Exotica and Dark Matter searches

Michele Gallinaro

LIP Lisbon

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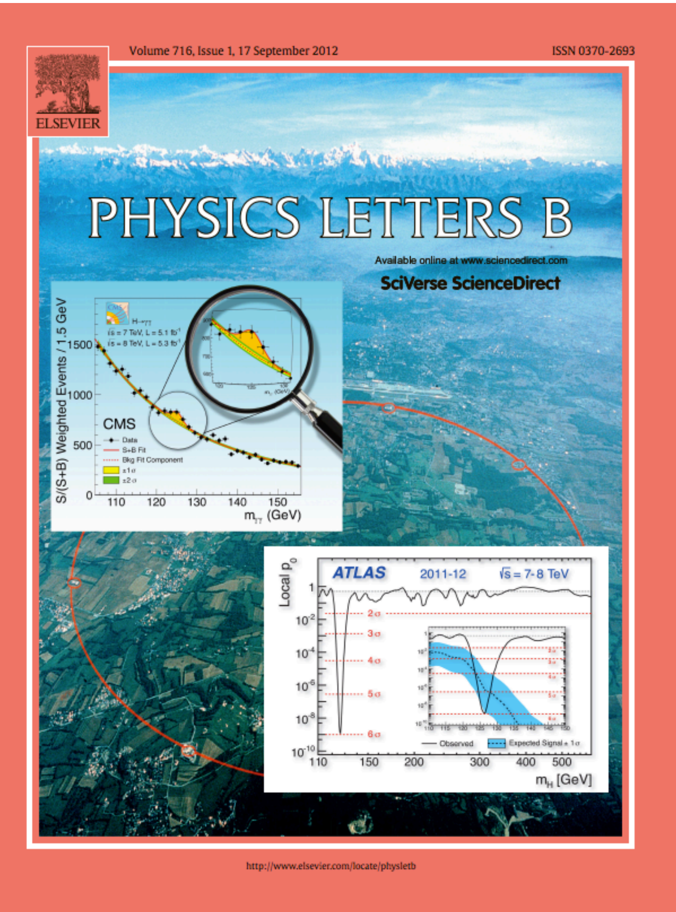
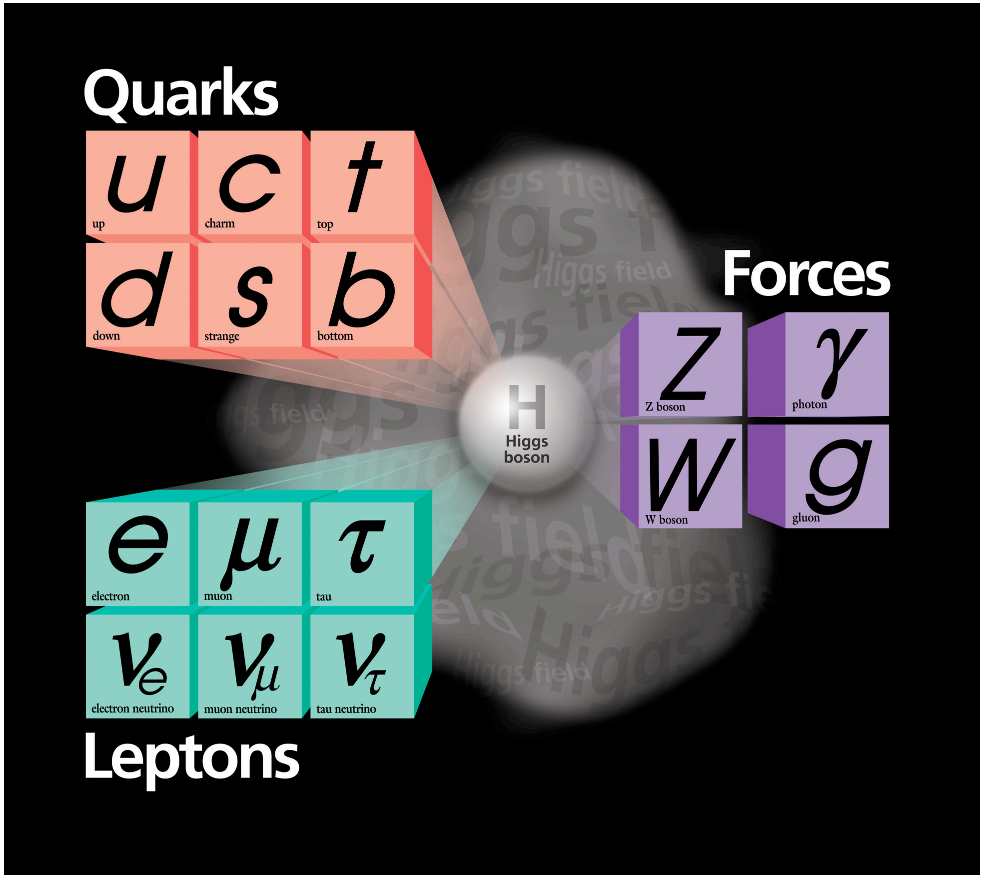
- ✓ Introduction
- ✓ Dark matter
- ✓ Exotica searches

2012: A new boson discovery

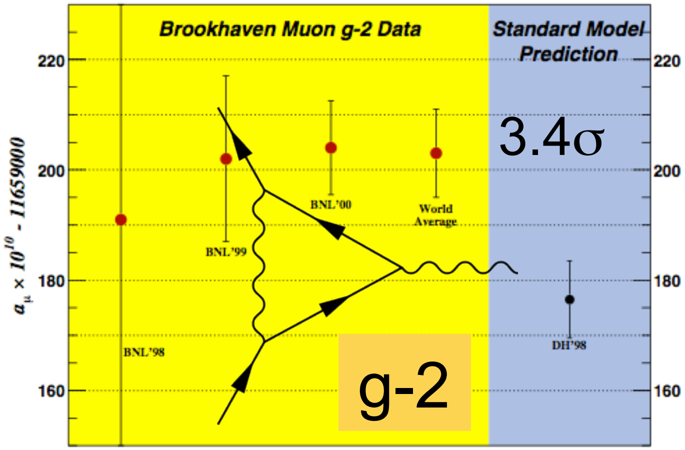


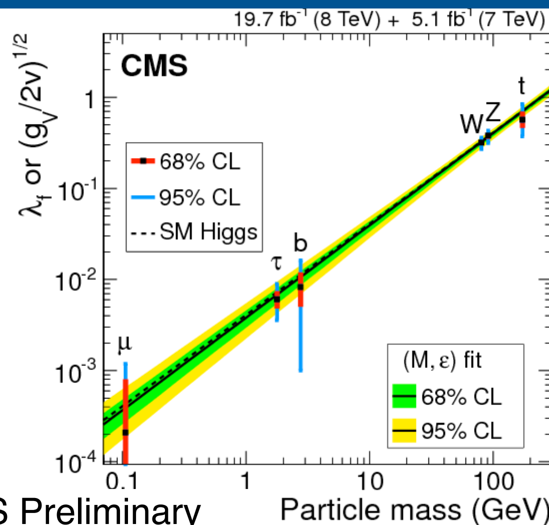
Standard Model theory of everything?

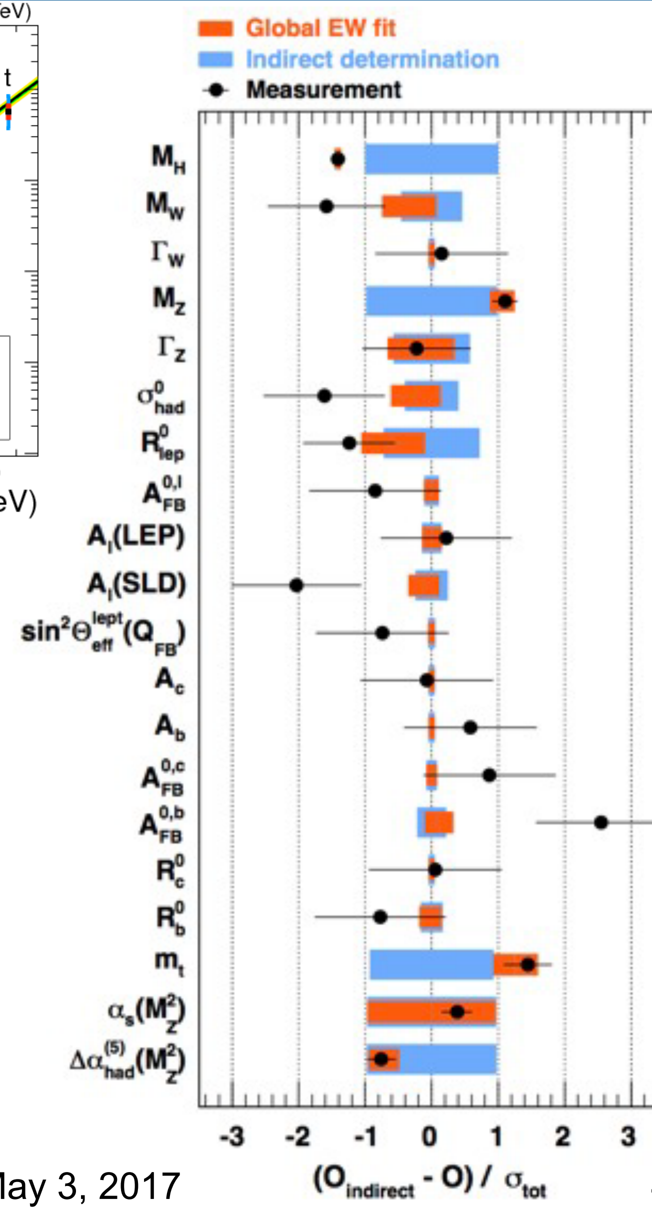
- Discovery of the Higgs boson marks the triumph of the SM
- However, even with the inclusion of the Higgs boson, SM is an incomplete theory

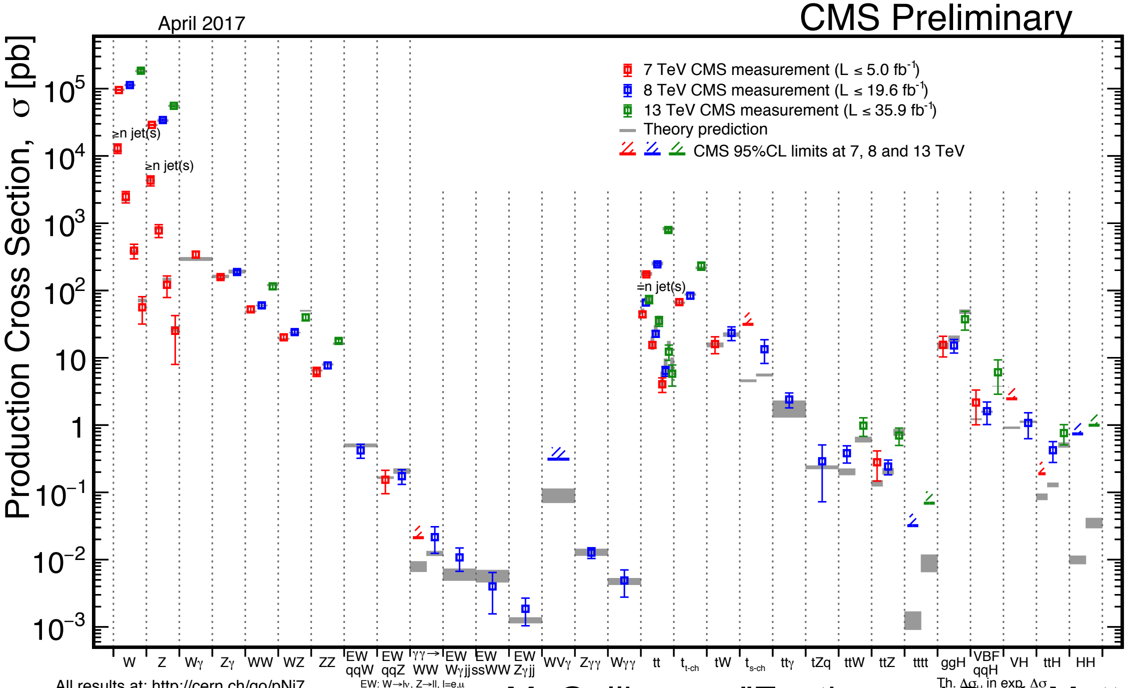


Tests of the SM









Beyond the Standard Model

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

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

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

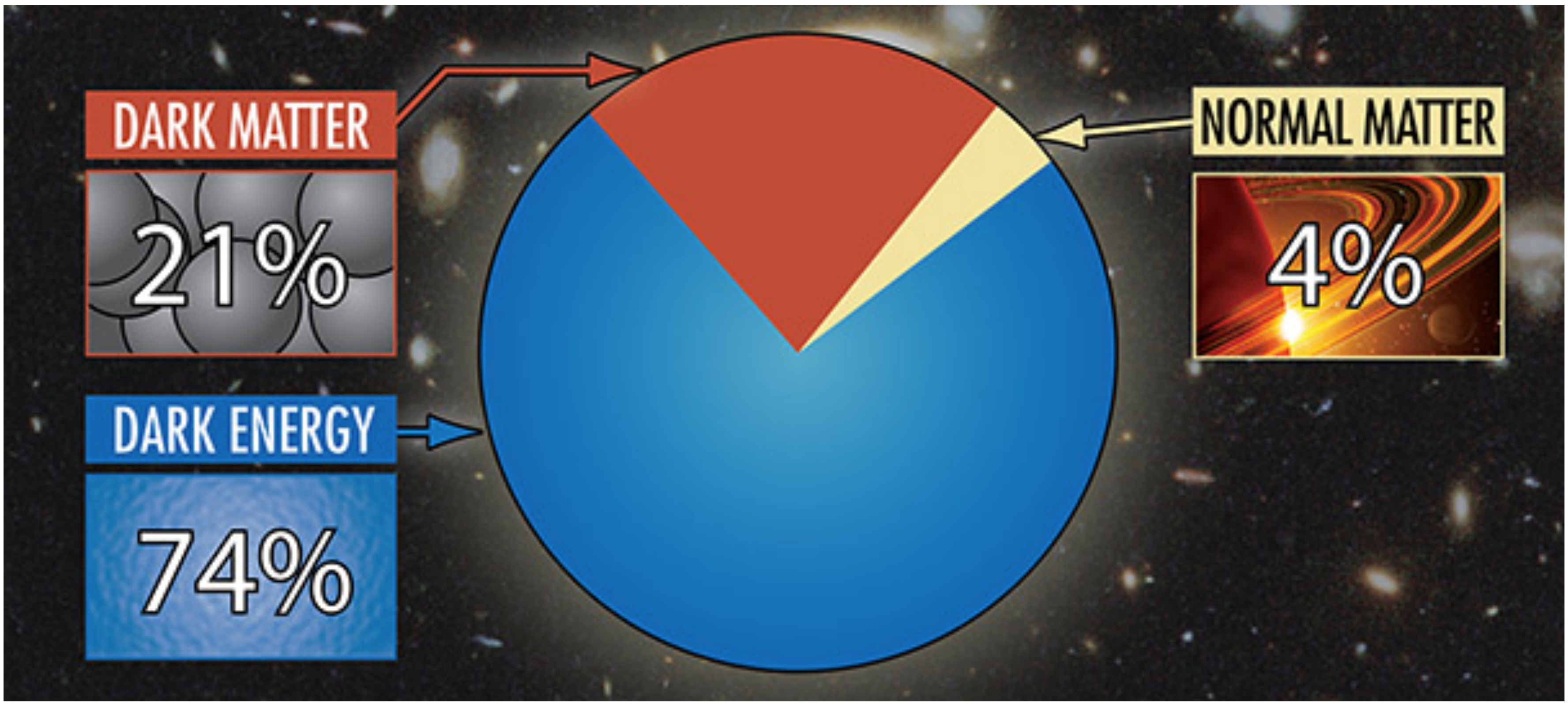
c) Are quarks and leptons actually fundamental, or made up of even more fundamental particles?

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

e) How does gravity fit into all of this?

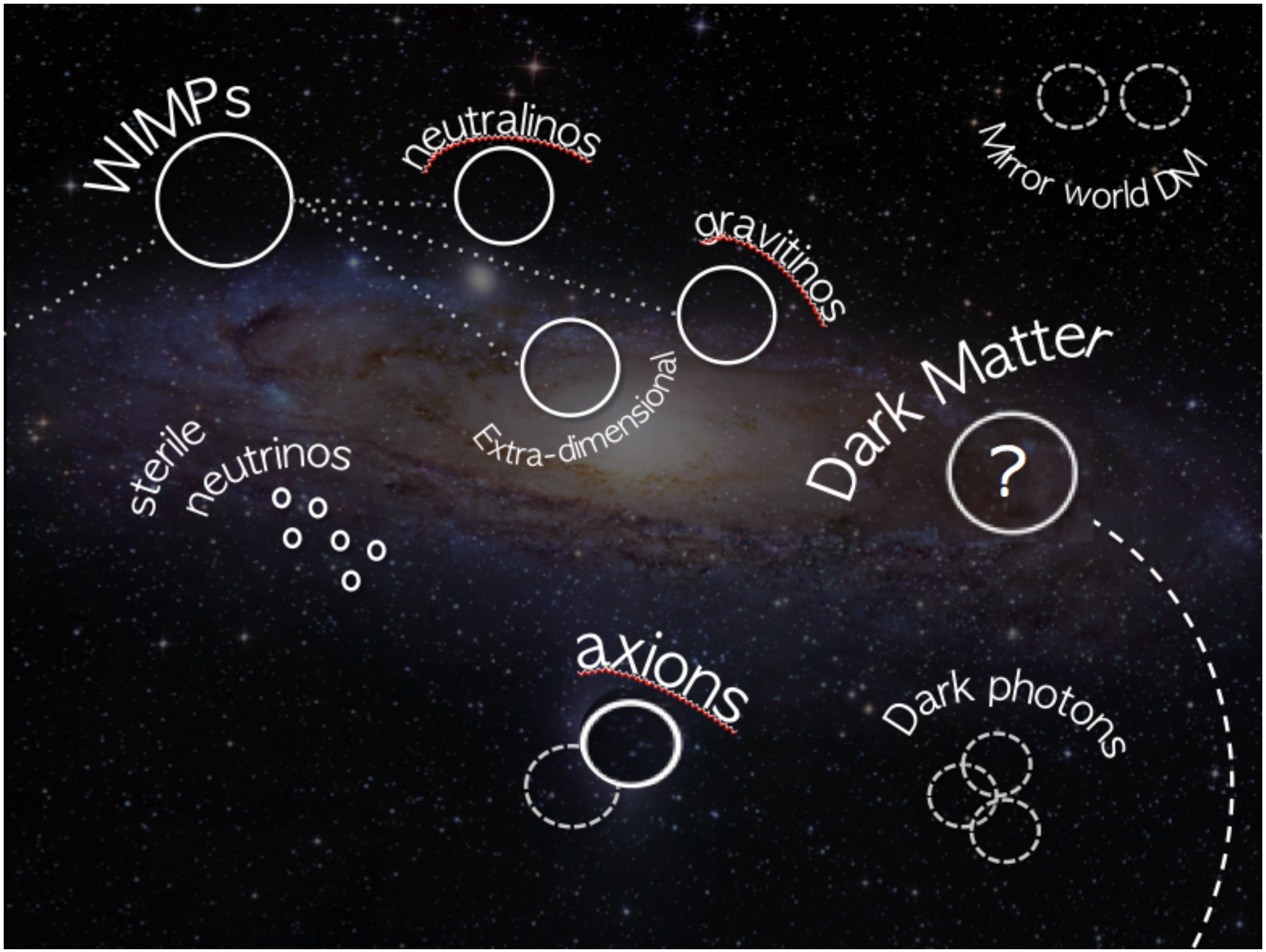
Dark matter and energy

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



What can we look for?

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



How?

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

Dark Matter

What is it?

- DM does not interact electromagnetically
- DM interacts gravitationally

Visual map

From P. Harris DM talk at Cern (July 2015)

Dark Matter (cont.)

Why is it interesting?

- We do not see it…
- …but we feel it

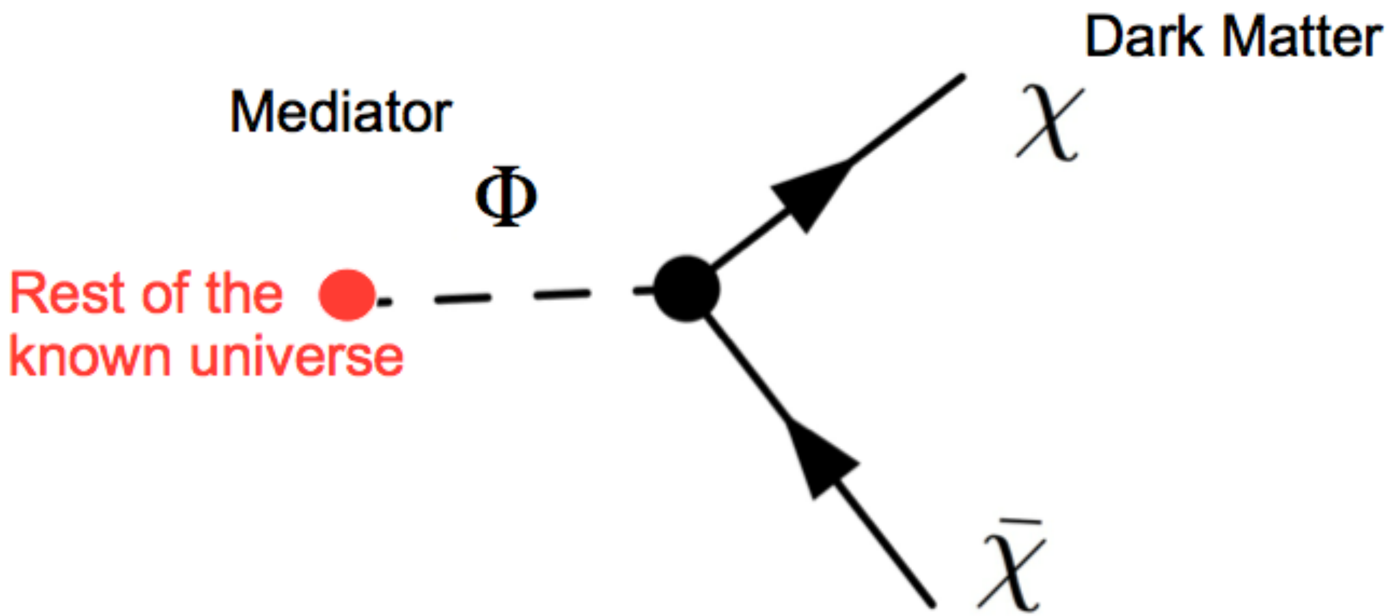
Mass map

From P. Harris DM talk at Cern (July 2015)

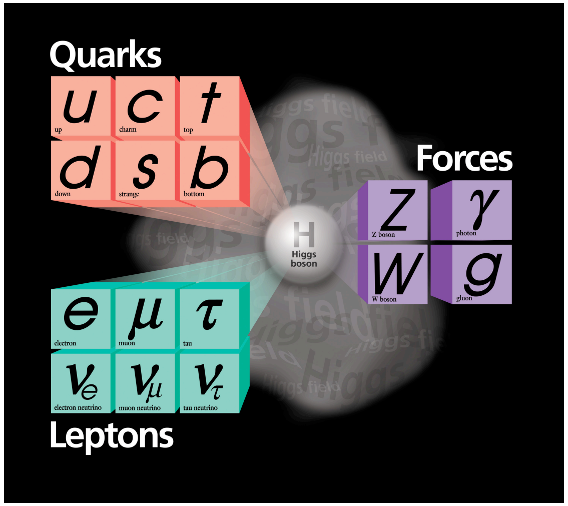
Dark Matter (cont.)

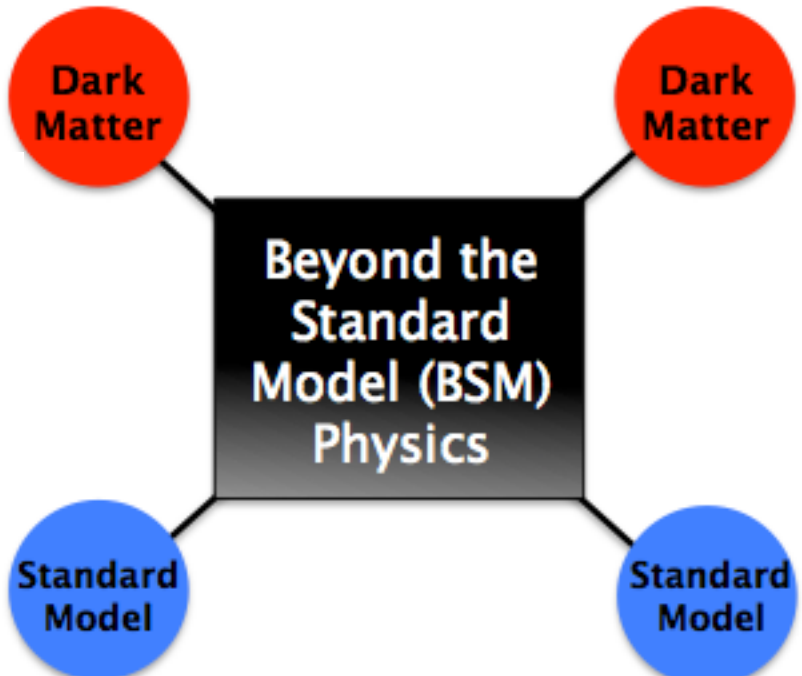
How do we find DM?

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



Searching for DM





Stable(-ish) particles:

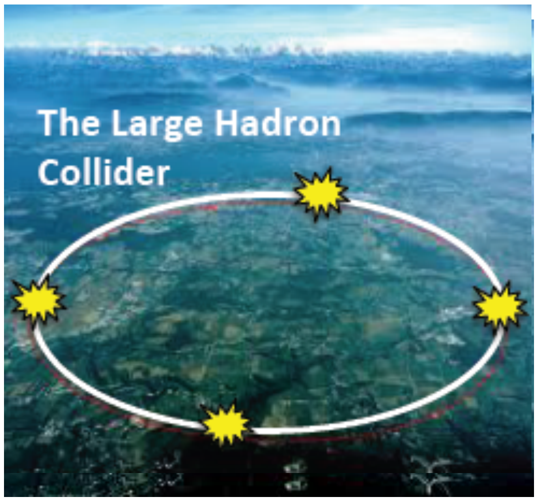
- Anti-nuclei
- Photons
- Anti-protons
- Positrons
- neutrinos

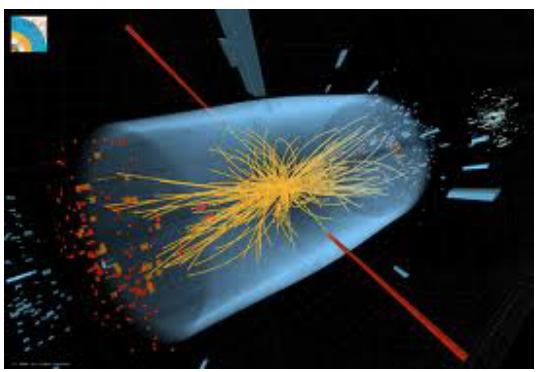
BSM:

- Supersymmetry, neutralinos, gravitinos
- Extra-dimensions
- Axions(-like) particles
- Sterile neutrinos

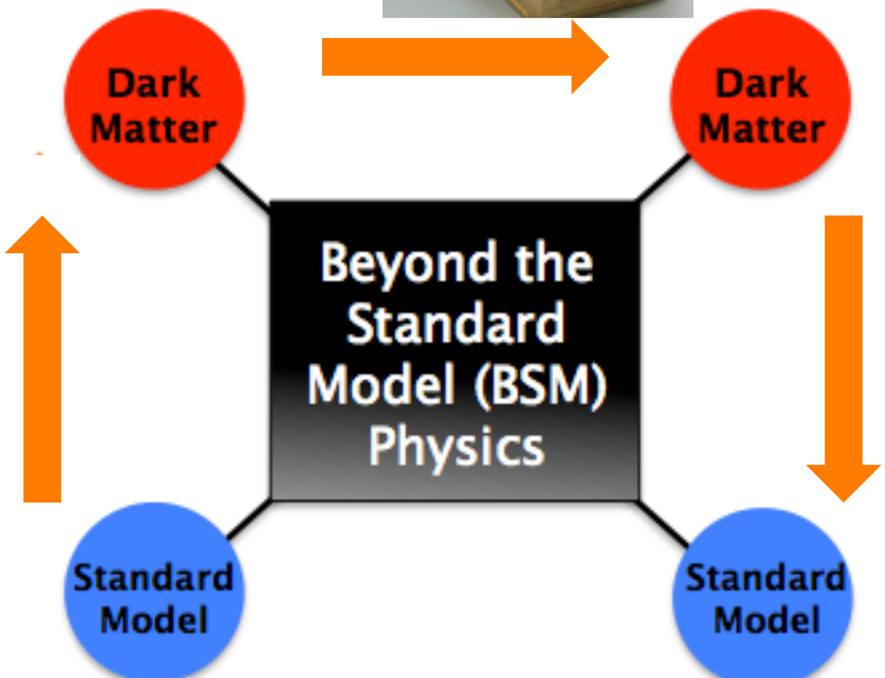
Searching for DM

Particle Colliders

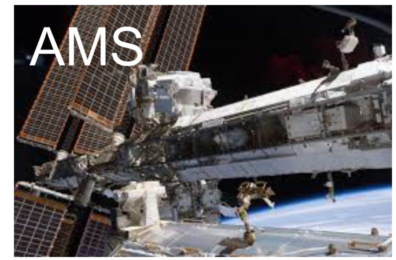


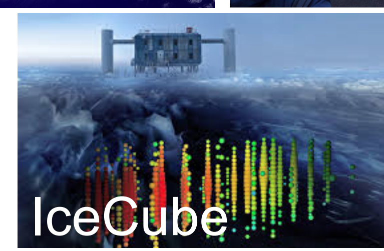


Direct Detection



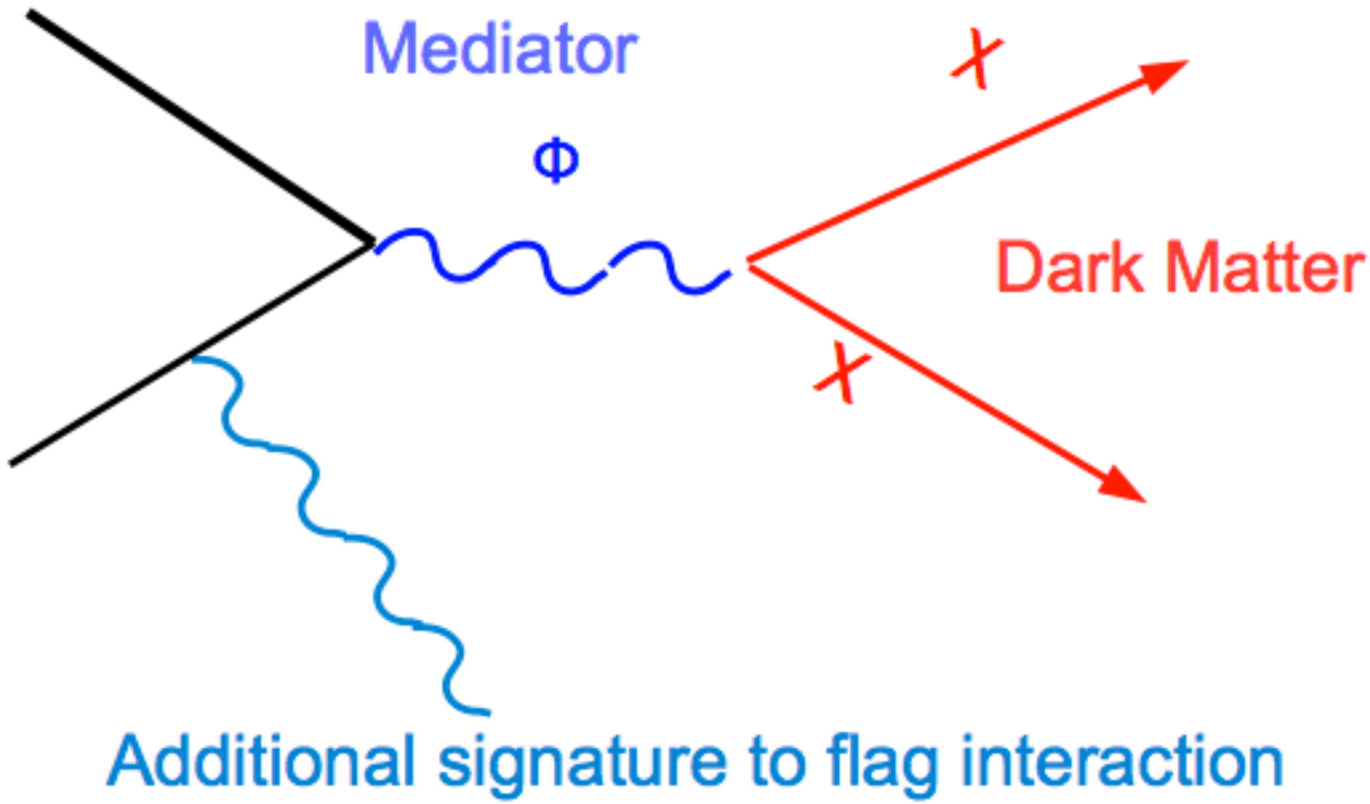
Indirect Detection





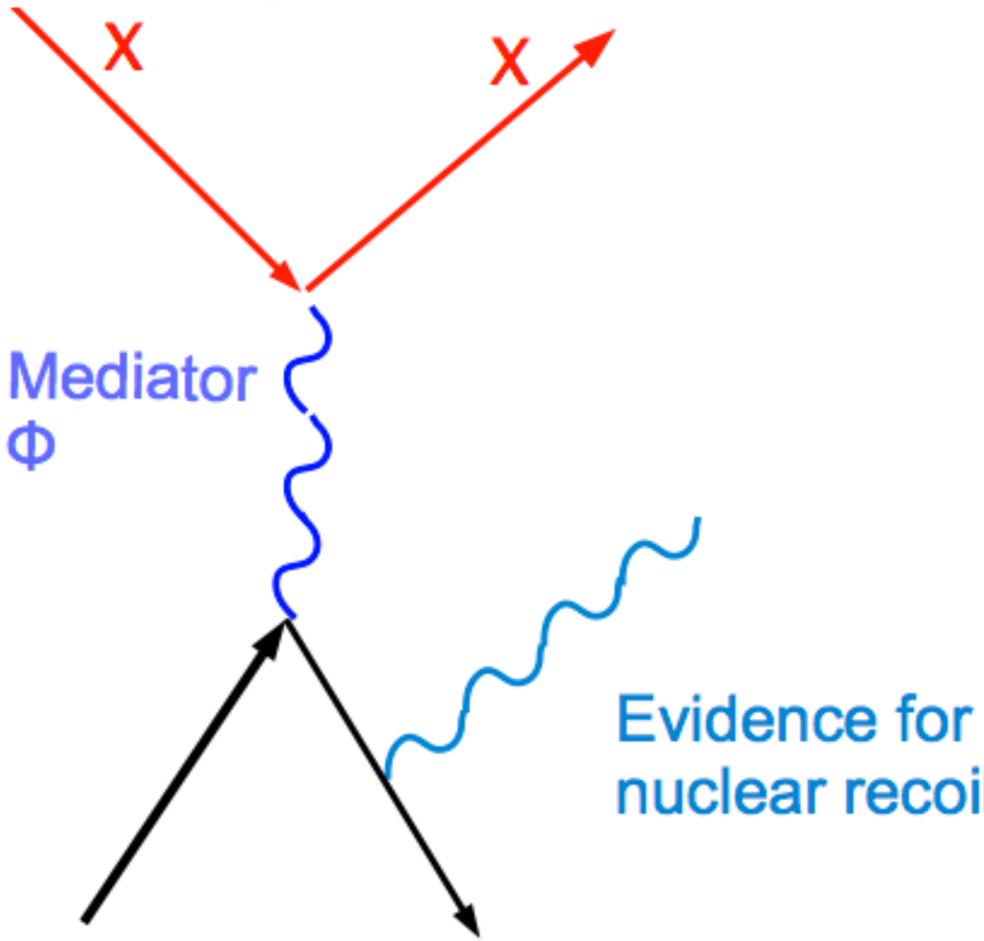
How do we find it: @LHC

- Produced it through a mediator



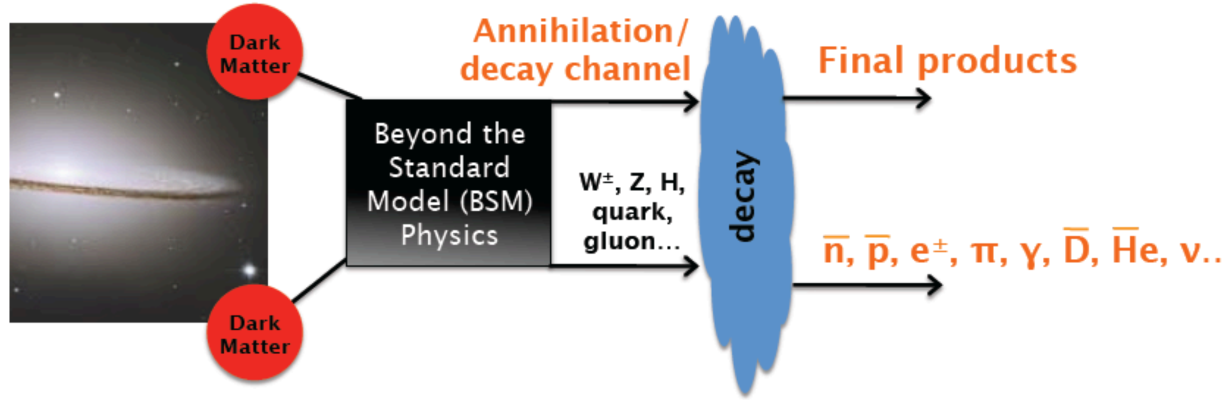
How do we find it: @underground

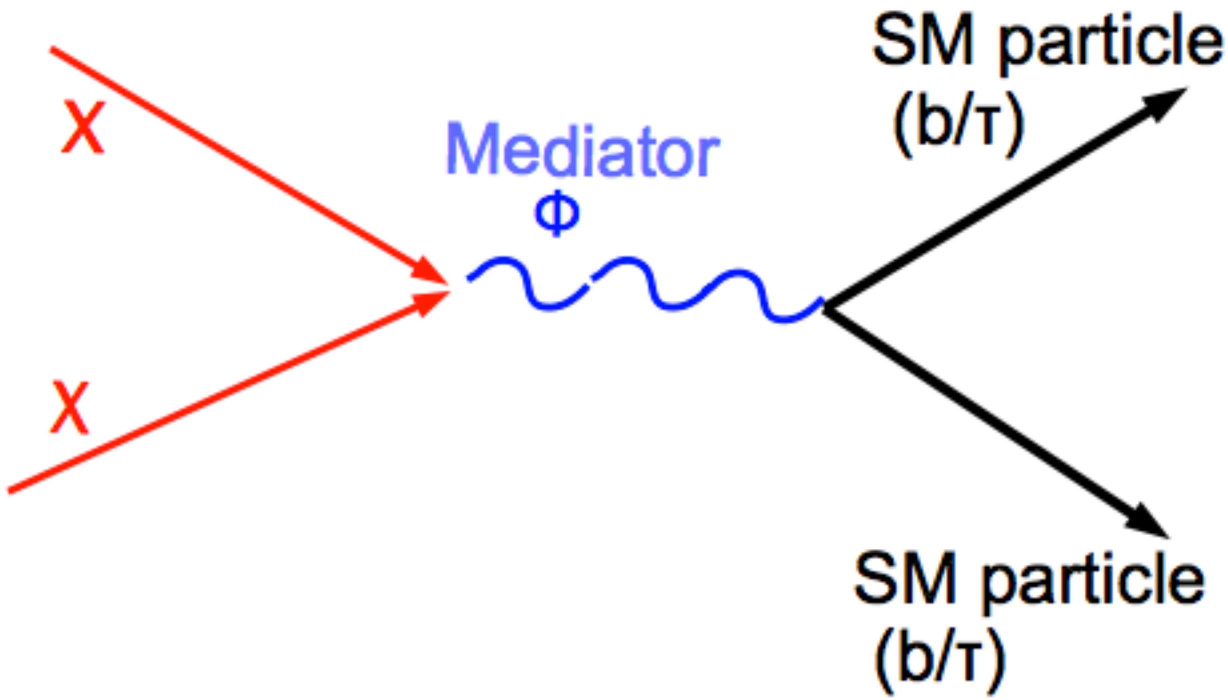
- Through a nuclear recoil



How do we find it: @Space

- Through annihilation
  - Cosmic rays from DM

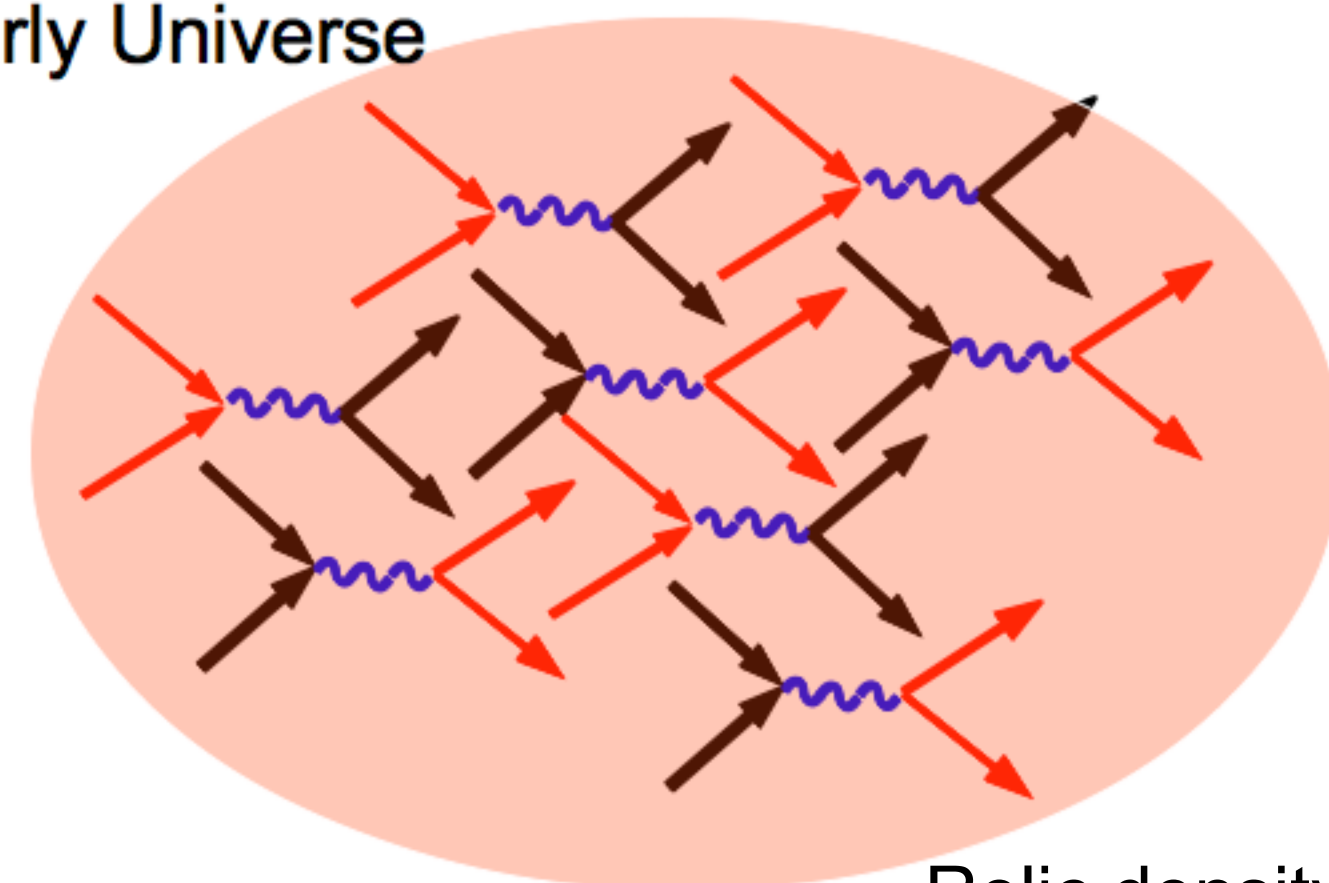




How do we find it: @nearUniverse

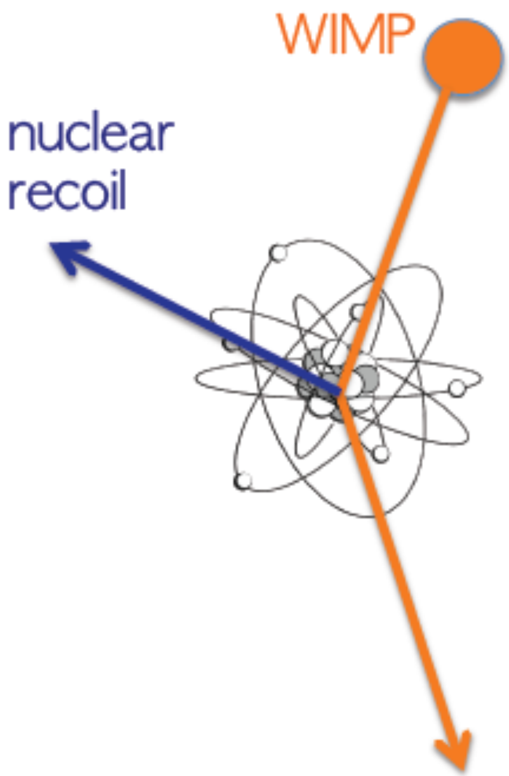
- Back and forth, production and annihilation
- Measure density and set constraints

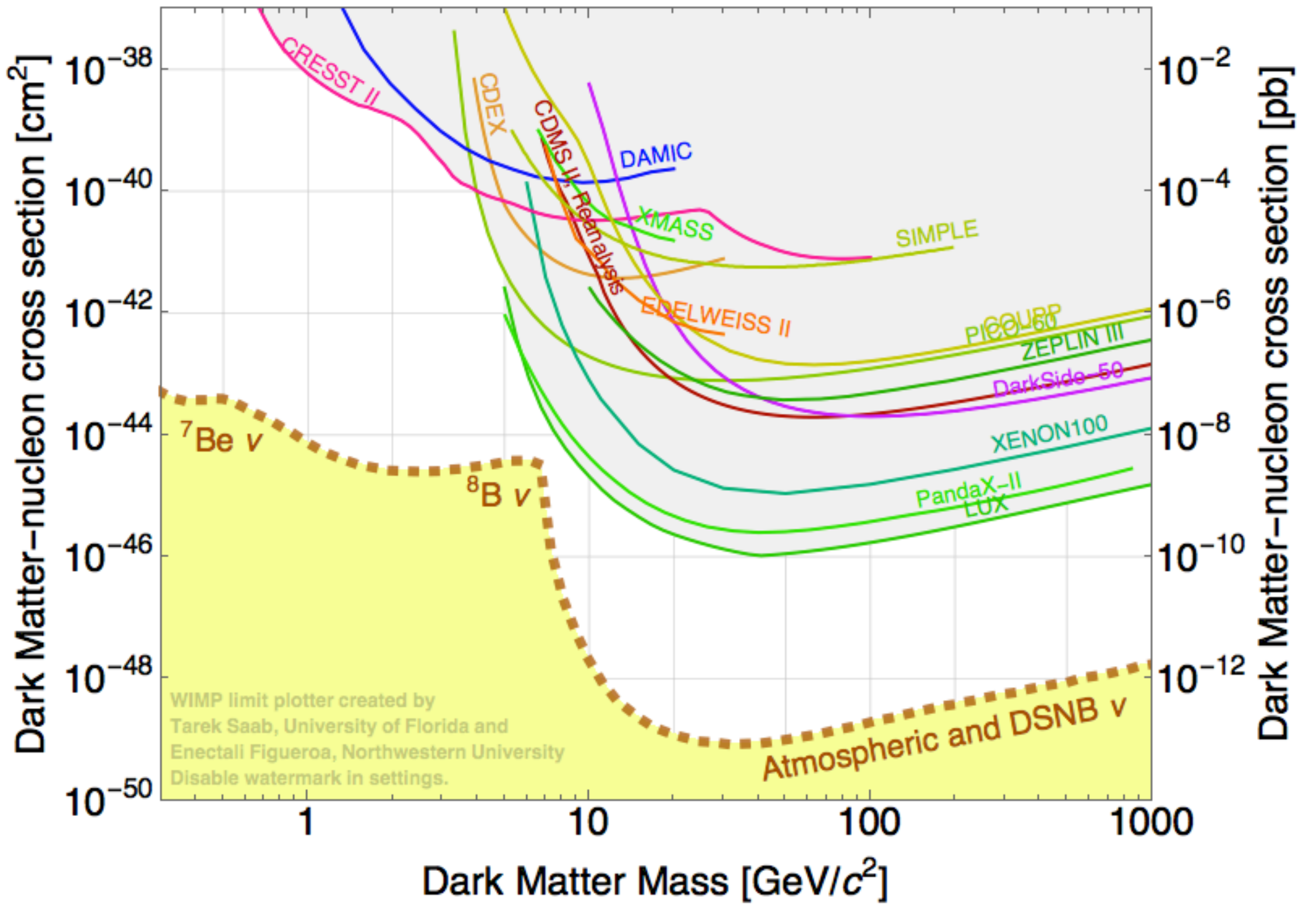
Early Universe



Relic density constraint

Experimental Results



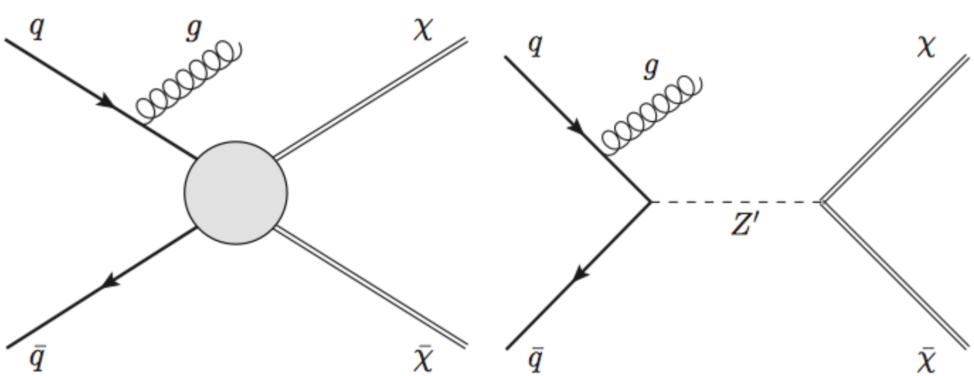


⇒Direct searches less sensitive to low masses due to energy threshold on nuclear recoil

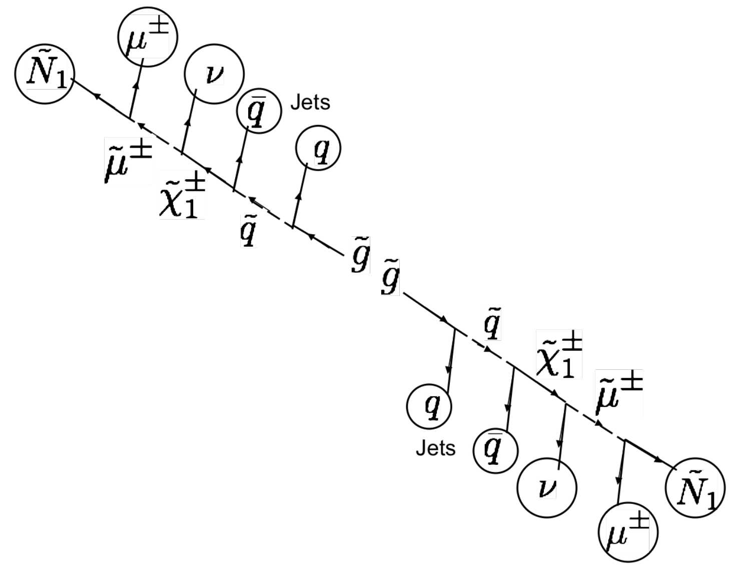
Collider searches

Weakly interacting massive particles

- Effective field theory, simplified models



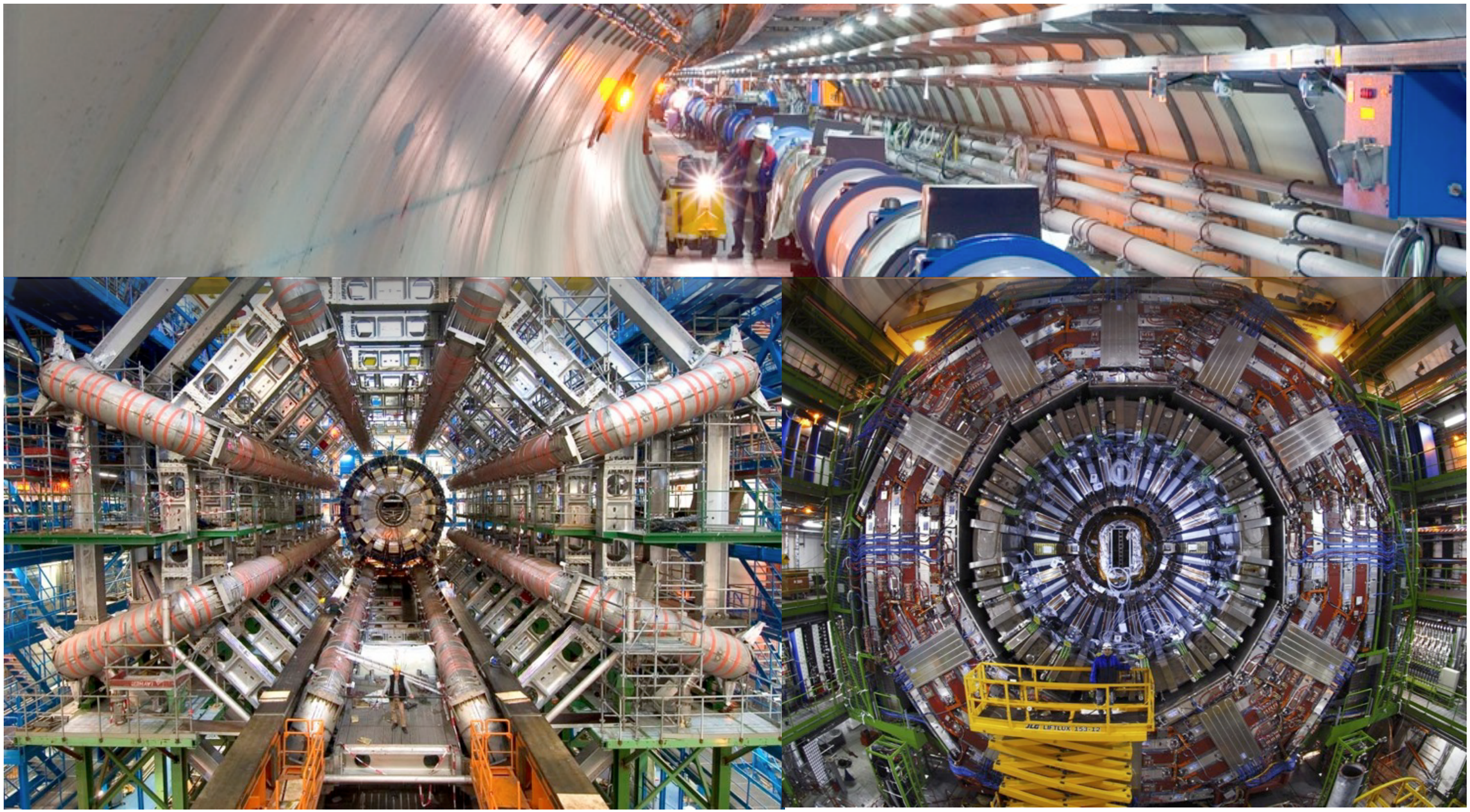
Model-dependent searches



Searches for particles stable within detector acceptance, sensitive to mediator mass

DM at the LHC

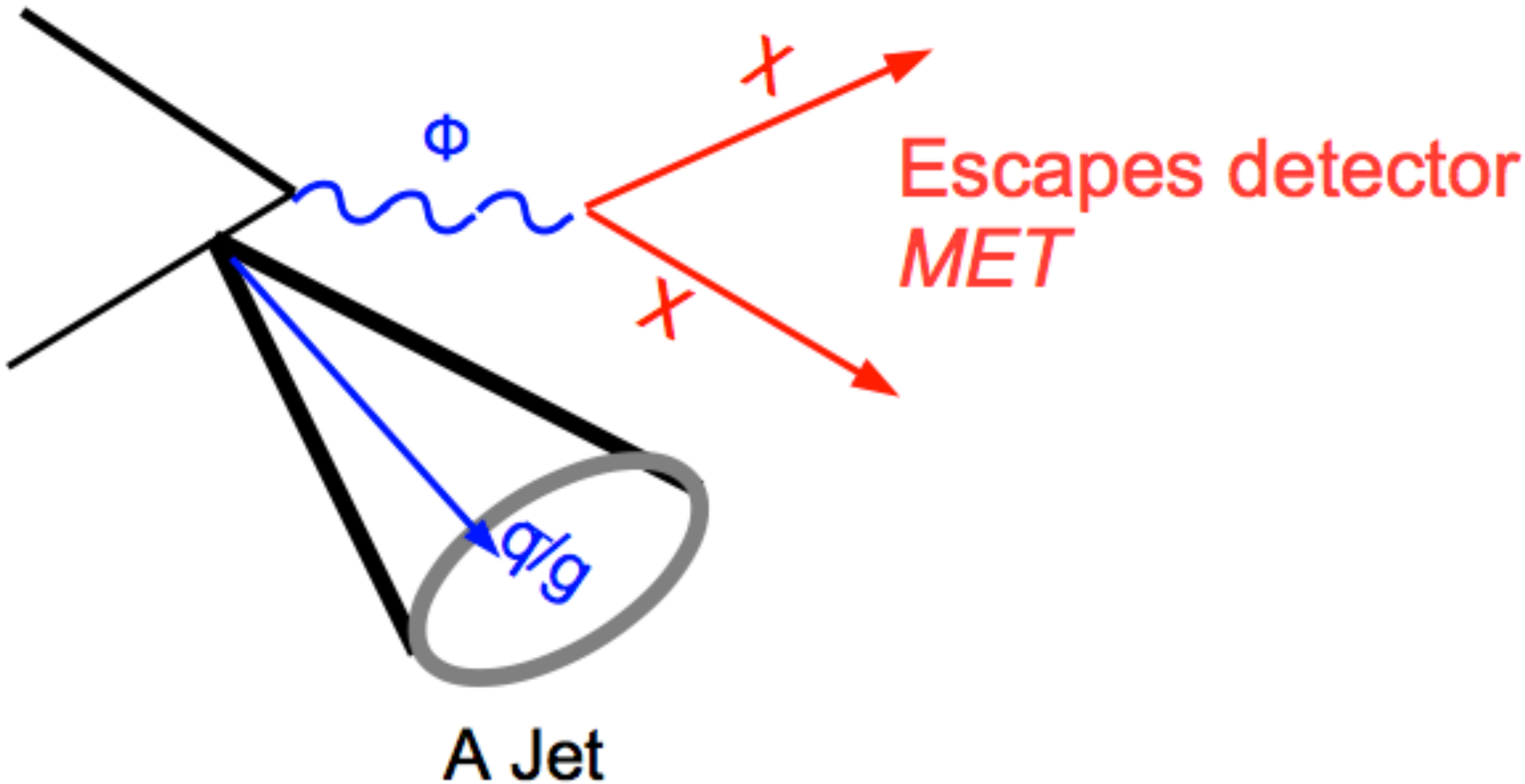
- CMS/ATLAS experiments not designed for DM searches



DM searches at LHC

How do we find DM at the LHC?

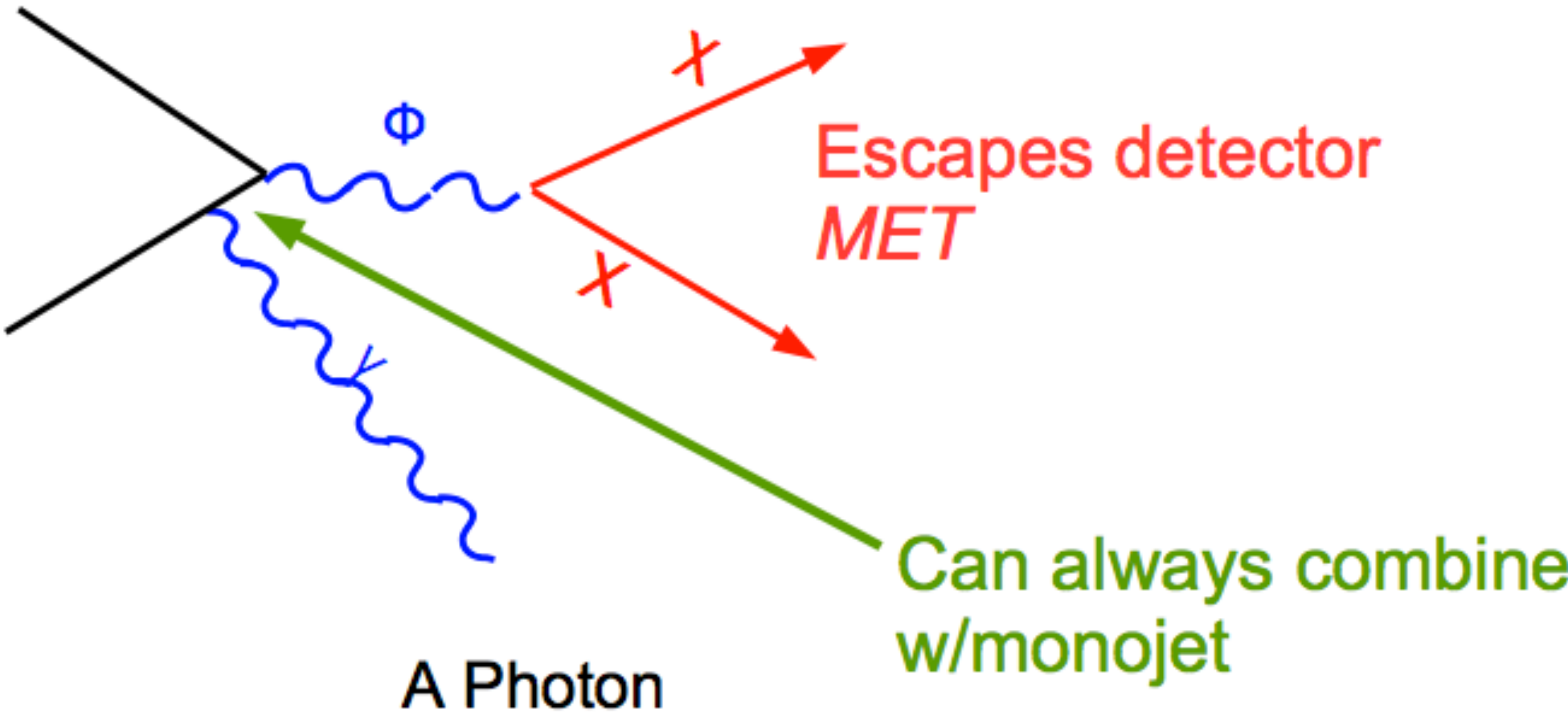
- DM production gives MET signature



DM searches at LHC

How do we find DM at the LHC?

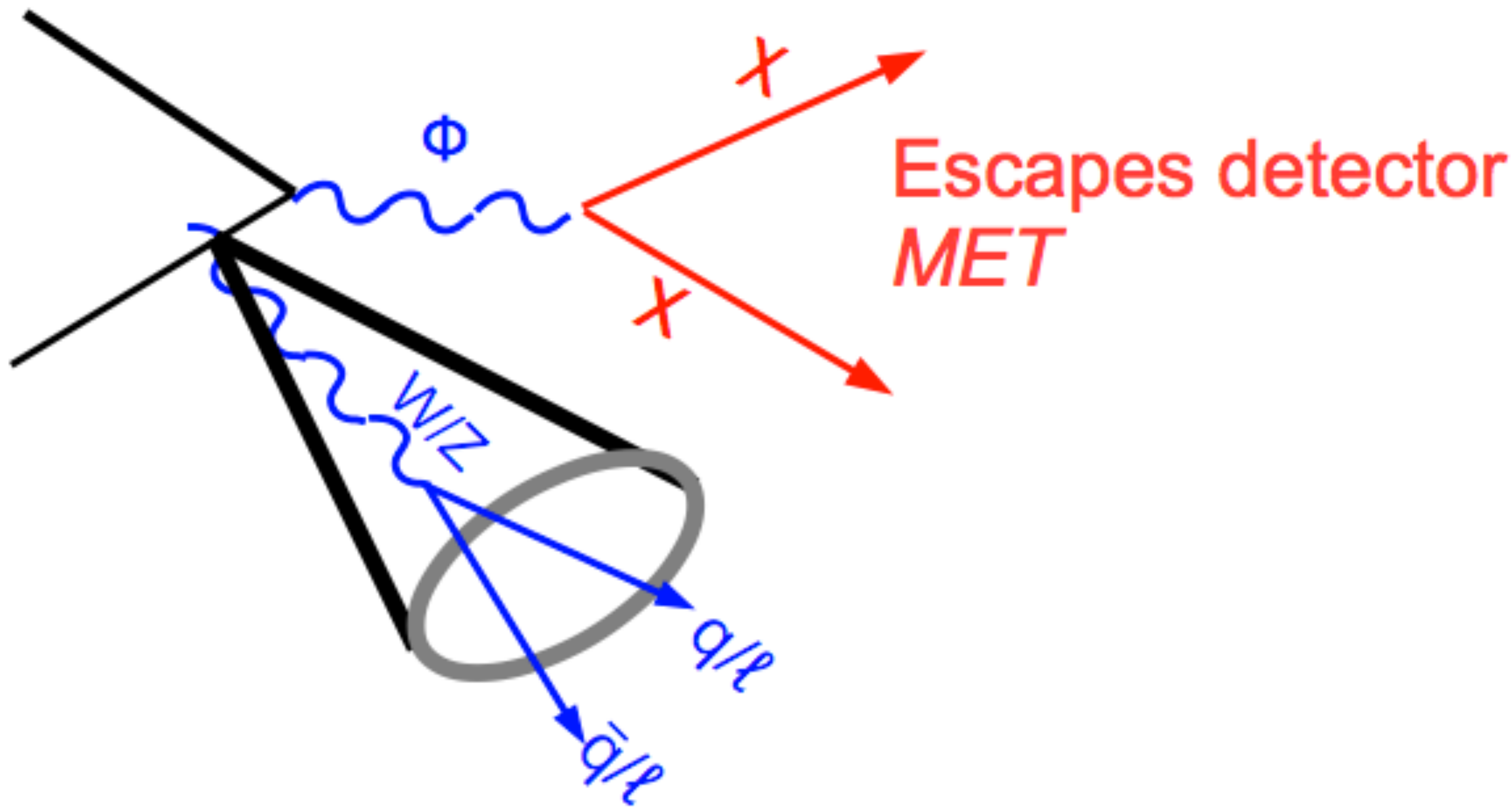
- Mono-photon: Can also tag events with a photon



DM searches at LHC

How do we find DM at the LHC?

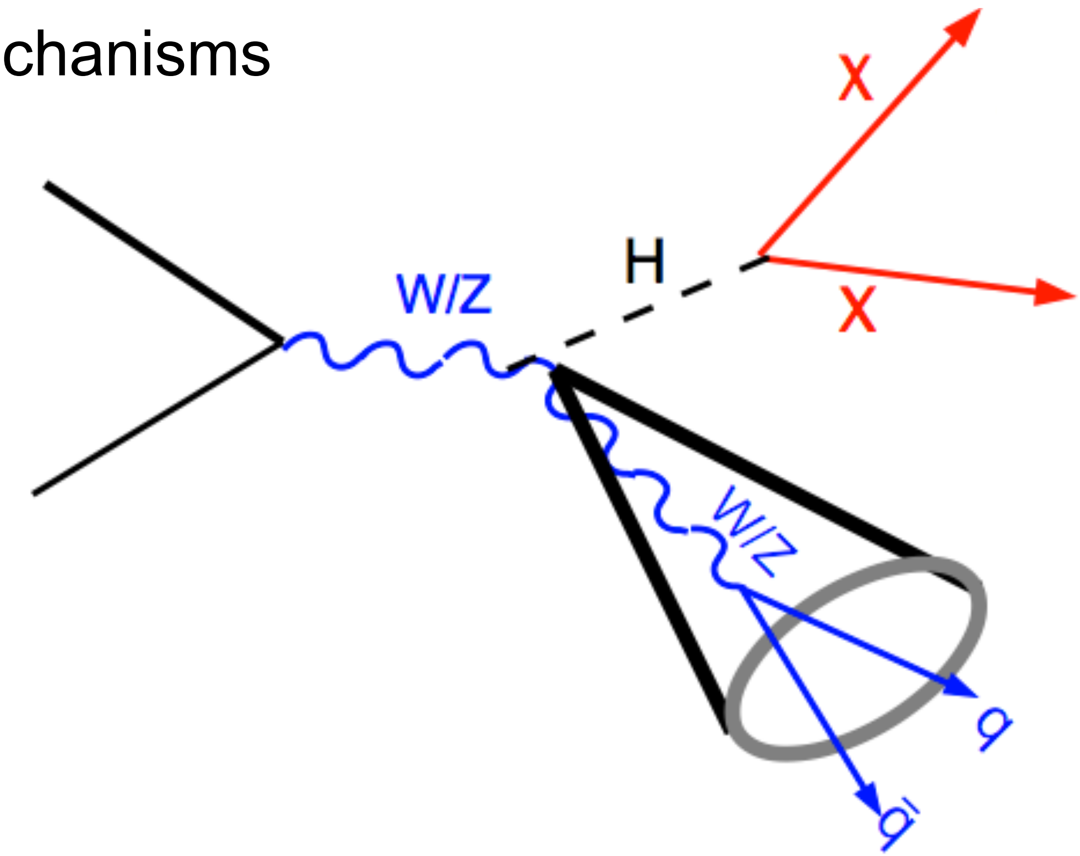
- Mono-V: Tag events with a boson



DM searches at LHC

How do we find DM at the LHC?

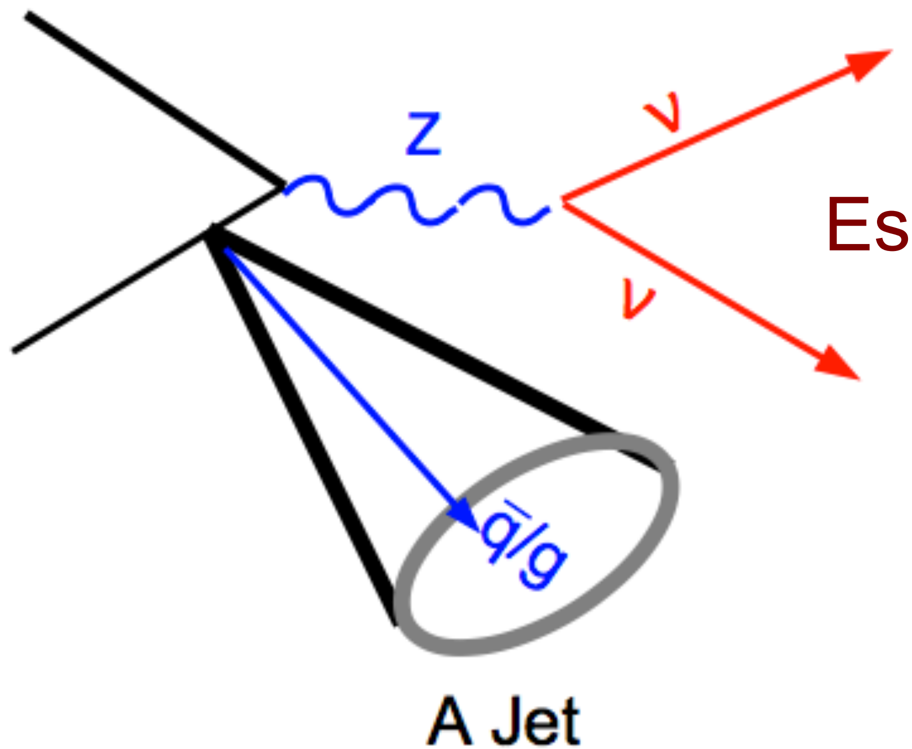
- Mono-V with (pseudo-) scalars
  - Different production mechanisms



DM searches: backgrounds

What are the backgrounds?

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

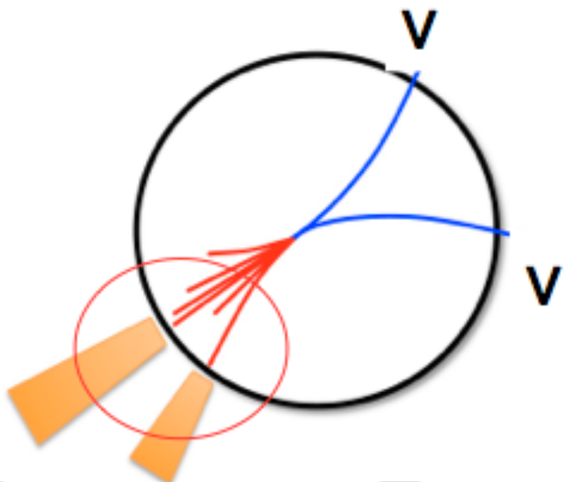


Escapes detection

DM searches: backgrounds (cont.)

How to discriminate signal against the background?

- Look for high MET:



Study hadronic recoil

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

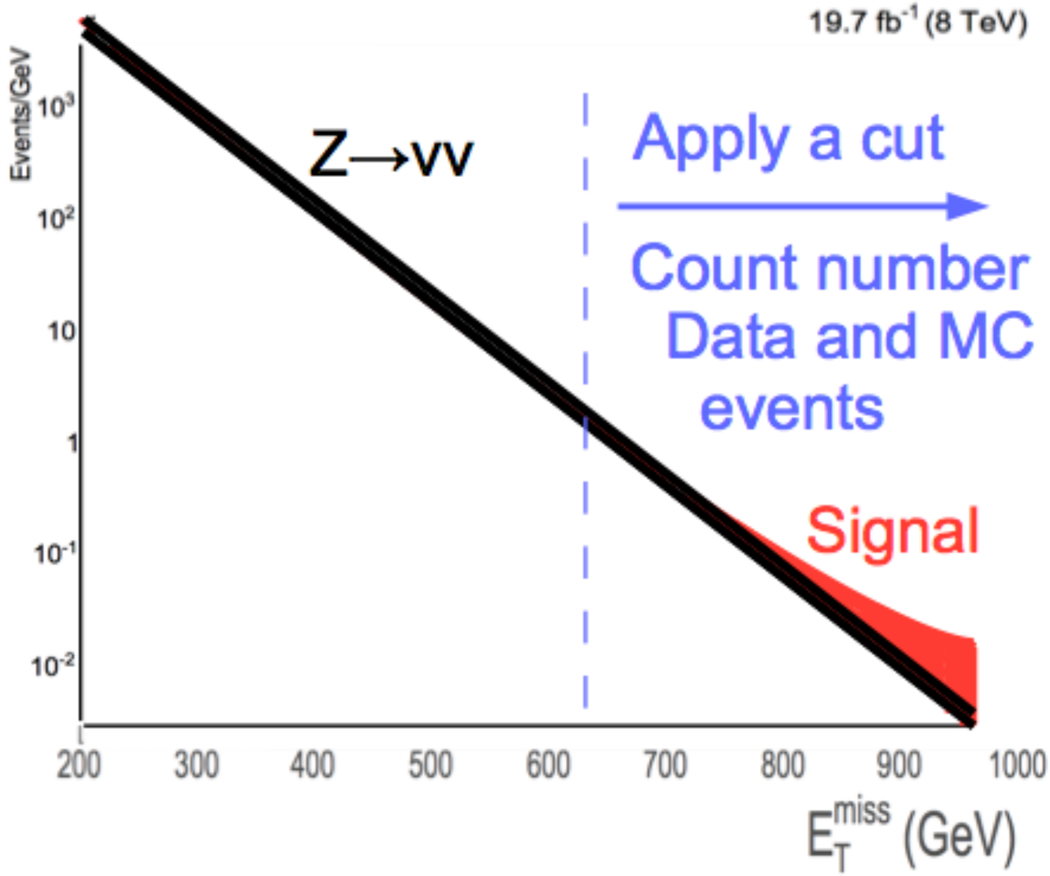
$$MET(Z \rightarrow \nu\nu) = -\ Z\ recoil + p_T(\nu\nu)$$

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

DM searches: backgrounds (cont.)

How to discriminate signal against the background?

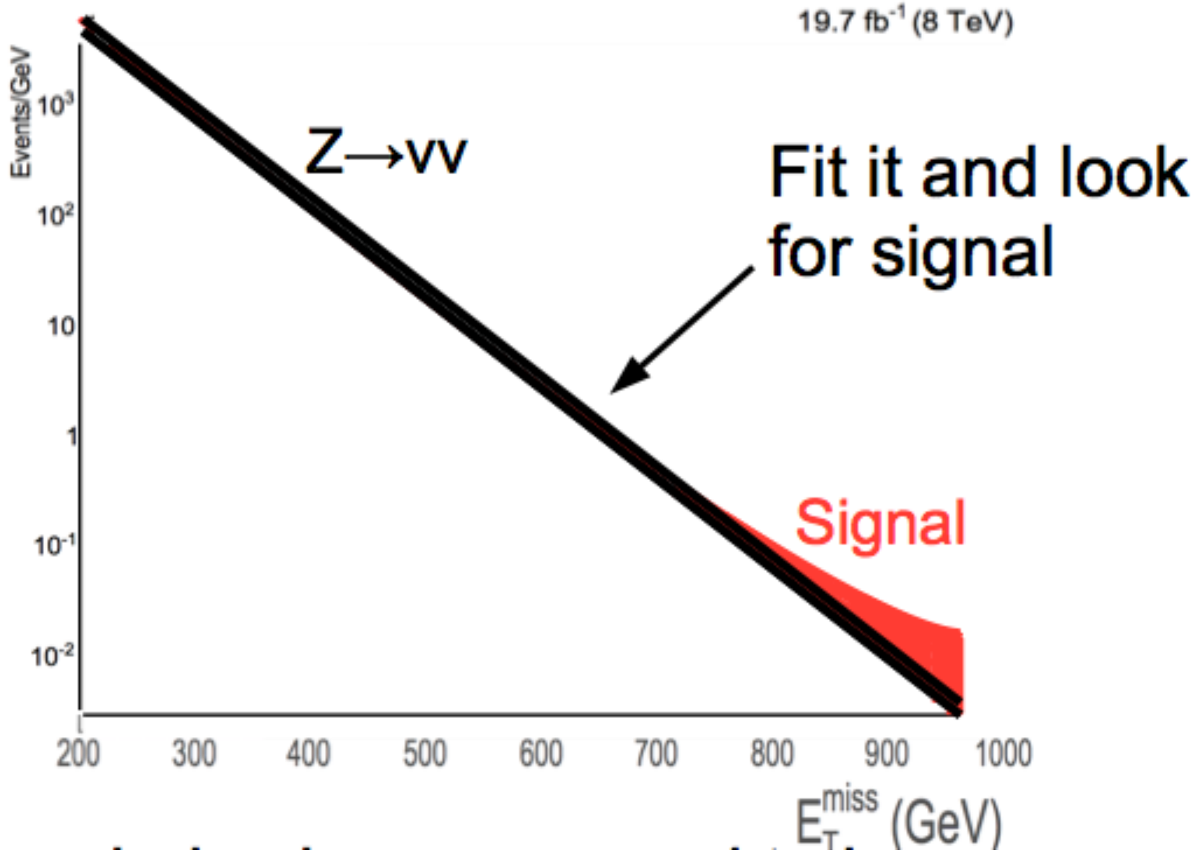
- Cut and count events or…



DM searches: backgrounds (cont.)

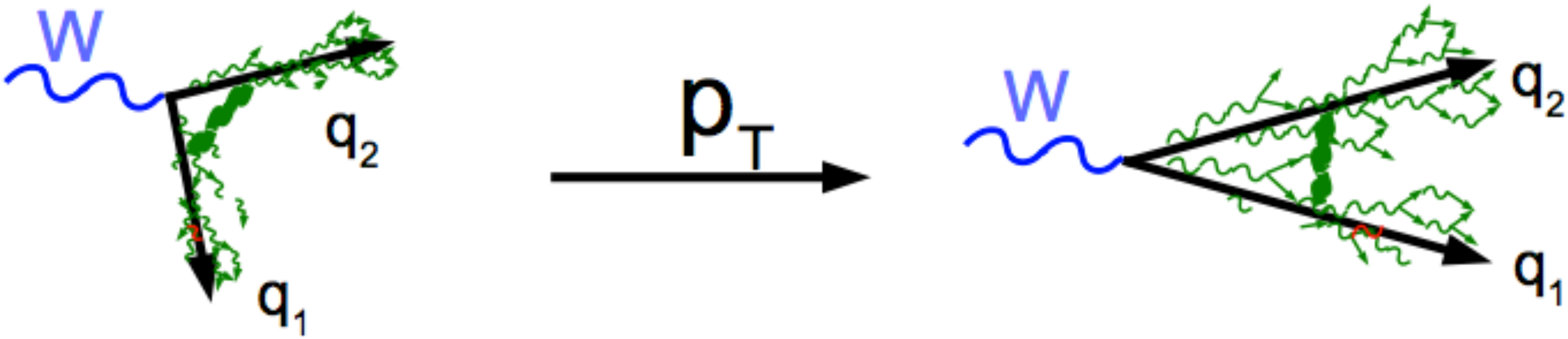
How to discriminate signal against the background?

- Can fit the shape and look for signal



Build a V-tagger

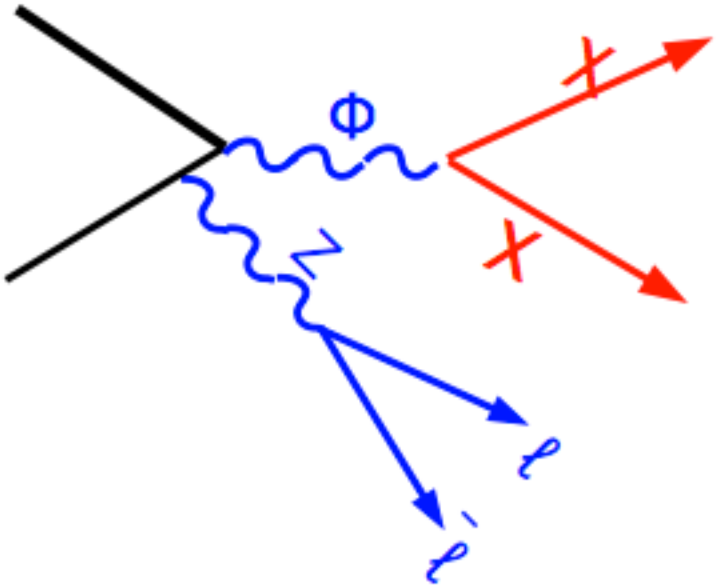
- Two jets are more collimated at high pT



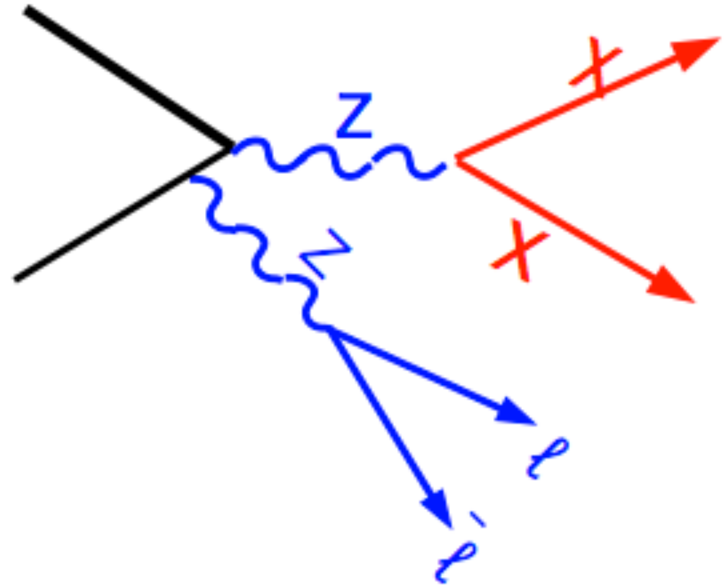
- At low pT jets are "resolved"
  - Focus on reconstructing di-jets with mass near W mass
- At high pT get one "fat" jet
  - Focus on identifying one jet with mass near W mass
- Use additional variables to improve discrimination

DM+Z

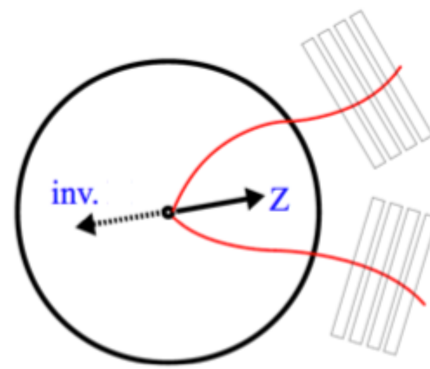
signal



background



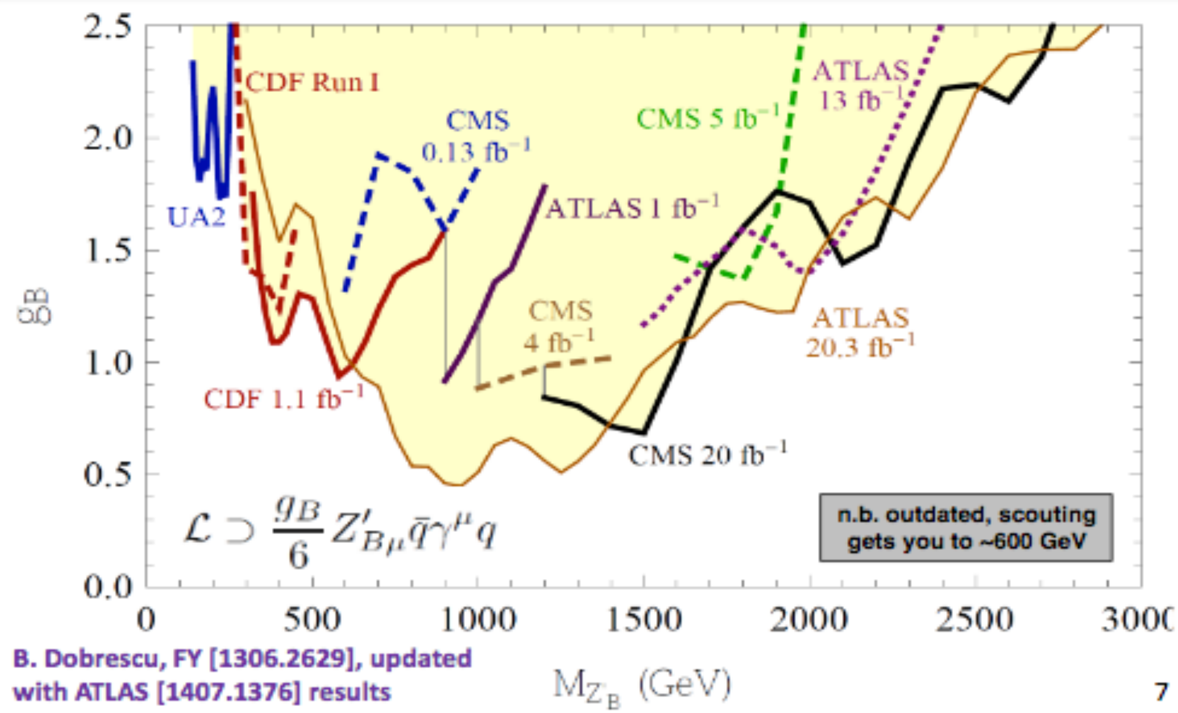
- Main background is from ZZ di-bosons
- Understanding ZZ di-boson pT is critical



DM+jets (j/V/γ)

CMS-EXO-16-030

- Search focused on light mass region (100-300 GeV)
- Experimental challenges
  - Large QCD background
  - Triggers

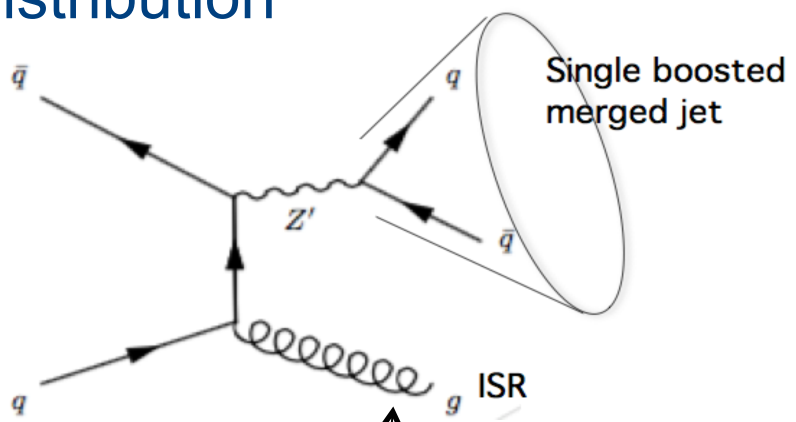


hole in collider dijet searches

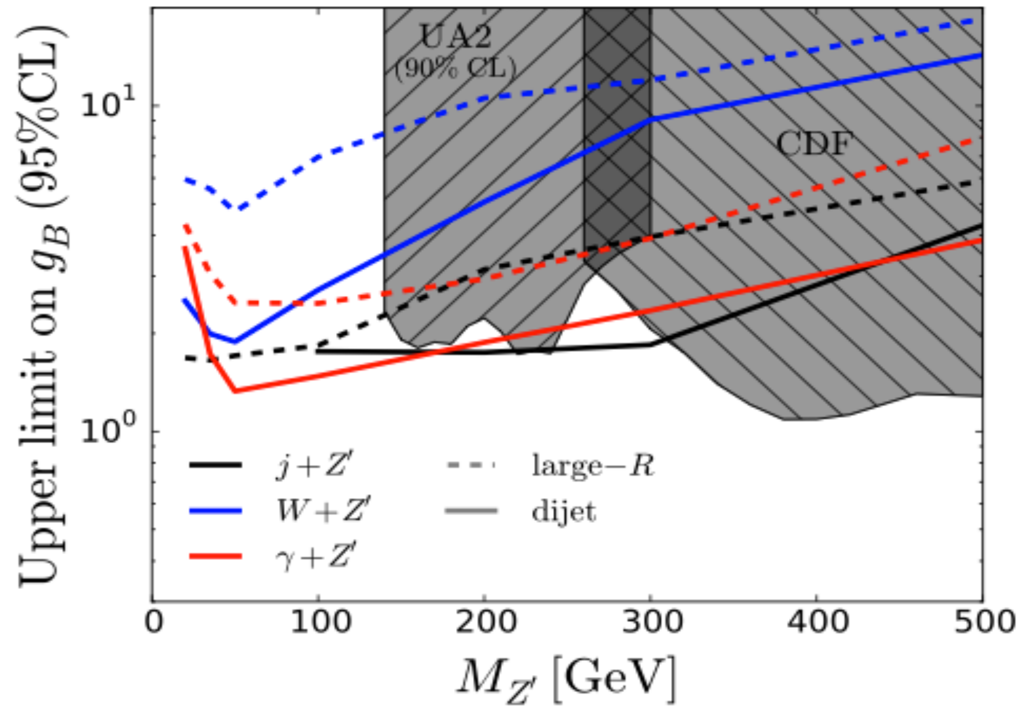
DM+jets (j/V/γ): Motivation

CMS-EXO-16-030

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



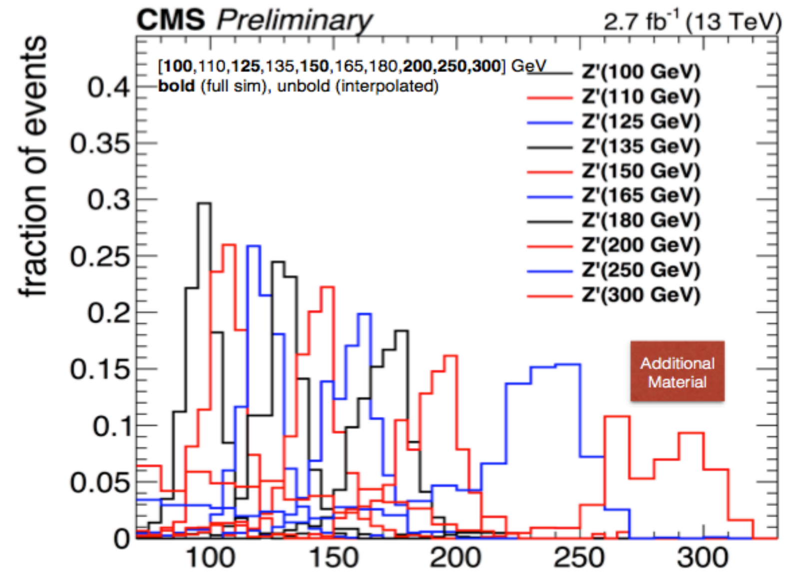
mono-jet/W/γ



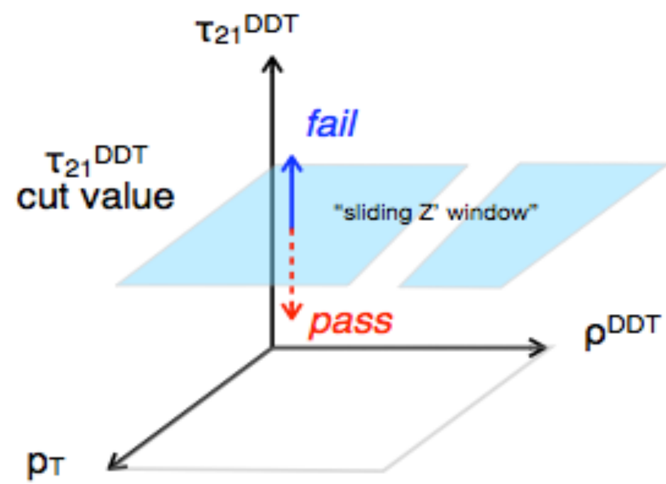
DM+jets (j/V/γ): Analysis

CMS-EXO-16-030

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



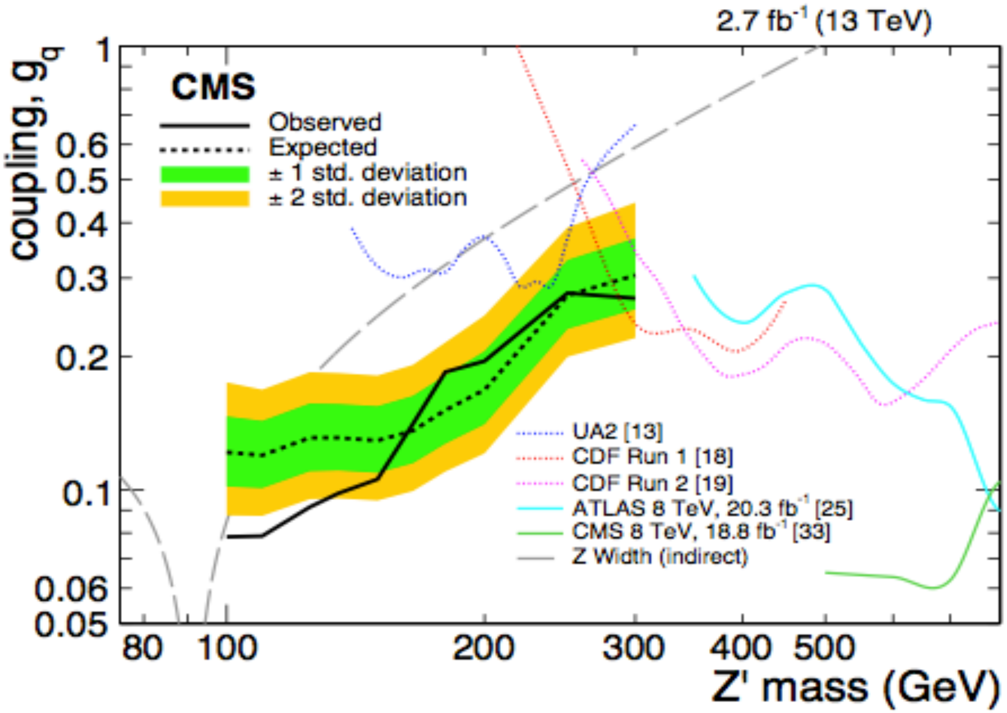
- QCD background estimated from sideband regions in data
- τ_{21}^{DDT} n-subjettiness: consistency with 2-prong structure
- τ_{21}^{DDT} defines "pass" or "fail" sidebands
  - Use TF from fail to pass region

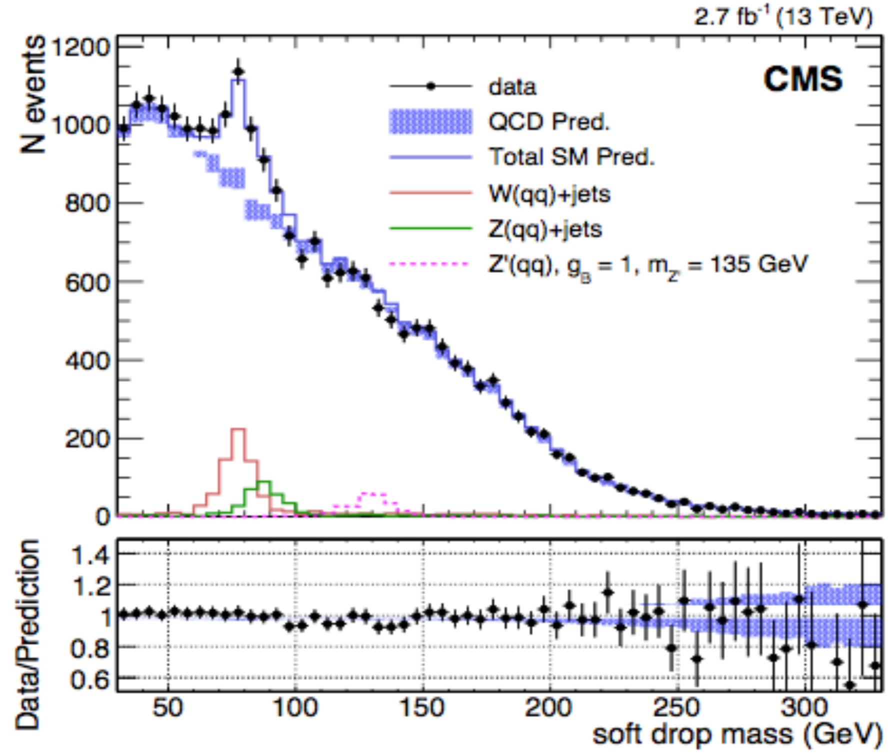


DM+jets (j/V/γ): Results

CMS-EXO-16-030

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



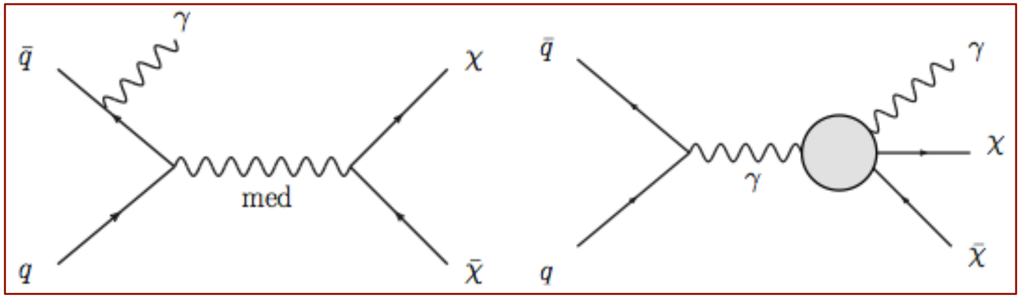


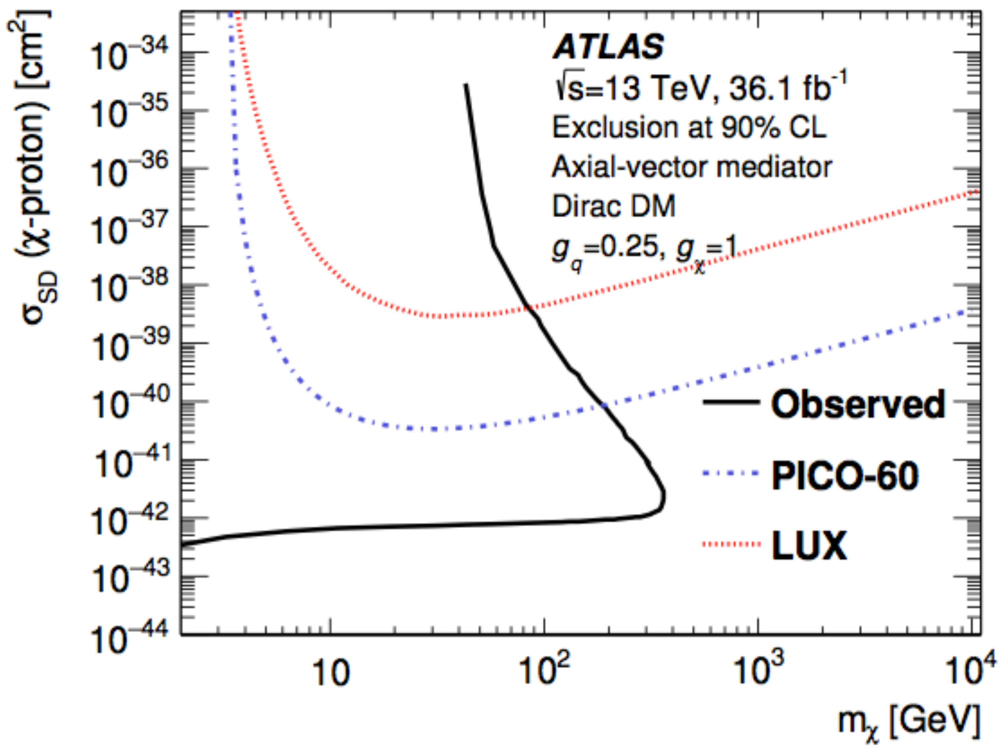
- Search for low-mass boosted dijet resonances
- Explores uncovered regions
- Limits in Z' mass at low mass

DM+photon

arXiv:1704.03848

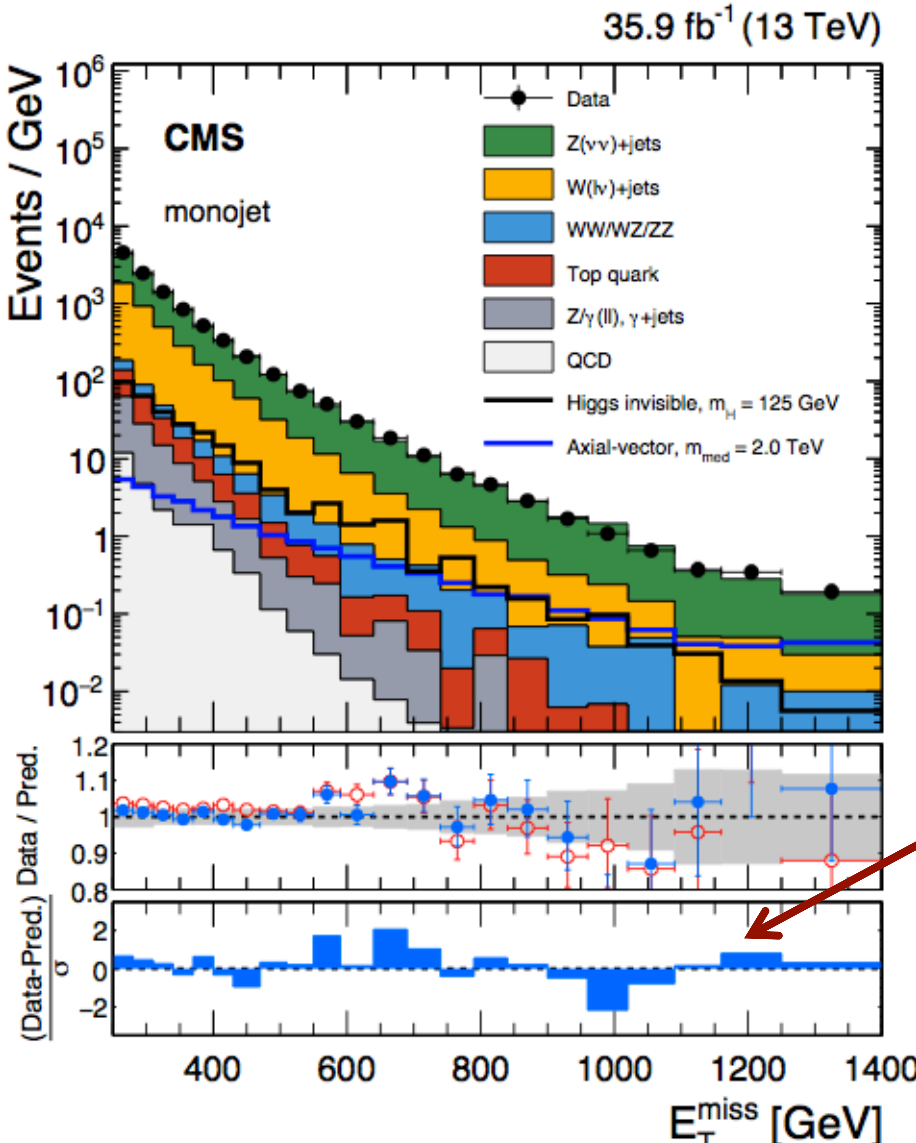
- BSM theories predict events with photon+MET
- Small SM background



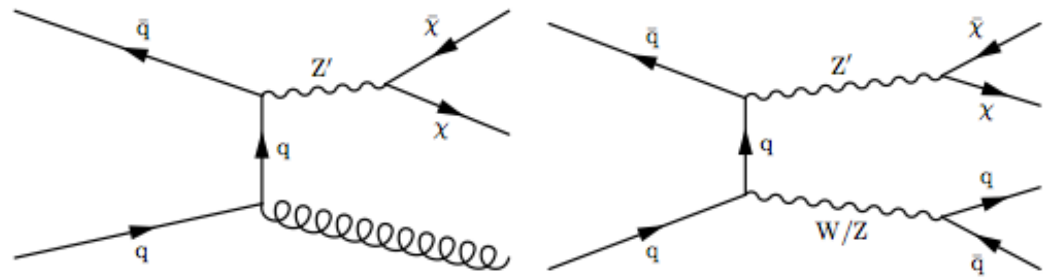


DM+jet/V

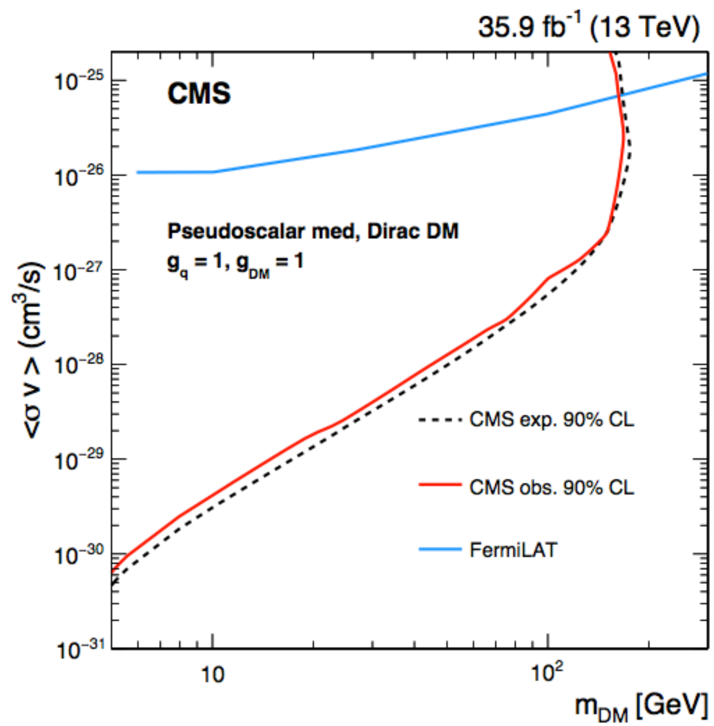
CMS-EXO-16-048



DM search in mono-jet/V



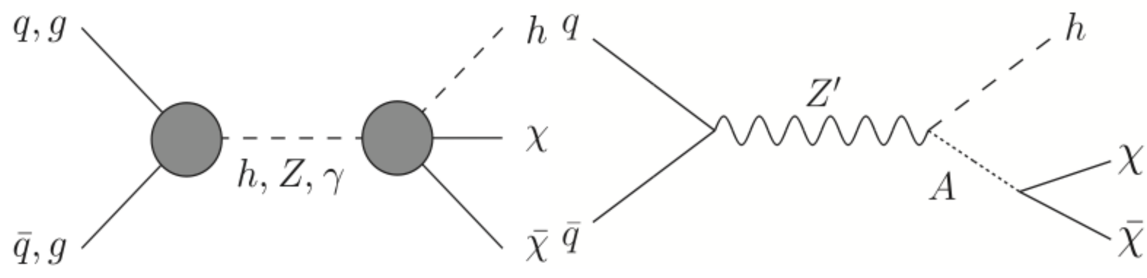
Need good control of systematics



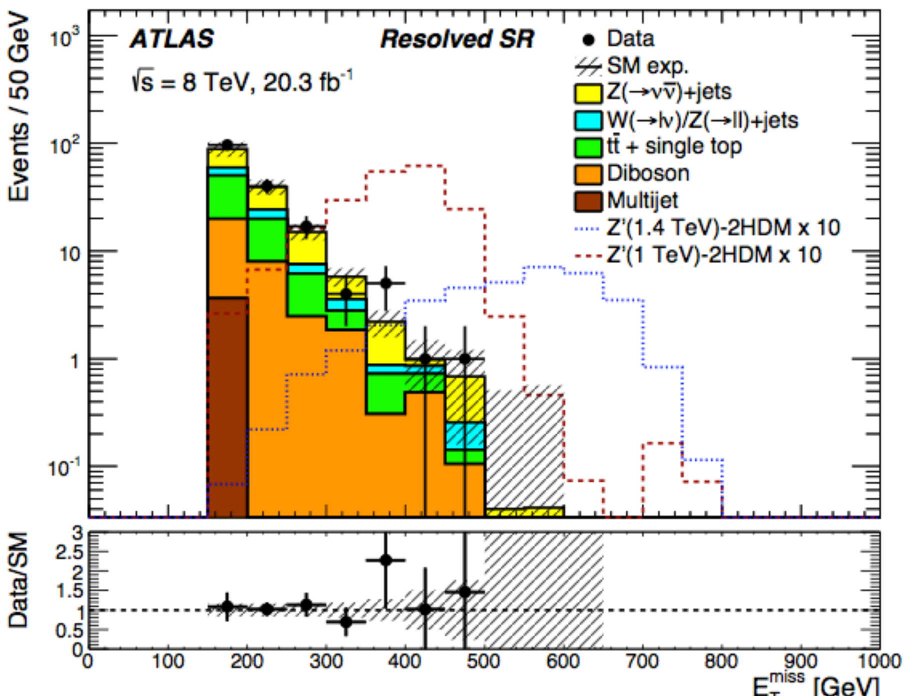
DM+Higgs

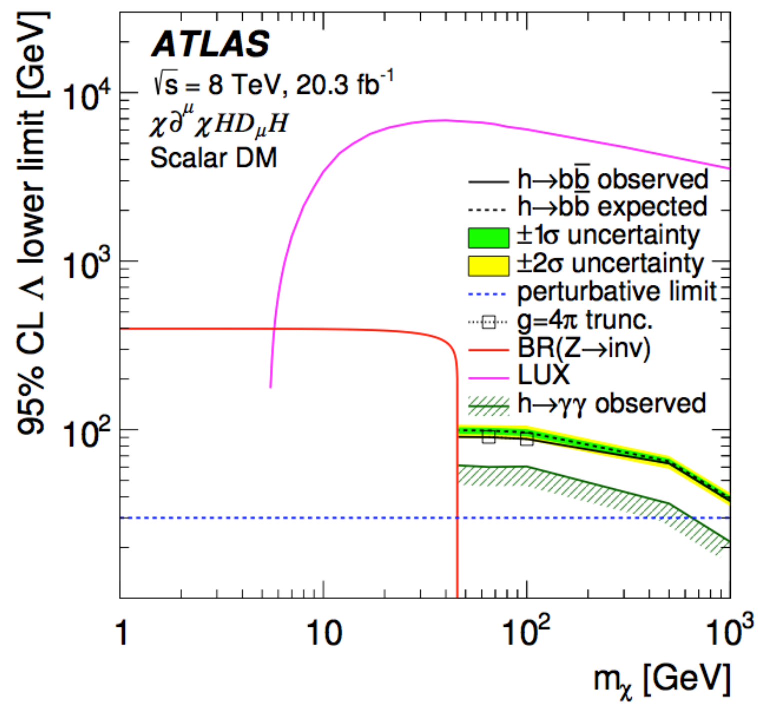
arXiv:1510.06218, arXiv:1506.01081

- Generic search: pp→X+MET
- Search for DM + h(→bb)
- Model-independent search
  - Signature: h(→ZZ/bb/γγ)+MET
  - Simplified model with Z' or pseudo-scalar Higgs A(→χχ)
- Signal events at large MET



DM particle (χ): can be scalar or fermion
Pseudo-scalar Higgs A

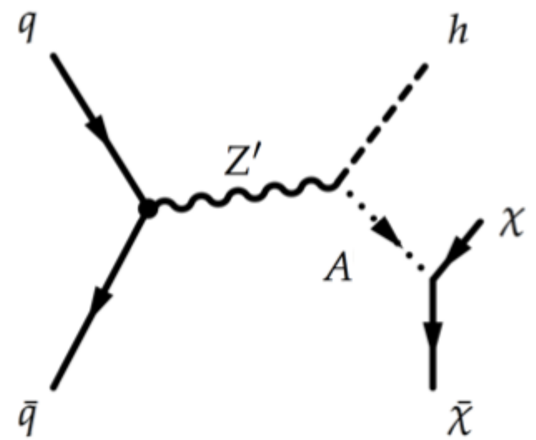


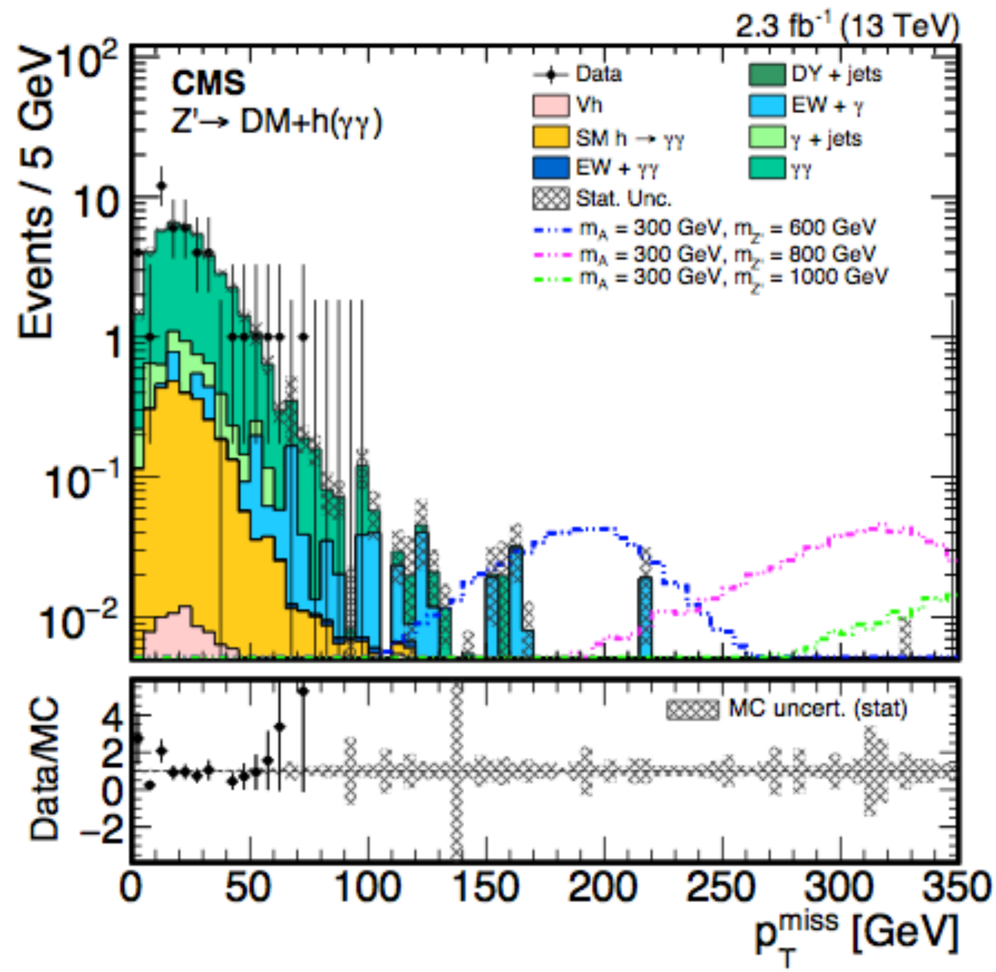


DM+Higgs (cont.)

arXiv:1703.05236

- DM search with H(→bb,γγ)
- Model dependent search
- Z' 2HDModel

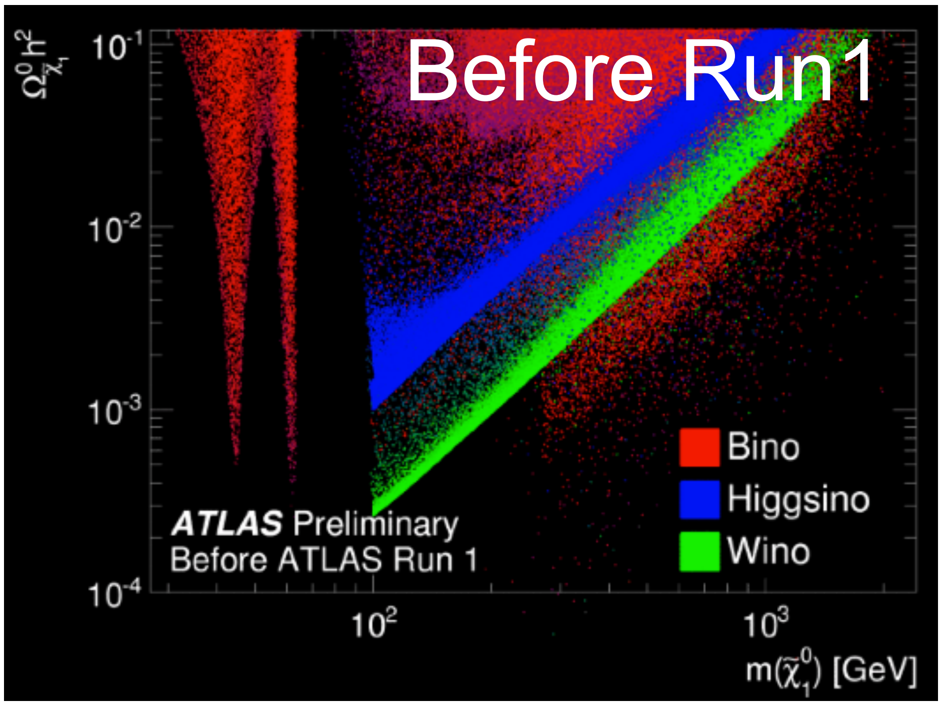


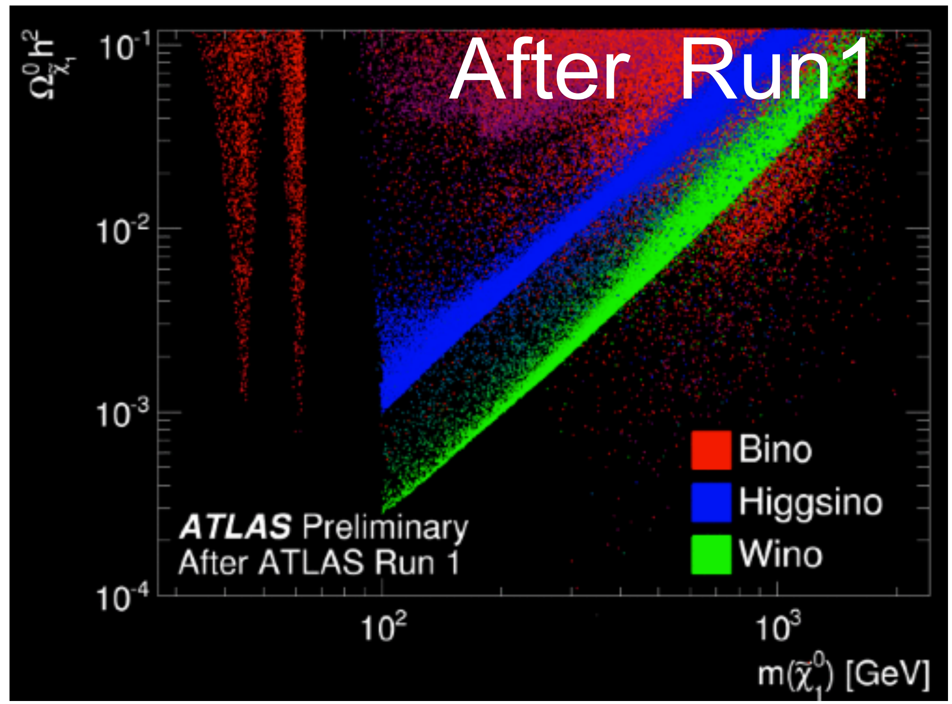


- No significant excess
- Set limits for coupling g=0.8

BSM/SUSY searches

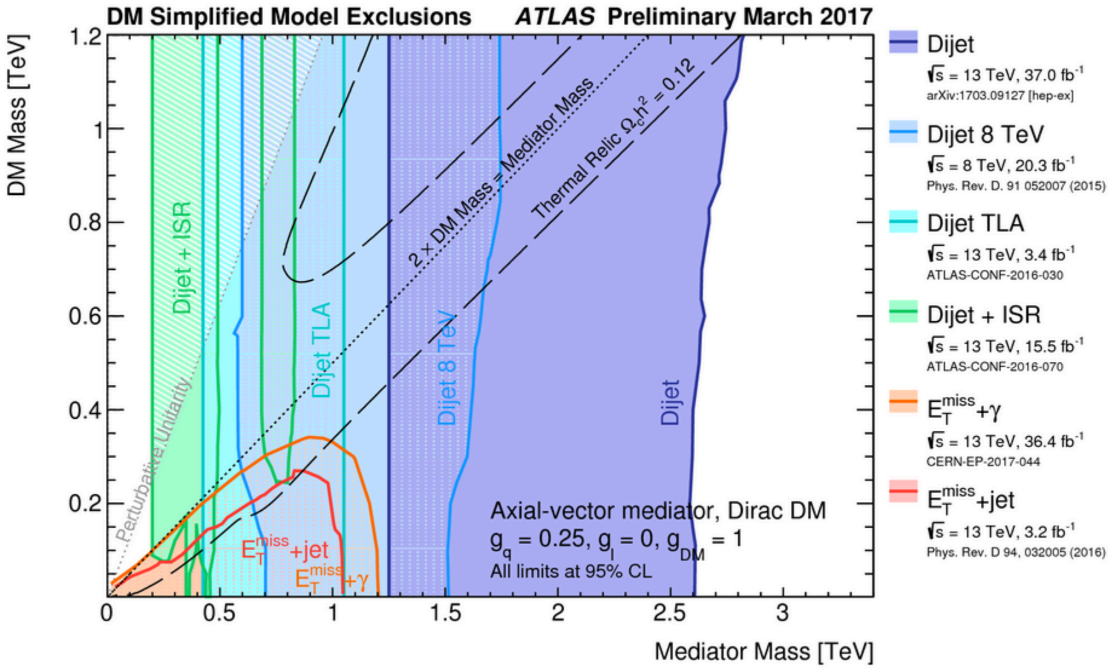
- Density of allowed supersymmetric models before and after Run 1

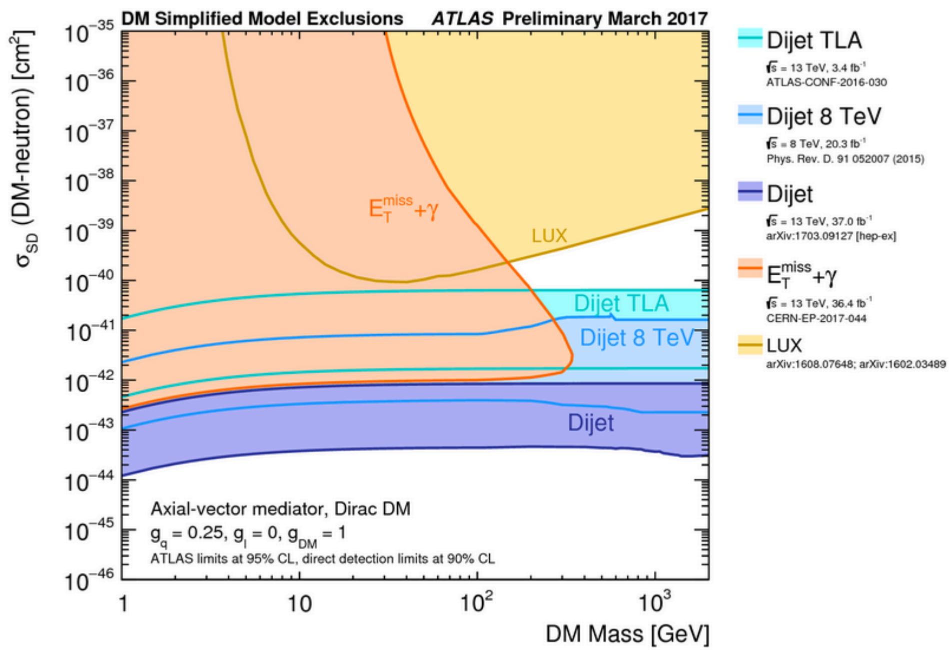




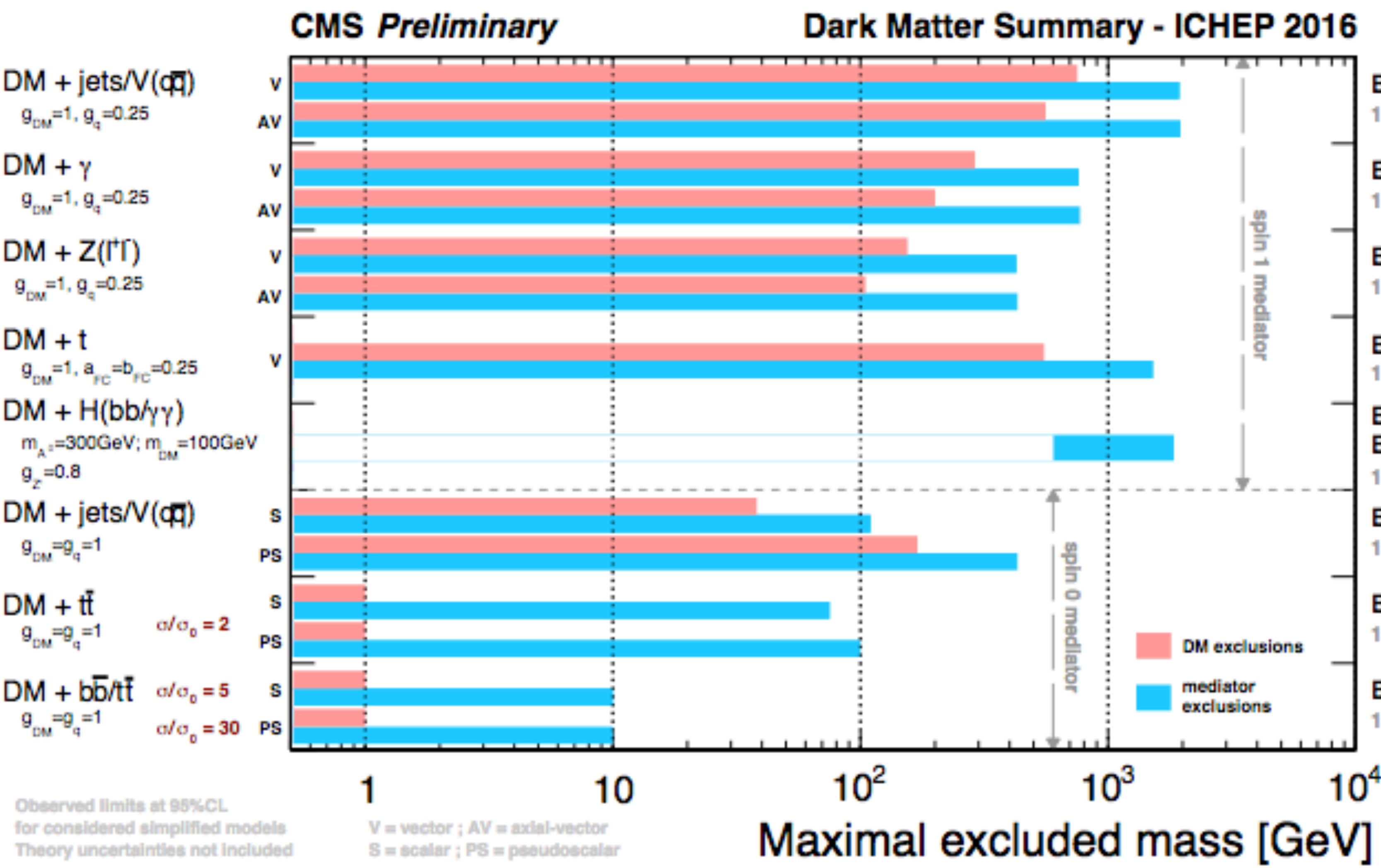
Experimental results

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



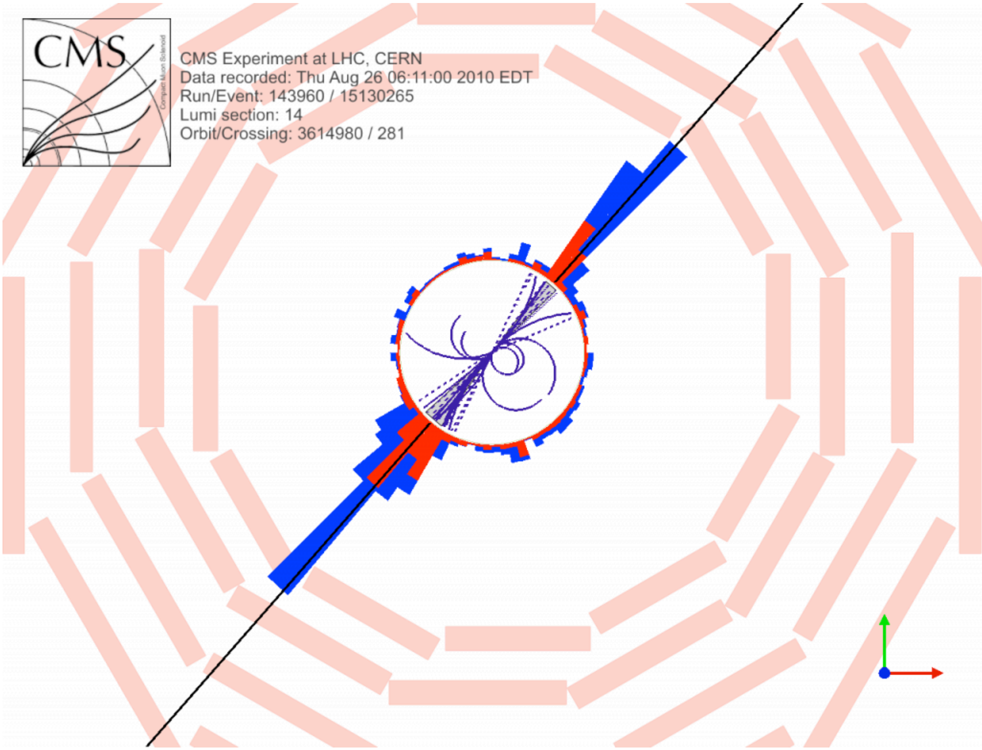


Experimental results (cont.)



Search for heavy 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)

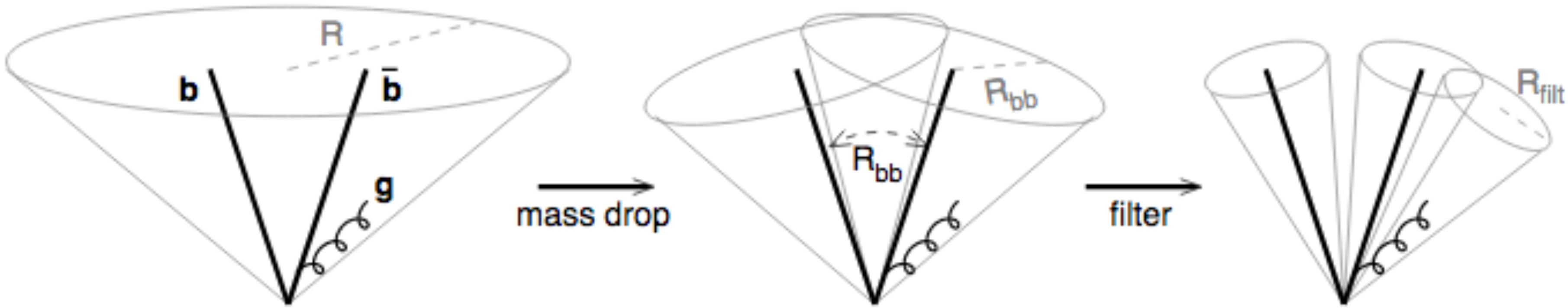


Jet grooming

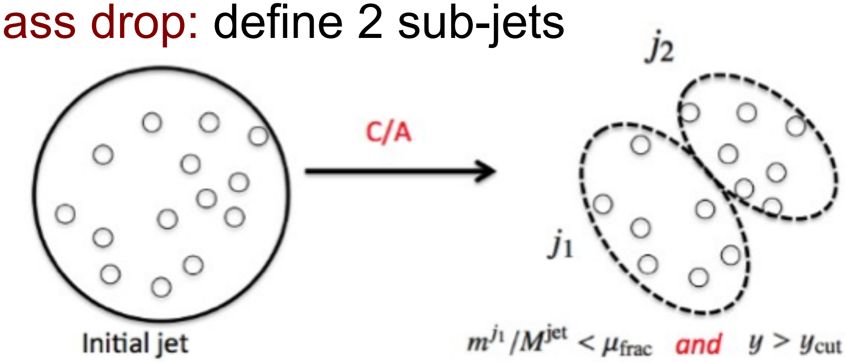
arXiv:0802.2470

Mass drop/filtering

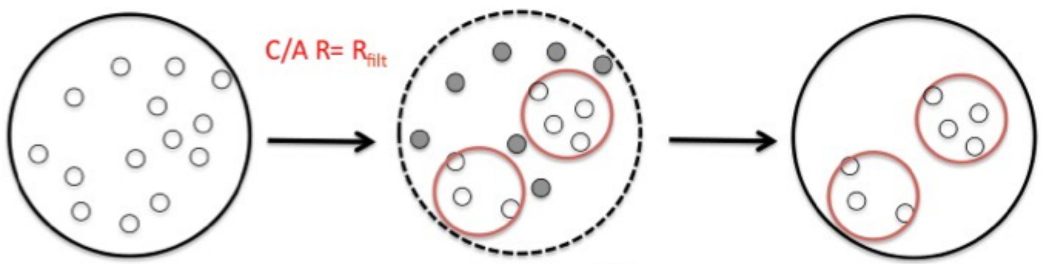
- Identify approx. symmetric sub-jets (with smaller mass than sum)



Mass drop: define 2 sub-jets



Filtering: re-cluster j1, j2 constituents

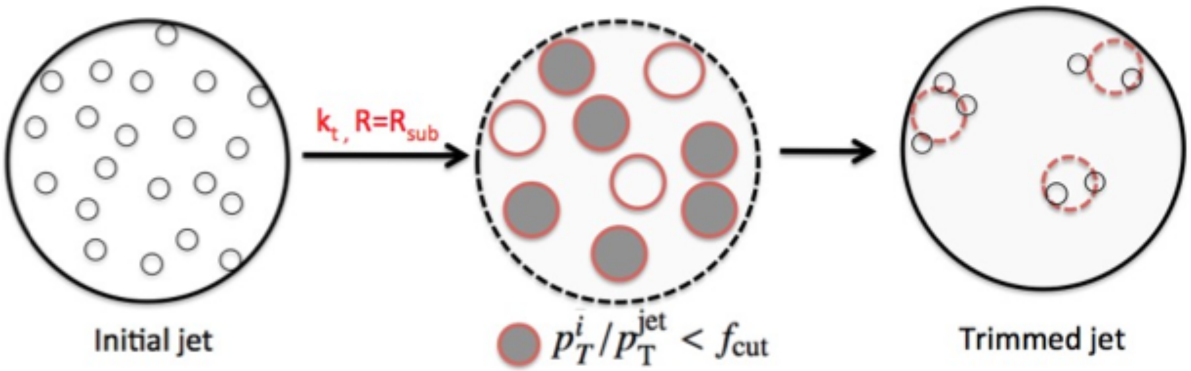


Jet grooming (cont.)

arXiv:0912.1342, arXiv:0912.0033

"Trimming"

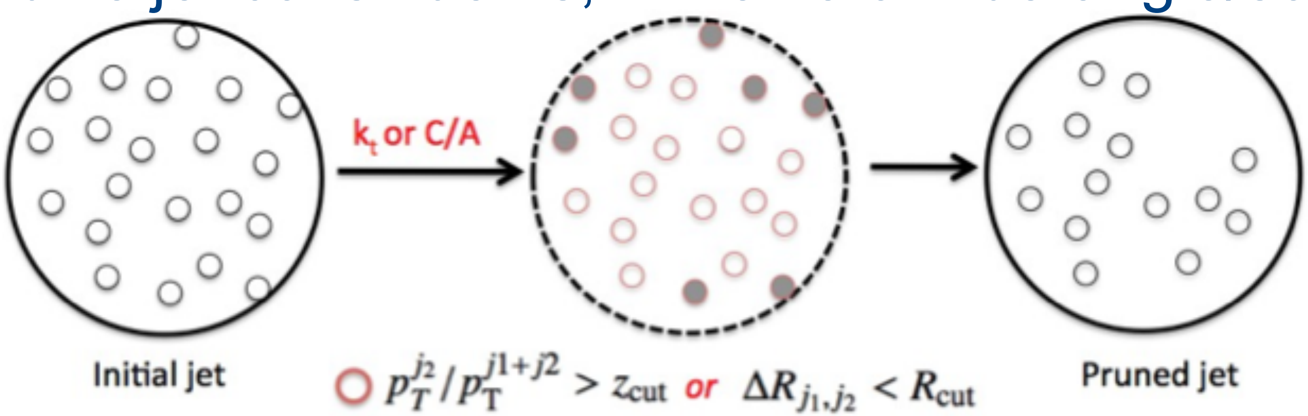
- Uses kT algorithm to make subjets (subjets with p_T^i/p_T<cut removed)



R_{sub}, f_{cut}

"Pruning"

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

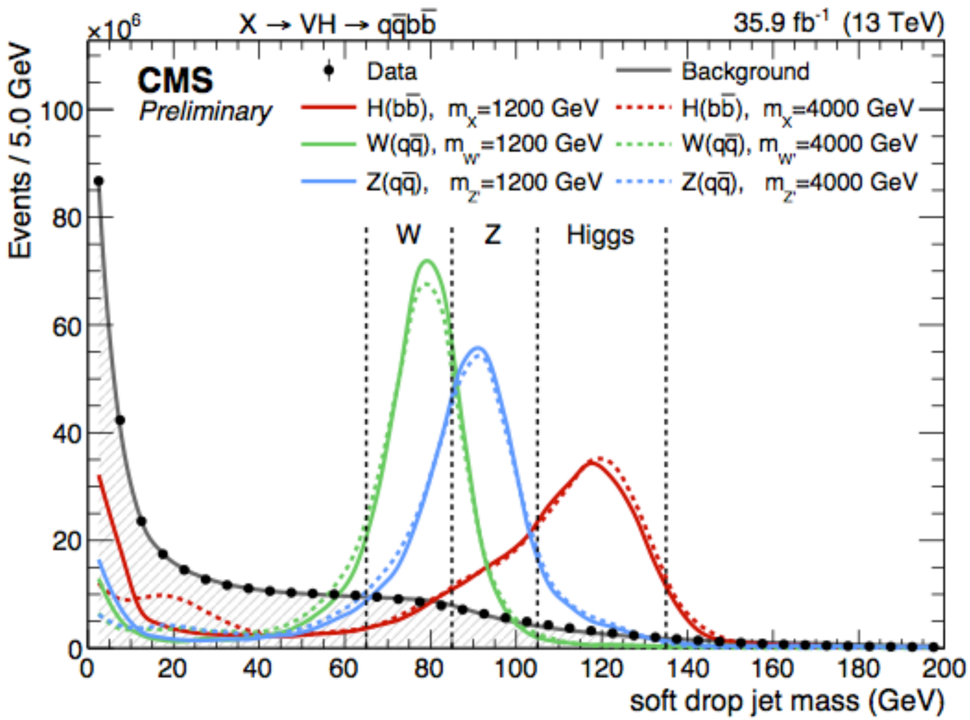


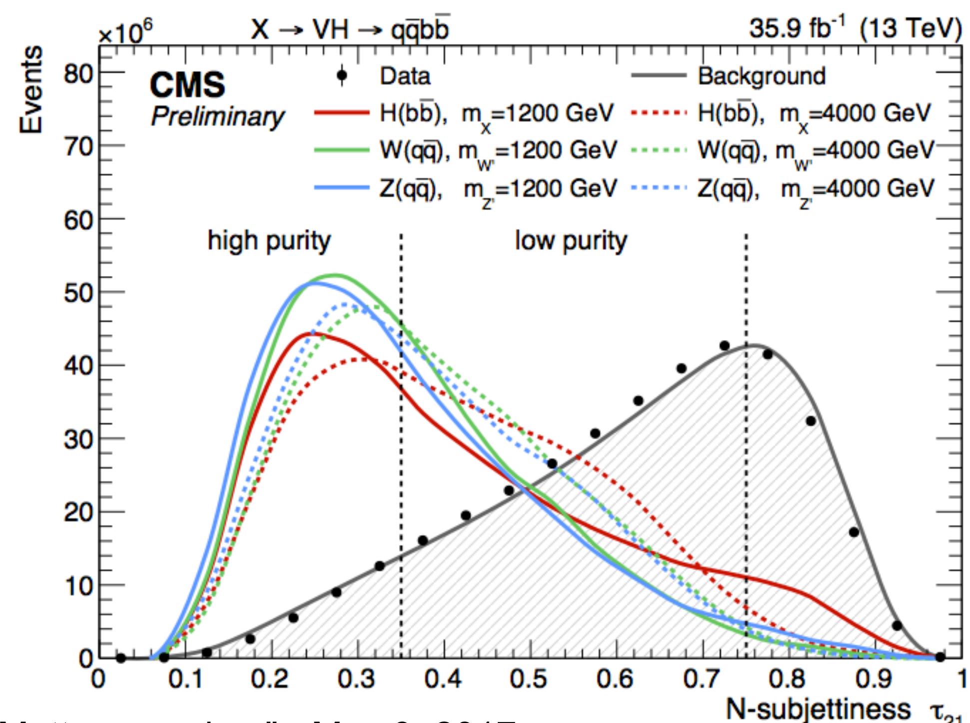
R_{cut}, z_{cut}

W, Z, H reconstruction

CMS-B2G-17-002

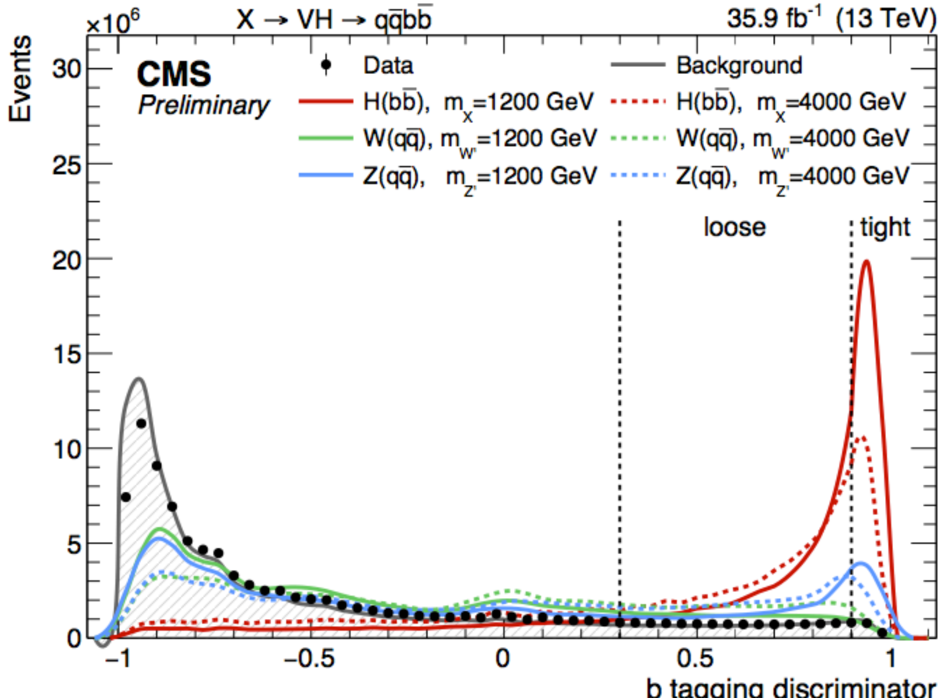
- Grooming and jet mass
  - Pruning
  - soft drop (stable w/pileup, and good jet mass resolution ~10%)
- Vector boson tagging ($V \rightarrow qq$)
  - n-subjettiness τ_{21}: how consistent with 2 sub-jets
  - Categorization according to purity: high (<0.35) and high (>0.35)





W, Z, H reconstruction (cont.)

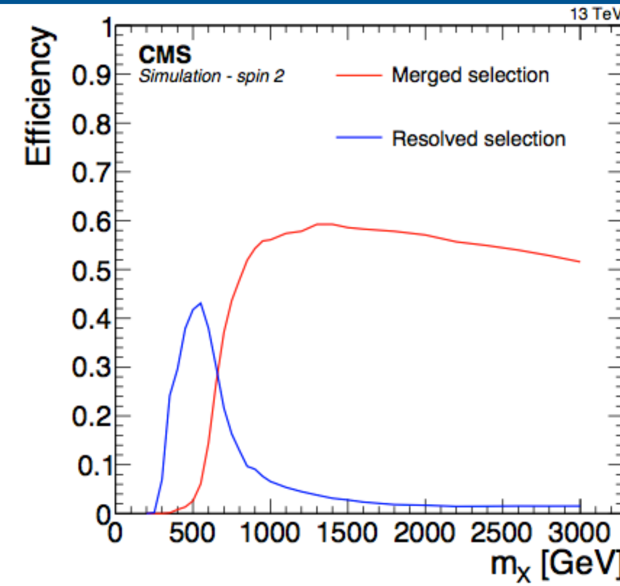
- Higgs boson tagging (H→bbar)
  - Double b-tagging
  - Exploit b-tagging to identify two b-quarks in same jet
  - Soft-lepton information
  - Combines tracking and vertexing in MVA

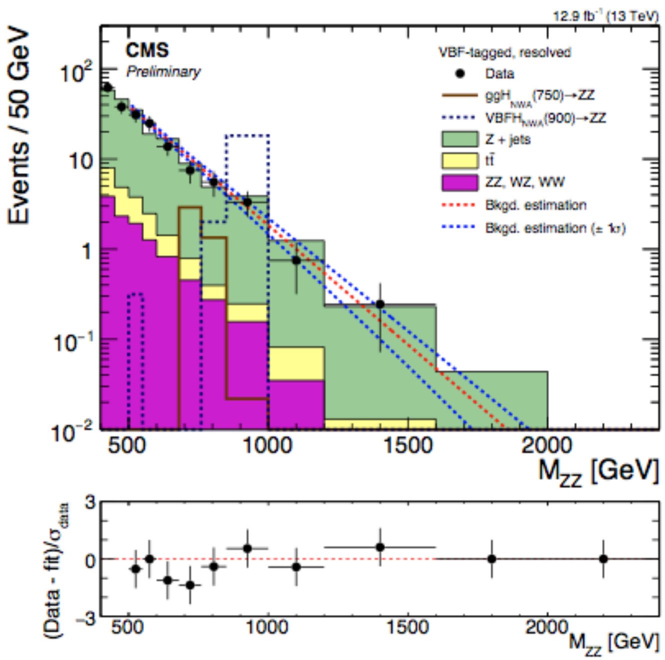


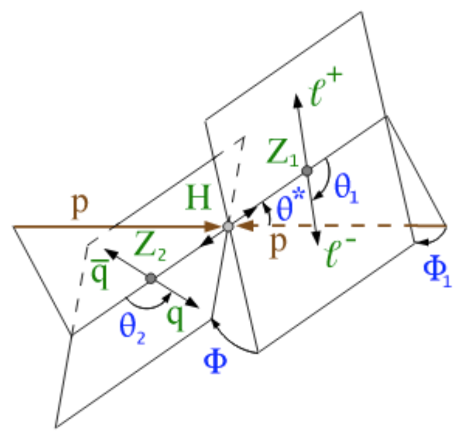
Diboson resonances

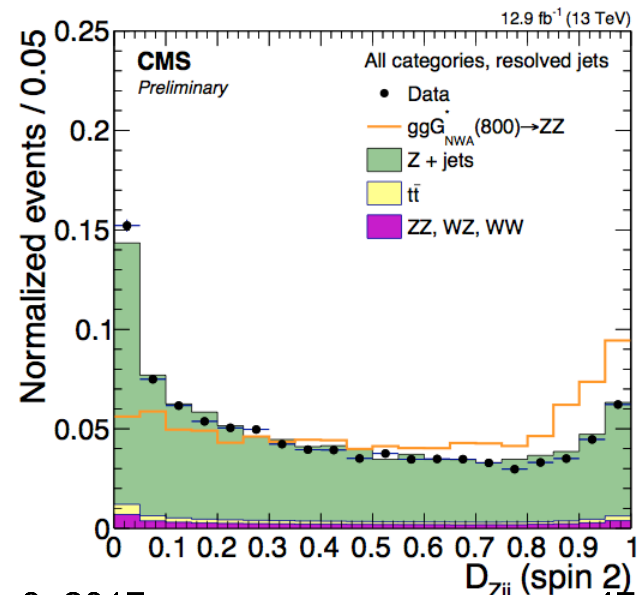
CMS-HIG-16-034, B2G-16-022

- Search for resonance: $X \to ZZ \to \ell\ell\, qq'$
- Use tools to identify jet substructure
  - N-subjettiness τ_{21}: $\tau_N \sim 1/d_0\, \Sigma pT$
  - Kinematic and flavor information to improve S-B separation
- Discriminant Z+JJ (using MELA)
- Upper limits on resonant spin-0/spin-2 hypotheses
- Cross section limits ~3-100fb



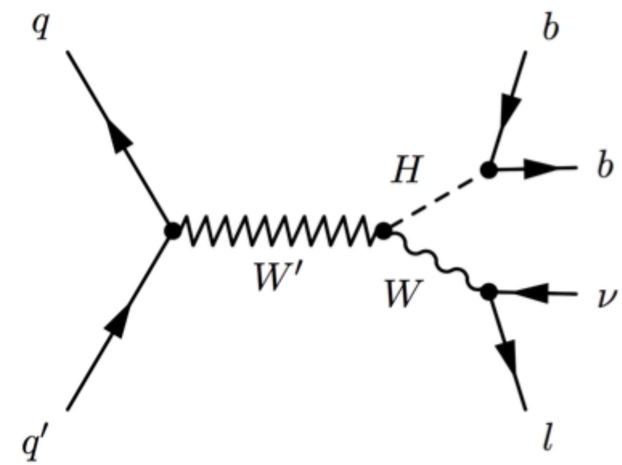


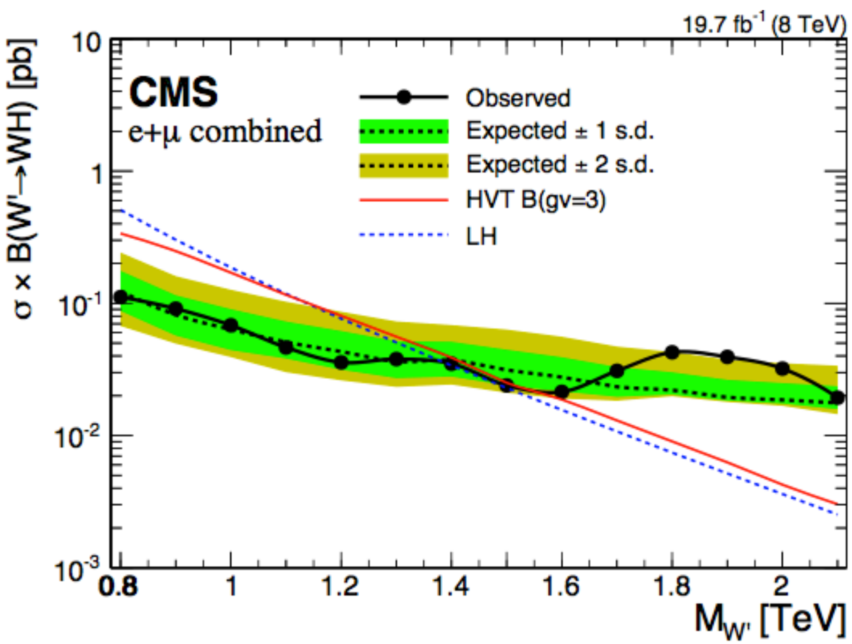


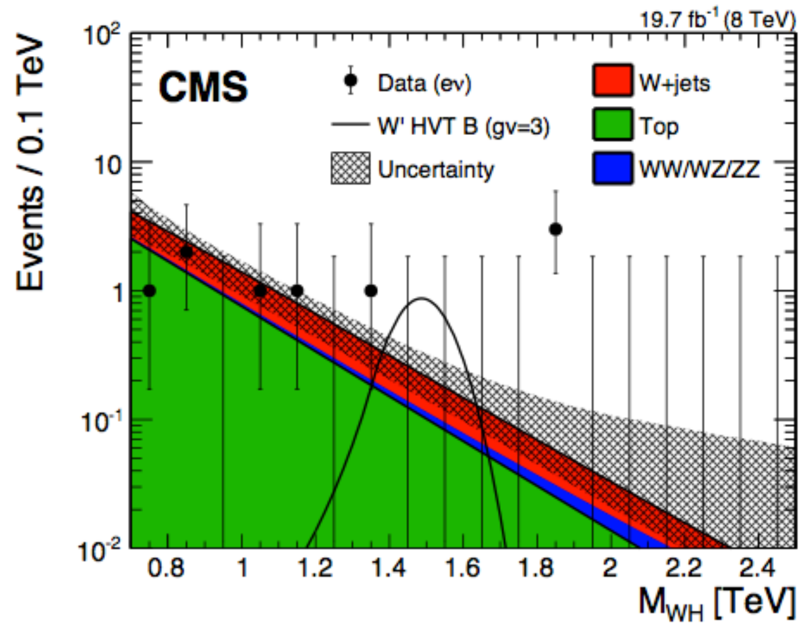


Heavy resonance: WH final state

- Search for massive resonance W'→WH
- Distinctive features of BSM models, i.e. composite/little Higgs, technicolor, etc.
- Lepton+jet final state
- Use jet substructure/btag for H→bb
- 2.2σ highest local significance at 1.8TeV



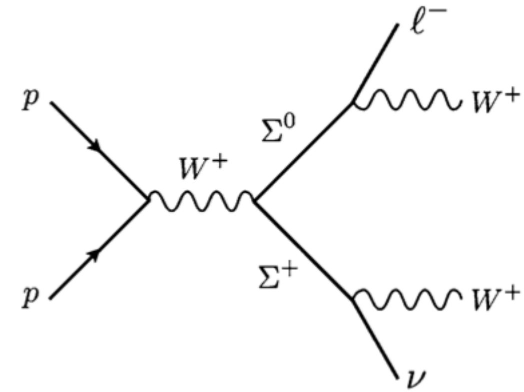


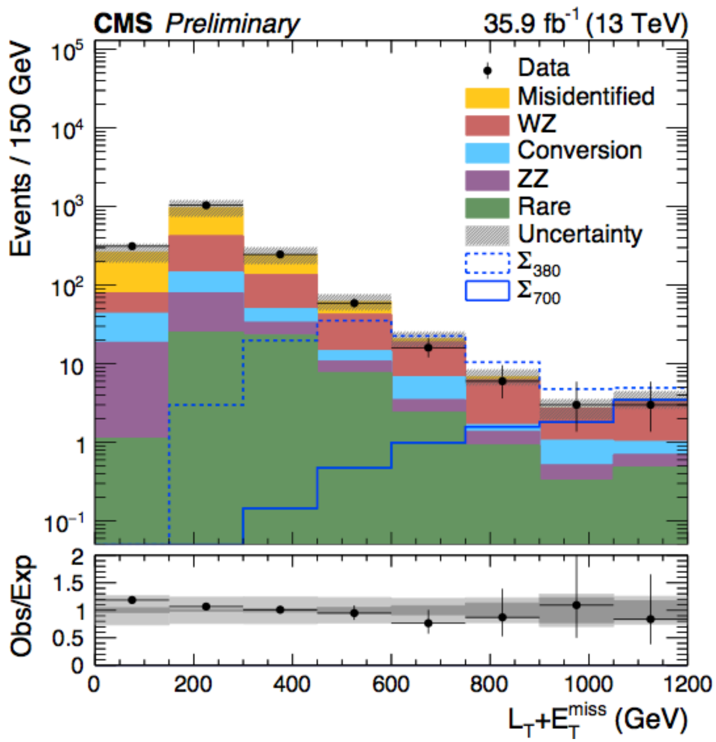


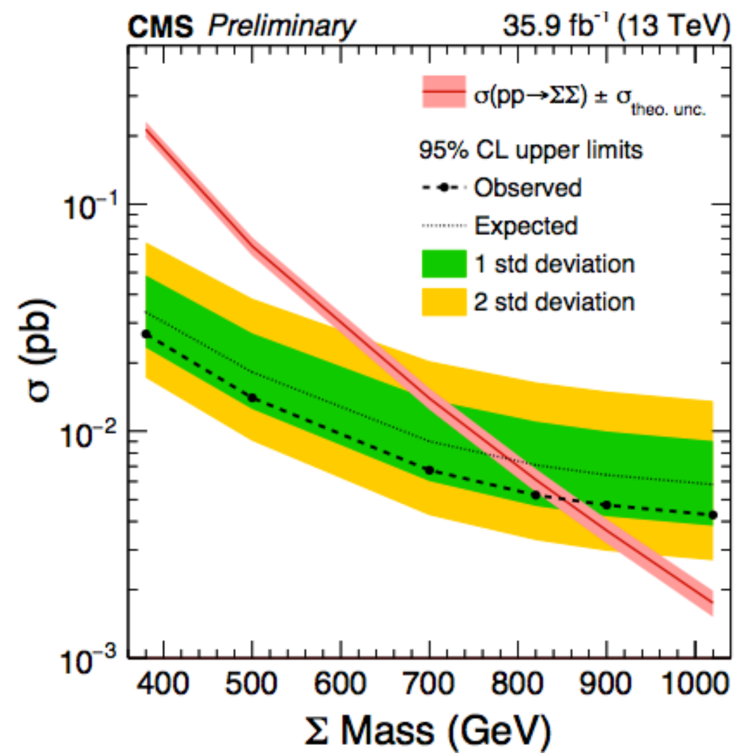
Search for multilepton final states

CMS-EXO-17-006

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



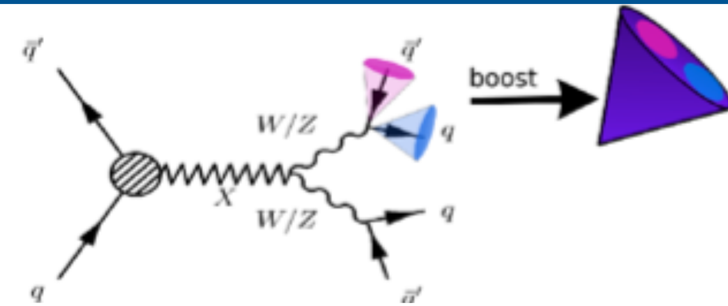


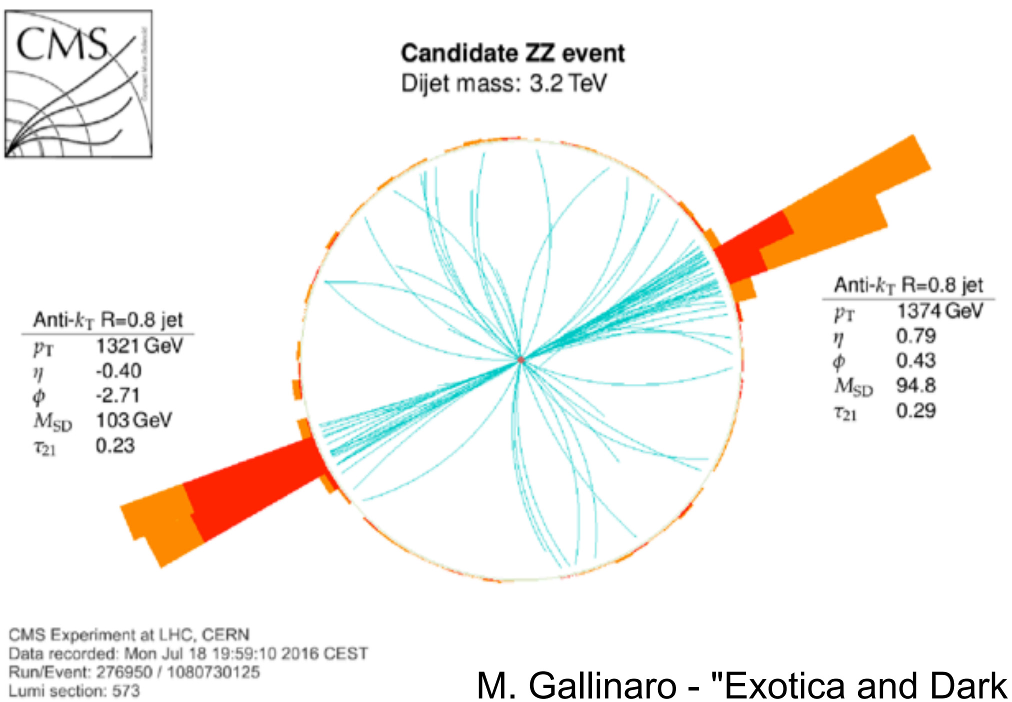


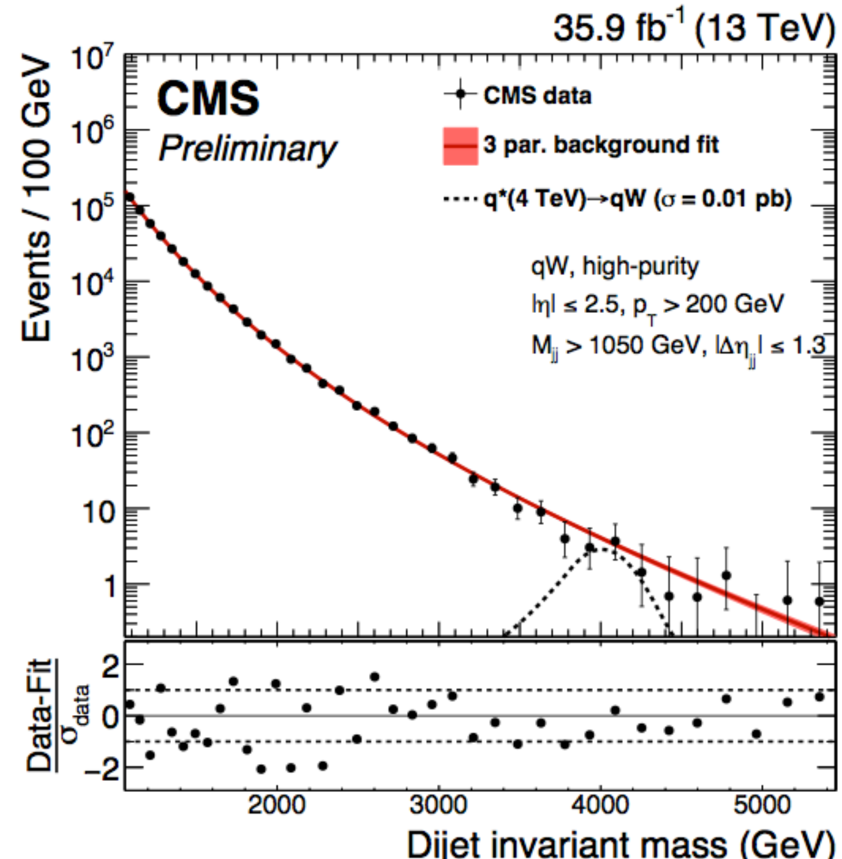
X→VV→qqqq

CMS-B2G-17-001

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



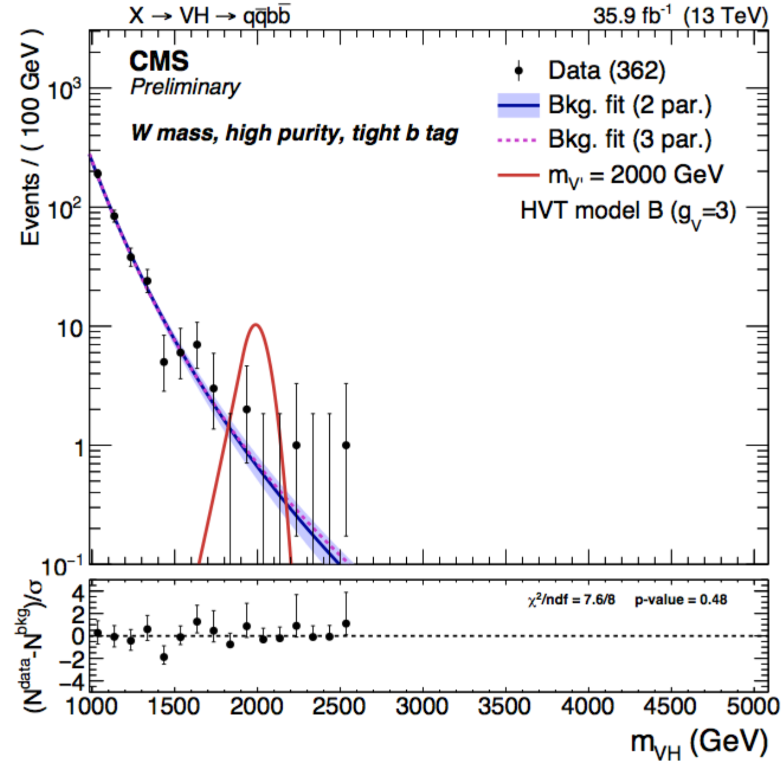


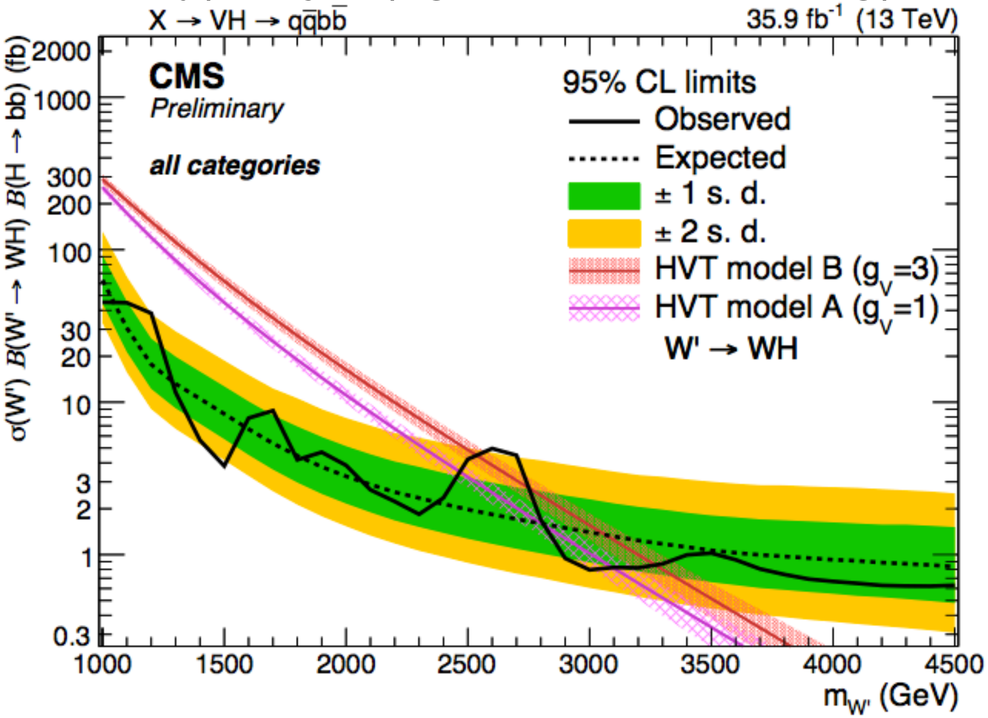


X→VH→qqbb

CMS-B2G-17-002

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



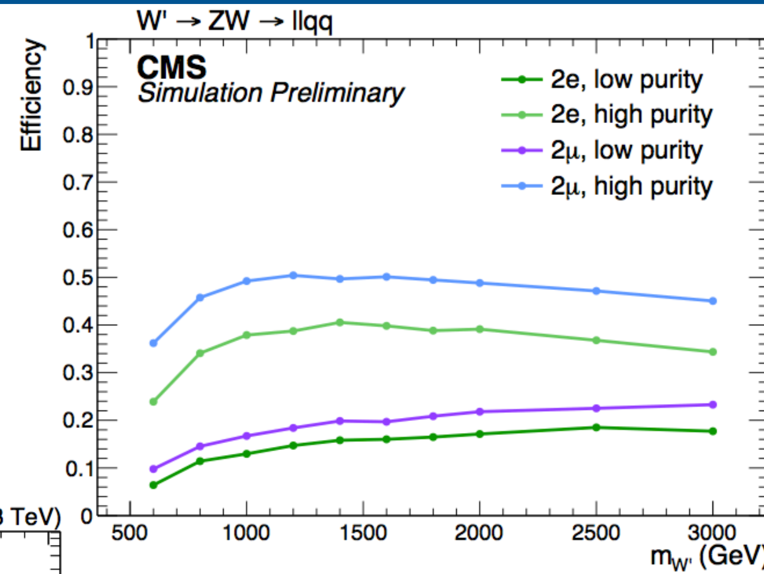


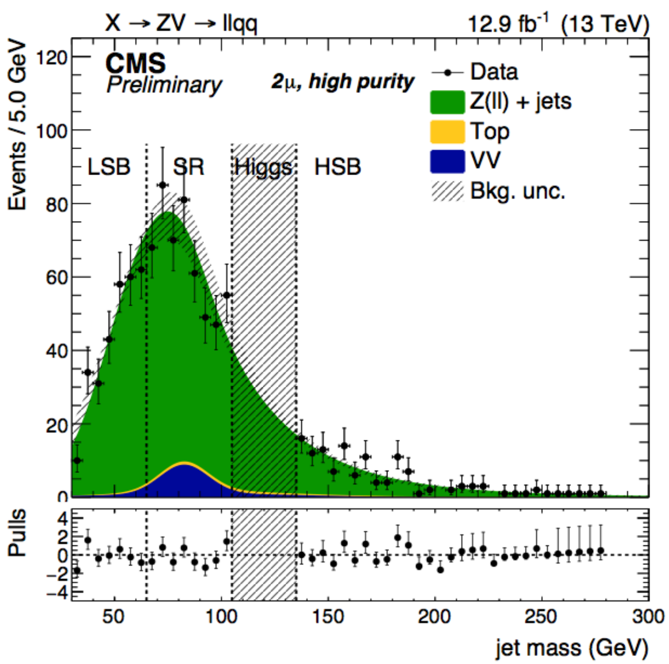
- Similar topology and background estimate to VV resonance search
- No significant excess found in data

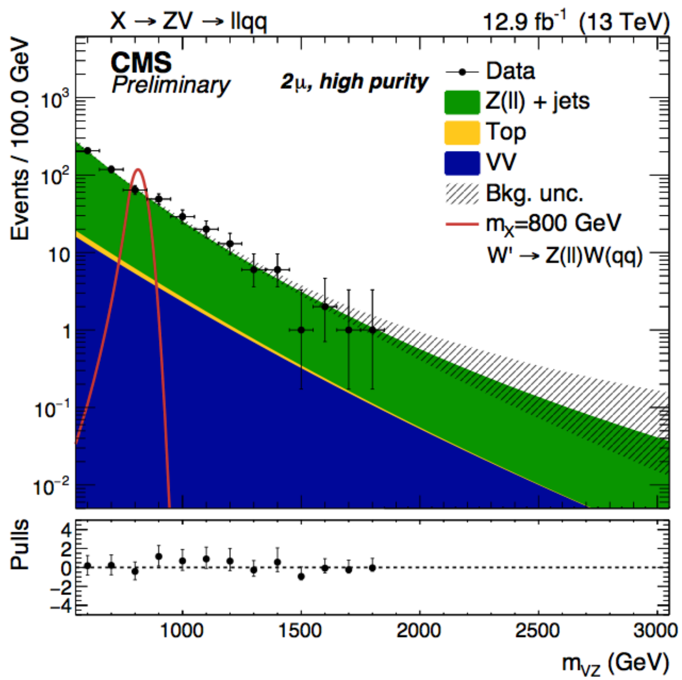
X→ZV→ℓℓqq

CMS-B2G-16-022

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





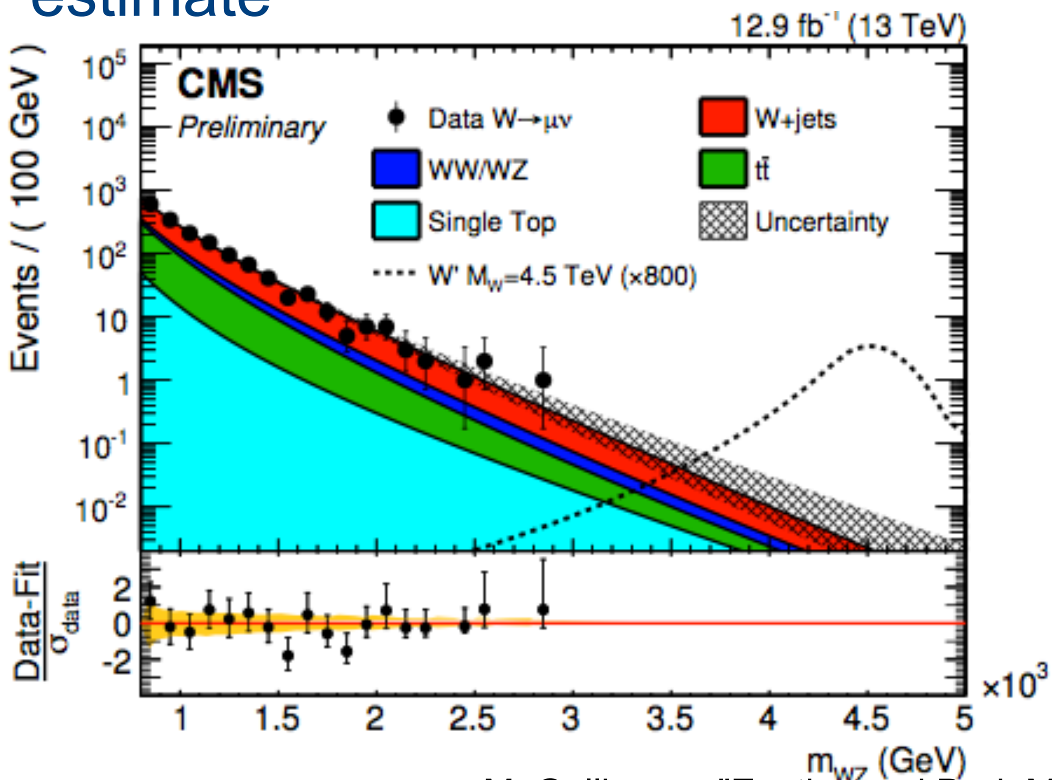


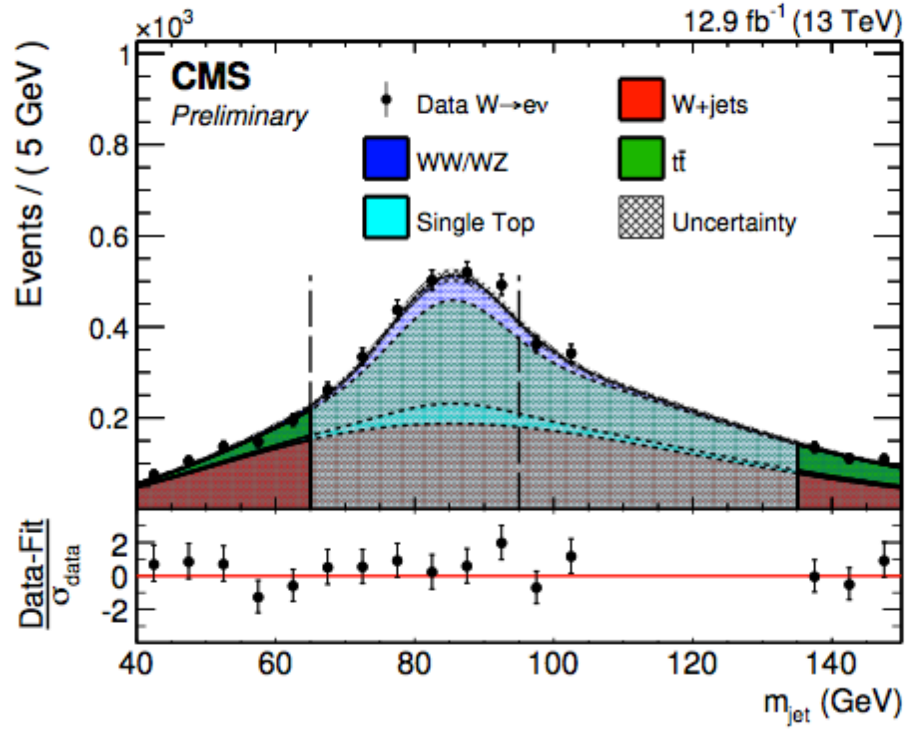
- Data compatible with SM-only hypothesis

X→WV→ℓνqq

CMS-B2G-16-020

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





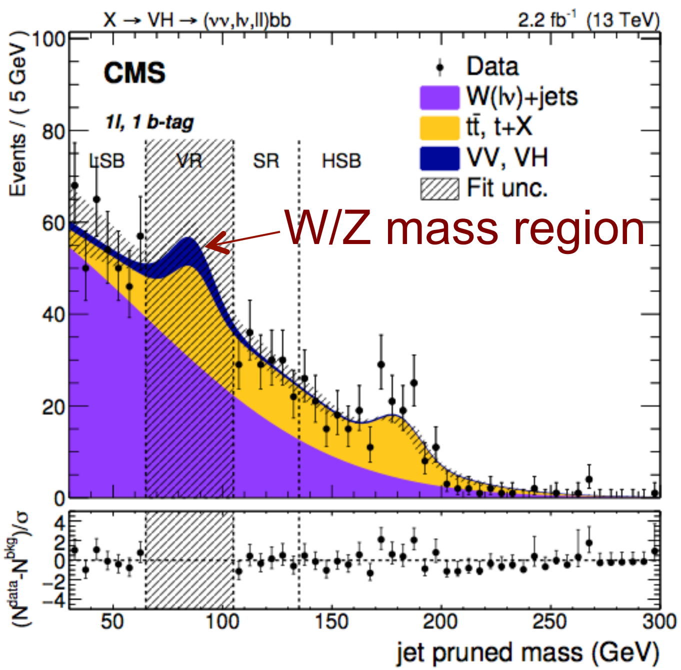
- Similar sensitivity to Z(ℓℓ)V(qq) search
- Excluded up to 2 TeV

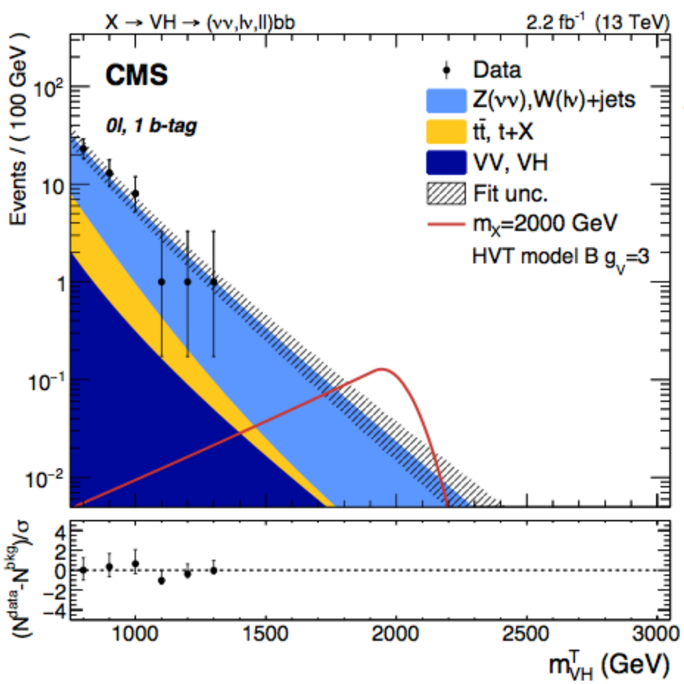
X→VH→ℓνqq

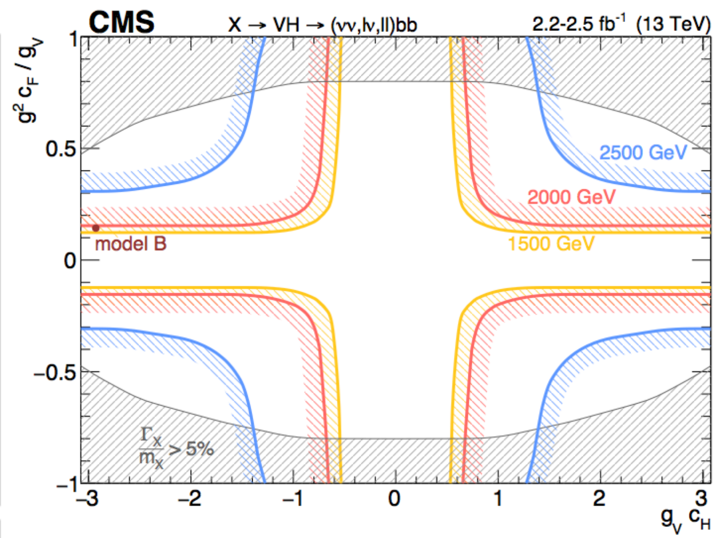
PLB 768(2017)137

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

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

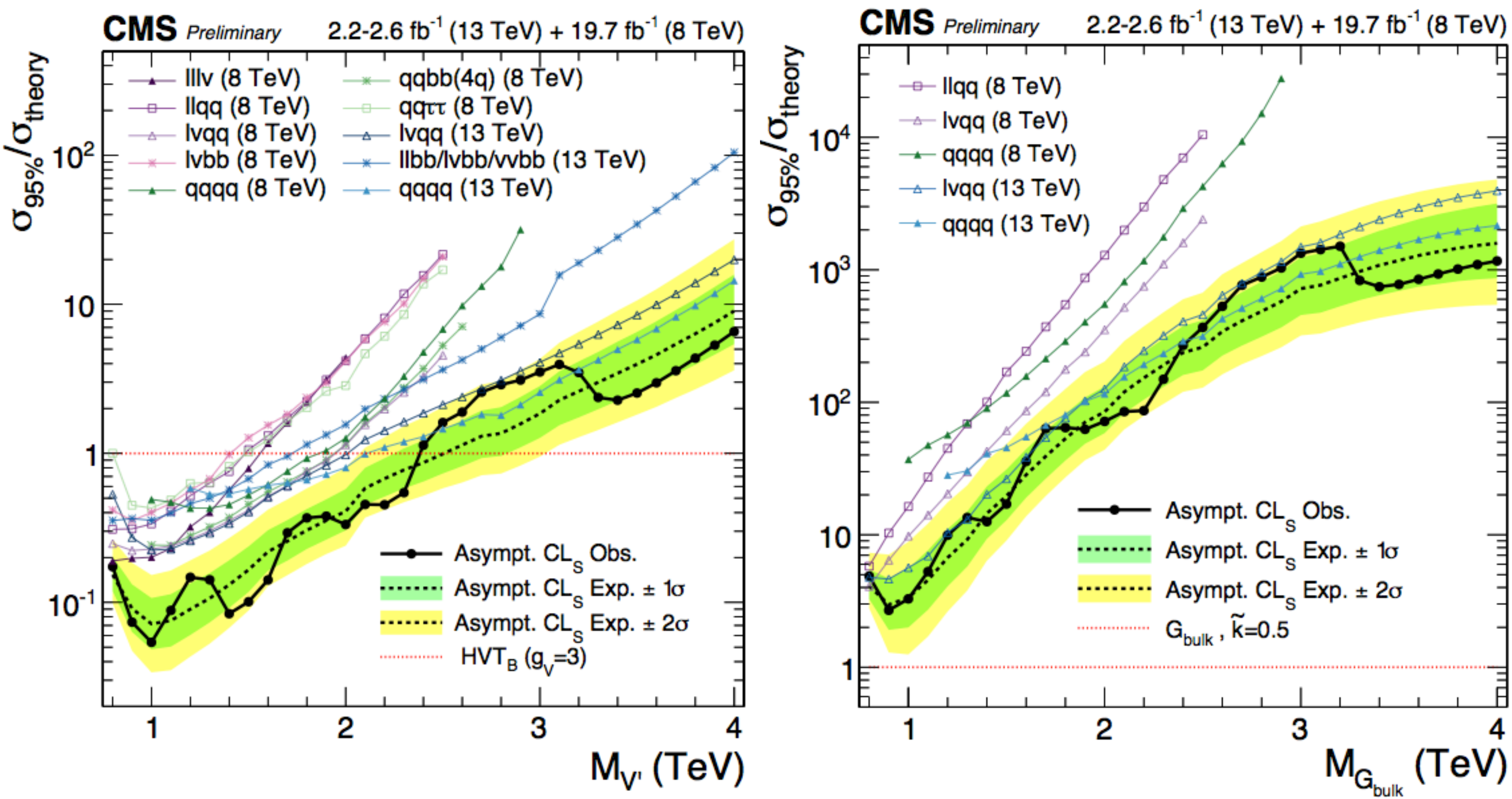






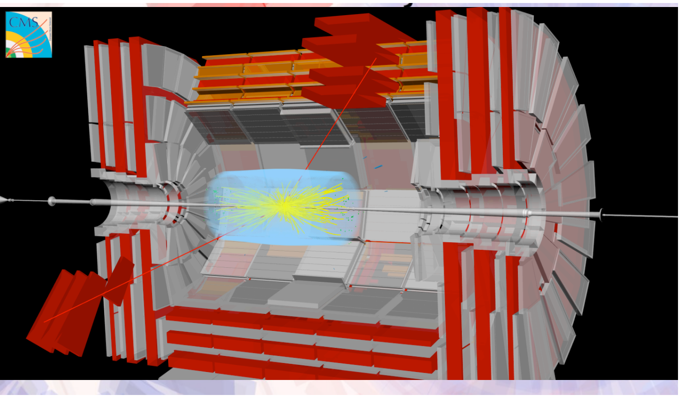
Combination of diboson searches

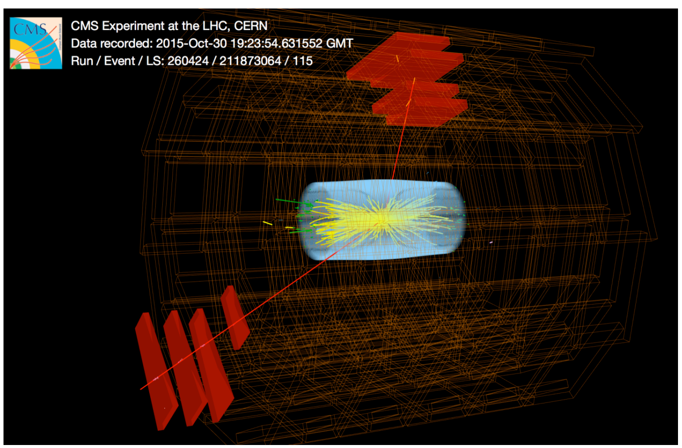
CMS-B2G-16-007

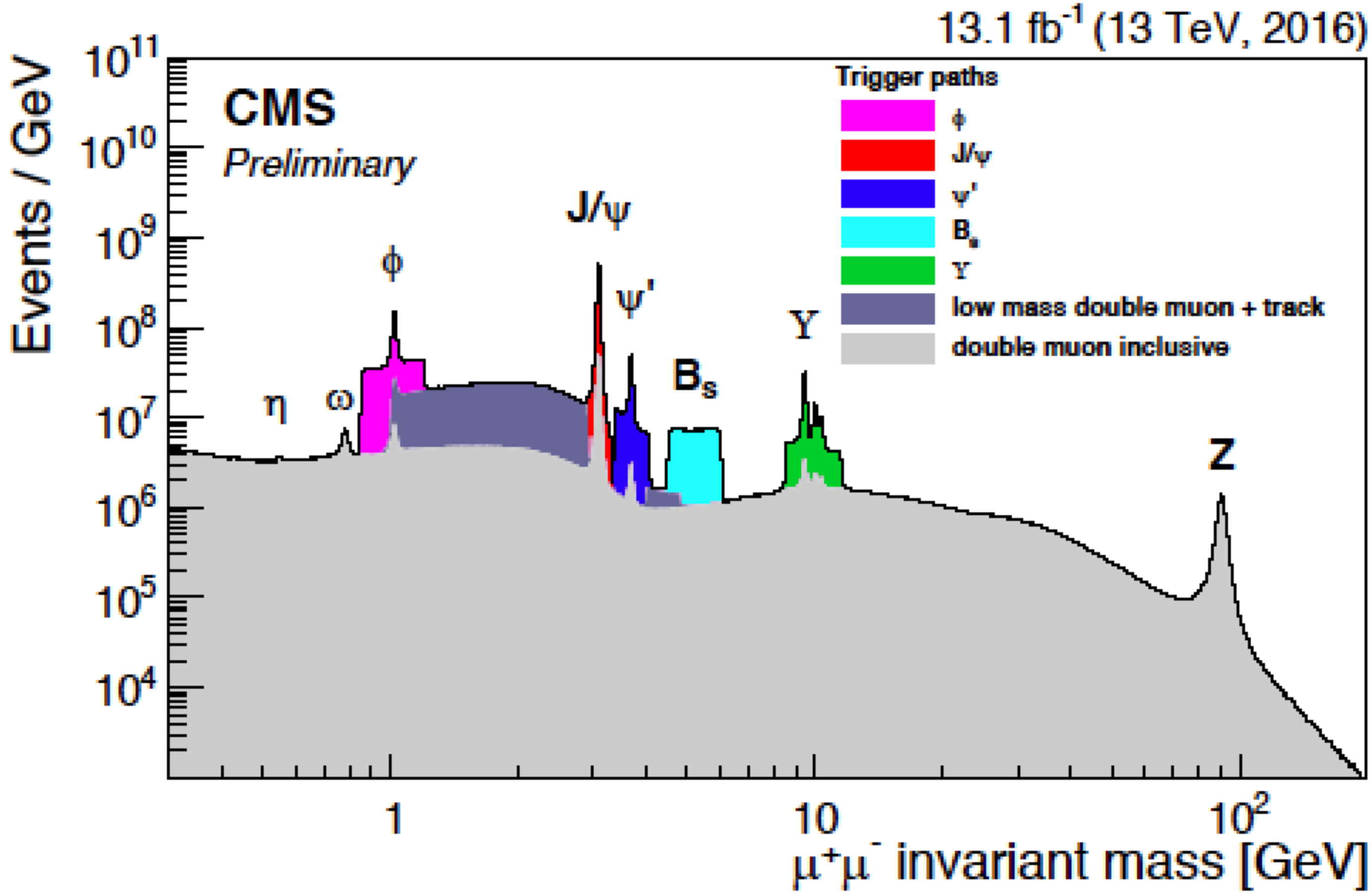


Di-muon events

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

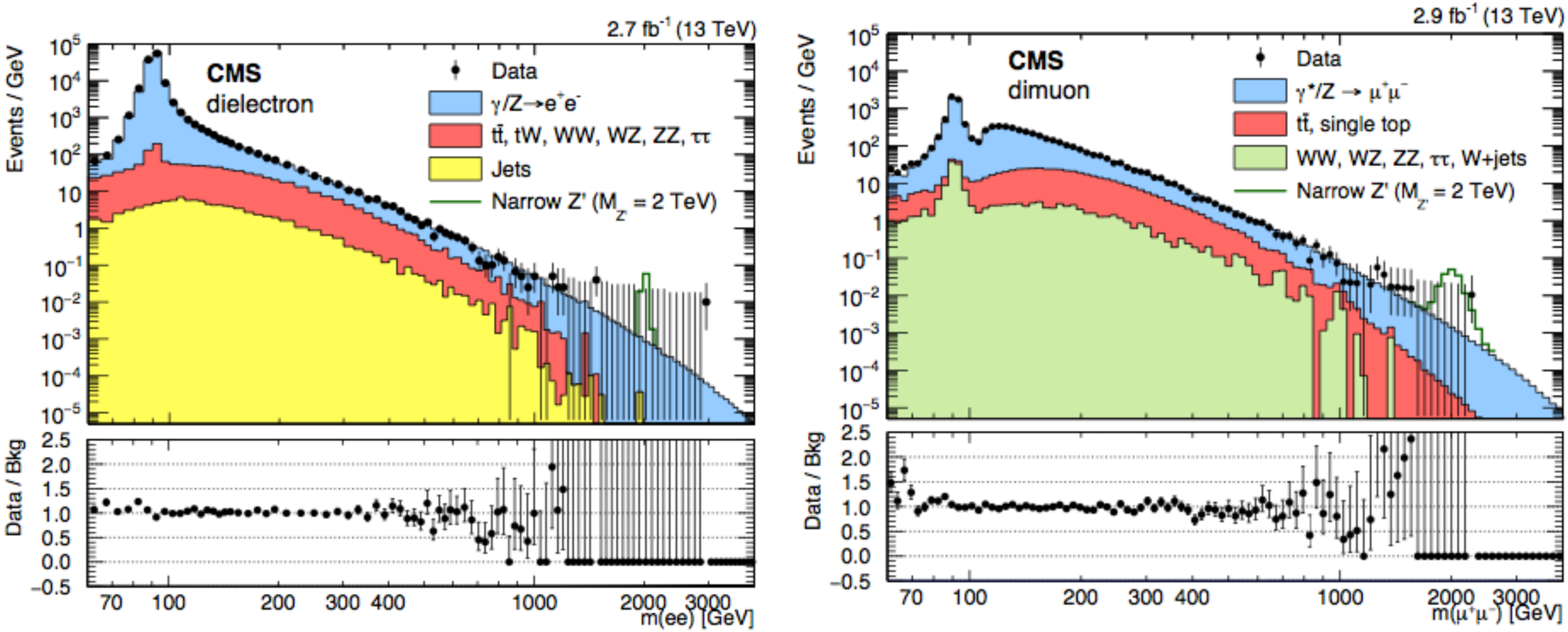






Dilepton resonance

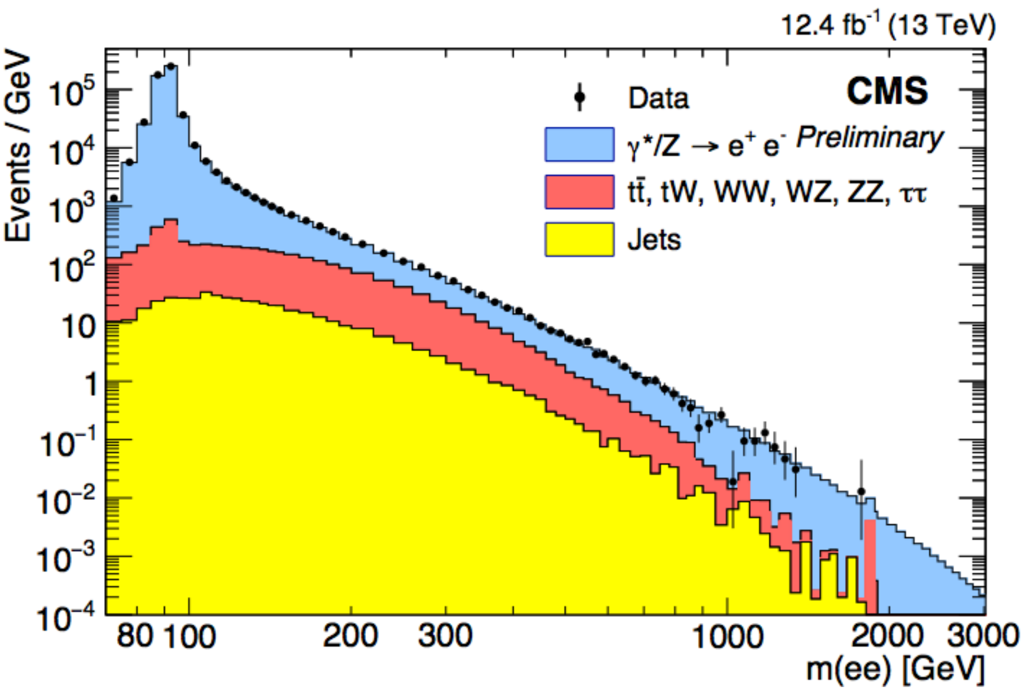
- Search for dilepton (ee,$\mu\mu$) resonance

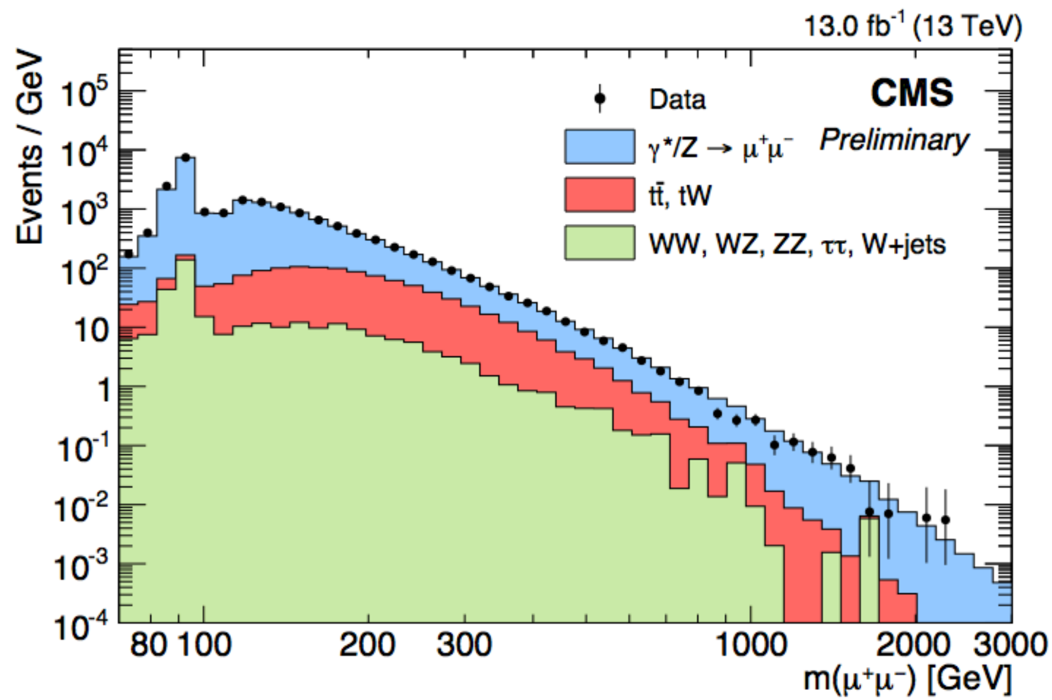


Dilepton resonance: updated

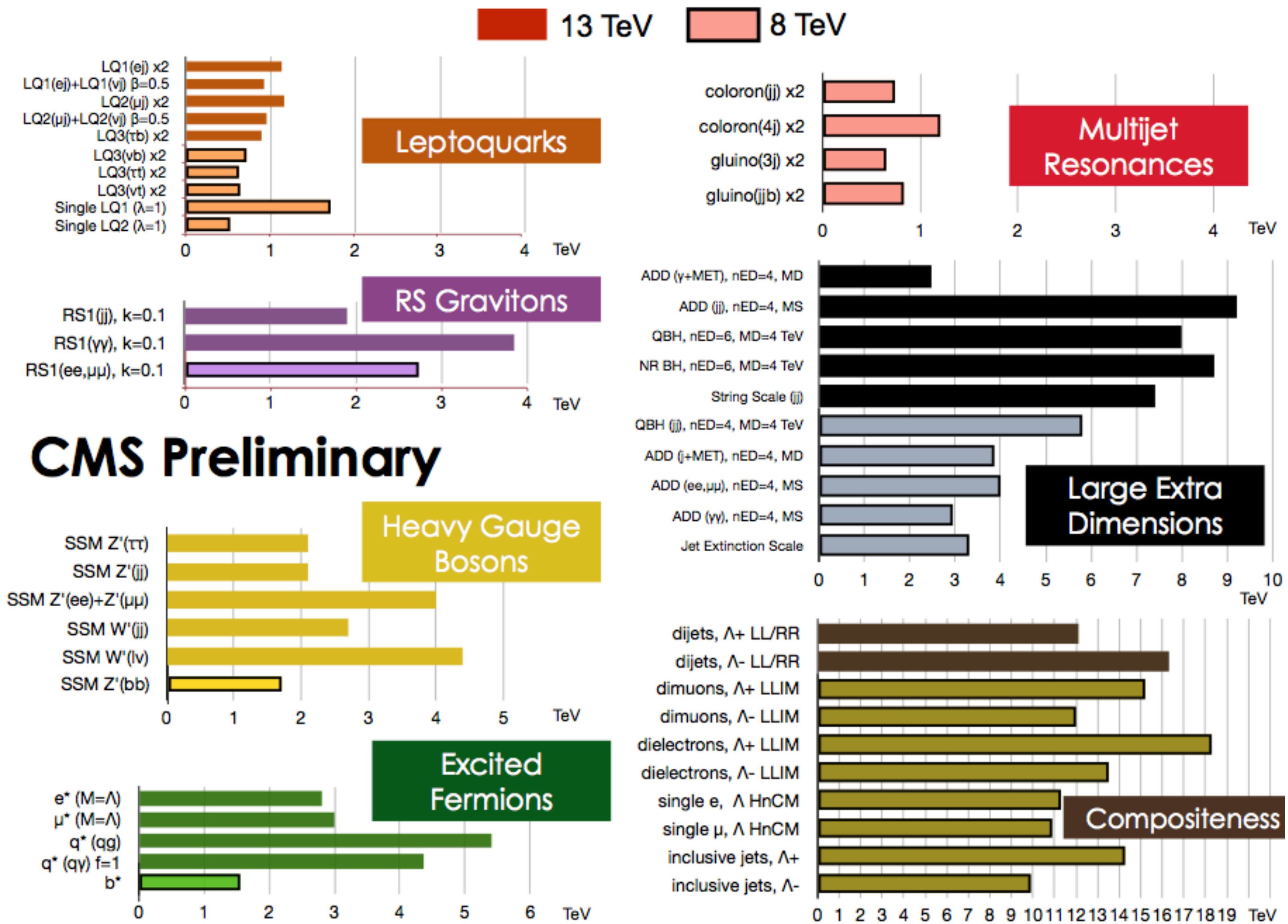
CMS-EXO-16-031

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





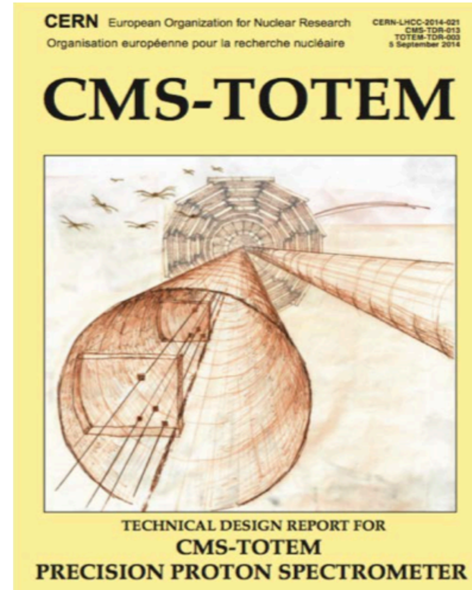
Resonance searches: Summary



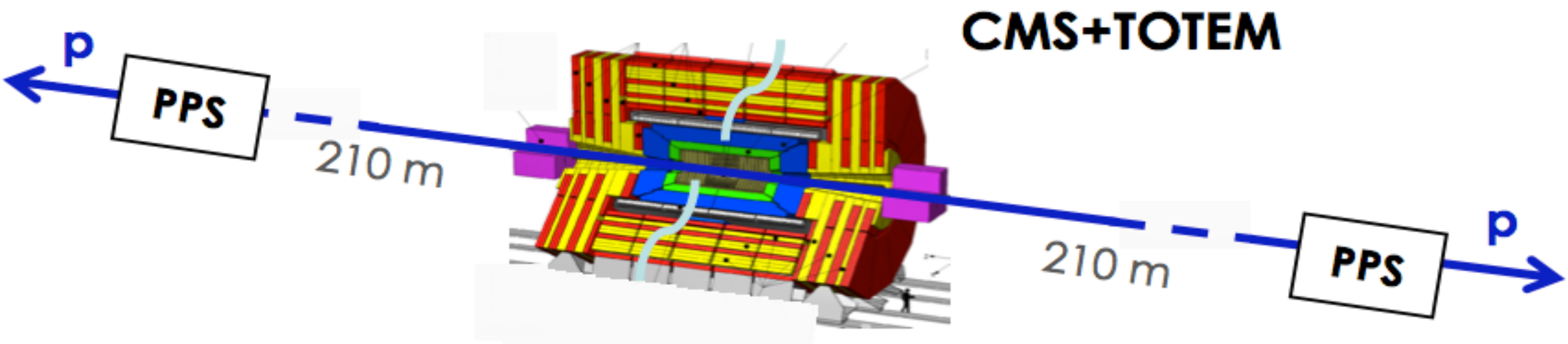
Looking forward: PPS

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)

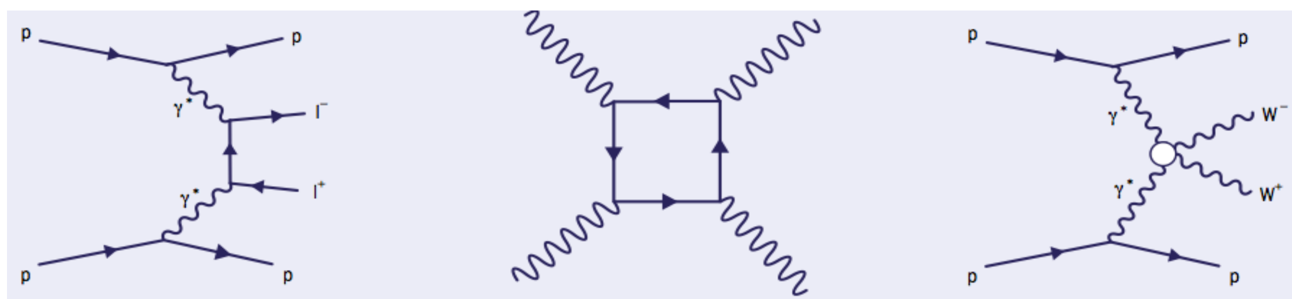


CERN-LHC-2014-021

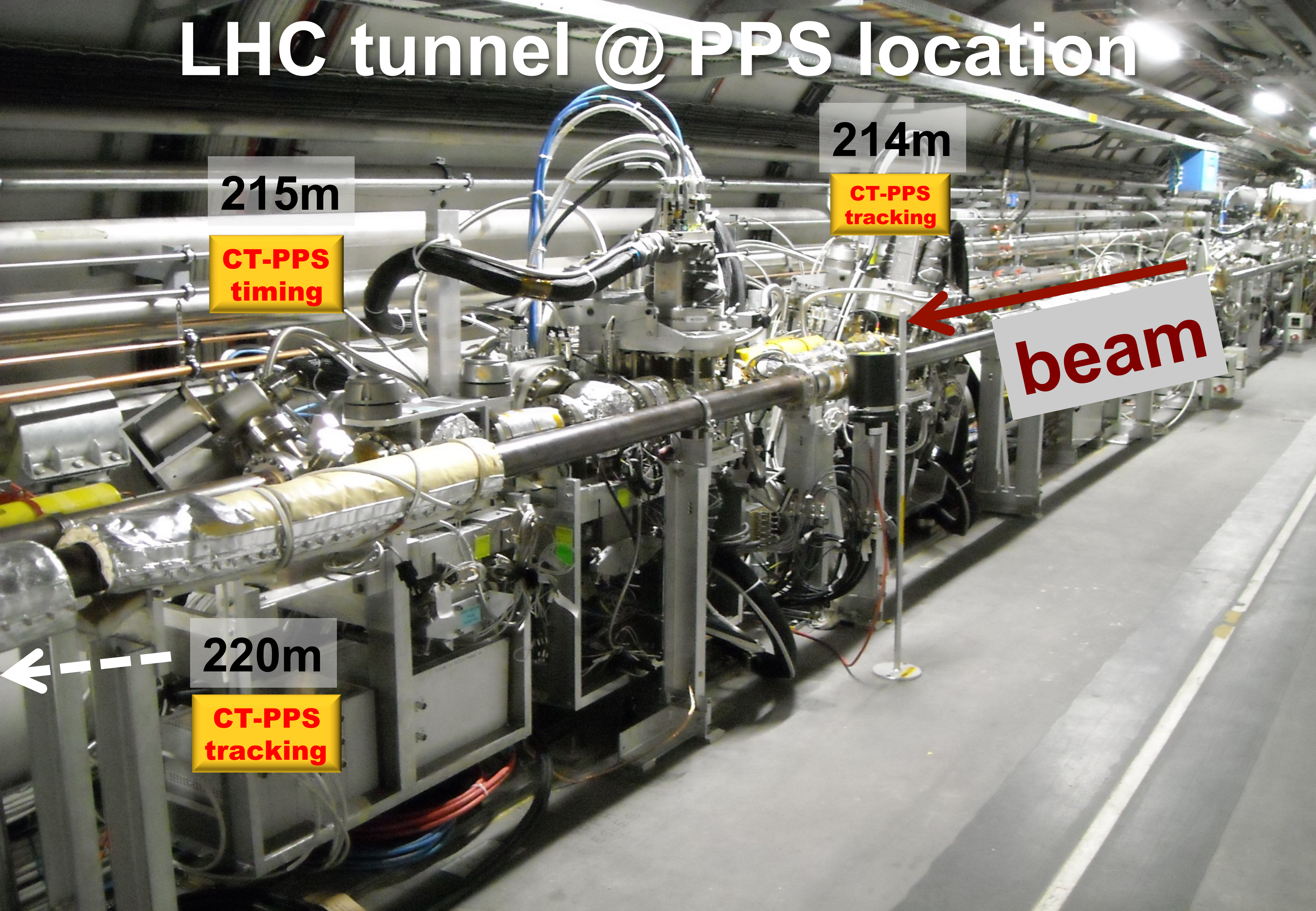


PPS physics motivations

- 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



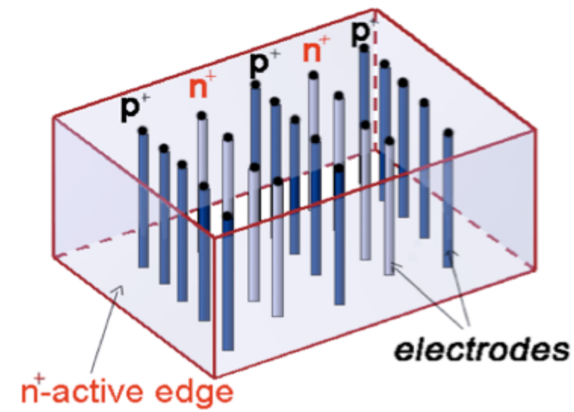
LHC tunnel @ PPS location



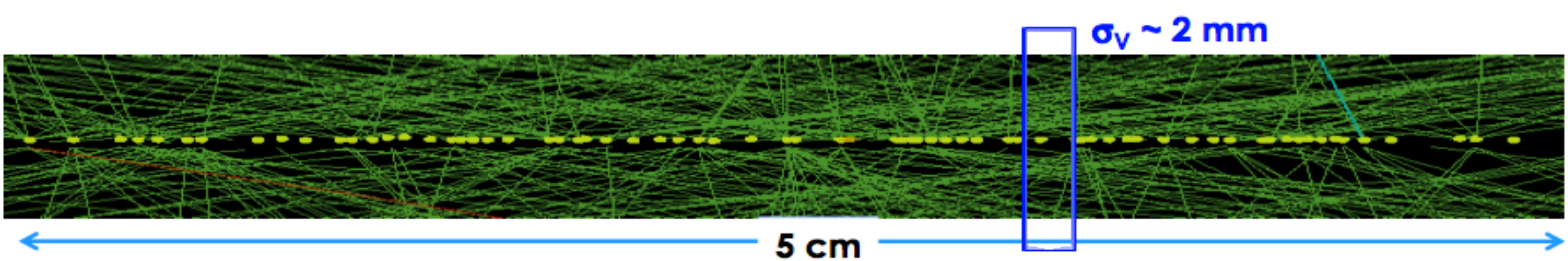
PPS detectors

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

“3D” pixel sensors with columnar electrodes



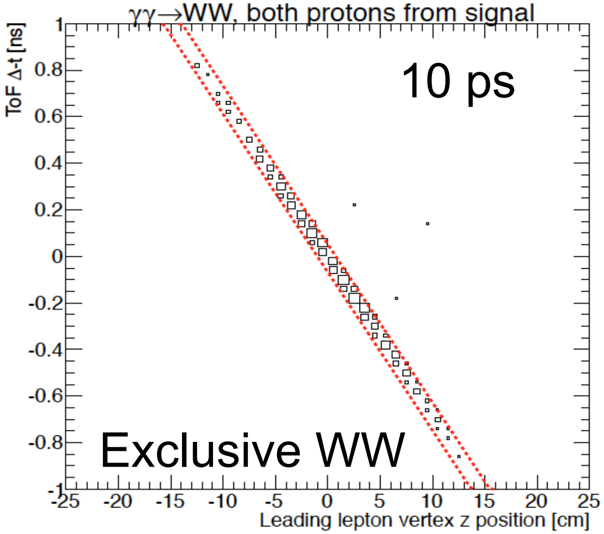
- Timing detectors
  - Goal: identify primary vertex, reject “pileup”
  - σ_{time}~10ps ⇒ σ_z~2mm
  - Technology: silicon/diamond

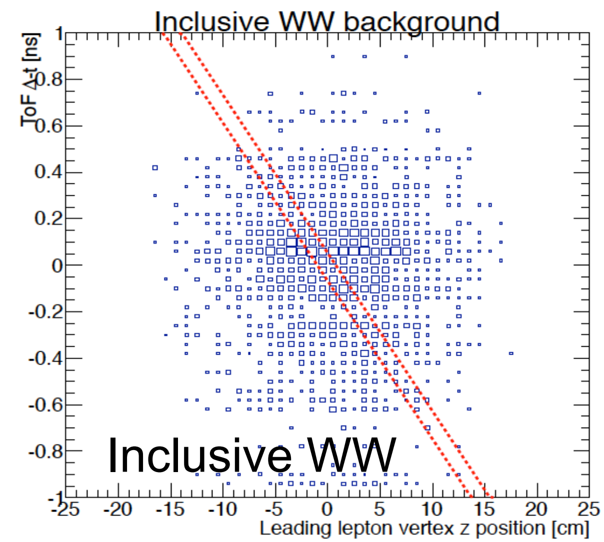


Timing detectors

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

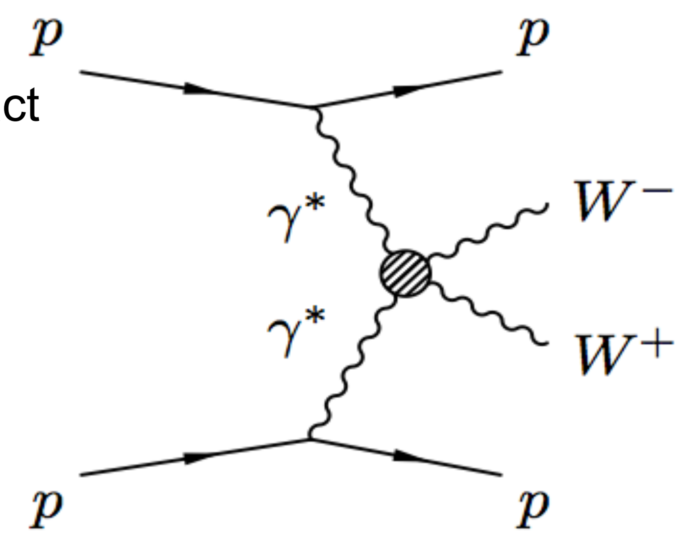




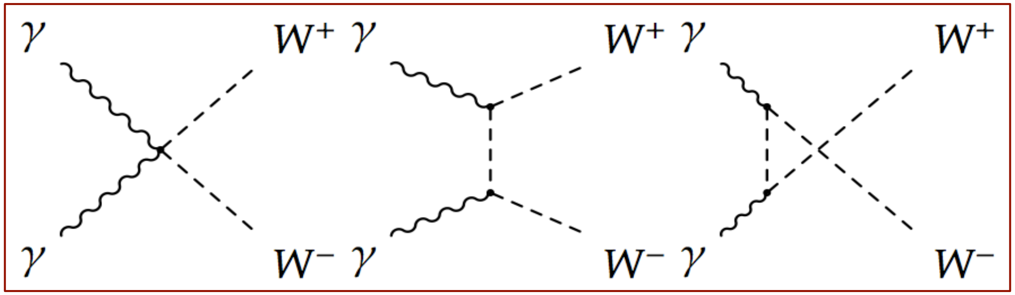
WW production

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

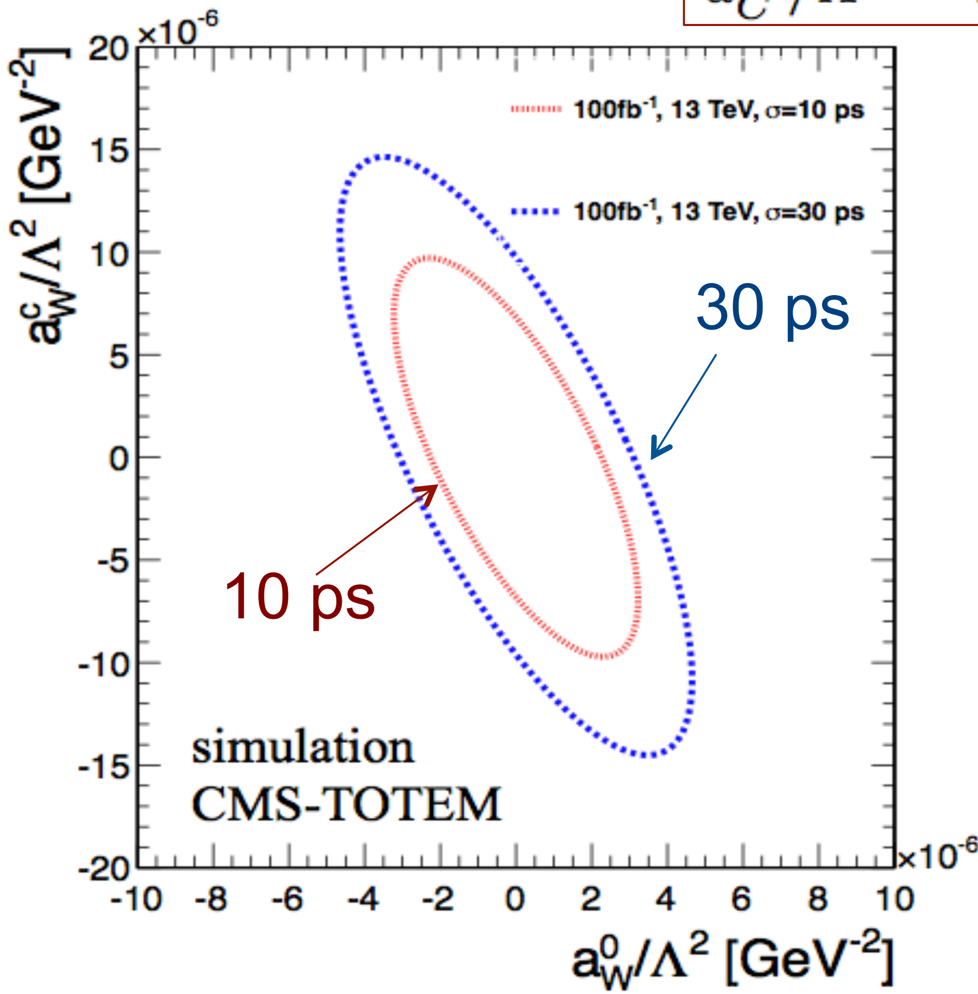


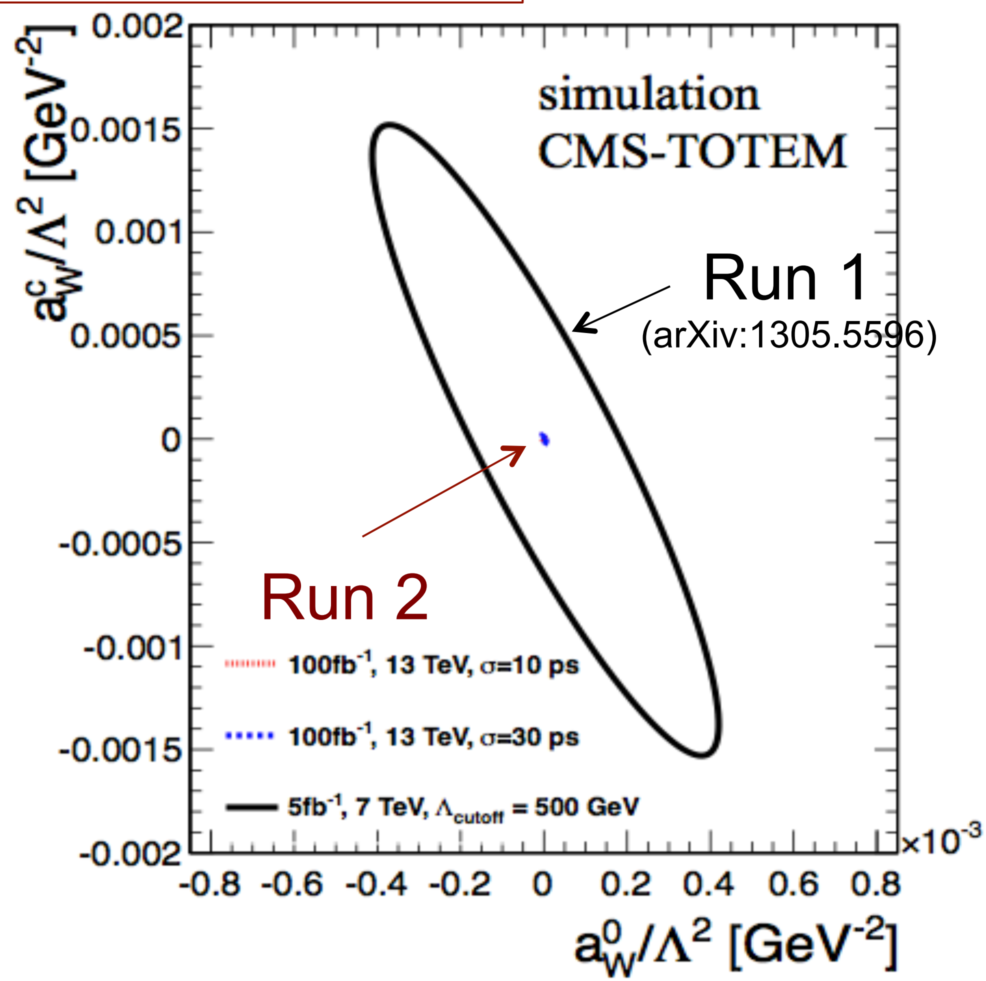
- Deviations from SM can be large

AQGC expected limits

Expected limits @95%CL:

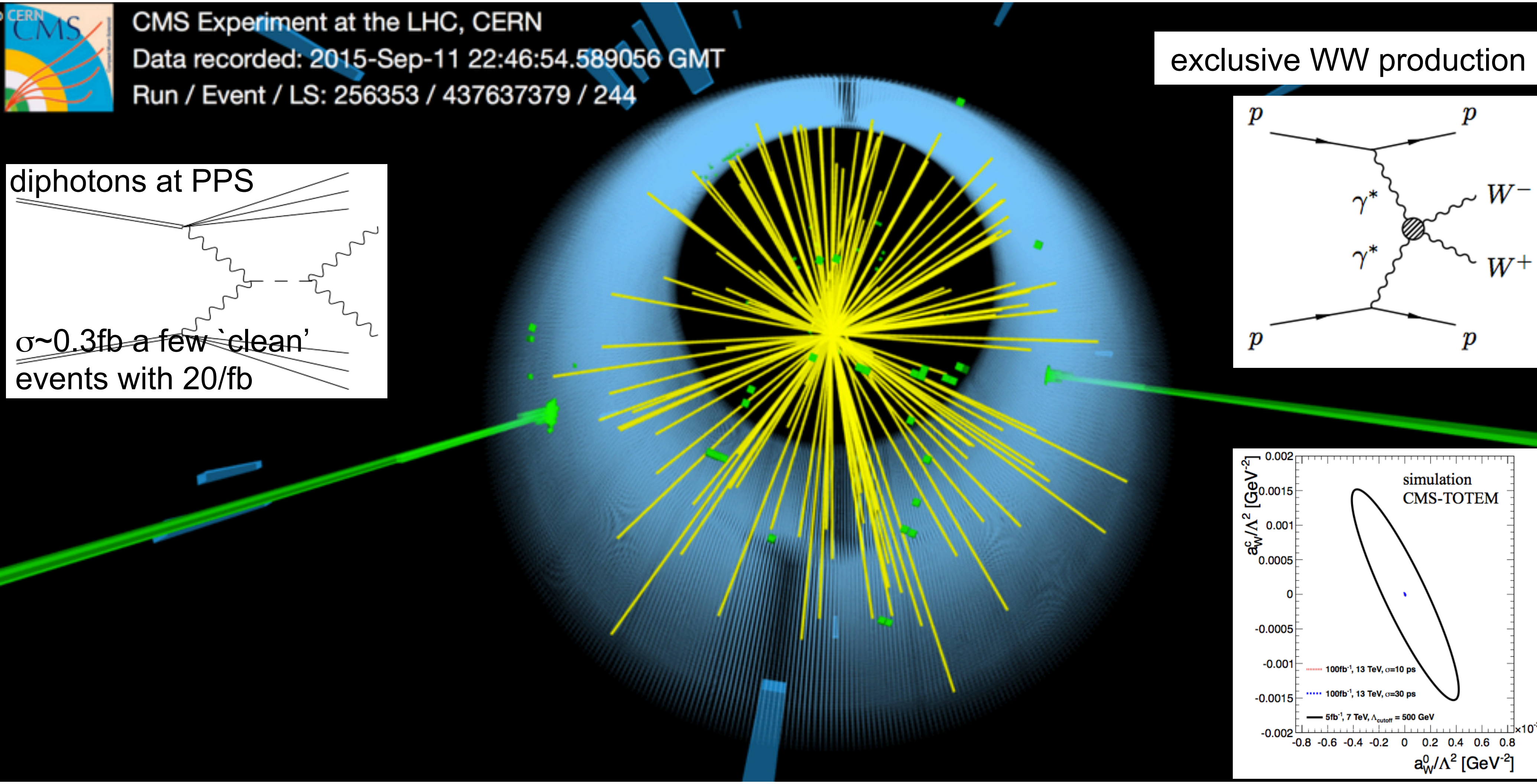
$$a_0^W/\Lambda^2 = 2 \times 10^{-6}\ (3 \times 10^{-6}),$$
$$a_C^W/\Lambda^2 = 7 \times 10^{-6}\ (10 \times 10^{-6}).$$



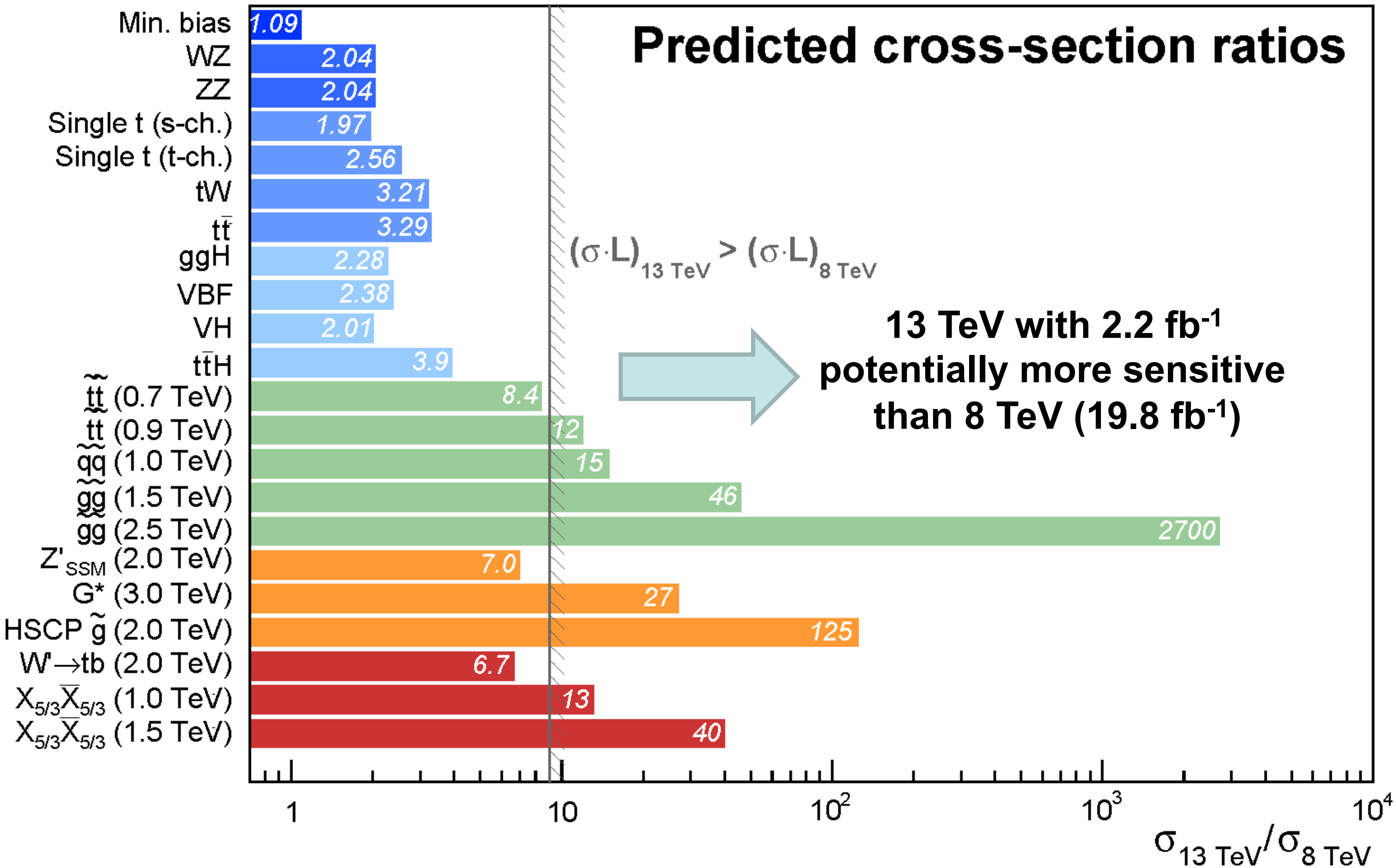


BSM searches: resonances, etc.

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



Increased reach at 13 TeV



Summary

- Excellent consistency of SM but SM is incomplete
- Direct and indirect searches for New Physics
  - Collected ~40/fb @13 TeV in 2015/2016
  - ~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