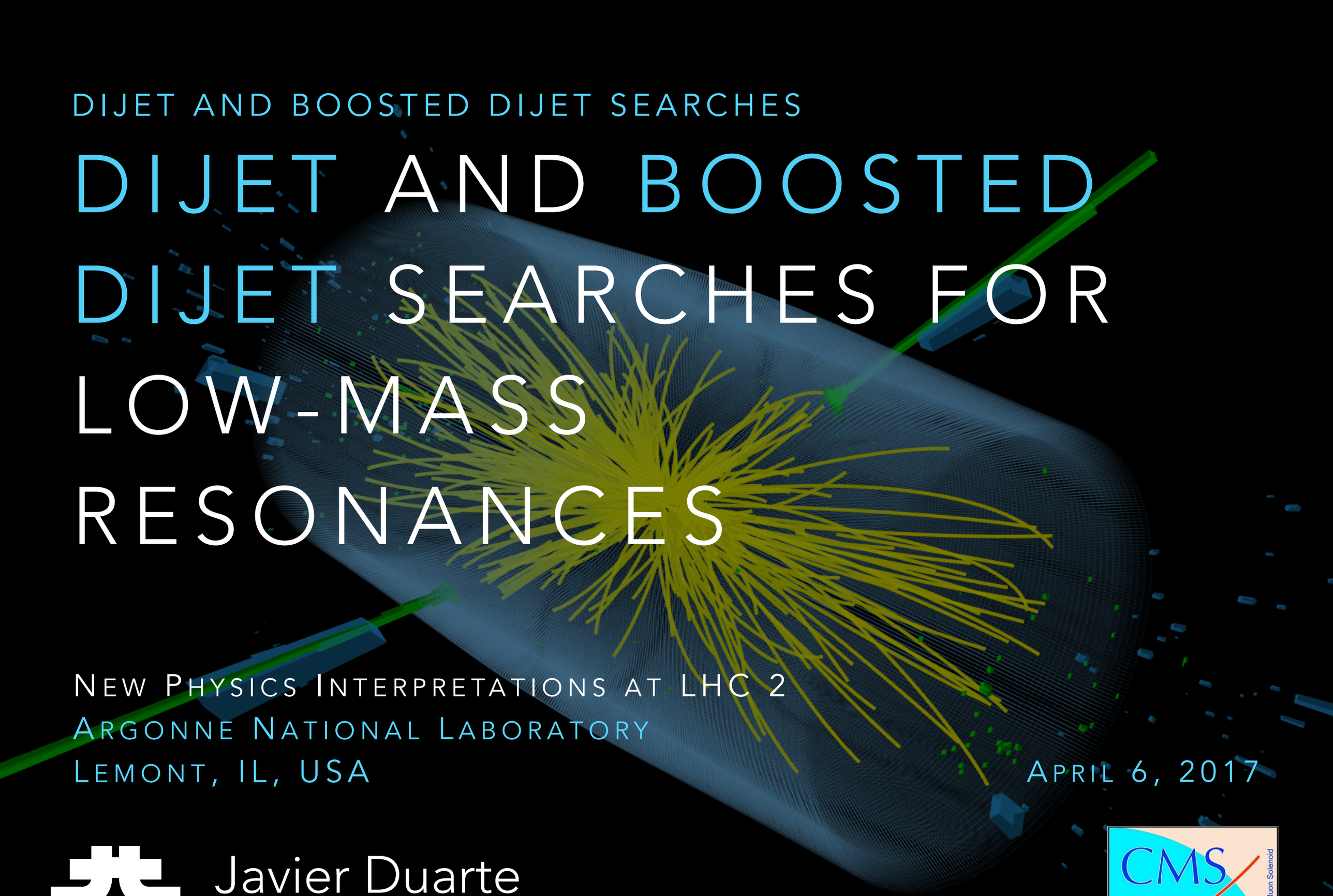
DIJET AND BOOSTED DIJET SEARCHES FOR LOW-MASS RESONANCES



NEW PHYSICS INTERPRETATIONS AT LHC 2
ARGONNE NATIONAL LABORATORY
LEMONT, IL, USA

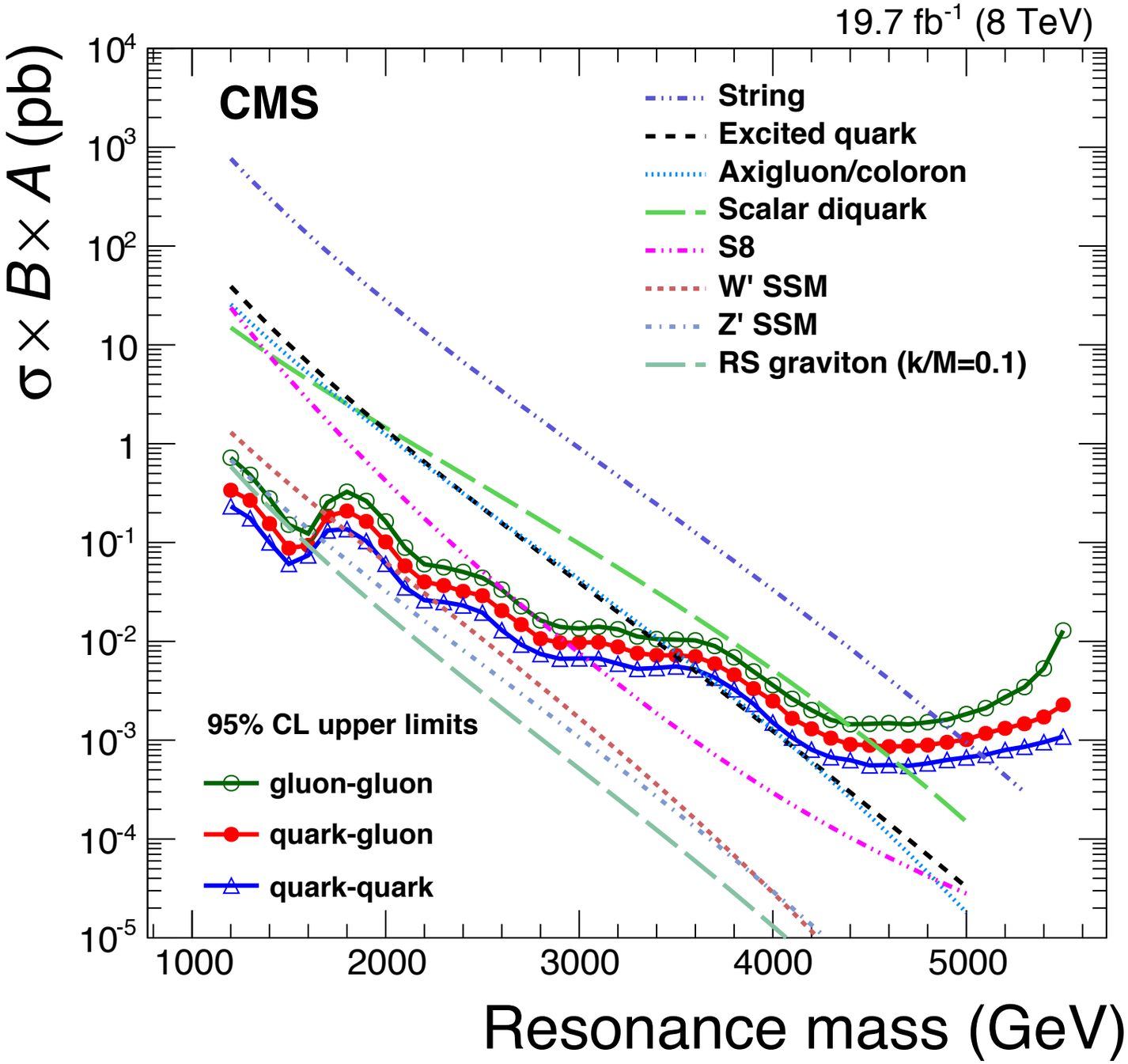
APRIL 6, 2017

Javier Duarte
Fermilab

A LOOK AT THE PHASE SPACE

arXiv:1501.04198

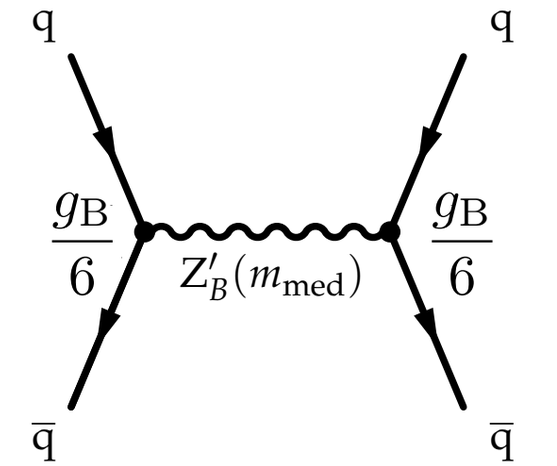
- Classic dijet search (Run 1) targets narrow resonances
- Sensitive to many signal models: axigluons, colorons, W′, Z′, excited quarks, string resonances, RS gravitons, S8 resonances, …
- But every model comes with a cross section assumption: low mass → very large cross section
- Have we really ruled out all possibilities at low mass?



NEW LOOK AT THE PHASE SPACE

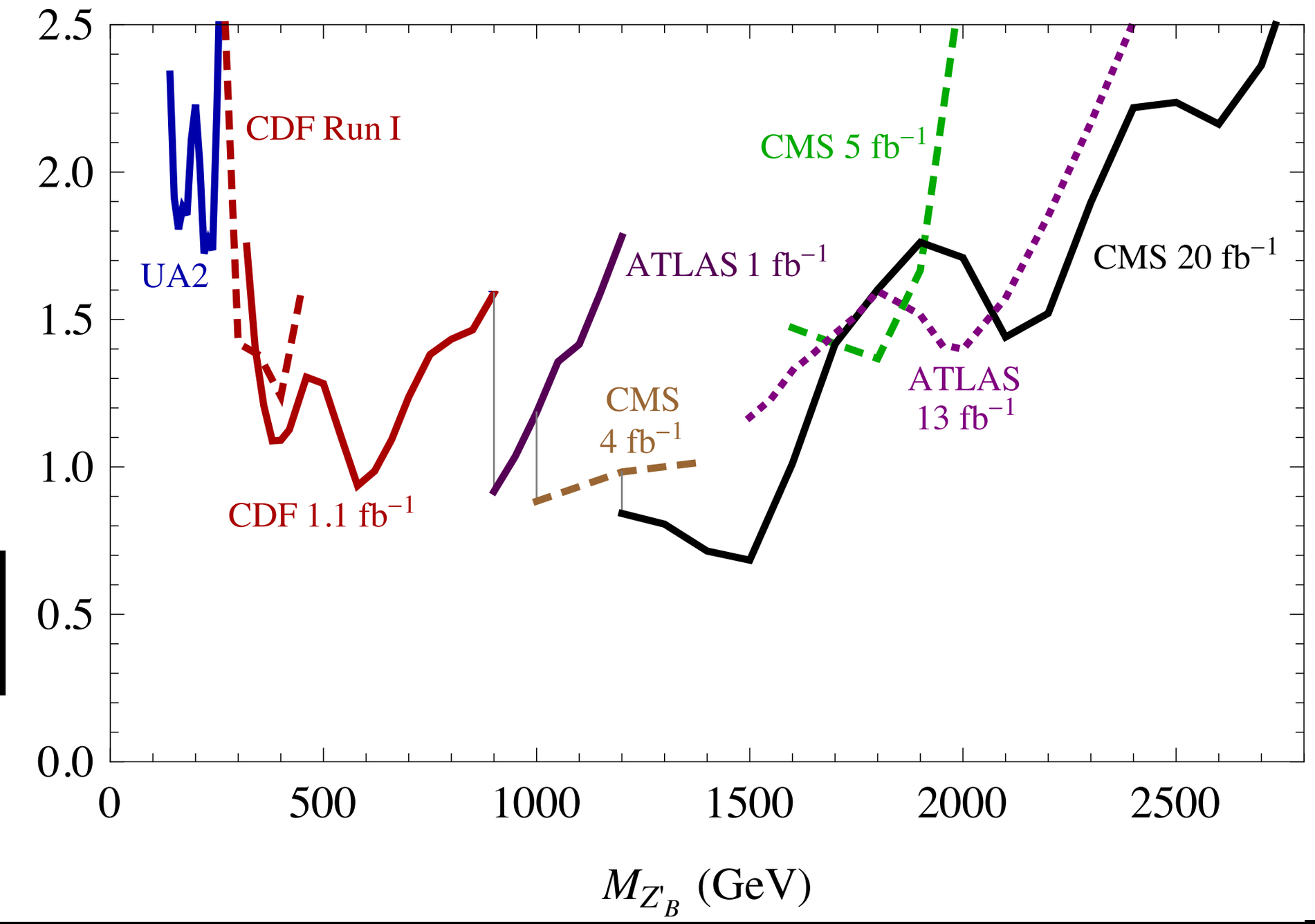
arXiv:1306.2629

- Generic model with a leptophobic Z′ before Run 2



UNIVERSAL QUARK COUPLING TO LEPTOPHOBIC Z_B'

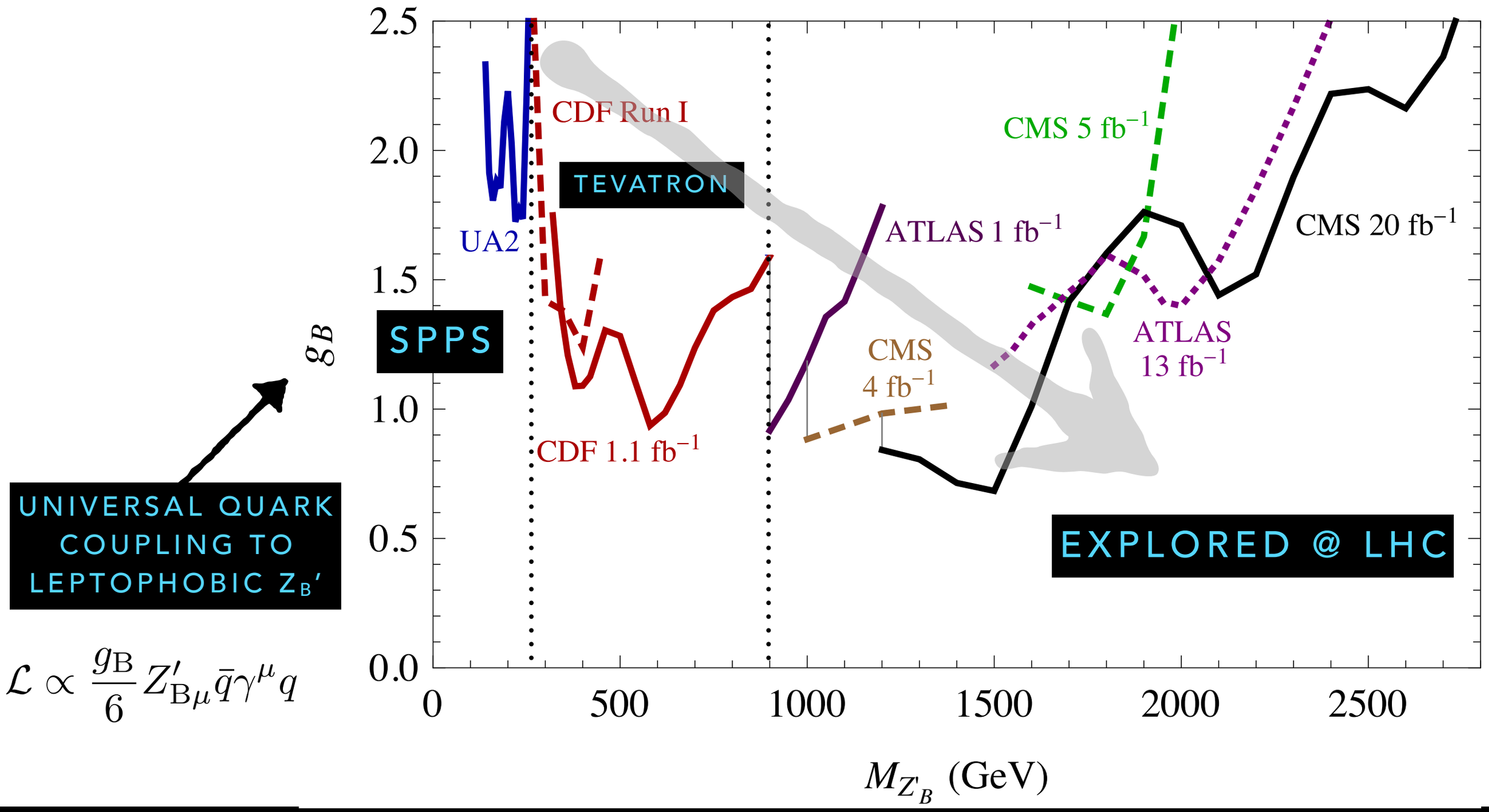
$$\mathcal{L} \propto \frac{g_B}{6} Z'_{B\mu} \bar{q} \gamma^\mu q$$



NEW LOOK AT THE PHASE SPACE

arXiv:1306.2629

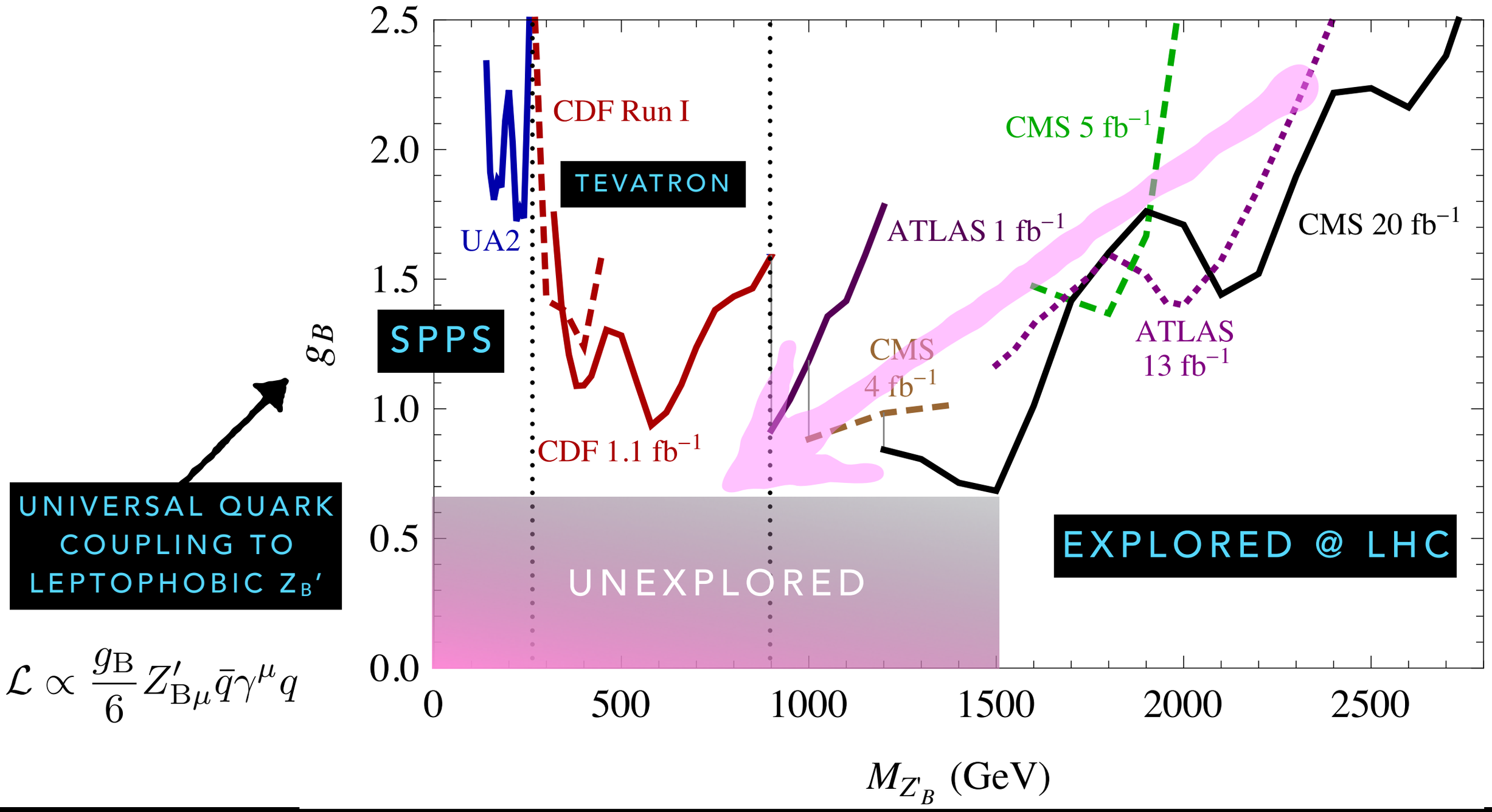
- Due to trigger thresholds and larger backgrounds, standard dijet search @ LHC explores lower in coupling at higher masses



NEW LOOK AT THE PHASE SPACE

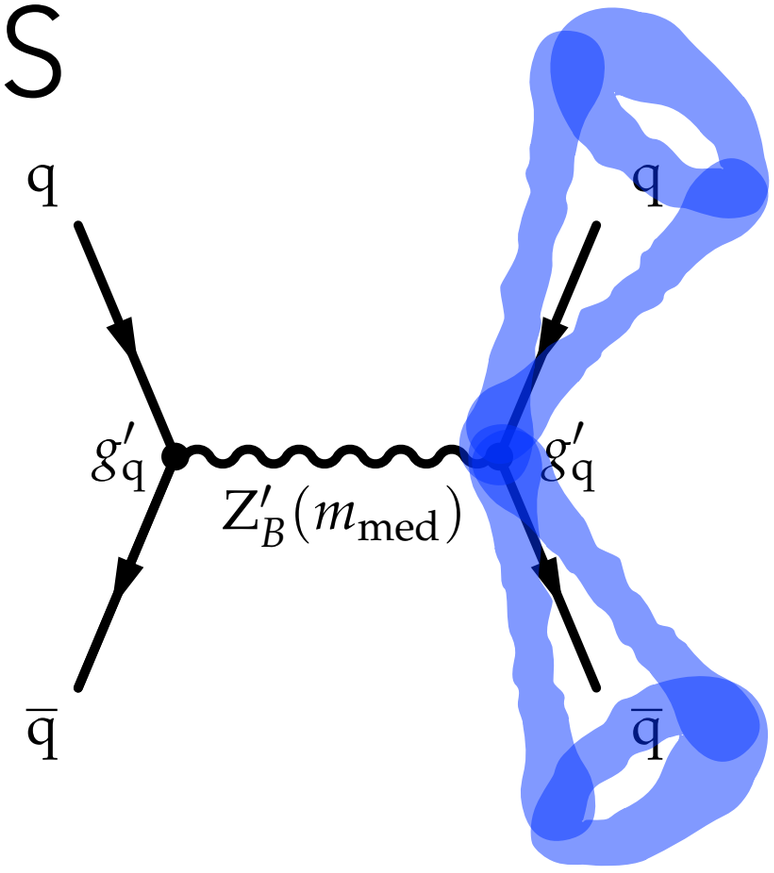
arXiv:1306.2629

- How can we go lower in coupling and lower in mass?

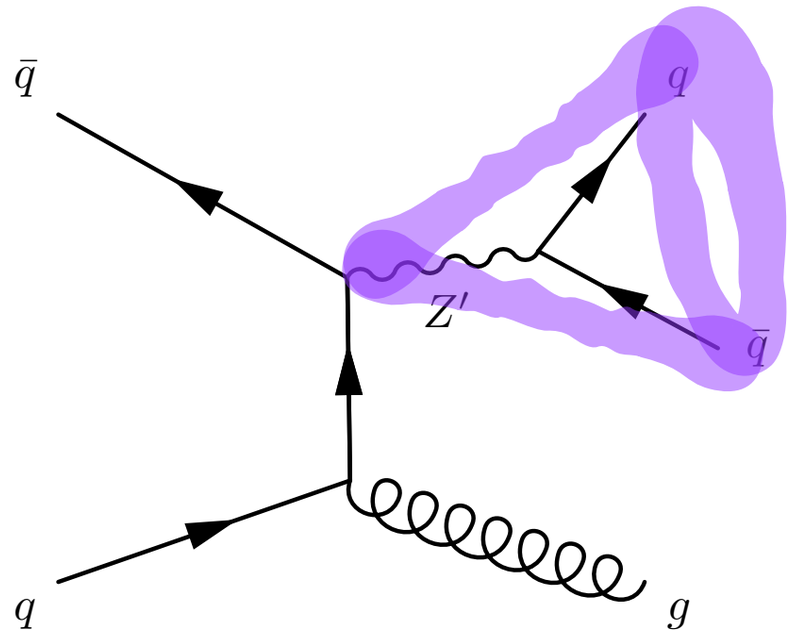


TWO METHODS

- **Data scouting**: lower trigger thresholds by recording only information necessary to perform analysis (to get around data-taking constraints)

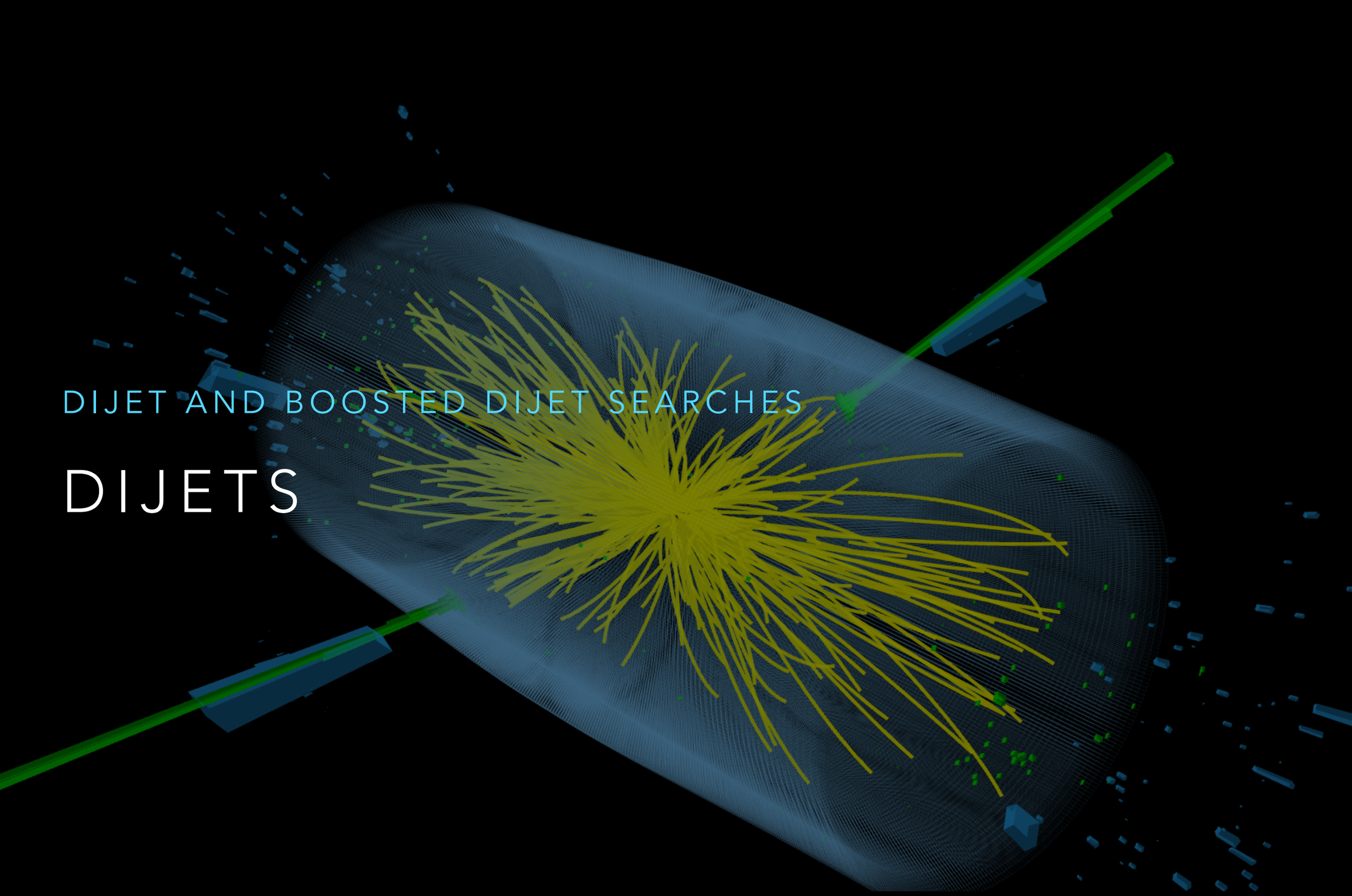


- **Boosted dijets + associated ISR jet**: Use ISR jet to get above the trigger thresholds



DIJET AND BOOSTED DIJET SEARCHES

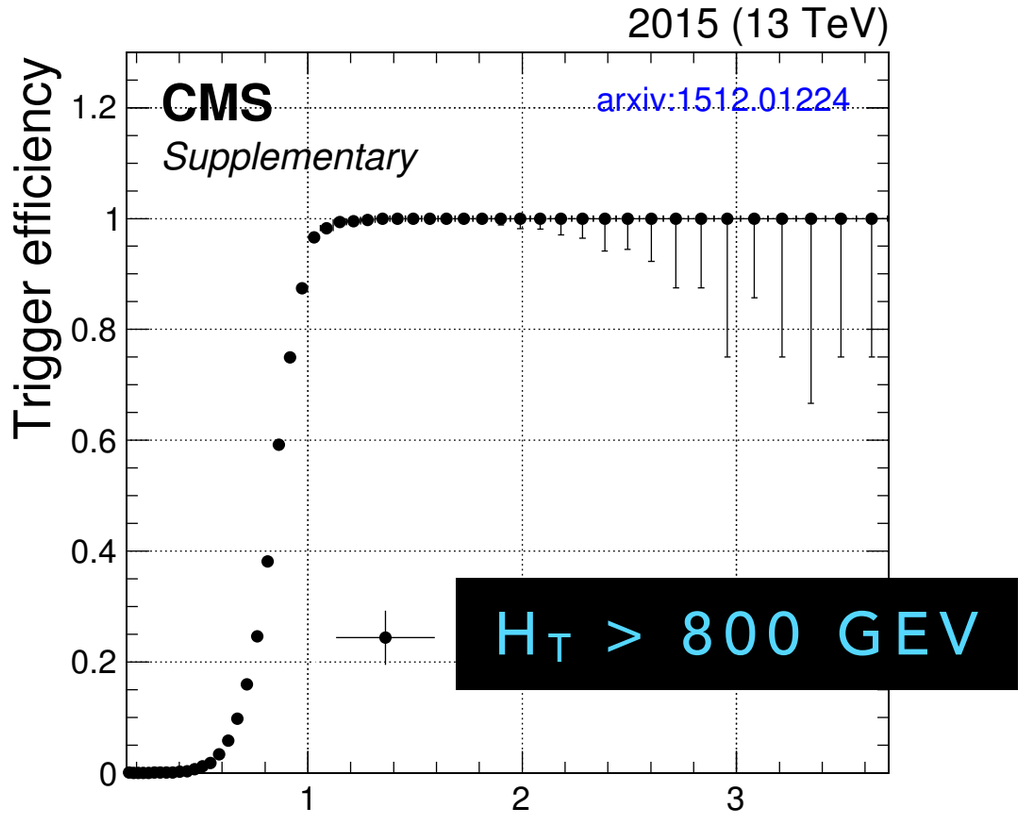
DIJETS

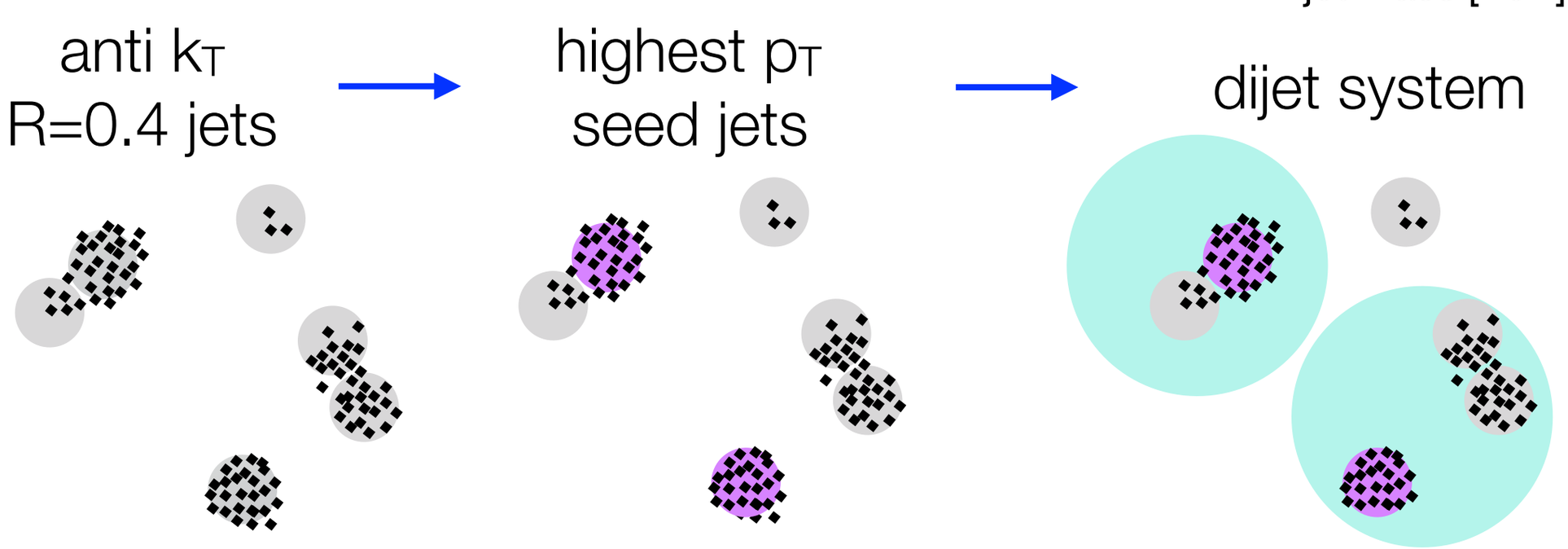


Javier Duarte
Fermilab

BASICS OF A DIJET SEARCH

- Collect (lots of) data with a trigger based on hadronic activity
- Cluster two "wide jets"





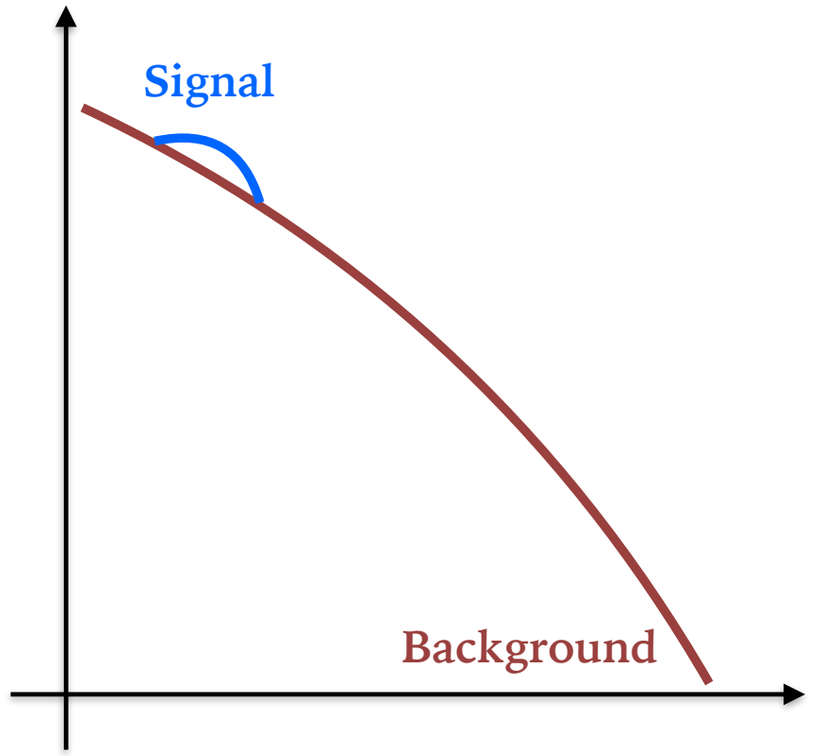
BASICS OF A DIJET SEARCH

- Collect (lots of) data with a trigger based on hadronic activity
- Cluster two "wide jets"
- Select events based on wide jet properties
- Search for a bump on a ***smoothly falling dijet mass spectrum***
- Set limits

☑ 2 jets with $p_T > 30$ GeV and $|\eta| < 2.5$

☑ Wide jets $|\Delta\eta| < 1.3$ to suppress t-channel QCD dijet production

☑ Wide jet $m_{jj} > 1.1$ TeV to ensure fully efficient trigger



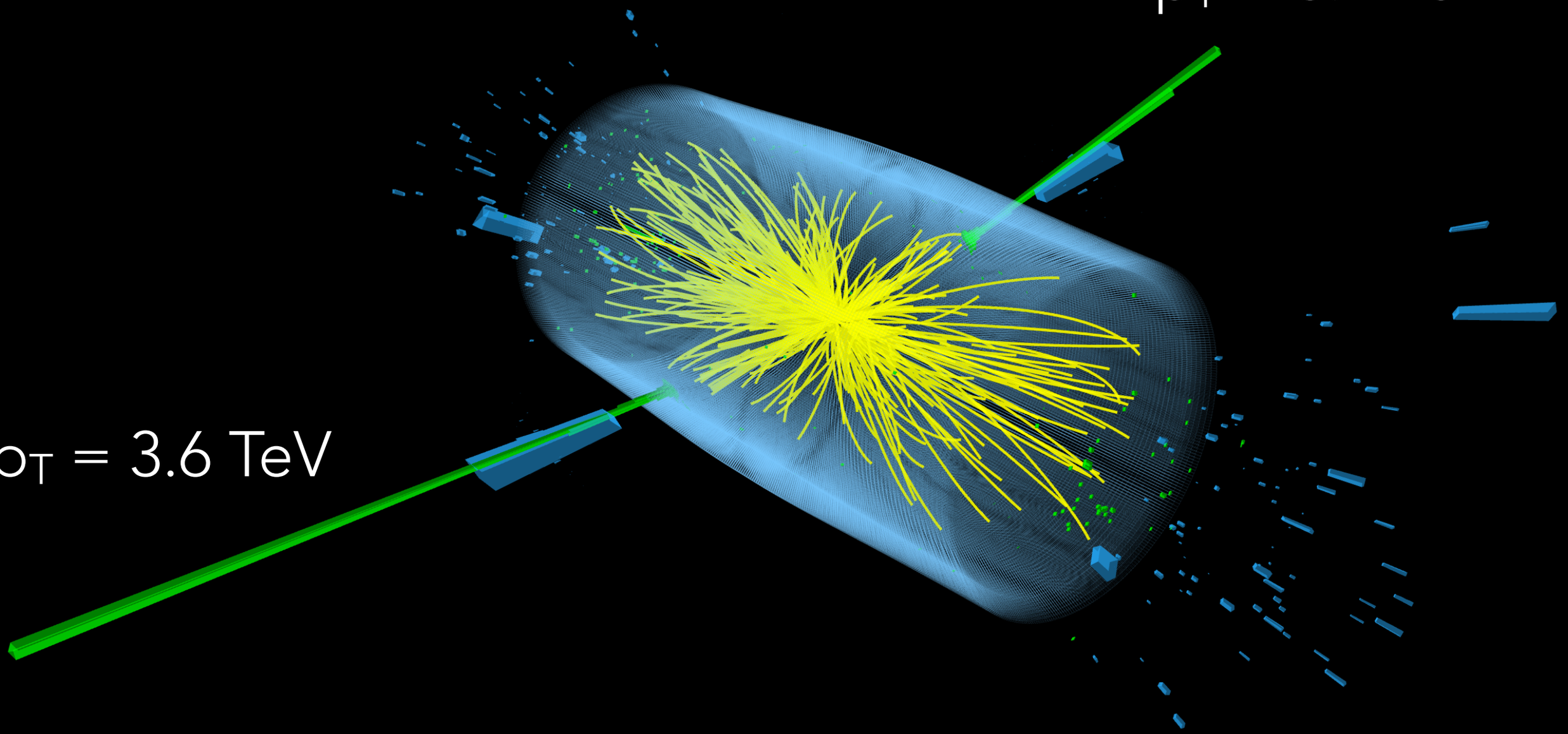
EXO-16-032

HIGH MASS EVENT

- Highest dijet mass event **m_{jj} = 7.7 TeV**

CMS Experiment at the LHC, CERN
Data recorded: 2016-May-11 21:40:47.974592 GMT
Run / Event / LS: 273158 / 238962455 / 150

p_T = 3.4 TeV



p_T = 3.6 TeV

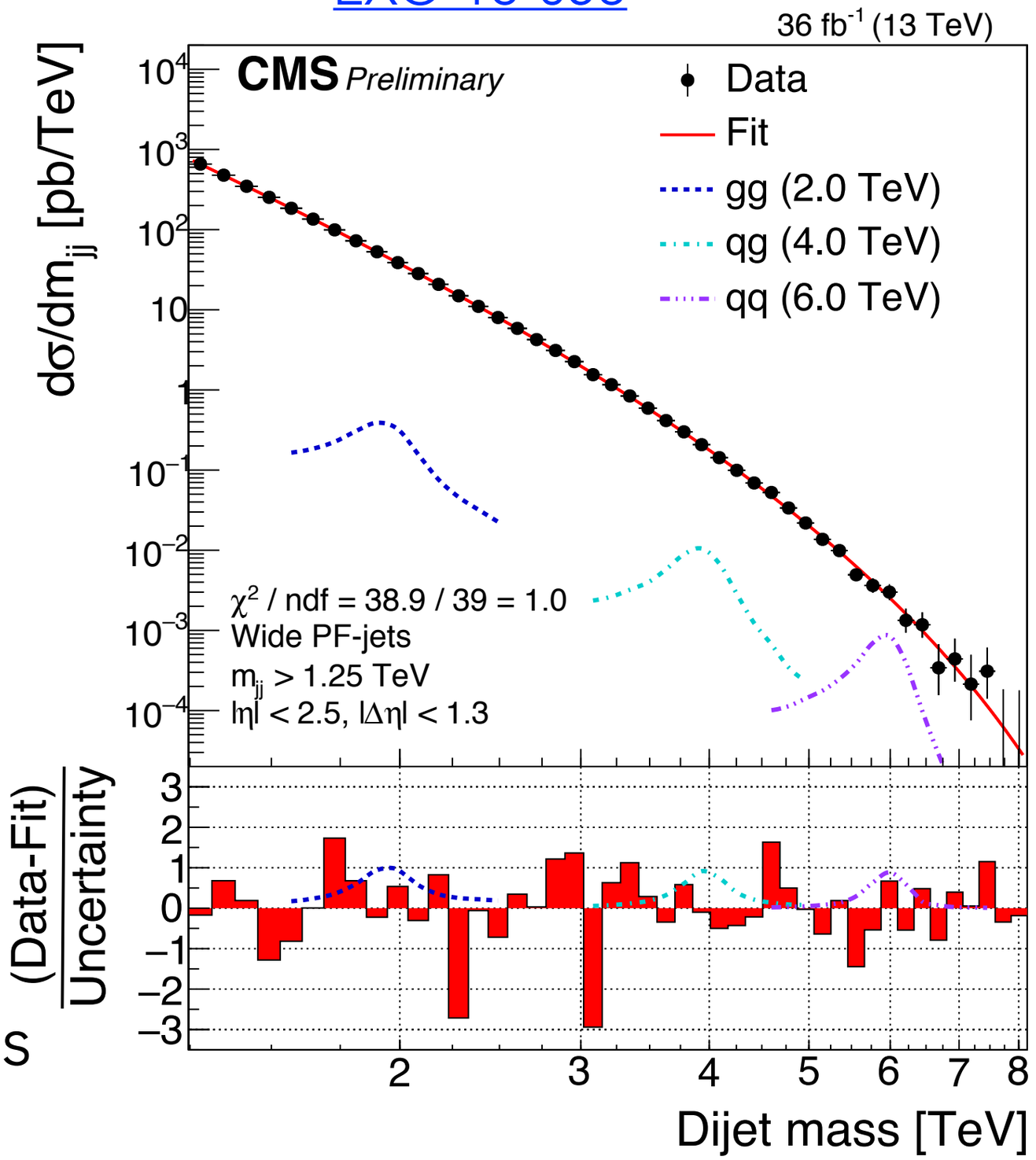
HIGH MASS SPECTRUM AND FIT

- With (updated) $H_T > 900$ GeV trigger, fit starts at $m_{jj} > 1.25$ TeV
- **High mass** spectrum is fit with 4-parameter function

$$\frac{\mathrm{d}\sigma}{\mathrm{d}m_{\mathrm{jj}}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)}}, \; x = m_{\mathrm{jj}}/\sqrt{s}$$

- χ^2/dof = 1.0
- No evidence for high-mass dijet resonances

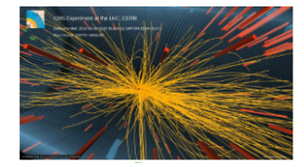
EXO-16-056



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

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



H. Brun, LP 2015

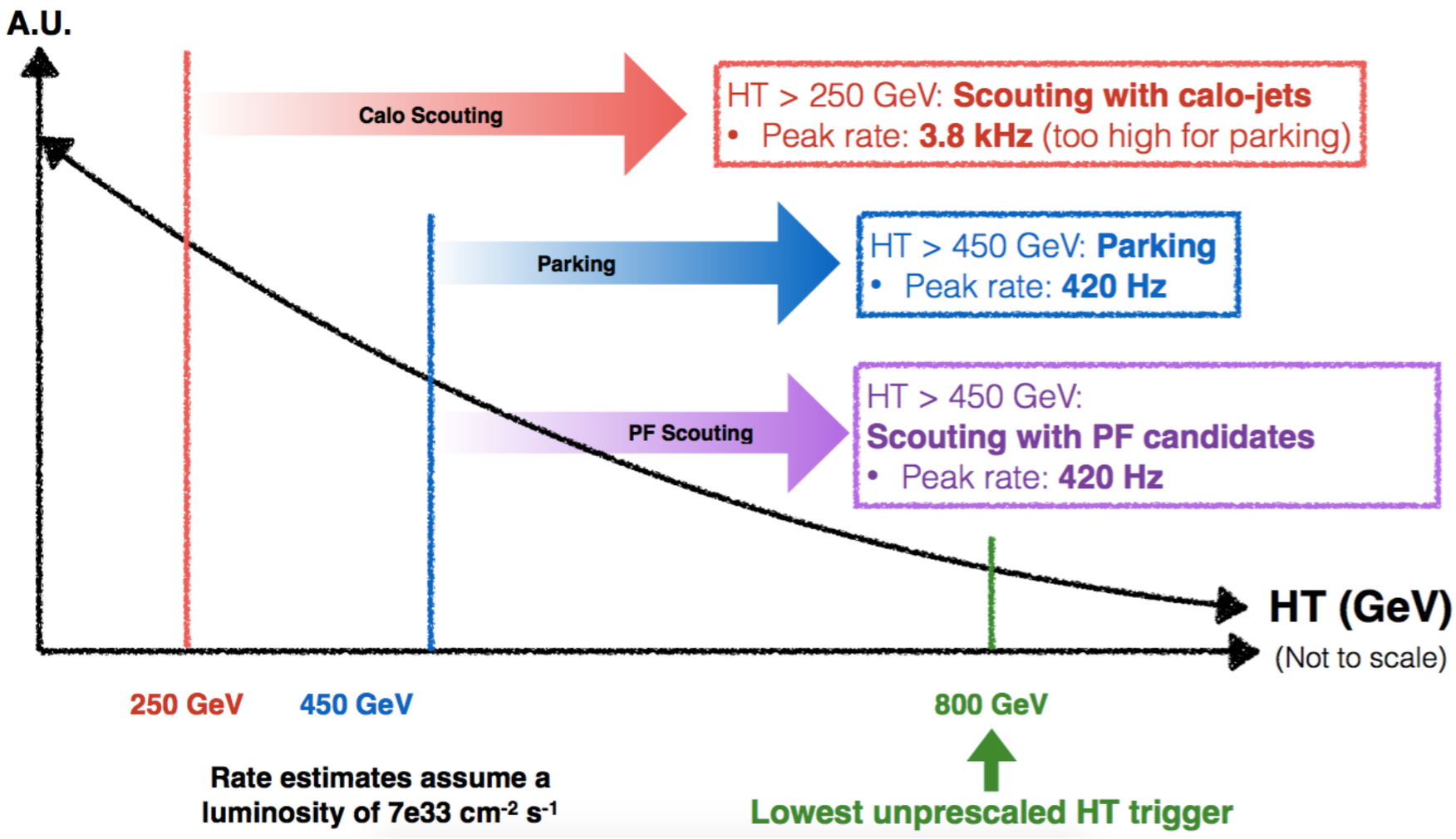
DATA SCOUTING

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

- Reconstruct/save only necessary information to perform analysis → record more events

- "**Calo Scouting**" allows us to get down to **H_T > 250 GeV**

Calo Scouting
3kHz × 1.5 kb



LOW MASS SPECTRUM AND FIT

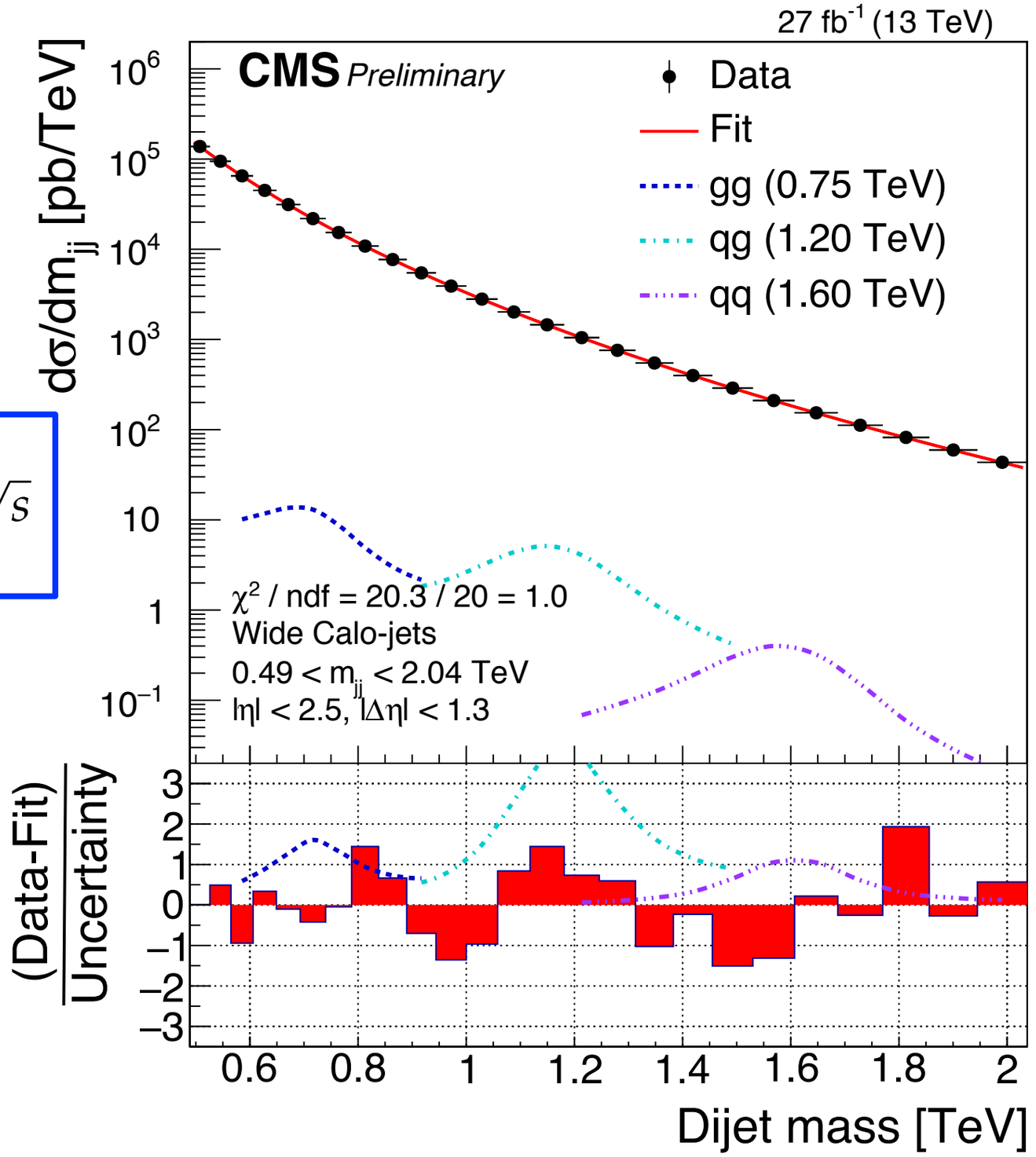
EXO-16-056

- Using "Calo Scouting," **low mass** spectrum✳ is fit with 5-parameter function above $m_{jj} > 489$ GeV

$$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)+P_4\ln(x)^2}} \quad x = m_{jj}/\sqrt{s}$$

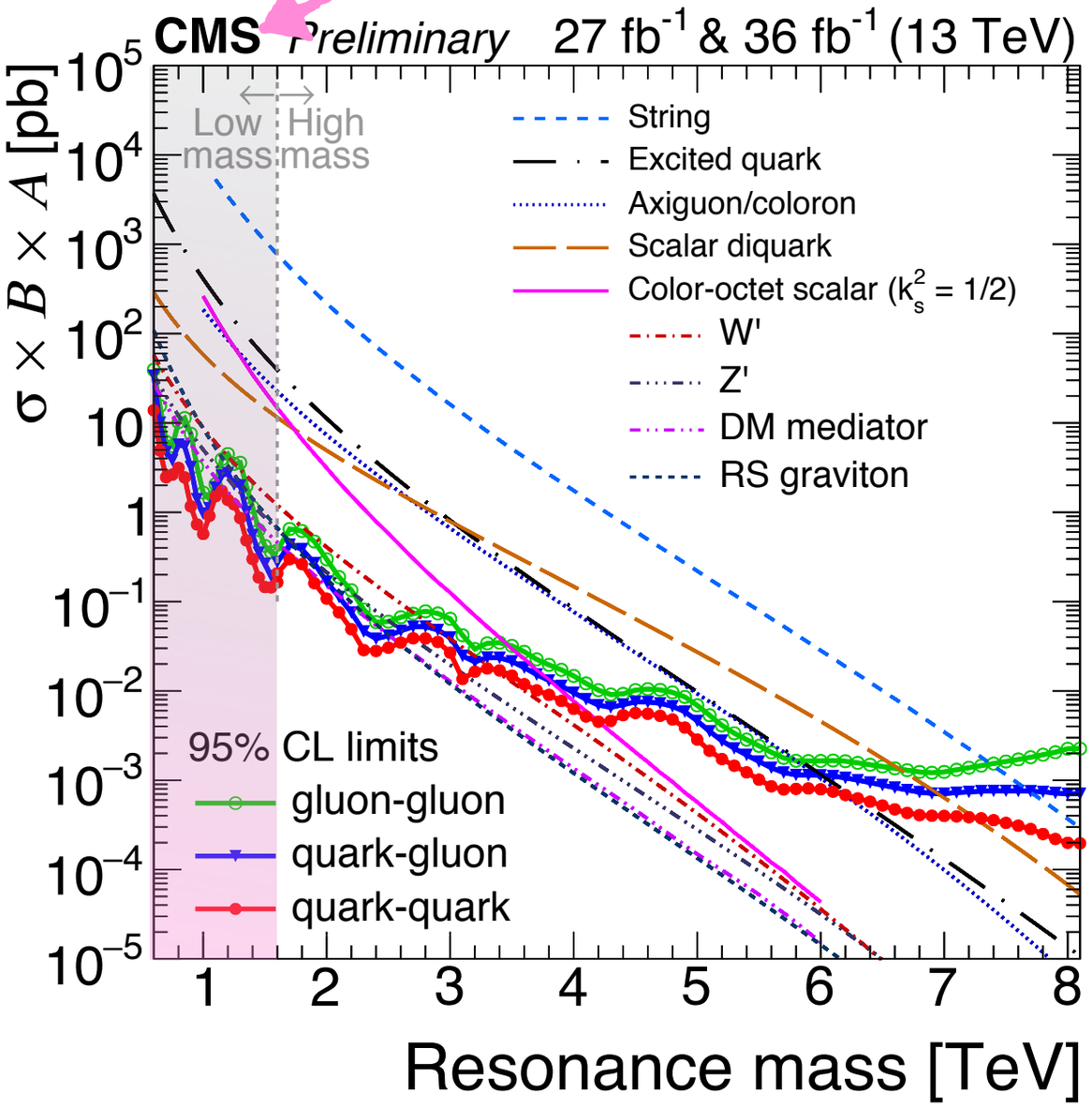
- χ^2/dof = 1.0
- No evidence for dijet resonance

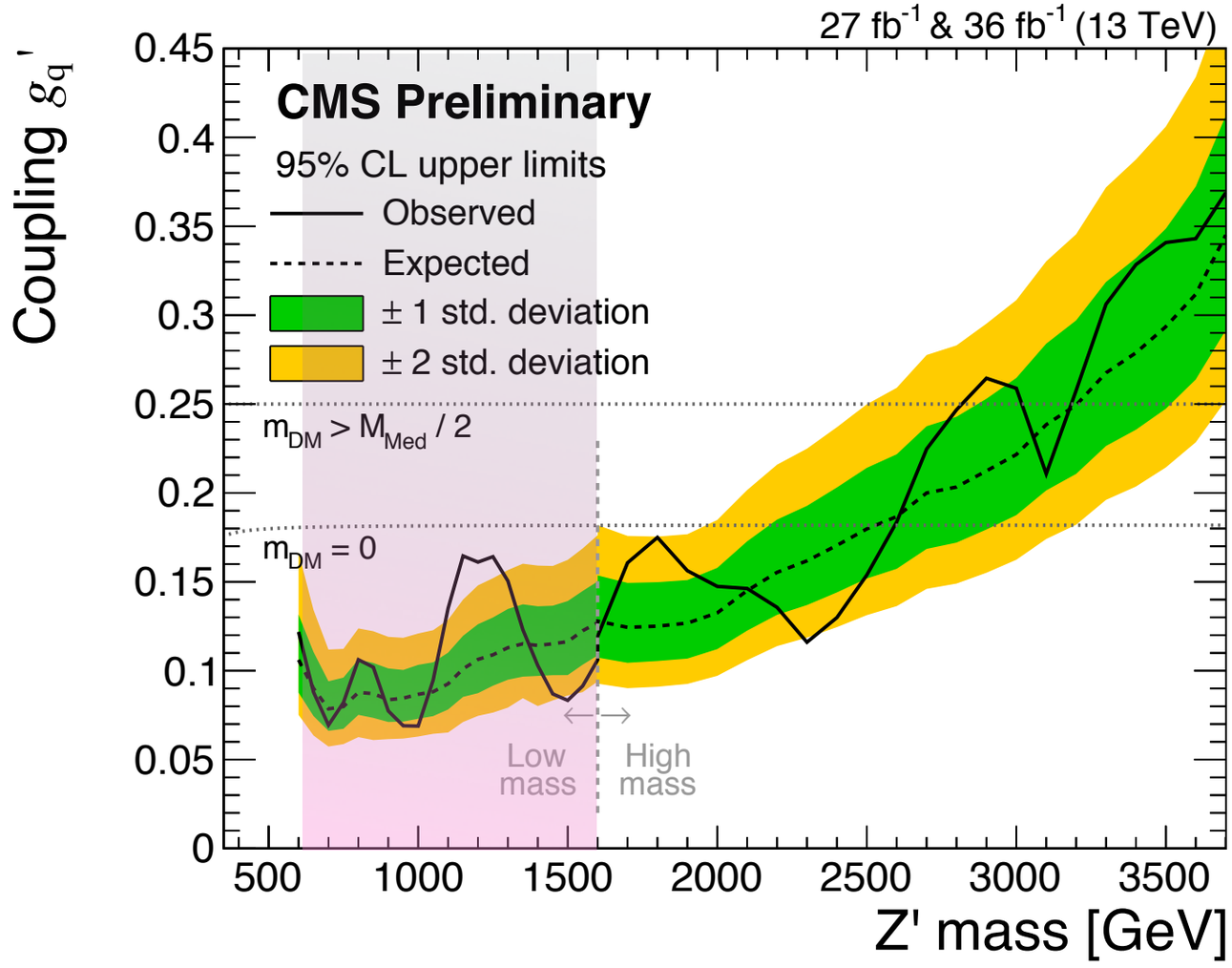
✳ Note: only the first 27 fb^{-1} is used due to an inefficiency in the L1 jet H_T trigger



LIMITS ON NARROW RESONANCES

- Expanded CMS reach at low mass

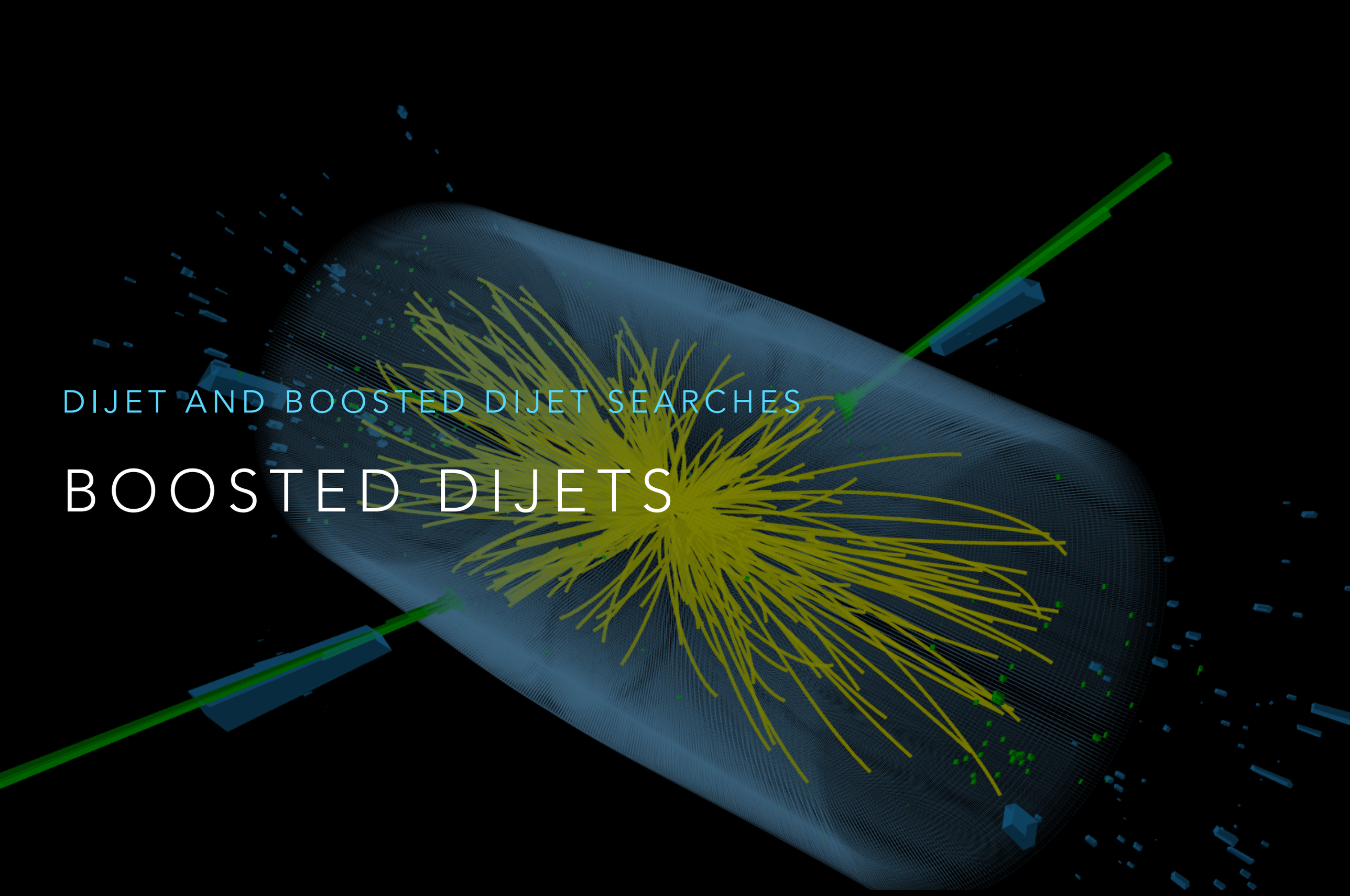




$$g_q' = g_B/6$$

DIJET AND BOOSTED DIJET SEARCHES

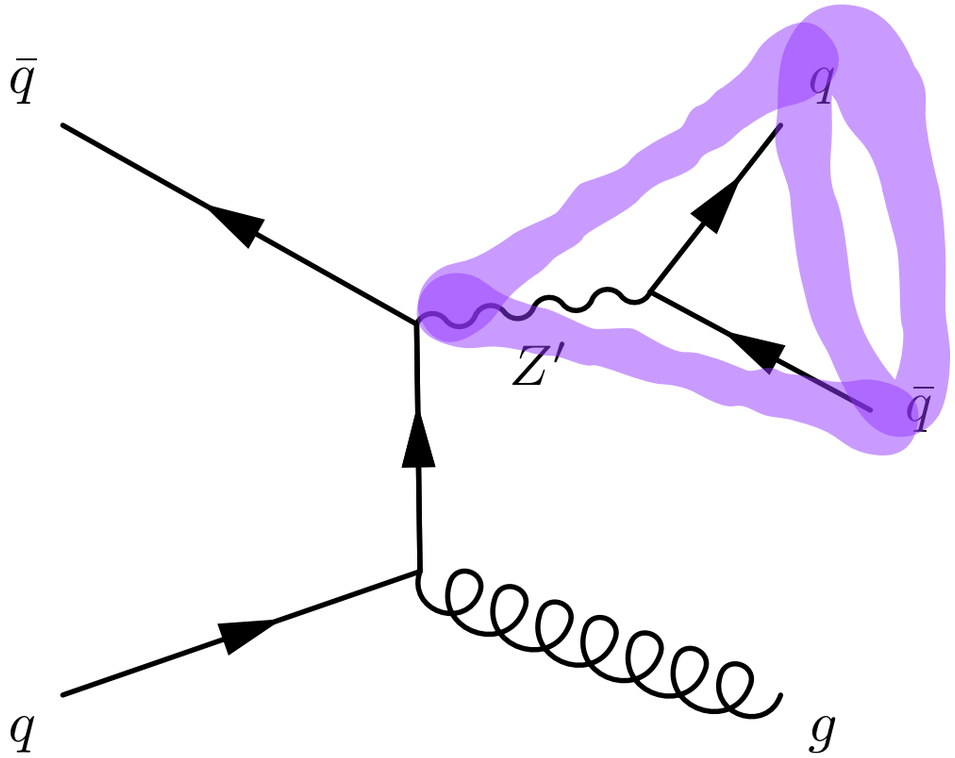
BOOSTED DIJETS

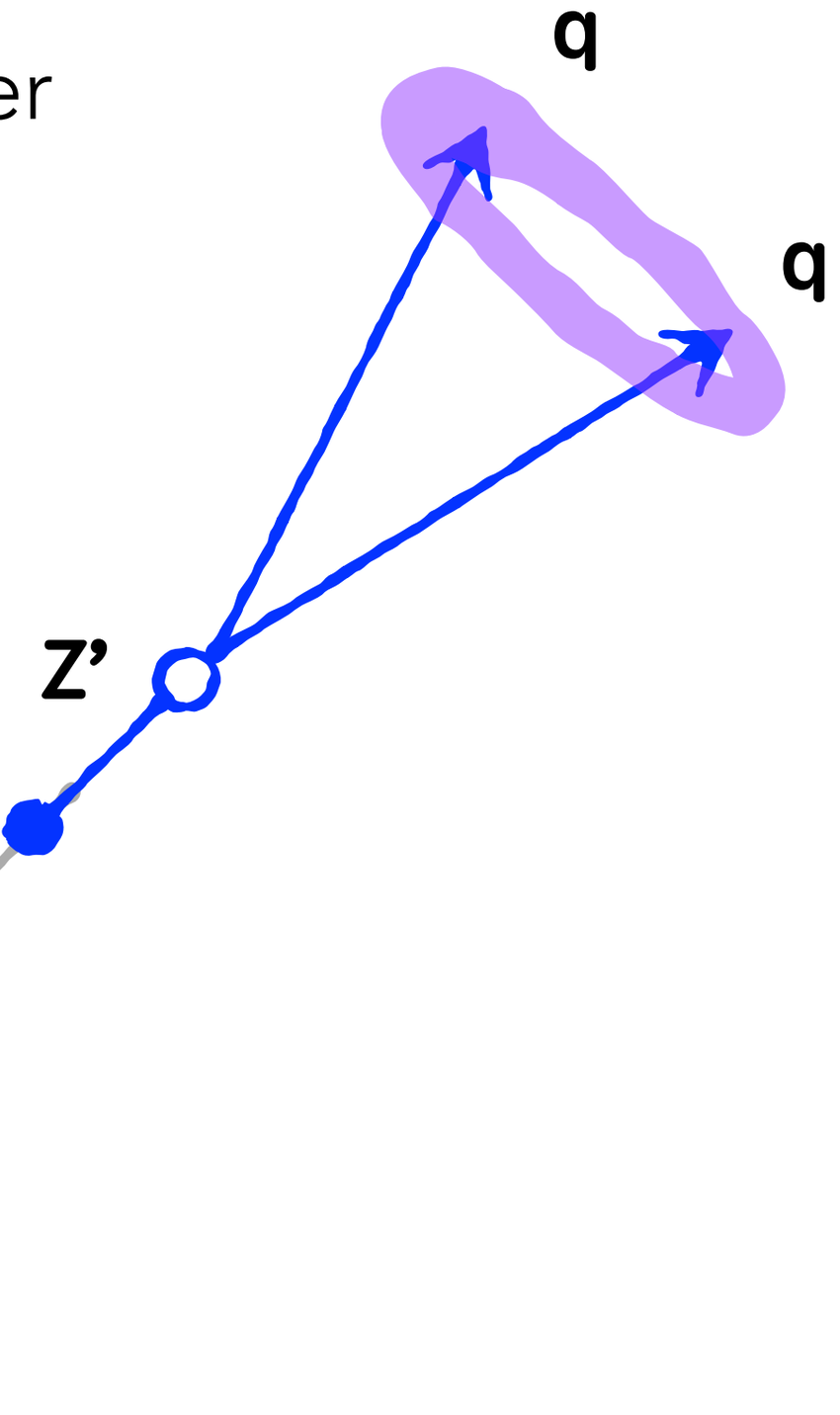


Javier Duarte
Fermilab

ASSOCIATED ISR JET TOPOLOGY

- Use ISR jet to get you above the trigger threshold
- Look for boosted light Z′ resonance

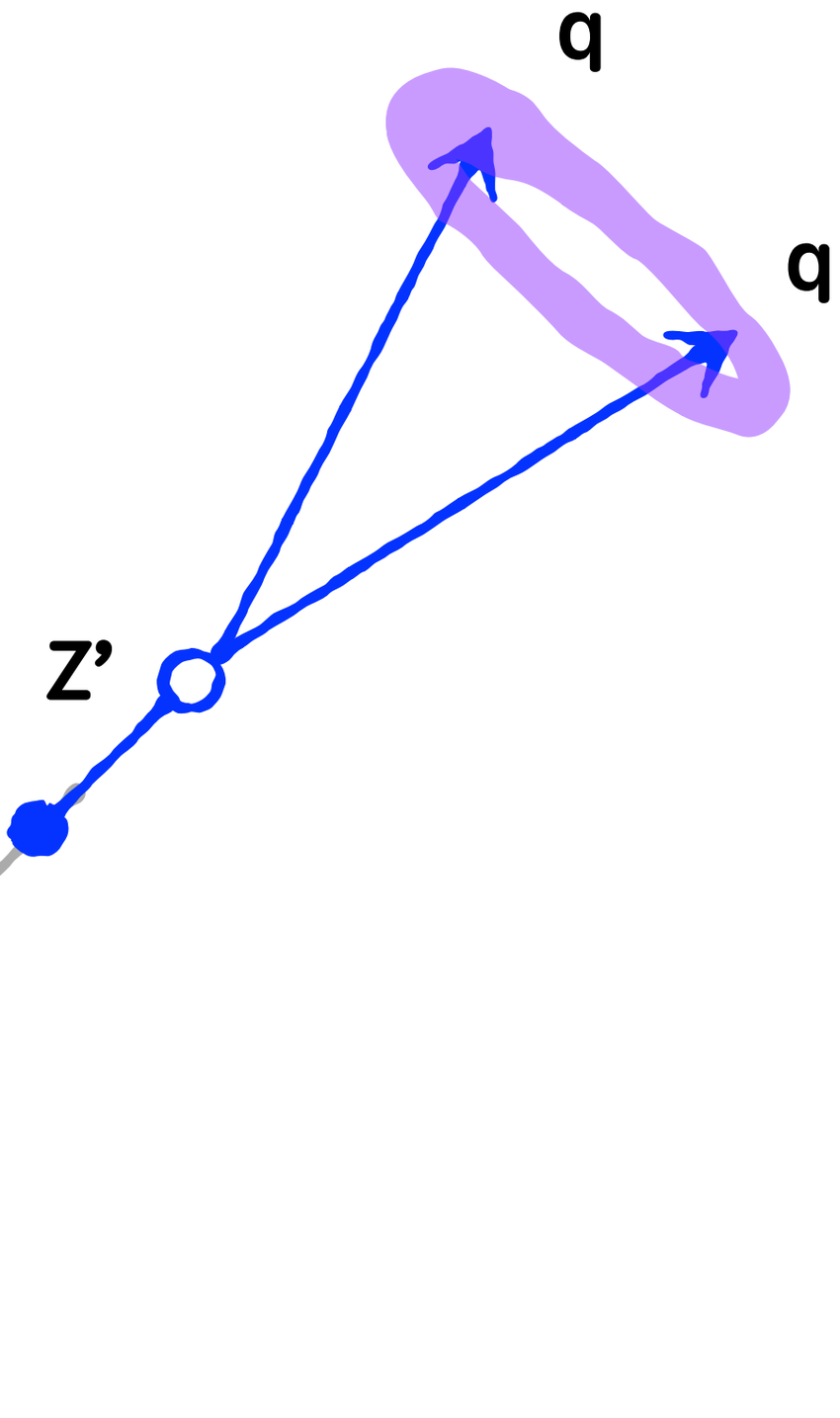




EXO-16-030

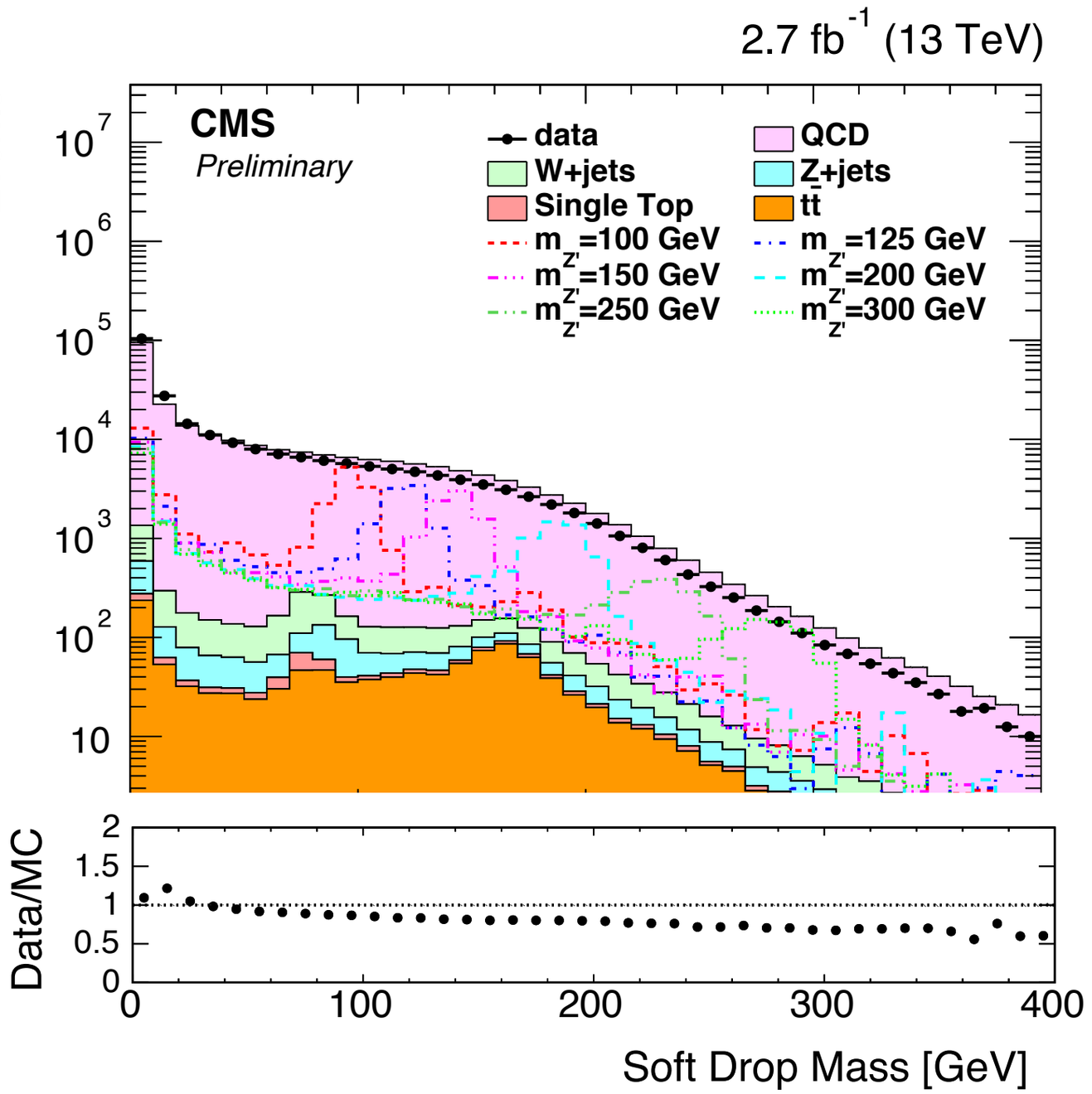
ANALYSIS SELECTION

- Kinematic Selections:
  - PUPPI AK8 jet p_T > 500 GeV, $|\eta|$ < 2.5 (veto e,μ > 10 GeV)
- Trigger:
  - AK8PFHT650,TrimMass50 OR AK8PFJet360,TrimMass30 OR PFHT800
- Substructure Selections:
  - Soft drop jet mass > 25 GeV (z = 0.1, β = 0)
  - τ_{21}^{DDT} < 0.38
- Backgrounds:
  - QCD
  - SM Candles: W/Z + jets



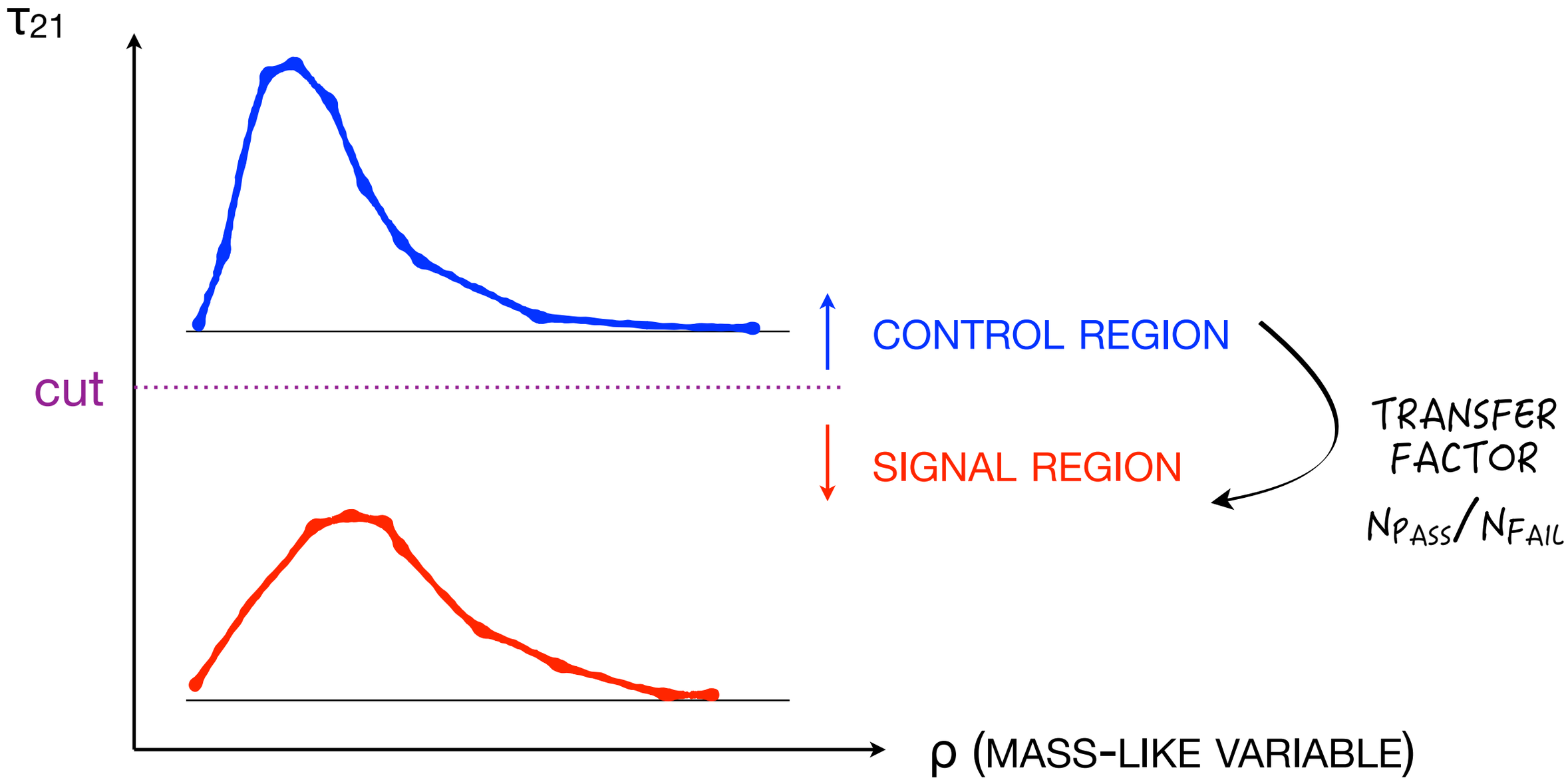
ANALYSIS SELECTION

- After kinematic selection
- Fitting this mass distribution directly requires high order polynomial → large background uncertainties
- Can we try a sideband prediction?



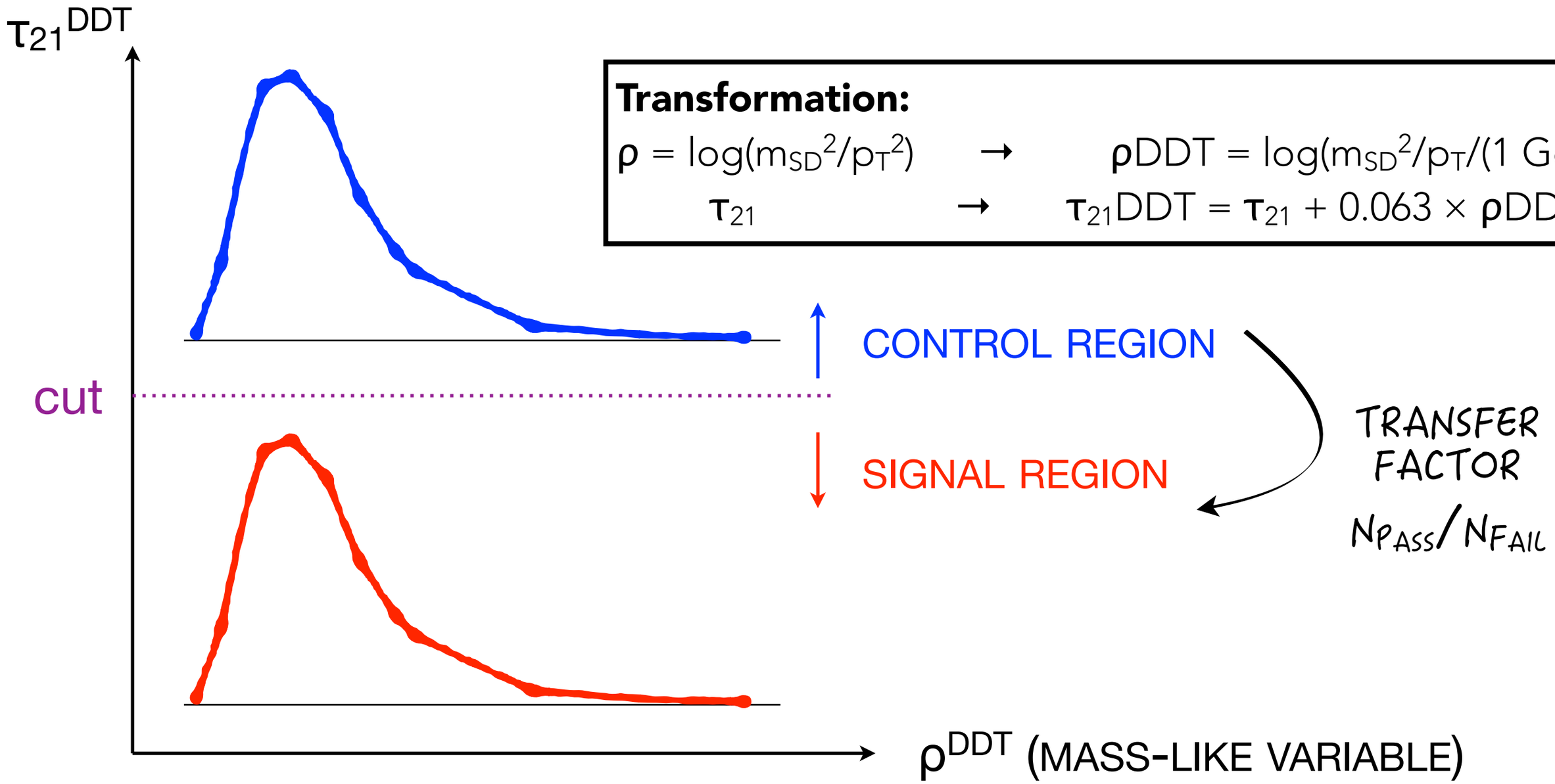
SIDEBAND QCD PREDICTION

- Core idea: predict QCD jet mass distribution from failing region
- Problem: cut on τ_{21} sculpts jet mass distribution!



SIDEBAND QCD PREDICTION

- Solution: define new substructure variable intended to be decorrelated from jet mass



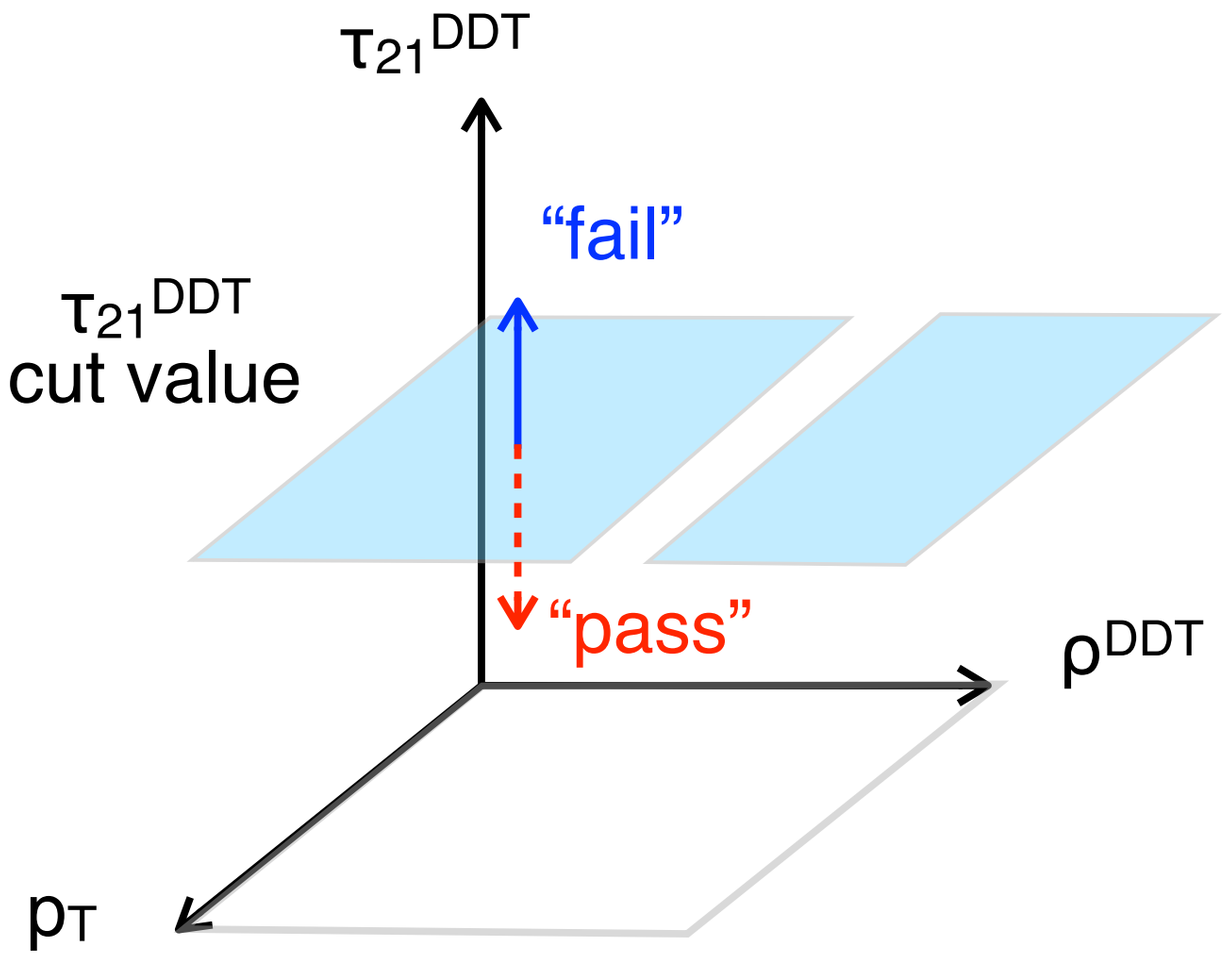
Transformation:

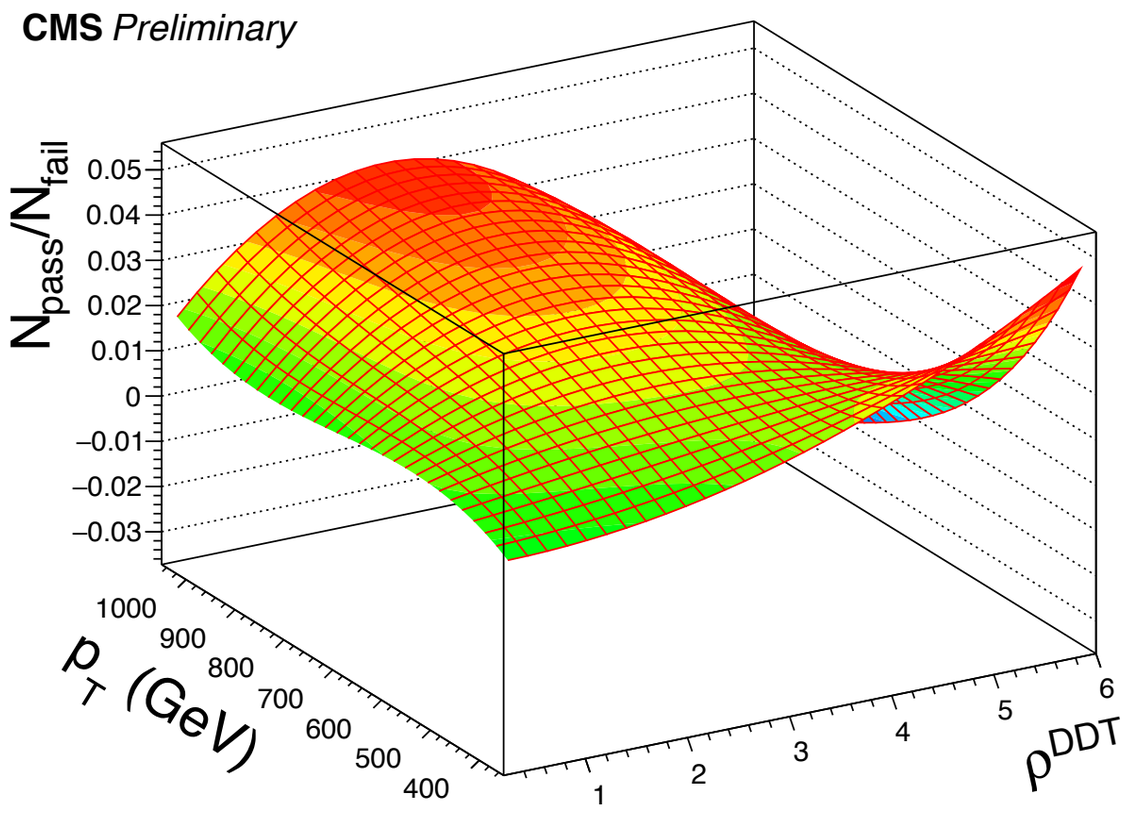
$\rho = \log(m_{SD}^2/p_T^2)$ → $\rho DDT = \log(m_{SD}^2/p_T/(1\ GeV))$

τ_{21} → $\tau_{21}DDT = \tau_{21} + 0.063 \times \rho DDT$

QCD TRANSFER FACTOR

- Translate events from fail region to pass region using a ***2D QCD transfer factor***
  - Transfer factor function is a polynomial in (p_T,ρ^{DDT}) and is fit excluding the mass region of interest



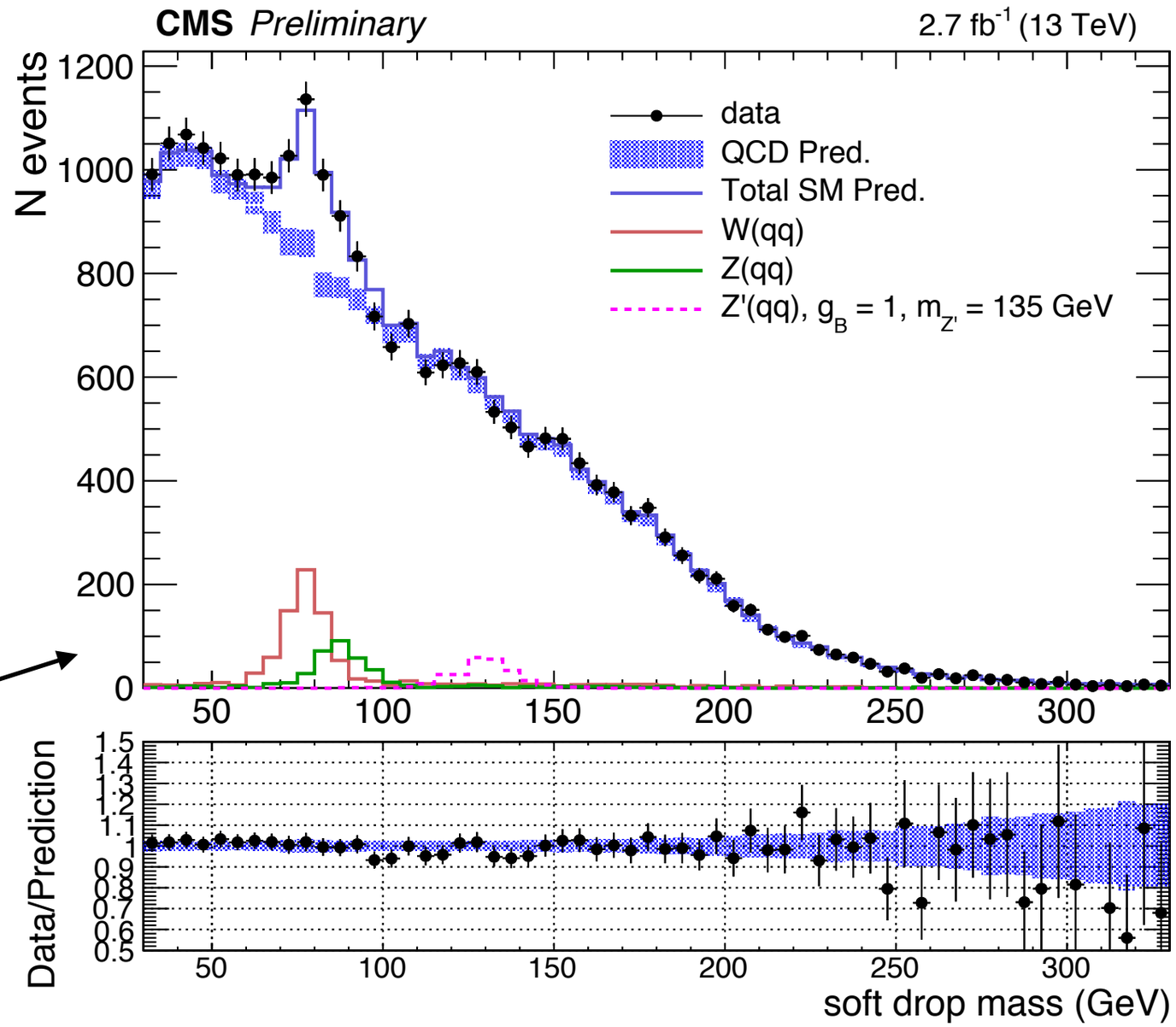


EXO-16-030

JET MASS SHAPE

- Jet mass distribution is fit down to 25 GeV
- Interpretation for resonance masses above 100 GeV

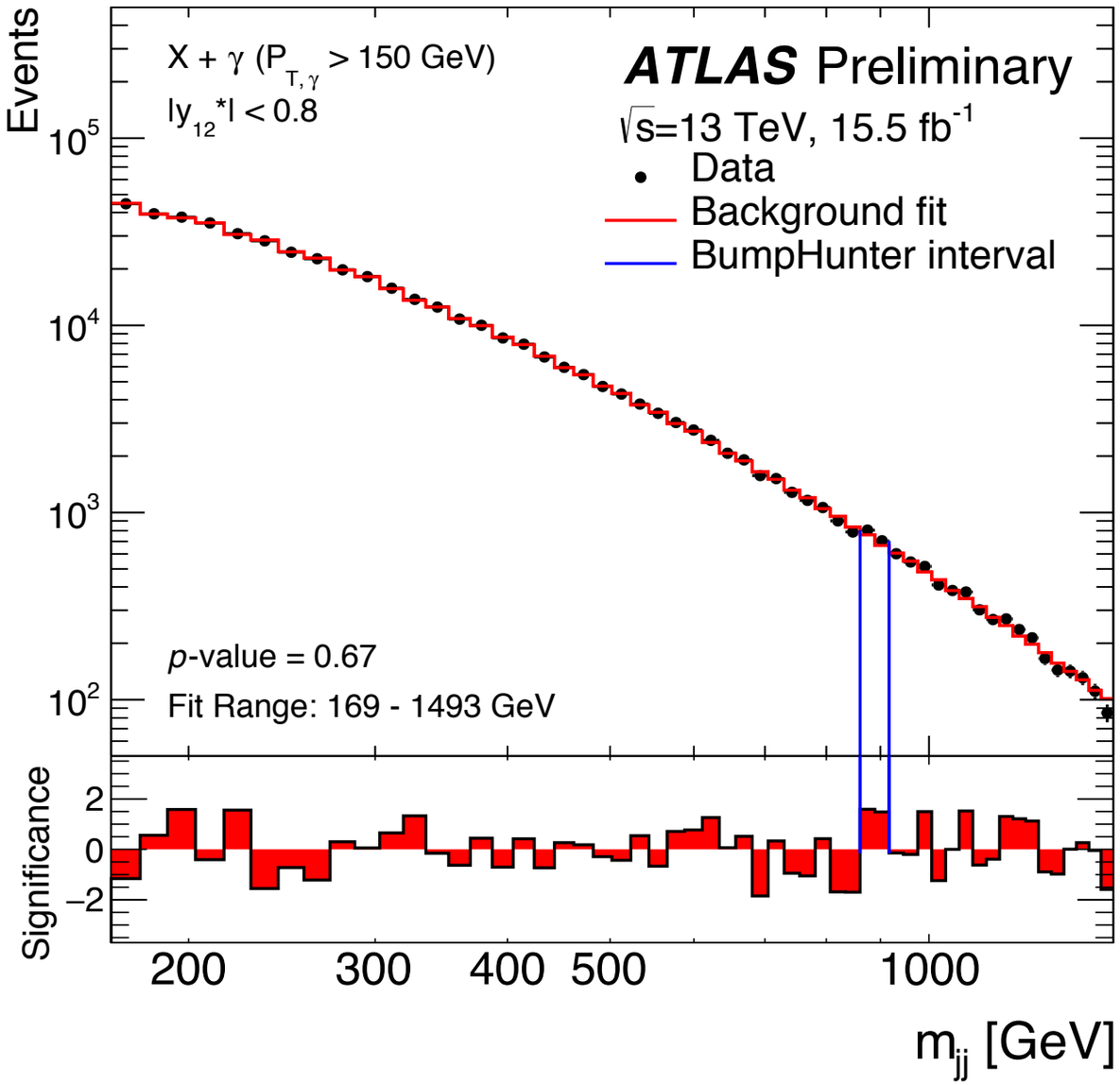
SM candles: W/Z peak provides in-situ constraint of Z′ signal systematics

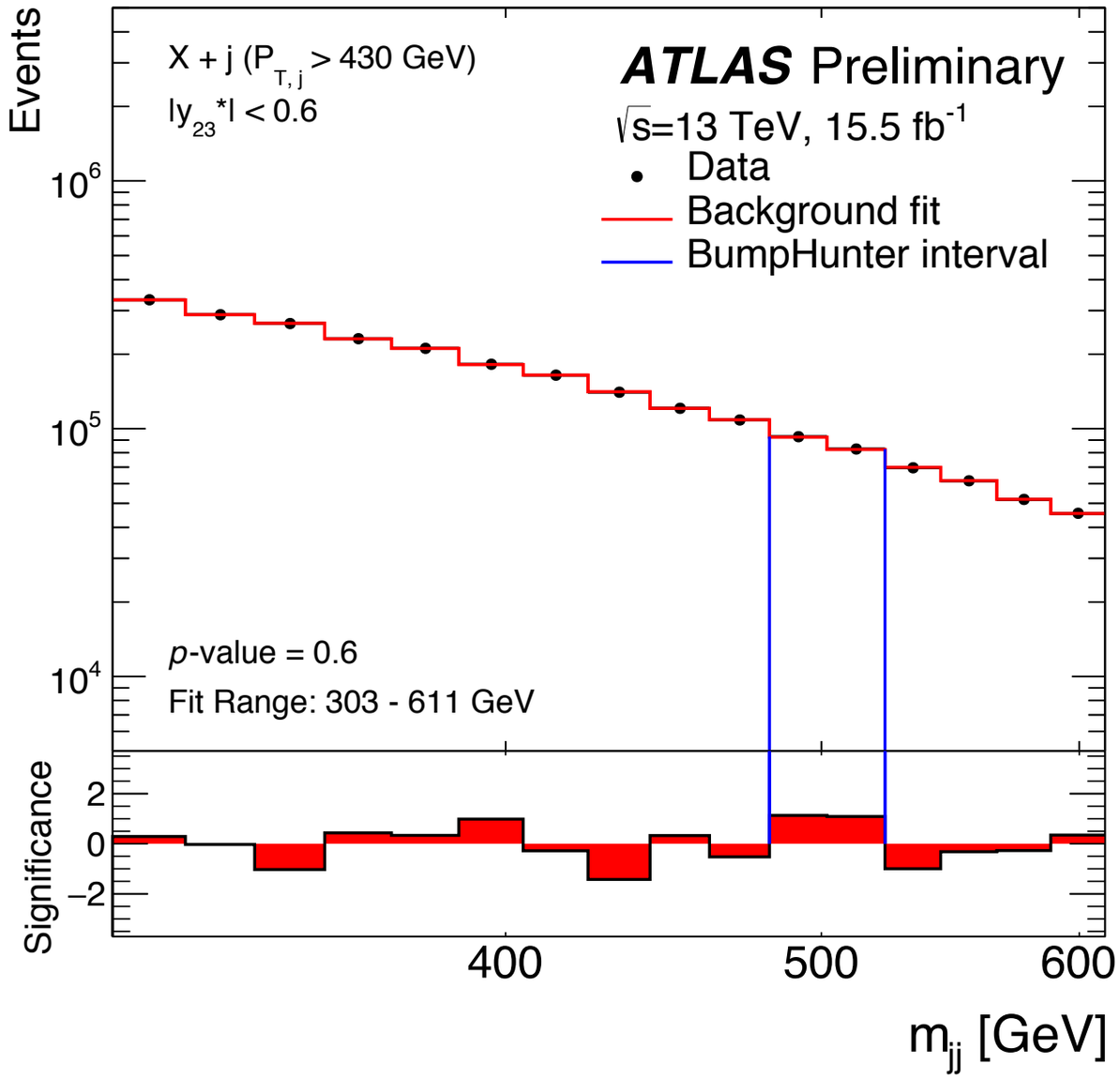


ATLAS DIJET + ISR

- Resolved dijet + ISR photon/jet
- Interpretation for resonance masses above 250 GeV

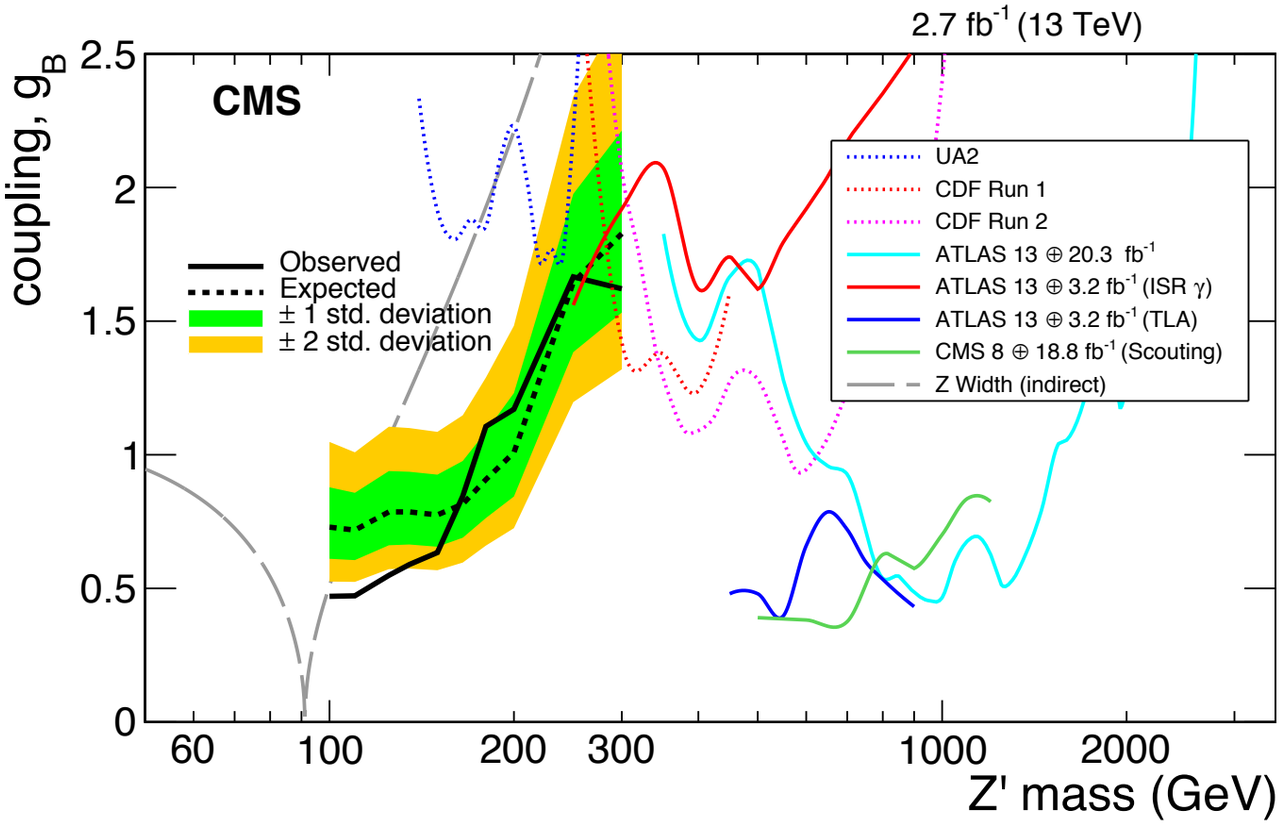
ATLAS-CONF-2016-070

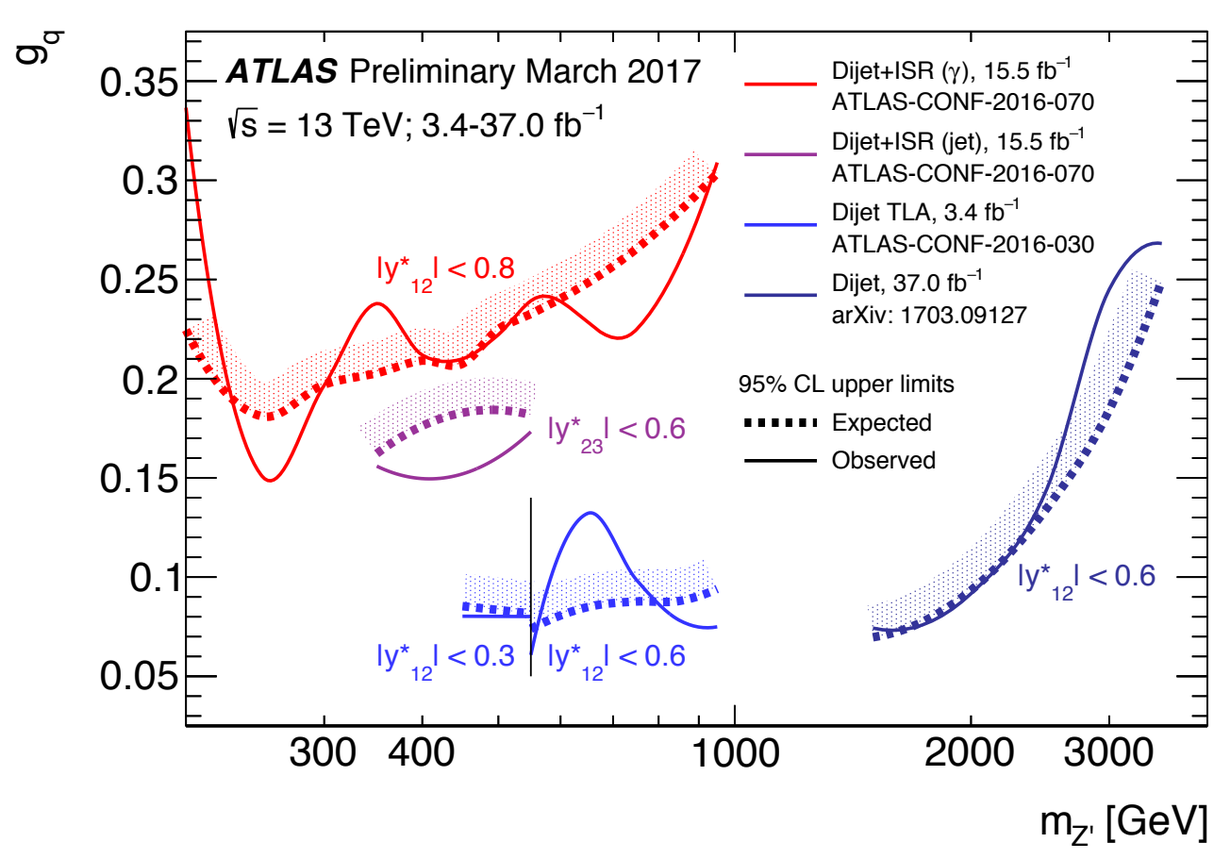




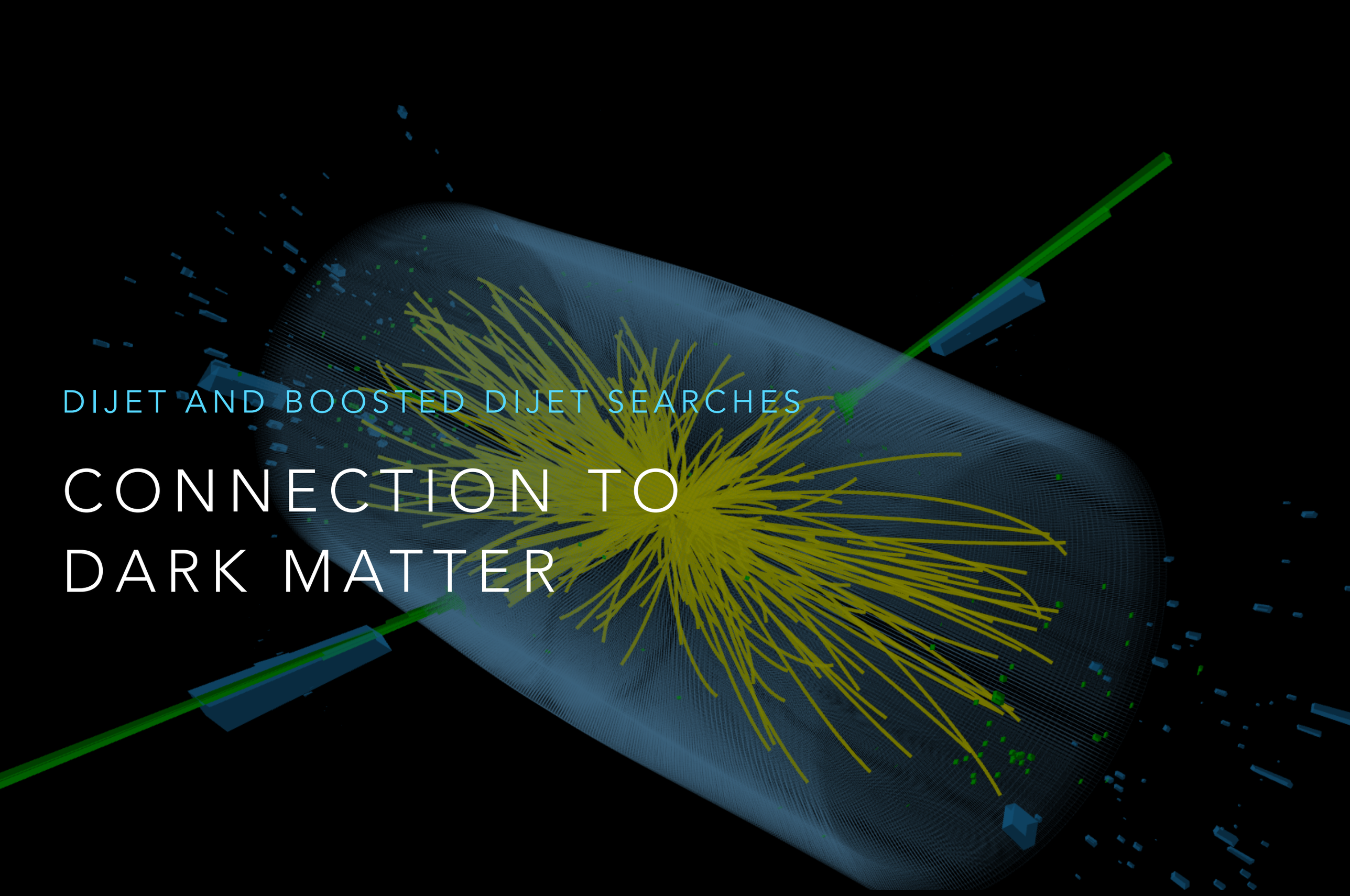
BOOSTED Z' INTERPRTATION

- CMS: first constraint from the LHC below 250 GeV
- ATLAS: resolved dijet + ISR photon/jet provides strong constraint above 250 GeV





$$g_q = g_B/6$$



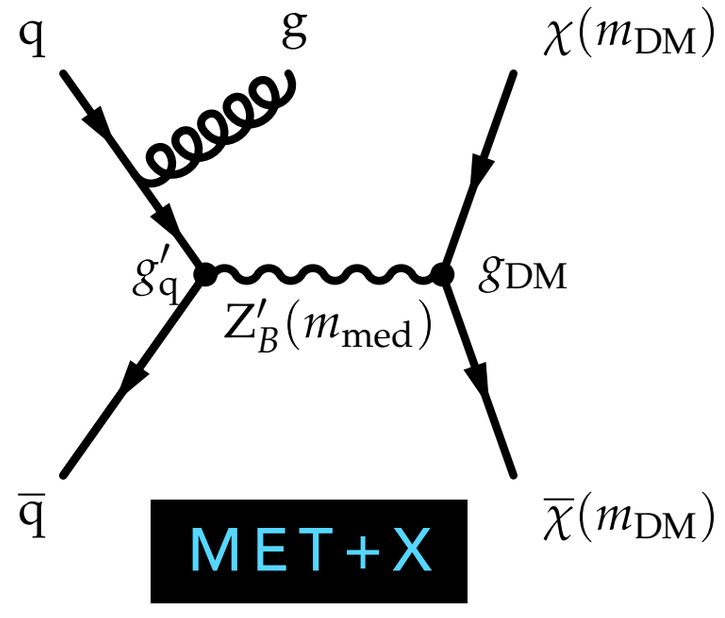
DIJET AND BOOSTED DIJET SEARCHES

CONNECTION TO DARK MATTER

Javier Duarte
Fermilab

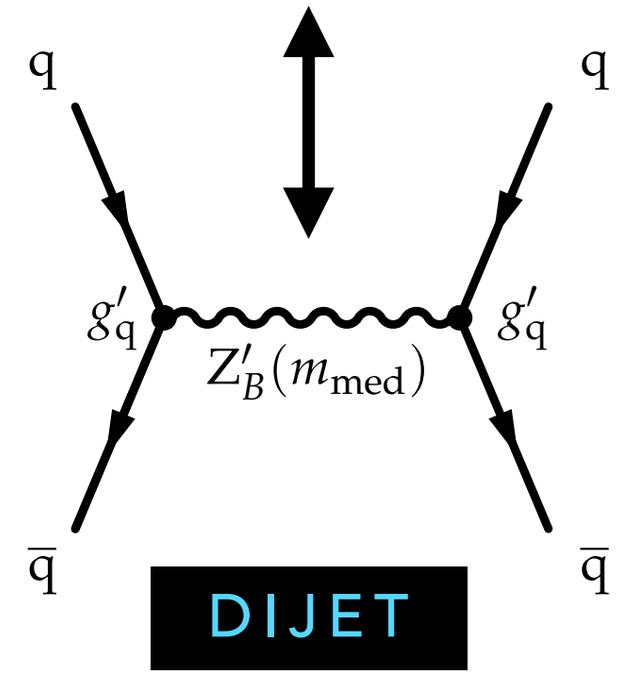
DARK MATTER MEDIATOR

- If our leptophobic Z′ couples to **dark matter** as well **quarks**, then it acts as **mediator** between the dark sector and visible sector (SM)



- How do our limits on the mediator change as we turn on $g_{DM} > 0$ and $m_{DM} < m_M/2$?

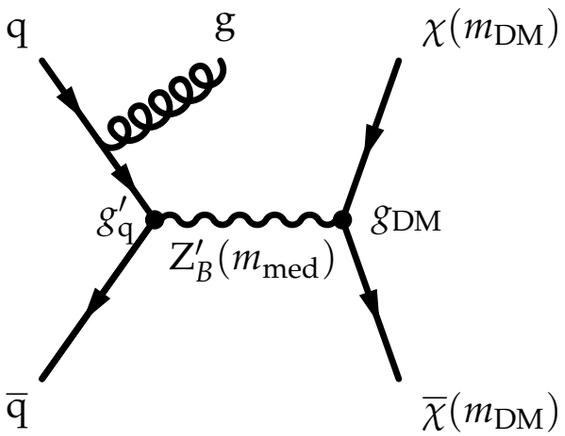
$$\mathcal{L}_{\mathrm{V}} = -g_{\mathrm{DM}} Z'_{B\mu} \overline{\chi} \gamma^{\mu} \chi - g'_{\mathrm{q}} \sum_{\mathrm{q}} Z'_{B\mu} \bar{q} \gamma^{\mu} q$$



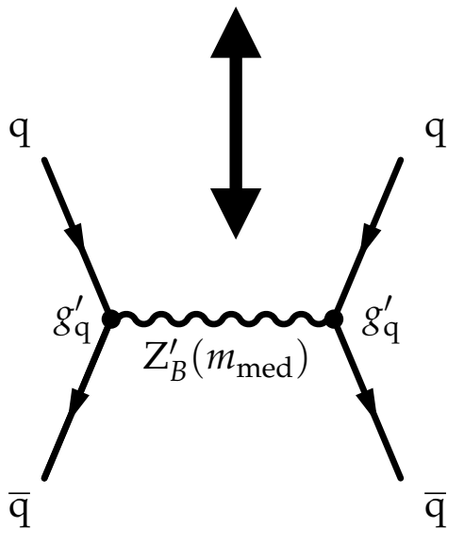
4D parameter space: g_{DM}, g_q, m_{DM}, m_M

SENSITIVITY TO DARK MATTER

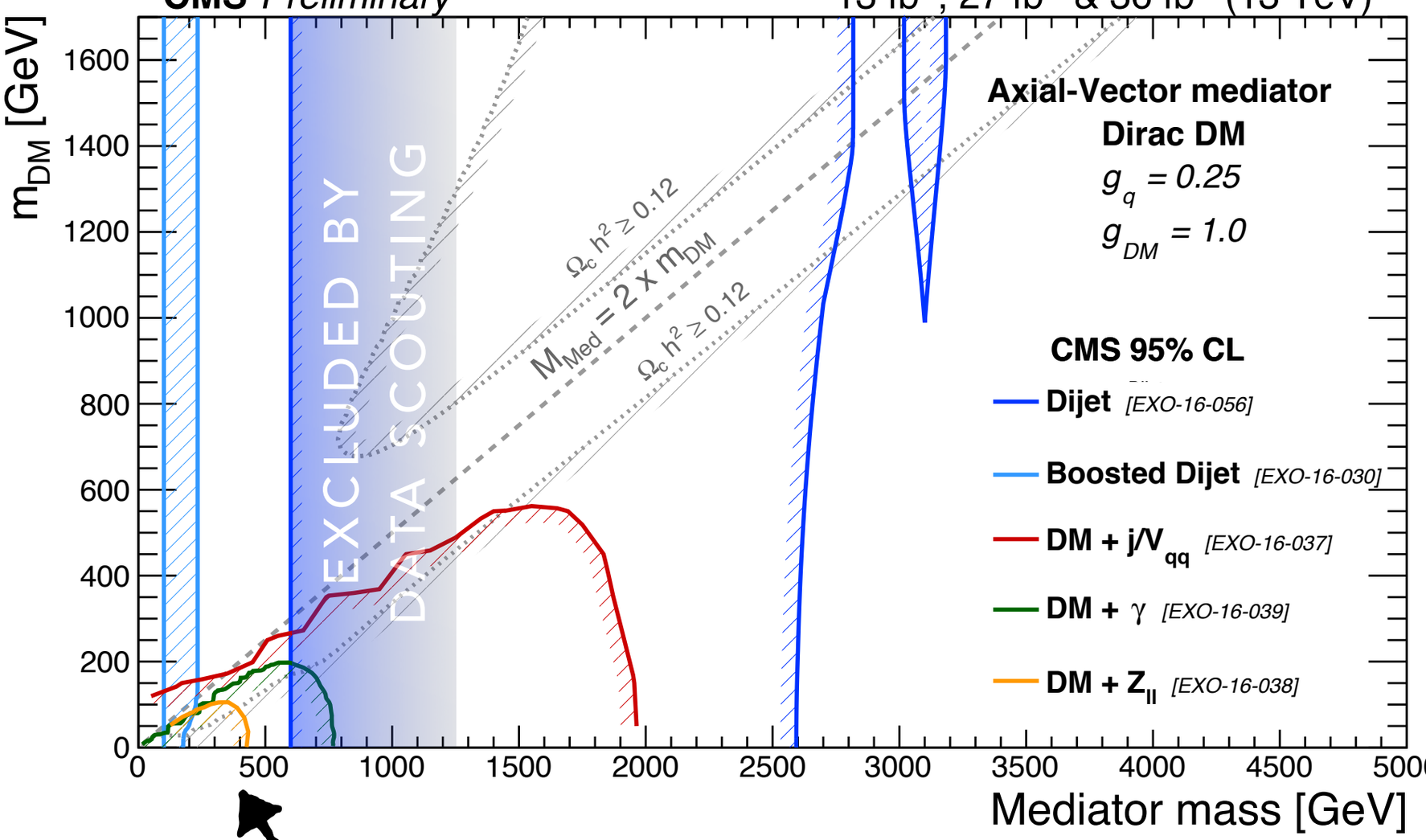
- Sensitive to large range of ***dark matter*** parameter space by looking directly for resonant production of the ***mediator***



MET+X



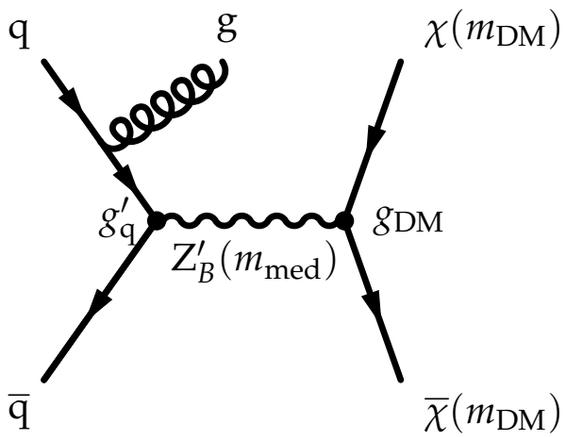
DIJET



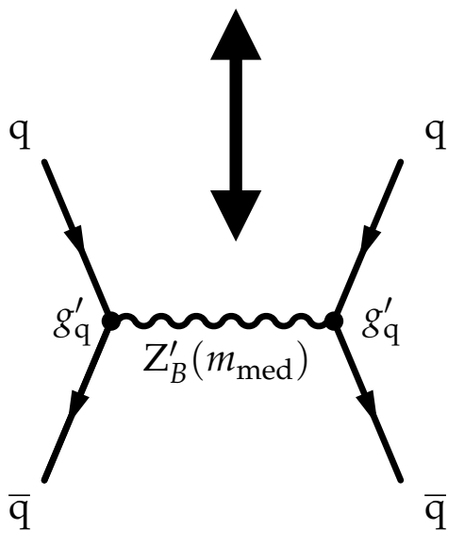
gap in mass coverage?

SENSITIVITY TO DARK MATTER

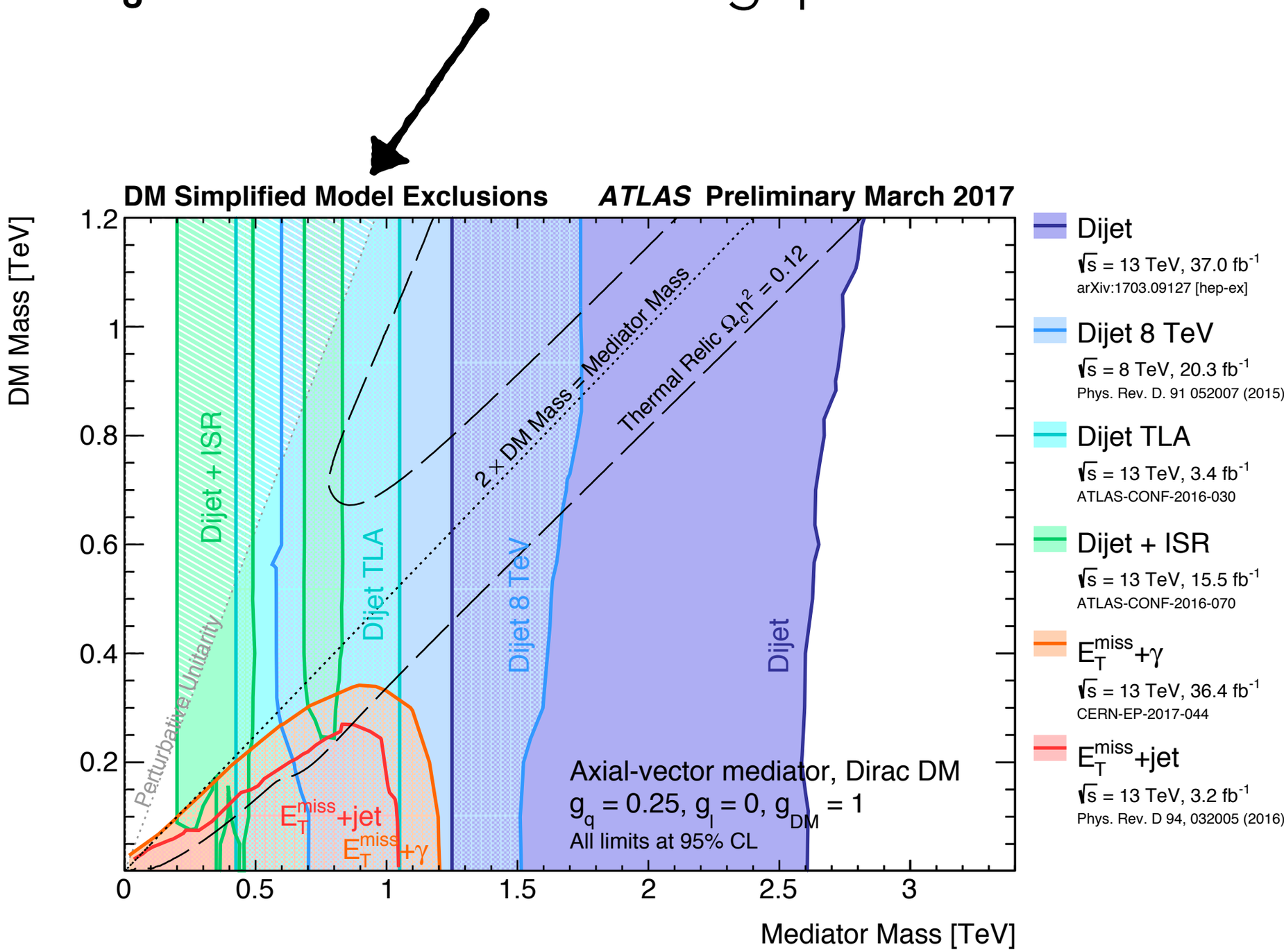
- ATLAS dijet + ISR γ searches closes this gap



MET+X

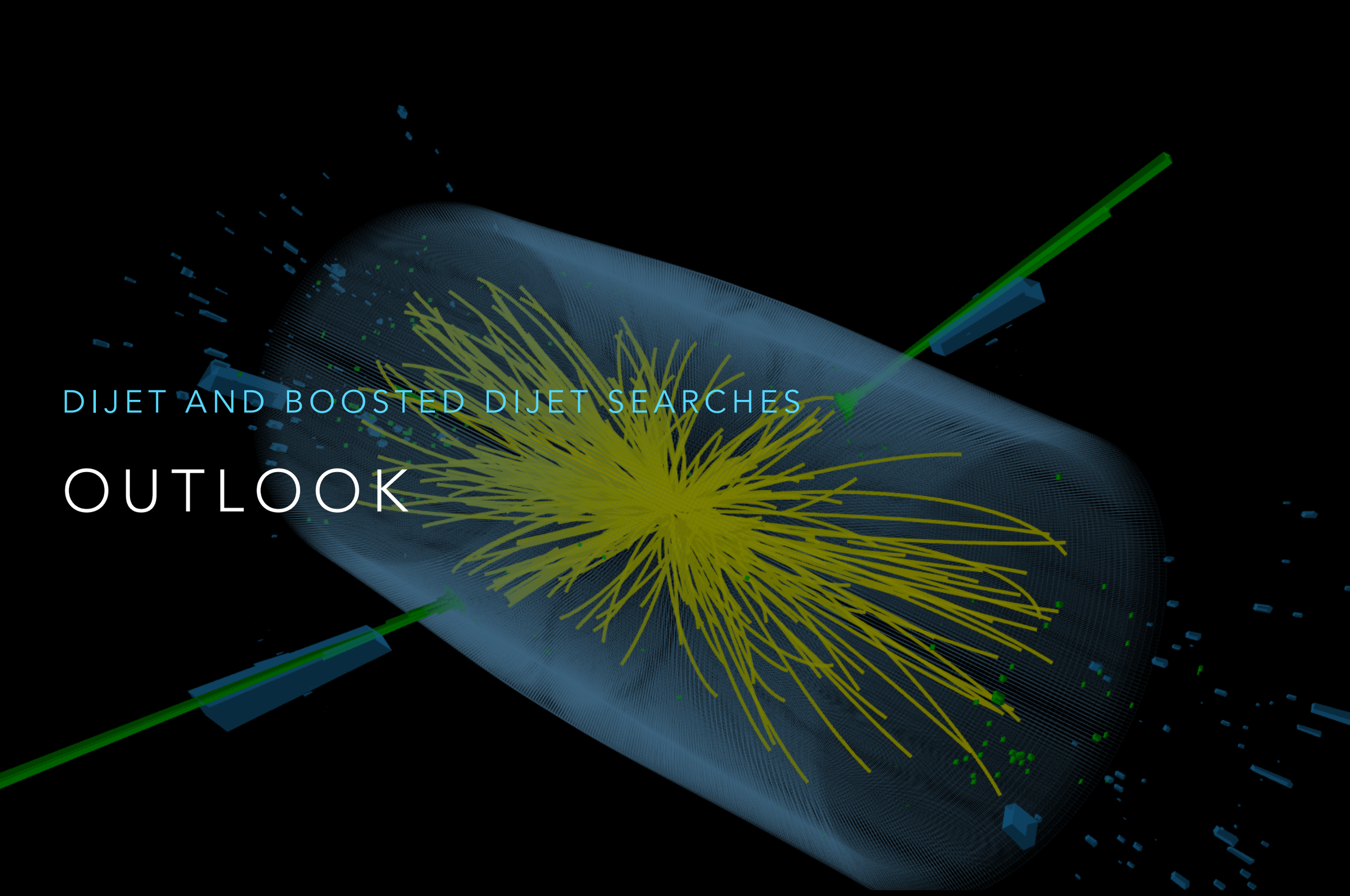


DIJET



DIJET AND BOOSTED DIJET SEARCHES

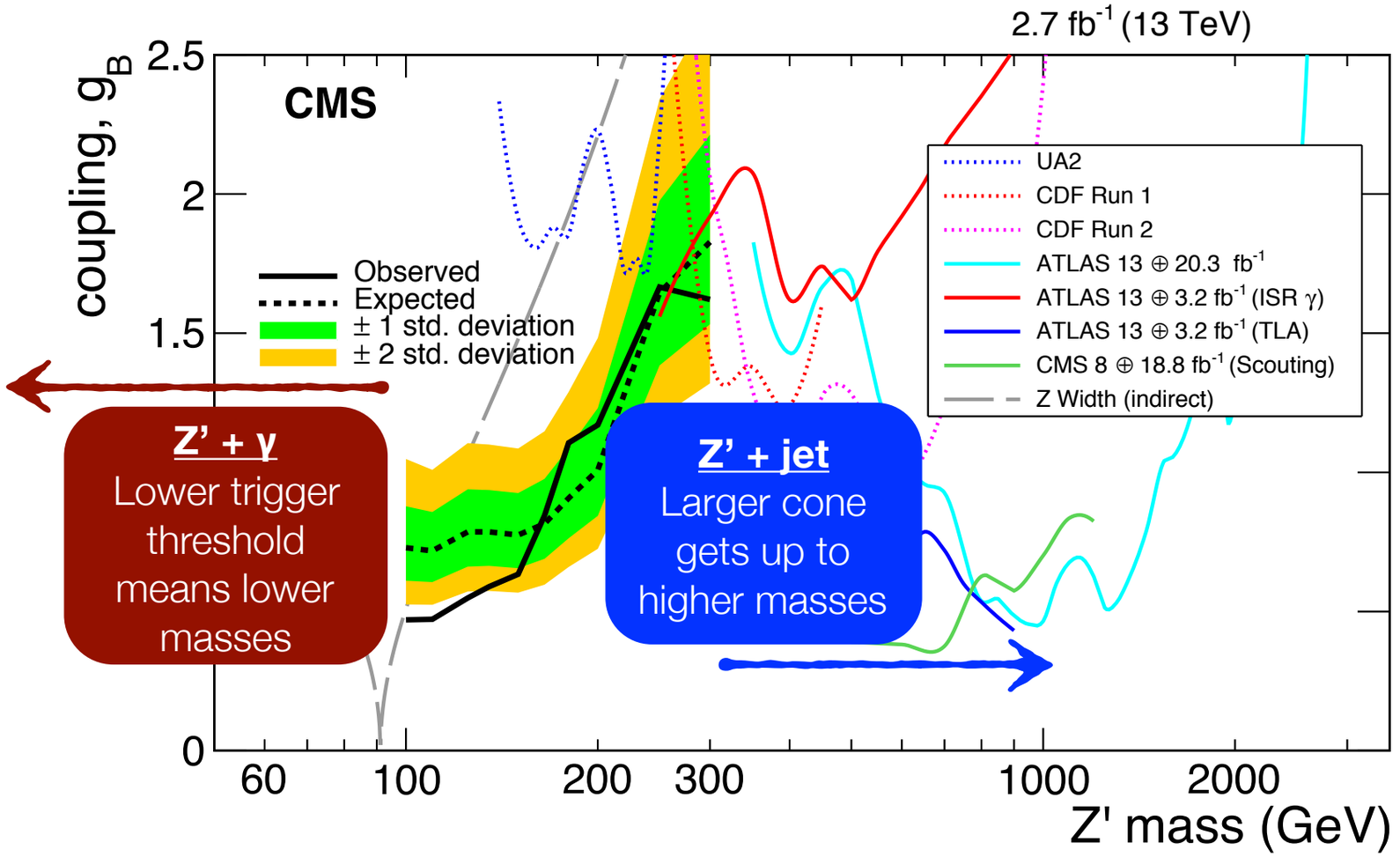
OUTLOOK



Javier Duarte
Fermilab

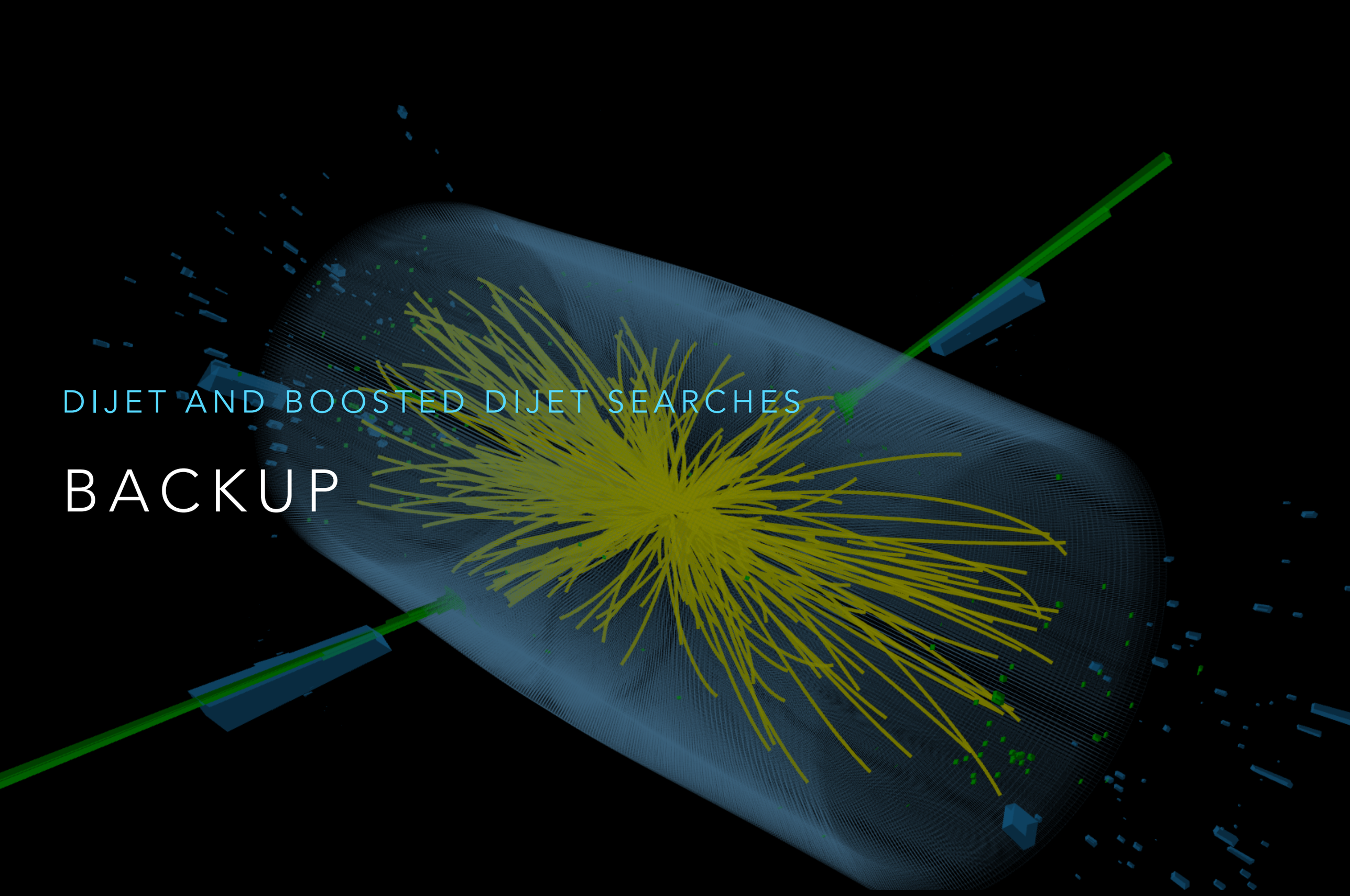
OUTLOOK FOR 2016 AND 2017

- Run 2 dijet searches at the LHC are probing lower in resonance mass and coupling
- More 2016 searches with full dataset (36 fb^{-1}) are already underway
  - Z'(qq) + ISR jet
  - Z'(qq) + ISR photon
  - dijet wide resonances
- New triggers for 2017
  - Scouting: dijet invariant mass trigger at L1 and HLT
  - Substructure: soft drop mass trigger at HLT



DIJET AND BOOSTED DIJET SEARCHES

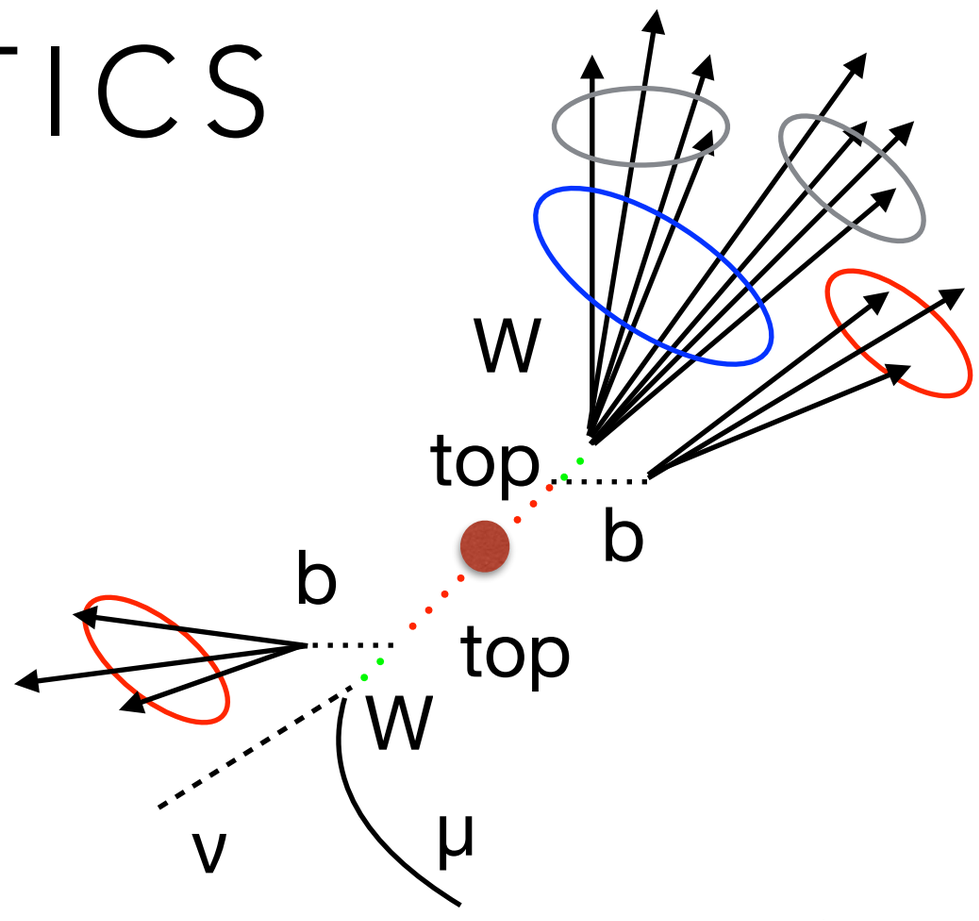
BACKUP

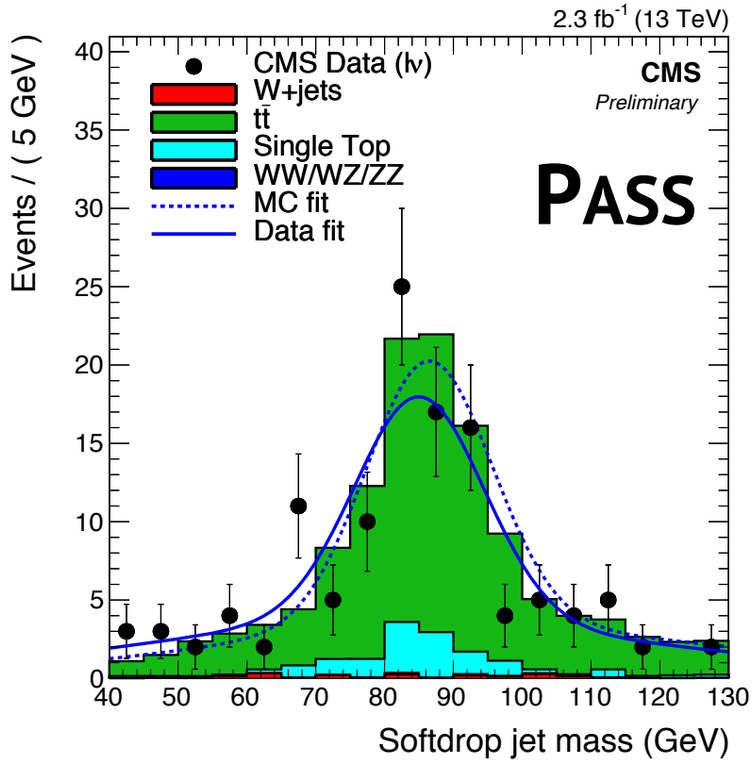


Javier Duarte
Fermilab

SYSTEMATICS

- Signal systematic uncertainties from merged W sample in semi-leptonic ttbar events (external constraint)
- SM candles: presence of W/Z in final jet mass distribution provides additional in-situ constraint, i.e. W/Z/Z’ nuisances are tied together





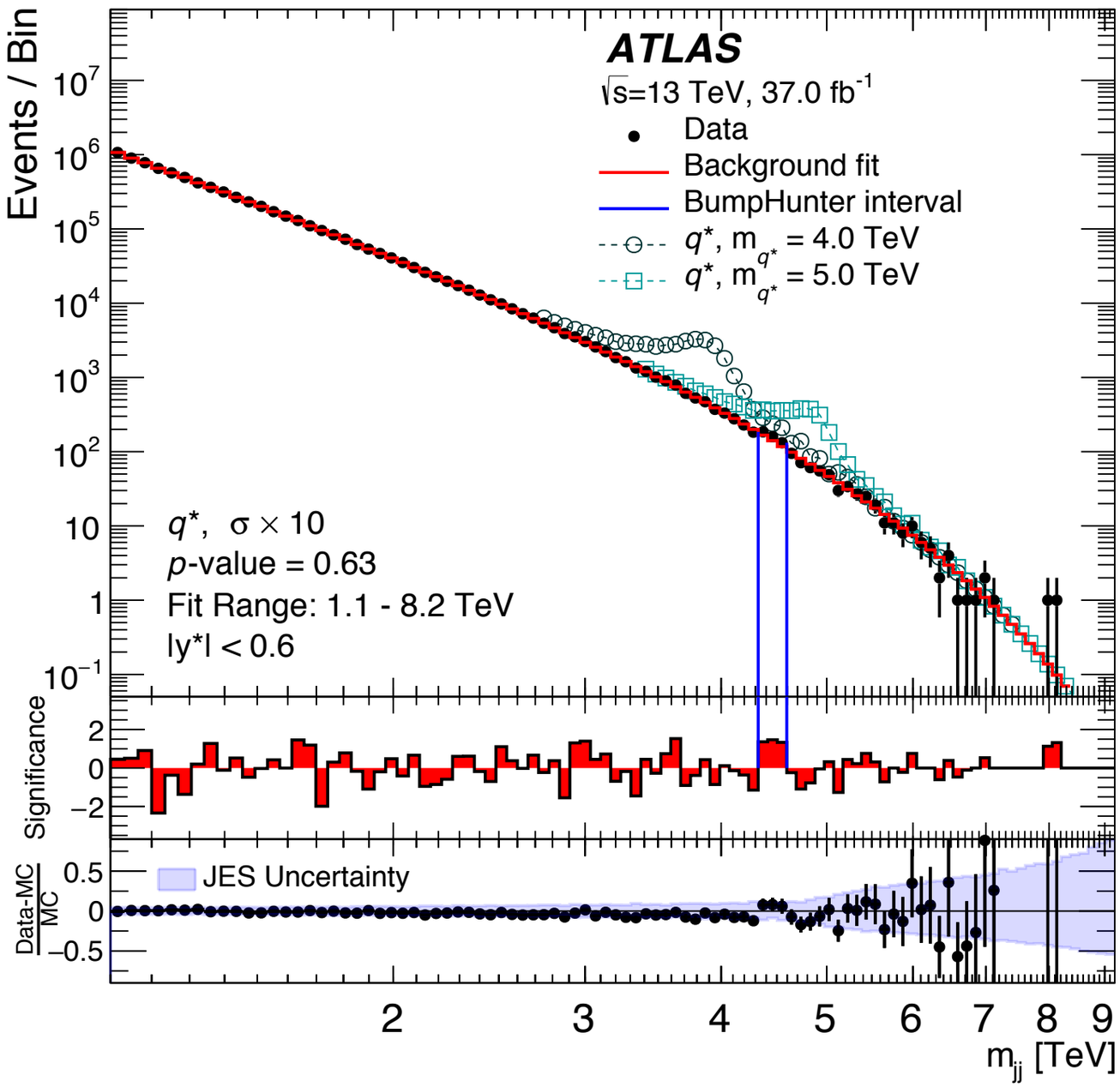
ATLAS HIGH MASS FIT

- ATLAS uses sliding-window fit rather than global fit
  - sliding window: approx. half the total bins
  - 3-parameter function

$$f(z) = p_1(1-z)^{p_2} z^{p_3} \qquad z = m_{jj}/\sqrt{s}$$

- p-value = 0.63
- No evidence for high-mass dijet resonances

arXiv:1703.09127



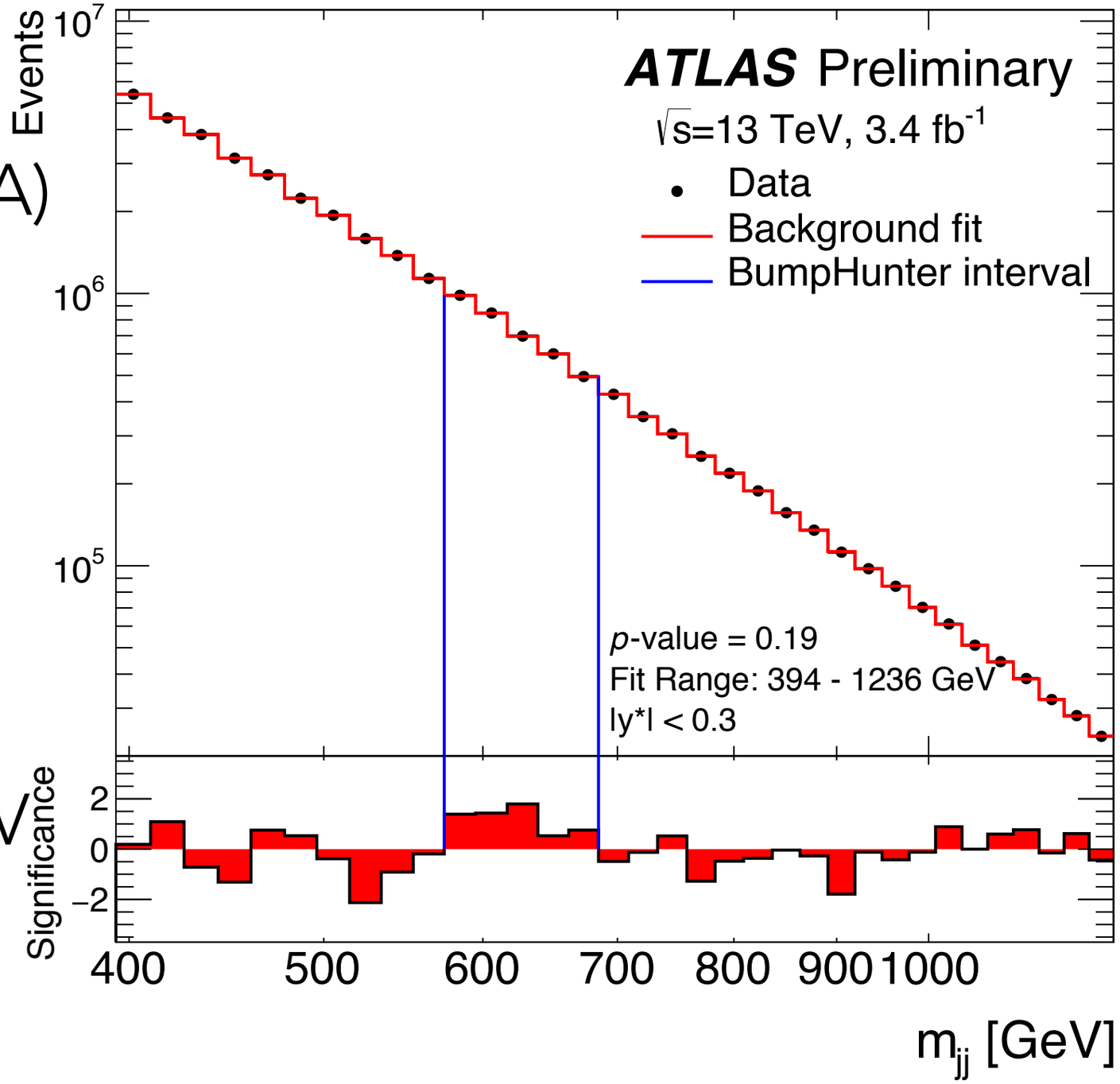
ATLAS TRIGGER-LEVEL ANALYSIS

ATLAS-CONF-2016-030

- ATLAS performs similar trigger-level analysis (TLA) using tighter centrality requirement and global function:

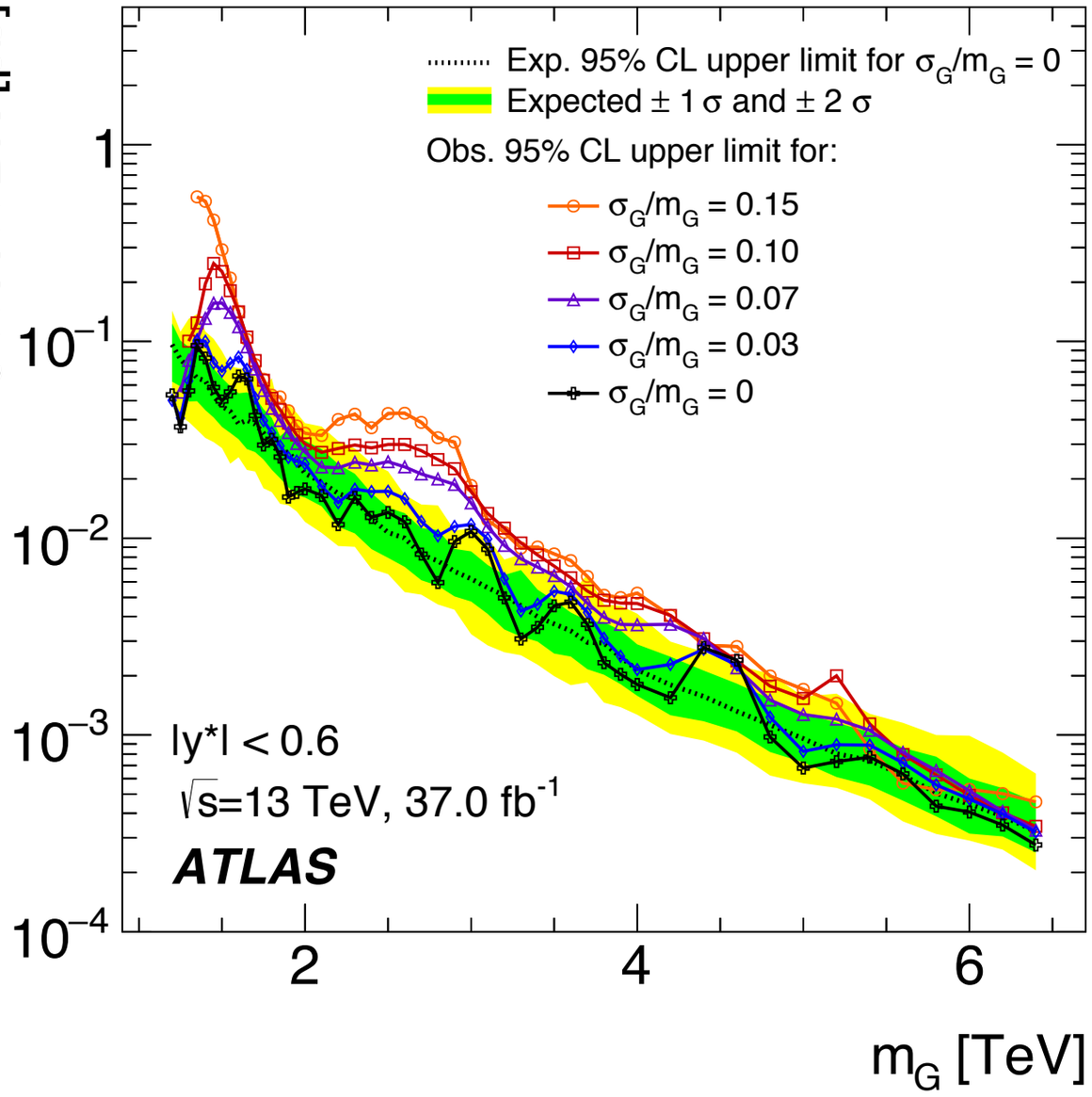
$$f(z) = \frac{p_1}{z^{p_2}} e^{-p_3 z - p_4 z^2}, \qquad z = m_{jj}/\sqrt{s}$$

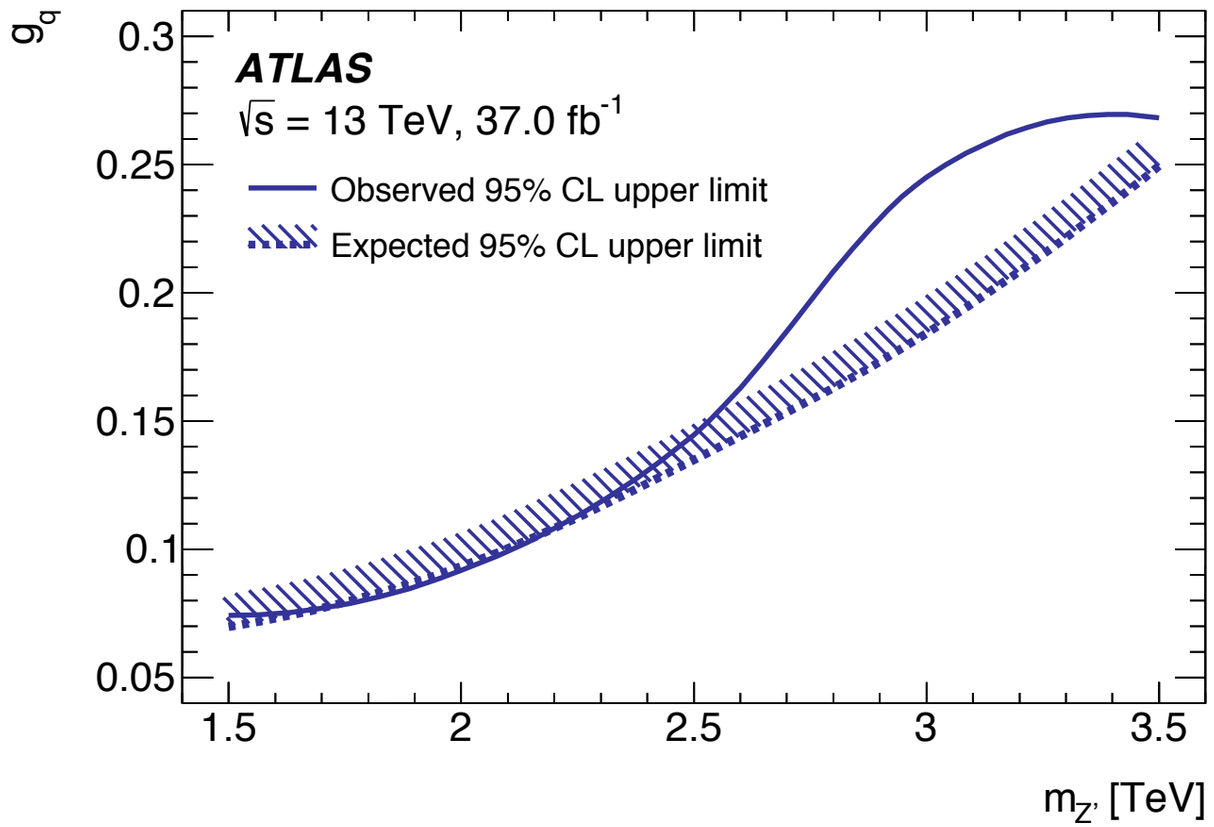
- Fit starts at $m_{jj} > 394$ GeV
- Future analysis will use sliding-window fit



LIMITS ON NARROW RESONANCES

- ATLAS reach at high mass





$$g_q = g_B/6$$

DARK MATTER MEDIATOR

- $\mathbf{m_{DM}}$ and $\mathbf{g_{DM}}$ affect mediator decay branching ratios
  - Smaller $\mathbf{m_{DM}} < m_M/2$ and larger $\mathbf{g_{DM}} > 0$ gives
    - larger BR(Z′ → χχ)
    - smaller BR(Z′ → qq)

$$\Gamma_V^{\chi\bar{\chi}} = \frac{g_{DM}^2 m_{med}}{12\pi}\left(1-4\frac{m_{DM}^2}{m_{med}^2}\right)^{1/2}\left(1+2\frac{m_{DM}^2}{m_{med}^2}\right)$$

$$\Gamma_V^{q\bar{q}} = \frac{(g'_q)^2 m_{med}}{4\pi}\left(1-4\frac{m_q^2}{m_{med}^2}\right)^{1/2}\left(1+2\frac{m_q^2}{m_{med}^2}\right)$$

- Same dijet cross section upper limit at $\mathbf{g_{DM}} = 0$ translates into weaker coupling limit at $\mathbf{g_{DM}} > 0$ (smaller branching to dijets)

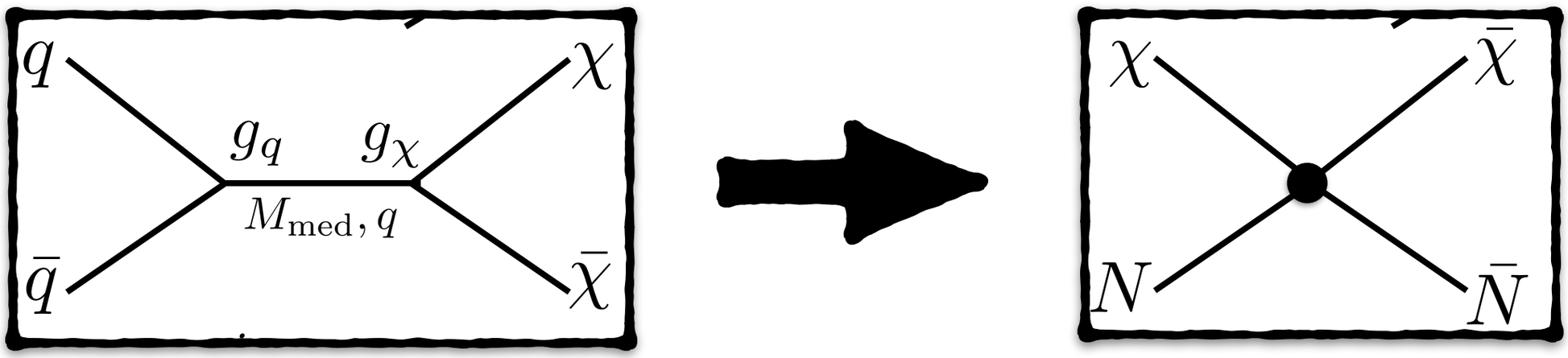
$$\Rightarrow \quad \sigma[Z'_B \to q\bar{q}|g'_B, g_{DM}] = \sigma(Z'_B \to q\bar{q}|g_B, g_{DM}=0)$$

$$\Rightarrow \quad \frac{(g'_B)^4}{\Gamma^{q\bar{q}}(g'_B)+\Gamma^{\chi\bar{\chi}}} = \frac{g_B^4}{\Gamma^{q\bar{q}}(g_B)}$$

$$\Rightarrow \quad (g'_B)^2 = \frac{g_B^2}{2}\left(1+\sqrt{1+4\frac{\Gamma^{\chi\bar{\chi}}}{\Gamma^{q\bar{q}}(g_B)}}\right)$$

SENSITIVITY TO DARK MATTER

- We can convert these limits in the (m_M, m_{DM}) plane into limits in the (m_{DM}, σ_{SD}) plane to compare with ID/DD DM experiments



For axial-vector mediator with universal quark coupling g_q', mediator-nucleon coupling is

$$f^{\mathrm{p}} = f^{\mathrm{n}} = 0.32 g'_{\mathrm{q}}.$$

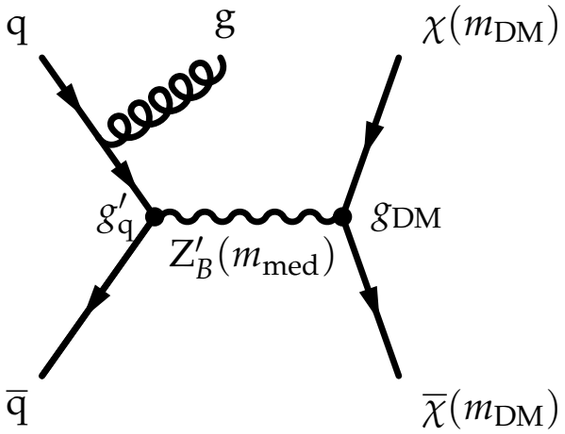
$$\sigma^{\mathrm{SD}}_{\mathrm{DM\text{-}p}} = \frac{3 f^2 (g'_{\mathrm{q}}) g^2_{\mathrm{DM}} \mu^2_{\mathrm{N}\chi}}{\pi m^4_{\mathrm{med}}}$$

$$\simeq 2.4 \times 10^{-42}\,\mathrm{cm}^2 \cdot \left(\frac{g'_{\mathrm{q}} g_{\mathrm{DM}}}{0.25}\right)^2 \left(\frac{1\,\mathrm{TeV}}{m_{\mathrm{med}}}\right)^4 \left(\frac{\mu_{\mathrm{N}\chi}}{1\,\mathrm{GeV}}\right)^2$$

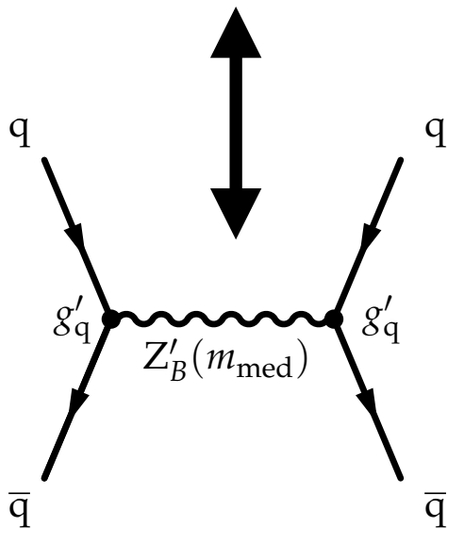
arXiv:1603.04156

SENSITIVITY TO DARK MATTER

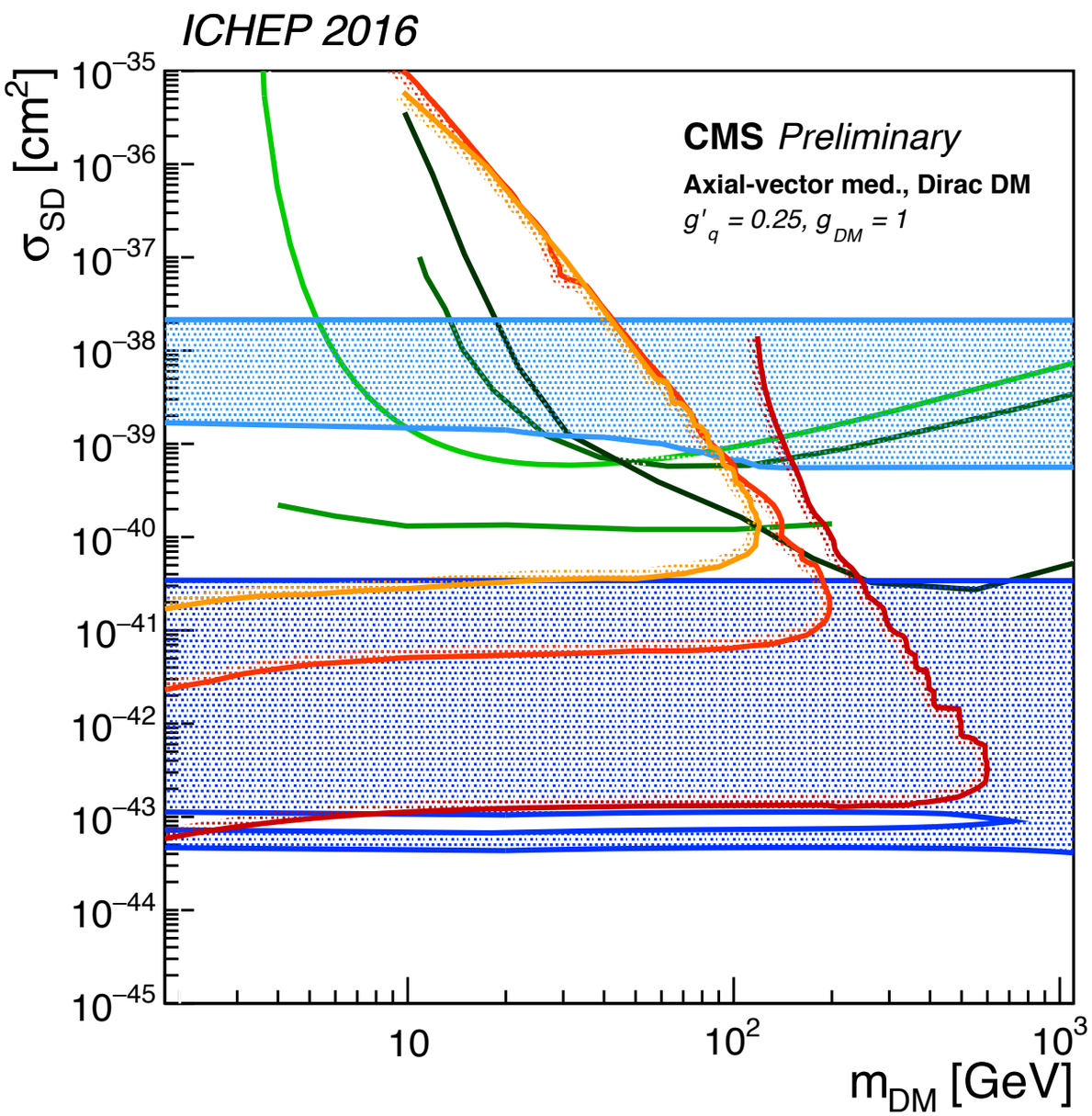
- ***Competitive*** with direct detection experiments (depending on the details of the model: couplings, mediator type, etc.)



MET+X



DIJET



CMS observed exclusion 90% CL

- Dijet *[EXO-16-032]* + *[arXiv:1604.08907]*
- Boosted dijet *[EXO-16-030]*
- CMS DM+j/V(qq) *[EXO-16-037]*
- CMS DM+γ *[EXO-16-039]*
- CMS DM+Z(ll) *[EXO-16-038]*

DD/ID observed exclusion 90% CL

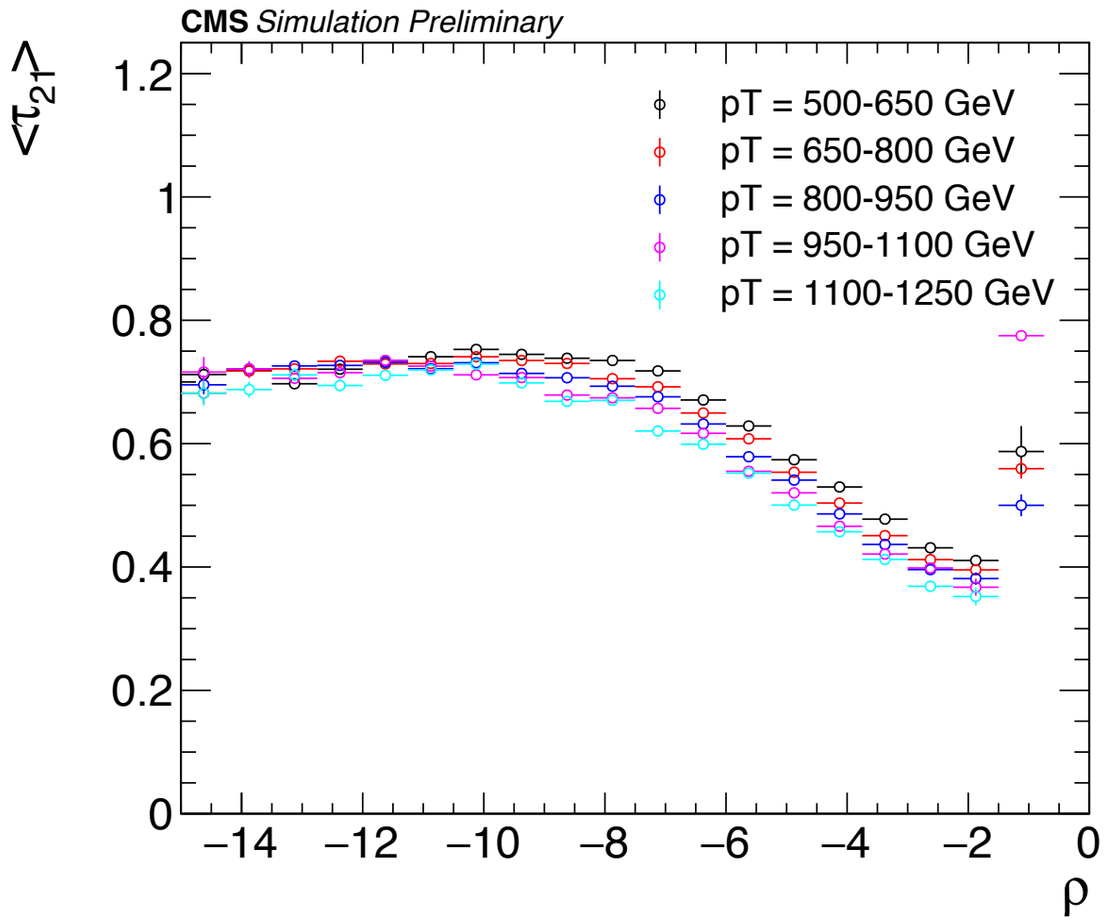
- Pico 2L *[arXiv:1601.03729]*
- Pico 60 *[arXiv:1510.07754]*
- Super-K $\tau^+\tau^-$ *[arXiv:1503.04858]*
- IceCube $\tau^+\tau^-$ *[arXiv:1601.00653]*

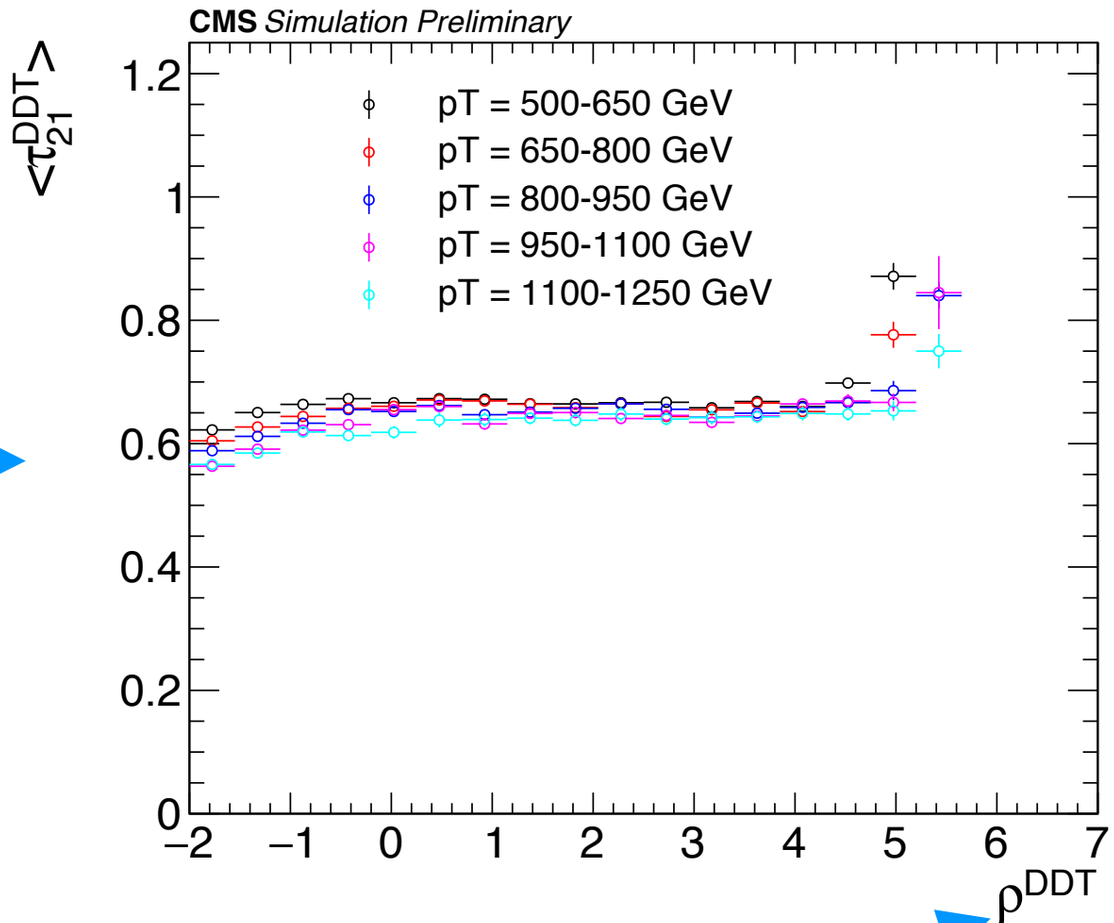
WHAT IS τ_{21}^{DDT}?

- Transformed substructure variable which has a flat profile with respect to jet mass and p_T in QCD MC

$$\rho = \log(m_{SD}^2/p_T^2) \quad \rightarrow \quad \rho DDT = \log(m_{SD}^2/p_T/(1\ \text{GeV}))$$

$$\tau_{21} \quad \rightarrow \quad \tau_{21}DDT = \tau_{21} + 0.063 \times \rho DDT$$

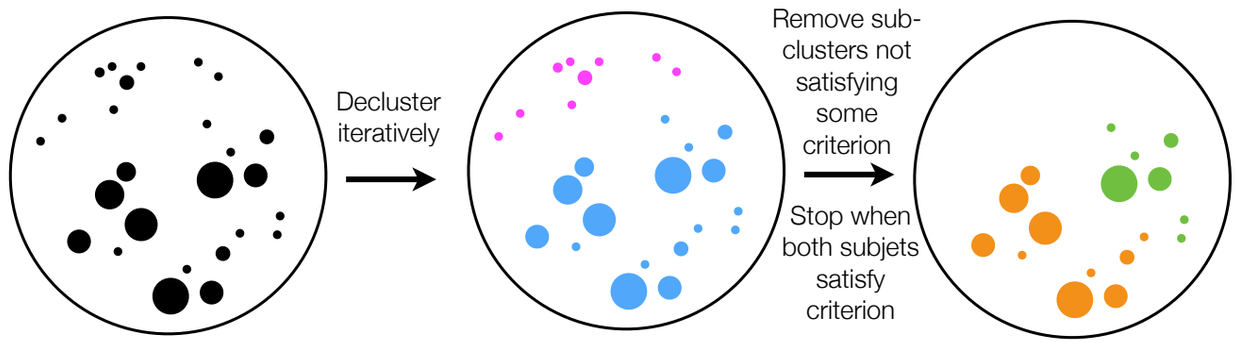




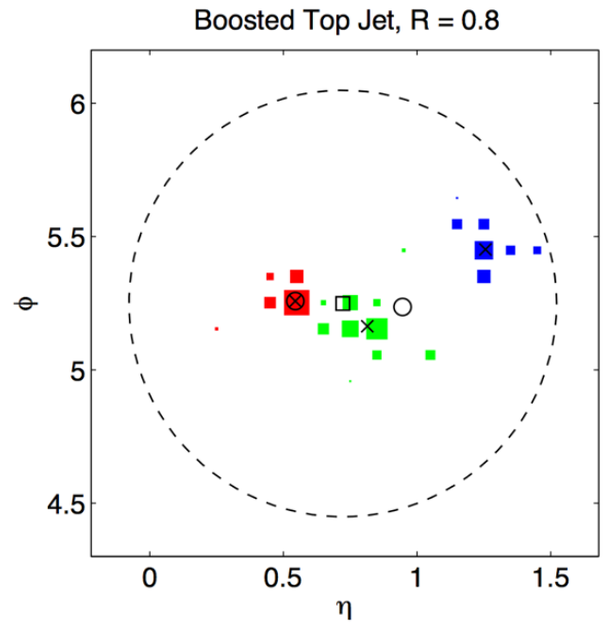
related to jet mass

ANALYSIS SELECTION

- Kinematic Selections:
  - PUPPI AK8 jet p_T > 500 GeV, $|\eta|$ < 2.5 (veto e,μ > 10 GeV)
- Trigger:
  - AK8PFHT650,TrimMass50 OR AK8PFJet360,TrimMass30 OR PFHT800
- Substructure Selections:
  - Soft drop jet mass > 25 GeV ($z = 0.1$, $\beta = 0$)
  - $\tau_{21}^{DDT} < 0.38$
- Backgrounds:
  - QCD
  - SM Candles: W/Z + jets



Soft Drop Condition: $\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$



$\tau_N \to 0 \Longrightarrow$ energy spread is close to the subjet axes

$$\tau_N = \frac{\sum_{i=1}^{n_{\text{constituents}}} p_{\text{T},i} \min\{\Delta R_{1,i}, \Delta R_{2,i}, ..., \Delta R_{N,i}\}}{\sum_{i=1}^{n_{\text{constituents}}} p_{\text{T},i} R}$$

SENSITIVITY TO DARK MATTER

For nucleons, $C_{n,p}$ are related to axial-vector current matrix elements by generalized Goldberger-Treiman relations,

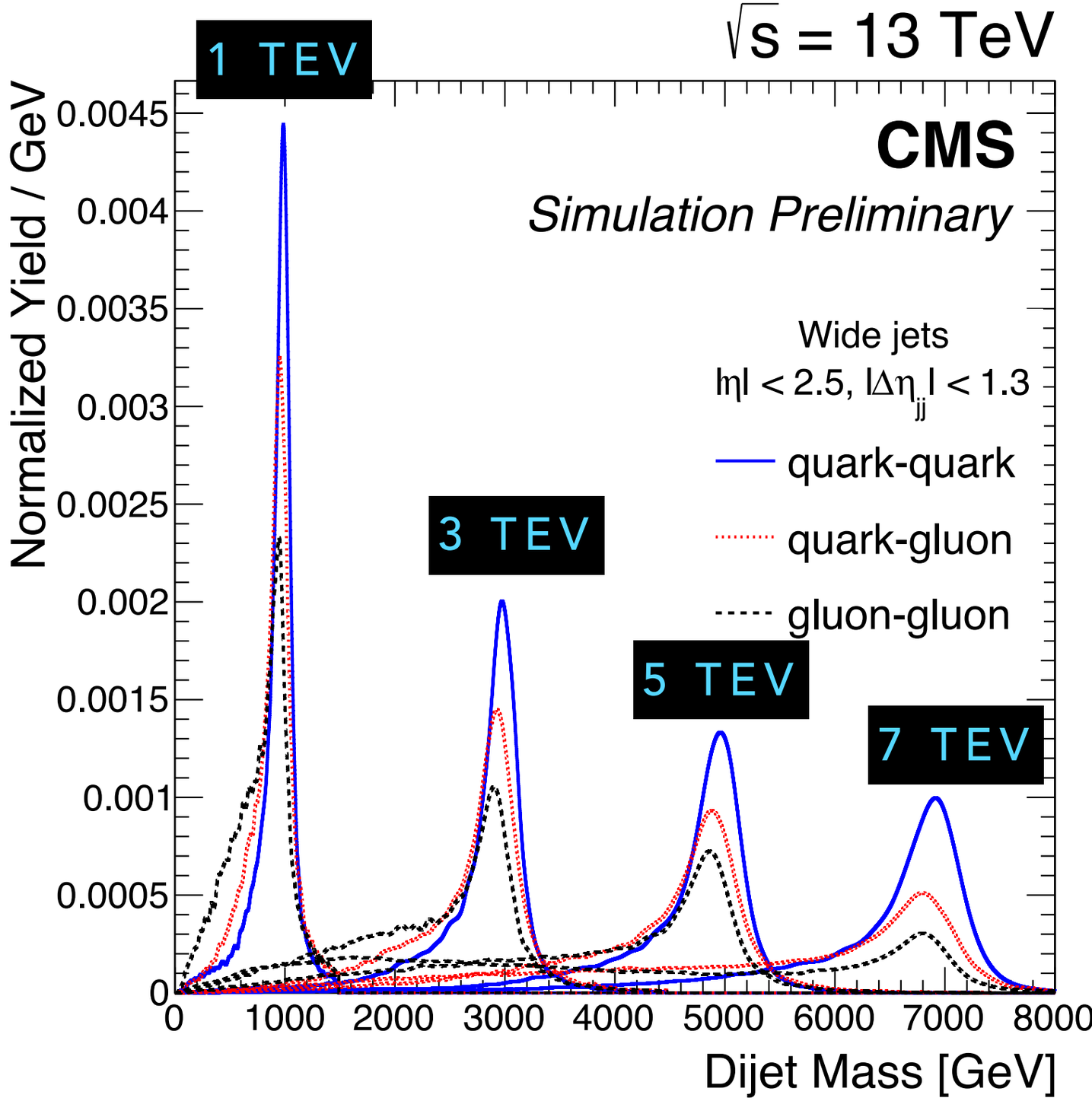
$$\begin{aligned} C_p &= (C_u - \eta)\Delta u + (C_d - \eta z)\Delta d + (C_s - \eta w)\Delta s\,, \\ C_n &= (C_u - \eta)\Delta d + (C_d - \eta z)\Delta u + (C_s - \eta w)\Delta s\,. \end{aligned} \tag{9}$$

Here, $\eta = (1+z+w)^{-1}$ with $z = m_u/m_d$ and $w = m_u/m_s \ll z$ and the Δq are given by the axial vector current matrix element $\Delta q\, S_\mu = \langle p|\bar{q}\gamma_\mu\gamma_5 q|p\rangle$ with S_μ the proton spin.

Neutron beta decay and strong isospin symmetry considerations imply $\Delta u - \Delta d = F + D = 1.269 \pm 0.003$, whereas hyperon decays and flavor SU(3) symmetry imply $\Delta u + \Delta d - 2\Delta s = 3F - D = 0.586 \pm 0.031$ [25]. The strange-quark contribution is $\Delta s = -0.08 \pm 0.01_{\text{stat}} \pm 0.05_{\text{syst}}$ from the COMPASS experiment [26], and $\Delta s = -0.085 \pm 0.008_{\text{exp}} \pm 0.013_{\text{theor}} \pm 0.009_{\text{evol}}$ from HERMES [25], in agreement with each other and with an early estimate of $\Delta s = -0.11 \pm 0.03$ [27]. We thus adopt $\Delta u = 0.84 \pm 0.02$, $\Delta d = -0.43 \pm 0.02$ and $\Delta s = -0.09 \pm 0.02$, very similar to what was used in the axion literature.

MANY SIGNAL MODELS

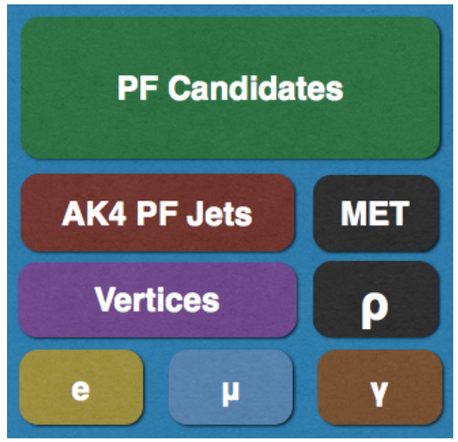
- quark-quark
  - axigluons: axial-vector particles predicted in a model where the QCD symmetry group $SU(3)_C$ is replaced by the chiral symmetry $SU(3)_L \times SU(3)_R$
  - colorons: vector particles predicted by the flavor-universal coloron model, in which the $SU(3)_C$ is embedded in a larger gauge group
  - W′, Z′, …
  - **dark matter mediators**
- quark-gluon
  - excited quarks: predicted in quark compositeness models
  - string resonances, ...
- gluon-gluon
  - RS graviton: predicted in the RS model of extra dimensions, with 5-dimensional anti de Sitter space and reduced Planck mass
  - S8 (color octet scalar) resonances, …



A: DATA SCOUTING

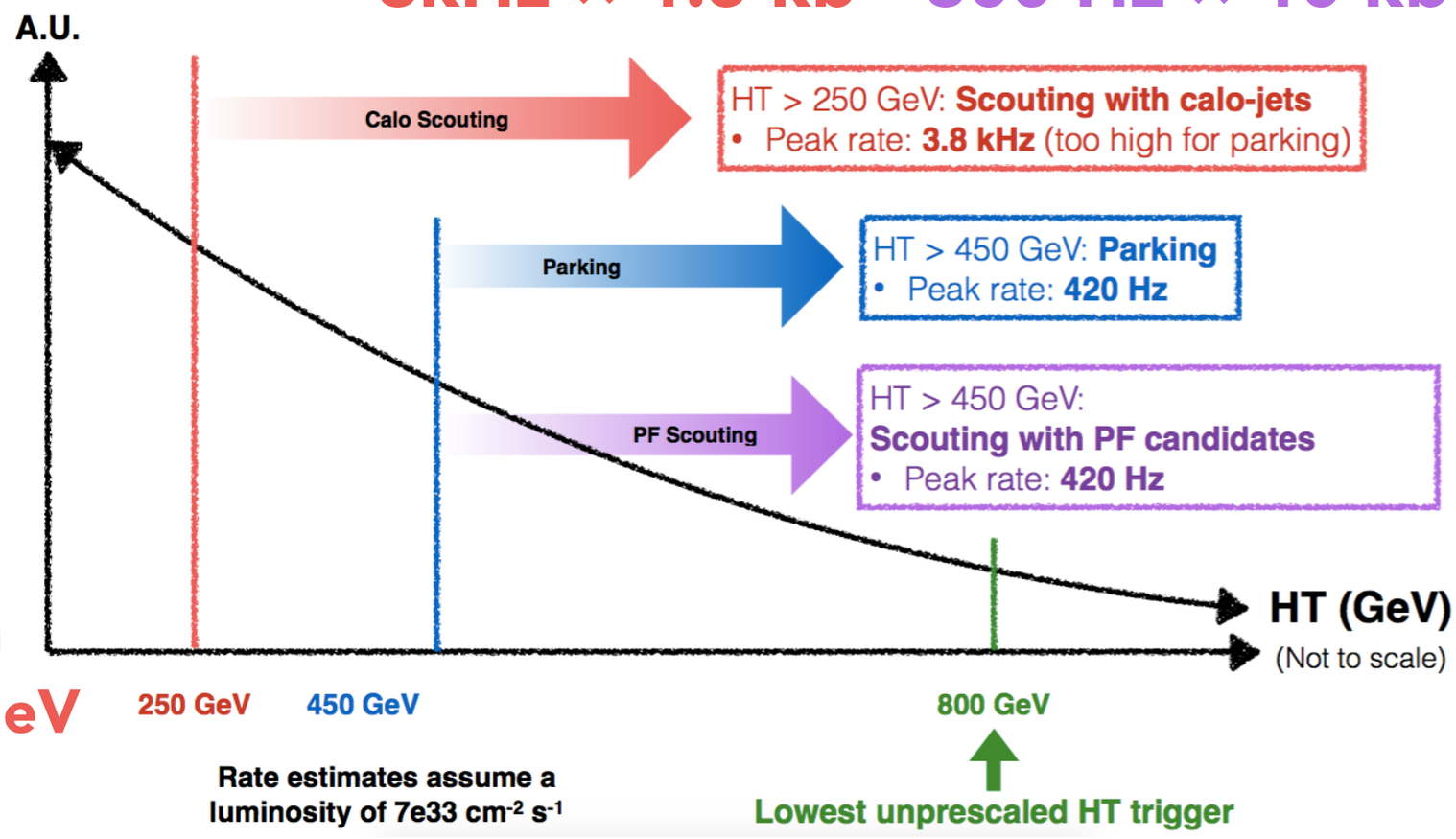
[D. Anderson "Data Scouting at CMS" 2015 IEEE NSS/MIC]

- 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**
  - **New in 2015:** "**Calo Scouting**" allows us to get down to **H_T > 250 GeV**
  - **New in 2016:** Saving tracking information around Calo jets to allow us to perform b-tagding down to **H_T > 250 GeV**



Calo Scouting
3kHz × 1.5 kb

PF Scouting
300 Hz × 10 kb

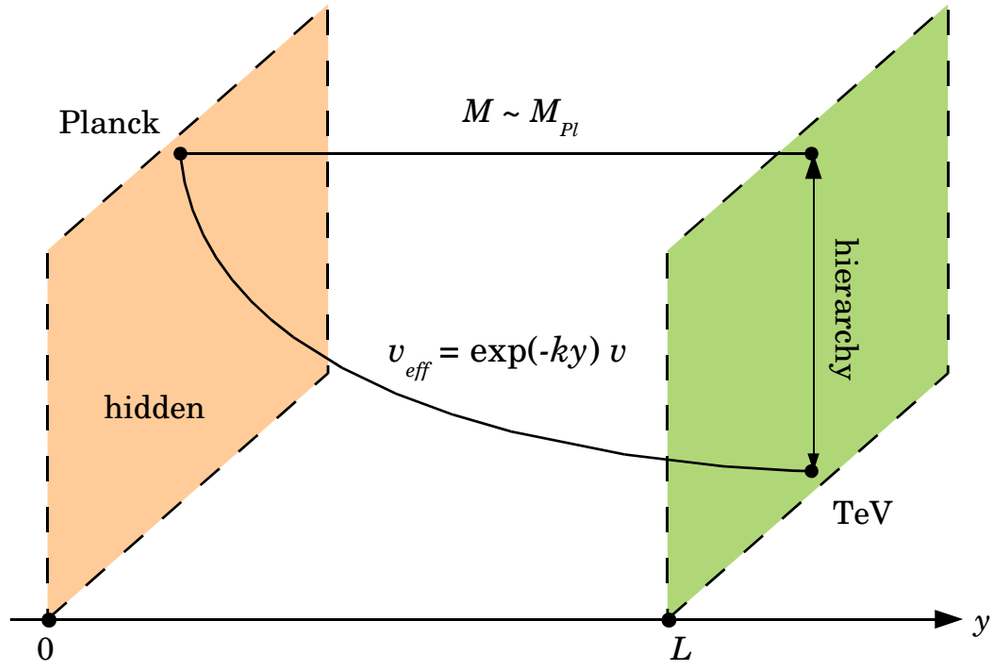


SIGNAL MODELS

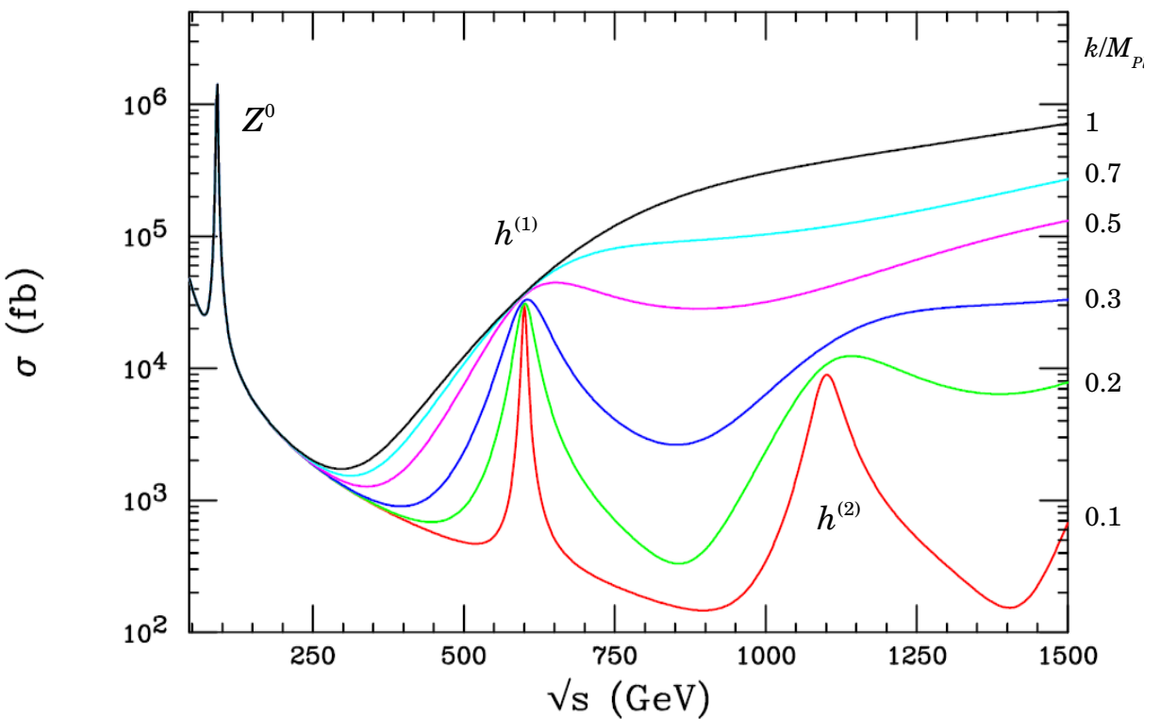
- String resonances (S), which are Regge excitations of quarks and gluons in string theory and decay predominantly to qg [1, 2].
- Scalar diquarks (D), which decay to qq and $\overline{\mathrm{q}}\overline{\mathrm{q}}$, predicted by a grand unified theory based on the E_6 gauge symmetry group [3].
- Mass-degenerate excited quarks (q^*), which decay to qg, predicted in quark compositeness models [4, 5]; the compositeness scale is set to be equal to the mass of the excited quark.
- Axial-vector particles called axigluons (A), which decay to $\mathrm{q}\overline{\mathrm{q}}$, predicted in a model where the symmetry group SU(3) of QCD is replaced by the chiral symmetry $\mathrm{SU(3)_L} \times \mathrm{SU(3)_R}$ [6].
- Color-octet colorons (C), which also decay to $\mathrm{q}\overline{\mathrm{q}}$; these are vector particles predicted by the flavour-universal coloron model, in which the SU(3) gauge symmetry of QCD is embedded in a larger gauge group [7].
- Scalar color-octet resonances (S8) [8] that appear in many dynamical electroweak symmetry breaking models such as Technicolor. We consider the decay channel into a pair of gluons.
- Massive scalar color-octet resonances ($\mathrm{S8_b}$) [9] that result from the breaking of an SU(3) × SU(3) gauge symmetry down to the QCD gauge group and that may have generically large couplings to b quarks. We consider the production of a coloron that subsequently decays into an $\mathrm{S8_b}$ and a light scalar singlet. We fix the singlet mass to 150 GeV. The $\mathrm{S8_b}$ and scalar singlet have branching fractions (B) of approximately 100% to $\mathrm{b}\overline{\mathrm{b}}$ and gg, respectively. The tangent of the mixing angle θ between the two SU(3) gauges is set to 0.15. This resonance search is inclusive of extra jets, so the search strategy is insensitive to the decay of the low-mass singlet state.
- New gauge bosons (W' and Z'), that decay to $\mathrm{q}\overline{\mathrm{q}}$, predicted by models that include new gauge symmetries [10]; the W' and Z' bosons are assumed to have standard-model-like couplings. Consequently, the ratio between the branching fraction of the Z' to $\mathrm{b}\overline{\mathrm{b}}$ and the branching fraction to a pair of quarks (excluding the top quark) is approximately 0.22.
- Randall-Sundrum (RS) gravitons (G), which decay to $\mathrm{q}\overline{\mathrm{q}}$ and gg, predicted in the RS model of extra dimensions [11]. The value of the dimensionless coupling $k/\overline{M}_{\mathrm{Pl}}$ is chosen to be 0.1, where k is the curvature scale in the 5-dimensional anti de Sitter space and $\overline{M}_{\mathrm{Pl}}$ is the reduced Planck scale. The ratio between the branching fraction of the RS graviton to $\mathrm{b}\overline{\mathrm{b}}$ and the branching fraction to a pair of quarks (excluding the top quark) or gluons is approximately 0.1 [12].

RANDALL-SUNDRUM MODEL

- Gravity propagates in a warped extra dimension with two fixed points
- SM fields are constrained to one brane
- Gravity wave function is concentrated on the hidden brane, falling off exponentially across the extra dimension
- **Prediction**: new TeV-scale resonances of Randall-Sundrum gravitons

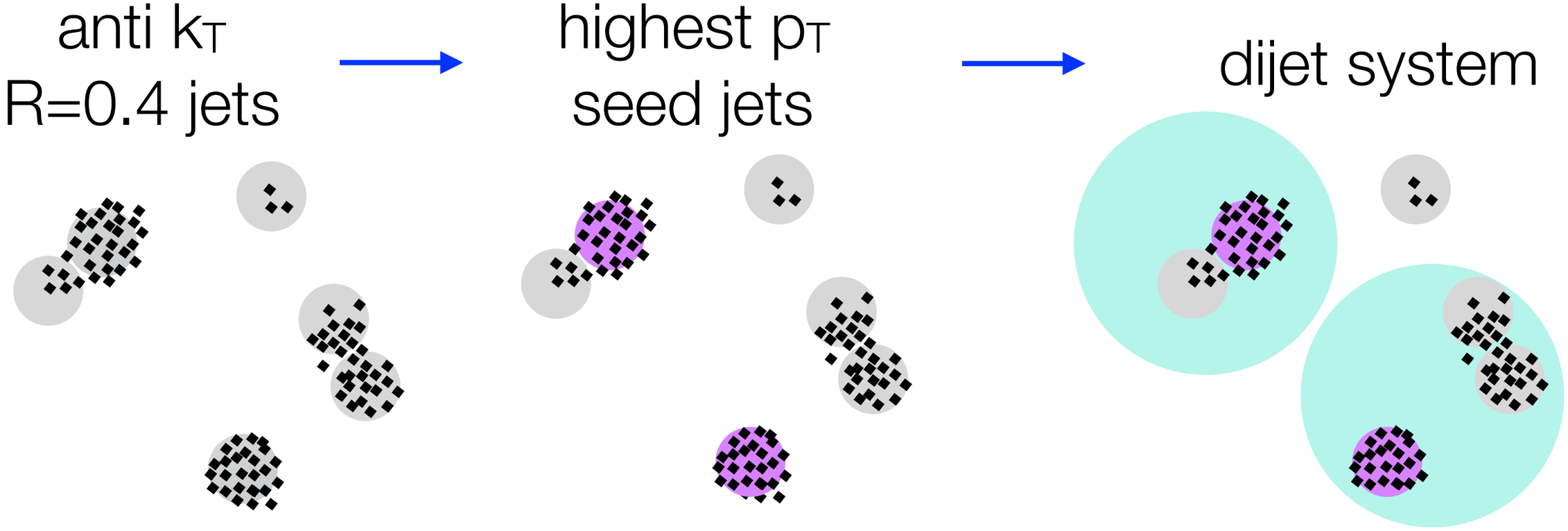


$$ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$$



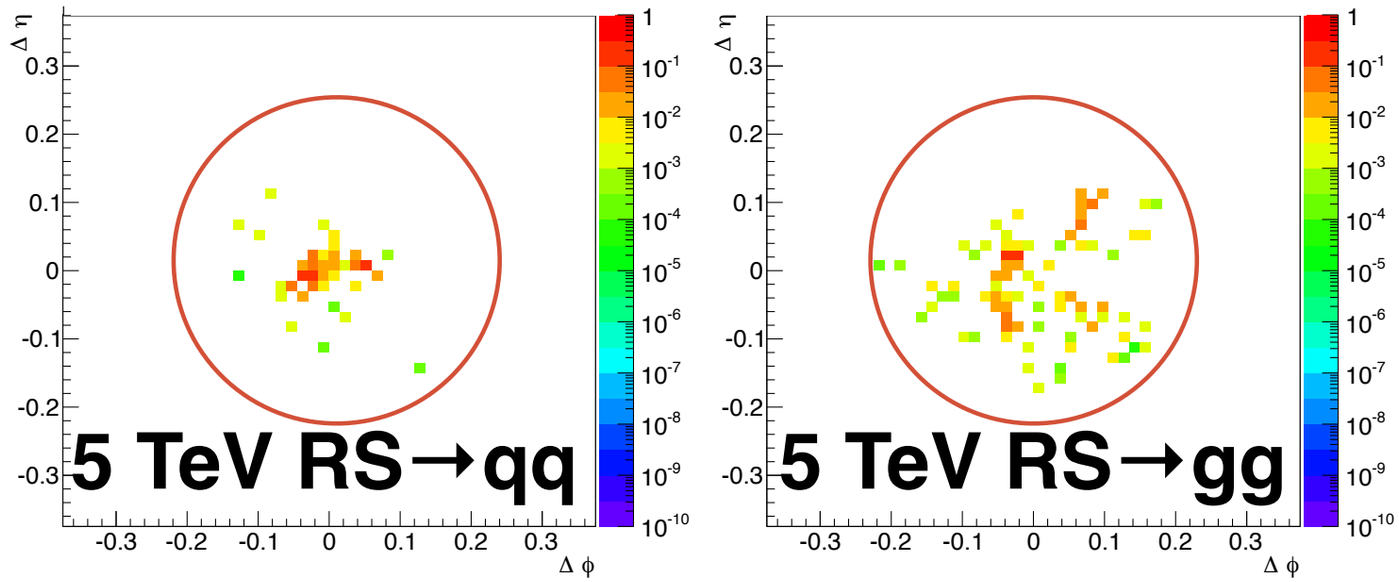
WIDE JETS

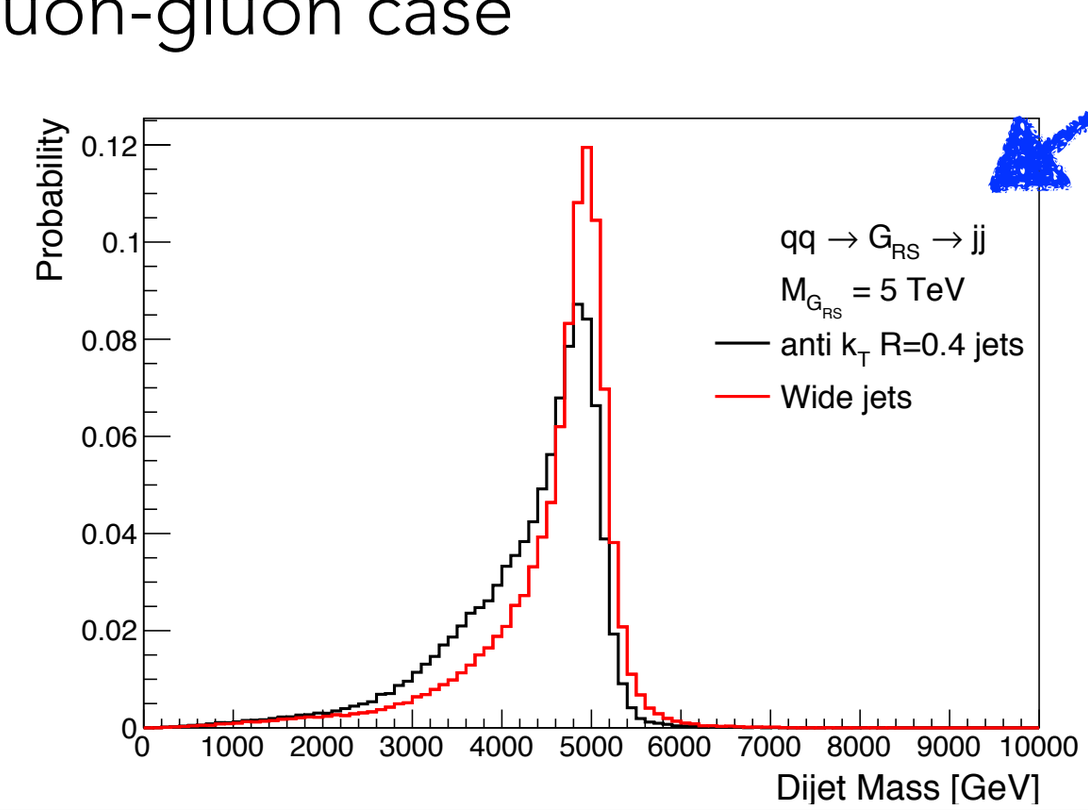
- Jets initially reconstructed with anti-k_T algorithm with R=0.4
- "Wide jet" algorithm uses two leading jets as seeds
  - Adds neighboring jets to nearest leading jet if within $\Delta R < 1.1$
  - Recover loss in mass response due to radiation

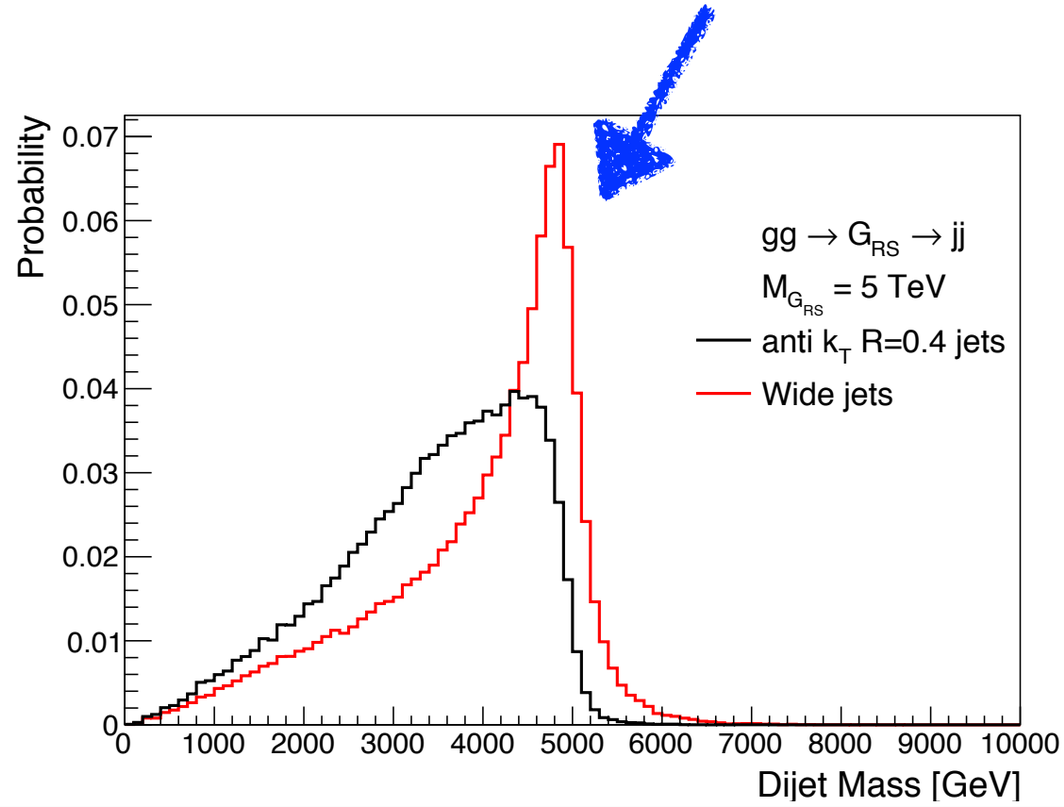


WIDE JETS

- Gluon-gluon resonances are wider than quark-quark resonances due to greater radiation (gluon color factor)
- Mass resolution improved with wide jets even in gluon-gluon case







DATA SCOUTING

Time to access data for analysis

Delayed data analysis

CMS
Data Parking

ATLAS
Delayed Stream

Standard data analysis

ATLAS/CMS/LHCb
Fully reconstructed data

Monitoring

ATLAS
TAg Data Analysis

ATLAS/CMS/LHCb
Express stream

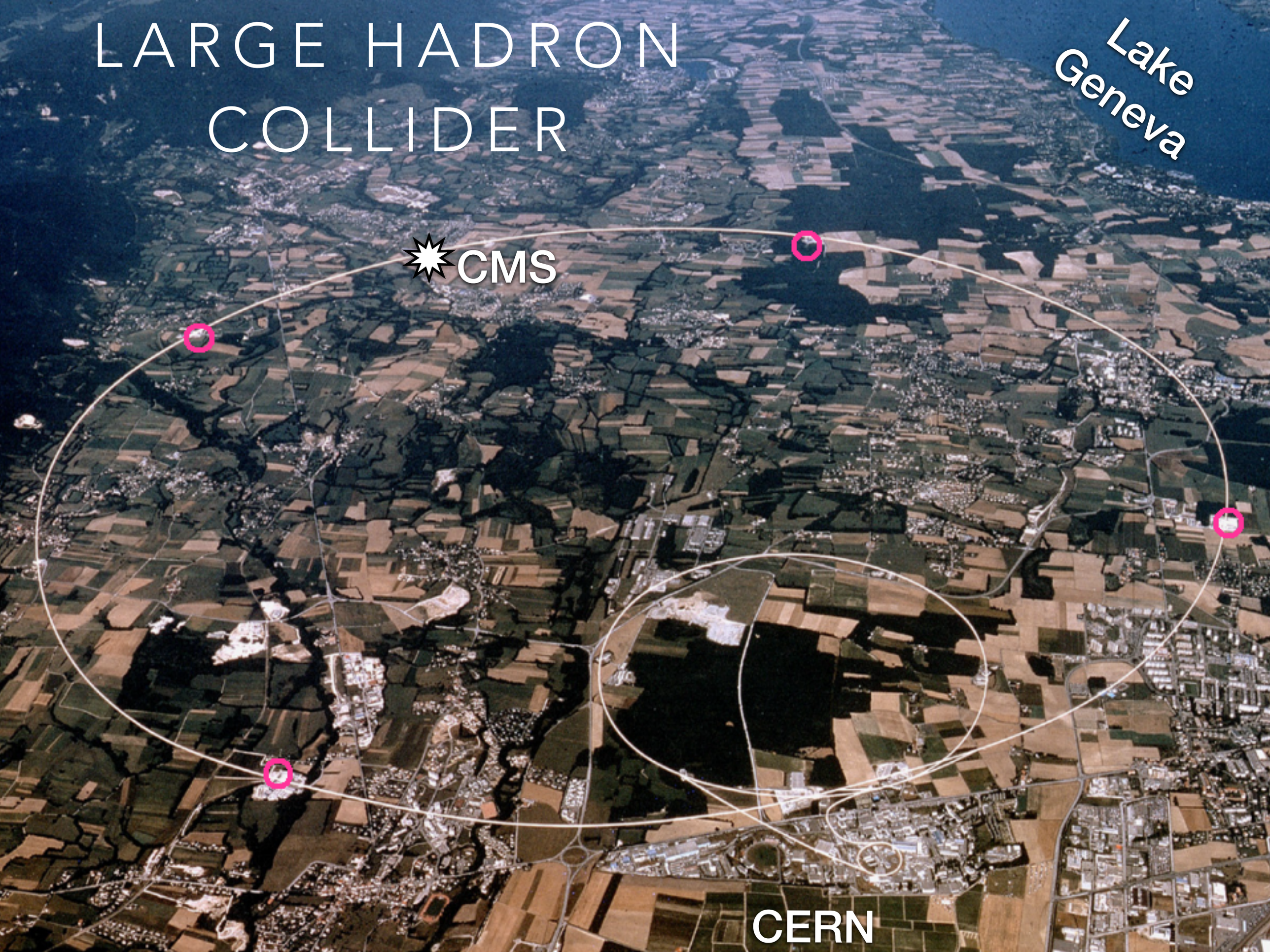
Real-time analysis

LHCb
Turbo Stream

ATLAS/CMS
Data Scouting

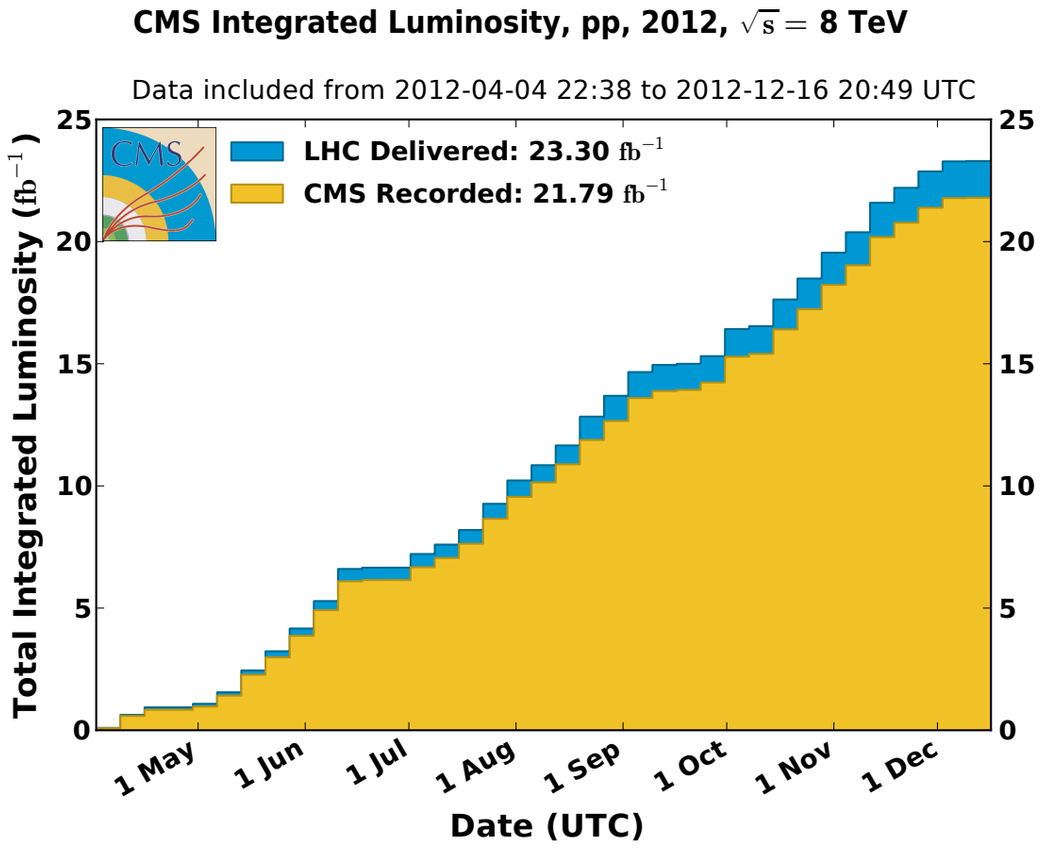
Data complexity

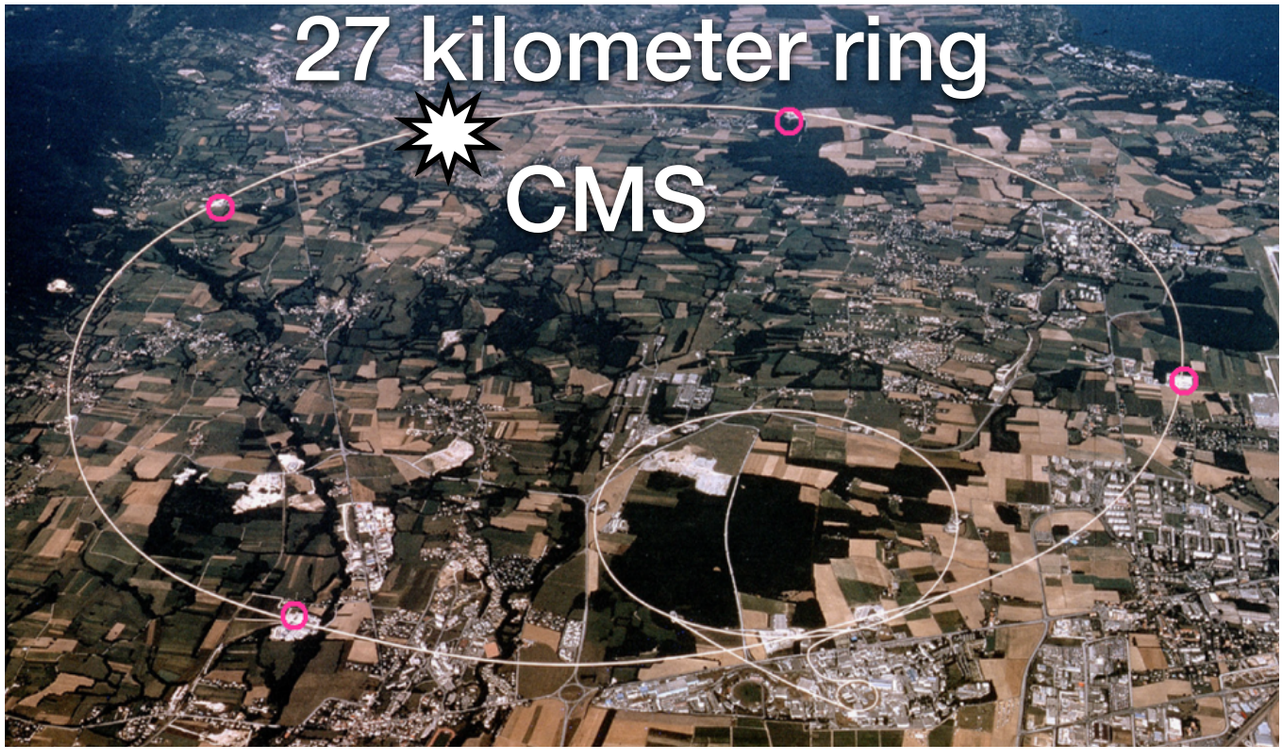
LARGE HADRON COLLIDER

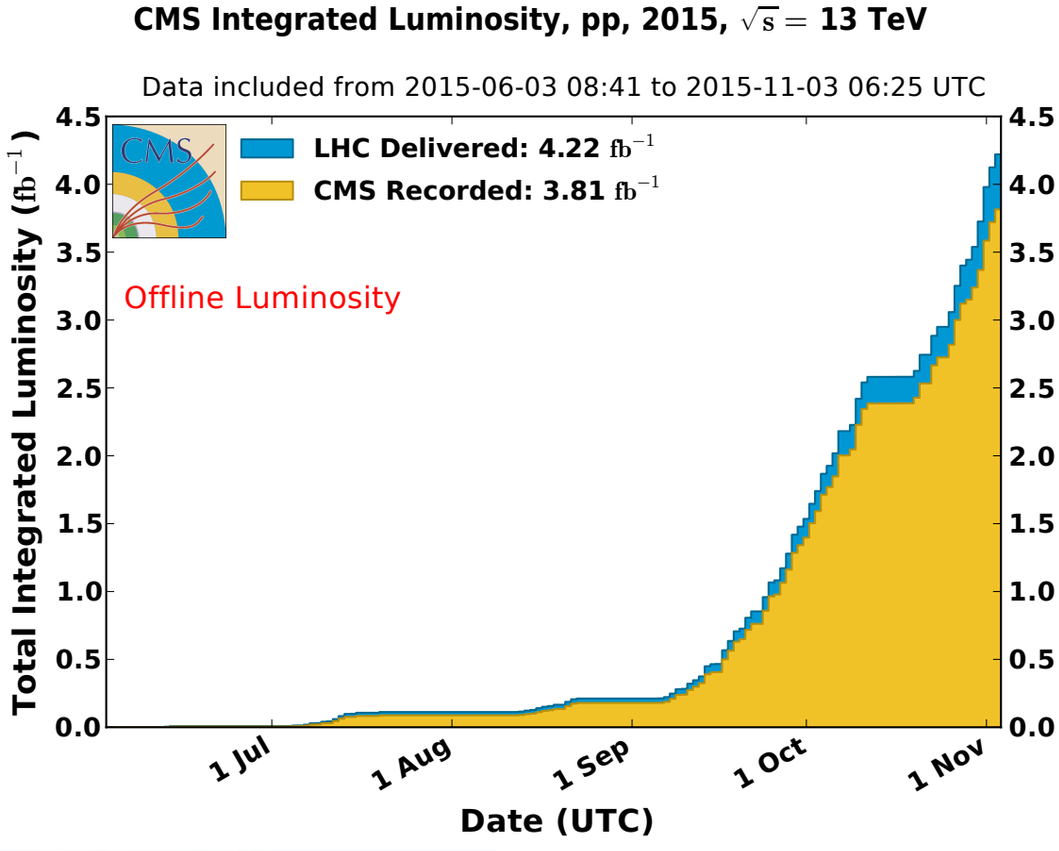
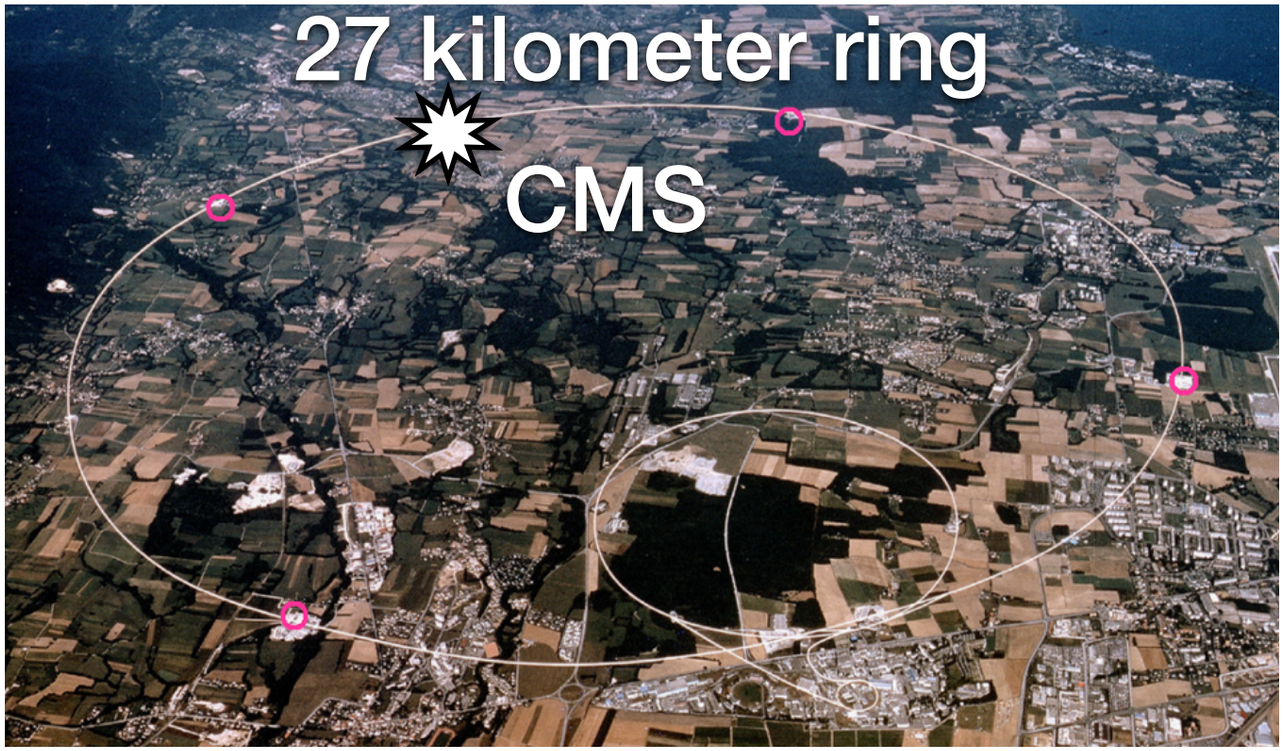


LARGE HADRON COLLIDER

- Proton-proton collisions at 8 TeV in 2012





LARGE HADRON COLLIDER

- Proton-proton collisions at 13 TeV in 2015