QCD@LHC

Aug 31–Sept 3 · 2020

QCD impact in BSM searches at LHC

Niki Saoulidou,

National and Kapodistrian University of Athens, Greece

On behalf of the ATLAS and CMS Collaboration

QCD@LHC-X, the 2020 edition of the joint theoretical-experimental conference on applications of QCD to collider physics, will be held online via Zoom.

QCD@LHC-X , 31st August– 3rd September 2020,

Virtually in Bologna, Italy

01/09/2020

Outline

- **Introduction**
- **QCD uncertainties in *selected powerful and general* BSM searches**
  - Dijet and Monojet searches (Mjj, χ, E_{Tmiss})
  - Dilepton resonant and non-resonant searches (M_{ll})
- **QCD uncertainties when *looking inside jets***
  - Quark-gluon separation
  - Jet taggers, jet mass
- **Summary and Outlook**

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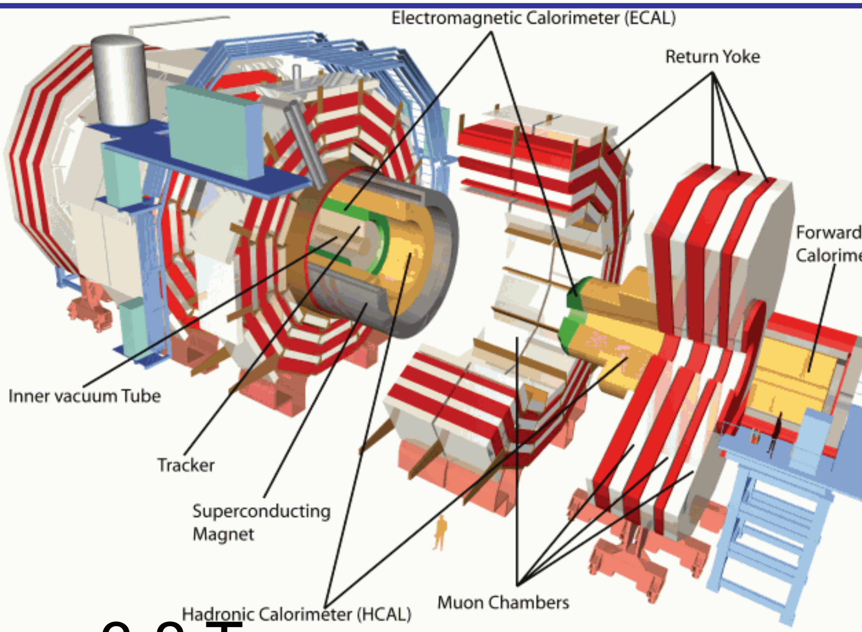
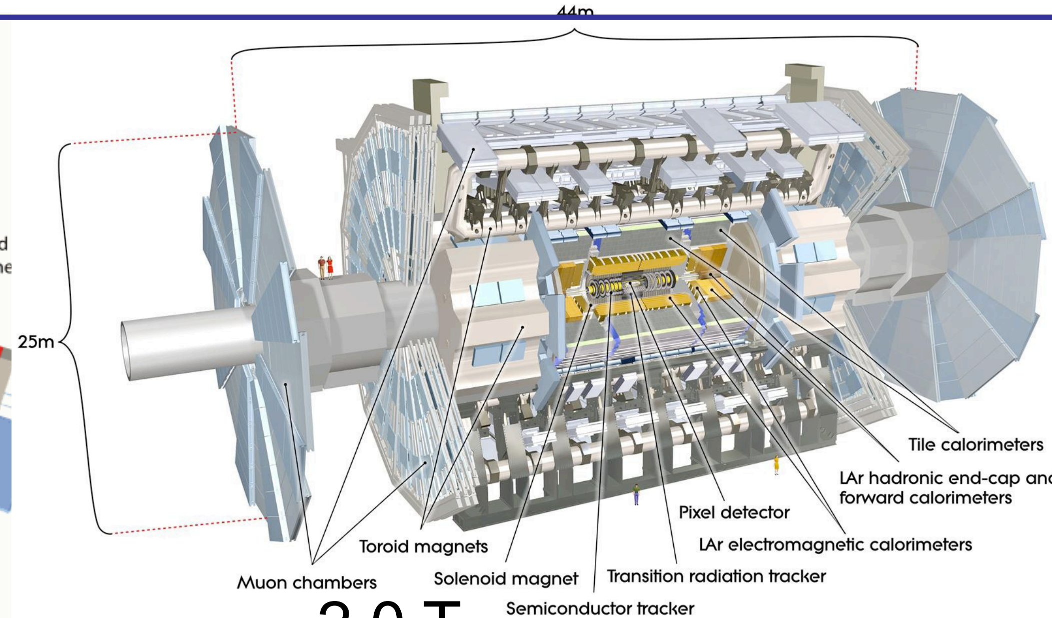
ATLAS and CMS Experiments





3.8 T

Pixels

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

Electromagnetic Calorimeter

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

Hadronic Calorimeter

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

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

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

Electromagnetic Calorimeter

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

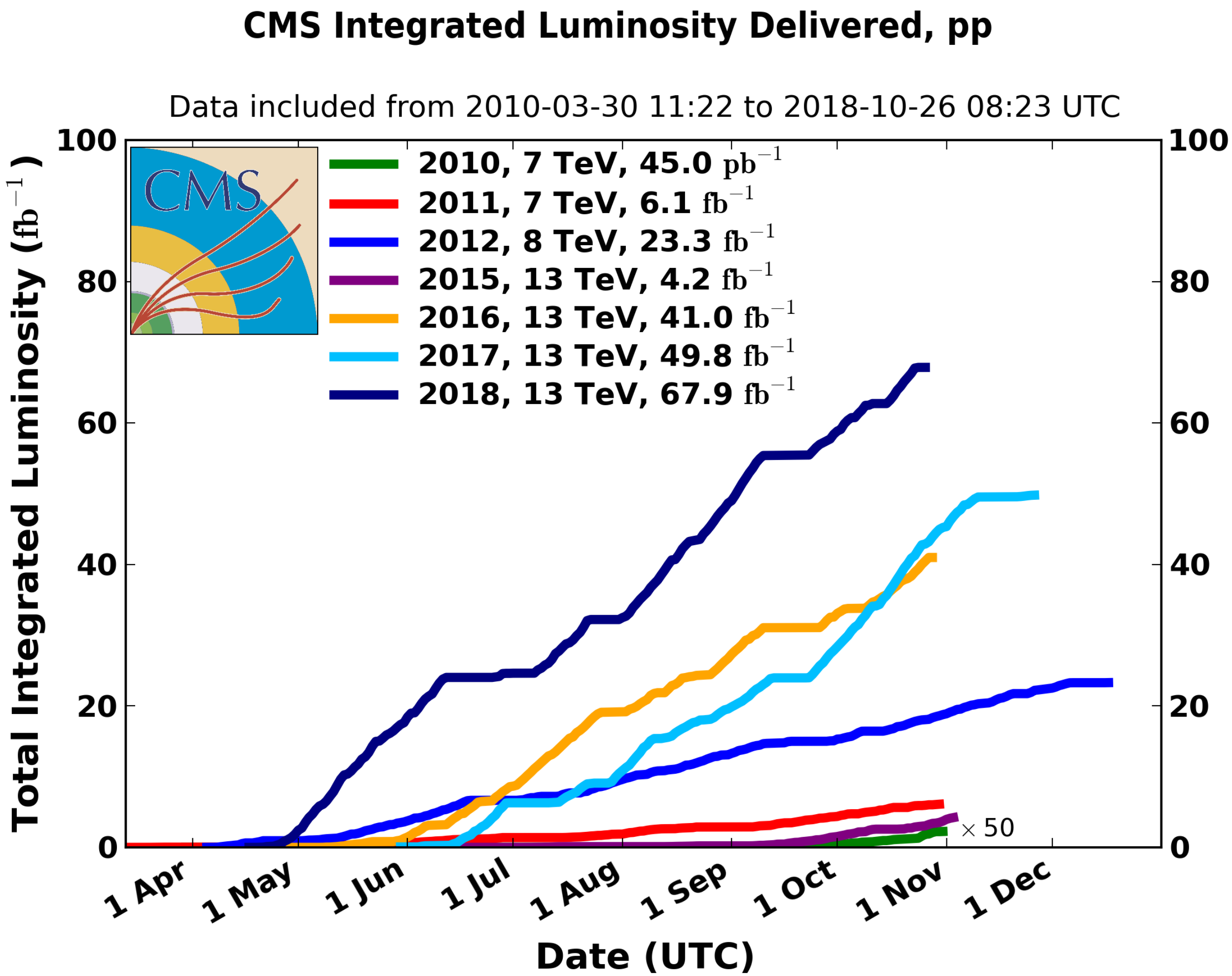
Hadronic Calorimeter

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

Muon Spectrometer

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

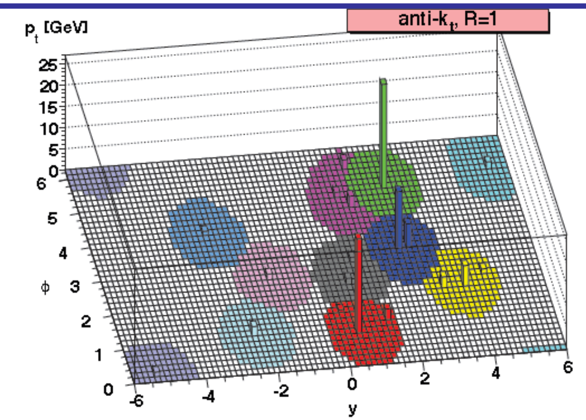
The LHC Accelerator



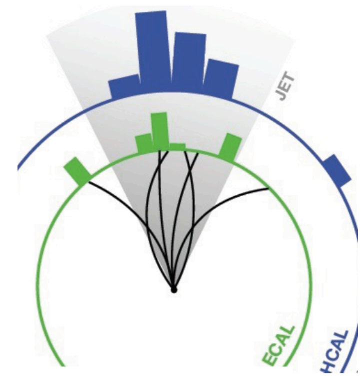
- LHC Accelerator had so far a superb performance.

Jet Reconstruction

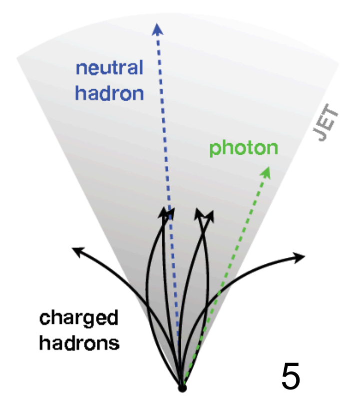
- **Most analyses use the Anti-kt clustering algorithm :** with a cone R = 0.4 and 0.8 for CMS and 0.4 and 1.0 for ATLAS, which is infrared and collinear safe, geometrically well defined, and tends to cluster around the hard energy deposits.



- **Calorimeter Jets :**Clustering of Calorimeter Towers composed of ECAL and HCAL energy deposits.



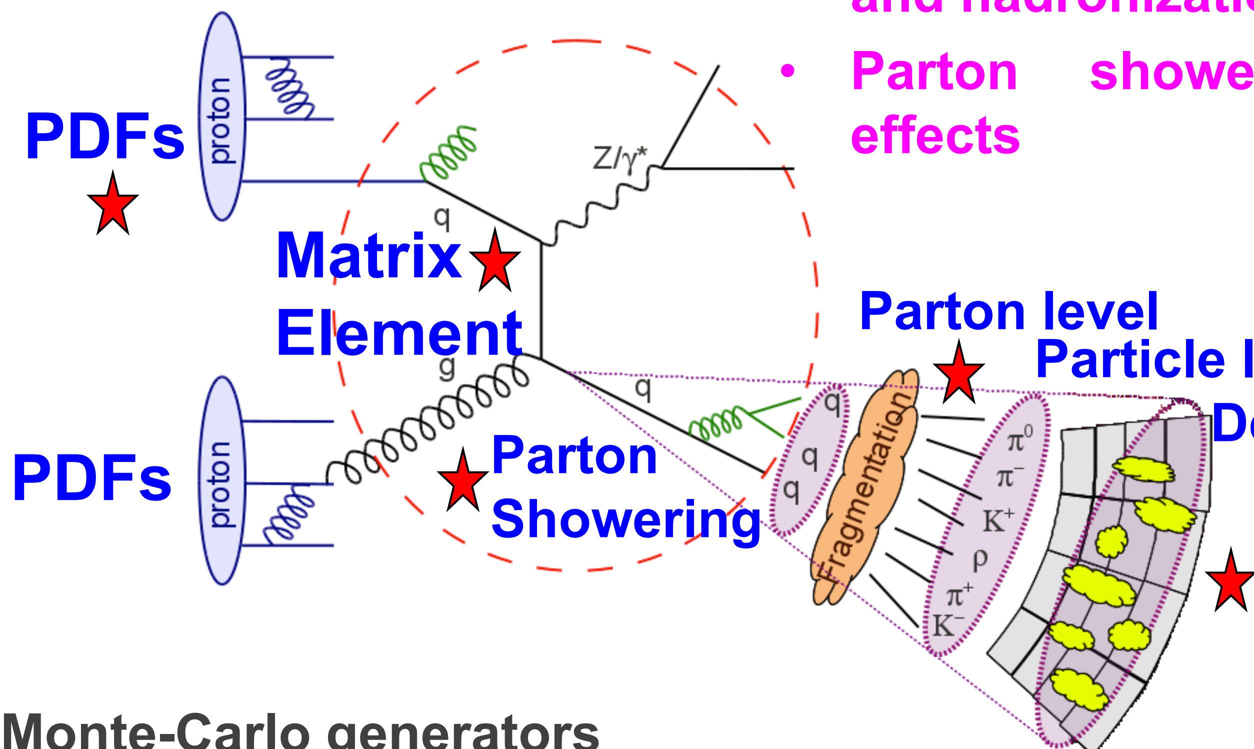
- **Particle Flow Jets:** Clustering of Particle Flow candidates constructed combining information from all sub-detector systems.



- **Jet taggers and jet - substructure :** several **jet taggers** and **jet substructure** techniques developed.

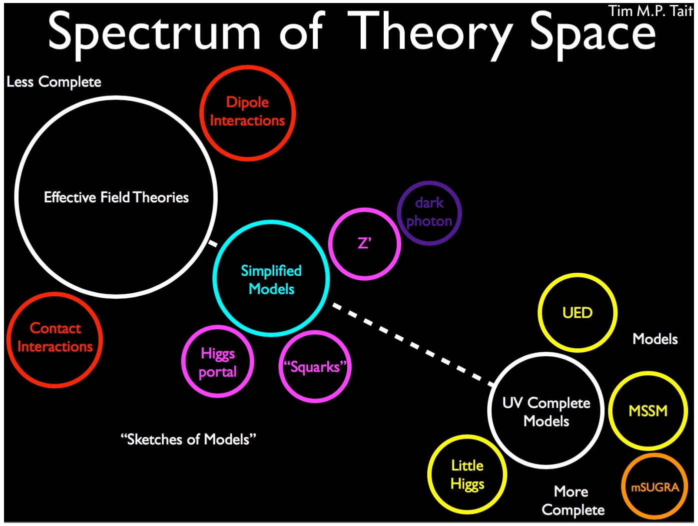
Theoretical Tools for Simulations ⇔ Sources of uncertainties★

- **Perturbative QCD calculations @ NLO**
- **Non-perturbative corrections for multi-parton interaction and hadronization.**
- **Parton showering (PS) effects**



- **LO QCD Monte-Carlo generators**

Dark Matter Searches at the LHC : A key part of the physics search program

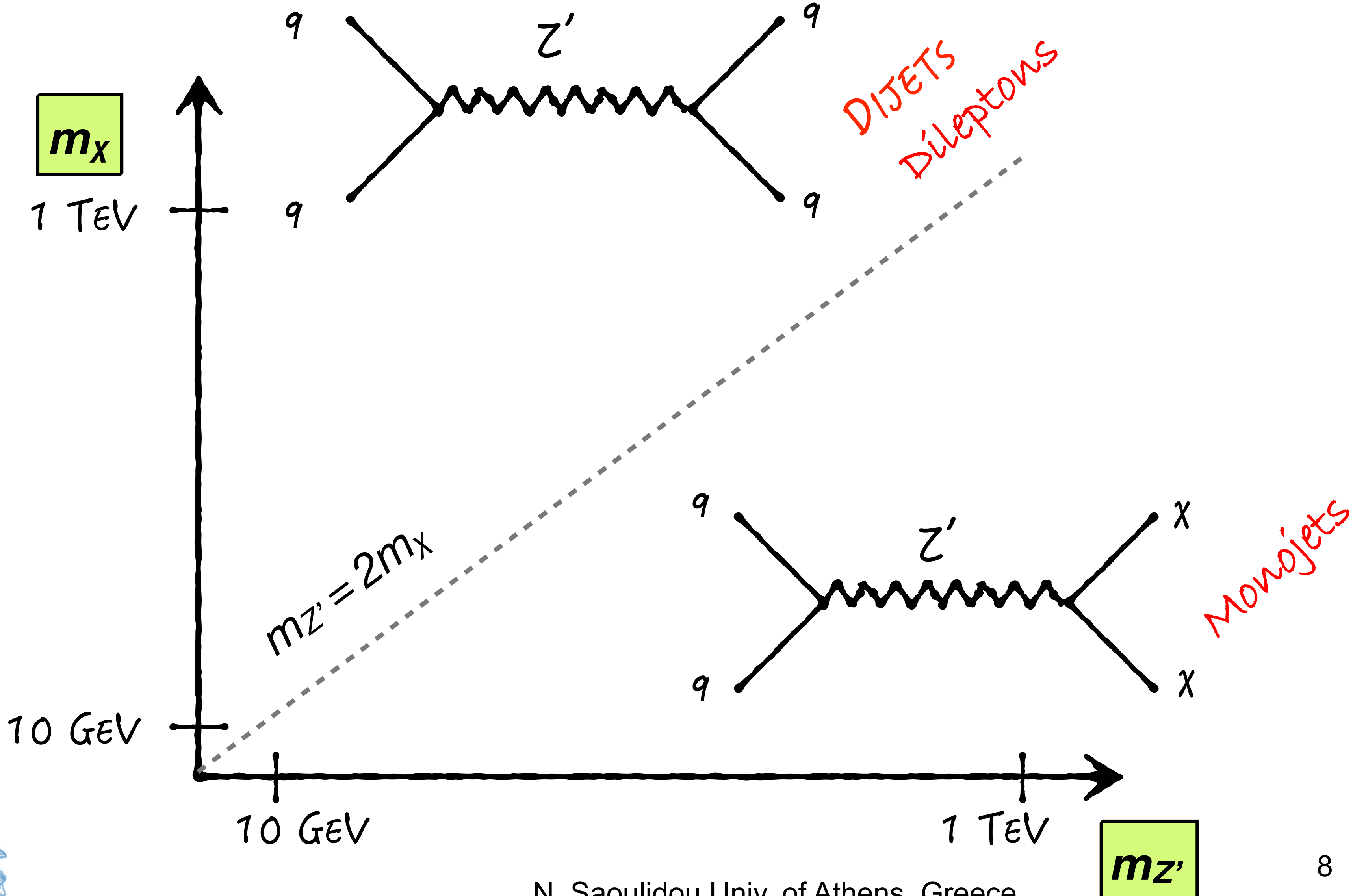


- There is plenty of evidence for the existence of **Dark Matter** which we have only **seen** so far **gravitationally**.

- ***Direct Dark Matter searches:*** *Detect interactions of DM particle (or particles) with 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 DM*** *and DM* ***mediators in the Lab***

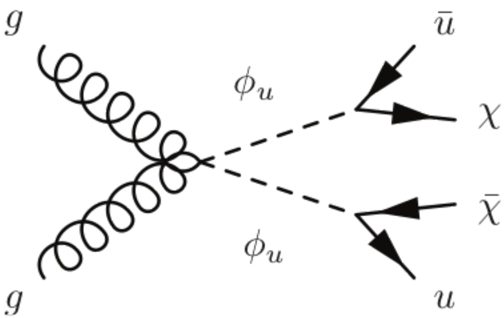
Dark Matter Searches @ the LHC :

Complementarity between difference searches

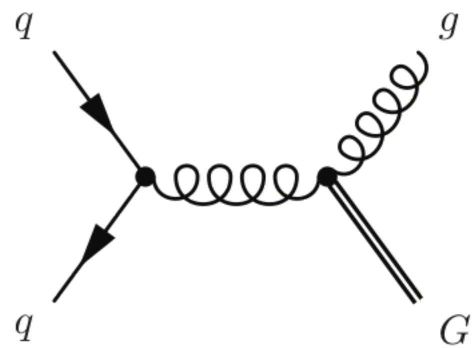


Monojet-monoV searches

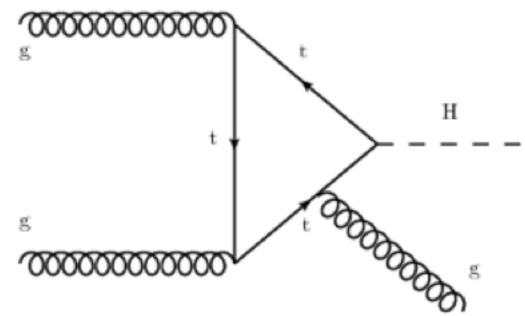
Access a broad range of new physics hypothesis



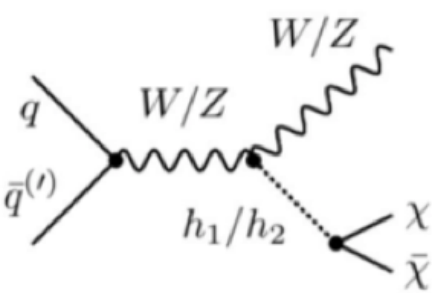
Dark Matter



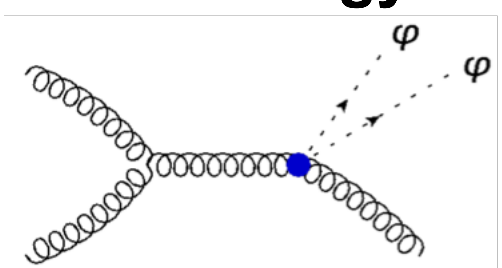
Gravitons (ADD model)



Higgs -> invisible



Dark Energy



- **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-monoV searches : Background estimation

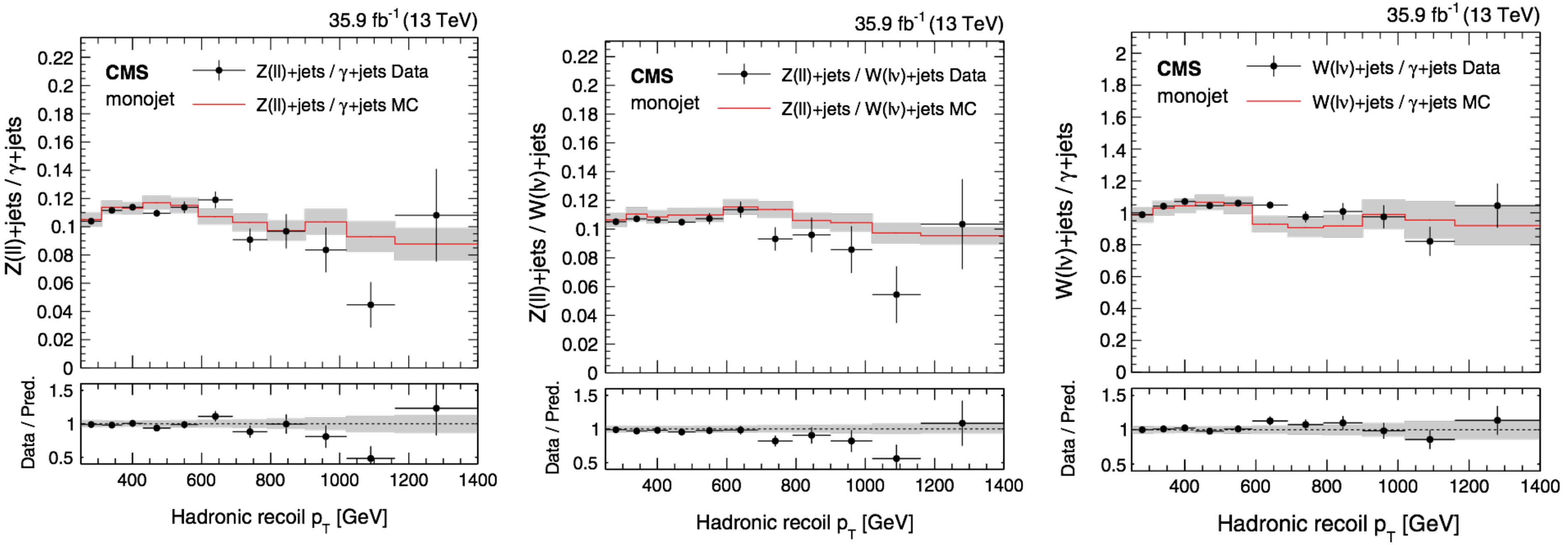
- **Background estimation :** Data-driven, in order to minimize dependence on simulation, and hence **significantly reduce theoretical systematic uncertainties.**

- Five **control regions** are used, **$Z \rightarrow ee$, $Z \rightarrow \mu\mu$, $W \rightarrow e\nu$, $W \rightarrow \mu\nu$, top (ATLAS) or γ+jets (CMS), to measure the E_{Tmiss} spectrum** excluding leptons and photons. The main assumption, for the CMS approach, is that Z+jets and γ+jets behave similarly.

- **Transfer factors, from simulation** are used to predict the backgrounds in the signal region. These, especially at the high end of the spectrum, **exhibit 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** ★

Monojet-monoV searches : Transfer Factors from simulation

Physical Review D 97, 092005 (2018)

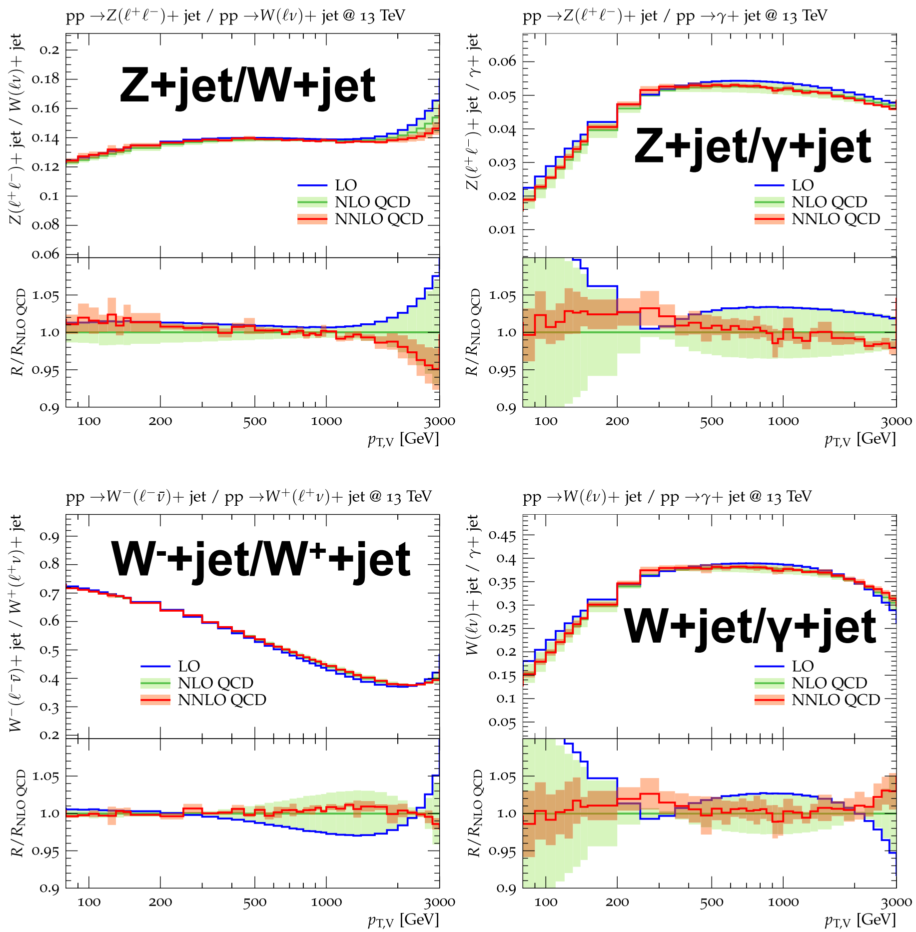


- The irreducible **Z→νν+jets** background could be measured from the **Z → ll+jets** events.

- Due to **low statistics**, **gamma+jets and W → lν+jets events** are **used instead** and the **Z/gamma and W/gamma** ratios **from simulation.**

Monojet-monoV searches : Guidance from Theory

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



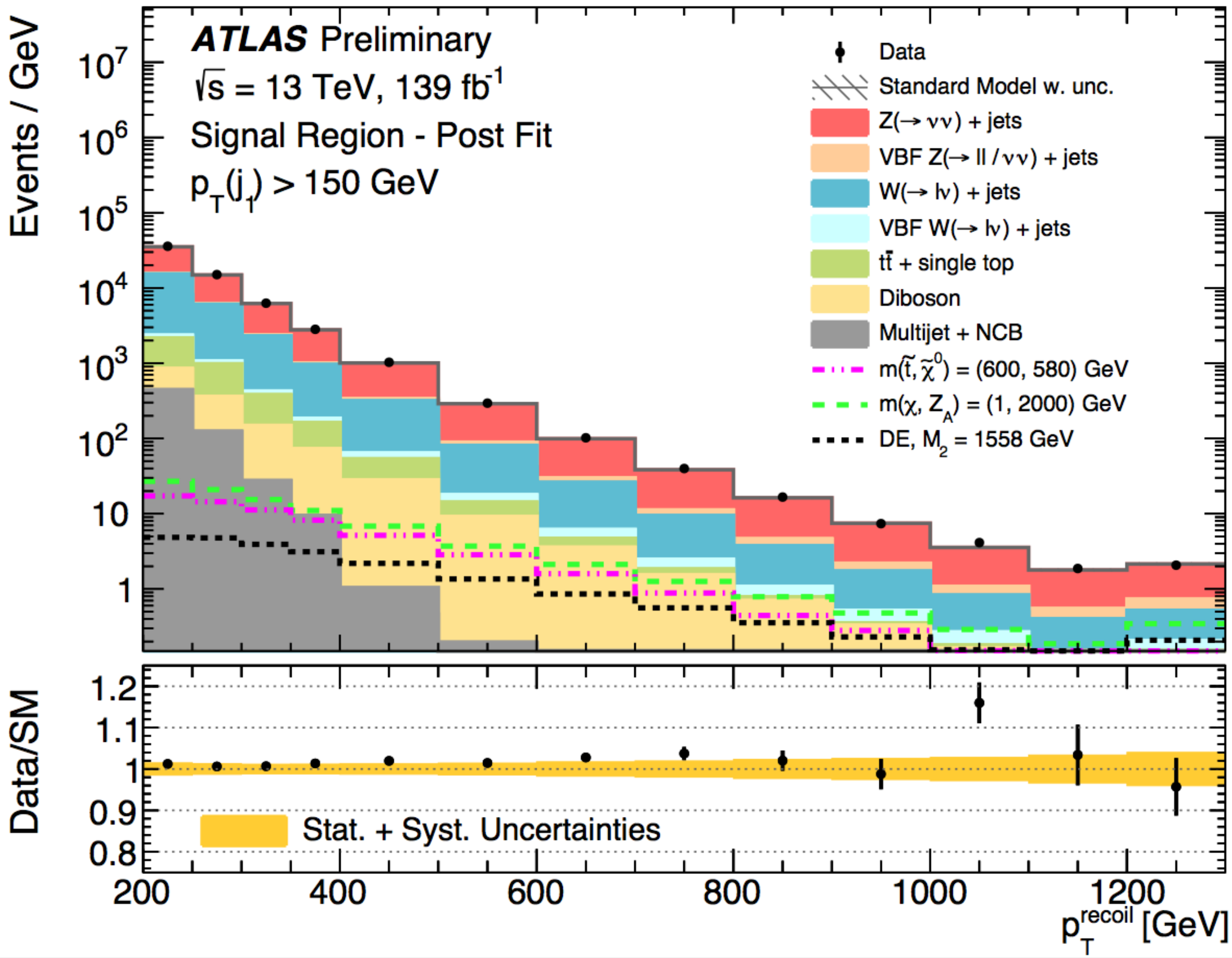
Simulated Transfer factors

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

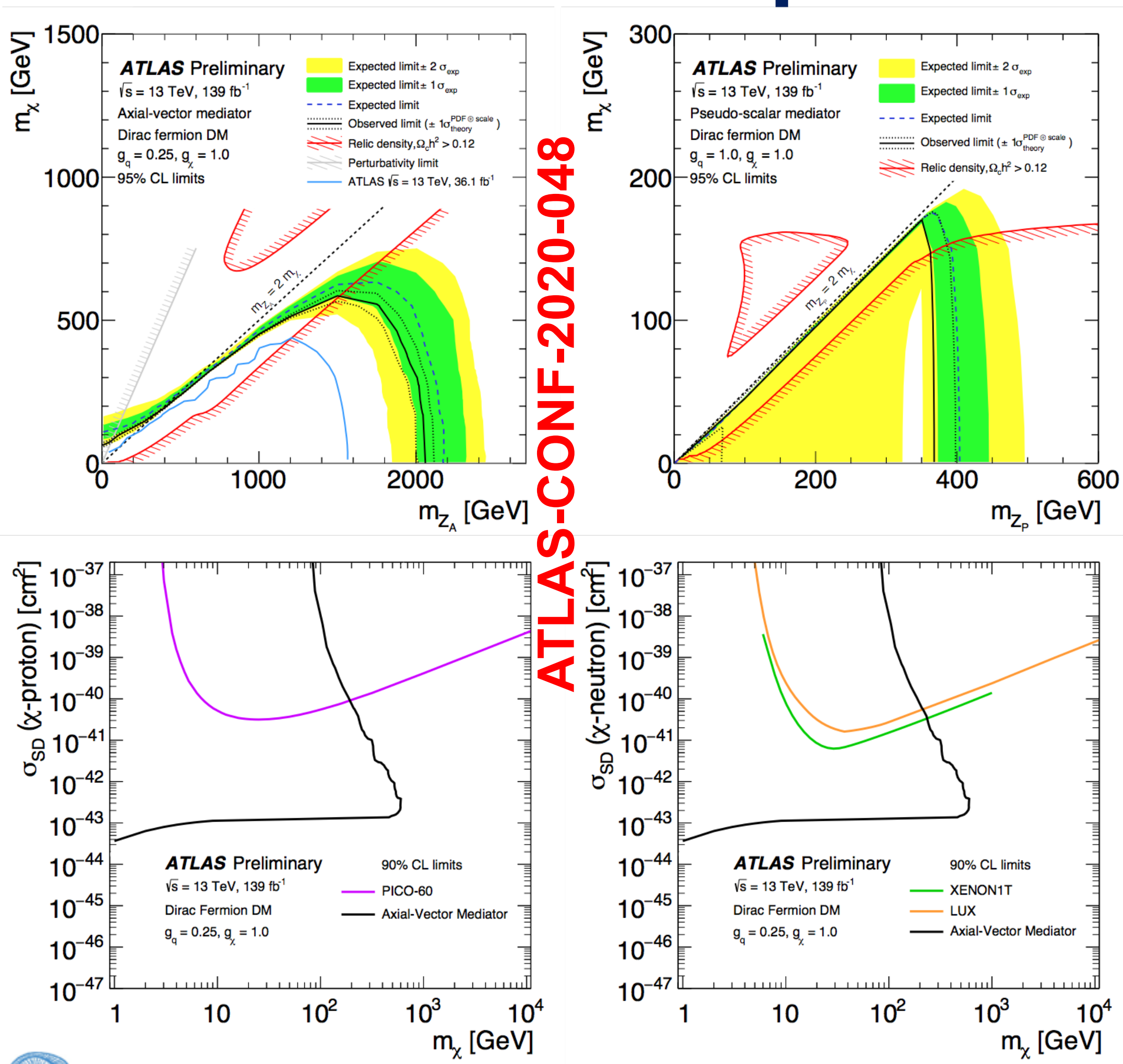
Monojet-monoV searches : Results

Theoretical uncertainties (QCD+EW) account for ~ half of the 5% uncertainty at the high end of the missing E_T spectrum.

ATLAS-CONF-2020-048



Monojet-monoV searches : Interpretations



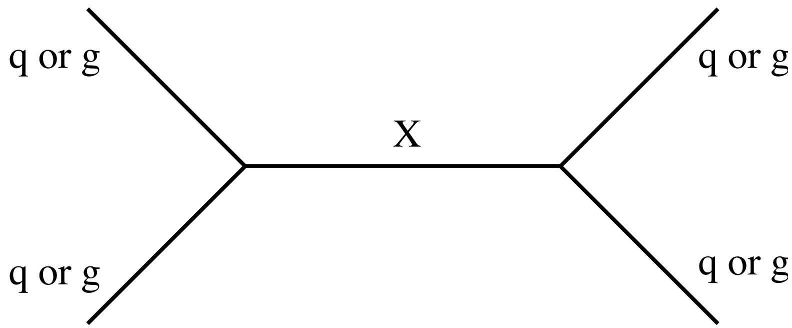
(a)

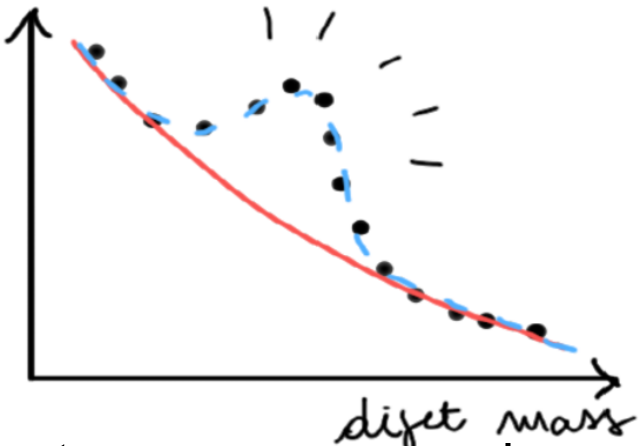
(b)

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?

Dijets Searches

Access a broad range of new physics hypothesis



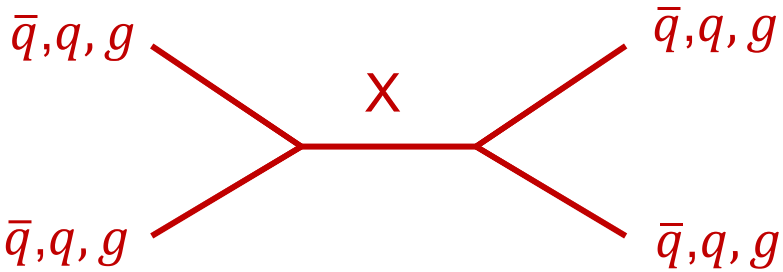


- **Powerful:** LHC is a dijet resonance factory at a new energy scale
- **Broad:** search for many sources of new physics in a single simple search
  - **String resonances** from string theory
  - **Excited quarks** from theories of quark compositeness
  - **W', Z'** and **scalar diquarks** from grand unified theory
  - **Gravitons** from the Randall-Sundrum model of extra dimensions
  - **Axigluons**, **Colorons** and **Color Octet Scalars** from other new models
  - **DM mediators**
- **Model Independent**: Search results are applicable to any model of narrow qq, qg, or gg resonances.

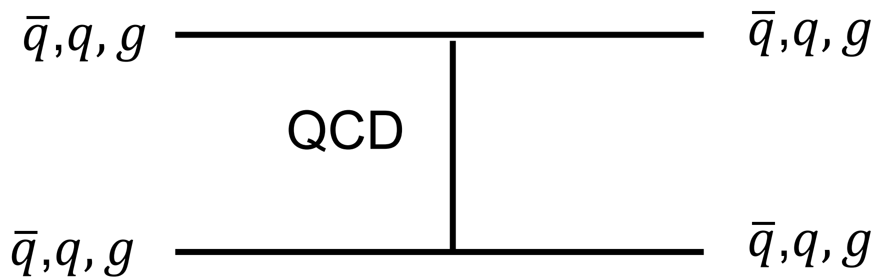
Dijet searche in a nutshell

Access a broad range of new physics hypothesis

Resonance Signal



SM Background



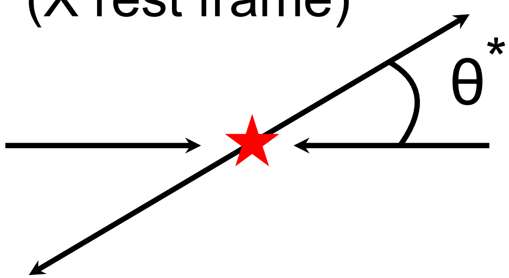
Physics observables

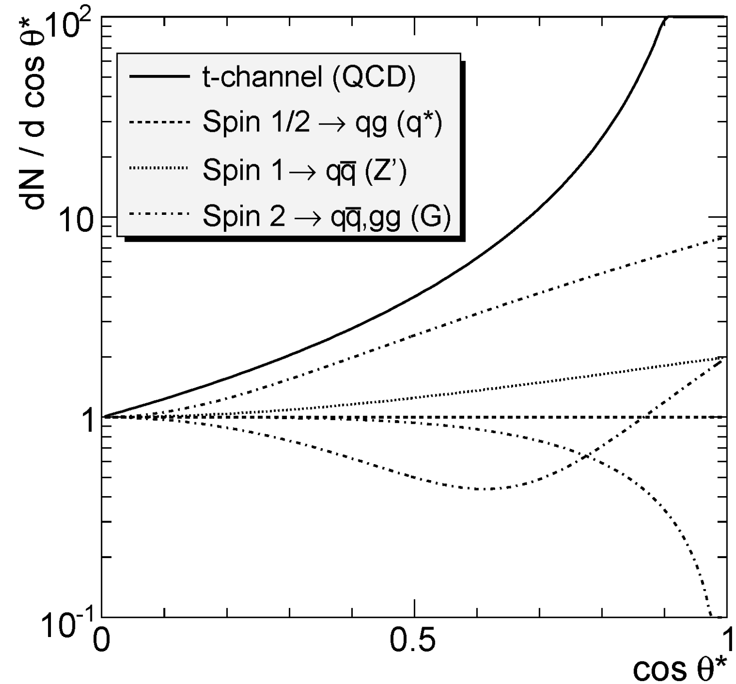
M(jj) → Resonance Mass

Δη(jj) → Resonance Spin

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

(X rest frame)





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New Background Estimation Method

JHEP 05 (2020) 033

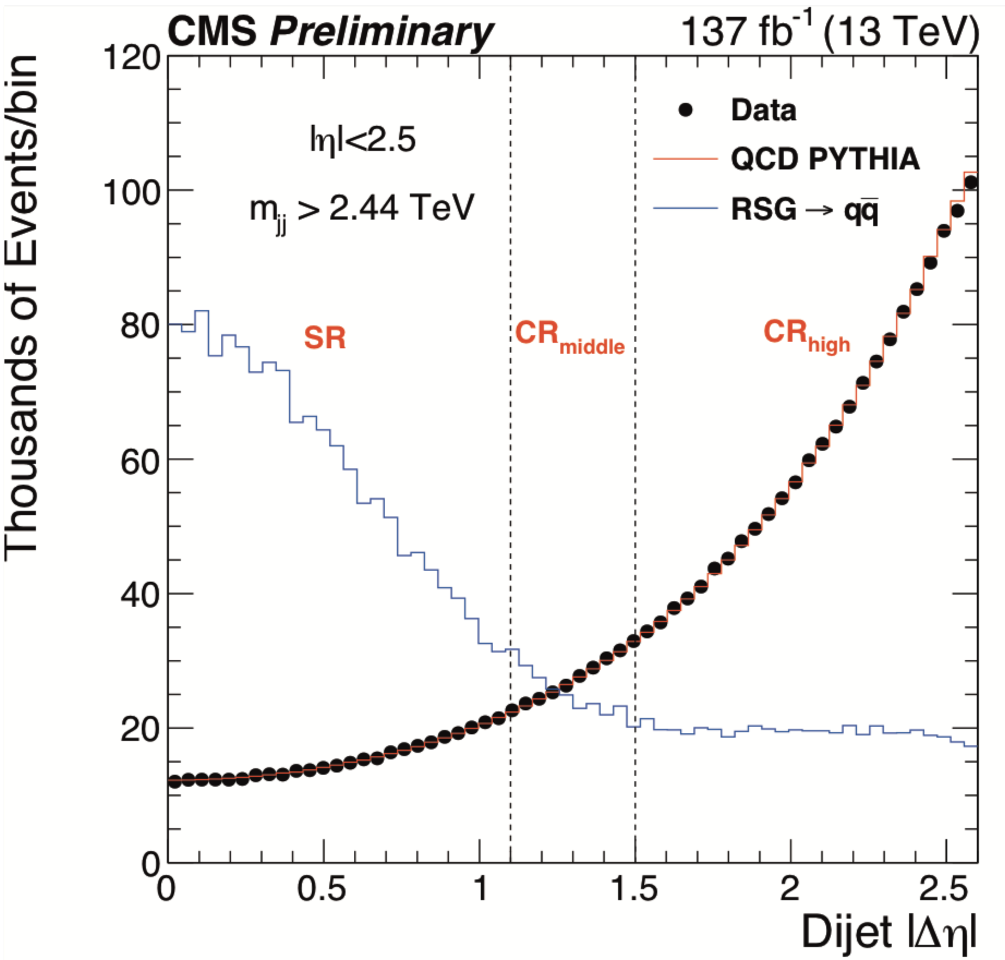
- **Traditional Background Modeling (used in the past 25 years) :** A **fit** with **empirical parametrizations** is performed to the data, with **its parameters treated as unconstrained (in CMS) nuisance parameters** in the final limit setting and significance estimation procedure.

- **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.

One Signal & two Control Regions

JHEP 05 (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

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

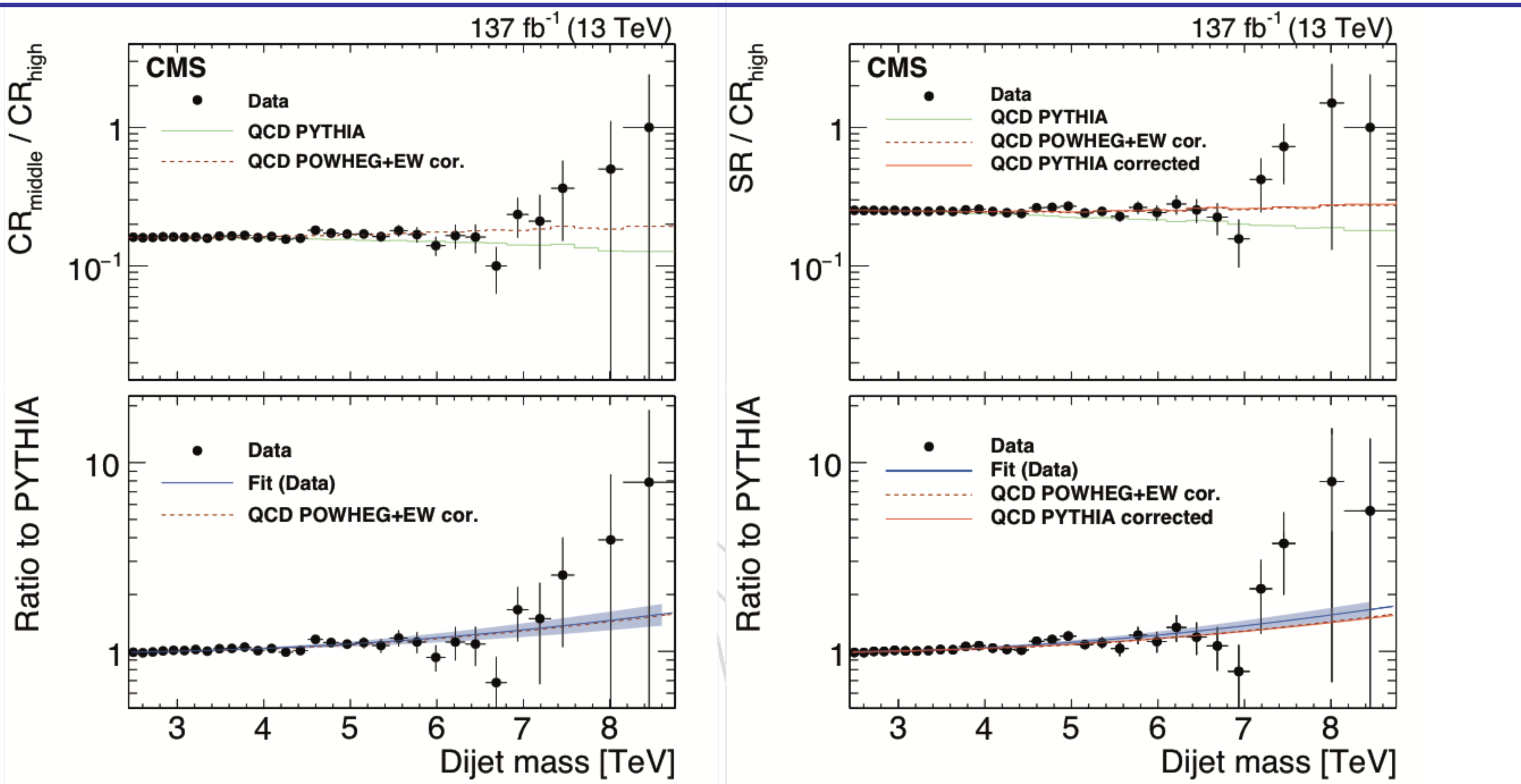
$$R_{\mathrm{aux.}} = N_{\mathrm{CR_{middle}}} / N_{\mathrm{CR_{high}}}$$

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

- 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 **constraint theoretical and experimental systematic effects,** responsible for the **differences between the data and simulated transfer factors**, in a **data-driven way using CR_{middle}**
- For the final result a **simultaneous fit** is performed in **SR, CR_{middle} and CR_{high},**

The Ratio Method in action

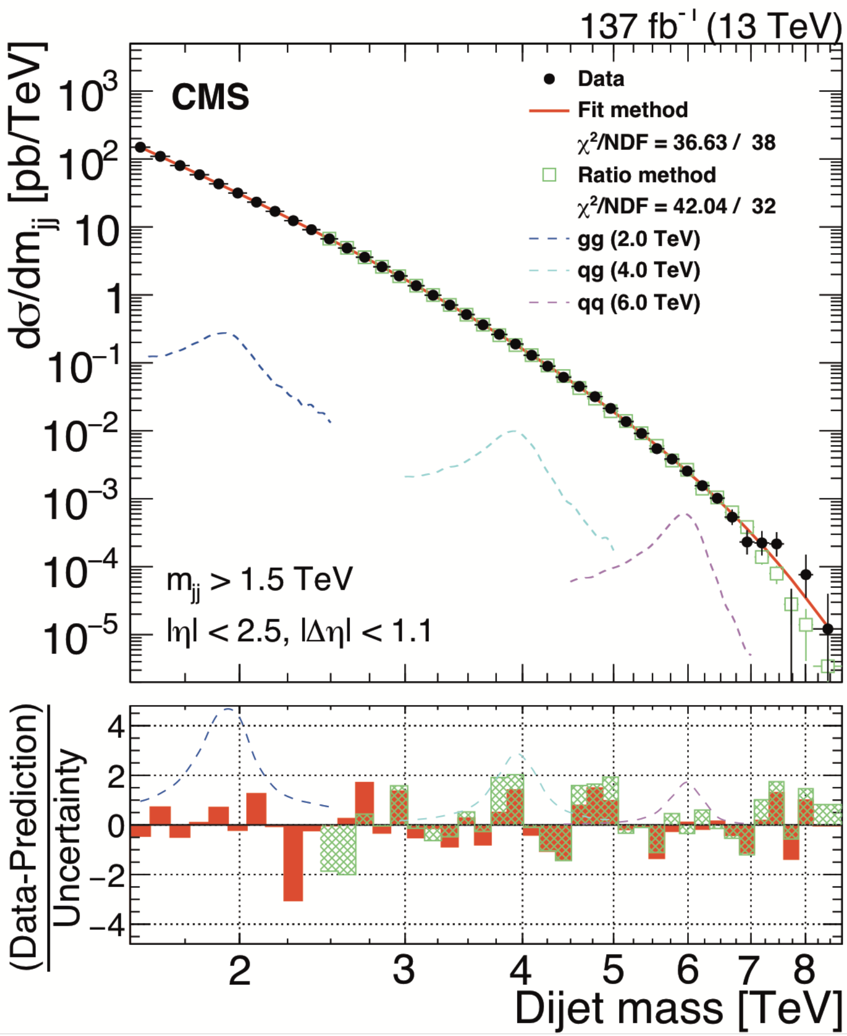
JHEP 05 (2020) 033



- **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.

Dijet Mass prediction

JHEP 05 (2020) 033



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

- **Systematic uncertainties:**

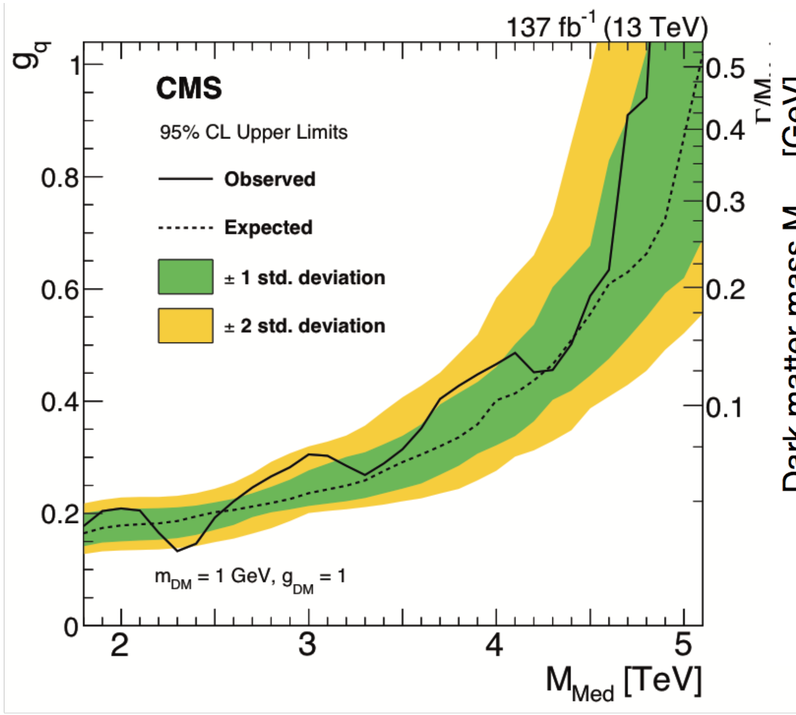
➢ ***Related to signal modeling:***

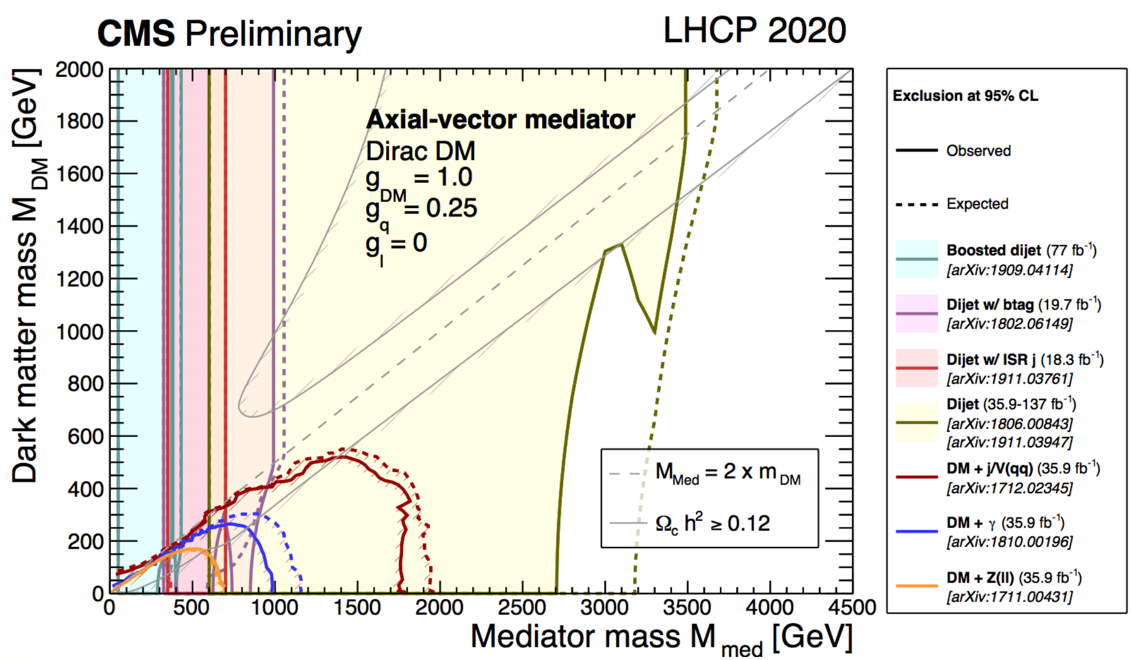
luminosity (log-normal constraints), jet energy scale and jet resolution (gaussian constraints).

➢ ***Related to background modelling:***

Missing higher QCD orders and EW effects, treated as freely floating automatically evaluated via profiling.

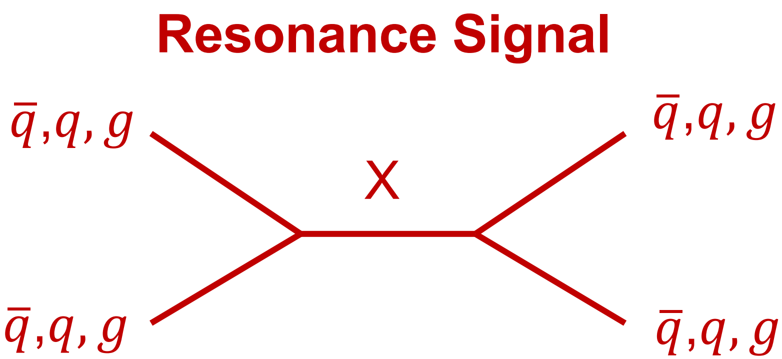
Narrow and Wide resonances : DM mediator limits

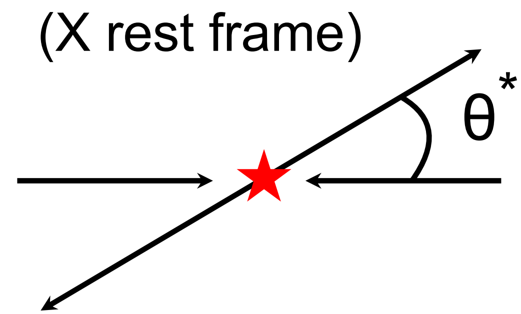




- Can further improve with **more data** and **a better, more precise, QCD NLO simulation including also EW effects.**

Dijet χ search



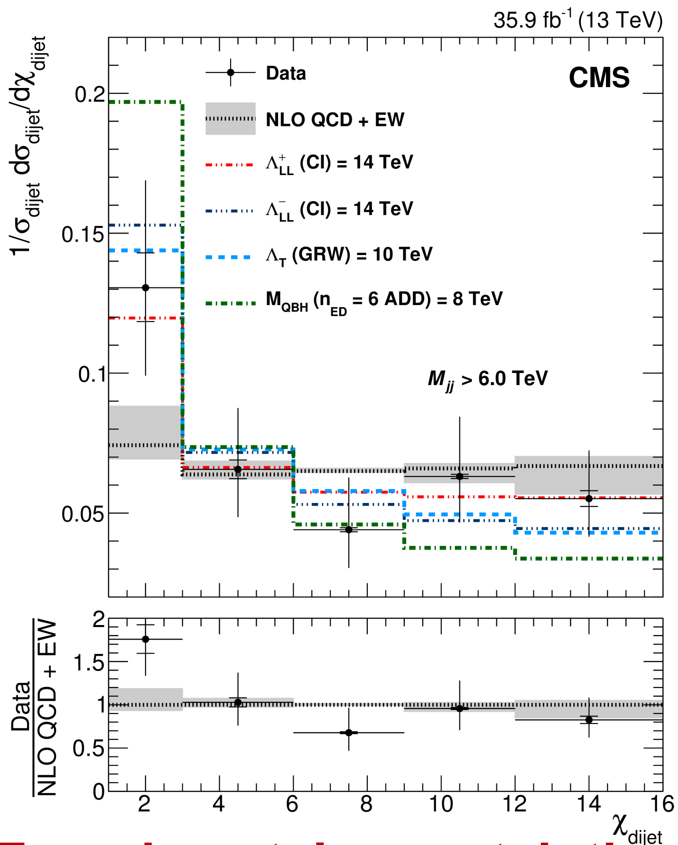


$$\chi = e^{|y_1 - y_2|} \approx \frac{1+|\cos\theta^*|}{1-|\cos\theta^*|}$$

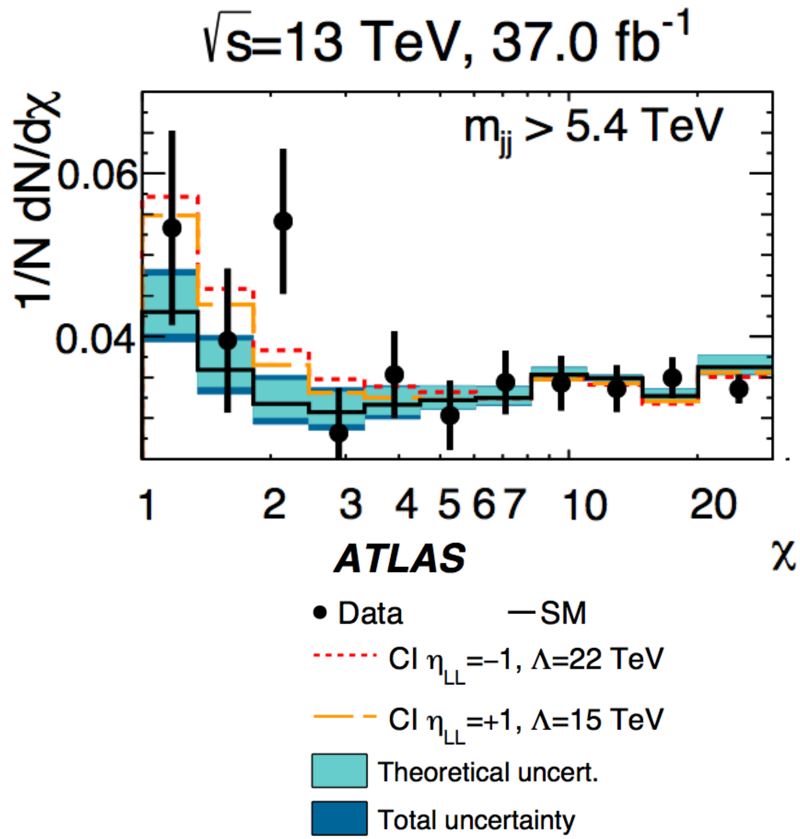
- χ chosen since **main QCD background is flat.**
- **Unique analysis with coupling limits extending to higher DM mediator masses and larger DM mediator widths.**
- Additional **limits** are placed to **a variety of new physics models like quark contact interactions, extra spatial dimensions, quantum black holes, and Dark Matter models.**

Dijet χ Distributions

Eur. Phys. J. C 78 (2018) 789



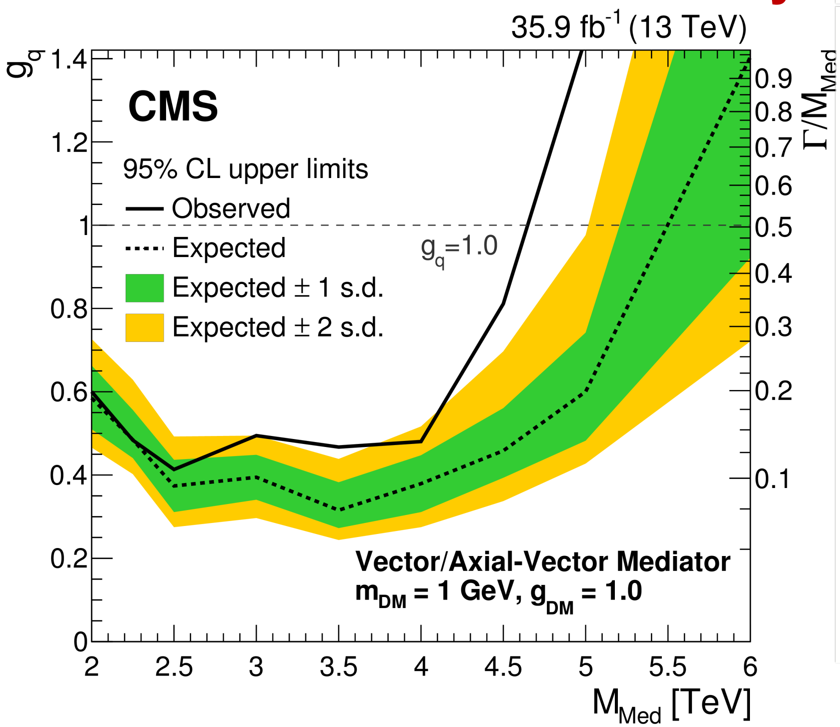
Phys. Rev. D 96 (2017) 052004

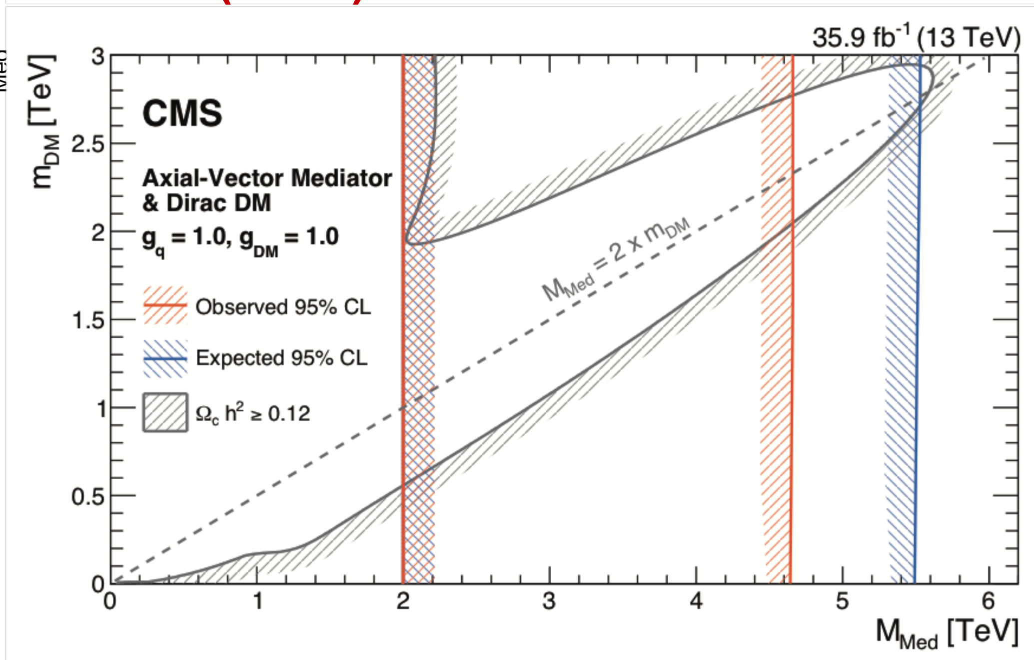


- **Experimental uncertainties** dominated by **jet resolution and relative JES** (absolute cancels)
- **Theoretical uncertainties dominated by non perturbative corrections and renormalization and factorization scales.** ★

Dijet χ Limits

Eur. Phys. J. C 78 (2018) 789



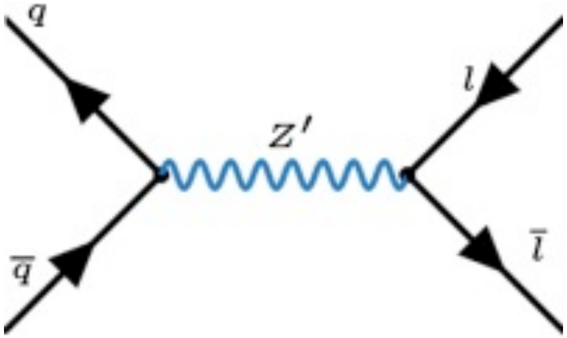


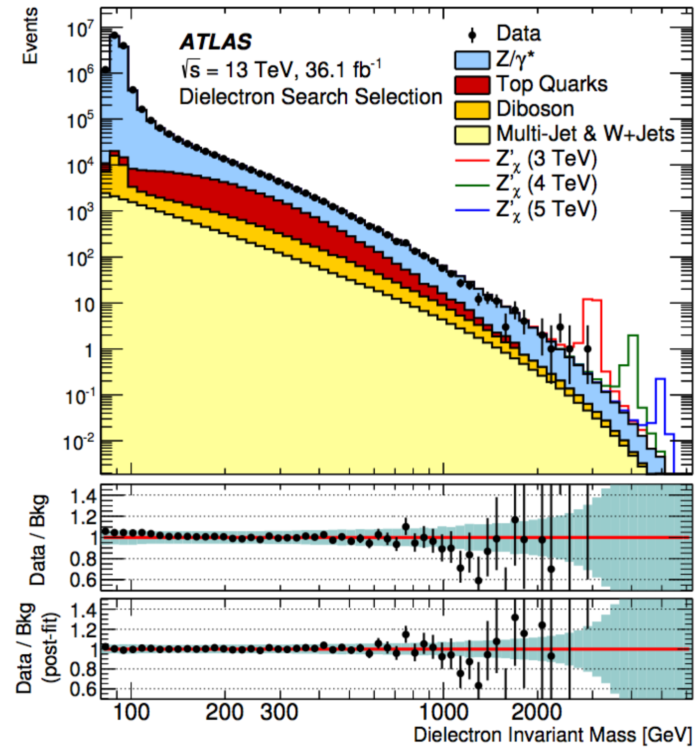
- This analysis is the **only one** being able to **access so large resonance widths.**

- For full Run II result changed background estimate **from NLO to NNLO QCD prediction, which significantly reduces uncertainties**

Dilepton searches

Phys. Lett. B 796 (2019) 68
ATLAS-EXOT-2019-16
JHEP 10 (2017) 182





- Search for **resonant and non-resonant signals** in final states **with a pair of leptons**, coming from **a variety of new physics models:**
  - Grand unified theories (GUTs)
  - Superstrings
  - Left-right-symmetric models (LR)
  - Dark Matter mediators
  - Contact Interactions

Dilepton searches in a nutshell

Phys. Lett. B 796 (2019) 68
ATLAS-EXOT-2019-16

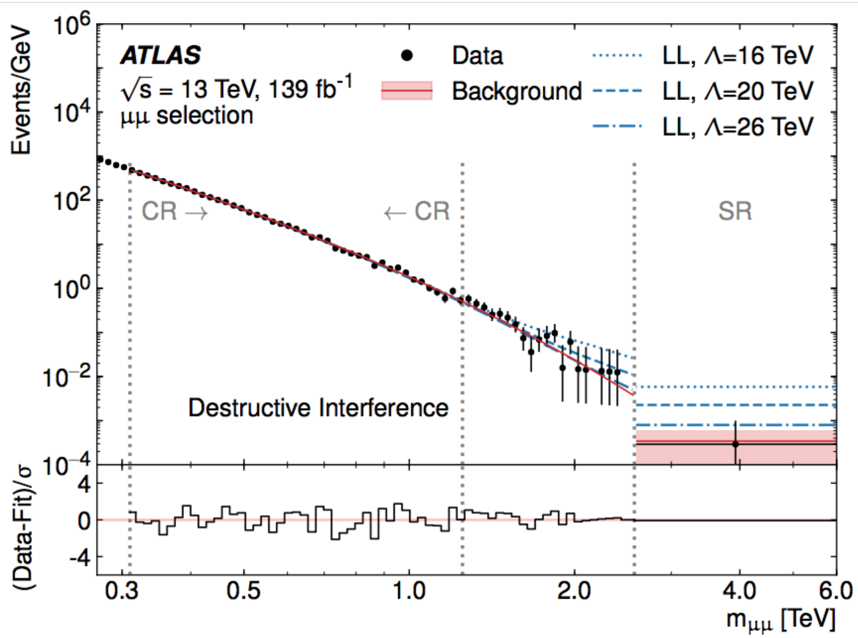
JHEP04(2019)114
CMS-PAS-EXO-19-019

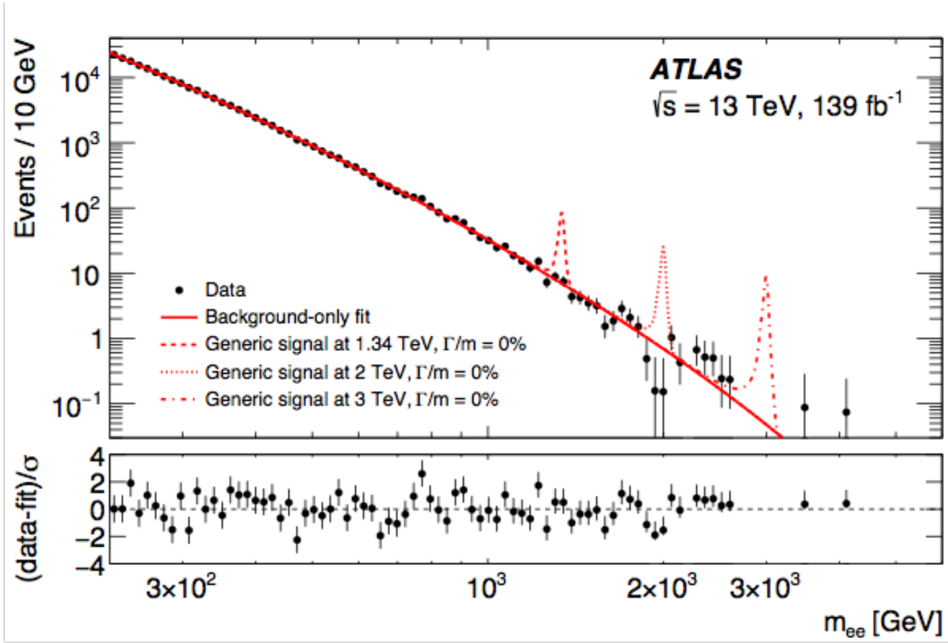
- **Resonant analysis strategy :**
  - To estimate the background **fit** the **simulated dilepton spectrum with an empirical function,** and use the **uncertainties** on the arbitrary **function parameters** as **constraints in the data fit.**

- **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 : uncertainties

Phys. Lett. B 796 (2019) 68
ATLAS-EXOT-2019-16



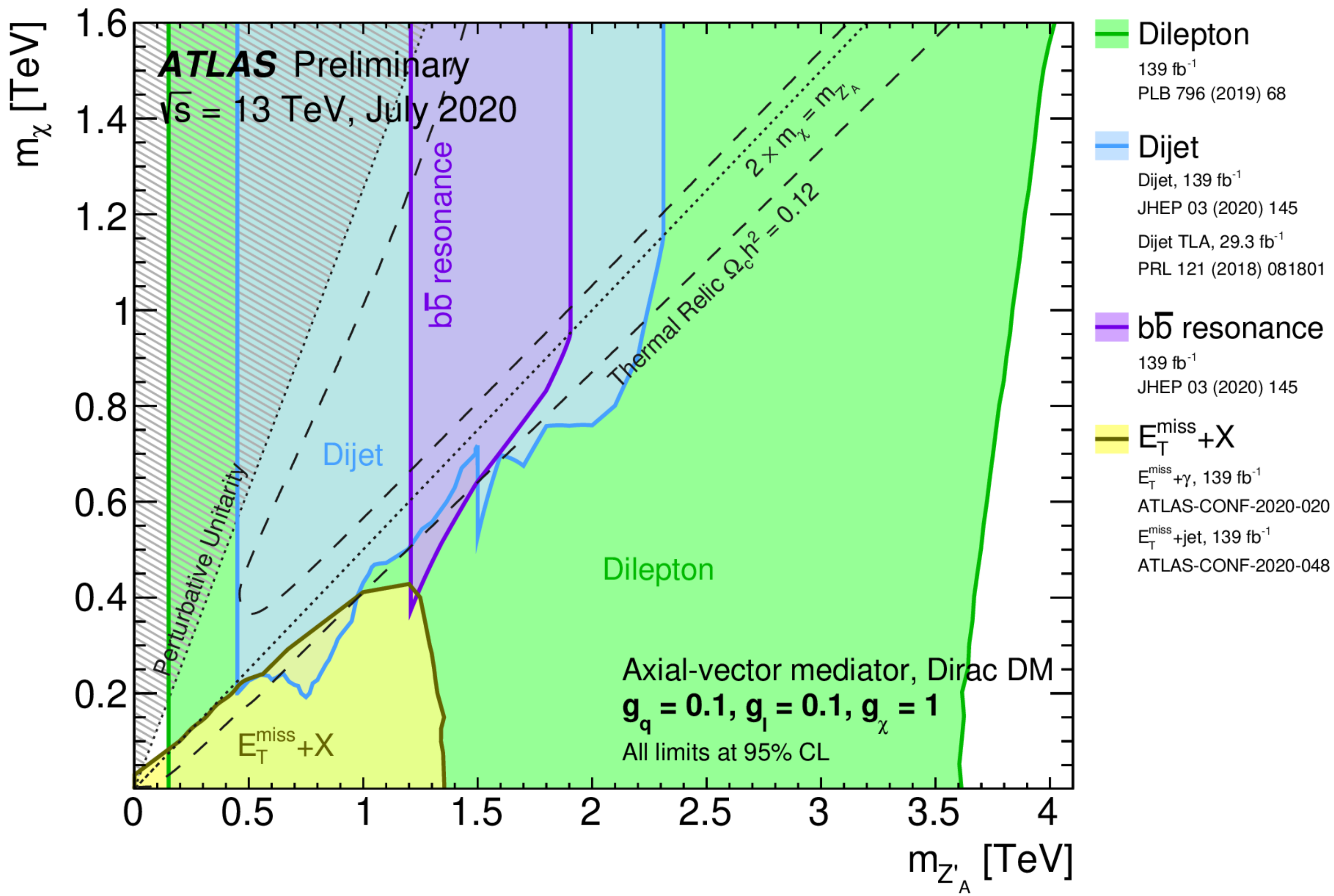


- **Main (or among largest) uncertainties** in the **non-resonant (resonant) search : PDF uncertainties!**

Dilepton searches : results

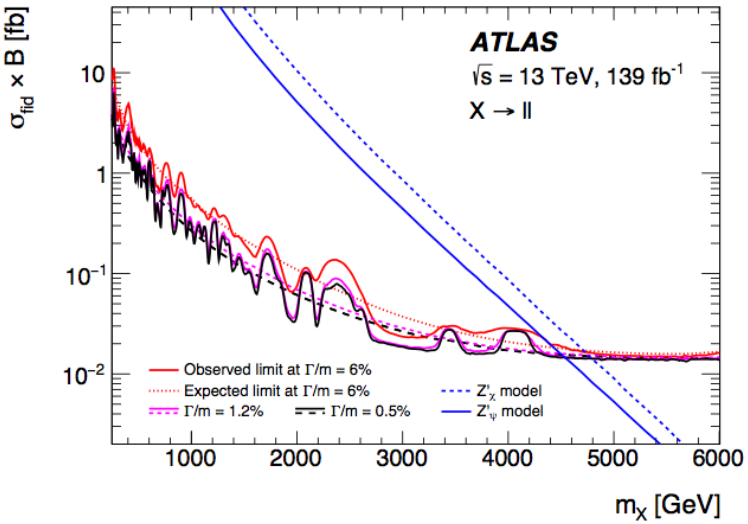
Phys. Lett. B 796 (2019) 68 **ATLAS-EXOT-2019-16**

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



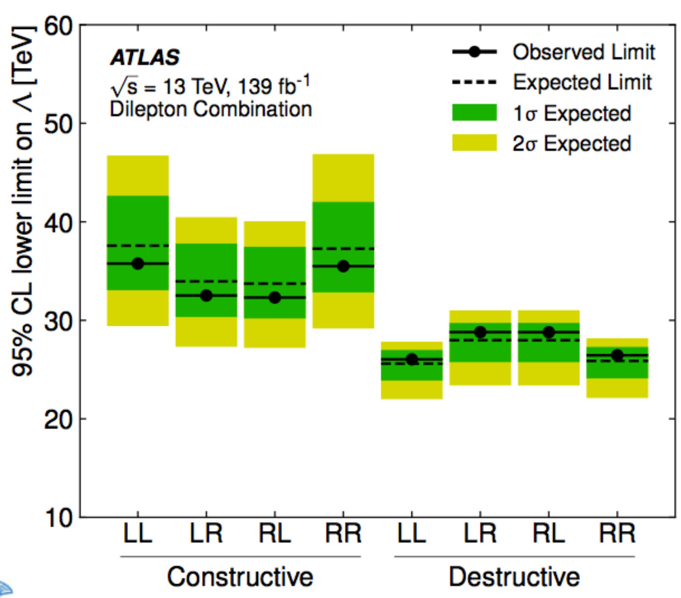
Dilepton searches : results con’t

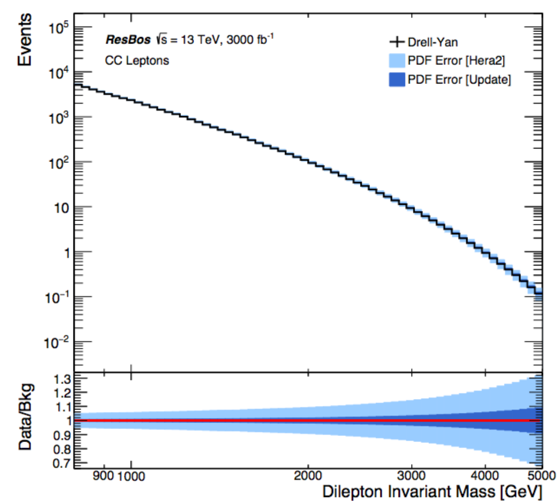
Phys. Lett. B 796 (2019) 68 **ATLAS-EXOT-2019-16**



- **Reduction of PDF uncertainties** will **increase** the **sensitivity** of these searches!

- A nice suggestion already : ***Phys.Rev.D*** **99 (2019) “ A new method for reducing PDF uncertainties in the high-mass Drell Yan spectrum”.**





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Looking Inside Jets ⇔

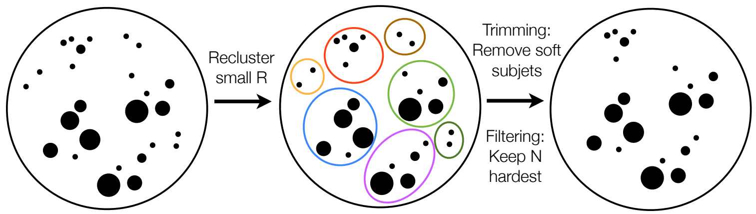
Sources of uncertainties

Phys.Rev.D80,05150 (2009)
JHEP05(2014),146

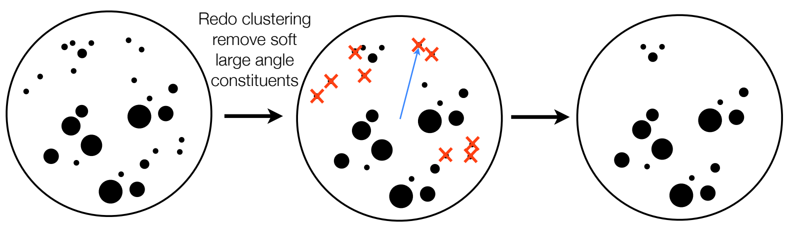
JHEP 1103:015,2011

J. Dolen

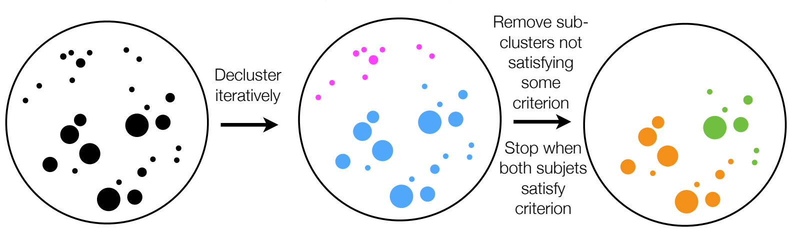
Trimming, Filtering - Recluster jet with smaller distance parameter. Condition based subjet removal.

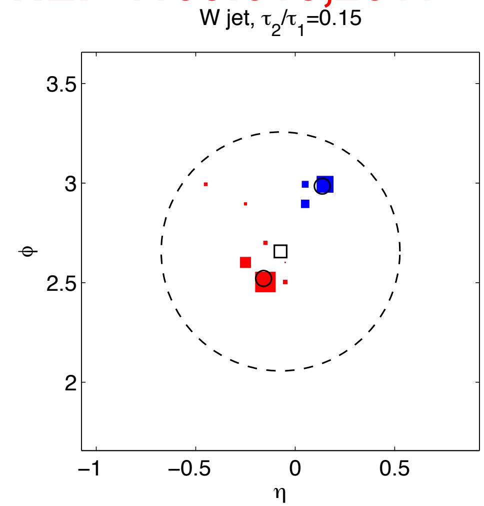


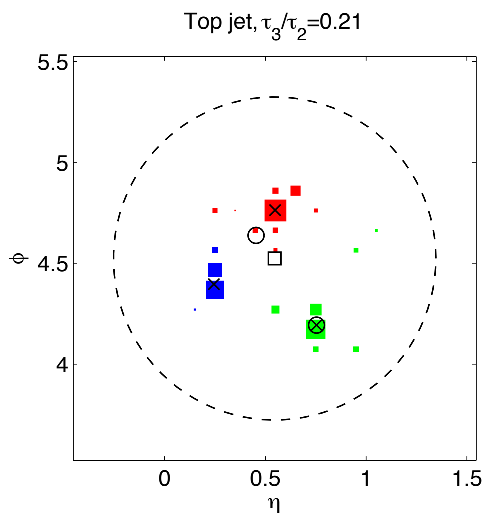
Pruning - Recluster jet. Remove soft large angle particles.

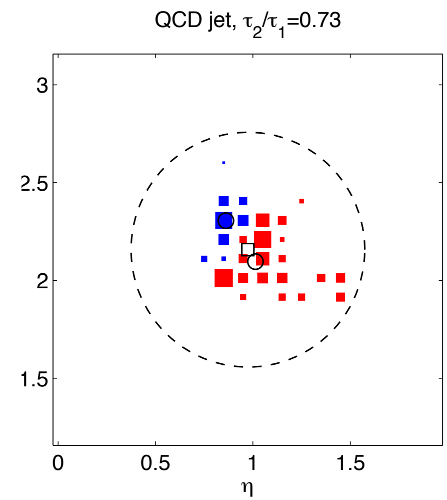


BDRS, MMDT, Soft Drop, JHU top tagger, CMSTT - Recursively decluster jet. Remove sub-clusters not satisfying algorithm condition. Stop declustering when both subjets satisfy condition.





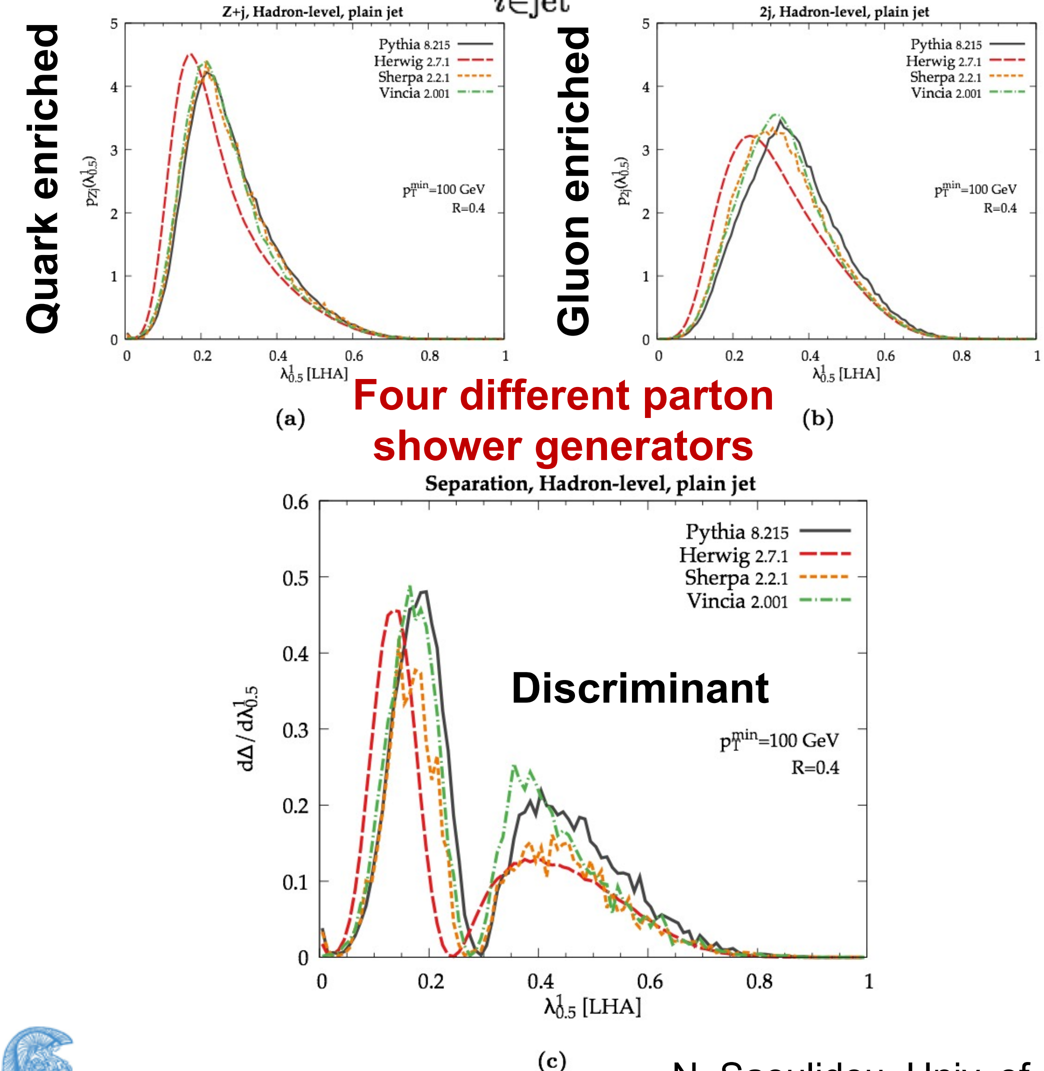




Quark – Gluon Separation

Quark-gluon discriminant (angularity)

$$\lambda_\beta^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \theta_i^\beta,$$



- **Identification** of **quark initiated** vs **gluon initiated jets** is **key** for many **BSM searches** : often **signals** are **dominated** by **quarks** whereas **backgrounds** by **gluons**

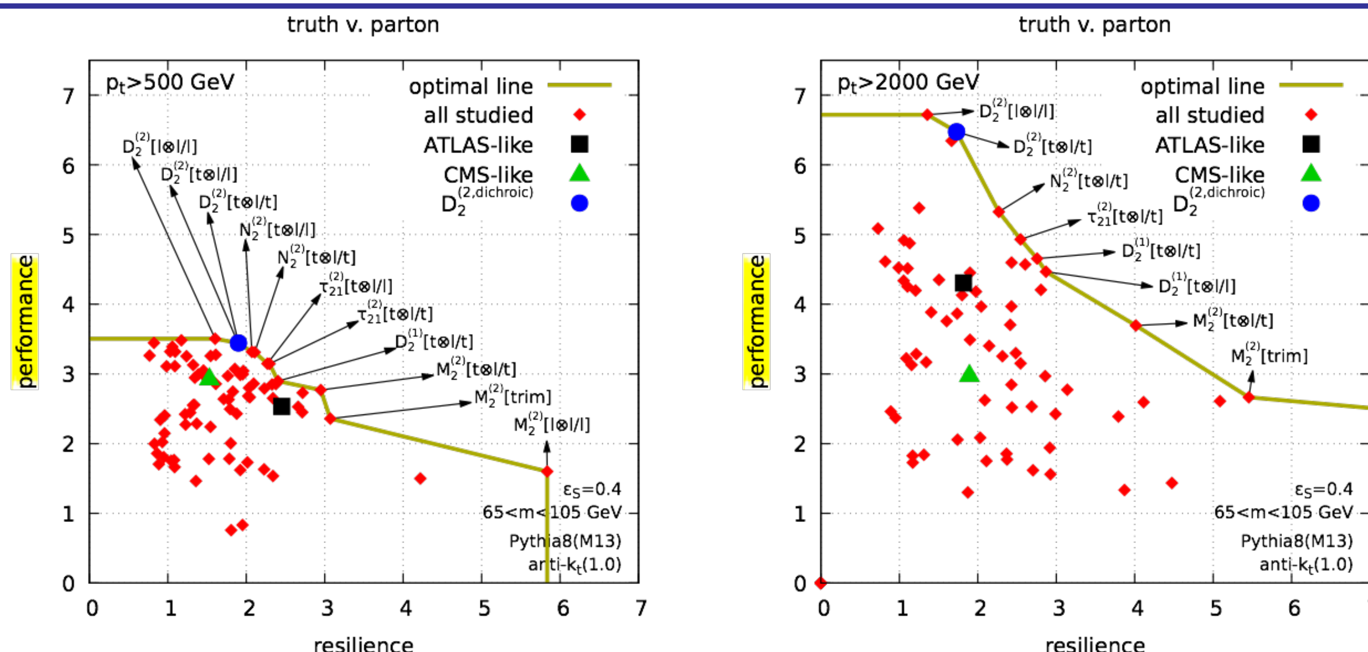
- **Radiation patterns** of **quark** and **gluon jets are not well understood**, and their modelling is **dependent on parton-shower generators.**

- *"LHC measurements are the best near-term strategy to constrain quark/gluon radiation patterns and enable quark/gluon discrimination to become a robust experimental tool."*

JHEP07(2017)091

Jet taggers (1)

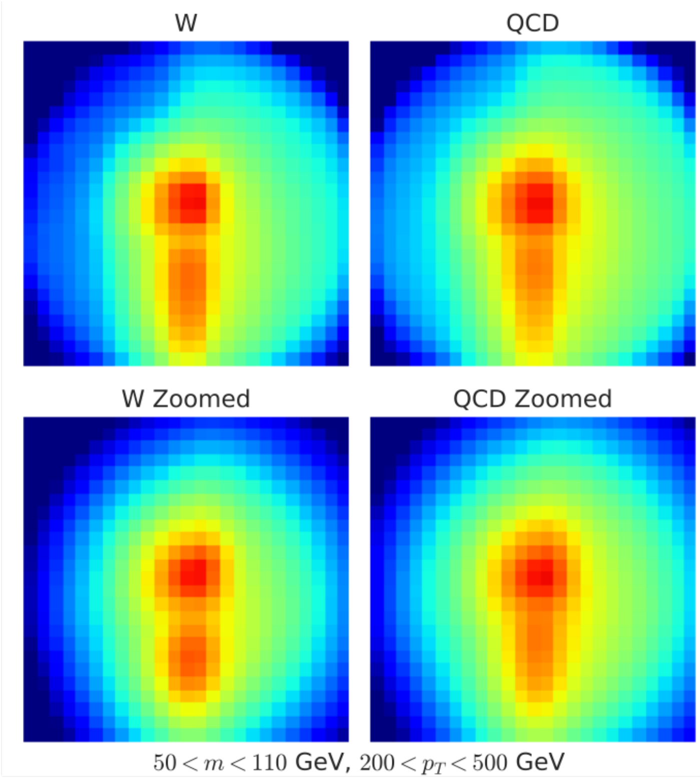
Lect. Notes Phys. 958 (2019)

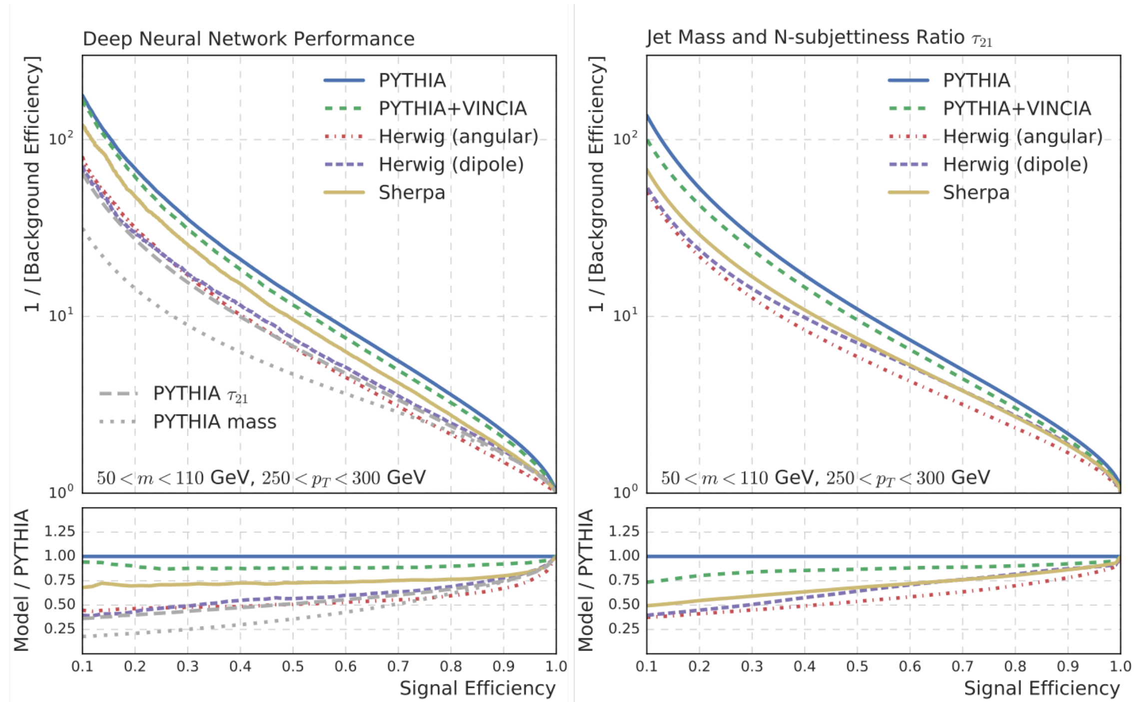


- **Many two-prong taggers** have been **developed**. These **are very important tools** as we **move into probing lower resonance masses**, and **lower couplings.**
- **Their performance depends** on the **non-perturbative effects**, and some are more robust (resilient) than others.
- *"Keeping* ***more radiation in the*** *jet or putting* ***tighter constraints on soft radiation at larger angles*** *typically leads to* ***more efficient taggers*** *but at the same time* ***yields more sensitivity to the regions where hadronisation and the Underlying Event have a larger impact, hence reducing resilience."***

Jet taggers :
A machine learning example

PhysRevD.95.014018

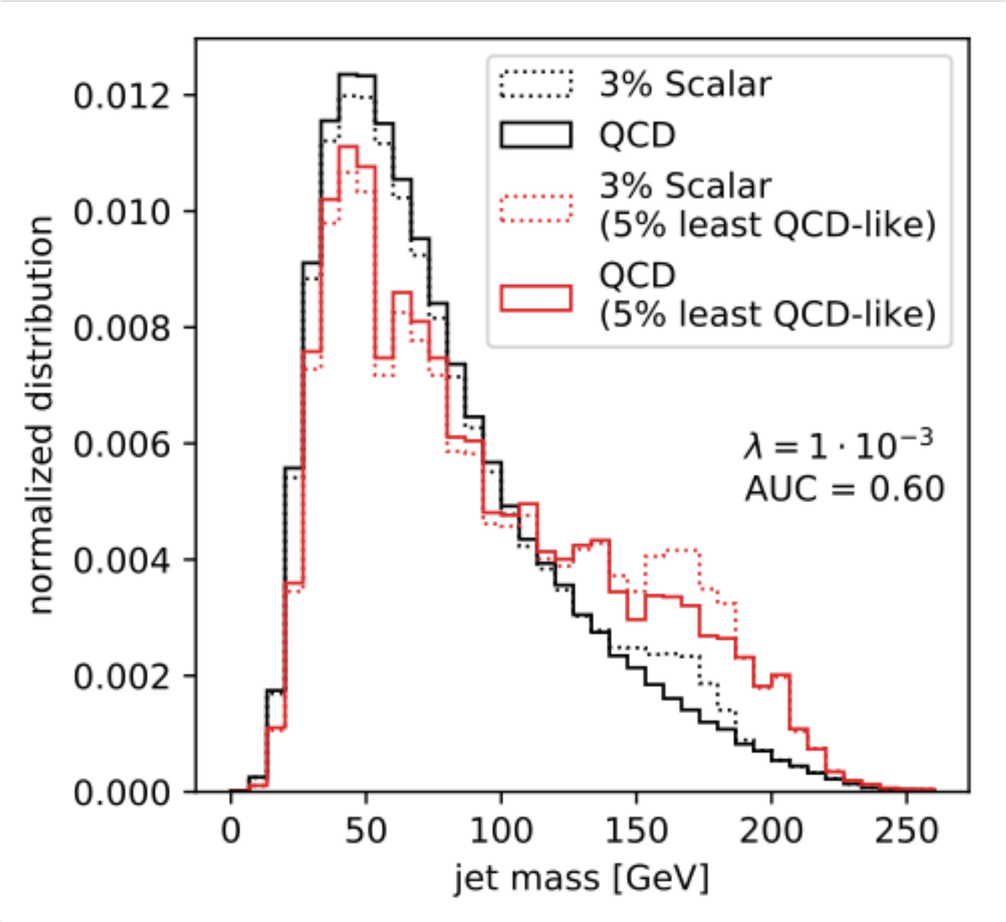




- **Parton shower uncertainties**, and **soft radiation** related ones (hadronization) are **large**, both for the ML cases, and for the “traditional” substructure ones (n-subjetiness)
- ***“…cautious and detailed studies of uncertainties…”*** are needed in order for these methodologies to be successfully applied to data analyses.

Jet taggers looking into the future : Unsupervised learning

SciPost Phys. **6 (2019) 3, 030**

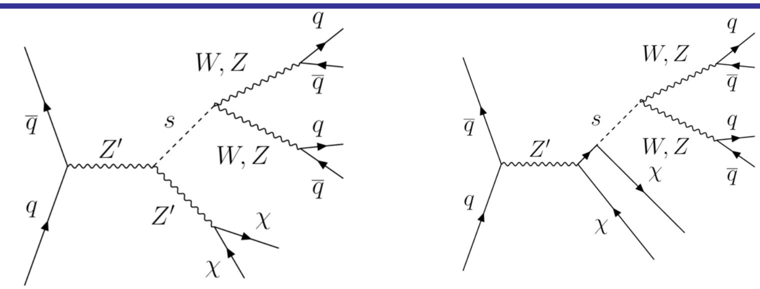


- Another way one can **overcome large parton showering and hadronization uncertainties in ML jet taggers is** to use **unsupervised leaning** and **use real data to "teach" the tagger QCD jets.**

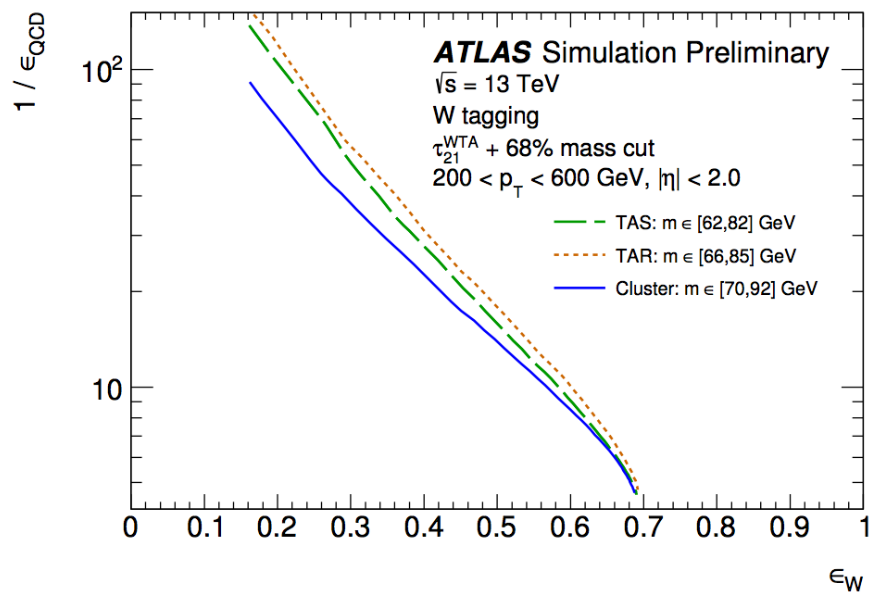
- An example of a **dark shower model**, with **dark mesons identified** through a **peak** in the **jet mass distributions.**

Jet taggers in action (ATLAS)

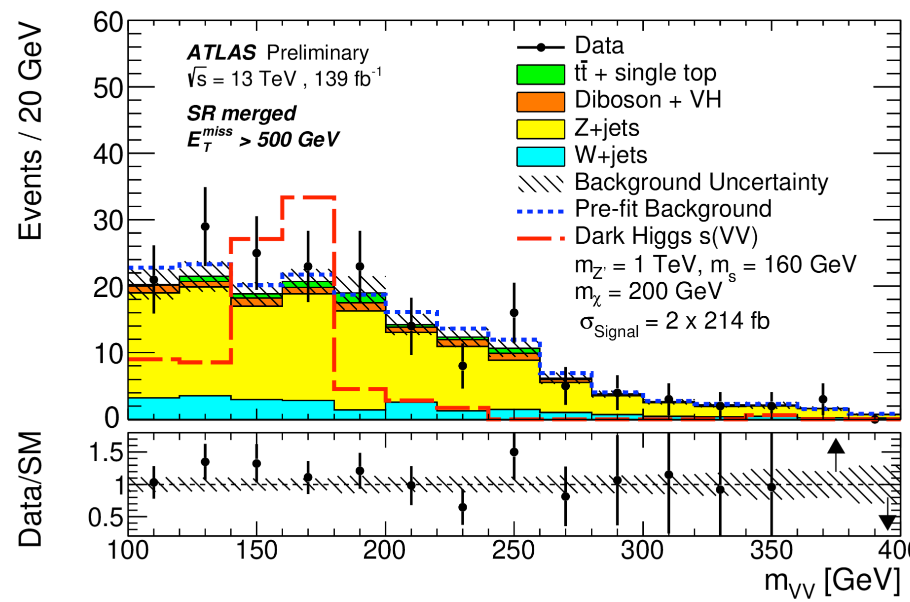
New algorithms developed **that combine tracking and calorimeter information** to calculate large-R jet **substructure observables**



https://cds.cern.ch/record/2630864



ATLAS-CONF-2020-036/

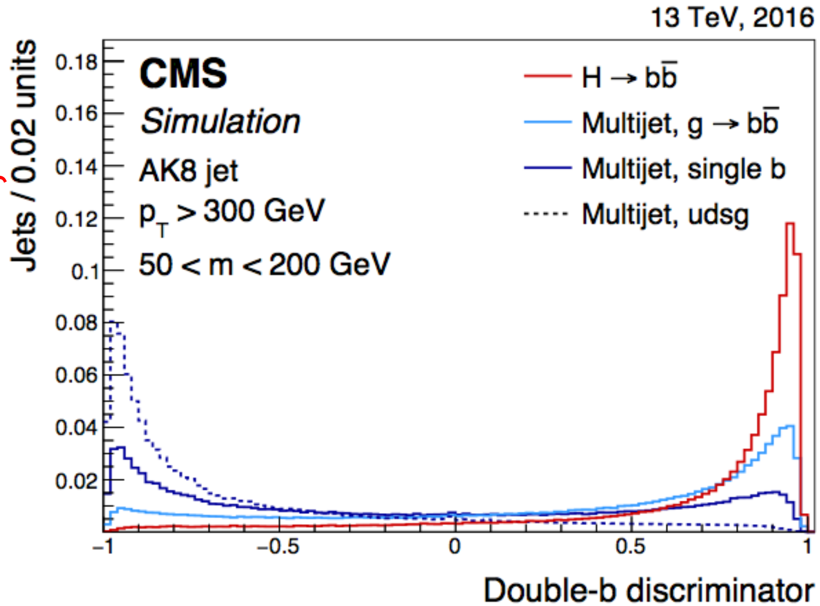


- **Hunting for Dark Higgs** with **novel jet taggers** in ATLAS.

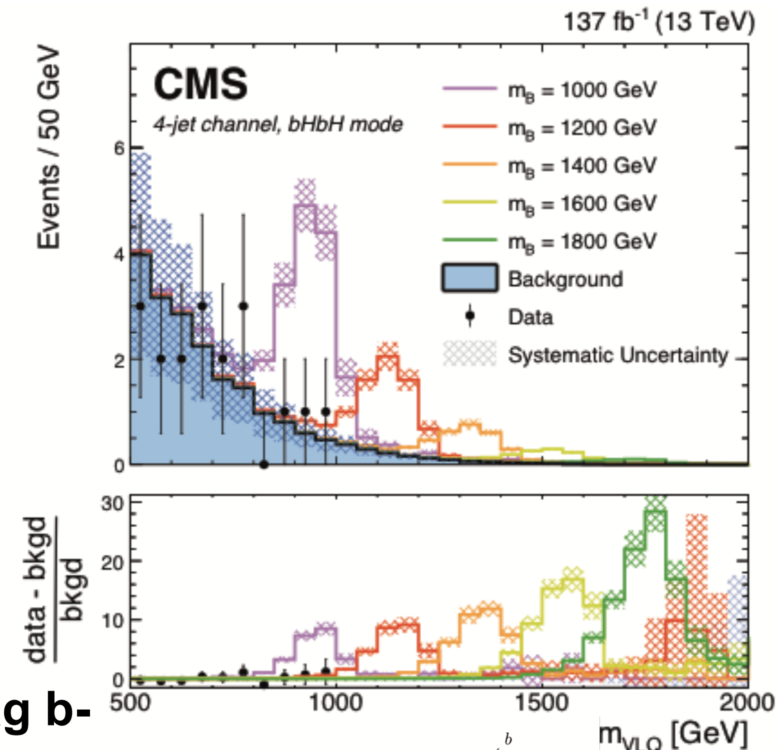
- **Theoretical systematic uncertainties** due to **PDF , renormalization** and **factorization scales, among dominant** ones

Jet taggers in action (CMS)

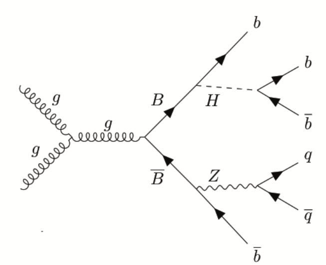
JINST 13 (2018) P05011
CMS-DP-2018-058, 2018.



CERN-EP-2020-154 CMS-B2G-19-005



DeepJet : jet-tagger using **DNNs** is utilized to **tag b-jets,** together with a **dedicated double b-jet tagger**



- **Hunting for vector-like quarks in CMS**
- **Main QCD background** estimated in **data-driven way. All background uncertainties** related to the **lack of knowledge of the QCD background** (freely floating parameters of empirical function used), and the **jet tagger efficiency and background rejection.**

Summary and outlook

- **QCD** related **uncertainties** concerning **PDFs, parton-showering**, non-perturbative effects (**hadronization and multi-parton interactions**), **higher orders**, **enter and play a key role in many powerful BSM searches.**

- **These uncertainties** play a **key role** in **developing sophisticated jet taggers,** that can **significantly increase** the **LHC discovery potential.**

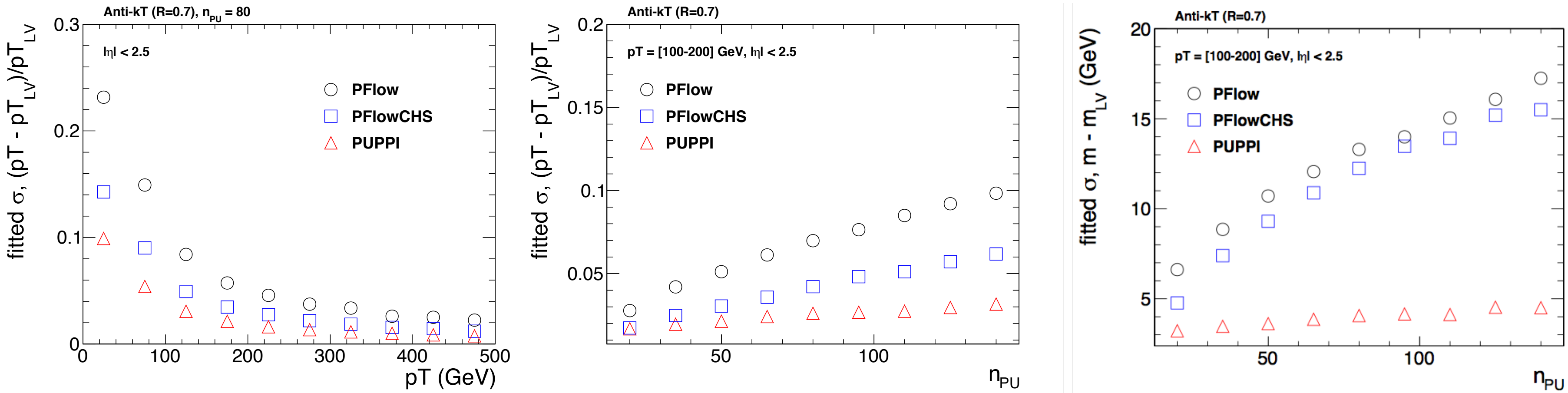
- Many **efforts** from the **theory** side in **collaboration** with **experiments** aim to **improve on these,** and **significantly enhance** the **LHC discovery potential.**

Thank you!

Backup slides follow

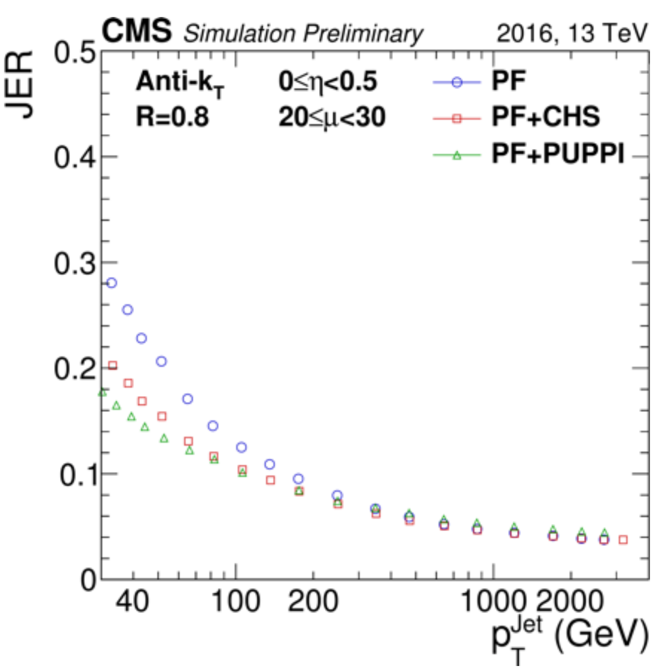
Jet Pileup Per Particle : PUPPI

JHEP 1410 (2014) 059



$$\alpha_i = \log \sum_{j \in \text{event}} \xi_{ij} \times \Theta(R_{\min} \leq \Delta R_{ij} \leq R_0),$$

$$\text{where } \xi_{ij} = \frac{p_{Tj}}{\Delta R_{ij}}.$$



- PUPPI assigns **a weight to particles of unknown origin to be coming** from pileup interactions, using it to rescale the particle's four-momentum.

- By applying corrections **at the particle level, before jet clustering one can simultaneously perform pileup jet mitigation,** and jet four-vector and shape corrections.

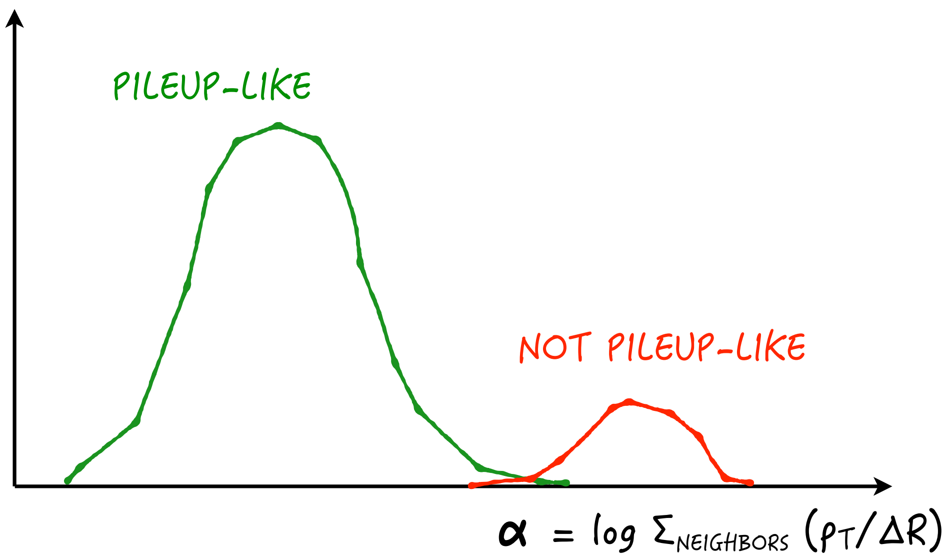
PileUp Per Particle Id, PUPPI

Bertolini, Harris, Low, **NT**, arXiv:1407.6013

- ***asymptotic behavior***
- ***vertexing information***
- ***collinear QCD radiation***
- ***precision timing***

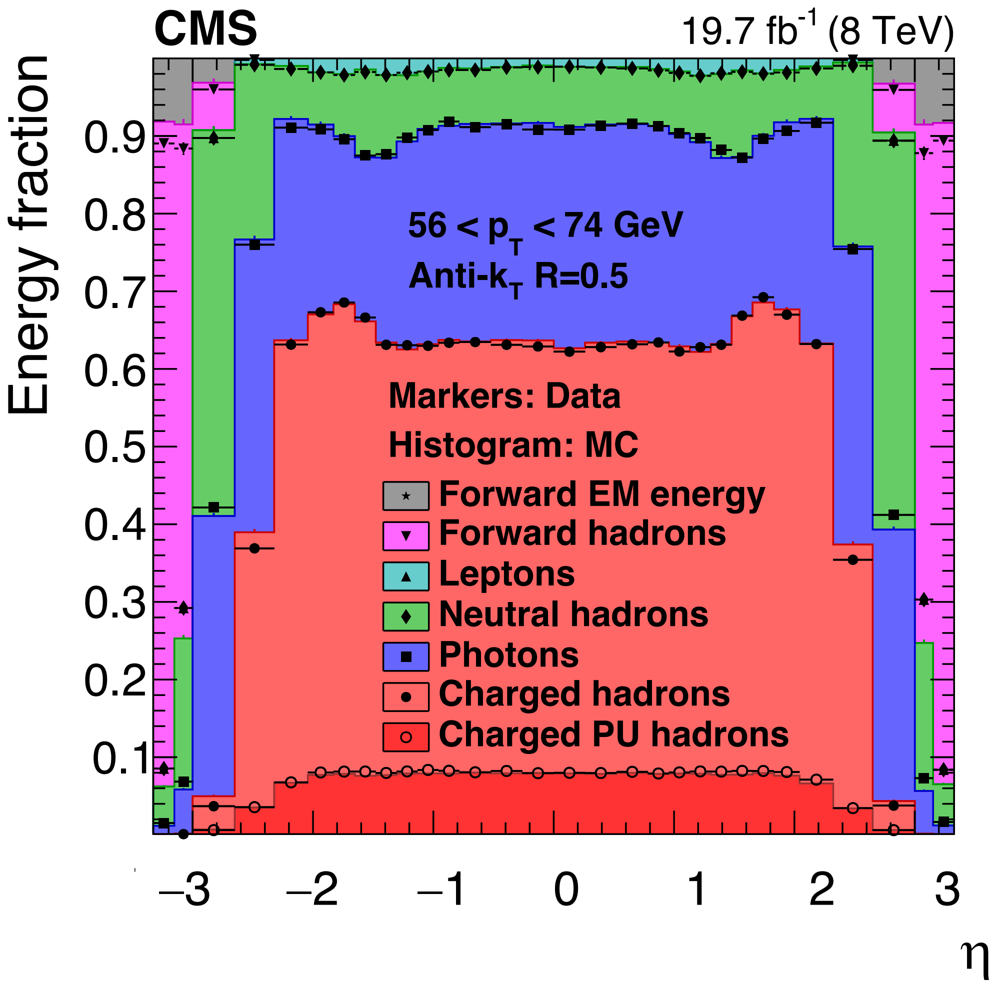
A general ***framework***, that assigns on a ***per particle*** basis a weight for ***how likely*** a particle is to be from pileup

key insight: using the QCD ansatz to infer neutral particles as pileup



PUPPI demonstrates large gains, even for current 2016 dataset

CMS-PRF-14-001



Particle flow jets, described by:

- Energy fractions
- Neutral and charged particle multiplicities
- Pileup weights per particle

provide several handles on noise, pileup, and mis-reconstruction rejection.

Anti-Kt Jet Algorithm

- For each input object (Topological Clusters), d_{ij} & d_{iB} are defined as:

$$d_{ij} = min(p_{Ti}^{-2}, p_{Tj}^{-2}) \frac{\Delta R_{ij}^2}{R^2}$$

$$d_{iB} = p_{Ti}^{-2}$$

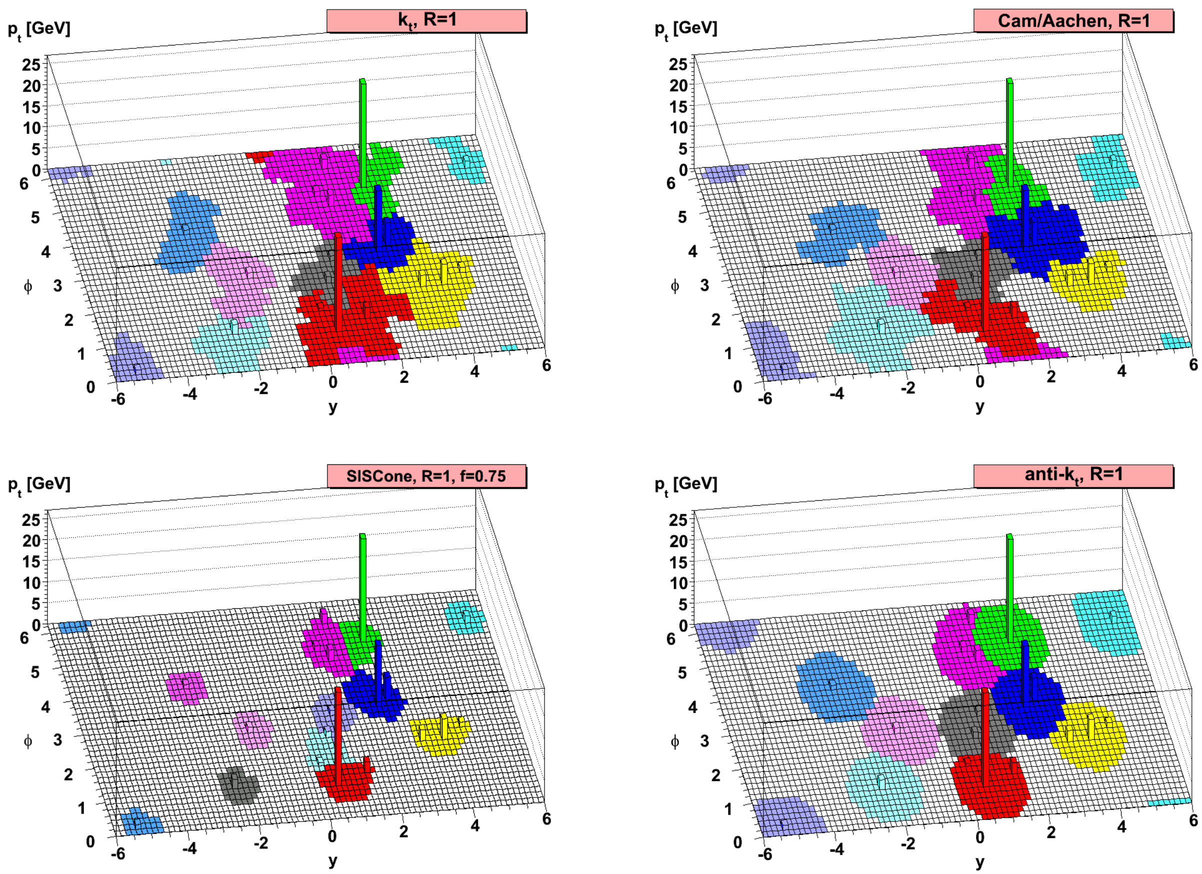
$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

- A list of d_{ij} & d_{iB} are formed;
  - If d_{ij} is the smallest entry; objects i & j are combined & the list is remade
  - If d_{iB} is smallest, it is a jet by itself
- Anti-Kt algorithm can be implemented in NLO QCD calculations
- The algorithm also produces geometrically well-defined (cone-like) jets.

Anti-kT Algorithm

arXiv:0802.1189

p=1 kT
p=0 CA
p=- Anti-kT



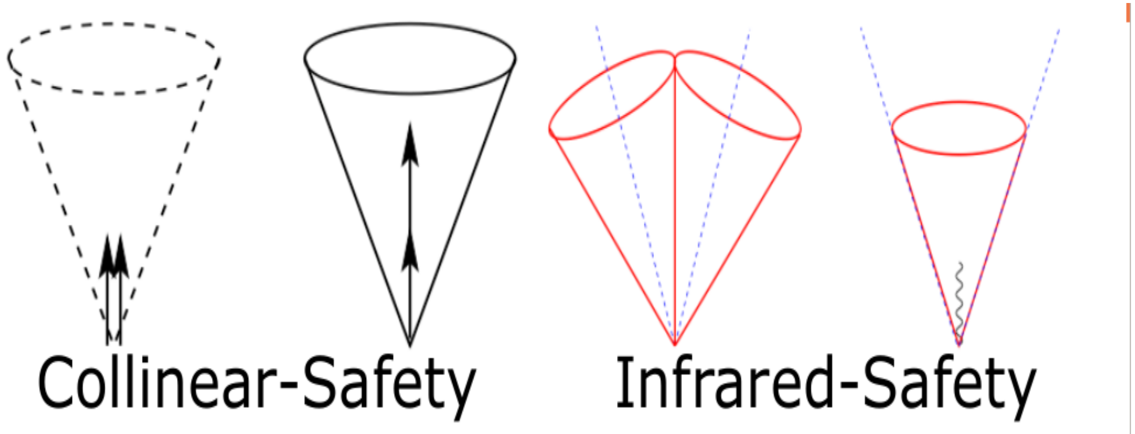
$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p})\frac{\Delta_{ij}^2}{R^2},$$

$$d_{iB} = k_{ti}^{2p},$$

Figure 1: A sample parton-level event (generated with Herwig [8]), together with many random soft "ghosts", clustered with four different jets algorithms, illustrating the "active" catchment areas of the resulting hard jets. For k_t and Cam/Aachen the detailed shapes are in part determined by the specific set of ghosts used, and change when the ghosts are modified.

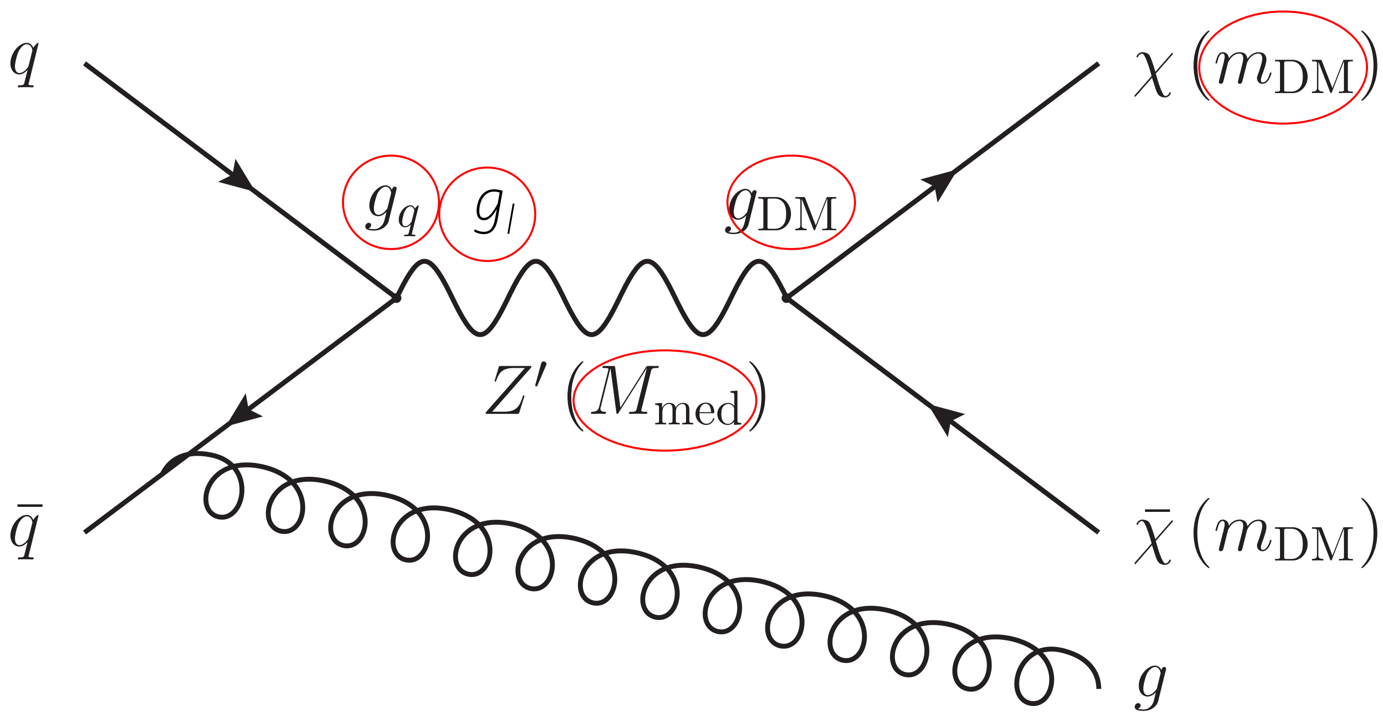
Jet clustering requirements

- **Collinear safety** :collinear splitting should not change jets
- **Infrared safety** : soft emissions should not change jets



Dark Matter Searches@ the LHC: Simplified Models

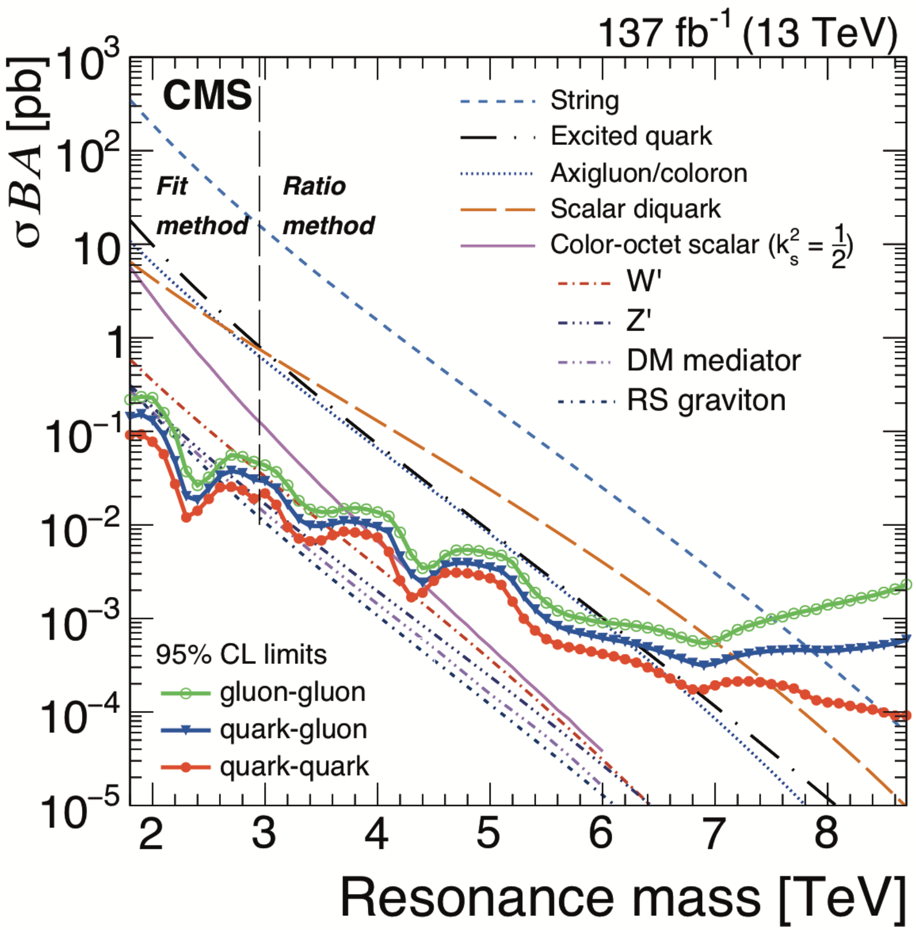
https://arxiv.org/pdf/1703.05703.pdf

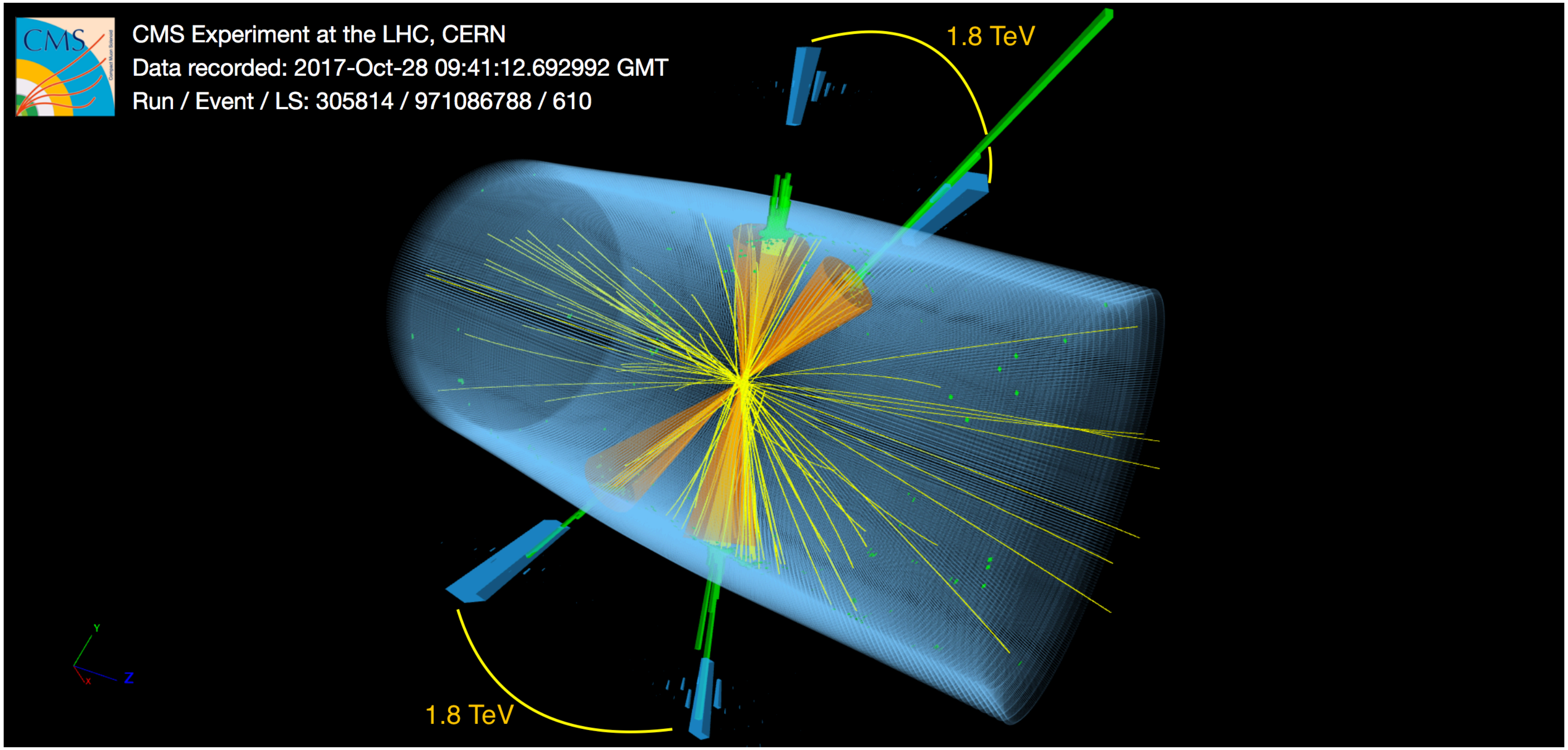


N. Saoulidou Univ. of Athens, Greece

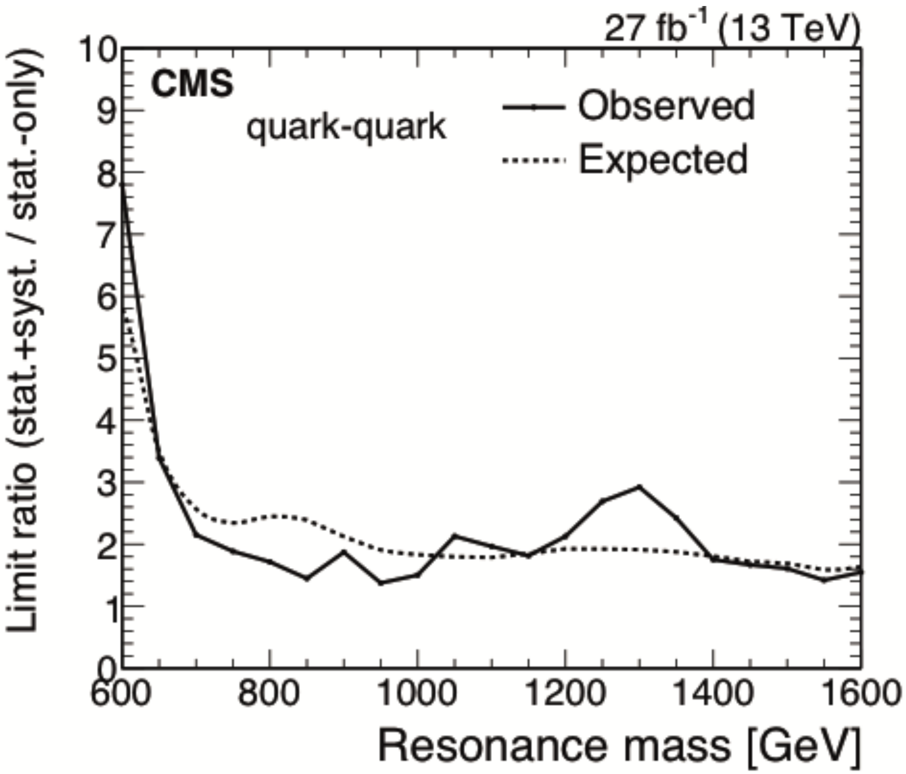
Narrow resonances: cross section limits

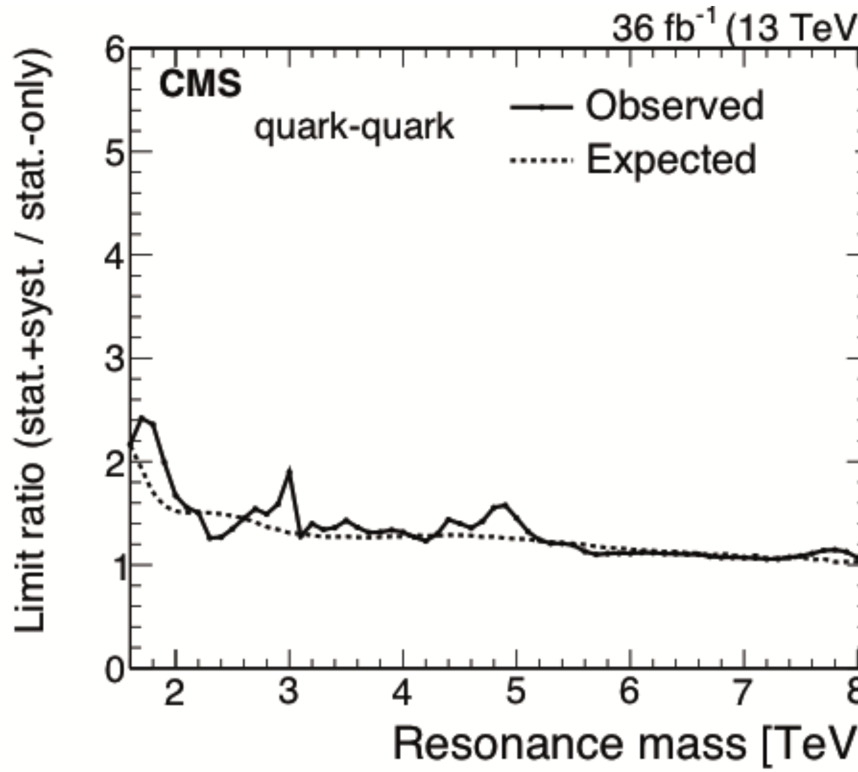
JHEP 05 (2020) 033

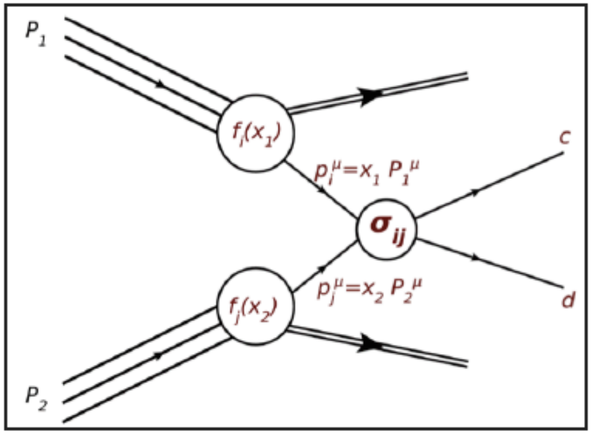



CMS Experiment at the LHC, CERN
Data recorded: 2017-Oct-28 09:41:12.692992 GMT
Run / Event / LS: 305814 / 971086788 / 610
1.8 TeV
1.8 TeV

Systematics vs Statistical Uncertainties







- Events with two energetic partons (quarks or gluons) arise in proton-proton collisions from parton-parton scattering.
- We observe this outgoing parton pair as two hadronic jets (dijets) in the detector.
- The dijet mass spectrum predicted by Quantum Chromodynamics (QCD) falls smoothly and steeply with increasing dijet mass.

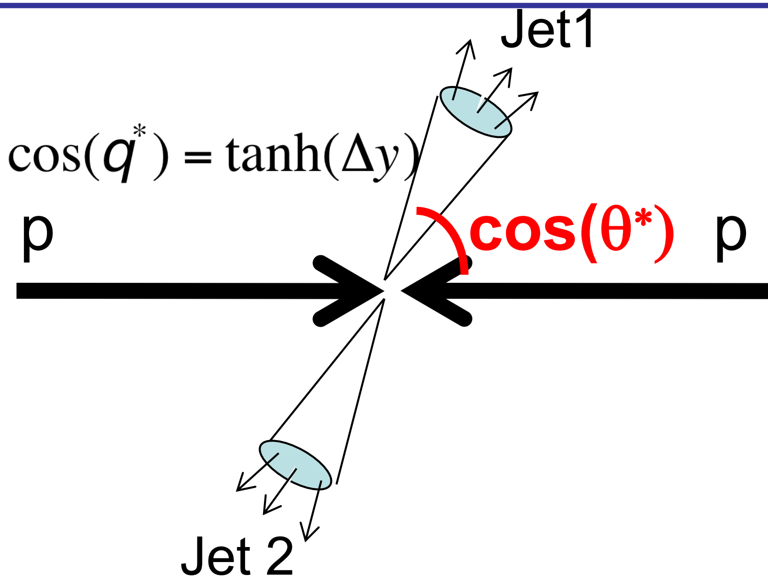
$$d\sigma(P_1P_2 \to cd) = \int_0^1 dx_1 dx_2 \sum_{q_i,q_j} f_i(x_1,\mu_F^2) f_j(x_2,\mu_F^2) d\hat{\sigma}_{q_i q_j \to cd}(\alpha_s(\mu_F^2), Q^2/\mu_F^2)$$

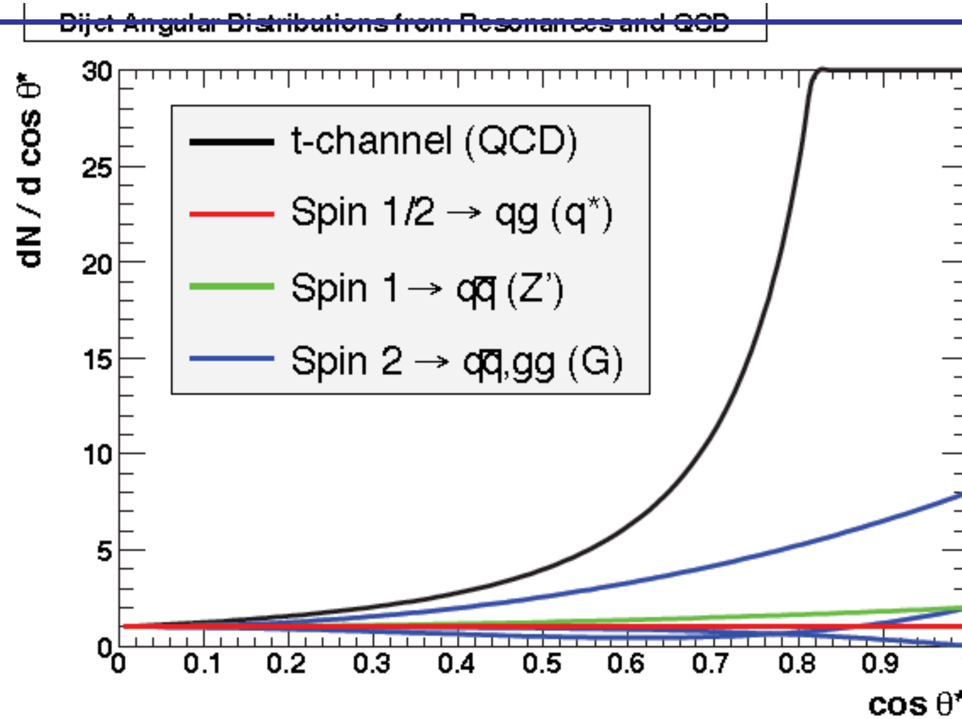
$$M^2{}_{jj} = 2 p_{T1} p_{T2} [\cosh(\Delta\eta) - \cos\Delta\phi] \approx 2 p^2{}_T [\cosh(\Delta\eta) + 1]$$

Higher η means increased $\Delta\eta$, which makes the Dijet mass higher

$$y = 1/2 \ln [(\mathrm{E} + \mathrm{p_L})/(\mathrm{E} - \mathrm{p_L})], |y| = \max(|y_1|, |y_2|)$$

Dijet Angular Distributions





- Parton-parton scattering in QCD is t-channel dominated.
- Stringent test of pQCD with no dependence on PDFs.
- New physics would show deviations from expectation at large scattering angles.

Dilepton searches : uncertainties

JHEP04(2019)114
CMS-PAS-EXO-19-019

Source	Dielectron channel [%]		Dimuon channel [%]	
	Signal	Background	Signal	Background
Luminosity	3.2 (3.2)	3.2 (3.2)	3.2 (3.2)	3.2 (3.2)
MC statistical	<1.0 (<1.0)	<1.0 (<1.0)	<1.0 (<1.0)	<1.0 (<1.0)
Beam energy	2.0 (4.1)	2.0 (4.1)	1.9 (3.1)	1.9 (3.1)
Pile-up effects	<1.0 (<1.0)	<1.0 (<1.0)	<1.0 (<1.0)	<1.0 (<1.0)
DY PDF choice	-	<1.0 (8.4)	-	<1.0 (1.9)
DY PDF variation	-	8.7 (19)	-	7.7 (13)
DY PDF scales	-	1.0 (2.0)	-	<1.0 (1.5)
DY α_S	-	1.6 (2.7)	-	1.4 (2.2)
DY EW corrections	-	2.4 (5.5)	-	2.1 (3.9)
DY γ-induced corrections	-	3.4 (7.6)	-	3.0 (5.4)
Top quarks theoretical	-	<1.0 (<1.0)	-	<1.0 (<1.0)
Dibosons theoretical	-	<1.0 (<1.0)	-	<1.0 (<1.0)
Reconstruction efficiency	<1.0 (<1.0)	<1.0 (<1.0)	10 (17)	10 (17)
Isolation efficiency	9.1 (9.7)	9.1 (9.7)	1.8 (2.0)	1.8 (2.0)
Trigger efficiency	<1.0 (<1.0)	<1.0 (<1.0)	<1.0 (<1.0)	<1.0 (<1.0)
Identification efficiency	2.6 (2.4)	2.6 (2.4)	-	-
Lepton energy scale	<1.0 (<1.0)	4.1 (6.1)	<1.0 (<1.0)	<1.0 (<1.0)
Lepton energy resolution	<1.0 (<1.0)	<1.0 (<1.0)	2.7 (2.7)	<1.0 (6.7)
Multi-jet & W+jets	-	10 (129)	-	-
Total	10 (11)	18 (132)	11 (18)	14 (24)

- **Resonant CMS search.**
- **Among largest uncertainties are the PDF related ones.**

Dilepton searches : uncertainties

Phys. Lett. B 796 (2019) 68
ATLAS-EXOT-2019-16

Uncertainty source for m_X [GeV]	Dielectron 300	Dielectron 2000	Dielectron 5000	Dimuon 300	Dimuon 2000	Dimuon 5000
Spurious signal	±12.5 (12.0)	±4.6 (10.8)	±0.1 (1.0)	±11.7 (11.0)	±3.8 (3.5)	±2.1 (2.2)
Lepton identification	±1.6 (1.6)	±5.6 (5.6)	±5.6 (5.6)	±1.8 (1.8)	$^{+12}_{-10}$ $\left(^{+12}_{-10}\right)$	$^{+25}_{-20}$ $\left(^{+25}_{-20}\right)$
Isolation	±0.3 (0.3)	±1.1 (1.2)	±1.1 (1.1)	±0.4 (0.4)	±0.4 (0.4)	±0.4 (0.5)
Luminosity	±1.7 (1.7)	±1.7 (1.7)	±1.7 (1.7)	±1.7 (1.7)	±1.7 (1.7)	±1.7 (1.7)
Electron energy scale	$^{-1.7}_{-4.0}$ $\left(^{+1.0}_{-1.8}\right)$	$^{-1.9}_{-6.0}$ $\left(^{+1.7}_{-2.9}\right)$	$^{+0.1}_{-0.4}$ (±0.8)	-	-	-
Electron energy resolution	$^{+7.9}_{-8.3}$ $\left(^{+1.1}_{-0.9}\right)$	$^{+9.0}_{-11.8}$ $\left(^{+0.7}_{-0.5}\right)$	$^{+0.4}_{-0.9}$ (±0.1)	-	-	-
Muon ID resolution	-	-	-	$^{+0.8}_{-2.3}$ $\left(^{+0.3}_{-0.8}\right)$	$^{+0.9}_{-1.3}$ $\left(^{+0.7}_{-1.1}\right)$	$^{+0.6}_{-0.4}$ $\left(^{+0.5}_{-0.3}\right)$
Muon MS resolution	-	-	-	$^{+2.8}_{-3.8}$ $\left(^{+1.0}_{-1.3}\right)$	$^{+3.2}_{-3.0}$ $\left(^{+2.6}_{-2.4}\right)$	±2.4 (2.1)
‘Good muon’ requirement	-	-	-	±0.6 (0.6)	$^{+9.0}_{-8.2}$ $\left(^{+9.0}_{-8.2}\right)$	$^{+55}_{-35}$ $\left(^{+55}_{-35}\right)$

- **Resonant ATLAS search.**
- **Among largest uncertainties are the background modeling related ones depicted in the “spurious” signal category.**

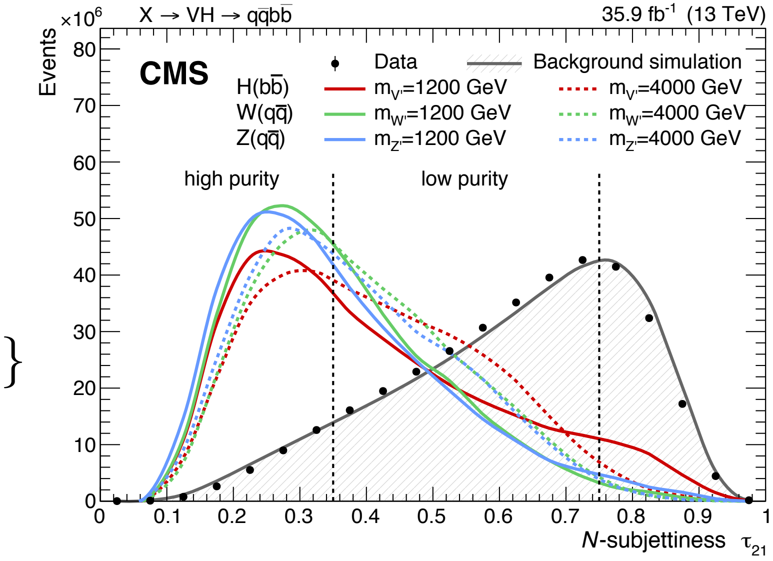
Jet Substructure : N-subjetiness

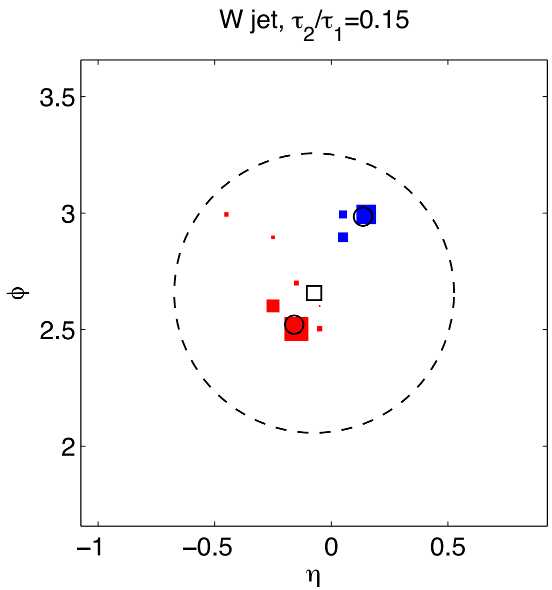
JHEP 1103:015,2011

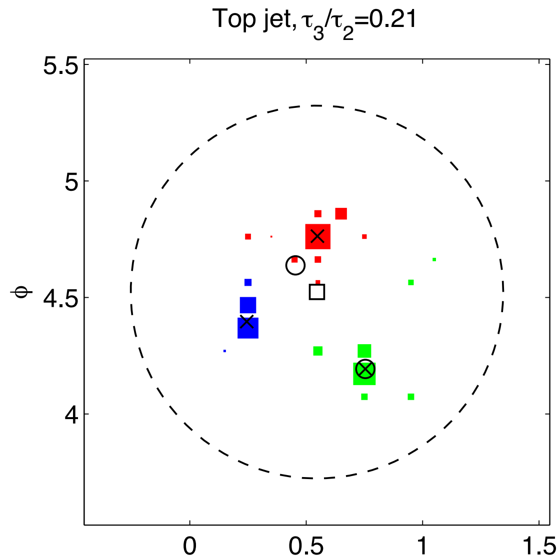
- Main discriminating variables between a ”uniform” jet and one experiencing inner “sub-structure” are the N-subjetiness ones

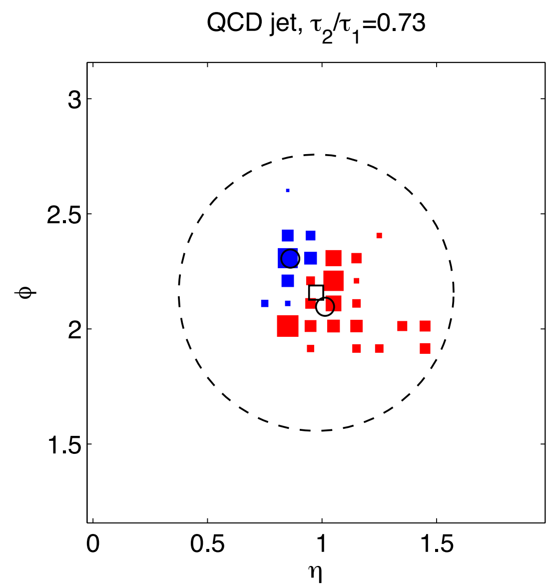
$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min\{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\}$$

$$d_0 = \sum_k p_{T,k} R_0,$$



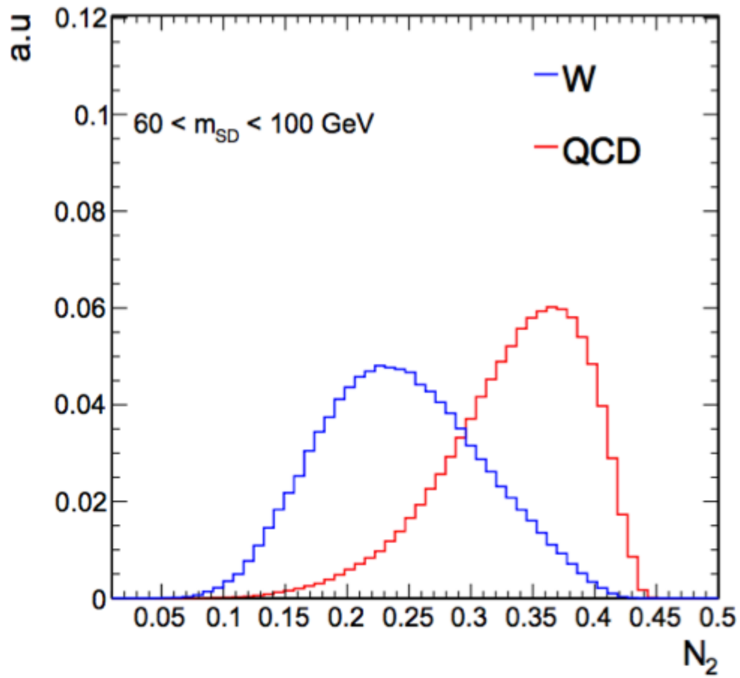






Jet Substructure : Energy Flow

JHEP 1306 (2013) 108



$$\mathrm{ECF}(N,\beta) = \sum_{i_1<i_2<\ldots<i_N\in J} \left(\prod_{a=1}^{N} E_{i_a}\right)\left(\prod_{b=1}^{N-1}\prod_{c=b+1}^{N}\theta_{i_b i_c}\right)^{\beta}.$$

Infrared, collinear safe, for all β>0.

- Main discriminating variables between a "uniform" jet and one experiencing inner "sub-structure" **using generalized energy correlation functions.**
- They use **information about the energies and pair-wise angles of particles within a jet.**
- They can identify **N-prong jet substructure without requiring a subjet finding procedure,** and hence can **optimize discriminating power depending on the problem.**

Two main methods for jet grooming: **Pruning [Phys.Rev.D80,05150 (2009)]** (recluster) and **Softdrop [JHEP05(2014),146]** (decluster).

Eur.Phys.J. C77 (2017) no.9, 636