Search for Physics Beyond Standard Model at the LHC

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WHY BSM

Several open issues implying Physics beyond Standard Model. Some examples:

1. **Why only three families of leptons and quarks?**
2. **Why four fundamental interactions and not one?**
   - unification is impossible even at very large energies
3. **Why only 5% of matter made of ordinary SM particles?**
   - what is dark matter?
4. **Why most massive particle“only” 200 times heavier than p?**
   - desert above 170 GeV

why searches at LHC?

- *large energy, large luminosity*
- *creation of massive new particles*
- *pletora of different final states to be explored*

BSM @ LHC

SUSY

Minimal Dark Matter

Resonances

Extra Dim.

Top partners

W', Z'

ATLAS

ALICE

LHCb

CMS

Long-Lived, unconventional signatures

Extended Higgs Sector

BSM in B physics, in loops, etc…

BSM @ LHC

Hot

Minimal Dark Matter

Resonances

Extra Dim.

Classic

W', Z'

Future

Long-Lived, unconventional signatures

ATLAS

CMS

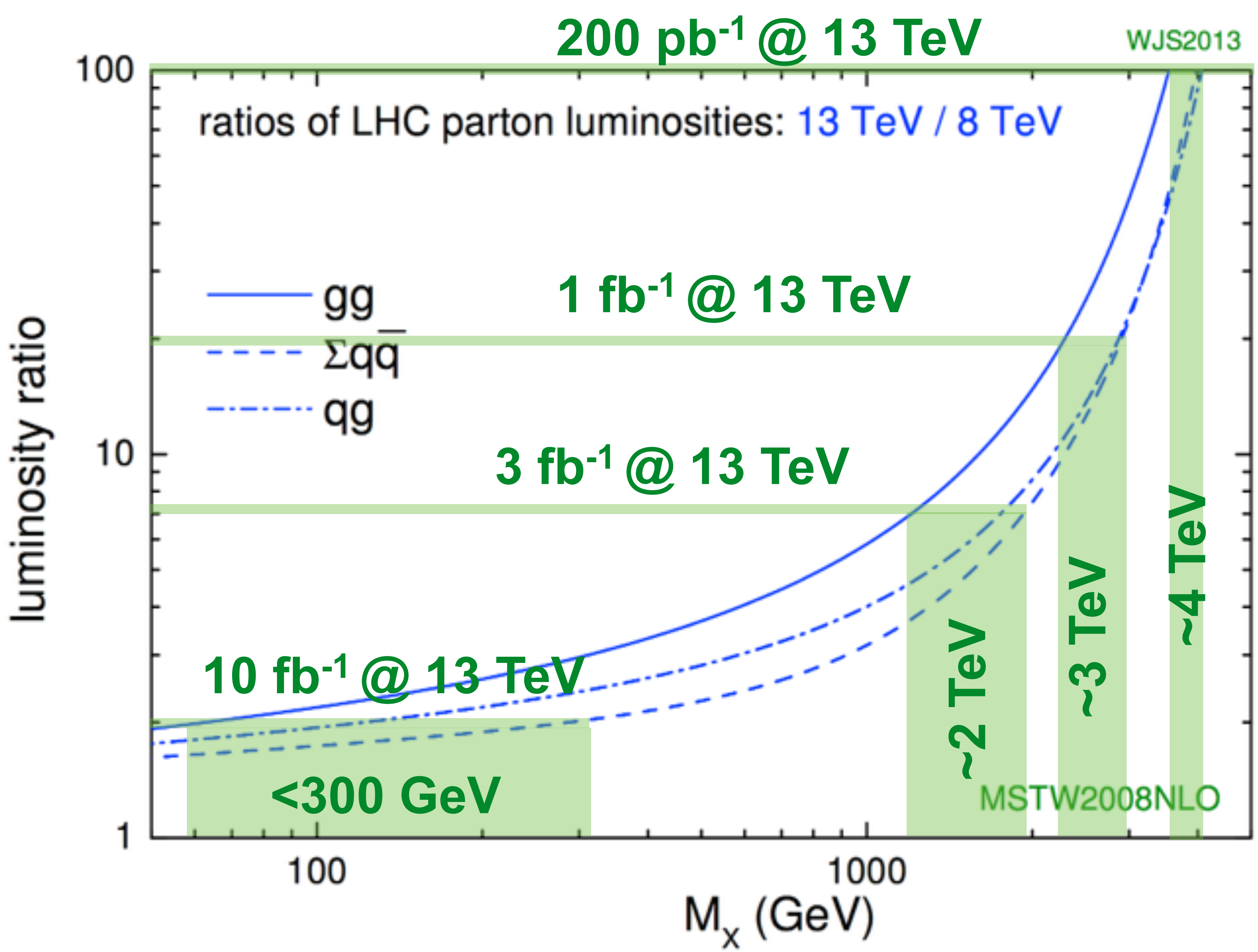
my choice

Last Summer Crucial for LHC

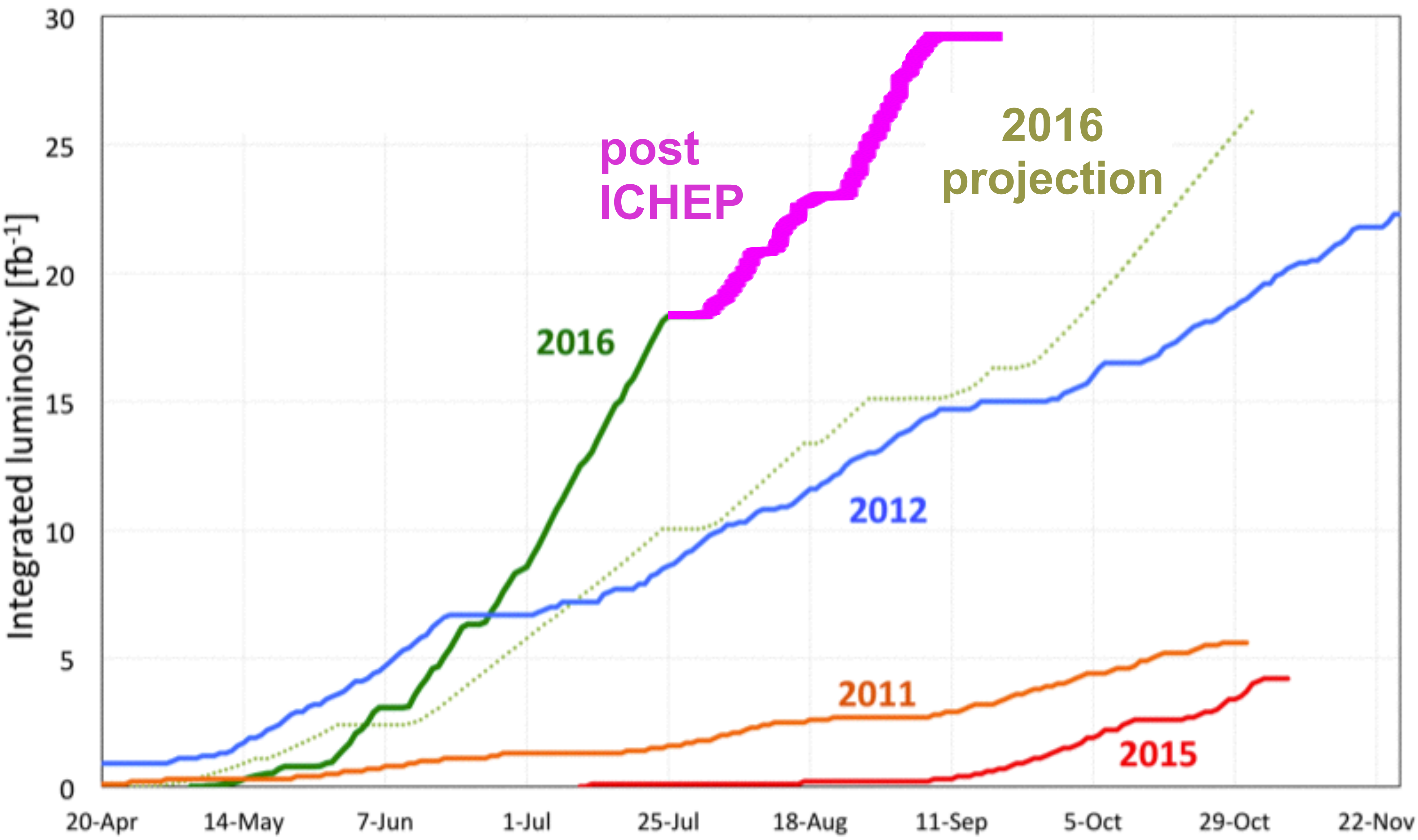
- **Center of mass increase**
  - 13 TeV (run2) vs 8 TeV (run1)
- **Luminosity increase**
  - improved LHC performance
  - reached 10^{34} cm^{-2} s^{-1}
  - > 2 fb^{-1} per week
  - ~15 fb^{-1} @ 13 TeV collected for Summer conferences (July)
    - to be compared with 20 fb^{-1} collected @ 8 TeV
- **Impressive number of new BSM results (non-SUSY) @ ICHEP**
  - **CMS**: **28**(22+6) results
  - **ATLAS**: **18** results

Importance of Energy Increase

- **For high mass searches parton luminosity counts!**
  - **Huge ratio in the interesting (not yet excluded) region**
- **End of 2016 (~40fb^{-1}) enough to supersede all 8 TeV results**

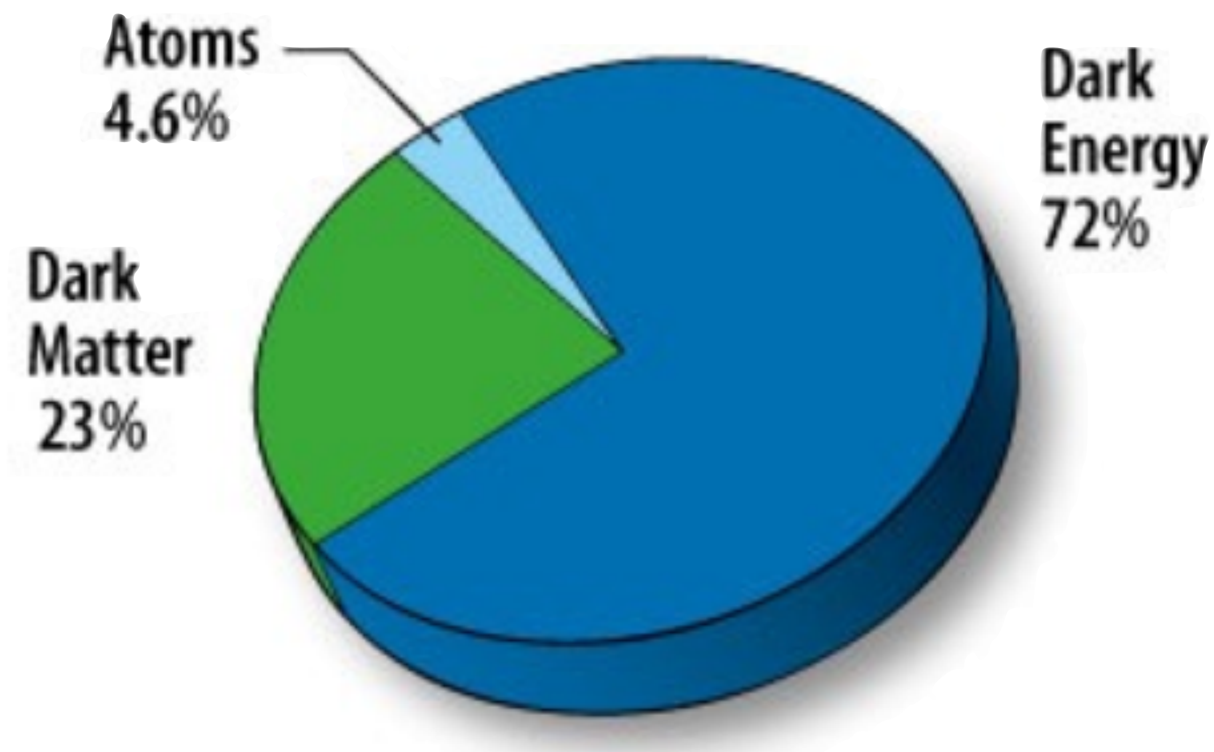


INCREASE IN LUMINOSITY



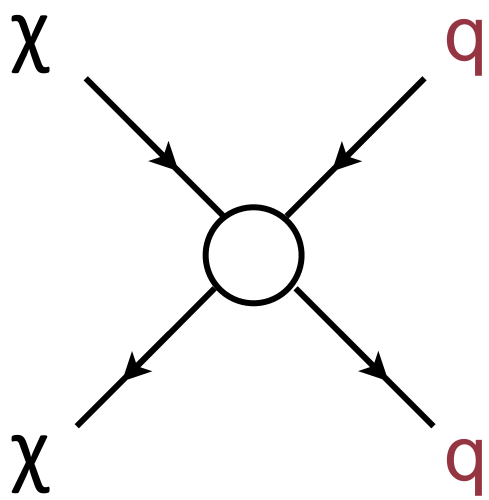
Dark Matter

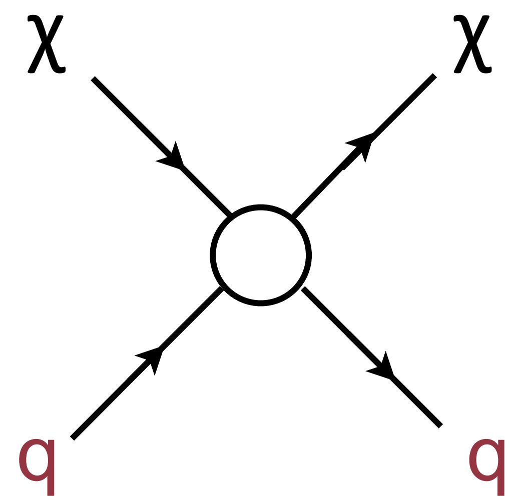
- **Properties**
  - stable
  - no electric or color charge
  - very weak interaction with Standard Model particles
  - subject to gravity interaction

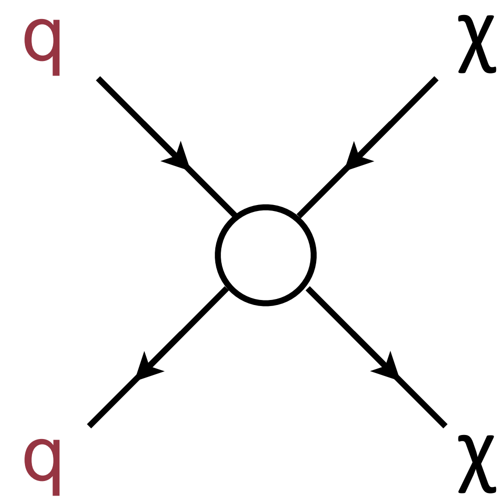


- **Several potential candidates fulfilling these requirements for dark matter**
  - Dark: weakly interacting with electromagnetic radiation
  - Hot & dark: ultra-relativistic velocities
    - neutrinos
  - Warm & dark: very high velocity
    - sterile neutrinos, gravitinos
  - Cold & dark: moving slowly
    - Lightest SUSY particle (neutralino, gravitino as LSP)

Dark Matter Interaction



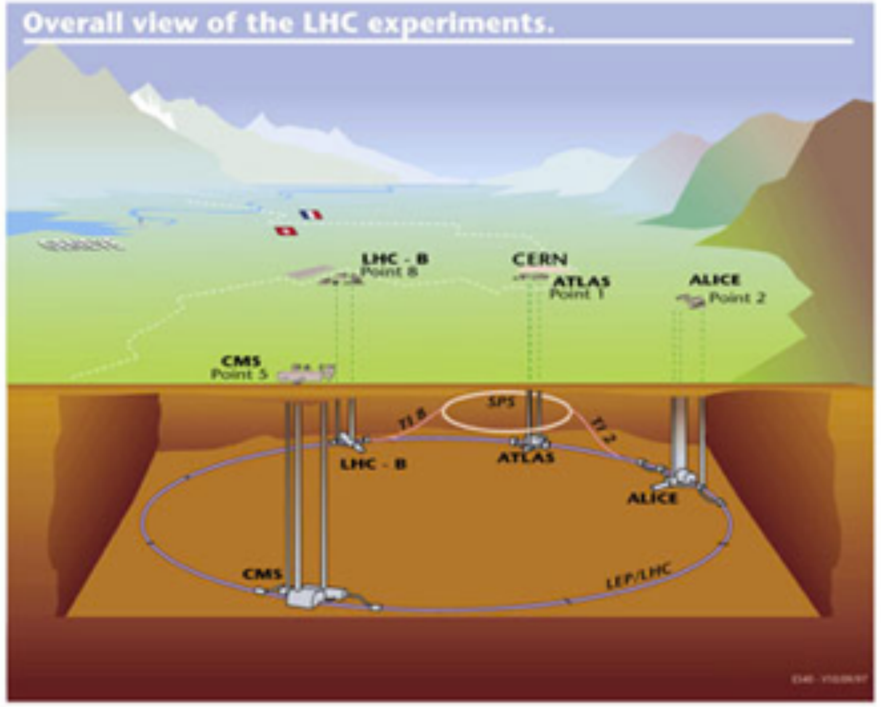




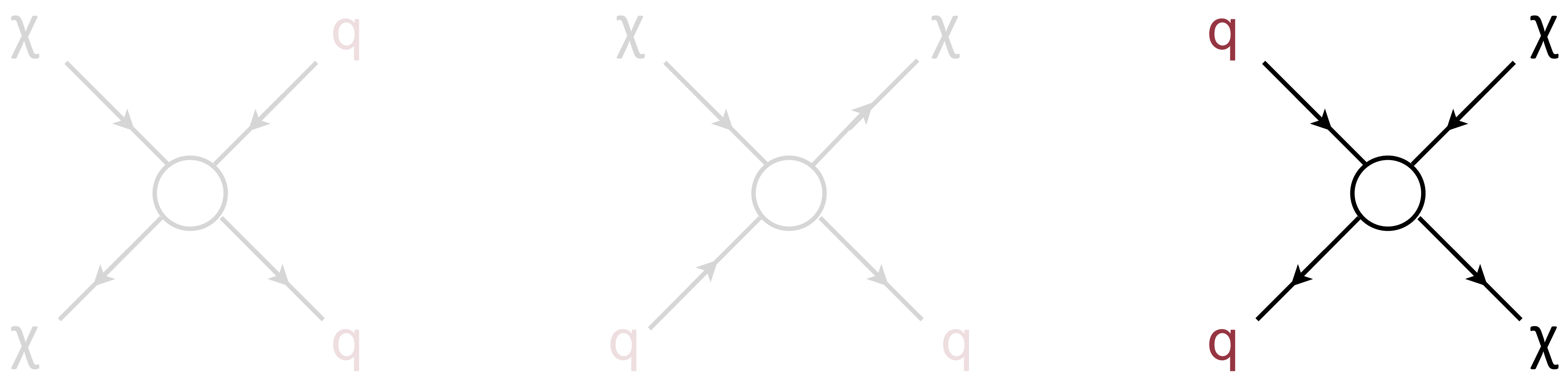
Indirect Detection

Direct Detection

Production at Colliders



DARK MATTER INTERACTION

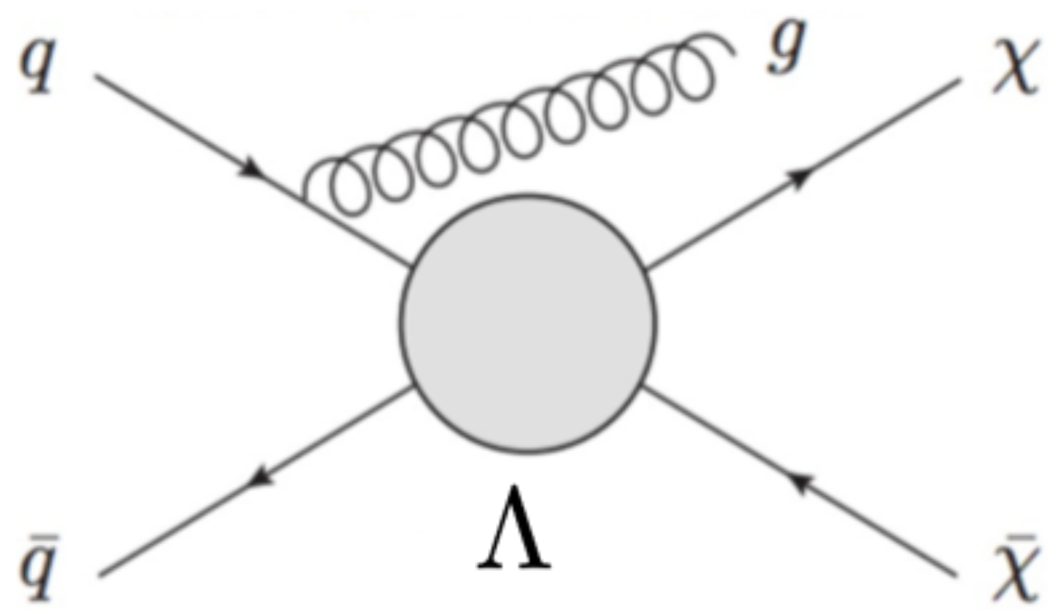


Indirect Detection *Direct Detection* *Production at Colliders*

- **Pair production at LHC**
  - DM candidates escape the detector (weekly interacting
    - large missing energy
  - need to identify ("tag") events of interest with some extra object
    - otherwise you see nothing in the detector

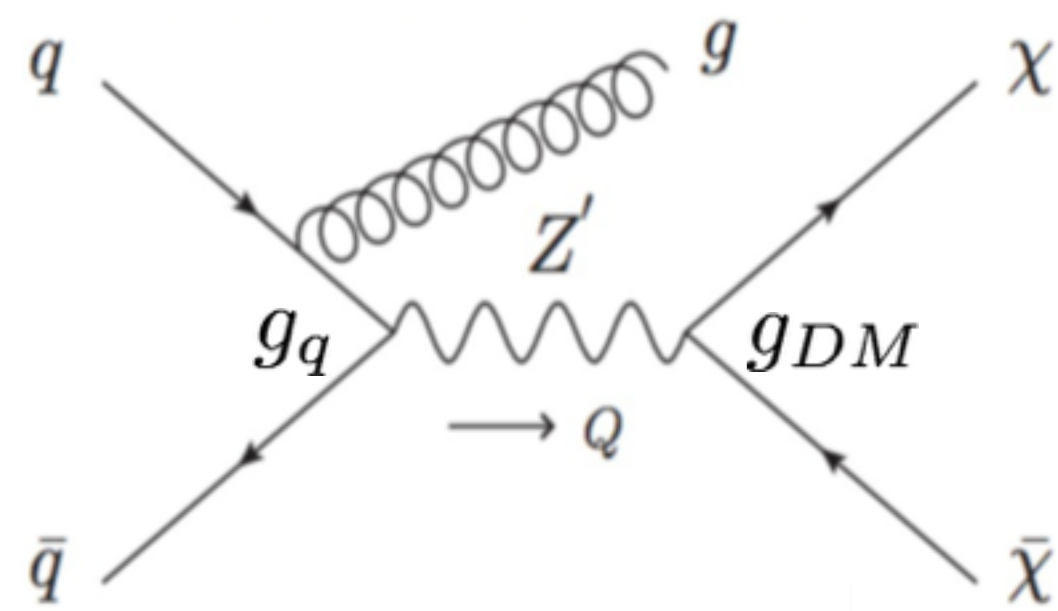
Modeling DM Candidate Interactions

Effective field theory



$$\sigma = \frac{K}{\Lambda^4}$$

Simplified model



$$\sigma = K' \frac{g_q^2 g_{DM}^2}{M^4 \Gamma_{med}}$$

$g_q =$ coupling to SM

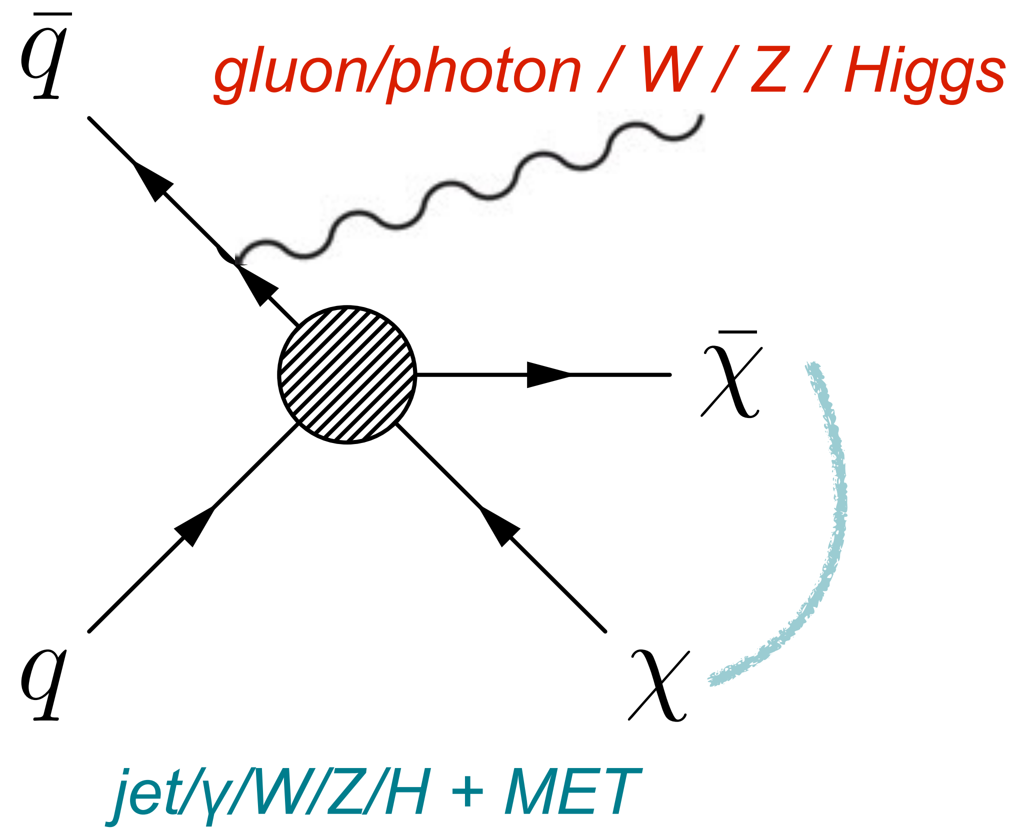
$g_{DM} =$ coupling to DM

$M =$ mediator mass

$\Gamma_{med} =$ mediator width

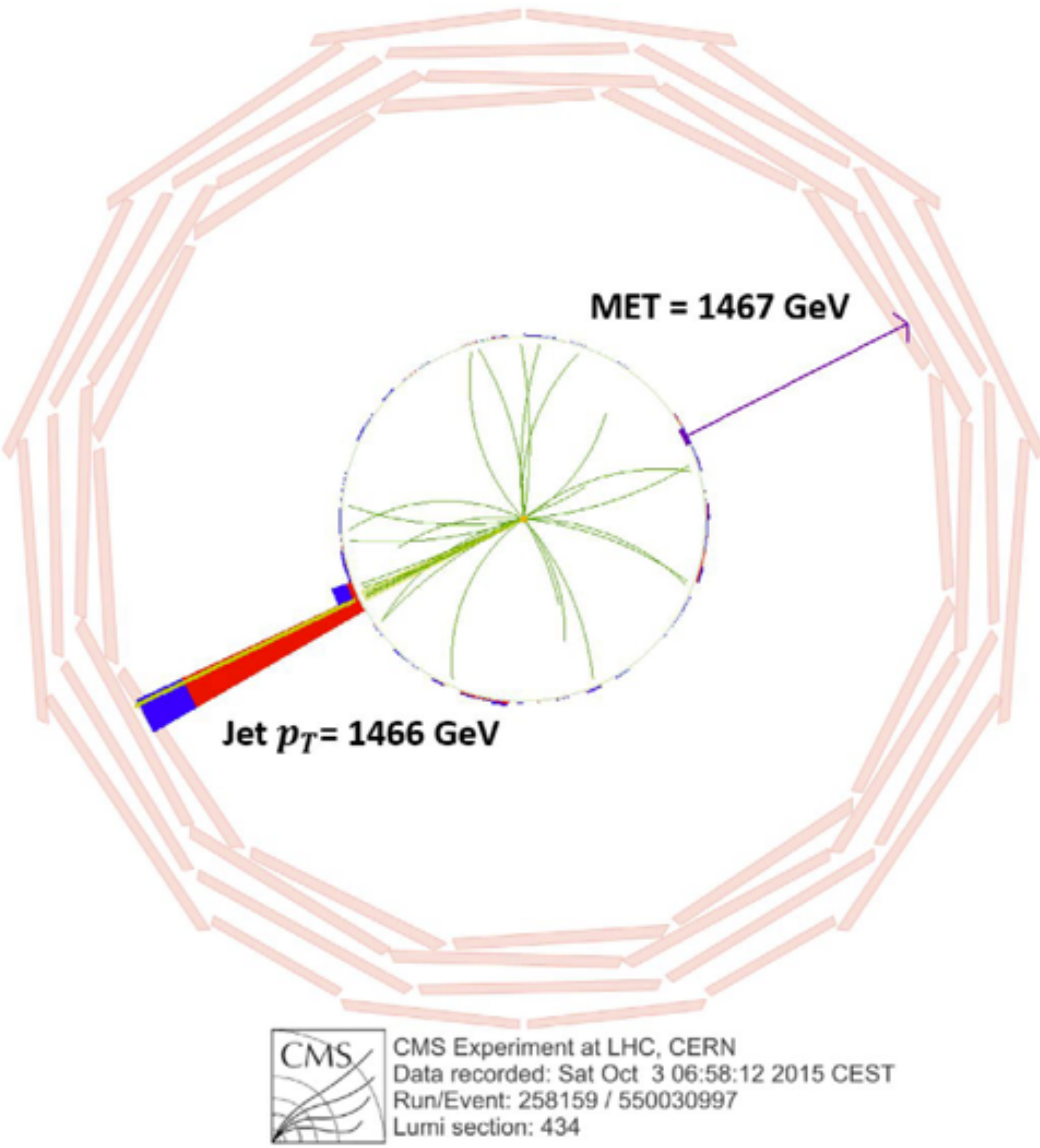
DARK MATTER SEARCH AT LHC

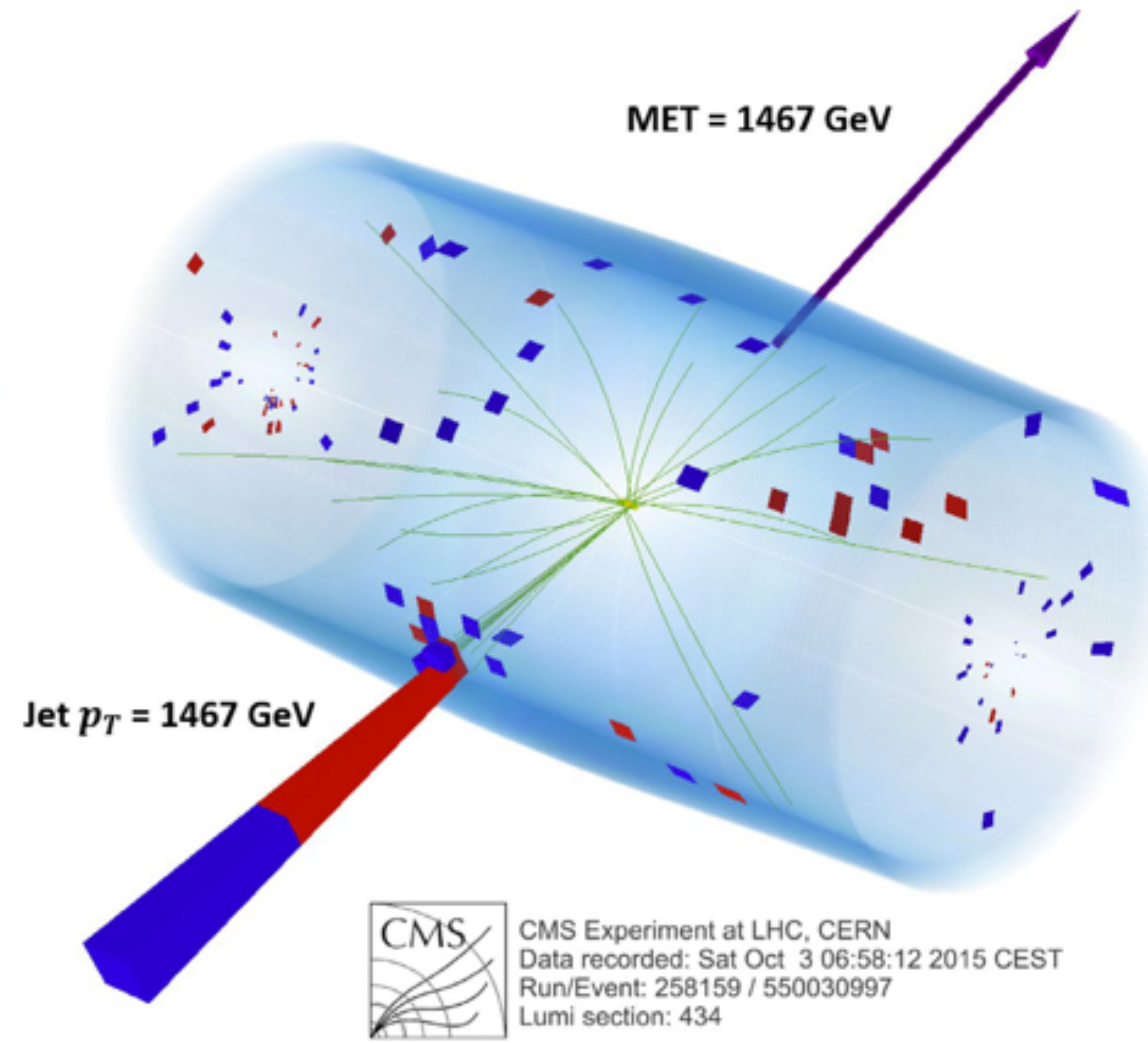
- **EW bosons and gluons** **can be** **radiated by initial partons**
- **Presence of high energy photon/W/Z/Higgs or jet(s)** ***in addition*** **to large missing transverse energy**
- **Gluon radiation at higher rate than EW bosons**
  - strong interaction vs. electromagnetic



- **mono-jet**
  - **strongest constraints**
- **mono-photon**
  - **more challenging for background estimation**
  - **less powerful: EW vs. strong interaction**
- **mono-W/Z leptonic**
  - **clean signature and simple trigger**
  - **penalized by W/Z branching fraction**
- **mono-W/Z hadronic**
  - **larger statistics with larger background**
- **tt+MET/bb+MET and mono-top**
  - **more complicated experimentally**
  - **powerful in some scenarios**
- **mono-Higgs**

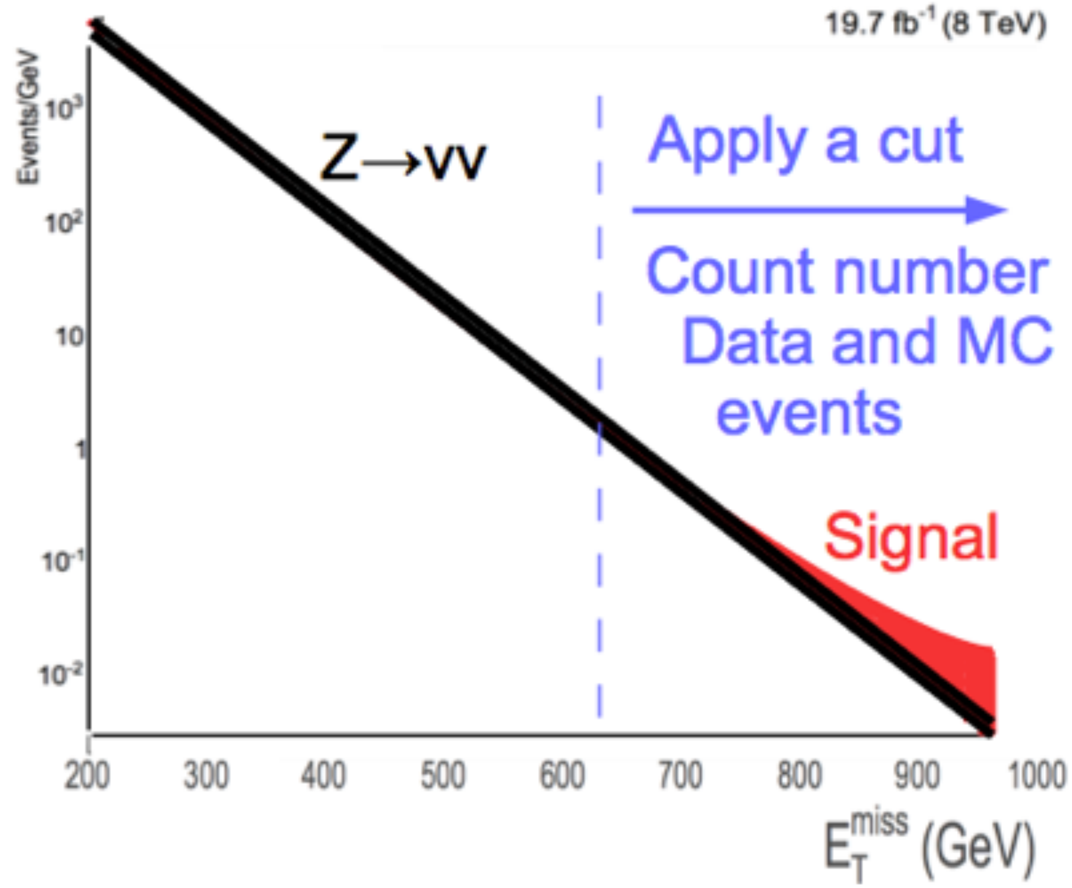
DM CANDIDATE



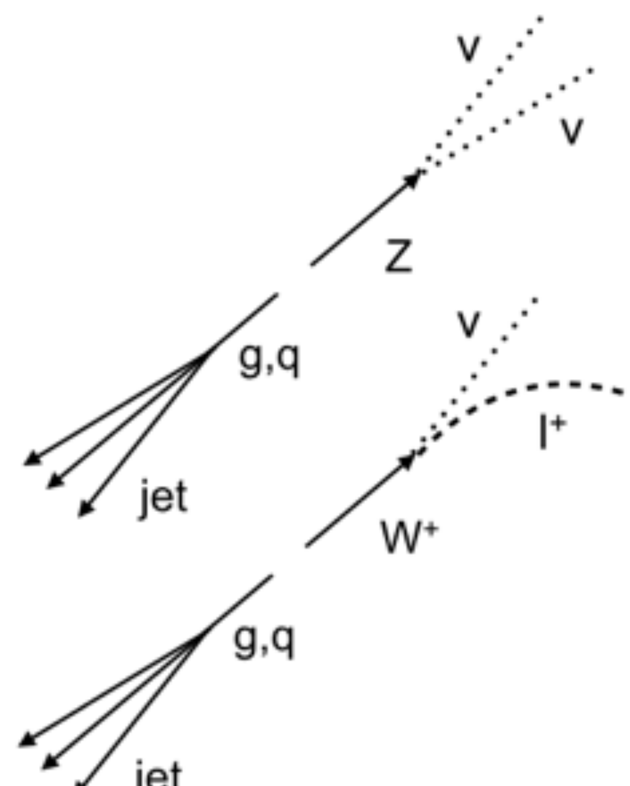


DM @ LHC: Analysis Strategy

- **Restrict to high MET region** to reduce impact of background
- **Count events after bkg subtraction**

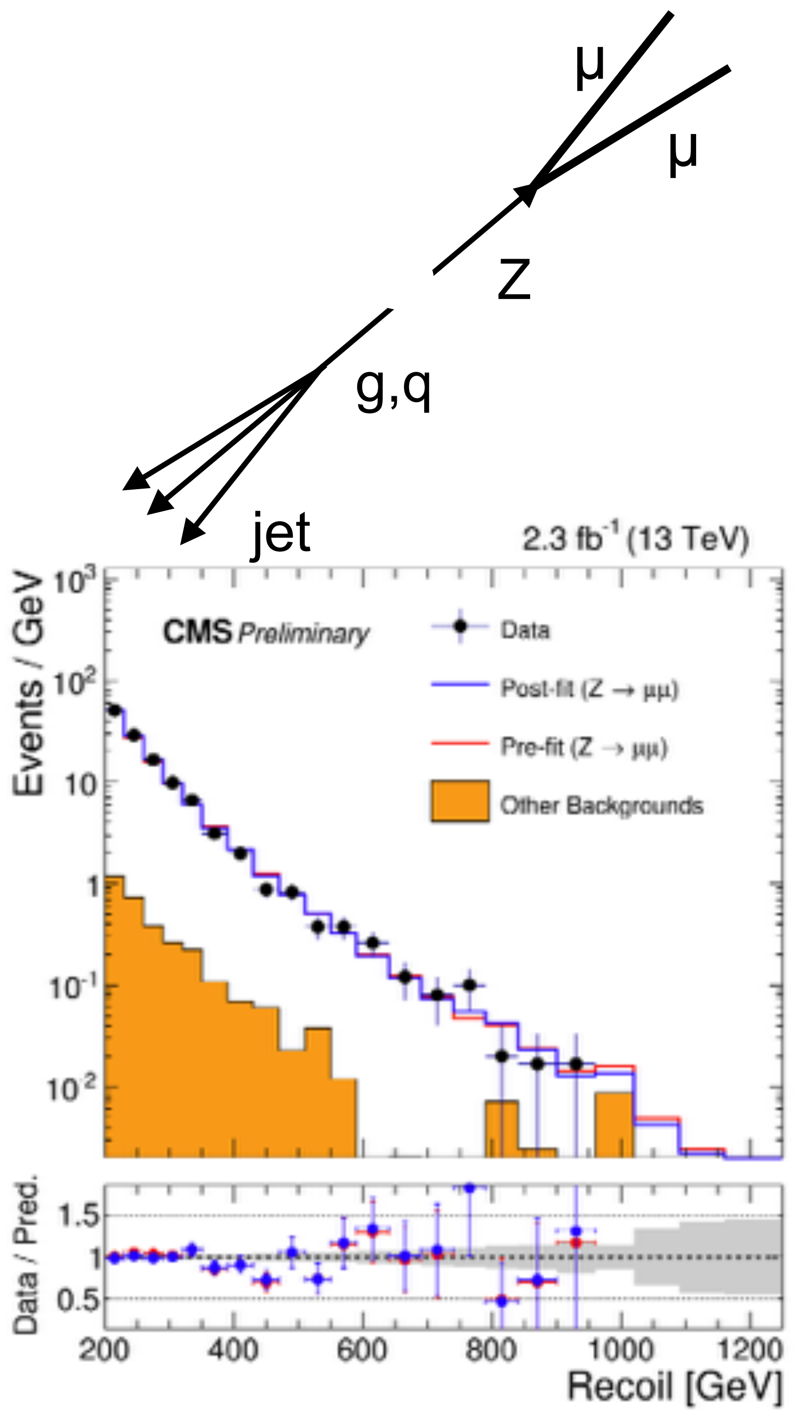


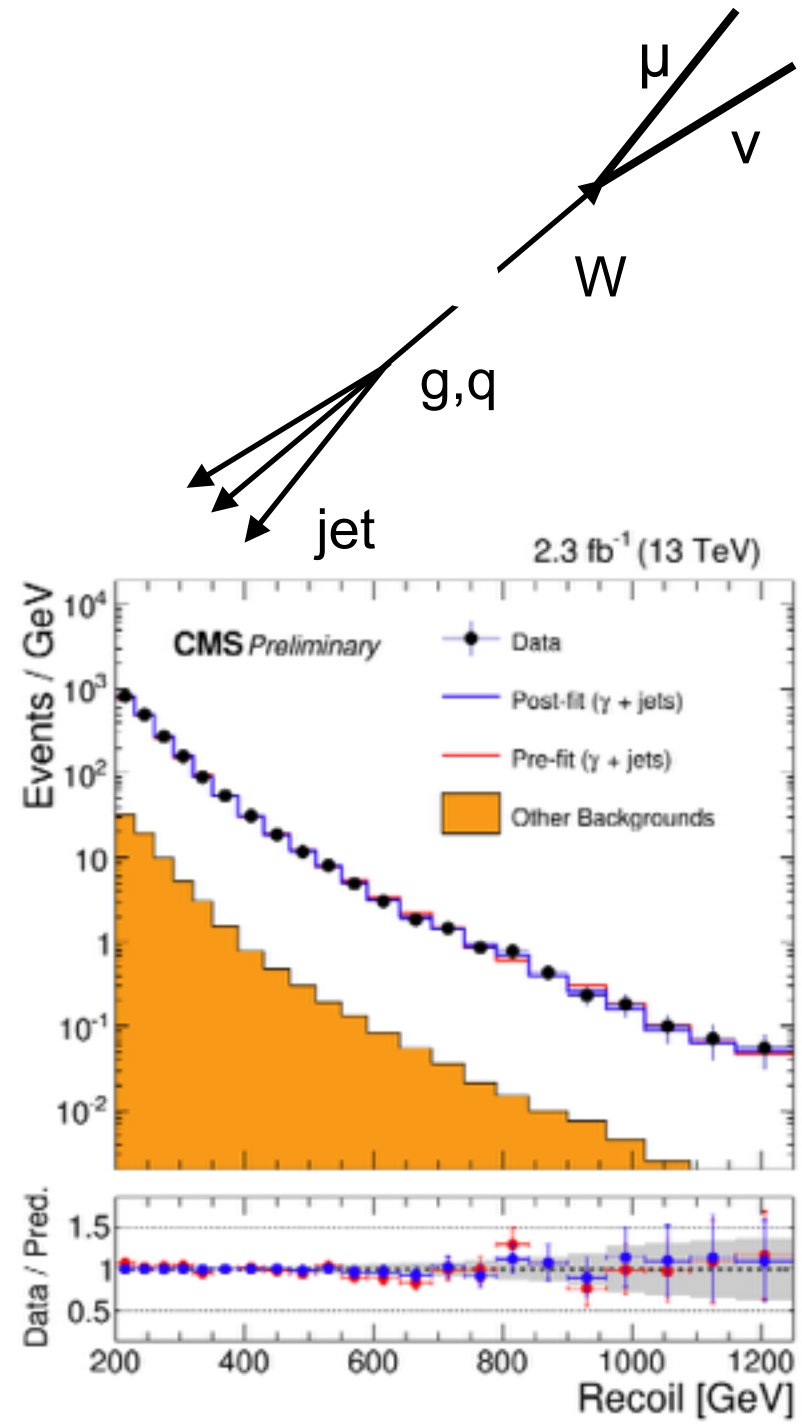
- **Background modeling very important**
- **Main contributions (monojet example)**
  - **Z(νν)+jet**
  - **W(lν)+jet**, where charged lepton is not reconstructed

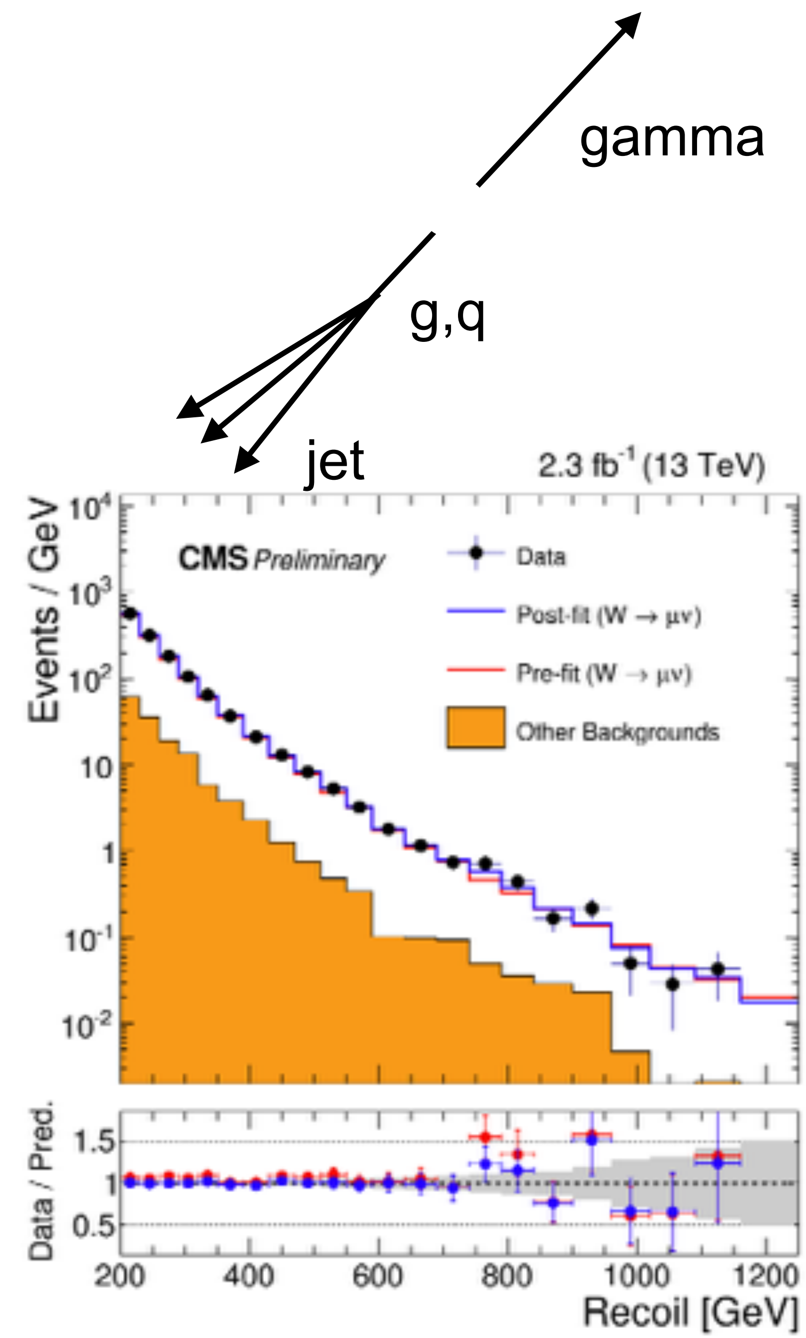


How to Derive Backgrounds

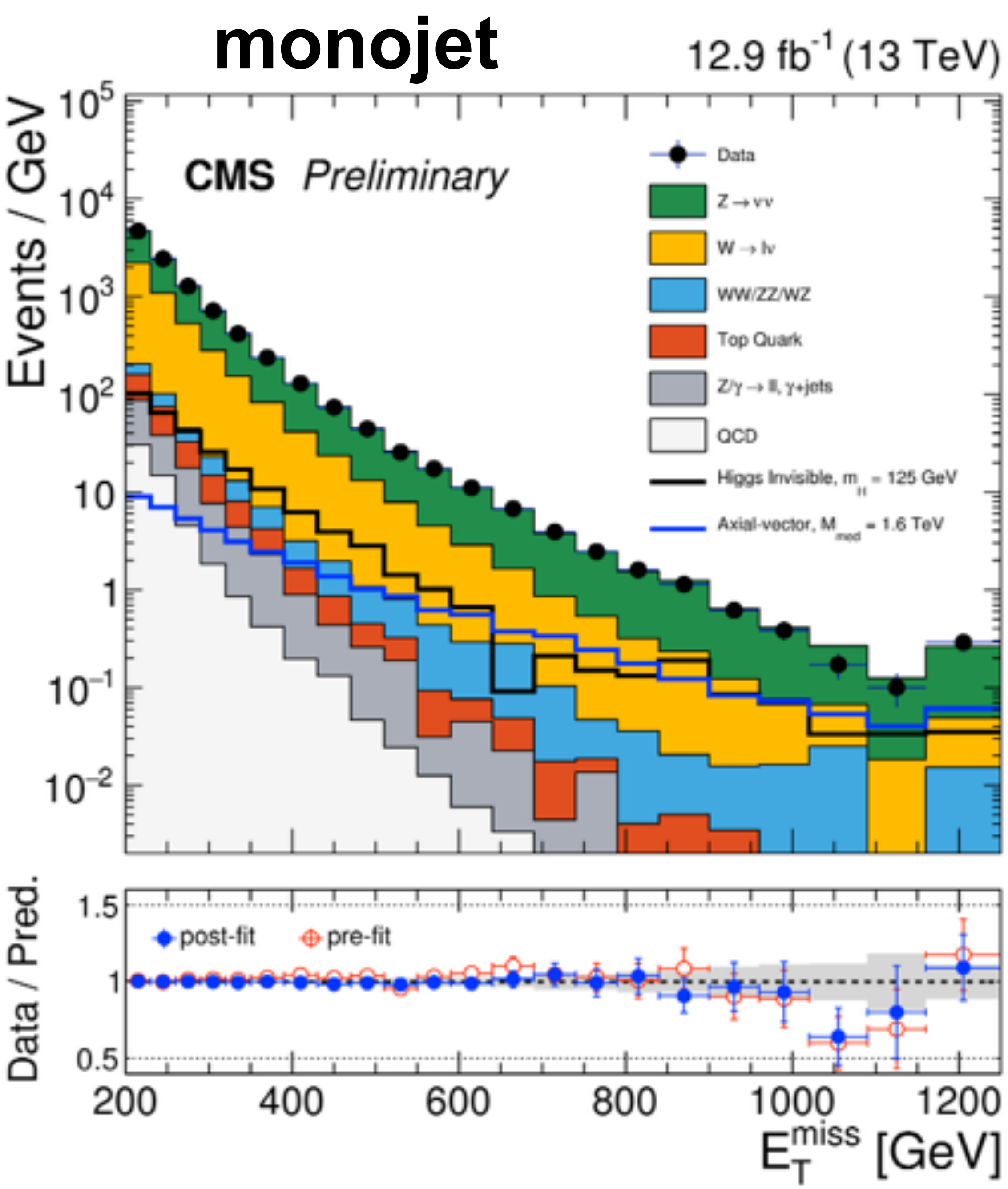
- **Main backgrounds (Z(vv)+jet and W(lv)+jet) modeled using control samples** (after removing reconstructed leptons or gamma)

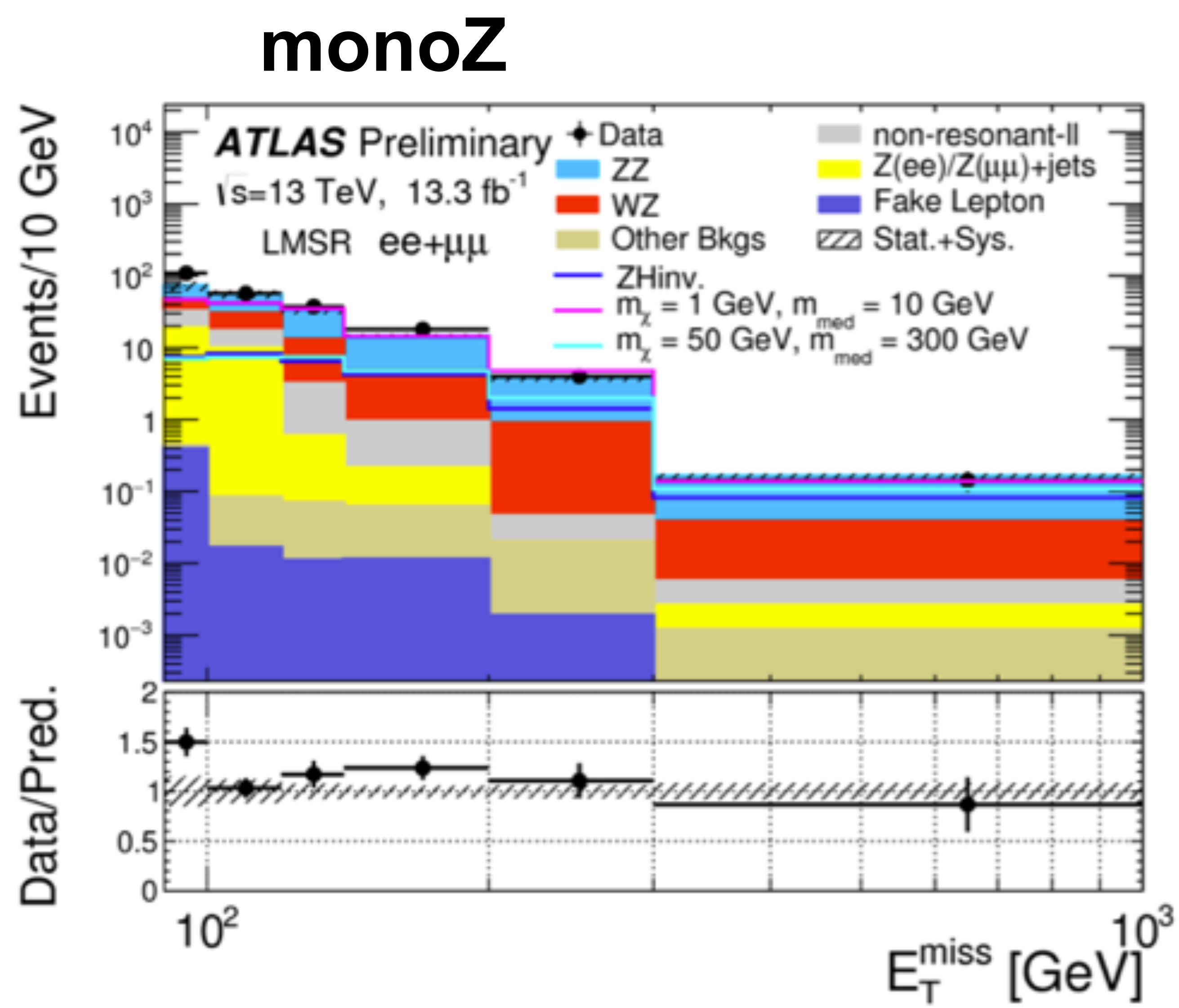






DM RESULTS

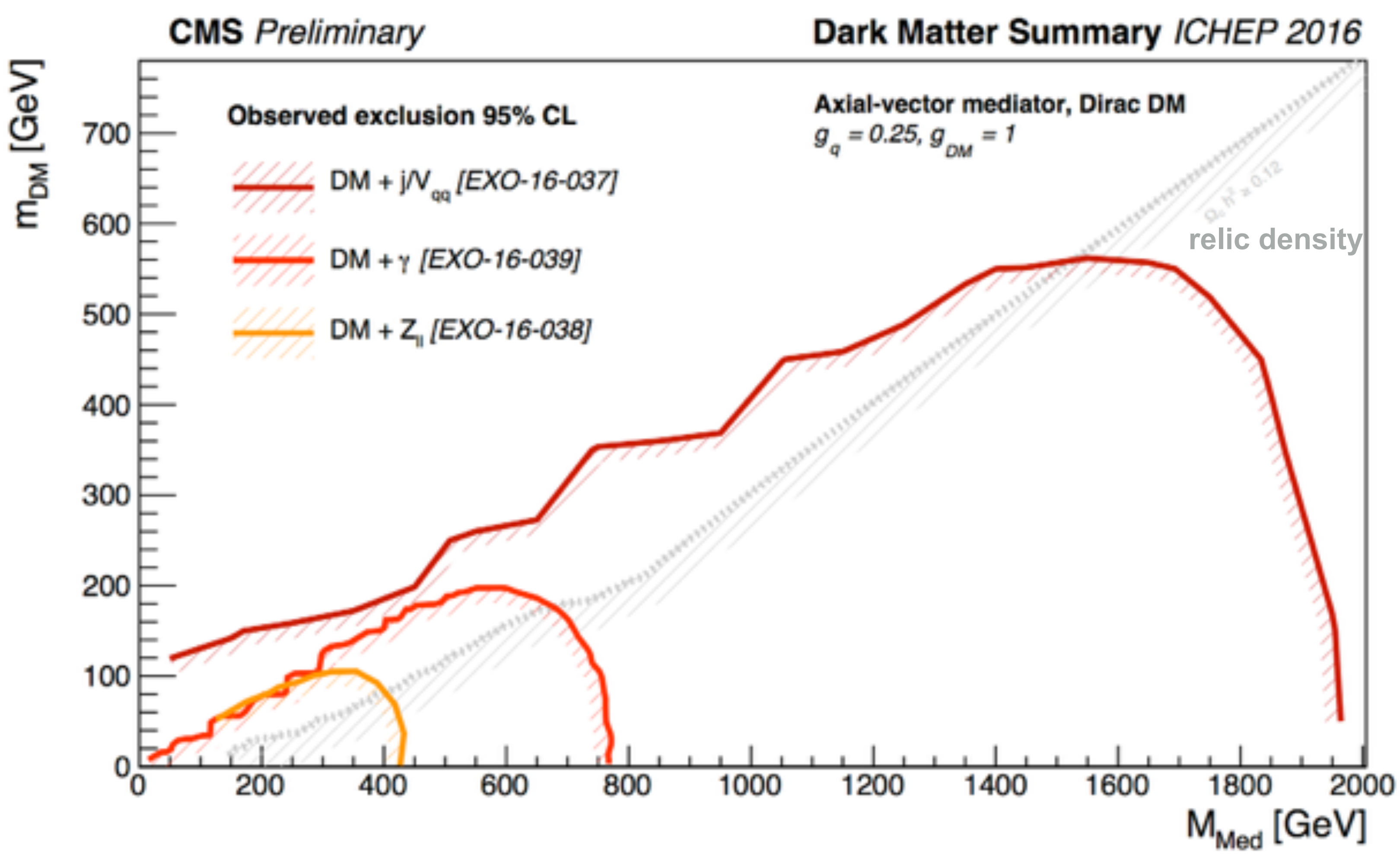




- **no evident excess** (similar for the other final states)
  - put constraints on the mass of DM and mediator

INTERPRETATION

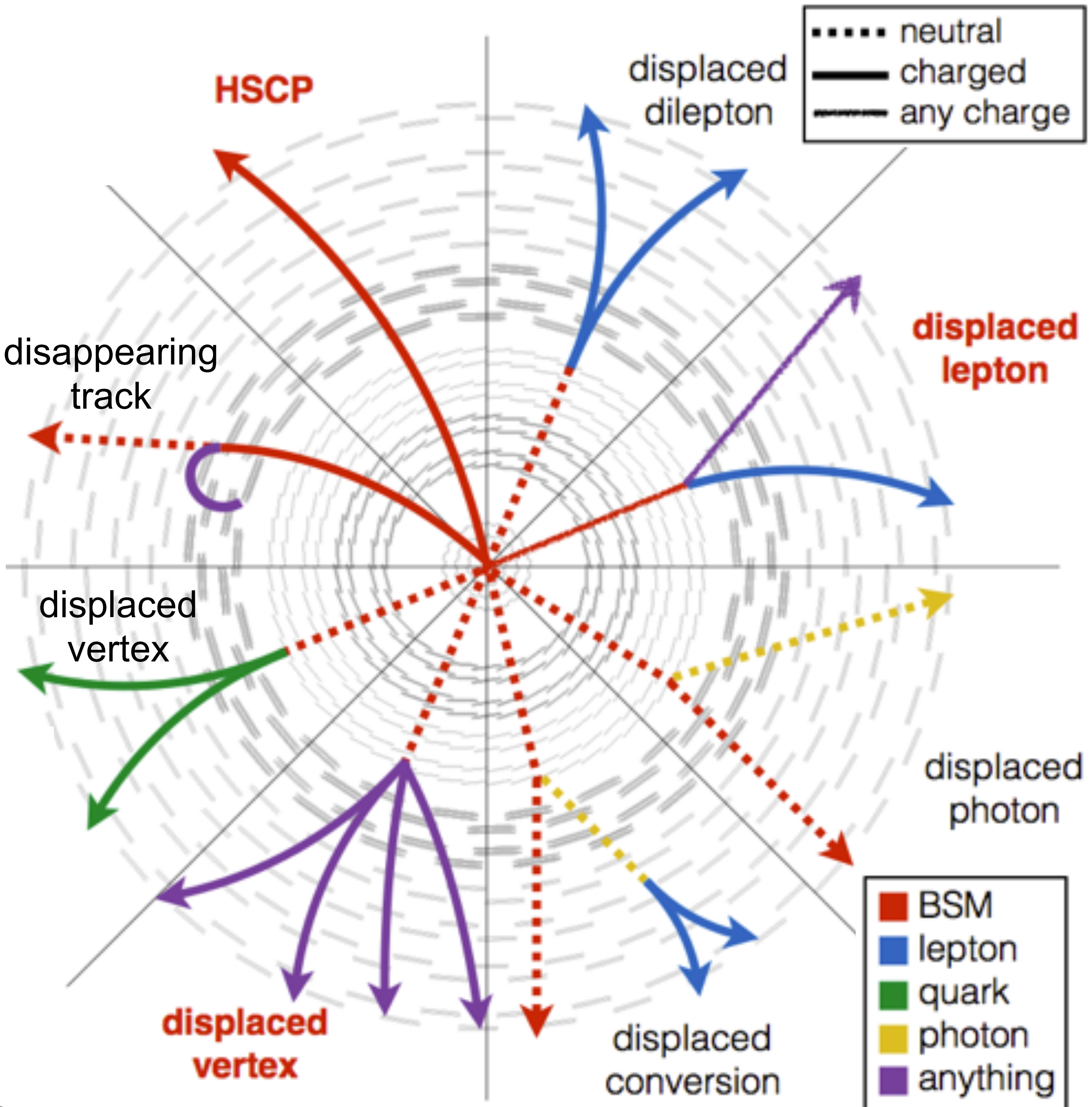
- **Report exclusion limits in m_{DM} vs M_{med} plane or vs M_{med}**
  - Constraints depend on the mediator type and on couplings
- **Can be compared with direct searches**



several other constraints from
- DM + tt_{bar}
- DM + bb_{bar}
- DM + V_{qq}
- DM + Higgs

not shown

LONG LIVED AND UNCONVENTIONAL SEARCHES



Courtesy J. Antonelli

Long-lived (LL) and unconventional exotic particles with striking signatures **predicted by many extensions of the Standard Model. Examples:**

- **Heavy, long-lived, charged particles (R-hadrons, Sleptons)**
  - speed < c
  - charge not equal to ±1e
  - lifetimes > few ns. Travel distances larger than the typical detector and appear stable
- **Particles can decay in the detector after few cm** (neutralinos in GMSB, mass-degenerate gauginos, particles of an Hidden Sector)
  - decay in displaced vertexes (jets, leptons, γ)
  - delayed interaction with calorimeters due to extra flight-length

TYPICAL LONG-LIVED ANALYSIS

- **Detector-based exotic signatures require:**
  - dE/dx
  - time of flight
  - displaced vertex
  - disappearing tracks
  - stopped particles
- **Possible additional requirements to identify SUSY-like topology:**
  - MET
  - large jet activity (HT, pT(leading jet)>threshold
  - the less the extra requirements, the smaller the model dependence
- **Specific control samples to model exotic signature in detector:**
  - LL signatures like detector noise. Deep knowledge of detector.
- **Very generic searches, driven by signatures**
  - open-minded searches. M**odels as benchmark** to report results

Many results at LHC. Reporting only the 13 TeV ones.

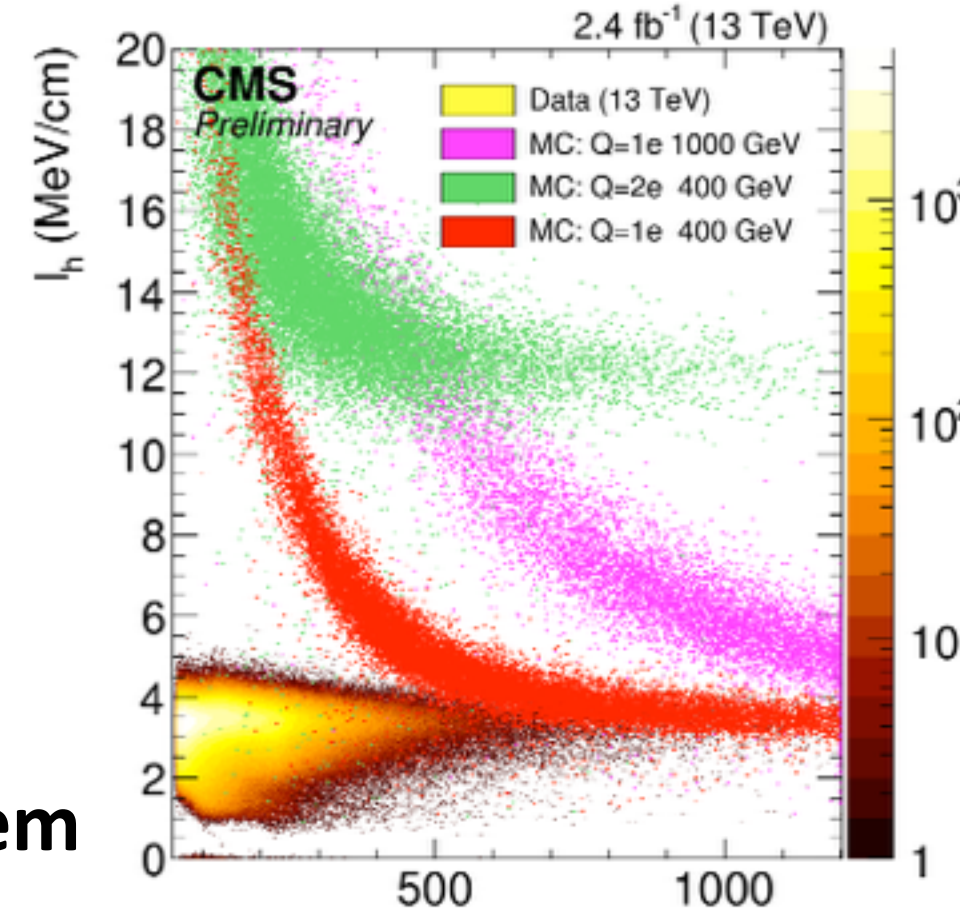
HEAVY STABLE CHARGED PARTICLES

Combination of several detector inputs to be sensitive to slepton (slow muon-like) and R-hadrons (maybe with short lifetime)

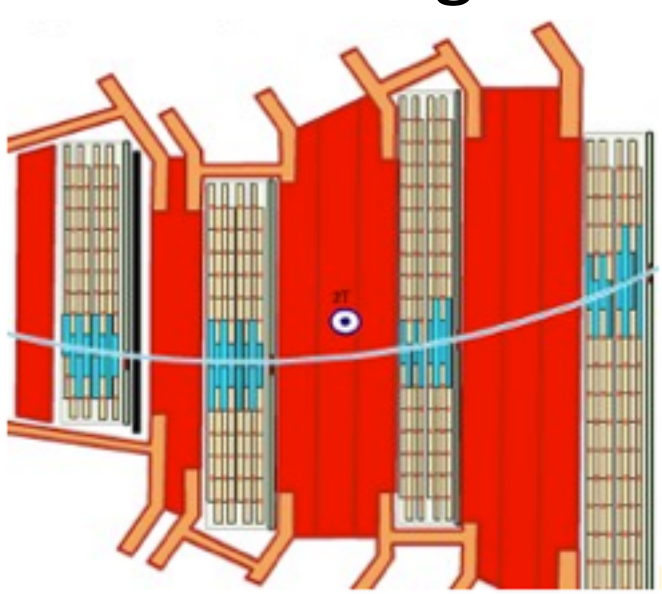
dE/dx: Large ionization left in tracker detectors by high mass R-hadrons or sleptons

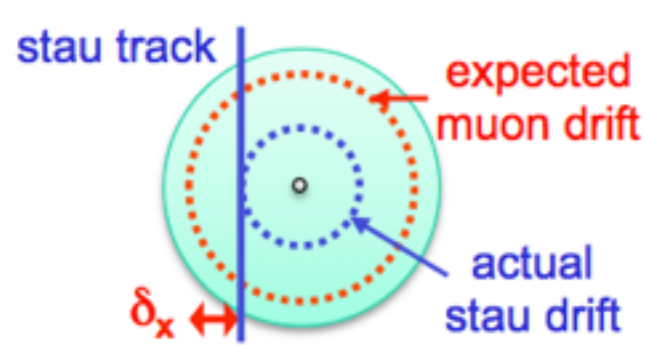
Enhanced if charge ≠ 1

In case of R-hadrons with short lifetimes, dE/dx and p_T only information available to identify them



slow moving high mass stable charged particles identified using **timing measured in muon system**





$$\beta^{-1} = 1 + \frac{\delta_x}{L}\frac{c}{v_{drift}}$$

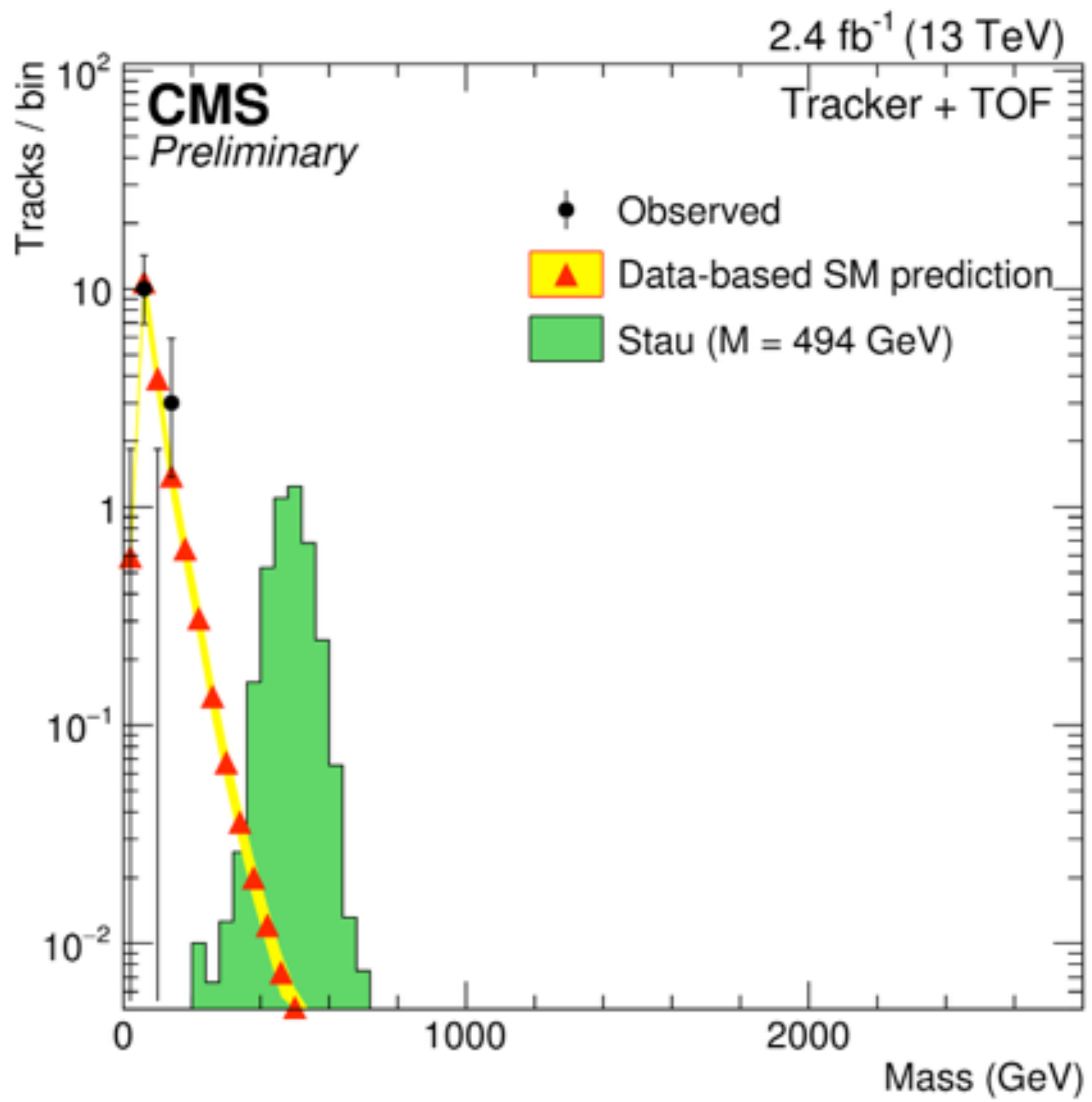
averaged over all layers

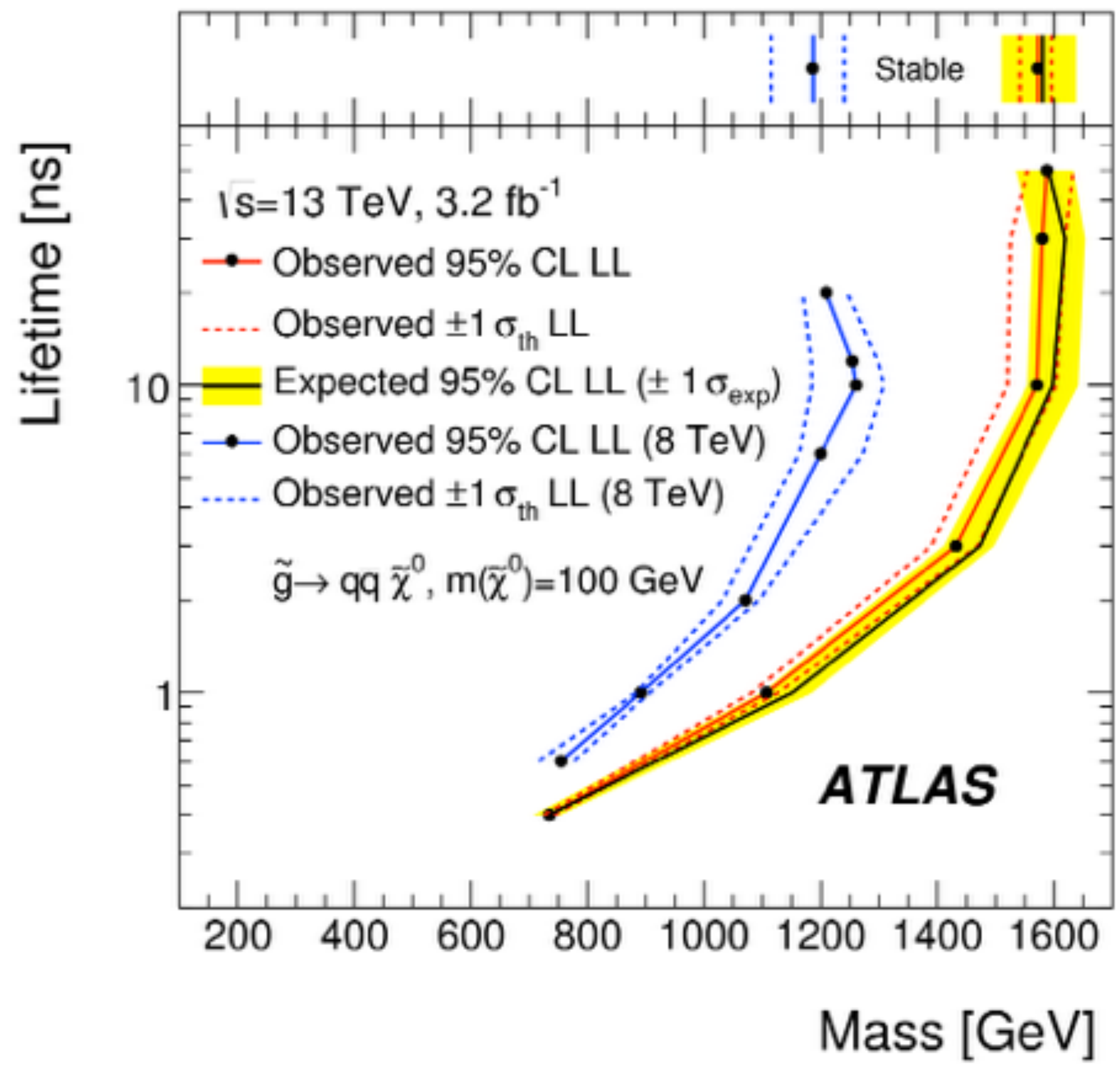
L=flight distance

β obtained as an average over the detector hits

HSCP: RESULTS

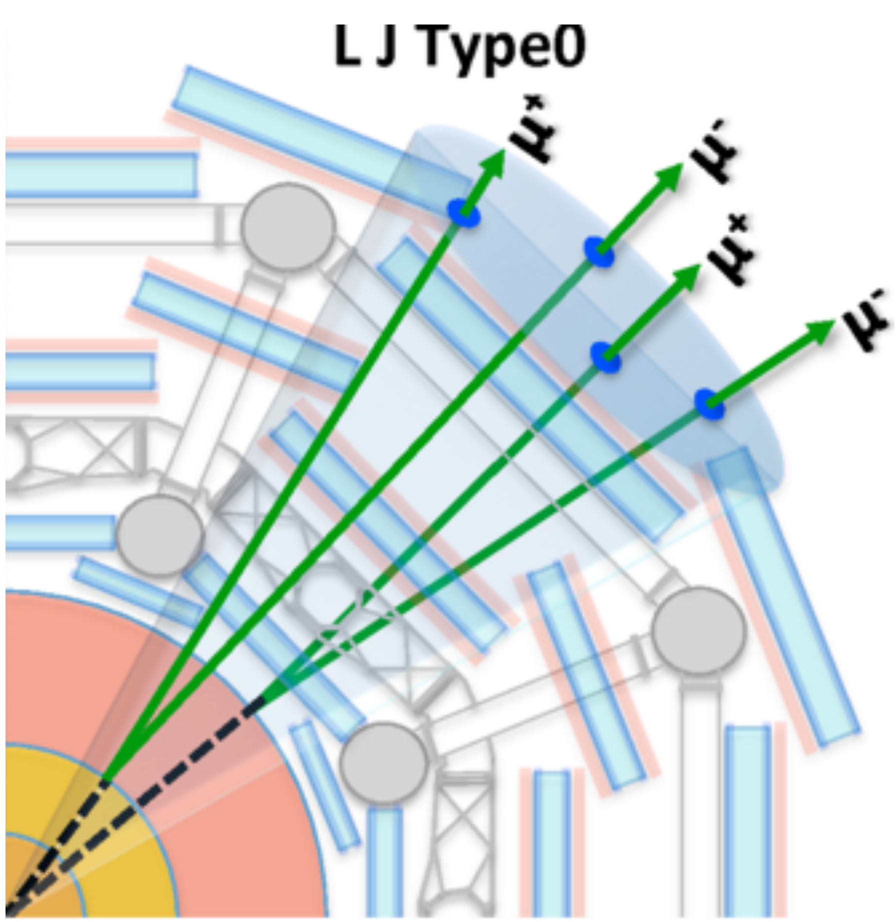
- **No excess seen**
- **Limits presented for different scenarios**
  - gluinos (also metastable), stop, stau (GMSB), lepton-like long-lived fermions

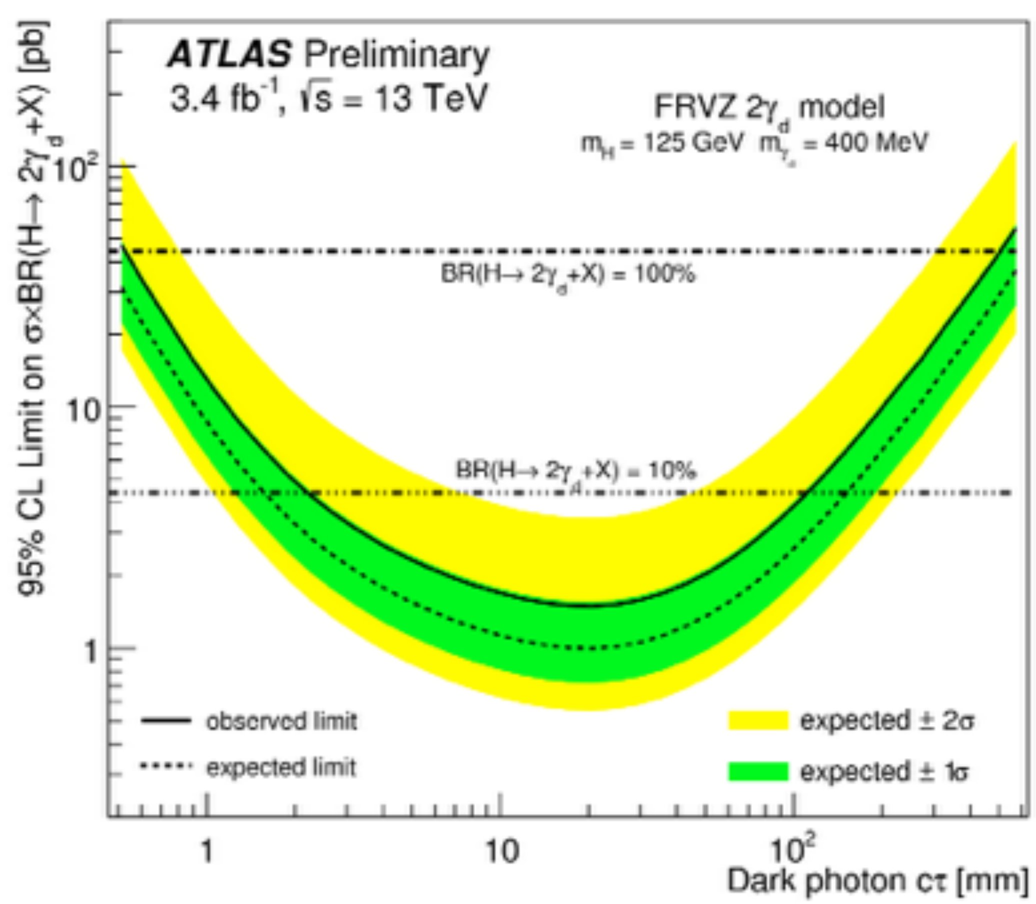


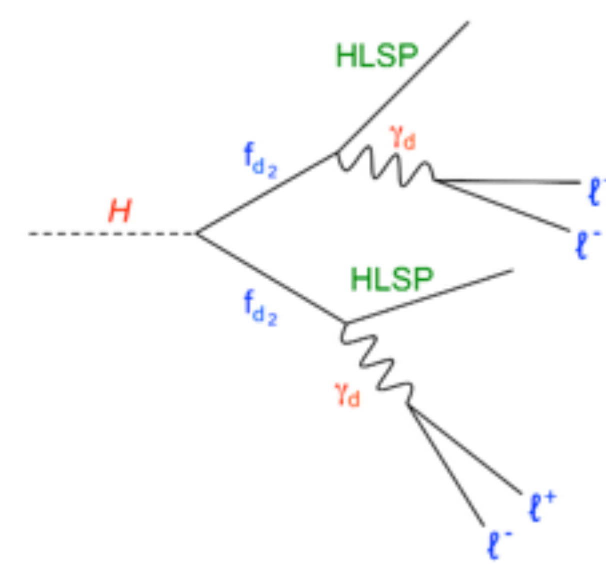


DISPLACED VERTEXES: LEPTON JETS

- **Long-lived particles** decaying in charged particles (hadrons, leptons) identified **via vertexing, displaced tracks** (large impact parameter) **or clustering of displaced tracks**
- **No excess. Limits in 2D (σ vs lifetime)**

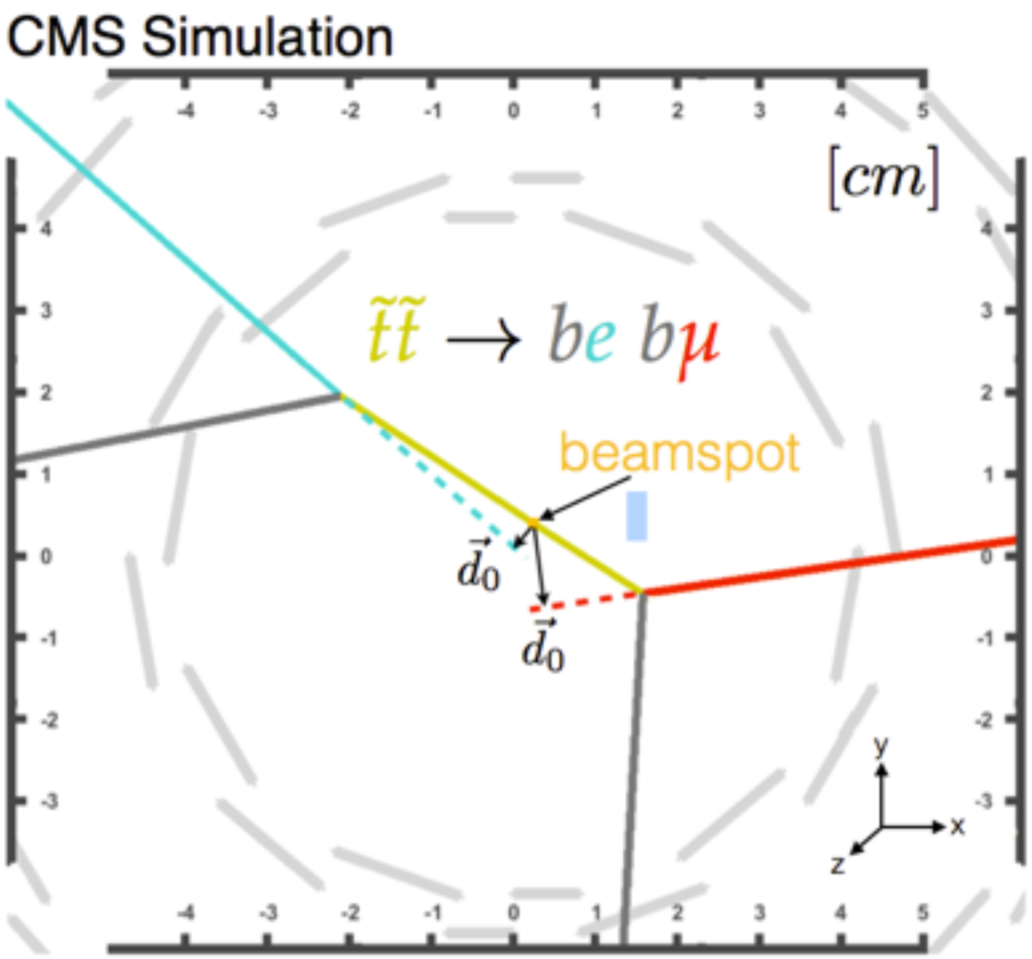


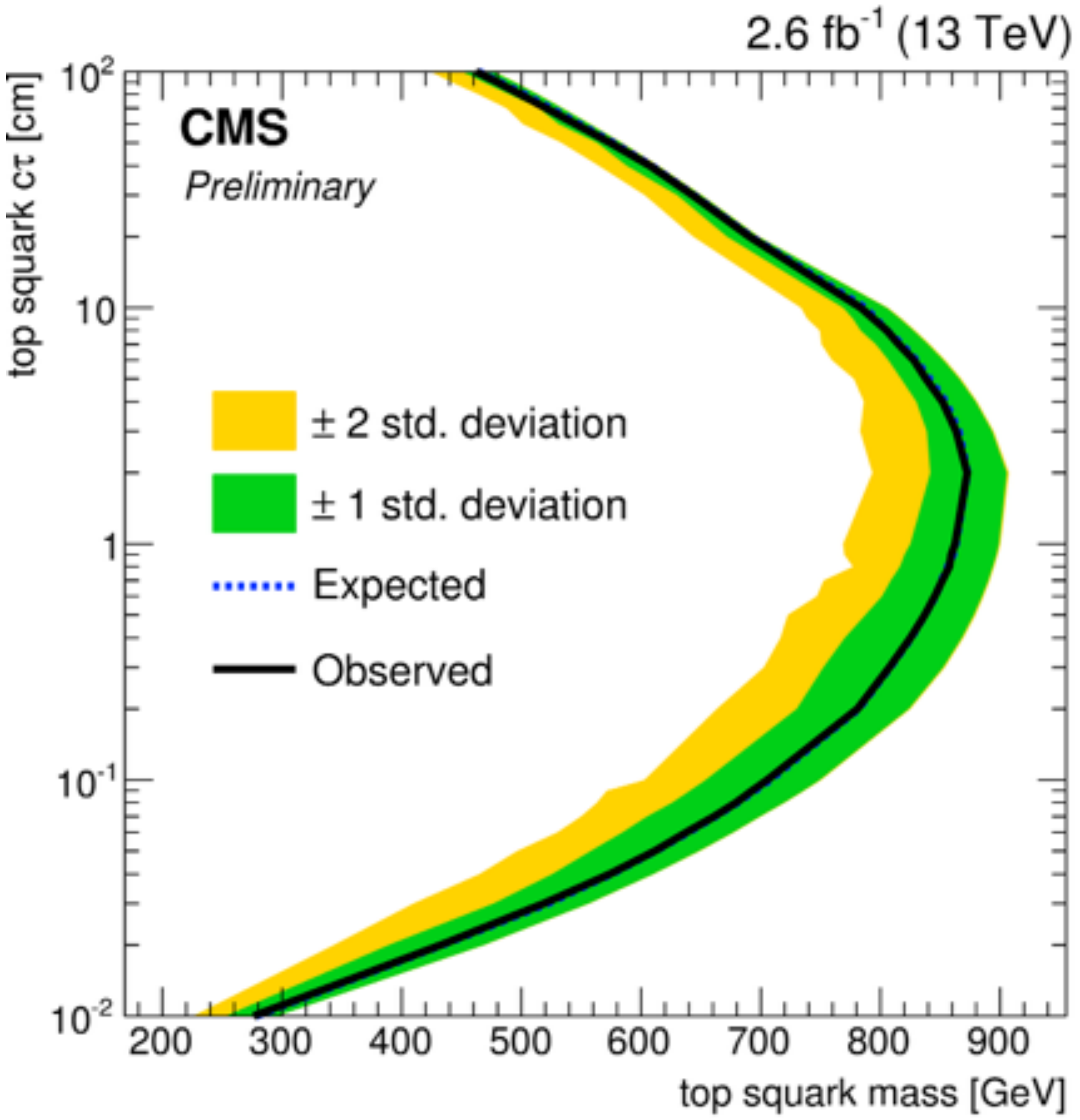




Displaced Vertexes

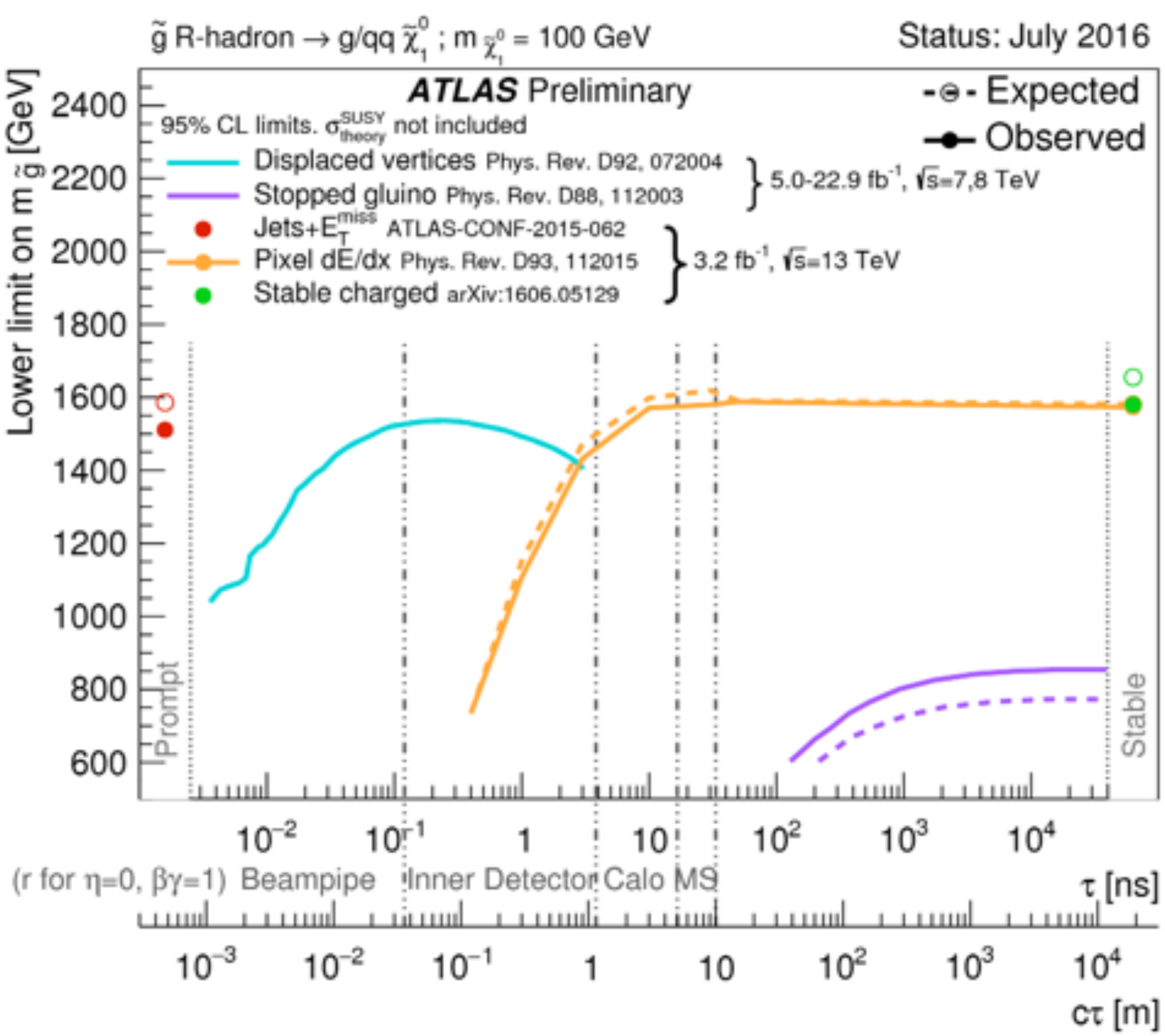
- **No Excess**
- **Limits in 2D (mass vs lifetime)**





SUMMARY OF LONG LIVED

Summary plot for some LL analyses (ATLAS)



7-8 TeV LL analyses for CMS

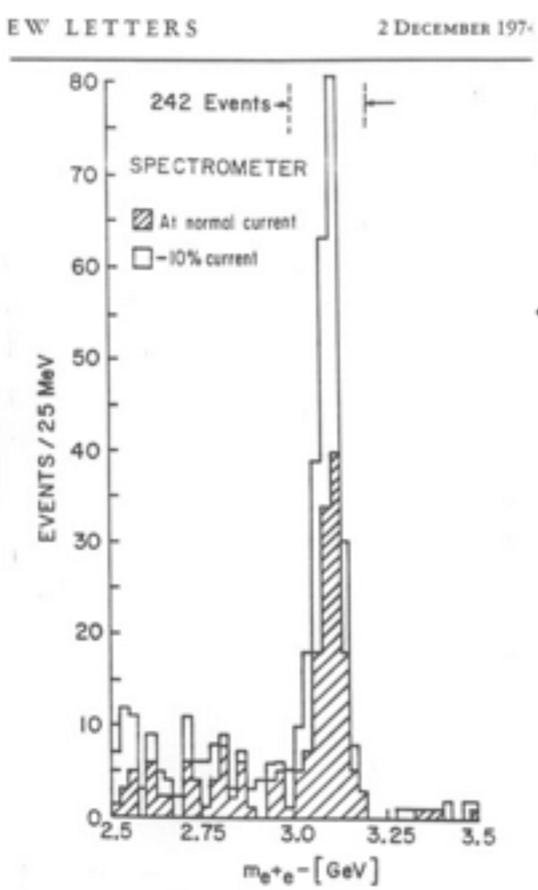
Final state targeted	7 TeV	8 TeV
displaced e-e/μ-μ pairs	1211.2472	1411.6977
displaced μ-μ pairs in muon system		2005761
displaced e-μ events		1409.4789
displaced μ-μ pairs (dark photons)		1506.00424
displaced photons using ECAL timing	1212.1838	2063495
displaced photons using conversions	1207.0627	2019862
displaced vertices		**2160356**
displaced dijets		1411.6530
short, highly ionizing disappearing tracks		thesis
disappearing tracks		1411.6006
kinked tracks		thesis
fractionally charged particles	1210.2311	1305.0491
heavy stable charged particles (HSCP)	1205.0272	1305.0491
stopped particles	1207.0106	1501.05603
out of time muons		thesis

Courtesy J. Antonelli

RESONANCES

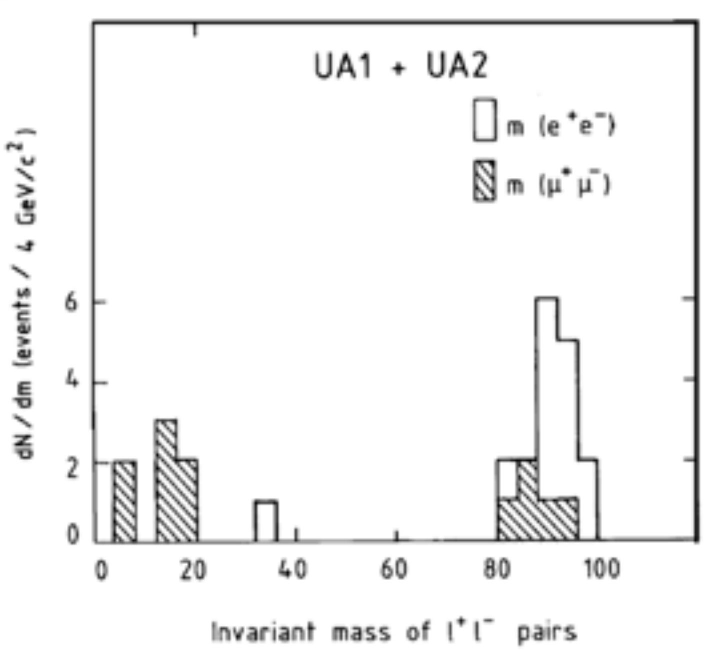
- **Fully reconstructed resonances represent the simplest way to discover new particles**
  - striking and incontrovertible signature
  - small systematics, robust

J/psi

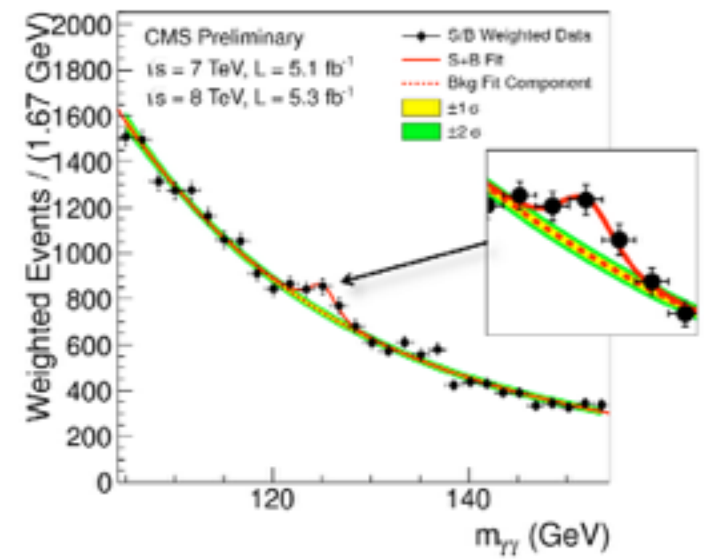


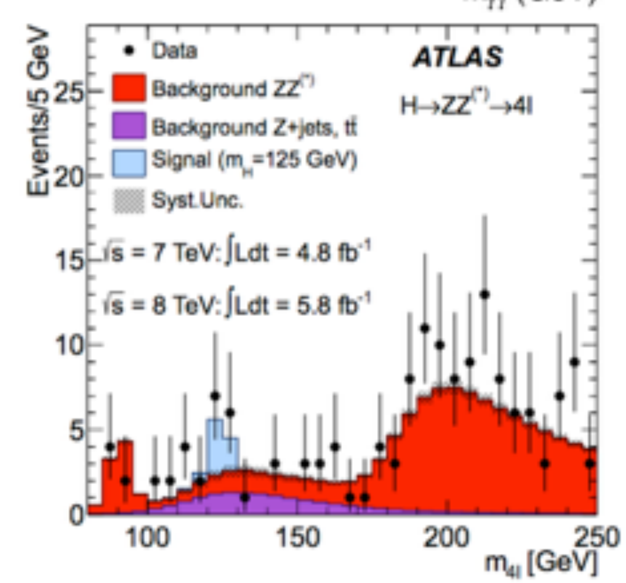
7IG. 2. Mass spectrum showing the existence of J. sults from two spectrometer settings are plotted wing that the peak is independent of spectrometer rents. The run at reduced current was taken two nths later than the normal run.

Z



Higgs

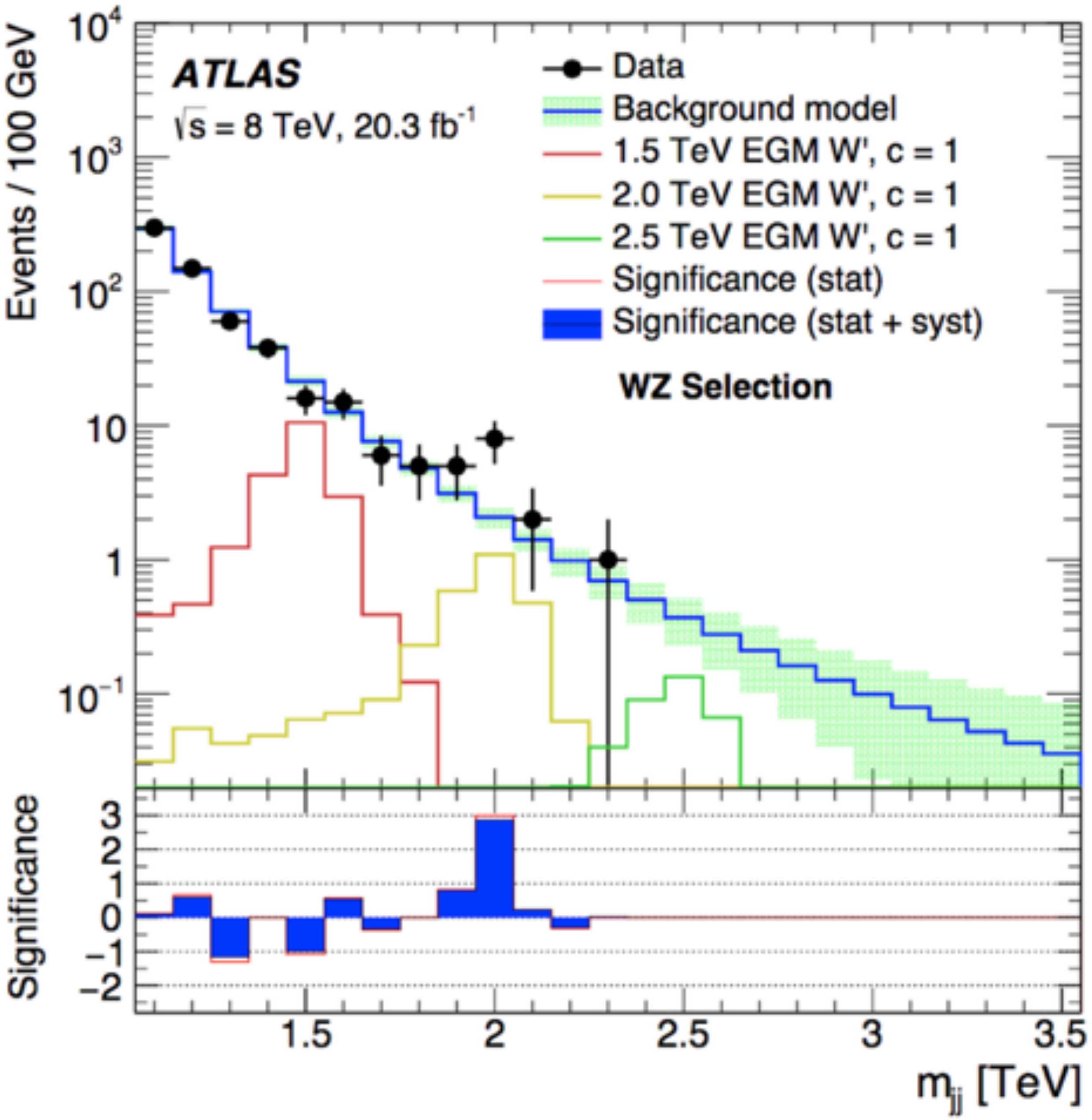




HINTS BEFORE ICHEP

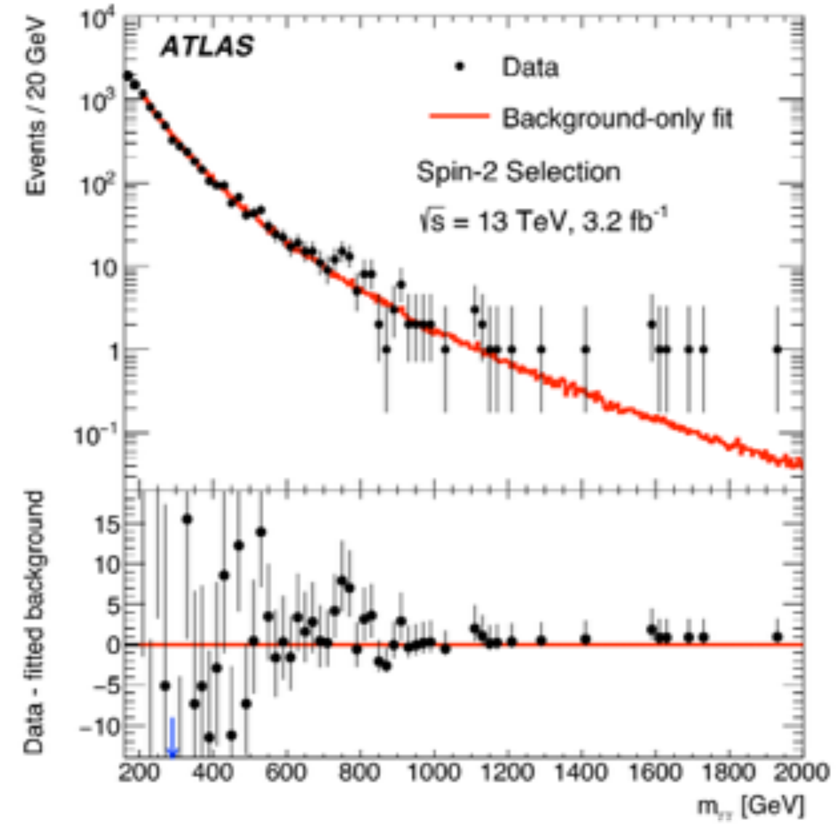
Dibosons

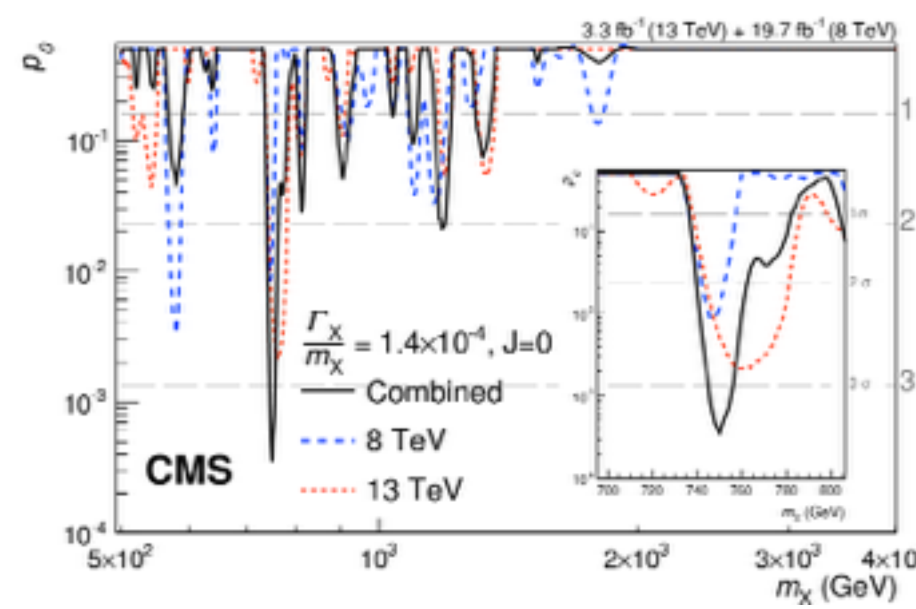
excesses at 1.9-2.0 TeV (up to 3 sigmas local) in different channels for both ATLAS and CMS



Diphotons

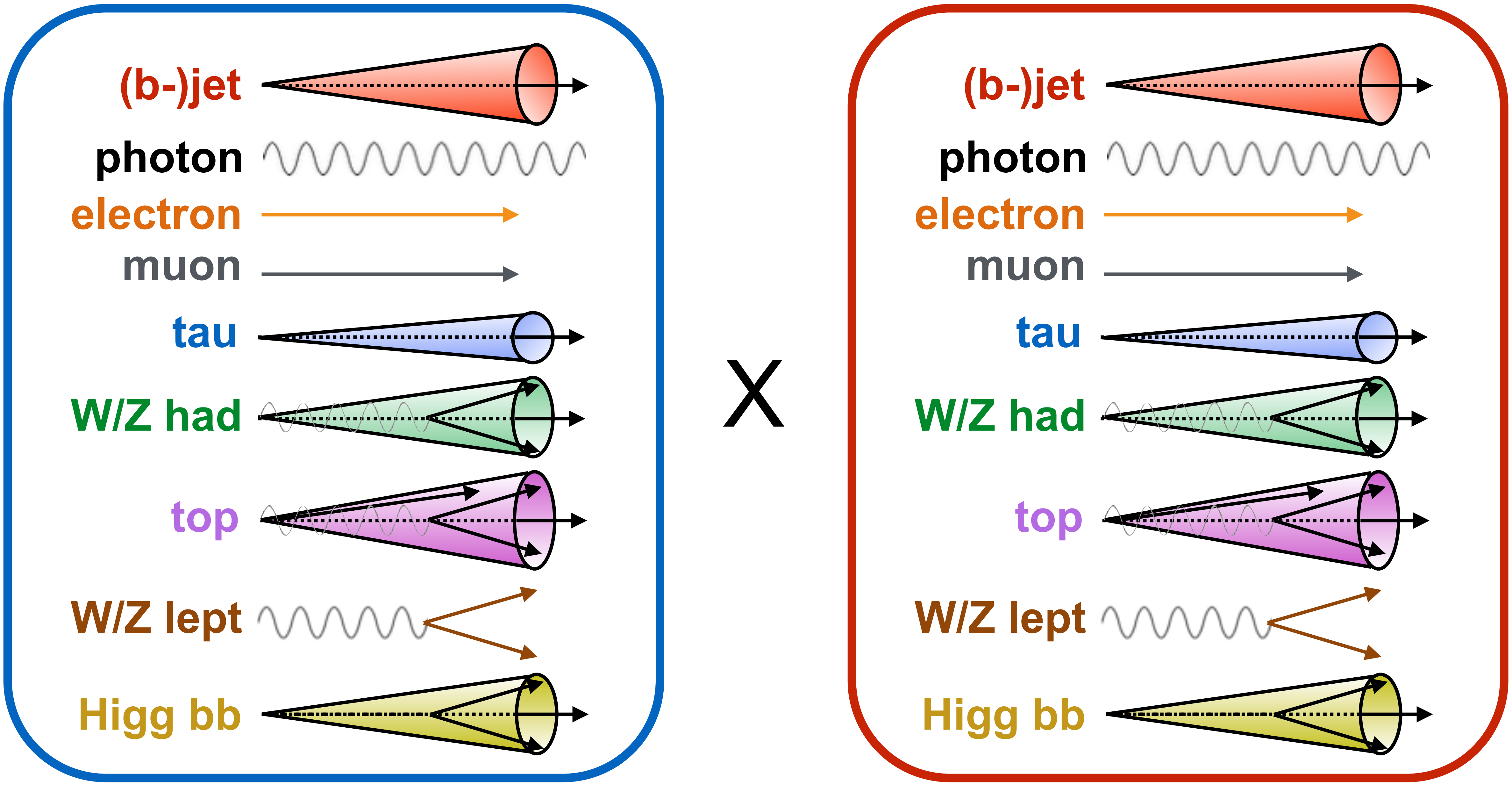
>3 sigmas (local) at 750 GeV for both ATLAS and CMS





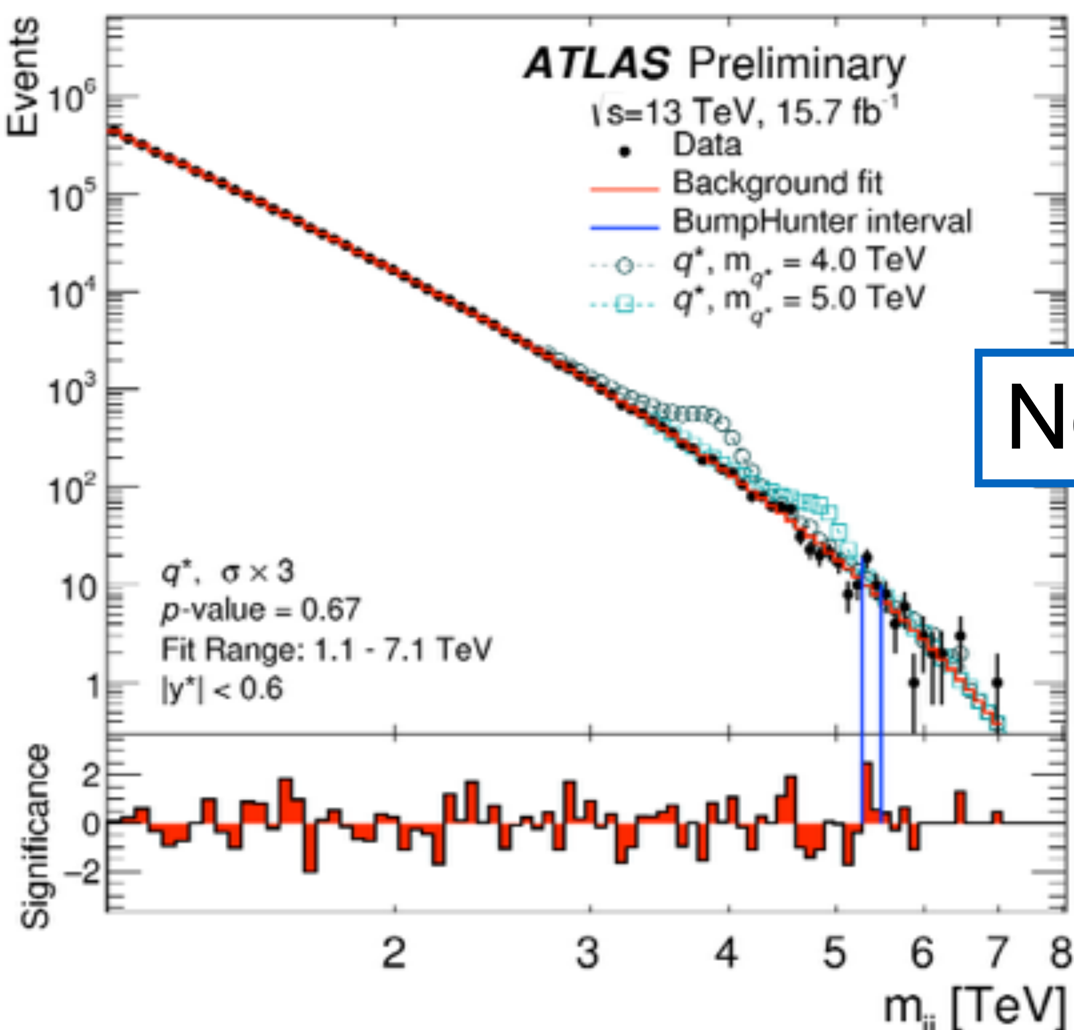
MANY COMBINATIONS

- **Most of resonance searches are two-body**
- **Many possible combinations and channels explored**
  - just focusing on the 3 channels
  - much more in next talk by Marcello!

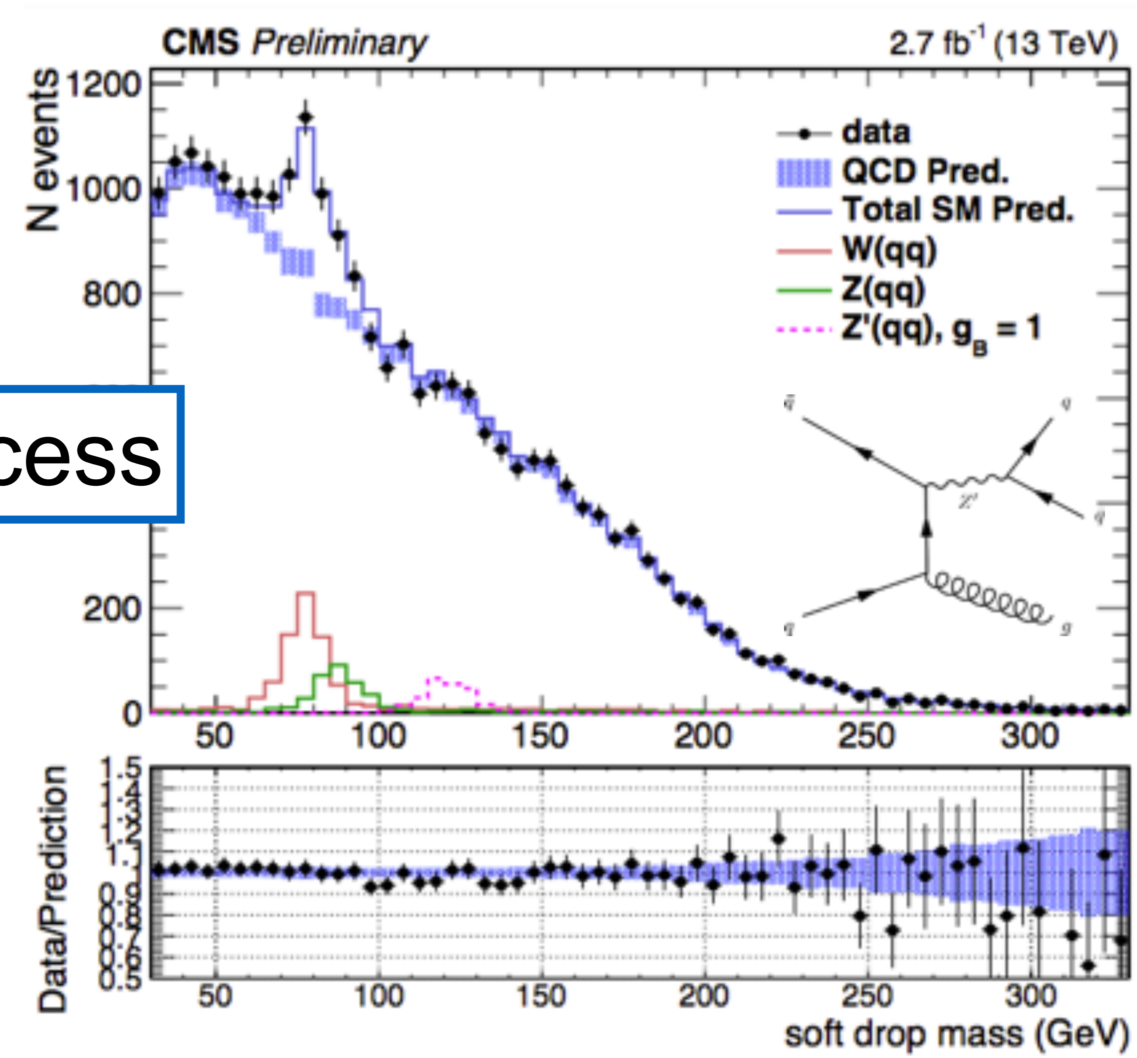


DIJET: HIGH AND LOW MASS

- **High mass (>~1.5 TeV):** selected with tight high p_T triggers
- **Intermediate mass (~0.5-1.5 TeV):** storing reduced event content on disk (*scouting, TLA*)
- **Low mass (~100-300 GeV):** using events with initial state jet radiation and boosted dijet

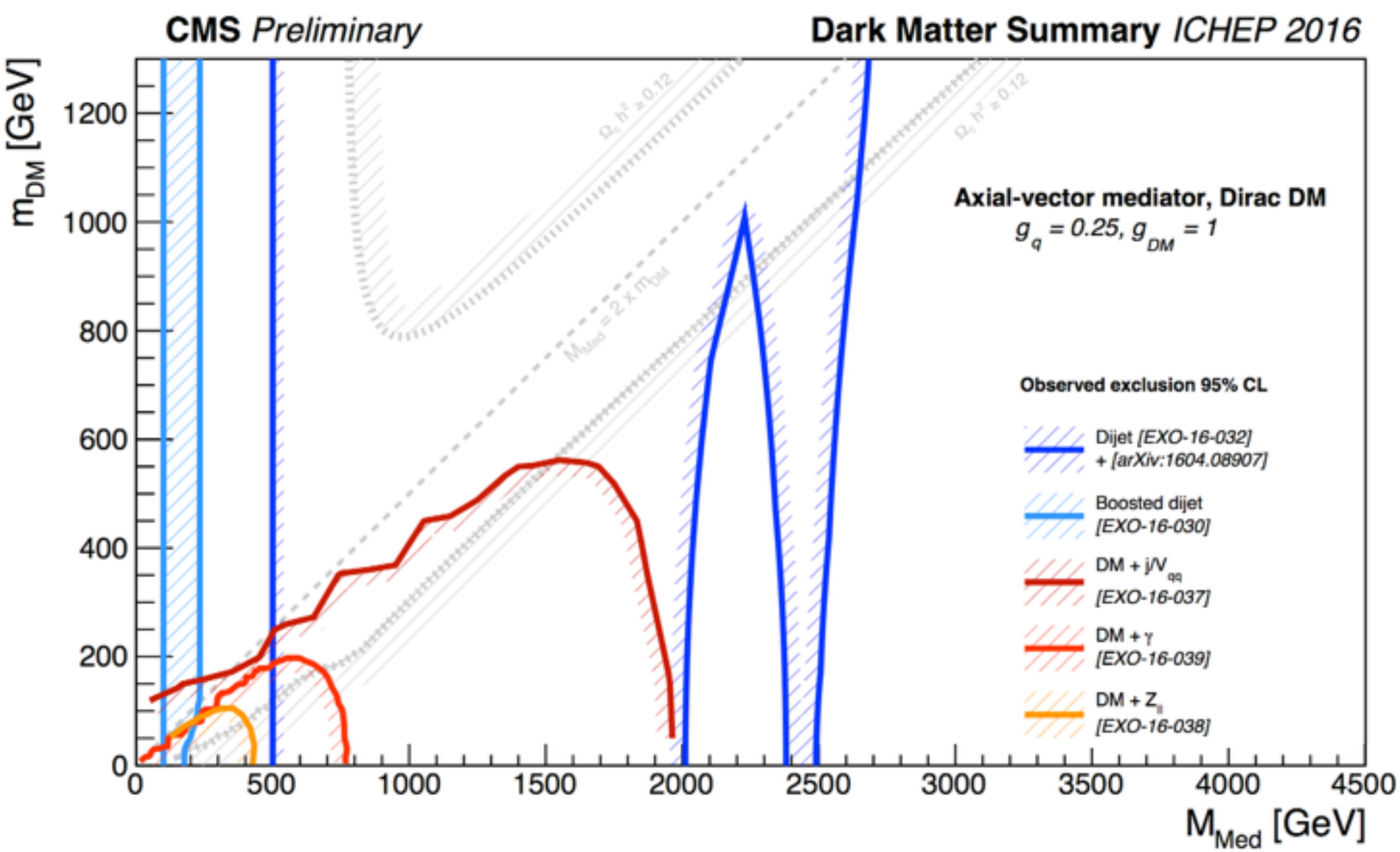


No excess

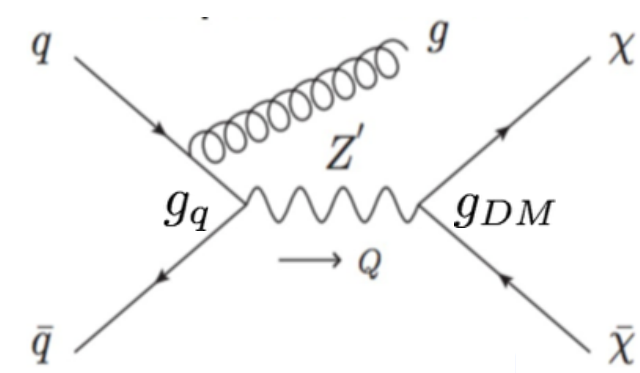


DIJET AND DM

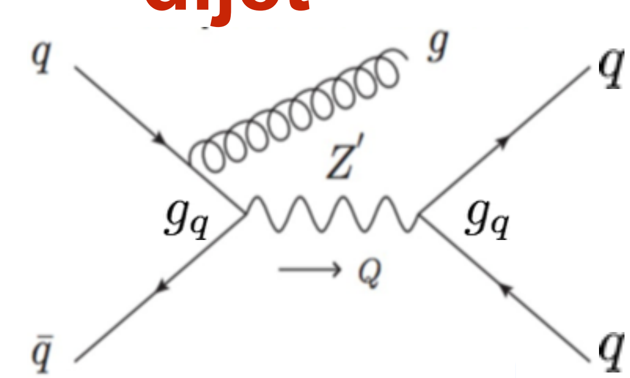
- **In simplified models, limits** on mass of mediator decaying into dijet **converted into constraints on DM mass**
  - with specific couplings to quarks (g_q) and DM (g_{DM})
- **Complementary to mono-X searches**



DM



dijet

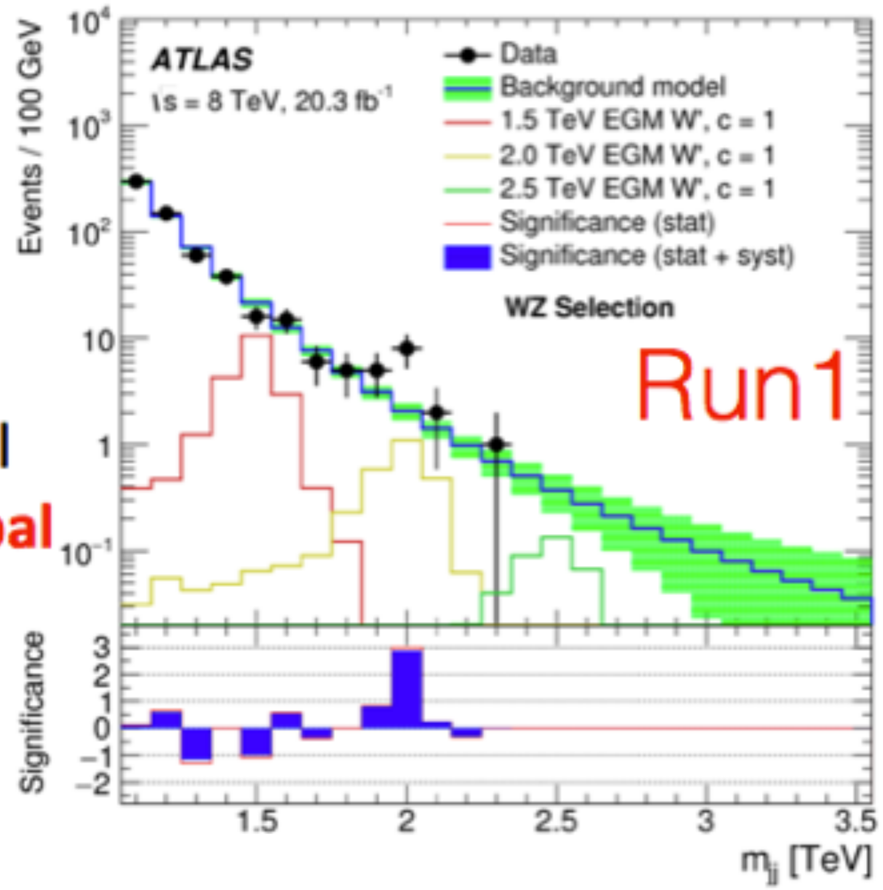


DIBOSON

m= 2TeV

3.4σ local

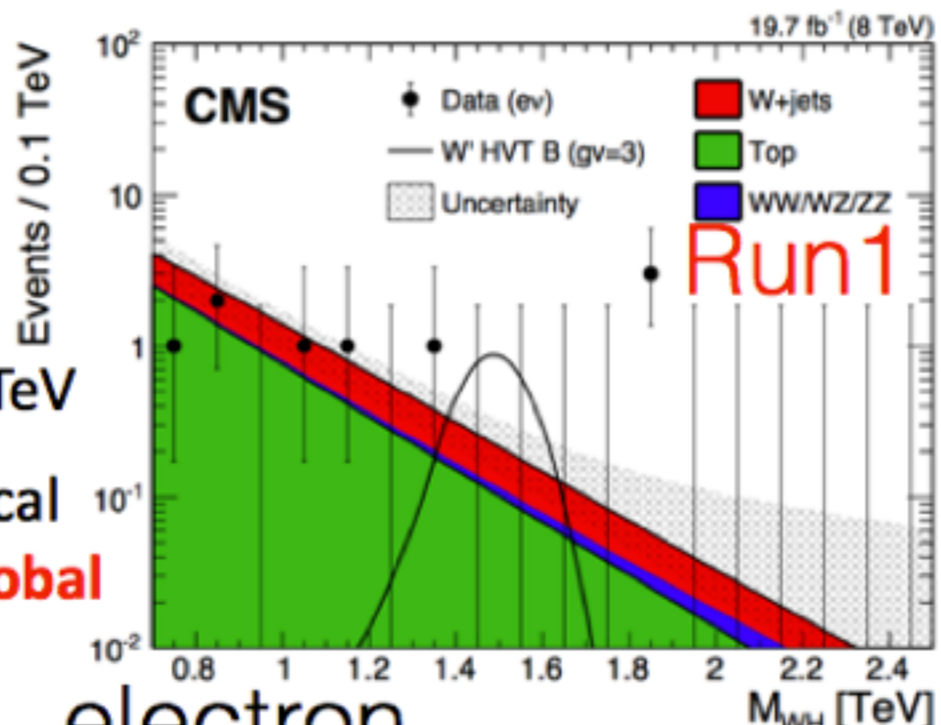
2.5σ global



m=1.8 TeV

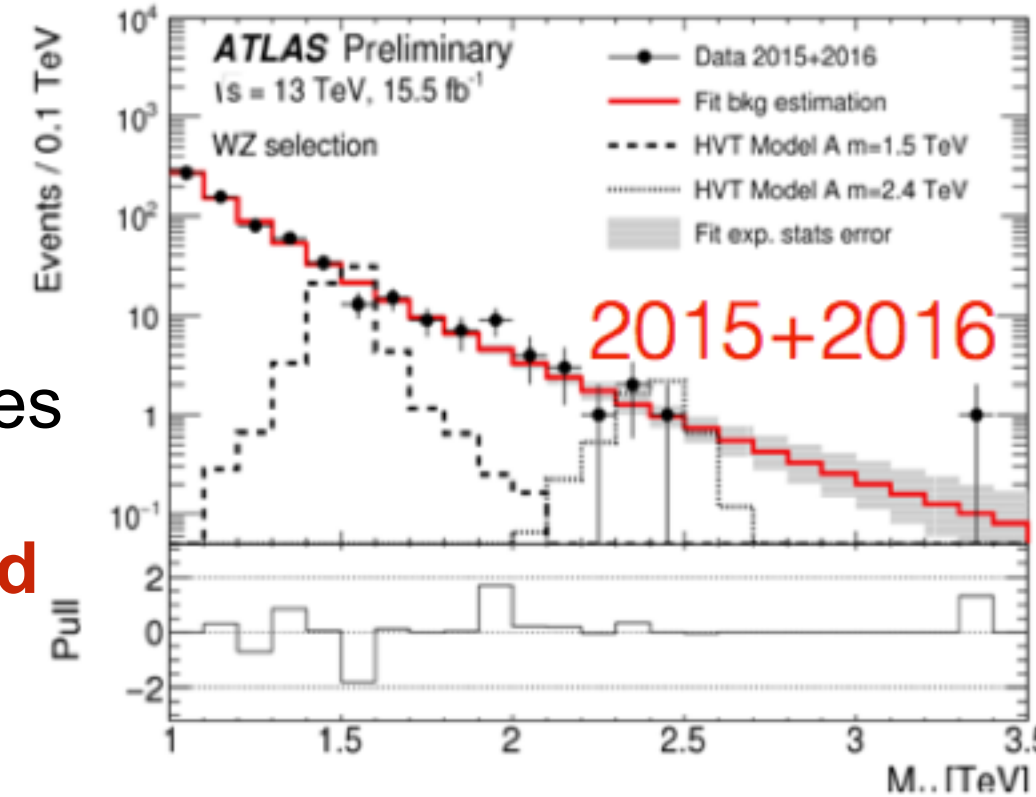
2.9σ local

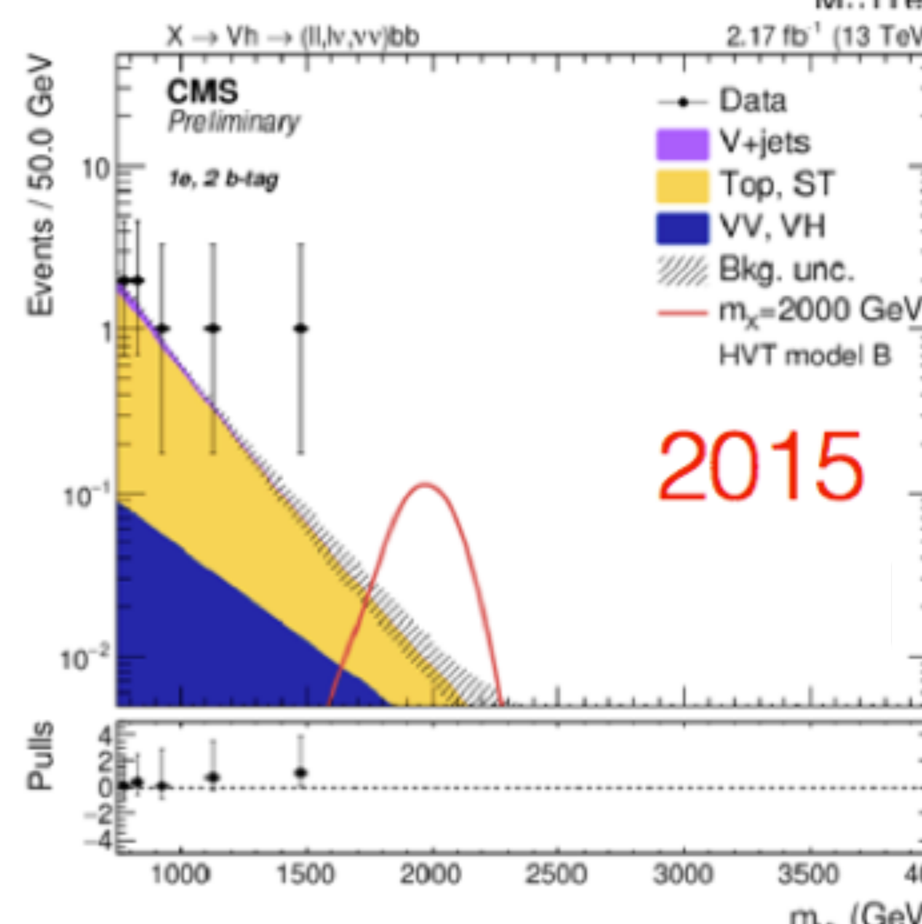
1.9σ global



electron

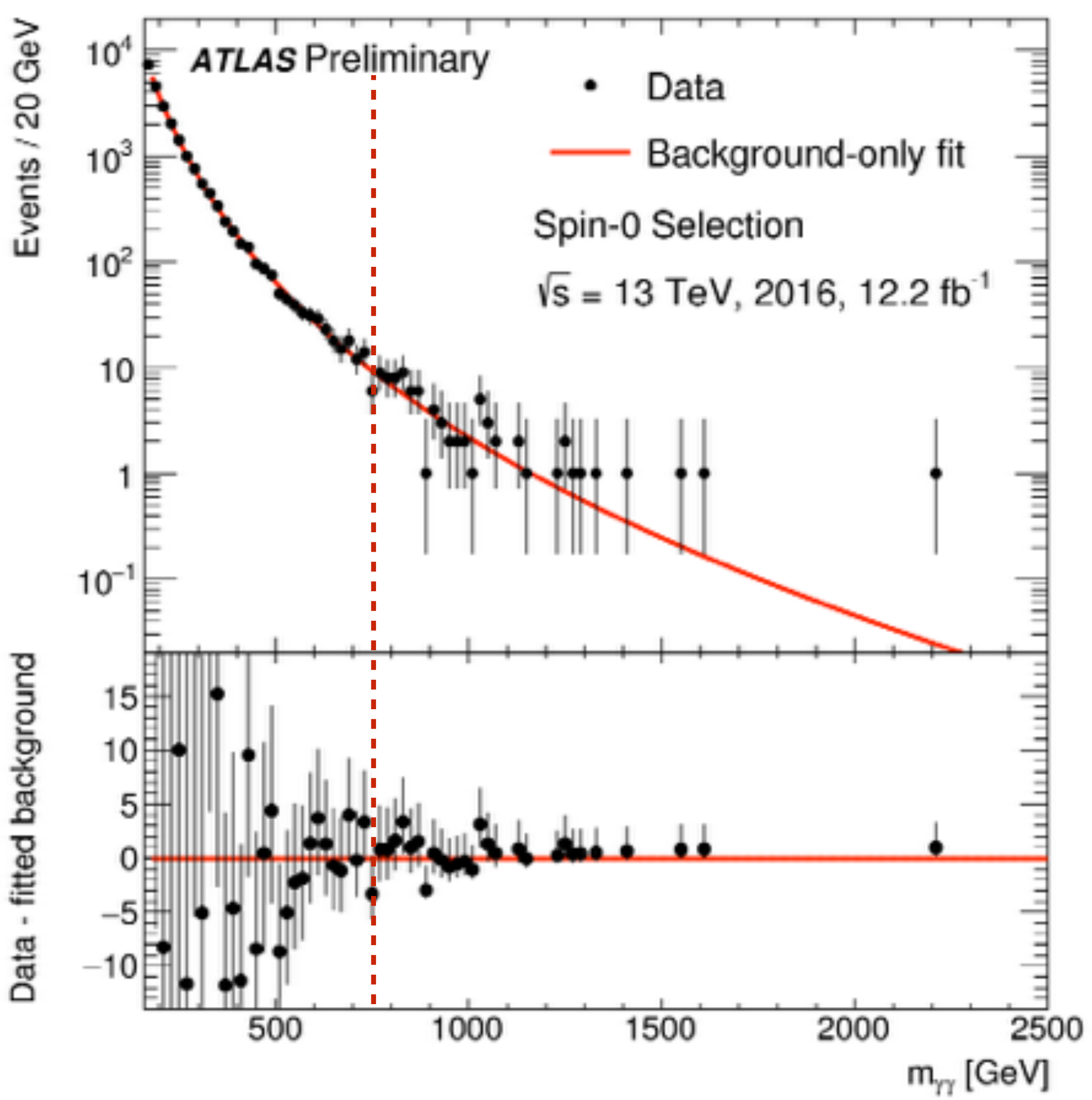
Large excesses seen in Run1 **not confirmed in Run2**

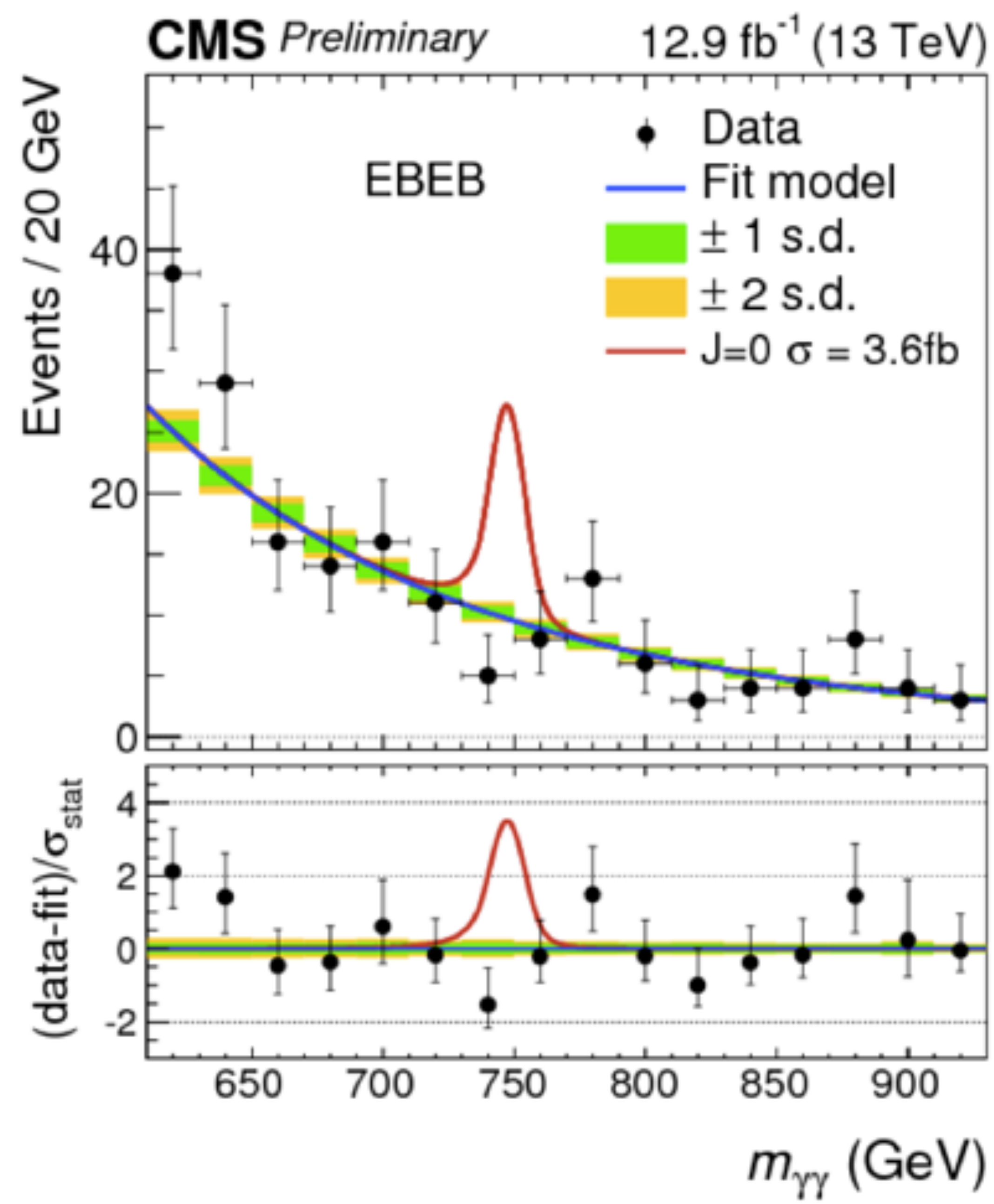




DIPHOTON

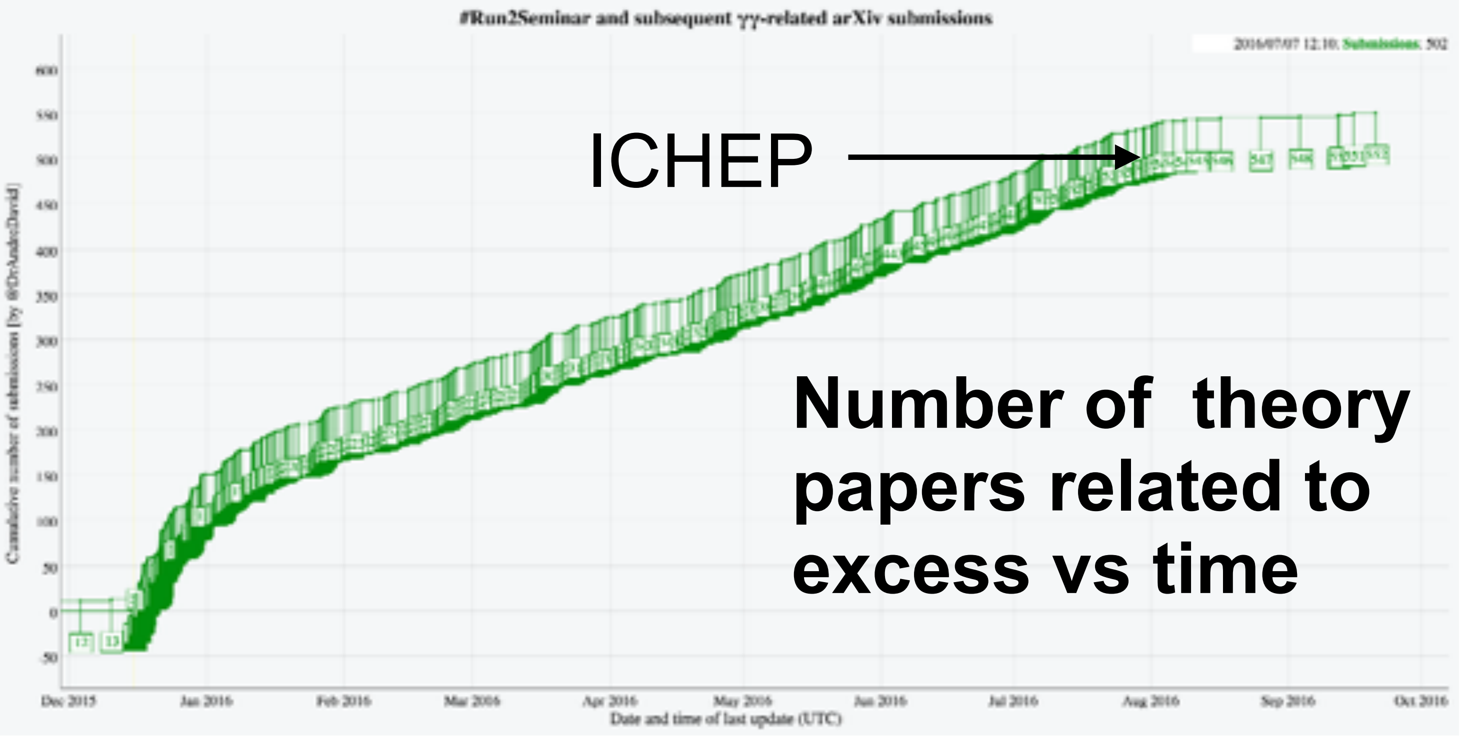
- Assuming the cross section seen in 2015 data, **large excess to be observed in 2016**
- Unfortunately **no peak showed up**





DIPHOTON: LESSONS LEARNT

- **Statistical fluke**
  - no mistake, fluctuations happen
- **Look-elsewhere effect is important**
  - @ LHC, results always presented with LEE included



- **"5 sigma local p-value per experiment for discovery"** rule is a **good one**
  - takes somehow into account the many searches we perform
- 750 GeV appeared in a **mass region already excluded** in some models (RS graviton) and **taken very seriously by theorists**
  - important to keep searching in intermediate mass range (200 GeV - 1 TeV)

CONCLUSIONS AND FUTURE

- **Impressive number of results** on BSM searches at LHC
  - thanks to increase in energy and luminosity
- **No new Physics seen yet**
  - large excesses on diphoton and diboson not confirmed
- **Null results put strong constraints on BSM**
  - for same states more than double/triple statistics to see >5 sigma excess
  - expect no huge surprises in the next year or so

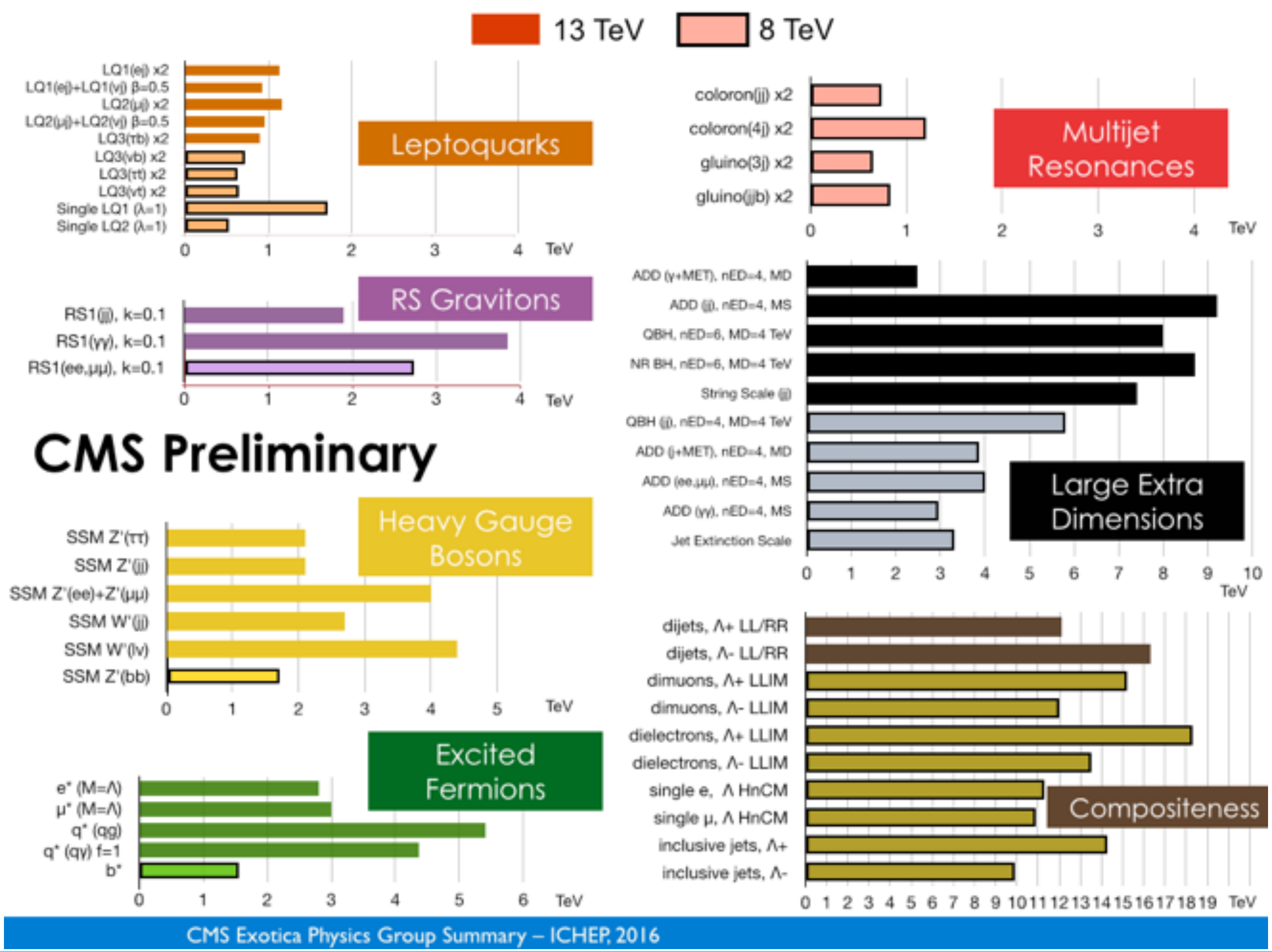
BUT

- **More than 100 fb^{-1} by end of 2018**
- **Run1 program not yet fully repeated!**
  - many searches still to be finalized and presented
- **Surprises may come** from mass regions already excluded in specific models and benchmarks
  - keep searching in the low/intermediate mass region
- **Next year still crucial for LHC BSM searches**

BACKUP

SUMMARY OF BSM

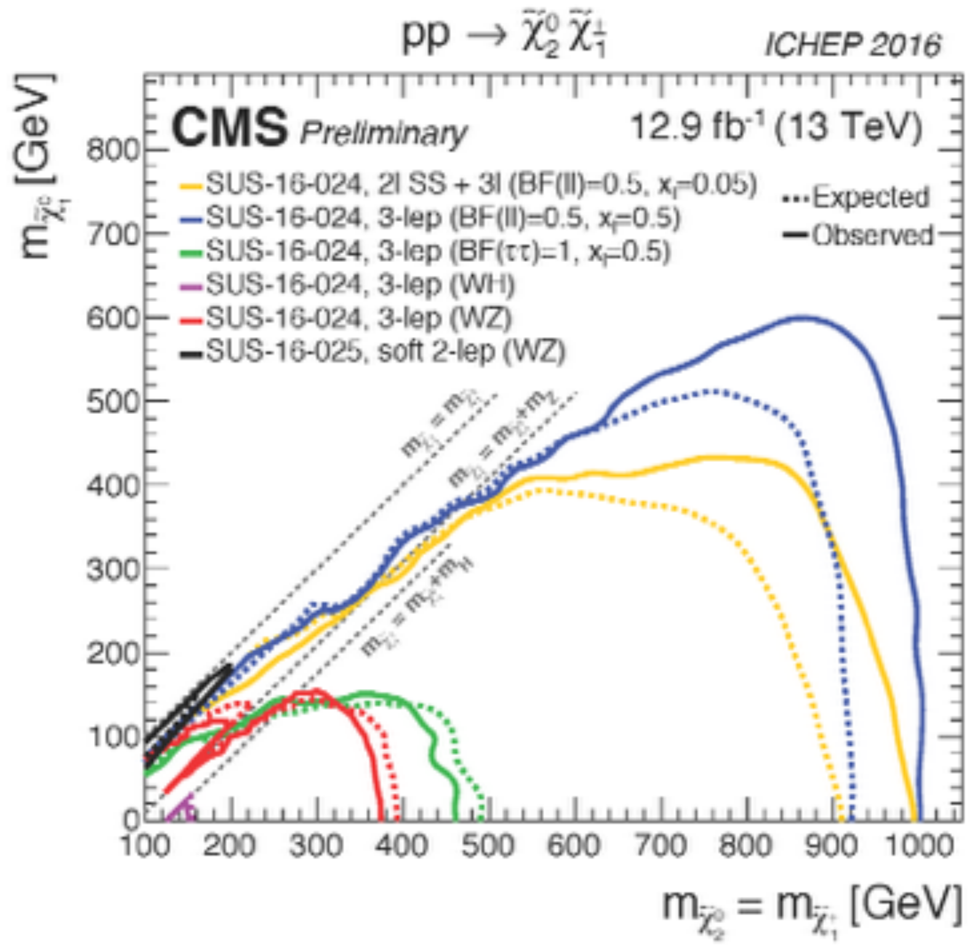
- 13 TeV results **dramatically extend exclusion limits**
- **Still many 8 TeV channels to be updated**
  - Lots of new results yet to come

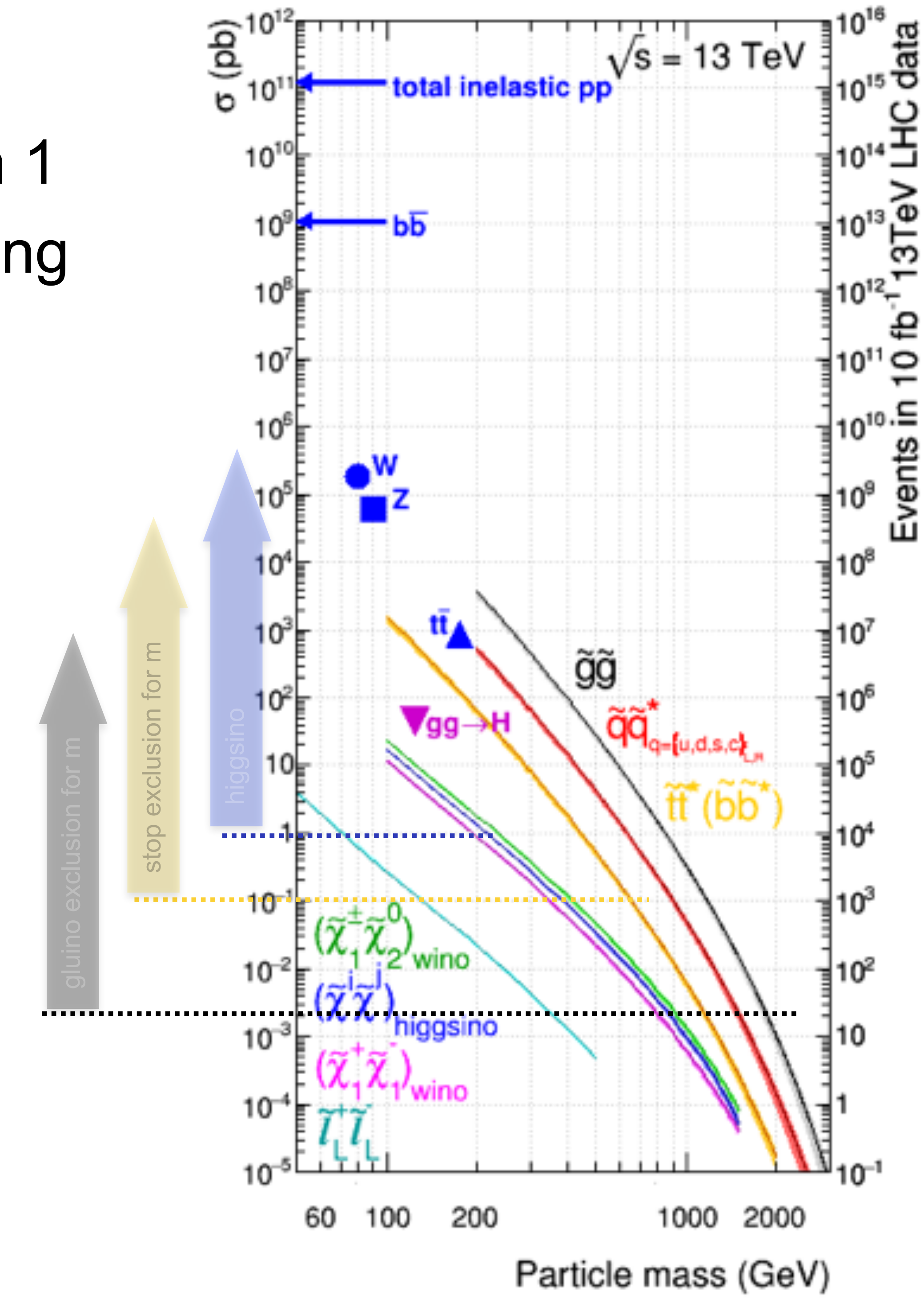


SUSY, DM and LL results not included in this plot

SUPERSYMMETRY

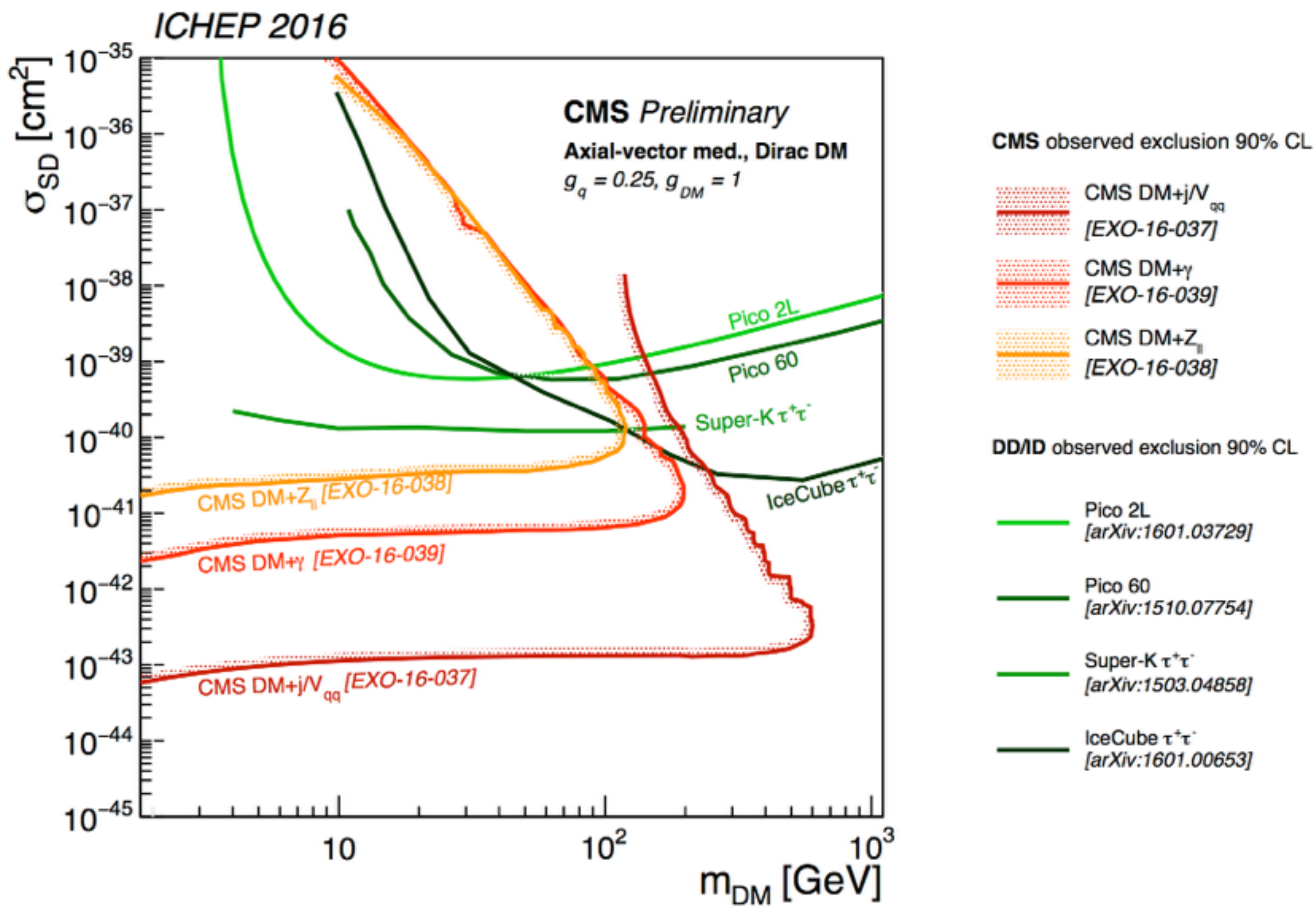
- **Strong-production searches already exceeding exclusion limits at 8 TeV**
- **Extending EWK-ino searches**
  - ICHEP results already competitive with Run 1
  - Not just top-up but new probes: Higgs-tagging





- **Next milestone: *higgsino***

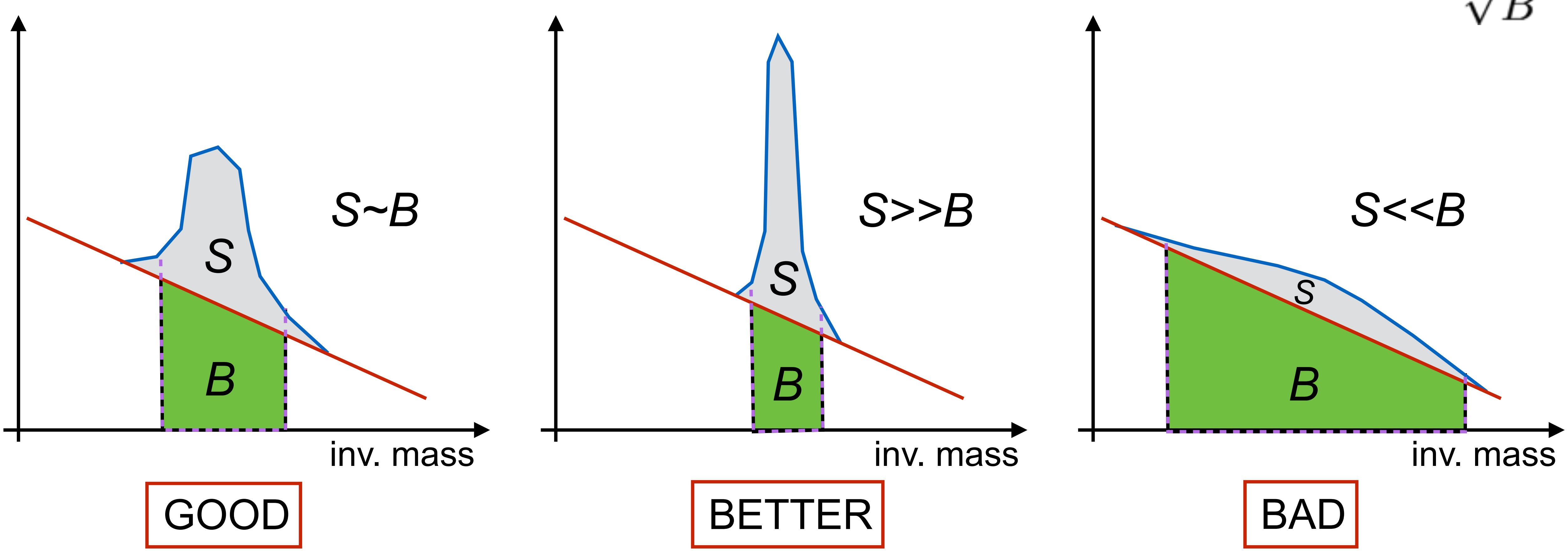
(IN)DIRECT DETECTION VS LHC



EXPERIMENTAL ISSUES: RESOLUTION

- **Mass resolution crucial in resonance searches**
  1. statistical power inversely proportional to the mass resolution
  2. resonance hidden by bad understanding of resolution
- **Need ad-hoc studies and calibration strategies at such large momenta**

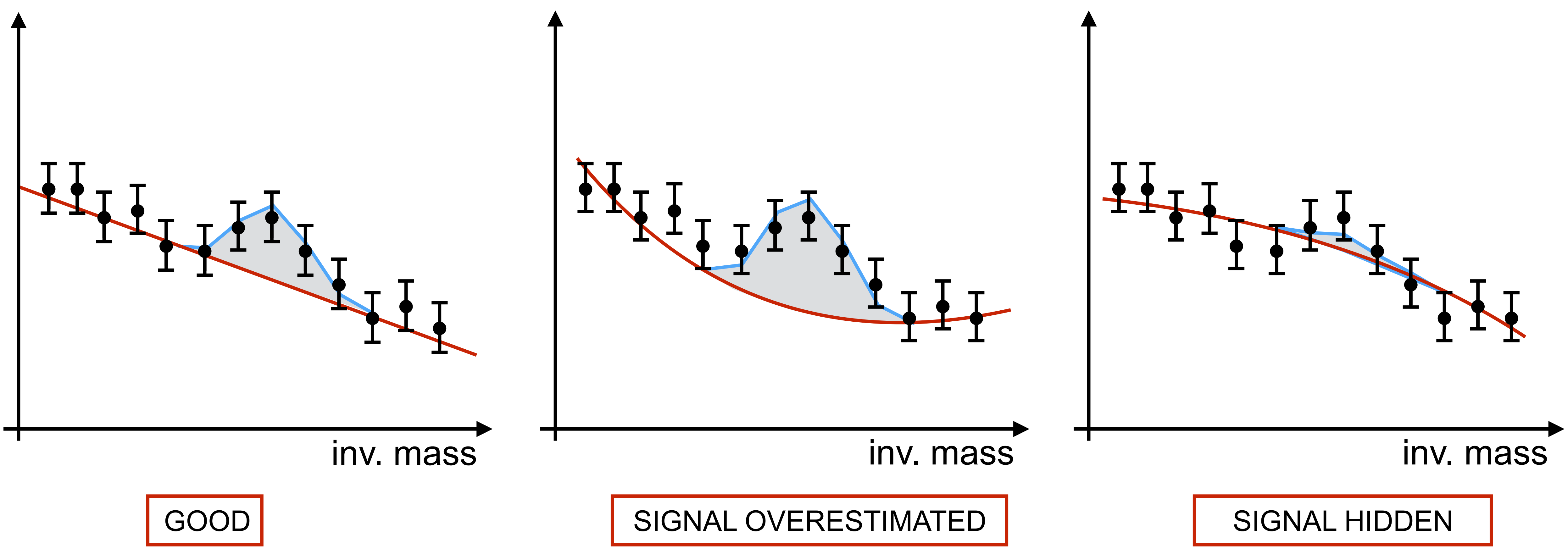
$$significance \sim \frac{S}{\sqrt{B}}$$



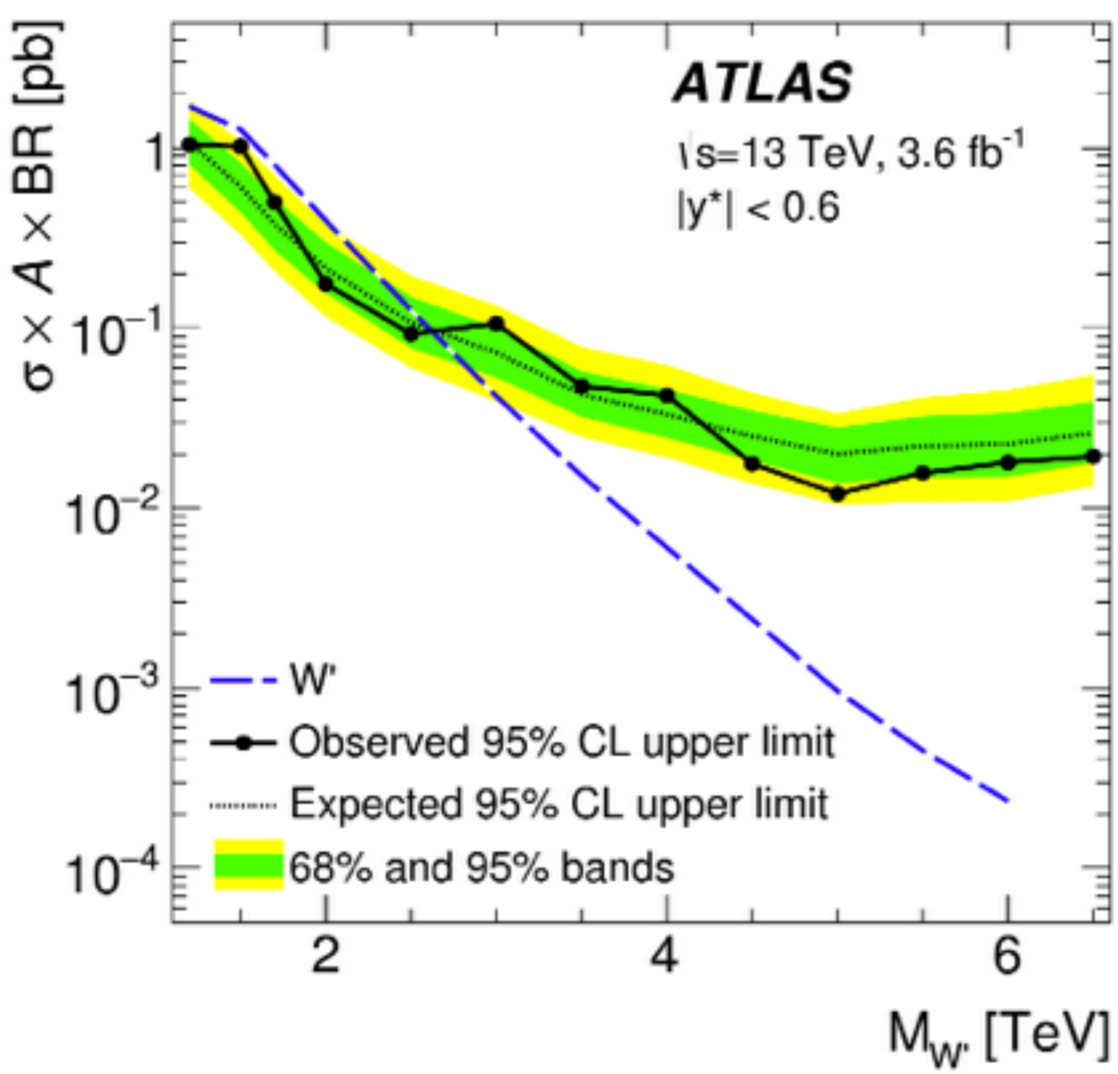
… and signal not distinguishable from background

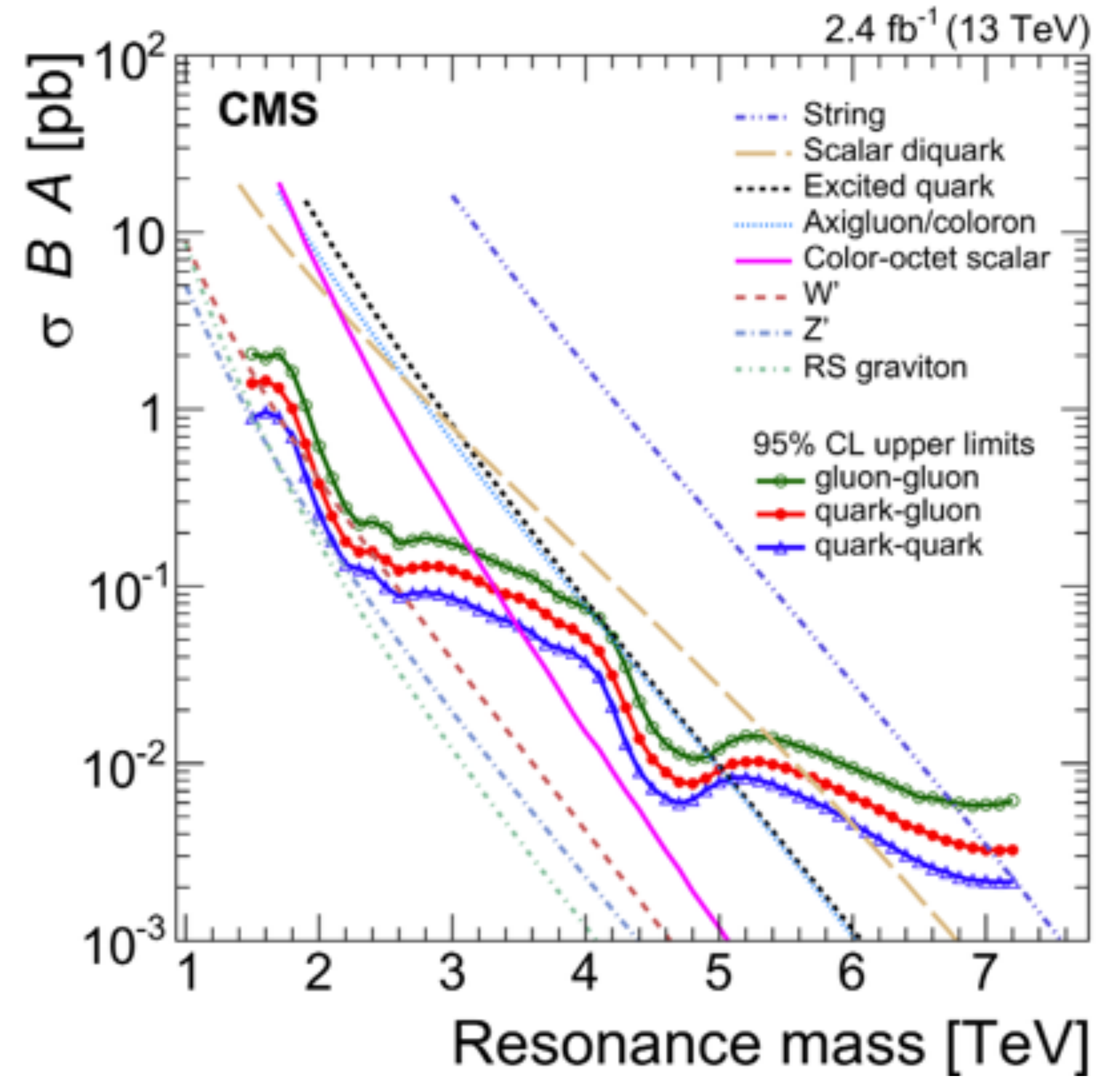
EXPERIMENTAL ISSUES: BACKGROUND

- **Accurate background estimate to not bias signal extraction**
  - signal can be overestimate (or even fake excess)
  - signal can be missed
- **Two techniques**
  - background shape from MC and normalize in control region (usually low mass) + theory/experimental systematics
  - parameterize background shape and fit parameters directly on data



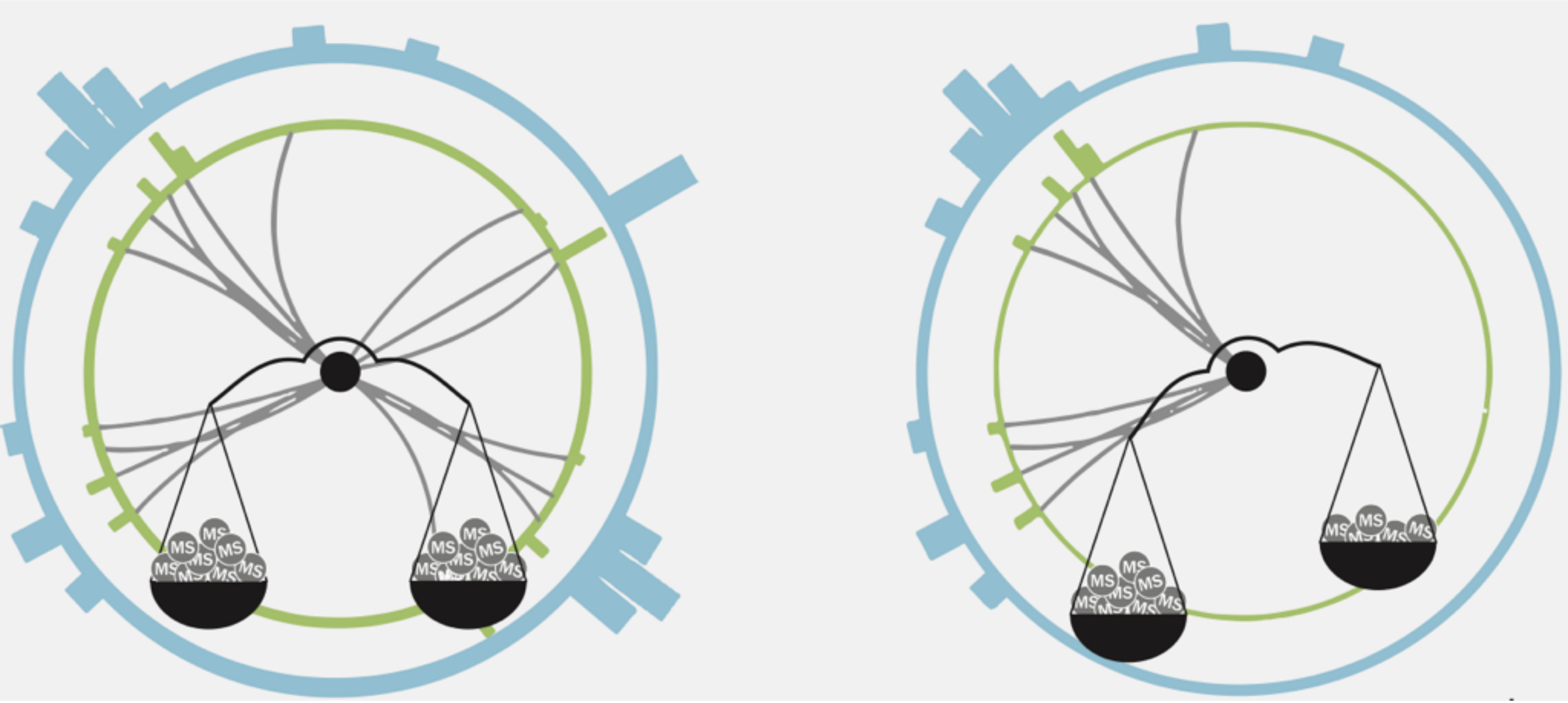
DIJET: RESULTS





- **Several interpretations:**
  - **maximum mass of the excluded region varying between 1 and 7 TeV**
  - **very similar performance between the two experiments**

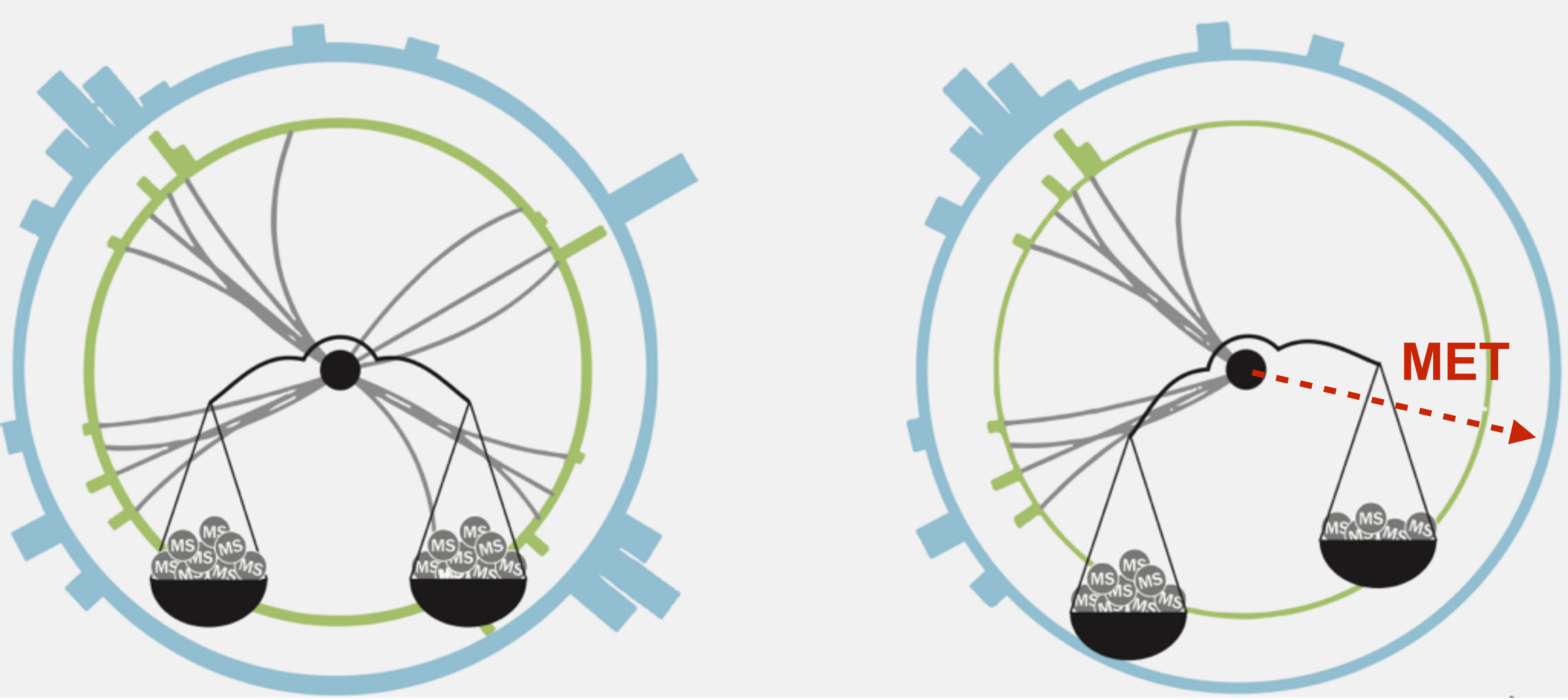
How Does It Look?



SM event

DM event

How Does It Look?

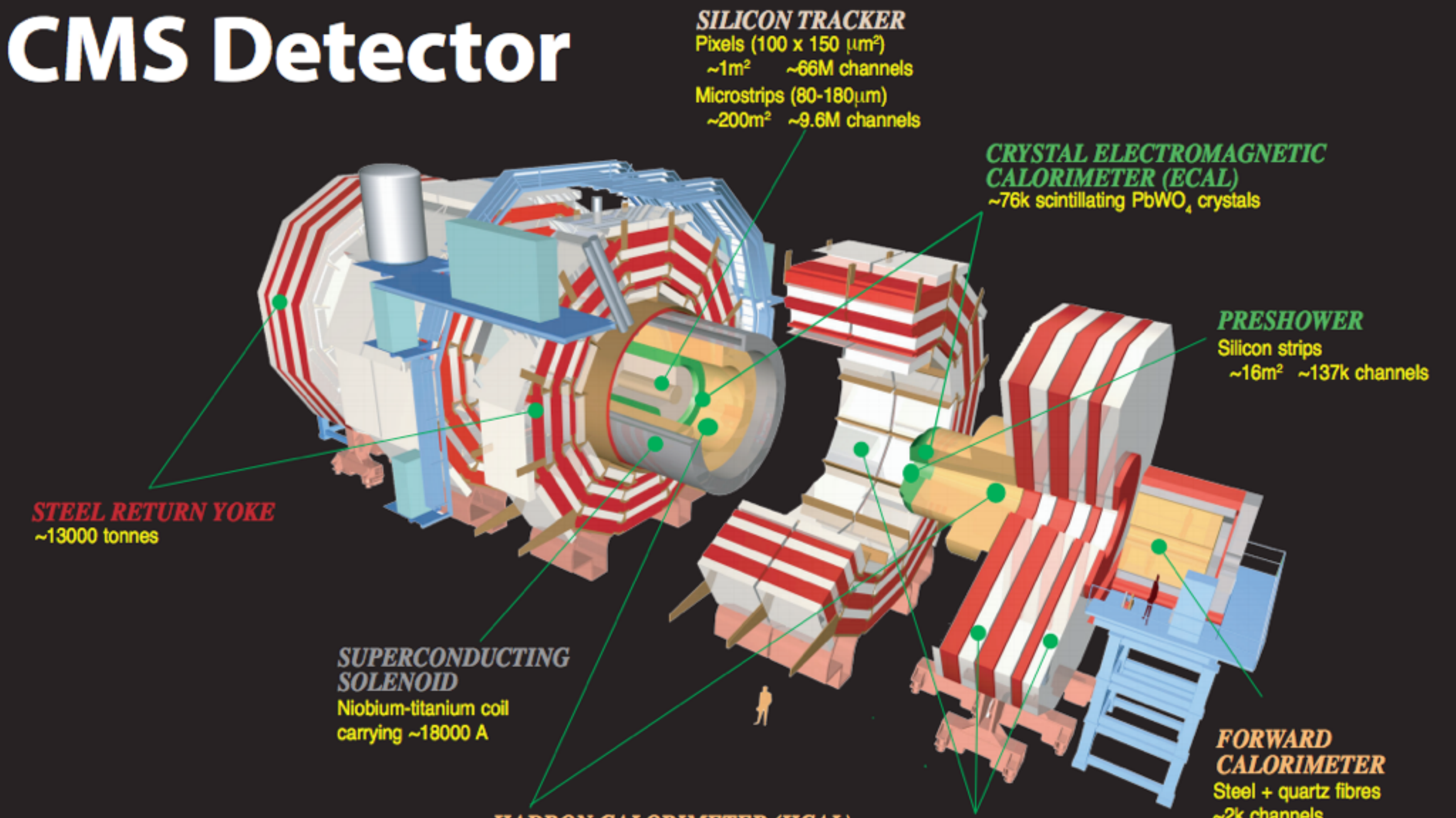


SM event

DM event

$$MET = |\vec{p_t}(missing)| = |-\Sigma_i \vec{p}_{Ti}(visible)|$$

CMS Detector

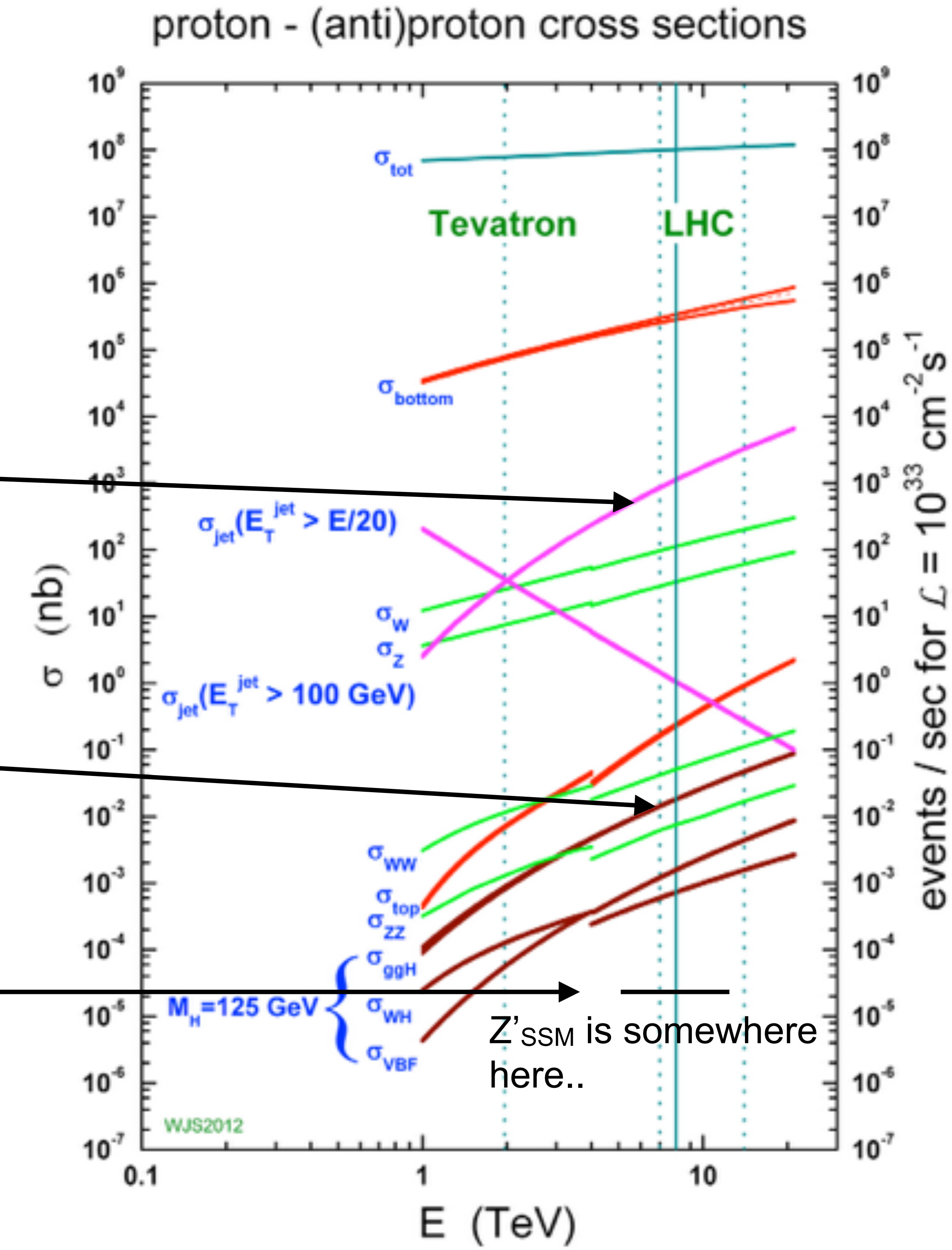


Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

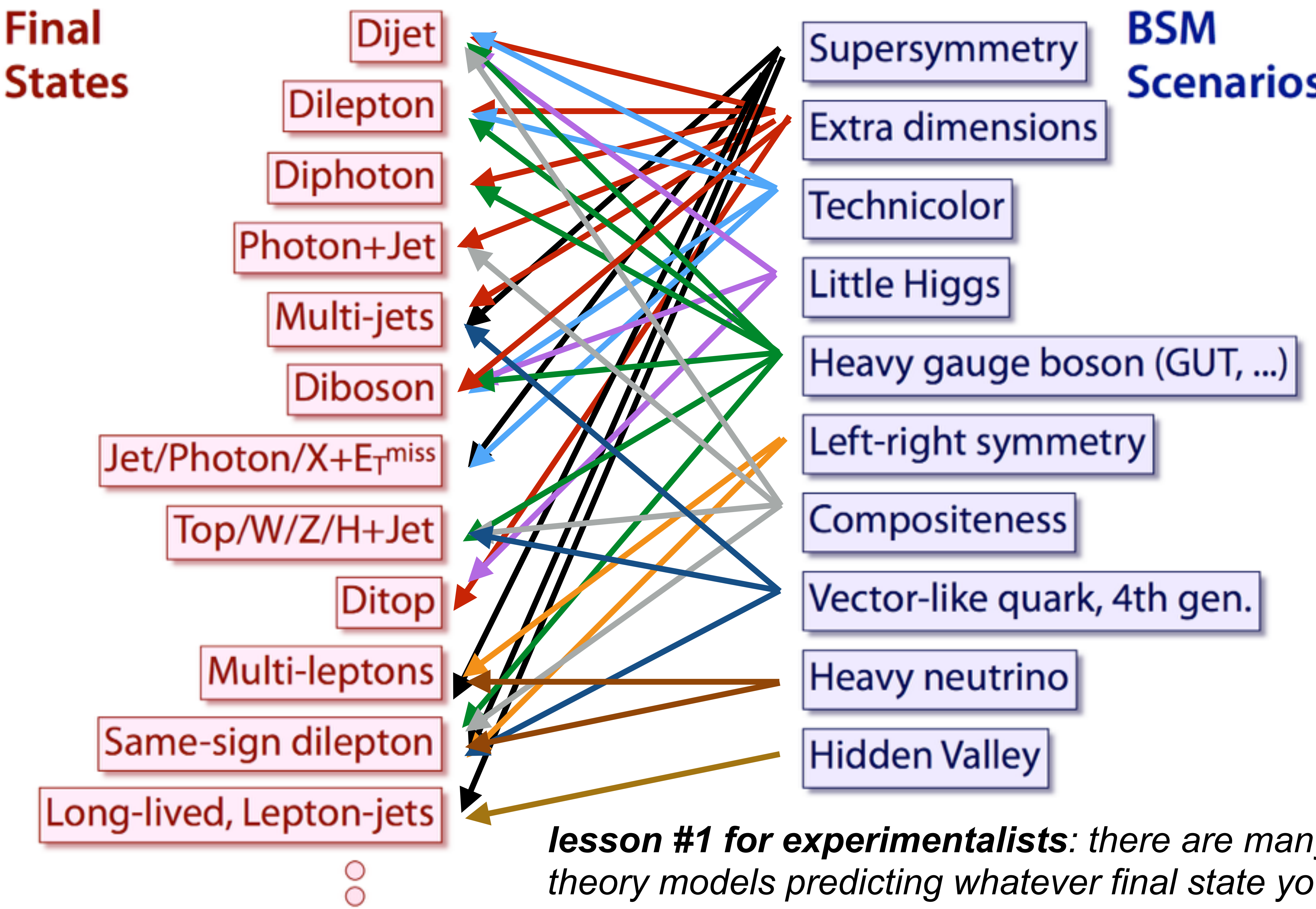
LHC

Cross sections

- **let's compare few cases**
  - jets (p_T>100GeV)
  - H(gluongluon)
  - Z'$_{SSM}$

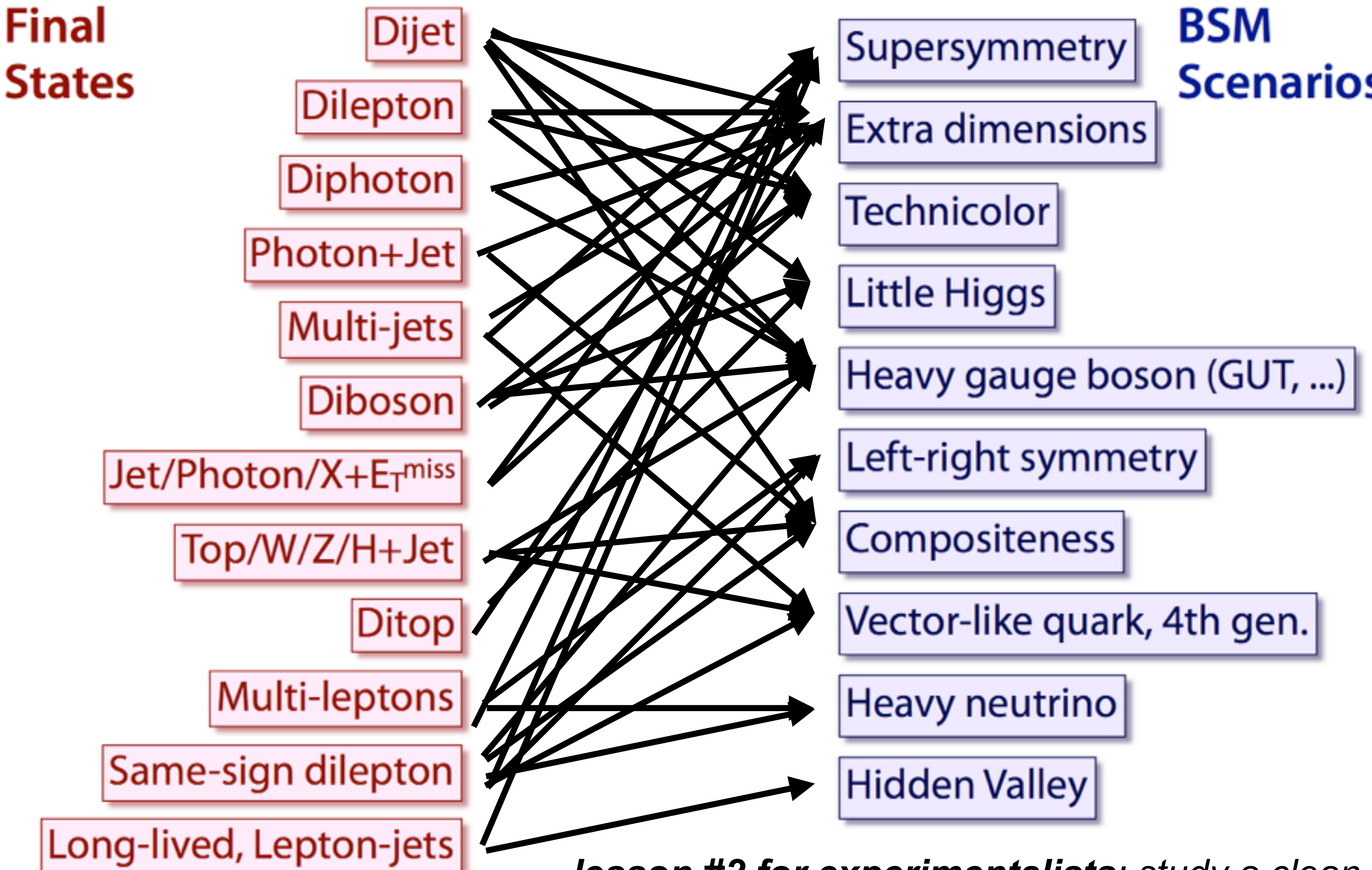


FROM THEORY TO SIGNATURES



lesson #1 for experimentalists*: there are many theory models predicting whatever final state you like*

FROM SIGNATURES TO THEORY



lesson #2 for experimentalists*: study a clean and striking signature. If (not) found, interpret the result*