Hunting for Dark Matter with the ATLAS and CMS Experiments

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On behalf of the ATLAS and CMS Collaborations

MOCa workshop (**Materia Oscura en Colombia**)
8-11 June 2021

Outline

- Brief Introduction and Motivation

- Dark Matter Hunting at LHC

(selected full Run II results will shown):

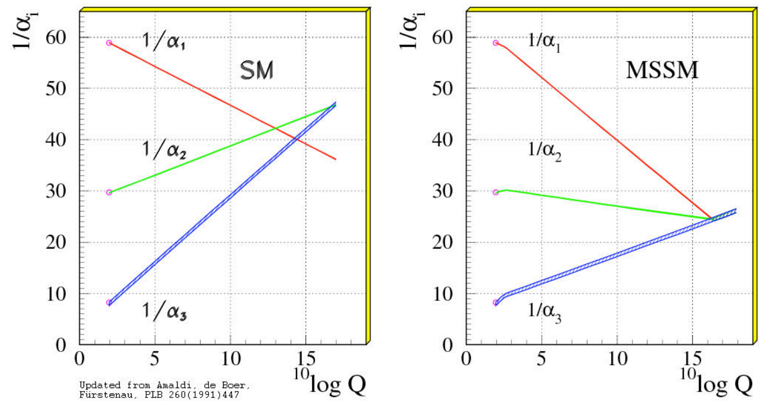
  - Mono-X searches
  - Di-X searches

- Outlook

Introduction : SM is incomplete

- **Hierarchy Problem :** *Why is $M_{Pl}/M_{EW} \sim 10^{15}$.*

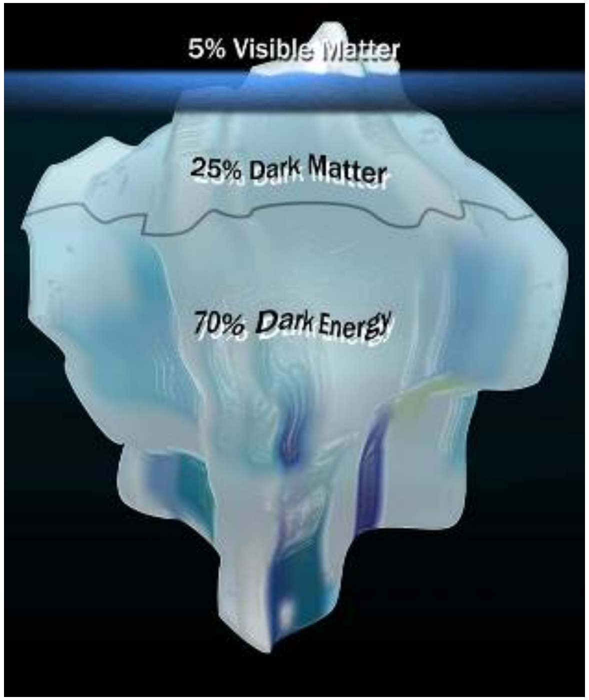
- **Unification of Gauge couplings** *: Why are gauge couplings so different, are they unified at a higher scale? Are there more forces in nature?*



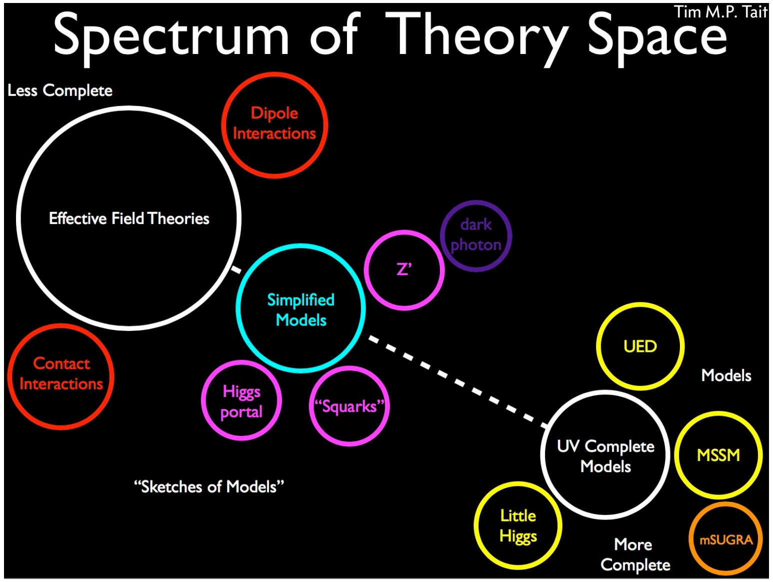
- **Origin of generations :** *Why do quarks and leptons come in three generations? Are they elementary particles?*

- **Gravity :** *SM describes three of the four fundamental interactions at the quantum level (microscopically) but gravity is only treated classically.*

- **Dark matter :** *What is 25% of the Universe made off, and how does it interact with ordinary matter?*

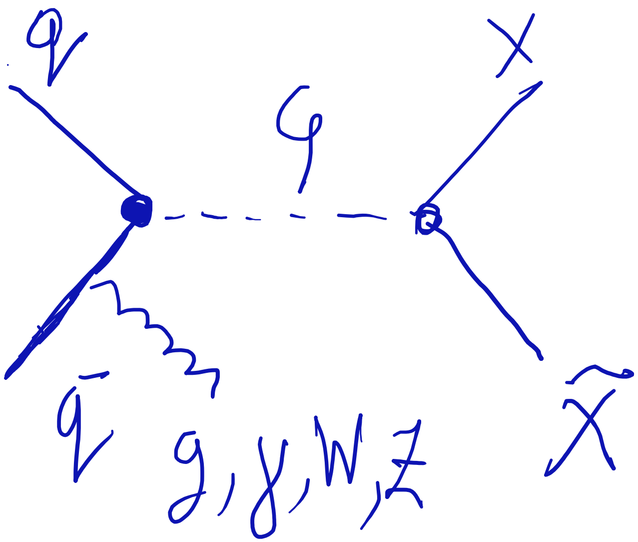


Dark Matter searches : Direct, Indirect, Collider

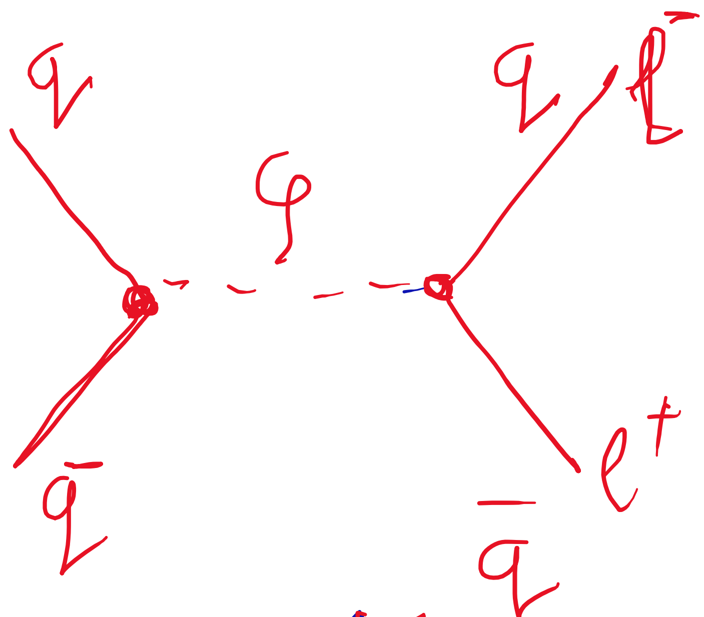


- There is plenty of evidence for the existence of **Dark Matter** which we have only **seen** so far **gravitationally**.
- ***Direct Dark Matter searches: Detect interactions*** *of* ***DM particle*** *(or particles)* ***in terrestrial detectors.***
- ***Indirect Dark Matter searches: Detect DM-DM interactions*** *in the* ***cosmos****, ie DM-DM interactions at the centre of the galaxy*
- ***Collider Searches : Produce and detect DM particles*** *and* ***DM mediators.***

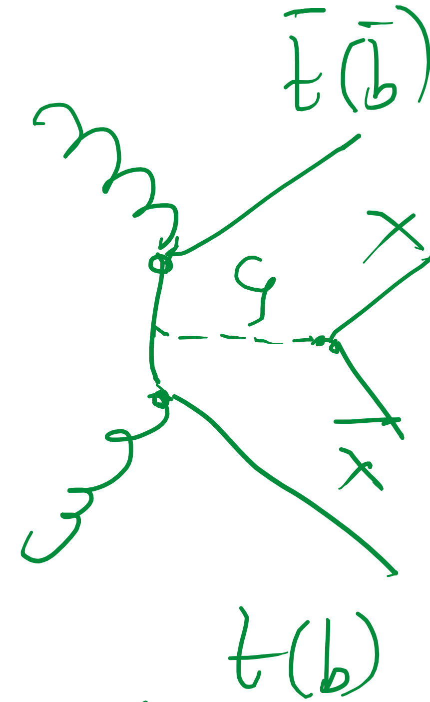
Dark Matter Searches in Colliders : The final states



mono-X



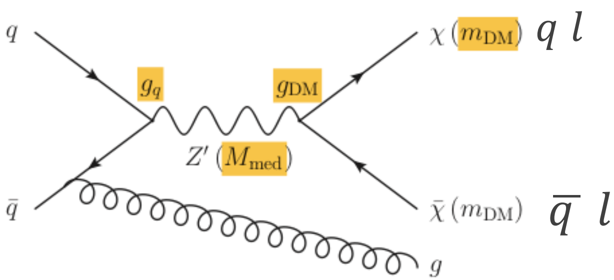
di-X

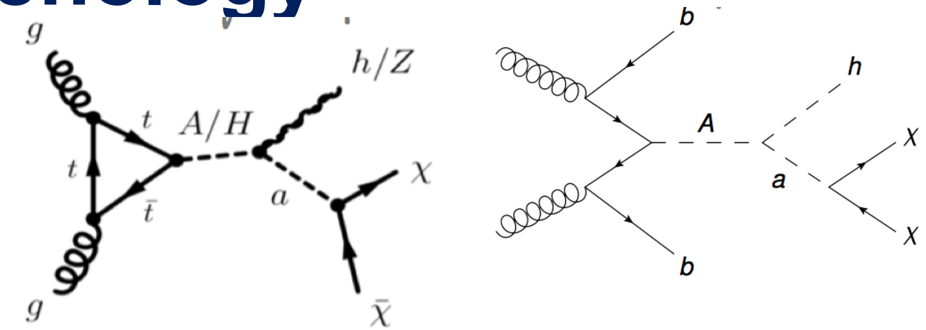


Associated Production

SM Higgs portal

Dark Matter Searches @LHC :Phenomenology





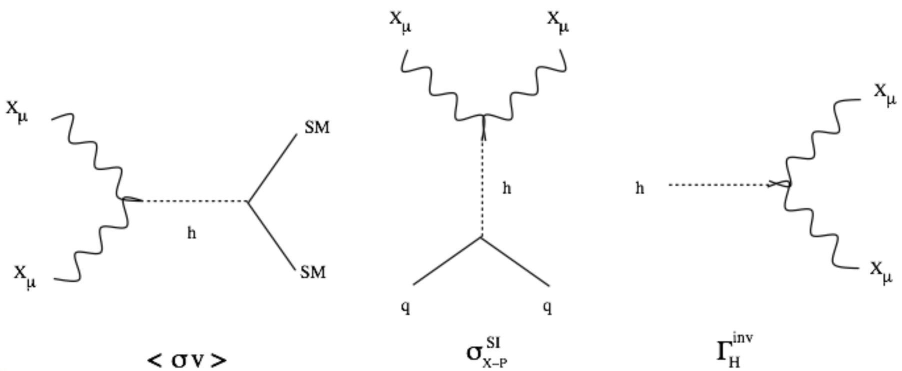
Simplified Models

https://arxiv.org/pdf/1507.00966
https://arxiv.org/pdf/1603.04156
https://arxiv.org/pdf/1703.05703.pdf

Two Higgs Doublet Models (2HDM)

Phys. Rept. 516 (2012) 1
Phys. Dark Univ. (2018) 100351
JHEP 05 (2017)

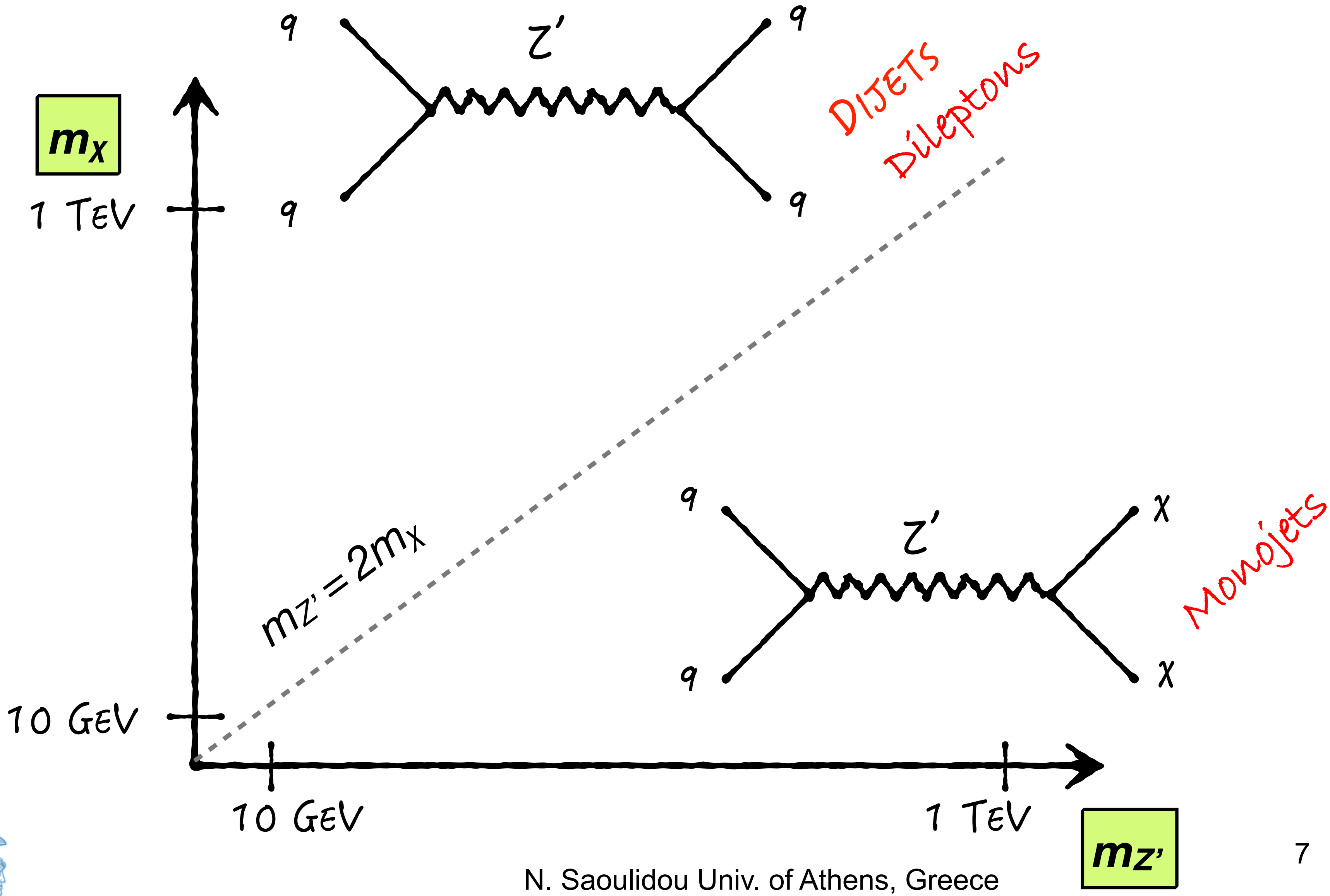
Higgs Portal Models



Phys. Rev. D 82 (2010) 055026,
Phys. Lett. B 707 (2012) 570
Phys. Lett. B 709 (2012) 65
(SM <1%)

Dark Matter Searches @ the LHC :

Complementarity between difference searches



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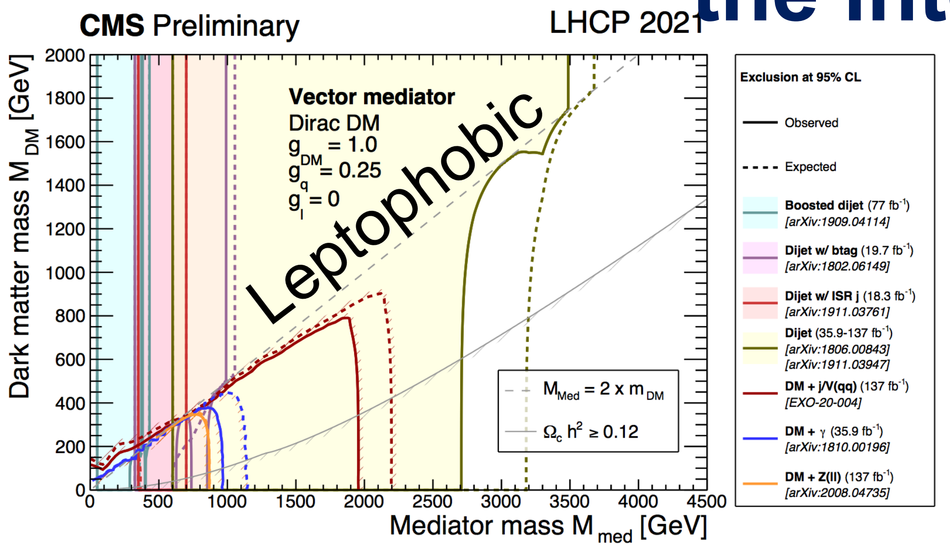
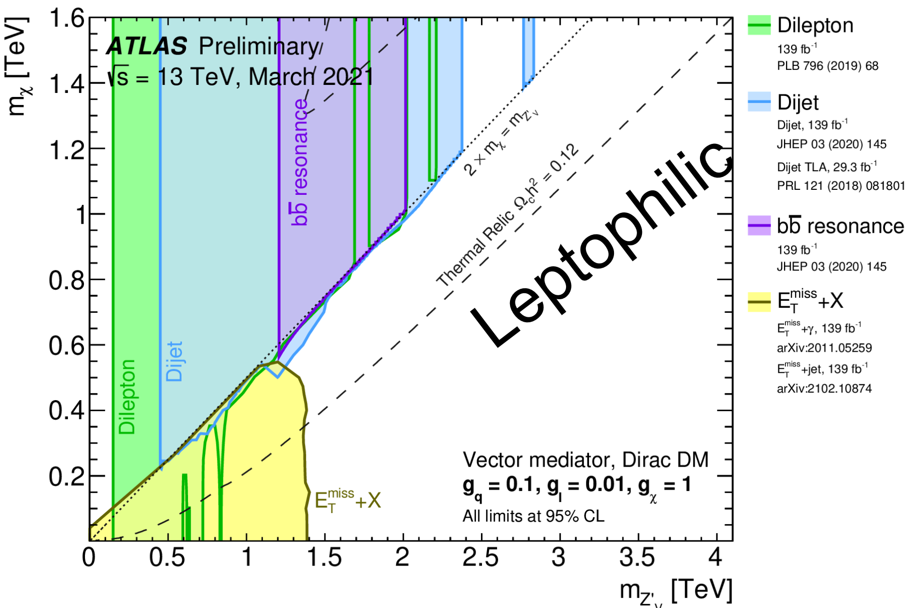
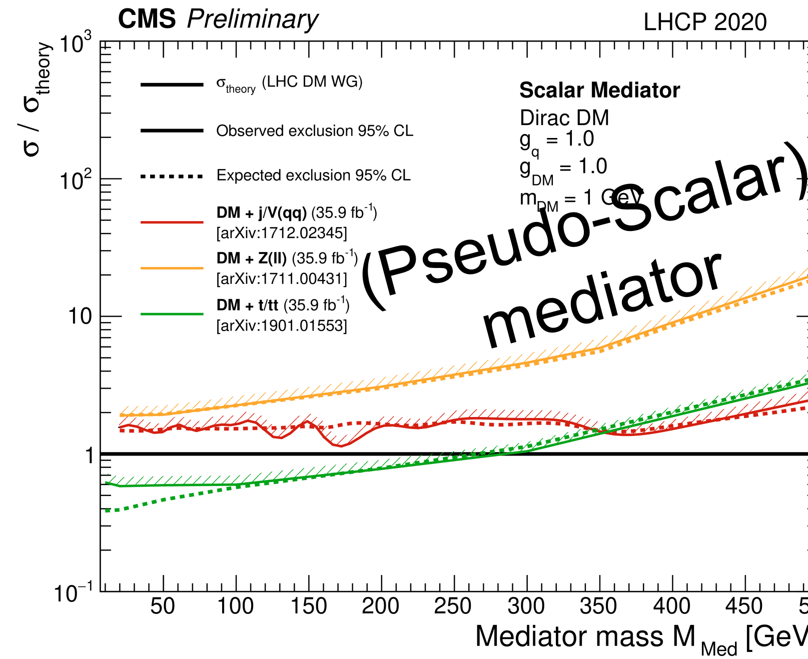
Dark Matter Searches in Colliders : the interplay

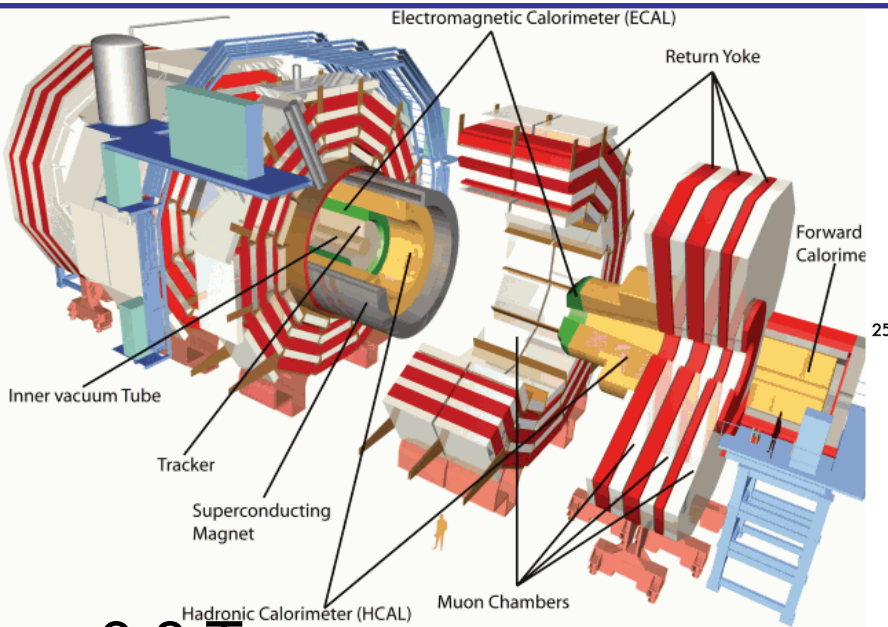


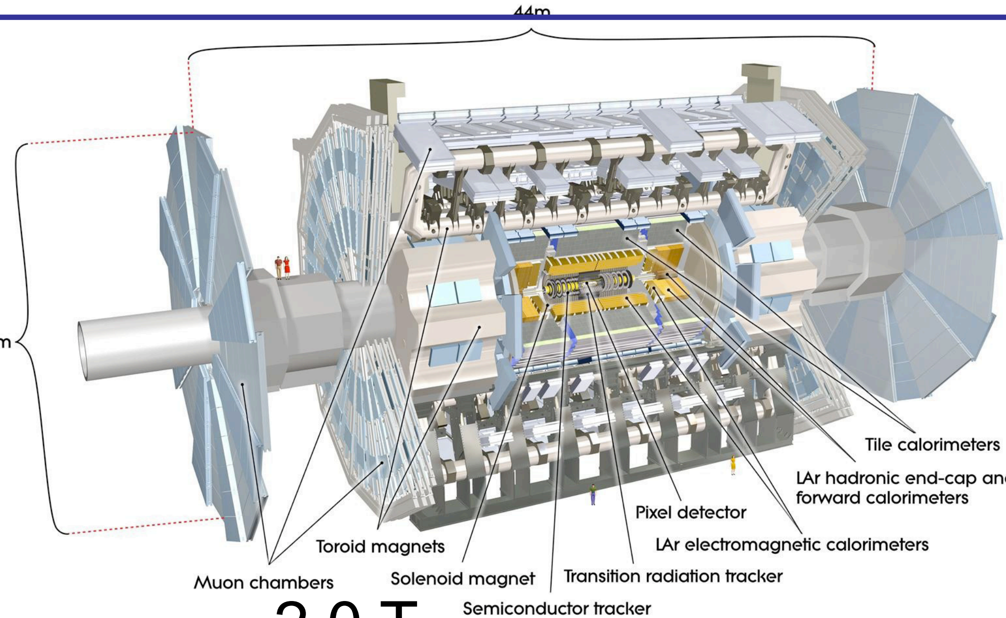




Extended Higgs model mediators with preferential couplings to heavy third-generation quarks.

ATLAS and CMS Experiments





3.8 T

Pixels

$\sigma/p_T \sim 1.5 \cdot 10^{-4} p_T(\mathrm{GeV}) \oplus 0.005$

Electromagnetic Calorimeter

$\sigma E/E \approx 2.9\%/\sqrt{E(\mathrm{GeV})} \oplus 0.5\% \oplus 0.13\mathrm{GeV}/E$

Hadronic Calorimeter

$\sigma E/E \approx 120\%/\sqrt{E(\mathrm{GeV})} \oplus 6.9\%$

Muon Spectrometer

$\sigma p_T/p_T \approx 1\%$ for low pT muons

$\sigma p_T/p_T \approx 5\%$ for 1 TeV muons

2.0 T

Pixels,Si strips & Straw tubes

$\sigma/p_T \sim 3.8 \cdot 10^{-4} p_T(\mathrm{GeV}) \oplus 0.015$

Electromagnetic Calorimeter

$\sigma E/E \approx 10\%/\sqrt{E(\mathrm{GeV})} \oplus 0.7\% \oplus 0.2\mathrm{GeV}/E$

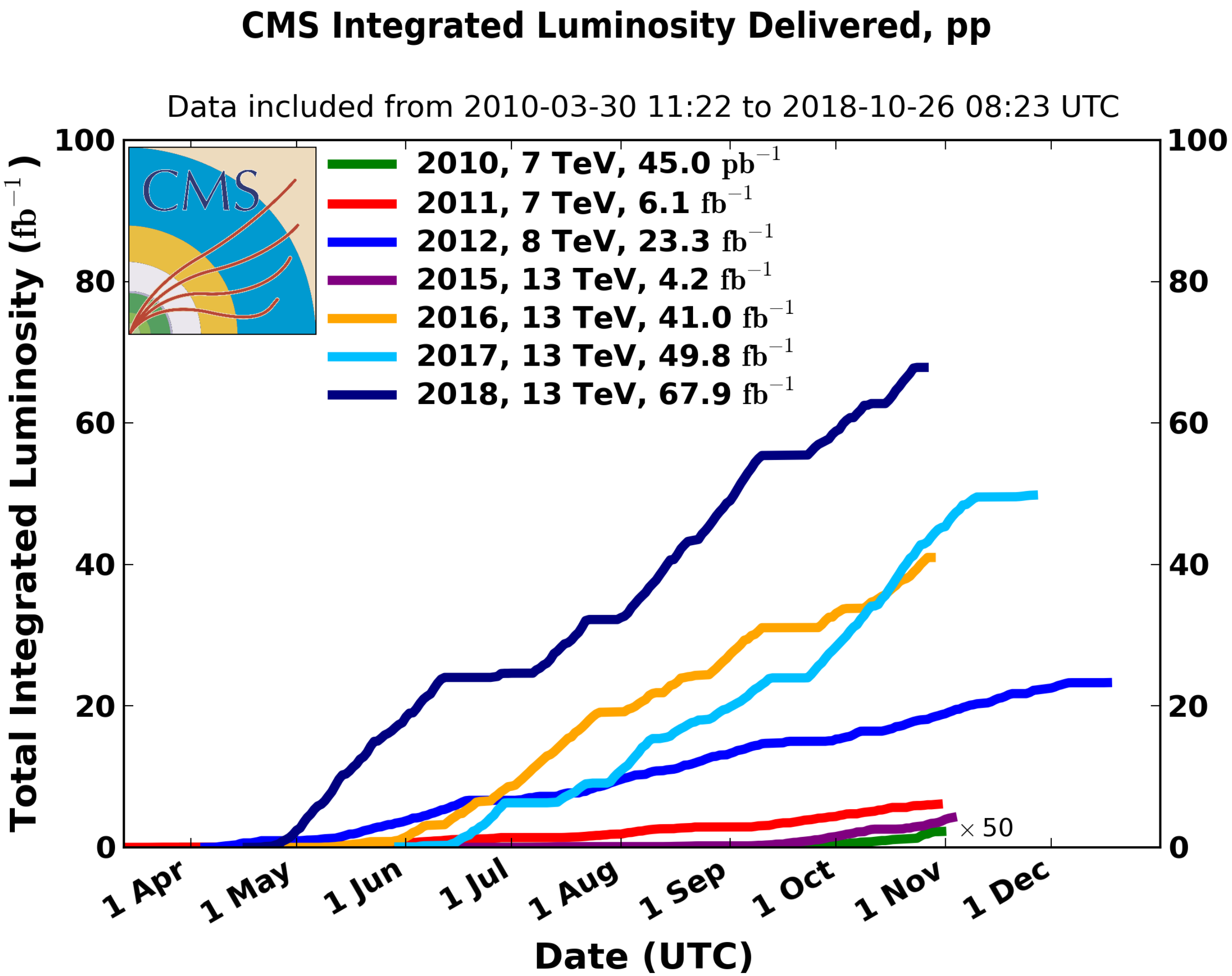
Hadronic Calorimeter

$\sigma E/E \approx 60\text{-}100\%/\sqrt{E(\mathrm{GeV})} \oplus 3\%$

Muon Spectrometer

$\sigma p_T/p_T < 10\,\%$ up to 1 TeV muons

The LHC Accelerator



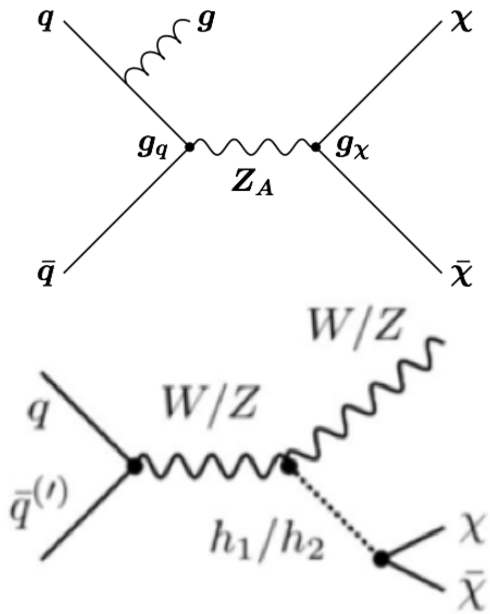
- LHC Accelerator had so far a superb performance.

Mono-X ($X = jet, \gamma, Z, W$)

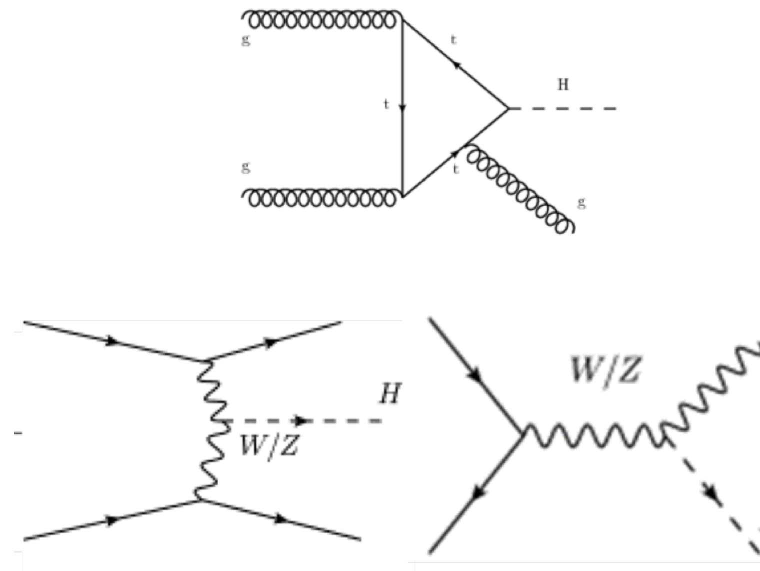
Monojet-monoV searches

Access a broad range of new physics hypothesis

Dark Matter



Higgs to invisible



- **Main Experimental Signature :**
  - **A jet or a Vector Boson decaying hadronically and Missing transverse energy**

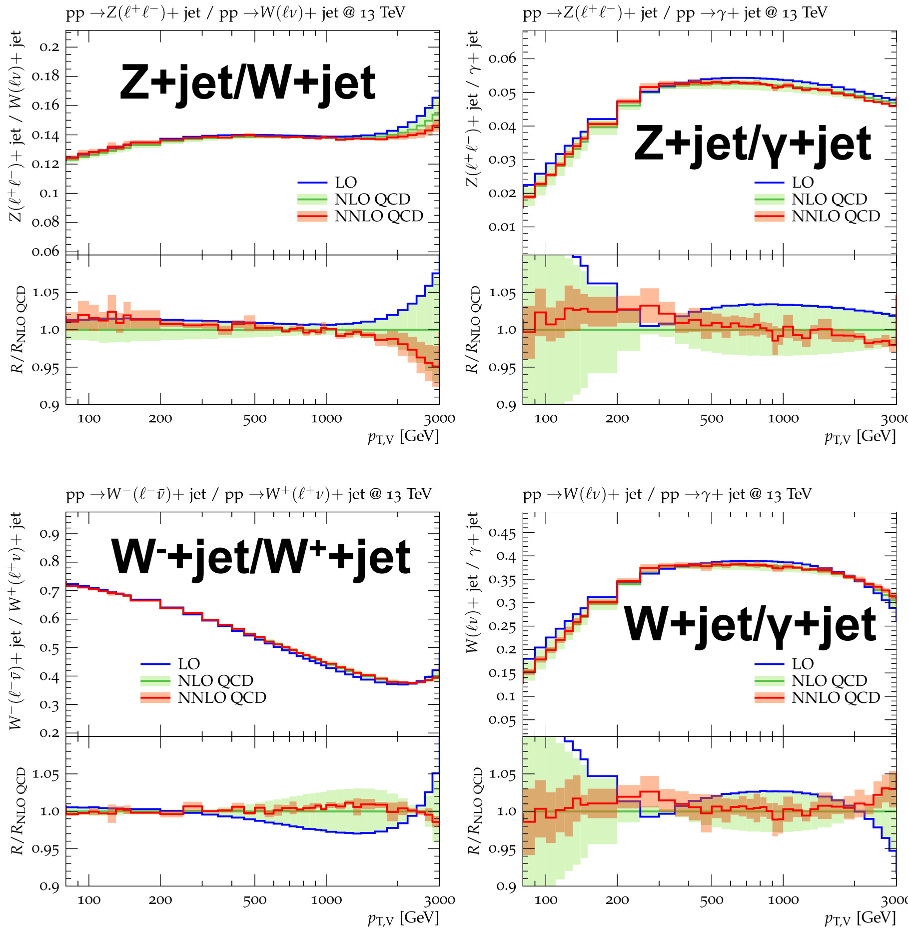
- **Main irreducible backgrounds:**
  - **Z→νν+jets, W → lν+jets**

Monojet(V) searches : Background estimation

- **Background estimation:** Data-driven, to minimize dependence on simulation, and **significantly reduce theoretical systematic uncertainties.**
- Five **control regions : Z → ee, Z → μμ,W → eν, W → μν, top (ATLAS) or γ+jets (CMS since** *Z+jets and γ+jets behave similarly*)**, to measure the E_{Tmiss} spectrum** excluding leptons and photons.
- **Control to signal region transfer factors from simulation** utilized, **exhibiting theoretical uncertainties due to**:
  - **QCD renormalization and factorization scales**
  - **QCD effects in γ+jets production** being **different than those in W+jets and Z+jets ones.**
  - **Mixed QCD-EW corrections**
- A **simultaneous maximum-likelihood (ML) fit** is performed in the **Signal and Control regions** to **estimate** the **SM backgrounds** and the **signal strength.**

Monojet(V) searches : Guidance from Theory

Eur. Phys. J. C (2017) 77:829



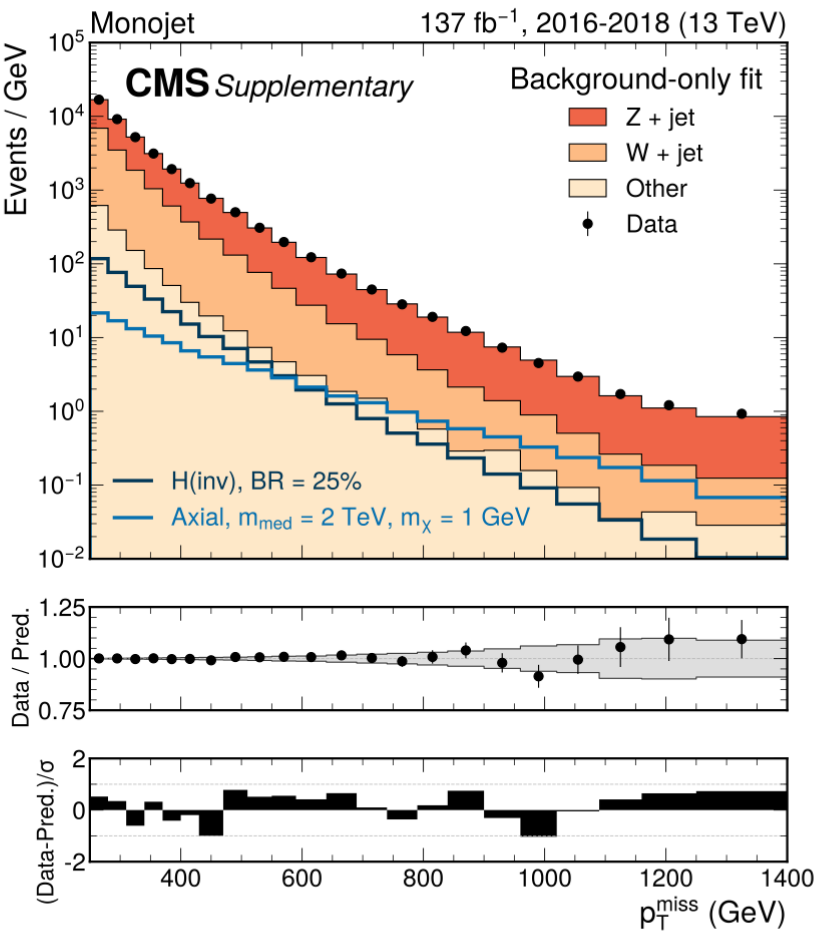
Simulated Transfer factors

Provided **accurate theoretical predictions** and **detailed prescriptions on how theoretical systematic uncertainties** should be **taken into account** in the **experimental analyses.**

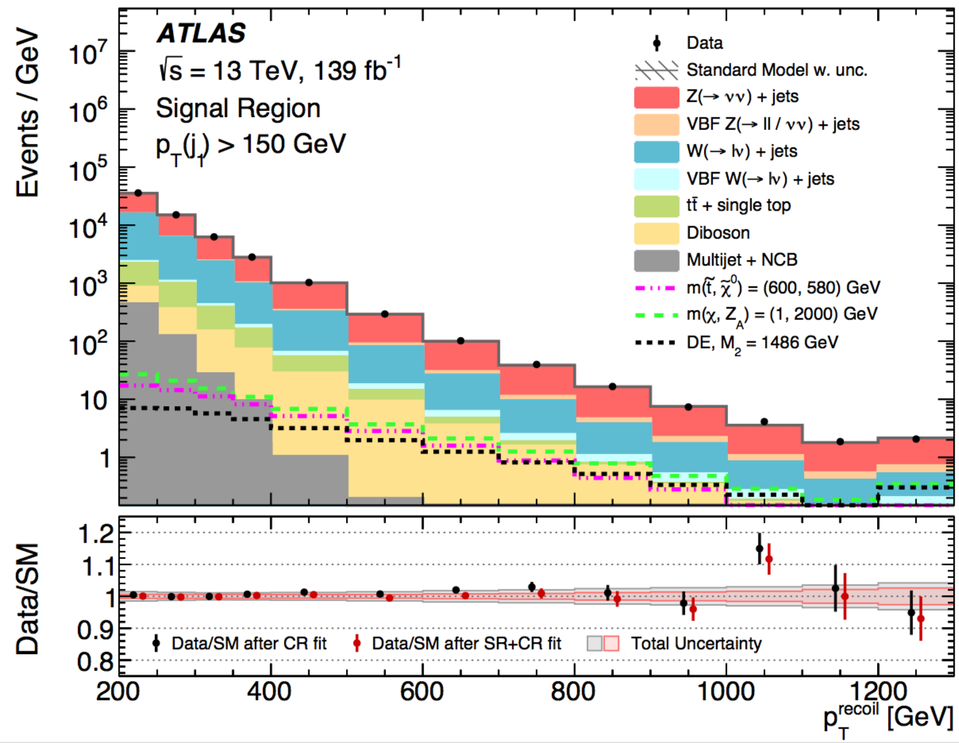
Monojet searches : Results

No deviations seen from the **SM expectation. Place limits**

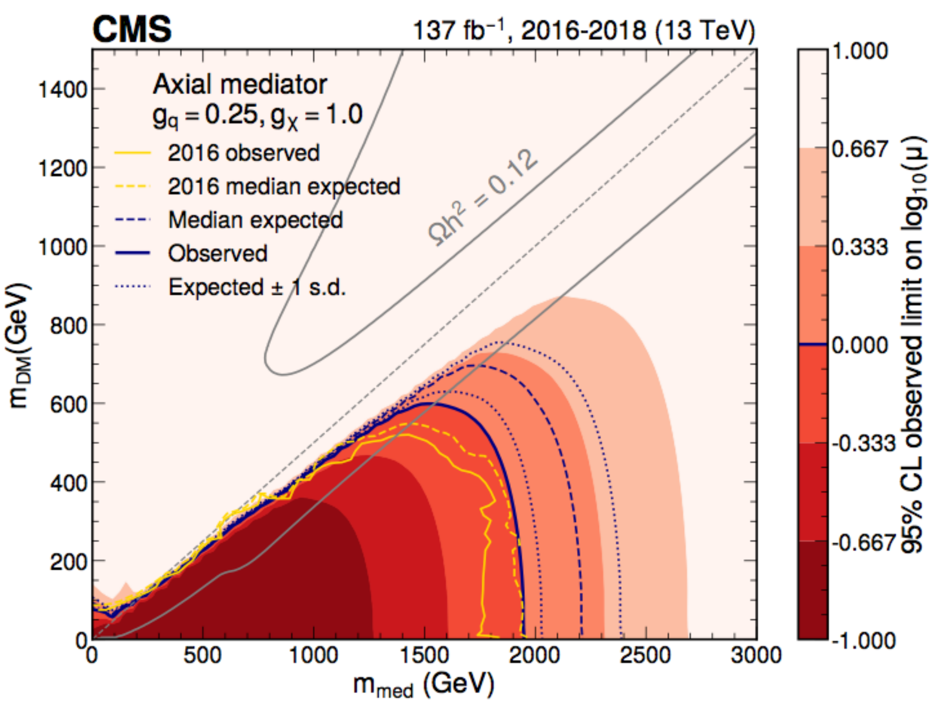
CMS-PAS-EXO-20-004

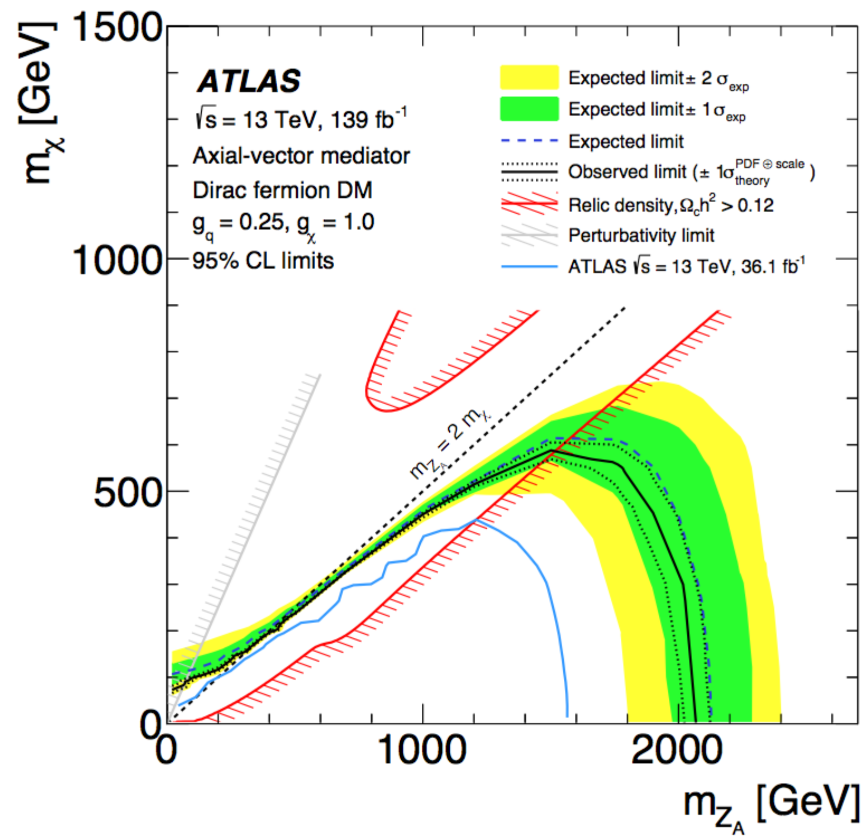


arXiv:2102.10874



Monojet searches : Interpretations

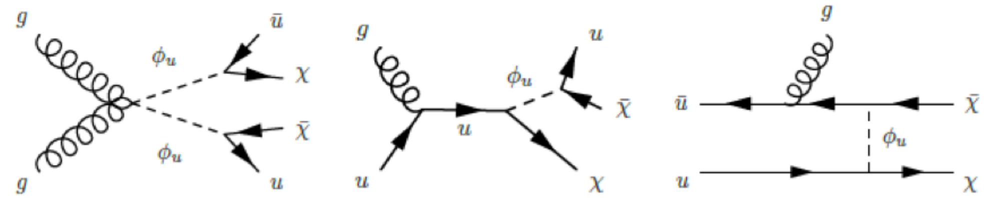


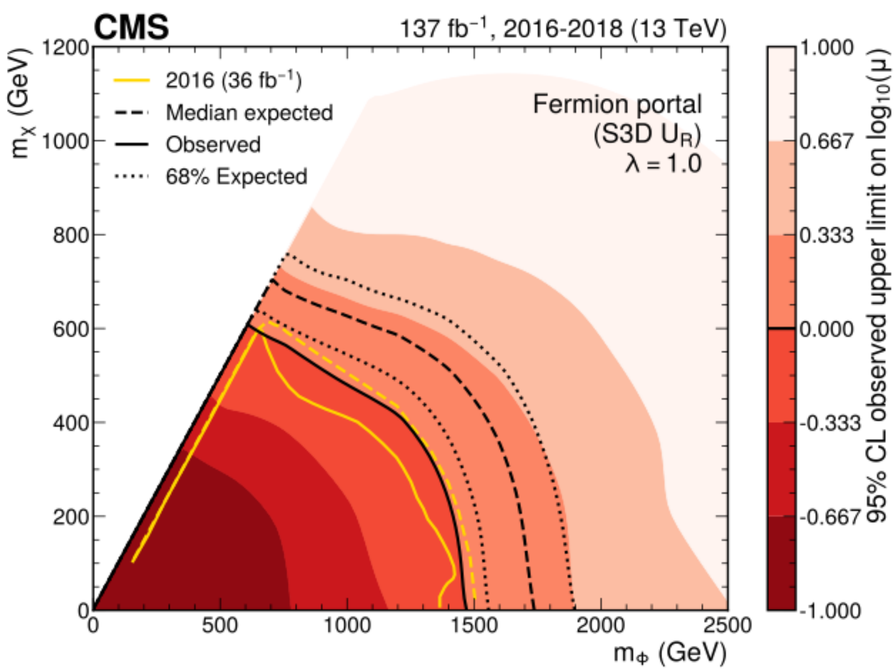


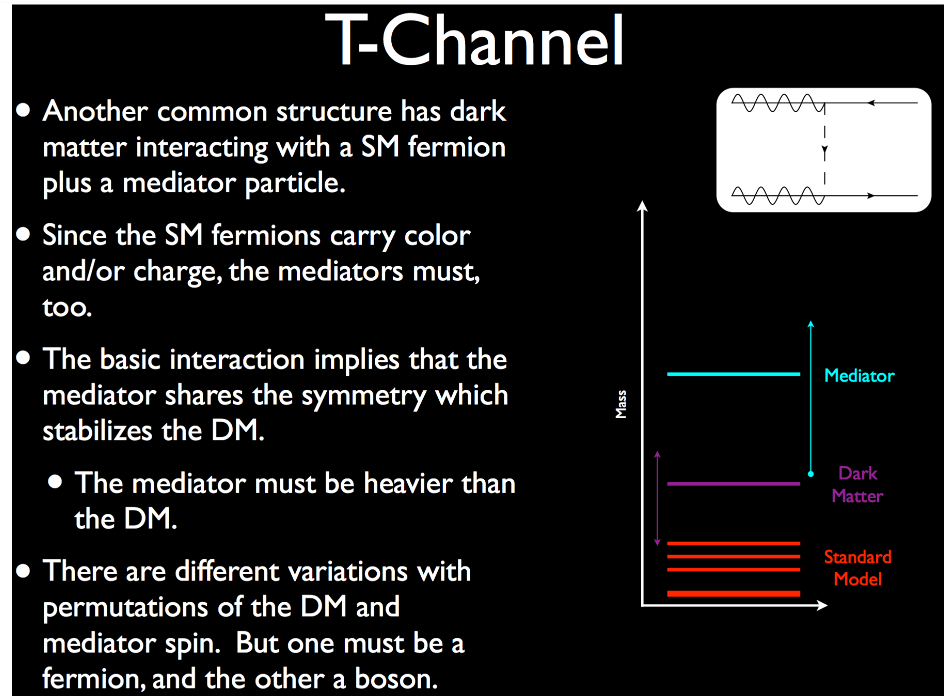
This search is one of the **most "direct" probes for dark matter at the LHC!** Expecting **further improvements** in **theoretical (and experimental) uncertainties** in the future?

Monojet searches : Interpretations

t-channel DM production



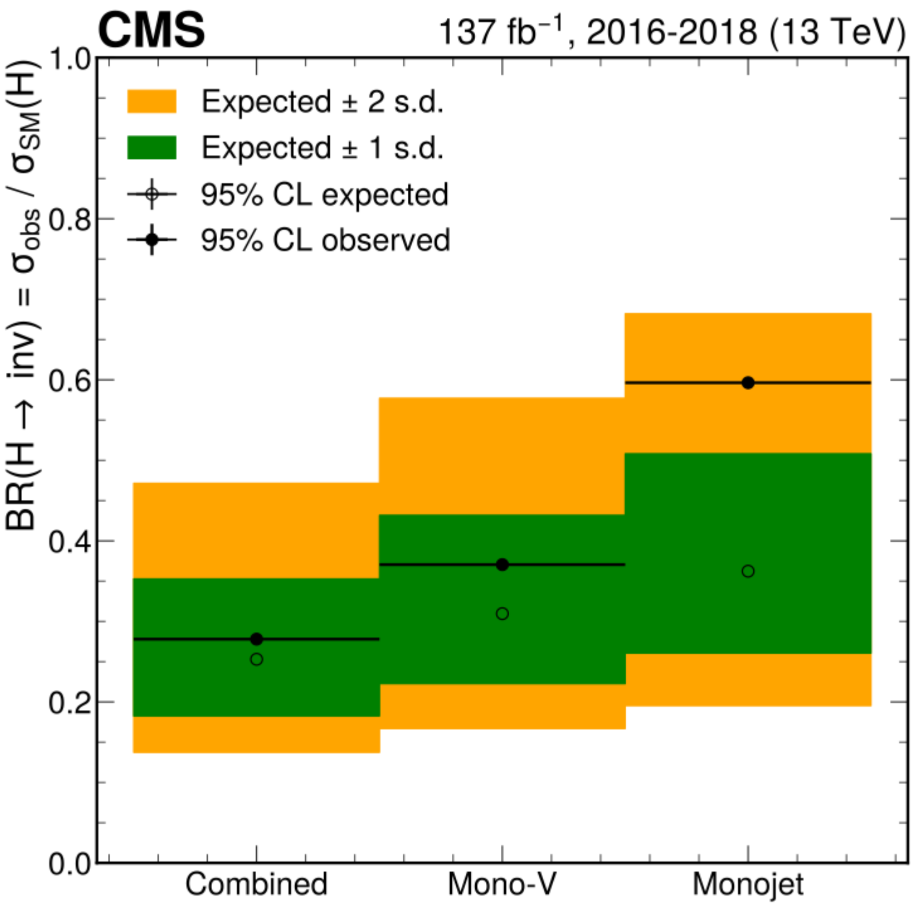




More **comprehensive work** on clear **common benchmark scenarios**, and **further explorations** in **Run III and beyond**

Tim Tait : Dark Matter Models with t-channel mediatros@ IHC
https://indico.cern.ch/event/806526/

Higgs to invisible



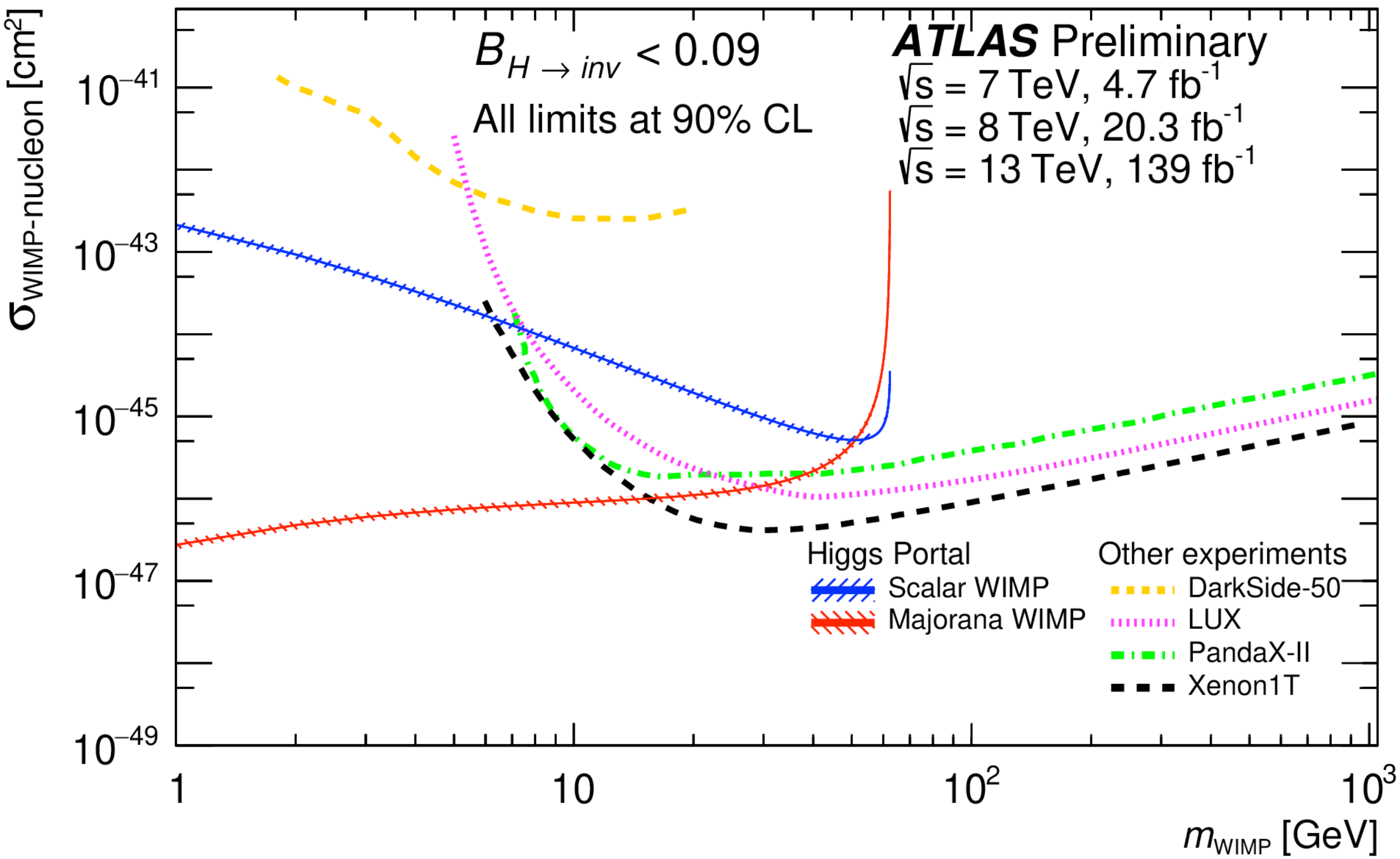
- **ATLAS : 95% CL observed (expected) exclusion limit** on the **invisible branching** ratio of the **Higgs boson** of **0.34 (0.39 expected) from monojet search**
  ATLAS: arXiv:2102.10874.

- **CMS :** The **monoV category** helps **further constraint the Higgs to invisible decays to <0.28 (0.25 expected).**

- Overall **current best** combination from **ATLAS at < 0.11**
  ATLAS: CONF-2020-052

Higgs to invisible

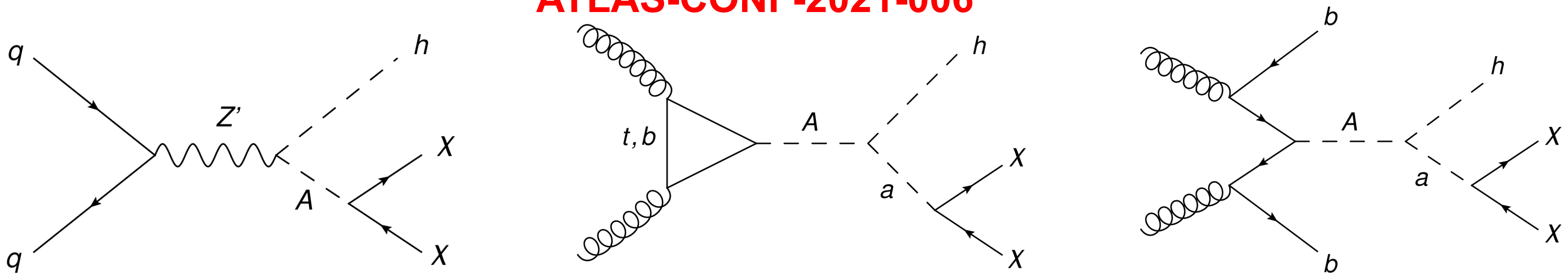
ATLAS: CONF-2020-052



- **Nice complementarity between non-collider experiments and LHC searches**

Mono-Higgs to bb

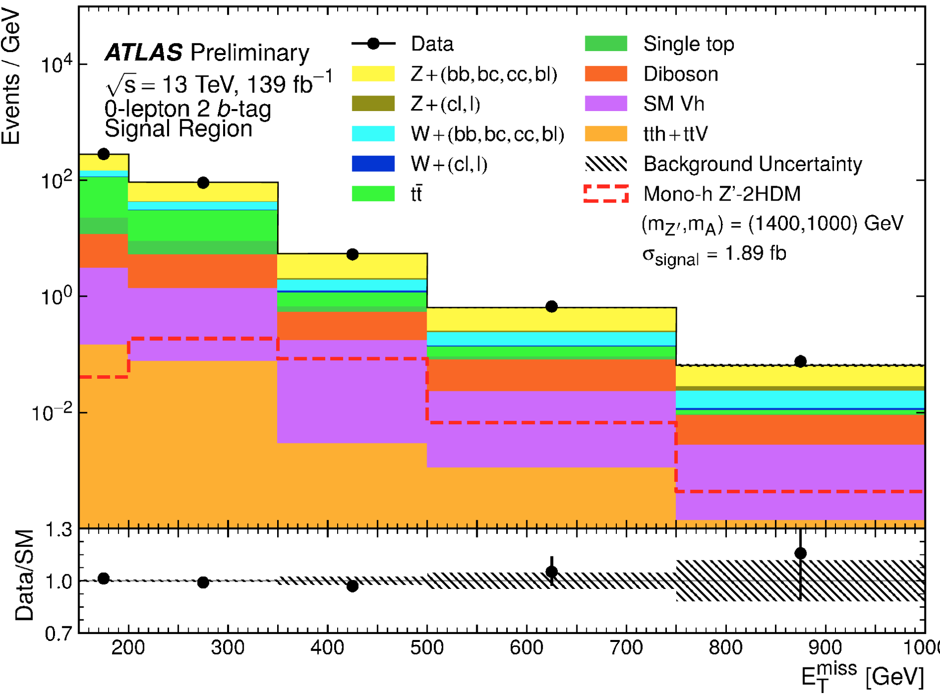
ATLAS-CONF-2021-006

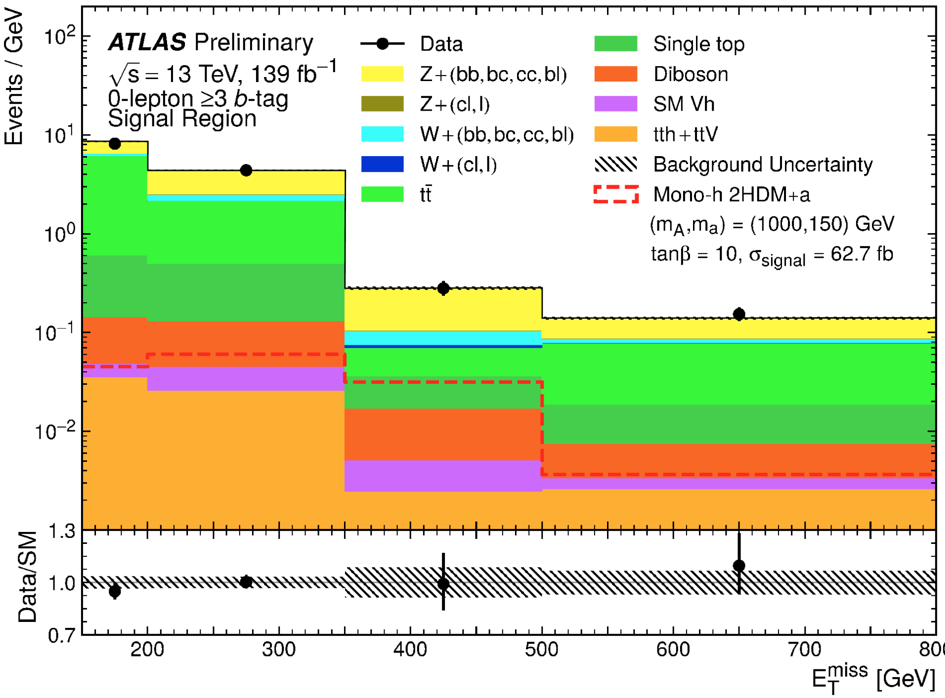


- **2HDM model with two benchmarks :**
  - Two Higgs doublets **extended** by a **heavy vector boson *Z'***
  - A **new pseudoscalar singlet *a*** is added which **mediates** the **interaction** between **SM and a dark matter** candidate ***χ***
- **Main Experimental Signature :**
  - **Missing transverse energy** and **at least two b-tagged jets** (signal region), **vetoing electrons or muons** (control regions).
- **Main backgrounds:**
  - **ttbar, W/Z** produced in association **with two heavy flavor (HF) jets. Their shape** is estimated **from simulation, normalization** is corrected using **data control regions.**

Mono-Higgs to bb

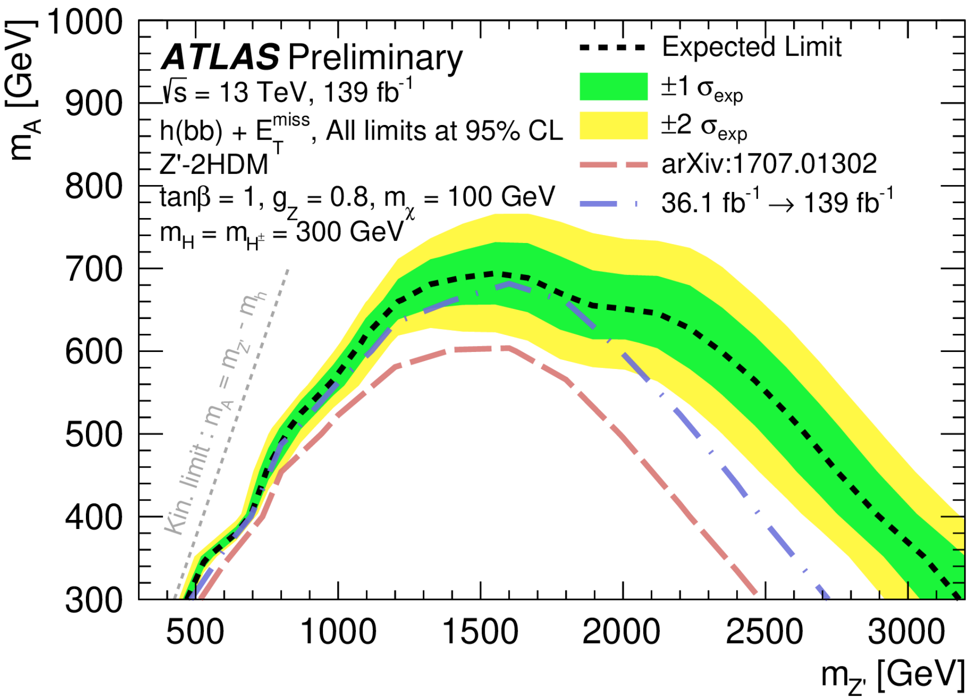
No deviations seen from the **SM expectation. Place limits.**

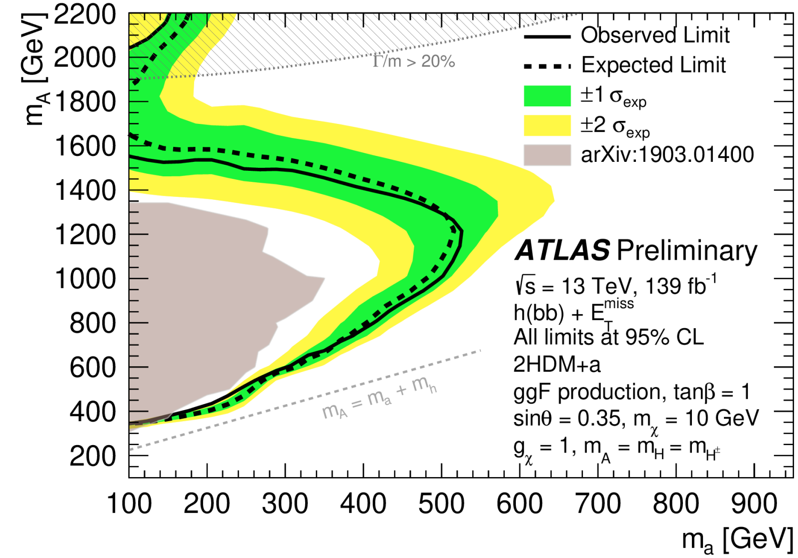


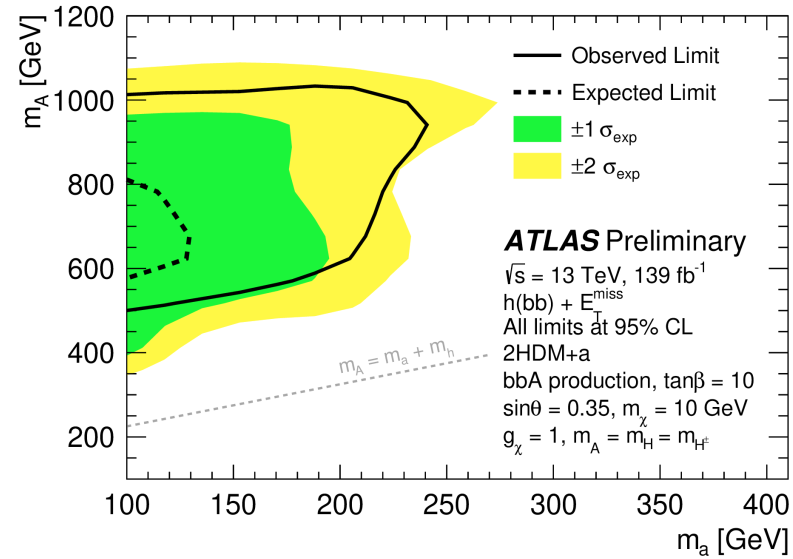


- **Elaborate experimental techniques** used to **identify** both **boosted** and **resolved b-tagged jet** categories.
- The **two b-tagged region** (ggF mechanism dominates) more **sensitive** to **small tanβ** *(the ratio of the vacuum expectation values of the two Higgs doublets)* and **the at least three b-tagged region** (bbA associate production dominates) more **sensitive** to **large tanβ.**

Mono-Higgs to bb







- **Significant improvements** in **reach** compared to previous analyses, for both the **Z'-2HDM** and the **2HDM+a models and** in both **large** and **small tanβ**

tt+DM

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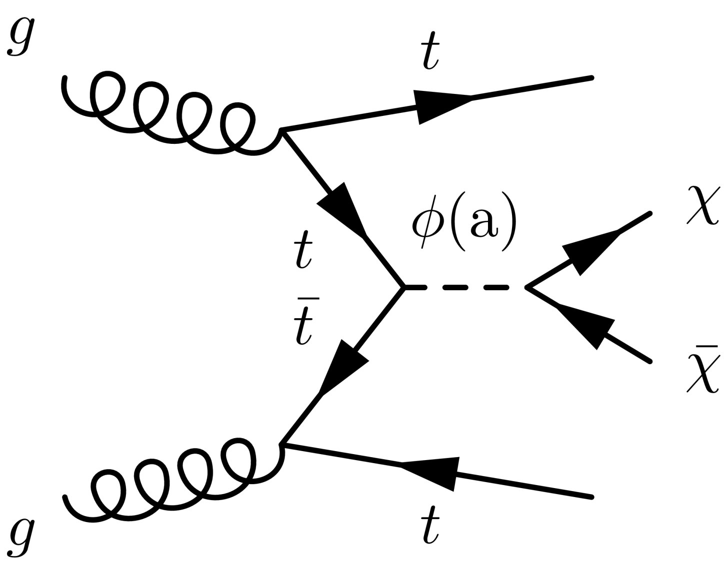
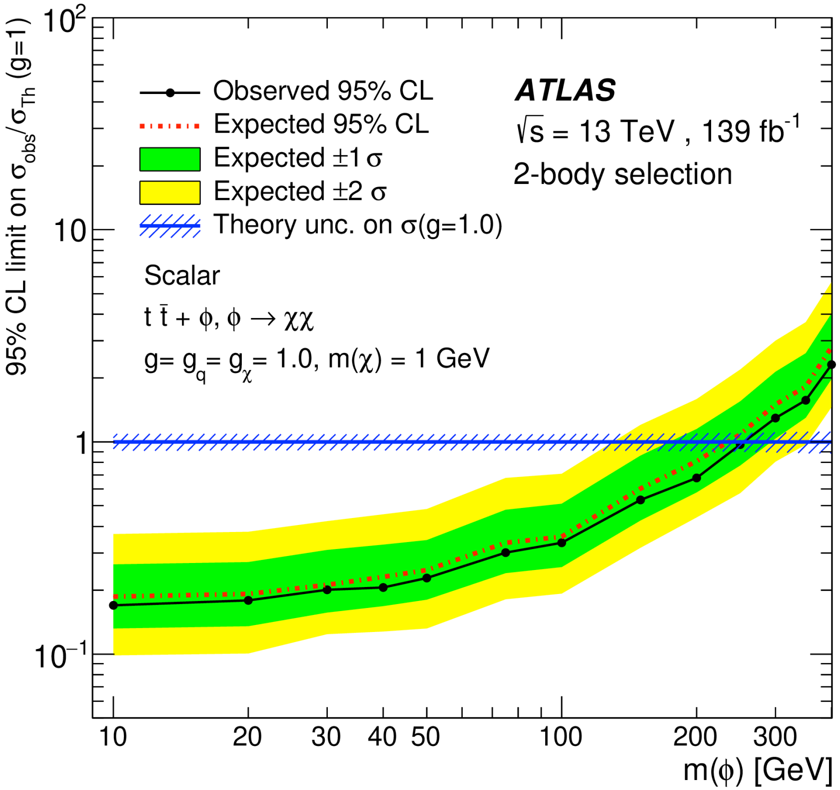
CMS-SUS-PAS-20-002

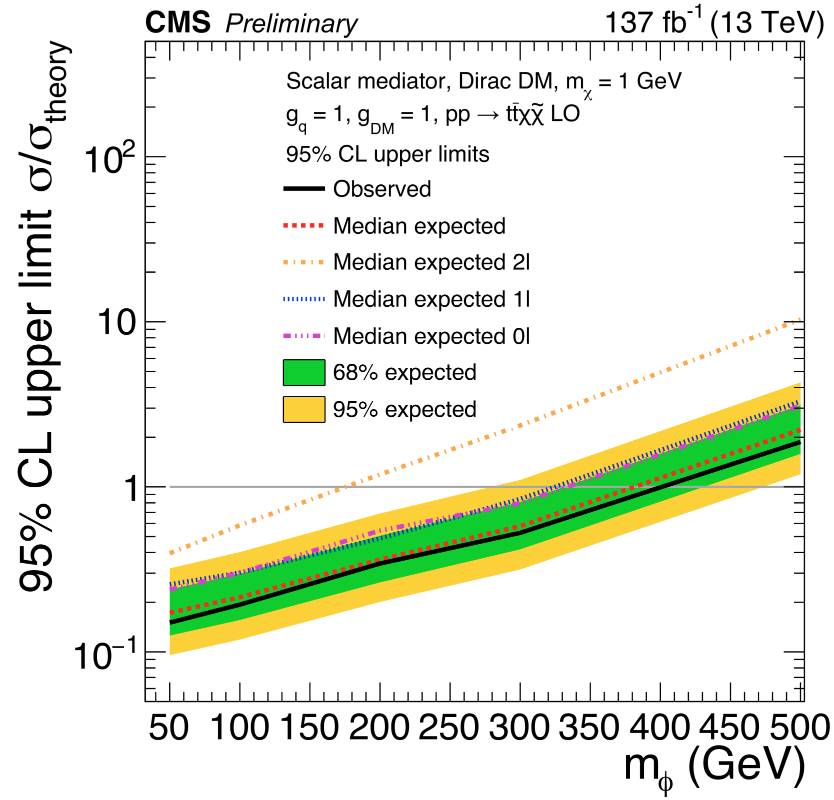


- **Main Experimental Signature :**
  - Missing transverse energy, at least two jets and 0,1,2 leptons
  - **ATLAS** search concentrates at the **dilepton channel**, **CMS** search considers a **combination** from **zero, one and two lepton final states**.
- **Main background** from **SM ttbar production. Shape** is estimated **from simulation, normalization from data.**

- **SUSY analysis** with **DM** simplified model **interpretations as a by-product and several** different **signal**, **control** and **validation** regions considered, with **several kinematic variables** utilized.
- **Signal** and **control** regions are **fitted simultaneously**, with systematic uncertainties introduced as **nuisances parameters**. **Background estimation** methods are **validated** in **independent** validation **regions**.

tt+DM





- **CMS results** from a **combination** of **hadronic, single lepton and dilepton final states** have **significantly higher exclusion power.**
- **Dedicated** analysis **anticipated** to **bring additional sensitivity, including production modes with a single top quark**

Dijet, Dilepton

General Analysis Methodology

- **Analysis Strategy :** search for a **narrow or wide resonance** on top of a **smoothly** falling **background**.

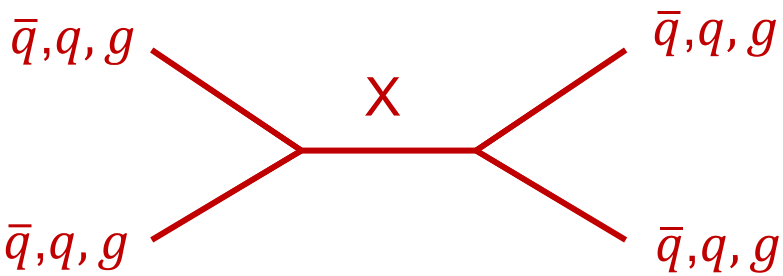
- **Background Estimation :**
  - **Data-driven :** Fitting the invariant di-object mass with an empirical function.
  - **Semi data-driven :** Predicting the SM background from control regions with transfer functions to the signal region from simulation.
  - **From simulation :** Obtaining **the SM background prediction** from the **simulation** when processes **very well modelled** (i.e. **Drell-Yan**)

- **Signal Modelling :** Intrinsic signal shape, either narrow (with width smaller than the detector resolution) or wide, convoluted with the CMS detector resolution.

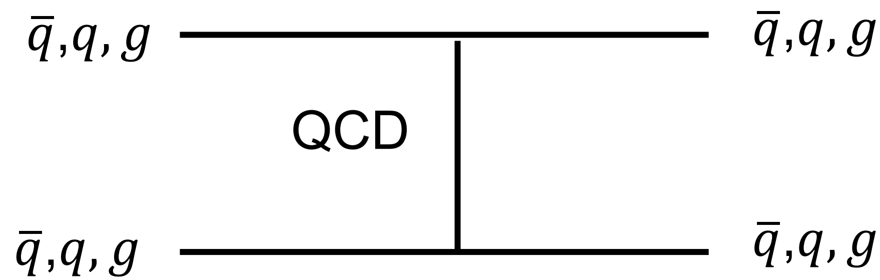
- **Limit extraction, significance estimation :** Fit the dijet, dilepton, invariant mass spectrum using background and signal templates with systematics as nuisance parameters

Resolved dijet in a nutshell

Resonance Signal



SM Background



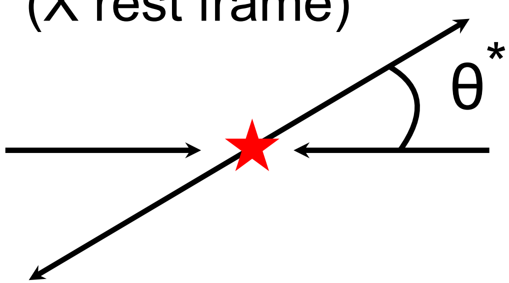
Physics observables

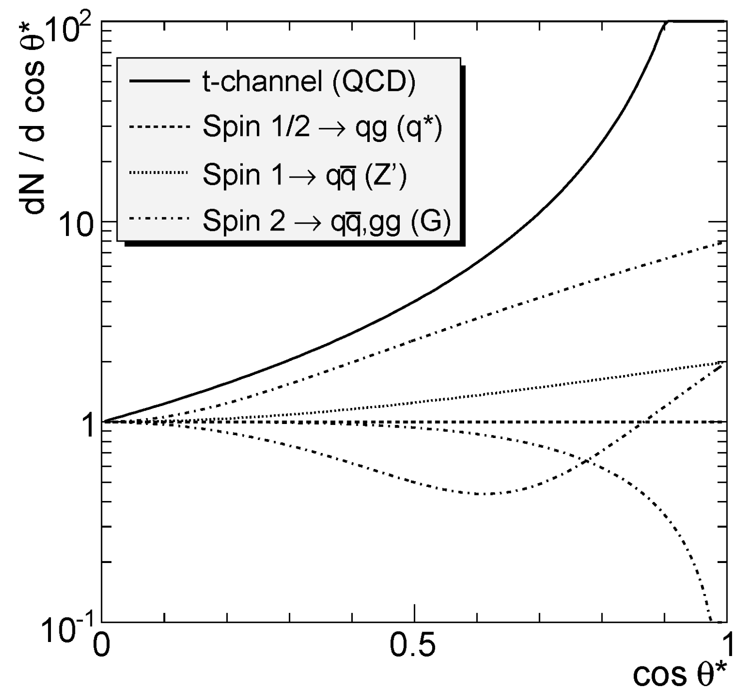
M(jj) → Resonance Mass

Δη(jj) → Resonance Spin

$$\Delta\eta_{12} = |\eta_{jet1} - \eta_{jet2}| = \ln\frac{1+|\cos\theta^*|}{1-|\cos\theta^*|}$$

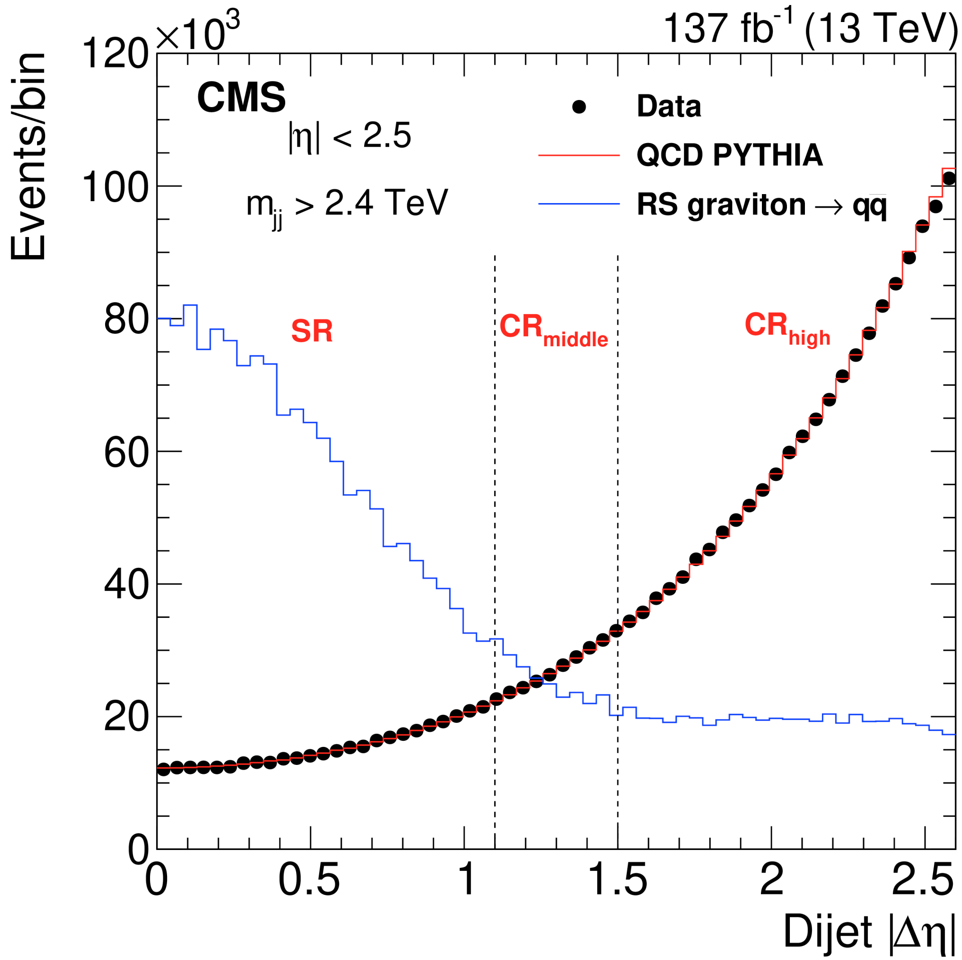
(X rest frame)





One Signal and two Control Regions
New Background Estimation Method

JHEP05(2020)033

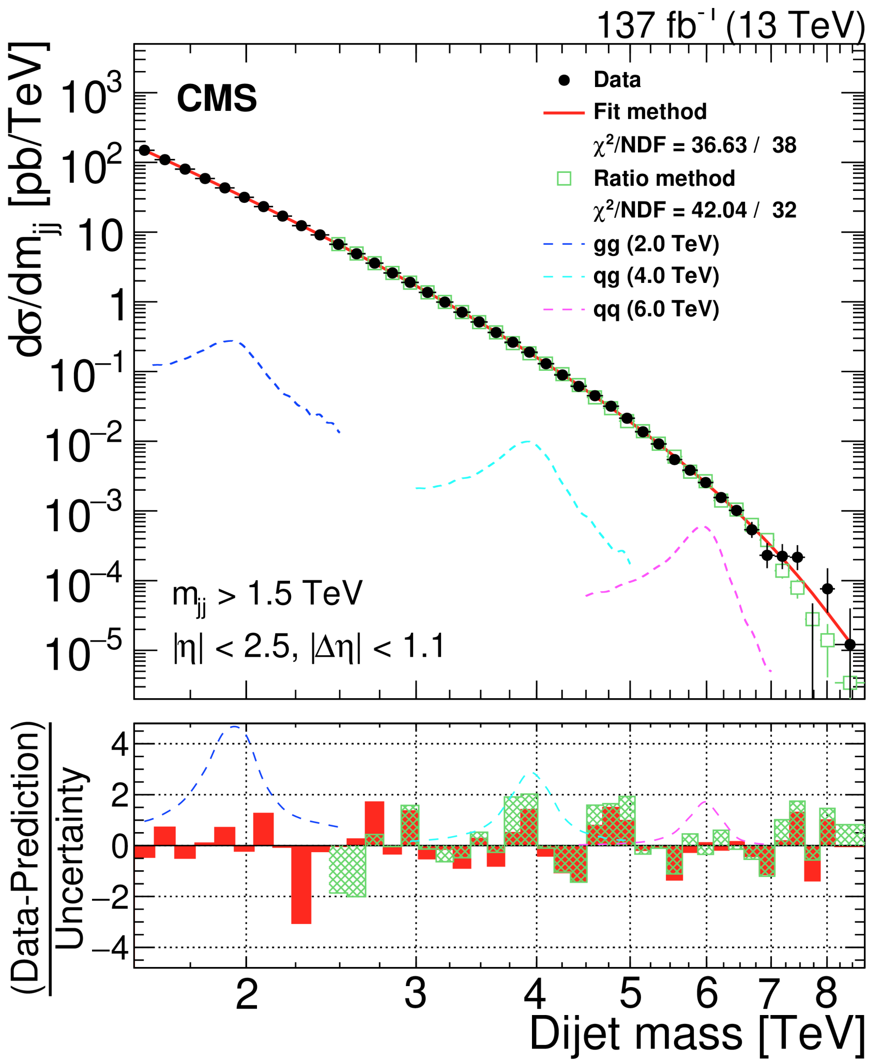


- The signal region (SR) is defined with $|\Delta\eta| < 1.1$.

Two control regions are defined

- **CR_{middle} with $1.1 < |\Delta\eta| < 1.5$** used to estimate the corrections to the simulated transfer factor, constraining systematic uncertainties
- **CR_{high} with $1.5 < |\Delta\eta| < 2.6$ used** to predict the dijet mass distribution of the QCD background

Dijet Mass prediction



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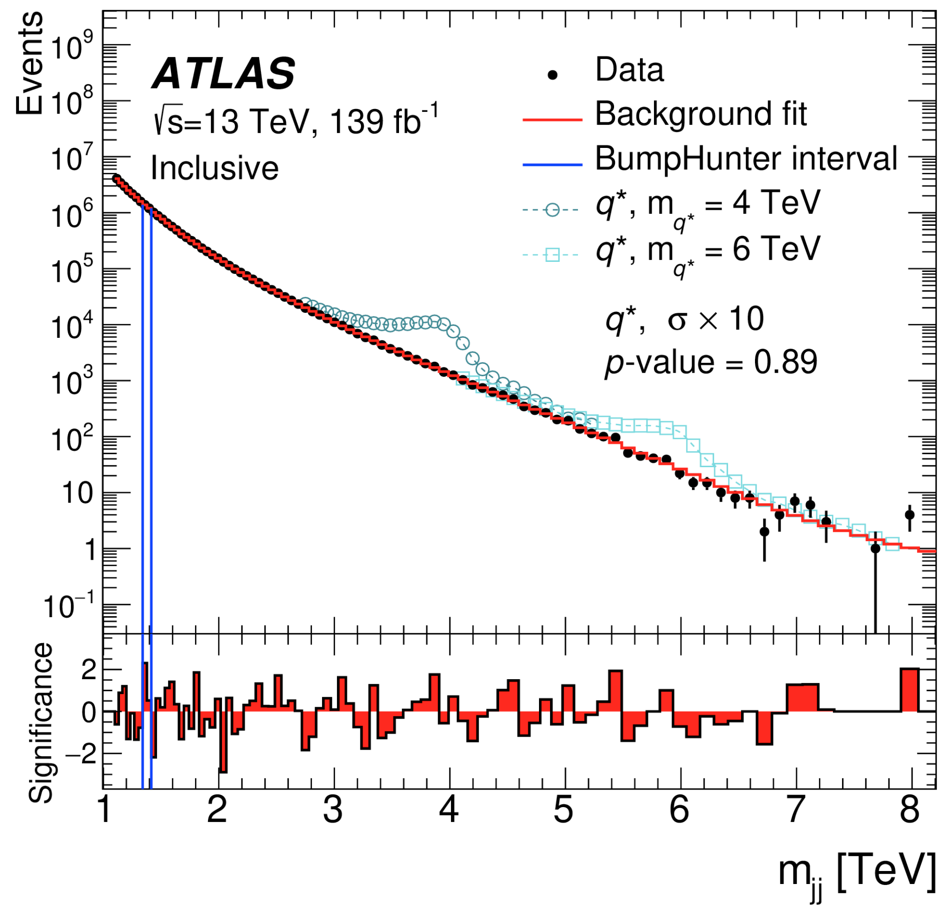
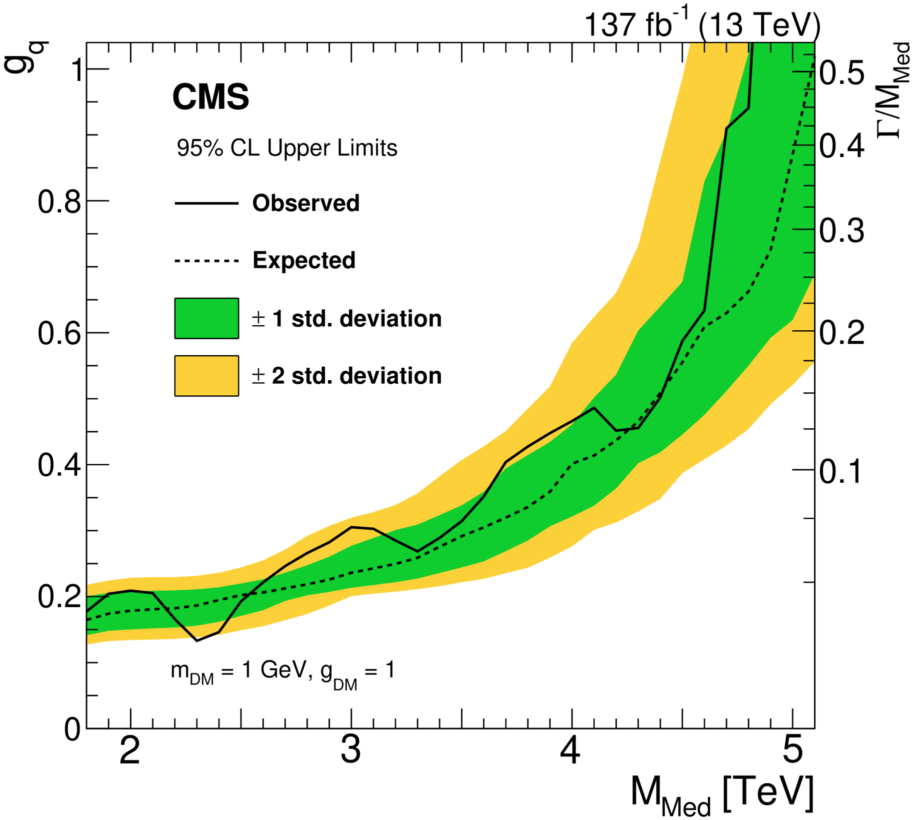
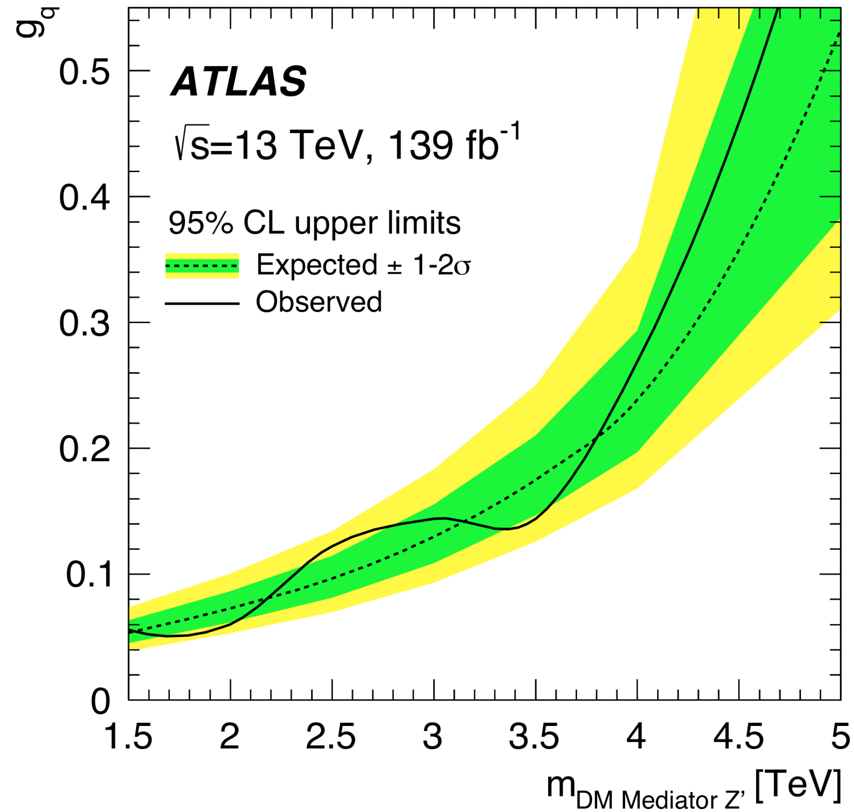


No significant deviation of the data compared to the SM expectation **set limits.**

Coupling Limits

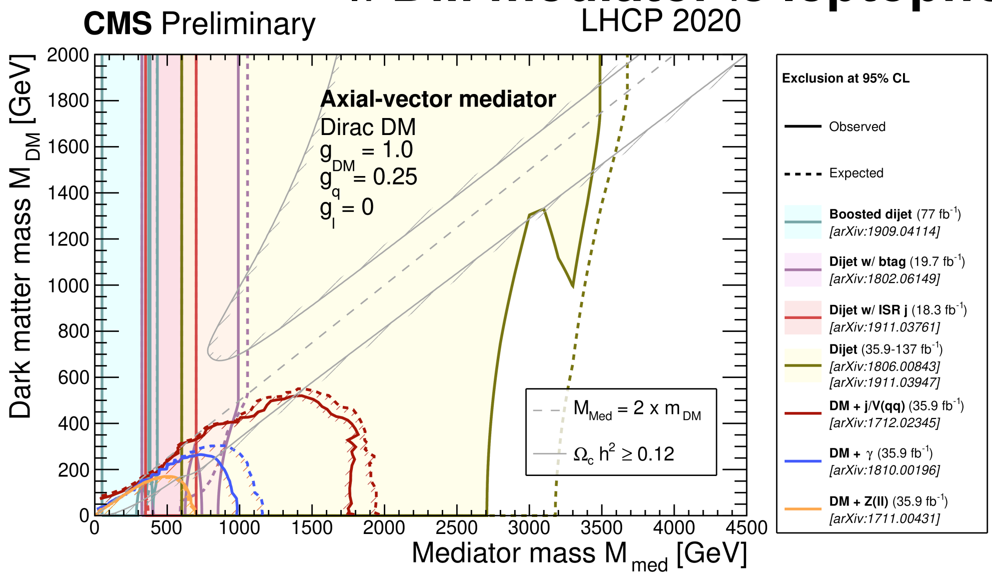


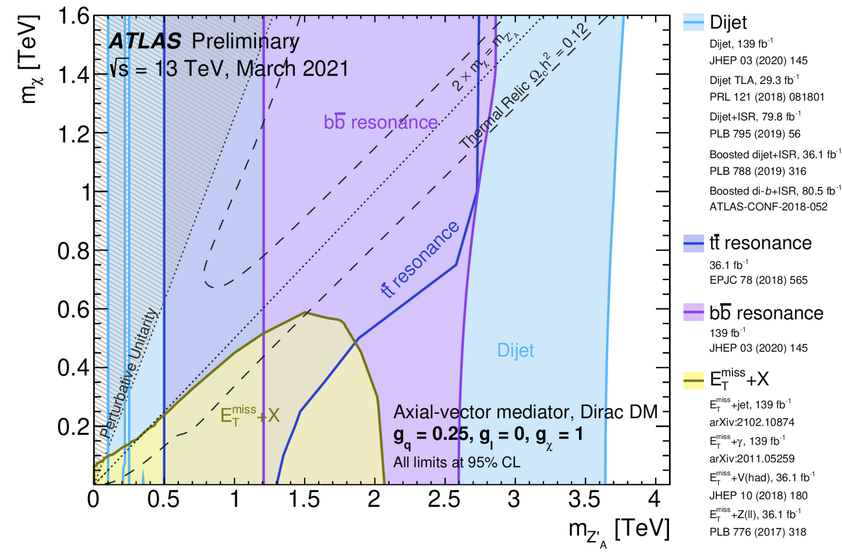


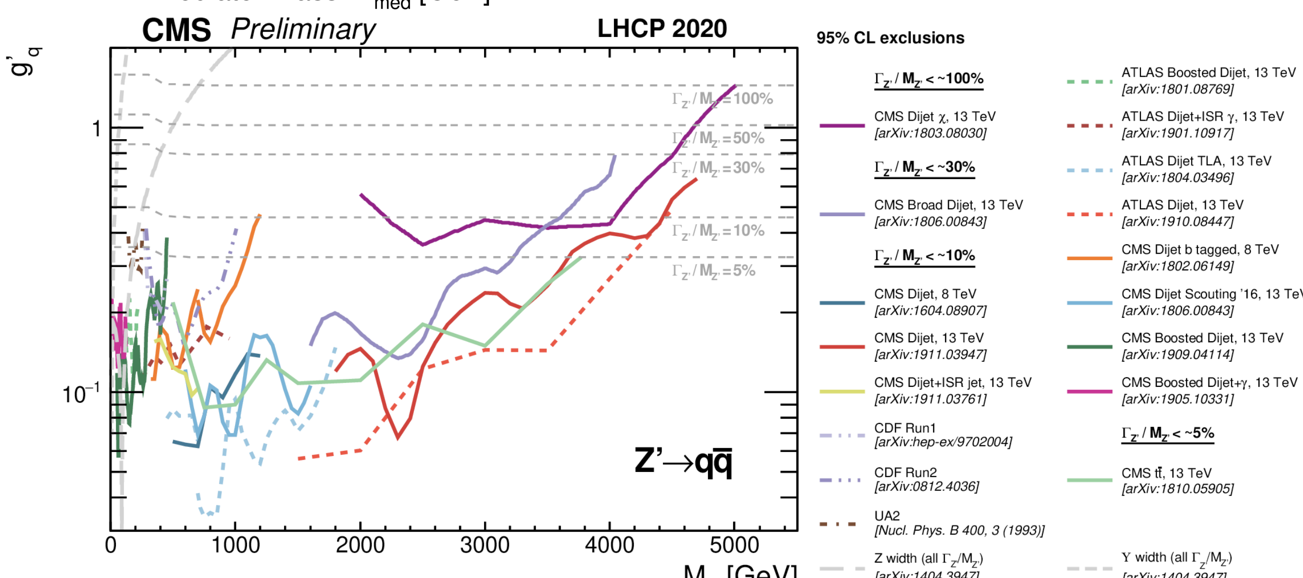
- **CMS limit extends** to **much high couplings** due to **new background prediction** method that allows to **hunt for wider resonances.**
- **ATLAS limit better** in **lower masses** due to **vastly different statistical approaches** (**CMS** one being **much more conservative**) , from now on **agreed to use a common one, that of CMS.**

Dijet searches : results

If **DM mediator** is **leptophobic dijet searches dominate**







Dilepton searches in a nutshell

Phys. Lett. B 796 (2019) 68

CMS-PAS-EXO-19-019
Sub. to JHEP

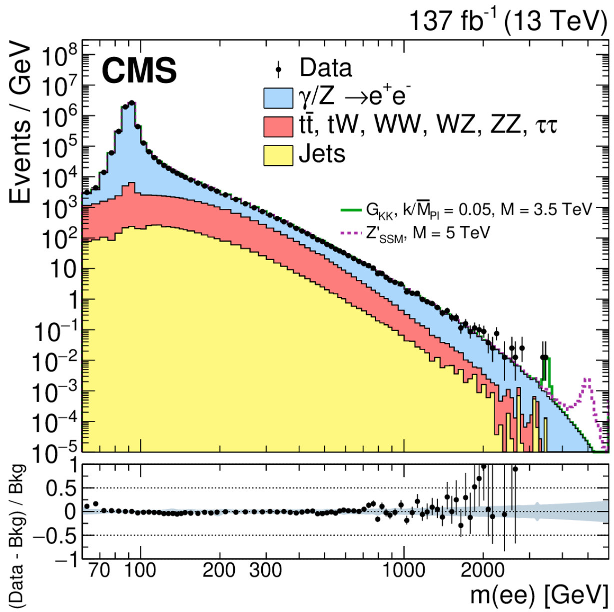
- **Resonant analysis strategy :**

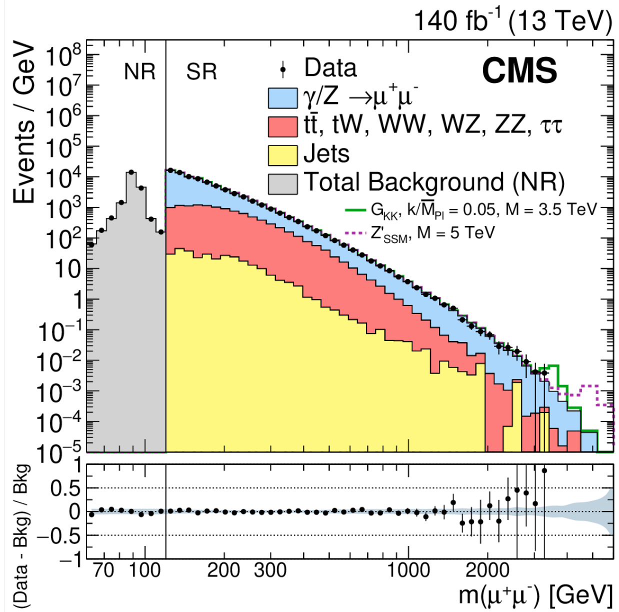
  - To estimate the background, **fit** the **simulated dilepton spectrum with an empirical function,** and use the **uncertainties** on the arbitrary **function parameters** as **constraints in the data fit.**

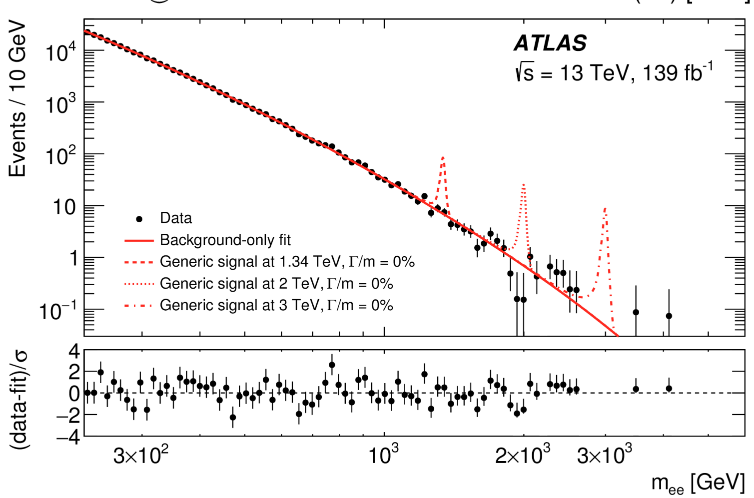
- **Non resonant analysis strategy :**

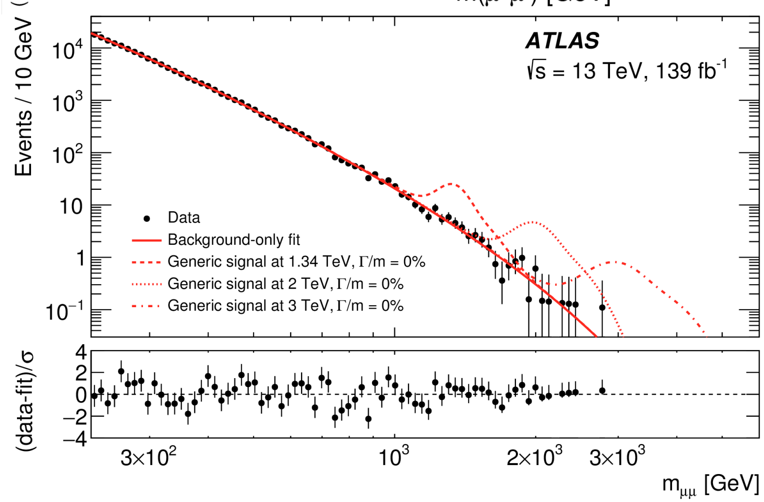
  - To estimate the background **fit the low mass end** of the **dilepton spectrum** and **extrapolate to the high end (ATLAS),** or use **Bayesian inference** using the **simulation for the background template (CMS)**

Dilepton searches





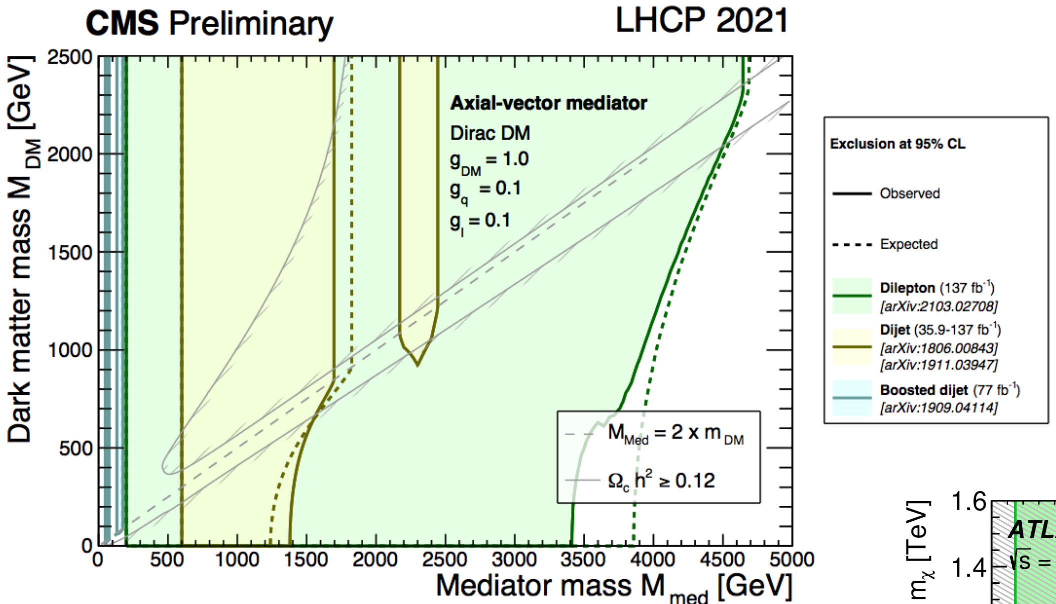


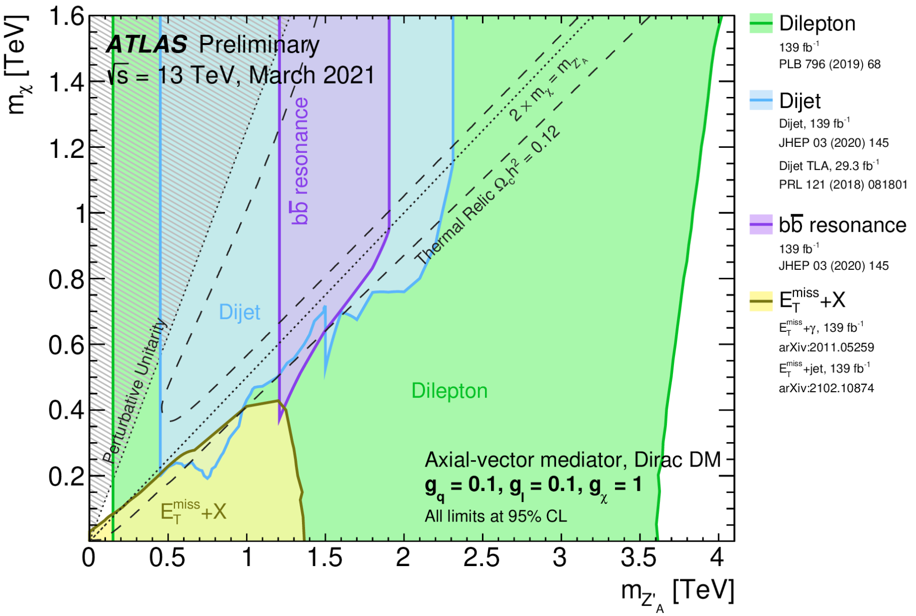


No significant deviation of the data compared to the SM expectation **set limits.**

Dilepton searches : results

If **DM mediator** is **leptophilic dilepton searches** play a **key role**





Near term future :

Complete analysis of what we have at hand!

- There are **several on-going analysis** with the **full Run II dataset**, both in the **mono-X** and the **di-X** categories in both **ATLAS and CMS.**

- Many **have already shown improvements beyond luminosity scaling**, and this is **expected to continue with remaining searches**.

- **Combinations** of the **legacy full Run II results** will also **provide more complete explorations** and boost reach even further.

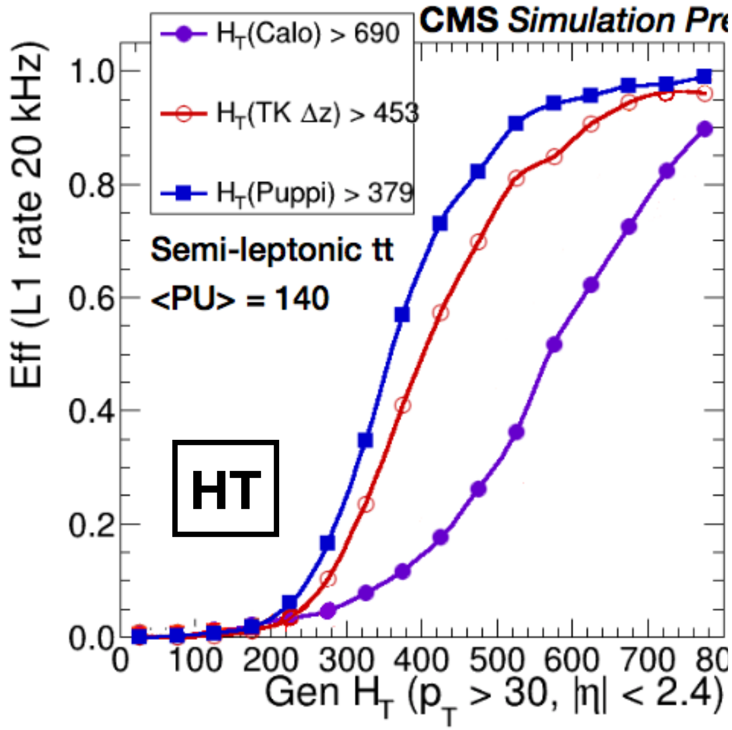
Intermediate Future : Run III

- Attempt to **improve and expand** on all **fronts**:
  - **Trigger :** try to go lower in thresholds, save PF information when necessary **in "Scouting" triggers**.
  - **Dijet mass resolution @ L1 and HLT:** try to improve using ML.
  - **Models considered:** try to expand in search design and simplified model interpretations **with t-channel mediators**
  - **New analysis methods : reduce systematics deploying new analysis method (i.e** ratio method)

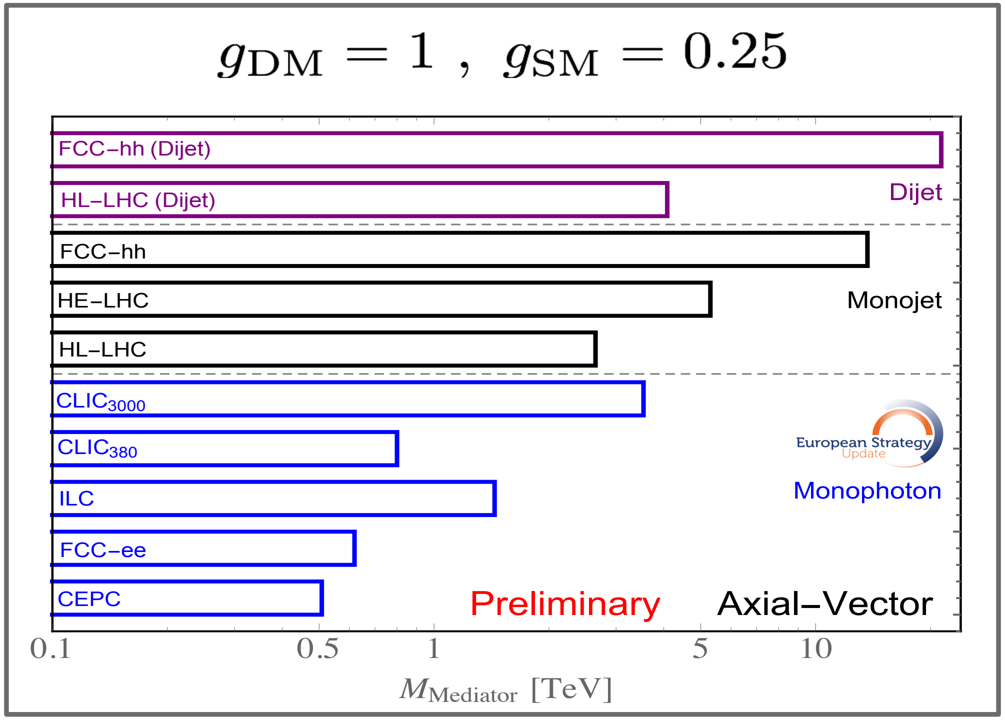
Long term future : HL-LHC & Beyond

Improve Detector, Trigger and Analysis methodologies

- **Light DM, m_χ=1GeV**



Particle Flow and Pileup mitigation at L1



Summary and Outlook

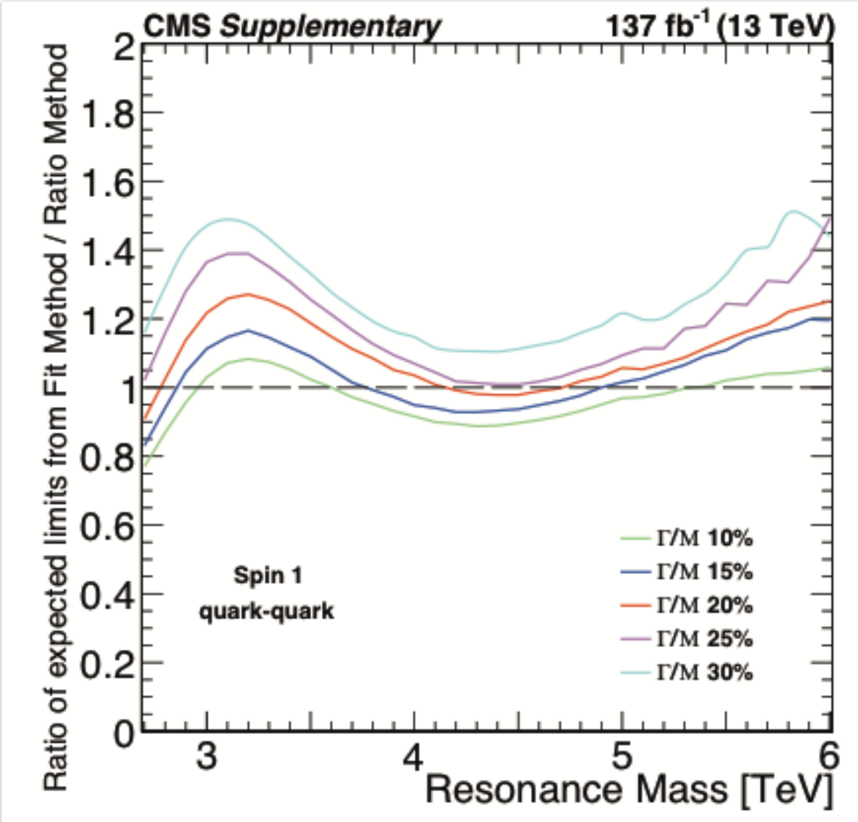
- Many **powerful** results from mono-X and di-X searches **with the full Run II datasets, extending reach beyond luminosity scaling. More analysis will be coming out in the near future.**

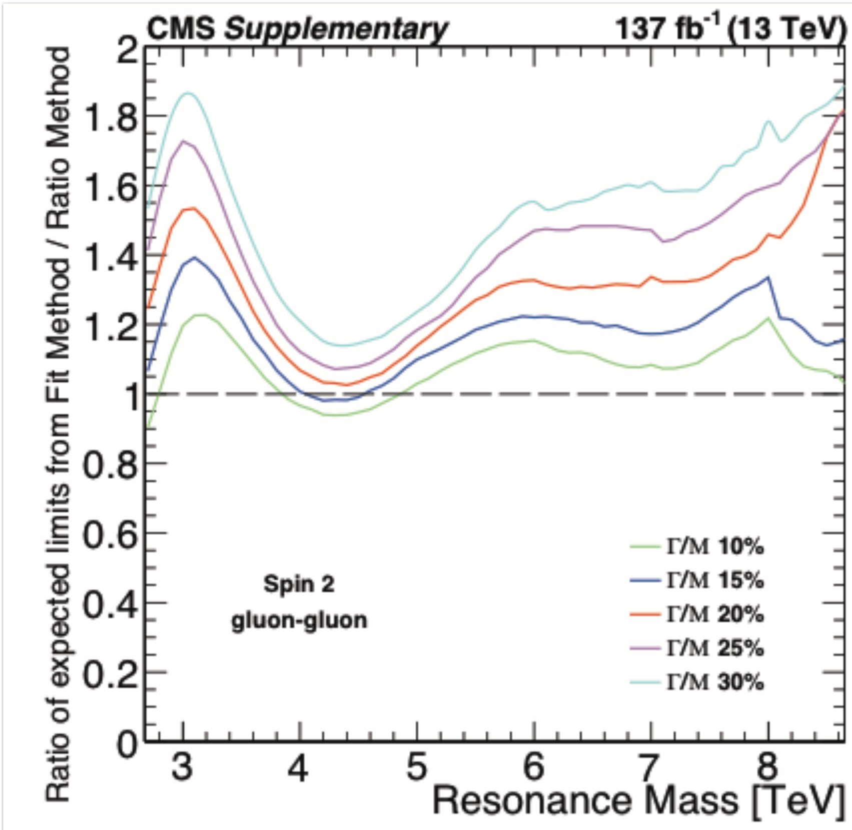
- However, with **140fb^{-1}** of the anticipated **500 fb^{-1} (Run III)** and **3000 fb^{-1} (HL-LHC) we have just started.**

- Anticipating additional data, we work on **improving our detectors, trigger, reconstruction, and analysis methods in order to significantly extend** the discovery reach for new physics.

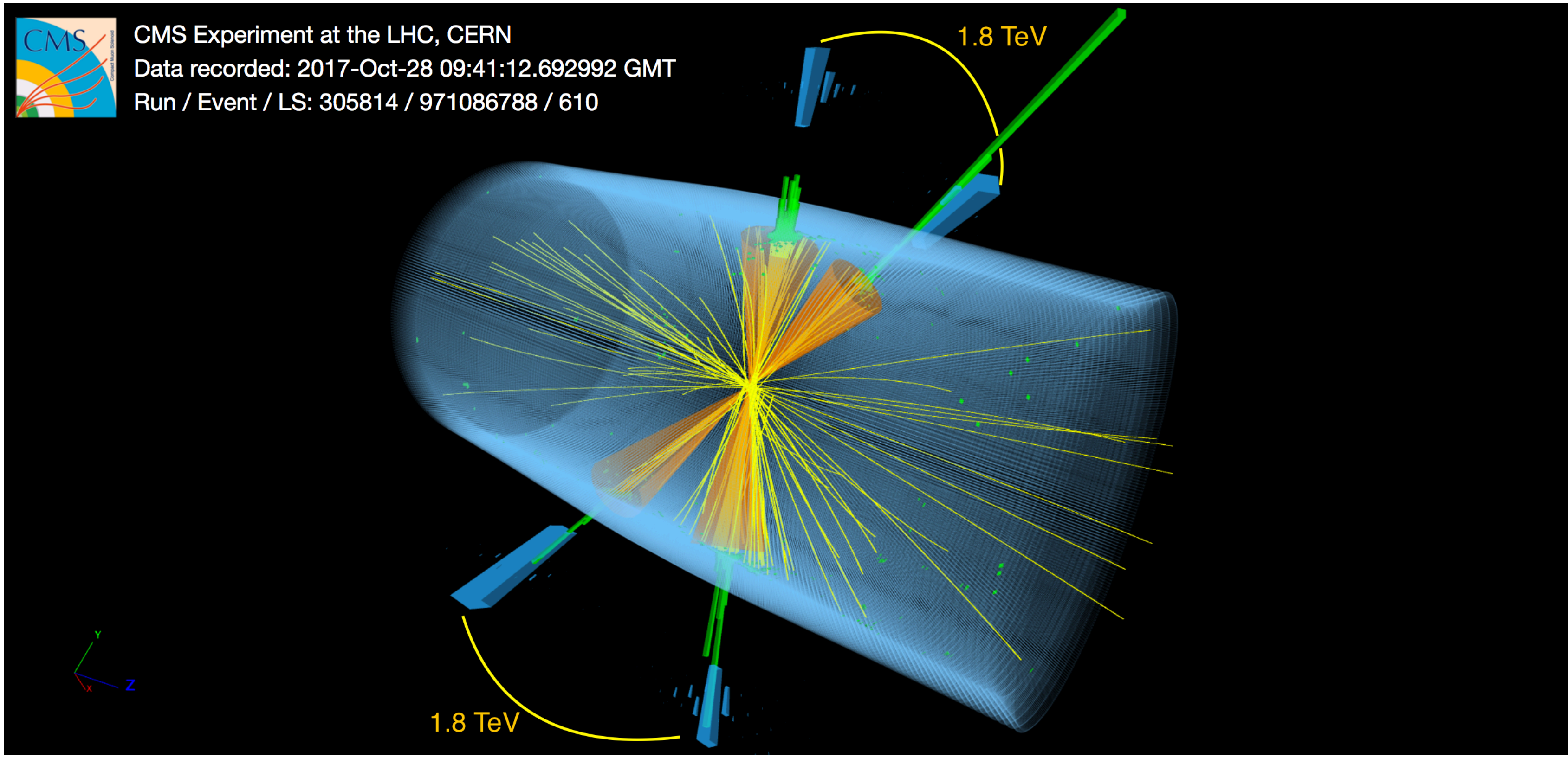
Backup slides follow

Ratio and Fit Methods : Wide Resonances





- The **ratio method**, having a more **rigid background parametrization,** and **smaller systematic uncertainties**, **improves** expected **cross section limits** by up to **factors of two**.


CMS Experiment at the LHC, CERN
Data recorded: 2017-Oct-28 09:41:12.692992 GMT
Run / Event / LS: 305814 / 971086788 / 610
1.8 TeV
1.8 TeV

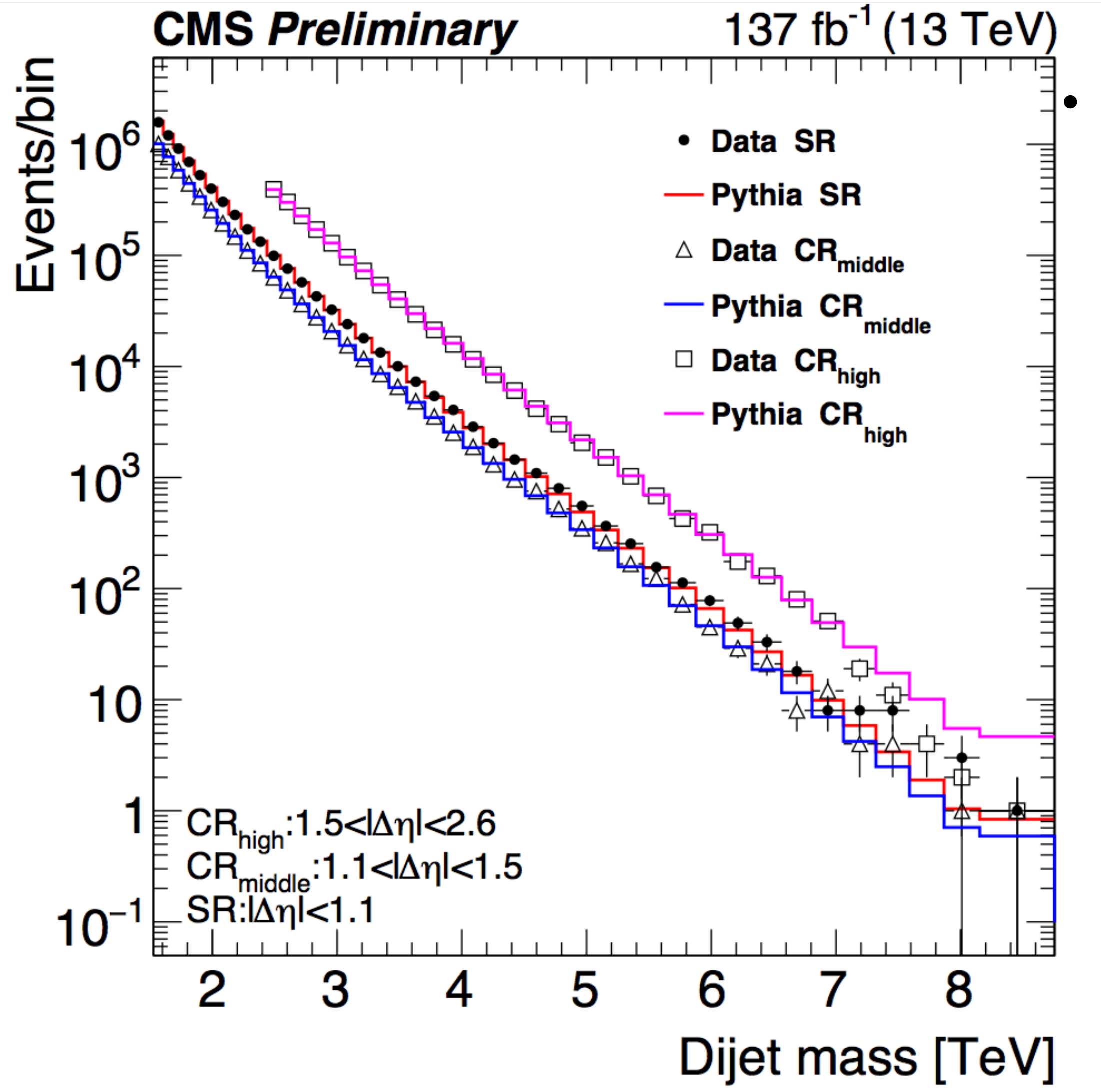
New Background Estimation Method

- **Traditional Background Modeling (used in the past 25 years) :** A **fit** with **empirical parametrizations** is performed to the data, with **its parameters treated as unconstrained (in CMS) nuisance parameters** in the final limit setting and significance estimation procedure.

- **Advantages : Well tested, well understood, significant expertise gained in many years.**

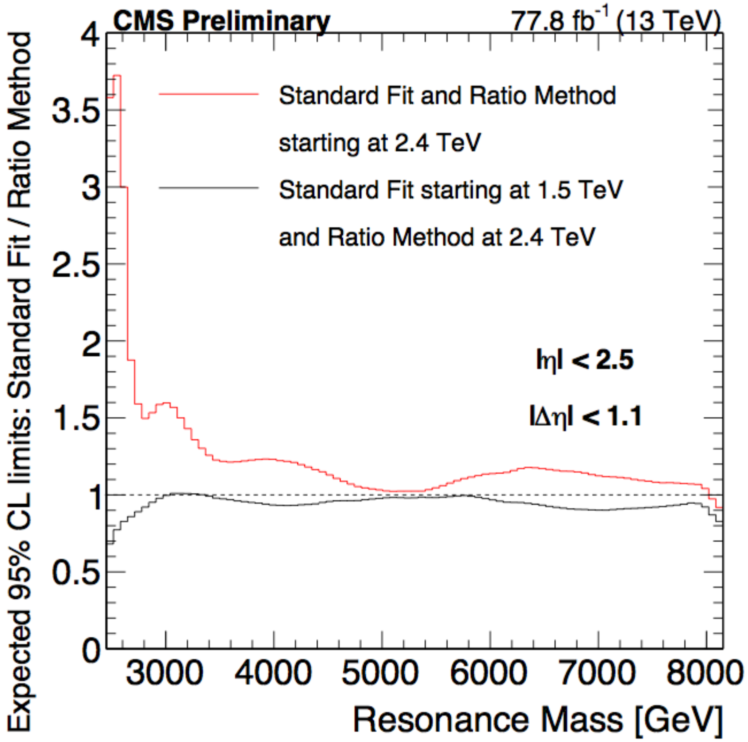
- **Disadvantages : Less robust and less performant in searches for wide resonances, or ones that might appear at the high mass tail of the distribution where not enough data exist to constrain the parametric fit.**

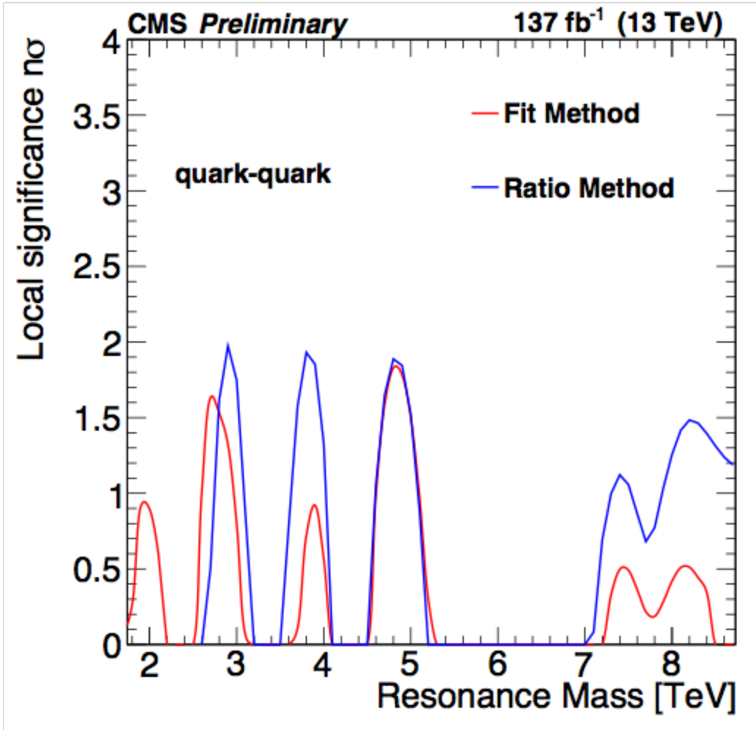
The dijet mass distributions in the signal and control regions



- The invariant mass of the dijet system in the signal and control regions:
  - **Are similar.**
  - **Show no pathologies.**
  - **In CR_{high} >99% trigger efficiency reached at 2.4 TeV. Below that dijet mass utilized standard fit.**

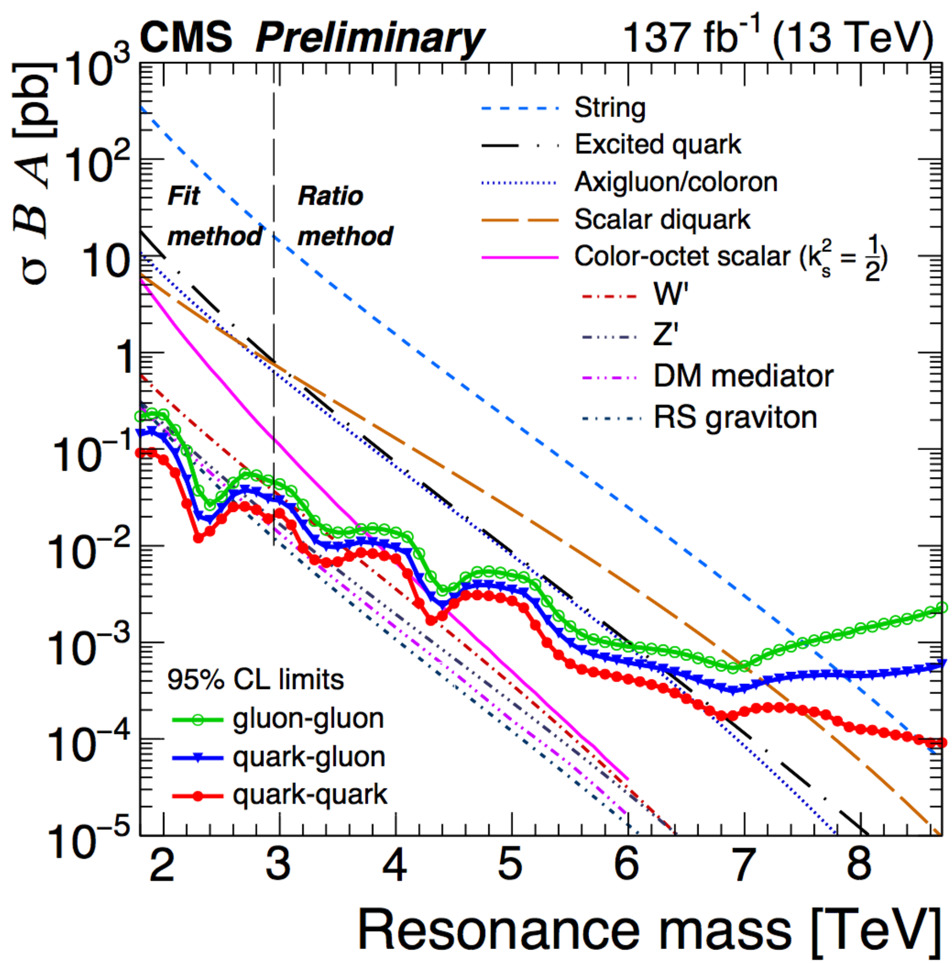
Narrow Resonances: Ratio and Fit Methods





- When **performing the parametric fit** at the **same dijet mass range,** the **ratio method** has **significantly smaller systematic** uncertainties, especially at **lower resonance masses**.
- The **ratio method "sees" larger significances** than the parametric fit, due to its **more rigid background parametrization**.
- **Local signal significance of 1.5 sigma** at **8.2 TeV near the unusual 4-jet event.**

Narrow resonances: cross section limits



- **Fitting :** Modified frequentist CL_s used for limit setting, performing a binned fit with a background and signal template.

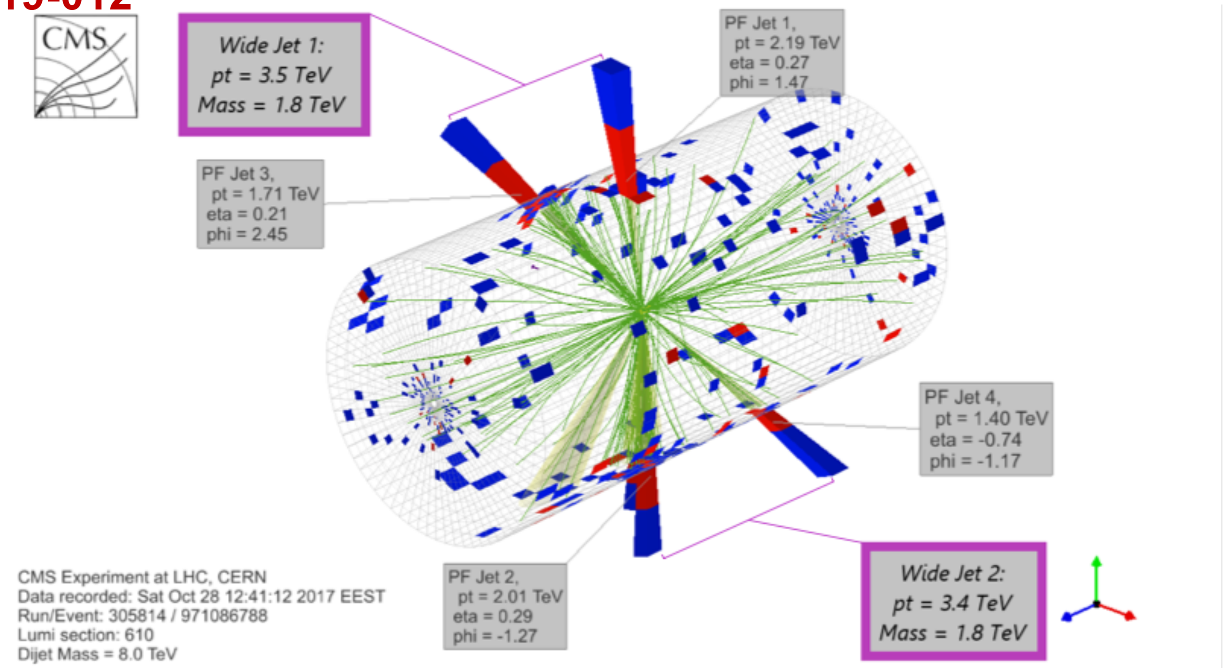
- **Systematic uncertainties:**

➢ ***Related to signal modeling :*** luminosity (log-normal constraints), jet energy scale and jet resolution (gaussian constraints).

➢ ***Related to background modelling:*** treated as freely floating automatically evaluated via profiling.

2nd Highest Dijet Mass Event

CMS-PAS-EXO-19-012



- Second highest dijet mass event at 8 TeV has unusual 4-jet topology.
  - ➢ Pairs of jets form **two wide jets** with **identical mass of 1.8 TeV.**
  - ➢ Probability of getting such a 4-jet event from QCD is approximately $5\text{x}10^{-5}$.

  [Dobrescu, Harris and Isaacson, arXiv:1810.09429**]**

- Possible **candidate** for a **massive resonance** decaying to **pairs of dijet resonances.**

The Ratio Method in math

QCD Prediction for the invariant mass of the dijet system

$$N_{\mathrm{SR}}^{\mathrm{Prediction}} = R \times N_{\mathrm{CR_{high}}}^{\mathrm{Data}}$$

Transfer factor

$$R = \mathrm{C} \times N_{\mathrm{SR}}^{\mathrm{Simulation}} / N_{\mathrm{CR_{high}}}^{\mathrm{Simulation}}$$

Transfer factor correction

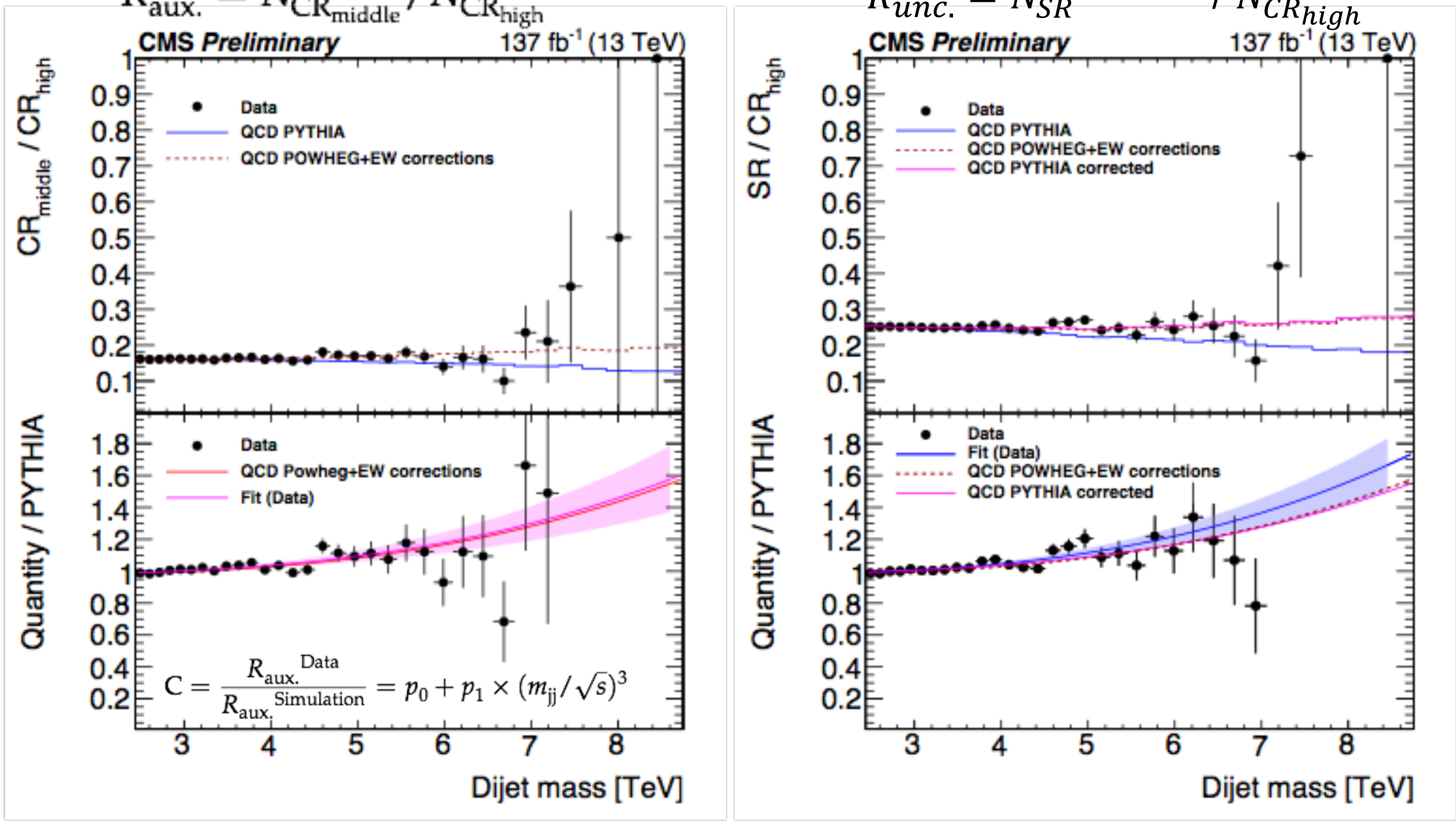
$$R_{\mathrm{aux.}} = N_{\mathrm{CR_{middle}}} / N_{\mathrm{CR_{high}}}$$

$$\mathrm{C} = \frac{R_{\mathrm{aux.}}{}^{\mathrm{Data}}}{R_{\mathrm{aux.}}{}^{\mathrm{Simulation}}} = p_0 + p_1 \times (m_{\mathrm{jj}}/\sqrt{s})^3$$

- N is the number of events in each bin of the **data dijet mass distribution, and R and R_{aux} the transfer factors from simulation.**
- We measure **(constraint)** theoretical and experimental **systematic effects,** creating **differences between the data and simulated** transfer factors, in a **data-driven way using CR_{middle}**
- A **simultaneous fit** is performed in **SR, CR_{middle} and CR_{high},** with p_0 and p_1 treated as **freely floating nuisance parameters, constrained by CR_{middle} with signal contamination taken into account.**

The Ratio Method in action

$R_{aux.} = N_{CR_{middle}} / N_{CR_{high}}$ $R_{unc.} = N_{SR}^{Simulation} / N_{CR_{high}}^{Simulation}$

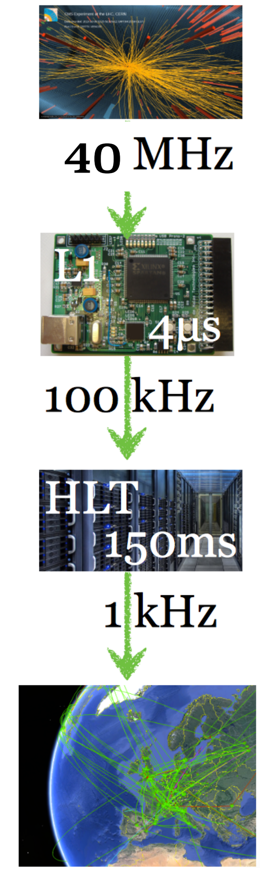


- **Transfer factors** are **flat** as a **function of dijet mass**, and **very similar** between **data and simulation ;** both the main and the auxiliary ones.

- **Missing higher QCD orders** from the simulation and **electroweak effects** are **well described by the functional form used**, and can account for the differences seen between data and simulation.

TRIGGER SYSTEM

- How can we trigger below H_T = 800-900 GeV?
- Two limitations:
  - Bandwidth = event rate × event size limited by read-out of O(100M) detector channels, disk storage, and everyone else's favorite physics channel
  - CPU time limited by computing resources for online reconstruction



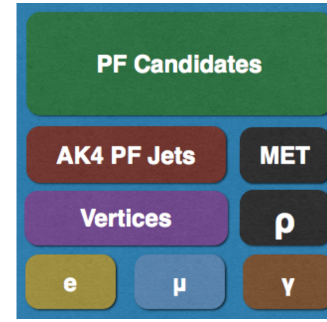
H. Brun, LP 2015

Total Reco.
BW: 1 kHz × 1 MB
CPU time: 150 ms

D. Anderson "Data Scouting at CMS" 2015 IEEE NSS/MIC

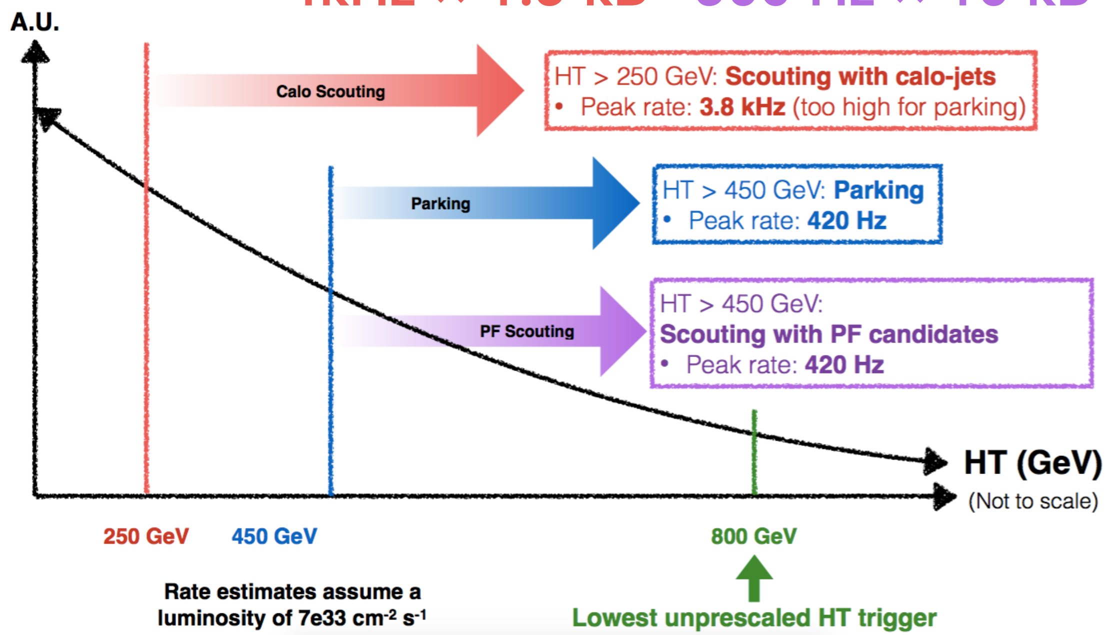
DATA SCOUTING

- Technique of data scouting
  - Reconstruct/save only necessary information to perform analysis → record more events
  - "**PF Scouting**" limited by CPU time: allows us to get down to **H_T > 450 GeV**
  - "**Calo Scouting**" allows us to get down to **H_T > 250 GeV** (L1 trigger limited)



Calo Scouting
4kHz × 1.5 kB

PF Scouting
500 Hz × 10 kB



STREAMS, DATASETS, AND CONTENT

ScoutingCaloMuon

- ➡ ScoutingCaloCommissioning
- ➡ ScoutingCaloHT
- ➡ ScoutingCaloMuon

~1.5 kB / event, 4 kHz

ScoutingPF

- ➡ ScoutingPFCommissioning
- ➡ ScoutingPFHT

~10 kB / event, ~ 500 Hz

Parking

- ➡ ParkingHT
- ➡ ParkingMuon

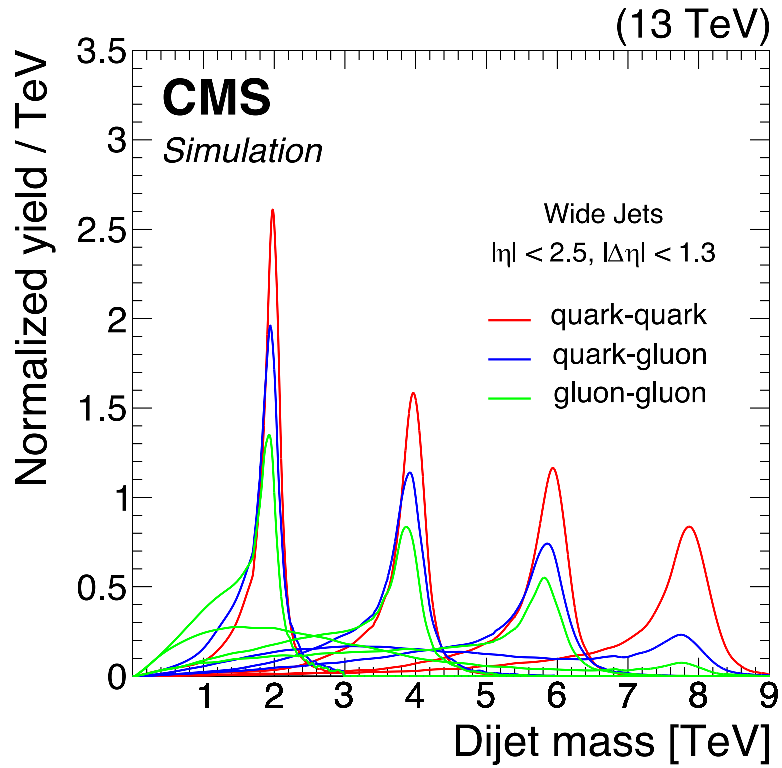
~ 1 MB / event,
~ 400 Hz

PhysicsParkingScoutingMonitor

- ➡ ParkingScoutingMonitor

~ 1 MB / event, ~ 30 Hz

Narrow resonances



Signal Modeling for Narrow Resonances : Convolution of a Breit-Wigner with a gaussian for detector resolution effects.

Int.J.Mod.Phys. A26 (2011) 5005-5055

$$\hat{\sigma}(m)\,(1+2\to R\to 3+4) = 16\pi\mathcal{N}\times\frac{\Gamma(1+2\to R)\times\Gamma(R\to 3+4)}{(m^2-m_R^2)^2+m_R^2\Gamma_R^2}$$

Narrow-width approximation

$$\frac{1}{(m^2-m_R^2)^2+m_R^2\Gamma_R^2}\approx\frac{\pi}{m_R\Gamma_R}\delta(m^2-m_R^2)$$

$$\sigma_{had}(m_R) = 16\pi^2\times\mathcal{N}\times\mathcal{A}_{\cos\theta^*}\times BR\times\left[\frac{1}{s}\frac{dL(\bar{y}_{min},\bar{y}_{max})}{d\tau}\right]_{\tau=m_R^2/s}\times\frac{\Gamma_R}{m_R}$$

Gluon-gluon vs qq resonances

- **Tails towards lower mass values primarily from QCD radiation.**

- The dijet mass resolution within the Gaussian core of gluon-gluon (quark-quark) resonances varies from 15 (11)% at a resonance mass of 0.5 TeV to 7.5 (6.3)% at 2 TeV for wide jets reconstructed using CaloJets, and varies from 6.2 (5.2)% at 2 TeV to 4.8 (4.0)% at 8 TeV for wide jets reconstructed using PF-Jets.

- The contribution of the low mass tail to the line shape also depends on the parton content of the resonance. Resonances decaying to gluons, which emit more QCD radiation than quarks, are broader and have a more pronounced tail. For the high-mass resonances, there is also a significant contribution that depends both on the parton distribution functions and on the natural width of the Breit–Wigner distribution. **The low-mass component of the Breit–Wigner distribution of the resonance is amplified by the rise of the parton distribution function at low fractional momentum. These effects cause a large tail at low mass values.**

- Interference between the signal and the background processes is model dependent and not considered.

Wide Spin 0,1,2 resonances

arXiv:hep-ph/0603175

$$\hat{\sigma} \propto \frac{\pi}{m^2} \frac{[\Gamma^{(i)}M]\,[\Gamma^{(f)}M]}{(m^2 - M^2)^2 + [\Gamma M]^2}$$

- For a Spin-2 resonance, a CP-even tensor such as a graviton, the partial widths in both the gluon-gluon channel and the quark-quark channel are proportional to the resonance mass cubed ($\Gamma \propto M^3$) and PYTHIA8 makes the following replacement for an RS graviton:

$$\Gamma M \to \left(\frac{m^4}{M^4}\right) \Gamma M$$

- For as Spin-1 resonance both for the CP-even vector and the CP-odd axial-vector cases, the partial width is proportional to the resonance mass ($\Gamma \propto M$) and generators make the well known replacement

$$\Gamma M \to \left(\frac{m^2}{M^2}\right) \Gamma M$$

- Shapes and limits for qq and gg resonances
  - Low mass tail from PDFs is suppressed by factor of $(m/M)^4$ in Breit-Wigner for the spin 0 or 2 case
  - No such suppression for the spin 1 case.

Wide Spin 0,1,2 resonances

JHEP 11 (2015) 150

- ***Spin-2 resonances decaying to dijets are required to be CP-even****, because the dijet decays of* ***any spin-2 CP-odd resonances are suppressed***

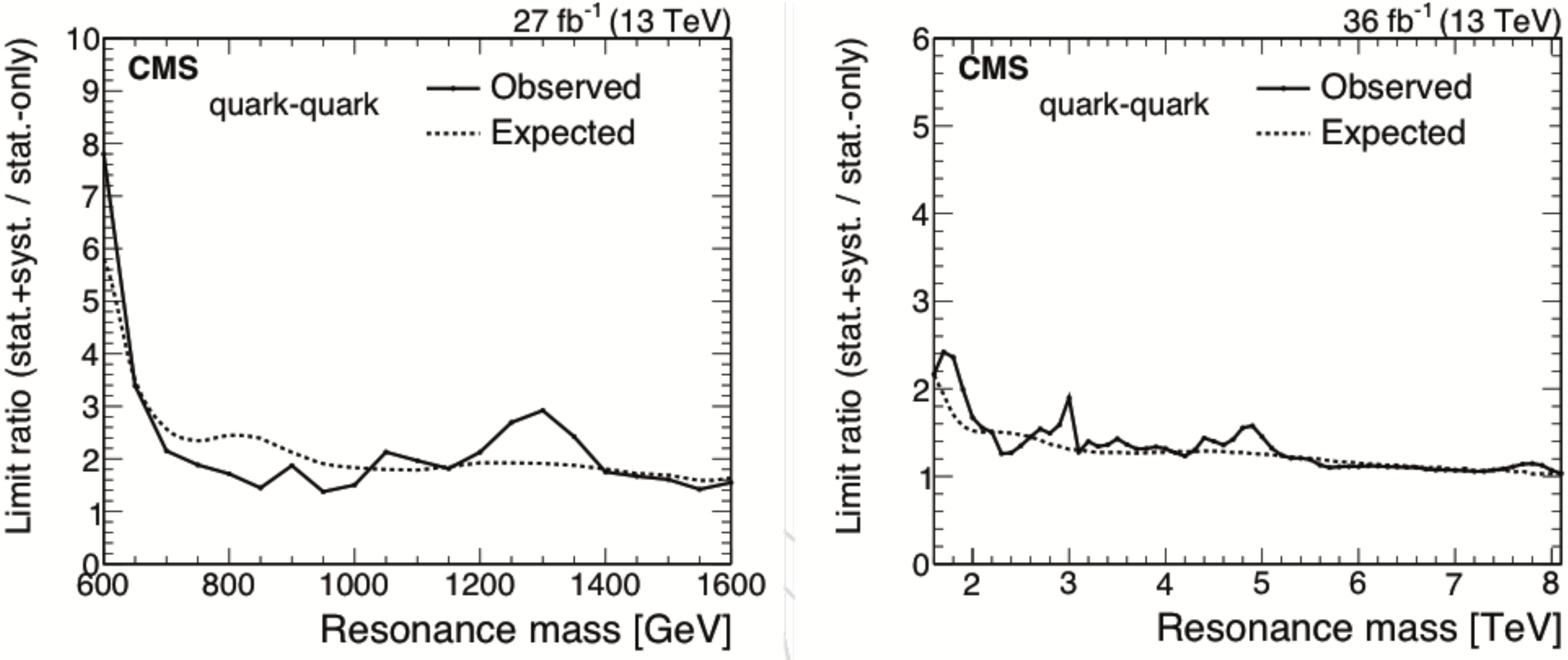
- ***Spin-0 resonances coupling directly to pairs of gluons or to pairs of gluons through fermion loops will have a partial width proportional to the resonance mass cubed*** *and should have a* ***similar shape as a spin-2 resonance*** *in the* ***gluon-gluon*** *channel.*

- ***Spin-0 resonances coupling to quark-quark will have a partial width proportional to the resonance mass*** *and should have a* ***similar shape as a spin-1 resonance*** *in the* ***quark-quark*** *channel.*

- *Therefore, the* ***three shapes we consider for spin-2 resonances coupling to quark-quark and gluon-gluon and for spin-1 resonances coupling to quark-quark, are sufficient to determine the shapes of all broad resonances decaying to quark-quark or gluon-gluon.***

- *We do not consider broad resonances with non-integer spin decaying to quark-gluon in this paper.*

Systematics vs Statistical Uncertainties



Main procedude-MaxLikelihood Fit

To set limits the Likelihood function $L\left(data|\mu,\vec{\theta}\right)$ is calculated:

$$L\left(data|\mu,\vec{\theta}\right)=\prod_{i=1}^{N_b}\frac{\left(\mu s_i+b_i\right)^{n_i}}{n_i!}\mathrm{e}^{-\left(\mu s_i+b_i\right)}p\left(\tilde{\theta}|\theta\right)$$

,where **μ is the signal strength modifier**, θ represents the full suite of nuisance parameters, n_i is the number of events in the i-th bin, s_i the corresponding signal yield and b_i the corresponding background yield.

For the unbinned likelihood with k total events the above product would be:

$$\prod_{i=1}^{k}\left(\mu S f_s\left(x_i\right)+B f_b\left(x_i\right)\right)\mathrm{e}^{-\left(\mu S+B\right)}$$

S : total expected signal yield
B : total expected bkg yield
fs, fb : signal and bkg pdf' s

Note: The Poisson probability to observe n_i events in the i-th bin is given by :

$$p_i=\frac{\left(\mu s_i+b_i\right)^{n_i}}{n_i!}\mathrm{e}^{-\left(\mu s_i+b_i\right)}$$

Test statistic q_μ

To compare the data vs the bkg, bkg+signal hypothesis we construct the test statistic:

$$\tilde{q}_\mu = -2\ln\left(\frac{L(data|\mu,\hat{\theta}_\mu)}{L(data|\hat{\mu},\hat{\theta})}\right)$$,with the constraint $0 \leq \hat{\mu} \leq \mu$

where $\hat{\theta}_\mu$ maximizes the likelihood for the given μ (typically μ=1),

and $\hat{\mu},\hat{\theta}$ are the values that maximize the likelihood when both are left freely to fluctuate (global maximum) .

For the perfect match the likelihood ratio becomes equal to one, which means that the lower the test statistic q, the better the agreement.

Asymptotic calculation of cross section upper limits

- On the absence of an observed resonance we proceed to set upper limits on the cross section for the production of any resonance.

Asimov Dataset Technique:

- Asimov Dataset ≡ *the dataset, that when used to evaluate the estimators for all parameters concerning our hypothesis (QCD background + signal resonance shape), one obtains the true parameter values.*
- **The Asimov dataset is approximated by the background prediction for each method**

We define the Likelihood for signal + background hypothesis:

$$\mathcal{L}(data|\vec{\theta}) = \prod_{i=1}^{n_b} Poisson(x_i|b_i(\vec{\theta}) + \mu s_i(\vec{\theta})) = \prod_{i=1}^{n_b} \frac{(b_i(\vec{\theta}) + \mu s_i(\vec{\theta}))^{x_i} e^{-(b_i(\vec{\theta})+\mu s_i(\vec{\theta}))}}{x_i!}$$

We evaluate this Likelihood with the Asimov Dataset and we set limits:

$$\sigma^2 \approx \frac{(\mu - \mu')^2}{q_{\mu,A}}$$

where

$$q_{\mu,A} \equiv -2ln\frac{\mathcal{L}(\mu,\hat{\theta})}{\mathcal{L}(\hat{\mu},\hat{\theta})}$$