Exotica and Dark Matter searches

Michele Gallinaro

LIP Lisbon

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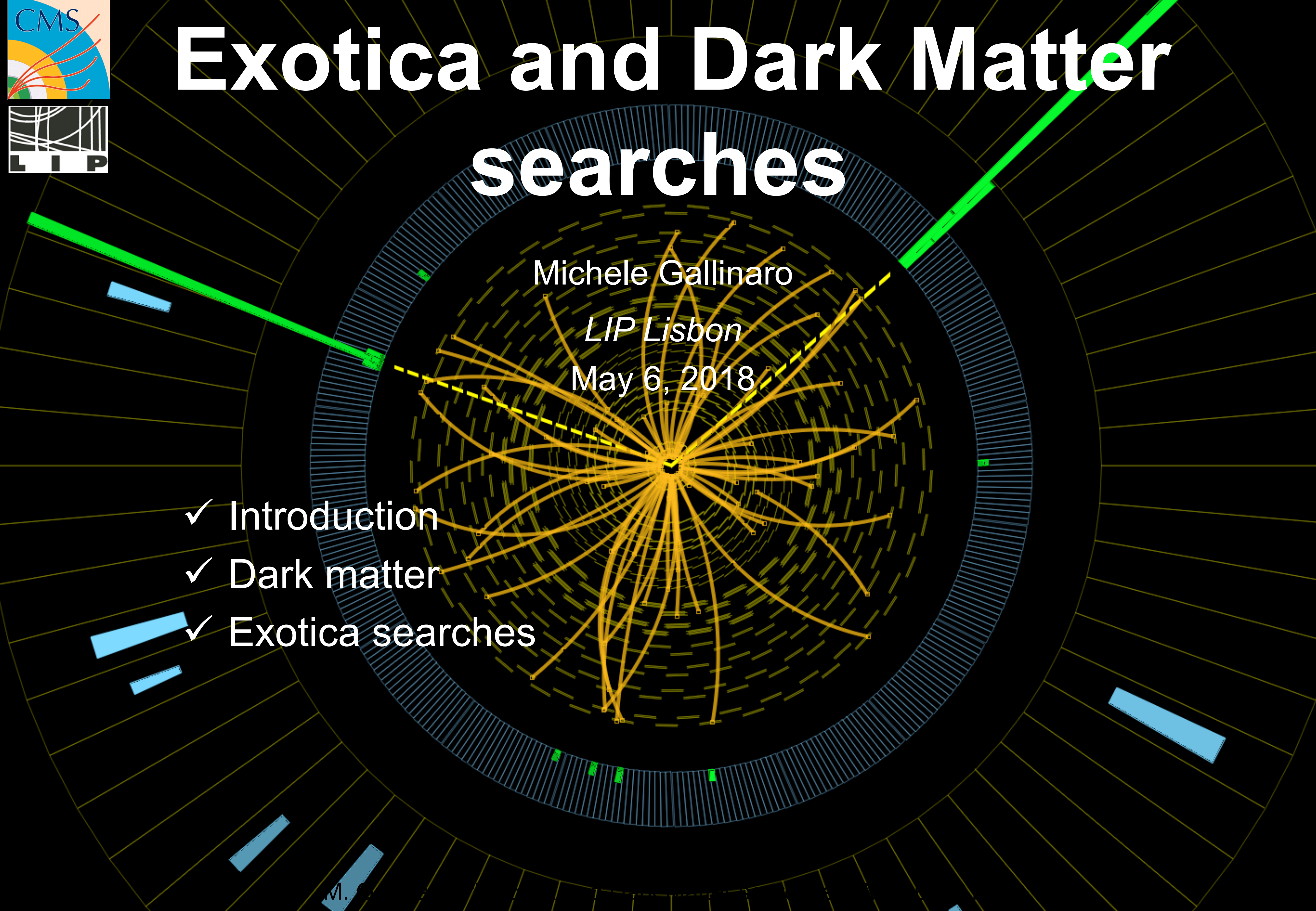
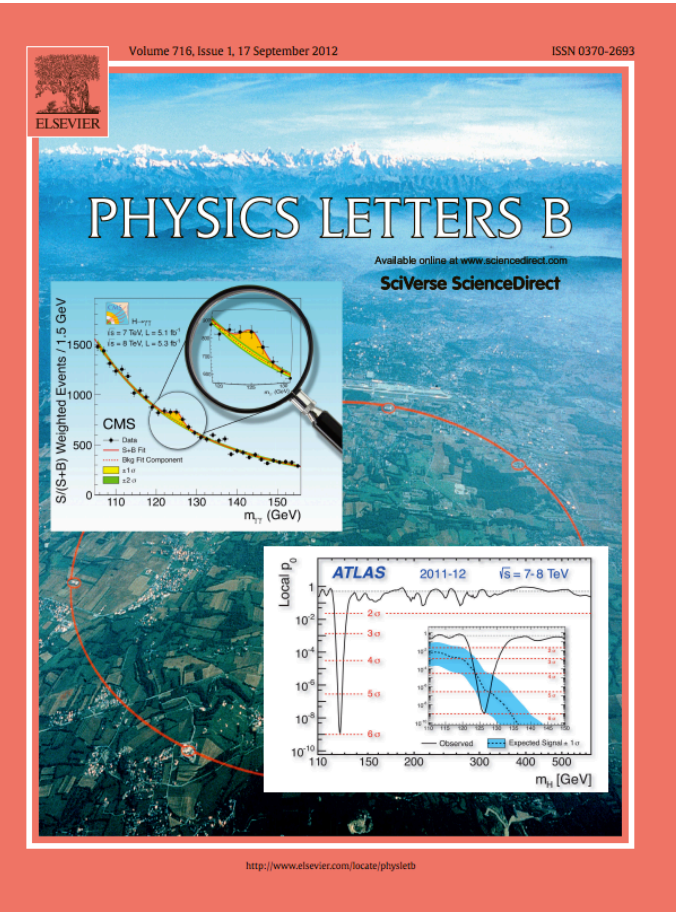


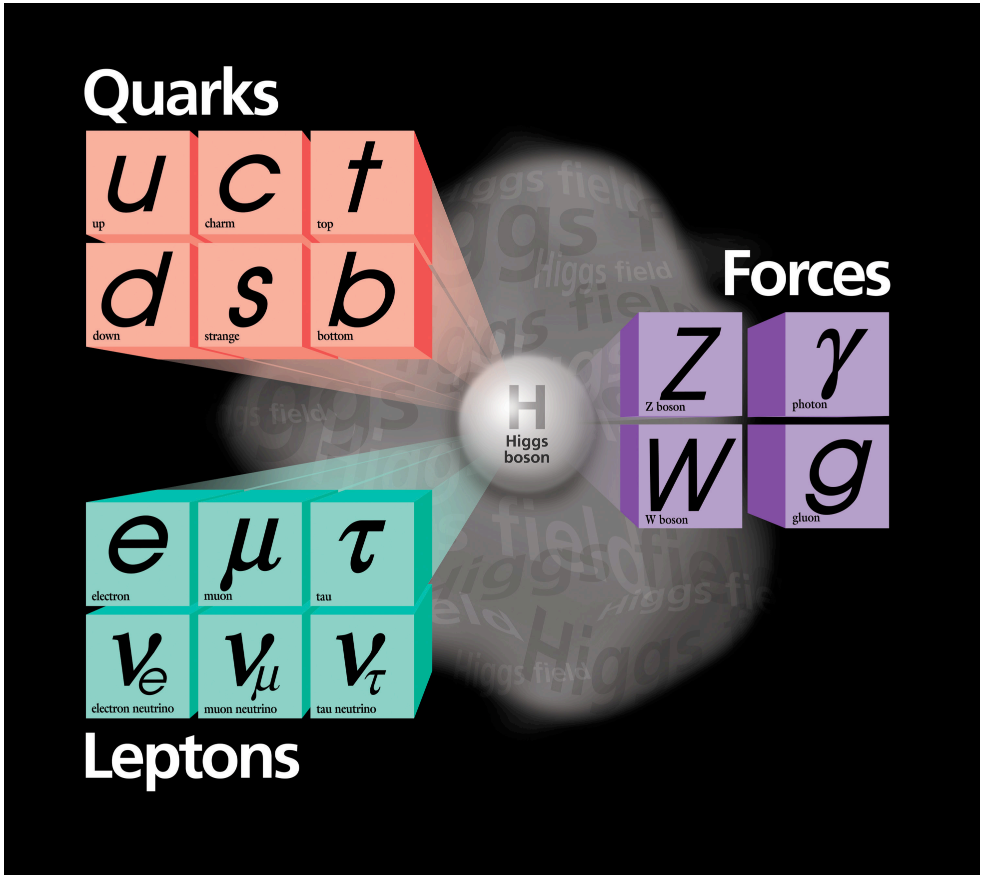
- ✓ Introduction
- ✓ Dark matter
- ✓ Exotica searches

2012: A new boson discovery

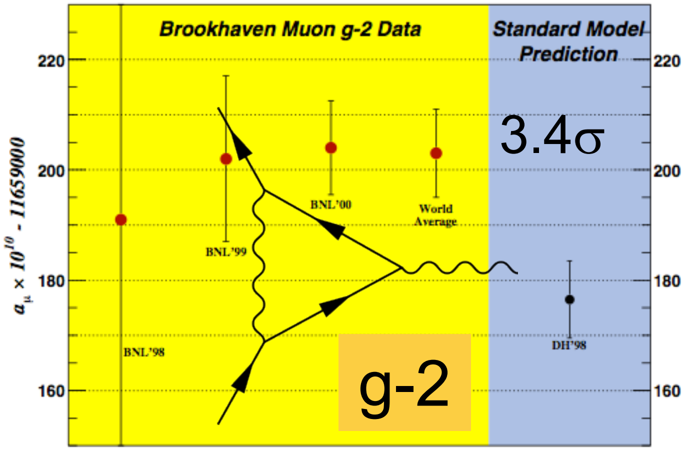


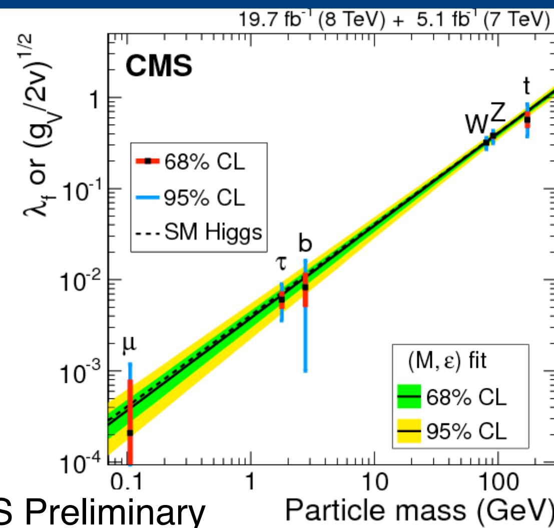
Standard Model theory of everything?

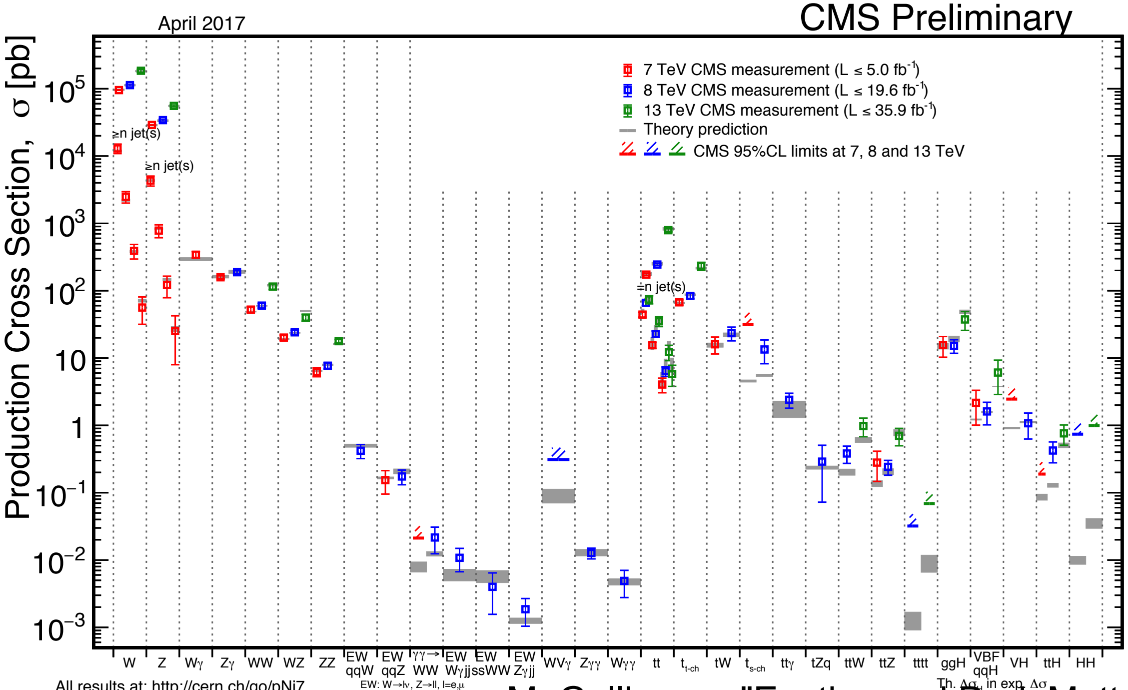
- Discovery of the Higgs boson marks the triumph of the SM
- However, even with the inclusion of the Higgs boson, SM is an incomplete theory

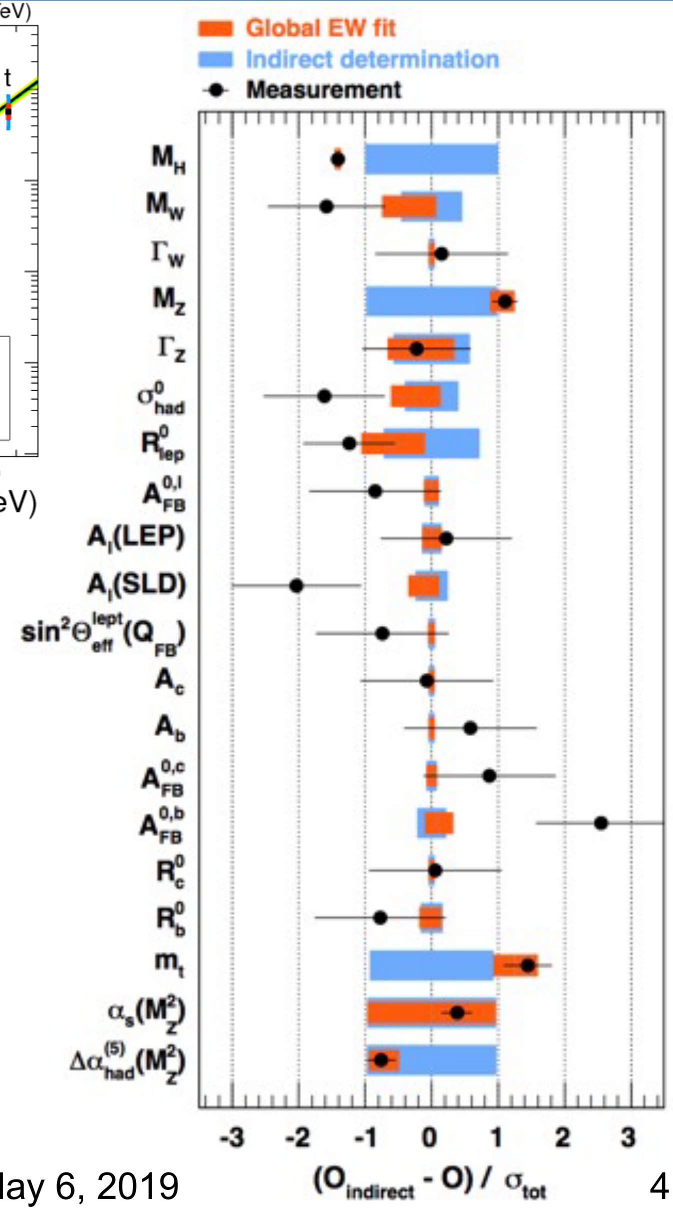


Tests of the SM









Beyond the Standard Model

The SM answers many of the questions about the structure of matter. But SM is not complete; still many unanswered questions:

a) Why do we observe matter and almost no antimatter if we believe there is a symmetry between the two in the universe?

b) What is this "dark matter" that we can't see that has visible gravitational effects in the cosmos?

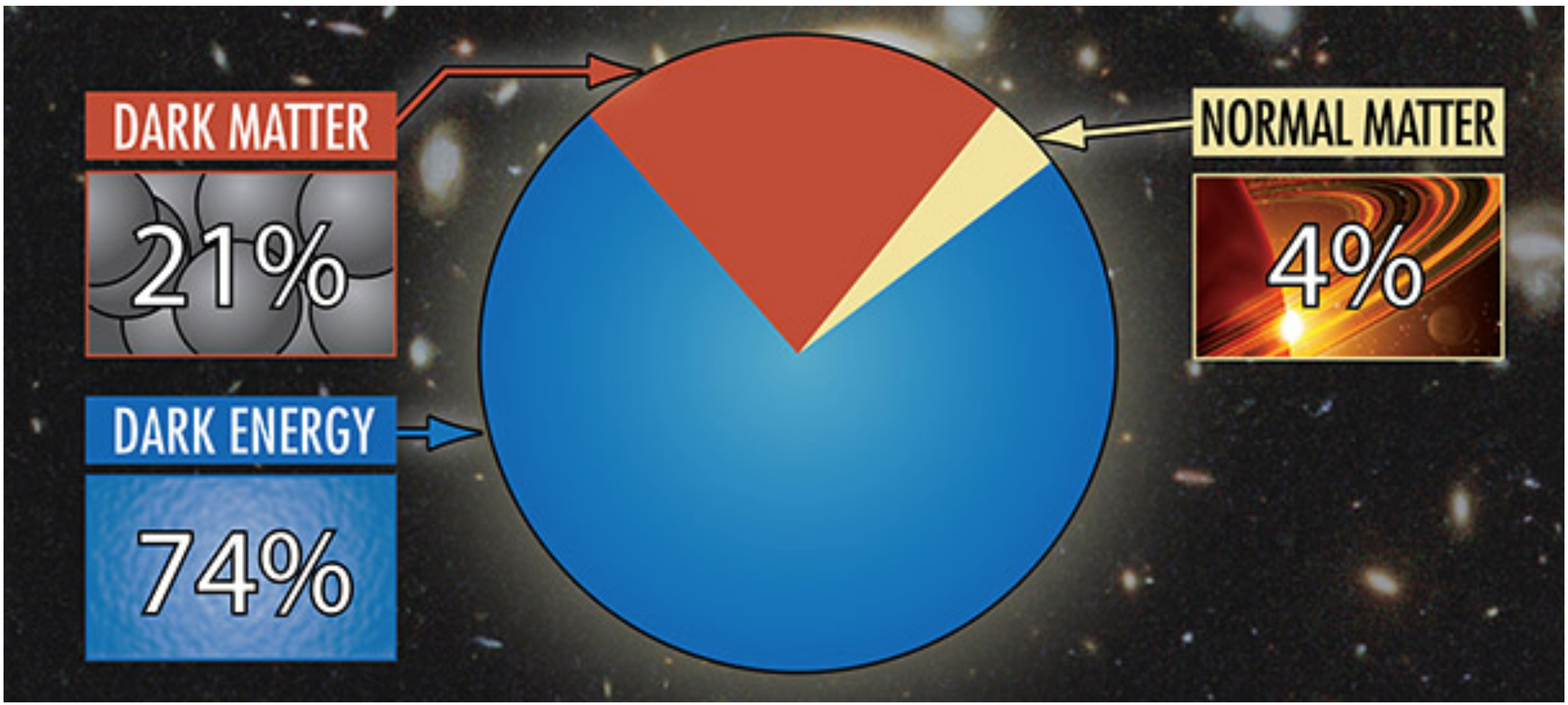
c) Are quarks and leptons actually fundamental, or made up of even more fundamental particles?

d) Why are there three generations of quarks and leptons? What is the explanation for the observed pattern for particle masses?

e) How does gravity fit into all of this?

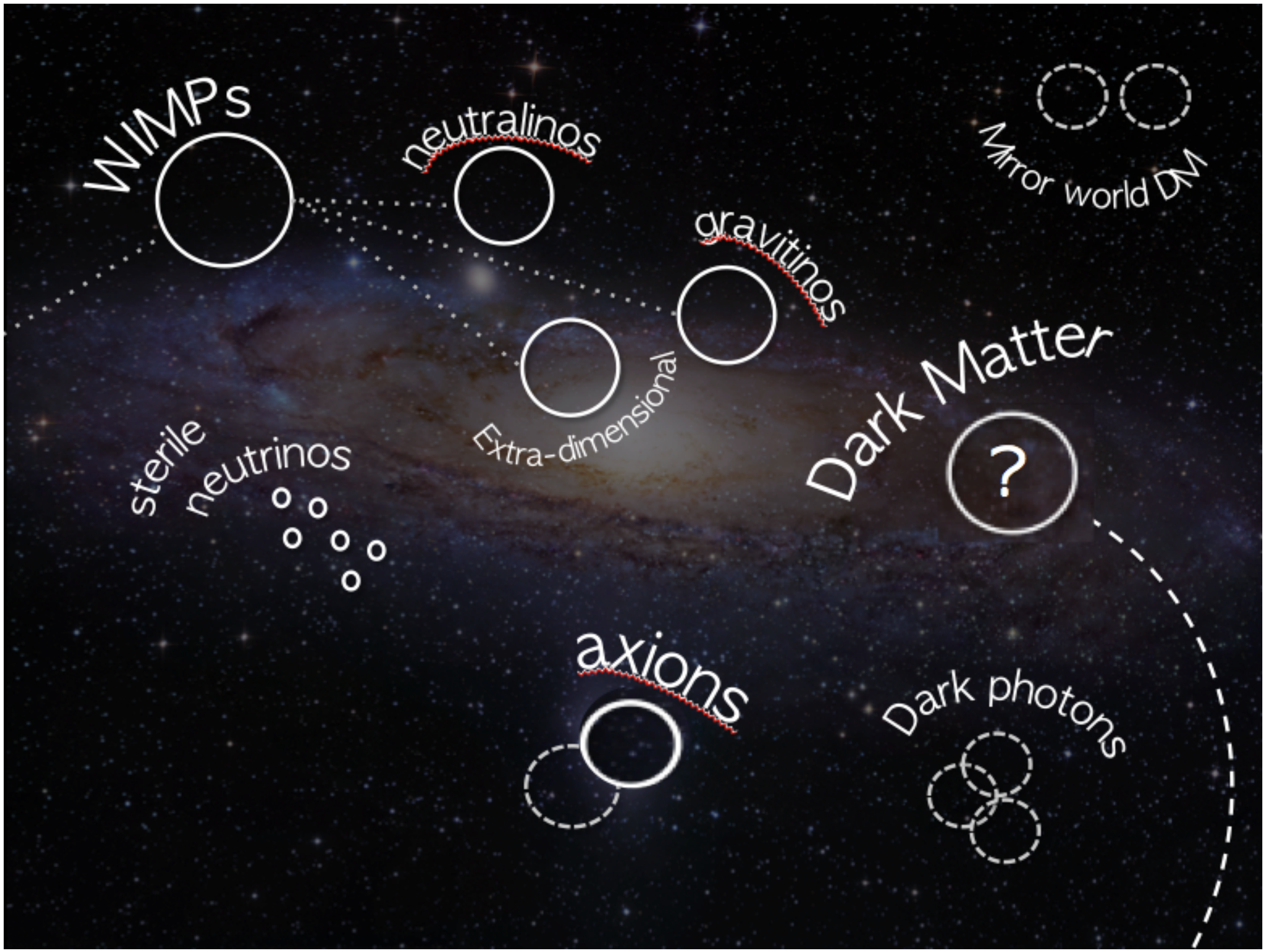
Dark matter and energy

- What is that accounts for 96% of the Universe? Nobody knows.
- It is one of the greatest mysteries of Science



What can we look for?

A crowded field. At the LHC we can search for some of these



How?

- Search for new phenomena
- Look for New Physics
- Indirect searches
  – precision measurements, event properties, etc.
- Direct searches
  – resonances, specific final states, model-(in)dependent searches, etc.
- Production and decay rates, event characteristics, advanced tools

Dark Matter

What is it?

- DM does not interact electromagnetically
- DM interacts gravitationally

Visual map

Dark Matter (cont.)

Why is it interesting?

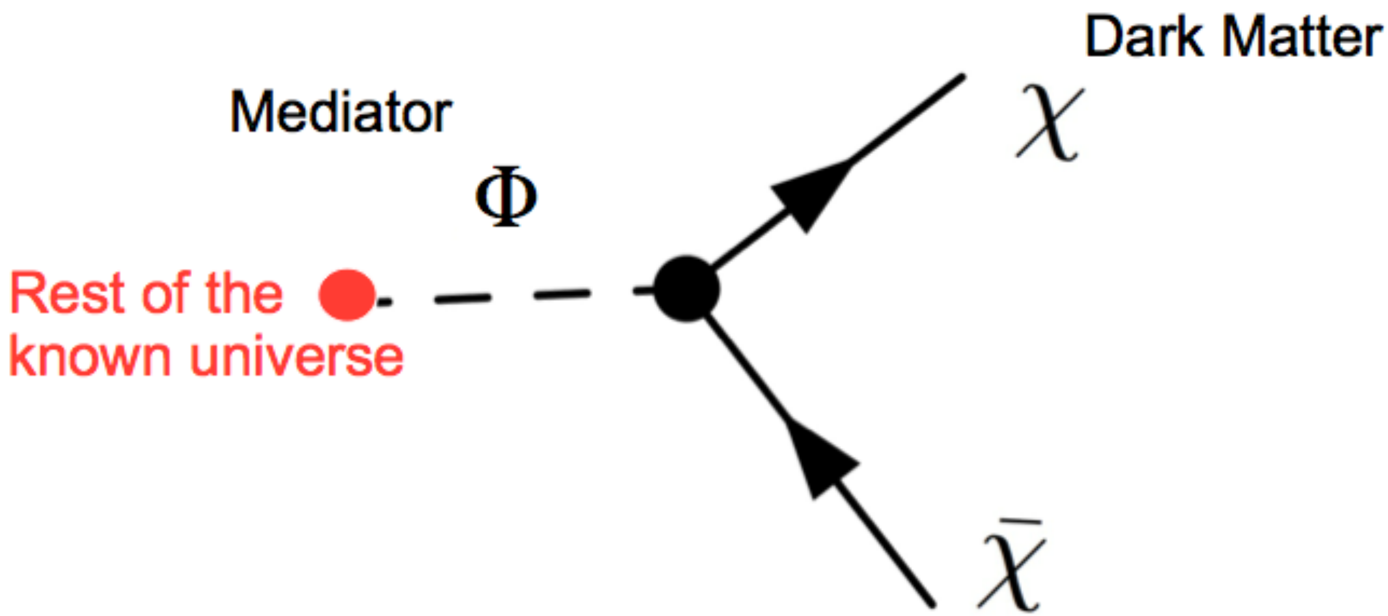
- We do not see it…but we feel it

Mass map

Dark Matter (cont.)

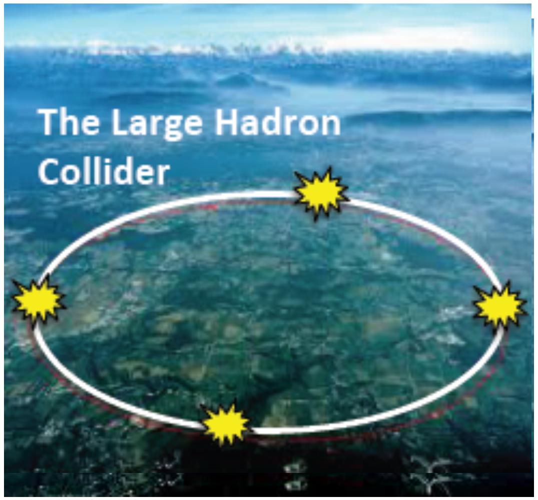
How do we find DM?

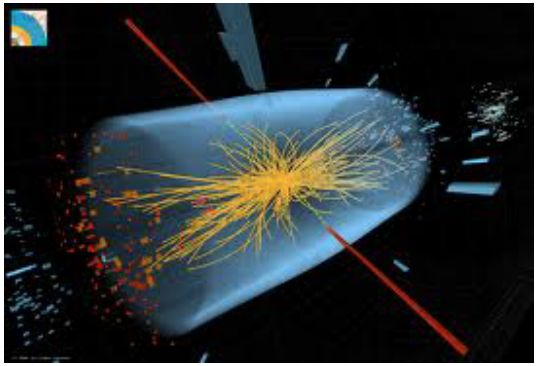
- Need to understand how it interacts with Universe
- Traditionally through a mediator
- Yields at least two new particles



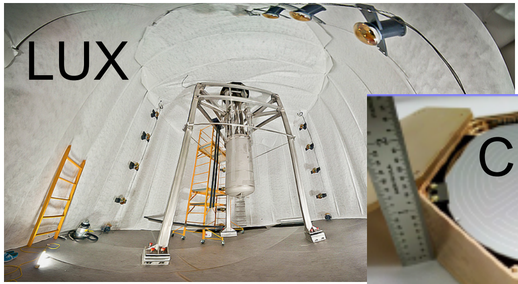
Searching for DM

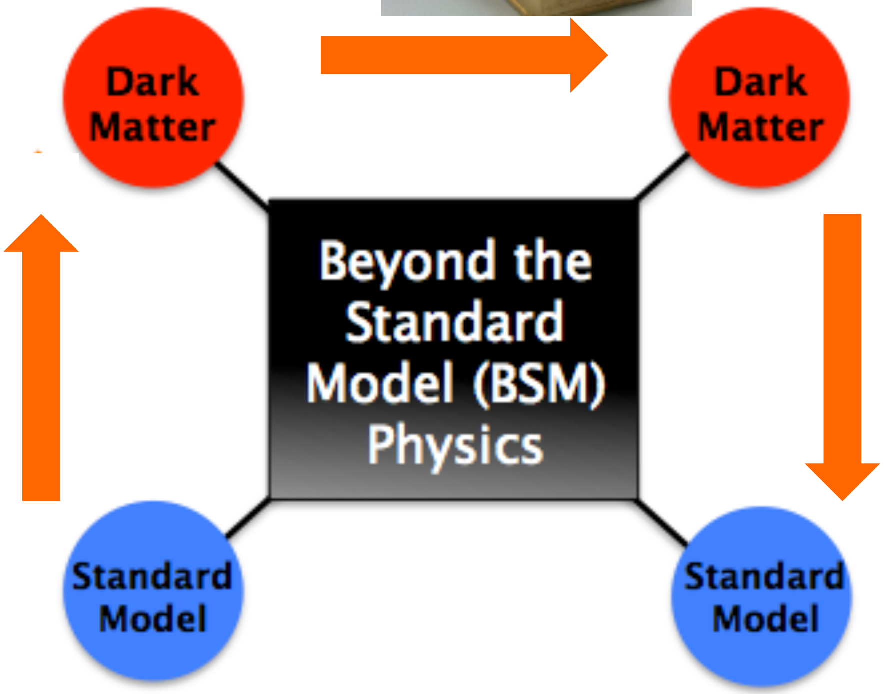
Particle Colliders



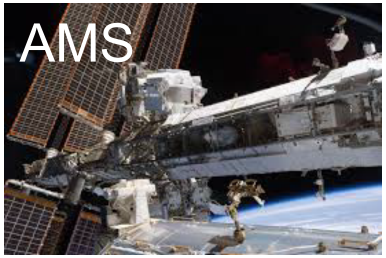


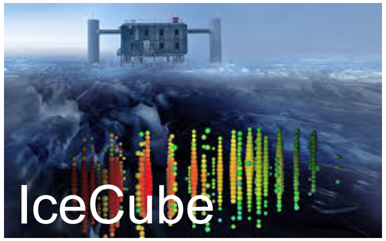
Direct Detection





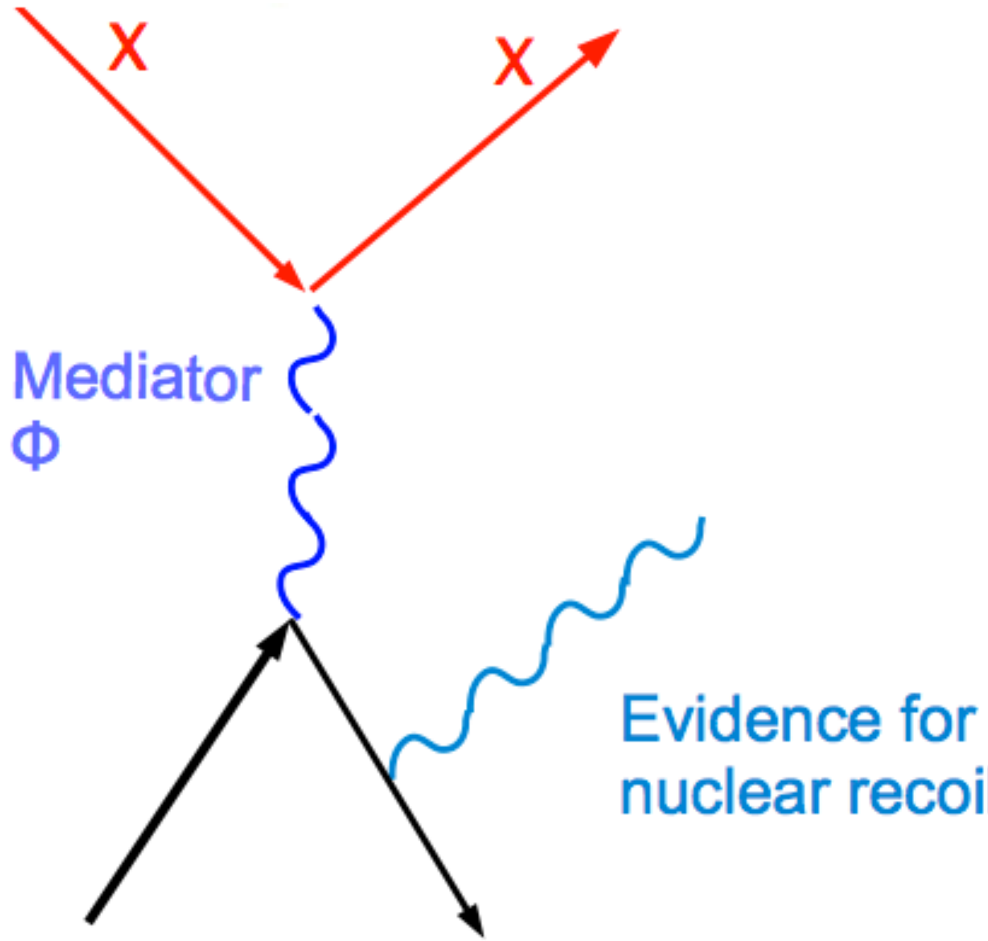
Indirect Detection





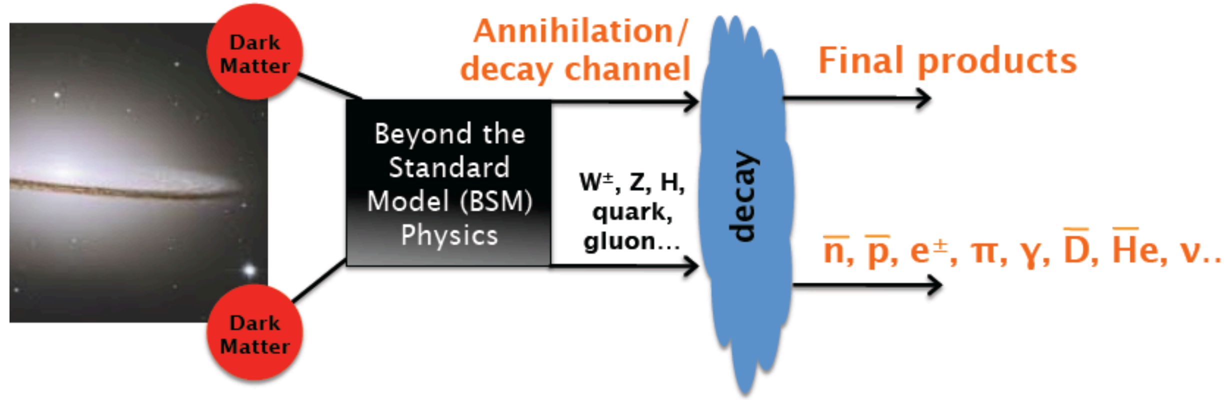
How do we find it: @underground

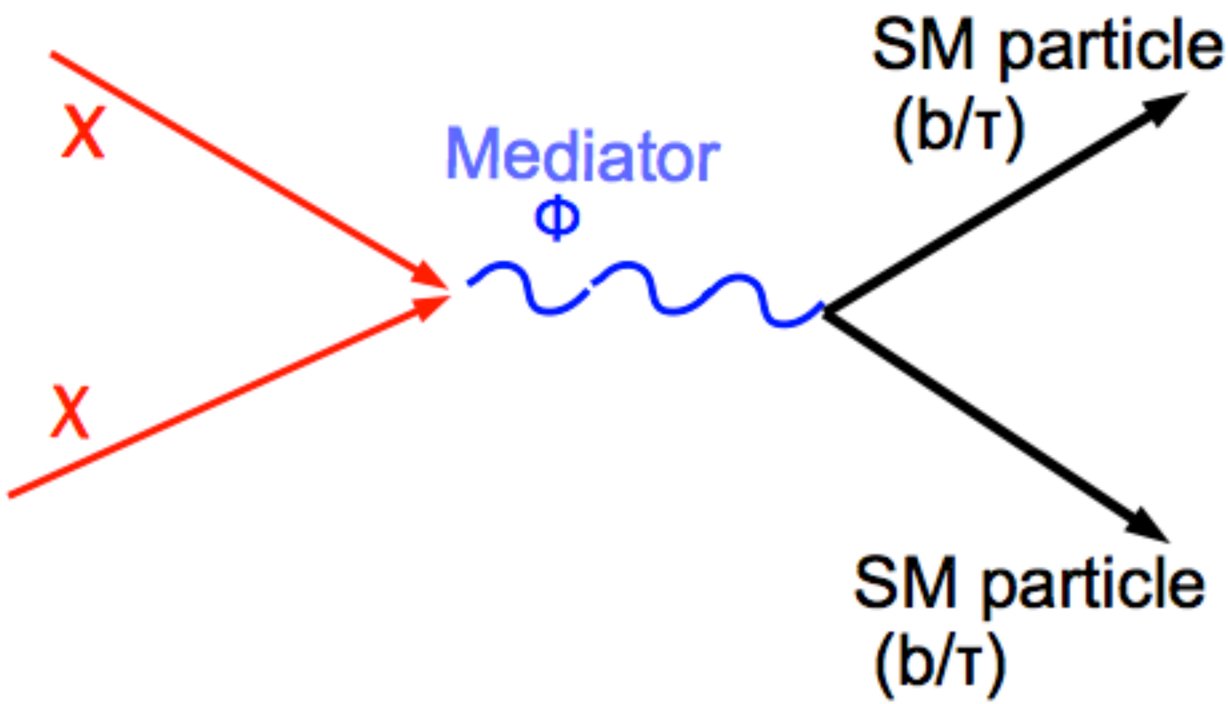
- Through a nuclear recoil



How do we find it: @Space

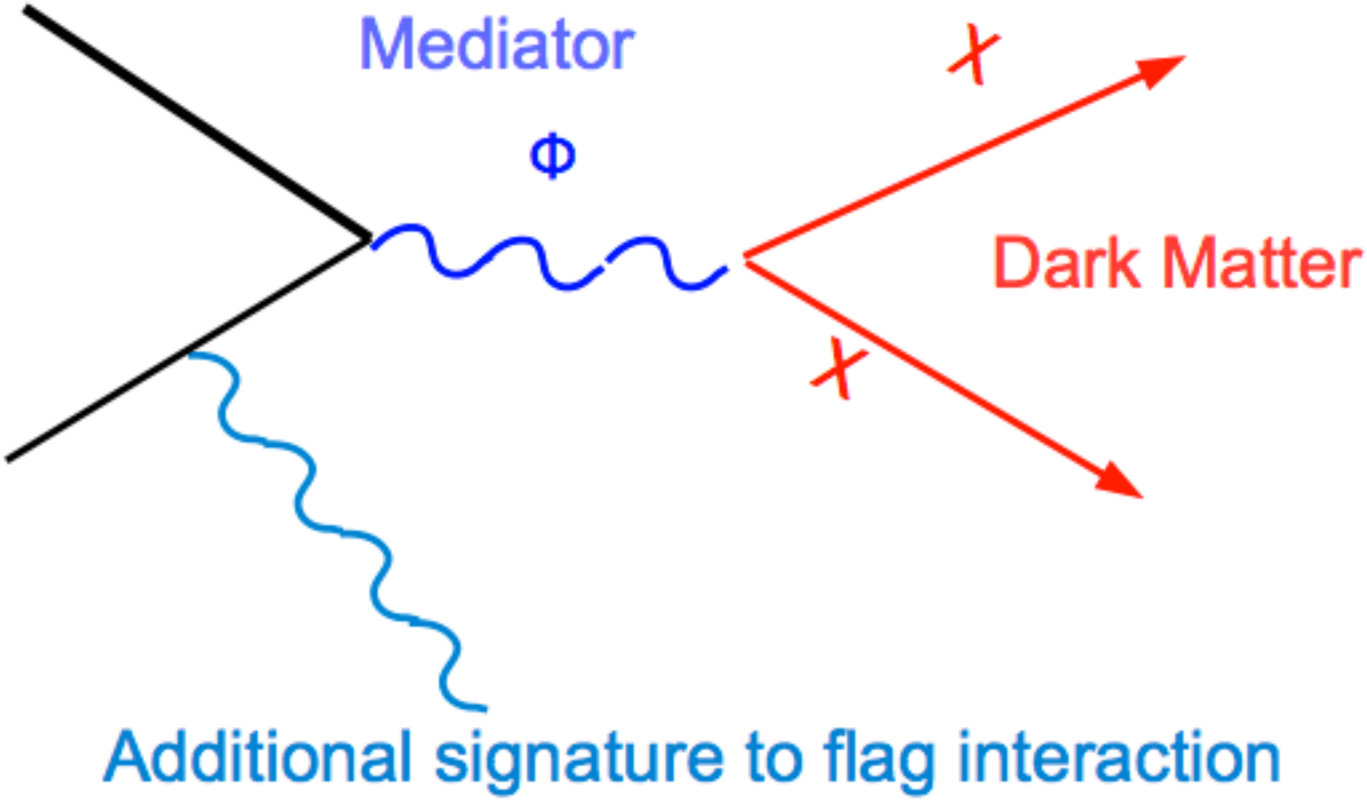
- Through annihilation
  - Cosmic rays from DM





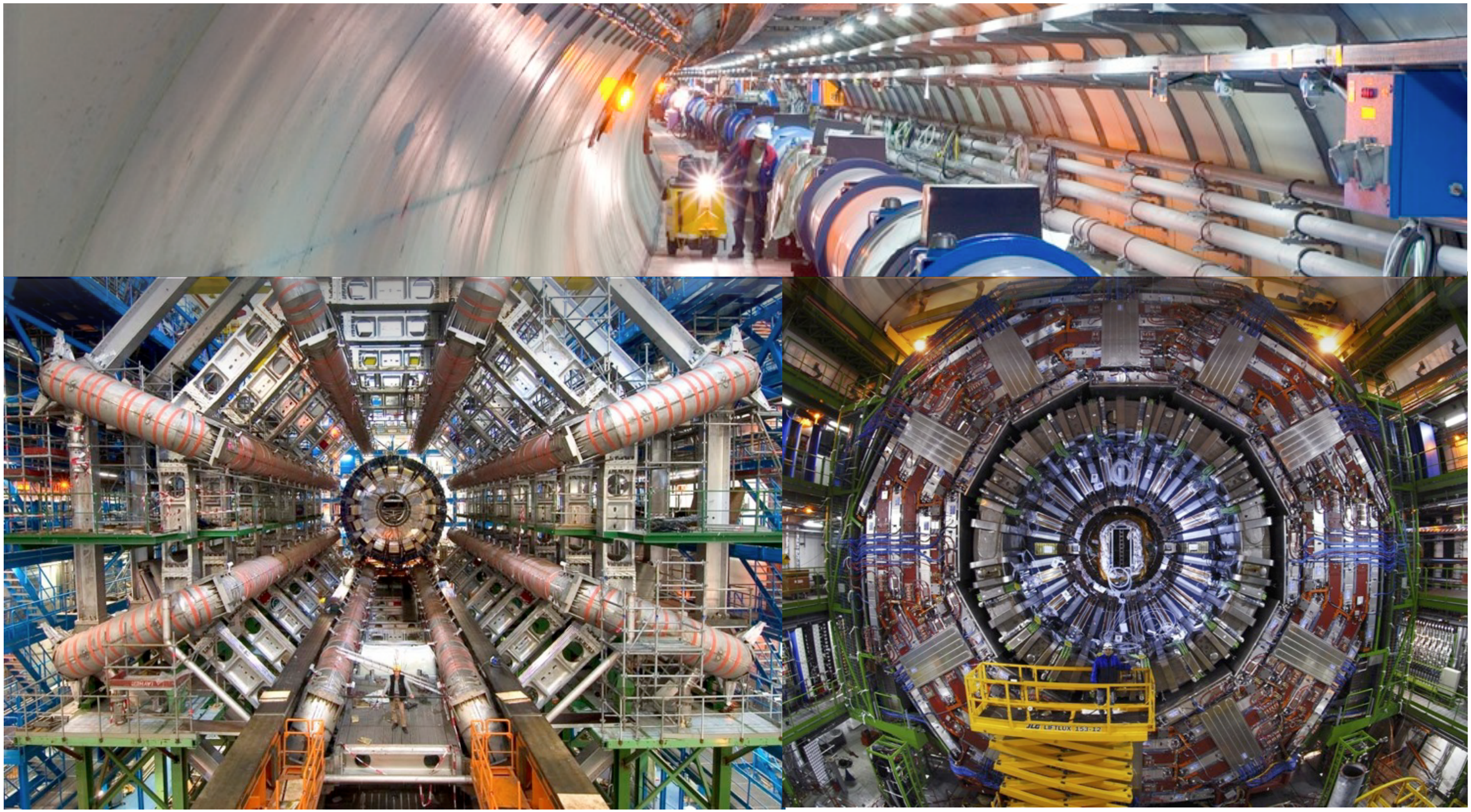
How do we find it: @LHC

- Produced it through a mediator



DM at the LHC

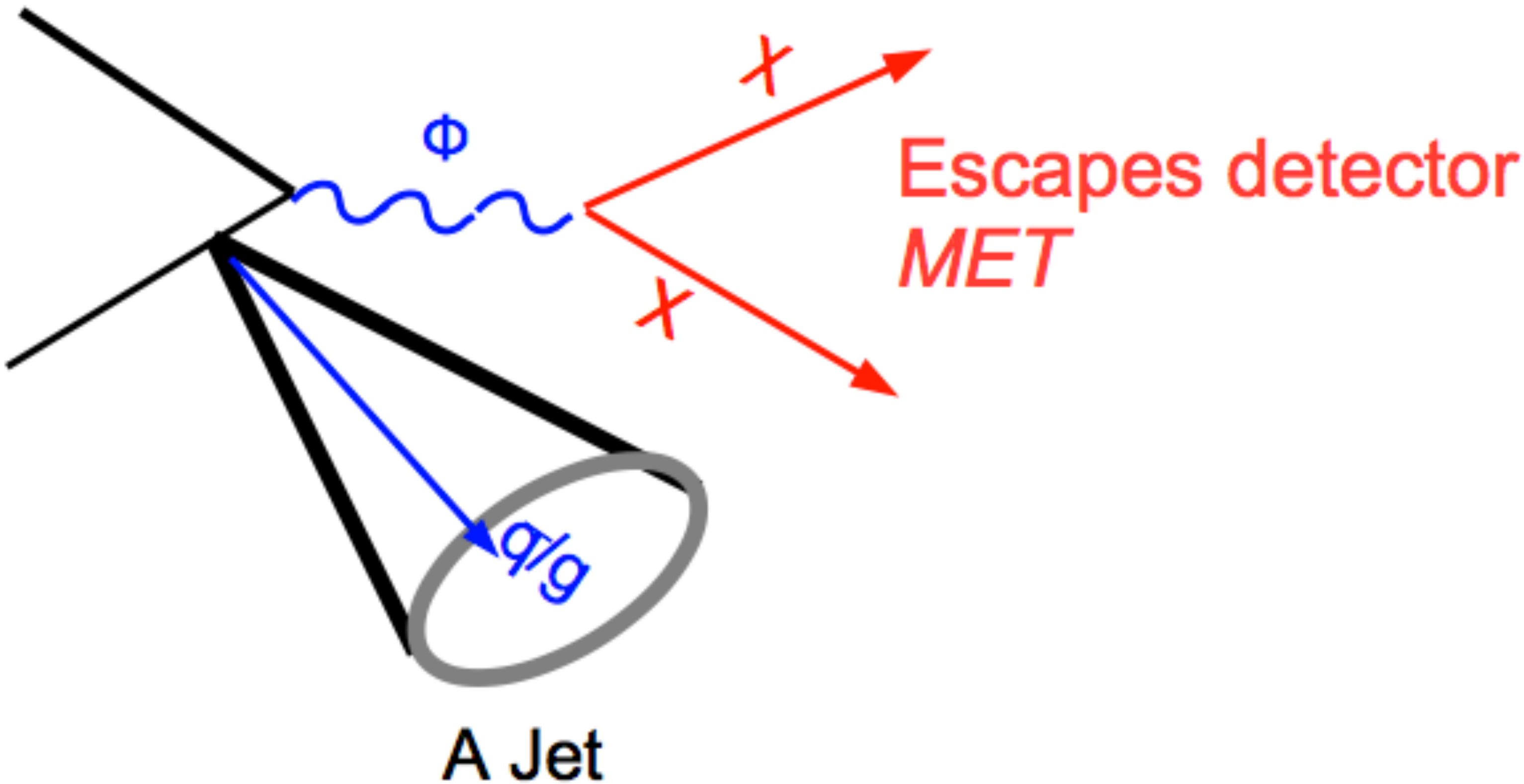
- CMS/ATLAS experiments not designed for DM searches



DM searches at LHC

How do we find DM at the LHC?

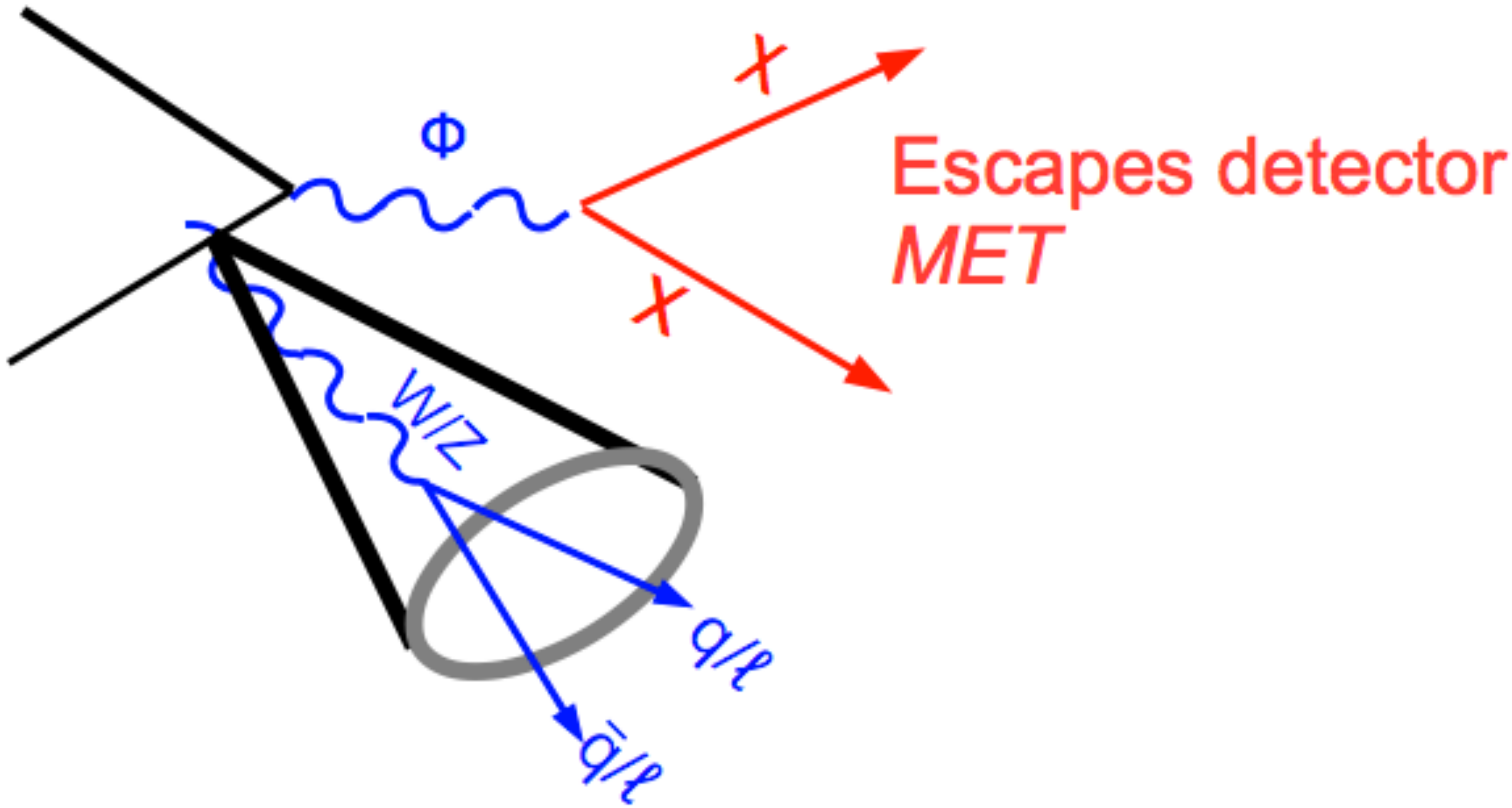
- DM production gives MET signature



DM searches at LHC

How do we find DM at the LHC?

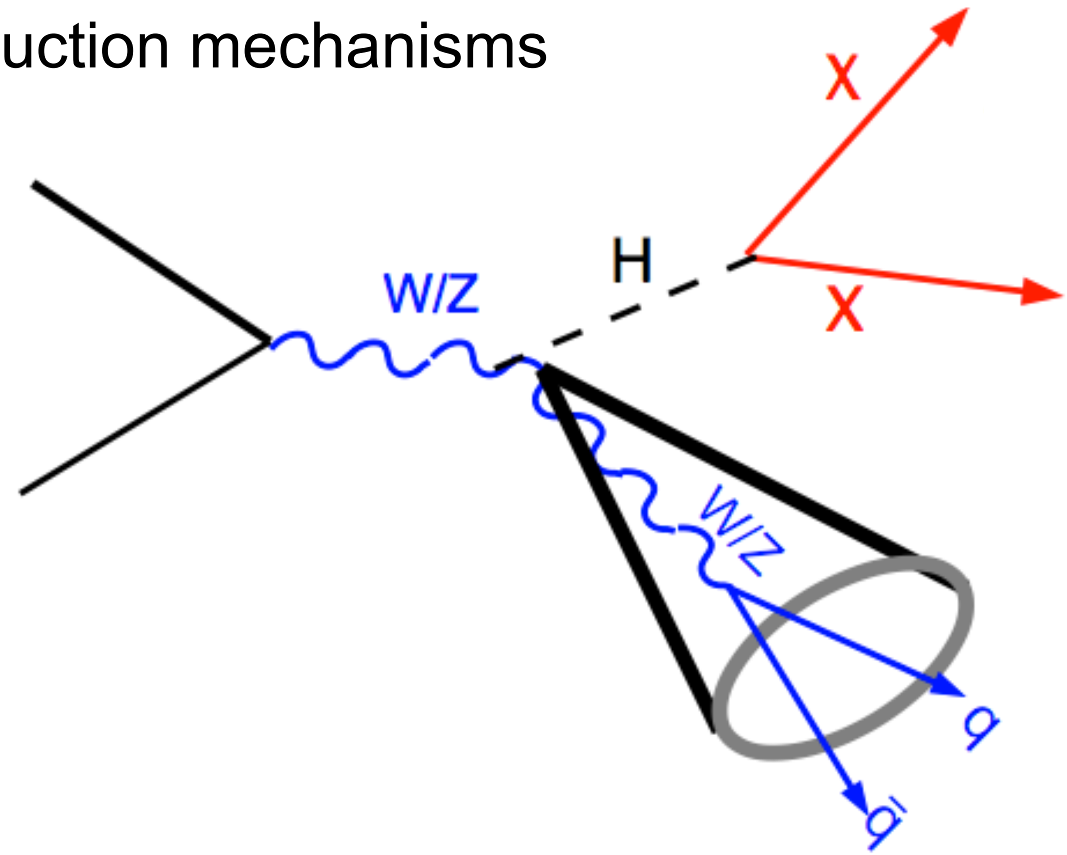
- Mono-V: Tag events with a boson



DM searches at LHC

How do we find DM at the LHC?

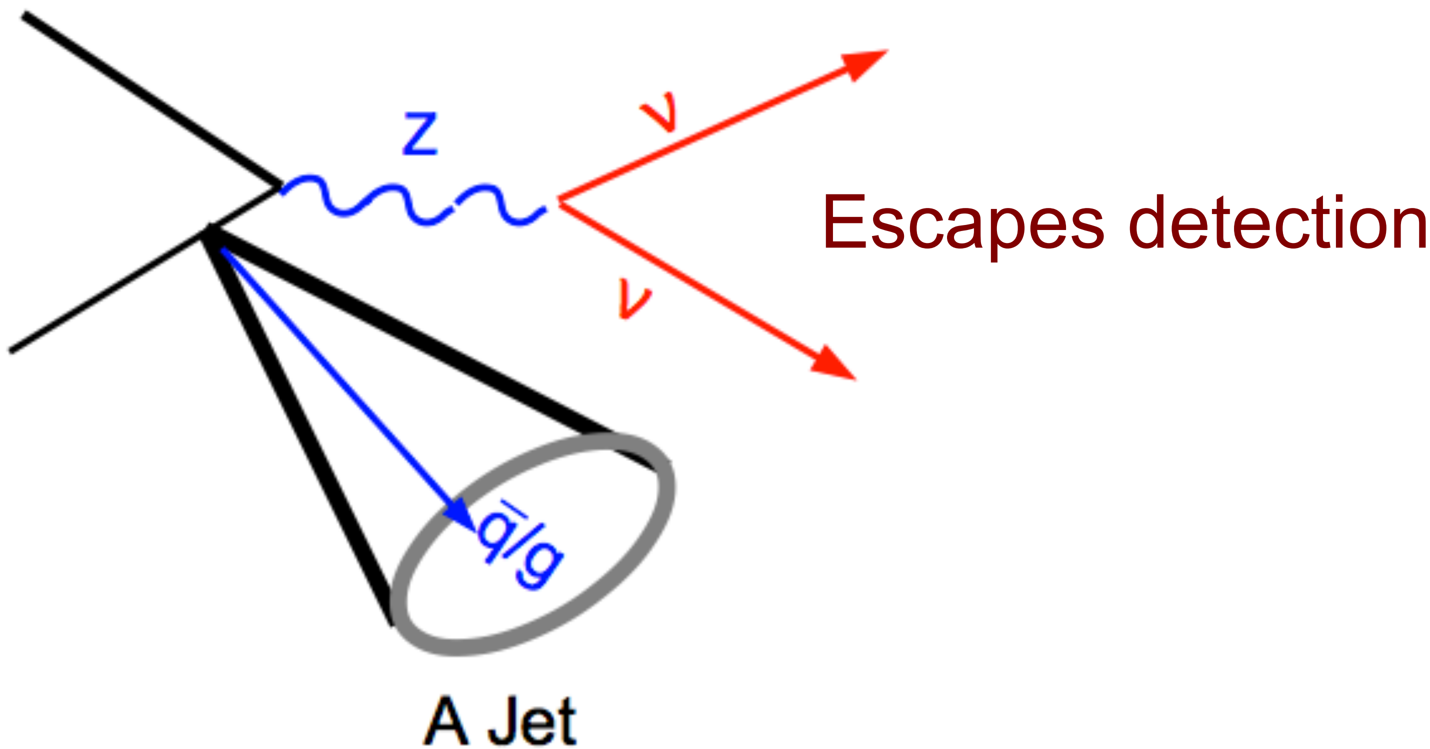
- Mono-V with (pseudo-) scalars
  - Different production mechanisms



DM searches: backgrounds

What are the backgrounds?

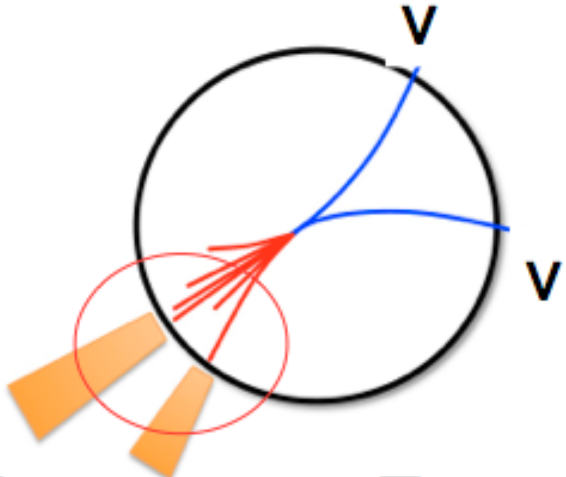
- $Z \rightarrow \nu\nu$
  - very similar to signal



DM searches: backgrounds (cont.)

How to discriminate signal against the background?

- Look for high MET:



Study hadronic recoil

$$MET = -\Sigma_{All\ particles}\, p_T$$

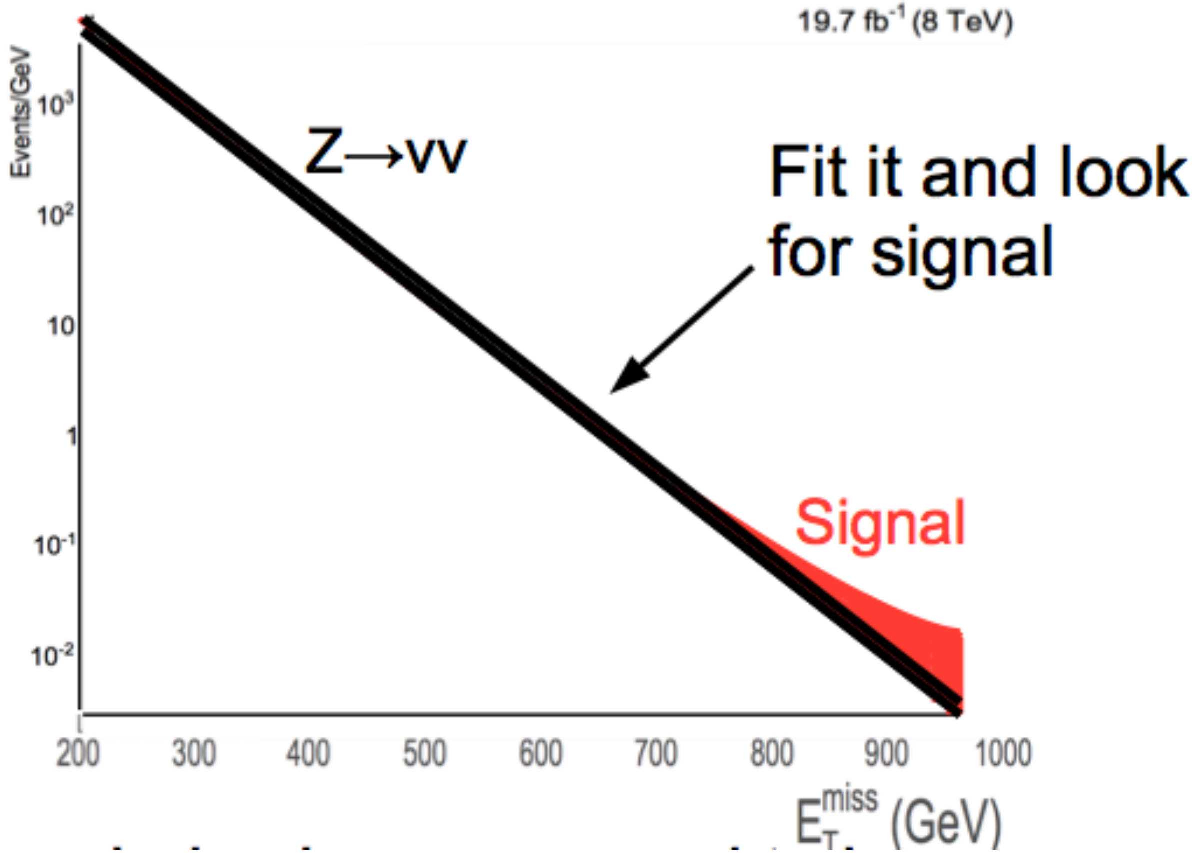
$$MET(Z \rightarrow \nu\nu) = -\ Z\ recoil + p_T(\nu\nu)$$

$$MET(Z \rightarrow \nu\nu) = -\ Z\ p_T$$

DM searches: backgrounds (cont.)

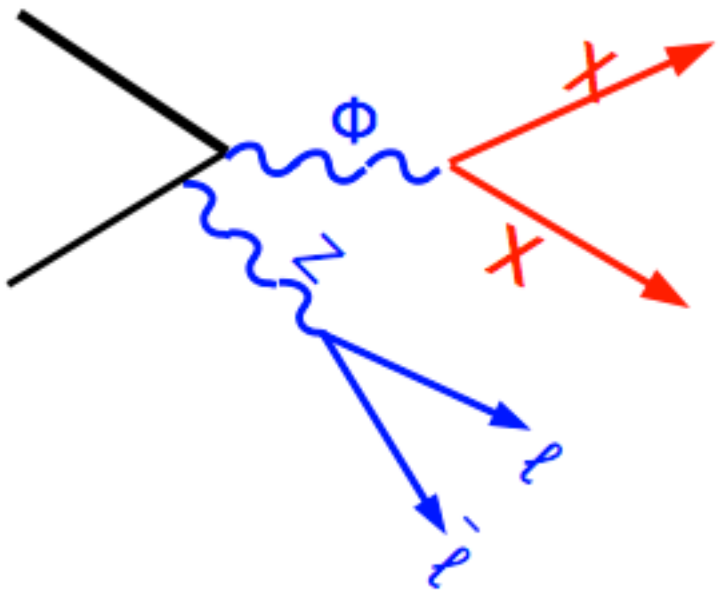
How to discriminate signal against the background?

- Can fit the shape and look for signal

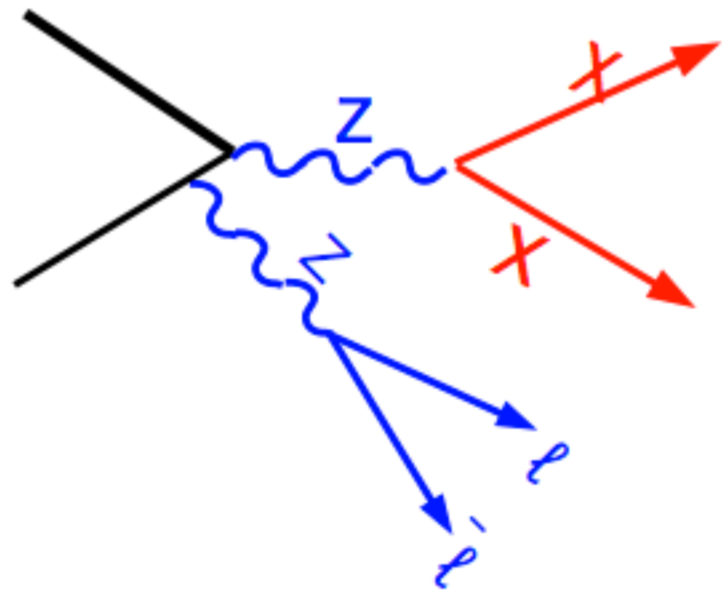


DM+Z

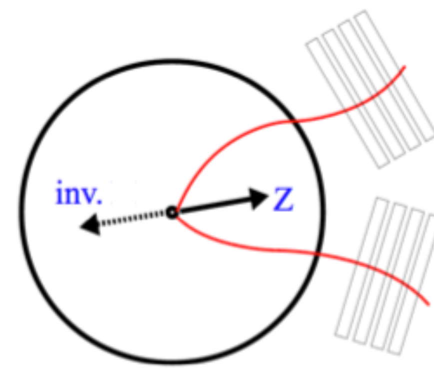
signal



background



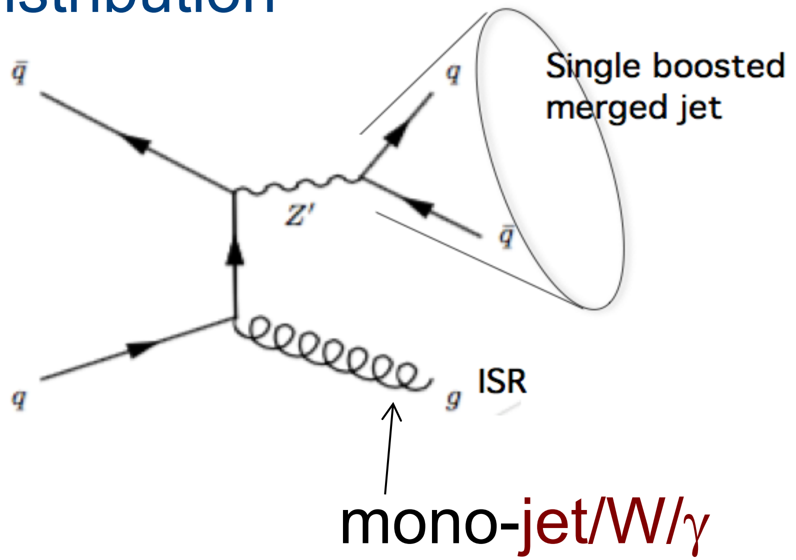
- Main background is from ZZ di-bosons
- Understanding ZZ di-boson pT is critical

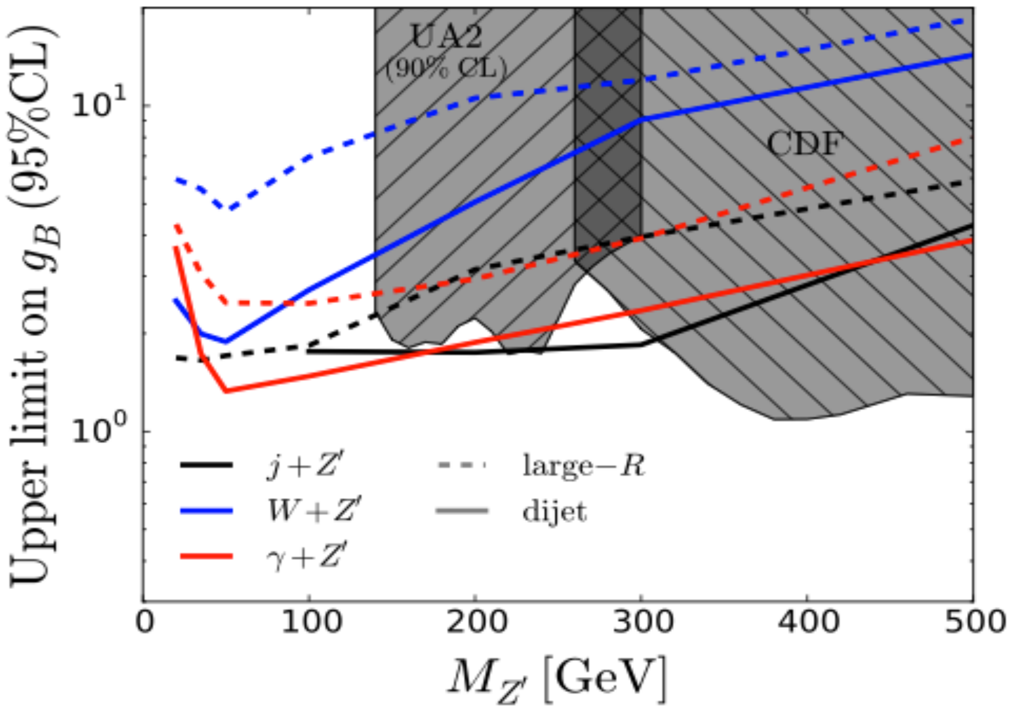


DM+jets (j/V/γ): Motivation

CMS-EXO-16-030

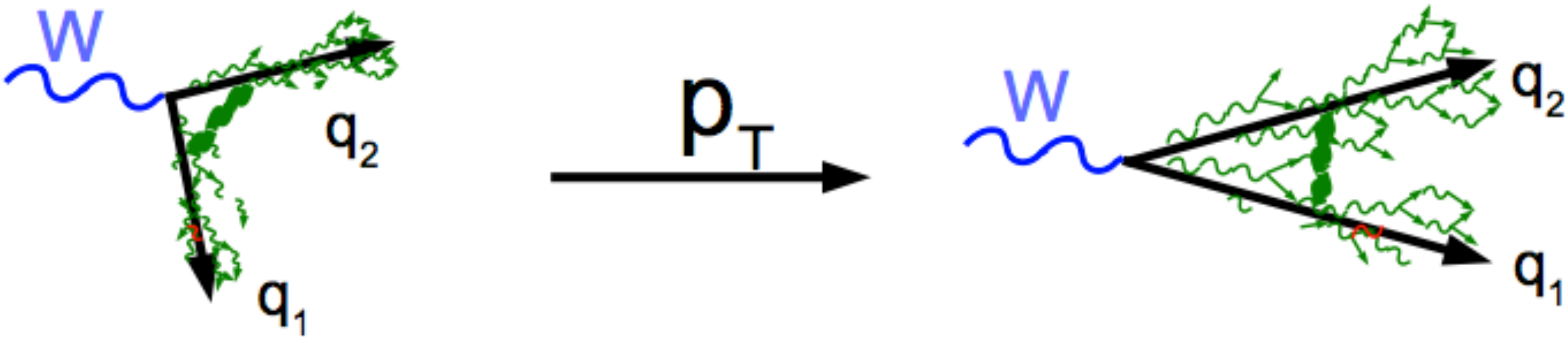
- Search for Z' leptophobic vector
- Strategy: Z'→qq
- Multijet topology with high-p_T jet
- Look at jet substructure
- Search for "bump" in jet mass distribution





Build a V-tagger

- Two jets are more collimated at high pT

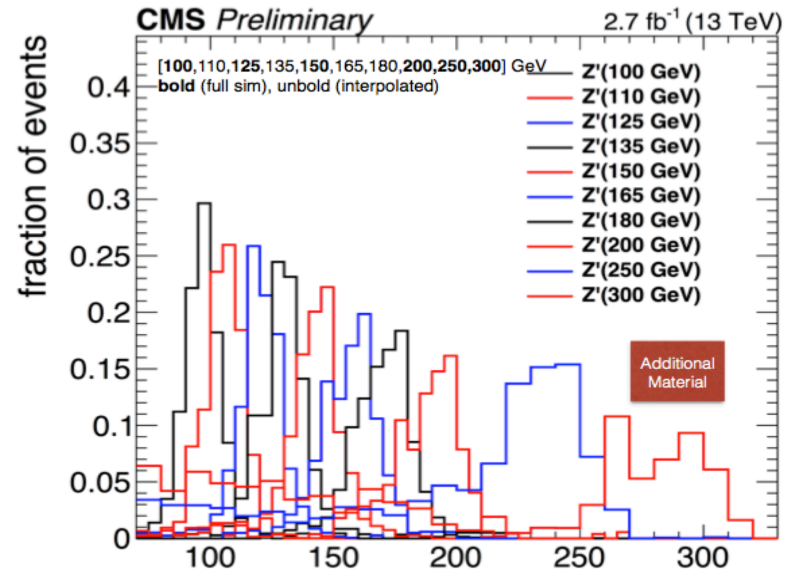


- At low pT jets are "resolved"
  - Focus on reconstructing di-jets with mass near W mass
- At high pT get one "fat" jet
  - Focus on identifying one jet with mass near W mass
- Use additional variables to improve discrimination

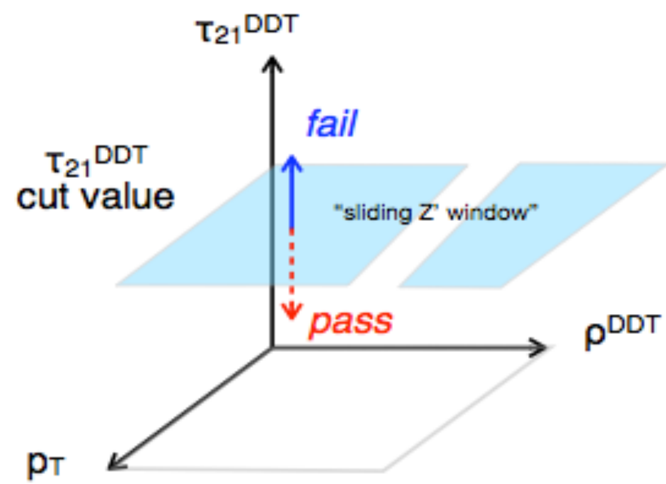
DM+jets (j/V/γ): Analysis

CMS-EXO-16-030

- Signal region
  - p_T>500 GeV
  - τ_{21}^{DDT}<0.38
  - lepton veto
- Soft drop mass m_{SD}: peaks at Z' mass
  - removes soft wide-angle radiation from jet



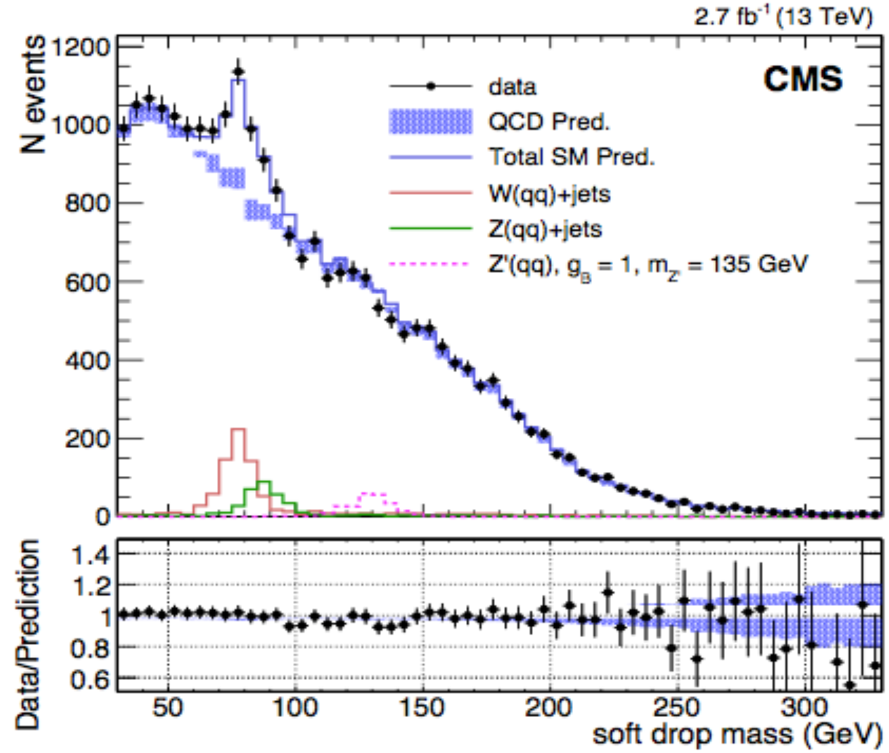
- QCD background estimated from sideband regions in data
- τ_{21}^{DDT} n-subjettiness: consistency with 2-prong structure
- τ_{21}^{DDT} defines "pass" or "fail" sidebands
  - Use "*transfer function*" from fail to pass region

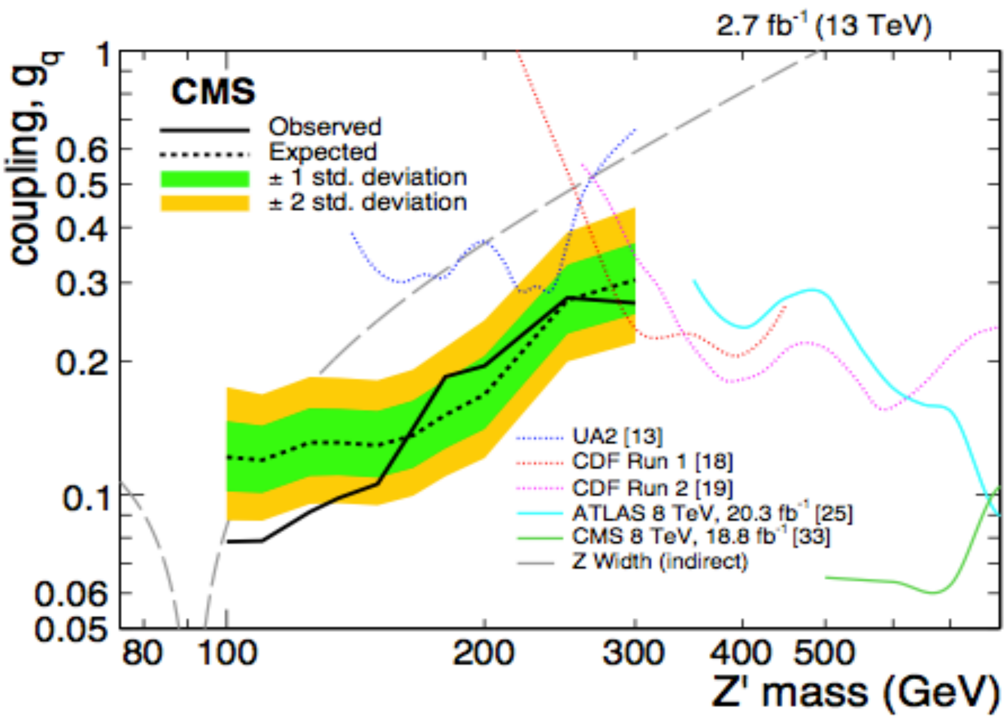


DM+jets (j/V/γ): Results

CMS-EXO-16-030

- Jet has 2-prong sub-structure
- Identify jet substructure using τ_{21}
- Set limits on light Z' →qq search (most sensitive at <140 GeV)

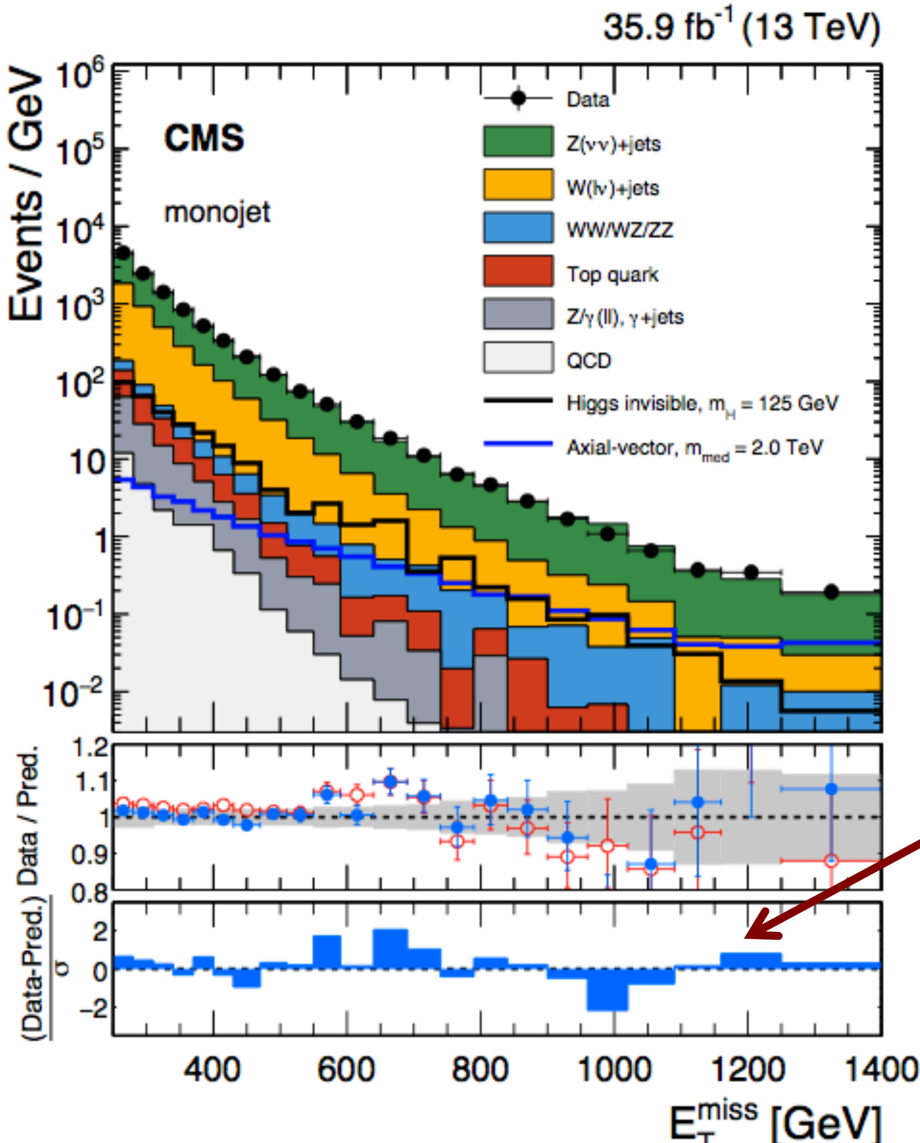




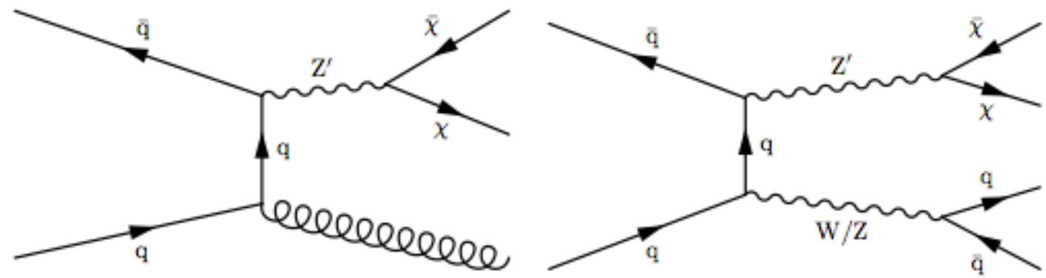
- Search for low-mass boosted dijet resonances
- Explores uncovered regions
- Limits in Z' mass at low mass

DM+jet/V

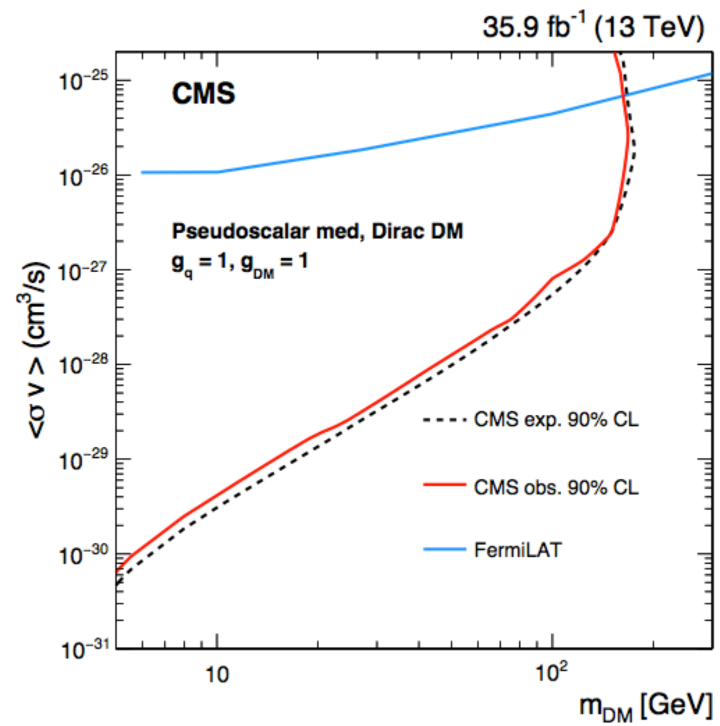
CMS-EXO-16-048



DM search in mono-jet/V



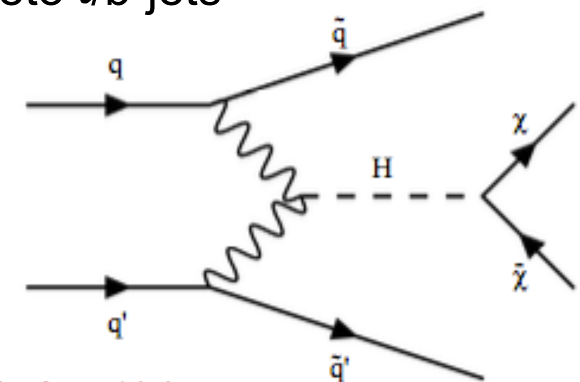
Need good control of systematics



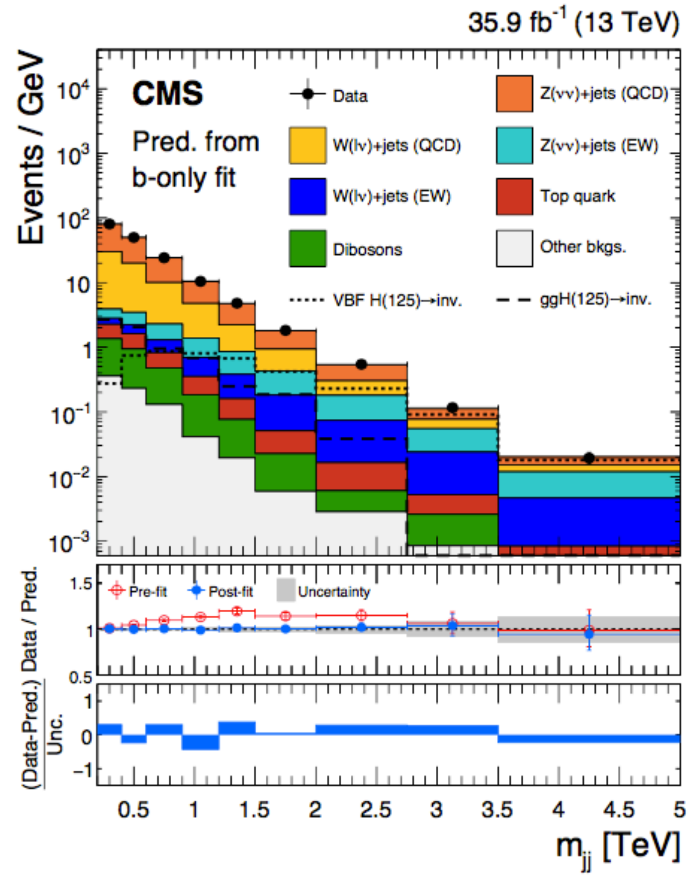
VBF: H(invisible)

arXiv:1809.06682, arXiv:1809.05937

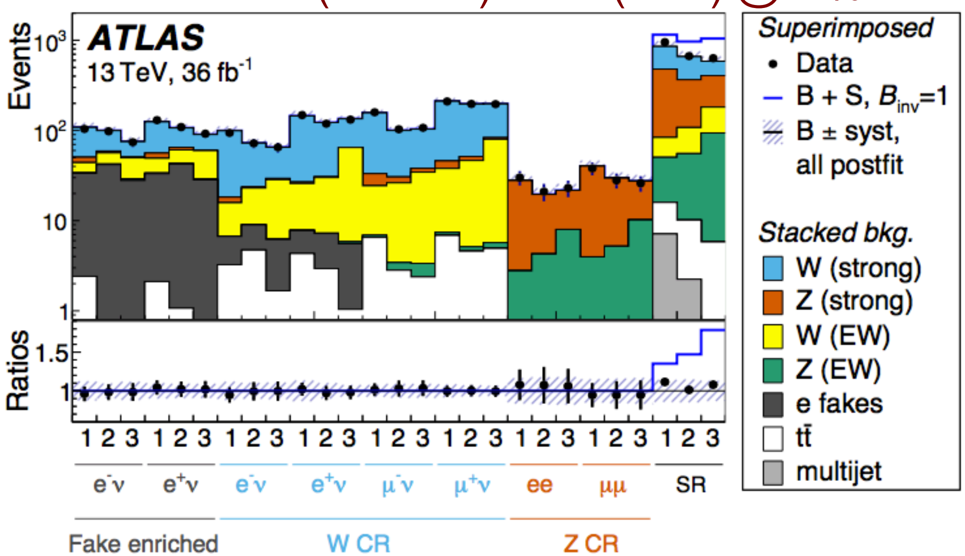
- In the SM, B(H→invisible) only 0.1%
- Any significant deviation would indicate BSM
- Signature: Large MET, $\Delta\phi(jj)$, veto ℓ/b-jets
  - C&C and shape fit of m(jj)
- Main bkg: V+jets (95%)
- Tag with forward jets+MET
- Cross section ~4pb
- Small background



Shape: bkg-only fit in CRs+SR



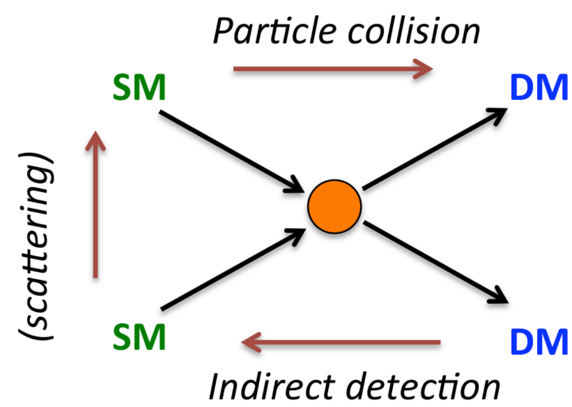
Set limits: B(H →inv.)<0.37 (0.28) @95%CL

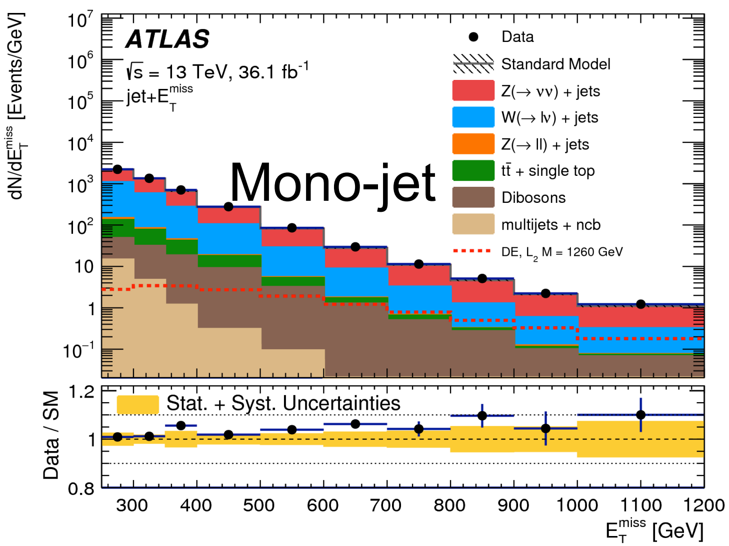


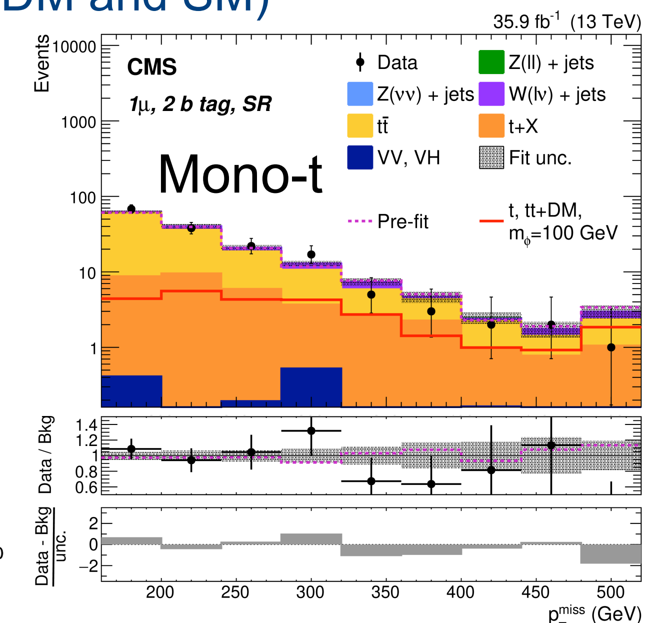
Dark Matter

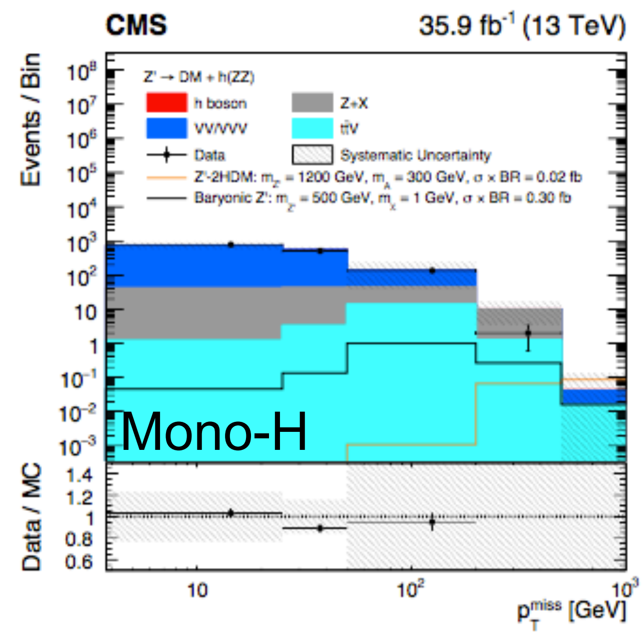
arXiv:1903.01400, arXiv:1901.0155, CMS-EXO-18-009

- Complementarity to direct/indirect searches
- DM particles:
  - interact via spin-0 & spin-1 mediators
  - are undetected (MET) recoiling against SM particle(s)
- Extensive program of mono-X searches (X=jet, γ, lepton, W, Z, t, tt, bb, H)
- No excess observed
- Interpretation through simplified models (DM and mediator masses, couplings to DM and SM)



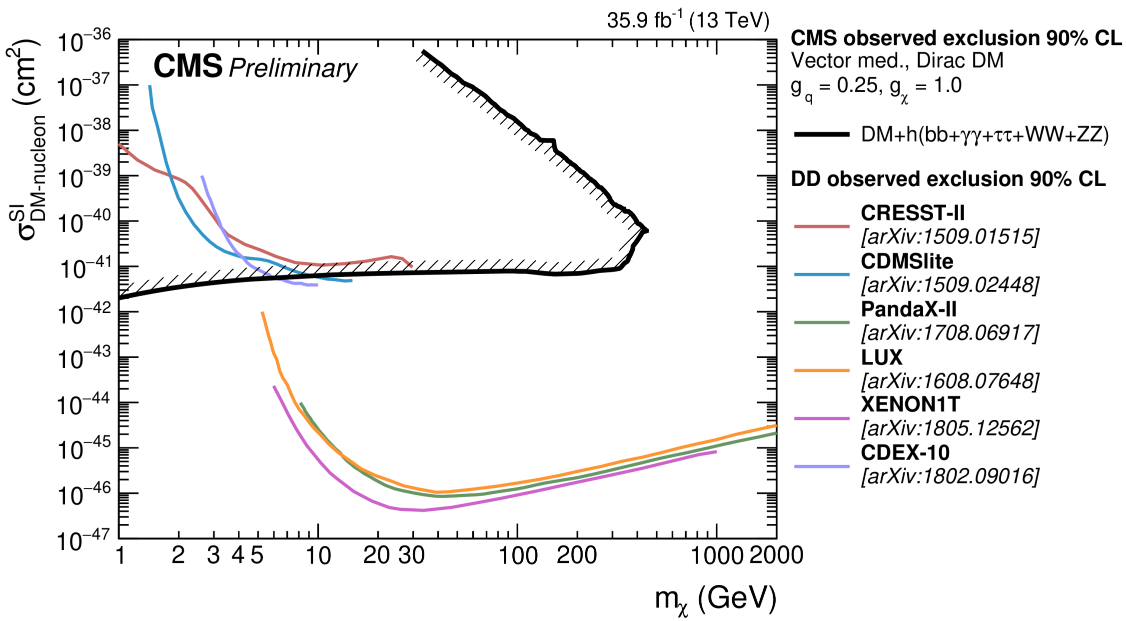


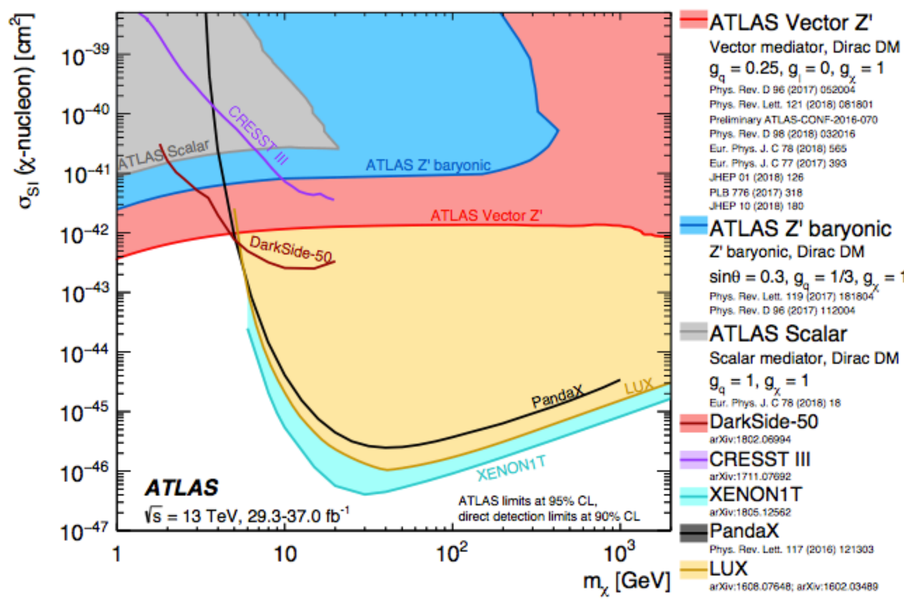




Experimental results

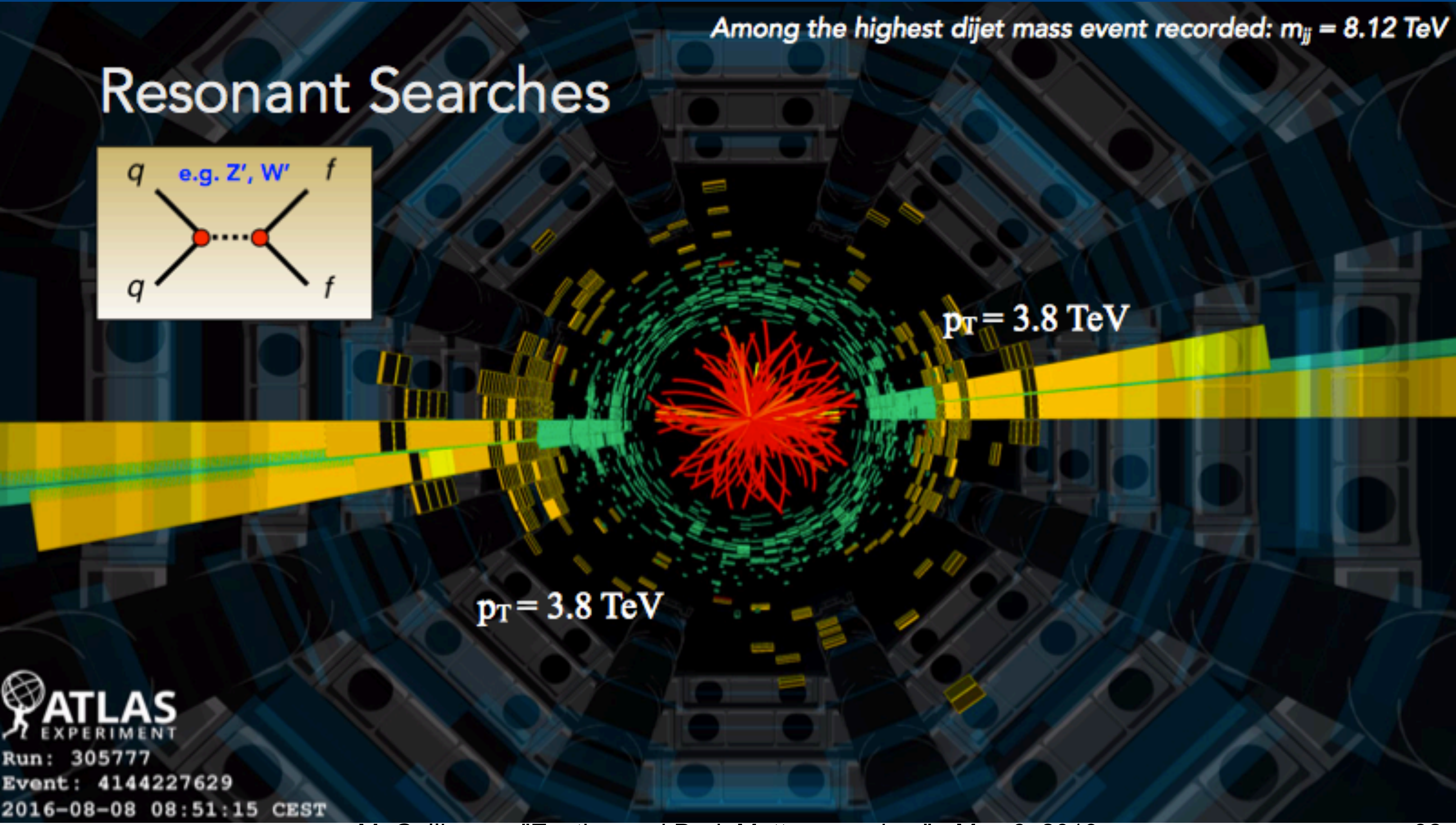
- Limits for given couplings between SM and DM interaction
- Competitive limits at low masses wrt other experiments





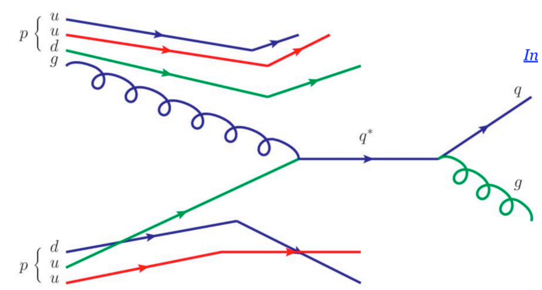
⇒ Collider results complement direct searches for low masses (<5-10GeV)

Resonant searches



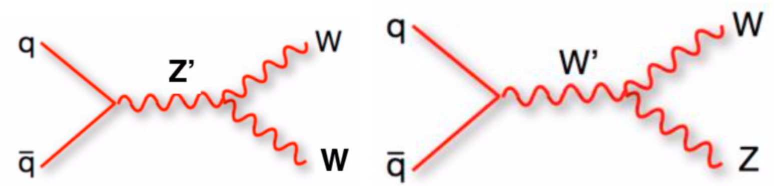
BSM models predict new resonances

- BSMs predict resonances with spin 0,1,2
- Are quarks fundamental particles?
  - Excited quarks in models of compositeness

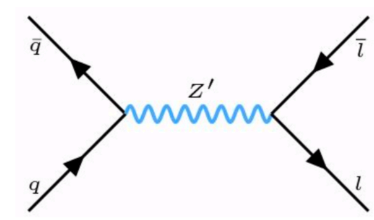


- Randall-Sundrum (RS) models
  - Spin-2 graviton (KK-particle)

- Heavy-Vector Triplets
  - Spin-1 resonance
  - Models based on strength of vector boson interactions



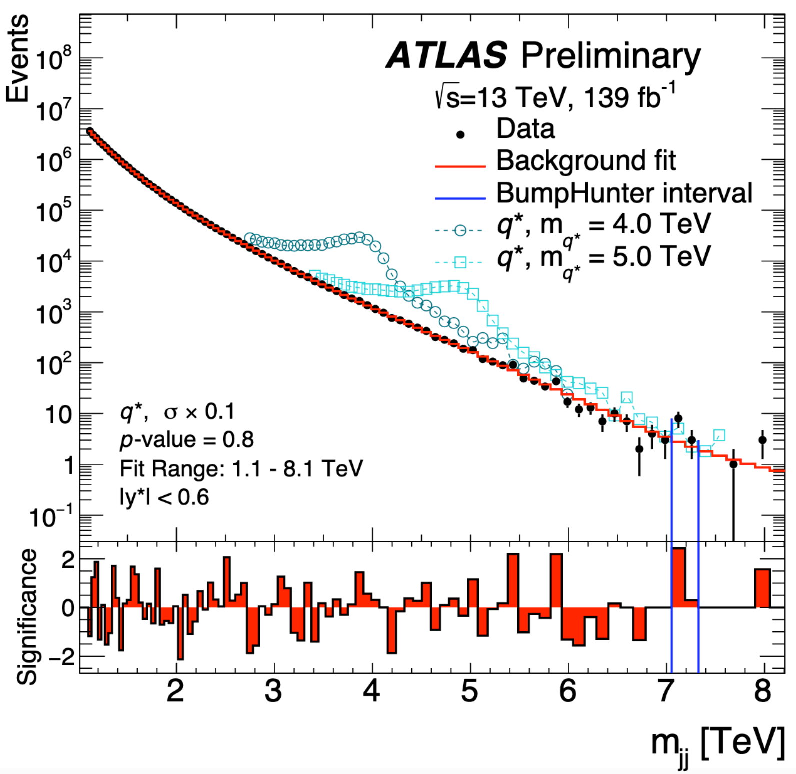
- Sequential SM
  - Z' and Z with same couplings to fermions
  - Width proportional to the mass

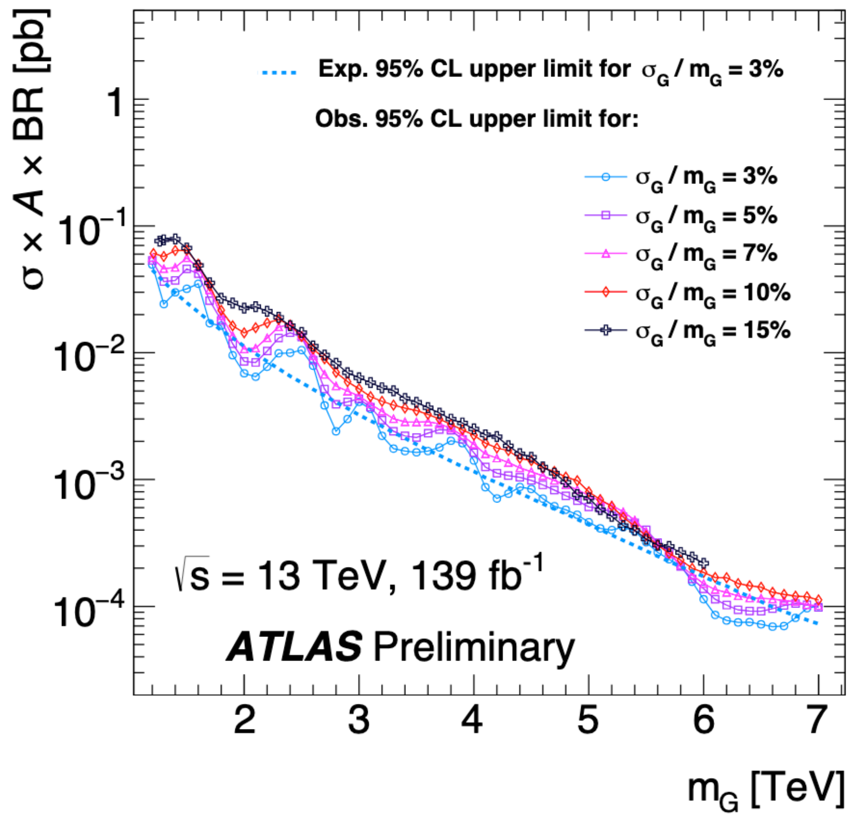


New phenomena in di-jet events

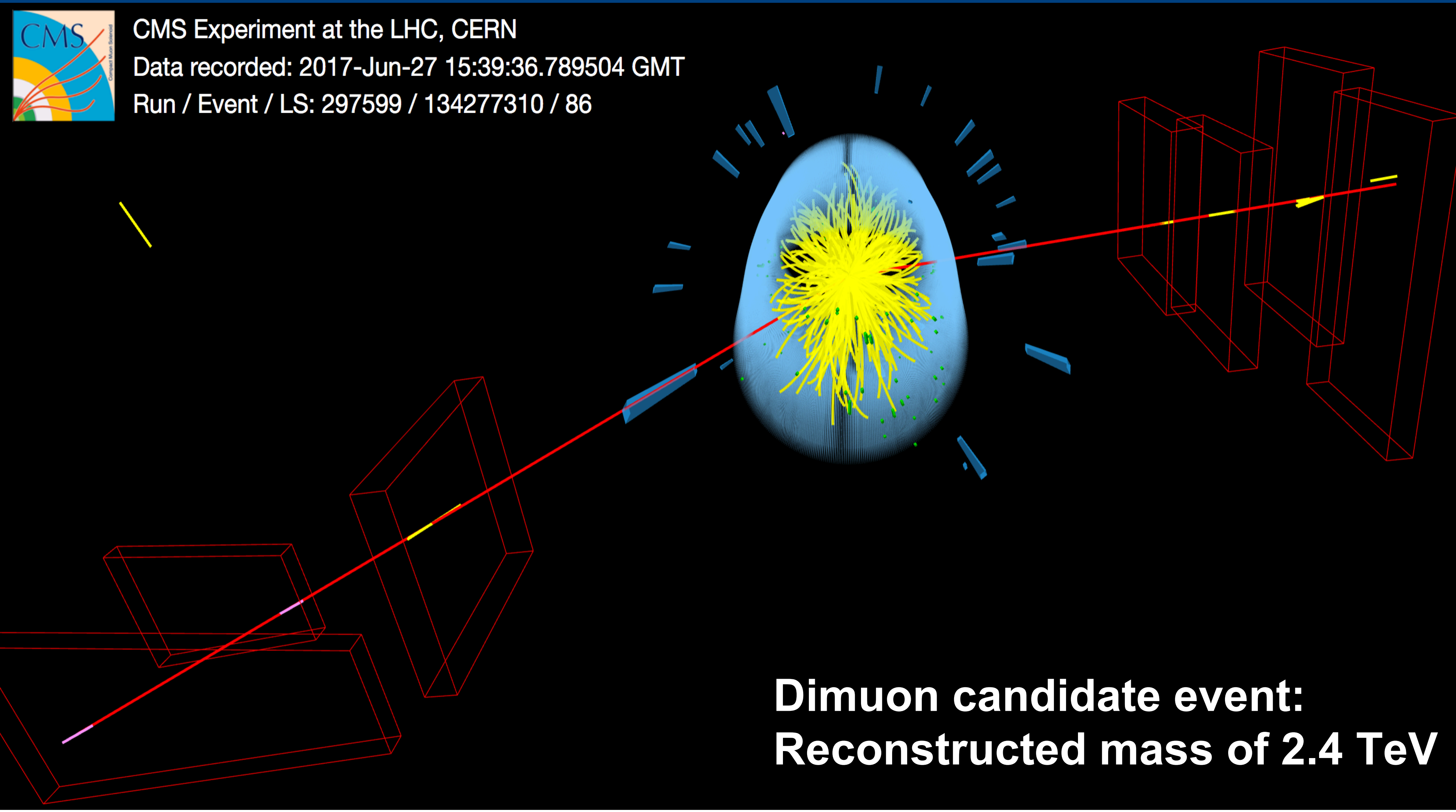
CMS-EXO-17-026, ATLAS-CONF-2019-007

- Searches up to high masses
- QCD predicts a smooth, monotonic decrease in dijet invariant mass
- Search for a localized excess
- No significant excess observed





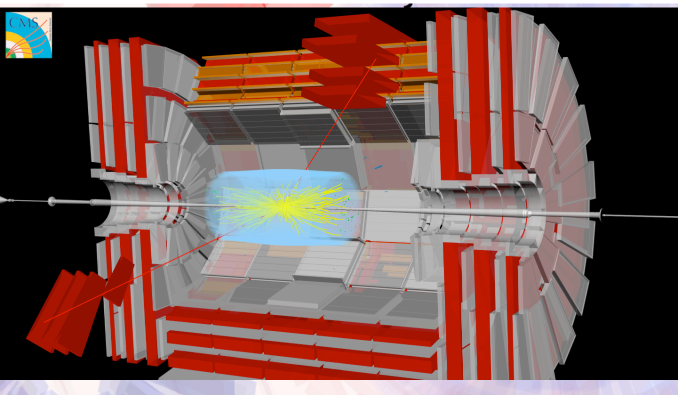
Searching for dilepton resonances

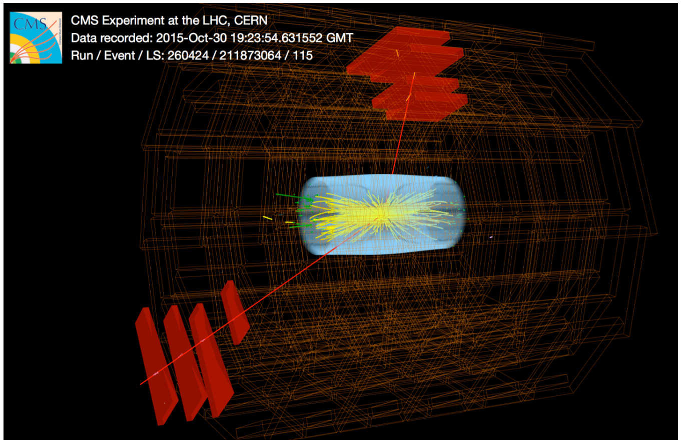


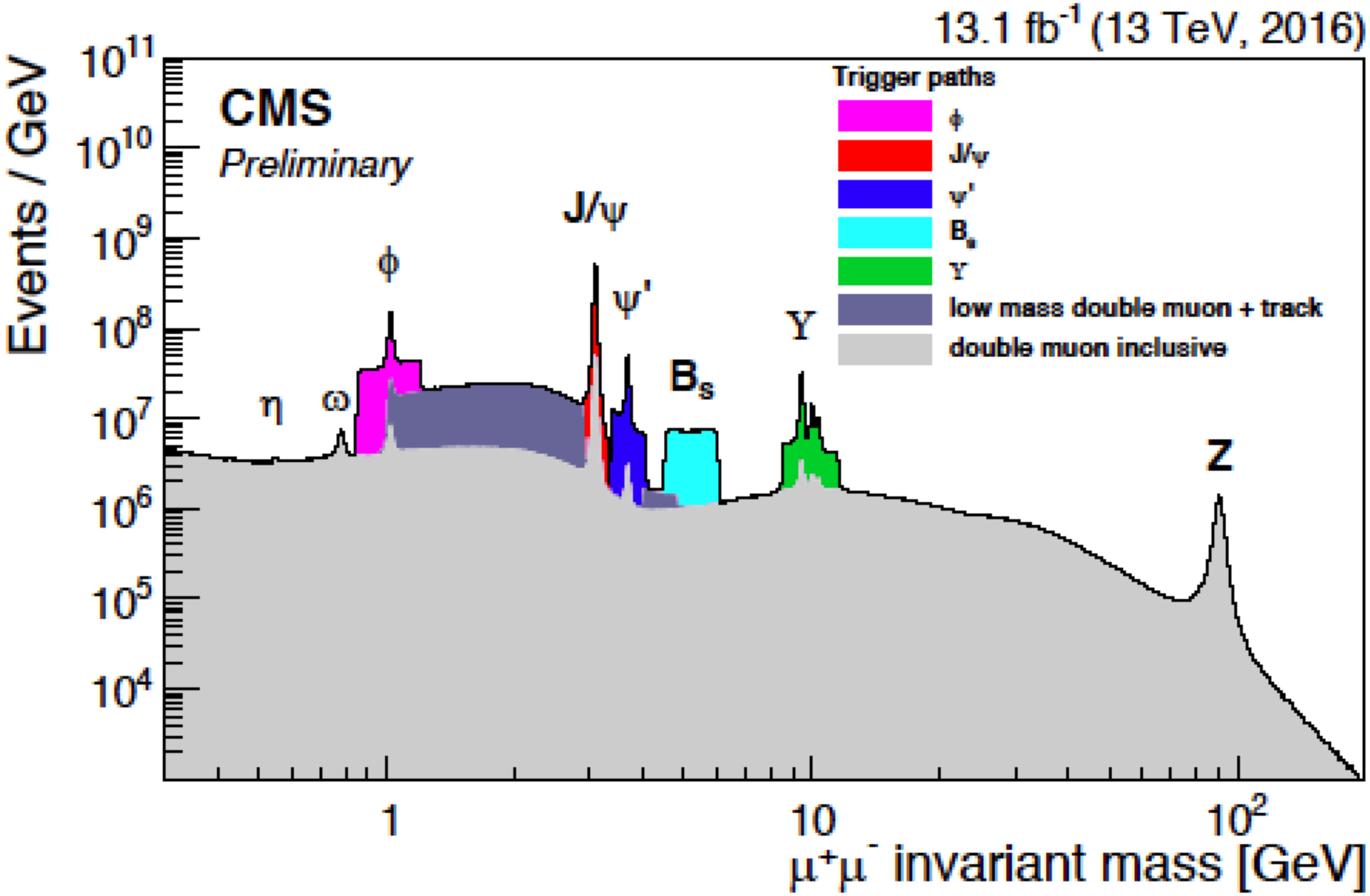
Dimuon candidate event:
Reconstructed mass of 2.4 TeV

Di-muon events

- Di-muon events: a re-discovery of the SM



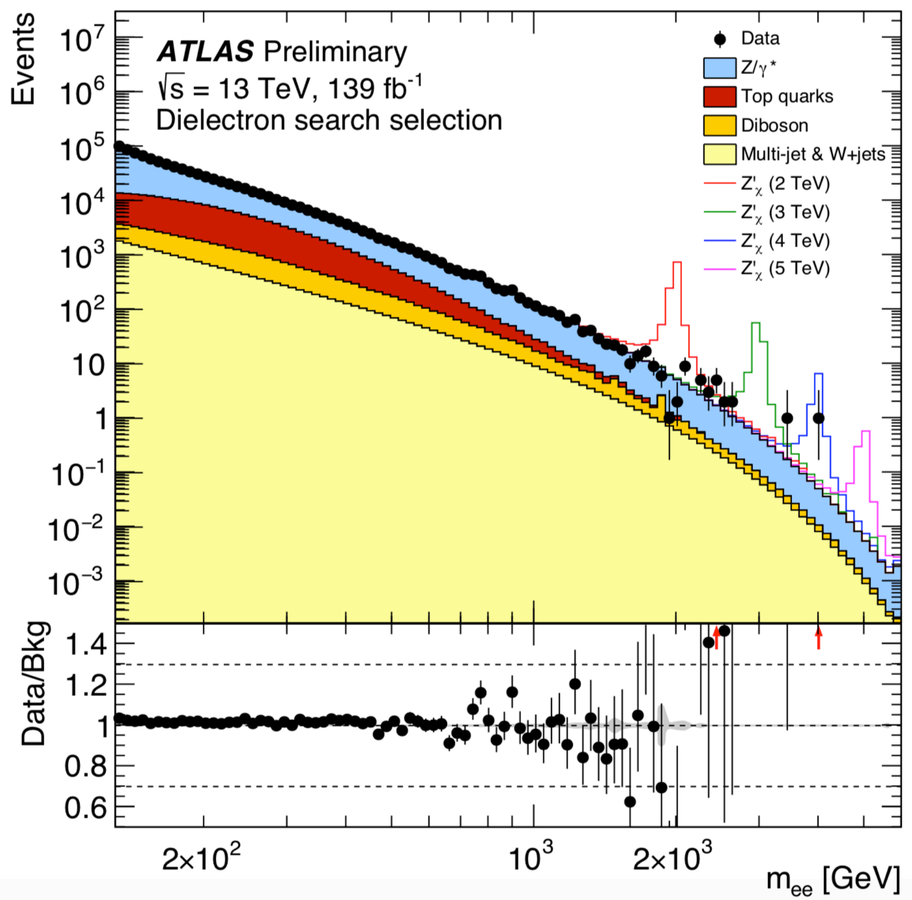


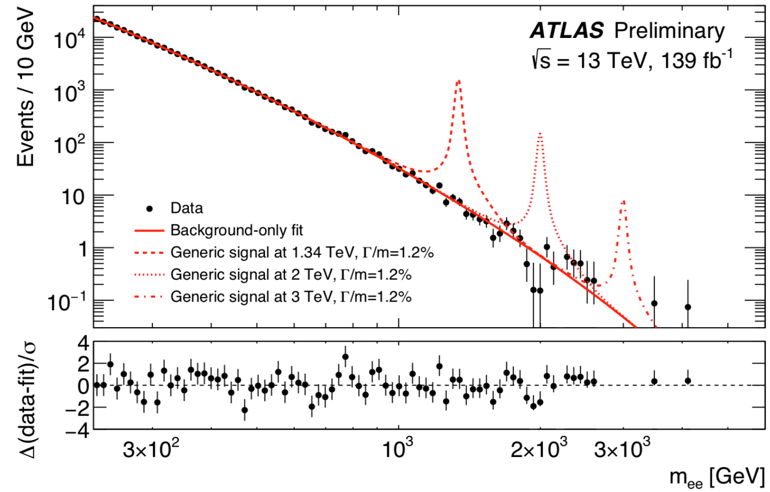


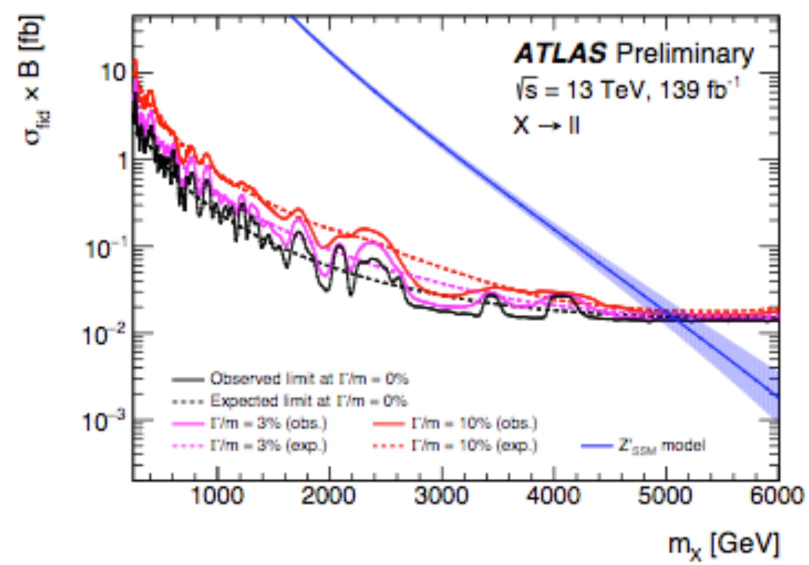
Dilepton resonance

arXiv:1803.06292, ATLAS-CONF-2019-001

- Search for dilepton (ee,μμ) resonance

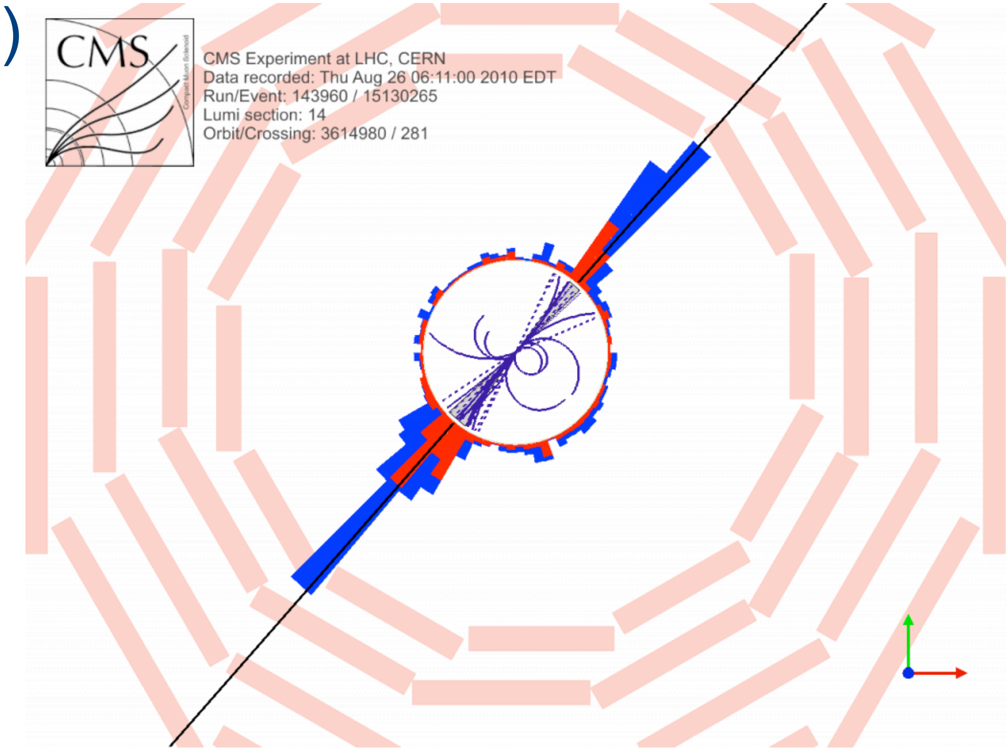






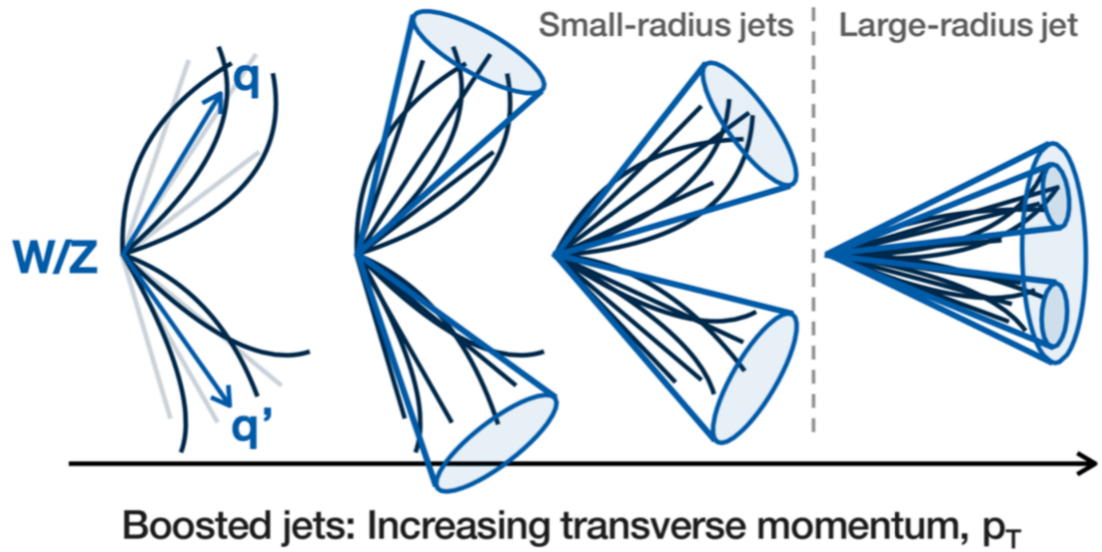
Search for diboson resonances

- Heavy BSM resonances (>1TeV) may decay into SM bosons (W,Z, H)
- Several final states
- Experimental challenges
  - SM bosons decay mostly to quarks
  - Due to large Lorentz boost, decay products merge into single jet
  - Clustered within a large-cone jet (R=0.8)
- Look into jet substructure
  - Jet "grooming": get rid of soft jet components from UE/pileup, keep constituents from hard scatter
  - Apply filters (mass drop, pruning, trimming)



Diboson resonances

- Many potential final states are possible
  - WW/WZ, ZW/ZZ, VV
- Hadronic channels with high sensitivity in high mass region

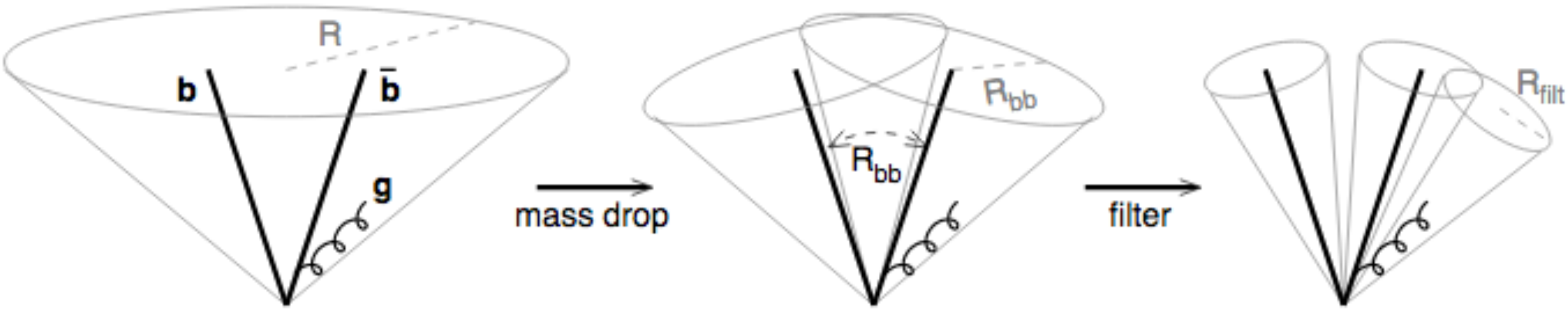


Jet grooming

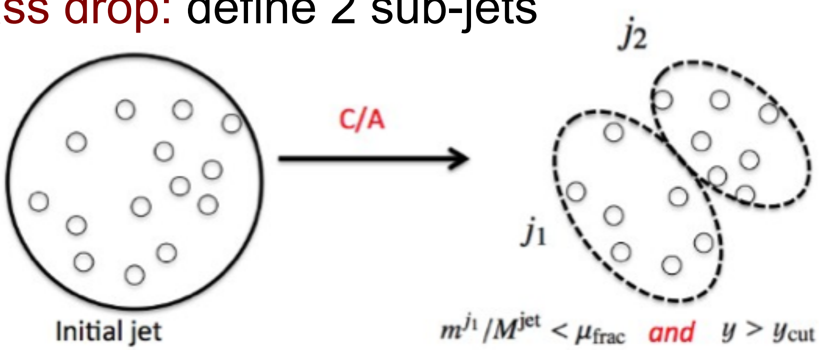
arXiv:0802.2470

Mass drop/filtering

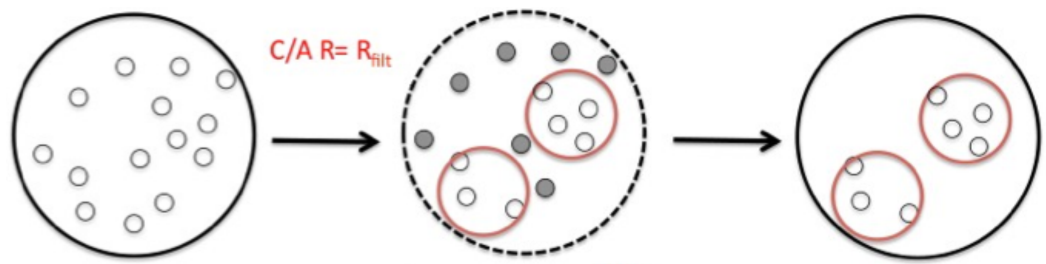
- Identify approx. symmetric sub-jets (with smaller mass than sum)



Mass drop: define 2 sub-jets



Filtering: re-cluster j1, j2 constituents

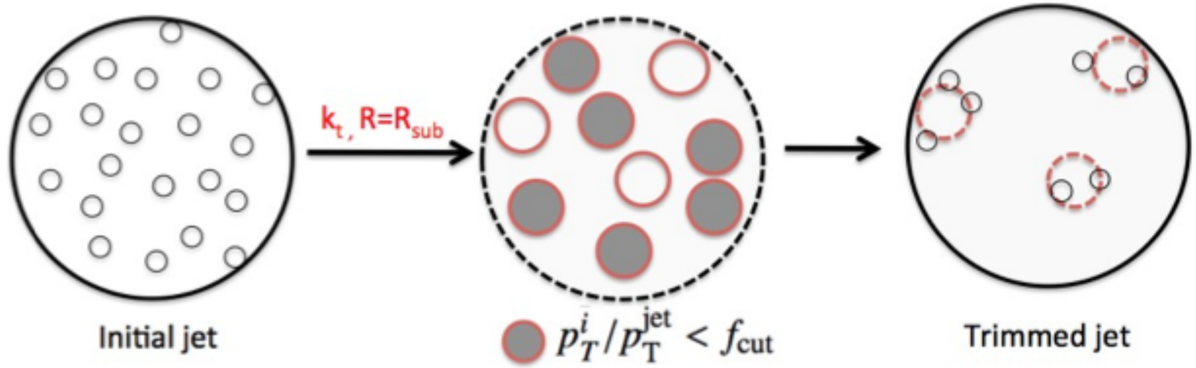


Jet grooming (cont.)

arXiv:0912.1342, arXiv:0912.0033

"Trimming"

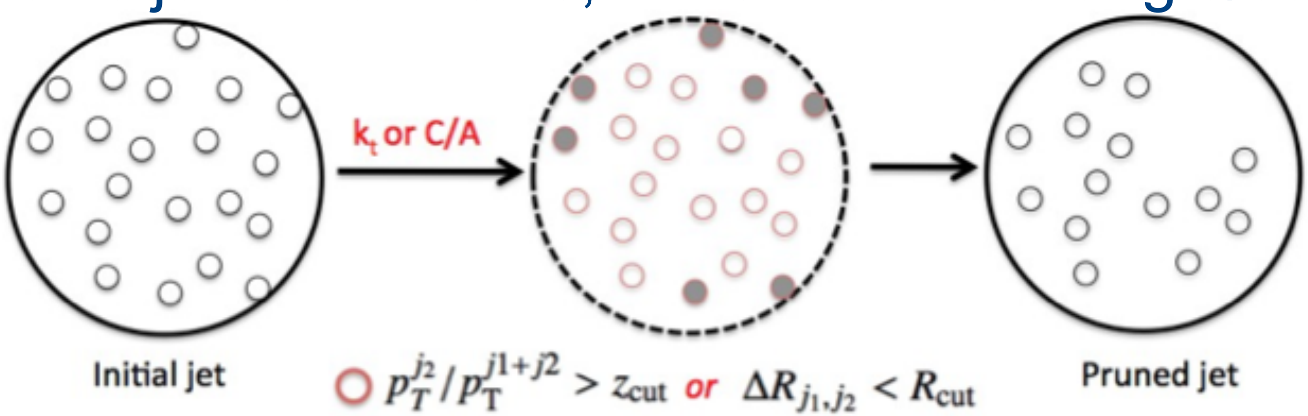
- Uses kT algorithm to make subjets (subjets with p_T^i/p_T<cut removed)



R_{sub}, f_{cut}

"Pruning"

- Recombine jet constituents, while veto wide-angle/softer constituents



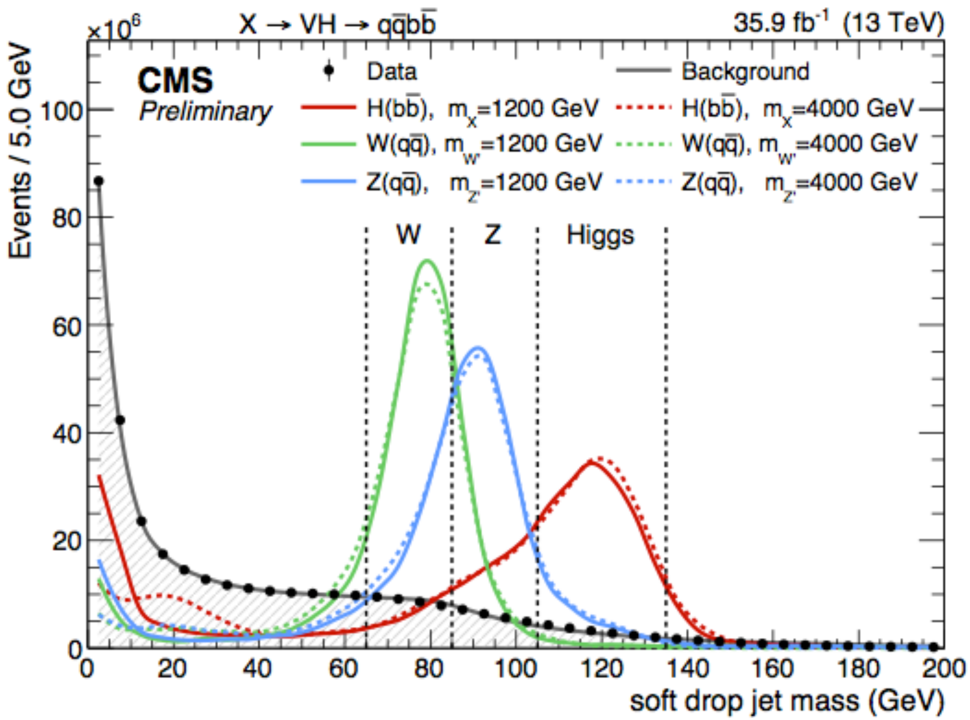
R_{cut}, z_{cut}

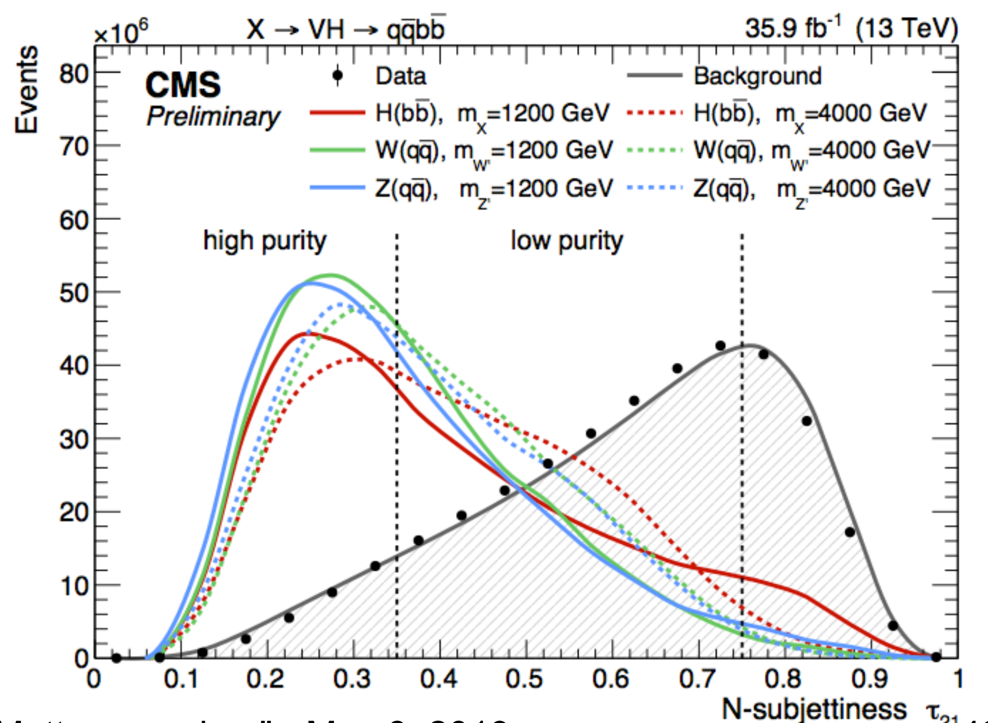
W, Z, H reconstruction

CMS-B2G-17-002

- Grooming and jet mass
  - Pruning
  - soft drop (stable w/pileup, and good jet mass resolution ~10%)

- Vector boson tagging (V→qq)
  - n-subjettiness τ_{21}: how consistent with 2 sub-jets
  - Categorization according to purity: high (<0.35) and high (>0.35)

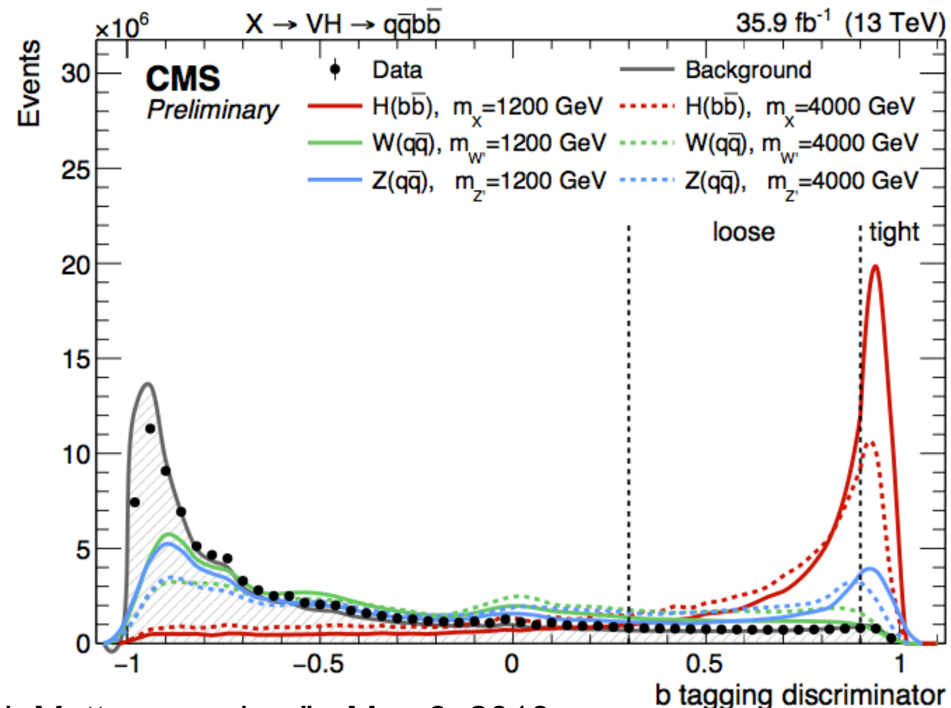




W, Z, H reconstruction (cont.)

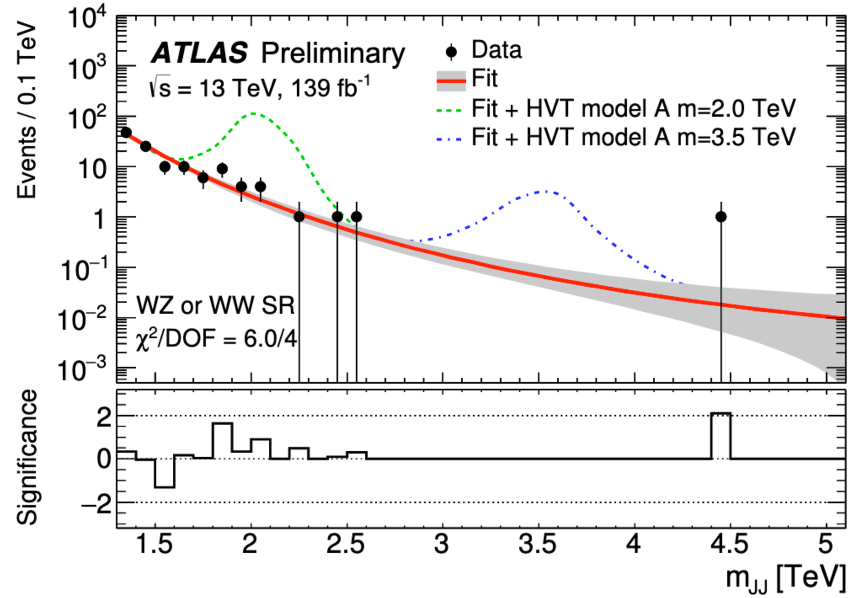
CMS-B2G-17-002

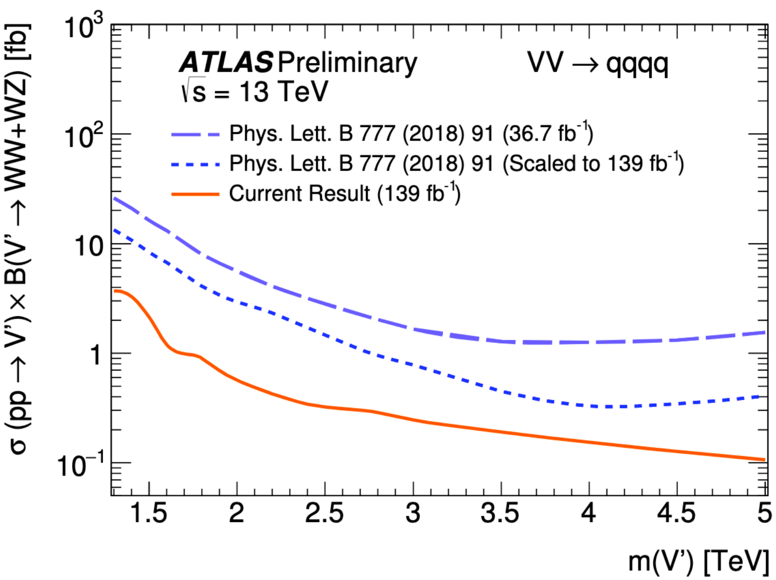
- Higgs boson tagging (H→bbar)
  - Double b-tagging
  - Exploit b-tagging to identify two b-quarks in same jet
  - Soft-lepton information
  - Combines tracking and vertexing in MVA

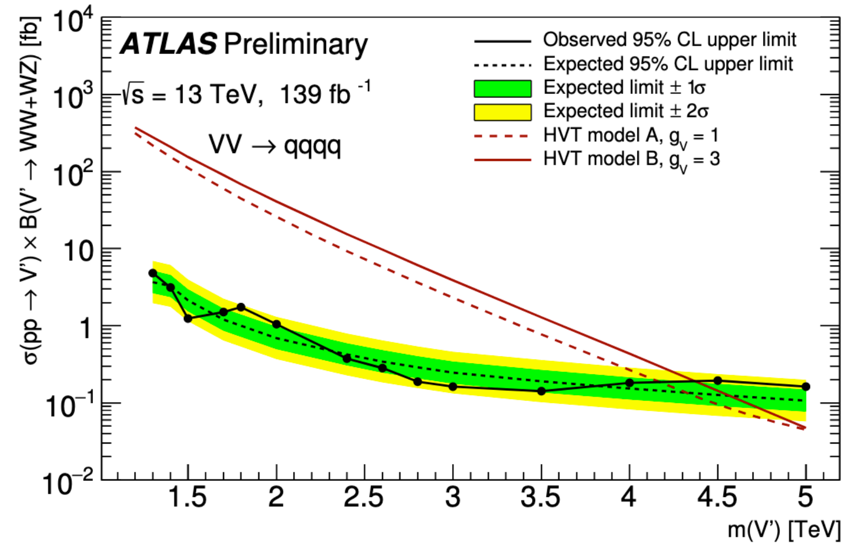


Searching for diboson resonances

- No significant excess in any of the observed final states
- Exclusion limits: HVT models excluded up to 4.1 TeV, Spin-2 RS models up to 2.8 TeV
- Large improvements due to new methods for jet reconstructions and boson tagging



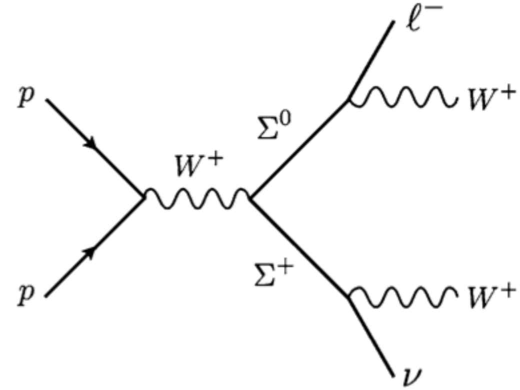


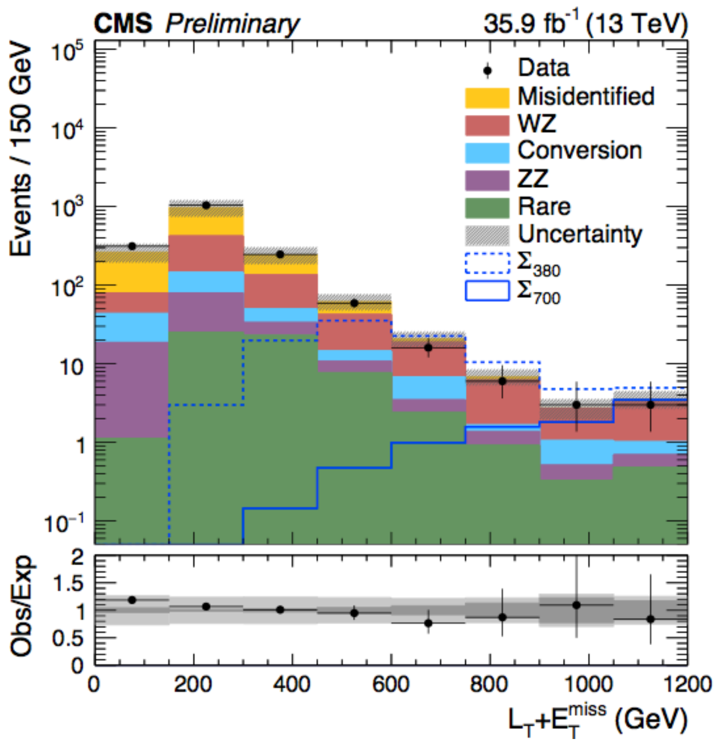


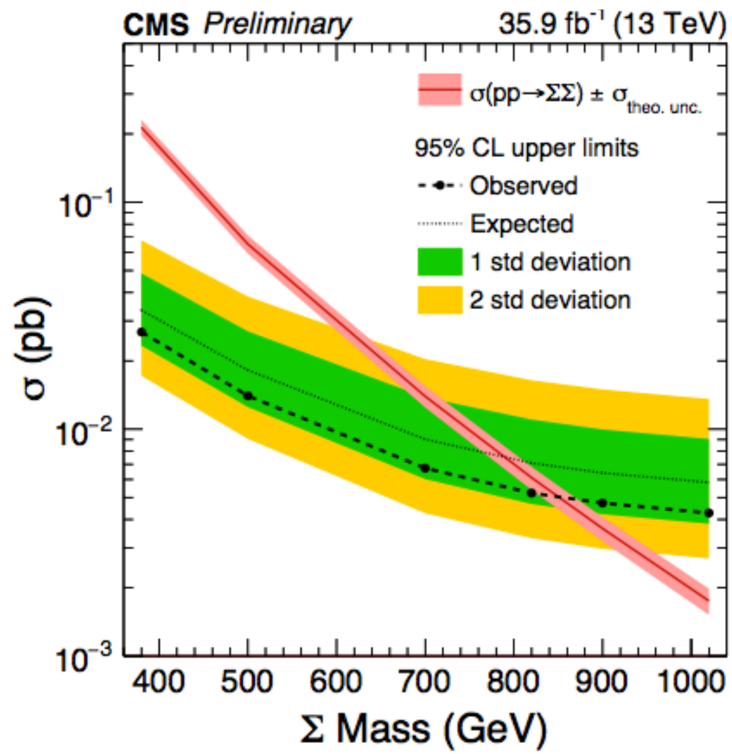
Search for multilepton final states

CMS-EXO-17-006

- Type-III extension to SM
- Search for 3 or more lepton final states
- Pair production of W/Z/H→ΣΣ
- Scalar sum of lepton p_T (L_T)
- Bin and count (L_T+MET)



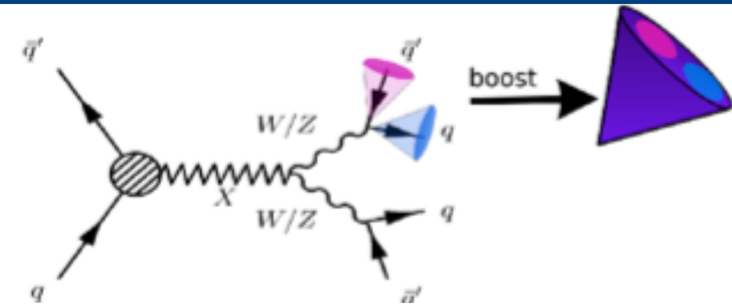


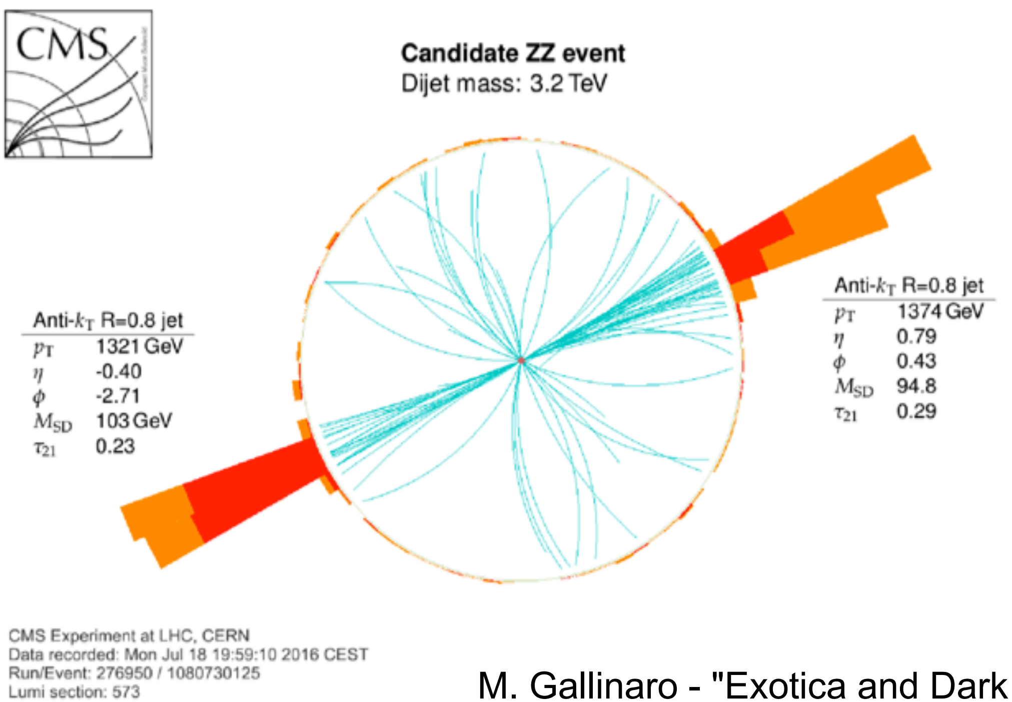


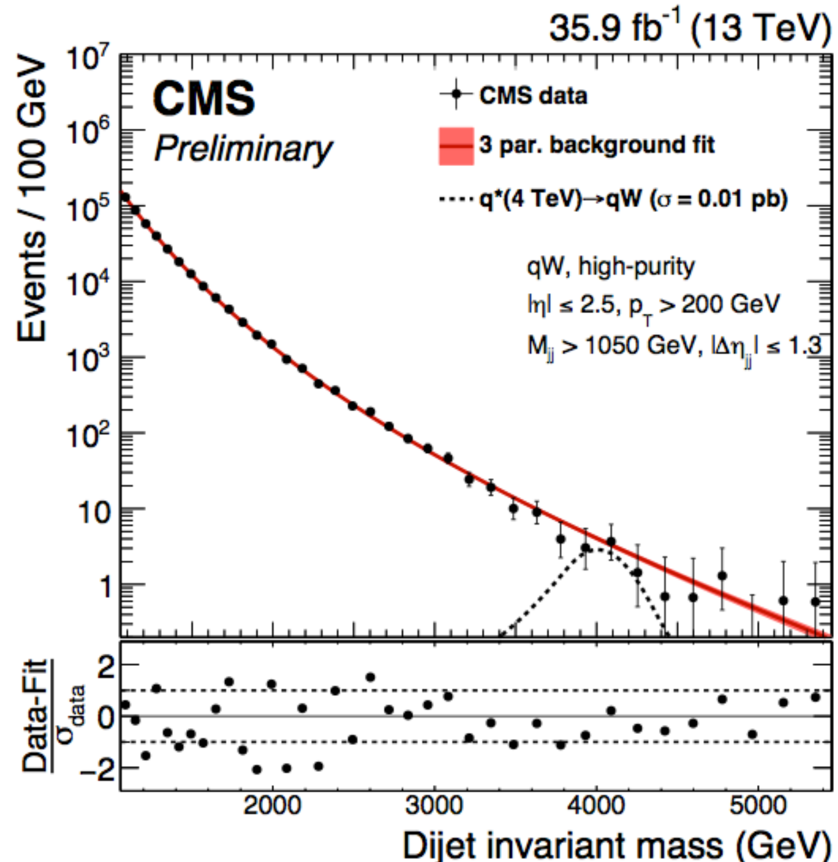
X→VV→qqqq

CMS-B2G-17-001

- All hadronic resonance search with single (qV) or double (VV) V-tag
  - At least 2 back-to-back jets p_T>200GeV
  - Categorization (jet mass, τ_{21})
- Background estimation: "bump hunt" fit data with power law



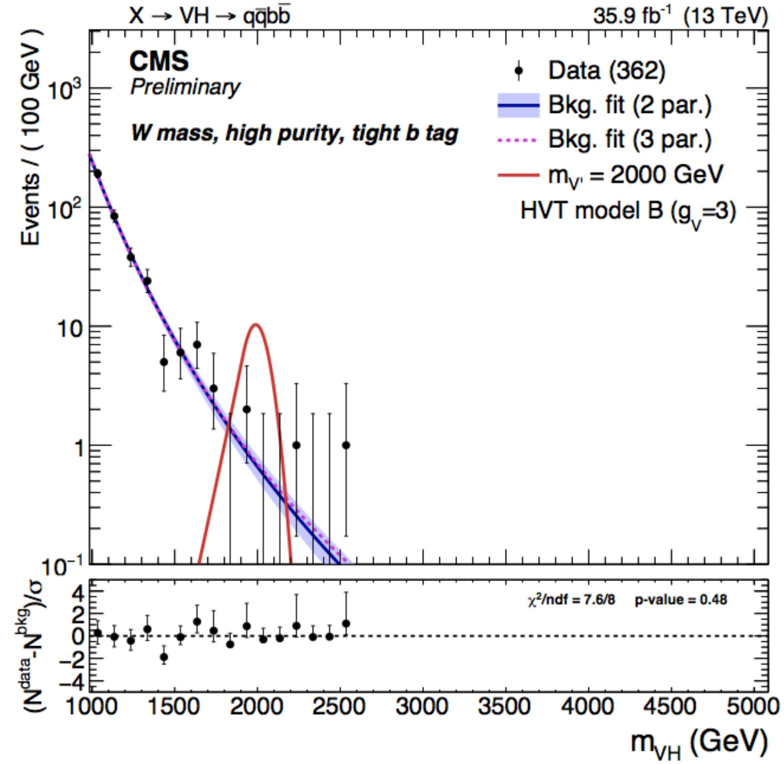


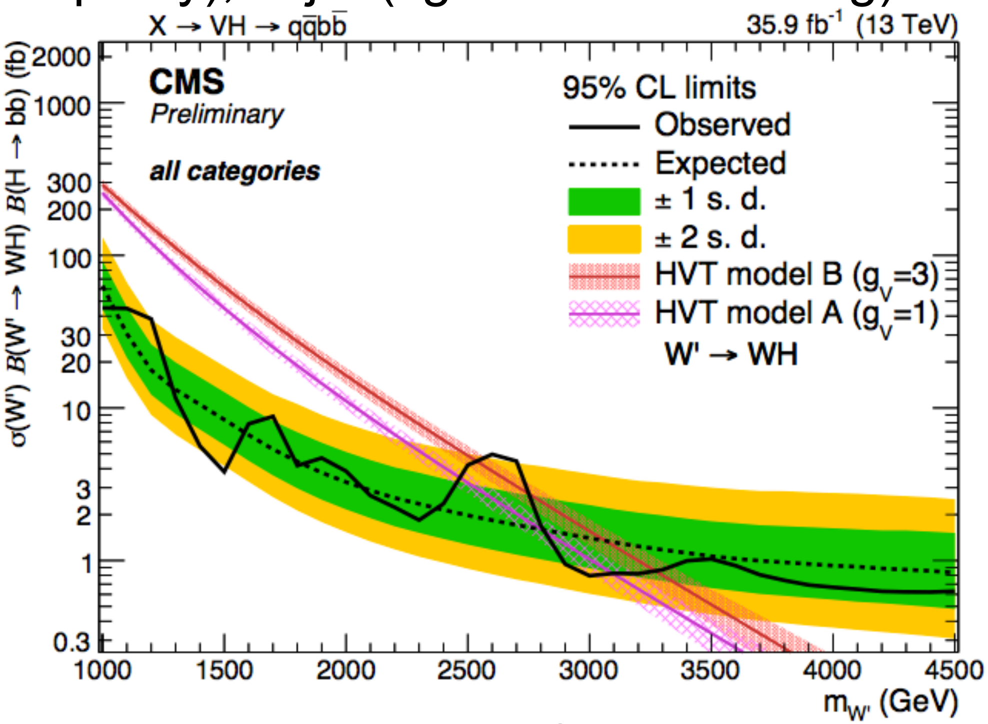


X→VH→qqbb

CMS-B2G-17-002

- All-hadronic search for V→qq and H→bb resonances
  - dedicated identification for H→bb (b-tagging)
- Use categories
  - V-jet mass (W or Z), V-jet τ_{21} (high-purity, low-purity), H-jet (tight and loose b-tag)



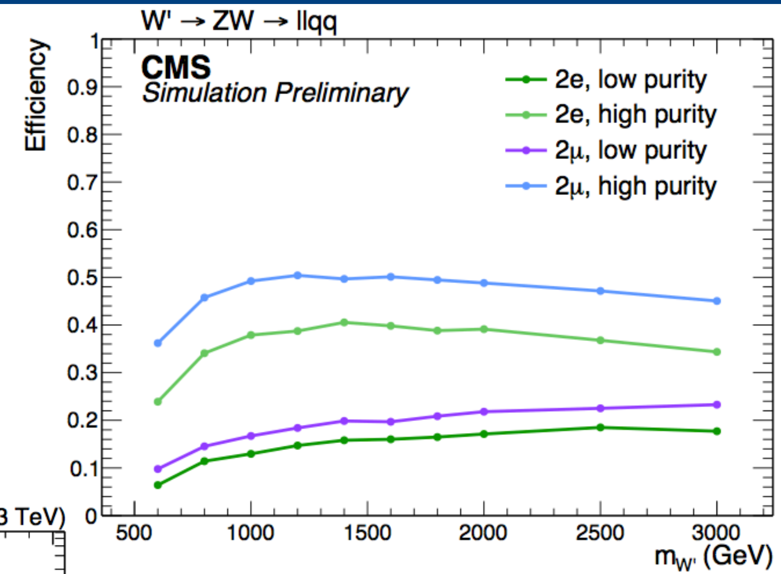


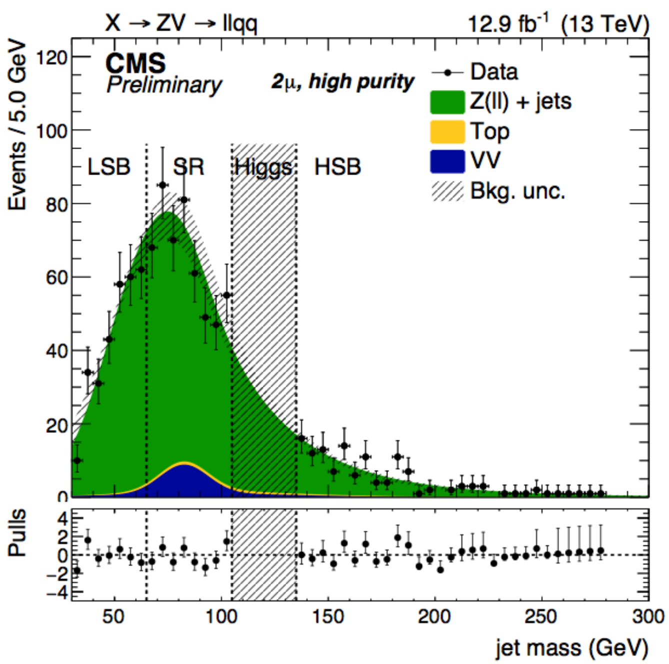
- Similar topology and background estimate to VV resonance search
- No significant excess found in data

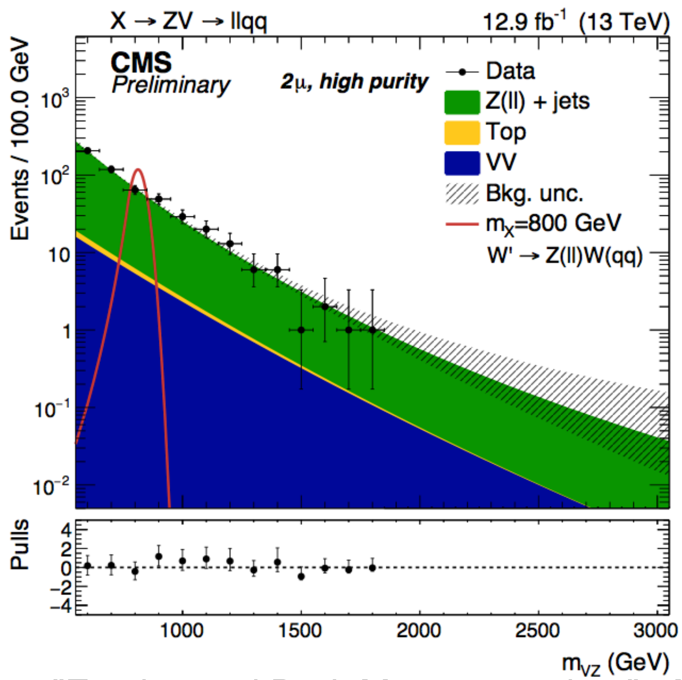
X→ZV→ℓℓqq

CMS-B2G-16-022

- Search for resonances in Z→ee/μμ, V→qq
- Clean final state (leptons)
  - Good mass resolution, good efficiency
- τ_{21} categorization (HP, LP)
- Parametrize main bkg (Z+jets), fit to data in sidebands, take shape from MC





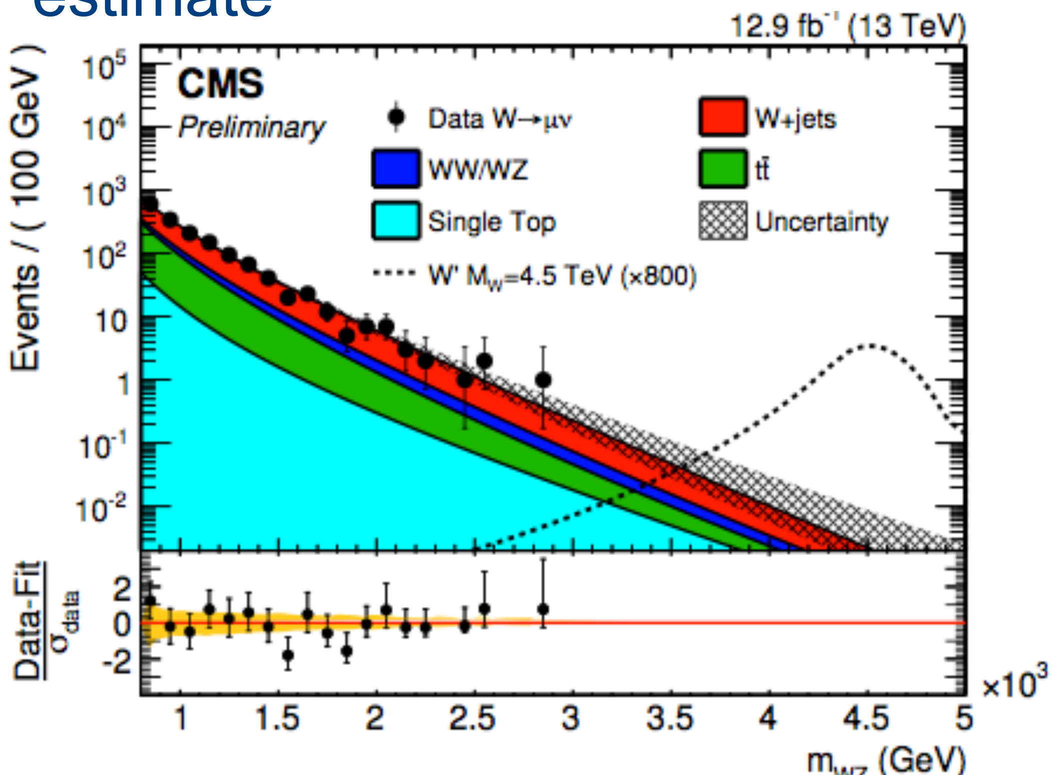


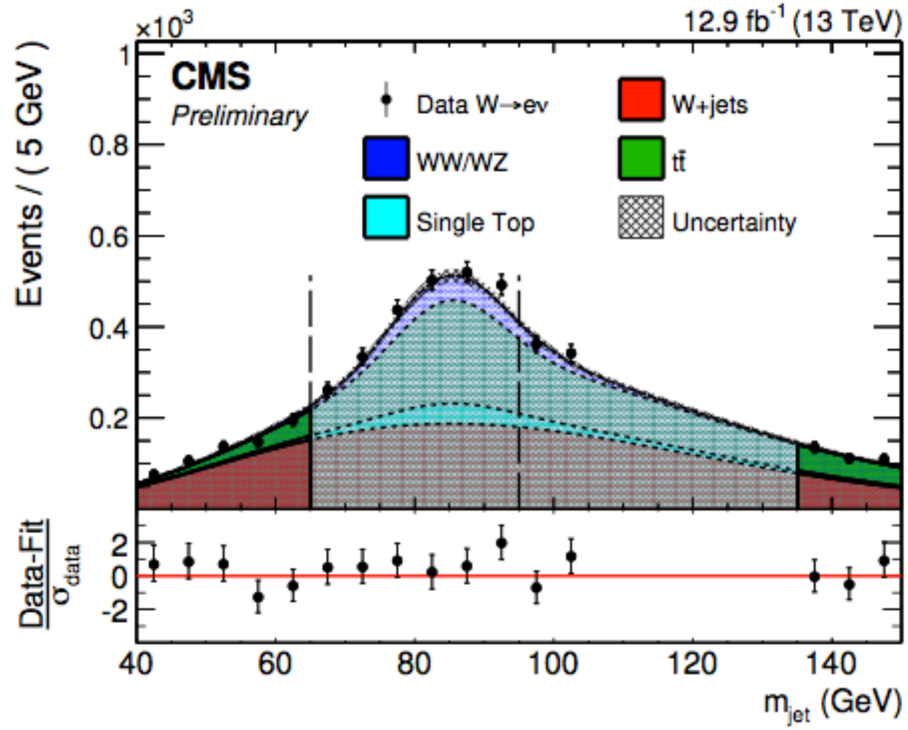
- Data compatible with SM-only hypothesis

$X \to WV \to \ell\nu qq$

CMS-B2G-16-020

- Search for a resonance decaying to WV in leptonic channel
- Categorization in τ_{21} and W/Z mass
- Sideband+transfer function for bkg estimate





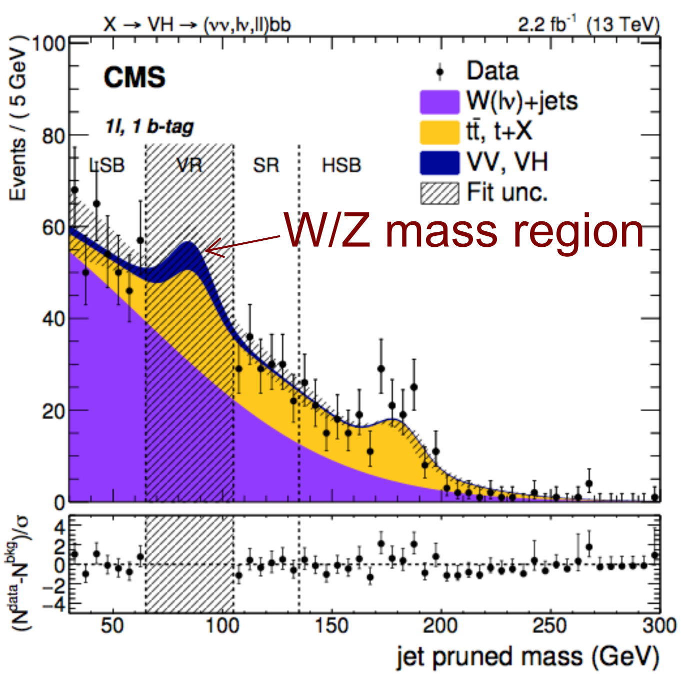
- Similar sensitivity to $Z(\ell\ell)V(qq)$ search
- Excluded up to 2 TeV

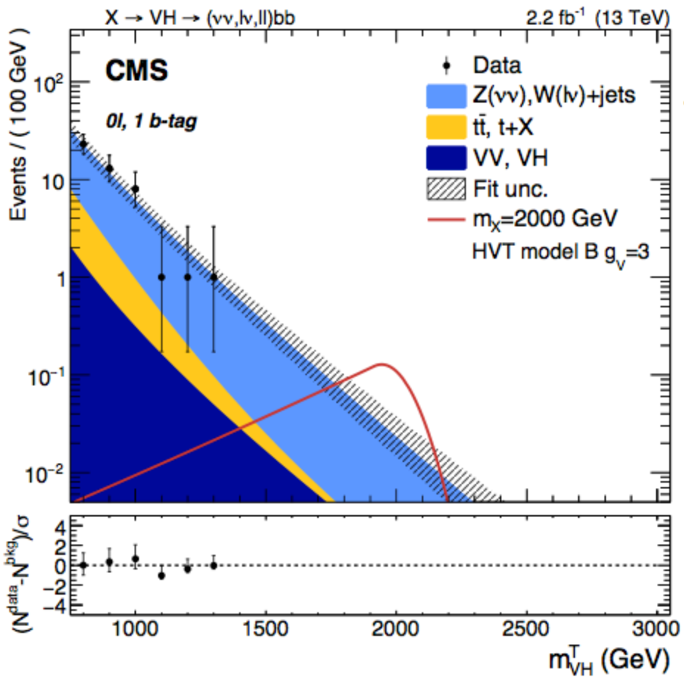
X→VH→ℓνqq

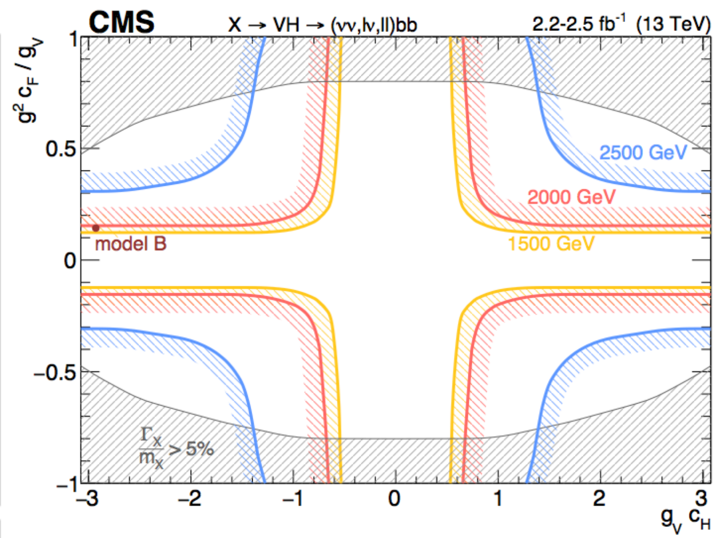
PLB 768(2017)137

- Search for a resonance decaying to VH in leptonic channels
  - Z→νν: transverse mass m_T(VH)
  - W→ℓν: top control region
  - Z→ℓℓ: high-efficiency dilepton ID
  - H(bb) b-tagging
- Sideband bkg prediction

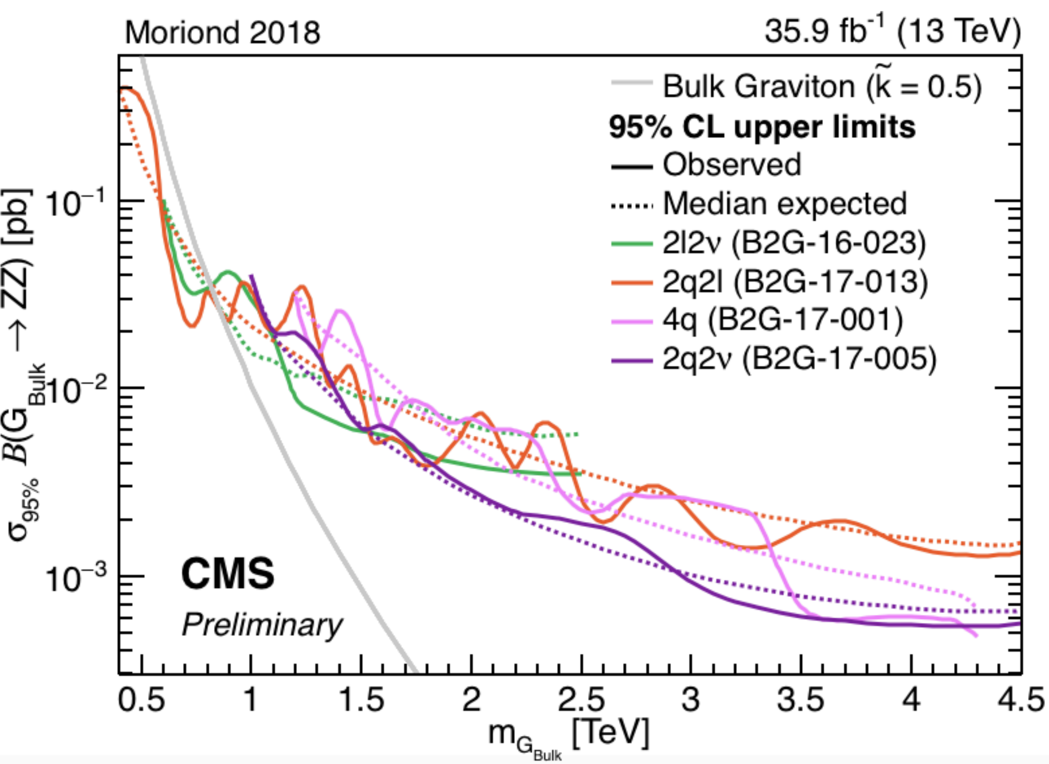
- Heavy vector triplet (Z', W')
- g_V, g_H (c_V, c_F): couplings

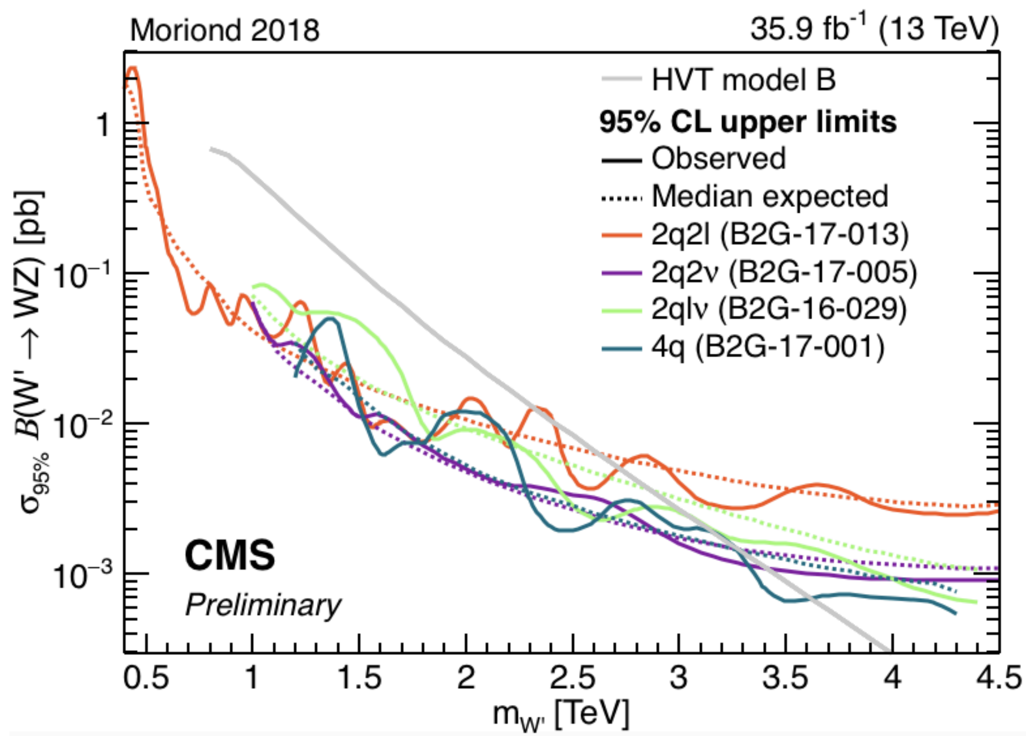






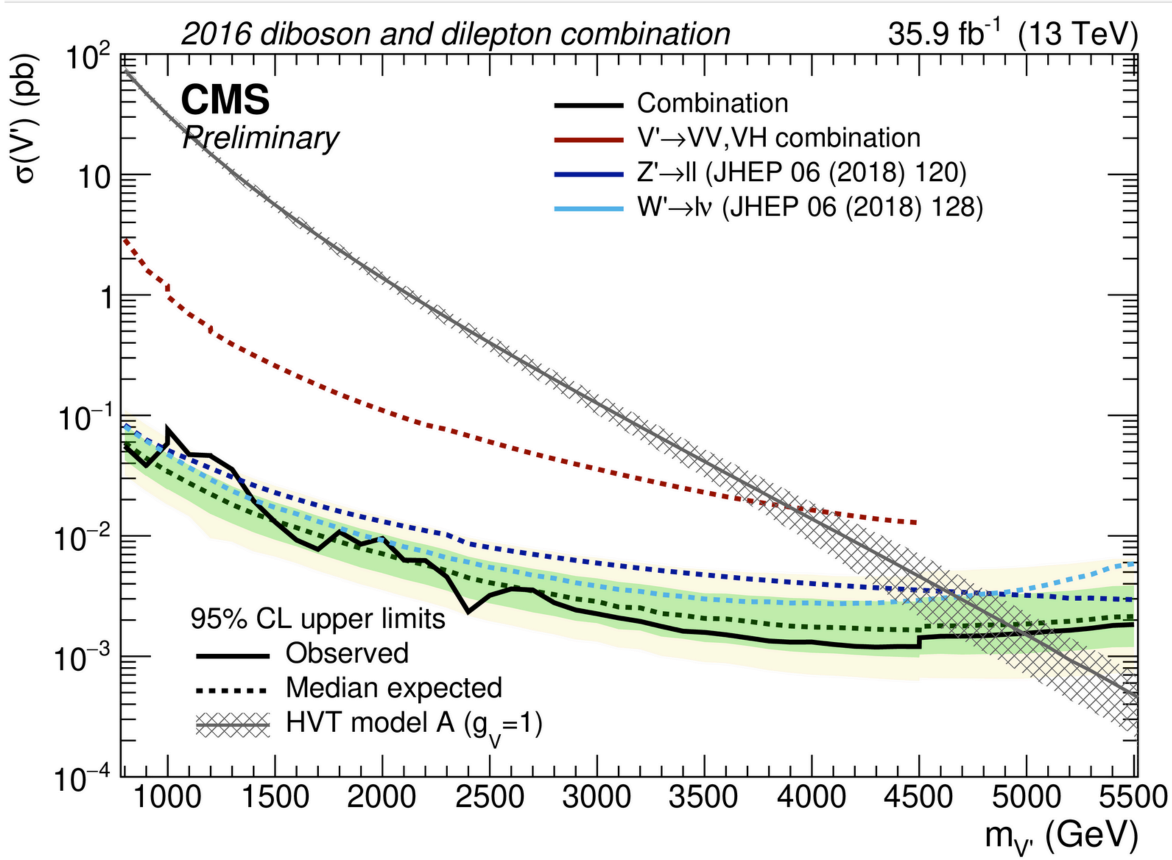
Combination of diboson searches



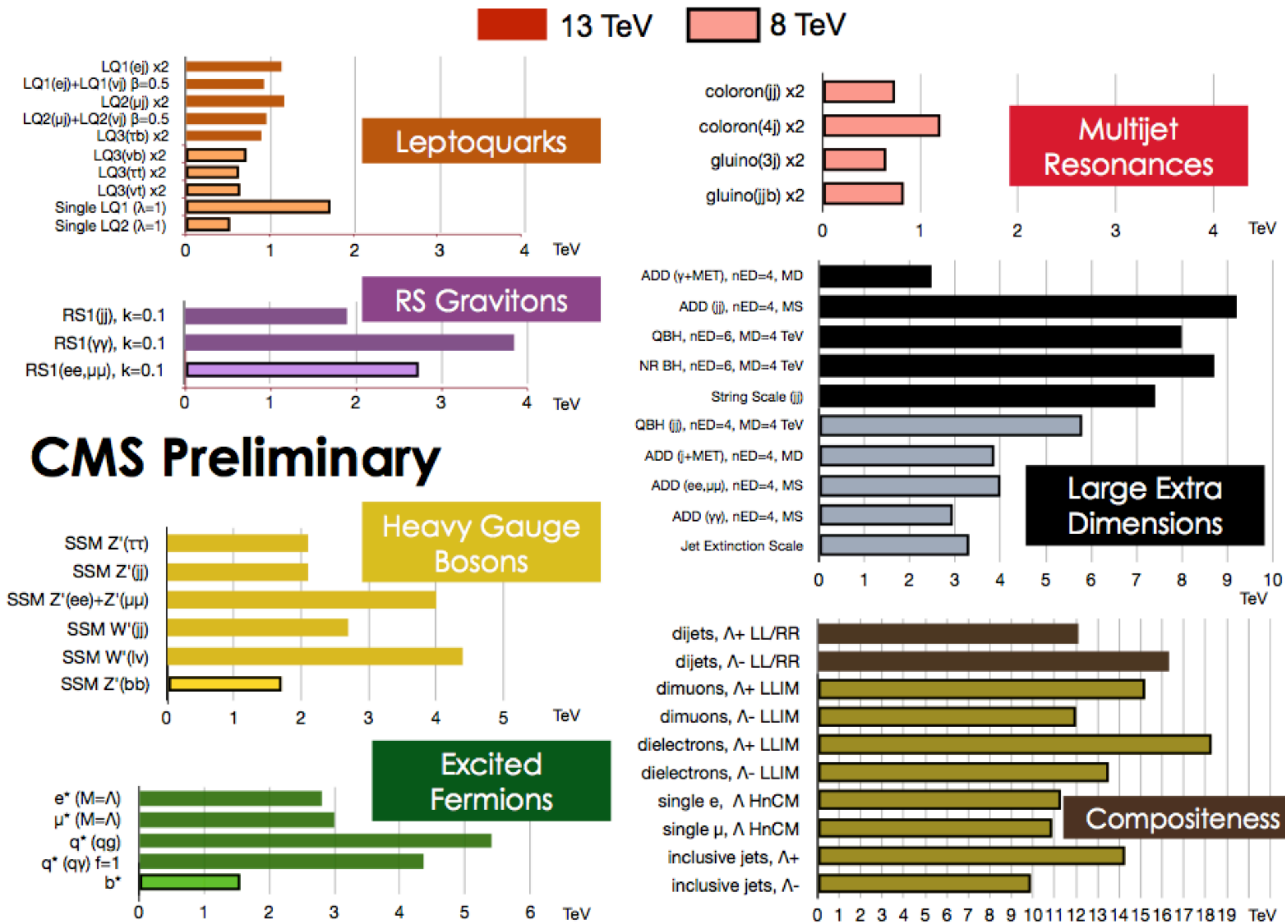


Combination of resonance searches

- Combination of searches for heavy resonances decaying to boson and lepton final states
- Large gain in statistical combination



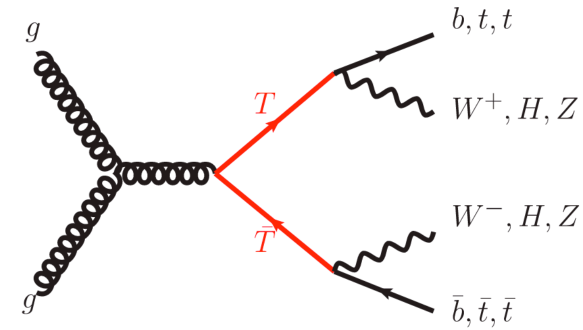
Resonance searches: Summary



Vector-like quarks

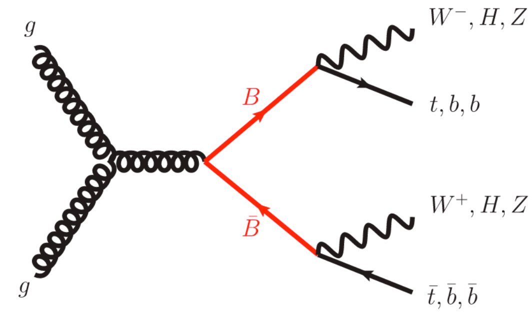
Motivation

- Simplest extension allowed in the quark sector
- Spin ½ fermions with vector coupling
- Can mix with SM quarks and modify their couplings to the W/Z/H bosons
- Sizeable mixing with 3[rd] family, b and t



Properties

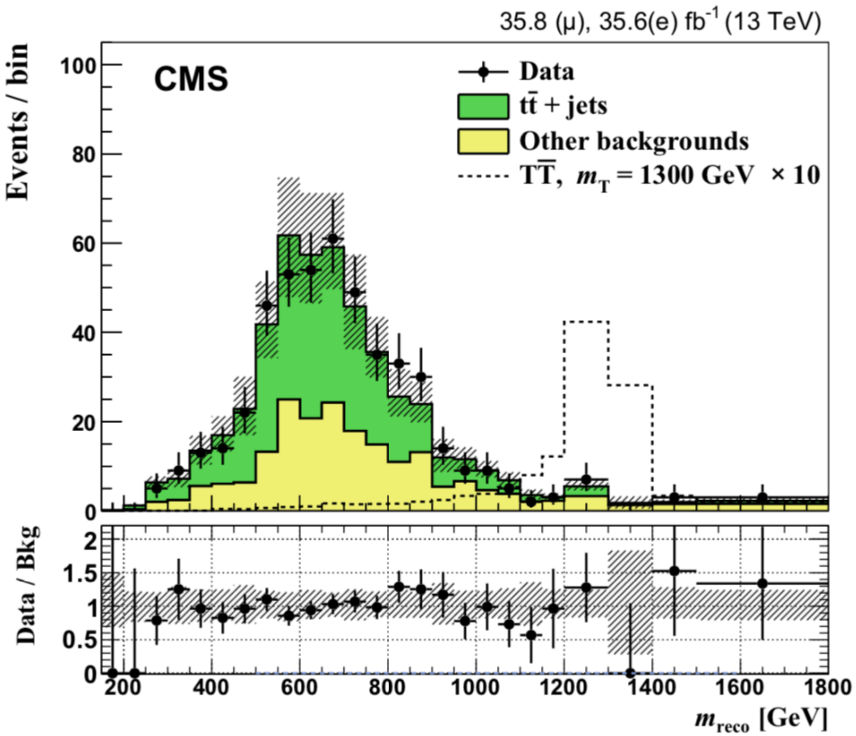
- Produced via strong and EWK interactions
- Mainly pair-produced
- Both CC and NC decay modes

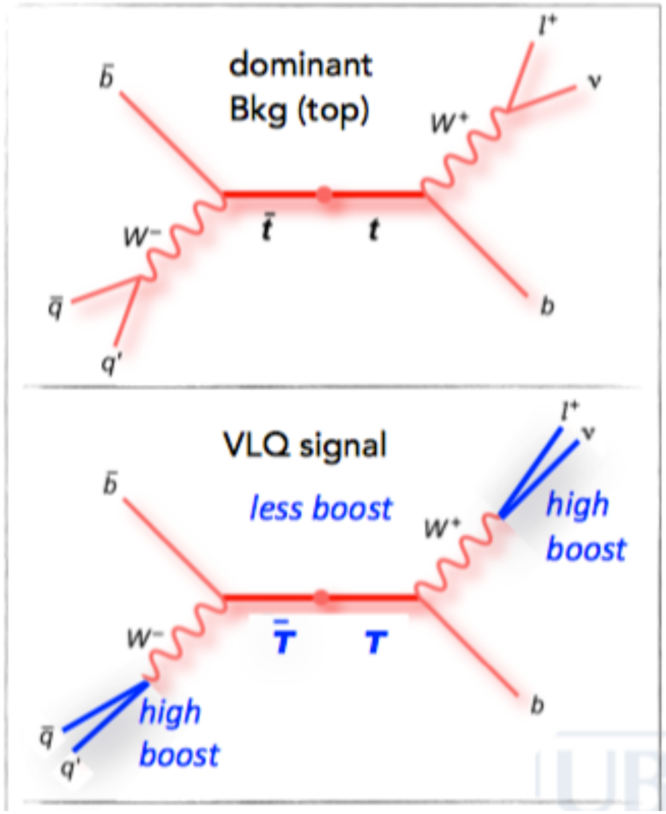


VLQ searches

PLB 779(2018)82

- Search for VLQ pair production decaying to WbWb
- Search in the boosted regime
- Can reconstruct the VLQ system

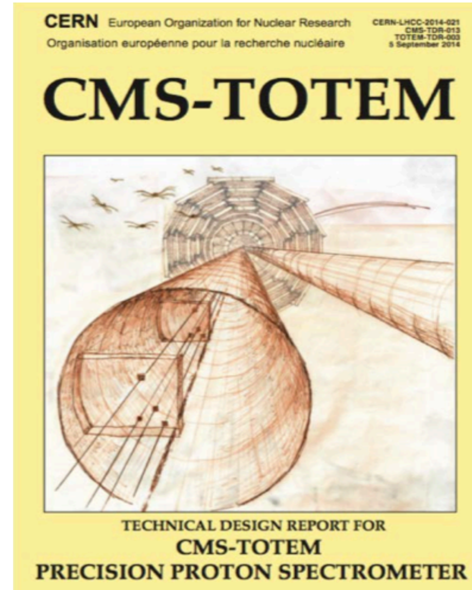




Looking forward: PPS

CERN-LHC-2014-021

- The Precision Proton Spectrometer is a joint CMS and TOTEM project that aims at measuring the surviving scattered protons on both sides of CMS in standard running conditions
- Tracking and timing detectors inside the beam pipe at ~210m from IP5
- Project approved in Dec. 2014 by LHCC
- Data taking started in 2016 (full scope from 2017)



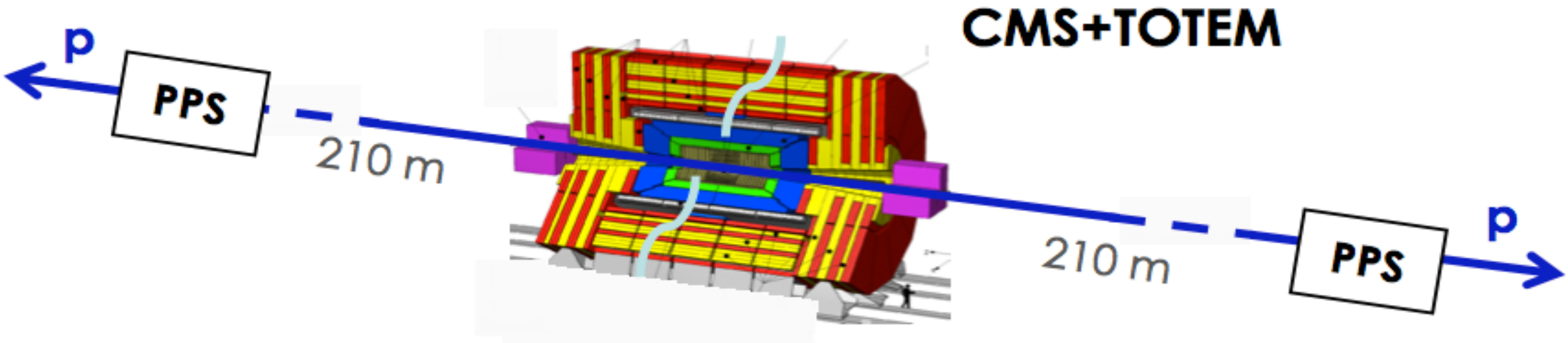
CERN European Organization for Nuclear Research
Organisation européenne pour la recherche nucléaire

CERN-LHCC-2014-021
CMS-TDR-013
TOTEM-TDR-003
5 September 2014

CMS-TOTEM

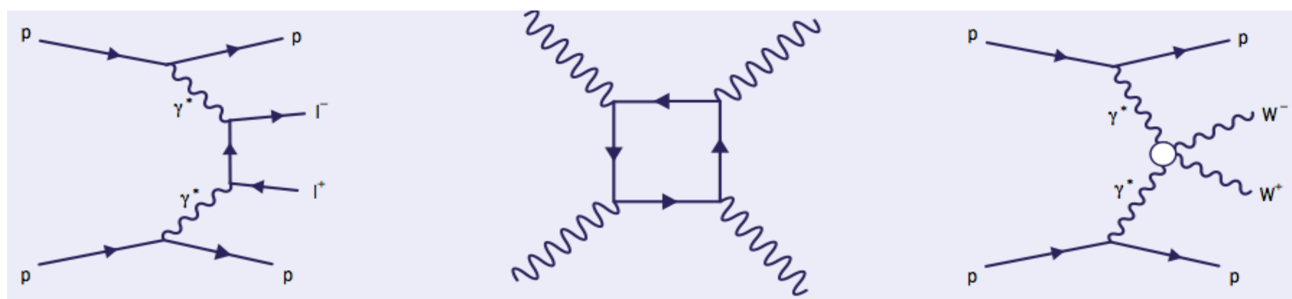
TECHNICAL DESIGN REPORT FOR
CMS-TOTEM
PRECISION PROTON SPECTROMETER

CERN-LHC-2014-021



PPS physics motivations

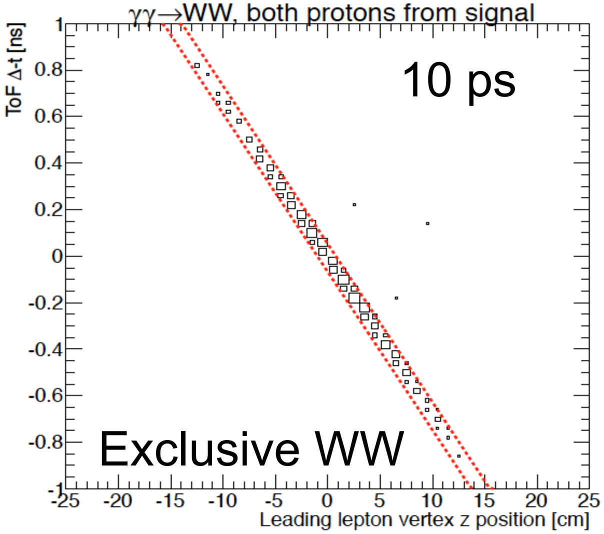
- Central Exclusive Production
  - photon-photon collisions
  - gluon-gluon fusion in color singlet, $J^{PC}=0^+$
- High-p_T system in central detector, together with very forward protons in PPS
  - momentum balance between central system and forward protons, provides strong kinematical constraints
  - Mass of central system measured by momentum loss of the two leading protons
- Gauge boson production by photon-photon fusion and anomalous couplings ($\gamma\gamma WW$, $\gamma\gamma ZZ$, and $\gamma\gamma\gamma\gamma$)
- Search for new BSM resonances
- Study of QCD in a new domain

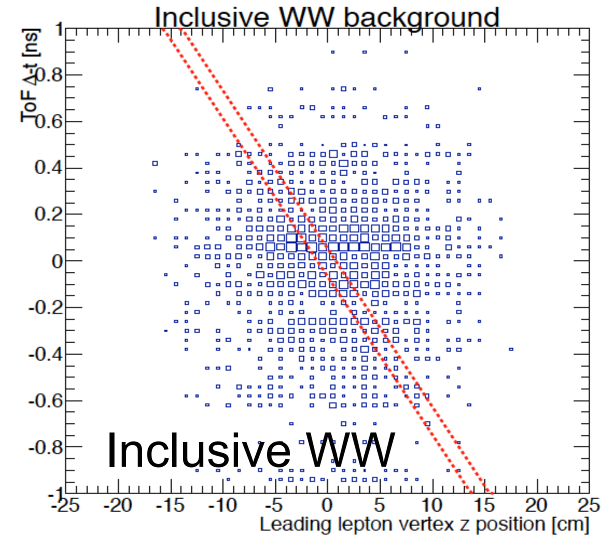


Timing detectors

Use timing to reject pileup background

- Two scenarios studied:
  - 10ps and 30ps time resolution
- Baseline: solid state detectors
- Detector options investigated:
  - Diamond sensors
  - Fast silicon sensors (UFSD, HFS)
- Status:
  - Diamond and LGAD detectors installed

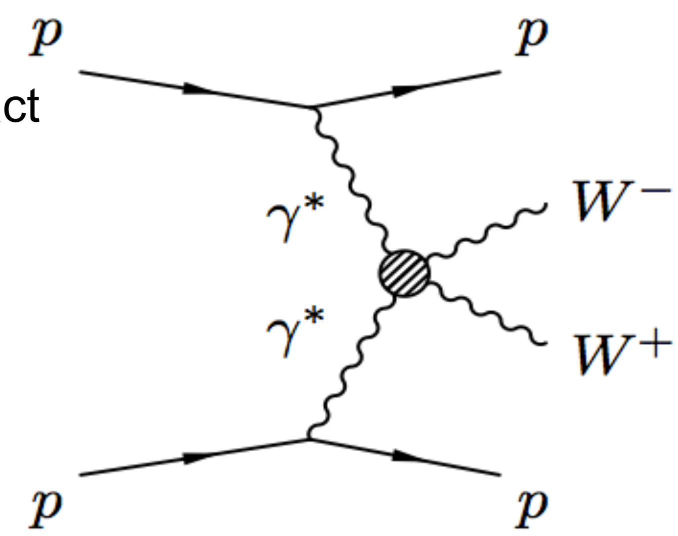




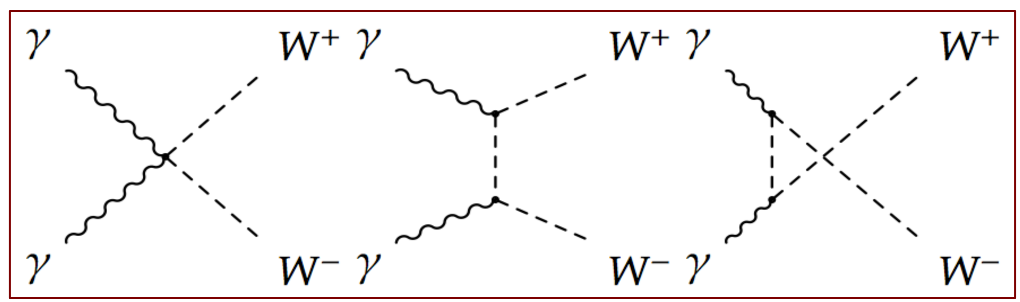
WW production

JHEP 08(2016)119

- Study of process: pp→pWWp
  - Clean process: W in central detector and “nothing” else, intact protons can be detected far away from IP
  - Exclusive production of W pairs via photon exchange: QED process, cross section well known



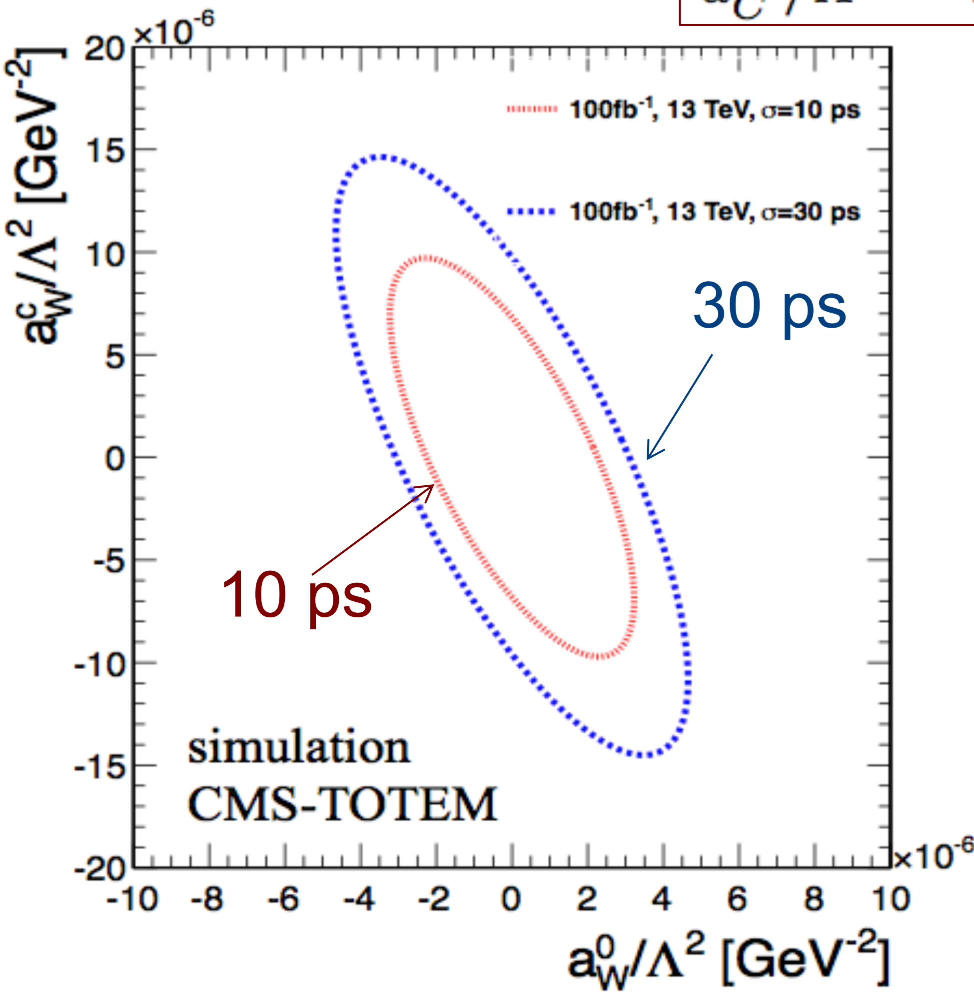
- Backgrounds:
  - inclusive WW, $\tau\tau$, exclusive two-photon $\gamma\gamma \rightarrow ll$, etc.
- Events:
  - WW pair in central detector, leading protons in PPS
- SM observation of WW events
- Anomalous coupling study
  - AQGCs predicted in BSM theories
  - parameters: a_0^W/Λ^2, a_c^W/Λ^2
- Deviations from SM can be large

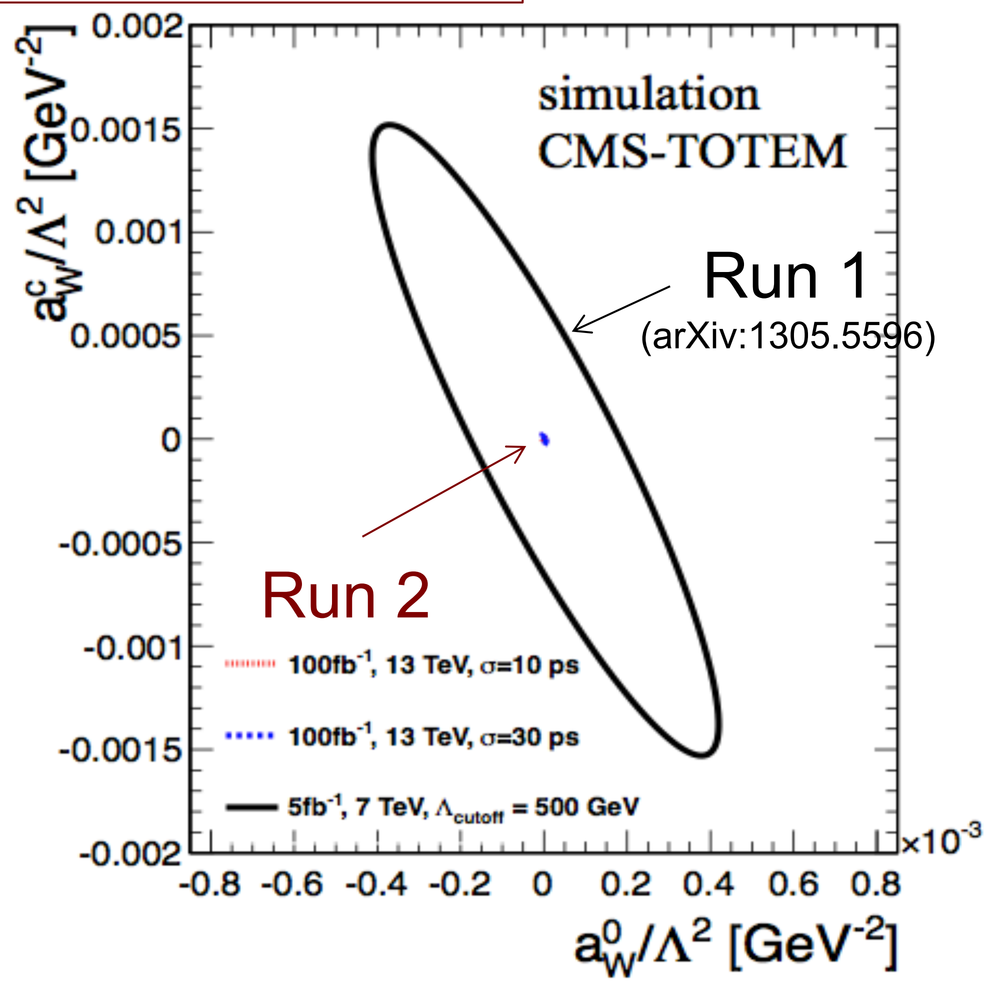


AQGC expected limits

Expected limits @95%CL:

$$a_0^W/\Lambda^2 = 2\times10^{-6}\ (3\times10^{-6}),$$
$$a_C^W/\Lambda^2 = 7\times10^{-6}\ (10\times10^{-6}).$$

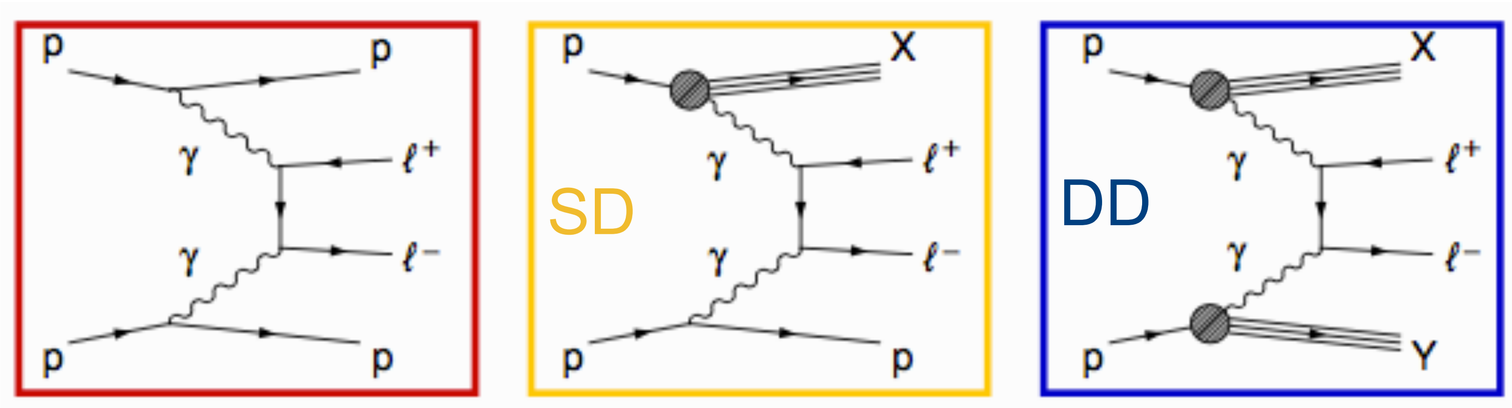




Exclusive Dileptons

CMS-PPS-17-001

- Study exclusive processes at the EWK scale
- Search for two-photon production of opposite charge lepton pair with forward proton tagging



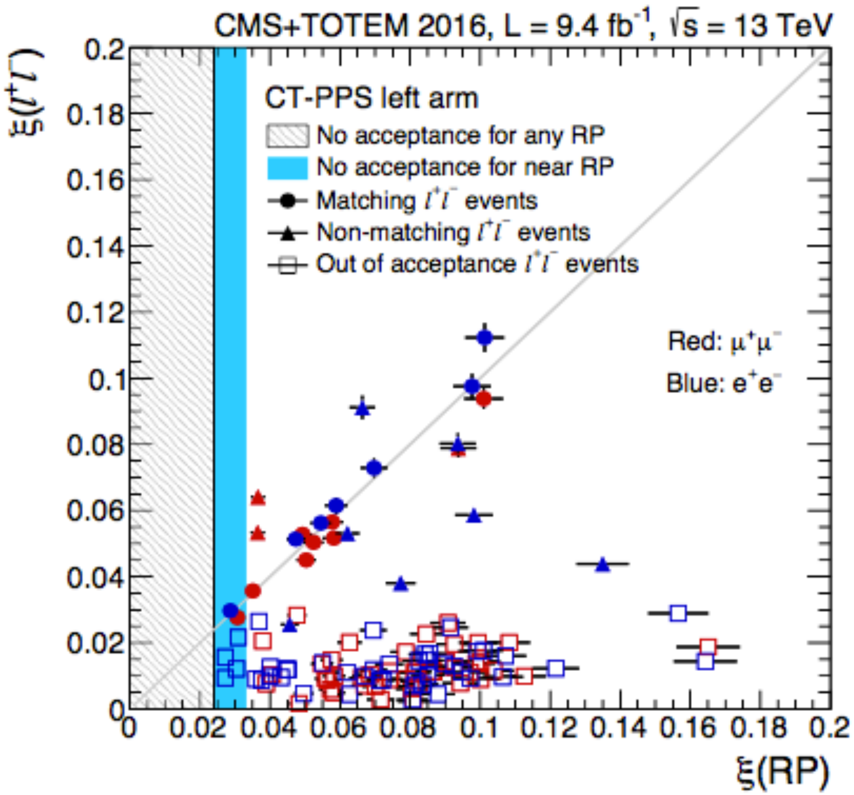
signal Background: SD, DD, DY, dibosons, PU

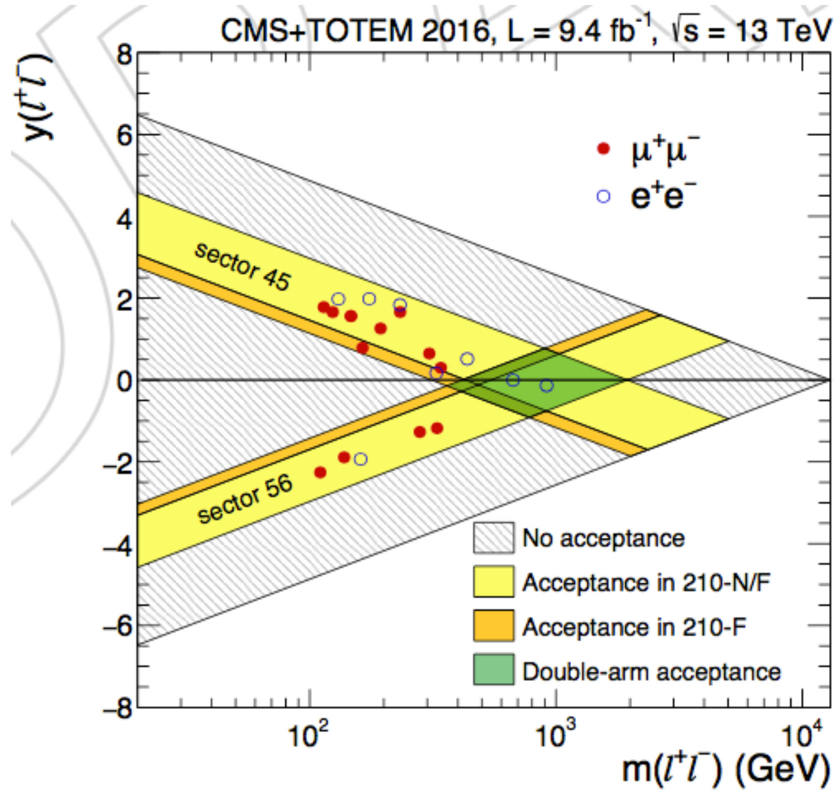
- Signal selected with:
- at least one proton tagged, muons, kinematic selection

Exclusive Dileptons (cont.)

CMS-PPS-17-001

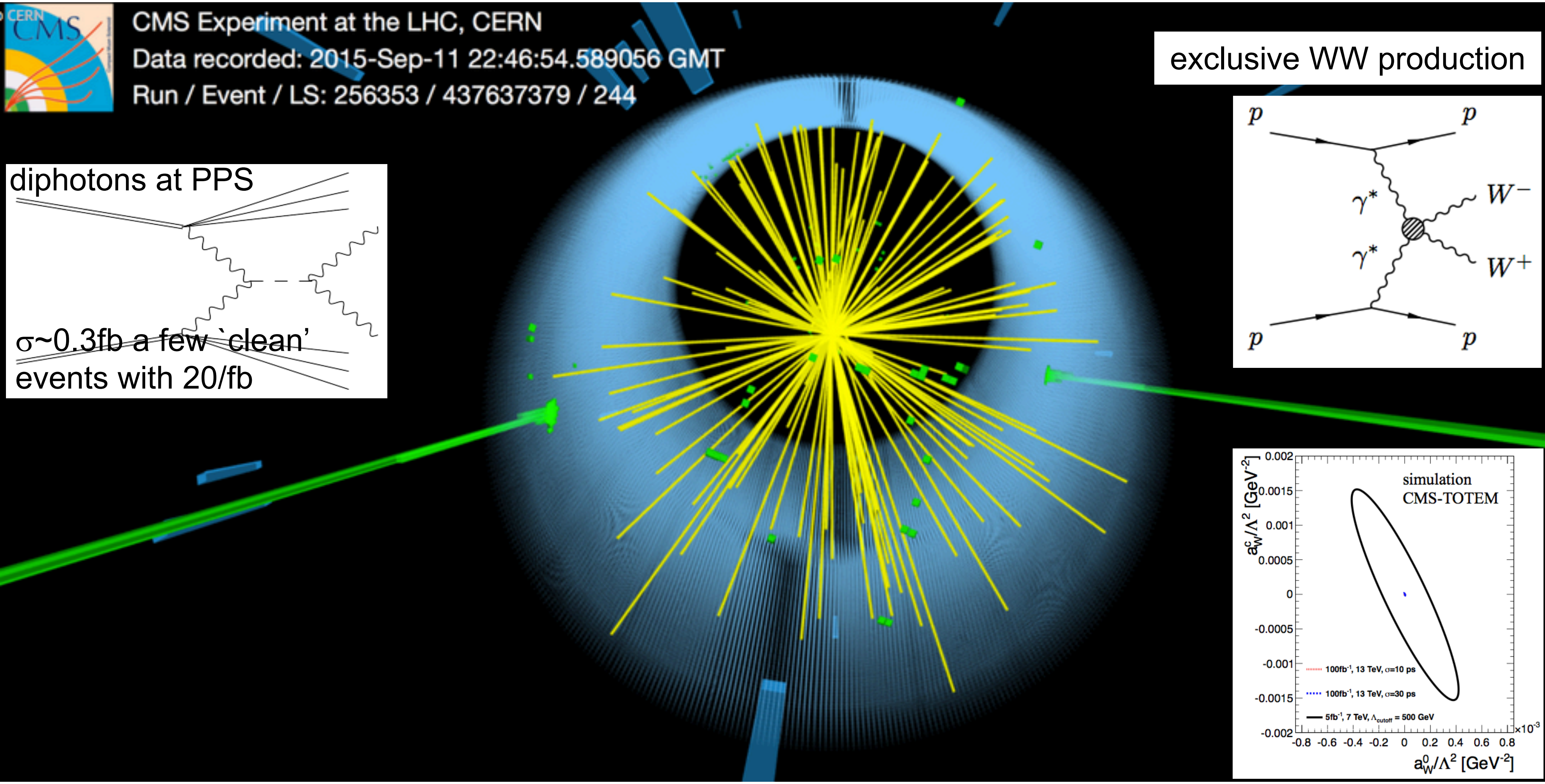
- Correlation between the ξ values in central system vs RP
- 12μμ, 8ee candidates observed (>5σ over expected bkg)
- First observation of two-photon production of a lepton pair at this mass range





BSM searches: resonances, etc.

CMS-EXO-15-004, CERN-LHC-2014-021



Summary

- Excellent consistency of SM but SM is incomplete
- Direct and indirect searches for New Physics
  - Collected ~80/fb @13 TeV in 2015-2017
  - ~300/fb to be collected in the next few years (up to LS3)
- Many studies performed with data collected so far
  - New dedicated algorithms being developed
  - Dark Matter, Exotica, signature-based searches
  - Other BSM searches
- Searches provide no hints for BSM yet