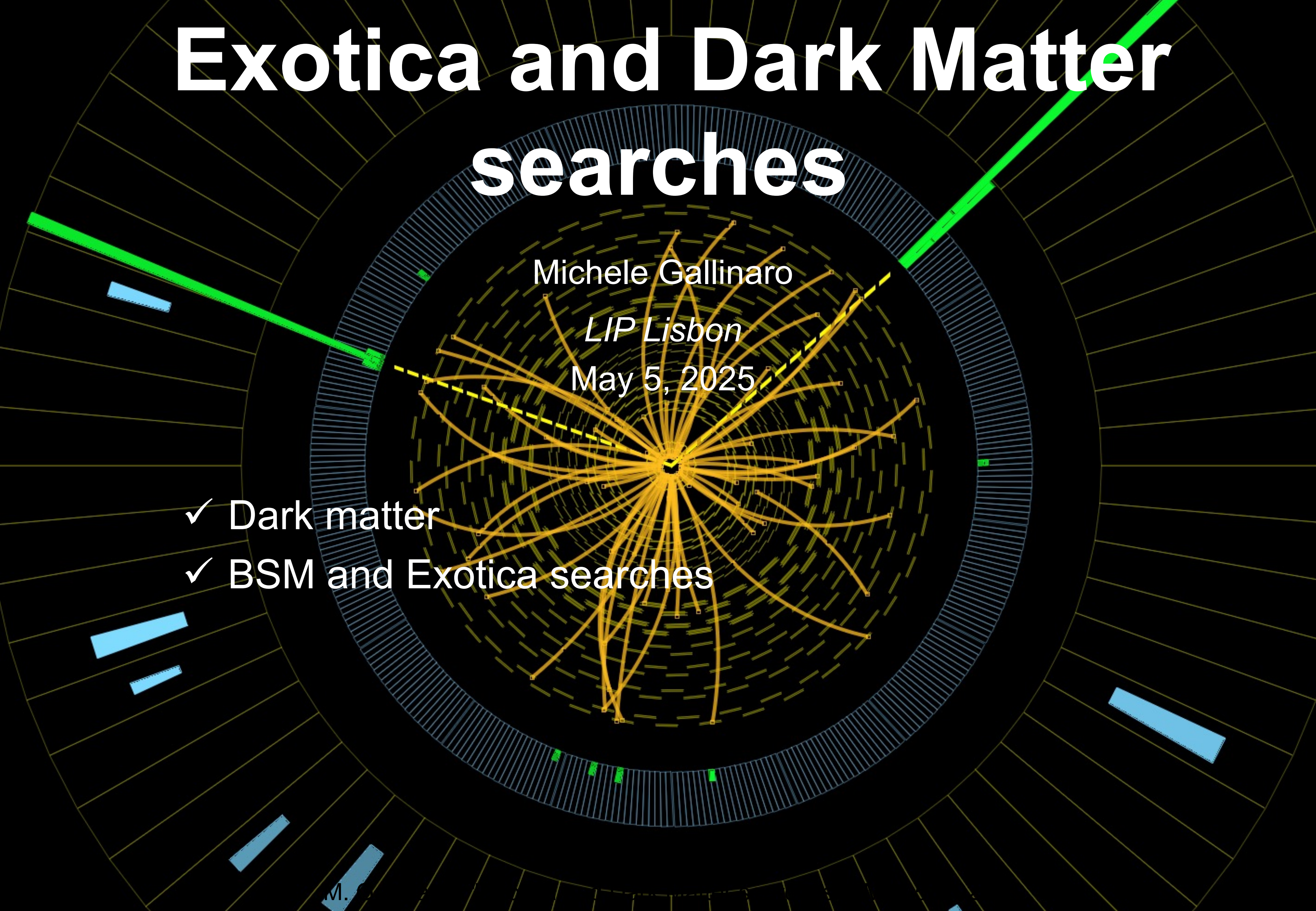


Exotica and Dark Matter searches

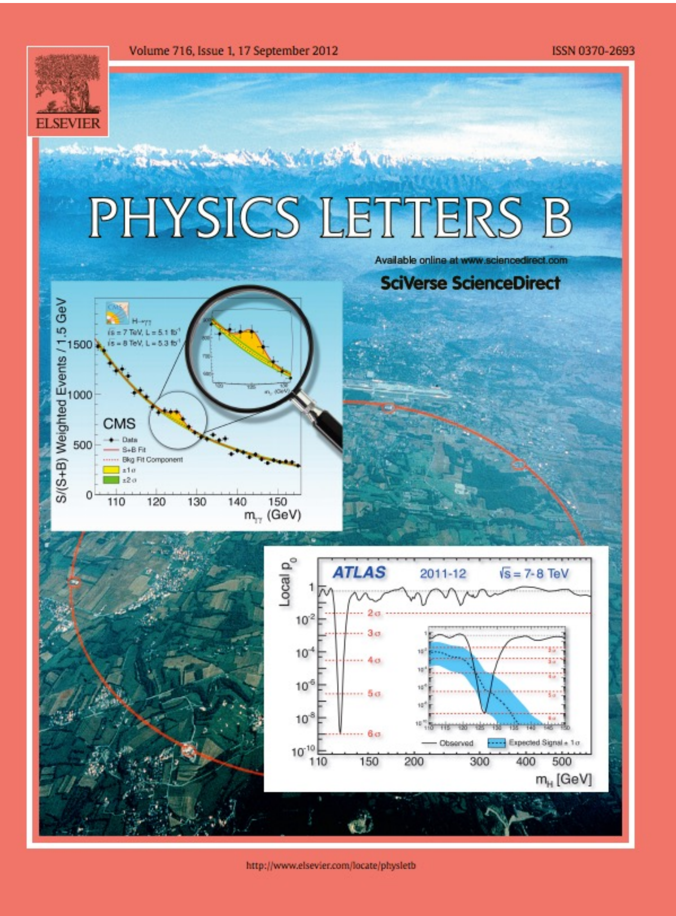
Michele Gallinaro

LIP Lisbon

May 5, 2025

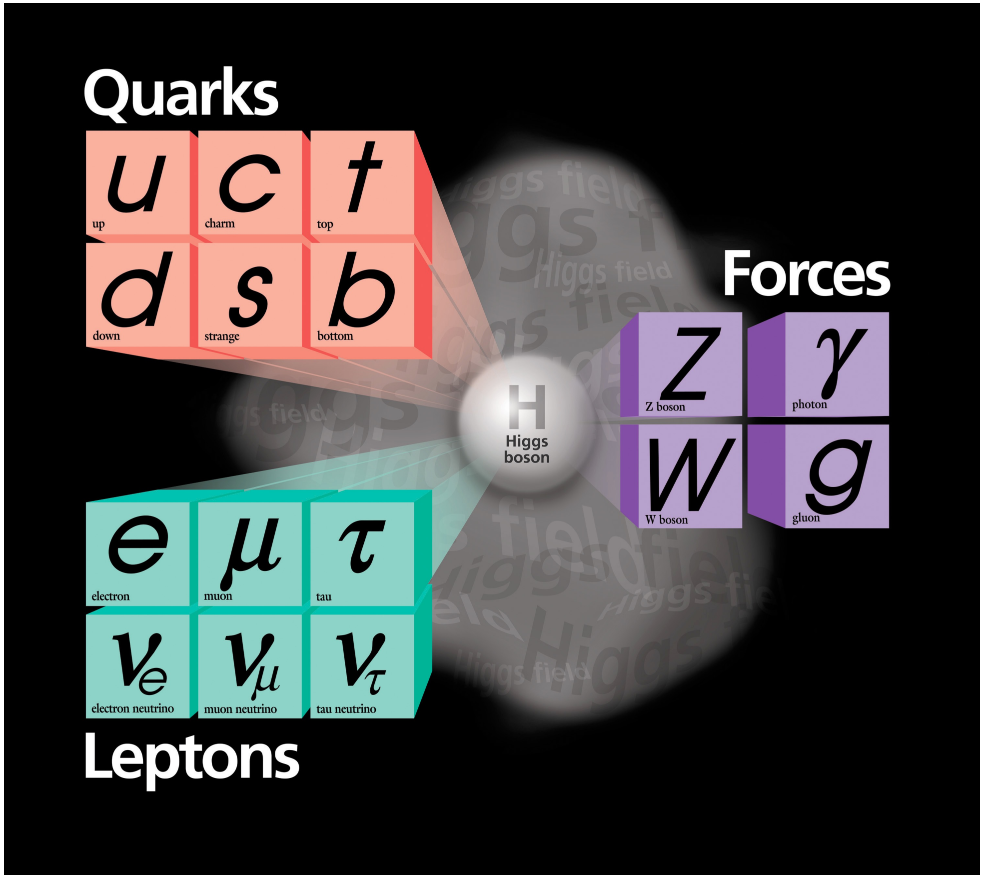
- ✓ Dark matter
- ✓ BSM and Exotica searches

2012: A new boson discovery

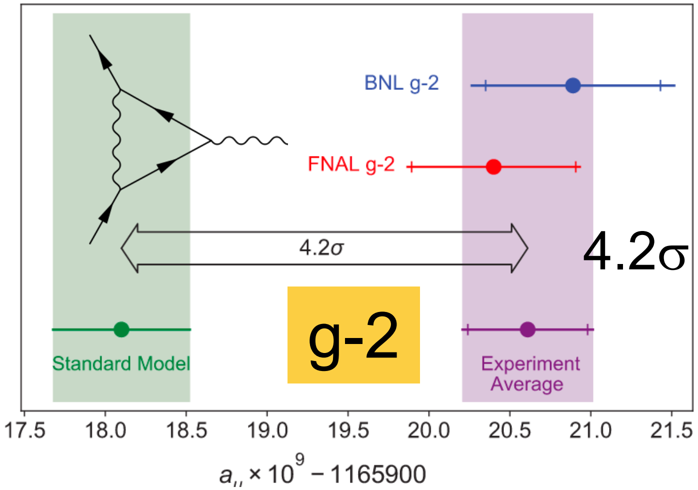


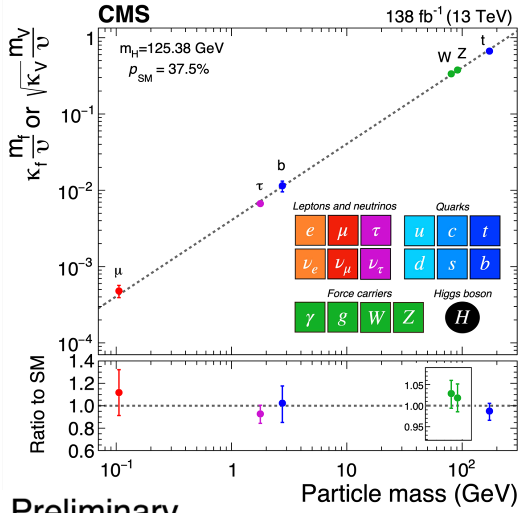
Standard Model theory of everything?

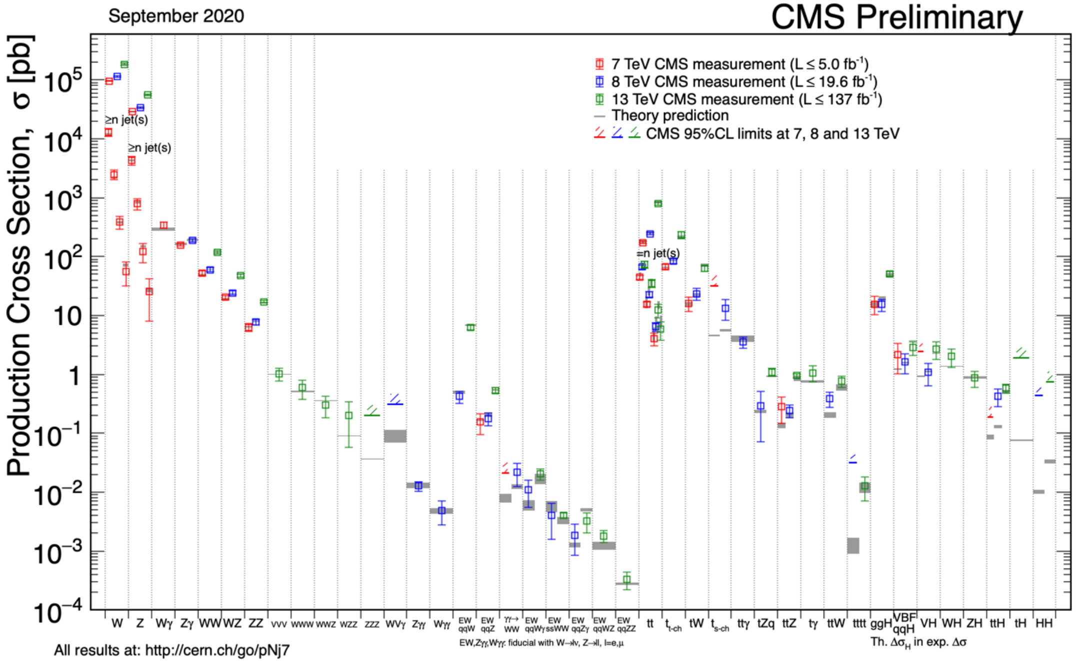
- Discovery of the Higgs boson marks the triumph of the SM
- However, even with the inclusion of the Higgs boson, SM is an incomplete theory

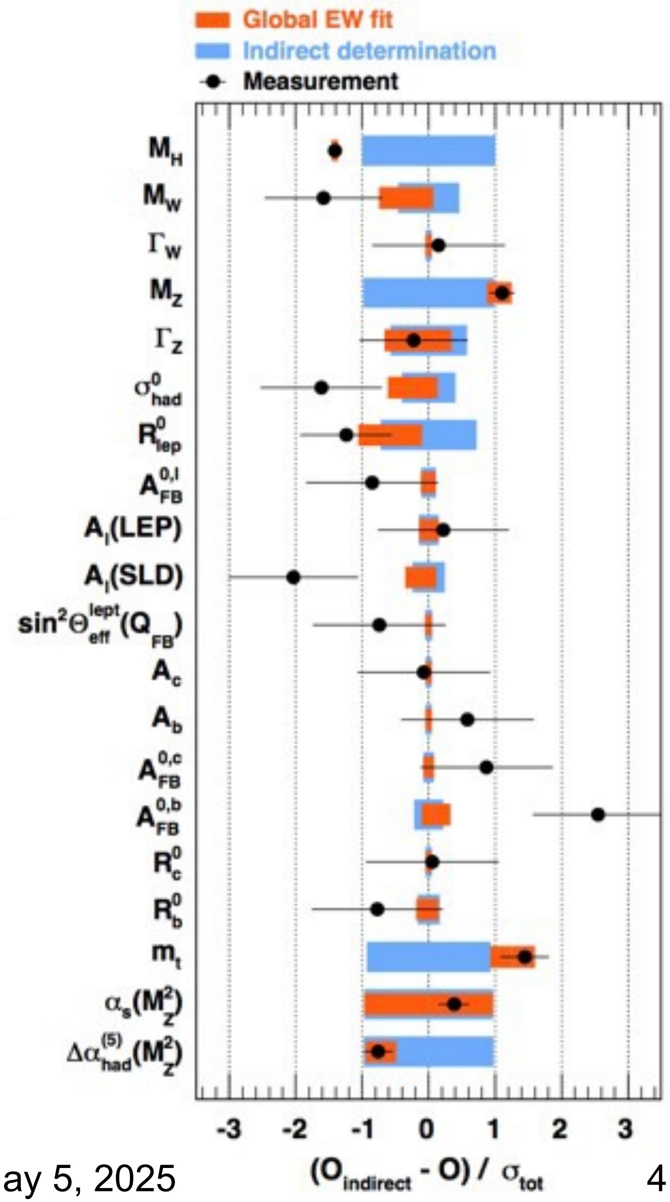


Tests of the SM









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?

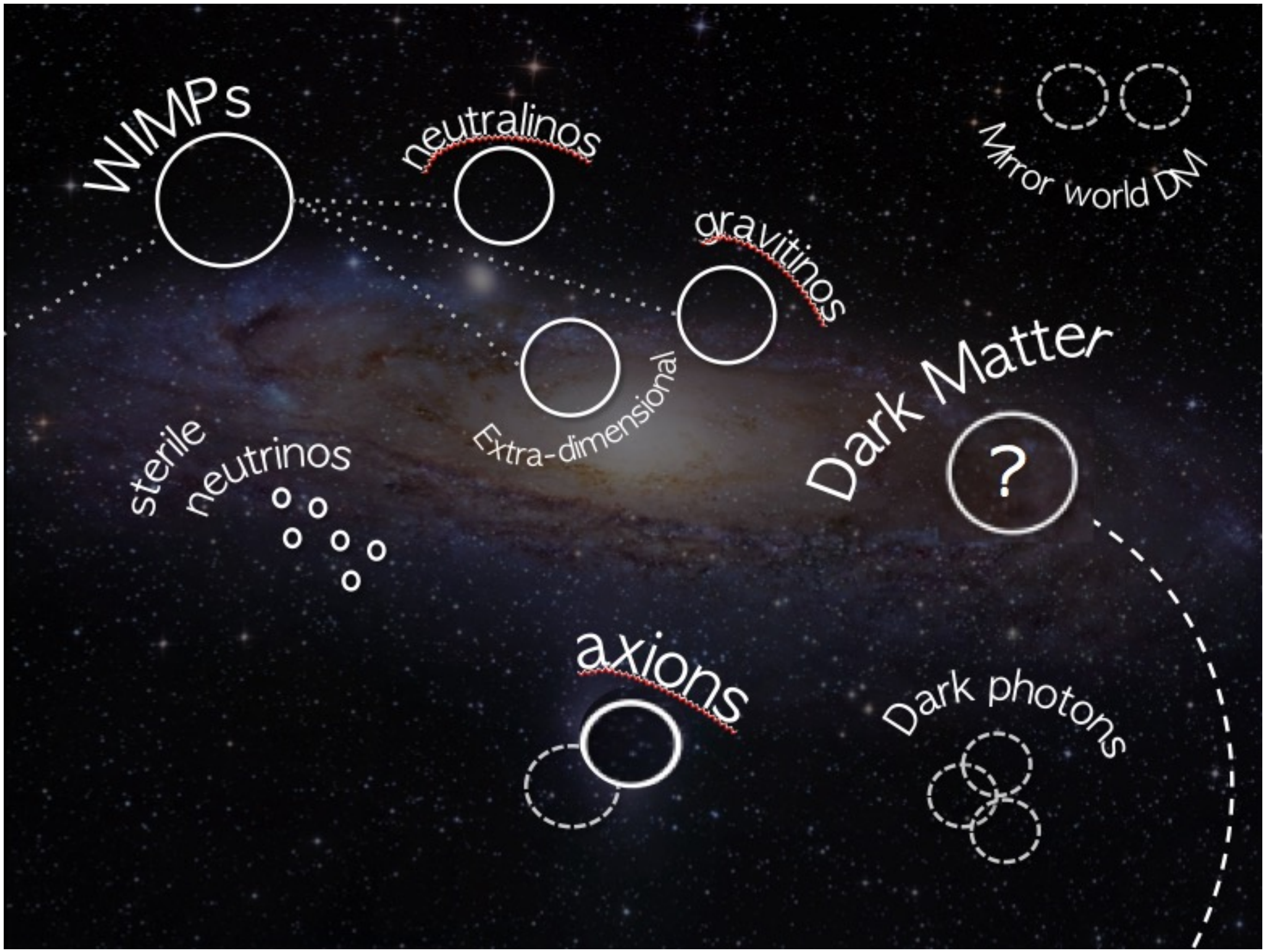
c) Are quarks and leptons actually fundamental, or made up of even more fundamental particles?

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?

What can we look for?

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

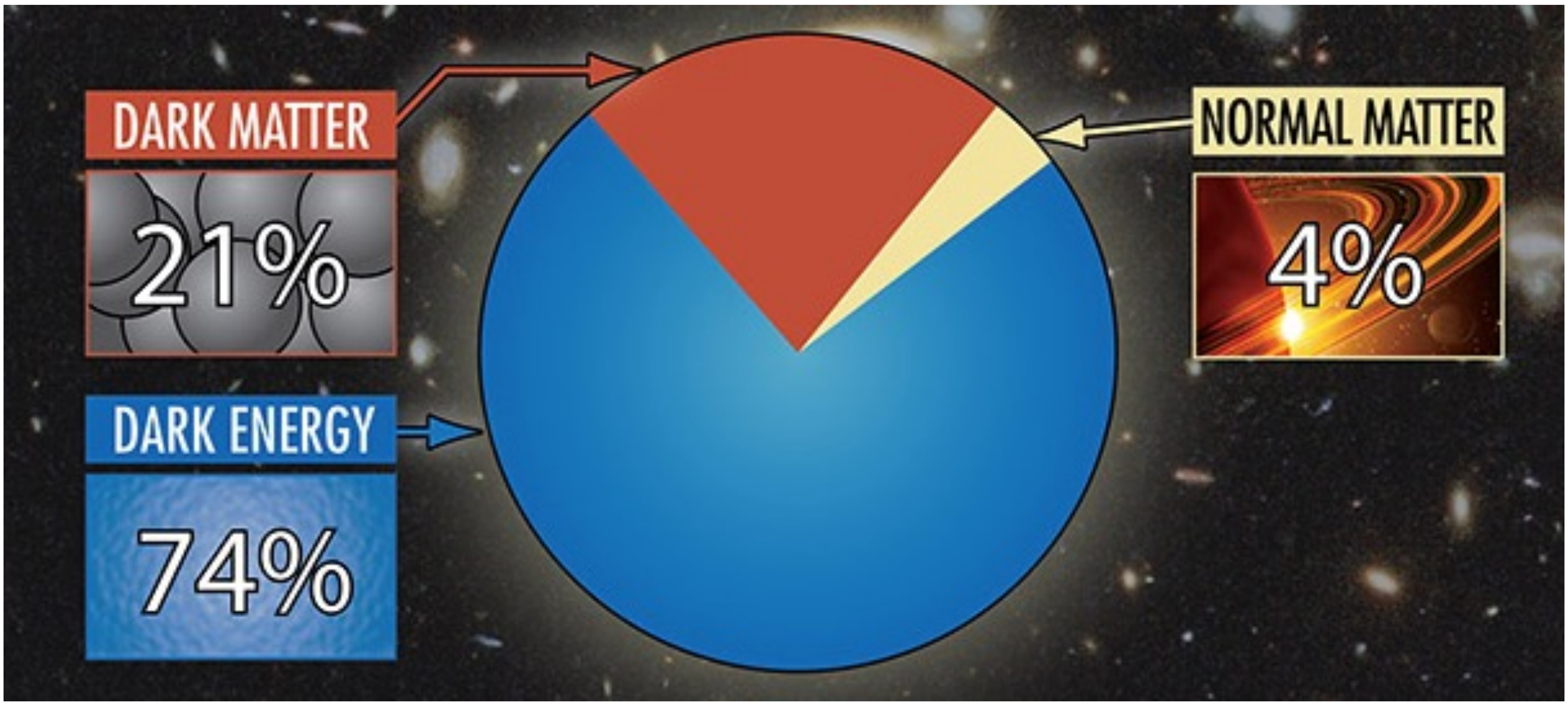


How?

- 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 and energy

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



Dark Matter

What is it?

- DM does not interact electromagnetically
- DM interacts gravitationally

Visual map

Dark Matter (cont.)

Why is it interesting?

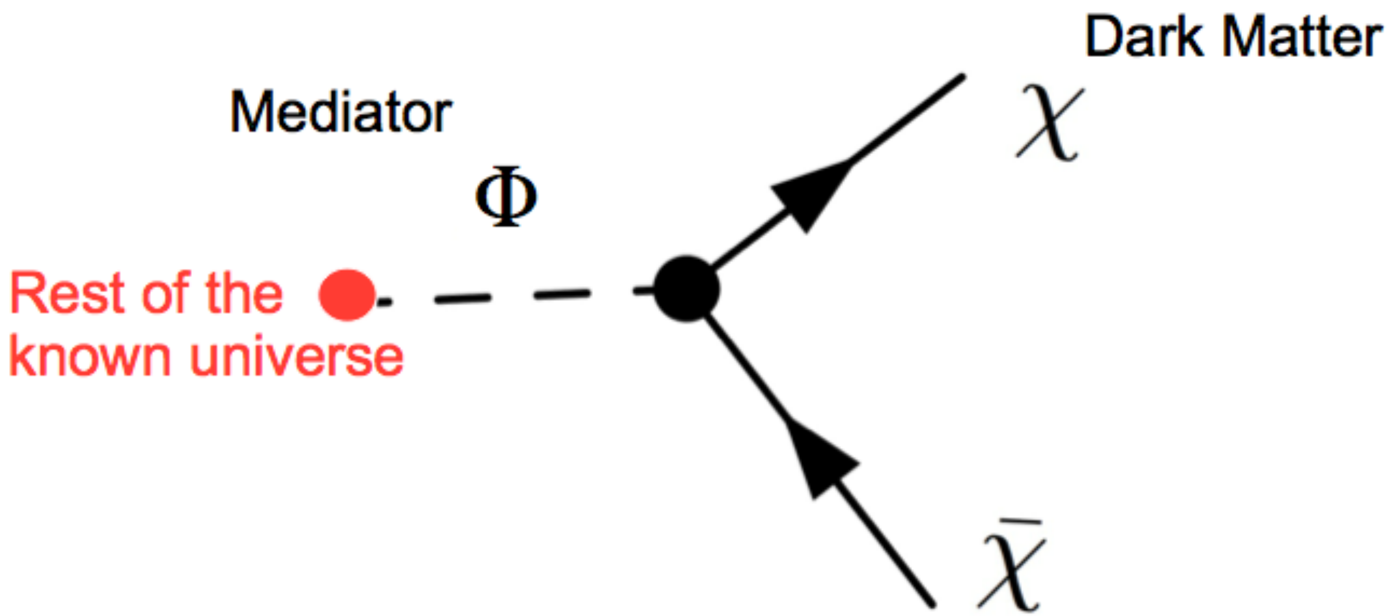
- We do not see it…but we feel it

Mass map

Dark Matter (cont.)

How do we find DM?

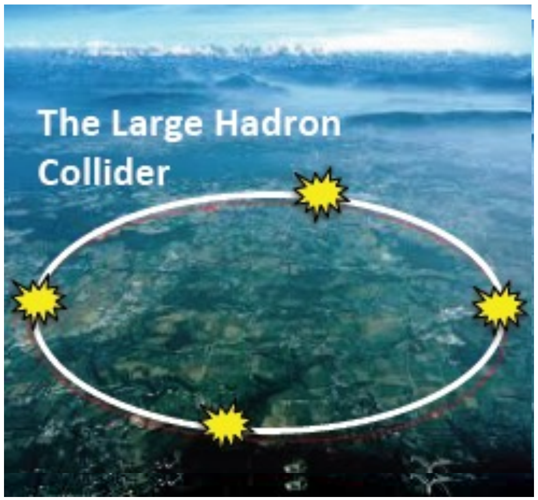
- Need to understand how it interacts with Universe
- Traditionally through a mediator
- Yields at least two new particles

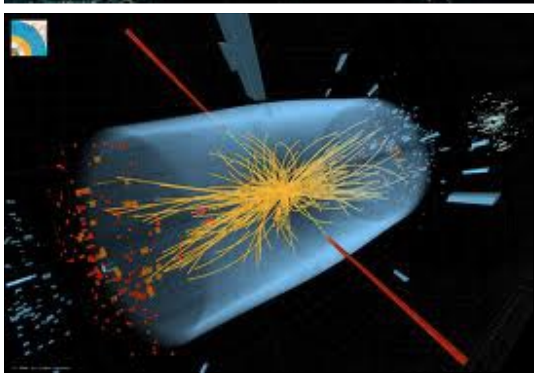


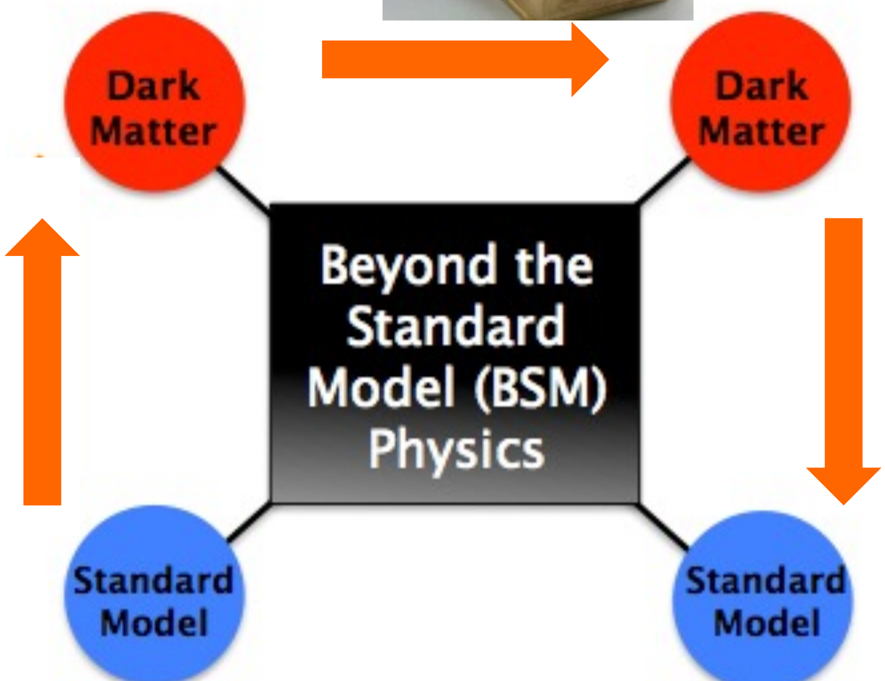
Searching for DM

Direct Detection

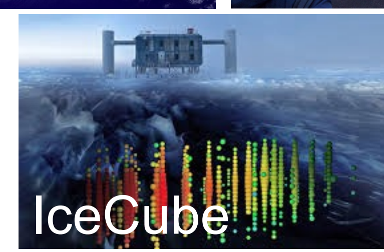
Particle Colliders





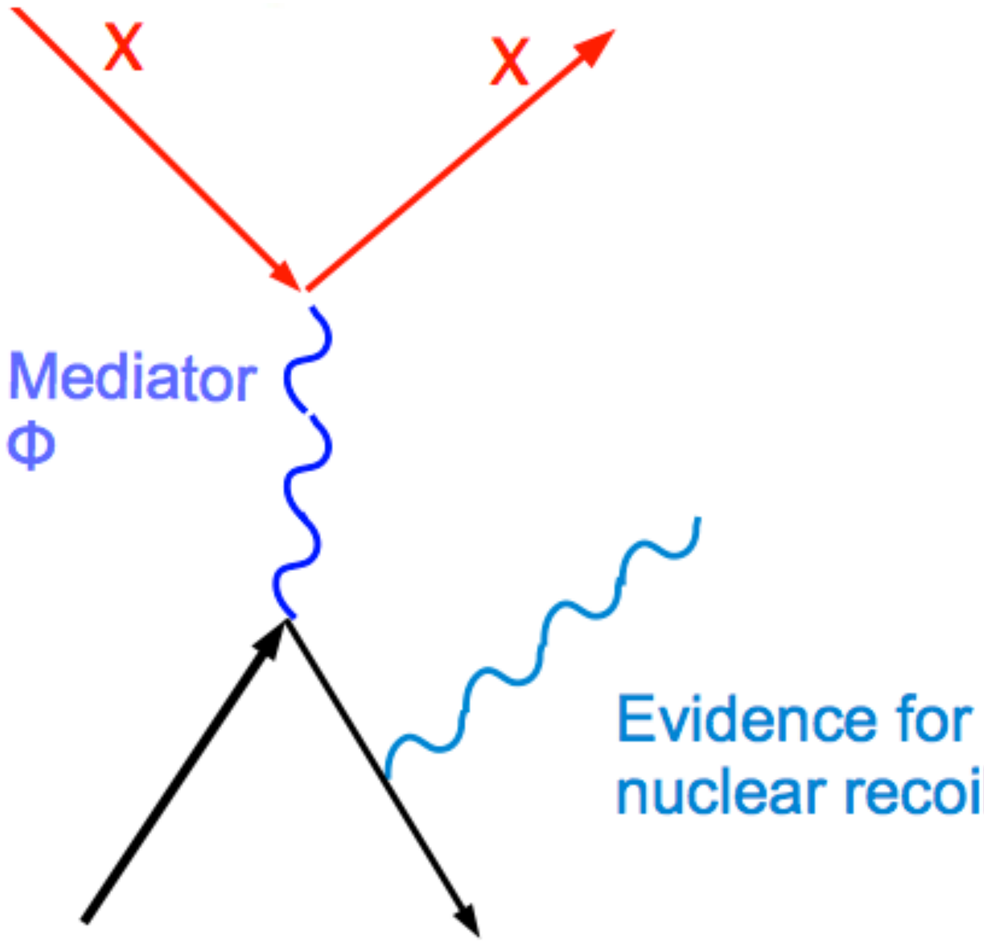


Indirect Detection



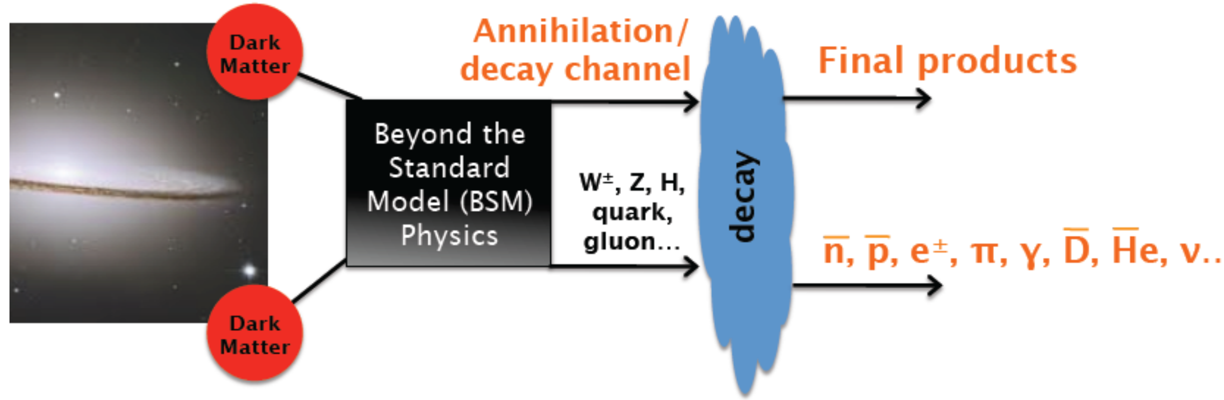
How do we find it: @underground

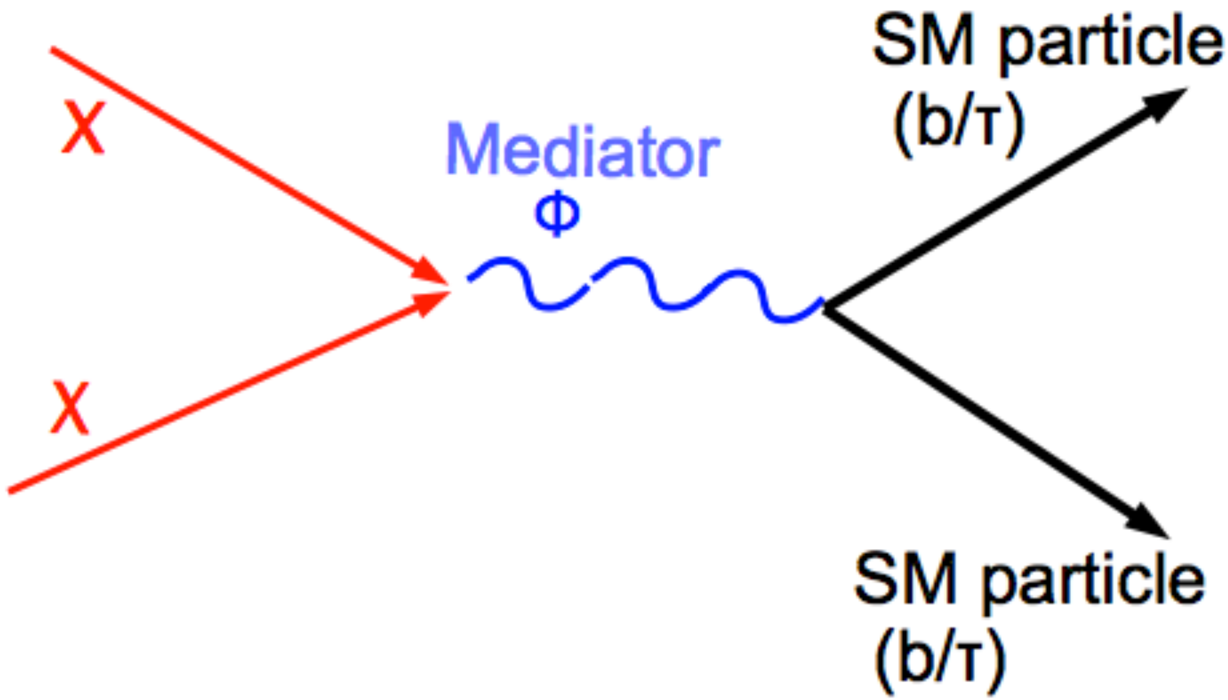
- Through a nuclear recoil



How do we find it: @Space

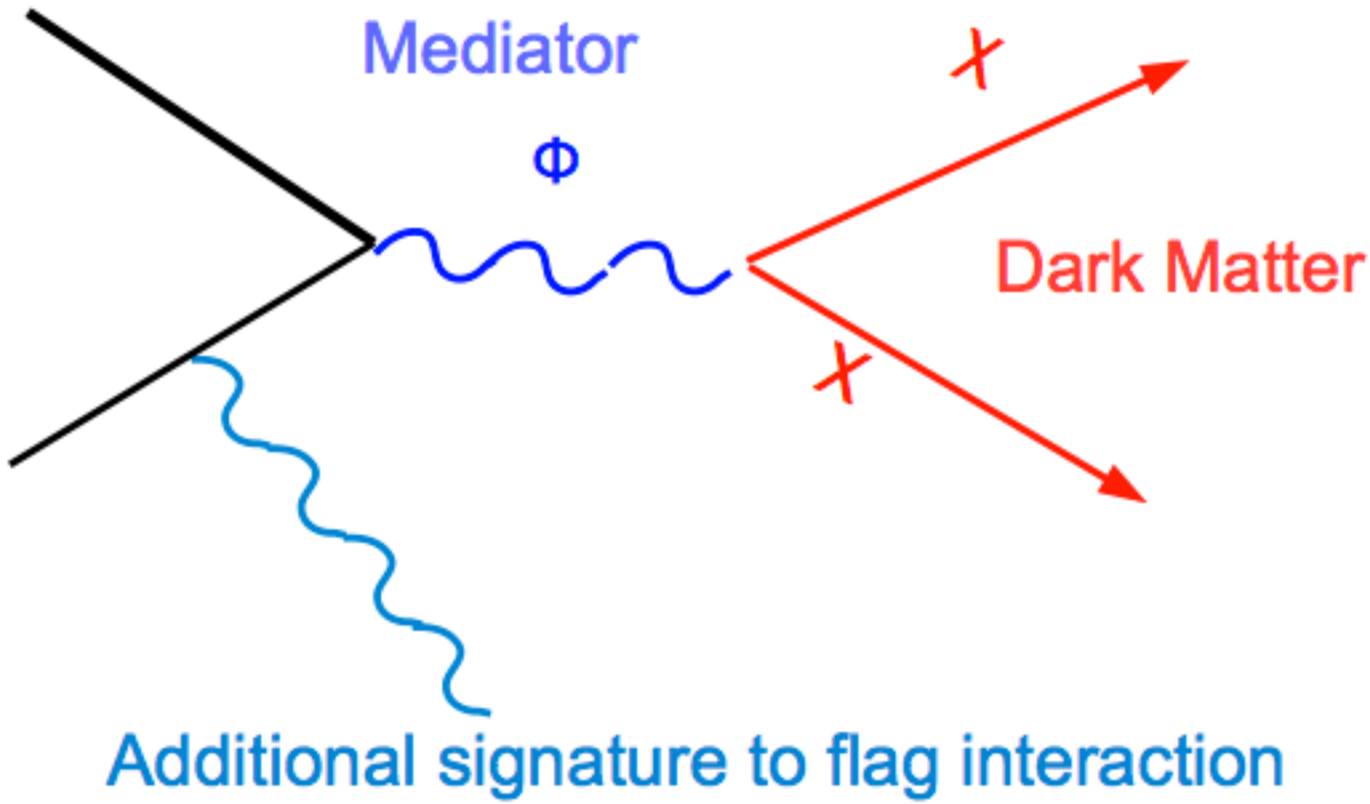
- Through annihilation
  - Cosmic rays from DM





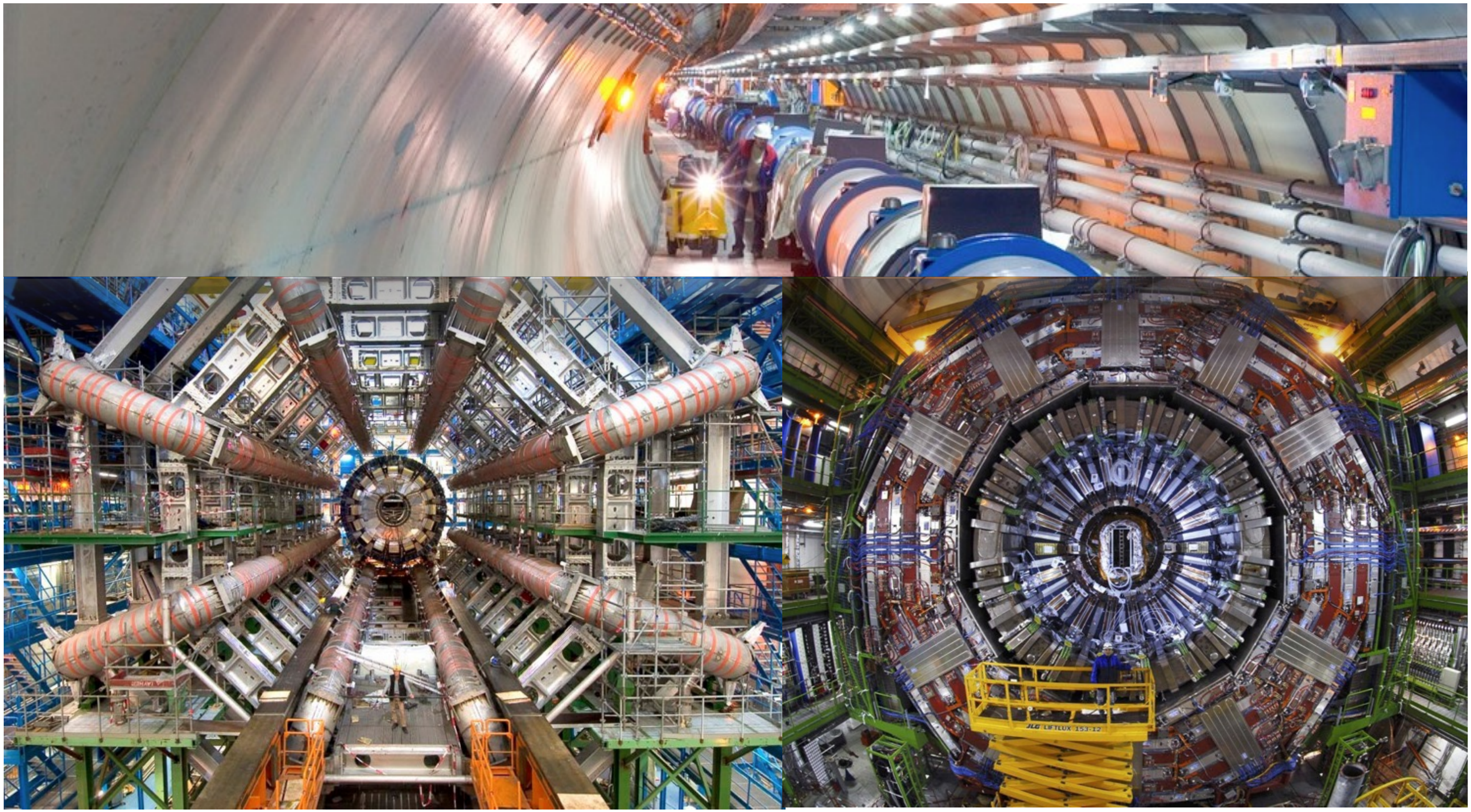
How do we find it: @LHC

- Produced it through a mediator



DM at the LHC

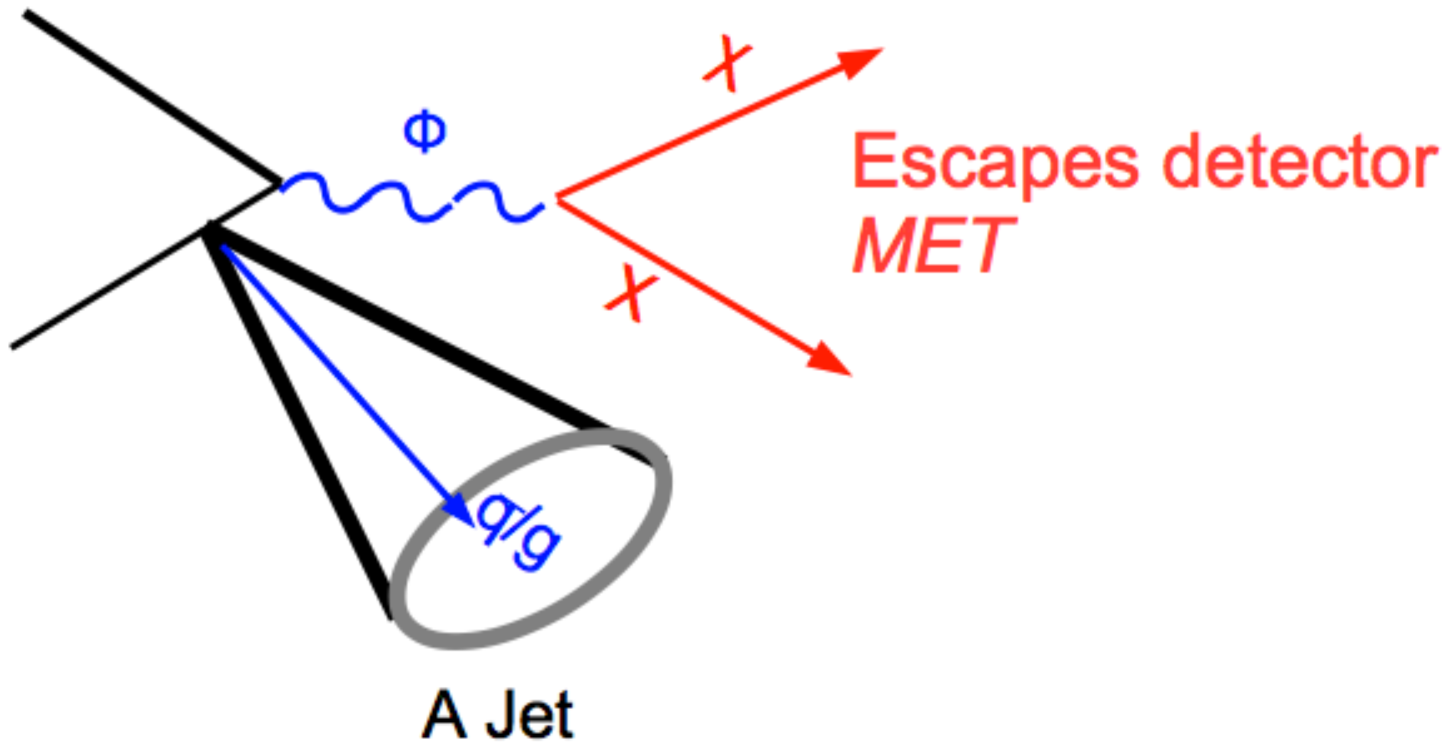
- CMS/ATLAS experiments not designed for DM searches



DM searches at LHC

How do we find DM at the LHC?

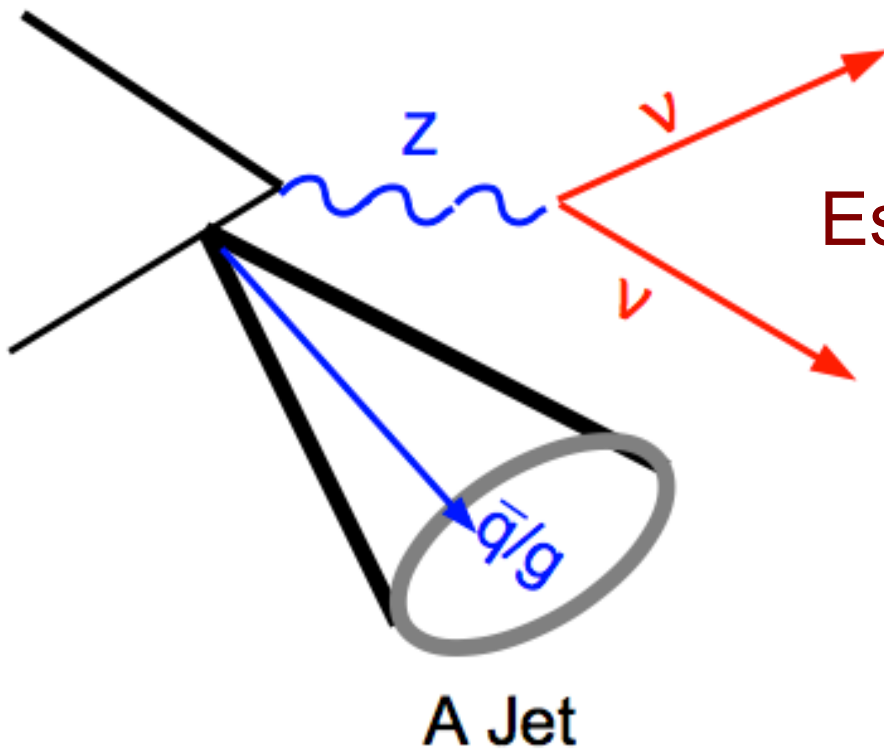
- DM production gives MET signature



DM searches: backgrounds

What are the backgrounds?

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

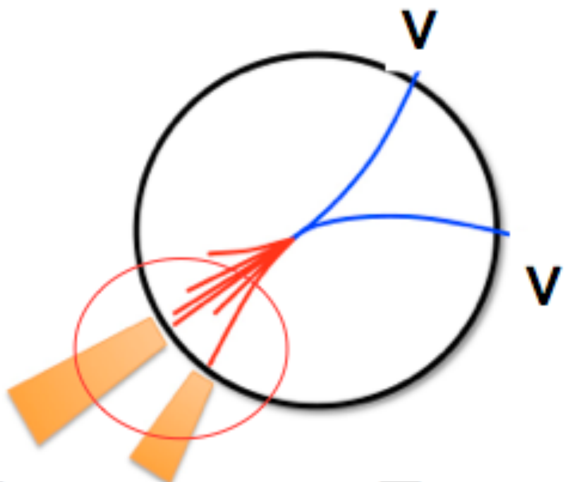


Escapes detection

DM searches: backgrounds (cont.)

How to discriminate signal against the background?

- Look for high MET:



Study hadronic recoil

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

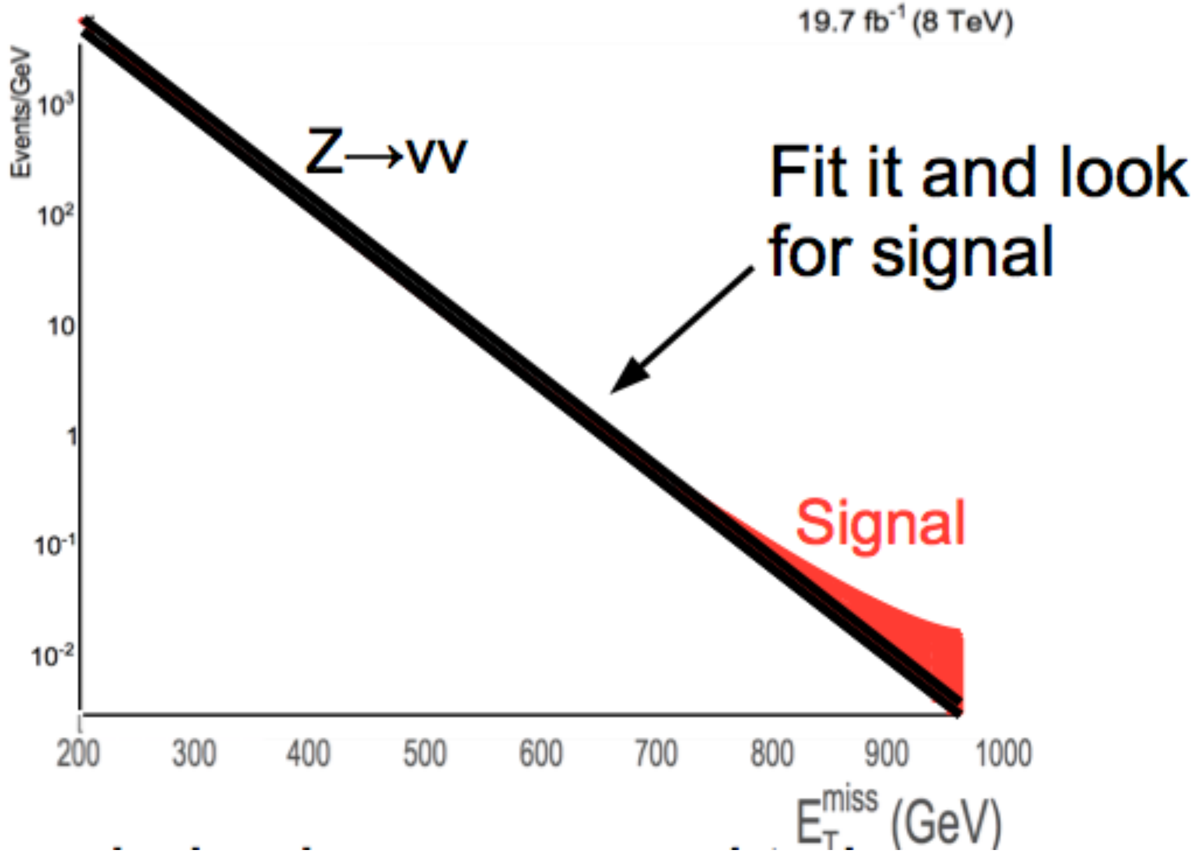
$$MET(Z\rightarrow\nu\nu) = -\, Z\ recoil + p_T(\nu\nu)$$

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

DM searches: backgrounds (cont.)

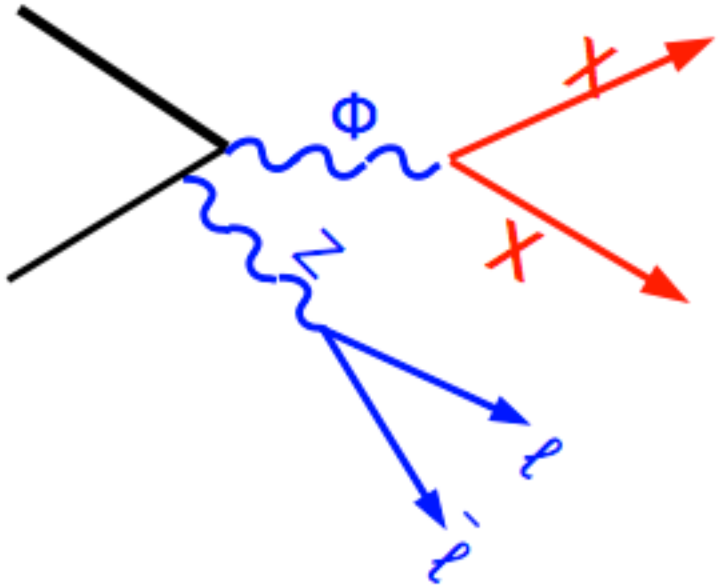
How to discriminate signal against the background?

- Can fit the shape and look for signal

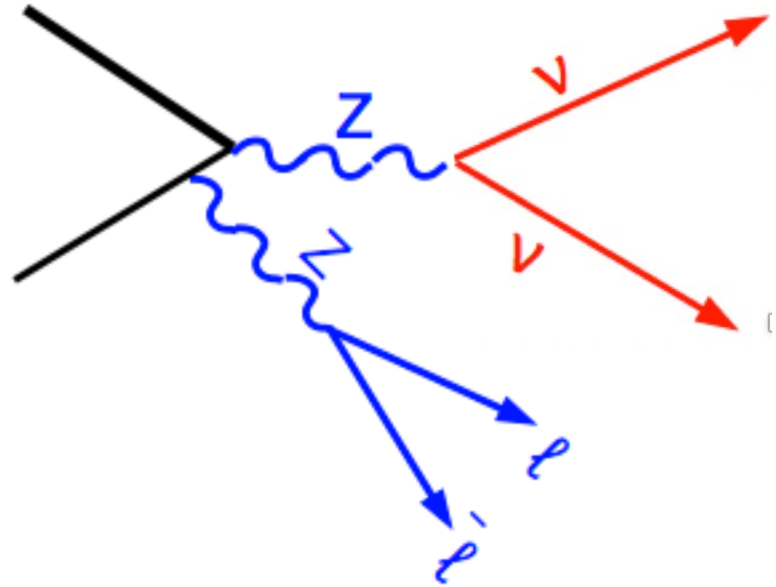


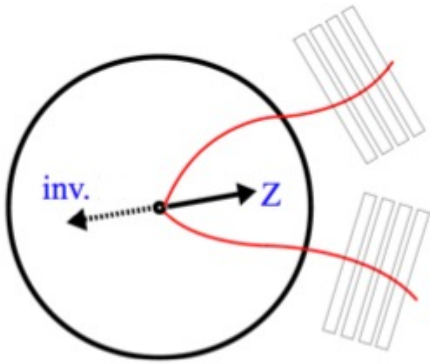
DM+Z

signal



background

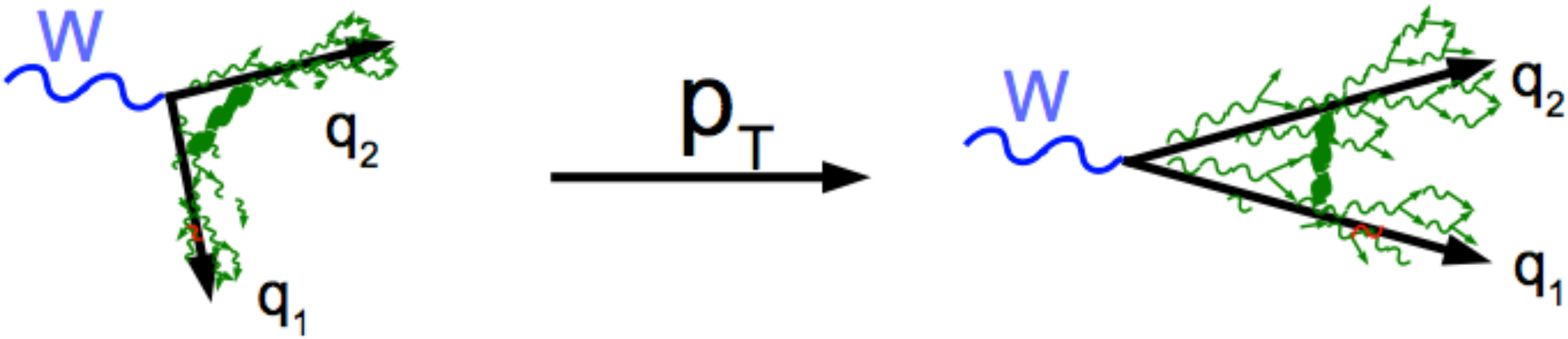




- Main background is from ZZ di-bosons
- Understanding ZZ di-boson pT is critical

Build a V-tagger

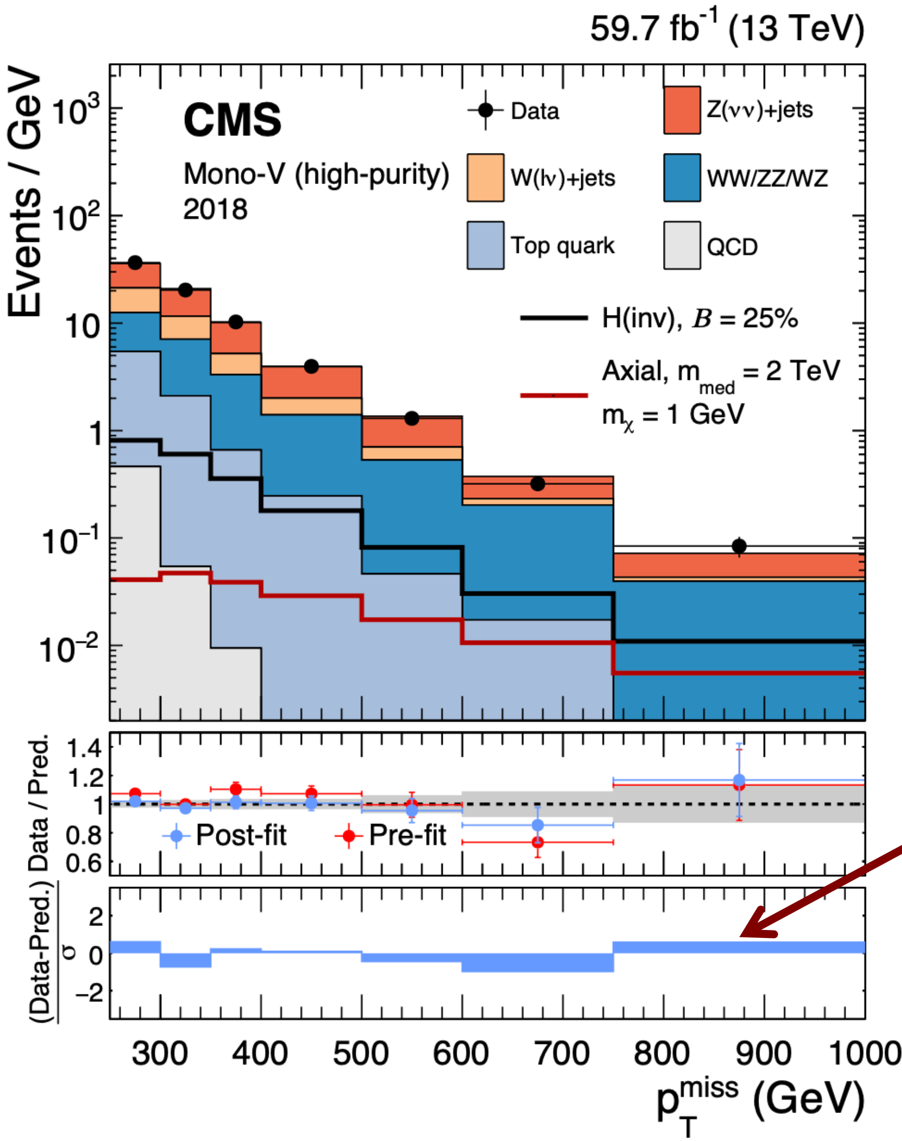
- Two jets are more collimated at high pT



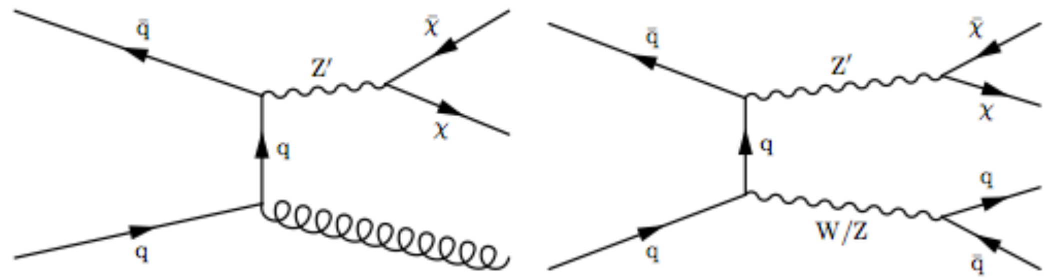
- At low pT jets are "resolved"
  - –Focus on reconstructing di-jets with mass near W mass
- At high pT get one "fat" jet
  - –Focus on identifying one jet with mass near W mass
- Use additional variables to improve discrimination

DM+jet/V

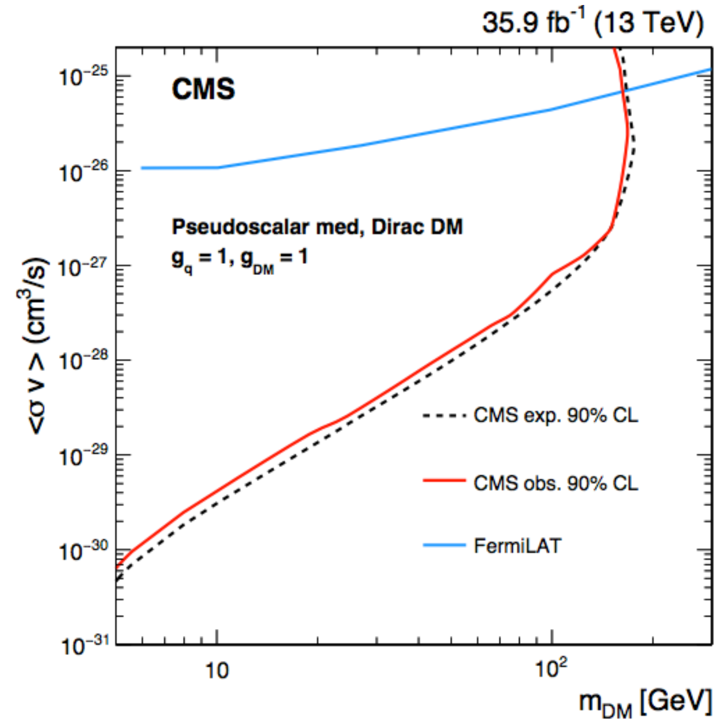
arXiv:2107.13021



DM search in mono-jet/V



Need good control of systematics

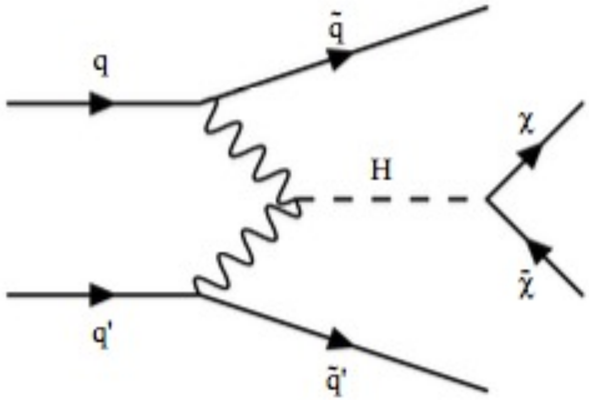


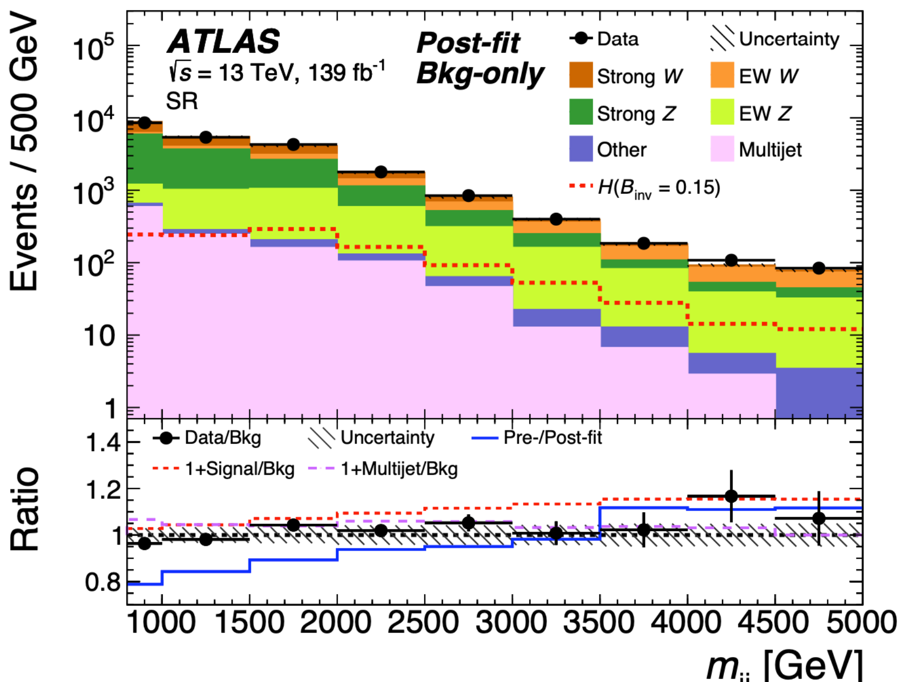
VBF: H(invisible)

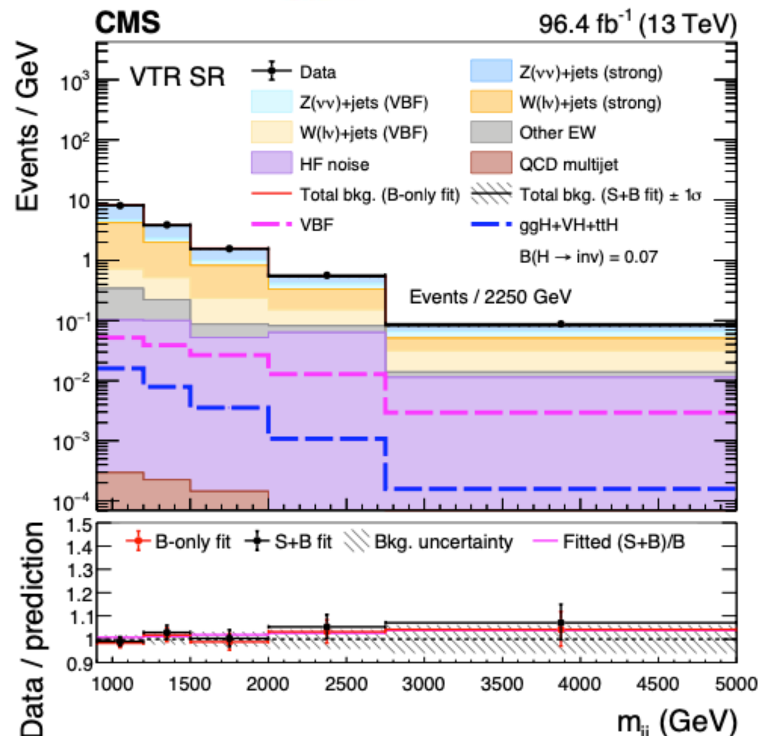
arXiv:2201.11585, arXiv:2201.11585

- 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

Set limits: B(H →inv.)<0.18 (0.10) @95%CL



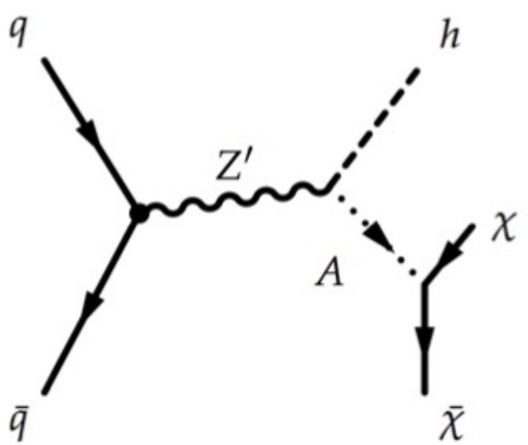




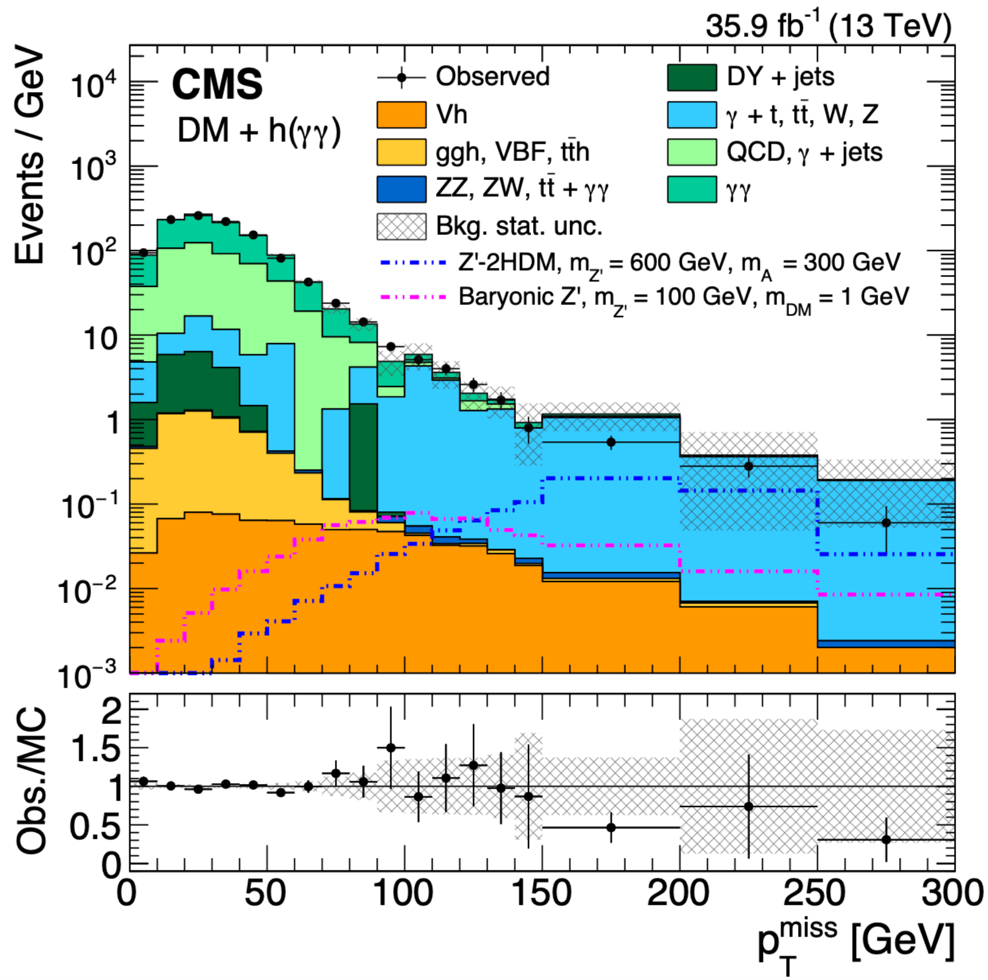
DM+Higgs

arXiv:1806.04771

- DM search with H(→ττ,γγ)
- Model dependent search
  - –Z' 2HDModel and barionic Z'



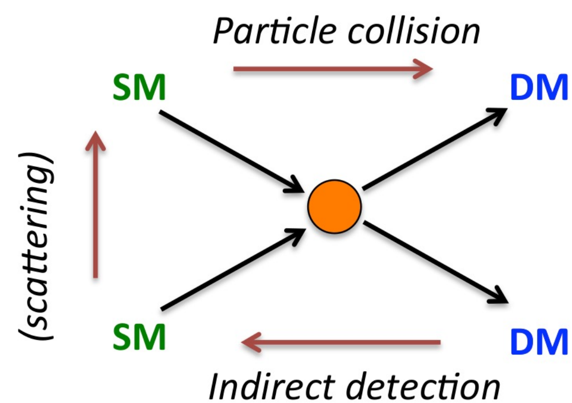
- No significant excess
- Set limits

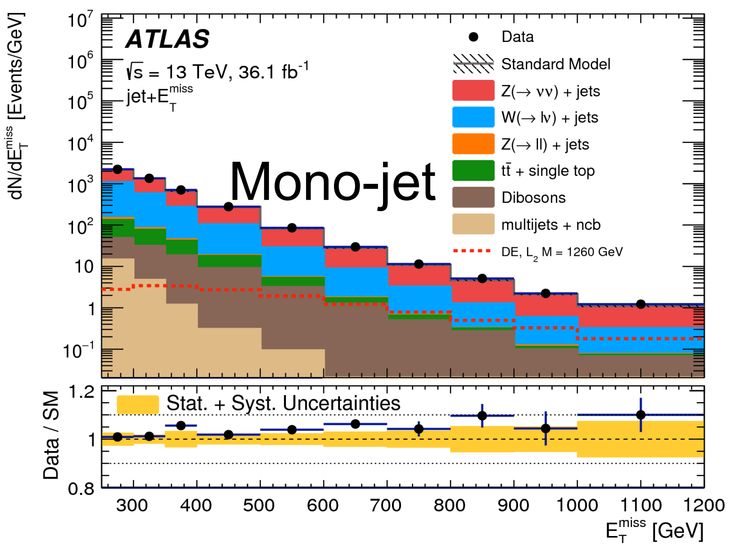


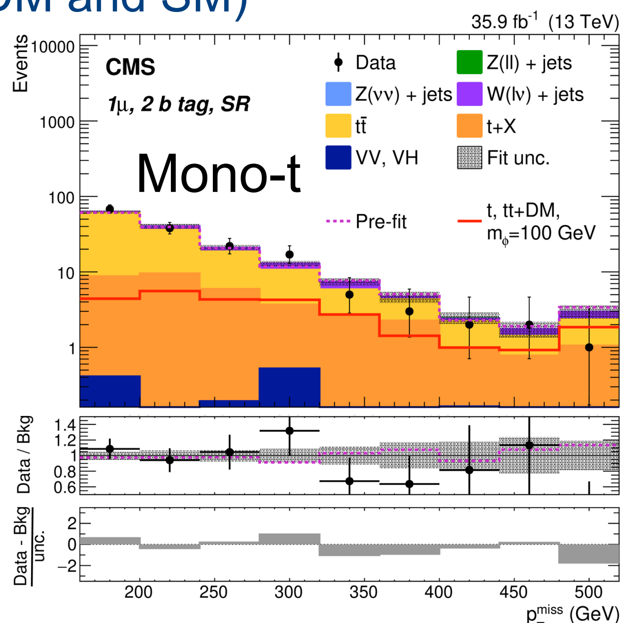
Dark Matter

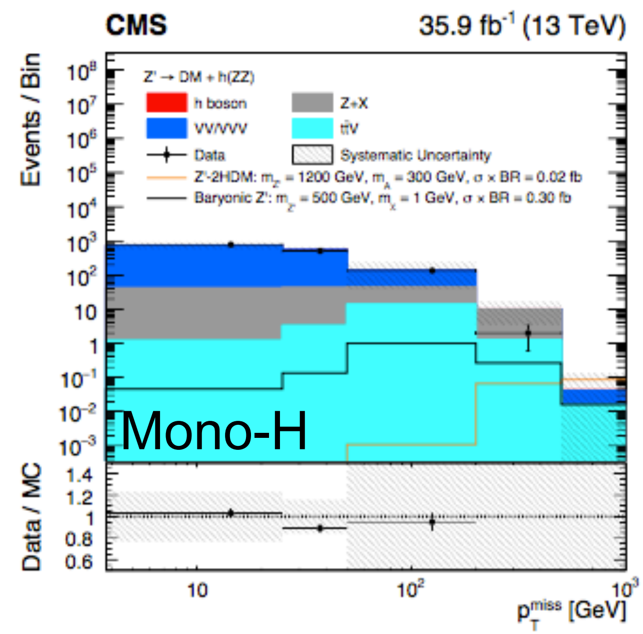
arXiv:1903.01400, arXiv:1901.0155, CMS-EXO-18-009

- 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)





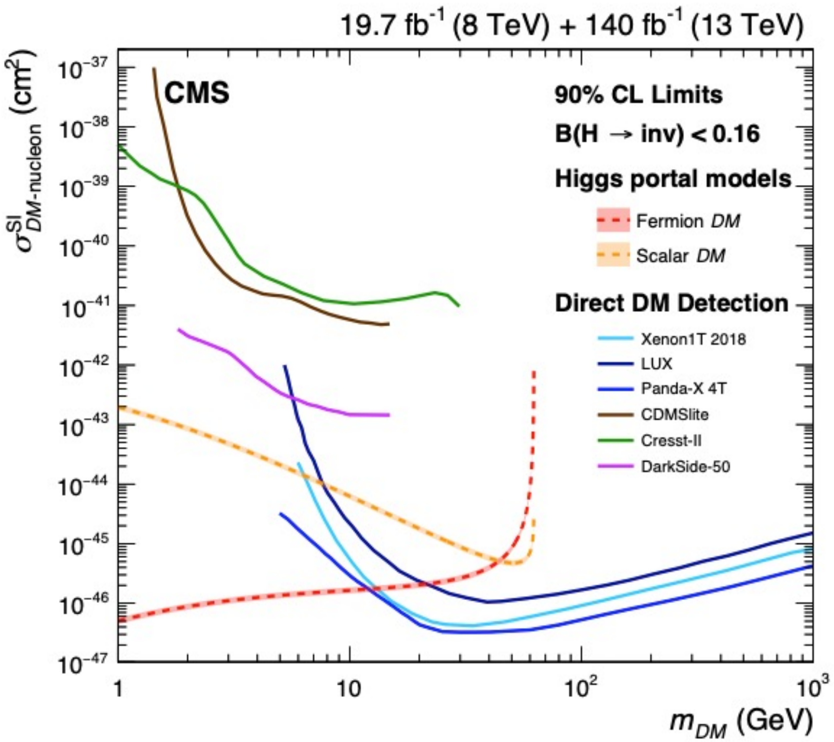


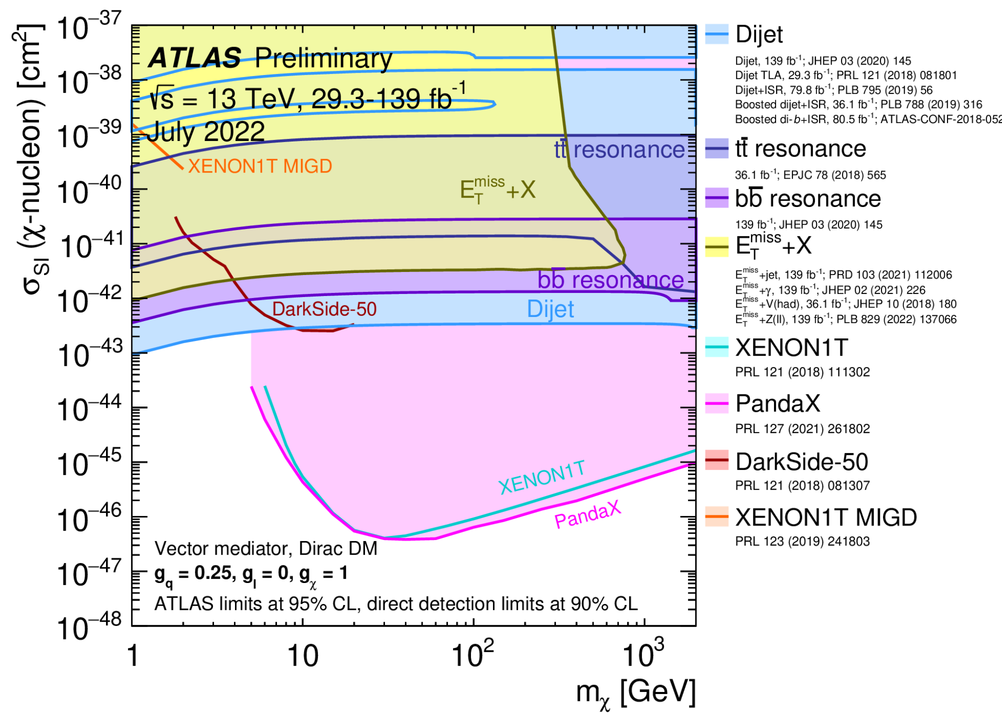


Experimental results

arXiv:2201.11585

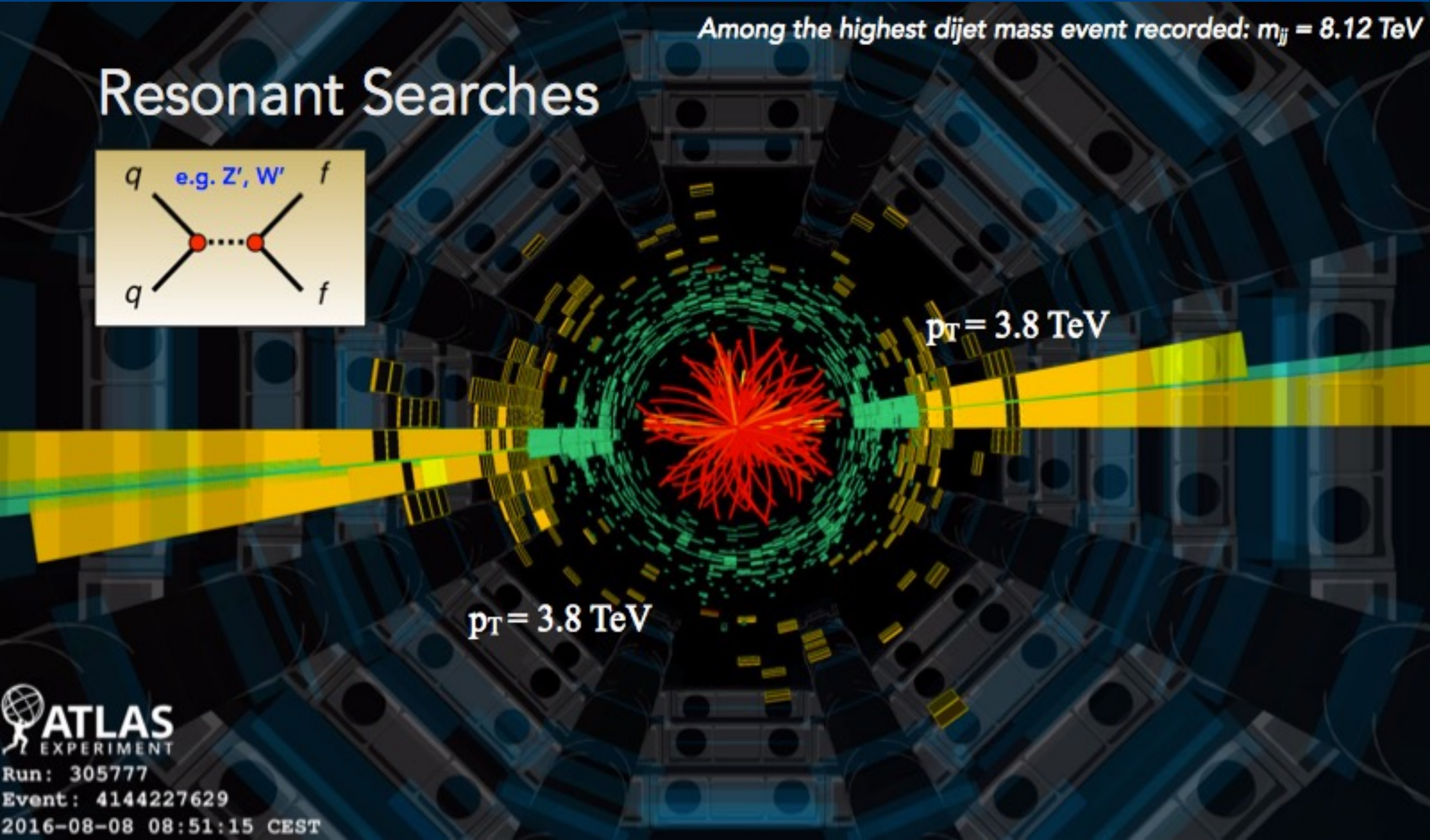
- Limits for given couplings between SM and DM interaction
- Competitive limits at low masses wrt other experiments





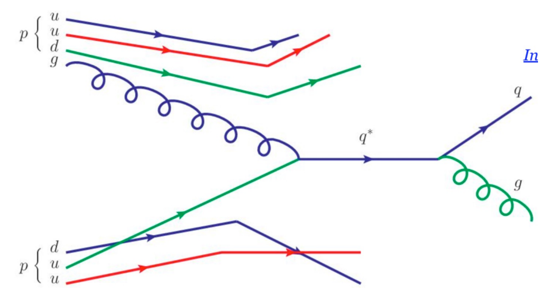
⇒ Collider results complement direct searches for low masses (<5-10GeV)

Resonant searches

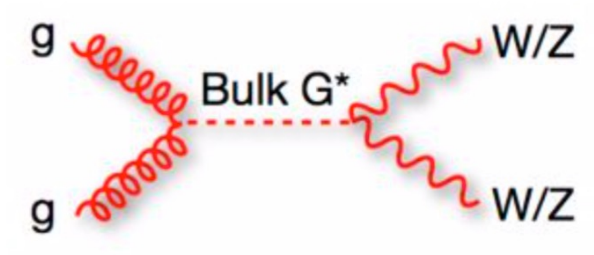


BSM models predict new resonances

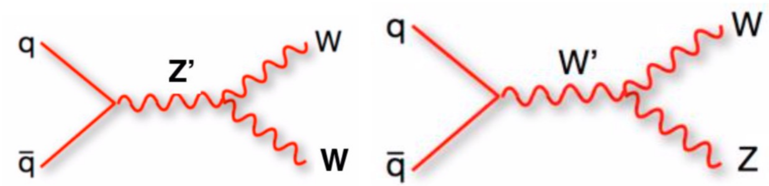
- BSMs predict resonances with spin 0,1,2



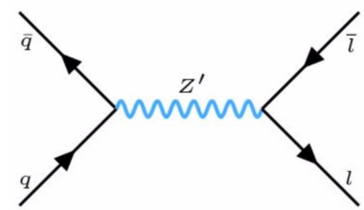
- Are quarks fundamental particles?
  - Excited quarks in models of compositeness
- Randall-Sundrum (RS) models
  - Spin-2 graviton (KK-particle)



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



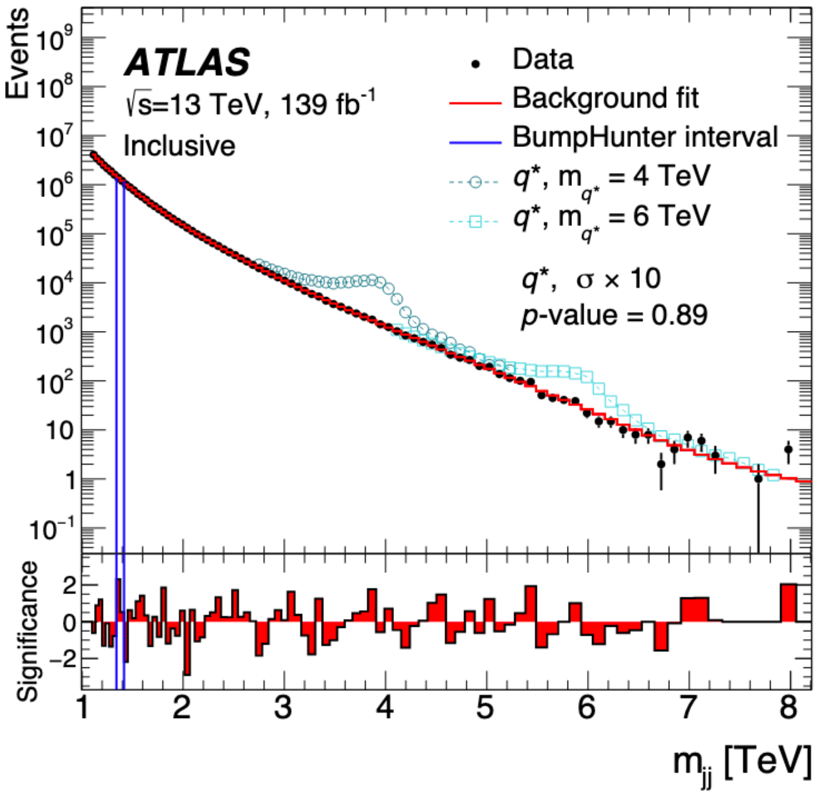
- Sequential SM
  - Z' and Z with same couplings to fermions
  - Width proportional to the mass

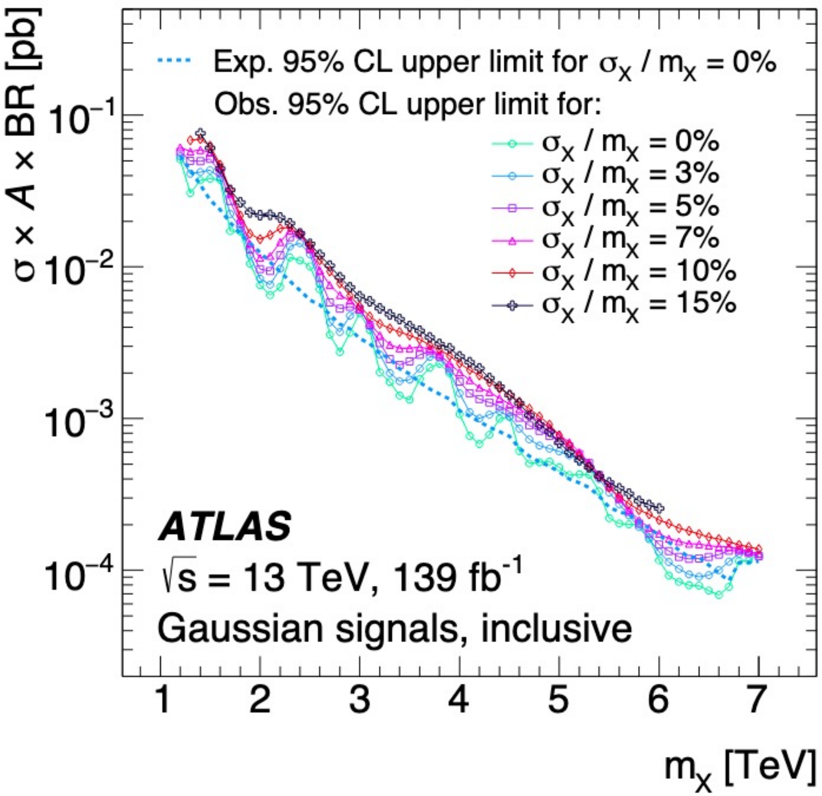


New phenomena in di-jet events

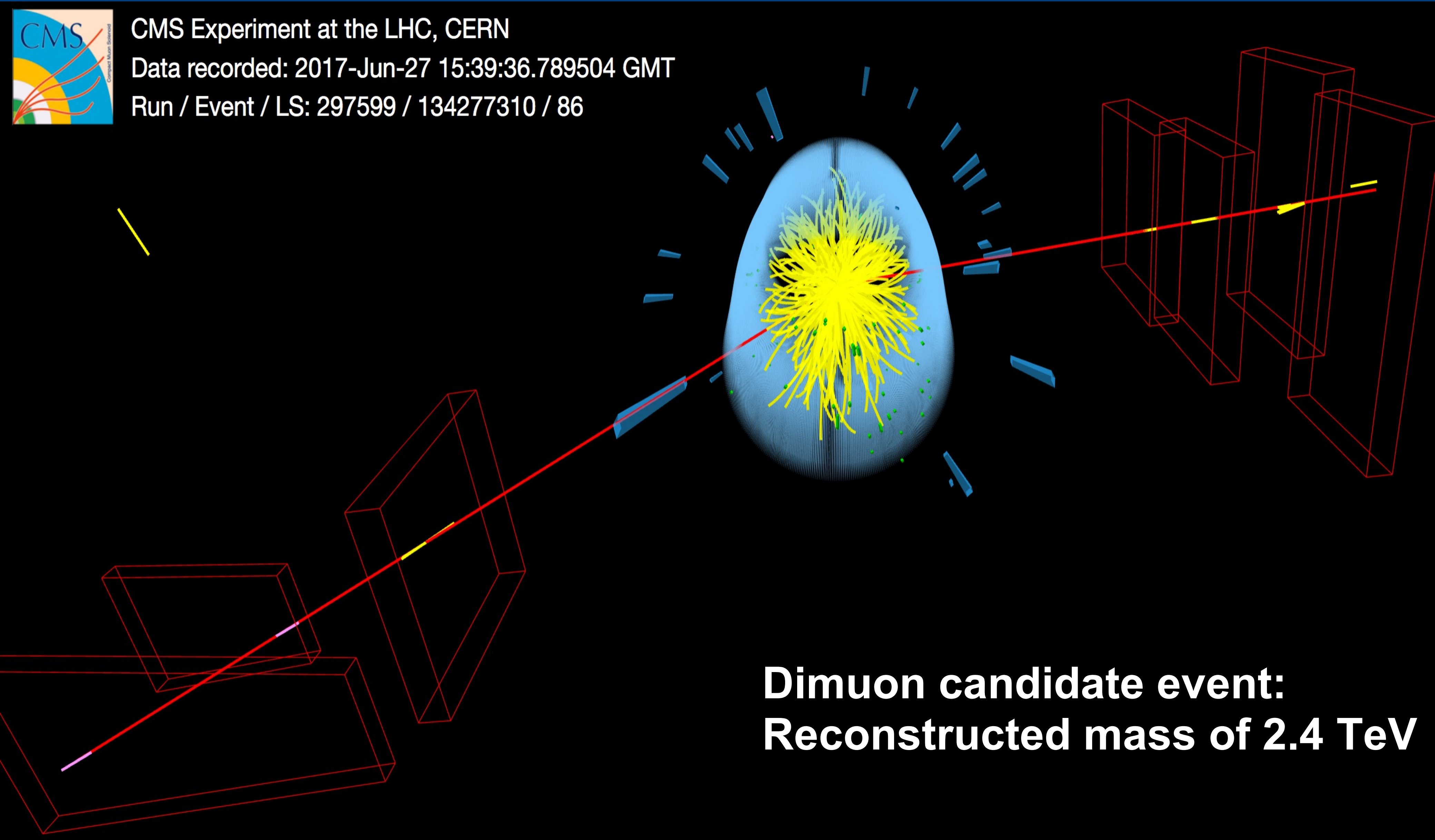
CMS-EXO-17-026, arXiv:1910.08447

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



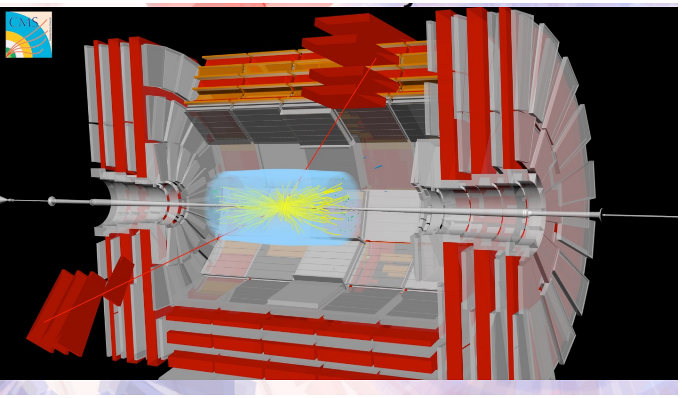


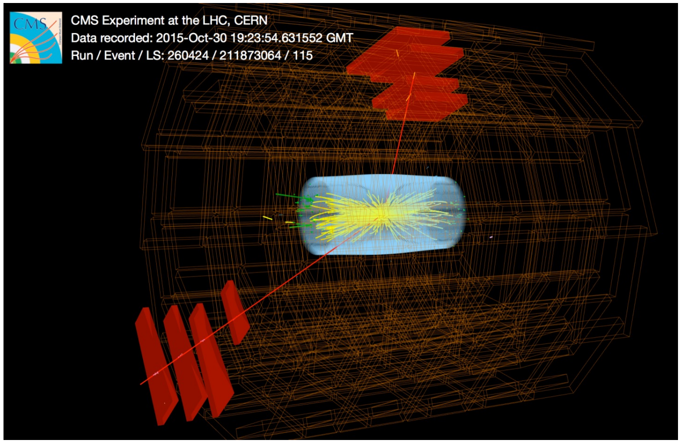
Searching for dilepton resonances

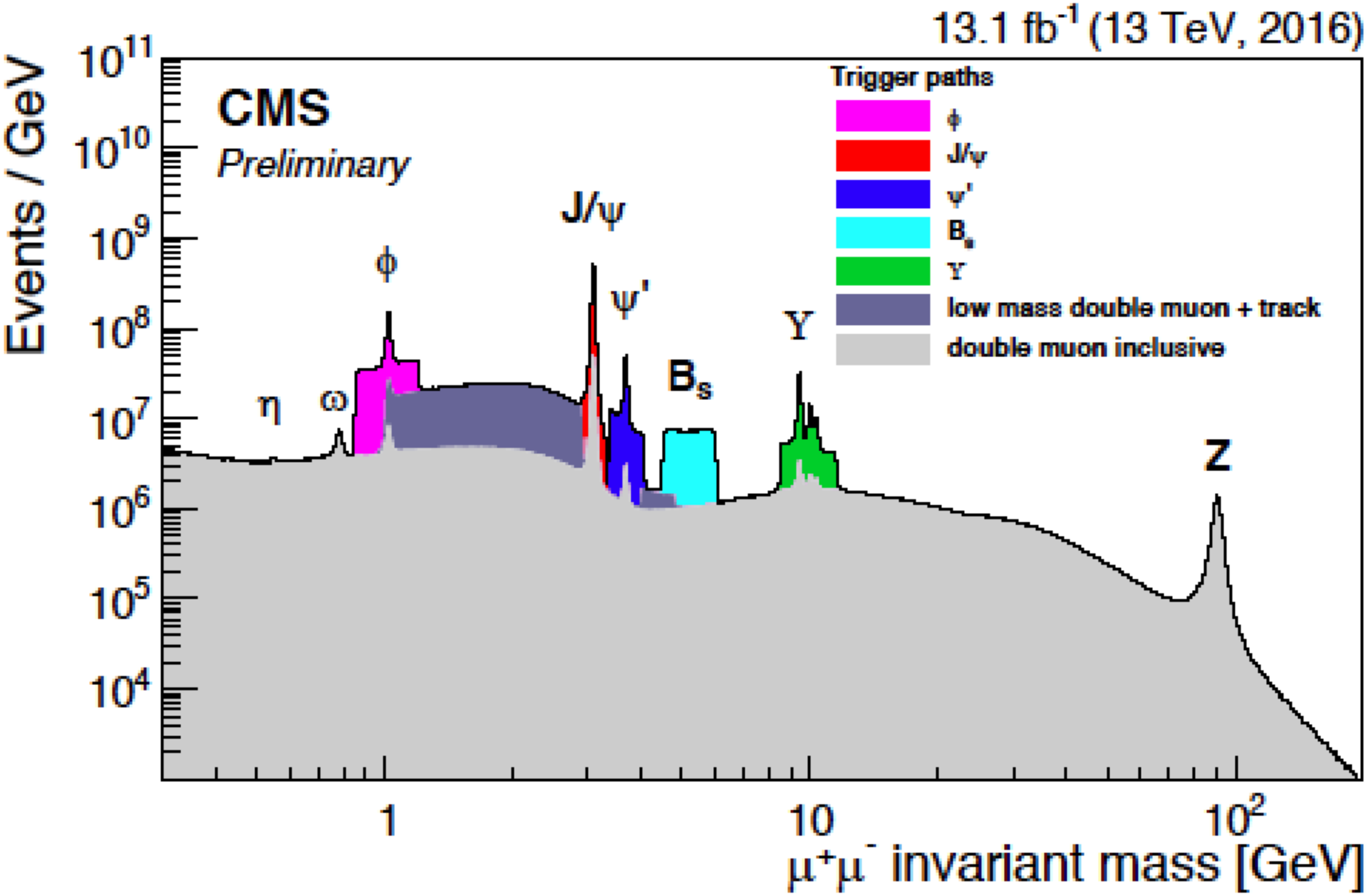


Di-muon events

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



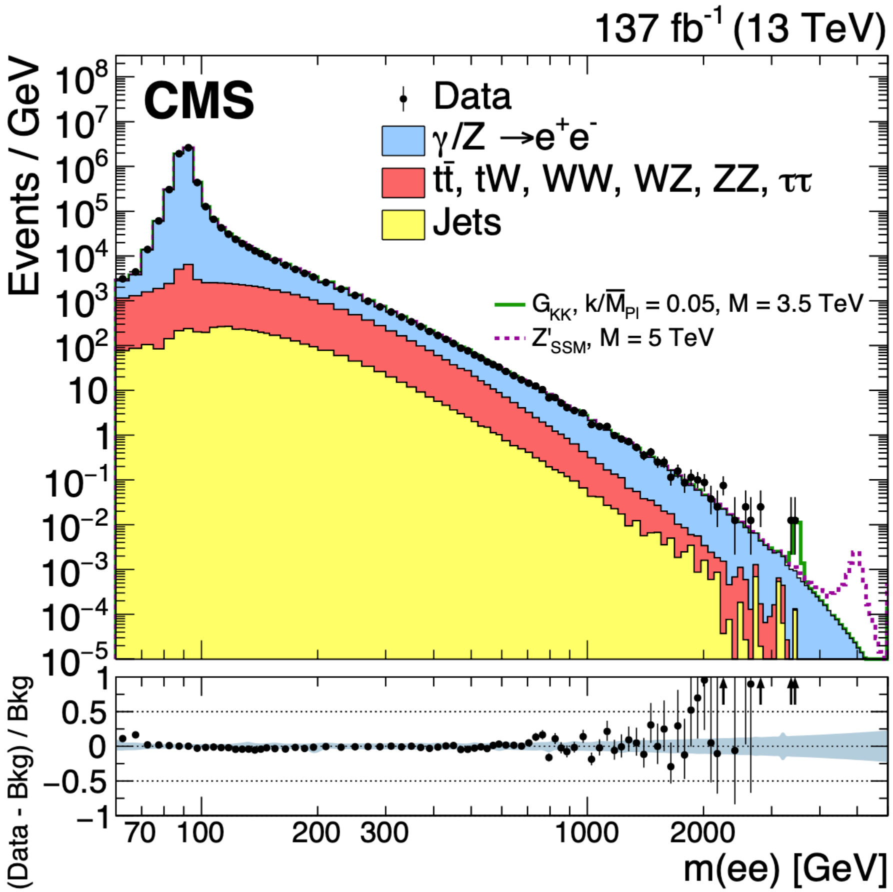


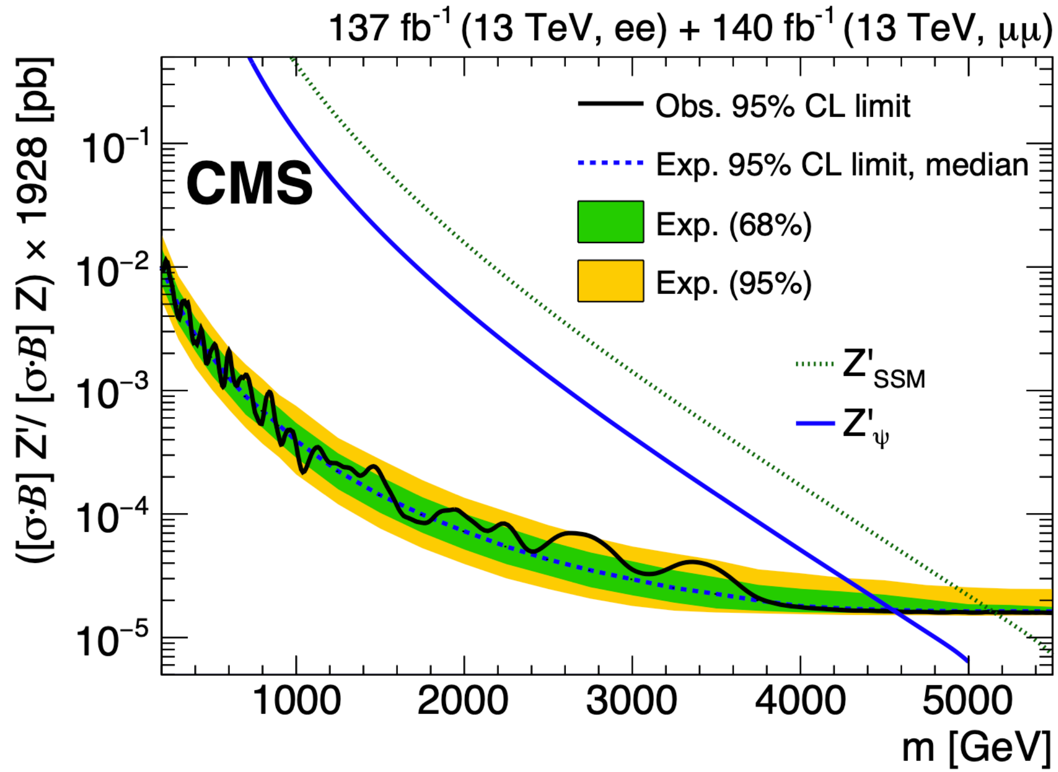


High-mass dilepton resonances

arXiv:1903:06248, arXiv:2103.02708

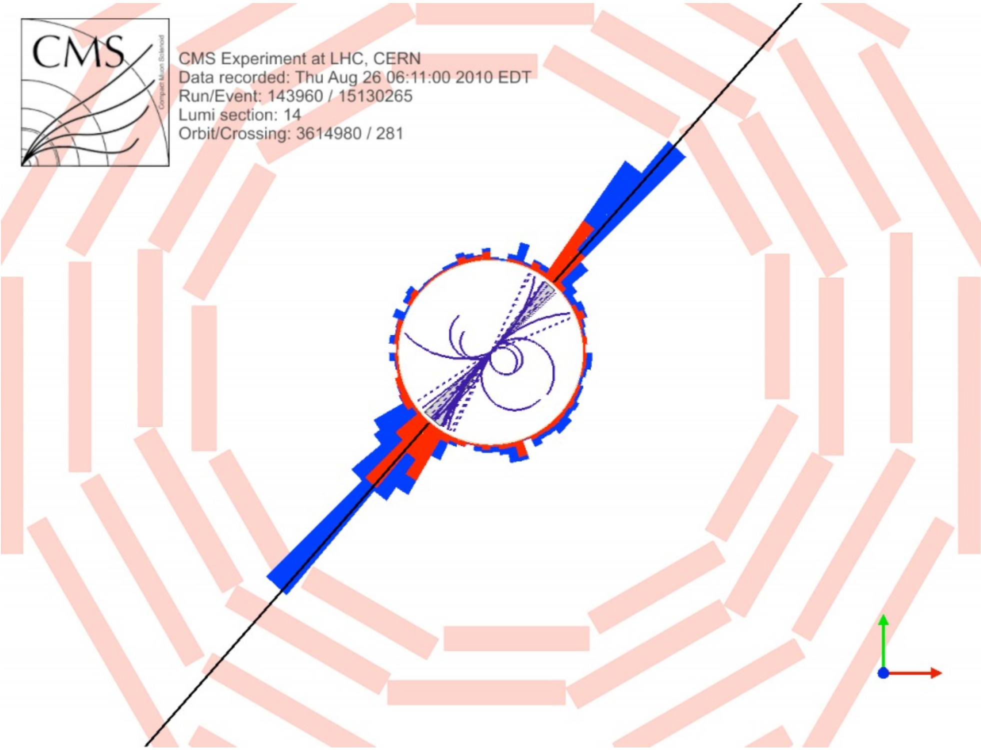
- Search for dilepton (ee,μμ) resonance





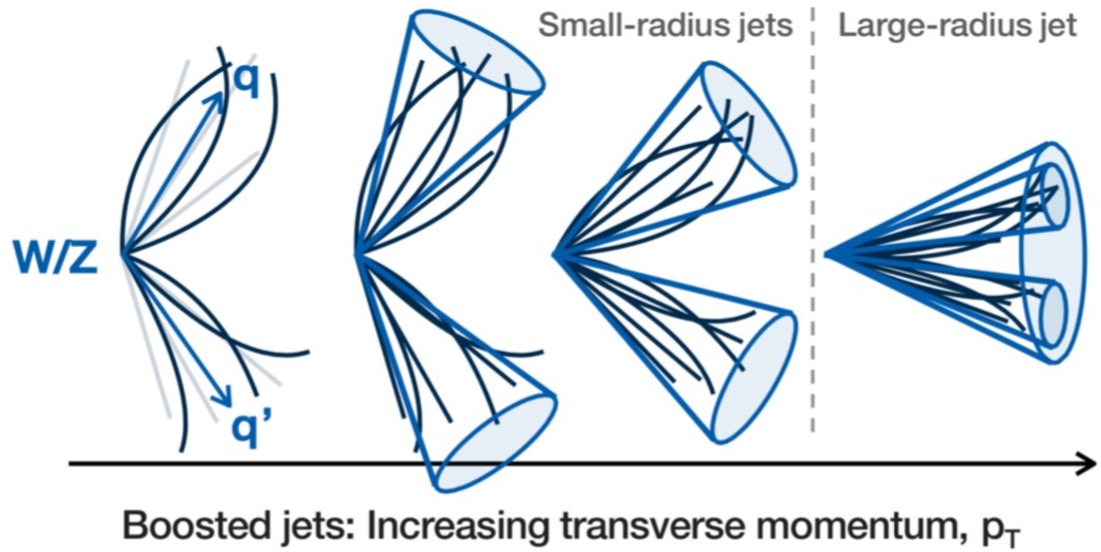
Search for diboson resonances

- 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

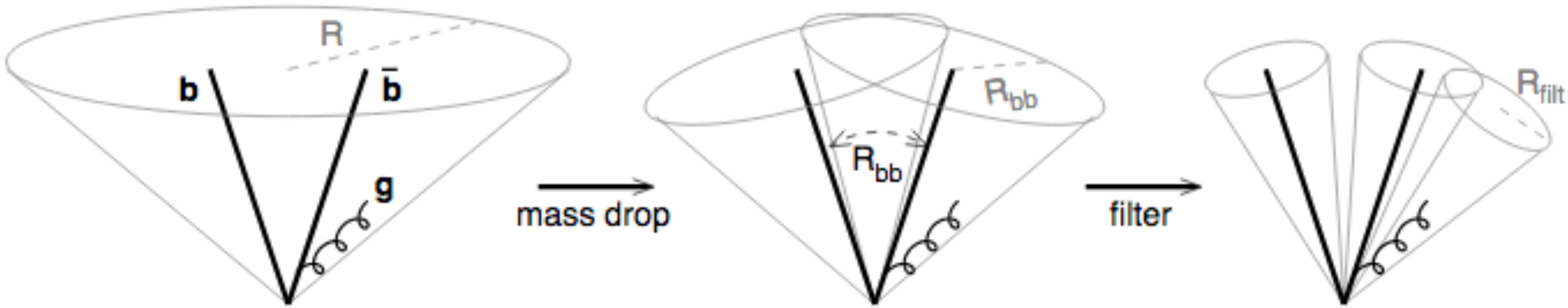
- Many potential final states are possible
  - WW/WZ, ZW/ZZ, VV
- Hadronic channels with high sensitivity in high mass region



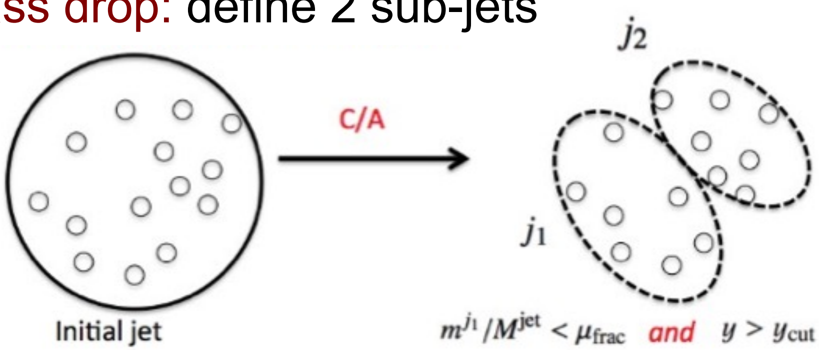
Jet grooming

Mass drop/filtering

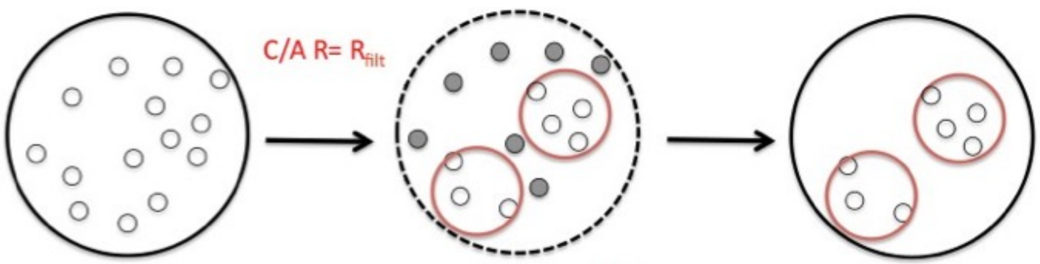
- Identify approx. symmetric sub-jets (with smaller mass than sum)



Mass drop: define 2 sub-jets



Filtering: re-cluster j1, j2 constituents

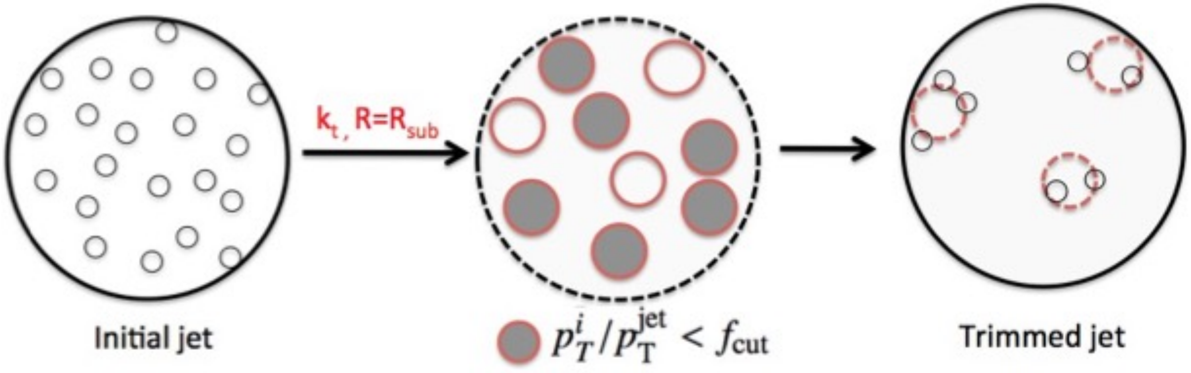


Jet grooming (cont.)

arXiv:0912.1342, arXiv:0912.0033

"Trimming"

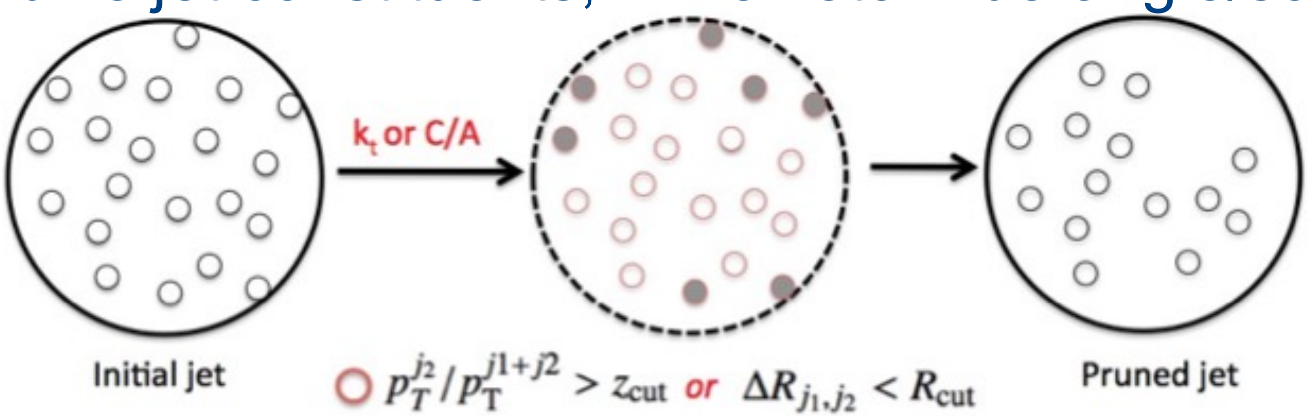
- Uses kT algorithm to make subjets (subjets with p_T^i/p_T<cut removed)



R_{sub}, f_{cut}

"Pruning"

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



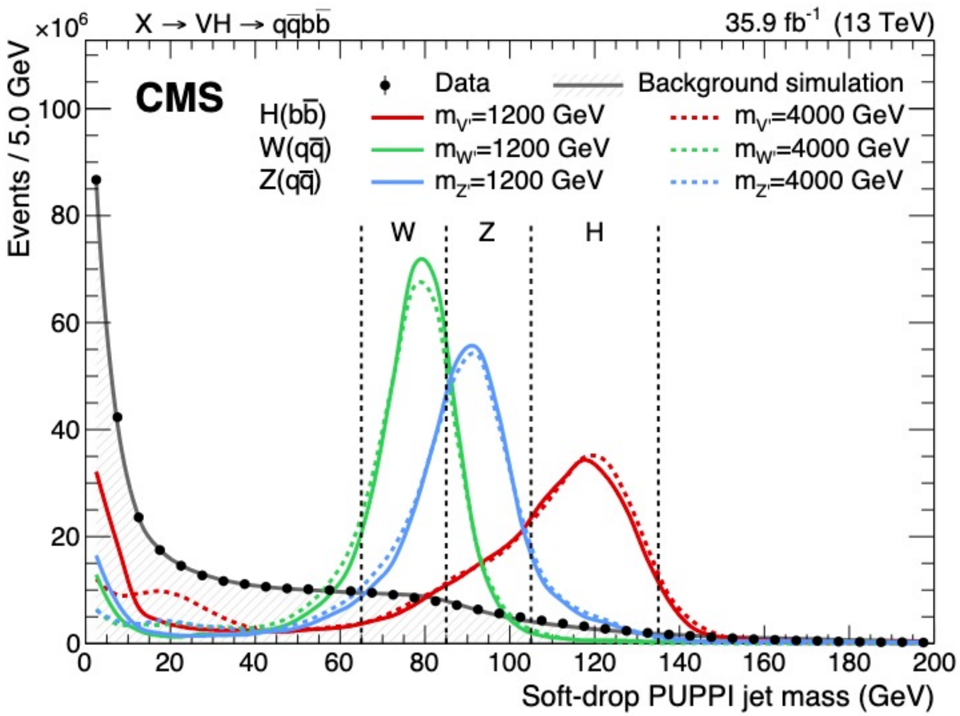
R_{cut}, z_{cut}

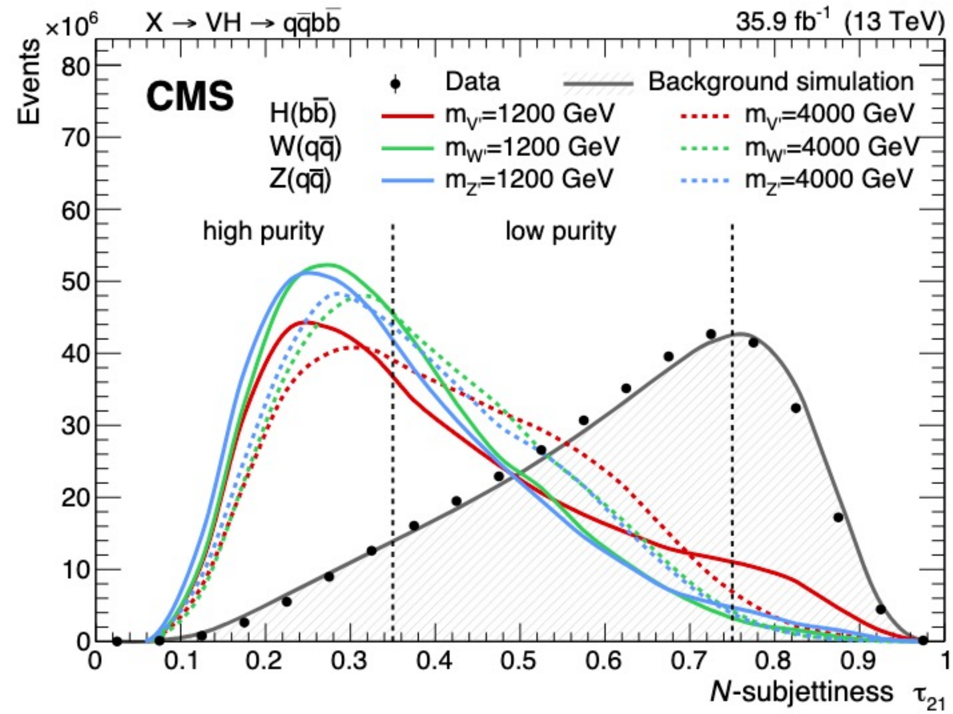
W, Z, H reconstruction

arXiv:1707.01303

- 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)

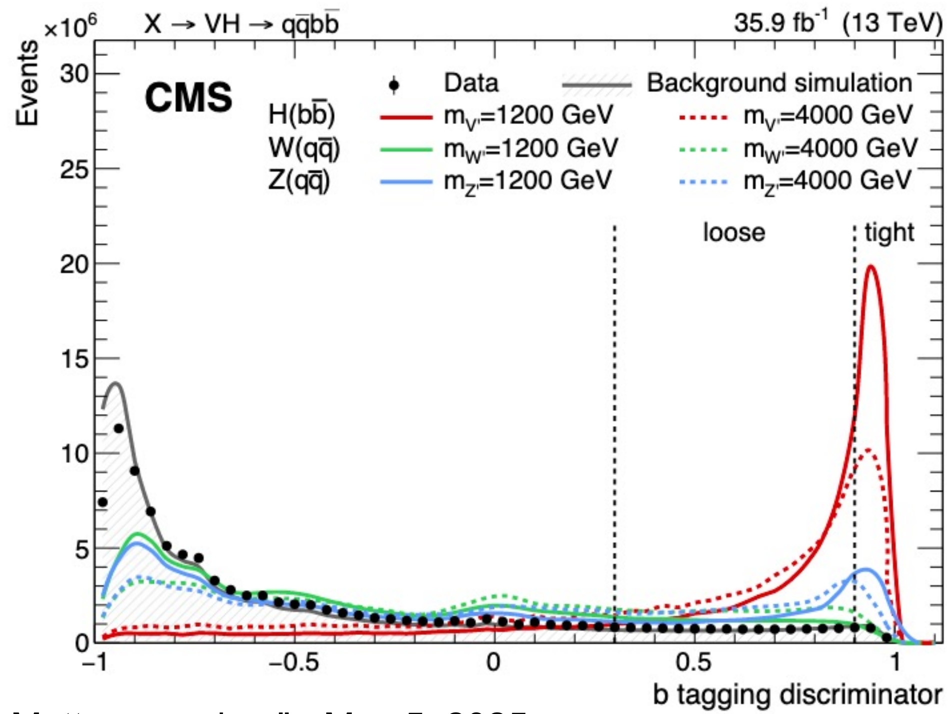




W, Z, H reconstruction (cont.)

arXiv:1707.01303

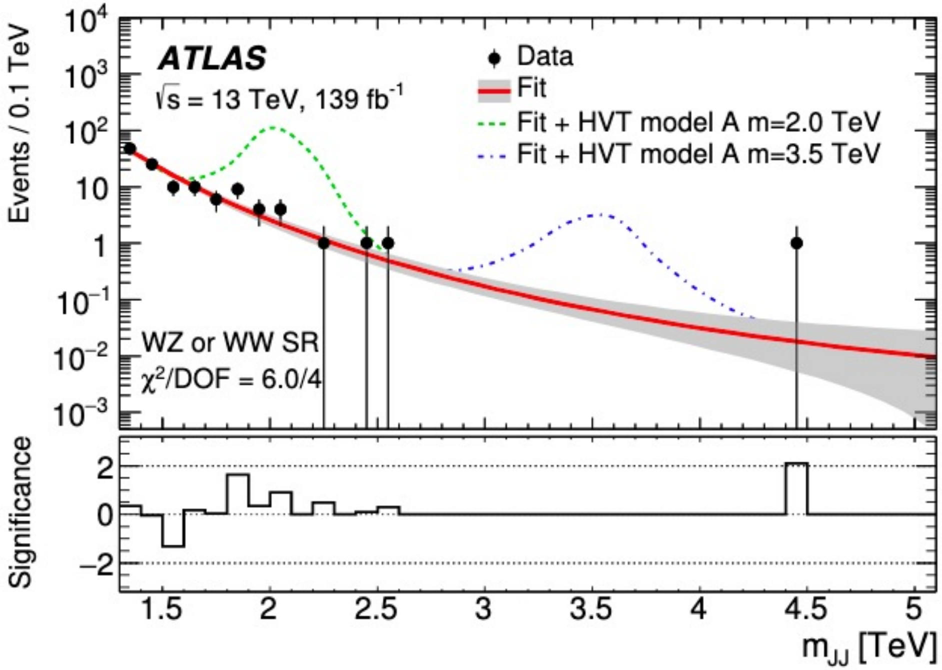
- Higgs boson tagging (H→bbar)
  - Double b-tagging
  - Exploit b-tagging to identify two b-quarks in same jet
  - Soft-lepton information
  - Combines tracking and vertexing in MVA

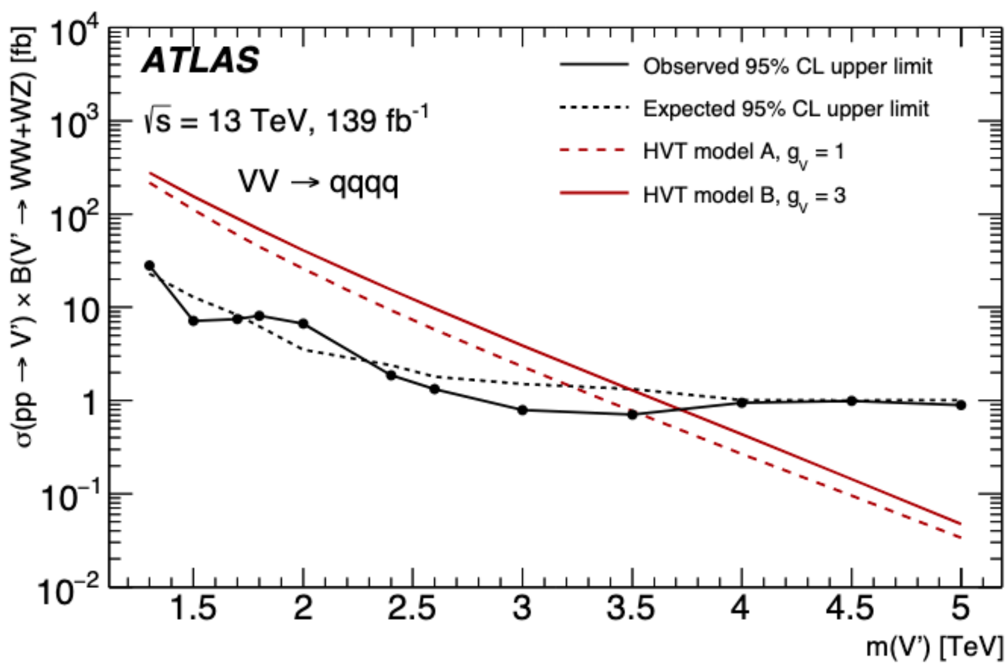


Searching for diboson resonances

arXiv:1906.08589

- 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

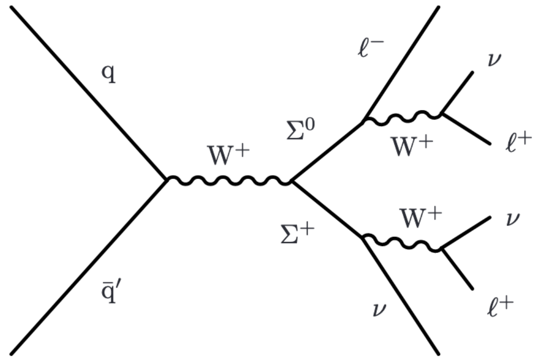


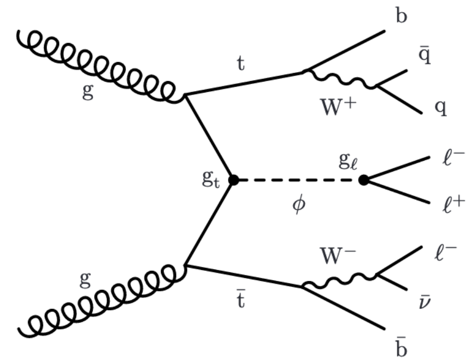


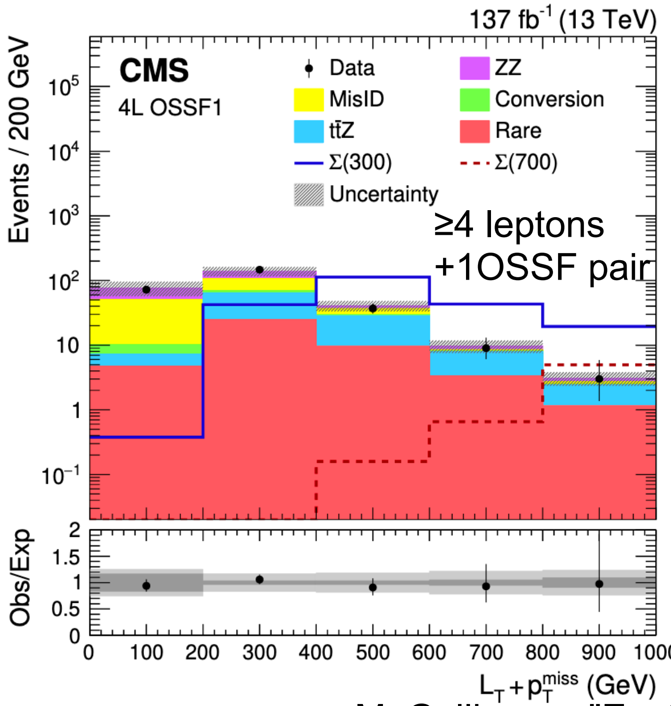
Search for multi-lepton final states

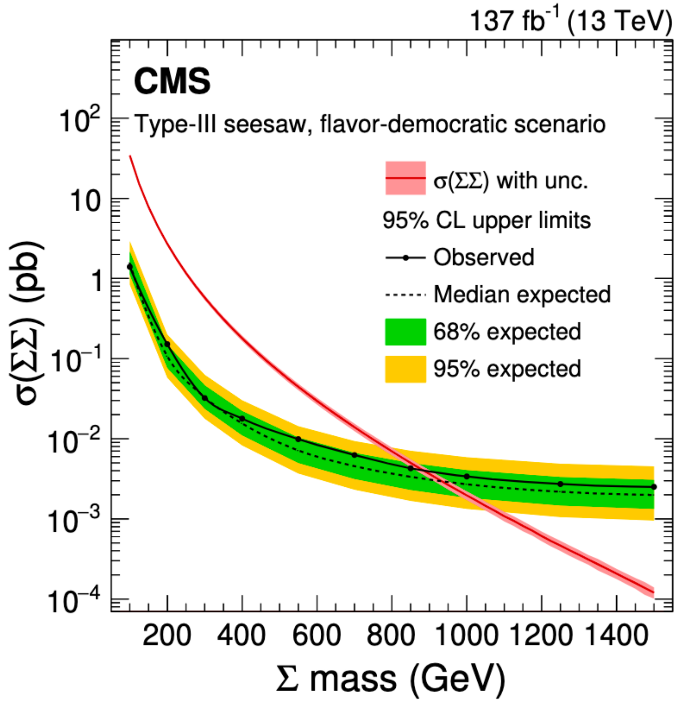
JHEP 03(2020)051

- Search for new heavy particles
  - Heavy fermions/scalars produced in association with ttbar
- 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)





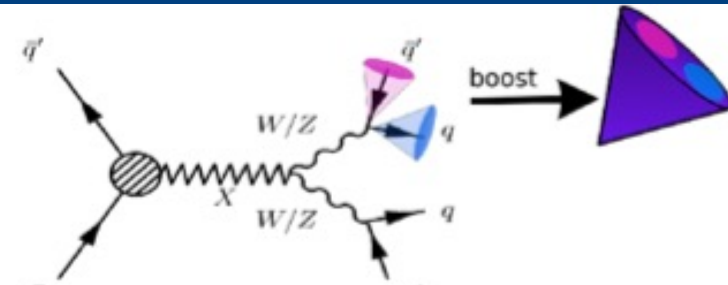


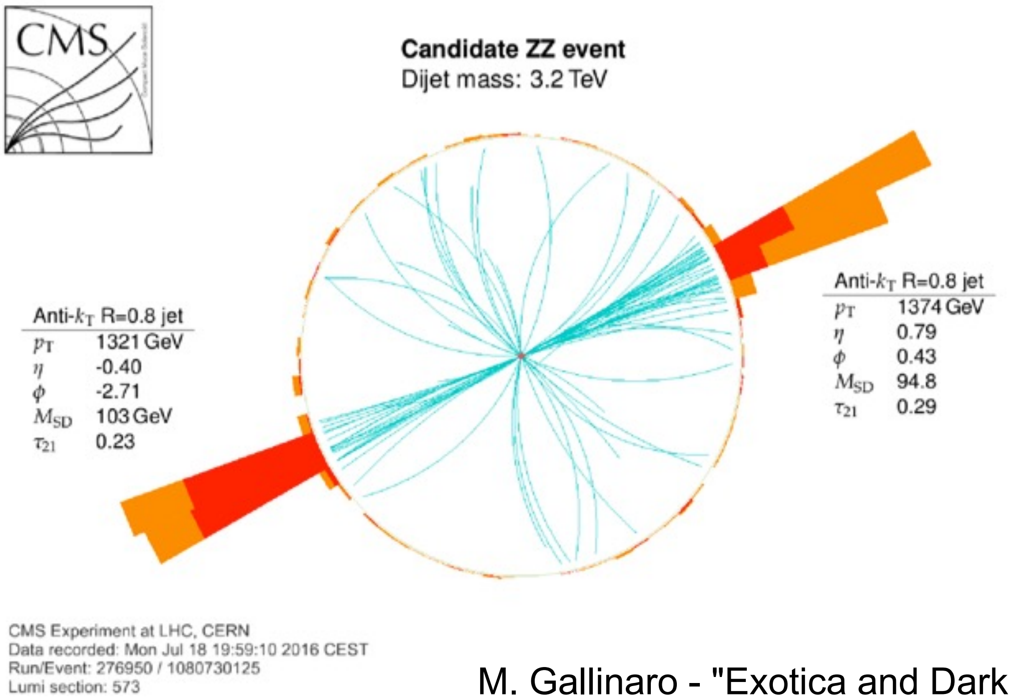


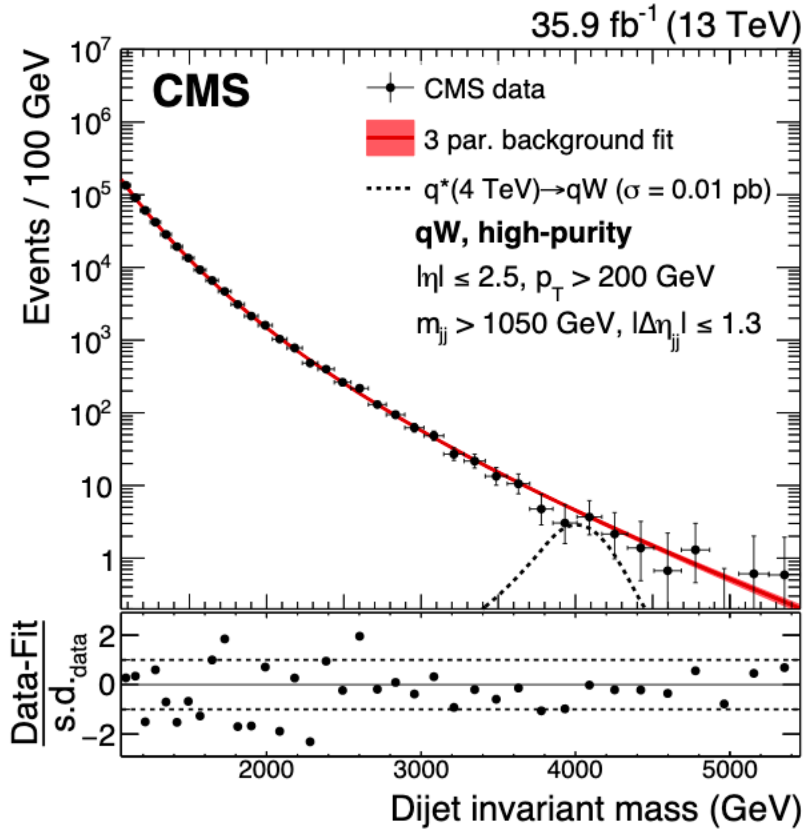
X→VV→qqqq

arXiv:1708:05379

- 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



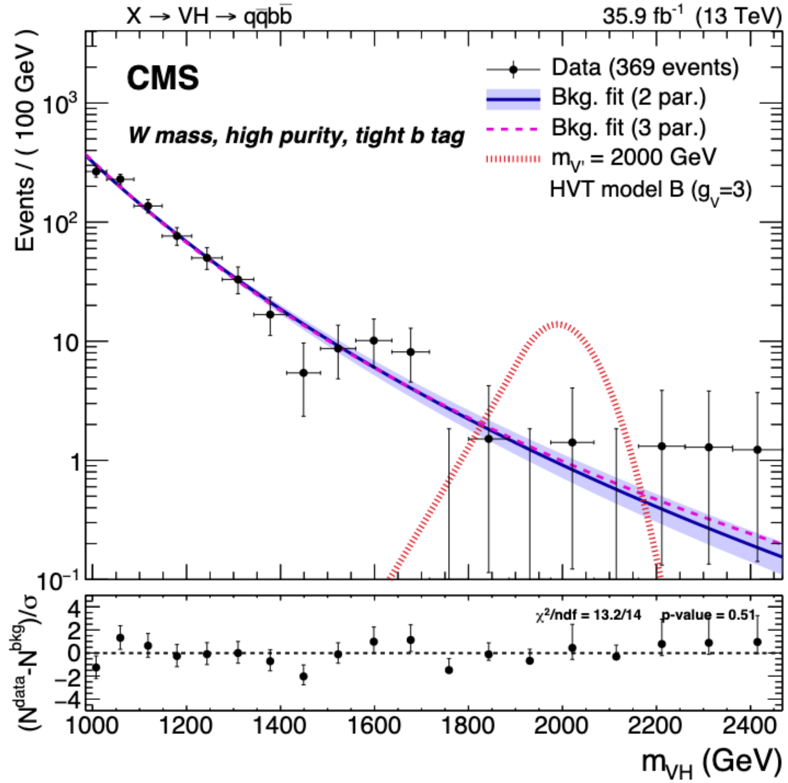


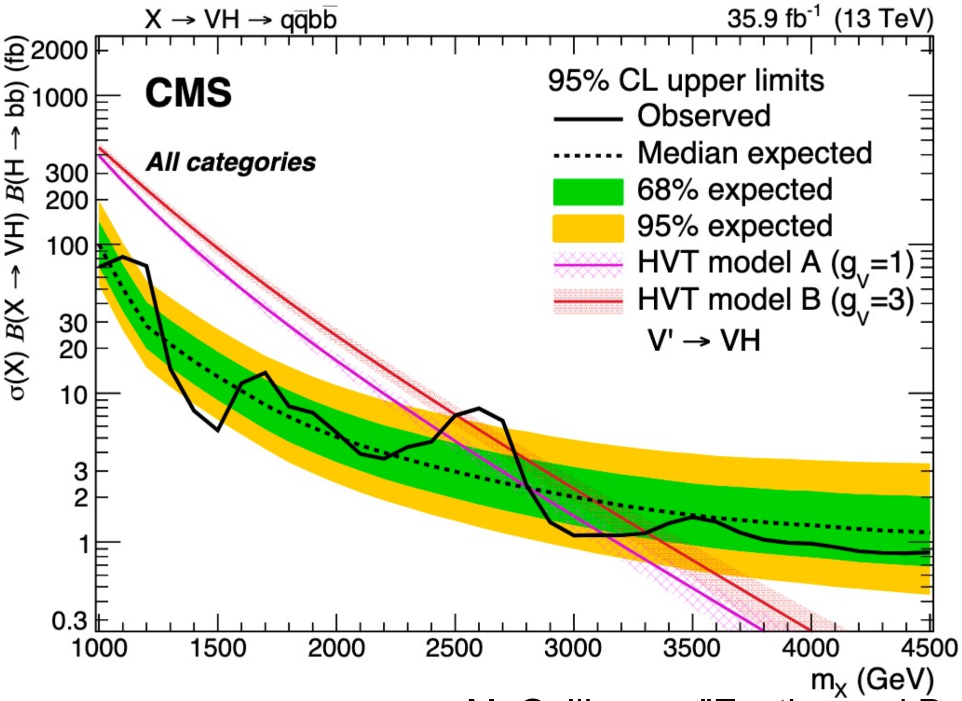


X→VH→qqbb

arXiv:1707.01303

- 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)



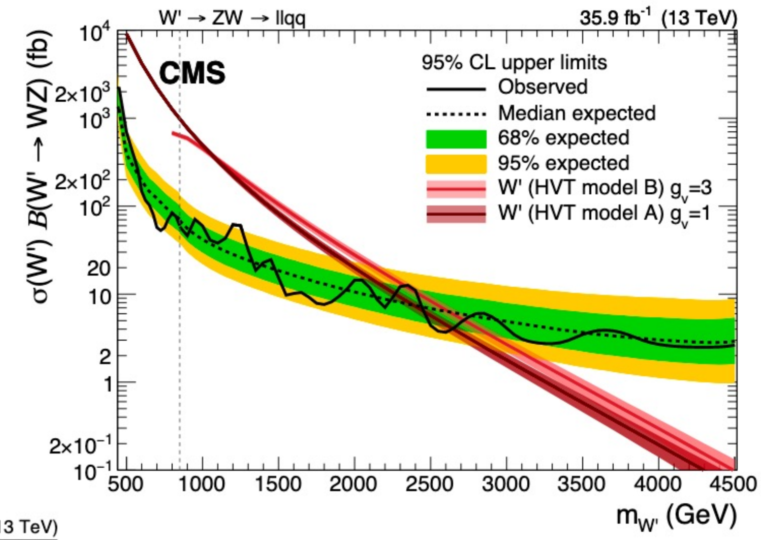


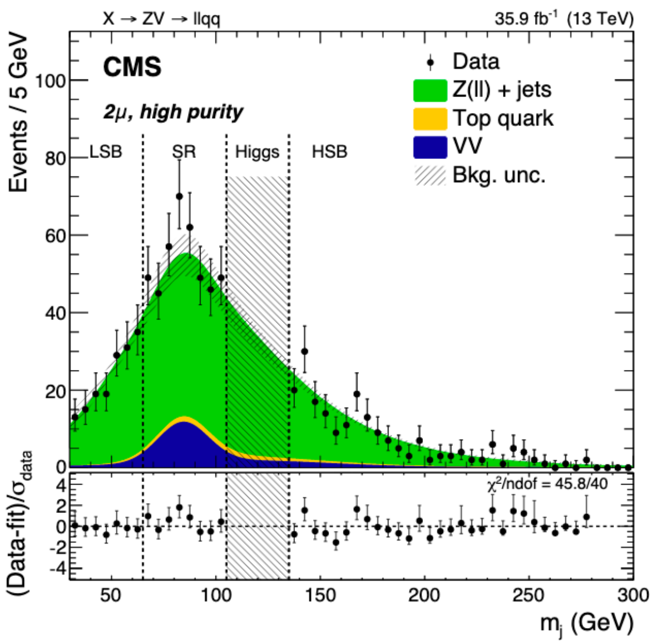
- Similar topology and background estimate to VV resonance search
- No significant excess found in data

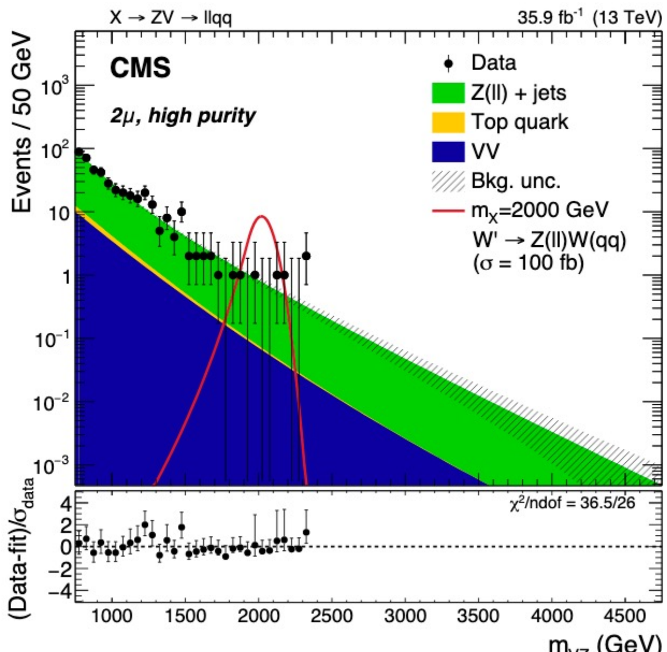
X→ZV→ℓℓqq

arXiv:1803.10093

- 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





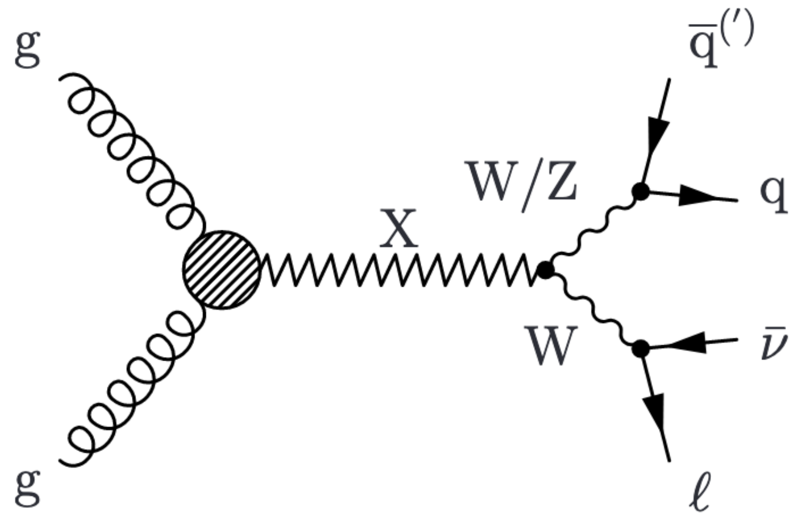


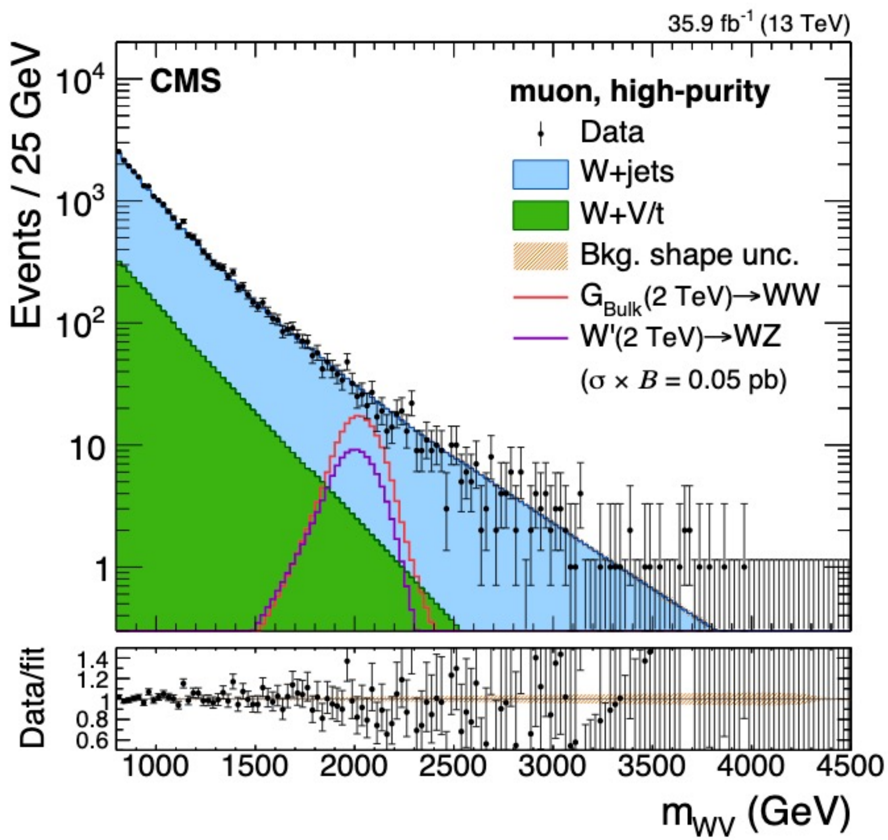
- Data compatible with SM-only hypothesis

X→WV→ℓνqq

arXiv:1802.09407, B2G-19-002

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





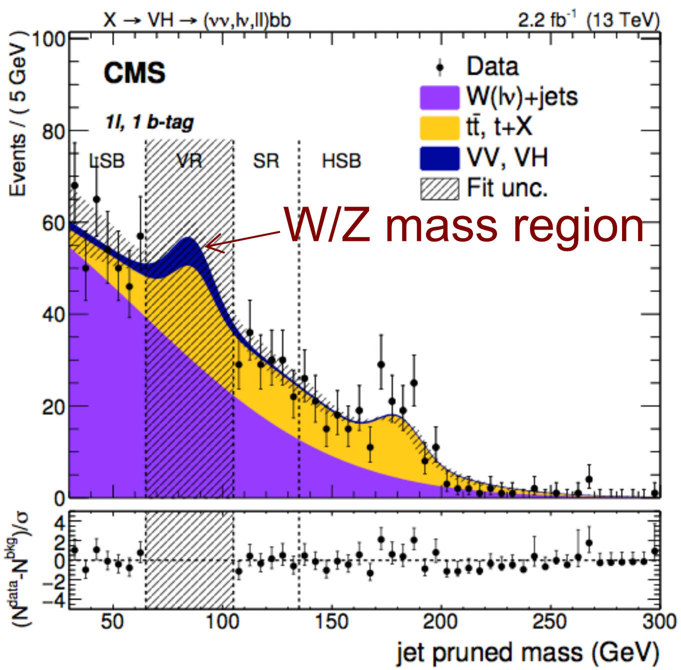
- Similar sensitivity to Z(ℓℓ)V(qq) search
- Excluded up to 1.1-3.1 TeV

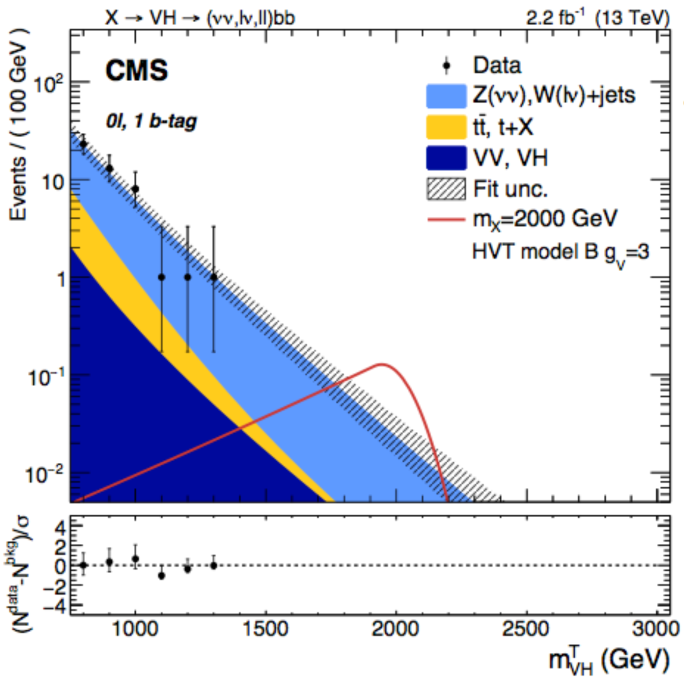
$X \to VH \to \ell\nu qq$

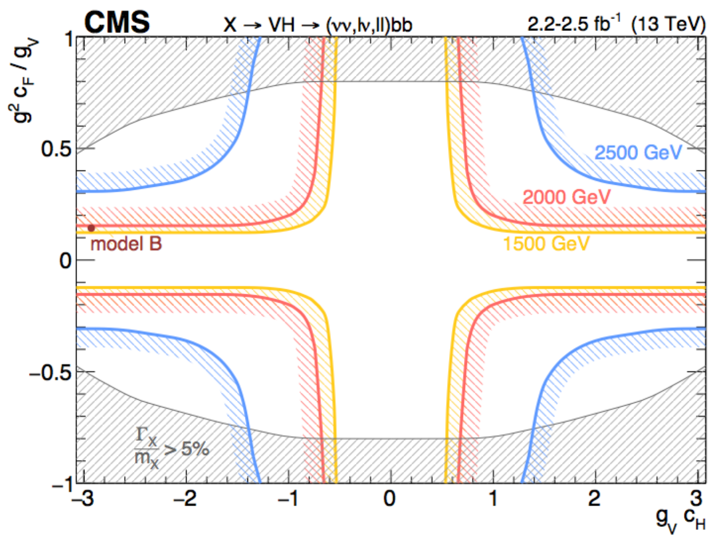
PLB 768(2017)137

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

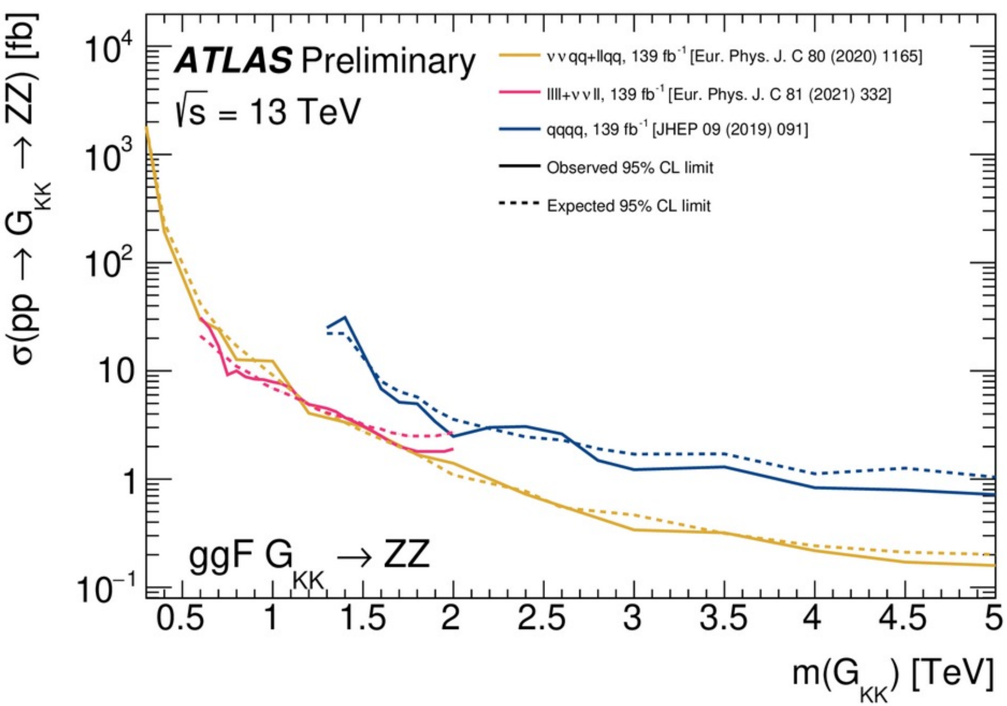
- Heavy vector triplet (Z', W')
- g_V, g_H (c_V, c_F): couplings

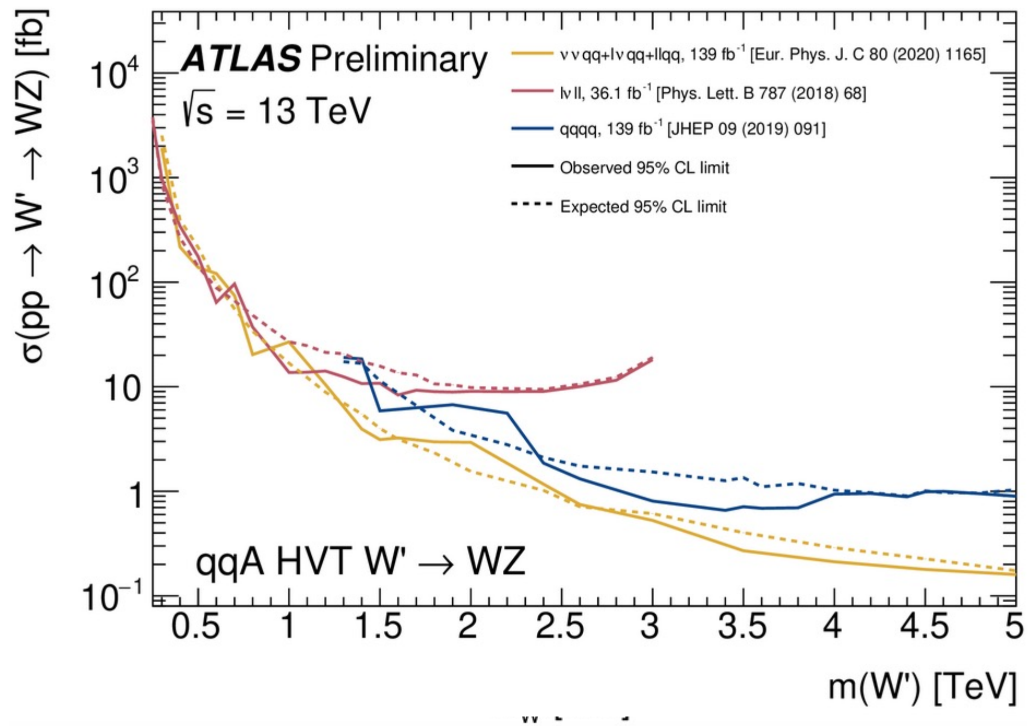






Combination of diboson searches

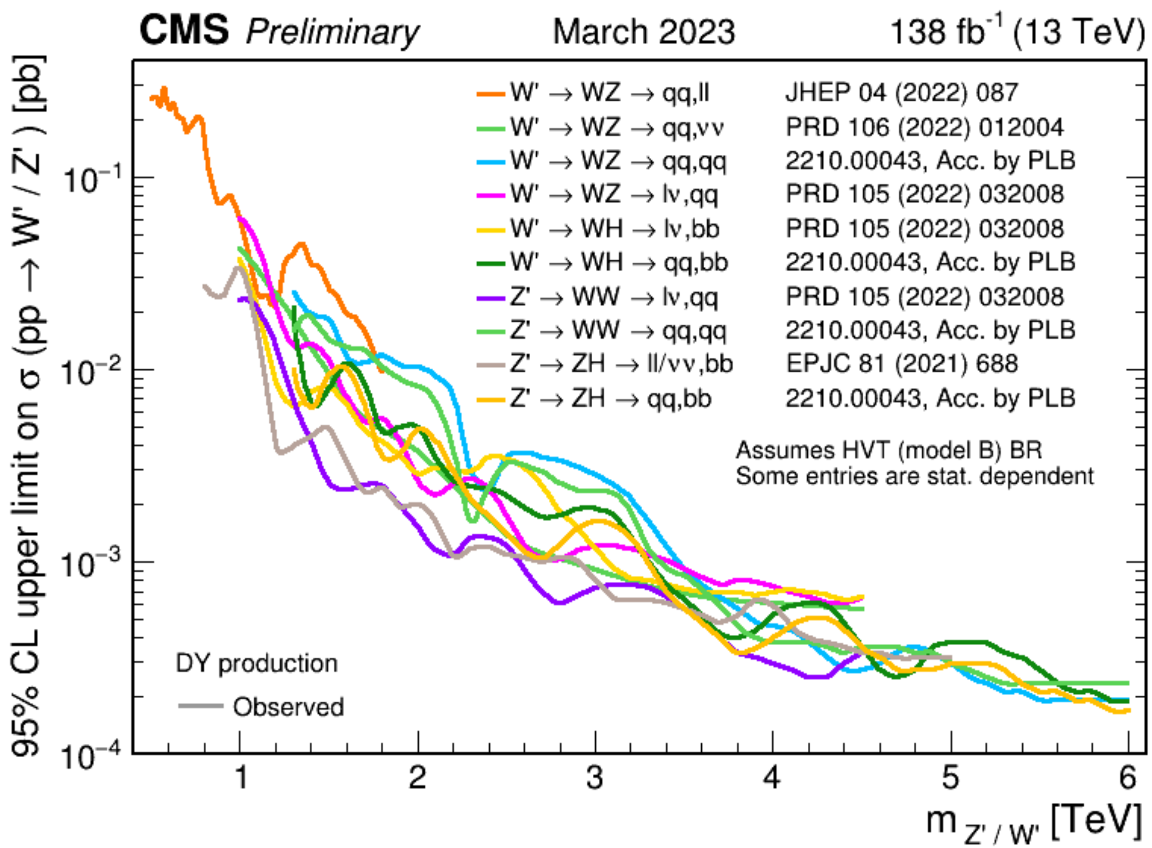




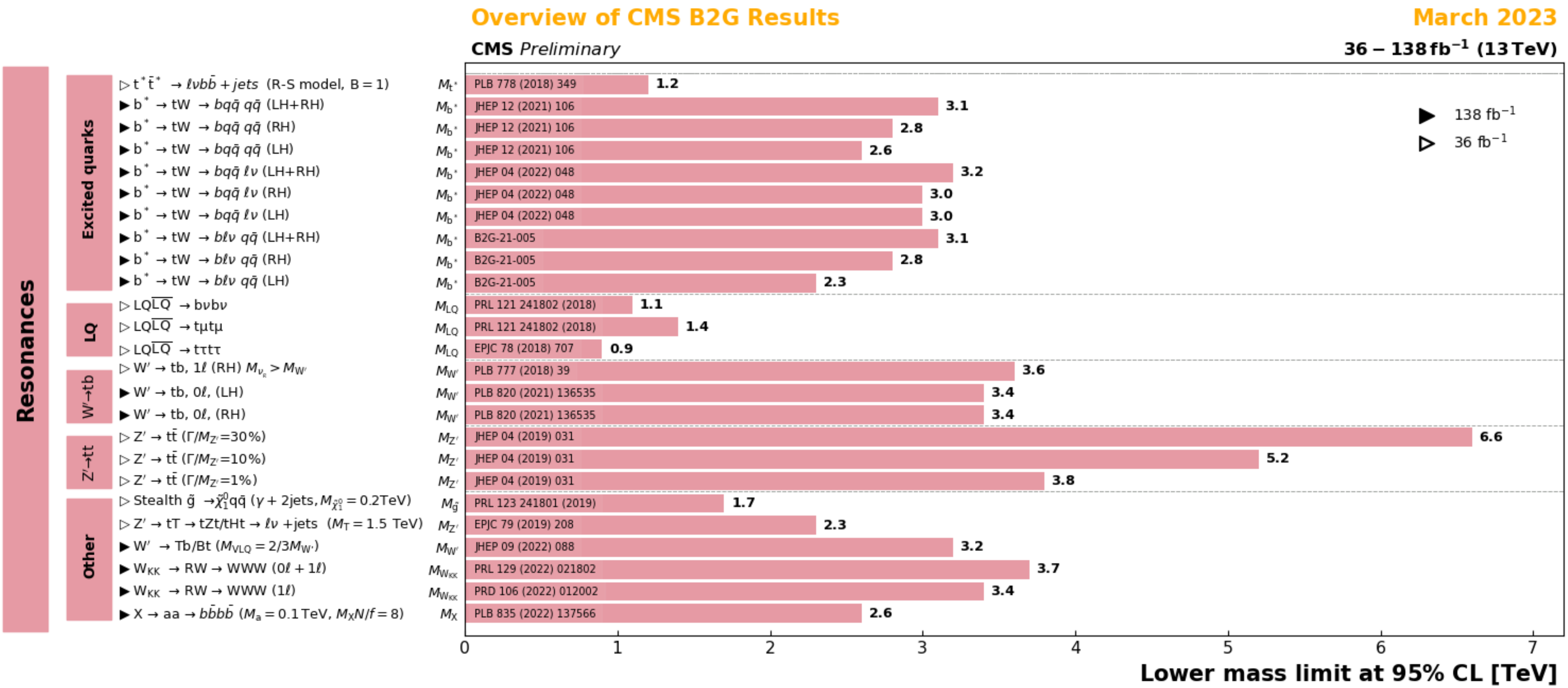
Combination of resonance searches

PLB 768(2019)134952

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



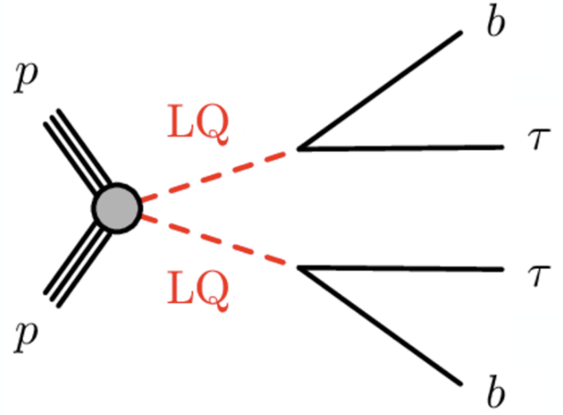
Resonance searches: Summary

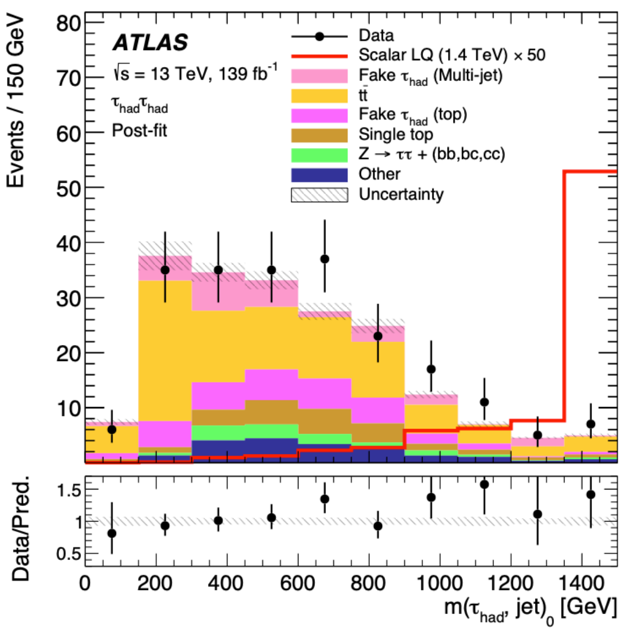


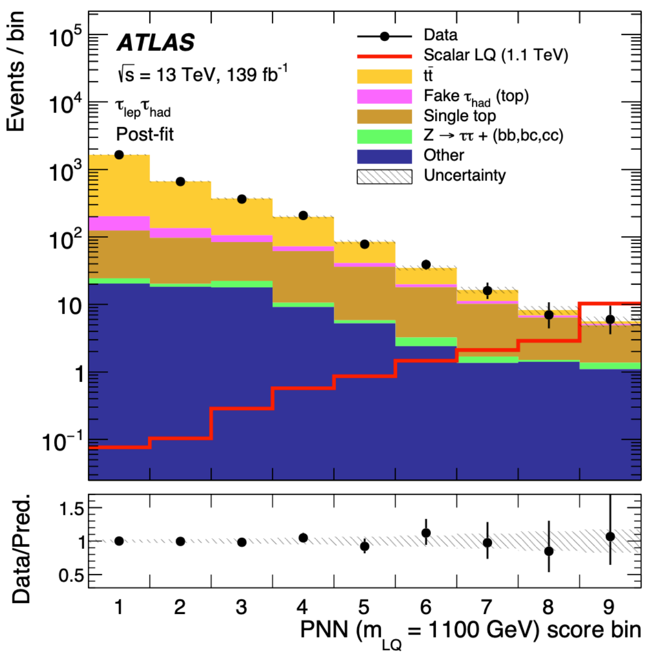
Leptoquarks

arXiv:2303.01294

- Pair production of leptoquarks
  - Study LQ⟶bτ final state
  - Can be interpreted in SUSY
- Main background from top quark pair events in different final states, determined from CRs
- Parametrized NN in terms of gen. LQ mass
- Signal: use M_{T2} (stransverse mass) and s_T (scalar sum of τ and jet p_T) variables



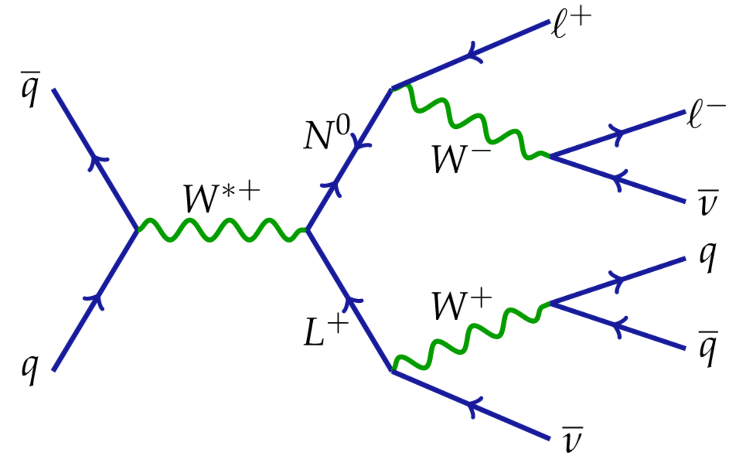


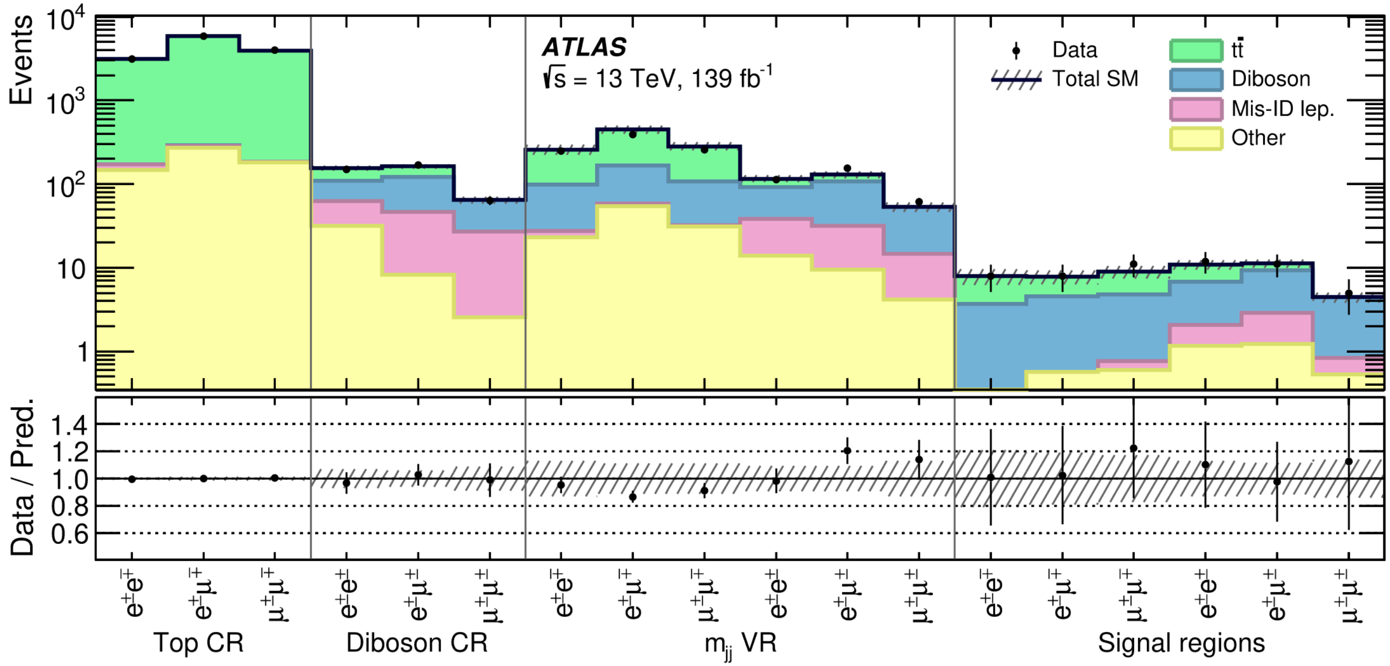


Heavy lepton resonances

EPJC 81(2021)218, arXiv:2202.02039

- Two resonances in one process: W→NL
- Off-shell W decays to two new particles
- Signal selection:
  - OS and SS lepton pairs possible
  - two jets and MET
- Backgrounds from simulations and data CRs

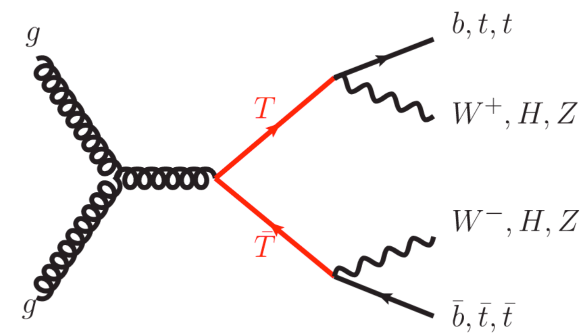




Vector-like quarks

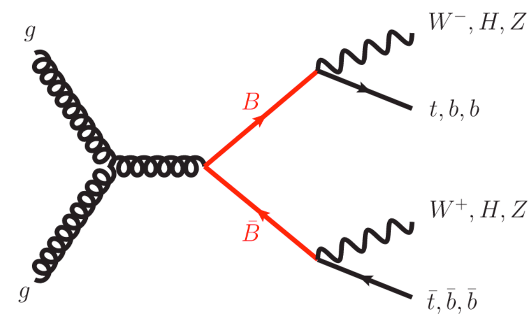
Motivation

- 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 3rd family, b and t



Properties

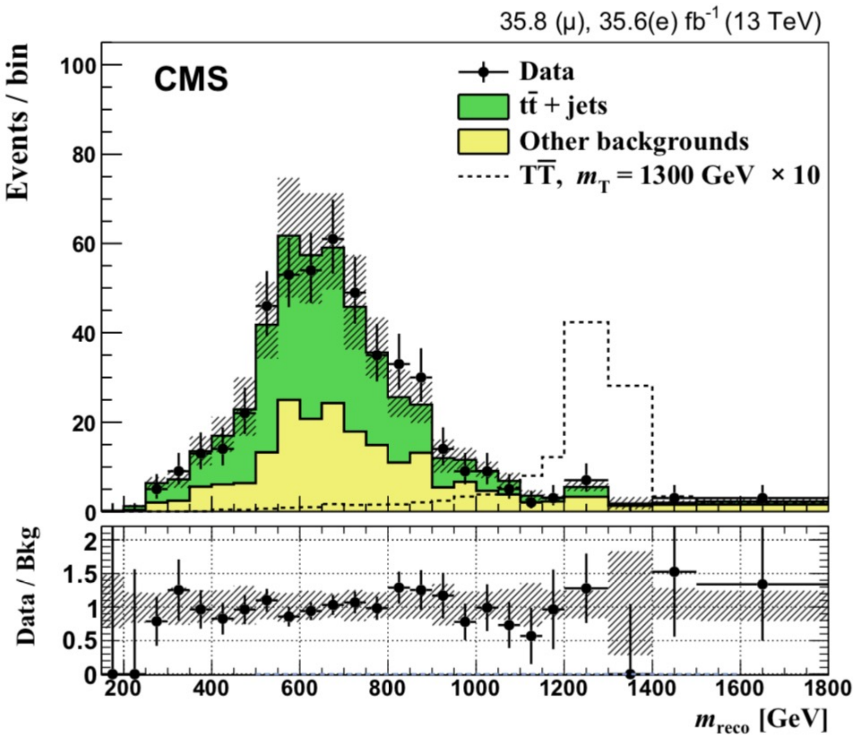
- Produced via strong and EWK interactions
- Mainly pair-produced
- Both CC and NC decay modes

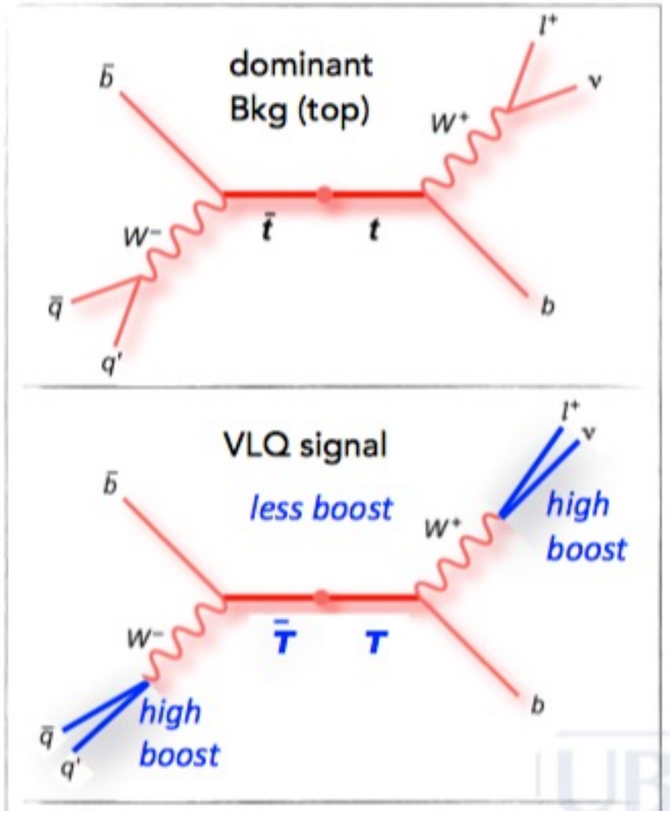


VLQ searches

PLB 779(2018)82

- VLQs usually decay via mixing with SM quarks of 3rd generation
- Search for VLQ pair production decaying to WbWb
- Search in the boosted regime
- Can reconstruct the VLQ system

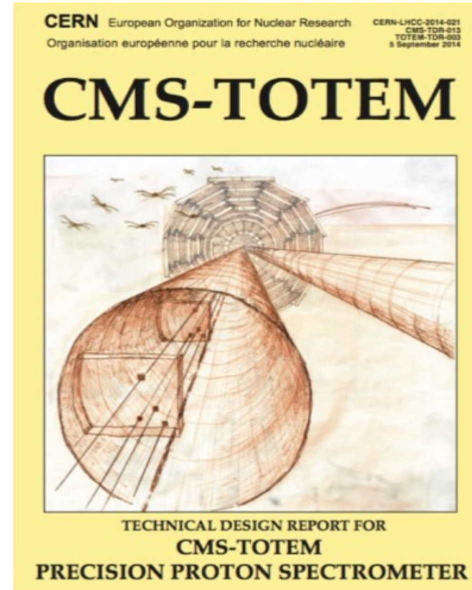




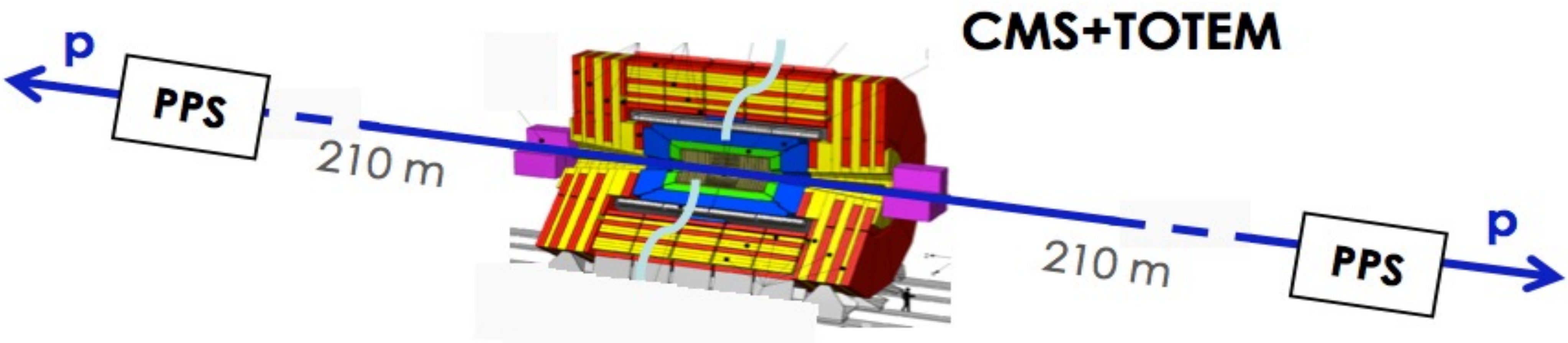
Looking forward: PPS

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)

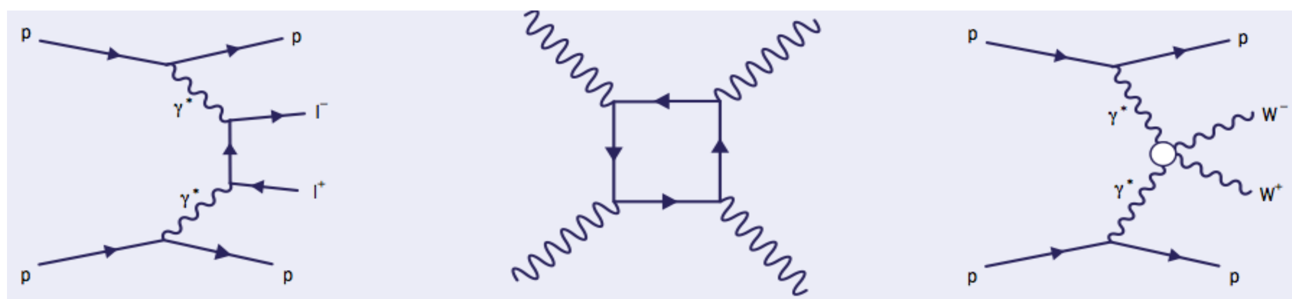


CERN-LHC-2014-021



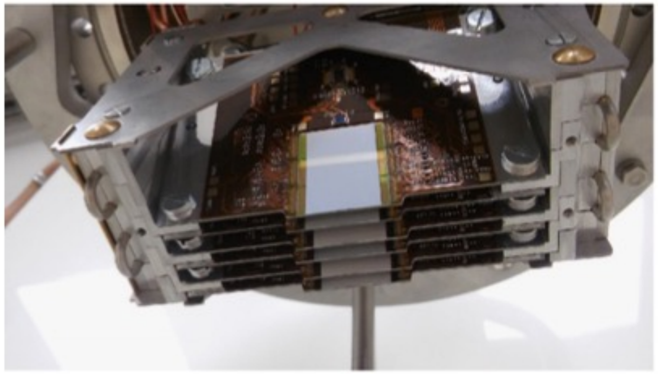
PPS physics motivations

- 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

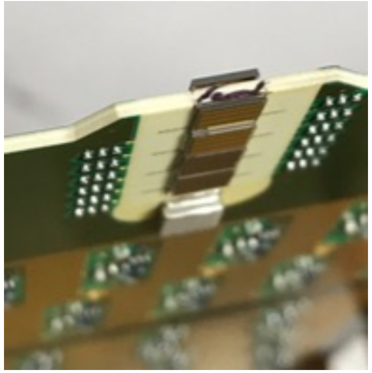


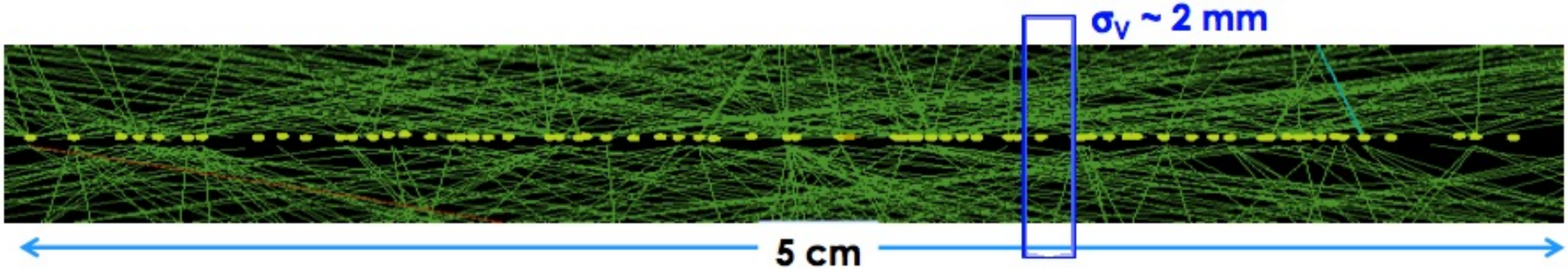
Detectors

- Tracking detectors
  - Goal: measure proton momentum
  - Technology: silicon 3D pixels (6 planes per pot)



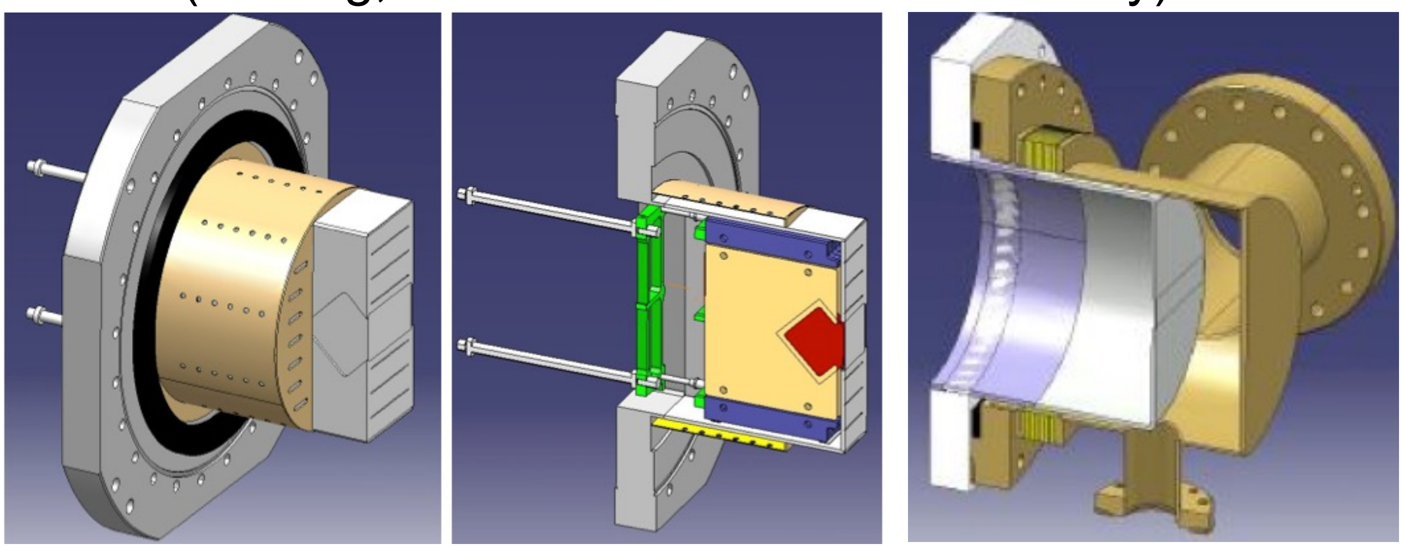
- Timing detectors
  - Goal: identify primary vertex, reject “pileup”
  - σ_{time}~10ps ⇒ σ_z~2mm
  - Technology: silicon/diamond

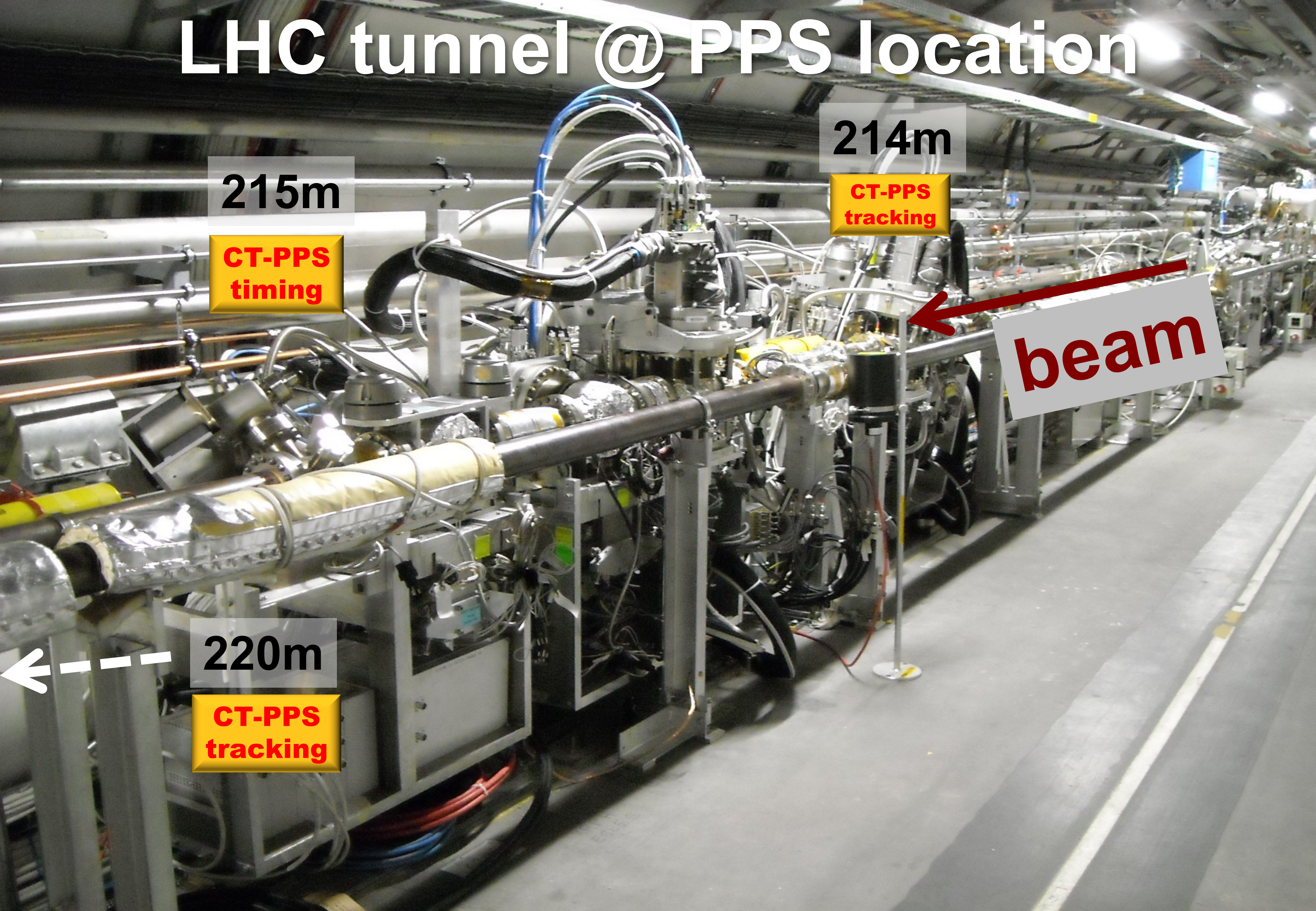




Roman Pot insertion

- Insertion procedure validated in 2016 by the LHC
  - Improvements carried out wrt earlier versions (RF shielding, cylindrical pots, ferrite, copper coating)
- Minimum distance of approach dramatically affects detector acceptance and physics reach
- A few mm (~15σ) from beam in nominal high-luminosity runs
  - Monitor beam losses, showers, interplay with collimators, beam impedance (heating, vacuum and beam orbit stability)

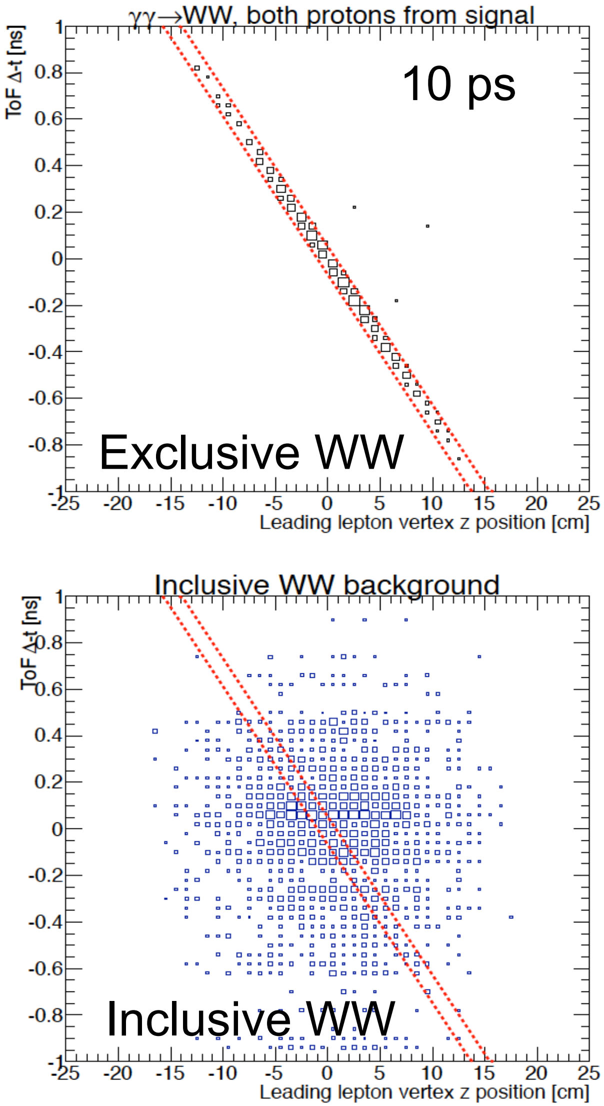



LHC tunnel @ PPS location
215m
CT-PPS timing
214m
CT-PPS tracking
beam
220m
CT-PPS tracking

Timing detectors

Use timing to reject pileup background

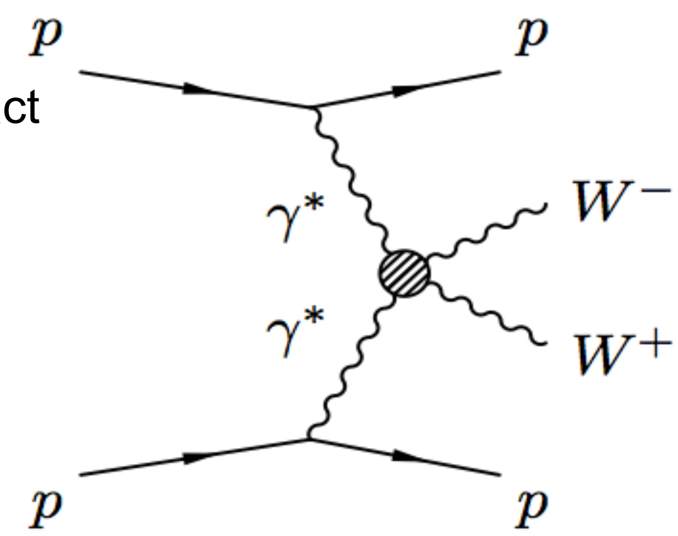
- Two scenarios studied:
  - 10ps and 30ps time resolution
- Baseline: solid state detectors
- Detector options investigated:
  - Diamond sensors
  - Fast silicon sensors (UFSD, HFS)
- Status:
  - Diamond and LGAD detectors installed



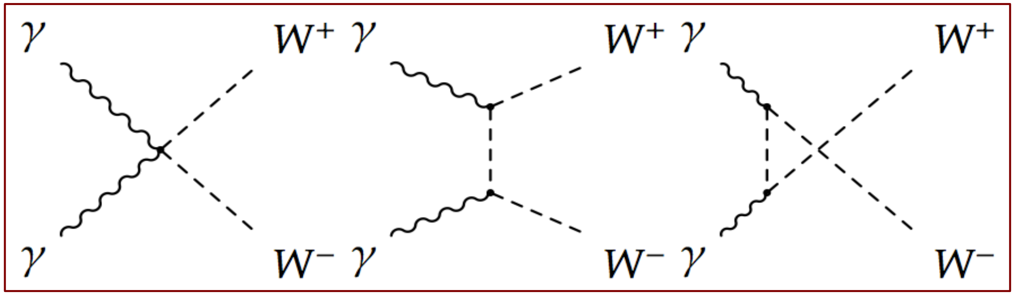
WW production

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



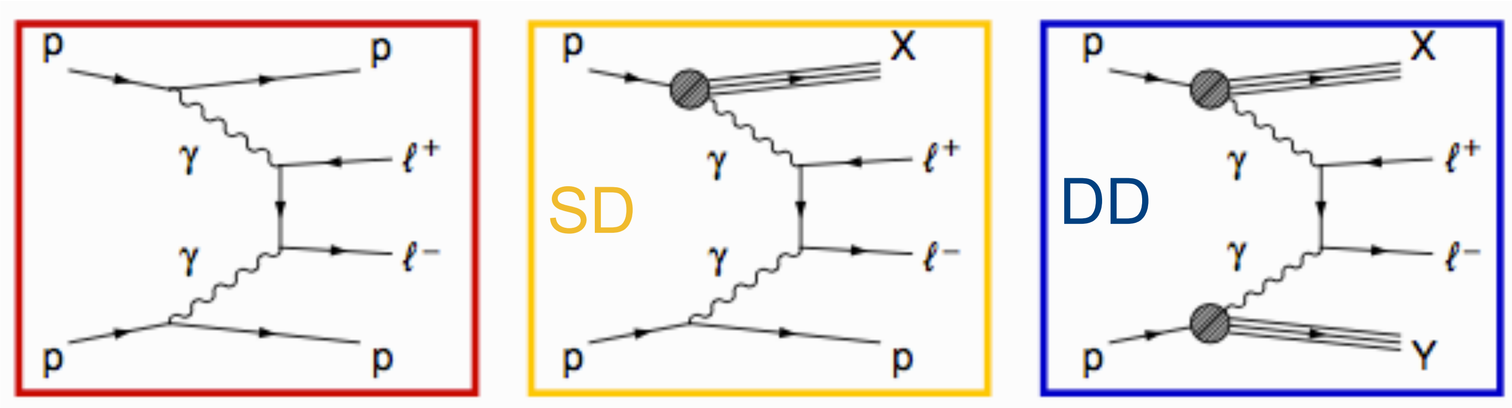
- Backgrounds:
  - inclusive WW, ττ, exclusive two-photon γγ→ll, etc.
- Events:
  - WW pair in central detector, leading protons in PPS
- SM observation of WW events
- Anomalous coupling study
  - AQGCs predicted in BSM theories
  - parameters: a_0^W/Λ^2, a_c^W/Λ^2
- Deviations from SM can be large



Exclusive Dileptons

JHEP 07(2018)153

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



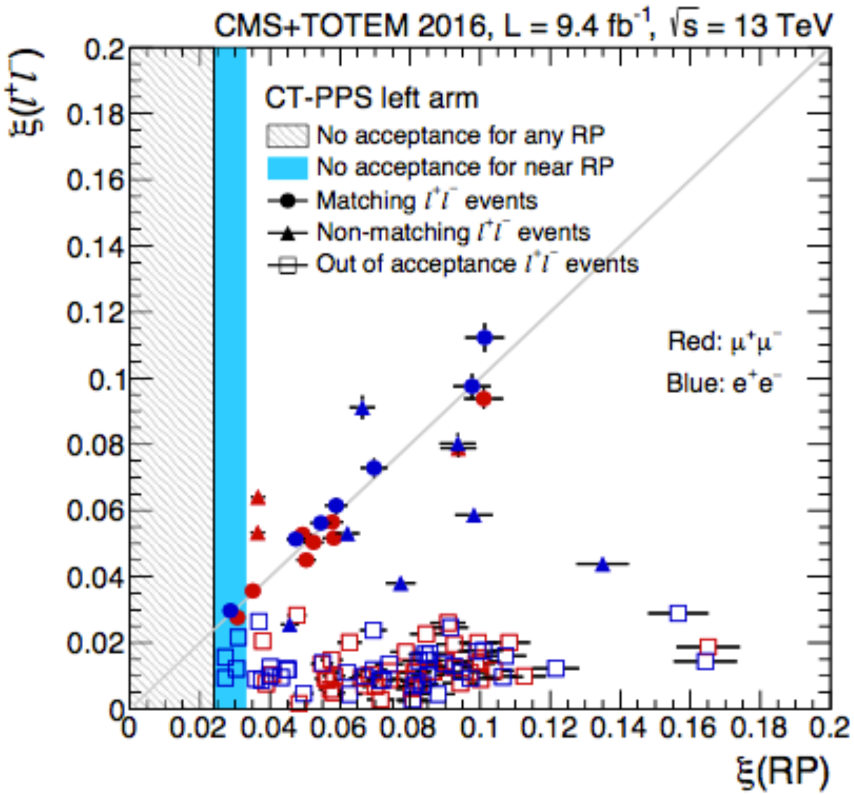
signal Background: SD, DD, DY, dibosons, PU

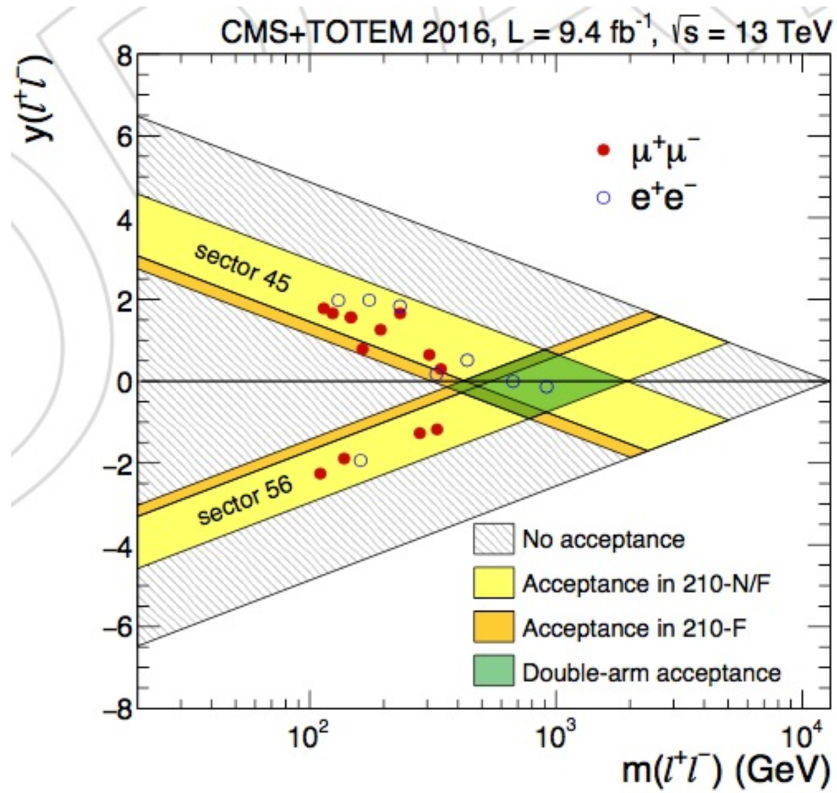
- Signal selected with:
- at least one proton tagged, muons, kinematic selection

Exclusive Dileptons (cont.)

JHEP 07(2018)153

- 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



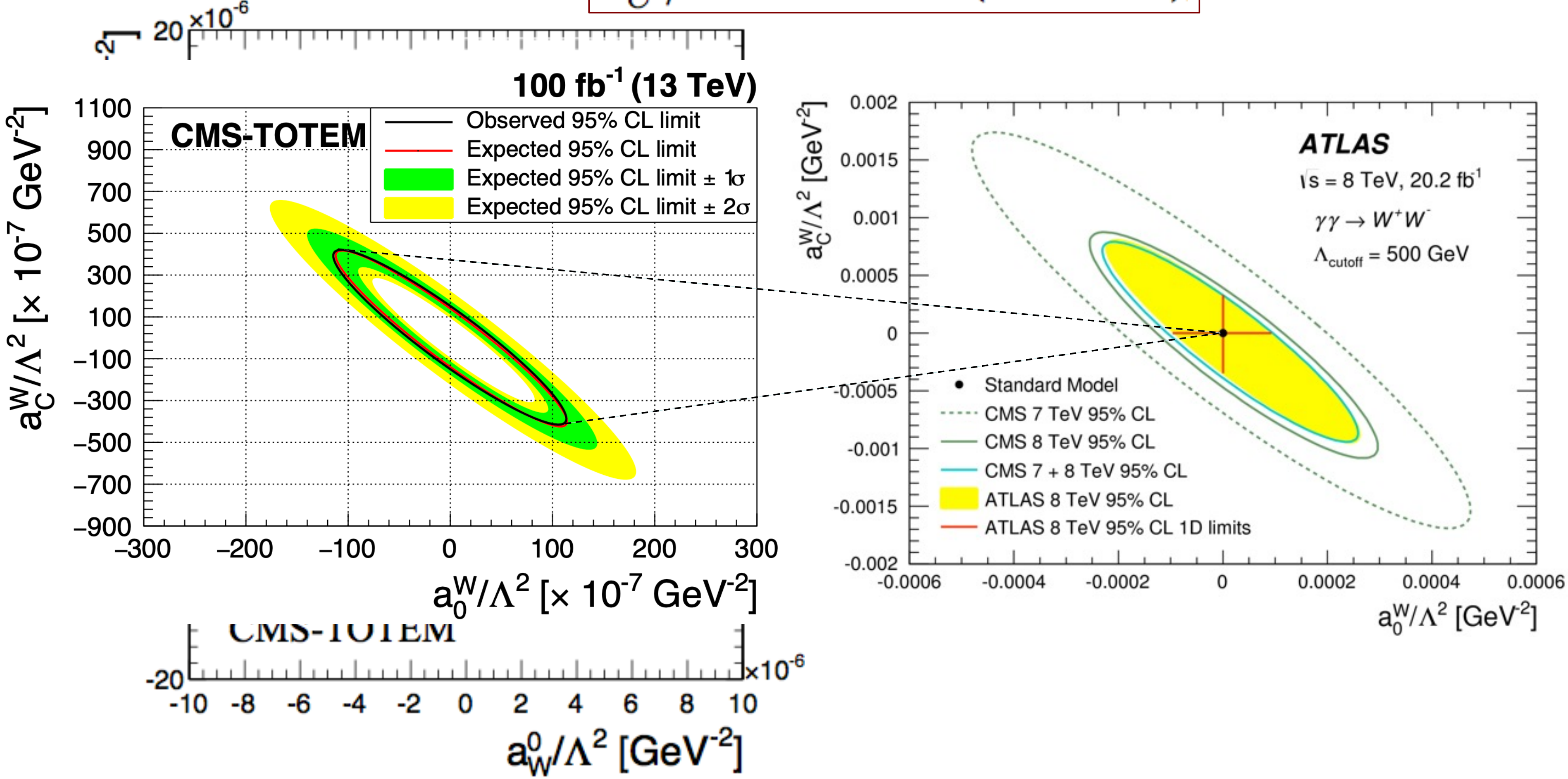


AQGC expected limits

arXiv:1607.03745

Expected limits @95%CL:

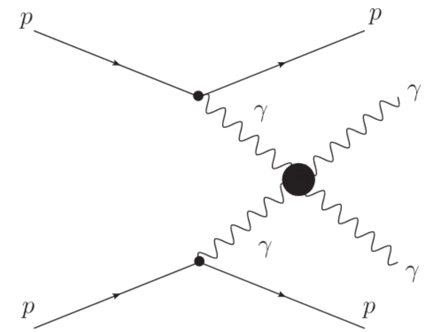
$$a_0^W/\Lambda^2 = 2 \times 10^{-6}\ (3 \times 10^{-6}),$$
$$a_C^W/\Lambda^2 = 7 \times 10^{-6}\ (10 \times 10^{-6}),$$

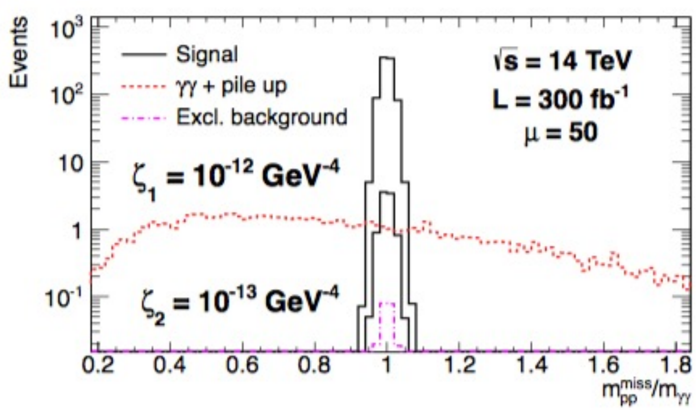


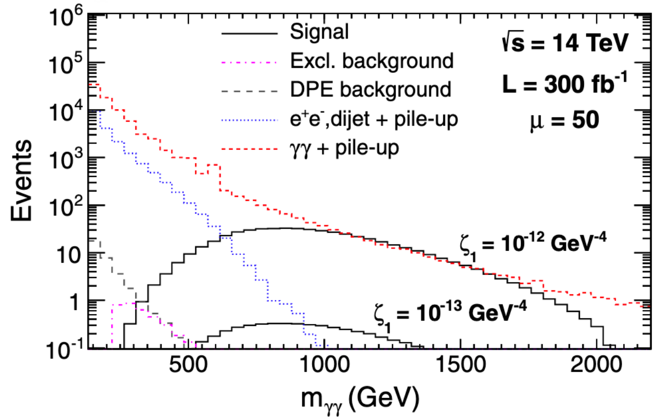
γγ→γγ: Anomalous couplings, etc.

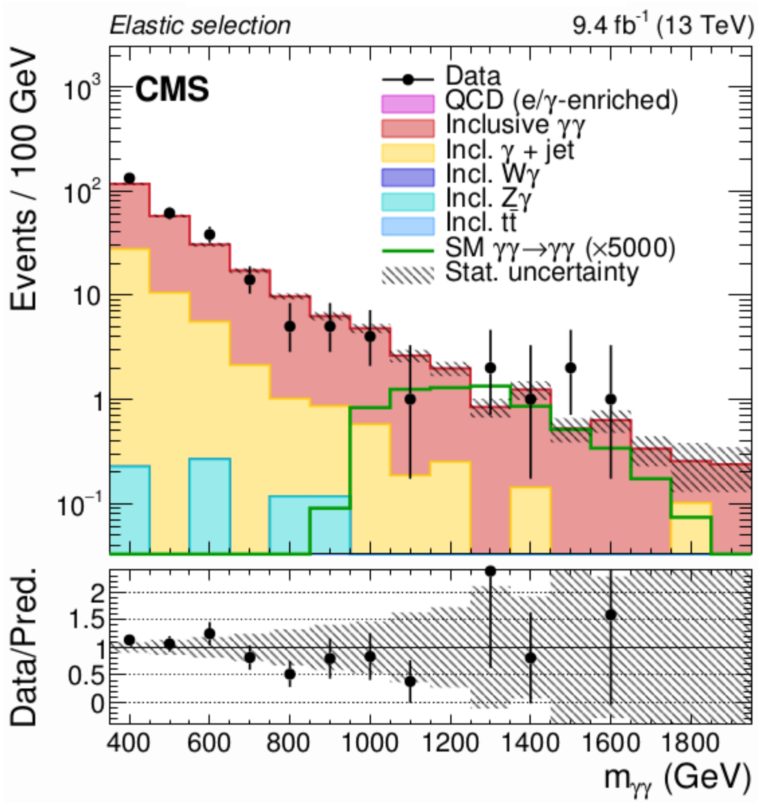
PRD 89(2014)114004, CMS-EXO-18-014

- Indirect search: neutral quartic gauge couplings (forbidden in SM) in γγ→γγ
- Expect to provide best sensitivity at LHC
- Sensitive to axion-like particles



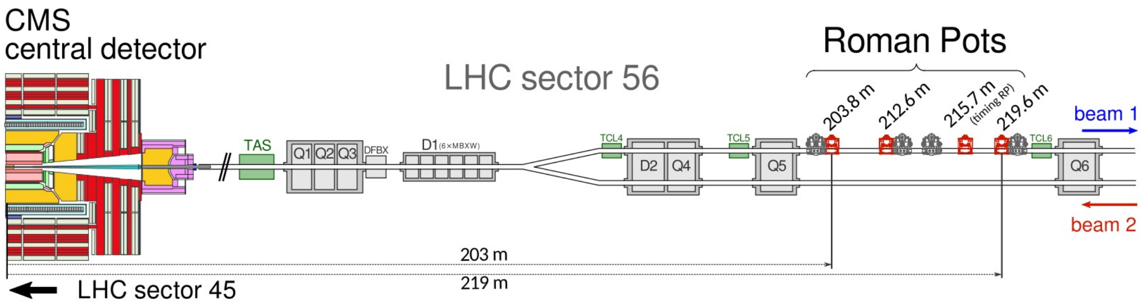


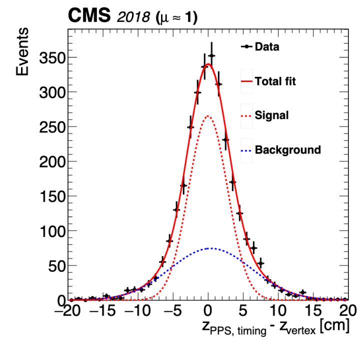




Physics with forward protons

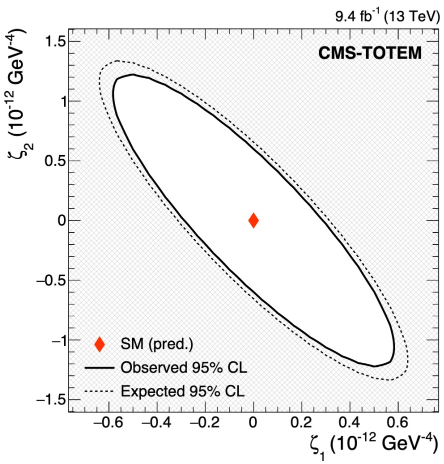
arXiv:2210.05854, arXiv:2310.11231, arXiv:2110.05916, arXiv:2303.04596, arXiv:2211.16320





Proton reconstruction

PPS collected more than 100/fb in Run2

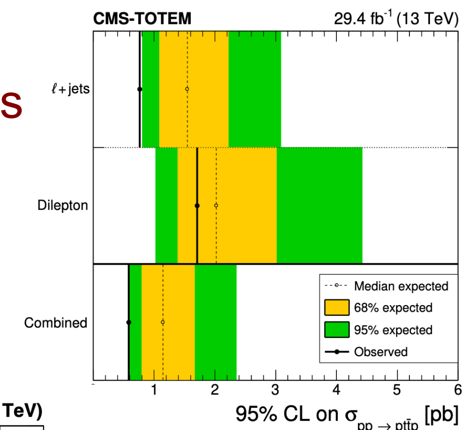


light-by-light scattering

$\gamma\gamma \to \gamma\gamma$ with forward protons, neutral quartic gauge couplings

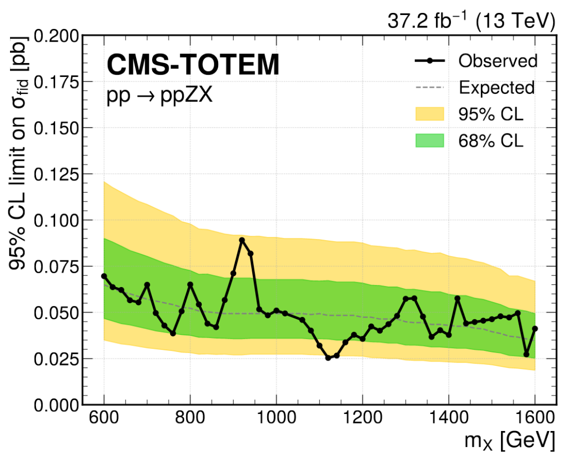
exclusive top quark pairs

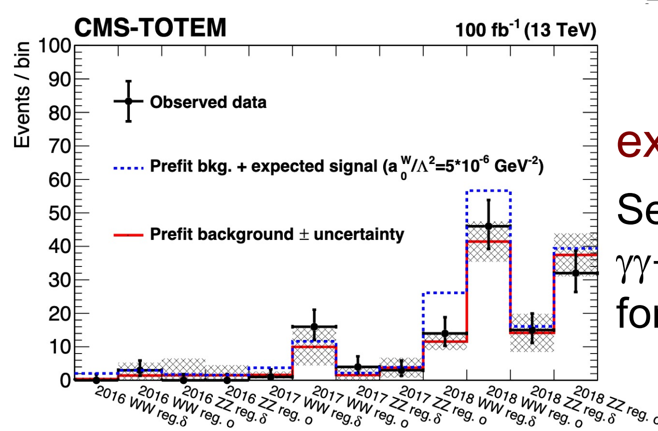
Search for ttbar central exclusive production in pp interactions with tagged protons



Z/γ*+X production

(2% resolution on missing mass)

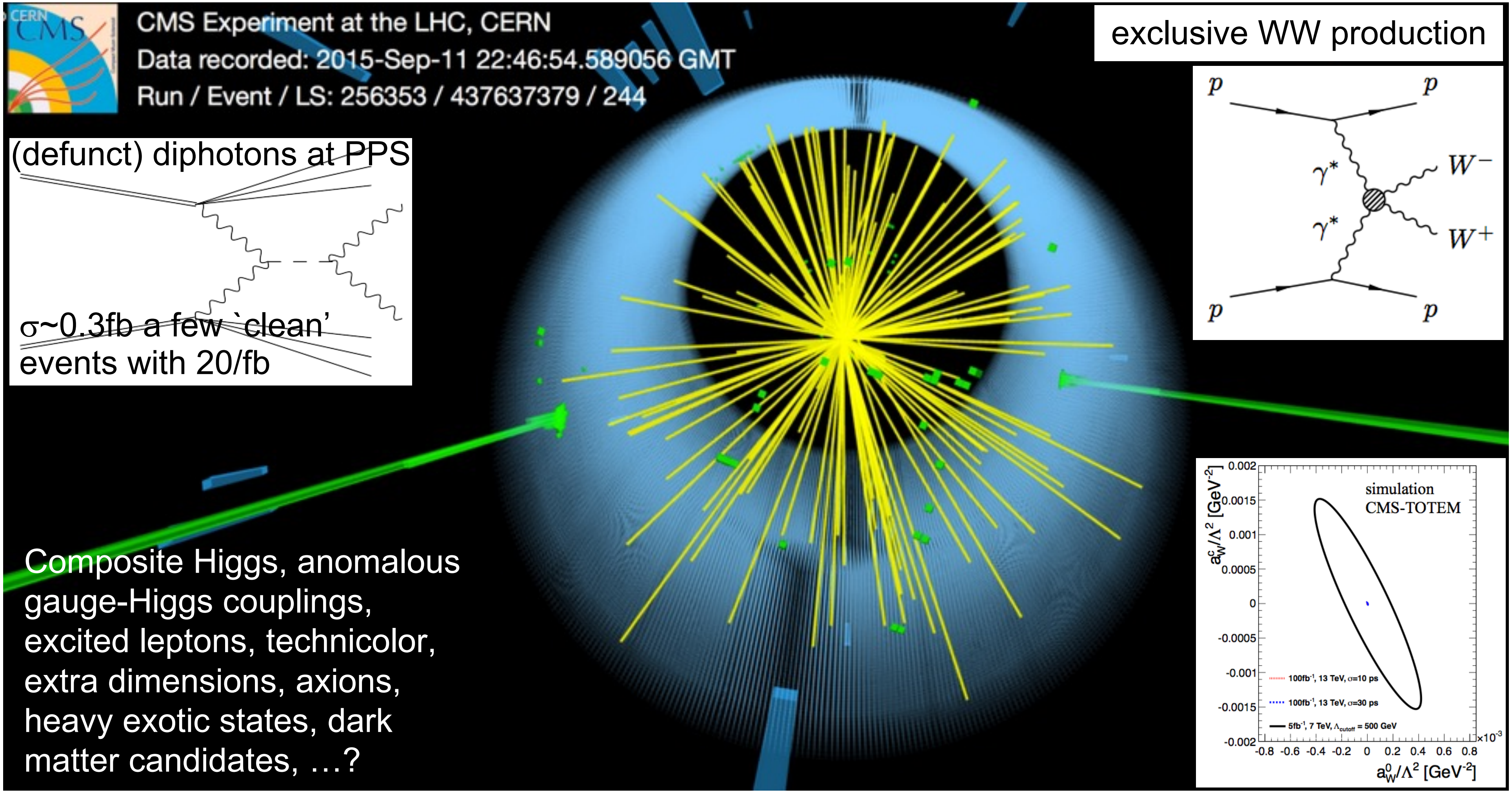




exclusive WW/ZZ

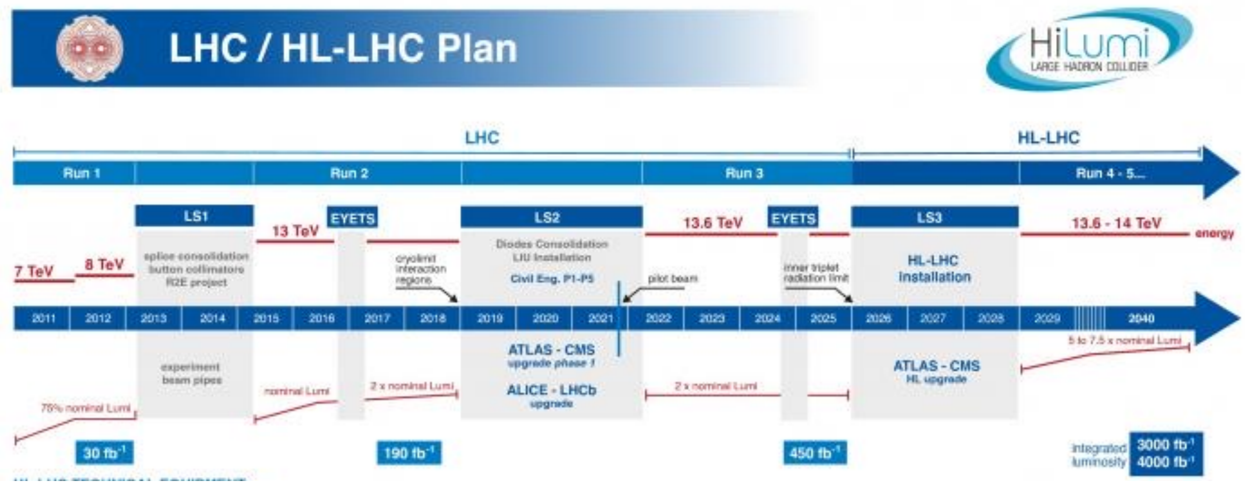
Search for $\gamma\gamma \to WW/ZZ$ with forward protons

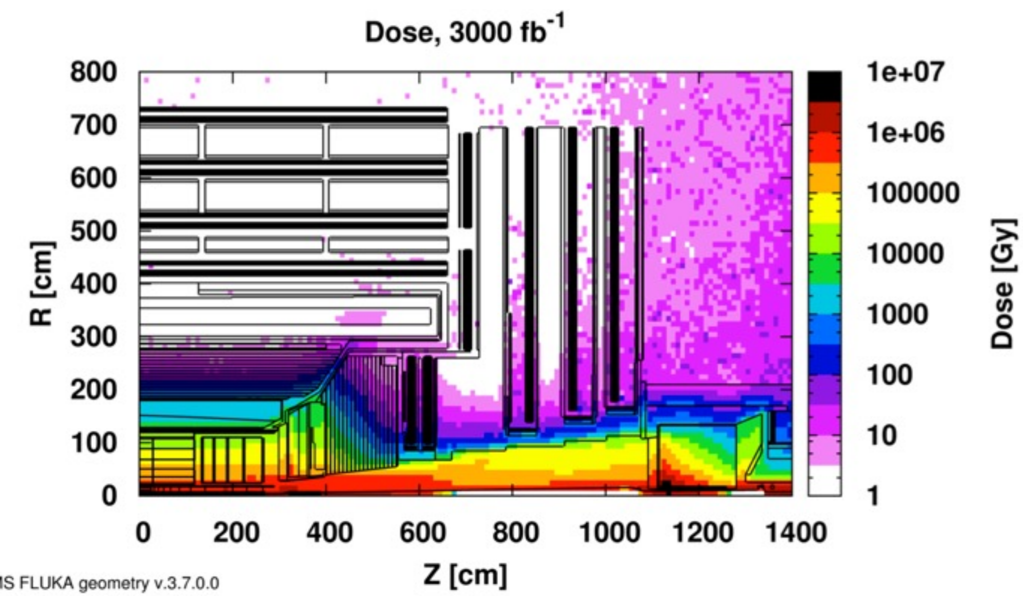
BSM searches: resonances, etc.



Prospects for Run3 and beyond

- More luminosity in a more challenging environment
- Will enhance the mass reach in the search for new particles
- Need to meet experimental challenges
  - Aging of detector, improve/adapt capability
  - Integrated luminosity: 300-3000/fb
  - peak luminosity of $2x10^{35}cm^{-2}s^{-1}$
  - pileup will be ~150 or higher (Phase2)
  - large radiation doses

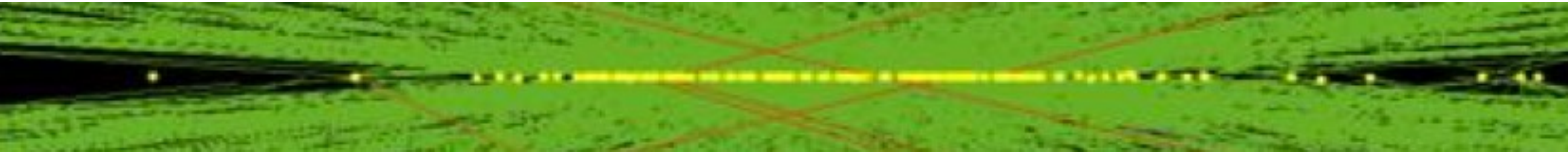




HL-LHC upgrades

Luminosity of ~3000 fb^{-1} expected for HL-LHC

- Tracking information in "L1 track-trigger"
  - Tracker designed to enable finding all tracks w/p_T>2GeV in <4μs
- Tracker is all silicon but with much higher granularity, up to $|\eta|=4$
  - >2billion pixels and strips
- High Granularity Endcap Calorimeters
  - Sampling of EM showers: every ~1λ (28 samples) w/pixels, and every ~0.35λ (24 samples) with pixels+scintillator to map 3D shower development
  - ~6M channels in all
- Precision timing to add a 4th dimension to object reconstruction

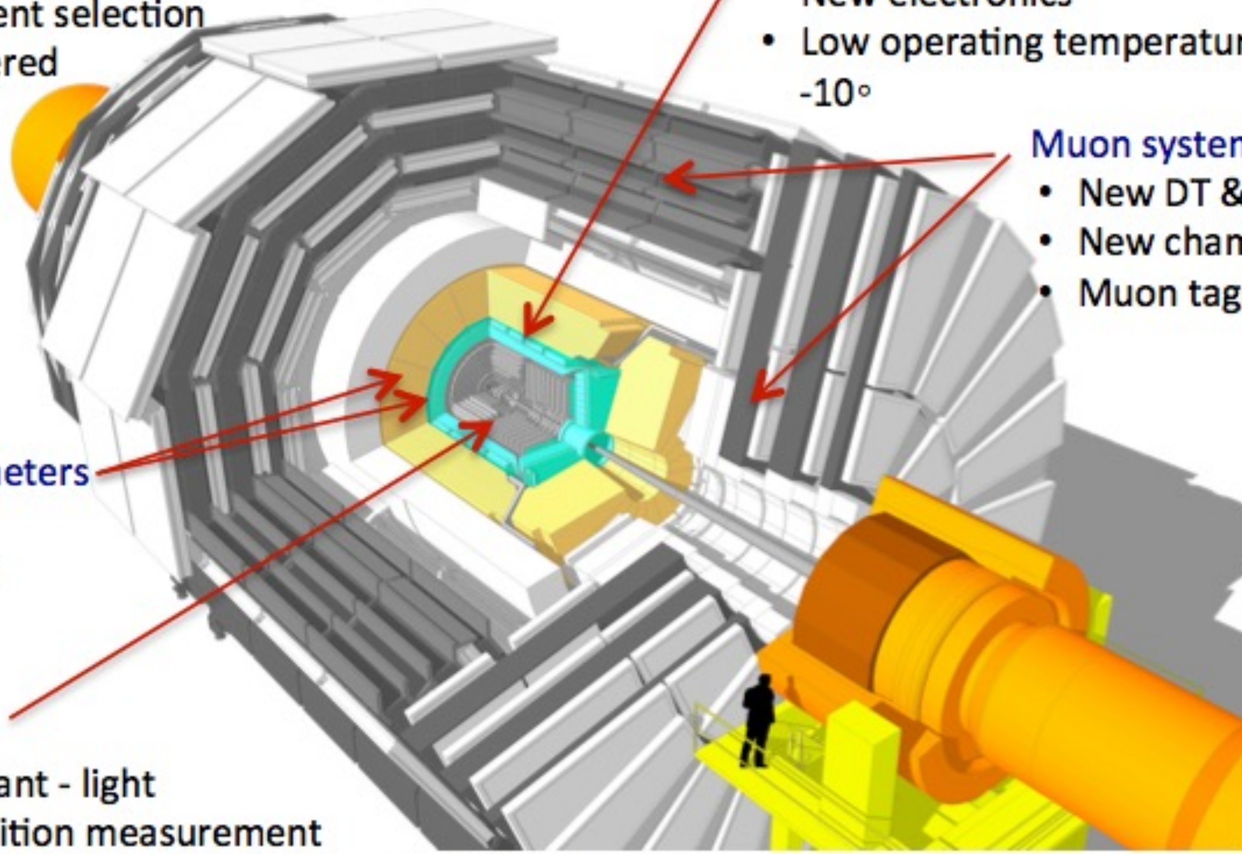


Future: HL-LHC upgrades

Trigger/HLT/DAQ
- Track information in hardware event selection
- 750 kHz hardware event selection
- 7.5 kHz events registered

Barrel EM calorimeter
- New electronics
- Low operating temperature ≈ -10°

Muon systems
- New DT & CSC electronics
- New chambers $1.6 < \eta < 2.4$
- Muon tagging $2.4 < \eta < 3$



New Endcap Calorimeters
- Rad. Tolerant
- 5D measurement

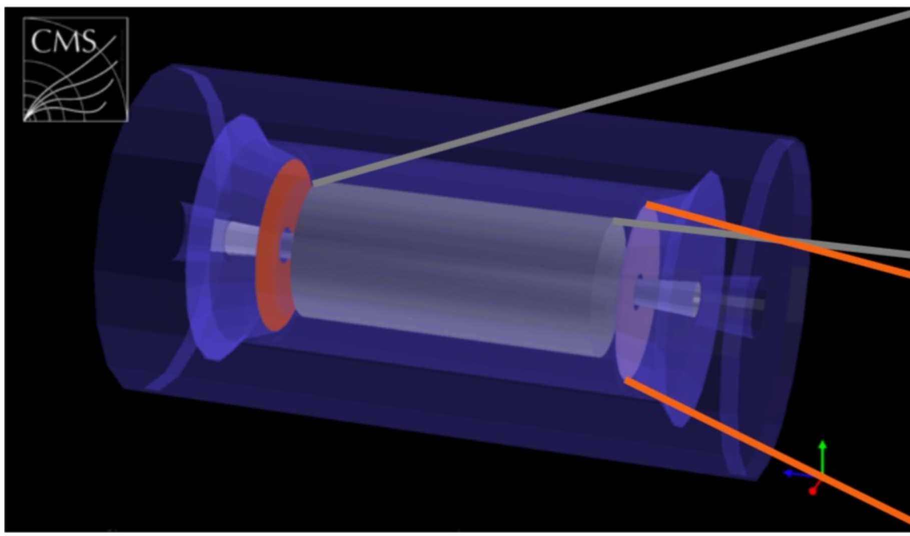
New Tracker
- Rad. Tolerant - light
- High Definition measurement
- 40 MHz selective readout for hardware trigger
- Extended Pixel coverage to $\eta \simeq 3.8$

Beam radiation and luminosity
Common systems and infrastructure

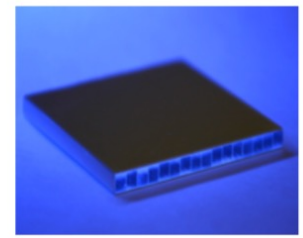
MIP Timing Detector @CMS

CERN-LHCC-2019-003

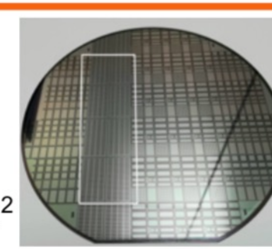
- High precision time measurement of MIPs
  - 30-40 ps at start, degrading to <60ps at 3000 fb^{-1}
  - Provide track-vertex association
  - Improve sensitivity to slow particles, add particle ID capabilities, etc.



BTL: LYSO bars + SiPM read-out
- ▹ TK / ECAL interface ~ 45 mm thick
- ▹ $|\eta|< 1.45$ and $p_T > 0.7$ GeV
- ▹ Active area ~ 38 m^2 ; 332k channels
- ▹ Fluence at 3 ab^{-1}: 2×10^{14} n_{eq}/cm^2

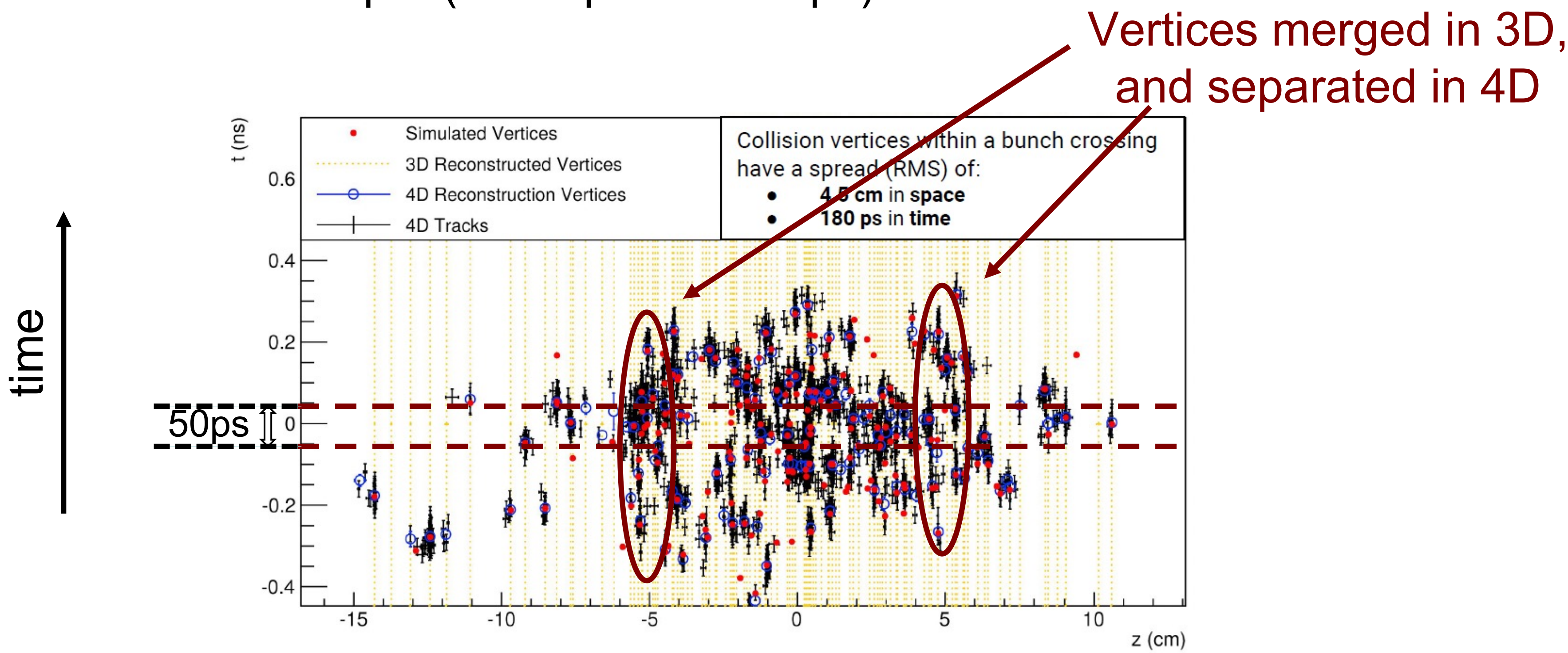


ETL: Si with internal gain (LGAD)
- ▹ On the HGC nose ~ 65 mm thick
- ▹ $1.6 < |\eta| < 3.0$
- ▹ Active area ~ 14 m^2; ~ 8.5M channels
- ▹ Fluence at 3 ab^{-1}: up to 2×10^{15} n_{eq}/cm^2

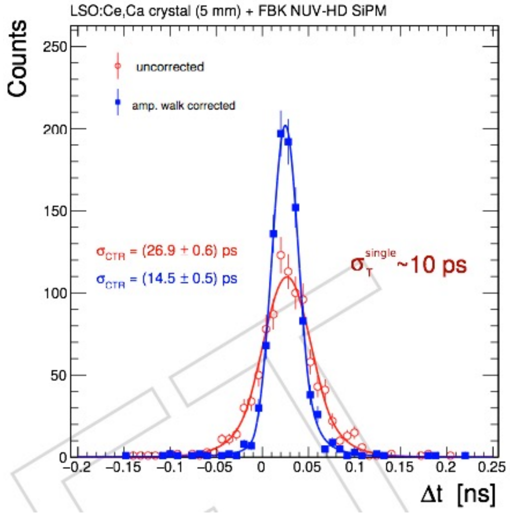


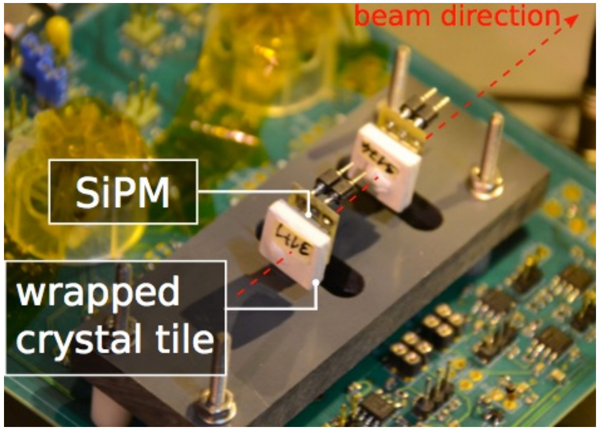
PU mitigation with ToF

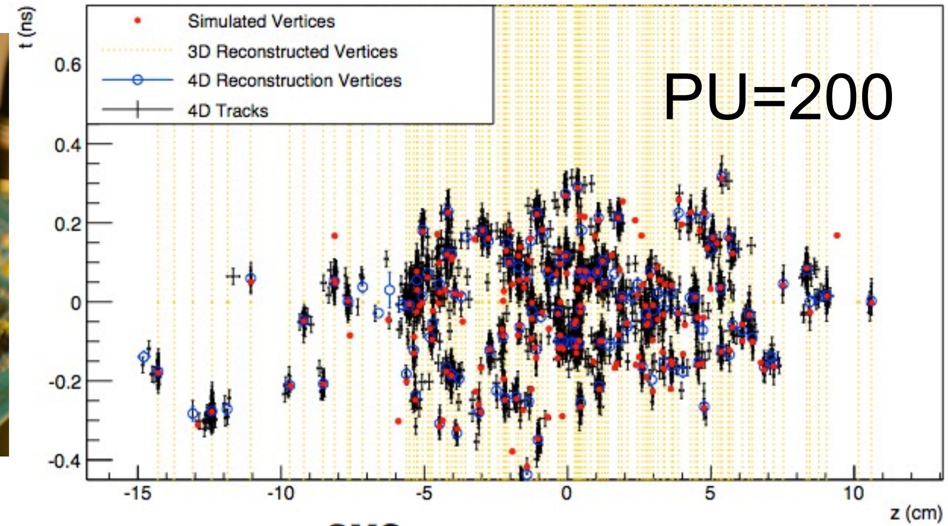
- Time-tagging tracks with a resolution of ~30-40 ps
  - 4D vertex reconstruction
  - Track-vertex association
- Reduce effective PU to the LHC Run2 level
  - Slice beam spot (time spread 180 ps)



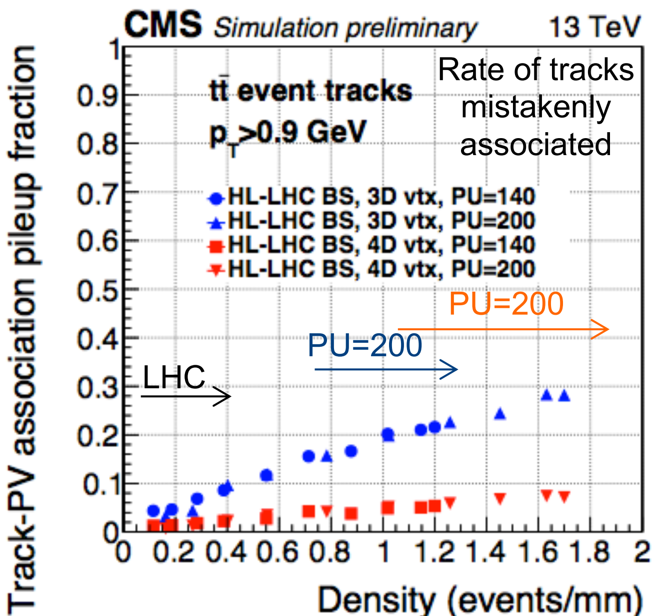
Precision Timing Layer





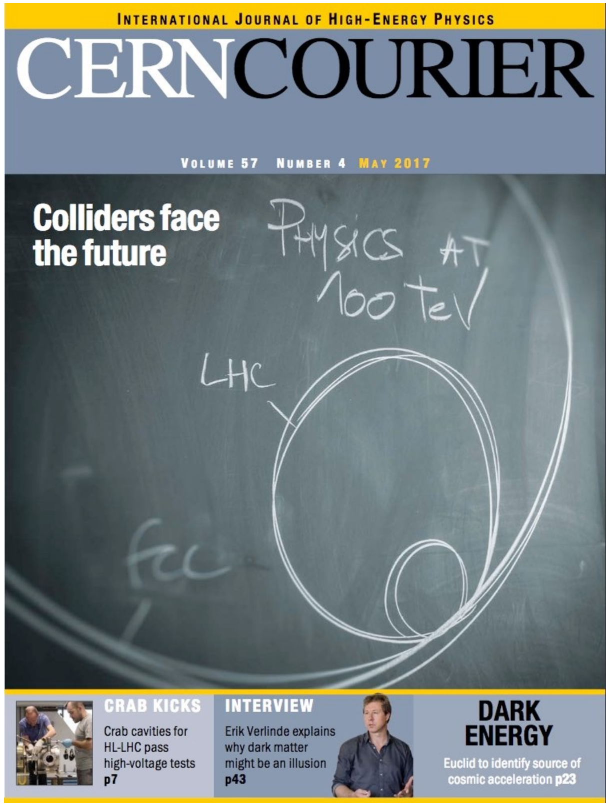


- Time-of-flight precision ~30ps
  - $|\eta|<3$, $p_T>0.7$GeV
  - Crystal+SiPM: rad hard to $2\times10^{14} n_{eq} cm^{-1}$
- Provide ~x4-5 effective PU reduction
  - 15% merged vertices reduce to 1.5%
  - Low PU track purity of vertices recovered
- Showers timed to 30ps in calorimeters



Summary

- Excellent consistency of SM but SM is incomplete
- Direct and indirect searches for New Physics
  - Collected ~150/fb @13 TeV in 2015-2018
  - ~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



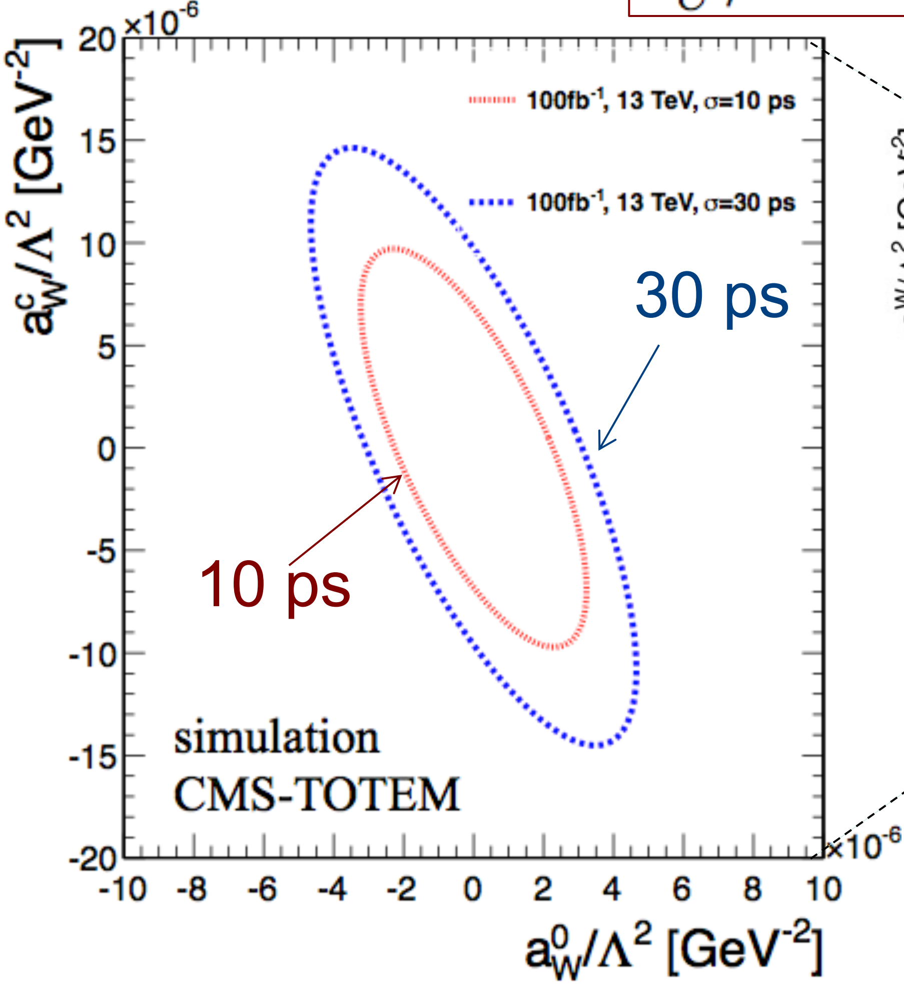
backup

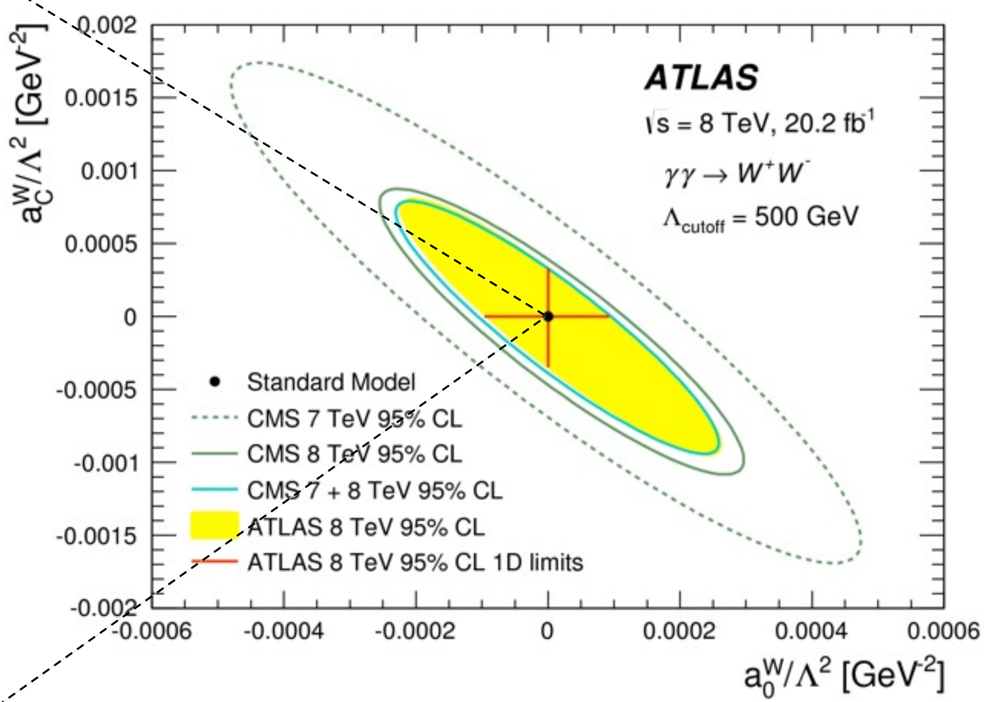
AQGC expected limits

arXiv:1607.03745

Expected limits @95%CL:

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





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