DIJET SEARCHES @ CMS

SEARCHES FOR BSM PHYSICS IN THE DIJET MASS SPECTRUM AT CMS

US LHC Users Association Meeting
Lawrence Berkeley National Laboratory
Berkeley, CA, USA

November 4, 2016

Javier Duarte
Fermilab

LONG HISTORY OF DIJET SEARCHES

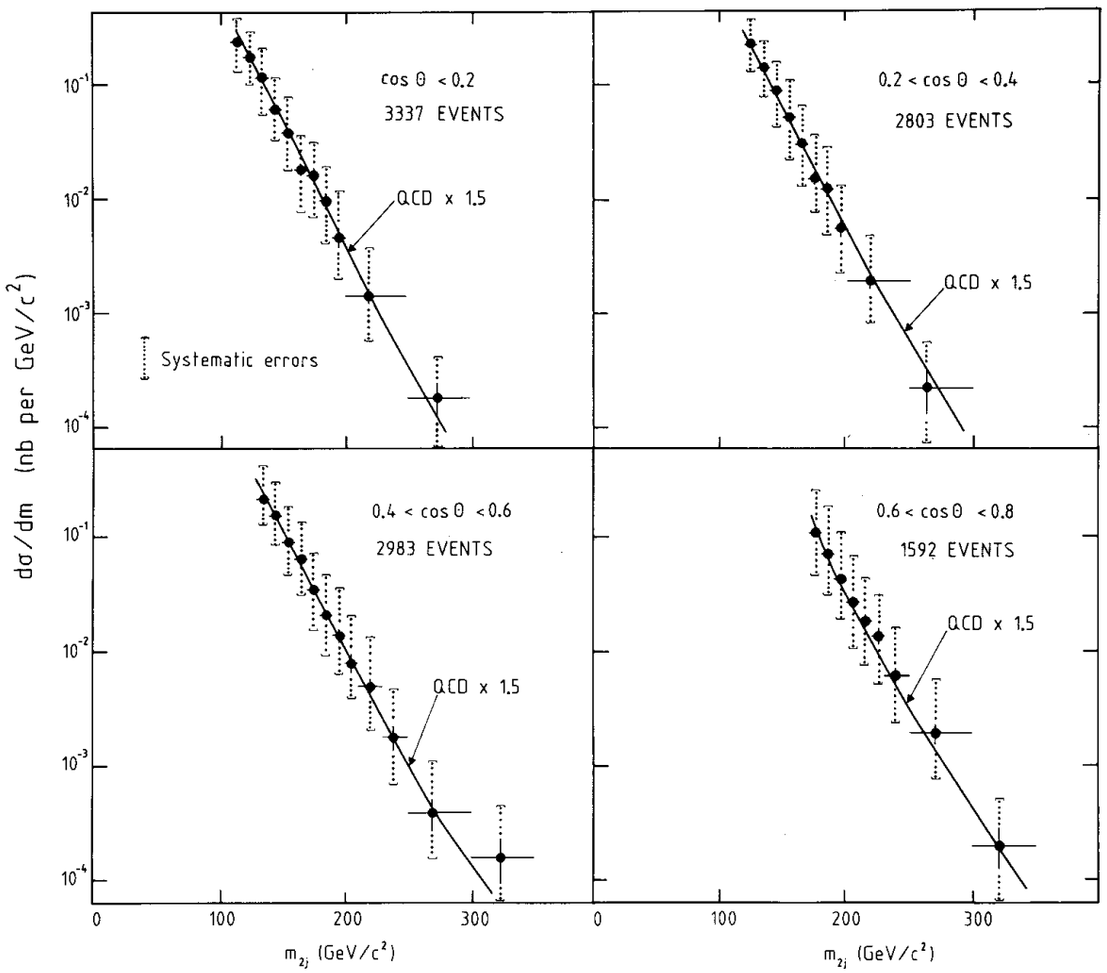
- Dijet resonance searches are fundamental discovery probes at hadron colliders

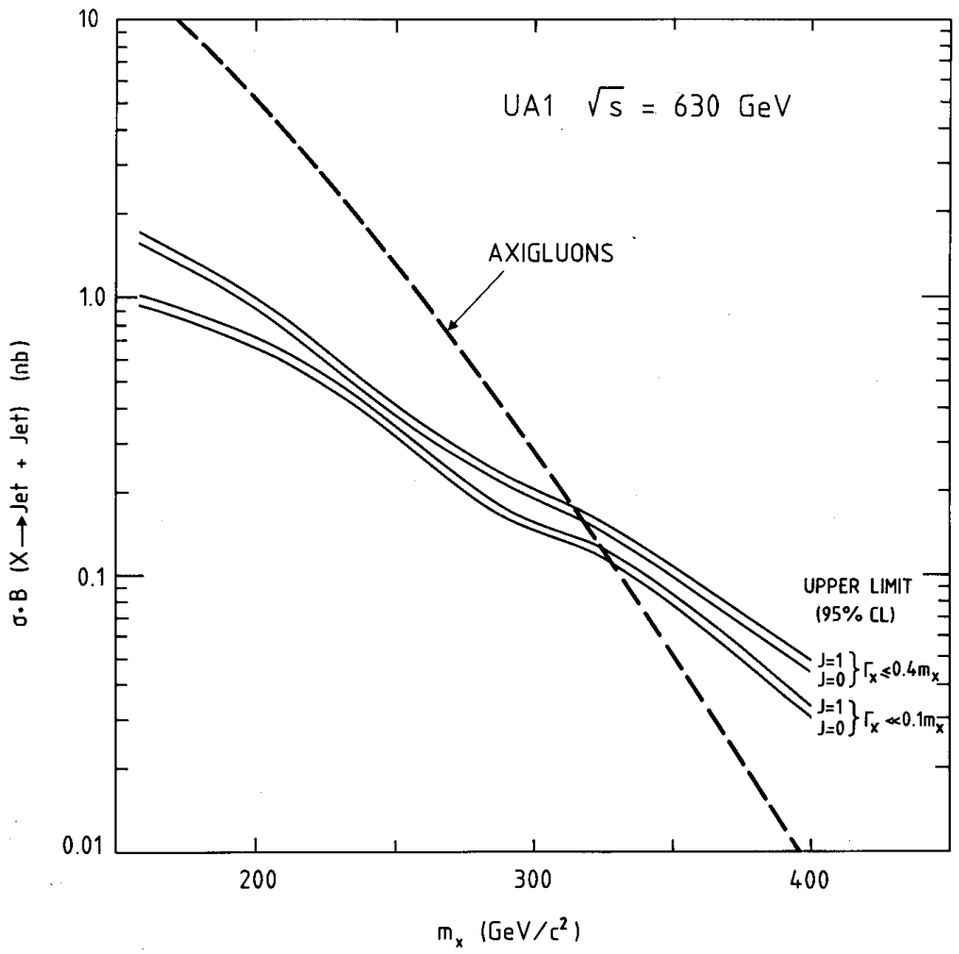
EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH

CERN-EP/88-54
April 28th, 1988

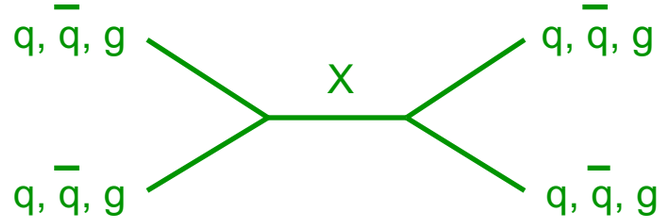
Two - Jet Mass Distributions at the CERN Proton - Antiproton Collider

UA1 Collaboration, CERN, Geneva, Switzerland





MOTIVATION AND OUTLINE

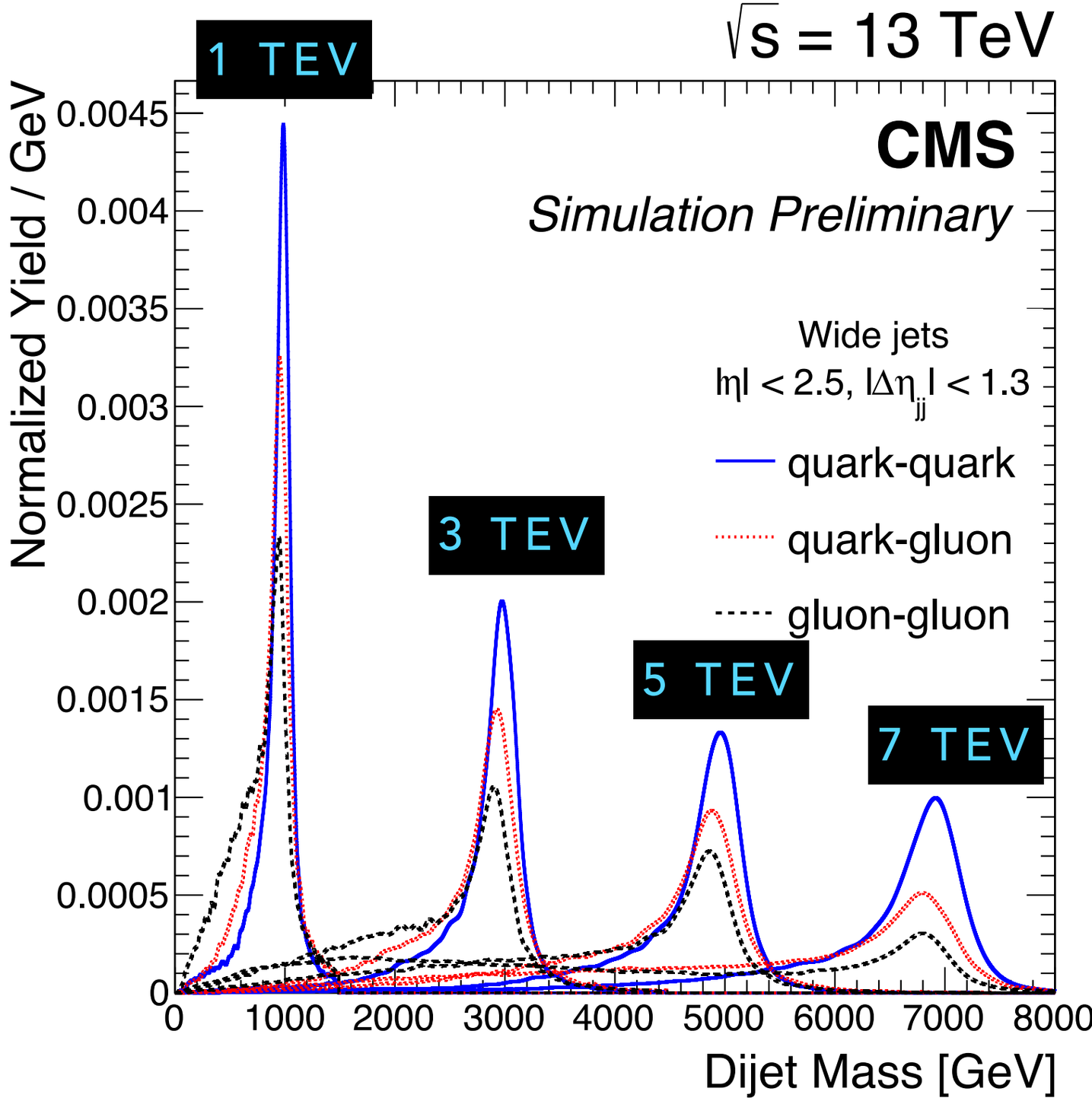


X = new particle beyond the standard model

- **Powerful**: LHC in Run 2 is a dijet resonance factory at a new energy scale
- **Broad and model independent**: many different BSM phenomena can be searched for
- This talk:
  - High-mass and low-mass searches at 13 TeV with 2016 data

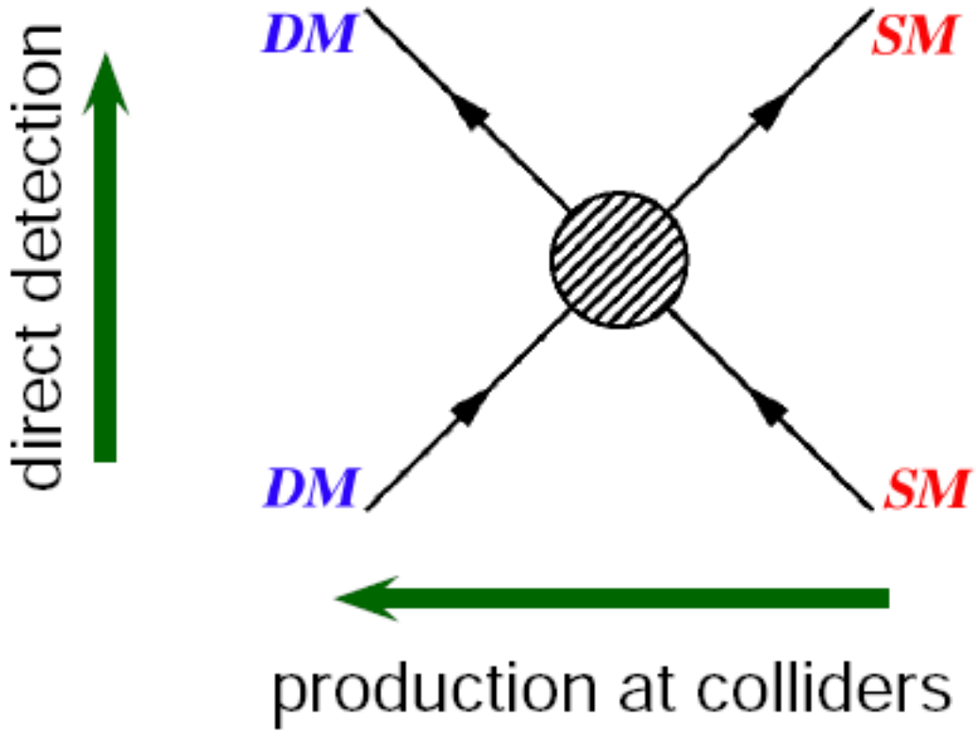
MANY SIGNAL MODELS

- 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, …



DARK MATTER MEDIATOR

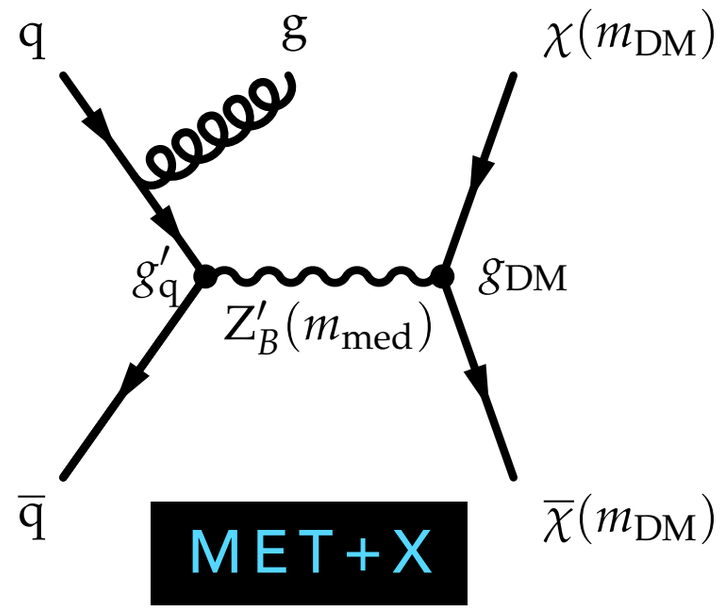
- At colliders, we search for dark matter production — but what is the interaction ⊗ ?

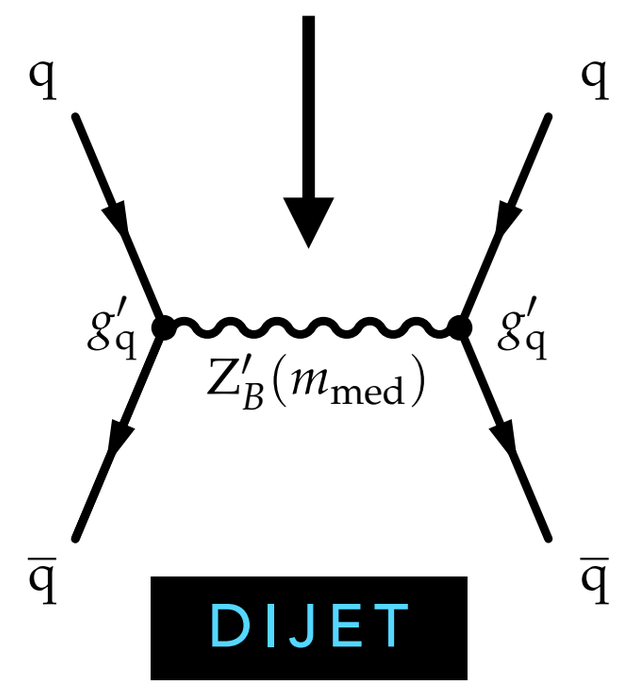


DARK MATTER MEDIATOR

$$\mathcal{L}_{\mathrm{AV}} = -g_{\mathrm{DM}} Z'_{B\mu} \bar{\chi} \gamma^{\mu} \gamma_5 \chi - g'_{\mathrm{q}} \sum_{\mathrm{q}} Z'_{B\mu} \bar{q} \gamma^{\mu} \gamma_5 q$$

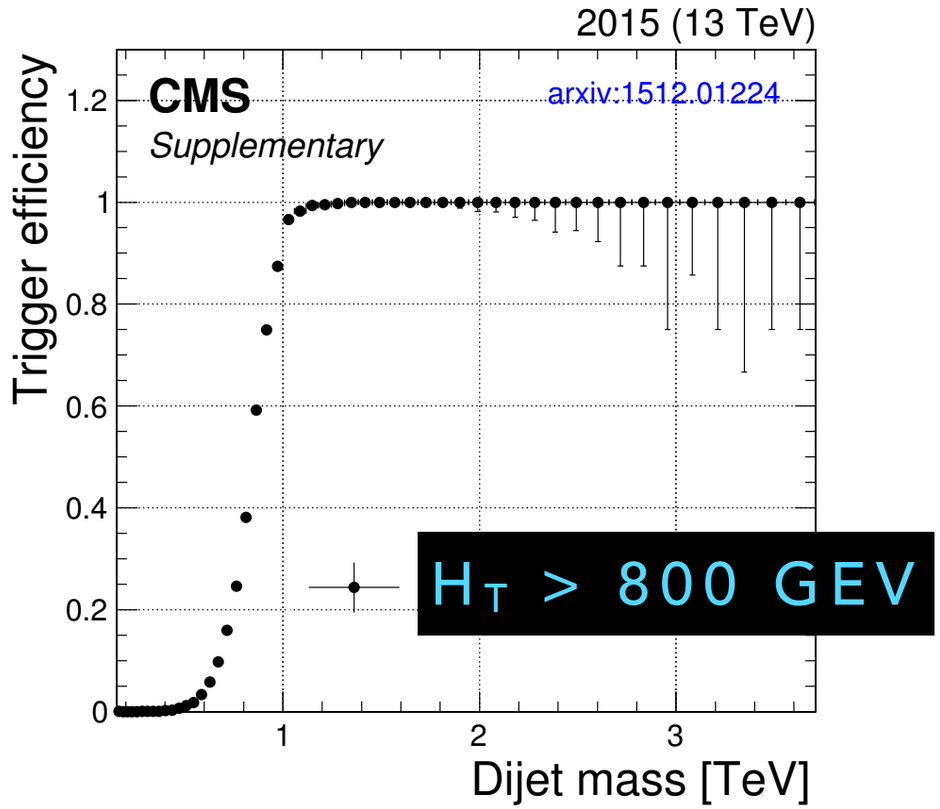
- At colliders, we search for dark matter production — but what is the interaction ⊘ ?
- We postulate the existence of **mediator** between the dark sector and visible sector (SM)
- Mediator may produce a **dijet resonance**

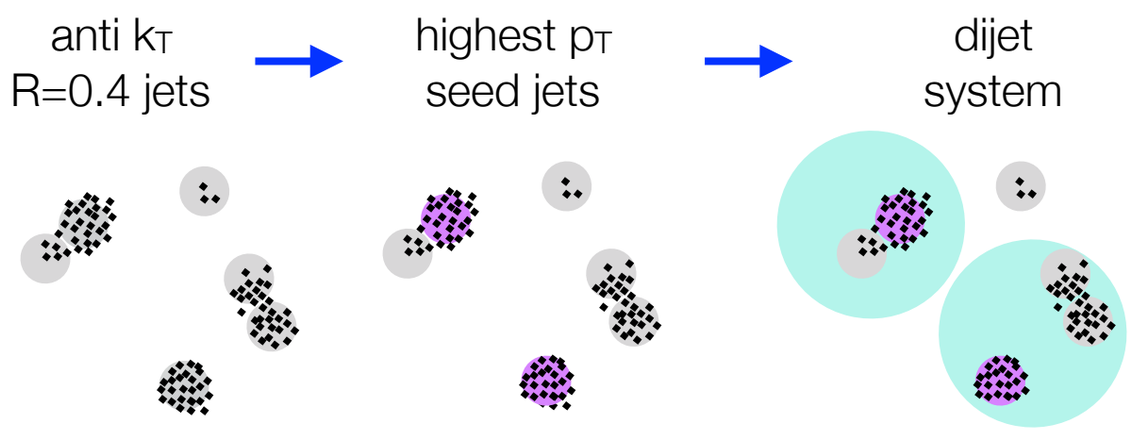




BASICS OF A DIJET SEARCH

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





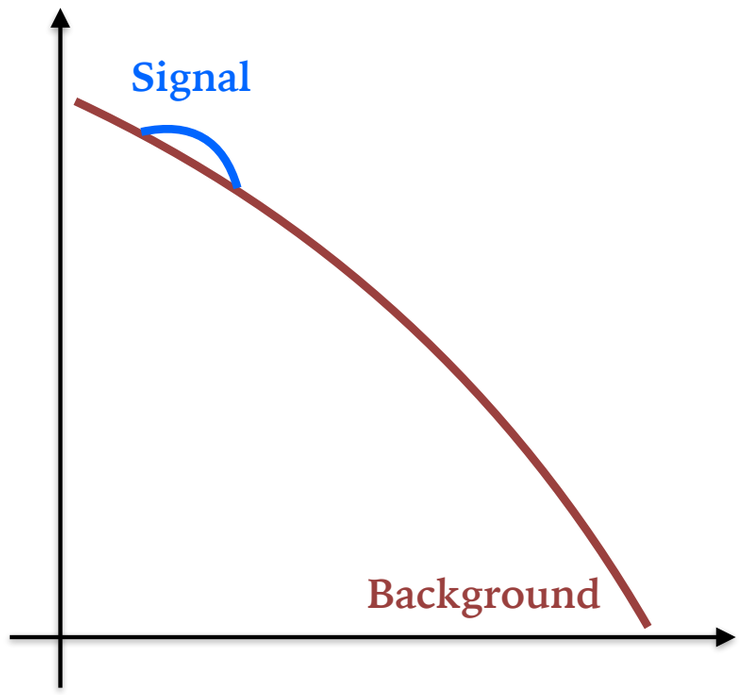
BASICS OF A DIJET SEARCH

- 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



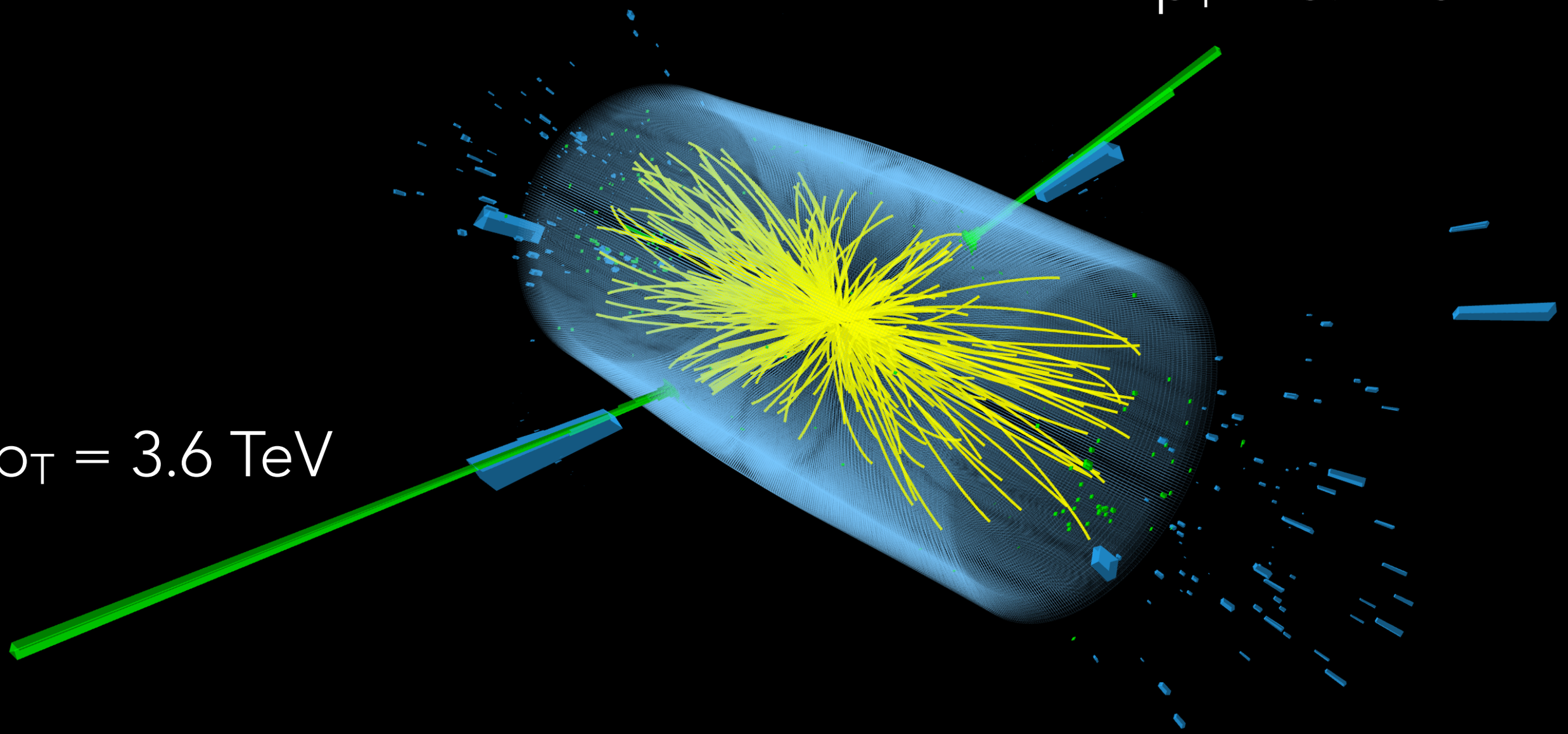
EXO-16-032

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

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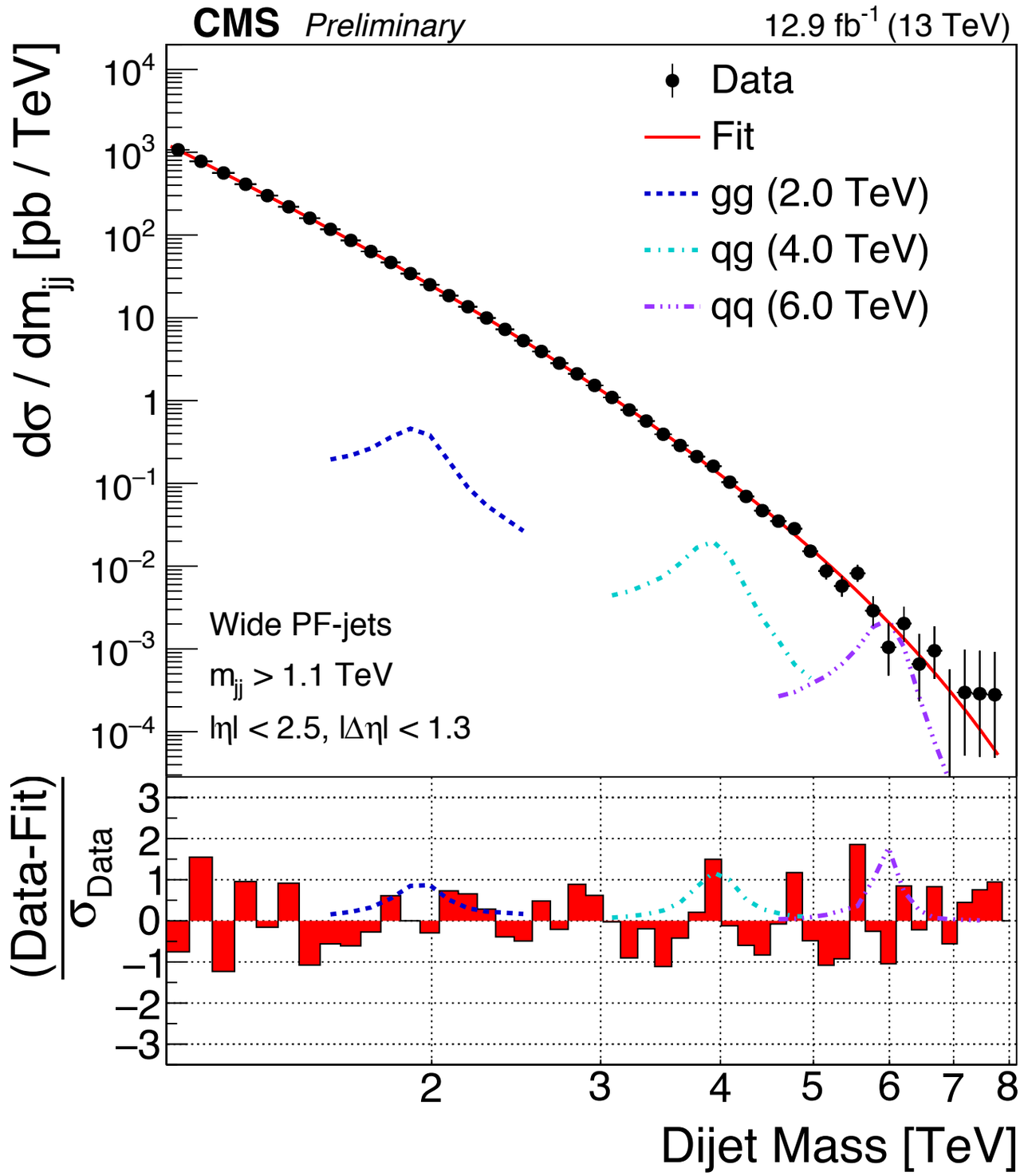
HIGH MASS SPECTRUM AND FIT

- **High mass** spectrum is fit with 4-parameter function

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

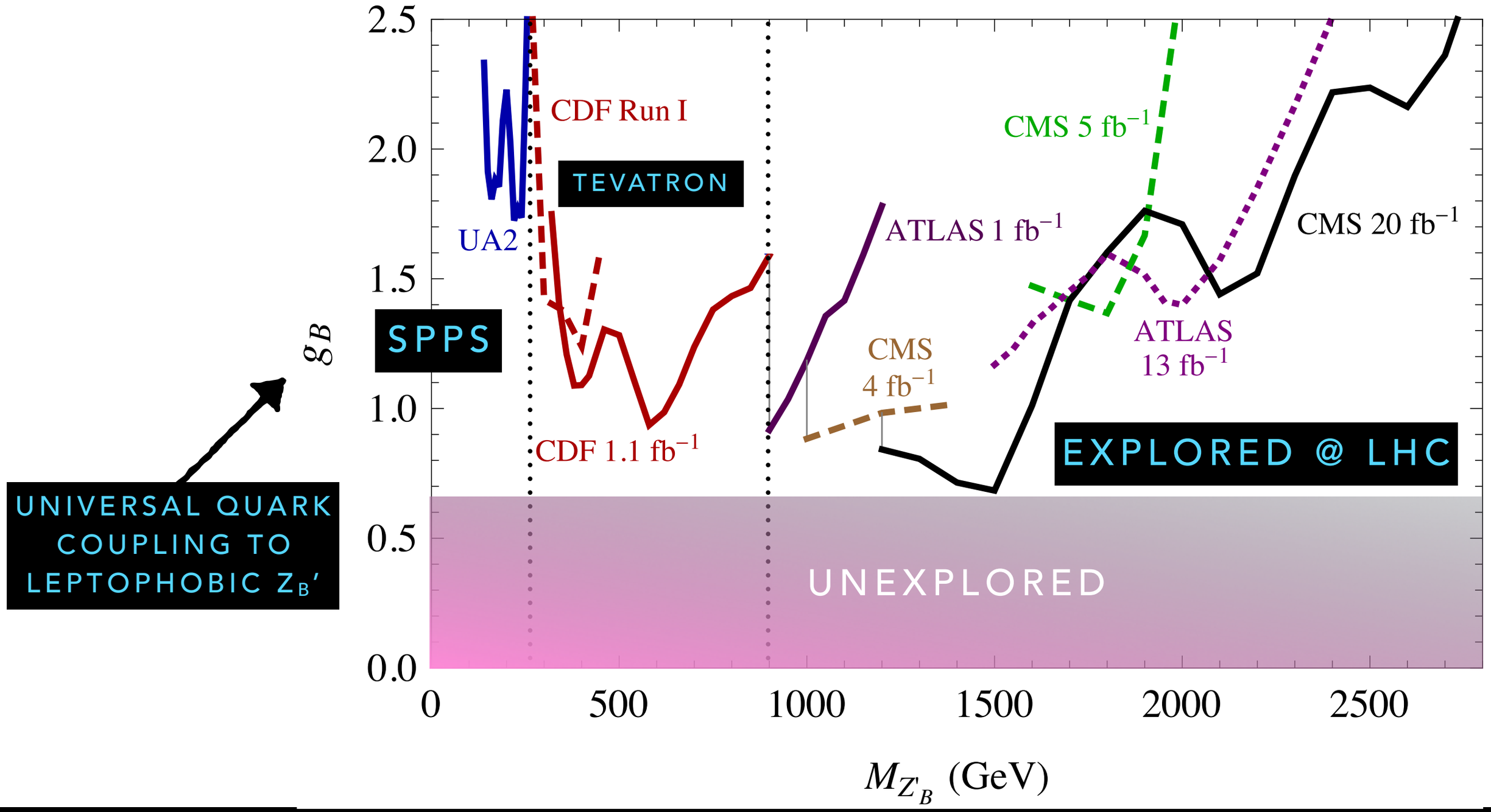
- $\chi^2/\mathrm{dof} = 0.8$
- No evidence for dijet resonance



HOW LOW CAN WE GO?

arXiv:1306.2629

- Using the standard $H_T > 800$ GeV trigger, we can only explore phase space above a resonance mass of ~1 TeV



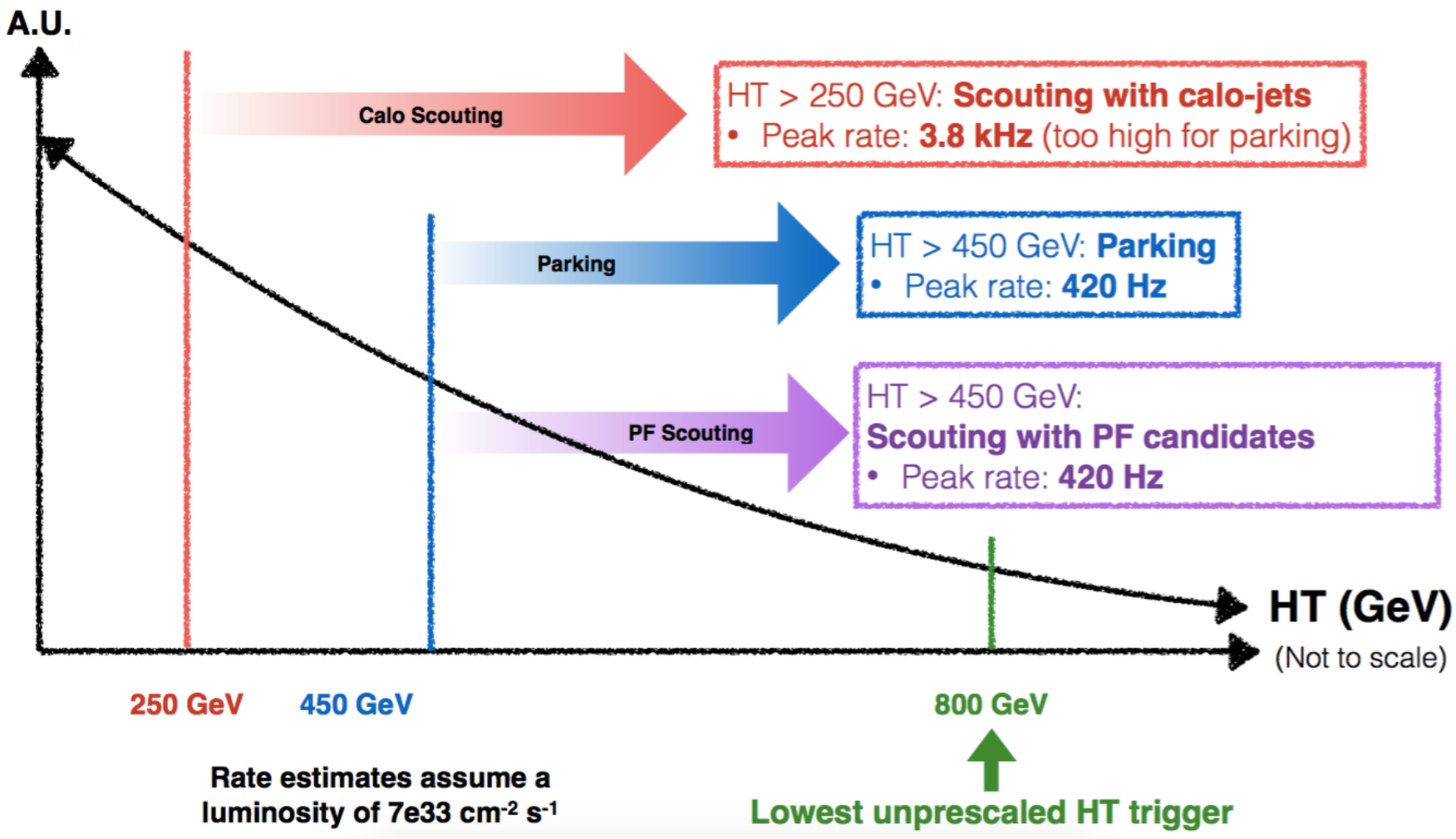
DATA SCOUTING

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

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

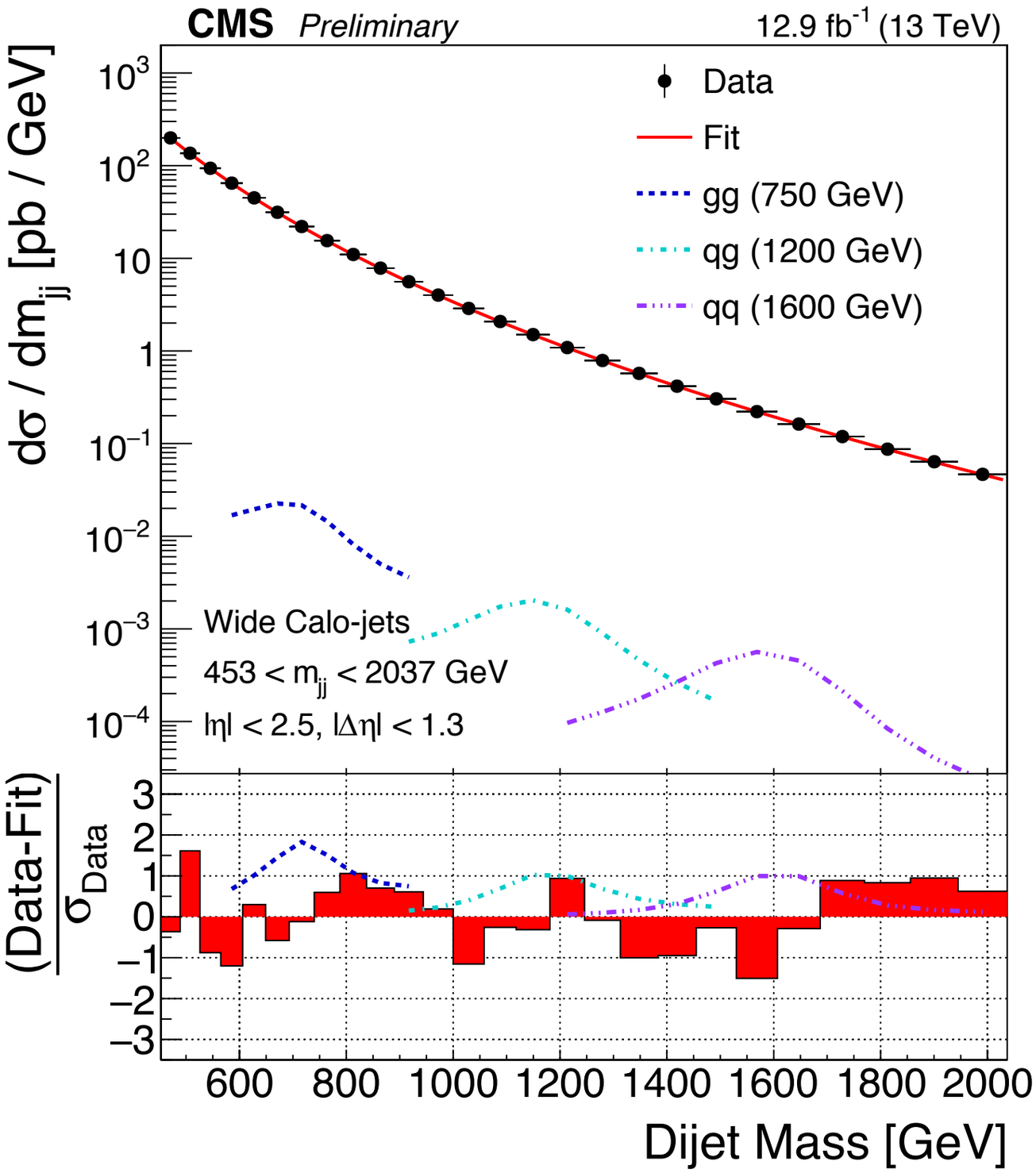
- "**Calo Scouting**" allows us to get down to **H_T > 250 GeV**

Calo Scouting
3kHz × 1.5 kb



LOW MASS SPECTRUM AND FIT

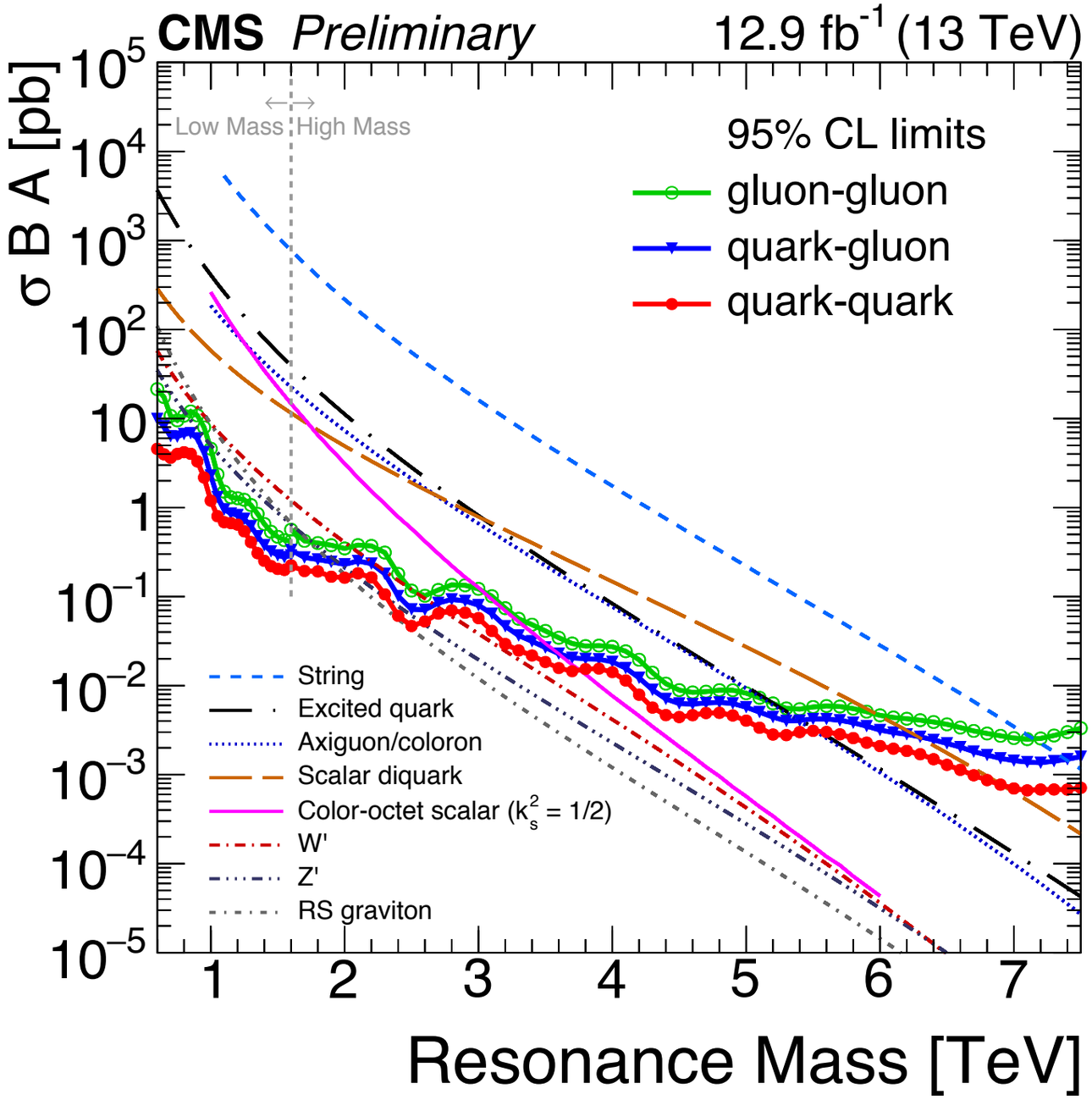
- Using "Calo Scouting," **low mass** spectrum is fit above $m_{jj} > 453$ GeV
- $\chi^2/\text{dof} = 0.8$
- No evidence for dijet resonance



LIMITS ON NARROW RESONANCES

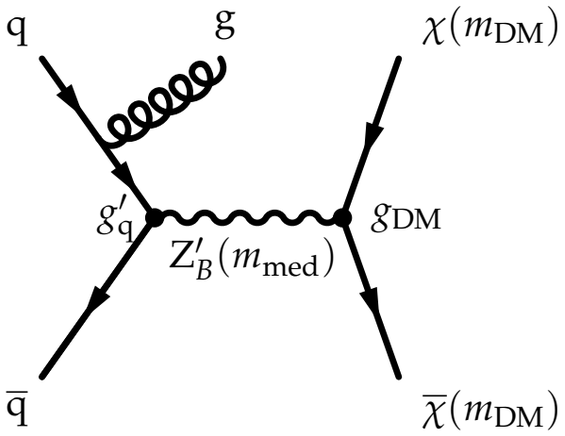
- ***Most stringent*** mass limits on 8 models of new physics

Model	Mass Limits (TeV)		
	2016 (12.9 fb^{-1})		2015 (2.4 fb^{-1})
	Obs.	Exp.	Exp.
String Resonance	7.4	7.4	6.9
Scalar Diquark	6.9	6.8	6.1
Axigluon / Coloron	5.5	5.6	5.1
Excited Quark	5.4	5.4	4.8
Octet Scalar ($k_s^2 = ½$)	3.0	3.3	—
W′ Boson	2.7	3.1	2.3
Z′ Boson	2.1	2.3	—
RS Graviton	1.9	1.8	—

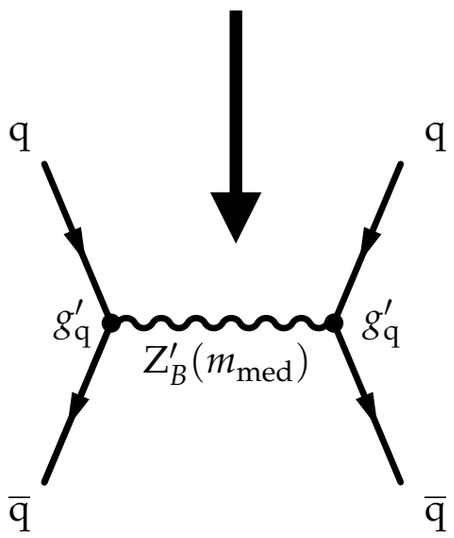


SENSITIVITY TO DARK MATTER

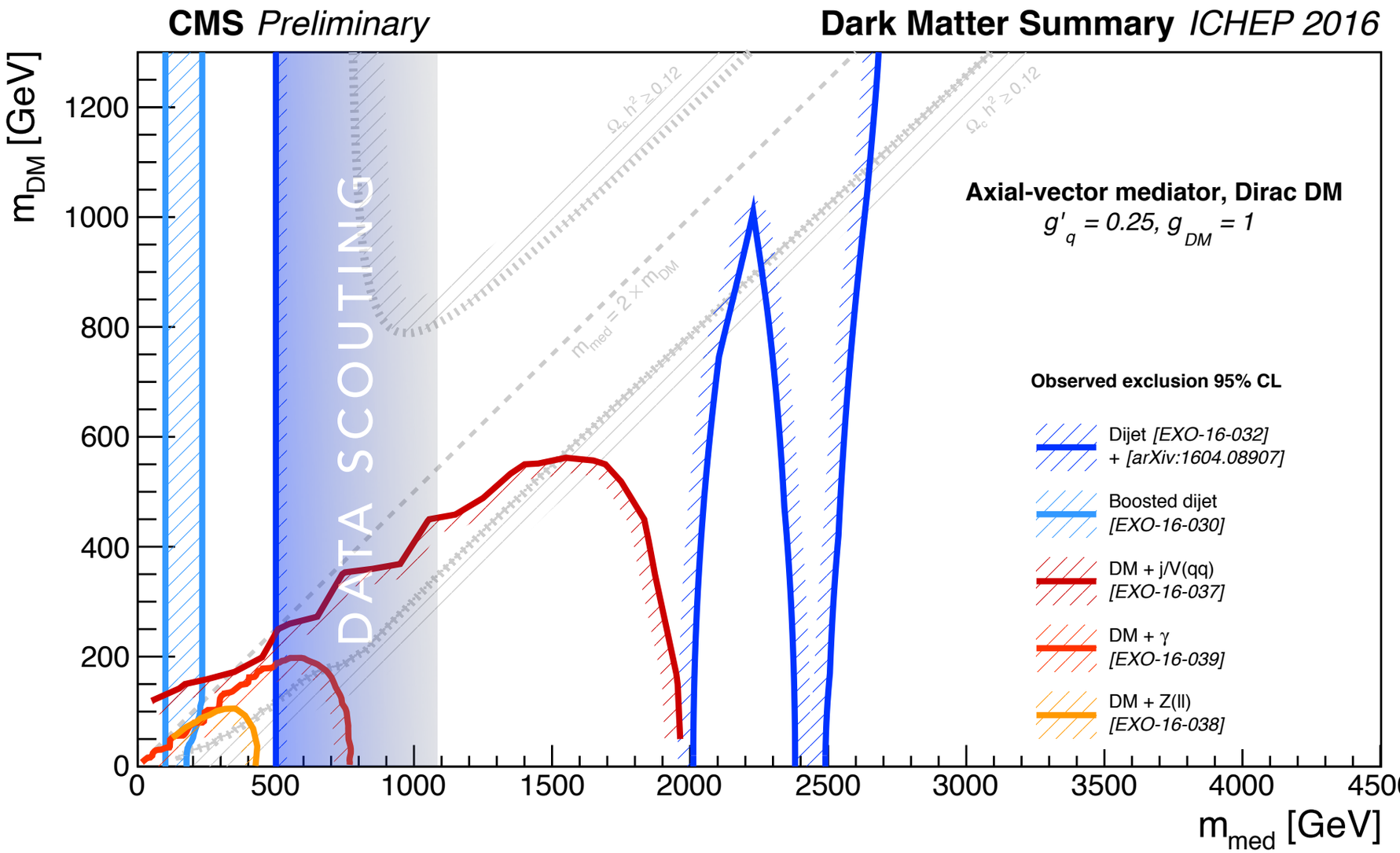
- Sensitive to large range of ***dark matter*** parameter space by looking directly for resonant production of the ***mediator***



MET+X

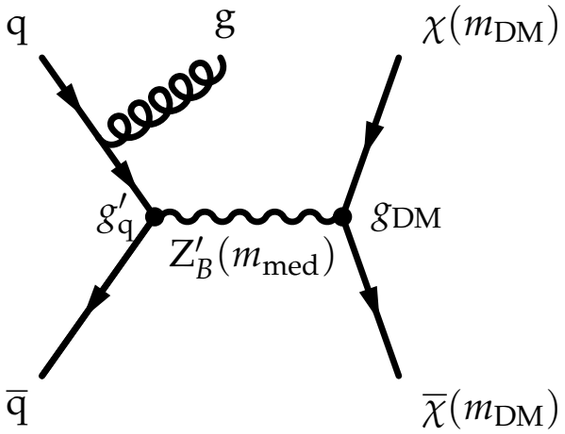


DIJET

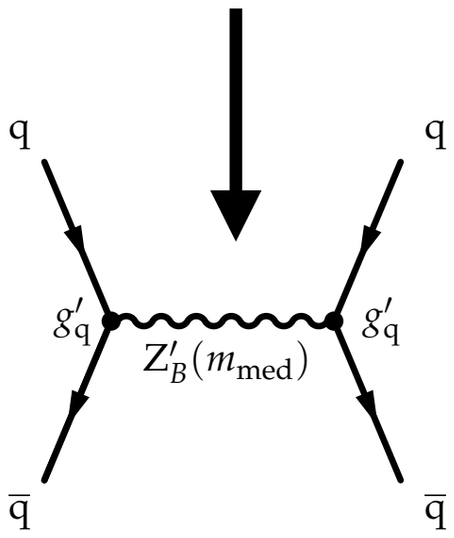


SENSITIVITY TO DARK MATTER

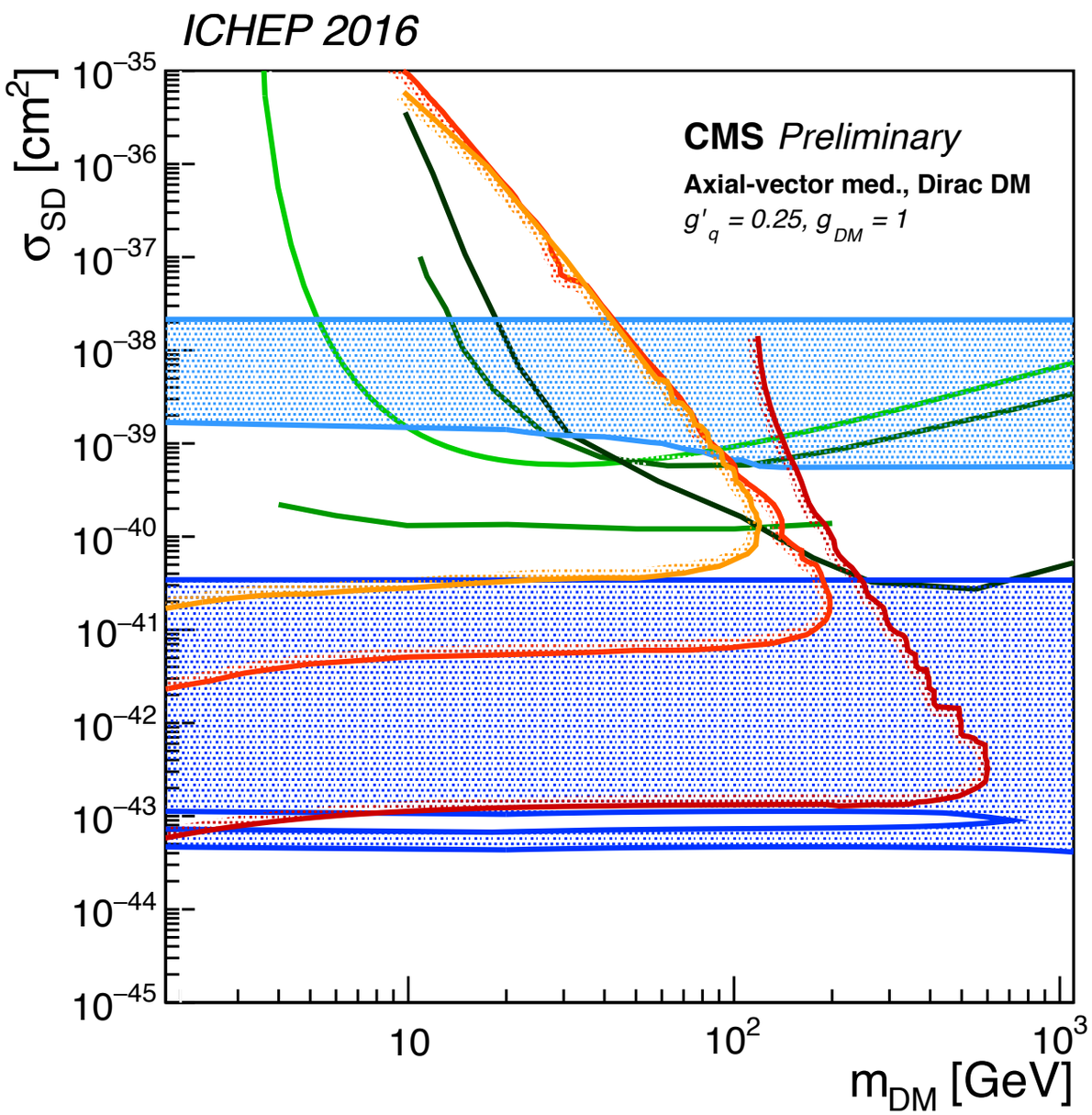
- ***Competitive*** with direct detection experiments (depending on the details of the model: couplings, mediator type, etc.)



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

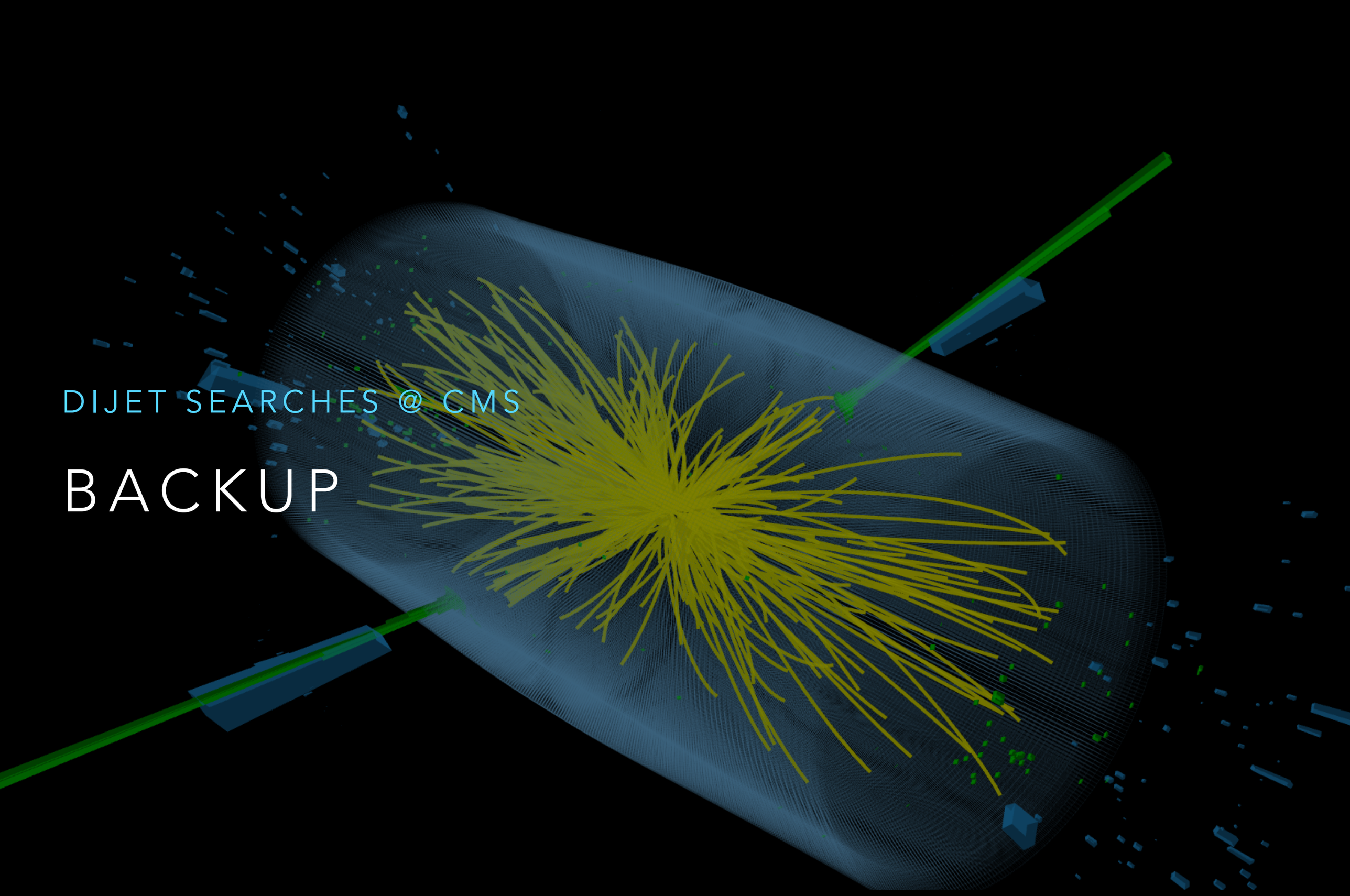
- Pico 2L *[arXiv:1601.03729]*
- Pico 60 *[arXiv:1510.07754]*
- Super-K $\tau^+\tau^-$ *[arXiv:1503.04858]*
- IceCube $\tau^+\tau^-$ *[arXiv:1601.00653]*

SUMMARY AND OUTLOOK

- No evidence for new phenomena... yet
  - Probing resonance masses from 0.6 TeV up to 7.5 TeV!
- 2016 search produced the most stringent limits on many new physics models
- First CMS constraints on dark matter mediators from dijet searches!
- Limits in DM-nucleon cross section vs. mass plane are competitive with direct detection experiments

DIJET SEARCHES @ CMS

BACKUP



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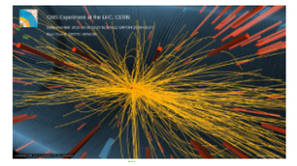
TRIGGER SYSTEM

CMS

- How can we trigger below H_T = 800 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



40 MHz

100 kHz

1 kHz

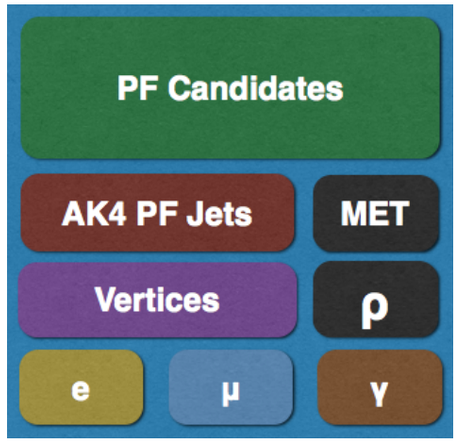
H. Brun, LP 2015

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

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

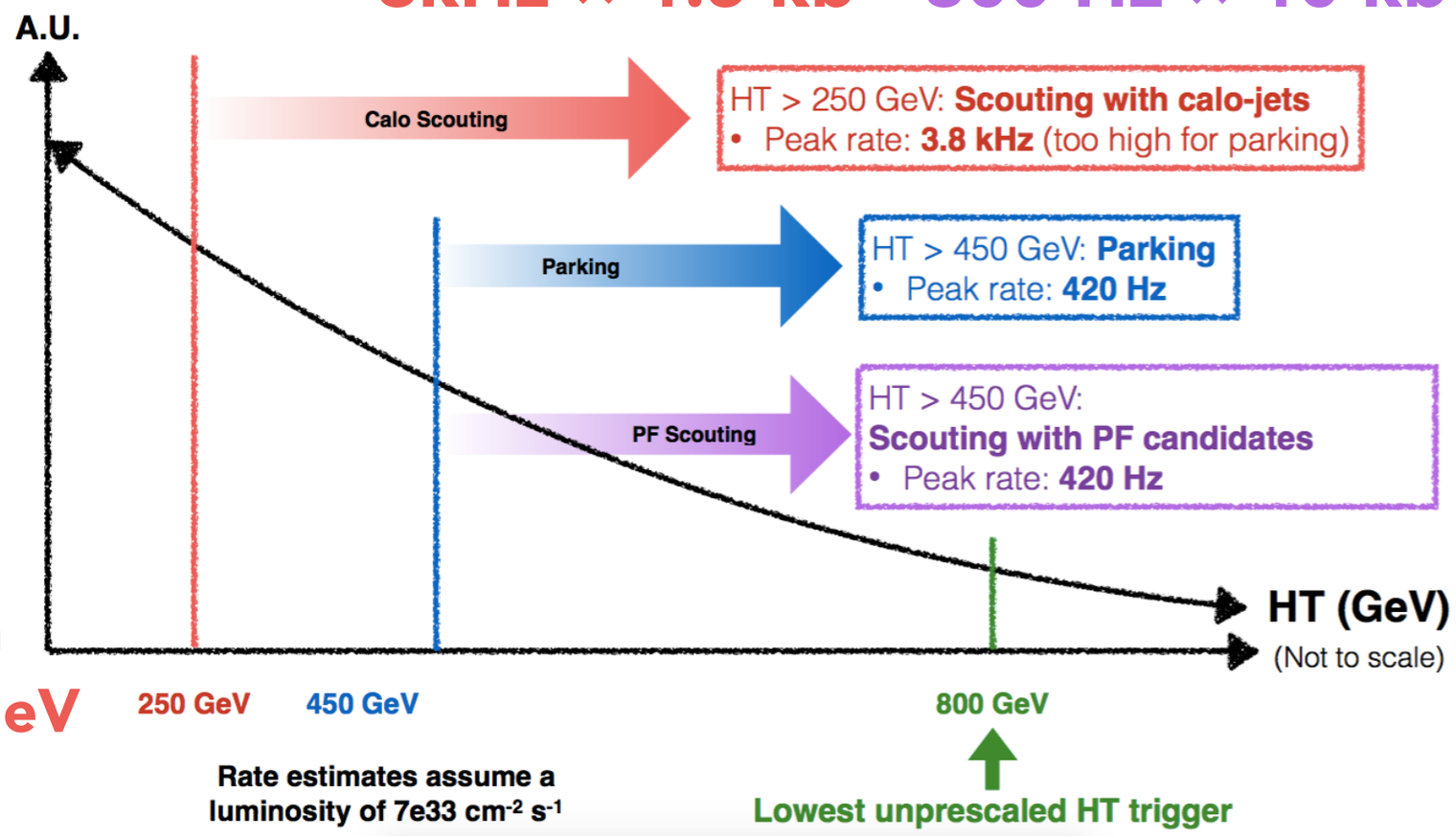
A: DATA SCOUTING

- 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**
  - **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

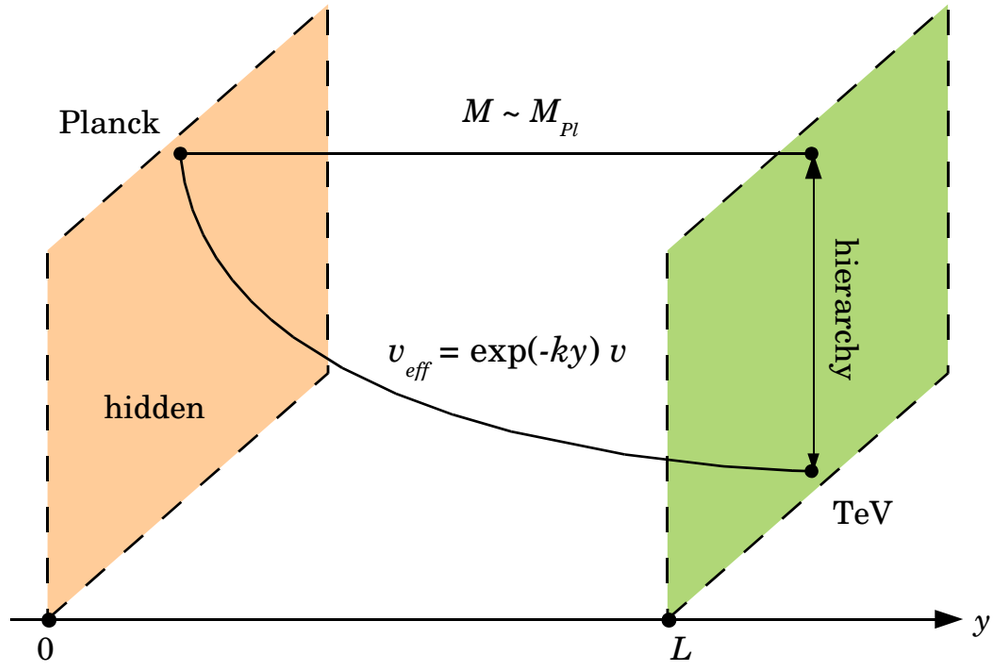


SIGNAL MODELS

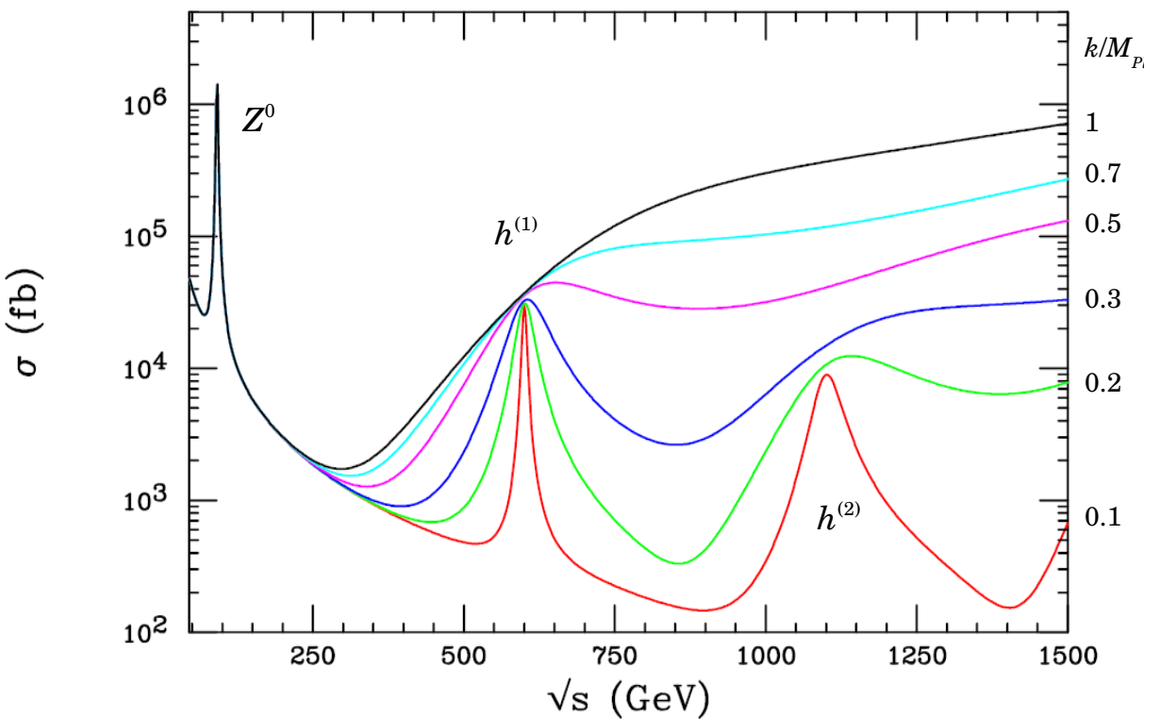
- String resonances (S), which are Regge excitations of quarks and gluons in string theory and decay predominantly to qg [1, 2].
- Scalar diquarks (D), which decay to qq and $\overline{\mathrm{q}}\overline{\mathrm{q}}$, predicted by a grand unified theory based on the E_6 gauge symmetry group [3].
- 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

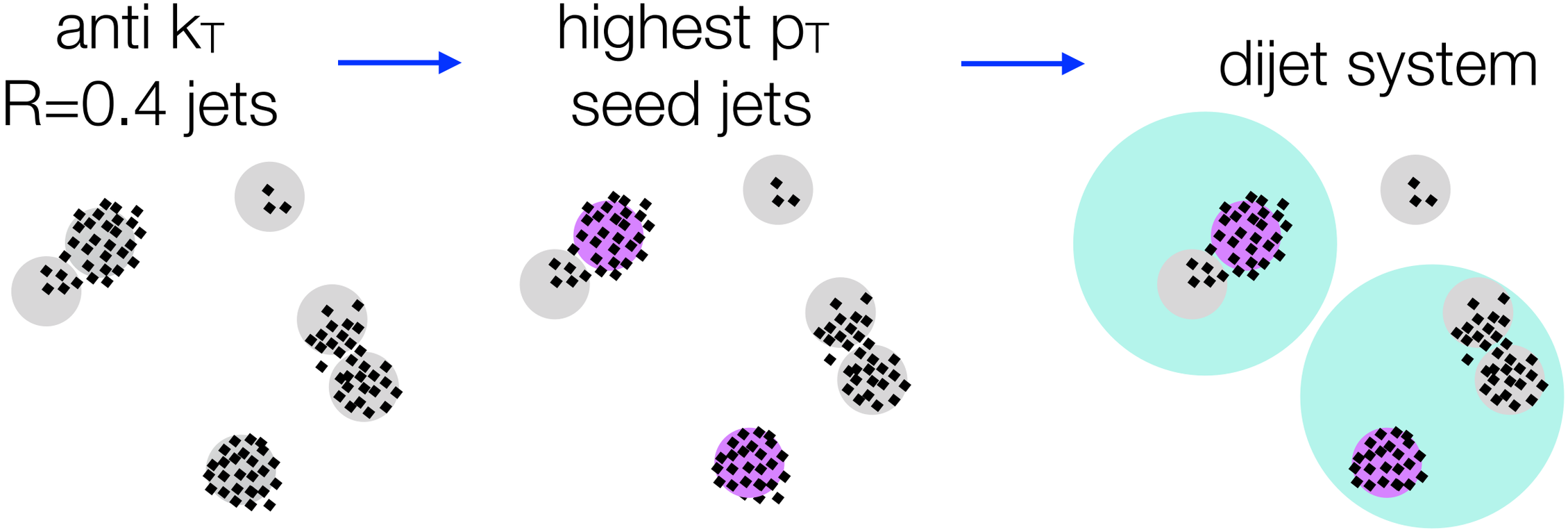


$$ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$$



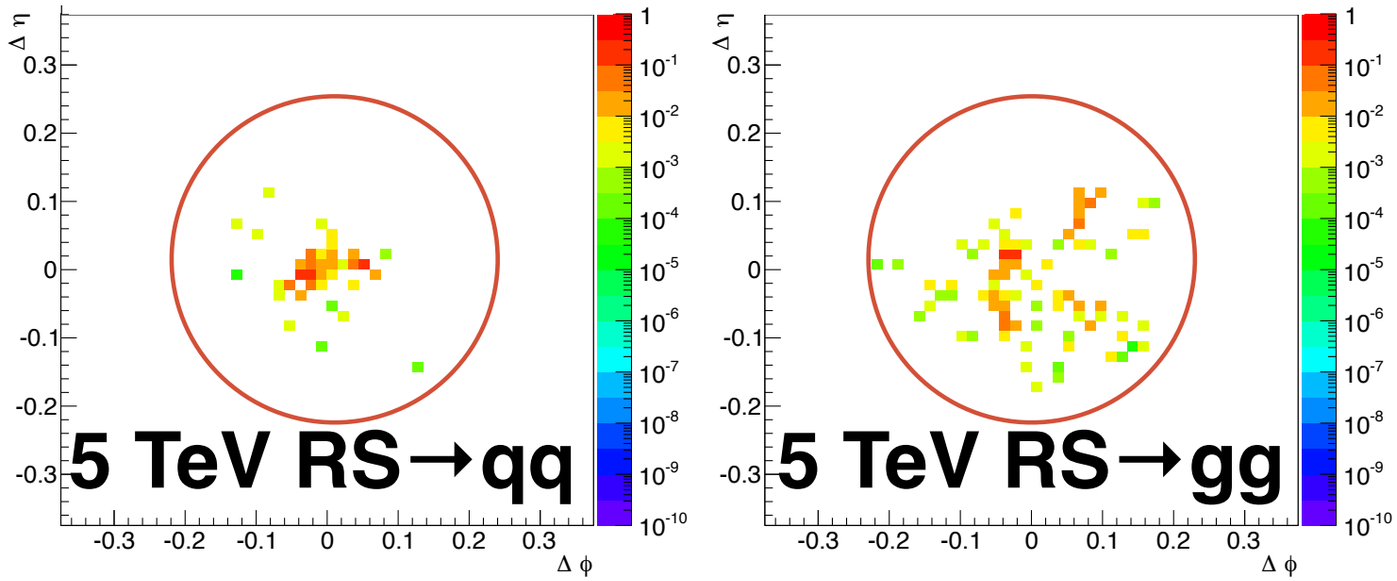
WIDE JETS

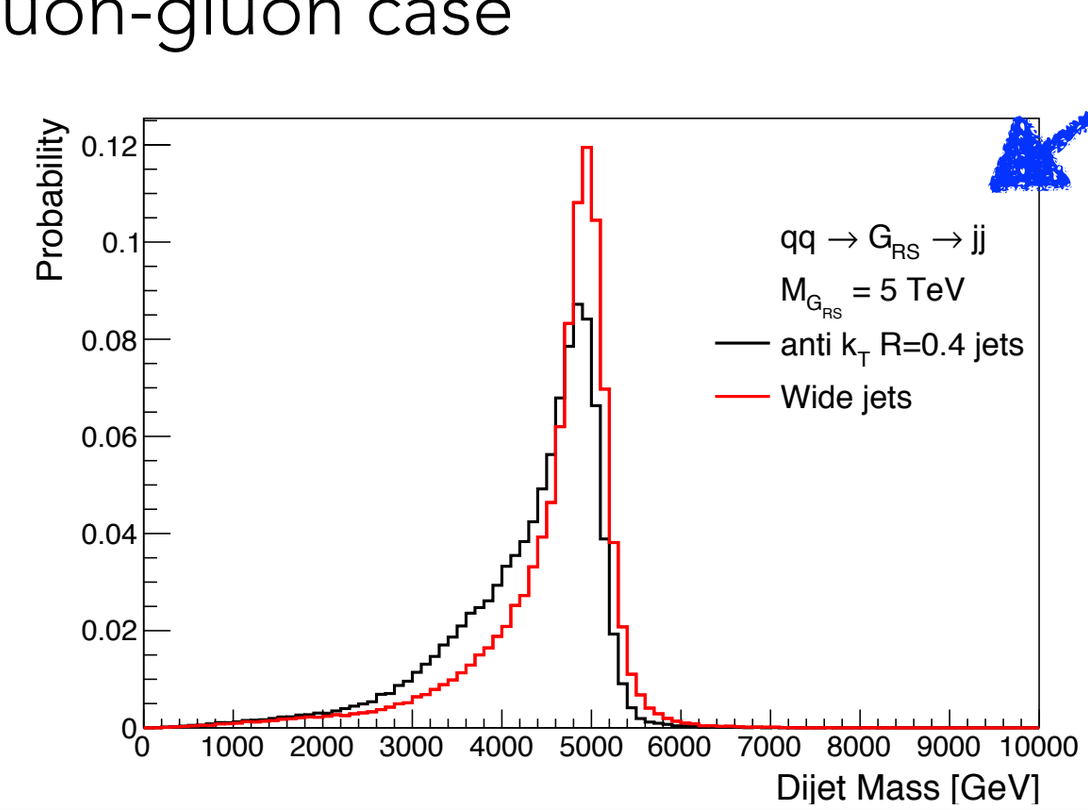
- Jets initially reconstructed with anti-k_T algorithm with R=0.4
- "Wide jet" algorithm uses two leading jets as seeds
  - Adds neighboring jets to nearest leading jet if within $\Delta R < 1.1$
  - Recover loss in mass response due to radiation

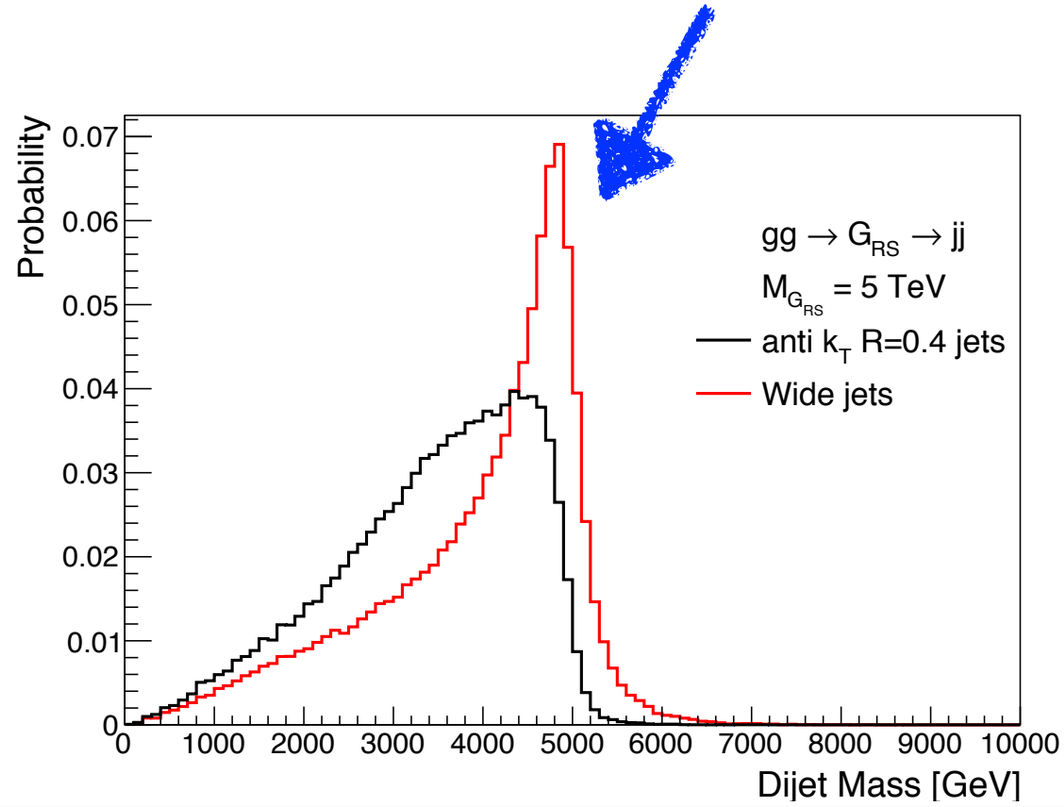


WIDE JETS

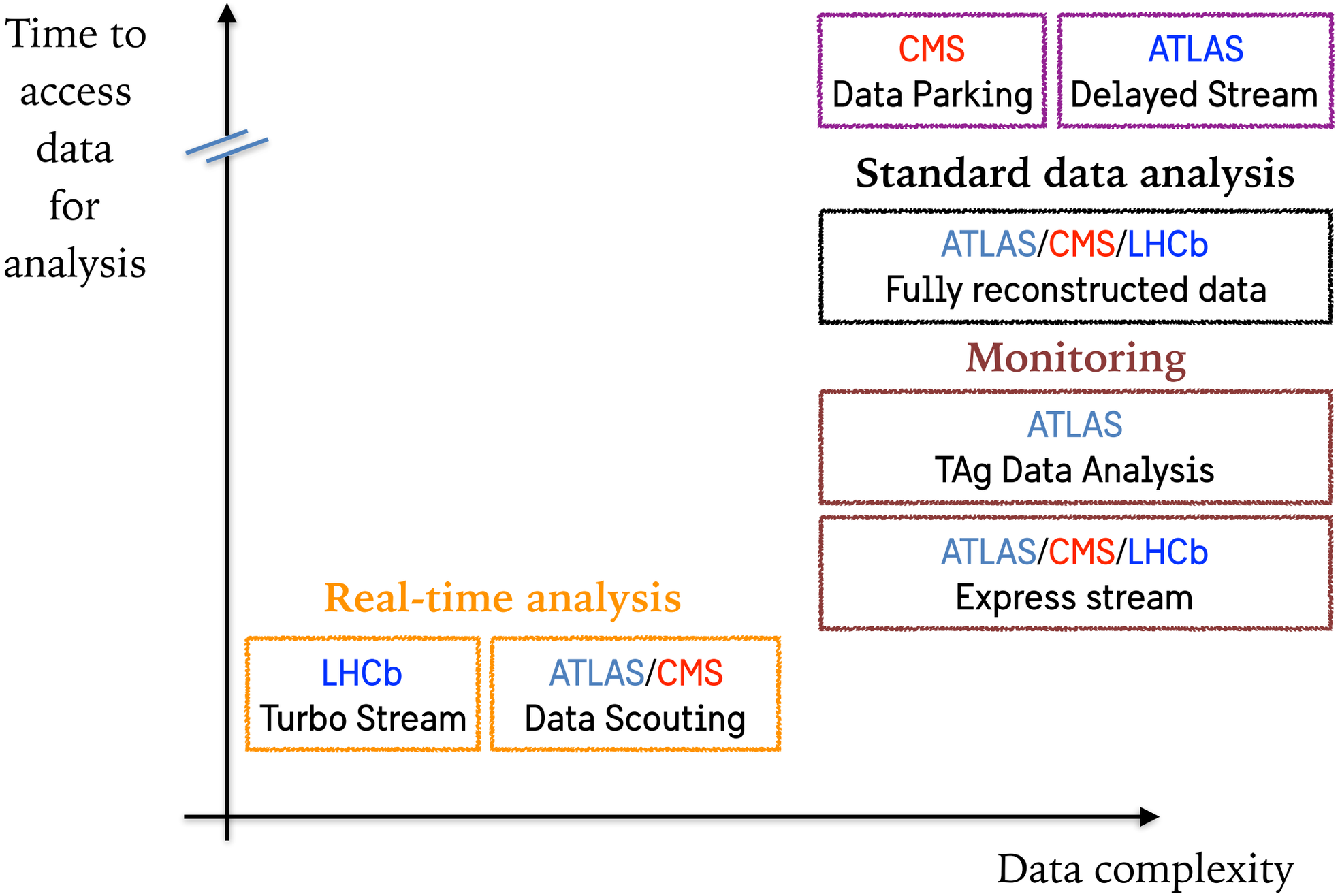
- Gluon-gluon resonances are wider than quark-quark resonances due to greater radiation (gluon color factor)
- Mass resolution improved with wide jets even in gluon-gluon case







DATA SCOUTING



LARGE HADRON COLLIDER

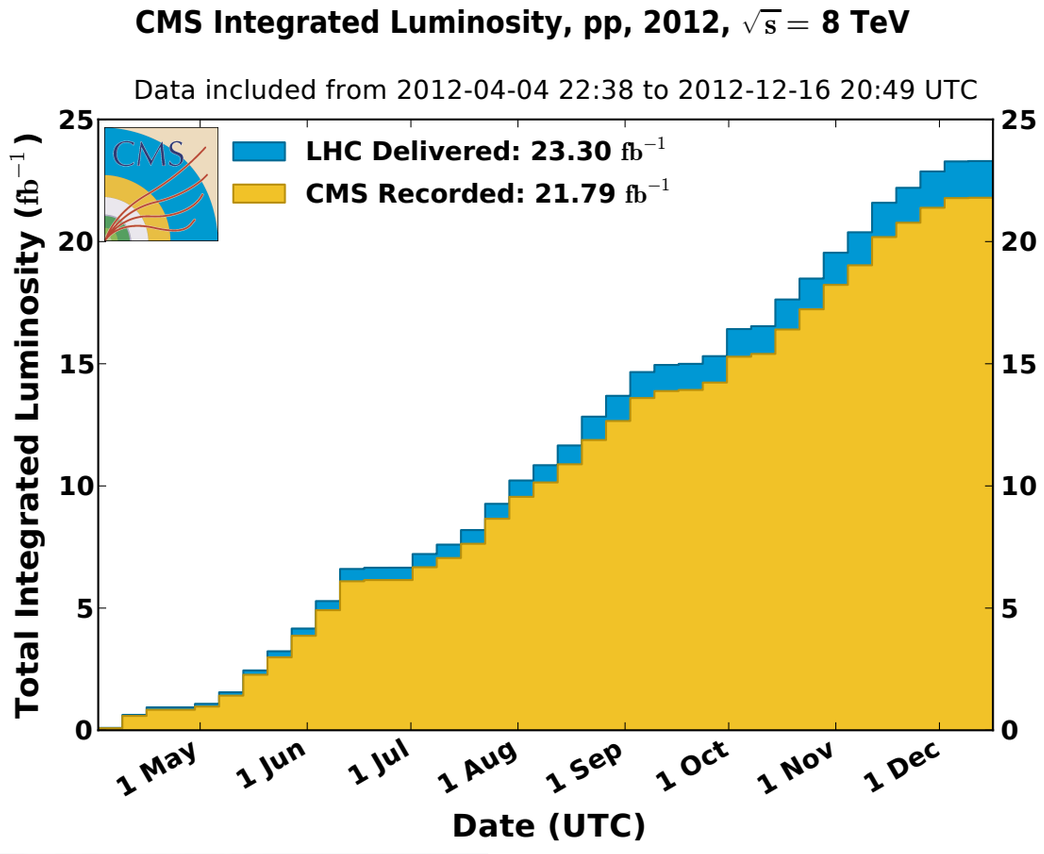
Lake Geneva

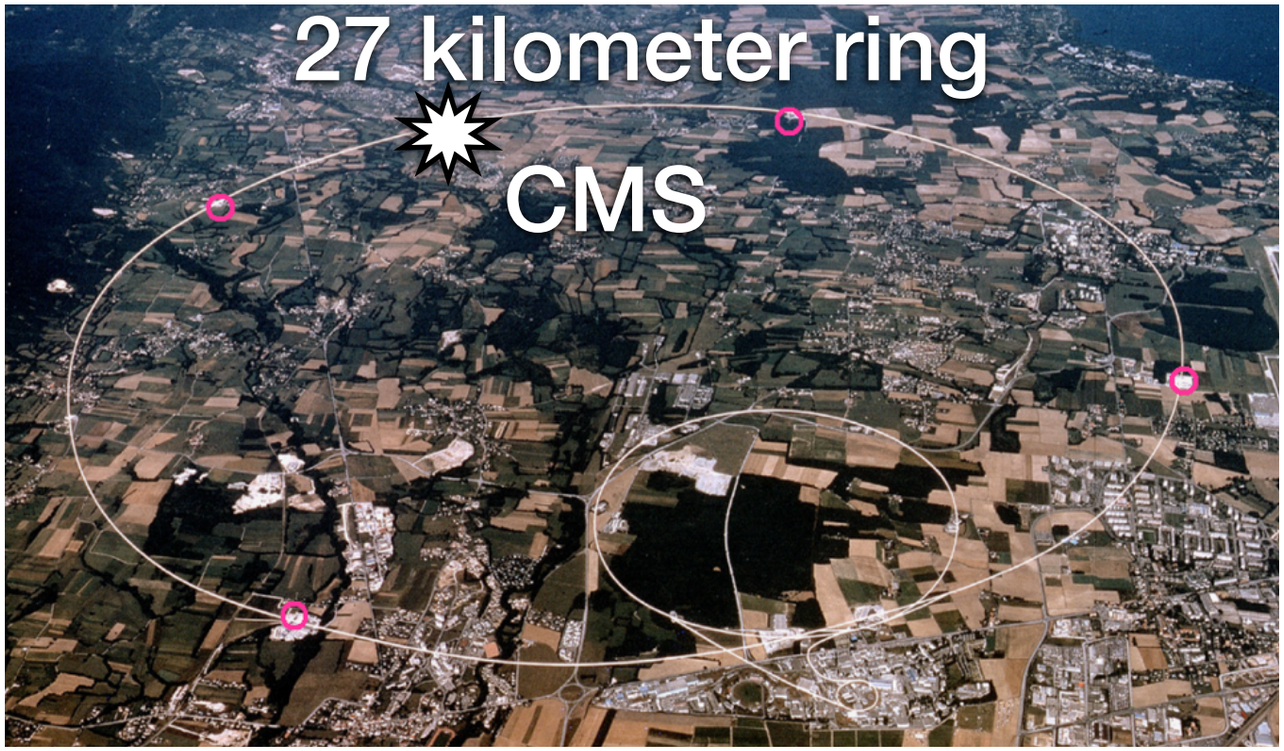
CMS

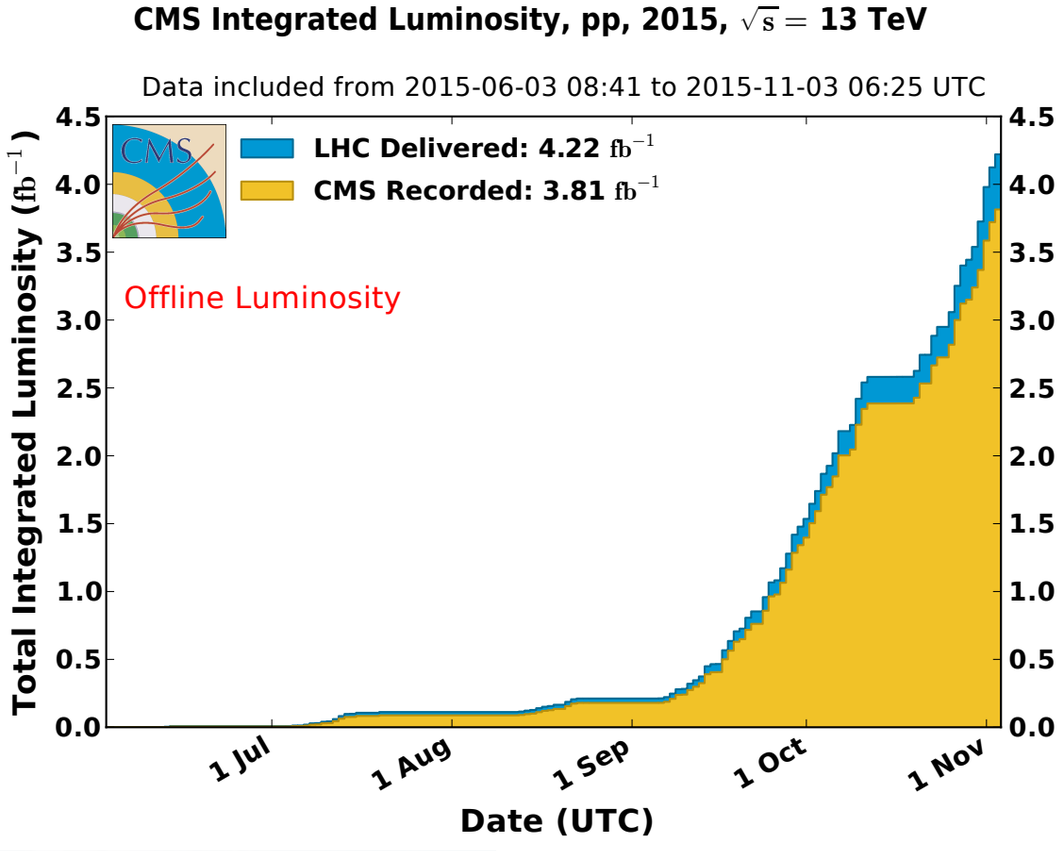
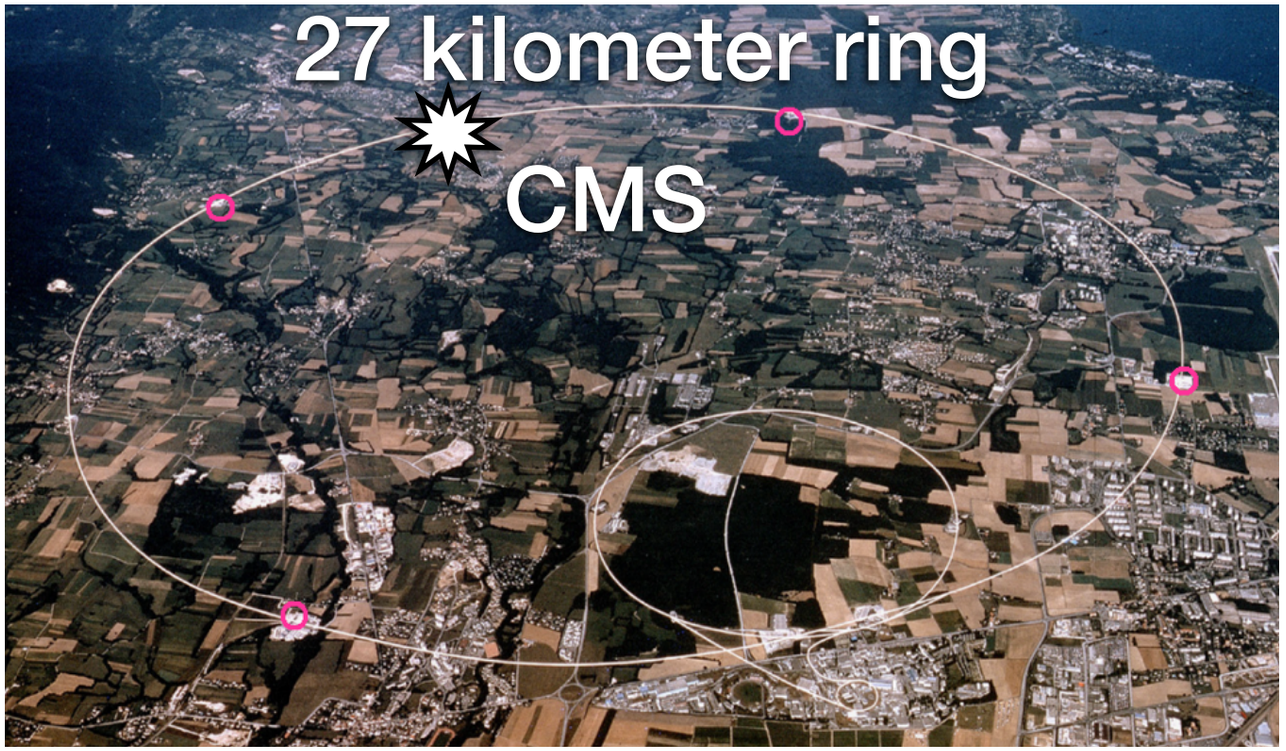
CERN

LARGE HADRON COLLIDER

- Proton-proton collisions at 8 TeV in 2012





LARGE HADRON COLLIDER

- Proton-proton collisions at 13 TeV in 2015