BOSTON UNIVERSITY

17th annual

Fermilab-CERN Hadron Collider Physics Summer School

August 15 - 25, 2022 Fermilab

# BSM Searches: Experiment I

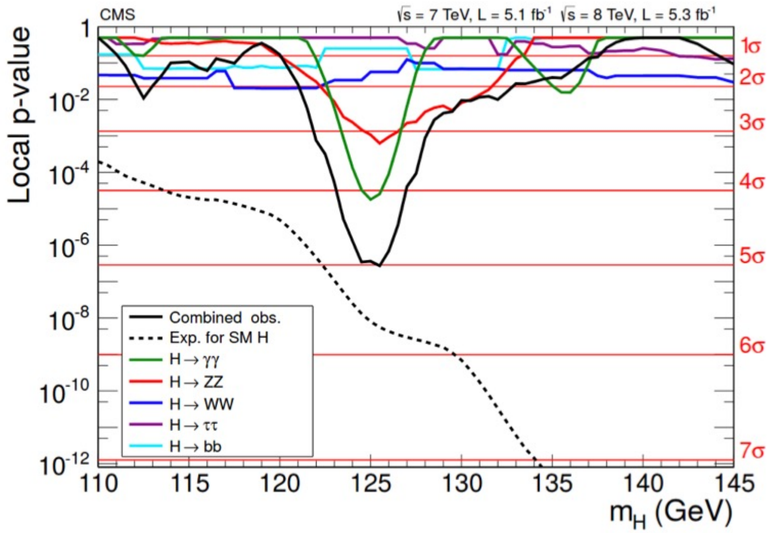
Zeynep Demiragli (Boston University)

FERMILAB-CERN HADRON COLLIDER PHYSICS Summer School

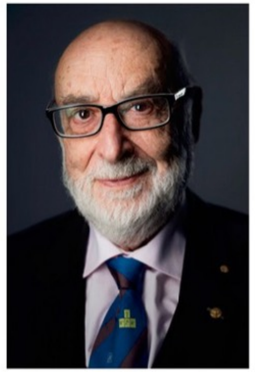
http://indico.fnal.gov/e/hcpss2022

# The Standard Model

Hugely successful! The Higgs particle was the last missing particle in the Standard Model.




## The Nobel Prize in Physics 2013



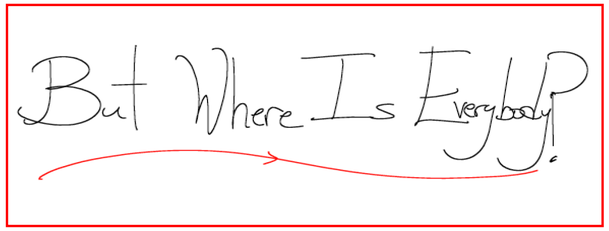
© Nobel Media AB. Photo: A. Mahmoud
François Englert

© Nobel Media AB. Photo: A. Mahmoud
Peter W. Higgs

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider."

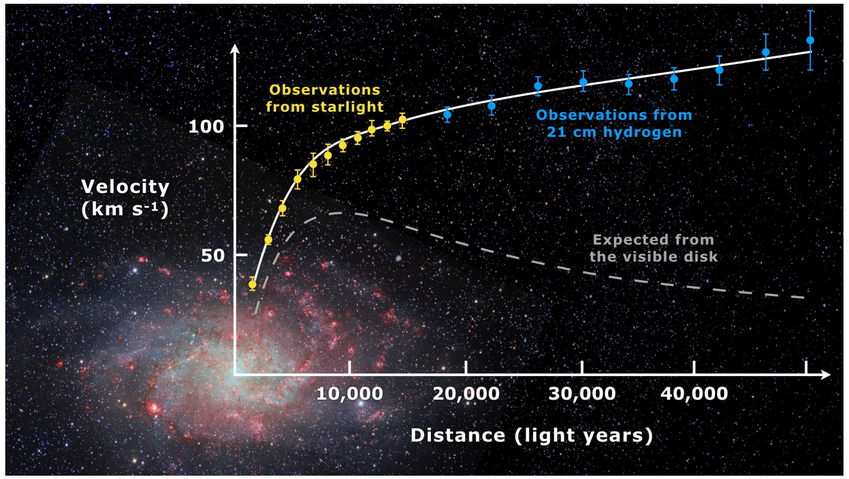
Many open questions remain…

- Why do we have 3 flavor families? Hierarchy?
- Fine tuning of parameters to level of $10^{-30}$
- SM has no connection with gravity, no unification of the forces at high energy, no explanation for the nature of dark matter



# Open Questions …

arxiv:9909252

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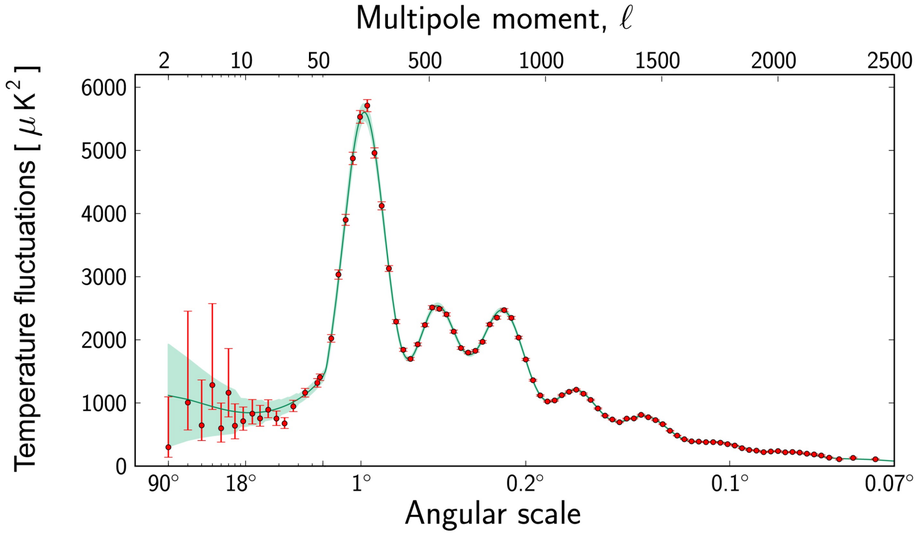


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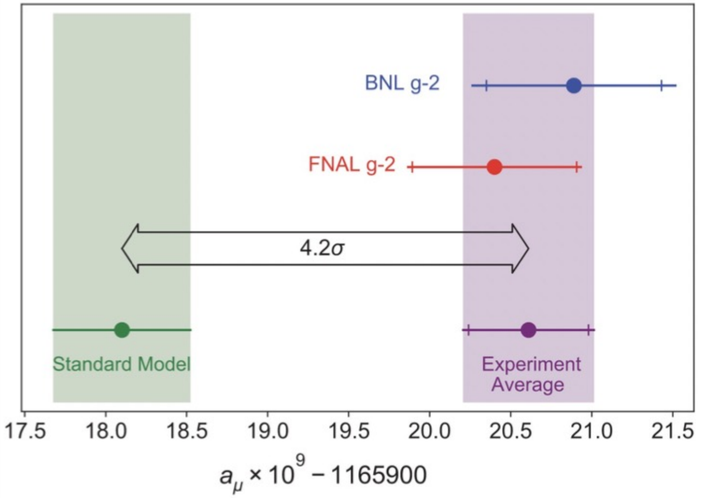
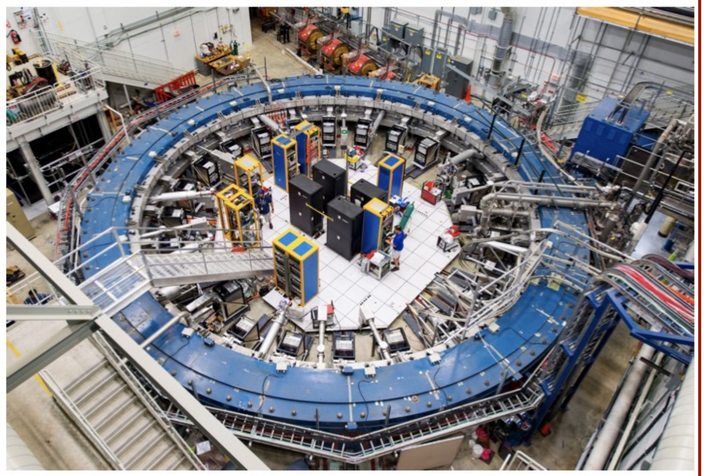
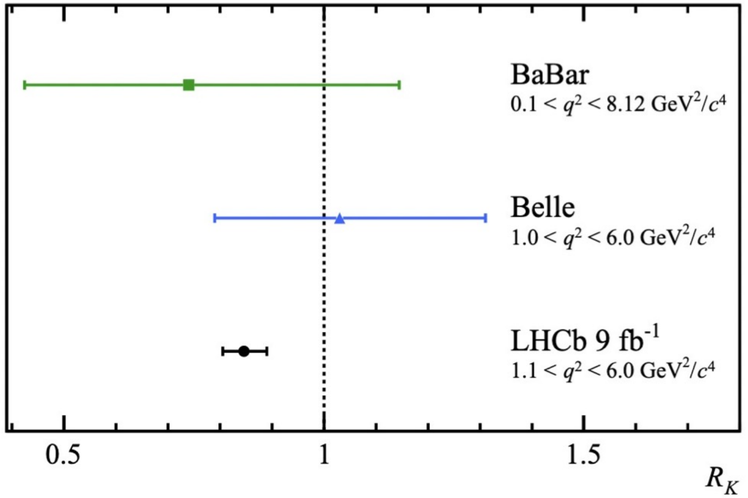
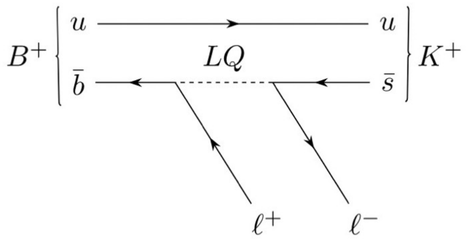
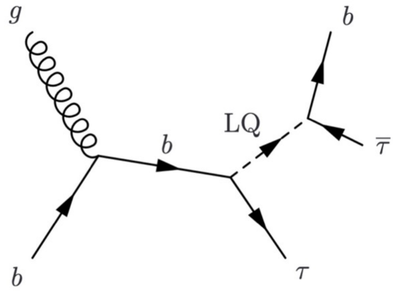


arxiv:2103.11769



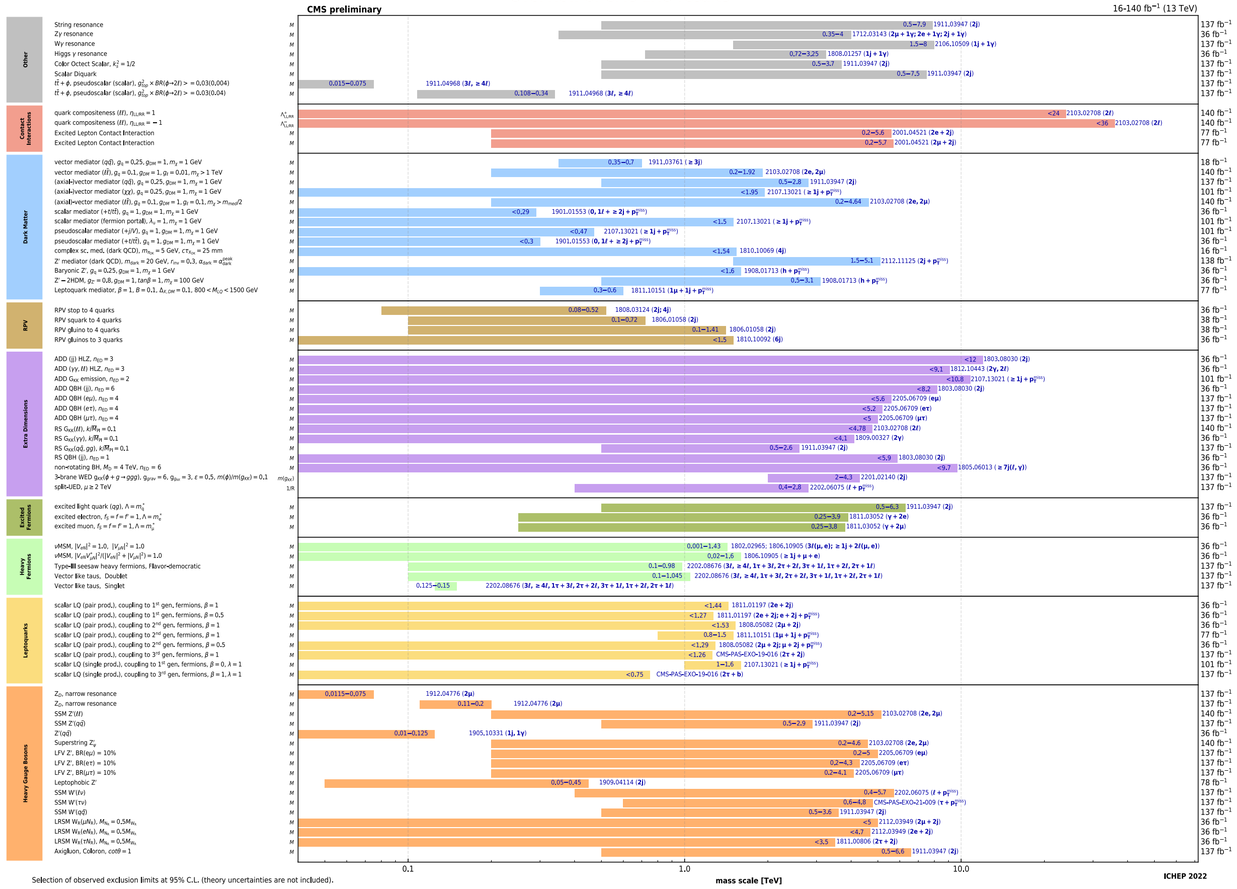




$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Big/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)}$$

# New physics can be anywhere

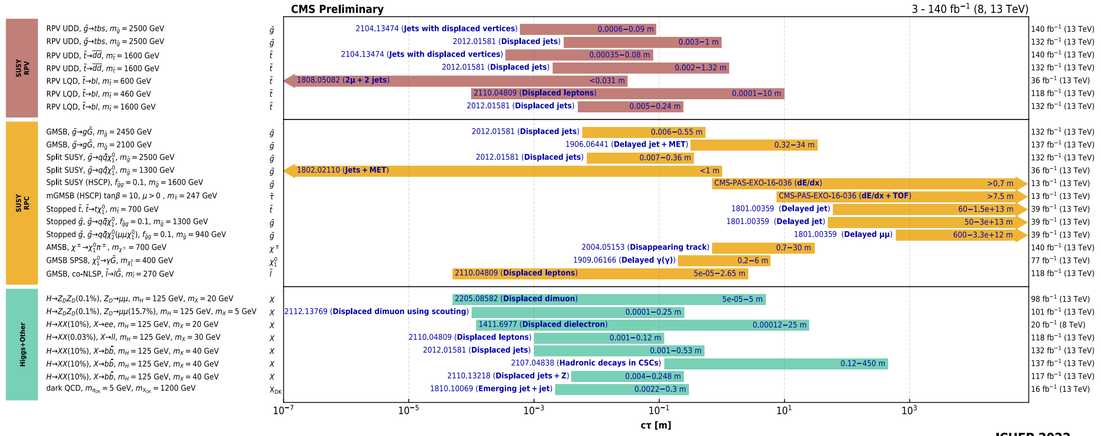
"Things that seem incredibly different can really be manifestations of the same underlying phenomena"
*– Nima Arkani Hamed*

**Overview of CMS EXO results**

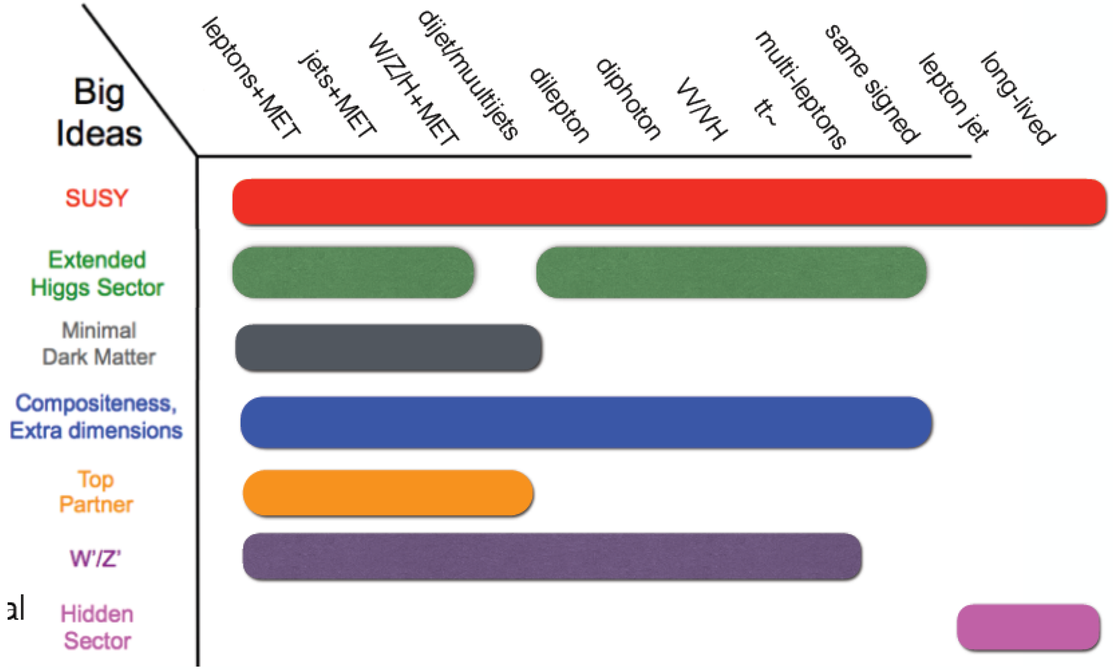



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

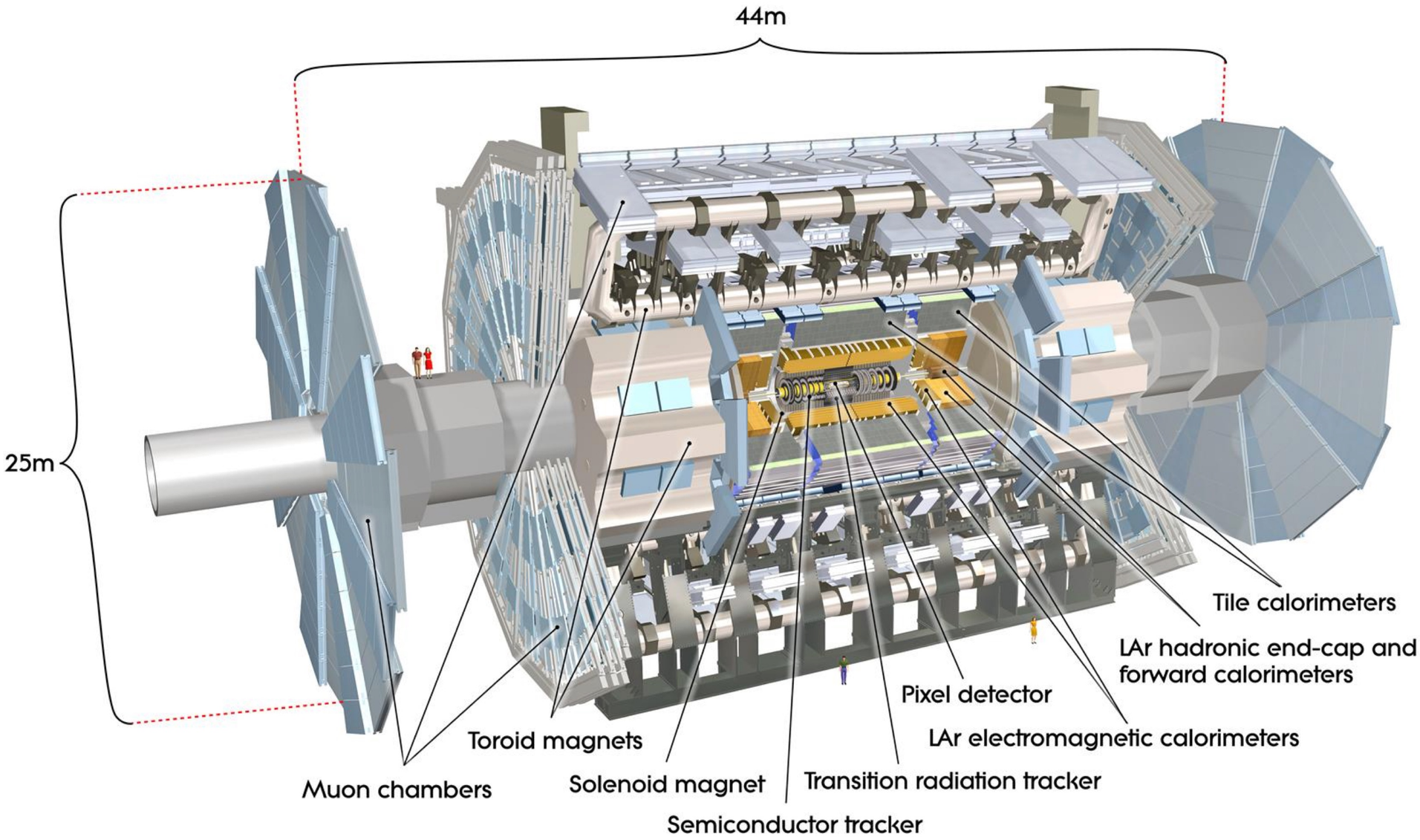
**Overview of CMS long-lived particle searches**




Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.



# Experiments at the collider



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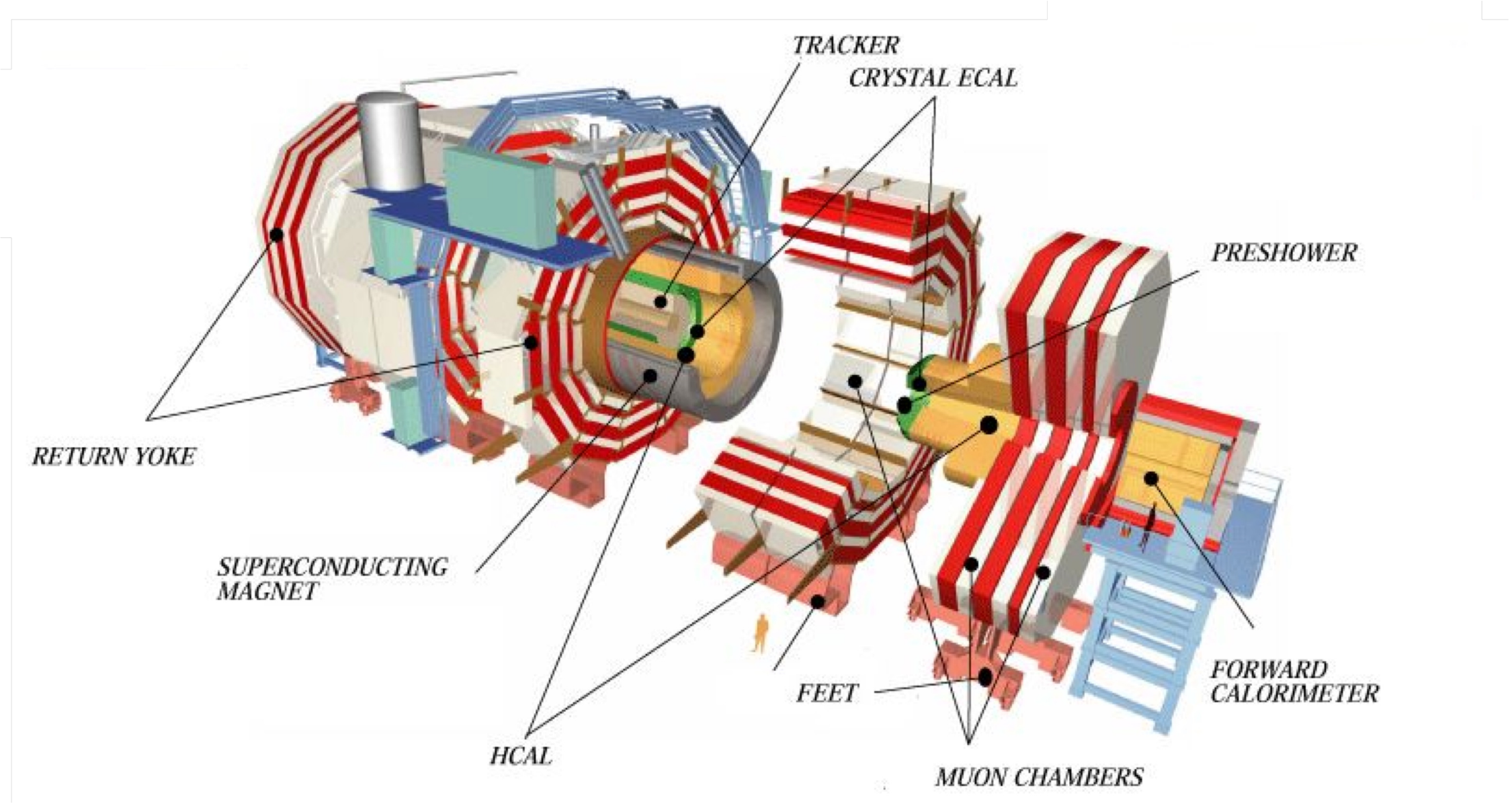
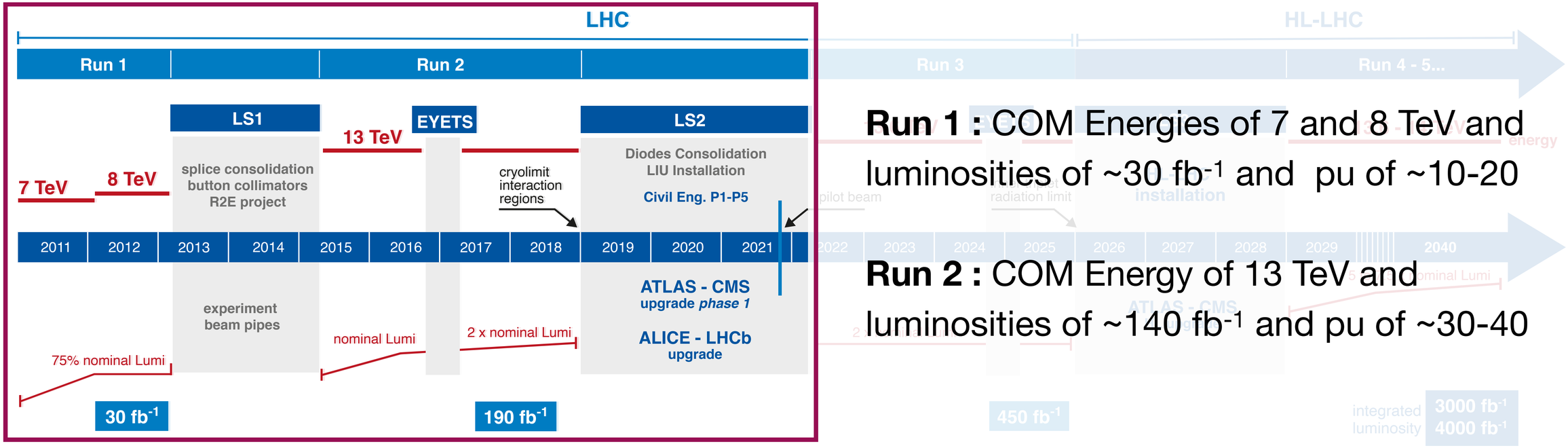
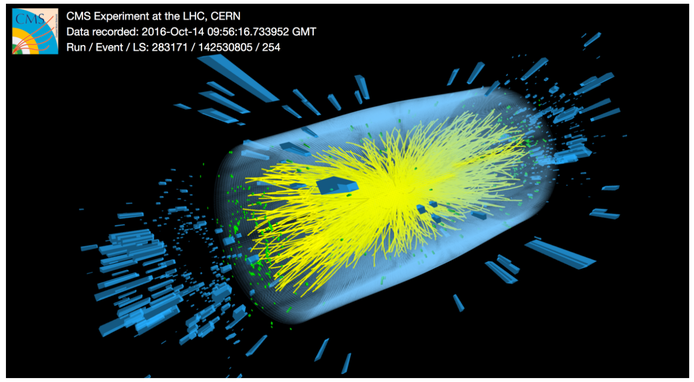


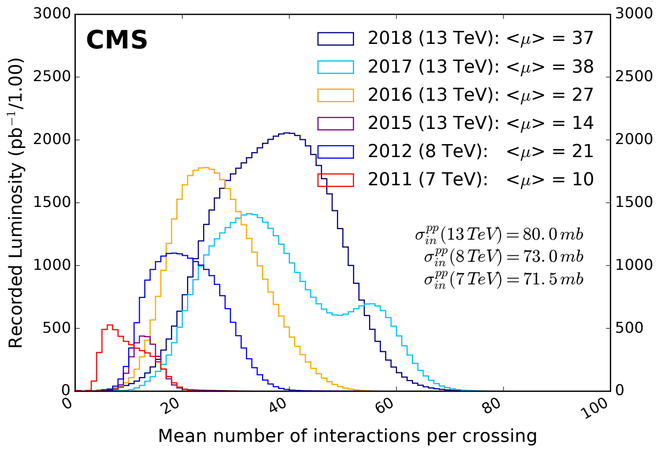
# Data Taking

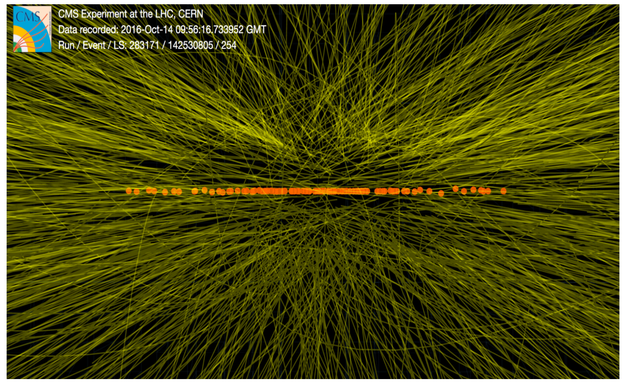



**Run 1 :** COM Energies of 7 and 8 TeV and luminosities of ~30 $fb^{-1}$ and pu of ~10-20

**Run 2 :** COM Energy of 13 TeV and luminosities of ~140 $fb^{-1}$ and pu of ~30-40



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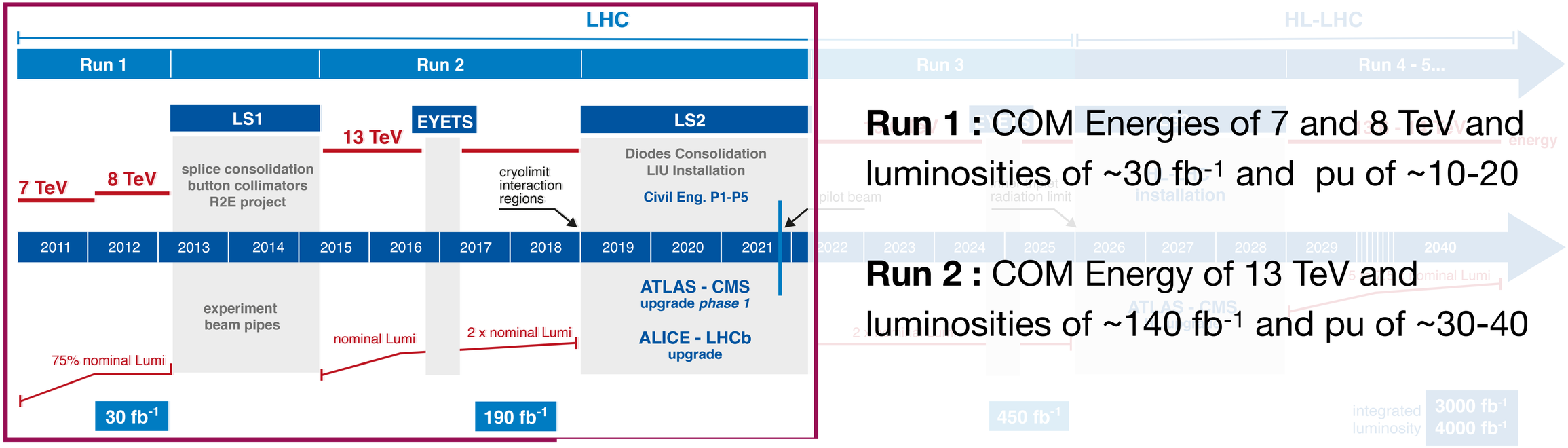


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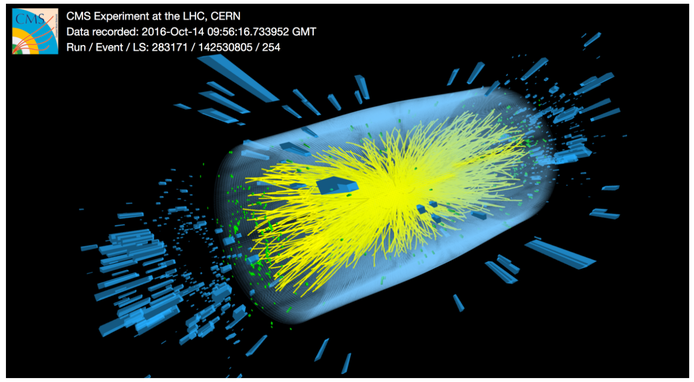
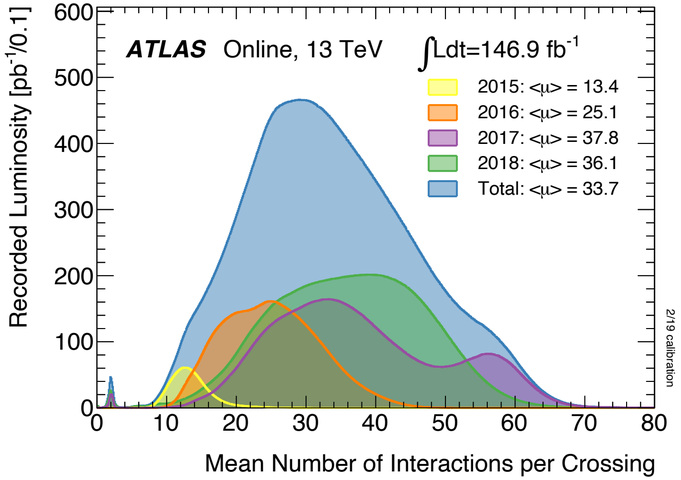
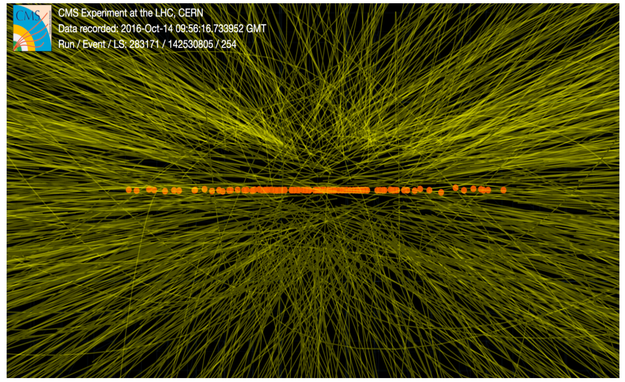
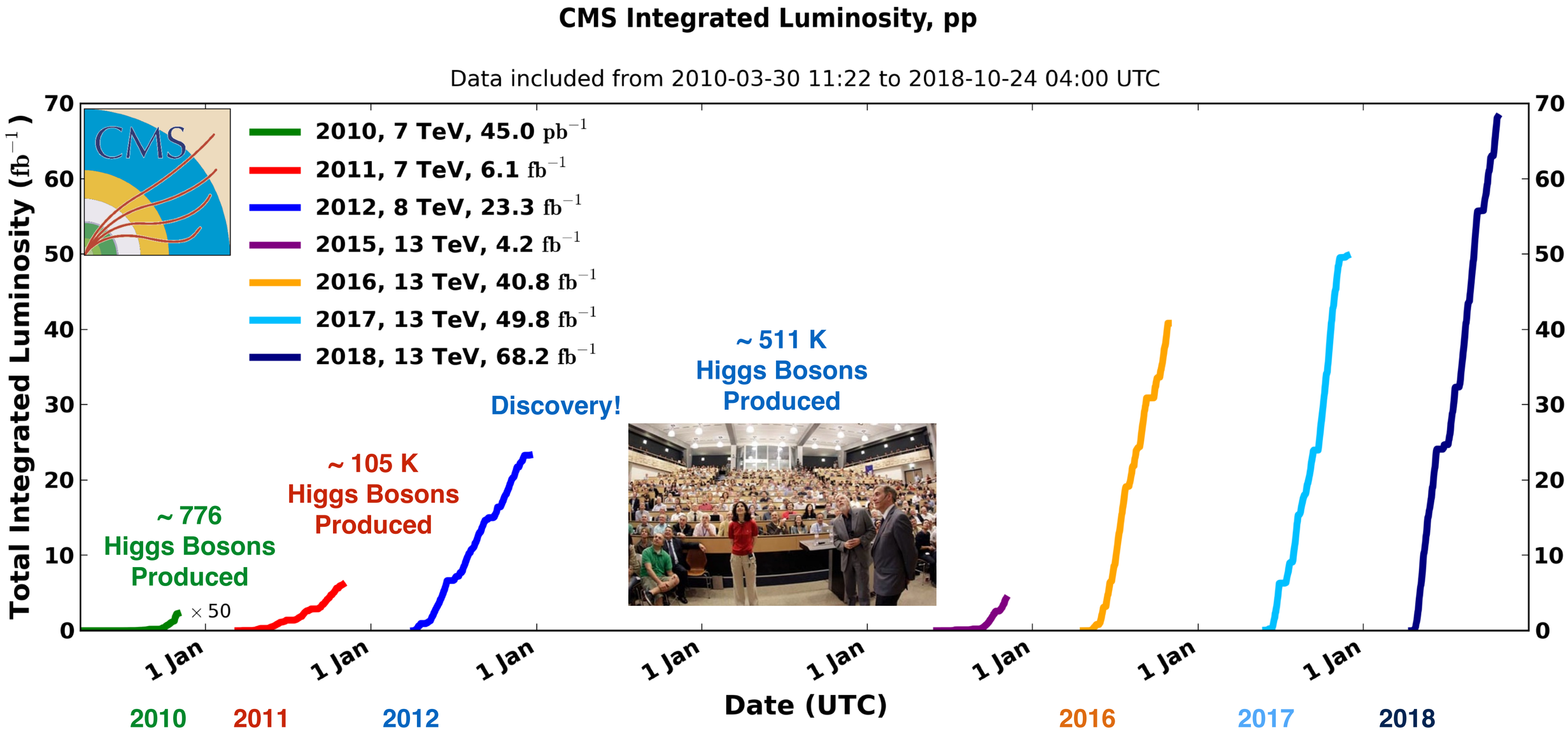


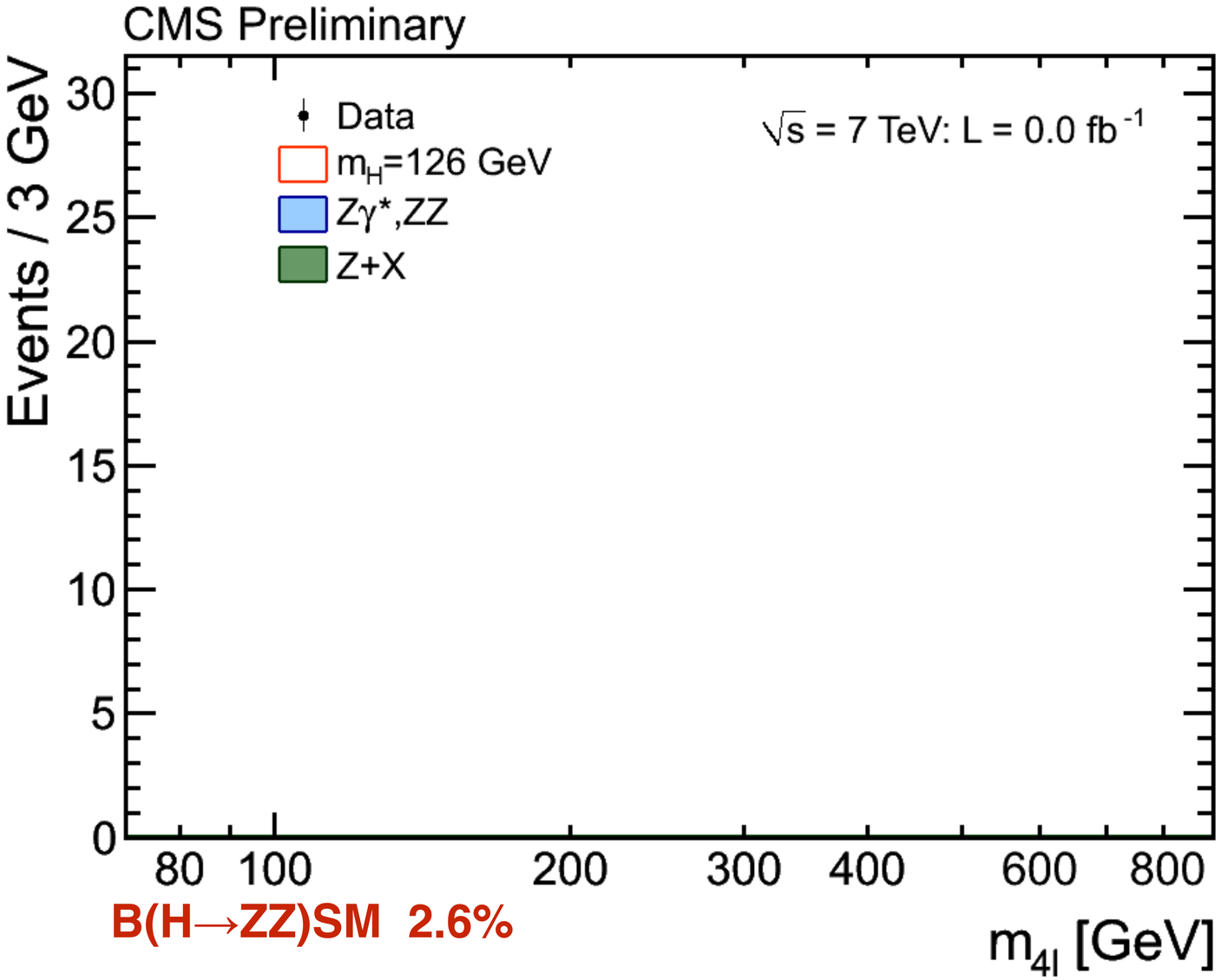



# Data collected so far

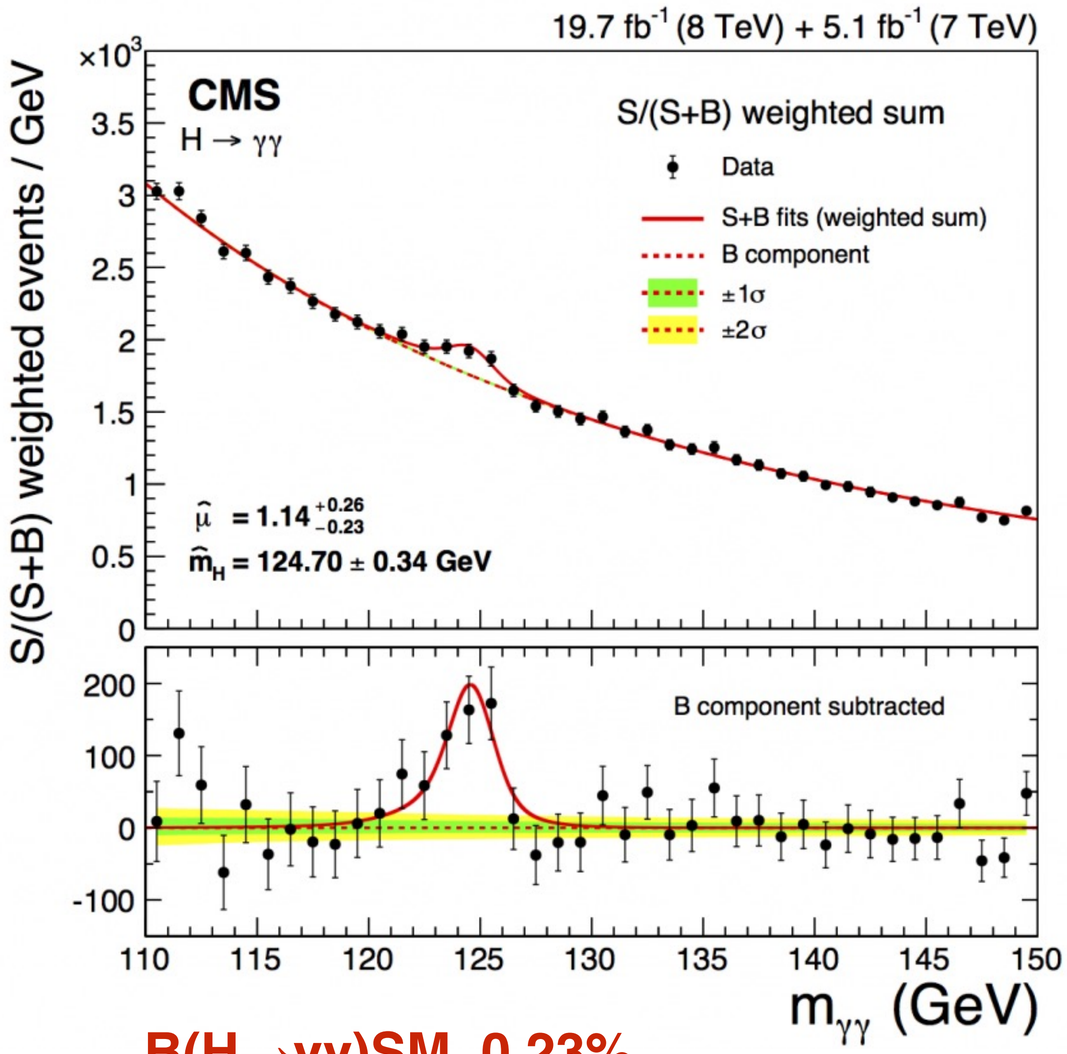
$$N_{Events} = \sigma \times \mathcal{L}$$



# Higgs Discovery …

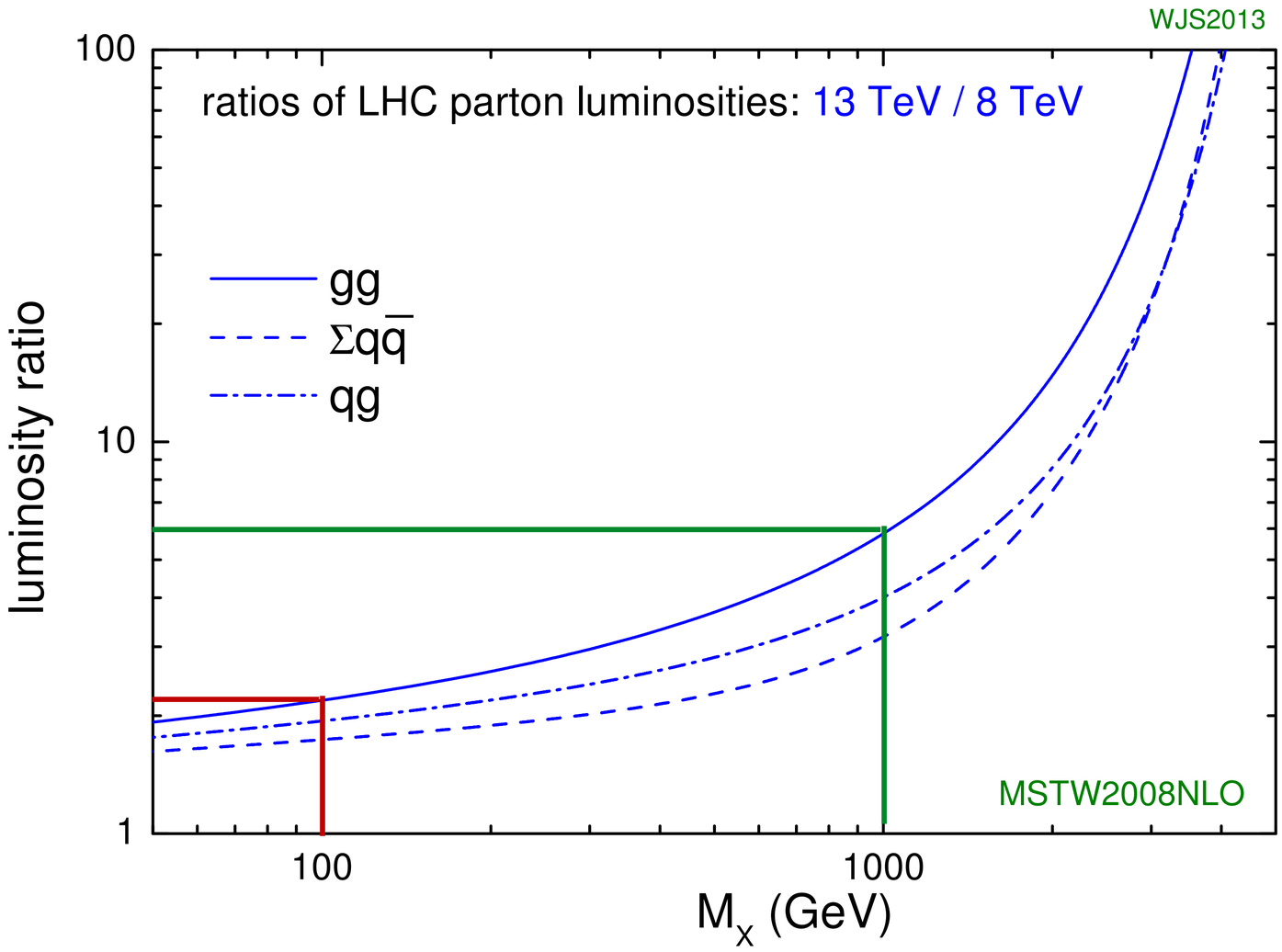



B(H→ZZ)SM 2.6%




B(H→γγ)SM 0.23%

# How many events?



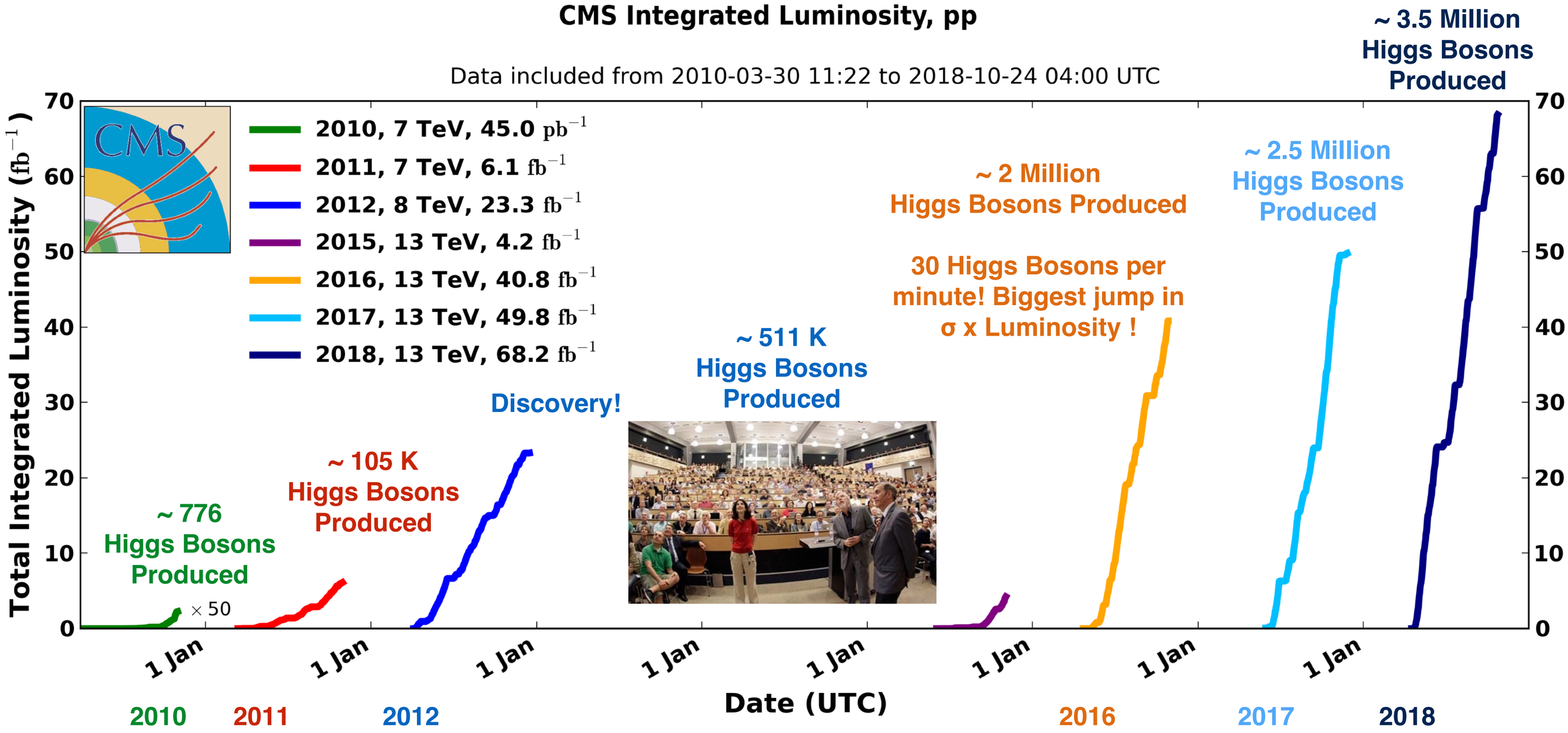

$$N_{\text{Events}} = \sigma \times \mathcal{L}$$

$$\frac{N^{13\ \text{TeV}}_{\text{Events}}}{N^{8\ \text{TeV}}_{\text{Events}}} = \frac{\sigma^{13\ \text{TeV}}}{\sigma^{8\ \text{TeV}}} \times \frac{\mathcal{L}^{13\ \text{TeV}}}{\mathcal{L}^{8\ \text{TeV}}}$$

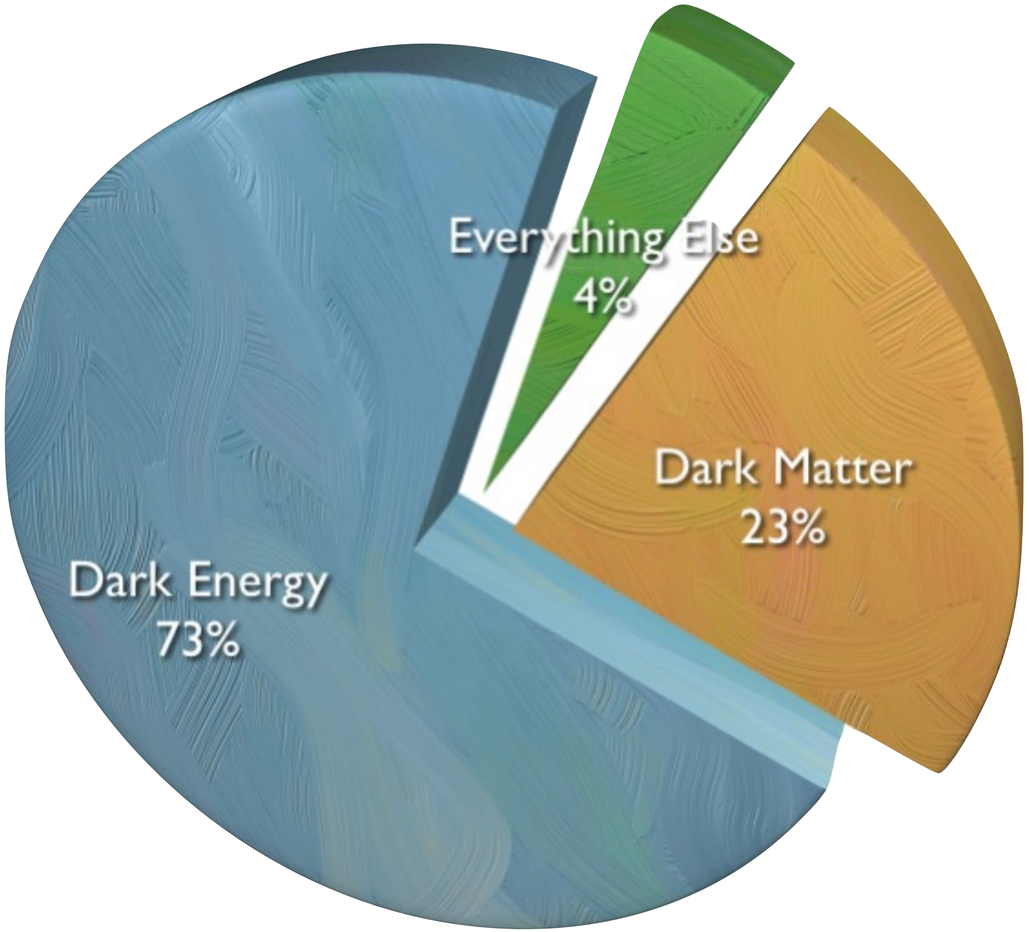
@ Higgs mass of O(100 GeV) ~ ratio of 2

@ Mass of O(1TeV) ~ ratio of 6

# Data collected so far



# The question I want to discuss: Dark Matter




"Standard" searches

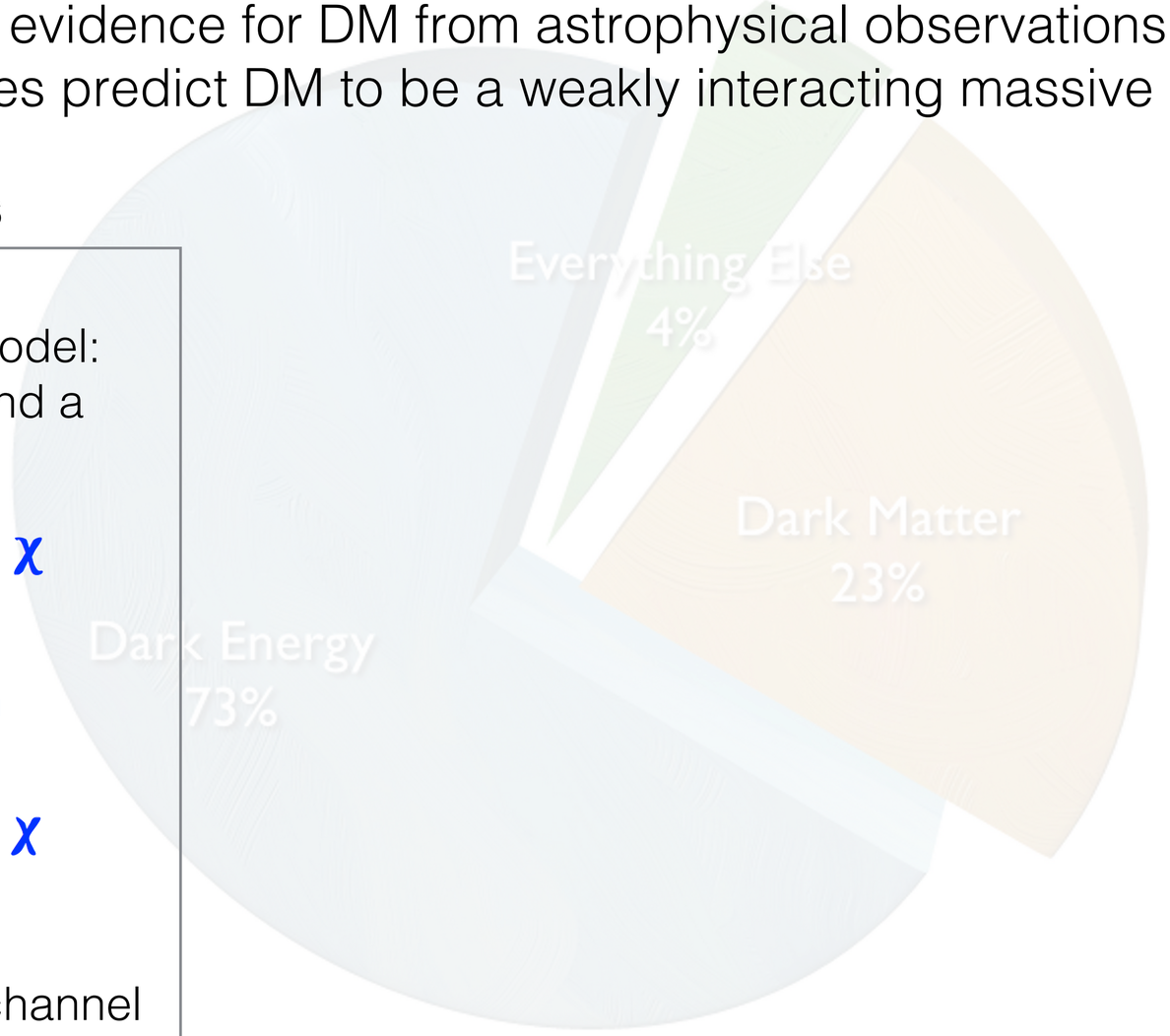
- Mono-X
- Dijet resonances
- Semi visible jets

More "exotic" searches

- Higgs Portals (Invisible Higgs, Mono-Higgs, Dark Higgs …)
- Long-lived searches
- Using PPS

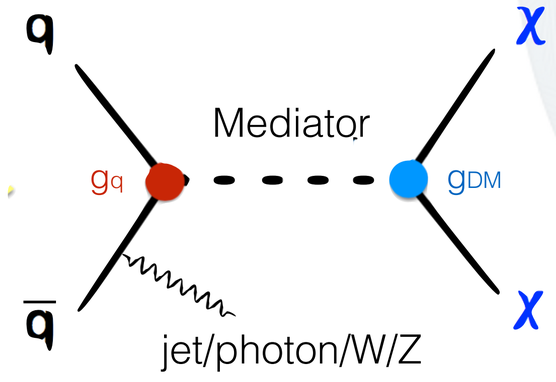
# Collider approach to Dark Matter

Strong experimental evidence for DM from astrophysical observations. Most studied class of theories predict DM to be a weakly interacting massive particle.



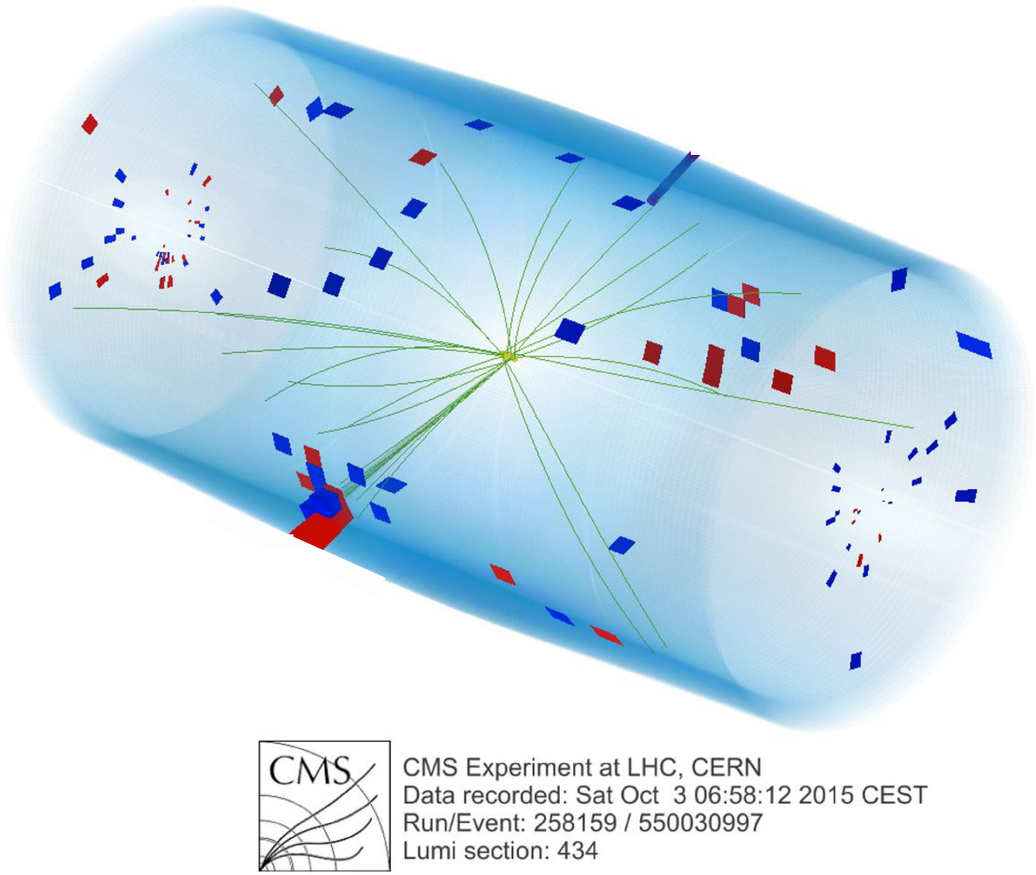

**Simplified Models**

Main parameters of the model: mediator, two vertices, and a DM candidate




Extended to models with t-channel mediator and dark sectors

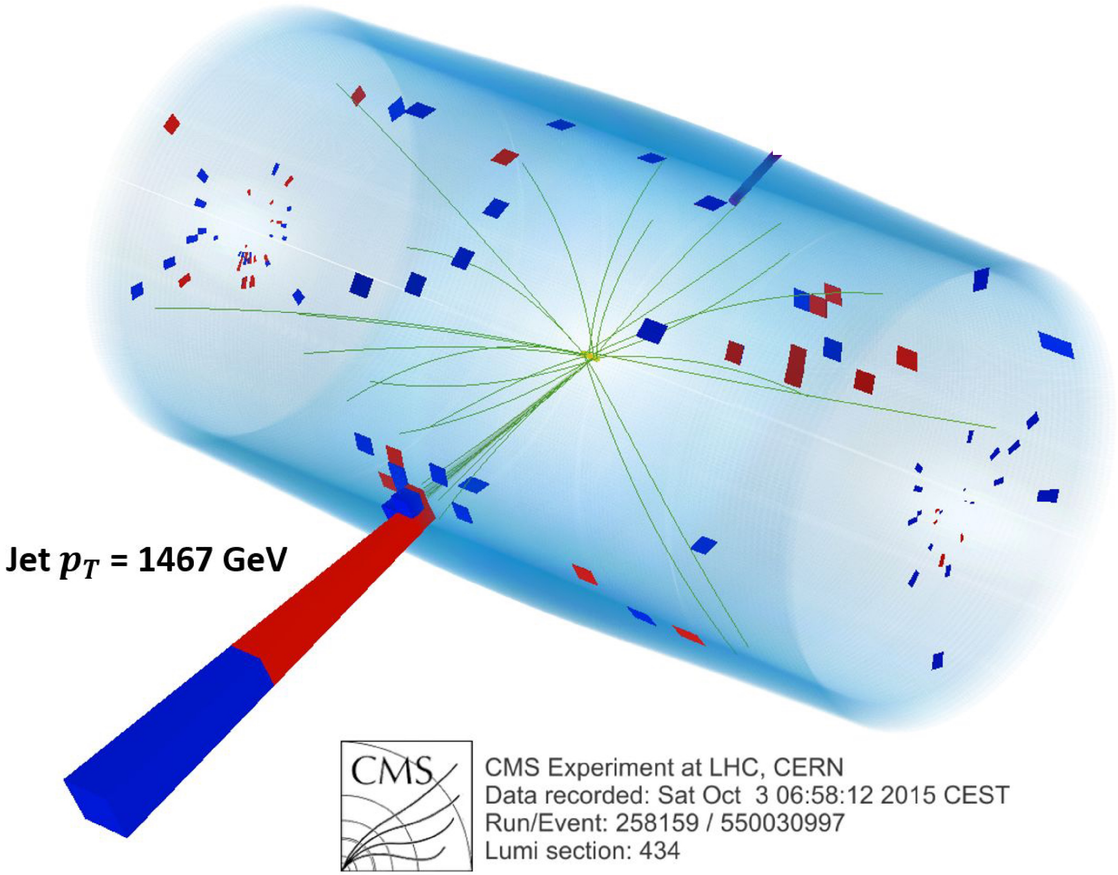
# How does dark matter look in our detectors?




**<u>What is the signature of dark matter?</u>**

- DM assumed to be **weakly interacting**, and will leave **no signature in the detector**!

# How does dark matter look in our detectors?




**<u>What is the signature of dark matter?</u>**

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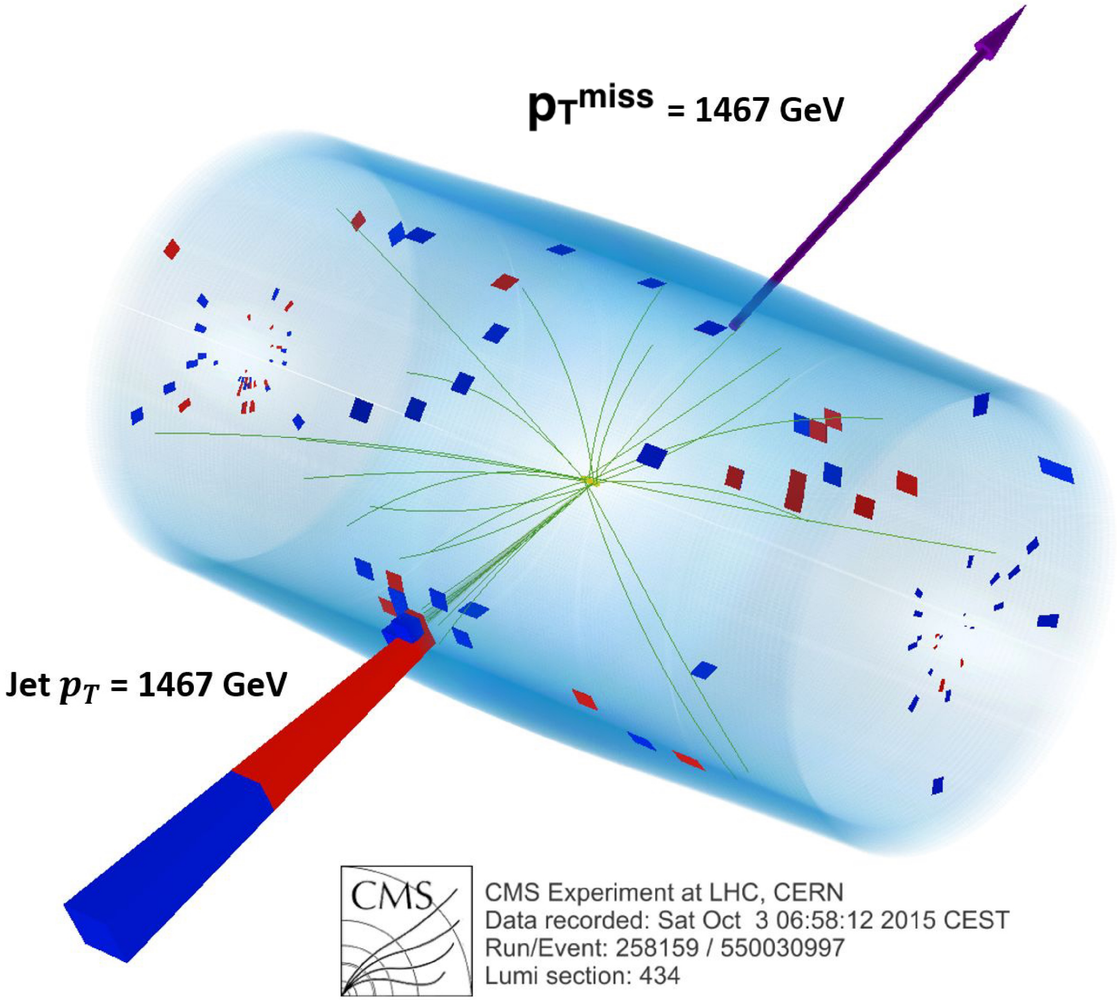
  - we can record these events if the DM is produced in **association** to an **initial state radiation**

# How does dark matter look in our detectors?




## What is the signature of dark matter?

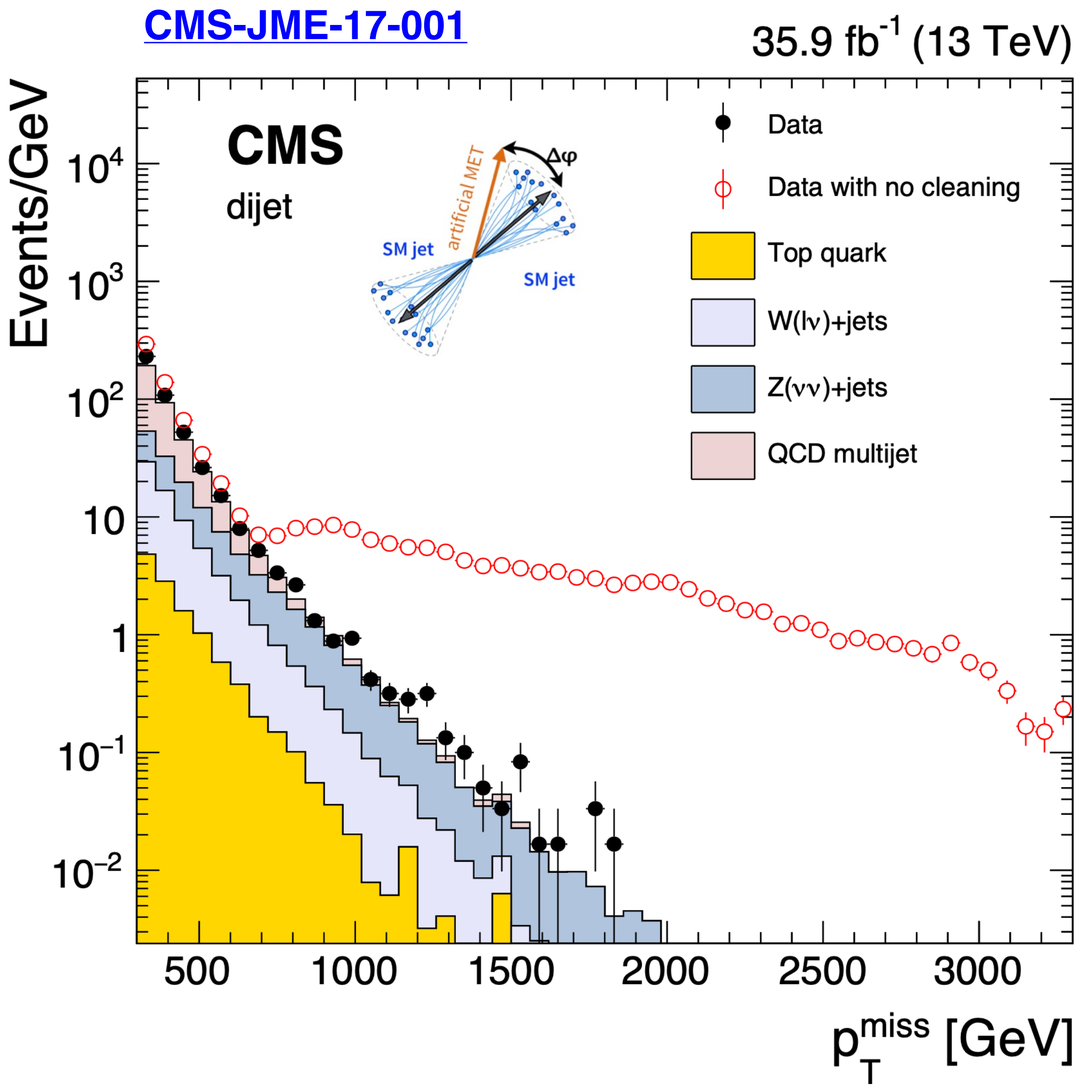
- DM assumed to be **weakly interacting**, and will leave **no signature in the detector**!
  - we can record these events if the DM is produced in **association** to an **initial state radiation**

**Total transverse momentum in the event has to be balanced! Initial transverse momenta = 0 !**

**observable: Missing transverse momentum ($p_T^{miss}$)**
defined as the imbalance in the transverse momentum of all particles that interact with the detectors

The existence of **$p_T^{miss}$** in the event => **Dark Matter ?**

# Challenges with Missing Transverse Momentum




Spurious detector signals can cause **fake** missing transverse momentum

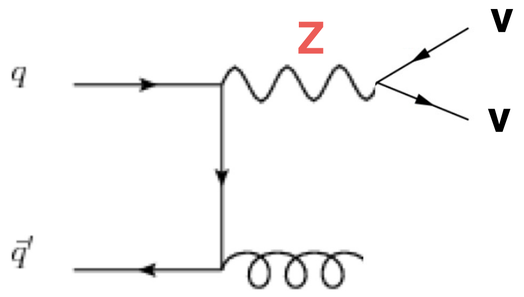
Anomalous **high $p_T^{miss}$** can be due to:

- Beam halo particles, cosmic rays
- Particles striking sensors in the calorimeter photodetectors
- Dead cells in the calorimeters
- Noise in readout electronics in calorimeters

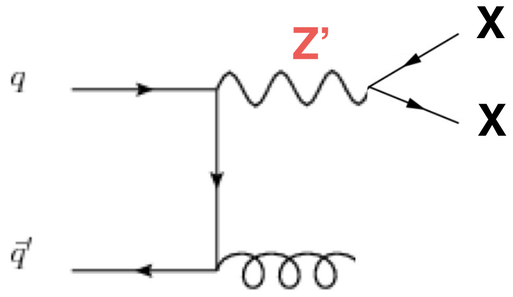
All **$p_T^{miss}$** based analysis uses data filters, and object based cleaning algorithms

# Standard Model Backgrounds

**Strategy** is to estimate all the "known" standard model processes in the final state of interest, and **look for deviations** from standard model that is compatible with the signal expectation.



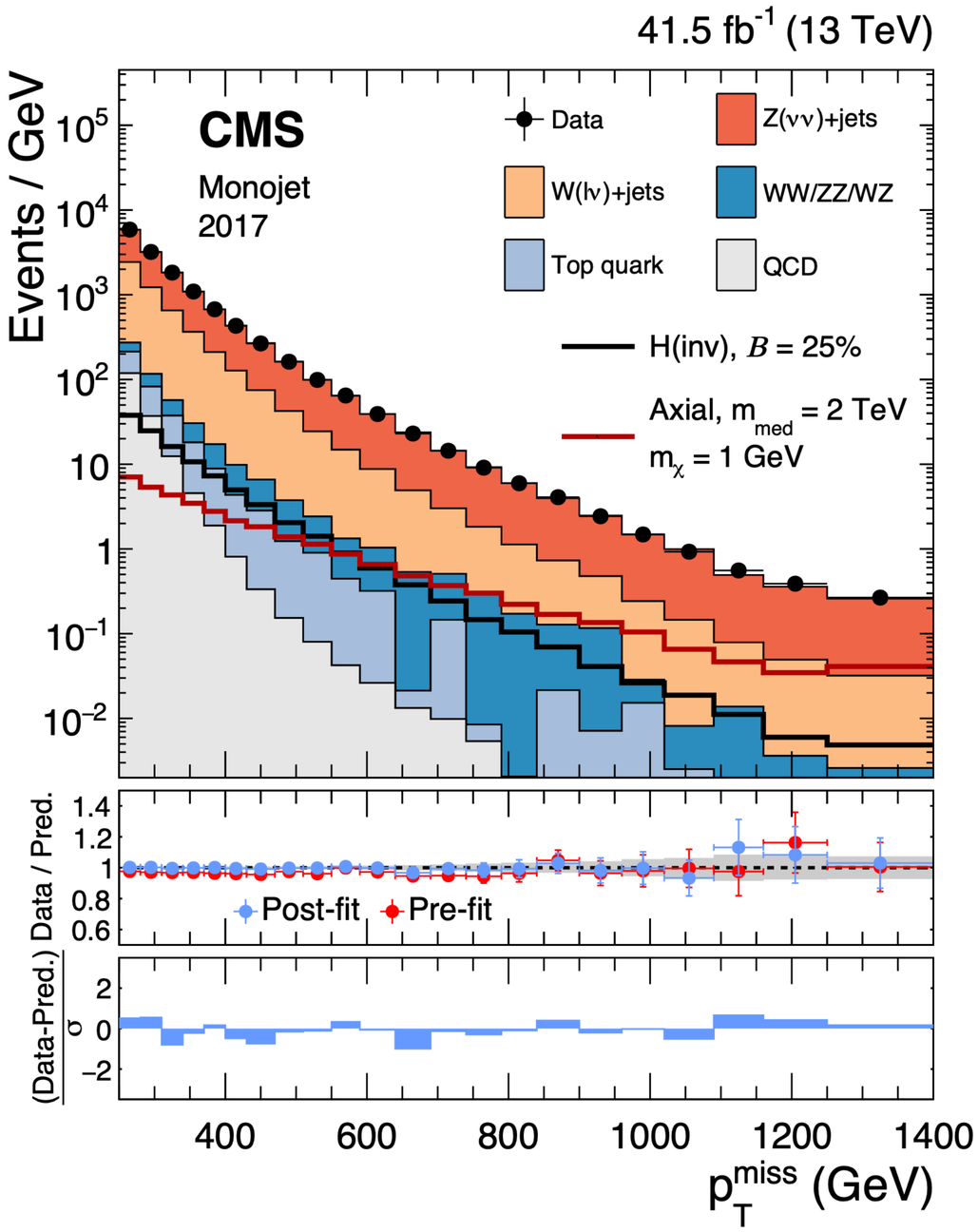

**Irreducible largest background (Standard Model)**



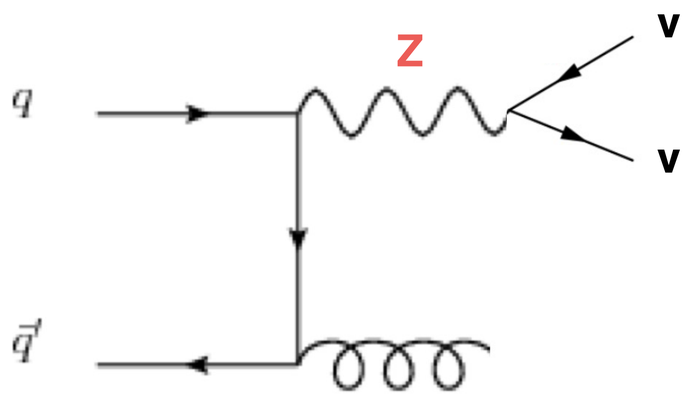

**Dark Matter Signal**

*Not so easy to distinguish! Identical in signature.*

**Conclusion:** Have to measure the standard model background very precisely (with lowest possible uncertainty)



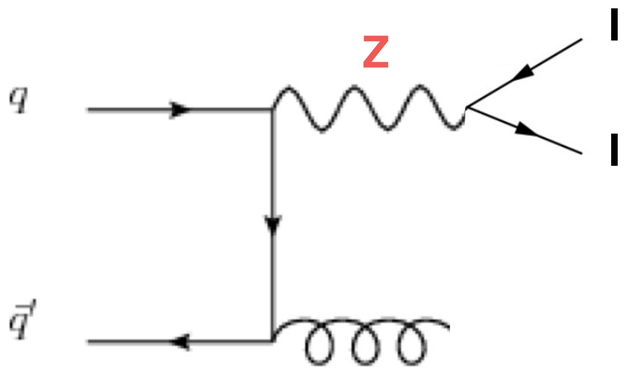
# Standard Model Background Estimation




**Z(νν)+jets:** Irreducible background and makes up **50-80%** of the total background estimation!

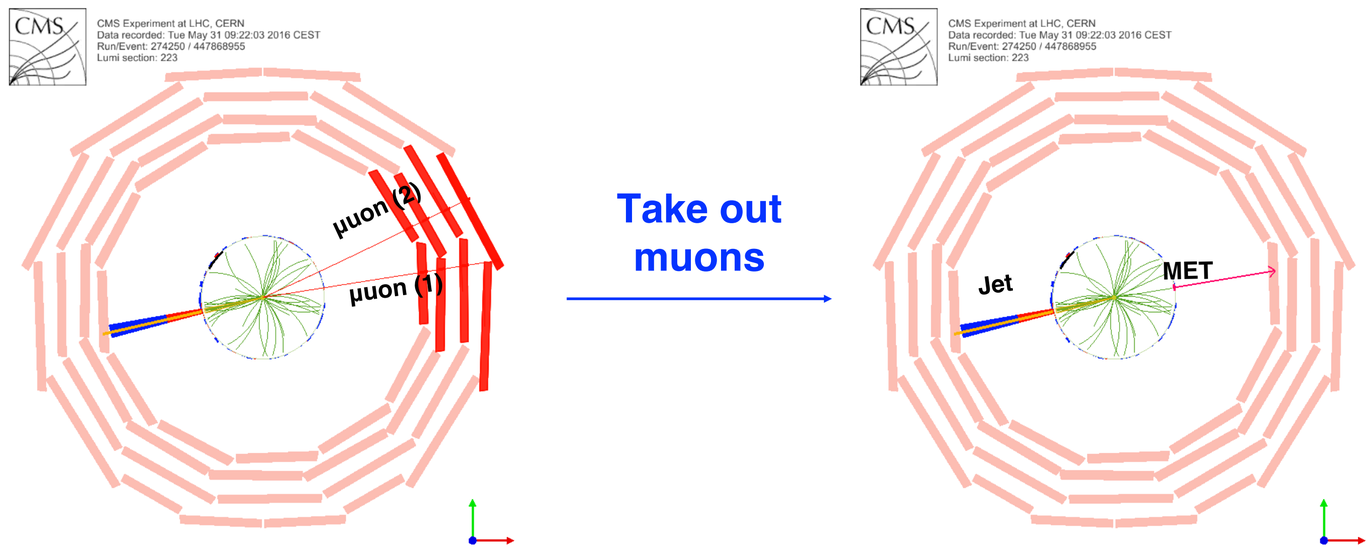
**Question:** What other standard model processes can we use to estimate the leading background more precisely?

***If we remove the muons from a Z→μμ event, it mimics a Z→νν event***

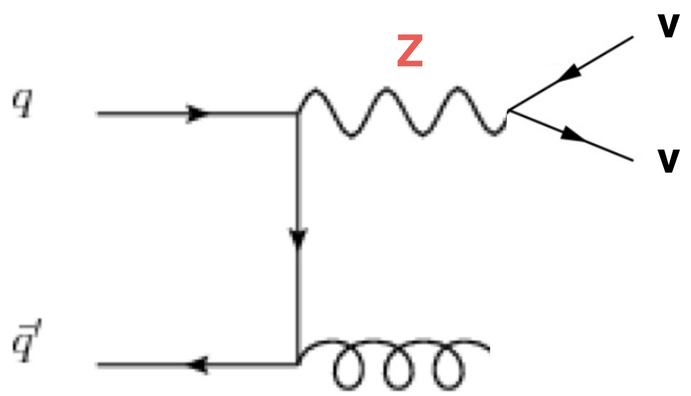



**statistically limited**

***~no theory uncertainties***



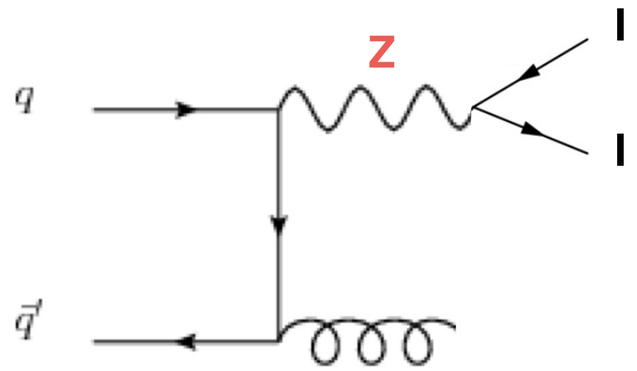
# Standard Model Background Estimation




**Z(νν)+jets:** Irreducible background and makes up **50-80%** of the total background estimation!

- Estimated from **5 orthogonal control regions**.
- Leading to precision measurement to test the standard model

***State of the art differential predictions, uncertainties and the correlation schema on the ratios***

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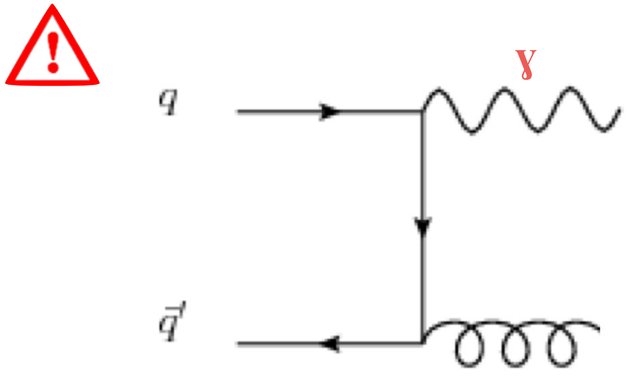
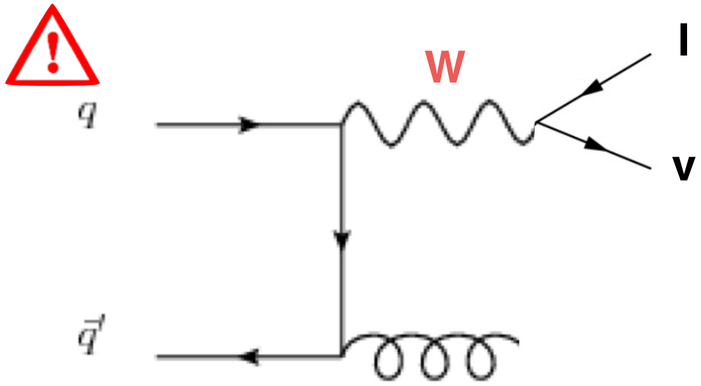



**statistically rich!**

***large theory uncertainties***

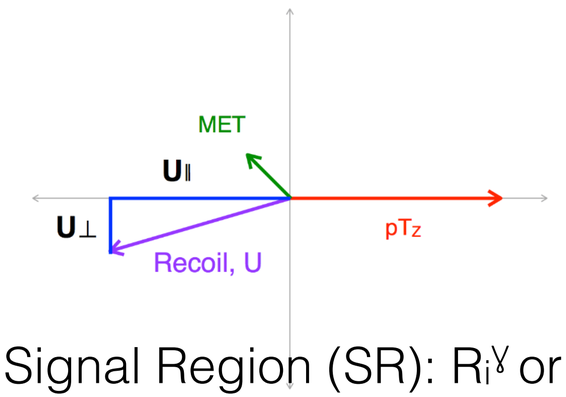



**statistically ~ Z (νν)**

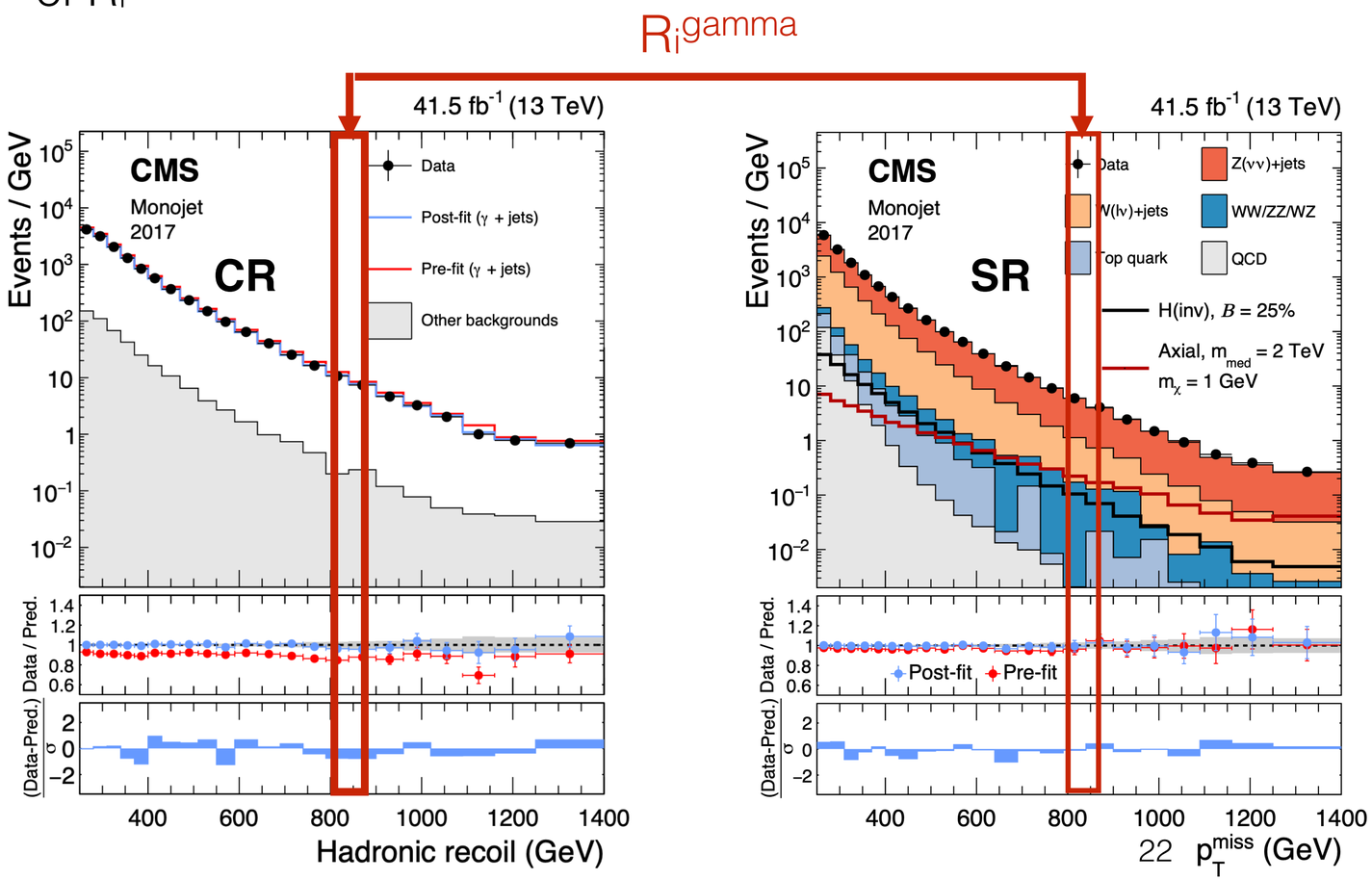
***large theory uncertainties***

# Standard Model Background Estimation

- **Step 1:** Compute a "Recoil" Variable (U) in the Control Regions (CRs)
  - U = Met + Pt $^{\mu\mu/ee}$ or Met + Pt $^{\mu/e}$ or Met + $P_T^{\gamma}$




- **Step 2:** Compute "Ratios" for each bin of recoil to translate between CRs to Signal Region (SR): $R_i^{\gamma}$ or $R_i^{Z}$ or $R_i^{W}$

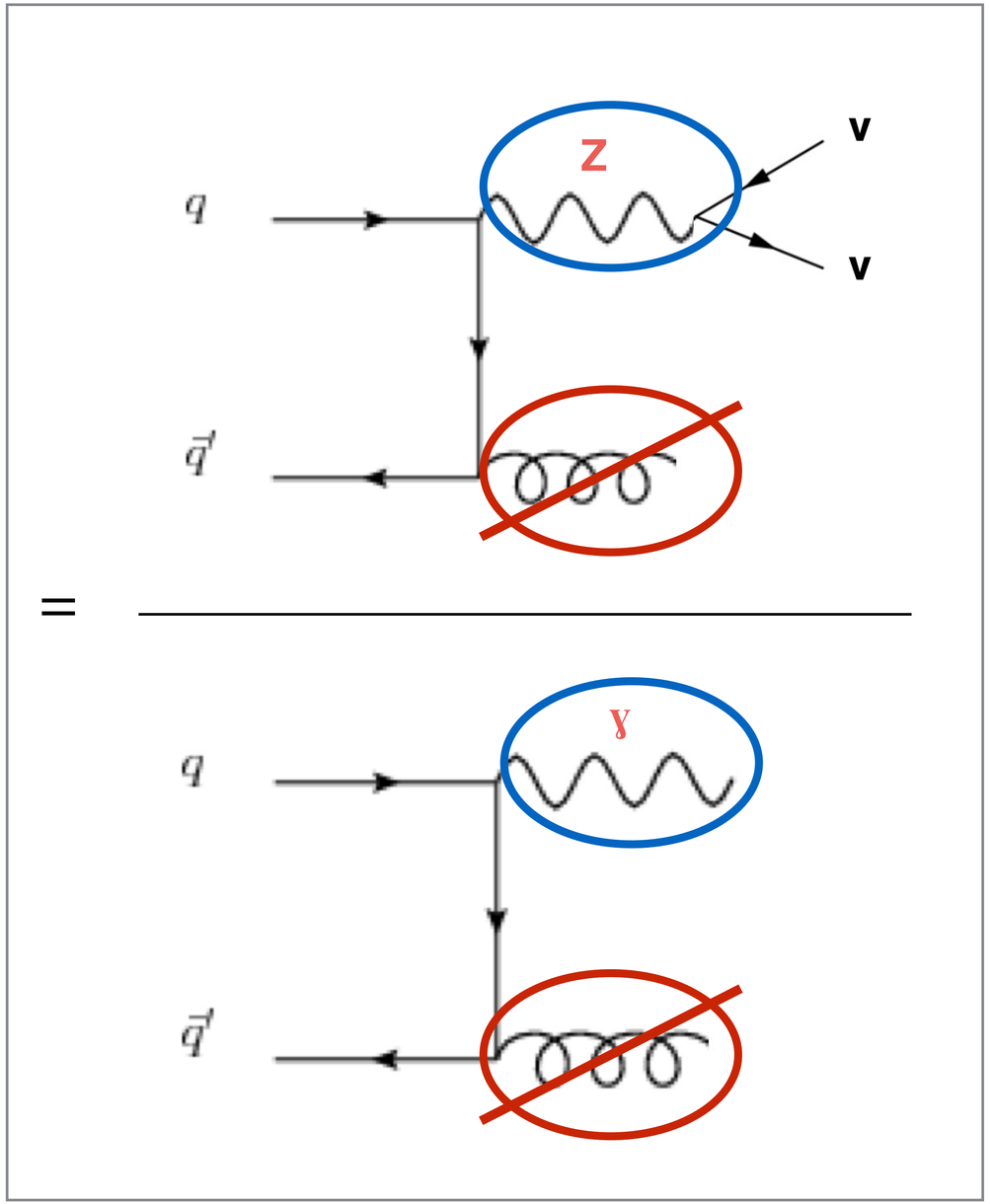



$$R_i = \frac{N_{i,MC}^{gamma}}{N_{i,MC}^{Z\to\nu\nu}}$$

$N_i$ is the number of events in bin i of the recoil distribution

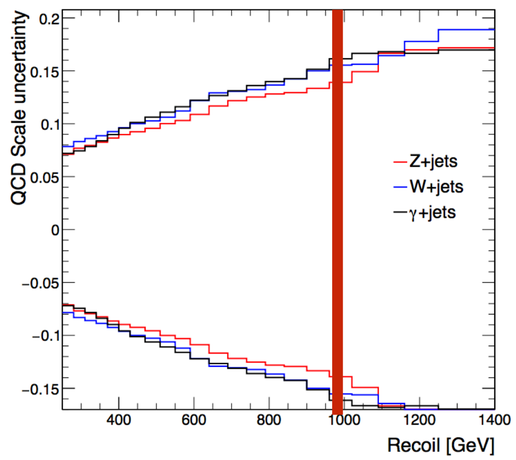
- **Step 3:** Allow these ratios to vary within experimental and theoretical uncertainties (θ) in the likelihood and fit to data!

# Why Ratios?

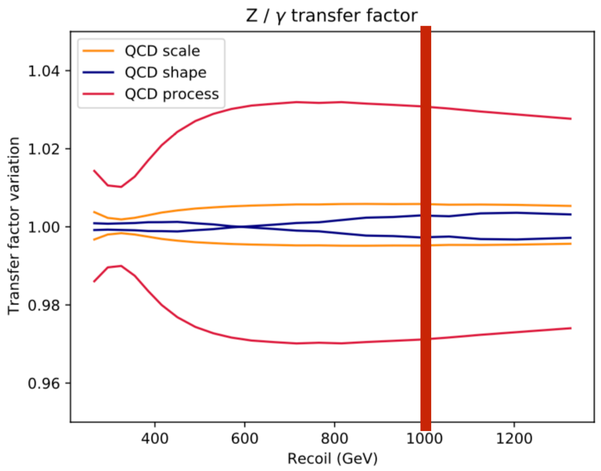



- Similar sources of **experimental uncertainties** will **cancel**:
  - jet energy scale and resolution
  - luminosity measurement
  - additional proton proton interactions

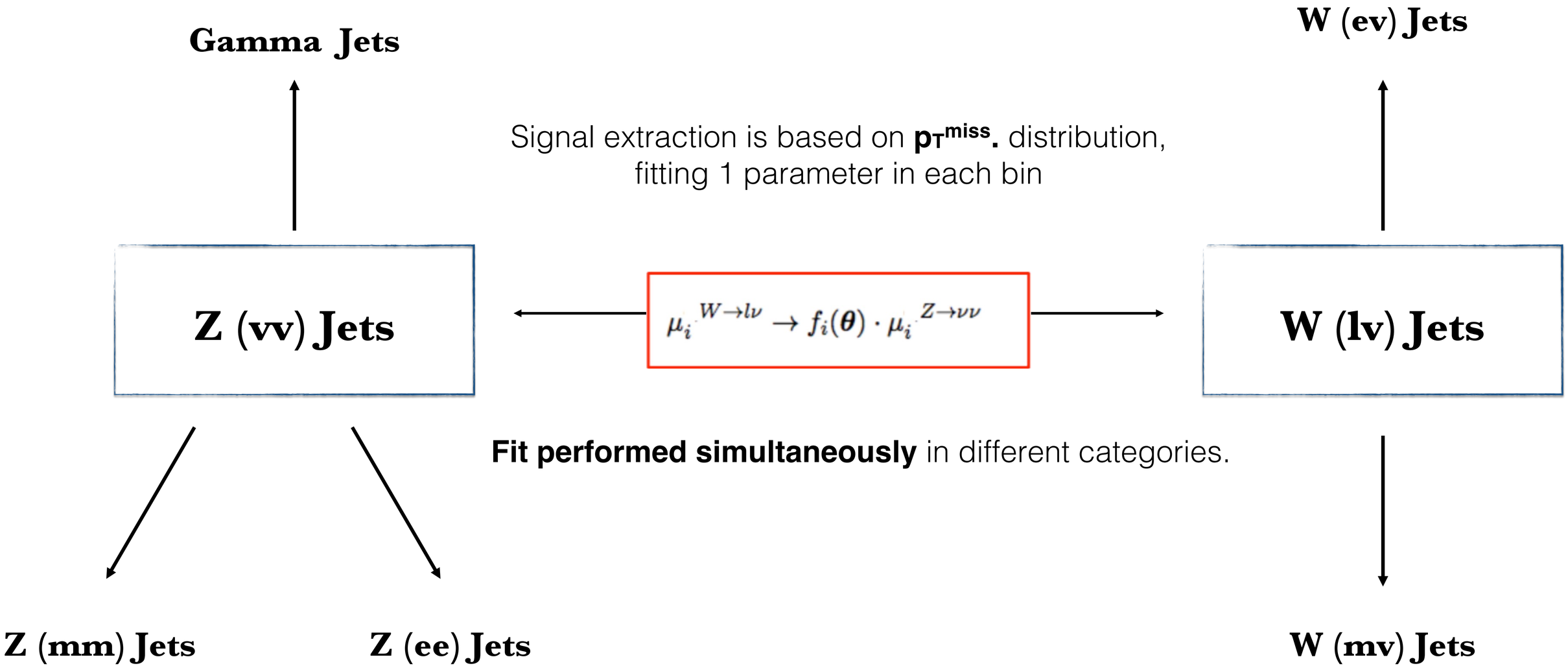
- Similar sources of **theoretical uncertainties** will partially **cancel**:




ratio



# Simultaneous Fitc



# Likelihood

**Objective:** Define a partial likelihood for each event category as the product over Poisson likelihoods for each bin in recoil, in each of the control regions

$$\mathcal{L}_k(\boldsymbol{\mu}^{Z(\nu\bar{\nu})}, \boldsymbol{\mu}, \boldsymbol{\theta}) = \prod_i \text{Poisson}\left(d_i^{\gamma} | B_i^{\gamma}(\boldsymbol{\theta}) + \frac{\boldsymbol{\mu}_i^{Z(\nu\bar{\nu})}}{R_i^{\gamma}(\boldsymbol{\theta})}\right) \quad \gamma + \text{jets}$$

$$\times \prod_i \text{Poisson}\left(d_i^{\mu\mu} | B_i^{\mu\mu}(\boldsymbol{\theta}) + \frac{\boldsymbol{\mu}_i^{Z(\nu\bar{\nu})}}{R_i^{\mu\mu}(\boldsymbol{\theta})}\right) \quad \text{Zmm + jets}$$

$$\times \prod_i \text{Poisson}\left(d_i^{ee} | B_i^{ee}(\boldsymbol{\theta}) + \frac{\boldsymbol{\mu}_i^{Z(\nu\bar{\nu})}}{R_i^{ee}(\boldsymbol{\theta})}\right) \quad \text{Zee + jets}$$

$$\times \prod_i \text{Poisson}\left(d_i^{\mu} | B_i^{\mu}(\boldsymbol{\theta}) + \frac{f_i(\boldsymbol{\theta})\boldsymbol{\mu}_i^{Z(\nu\bar{\nu})}}{R_i^{\mu}(\boldsymbol{\theta})}\right) \quad \text{Wmv + jets}$$

$$\times \prod_i \text{Poisson}\left(d_i^{e} | B_i^{e}(\boldsymbol{\theta}) + \frac{f_i(\boldsymbol{\theta})\boldsymbol{\mu}_i^{Z(\nu\bar{\nu})}}{R_i^{e}(\boldsymbol{\theta})}\right) \quad \text{Wev + jets}$$

Signal Region

$$\times \prod_i \text{Poisson}\left(d_i | B_i(\boldsymbol{\theta}) + (1 + f_i(\boldsymbol{\theta}))\boldsymbol{\mu}_i^{Z(\nu\bar{\nu})} + \boldsymbol{\mu} S_i(\boldsymbol{\theta})\right)$$

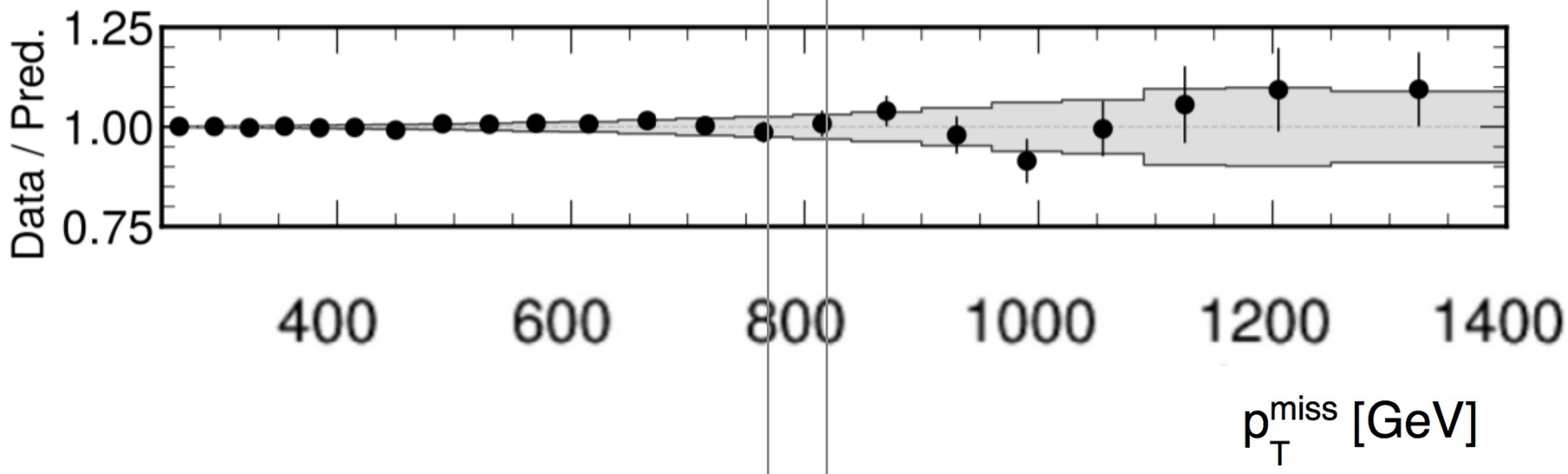
Number of observed events

Number of background events

Transfer factors with embedded uncertainties

# Leads to a … Precision Search

**Signal Region**



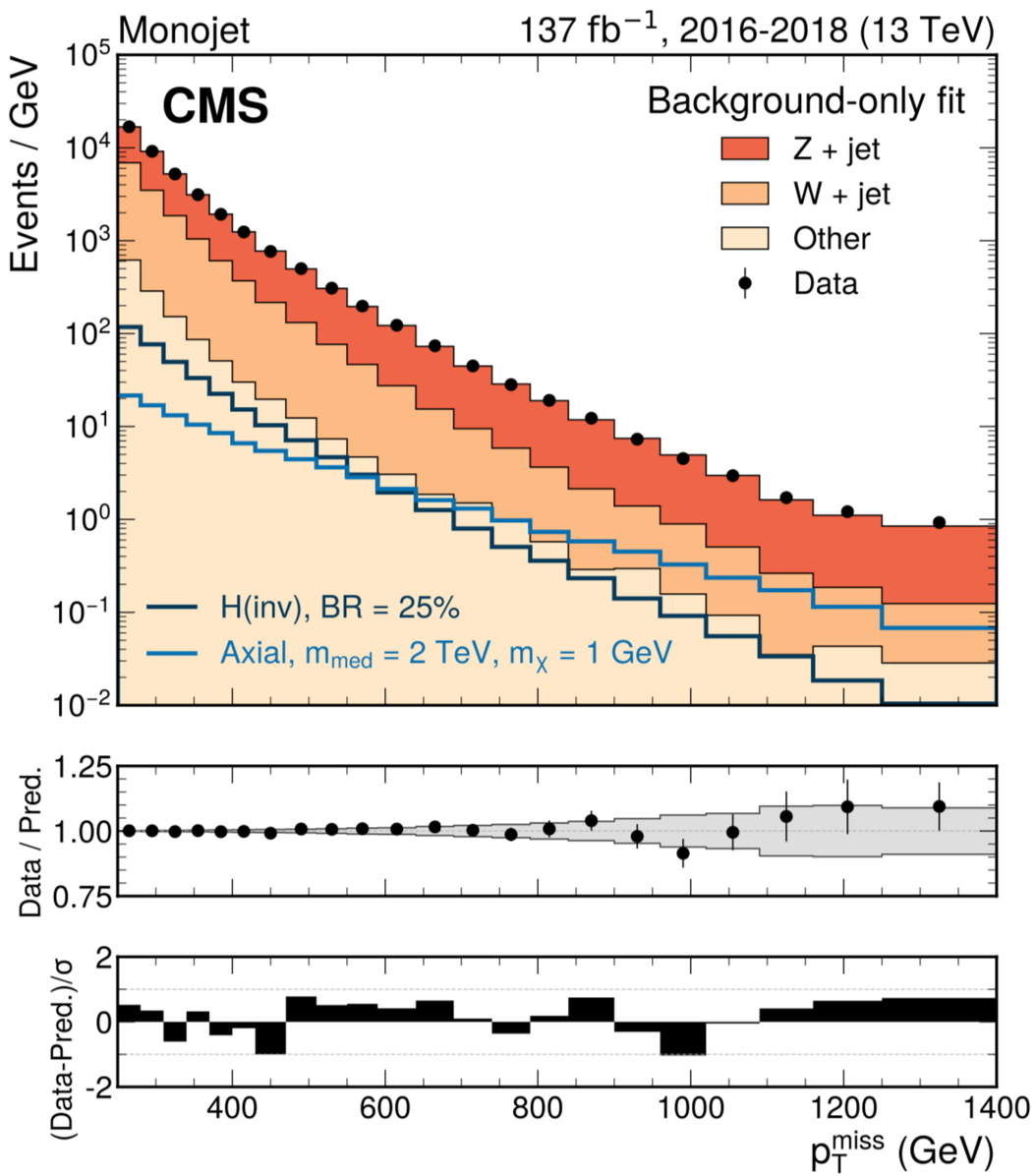

**In the low $p_T^{miss}$ region: ~2-3% unc.**

- Z regions drive the background fit
- Experimental sources dominate:
  - Trigger uncertainty
  - Object identification and reconstruction

**In the high $p_T^{miss}$ region: ~ 10% unc**

- γ, W regions drive the background fit
- Theoretical sources dominate:
  - Statistical variations in the simulation
  - Theoretical uncertainties on Z/γ,W ratios

# Leads to a … Precision Search




No deviation is observed with respect to the Standard Model expectation :(

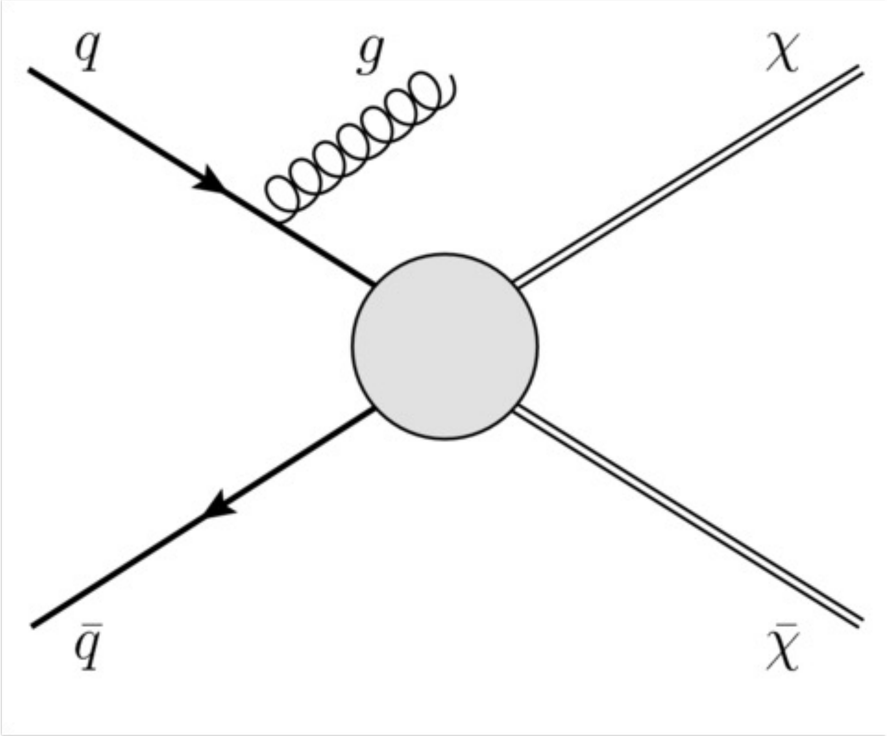
However, good post fit agreement
σ = post fit uncertainty ⊕ data statistical uncertainty

In situations like this (i.e. with no interesting excess), we provide limits on what we are able to exclude…

# We need a model…

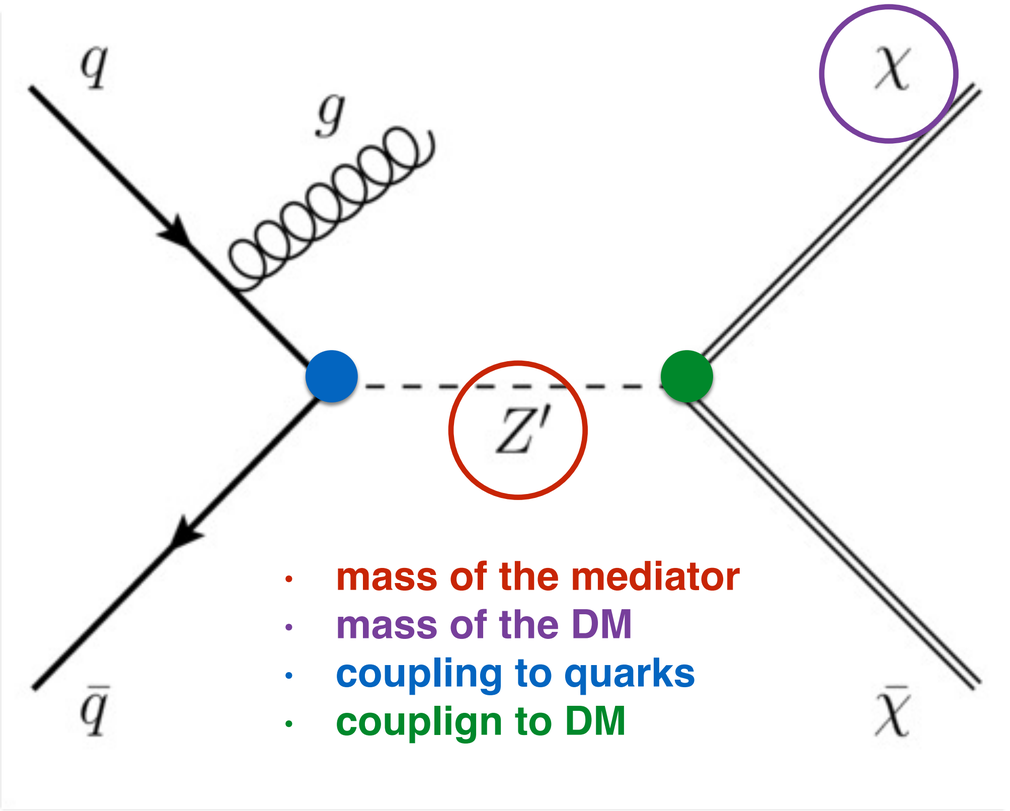
## Effective field theories

Mediator energies >>
energy transfer at the LHC

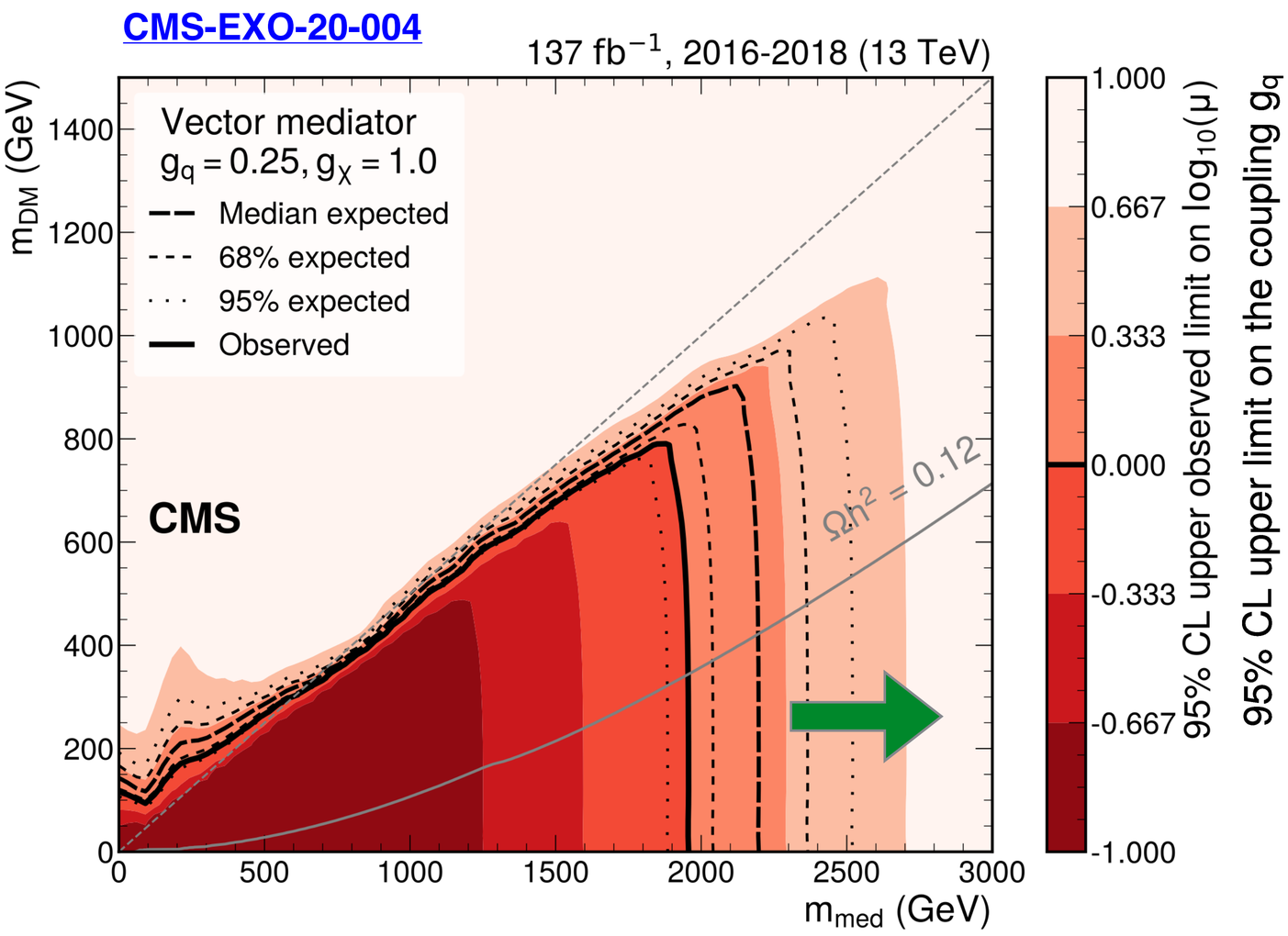


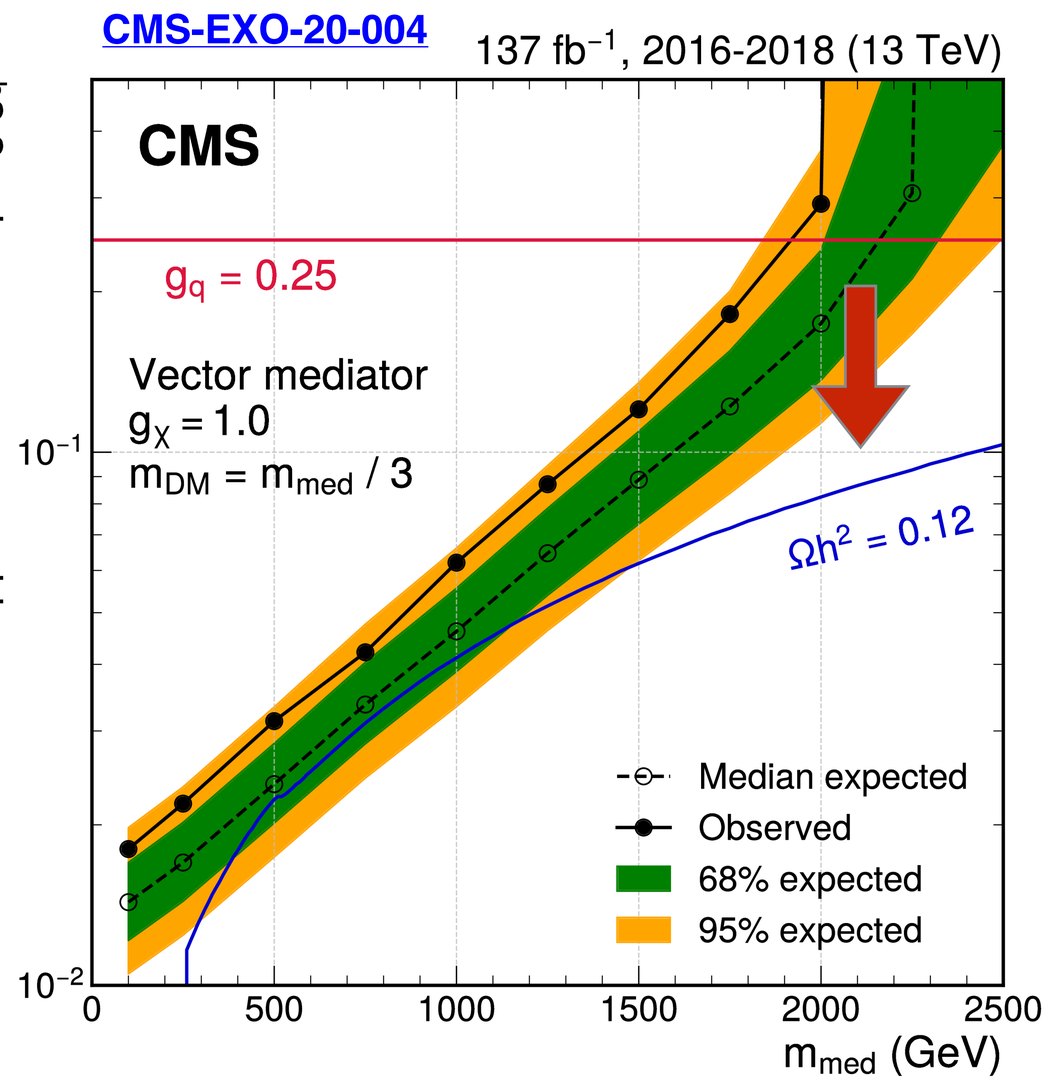

## Simplified models

Mediator is light enough to be produced at the LHC!



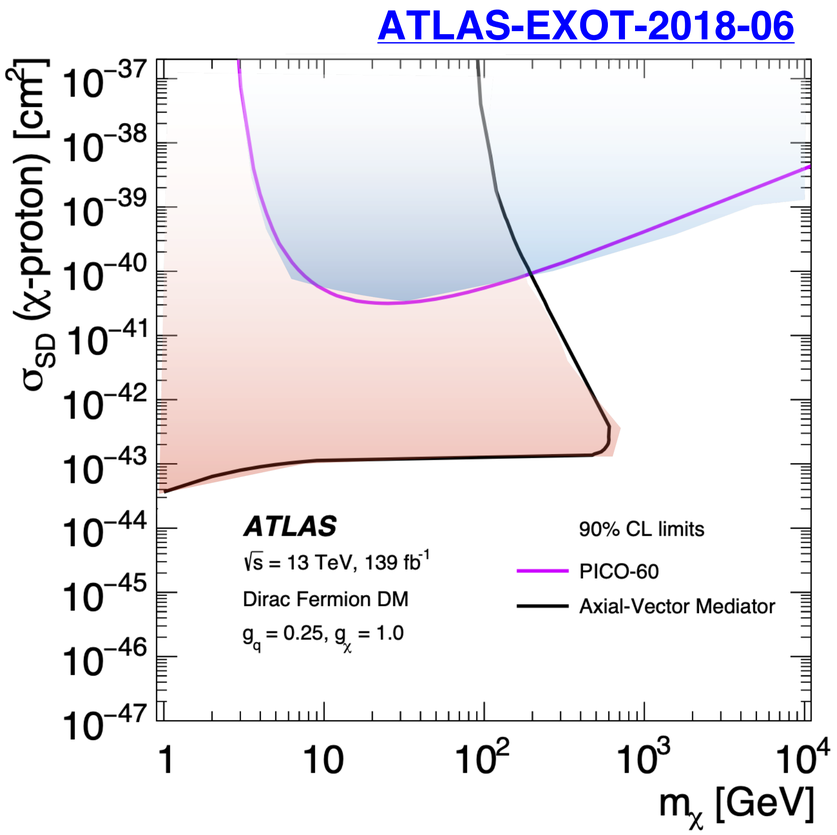
# Selected Results

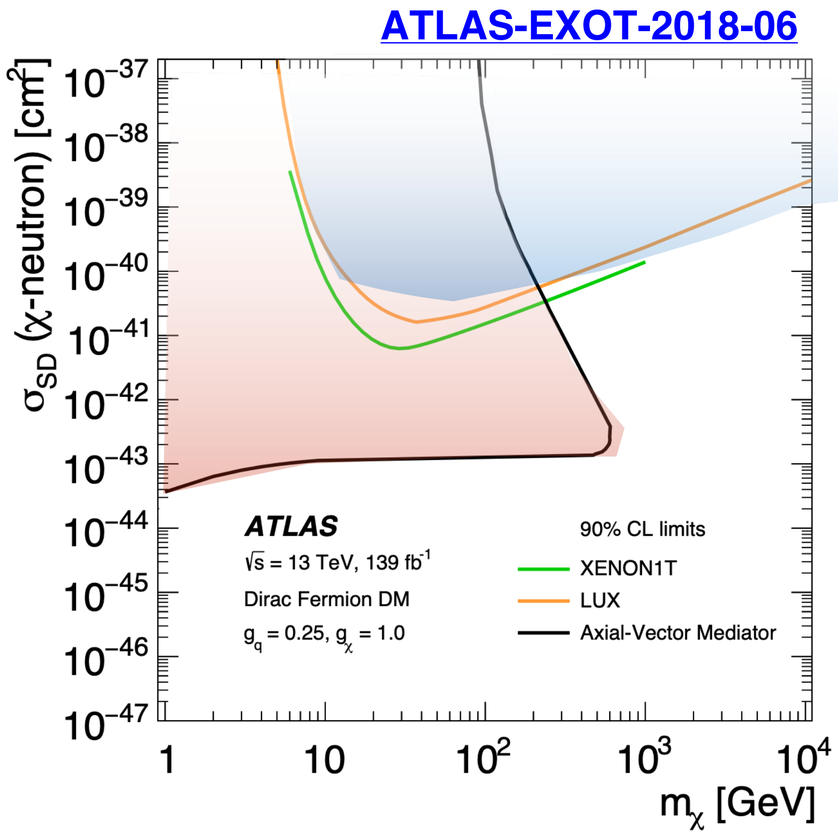


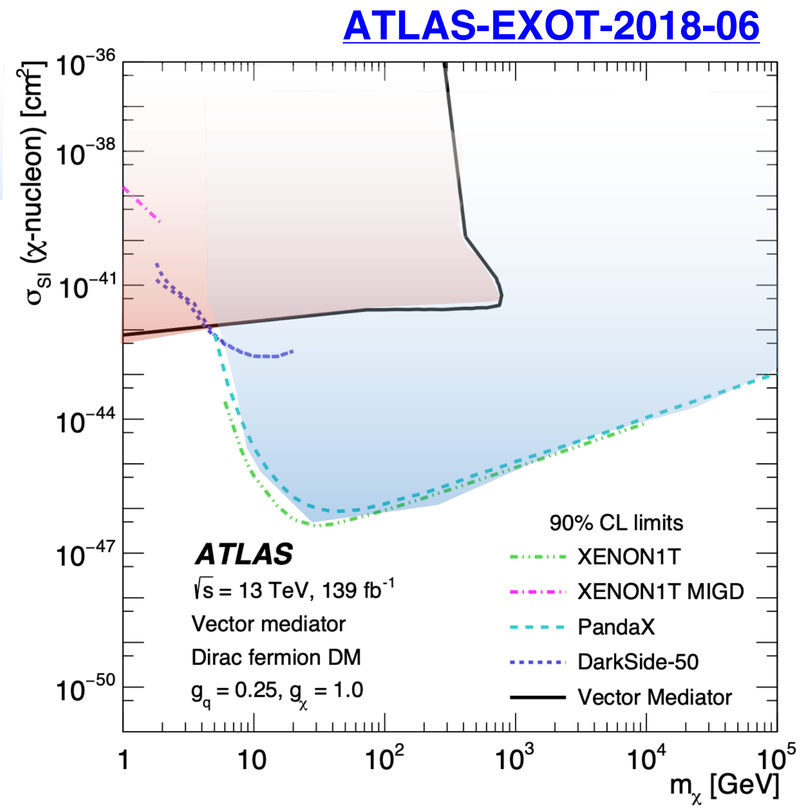




Goal is to probe **higher masses** and **lower couplings**

# Comparing against the rest of the word…




<u>For light DM</u>, **Collider** has higher sensitivity **(red)**, compared **other experiments** (**blue**)

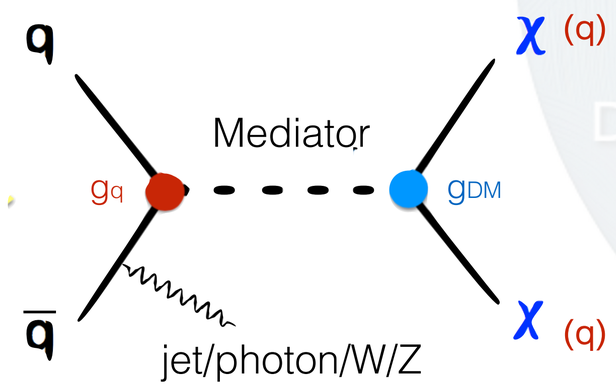
At colliders, sensitivity is limited by threshold effects, resolution and background estimation.

# Collider approach to Dark Matter: Mediator Searches

Strong experimental evidence for DM from astrophysical observations. Most studied class of theories predict DM to be a weakly interacting massive particle.

**Simplified Models**

Main parameters of the model: mediator, two vertices, and a DM candidate




Extended to models with t-channel mediator and dark sectors

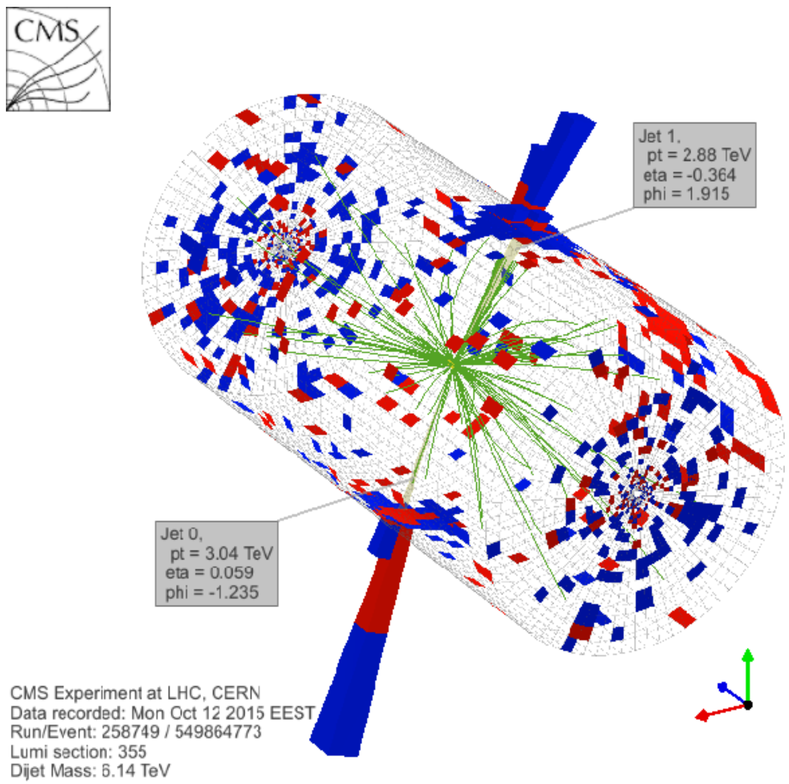
- We can look for a relatively narrow resonance on top of smoothly falling background
- Do not have to rely on simulation for background, instead use the locality of the signal (excess) and estimate the background from signal sidebands or through a fit
- **Method**: Pick a window to look based on your signal width, then slide the window along the distribution and look for the signal!

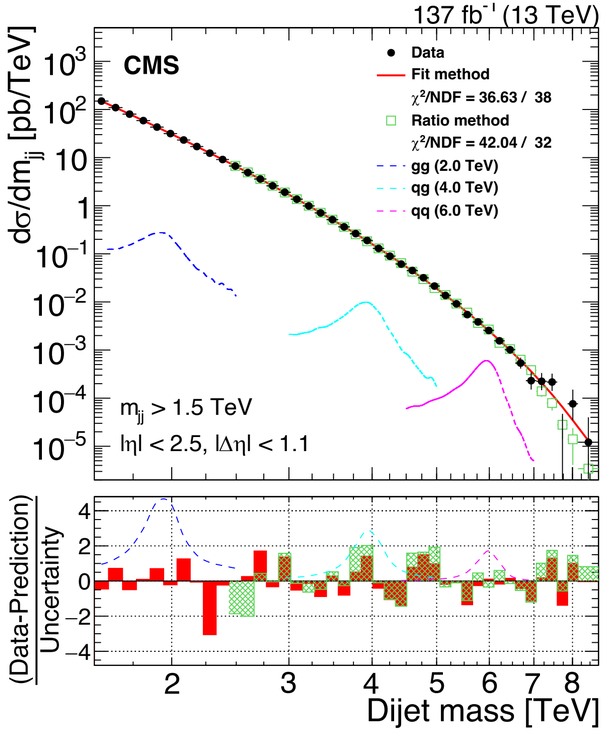
This type of searches is known as **"bump hunt"**

# Collider approach to Dark Matter: Mediator Searches with dijets

Mediator searches are MET-less! Looking at the dijet mass spectra!

Have large QCD multi-jet background




Two important questions:

- Can the background function create a signal-like structure in the lack of signal in data?
- Can the background function "fit away" the signal present in data?

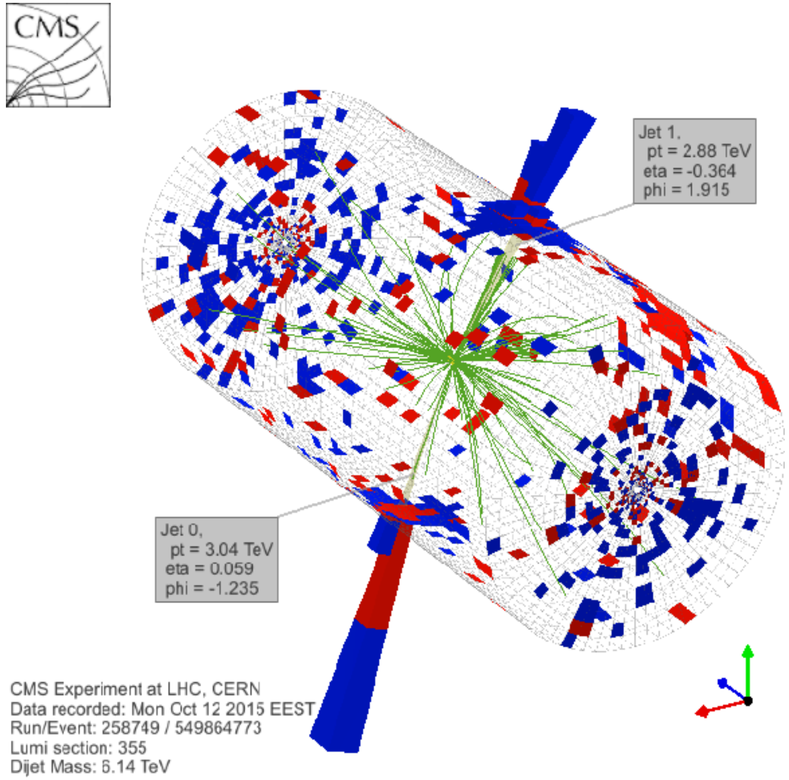
Come to the rescue… Bias studies

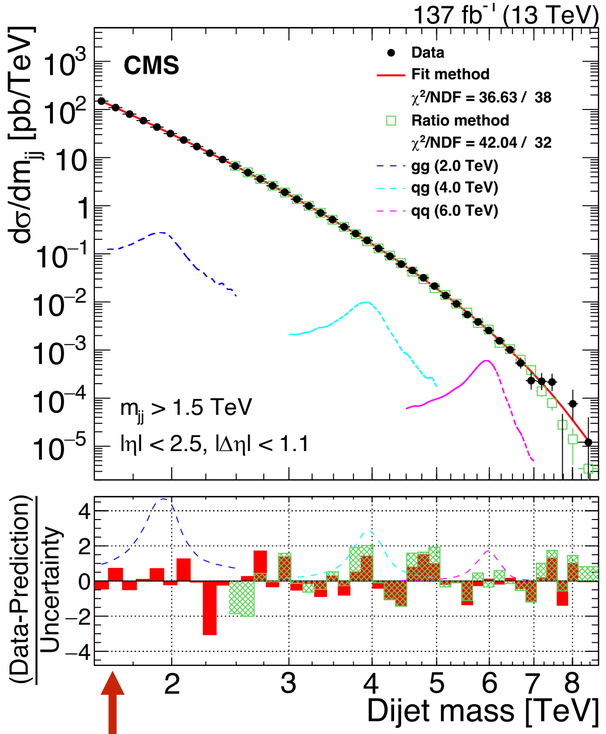
Simply put: Generate pseudo-data sets using one function, and fit it with other functions

# Collider approach to Dark Matter: Mediator Searches with dijets

Mediator searches are MET-less! Looking at the dijet mass spectra!

Have large QCD multi-jet background, therefore **VERY hard** to keep low thresholds for the **triggers**!




**1.5 TeV (Traditional data taking)**

**Data Scouting:** Limited event content is kept …

… enables us to record data with lower trigger thresholds!

<Event Rate> x <Event Size> = Bandwidth

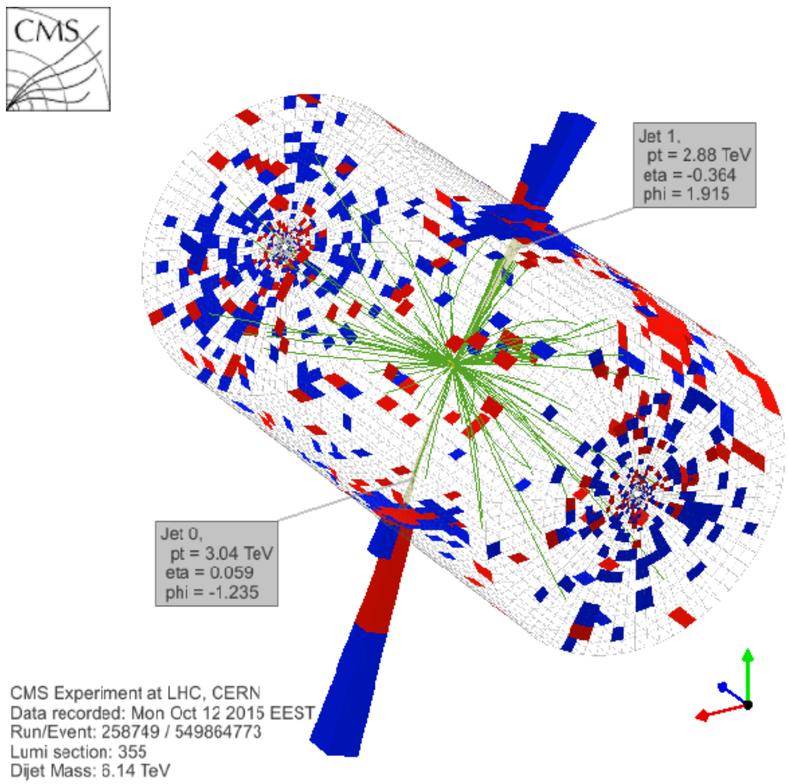
"Standard" Analysis: 1000 Hz x 1 MB = 1000 MB/s

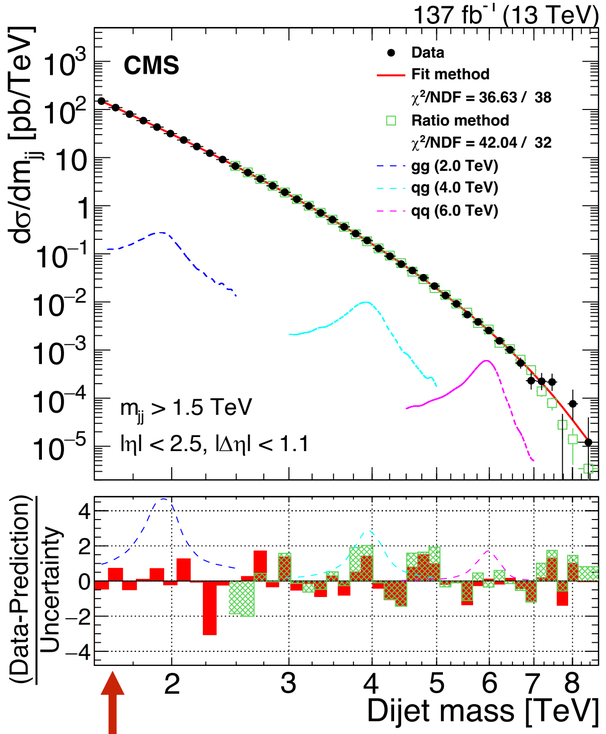
"Scouting" Analysis: 100 kHz x 10 KB = 1000 MB/s

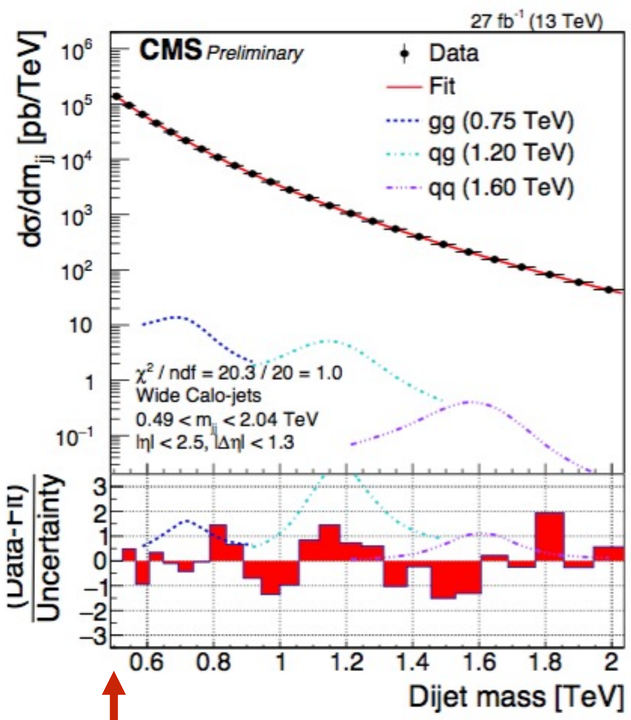
# Collider approach to Dark Matter: Mediator Searches with dijets

Mediator searches are MET-less! Looking at the dijet mass spectra!

Have large QCD multi-jet background, therefore **VERY hard** to keep low thresholds for the **triggers**!




**1.5 TeV (Traditional data taking)**

**450 GeV (Data Scouting)**

**Data Scouting:** Limited event content is kept …

… enables us to record data with lower trigger thresholds!

CERNCOURIER

CMS

# Dijet excess intrigues at CMS

The Standard Model (SM) has been extremely successful in describing the behaviour of elementary particles. Nevertheless, conundrums such as the nature of dark matter and the cosmological matter–antimatter asymmetry strongly suggest that the theory is incomplete. Hence, the SM is widely viewed as an effective low-energy limit of a more fundamental underlying theory that must be modified to describe particles and their interactions at higher energies.

A powerful way to discover new particles expected from physics beyond the SM is to search for high-mass dijet or multi-jet resonances, as these are expected to have large production cross-sections at hadron colliders. These searches look for a pair of jets originating from a pair of quarks or gluons, coming from the decay of a new particle "X" and appearing as a narrow bump in the invariant dijet-mass distribution. Since the energy scale of new physics is most likely high, it is natural to expect these new particles to be massive.

CMS and ATLAS have performed a suite of single-dijet-resonance searches. The next step is to look for new identi-cal-mass particles "X" that are produced in pairs, with (resonant mode) or without (non-resonant mode) a new intermedi-ate, heavier particle "Y" being produced and decaying to pairs of X. Such processes would yield two dijet resonances and four jets in the final state: the dijet mass would correspond to particle X and the four-jet mass to particle Y. The CMS experiment was also motivated to search for Y → XX → four

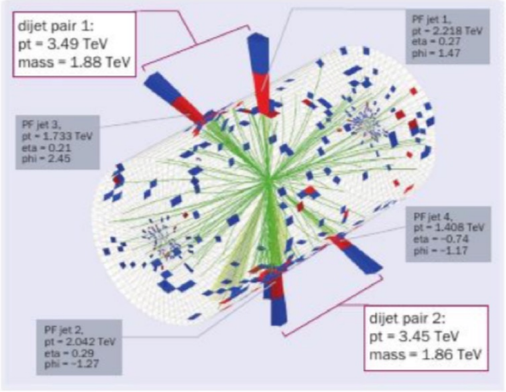



**Fig. 1.** *Display of the highest mass event with a four-jet mass of 8 TeV, in which each pair of jets has a dijet mass of 1.9 TeV.*

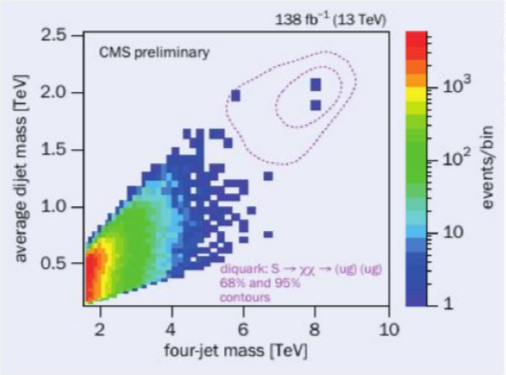



**Fig. 2.** *Number of events observed (colour scale) within bins of the four-jet mass and the average mass of the two dijets. Purple ellipses show the 1 and 2σ resolution contours, respectively, from a signal simulation of a four-jet resonance (Y), with a mass of 8.4 TeV, decaying to a pair of dijet resonances (XX), each with a mass of 2.1 TeV.*

jets by a candidate event recorded in 2017, which was presented by a previous CMS search for dijet resonances (figure 1). This spectacular event has four high-transverse-momentum jets forming two dijet pairs, each with an invariant mass of 1.9 TeV and a four-jet invariant mass of 8 TeV.

The CMS collaboration recently found another very similar event in a new search optimised for this specific Y → XX → four-jet topology. These events could origi-nate from quantum-chromodynamics processes, but those are expected to be extremely rare (figure 2). The two can-didate events are clearly visible at high masses and distinct from all the rest. Also shown in the figure (in purple) is a simulation of a possible new-physics signal – a diquark decaying to vector-like quarks – with a four-jet mass of 8.4 TeV and a dijet mass of 2.1 TeV, which very nicely describes these two candidates.

The hypothesis that these events originate from the SM at the observed X and Y masses is disfavoured with a local significance of 3.9σ. Taking into account the full range of possible X and Y mass values, the compatibility of the observation with the SM expectation leads to a global significance of 1.6σ.

The upcoming LHC Run 3 and future High-Luminosity LHC runs will be cru-cial in telling us whether these events are statistical fluctuations of the SM expectation, or the first signs of yet another groundbreaking discovery at the LHC.

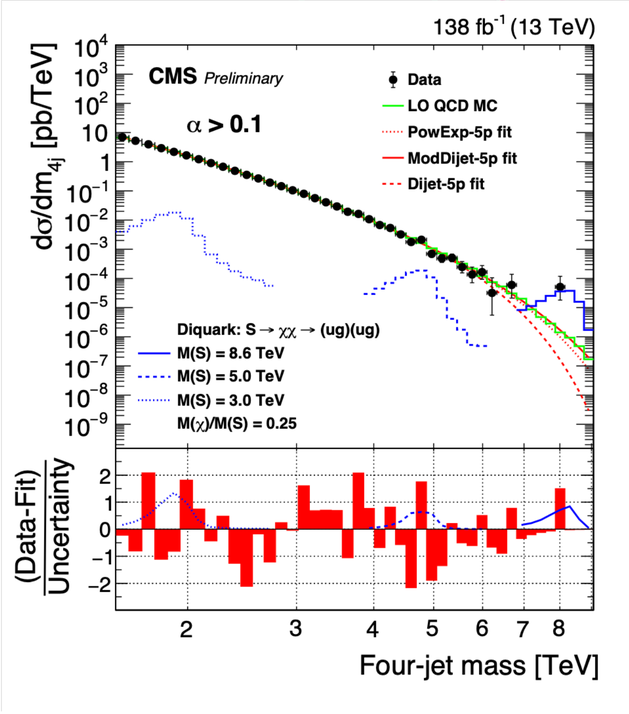
**Further reading**

CMS Collab. 2022 CMS-PAS-EXO-21-010.

## Search for resonant and non-resonant production of pairs of identical dijet resonances EXO-21-010

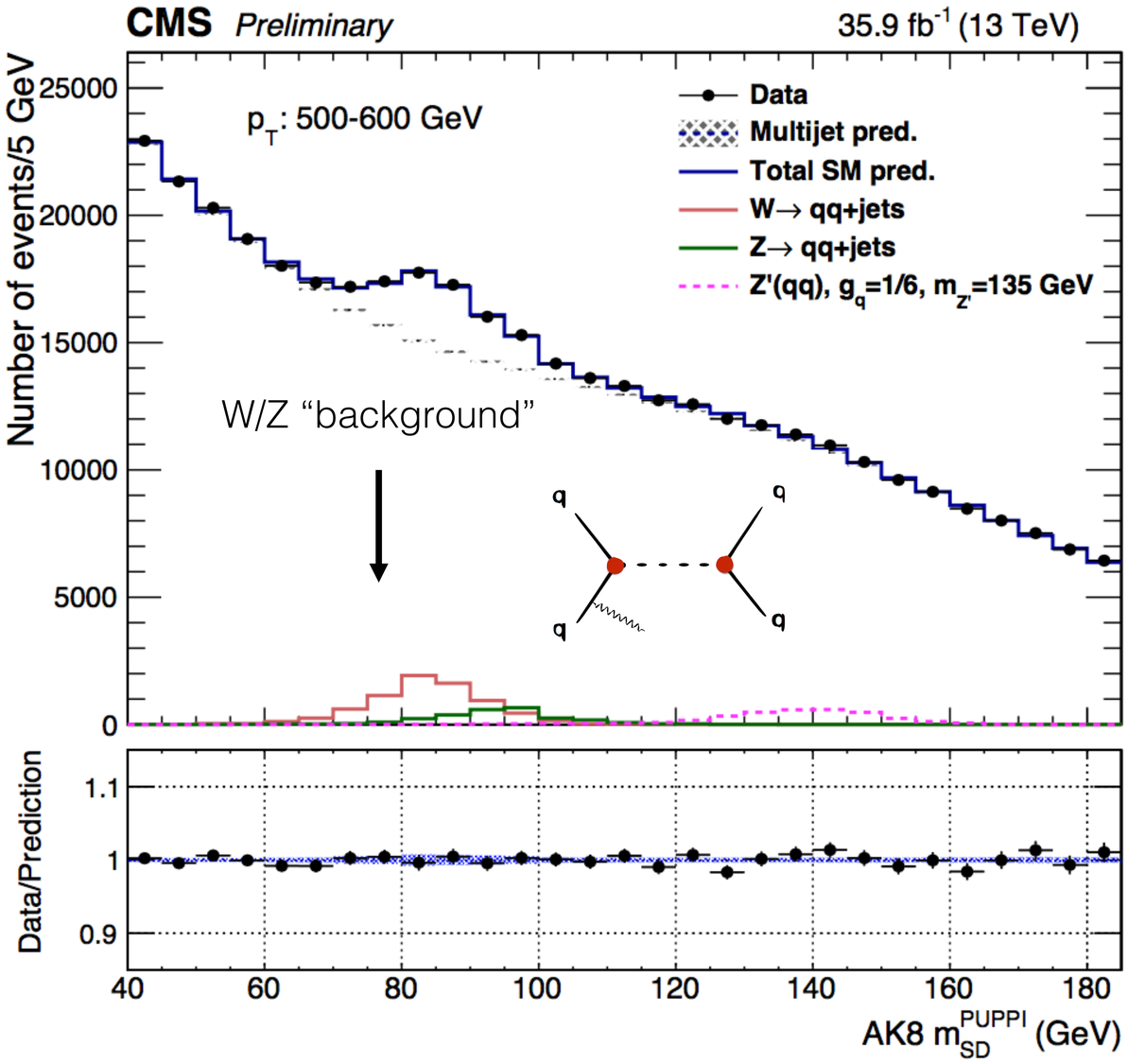
Data-driven search for pairs of dijet resonances in final states with at least four jets:

- Resonant: Two events on the tail of the distributions, with a four-jet mass of 8 TeV and an average dijet mass of 2 TeV. **Local (Global) significance: 3.9 σ (1.6 σ)**
- Non-resonant: Excess at average dijet mass of 0.95 TeV, **Local (Global) significance: 3.6 σ (2.5 σ)**




First ~ **30/fb (70/fb)** of Run 3 data could lead to **"evidence" for resonant (non-resonant)** signal at 8 TeV (1 TeV)

# Collider approach to Dark Matter: Mediator Searches with Trijets



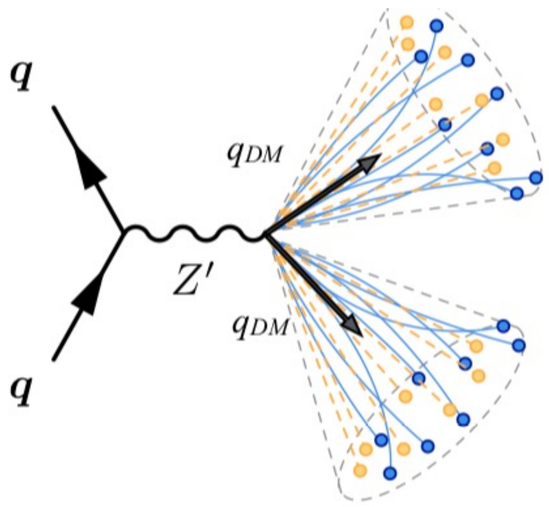

One way to "cope with QCD" is to go to high pTs, and use substructure:

- Soft drop groomed jets ECFs (discuss more in the next lecture) :
  - The ratio of 2-point correlation and a 3-point correlation function.
- **Danger:** Selection **sculpts the jet mass!** Searching for a resonant peak in the jet mass over a large range becomes challenging.
- **Solution**: Define a transformation to de-correlate the shape sculpting from pt and ensure a constant QCD background efficiency of 5% across all the pT range.

# Collider approach to Dark Matter: Semi-visible jets

CMS-EXO-19-020

First collider search for resonant production of dark matter from a strongly-coupled hidden sector!



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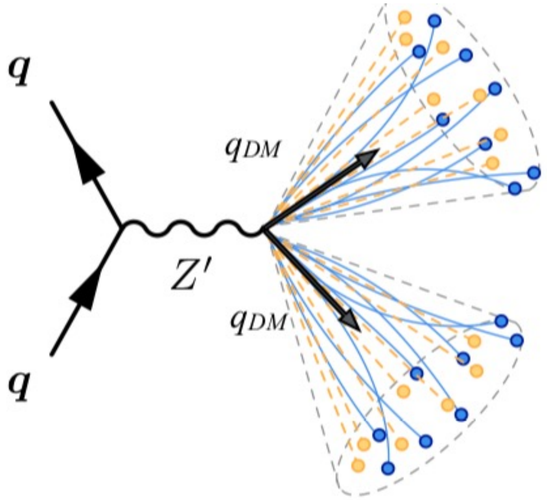
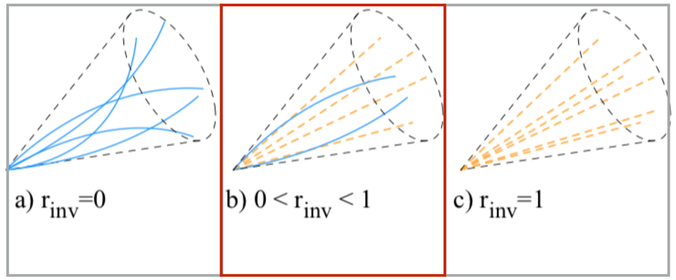



$$r_{inv} = \left\langle \frac{\textbf{N stable dark hadrons}}{\textbf{N dark hadrons}} \right\rangle$$




dijet-like monojet-like

Existing searches (including dijet and WIMP searches) not sensitive enough to signal models considered here

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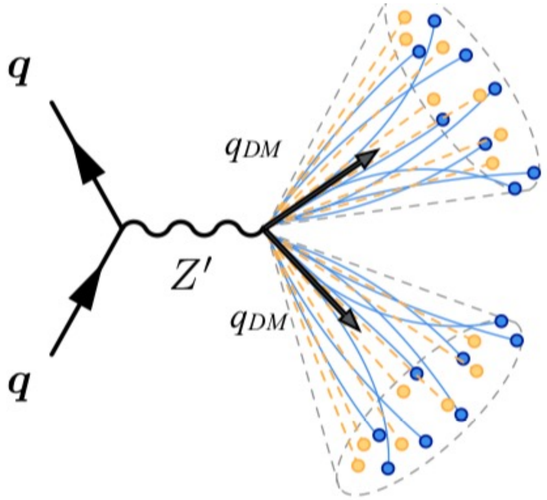


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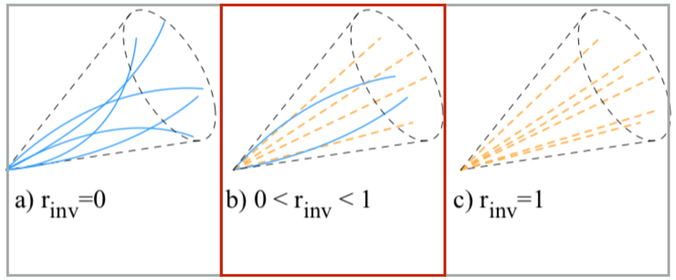
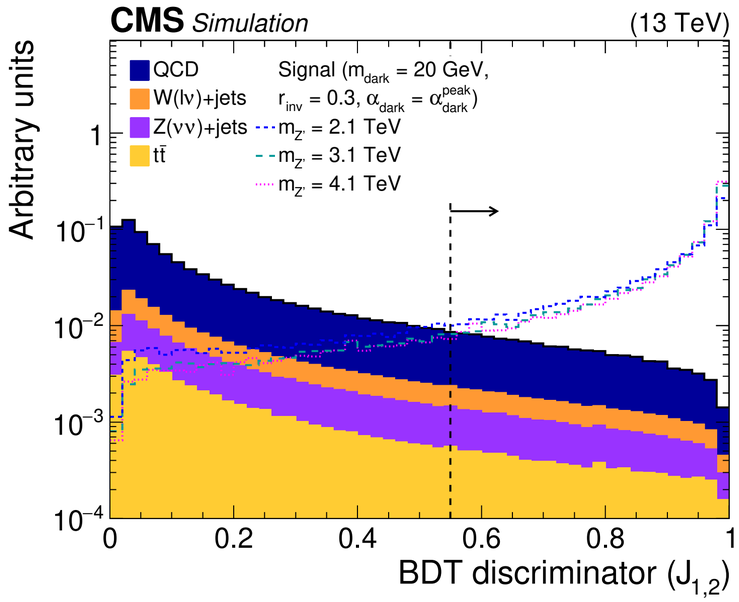



dijet-like monojet-like

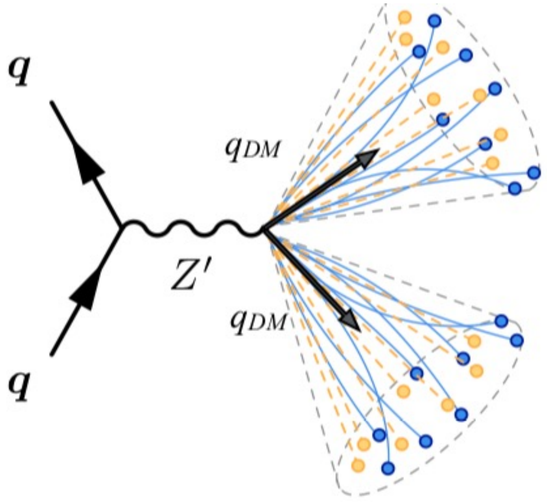



Existing searches (including dijet and WIMP searches) not sensitive enough to signal models considered here

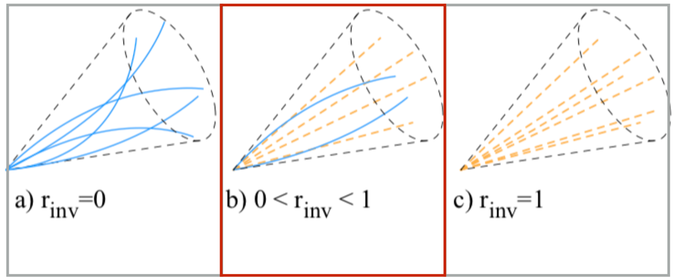
Analysis using dedicated semi visible jet tagger reduces background by ~O(100).

# Collider approach to Dark Matter: Semi-visible jets

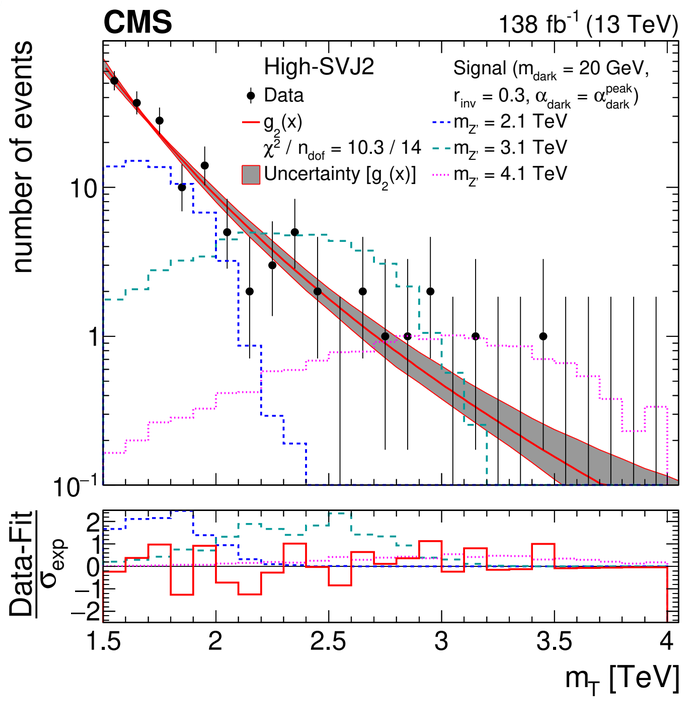
First collider search for resonant production of dark matter from a strongly-coupled hidden sector!

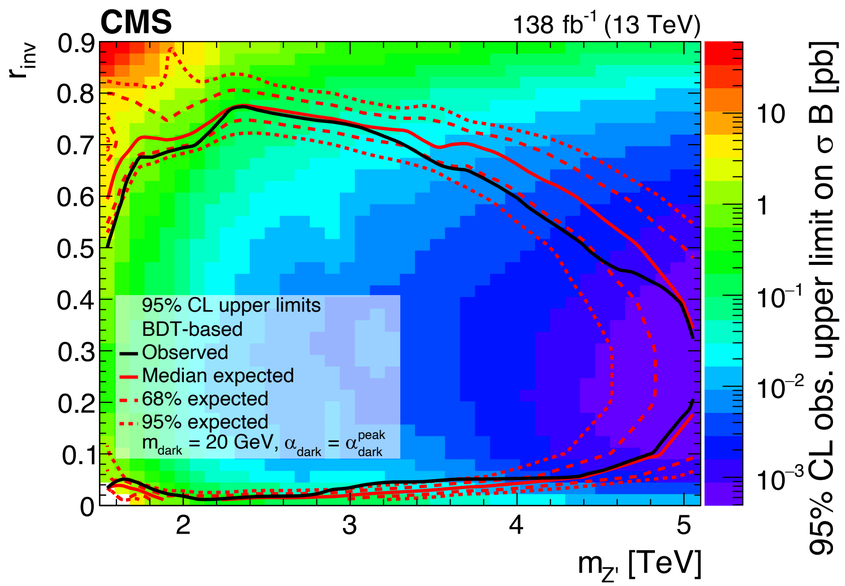



$$r_{inv} = \left\langle \frac{\textbf{N stable dark hadrons}}{\textbf{N dark hadrons}} \right\rangle$$




dijet-like monojet-like




Existing searches (including dijet and WIMP searches) not sensitive enough to signal models considered here

Analysis using dedicated semi visible jet tagger reduces background by ~O(100).

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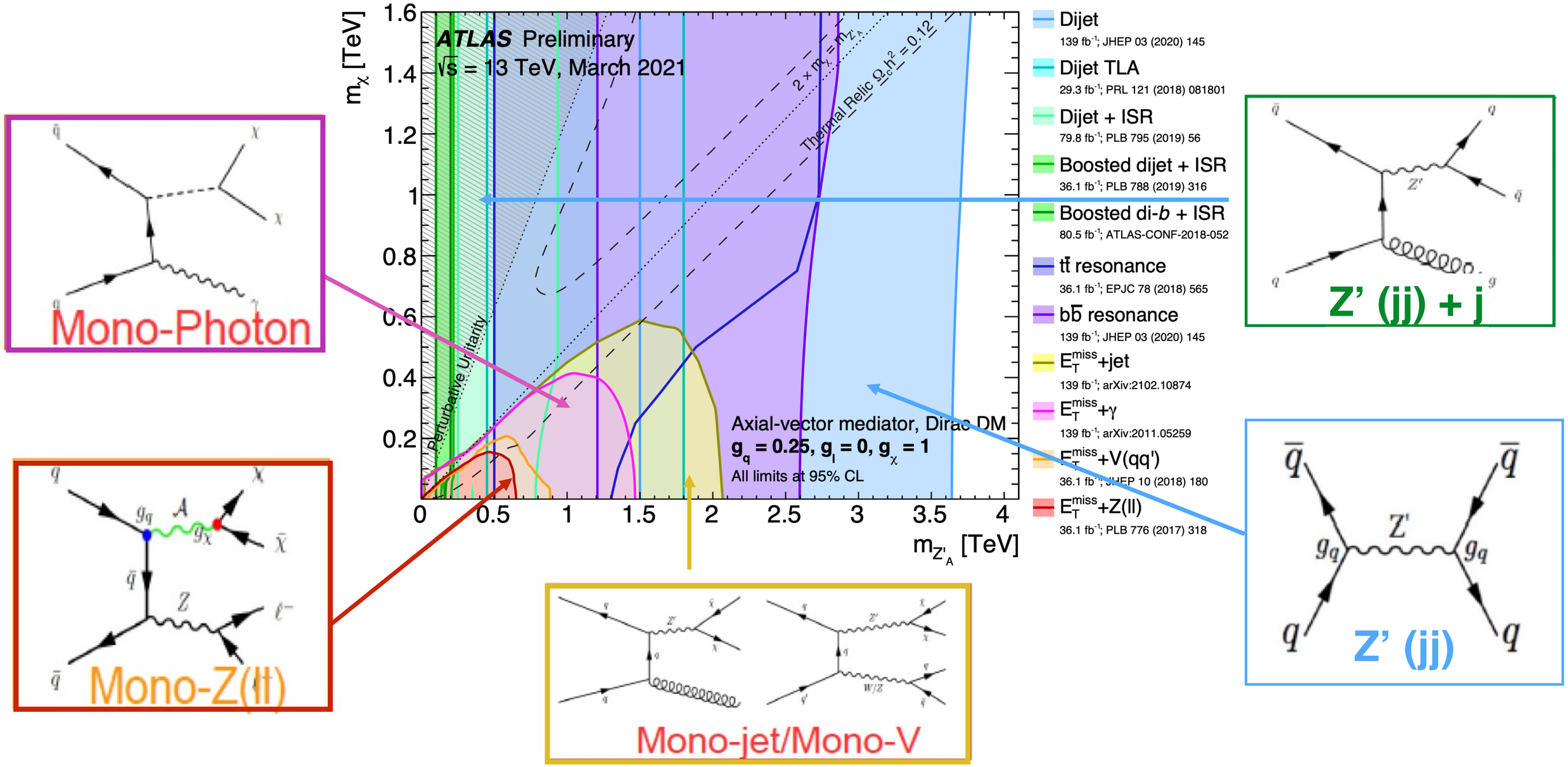
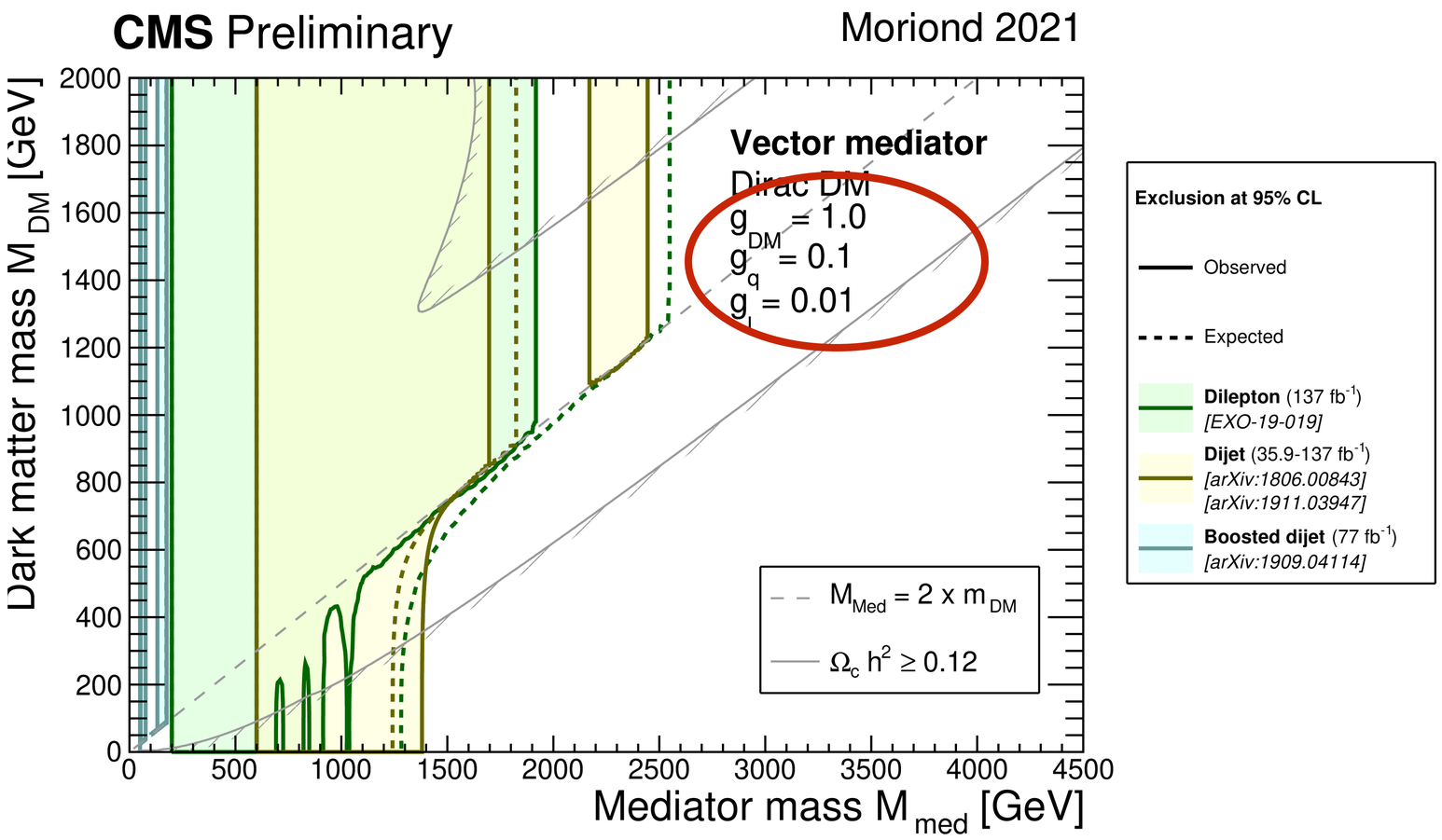
# WIMP: It all comes together: Mono-mania

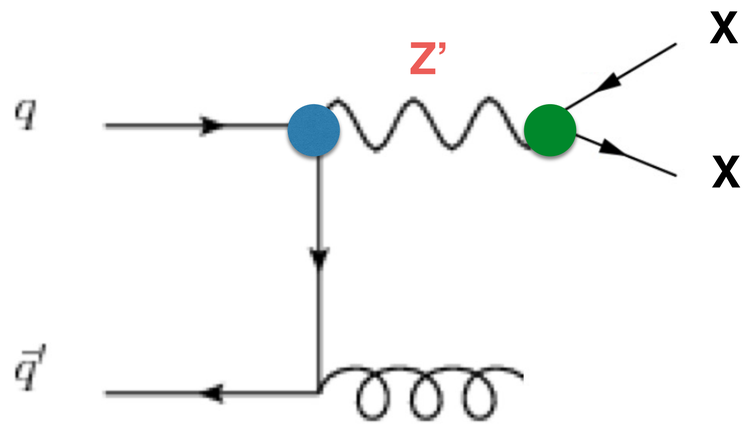


# Coupling strength matters!

With a simple change of coupling strength ($g_q$ = 0.25 —> 0.1), the sensitivity is back to square one!

*and we don't know what the coupling really is …*




coupling to quarks

coupling to dark matter

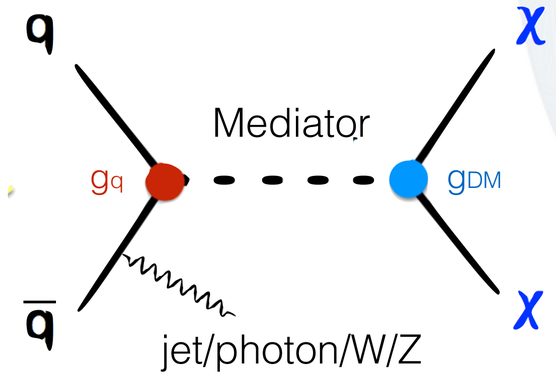
does the mediator also couple to leptons? …

# An other look at the Simplified Models

From EFTs to Simplified Models… multiple type of mediators are studied:

**Simplified Models**

Main parameters of the model: mediator, two vertices, and a DM candidate




Extended to models with t-channel mediator and dark sectors

| | | |
|---|---|---|
| spin-1 | vector | axial-vector |
| | $g_q \sum_q V_\mu \bar{q}\gamma^\mu q$ | $g_q \sum_q A_\mu \bar{q}\gamma^\mu\gamma^5 q$ |
| spin-0 | scalar | pseudoscalar |
| | $g_q \frac{\phi}{\sqrt{2}} \sum_f y_f \bar{f} f$ | $g_q \frac{iA}{\sqrt{2}} \sum_f y_f \bar{f}\gamma^5 f$ |

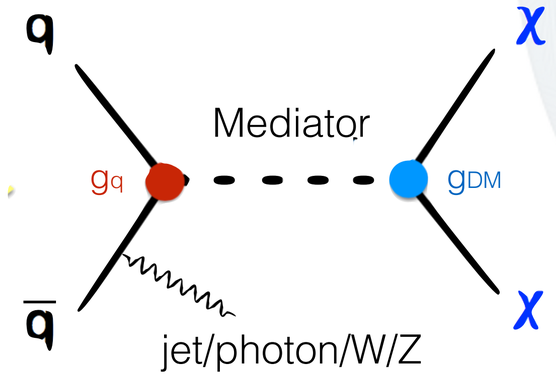
# Higgs Portals

From EFTs to Simplified Models… multiple type of mediators are studied

We have a special scalar particle!

## Simplified Models

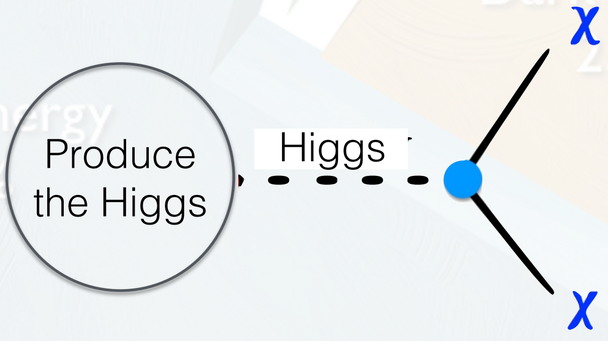
Main parameters of the model: mediator, two vertices, and a DM candidate




Extended to models with t-channel mediator and dark sectors

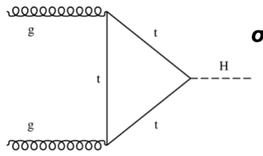
## Higgs Portal

Known Higgs decay branching fractions allow decays to invisible particles ~20%




All Higgs production modes can be studied to tag the event

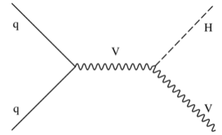
**Gluon Fusion**




$\sigma(gg \to H) = 48.52$ pb
±3.9% (th.)
±3.2% (pdf)

(N³LO QCD + NLO EW)

**Associated Production with vector boson**

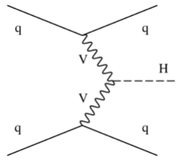



$\sigma(pp \to WH) = 1.369$ pb
±0.7% (th.) ±1.9% (pdf)

$\sigma(pp \to ZH) = 0.8824$ pb
±3.8% (th.) ±1.9% (pdf)

(NNLO QCD + NLO EW)

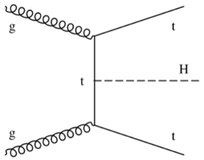
**Vector Boson fusion**




$\sigma(VBF) = 3.779$ pb
±0.4% (th.)
±2.1% (pdf)

(NNLO QCD + NLO EW)

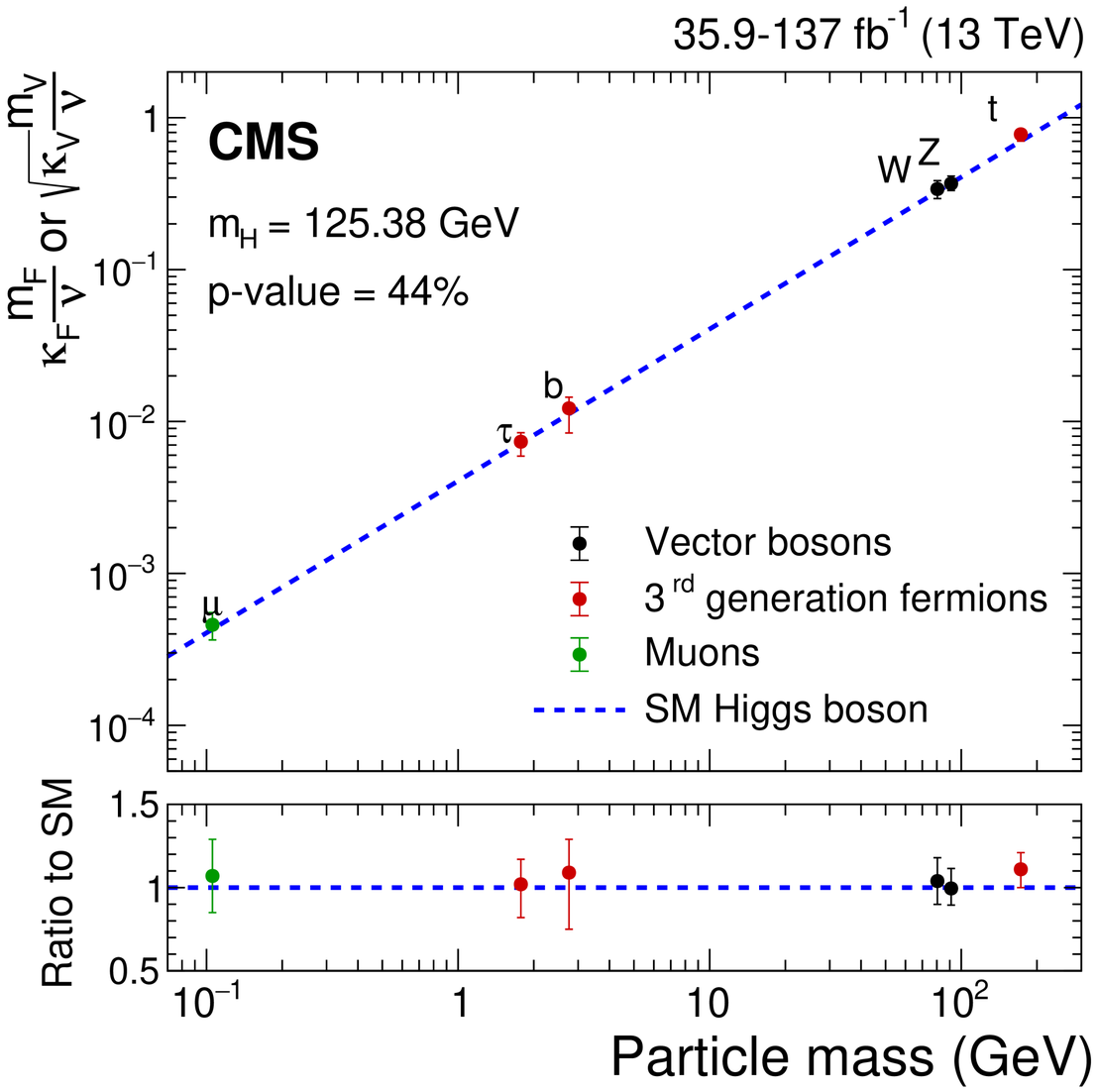
**Associated Production with top quarks**

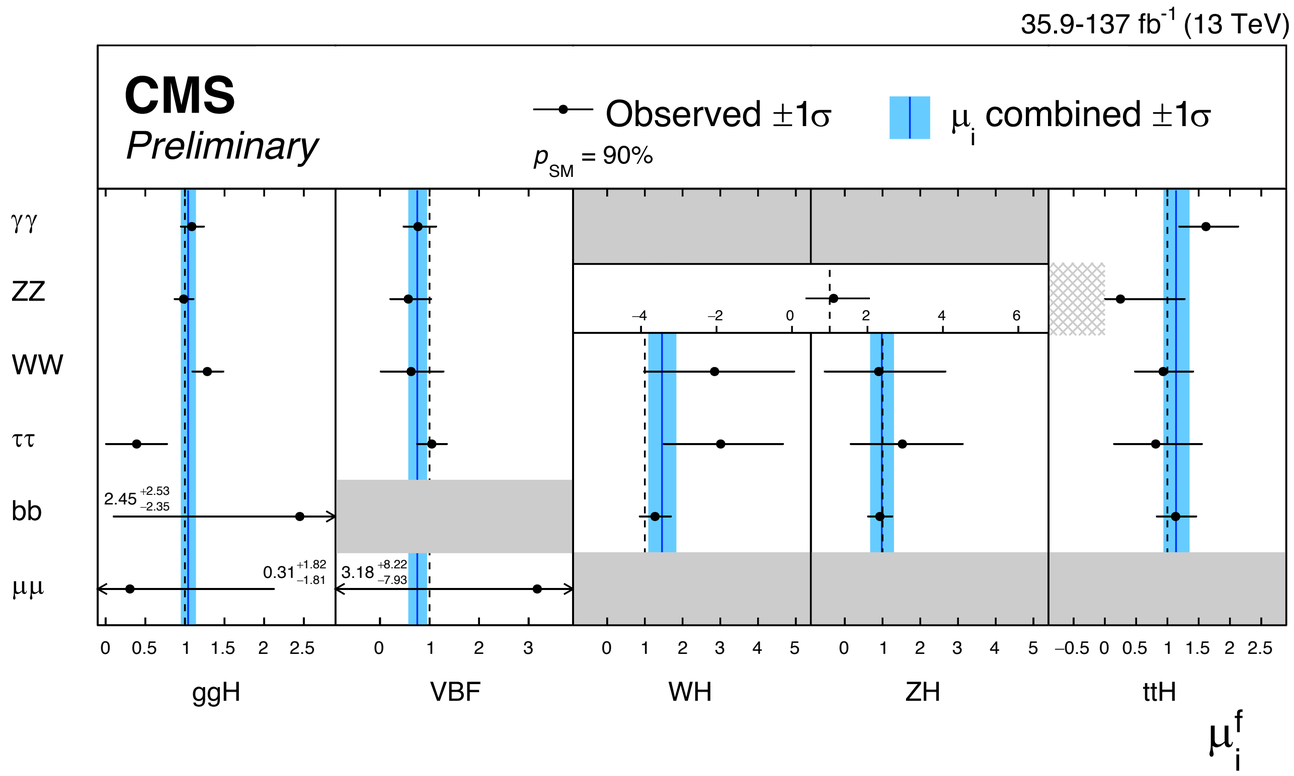



$\sigma(ttH) = 0.5065$ pb
$\pm\,^{5.8}_{9.2}$% (th.)
±3.6% (pdf)

(NLO QCD + NLO EW)

# How much can we constrain the exotic Higgs width?

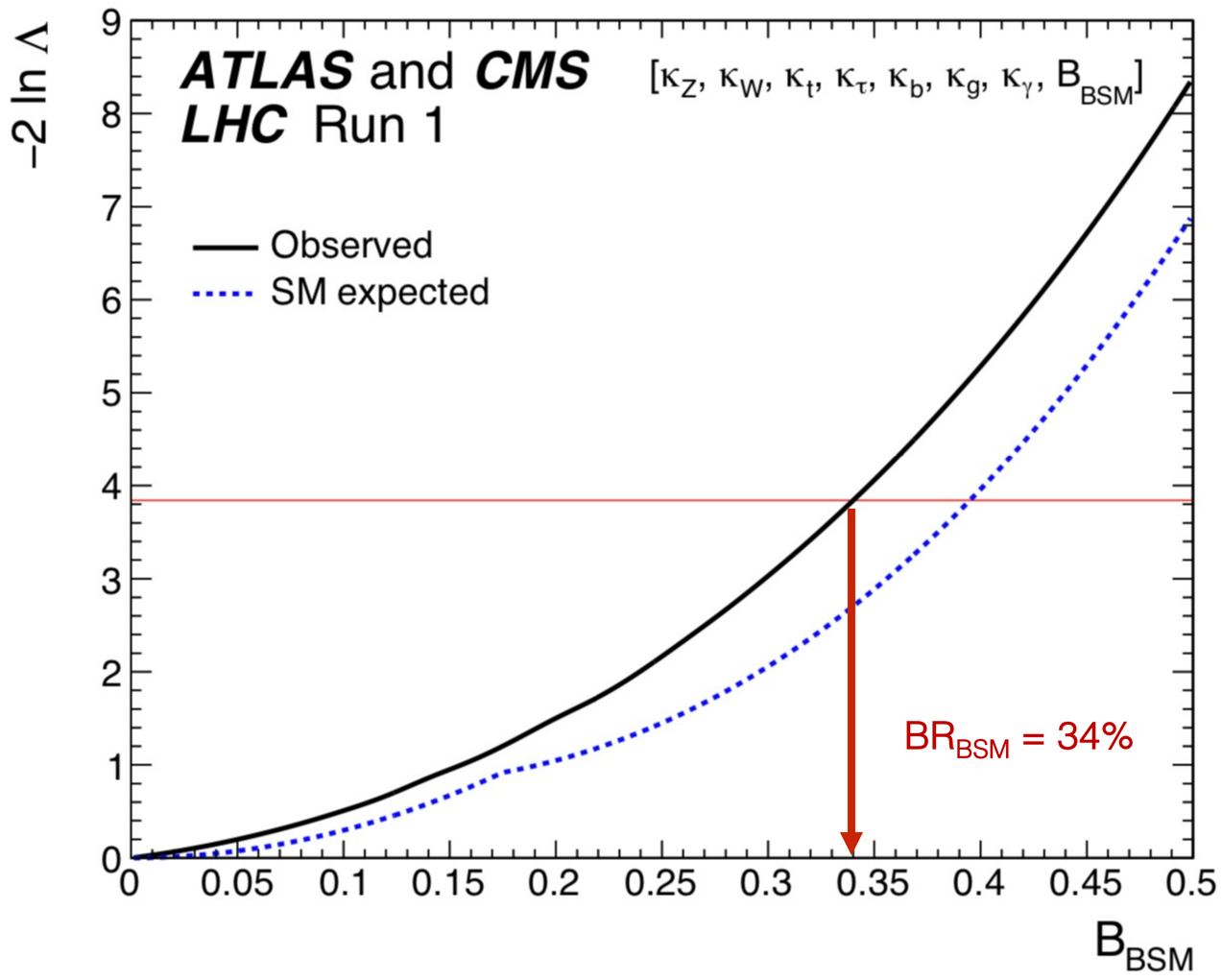



We can constrain the Exotic Higgs BR from the Higgs couplings measurements by combining the information from all measured Higgs decay channels…

HIG-19-005

# What does the combined coupling fit say?




Changes in the values of the couplings will result in a variation of the Higgs boson width

$$\Gamma_H = \frac{\kappa_H^2 \cdot \Gamma_H^{SM}}{1 - B_{BSM}}$$

BSM decays can be of three types:

- **invisible to the detector**
- Topologies (SM or BSM) that are not searched for (undetected)

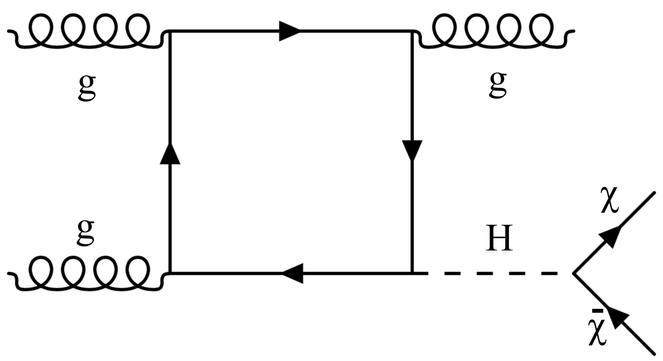
https://arxiv.org/pdf/1606.02266.pdf

End of lecture one

# Higgs Production Modes

Higgs Production modes will determine the signature.

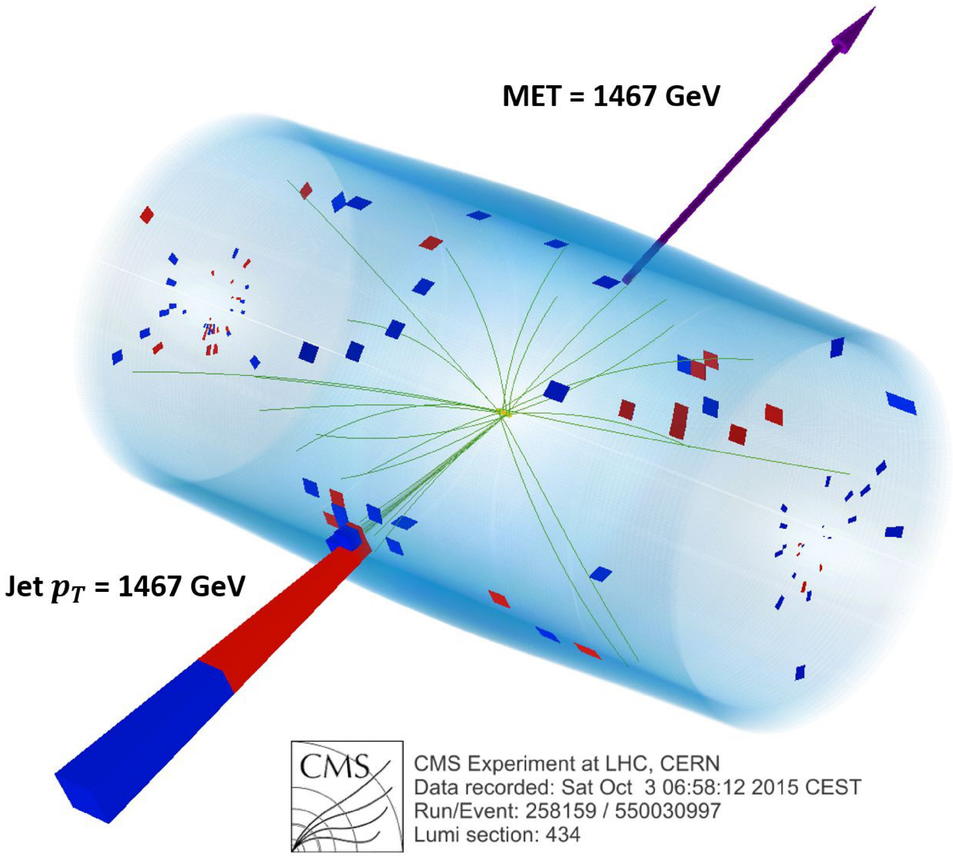
We discussed gluon fusion production mode => That's just monojet!




**Gluon fusion**

JHEP11(2021)153

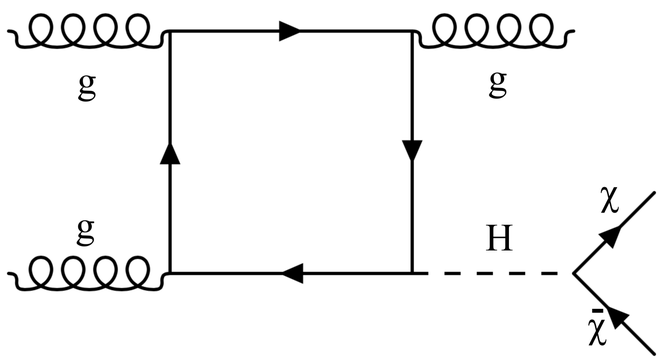
- Largest production production cross section
- Needs to be tagged with a visible object



# Higgs Production Modes

Higgs Production modes will determine the signature.

Now lets look at VH production => Let us call it “mono-V”

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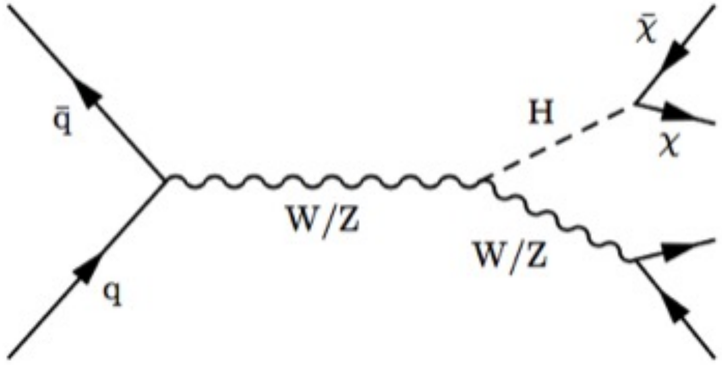


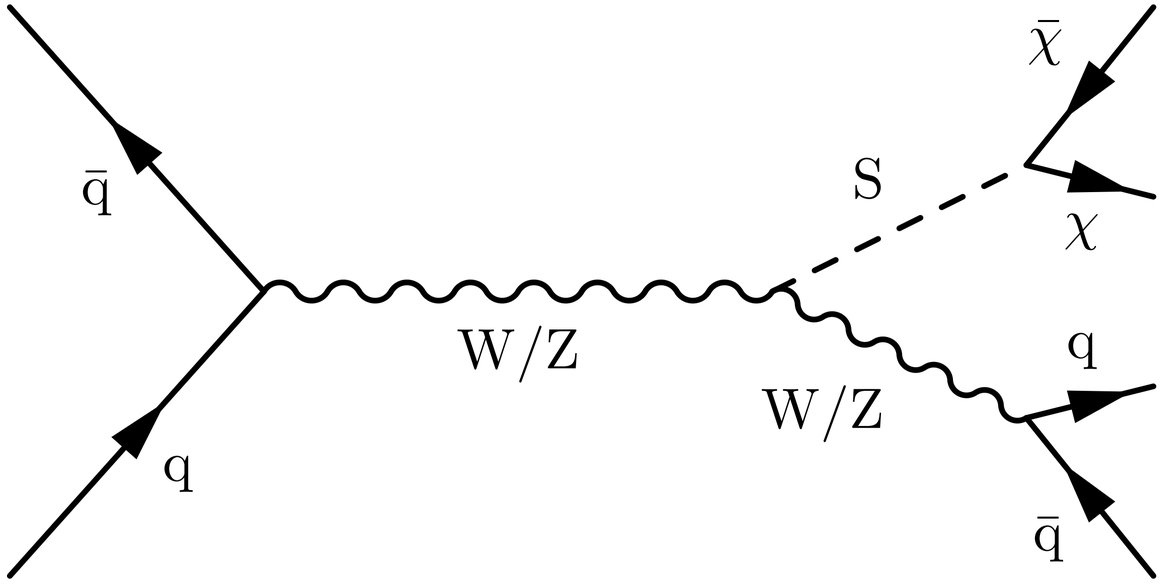

**Associated vector boson**

JHEP11(2021)153

- Less cross section: σ(monojet) ~ 30xσ (monoW)
- Boosted topologies & use of substructure - fatter jets

# Mono-V Experimental Techniques

… even with state of the art background estimation strategies, we are often overwhelmed by SM rescue: **boosted topologies** & **substructure.**




**σ(ggf) ~ 30 x σ (VH)**

… but similar sensitivity in both searches!

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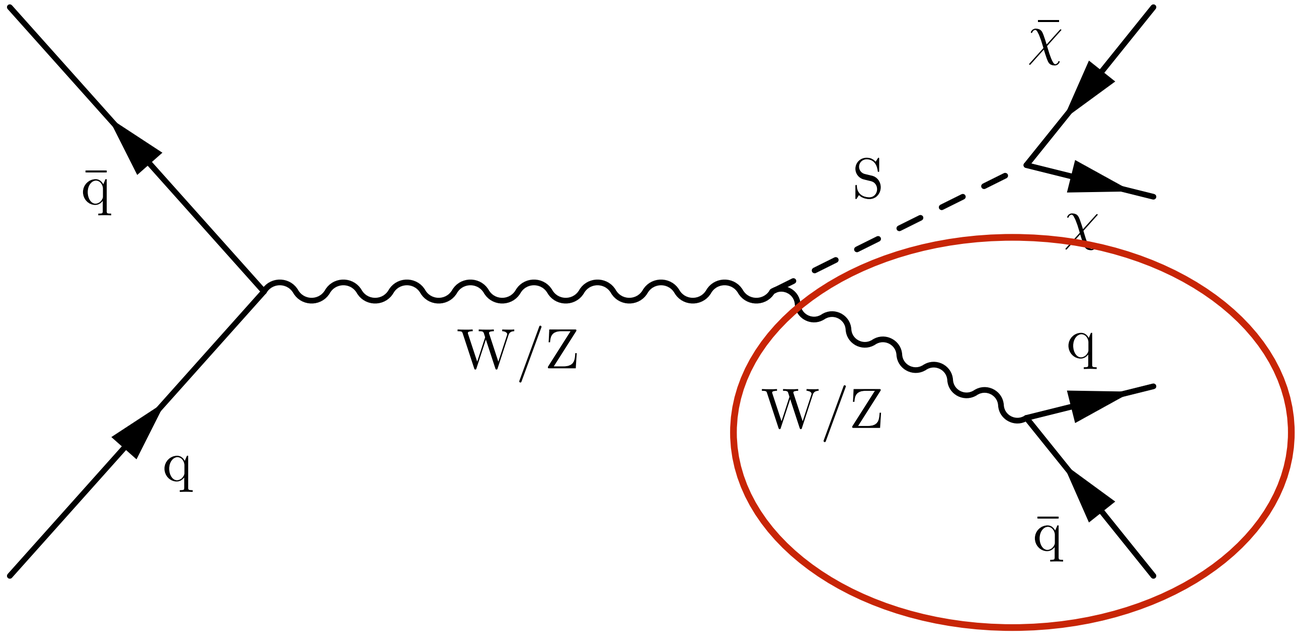
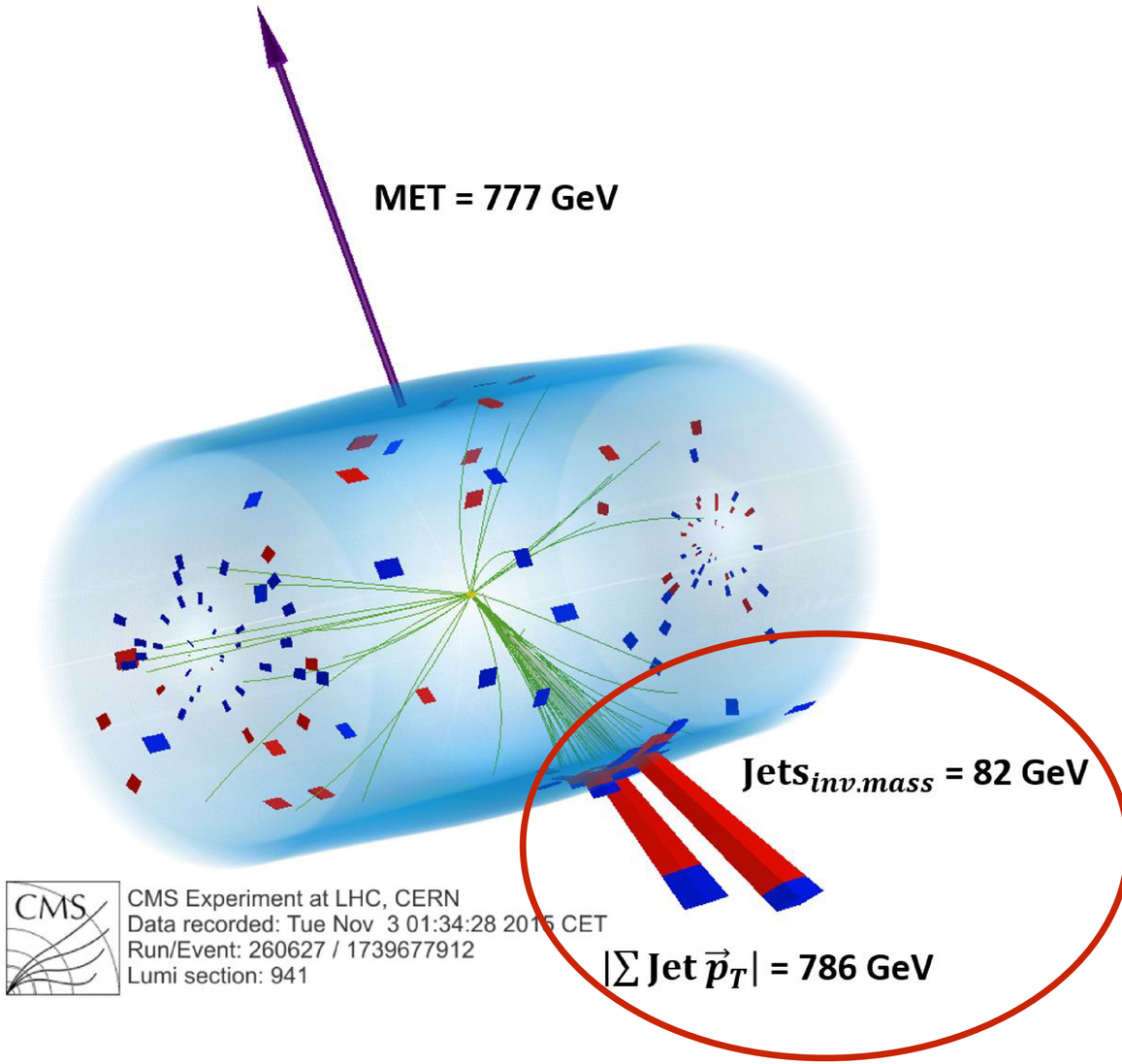



**σ(ggf) ~ 30 x σ (VH)**

… but better sensitivity with Mono-V!



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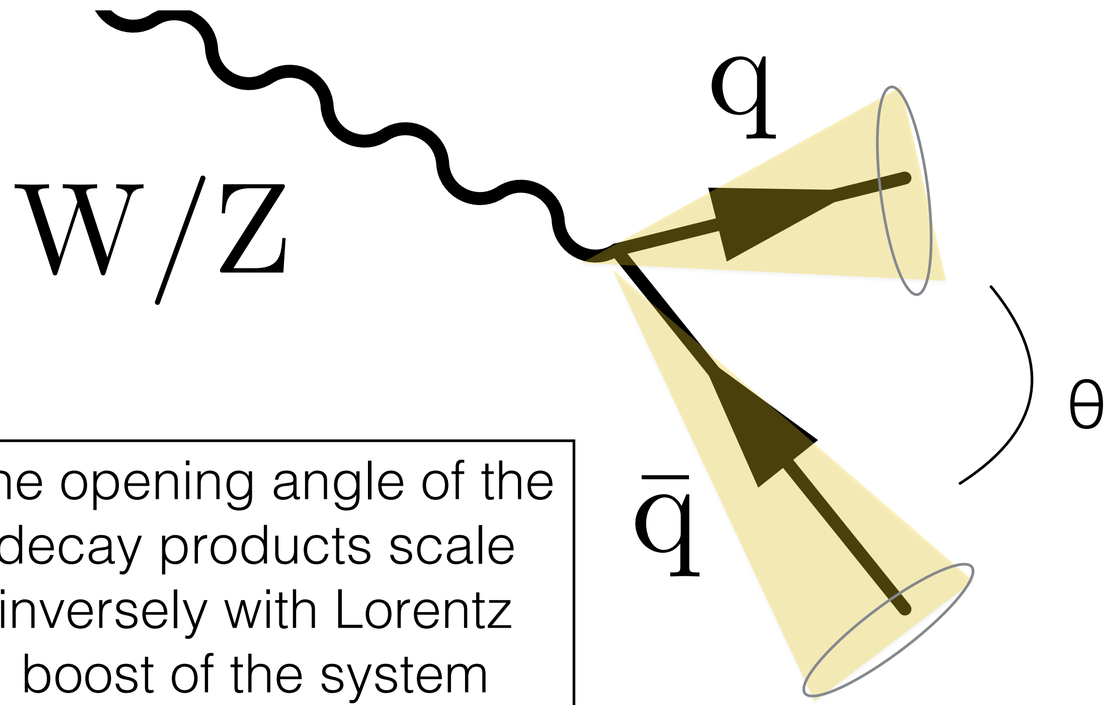
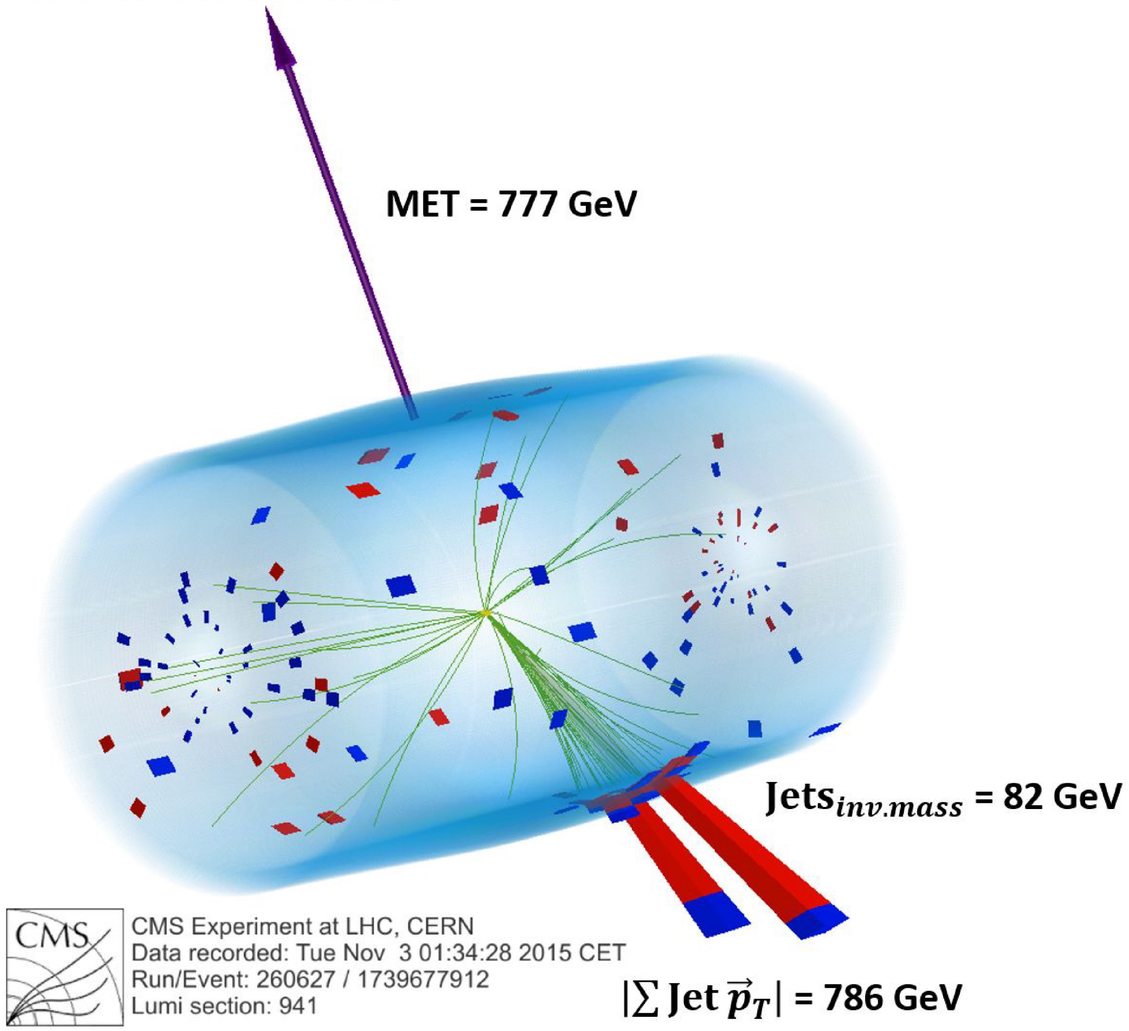



The opening angle of the decay products scale inversely with Lorentz boost of the system



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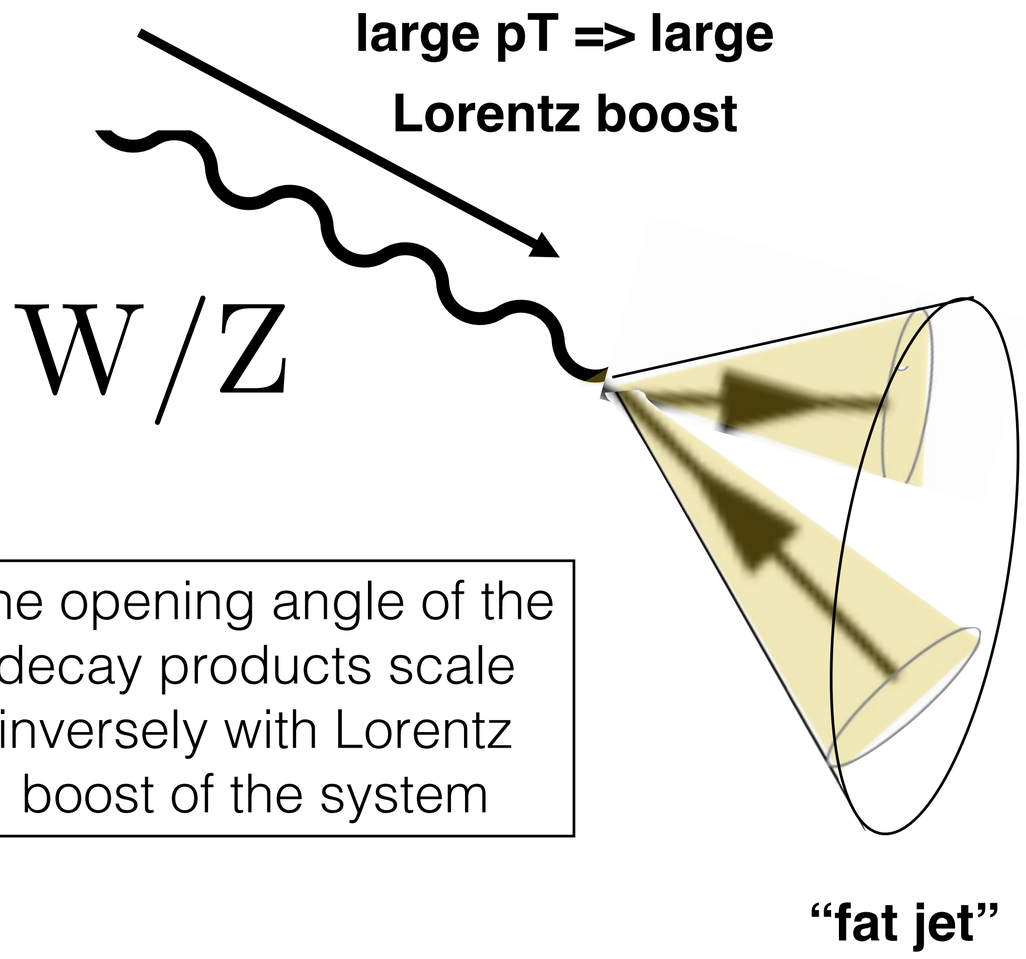


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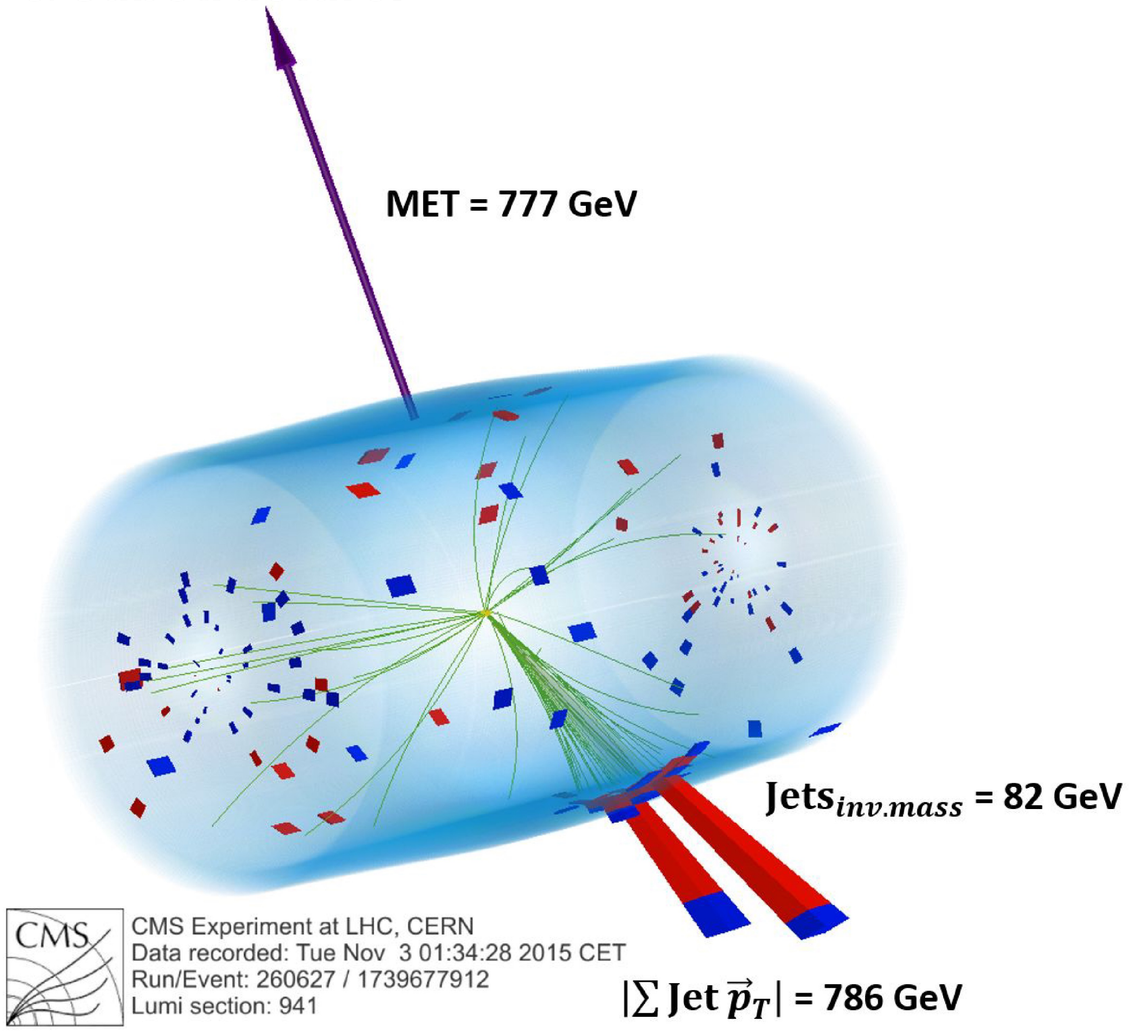

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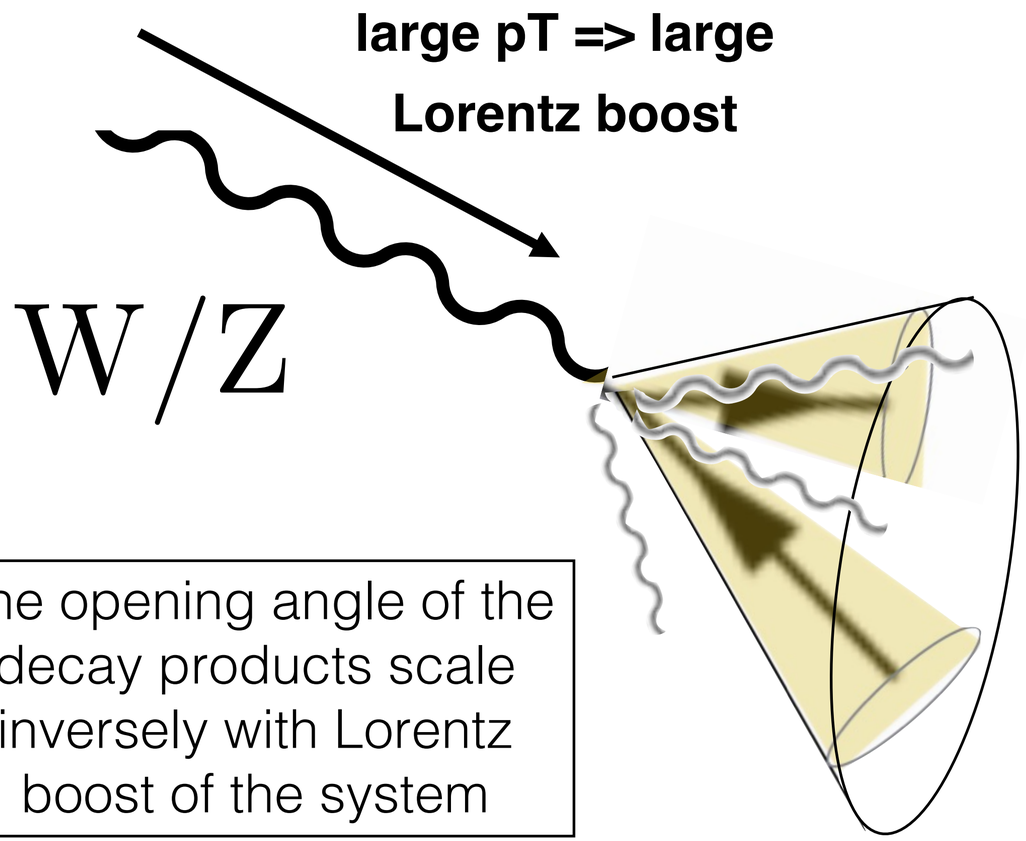
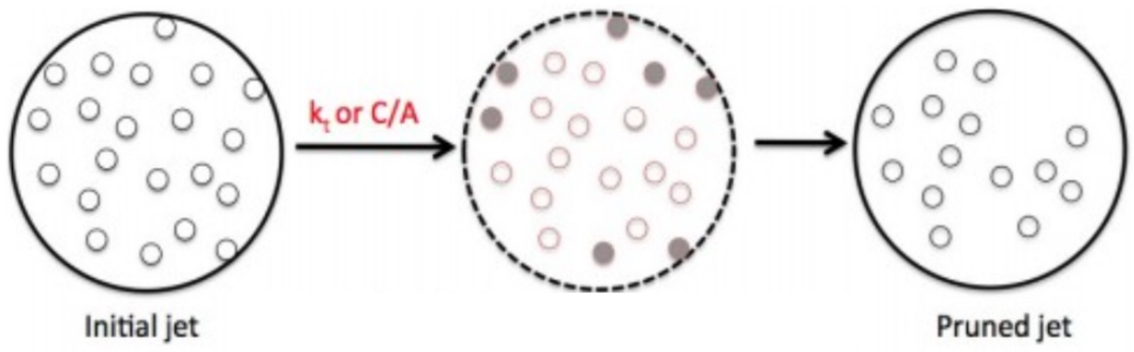
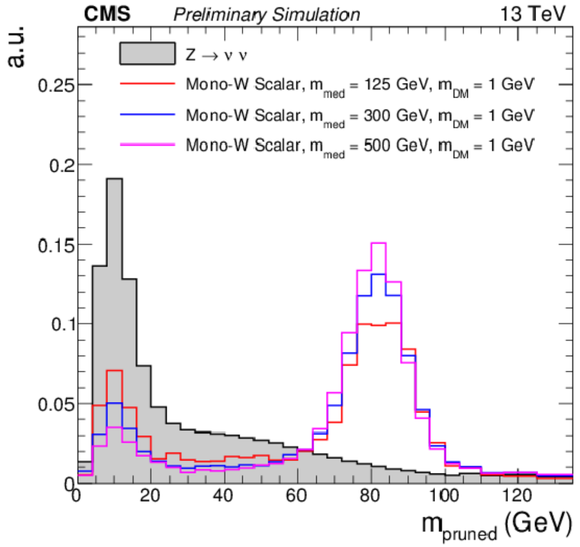



The opening angle of the decay products scale inversely with Lorentz boost of the system

**"fat jet"**




**Pruning**



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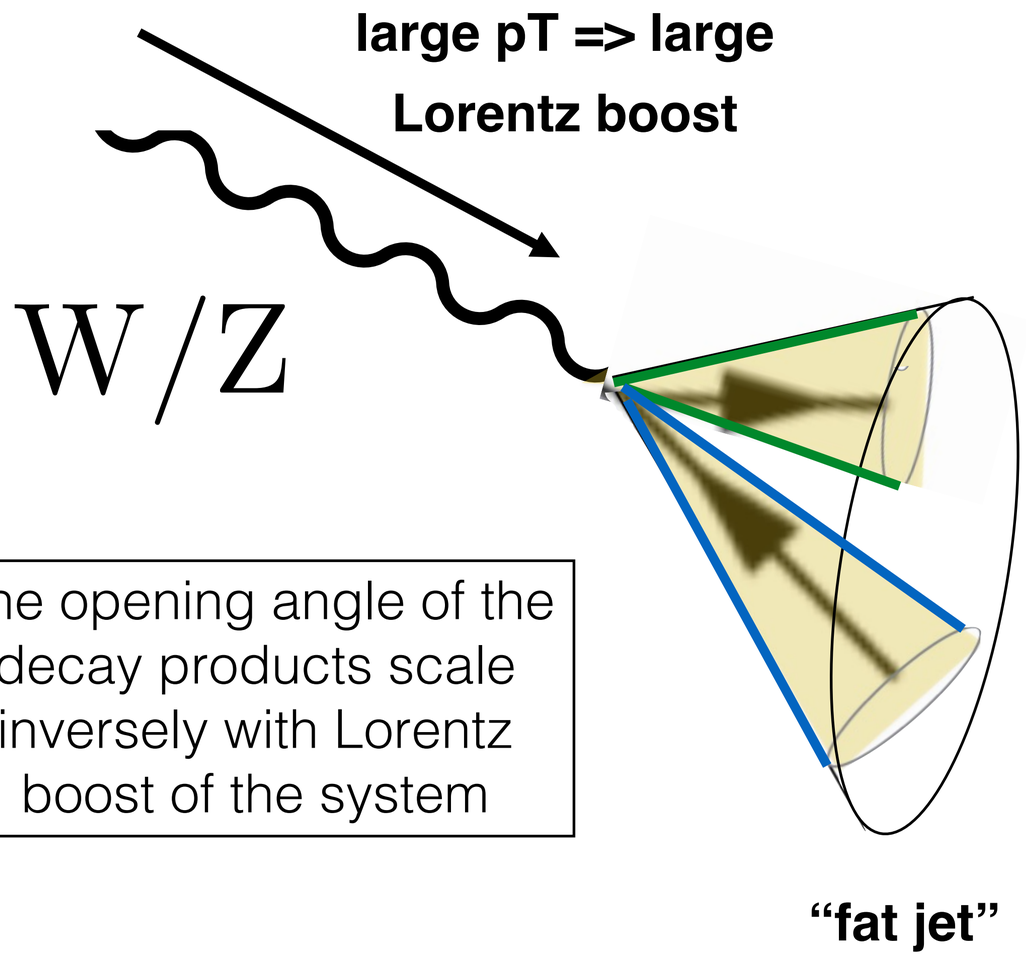


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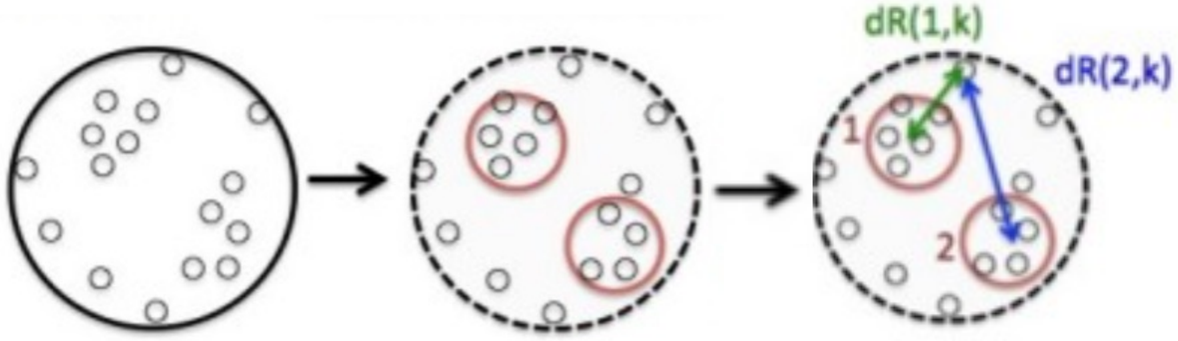


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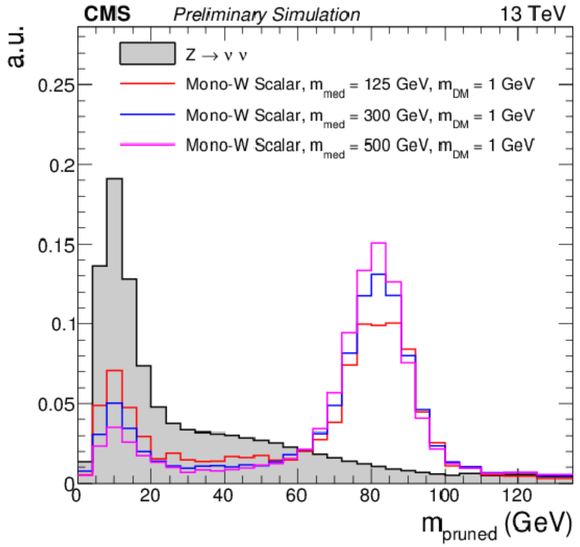
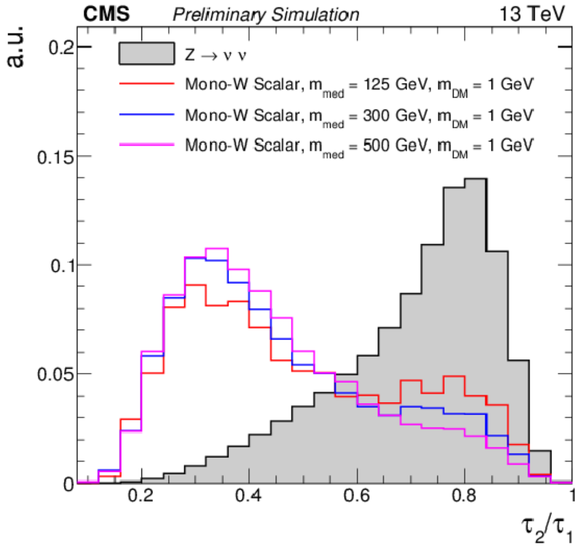


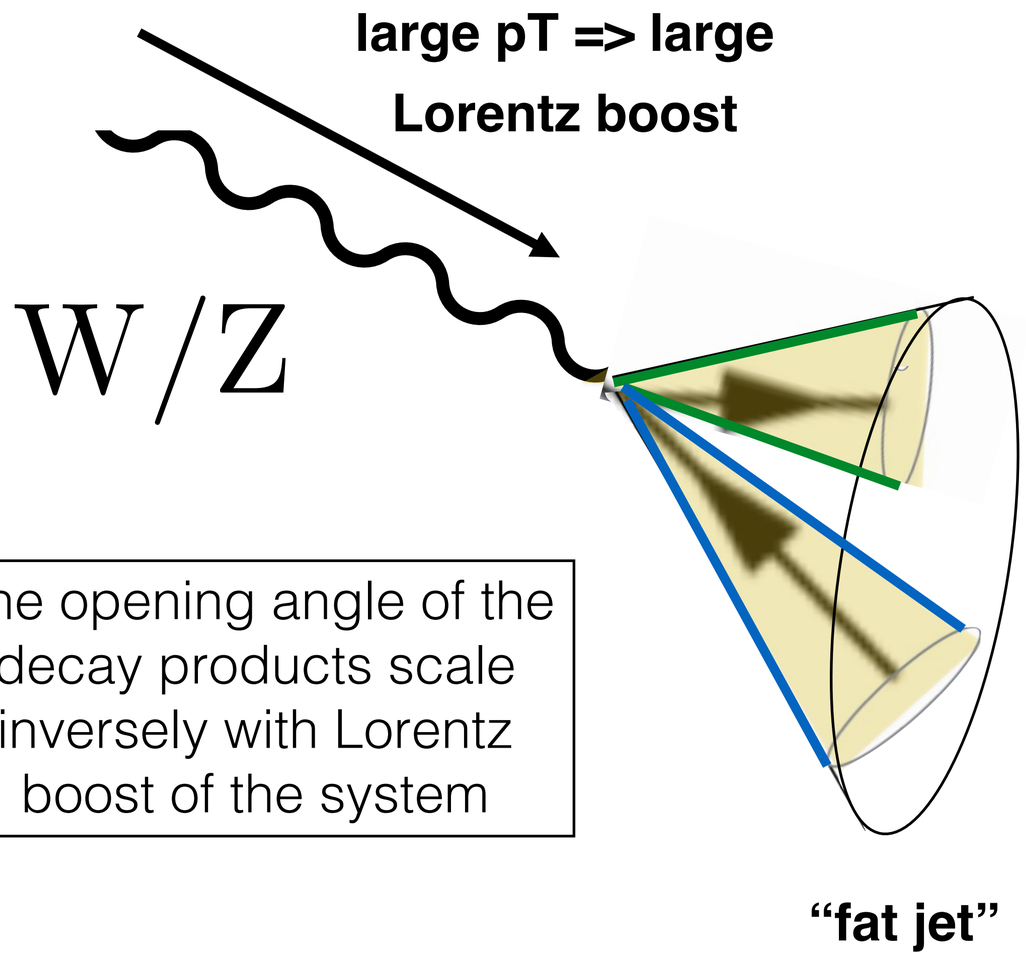

**N-subjetiness**



# Mono-V Experimental Techniques

… even with state of the art background estimation strategies, we are often overwhelmed by SM

rescue: **boosted topologies** & **substructure.**

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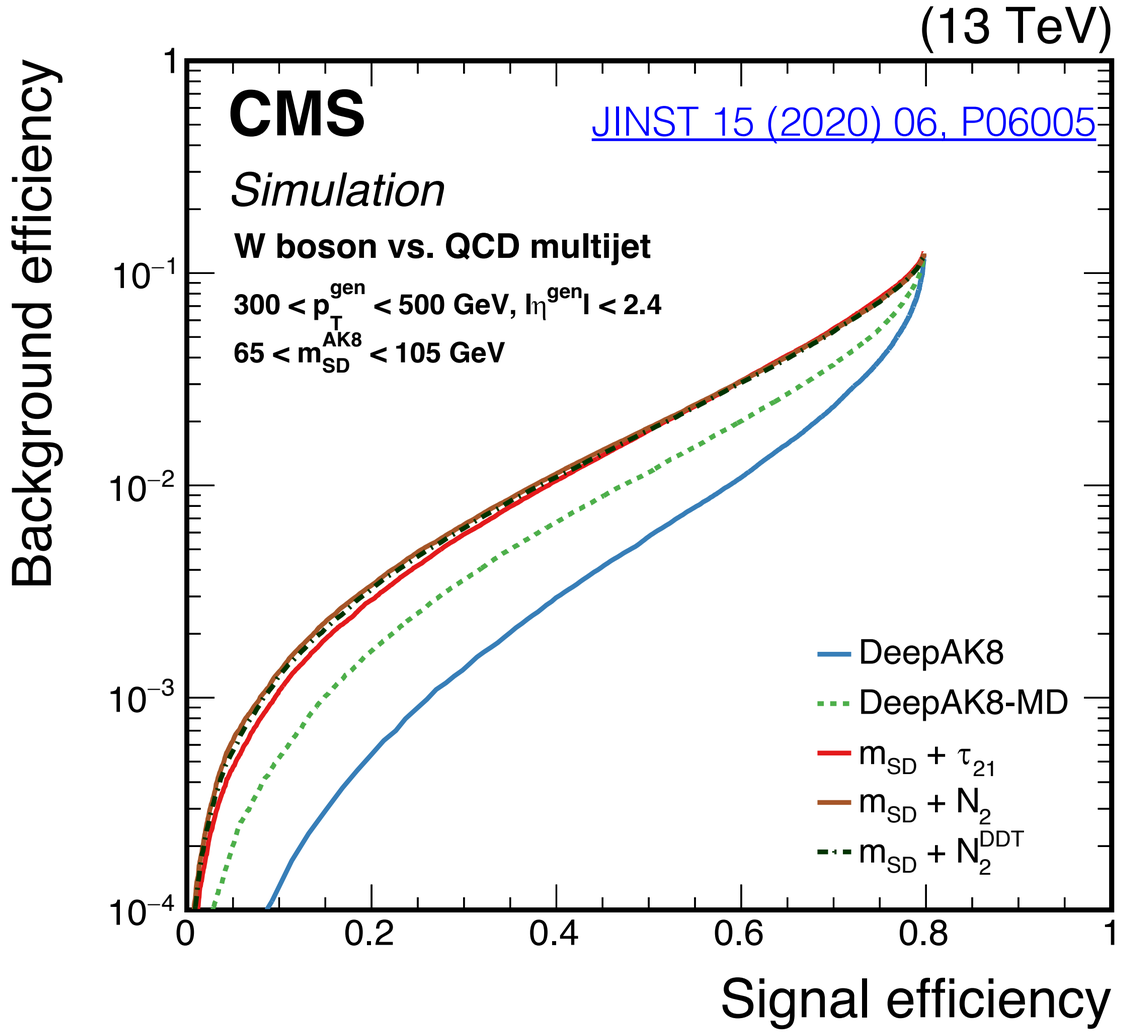

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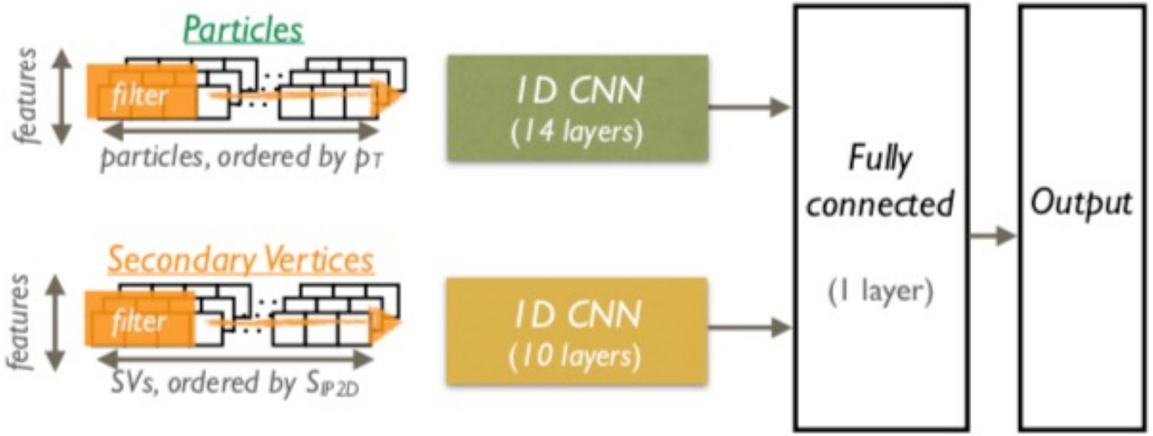
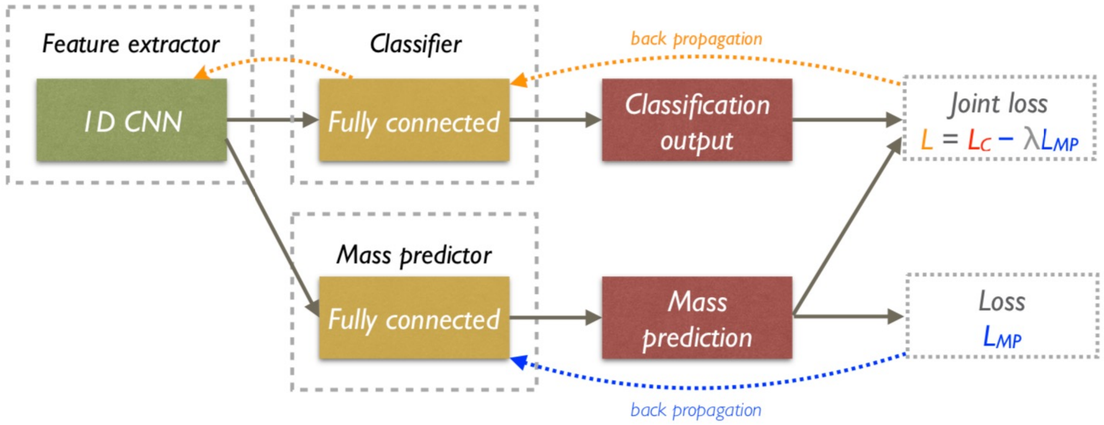
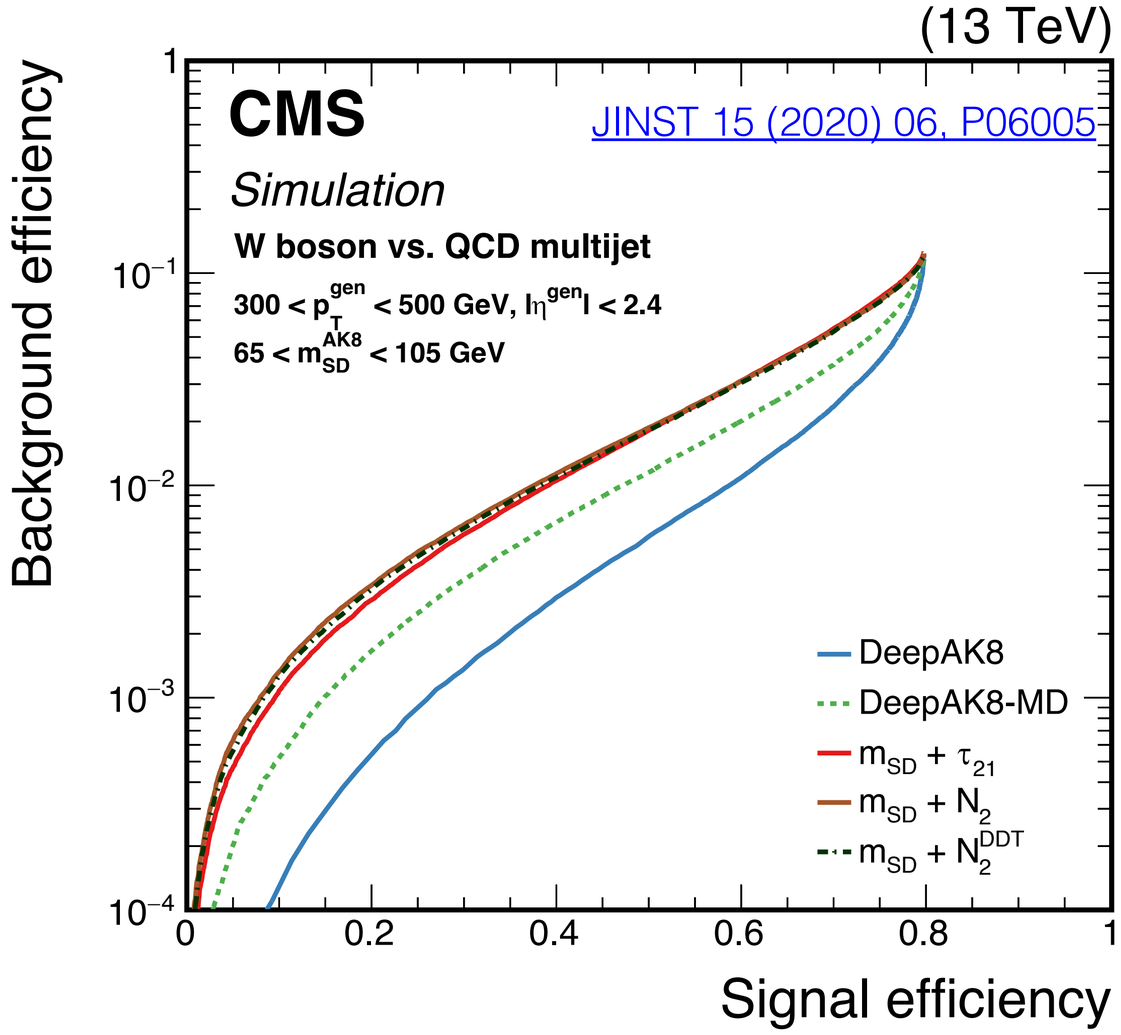


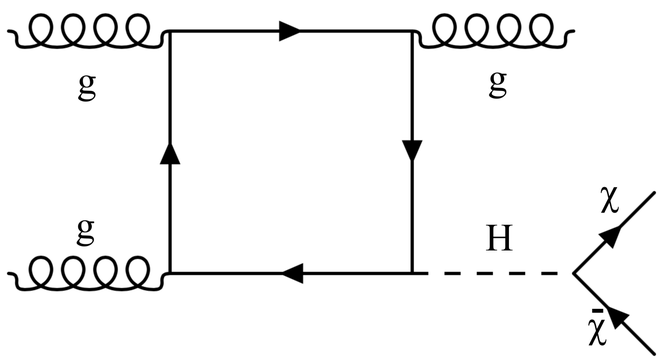



# Higgs Production Modes

Higgs Production modes will determine the signature.

… and vector boson fusion!




**Gluon fusion**

JHEP11(2021)153

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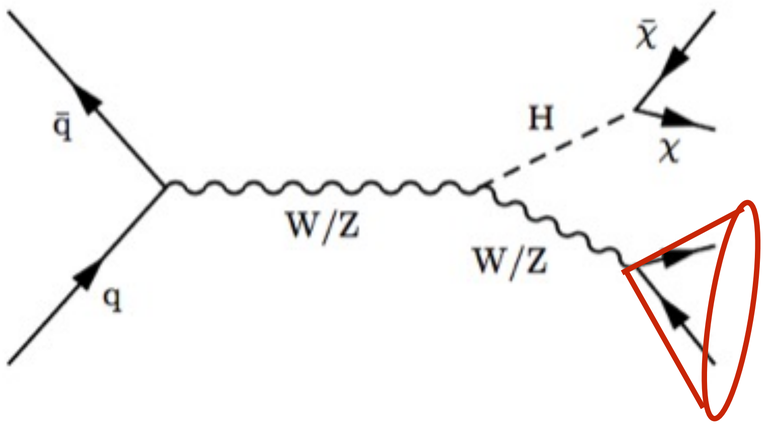


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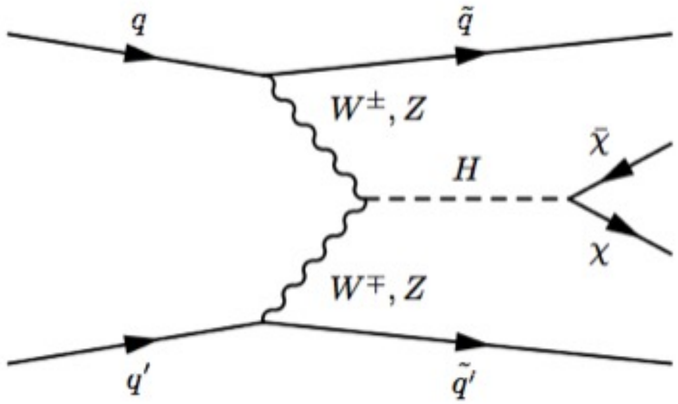


**Vector boson fusion**

Submitted to Phys. Rev. D

- Largest sensitivity among all approaches!
- Experimentally most challenging with 2 forward jets