Dijet Resonance Searches at CMS

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Outline

- Introduction
- Brief overview of the CMS Experiment
- The Physics we are after
- Dijet Resonances Searches:
  - Resolved
  - Boosted
  - Angluar

- Summary and Outlook

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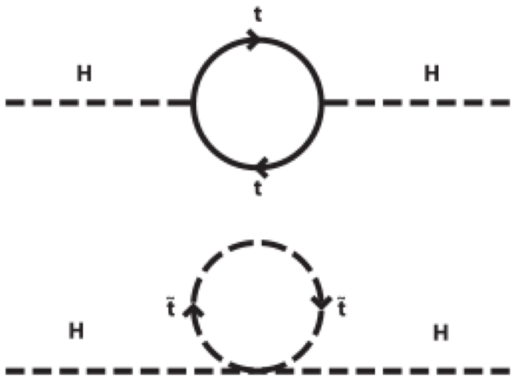
Introduction : SM incomplete

Theoretical point of view

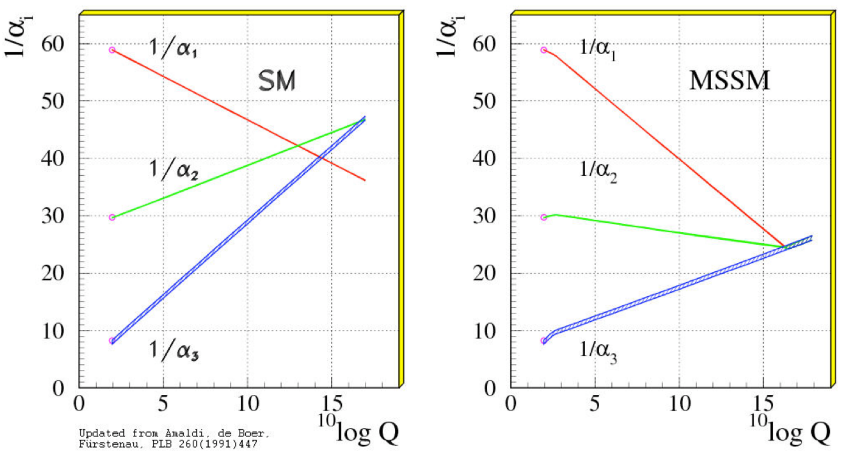


- **Quantum Gravity** : *SM describes three of the four fundamental interactions at the quantum level (microscopically) BUT gravity is only treated classically.*

- **Hierarchy Problem :** *Why is $M_{Pl}/M_{EW} \sim 10^{15}$*
  What is the mechanism of cancelation of quadratic divergencies?

- **Unification of Gauge couplings** *: Why couplings are so different?*

- **Origin of generations :** Why three?



Experimental point of view

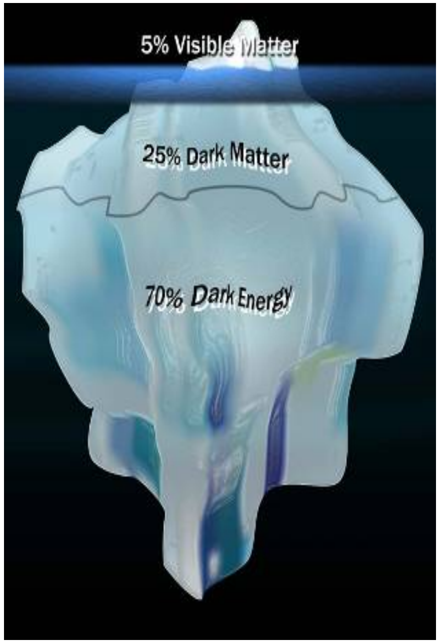
- **Dark matter – Dark Energy :** *What is 95% of the Universe made off?*

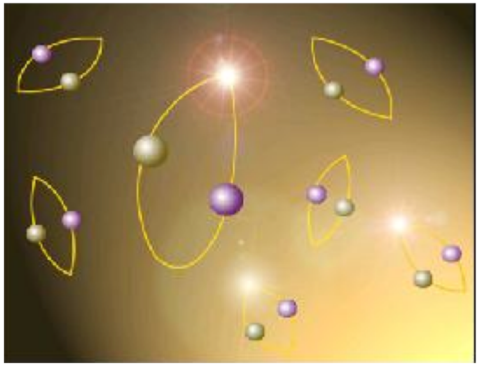
- **Cosmological constant** *: Why is vacuum energy SO small?*

  $\rho_{VAC} = M_{Pl}^4 = 10^{120}\rho_{VAC}^{obs}$ (!!!)

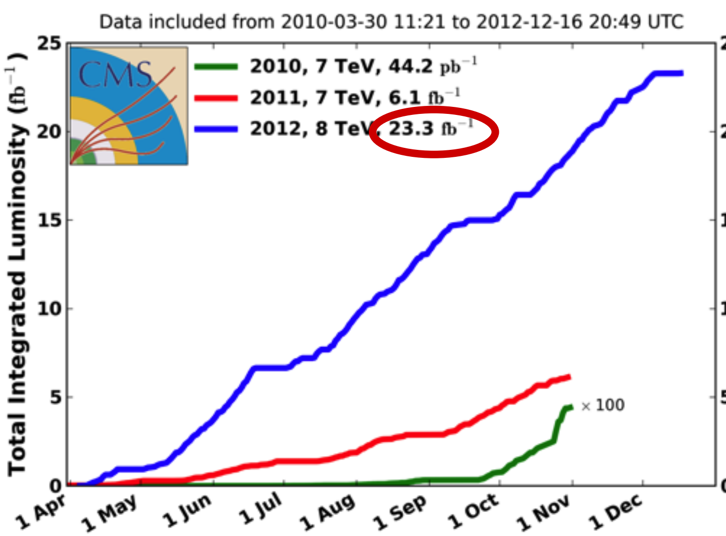
- **CP Violation***: Why are we here? OR What is the source of the dramatic matter-antimatter asymmetry in the Universe?*

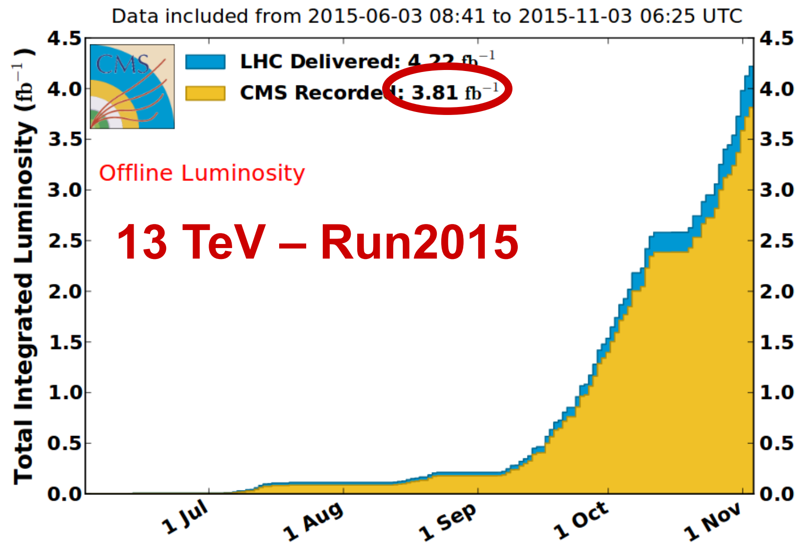
- **Neutrino masses and mixings** *: What is the Origin of neutrino masses, what is the nature of neutrino, why are ν mixings so different than quark ones?*

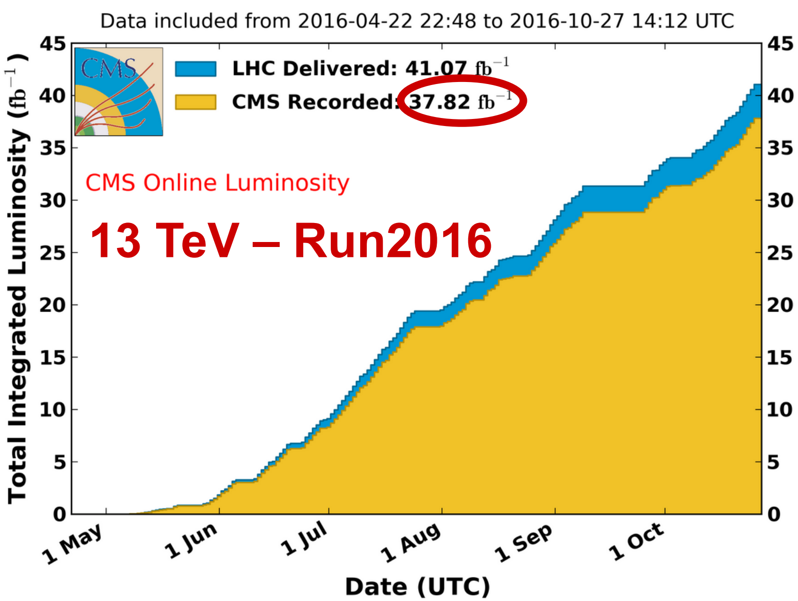


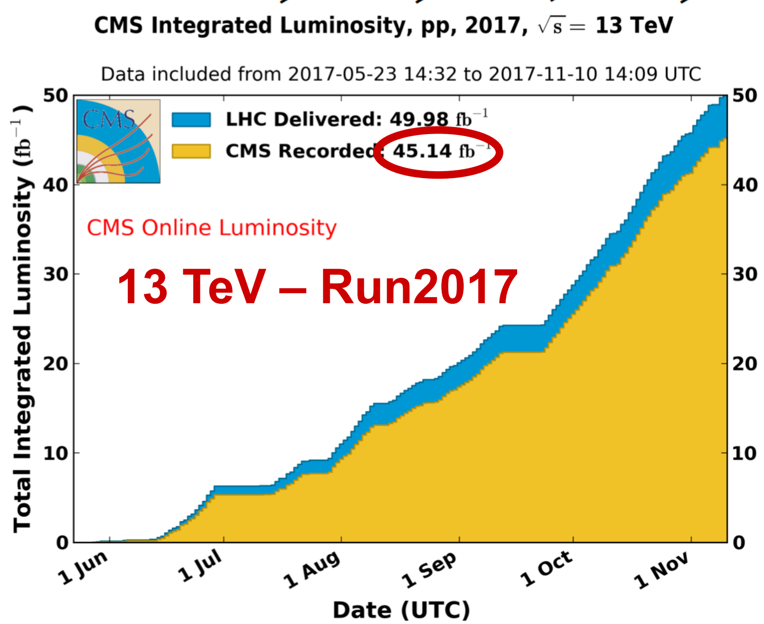


Data Collection

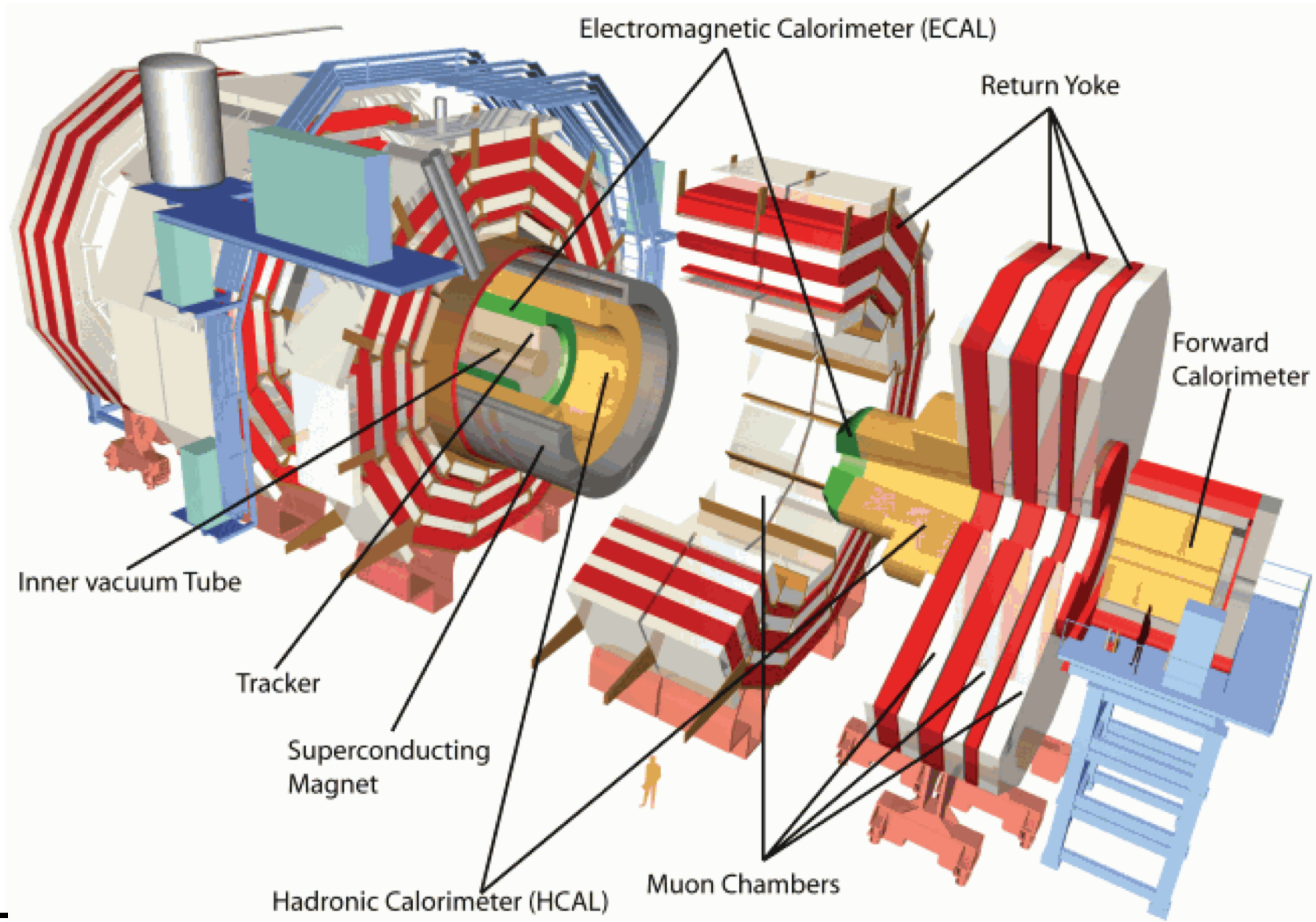








The CMS Detector



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

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

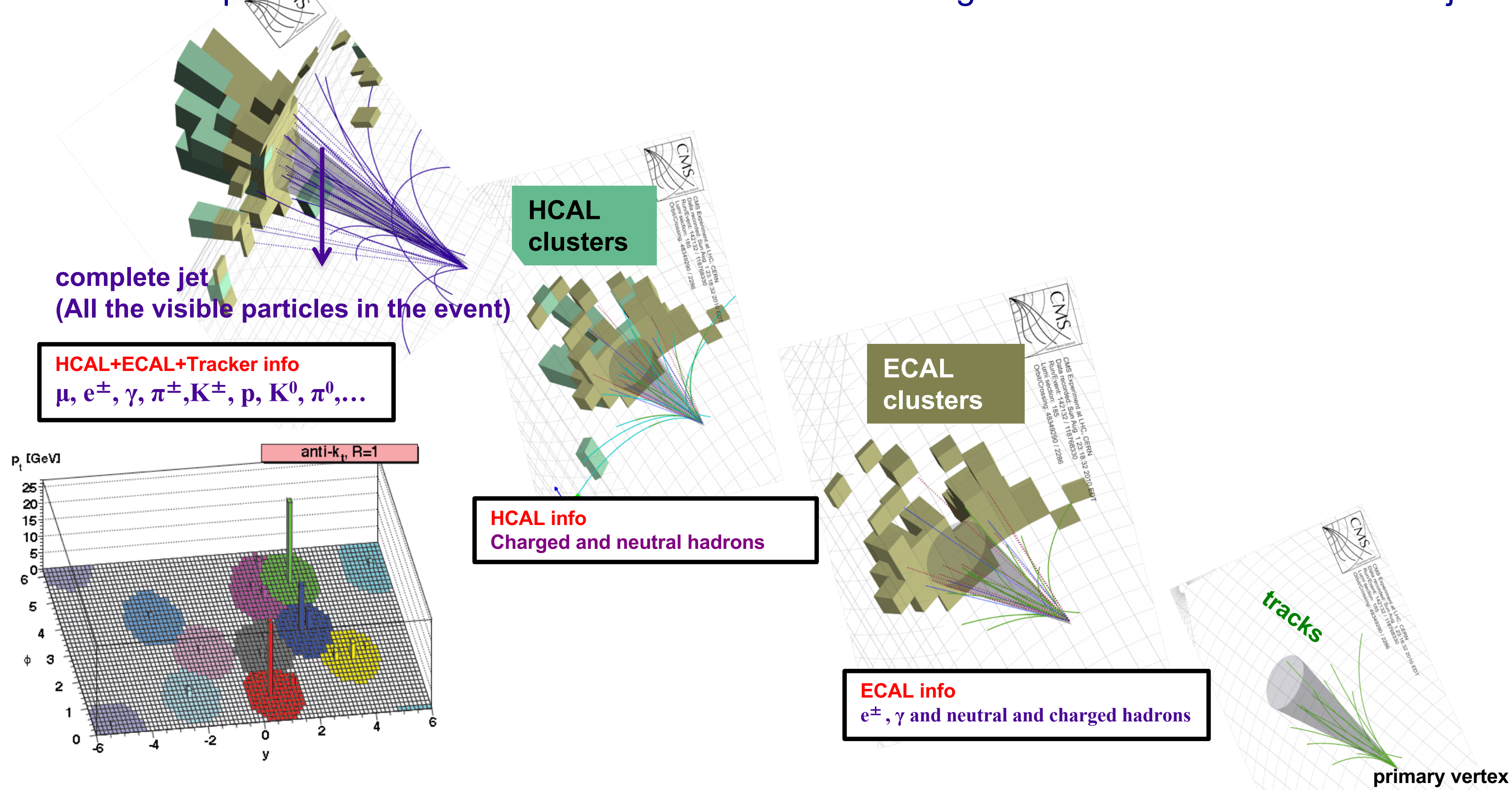
Muon Spectrometer

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

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

Jet Reconstruction

- Particle Flow Algorithm combines all information from several sub-detector systems
- Individual particles are reconstructed with Particle Flow Algorithm and then clustered into jets.



Silicon Tracker info
μ, e±, and all charged hadrons

Anti-kt clustering algorithm : with R = 0.4 and 0.8 for CMS It is infrared and collinear safe, geometrically well defined, and tends to cluster around the hard energy deposits.

Jet Calibration

Physics Object

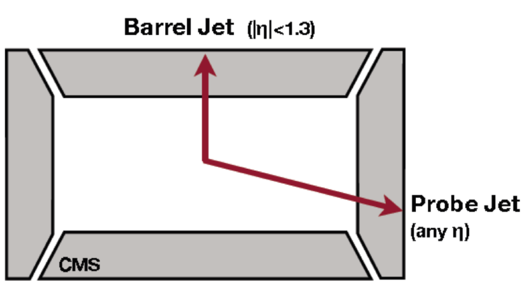
Raw Jet × Offset Correction (pile up) × Relative Response (vs. η) × Absolute Response (vs. p_T) = Calibrated Jet

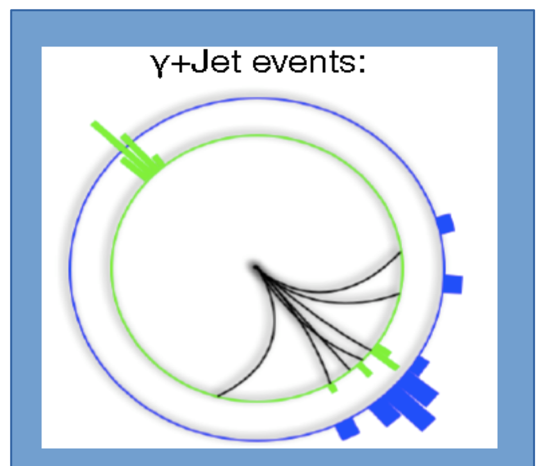
$$E_{corrected} = (E_{uncorrected} - E_{offset}) \text{ x } C_{rel}(\eta, pT'') \text{ x} C_{Abs}(pT')$$

where p_T'' is the transverse momentum of the jet corrected for offset and $p_T'' = p_T \times C_{Rel}(\eta, p''T)$

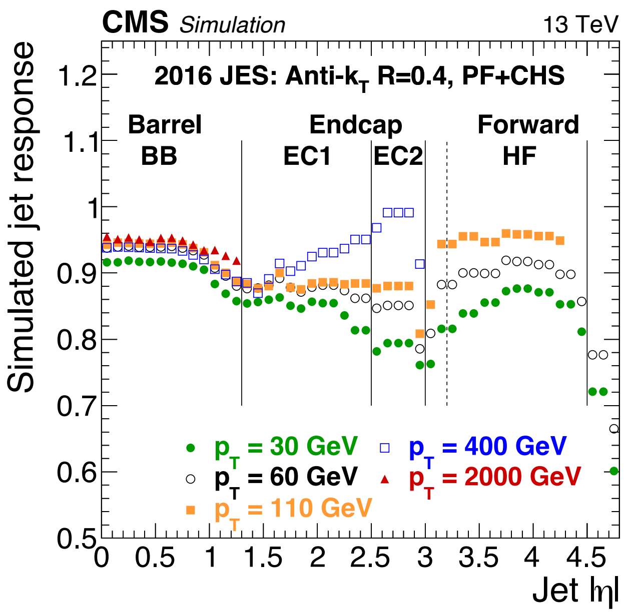
Data driven methods used for the residual corrections

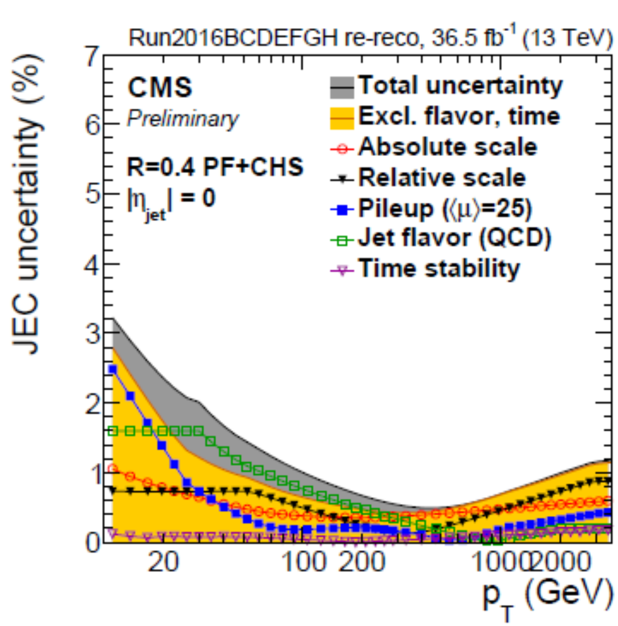
Dijet asymmetry

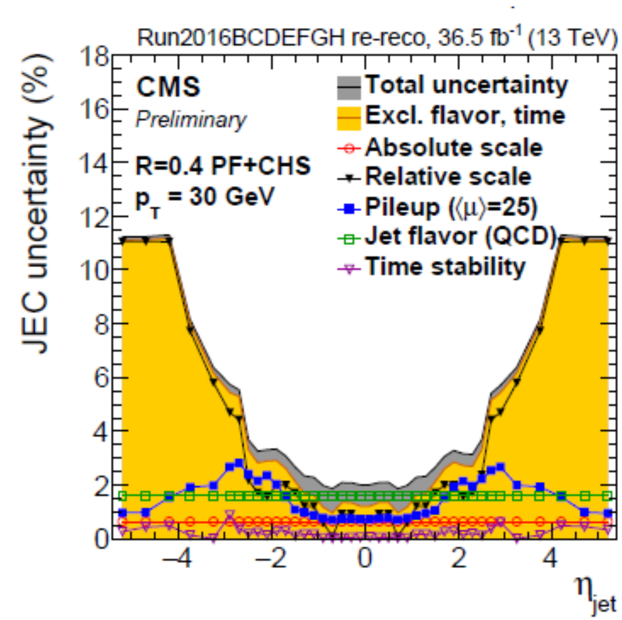




Jet Calibration





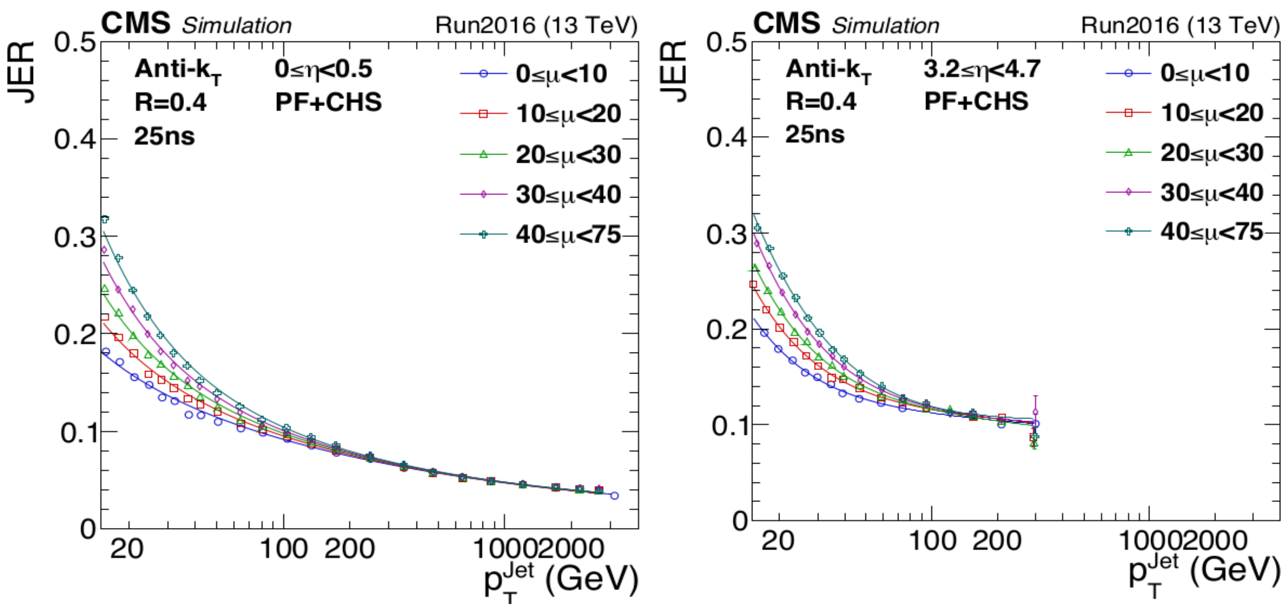


- Response very close to 1 for PF jets.
- Uncertainties <1% for pT>100 GeV

Jet Resolution

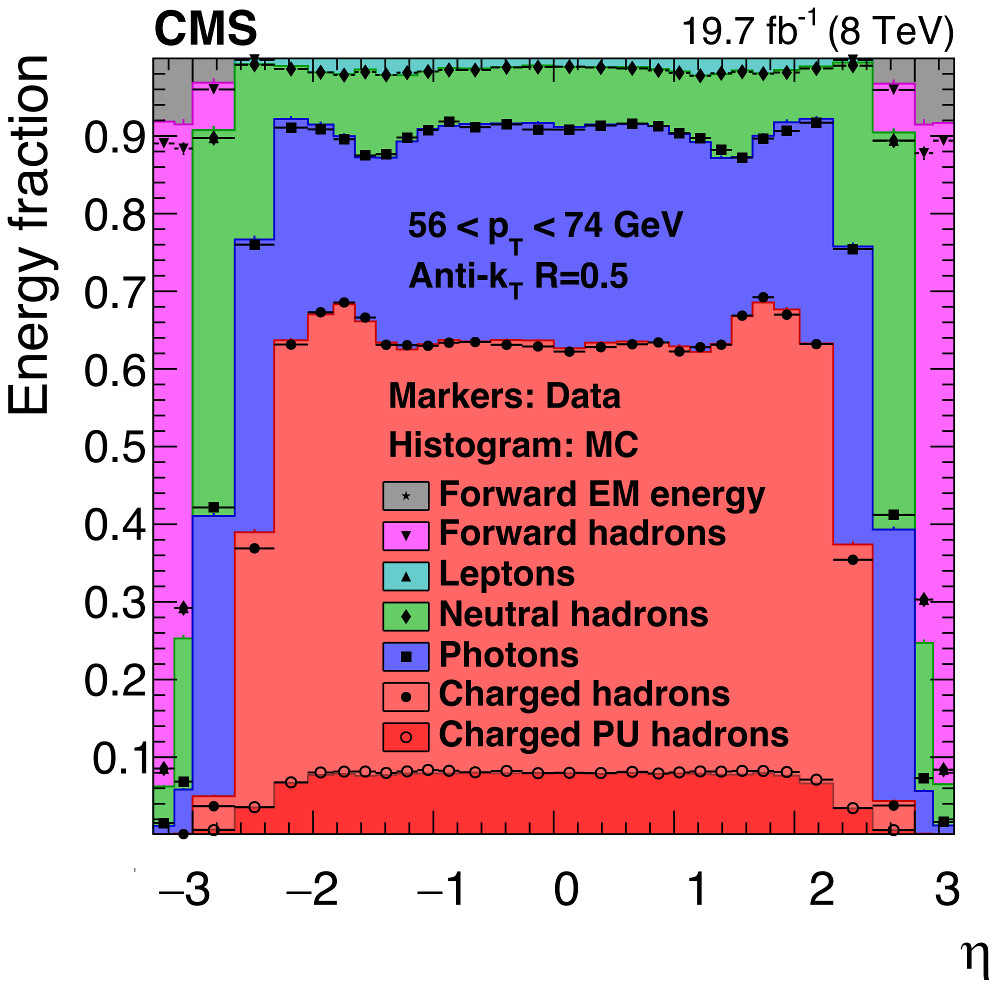
p_T asymmetry method, in dijet samples, is used:

$$\mathcal{A} = \frac{p_T^{Jet1} - p_T^{Jet2}}{p_T^{Jet1} + p_T^{Jet2}} \quad \sigma_{\mathcal{A}}^2 = \left|\frac{\partial \mathcal{A}}{\partial p_T^{Jet1}}\right|^2 \cdot \sigma^2(p_T^{Jet1}) + \left|\frac{\partial \mathcal{A}}{\partial p_T^{Jet2}}\right|^2 \cdot \sigma^2(p_T^{Jet2}) \quad \boxed{\frac{\sigma(p_T)}{p_T} = \sqrt{2}\sigma_{\mathcal{A}}}$$



Better than 10% (5%) resolution above 100GeV (1TeV).

Jet Quality

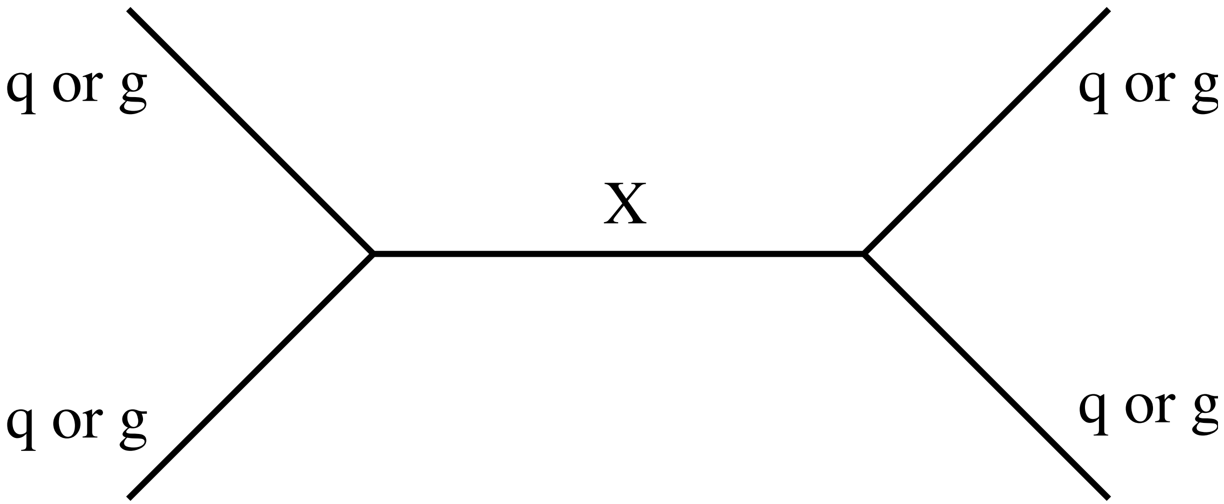


Particle flow jets, described by:

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

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

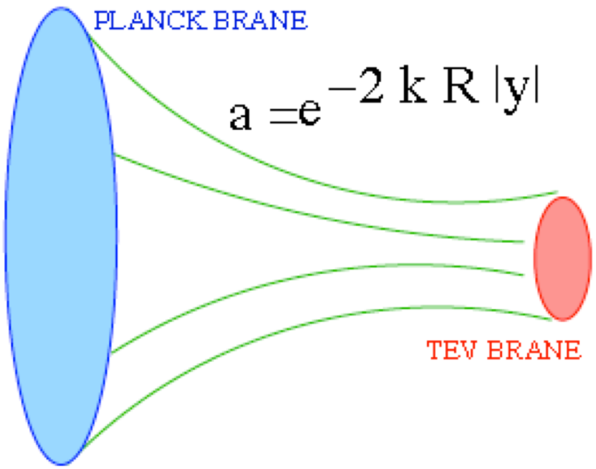
New Physics Searches with Dijets



Access a broad range of new physics hypothesis

New Resonances : Extra Dimensions

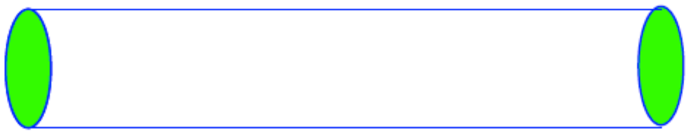
arXiv:hep-ph/0606153



- **Randall Sundrum** : A single "warped" extra dimension so that large scales at the Planck brane are redshifted at the TeV brane

- Then $M_w = e^{-2k\pi R} M_{Pl}$

arXiv:hep-ph/0606153



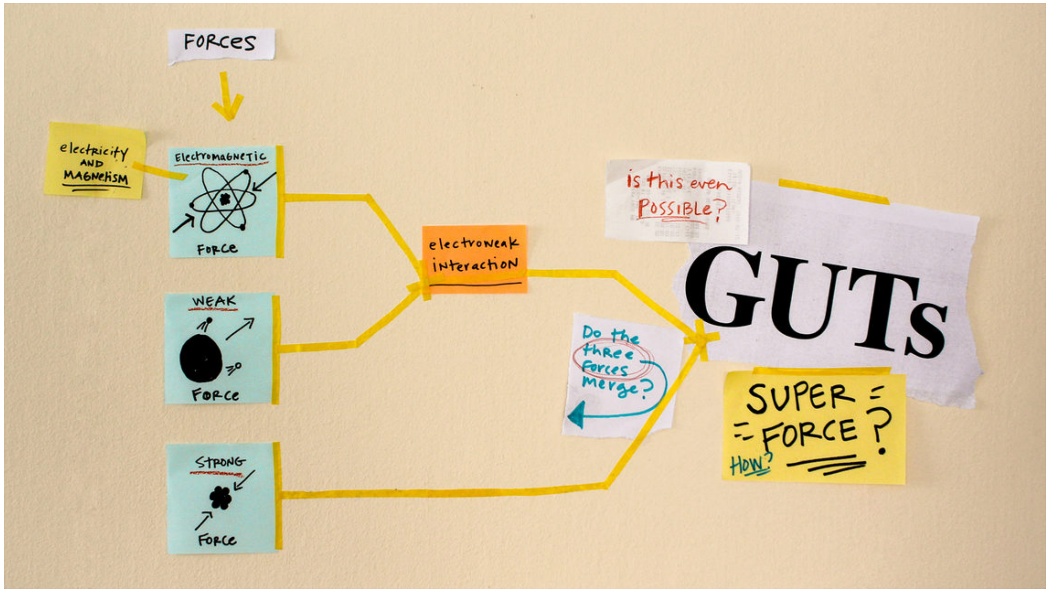
FLAT EXTRA DIMENSION

- **ADD** : n large extra dimensions where only gravity propagates, then the Planck scale is "reduced" by the large compactification volume V ~ R^n.

- Then $M_w \cong [M_{Pl}R]^{-\frac{n}{n+2}} M_{Pl}$

New Resonances: Grand Unified Theories

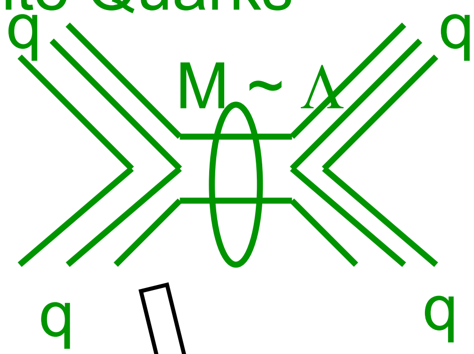
http://www.symmetrymagazine.org/article/a-gut-feeling-about-physics



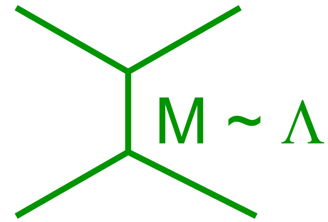
- Is there a larger gauge group containing SU(3) x SU(2) x U(1) making the extremely successful SM the low-energy limit of a more fundamental theory?
- Extended gauge group models always predict new heavy neutral and charged resonances like W', Z'.

New Resonances : Compositeness

Composite Quarks

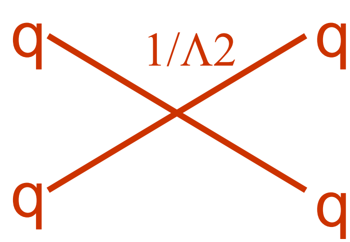


New Interactions



Dijet Mass << Λ

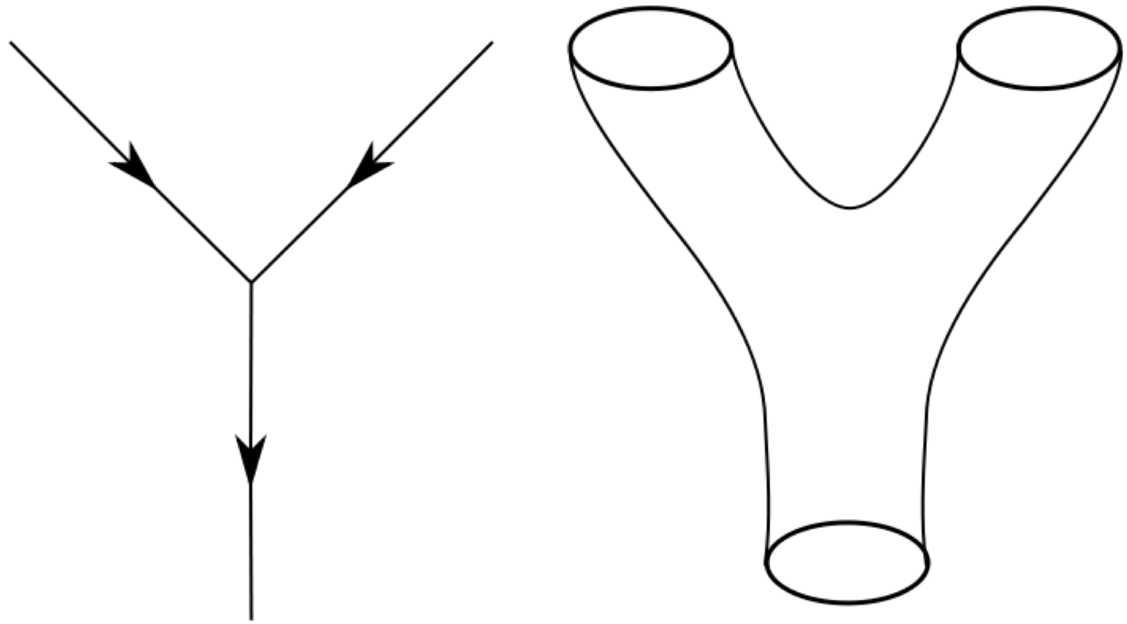
Quark Contact Interaction & Excited quarks $qg \rightarrow q^* \rightarrow qg$



E. Eichten, K. Lane, and M. Peskin, "New Tests for Quark and Lepton Substructure", Phys. Rev. Lett. **50 (1983) 811, doi:10.1103/PhysRevLett.50.811.**

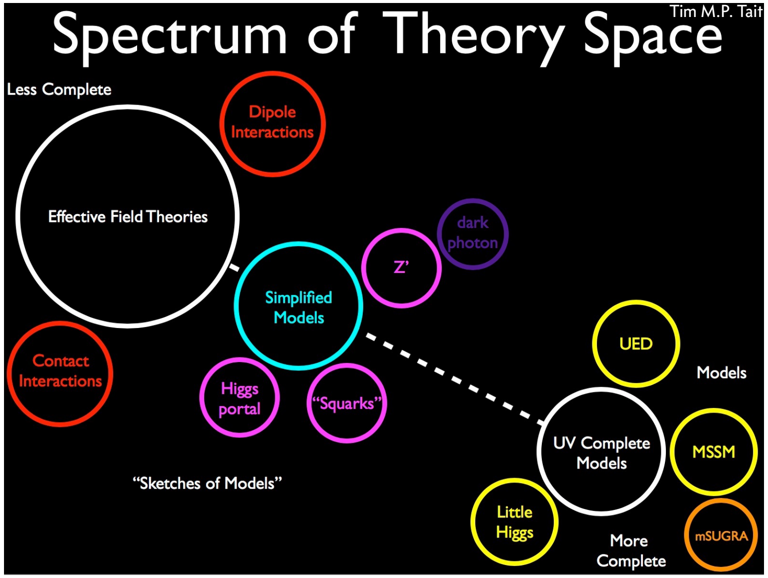
"The proliferation of quarks and leptons has naturally led to the speculation that they are composite structures, bound states of more fundamental constituents which are often called "preons. "

New Resonance : String Theory



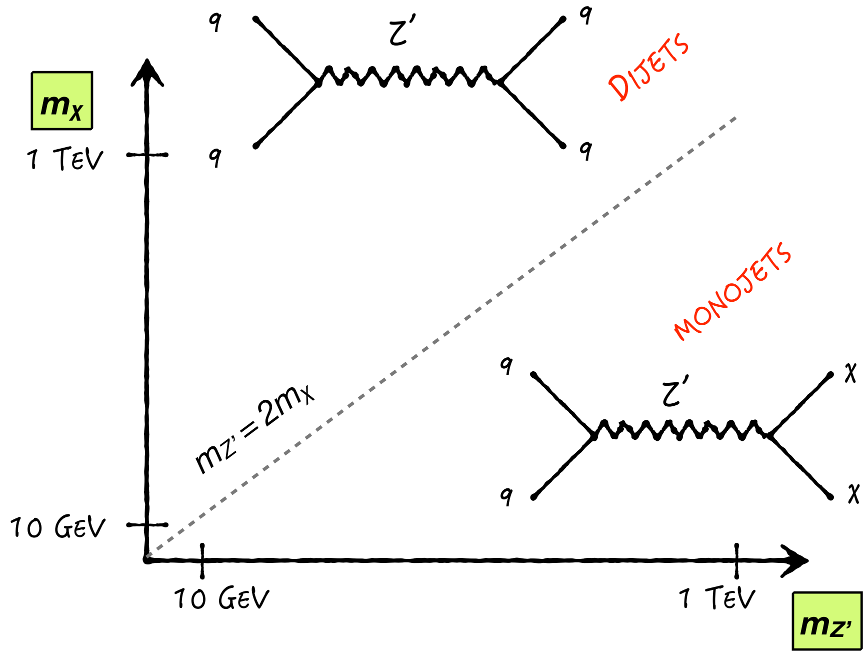
- Our world might be composed from string-like rather than point-like objects.
- Vibrating strings can produce resonances which in some theories with large extra dimensions lie in the TeV scale.

New Resonance : Dark Matter



- 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: Simplified Models



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

$$\Gamma^{\rm tot}_{\rm AV} = \Gamma^{\chi\bar\chi}_{\rm AV} + 3\times \sum_{q=u,d,s,c,b,t} \Gamma^{q\bar q}_{\rm AV}$$

$$\Gamma^{q\bar q}_{\text{axial-vector}} = \frac{g_q^2\,M_{\rm med}}{4\pi}\,(1-4\,z_q)^{3/2}\ ,$$

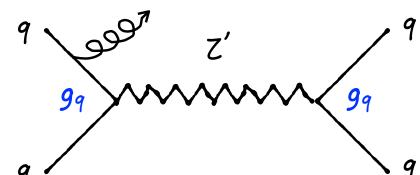
$$\Gamma^{q\bar q}_{\rm vector} = \frac{g_q^2\,M_{\rm med}}{4\pi}\,(1-4\,z_q)^{1/2}\,(1+2\,z_q)\ ,$$

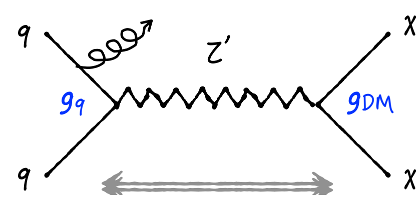
$$z_i = m_i^2/M_{\rm med}^2$$

- DM-nucleon scattering cross section:

vector: $\sigma_{\rm SI} \simeq 6.9\times 10^{-41}\ {\rm cm}^2 \cdot \left(\frac{g_q g_{\rm DM}}{0.25}\right)^2 \left(\frac{1\ {\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ {\rm GeV}}\right)^2$

axial-vector: $\sigma^{\rm SD} \simeq 2.4\times 10^{-42}\ {\rm cm}^2 \cdot \left(\frac{g_q g_{\rm DM}}{0.25}\right)^2 \left(\frac{1\ {\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ {\rm GeV}}\right)^2$





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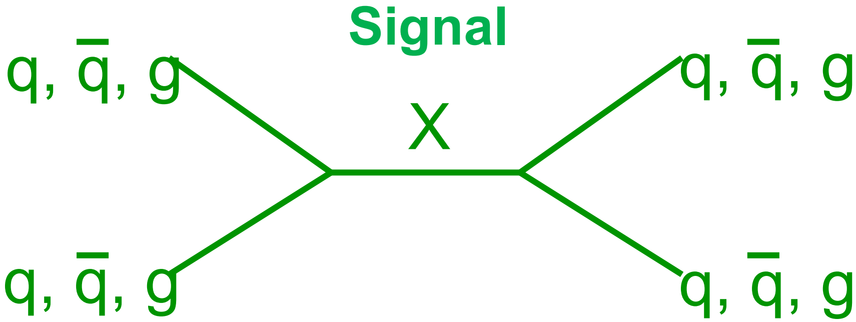
General Analysis Methodology

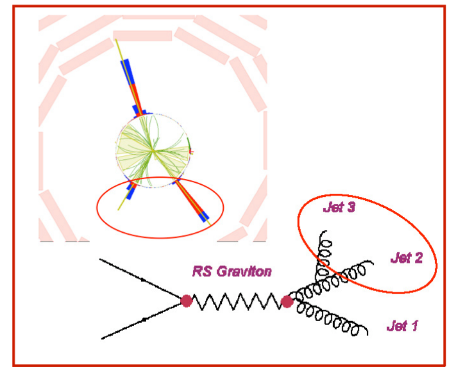
- **Analysis Strategy :** search for a narrow or wide resonance on top of a smoothly falling background.
- **Background Estimation :**
  - **Data-driven :** Fitting the invariant di-object mass with an empirical function.
  - **Semi data-driven :** Predicting the SM background from control regions with transfer functions from simulation.
  - **Using simulation** for the SM template, validating it with data when possible.
- **Signal Modelling :** Intrinsic signal shape, either narrow (with width smaller than the detector resolution) or wide, convoluted with the CMS detector resolution.
- **Limit extraction** : Fitting the invariant mass spectrum using the background and signal shapes and systematics as nuisance parameters

Dijet (resolved) Search in a nutshell



- **Reconstructed objects**
-

-Particle Flow Jets, Calorimeter Jets

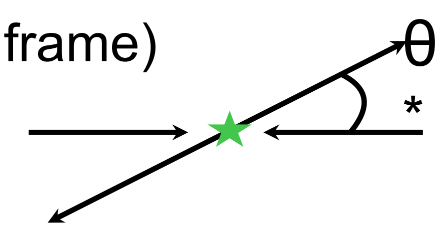


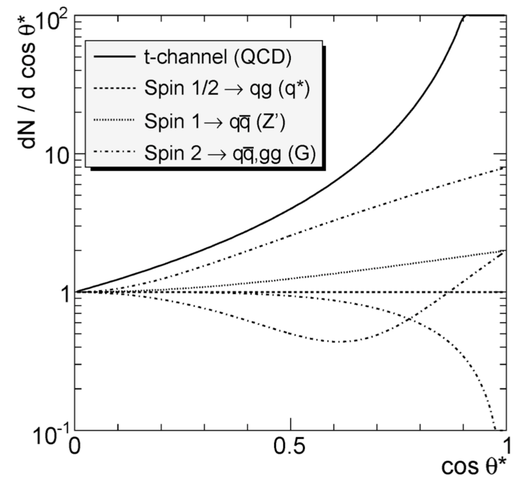
- **Physics observables**

M(jj) → Resonance Mass
Δη(jj) → Resonance Spin

(X rest frame)

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





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Reconstruction and Event Selection

- Selecting events with:

Number of jets >=2

$pT_1 > 60$ GeV, $pT_2 > 30$ GeV,

$|\eta|<2.5$ (tracker acceptance),

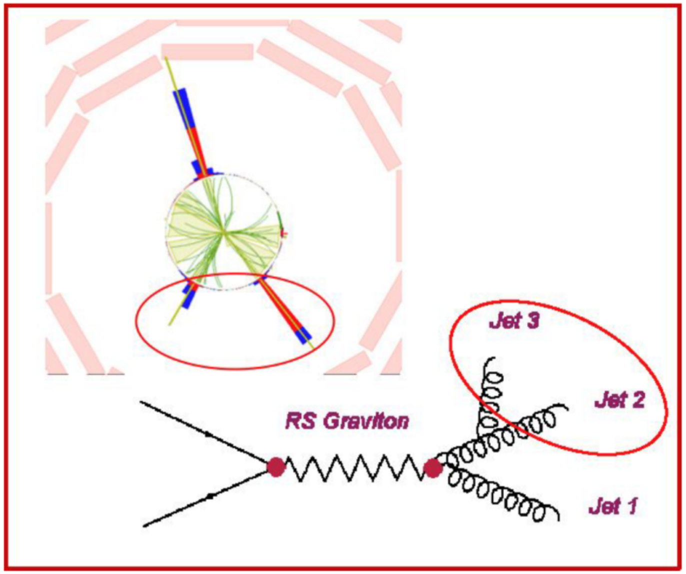
JetID criteria for all jets -> remove noise

- For recovering the Final State Radiation

Use "Wide Jets" (gives better sensitivity) on AK4:

The clustering starts with the two leading jets which have to satisfy jet criteria. All other jets are added to the closest leading jet if they are within **$\Delta R=1.1$** and have **pT > 30 GeV**.

Wide Jet Reconstruction

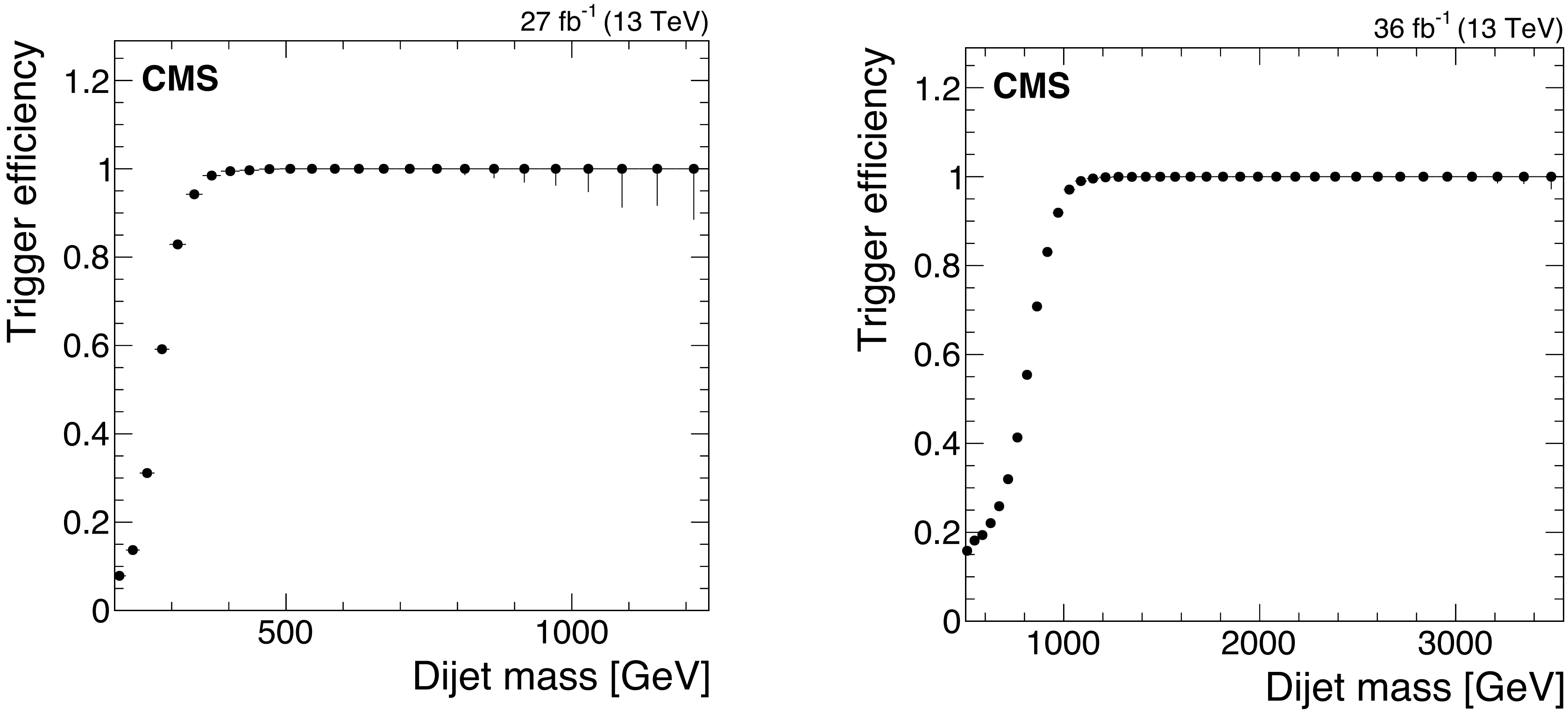


- Dijet Event Selection:

$|\Delta\eta^{wide}| < 1.3$ suppresses QCD (t-channel) and enhances signal (s-channel)

Dijet Mass > Trigger Cut for full efficiency

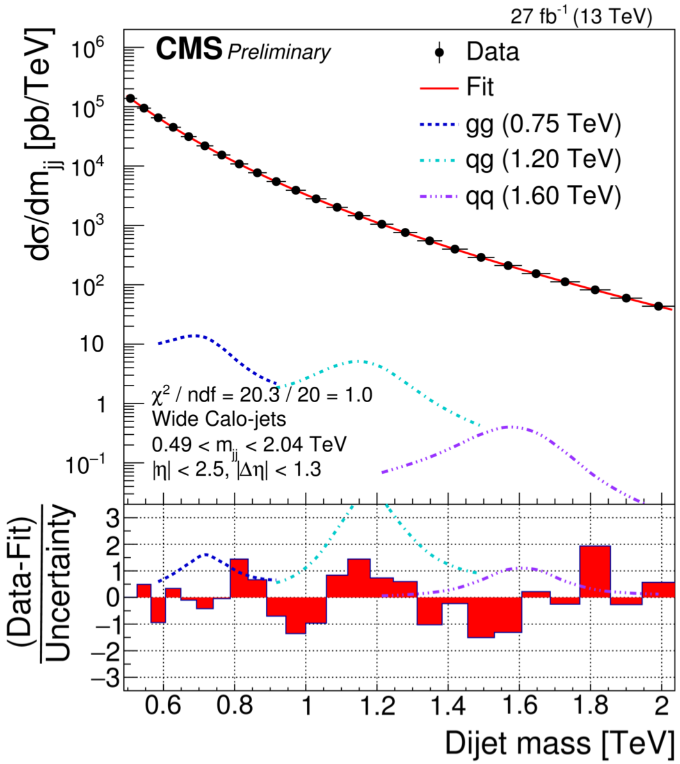
Triggers

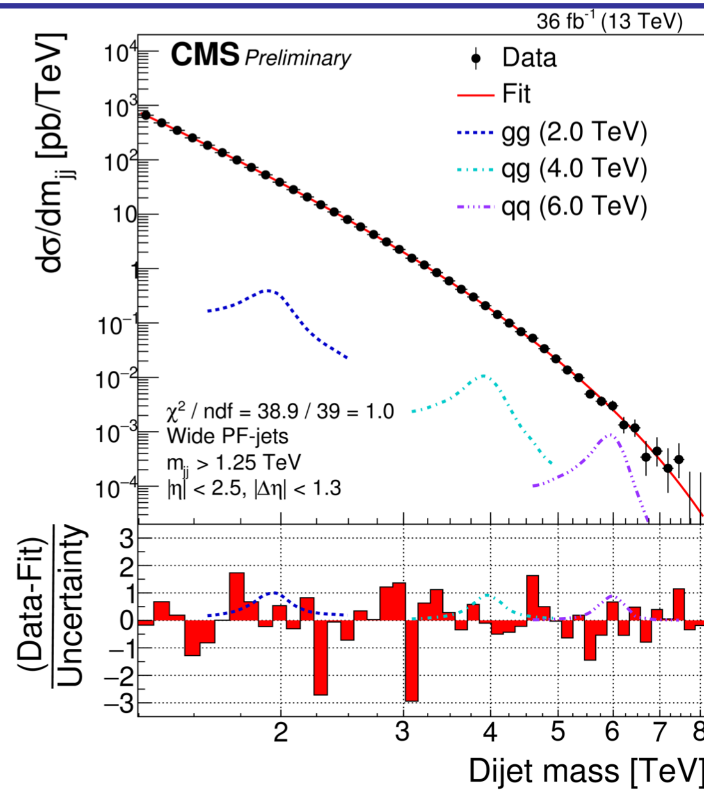


- User unprescaled Particle Flow Triggers for the High Mass Analysis and Calorimeter “Scouting” Triggers for the Low Mass Analysis

- Both are examined against orthogonal, as well as and jet-related ones for the absolute and relative efficiency calculations

Experimental Results





- **Event selection:** Two "wide" jets ($\Delta R<1.1$), formed from jets with p_T>30 GeV and $|\eta|<2.4$, $\Delta\eta(j,j) < 1.3$, M_{jj} > 1246 GeV (PF Jets), M_{jj} > 489 GeV (Calorimeter Jets)

- **Background Modeling :** A fit with an empirical parametrization is performed to the data , with its parameters are treated as unconstrained nuisance parameters in the hypothesis testing

$$\frac{d\sigma}{dm_{jj}} = \frac{p_0(1-x)^{p_1}}{x^{p_2+p_3\log(x)}} \qquad x = \frac{m_{jj}}{\sqrt{s}}$$

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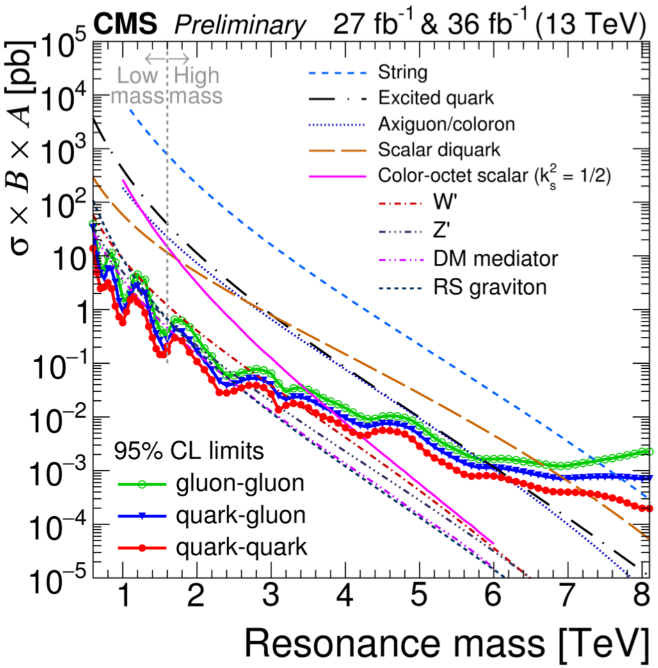
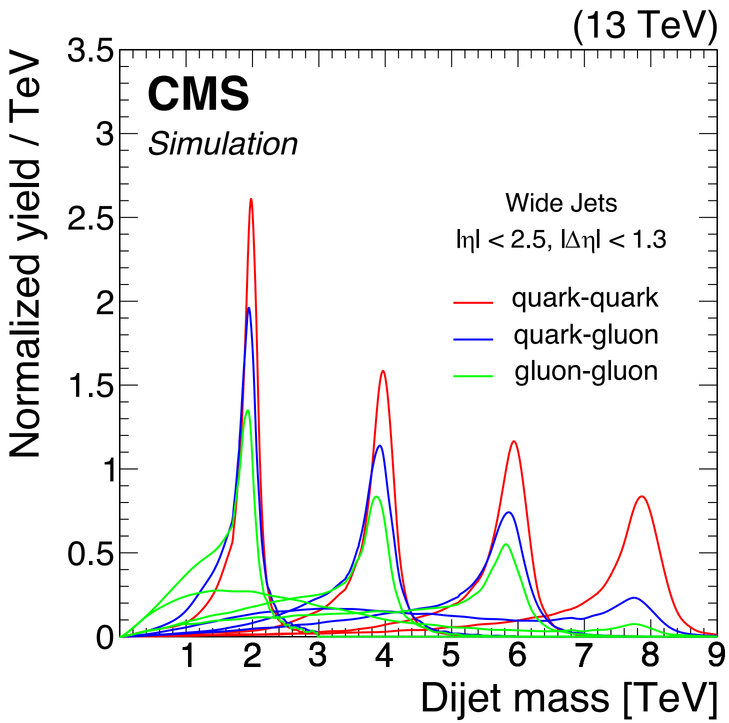
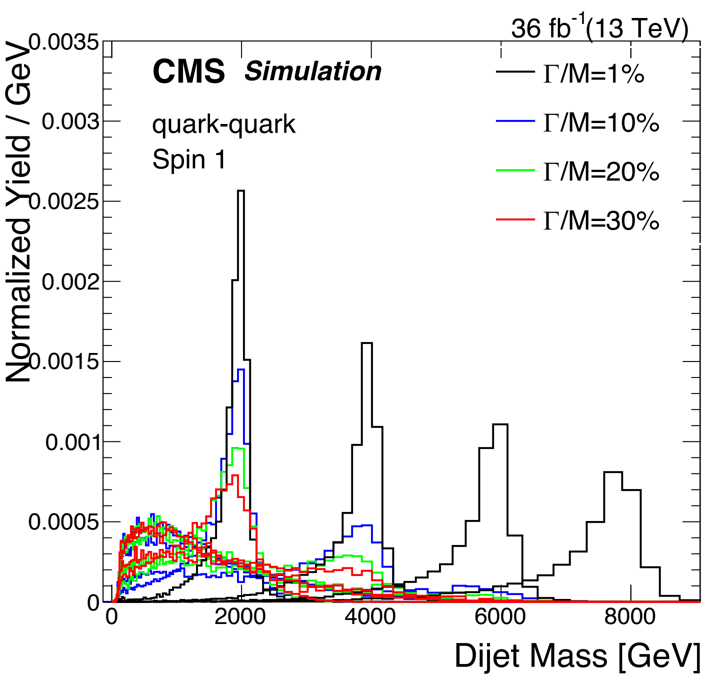
Cross section limits & Mass limits : narrow resonances

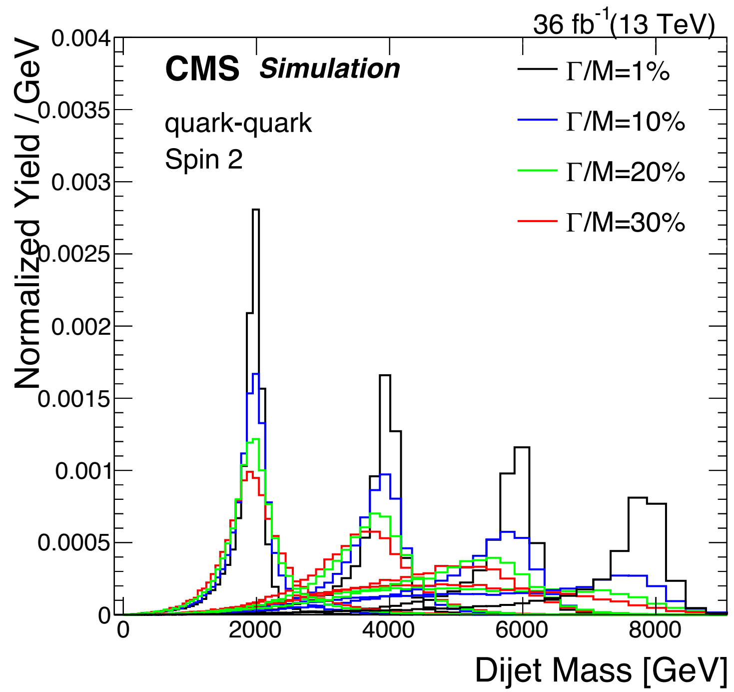




- **Signal Modeling :** pdf is convolution of a nonrelativistic Breit-Wigner with a gaussian for detector resolution effects. Narrow resonances considered here
- **Fitting :** Modified frequentist CLs is used for limit setting, performing a binned fit with a background and signal template.
- **Systematic uncertainties:** Only related to signal modeling : luminosity, jet energy scale and jet resolution. Analysis at low masses starts to become systematics limited.

Wide Resonances : DM interpretations





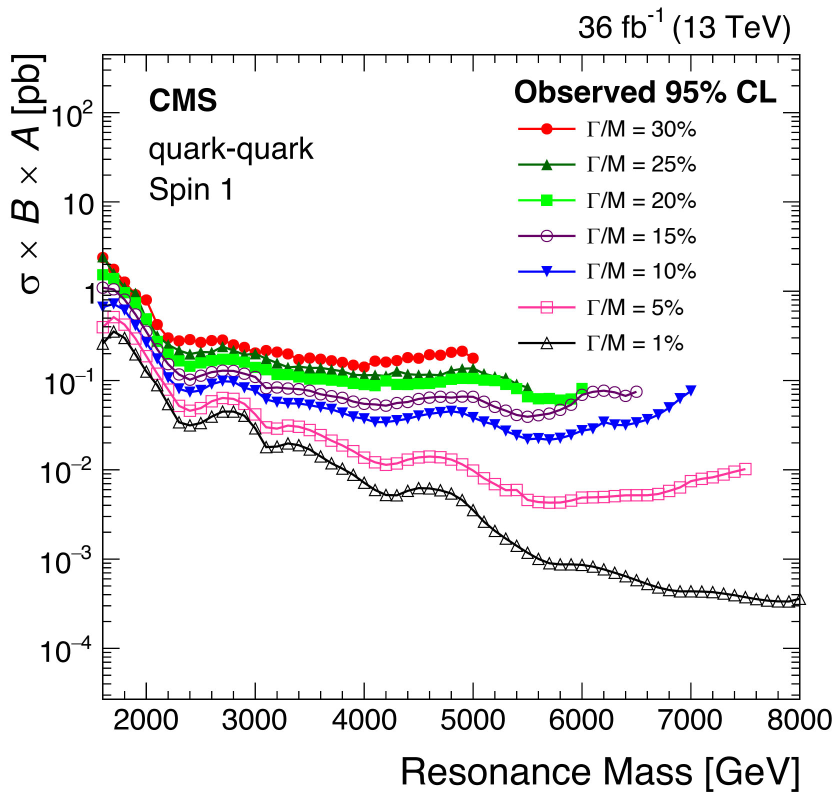
$$H_R^{(i,f)}(\hat{s}) = \frac{\hat{s}\Gamma_R^{(i,f)}}{M_X}.$$

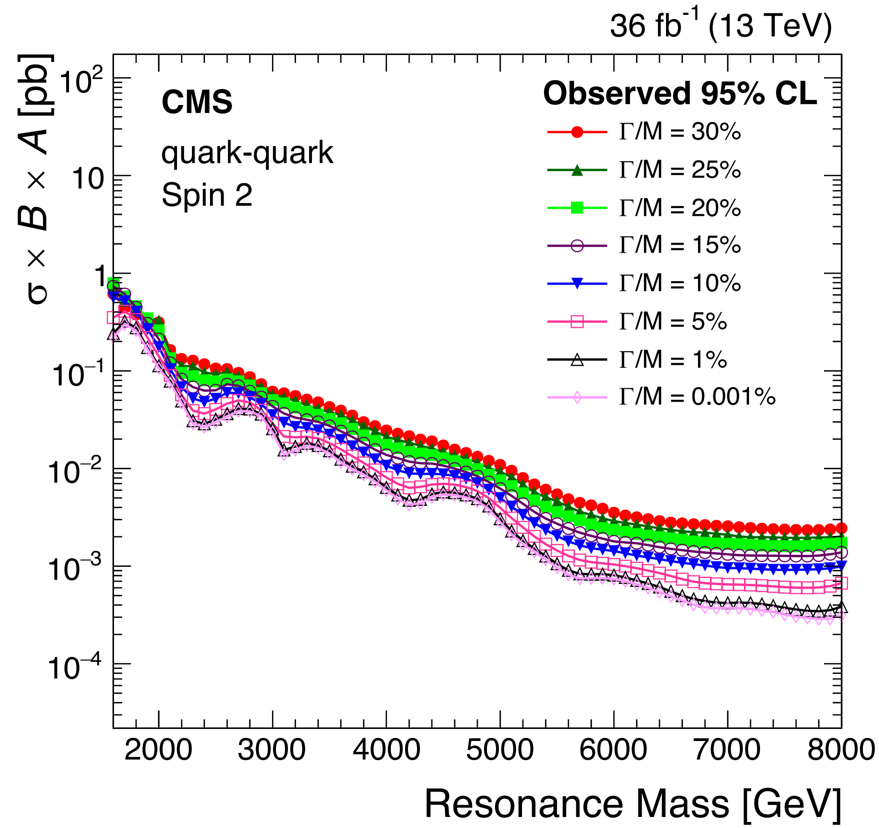
$$\hat{\sigma}_{i\to R\to f}(\hat{s}) \propto \frac{\pi}{\hat{s}} \frac{H_R^{(i)}(\hat{s})\, H_R^{(f)}(\hat{s})}{(\hat{s}-M_X^2)^2 + H_R^2(\hat{s})},$$

$$H_R^{(i,f)}(\hat{s}) = \left(\frac{\hat{s}}{M_X^2}\right) \frac{\hat{s}\Gamma_R^{(i,f)}}{M_X}$$

- 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 Resonances : Cross section limits

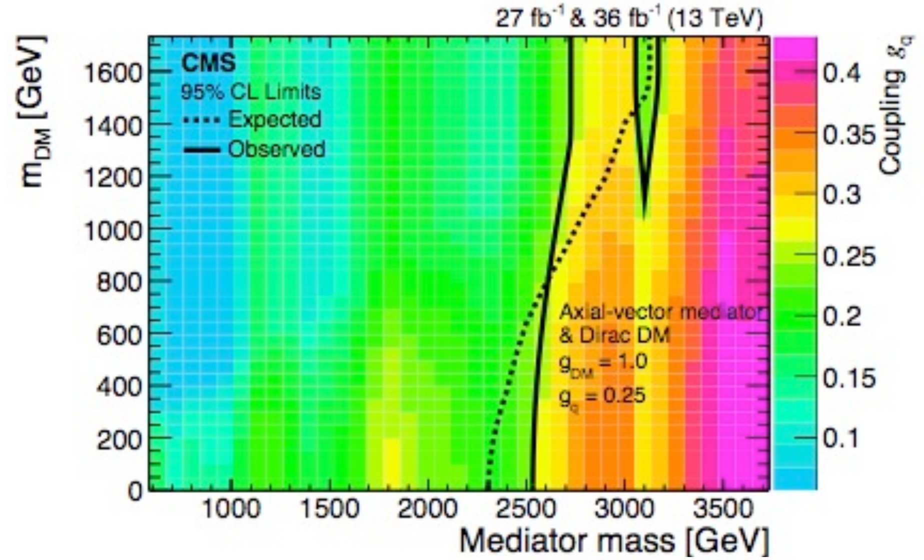


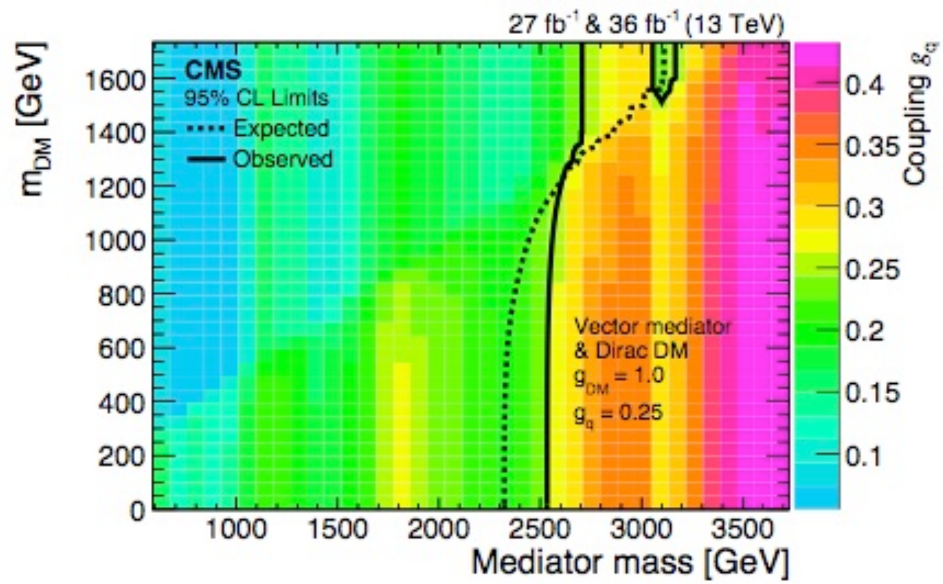


- Degradation of limits as width of resonance increases, more so for the Spin 2 case than the Spin 1 one.

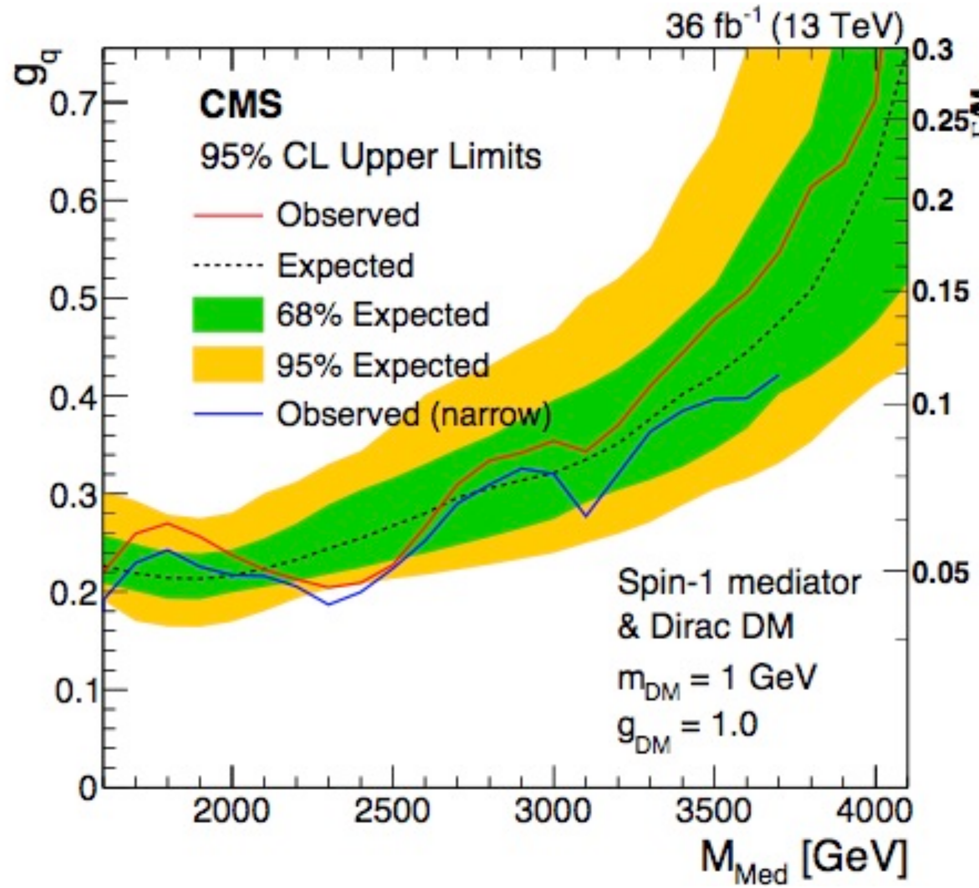
Dark Matter Searches: Simplified Models

- Limits on DM mediator improve as the mass of the DM particle increases
- Limits on DM mediator coupling to quarks stronger for smaller DM particle masses.
- Limits on DM mediator coupling to quarks strongly dependent on resonance width.





Dark Matter Searches: Simplified Models



- Limits on DM mediator coupling to quarks strongly dependent on resonance width.

- As statistics increase, at the same centre-of-mass energy, **improvements become marginal unless significant analysis improvements take place with a target to reduce systematic uncertainties.**

Improve the Analysis

Define a control region, NP depleted , (1.3<Δη<2.5) and with similar kinematical characteristics as the signal region, in order to perform additional quality checks **[part of the analysis already],** and predict the QCD background in the signal region as follows, using the simulation to estimate the following ratio [R_{ext}] :

$$M_{jj}^{Prediction}\ (Signal\ region) = R_{ext} \times M_{jj}^{Data}\ (Control\ region)$$

$$R_{ext} = M_{jj}^{Simulation}\ (Signal\ Region)/M_{jj}^{Simulation}\ (Control\ Region)$$

Advantages:

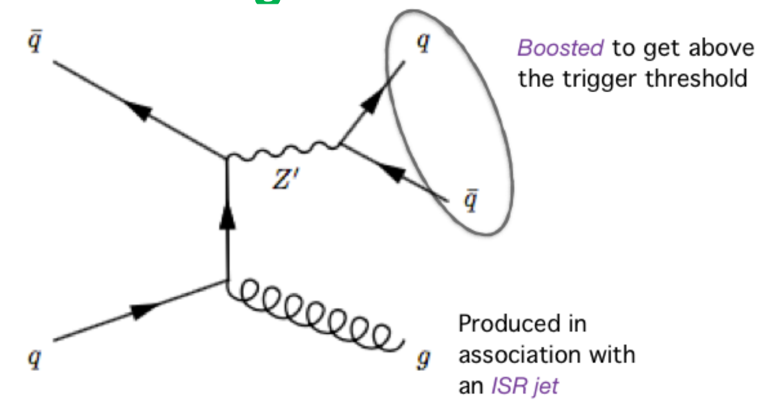
- **It is data-driven, and hence with lower systematic uncertainties**, since many cancel out in the ratio.
- **It does not assume a model** for the shape of the QCD background in the signal region since it derives it from data in the control region.
- It is potentially **less biased** with respect to signal-template fitting.

Extend the analysis

- **Use b-tagging to increase** sensitivity to resonances decaying to a b-quark
  - Searches for Excited b quark, b* -> b g, and Coloron, C->b bbar
- Standard CMS b-tagging loose working point gives more sensitivity than medium or tight.
  - Investigating whether we can use even looser working points which appear to give significantly more sensitivity.
- **DeepFlavour b-tagging being actively investigated as well for additional sensitivity**
- Expect that with improved b-tagging and the 2016 and 2017 data sample the sensitivity to b* will be sufficiently better than Run I.

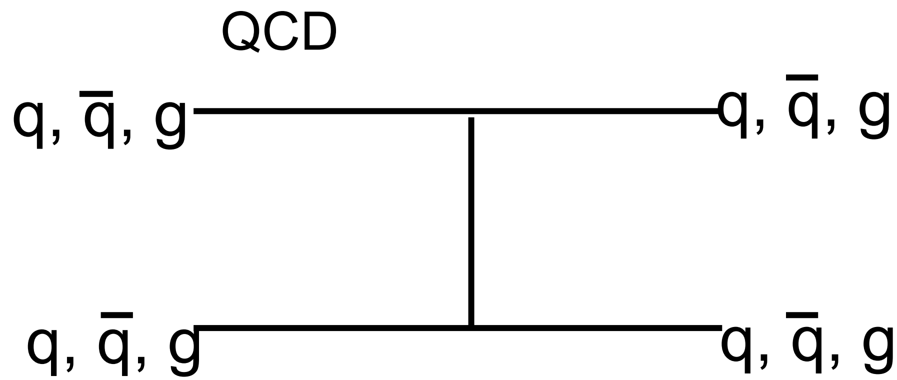
Dijet (boosted) Search in a nutshell

Signal



https://arxiv.org/pdf/1212.2221.pdf
https://arxiv.org/abs/1602.07727

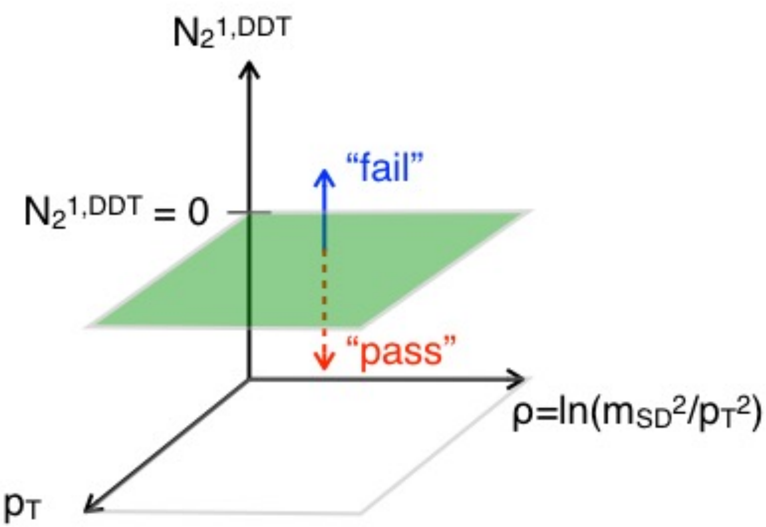
SM Backgrounds



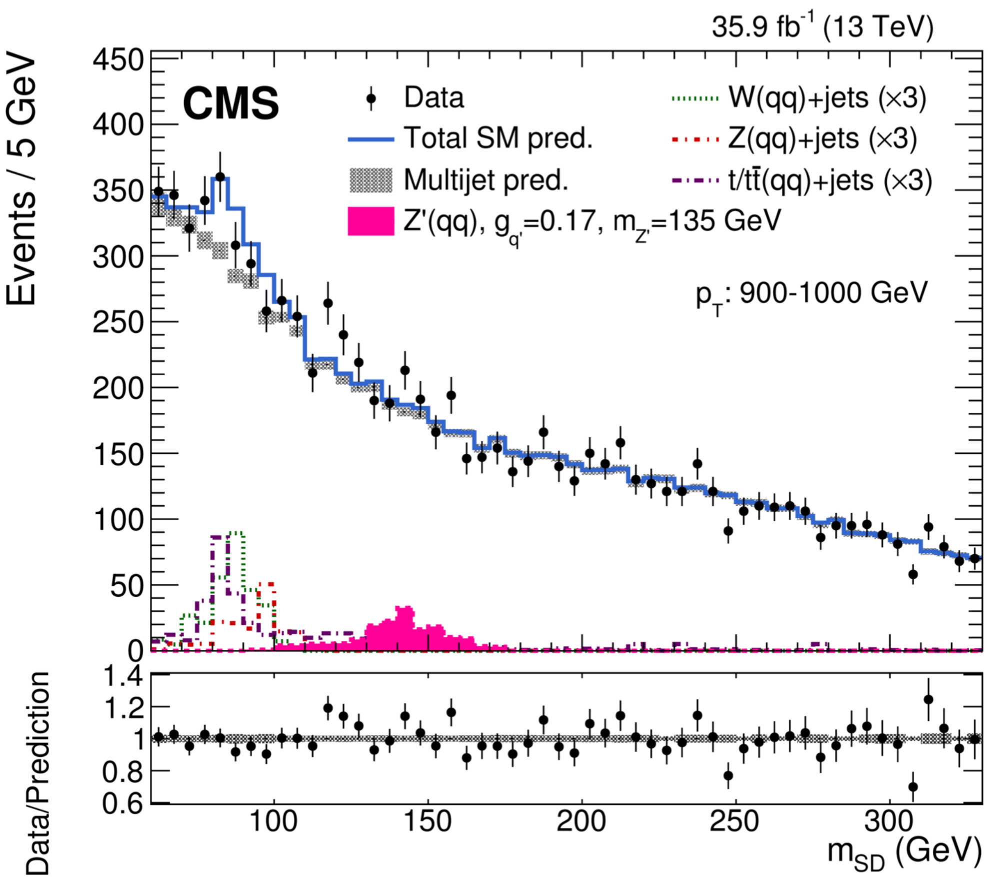
- **Reconstructed objects**
  -Particle Flow Jets

- **Physics observables**
  - Jet Mass → Resonance Mass

- Search exploits the use of a new substructure variable decorrelated from the jet mass and jet transverse momentum, which largely avoids sculpting of the jet mass distribution.



Dijet (boosted) : Experimental Results



- **Event selection :**

Anti-kT jet with cone-size 0.8 with p_T>200 GeV and |η|<2.5 and jet sub-structure selection to reduce backgrounds. No electrons or muons.

- **Background Modeling**:

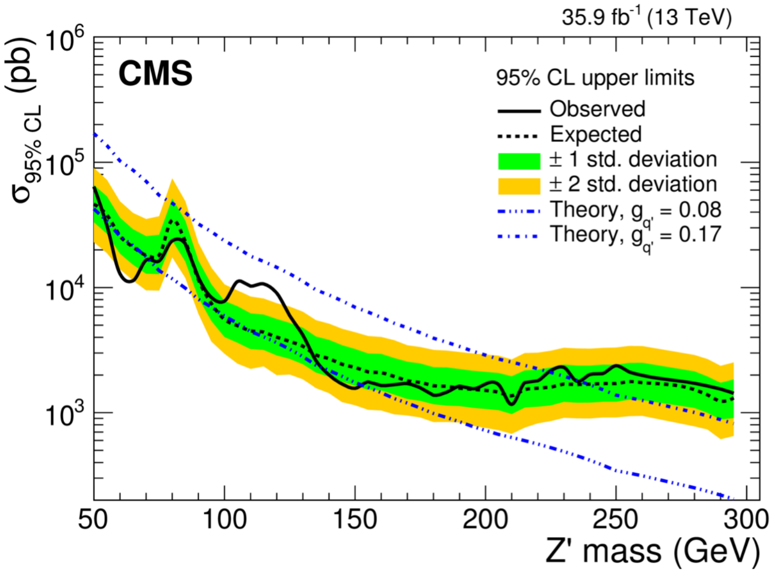
❖ QCD predicted from a control region with a transfer factor, F, from simulation (fitted to the data).

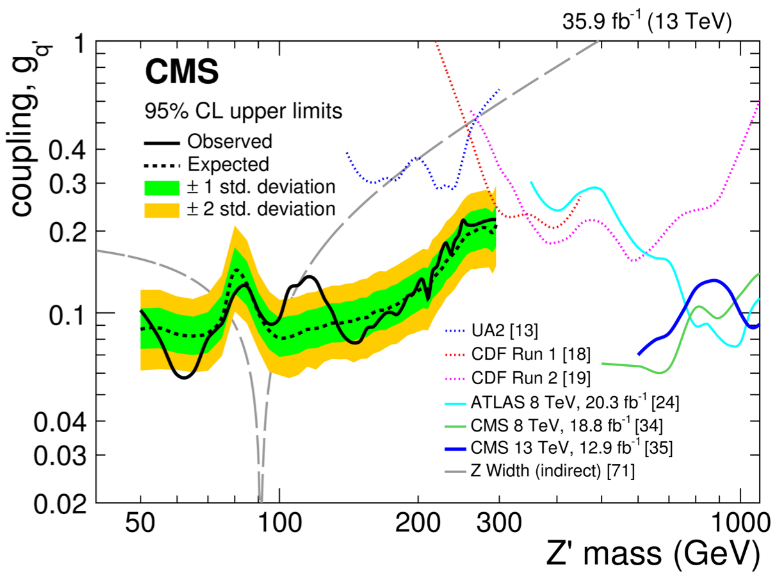
$$p^{\rm QCD}_{\rm pass}(m_{SD}, p_{\rm T}) = \mathcal{F}(\rho(m_{SD}, p_{\rm T}), p_{\rm T}) \times p^{\rm QCD}_{\rm fail}(m_{SD}, p_{\rm T})$$

◦ background modeling uncertainties come from the parametric uncertainties on the transfer factor fit.

❖ W/Z backgrounds taken from simulation

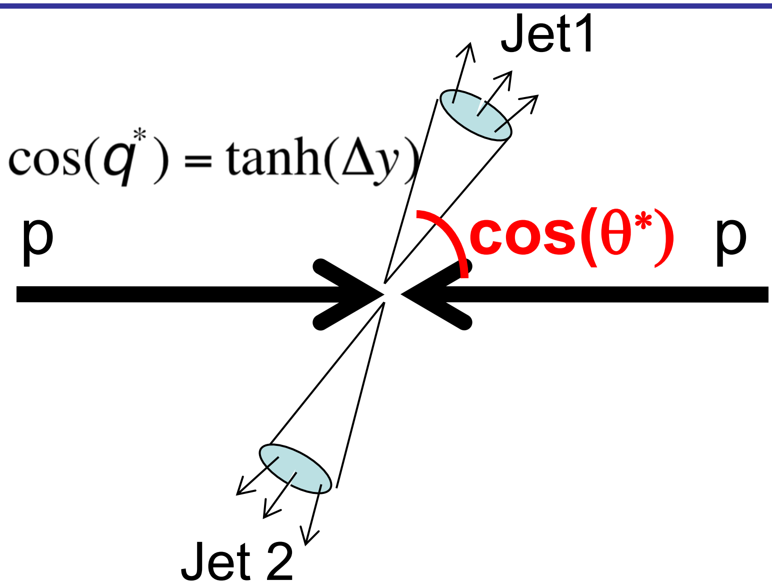
Dijet (boosted) : Limits

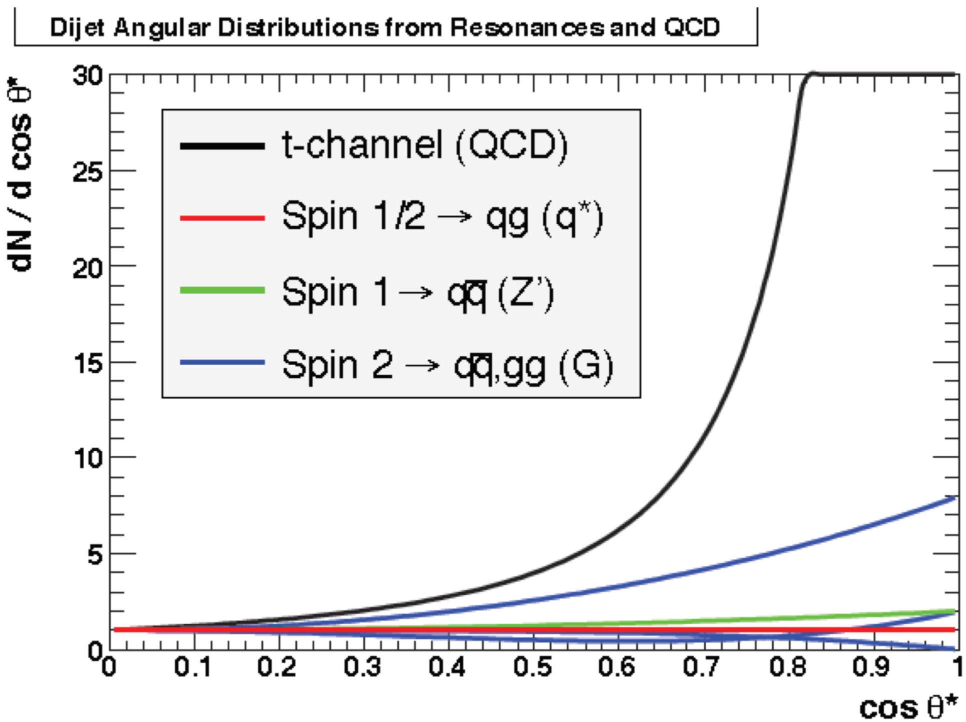




- **Signal Modeling** :The benchmark Z′ signal events are simulated using the MADGRAPH5)_AMC@NLO 2.2.2 generator
- **Fitting :** Upper limits are computed using the modified frequentist approach for confidence levels (CLs), taking the profile likelihood as the test statistic in the asymptotic approximation.
- **Systematic uncertainties:** Background related ones from the transfer factor from the control to signal region, several systematics on signal.
- **Significantly extend limits to lower mediator masses and couplings, compared to the dijet resolved resonance search.**

Dijet Angular Distributions



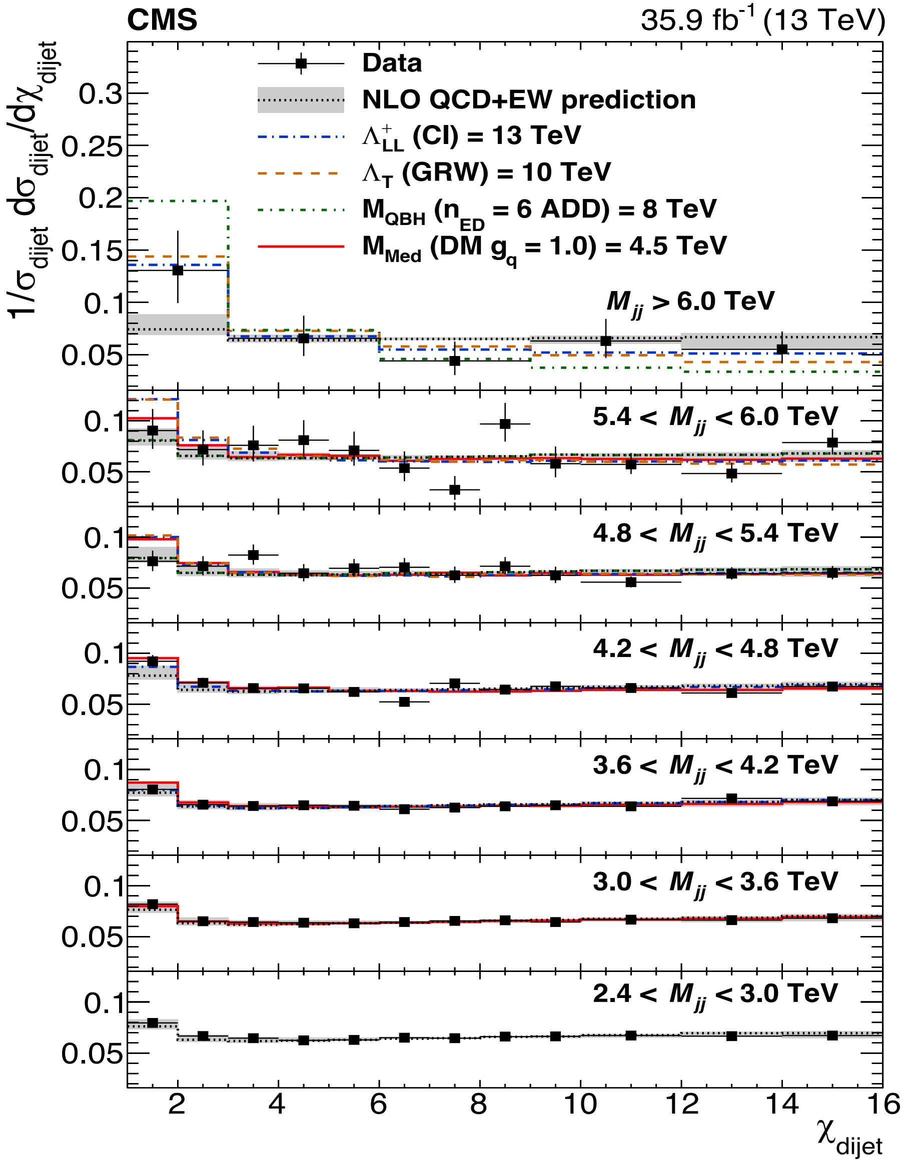


- Parton-parton scattering in QCD is t-channel dominated.
- Stringent test of pQCD with no dependence on PDFs.
- New physics would show deviations from expectation at large scattering angles.

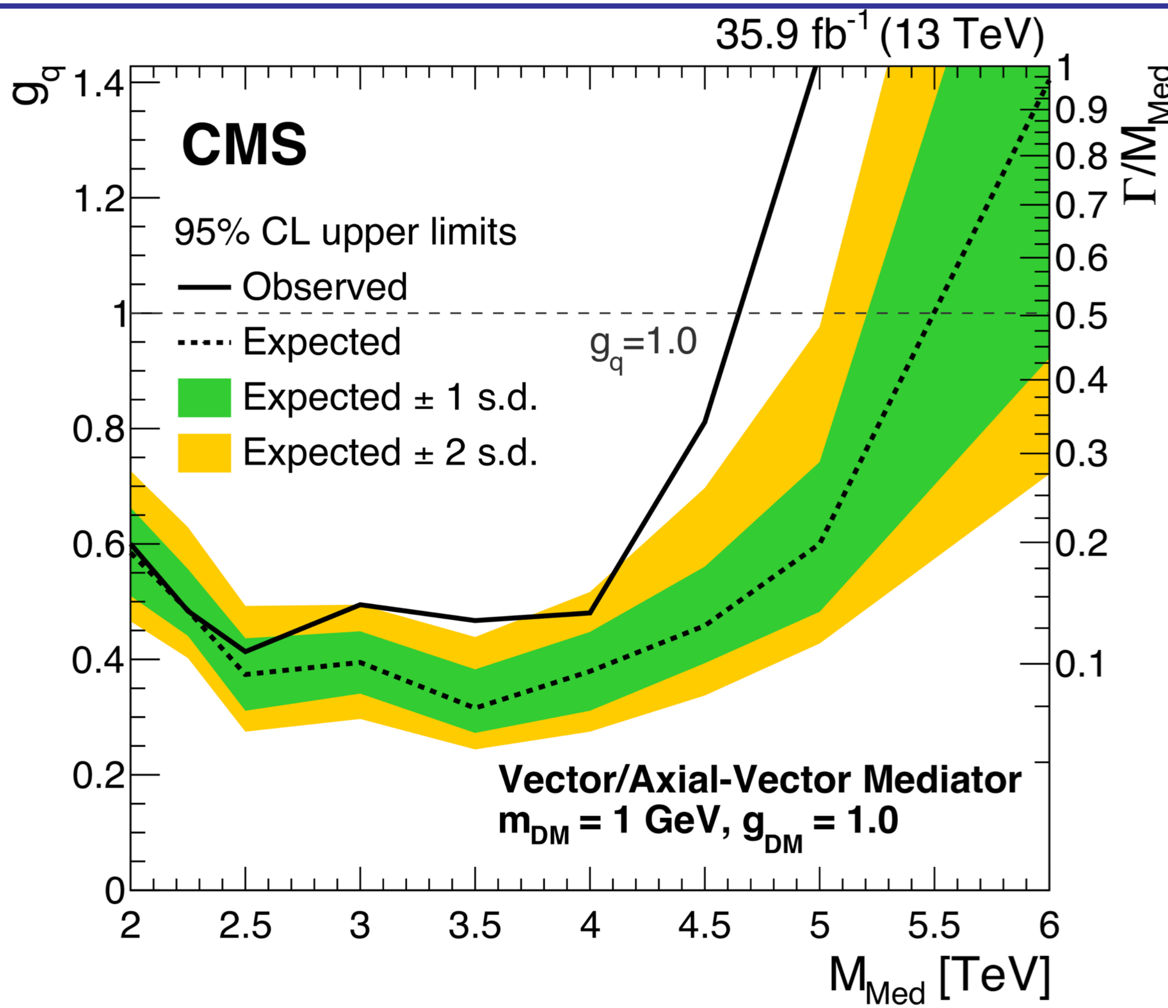
Dijet χ : Experimental Results

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

- X chosen since QCD flat as a function of x.
- Experimental uncertainties dominated by jet resolution and relative (vs η) JES (absolute cancels)
- Theoretical uncertainties dominated by non perturbative corrections and renormalization scale.
- **Good agreement between data and theory. Highest mass bins sensitive to many new physics models!**

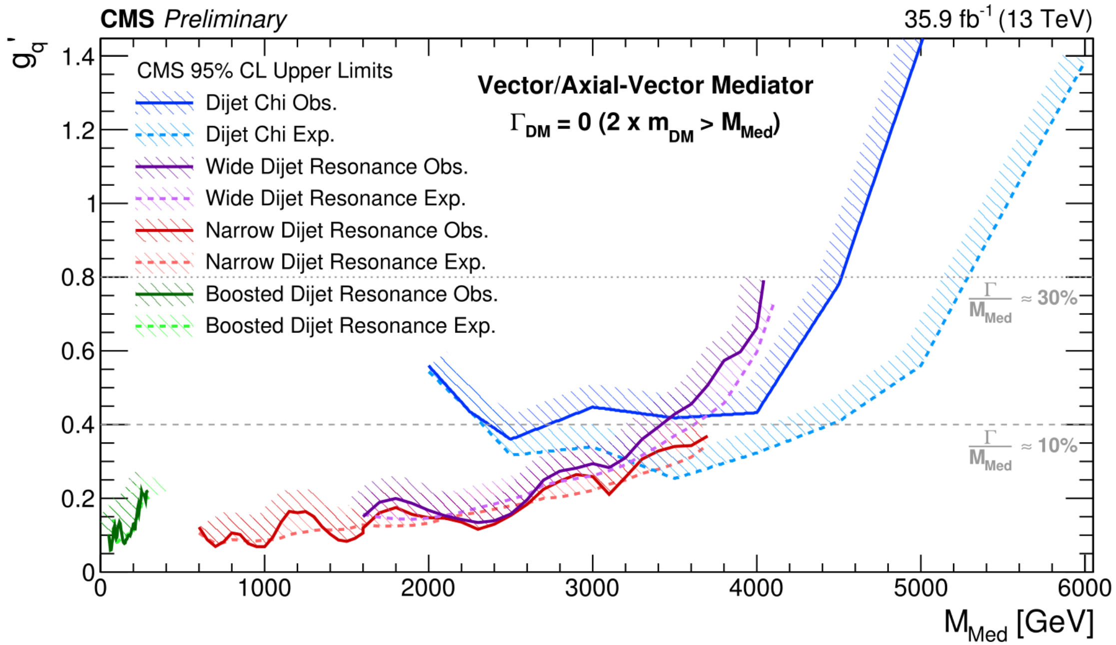


Dijet χ : Exclusion Limits



- **Significantly extend limits to higher mediator masses and higher couplings, compared to the dijet resolved resonance search.**

Where we stand : What is next

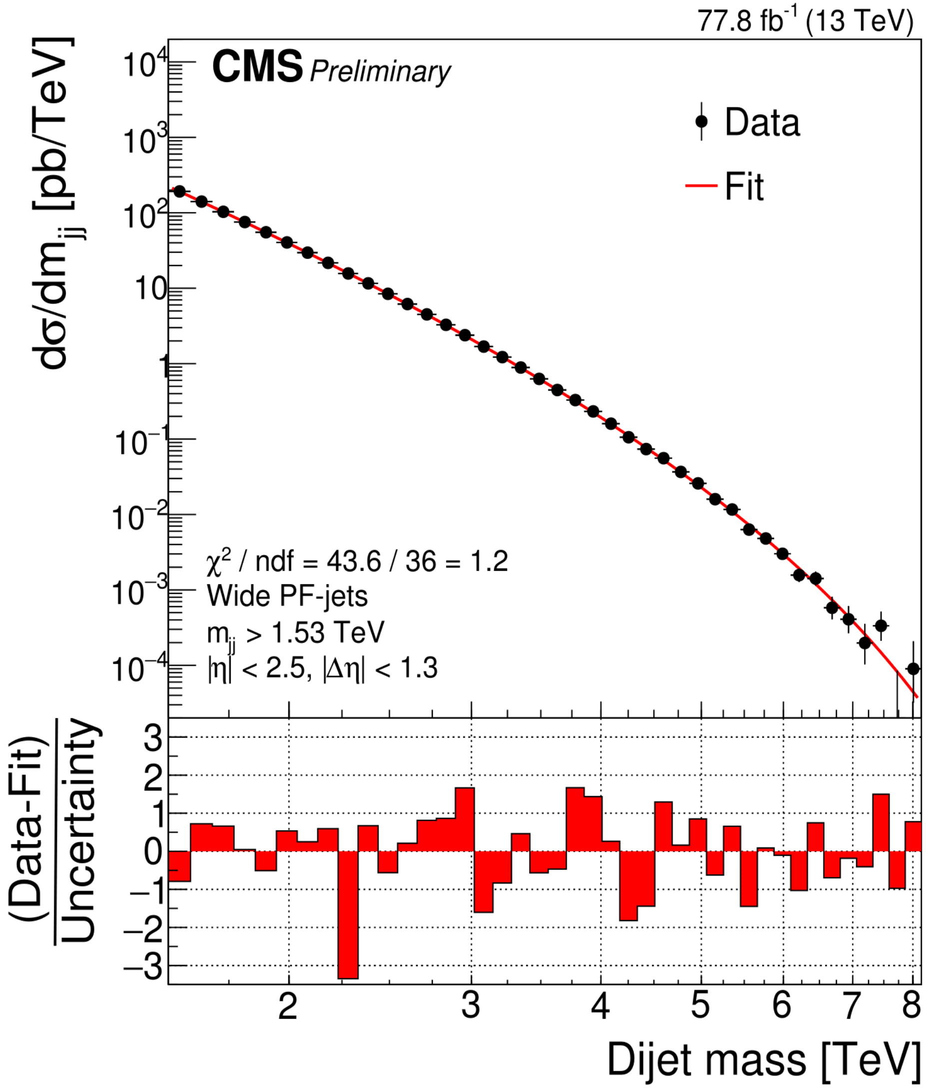


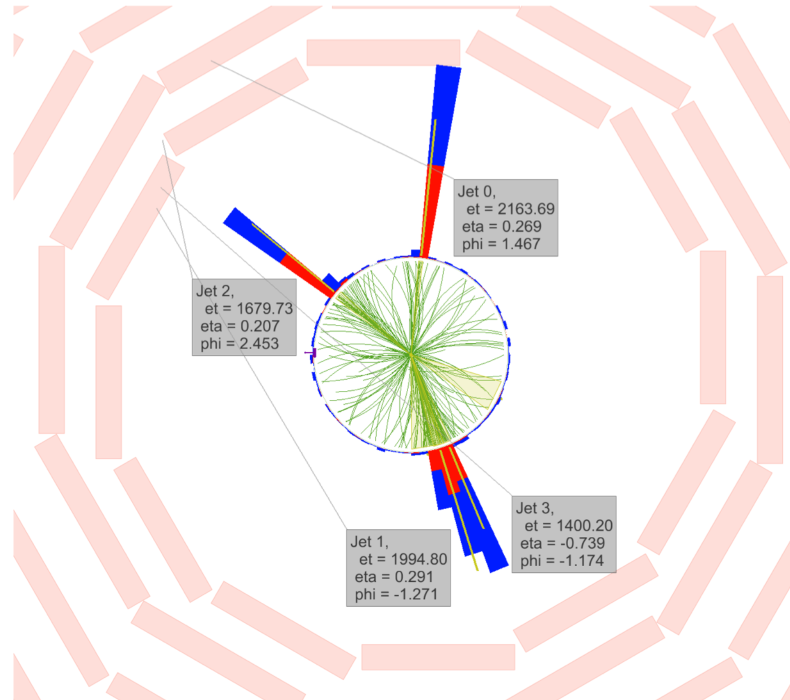
- There are currently no dijet searches in the resonance mass region 300<M<600 GeV :
  - Creates noticeable gap in the limits on gq for a dark matter mediator

- Searches using events with three jets have been proposed to fill this gap
  - A dijet resonance from two resolved jets recoiling off an ISR jet
  - The three jets then have sufficient HT to satisfy the trigger at low dijet mass.
- Dijet team is currently planning on using the calo scouting triggers for this search.
- **Dijet team is also thinking of a combined 2D analysis between the resolved and and angular analyses.**

Dijet Resonances : Current Status

2017+2016 Dataset





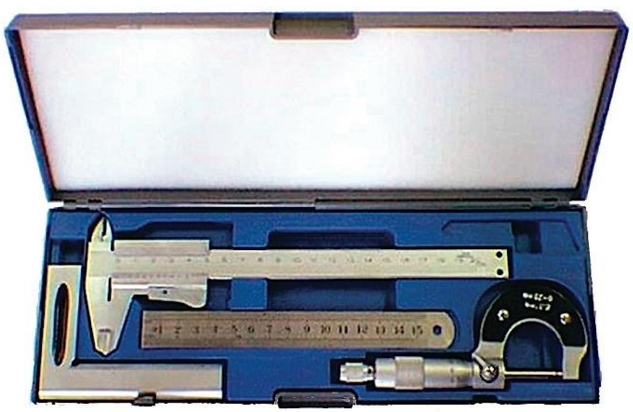
- Nice description of the data
- An spectacular four jet event at 8 TeV!

Summary and Outlook

- Many wonderful results from 2015-2016-2017 running, no hint of new physics yet…

- After the "energy jump" from 8 TeV to 13 TeV analyses have to improve significantly both in terms of systematics and methodology in order to surpass previous results.

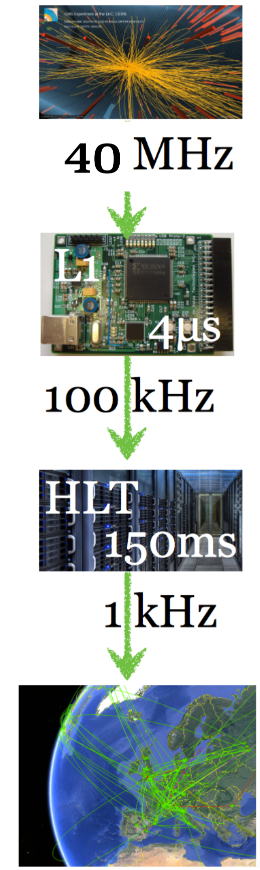
- Getting ready *and getting smarter* in order to be able to perform "precision measurements" with the new data that are imminent…



TRIGGER SYSTEM

CMS

- 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

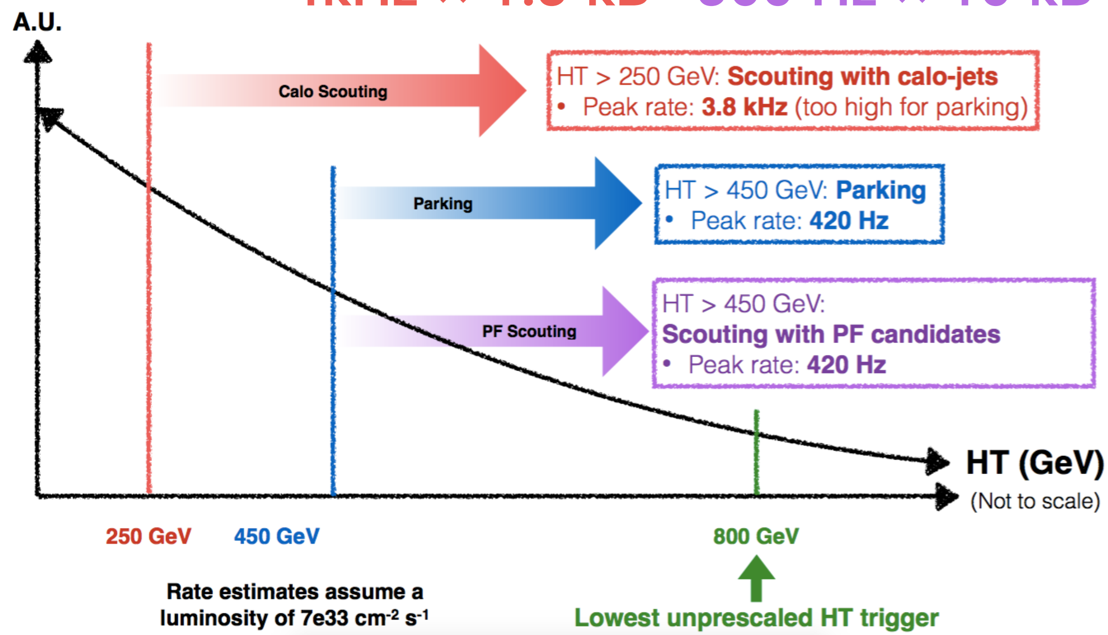
[D. Anderson "Data Scouting at CMS" 2015 IEEE NSS/MIC]

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,

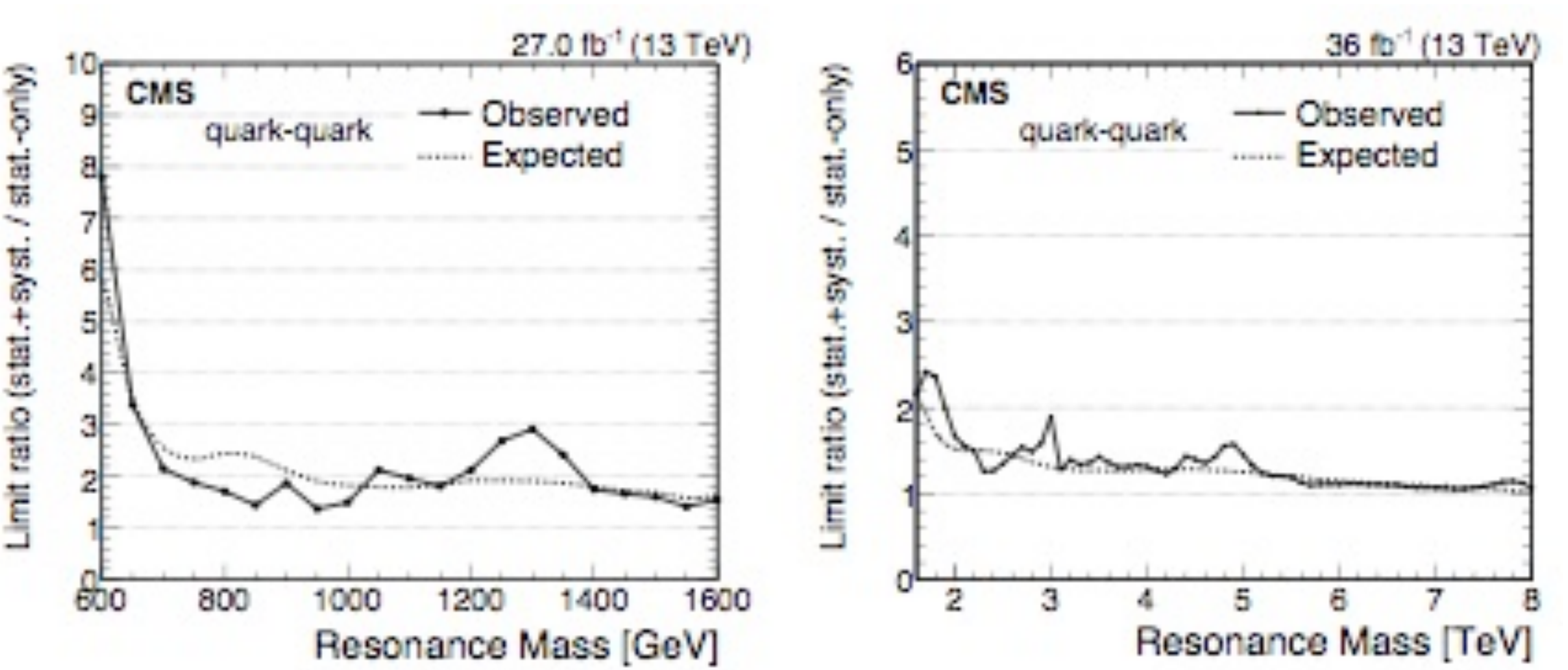
~ 400 Hz

PhysicsParkingScoutingMonitor

➡ ParkingScoutingMonitor

~ 1 MB / event, ~ 30 Hz

Systematics vs Statistical Uncertainties



Main procedude-MaxLikelihood Fit

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

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

,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:

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

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 :

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

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 $0 \le \hat{\mu} \le \mu$

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

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

Limits and corresponding confidence intervals on the parameter of interest σ_s can be calcula
from the posterior distribution given by

$$\Pi_{\text{post}}(\sigma|N_{\text{obs}}) = \int d\epsilon_s \, d\epsilon_b \, d\sigma_b \prod_{i,j} d\nu_{i,s} \, d\nu_{j,b} \frac{a^{N_{\text{obs}}}}{N_{\text{obs}}!} \cdot e^{-a} \cdot \pi(\epsilon_s, \epsilon_b, \nu_{i,s}, \nu_{j,b}, \sigma_b) \cdot \pi_{poi}(\sigma_s)$$

where the terms $\pi(\cdot)$ refers to the combined prior function for the nuisance parameters. A uniform (flat) distribution $\pi_{\text{poi}}(\sigma_s)$ is applied as prior function of the parameter of interest.

With this setup, a cross section upper limit corresponding to a 95% credible interval can be calculated via

$$0.95 \stackrel{!}{=} \int_0^{\sigma_{\text{lim}}} \Pi_{\textbf{post}}(\sigma_s|N_{\text{obs}}) \, d\sigma_s \qquad (14)$$

The RooStats based `Higgs Combine Tool` is used to implement the model for the counting experiment and calculate the limits.

Fisher Test

Two models:
Model A with n_A parameters
Model B with n_B parameters > n_A

$$F_{BA} = \frac{\frac{RSS_A - RSS_B}{n_B - n_A}}{\frac{RSS_B}{N - n_B}}$$

where $RSS_i = \sum_{bins} \left(data_{bin} - fit_{bin} \right)^2$

and N = data points

CL is defined as:

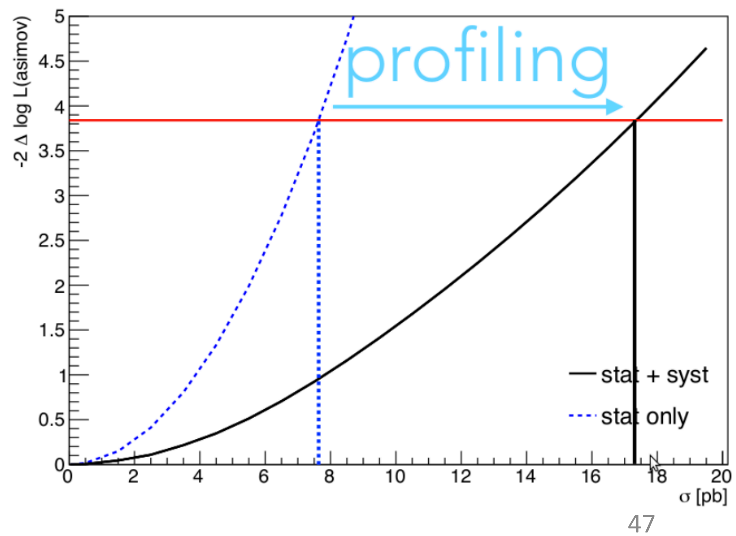
$$CL_{BA} = 1 - \int_{-\inf}^{F_{BA}} F - distribution(n_B - n_A, N - n_B)$$

If $CL_{BA} > \alpha$ → Model A is sufficient to describe the data, else go to B

In our case α=0.05

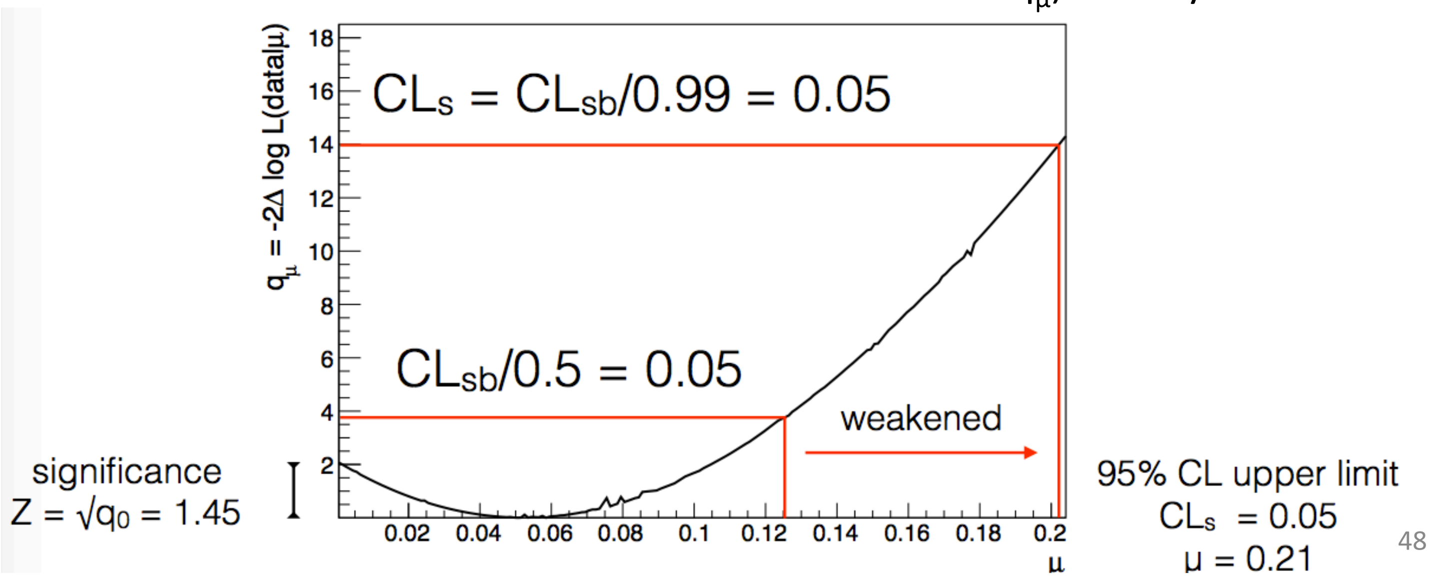
Systematics

- Jet energy scale (JES)
  - 2% value from JetMET propagated by shifting dijet resonance shapes by ±2%
- Jet energy resolution (JER)
  - 10% value from JetMET propagated by changing width of dijet resonance shapes by ±10%
- Integrated luminosity: 2.6%
- Background shape & normalization
  - Uncertainty is propagated by allowing background shape and normalization parameters to float unconstrained in profile likelihood test statistic
  - This ”profiling” increases the width of the test statistic thus increasing the uncertainty on the parameter-of-interest

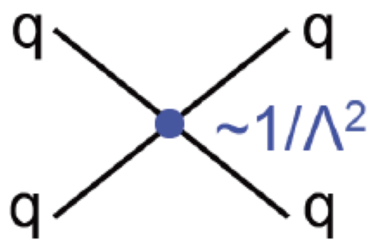


- Reference is 1.2 TeV qg, σ×B×A= 10 pb
- Difference between limit and significance is a reflection of the fact that they are quantified using different asymptotic formulae and the Profile Likelihood is asymmetric (significance is evaluated on the left, limits are evaluated on the right)

- Asymptotic limit:
  - shows 2.3σ "excess"
  - uses $CL_s = CL_{sb}/CL_b$ (in this case CL_b = 0.99 meaning background-only mode is not a great fit so **observed** upper limit is weakened)
- Asymptotic significance:
  - shows 1.45σ excess
  - uses $CL_{sb} = 1 - \Phi(\sqrt{q_\mu})$ (i.e. the Profile Likelihood q_μ) directly



Exotic New Physics : Compositeness



$$\frac{d\sigma}{d\Omega} = \mathrm{SM}(s,t) + \varepsilon \cdot C_{\mathrm{Int}}(s,t) + \varepsilon^2 \cdot C_{\mathrm{NewPh}}(s,t)$$

By construction, the contact interaction modifies the QCD subprocesses with two quarks in the initial and final state, whereas the processes $qq \to gg$, $gq \to gq$, $q\bar{q} \to gg$ and $gg \to q\bar{q}$ are not altered and contribute to the QCD background in the analysis. The differential partonic cross sections for the modified subprocesses are given e. g. in [40], differentially in $\hat{t}$. The angular dependence can be shown more explicitly by writing the cross section differentially in $\cos\theta^*$, with

$$\frac{d\hat{\sigma}}{d\cos\theta^*} = \frac{\hat{s}}{2}\frac{d\hat{\sigma}}{d\hat{t}}. \tag{2.15}$$

For example,

$$\frac{d\hat{\sigma}(q_iq_i \to q_iq_i)}{d\cos\theta^*} = \frac{d\hat{\sigma}(\bar{q}_i\bar{q}_i \to \bar{q}_i\bar{q}_i)}{d\cos\theta^*} = A, \tag{2.16}$$

with

$$A := \frac{\pi}{2\hat{s}}\left\{\frac{4}{9}\alpha_S^2\left[\frac{\hat{u}^2+\hat{s}^2}{\hat{t}^2} + \frac{\hat{t}^2+\hat{s}^2}{\hat{u}^2} - \frac{2}{3}\frac{\hat{s}^2}{\hat{t}\hat{u}}\right] + \frac{8}{9}\alpha_S\frac{\eta}{\Lambda^2}\hat{s}^2\left[\frac{1}{\hat{t}} + \frac{1}{\hat{u}}\right] + \frac{8}{3}\frac{\hat{s}^2}{\Lambda^4}\right\}. \tag{2.17}$$

Terms proportional to α_S^2 are due to QCD contributions, terms proportional to $1/\Lambda^4$ arise from the contact interaction, and terms proportional to α_S/Λ^2 characterise the interference between the contact interaction and QCD. As described in section 2.1, the QCD part contains a term proportional to $1/\hat{t}^2$, corresponding to forward, Rutherford-like scattering from $\hat{t}$-channel gluon exchange. In contrast, the plain contact interaction term is proportional to $\hat{s}^2$ and does not depend on the scattering angle θ^*. The other subprocesses are characterised by similar angular dependencies, with the contact interaction term either being proportional to $\hat{u}^2$, corresponding to a mild dependence on $\cos\theta^*$, or being proportional to $\hat{s}^2$, yielding a completely isotropic behaviour with respect to $\cos\theta^*$. As discussed in the previous section, a cross section constant in $\cos\theta^*$ corresponds to a rise in the cross section towards low values of χ, different from the almost constant χ-dependence of pure QCD.

"The proliferation of quarks and leptons has naturally led to the speculation that they are composite structures, bound states of more fundamental constituents which are often called "preons."

E. Eichten, K. Lane, and M. Peskin, "New Tests for Quark and Lepton Substructure", Phys. Rev. Lett. **50 (1983) 811, doi:10.1103/PhysRevLett.50.811.**

Models of New Physics with Dijets

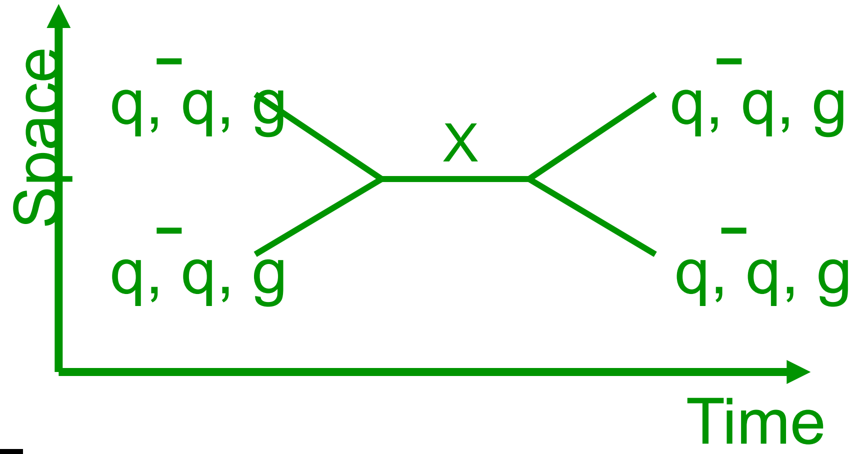
- Two types of observations will be considered.
  - Dijet resonances are new particles beyond the standard model.
  - Quark contact Interactions are new interactions beyond the standard model.

- Dijet resonances are found in models that try to address some of the big questions of particle physics beyond the SM, the Higgs, or Supersymmetry
  - Why Flavor ? → Technicolor or Topcolor → Octet Technirho or Coloron
  - Why Generations ? → Compositeness → Excited Quarks
  - Why So Many Forces ? → Grand Unified Theory → W' & Z'
  - Can we include Gravity ? → Superstrings → E6 Diquarks
  - Why is Gravity Weak ? → Extra Dimensions → RS Gravitions

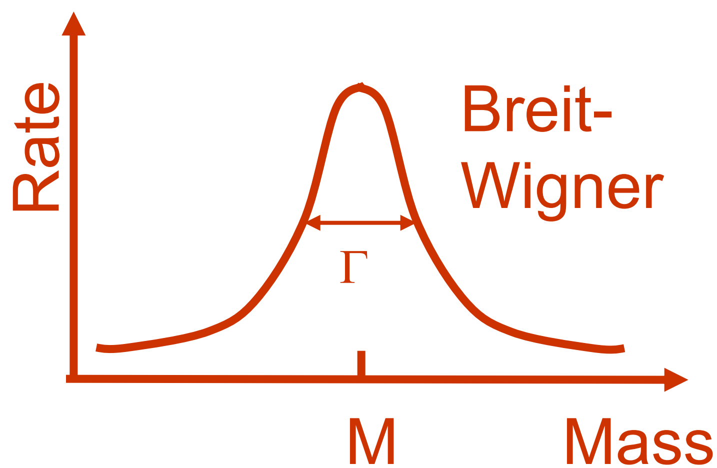
- Quark contact interactions result from most new physics involving quarks.
  - Quark compositeness is the most commonly sought example.

Dijet Resonances

- New particles that decay to dijets
  - Produced in "s-channel"
  - Parton - Parton Resonances
    - Observed as dijet resonances.
  - Many models have small width Γ
    - Similar dijet resonance shapes.

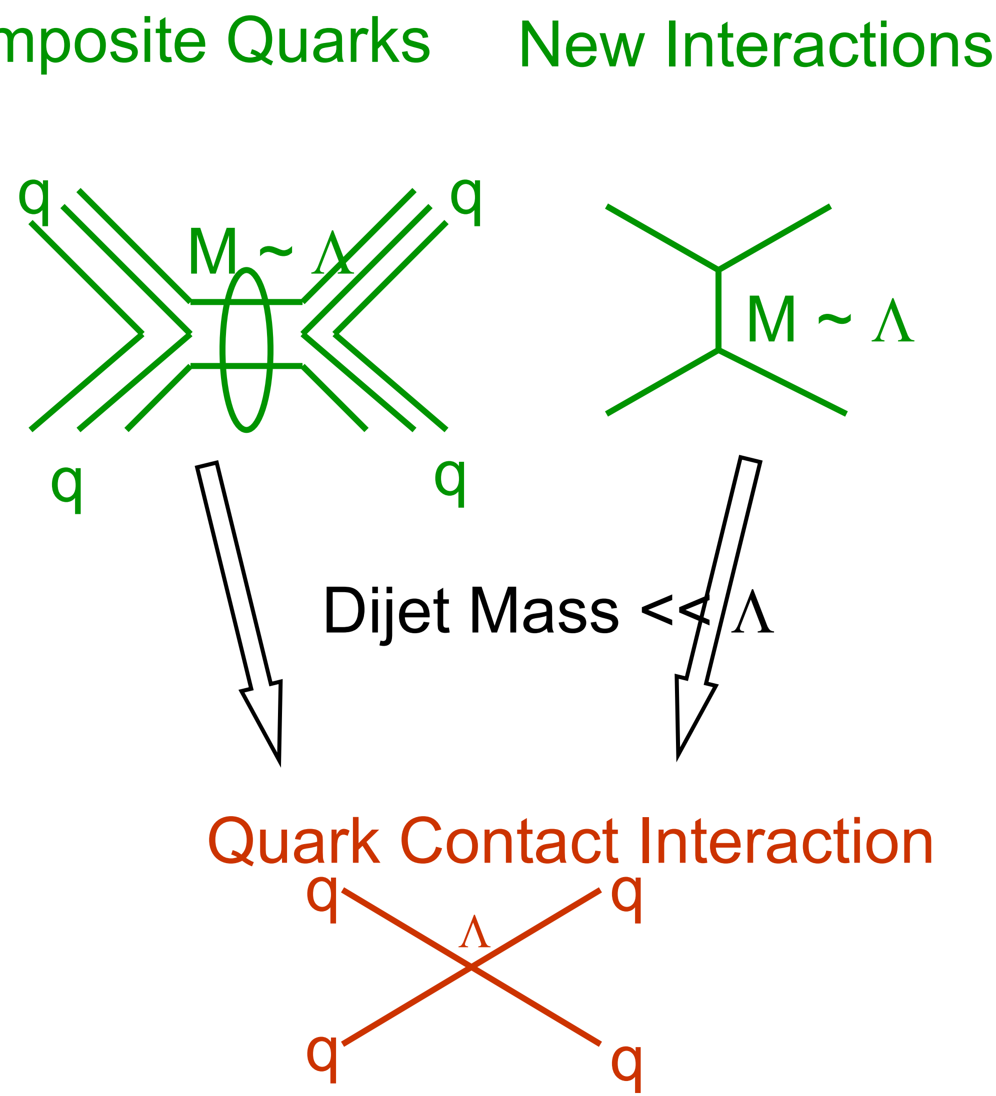


Model Name	X	Color	J^P	Γ / (2M)	Chan
E_6 Diquark	D	Triplet	0^+	0.004	ud
Excited Quark	q*	Triplet	$½^+$	0.02	qg
Axigluon	A	Octet	1^+	0.05	$q\bar{q}$
Coloron	C	Octet	1^-	0.05	$q\bar{q}$
Octet Technirho	ρ_{T8}	Octet	1^-	0.01	$q\bar{q}$,gg
R S Graviton	G	Singlet	2^-	0.01	$q\bar{q}$,gg
Heavy W	W '	Singlet	1^-	0.01	$q_1\bar{q}_2$
Heavy Z	Z '	Singlet	1^-	0.01	$q\bar{q}$



Quark Contact Interactions

- New physics at large scale Λ
  - Composite Quarks
  - New Interactions
- Modelled by contact interaction
  - Intermediate state collapses to a point for dijet mass << Λ.
- Observable Consequences
  - Has effects at high dijet mass.
  - Higher rate than standard model.
  - Angular distributions can be different from standard model.
    - This is true for the canonical model of a contact among left-handed quarks by Eichten, Lane and Peskin.



Compositeness: Excited Quarks

Baur, Spira & Zerwas, PRD42,815(1990)

- Motivation
  - Three nearly identical generations suggests compositeness. Periodic table ?
  - Compositeness is also historically motivated.
    - Matter → Molecules → Atoms → Nucleons → Quarks → Preons ?

- If quarks are composite particles then excited states, q*, are expected
  - Excited quarks are produced when a ground state quark absorbs a gluon.
  - q* decay to the ground state q by emitting any gauge boson: γ, W, Z or g
  - The dijet process is qg → q* → qg, and cross section is large (color force).

- J = 1/2 and J =3/2 are possible, but searches have been done for J = 1/2.
  - For example, imagine a non-relativistic model with two preons, one S=0, the other S=1/2, ground state L=0, excited state L=1, J=1/2.

- Lagrangian is of magnetic moment type (see Review of Particle Physics)
  - Usually the couplings f, f_s, f' are set to 1, and Λ is set to q* mass M.

$$\mathcal{L} = \frac{1}{2\Lambda}\bar{q}^*\sigma^{\mu\nu}\left(g_s f_s \frac{\lambda^a}{2} G^a_{\mu\nu} + g f \frac{\tau^a}{2} W^a_{\mu\nu} + g' f' Y B_{\mu\nu}\right)\frac{1-\gamma_5}{2} q + h.c.$$

Superstrings: E_6 Diquarks

Angelopoulous, Ellis, Kowalski, Nanopoulos, Tracas & Zwirner

- Superstrings, supersymmetric string theories, claim to be a theory of everything
  - They unify gravity with other forces and claim all particles are string excitations.
- They require 10 dimensions, 6 of which must be compactified (curled up).
  - One attractive compactification proposal leads to 27 fields in the fundamental representation of E_6.
  - This Grand Unified Theory breaks down via SO(10) and SU(5) to the Standard Model: $SU(3)_C \times SU(2)_L \times U(1)_Y$.
- Model has color triplet, charge $\pm 1/3$, scalar diquarks: D.
  - 1st generation production and decay: ud → D → ud.
  - Yukawa type Lagrangian with each generation:

$$\mathcal{L} = \lambda u d D$$

  - λ, is usually assumed to be an electromagnetic strength coupling: λ = e.
  - Cross section is large because u and d are valence quarks of proton.
    - Would be two orders of magnitude larger if color strength couplings were considered!

Extra SU(3): Axigluons and Colorons

- Chiral Color was proposed by Frampton & Glashow
  - "We regard chiral color as a logical alternative to the standard model that is neither more nor less compelling".
  - Fundamental gauge groups are $SU(3)_L$ x $SU(3)_R$ x $SU(2)_L$ x $U(1)_Y$
  - Breaks down to SM plus color octet of massive axial-vector gluons: Axigluons.
  - Axigluons couple to quark anti-quark pairs with usual color strength.
  - LHC cross sections are large despite needing an anti-quark from the proton.

- Colorons exist in many models.
  - Topcolor, Topcolor Extended Technicolor, and Flavor Universal Colorons
  - Last model by Chivukula, Cohens and Simmons is like Chiral Color "sans spin"
  - Gauge group simply has another SU(3): $SU(3)_1$ x $SU(3)_2$ x $SU(2)_L$ x $U(1)_Y$
  - Breaks down to the SM plus a color octet of massive vector gluons: Colorons.
  - Colorons couple strongly to quark anti-quark pairs.
  - Cross sections are same as axigluons if the additional mixing angle cot $\theta = 1$.

Technicolor: Color Octet Technirhos

(Ken Lane, hep-ph/9605257)

- Technicolor has been around a long time and is not dead.
  - Originally proposed as a model of dynamical electroweak symmetry breaking:
    - The Higgs boson is not a fundamental scalar.
    - Higgs is a technipion that is a bound state of two technifermions interacting via technicolor.
    - Theorists have analogies why this is better than a fundamental scalar.
      - Cooper Pairs in Superconductivity, QCD naturally breaking symmetries, etc.
  - Minimal model has at least a single family of technifermions that bind to form color singlet π_T, ρ_T, and ω_T, etc.
  - One family model has both color triplet techniquarks and color singlet technileptons, and in this model there are color octet technirhos, ρ_{T8}.
- Extended Technicolor attempts to generate flavor dynamically
  - Quark & lepton masses come from emitting and absorbing ETC gauge bosons.
  - The model tries to address a difficult problem, but is far from complete.
- Color Octet Technirhos are produced via mixing with gluons
  - Dijet production at LHC is q qbar, gg → g → ρ_{T8} → g → q qbar, gg.
  - Mixing reduces the size of cross section compared to other colored resonances

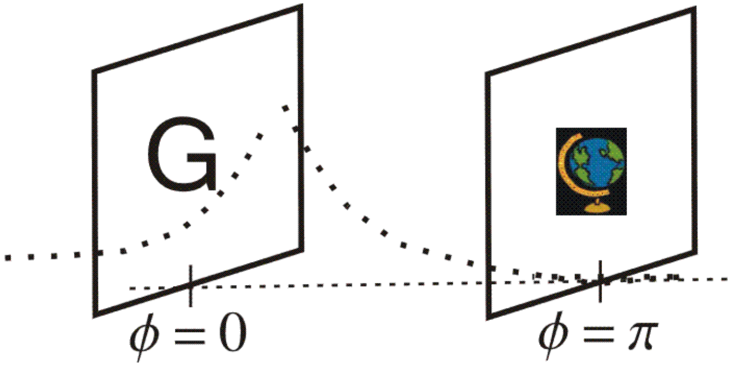
GUTS: W' and Z'

- W' is a heavy W boson
  - One model is the W_R boson in left-right symmetric models.
    - Gauge group is $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)$
    - Seeks to provide a spontaneous origin for parity violation in weak interactions.
  - Also a W' in "alternative left-right model" in E_6 GUT.
  - We consider the Sequential Standard Model (SSM) W'
    - W' is same as W but more massive.
    - LHC cross section is same as W scaled by $(M_W/M_{W'})^2$. Small.

- Z' boson is a heavy Z boson
  - These are common features of models of new physics.
  - GUTS frequently produce an extra U(1) symmetry when they break down to SM.
    - Each U(1) gives a new Z'
  - We consider the Sequential Standard Model (SSM)
    - Z' is same as Z but more massive.
    - LHC cross section is same as for Z scaled by $(M_Z/M_{Z'})^2$. Small.

Extra Dimensions: Randall-Sundrum Gravitons

- Randall-Sundrum Model
  - Adds 1 small extra dimension ϕ
  - Warps spacetime by $\exp(-2kr_c\phi)$
  - Results in a possible solution to Plank scale hierarchy problem.
- Predicts Graviton Resonances, G.
  - Massive spin-2 particles
  - G → fermion pairs, boson pairs
- Model has two parameters
  - Mass of lightest graviton resonance
  - Coupling parameter k / M_{PL}
    - Usually considered to be 0.1 or less.
- Dijet production at LHC
  - q qbar, gg → G → q qbar, gg.
  - Cross section small except at low mass where benefits from gg process.



gravity localized at ϕ=0,

exponentially weaker at $\phi=\pi$

Solution to Hierarchy Problem

Masses of particles on our brane exponentially reduced from Planck scale masses m_0.

$m = m_0 \exp(-kr_c\pi)$

Model-less Motivation

- **Theoretical Motivation**
  - The many models of dijet resonances are ample theoretical motivation.
  - But experimentalists should not be biased by theoretical motivations . . .
- **Experimental Motivation**
  - The LHC collides partons (quarks, antiquarks and gluons).
    - LHC is a parton-parton resonance factory in a previously unexplored region
    - Motivation to search for dijet resonances and contact interactions is obvious
      - We must do it.
  - We search for generic dijet resonances, not specific models.
    - Nature may surprise us with unexpected new particles.
    - One search encompasses ALL narrow dijet resonances.
  - We search for deviations in dijet angular distributions vs. dijet mass
    - Now the search is focused on a model of quark contact interactions.
    - It will also be applicable for generic parton contact interactions.
    - And essential for confirming and understanding any resonances seen.