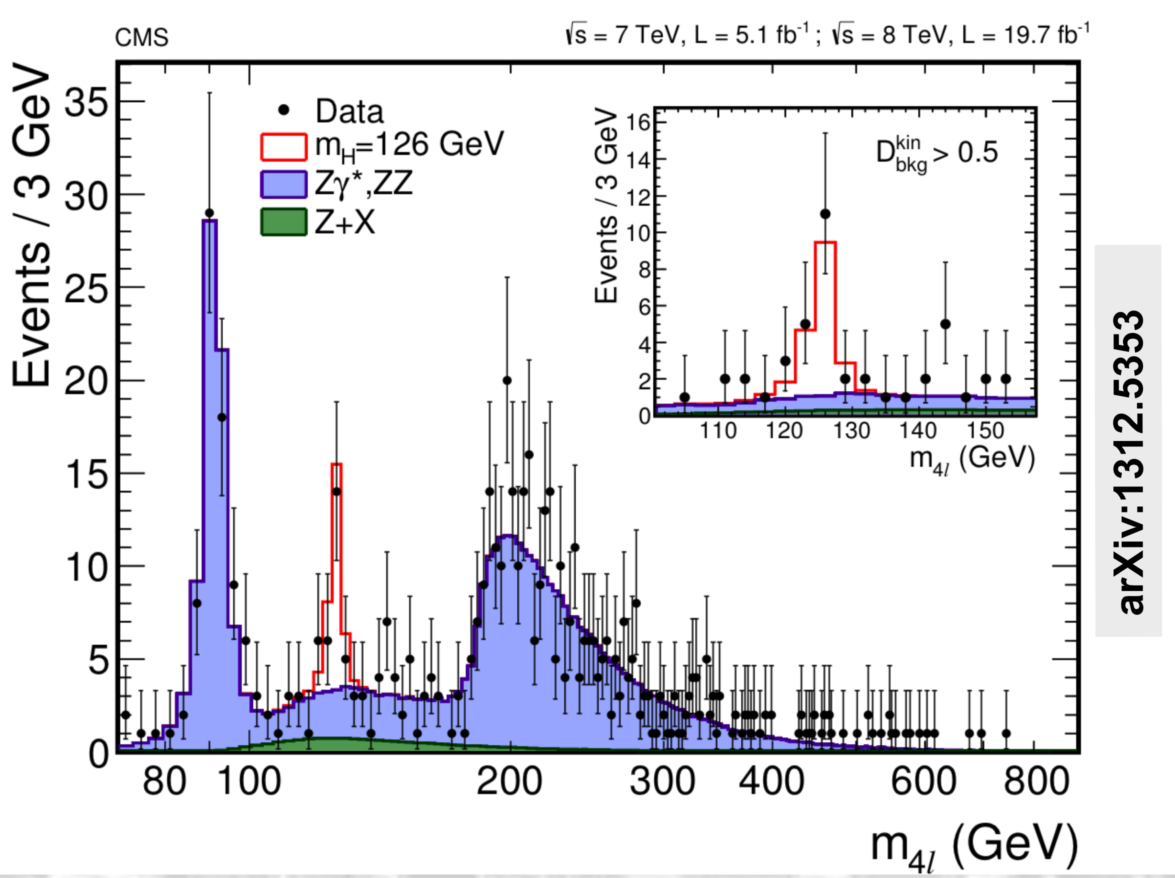
σ(ttH)/σ(tt+X) ~ 10^{-4}

$H \to ZZ^{(*)} \to 4\ell$

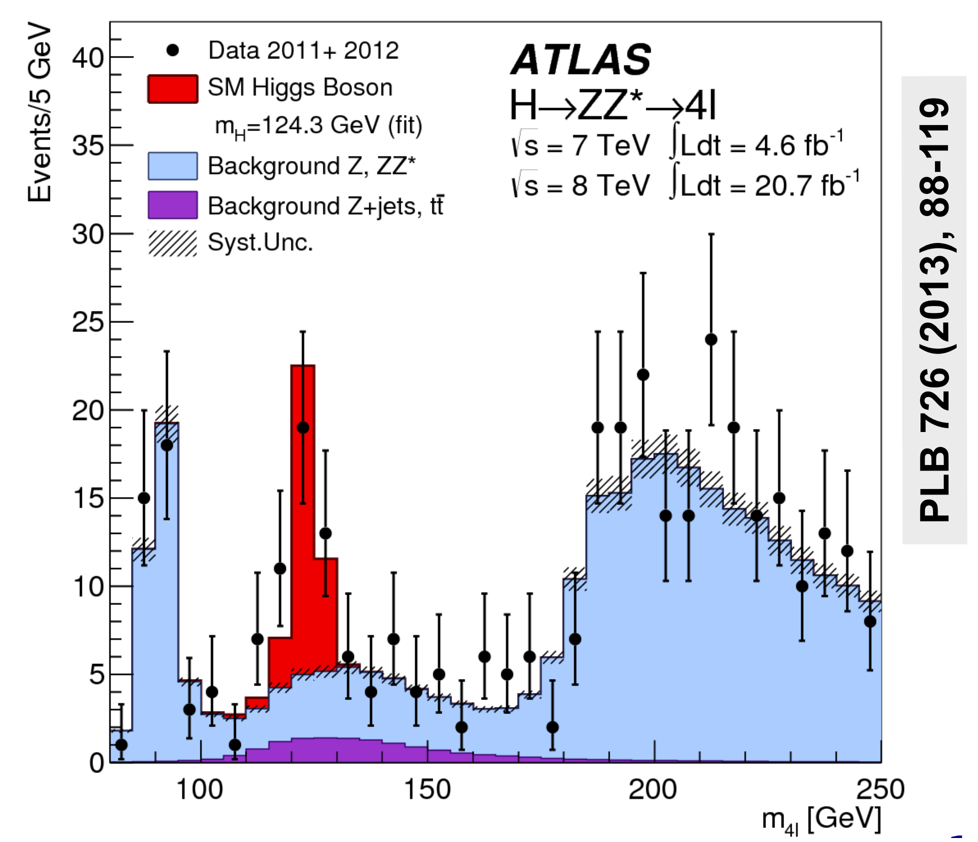


$H \to ZZ^{(*)} \to 4\ell$

- Require 4ℓ (ℓ=e,μ) isolated (not inside a jet)
- For bkg, this is expensive to produce (need W or Z)
- For signal, there is a (smaller) suppression due to Z→ℓℓ branching ratio
- This is a signal difficult to miss
- **If we did not know about the Higgs boson, we would have found it in this channel (but most likely with a less-tuned analysis, i.e. we did not have a discovery by now, w/o the underlying model)**

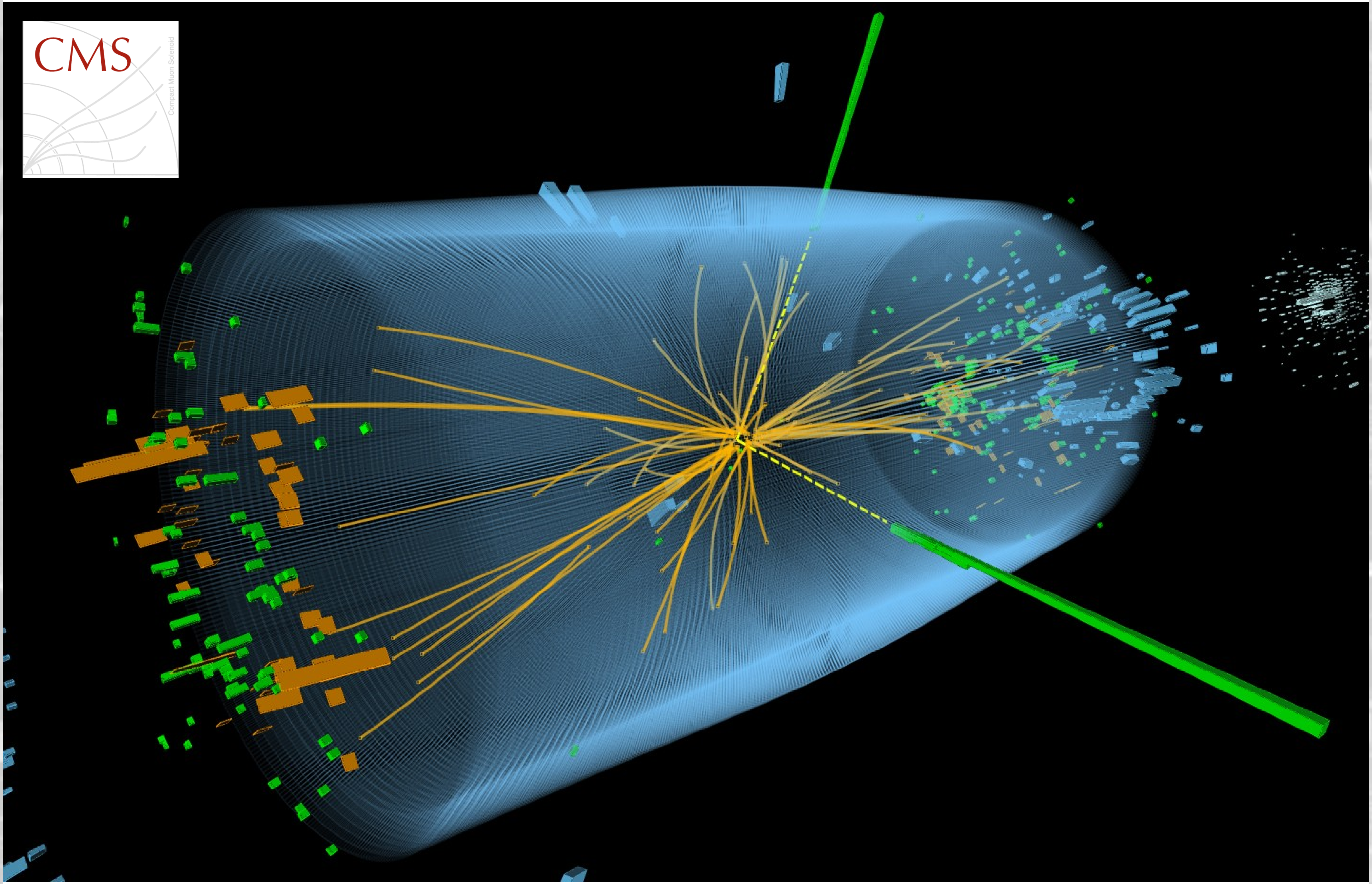


arXiv:1312.5353

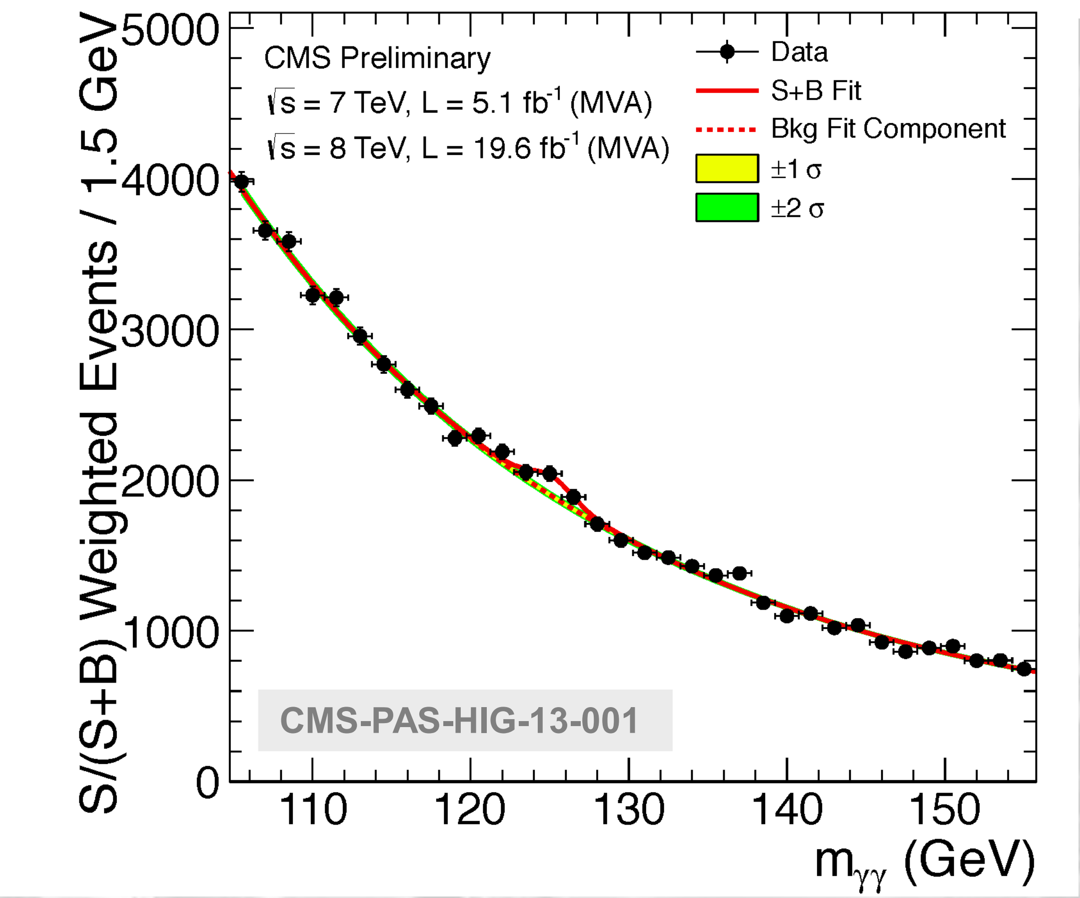


PLB 726 (2013), 88-119

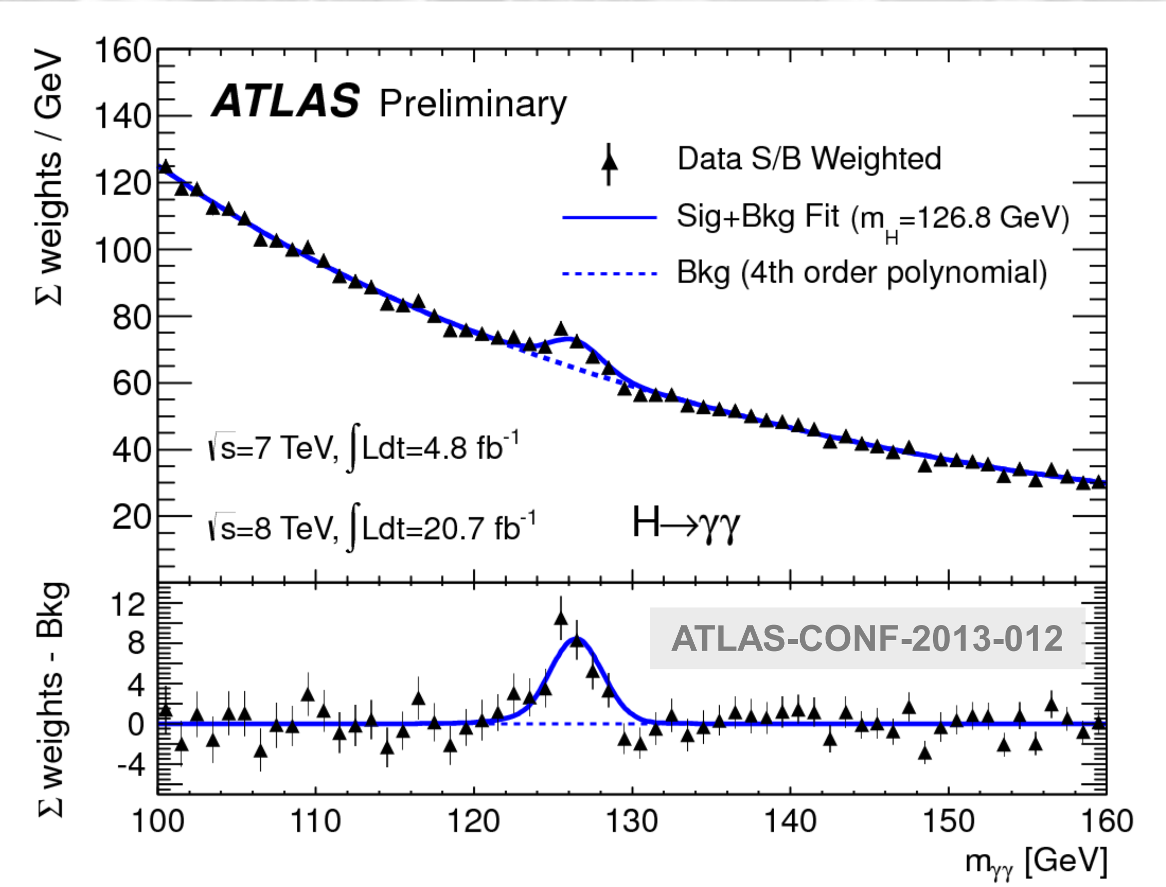
$H \to \gamma\gamma$



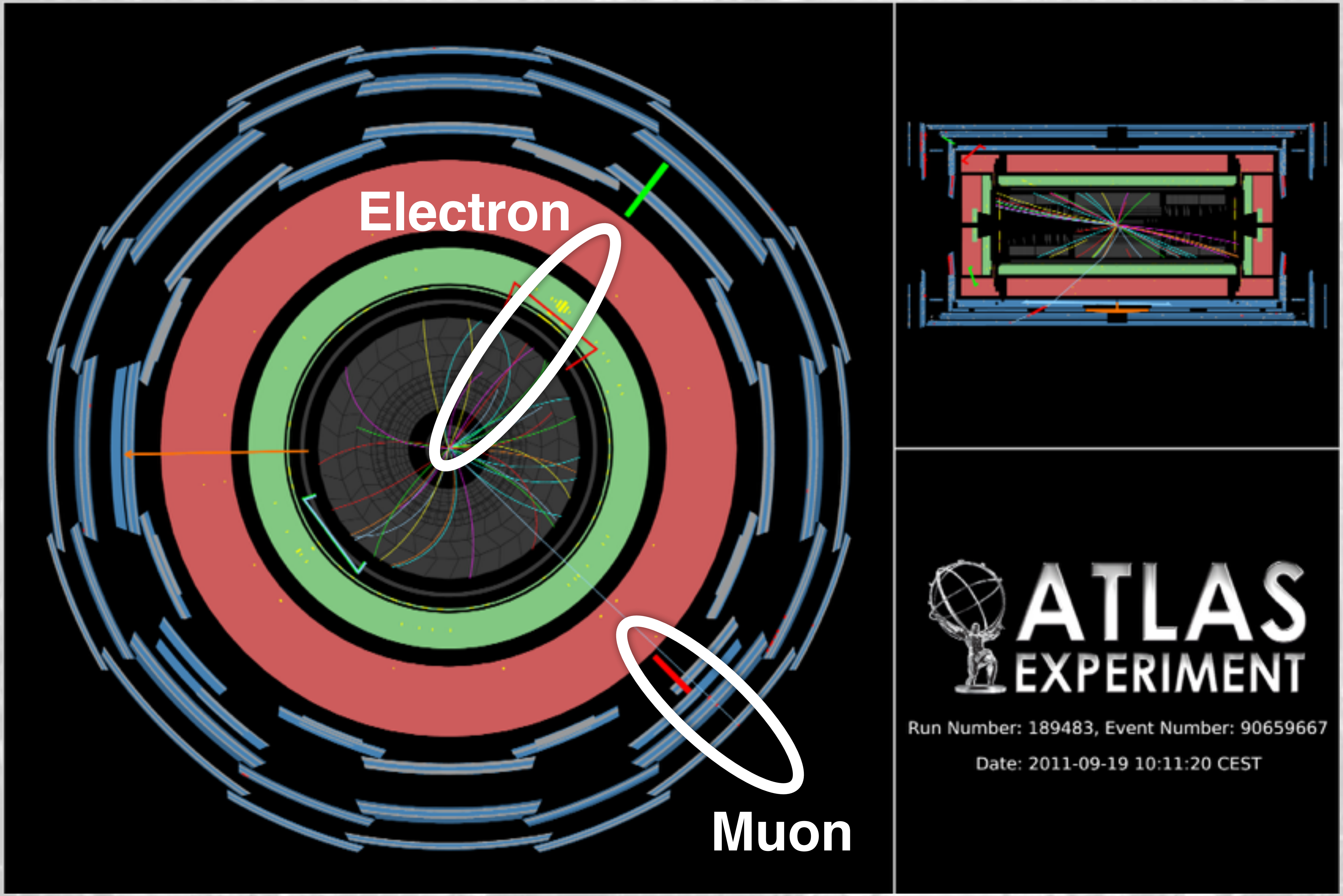
H→γγ



- Select events with two photons
- Classify events according to the “goodness” of the photon reconstruction (high purity vs. high efficiency)
- Perform di-photon invariant mass fit in each category
  - signal hypothesis from signal MC
  - bkg from analytic function (tested on MC and QCD data control samples)
- Combine the categories



$H \rightarrow WW^{(*)} \rightarrow 2\ell\ 2\nu$

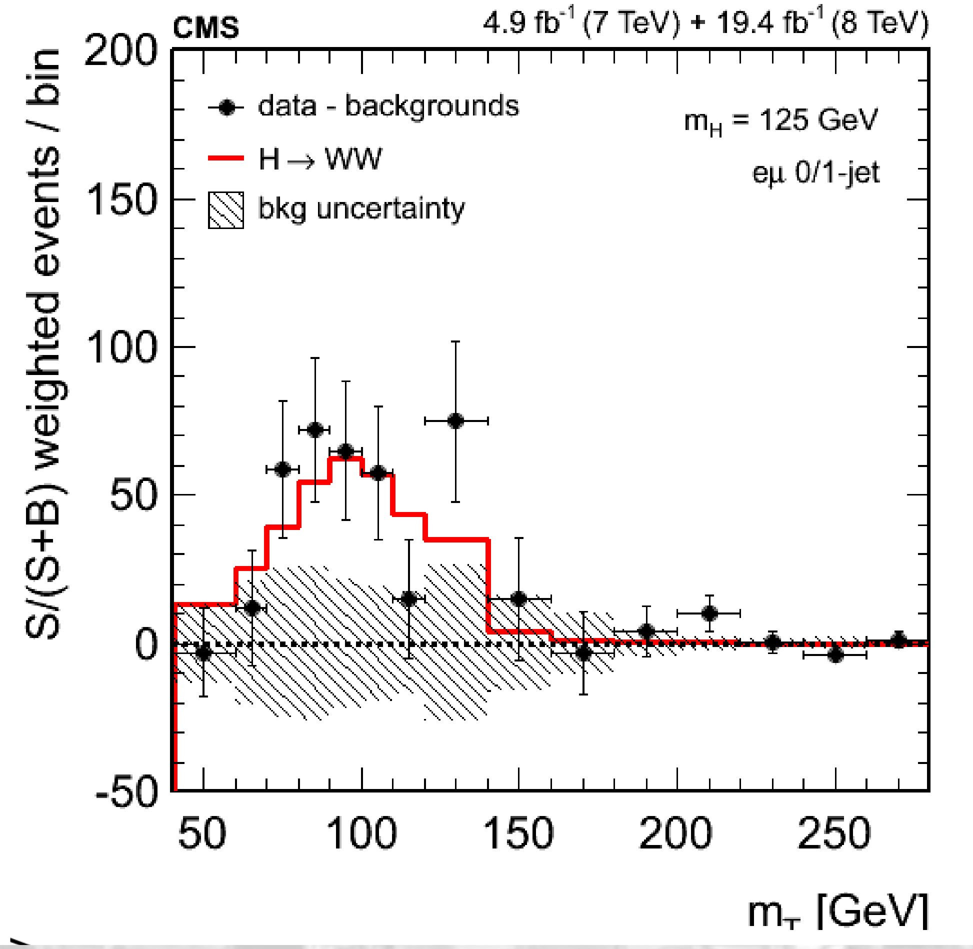


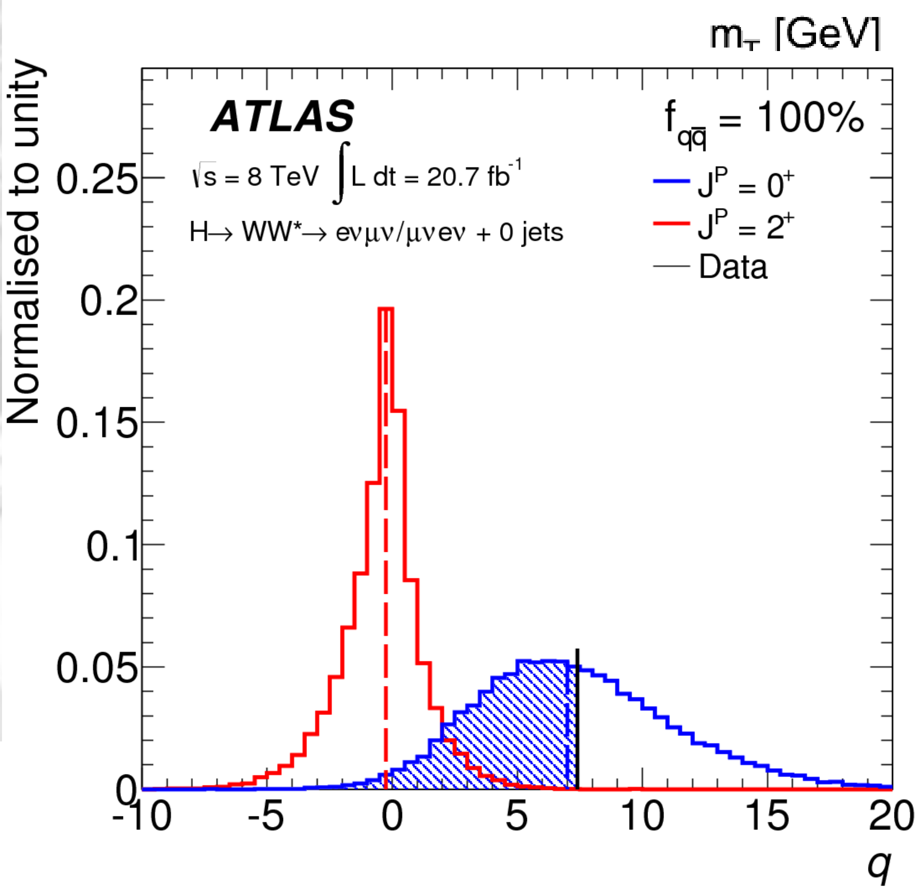
Run Number: 189483, Event Number: 90659667

Date: 2011-09-19 10:11:20 CEST

$H \to WW^{(*)} \to 2\ell\ 2\nu$

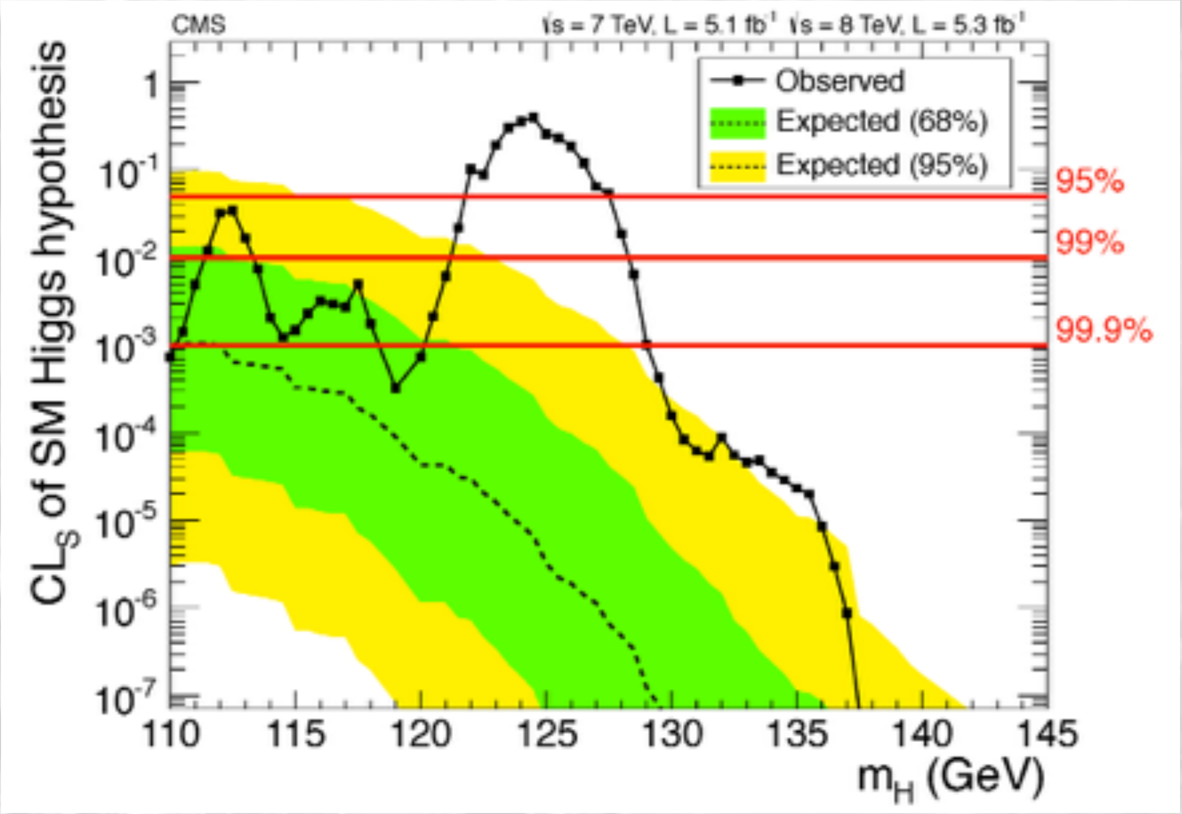
- Select events with 2ℓ (ℓ=e,μ) and missing transverse energy (unobserved neutrinos should balance observed ℓs)
- Open kinematic in the final state
- Conservation of transverse momentum allows to guess the Higgs mass (with worse resolution
- We can "see" a signal, but we cannot measure the resonance mass with good accuracy
- Or we can use Machine Learning to

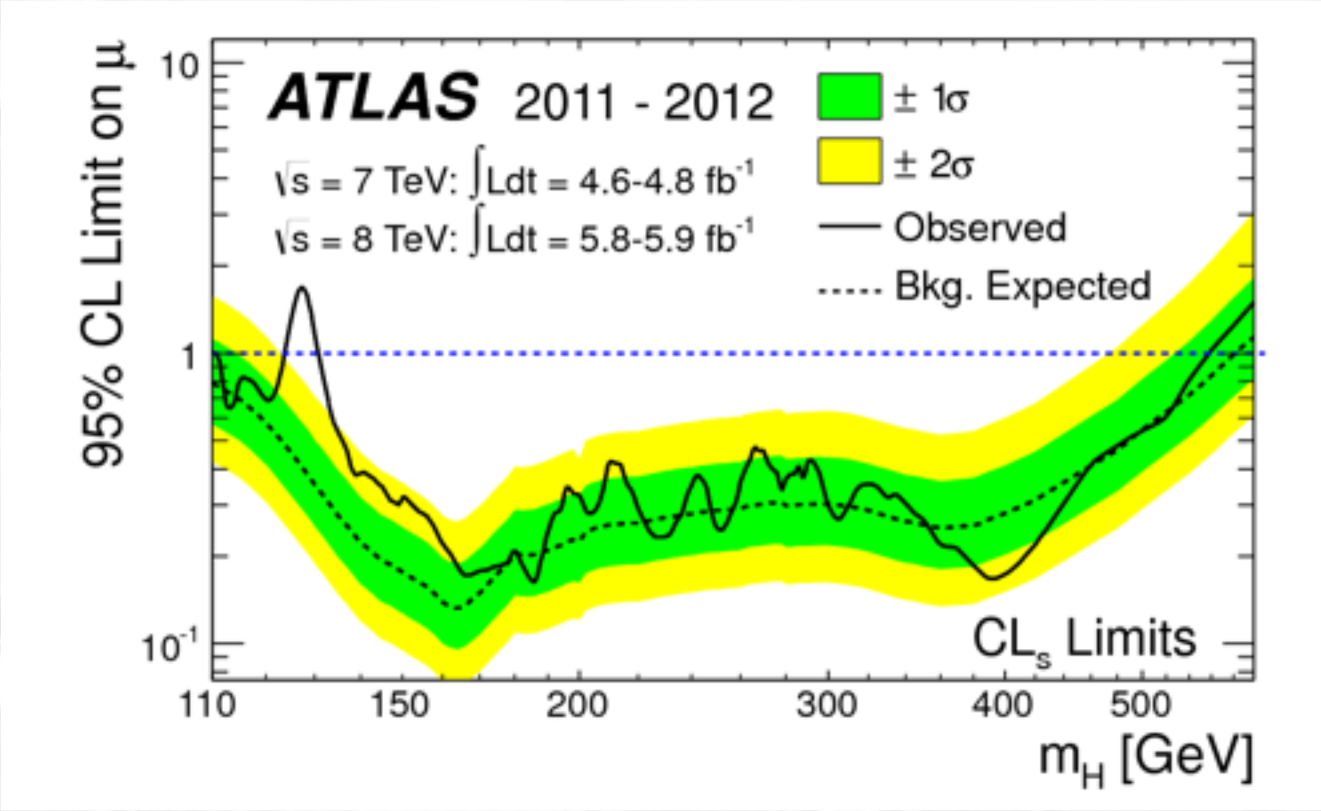




TRYING TO EXCLUDE A SIGNAL

- 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



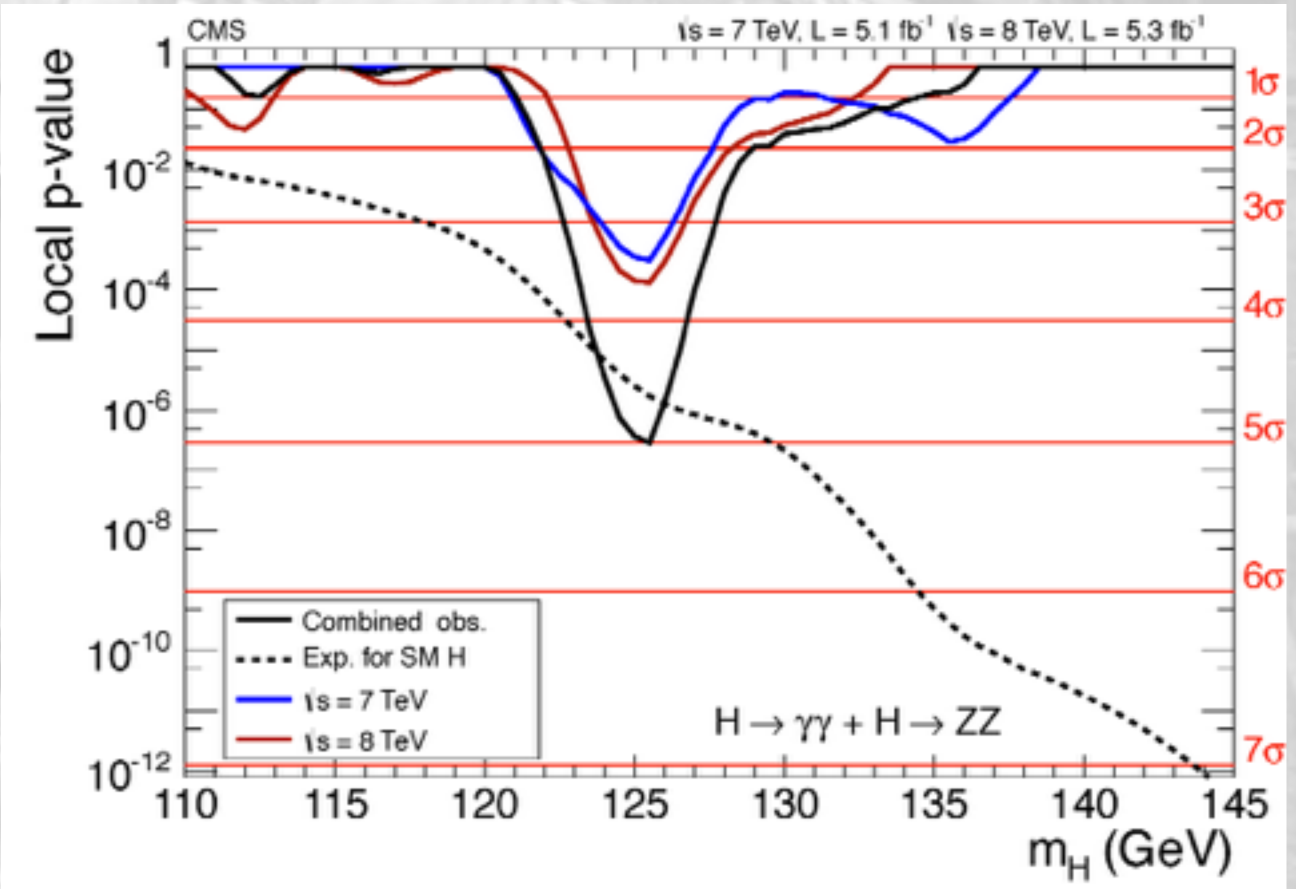


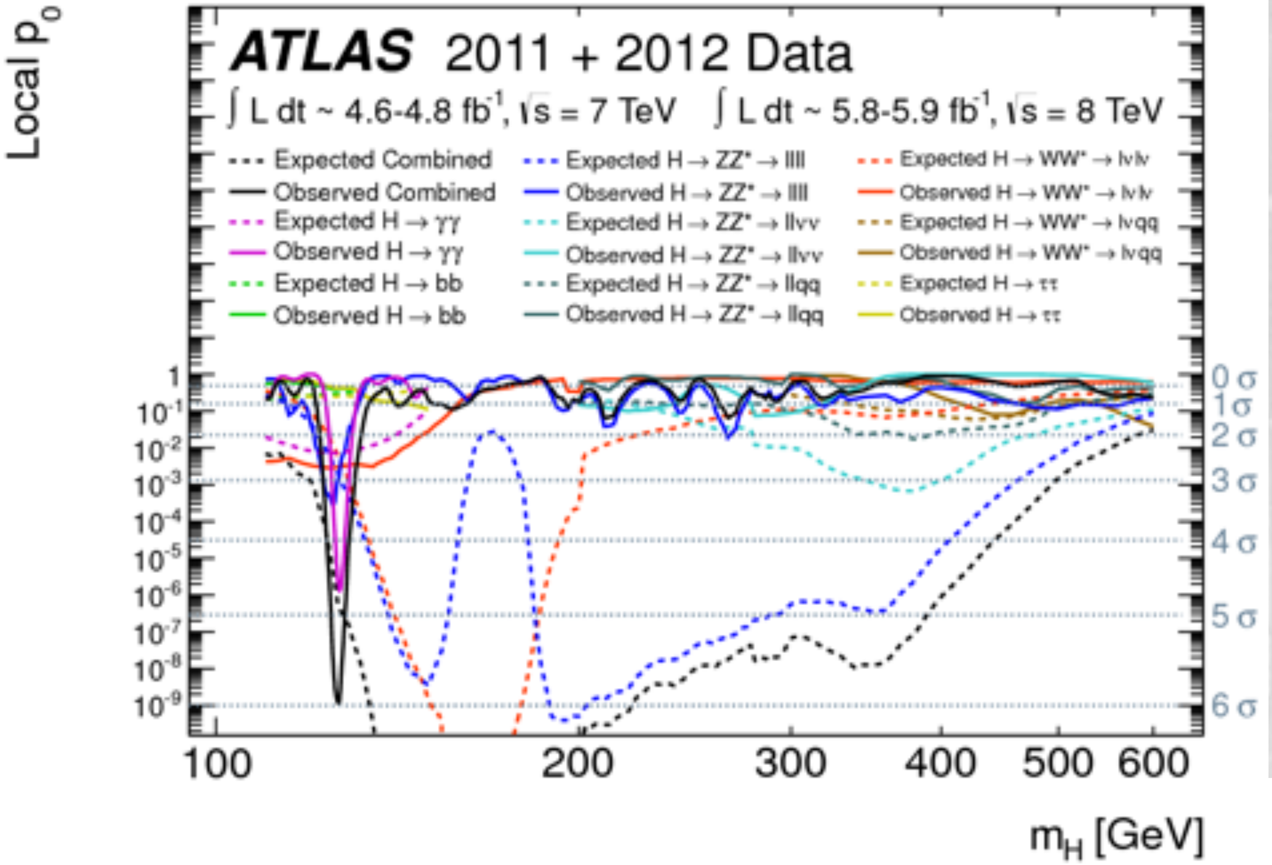
ESTABLISHING A DISCOVERY

- 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

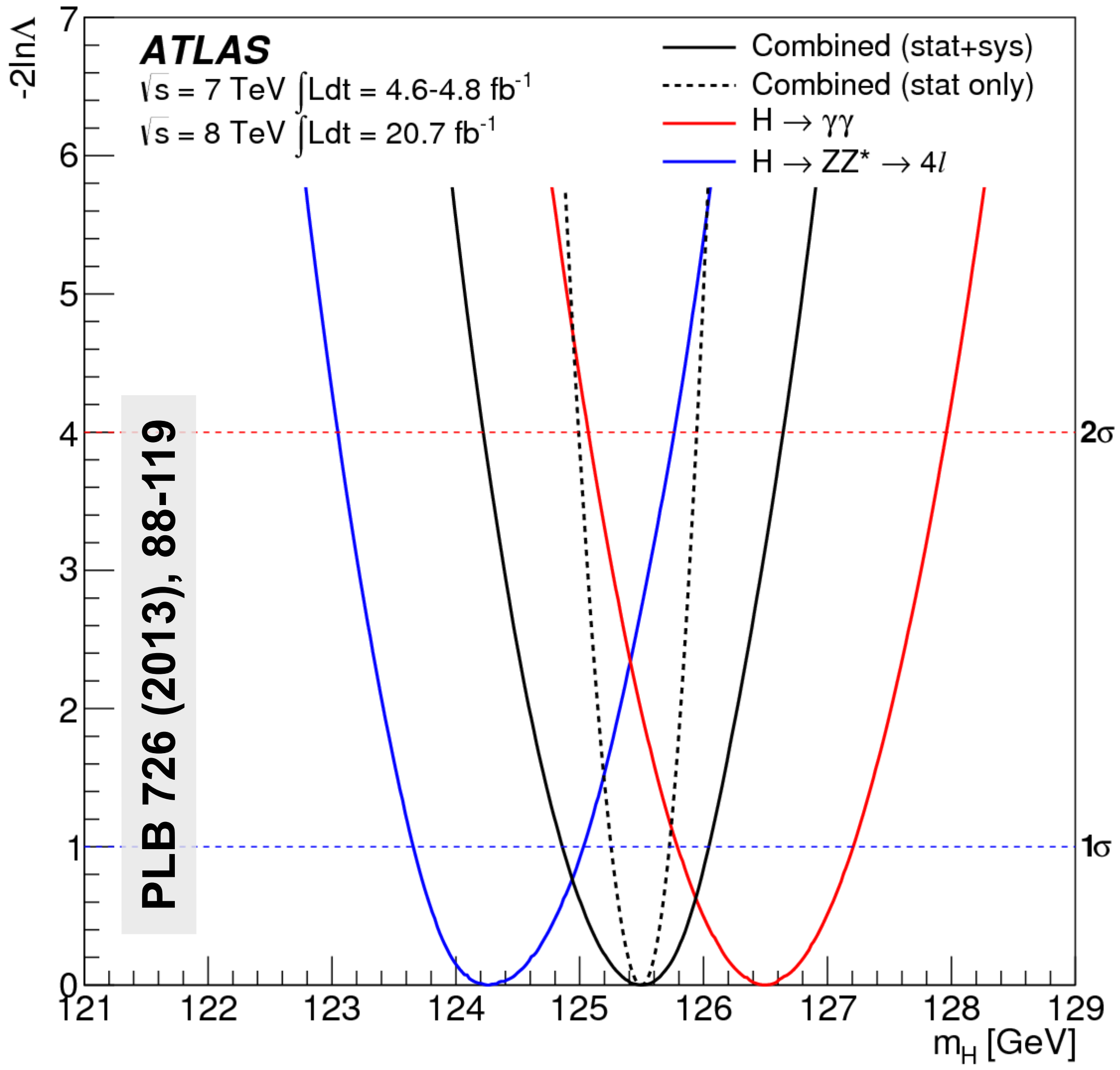
- The signal is stringer than the conventional 5σ threshold so…



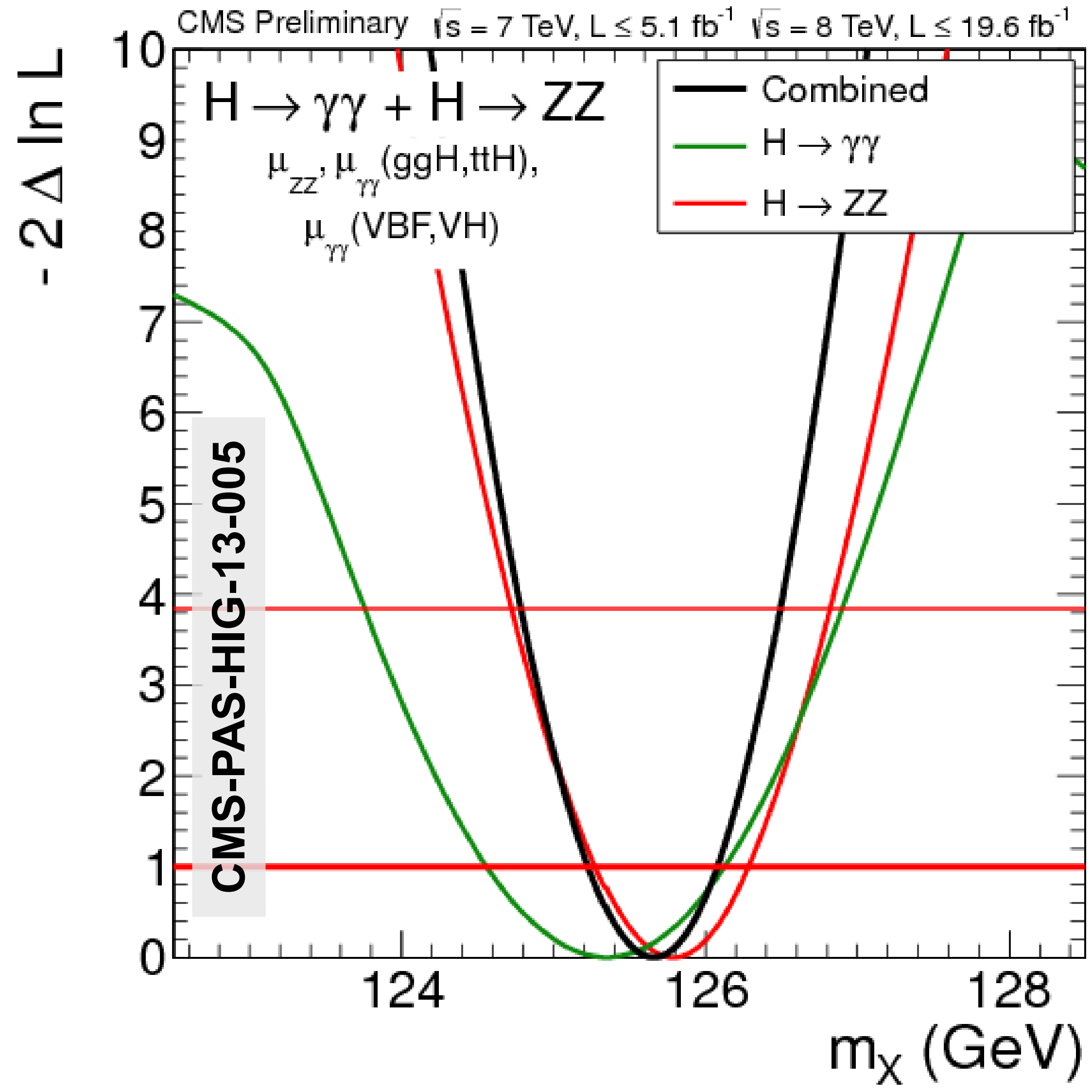


ESTABLISHING A DISCOVERY

THE HIGGS BOSON MASS



PLB 726 (2013), 88-119

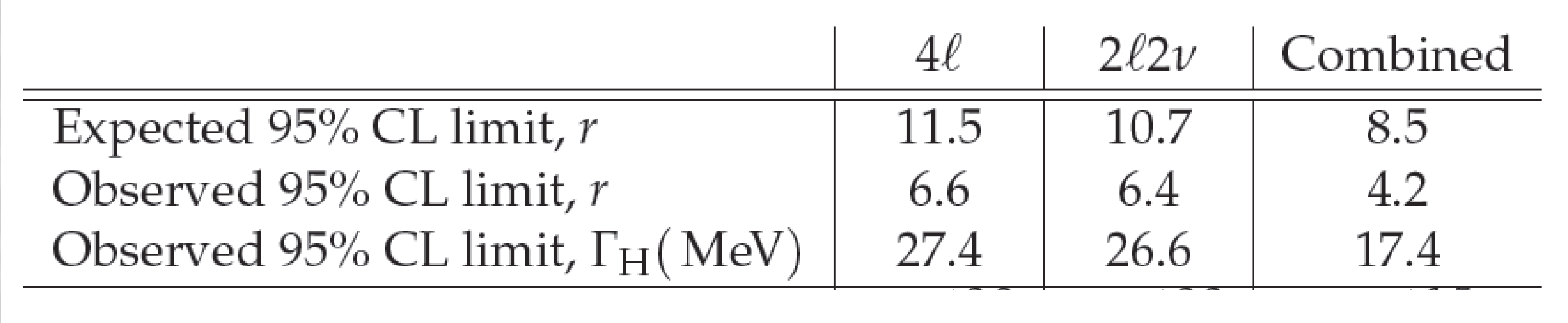


CMS-PAS-HIG-13-005

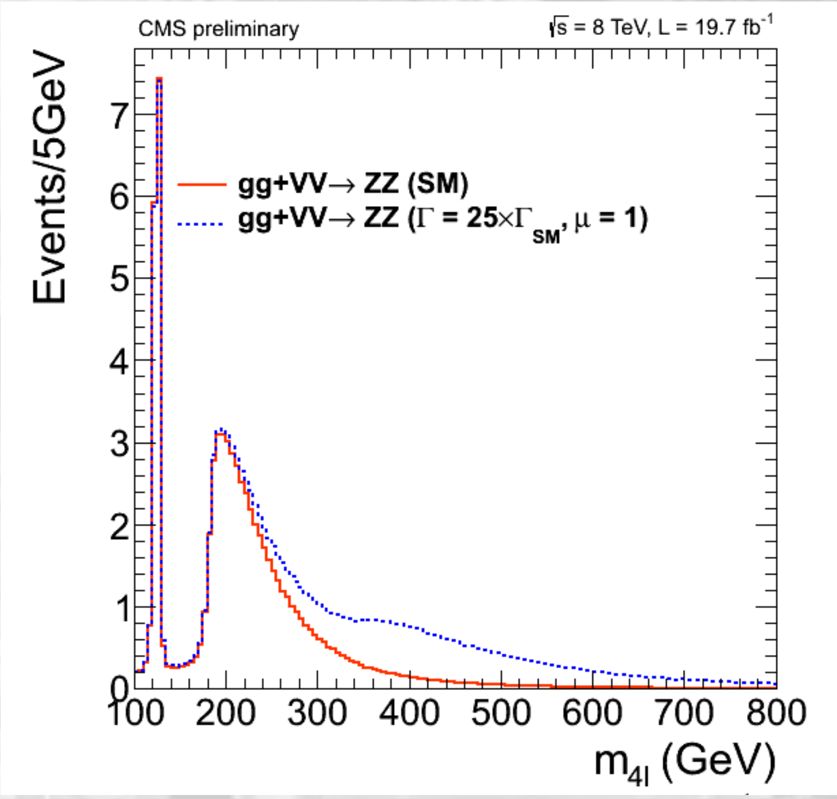
ATLAS	CMS (new ZZ(4l) not used)
125.5 +-0.2 (stat) $^{+0.5}_{-0.6}$(syst) GeV	**125.7 +- 0.3(stat) +- 0.3(syst) GeV**

THE HIGGS BOSON WIDTH

- The Higgs width (~4 MeV) was considered too small for the LHC to measure it (expected precision ~ 5 GeV)



	4ℓ	$2\ell 2\nu$	Combined
Expected 95% CL limit, r	11.5	10.7	8.5
Observed 95% CL limit, r	6.6	6.4	4.2
Observed 95% CL limit, Γ_H(MeV)	27.4	26.6	17.4

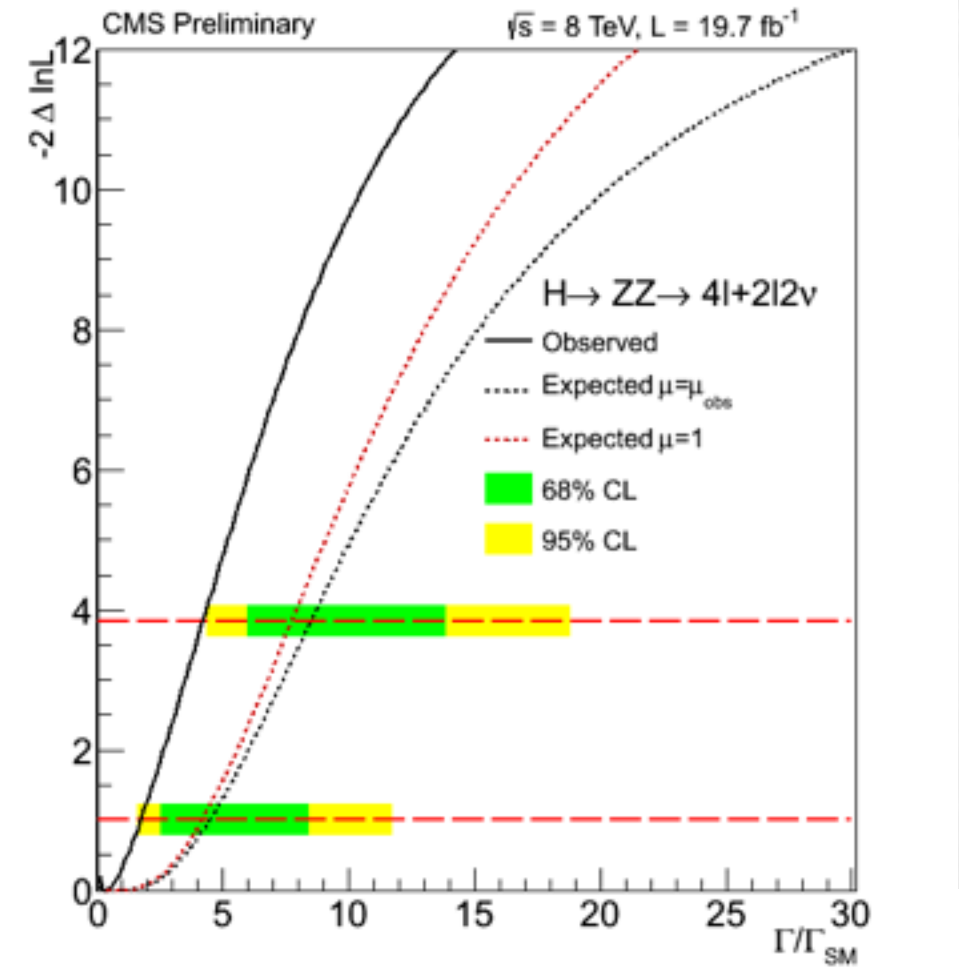


- It was pointed out how to exploit interference effects with ZZ events

Caola & Melnikov

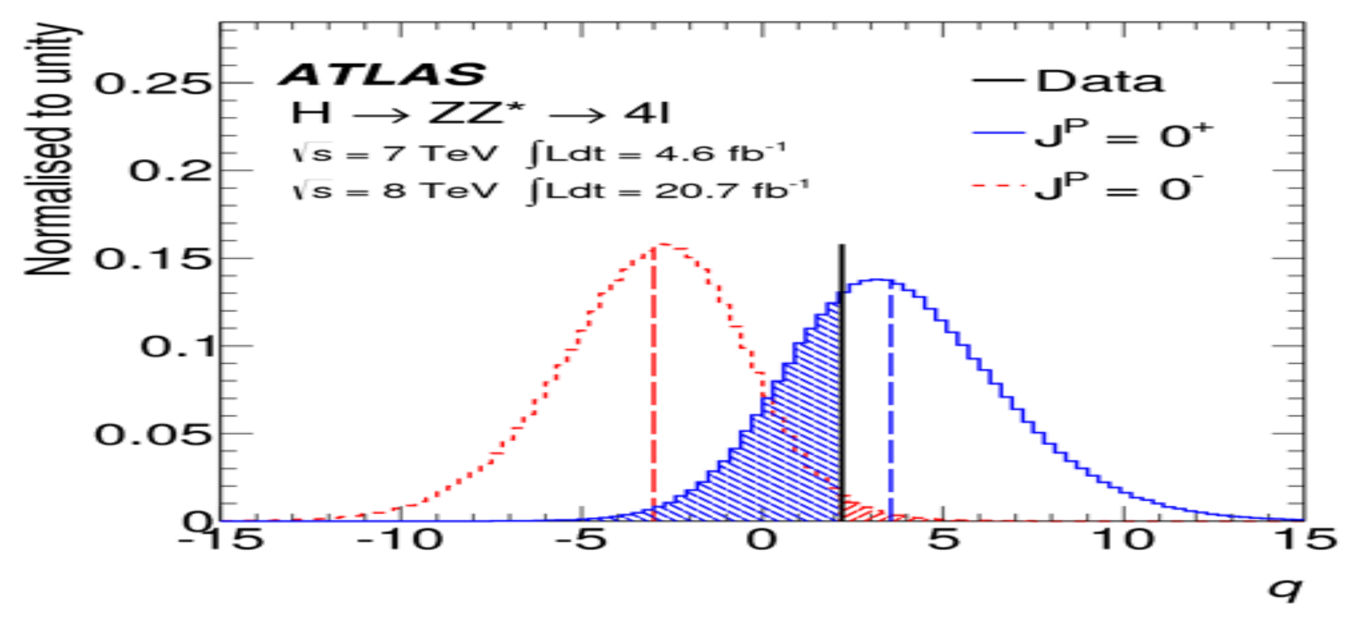
http://arxiv.org/abs/1307.4935

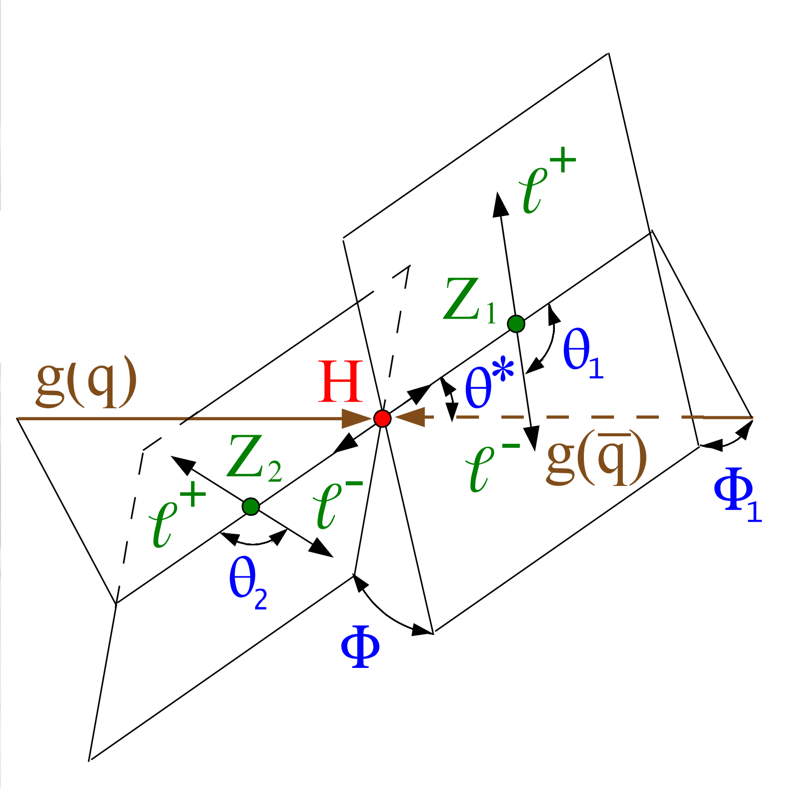
- Limit obtained ~ 20 MeV (not there yet, but not that far)



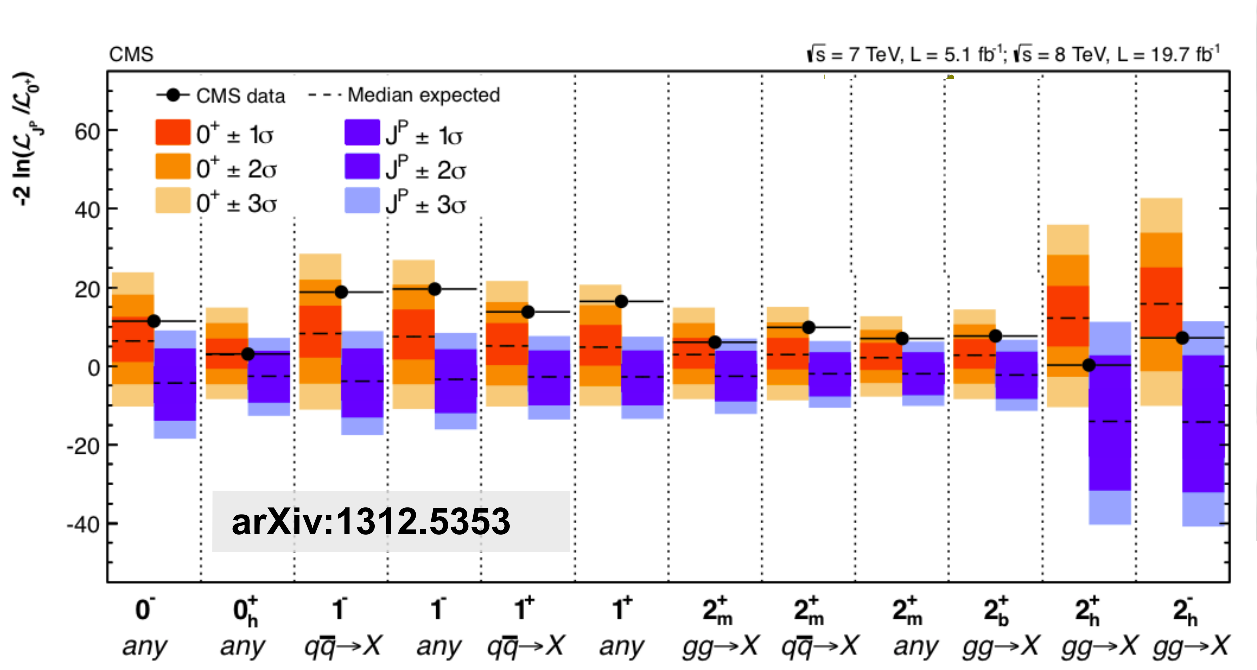
HIGGS PROPERTIES

- Quantum numbers can be measured from angular distribution of the H decay products

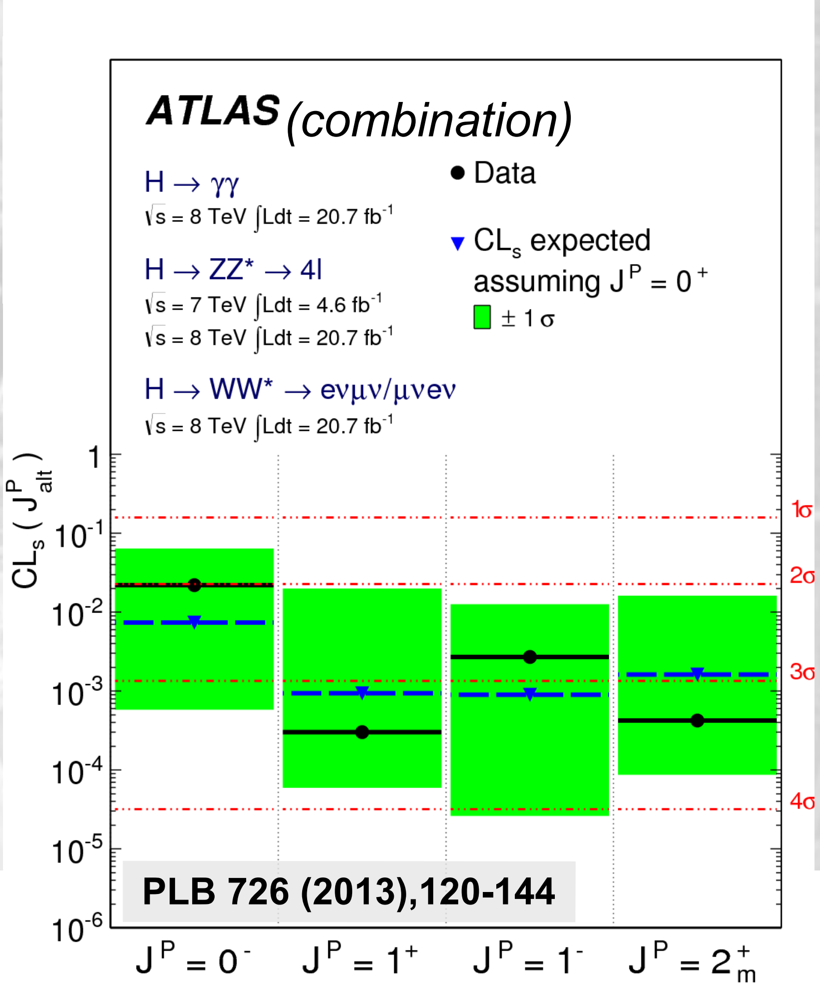




- Different channels probe different Higgs properties (e.g., spin, CP, etc)



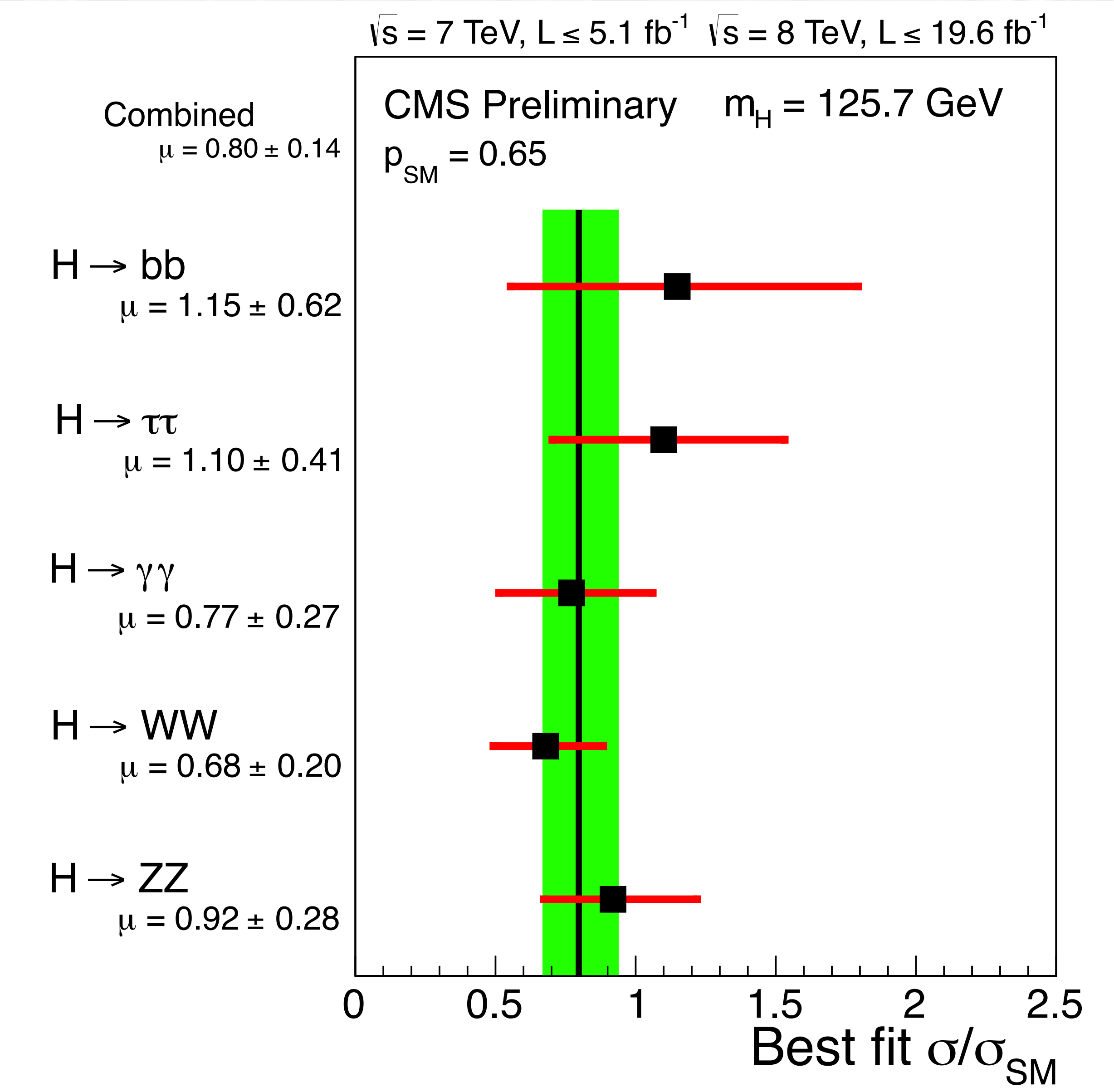
arXiv:1312.5353

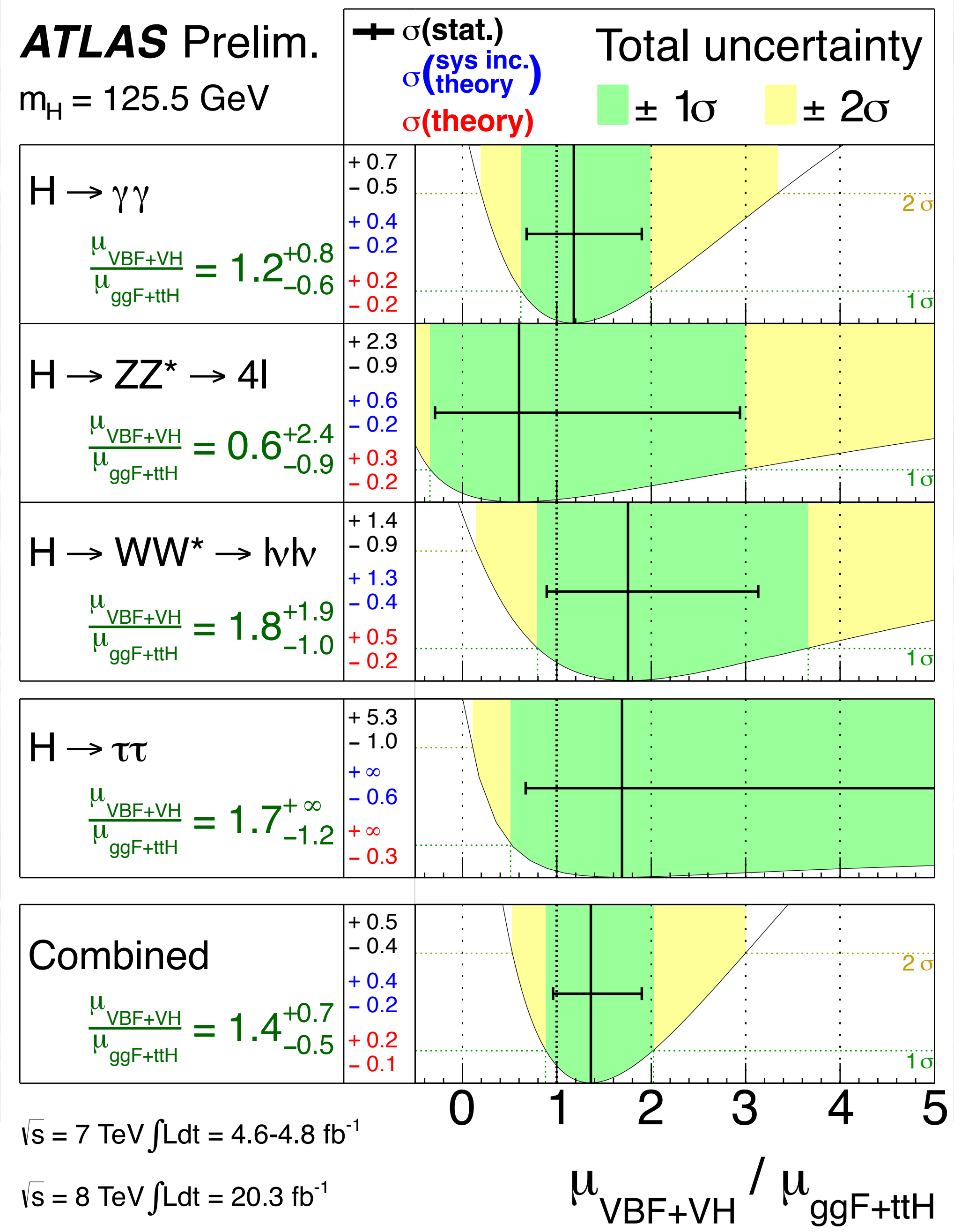


PLB 726 (2013),120-144

COUPLING FIT

- 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

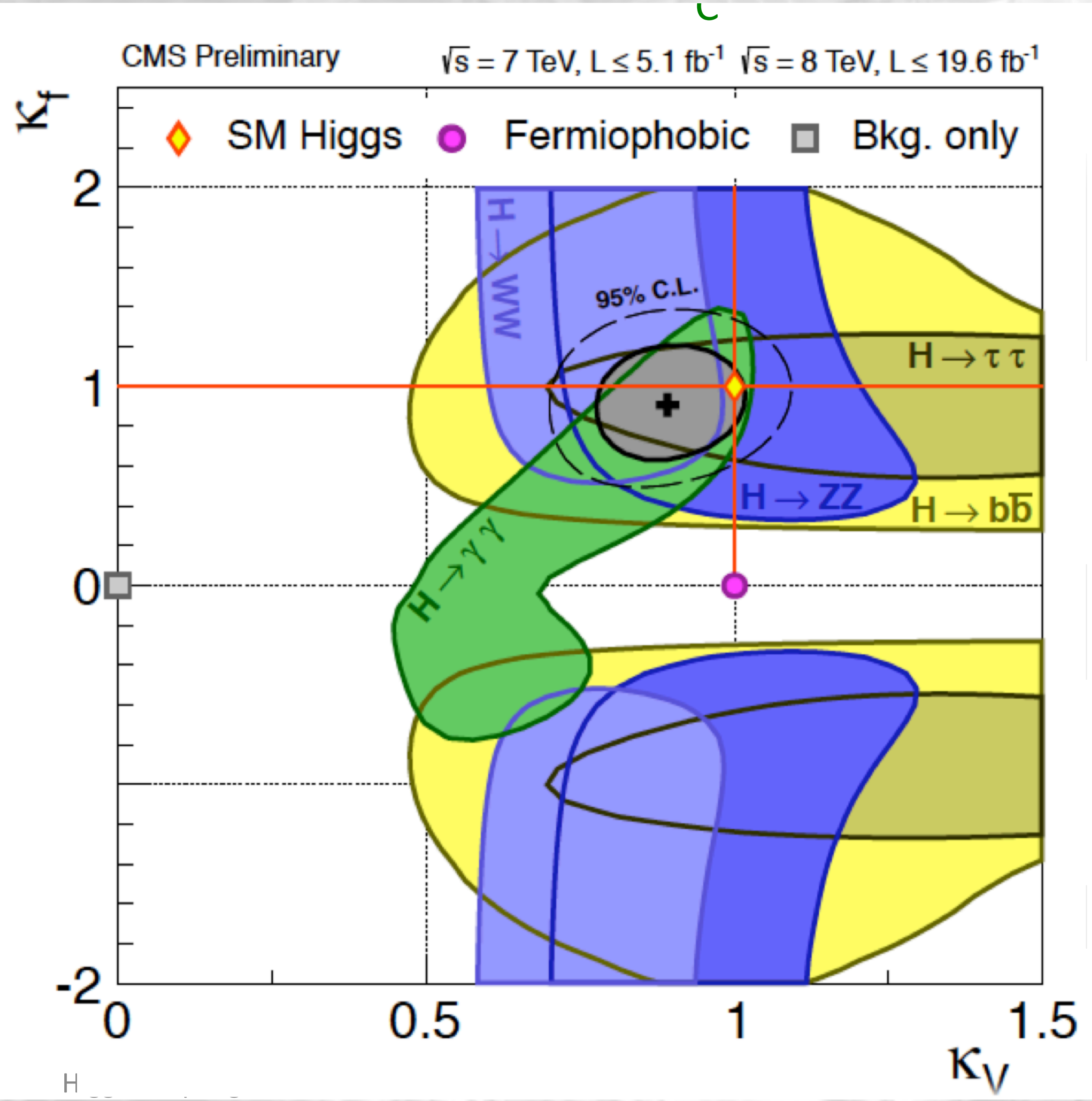
- Generalize couplings introducing multiplicative factors
- One channel can be function of more than one parameter

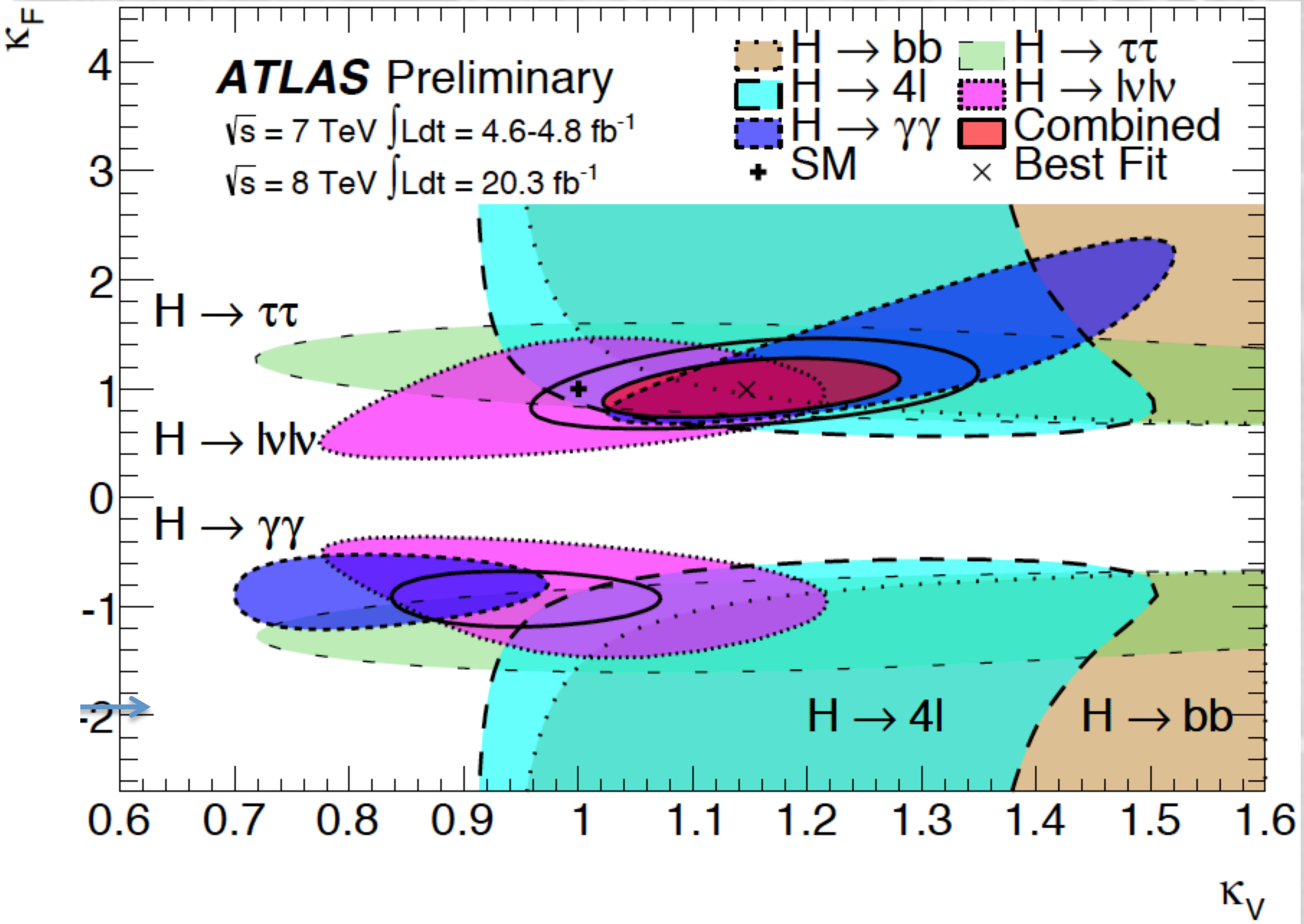
$$\kappa_g^2(\kappa_b,\kappa_t) = \frac{\kappa_t^2 \cdot \sigma_{ggH}^{tt} + \kappa_b^2 \cdot \sigma_{ggH}^{bb} + \kappa_t\kappa_b \cdot \sigma_{ggH}^{tb}}{\sigma_{ggH}^{tt} + \sigma_{ggH}^{bb} + \sigma_{ggH}^{tb}}$$

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

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

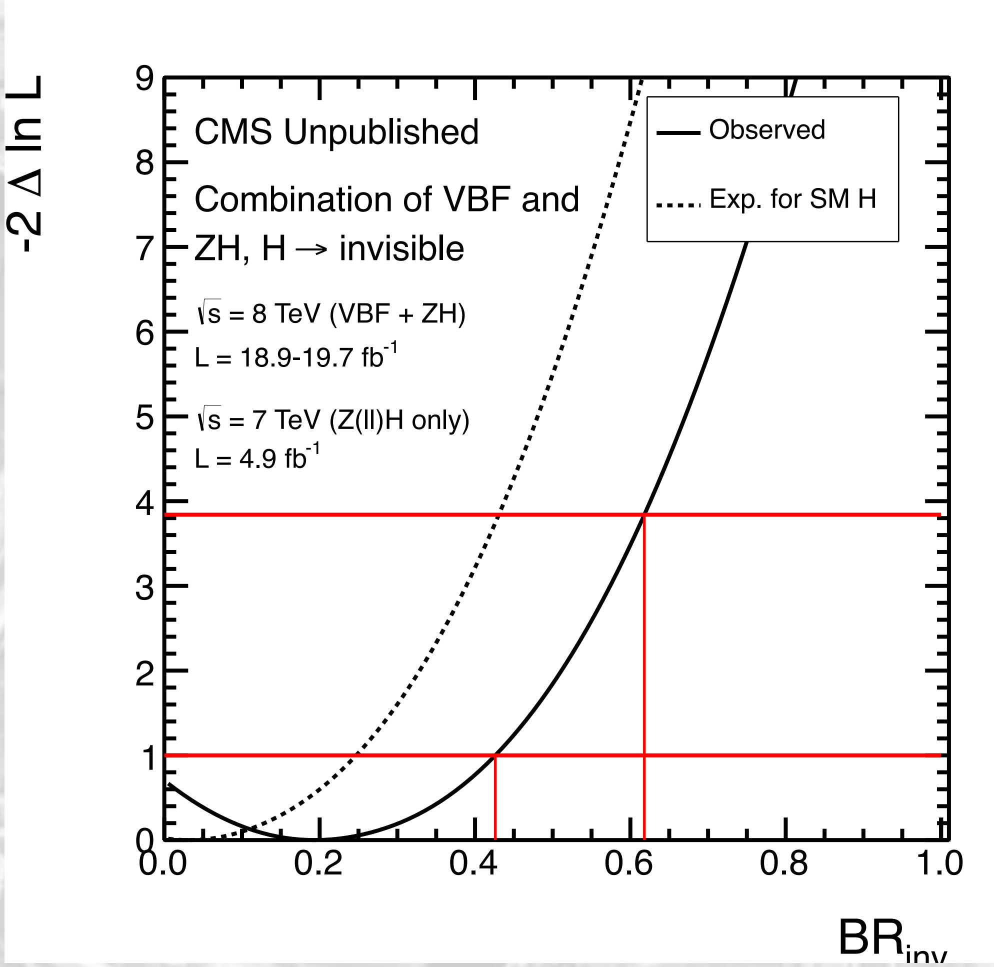
COUPLING FIT

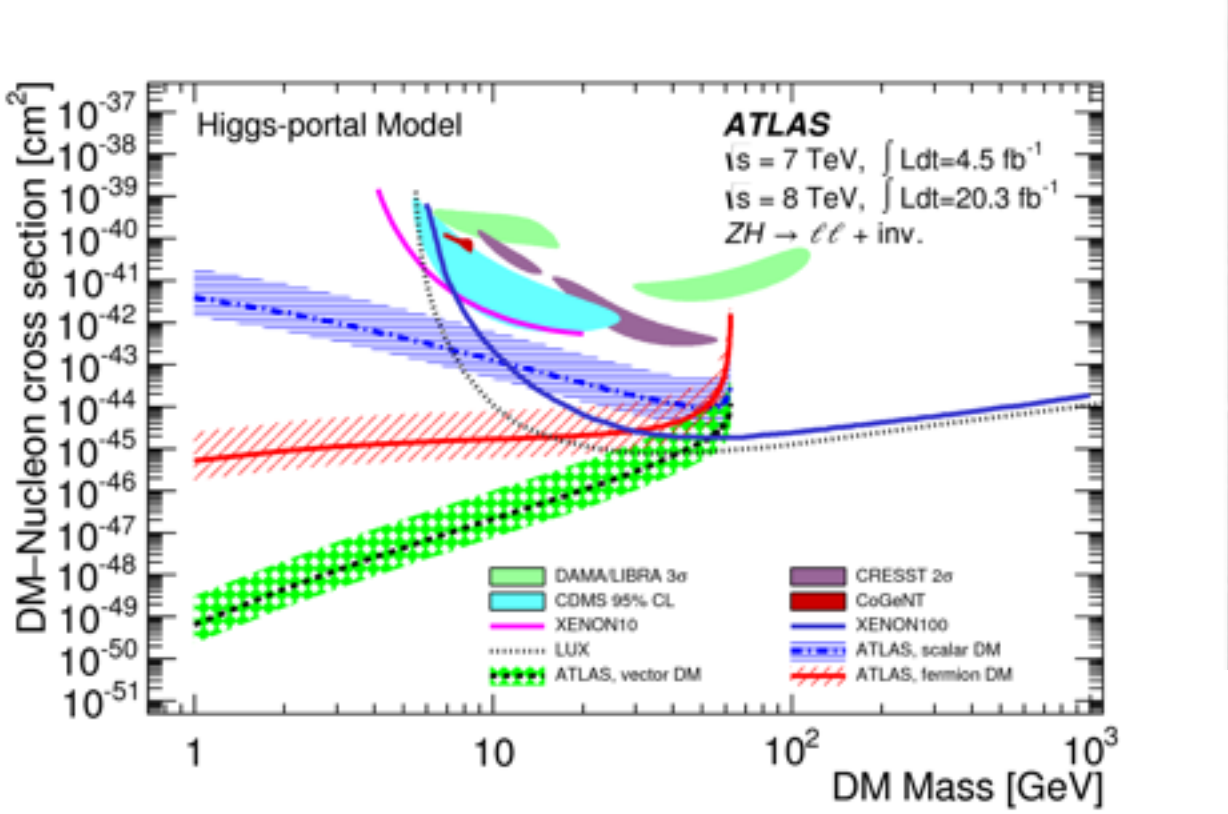




HIGGS AND NEW PHYSICS

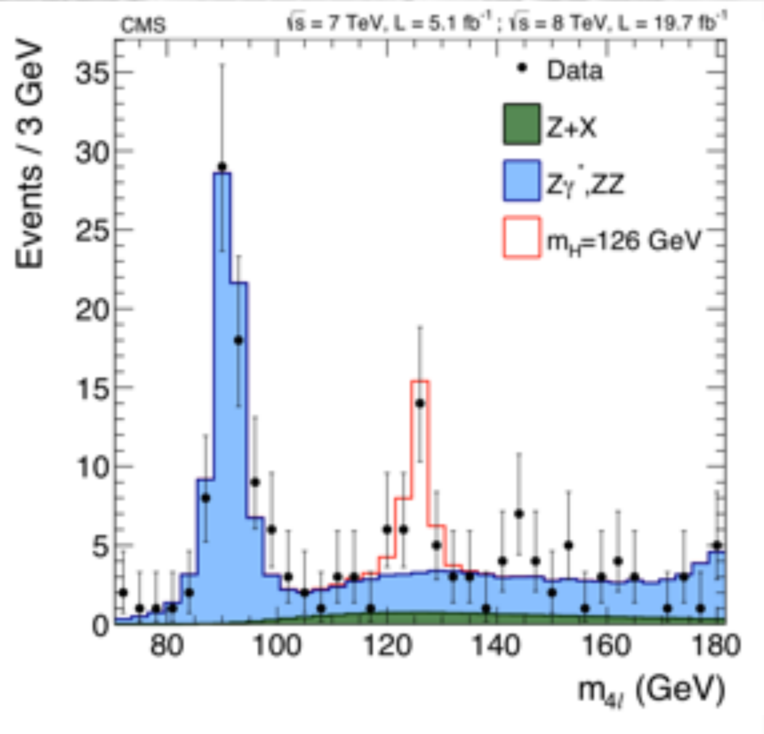
- The Higgs could give us access to new particles in the decay
- These particles could be invisible, and probed with W/Z +invisible searches
- Beside constraining the BR to invisible, these searches have implication on DM models
- Any conclusion, on the other hand, is model dependente (i.e., mind the assumptions)

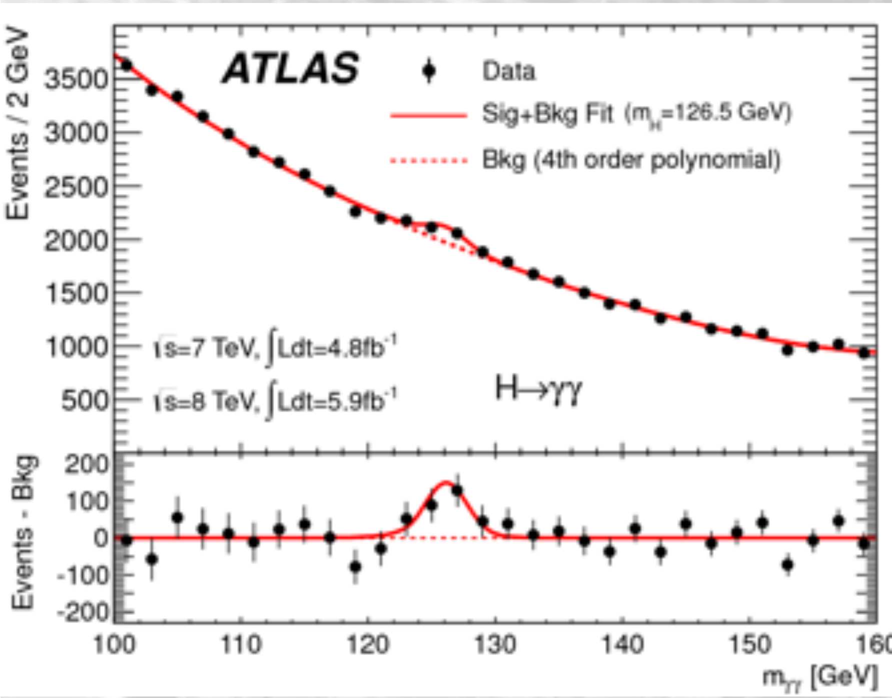


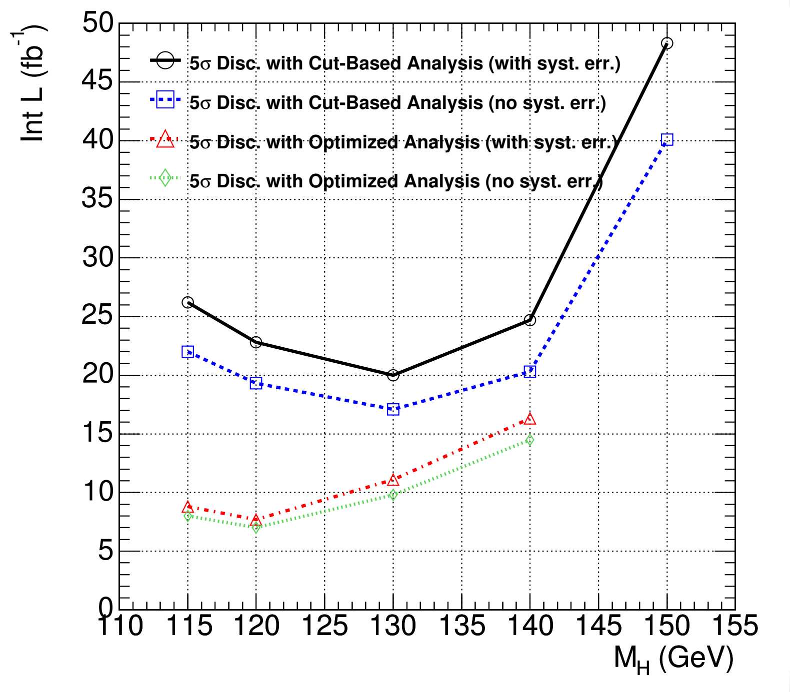


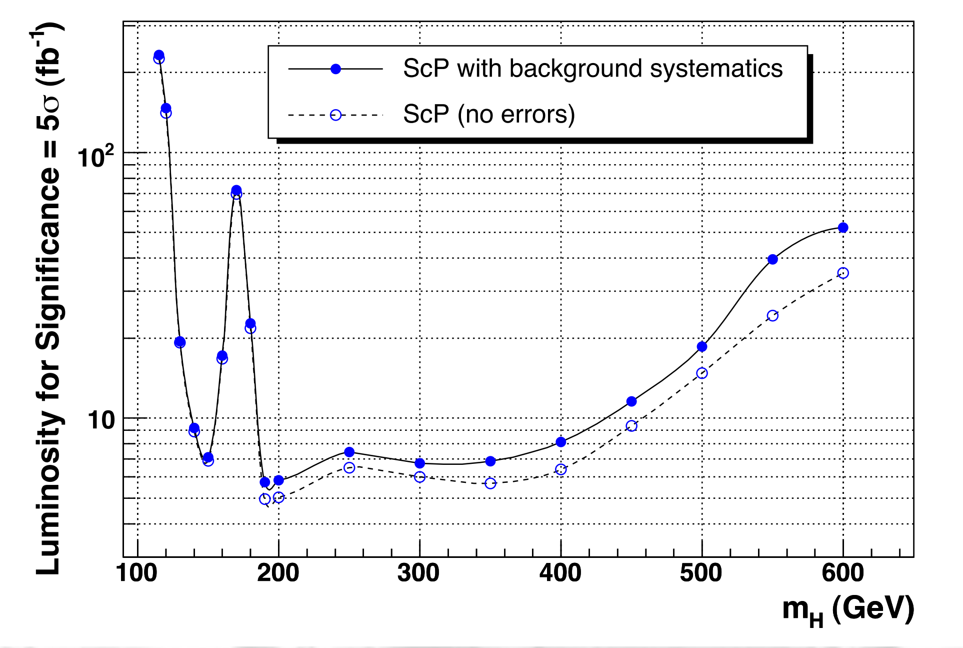
THIS WAS FAST!!!

- 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)

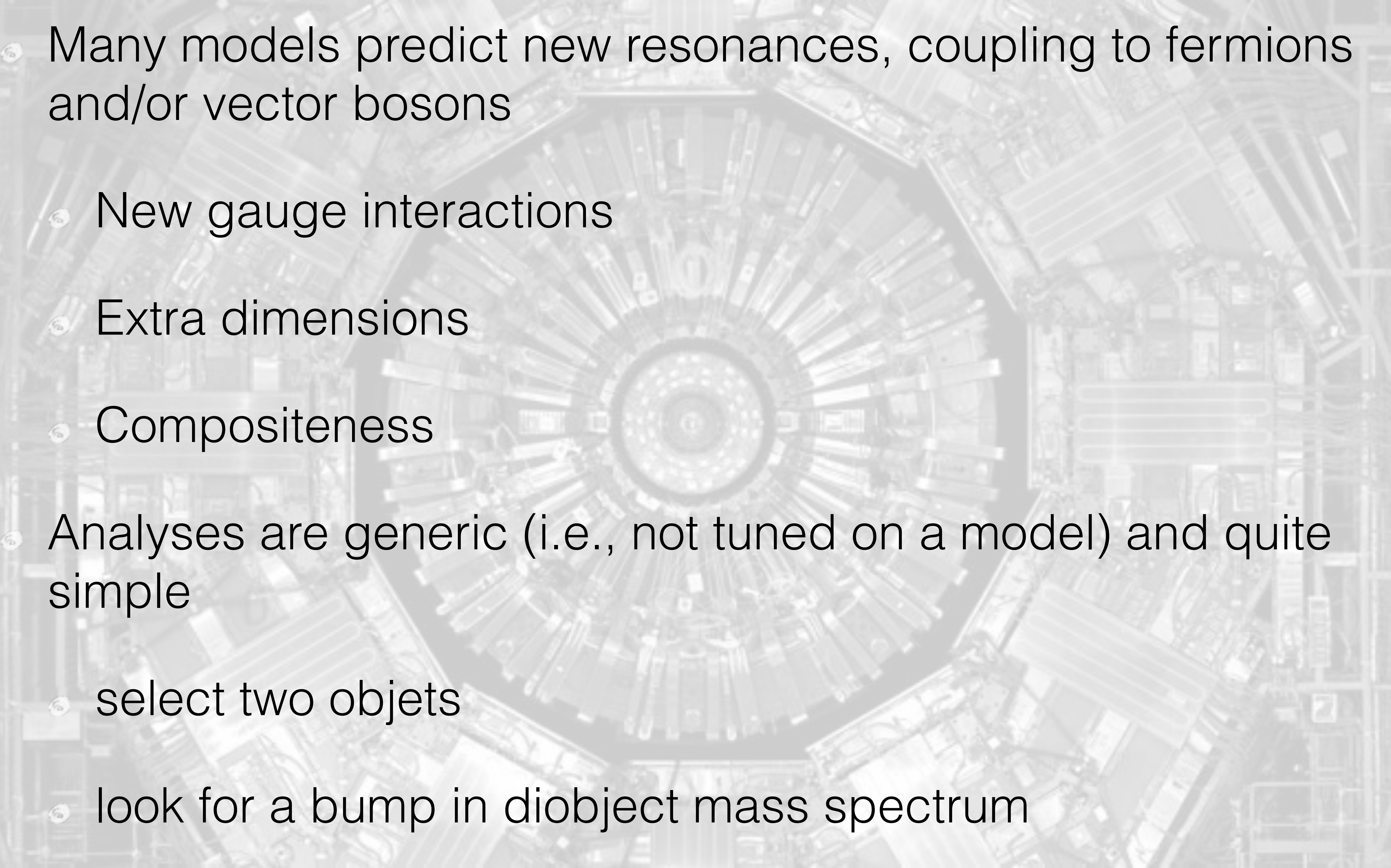
Two things to keep in mind

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

Highlights from Run I:

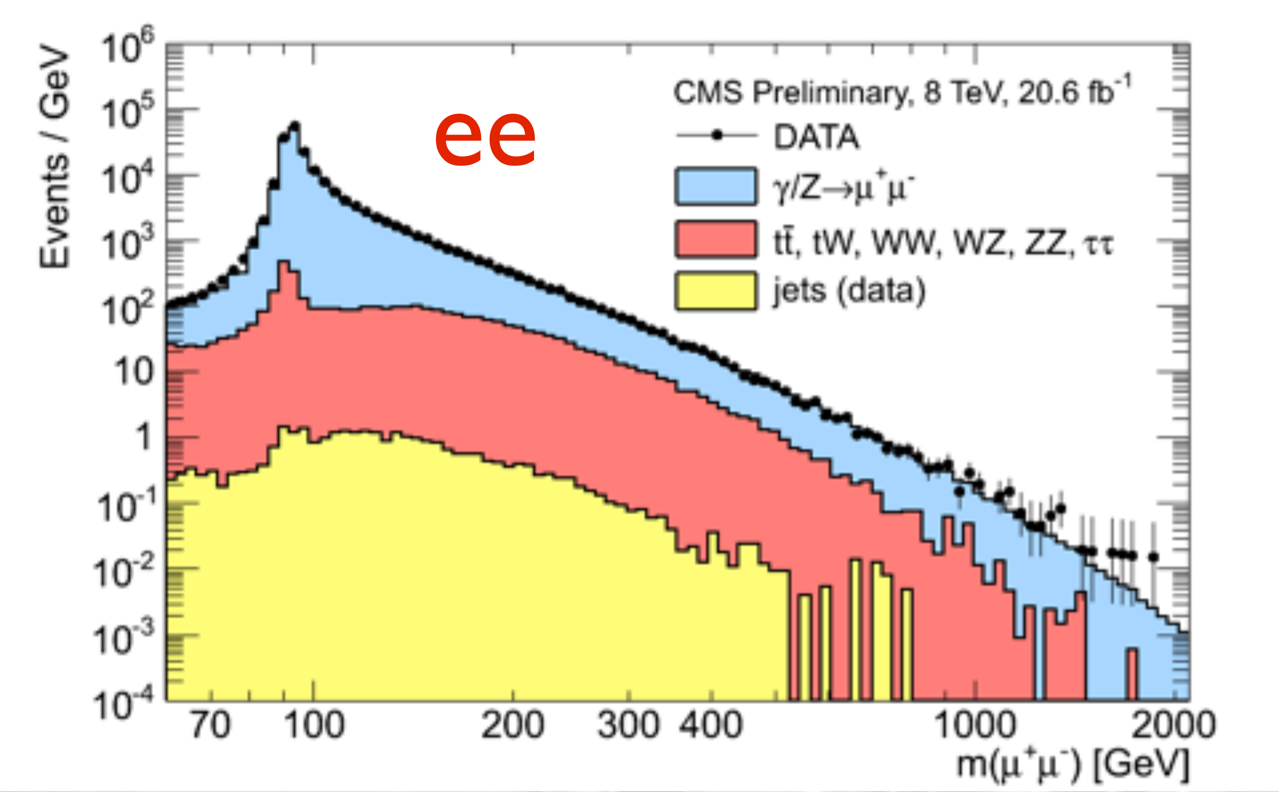
search for heavy resonances

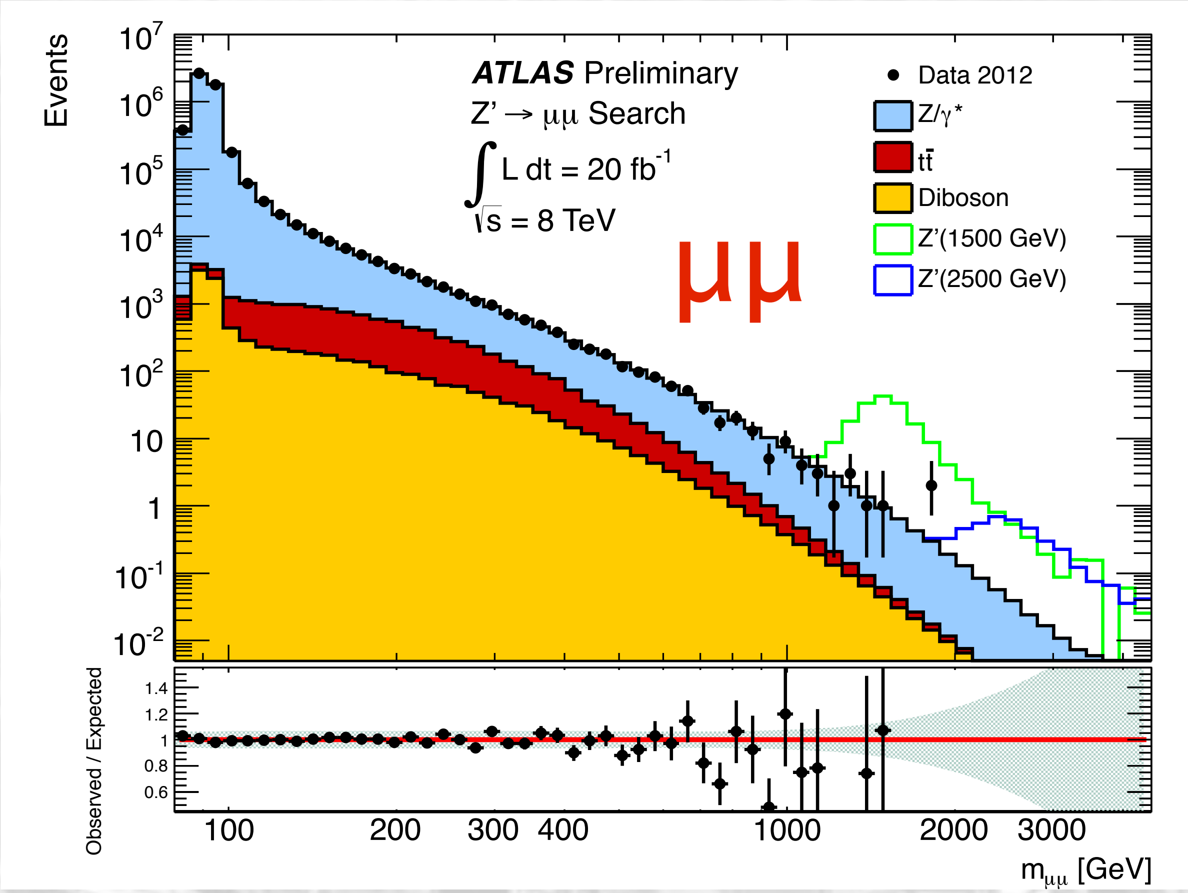
MOTIVATION

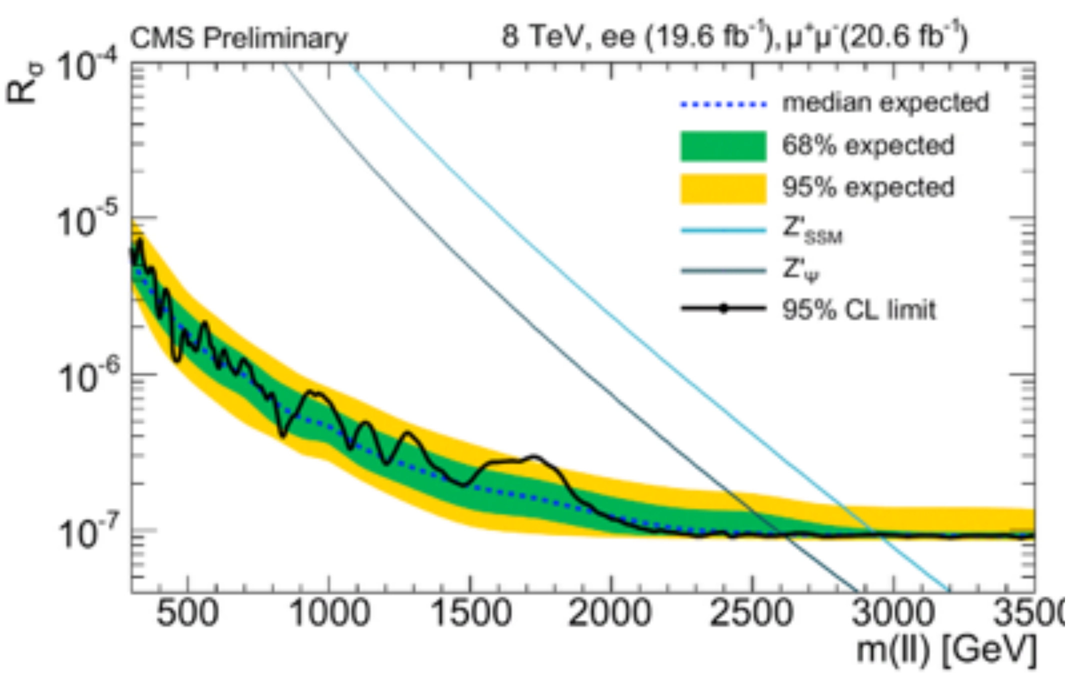


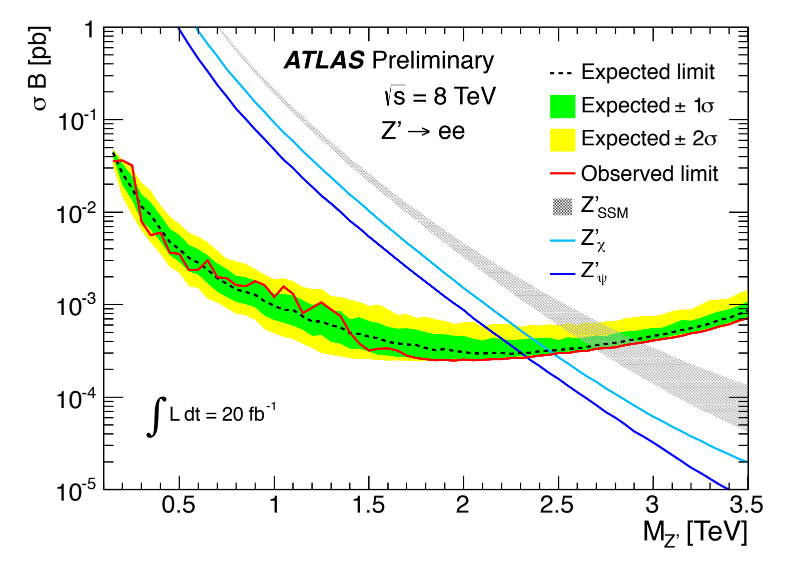
- Many models predict new resonances, coupling to fermions and/or vector bosons
  - New gauge interactions
  - Extra dimensions
  - Compositeness
- Analyses are generic (i.e., not tuned on a model) and quite simple
  - select two objets
  - look for a bump in diobject mass spectrum

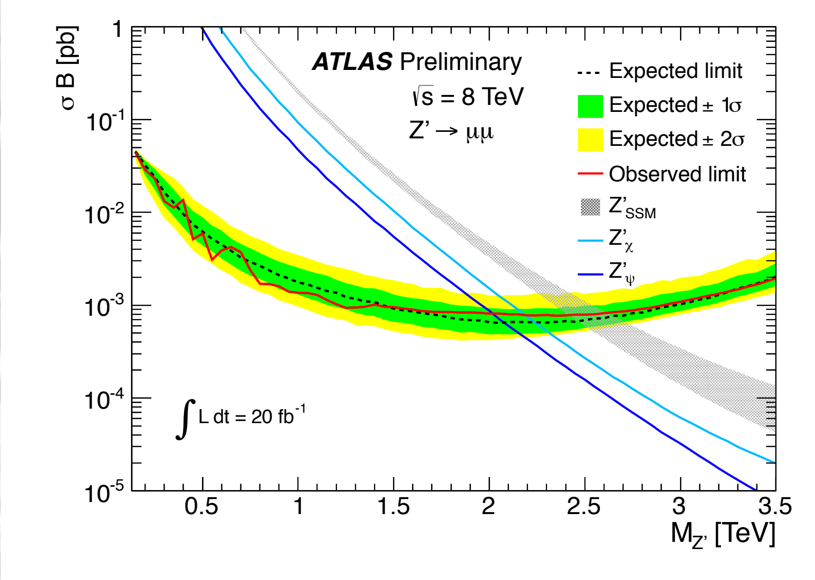
DILEPTON SEARCH



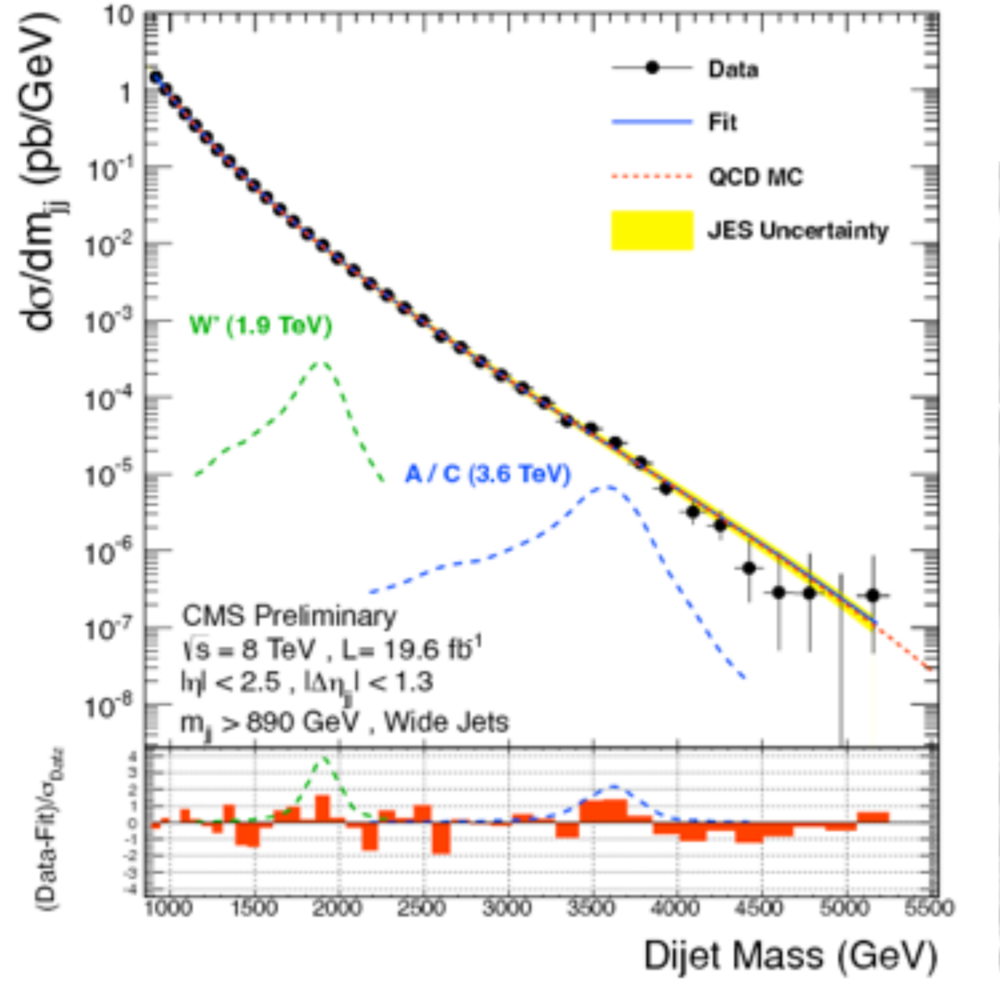


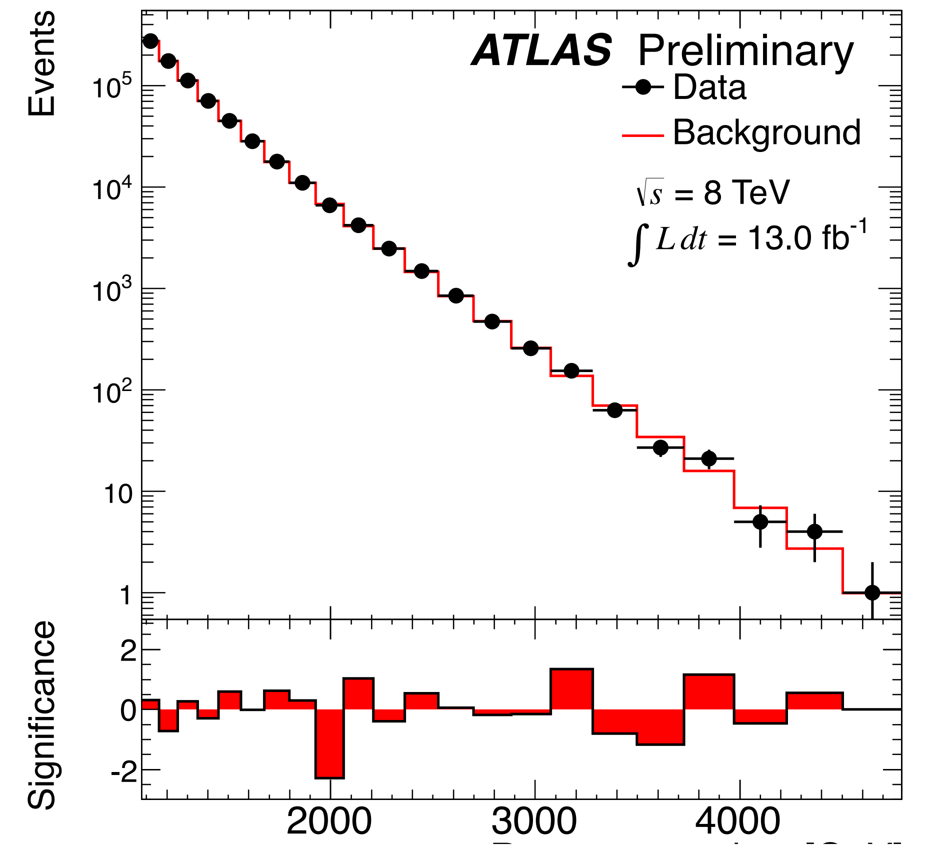


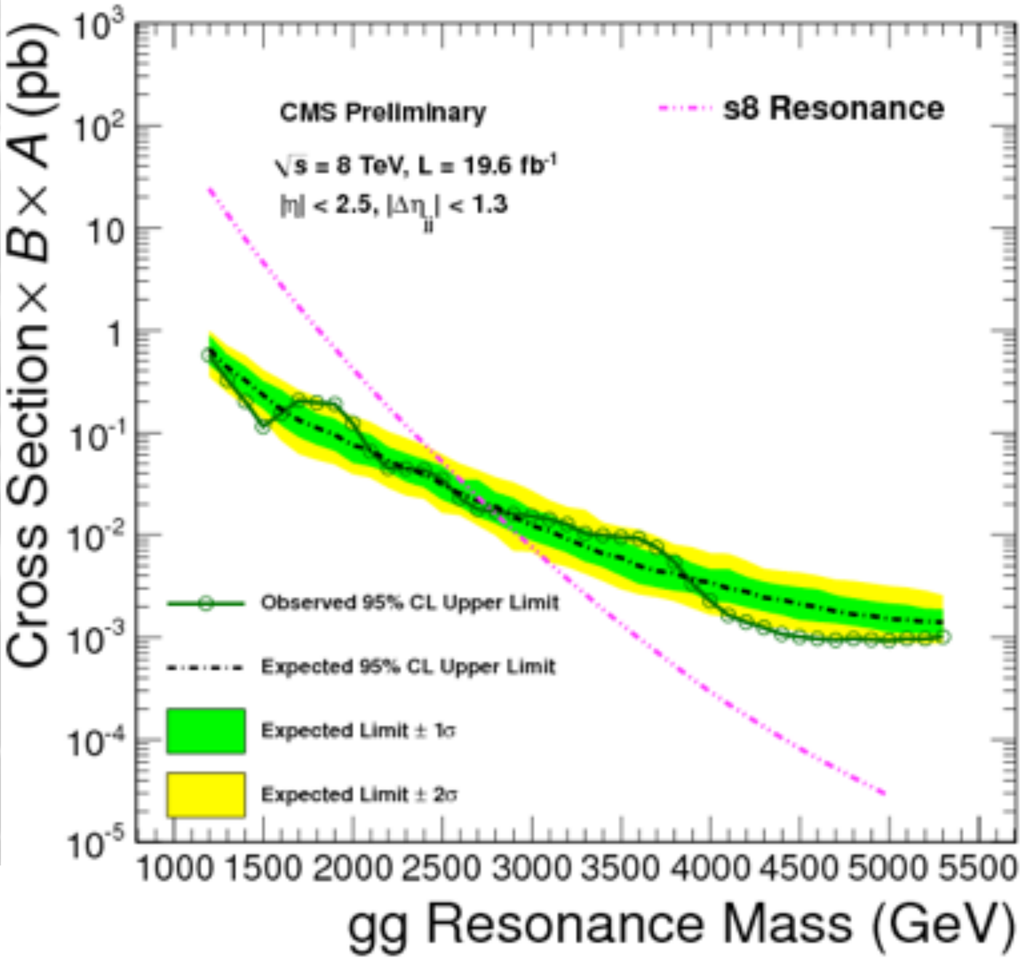


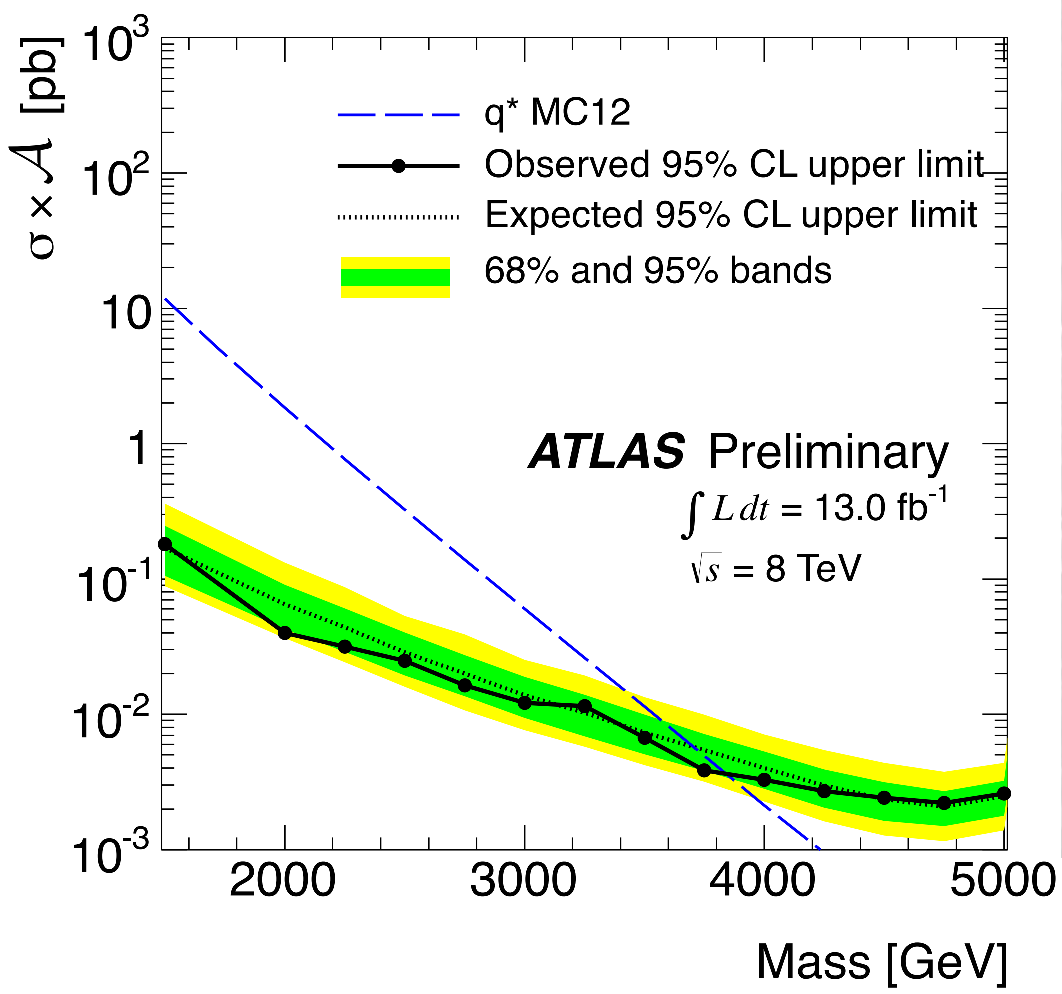


Dijet Search









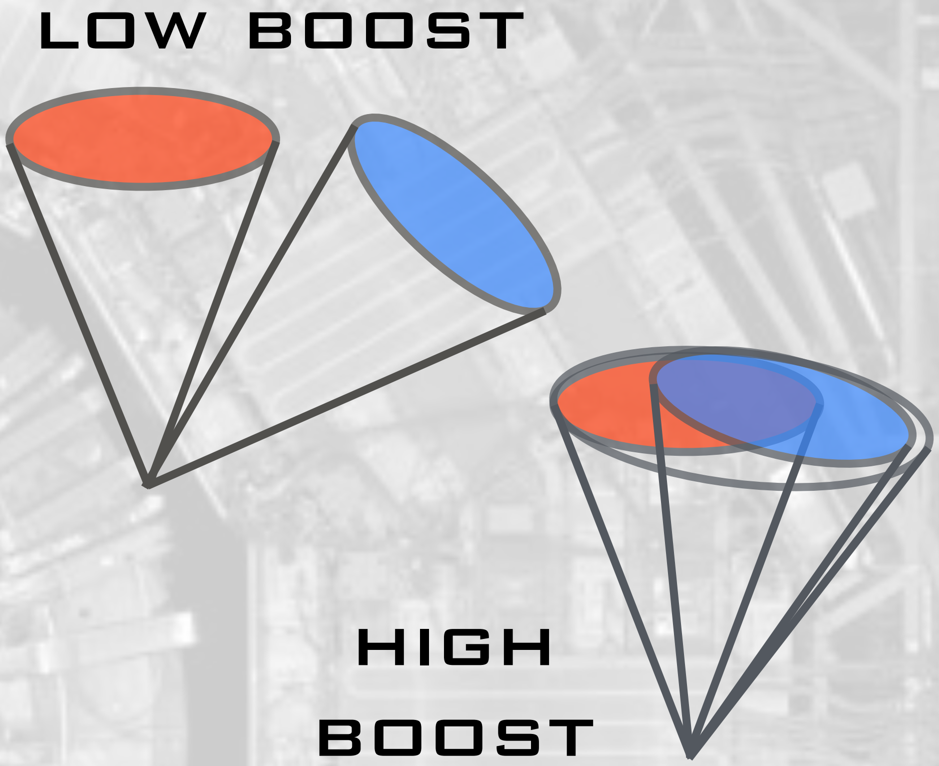
FROM JETS TO BOOSTED OBJECTS

- Jet substructure is now a common approach to look for boosted objects reconstructed as single jets

- Several techniques implemented. But a cut on the “right” jet mass is still the strongest ingredient for bkg rejection in NP searches (at least for Ws and Zs)

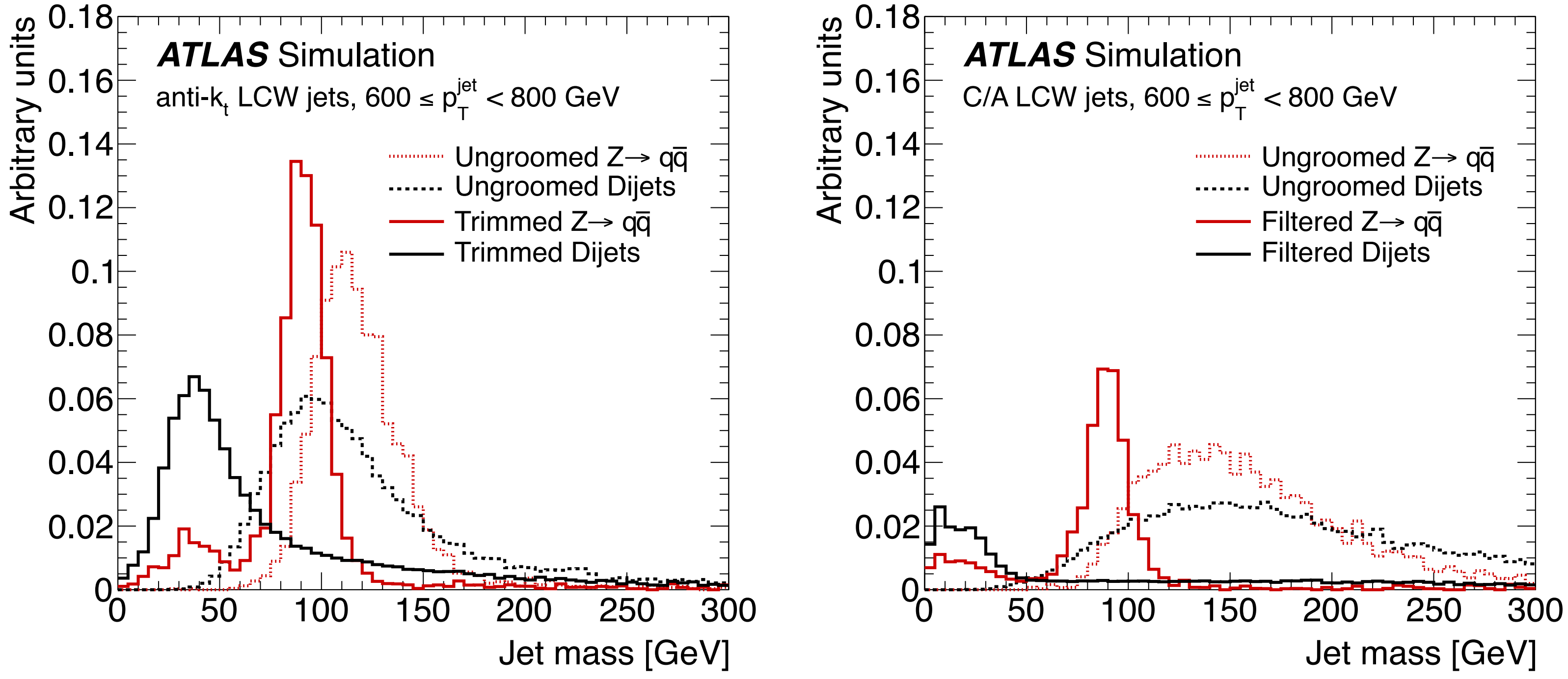
- The right mass comes from grooming. We are still exploring possibilities

- This is the Run II Jet R&D



LOW BOOST

HIGH BOOST

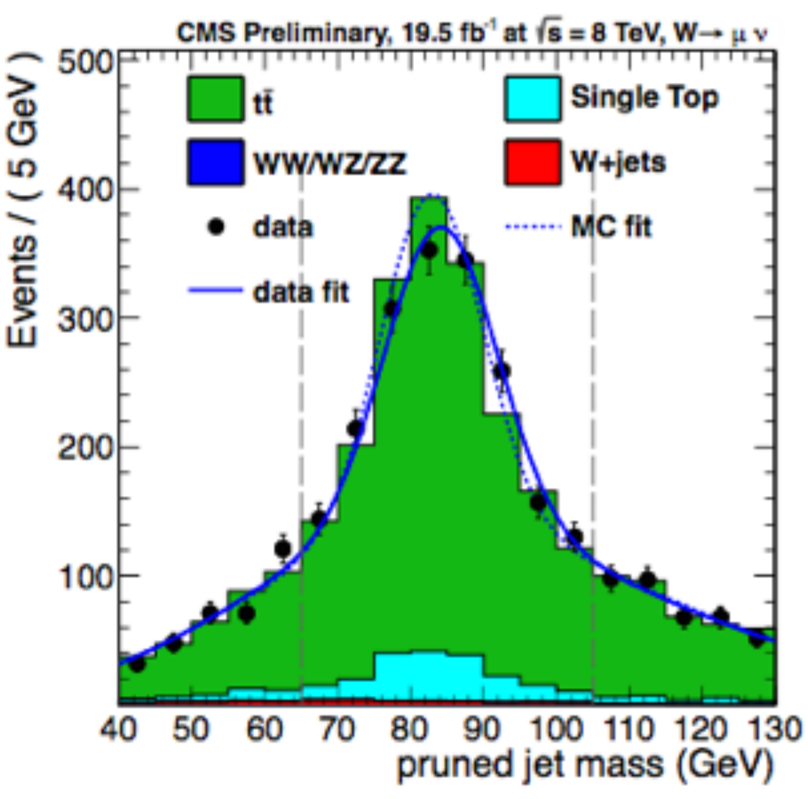


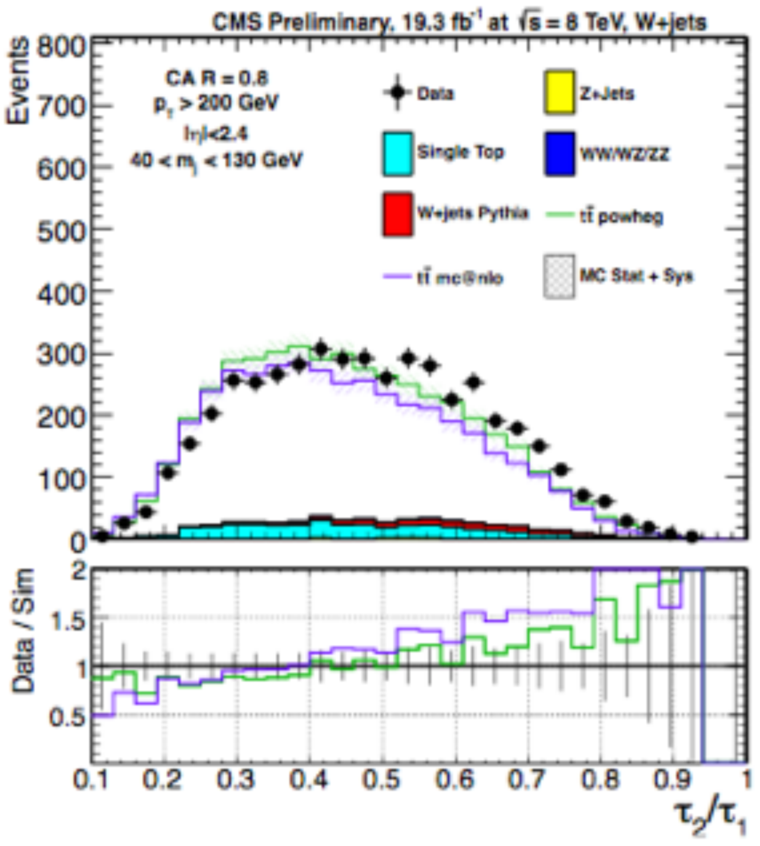
(a) anti-k_t, $R = 1.0$

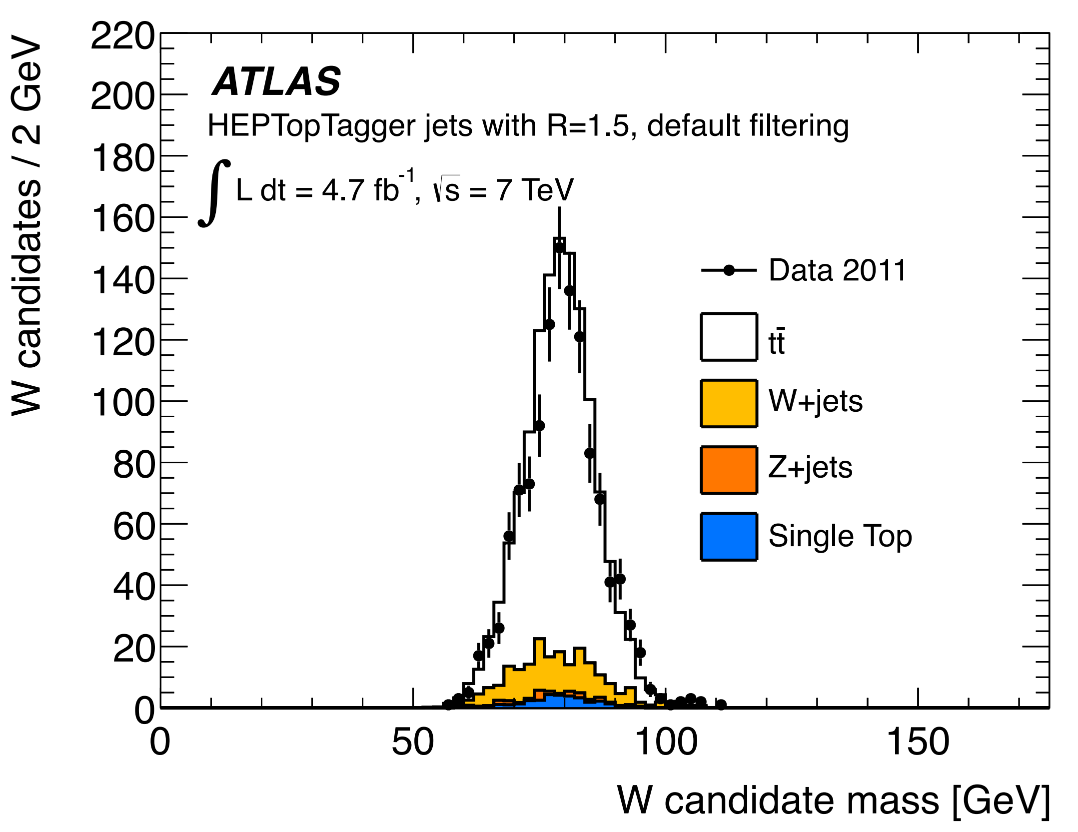
(b) C/A, $R = 1.2$

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)



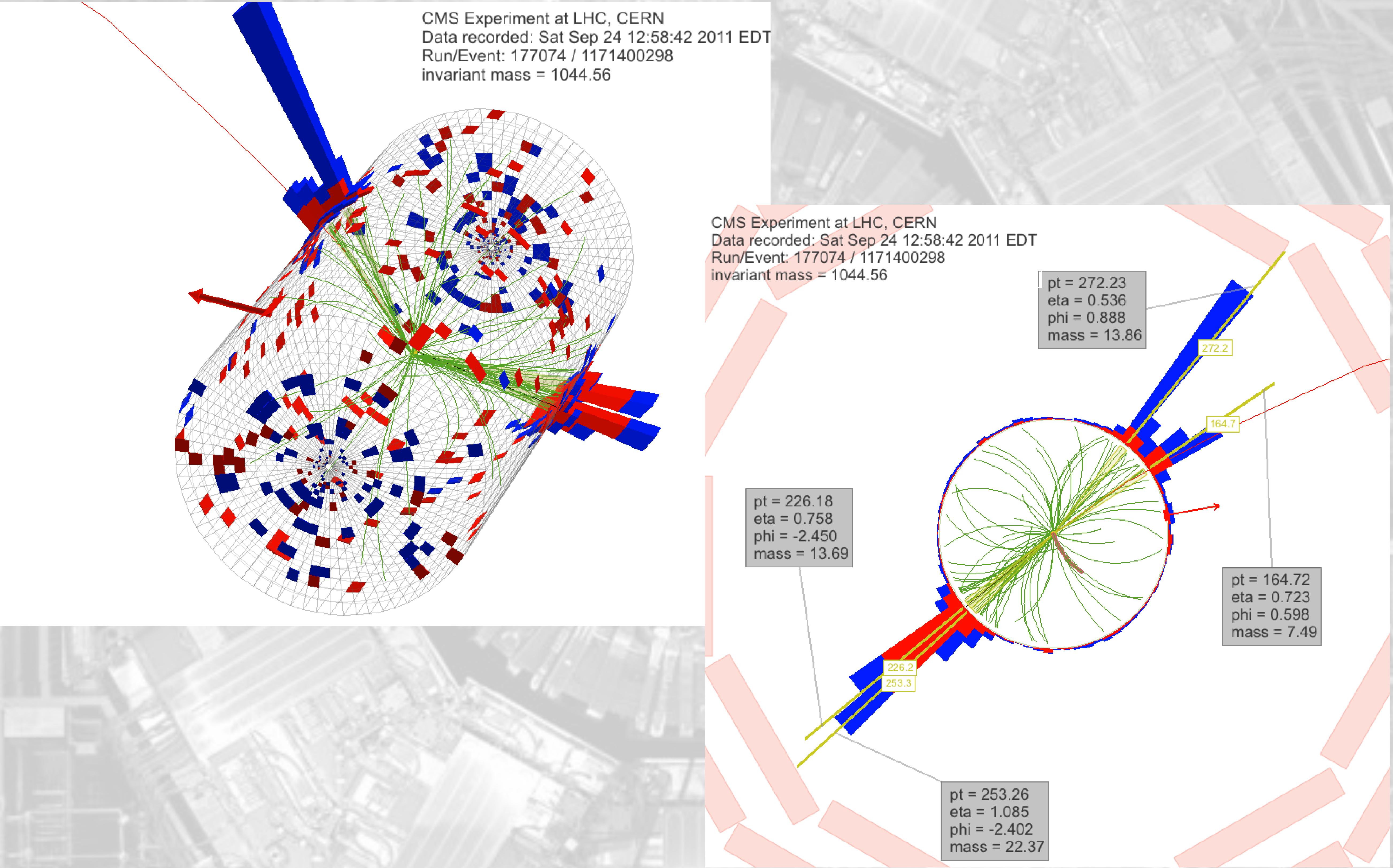




CMS-PAS-JME-13-006

ATLAS arXiv 1306.4945

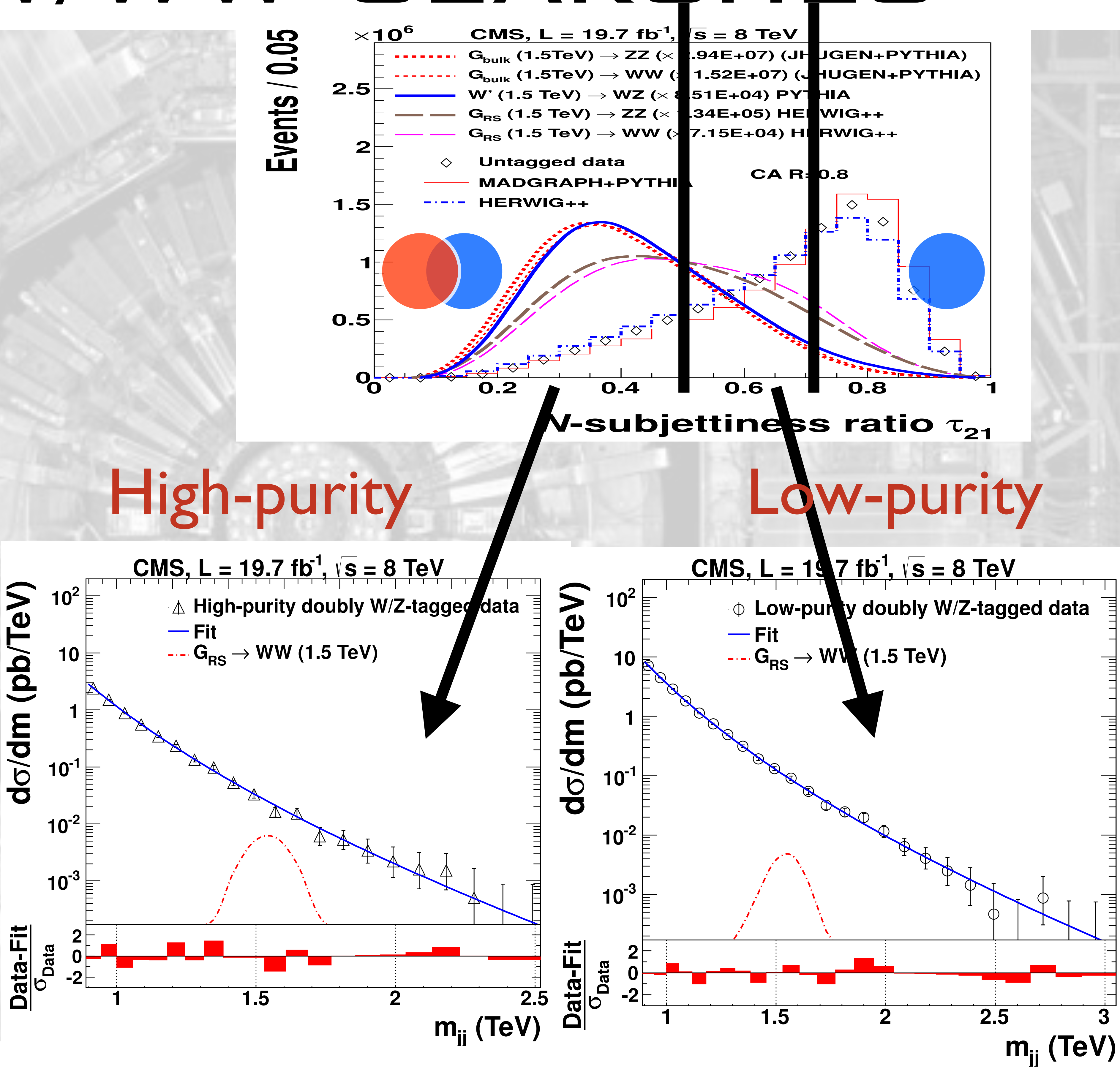
A DOUBLE-TAG EVENT



ZZ/ZW/WW SEARCHES

- Technique applied to **jj (WW/WZ/ZZ)**, $j\ell\nu$(WW/WZ) and $j\ell\ell$(WZ/ZZ) final states

- Background determined with shape fit (as Hgg) or with absolute prediction from jet sideband



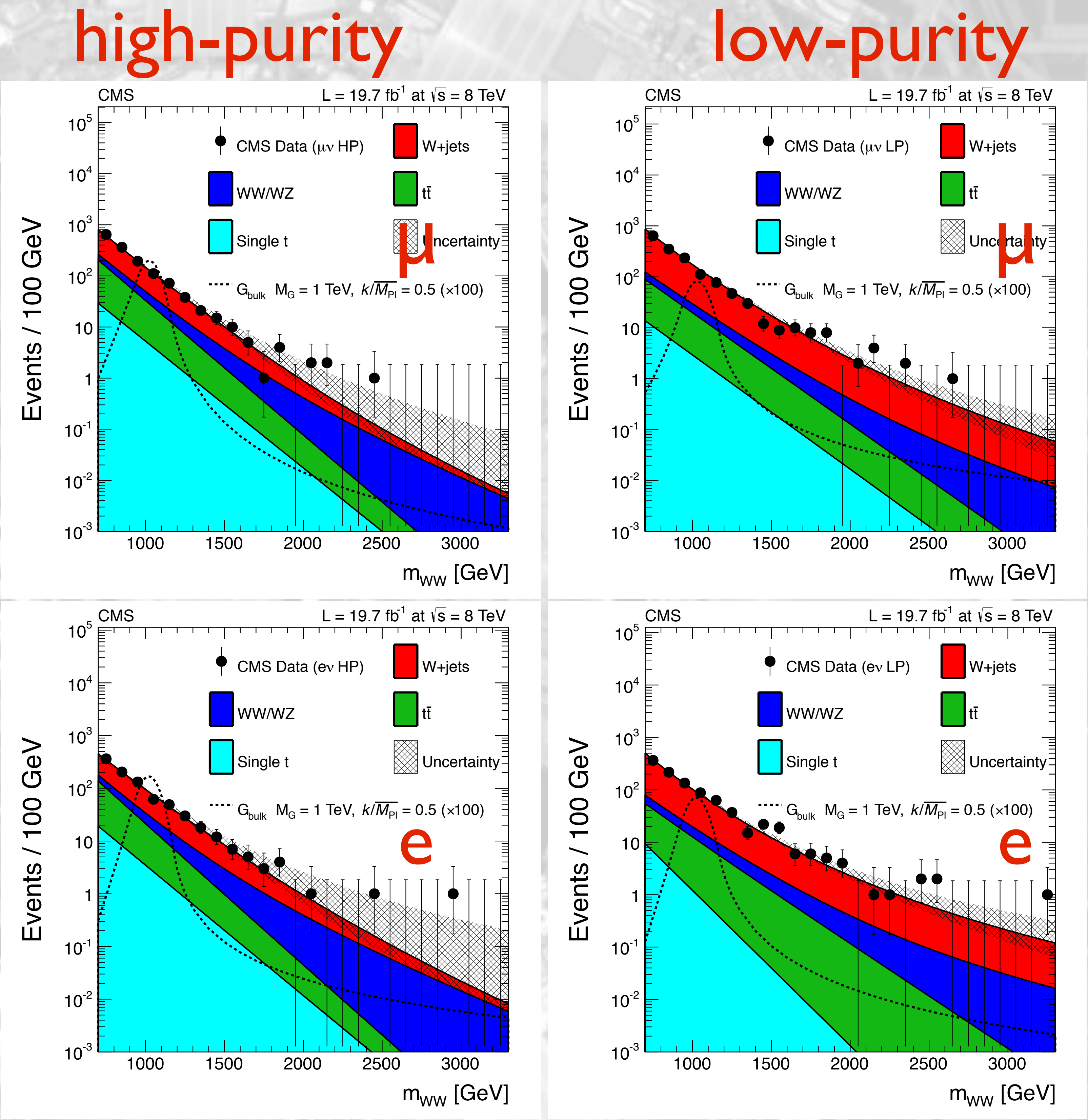
High-purity

Low-purity

ZZ/ZW/WW SEARCHES

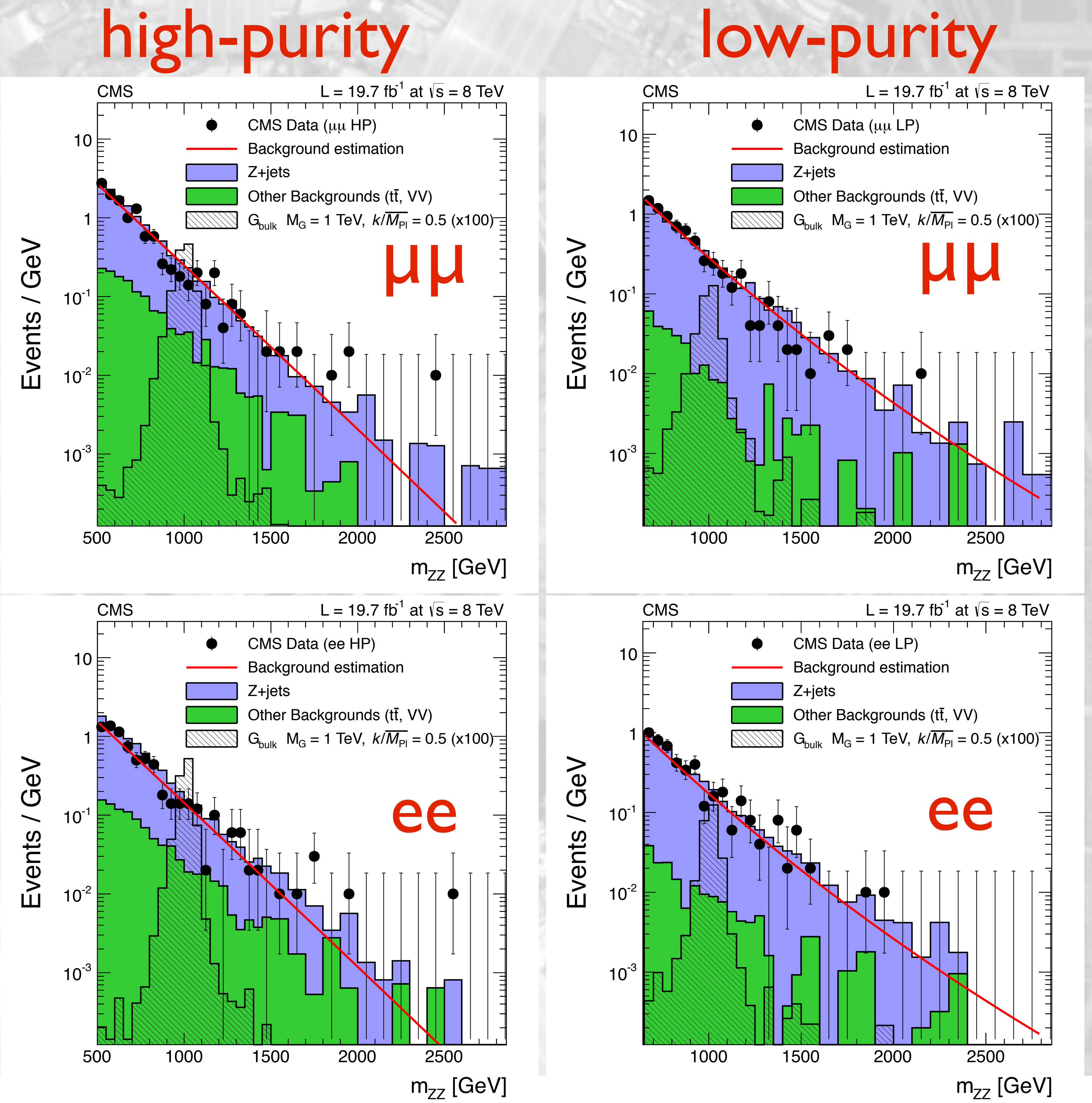
- Technique applied to jj (WW/WZ/ZZ), **jℓν(WW/WZ)** and jℓℓ(WZ/ZZ) final states

- Background determined with shape fit (as Hgg) or with absolute prediction from jet sideband

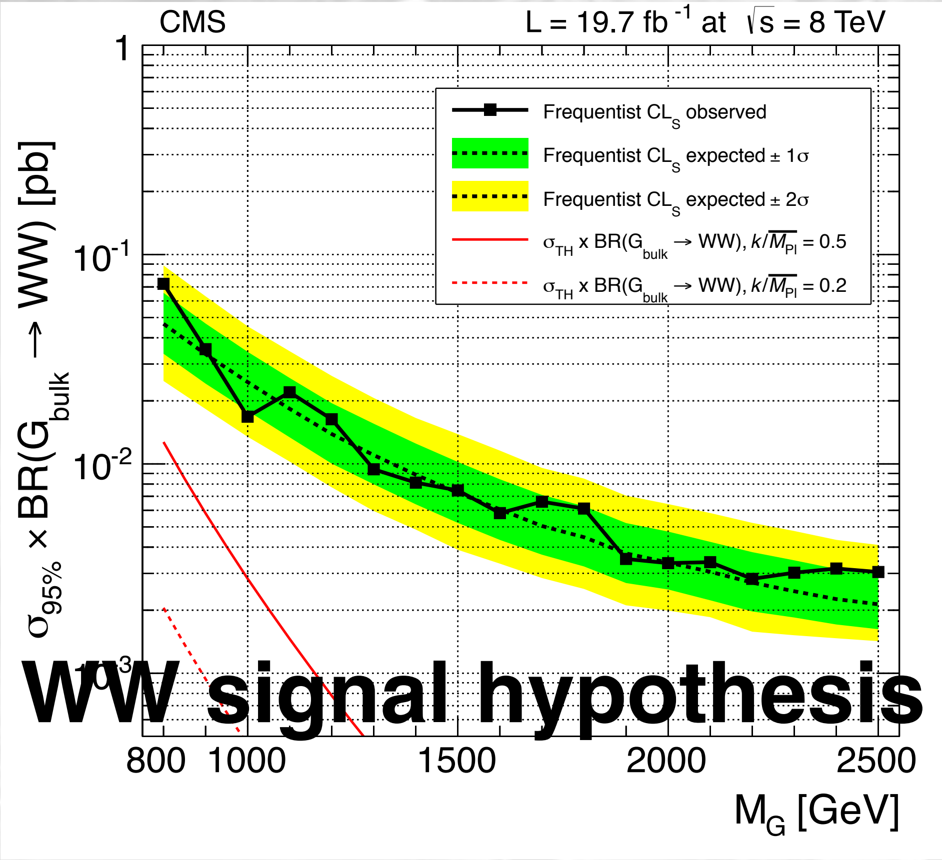


ZZ/ZW/WW SEARCHES

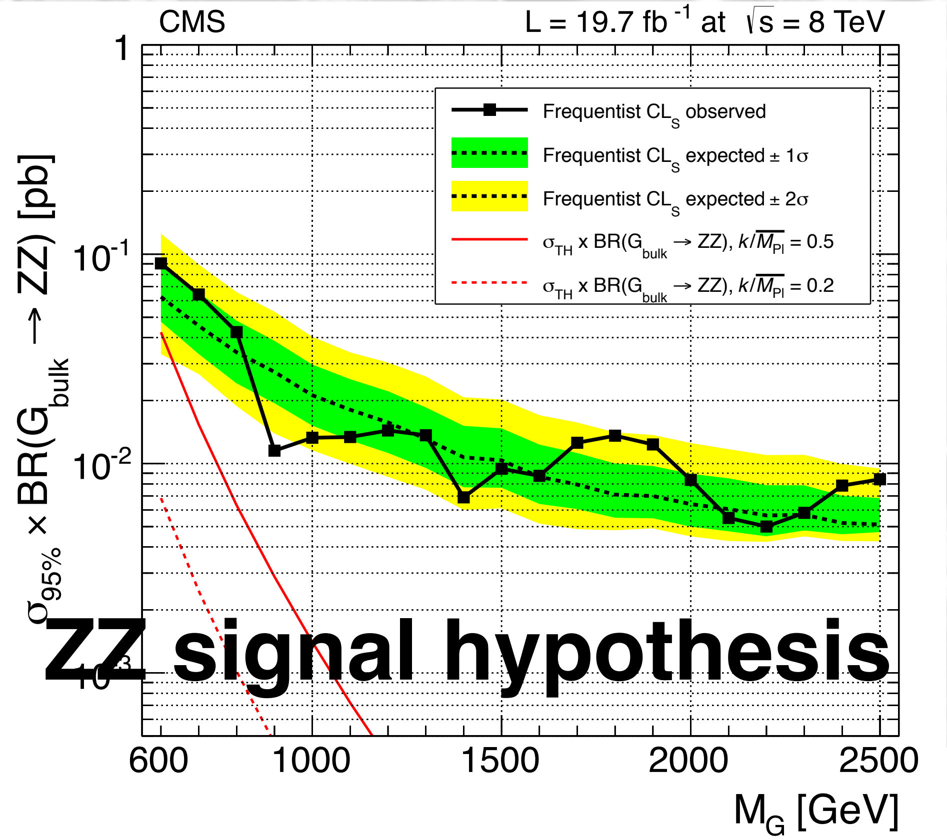
- Technique applied to jj (WW/WZ/ZZ), j$\ell\nu$(WW/WZ) and **j$\ell\ell$(WZ/ZZ)** final states
- Background determined with shape fit (as Hgg) or with absolute prediction from jet sideband



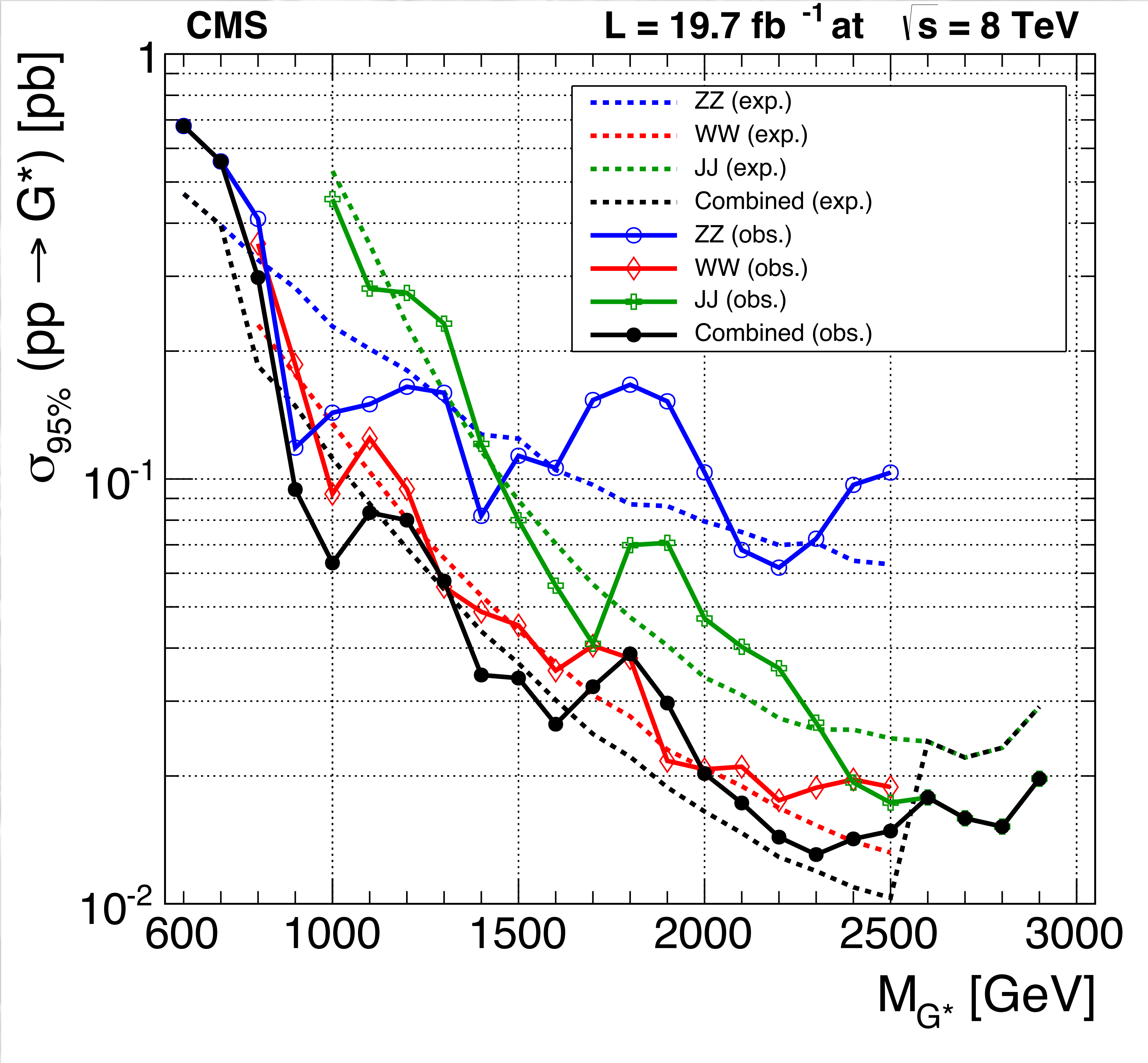
INTERPRETATION



WW signal hypothesis



ZZ signal hypothesis

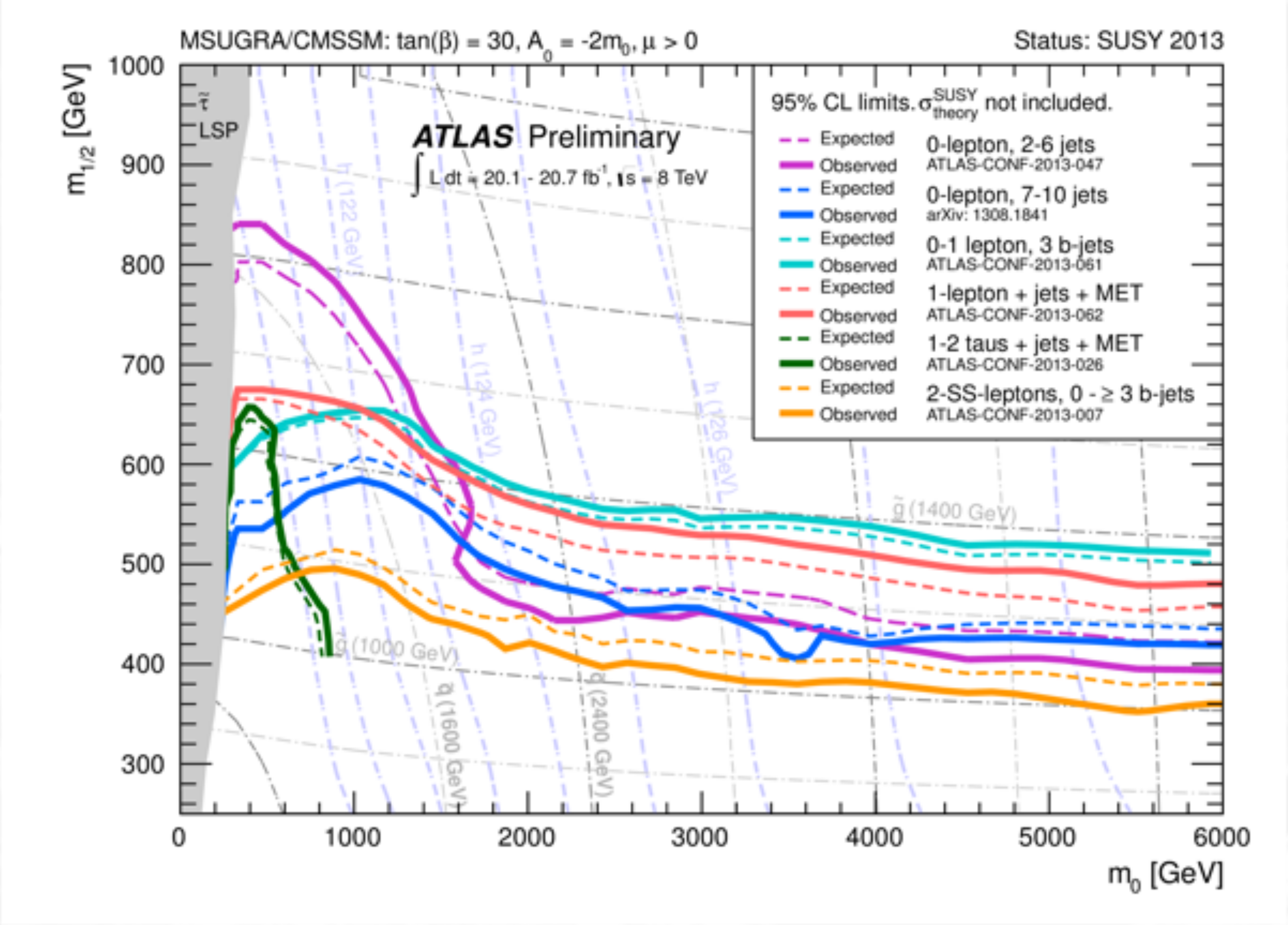


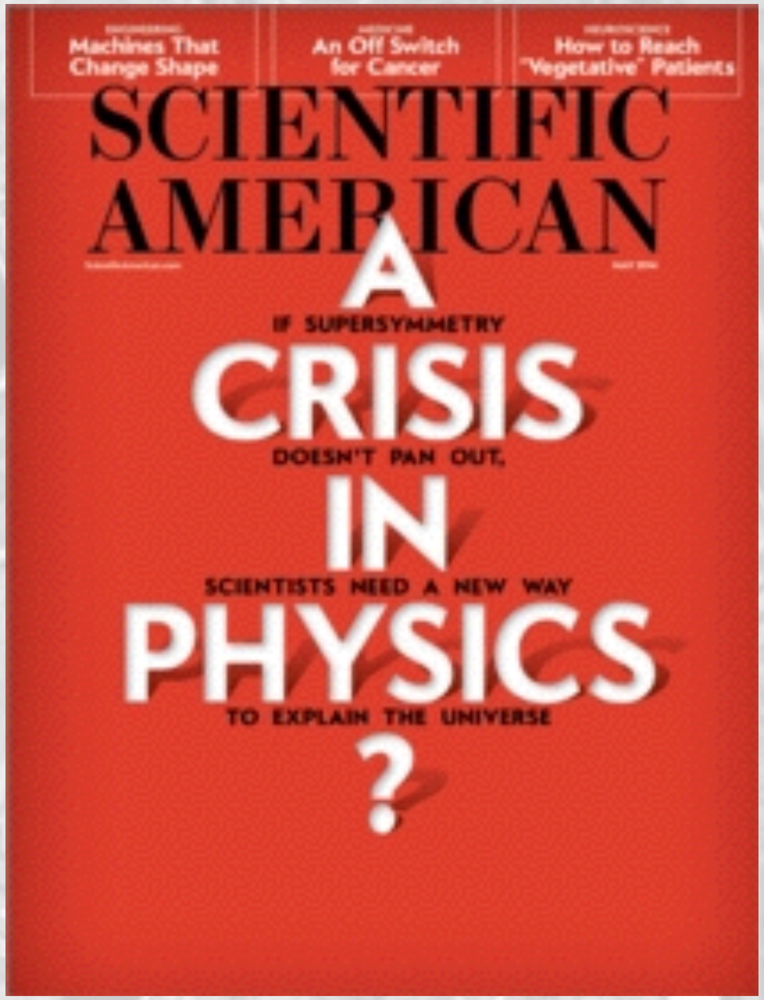
Highlights from Run I:

search for DM in cascade (aka SUSY searches)

THERE WAS NOTHING BEHIND THE CORNER

- this was somehow expected (e.g. EW precision, flavour)
- Now we know it as a fact

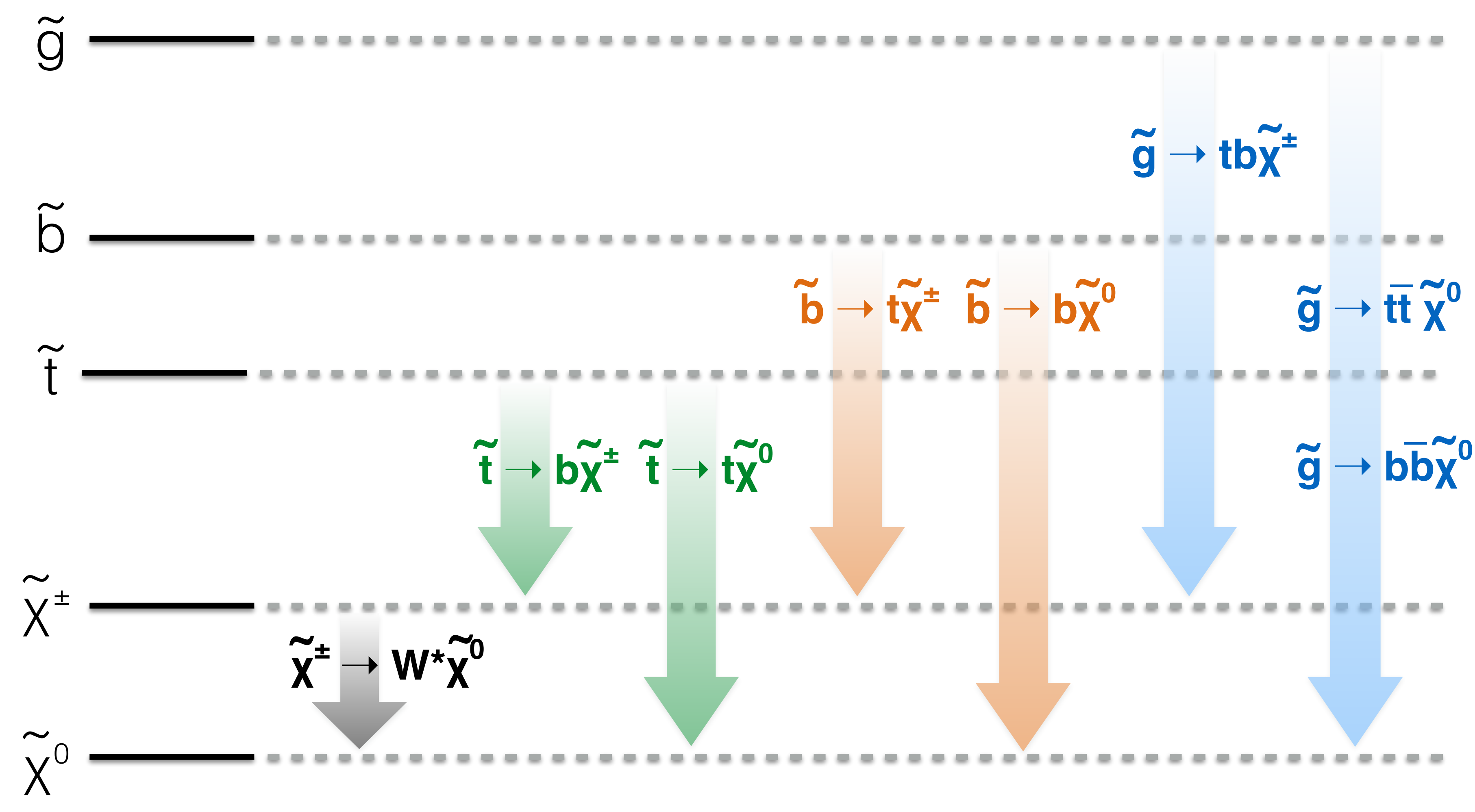




Run I forced us to look for “new” paradigms

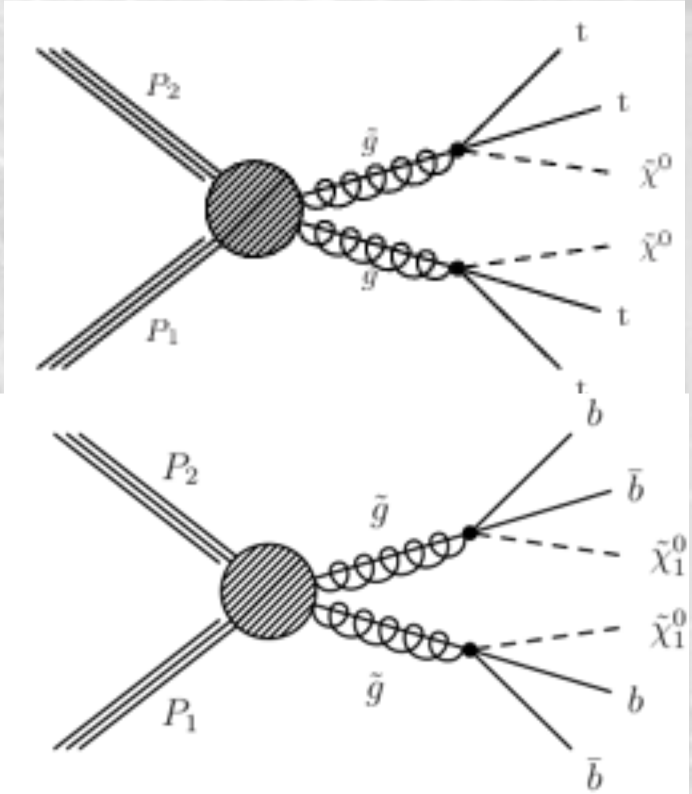
NATURAL SUSY

- Multijet final states with many b quarks (4t, 3t1b, 2t2b, 1t3b, 4b) from gluinos
- High-pT leptons from W decays
- Same/opposite charge lepton pairs, with same or different flavour

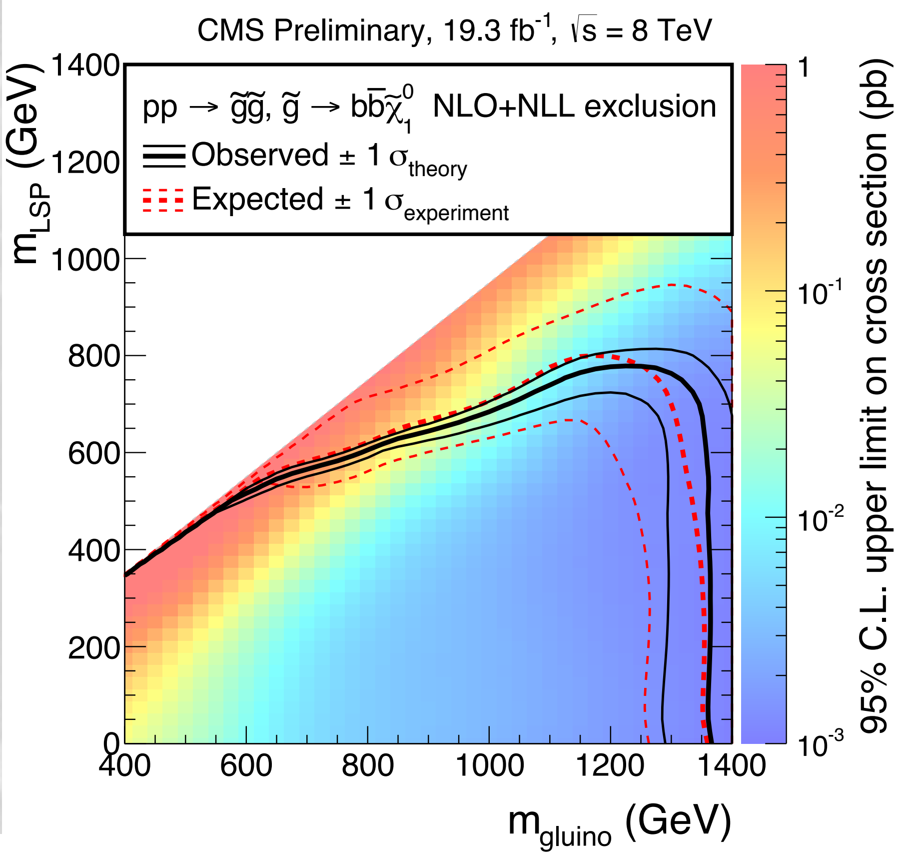


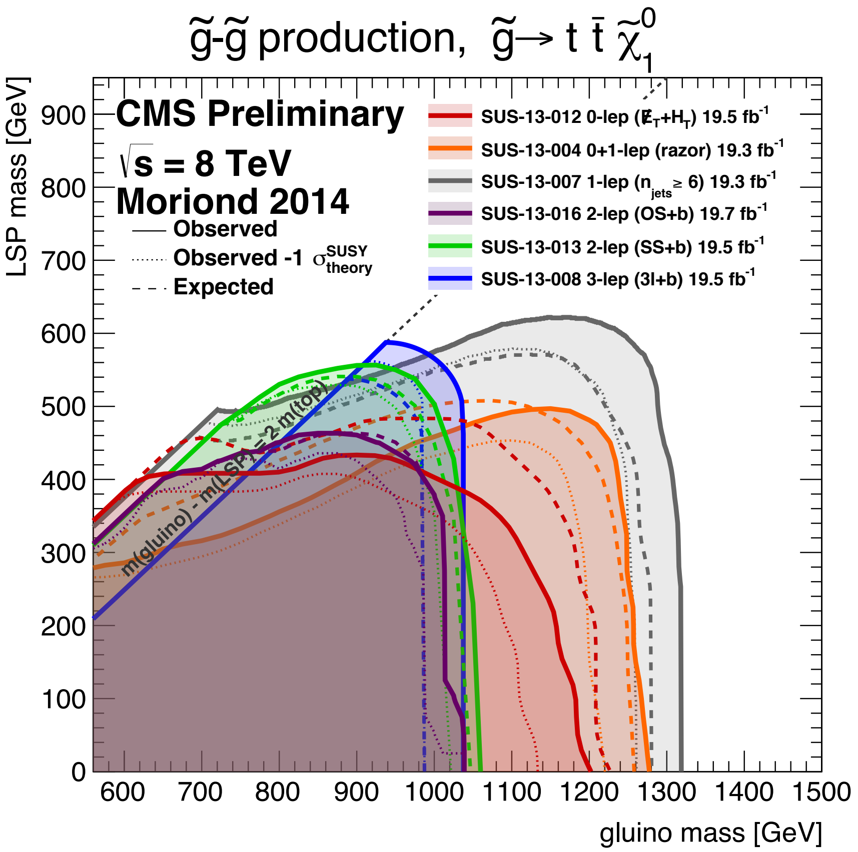
- Rather than focusing on one signature, we decided to design an inclusive search
- Rather than focusing on the tail of some kinematic distribution, we decided to use a loose selection: more signal, but also more background

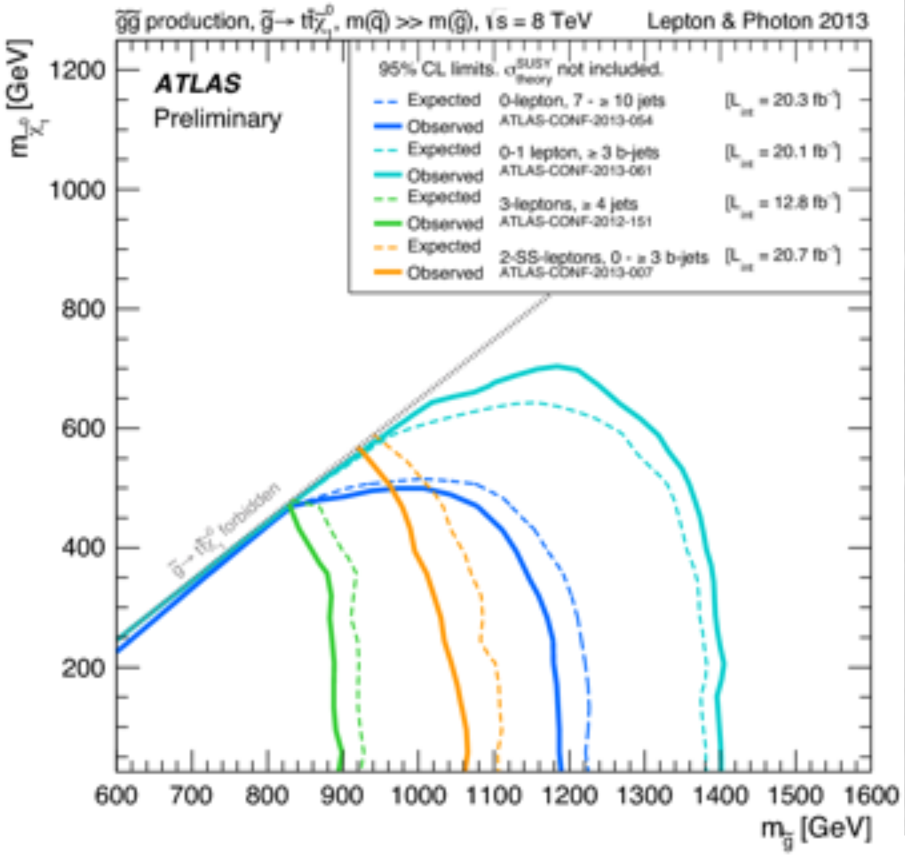
SEARCH FOR GLUINOS



- Gluino is a model killer if kinematically accessible
  - large xsec
  - rich final states
- Loose sensitivity if gluino (LSP) heavier than ~1300 (~600) GeV
- As long as this is not the case, squarks produced in cascade are also largely excluded (limits robust vs intermediate squark masses)

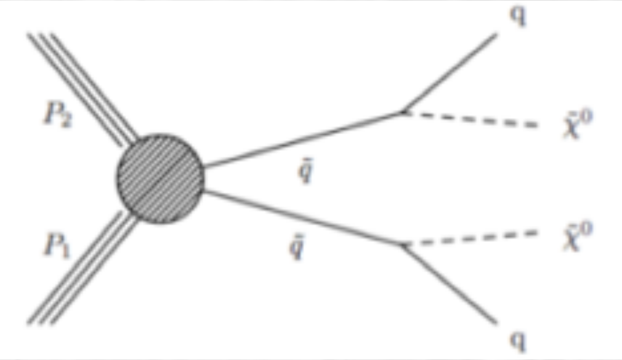


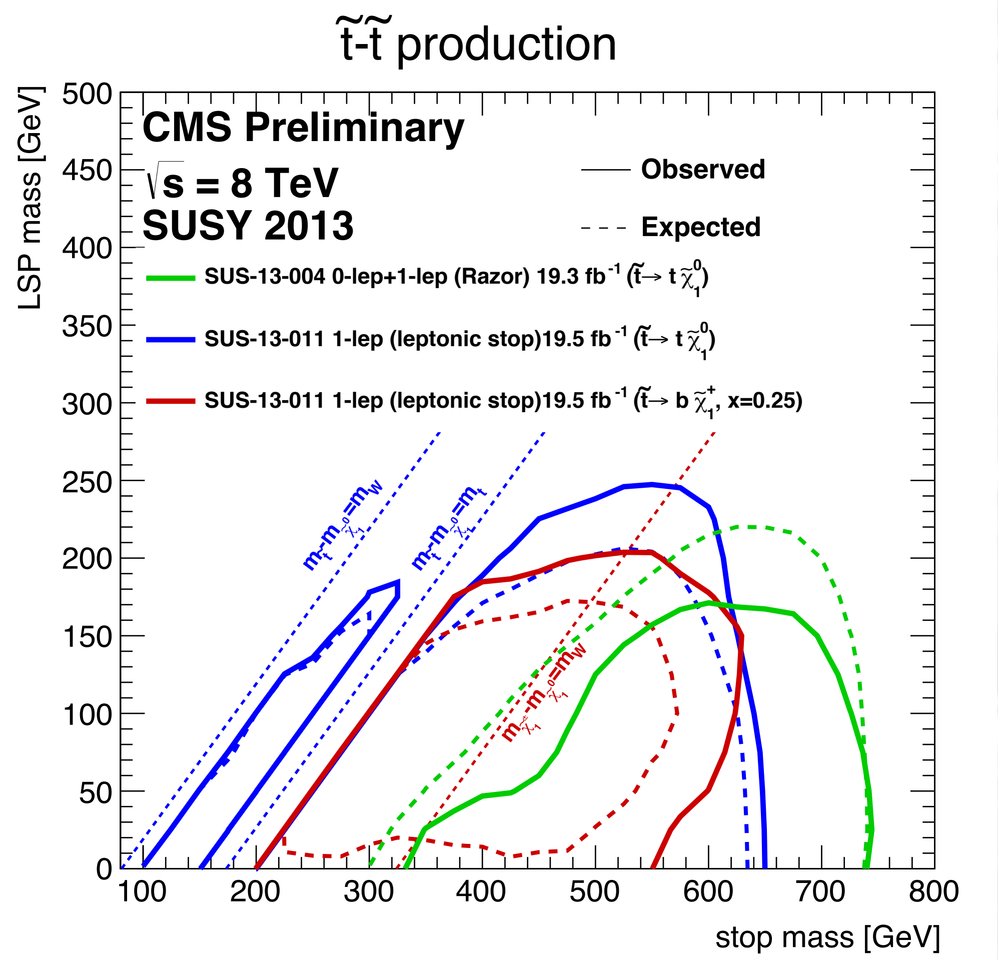


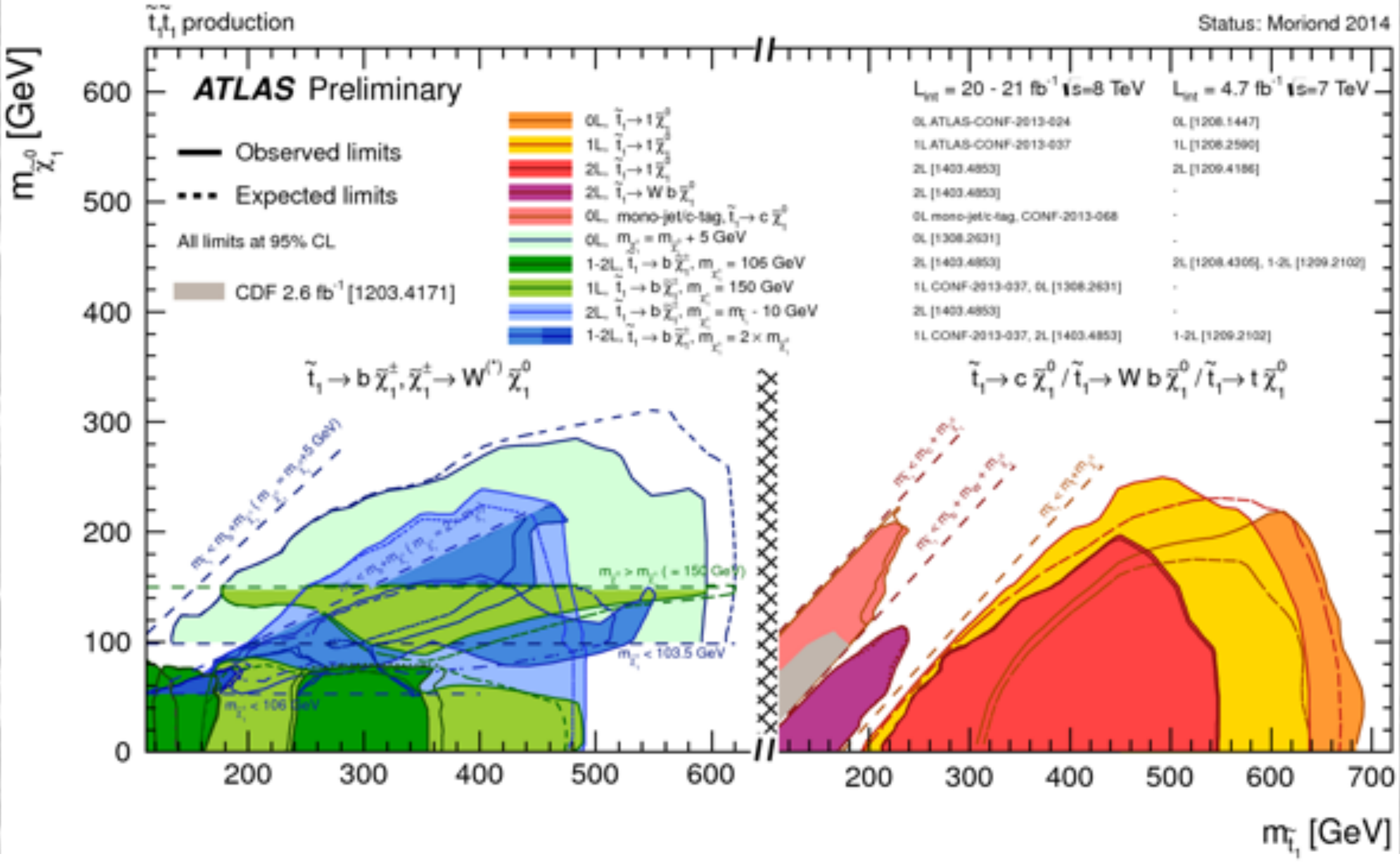


SEARCH FOR SQUARKS

- Both inclusive and exclusive searches
  - sbottom and stop excluded up to m~750 for large mass splits
  - reduced sensitivity for heavy LSP or for split ~ m_{top}

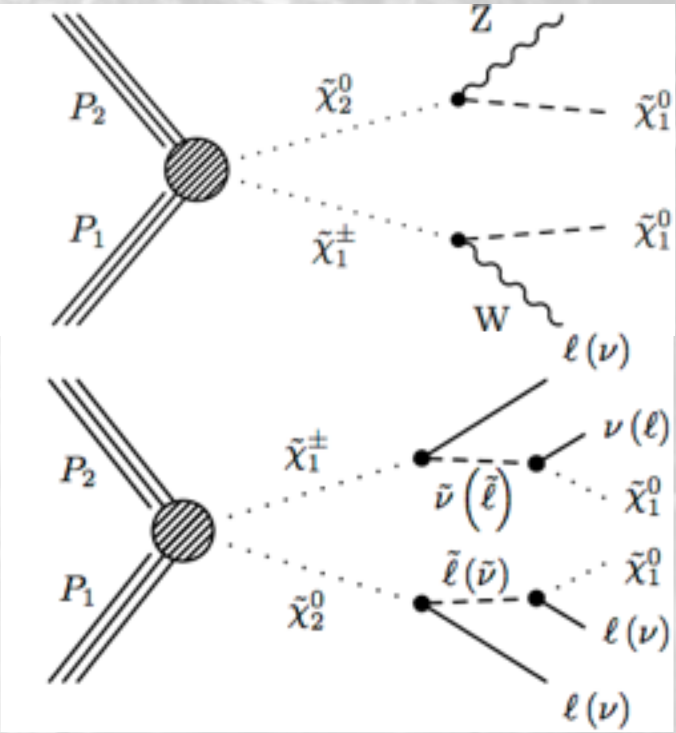


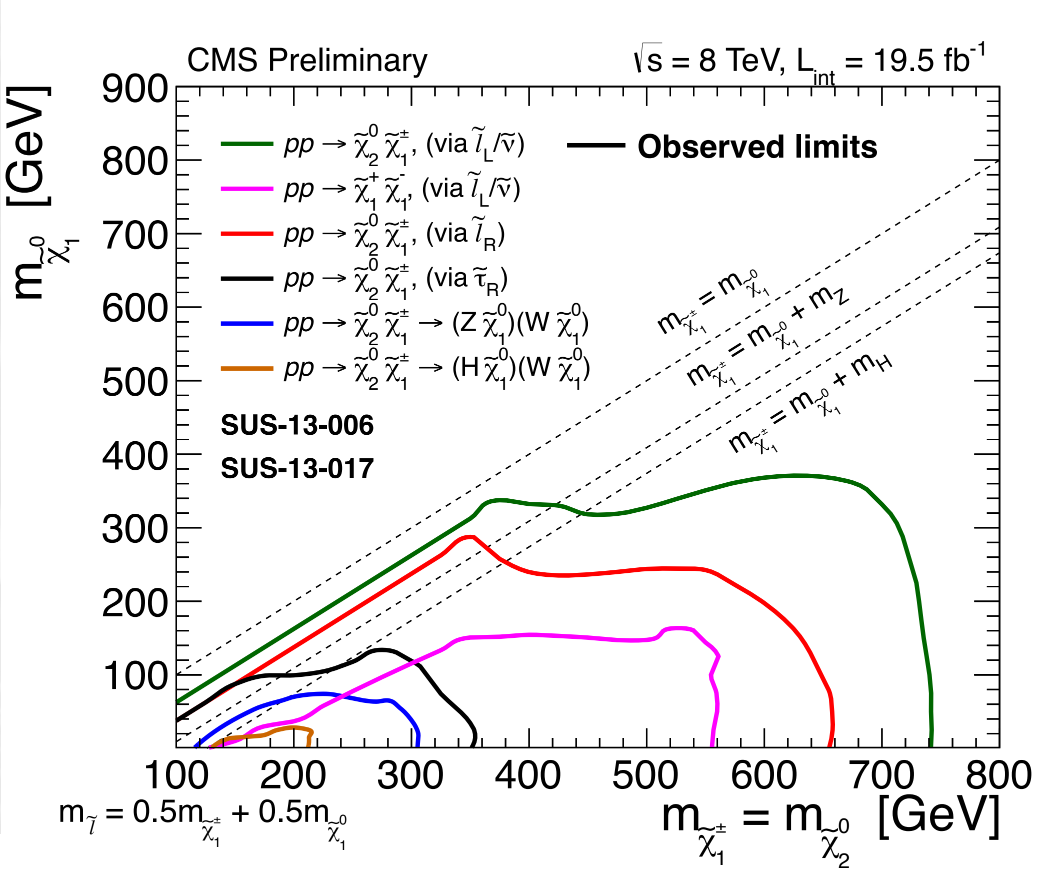


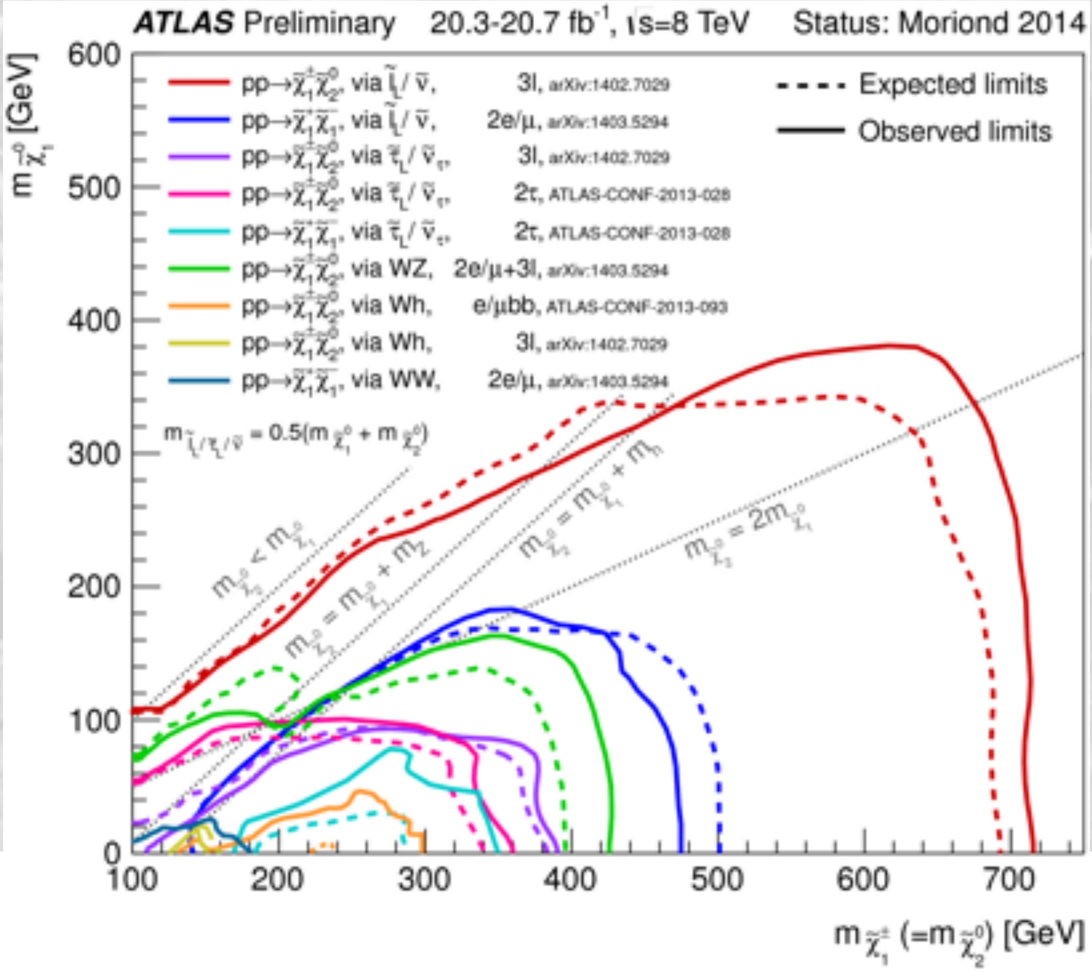


SEARCH FOR EWINOS

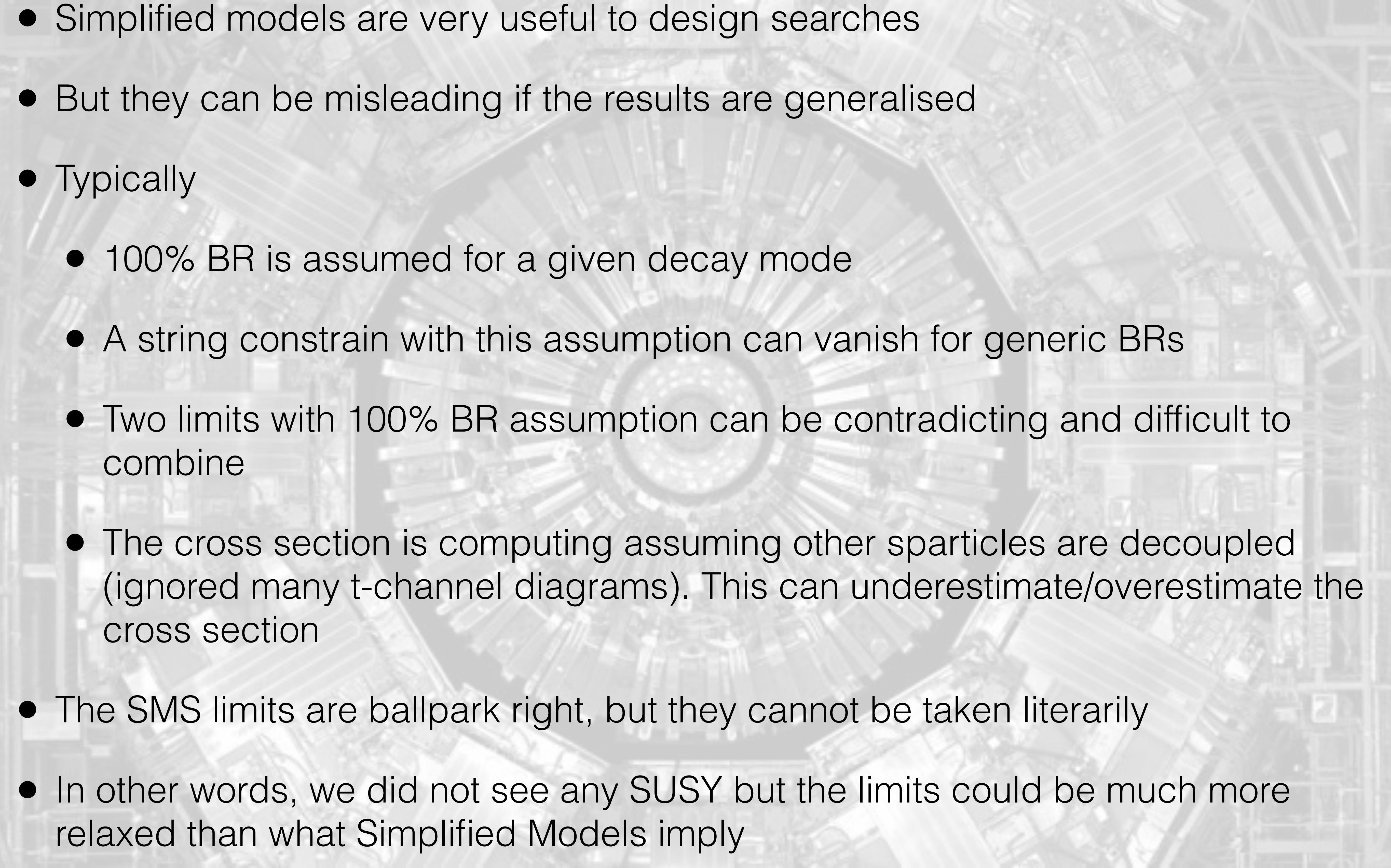
- Search for Ewkino direct production more challenging
  - smaller xsec
  - limited kinematic handles (particularly at small splits)
- Use combination of several final states, including Higgs bosons (now that we know the mass)







A Few Remarks



- Simplified models are very useful to design searches
- But they can be misleading if the results are generalised
- Typically
  - 100% BR is assumed for a given decay mode
  - A string constrain with this assumption can vanish for generic BRs
  - Two limits with 100% BR assumption can be contradicting and difficult to combine
  - The cross section is computing assuming other sparticles are decoupled (ignored many t-channel diagrams). This can underestimate/overestimate the cross section
- The SMS limits are ballpark right, but they cannot be taken literarily
- In other words, we did not see any SUSY but the limits could be much more relaxed than what Simplified Models imply

Highlights from Run I:

search for DM production (aka monojet)

INVISIBLE AND MONOJET

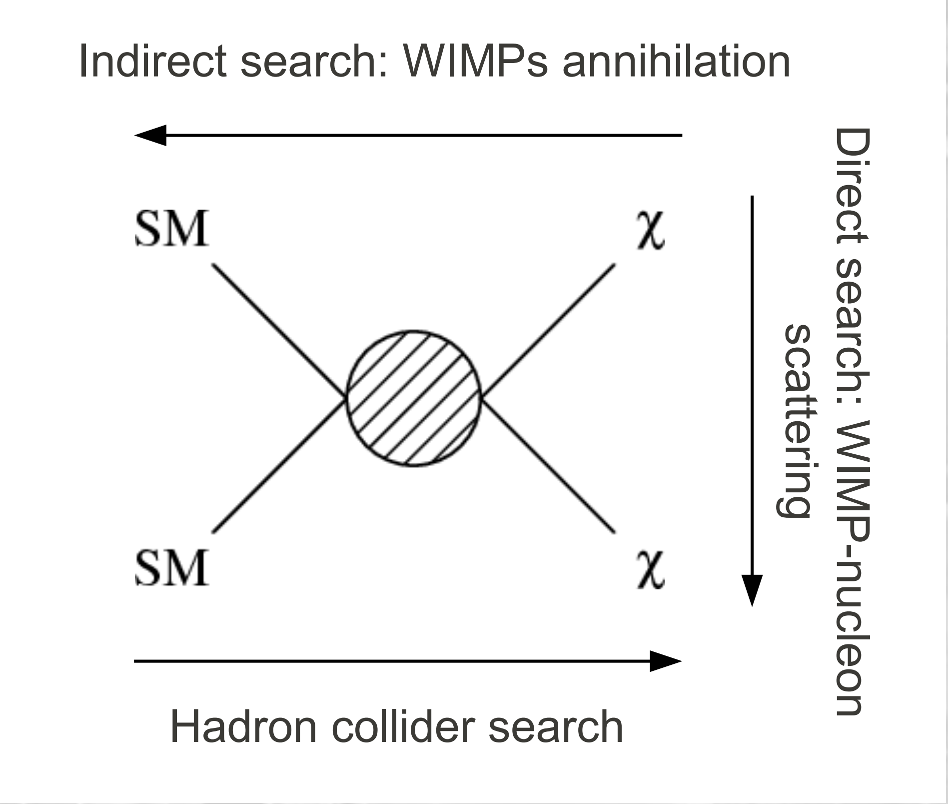
- DM can be produced at the LHC with a similar process than scattering in underground experiments

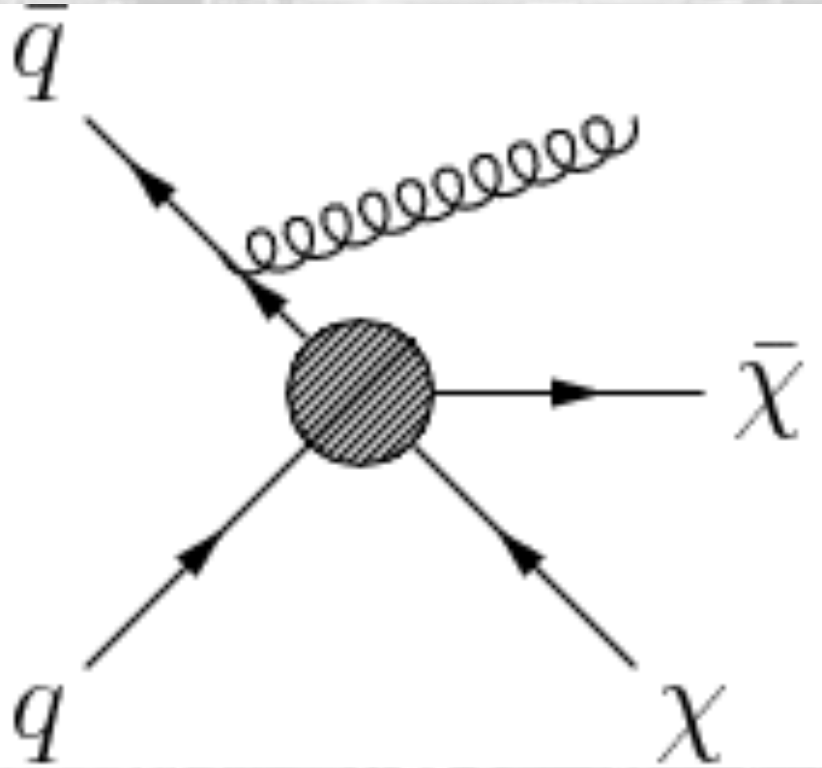
- But DM is invisible with our detectors, so these events don’t even pass the trigger

- We then exploit Initial State Radiation to look for 2DM+jet production

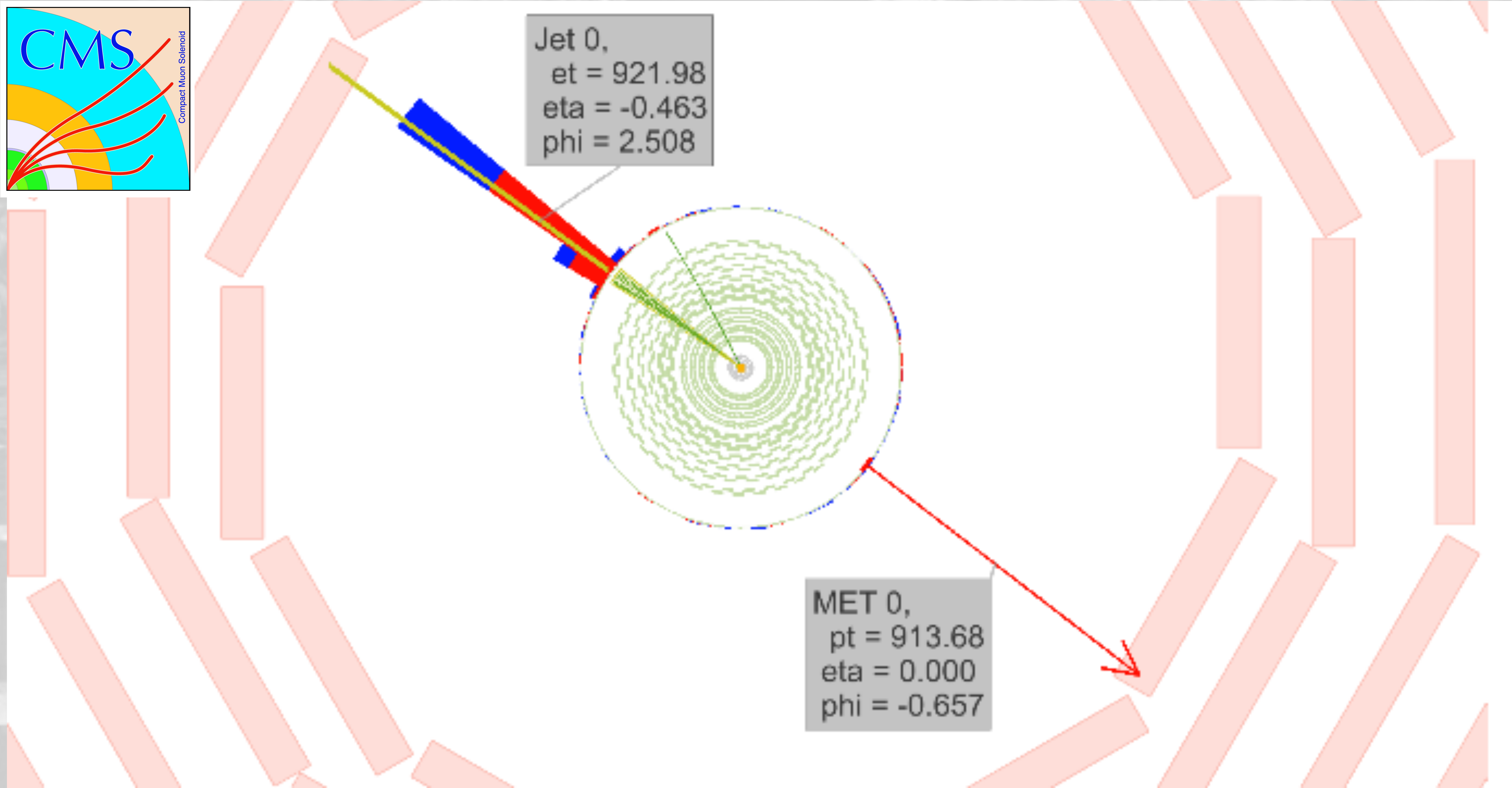
- These events look like a jet recoiling against nothing

- The main SM background (e.g., Z(nn)+jets) can be studied with data (e.g., Z(mm)+jets)



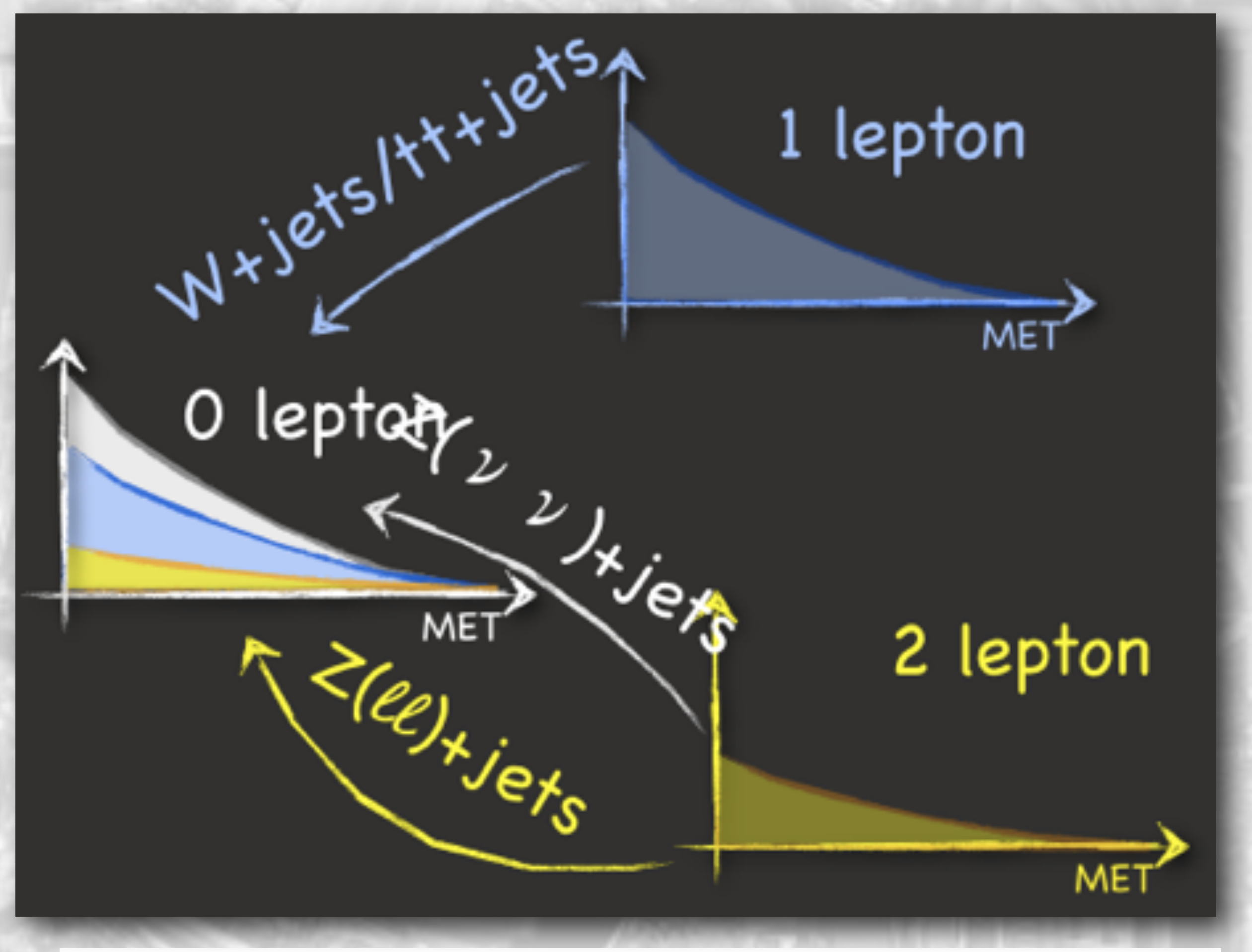


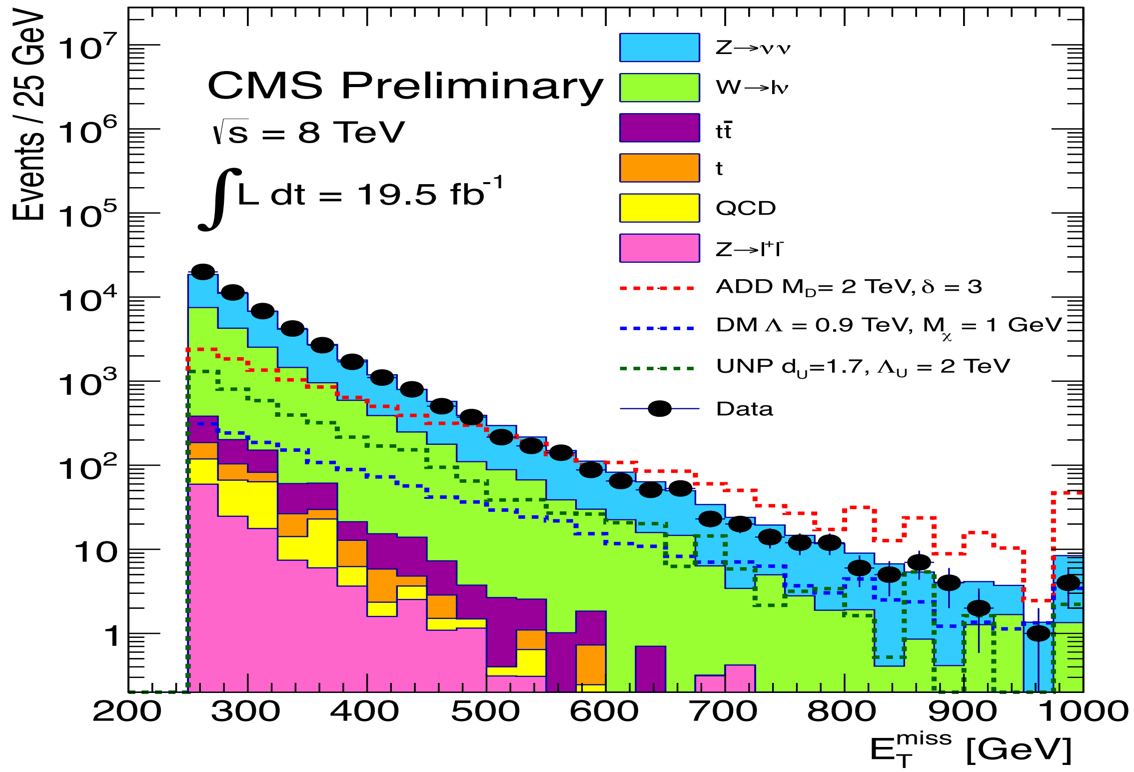
INVISIBLE AND MONOJET



SEARCH STRATEGY

- Reject the QCD background by kinematic cuts (large missing E_T, large jet p_T)
- Left with W/Z+jets and tt production
- Measure the background in control samples (1 lepton, 2 lepton, etc)
- Use the MC to scale the observed data yield to the 0lepton sample: $(1-\varepsilon)/\varepsilon$
- Compare prediction to observation



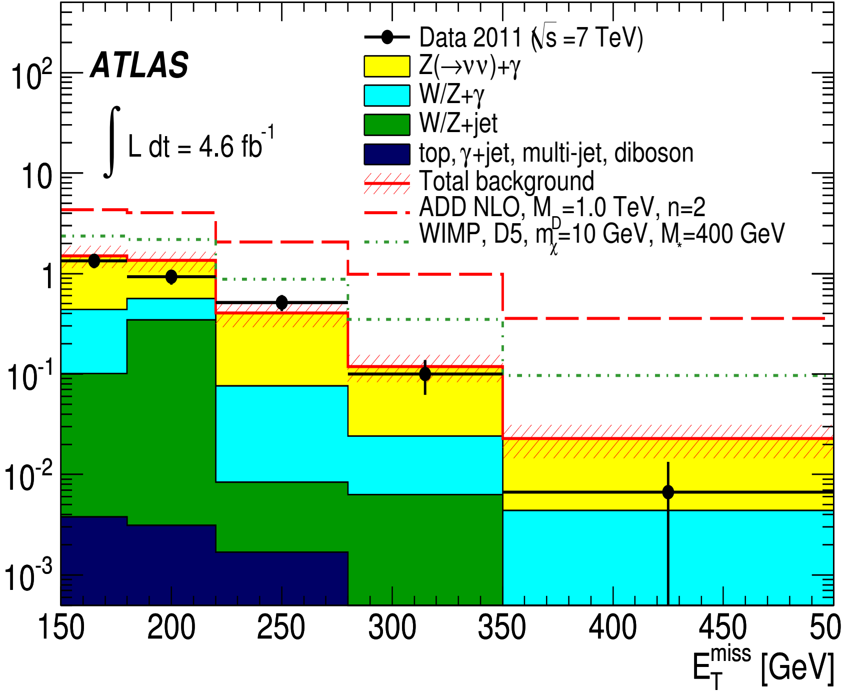


More than Monojet

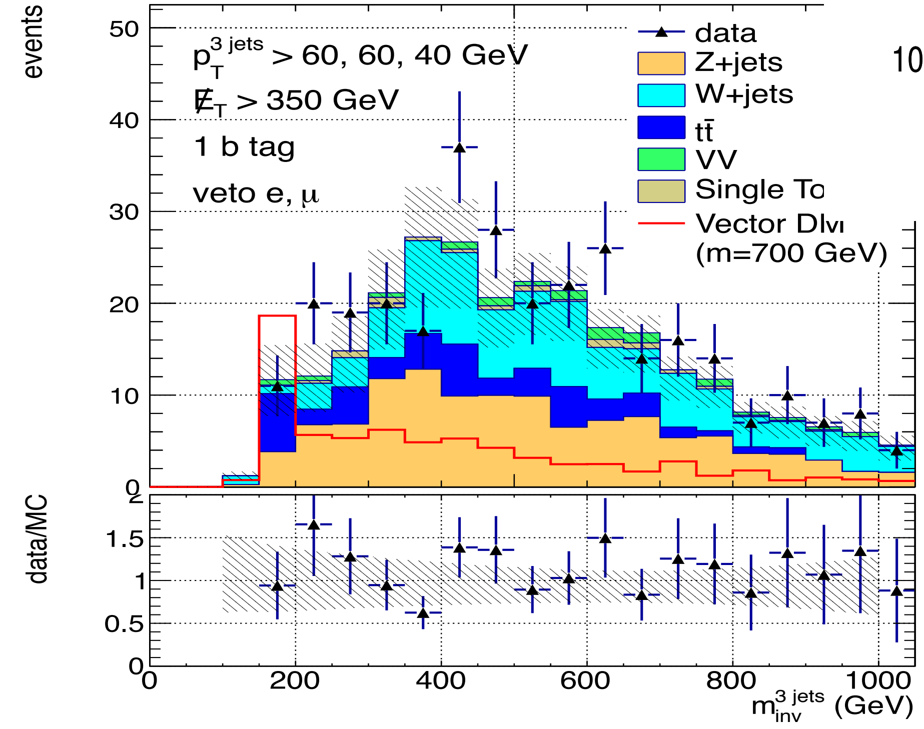
More rare objects than a jet could be radiated (i.e., less background)

Depending on the object, one could be sensitive to different models (e.g. DM coupling more to 3rd generation quarks, etc)

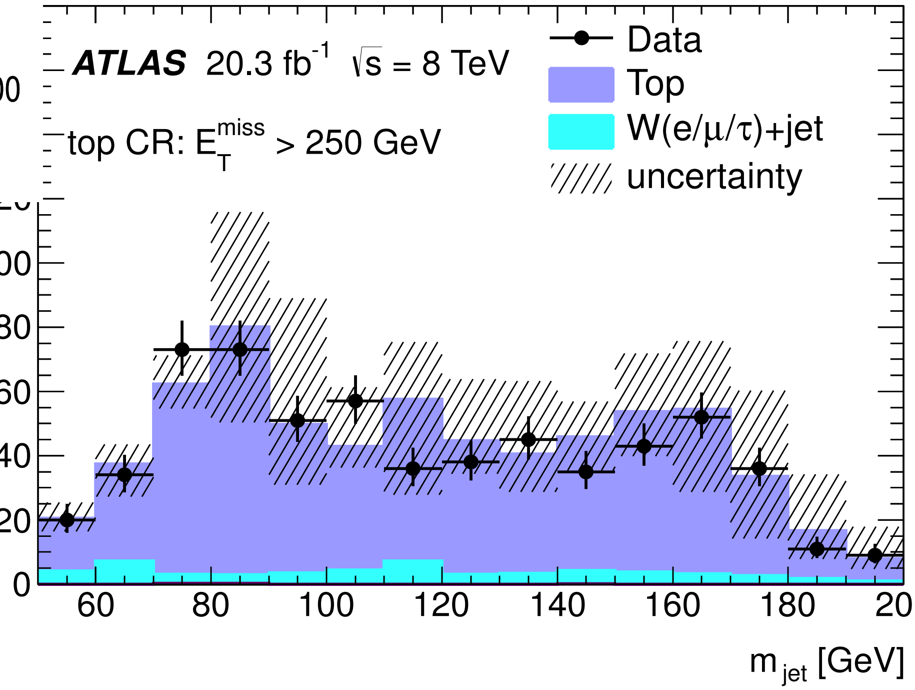
Monophoton



Monotop



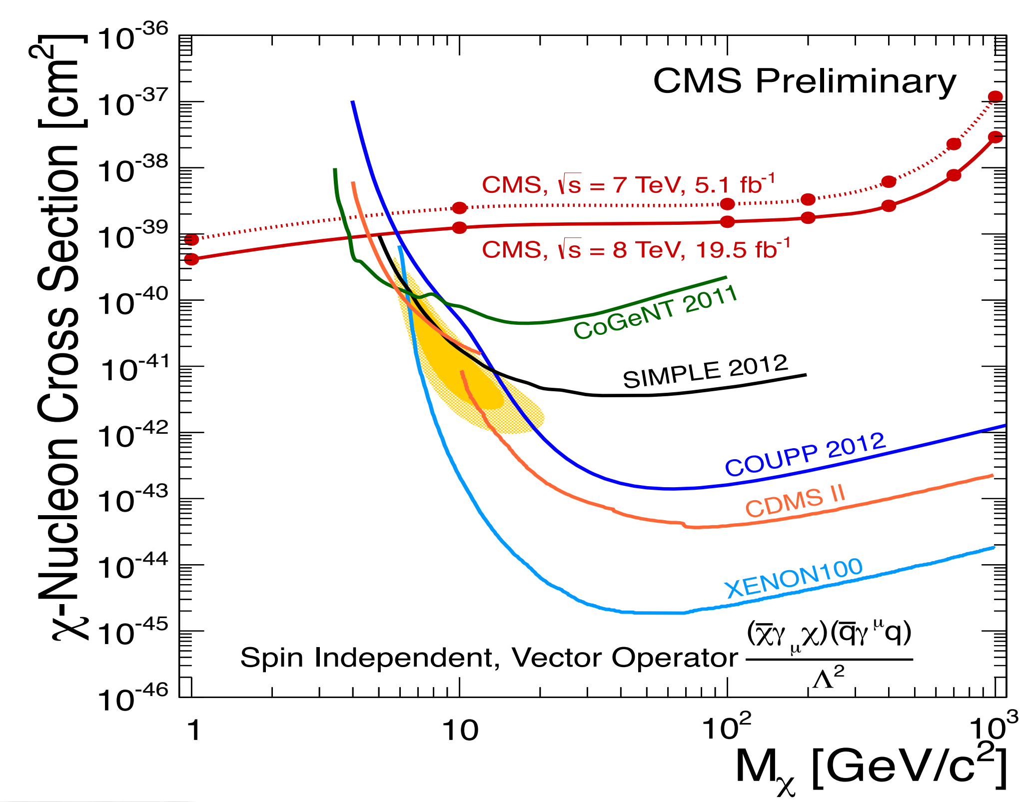
MonoZ/W

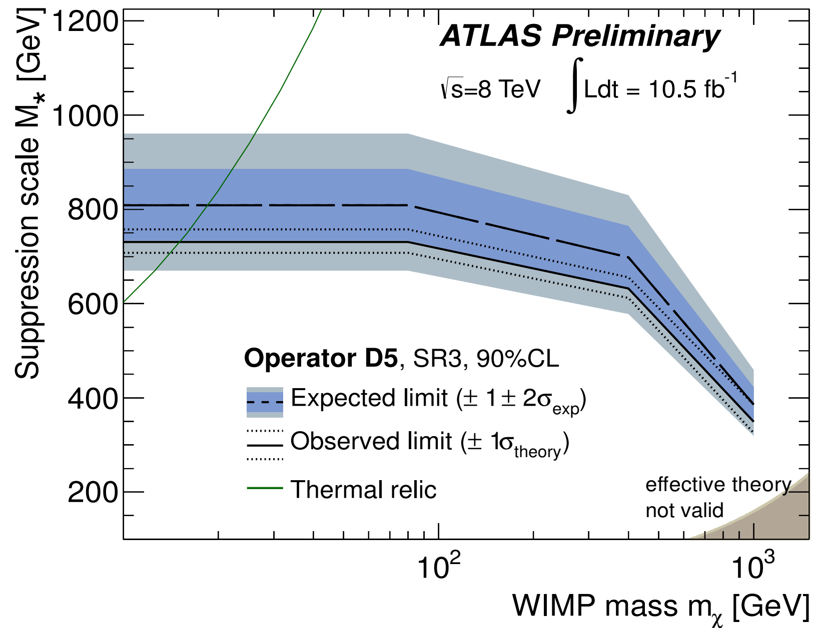


INTERPRETATION

Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

- So far, result interpreted in terms of EFT, integrating out some heavy mediator
- Different kinds of mediator imply different operators
- This allows to project our results on the same plane as the underground experiment…
- … but is an EFT with mediator masses < 1 TeV and collision energy 8 TeV reasonable?
- Work ongoing to adopt more specific models (e.g. SUSY simplified Models)

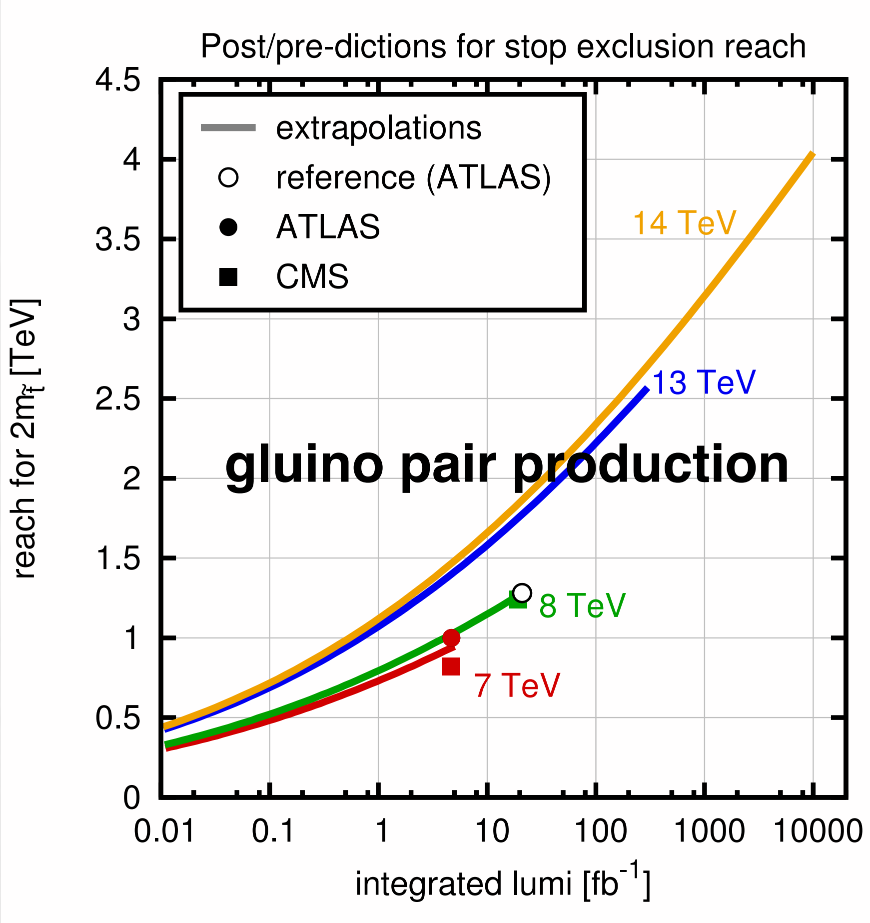


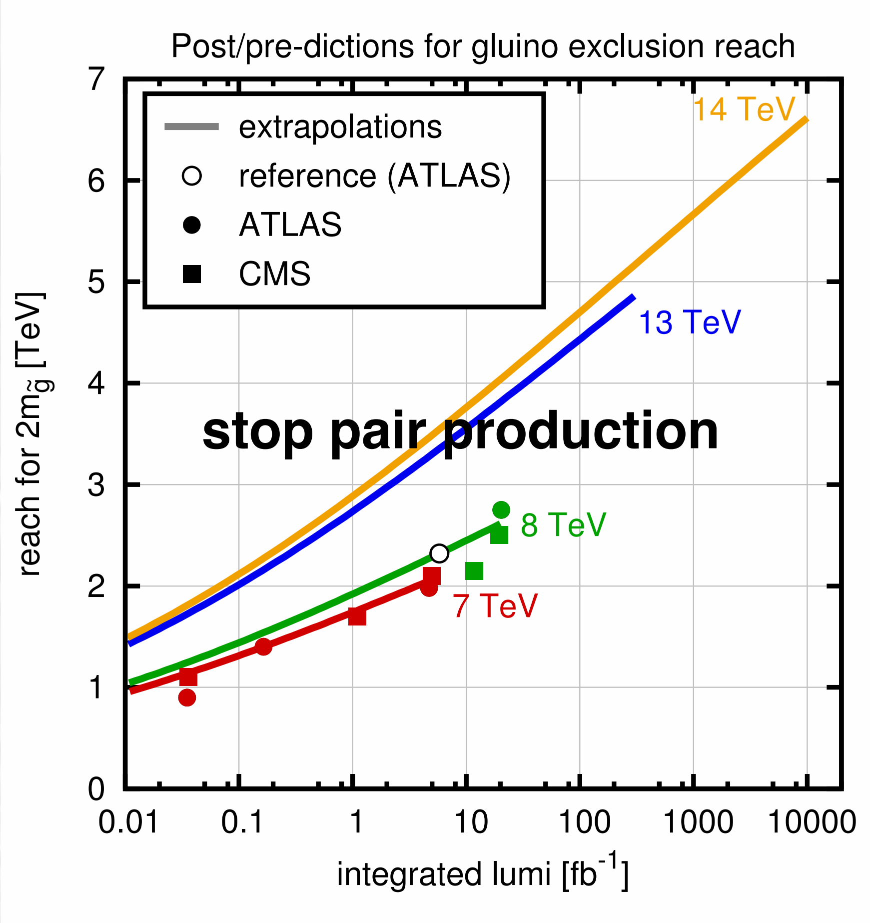


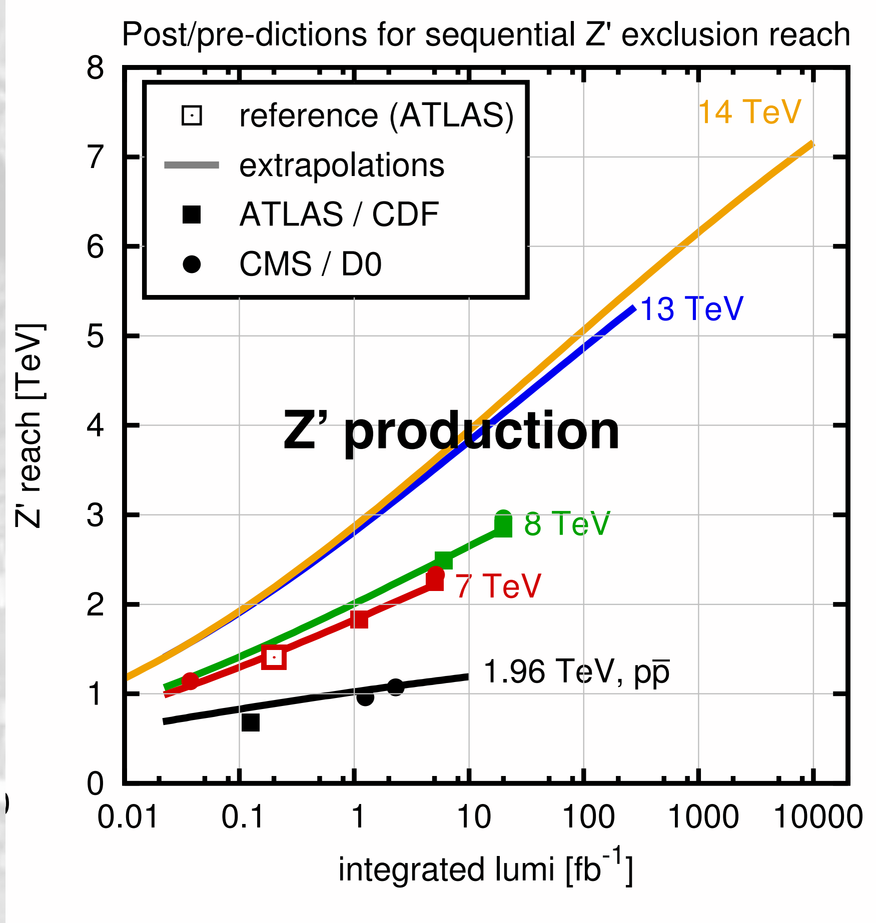
Perspectives for Run II

WHY GOING TO HIGHER ENERGY?

- Going higher in energy we gain faster than integrating more data



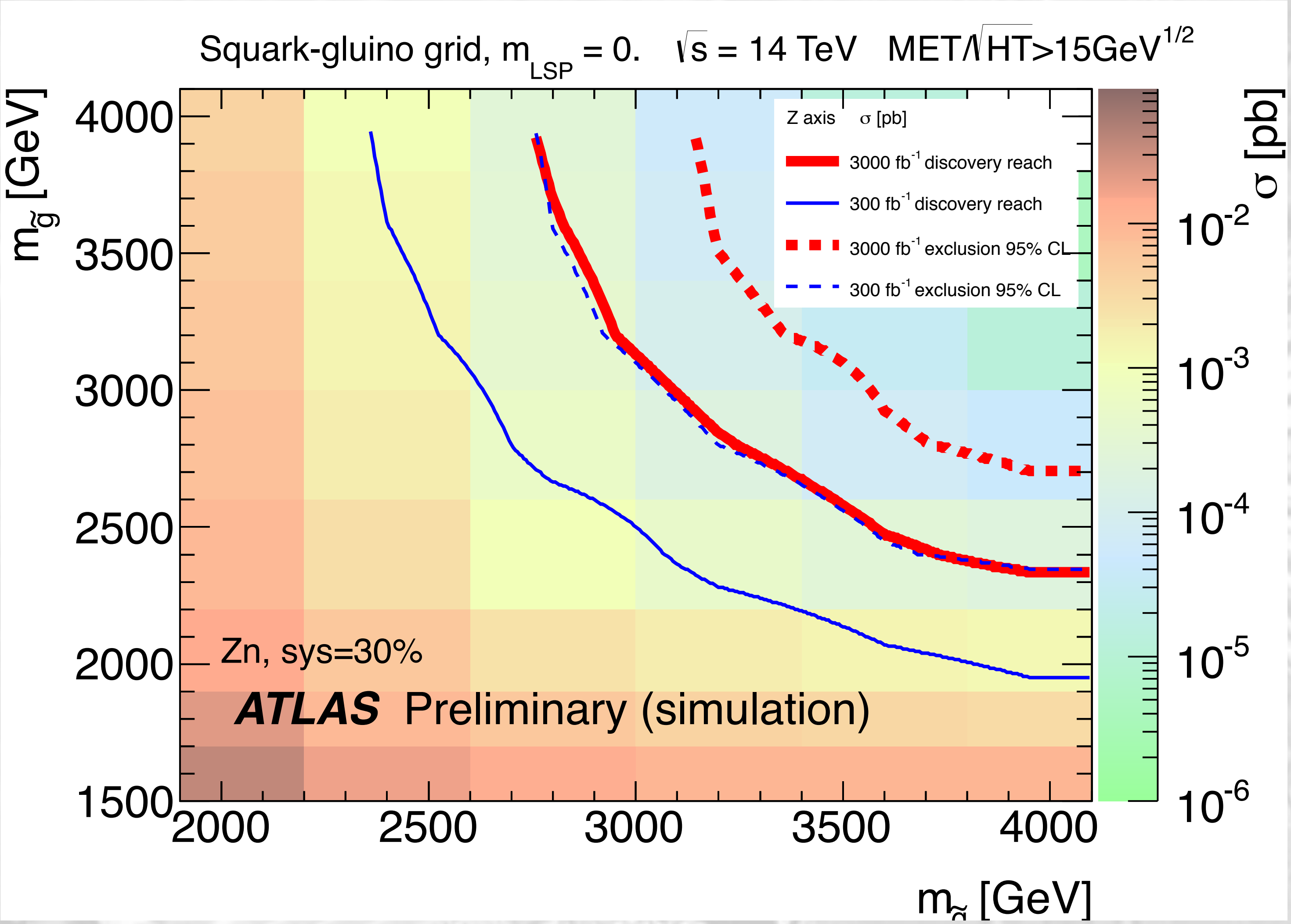


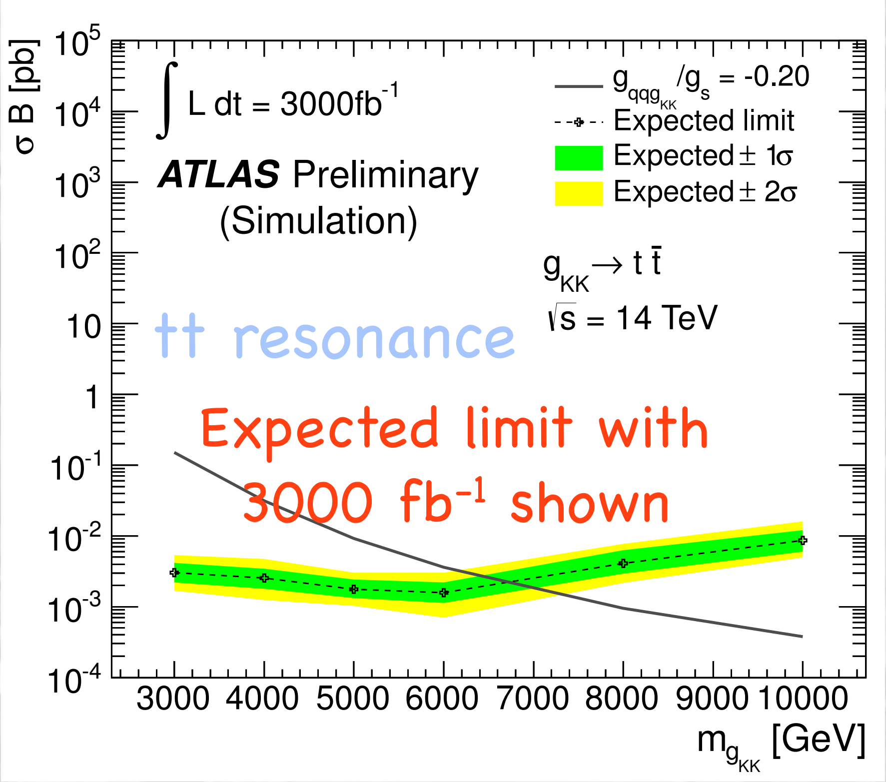


By G. Salam & A. Weiler (http://cern.ch/collider-reach/)

- As a thumb rule, increase energy by X is like increasing lumi by X2
- And there are things which could be just too heavy to be produce at low energy

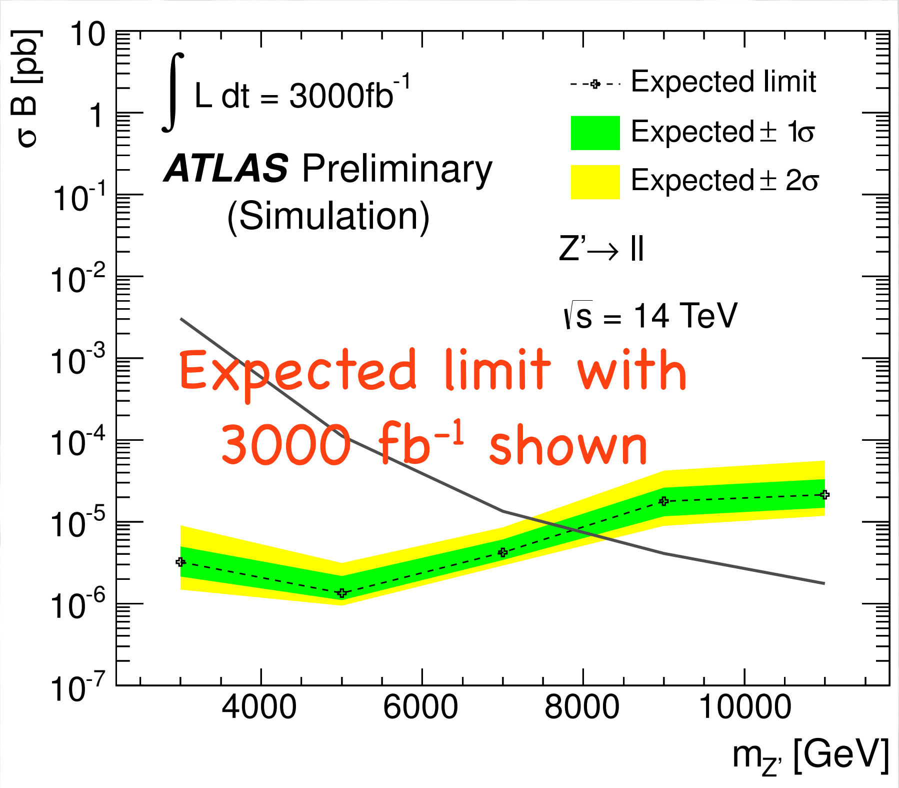
PERSPECTIVES FOR 13 TEV





tt resonance

Expected limit with 3000 fb^{-1} shown

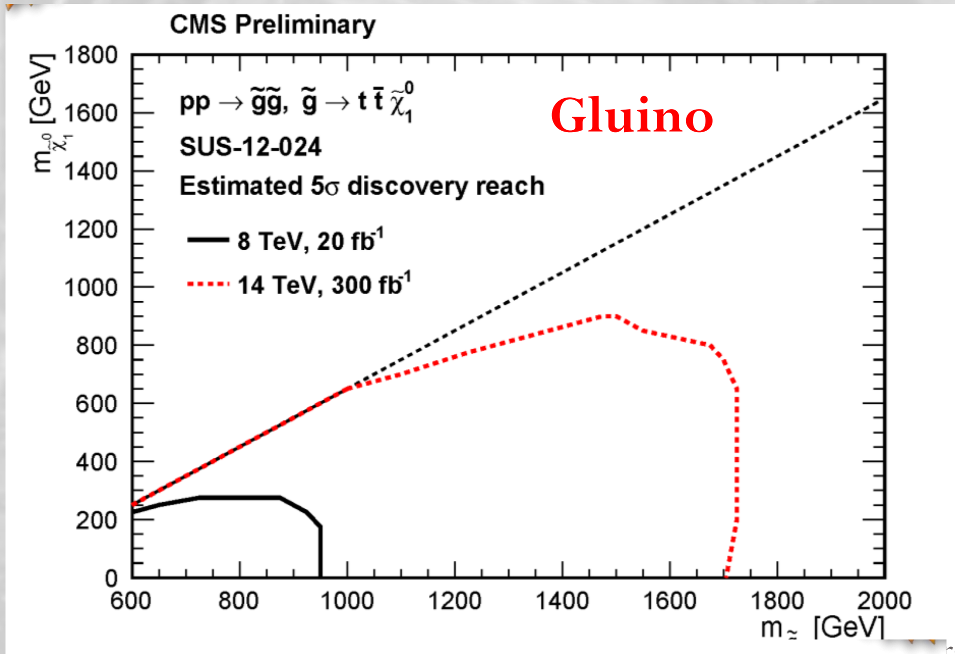


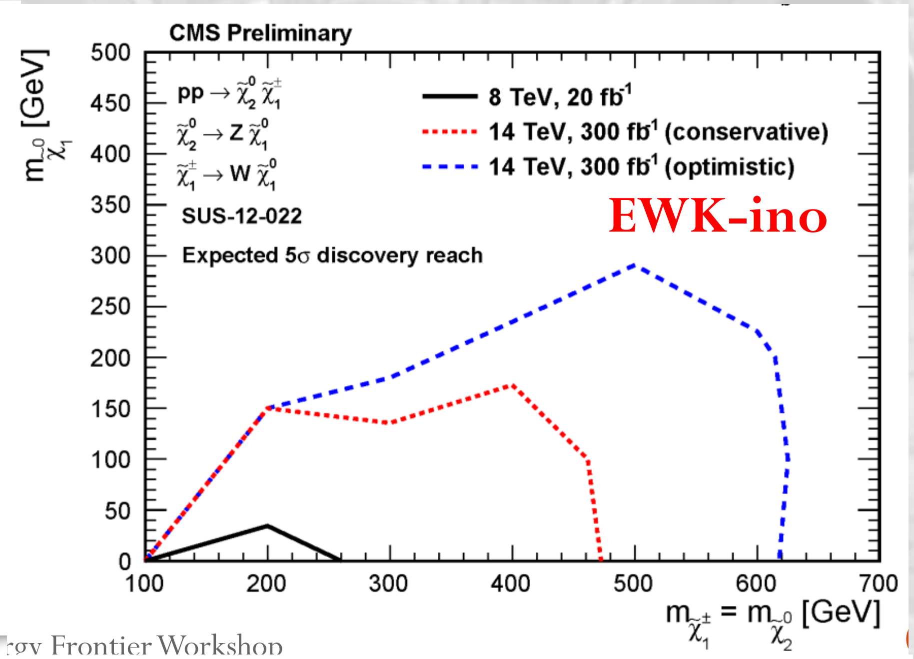
Expected limit with 3000 fb^{-1} shown

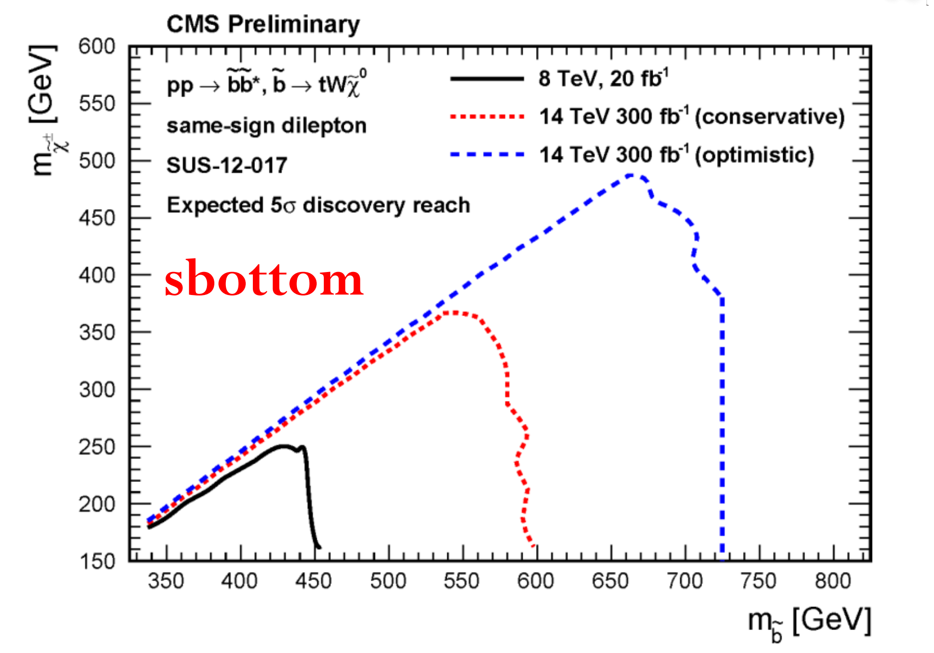
Similar extrapolations from CMS

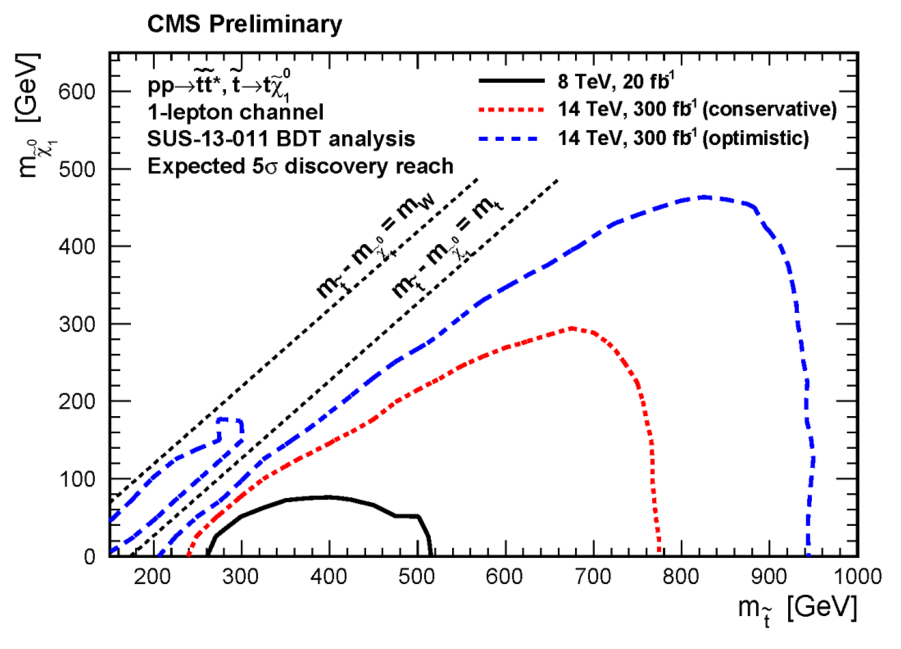
PERSPECTIVES FOR 13 TEV

- Extrapolated with pessimistic (same systematics as now) and optimistic (scale systematics with luminosity) models
- The true value should be in the middle
- 5σ discovery reach shown









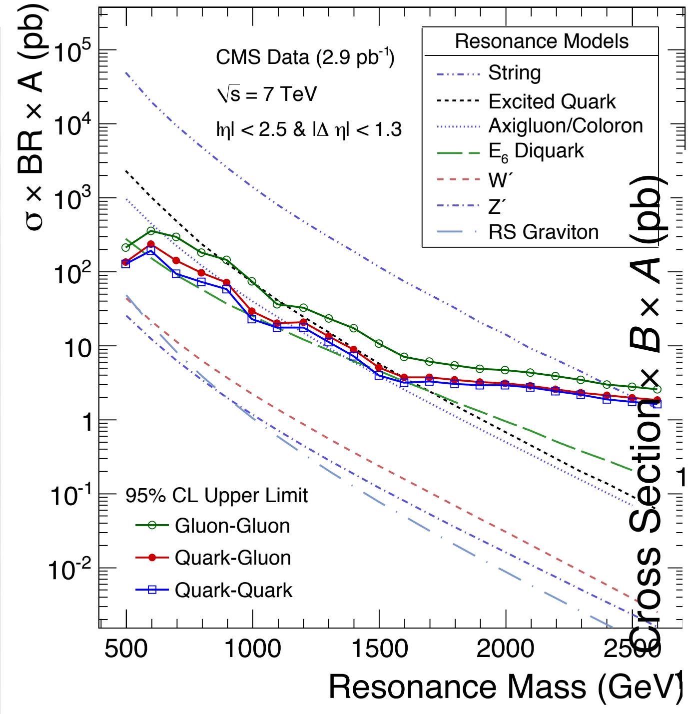
5σ discovery reach

- **Guino: up to 1.7TeV**
- **Sbottom: ~600 – 700 GeV**
- **EWK-ino: ~500 – 600 GeV**

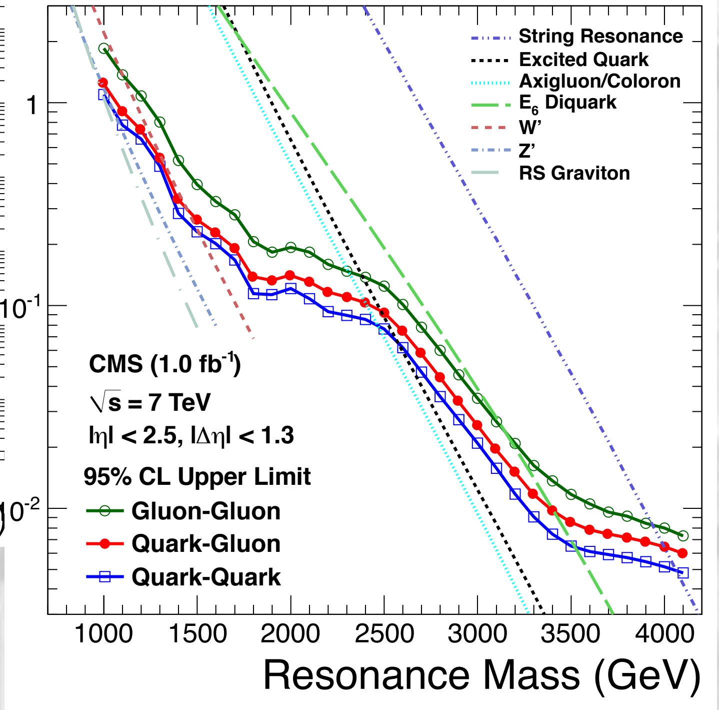
SIMILAR EXTRAPOLATIONS FROM ATLAS

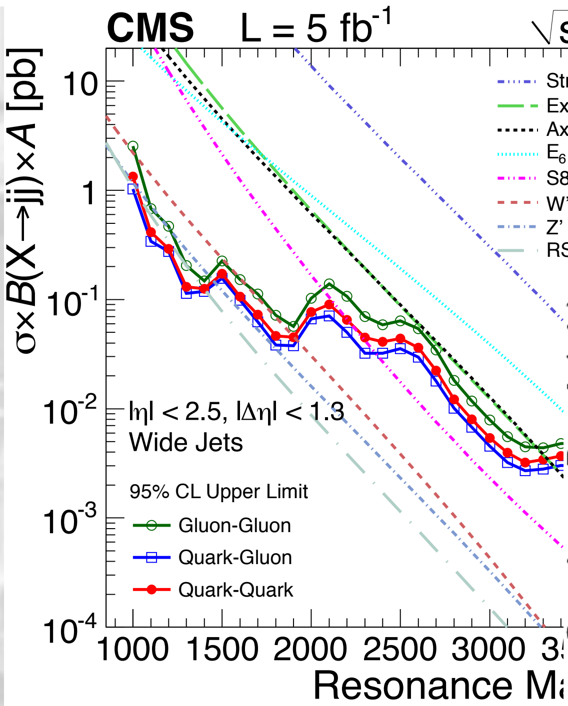
LOW MASS & SMALL XSEC

3pb⁻¹ 7TeV



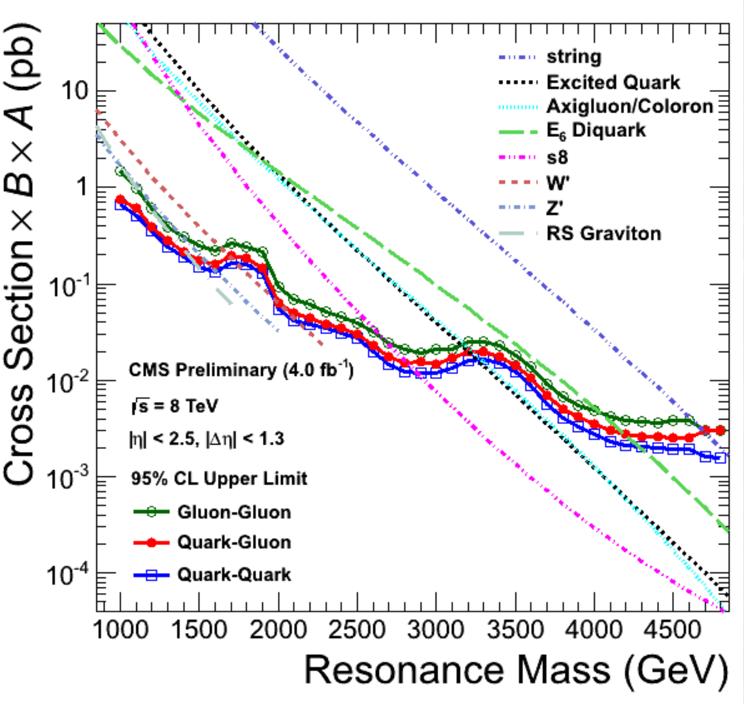
1 fb⁻¹ 7TeV





5 fb⁻¹ 7TeV

3 fb⁻¹ 8TeV

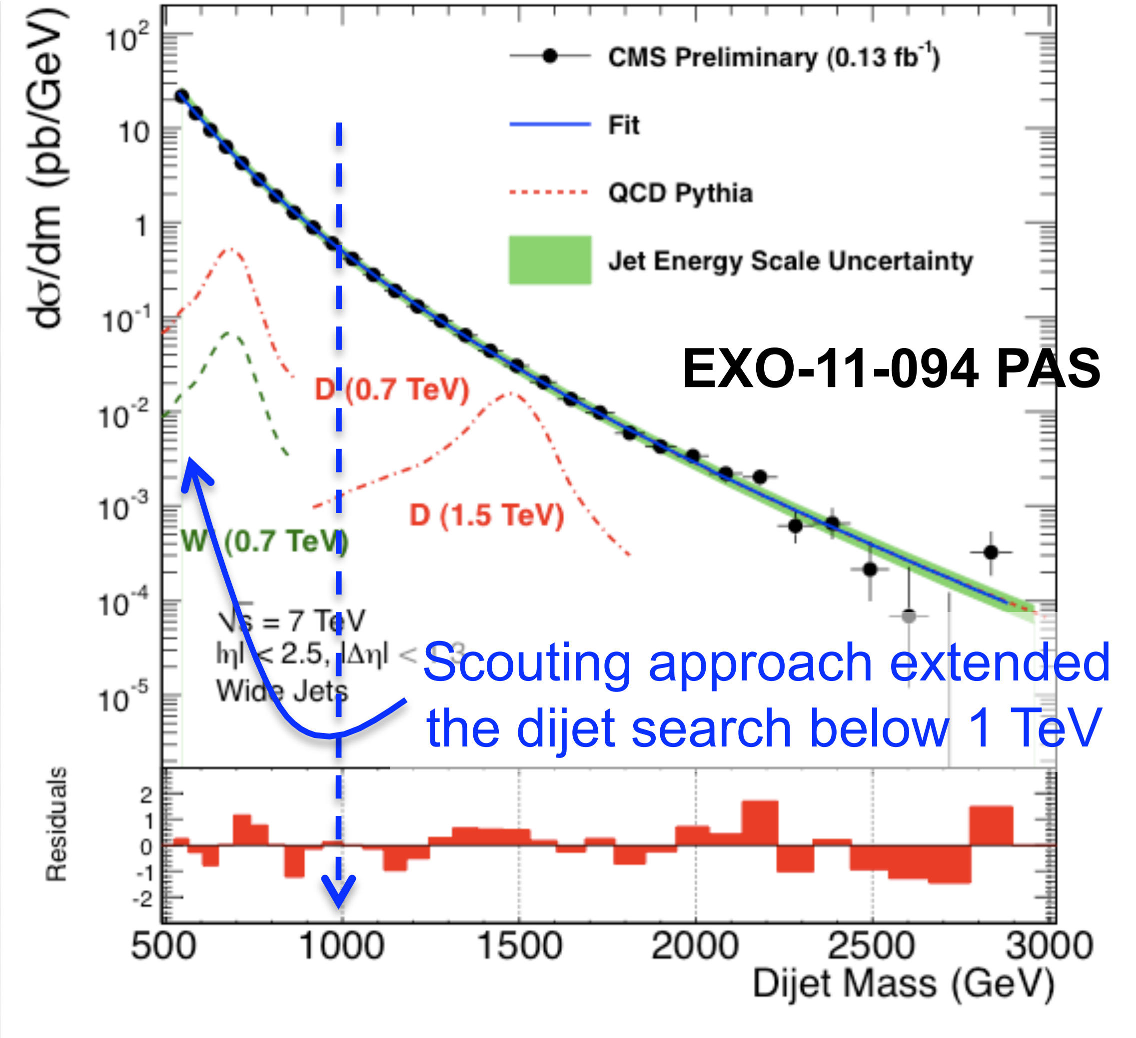


E [	L [	MINMASS [	σ MINMASS
7	0.003	400	~ 200
7	1	900	~ 1
7	5	1000	~ 1
8	3	1000	~ 0.6

- UNEXPLORED TERRITORY LEFT BEHIND WHEN THE LUMINOSITY INCREASED

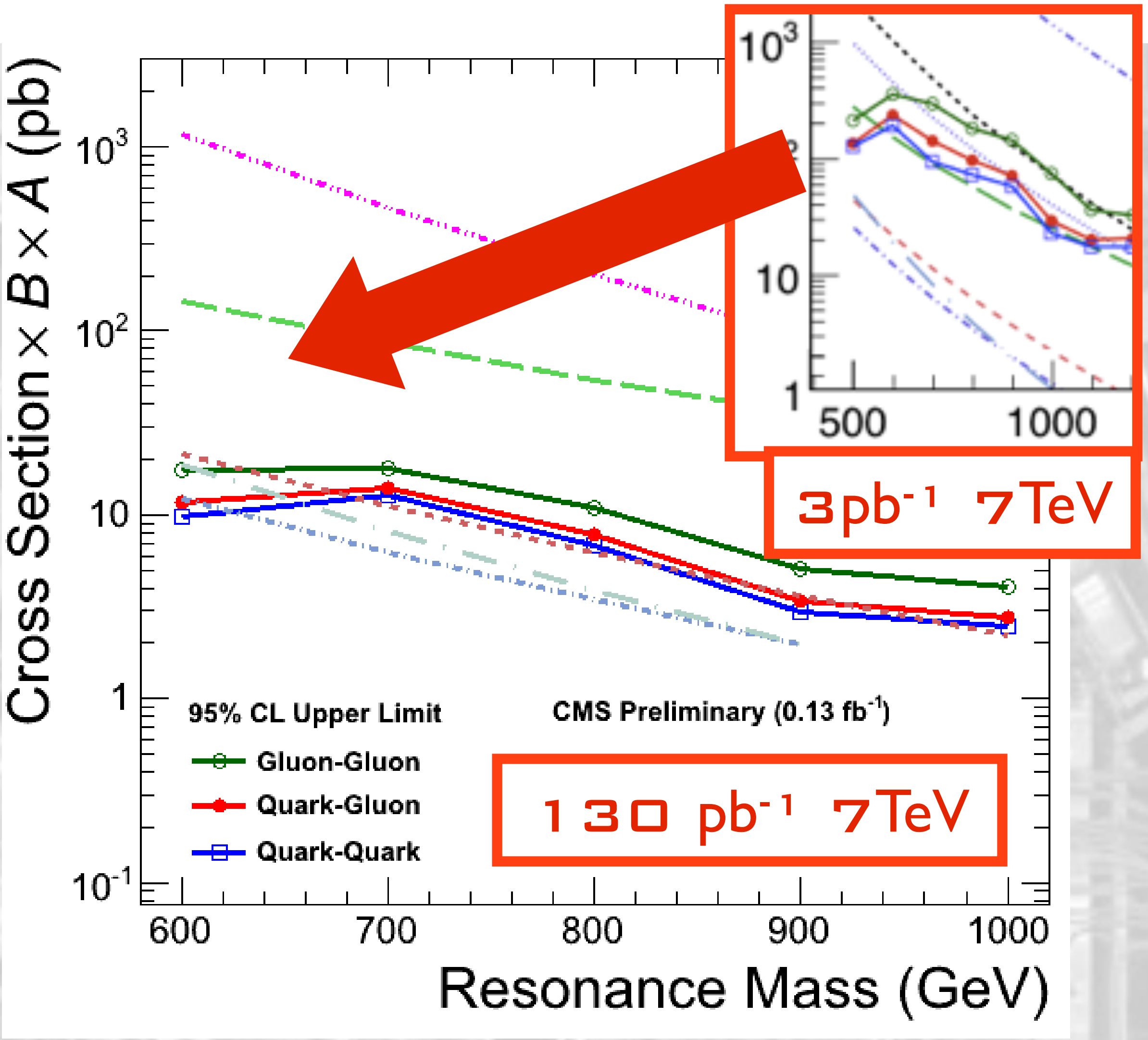
- TRIGGER IMPROVEMENTS COMPENSATED THE (SLOWER) RATE INCREASE AFTER

THE DIJET DATA SCOUTING



EXO-11-094 PAS

Scouting approach extended the dijet search below 1 TeV

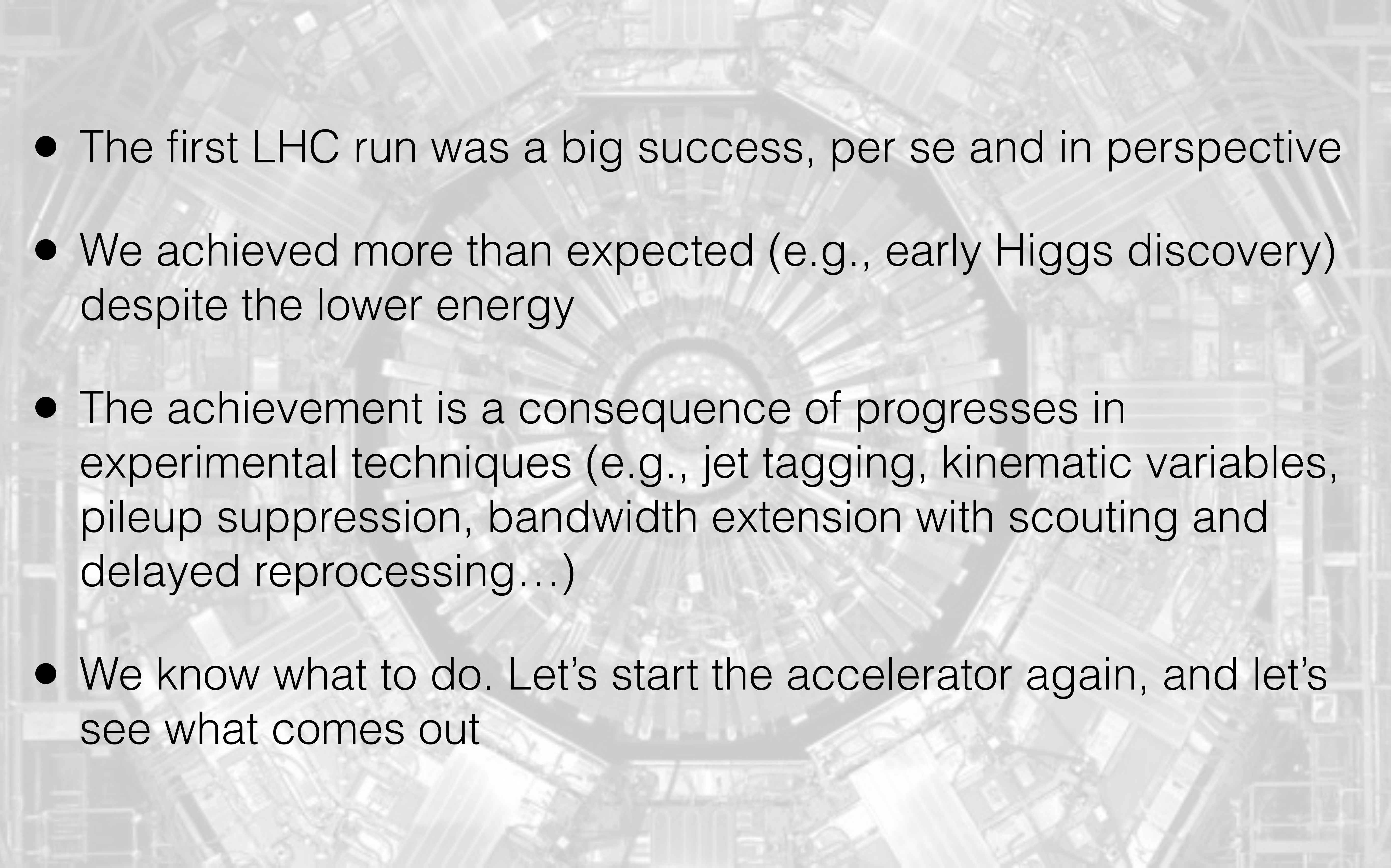


3pb^{-1} 7TeV

130 pb^{-1} 7TeV

- 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 first LHC run was a big success, per se and in perspective
- We achieved more than expected (e.g., early Higgs discovery) despite the lower energy
- The achievement is a consequence of progresses in experimental techniques (e.g., jet tagging, kinematic variables, pileup suppression, bandwidth extension with scouting and delayed reprocessing…)
- We know what to do. Let’s start the accelerator again, and let’s see what comes out