

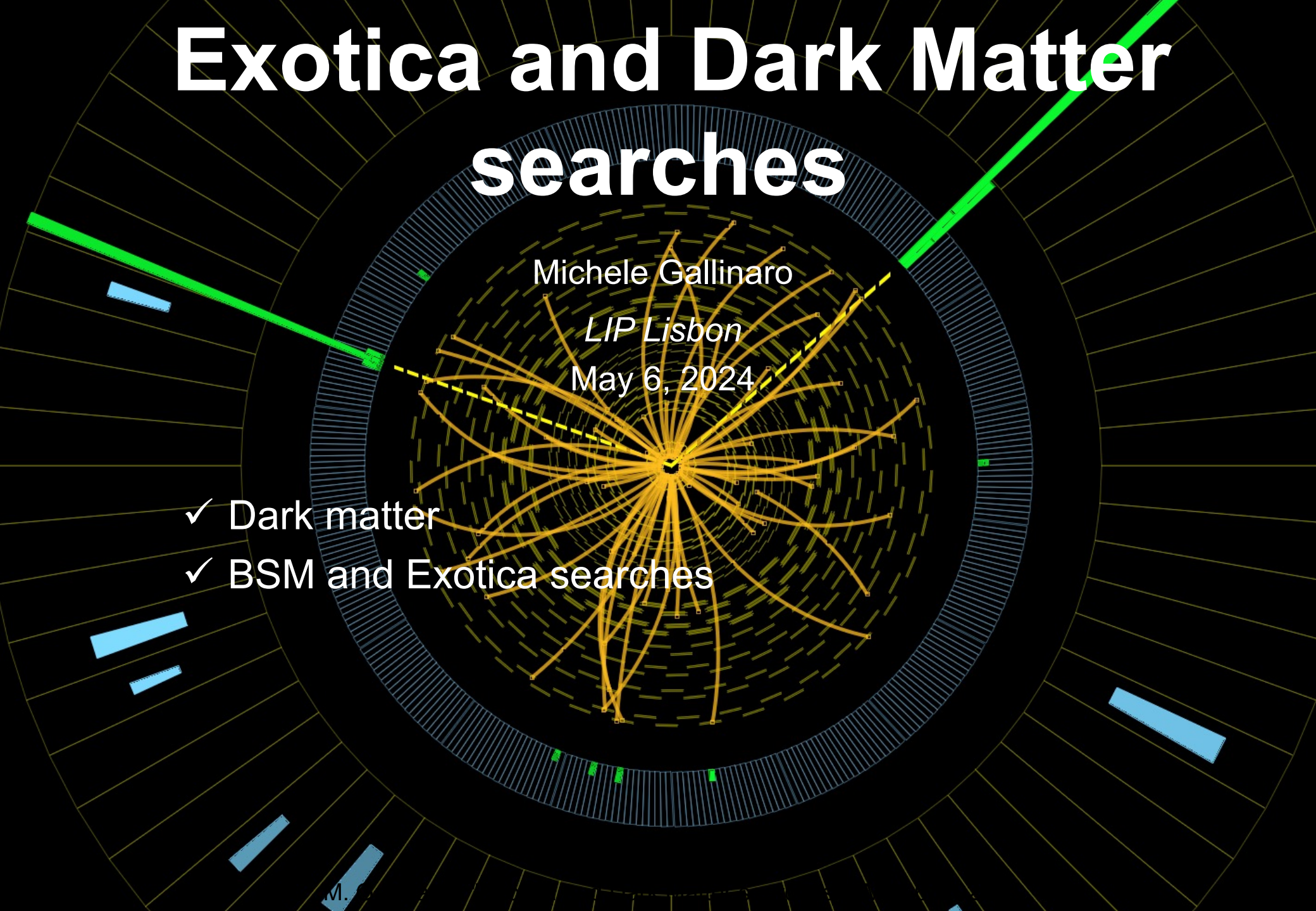
Exotica and Dark Matter searches

Michele Gallinaro

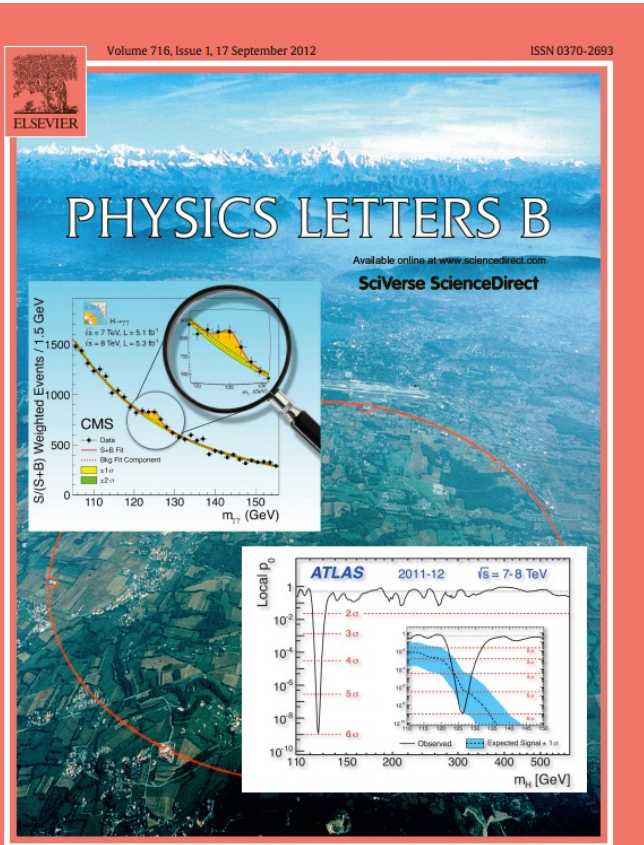
LIP Lisbon

May 6, 2024

- ✓ Dark matter
- ✓ BSM and Exotica searches

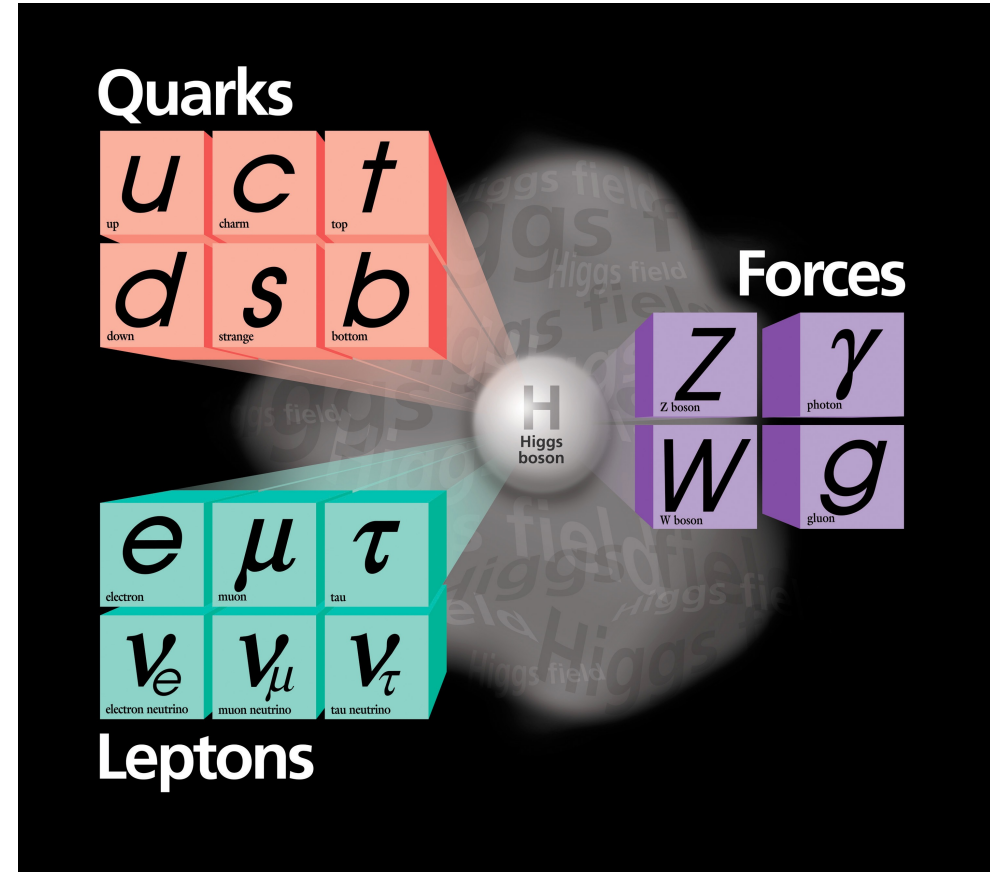


2012: A new boson discovery

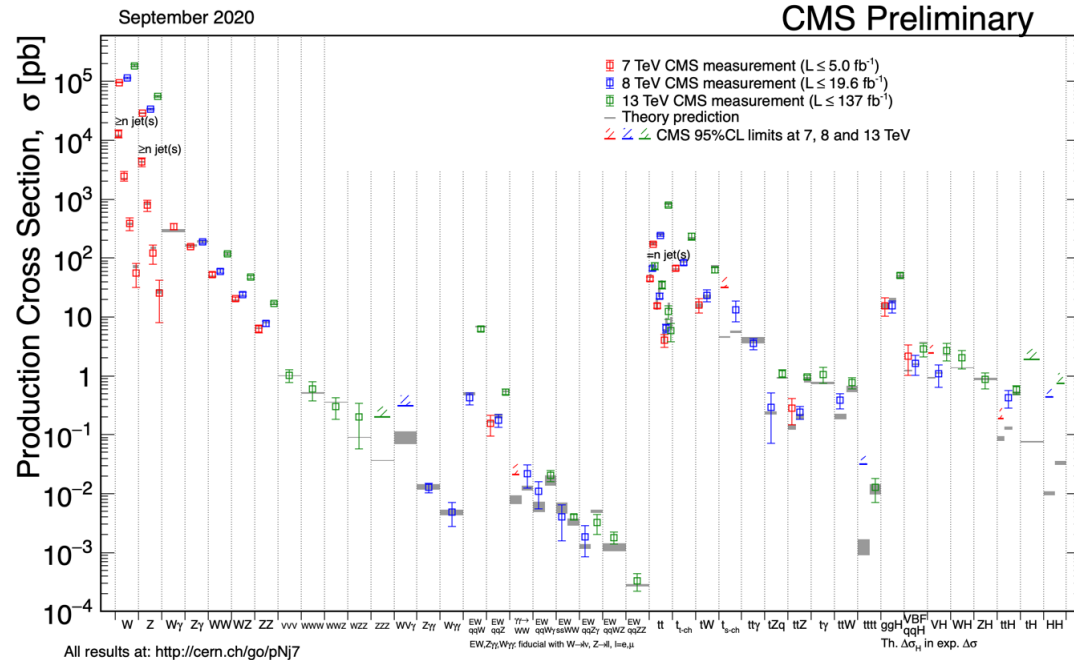
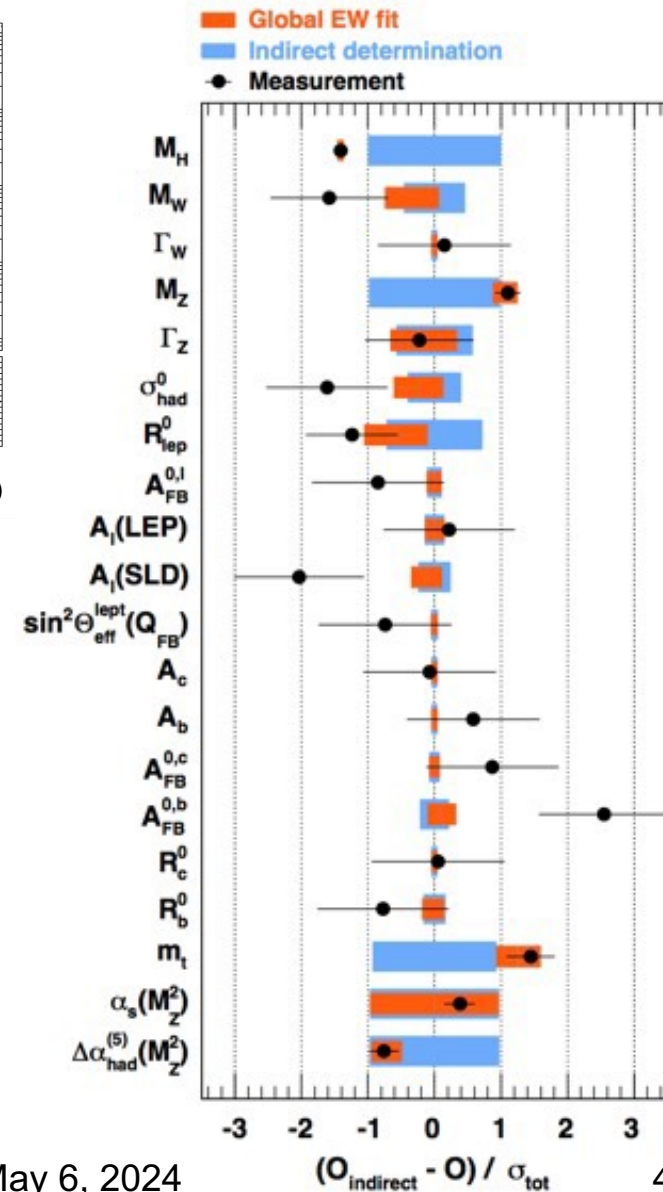
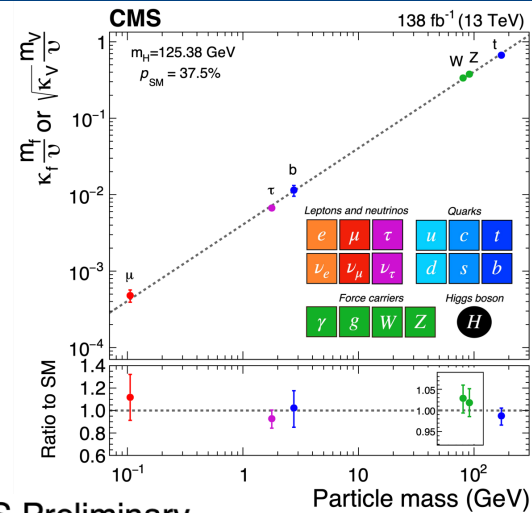
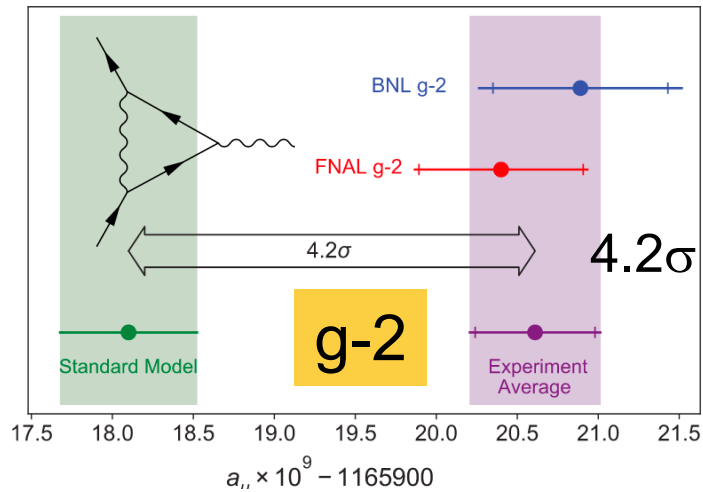


Standard Model theory of everything?

- 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**

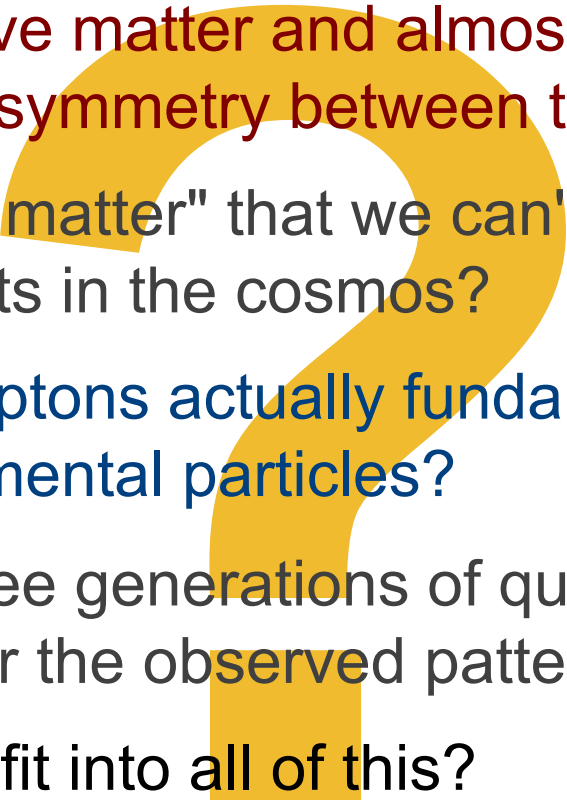


Tests of the SM



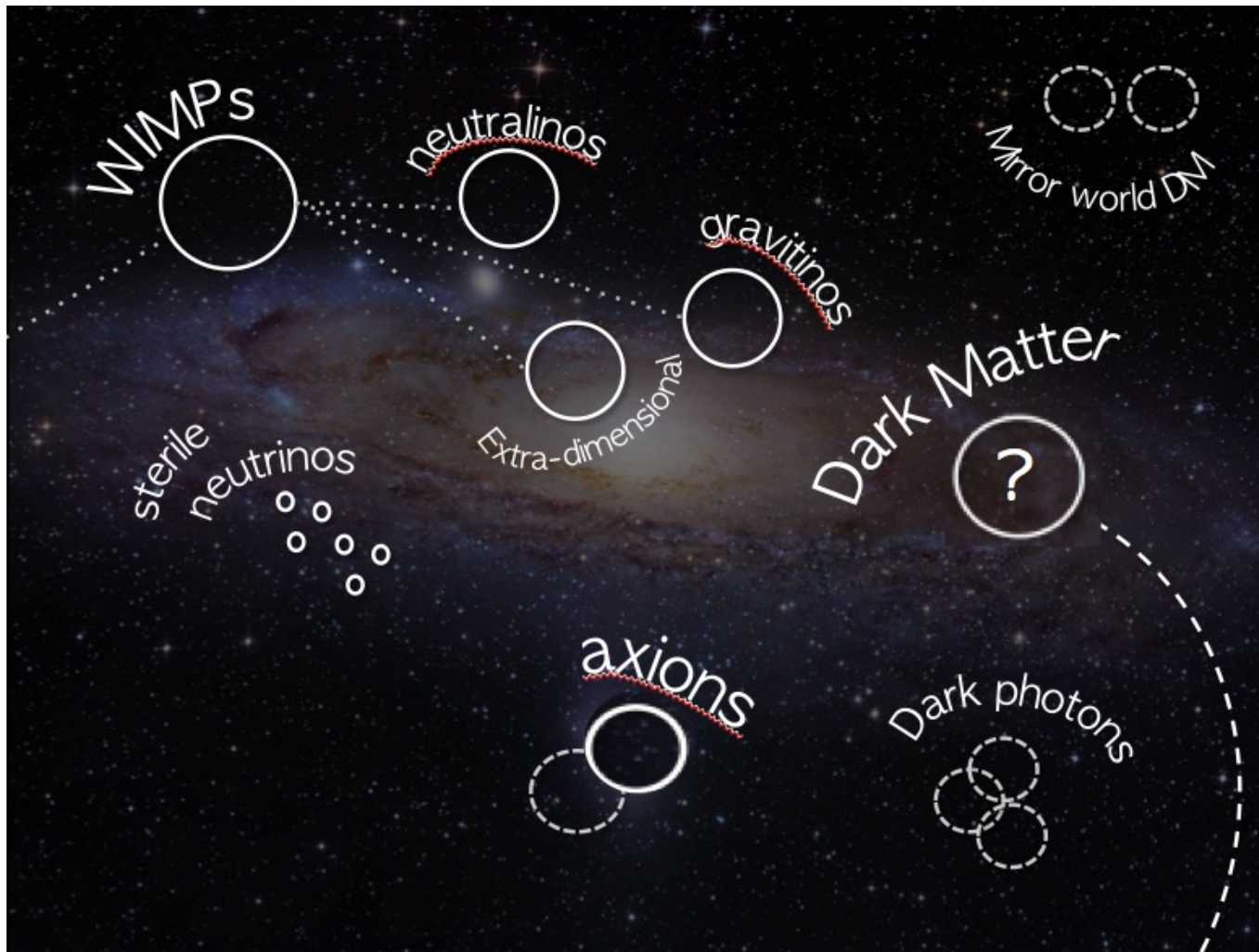
Beyond the Standard Model

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



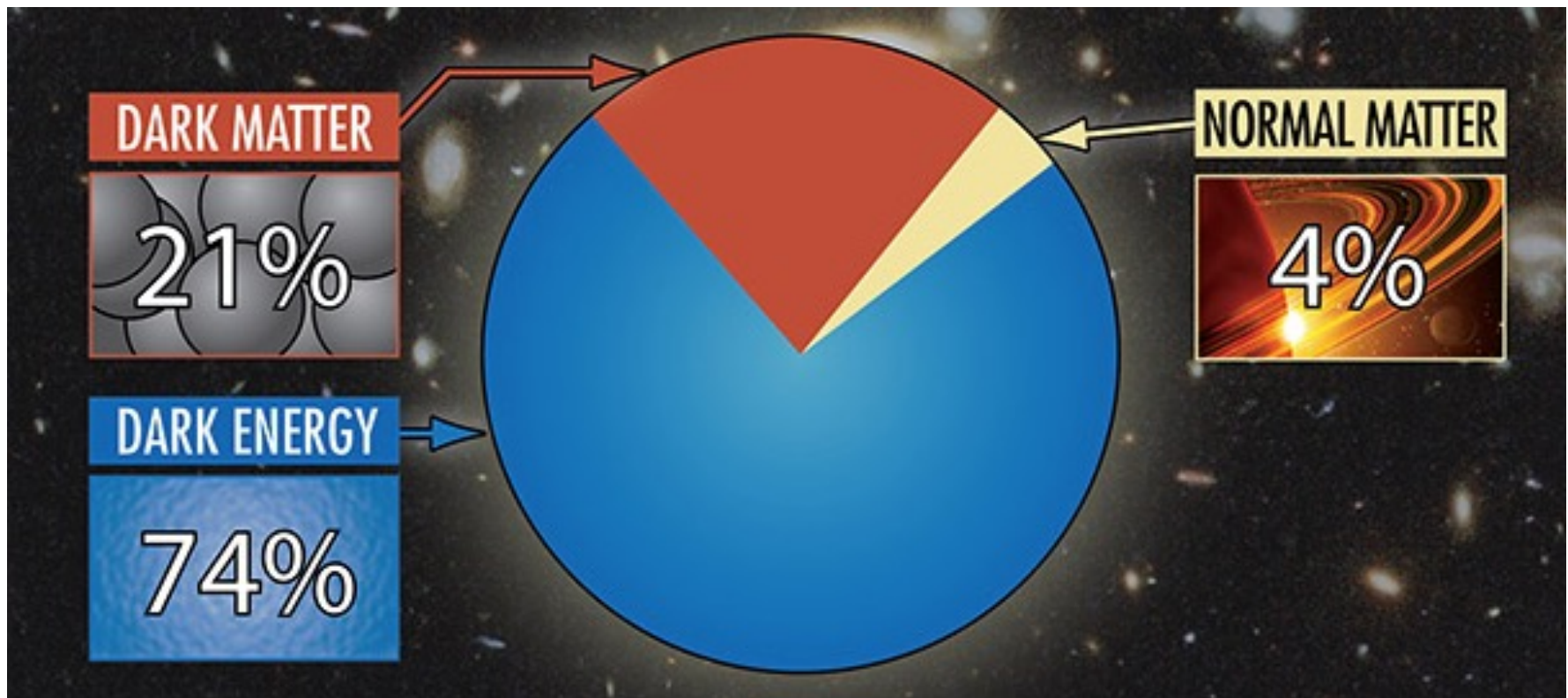
How?

- 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

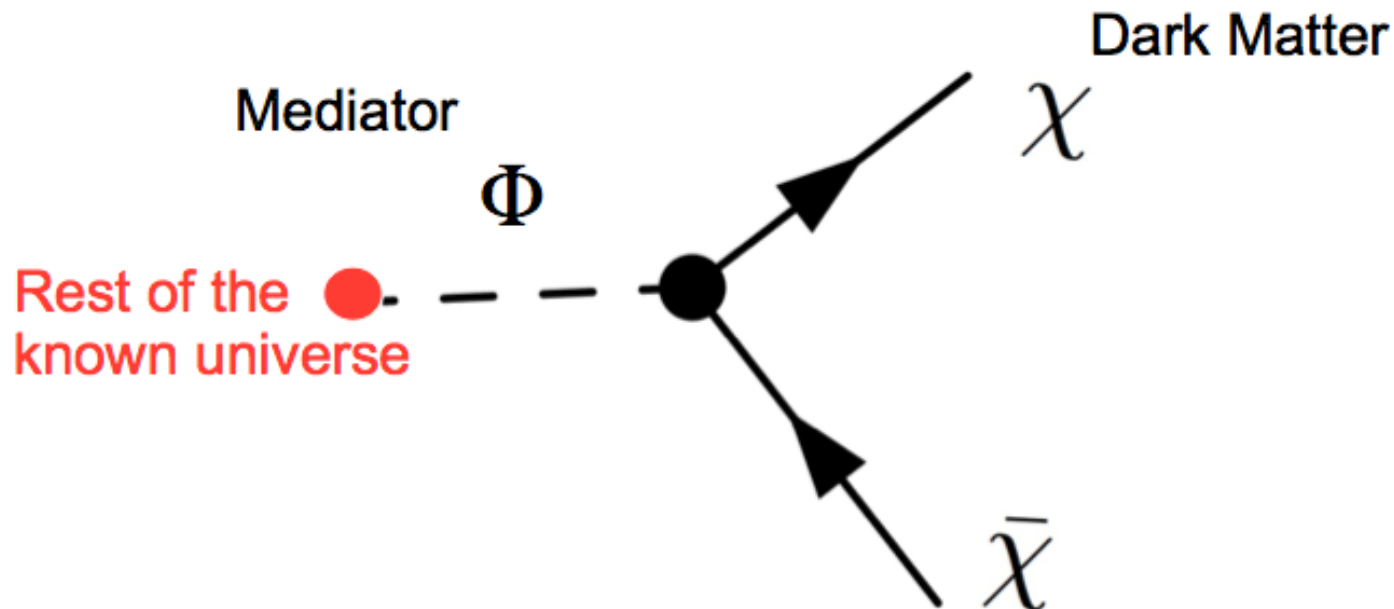
Mass map



Dark Matter (cont.)

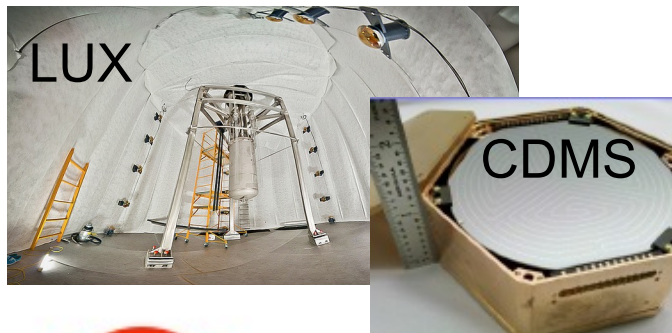
How do we find DM?

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

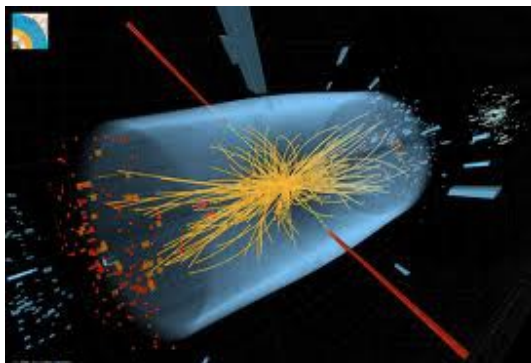
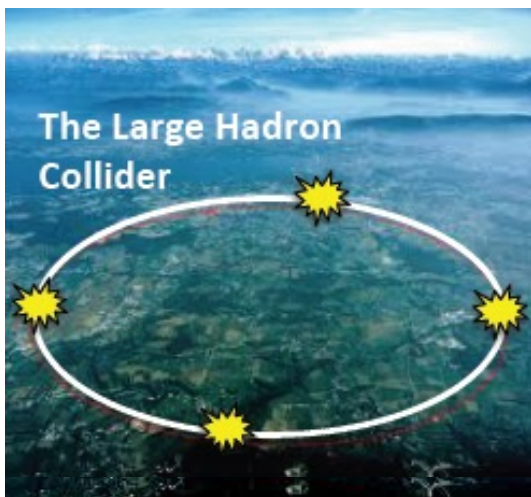


Searching for DM

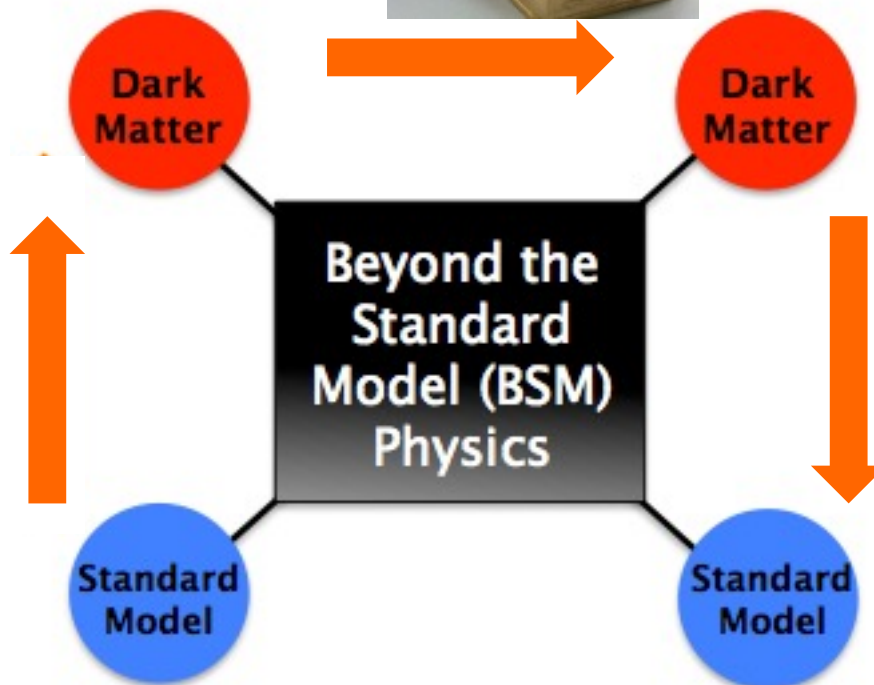
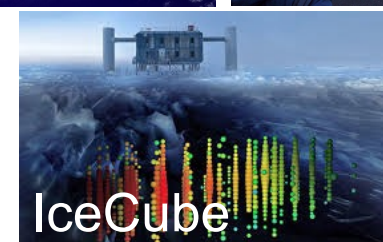
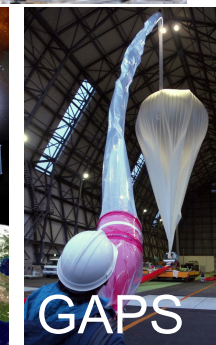
Direct Detection



Particle Colliders

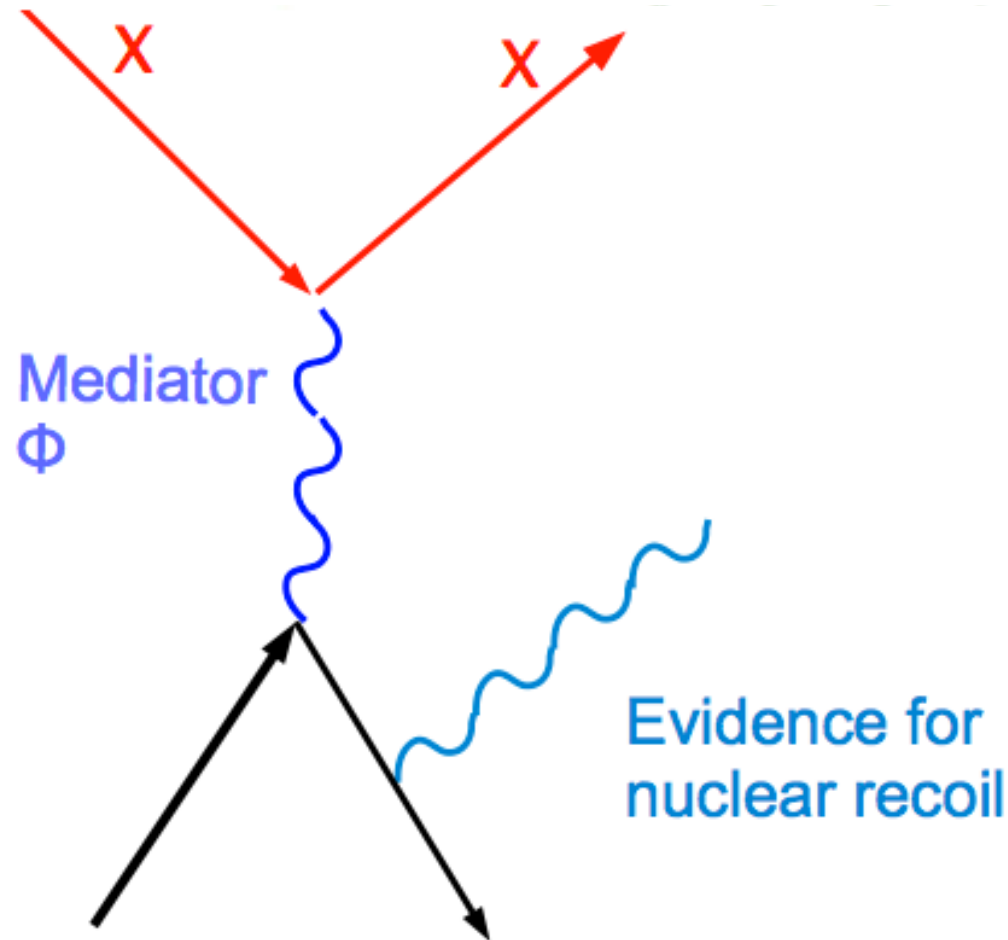


Indirect Detection



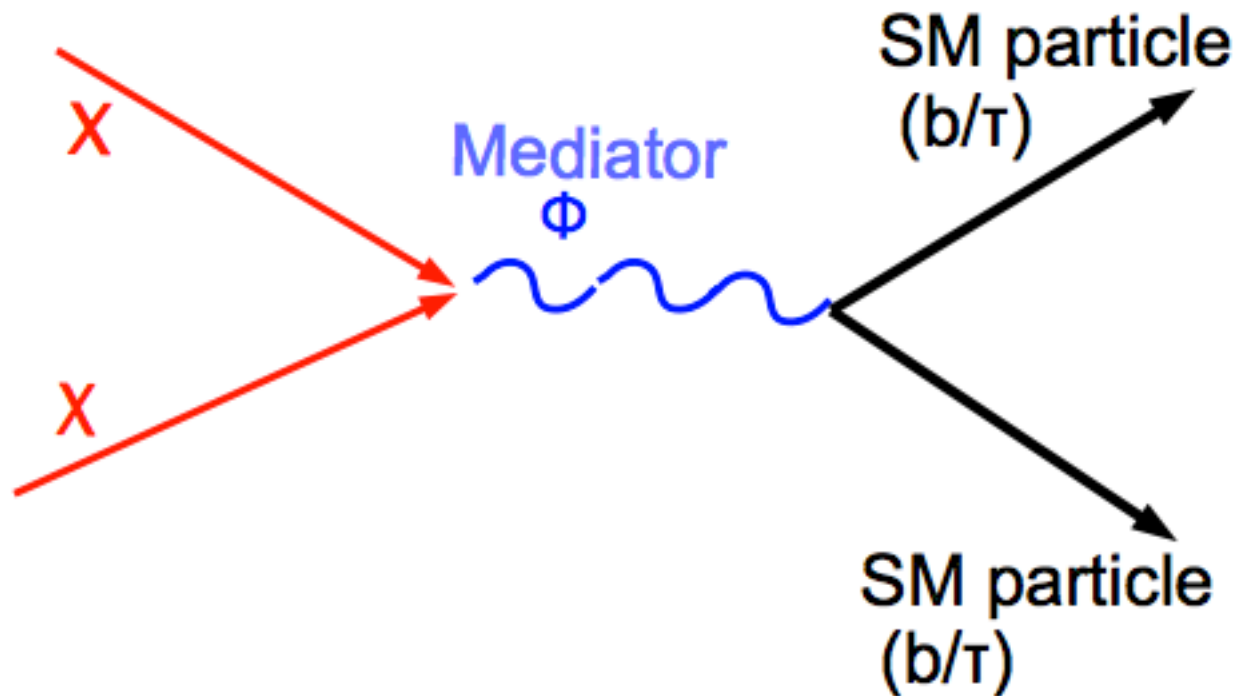
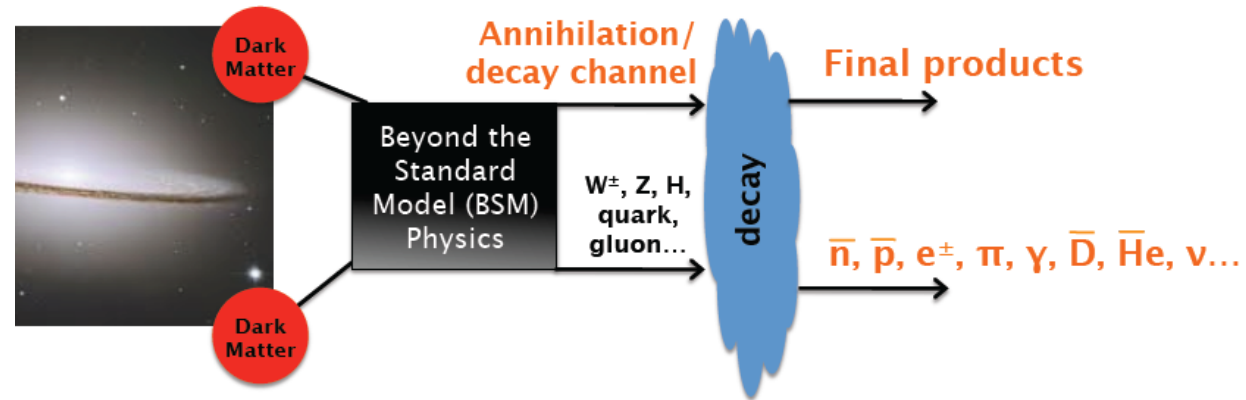
How do we find it: @underground

- Through a nuclear recoil



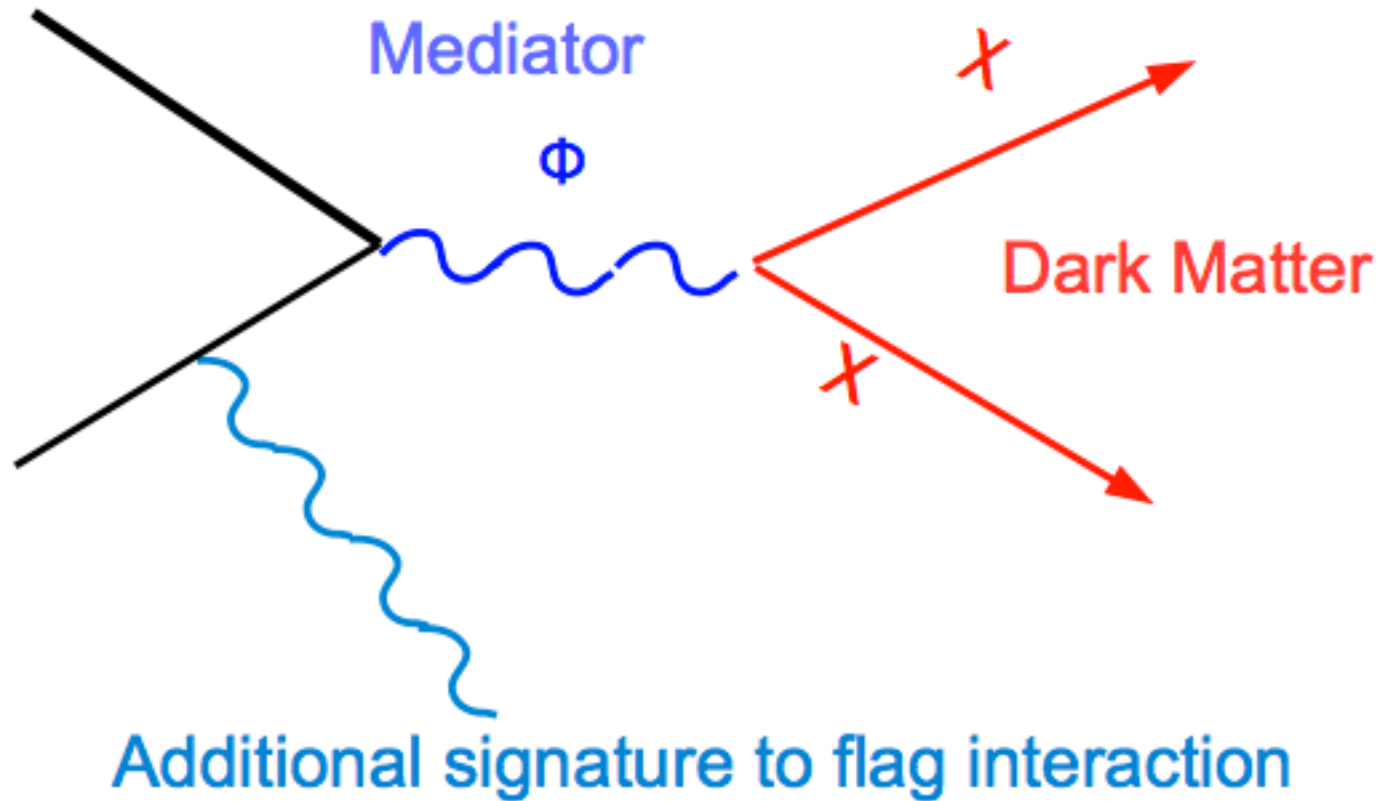
How do we find it: @Space

- Through annihilation
 - Cosmic rays from DM



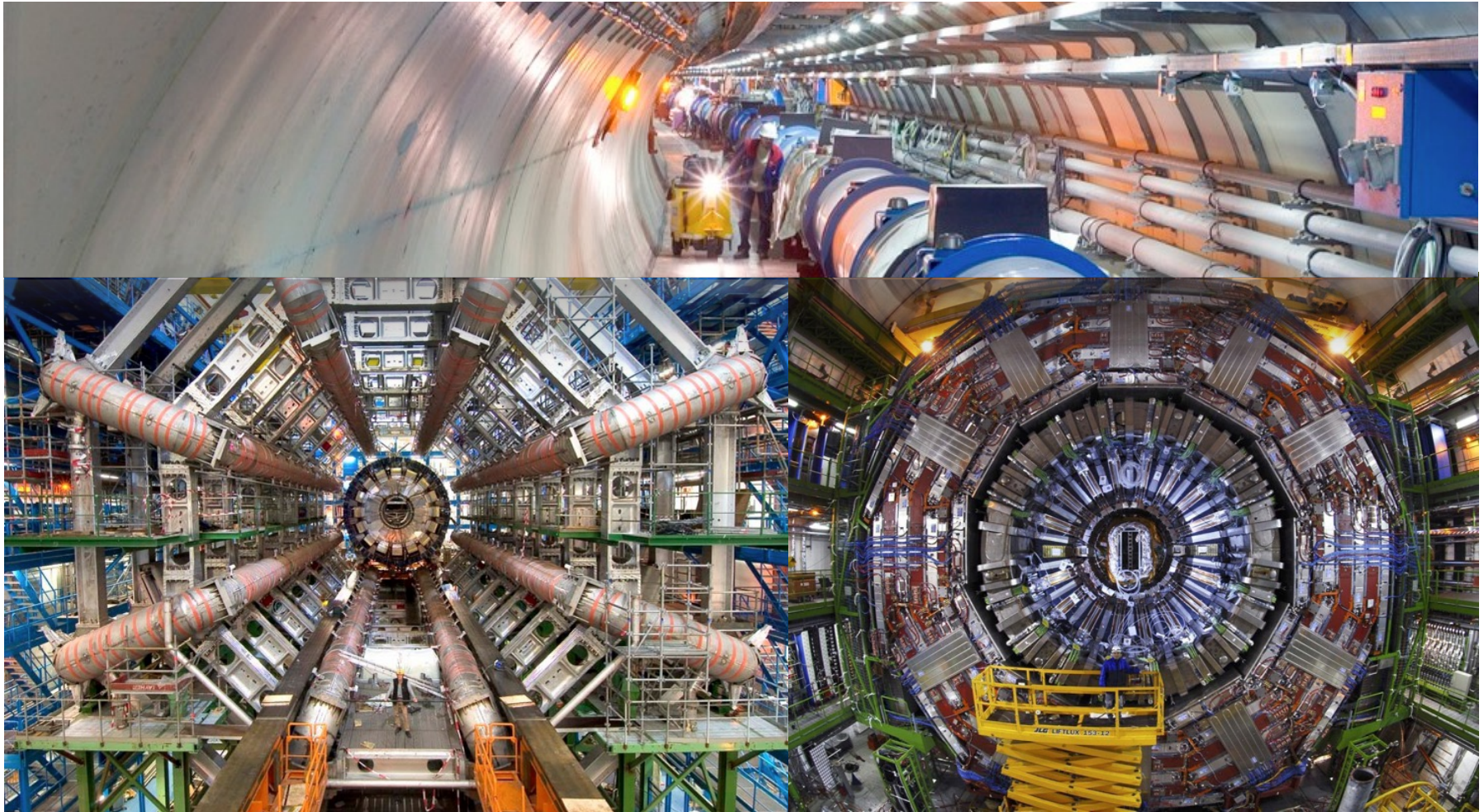
How do we find it: @LHC

- Produced it through a mediator



DM at the LHC

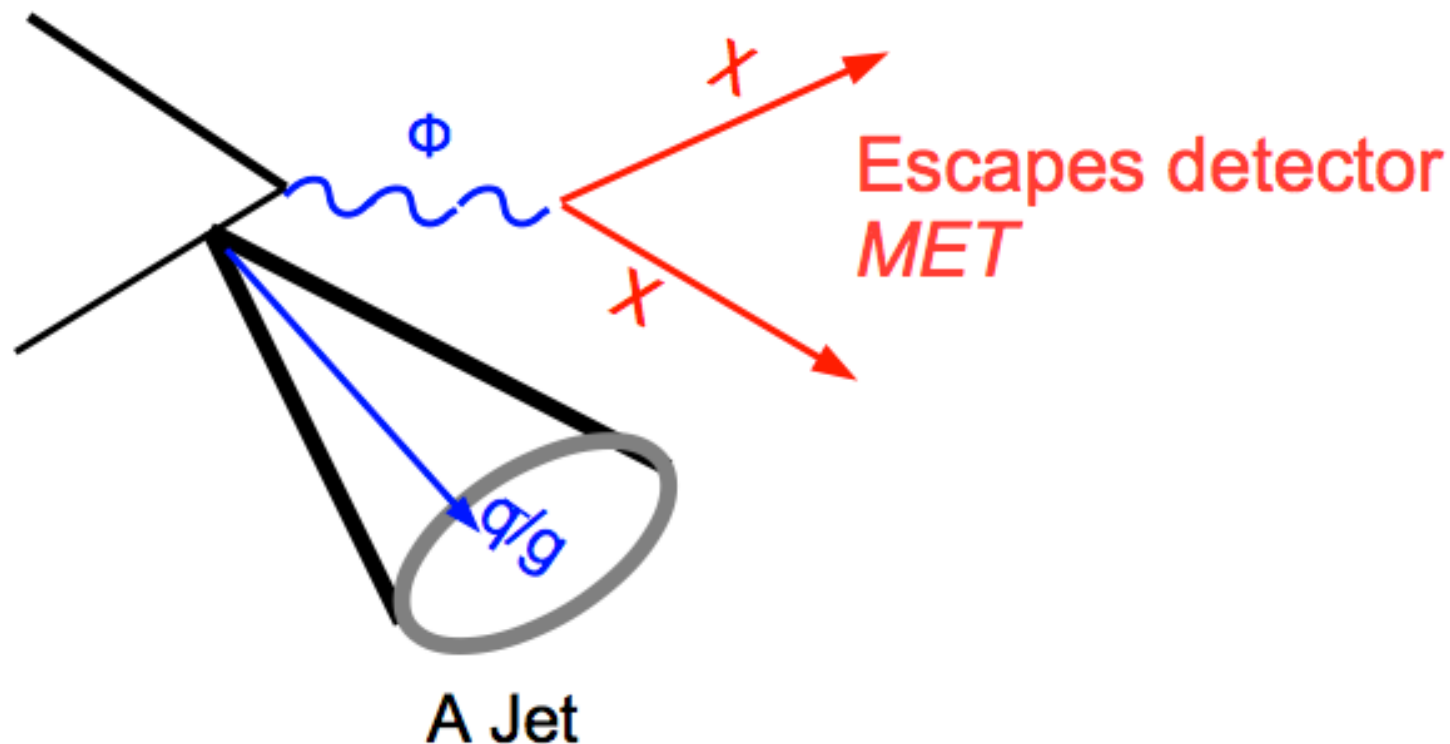
- CMS/ATLAS experiments **not** designed for DM searches



DM searches at LHC

How do we find DM at the LHC?

- DM production gives MET signature

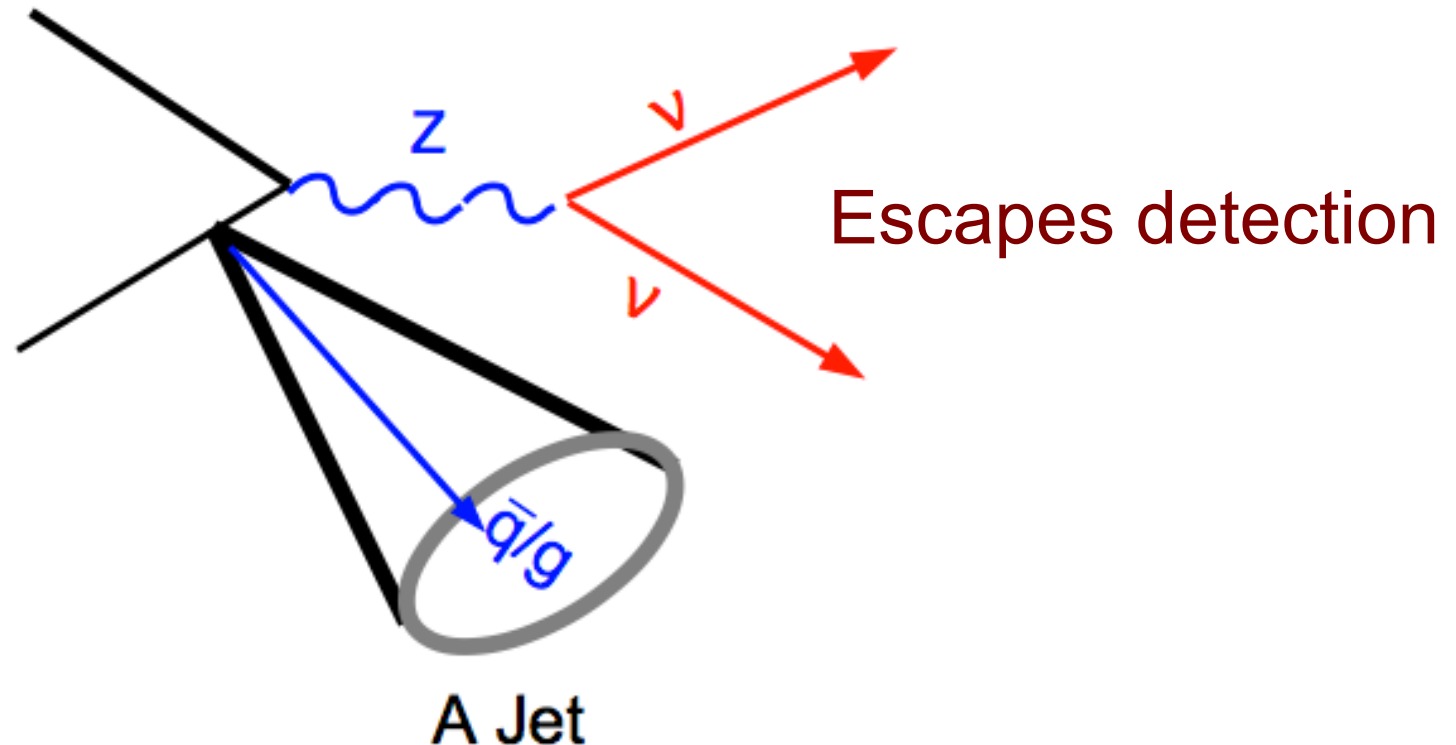


DM searches: backgrounds

What are the backgrounds?

- $Z \rightarrow \nu\nu$

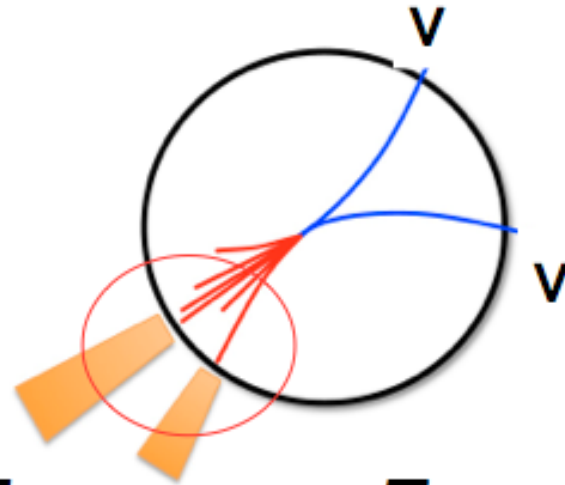
–very similar to signal



DM searches: backgrounds (cont.)

How to discriminate signal against the background?

- Look for high MET:



Study hadronic recoil

$$MET = -\sum_{All\ particles} p_T$$

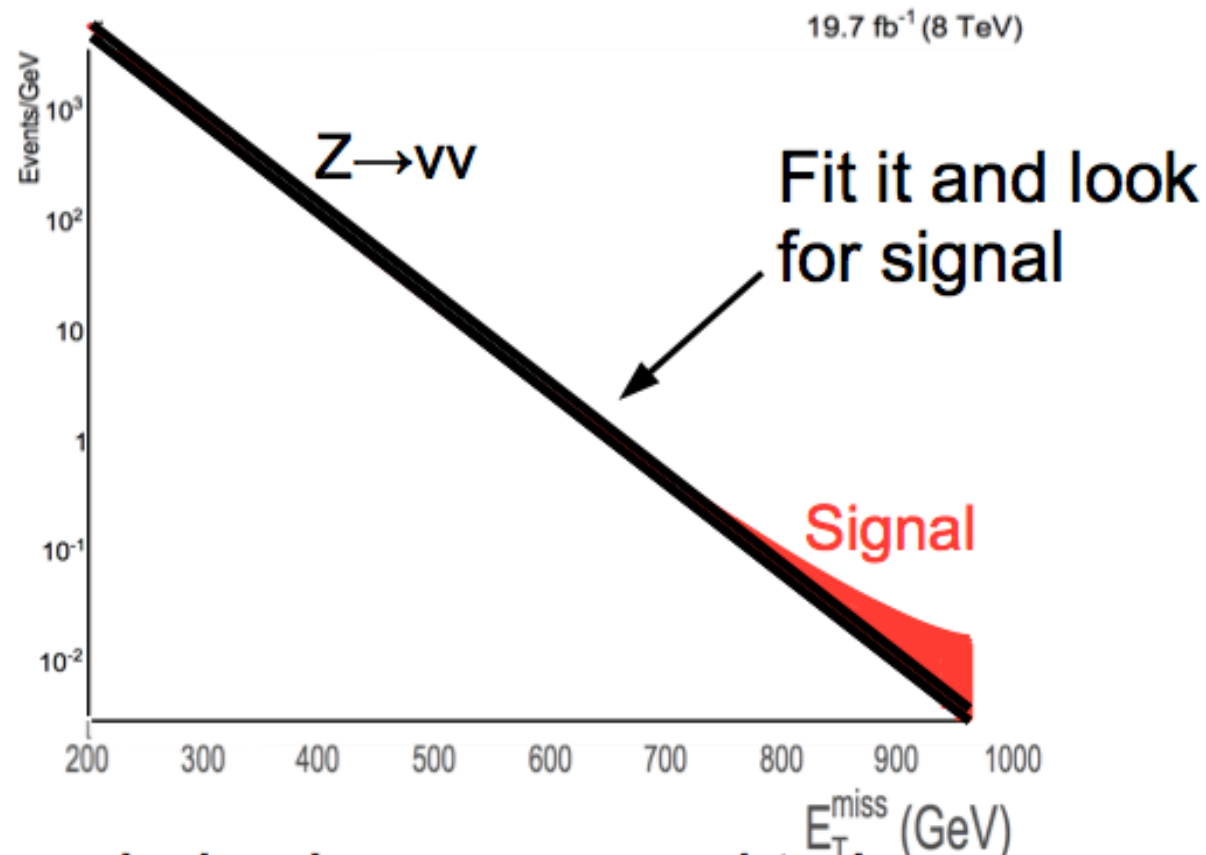
$$MET(Z \rightarrow \nu\nu) = - \text{Z recoil} + p_T(\nu\nu)$$

$$MET(Z \rightarrow \nu\nu) = - \text{Z } p_T$$

DM searches: backgrounds (cont.)

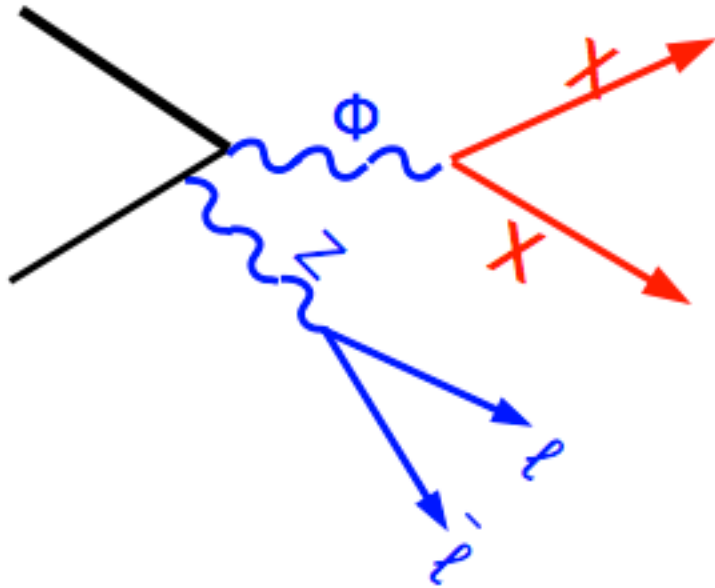
How to discriminate signal against the background?

- Can fit the shape and look for signal

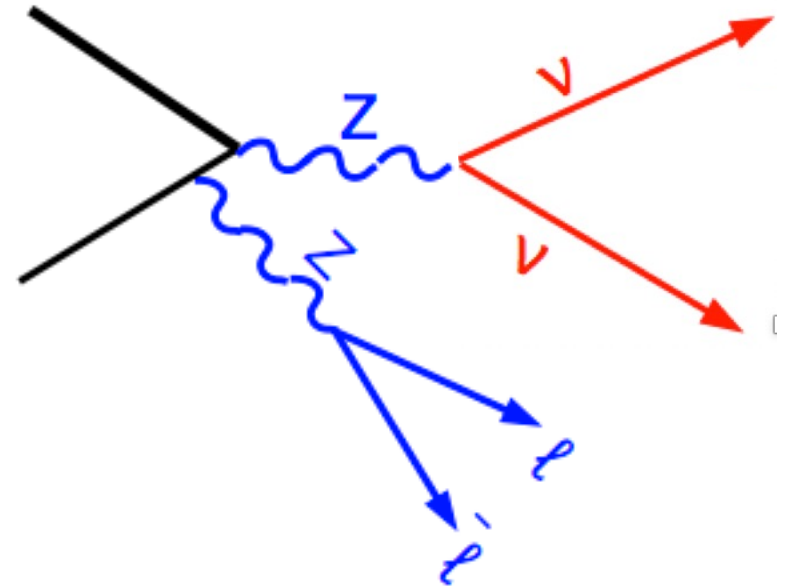


DM+Z

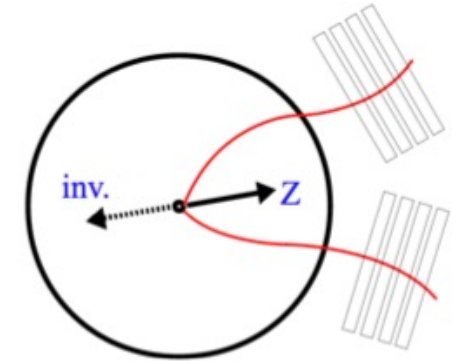
signal



background

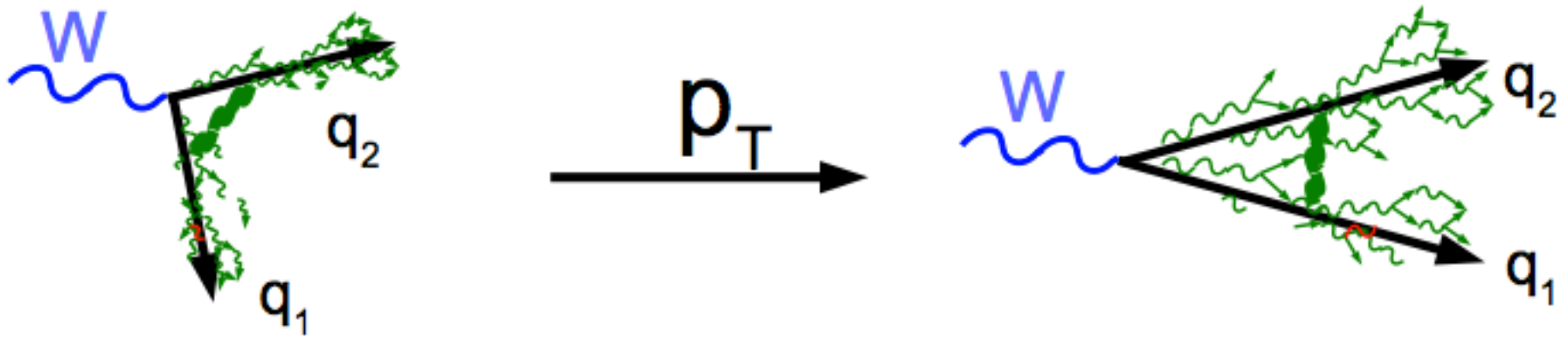


- Main background is from ZZ di-bosons
- Understanding ZZ di-boson pT is critical



Build a V-tagger

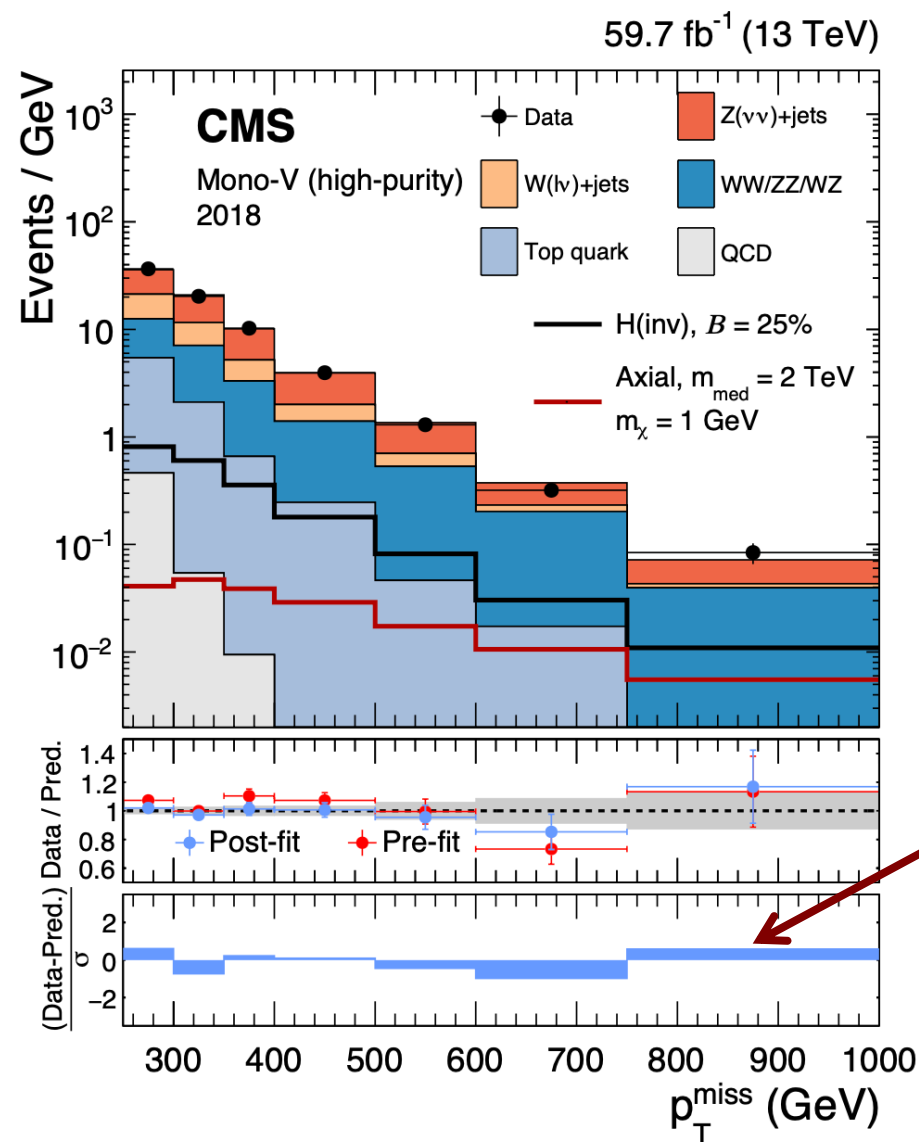
- Two jets are more collimated at high p_T



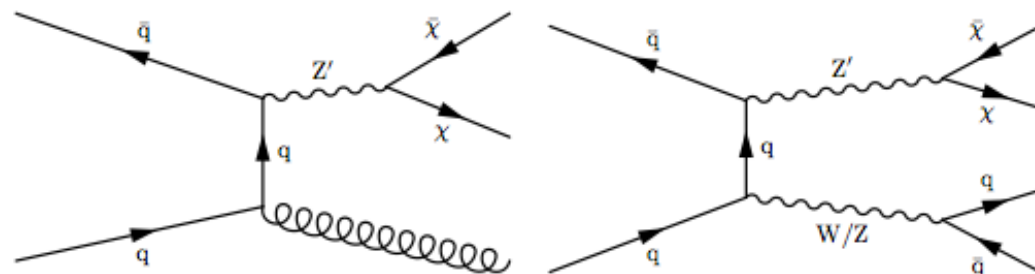
- At **low p_T** jets are “resolved”
 - Focus on reconstructing di-jets with mass near W mass
- At **high p_T** get one “fat” jet
 - Focus on identifying one jet with mass near W mass
- Use additional variables to improve discrimination

DM+jet/V

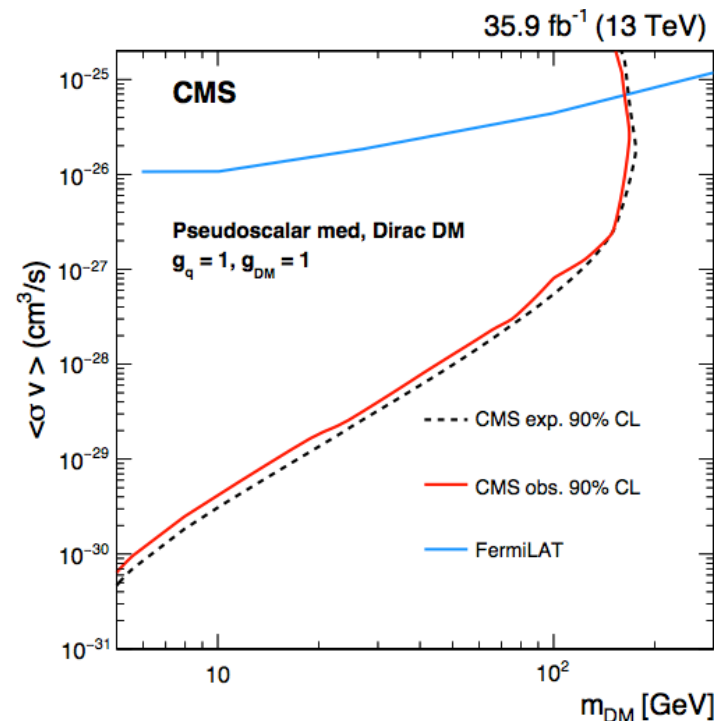
arXiv:2107.13021



DM search in mono-jet/V



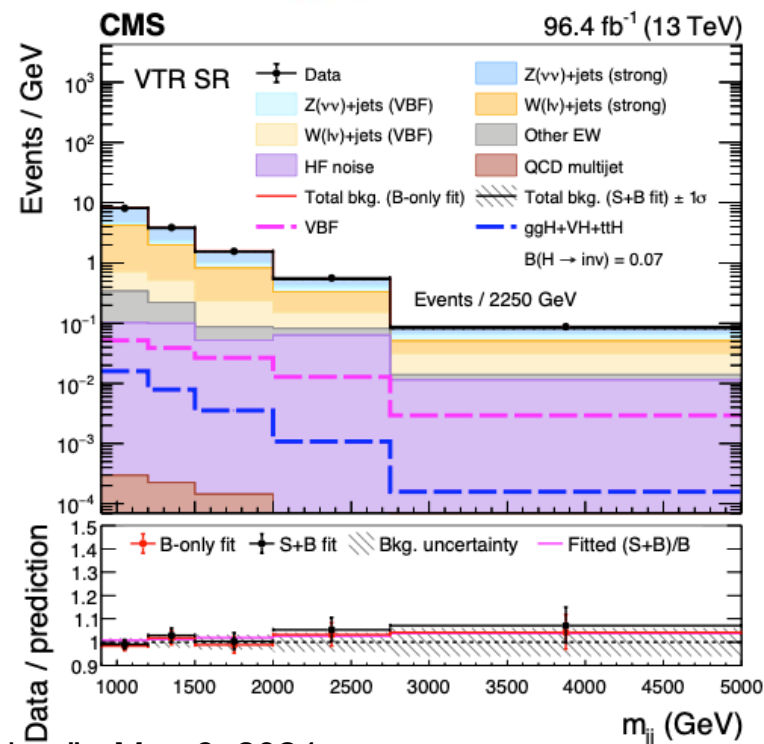
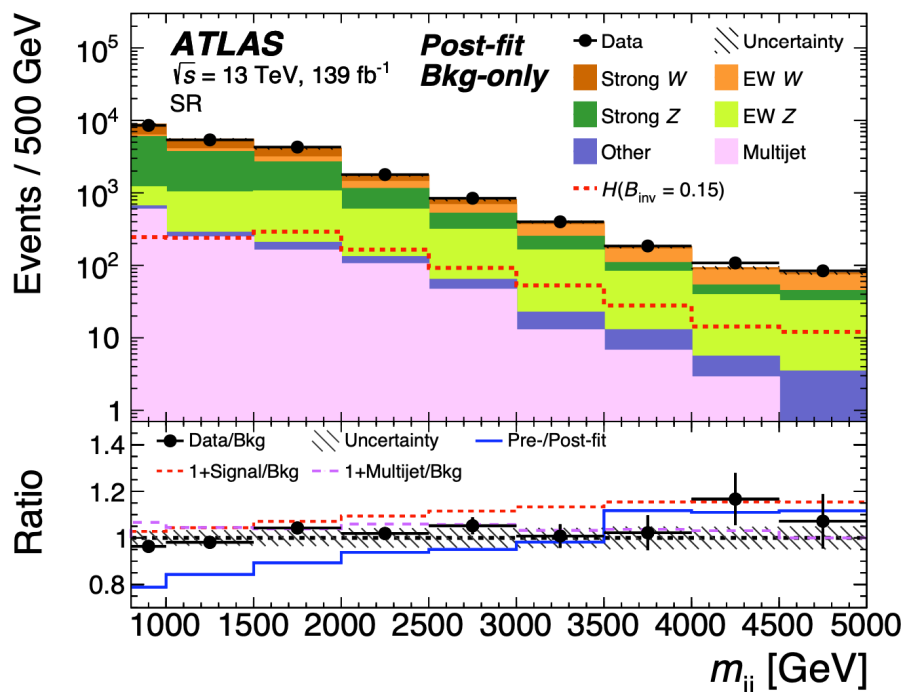
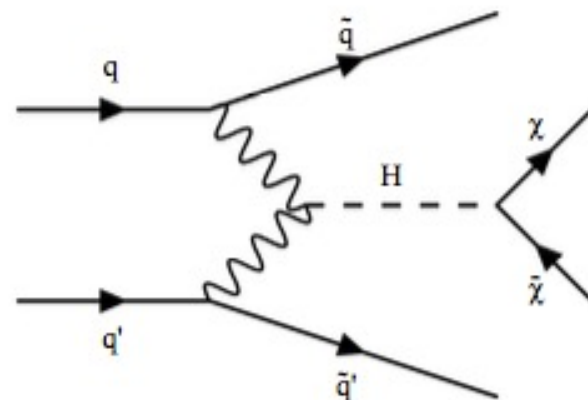
Need good control of systematics



VBF: H(invisible)

arXiv:2201.11585, arXiv:2201.11585

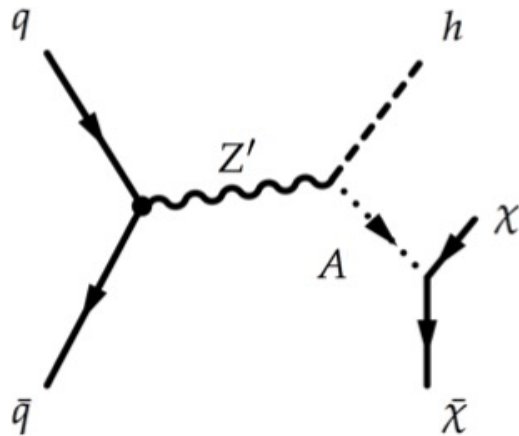
- In the SM, $B(H \rightarrow \text{invisible})$ only 0.1%
 - Any significant deviation would indicate BSM
 - Signature: Large MET, $\Delta\phi(jj)$, veto ℓ/b -jets
 - C&C and shape fit of $m(jj)$
 - Main bkg: V+jets (95%)
 - Tag with forward jets+MET
- Set limits: $B(H \rightarrow \text{inv.}) < 0.18$ (0.10) @95%CL



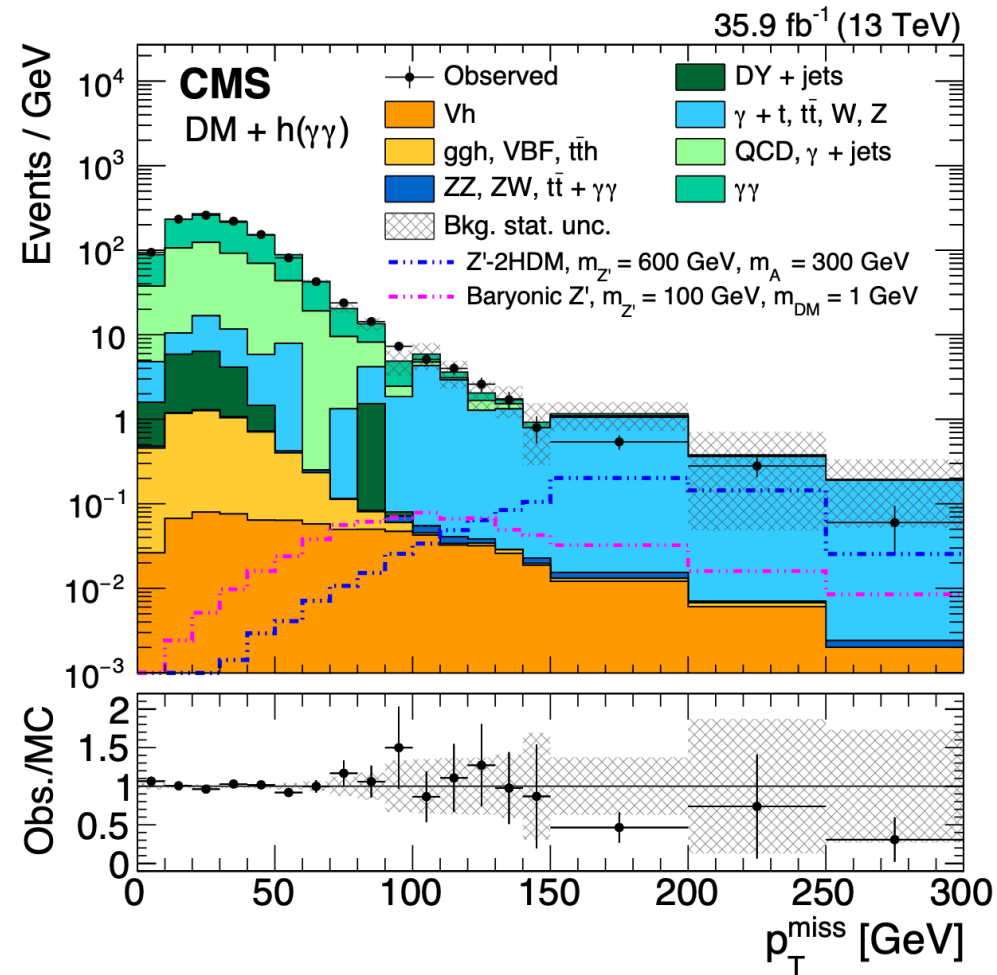
DM+Higgs

arXiv:1806.04771

- DM search with $H(\rightarrow \tau\tau, \gamma\gamma)$
- Model dependent search
 - Z' 2HDM Model and barionic Z'



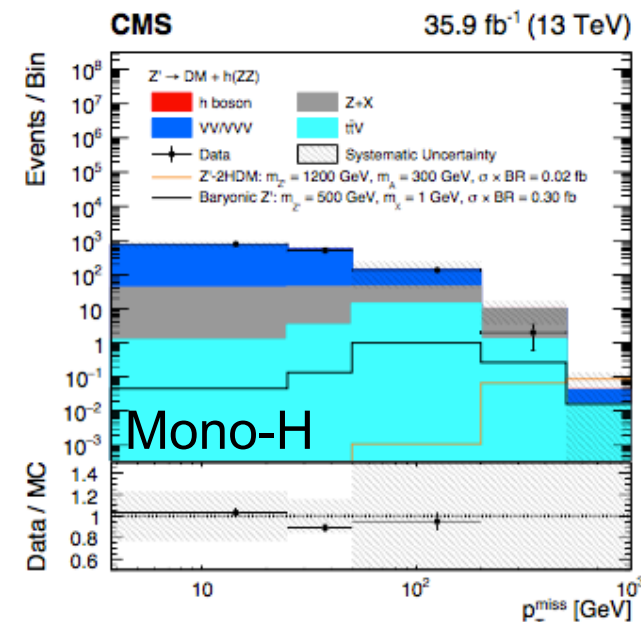
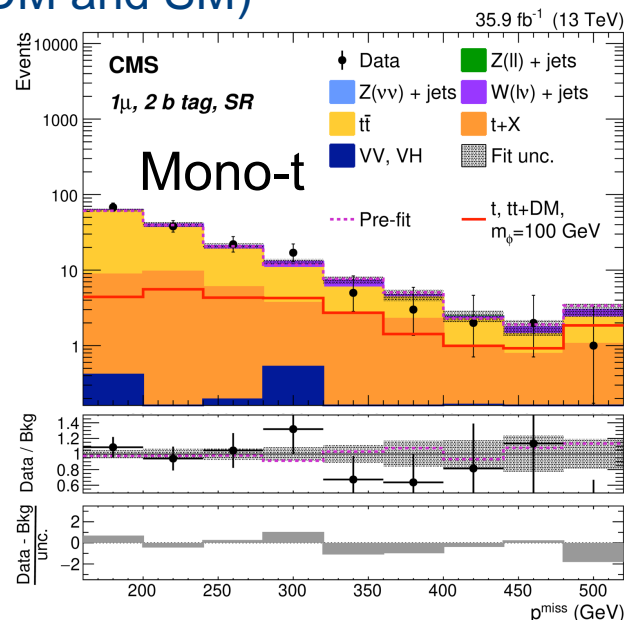
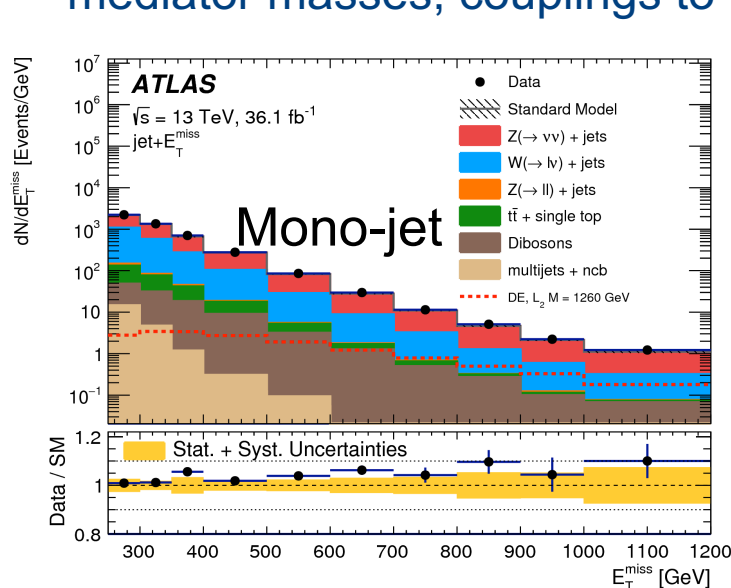
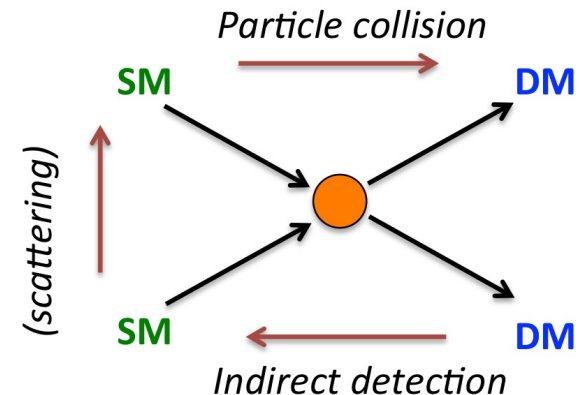
- No significant excess
- Set limits



Dark Matter

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

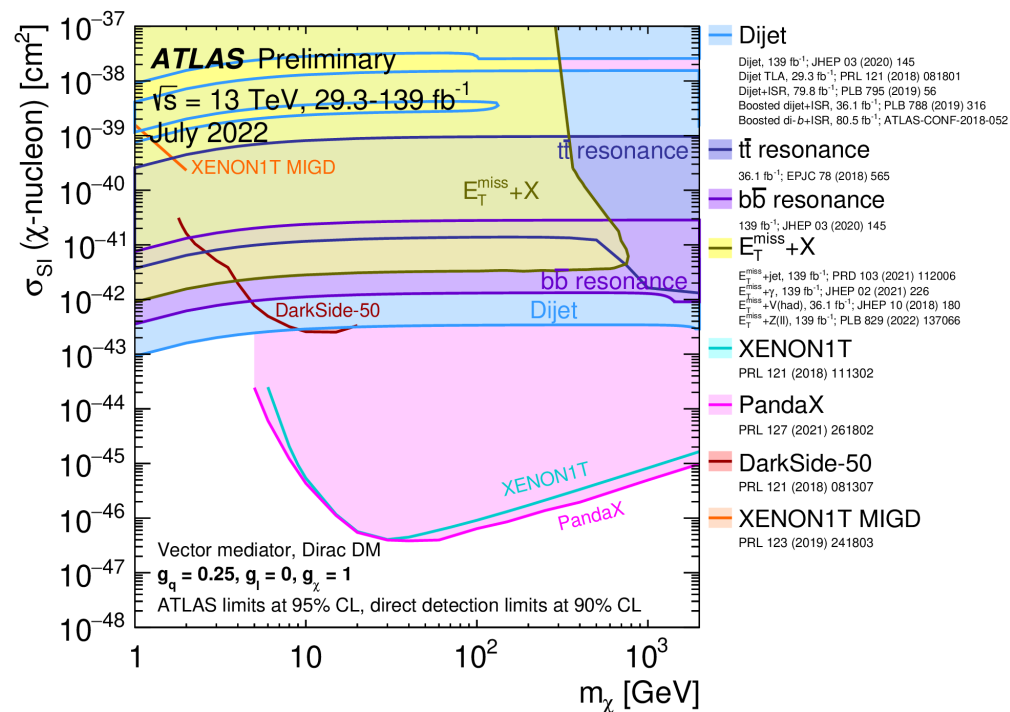
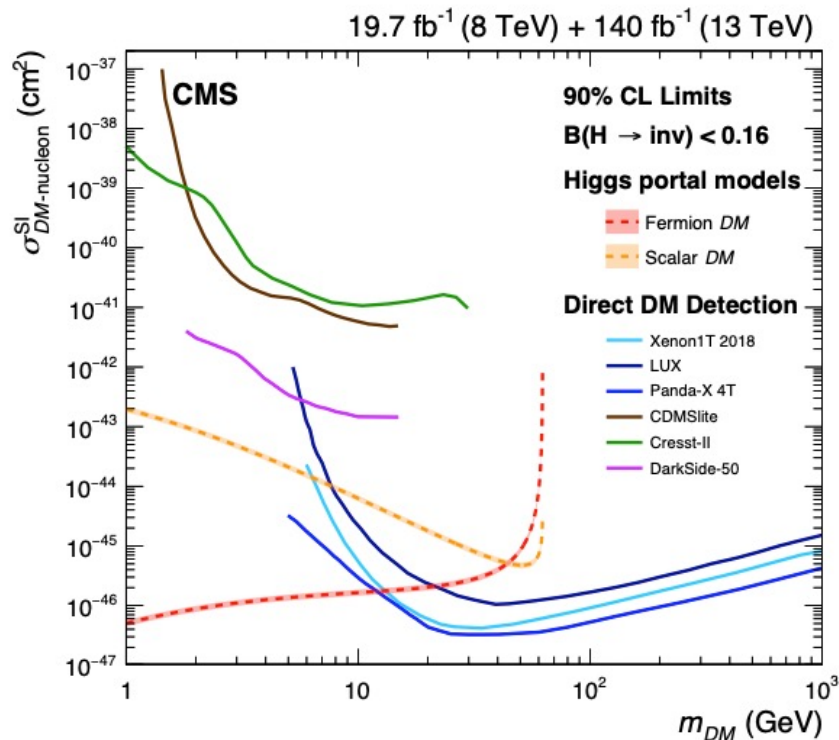
- Complementarity to direct/indirect searches
- DM particles:
 - interact via spin-0 & spin-1 mediators
 - are undetected (MET) recoiling against SM particle(s)
- Extensive program of mono-X searches (X=jet, γ , lepton, W, Z, t, tt, bb, H)
- No excess observed
- Interpretation through simplified models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

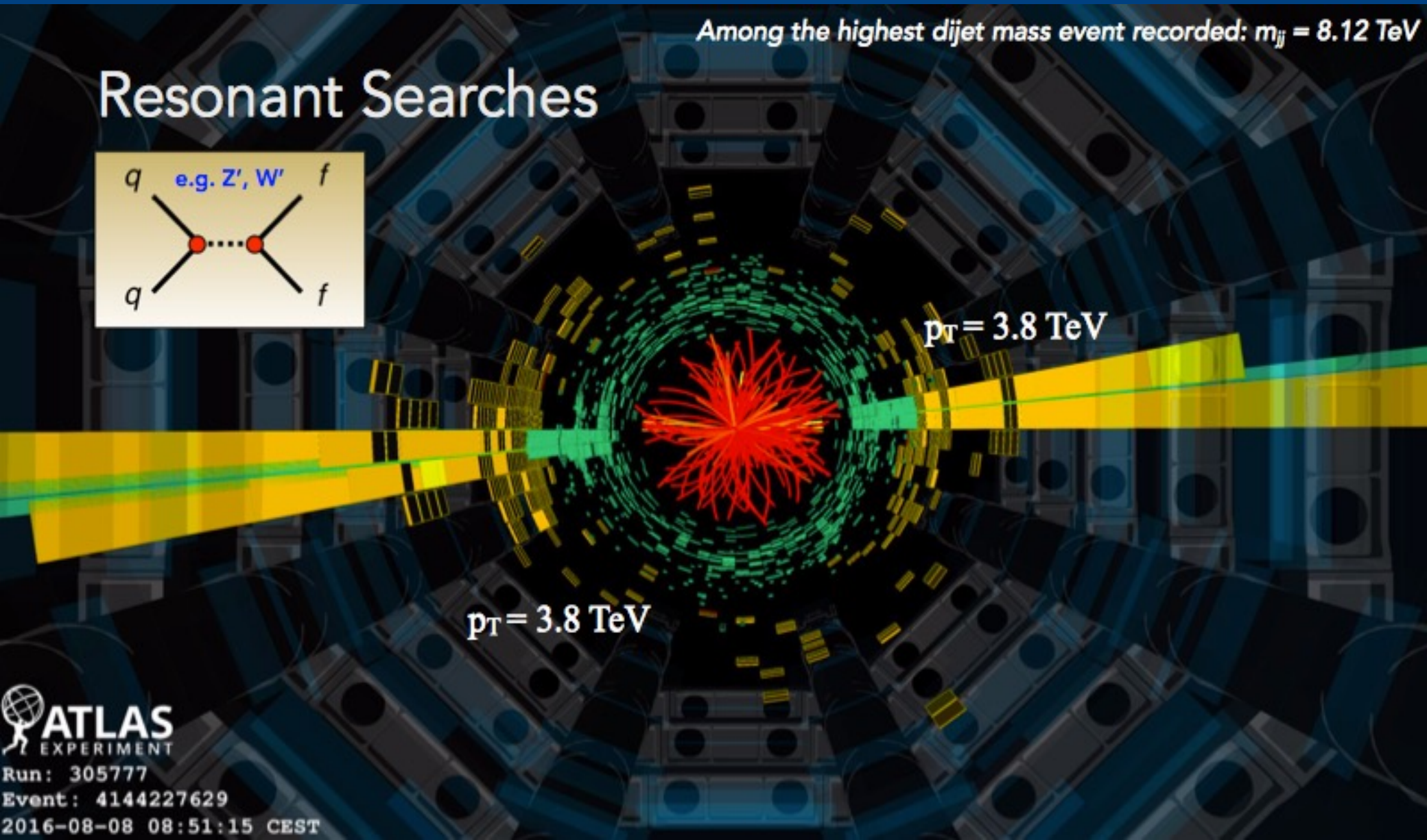
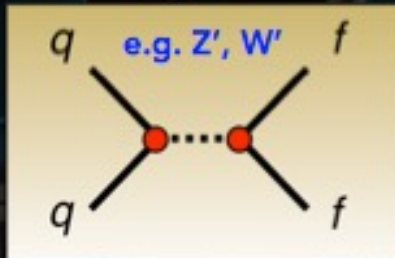


⇒ Collider results complement direct searches for low masses (<5-10GeV)

Resonant searches

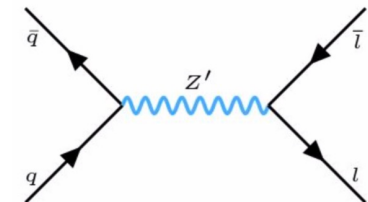
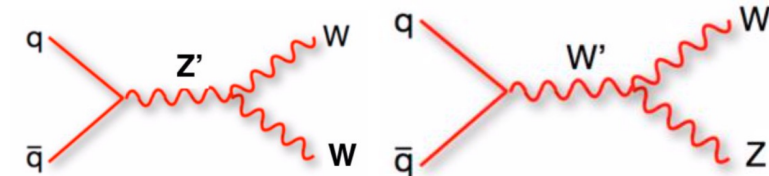
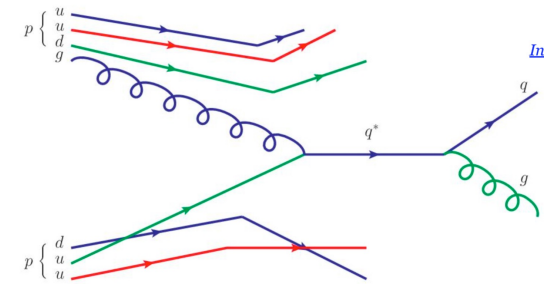
Among the highest dijet mass event recorded: $m_{jj} = 8.12 \text{ TeV}$

Resonant Searches



BSM models predict new resonances

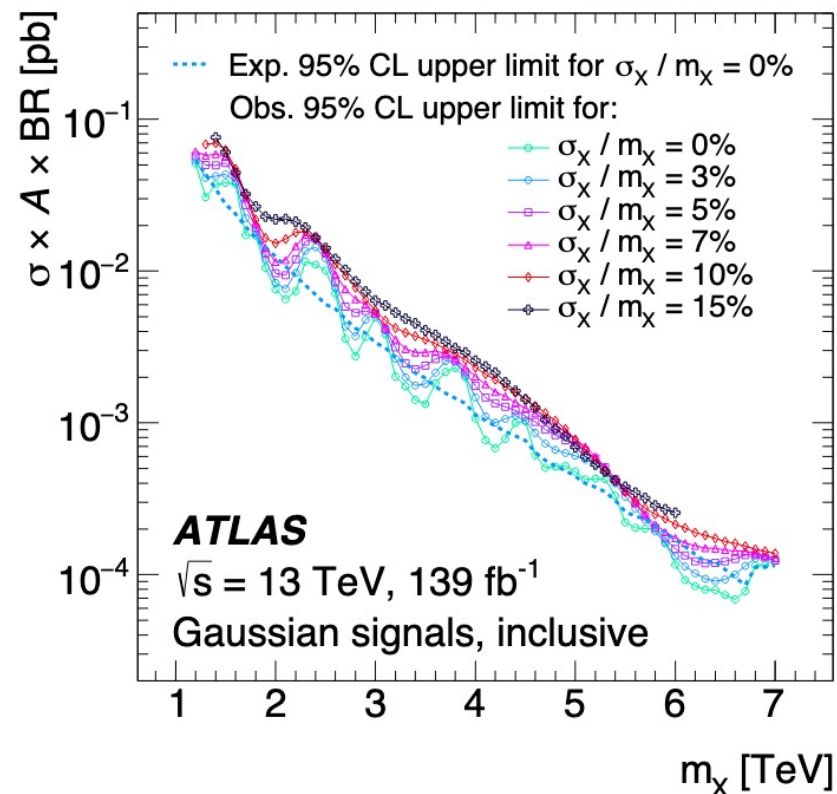
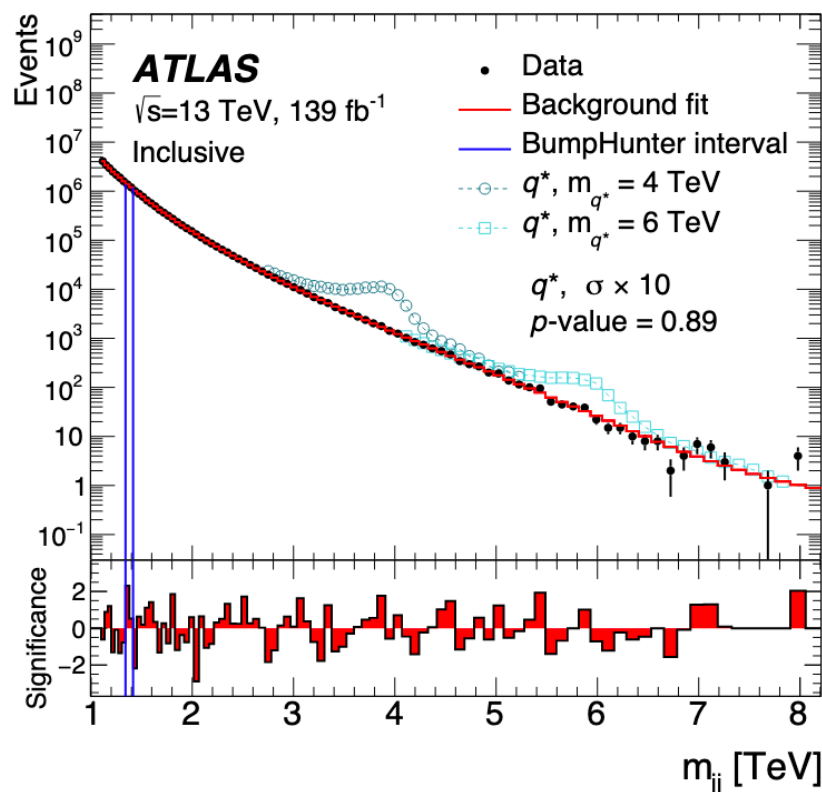
- BSMs predict resonances with spin 0,1,2
- Are quarks fundamental particles?
 - Excited quarks in models of compositeness
- Randall-Sundrum (RS) models
 - Spin-2 graviton (KK-particle)
- Heavy-Vector Triplets
 - Spin-1 resonance
 - Models based on strength of vector boson interactions
- Sequential SM
 - Z' and Z with same couplings to fermions
 - Width proportional to the mass



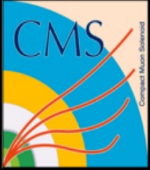
New phenomena in di-jet events

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



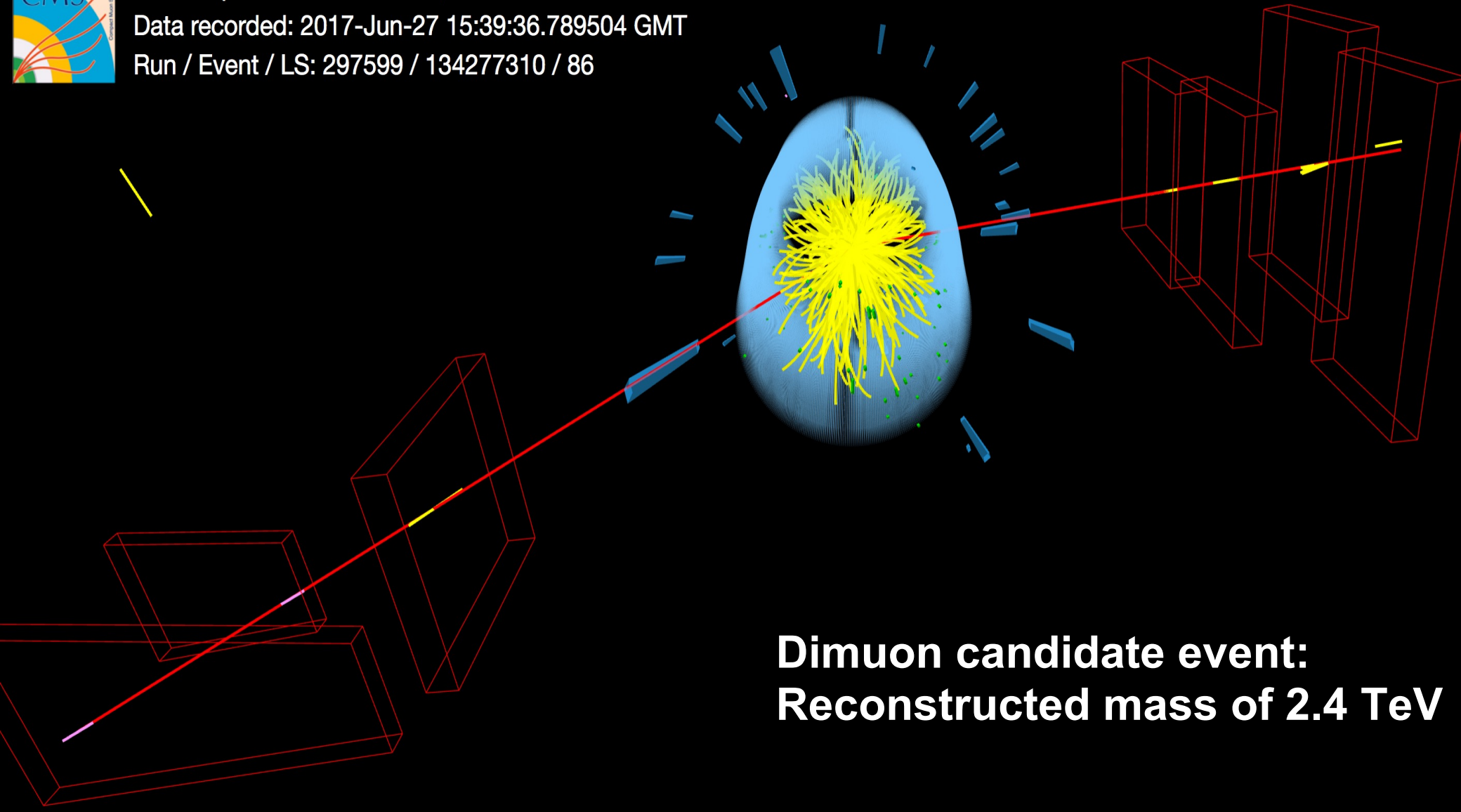
Searching for dilepton resonances



CMS Experiment at the LHC, CERN

Data recorded: 2017-Jun-27 15:39:36.789504 GMT

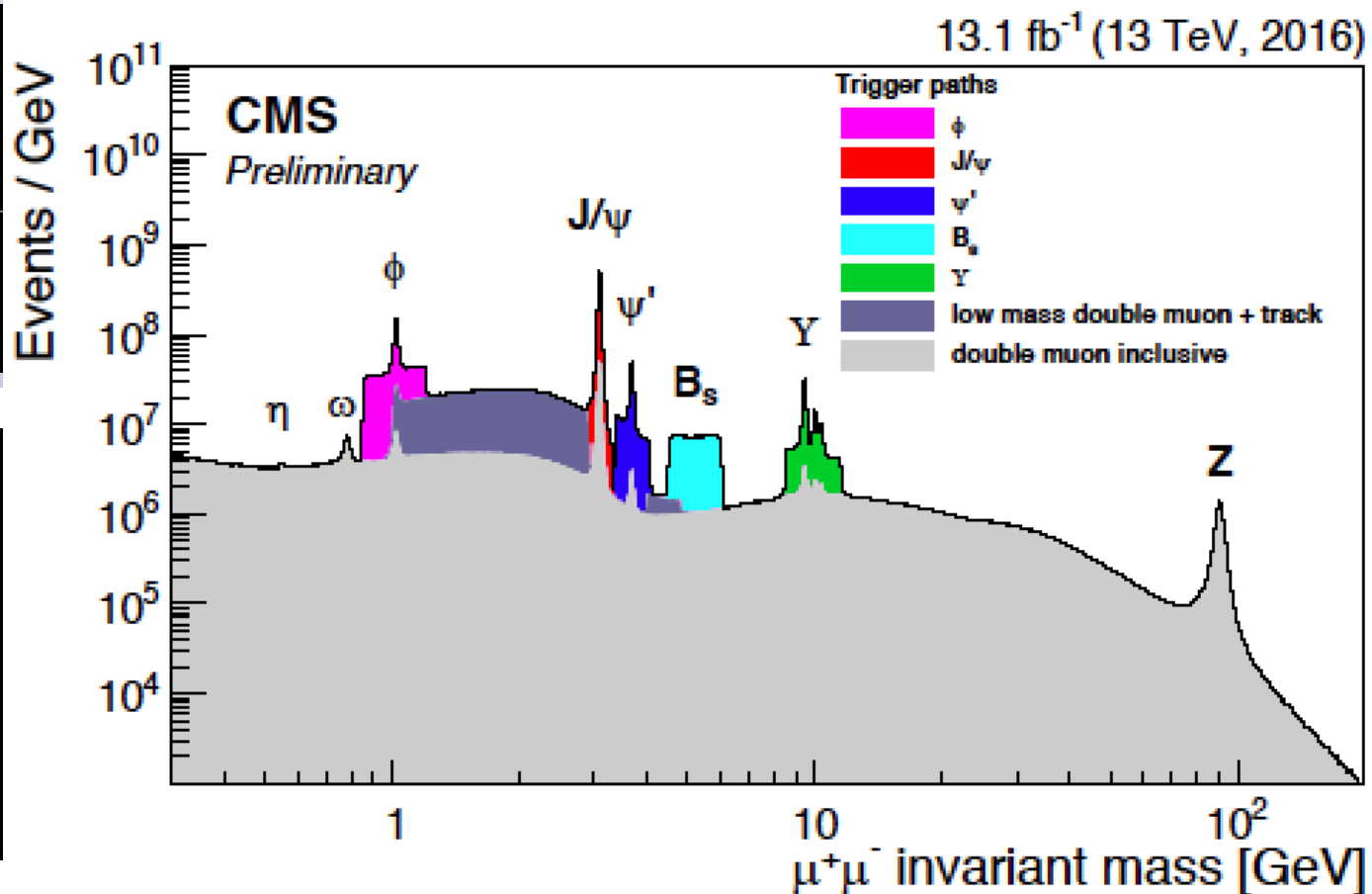
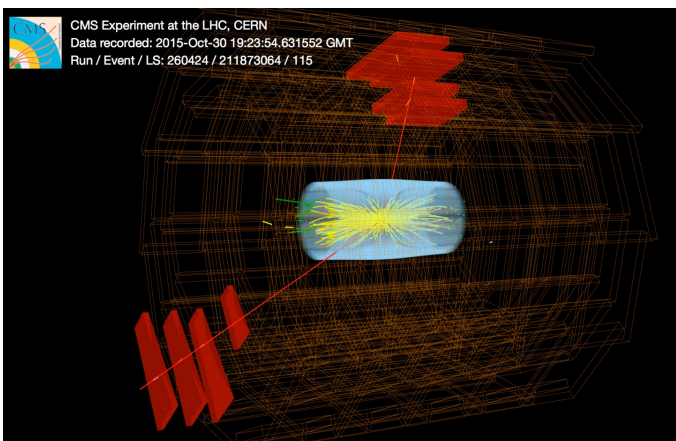
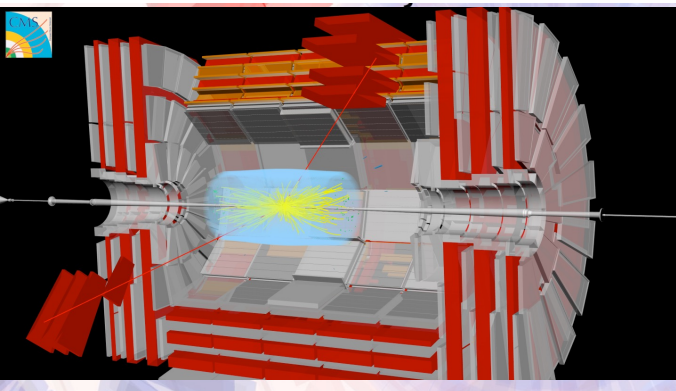
Run / Event / LS: 297599 / 134277310 / 86



**Dimuon candidate event:
Reconstructed mass of 2.4 TeV**

Di-muon events

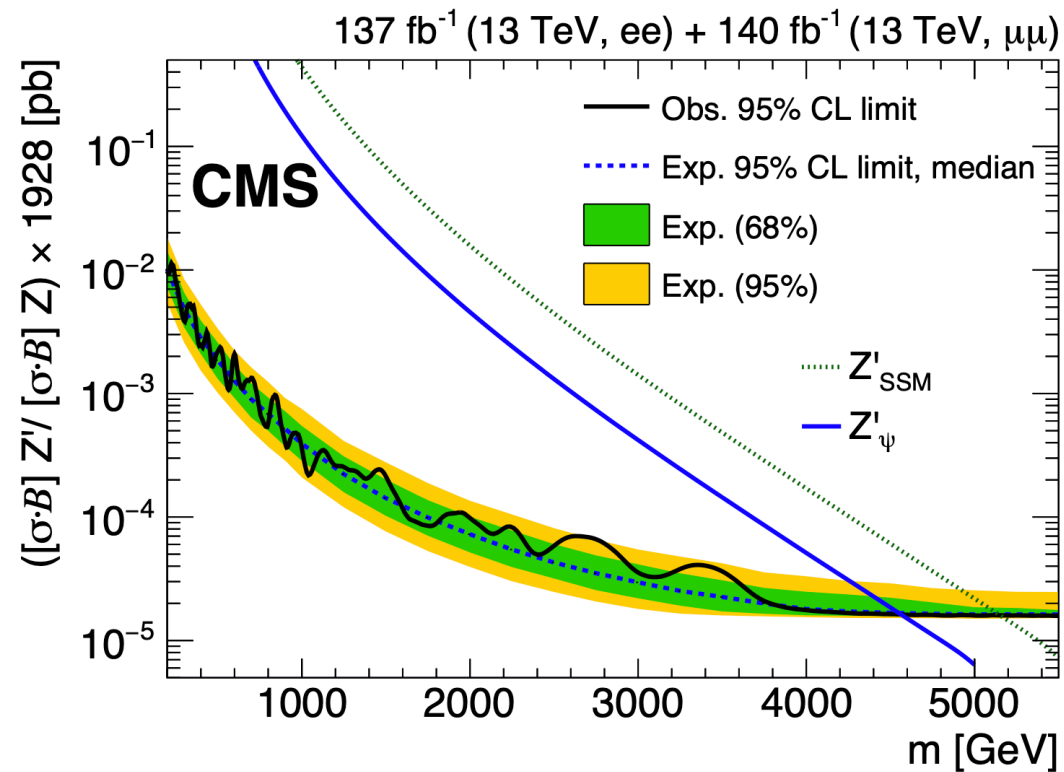
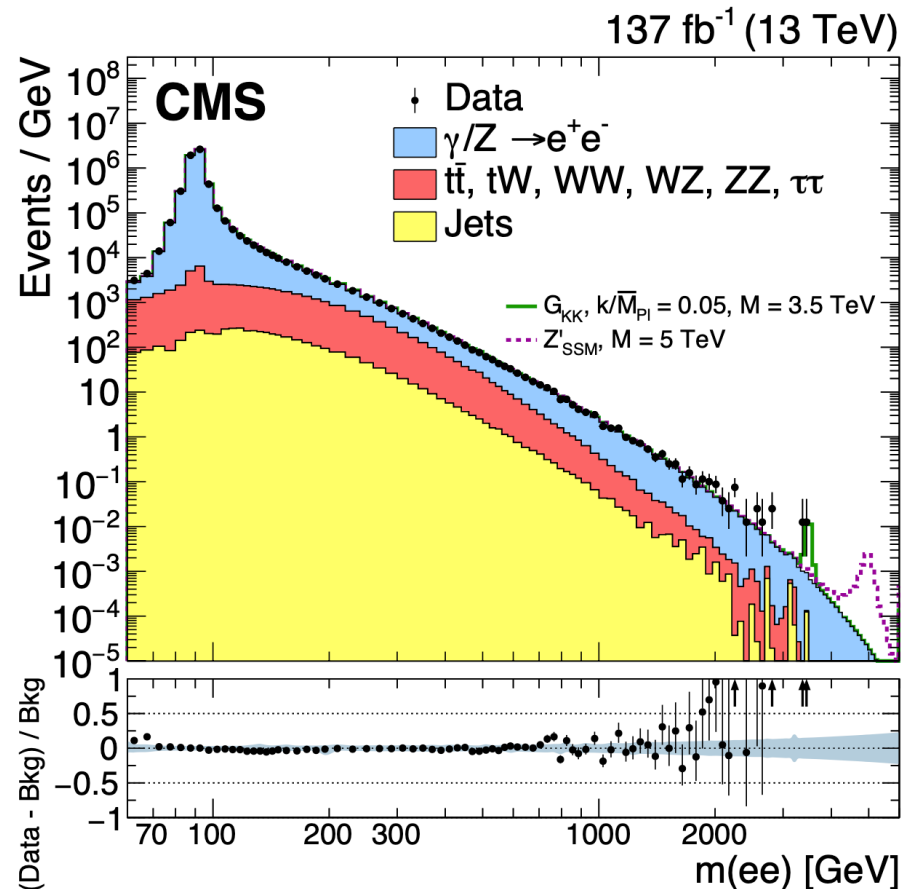
- Di-muon events: a re-discovery of the SM



High-mass dilepton resonances

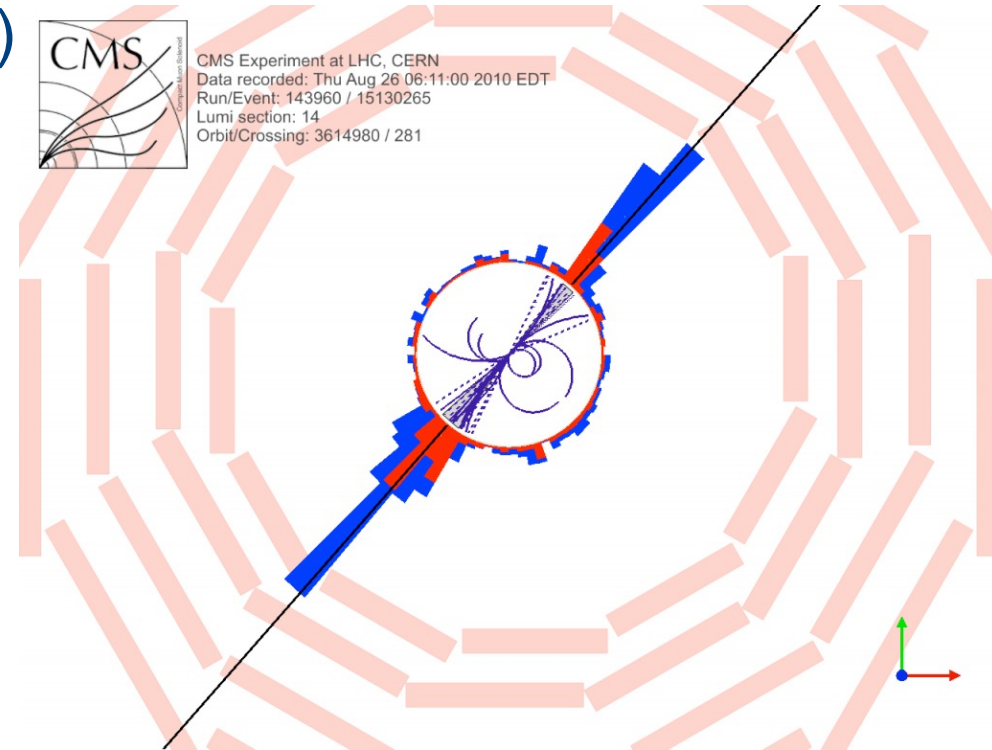
arXiv:1903.06248, arXiv:2103.02708

- Search for dilepton ($ee, \mu\mu$) resonance



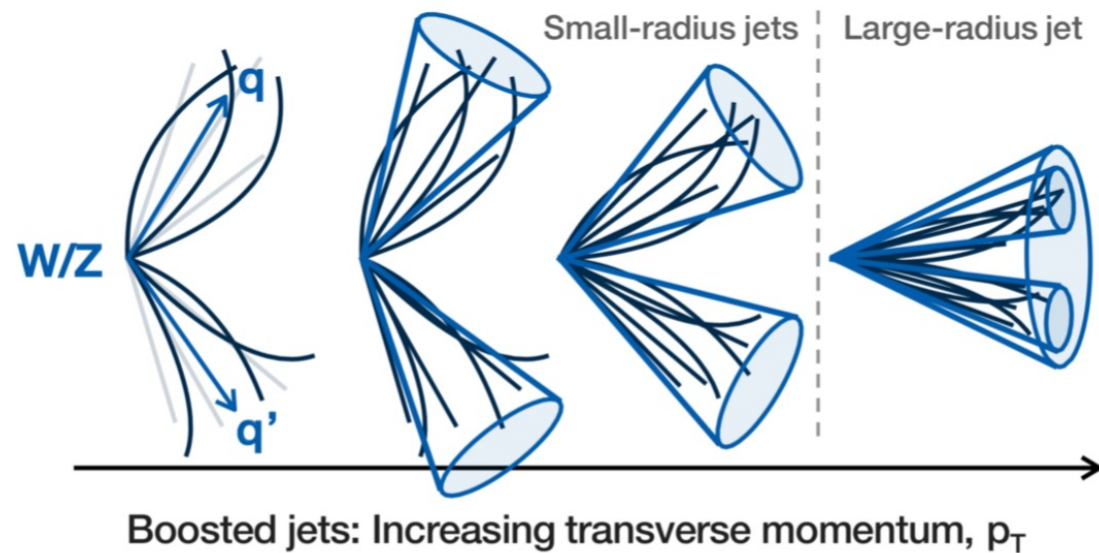
Search for diboson resonances

- Heavy BSM resonances ($>1\text{TeV}$) 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

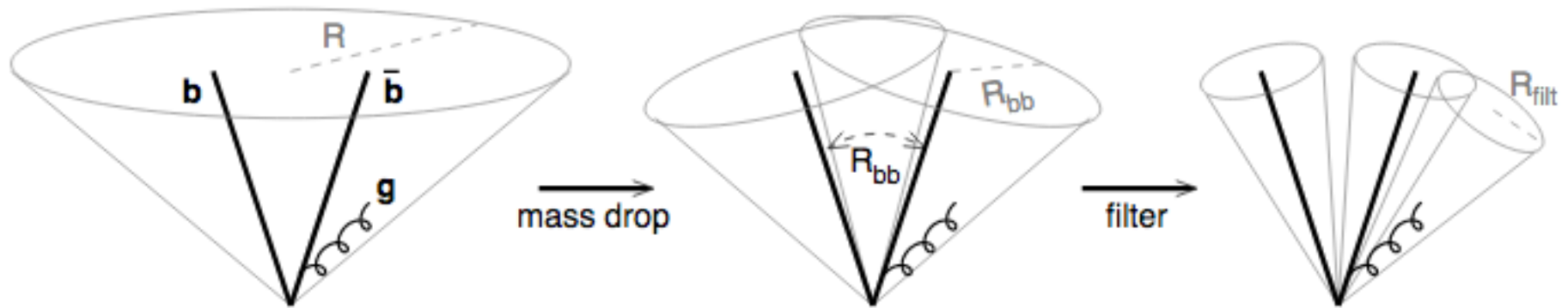


Jet grooming

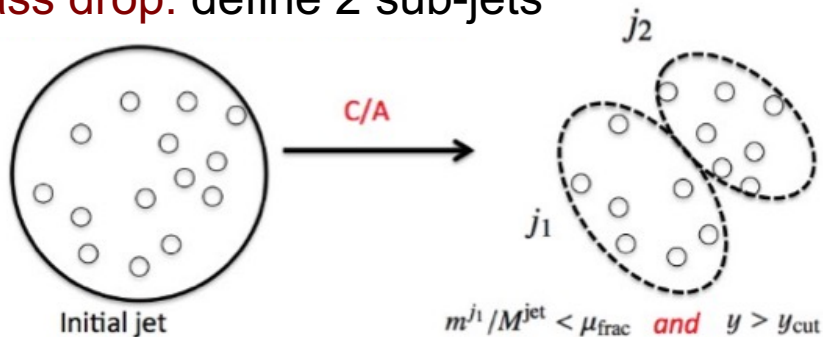
arXiv:0802.2470

Mass drop/filtering

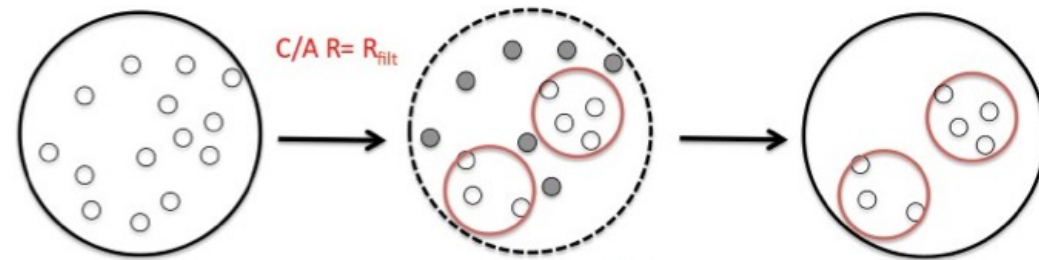
- Identify approx. symmetric sub-jets (with smaller mass than sum)



Mass drop: define 2 sub-jets



Filtering: re-cluster j_1, j_2 constituents

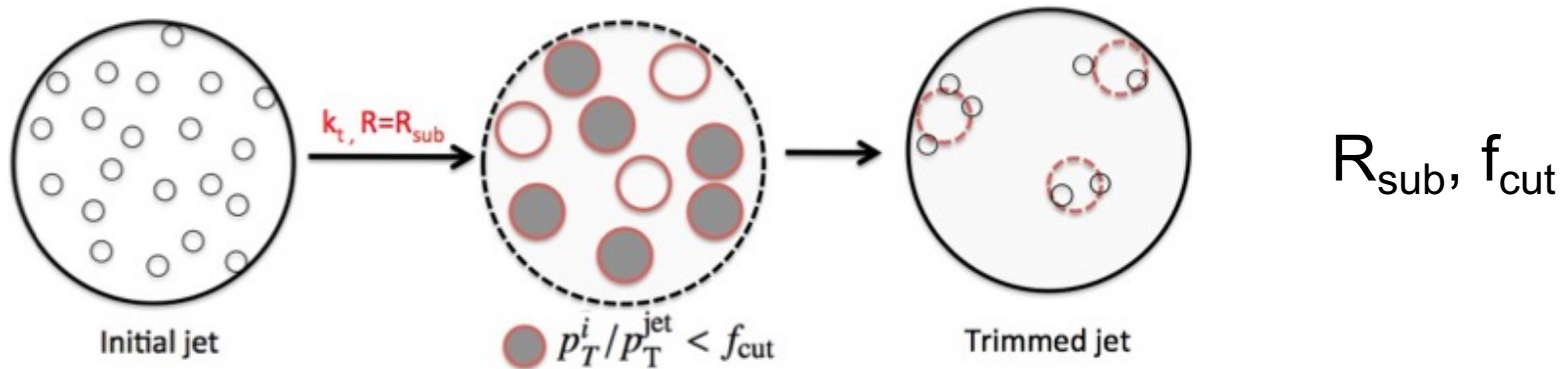


Jet grooming (cont.)

arXiv:0912.1342, arXiv:0912.0033

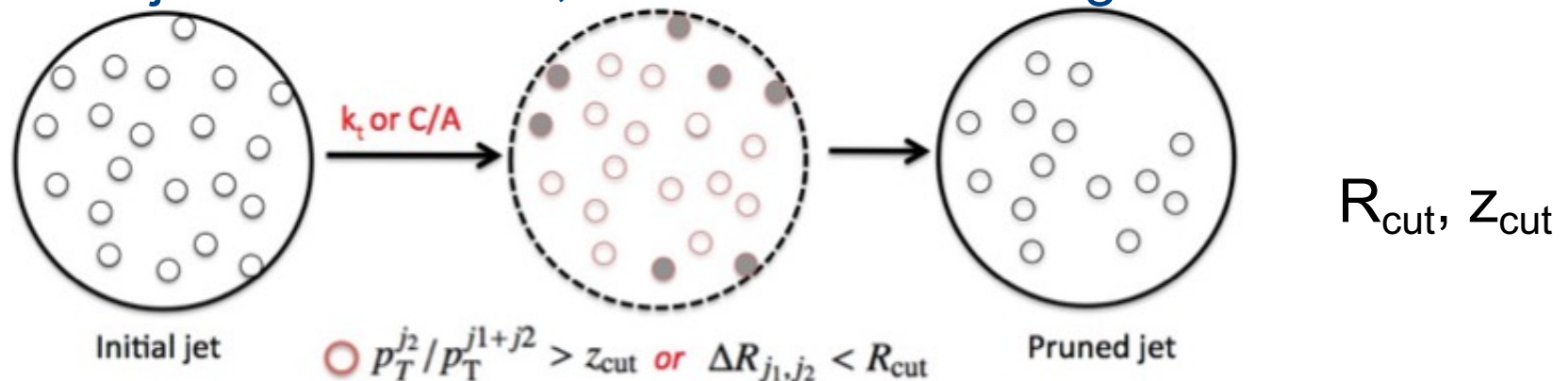
“Trimming”

- Uses kT algorithm to make subjets (subjets with $p_T^i/p_T < \text{cut}$ removed)



“Pruning”

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

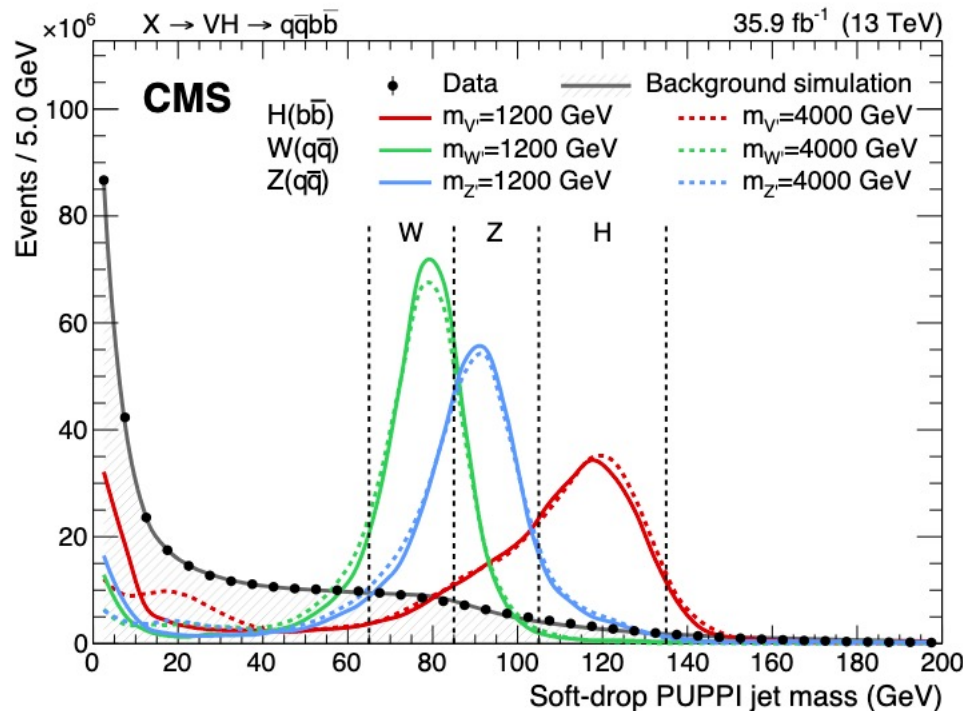


W, Z, H reconstruction

arXiv:1707.01303

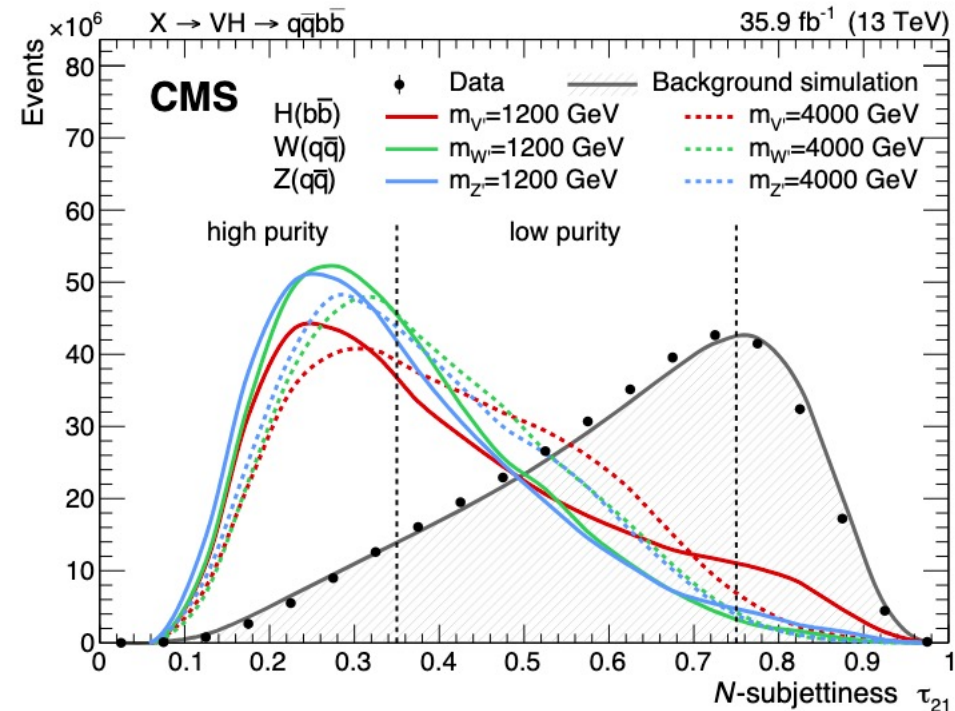
- Grooming and jet mass

- Pruning
- soft drop (stable w/pileup, and good jet mass resolution $\sim 10\%$)



- Vector boson tagging ($V \rightarrow qq$)

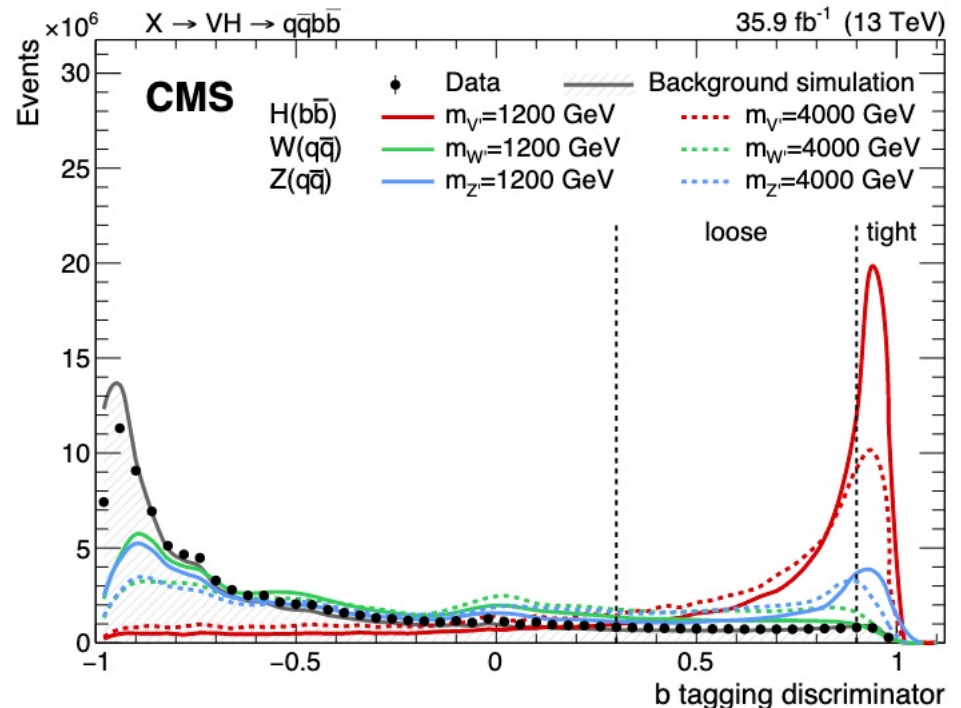
- n-subjettiness τ_{21} : how consistent with 2 sub-jets
- Categorization according to purity: high (<0.35) and high (>0.35)



W, Z, H reconstruction (cont.)

arXiv:1707.01303

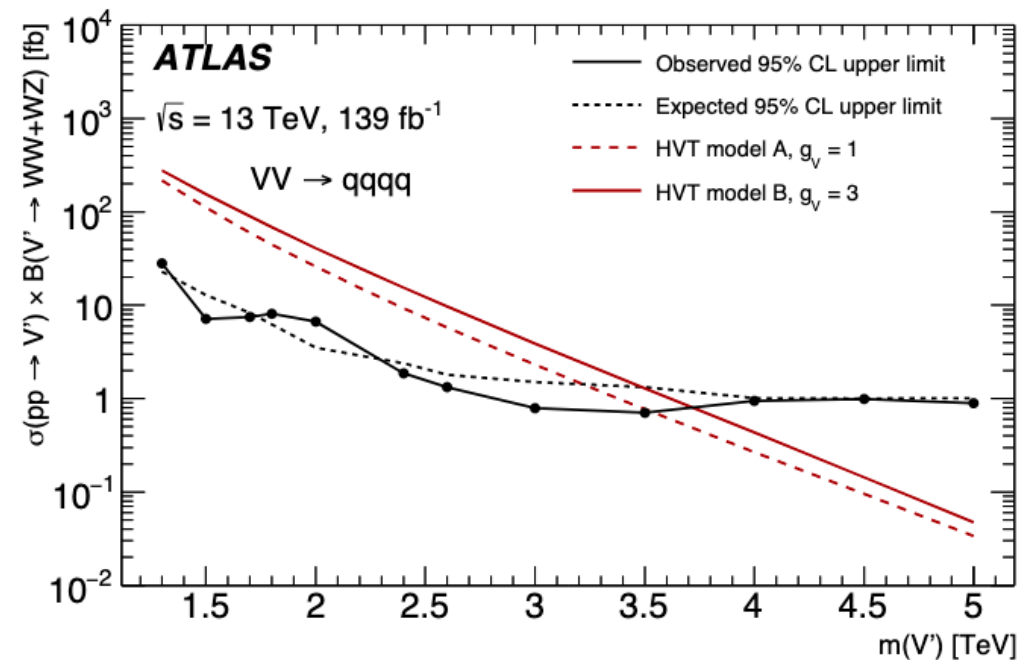
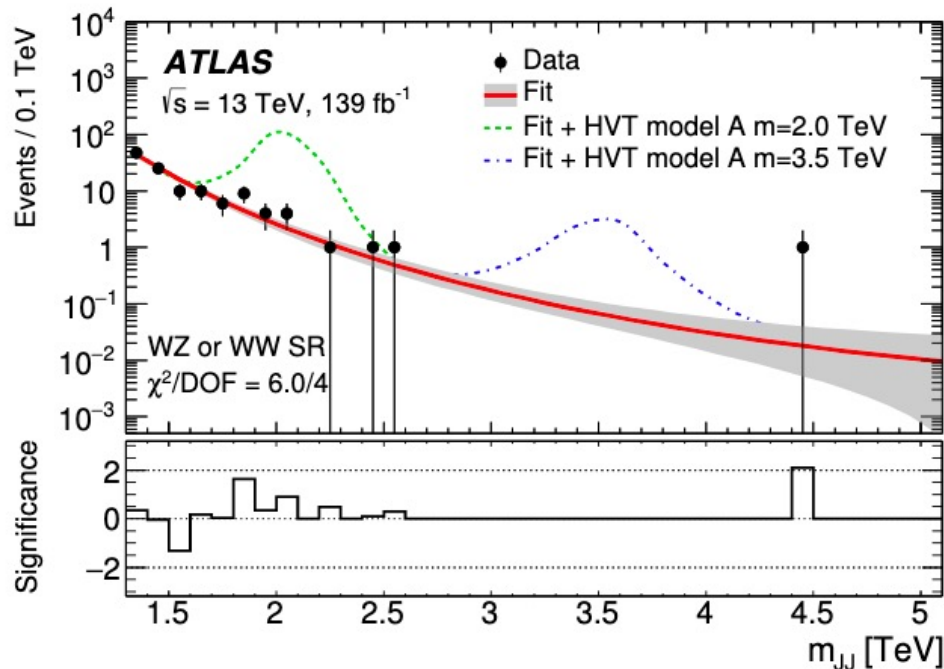
- Higgs boson tagging ($H \rightarrow b\bar{b}$)
 - Double b-tagging
 - Exploit b-tagging to identify two b-quarks in same jet
 - Soft-lepton information
 - Combines tracking and vertexing in MVA



Searching for diboson resonances

arXiv:1906.08589

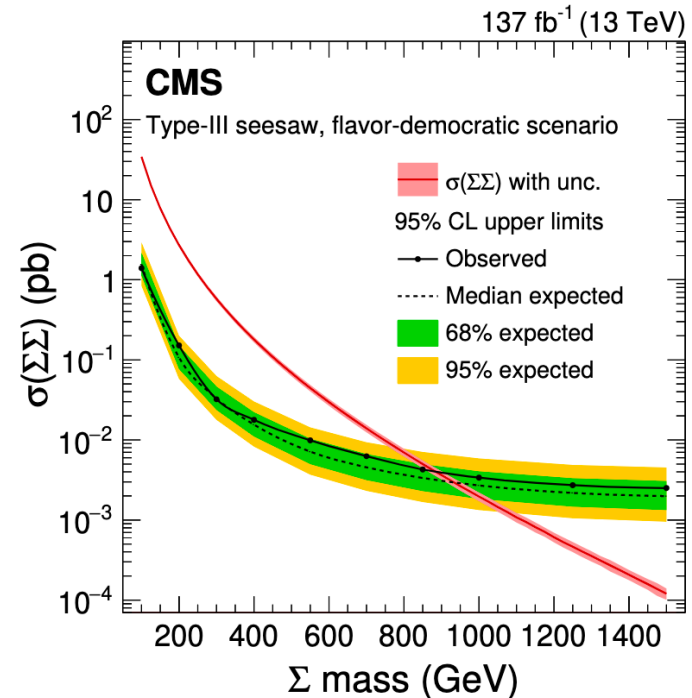
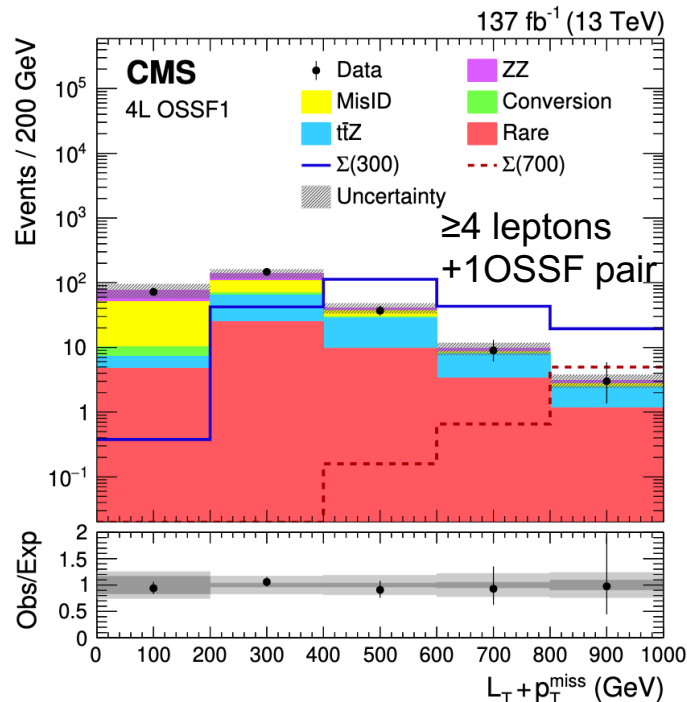
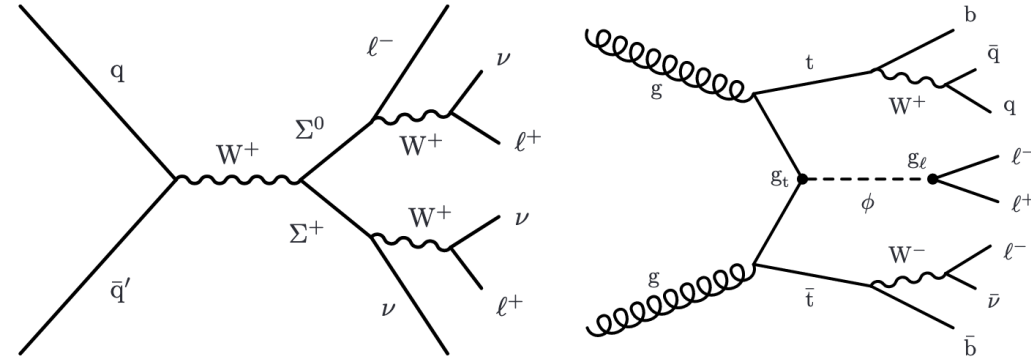
- No significant excess in any of the observed final states
- Exclusion limits: HVT models excluded up to 4.1 TeV, Spin-2 RS models up to 2.8 TeV
- Large improvements due to new methods for jet reconstructions and boson tagging



Search for multi-lepton final states

JHEP 03(2020)051

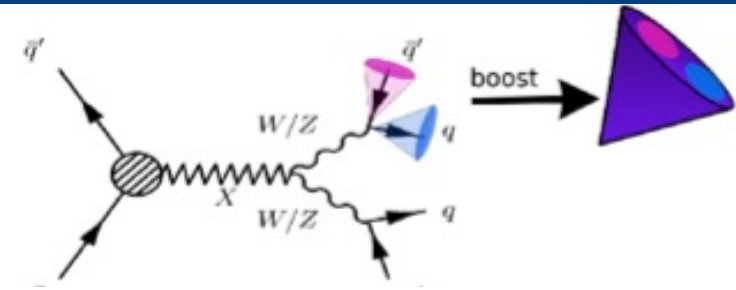
- Search for new heavy particles
 - Heavy fermions/scalars produced in association with $t\bar{t}$
- Search for 3 or more lepton final states
- Pair production of $W/Z/H \rightarrow \Sigma\Sigma$
 - Scalar sum of lepton p_T (L_T)
 - Bin and count ($L_T + \text{MET}$)



$X \rightarrow VV \rightarrow qqqq$

arXiv:1708:05379

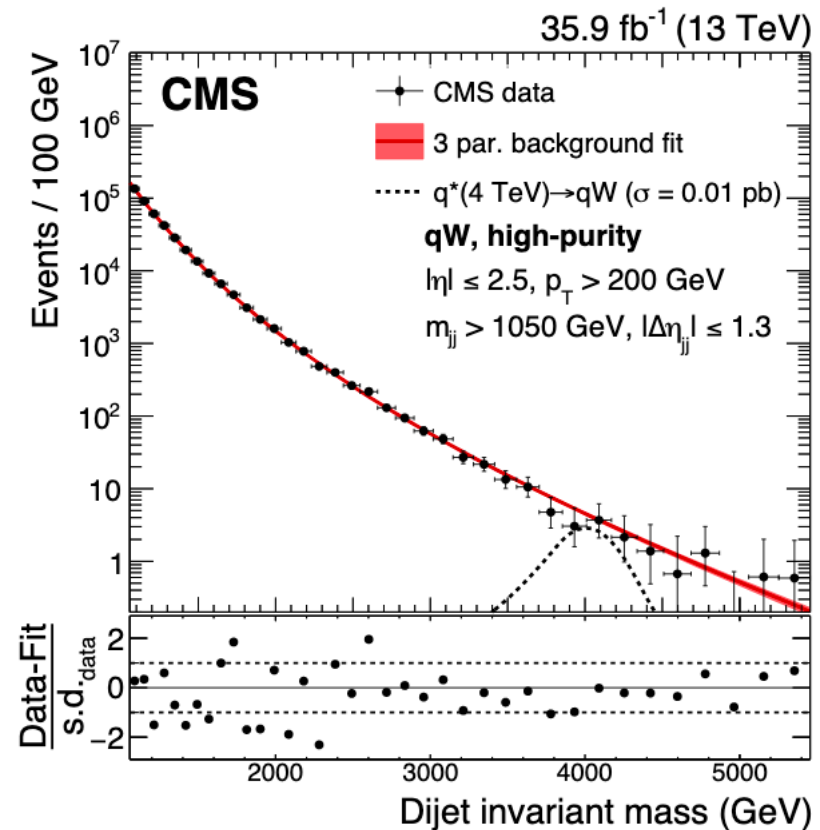
- All hadronic resonance search with single (qV) or double (VV) V-tag
 - At least 2 back-to-back jets $p_T > 200 \text{ GeV}$
 - Categorization (jet mass, τ_{21})
- Background estimation: “bump hunt” fit data with power law



Candidate ZZ event
Dijet mass: 3.2 TeV

Anti- k_T R=0.8 jet
 p_T 1321 GeV
 η -0.40
 ϕ -2.71
 M_{SD} 103 GeV
 τ_{21} 0.23

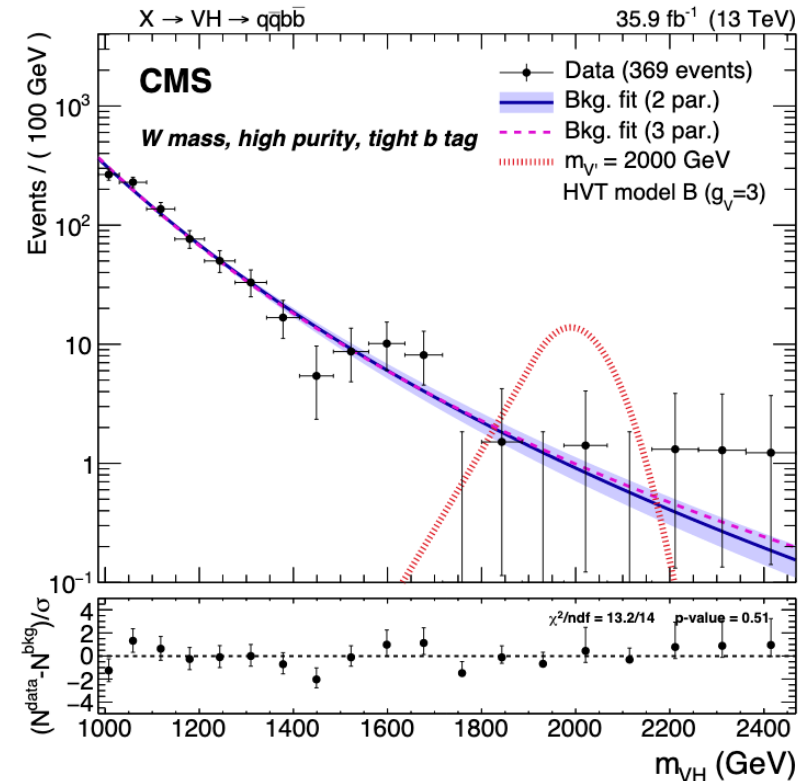
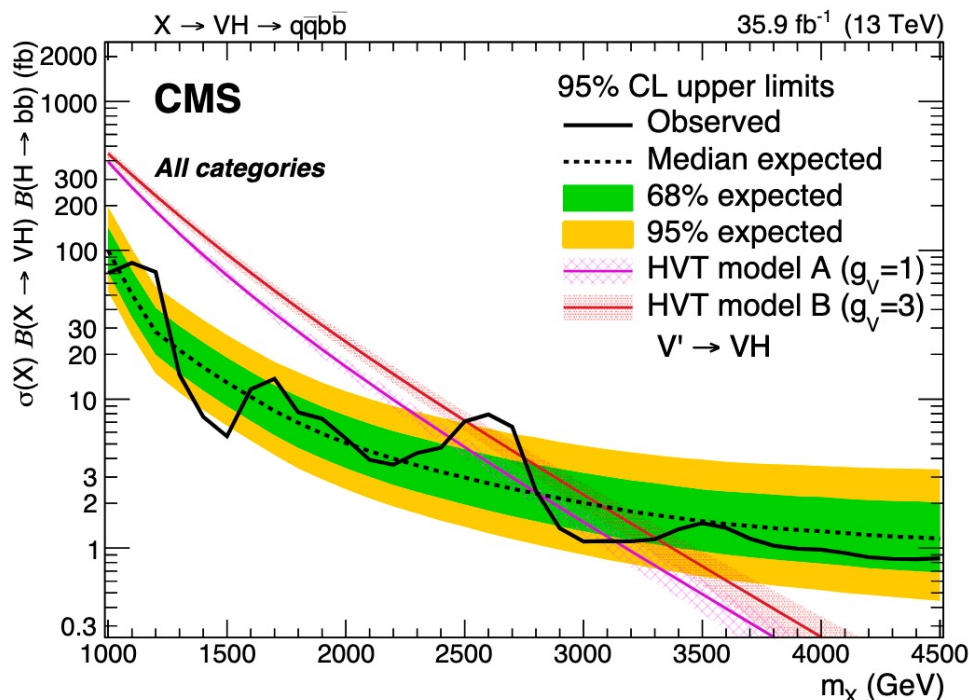
Anti- k_T R=0.8 jet
 p_T 1374 GeV
 η 0.79
 ϕ 0.43
 M_{SD} 94.8
 τ_{21} 0.29



$X \rightarrow VH \rightarrow qqbb$

arXiv:1707.01303

- All-hadronic search for $V \rightarrow qq$ and $H \rightarrow bb$ resonances
 - dedicated identification for $H \rightarrow bb$ (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)

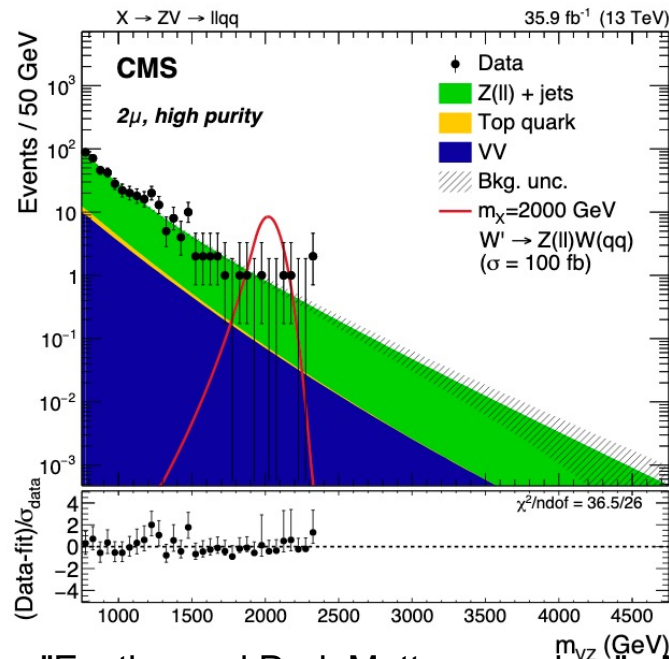
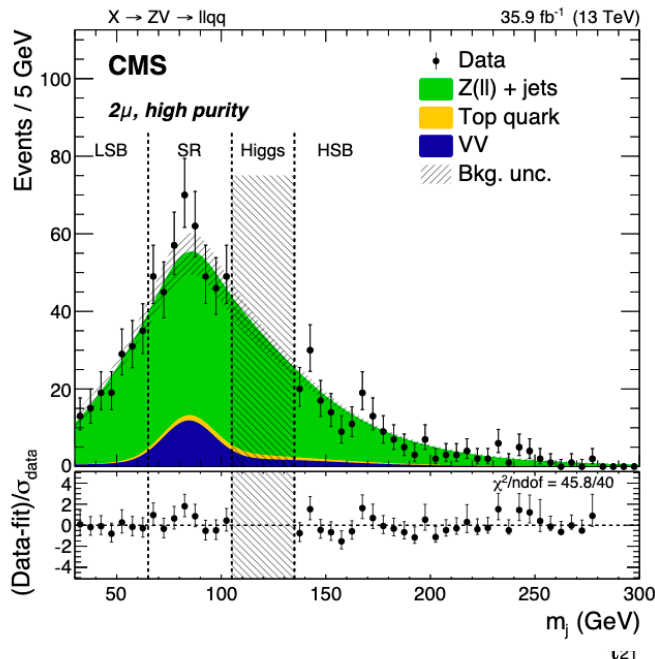
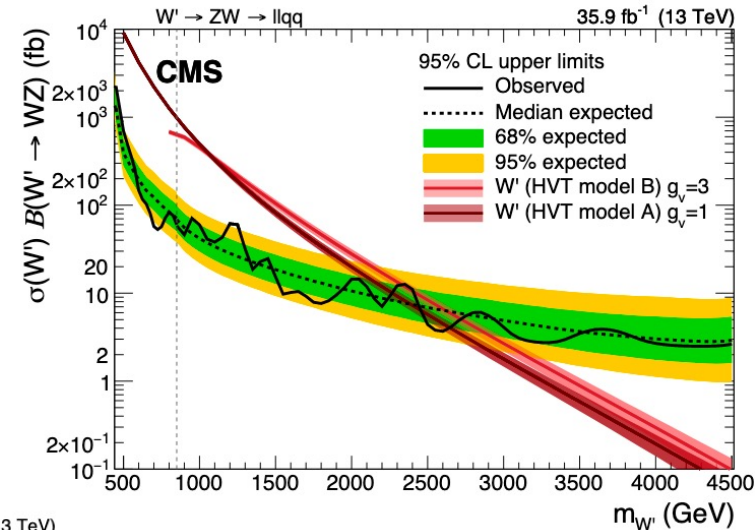


- Similar topology and background estimate to VV resonance search
- No significant excess found in data

$X \rightarrow ZV \rightarrow \ell\ell qq$

arXiv:1803.10093

- Search for resonances in $Z \rightarrow ee/\mu\mu$, $V \rightarrow qq$
- 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

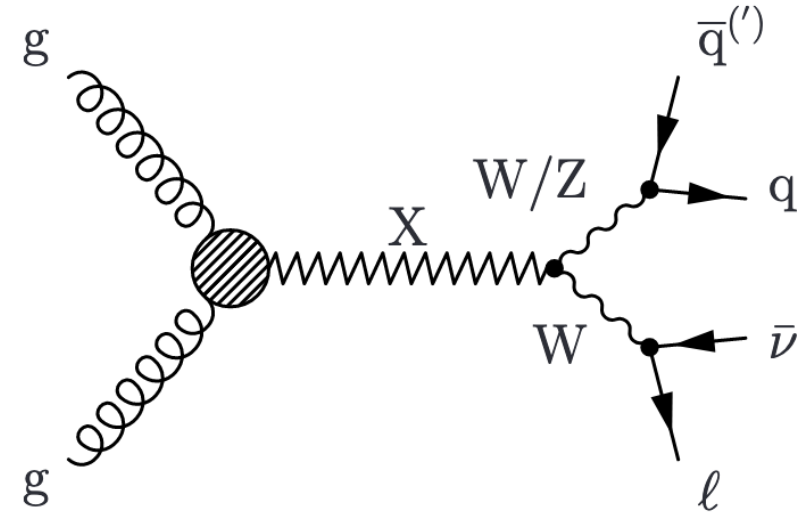
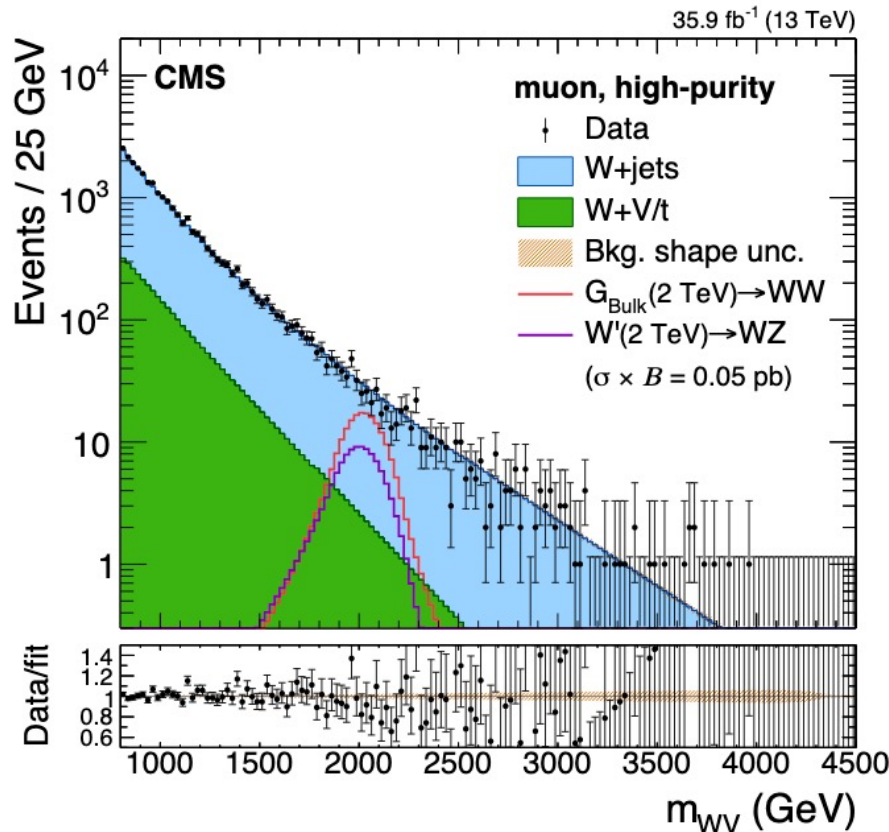


- Data compatible with SM-only hypothesis

$X \rightarrow WV \rightarrow \ell \nu qq$

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



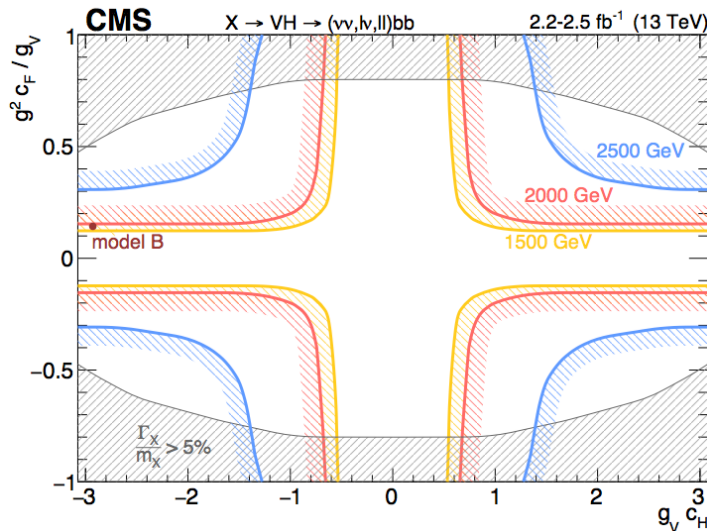
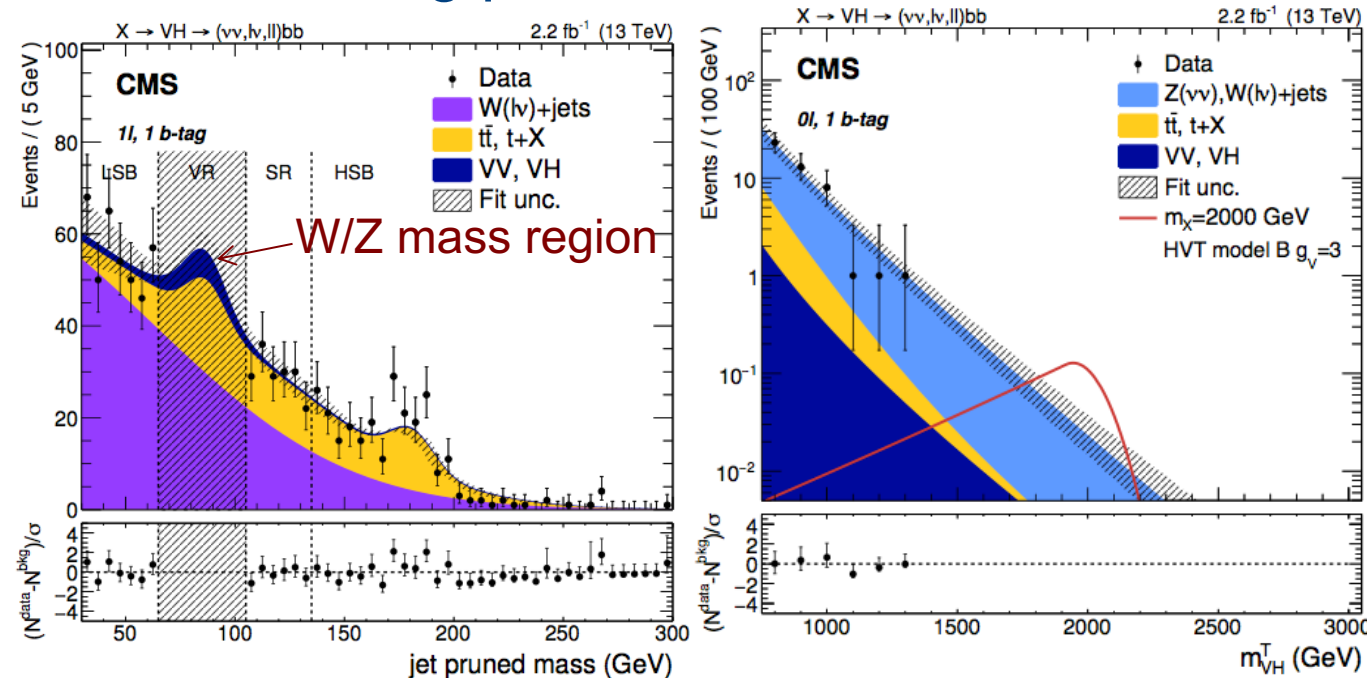
- Similar sensitivity to $Z(\ell)V(qq)$ search
- Excluded up to 1.1-3.1 TeV

$X \rightarrow VH \rightarrow \ell \nu qq$

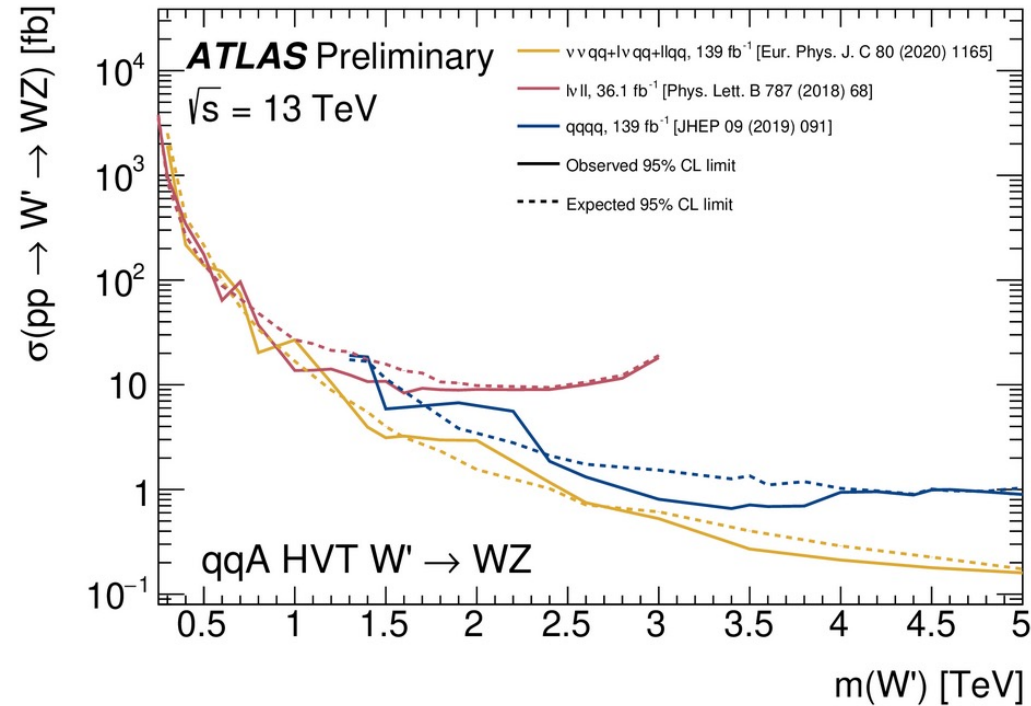
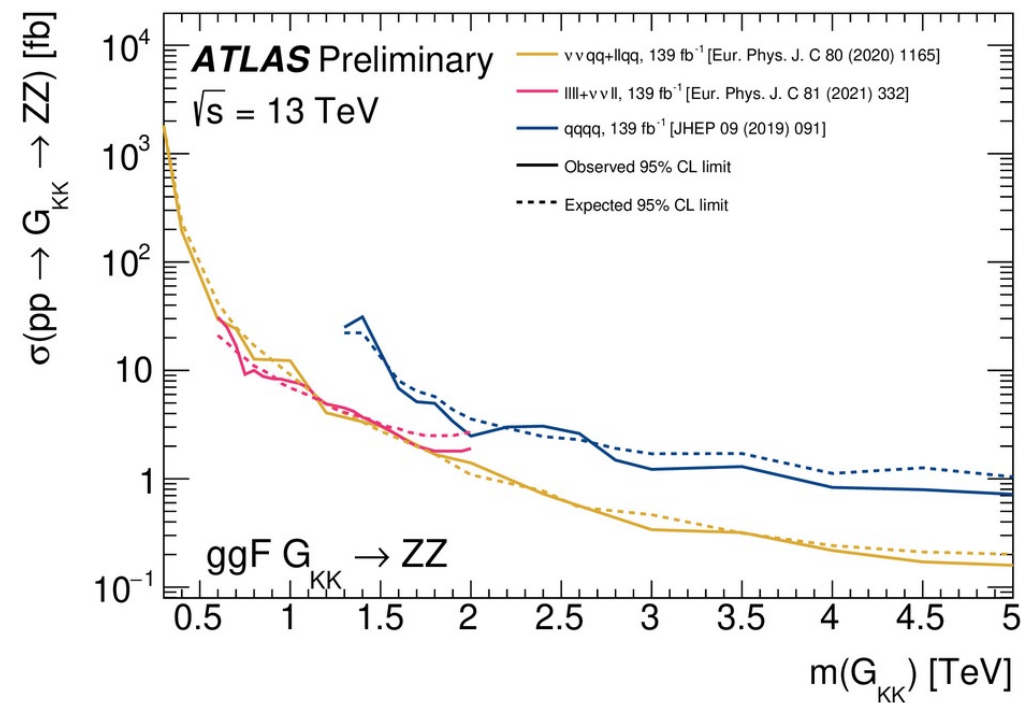
PLB 768(2017)137

- Search for a resonance decaying to VH in leptonic channels
 - $Z \rightarrow \nu\nu$: transverse mass $m_T(VH)$
 - $W \rightarrow \ell\nu$: top control region
 - $Z \rightarrow \ell\ell$: 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



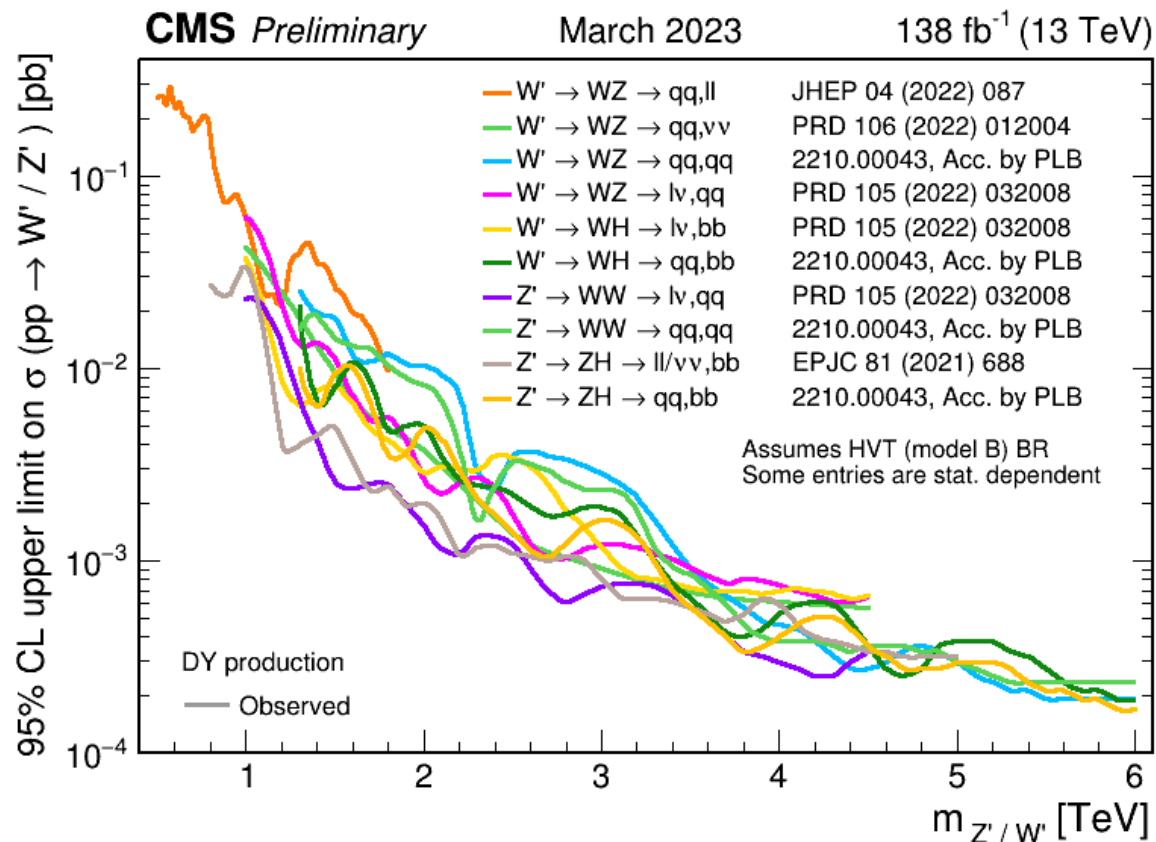
Combination of diboson searches



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



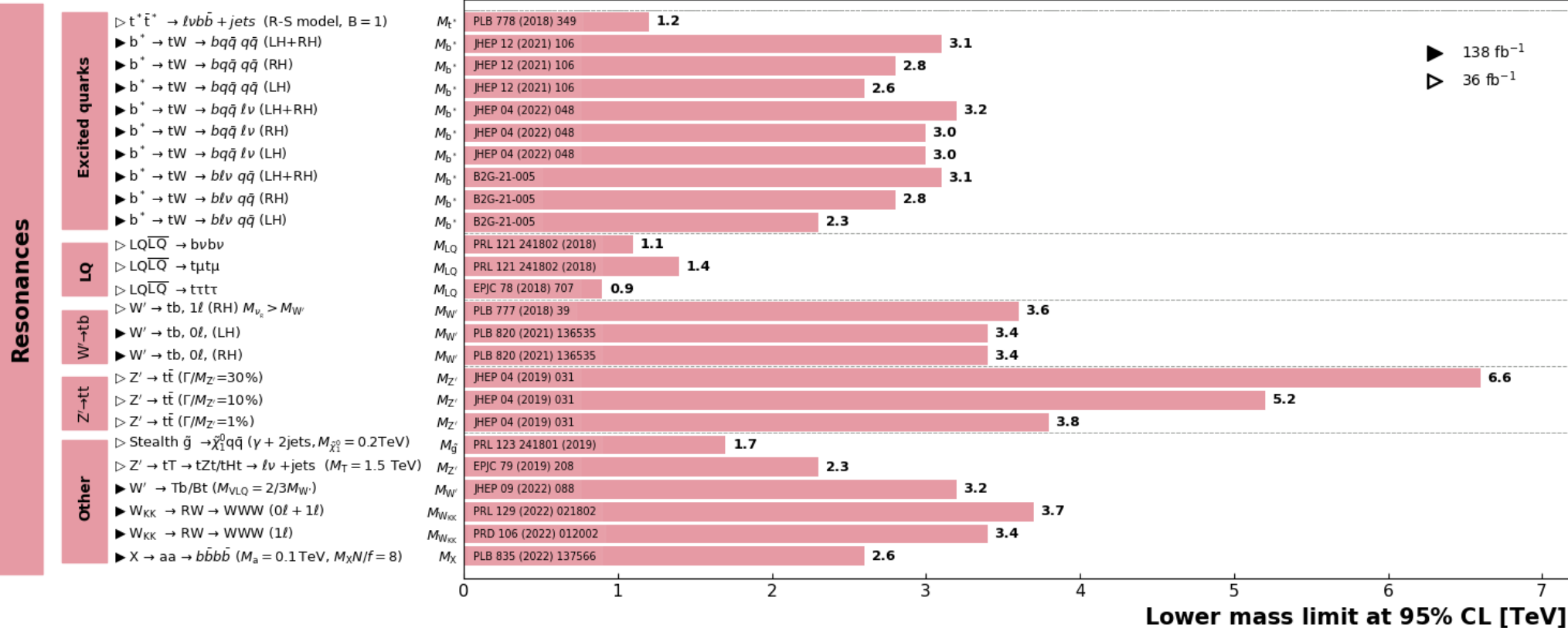
Resonance searches: Summary

Overview of CMS B2G Results

March 2023

CMS Preliminary

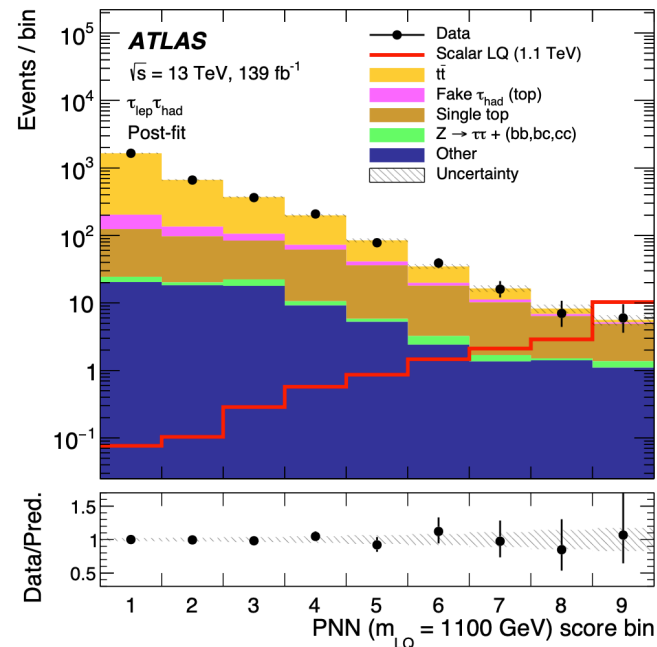
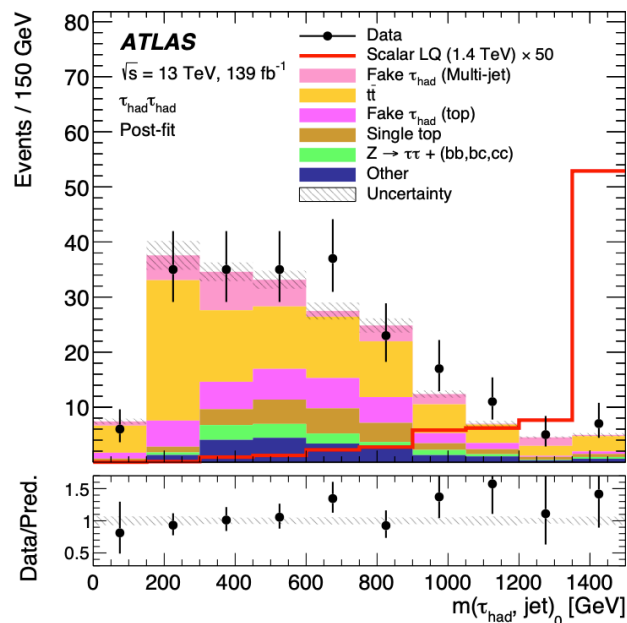
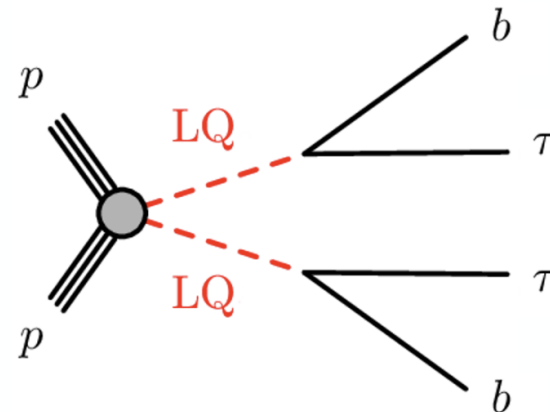
36 – 138 fb⁻¹ (13 TeV)



Leptoquarks

arXiv:2303.01294

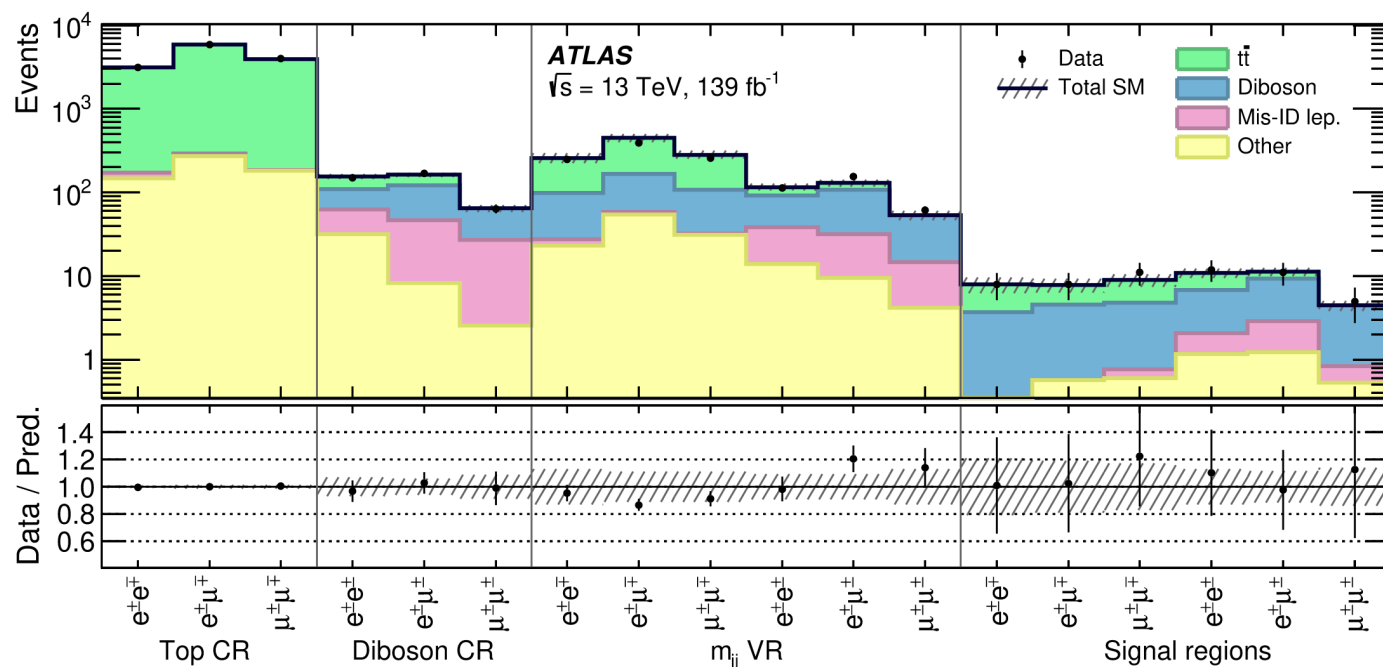
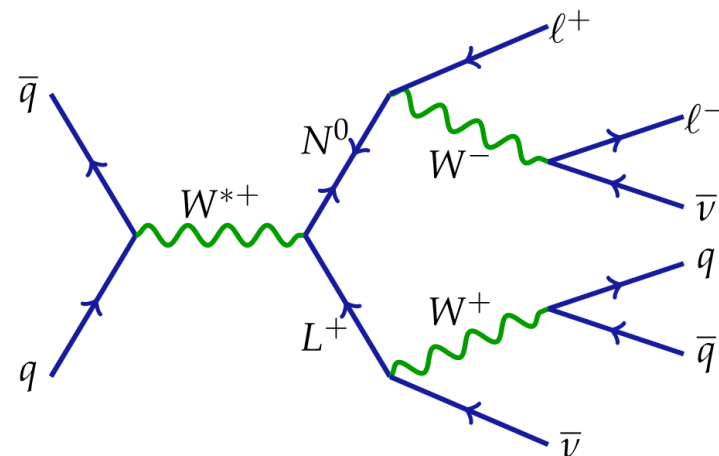
- Pair production of leptoquarks
 - Study $LQ \rightarrow b\tau$ final state
 - Can be interpreted in SUSY
- Main background from top quark pair events in different final states, determined from CRs
- Parametrized NN in terms of gen. LQ mass
- Signal: use M_{T2} (stransverse mass) and s_T (scalar sum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



Heavy lepton resonances

EPJC 81(2021)218, arXiv:2202.02039

- Two resonances in one process: $W \rightarrow NL$
- 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



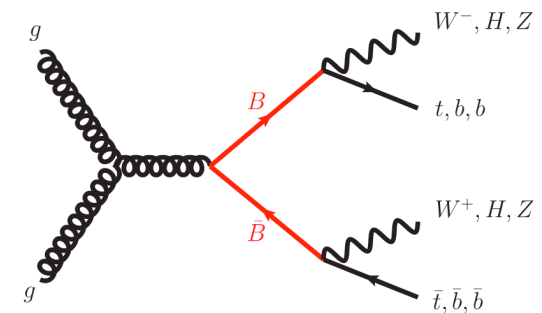
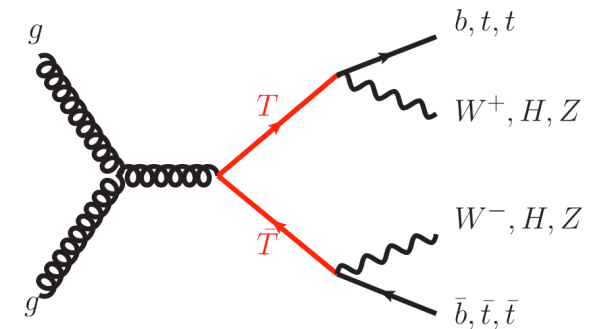
Vector-like quarks

Motivation

- Simplest extension allowed in the quark sector
- Spin $\frac{1}{2}$ 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

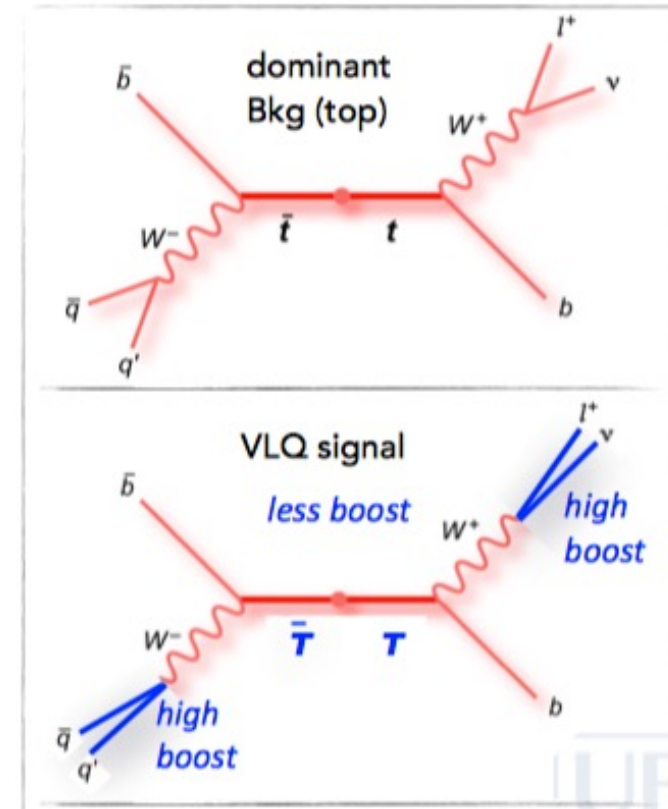
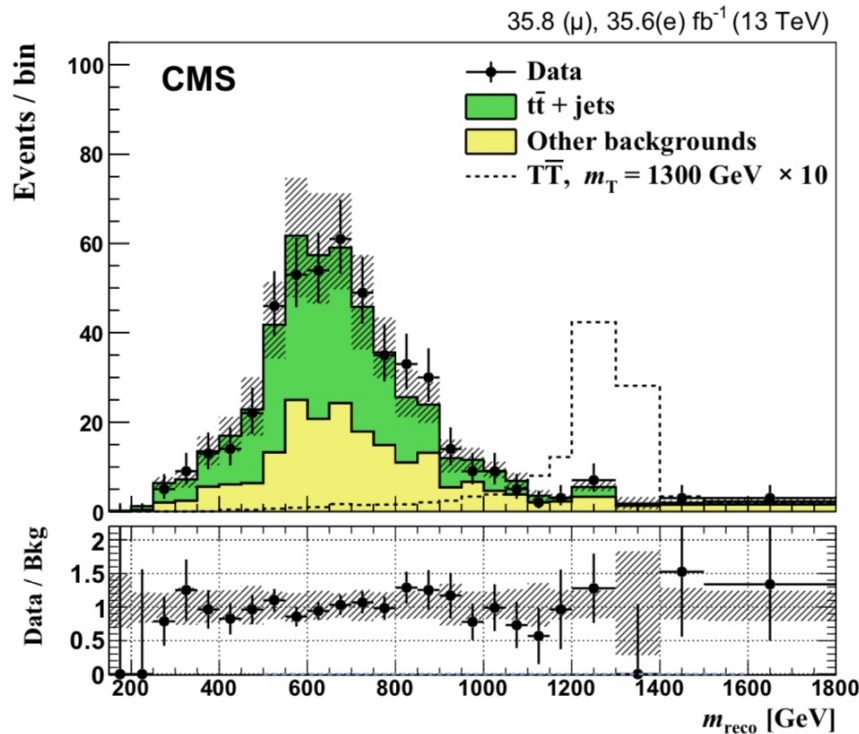
- Produced via strong and EWK interactions
- Mainly pair-produced
- Both CC and NC decay modes



VLQ searches

PLB 779(2018)82

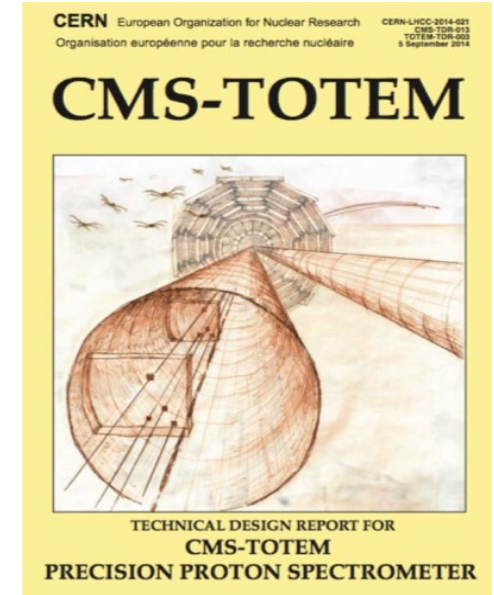
- VLQs usually decay via mixing with SM quarks of 3rd generation
- Search for VLQ pair production decaying to $WbWb$
- Search in the **boosted regime**
- Can reconstruct the VLQ system



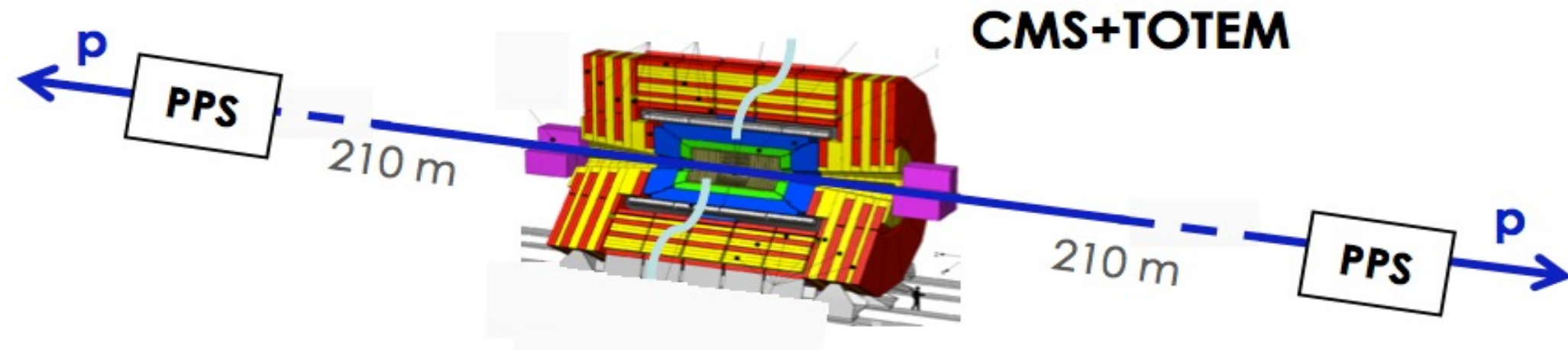
Looking forward: PPS

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)

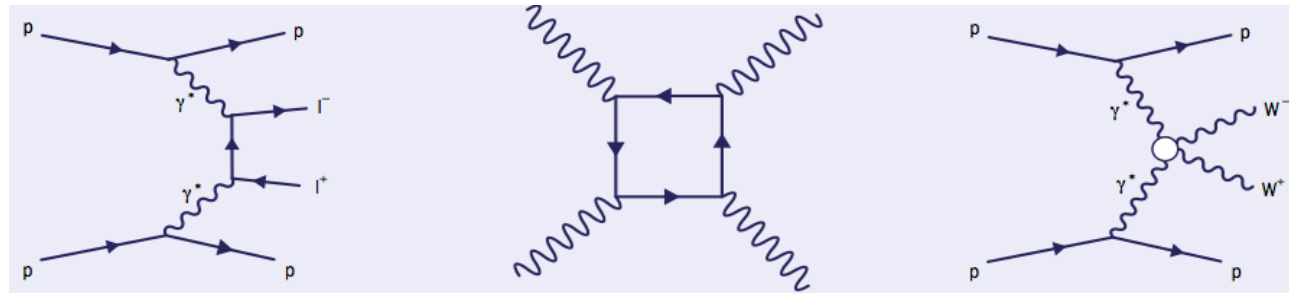


CERN-LHC-2014-021



PPS physics motivations

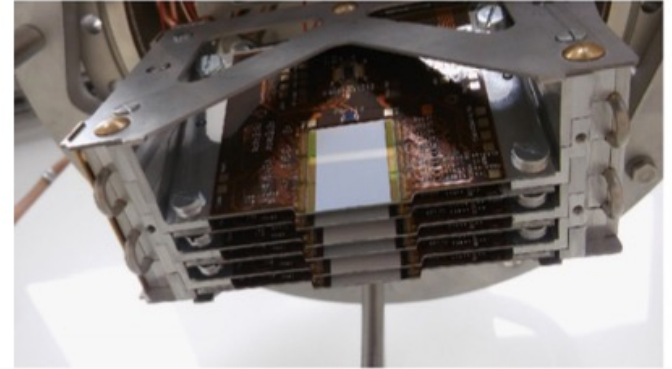
- **Central Exclusive Production**
 - photon-photon collisions
 - gluon-gluon fusion in color singlet, $J^{PC}=0^+$
- **High- p_T system in central detector, together with very forward protons in PPS**
 - momentum balance between central system and forward protons, provides strong kinematical constraints
 - 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

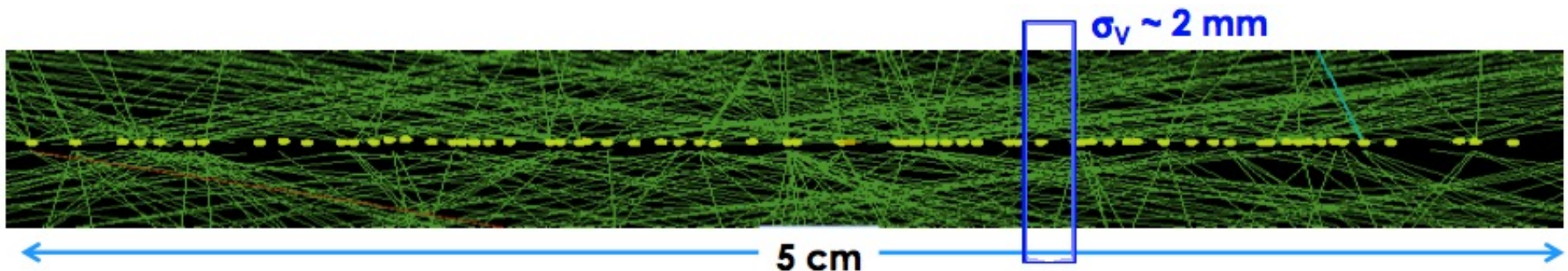
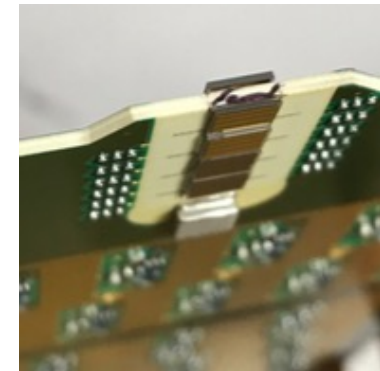
- Tracking detectors

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



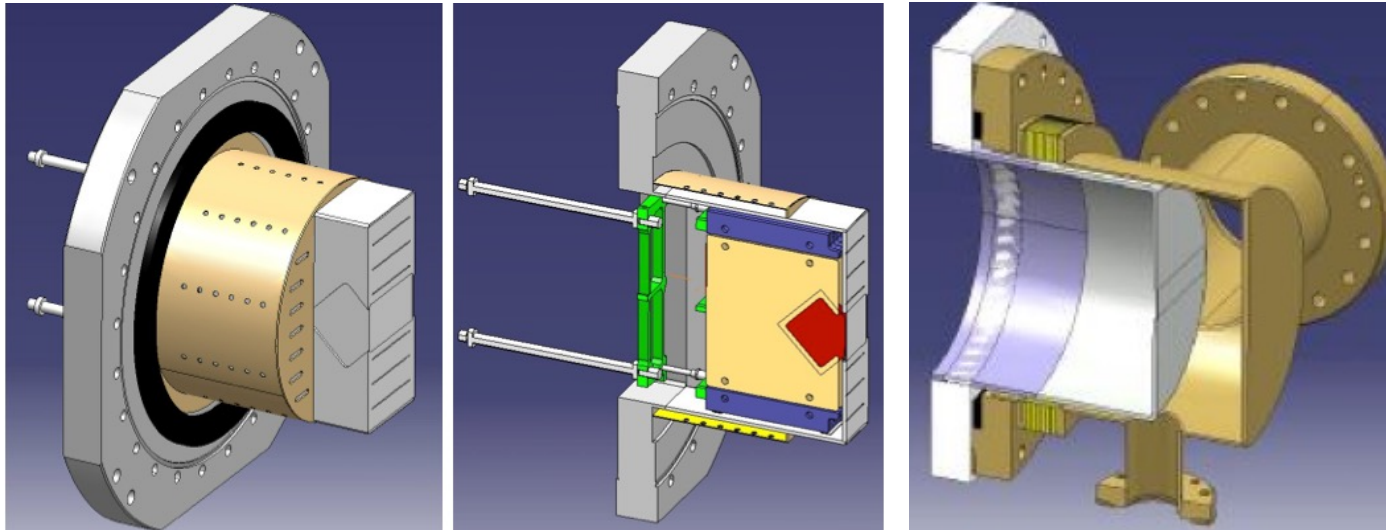
- Timing detectors

- Goal: identify primary vertex, reject “pileup”
- $\sigma_{\text{time}} \sim 10\text{ps} \Rightarrow \sigma_z \sim 2\text{mm}$
- 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 ($\sim 15\sigma$) 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

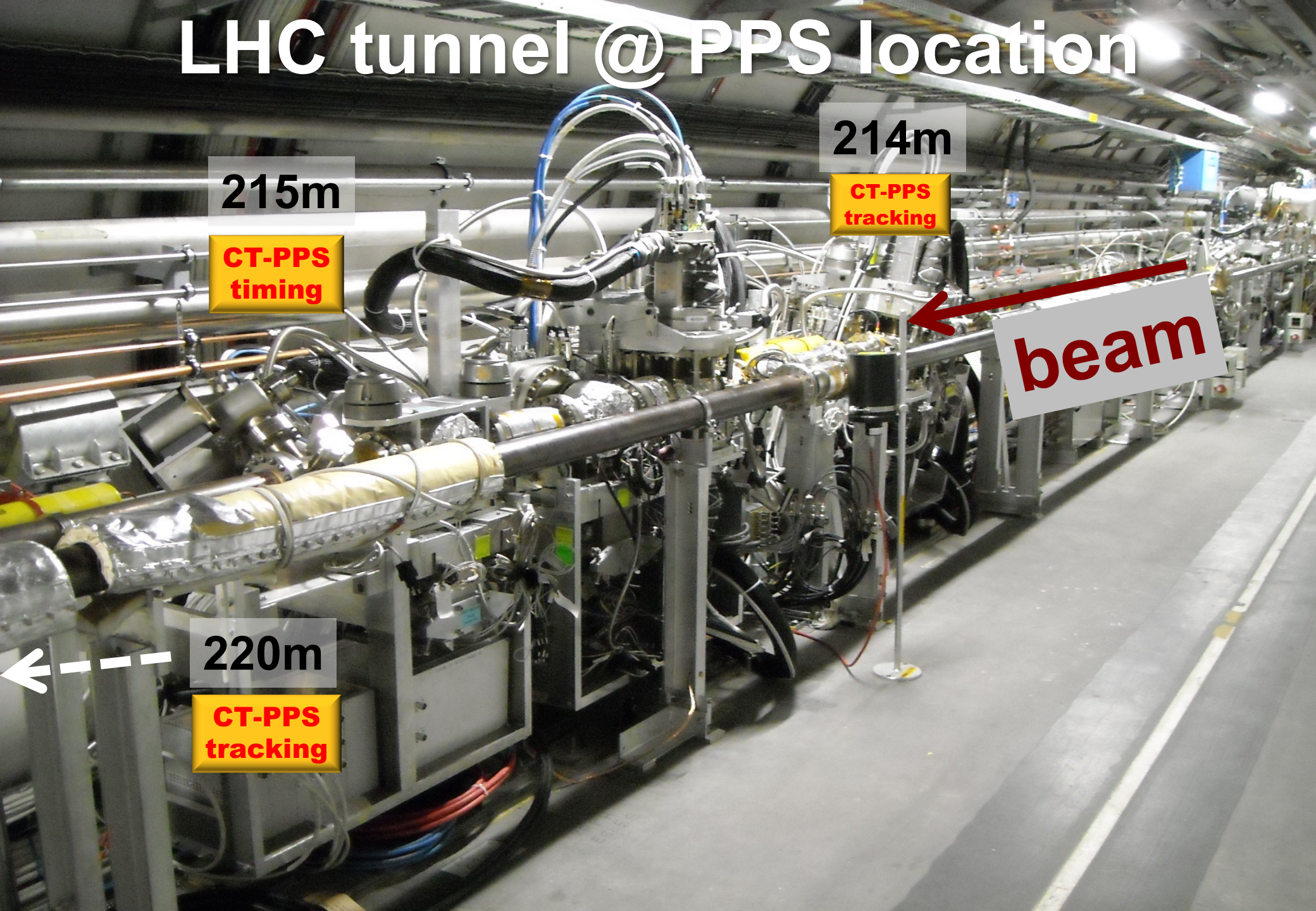
214m

CT-PPS
tracking

beam

220m

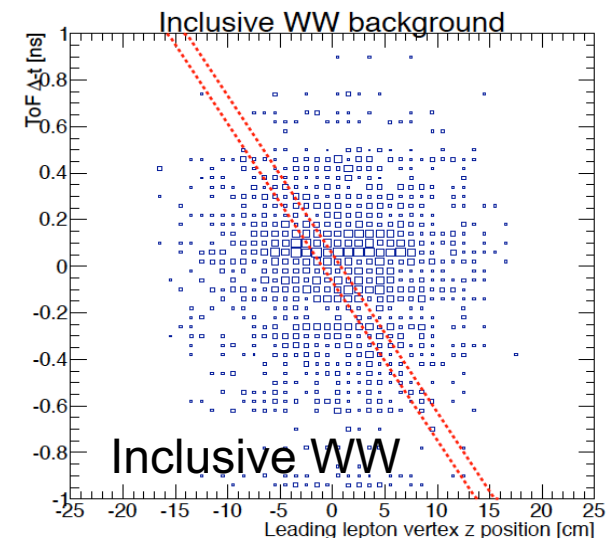
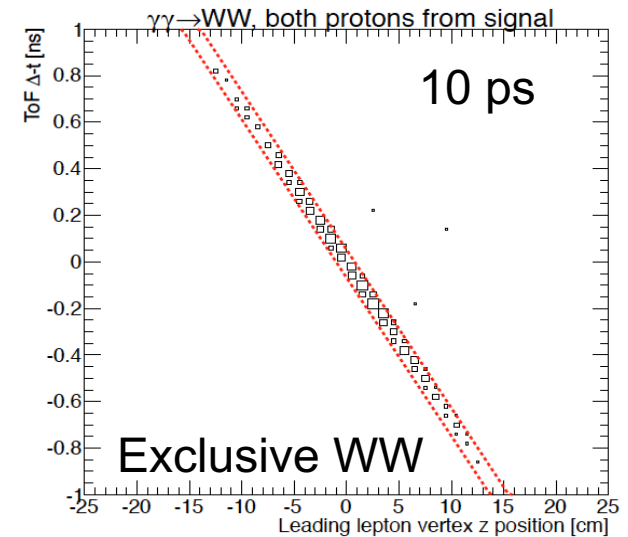
CT-PPS
tracking



Timing detectors

Use timing to reject pileup background

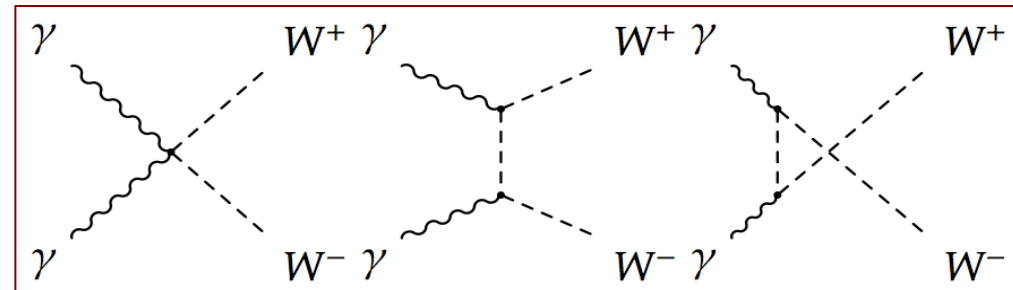
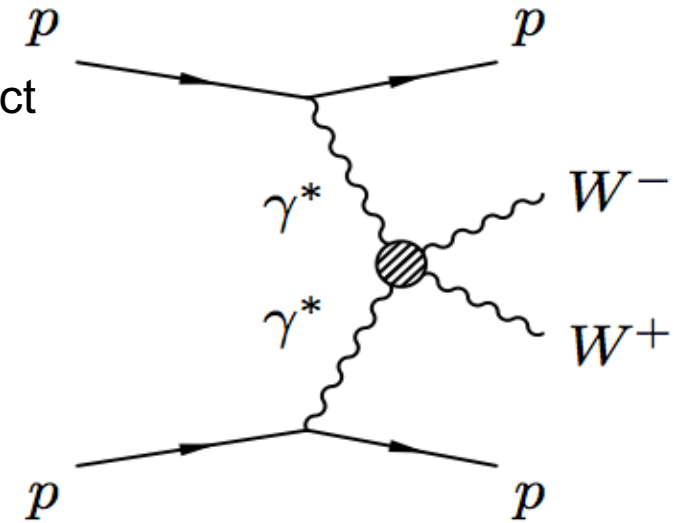
- Two scenarios studied:
 - 10ps and 30ps time resolution
- Baseline: solid state detectors
- Detector options investigated:
 - Diamond sensors
 - Fast silicon sensors (UFSD, HFS)
- Status:
 - Diamond and LGAD detectors installed



WW production

JHEP 08(2016)119

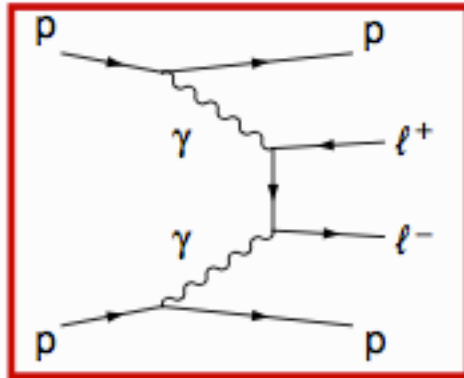
- Study of process: $pp \rightarrow pWWp$
 - Clean process: W in central detector and “nothing” else, intact protons can be detected far away from IP
 - Exclusive production of W pairs via photon exchange: QED process, cross section well known
- Backgrounds:
 - inclusive WW, $\tau\tau$, exclusive two-photon $\gamma\gamma \rightarrow ll$, 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



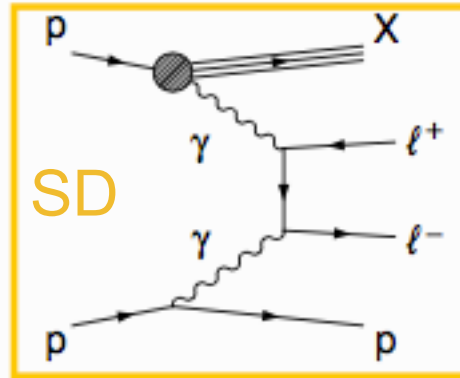
Exclusive Dileptons

JHEP 07(2018)153

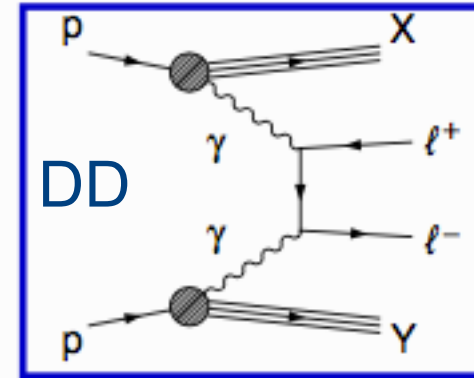
- Study exclusive processes at the EWK scale
- Search for two-photon production of opposite charge lepton pair with forward proton tagging



signal



SD



DD

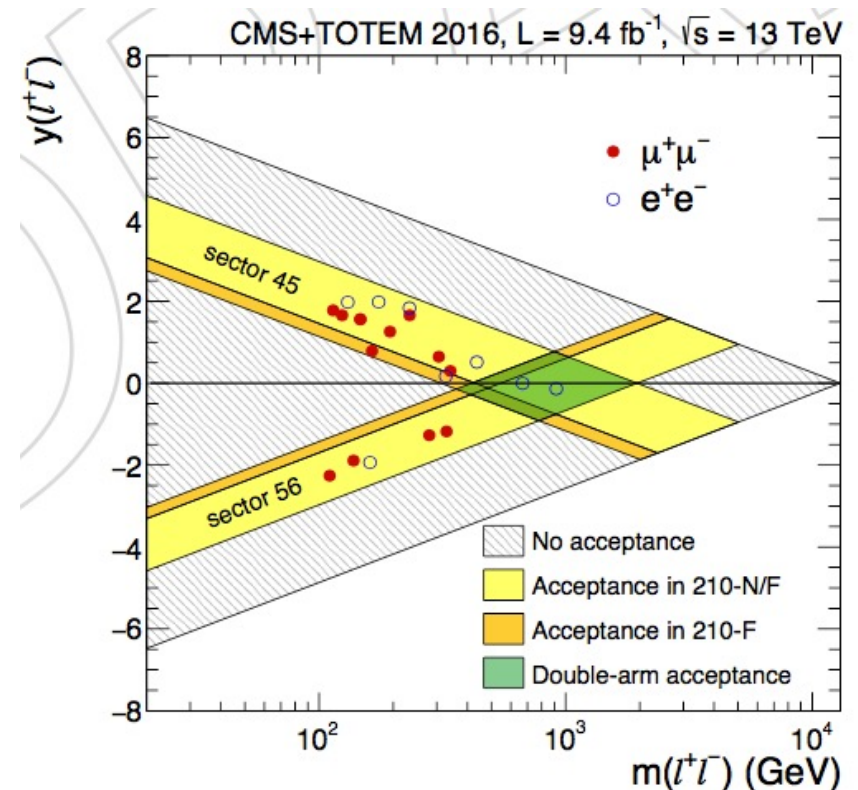
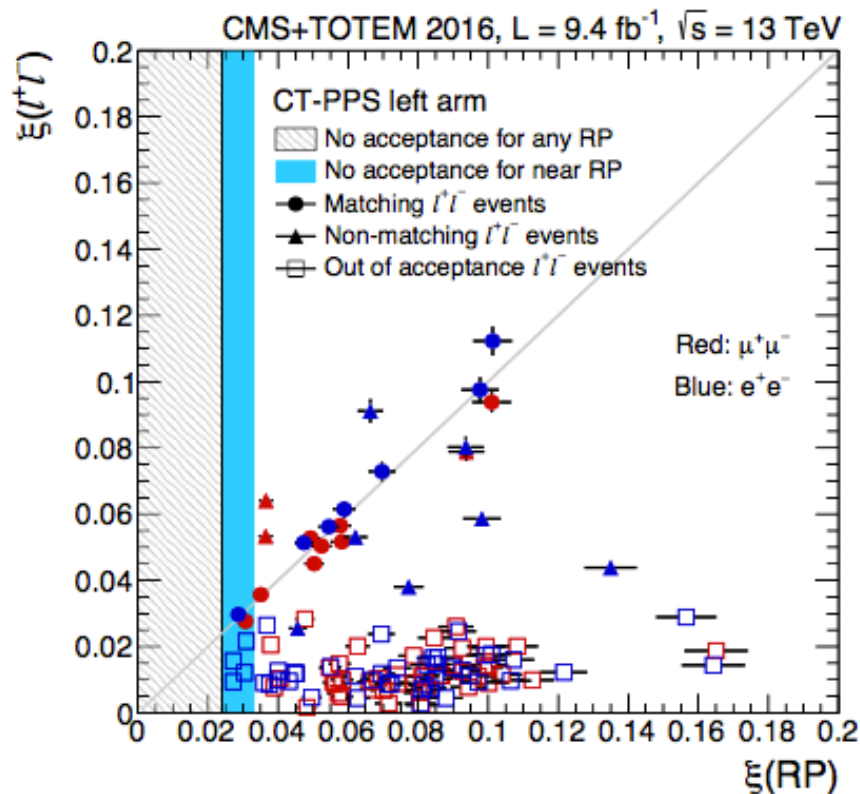
Background: SD, DD, DY, dibosons, PU

- 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
- $12\mu\mu$, $8ee$ candidates observed ($>5\sigma$ over expected bkg)
- First observation of two-photon production of a lepton pair at this mass range



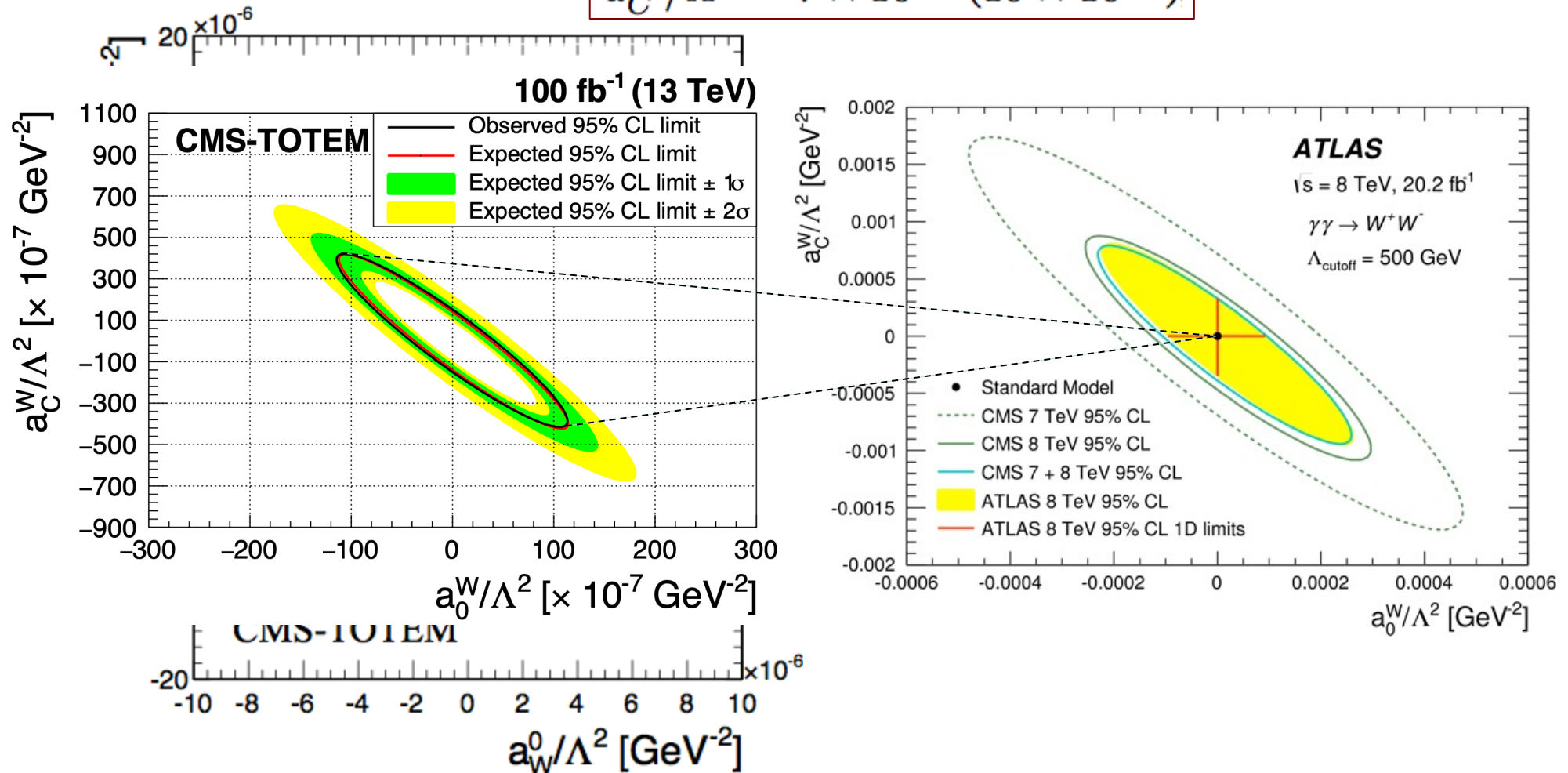
AQGC expected limits

arXiv:1607.03745

Expected limits @95%CL:

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

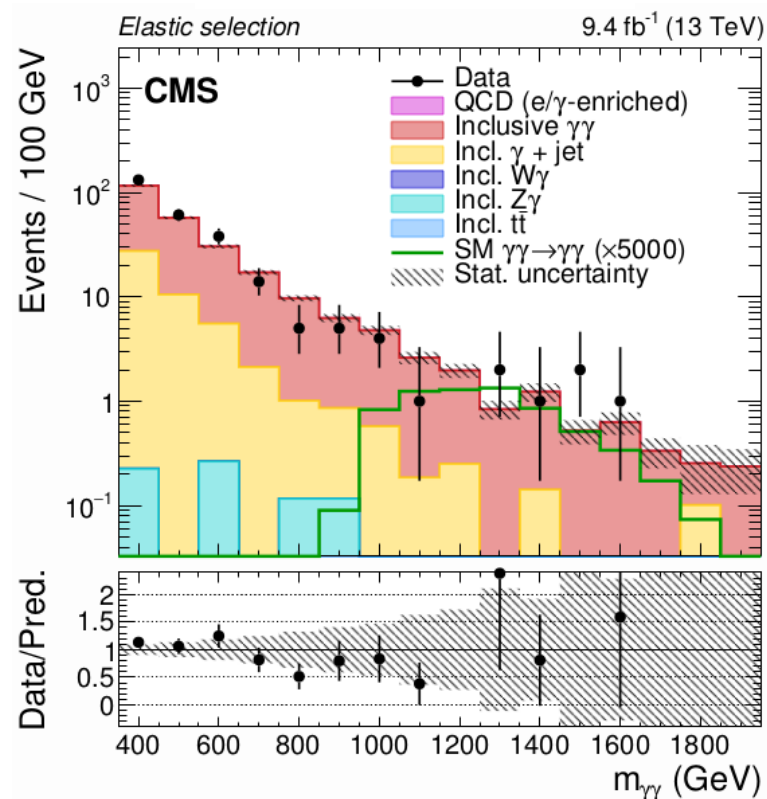
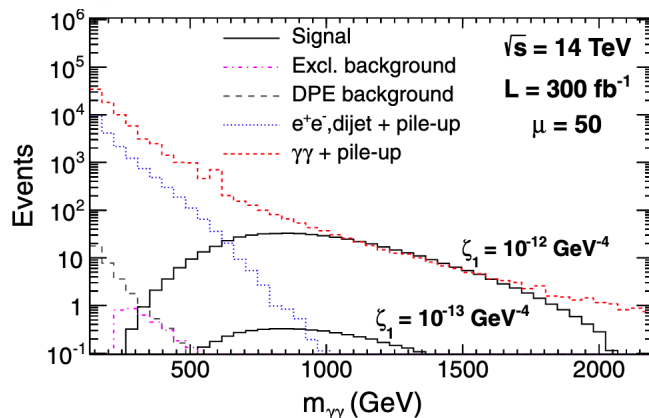
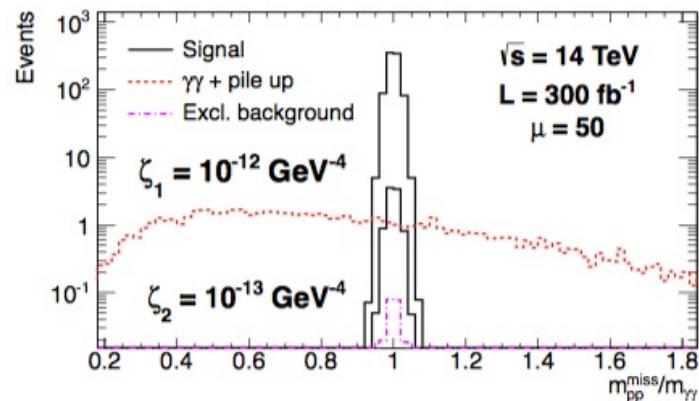
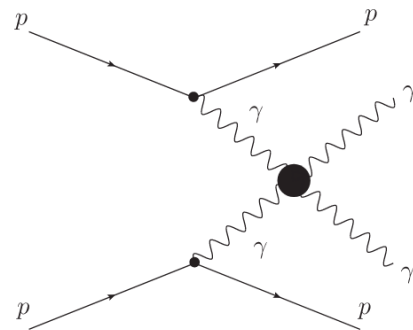
$$a_C^W / \Lambda^2 = 7 \times 10^{-6} \quad (10 \times 10^{-6})$$



$\gamma\gamma \rightarrow \gamma\gamma$: Anomalous couplings, etc.

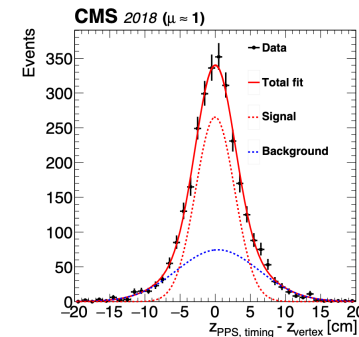
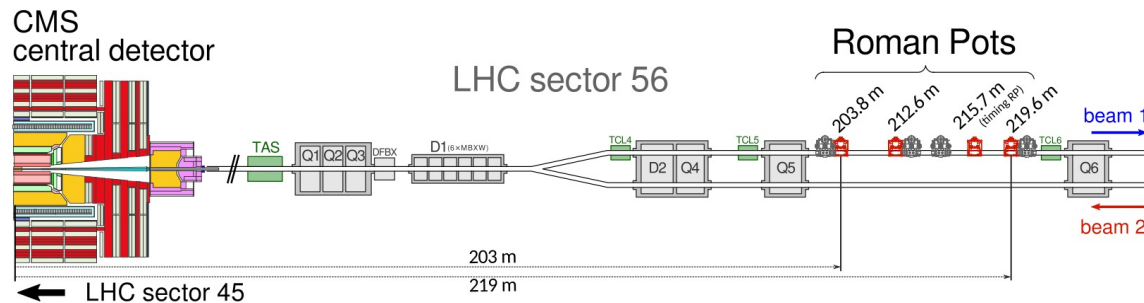
PRD 89(2014)114004, CMS-EXO-18-014

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



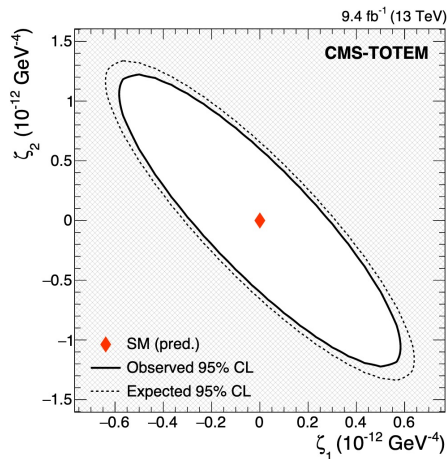
Physics with forward protons

arXiv:2210.05854, TOP-21-007, arXiv:2110.05916, arXiv:2303.04596, arXiv:2211.16320



Proton reconstruction

PPS collected more than 100/fb in Run2

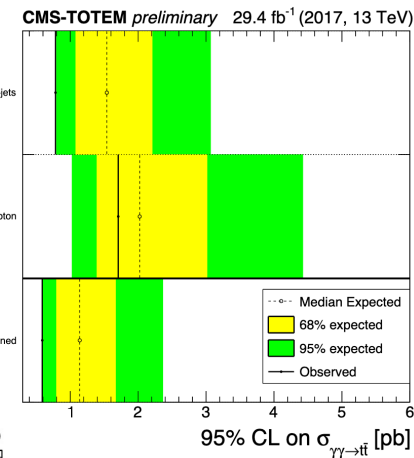


light-by-light scattering

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

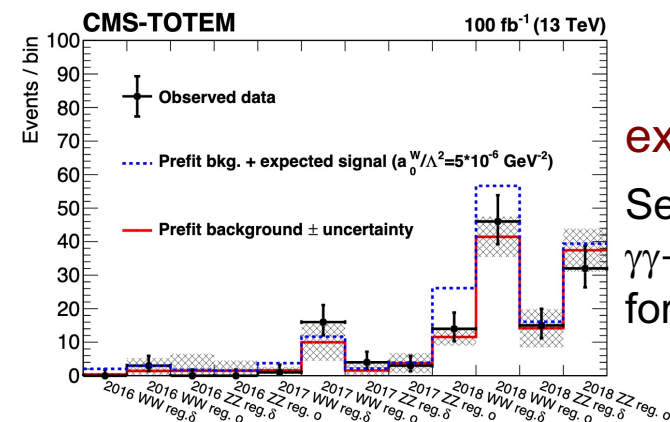
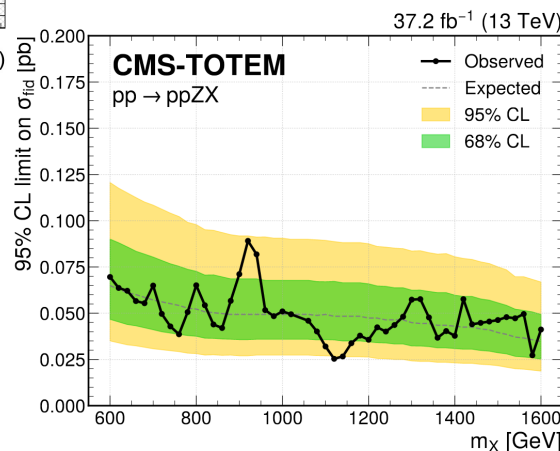
exclusive top quark pairs

Search for $t\bar{t}$ central exclusive production in pp interactions with tagged protons



Z/γ*+X production

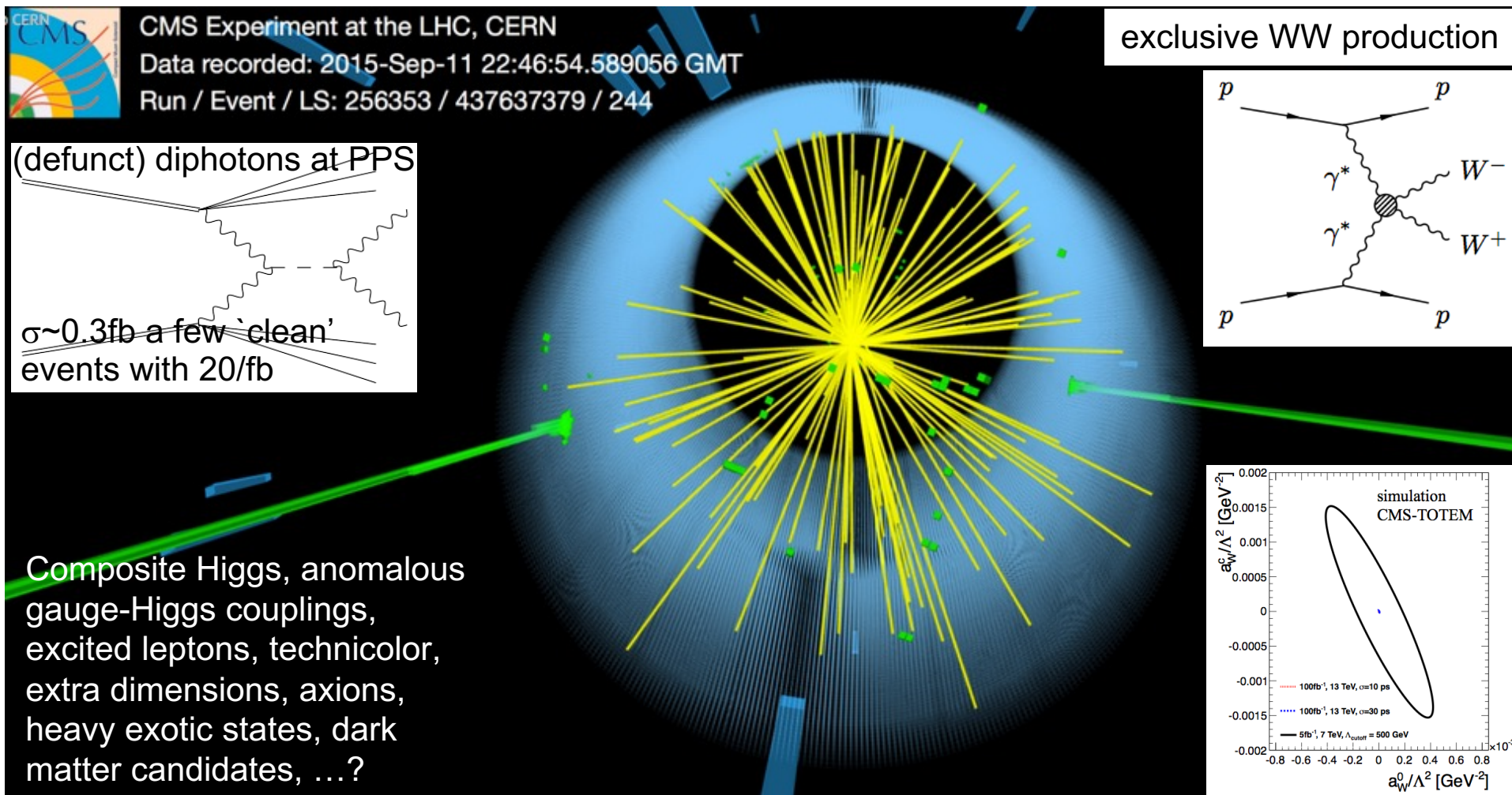
(2% resolution on missing mass)



exclusive WW/ZZ

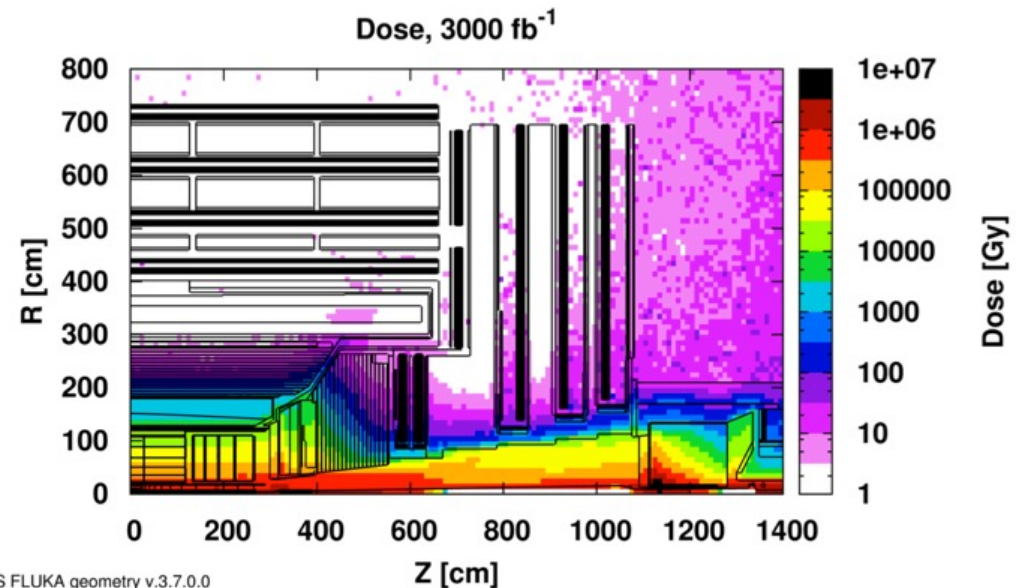
Search for $\gamma\gamma \rightarrow WW/ZZ$ with forward protons

BSM searches: resonances, etc.



Prospects for Run3 and beyond

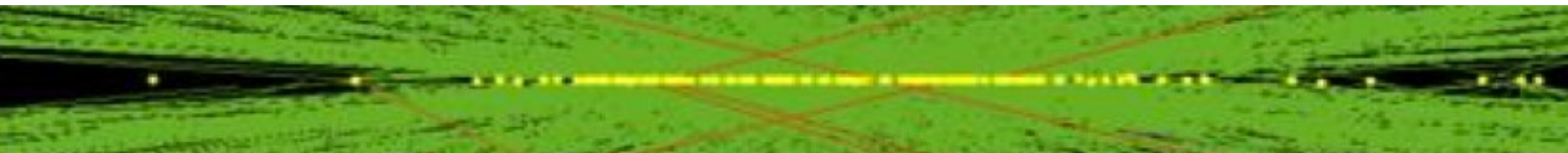
- More luminosity in a more challenging environment
- Will enhance the mass reach in the search for new particles
- Need to meet experimental challenges
 - Aging of detector, improve/adapt capability
 - Integrated luminosity: 300-3000/fb
 - peak luminosity of $2 \times 10^{35} \text{cm}^{-2}\text{s}^{-1}$
 - pileup will be ~ 150 or higher (Phase2)
 - large radiation doses



HL-LHC upgrades

Luminosity of $\sim 3000 \text{ fb}^{-1}$ expected for HL-LHC

- Tracking information in “L1 track-trigger”
 - Tracker designed to enable finding all tracks w/ $p_T > 2 \text{ GeV}$ in $< 4 \mu\text{s}$
- Tracker is all silicon but with much higher granularity, up to $|\eta|=4$
 - > 2 billion pixels and strips
- High Granularity Endcap Calorimeters
 - Sampling of EM showers: every $\sim 1\lambda$ (28 samples) w/pixels, and every $\sim 0.35\lambda$ (24 samples) with pixels+scintillator to map 3D shower development
 - $\sim 6 \text{ M}$ 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 $\approx -10^\circ$

Muon systems

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

New Endcap Calorimeters

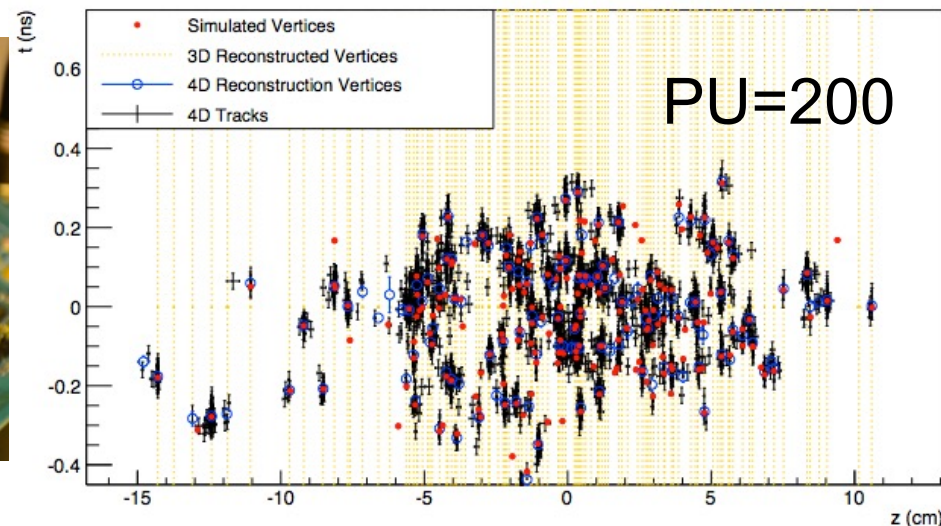
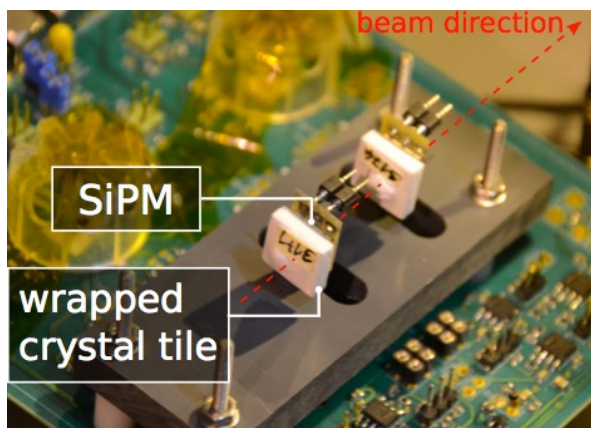
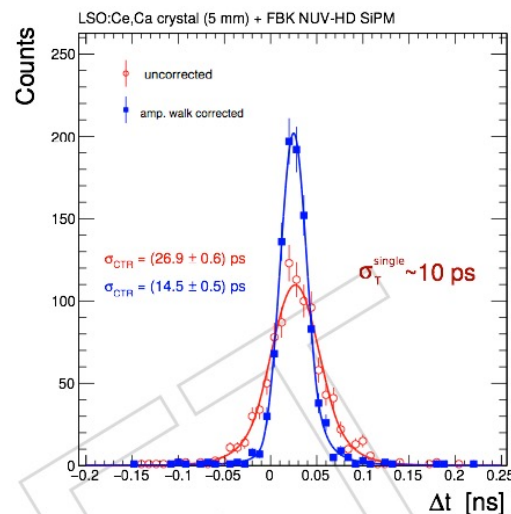
- Rad. Tolerant
- 5D measurement

New Tracker

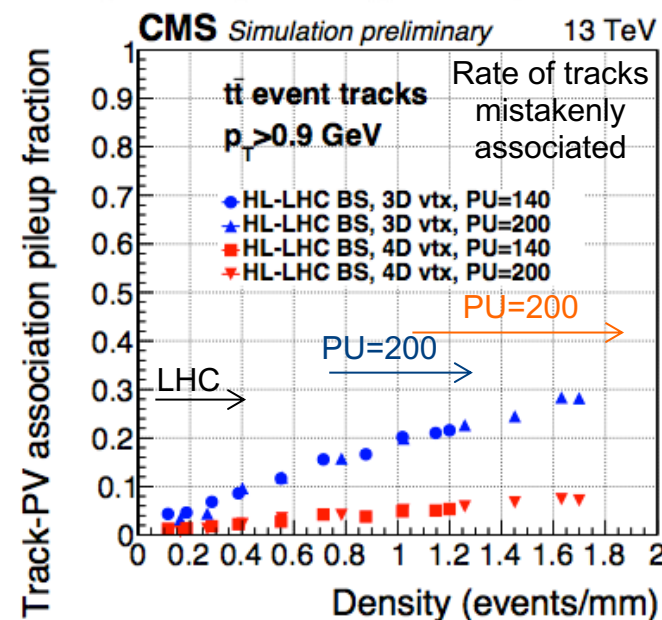
- Rad. Tolerant - light
- High Definition measurement
- 40 MHz selective readout for hardware trigger
- Extended Pixel coverage to $\eta \approx 3.8$

Beam radiation and luminosity
Common systems and infrastructure

Precision Timing Layer



- Time-of-flight precision $\sim 30\text{ps}$
 - $|\eta| < 3$, $p_T > 0.7\text{GeV}$
 - Crystal+SiPM: rad hard to $2 \times 10^{14} n_{eq} \text{cm}^{-1}$
- Provide $\sim x4-5$ 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 $\sim 150/\text{fb}$ @13 TeV in 2015-2018
 - $\sim 300/\text{fb}$ 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

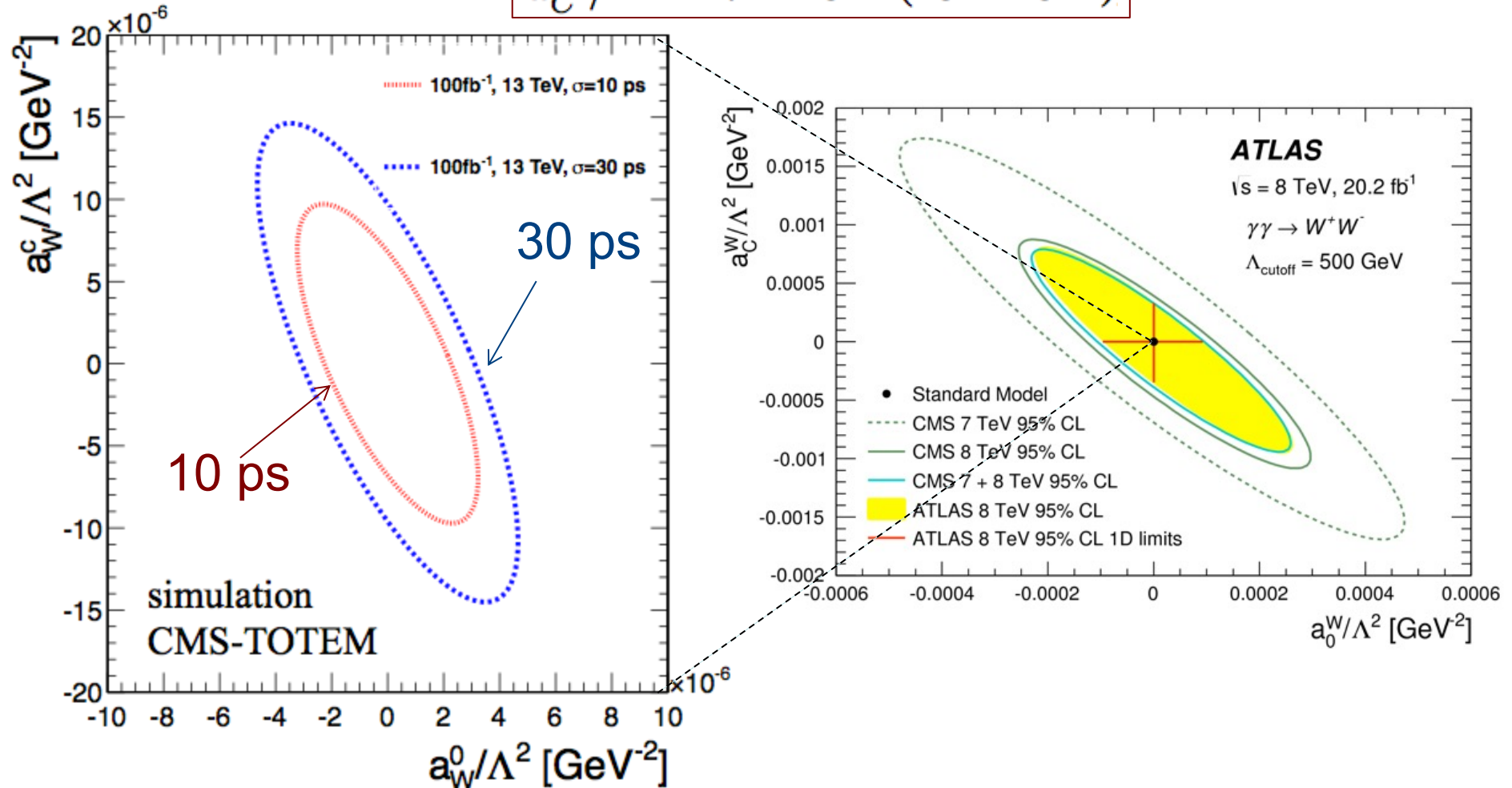
AQGC expected limits

arXiv:1607.03745

Expected limits @95%CL:

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

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



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