SEARCHES FOR NEW HEAVY RESONANCES AT THE LHC

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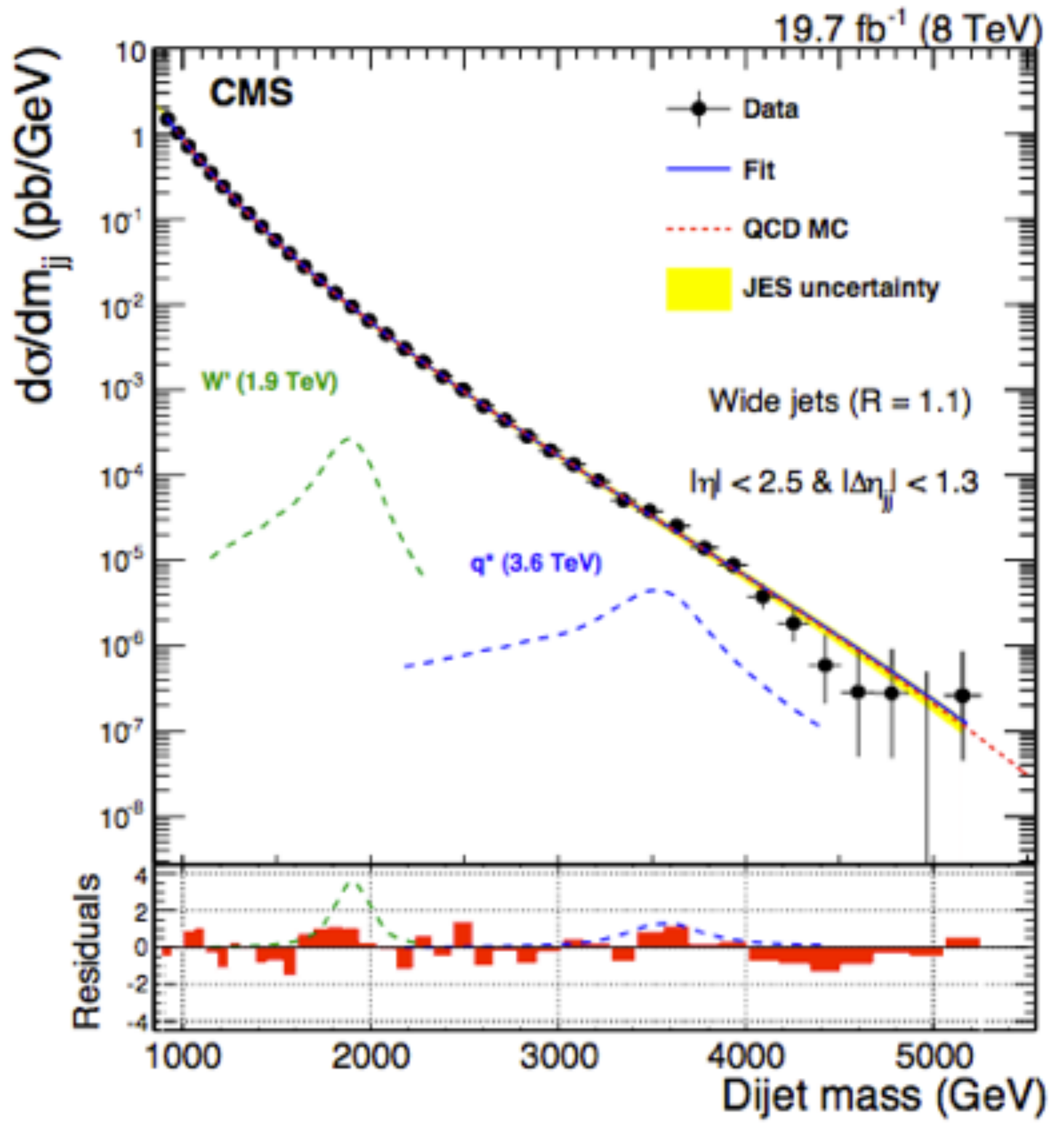
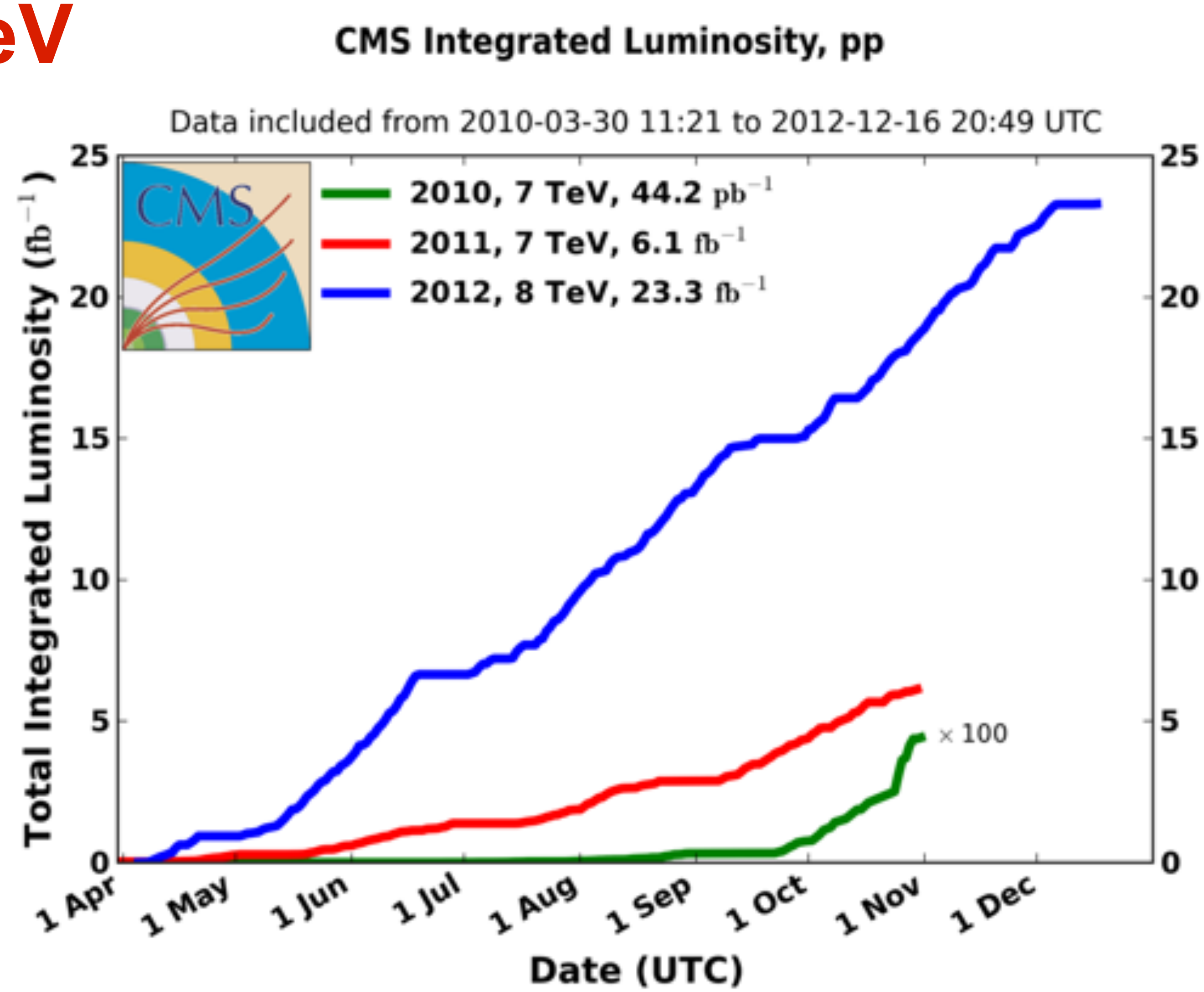
CONTENT

- Intro on **LHC detectors and object reconstruction**
- Intro on **main issues in resonance search**
- **Analysis in a nutshell**
- **High p_T objects**
  - trigger
  - performance of different objects
  - resolution estimate
  - efficiency estimate
- **Signal extraction**
  - statistical treatment
  - main uncertainties
  - UL determination
- **Extrapolation at higher lumi** and center of mass



LHC

- **pp collisions at 7TeV and 8TeV**
- **great performance, beyond expectations**
  - luminosity peak ~8 10^{33} $cm^{-2}s^{-1}$
  - 300 pb^{-1}/day
  - 50 ns bunch spacing

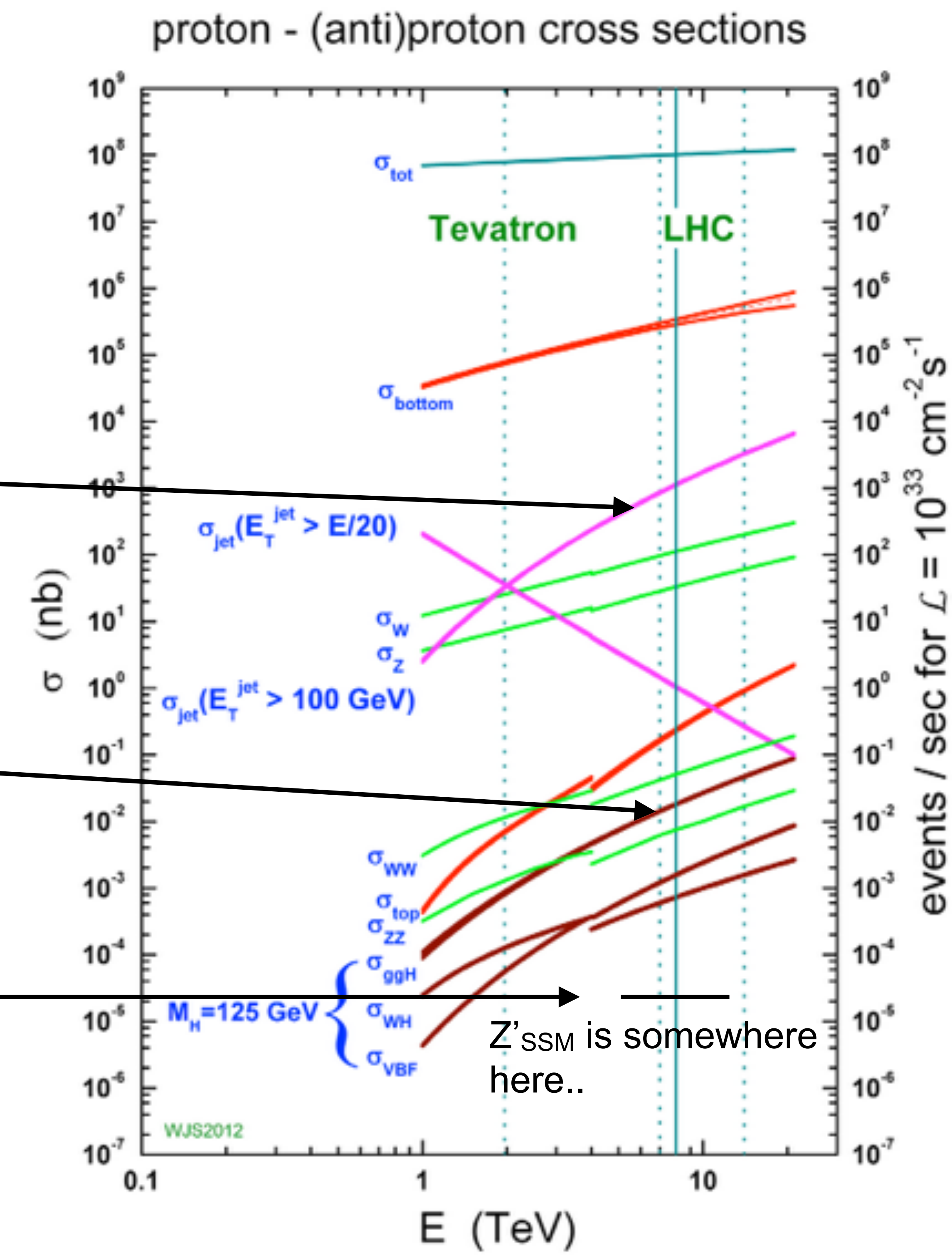


- **~23 fb^{-1} @ 8TeV** recorded (+~6fb^{-1}@ 7TeV)
  - **results shown with ~20 fb^{-1} at 8 TeV**
- **~ <20 collisions> per crossing**

LHC

Cross sections

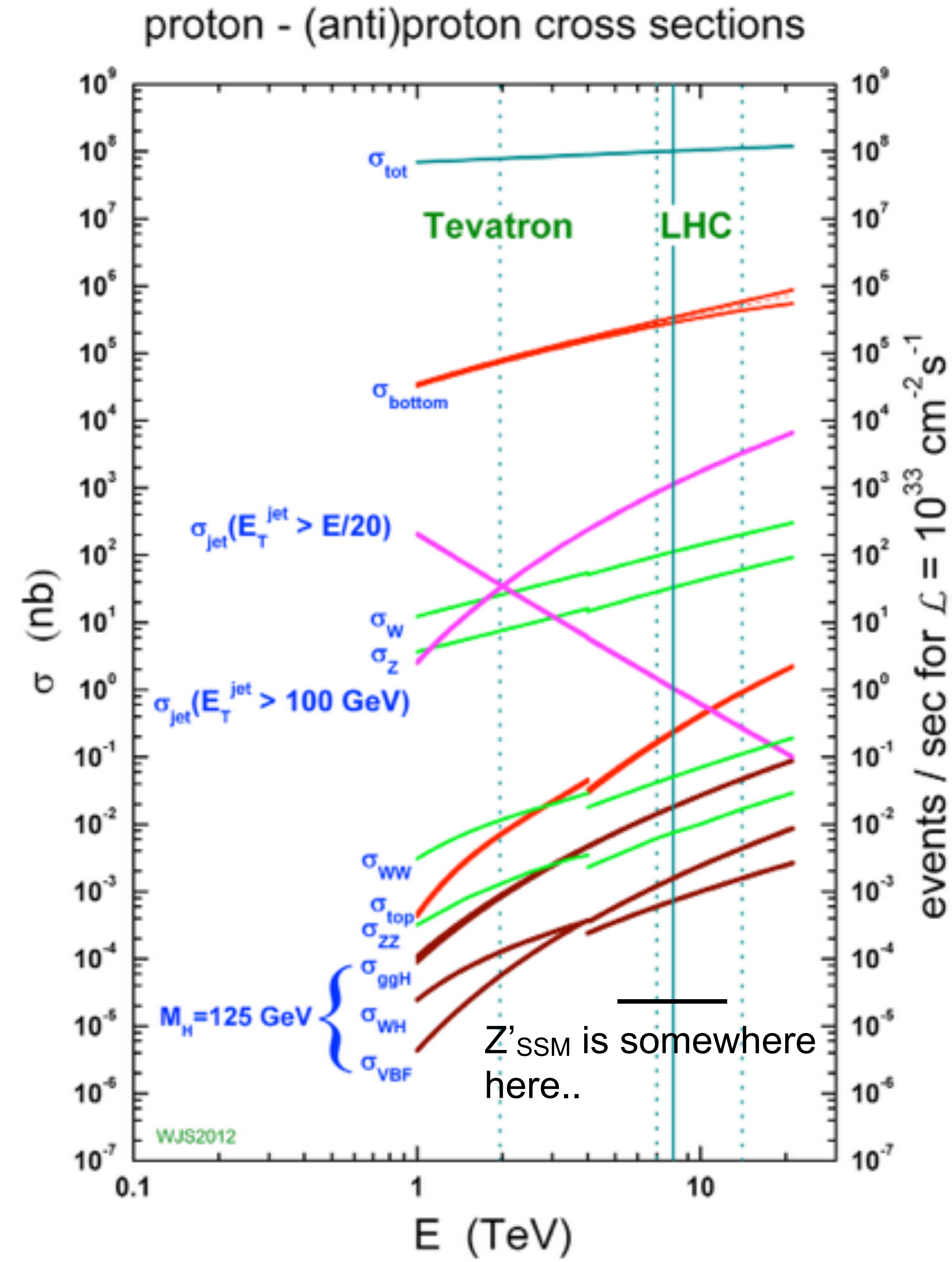
- let's compare few cases
  - jets (p_T>100GeV)
  - H(gluongluon)
  - Z'_{SSM}



LHC

Translate into # events (1 year)

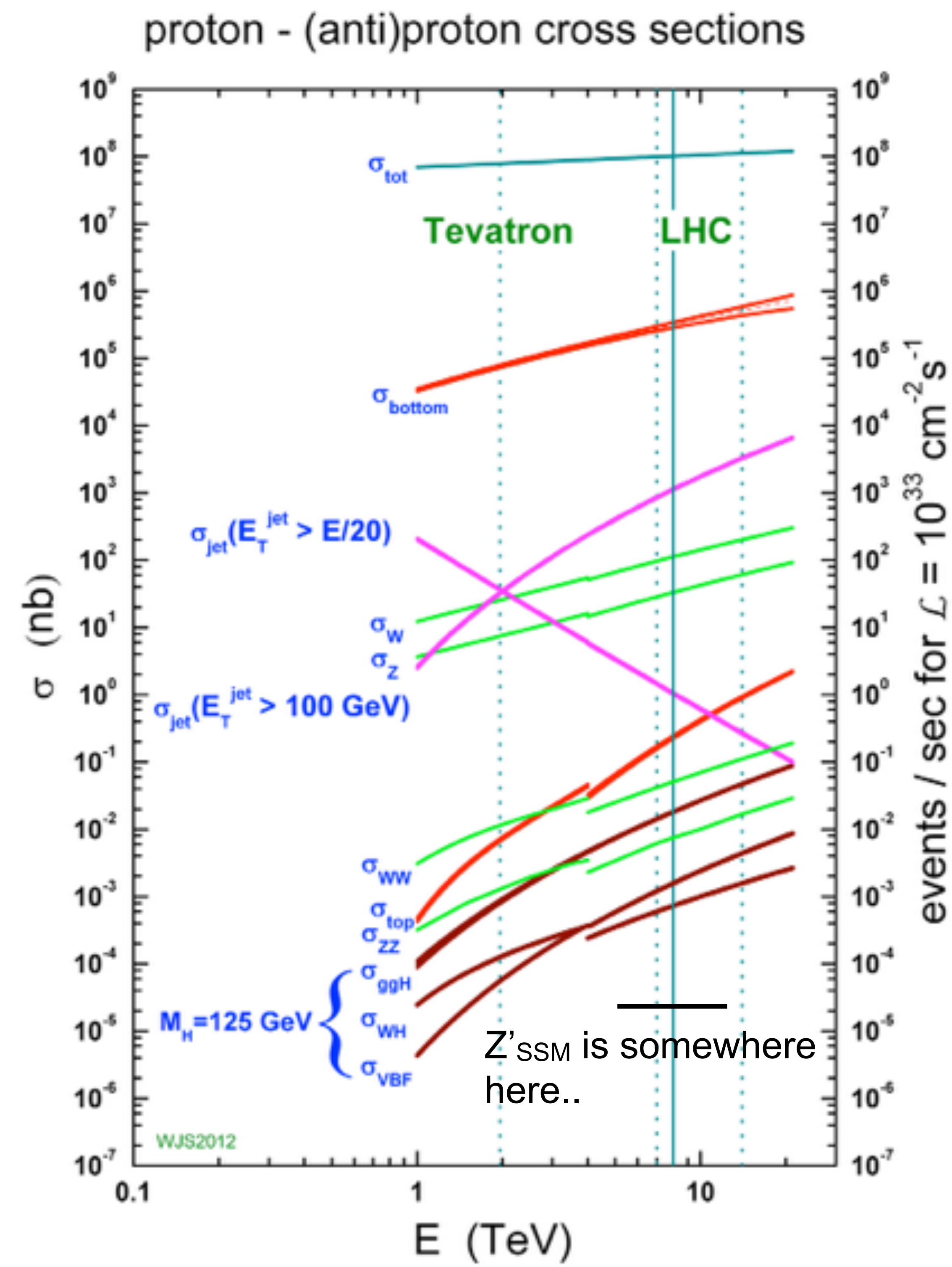
- let's compare few cases
  - jets (p_T>100GeV) ~ 10^{11}
  - H(gluongluon) ~ 10^5
  - Z'_{SSM} ~ 10^2



LHC

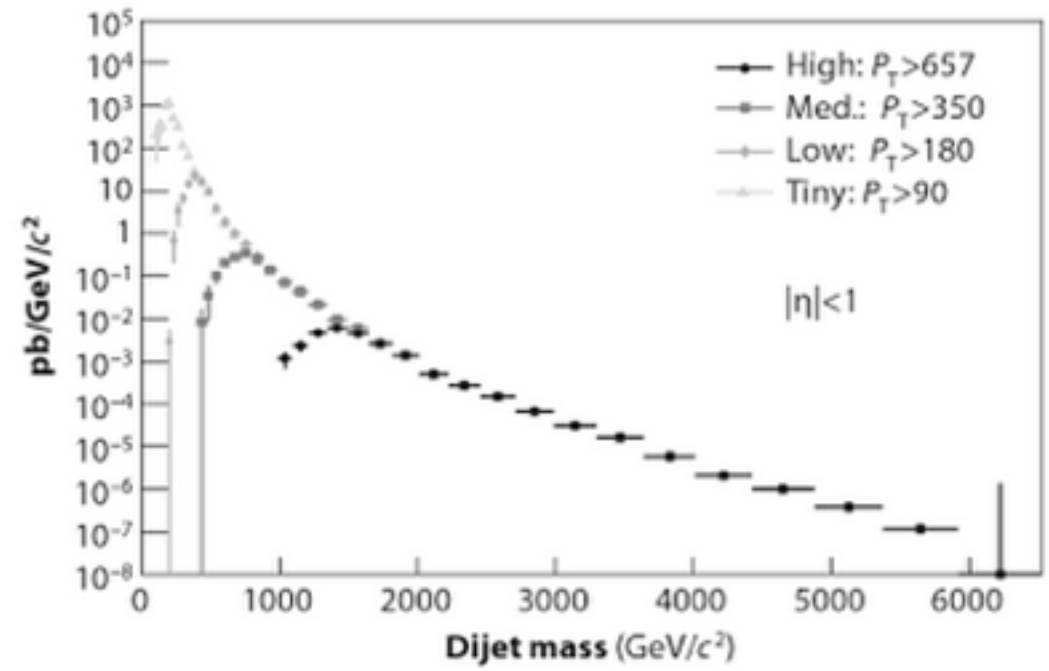
triggers

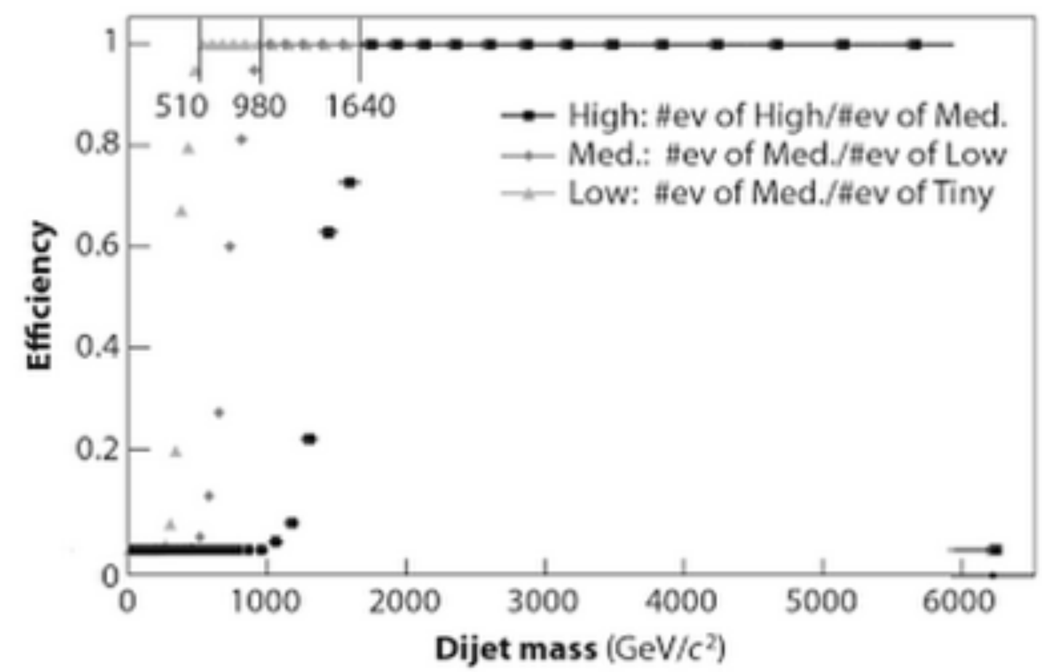
- for dilepton resonances no trigger issue
  - main contribution is from Z and W
- for dijet resonances need to cut tight, rate is too high
  - tipical threshold 1TeV in dijet mass.



TRIGGERS

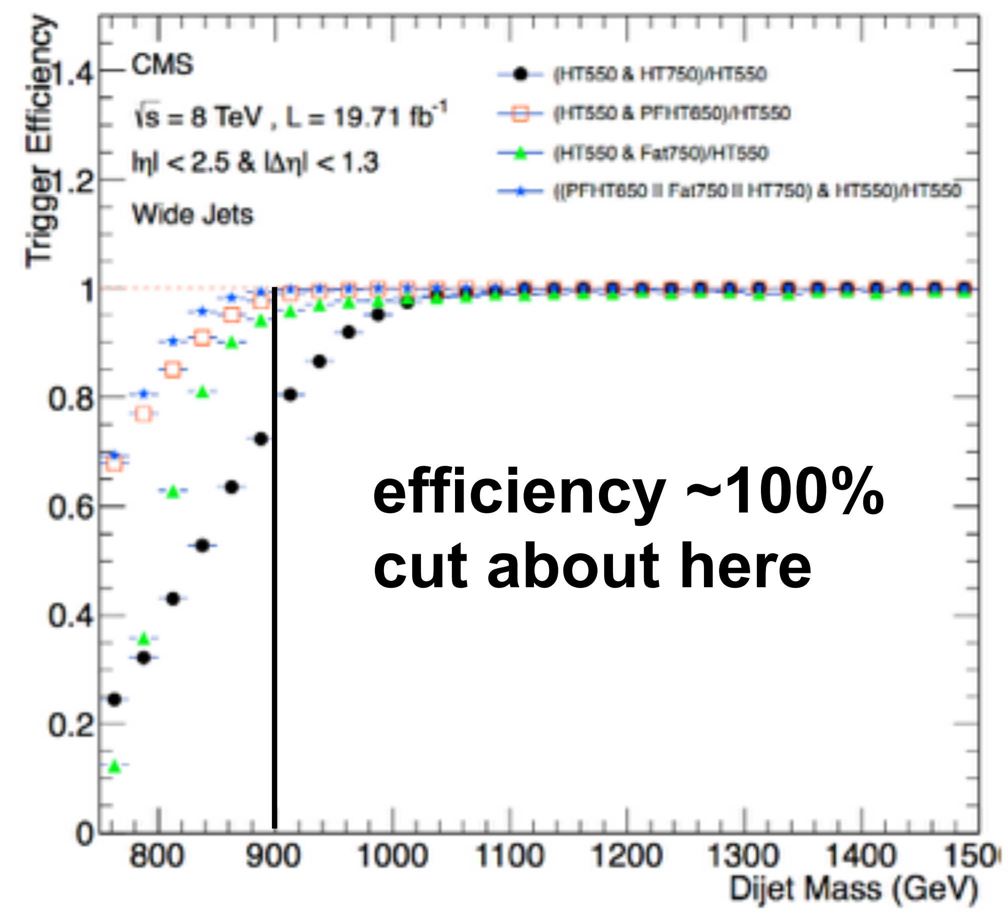
- **Hardware** (fast, L1) and **software** (slow, HLT) triggers implemented
- **Low p_T triggers are kept for monitor purposes**
  - need to pre-scale them to have reasonable rate
- **Turn-on curve**: performance of triggers monitored using pre-scaled triggers
  - ratio of event passing tighter triggers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

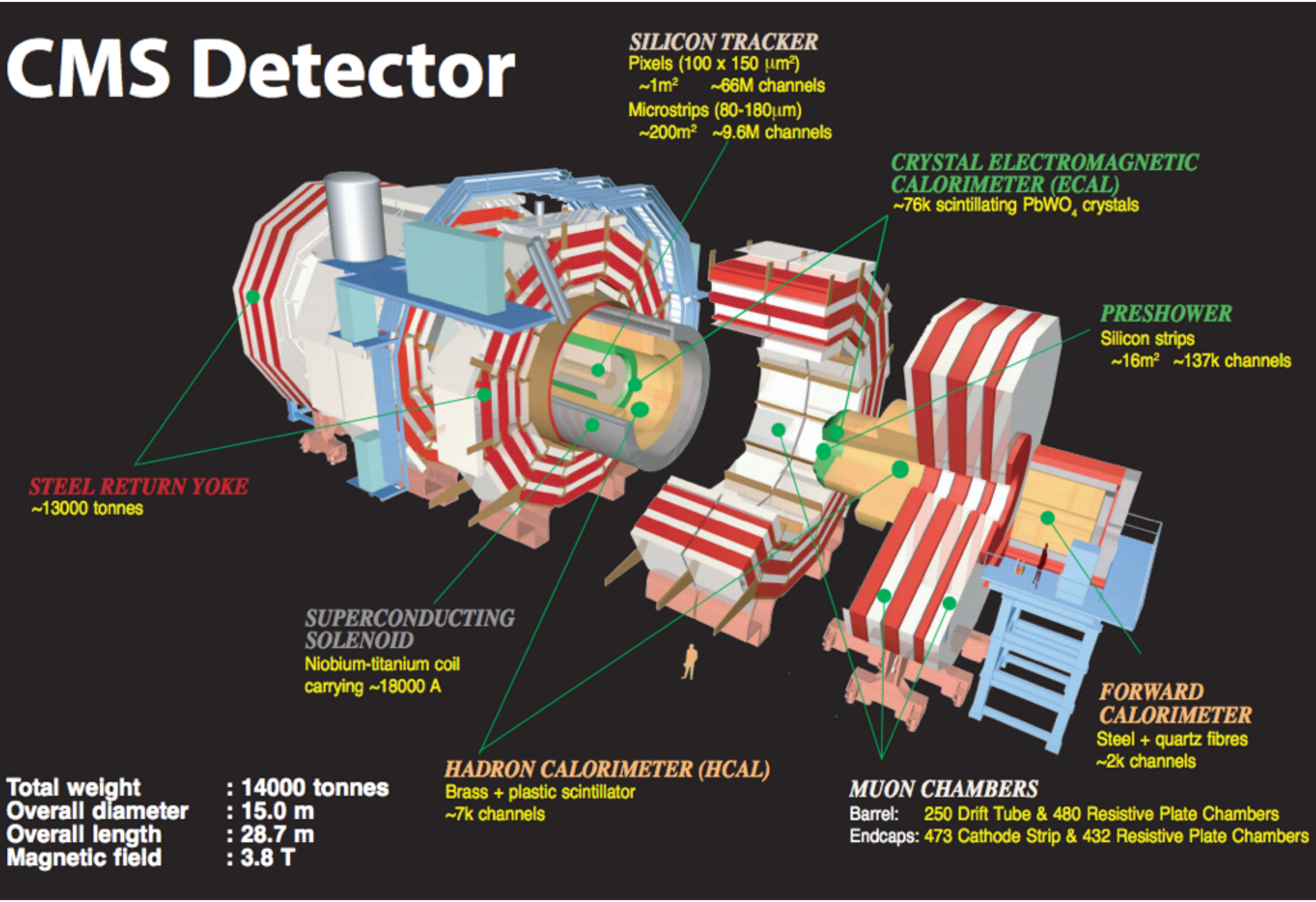


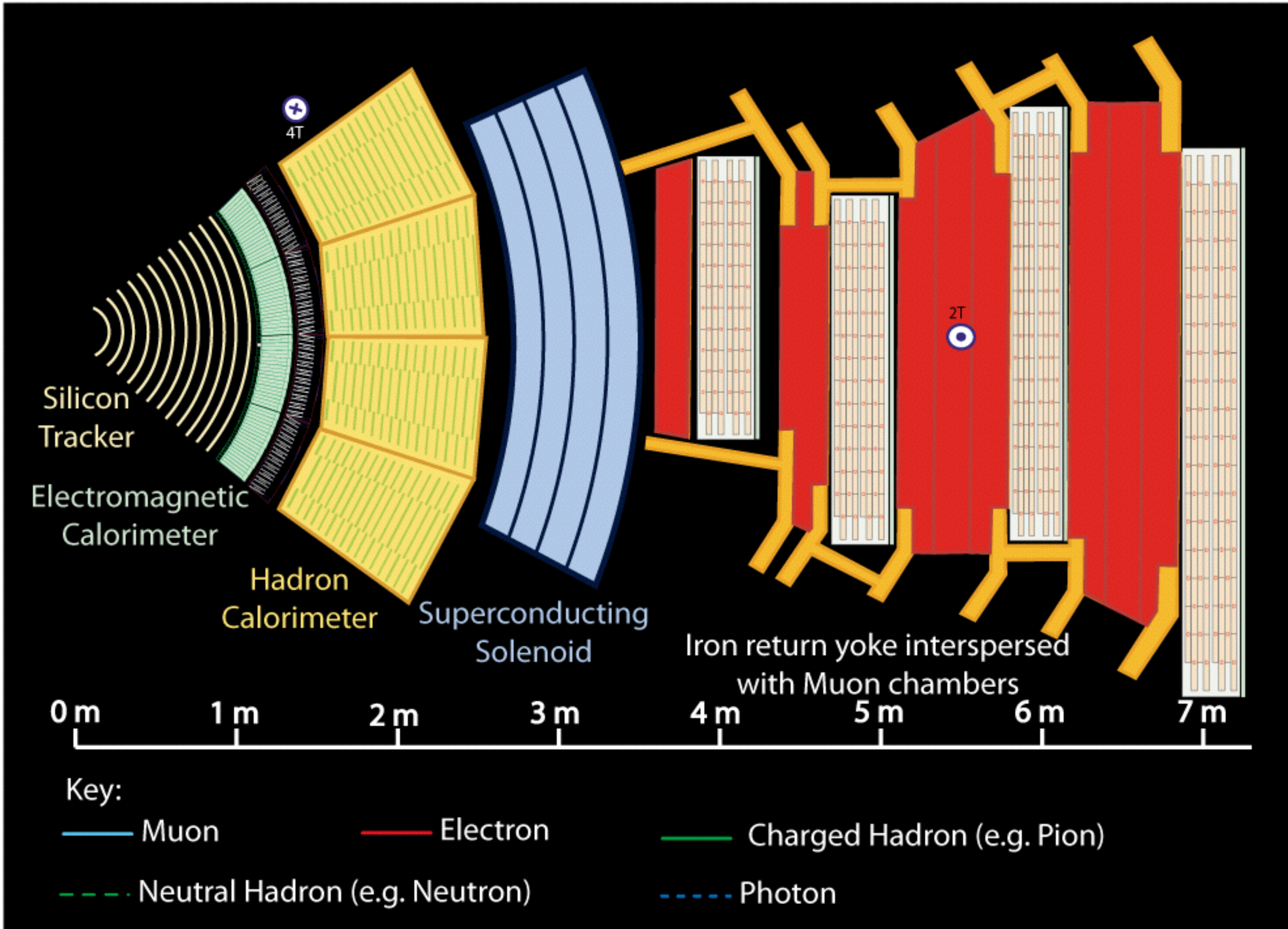


Trigger: Where to Set Cuts

- **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




CMS Detector
SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² ~66M channels
Microstrips (80-180μm)
~200m² ~9.6M channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76k scintillating PbWO₄ crystals
PRESHOWER
Silicon strips
~16m² ~137k channels
STEEL RETURN YOKE
~13000 tonnes
SUPERCONDUCTING SOLENOID
Niobium-titanium coil carrying ~18000 A
FORWARD CALORIMETER
Steel + quartz fibres
~2k channels
HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
~7k channels
MUON CHAMBERS
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 473 Cathode Strip & 432 Resistive Plate Chambers
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:
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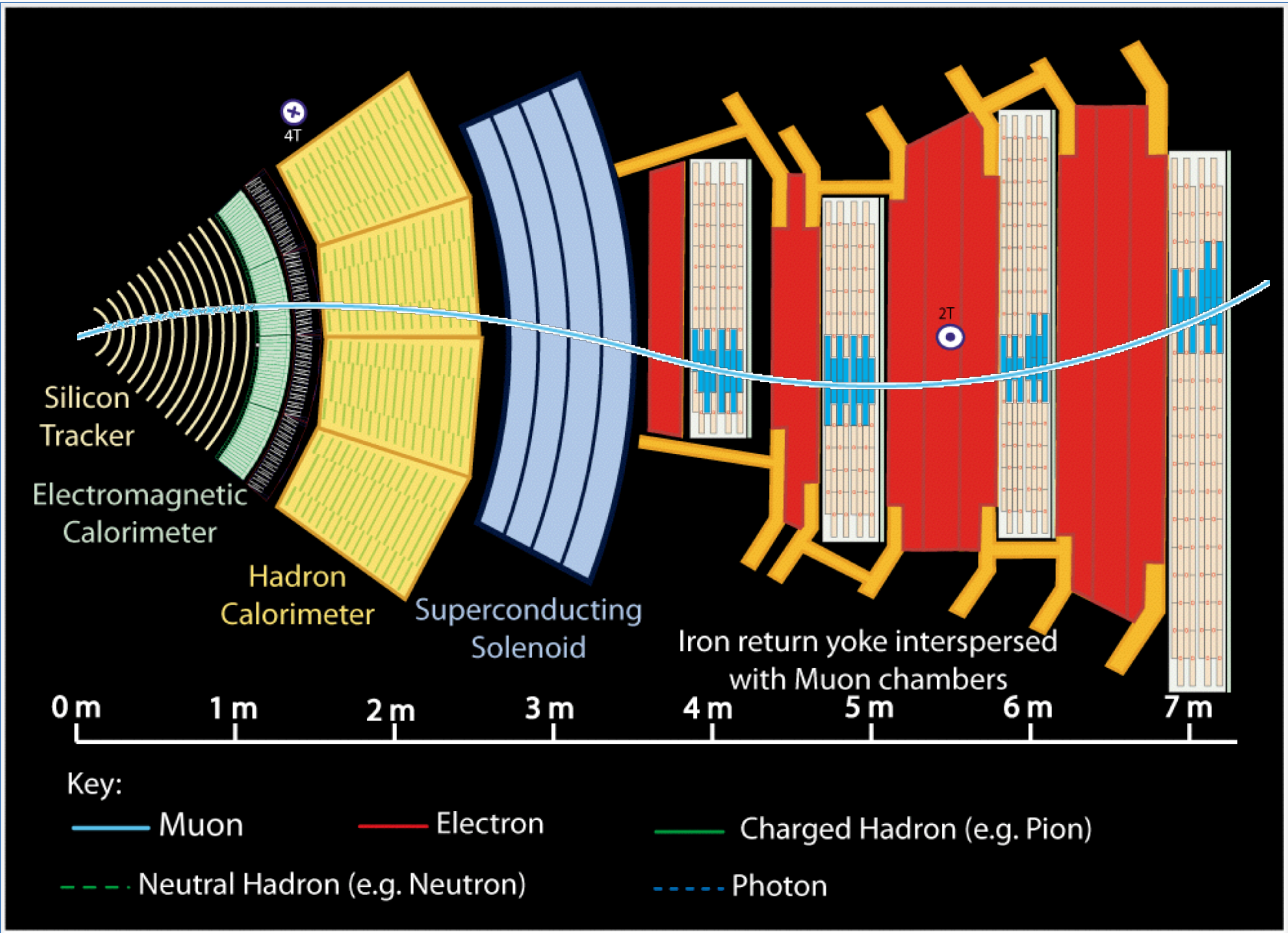
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon



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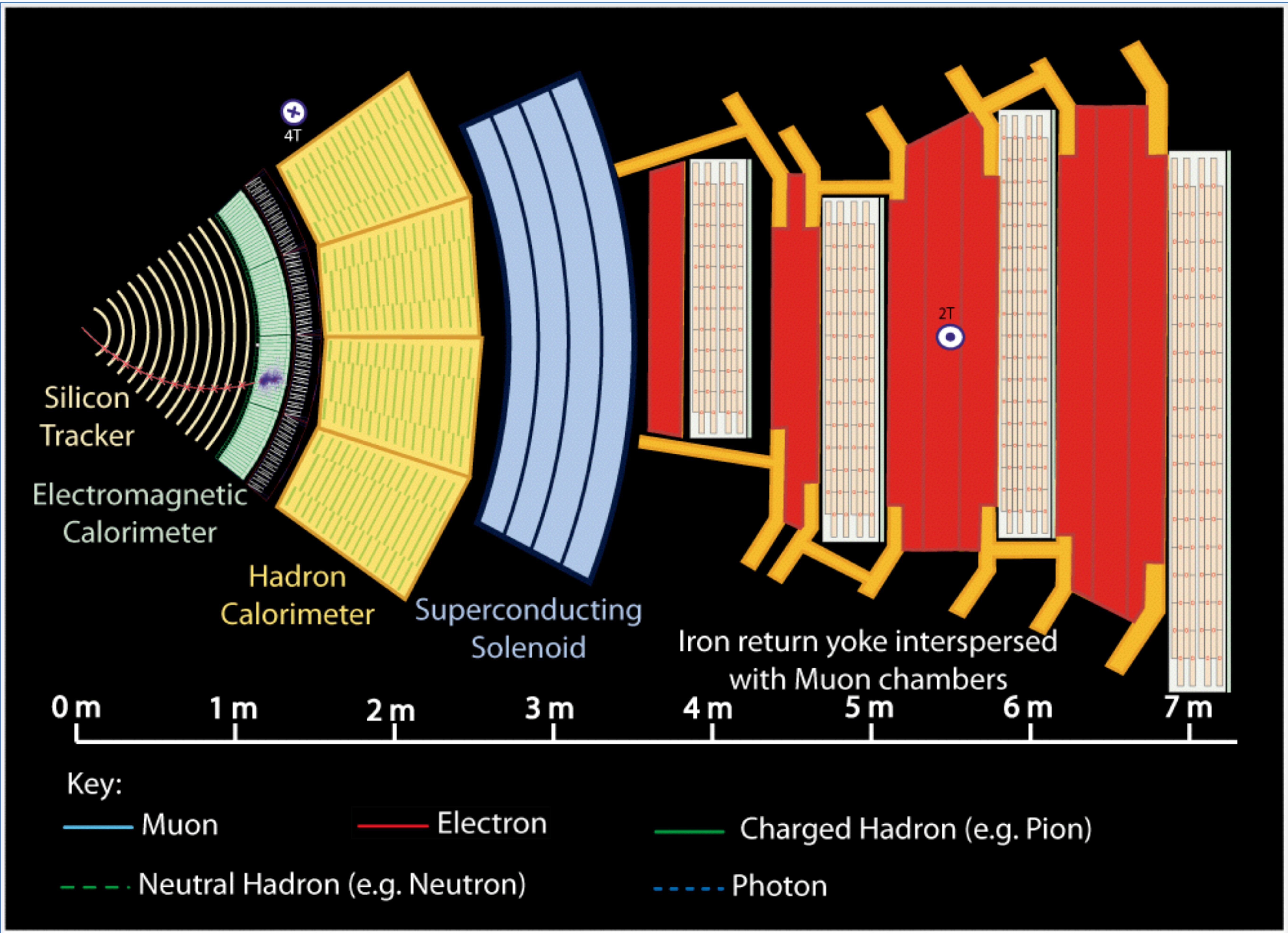
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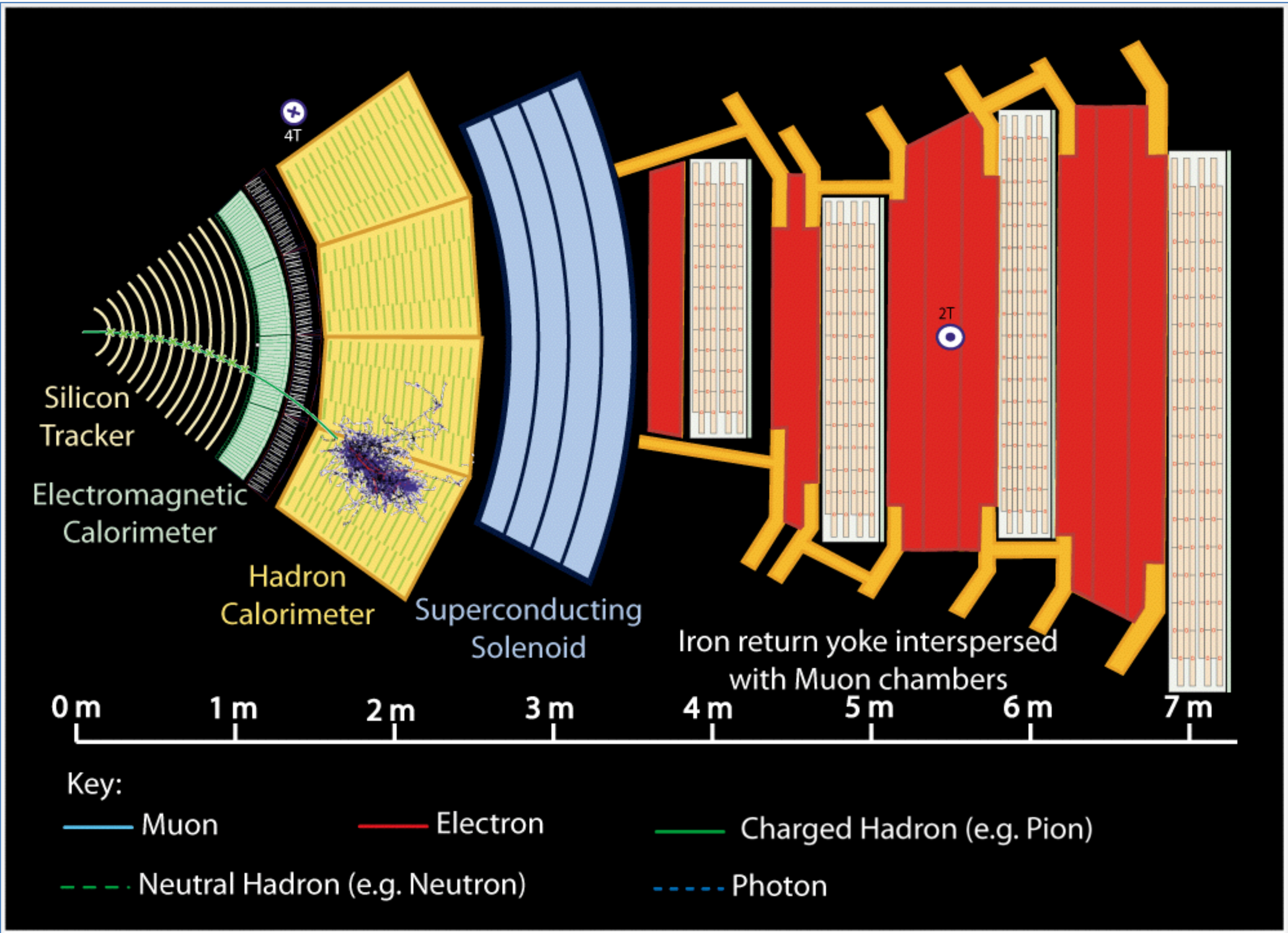
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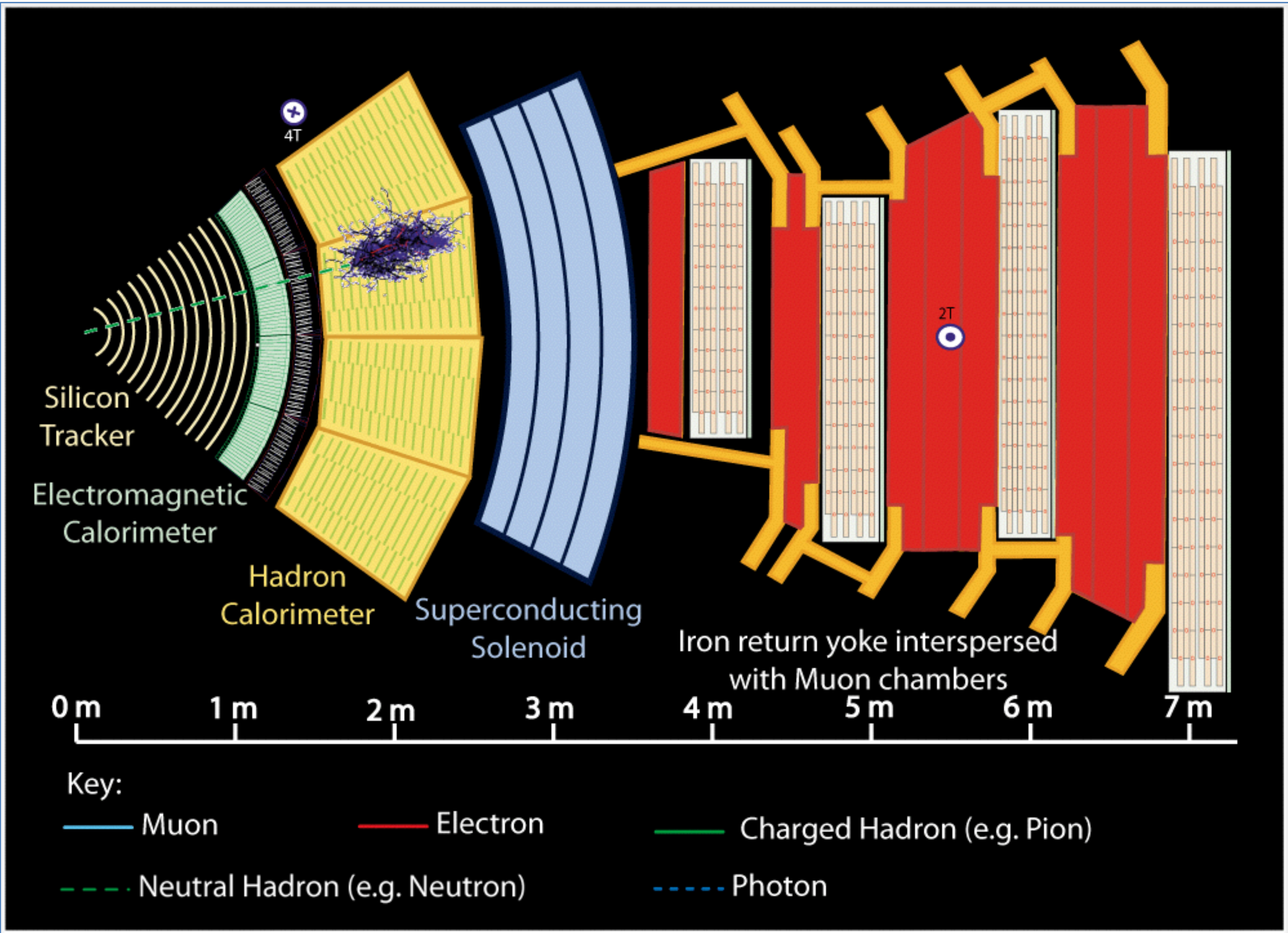
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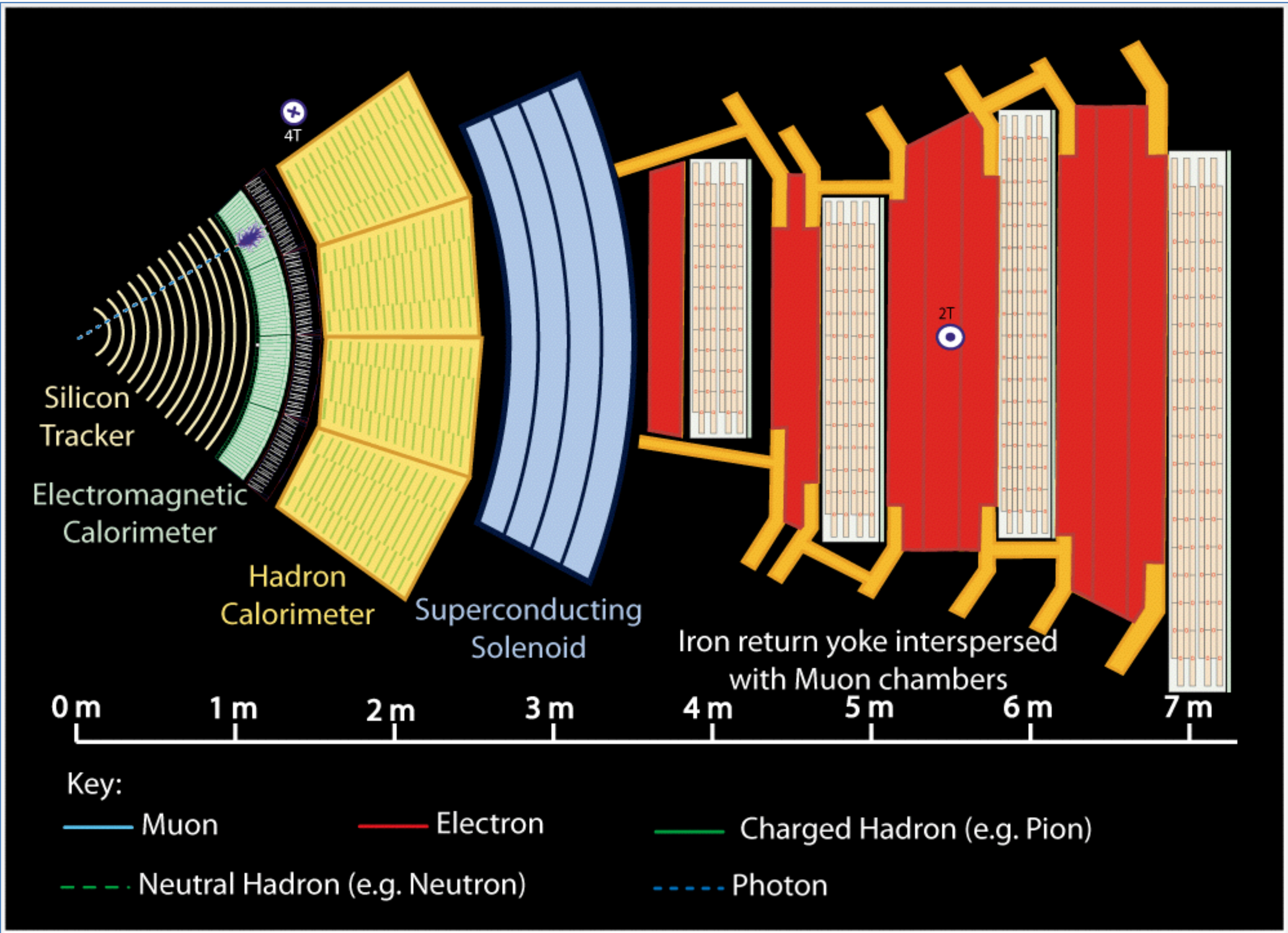
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Analysis in a Nutshell

1. **Loose-enough trigger**
   - not so complicated since momenta are large
2. **Kinematic selection as model-independent as possible**
   - do not design selection based on a particular model
   - be loose in kinematics (usually p_T decay products and
3. **Reconstruct invariant mass**
   - to be carefully calibrated
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

TAGGING A HIGH MASS RESONANCE

- Invariant mass for **resonance decaying to two light (~zero mass) objects**

$$M = \sqrt{2E_1 E_2(1 - cos\theta)}$$

TAGGING A HIGH MASS RESONANCE

- Invariant mass for **resonance decaying to two light (~zero mass) objects**

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

- Impact on **resolution**

dominant

electrons, photons, jets:
energy measurement dominated by calorimeters
muons:
energy measurement dominated by tracking

in general not relevant

electrons, muons:
direction from tracking
jets:
subdominant wrt energy
photons:
mildly impacted by primary vertex position

TAGGING A HIGH MASS RESONANCE

- Invariant mass for **resonance decaying to two light (~zero mass) objects**

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

- Case for **diboson resonances more complicated** (mass of decay products != 0)
- Also here energy calibration counts more than p direction
- **WV** is special.
  - an use kinematic constraints (impose mass of the W to determine neutrino direction and improve resolution)

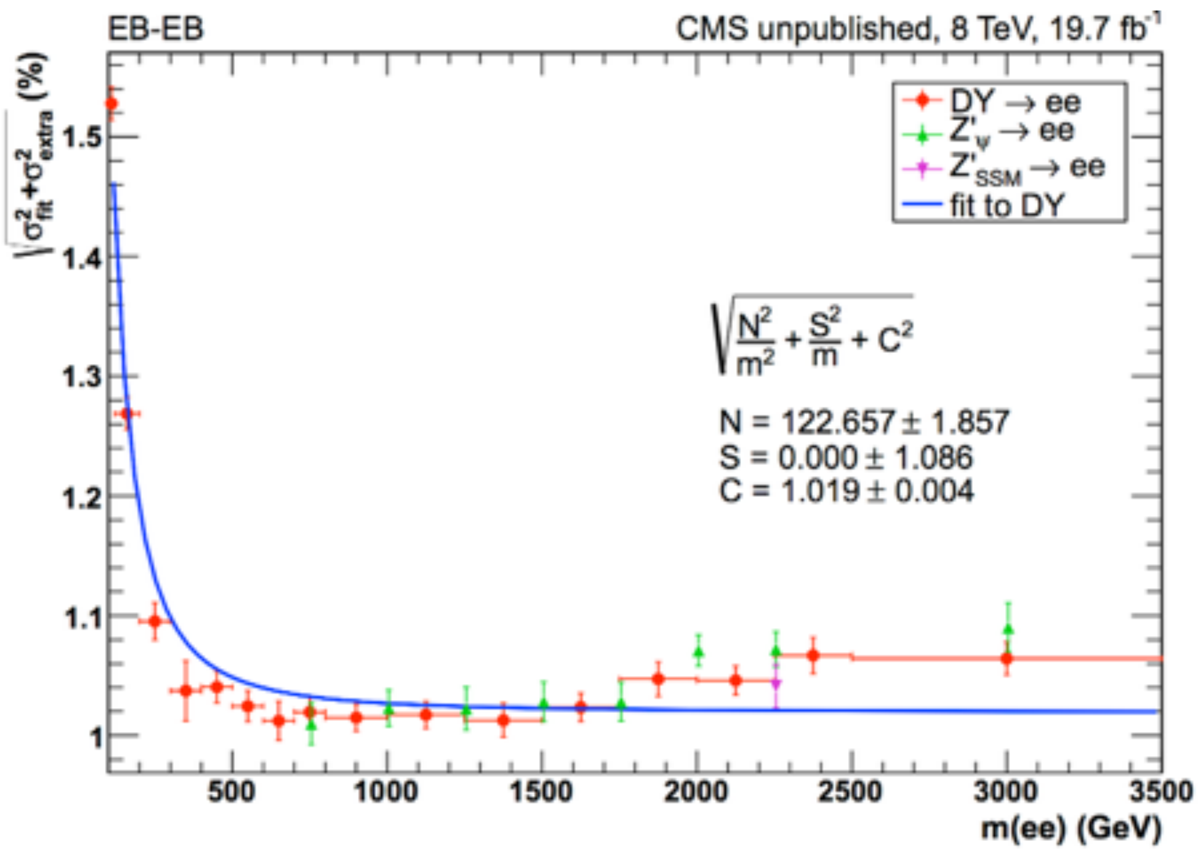
RECONSTRUCTING HIGH PT OBJECTS

- **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

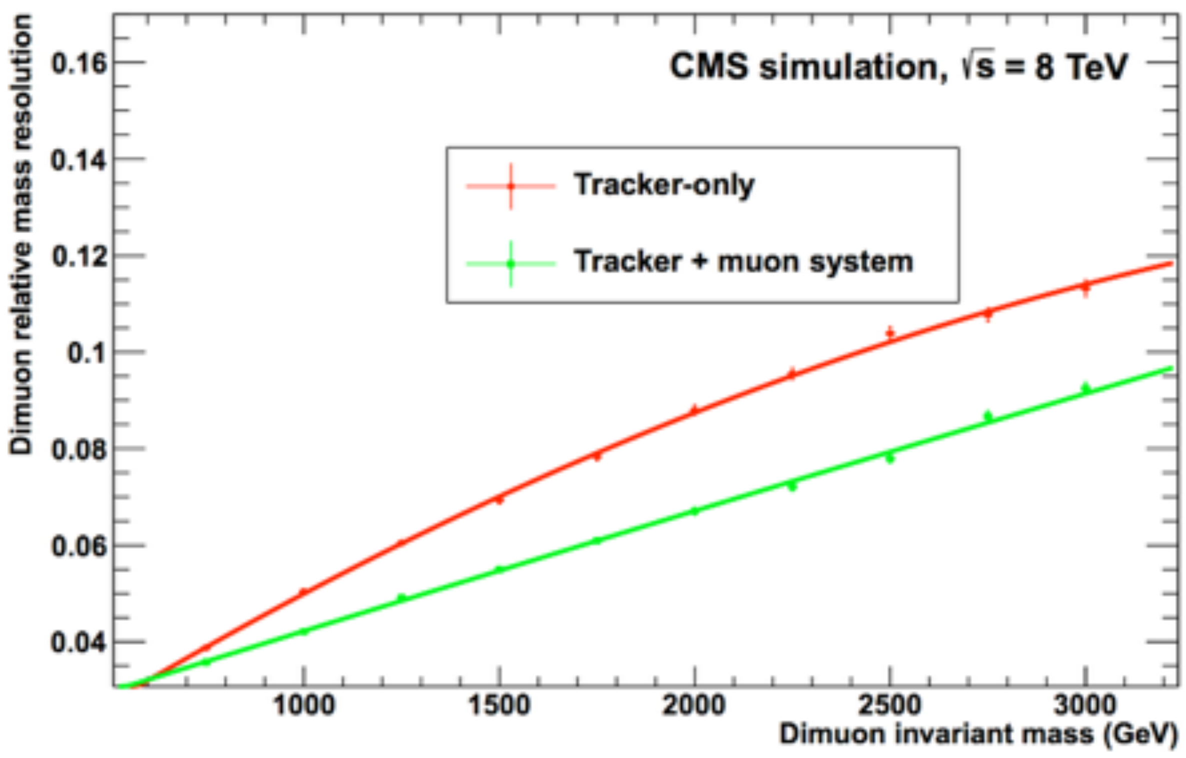
Resolution vs P_T: Electrons

- 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**



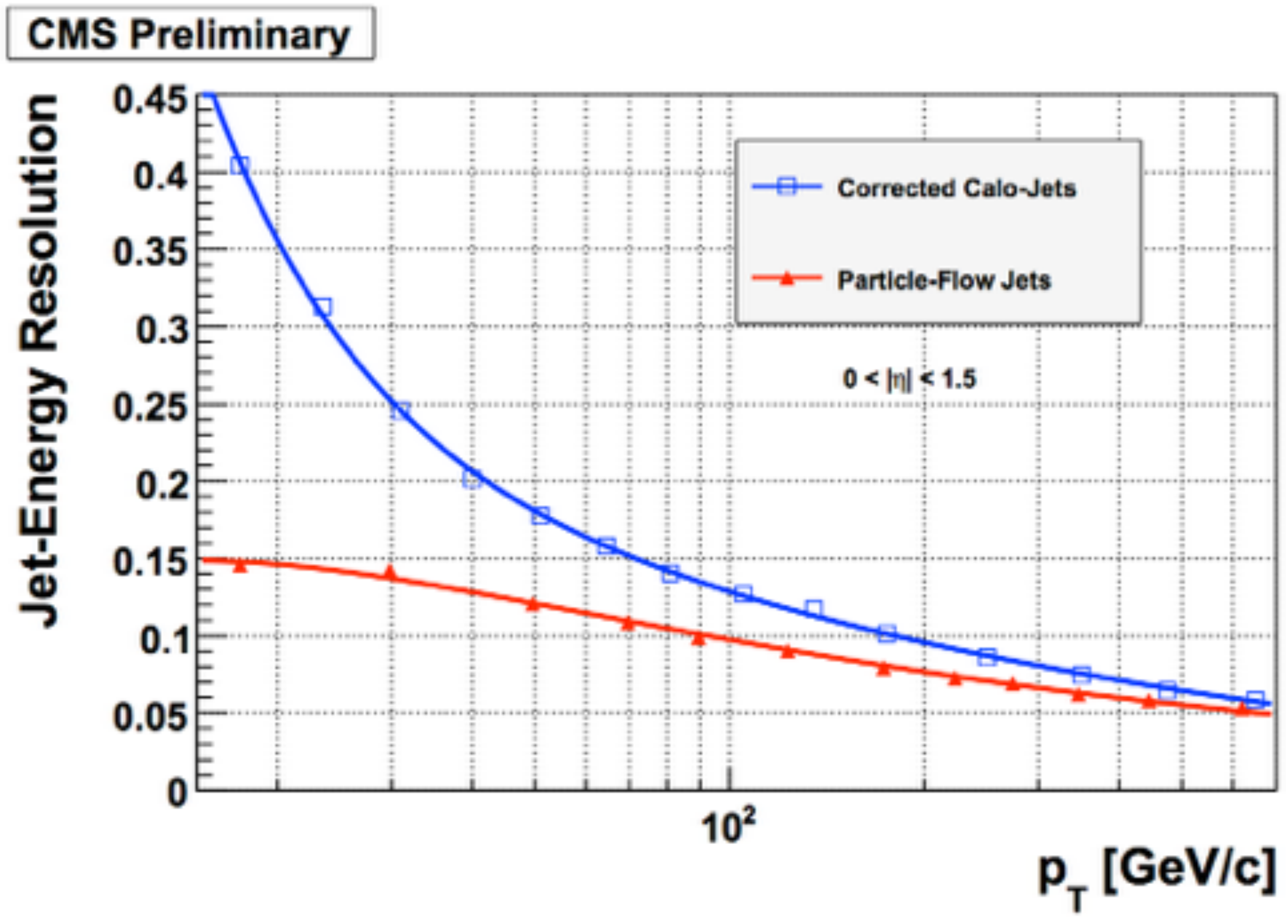
RESOLUTION VS P_T: MUONS

- **Resolution worsens vs p_T** (as for every track)
- At beginning of data taking, **dominated by other systematic effects** (e.g. detector alignment)

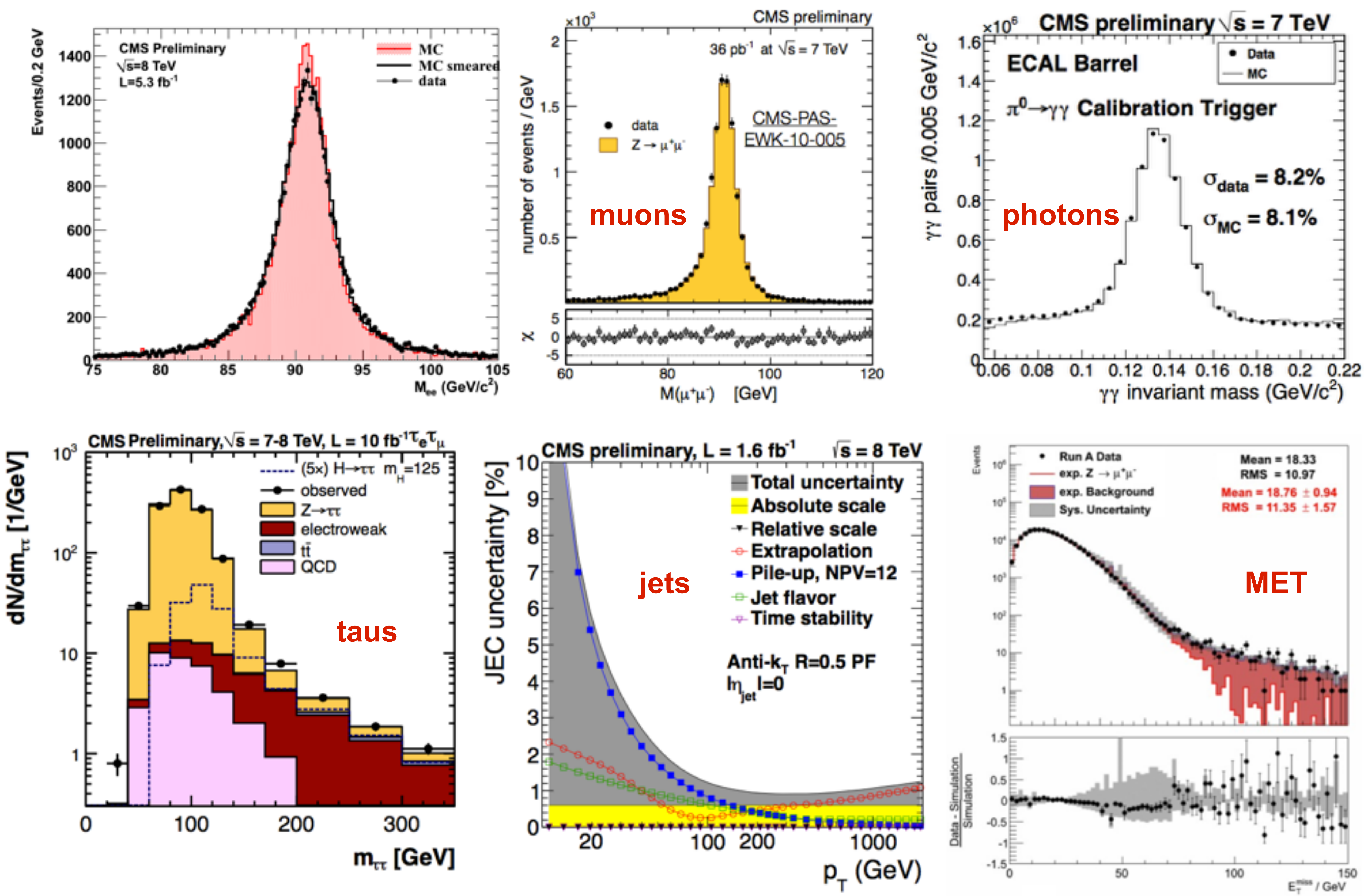


Resolution vs P_T: Jets

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



Calibrating Objects on Data



Calibrating Objects on Data

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

CALIBRATING OBJECTS ON DATA

electrons

scale known to 0.5%

muons

scale known to bet
than

pho

But this is for particles from SM processes!

Heavy resonances produce **very energetic objects!**

ide ~70%
efficiency and ~5% fake
rate

(b-)jets

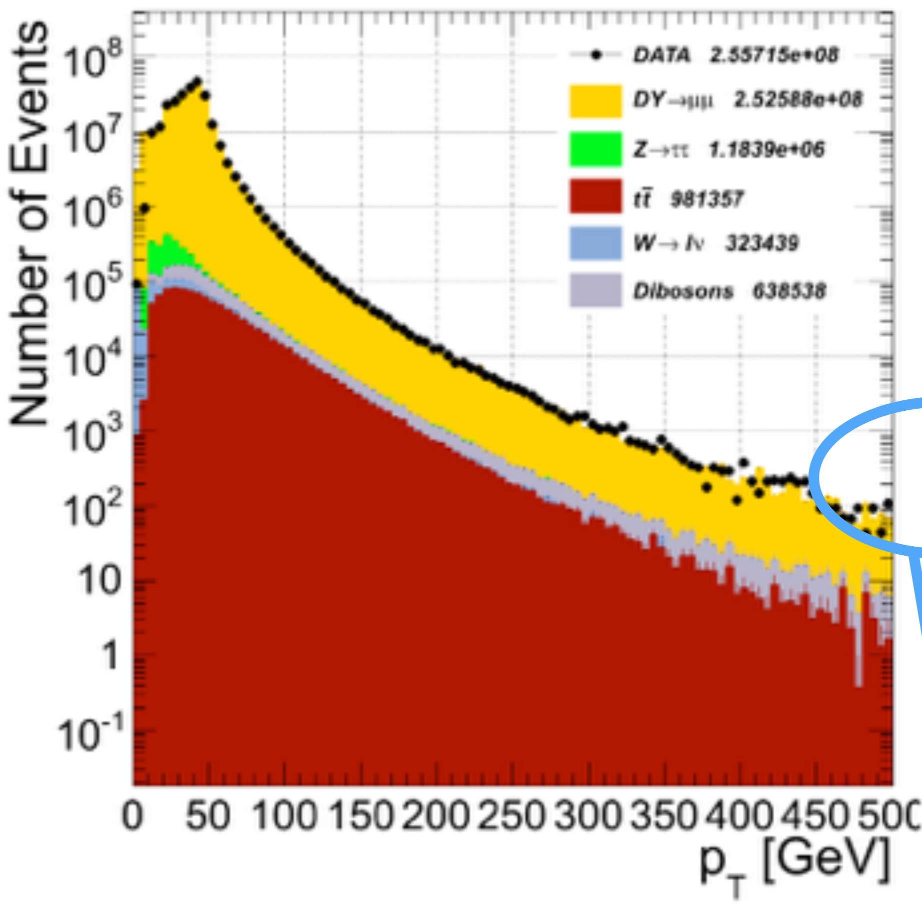
scale known to 1%-5%
(p_T and η dep.)

MET

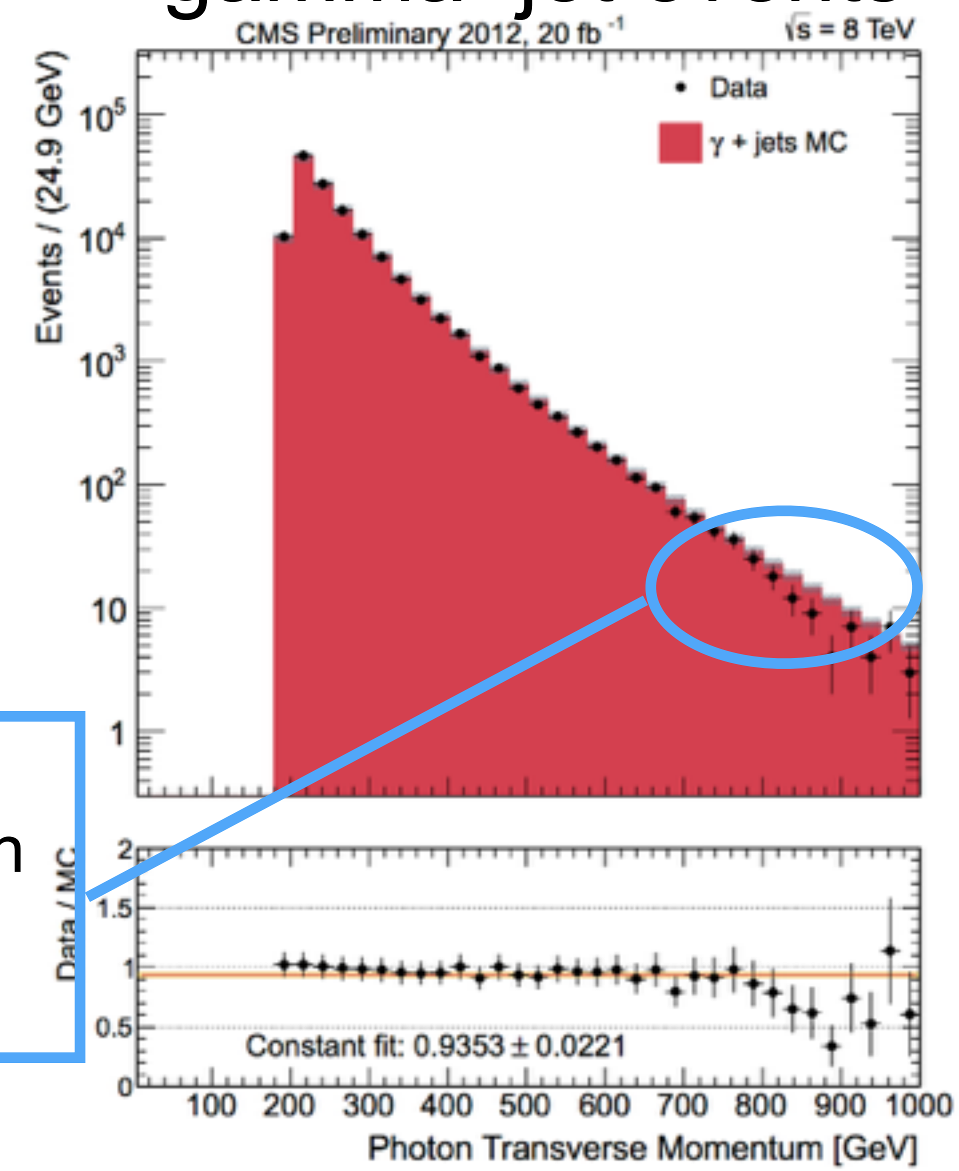
Nice agreement with simulation
Deep understanding of impact of PU

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!

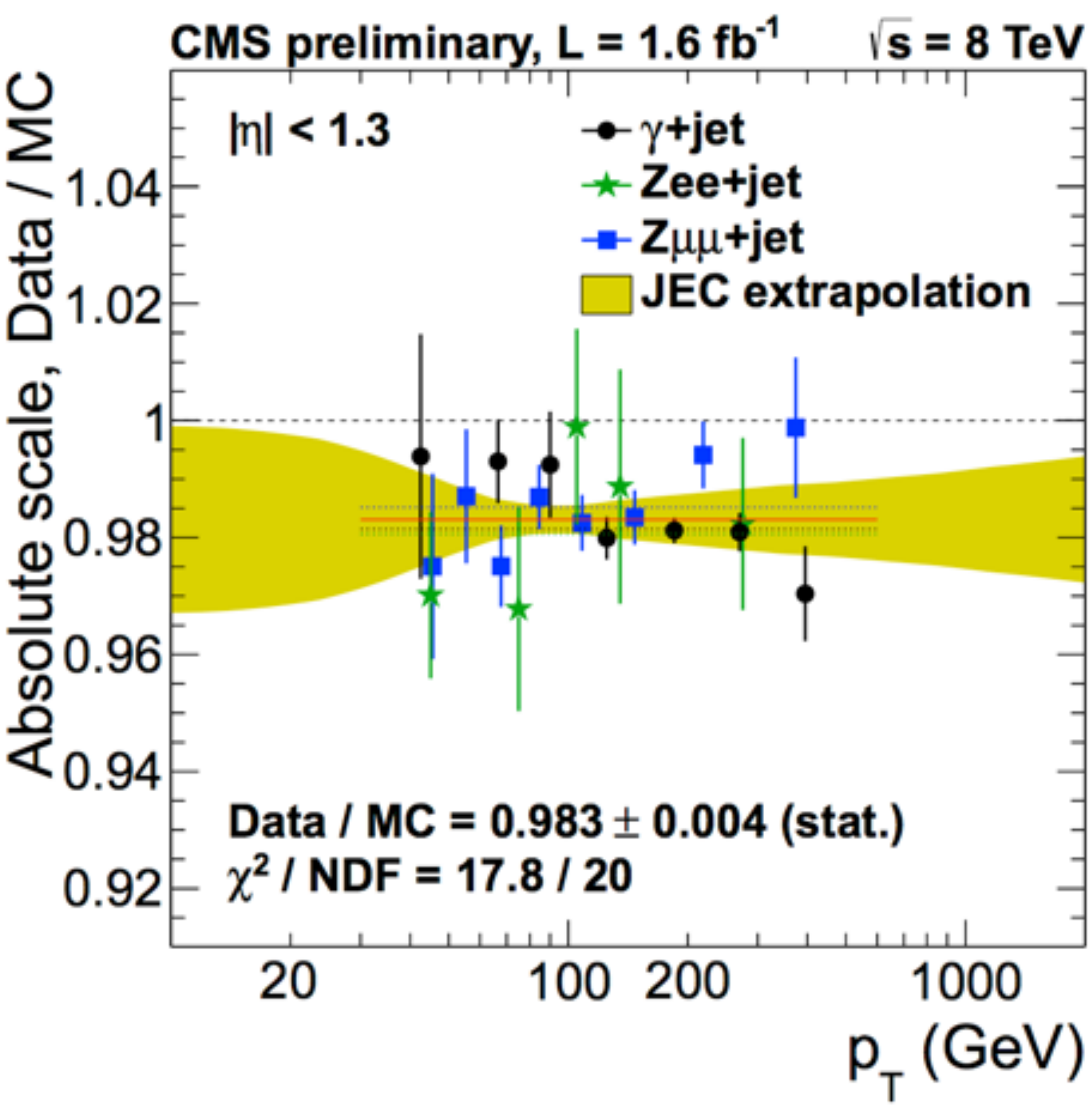
- Need to be sure that:
  - **efficiency of energetic objects is not zero**
  - **resolution under control**
- In extreme cases **resonance can be hidden!**

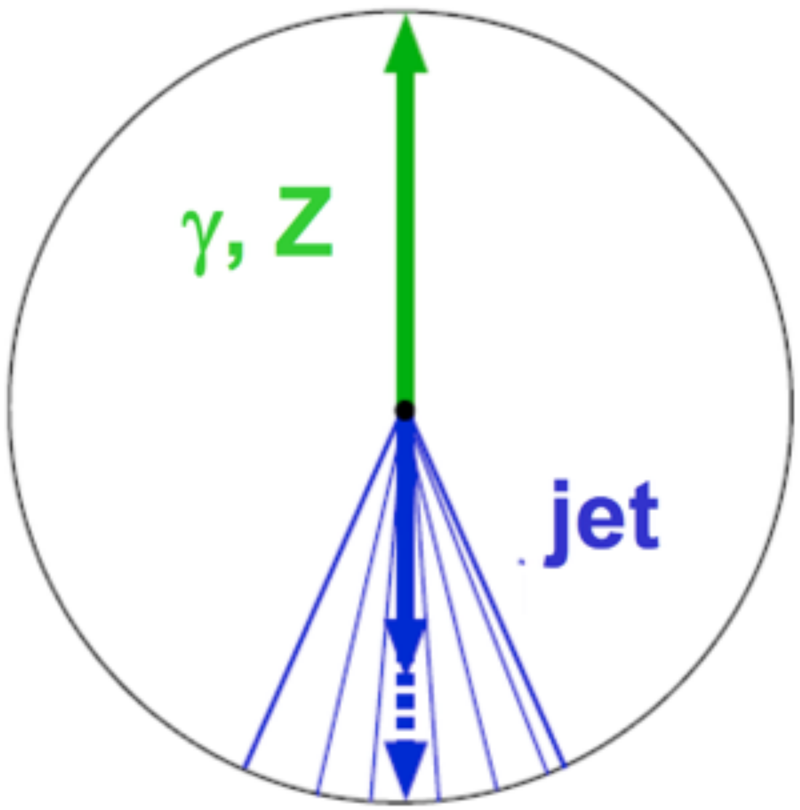
SCALE FOR HIGH PT OBJECTS

- Due to the **lack of statistics at high p_T**, **alternative methods** to determine energy scale
- Example:
  - Use MC to determine extrapolation and linearity from low to high p_T regime
  - Use of control samples to check the relative scale between low and high p_T regimes

JET SCALE CALIBRATION IN SM P_T REGIME

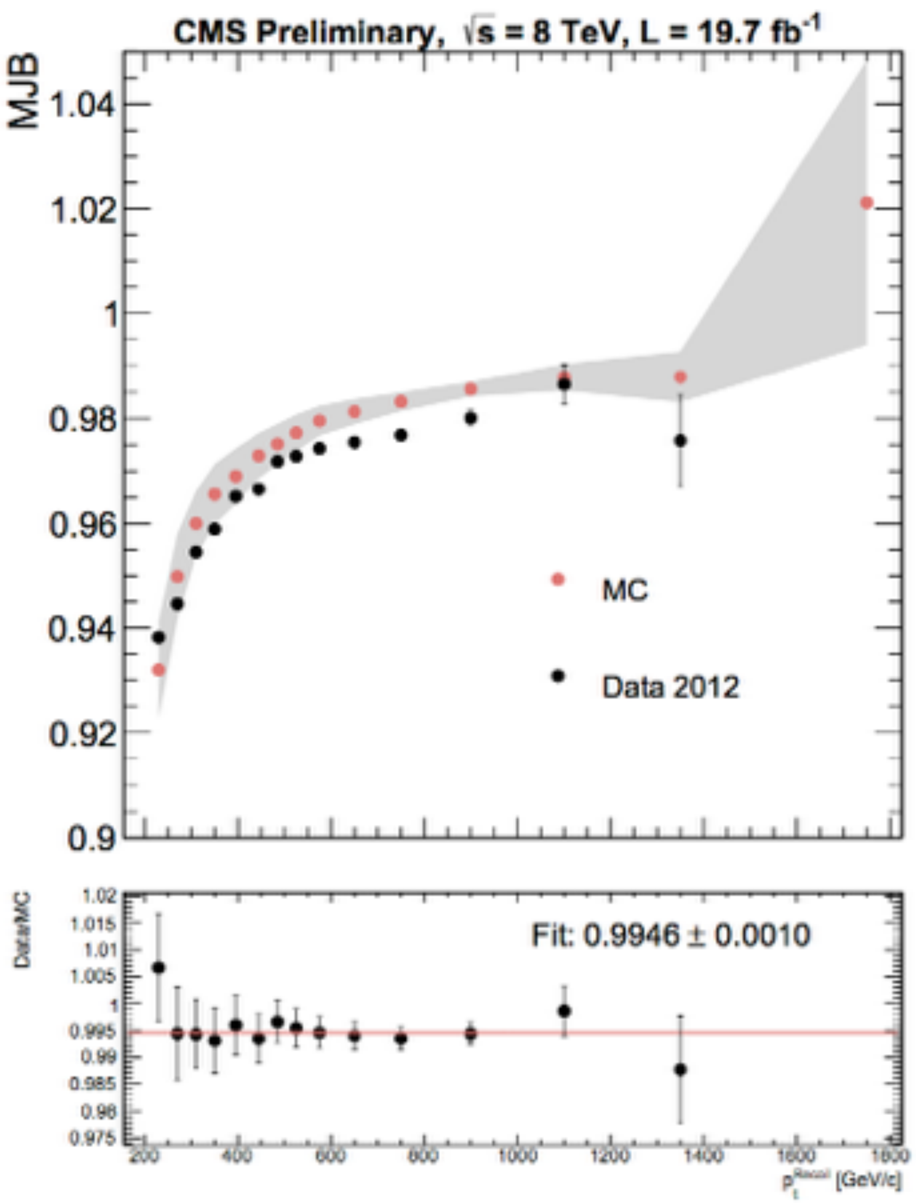
- **Calibration for ~100 GeV Jets**
  - Event balancing in the transverse plane with gamma+jets or Z+jets events
  - **no events above ~ 400 GeV**

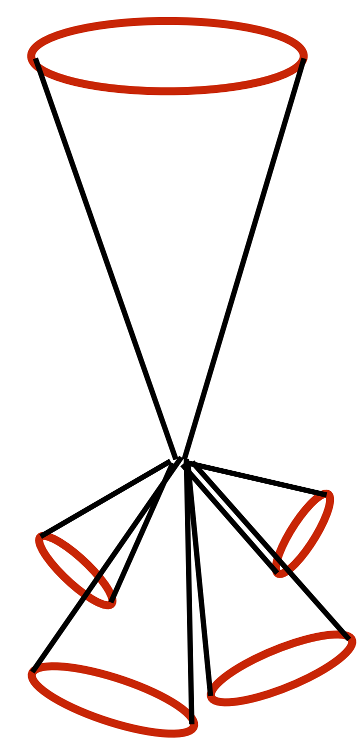




The Example of Jets

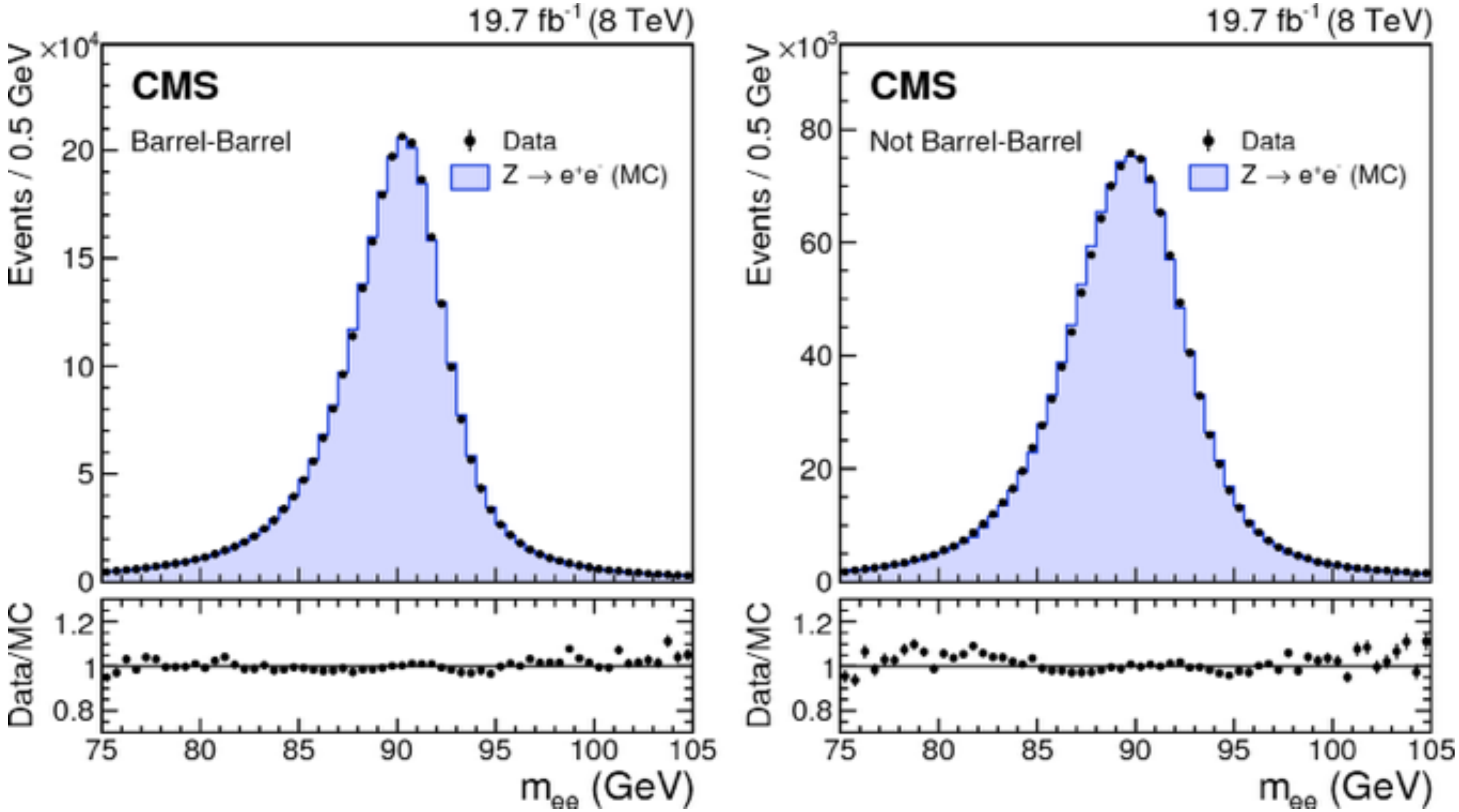
- **Multijet events** to evaluate low vs high p_T relative scale
  - **one high p_T jet recoils to many low p_T jets**
  - p_T jet scale from Z/gamma+jet (previous slides)
  - **by imposing balancing** high p_T jet can be calibrated





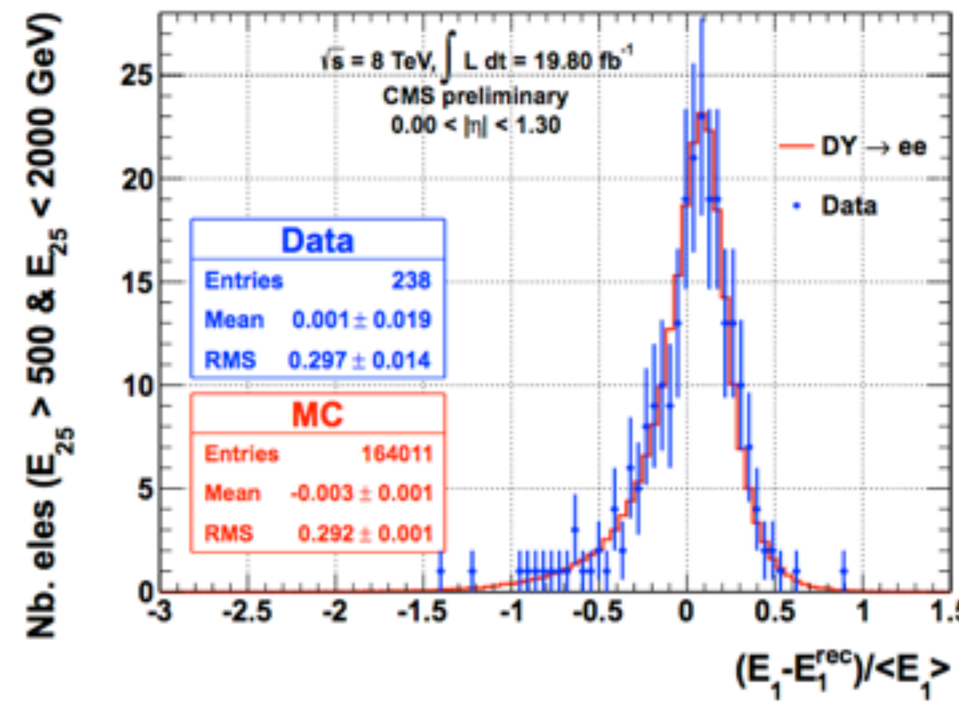
ELECTRON SCALE AND RESOLUTION

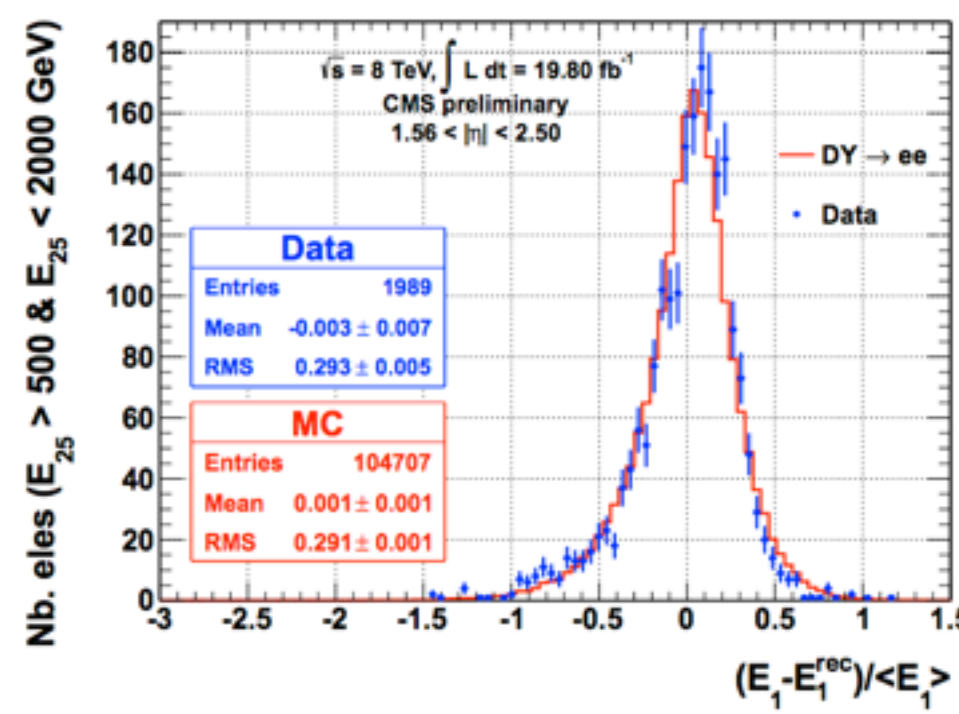
- Basically use **Z to monitor energy scale and resolution**
- Reconstruct Z invariant mass
- **Rescale energy response to make Z line shapes for data and MC talk each other**

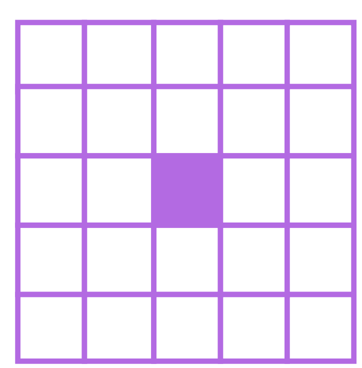


Electrons at Large P_T

- 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

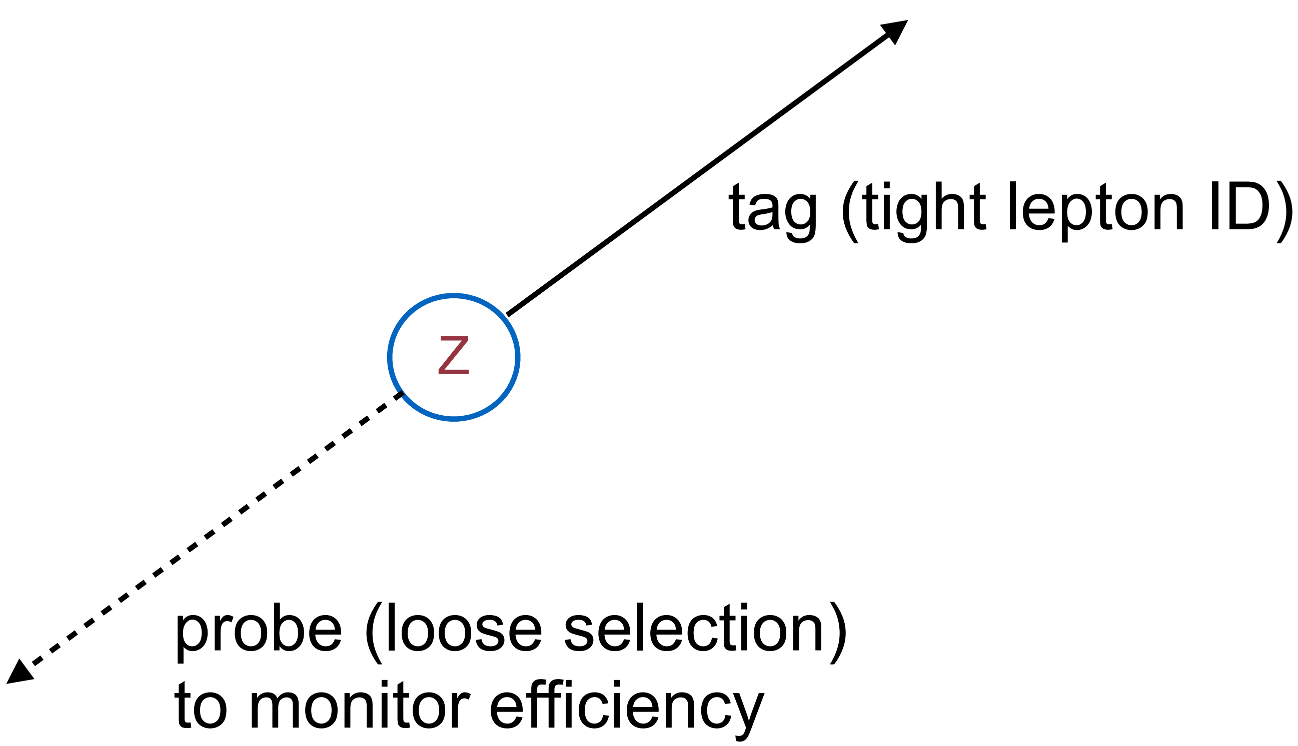


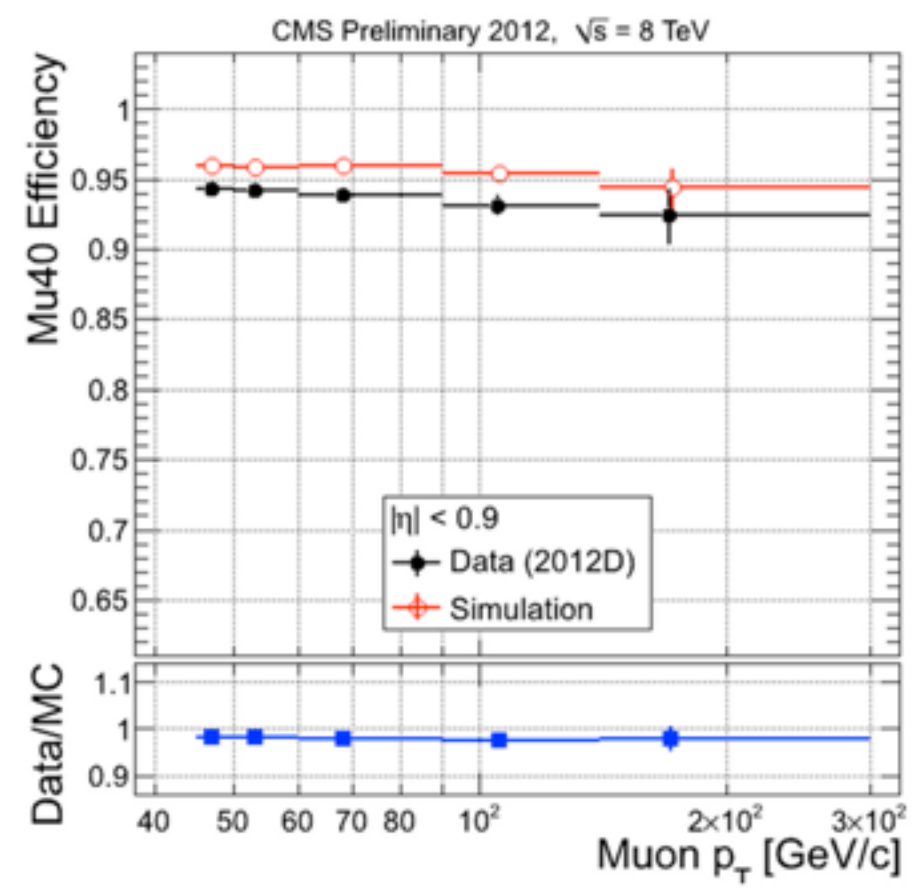




Efficiency Example of Electrons

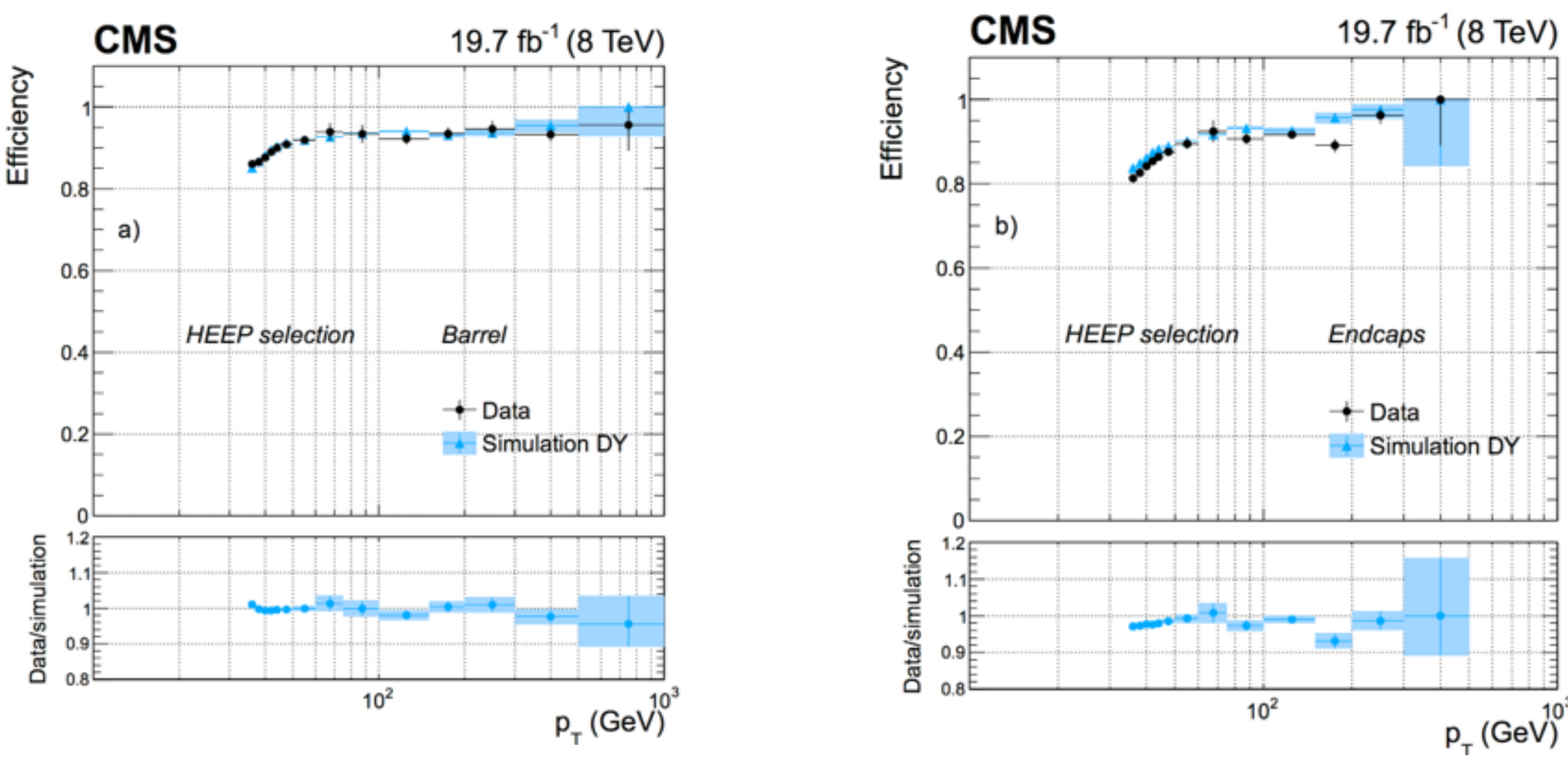
- Calibration for ~50-100 GeV electrons done by using Z->ll events
- Used so-called **tag-and-probe method**
  - one lepton fully identified
  - other lepton selected with loose criteria
  - with inv. requirement (around 91 GeV), measure trigger and selection efficiency





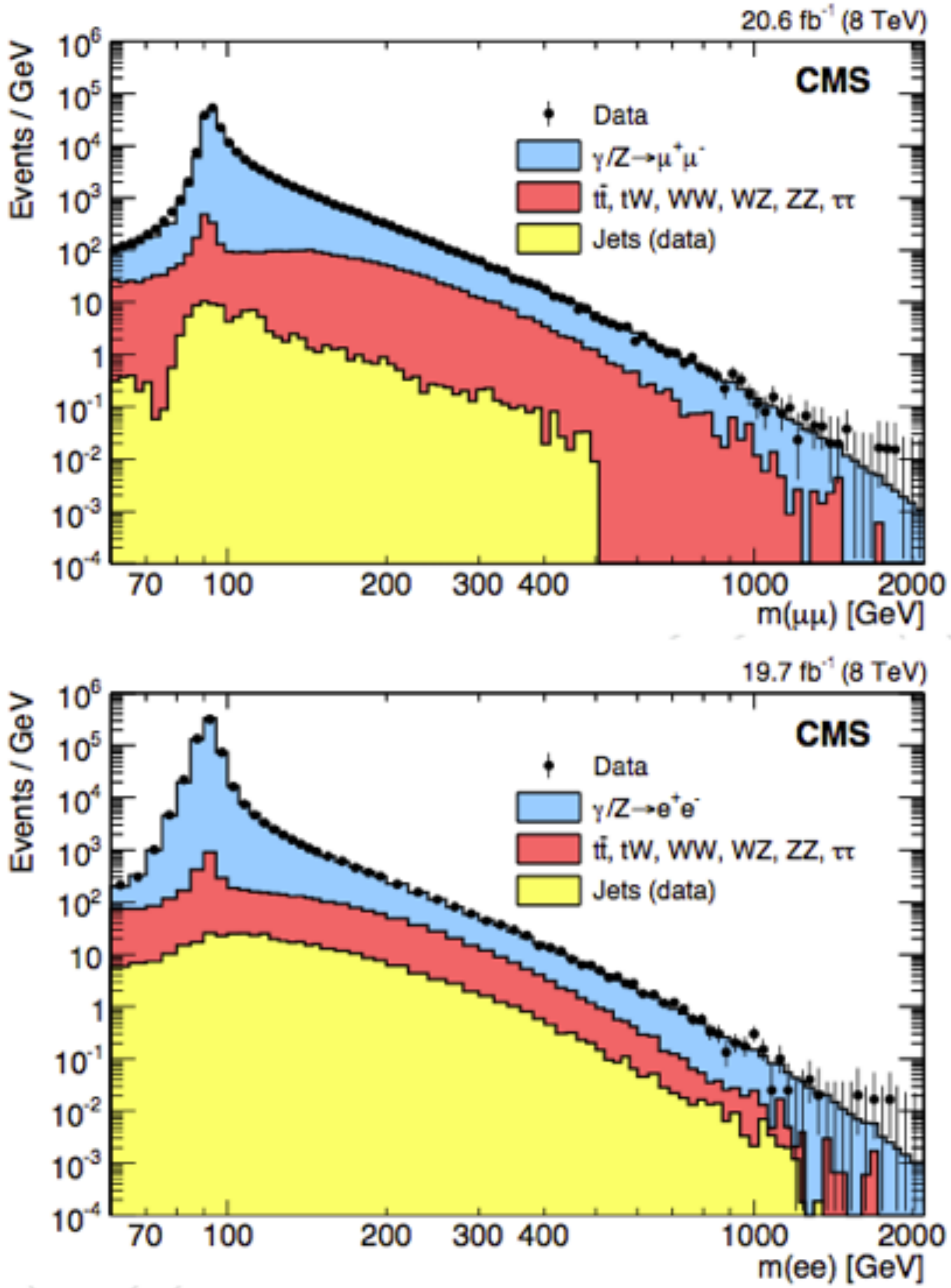
EFFICIENCY AT LARGE PT

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



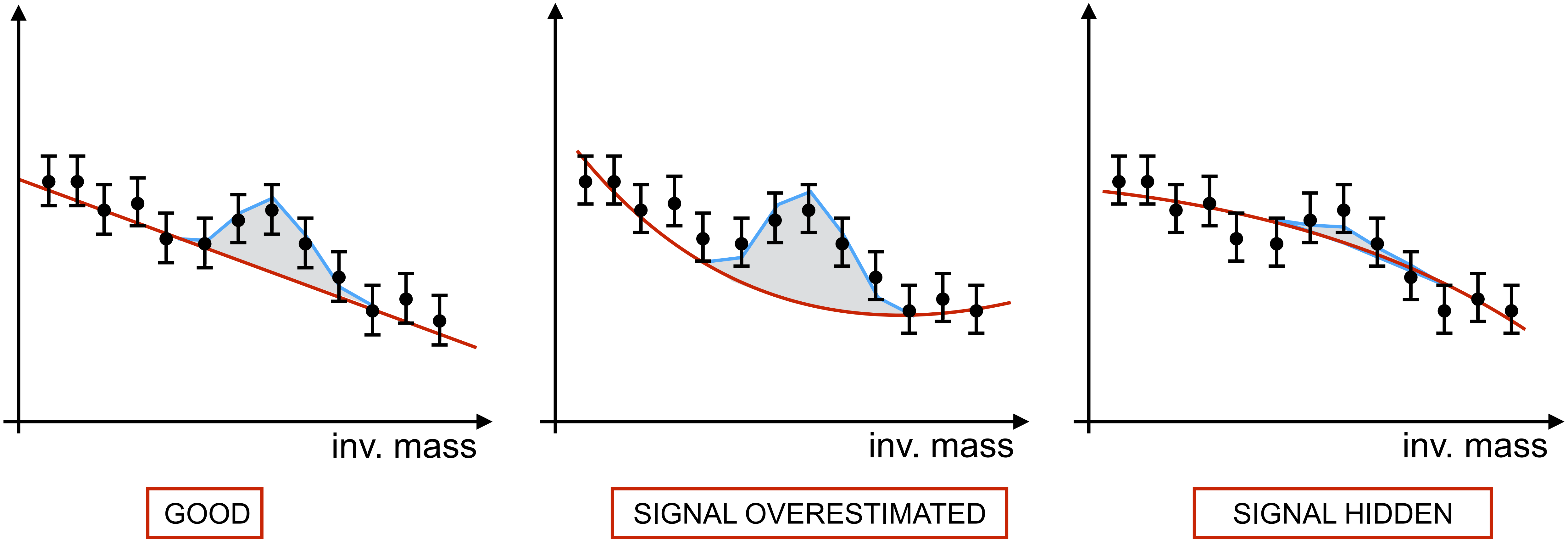
SIGNAL EXTRACTION

- Final spectrum is exponentially falling distribution for background
- Gaussian-like for signal
- Low statistics in tail makes the game tricky



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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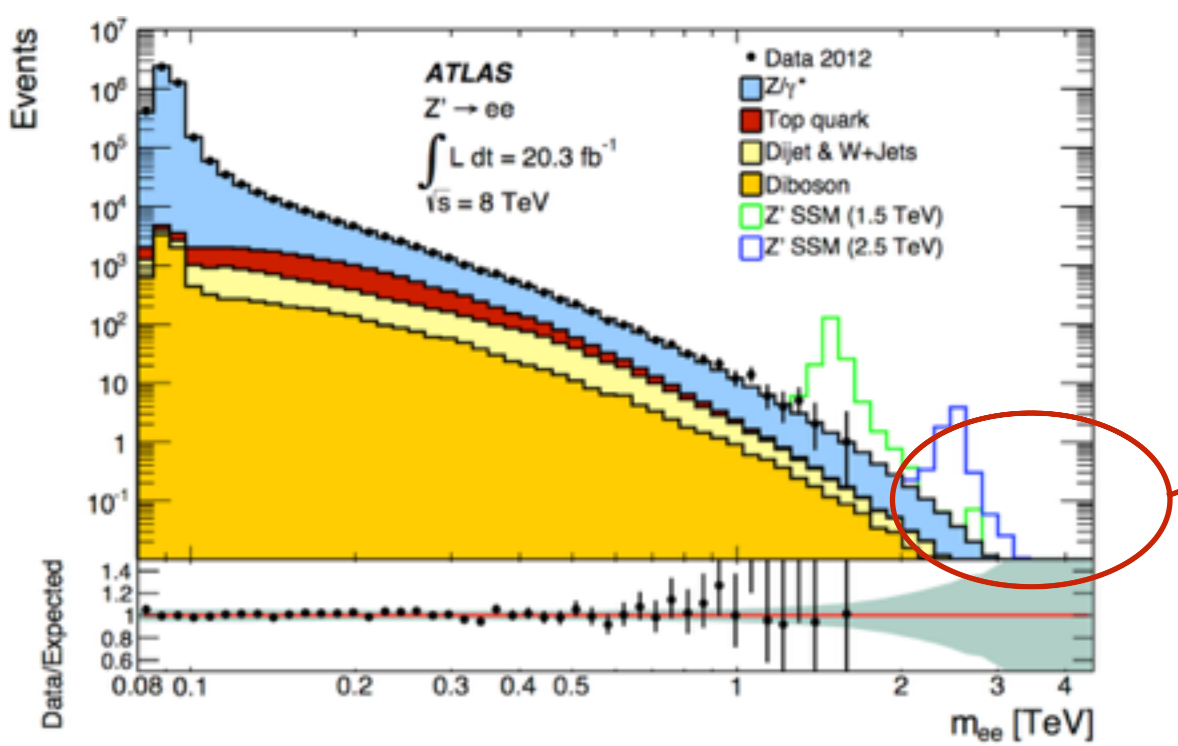


At very high masses no events to tune background. Extrapolation needed

SIGNAL AND BACKGROUND SYSTEMATICS

Background systematics

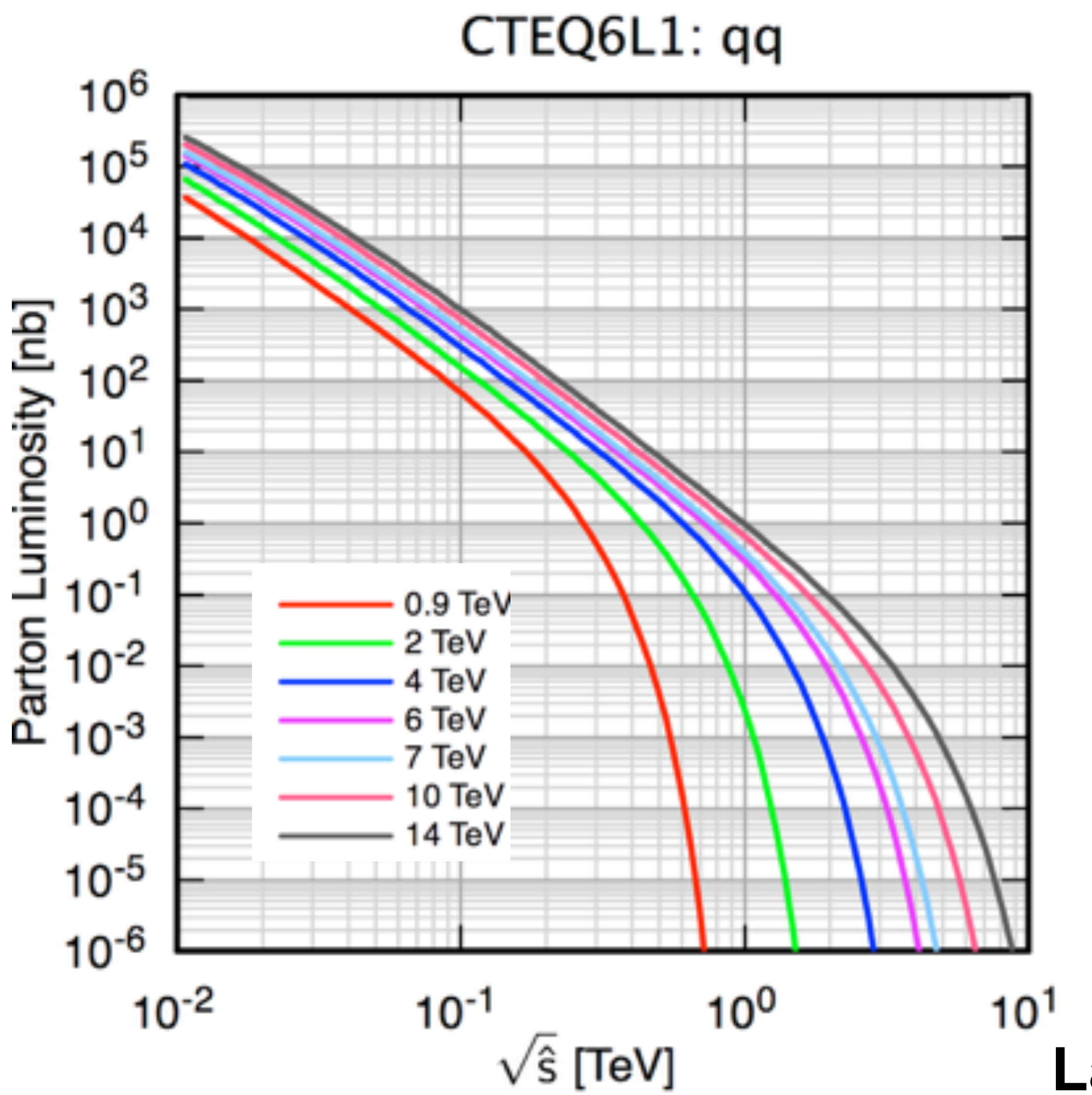
- If shape extracted from MC, background is mainly affected by theory uncertainties (experimental ones are usually minor)
- Theory error means mainly:
  - uncertainties on PDFs
  - missing diagrams in cross section calculation
    - both QCD and EW

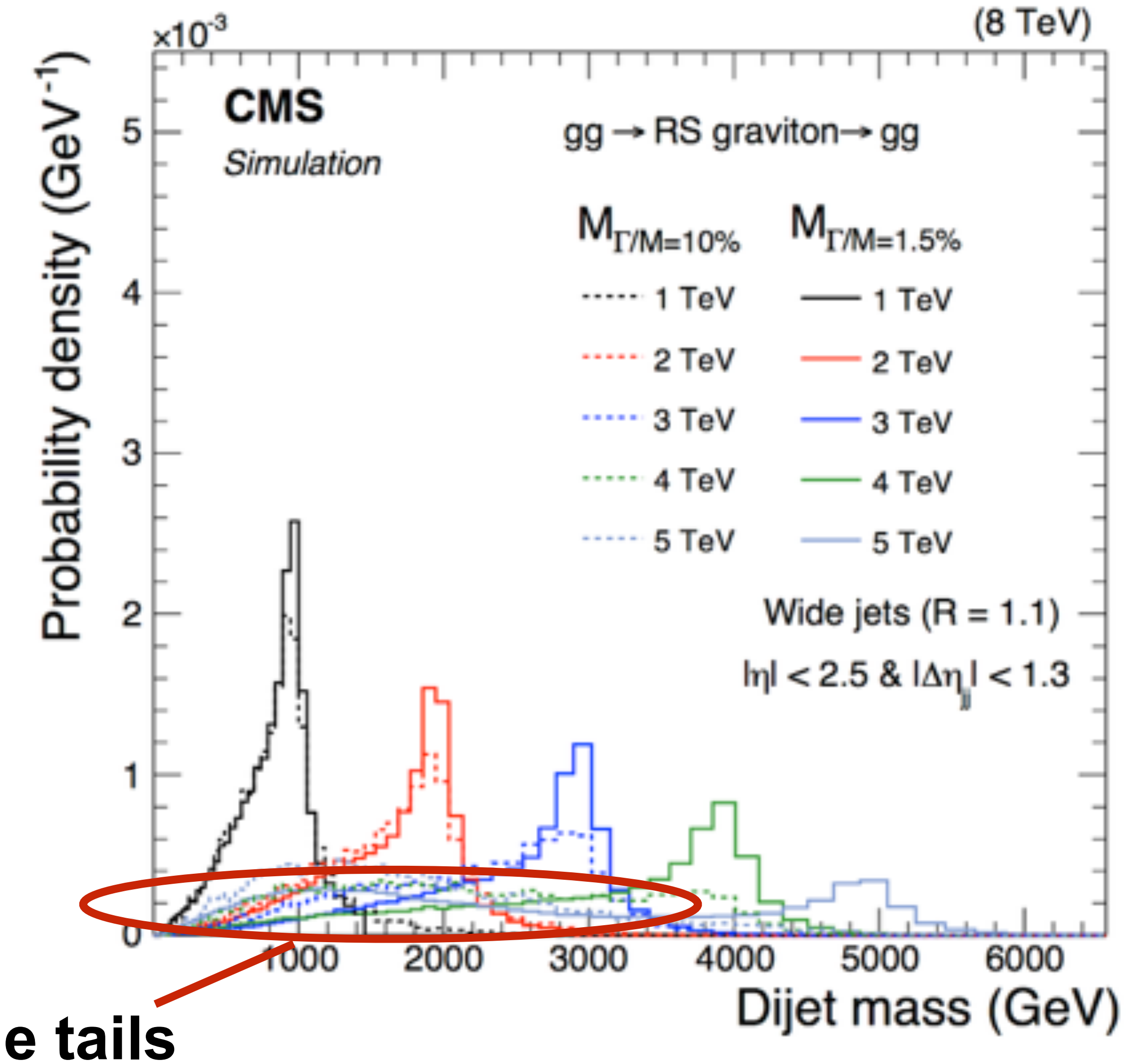
Signal systematics

- less important (become relevant if you see a signal and want to measure a cross section)
- need when interpreting results (but still second order)
  - convert upper limit into mass exclusion
- important if they affect signal shape

IMPACT OF PDFs ON SIGNAL

- **PDFs not only** affect **cross sections but also signal shape**
- If width not negligible, distortion due to **huge ratio between parton luminosity at low and high masses**





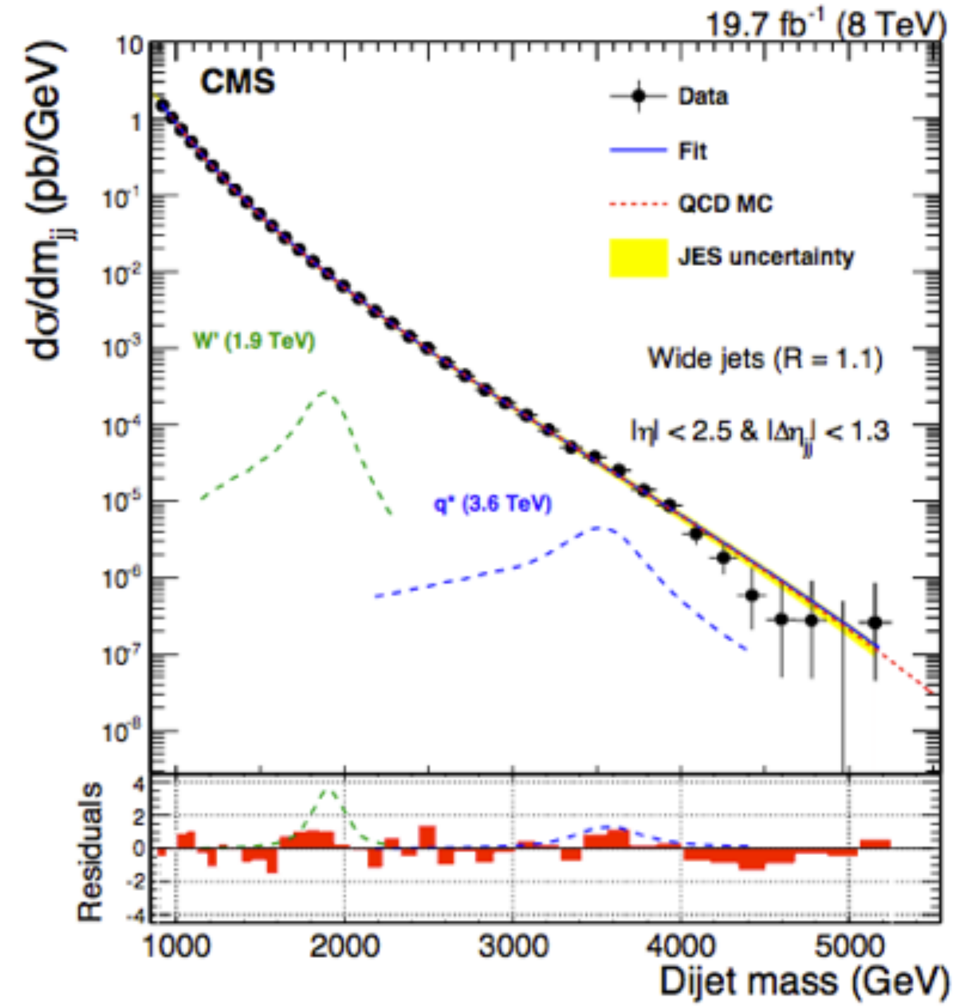
UL DETERMINATION

- 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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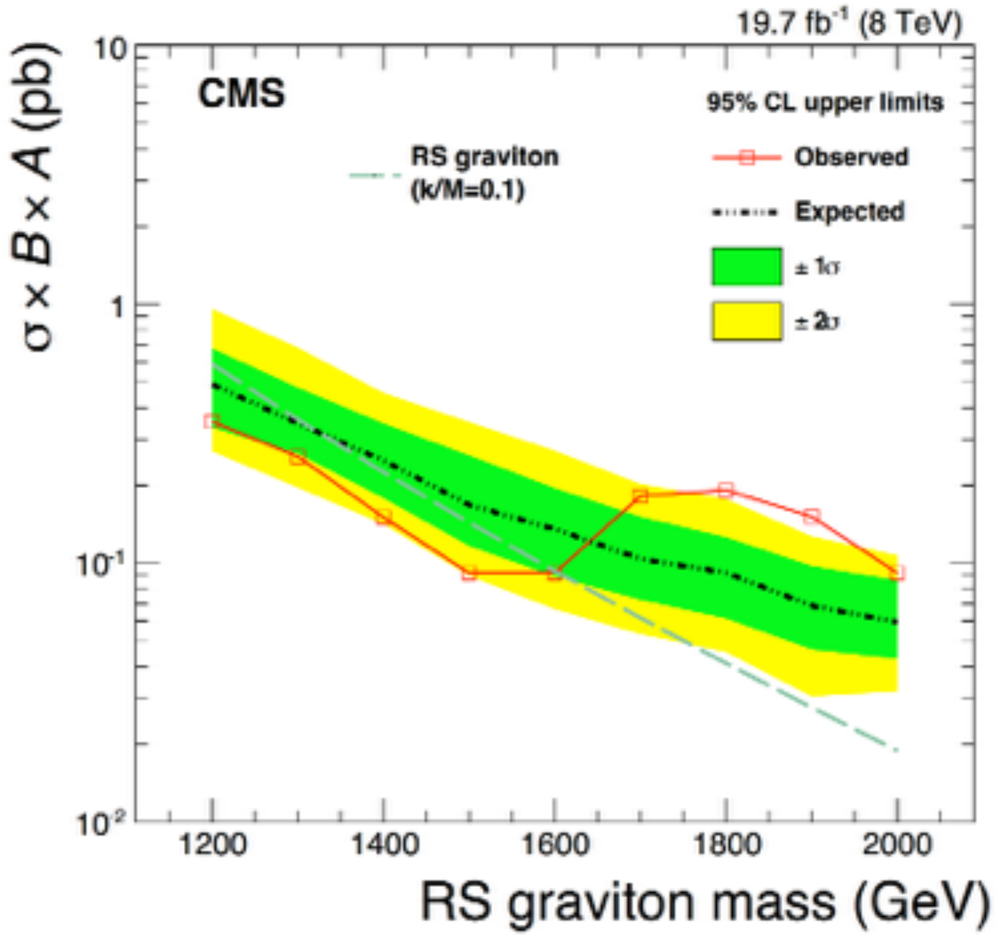

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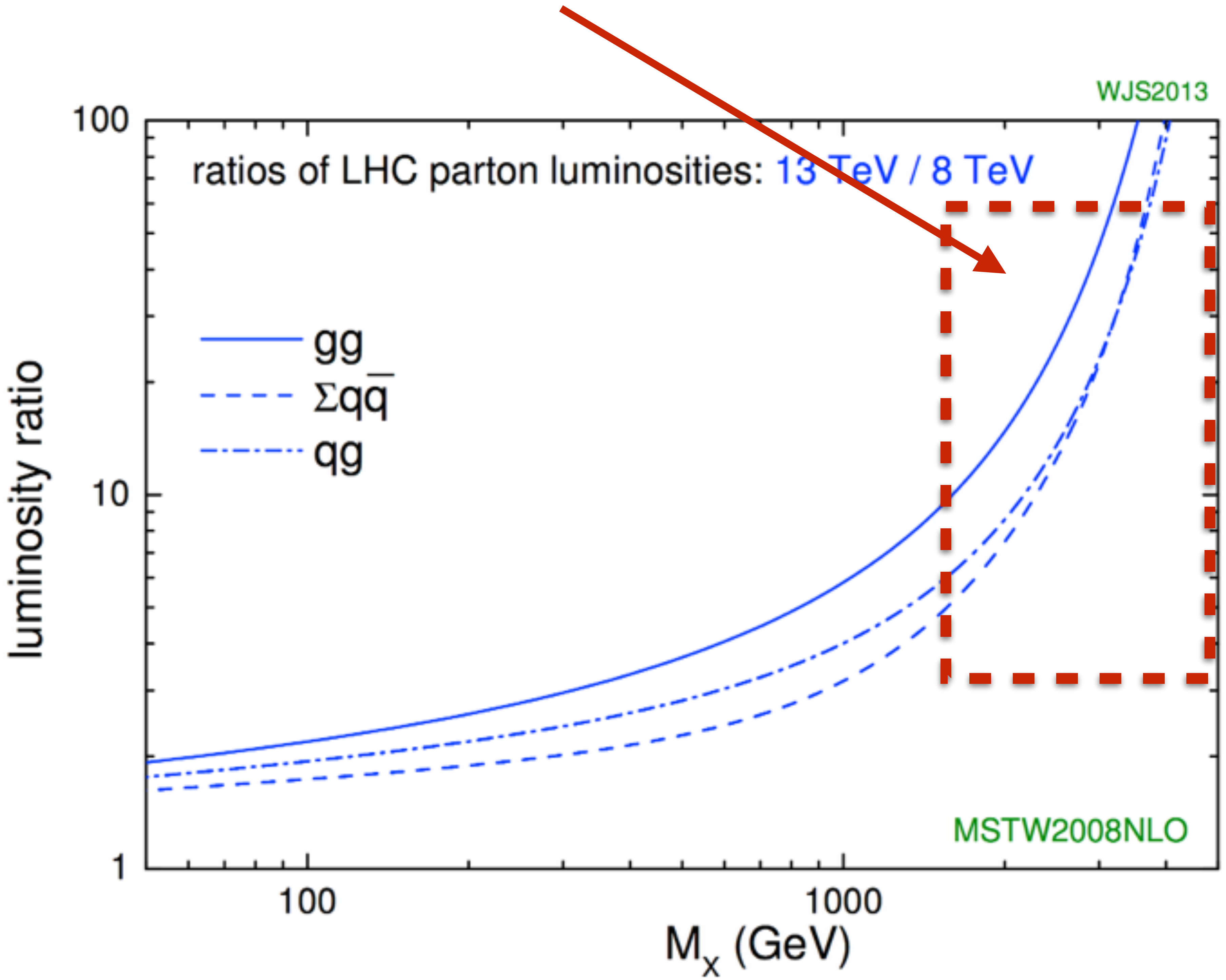
- i is the bin number
- $\lambda_i = \mu N_i(S) + N_i(B)$
- $N_i(S)$ is the number of signal events for a given model
- $N_i(B)$ is the number of background events (can be either parameterized of coming from MC)
- detector uncertainties are taken into account in the likelihood by "marginalizing" (i.e. integrating out), assuming a log-normal distribution
- flat prior (bayesian) for cross section

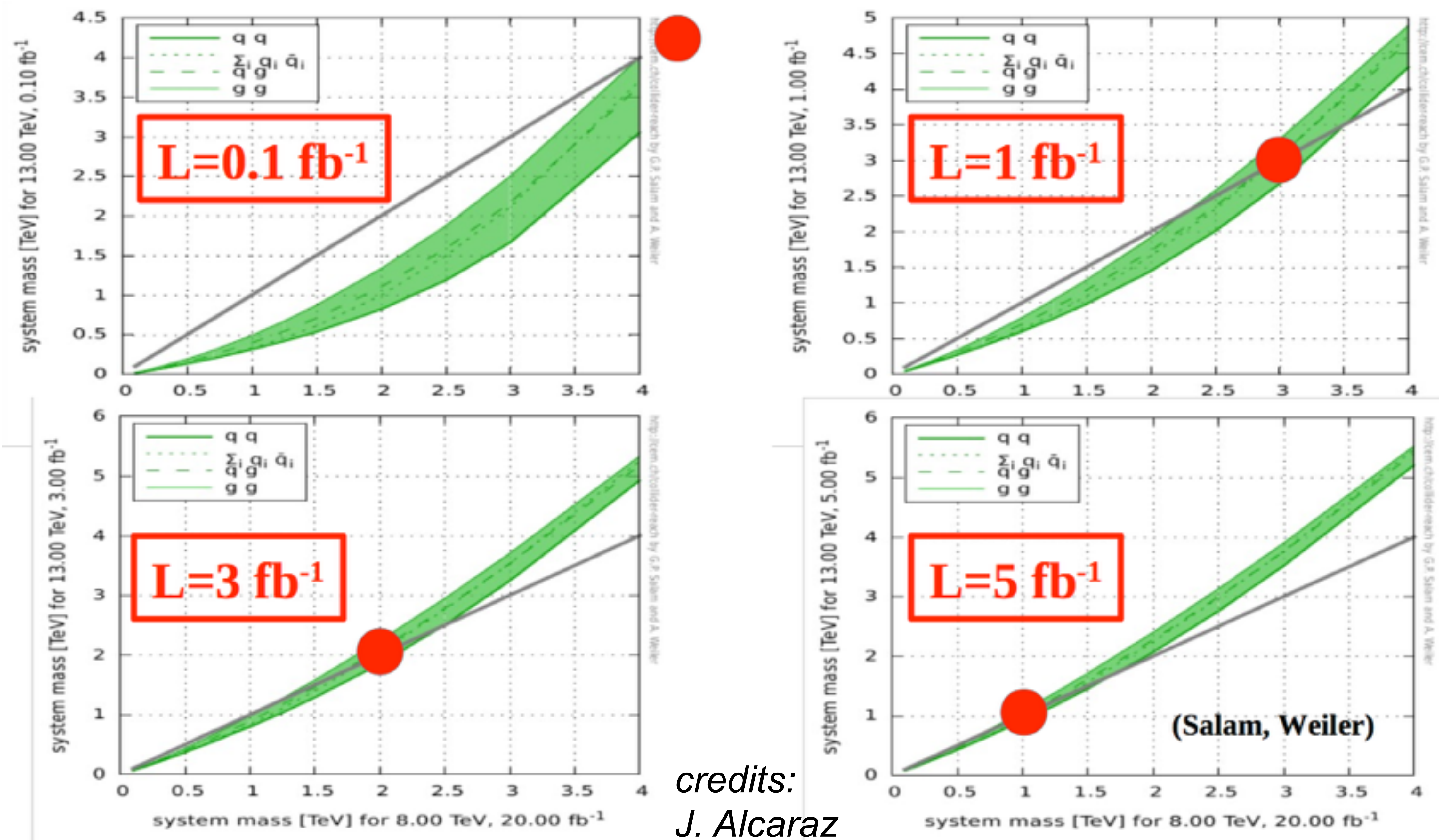
EXTRAPOLATION AT HIGH LUMI AND CM

- For high mass searches **parton luminosity counts**!
  - **Huge ratio in the interesting (not yet excluded) region**



Physics Potential vs Luminosity

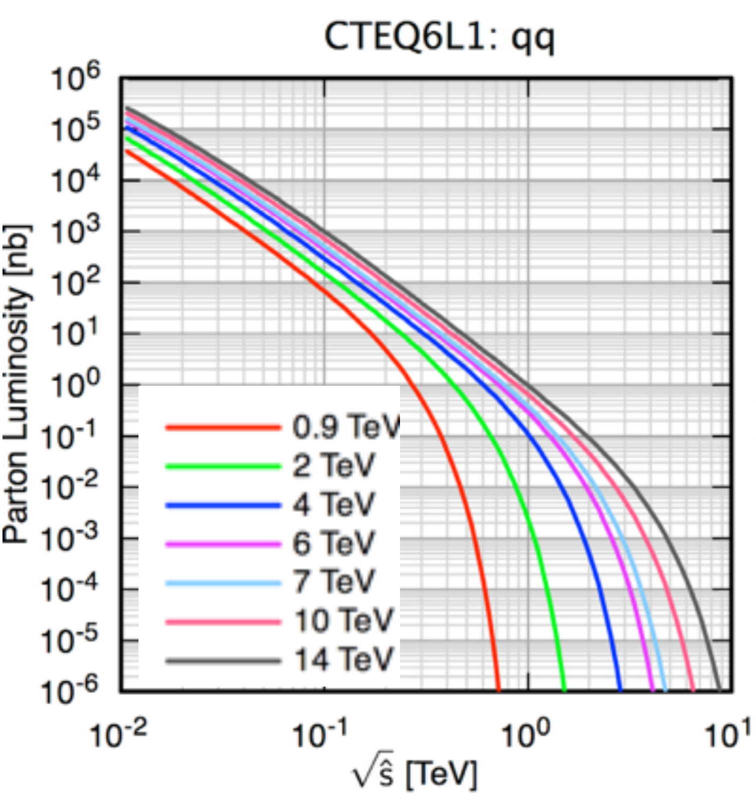
- Sensitive to **masses above 3 TeV with just 1 fb^{-1}**
- We can redo **all past searches with 5 fb^{-1}** (i.e. results for Moriond 2016)

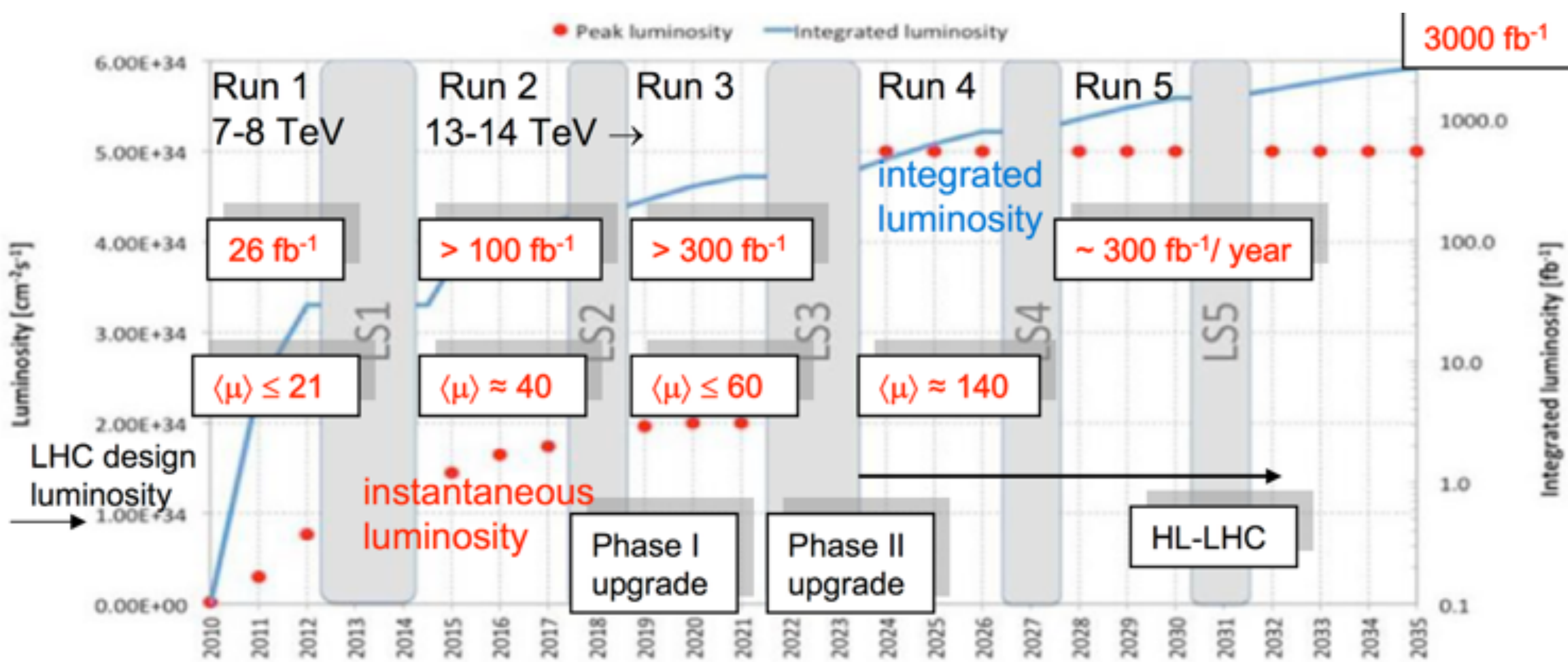


credits: J. Alcaraz

Even Longer Timescales: Run3, Run4

- **After end of Run2 statistics won't help much** in extending physics potential
  - fast **drop of parton luminosities** kills the high mass searches
- Maybe with **14 TeV energy another small addition** in reach
- **HL-LHC not very interesting for high mass searches**
- Maybe invest more on **intermediate mass region** (<1-2 TeV)





Slides from Seminar

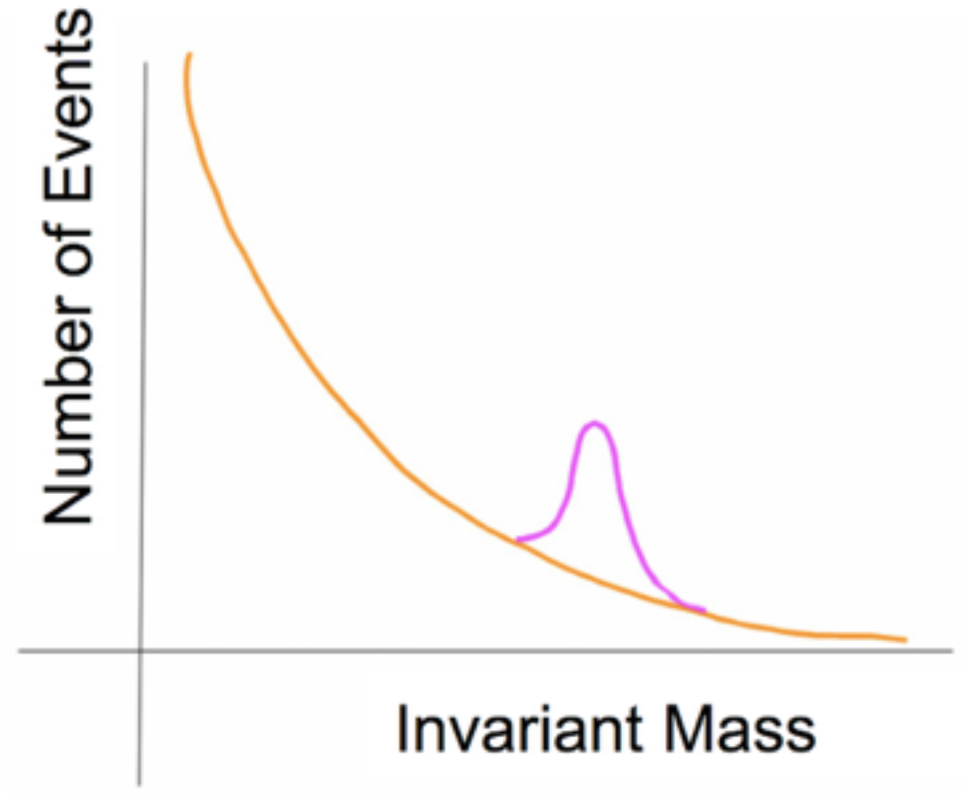
SEARCHES FOR NEW HEAVY RESONANCES AT THE LHC

Daniele del Re

Sapienza Università & INFN Sezione Roma

WHY HIGH MASS RESONANCES

- 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 when new energies** are explored
  - the goal of LHC
  - particularly relevant at start-up (Run2)



RESONANCES IN PAST DISCOVERIES

EW LETTERS 2 DECEMBER 197

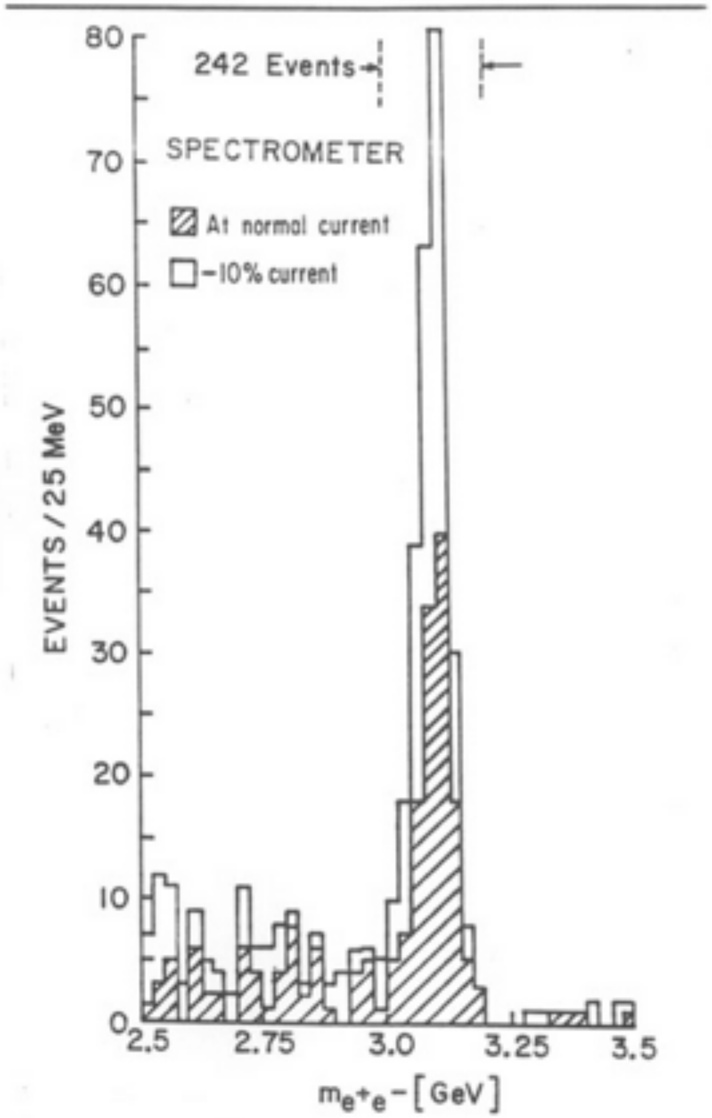
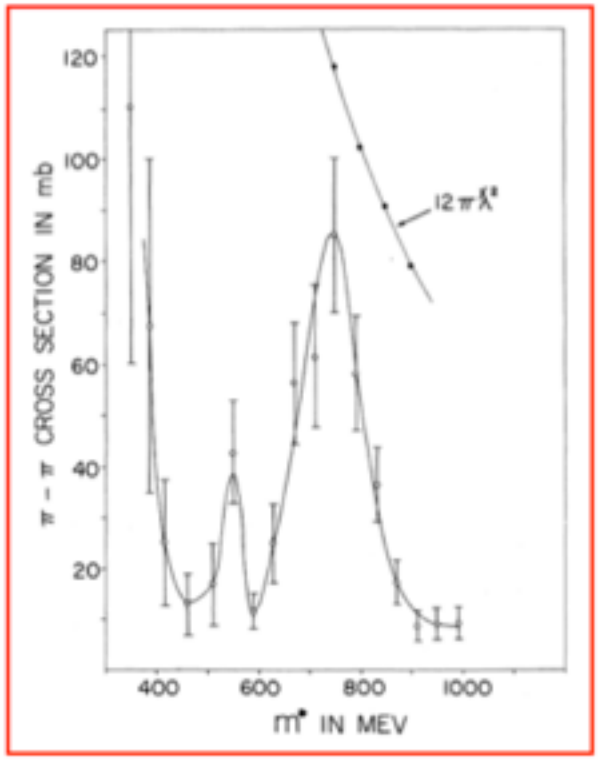


FIG. 2. Mass spectrum showing the existence of J. sults from two spectrometer settings are plotted wing that the peak is independent of spectrometer rents. The run at reduced current was taken two nths later than the normal run.

1961: ρ(770)→ππ



PhysRevLett.6.628

1961: K*(892)→Kπ

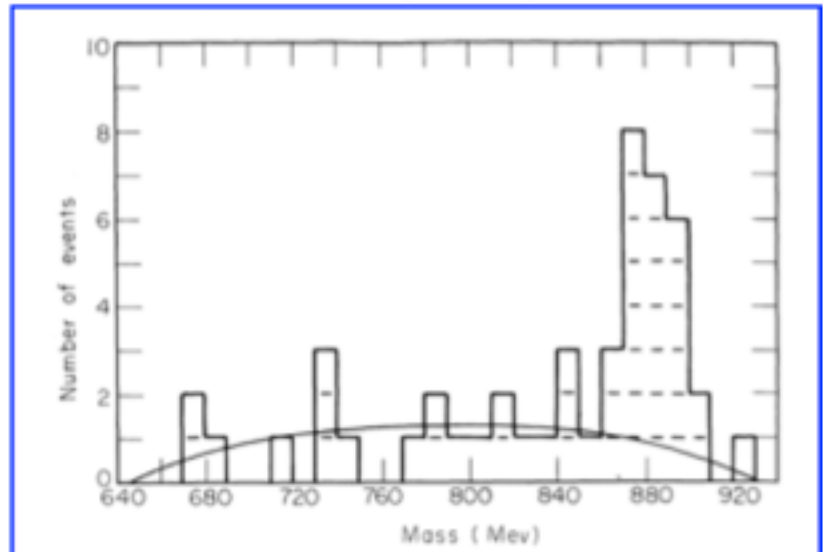
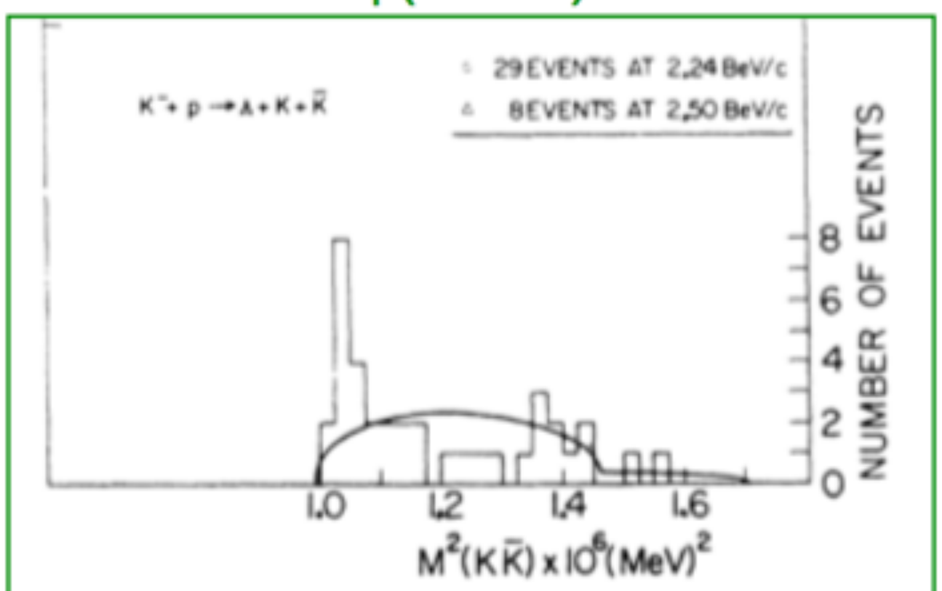


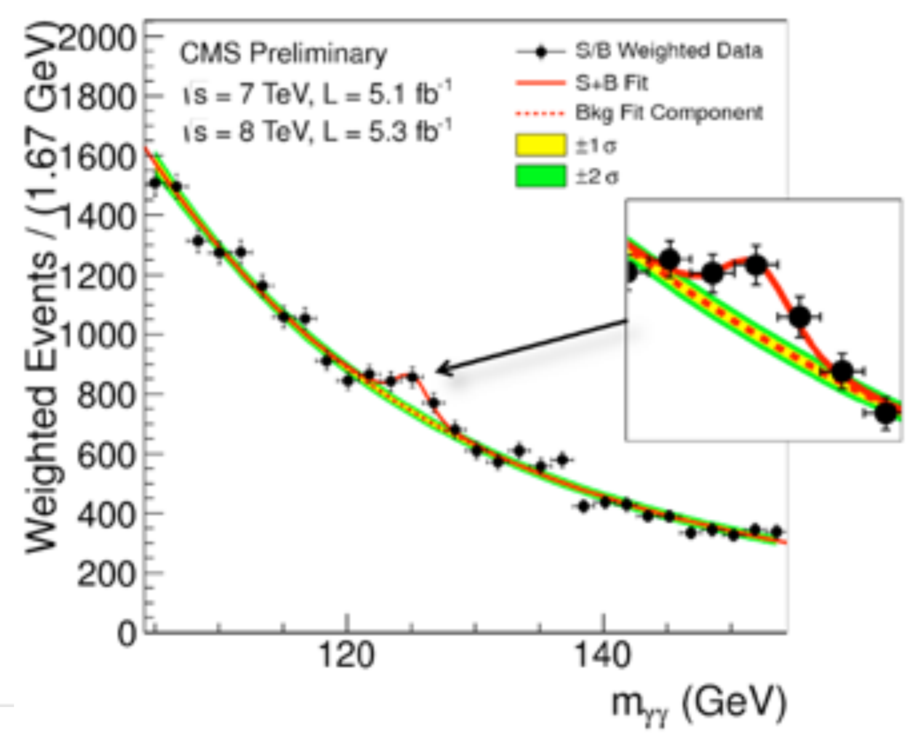
FIG. 2. Mass spectrum of the $\bar{K}^0-\pi^-$ system. The solid line represents the phase-space curve normalized to background events.

PhysRevLett.6.300

1961: ϕ(1020)→KK

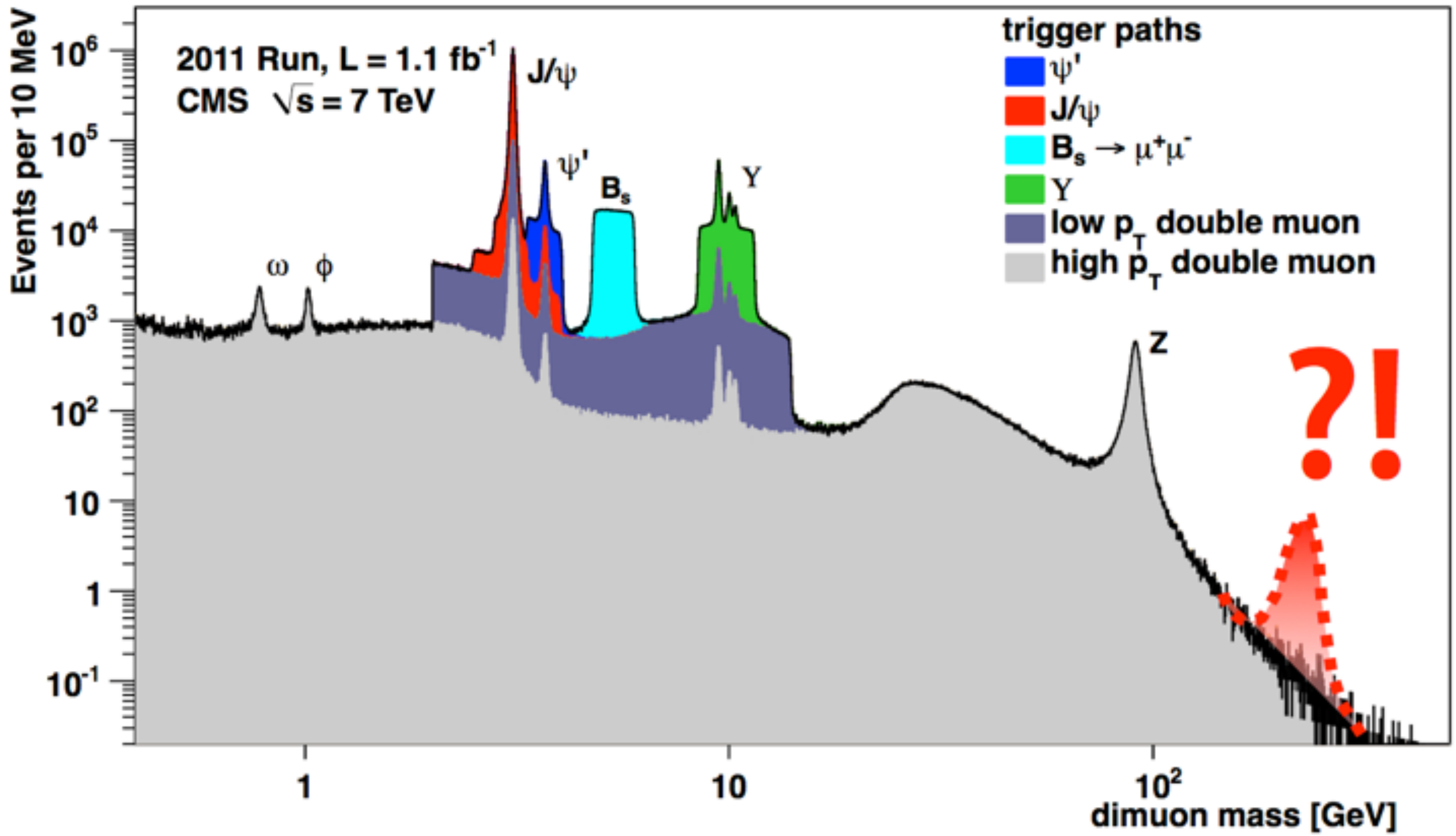


PhysRevLett.9.180



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**



FROM THEORY TO SIGNATURES

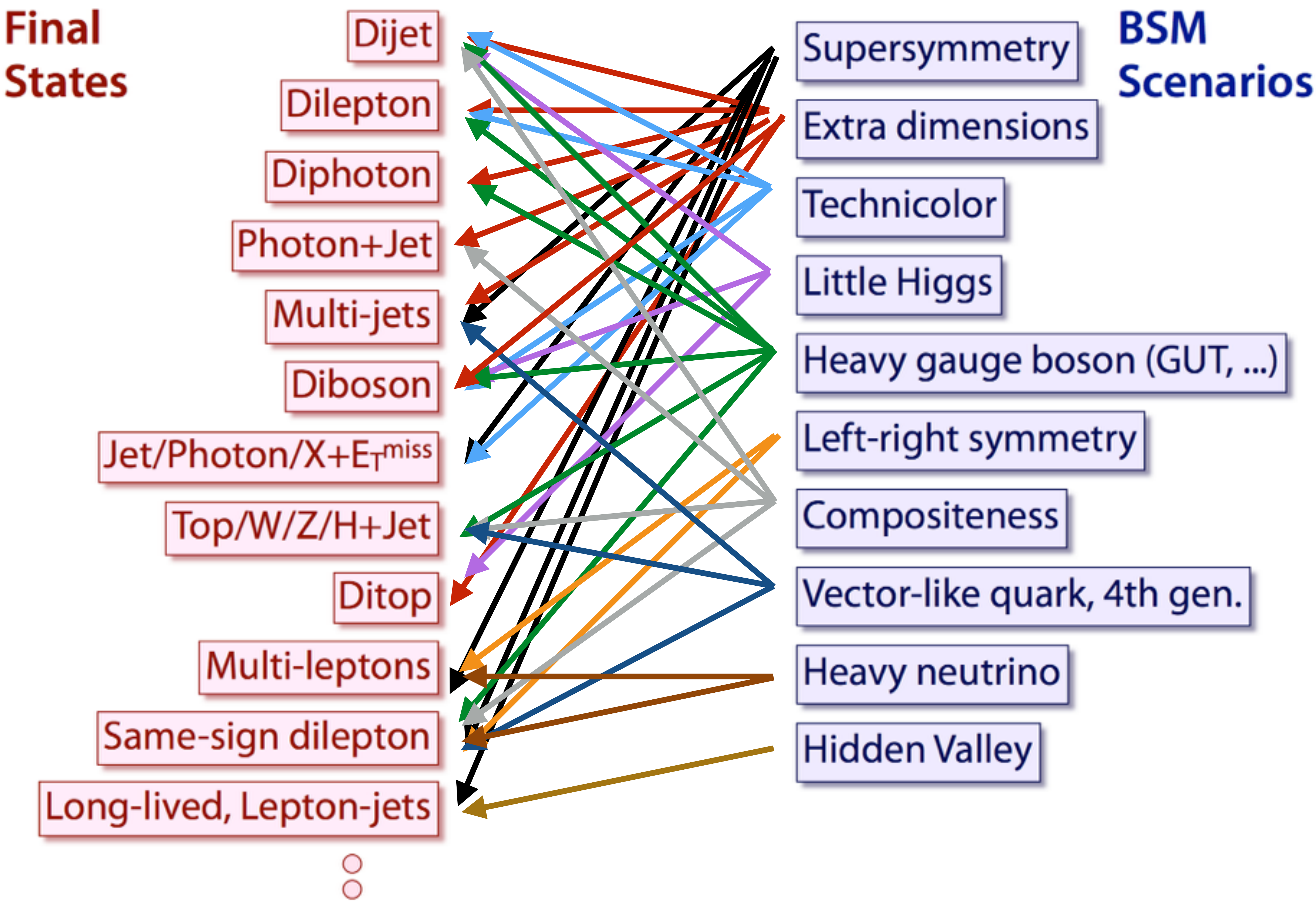
Final States

- 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
- ⋮

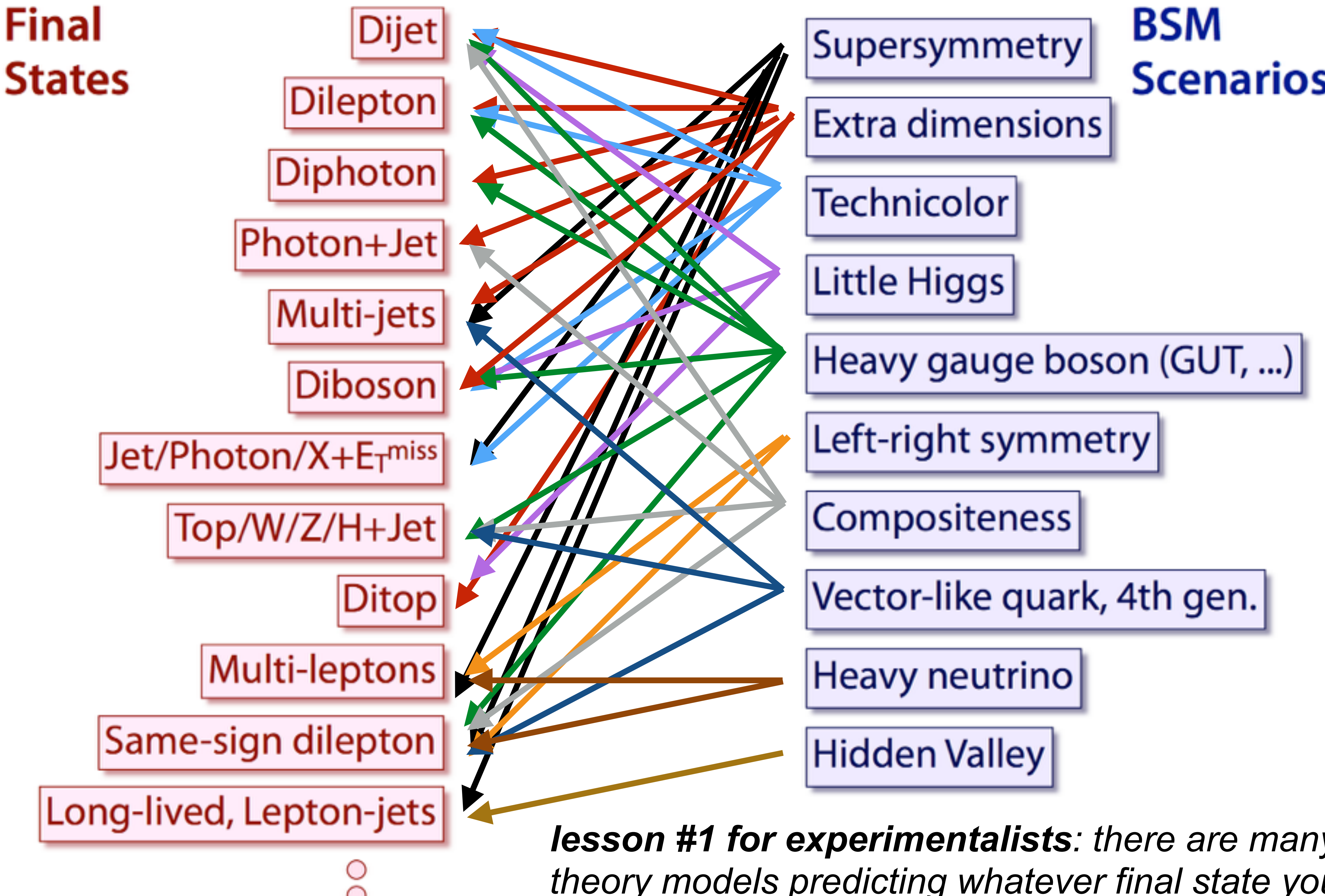
BSM Scenarios

- 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

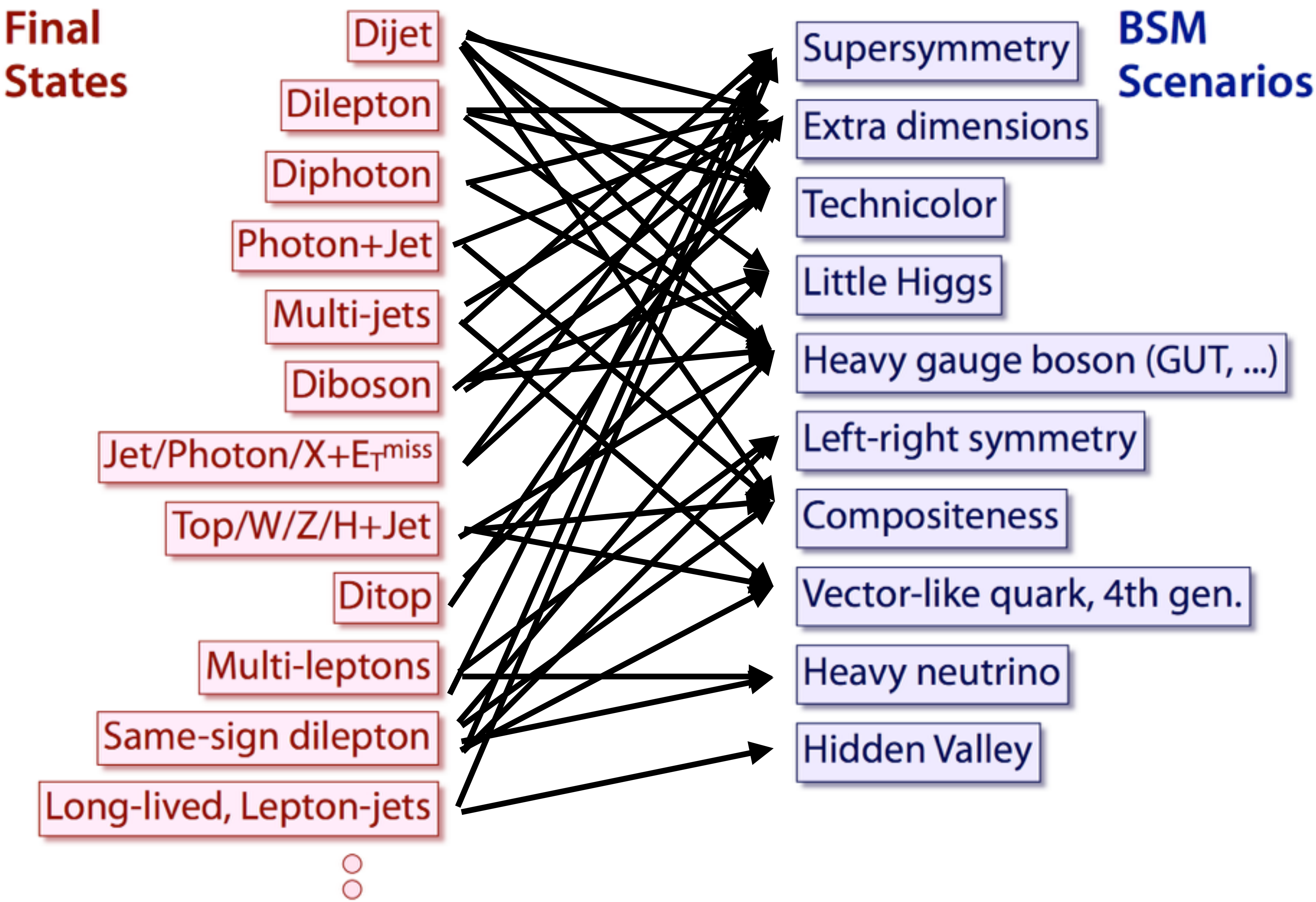


FROM THEORY TO SIGNATURES

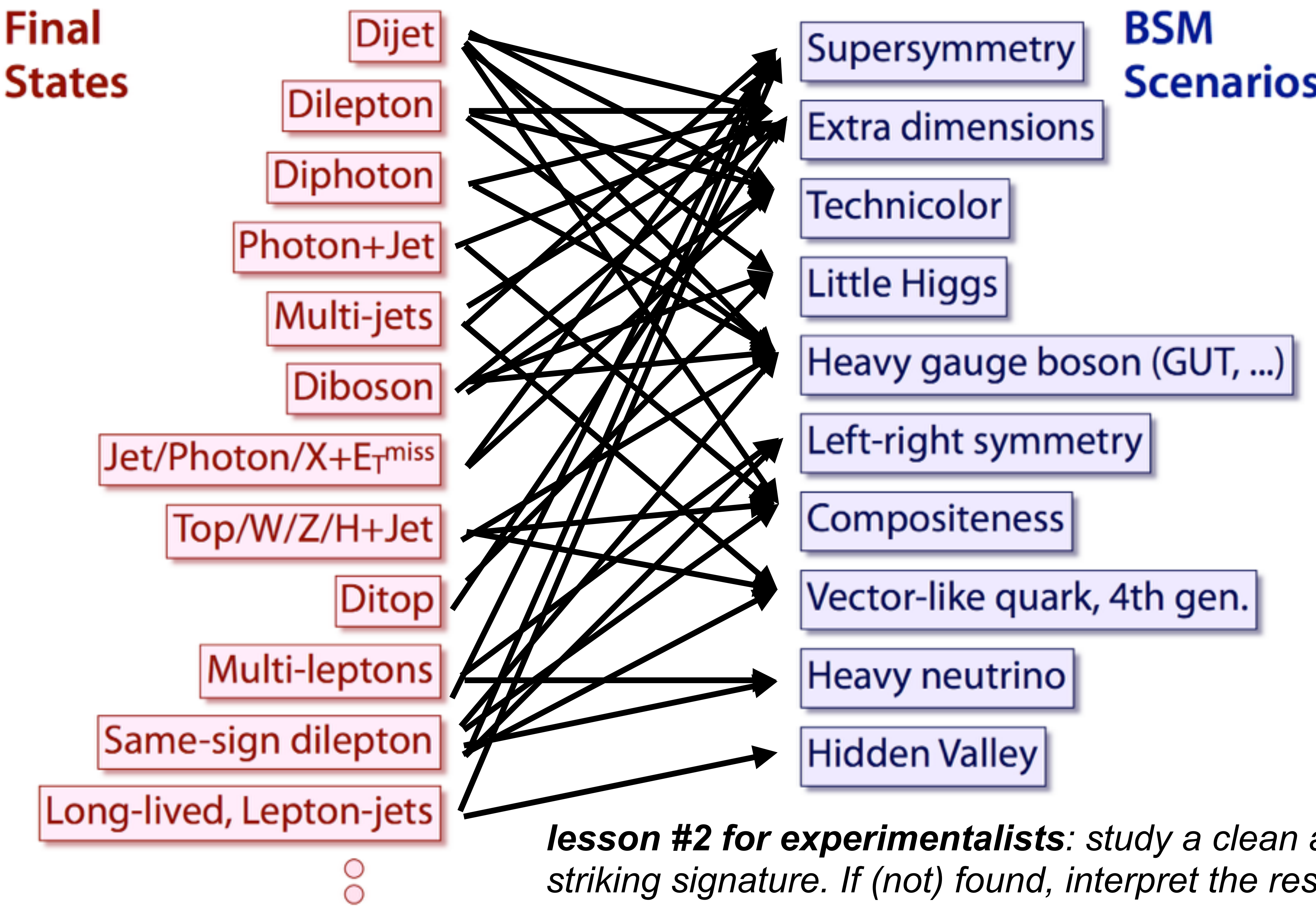


***lesson #1 for experimentalists**: there are many theory models predicting whatever final state you like*

FROM SIGNATURES TO THEORY



FROM SIGNATURES TO THEORY



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
- Photon+Jet
- Diboson

This Talk

Biased list!

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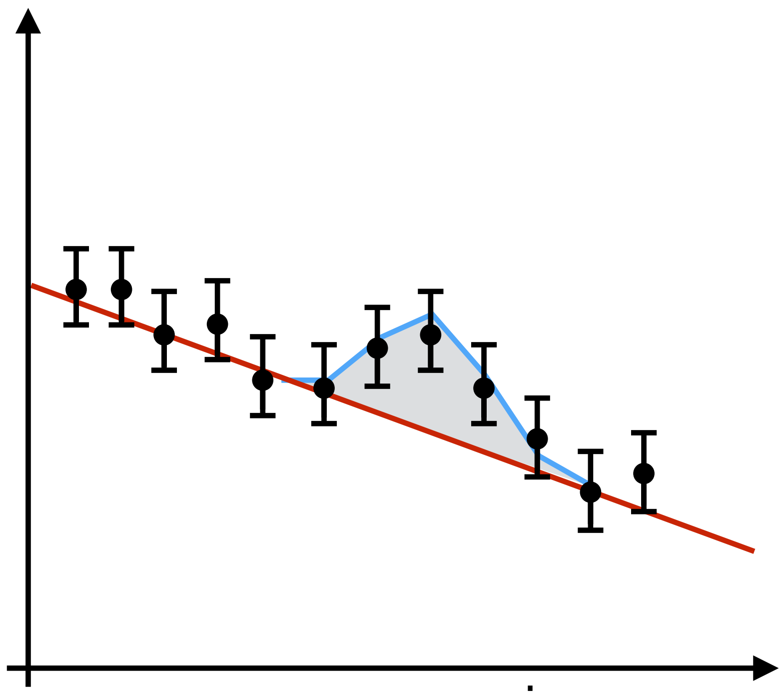
4. Simple **signal extraction**
   – cut and count techniques
   – likelihood fit based on a smooth background + gaussian-like signal



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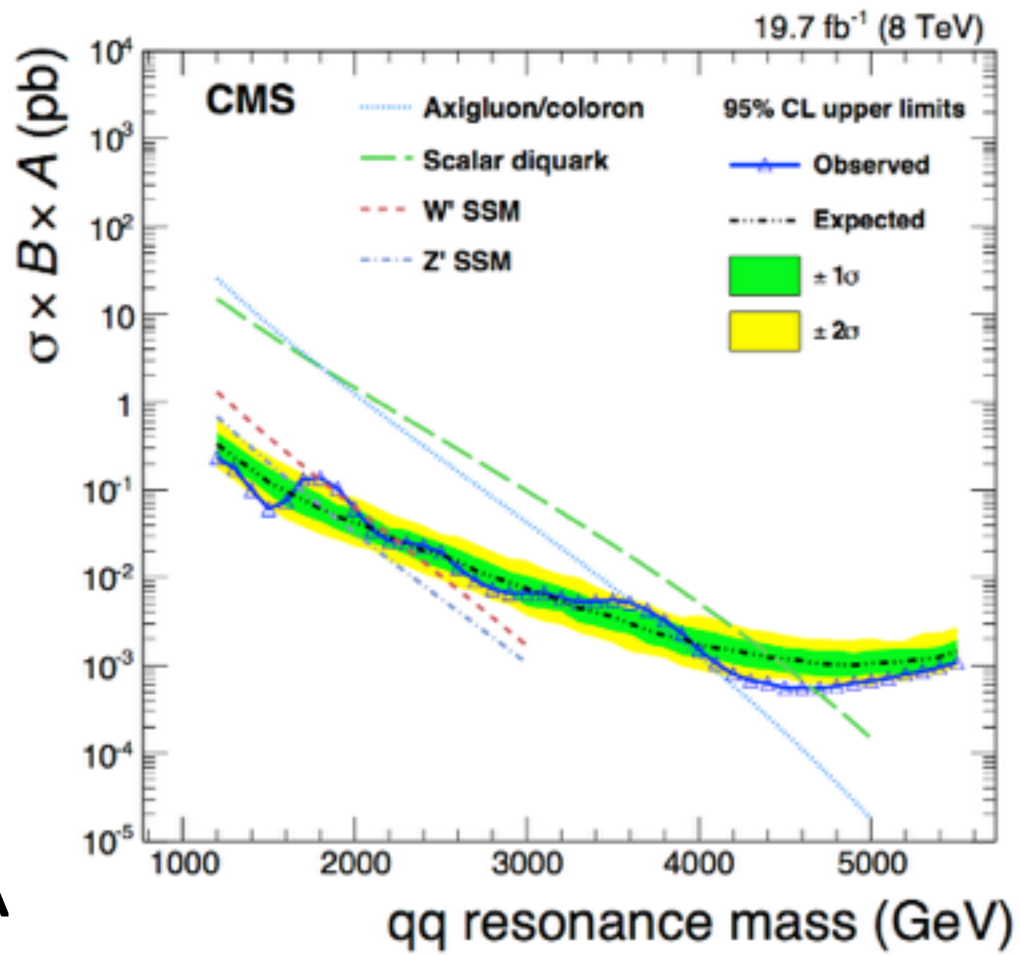
   - e.g. report excesses/limits in σ x BR x A



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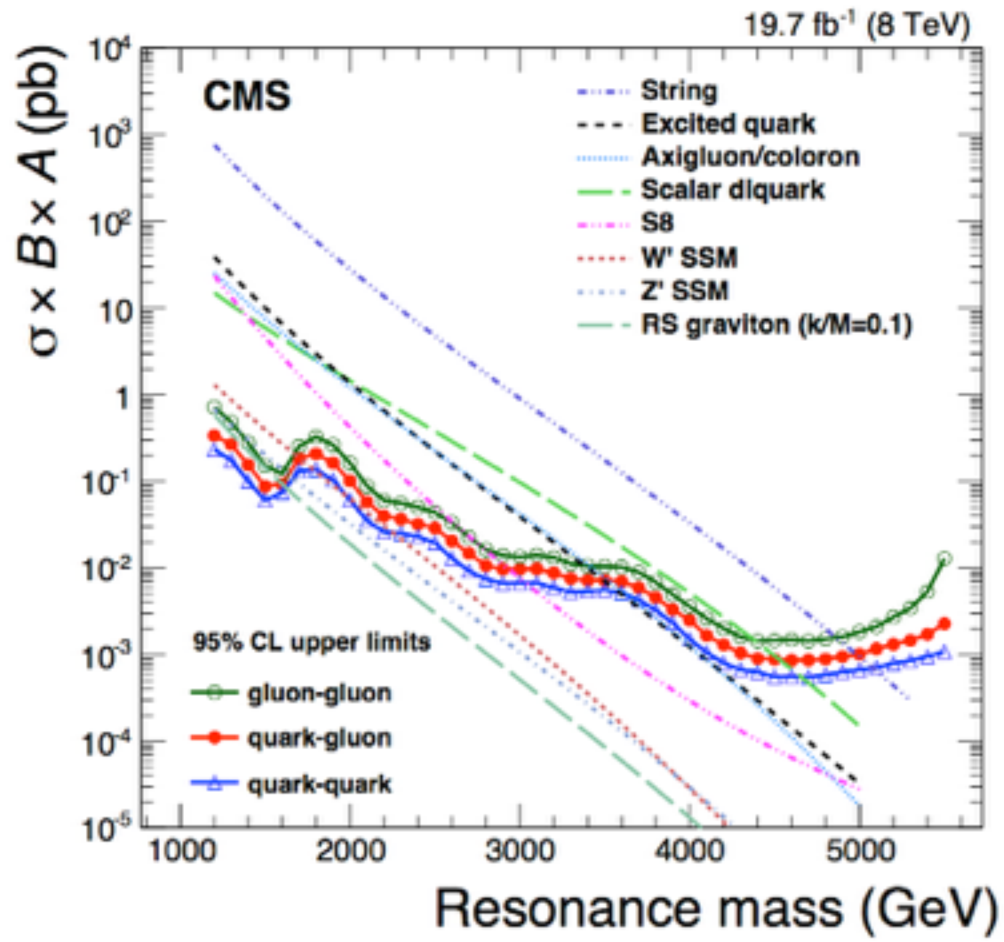
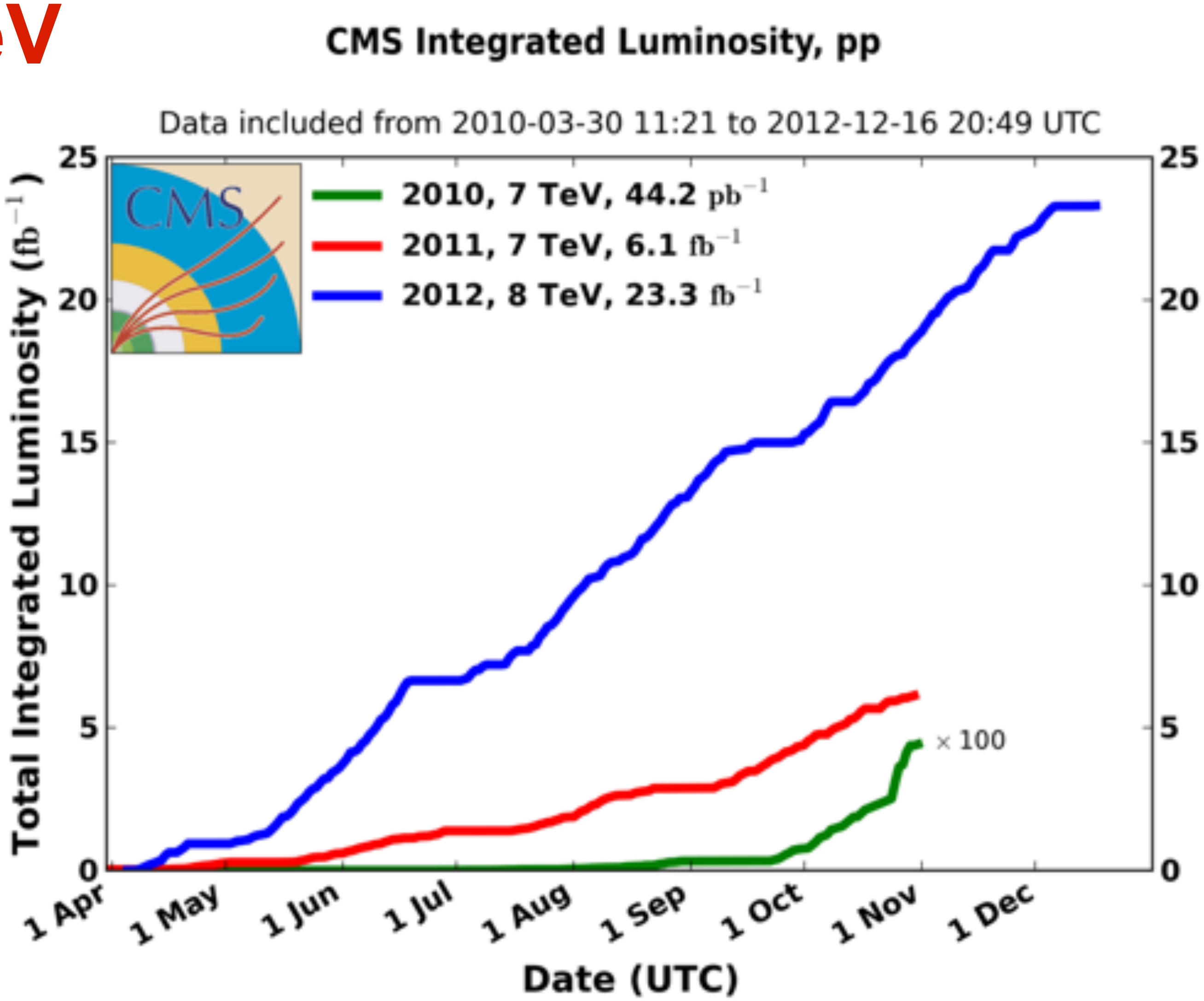


6. Put **constraints in several BSM scenarios**

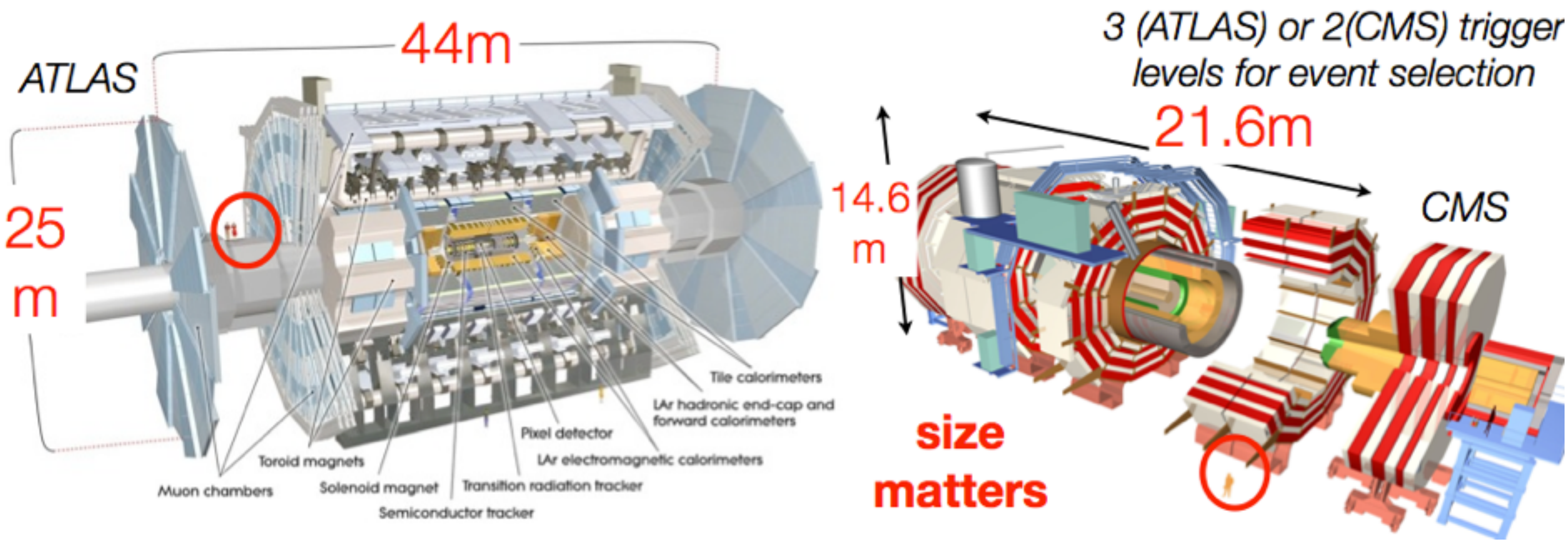
LHC

- **pp collisions at 7TeV and 8TeV**
- **great performance, beyond expectations**
  - luminosity peak ~8 10^{33} $cm^{-2}s^{-1}$
  - 300 pb^{-1}/day
  - 50 ns bunch spacing



- **~23 fb^{-1} @ 8TeV** recorded (+~6fb^{-1}@ 7TeV)
  - **results shown with ~20 fb^{-1} at 8 TeV**
- **~ <20 collisions> per crossing**

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

Objects in High Mass Searches

	pros	*cons*	*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 ET	tagging for W'	hard to calibrate, tails due to detector noise	-	gamma,Z + jets

OBJECTS IN HIGH MASS SEARCHES

I will concentrate on these ones

				on
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
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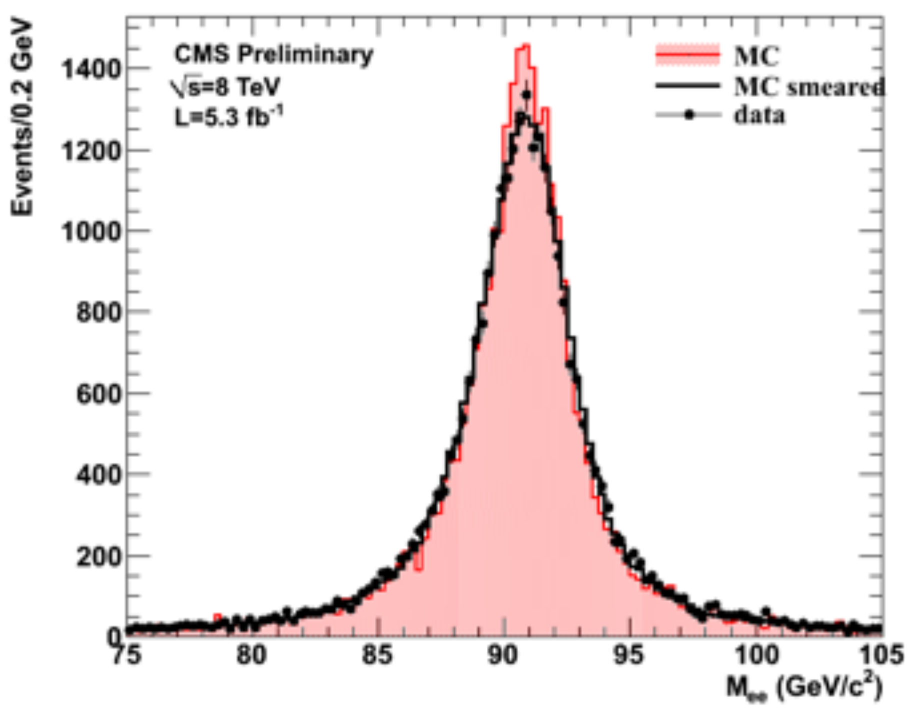
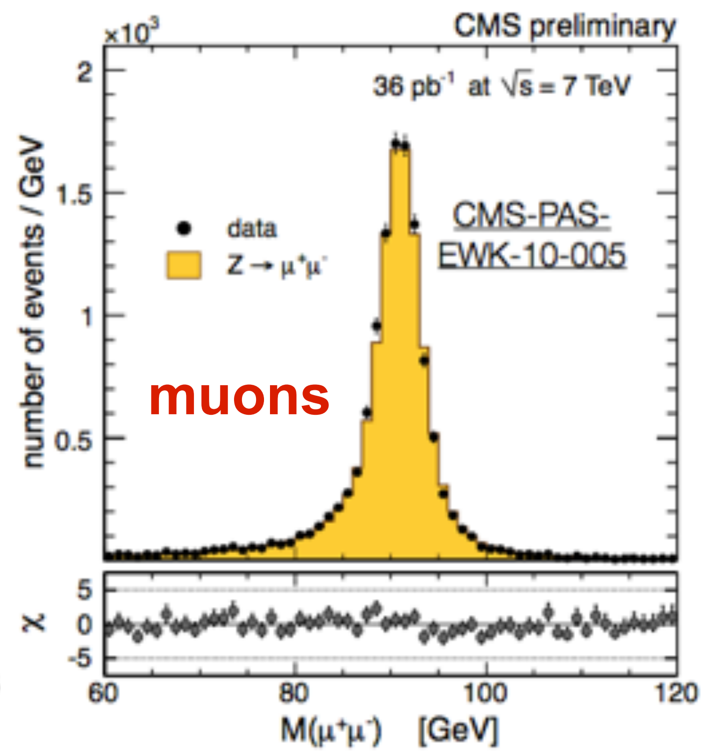
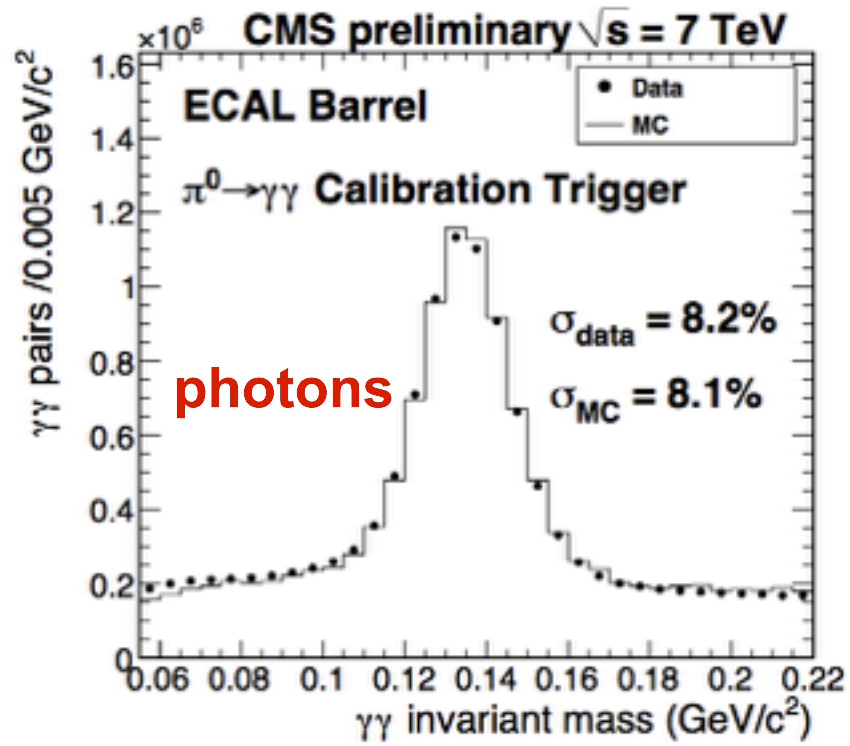
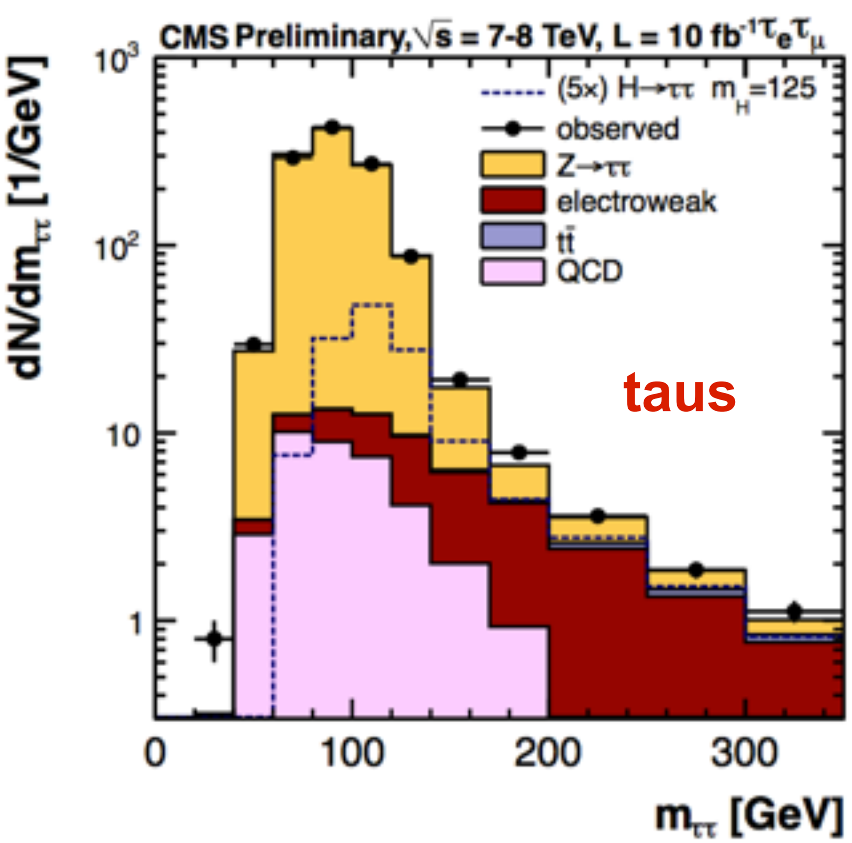
photons	relatively clean	no control samples for scale determination	1-2% at high masses	Z->ee and extrapolations
missing ET	tagging for W’	hard to calibrate, tails due to detector noise	-	gamma,Z + jets

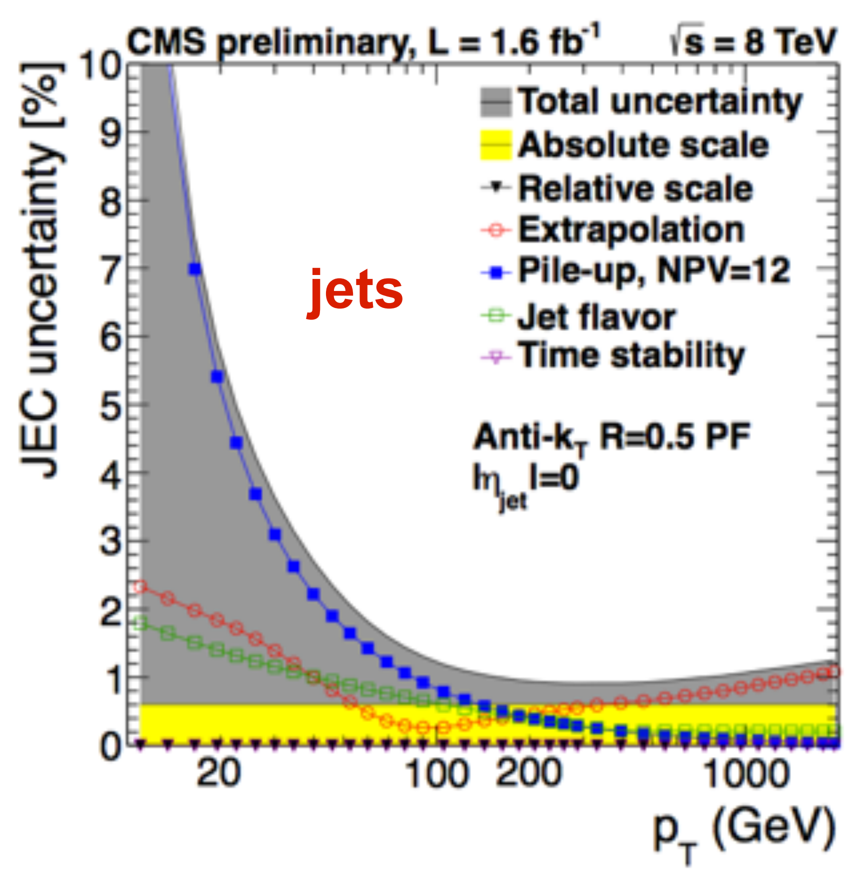
PERFORMANCE OF RECONSTRUCTION

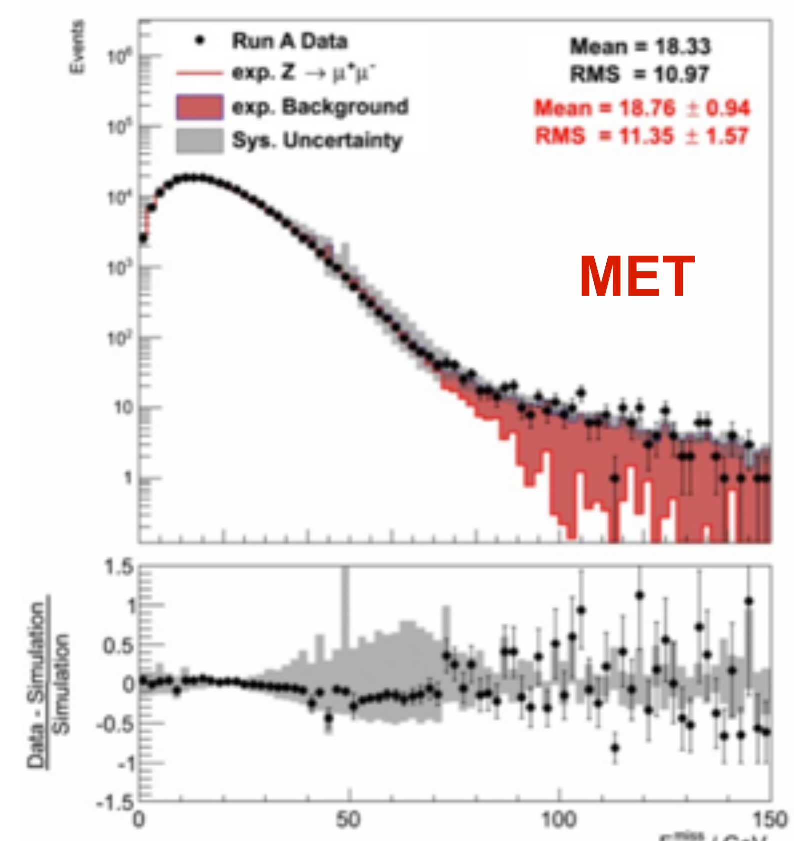












Performance of Reconstruction

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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pho

ide ~70%
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(b-)jets

scale known to 1%-5%
(p_T and η dep.)

MET

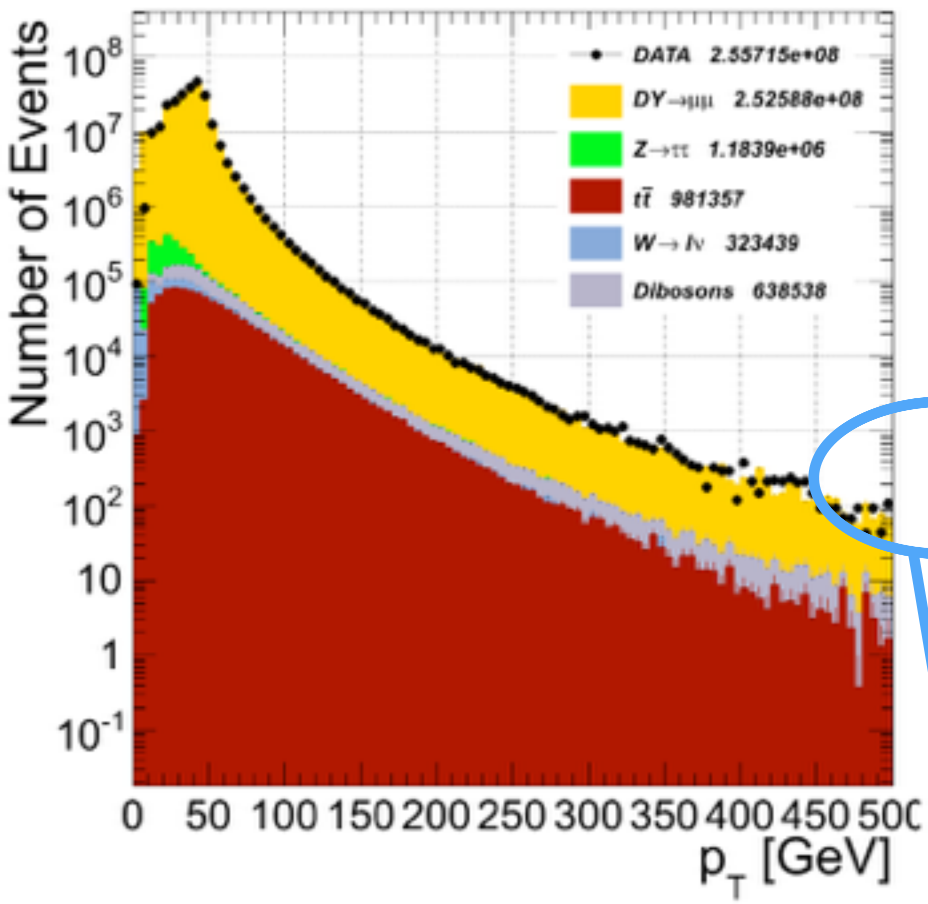
Nice agreement with
simulation
Deep understanding of
impact of PU

But this is for particles from SM processes!

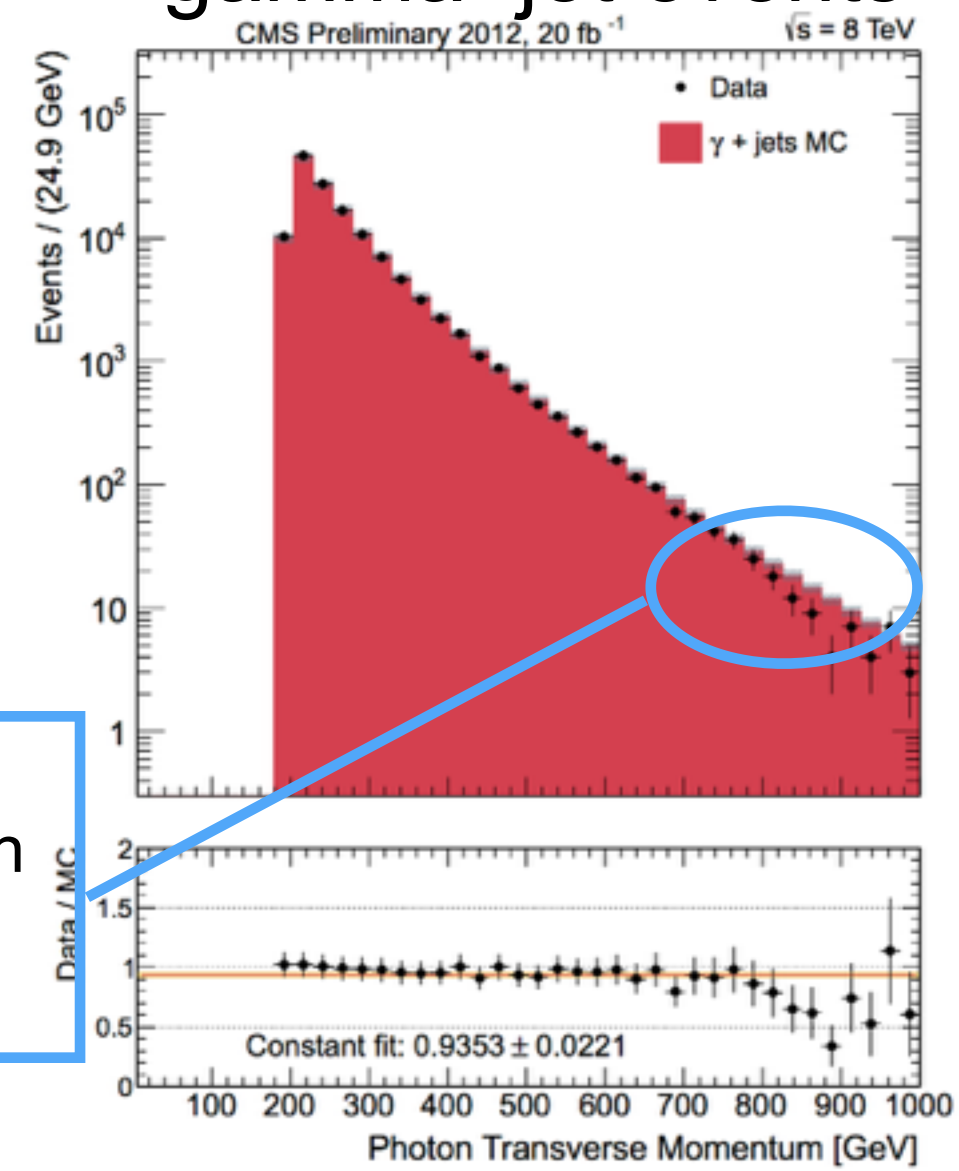
Heavy resonances produce **very energetic objects!**

HIGH MASS: A LIFE W/OUT CONTROL SAMPLES

Z->mumu events



gamma+jet events

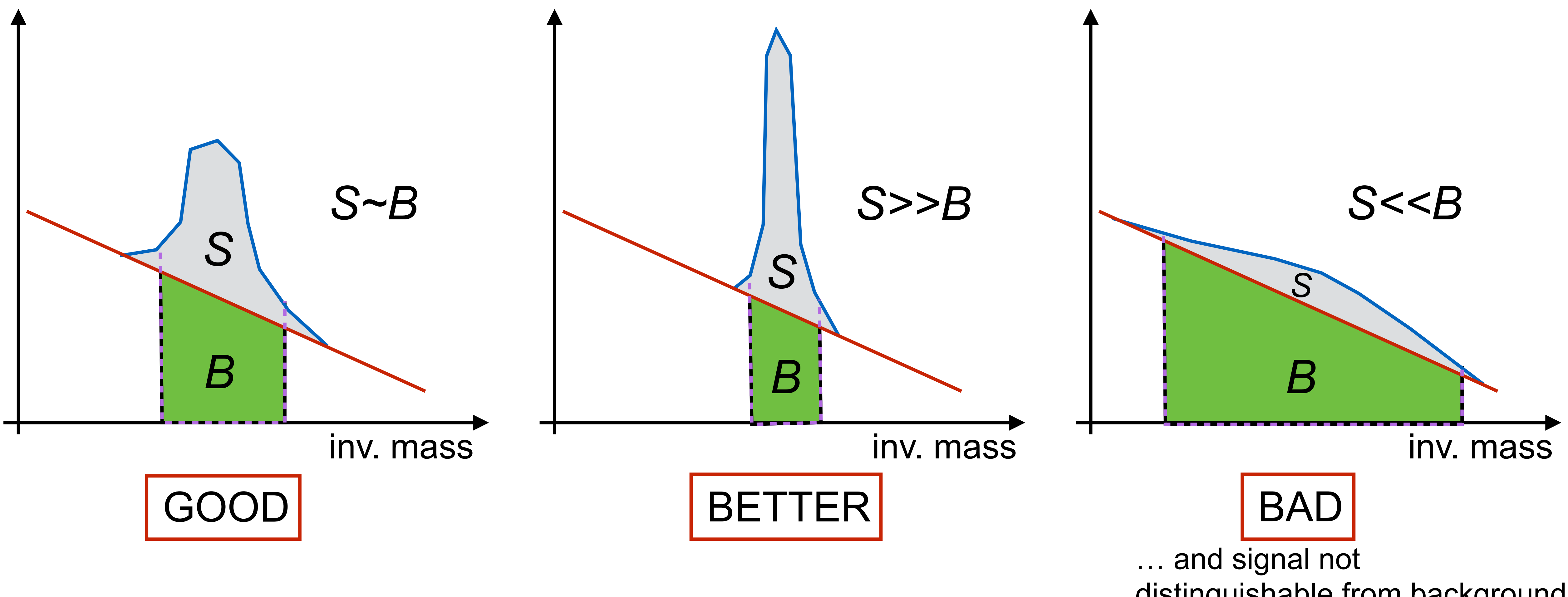


not enough events to calibrate in region where signal is expected!

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

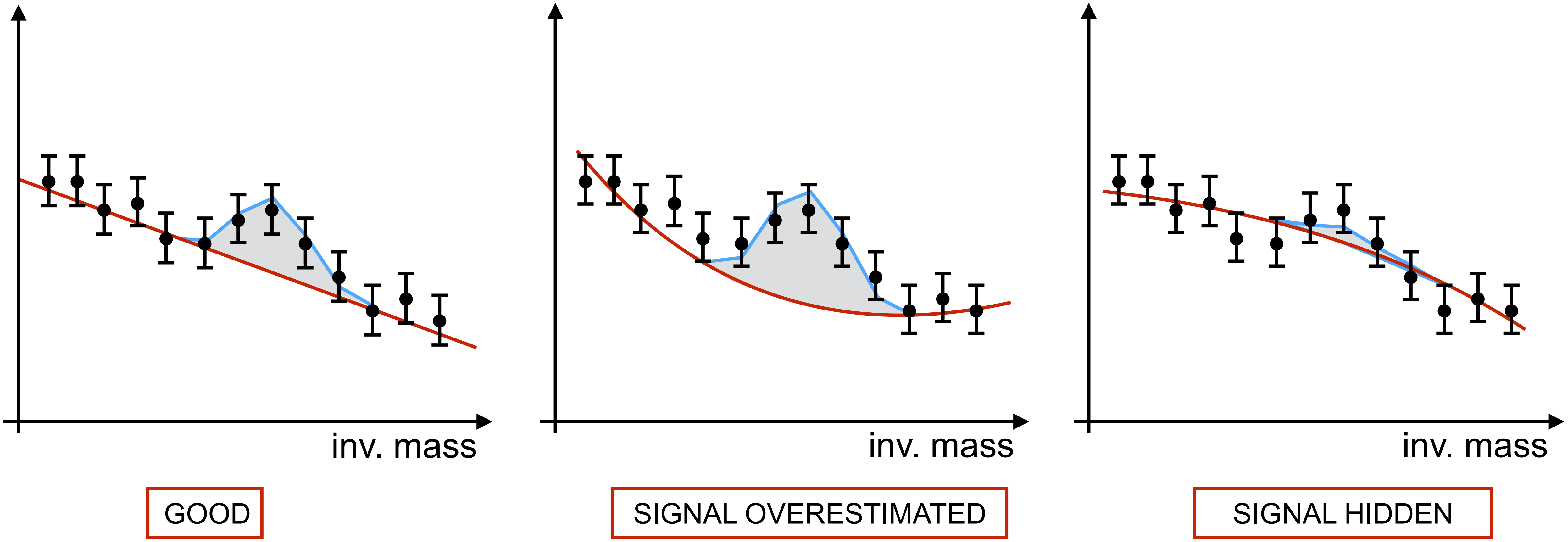
Experimental Issues: Resolution

- **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



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



EXPERIMENTAL ISSUES: BACKGROUND

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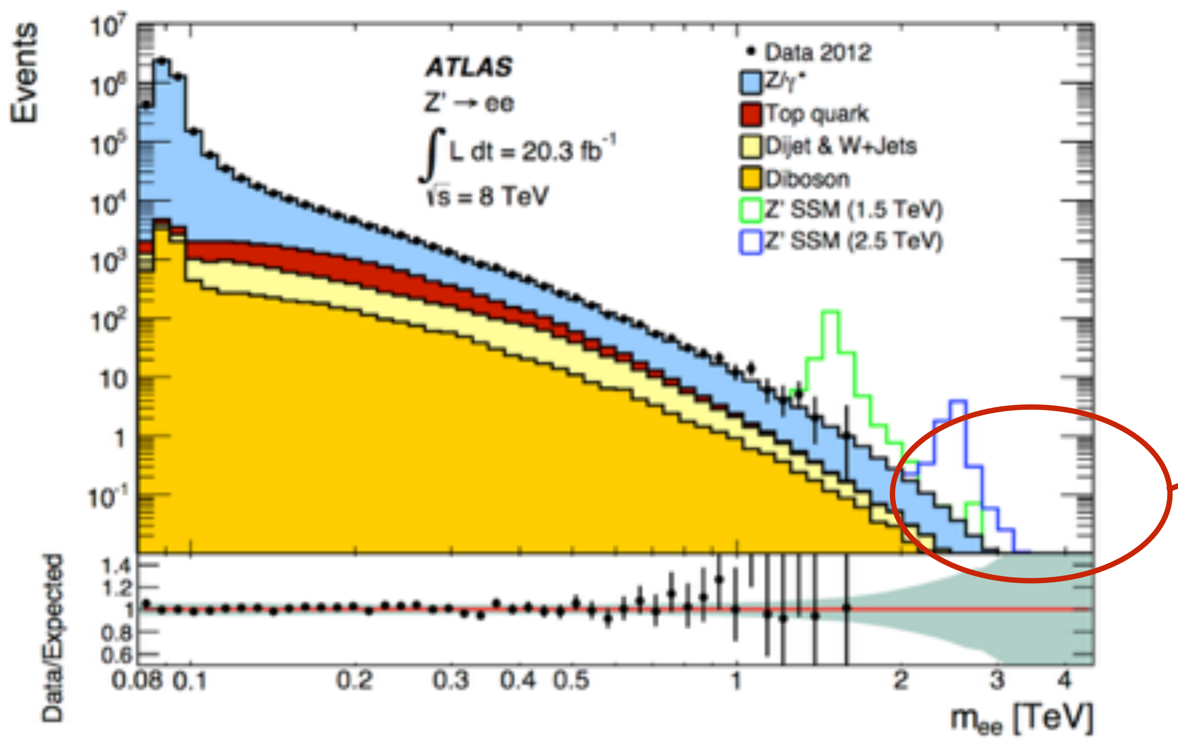
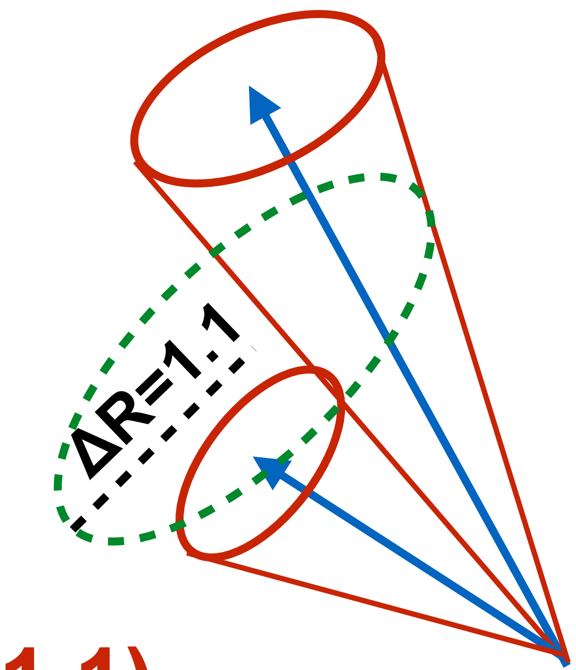


At very high masses no events to tune background. Extrapolation needed

DIJET: INTRODUCTION

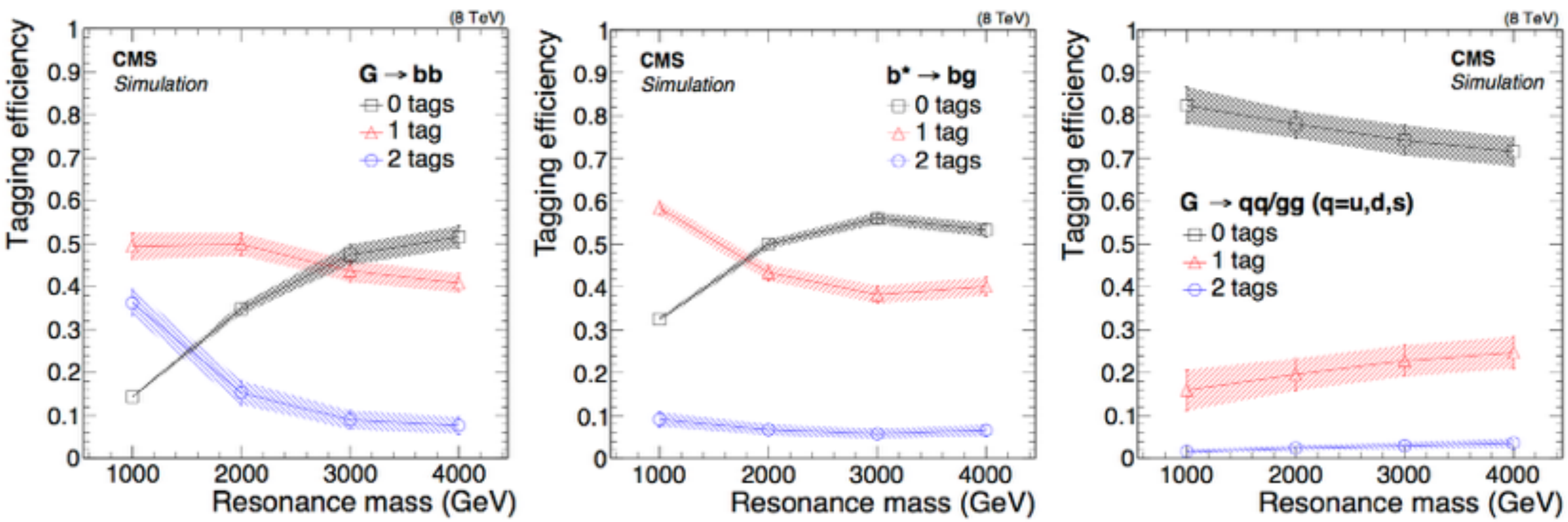
- **Straightforward search, two high pT jet**
- **Different search strategies:**
  - narrow resonances
  - resonances in b jets
  - wide resonances



- **Gluon radiation recovered in wide jets (ΔR=1.1)**
- **Several interpretations. Among them:**
  - excited quarks (q_*) including excited b quarks (b_*)
  - the color-octet scalar (S8) resonances
  - new gauge bosons (W′ and Z′) with SM-like couplings (SSM);
  - Randall–Sundrum (RS) gravitons (G)
  - QBHs

DIJET: SELECTION (CMS)

- **Trigger** requirements:
  - **L1**: HT > 150GeV,
  - **HLT:** HT>650GeV or m_{jj}>750GeV with |Deta|<1.5
- **Kinematics**: pT(jet) > 30GeV, |eta| < 2.5, m_{jj} > 890GeV
- **btagging**: combined secondary vertex (CSV)
  - to increase sensitivity in resonances decaying in bjets (Z', RS graviton, b*)

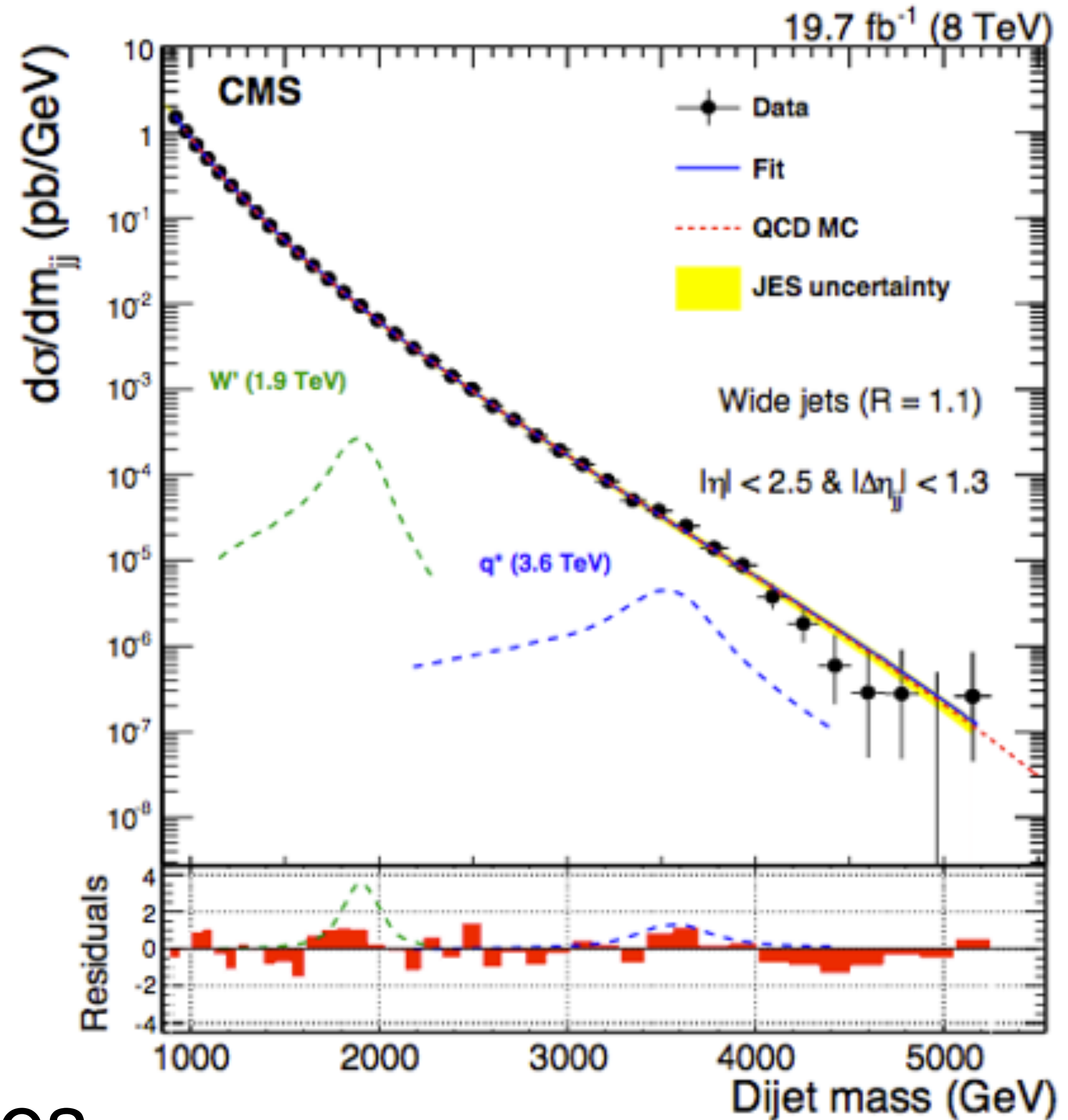


DIJET: SPECTRUM AND MODELING (CMS)

- **Background fitted** with

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

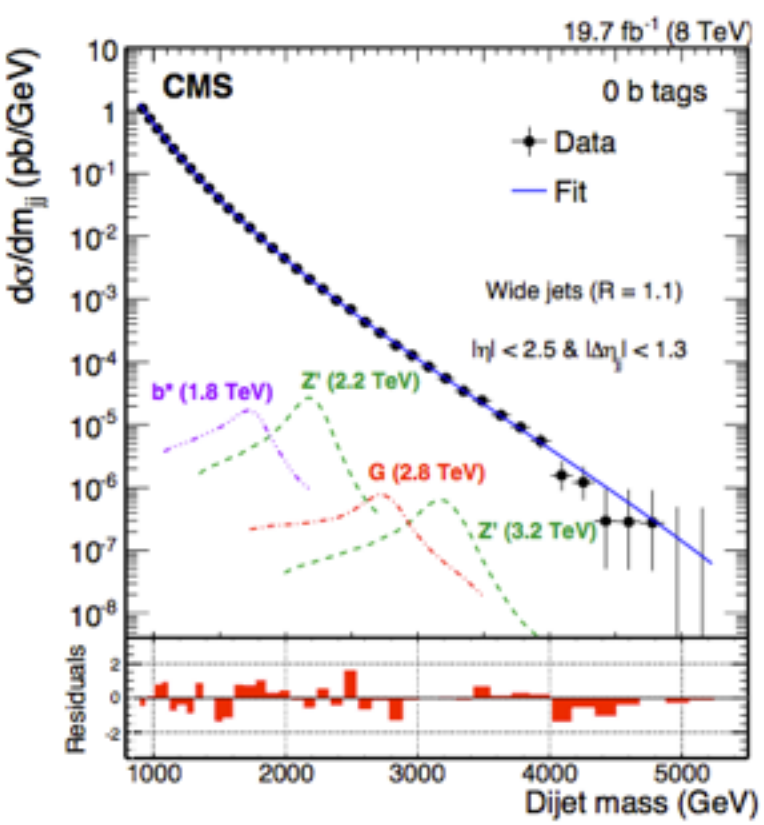
- **Signal shape** for:
  - RS gravitons (gg and qq)
  - excited quarks for (gq)
  - for b* enriched b categories used
- **Wide resonances** RS gravitons
  - k/MPl parameter varied, up to 30%
- **QBH modeled** with different masses
  - shapes independent on MD and n
- **Signal extracted** using a binned likelihood approach



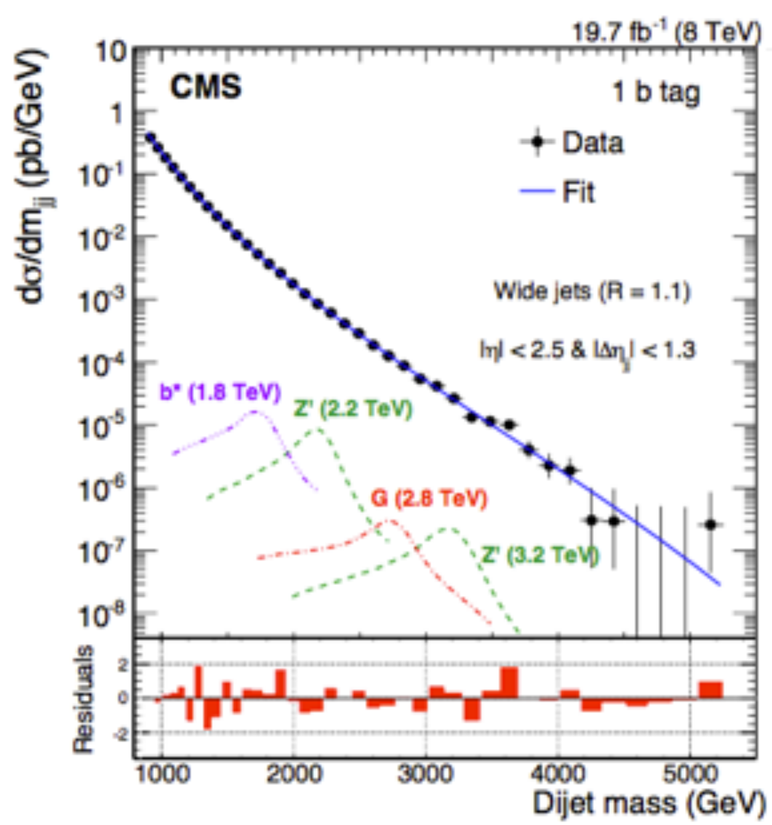
DIJET: B-TAGGING CATEGORIES

- no excess

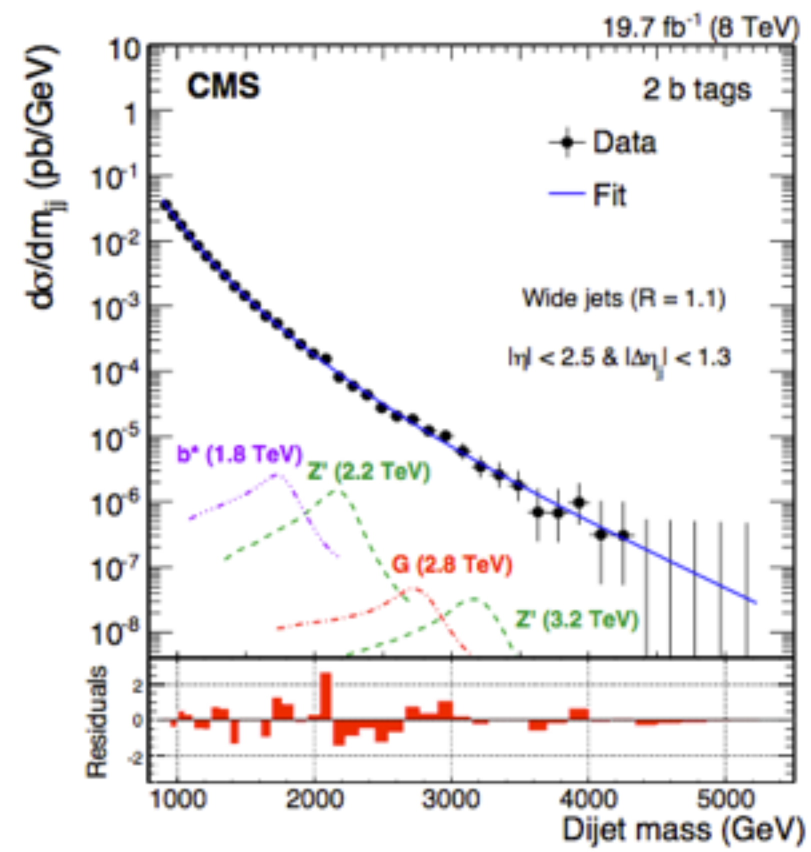
0 btag



1 btag

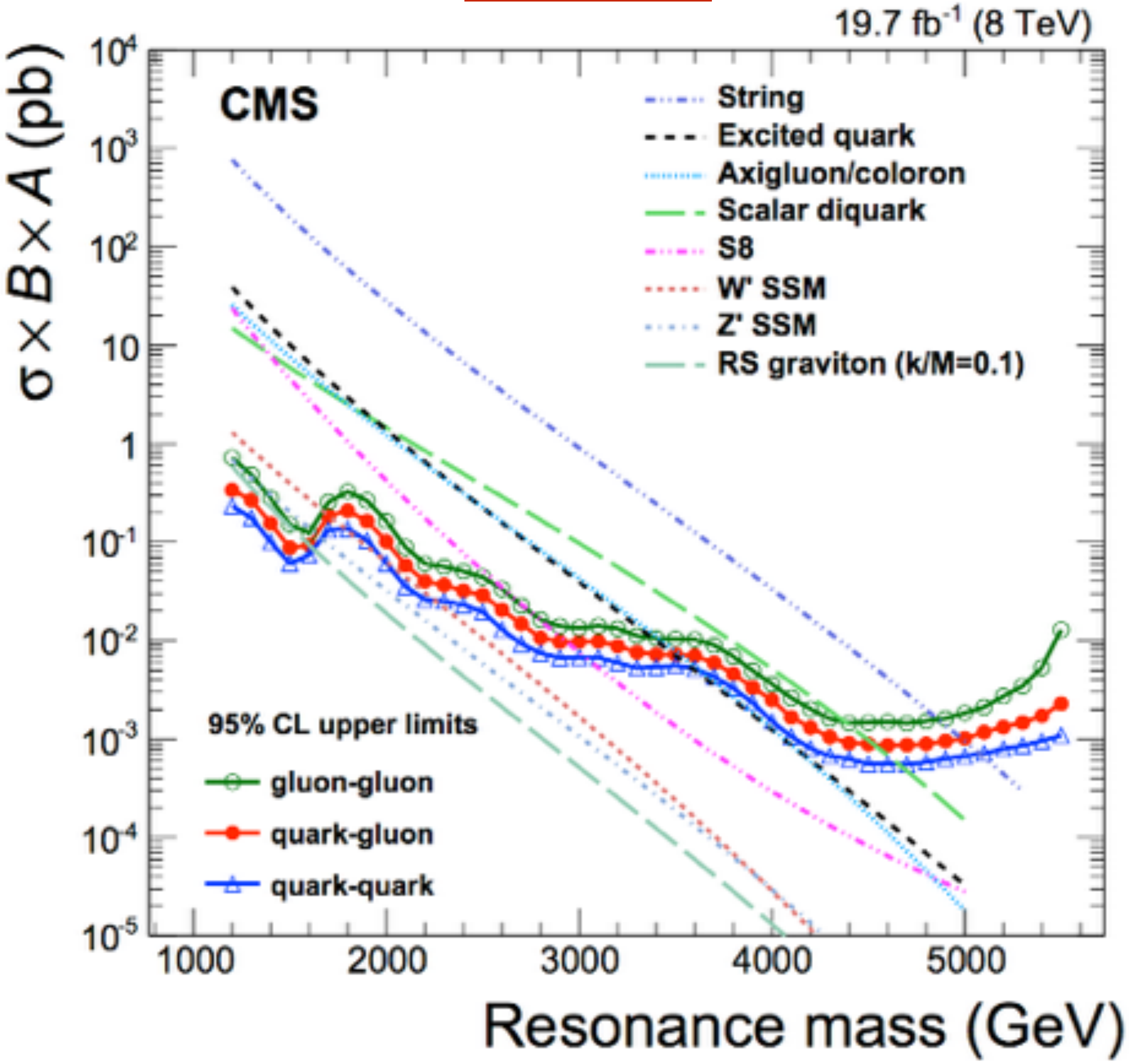


2 btags

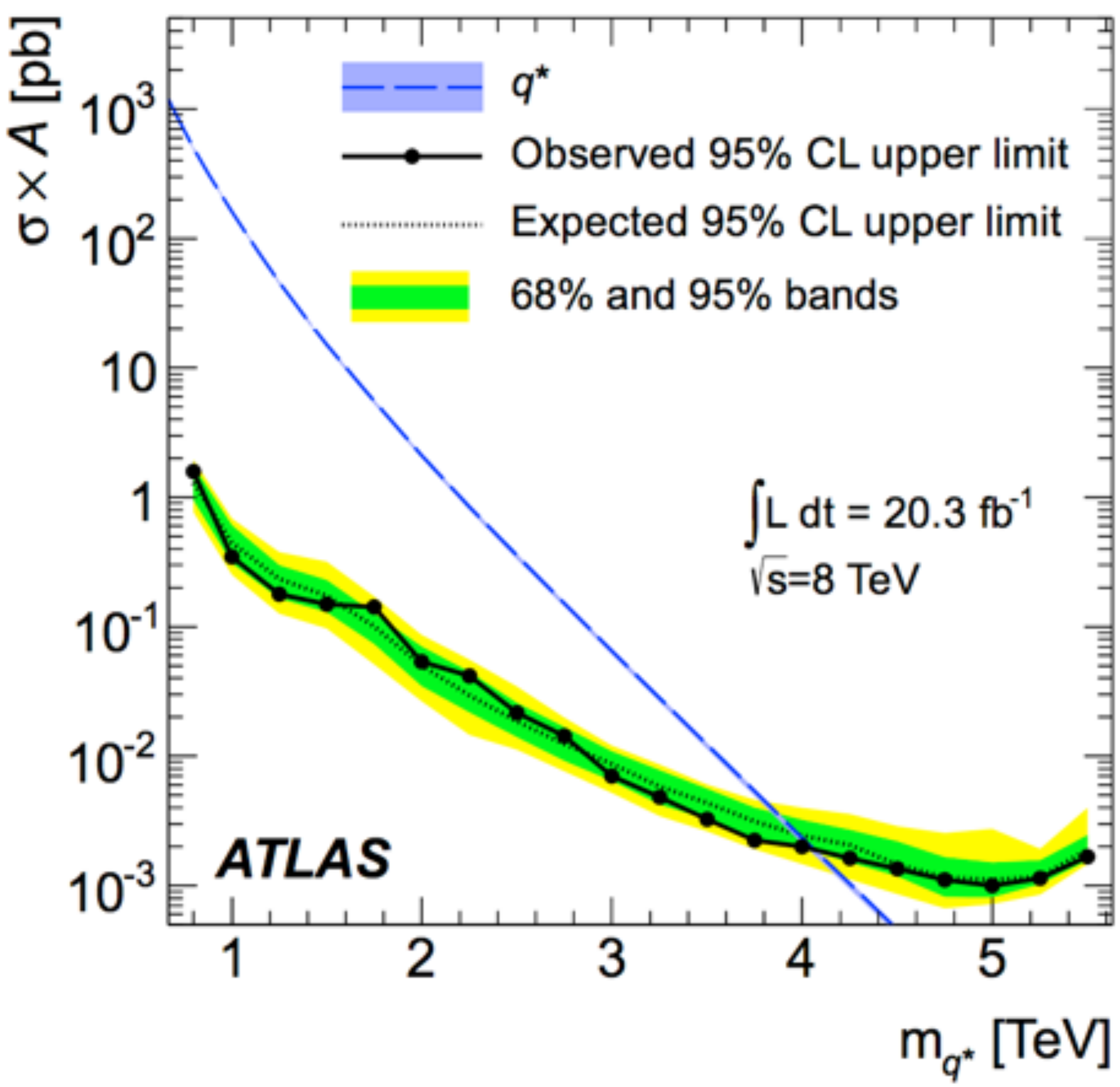


DIJET: LIMITS (I)

CMS



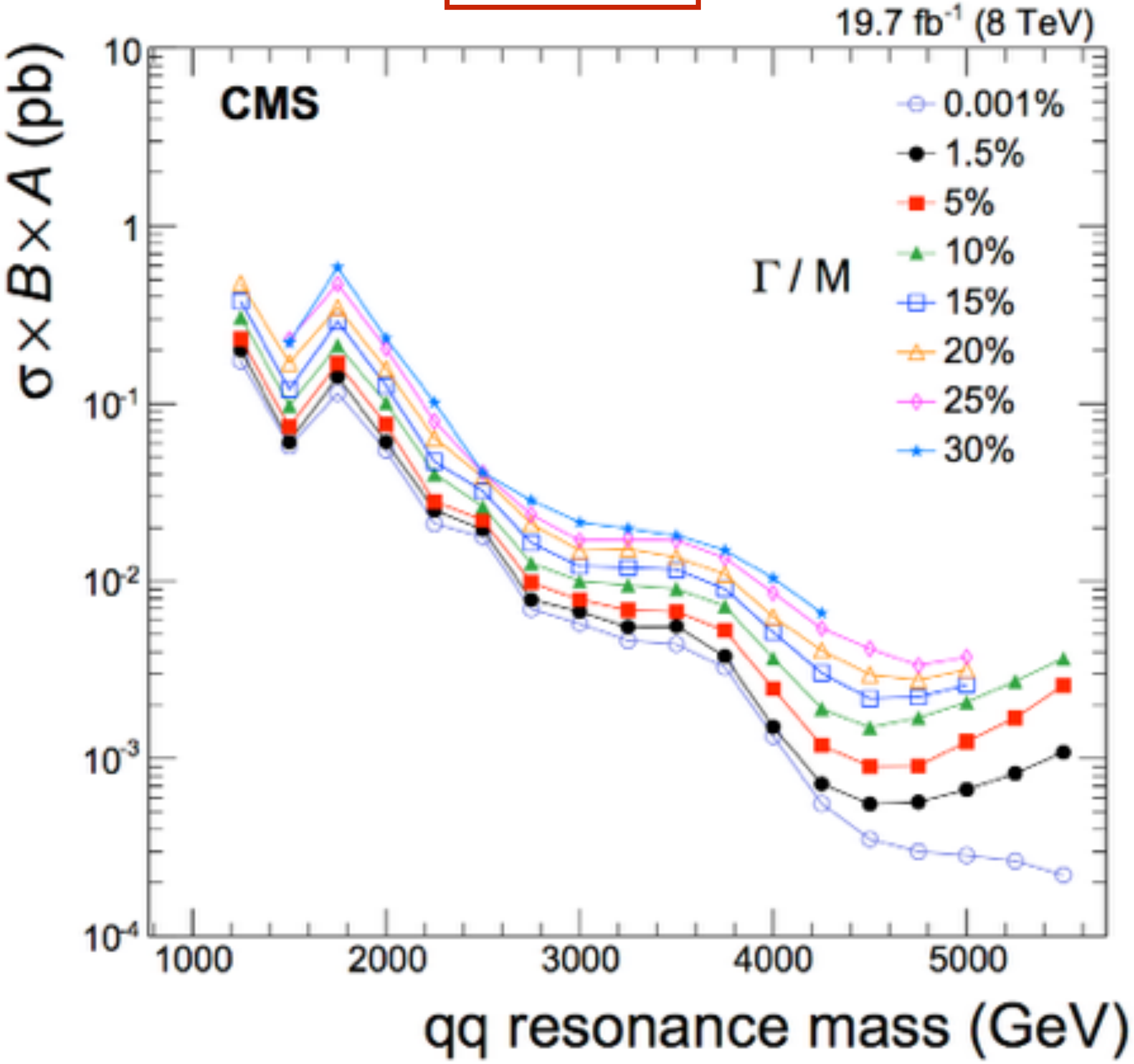
ATLAS



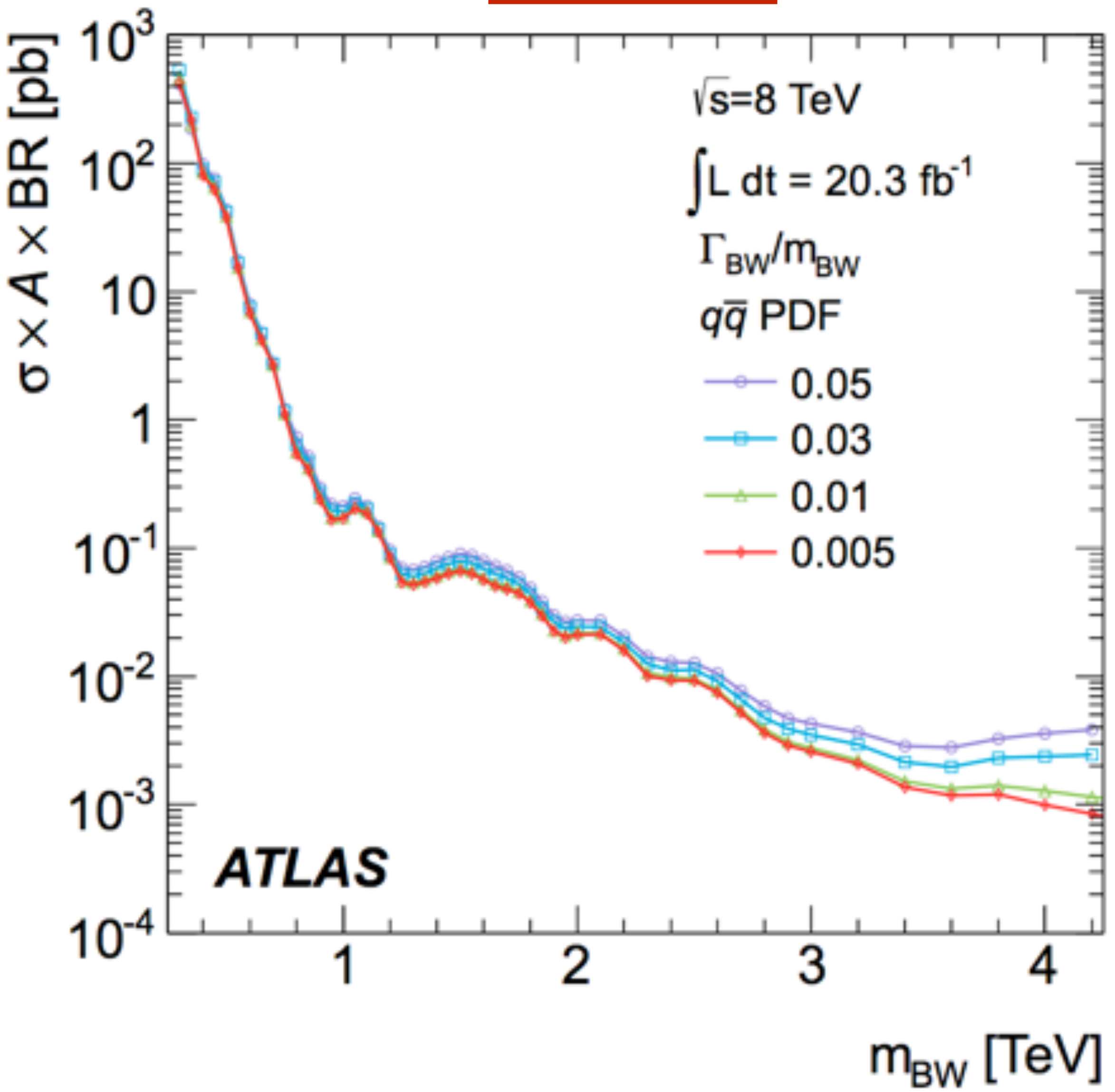
DIJET: LIMITS (II)

- **Limits for wide resonances**
- Similar results for ATLAS and CMS

CMS



ATLAS



DIJET: INTERPRETATION

CMS

Model	Final state	Observed mass exclusion (TeV)	Expected mass exclusion (TeV)
Inclusive search			
String resonance (S)	qg	[1.2,5.0]	[1.2,4.9]
Excited quark (q^*)	qg	[1.2,3.5]	[1.2,3.7]
E_6 diquark (D)	qq	[1.2,4.7]	[1.2,4.4]
W' boson (W')	$q\bar{q}$	[1.2,1.9] + [2.0,2.2]	[1.2,2.2]
Z' boson (Z')	$q\bar{q}$	[1.2,1.7]	[1.2,1.8]
RS graviton (G), $k/\overline{M}_{\mathrm{Pl}} = 0.1$	$q\bar{q} + gg$	[1.2,1.6]	[1.2,1.3]
b-enriched search			
Excited b quark (b^*)	bg	[1.2,1.6]	
Wide resonance search			
Axigluon (A)/coloron (C)	$q\bar{q}$	[1.3,3.6]	
Color-octet scalar (S8)	gg	[1.3,2.5]	

ATLAS

Model and Final State	95% CL Limits [TeV] Expected	Observed
$q^* \to qg$	3.99	4.09
$s8 \to gg$	2.83	2.72
$W' \to q\bar{q}'$	2.51	2.45
Leptophobic $W^* \to q\bar{q}'$	1.93	1.75
Leptophilic $W^* \to q\bar{q}'$	1.67	1.66
QBH black holes (q and g decays only)	5.82	5.82
BLACKMAX black holes (all decays)	5.75	5.75

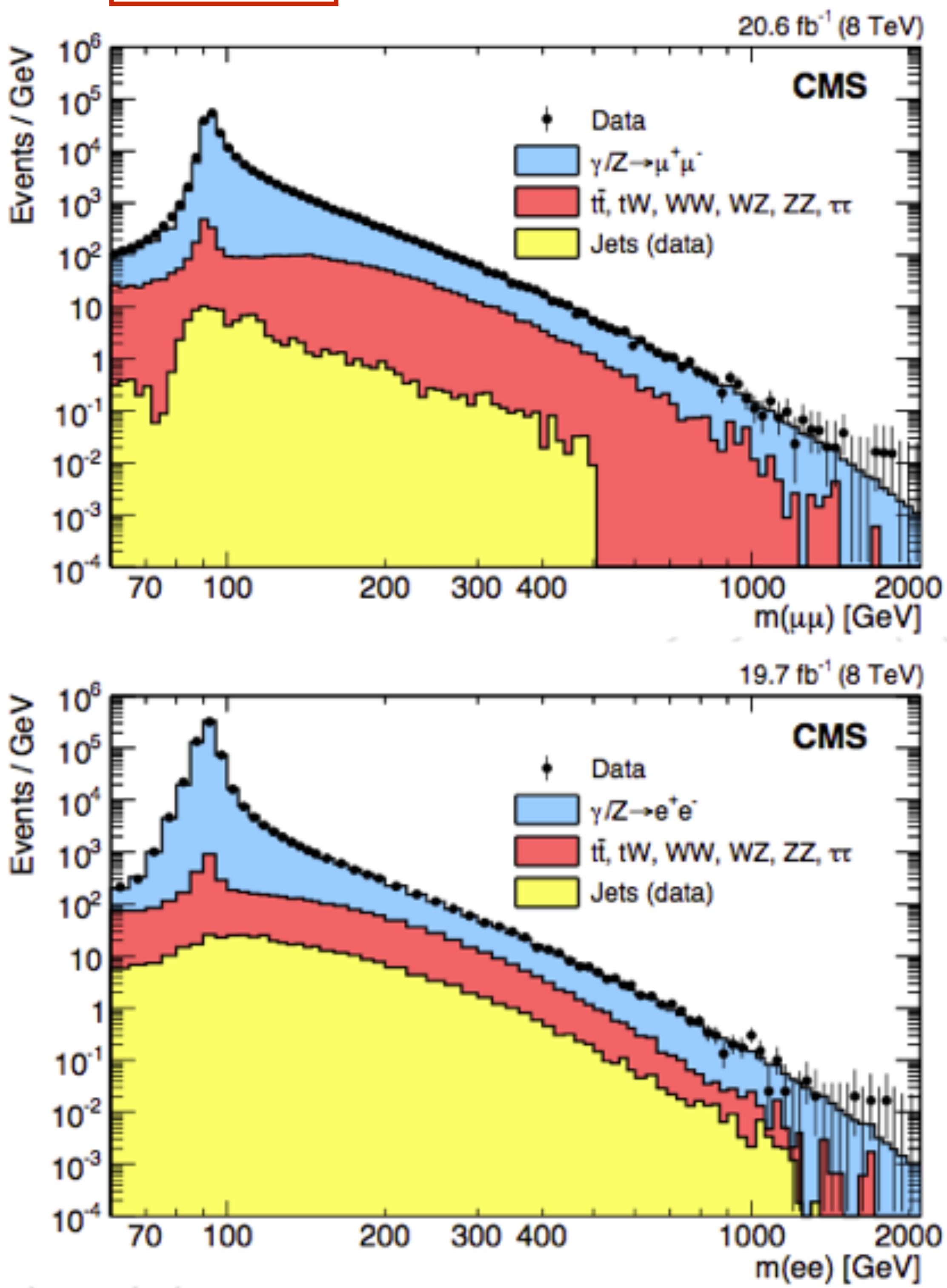
Dilepton: Intro

- **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:**
  - trigger: single and double lepton triggers
  - offline: pt(leptons)>25-40 GeV + isolation
  - A x efficiency not very different between spin 1 and 2 resonances
- **Efficiency**: Z-based tag and probe for linearity check
- **Interpretations for resonance:**
  - Z'_{SSM}, Z'_{ψ}
  - Kaluza-Klein graviton (G_{kk})

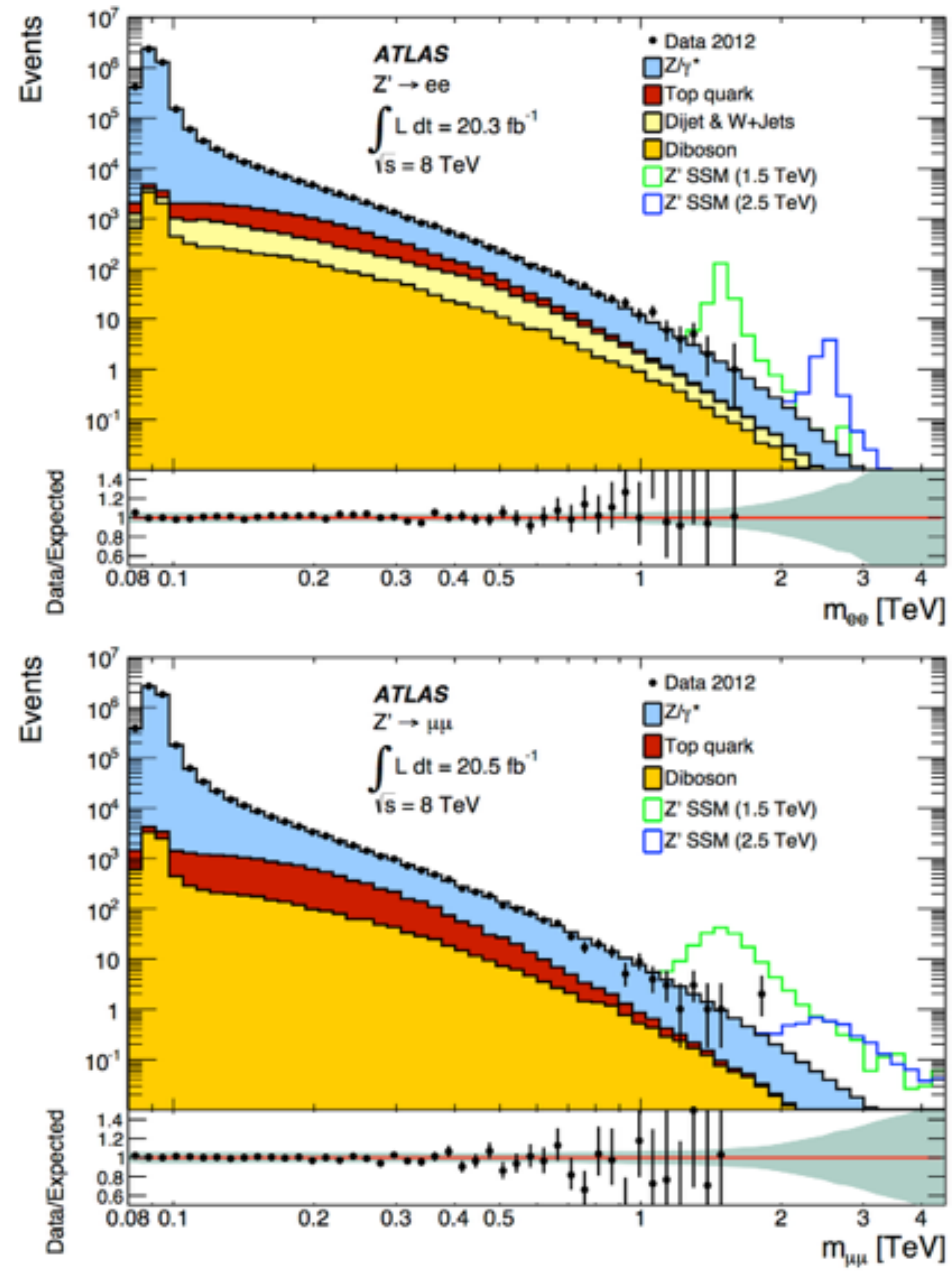
DILEPTON: SPECTRUM

no evident excess

CMS



ATLAS



DILEPTON: LIMIT EXTRACTION

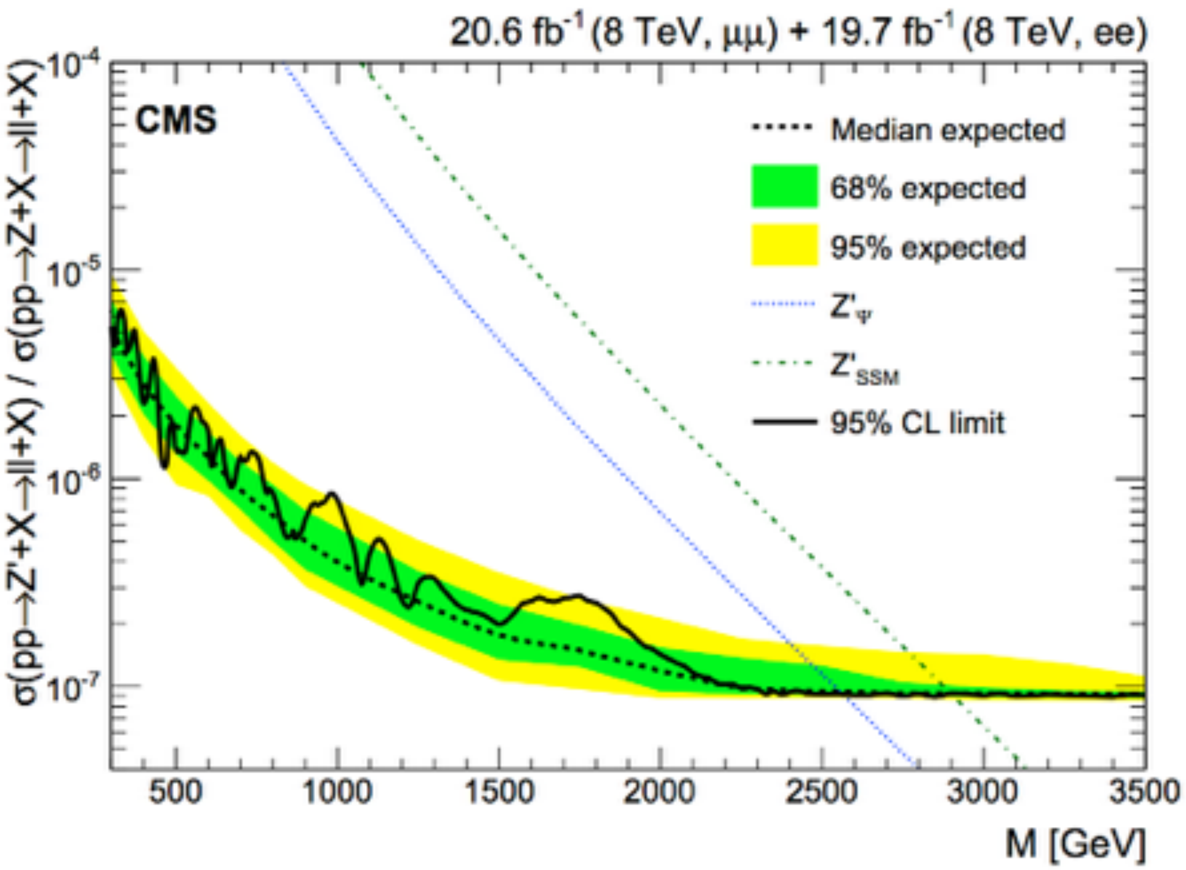
- **CMS**: to reduce systematics due to efficiency, extracted via :

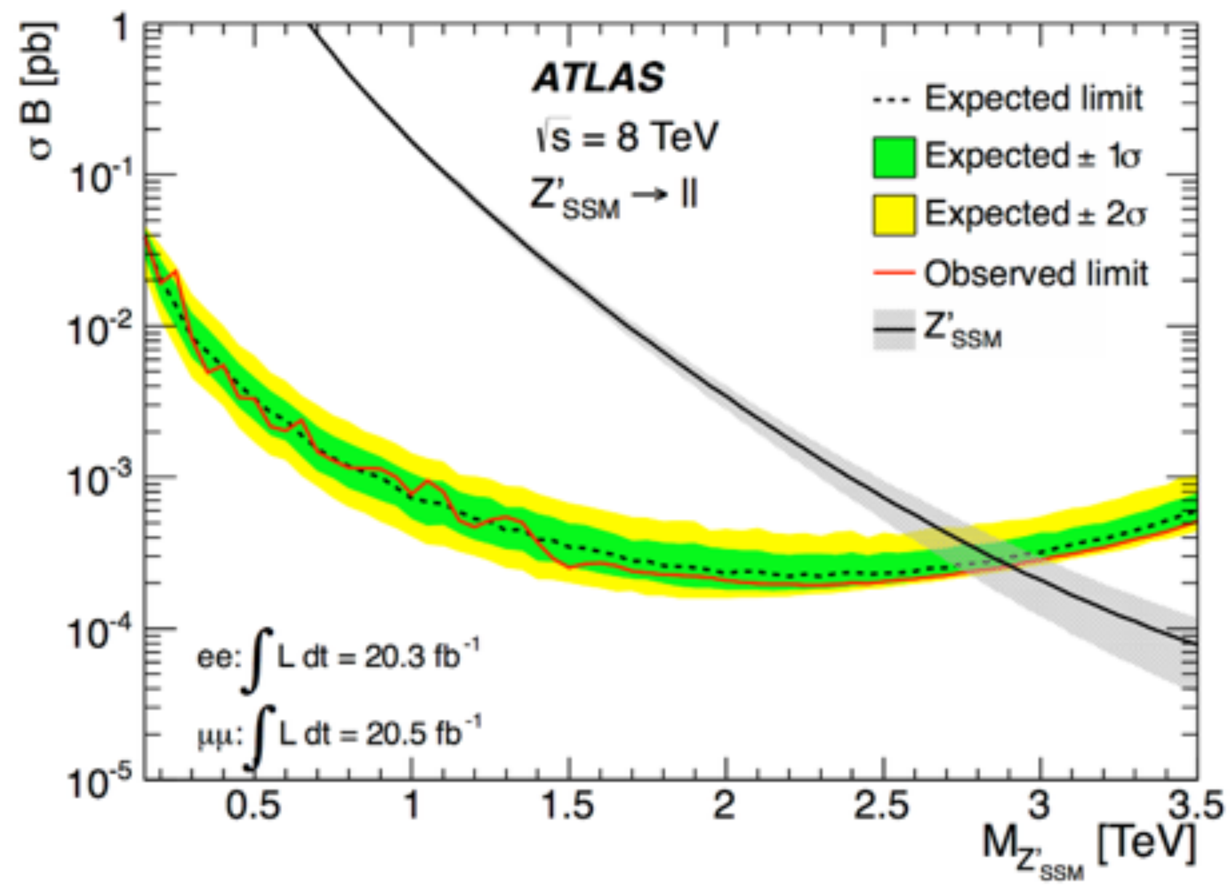
$$R_\sigma = \frac{\sigma(\mathrm{pp} \to \mathrm{Z}' + X \to \ell\ell + X)}{\sigma(\mathrm{pp} \to \mathrm{Z} + X \to \ell\ell + X)}$$

  - Z' events counted in mass ± 5%, Z in mass ± 30GeV
  - mass window form Z' to reduce interference and PDF effects
- **ATLAS**: MC shapes with a likelihood fit assuming no interference
- **DY background from MC** (shape is parametrized for CMS)
- **Fake leptons** from data-driven approaches
- **Systematics** (similar between experiments):
  - efficiency (PDF-detector) 3-6% in acceptance
  - alignment in muons 5%(resonant) up to 41% for non-resonant
  - PDF in background 5-10% dependent on mass

DILEPTON: INTERPRETATION

- **Very similar limits set by the two experiments**
- **Z' excluded below 2.5 - 3 TeV**





Z'_{SSM} m < 2.90 TeV
Z_{ψ} m < 2.57 TeV
G_{KK} m < 2.73, 2.35, and 1.27 TeV
for couplings of 0.10, 0.05, and 0.01

Z'_{SSM} m < 2.90 TeV
Z_{ψ} m < 2.51 TeV
G_{KK} m < 2.68, 2.28, and 1.25 TeV
for couplings of 0.10, 0.05, and 0.01

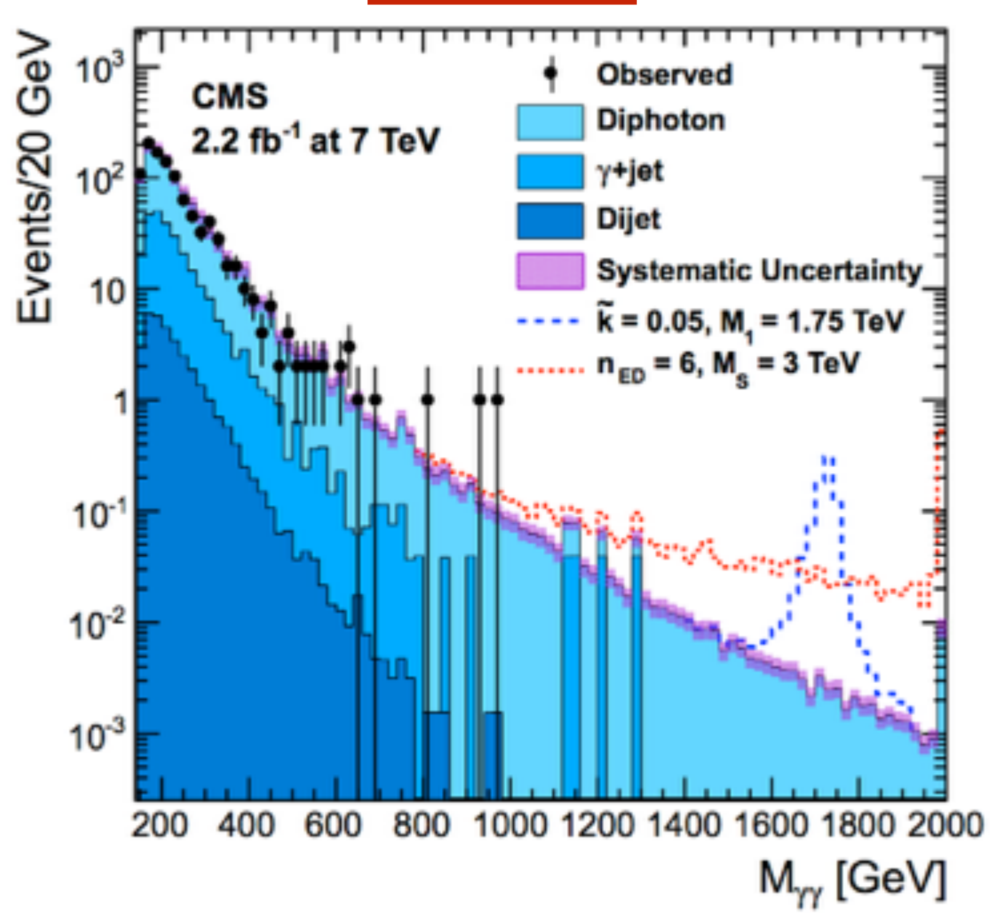
DIPHOTON: INTRO

- Approach **very similar to the dielectron analysis**
- **Diphoton triggers**, pT > 20 GeV
- Selection based on simple kinematics and isolation criteria
- **Main background**: SM diphoton production
  - shape taken from MC
  - normalization from low mass region
- **Fake photon contribution from control samples**
  - less than 10% of total background

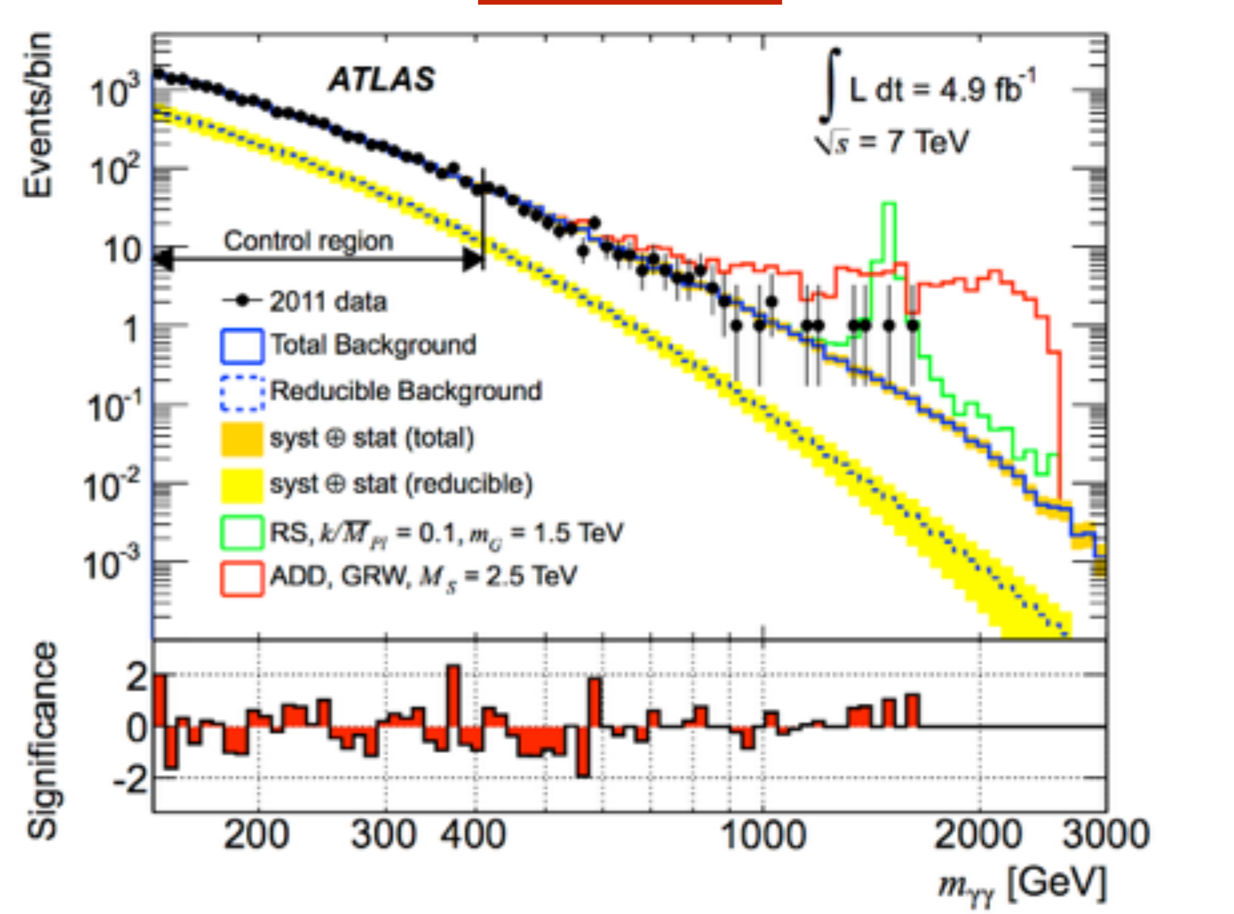
DIPHOTON: SELECTION AND SPECTRA

- Results only **with partial statistics (2 - 5 fb^{-1})**
  - maybe update soon with full statistics
- **No excess**
- Limits on RS Graviton set in the range ~1 – 2 TeV depending on k/M_{Pl}

CMS

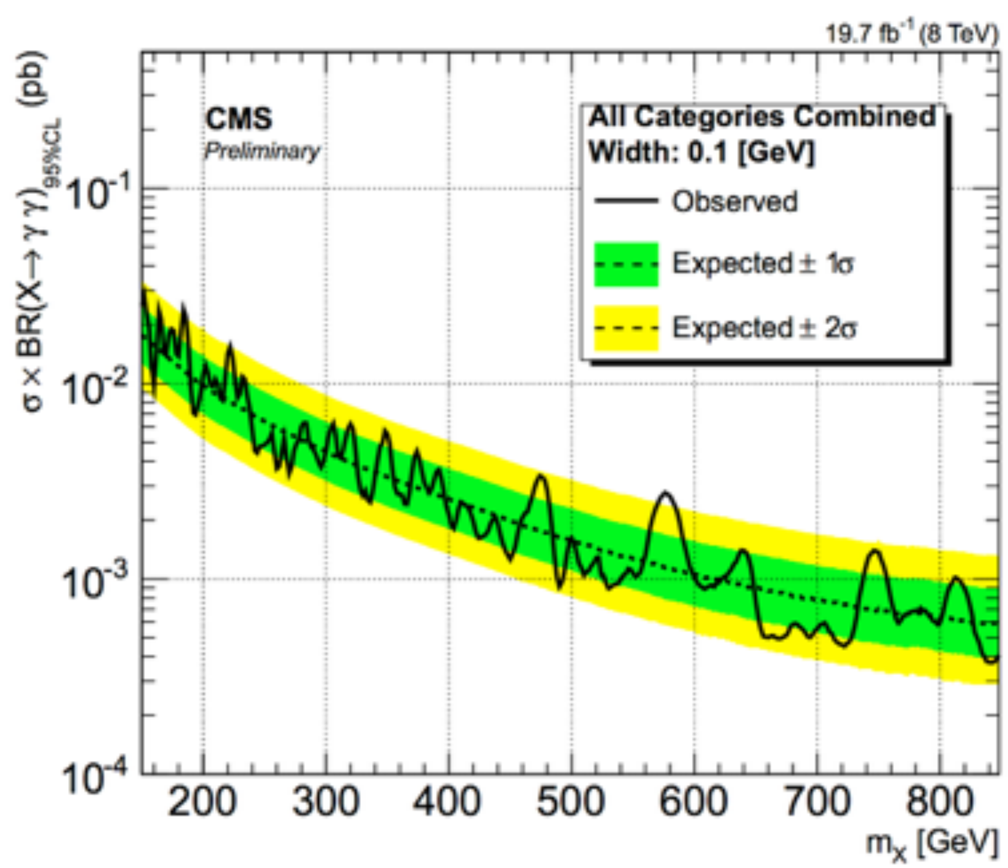


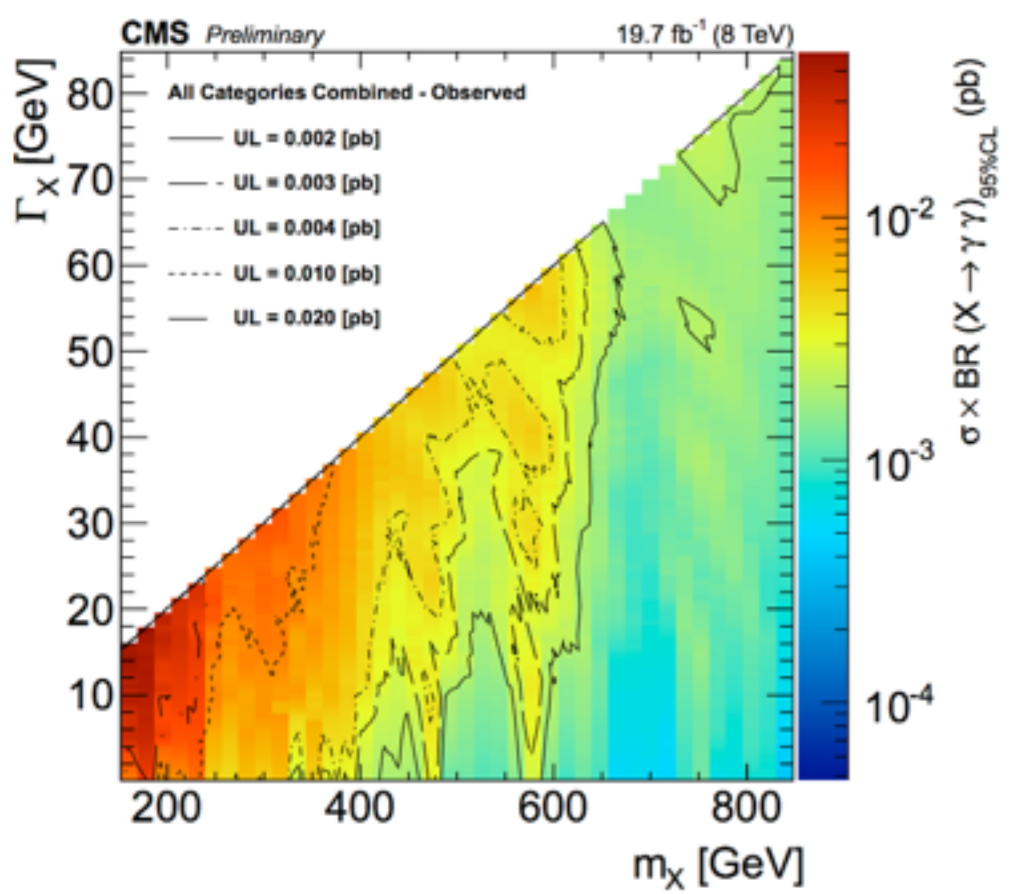
ATLAS



DIPHOTON: INTERMEDIATE MASSES

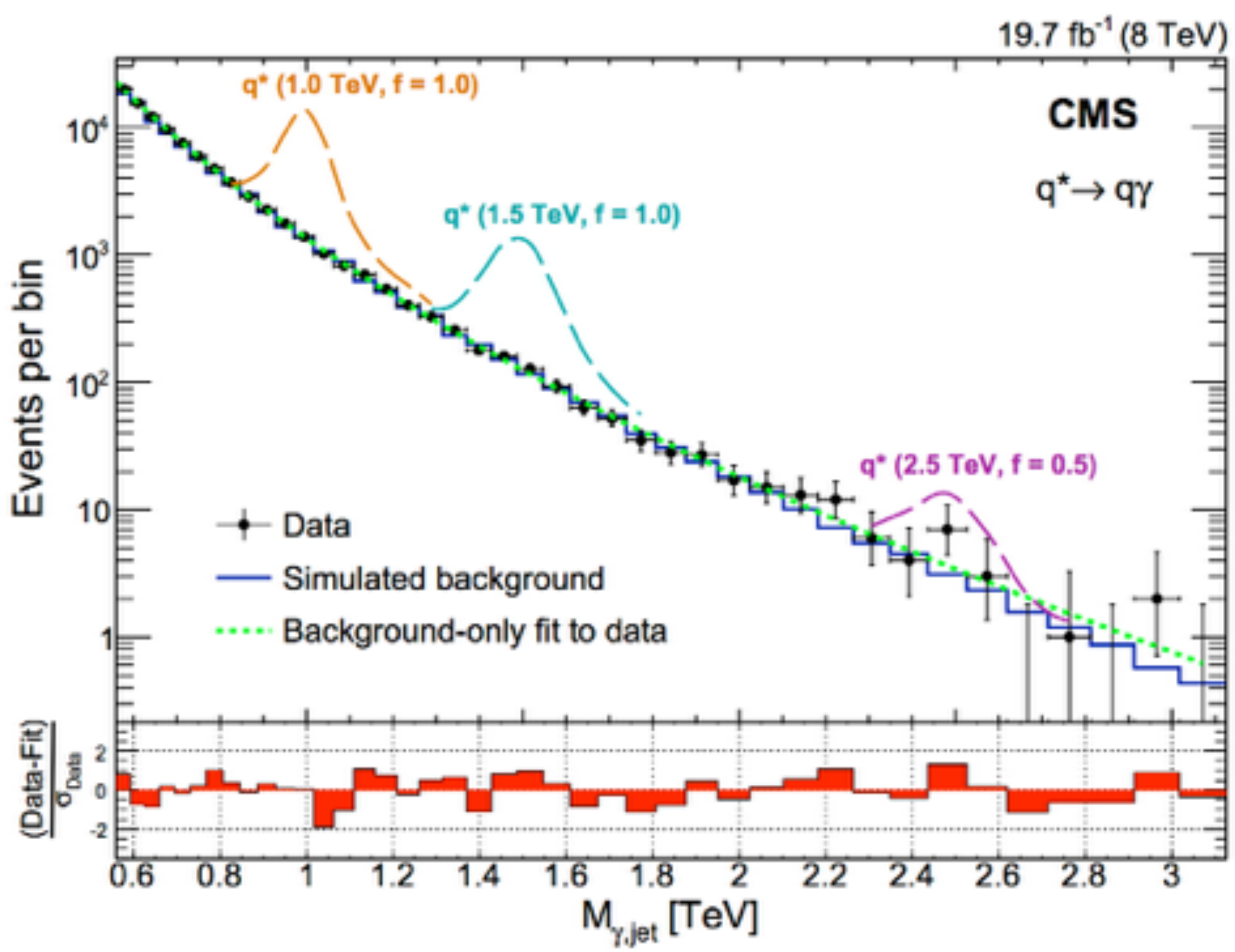
- New interest in **scrutinize the intermediate mass range** (<1TeV), done in both experiments
  - in principle RS gravitons already excluded in such region
- Simple **by-product of Higgs to diphoton** analysis, extending search to larger masses and **studying different widths**
- Mass limits for a possible Higgs-like scalar

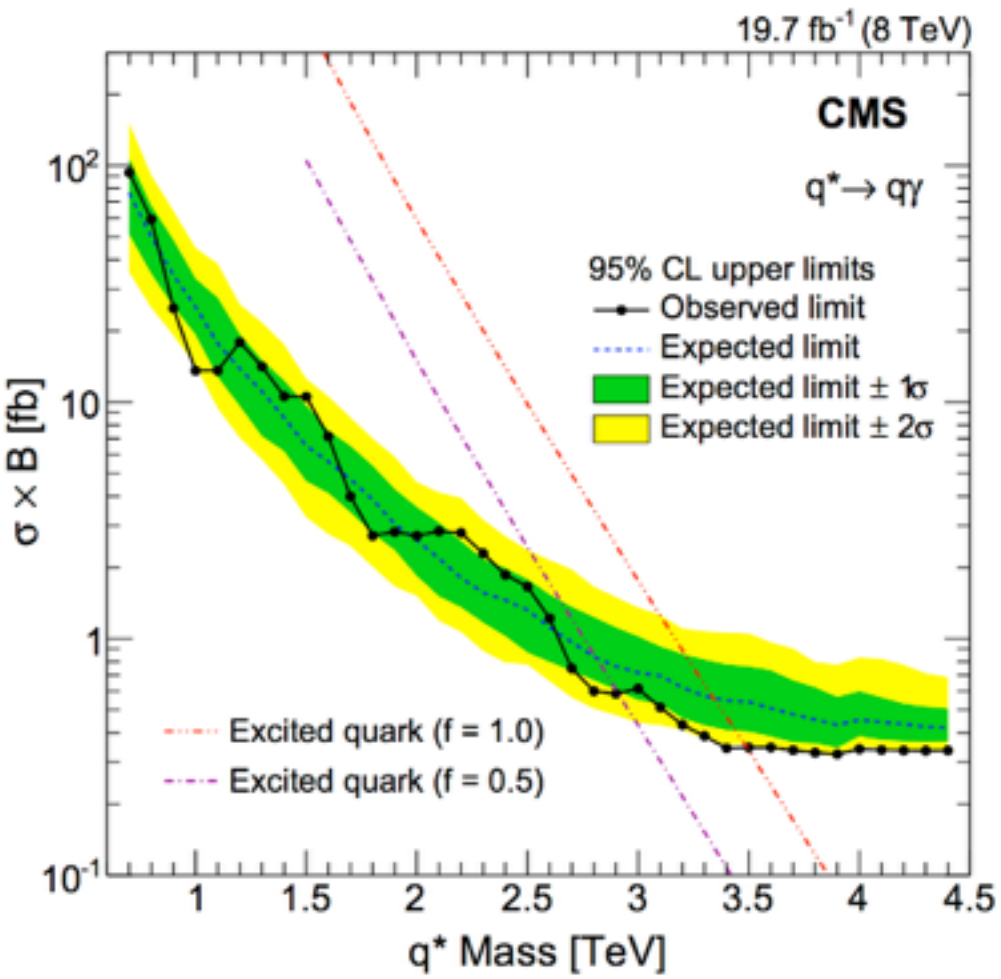




PHOTON+JET

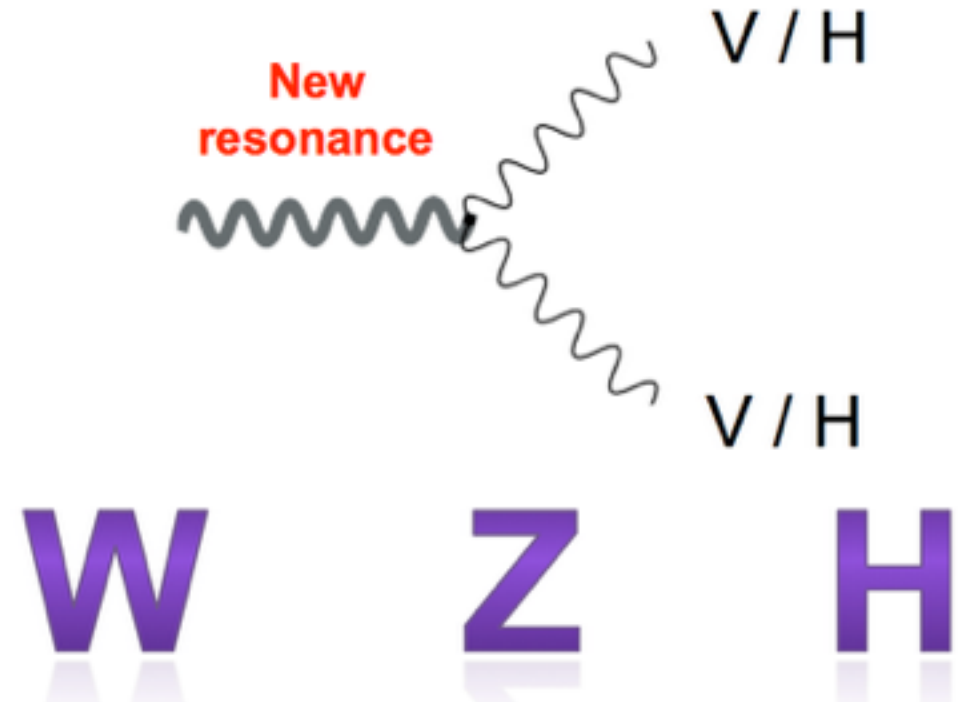
- **≥1 photon + ≥1 jet** (p_T >170 GeV)
- Further **requirements on topology**
  - $\Delta R(\gamma, \text{jet}) > 0.5$
  - $\Delta\eta(\gamma, \text{jet}) < 2.0$, $\Delta\varphi(\gamma, \text{jet}) > 1.5$
- Interpreted in **excited quarks scenario**





DIBOSON: INTRO

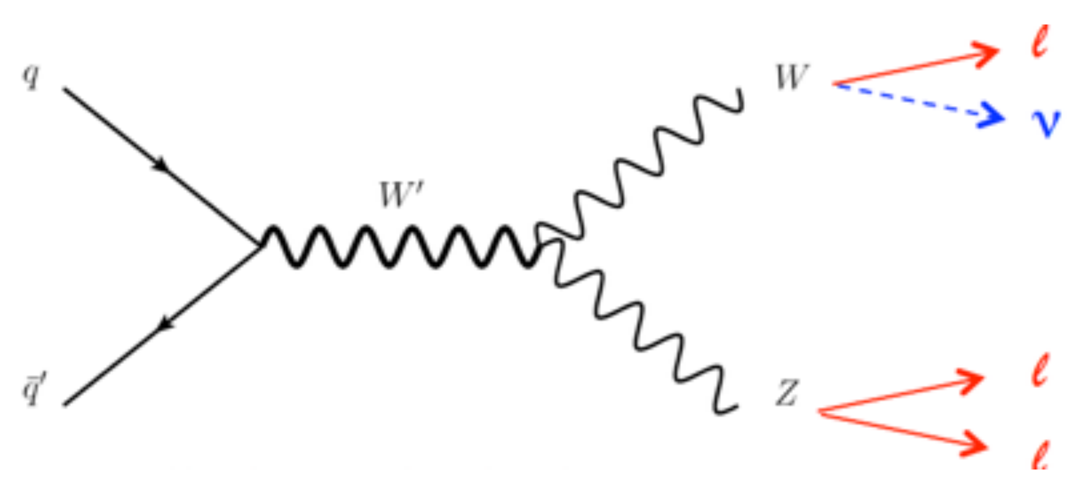
- Searching from **new resonances** decaying in **two massive bosons**
- **Analysis strategy** determined by
  - boson decay modes
  - mass of the resonance and boost
- **Clean experimental signature**
- In case of discovery, possible to measure properties from **angular distributions** of the decay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

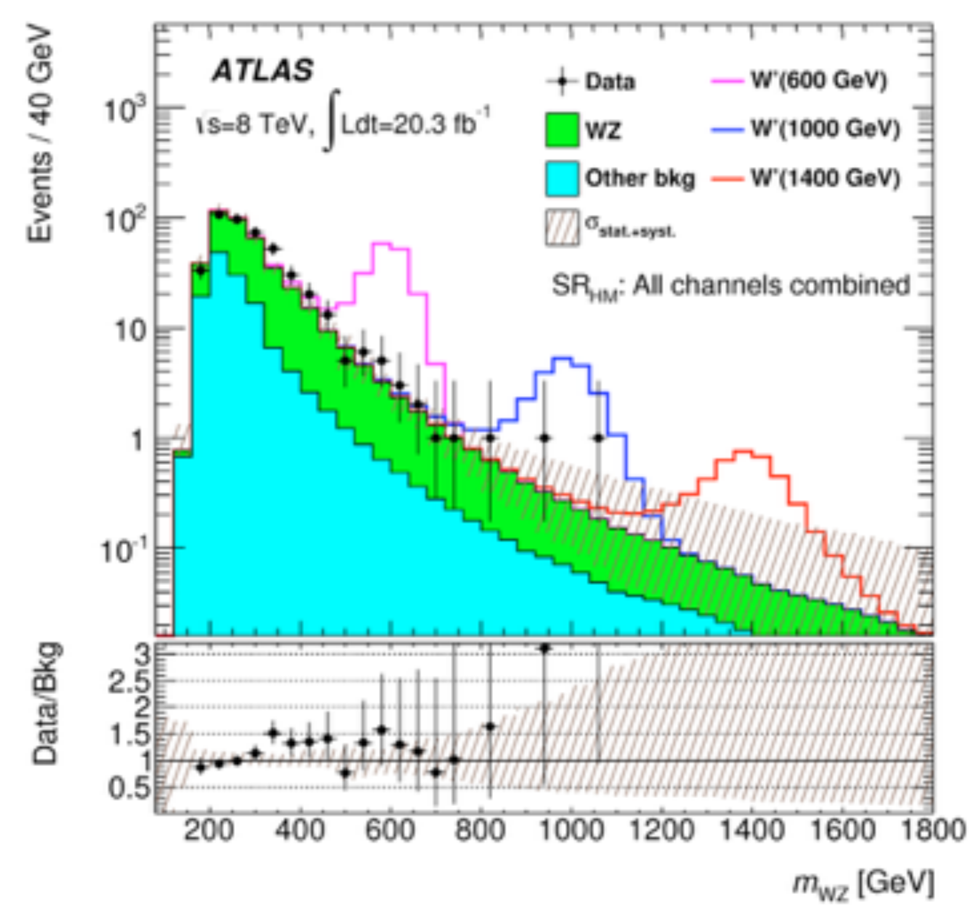


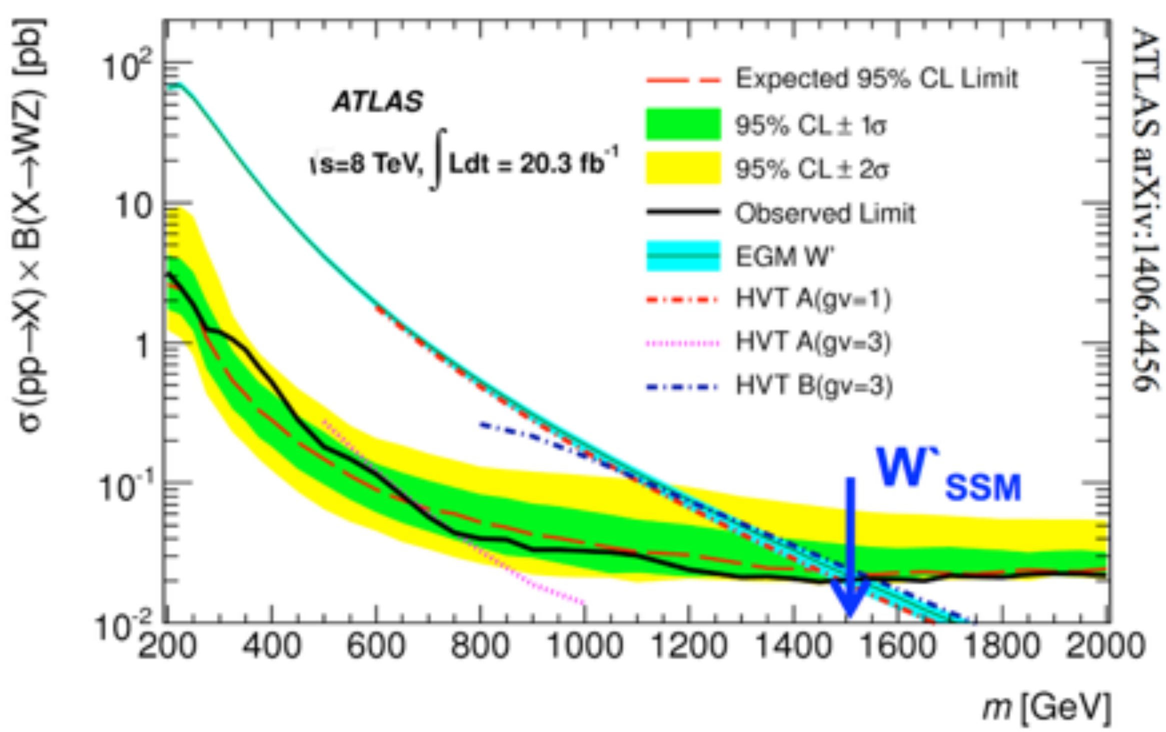
$M_W \sim 80.3$ GeV	$M_Z \sim 91.2$ GeV	$M_H \sim 125$ GeV
W→qq ~ 67%	Z→qq ~ 70%	H→bb ~ 57%
W→ℓν ~ 33%	Z→νν ~ 20%	H→WW ~ 21% H→ZZ ~ 2.5%
	Z→ℓℓ ~ 10%	H→ττ ~ 6%
		H→γγ ~ 0.2%

DIBOSON: LEPTONIC CHANNELS

- **Fully leptonic final state**
- **Small background from MC**
  - non resonant WZ
- Low BR but **very clean**
- **Analysis Strategy**
  - search for bump in M_{WZ} spectrum
  - neutrino p_z from W mass constraint
  - acceptable resolution
    - (~10% at 1 TeV)

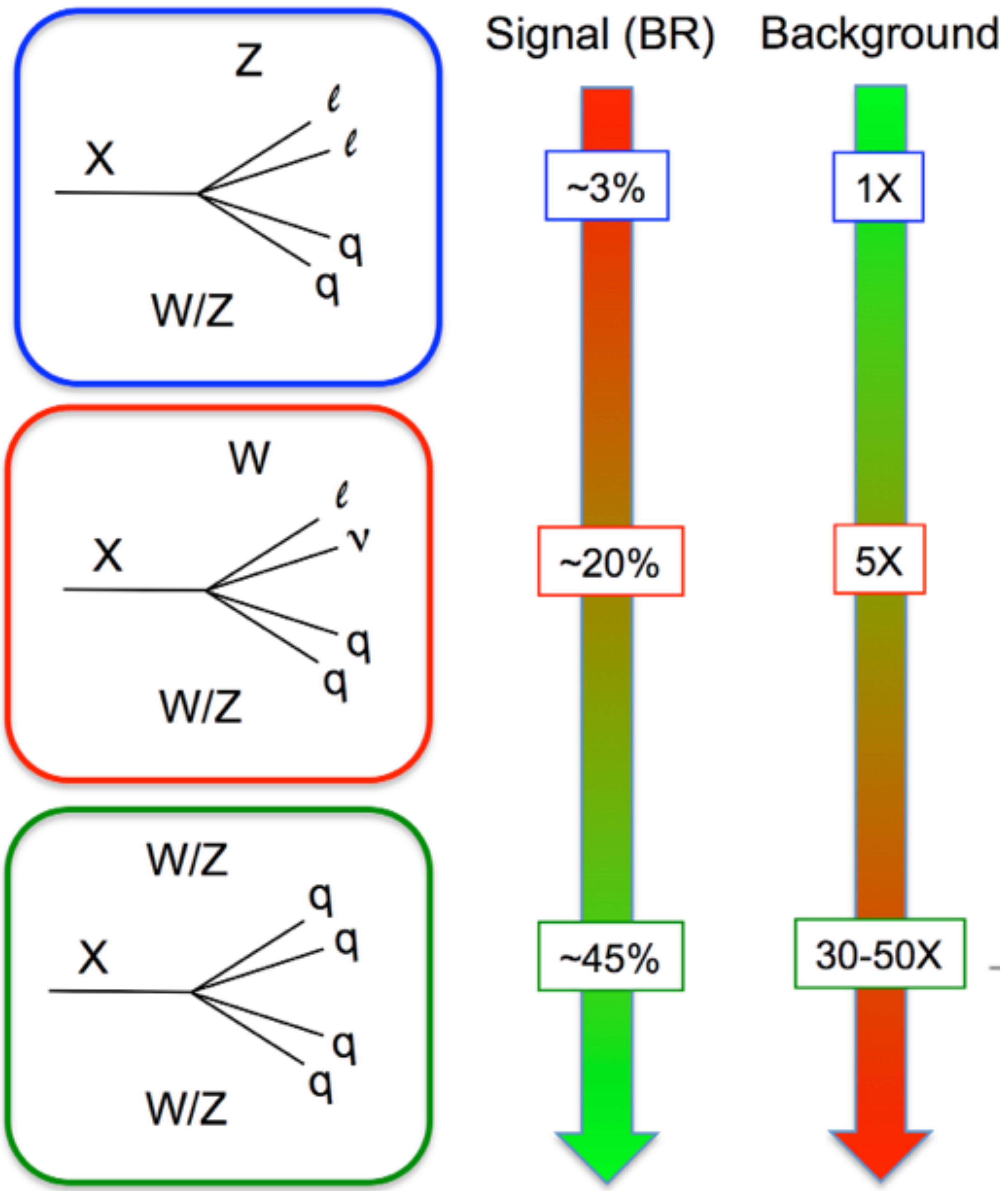






DIBOSON: HADRONIC CHANNELS

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

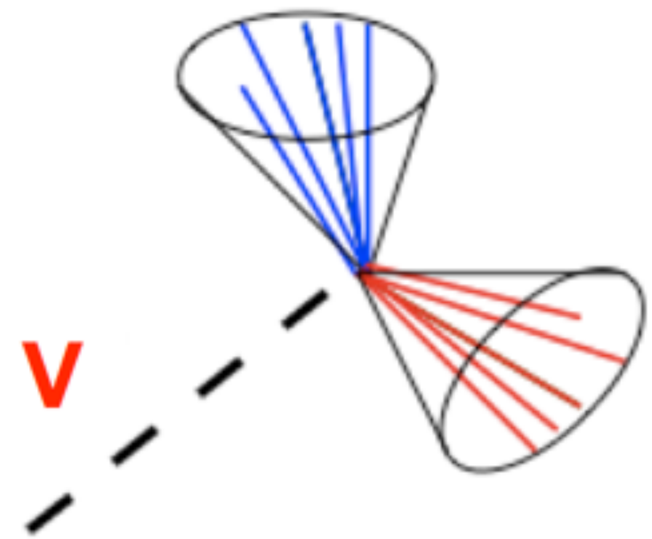


Diboson: Boosted Hadronic V Decays

- Opening angle between jets

$$\Delta R_{qq}^{\min} \approx \Delta\theta_{qq}^{\min} \approx 2\frac{M_V}{p_{T,V}}$$

- **Low p_T**: separated



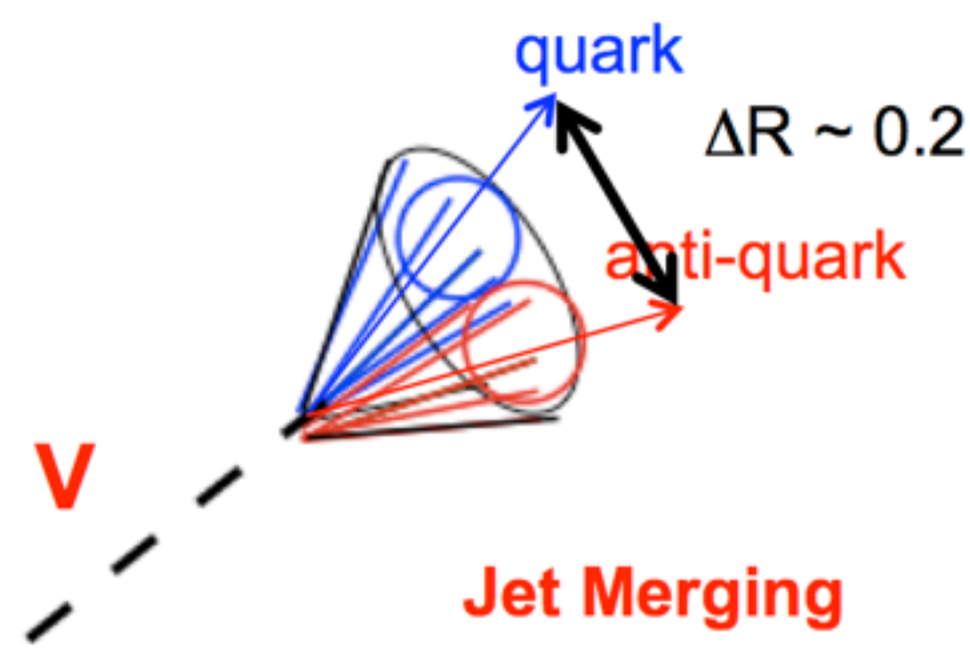
- **High p_T**: merging

Example

$M_{reso} = 2$ TeV

$p_T(V) \sim 1$ TeV ➡ $\Delta R_{qq}^{\min} \approx 0.2$

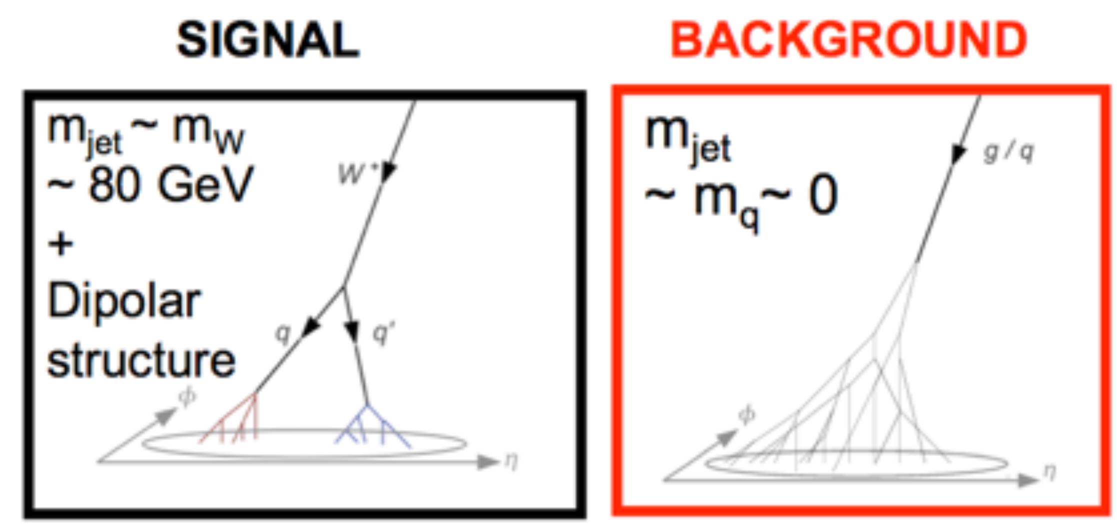
$M_V \sim 100$ GeV



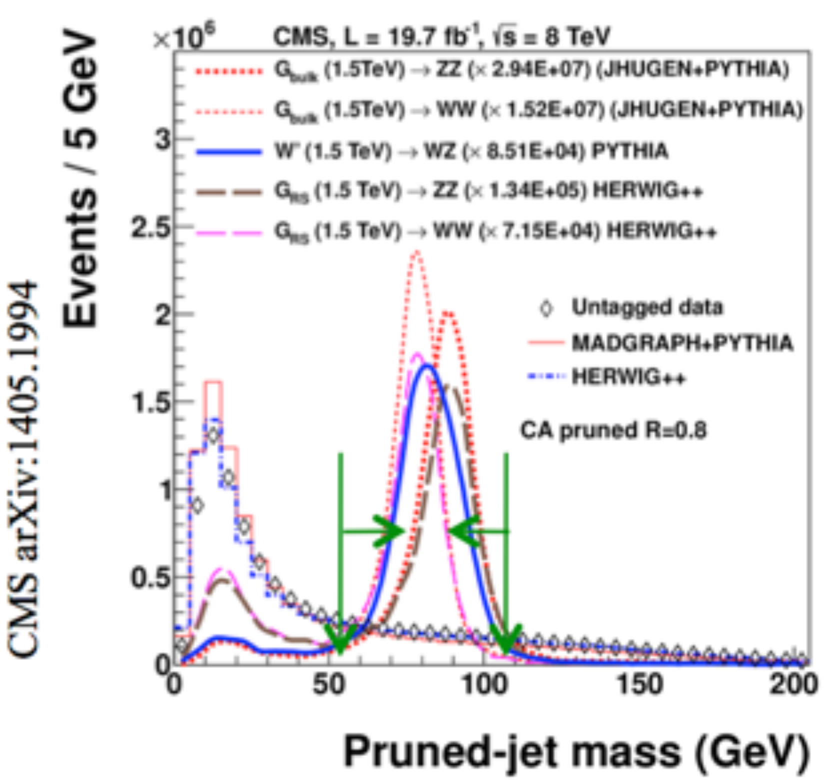
How to Tag Boosted V Decays

Several algorithms:

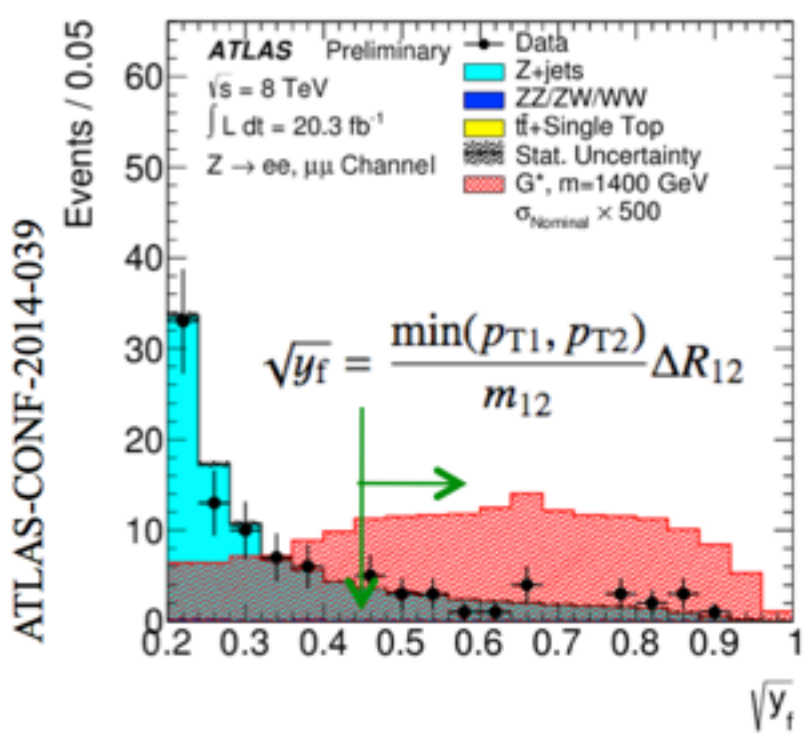
- **Jet trimming, pruning, filtering, …**
  - Remove soft component of jet, reducing effects of pileup and UE
- **Substructure variables**
  - Built from subjets after jet declustering



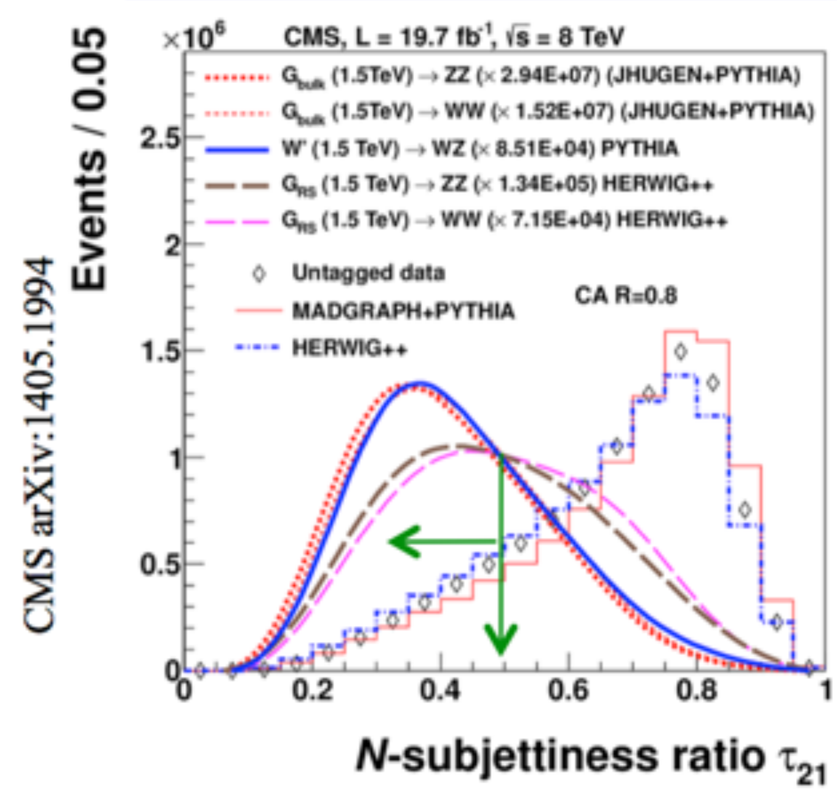
Jet mass



Momentum Balance

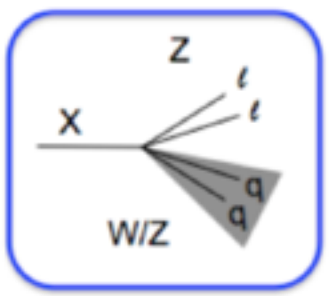


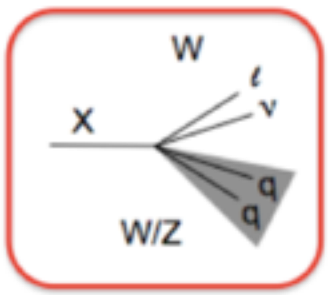
N-subjettiness τ_N (topological compatibility with N subjets)

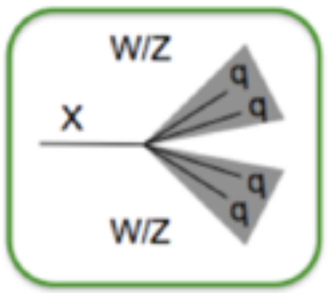


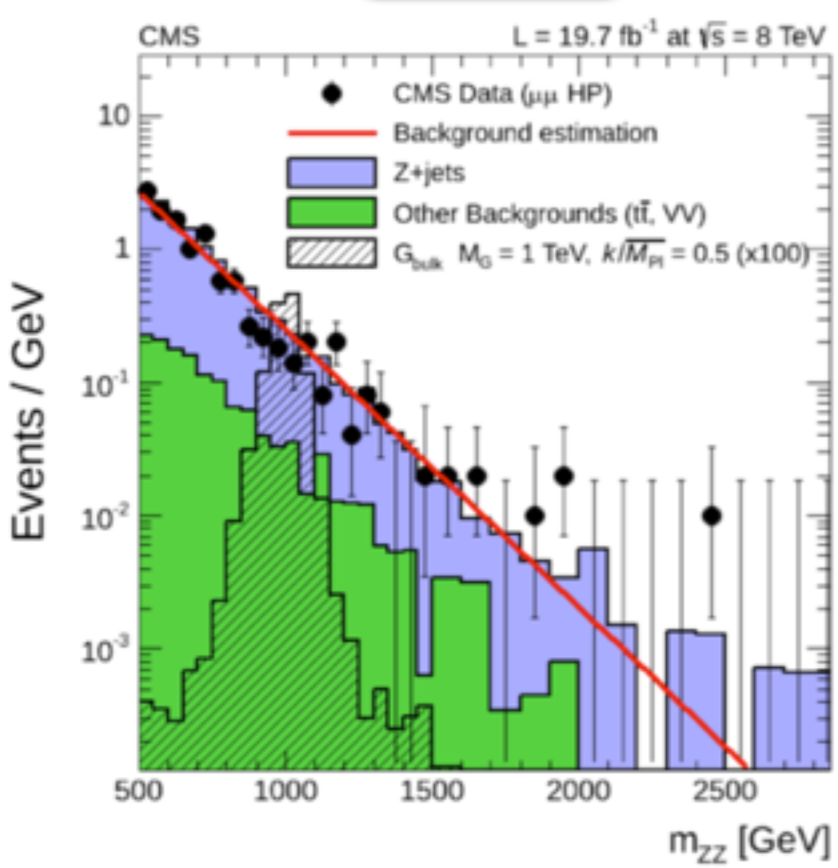
DIBOSON: SPECTRUM AND FIT

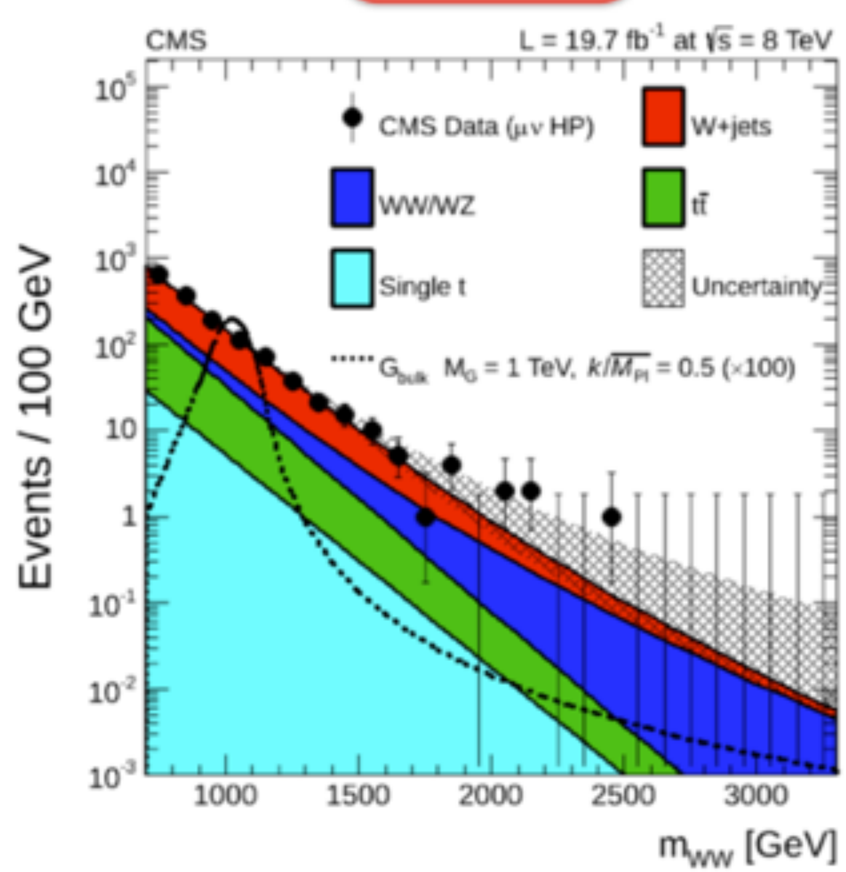
- **Background** from 1) jet mass sideband in data 2) fit to data with smoothly falling function (a-la dijet analysis)
- **m_{VV} resolution ~3-6%**

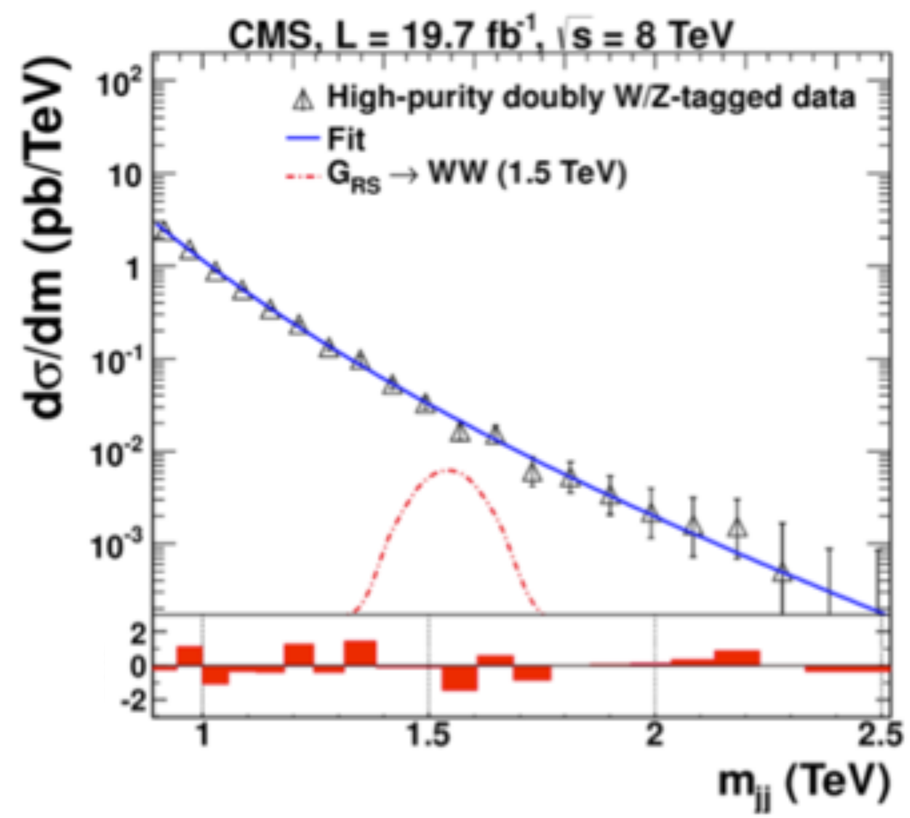




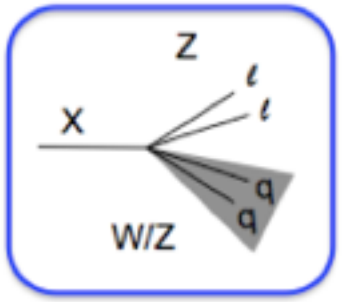


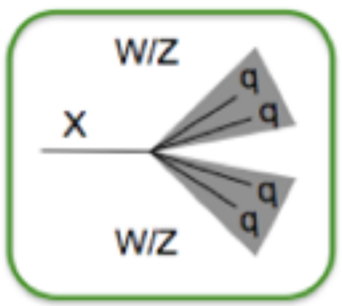


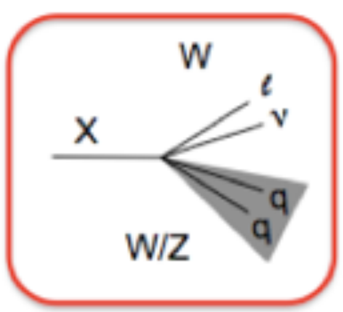


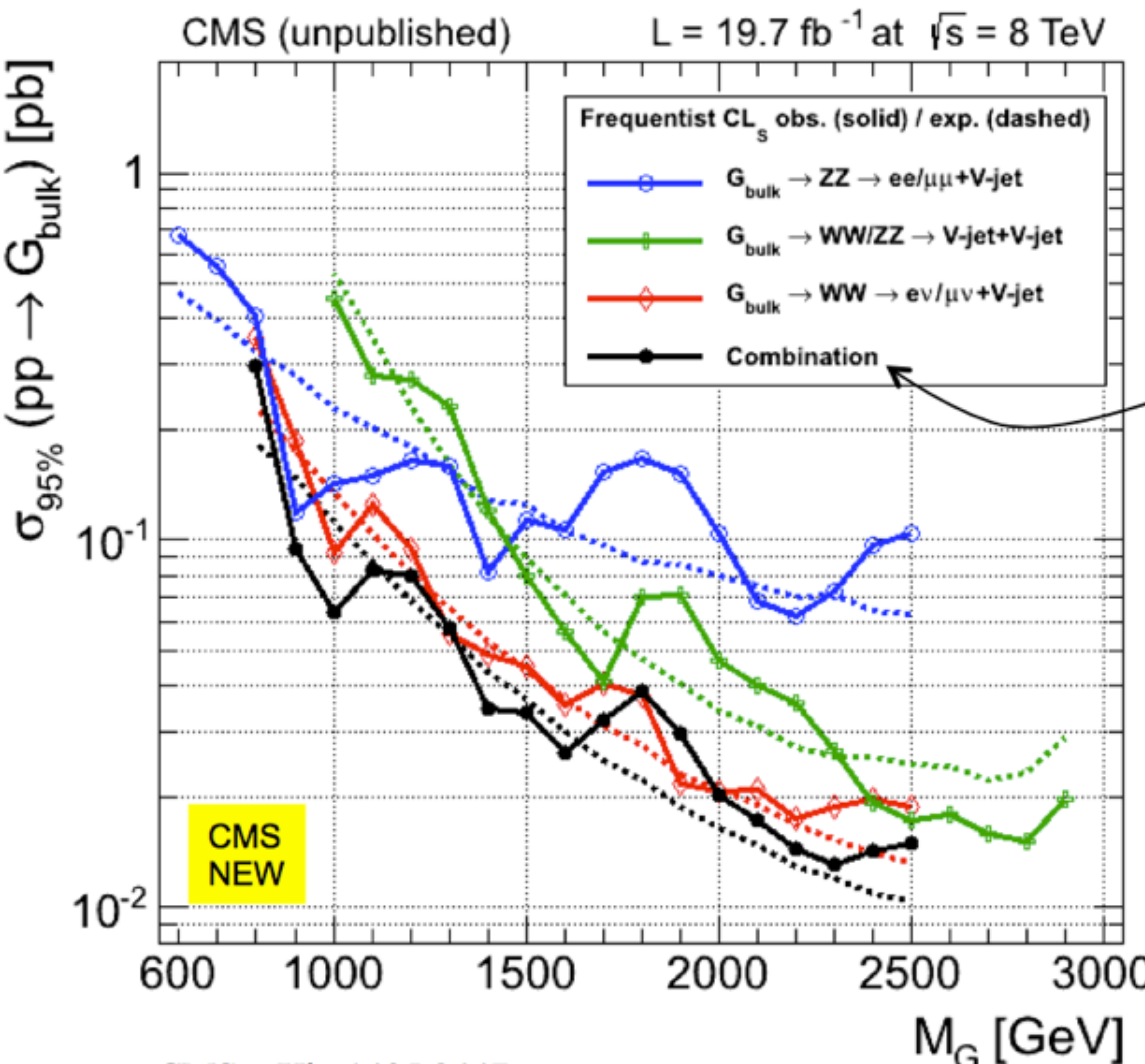


DIBOSON: INTERPRETATION









CMS arXiv:1405.3447

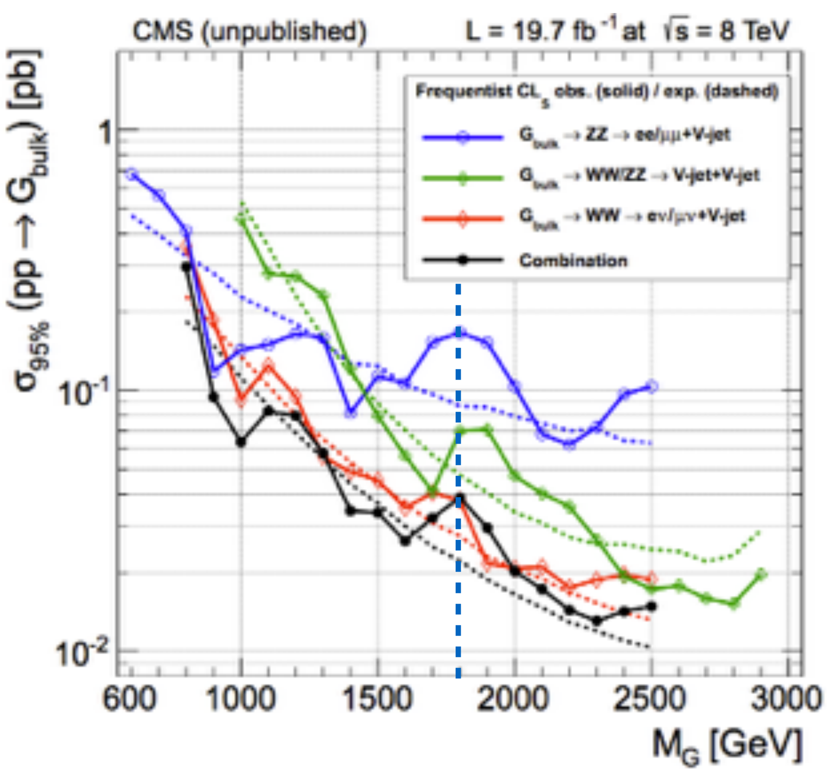
Bulk graviton (arXiv:hep-ph/0701186)

Combination assuming **BRs and efficiencies of narrow bulk graviton** model

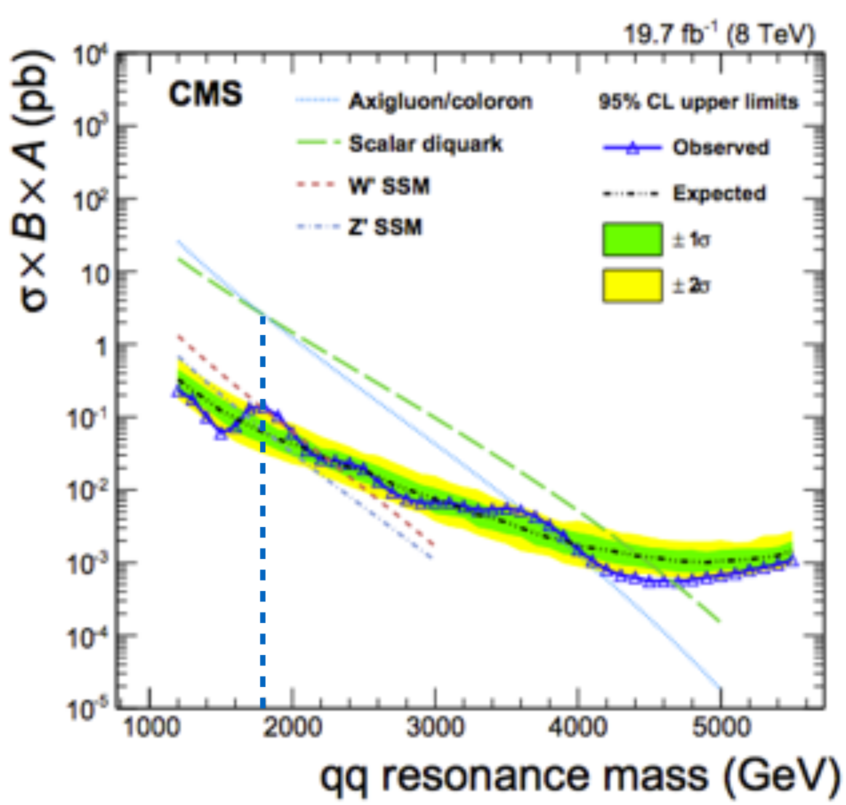
Largest excess at M~1.8 TeV (<1.5σ)

IN SUMMARY: DID WE SEE ANYTHING?

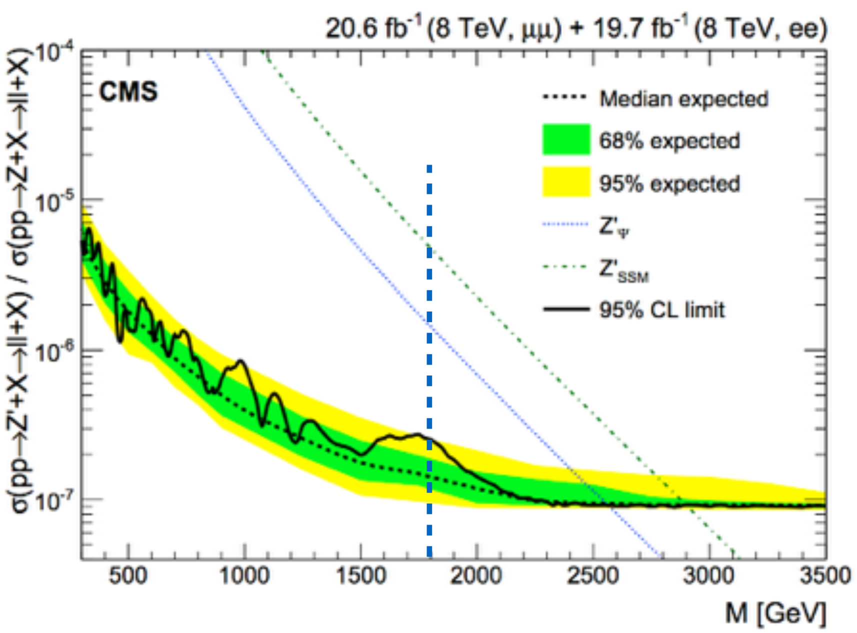
- **The answer is NO**
- But **excesses** (not very significant) here and there **deserving another look** with more data
- **Example**: some activity at 1.8 TeV seen by CMS
  - different excesses seen in other analyses not covered in this talk



~1.5 σ (local)



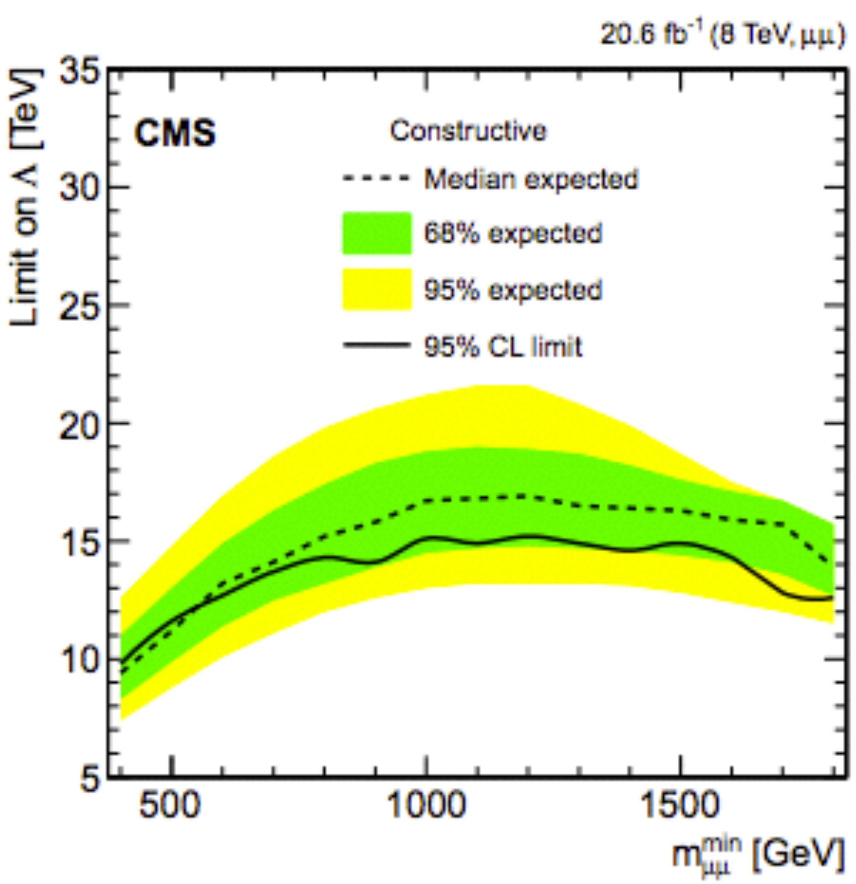
~2 σ (local)

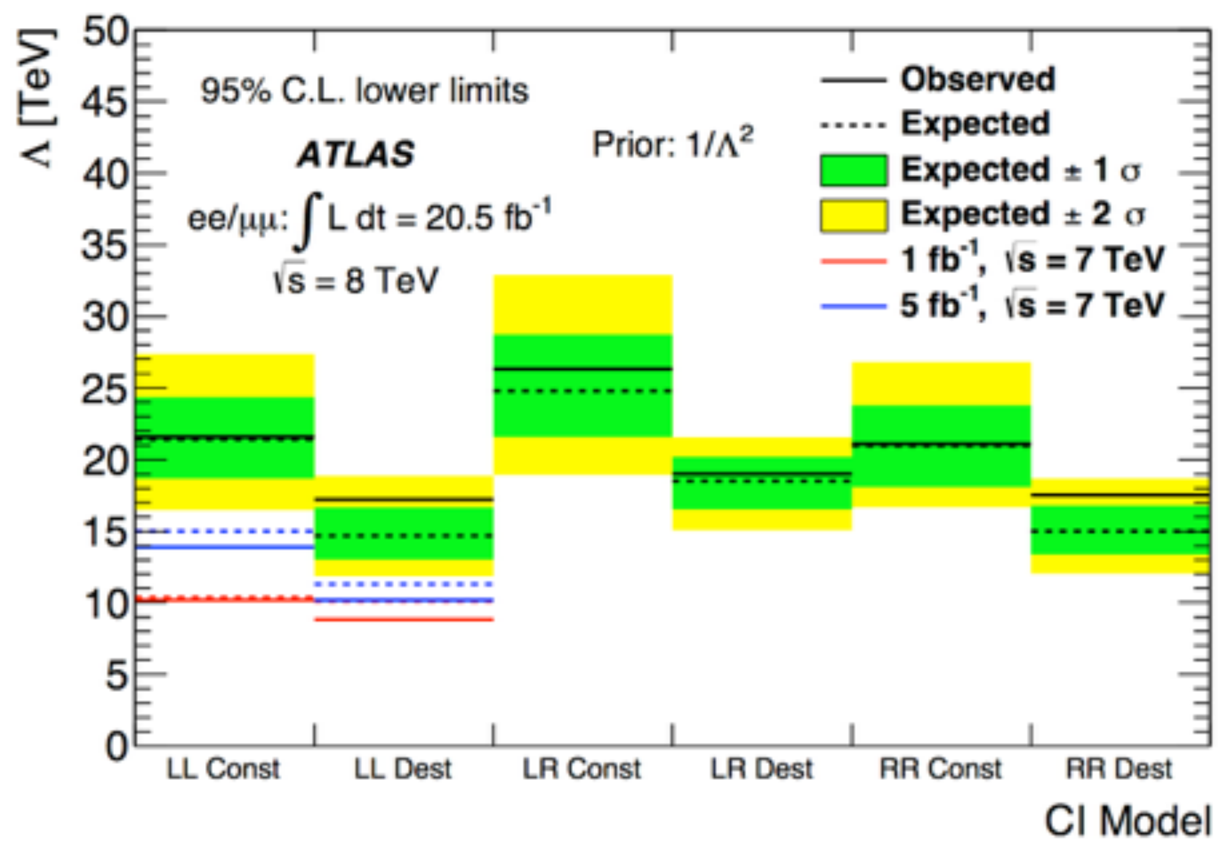


~2 σ (local)

NON-RESONANT SEARCHES

- Not discussed in this talk but almost **every bump hunting converted in the search for broad excess**
  - interpreted in several scenarios, Contact Interactions, ADD, etc…
  - **more difficult than resonance search** (just cut-and-count and conservative systematics)
  - **no excess**





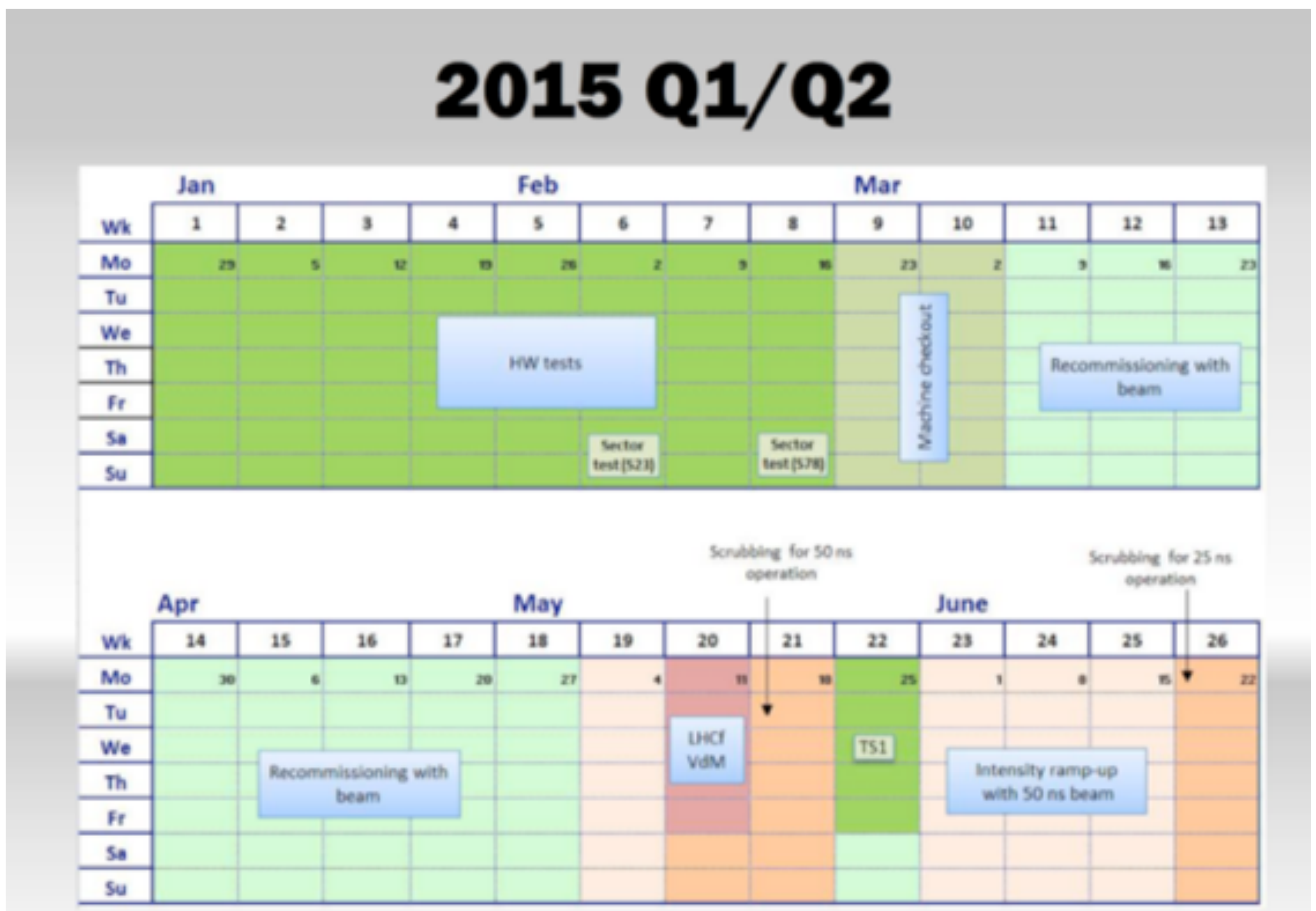
Expand the Searches

Expand the Searches

INCREASE CENTER OF MASS ENERGY

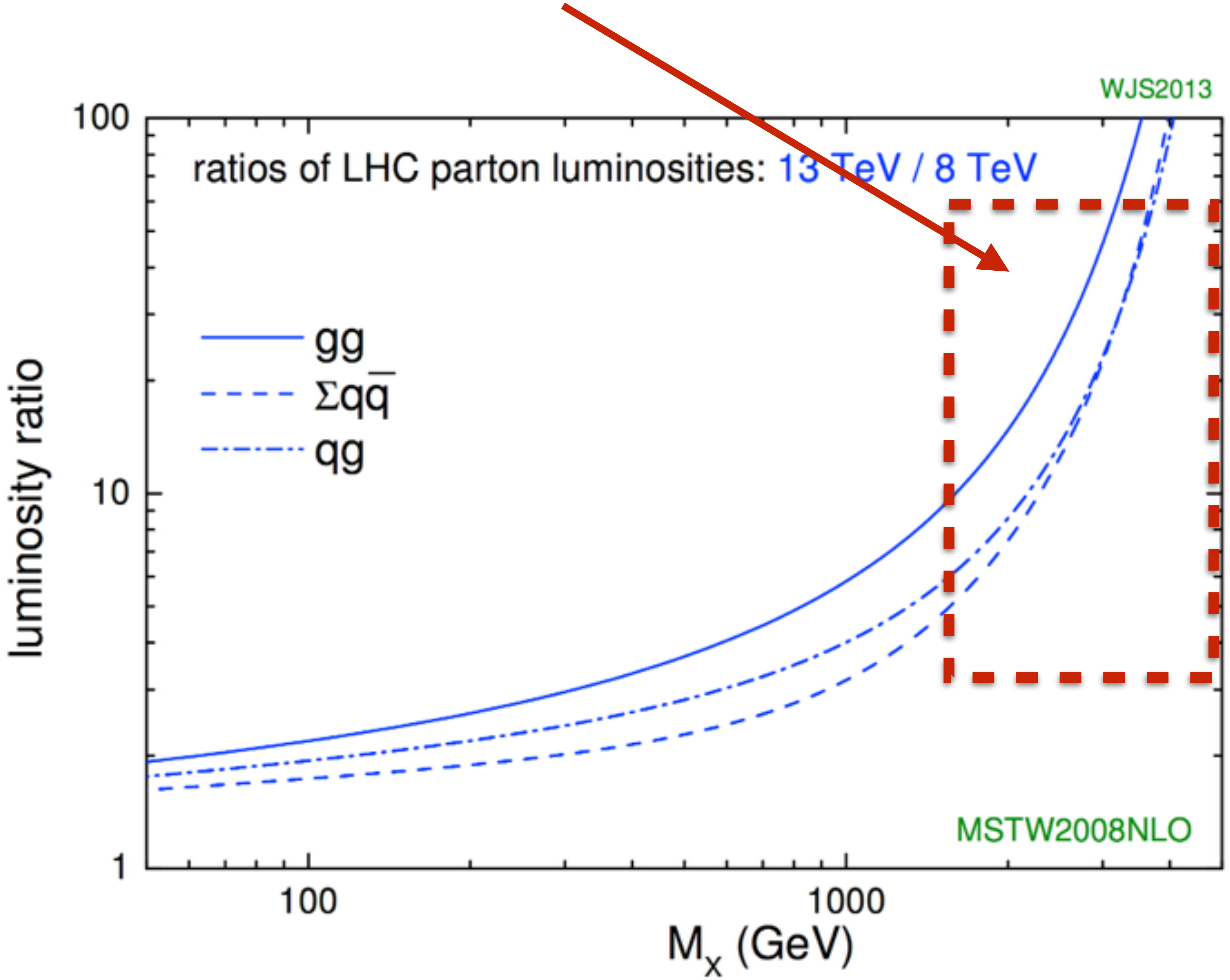
LHC Plans

- **First collisions**: **middle of May** (no scrubbing)
- **Collisions for Physics**: **June/July**
- **~1 fb^{-1}** with **50ns** bunch spacing (first three weeks)
- **~10 fb^{-1}** with **25ns** bunch spacing (by the end of the year)



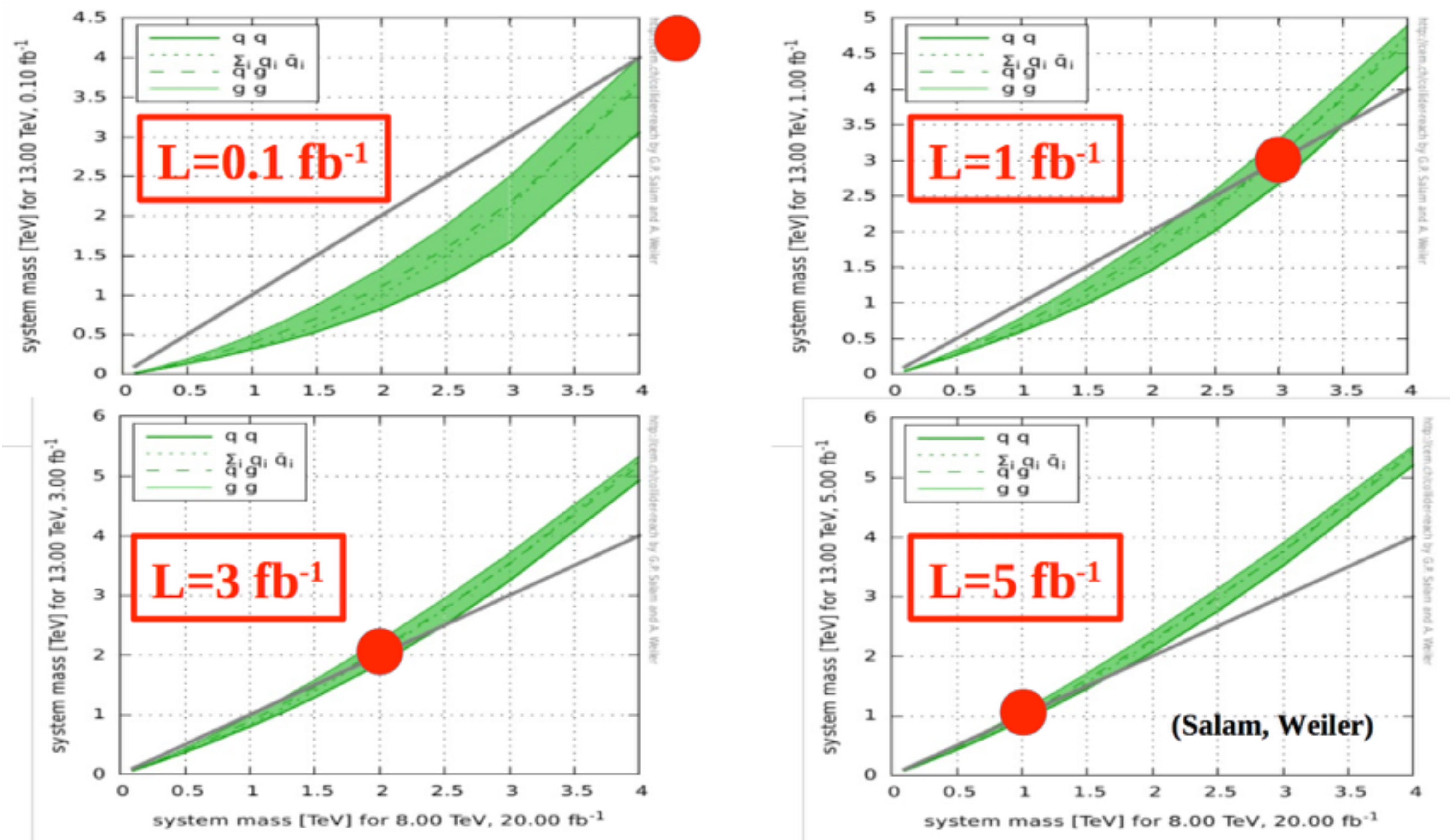
PARTON LUMINOSITY RATIO

- For high mass searches **parton luminosity counts**!
  - **Huge ratio in the interesting (not yet excluded) region**



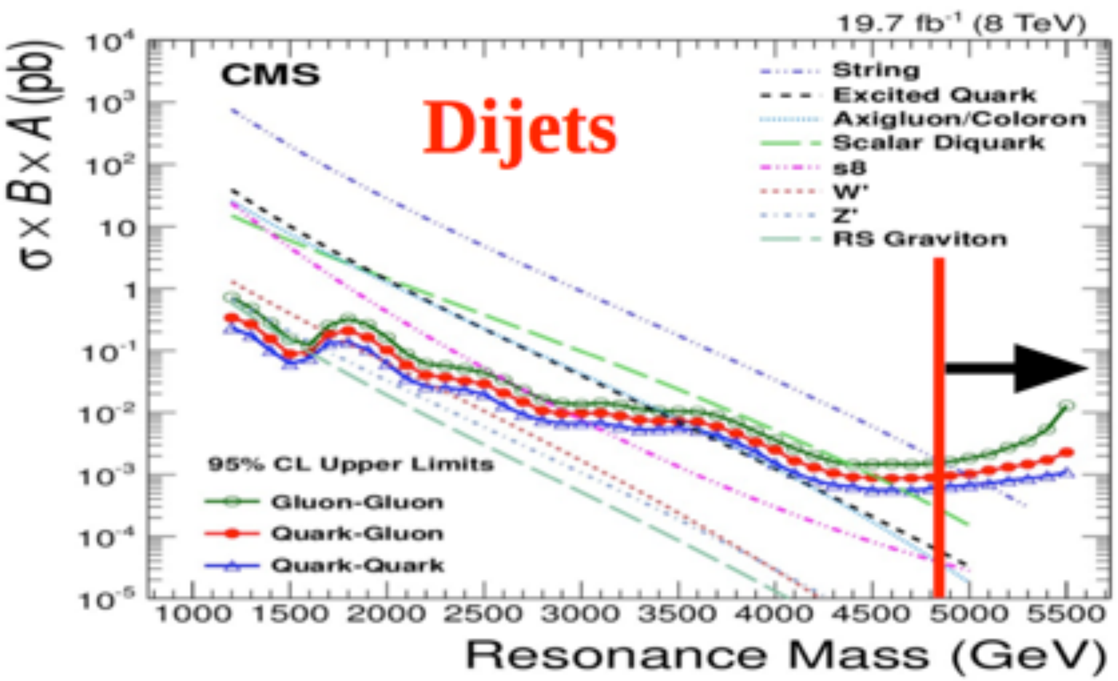
Physics Potential vs Luminosity

- Sensitive to **masses above 3 TeV with just 1 fb^{-1}**
- We can redo **all past searches with 5 fb^{-1}** (i.e. results for Moriond 2016)

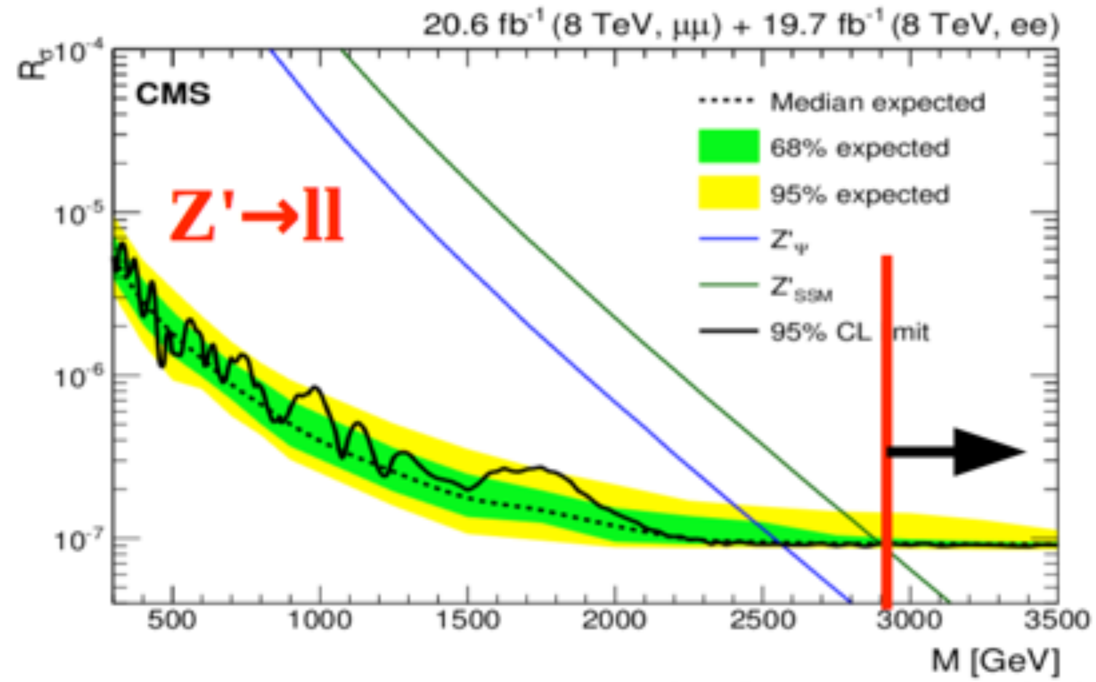


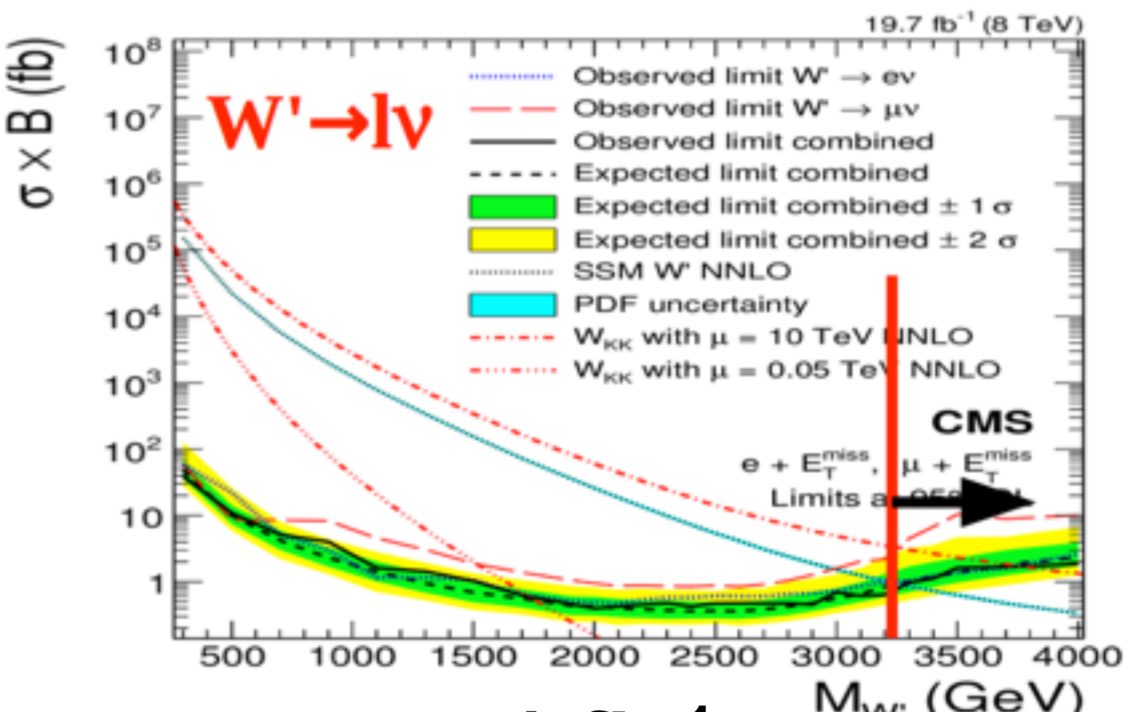
How Much Luminosity?

100 pb^{-1}

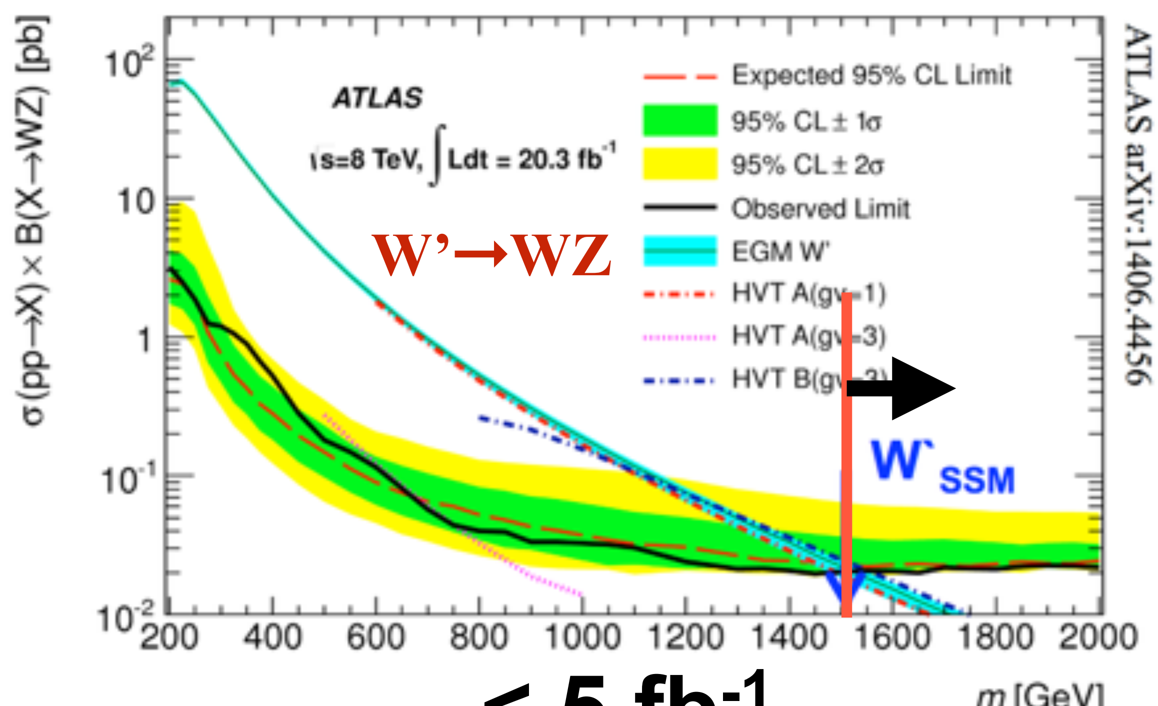


1 fb^{-1}





1 fb^{-1}



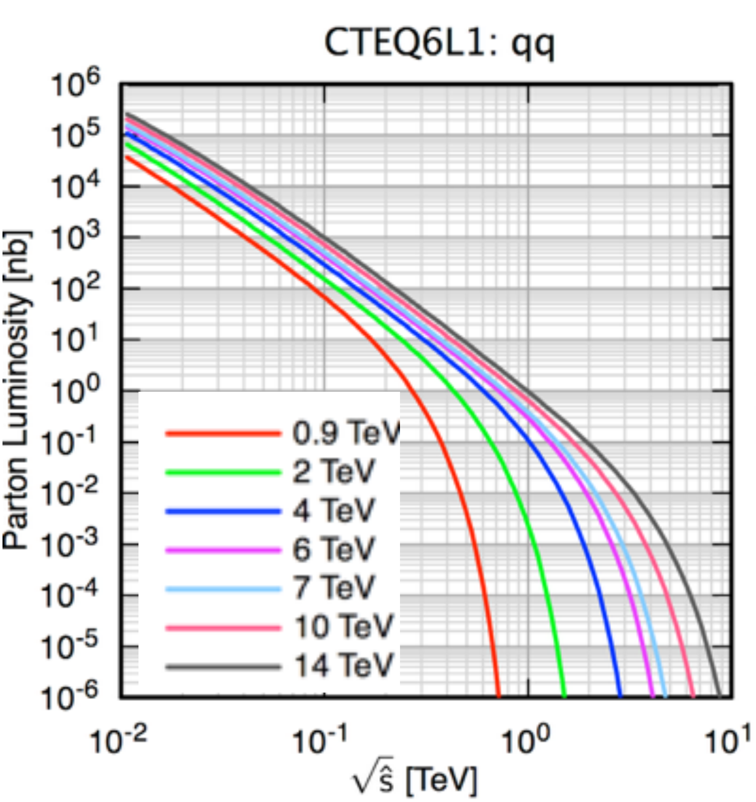
< 5 fb^{-1}

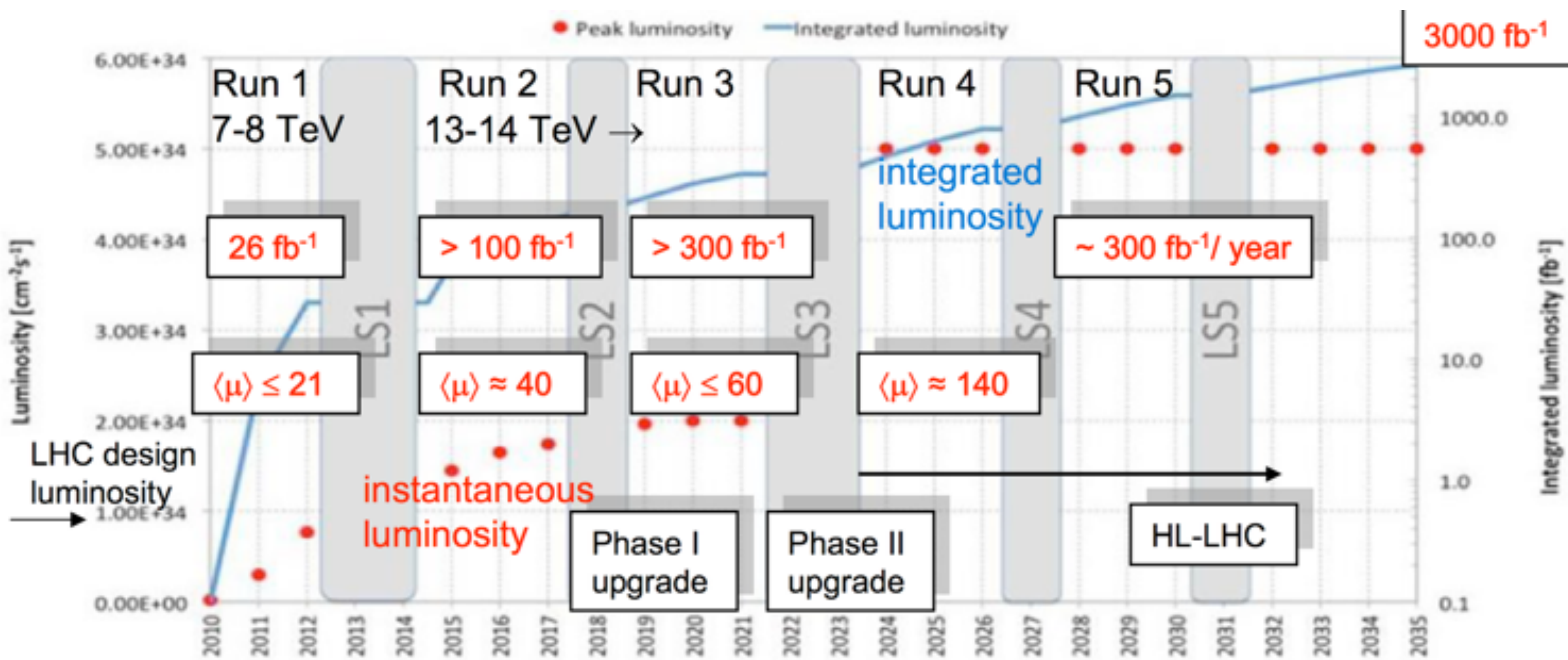
WHAT TO EXPECT IN '15-'16: SUMMARY

- **After 1 fb^{-1} at 50 ns** bunch spacing (three weeks after startup)
  - first dijet results
  - all bump huntings look for "unexpected signals"
- **After 3 fb^{-1} at 25 ns** bunch spacing (September 2015?)
  - almost all high mass resonance searches start to be sensitive and can produce a public result
  - check 8 TeV excesses
  - look for more "unexpected signals"
- **After 10 fb^{-1}**, i.e. end of the year but presented in Moriond 2015
  - in principle all analyses can be repeated
- **End of 2015**: almost all high mass searches public
- **End of 2016 (>30 fb^{-1})**: full CMS physics program
  - with several additions and new ideas

Even Longer Timescales: Run3, Run4

- **After end of Run2 statistics won't help much** in extending physics potential
  - fast **drop of parton luminosities** kills the high mass searches
- Maybe with **14 TeV energy another small addition** in reach
- **HL-LHC not very interesting for high mass searches**
- Maybe invest more on **intermediate mass region** (<1-2 TeV)



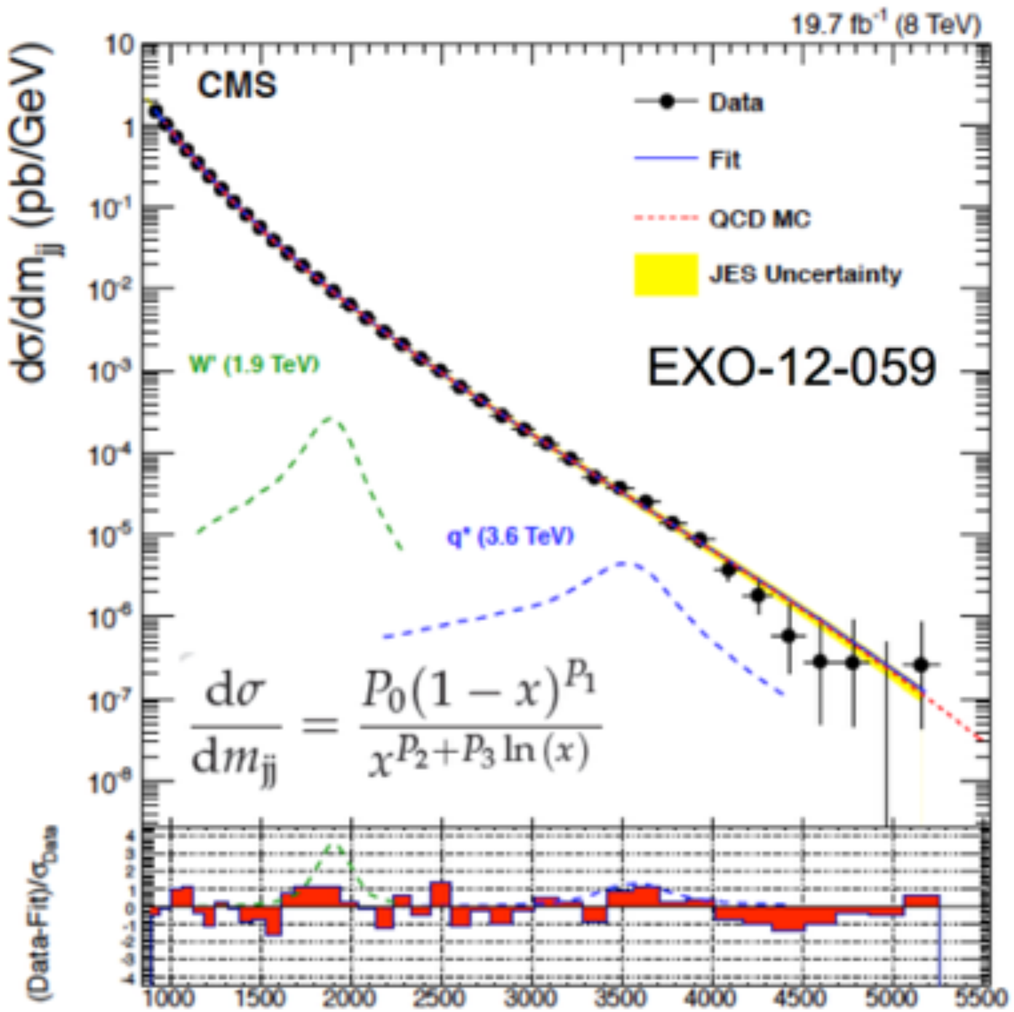


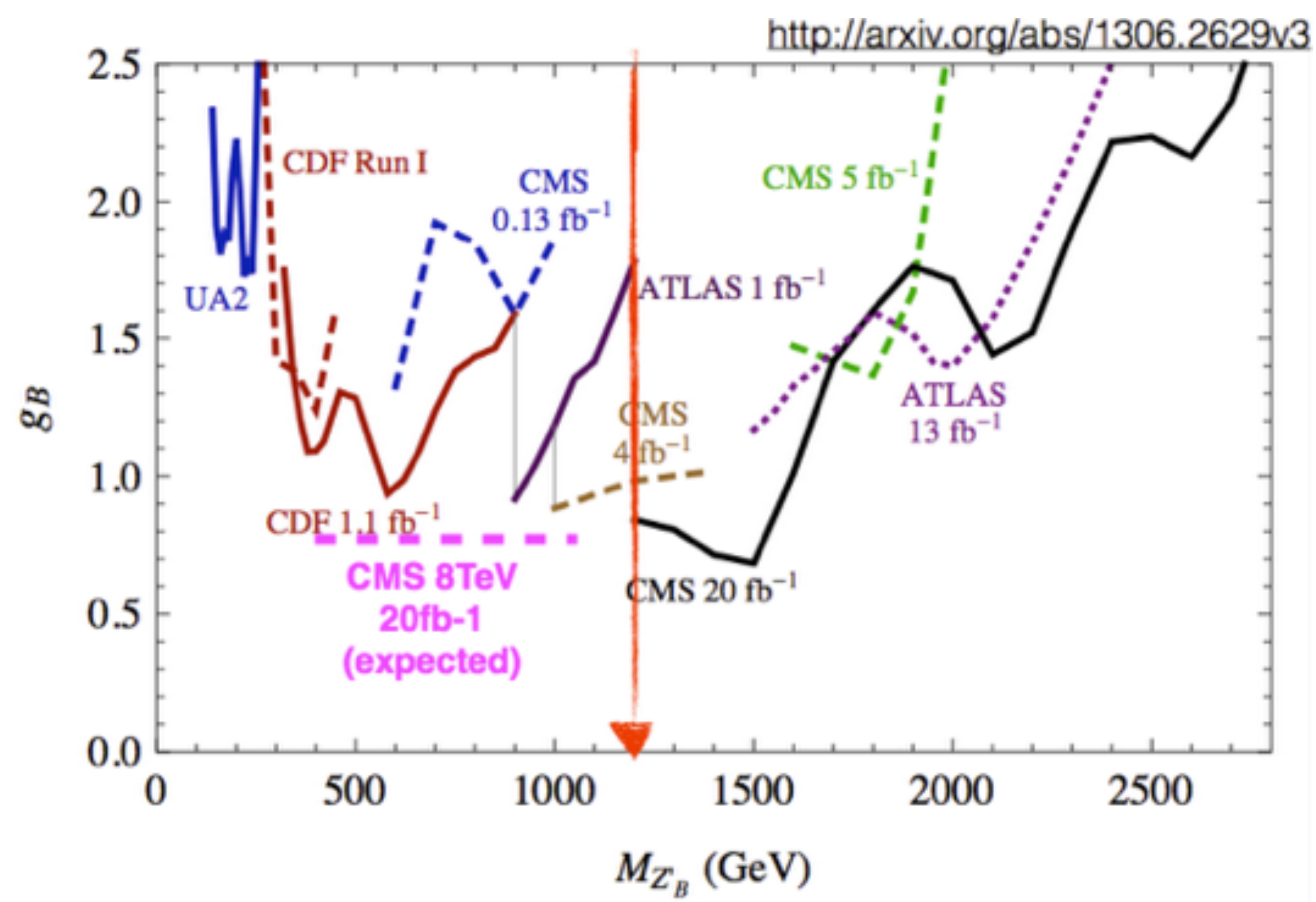
Expand the Searches

Some New Ideas

Expand the Searches: Lower Masses?

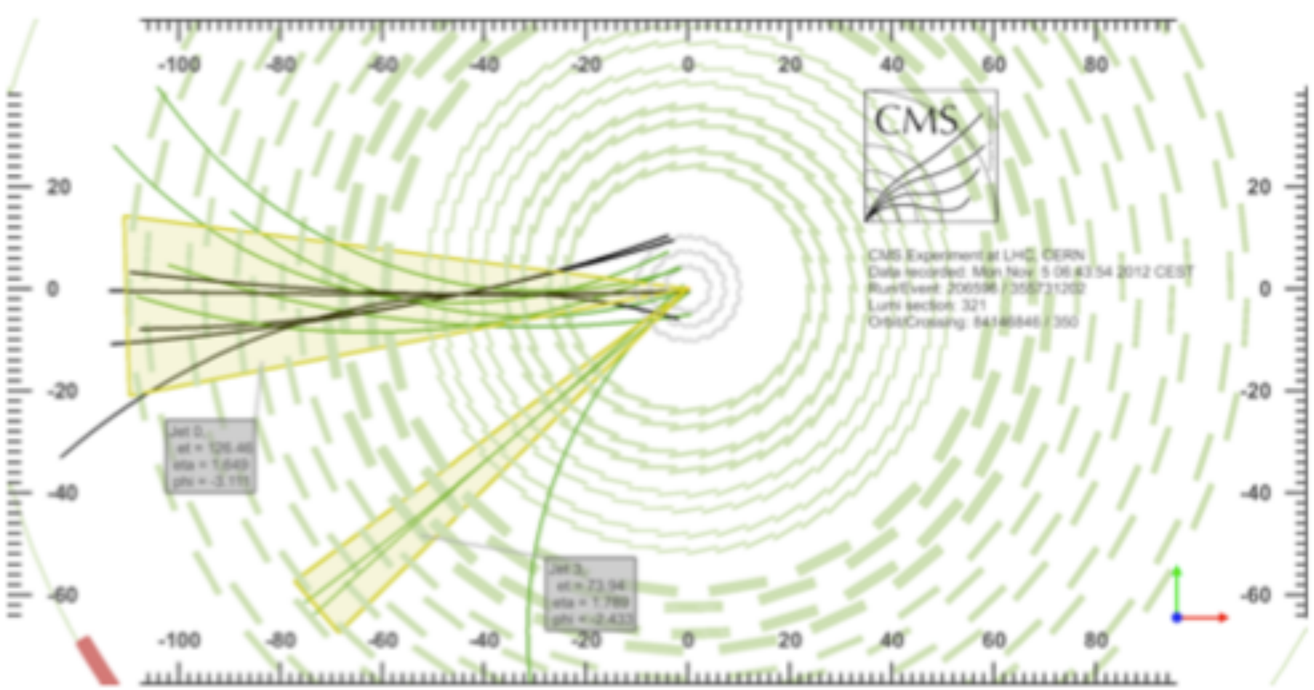
- **Resonance searches** often **done at large masses**
  - example: dijet (1 TeV)
- **Region below** still **interesting**
- In case limit due to trigger, need to implement alternative ways of storing data

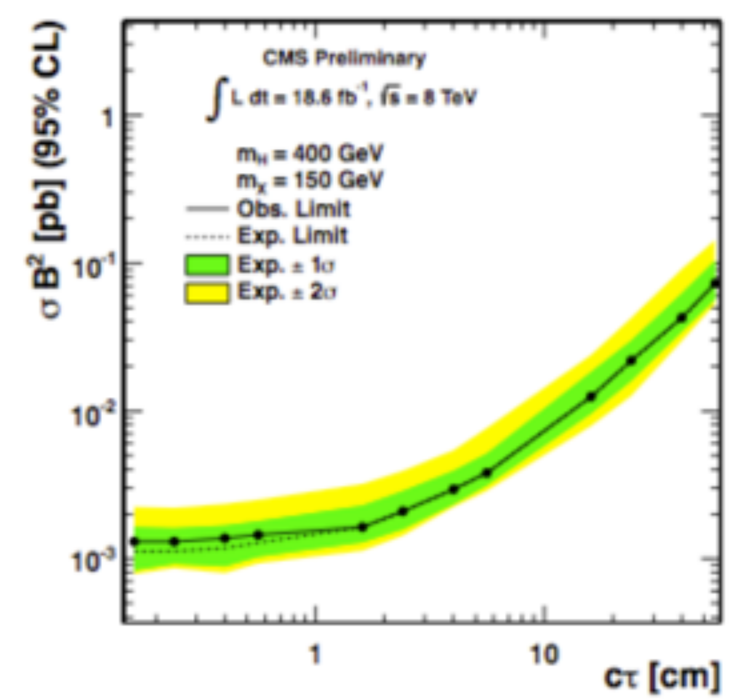




Expand the Searches: Long-Lived

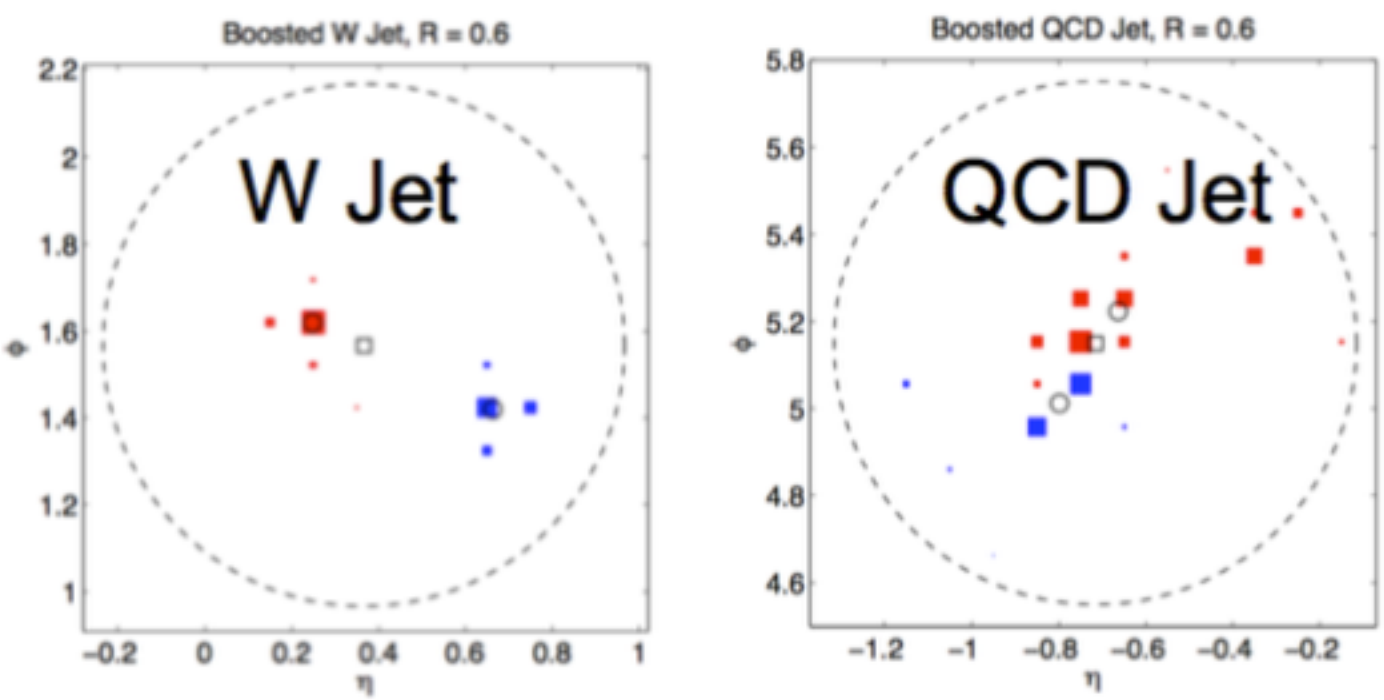
- Many LHC searches for **exotics signature search for long-lived displaced searches**
  - below case for displaced dijet analysis
- Maybe possible to **expand the resonance search by including displacement** tagging
  - feasible only at lower mass regime



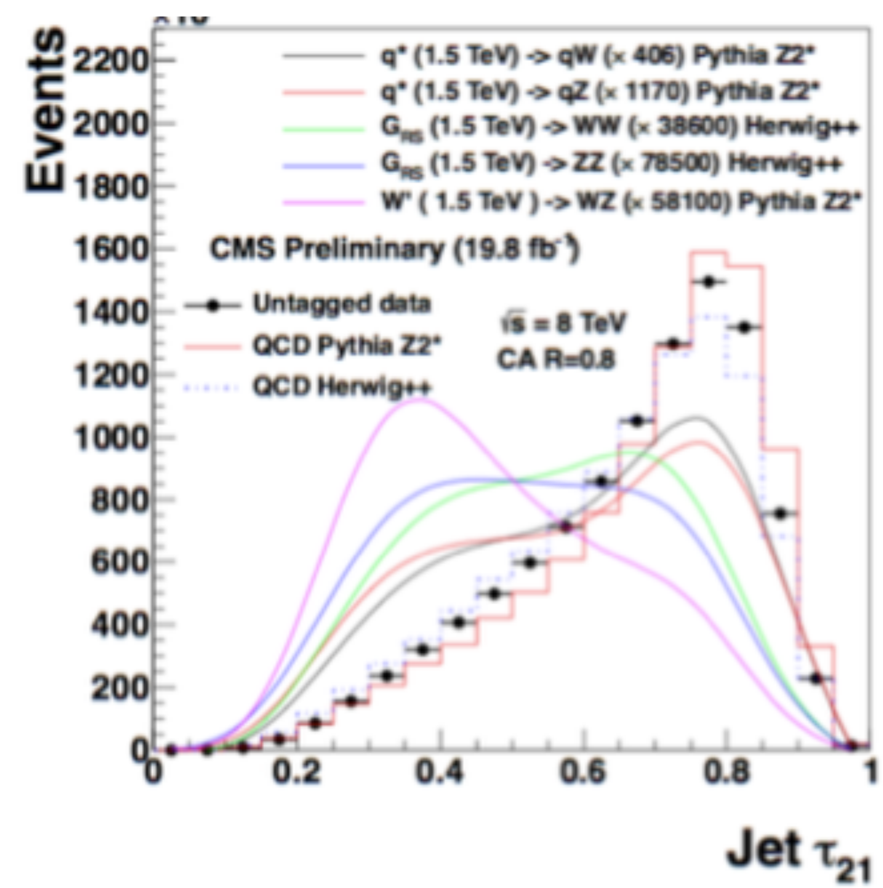


MORE SUB-STRUCTURES

- **Substructures** now successfully used to **identify W, Z, top, and Higgs**
- Could be good to **explore use of substructures when the particle is not SM**
  - handle to **reduce backgrounds** and increase physics potential, mainly at lower masses



[Thaler, Tilburg, arXiv:1011.2268]



CONCLUSIONS

- Find **high mass resonances is the best/easiest way to discover new physics**
- **Comprehensive program for high mass resonance** searches at LHC
- Unfortunately **no sign of new physics yet**

- **Run2 @ 13TeV** (~10fb^{-1} by end of the year)
  - increase in energy **dramatically expand reach in mass**
  - **2015 is the year** of the high mass resonance searches!
- **Expect big news at Moriond 2016**
  - hopefully good news. Maybe even earlier