SEARCH FOR NEW PHYSICS AT THE LHC

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Brief Outline

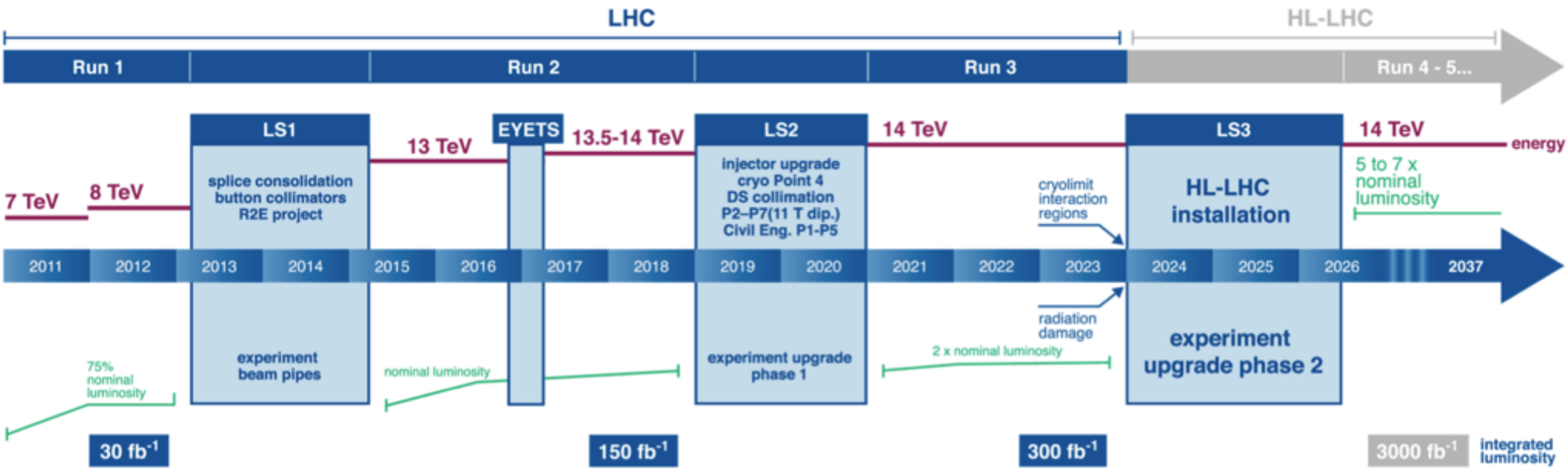
- **Summary of current new physics searches at the LHC (ATLAS and CMS)**
  – focus on resonances, dark matter searches, long-lived particles
  – many other scenarios not discussed, e.g. SUSY

- **Some perspectives**
  – how do we do in the next 10 years or so?

- **Link to the activities of the department**

LHC Plans

- From Leandro's talk
- **Nota bene**: l**uminosity collected at 13 TeV is not equivalent to 8 TeV for new physics searches** (more later)



Run 1	Magnet splice update	Run 2 at ~full design energy	Phase I upgrades (injectors)	Run 3 → original design lumi	Phase II upgrades (final focus)	HL-LHC: ten times design lumi

LHC PLANS

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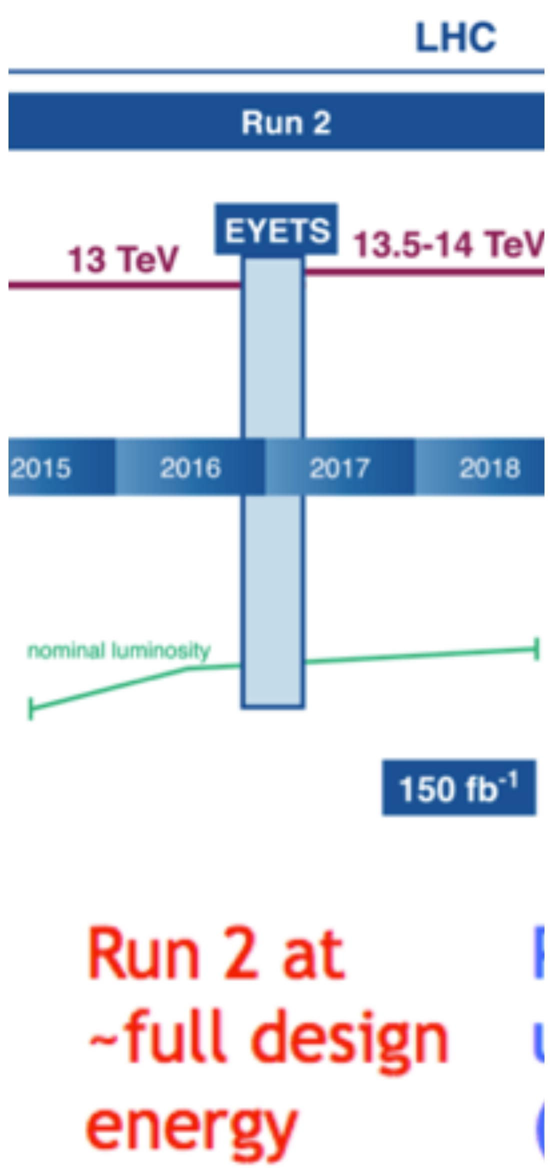
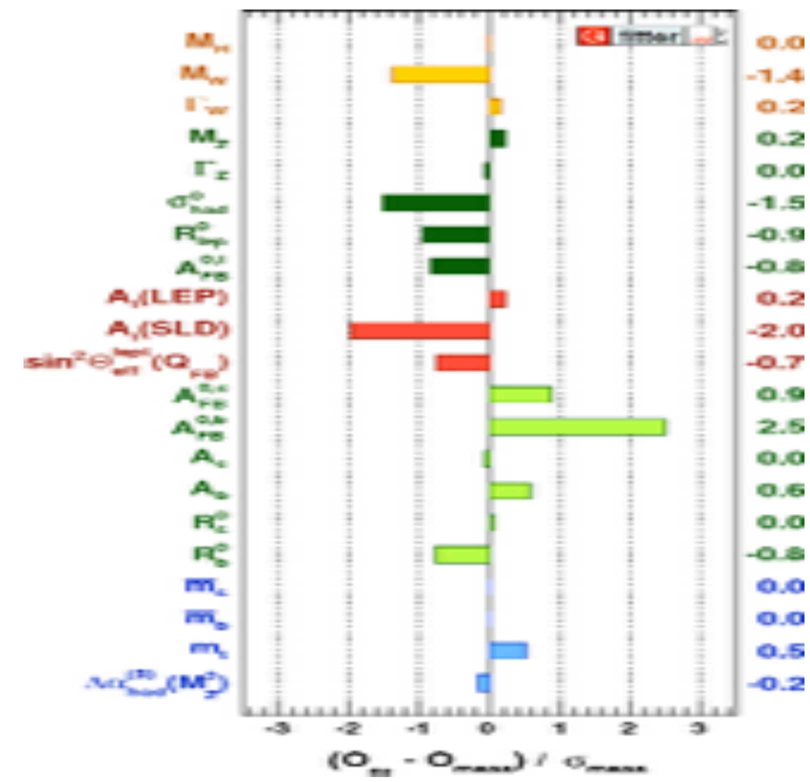


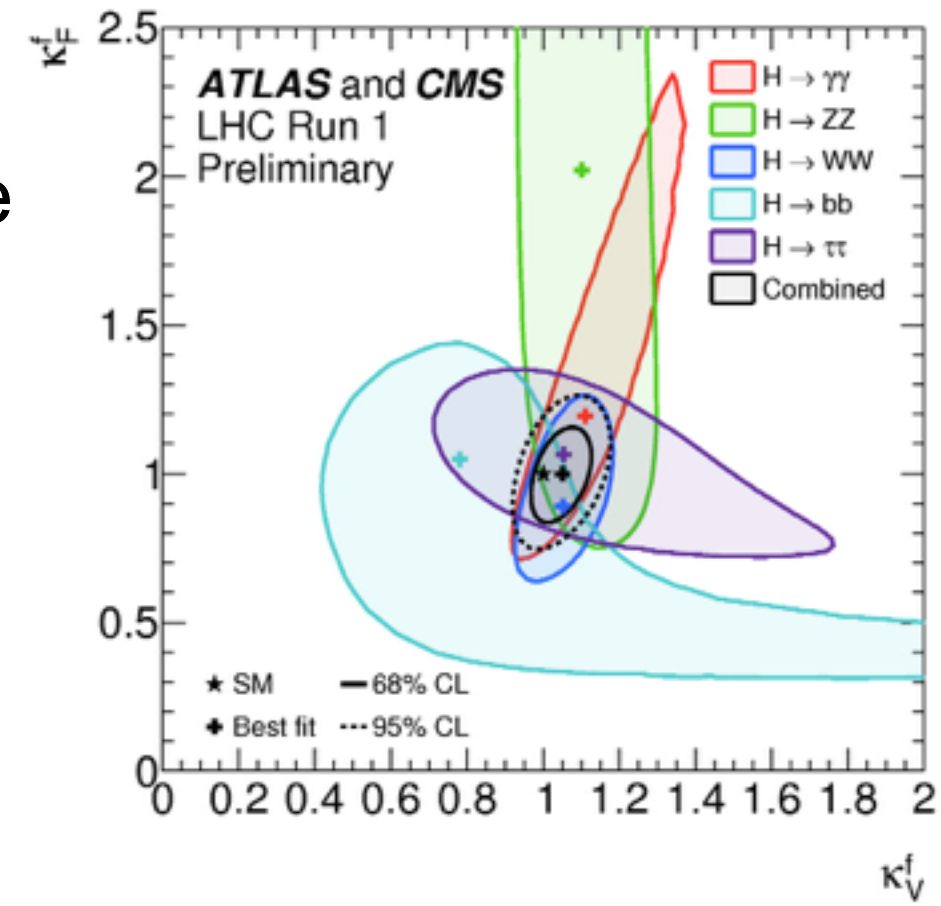
I will talk mainly about this period, now to 2018-2020

WHY NEW PHYSICS? SM LOOKS HEALTHY

- **Precision tests successful (e.g. LEP)**
  - small discrepancies but not so worrisome



- **Higgs was predicted and then discovered (by LHC)**
  - present measurements indicate it is SM-like



- ***<u>Why looking for something else?</u>***

OPEN ISSUES (JUST A FEW)

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 **gravity is so weak**?
   – 40 orders of magnitude weaker than e-m!
4. Why only **5% of matter is made of ordinary SM particles**?
   – what is the dark matter?
5. Why the most massive particle **(top) is "only" 200 time heavier than the proton**?
   – desert above 170 GeV

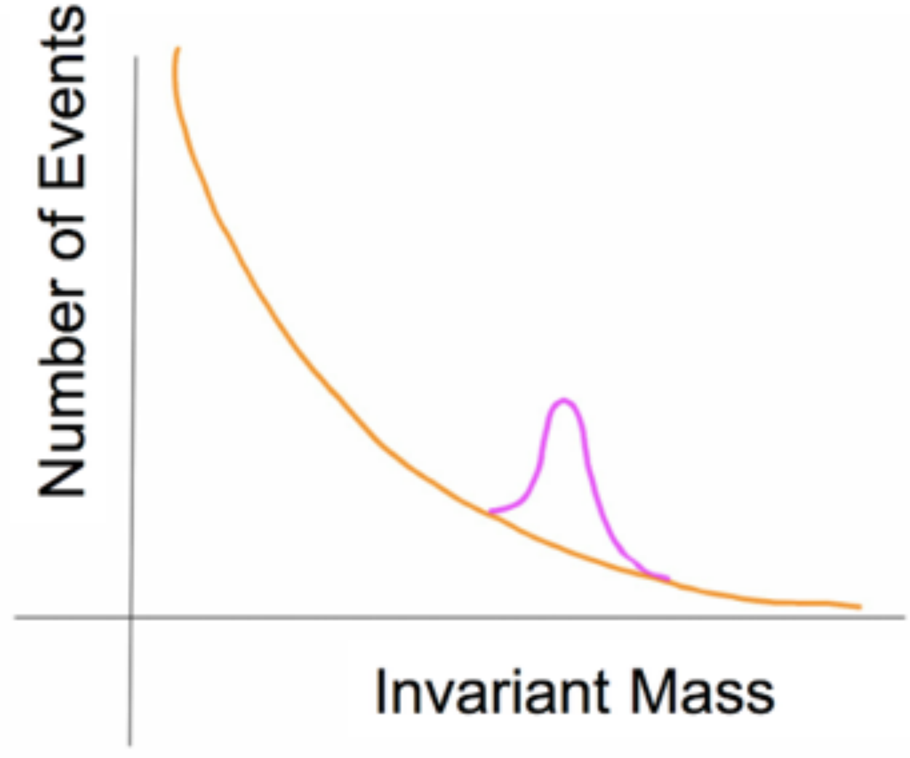
FEW SOLUTIONS

- **Supersimmetry**
  - may predict heavy resonances
  - may explain dark matter
  - some new SUSY particles can be long-lived
- **Extra Dimensions**
  - may predict heavy resonances
- **Weakly interacting particles**
  - candidates for dark matter
  - interact with ordinary matter via new mediators (which would represent new resonances)
- …

High Mass Resonances

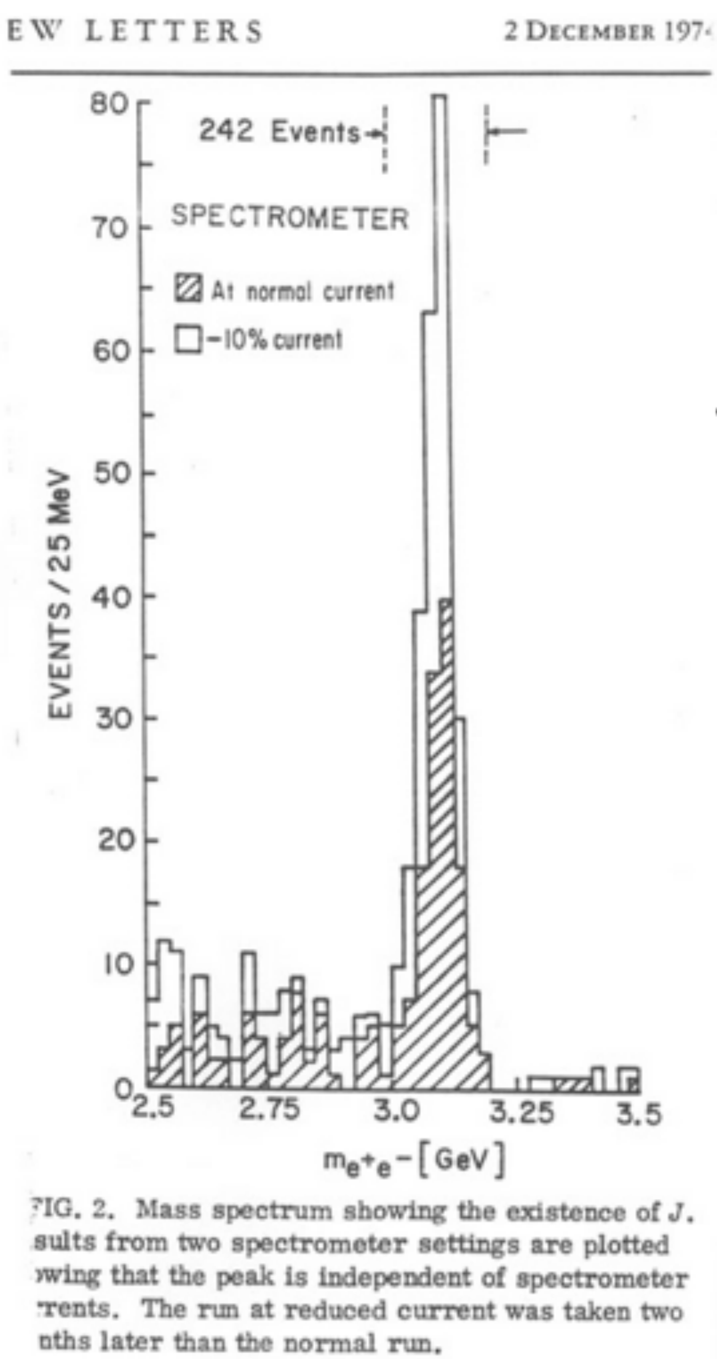
WHY HIGH MASS RESONANCES

- Fully reconstructed resonances represent **the simplest way to discover new particles**
  - striking and incontrovertible signature
- A **statistically significant peak over a smooth background**
  - experimentally robust
  - small systematics
  - difficult for unknown backgrounds to mimic
- The **most important search method when new energies** are explored
  - the goal of LHC
  - particularly relevant at start-up (Run2)

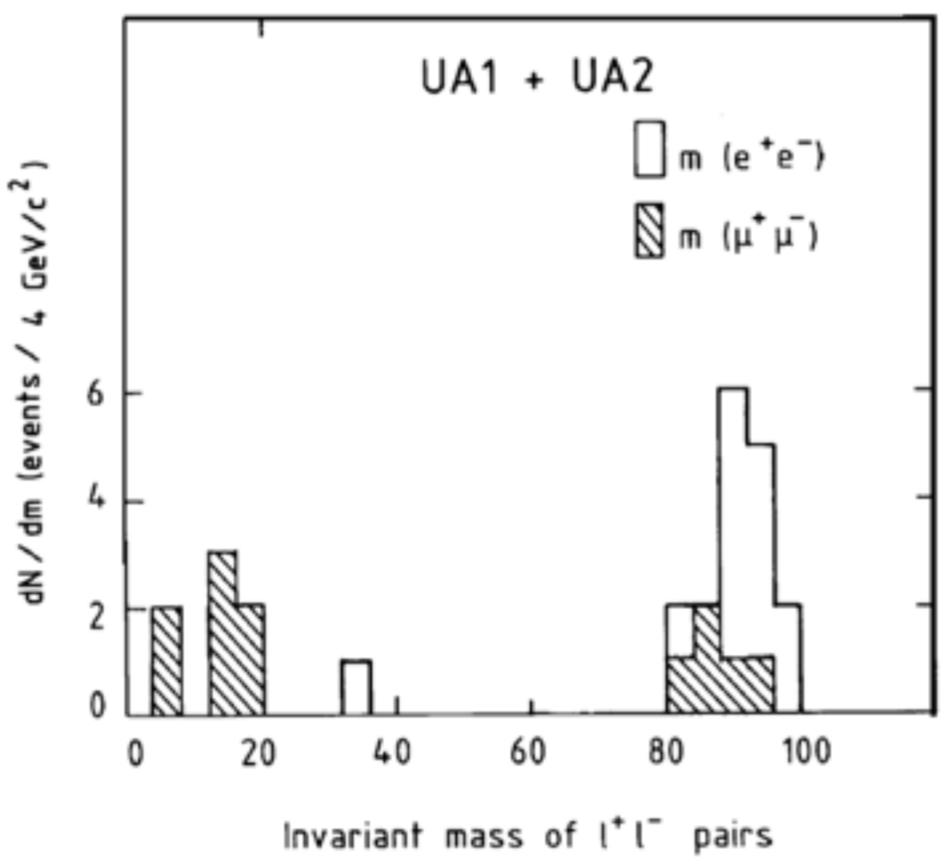


Resonances in Past Discoveries

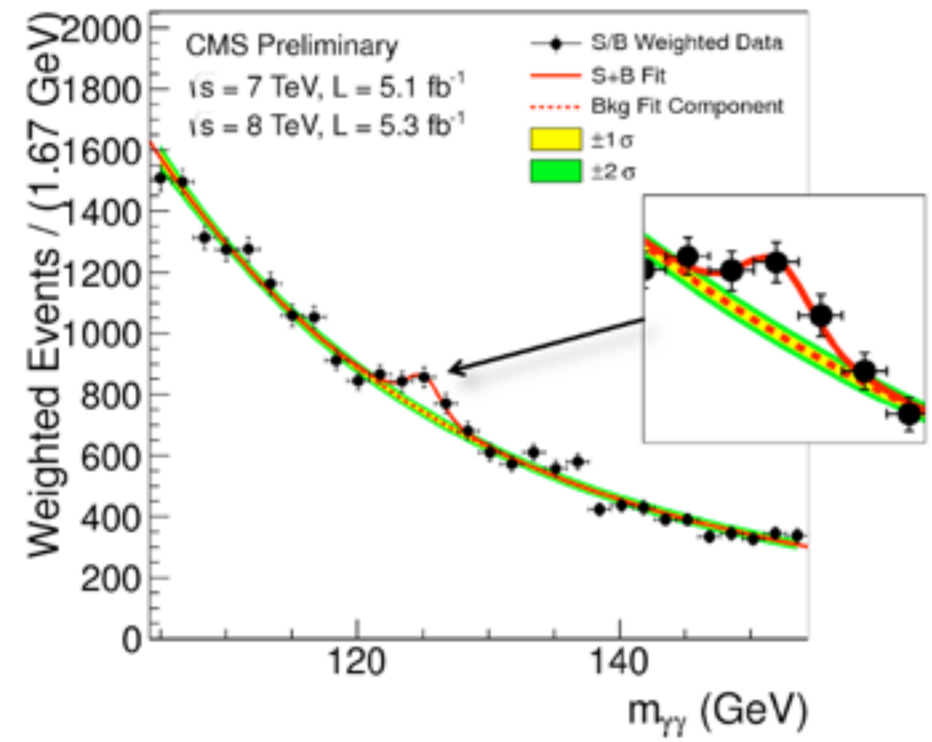
J/psi

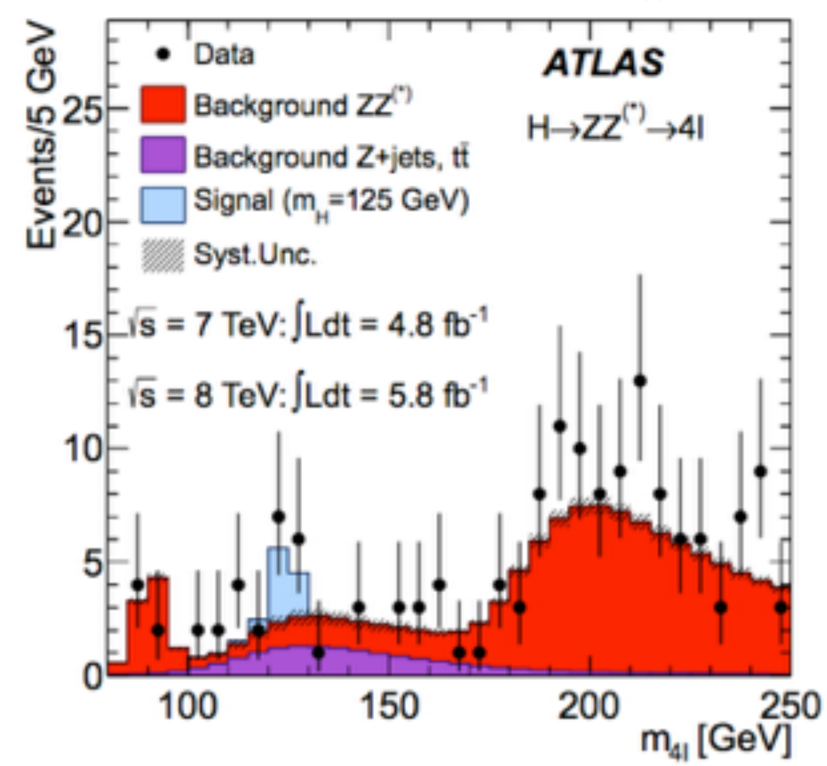


Z



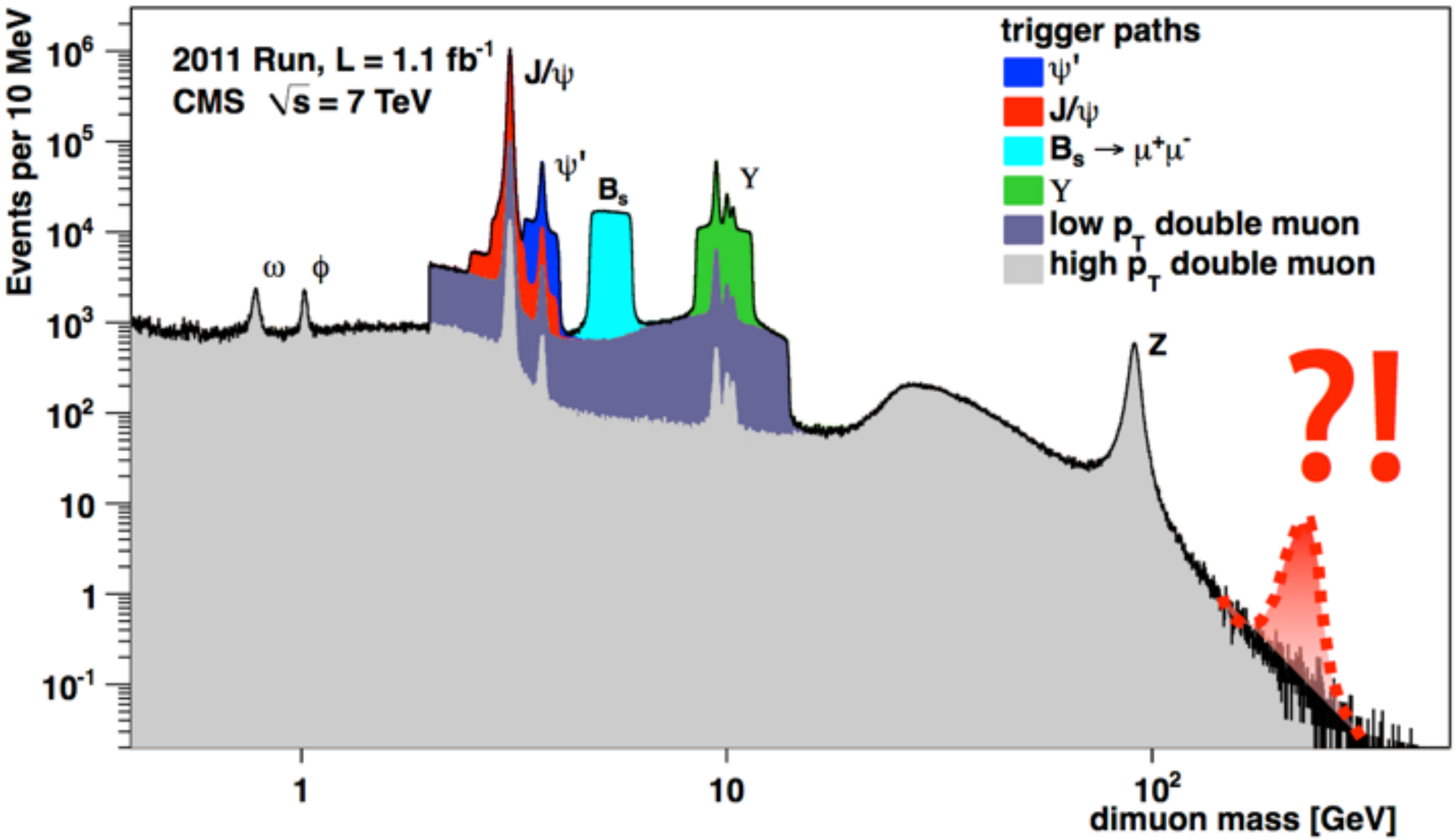
Higgs





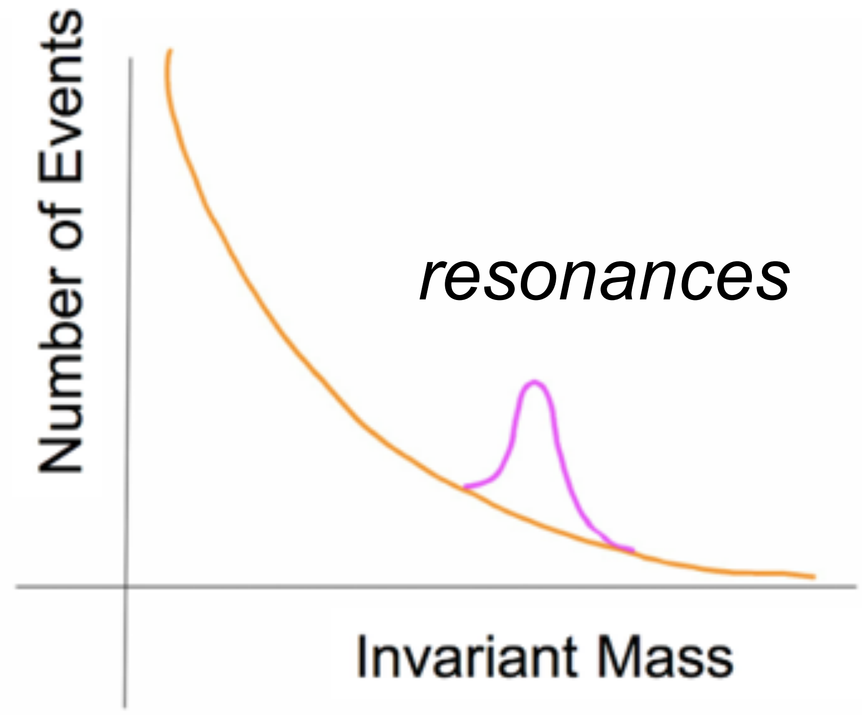
PROS IN HIGH MASS SEARCHES

- Searches with **small systematics**
  - compared to searches based on tails (Missing ET)
- **Model-independent probe** to new physics
- Predicted in **many beyond SM scenarios**



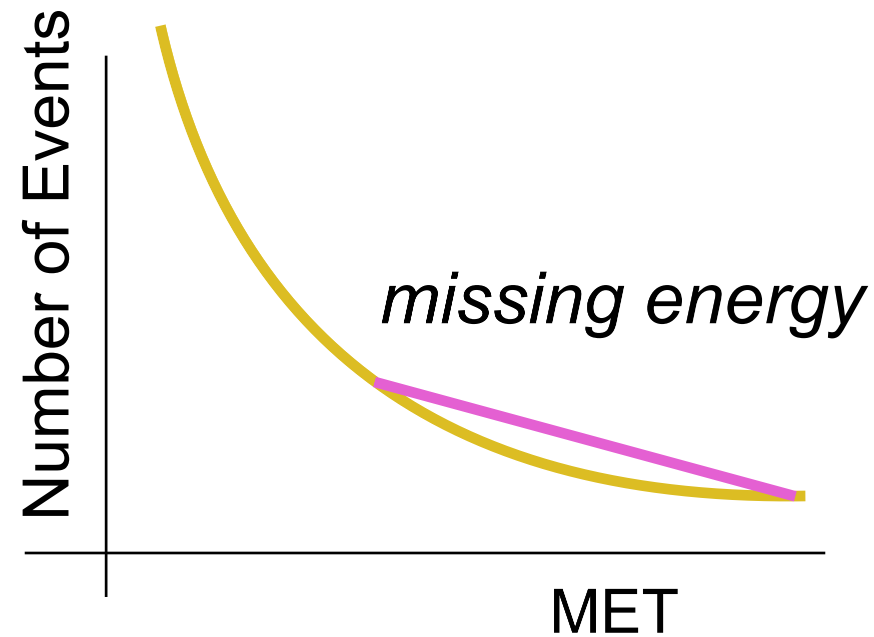
Resonances vs Missing Energy

- Resonances are **not the only candle** to find new physics
- **Missing energy (MET) if weekly interacting particles are involved** (Dark Matter, SUSY, etc…)



- Striking signatures but **sensitive to tails in detector**
  - noise, dead hot channels, calibrations

- **MET powerful to set limits, complicated to claim discoveries**

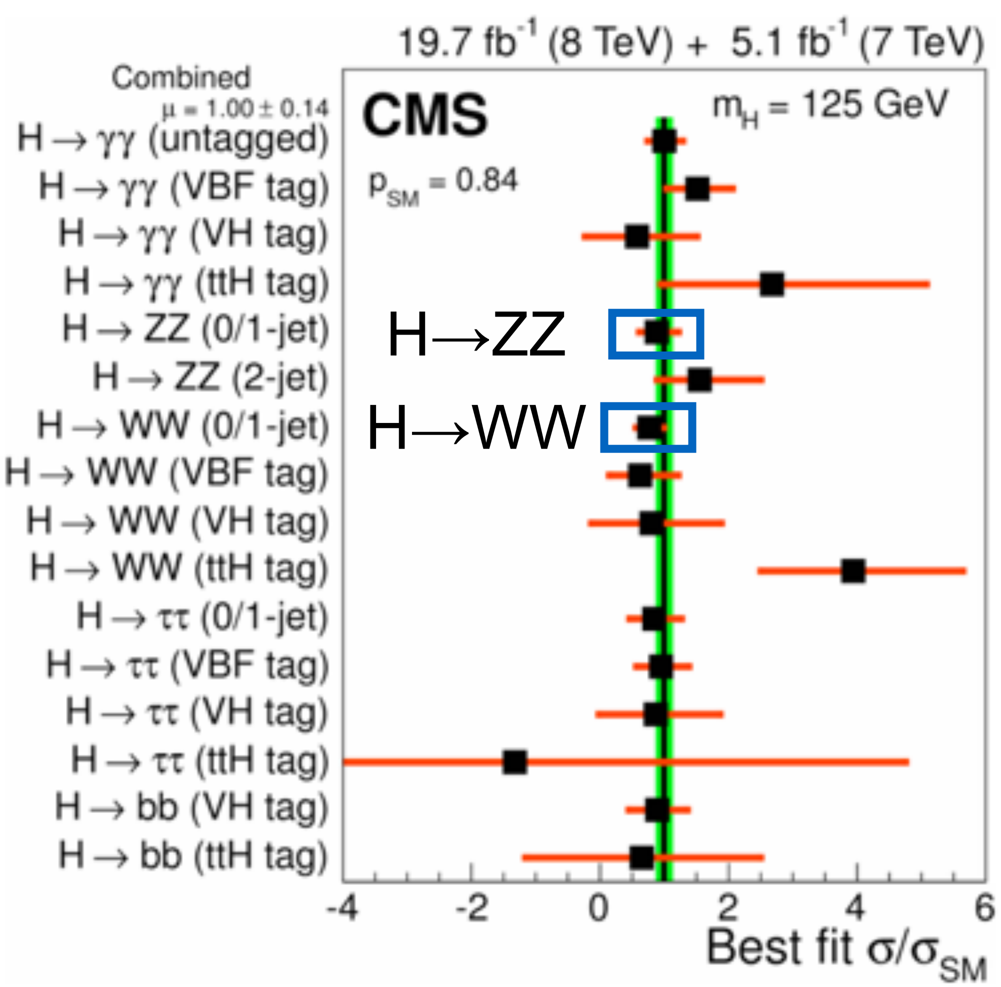


EXAMPLE: H→ZZ VS H→WW

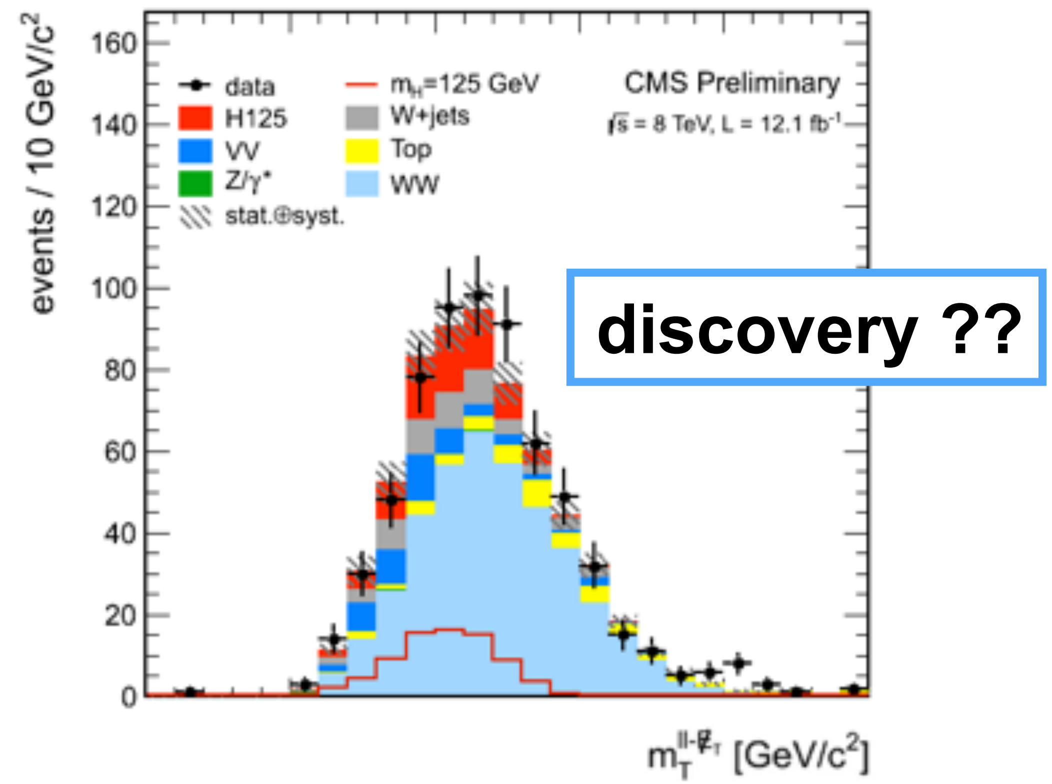
Decay channel	Branching ratio [%]
$H \to b\bar{b}$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to c\bar{c}$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

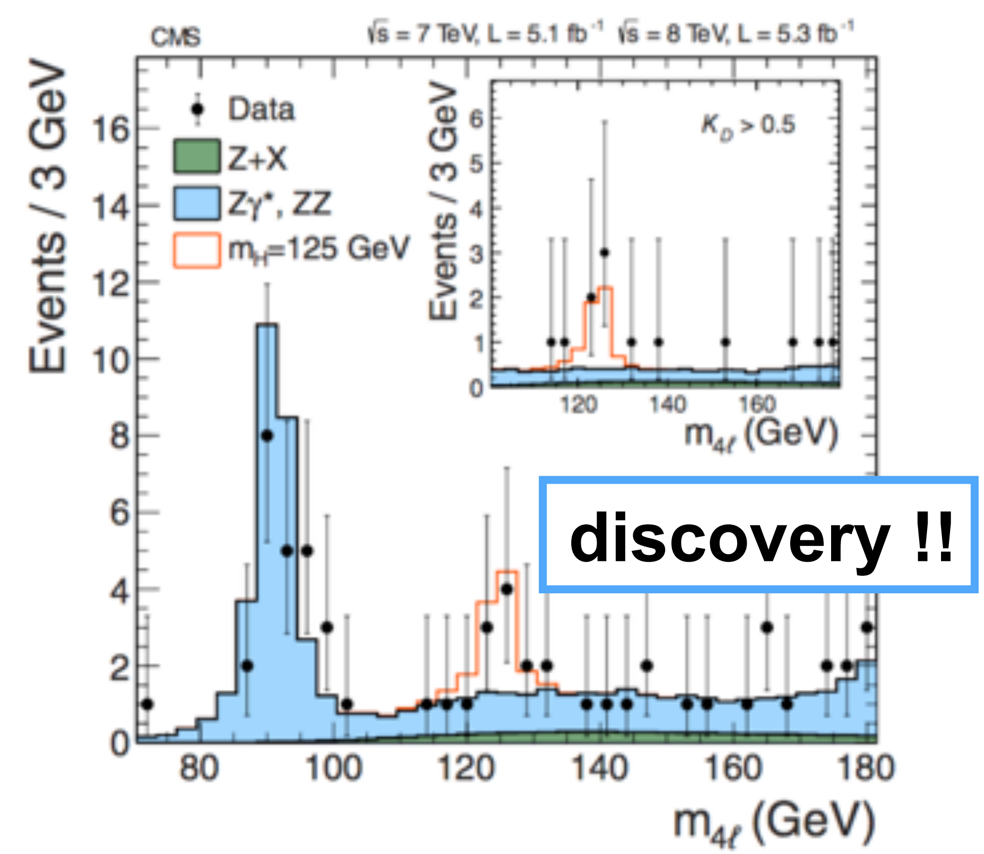
includes MET ($H \to WW$)

fully reco'ed ($H \to ZZ$)



but →





From Theory to Signatures

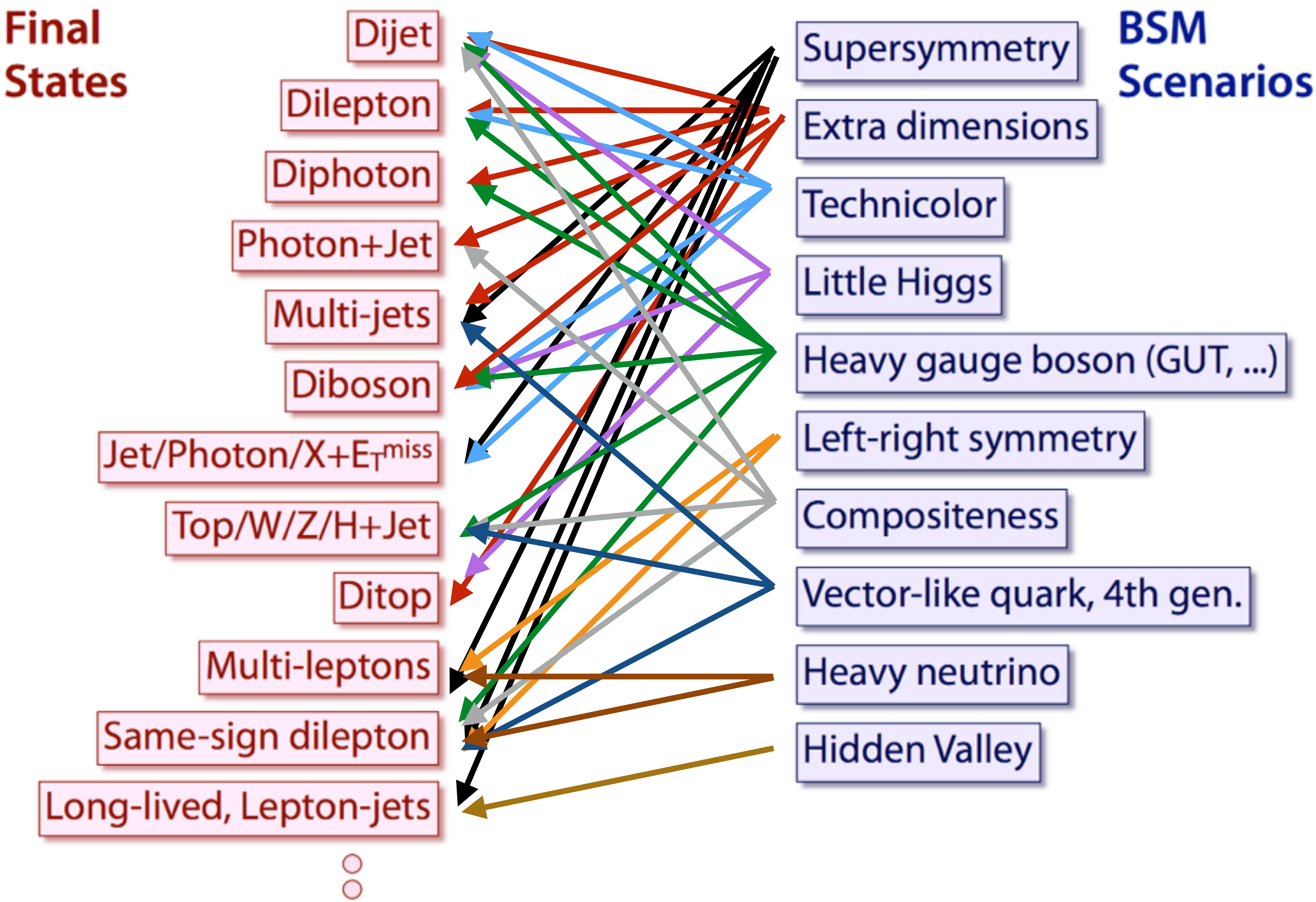
Final States

- Dijet
- Dilepton
- Diphoton
- Photon+Jet
- Multi-jets
- Diboson
- Jet/Photon/X+E_T^{miss}
- Top/W/Z/H+Jet
- Ditop
- Multi-leptons
- Same-sign dilepton
- Long-lived, Lepton-jets
- ⋮

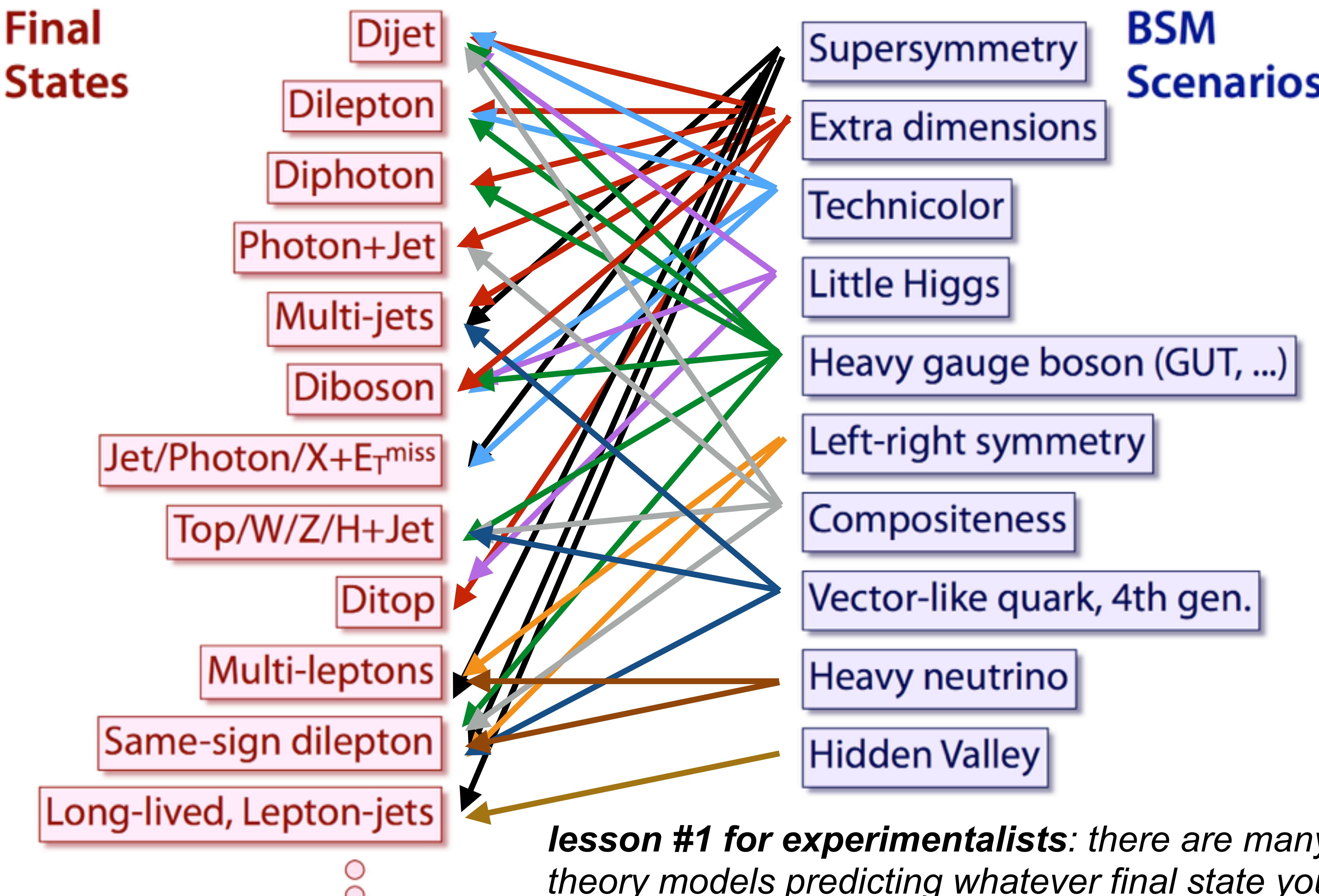
BSM Scenarios

- Supersymmetry
- Extra dimensions
- Technicolor
- Little Higgs
- Heavy gauge boson (GUT, ...)
- Left-right symmetry
- Compositeness
- Vector-like quark, 4th gen.
- Heavy neutrino
- Hidden Valley

From Theory to Signatures

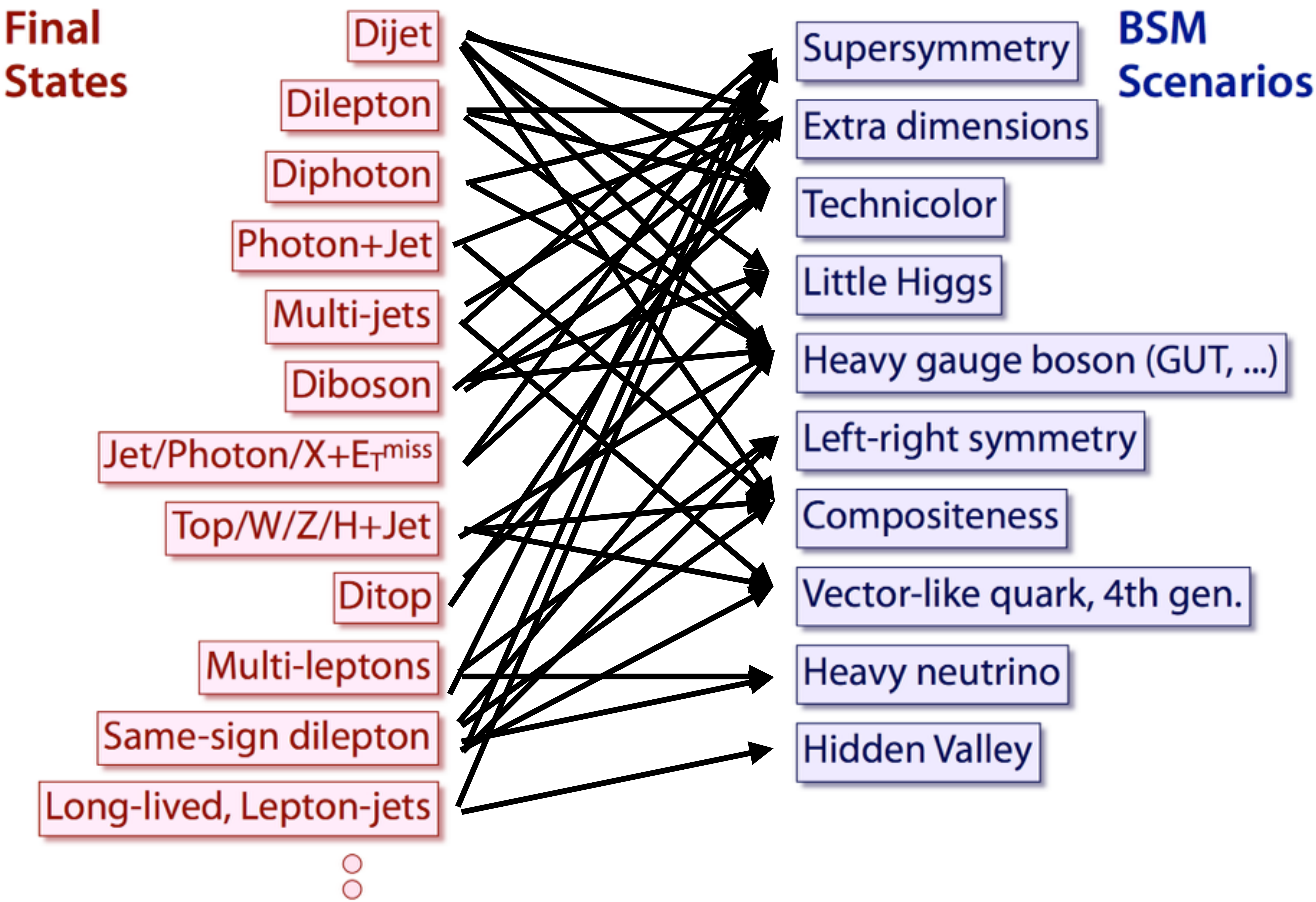


FROM THEORY TO SIGNATURES



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

From Signatures to Theory



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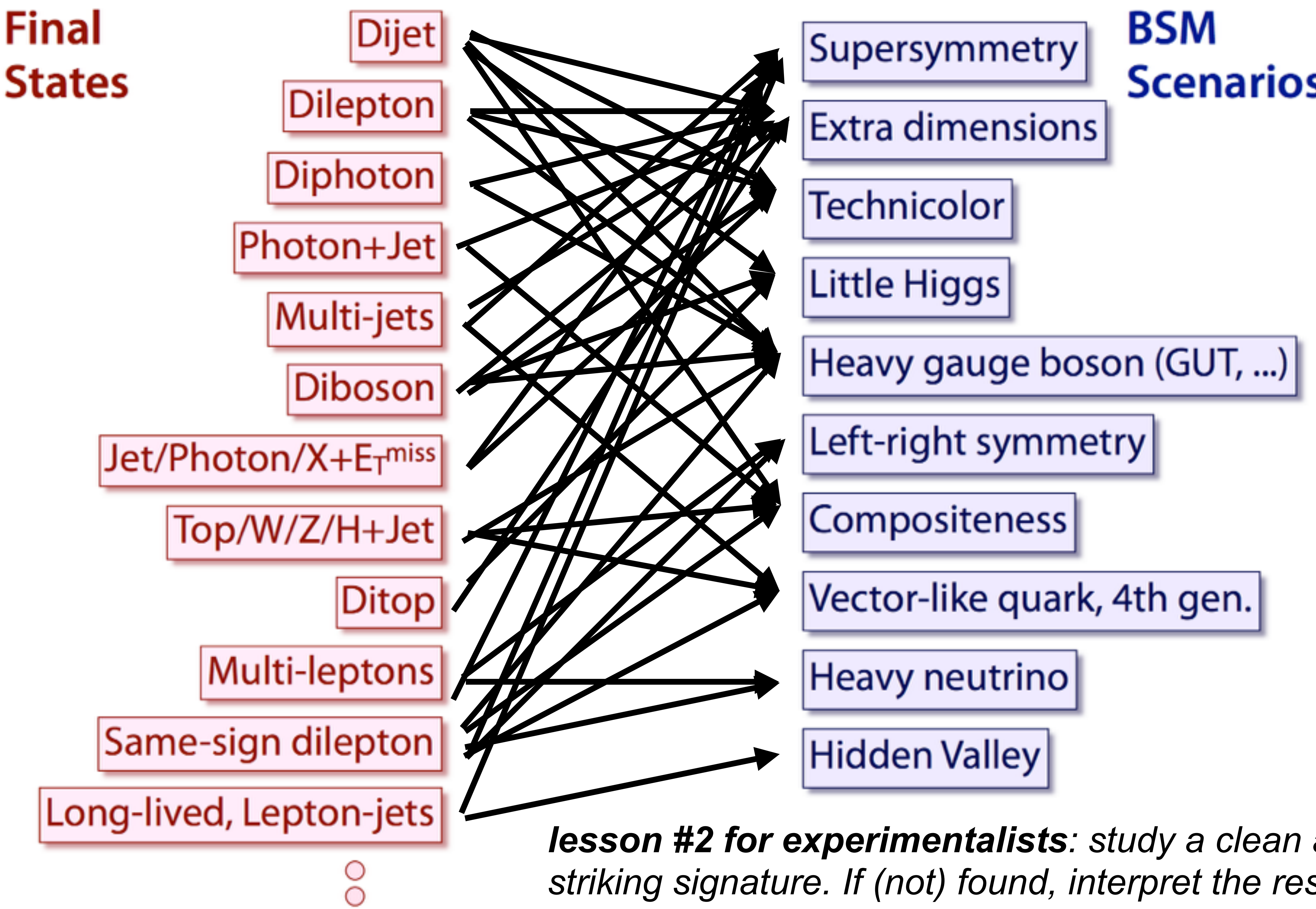


***lesson #2 for experimentalists**: study a clean and striking signature. If (not) found, interpret the result*

From Signatures to Theory

Final States

Dijet

Dilepton

Diphoton

Diboson

This Talk

Biased list!

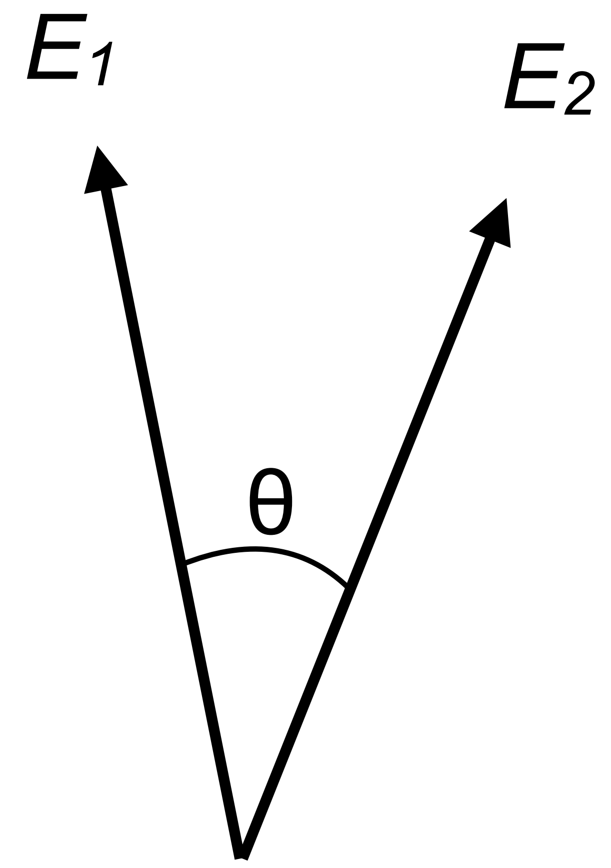
– corresponds to some of the signatures with largest discovery potential at the start of Run2

SEARCH STRATEGY

1. Pick your **favorite di-object** final state
   - crucial expertise in reconstruction and detector
2. Be **as model-independent as possible**
   - do not design selection based on a particular model
   - be loose in kinematics
3. **Reconstruct invariant mass**

at high energies

$$M = \sqrt{2E_1E_2(1 - cos\theta)}$$



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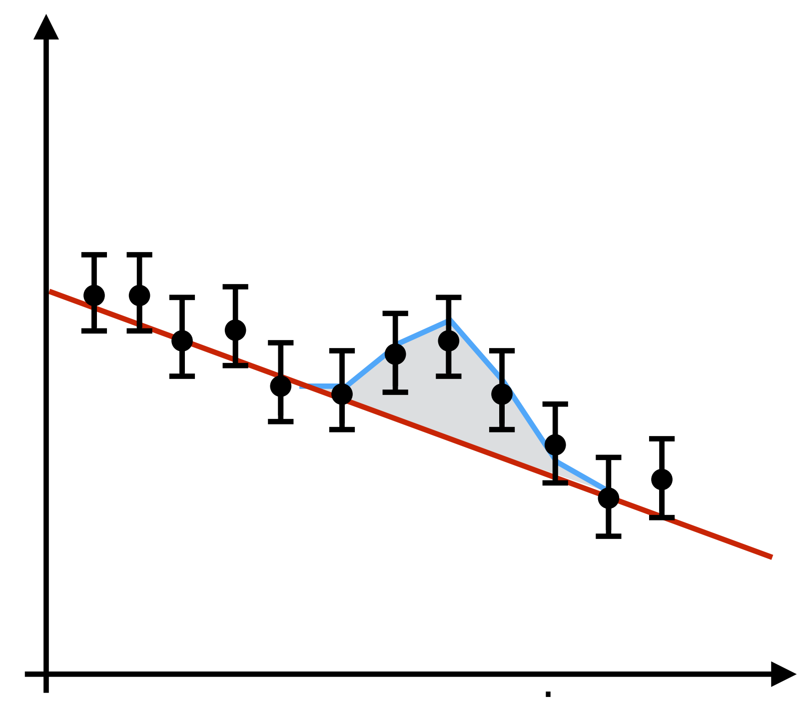
4. Simple **signal extraction**
   - cut and count techniques
   - likelihood fit based on a smooth background + gaussian-like signal



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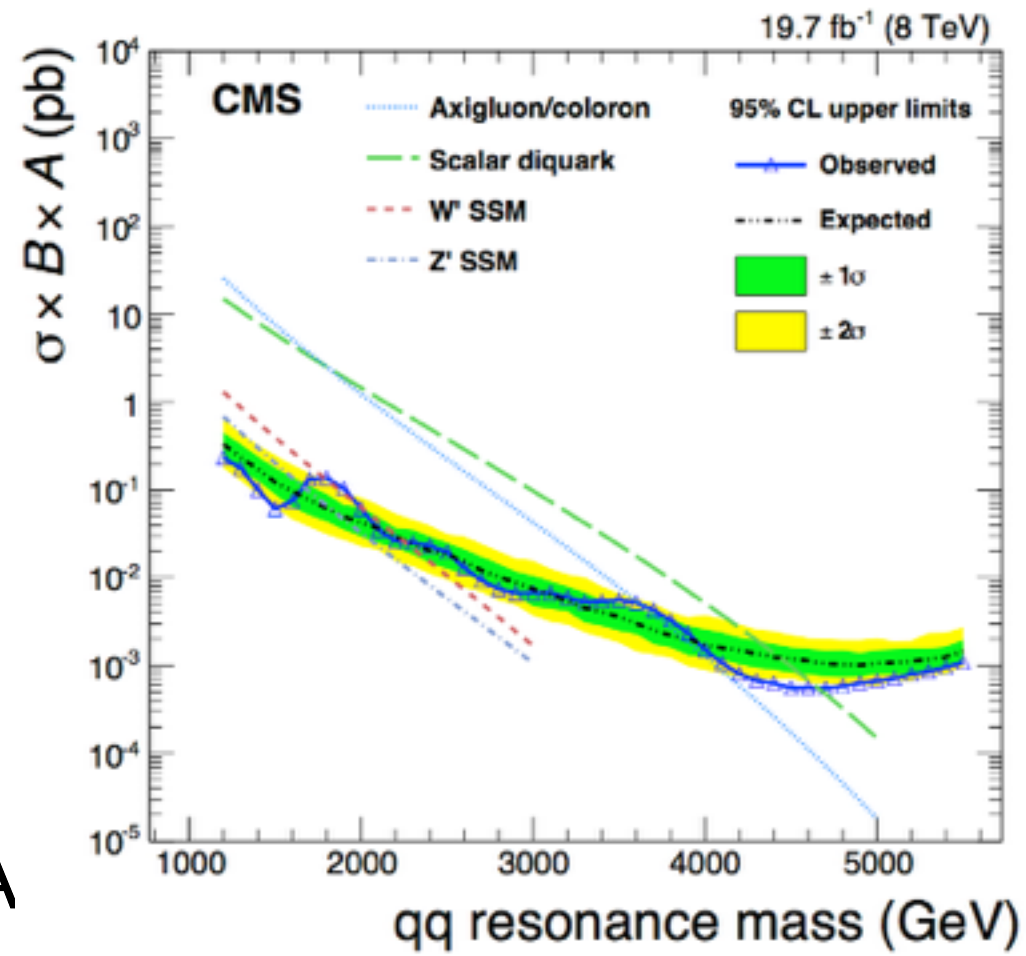
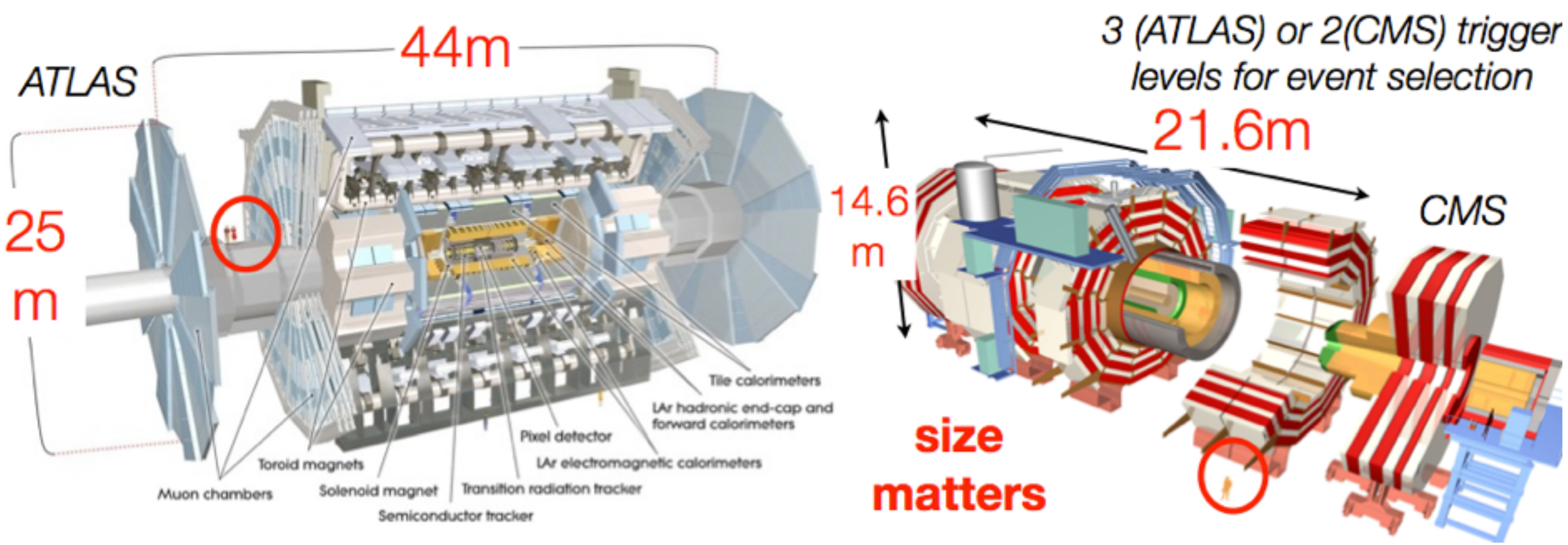
4. Simple **signal extraction**
   – cut and count techniques
   – likelihood fit based on a smooth background + gaussian-like signal
5. **Model-independent limits**
   – e.g. report excesses/limits in σ x BR x A
6. Put **constraints in several BSM scenarios … or … discover new physics**



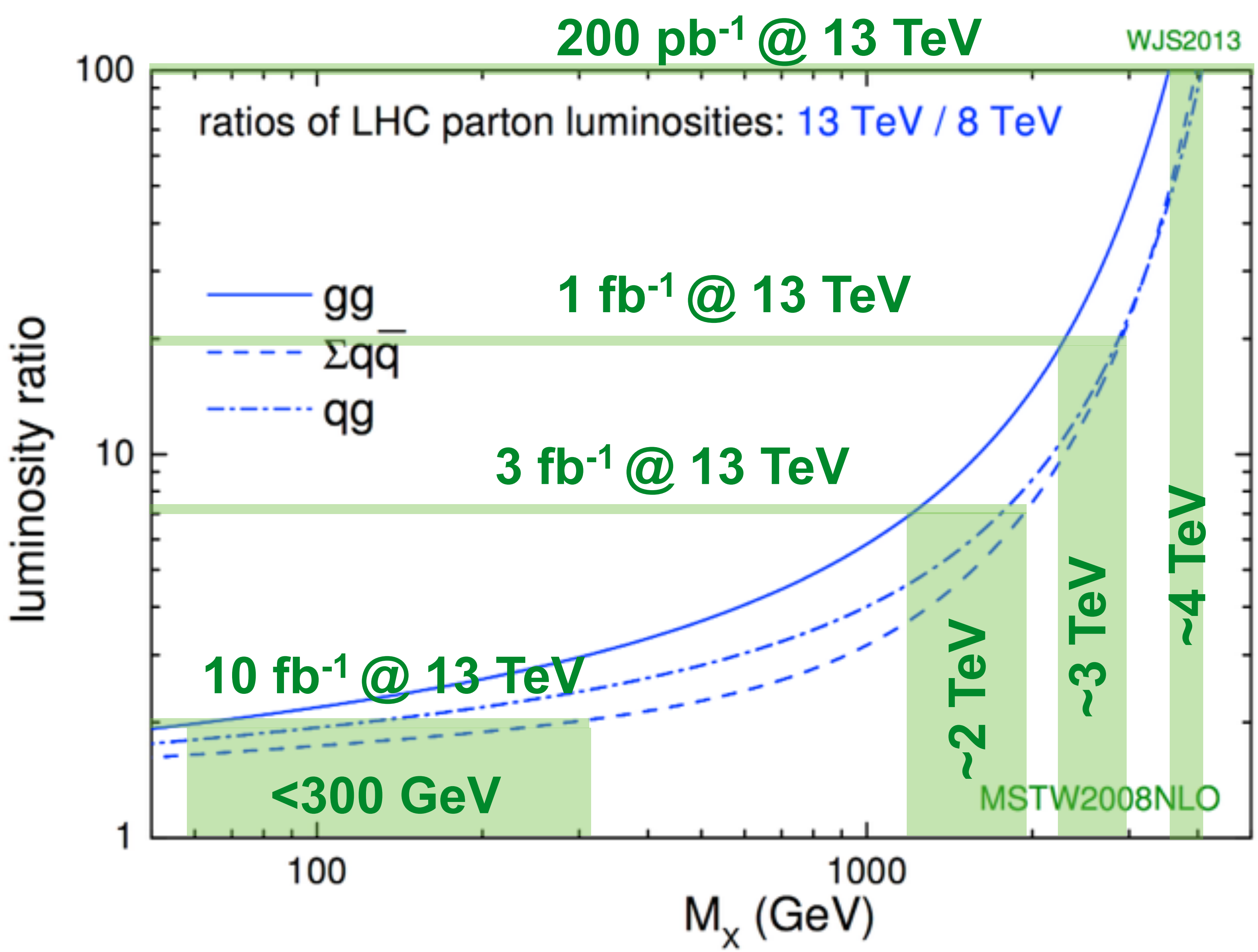
ATLAS AND CMS



	ATLAS	CMS
Magnetic Field	solenoid (2 T) + toroid (0.5÷1T)	3.8 T solenoid + return yoke
Tracker	Si pixel, strips + TRT	Si pixel, strips
EM Calorimeter	Pb + LAr	PbWO4 crystals
Had Calorimeter	Fe+scint./Cu+LAr/W+Lar (≥11λ)	Brass+scintillator(≥7λ)/Fe+quartz
Muon	air-toroid muon spectrom.	iron return-yoke muon spectrom.
Trigger	L1+RoI-based HLT	L1+HLT

13 TeV Superseding 8 TeV Results

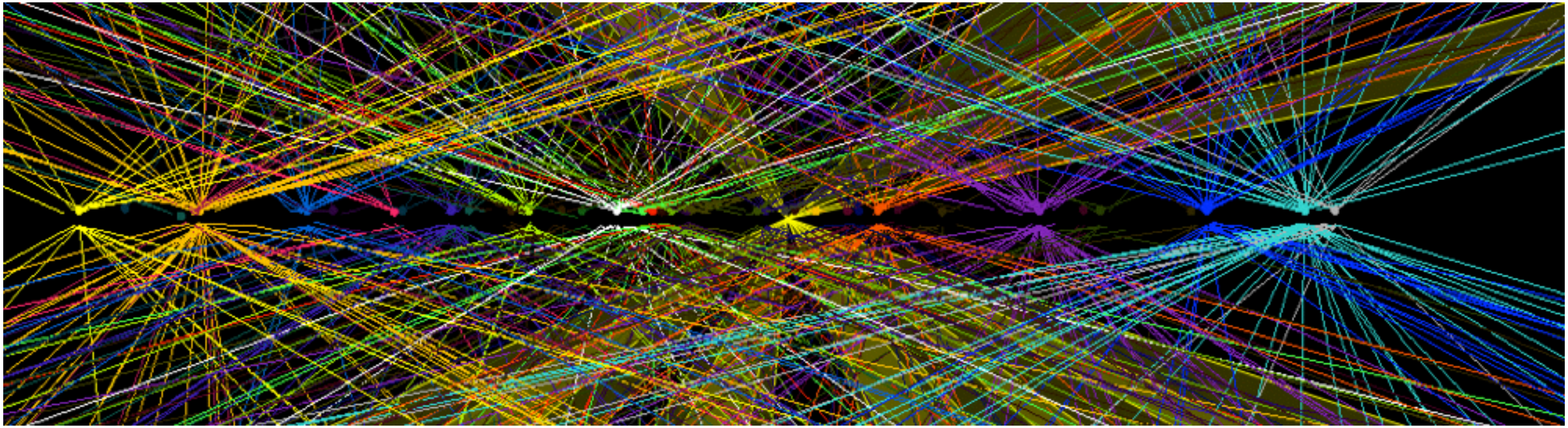
- For high mass searches **parton luminosity counts**!
  - **Huge ratio in the interesting (not yet excluded) region**
- **End of 2016 enough to supersede all 8 TeV results**



EXPERIMENTAL ISSUES: PILE-UP

Many pp interactions per single bunch crossing (pile-up). Issues:

- find the **right one**
- **subtract additional energy** due to extra interactions
- **retune triggers** (big increase in rate)
- **more stuff on disk** to be stored **and time to reconstruct**

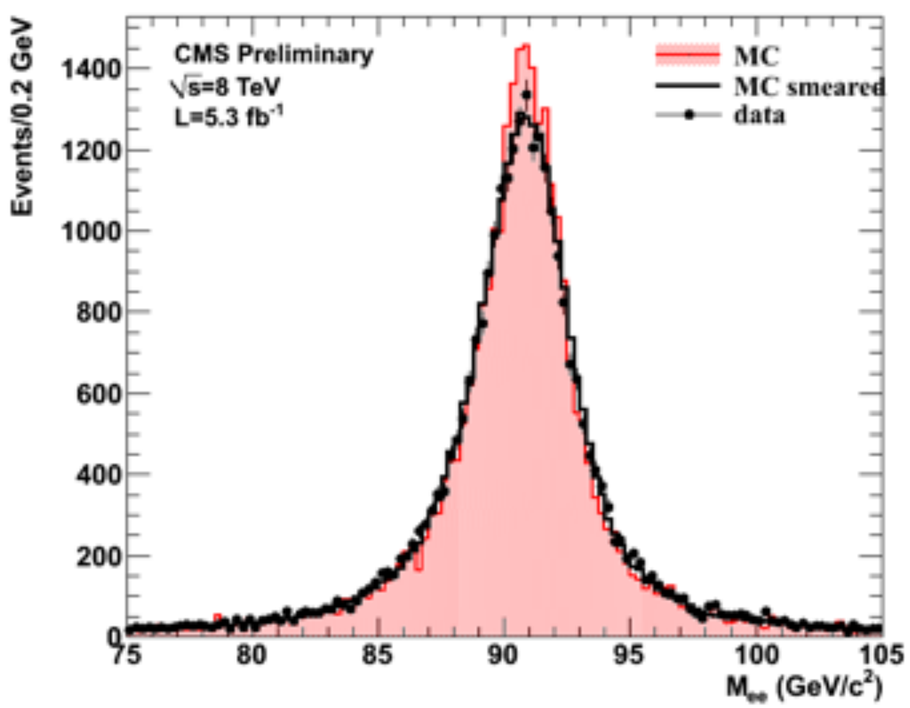


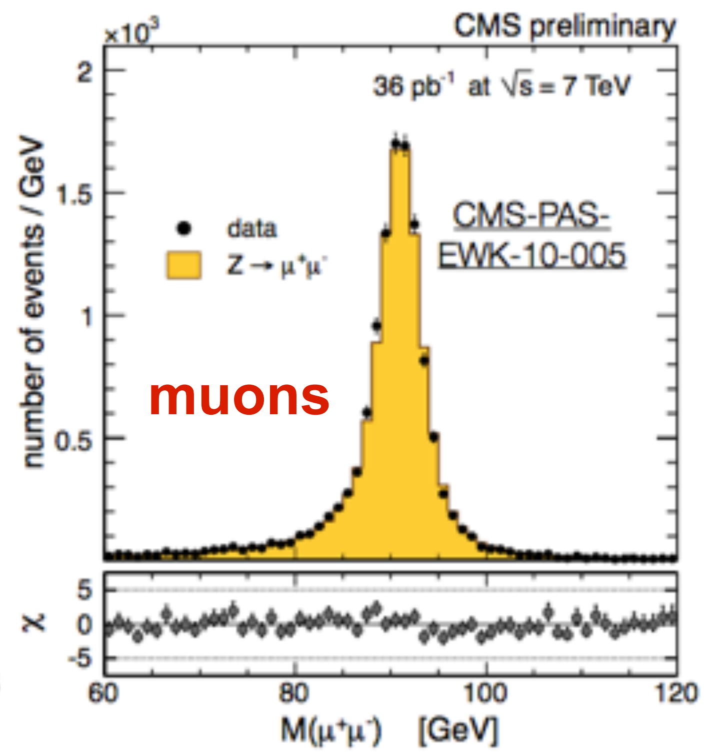
Events with up to 80 vertexes!

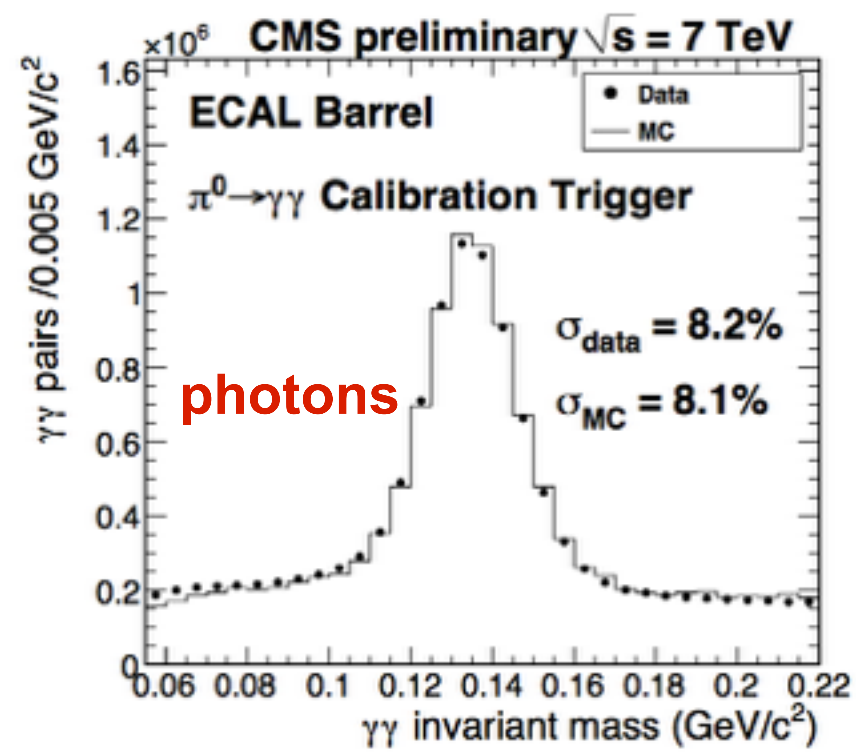
Objects in High Mass Searches

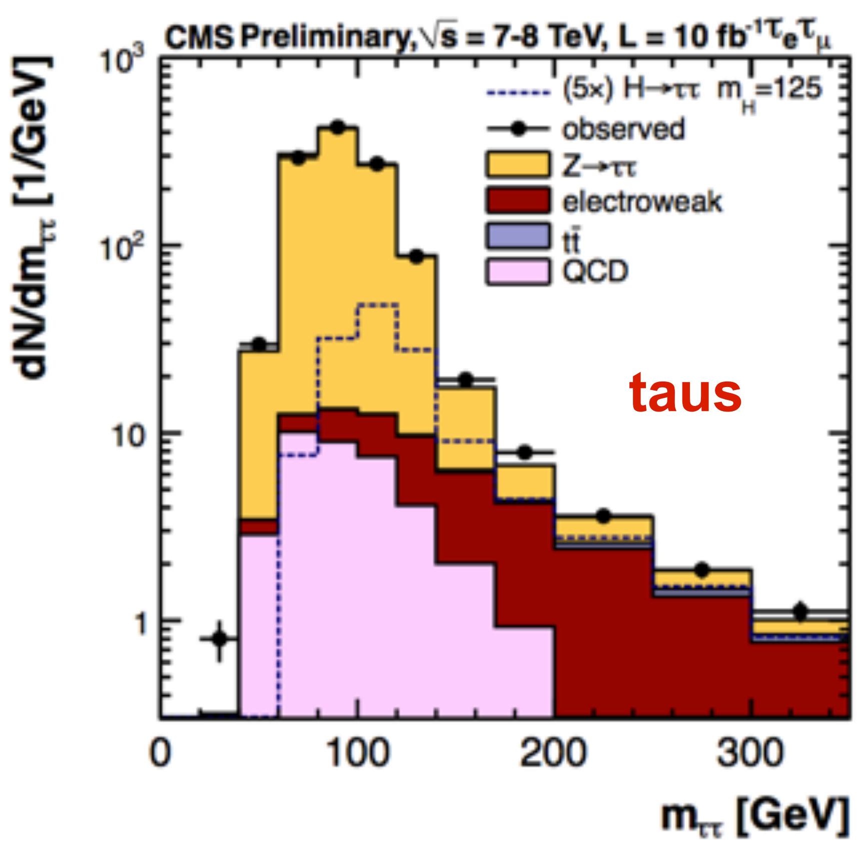
	pros	cons	energy resolution	calibration
jets	large cross sections involved	resolution not great. calibration not trivial	5-10%	gamma+jet, multijet, extrapolations
electrons	relatively clean	high pt electrons not fully contained	1-2% at high masses	Z->ee and extrapolations
muons	very clean	need precise tracker alignment	3-10% at high masses	Z->mumu and extrapolations
photons	relatively clean	no control samples for scale determination	1-2% at high masses	Z->ee and extrapolations
missing E	tagging for W'	hard to calibrate, tails due to detector noise	-	gamma,Z + jets

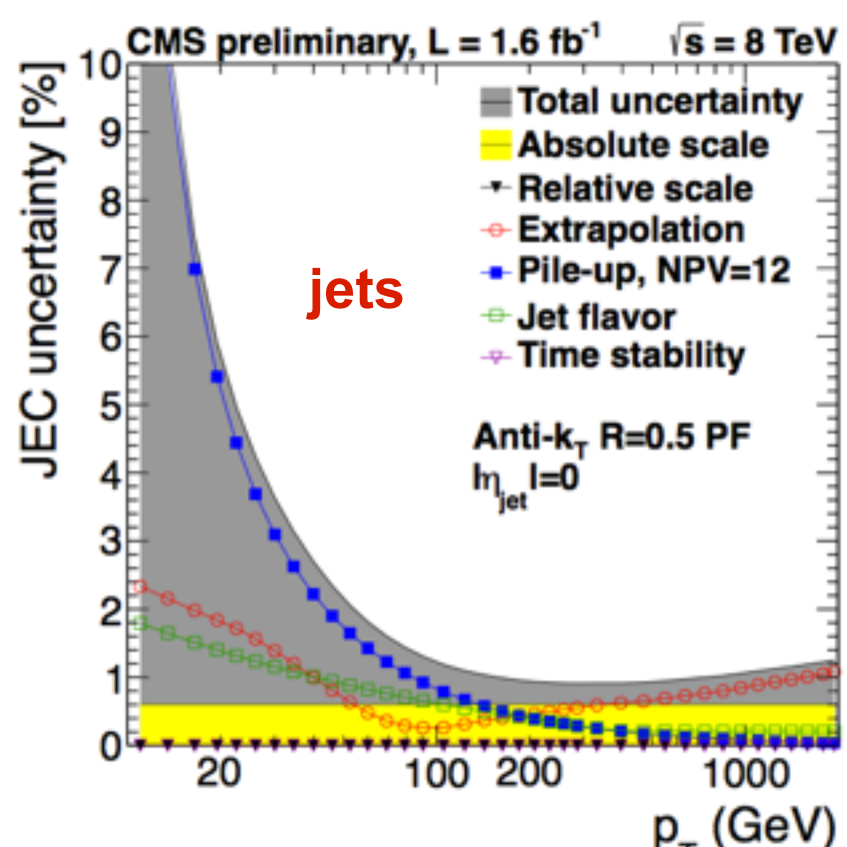
Performance of Reconstruction

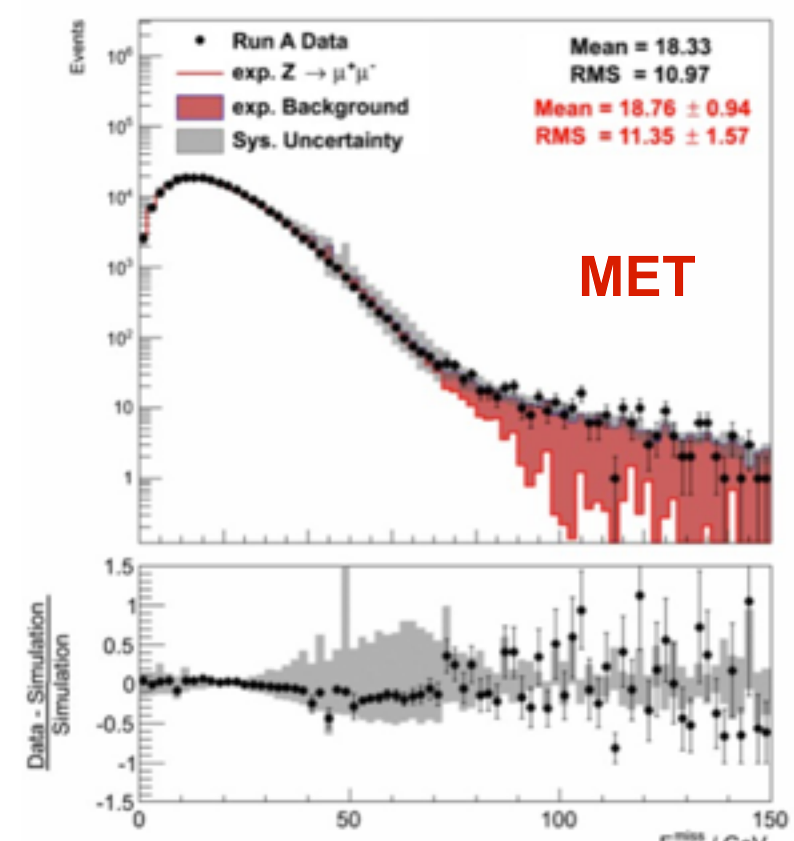












Performance of Reconstruction

electrons

scale known to 0.5%

muons

scale known to better than 1.0%

photons

scale known to better than 1.0%

taus

identified with ~70% efficiency and ~5% fake rate

(b-)jets

scale known to 1%-5% (p_T and η dep.)

MET

Nice agreement with simulation
Deep understanding of impact of PU

Performance of Reconstruction

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MET

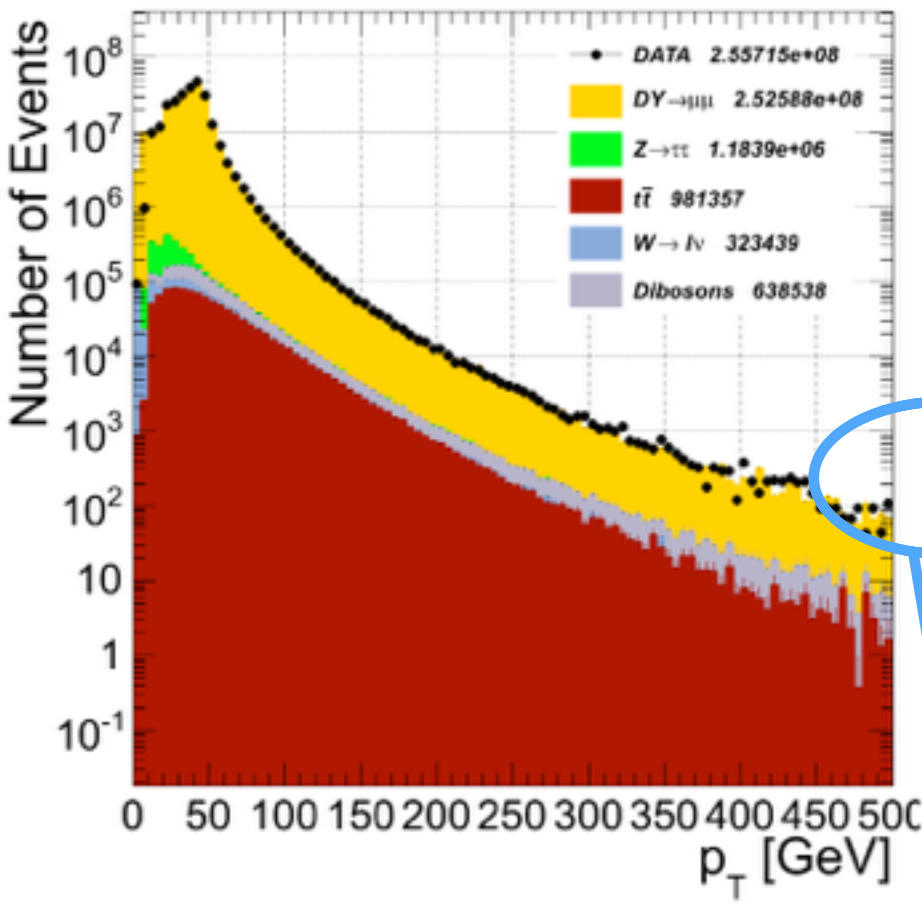
Nice agreement with
simulation
Deep understanding of
impact of PU

But this is for particles from SM processes!

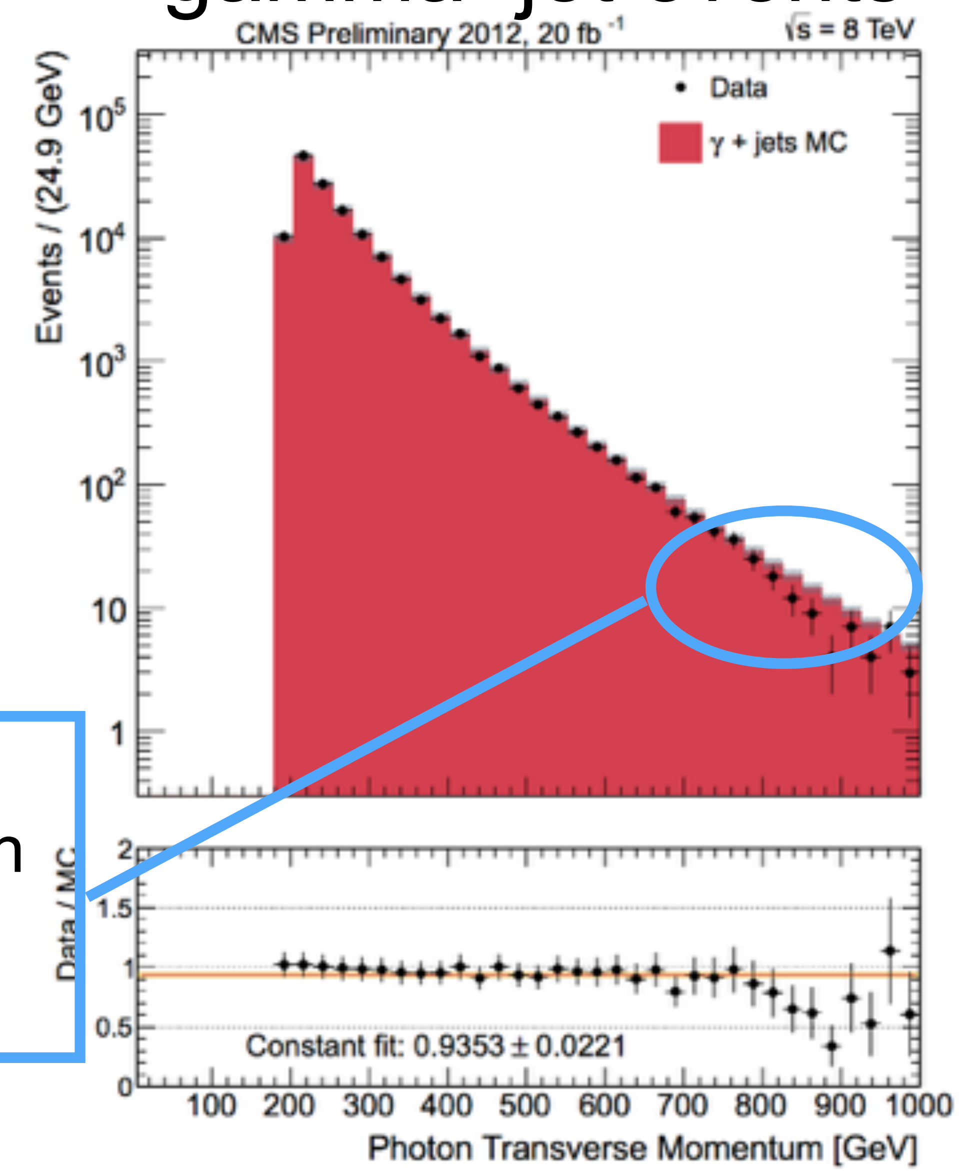
Heavy resonances produce **very energetic objects!**

HIGH MASS: A LIFE W/OUT CONTROL SAMPLES

Z->mumu events



gamma+jet events



not enough events to calibrate in region where signal is expected!

- Need to be sure that:
  - **efficiency of energetic objects is not zero**
  - **resolution under control**
- In extreme cases **resonance can be hidden!**

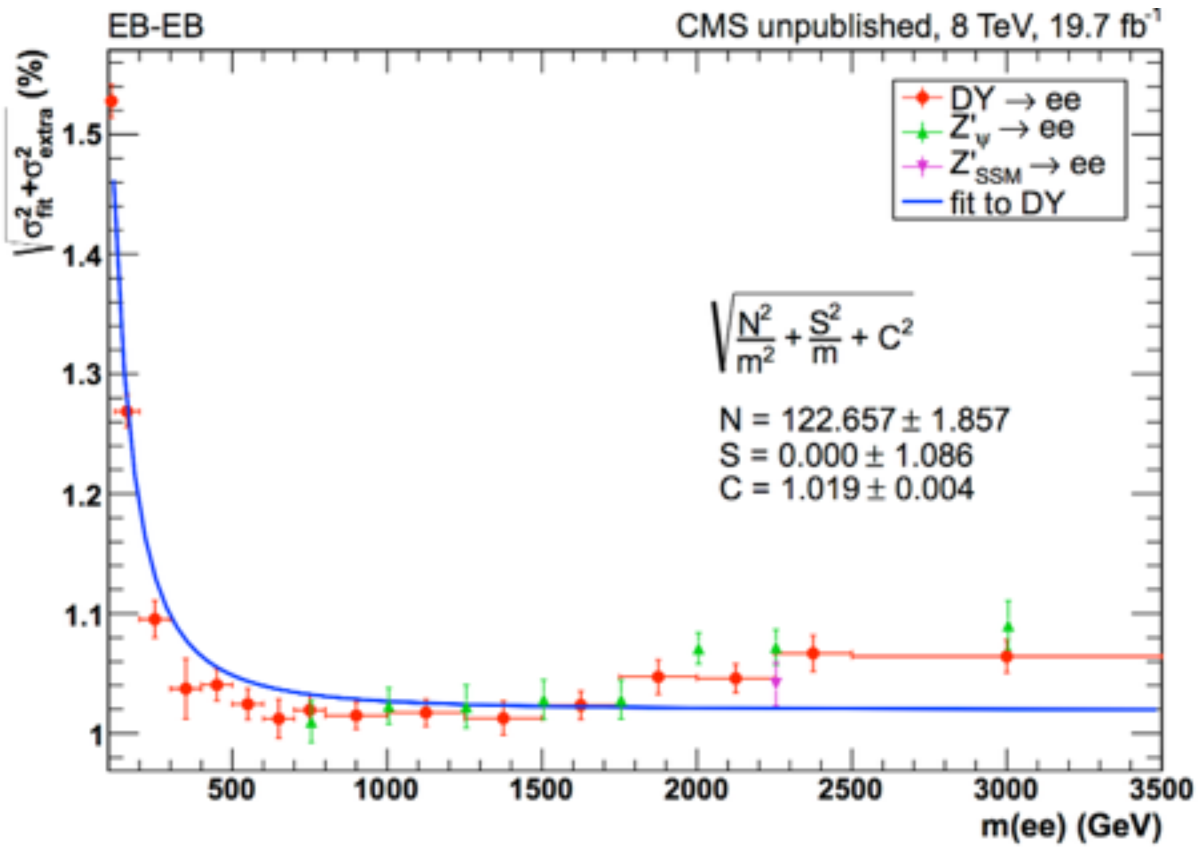
RECONSTRUCTING HIGH PT OBJECTS

- **Reconstruction in general quite similar** compared to low p_T (SM-like) objects
- **But there are non-negligible differences**:

1. **straight tracks** do not allow a perfect charge determination
2. **very energetic calorimetric deposits** could be not fully contained in the calorimeters (both em and had)
3. **electron/photon isolation** (to reject jet contamination) slightly **different because of non-containment** (point 2)
4. modified isolation i**n case of overlapping leptons** (for boosted Z decays in Z'->VV, VH channels)
5. **not easy to find control samples** to tune energy measurements and efficiencies

RESOLUTION VS P_T: ELECTRONS/PHOTONS

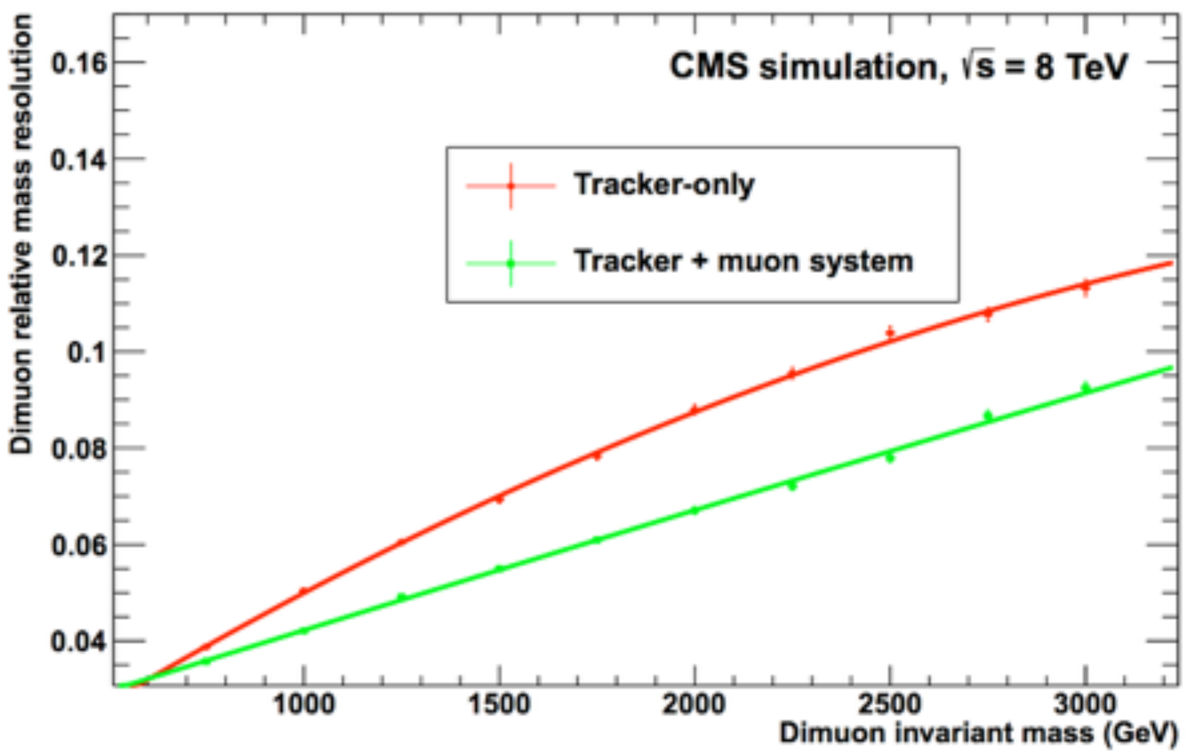
- At **large masses mainly** **dominated by the em calorimeter resolution**
  - p_T measurement from tracker not very precise
- At large energies, **shower containment** starts to be important
  - CMS: after 30 radiation length (equivalent to a single crystal) leakage is possible for TeV deposit
- **Similar behavior for photons**



Resolution vs P_T: Muons

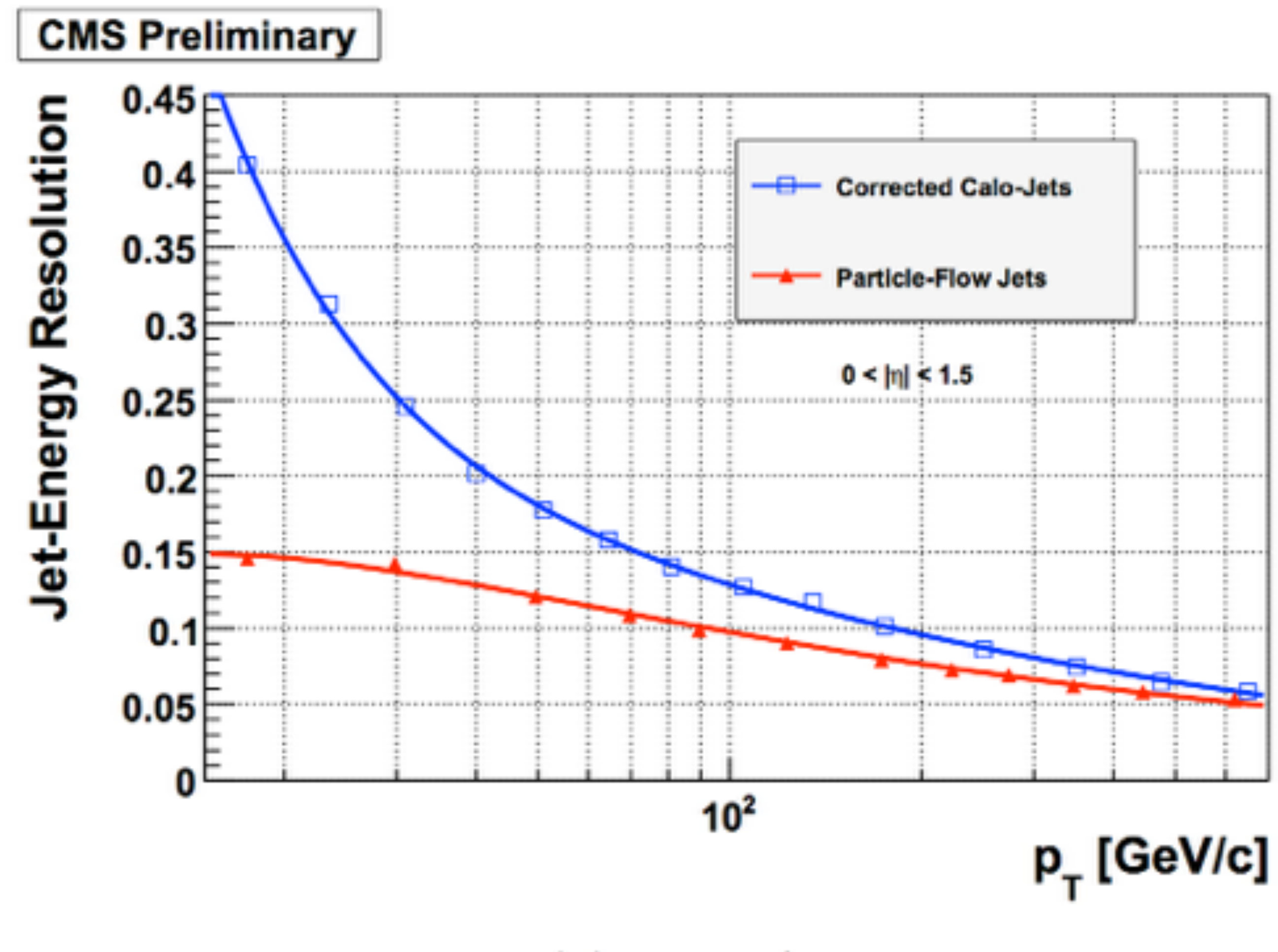
- **Resolution worsens vs p_T** (as for every track)

- At beginning of data taking, **dominated by other systematic effects** (e.g. detector alignment)



Resolution vs P_T: Jets

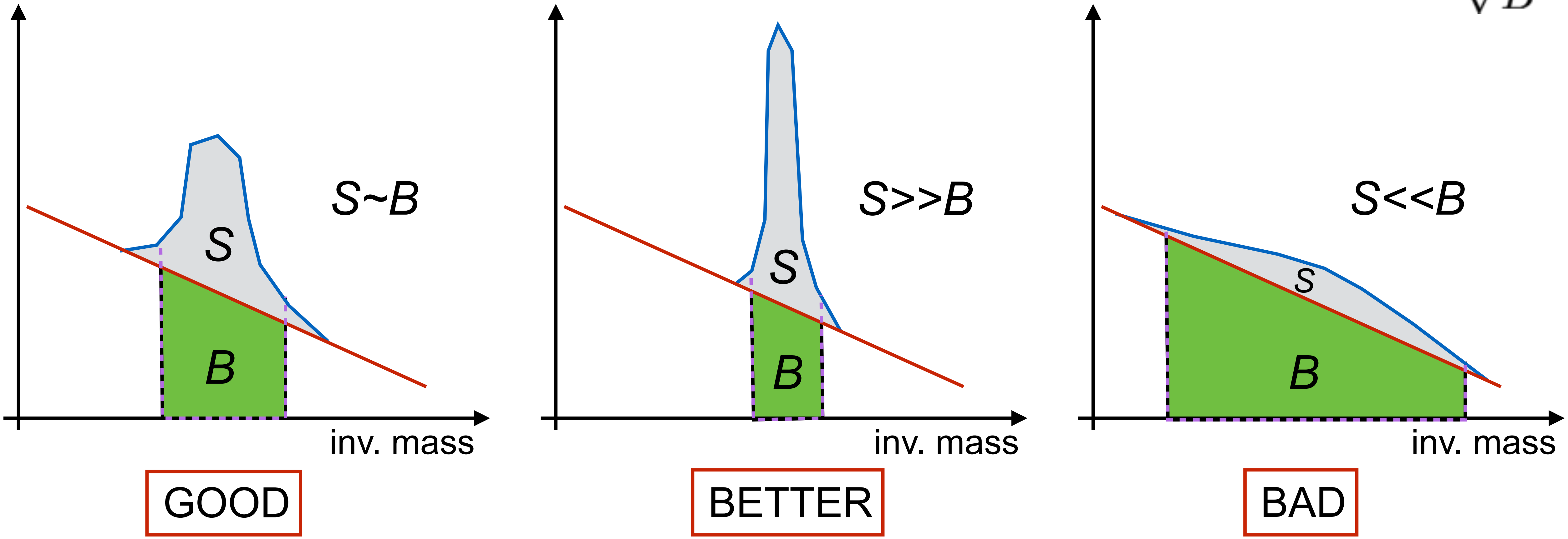
- **Resolution improves vs p_T**
  - particle flow (combined use of tracks and calorimeters) better than simple calorimeter-based jet resolution
- **At very high p_T resolution around 5%** (dominated by calorimeters)



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

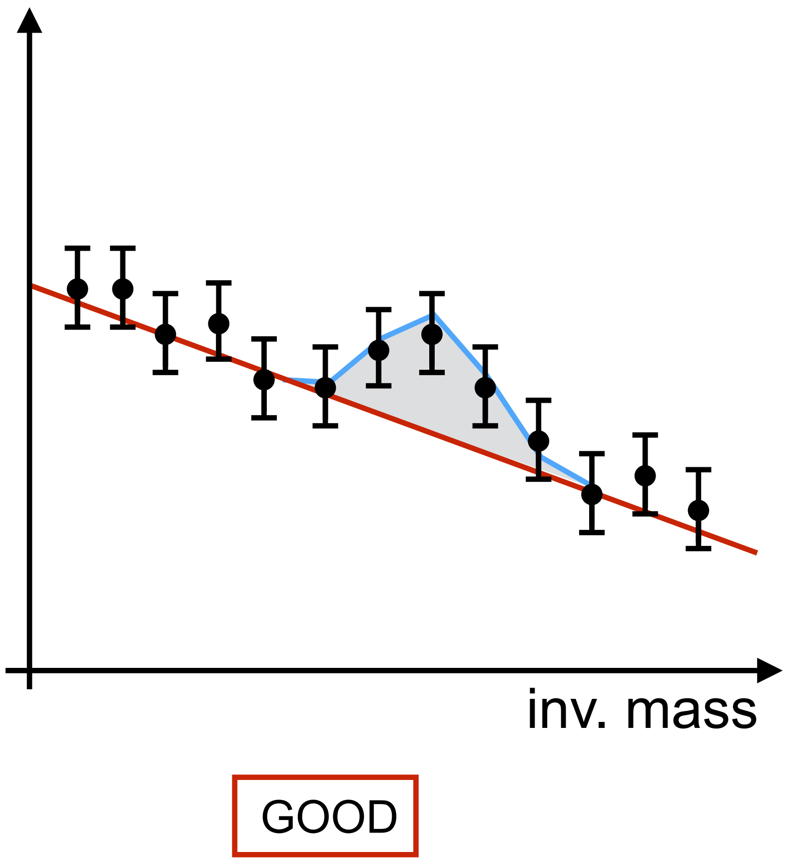
$$significance \sim \frac{S}{\sqrt{B}}$$

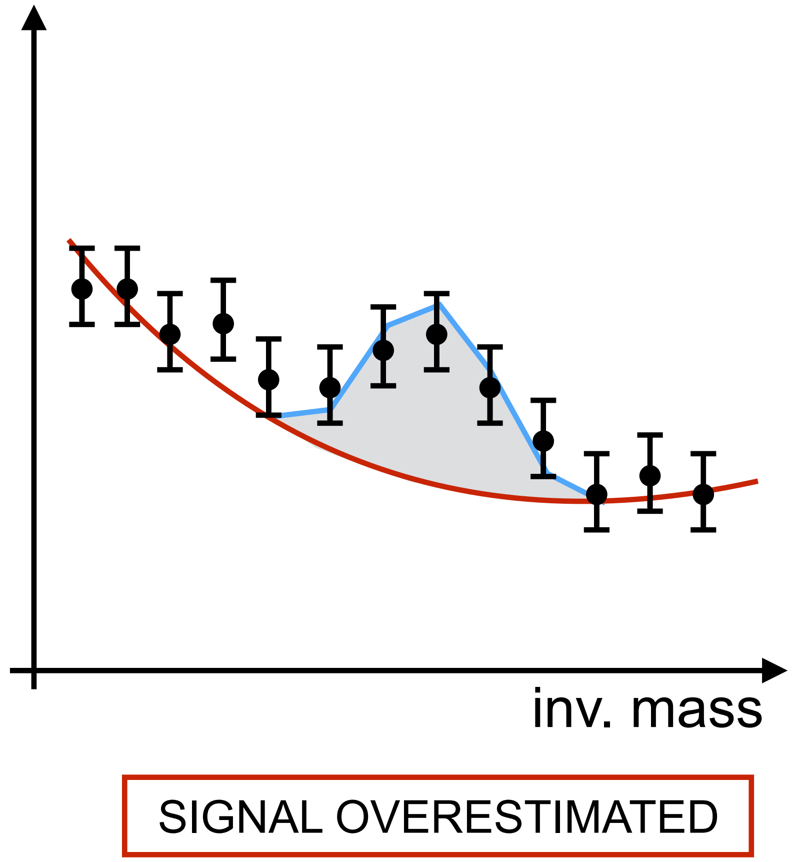


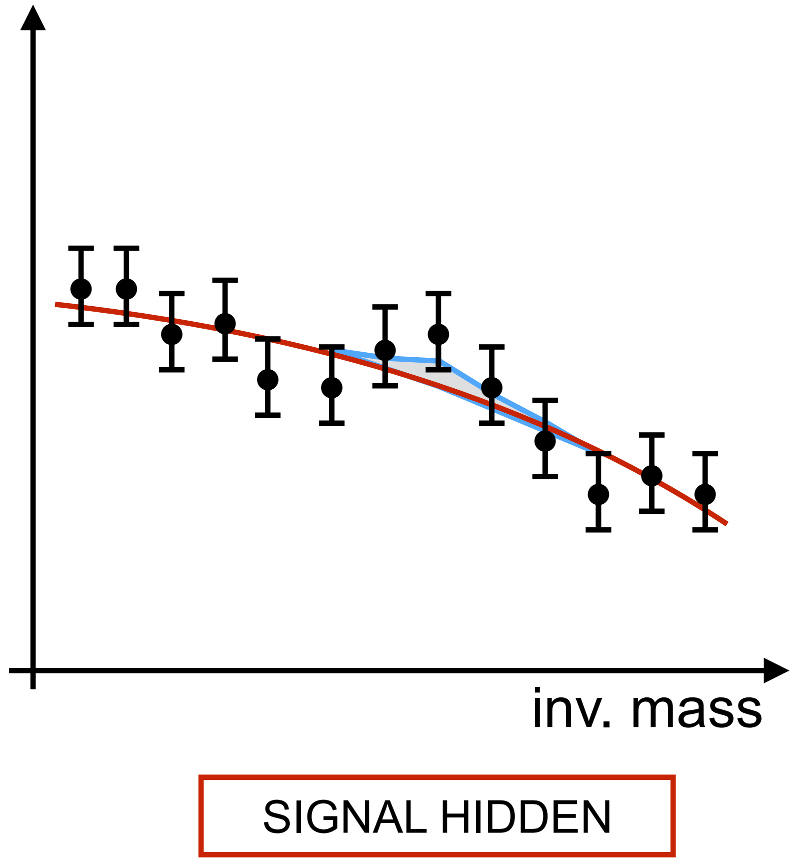
… and signal not distinguishable from background

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







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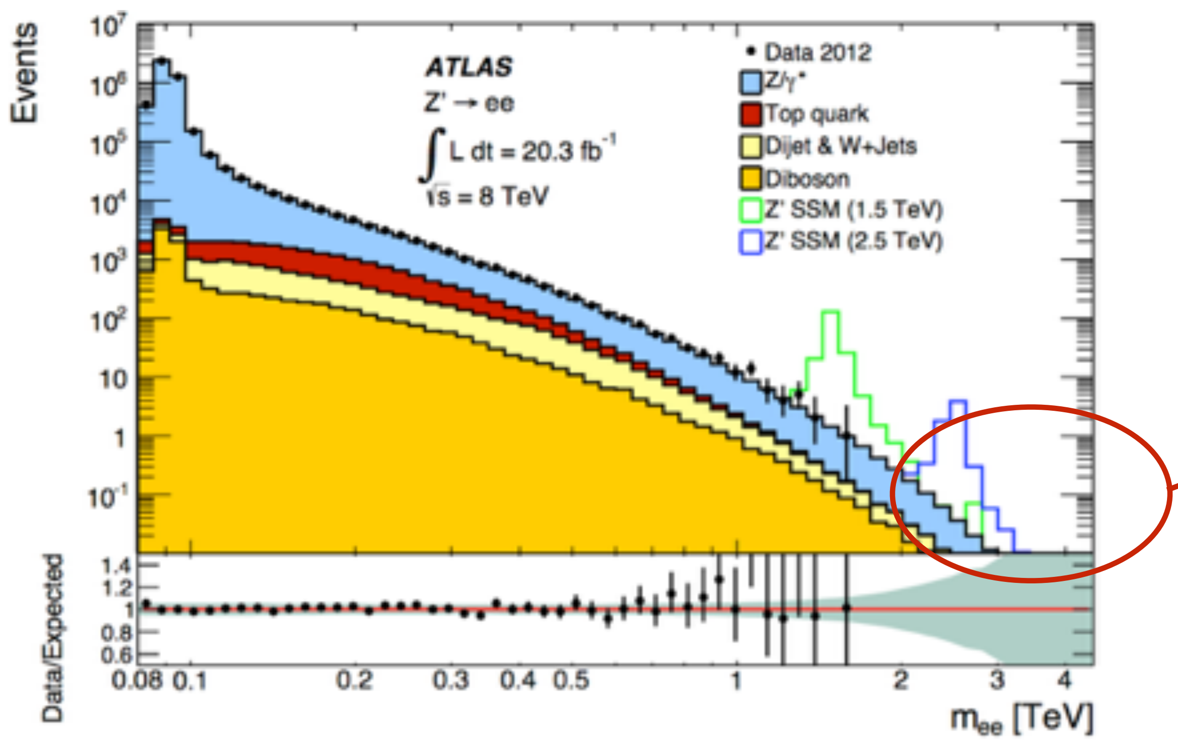


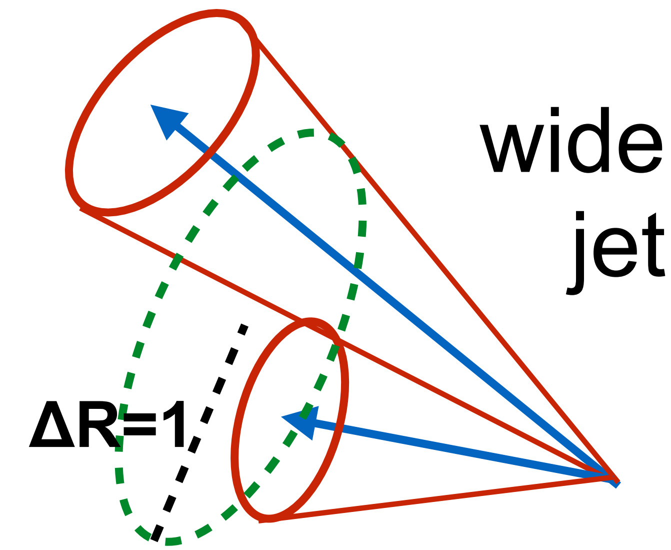
At very high masses no events to tune background. Extrapolation needed

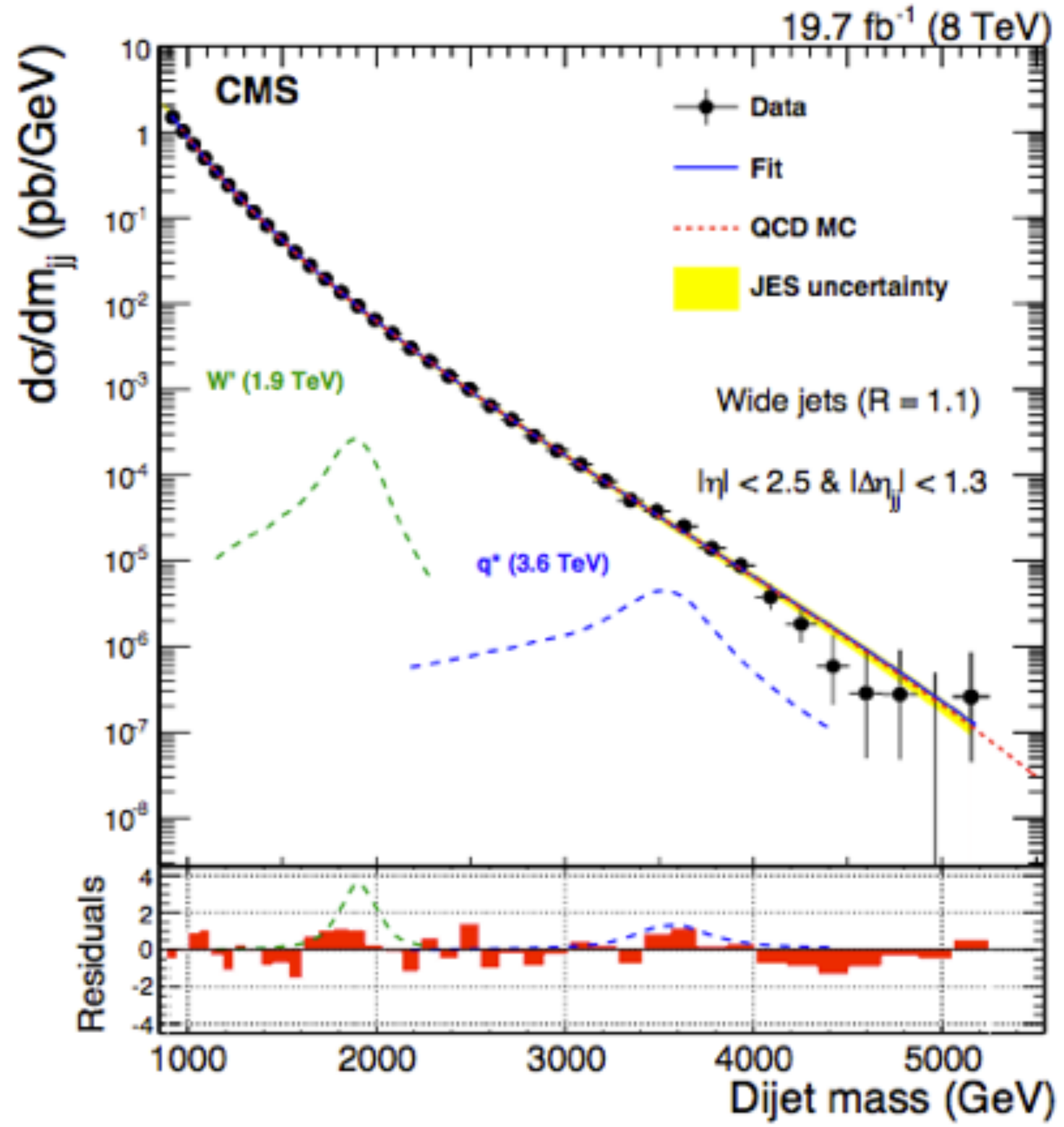
DIJET

- **Straightforward search, two high pT jet:** pT(jet) >~ 30GeV
- **Gluon radiation recovered** in wide jets (ΔR=1.1) for CMS
- **Background fitted** (CMS) with

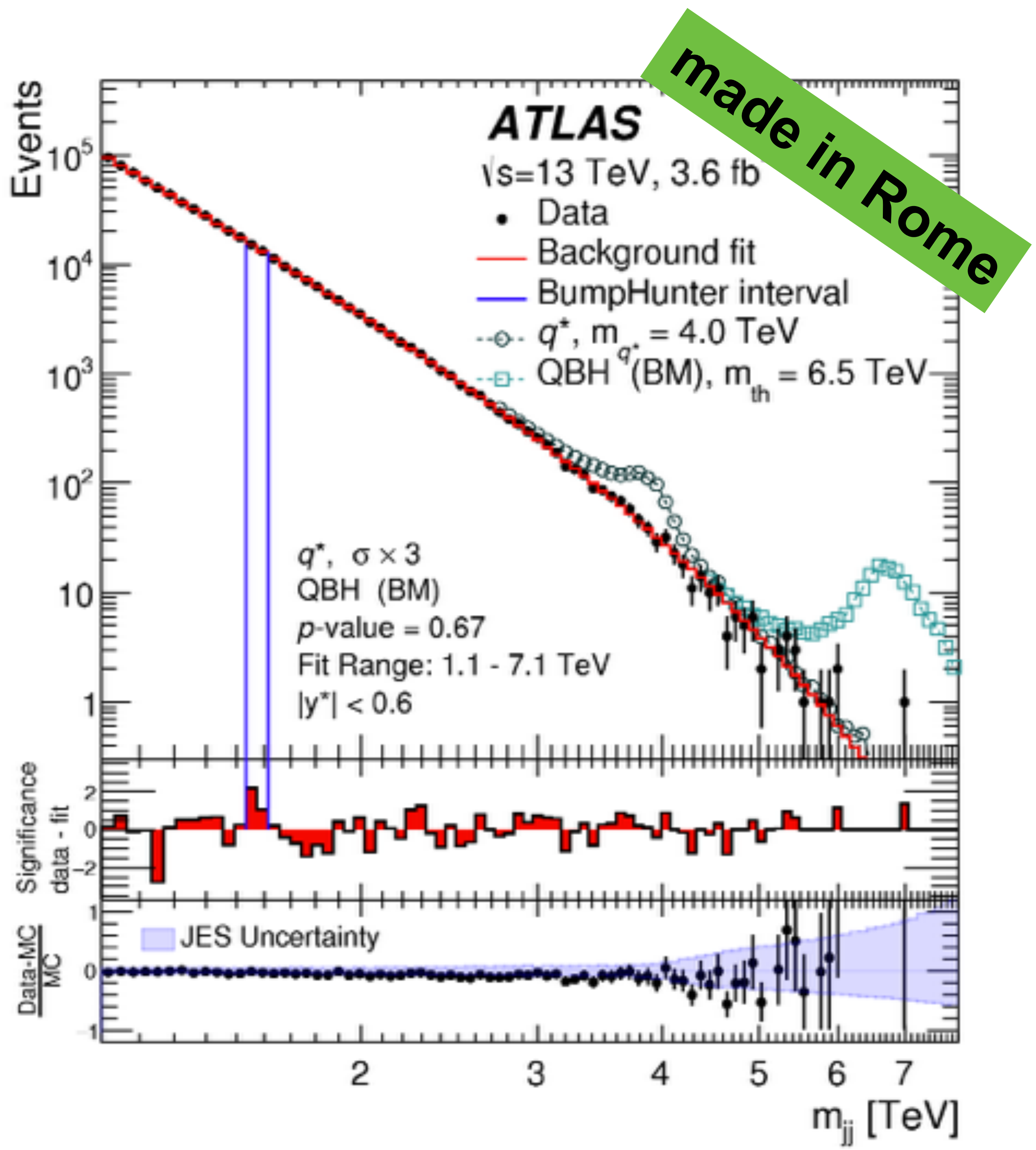
$$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)}} \qquad x = m_{jj}/\sqrt{s}$$

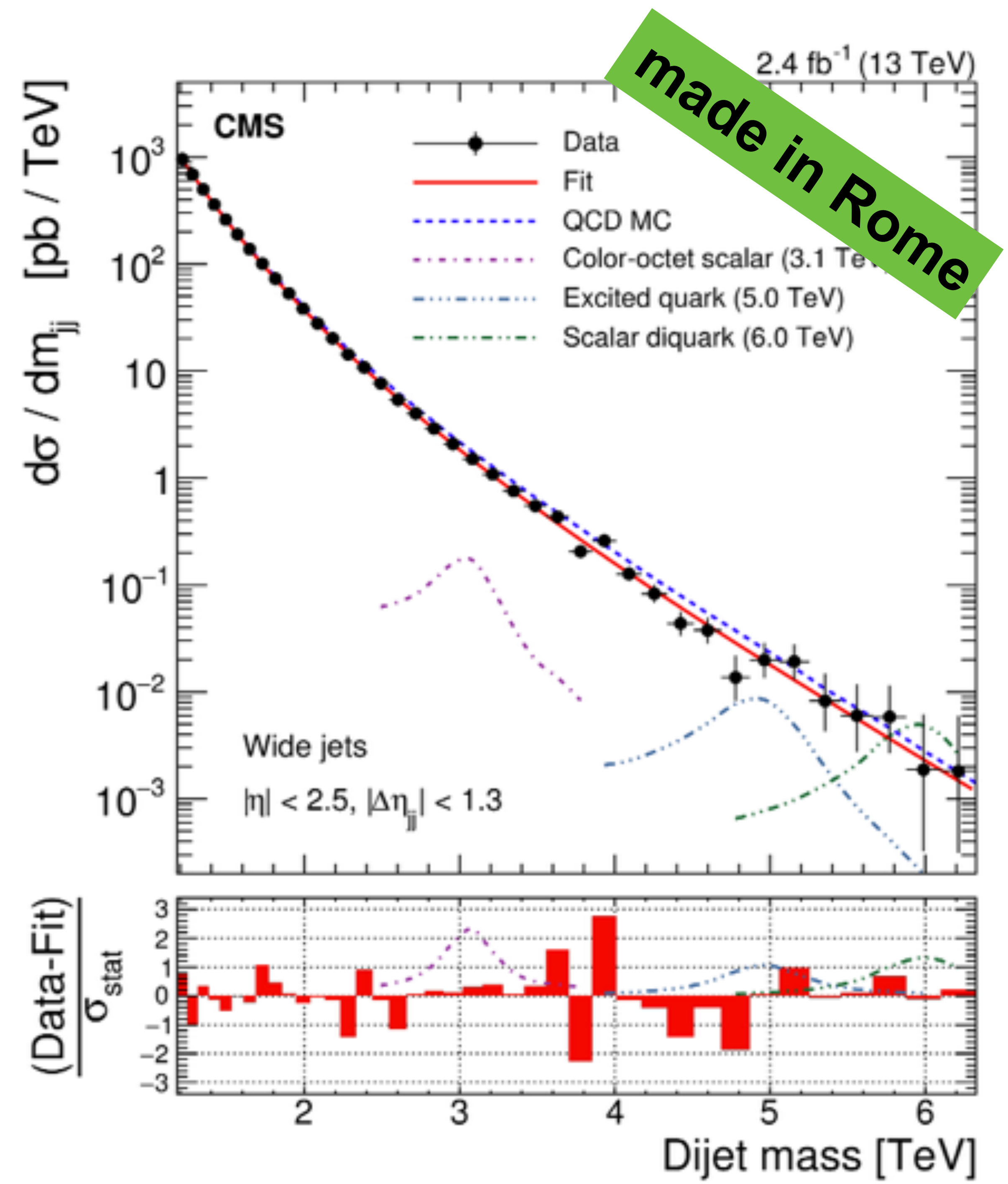
- **Signal shape:**
  - gaussian-like (resolution ~3-4%)
  - left tail due to radiation and parton density functions
- **Signal extracted** using a likelihood approach





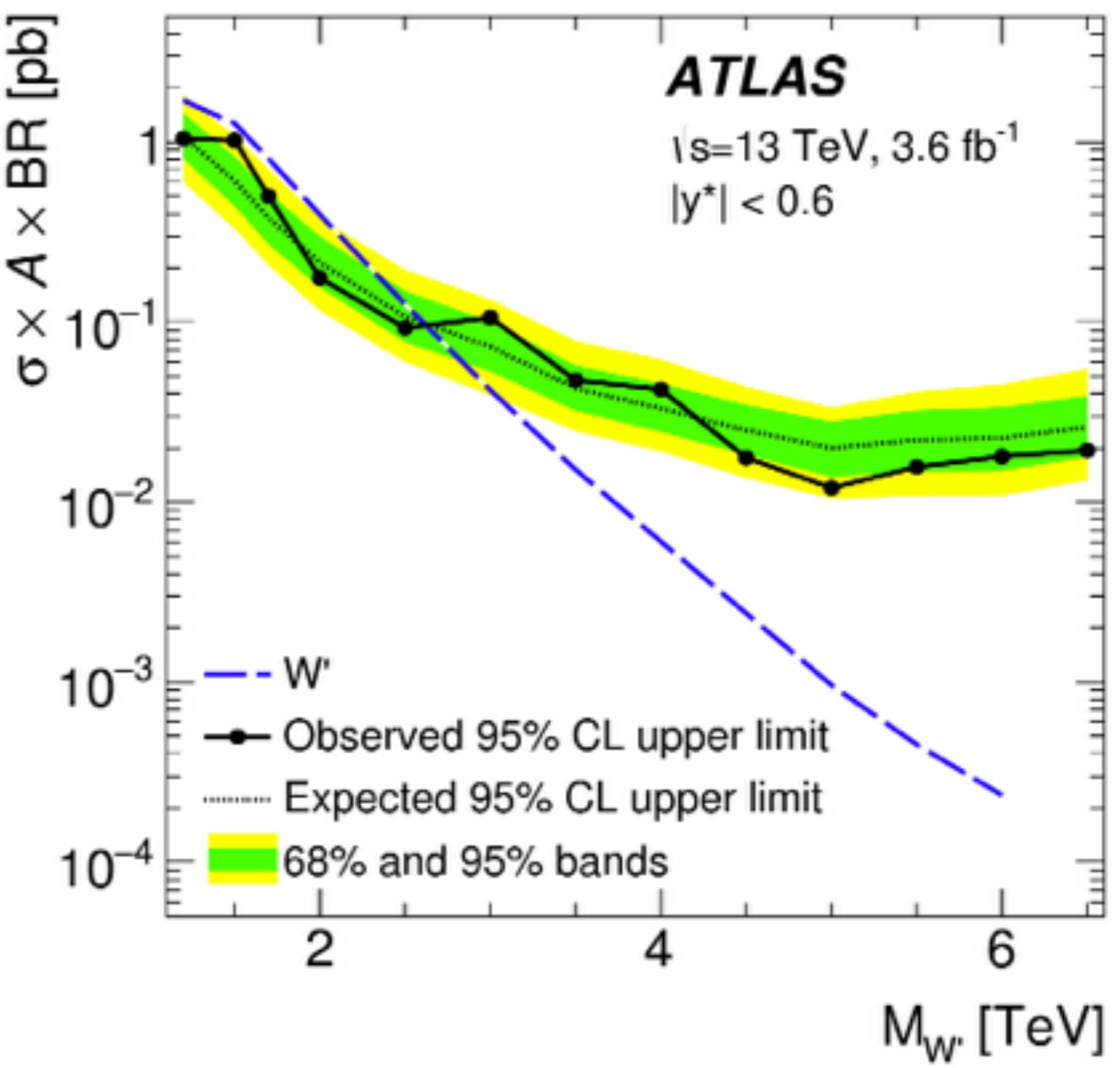
DIJET: RESULTS

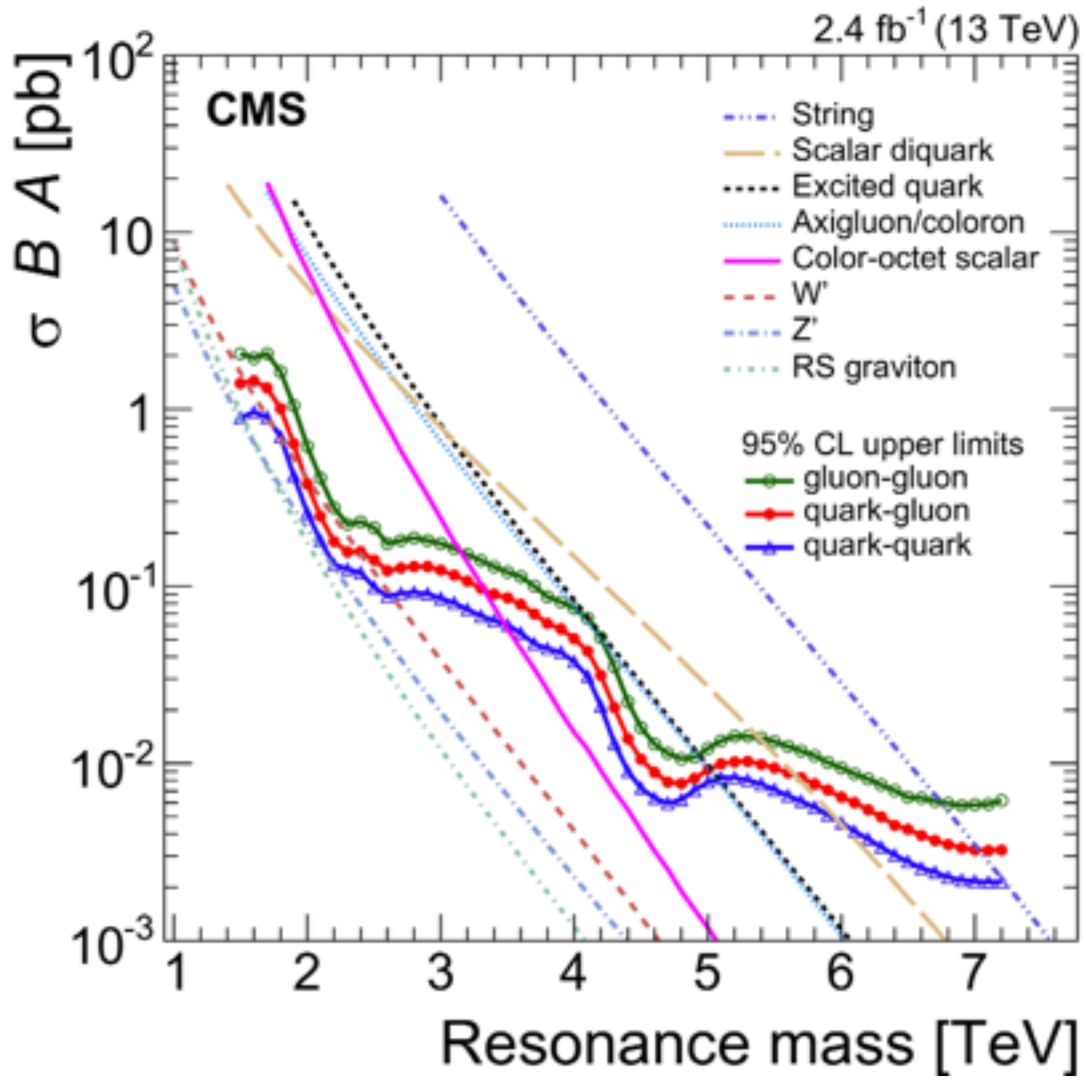




No excess

DIJET: RESULTS

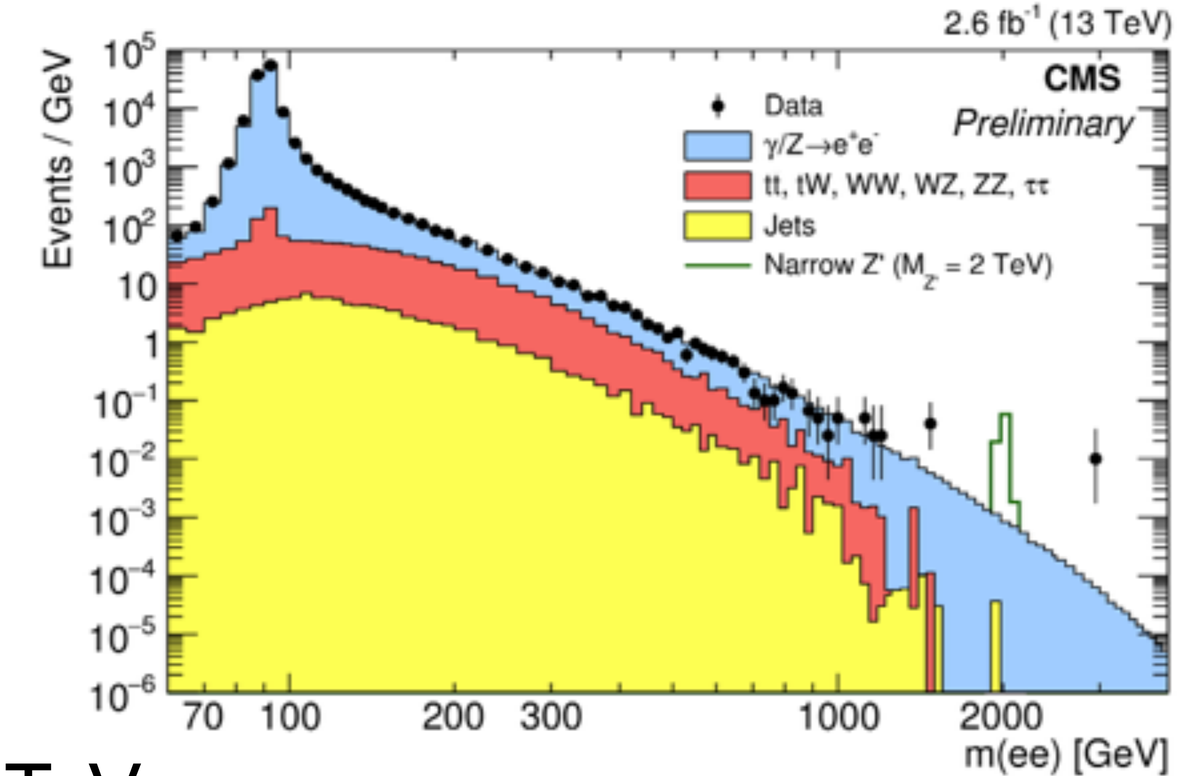


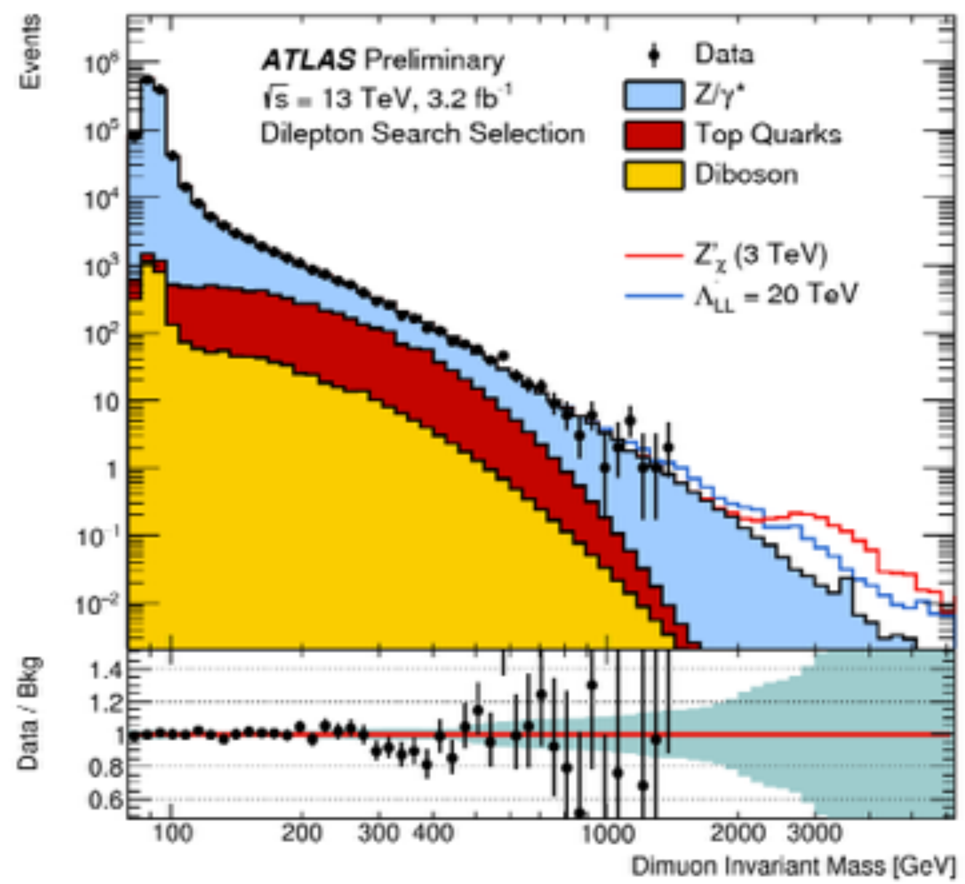


- **Several interpretations:**
  - maximum mass of the excluded region varying between 1 and 7 TeV
  - very similar performance between the two experiments

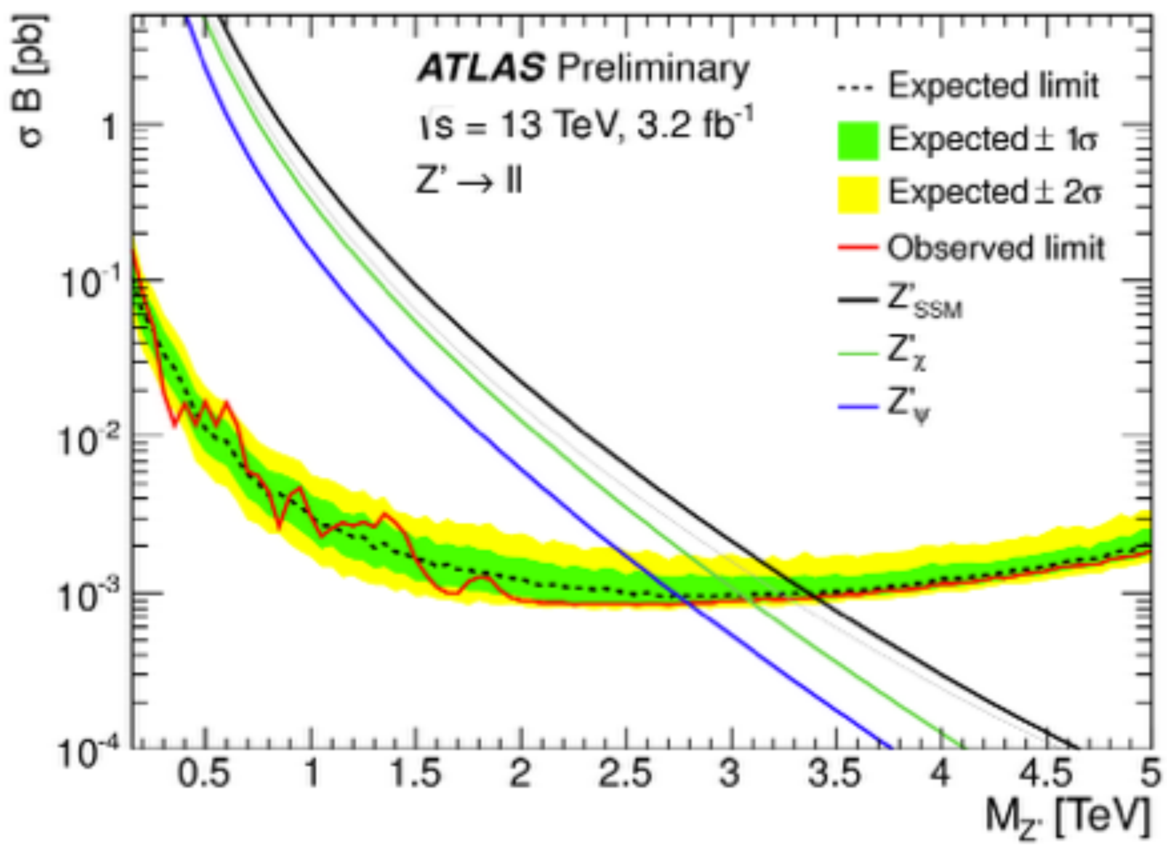
DILEPTON

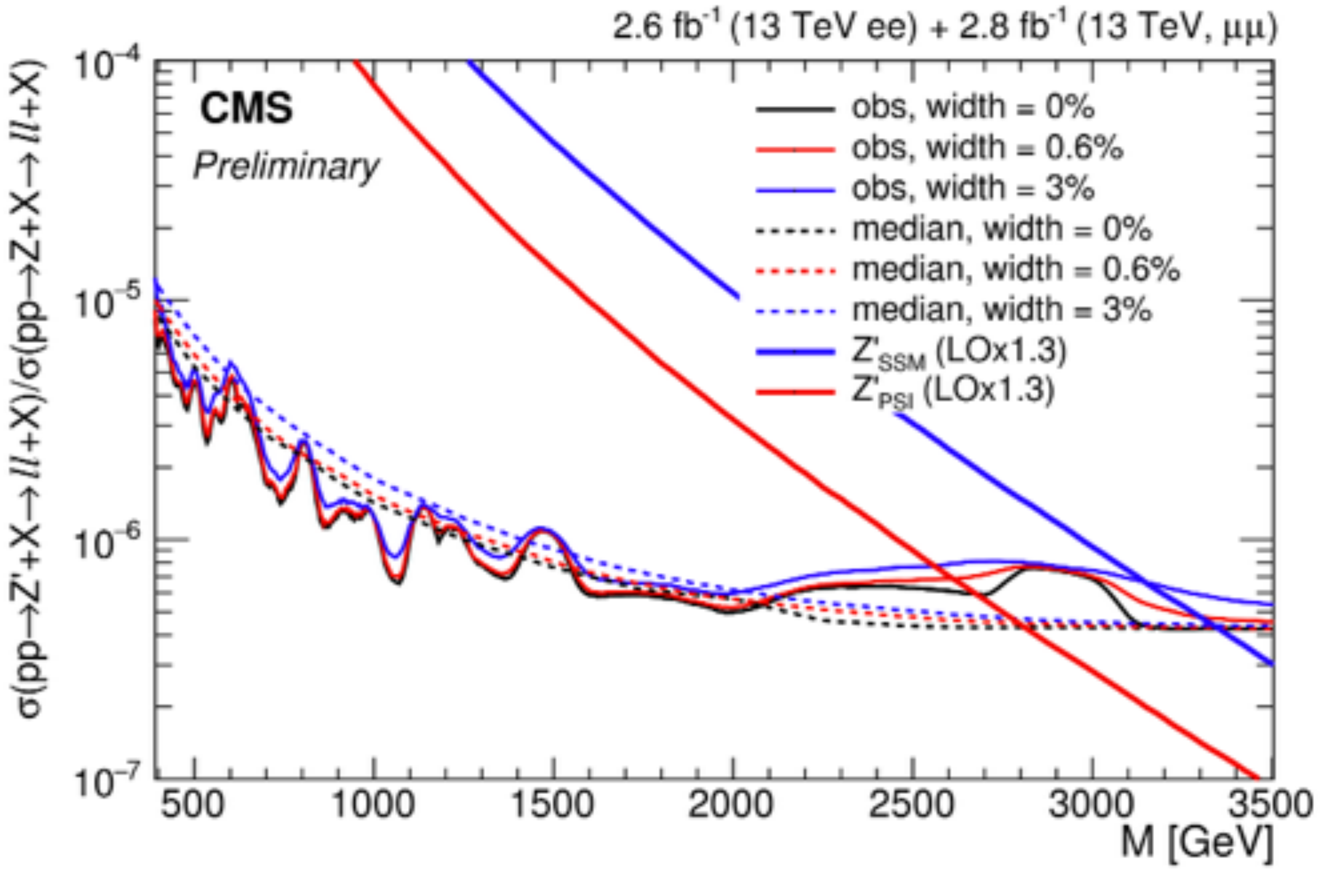
- **Both di-electron and di-muon channels**
  - loose selection search for a narrow resonance
  - main background Drell-Yan events
  - virtually background-free above 1.5 TeV
- **Kinematic selection:**
  - pt(leptons)>25-40 GeV + isolation
- **Interpretations for resonance:**
  - Z'_{SSM}, Z'_{ψ}





DILEPTON: LIMITS





Z'_{SSM} m ≲ 3.4 TeV

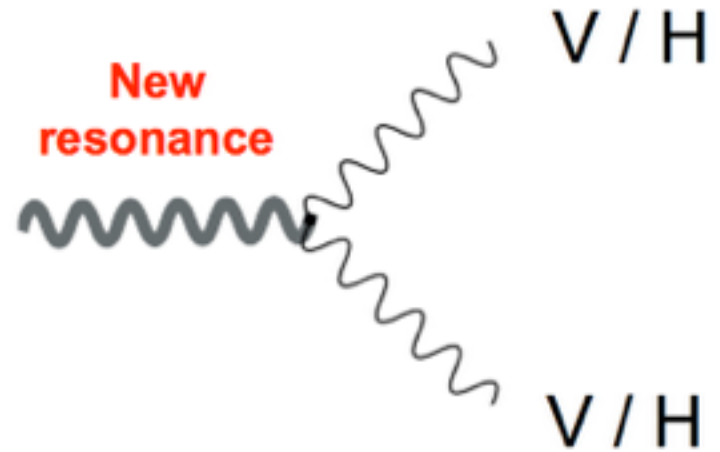
Z_{ψ} m ≲ 2.7 TeV

No large excess

Consistent results between the two experiments

DIBOSON: INTRO

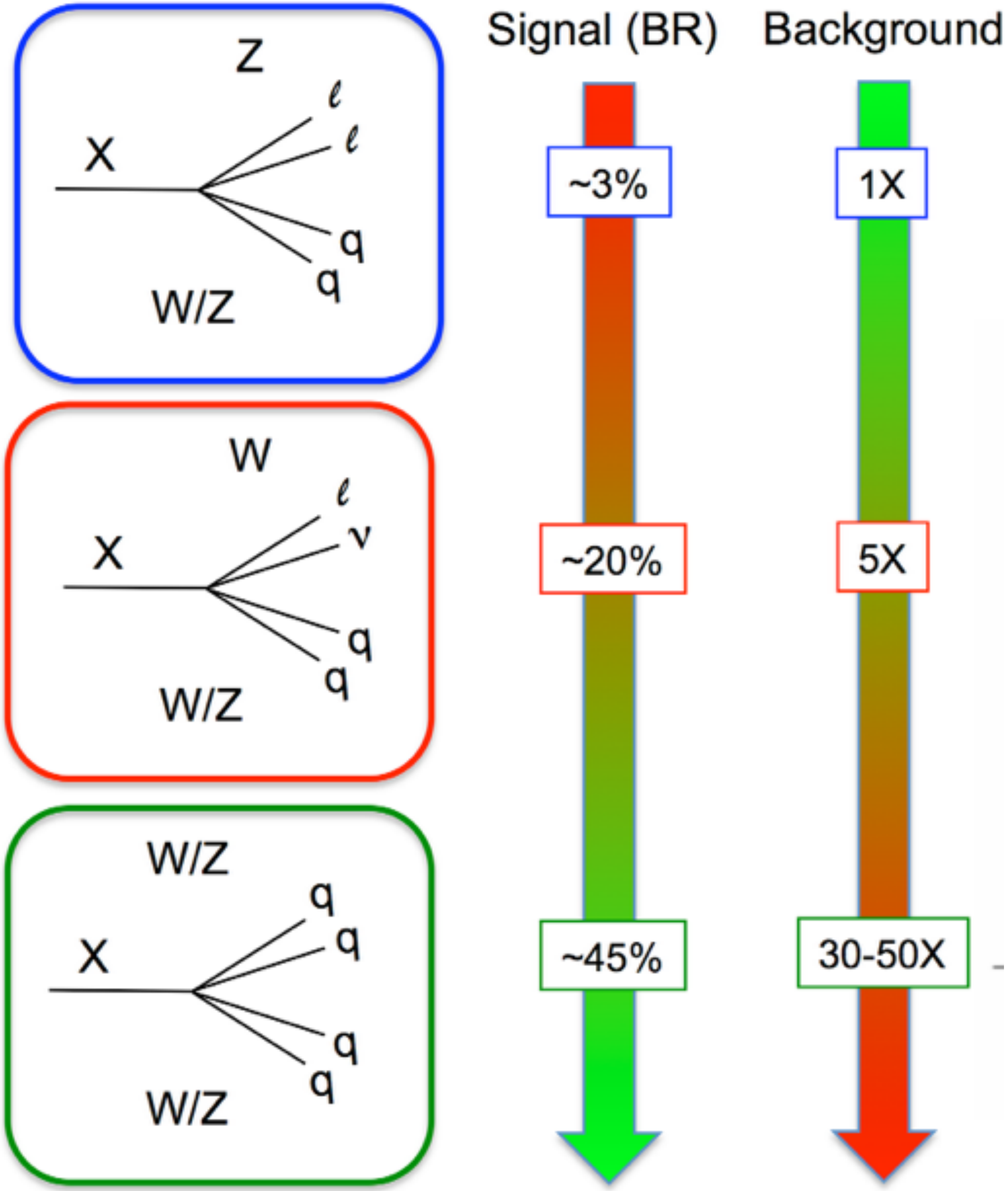
- Searching from **new resonances** decaying in **two massive bosons**
- **Analysis strategy** determined by
  - boson decay modes
  - mass of the resonance and boost
- **Clean experimental signature**
- In case of discovery, possible to measure properties from **angular distributions** of the decay products
- Several **different combinations** studied
- **Only few examples given** in the talk



W	Z	H
$M_W \sim 80.3$ GeV	$M_Z \sim 91.2$ GeV	$M_H \sim 125$ GeV
$W \to qq$ ~ 67%	$Z \to qq$ ~ 70%	$H \to bb$ ~ 57%
$W \to \ell\nu$ ~ 33%	$Z \to \nu\nu$ ~ 20%	$H \to WW$ ~ 21% $H \to ZZ$ ~ 2.5%
	$Z \to \ell\ell$ ~ 10%	$H \to \tau\tau$ ~ 6%
		$H \to \gamma\gamma$ ~ 0.2%

DIBOSON: HADRONIC CHANNELS

- **Pro and cons** of different decay modes
  - **leptons**: cleaner but less frequent
  - **jets**: large BRs but dirty



DIBOSON: BOOSTED HADRONIC V DECAYS

- Opening angle between jets

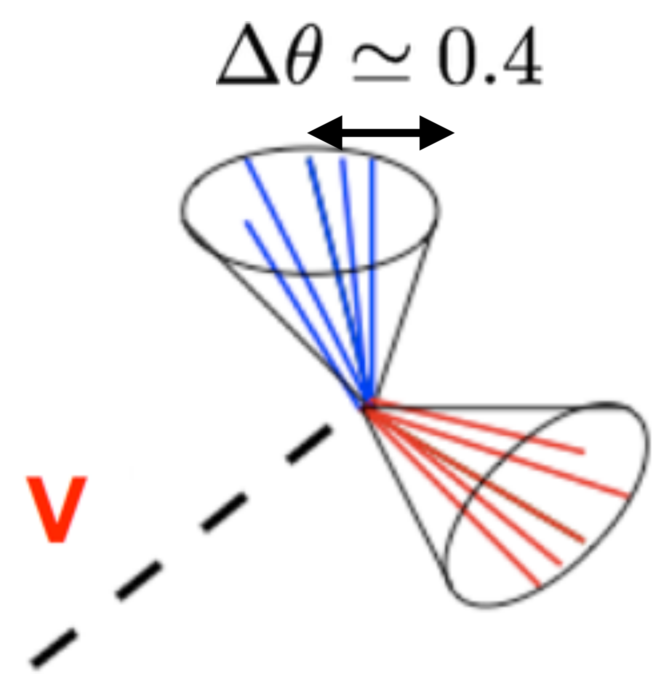
$$\Delta\theta_{qq}^{min} \simeq 2\frac{M_V}{p_{T,V}} \qquad V = W, Z$$

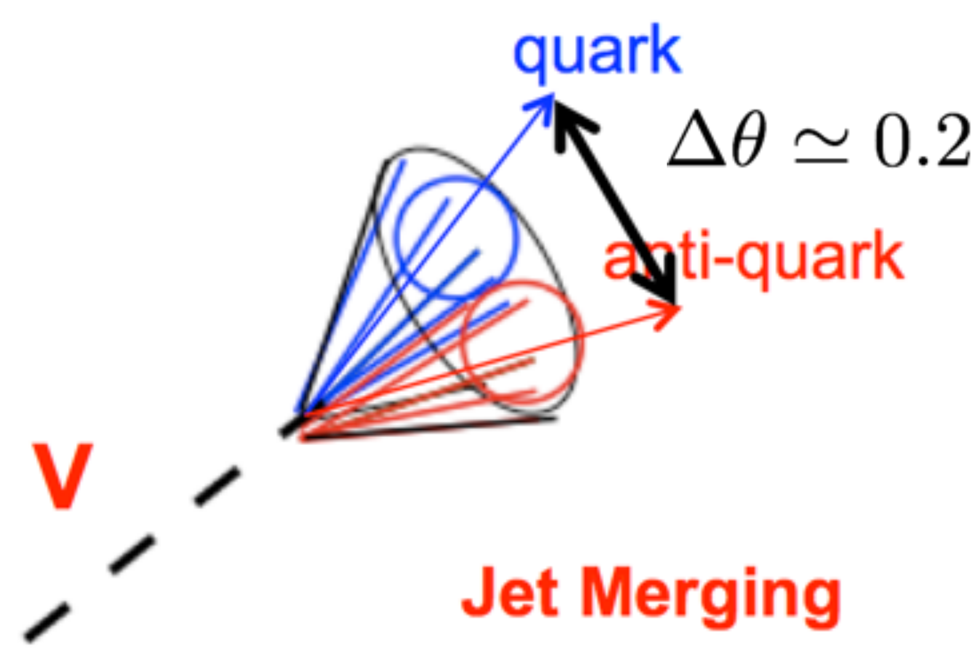
- **Low p_T**: separated
- **High p_T**: merging

Example

M_X = 2 TeV		
$p_T(V)$ ~ 1 TeV	→	$\Delta\theta \simeq 0.2$
M_V ~ 100 GeV		

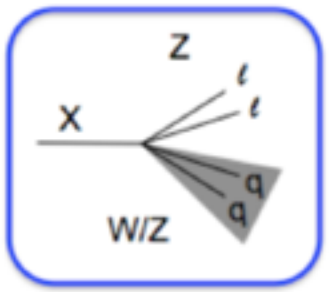
- **Ad hoc clustering algorithms** to cluster jet substructures and remove noise (trimming, pruning, etc)

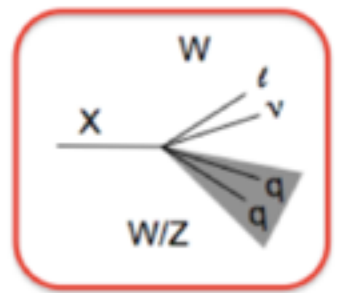


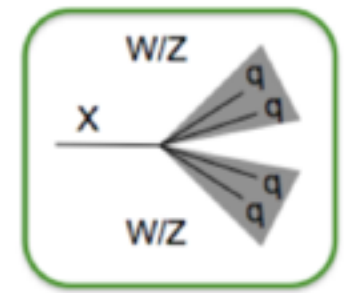


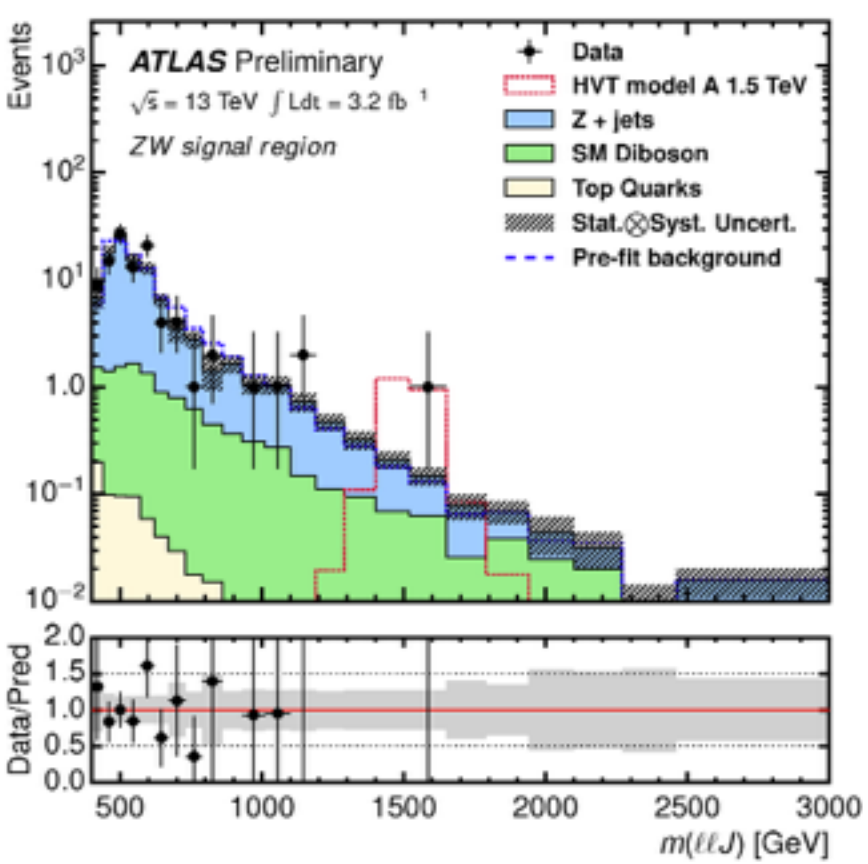
DIBOSON: SPECTRUM AND FIT

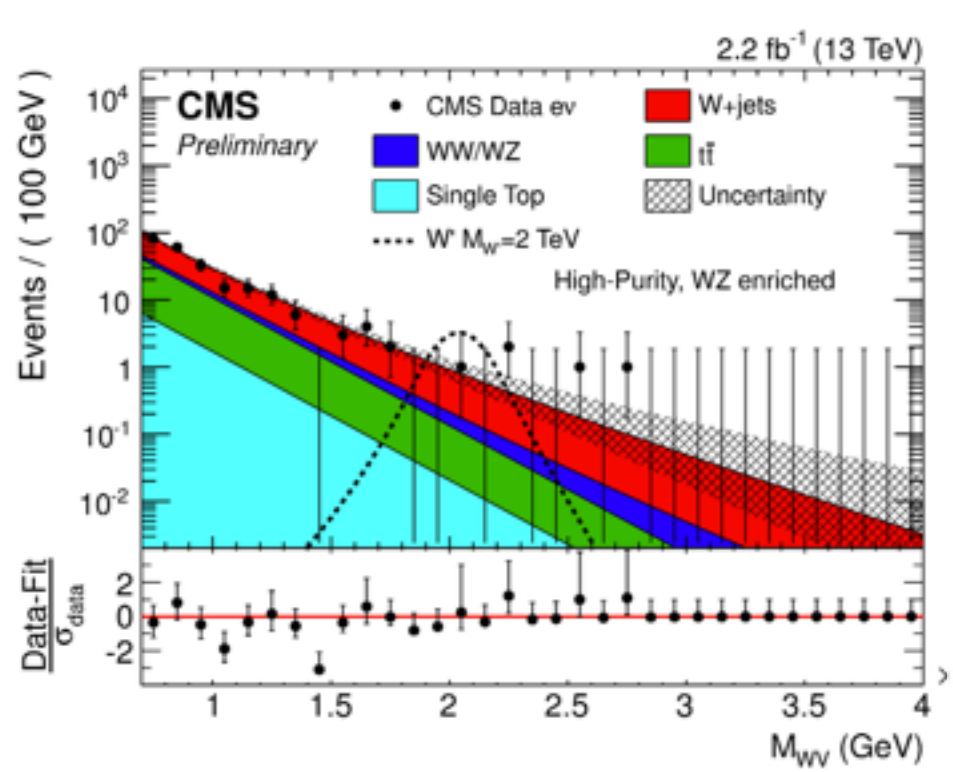
- **Background** from either mass sidebands or control samples in data or fit to data with smoothly falling function
- **m_{VV} resolution ~3-6%**
- **no excess**

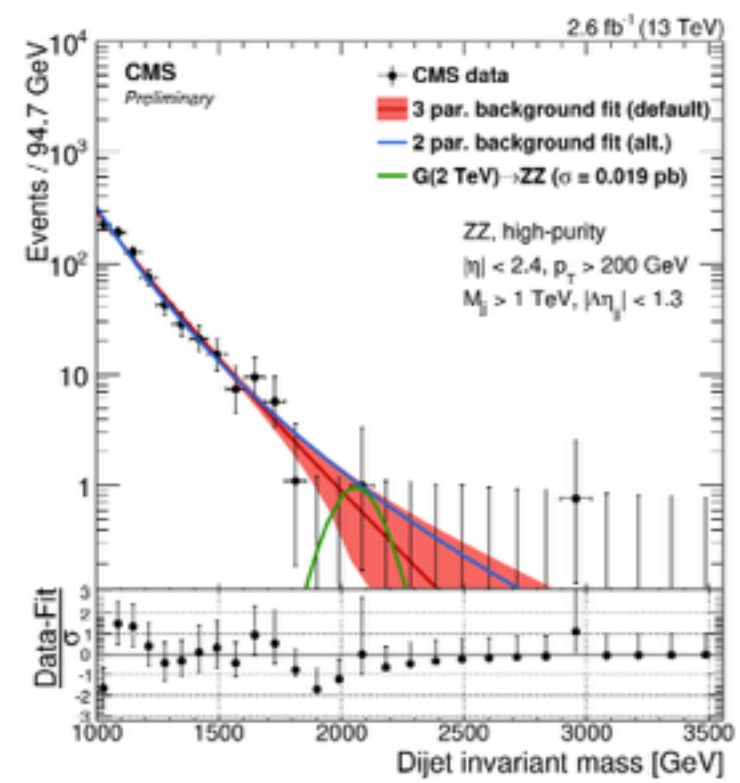












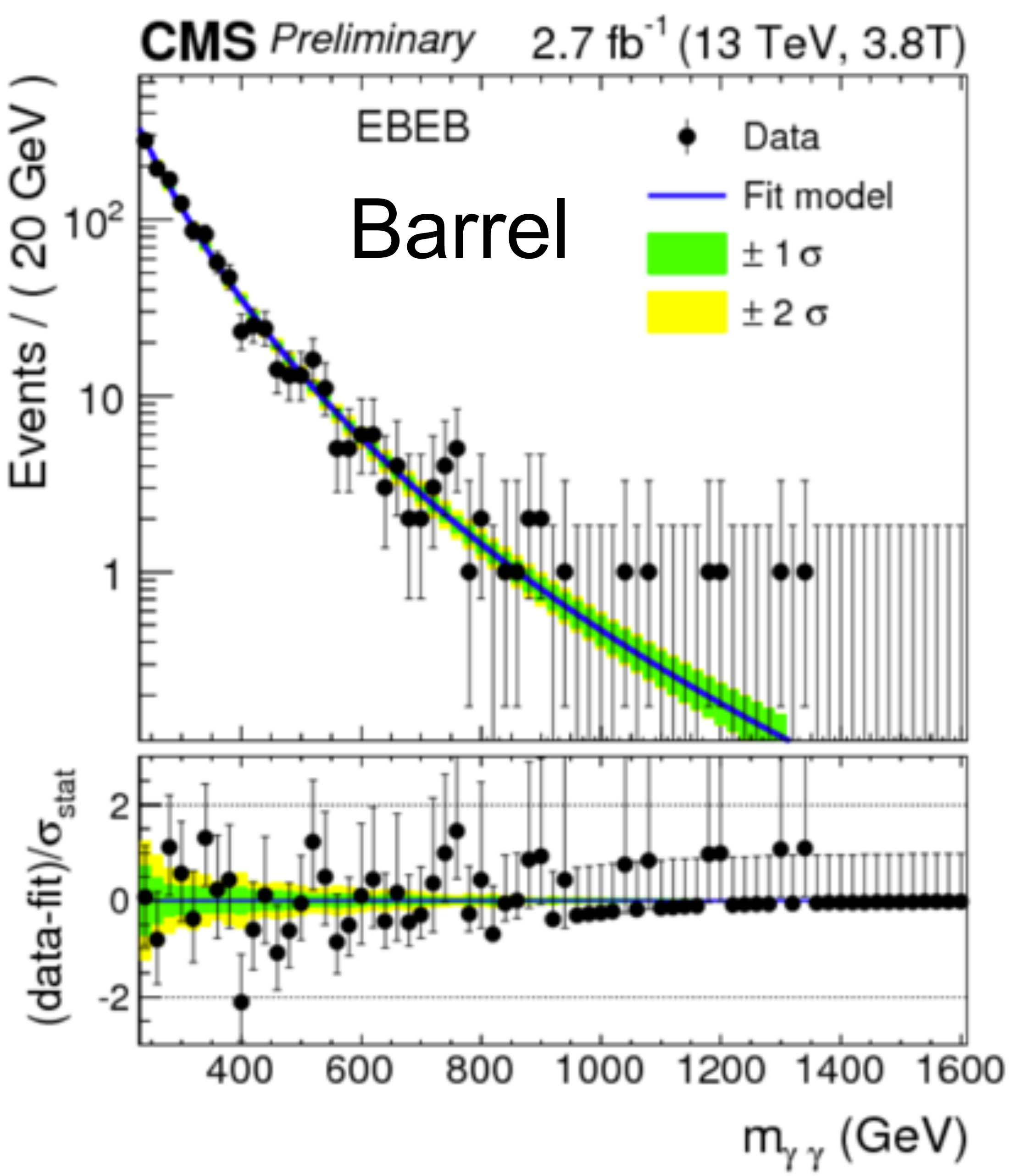
DIPHOTON: INTRO

- Approach **very similar to other the high mass resonance analysis**
- **Two high pt photons**
- Selection based on simple kinematics and isolation criteria
- **Main background**: SM diphoton production
  - contribution estimated from invariant mass fit
- **Resolution from control samples (e.g. Z->ee)**
- **Fake photon contribution from control samples**
  - less than 10% of total background

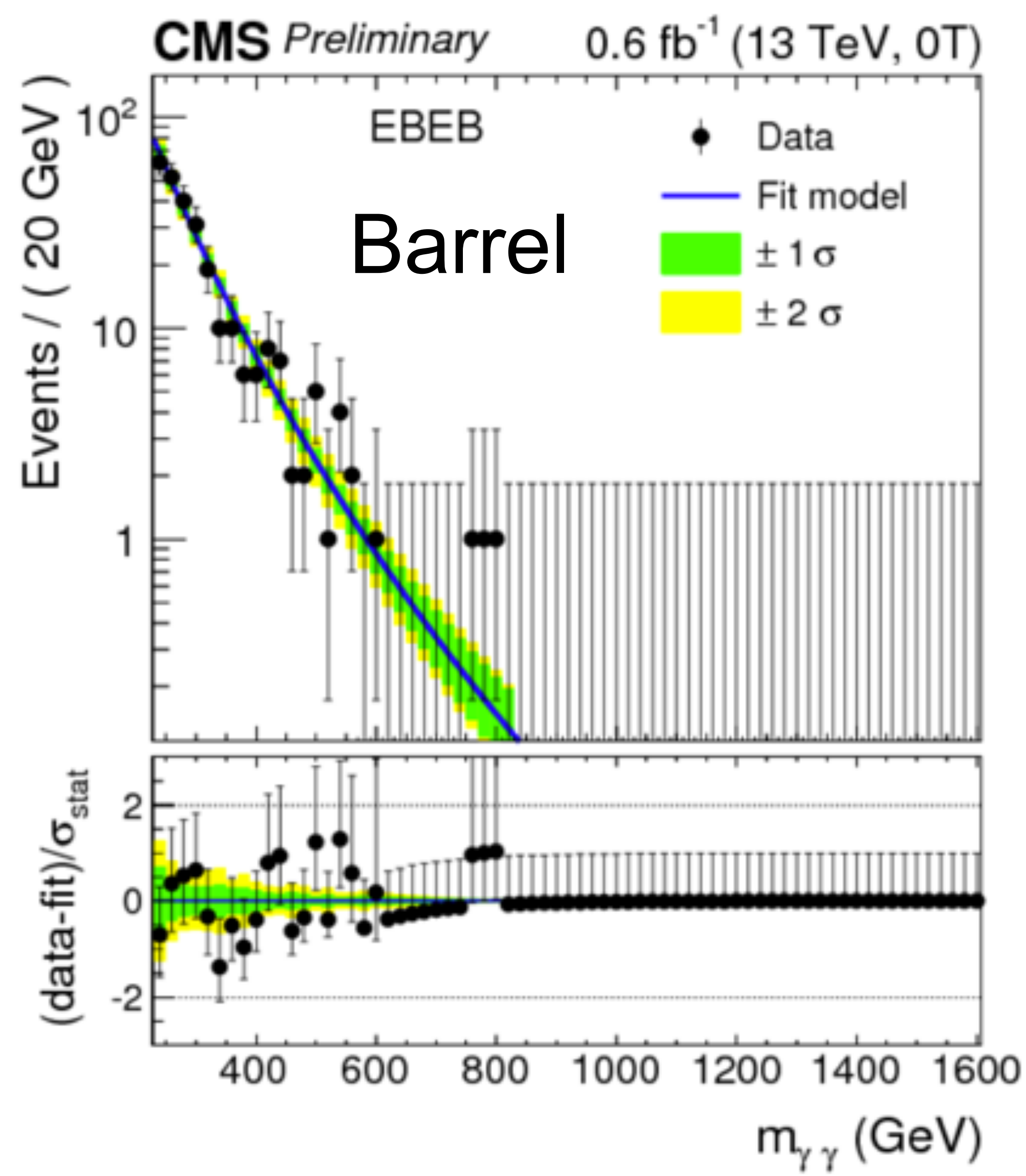
CMS DIPHOTON RESULTS

made in Rome

3.8 T data



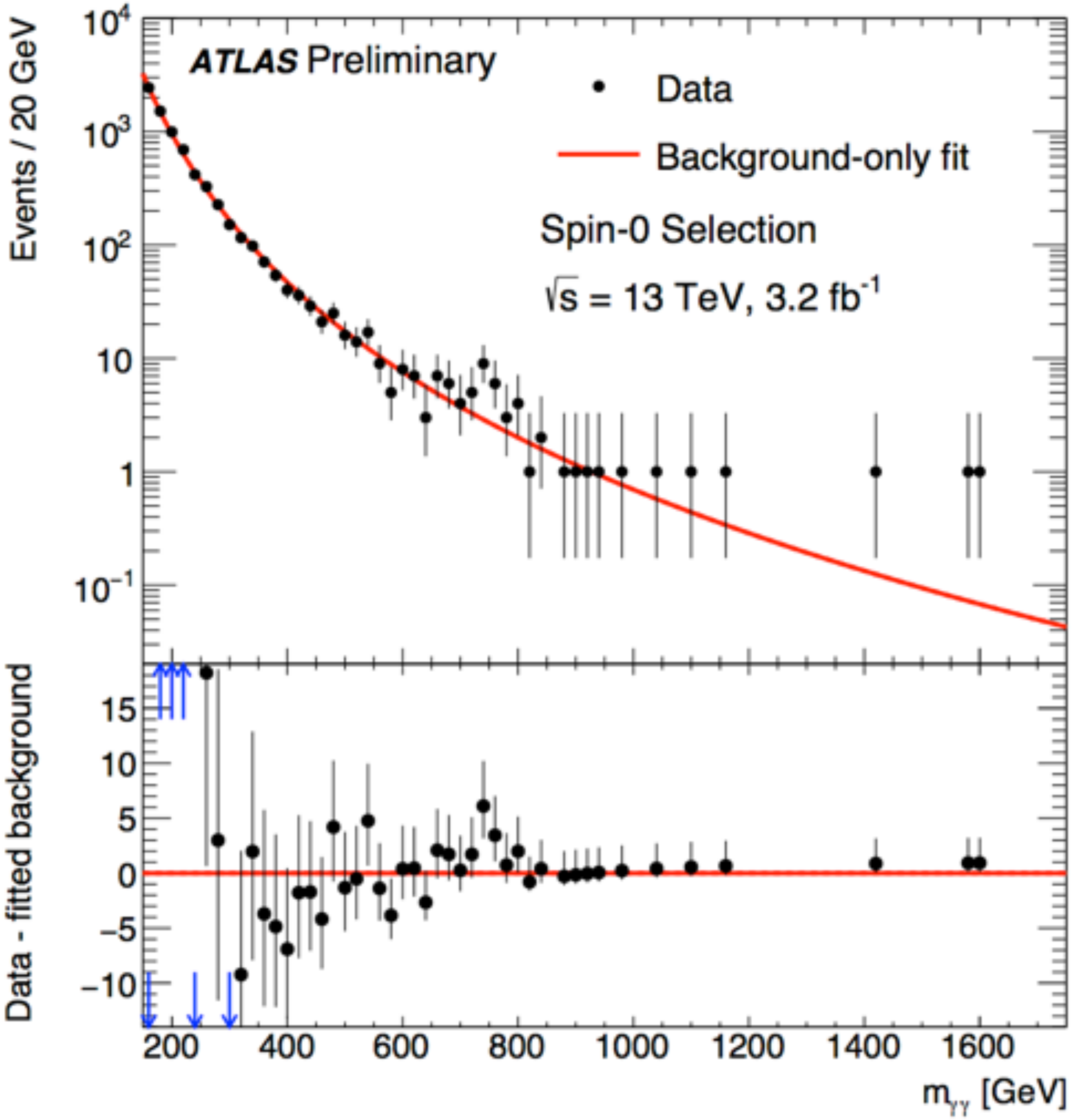
0 T data



ATLAS Diphoton Results

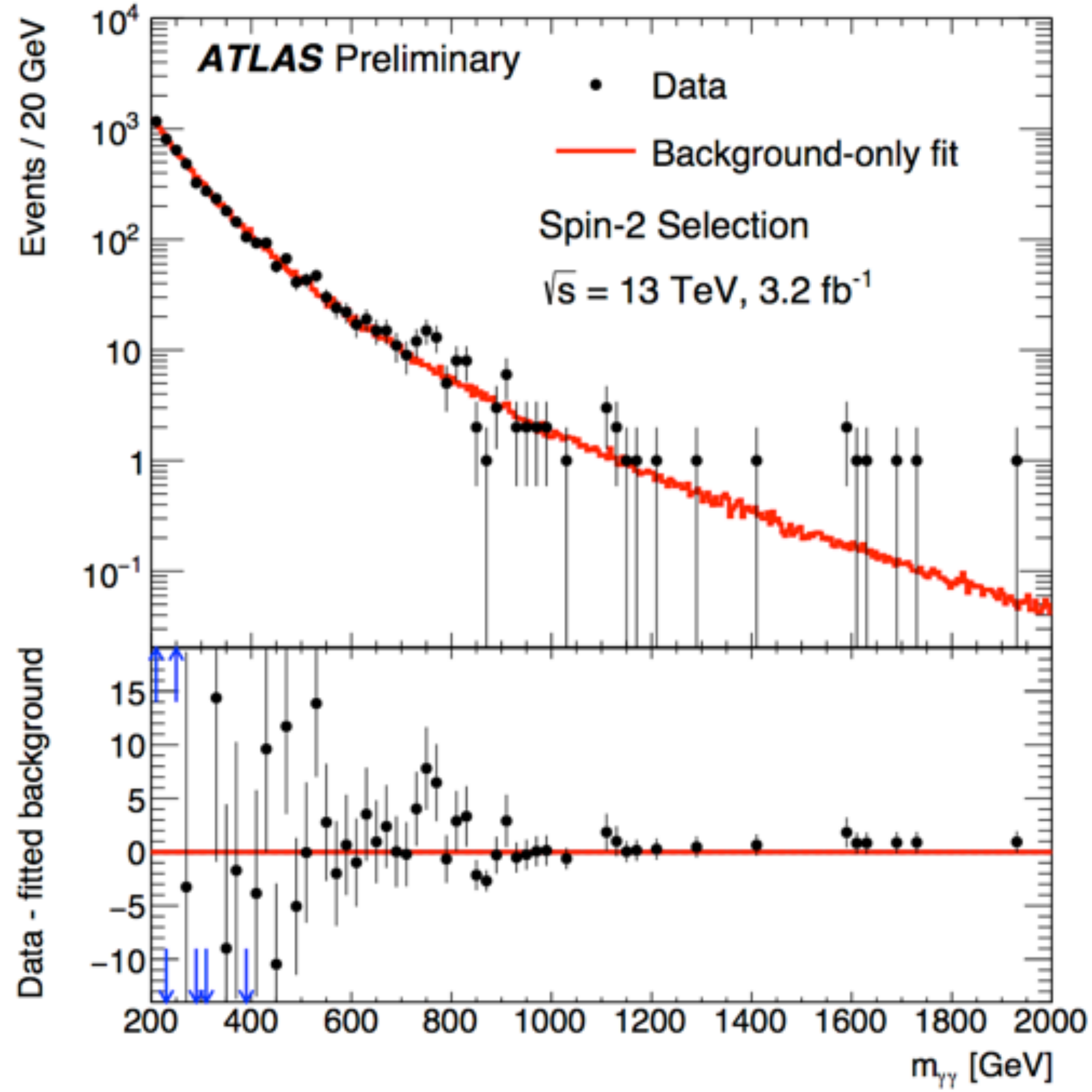
SPIN-0 ANALYSIS

background-only fit

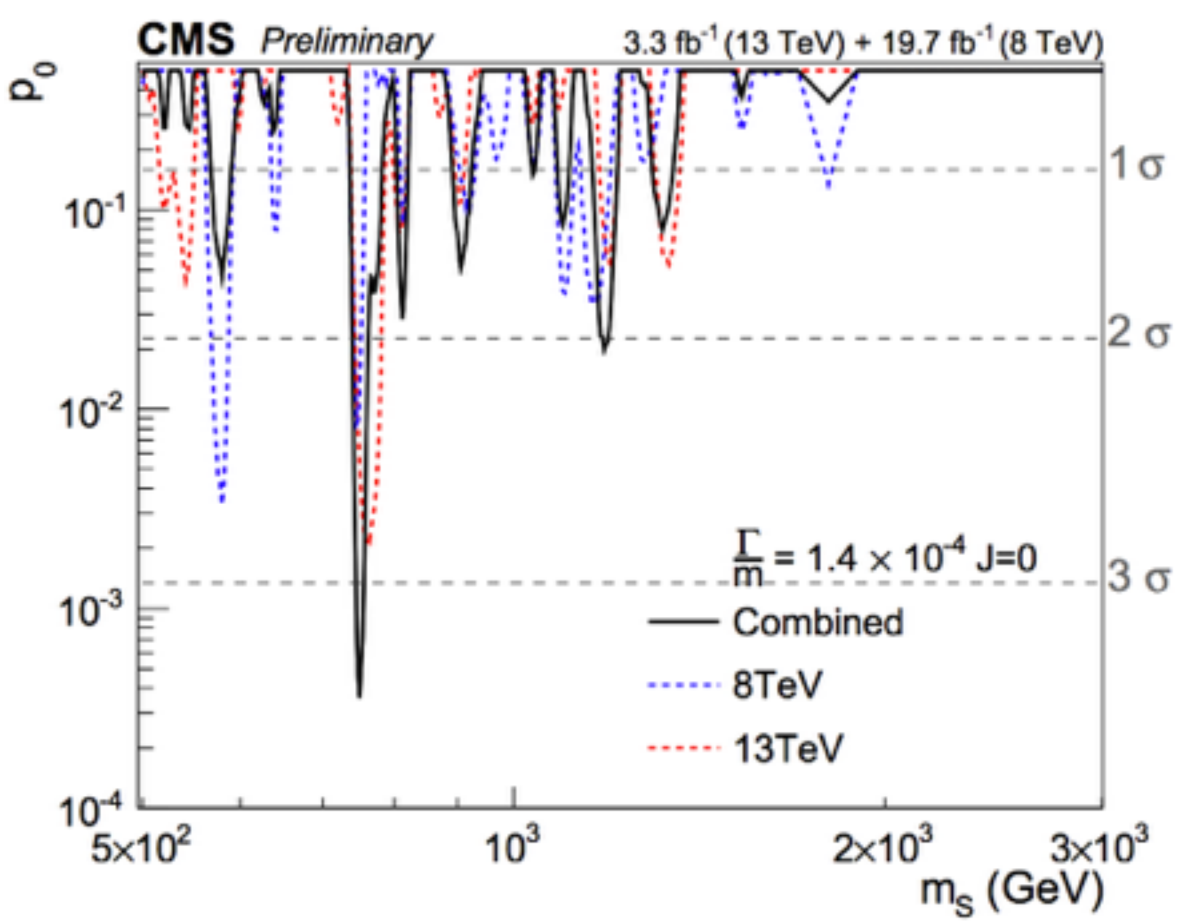


SPIN-2 ANALYSIS

background-only fit

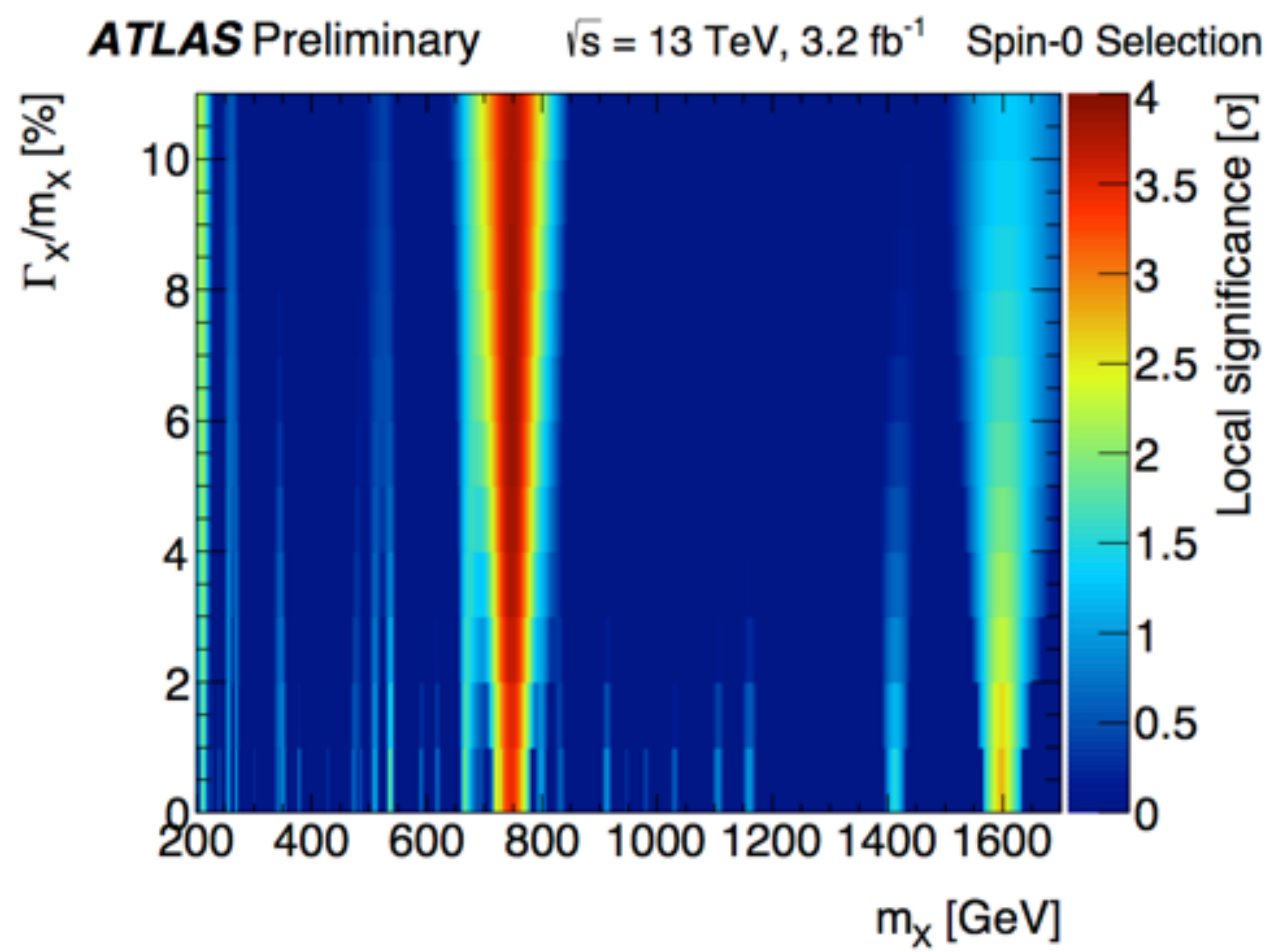


QUANTIFYING THE EXCESS



8 TeV/13 TeV combined pvalue assuming spin 0 narrow resonance decaying to diphoton. Max local significance 3.4 σ @ 750 GeV

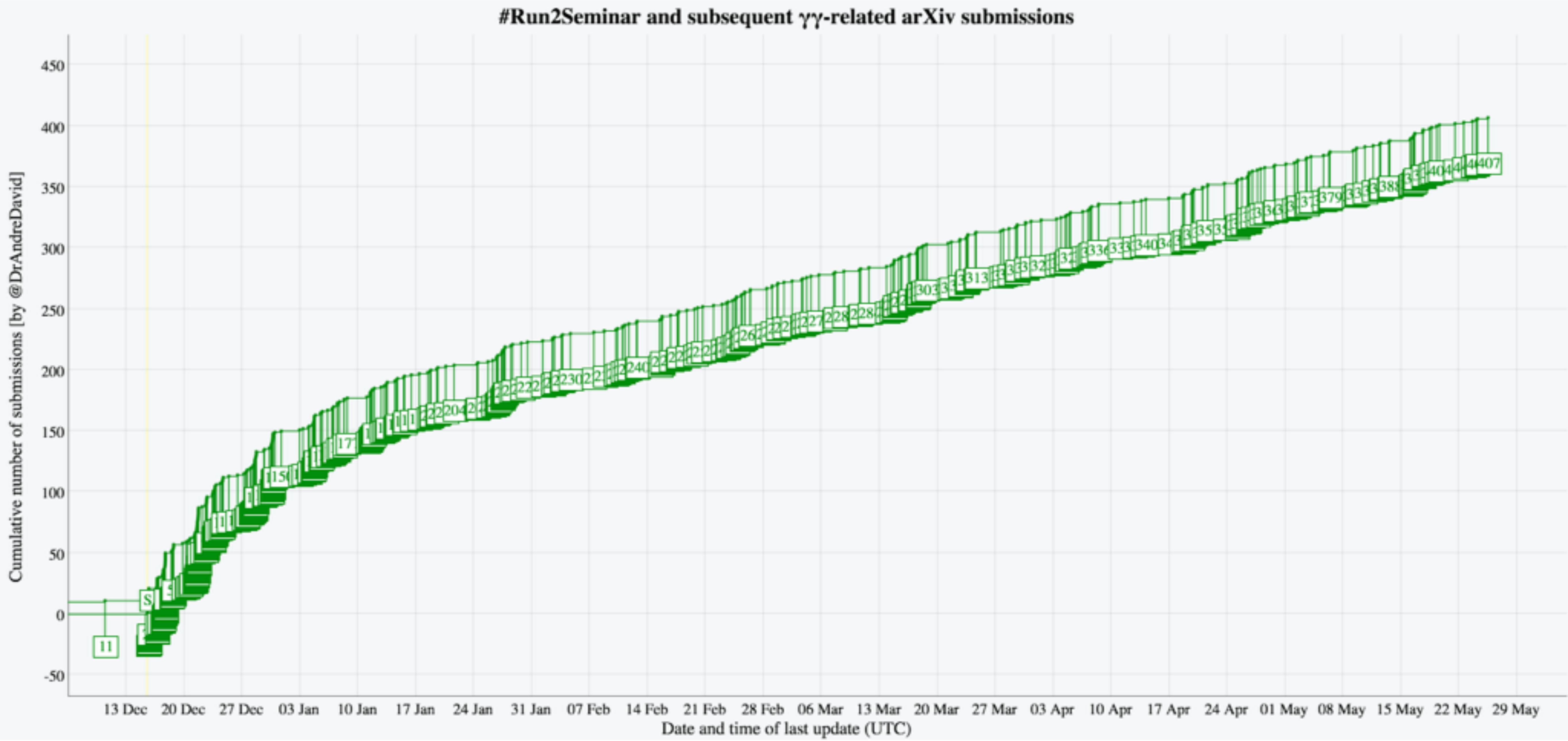
SPIN-0 ANALYSIS



- Largest deviation from B-only hypothesis
  - ✓ $m_X \sim 750$ GeV, $\Gamma_X \sim 45$ GeV (6%)
  - ✓ Local Z = **3.9 σ**
  - ✓ Global Z = **2.0 σ**
    - m_X = [200 GeV - 2 TeV]
    - Γ_X/m_X = [1% - 10%]

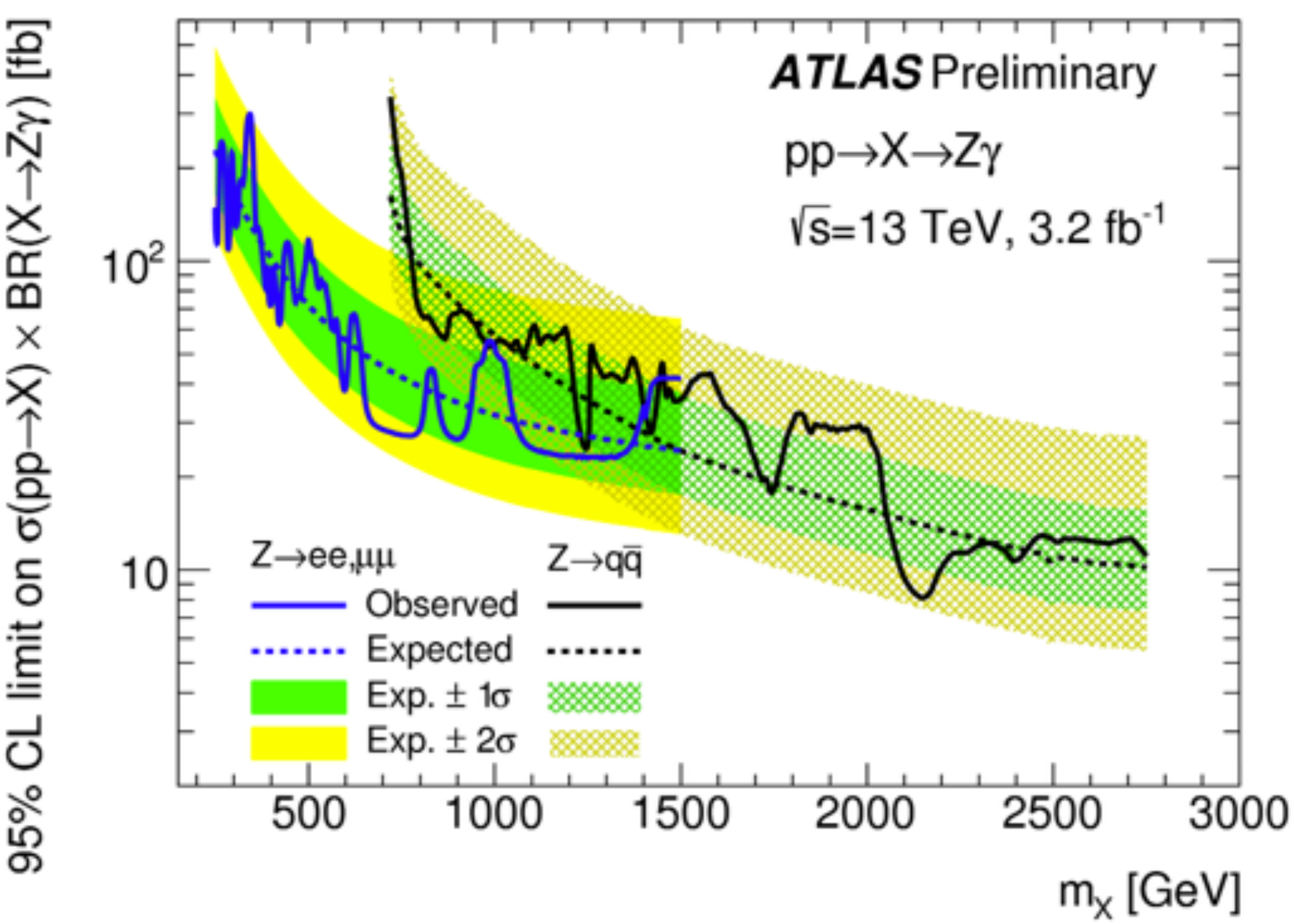
EXCITEMENT IN THEORY LAND

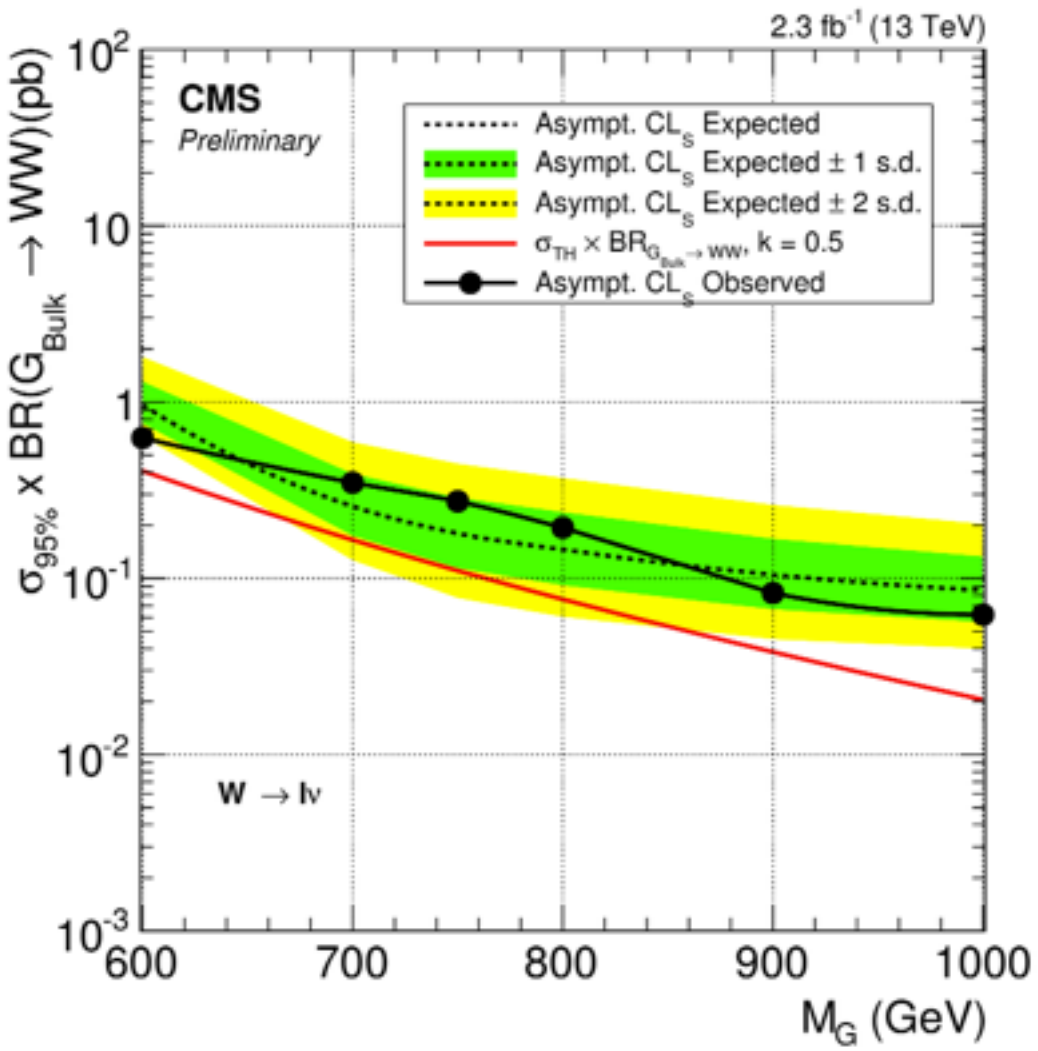
- So far, about **400 theory paper citing diphoton excess**



CONFIRMING THE EXCESS (I)

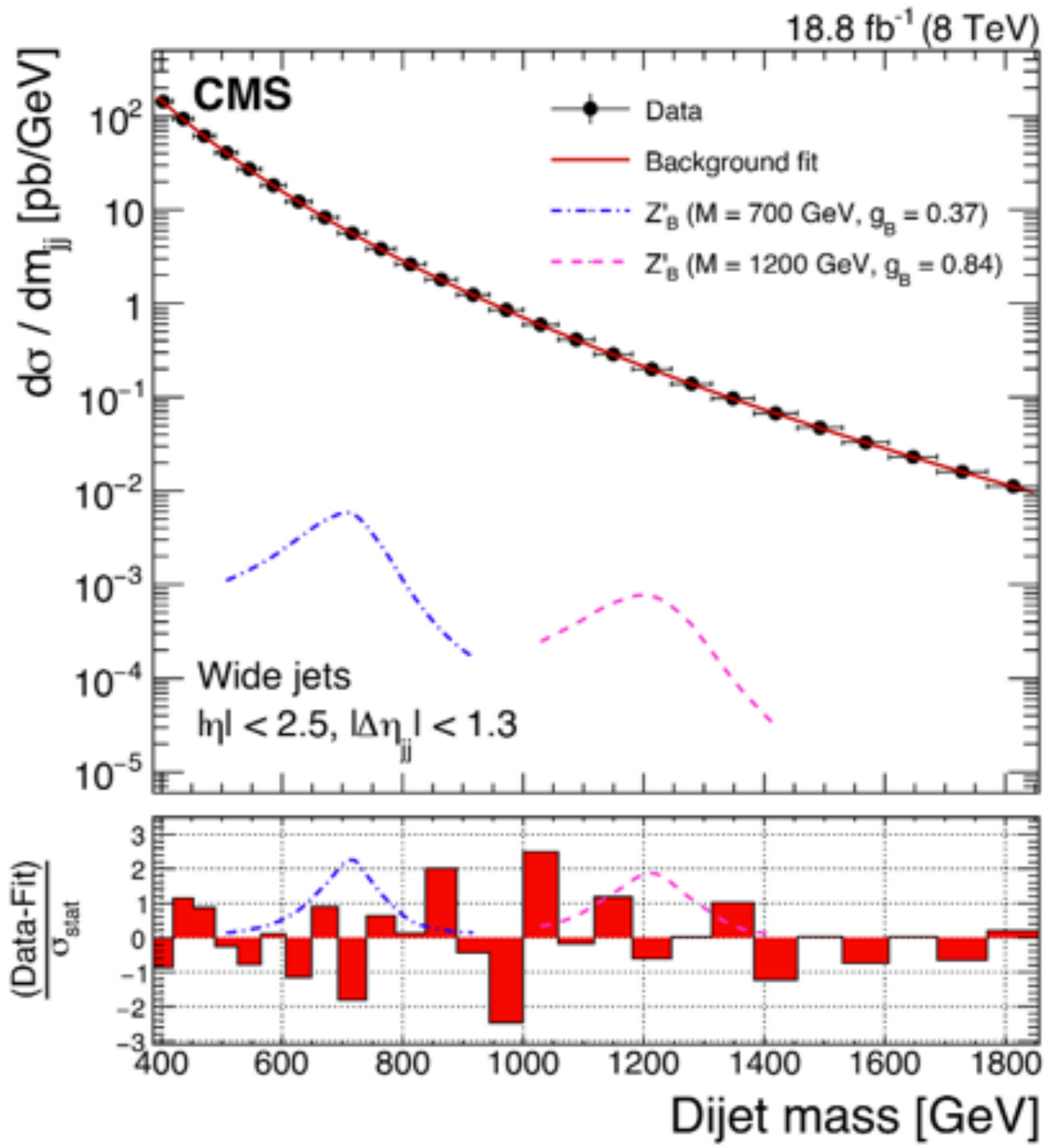
- **Look for excesses at 750 GeV in other channels**
  - examples: Zgamma, ZZ, ZW, WW at low mass
- **No excess found so far**

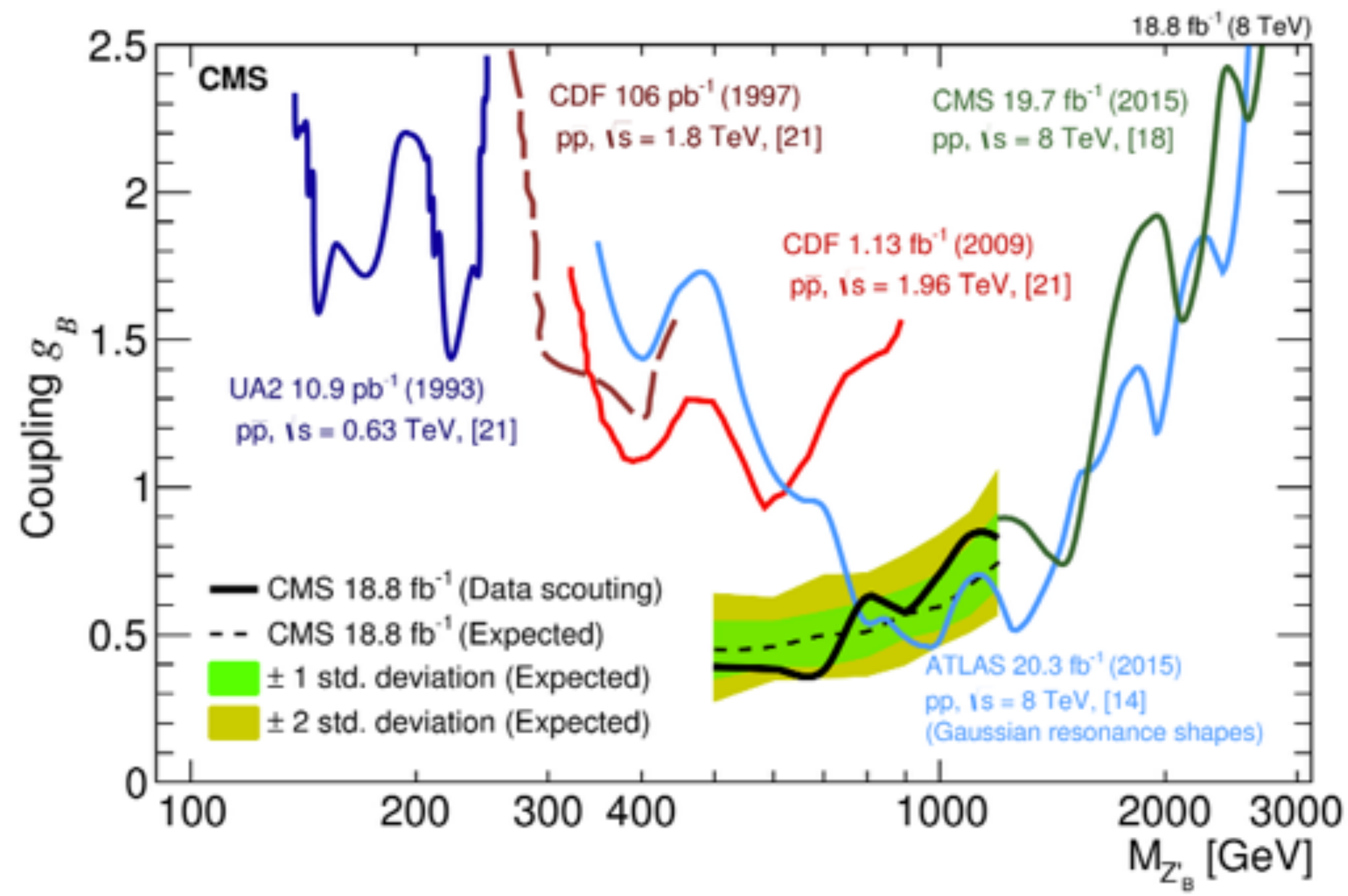




CONFIRMING THE EXCESS (II)

- Dijet **resonance searches** usually **done at large masses**
  - example: dijet (1 TeV)
- In order to **extend to lower masses**, due to trigger limitations, implemented **alternative ways of storing data (scouting)**





DARK MATTER

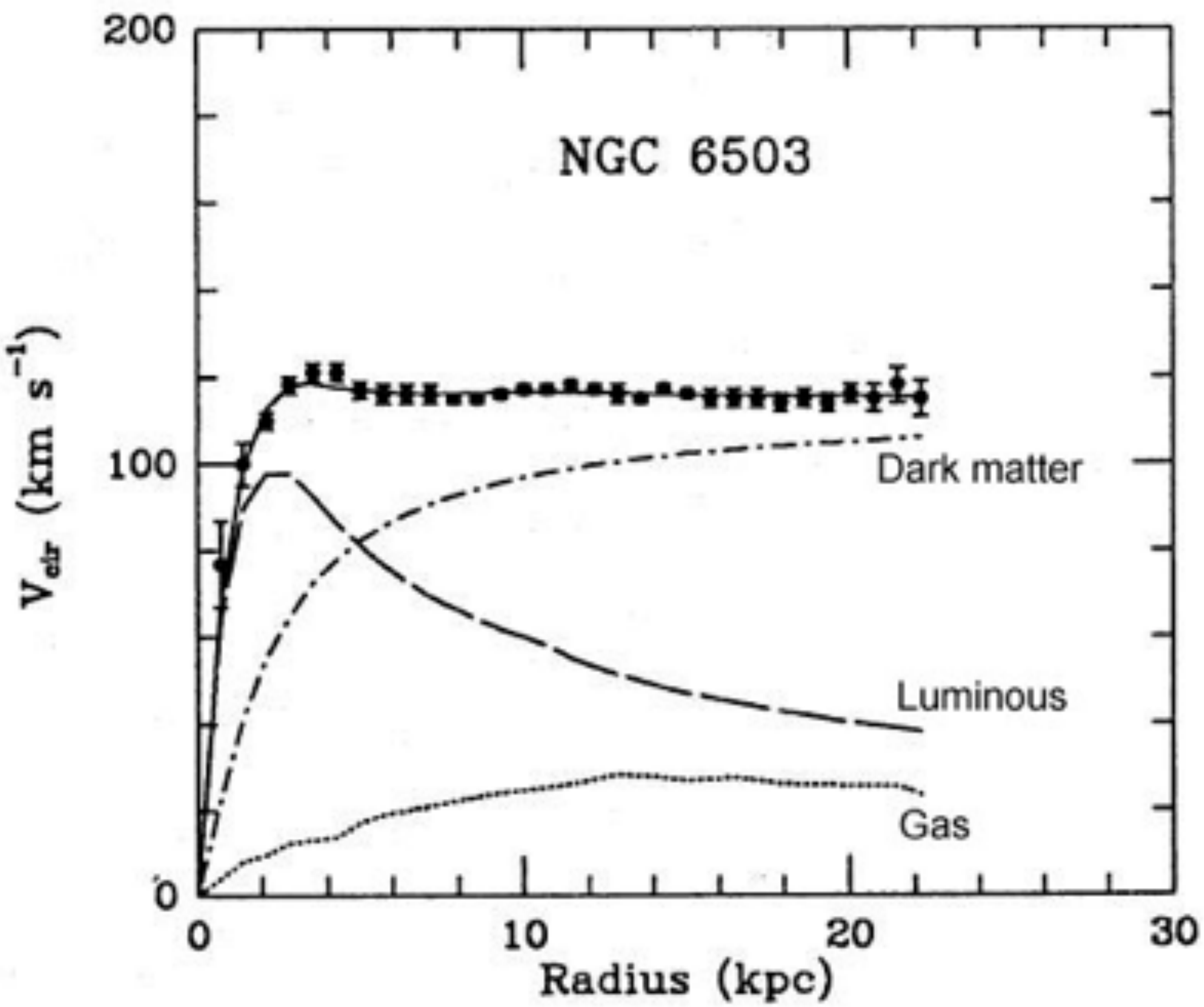
First Indications of Dark Matter

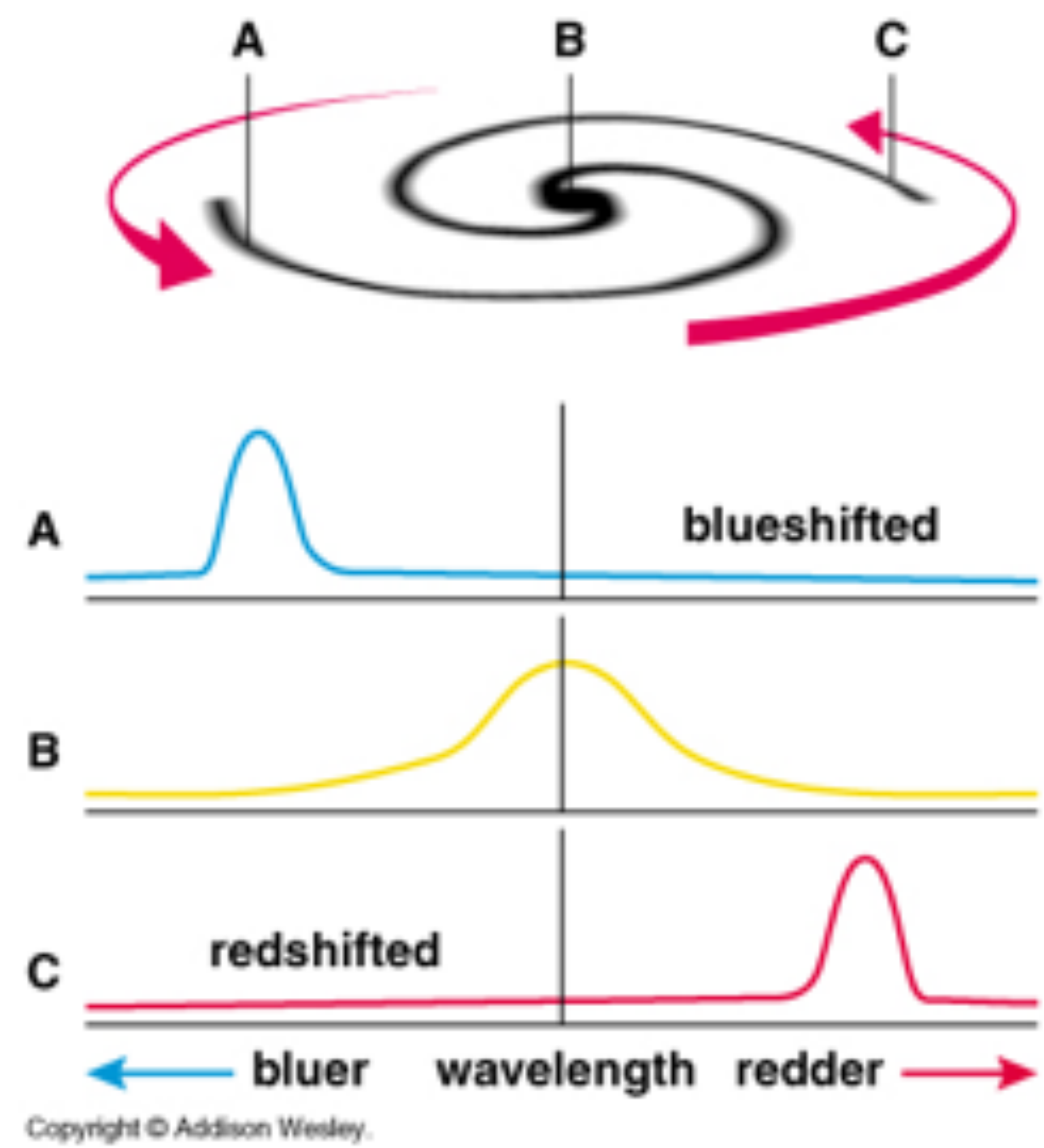
In 1933, Fritz Zwicky calculated the mass of the Coma cluster using galaxies on the outer edge, and came up with a number 400 times larger than expected.

Now we know 90% of its mass due to Dark Matter

GALACTIC ROTATION

- Starting in 1970's, first measurements of velocity curve of edge-on spiral galaxies
- Velocity found to be flat, consistent with ~10x as much "dark"





Galactic Rotation Velocity

- For a star of mass m at distance r from center of the galaxy

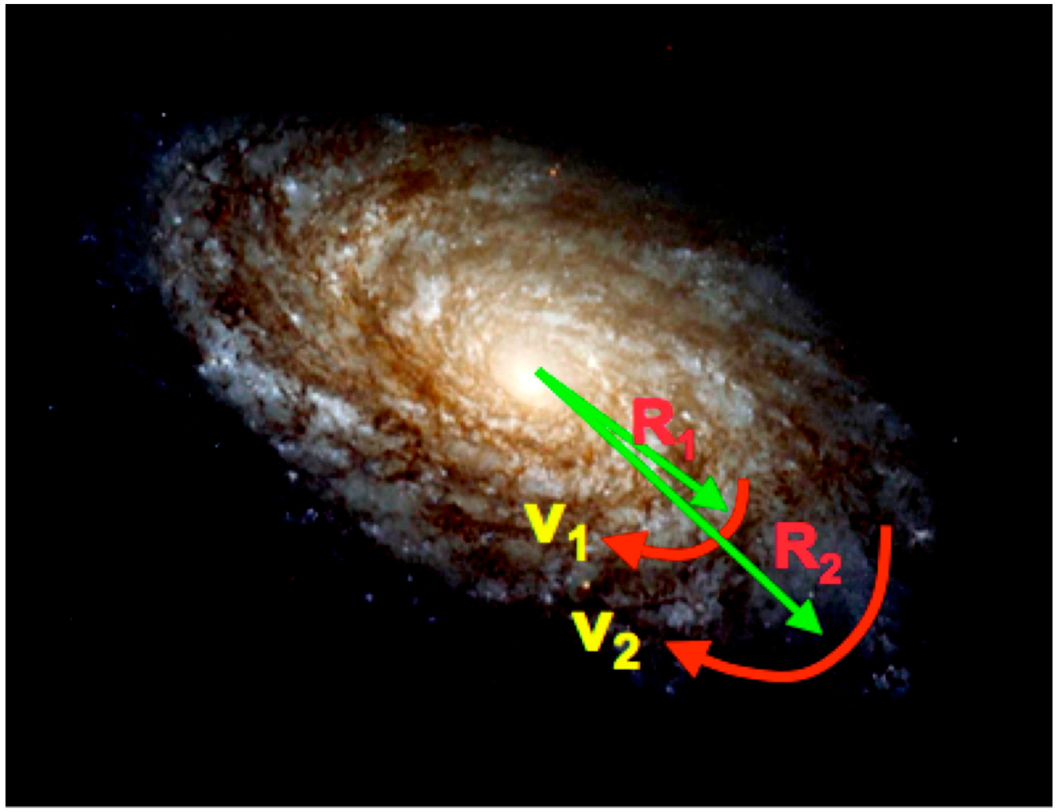
$$\frac{mv^2(r)}{r} = \frac{mM(r)G}{r^2}$$

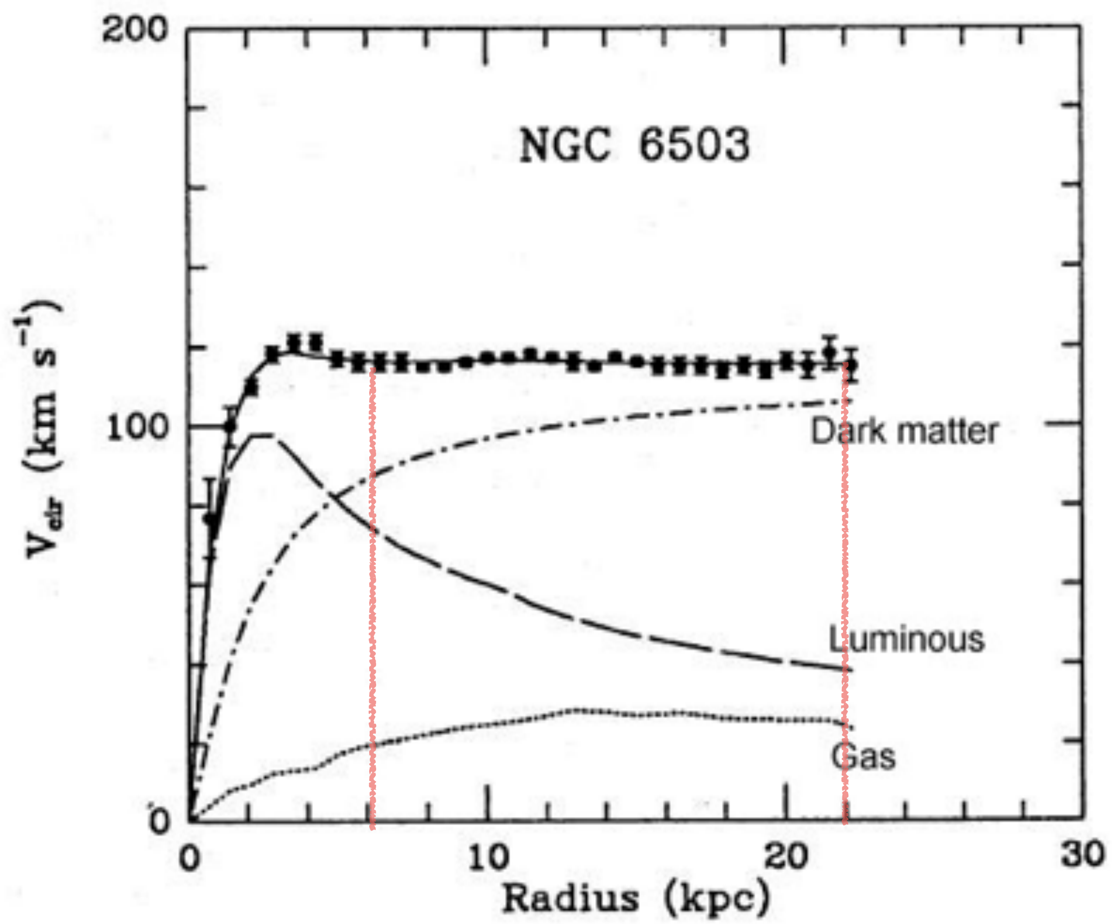
- Galaxy mass mainly within core radius of R_0

$$M(r) = \begin{cases} \rho r^3 & r < R_0 \\ \rho R_0^3 & r \geq R_0 \end{cases}$$

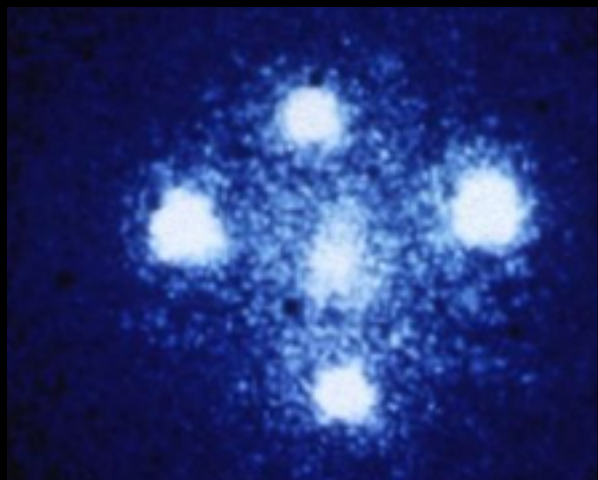
$$v(r) = \begin{cases} \propto r & r < R_0 \\ \propto r^{-1/2} & r \geq R_0 \end{cases}$$

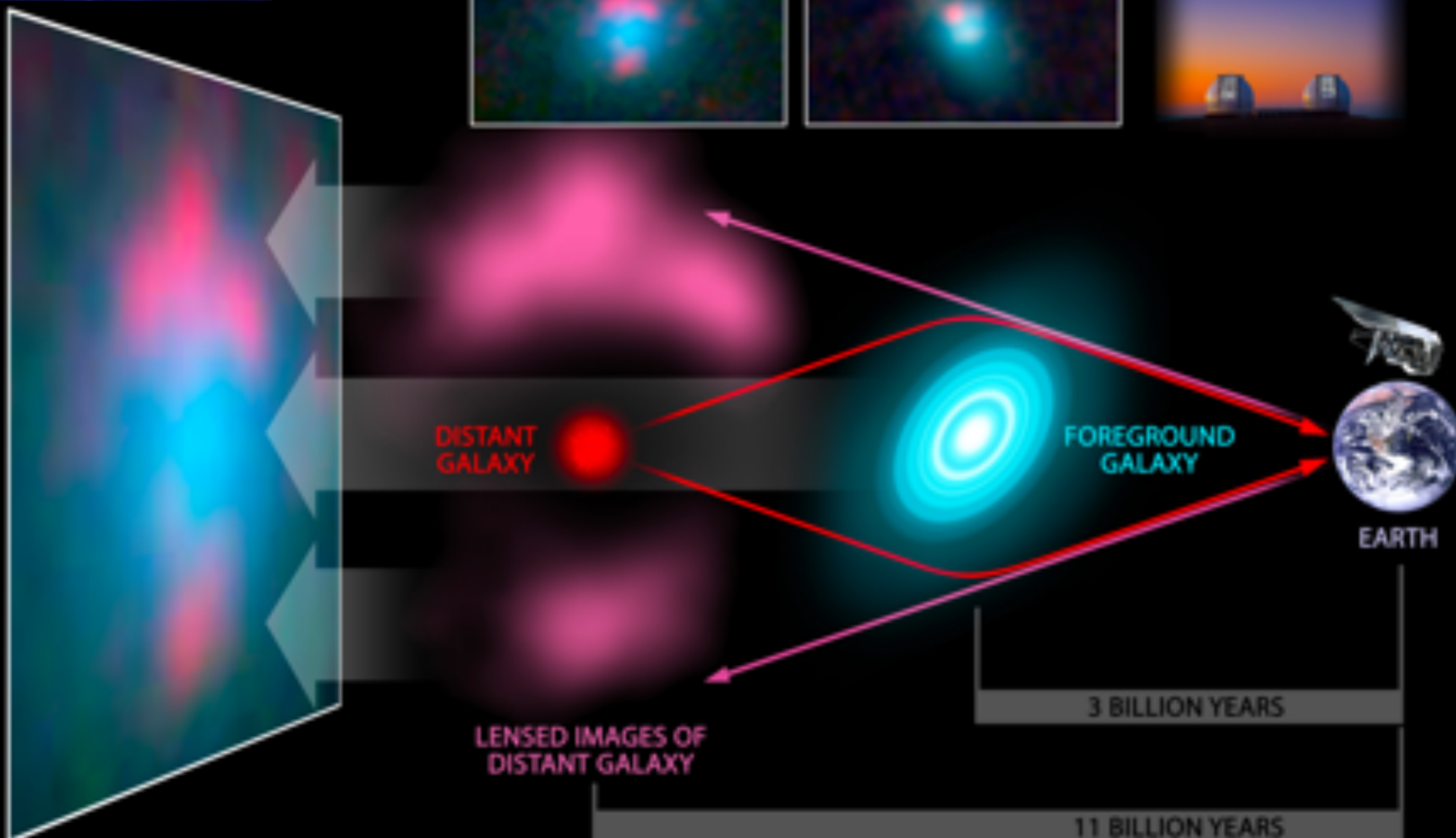
- Galaxy rotation velocity



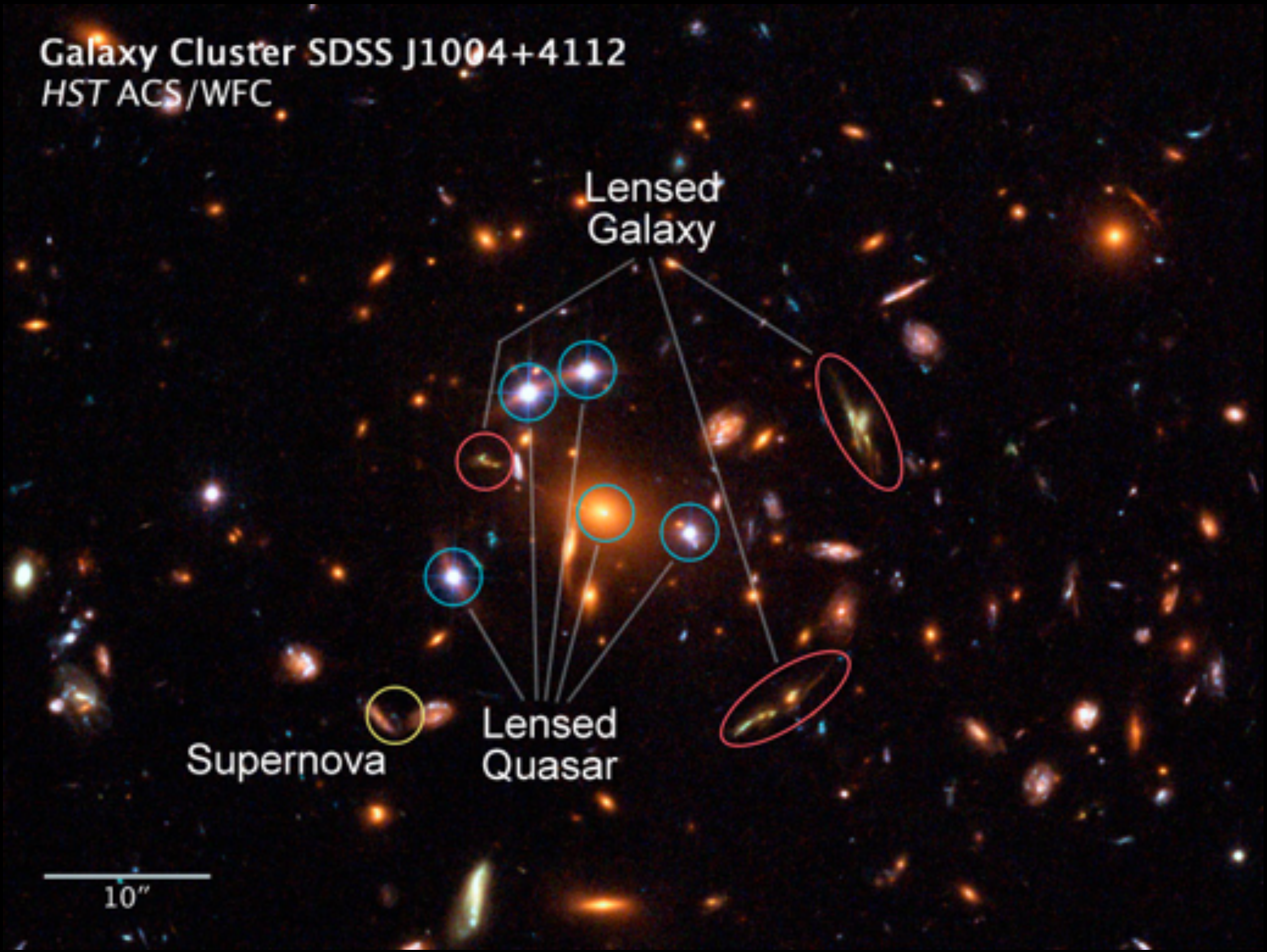


Gravitational Lensing

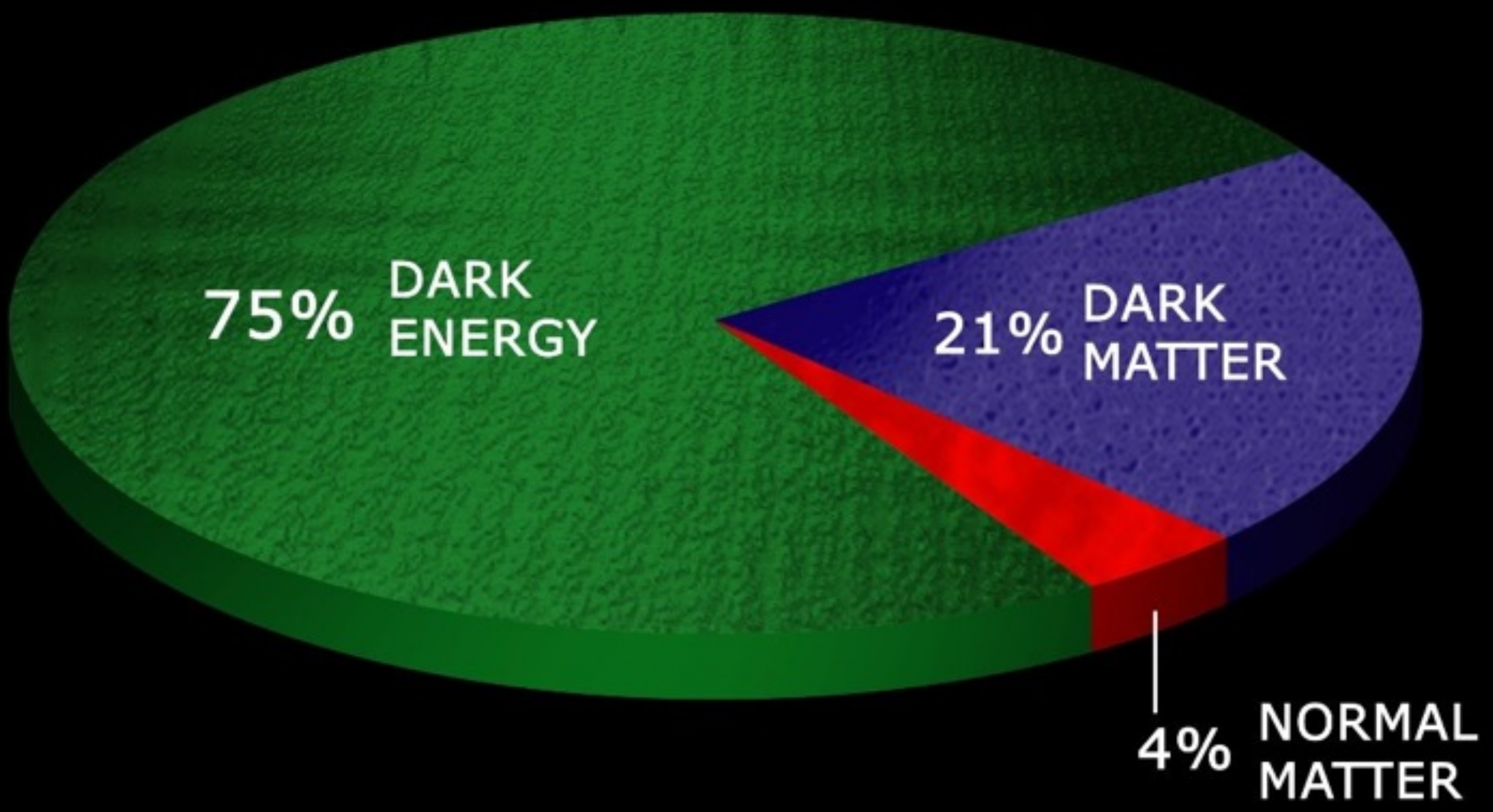




Gravitational Lensing



UNIVERSE COMPOSITION

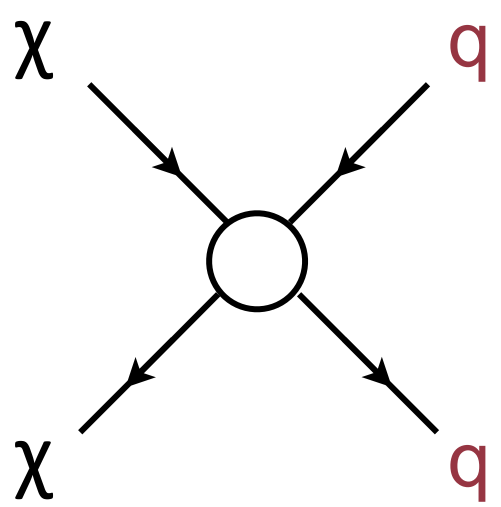


- Strong astrophysical evidence for the existence of dark matter
  - Evidence from bullet cluster, gravitational lensing, rotation curves
  - Dark Matter 5 times more abundant than baryons
  - Contributes ~1/4 of the total energy budget!

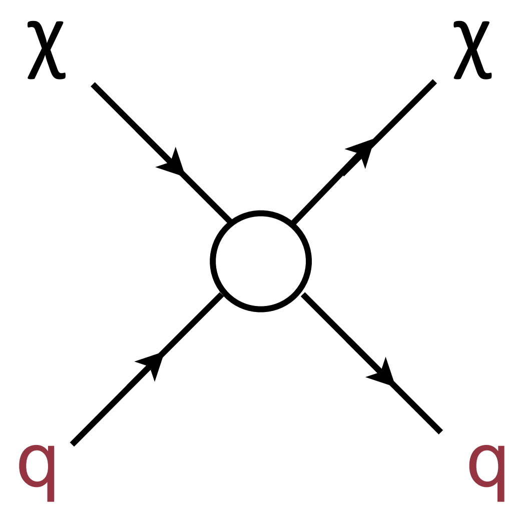
Candidate Dark Matter Particles

- **Properties**
  - long lived (old)
  - non-relativistic (slow)
  - 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)
  - …

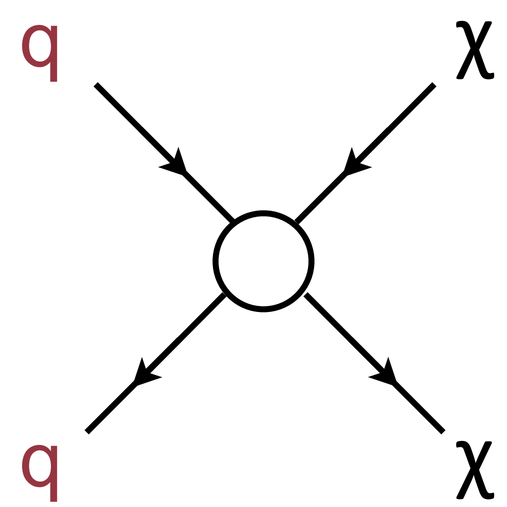
DARK MATTER INTERACTION



Indirect Detection

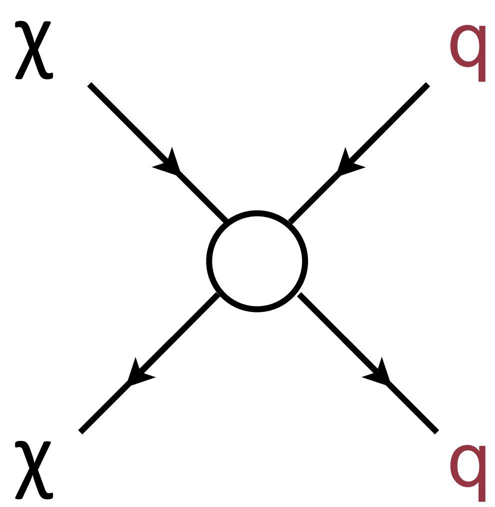


Direct Detection



Production at Colliders

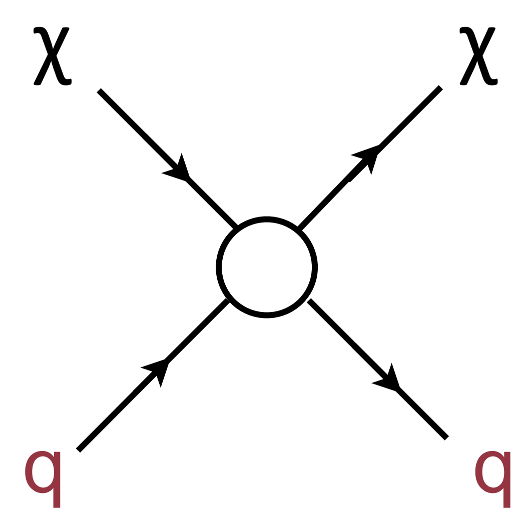
DARK MATTER INTERACTION



Indirect Detection

- **Indirect detection**
  - search for production of DM annihilation
  - high energy photons, particle-anti-particle pairs
  - search for ultra-relativistic objects produced in galactic halo
  - observatory on earth-bound or with satellites

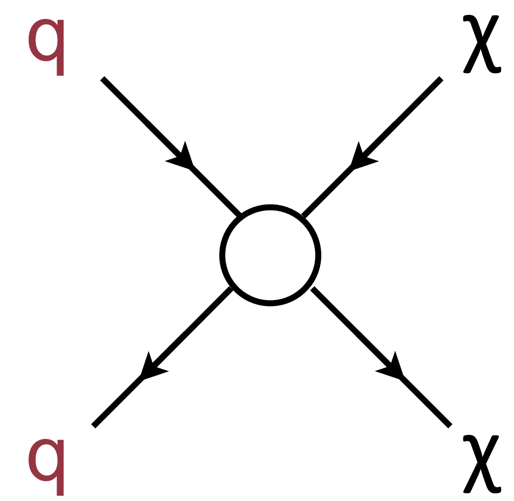
Dark Matter Interaction



Direct Detection

- **Direct detection**
  – Observe recoil of dark matter from nucleus

DARK MATTER INTERACTION

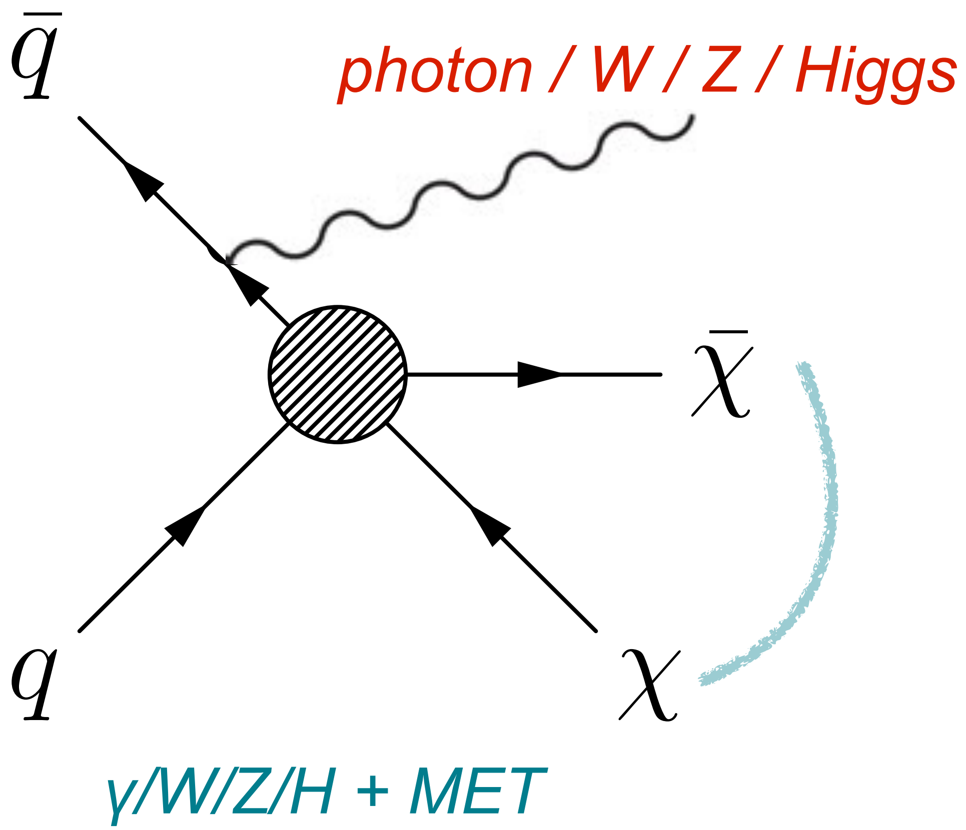


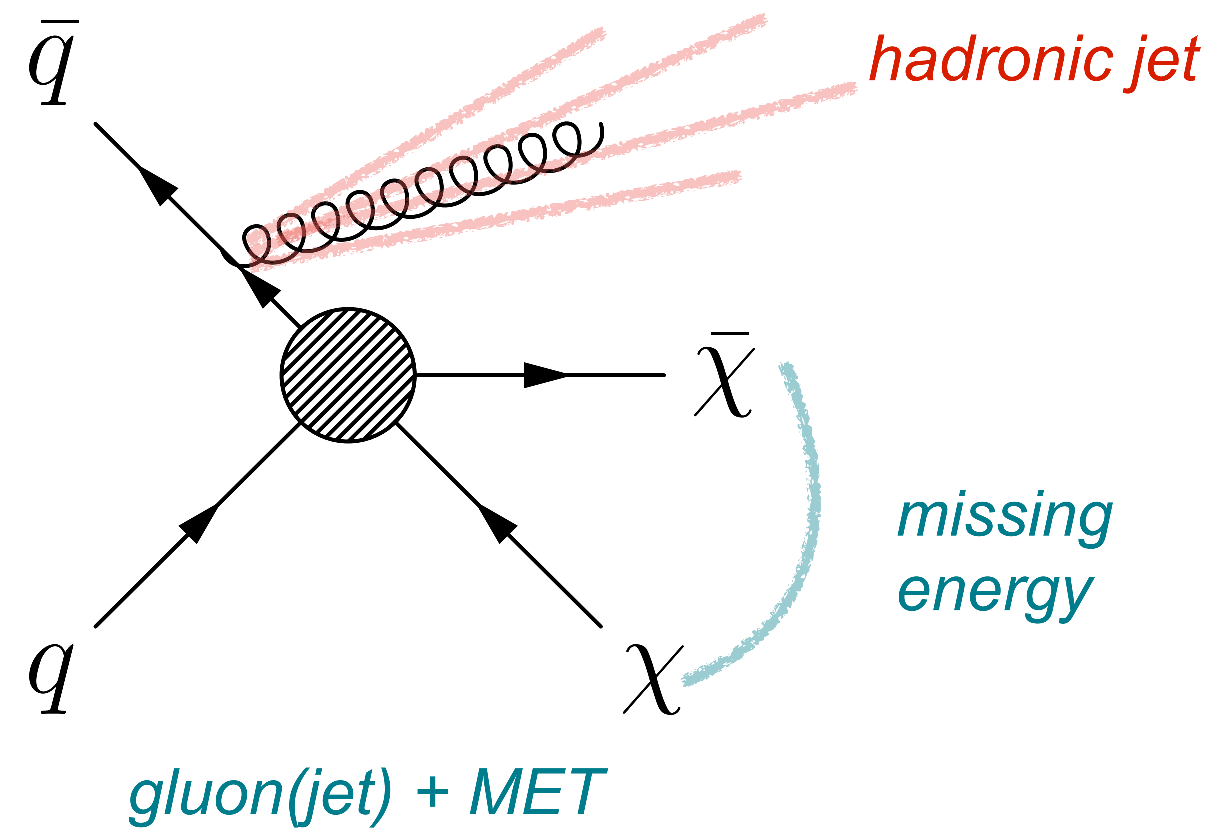
Production at Colliders

- **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

DARK MATTER IDENTIFICATION 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



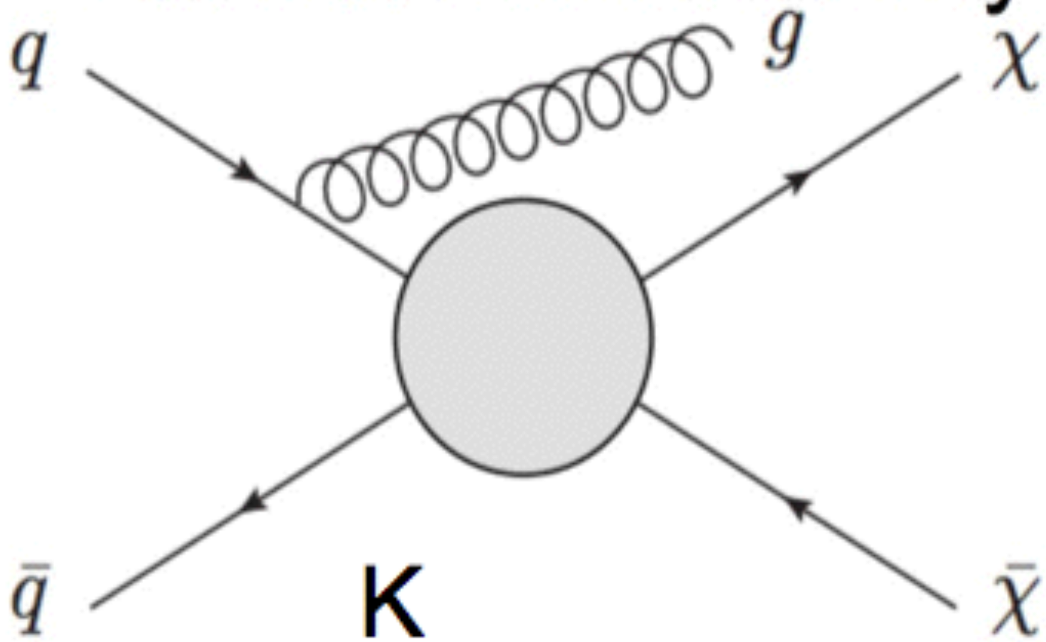


Different Possible Signatures

- **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**

MODELING DM CANDIDATE INTERACTIONS

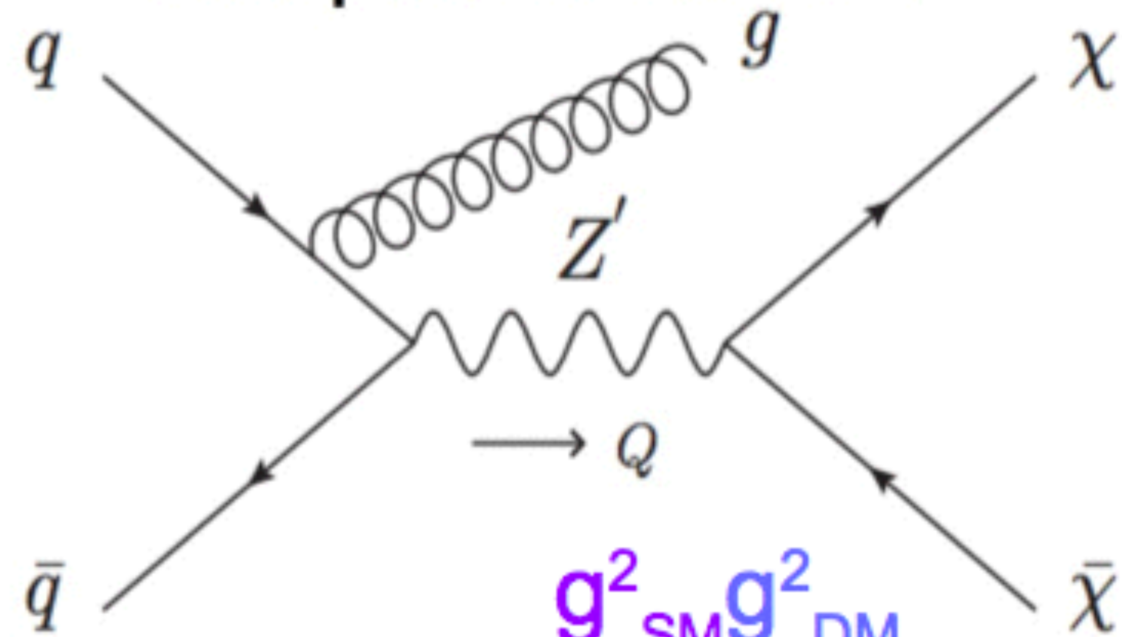
Effective field theory



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

One free parameter

Simplified model

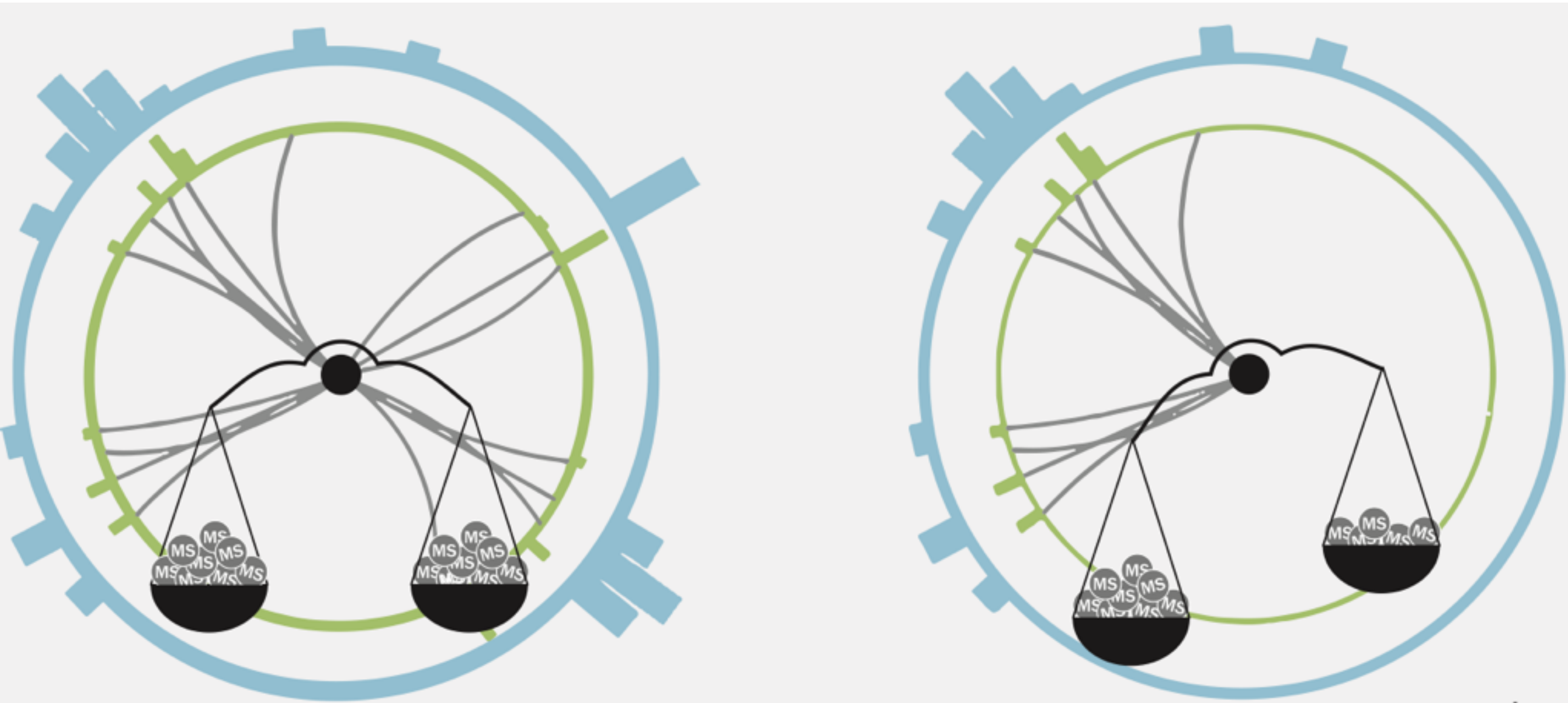


$$\sigma = K' \frac{g^2_{SM} g^2_{DM}}{M^4 \Gamma_{med}}$$

4 free parameters

- M = mediator mass
- Γ = mediator width
- g_{SM} = coupling to SM
- g_{DM} = coupling to DM

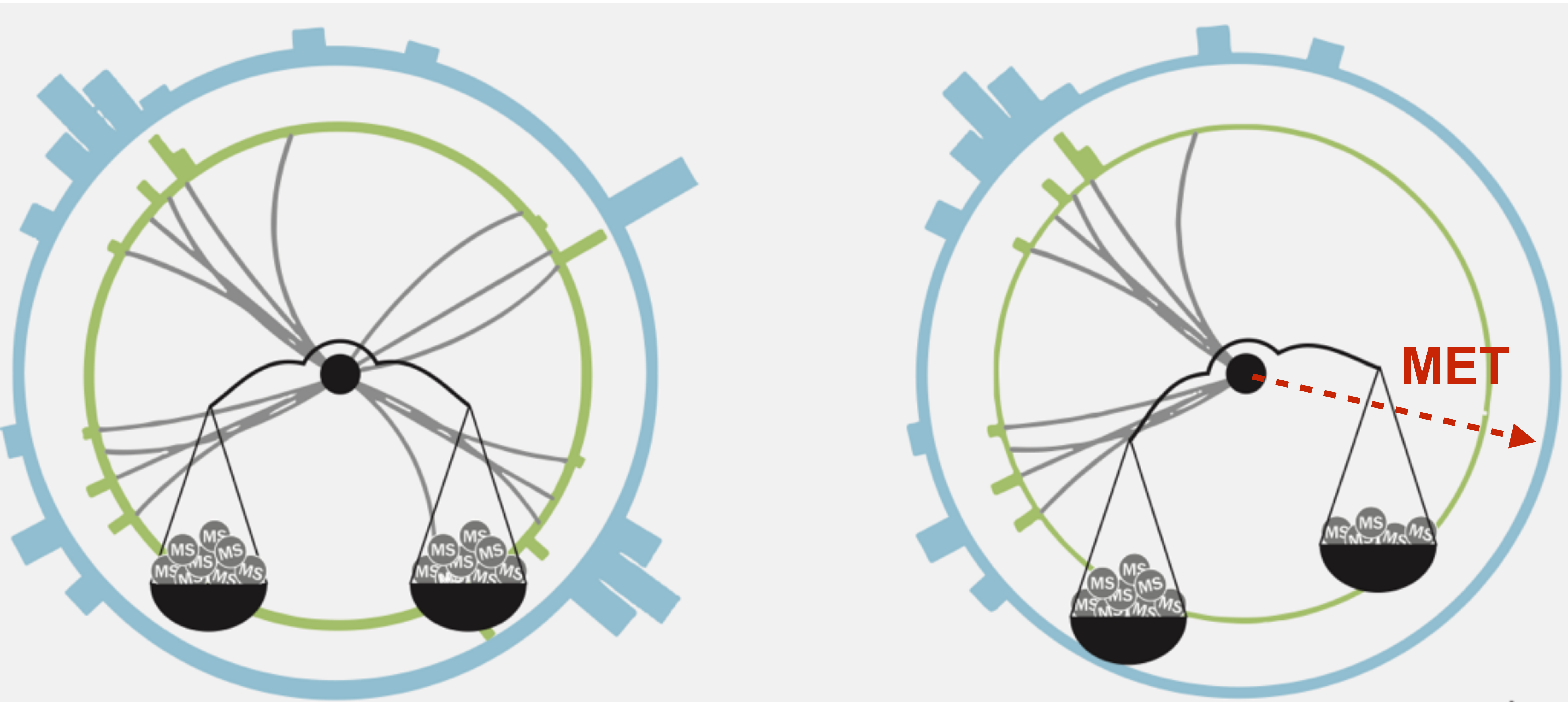
How Does It Look?



SM event

DM event

How Does It Look?

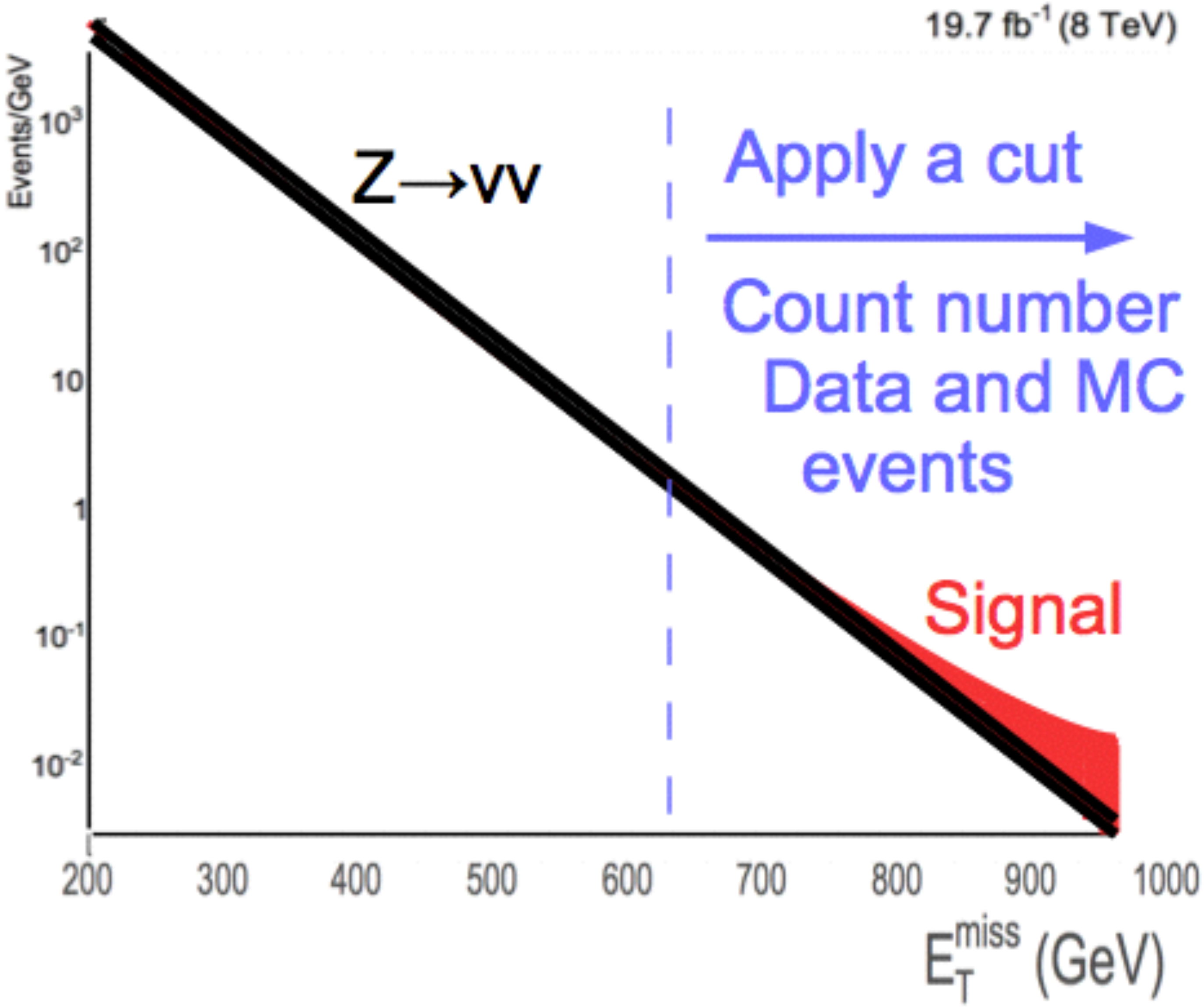


SM event

DM event

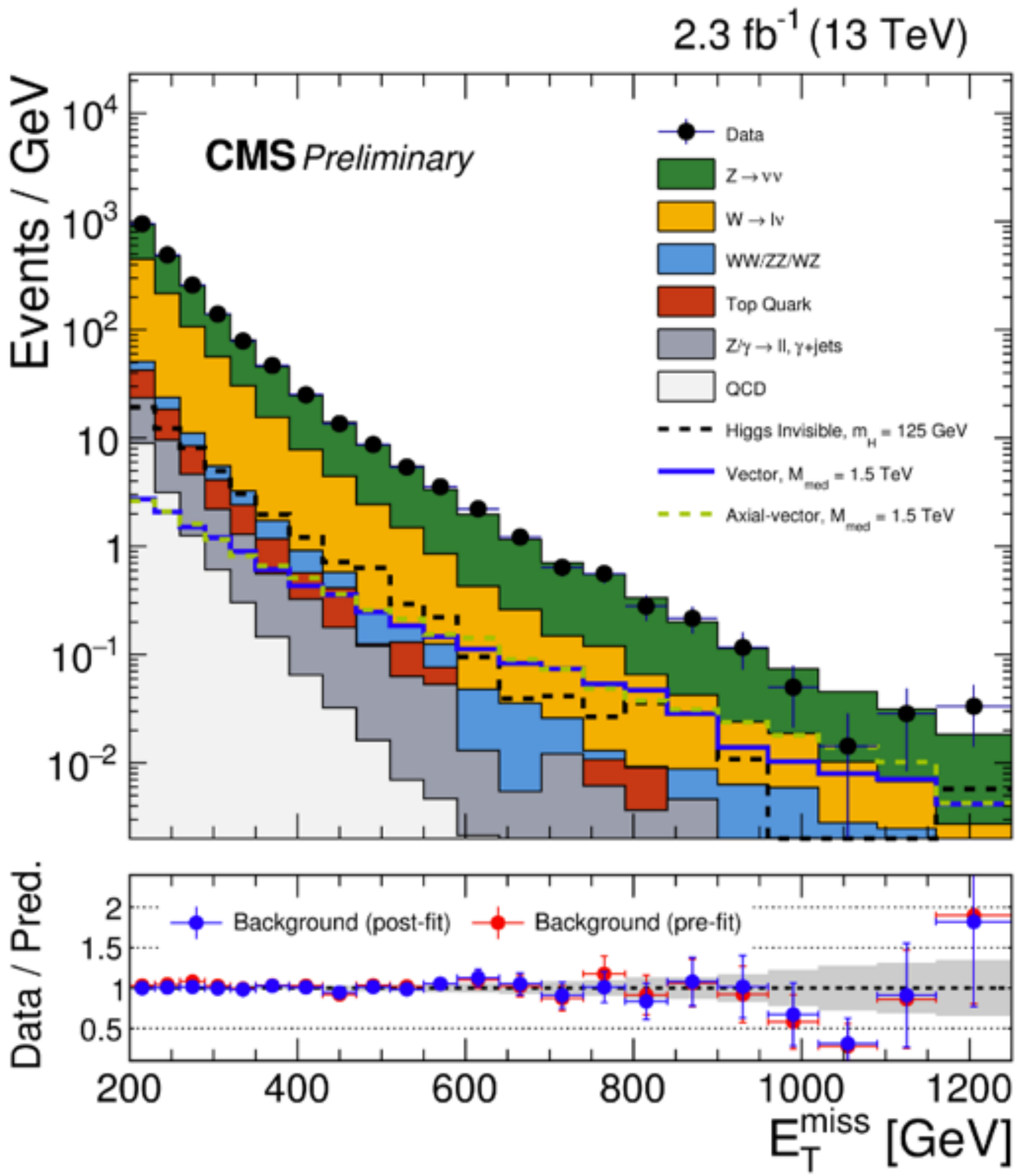
$$MET = |\vec{p_t}(missing)| = |-\Sigma_i \vec{p}_{Ti}(visible)|$$

ANALYSIS STRATEGY

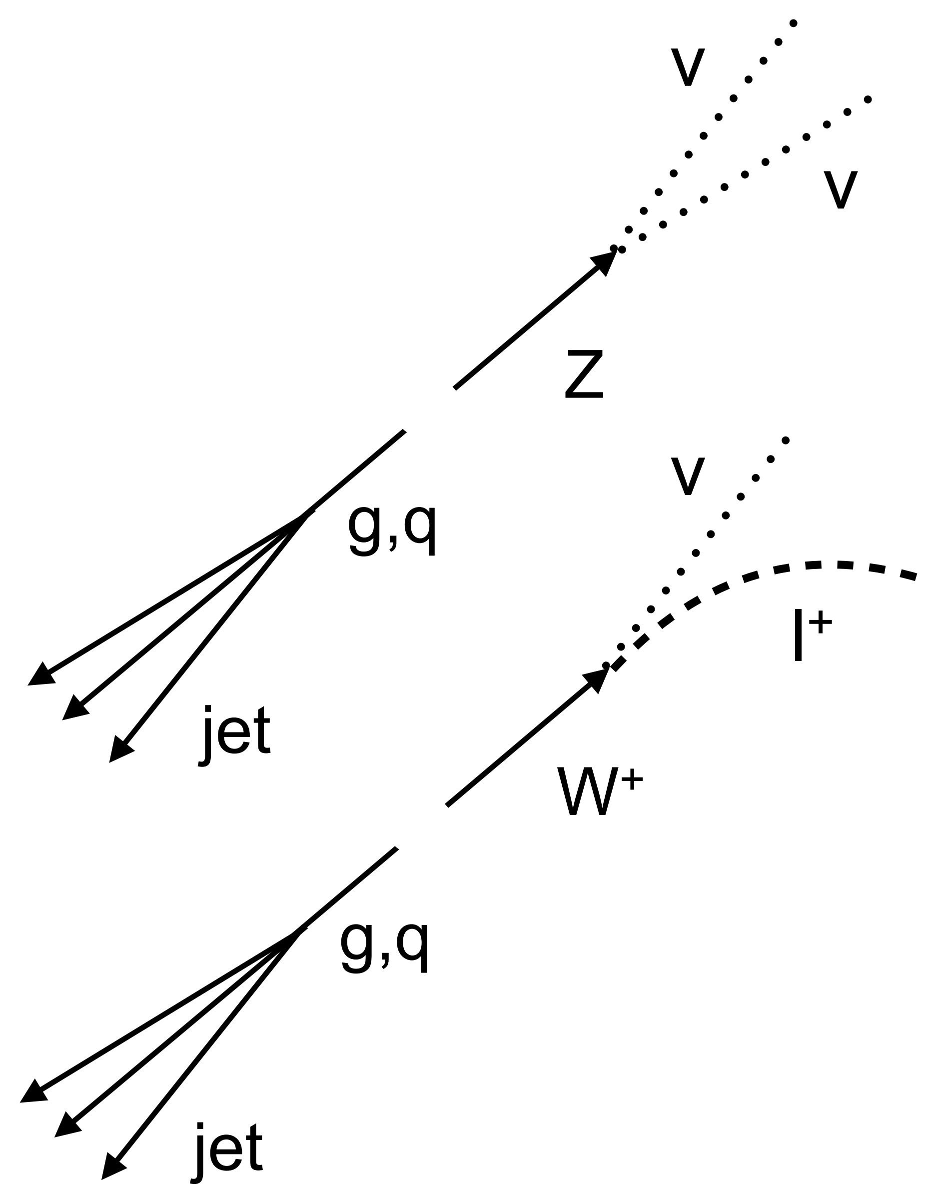


- Restrict to **high MET region** to reduce impact of background
- **Count** events after bkg subtraction
- **Proper model background** very important t

BACKGROUNDS

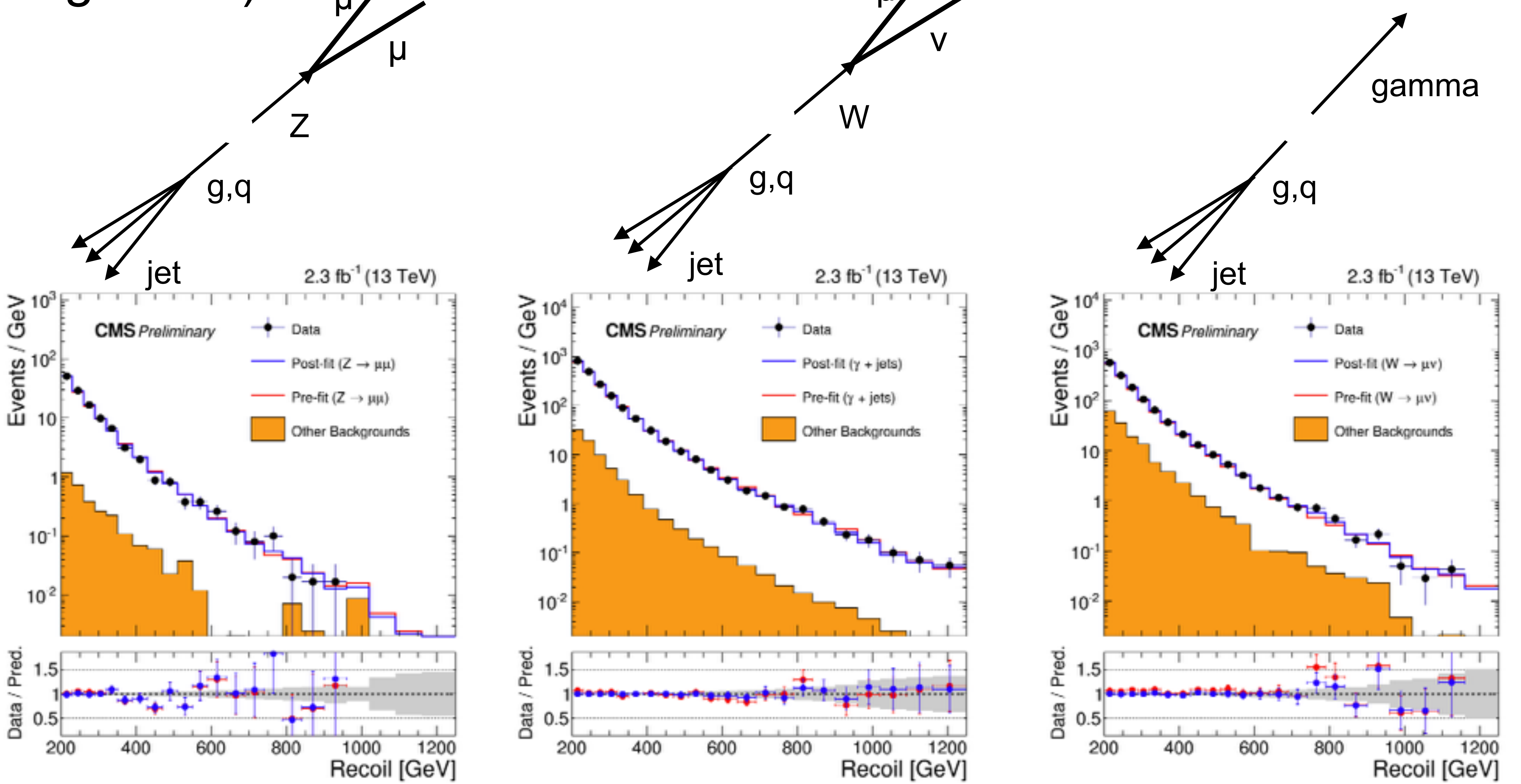


- Main backgrounds are:
  - **Z(vv)+jet**
  - **W(lv)+jet**, where charged lepton is not reconstructed



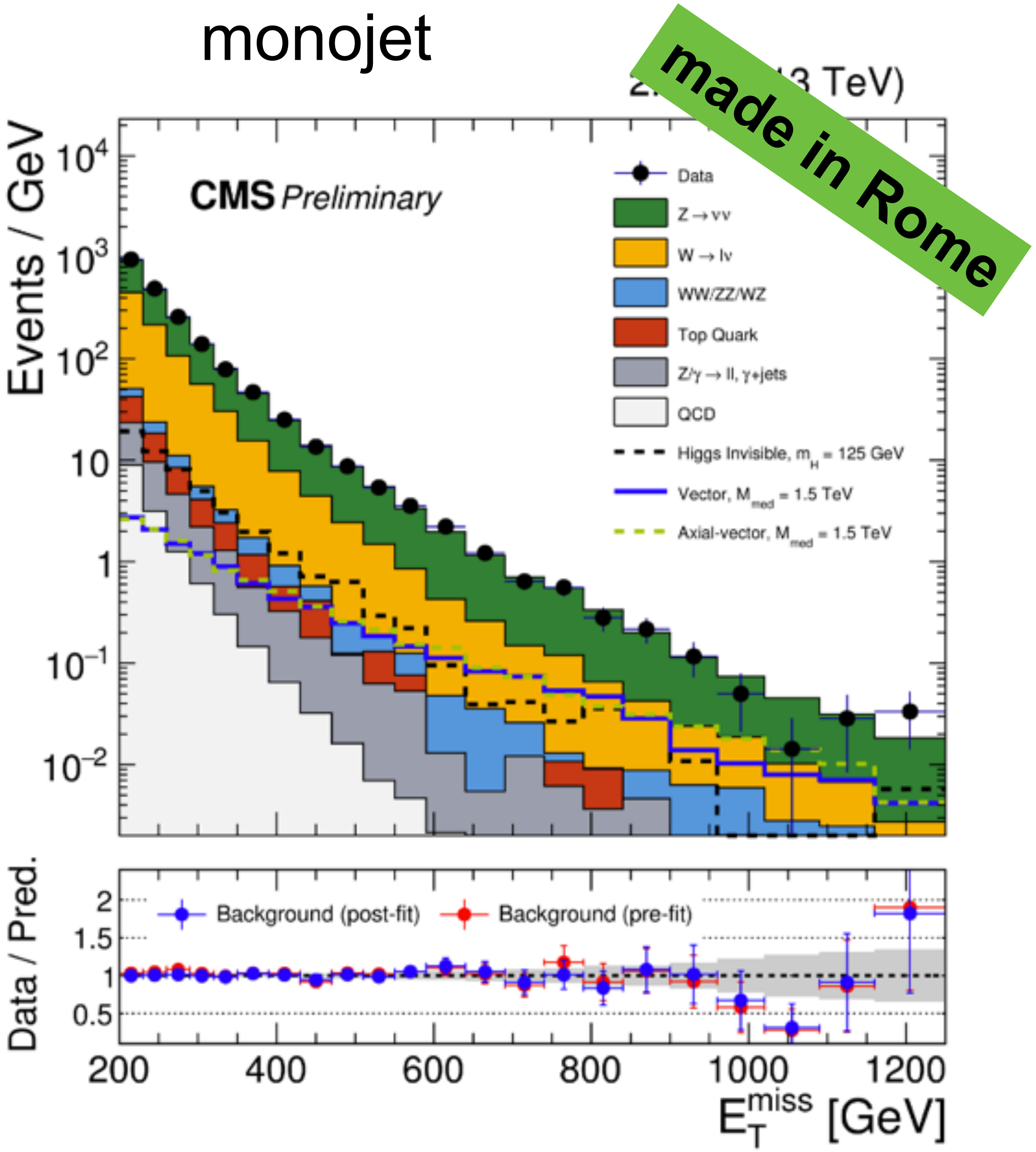
How to Derive Backgrounds

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

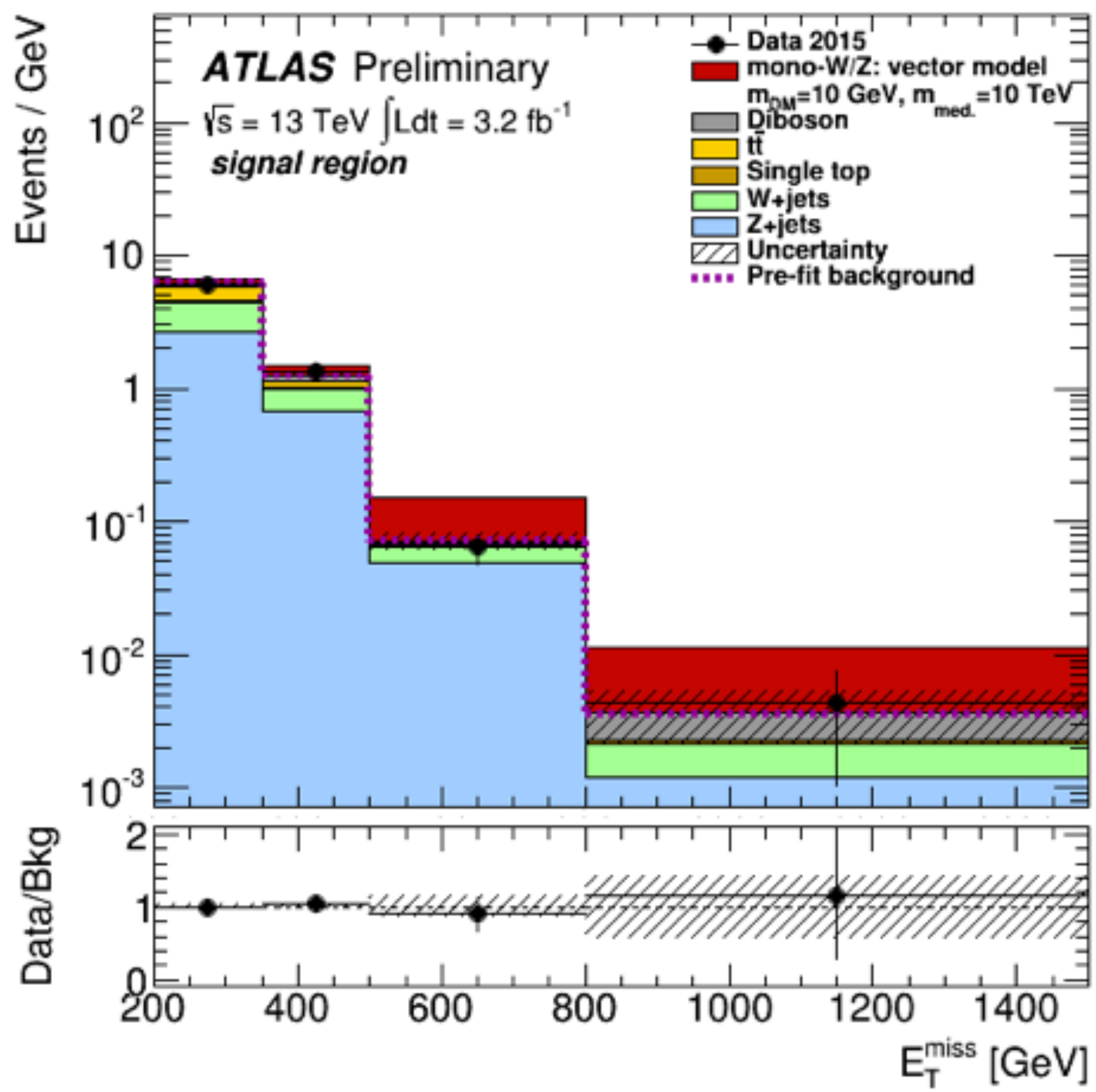


RESULTS (I)

monojet



monoZ/W

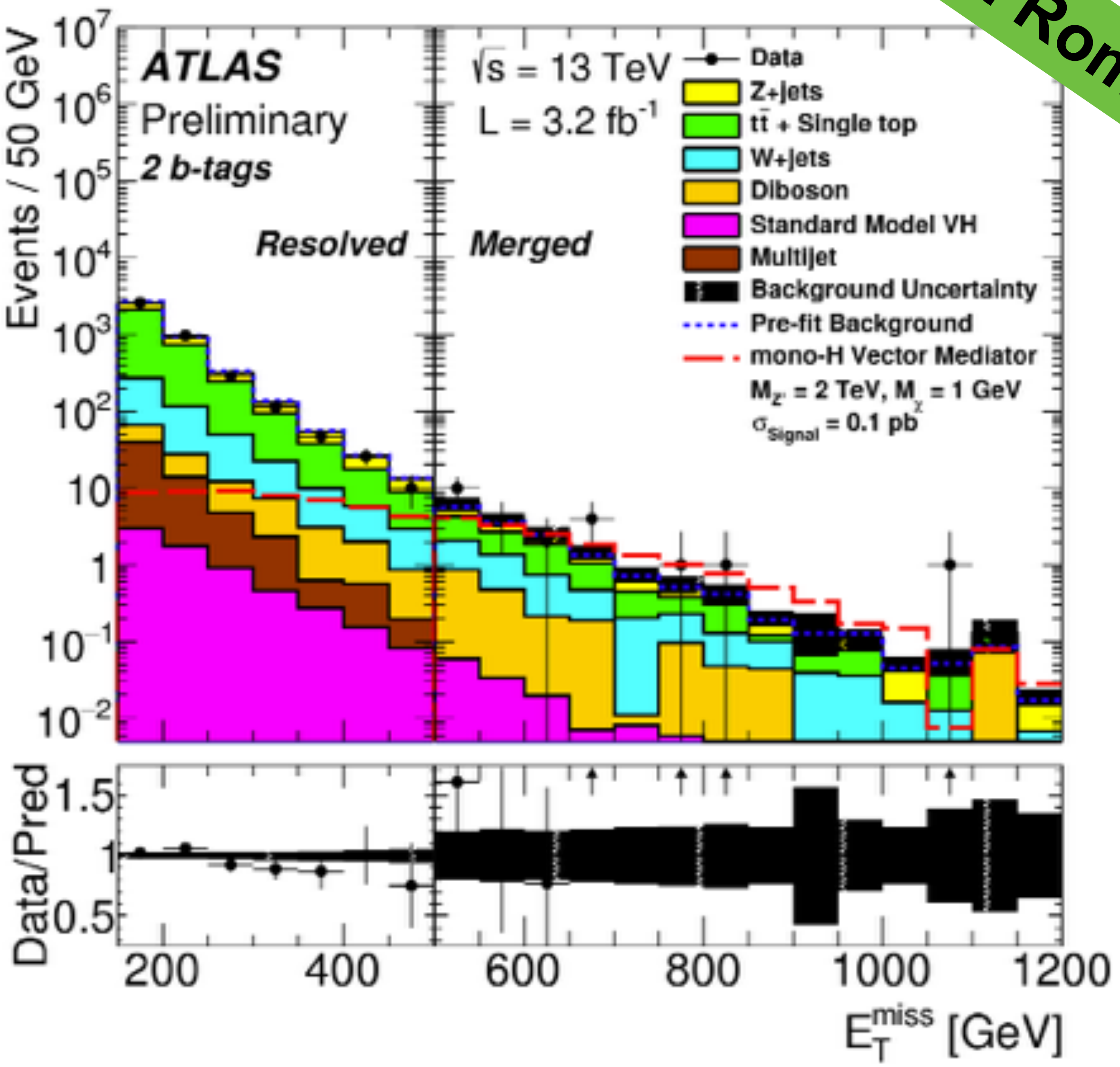


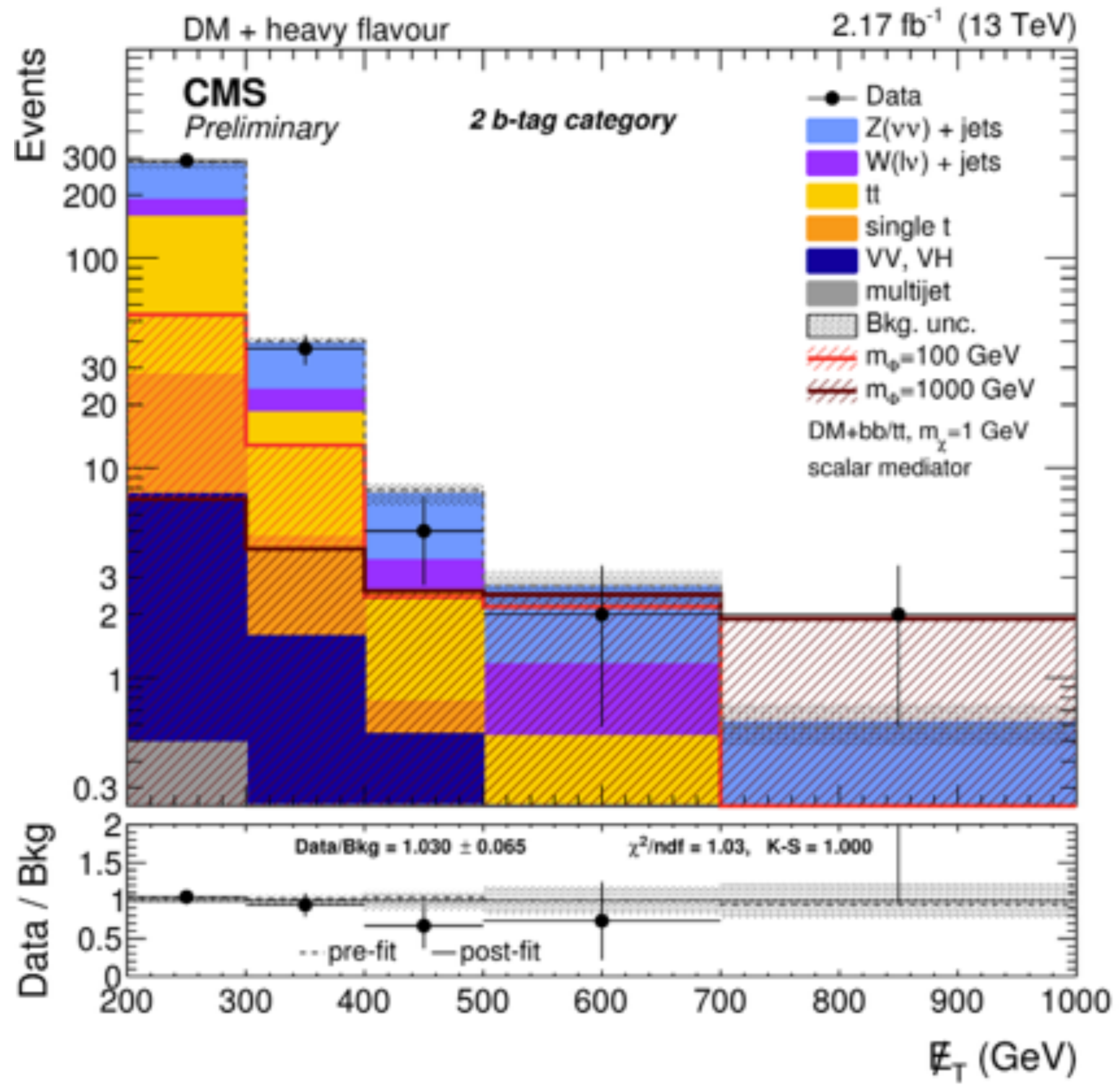
RESULTS (II)

monoHiggs

made in Rome

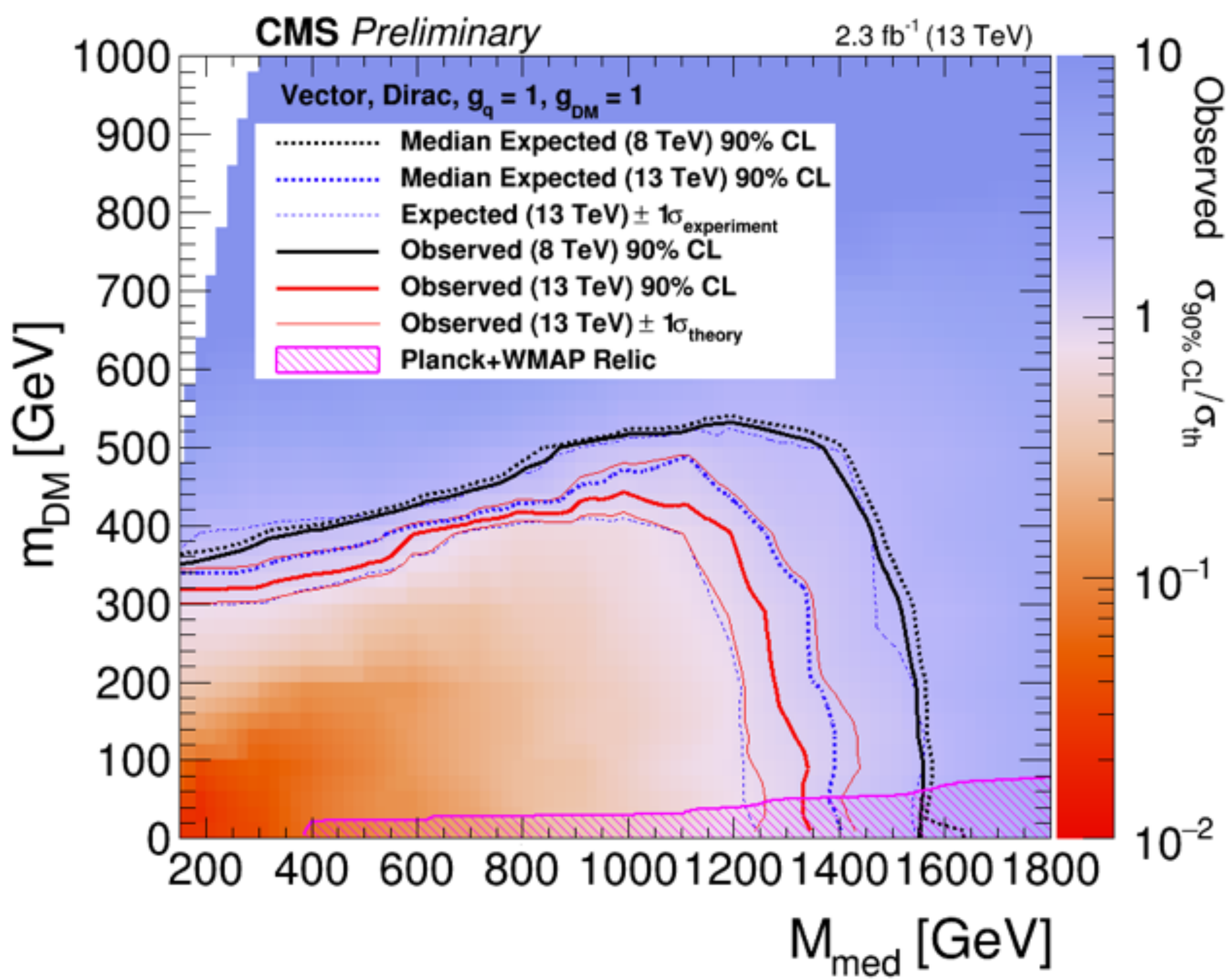
bb+MET





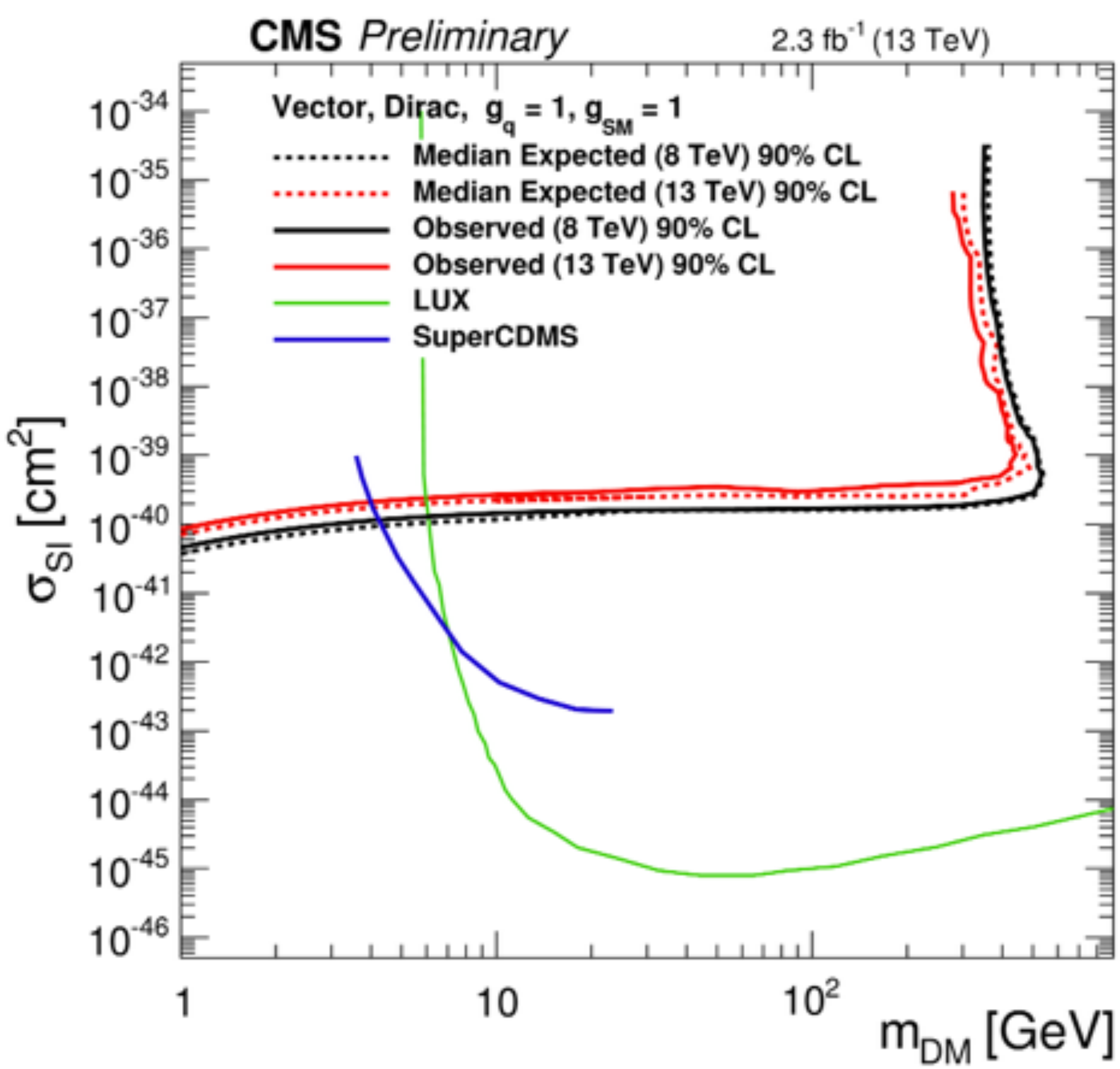
RESULTS (III)

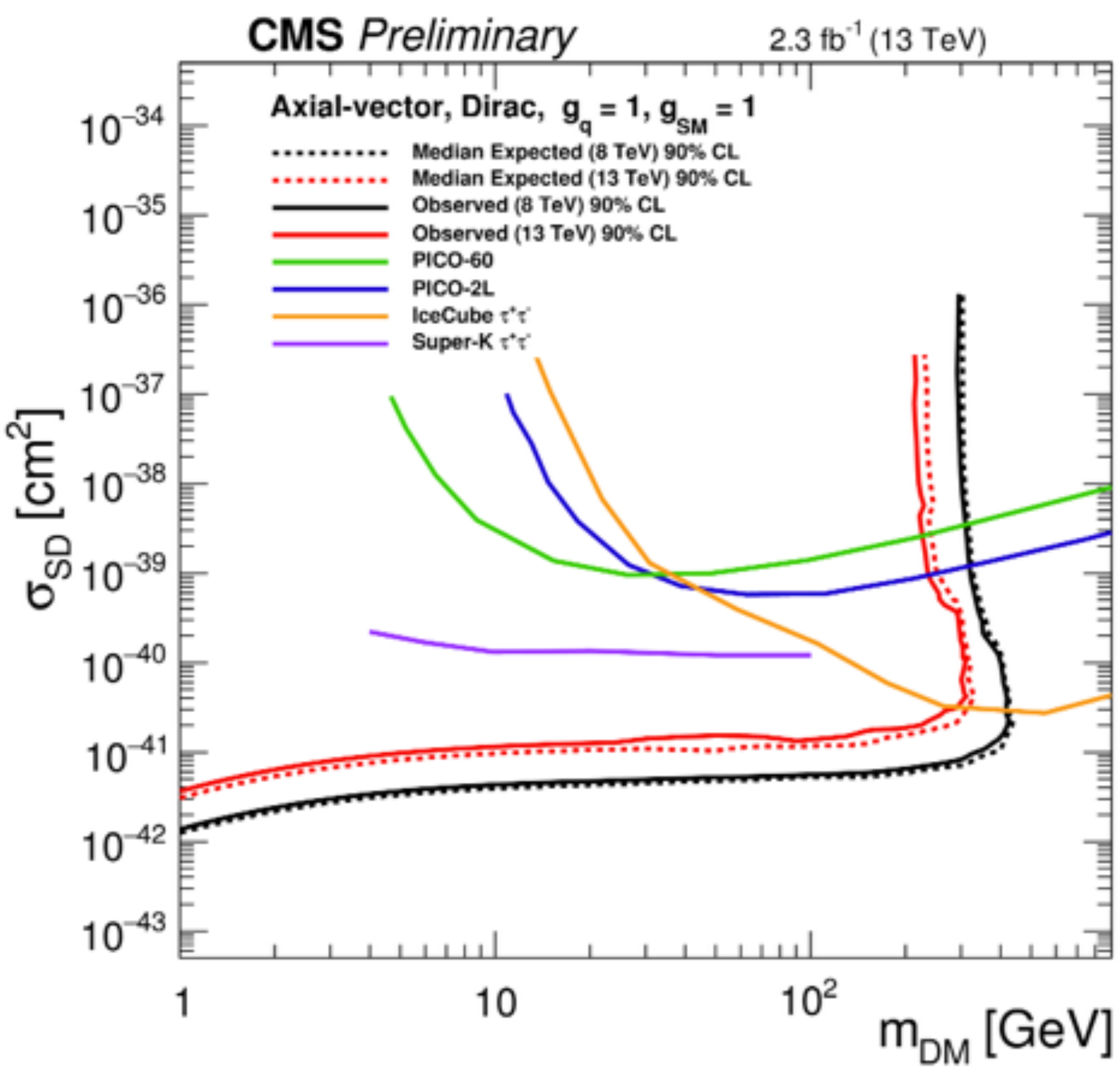
- Provide results in terms of two out of 4 parameters (M_{med}, M_{DM}, g_{SM}, g_{DM})



Comparison With Direct Searches

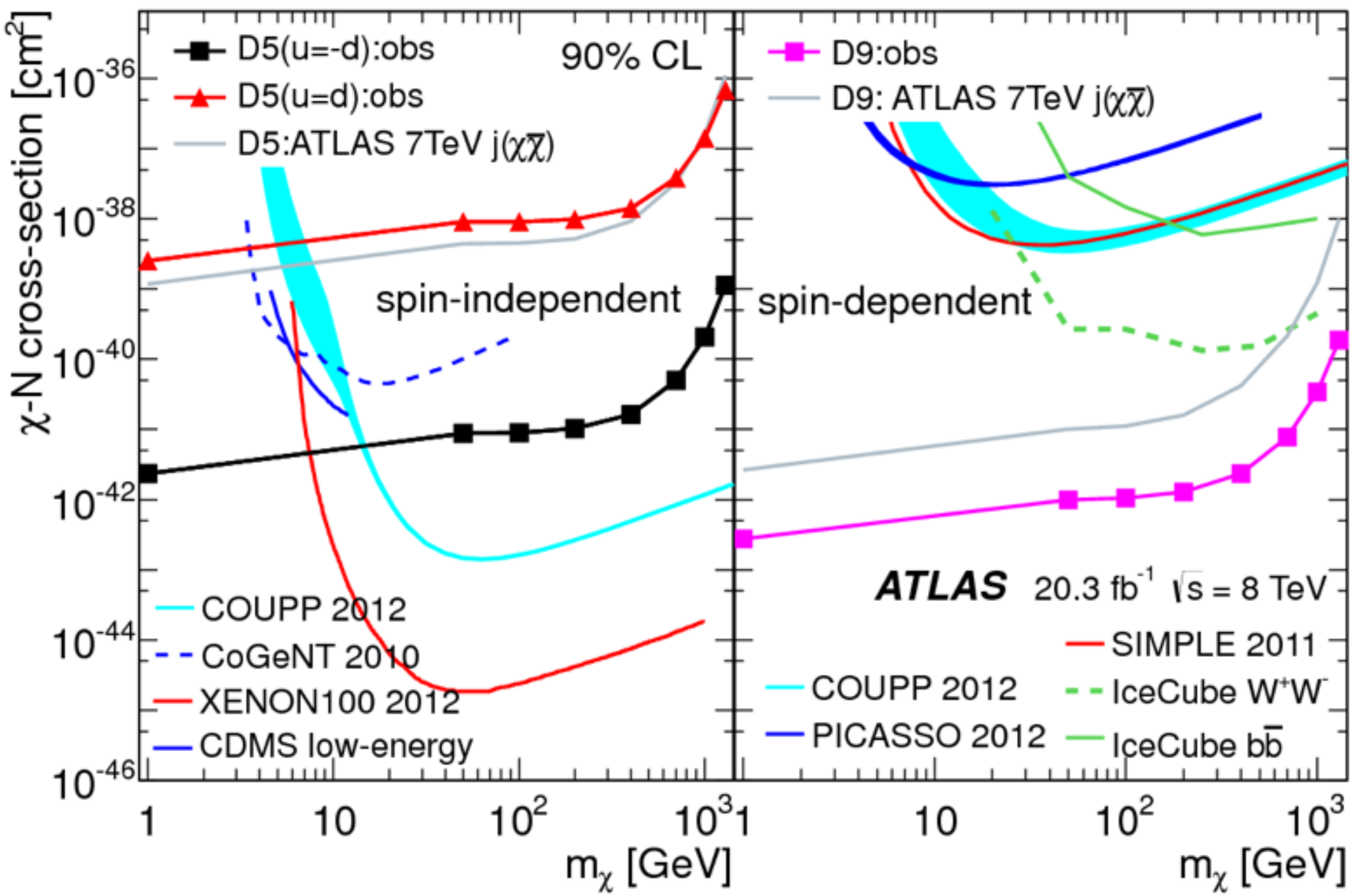
- CMS monojet+monoZ results
  - constraints are **complementary** to the ones of direct searches





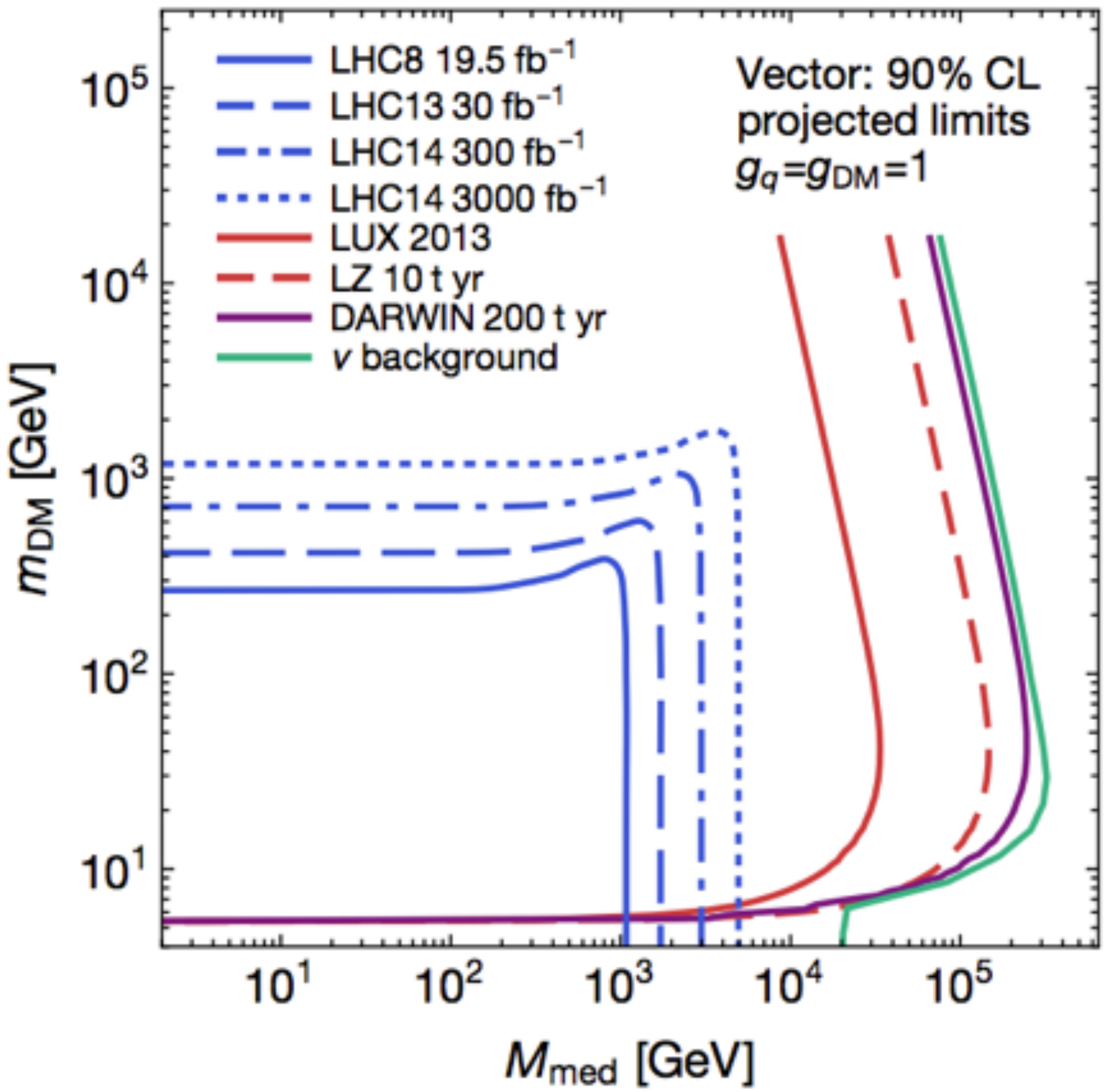
Comparison With Direct Searches

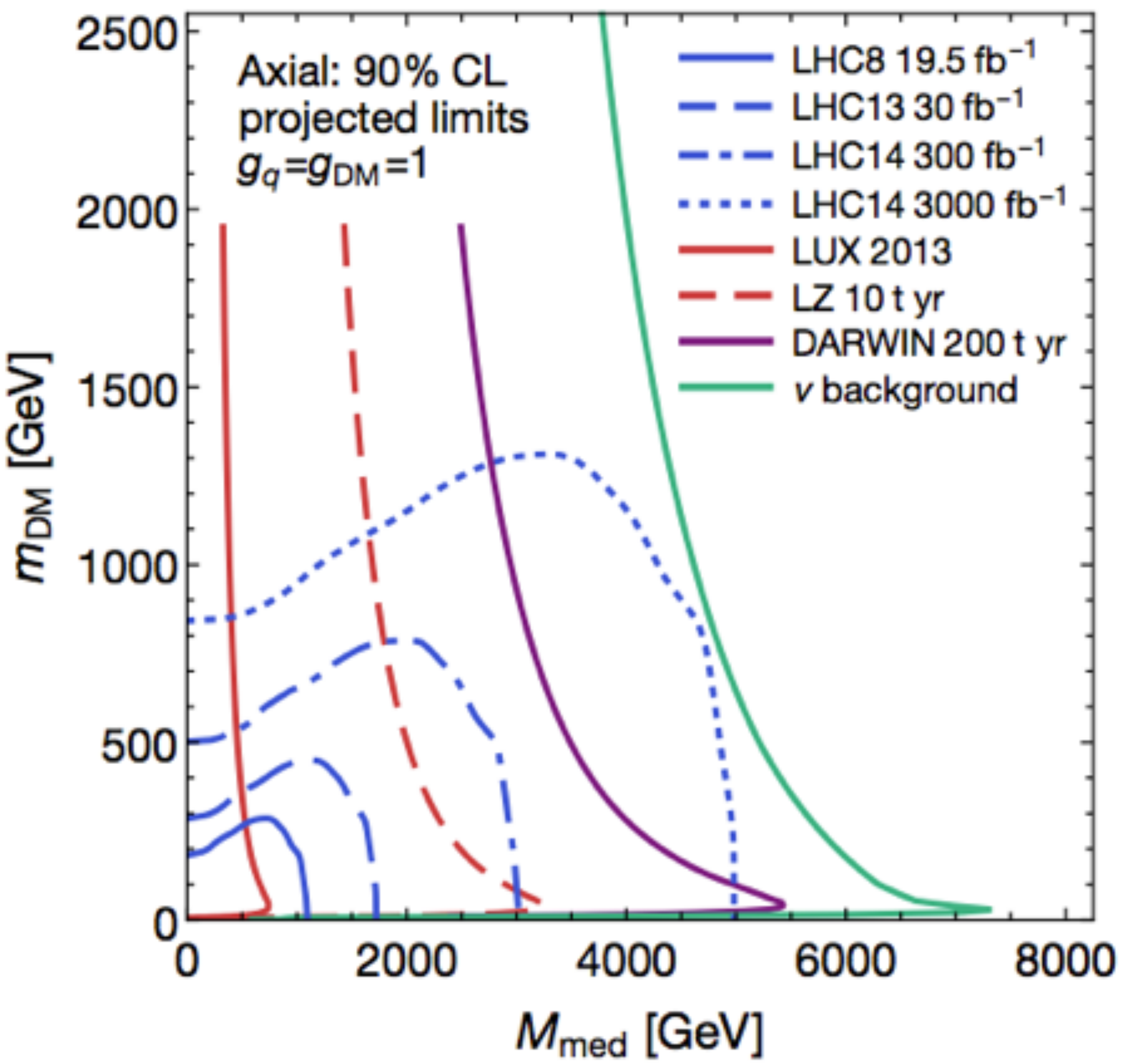
- ATLAS monoZ



PERSPECTIVES

- Still a lot of room for exploring (especially at low M_{DM})





LONG LIVED PARTICLES

New Physics and Long-lived Particles

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

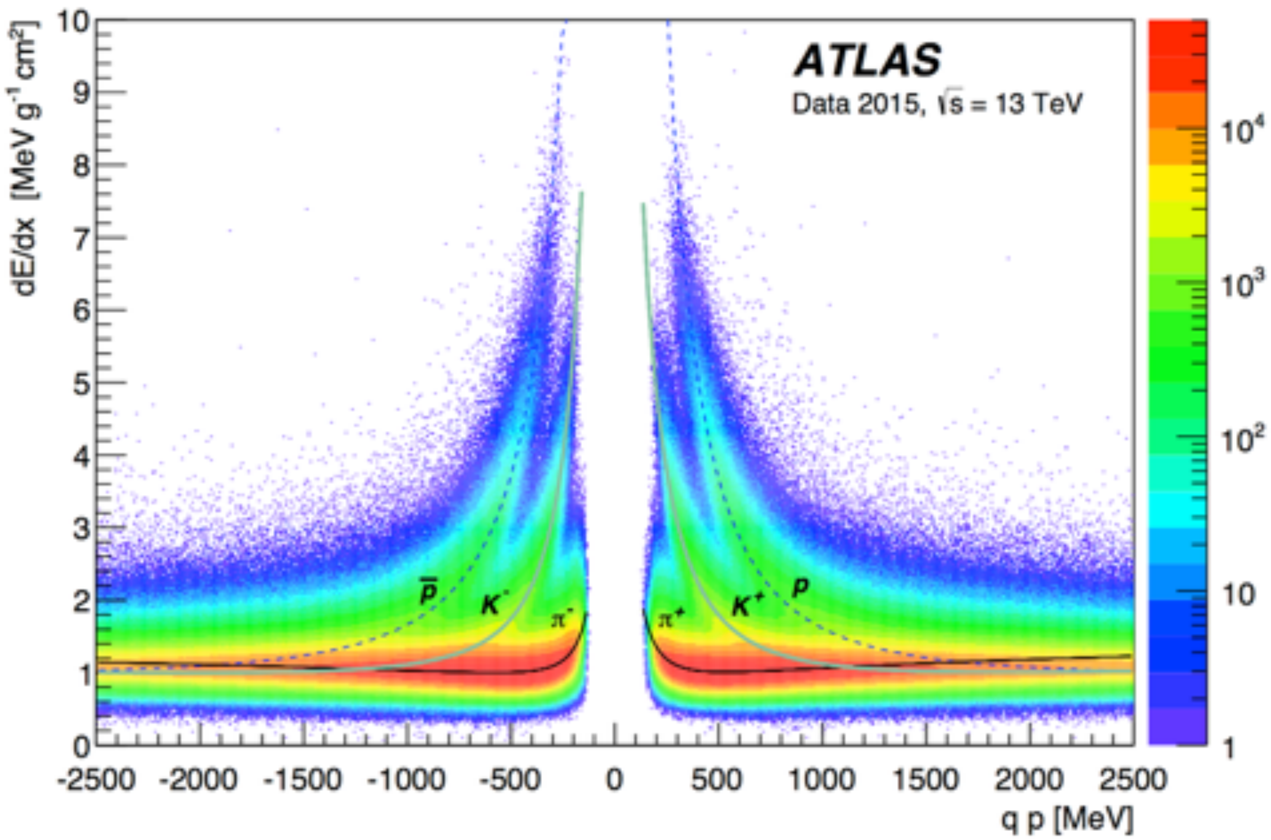
- **Heavy, long-lived, charged particles** (R-hadrons, Sleptons)
  - speed < c
  - charge not equal to ±1e
  - lifetimes > few ns. Travel distances larger than the typical collider detector and appear stable
- **Particles decaying in the detector after few cm** (neutralinos in GMSB, mass-degenerate gauginos,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

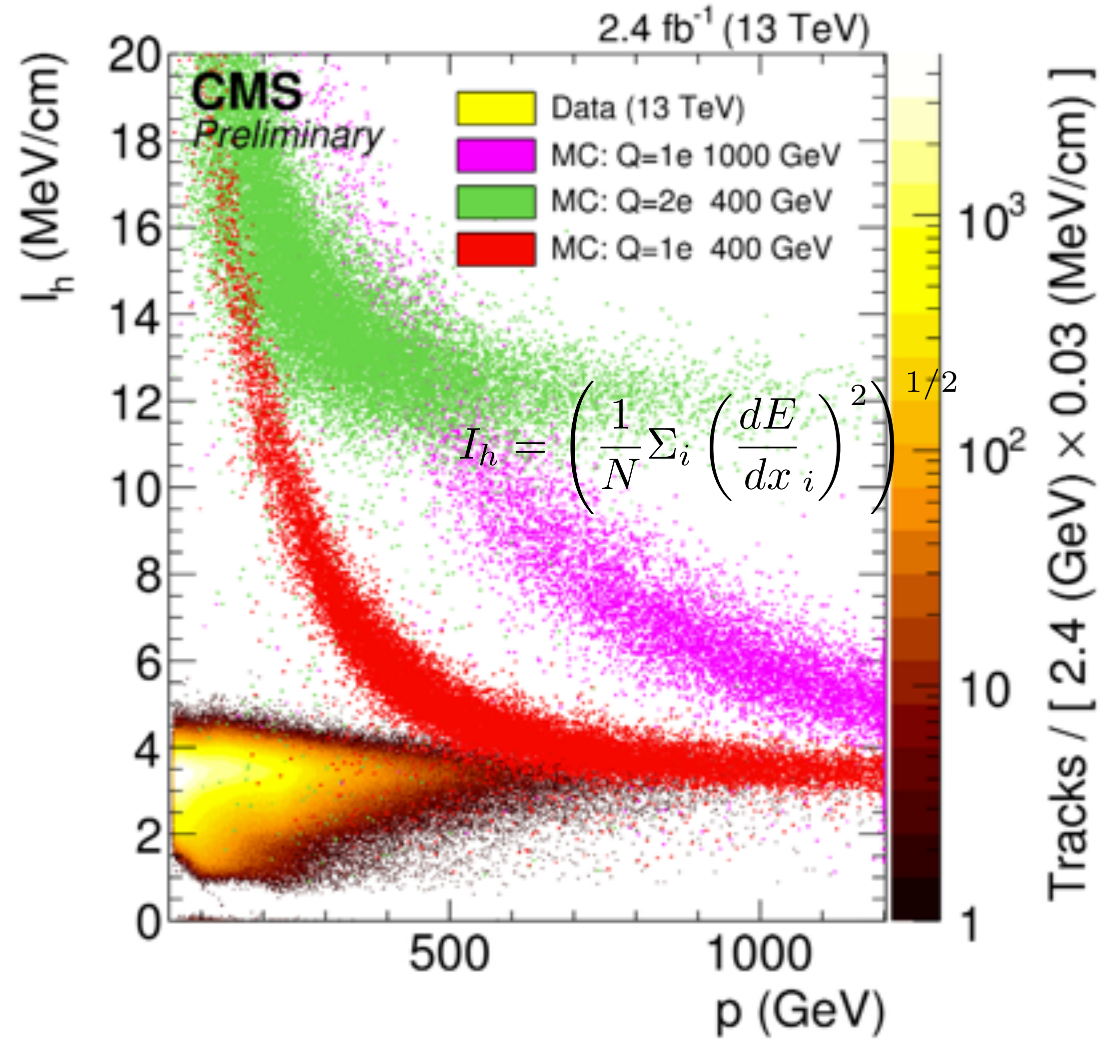
Typical Long-Lived Analysis

- **Detector-based exotic signatures** required:
  - 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:
  - non-trivial job. LL signatures look like detector noise

SIGNATURES: 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 pT only information available to identify them

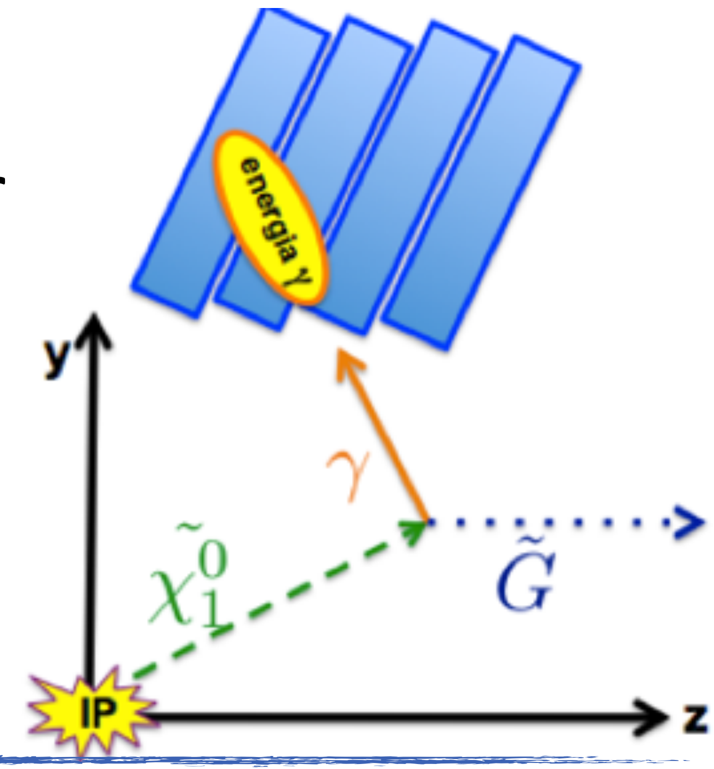




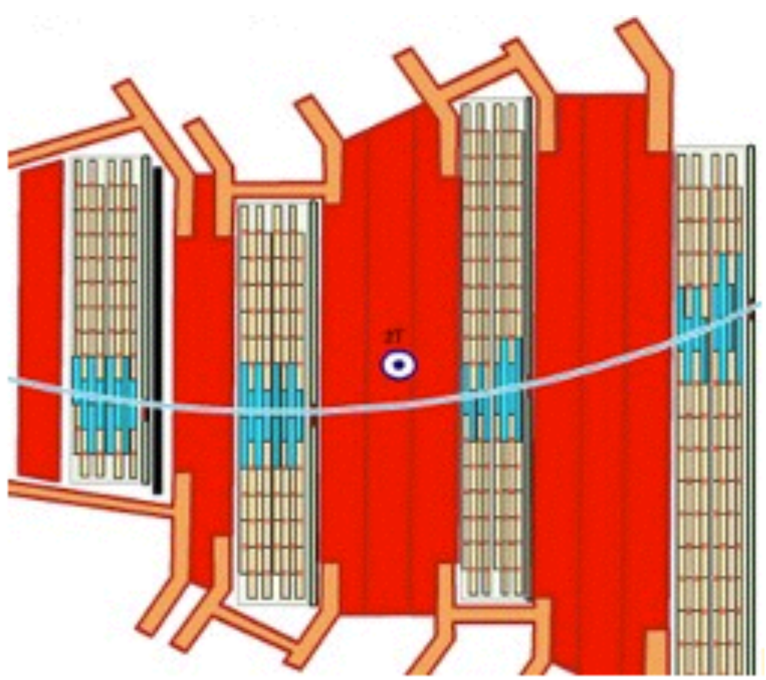
SIGNATURES: TIME OF FLIGHT

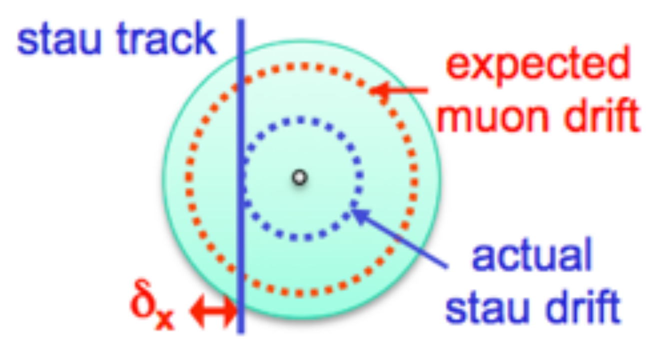
Neutral particles

- **produced in flight** (also from slow particles) and far from beam spot
- **time of arrival at calorimeter longer** than for SM contribution coming from beam spot
- tagged looking at measured timing



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





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

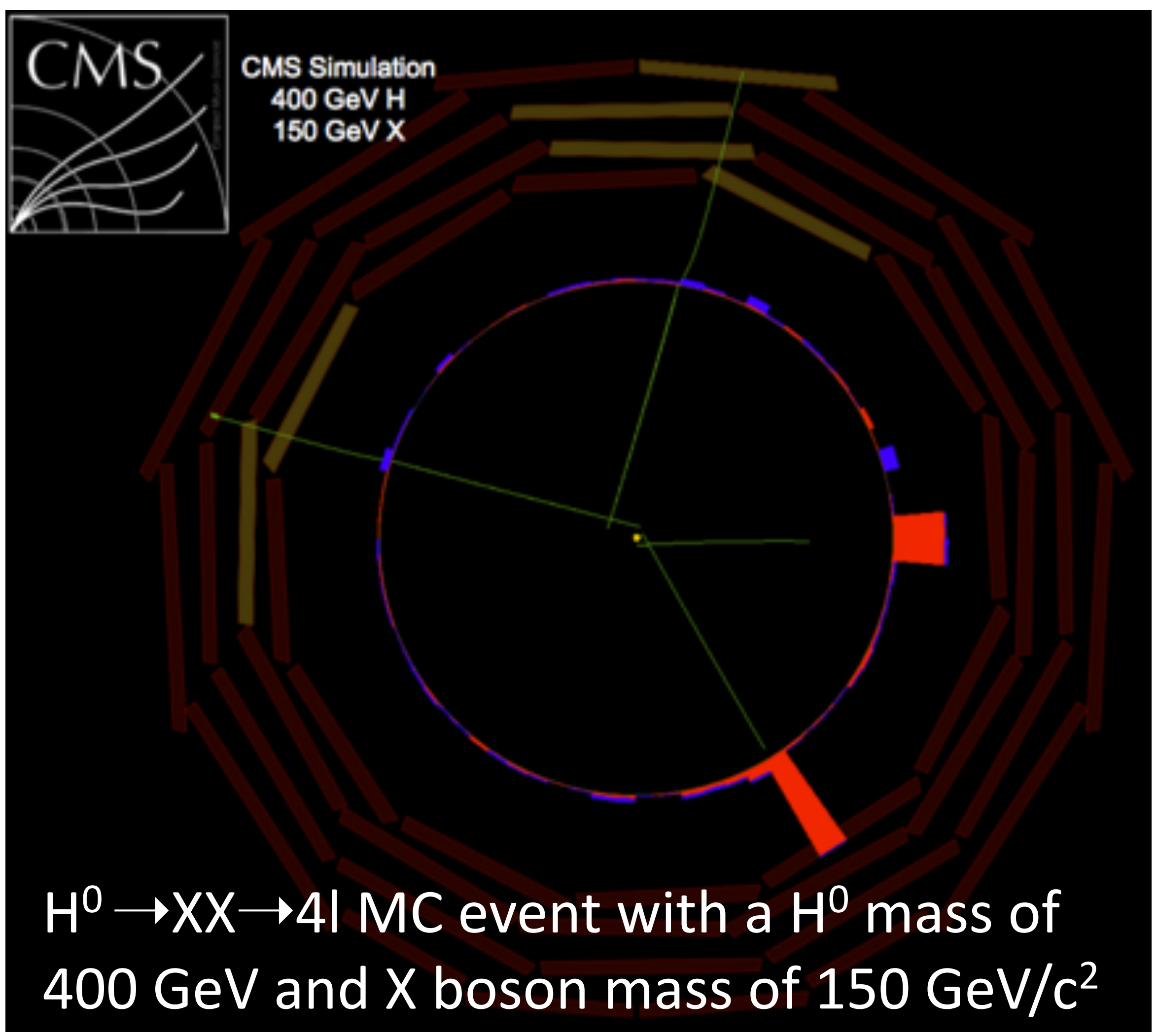
averaged over all layers

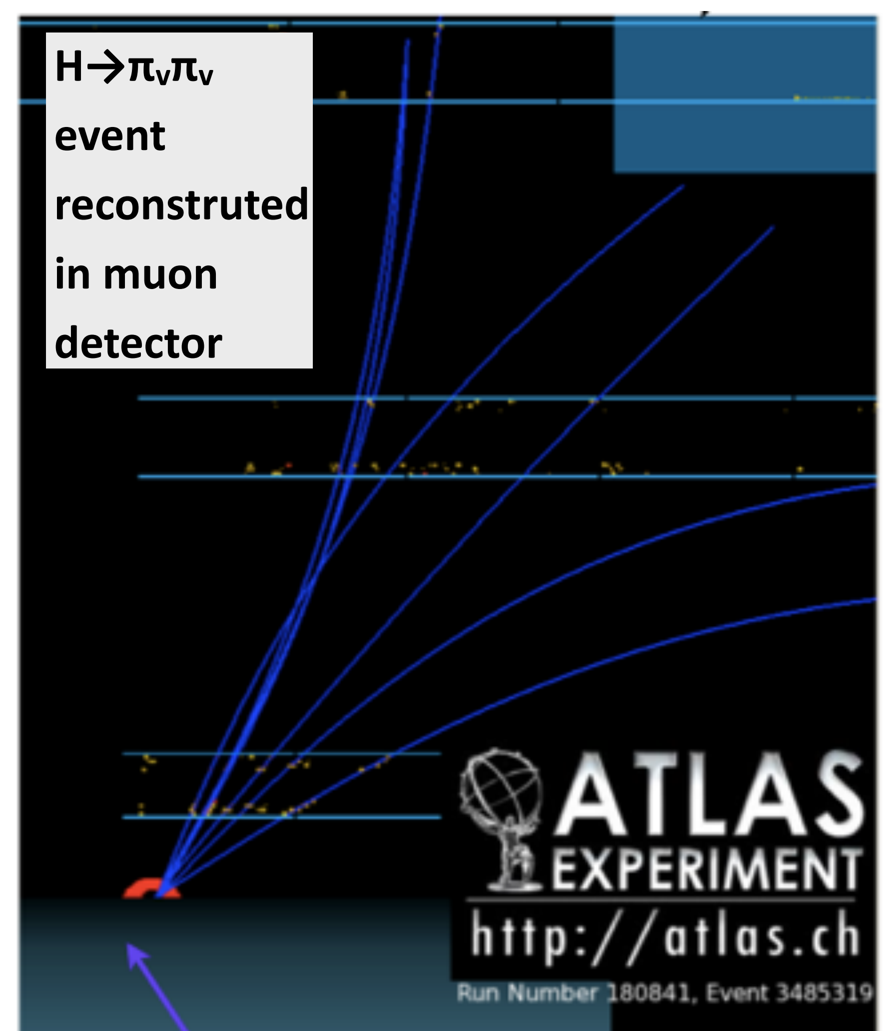
L=flight distance

β obtained as an average over the detector hits

SIGNATURES: DISPLACED VERTEXES

- **Long-lived particles decaying in charged particles** (hadrons, leptons) **identified via vertexing**
- **Requirement of small activity** along the track in detector sectors closer to the beamspot

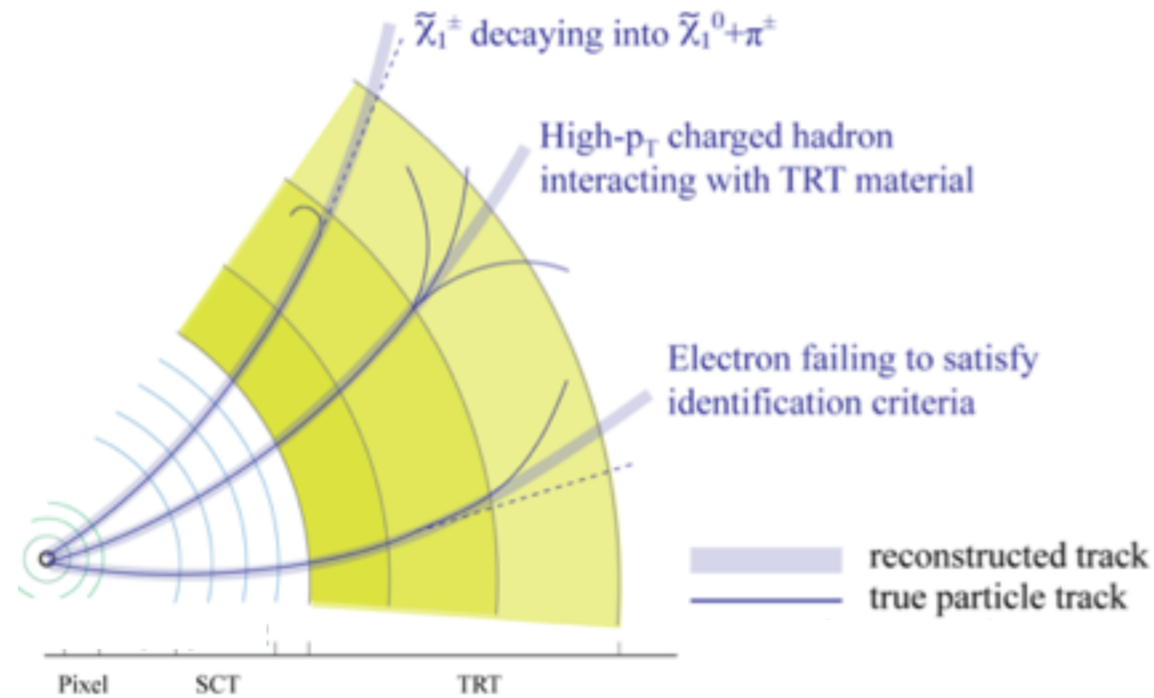




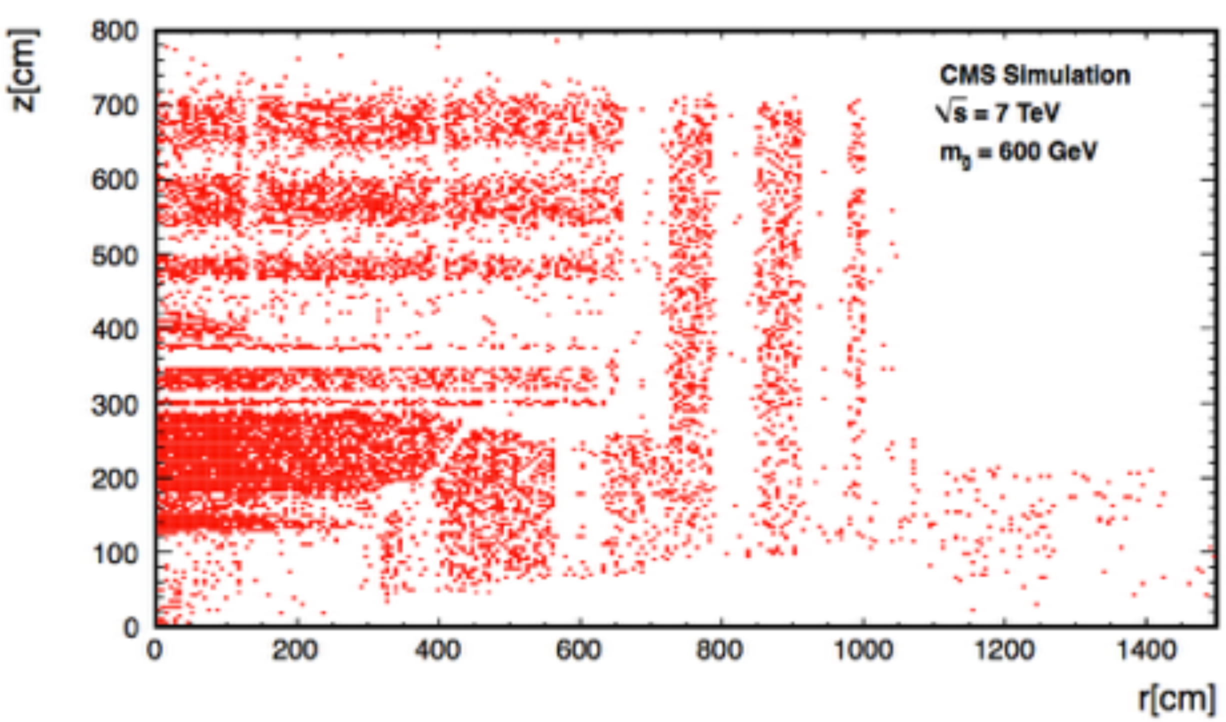
Signatures: Disappeared/Stopped

Long-lived charged exotic particles decaying in flight within the detector

- identified as **truncated tracks**
- **small activity in the calorimeter** along the propagated track direction
- track inefficiency need to be modeled carefully



Stopping position in r-z view for a 600 GeV gluino



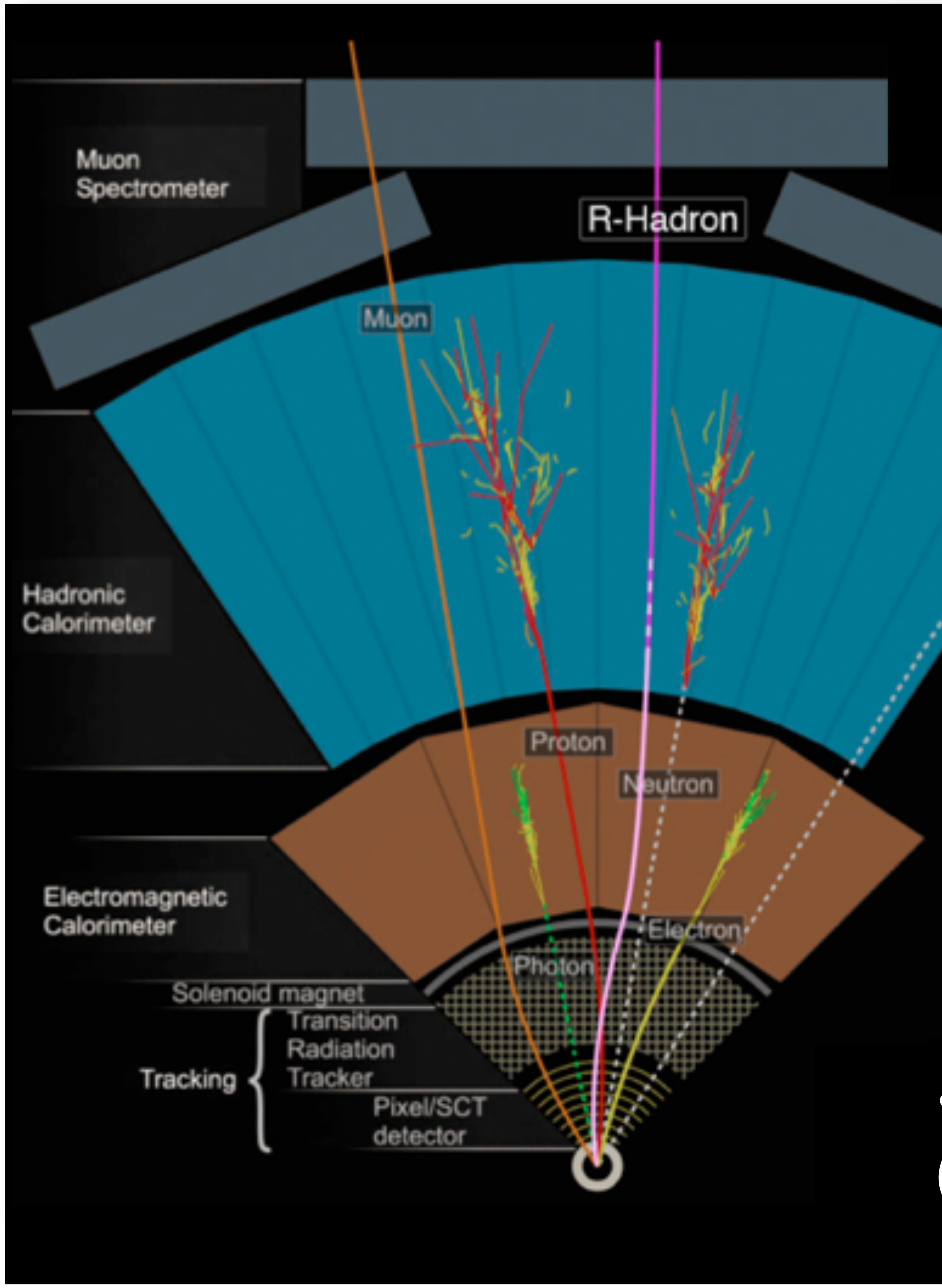
- **Charge particles** with low velocity may **stop in detector volume**
  - preferentially in the densest detector elements (calorimeters)
- When decaying, **energy deposit similar to jet**
- **Searched when no pp collision** (gaps between proton bunches)

First Summary on Long-Lived Searches

- **Several striking exotic signatures**
  - some searches use more than one
- **Very generic searches**, driven by signatures
  - open-minded searches
  - **models are used as benchmark** to report results
- **Limits are very model dependent**
- Results are **limited by detector acceptance and triggers** (non-standard signatures)
  - difficult to find good control samples
- **Experimentally challenging analyses**
  - look where background for SM analyses is

HEAVY STABLE CHARGED PARTICLES

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

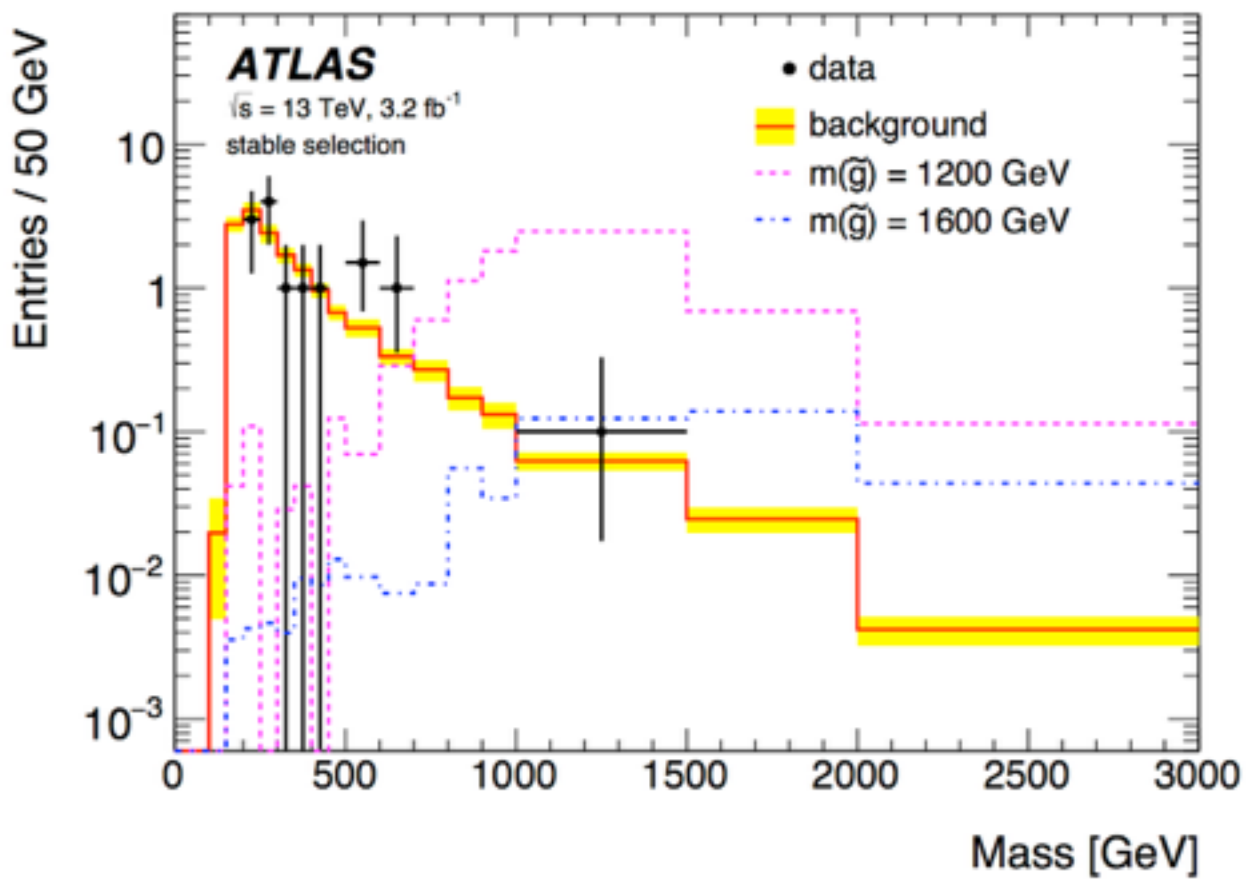


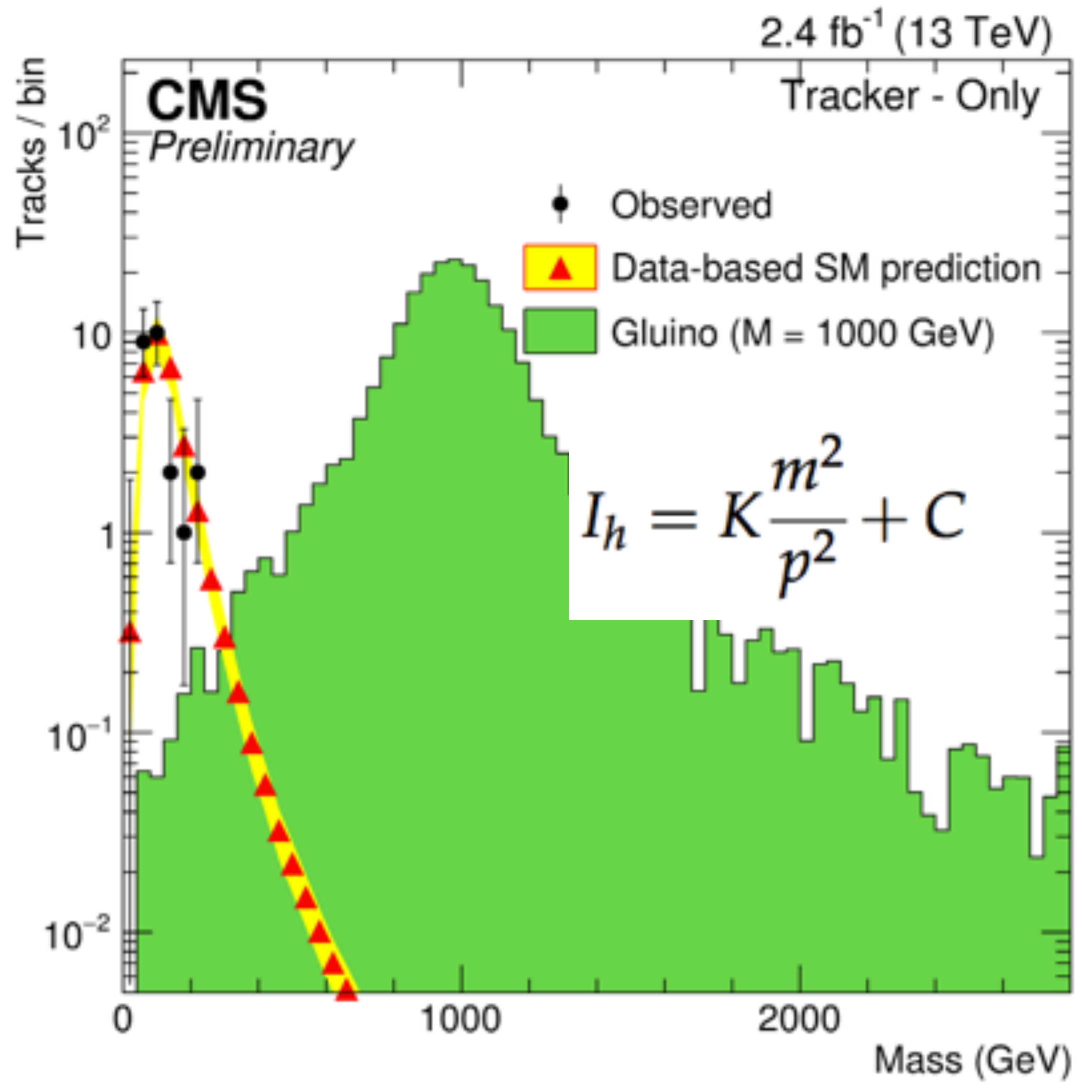
ATLAS EXAMPLE

- Muon Spectrometer + ID (β,μ-like) **(<u>sleptons</u>)**
- ID + Calo + Muon Spectrometer **(R-hadrons, <u>full-detector</u> analysis)**
- Pixel + Tracker + Tile Calorimeter (β) **(R-hadrons, <u>μ-agnostic</u> analysis)**
- Pixel Detector(dE/dx,p)+SCT(p) **(R-hadrons with short lifetimes, <u>ID-only</u> analysis)**

HSCP: Analysis Technique

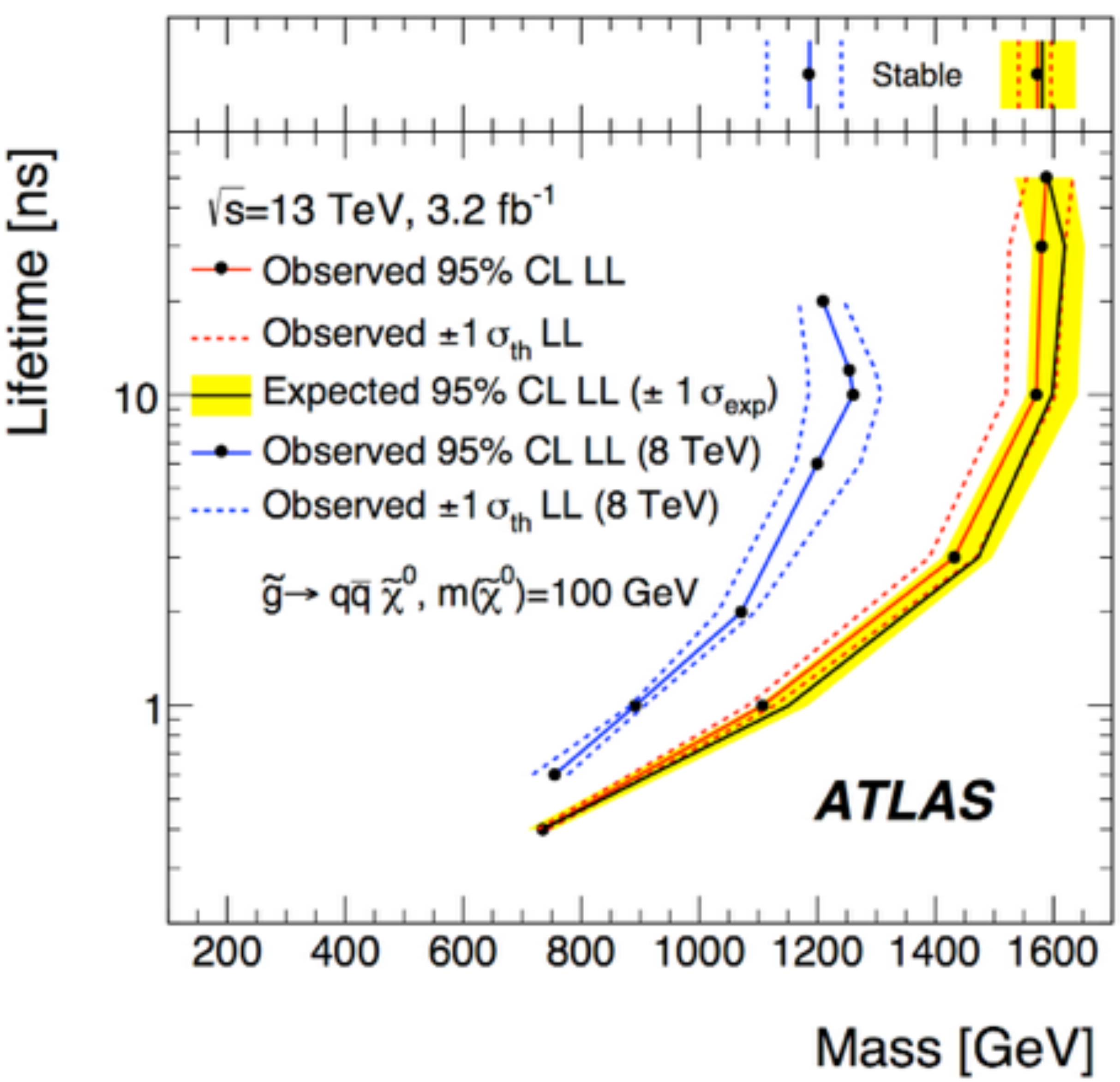
- **Information from dE/dx and p_T** (tracker) used to calculate **mass**
- **Time of flight** from muon detector and calorimeters to **measure β**
  - calibrated using cosmics and $Z \rightarrow \mu^+\mu^-$
- **Background** dominated by high p_T, **misreconstructed muons**

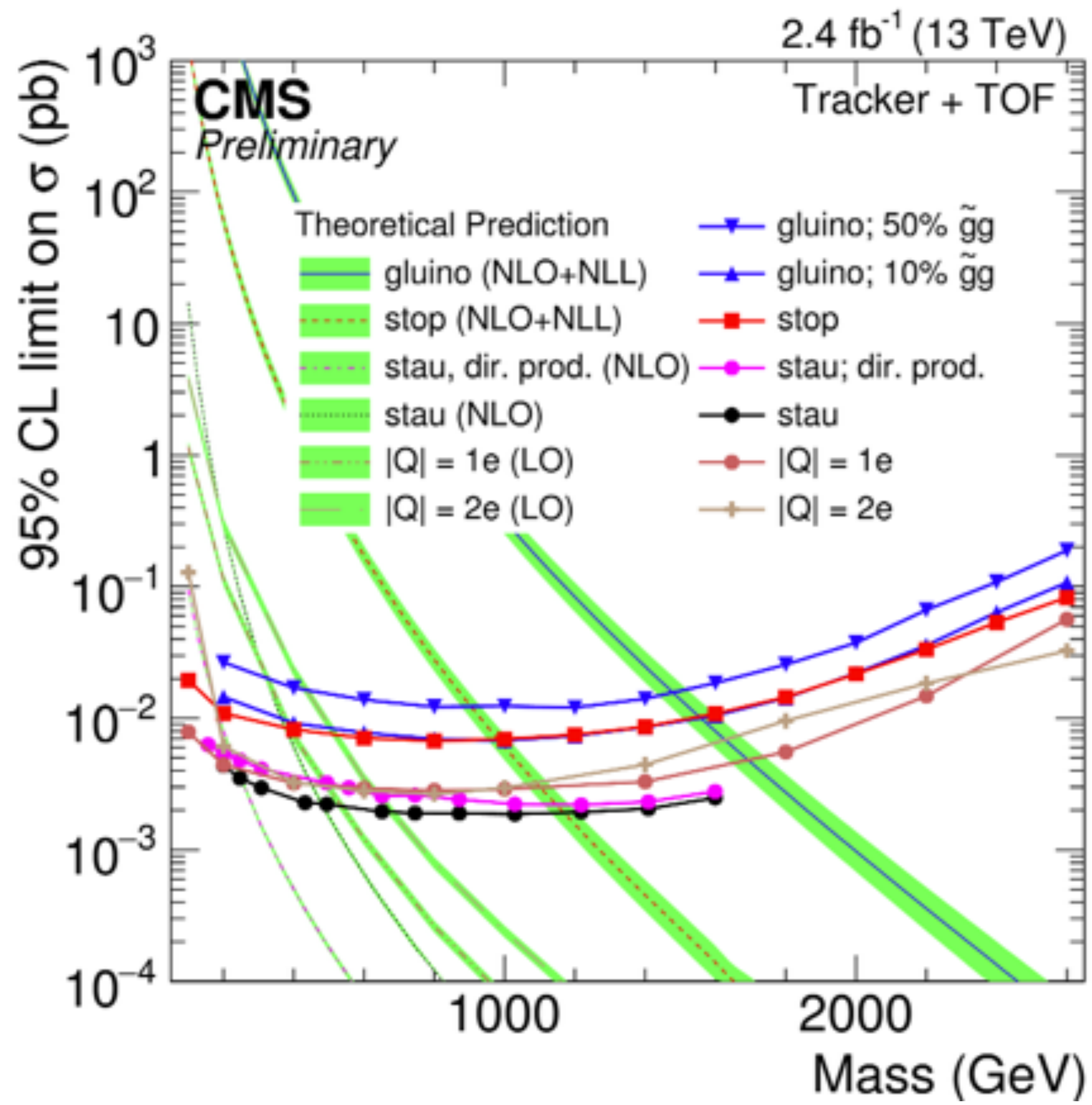




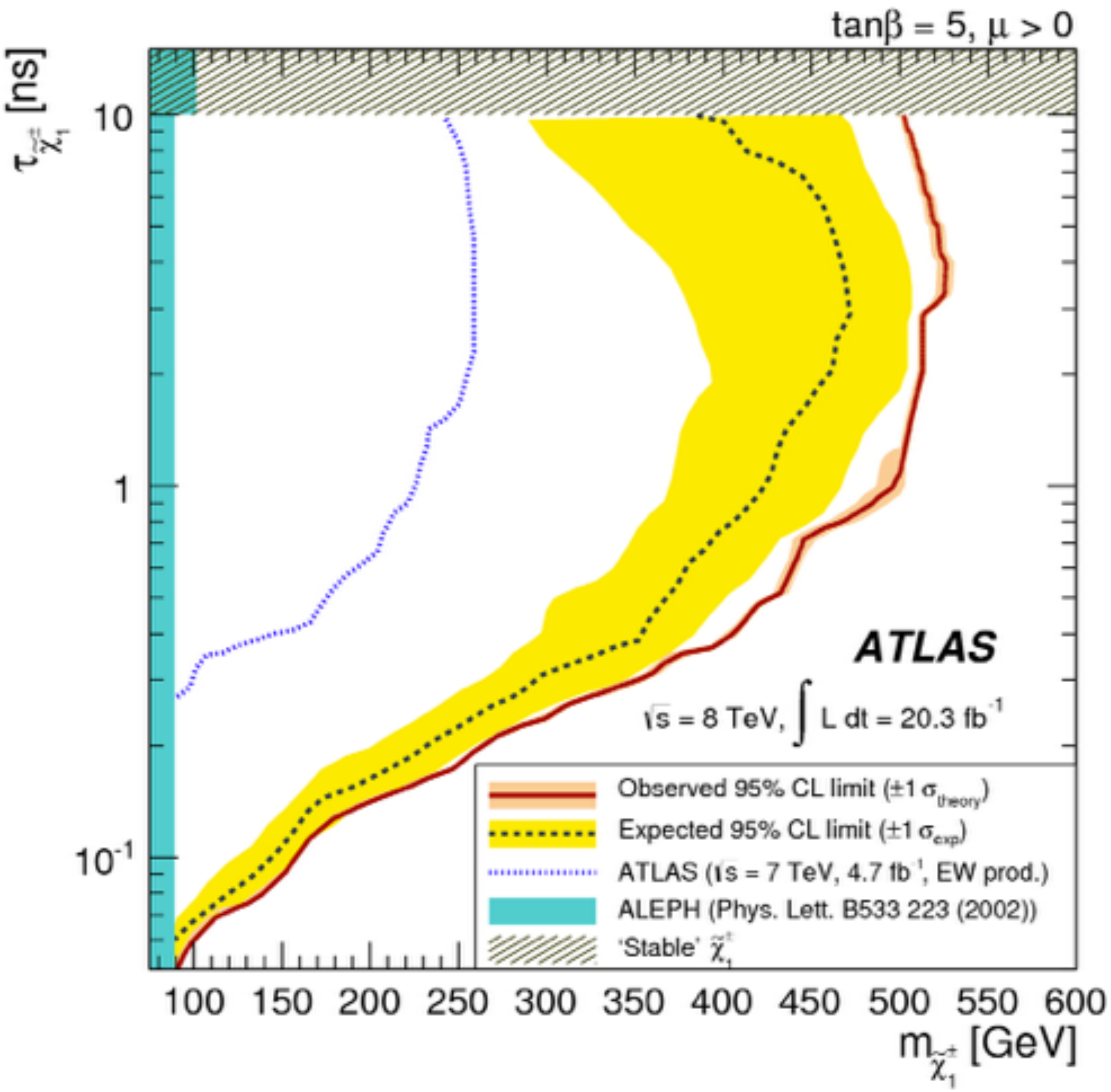
HSCP Results

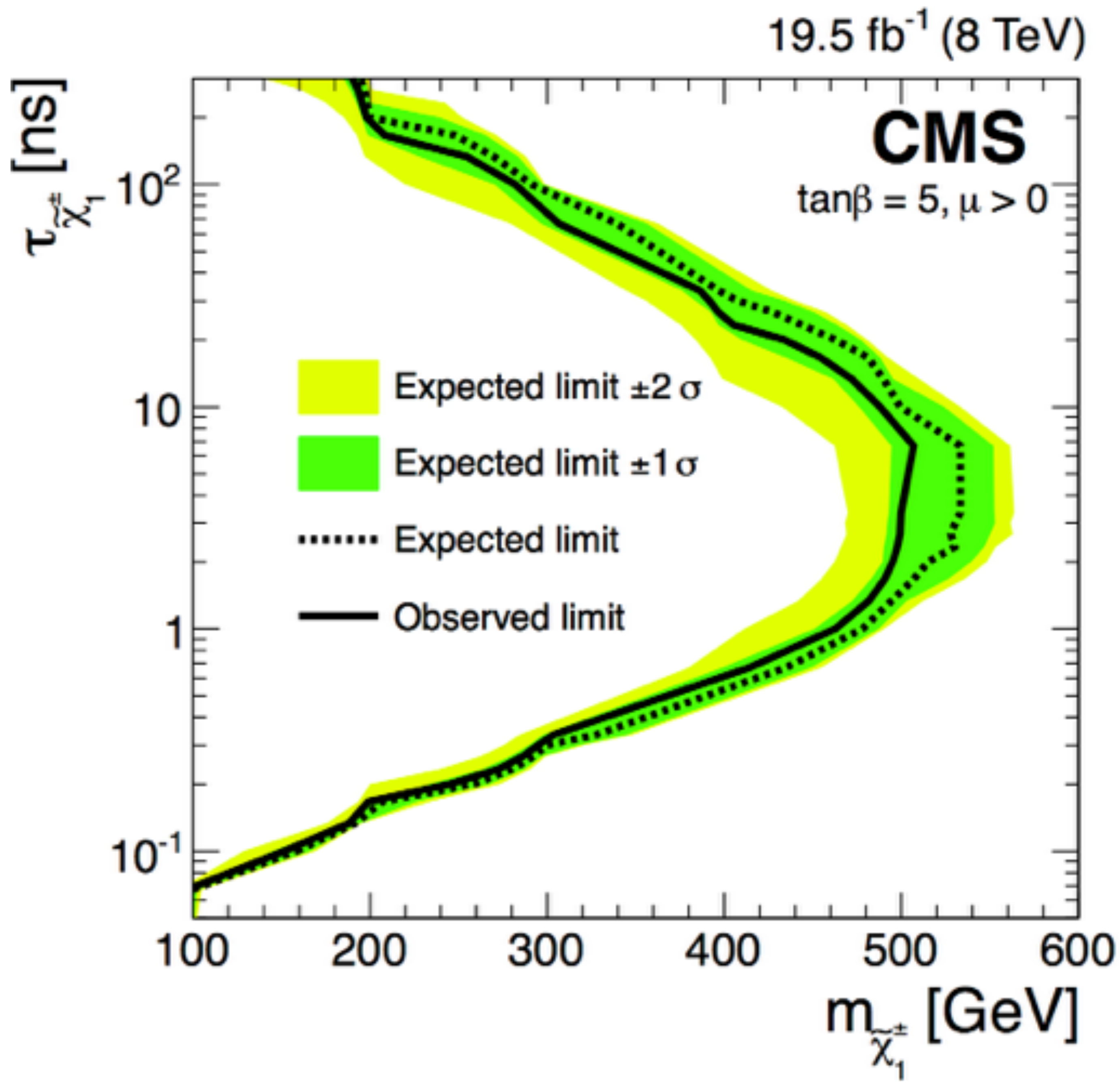
- **No indication of signal** above expected background is observed
- Cross-section **limits at 95% confidence level** → translating into limits on the **R-hadron/slepton mass**





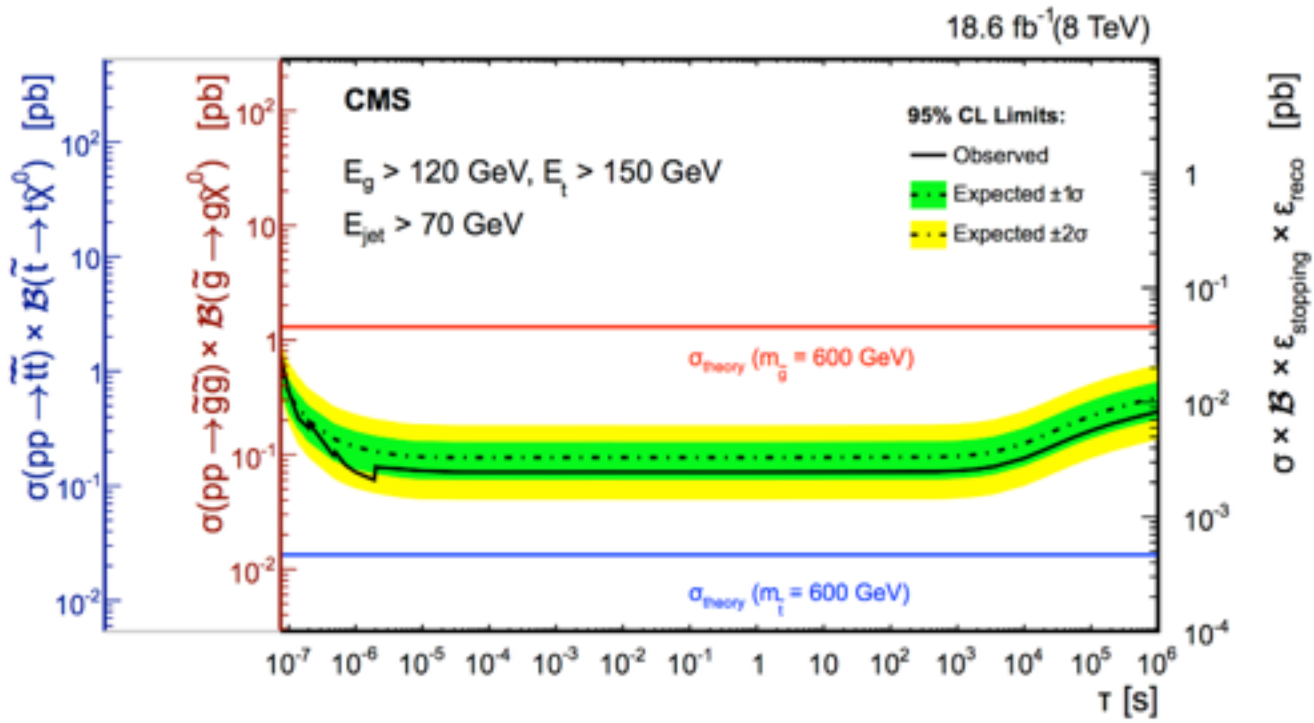
Disappearing Tracks

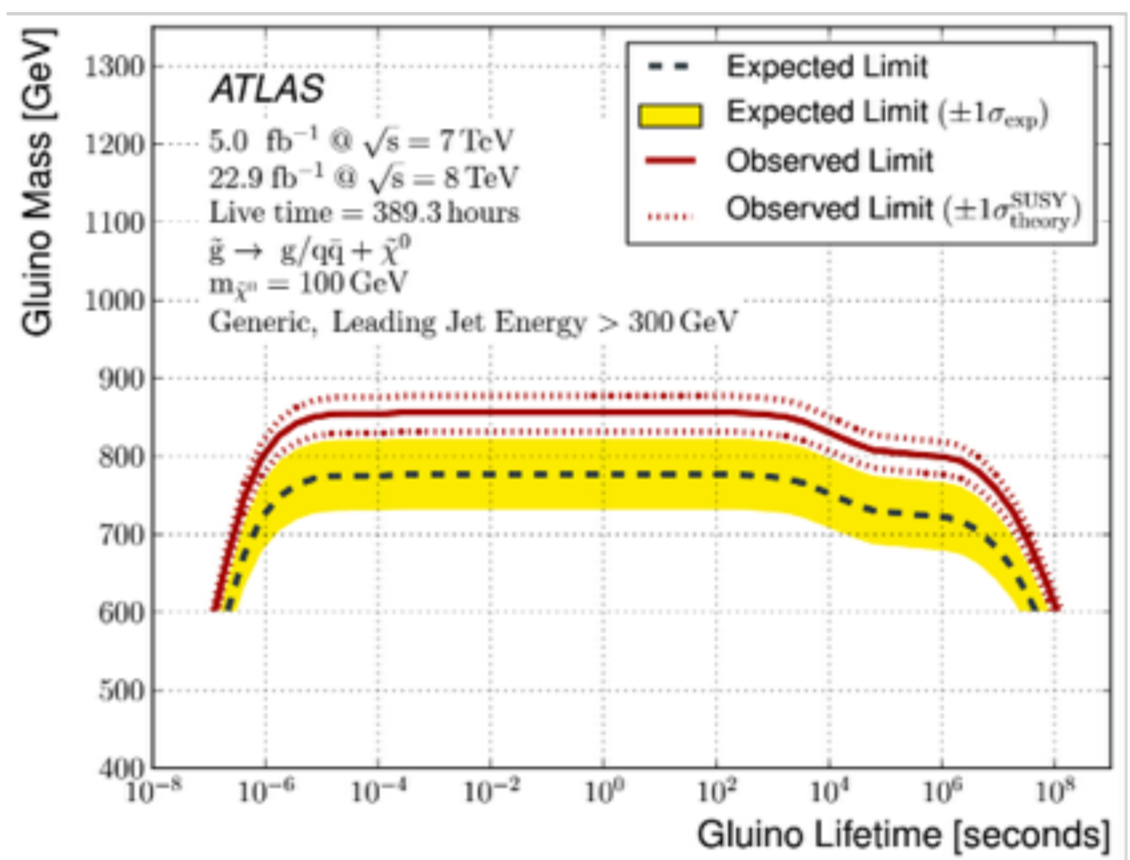




Stopped Particles

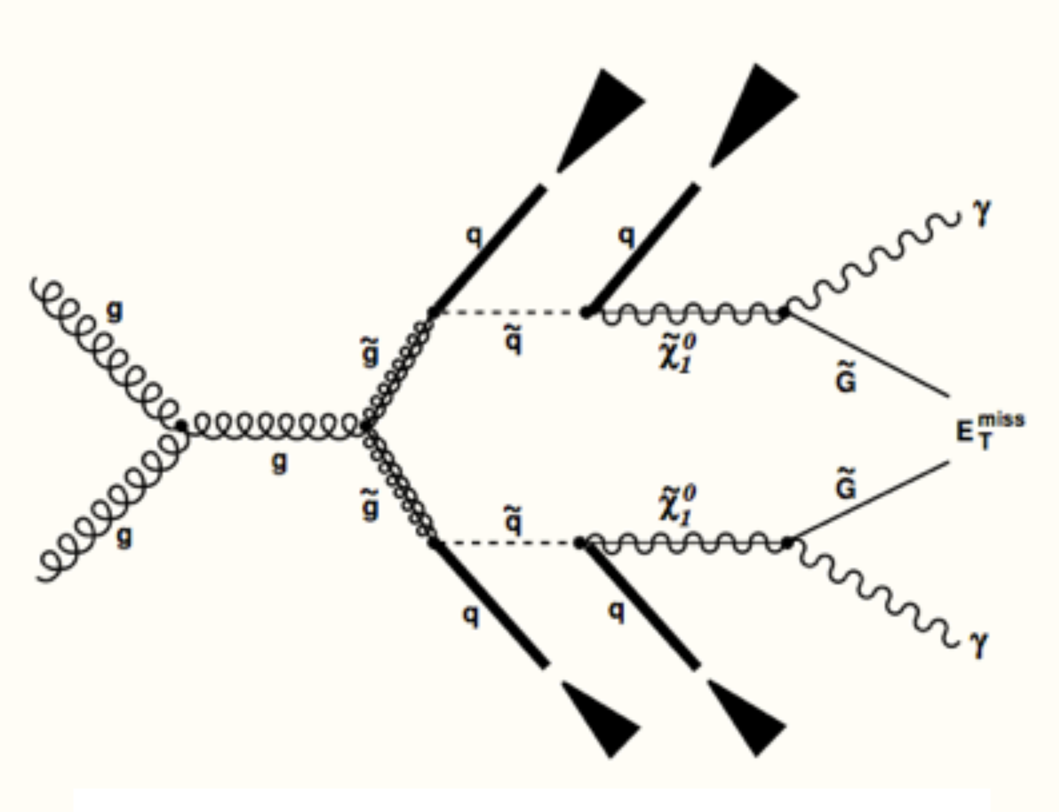
- **Dedicated calorimeter trigger** to selected events in **gaps between LHC beam crossings**
- **Selection based on jet p_T and criteria to reject residual backgrounds**
  - beam halo, cosmics, out-of-time pp collisions, detector noise
- Limits presented in a **long-lived gluino or stop in R-hadrons scenario**

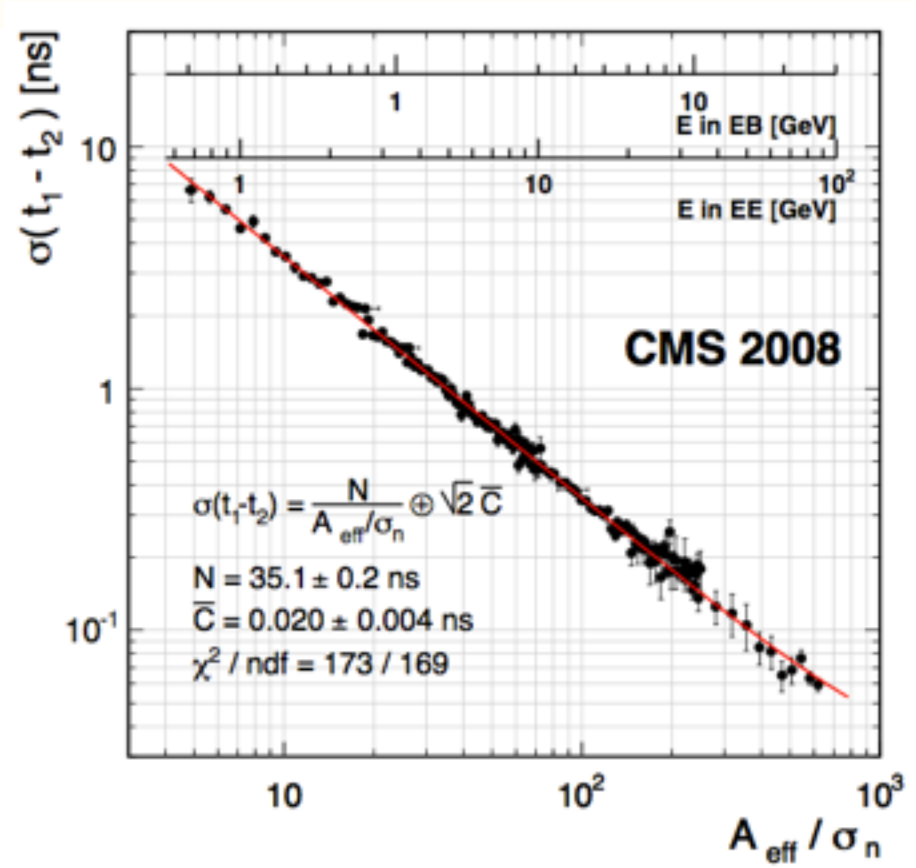




DISPLACED PHOTONS: THEORY

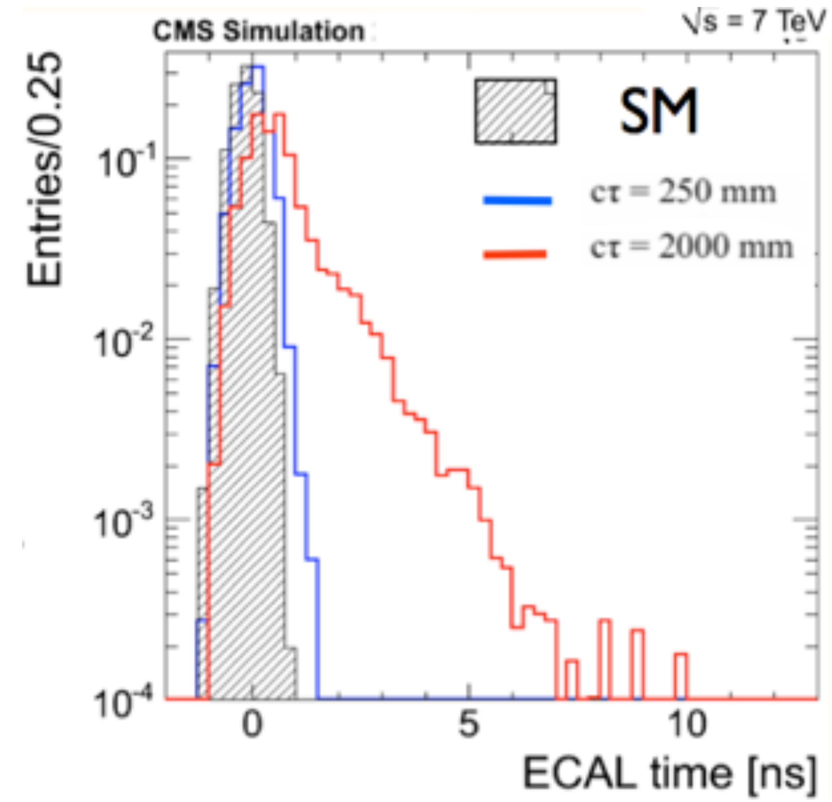
- In models like **Gauge Mediated Supersymmetry Breaking**, Neutralino decays to Gravitino (lightest supersymmetric particle)
  - Missing ET
  - high pT jets and photons
- **Gravitino can be long-lived**
  - displaced/delayed photons
- **Tagged using em calorimeter time**
  - design resolution: < 100ps
- **Topology requirements**
  - >=1 photon with p_T>100GeV
  - 3 high pT jets and large Missing E_T

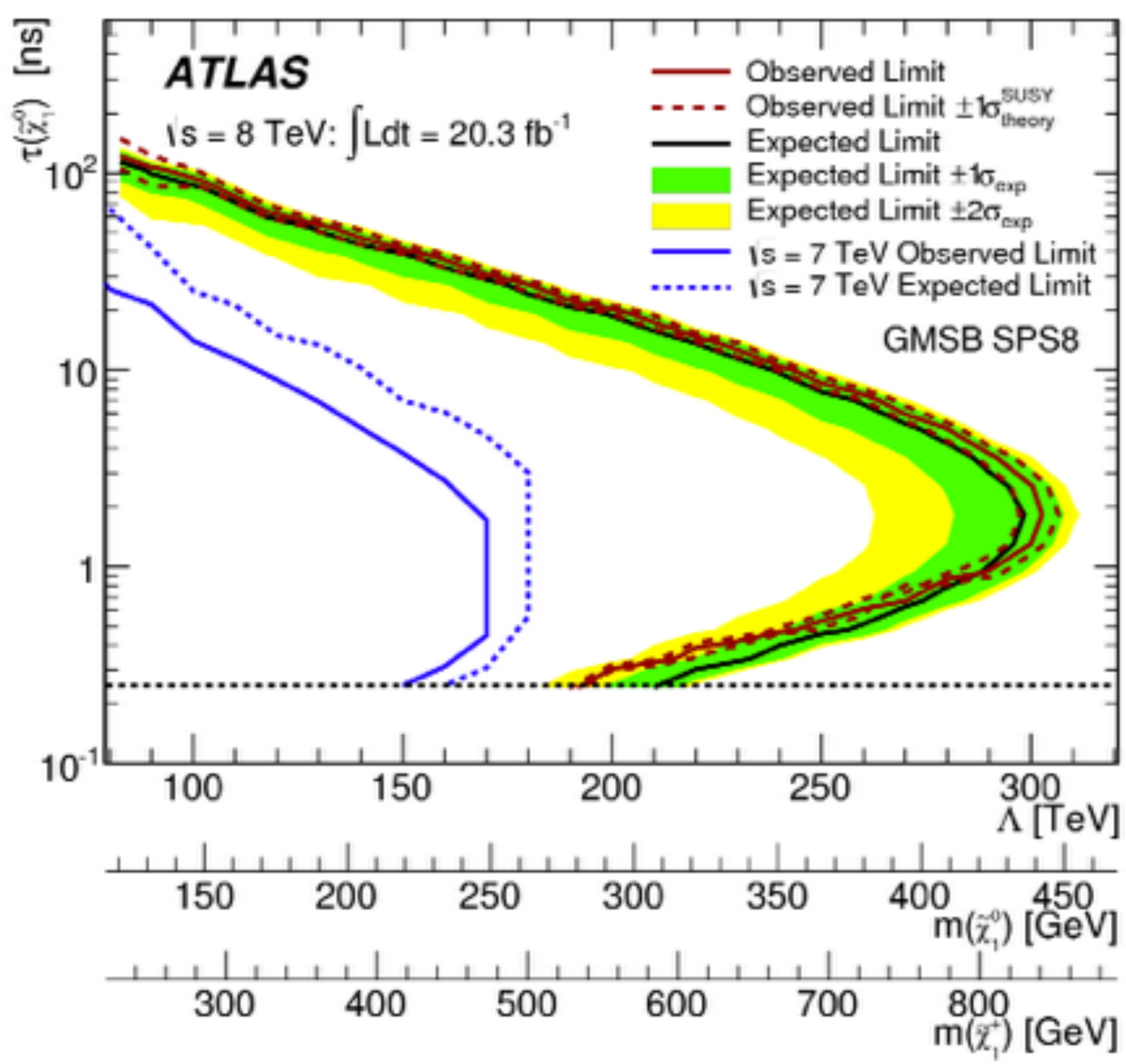


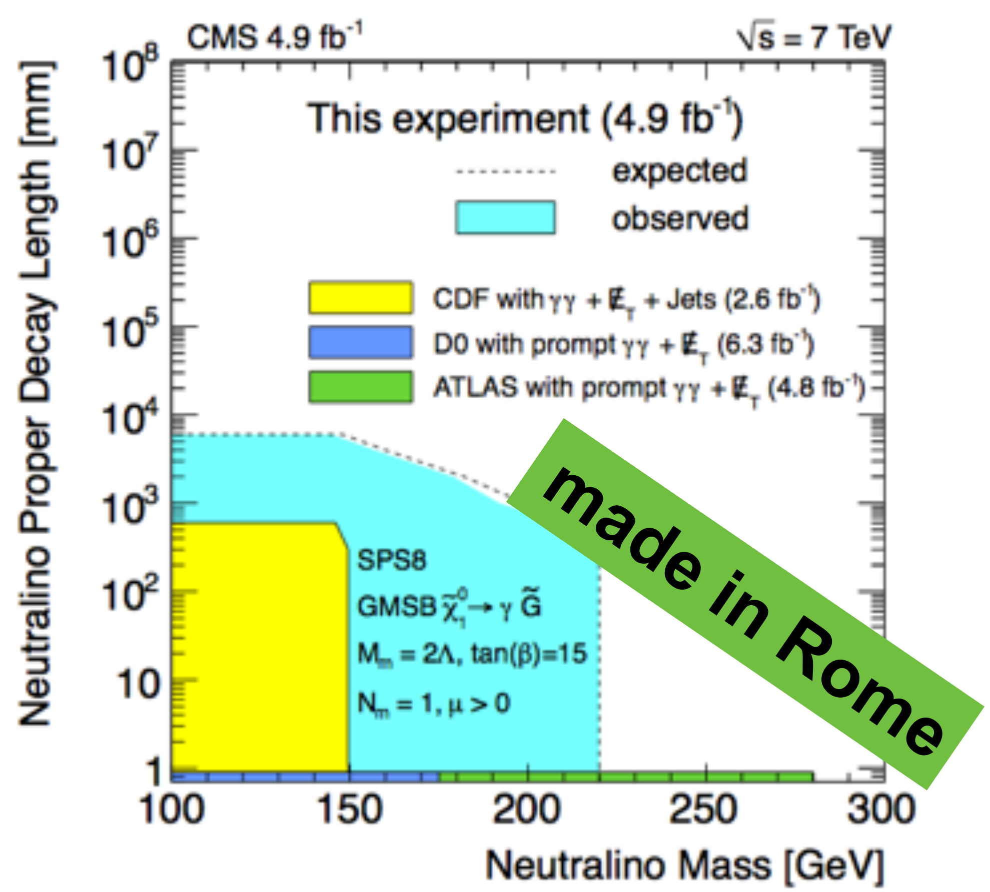


DISPLACED PHOTONS: RESULTS

- Striking signature if Neutralino is long-lived
- **No excess observed**
- Limits are set varying **Neutralino masses and lifetimes**





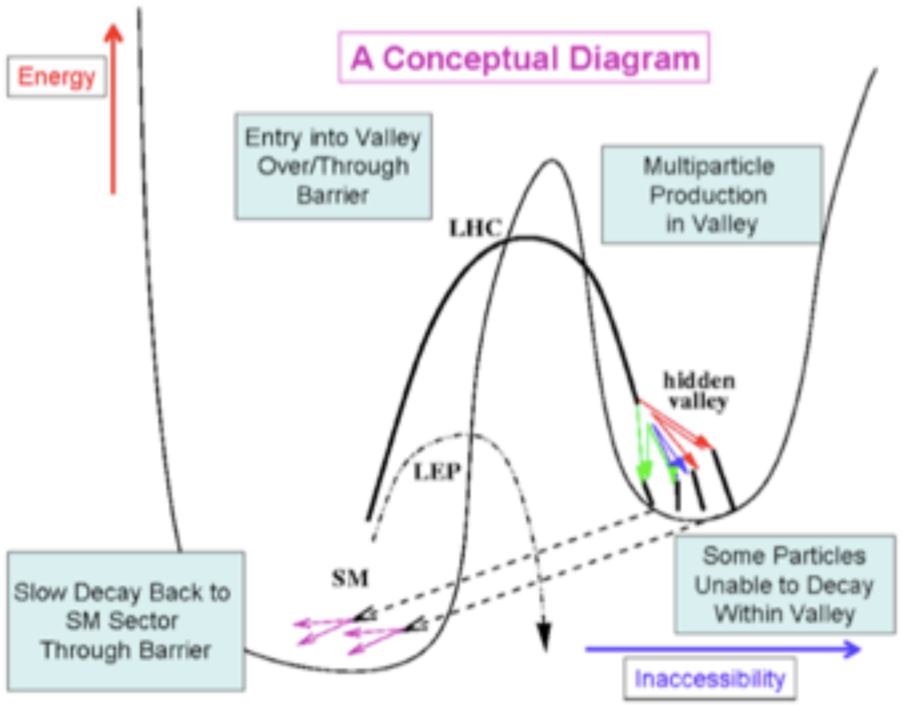


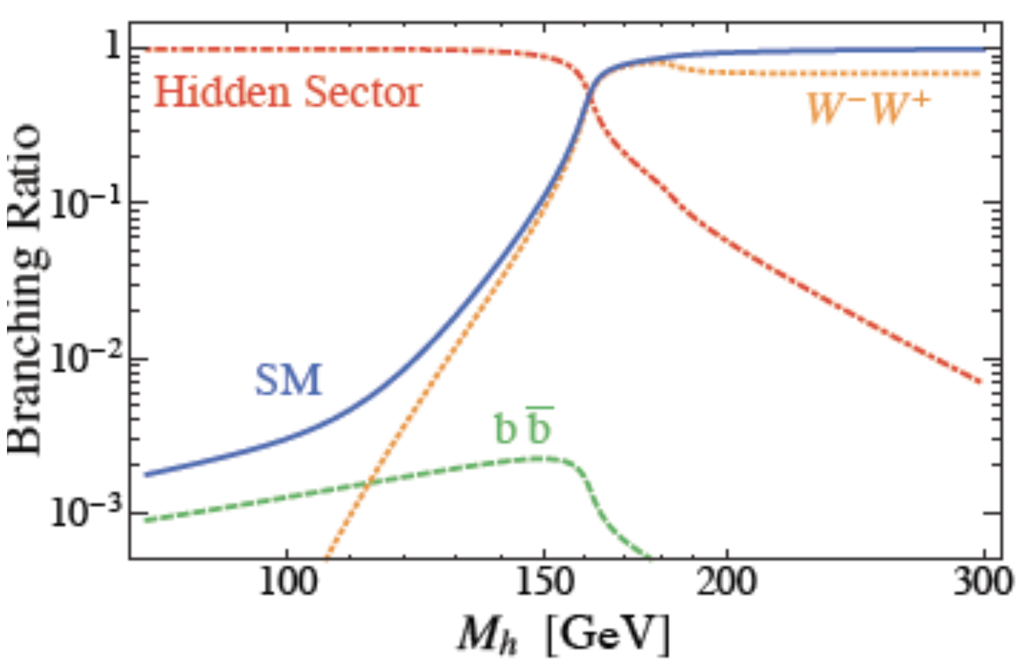
Displaced Vertexes: Models

- **Hidden Sector weakly coupled to SM**

  - motivated by $(g-2)_\mu$ and Pamela results

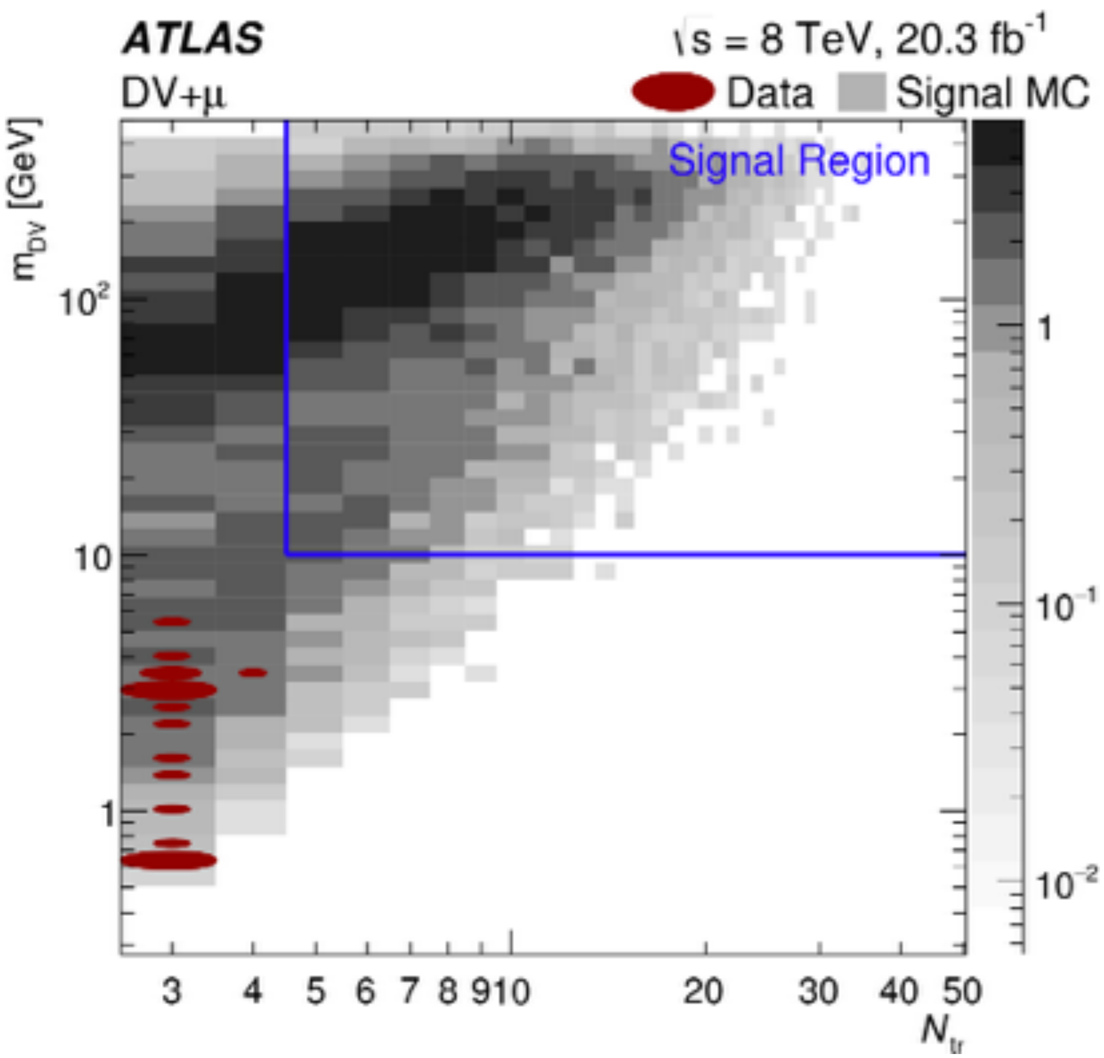
- Communicate through **heavy mediator particles** (Higgs, Z´, loop of SUSY particles)
- **Heavy particles** (e.g. Higgs boson) **decay to particles of the hidden sector** and back to the standard sector via:
  - hadronic jets
  - collimated jets of leptons: lepton-jets
- Hidden particles can be long-lived and neutral (LLNP)
- **Identified reconstruction displaced vertexes**

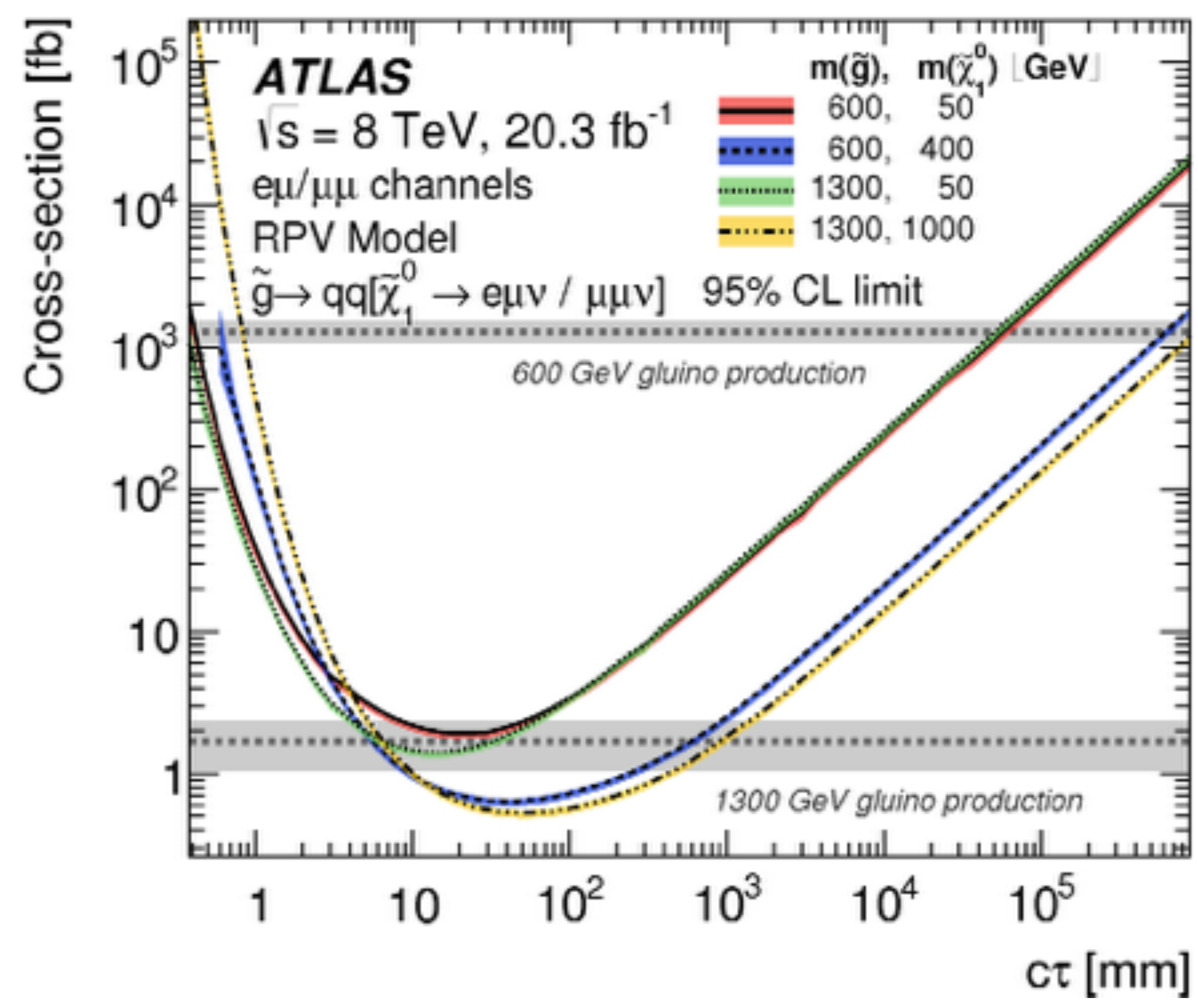




DISPLACED VERTEXES: ATLAS

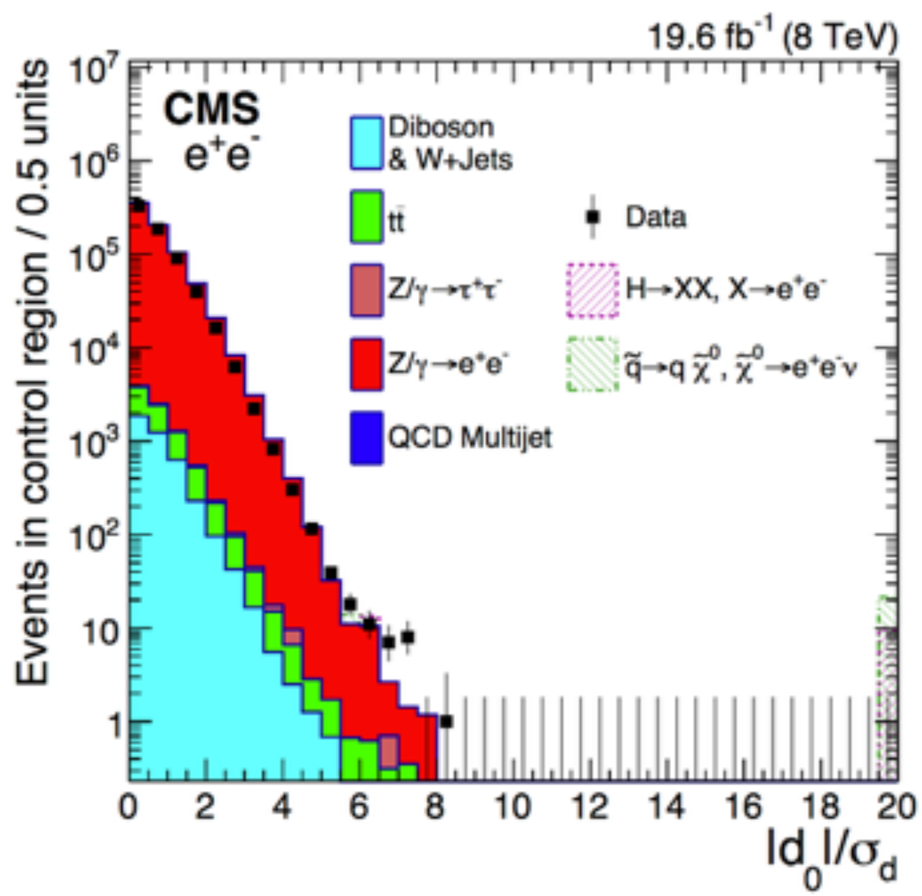
- In RPV SUSY, **neutralino can decay in leptons + jets**
  - leptons good for triggering, jets for vertexing
  - dedicated vertex reconstruction
- **No excess seen**

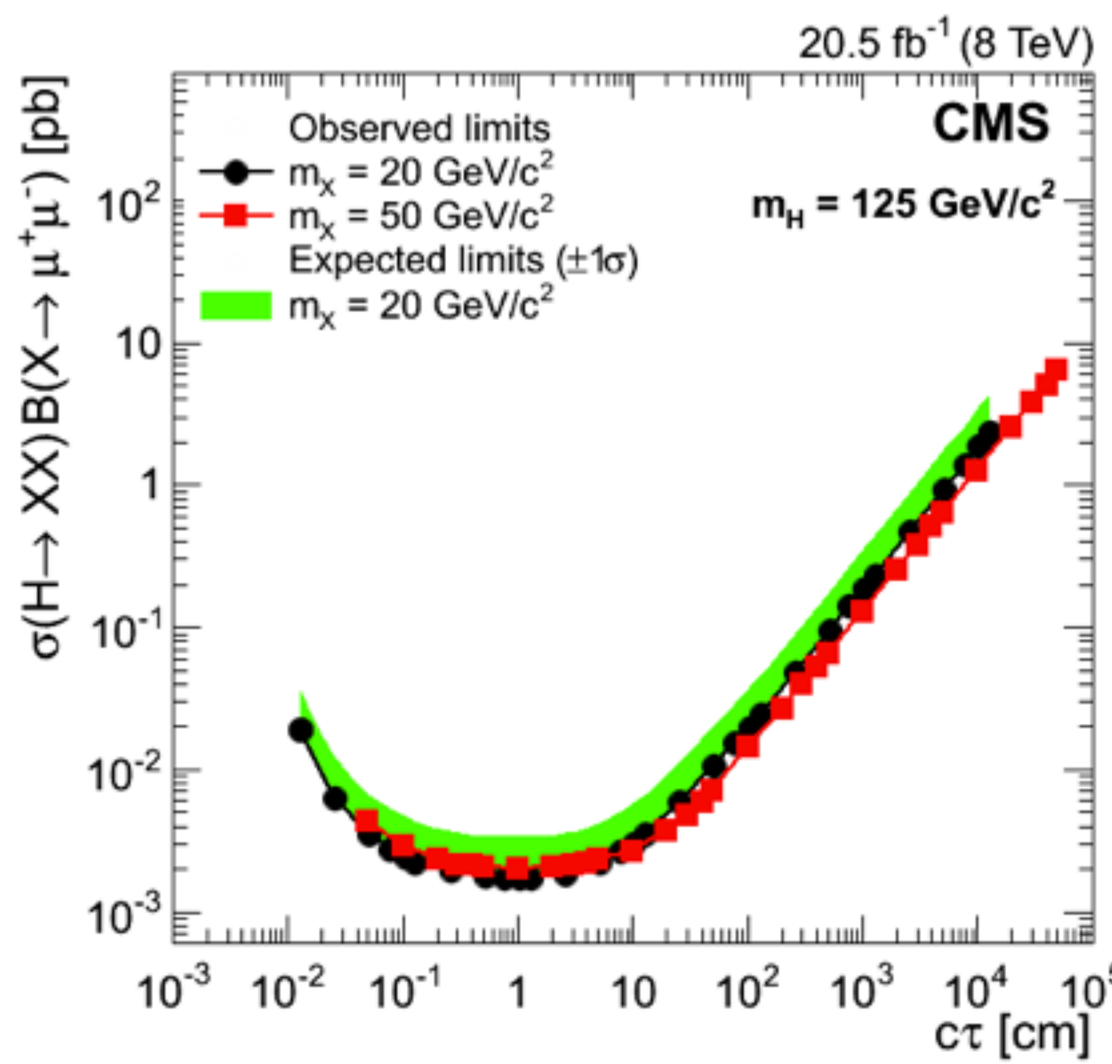




DISPLACED LEPTONS

- Signature of **oppositely charged leptons originating at a separated secondary vertex within the inner tracker volume**
- **Benchmark model:** Higgs → 2X, X → l^+l^-
- Main selection variable: **transverse decay length significance L_{xy}/σ_{xy}**
- **No excess**

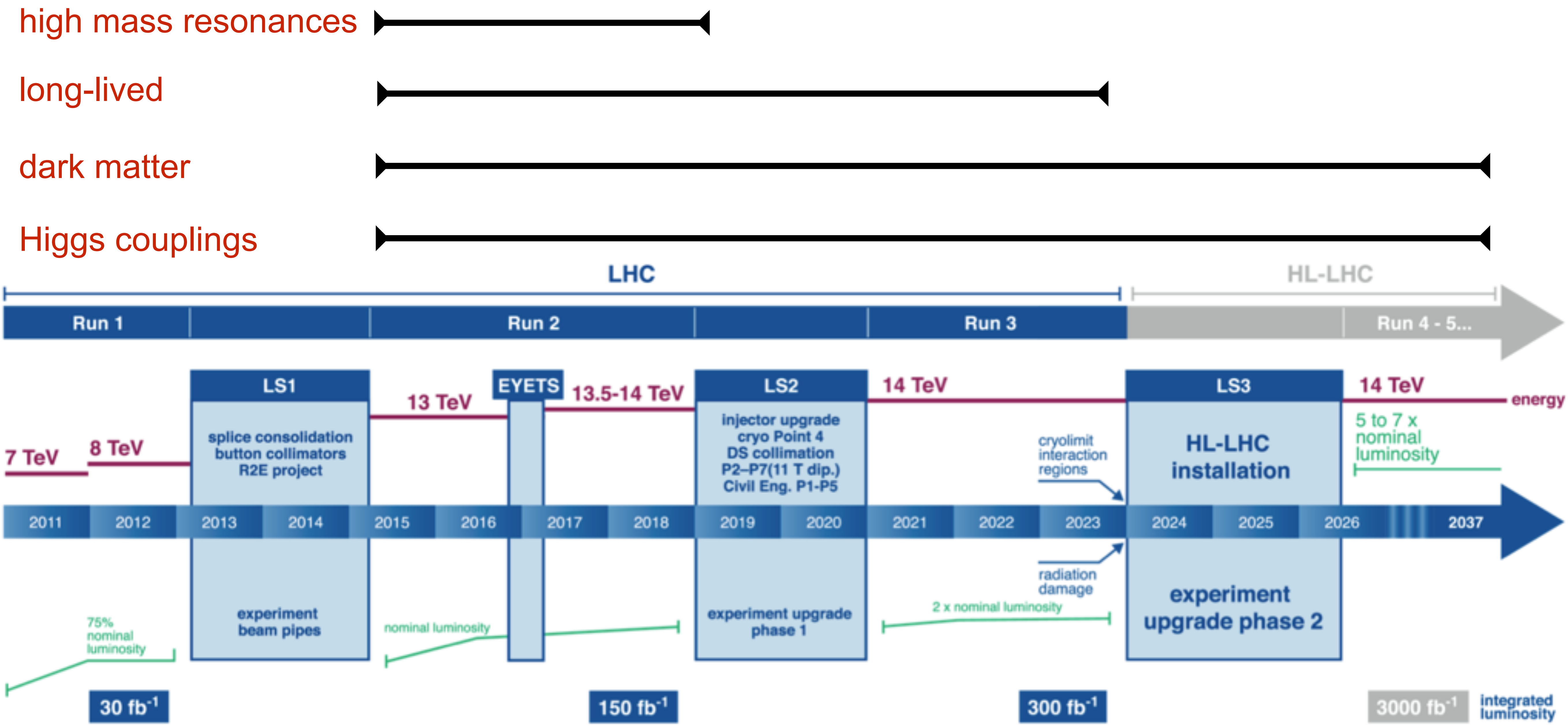




GRAND SUMMARY

- **Search for New physics** main goal these days at LHC
  - increase in center of mass energy (13 TeV) boosted the reach
  - new territories to explore
- **ATLAS and CMS physics programs very broad**
  - in particular for searches for new high mass resonances, dark matter and long-lived particles
- **No discovery so far but**
  - **hint of excess in the diphoton channel at m ~ 750 GeV**
    - ATLAS: 3.9 σ, CMS: 3.4 σ
    - more statistics needed. Answer in few months
- **LHC** still **unique place** to probe Standard Model and **look for New Physics for the next 20 years**
- **This department deeply involved in these searches**

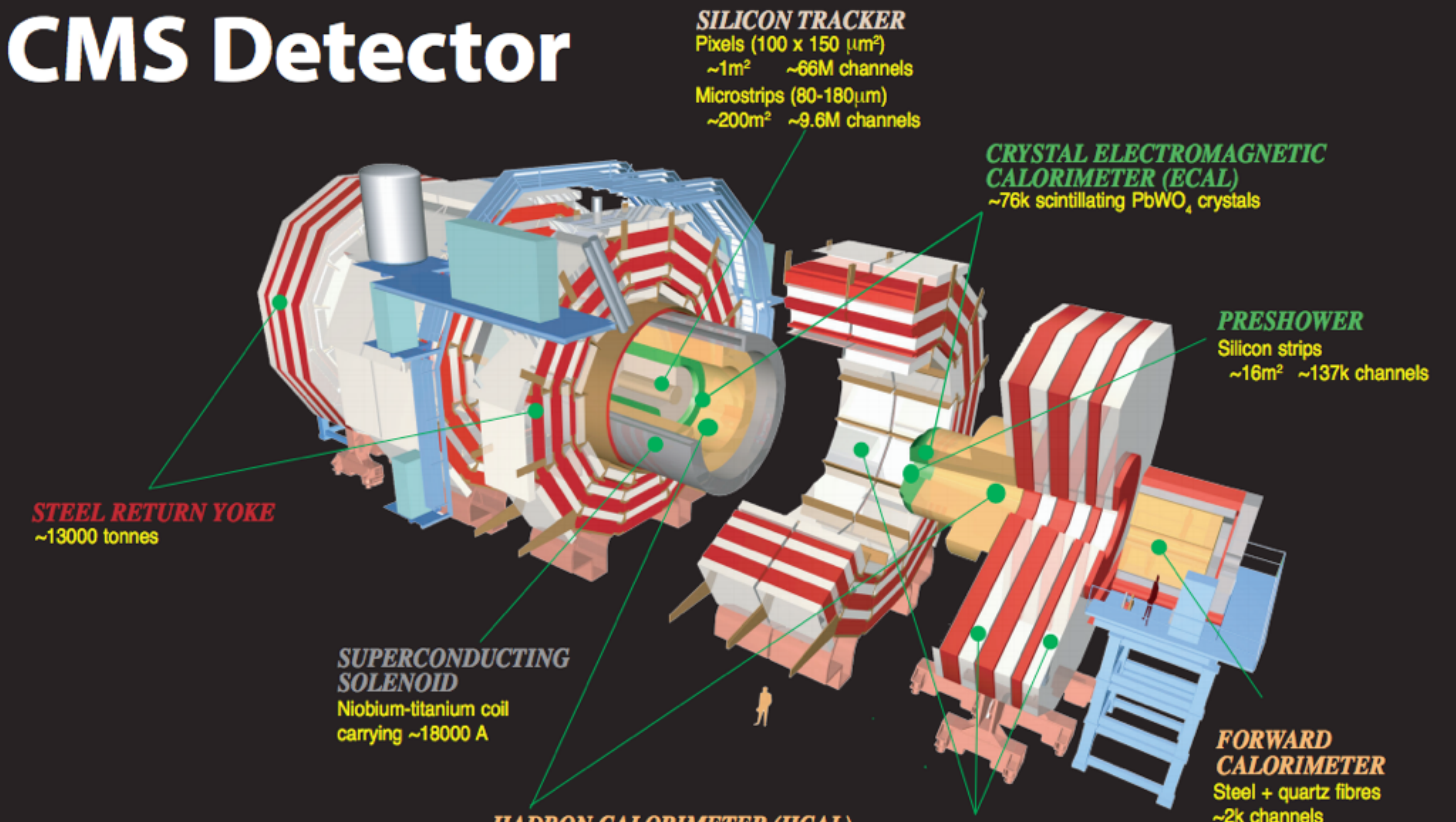
PERSPECTIVES



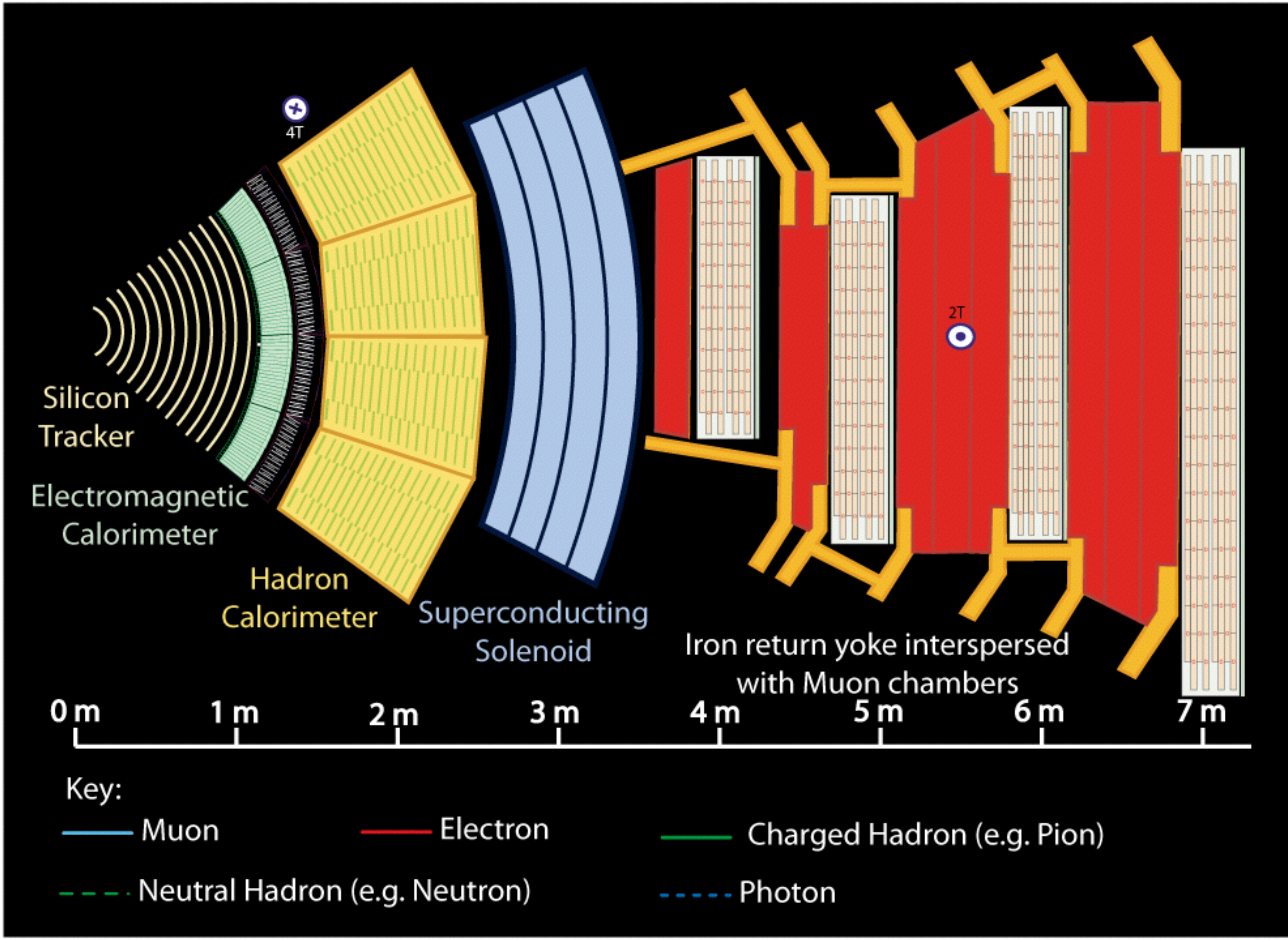
Run 1	Magnet splice update	Run 2 at ~full design energy	Phase I upgrades (injectors)	Run 3 → original design lumi	Phase II upgrades (final focus)	HL-LHC: ten times design lumi

BACKUP

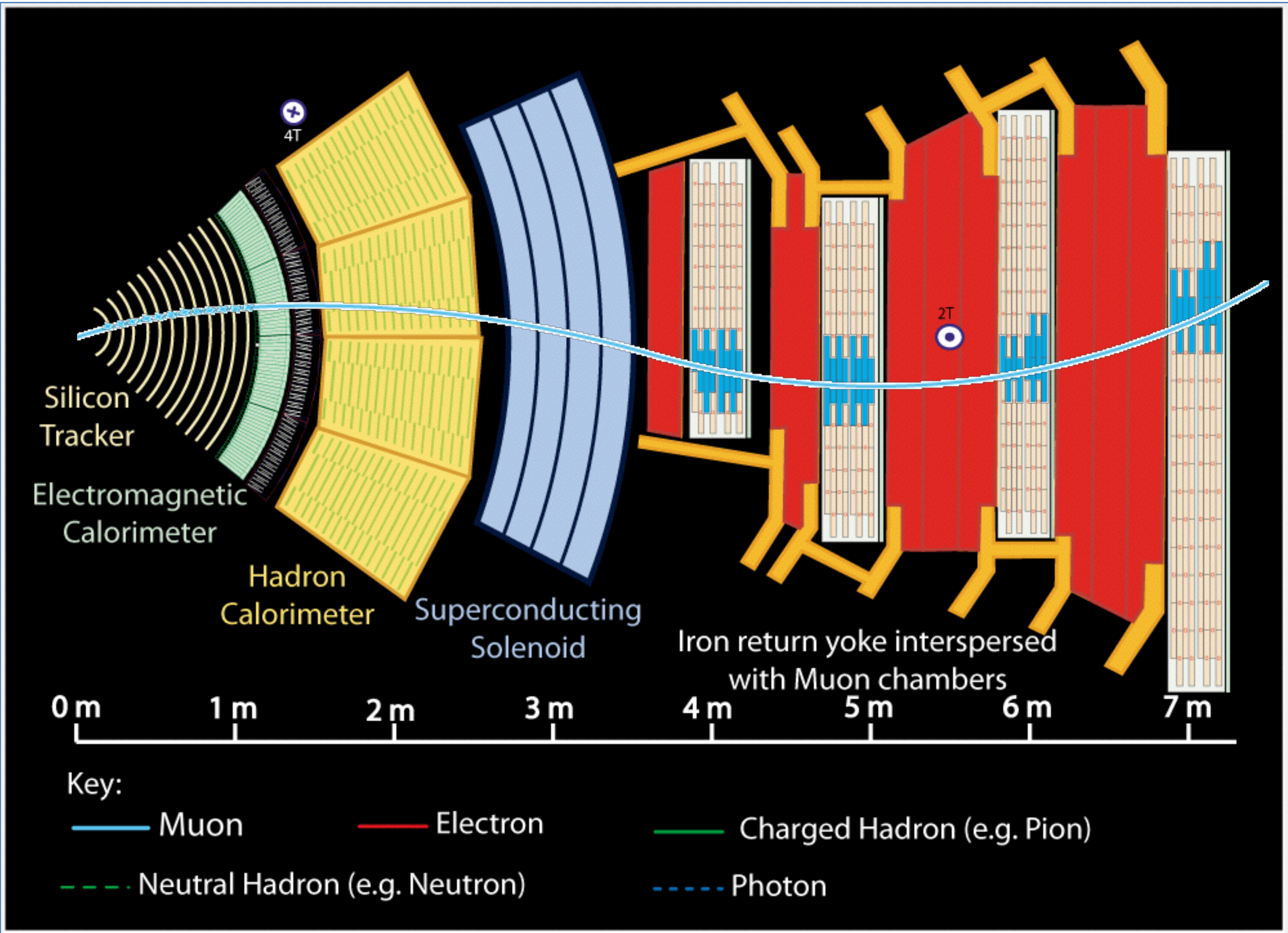
CMS Detector



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



4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon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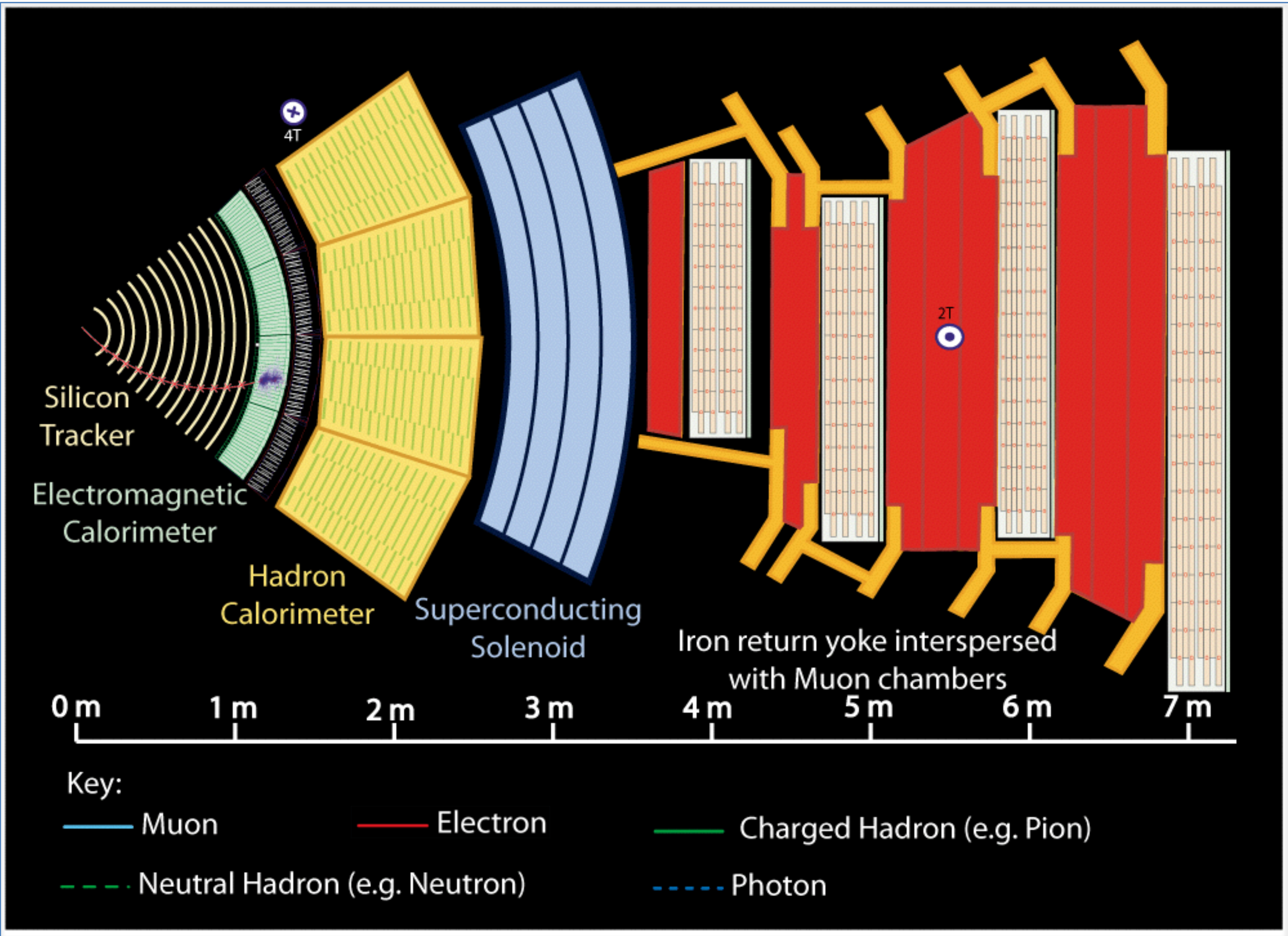
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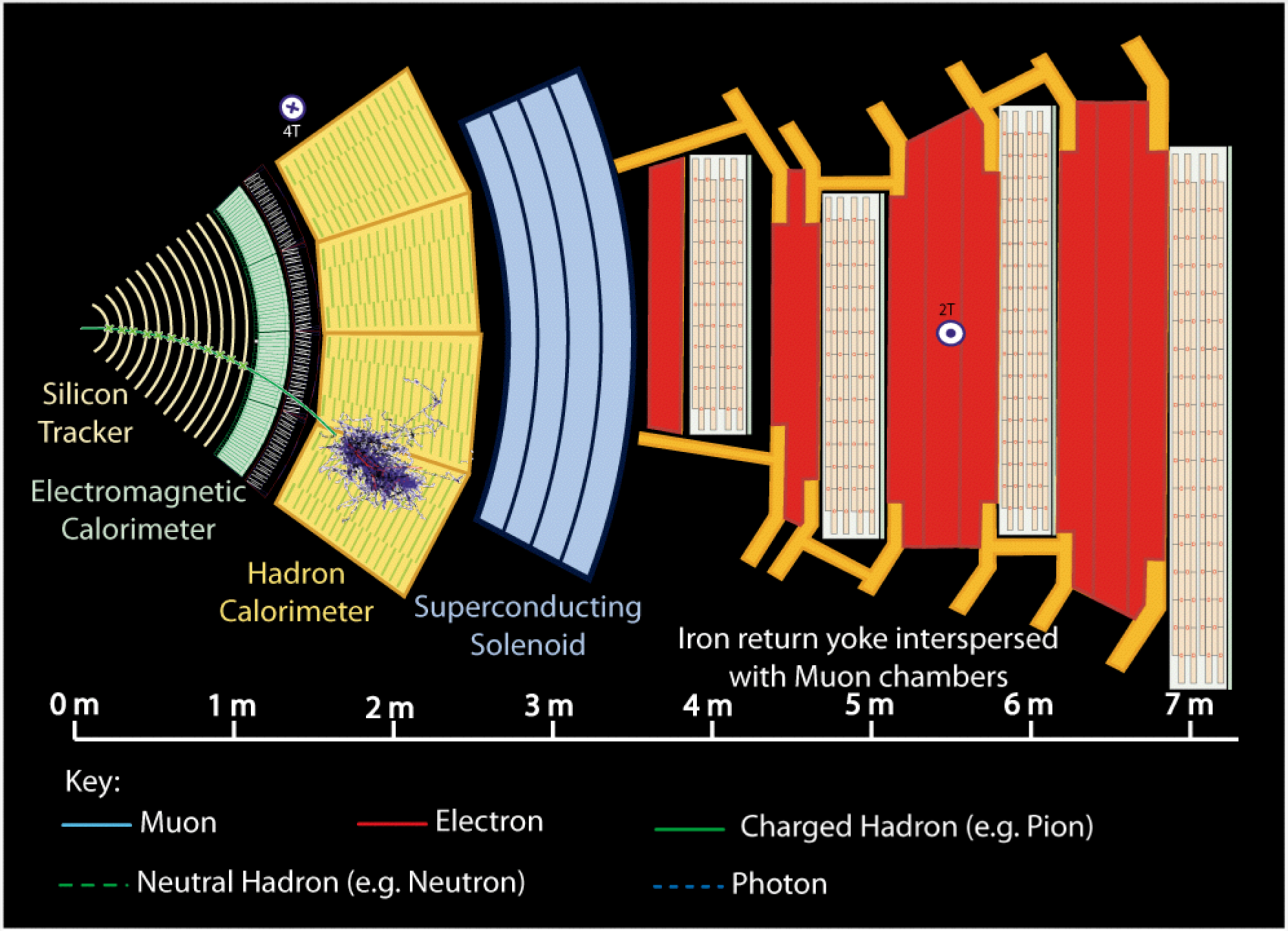
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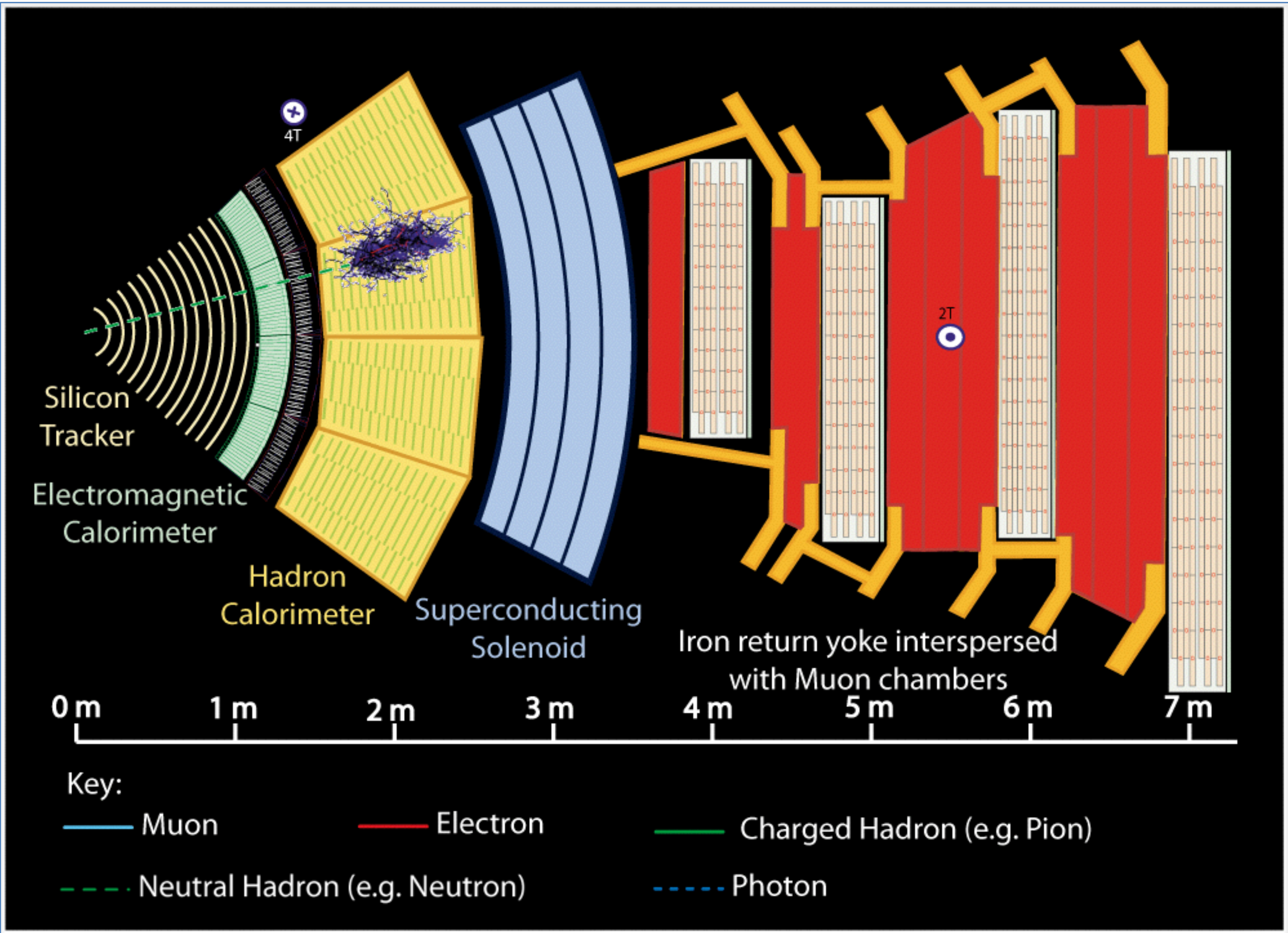
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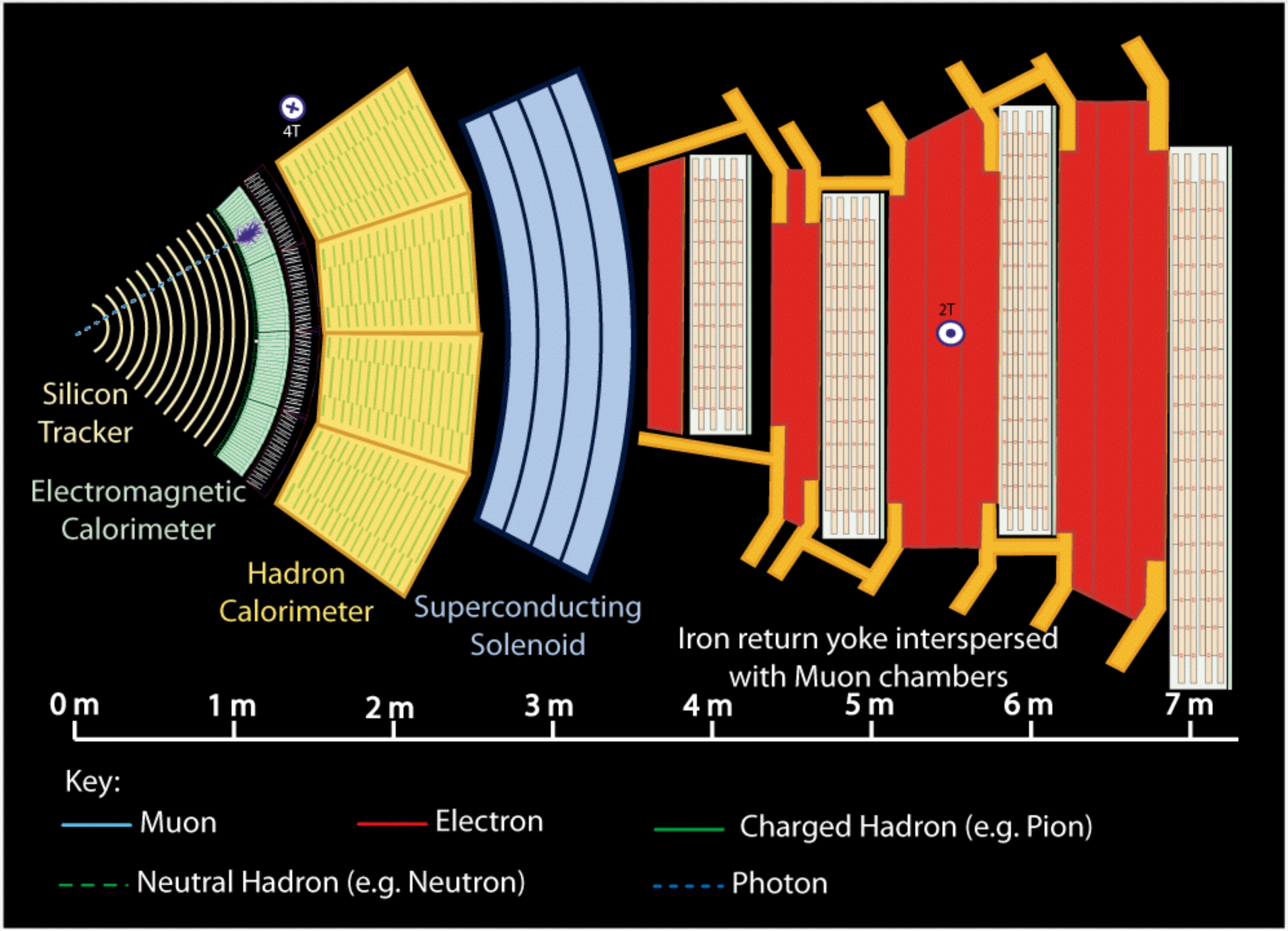
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Key:
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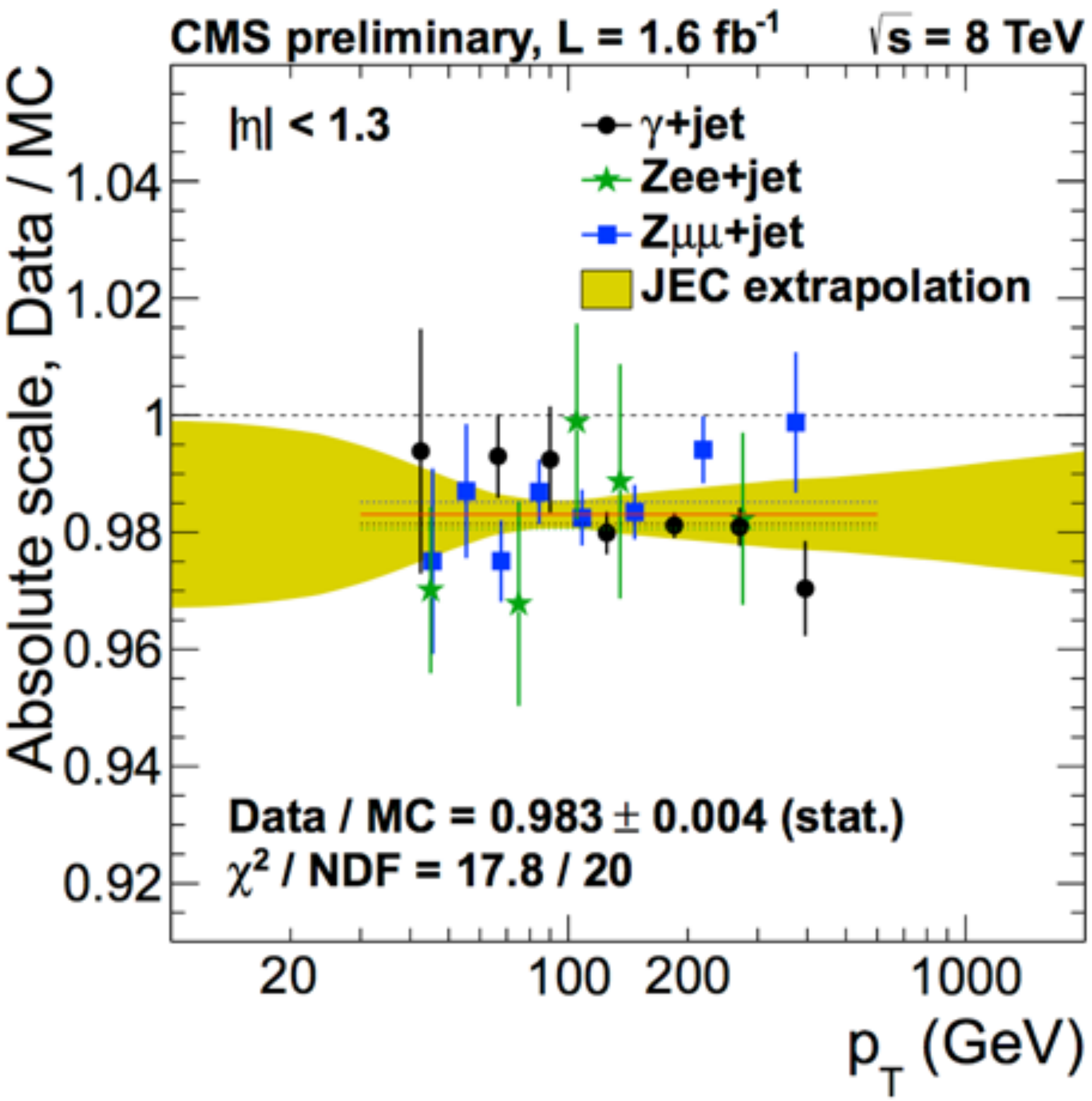
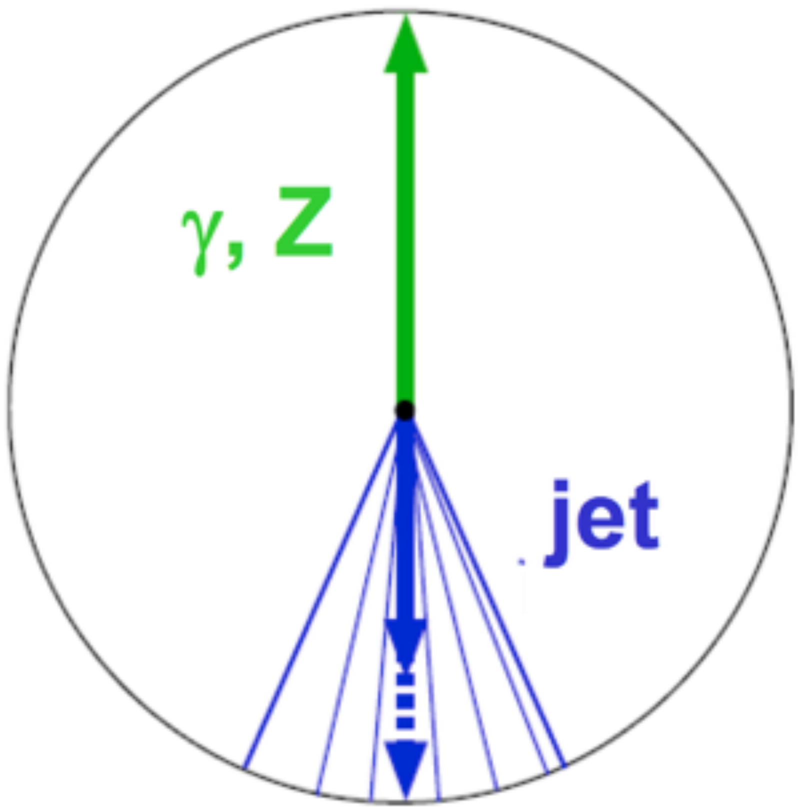
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon

JET SCALE CALIBRATION IN SM P_T REGIME

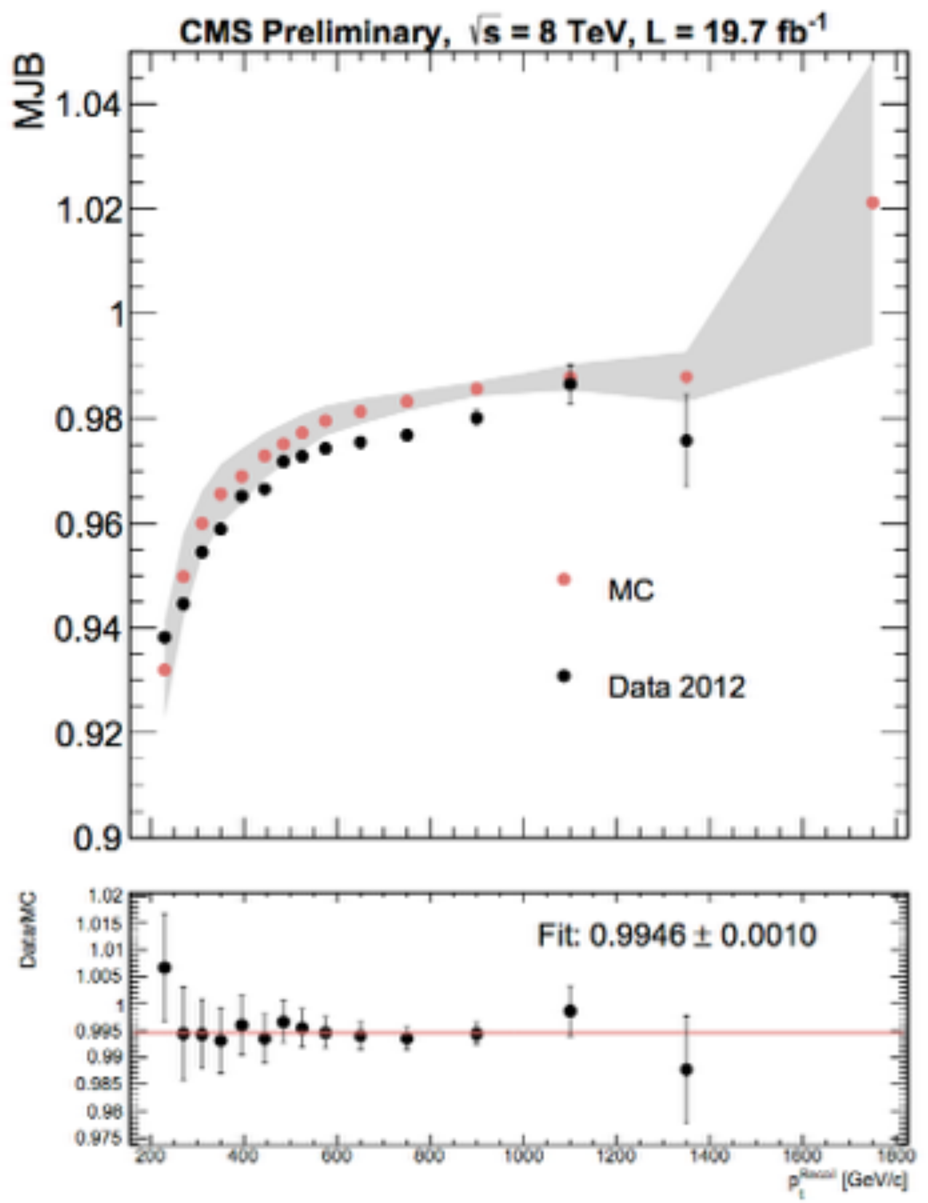
- **Calibration for ~100 GeV Jets**
  - Event balancing in the transverse plane with gamma+jets or Z+jets events
  - **no events above ~ 400 GeV**

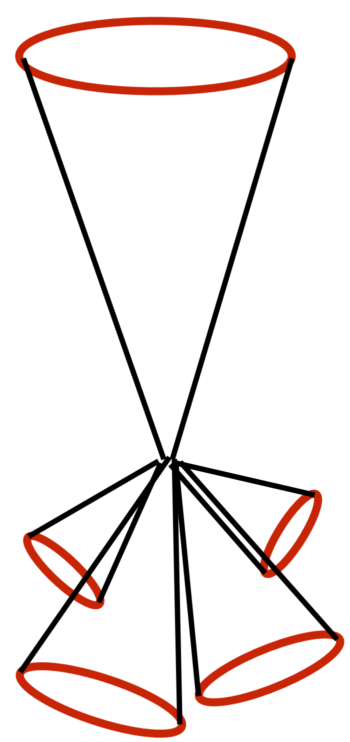




THE EXAMPLE OF JETS

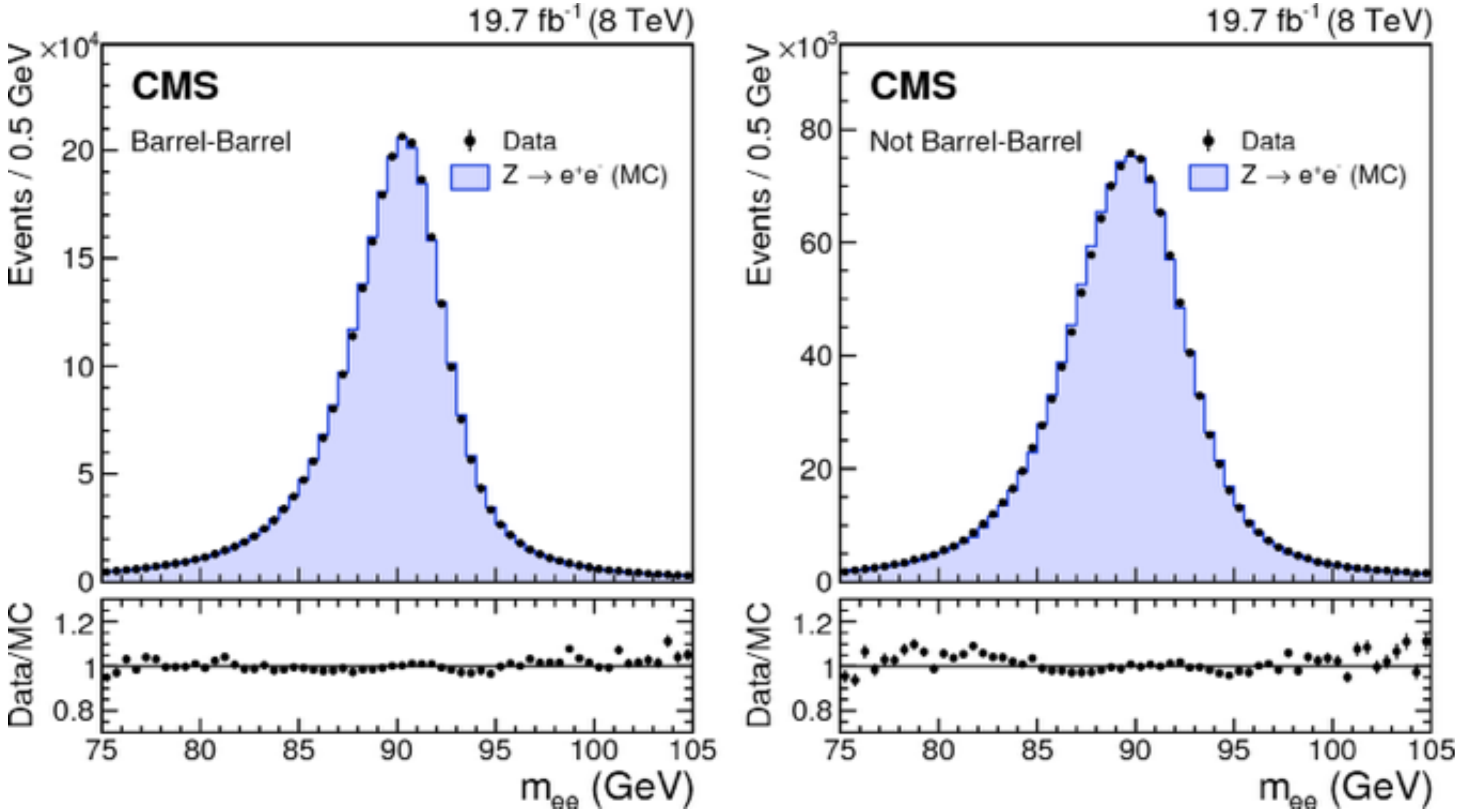
- **Multijet events** to evaluate low vs high p_T relative scale
  - **one high p_T jet recoils to many low p_T jets**
  - p_T jet scale from Z/gamma+jet (previous slides)
  - **by imposing balancing** high p_T jet can be calibrated





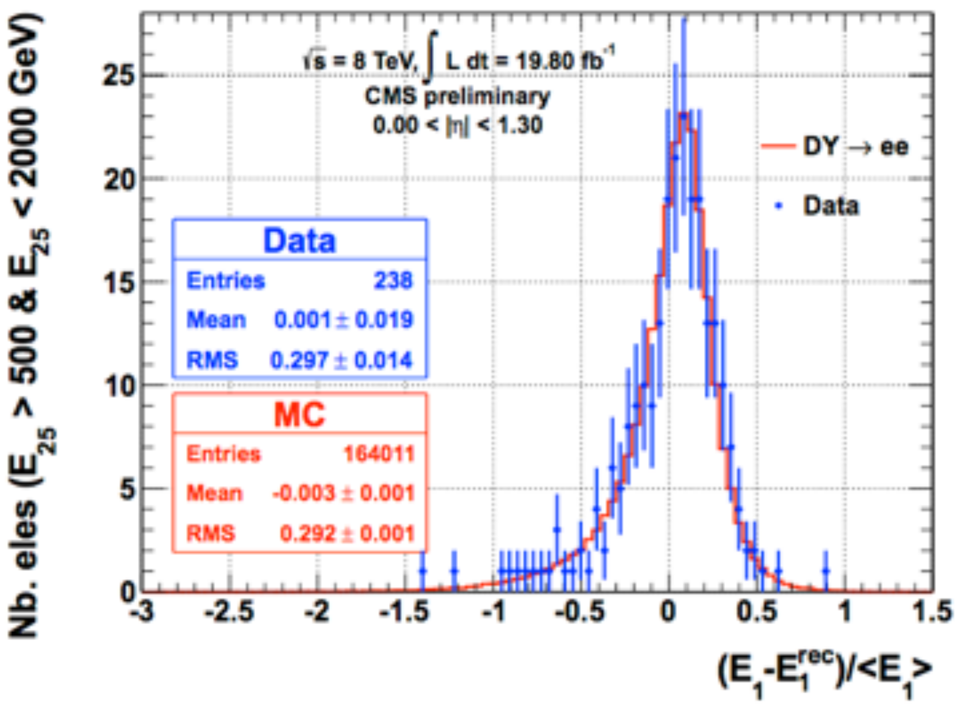
Electron Scale and Resolution

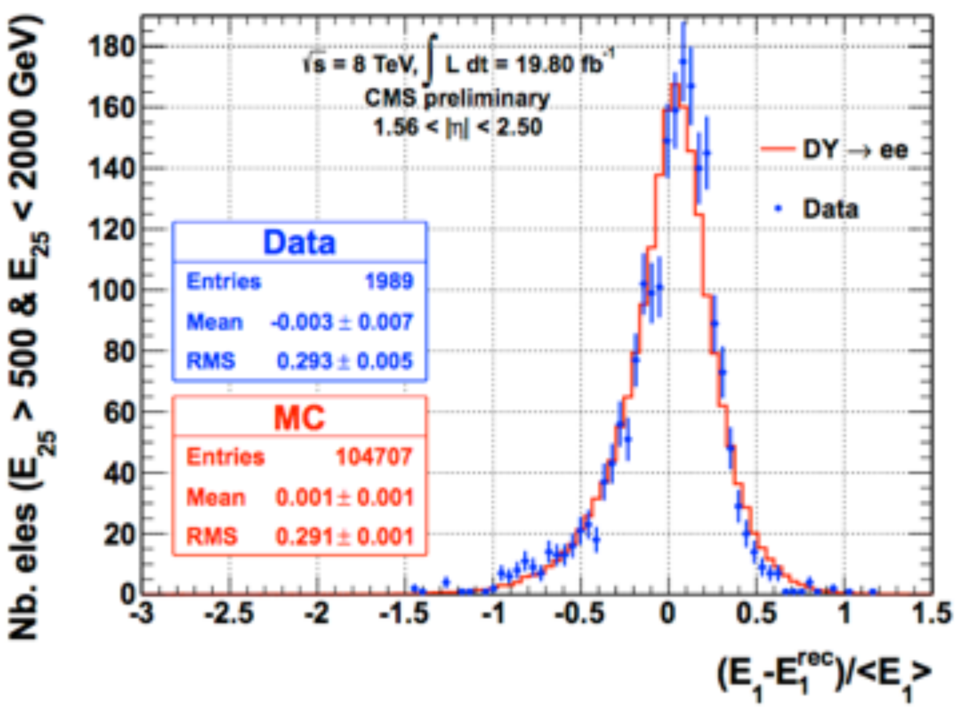
- Basically use **Z to monitor energy scale and resolution**
- Reconstruct Z invariant mass
- **Rescale energy response to make Z line shapes for data and MC talk each other**

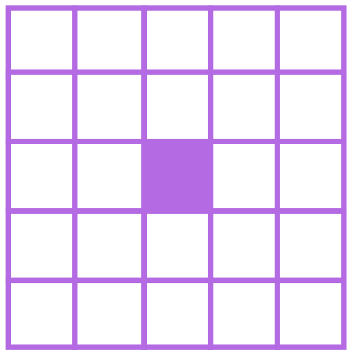


ELECTRONS AT LARGE PT

- Electron release energy in 5x5 array of crystals
- **About 80% in central crystal**
- Extract electron energy **from the 24 low energy surrounding crystals** (assuming average em cluster shape)
- **Compare** the resulting energy **with the one of the most energetic crystals**
- Data-MC comparison of this ratio to set high p_T scale

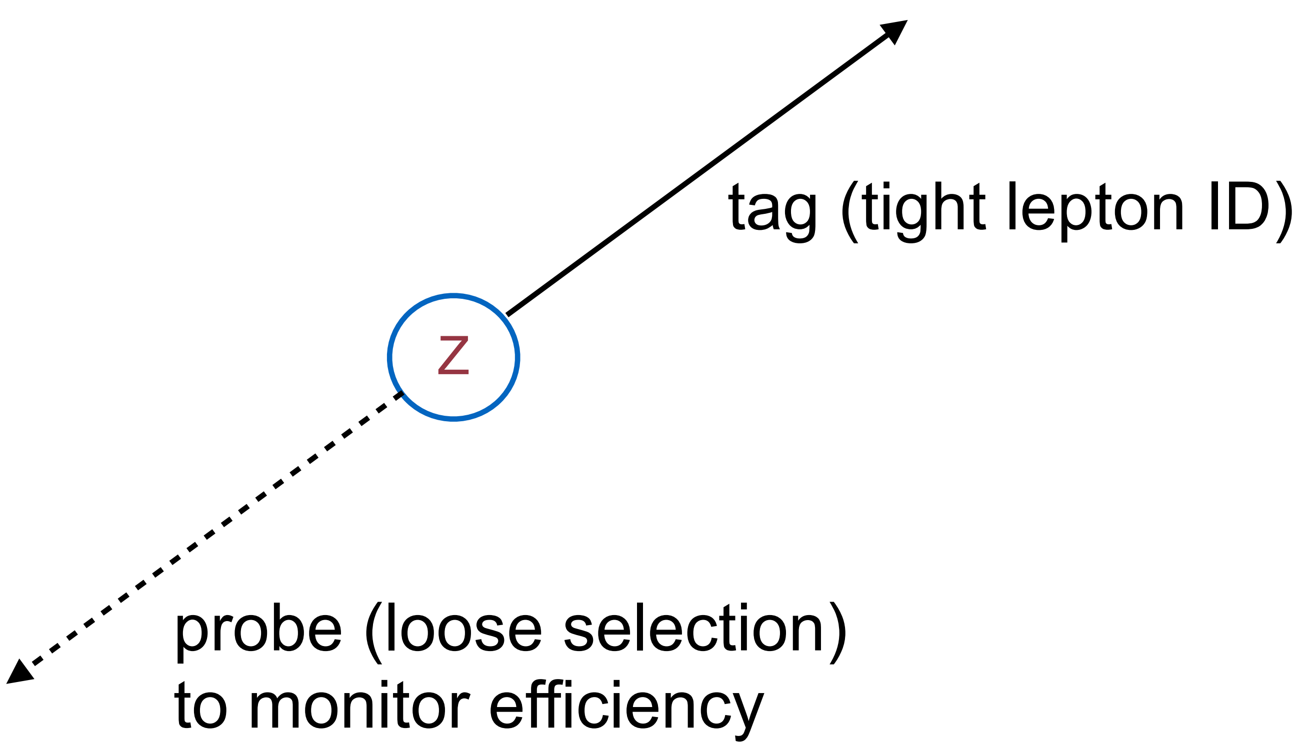


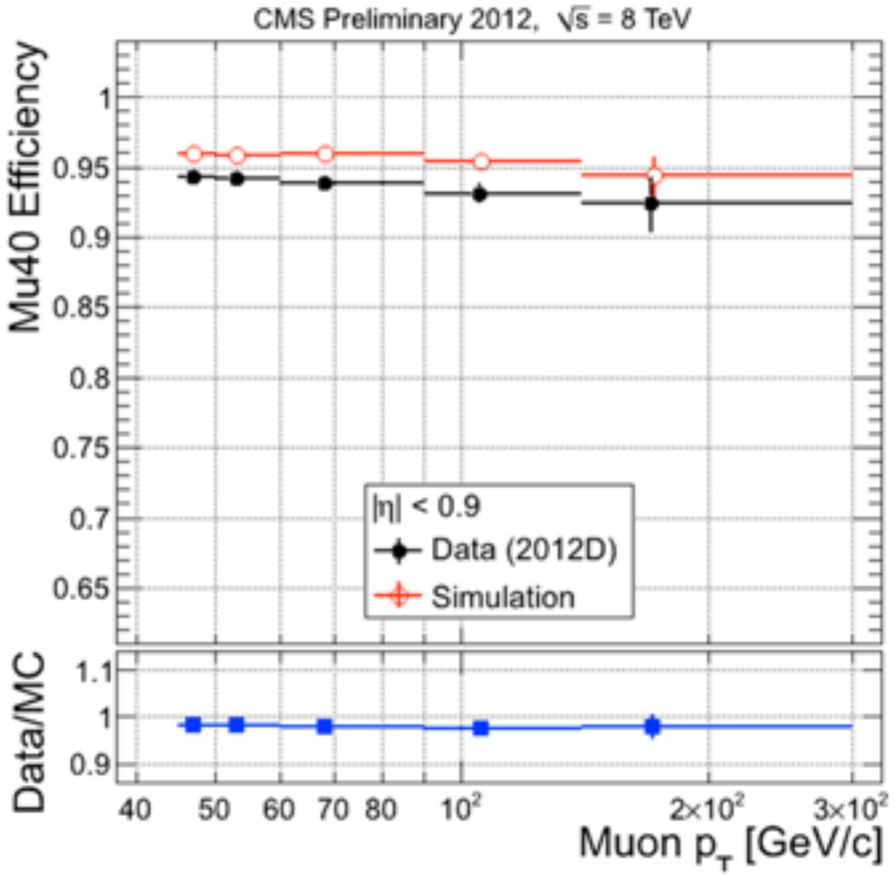




EFFICIENCY EXAMPLE OF ELECTRONS

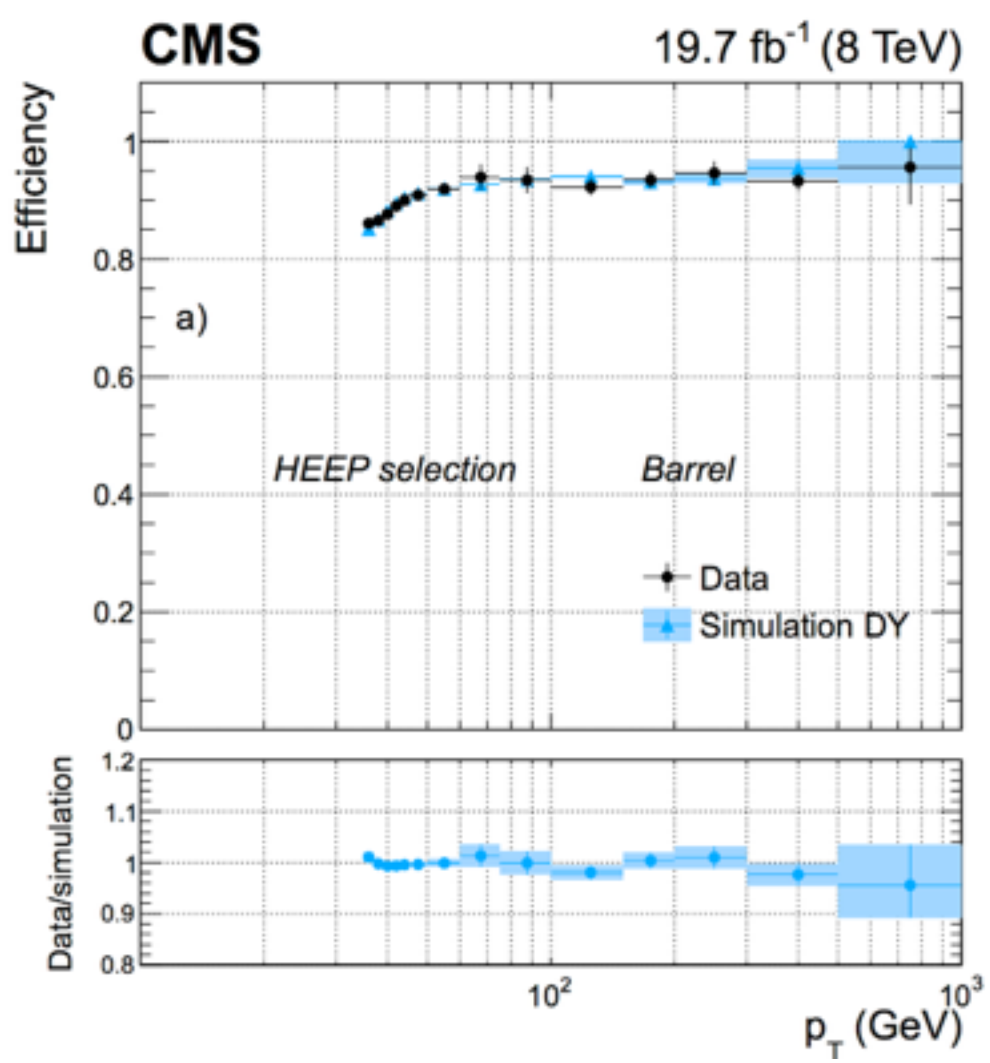
- Calibration for ~50-100 GeV electrons done by using Z->ll events
- Used so-called **tag-and-probe method**
  - one lepton fully identified
  - other lepton selected with loose criteria
  - with inv. requirement (around 91 GeV), measure trigger and selection efficiency

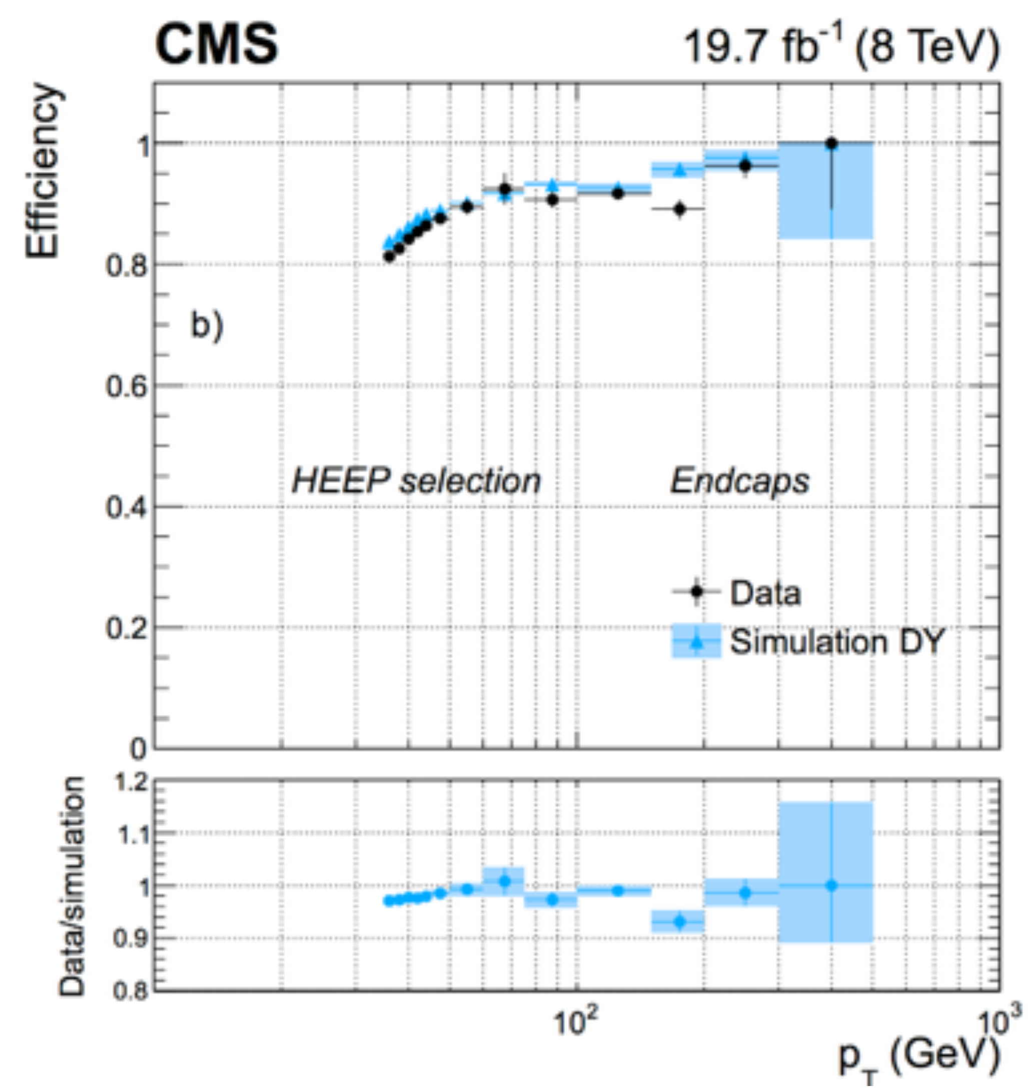




EFFICIENCY AT LARGE PT

- **Still low statistics**
  - but **you don't need much to evaluate efficiency** (O(50-100 events))

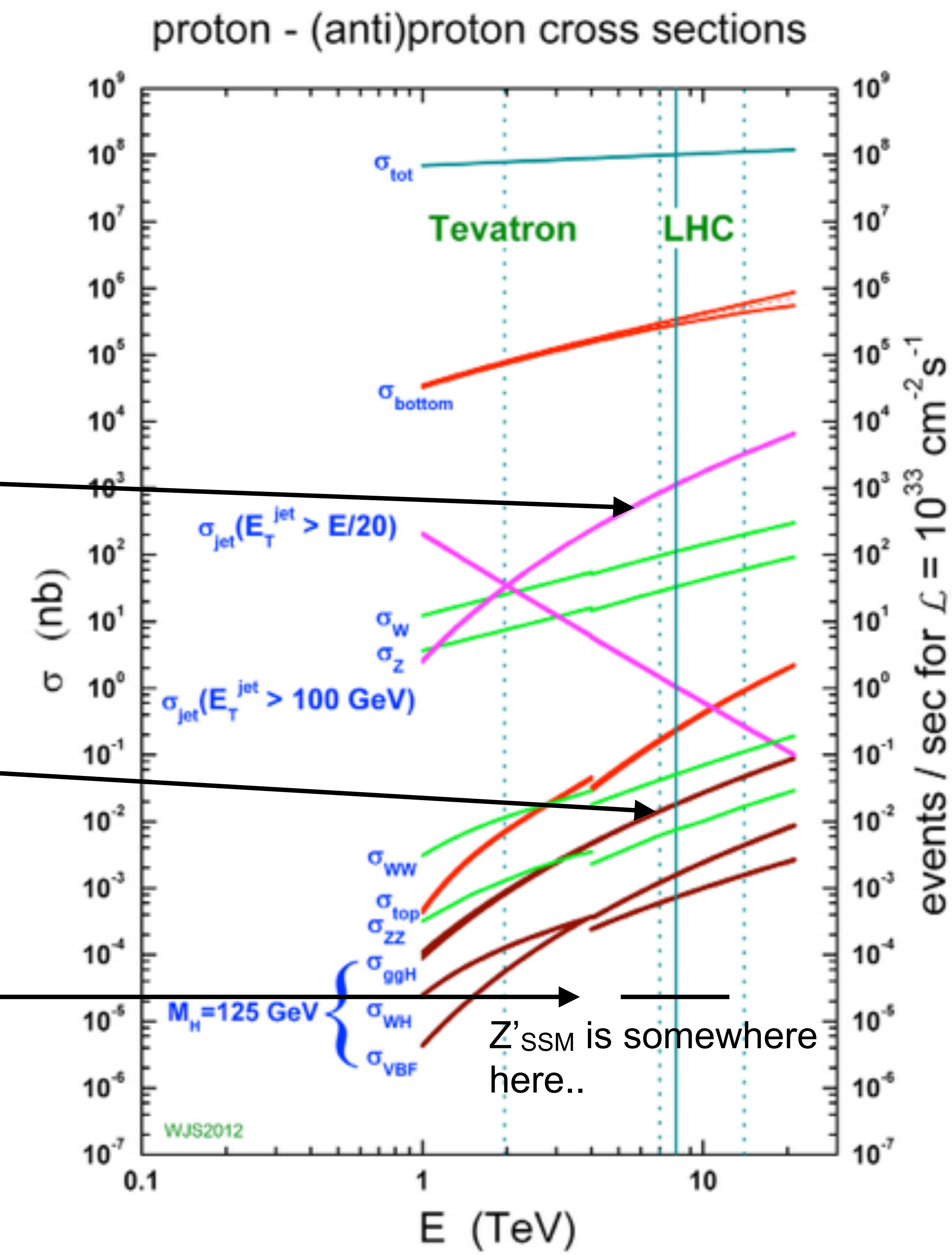




LHC

Cross sections

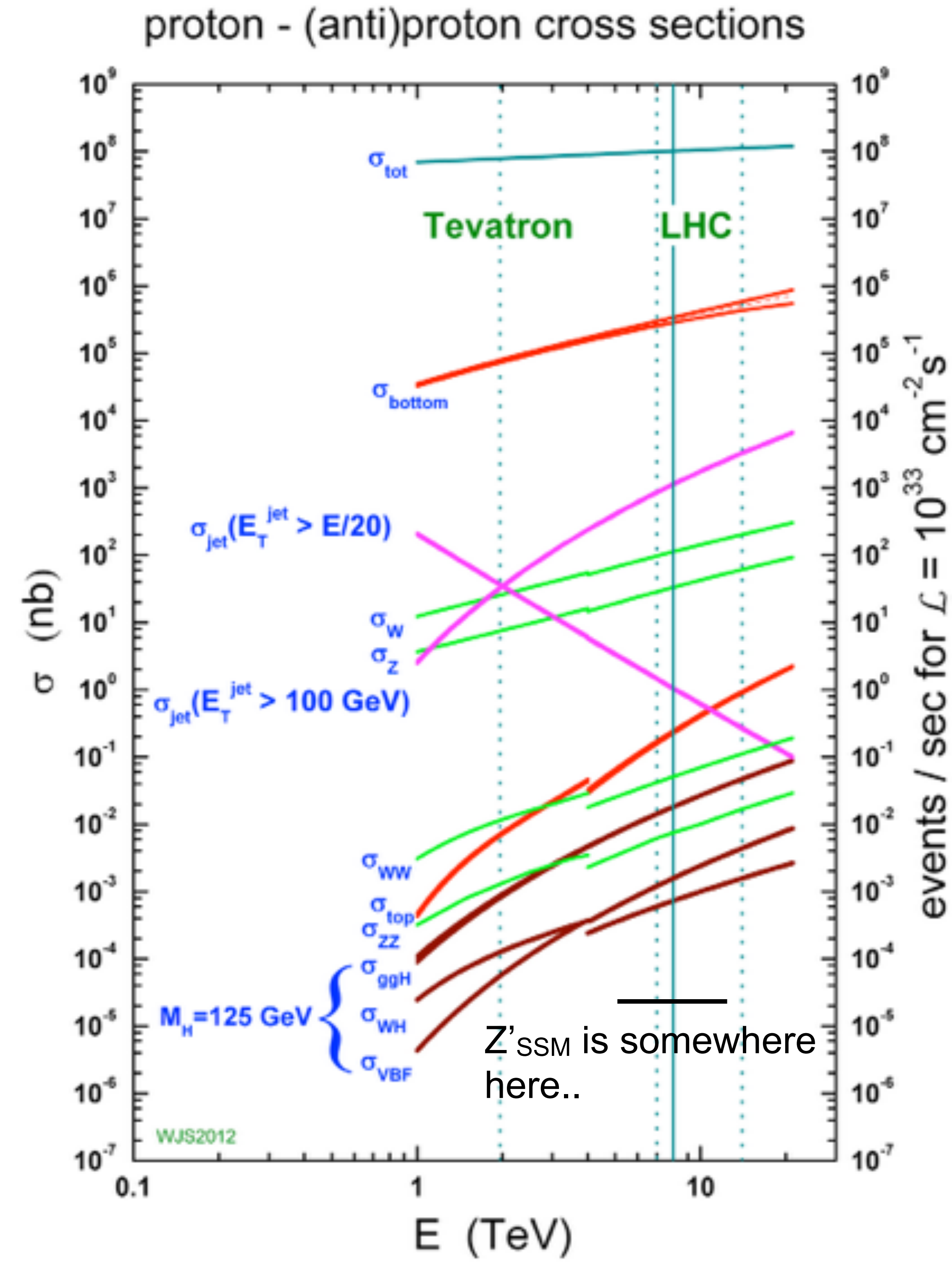
- let's compare few cases
  - jets (p_T>100GeV)
  - H(gluongluon)
  - Z'_{SSM}



LHC

Translate into # events (1 year)

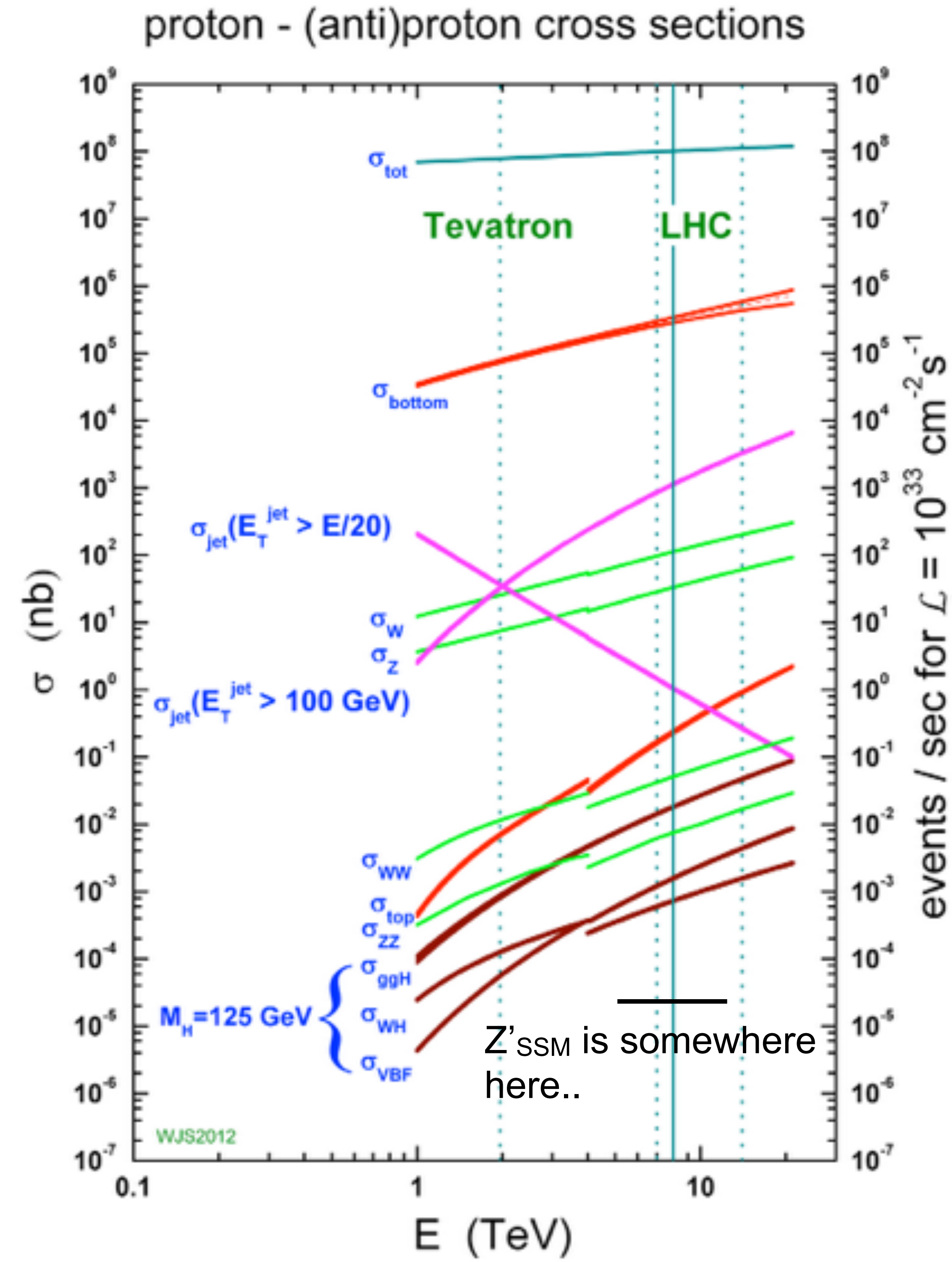
- let's compare few cases
  - jets (p_T>100GeV) ~ 10^{11}
  - H(gluongluon) ~ 10^5
  - Z'_{SSM} ~ 10^2



LHC

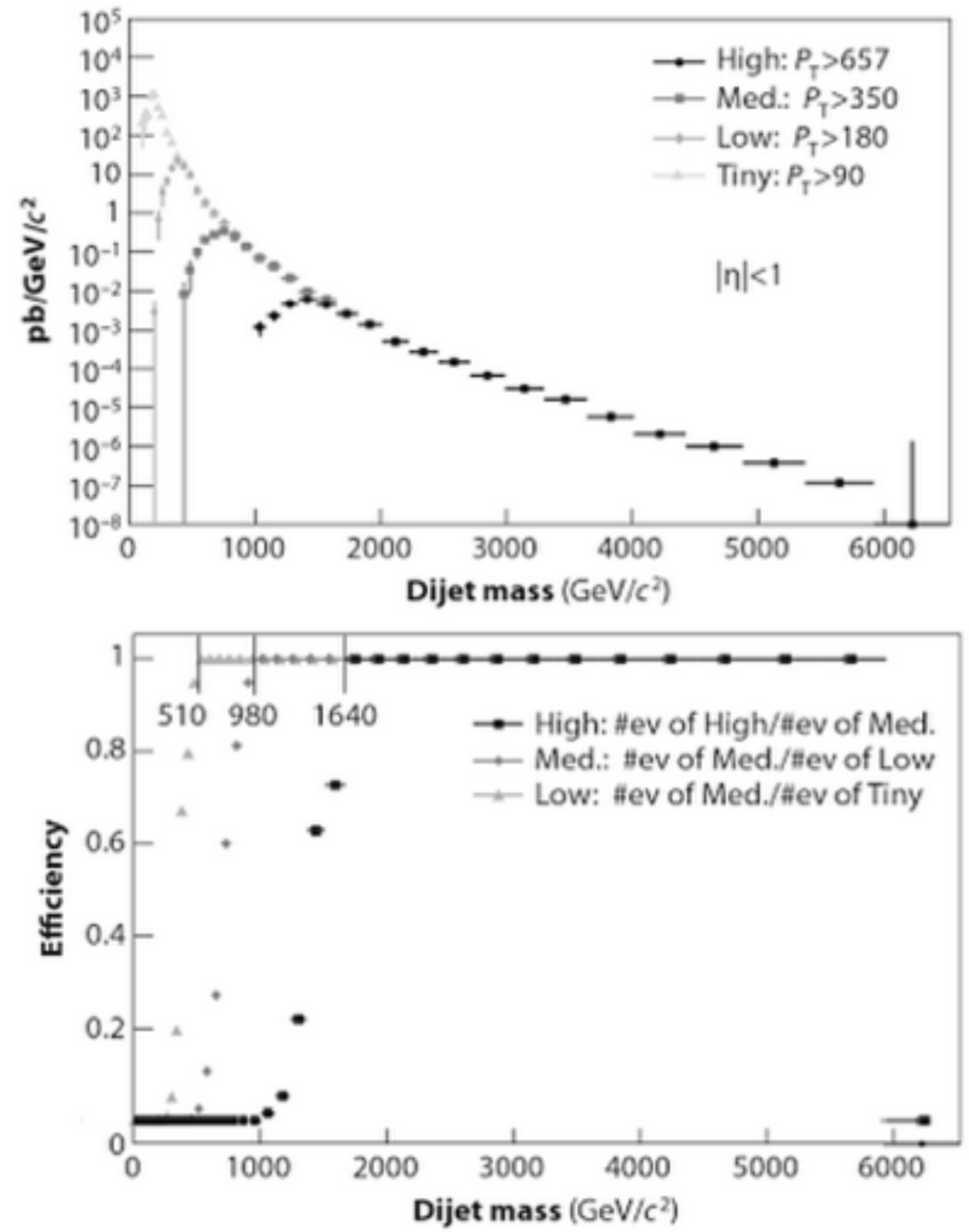
triggers

- for dilepton resonances no trigger issue
  - main contribution is from Z and W
- for dijet resonances need to cut tight, rate is too high
  - tipical threshold 1TeV in dijet mass.



TRIGGERS

- **Hardware** (fast, L1) and **software** (slow, HLT) triggers implemented
- **Low p_T triggers are kept for monitor purposes**
  - need to pre-scale them to have reasonable rate
- **Turn-on curve**: performance of triggers monitored using pre-scaled triggers
  - ratio of event passing tighter triggers monitors the efficiency of the trigger

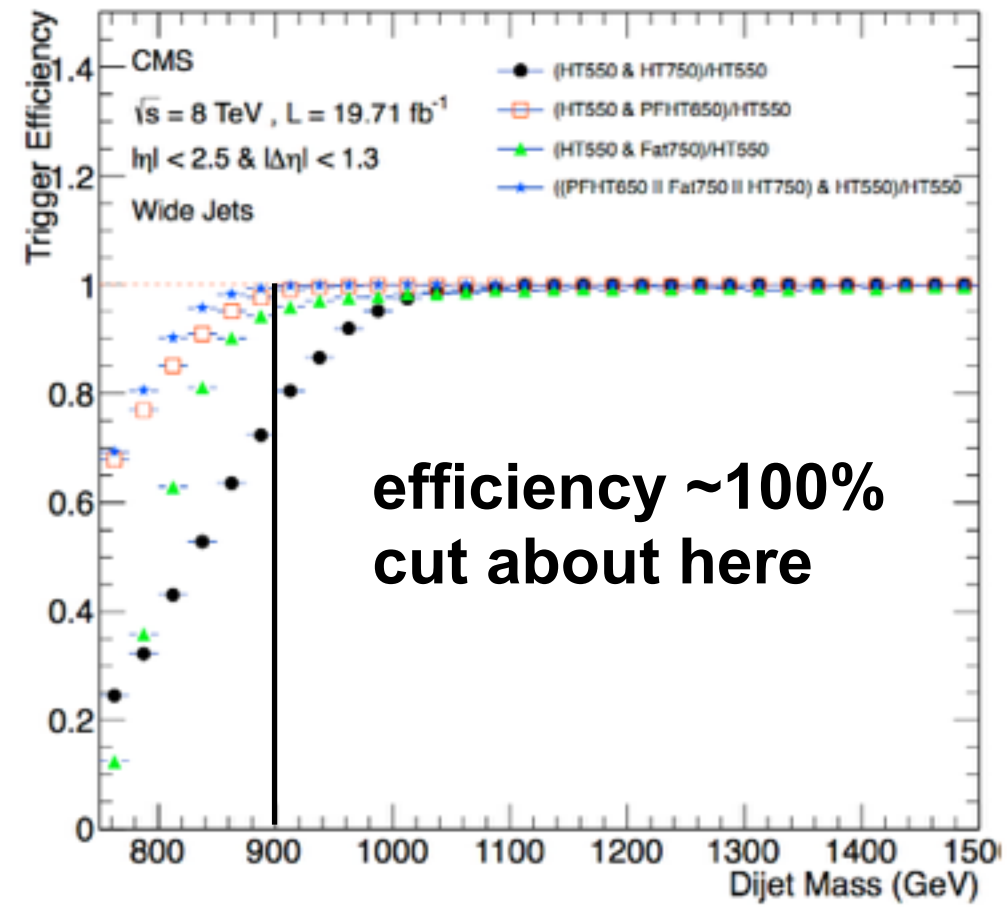


TRIGGER: WHERE TO SET CUTS

- **Triggering high mass object is not a big issue**
  - hard cut in p_T can be implemented with minor efficiency loss

- **Dijet is special**
  - jet background too high
  - tight cut required and physics potential is affected

- Selection criteria to **guarantee no efficiency loss from trigger**
  - tight requirement on dijet inv. mass
  - analysis cannot be performed below ~ 1 TeV



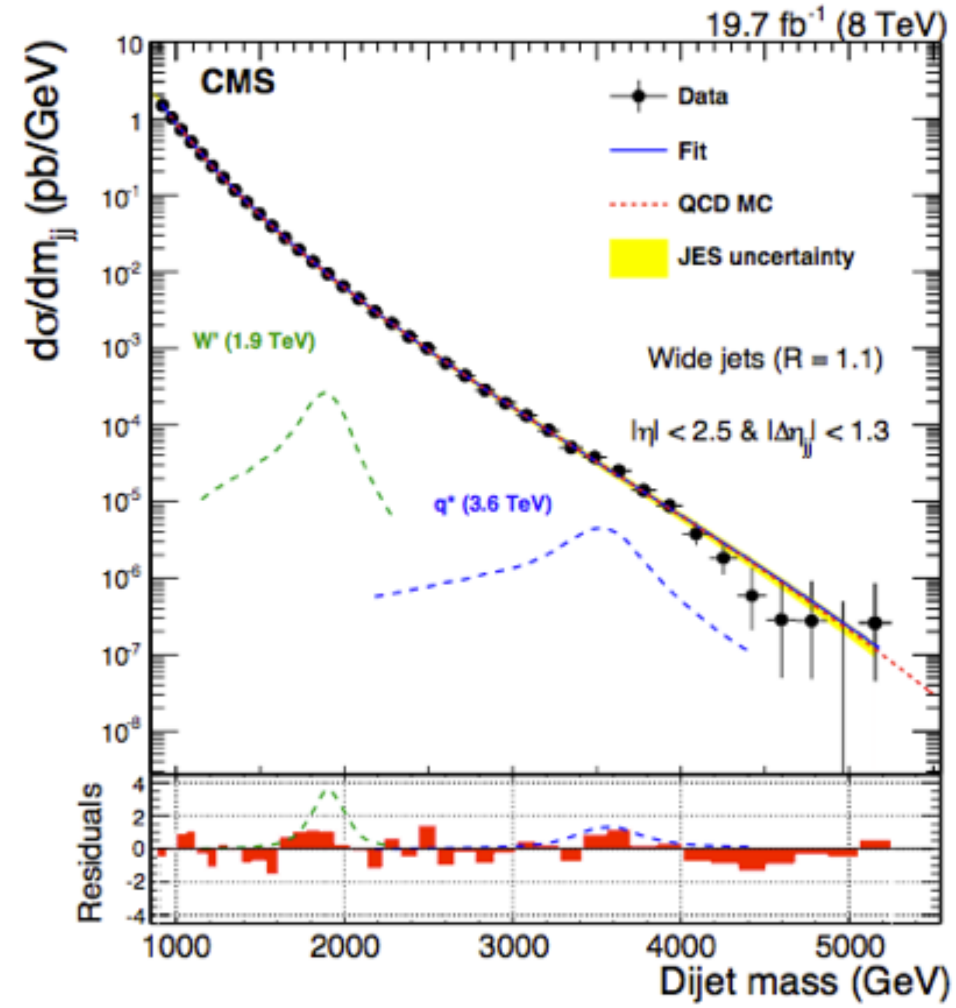
UL DETERMINATION

- Example of **binned likelihood** for diet analysis

$$L = \prod_i \frac{\lambda_i^{n_i} e^{-\lambda_i}}{n_i!}$$

where

- i is the bin number
- $\lambda_i = \mu N_i(S) + N_i(B)$
- $N_i(S)$ is the number of signal events for a given model
- $N_i(B)$ is the number of background events (can be either parameterized of coming from MC)



- detector uncertainties are taken into account in the likelihood by "marginalizing" (i.e. integrating out), assuming a log-normal distribution
- flat prior (bayesian) for cross section

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