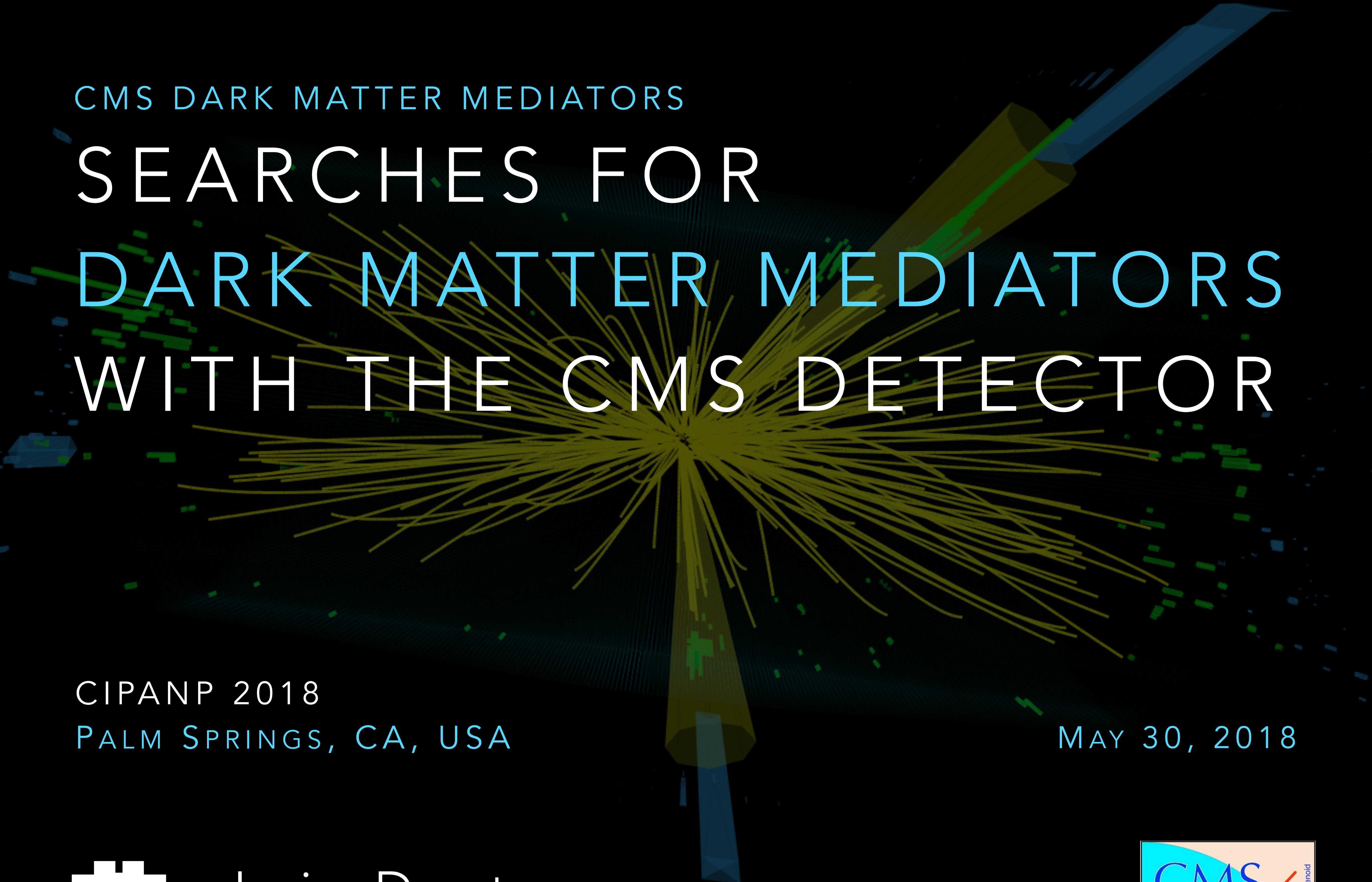
CMS DARK MATTER MEDIATORS

SEARCHES FOR DARK MATTER MEDIATORS WITH THE CMS DETECTOR



CIPANP 2018

Palm Springs, CA, USA

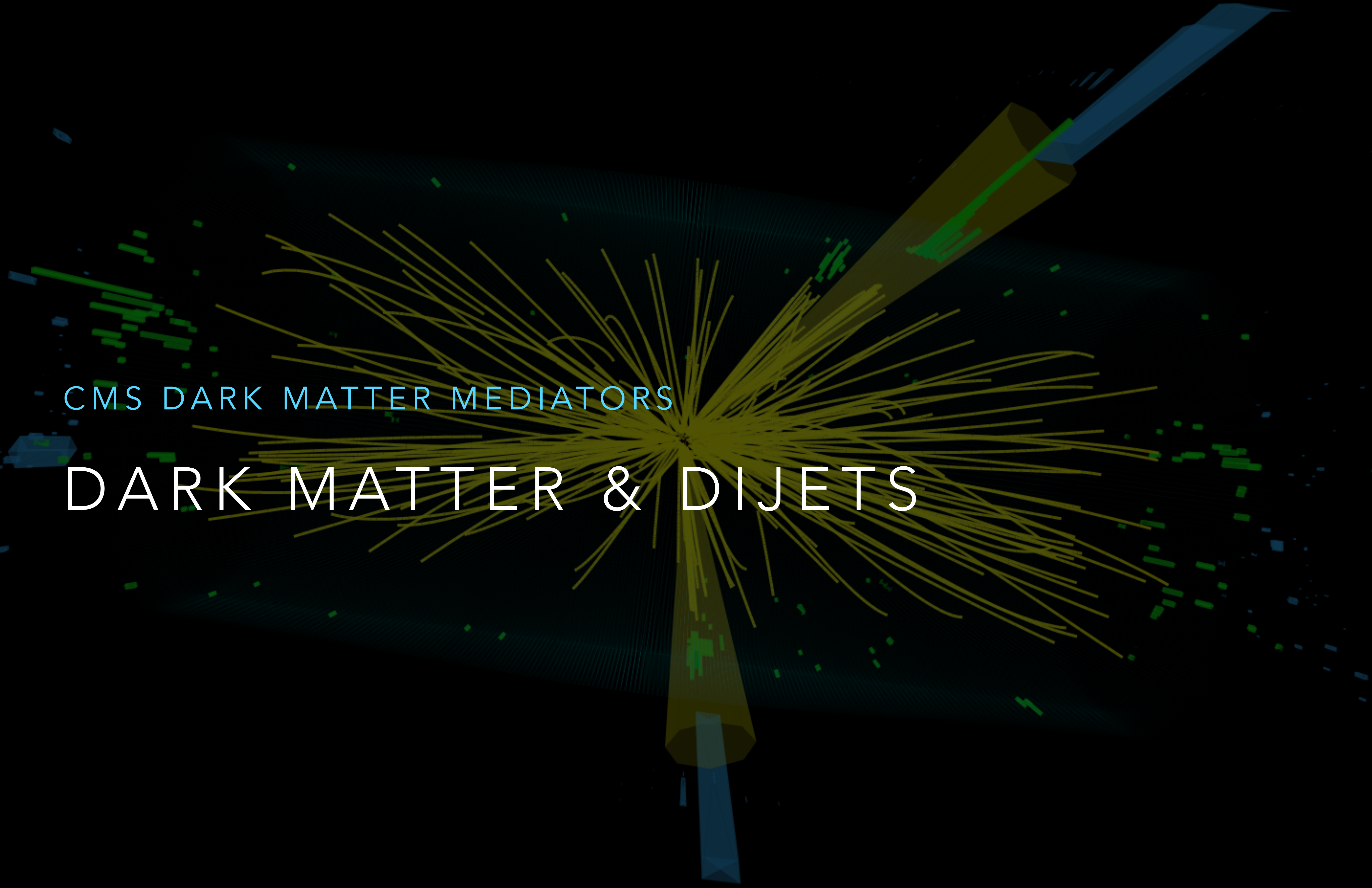
May 30, 2018

Javier Duarte

Fermilab

OUTLINE

- What can we do with dijet searches?
  - **Dark Matter & Dijets**
- How can we do more with dijet searches?
  - A new trigger-to-analysis paradigm
    - **Data Scouting**
  - Twist on a classic search
    - **Boosted Dijets**
- Summary and outlook



CMS DARK MATTER MEDIATORS

DARK MATTER & DIJETS

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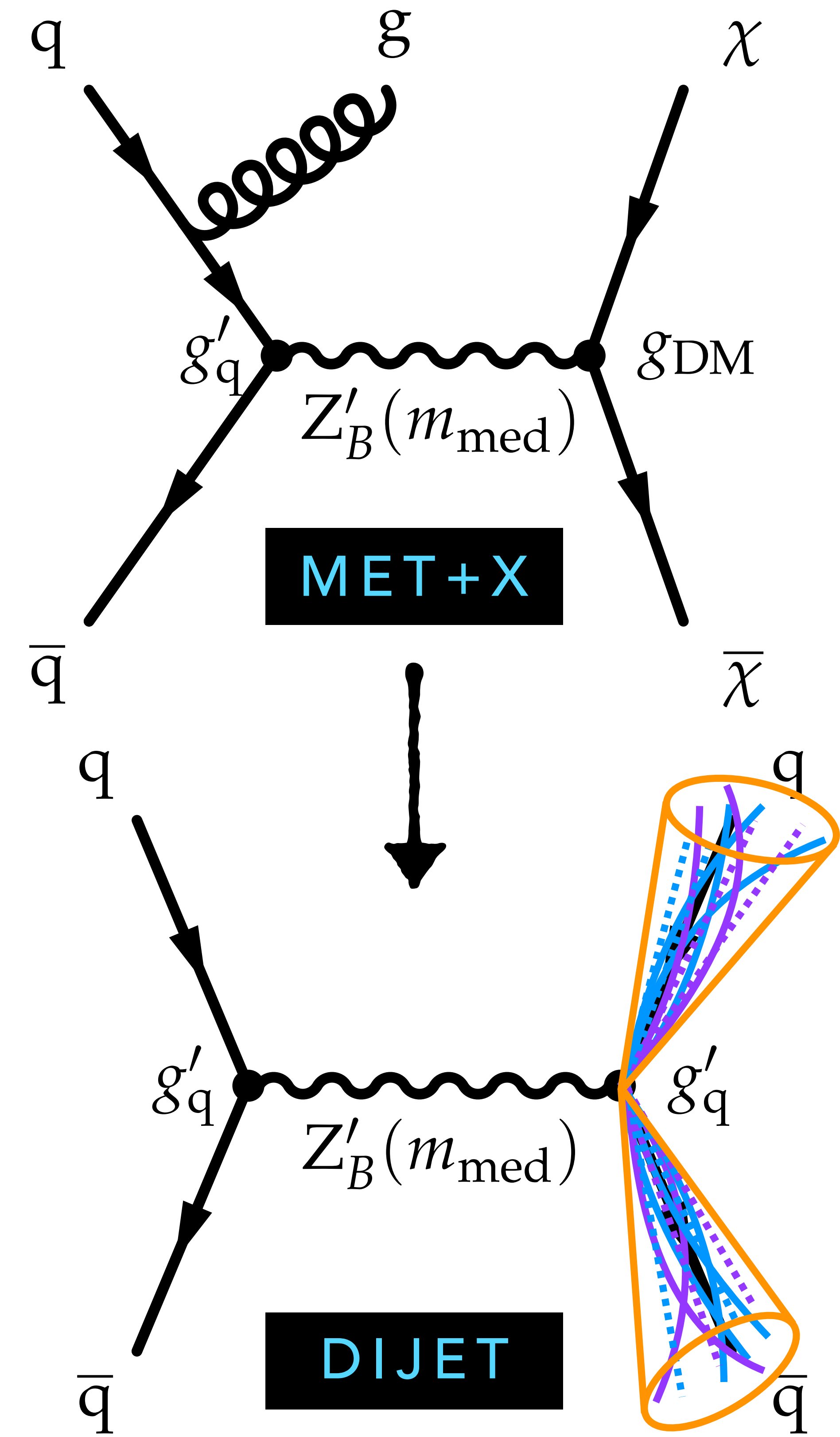
EXAMPLE DARK MATTER MEDIATOR

- At colliders, we search for dark matter production with large missing energy and some radiation to trigger on (**MET+X**)

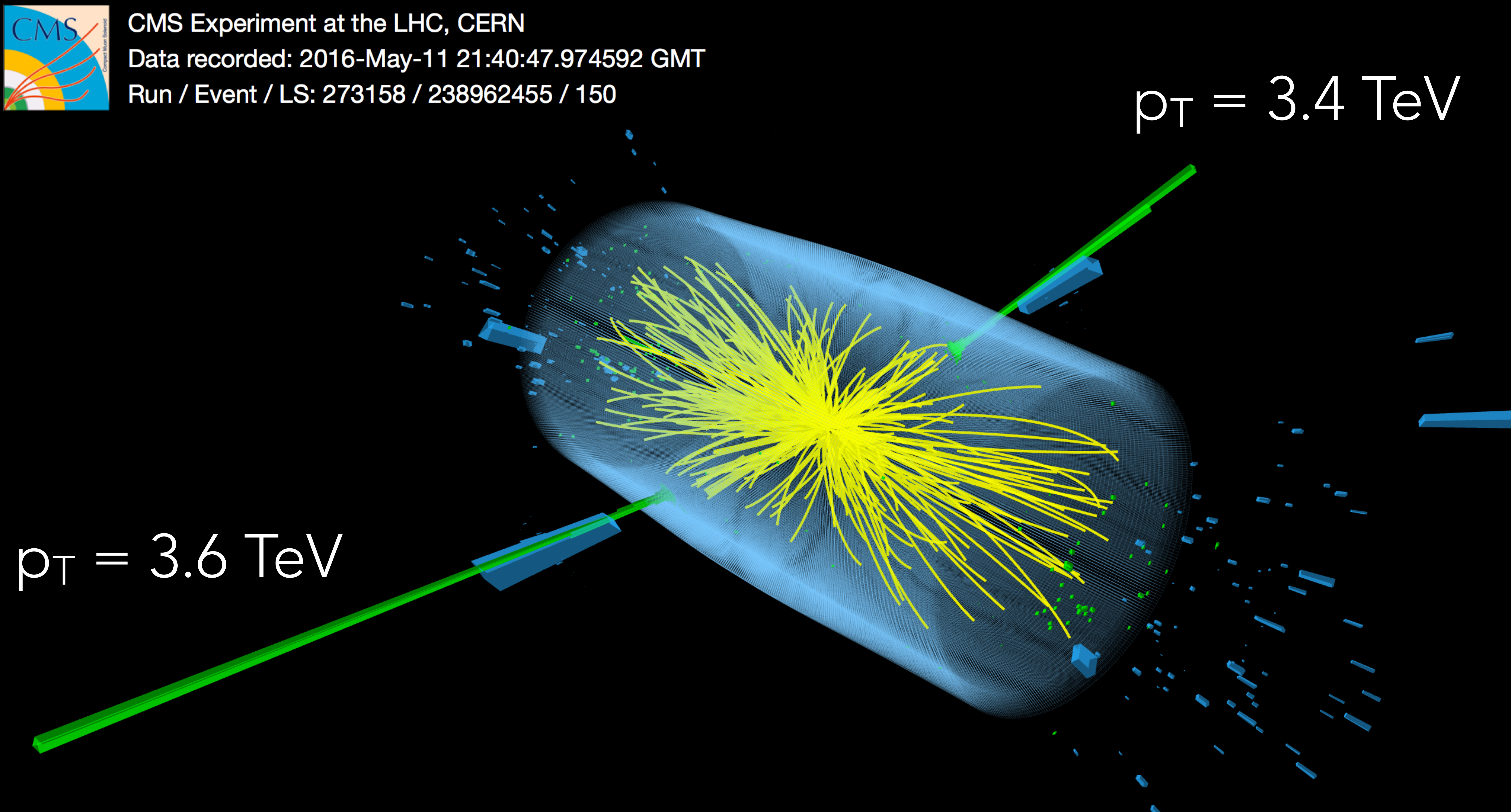
- Mediator may directly produce a **low-mass dijet resonance**



PLB 769 (2017) 520
EXO-16-056

DIJET EVENT IN CMS

- Dijet mass $\mathbf{m_{jj} = 7.7}$ **TeV**



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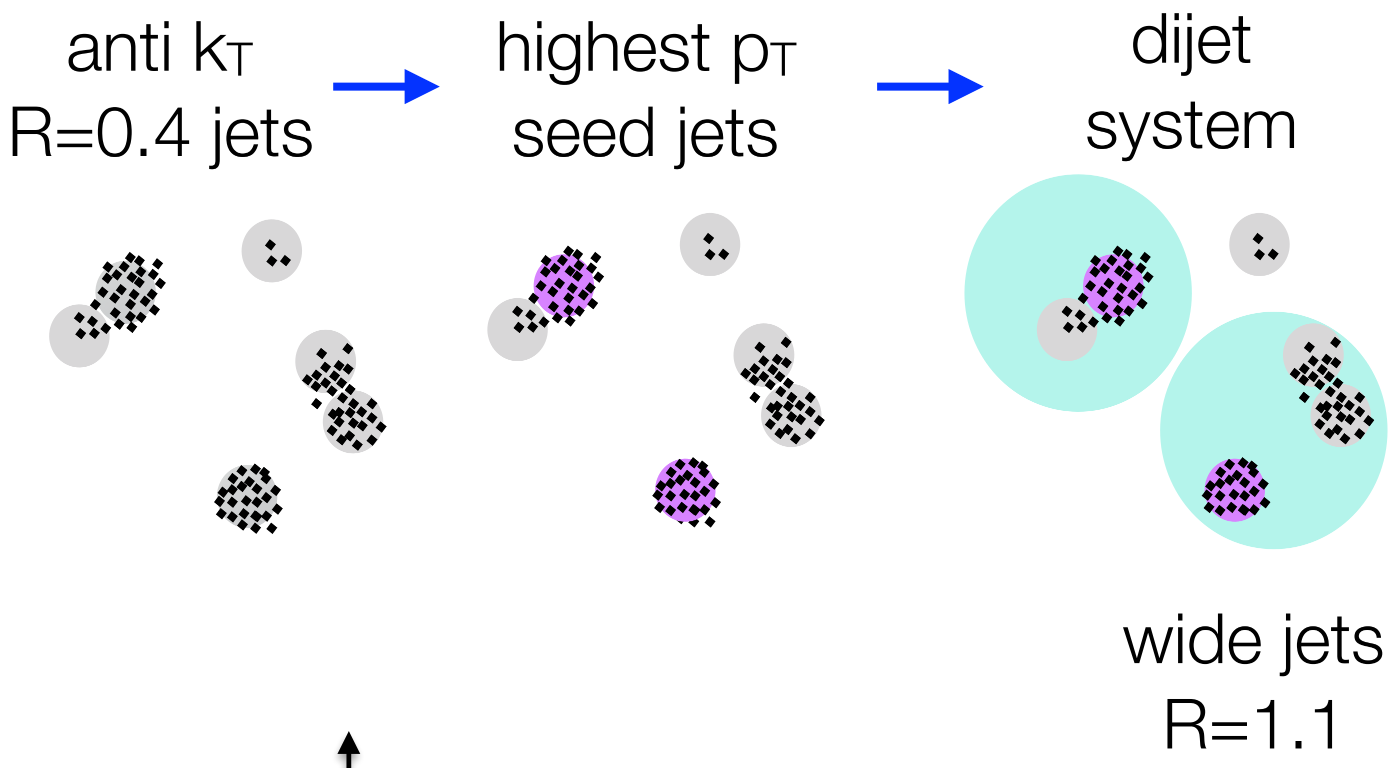
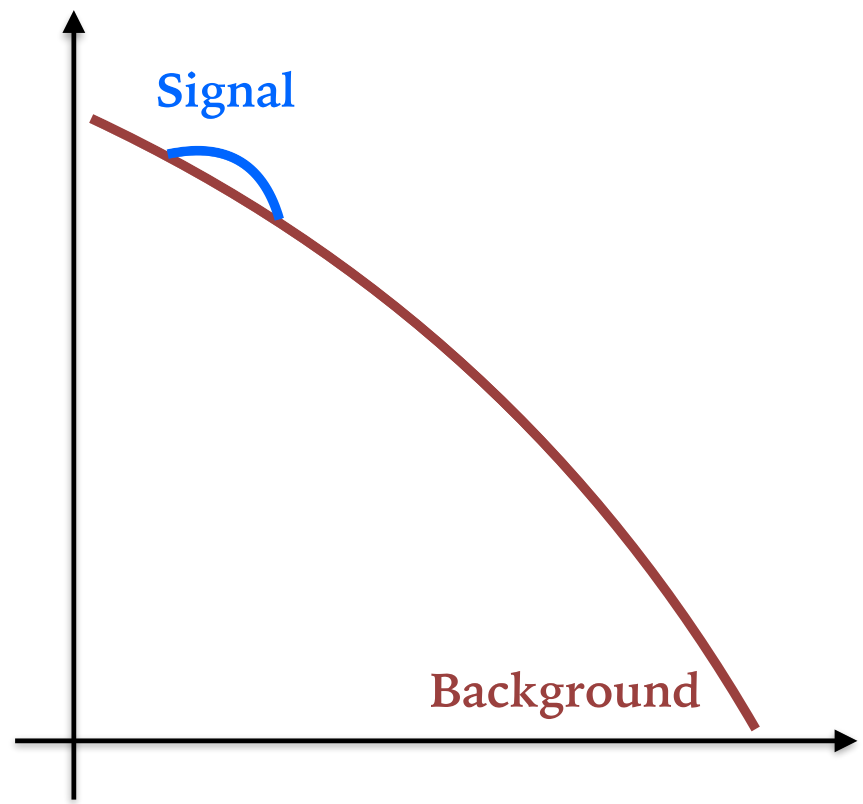
BASICS OF A DIJET SEARCH

- Collect data with a trigger based on $\mathbf{H_T}$ (sum of all transverse jet energies in the event)
- Cluster and select two "wide jets"
- Search for a **bump** on top of the ***smoothly falling QCD dijet background***





HIGH MASS FIT

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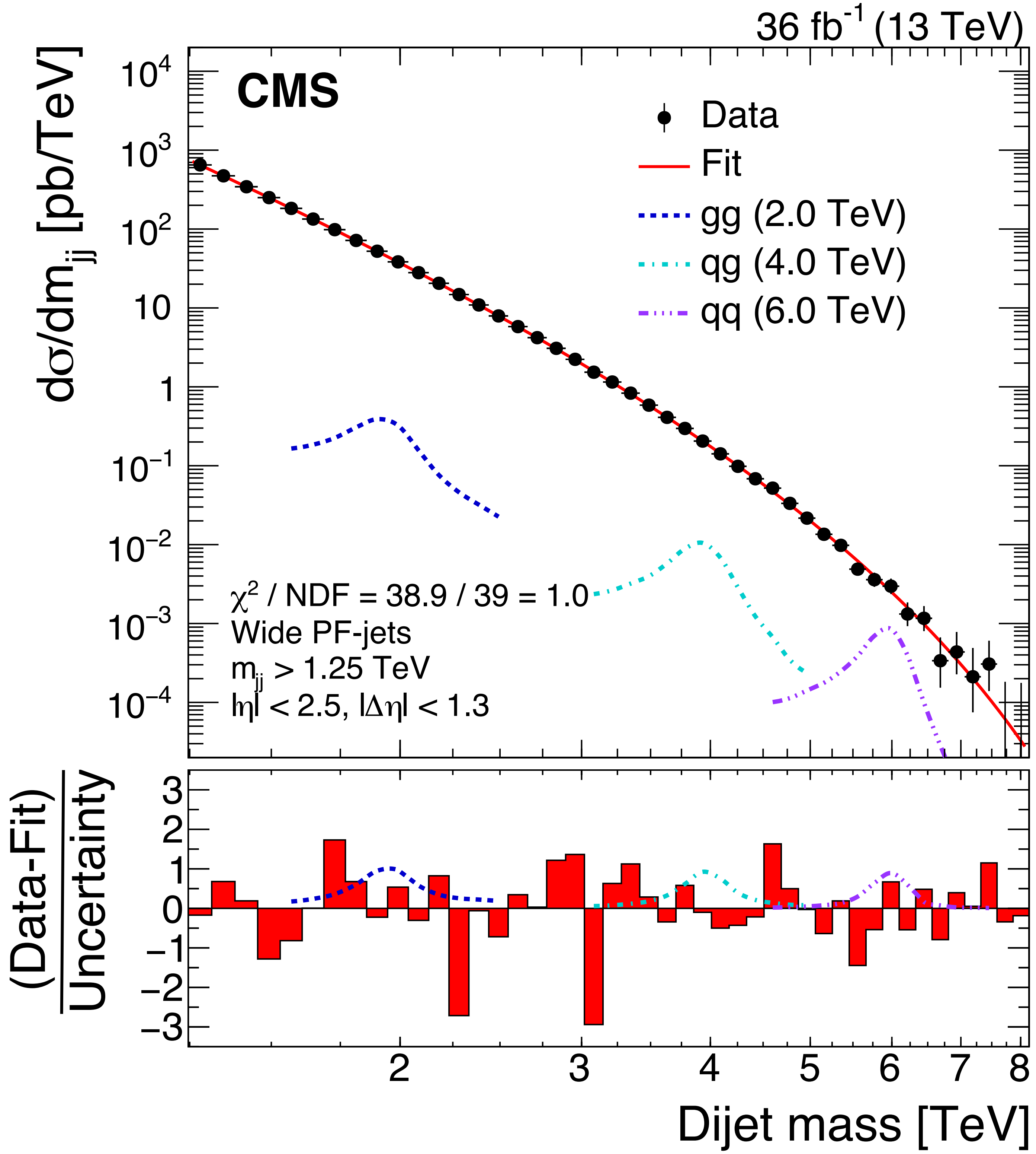
- With **H_T > 900 GeV** trigger, high mass spectrum fit starts at **m_{jj} > 1.25 TeV**

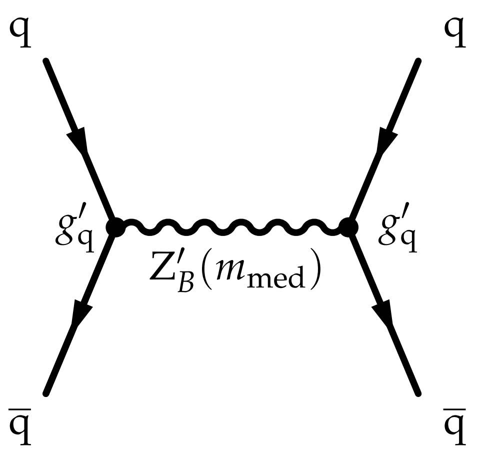
$$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)}}, \quad x = m_{jj}/\sqrt{s}$$

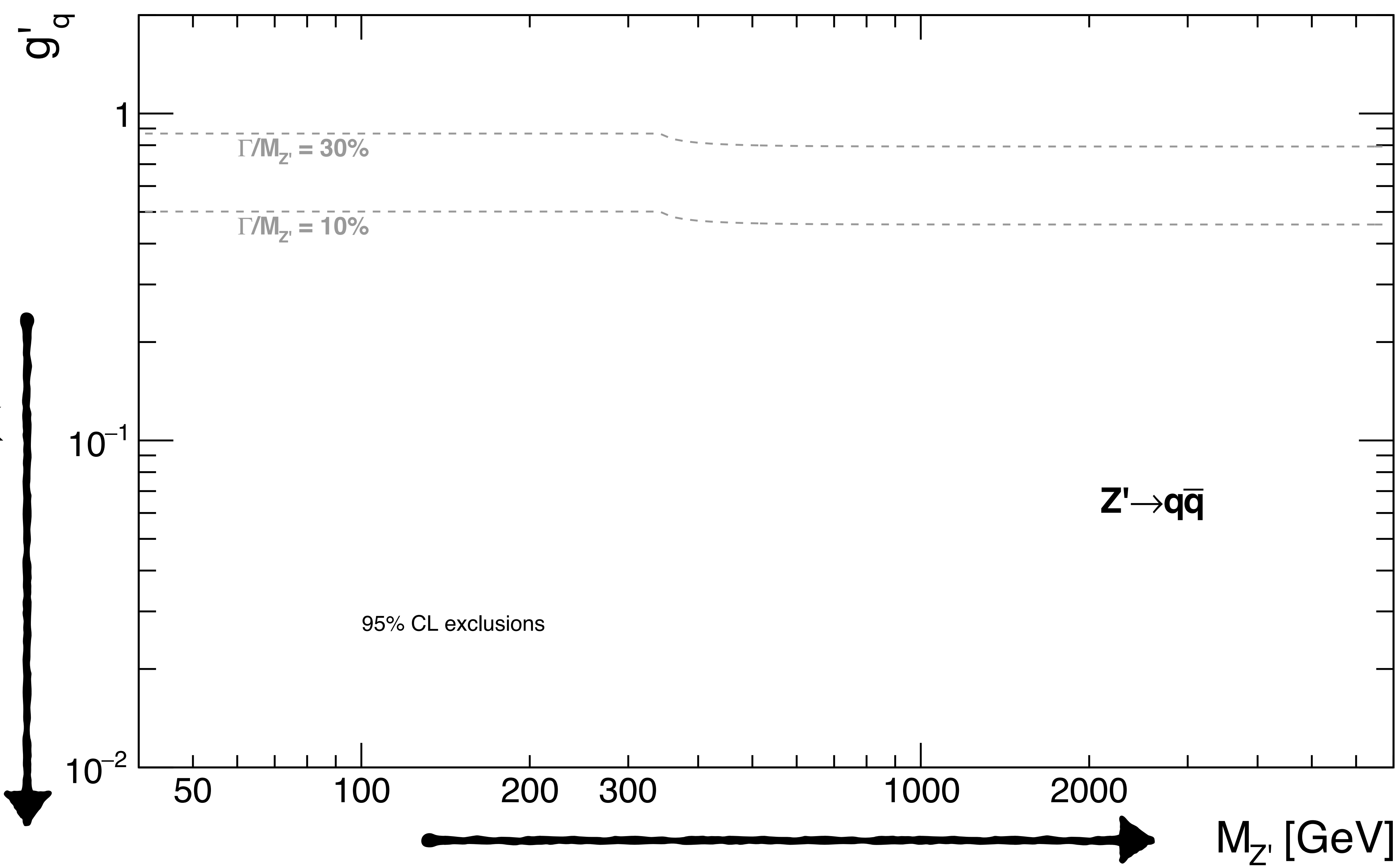
- χ^2/dof = 1.0
- How do we get **constraints** on **dark matter models**?



DARK MEDIATOR

- A **simplified model** of a **dark matter mediator**



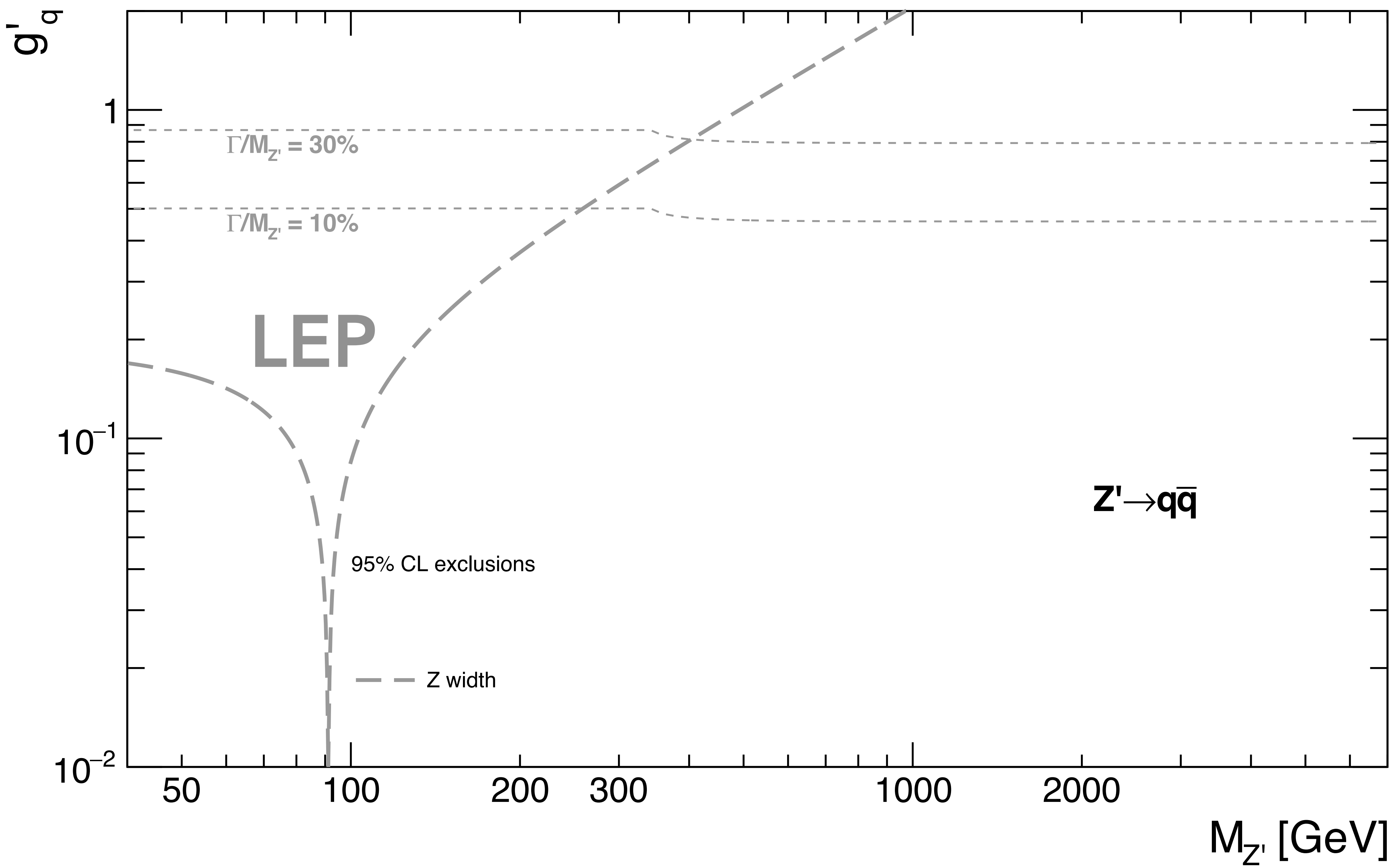


weaker quark coupling → smaller cross section

higher resonance mass

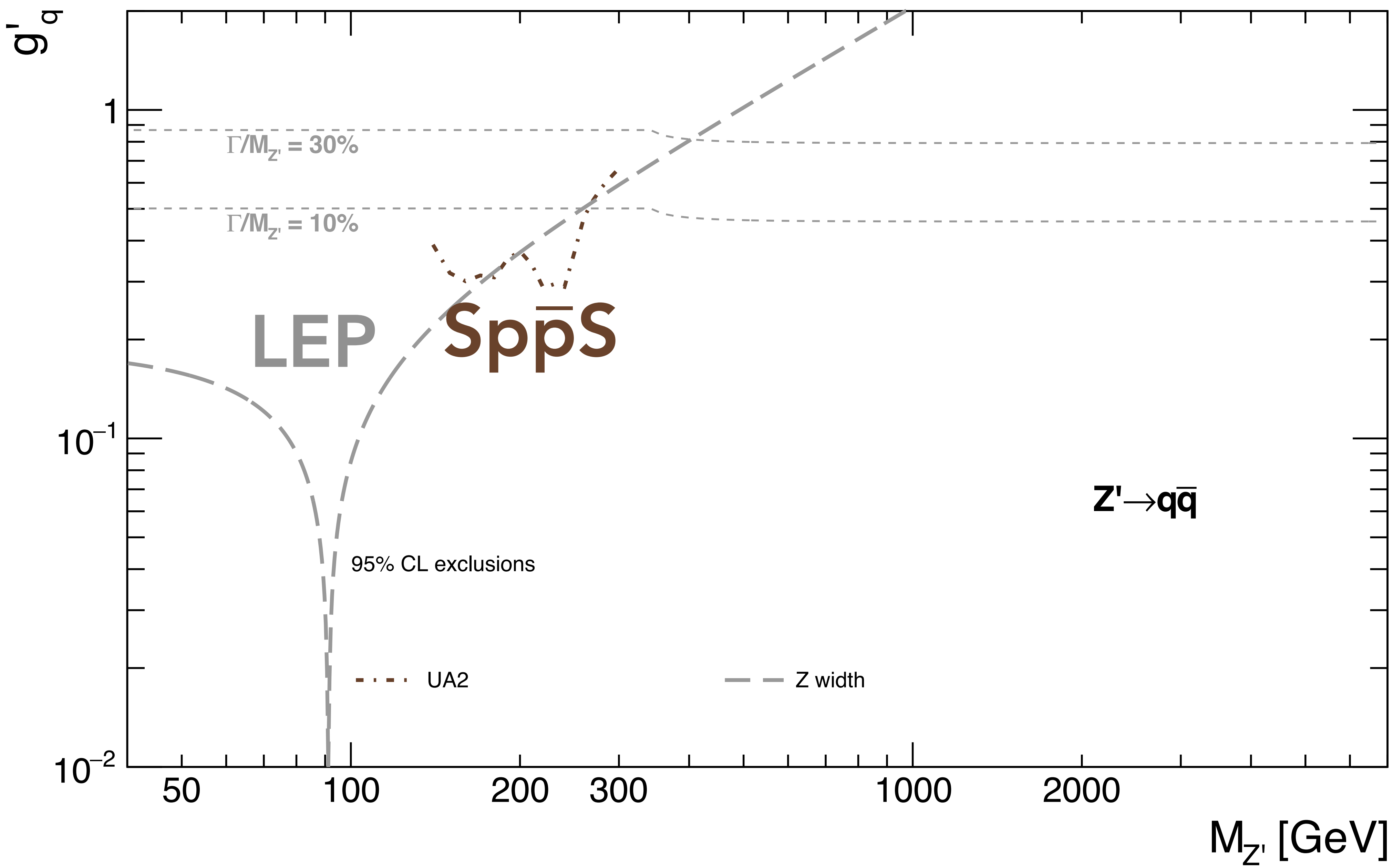
DARK MEDIATOR

- Precision measurements of the Z boson width from LEP



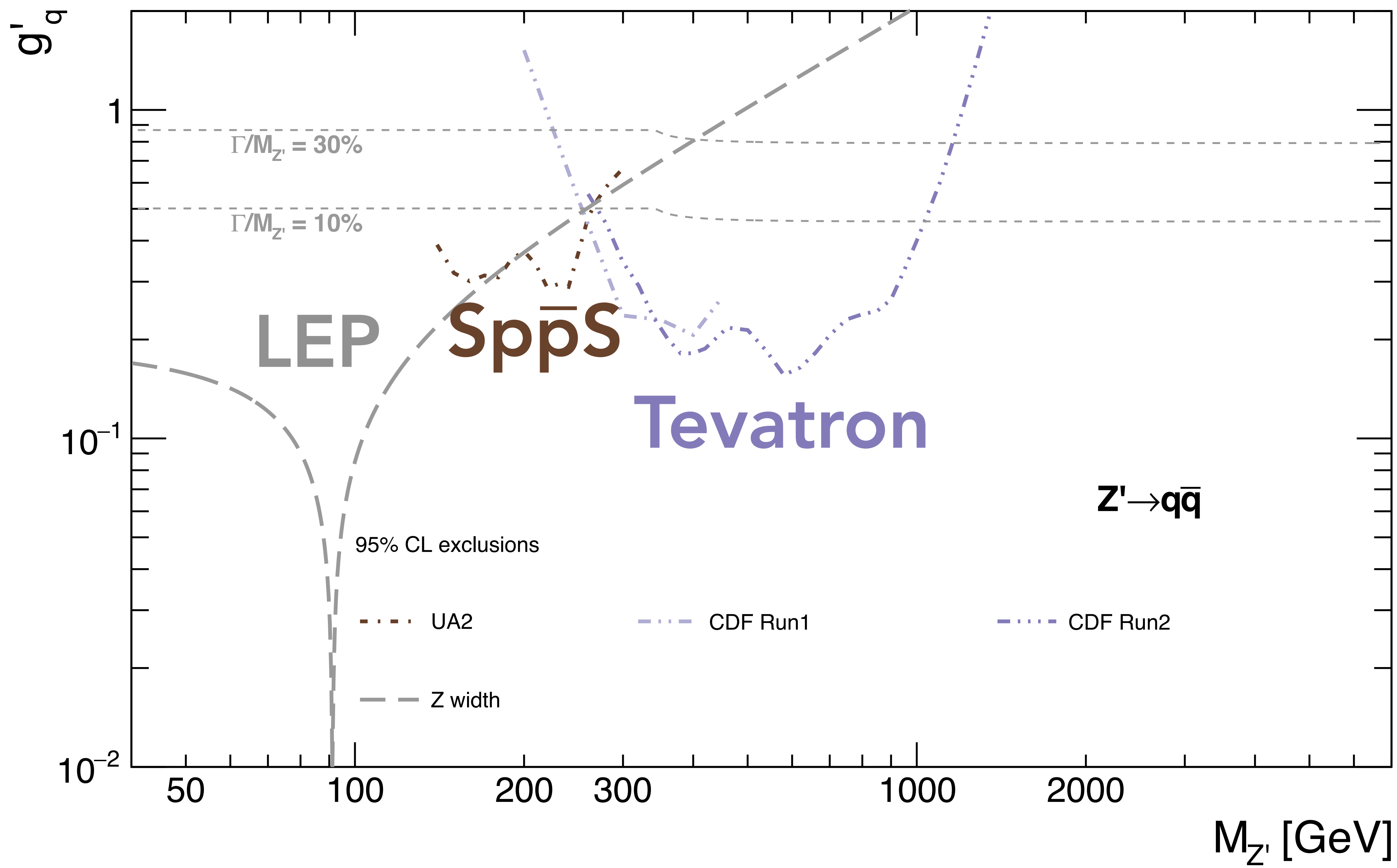
DARK MEDIATOR

- UA2 dijet search at the S$p\bar{p}$S at CERN, 1993



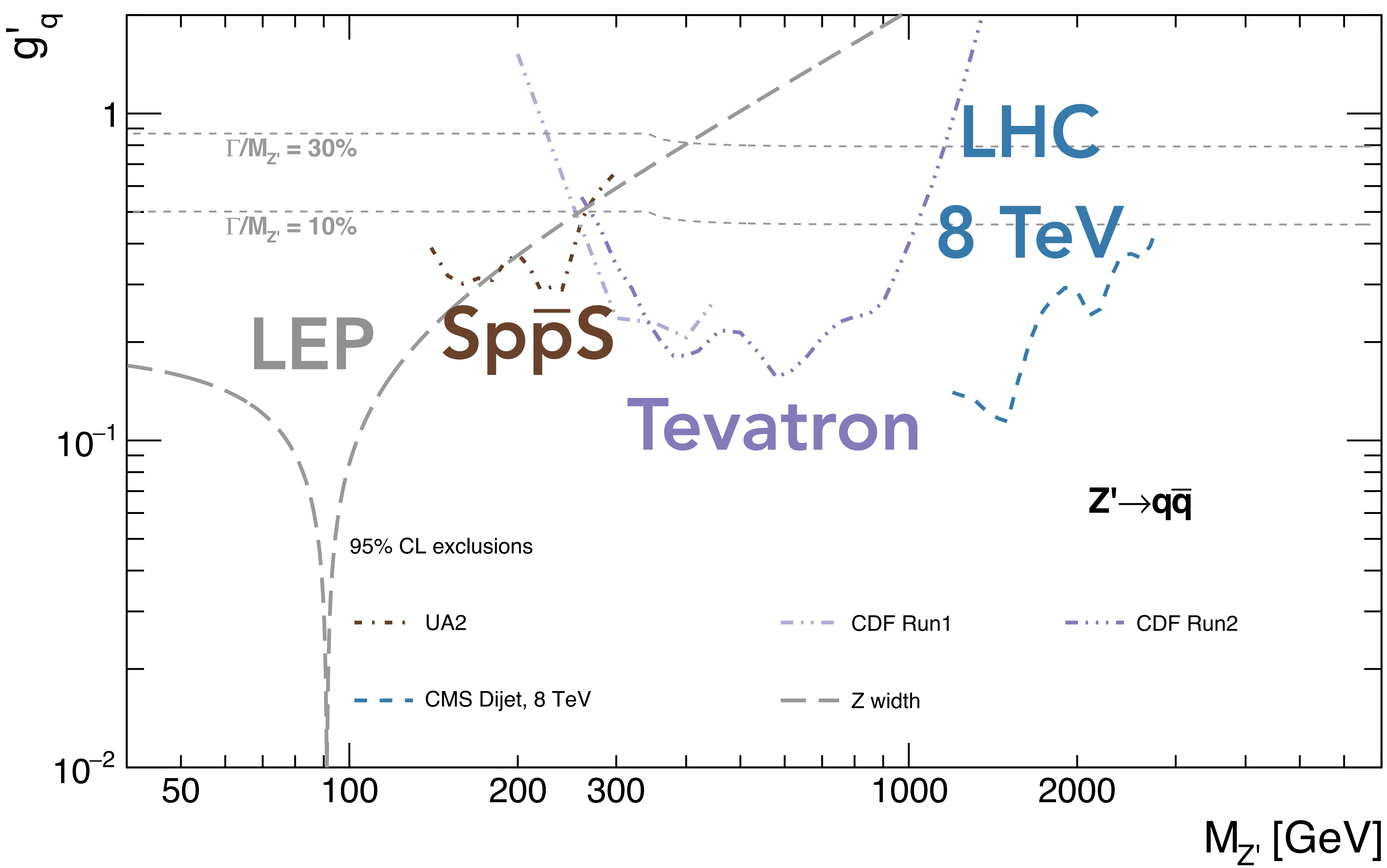
DARK MEDIATOR

- CDF dijet search at the Tevatron at Fermilab, 2009



DARK MEDIATOR

- CMS dijet search the LHC (8 TeV), 2012



DARK MEDIATOR

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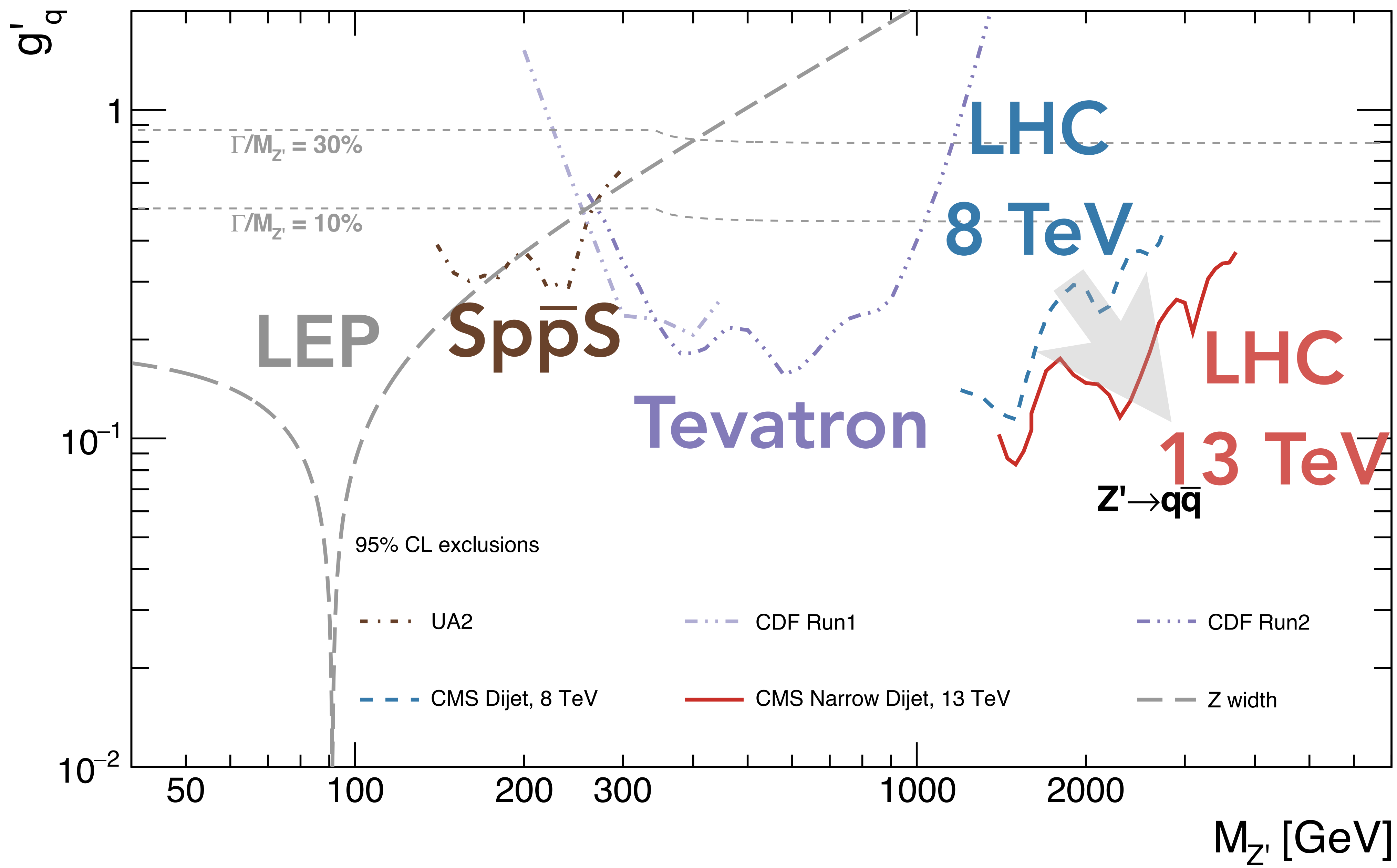
- Higher energy only let us exclude new physics at **high mass**



DARK MEDIATOR

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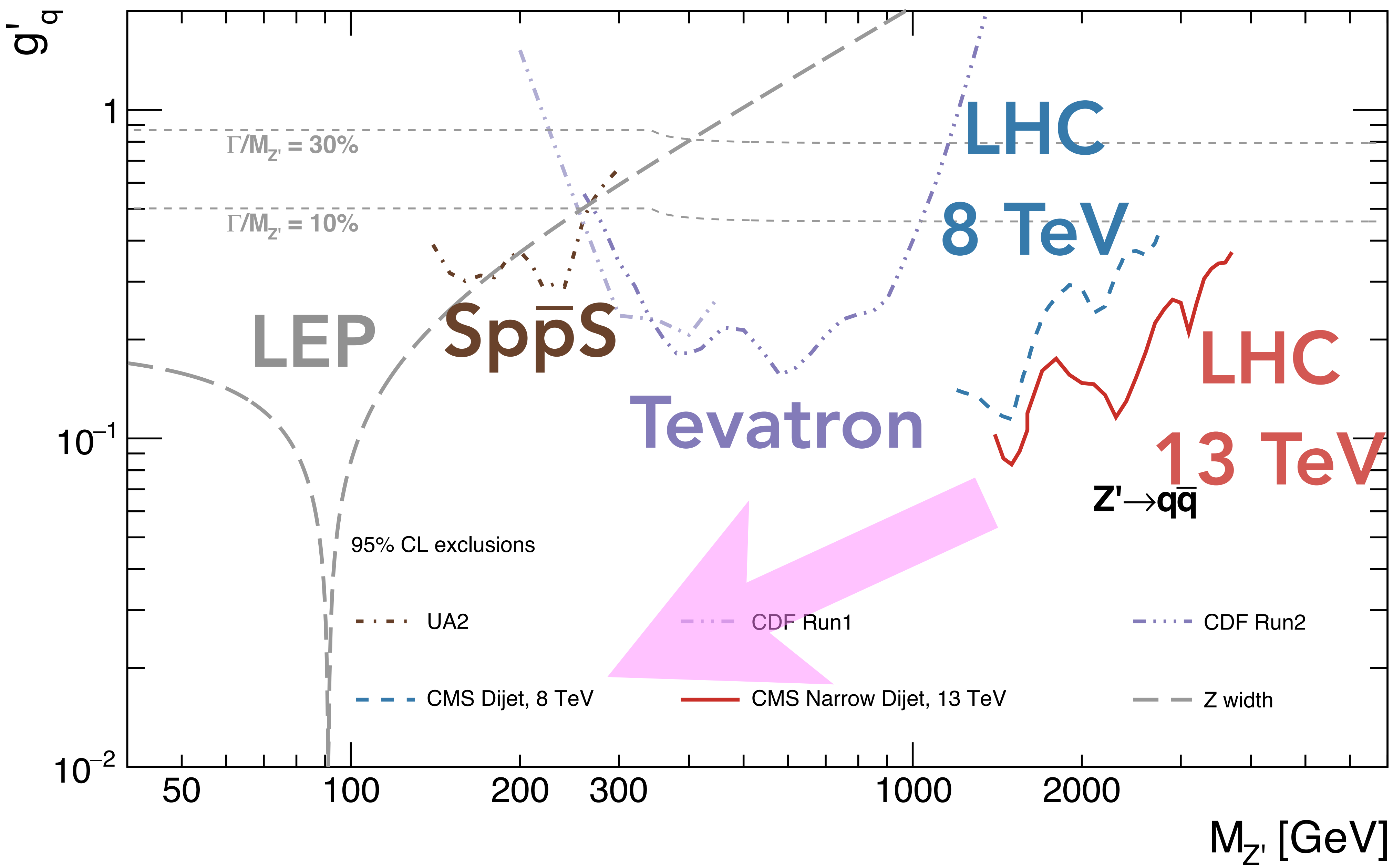
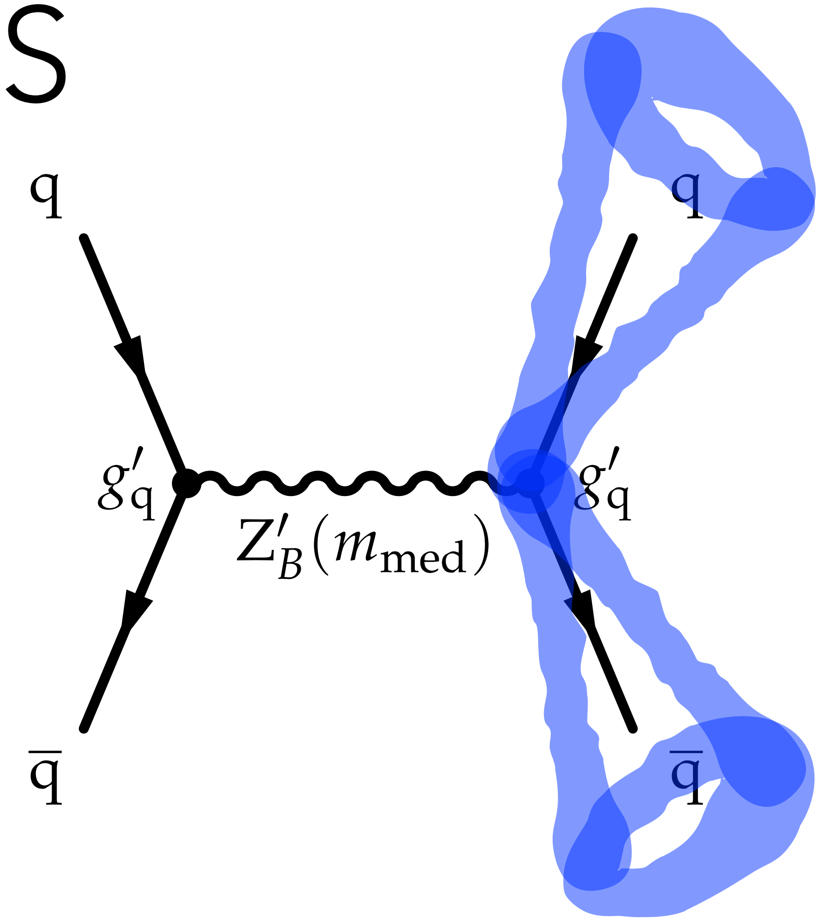
EXO-16-056

- How can we look for **weakly-coupled** new physics at **low mass**?

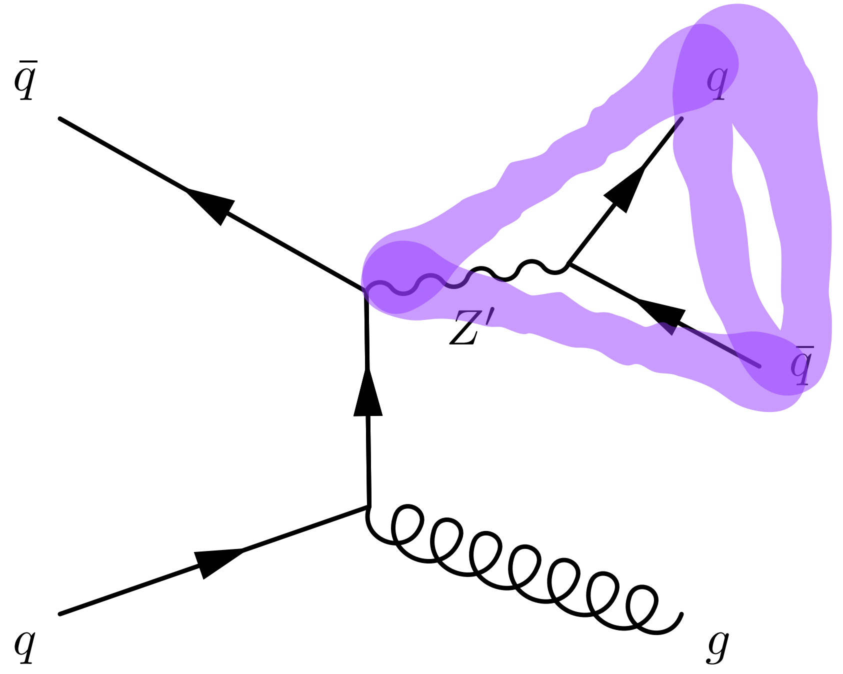


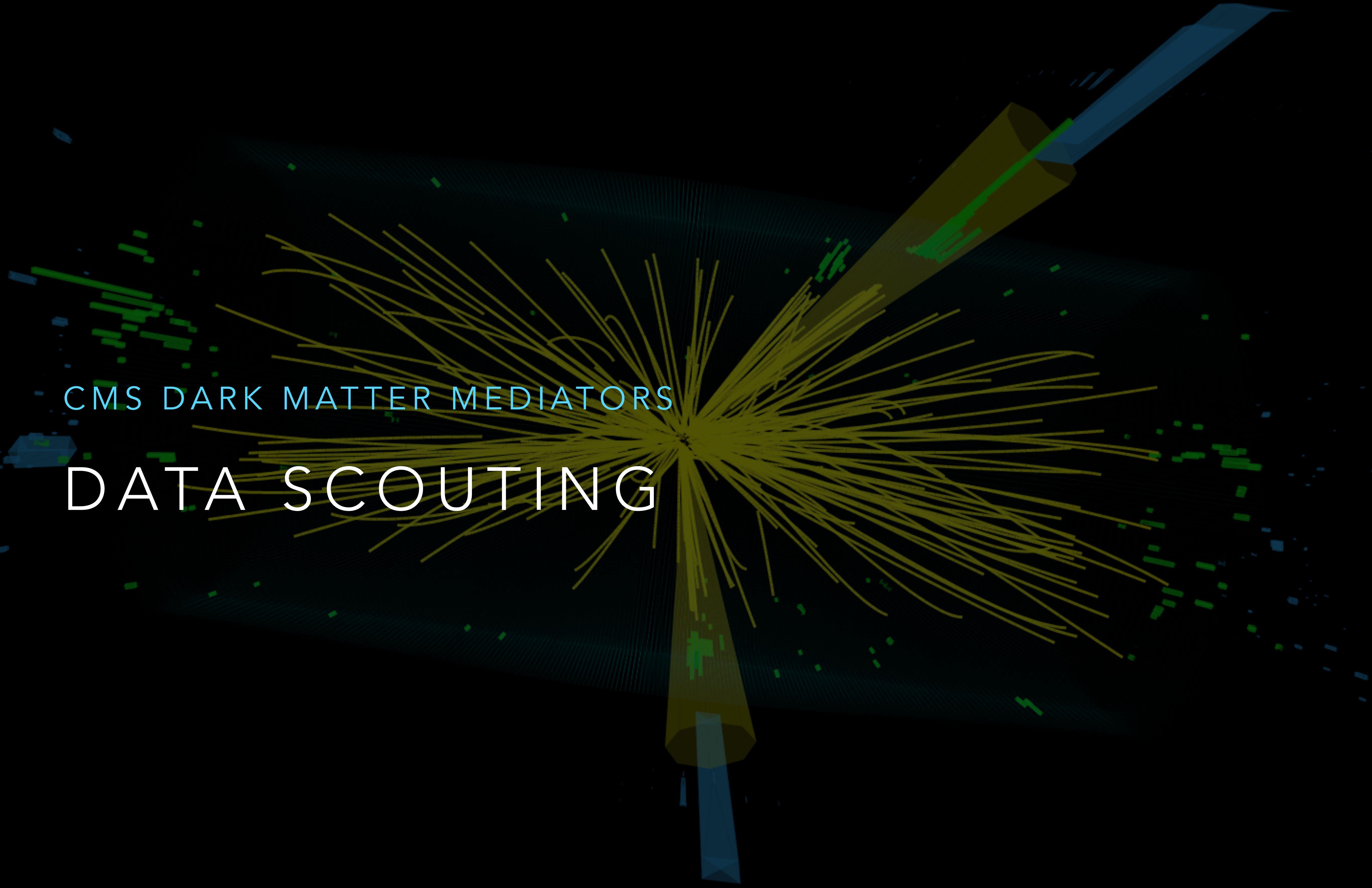
TWO METHODS

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



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





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DATA SCOUTING

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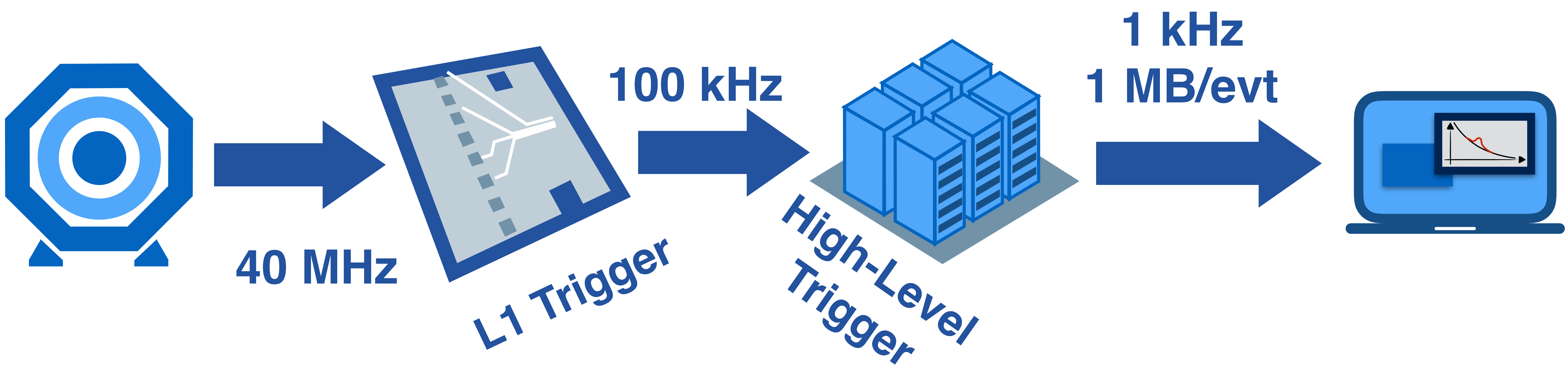
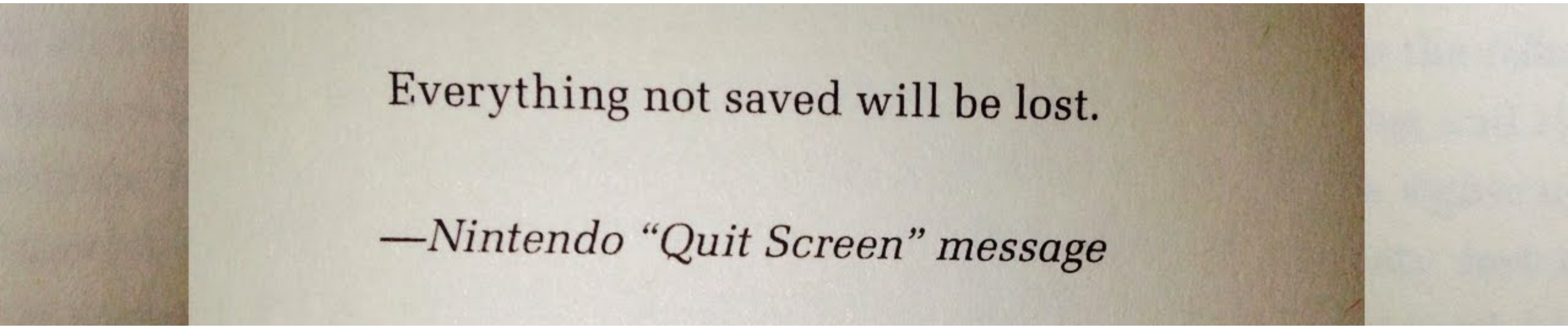
TWO-LEVEL TRIGGER



- Level-1 Trigger (hardware)
  - **99.75% rejected**
  - decision in **~4 μs**
- High-Level Trigger (software)
  - **99% rejected**
  - decision in **~100s ms**

- After trigger, **99.99975%** of events are gone forever

TWO-LEVEL TRIGGER


Everything not saved will be lost.

—*Nintendo "Quit Screen" message*

- After trigger, **99.99975%** of events are gone forever

TRIGGER LIMITATIONS

- Two limitations for standard stream given data acquisition and computing resources:

- **CPU time** < **~100s ms**

- **Total Bandwidth** = event size × event rate **< ~1 GB/s**
  = **1 MB** **×** **1 kHz** **< ~1 GB/s**

TRIGGER LIMITATIONS

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- **CPU time** < **~100s ms**

- **Total Bandwidth** = event size × event rate **< ~1 GB/s**

  = **1 MB** **×** **1 kHz** **< ~1 GB/s**

Can we shrink **size** to increase **rate**?

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

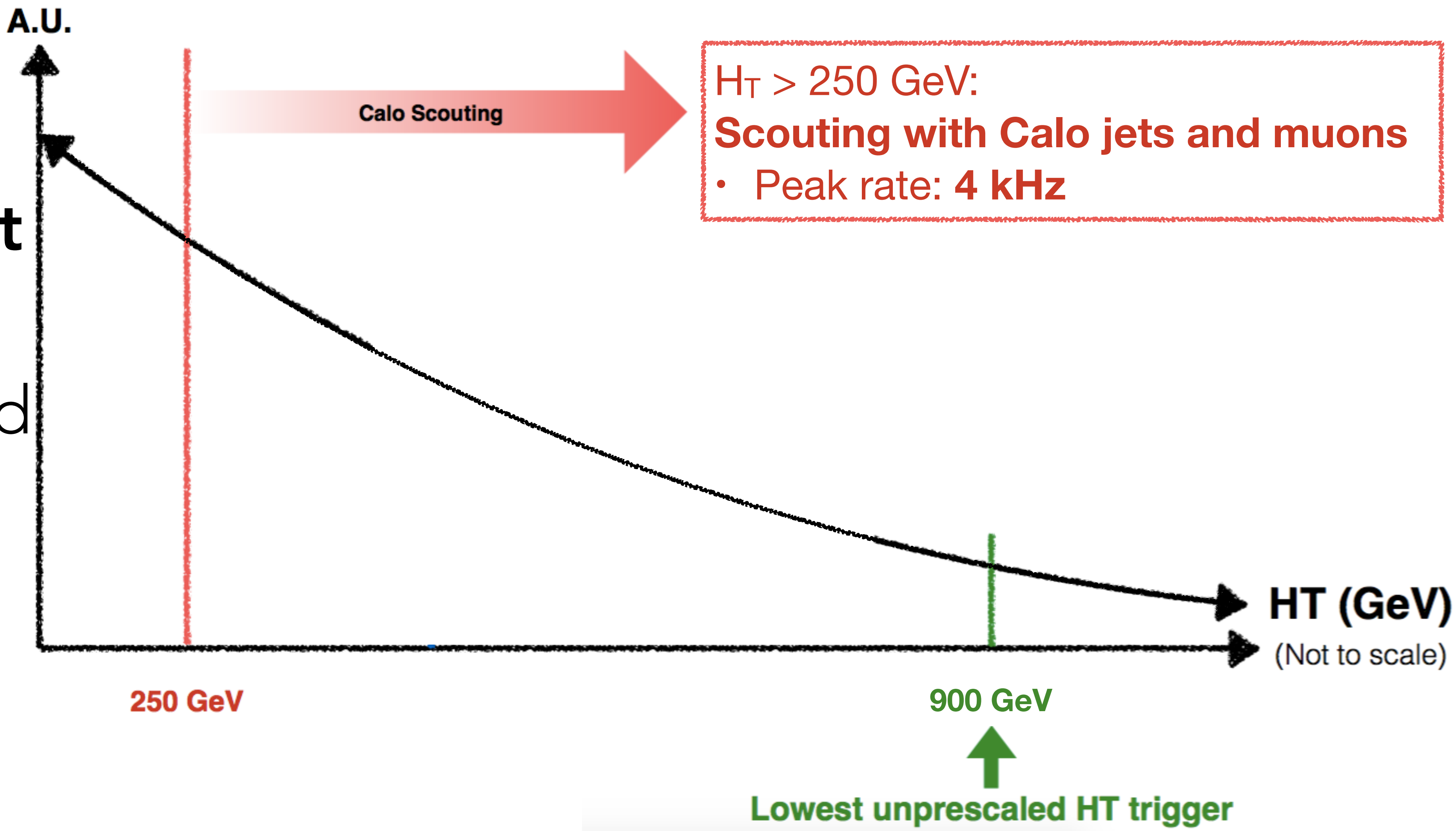
DATA SCOUTING

- **Reconstruct & store** only the information necessary to perform certain analyses → record many more events
- **Monitoring dataset** (~1/200 of events) is fully reconstructed
- "**Calo Scouting**" gets down to **H_T > 250 GeV**

Calo Scouting

4 kHz × 3 kB

= 12 MB/s



LOW MASS FIT

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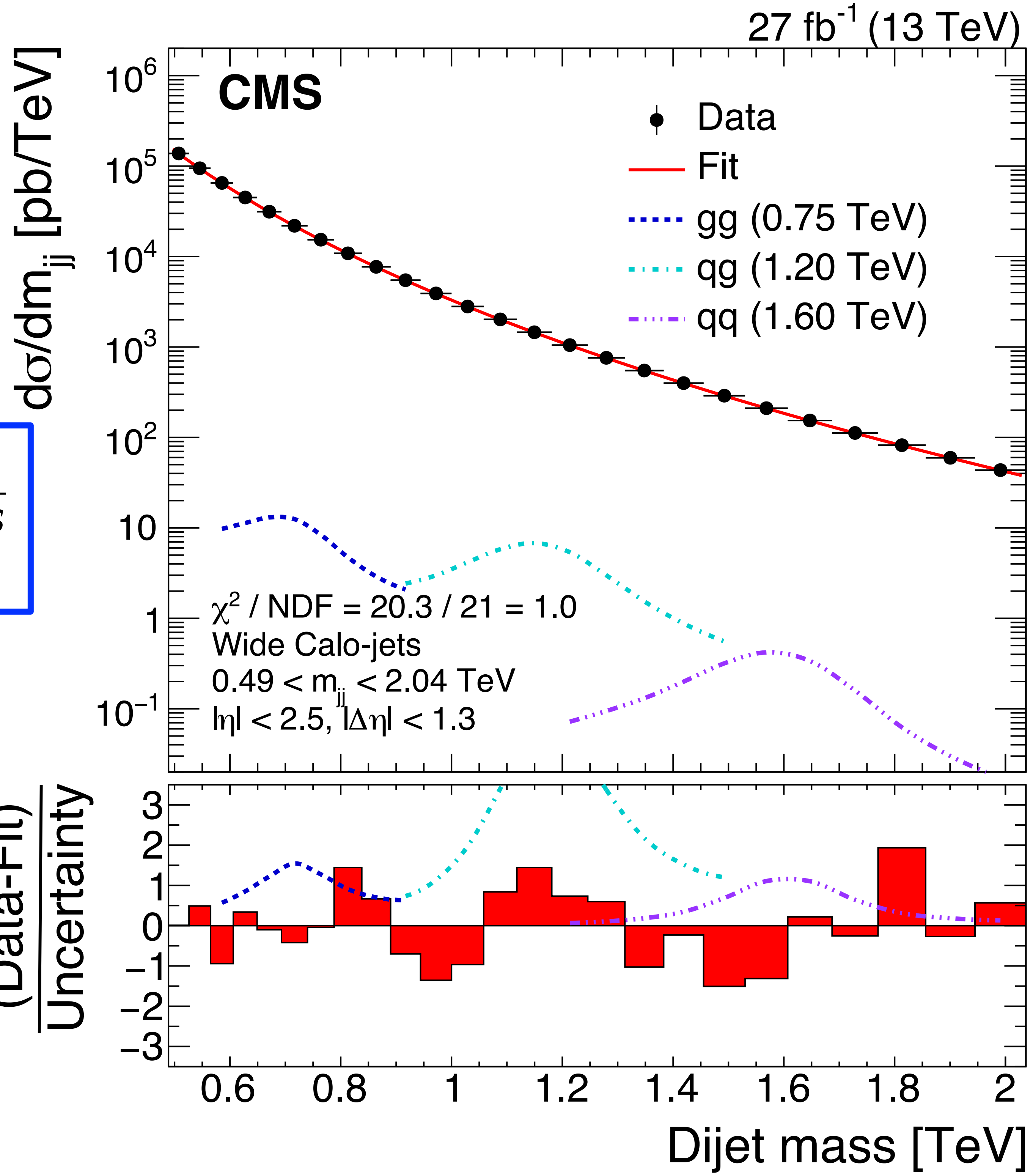
[EXO-16-056](#)

- Using "Calo Scouting," **low mass** spectrum* is fit above $\mathbf{m_{jj} > 489}$ **GeV**

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

- $\chi^2/\text{dof} = 1.0$
- What does this mean for **dark mediators**?



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

DARK MEDIATOR

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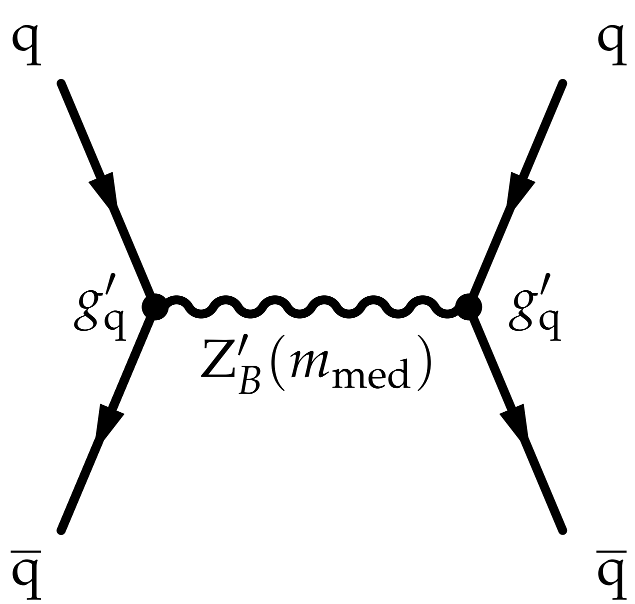

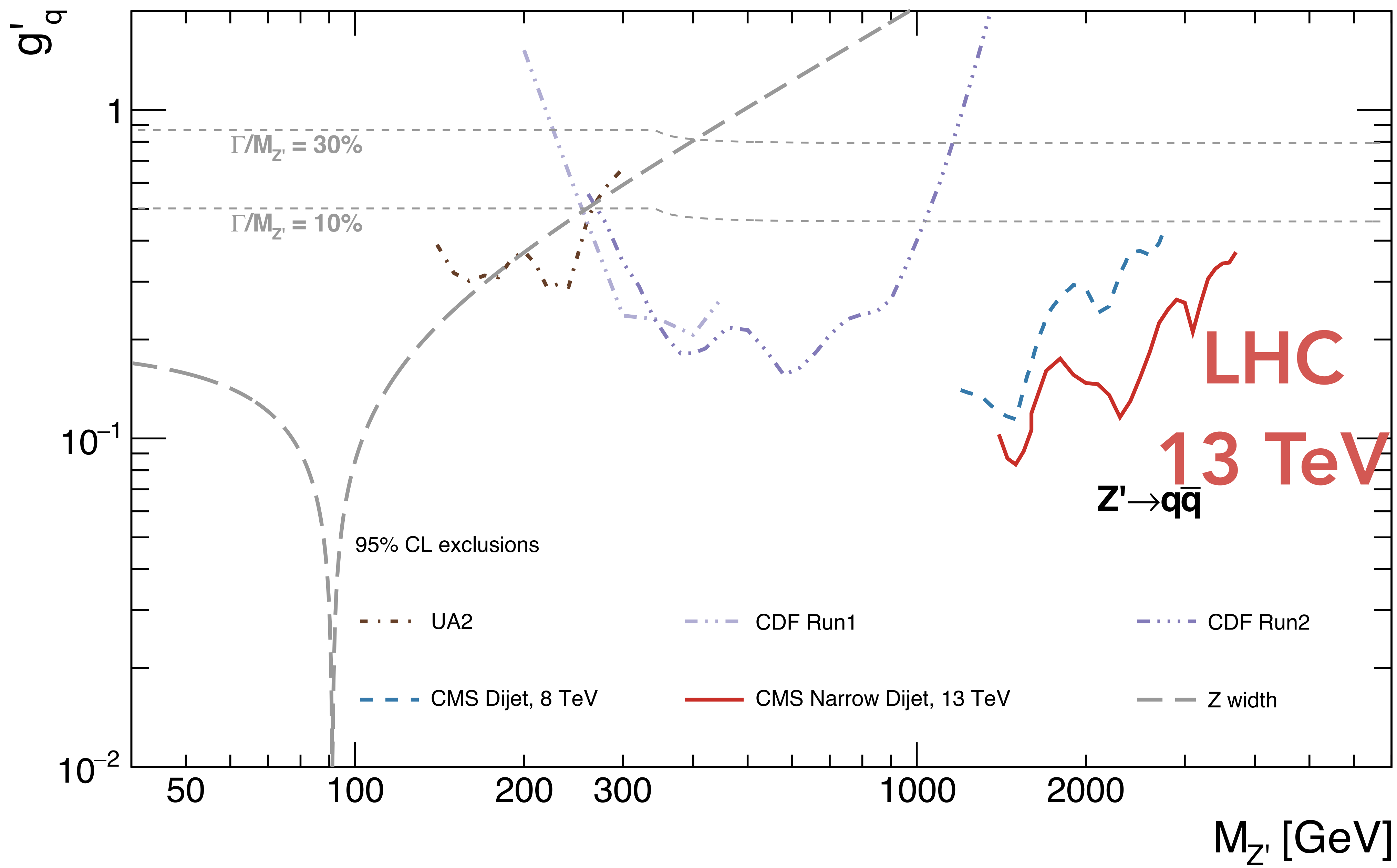

DARK MEDIATOR

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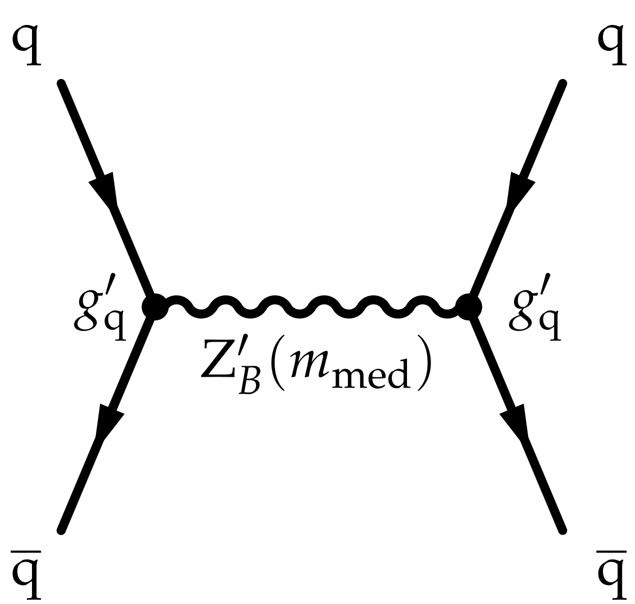
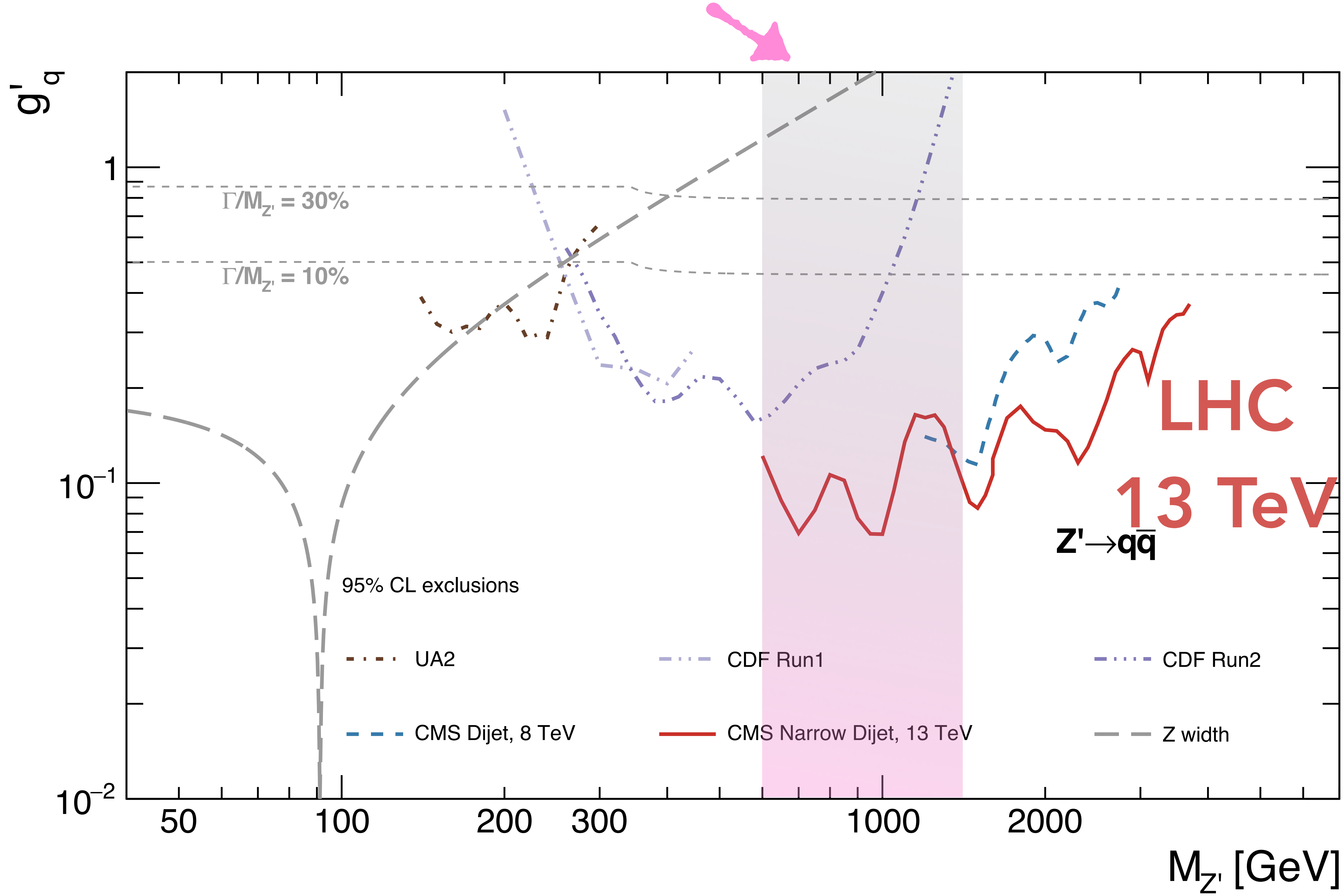
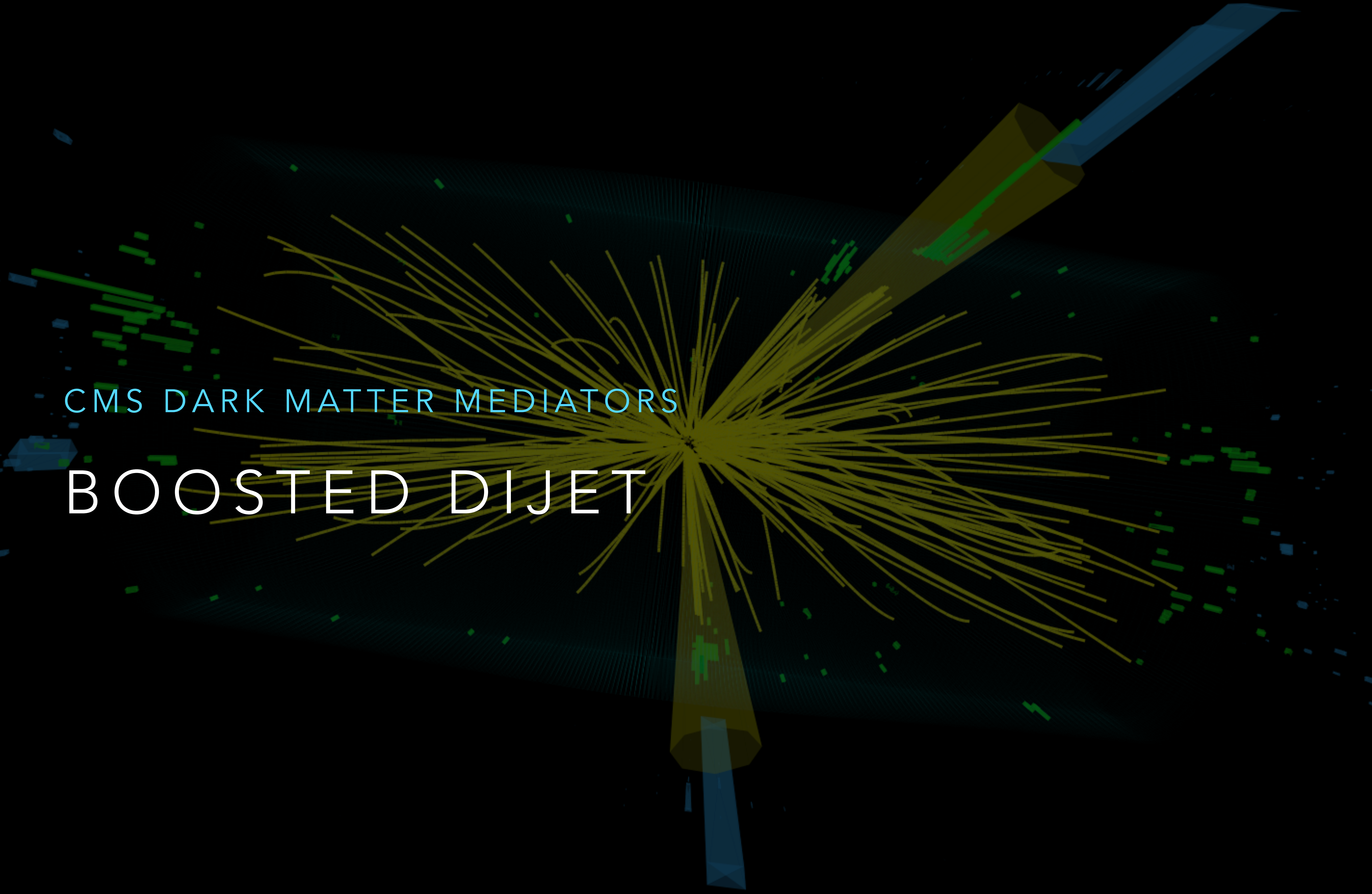
- Expanded CMS reach down to 600 GeV







CMS DARK MATTER MEDIATORS

BOOSTED DIJET

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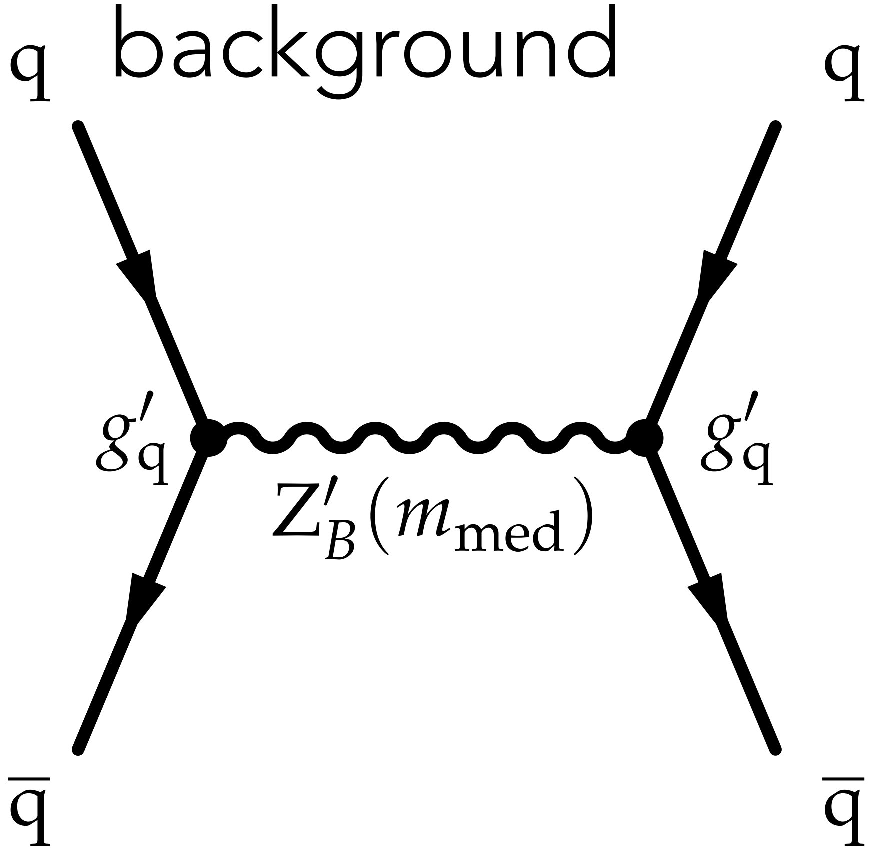
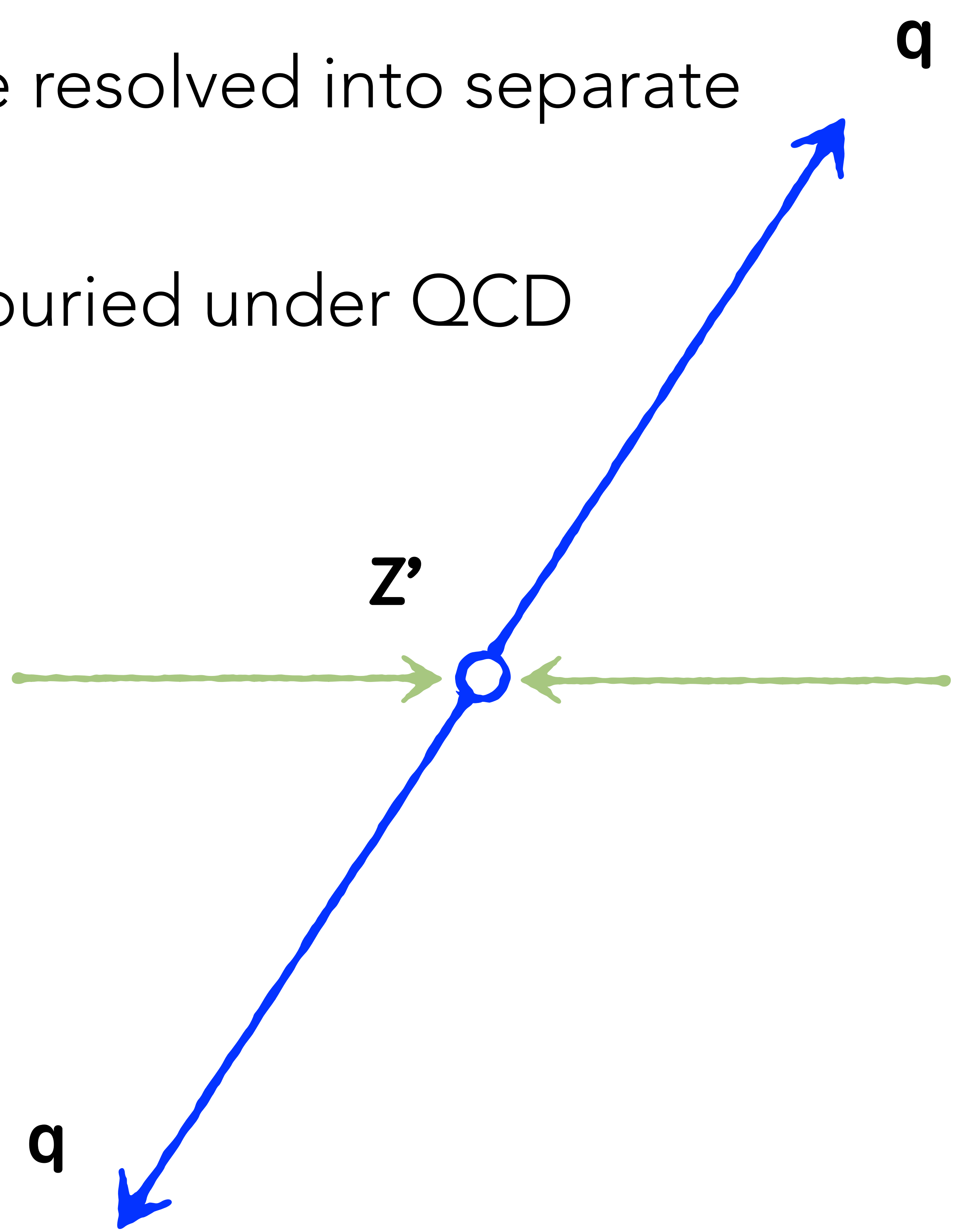
DIJET TOPOLOGY

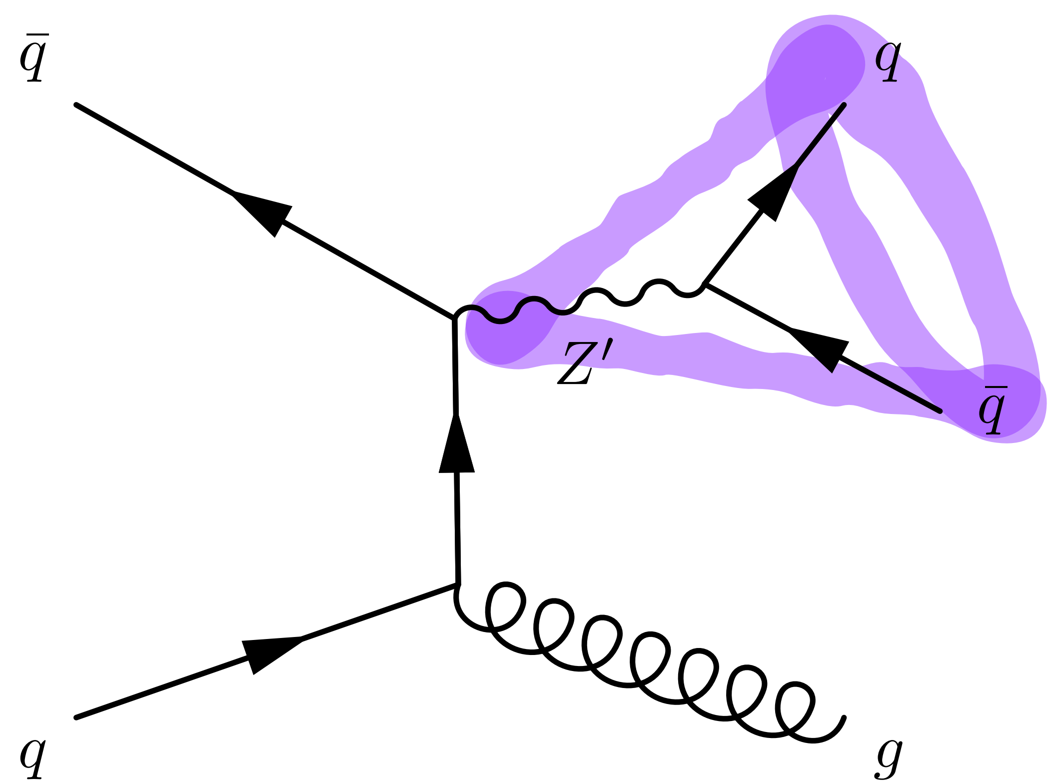
- At low p_T, the quarks are resolved into separate jets
- Difficult to trigger and buried under QCD background

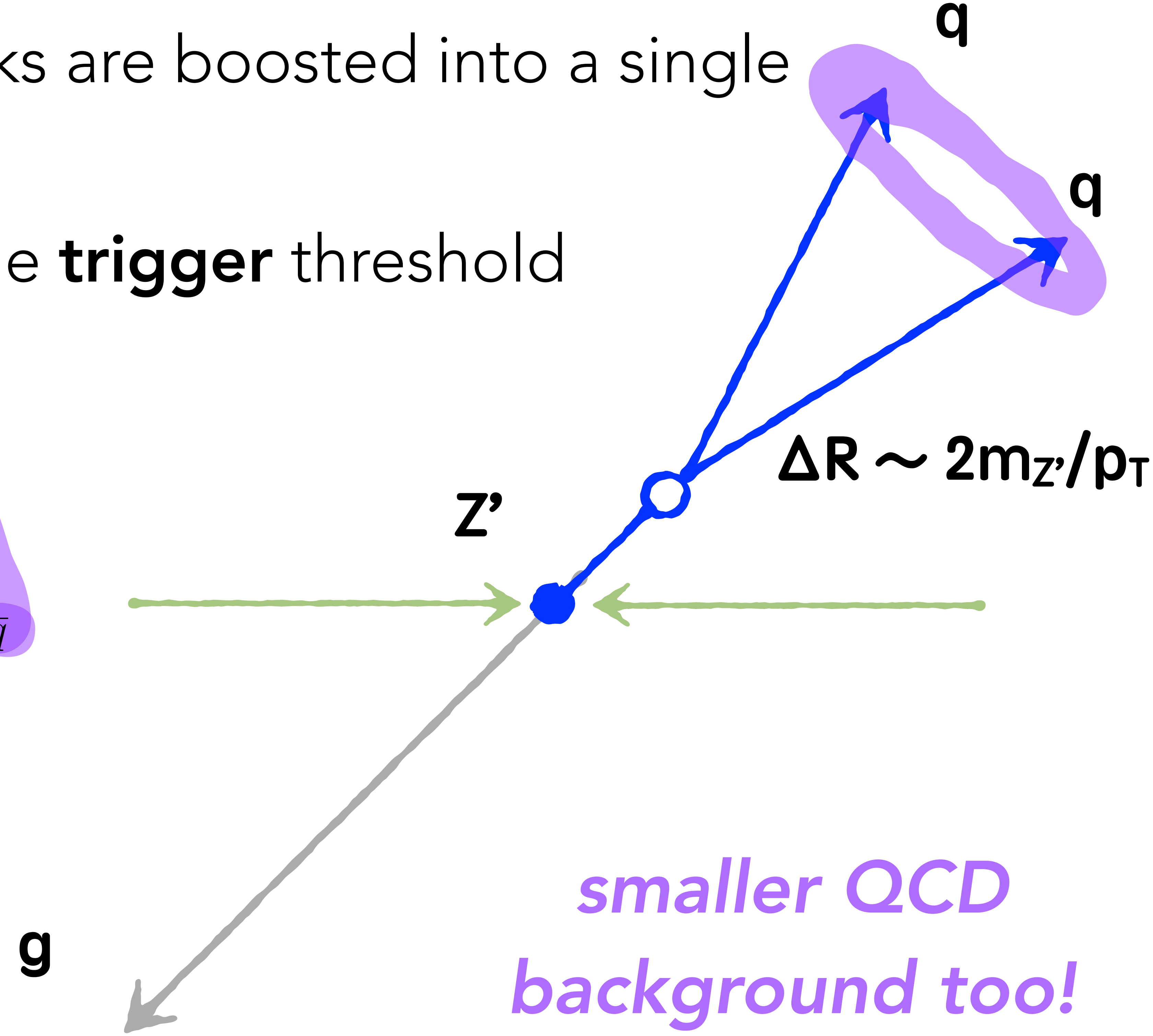




BOOSTED DIJET TOPOLOGY

- At high p_T, the quarks are boosted into a single large-radius jet
- ISR gets us above the **trigger** threshold

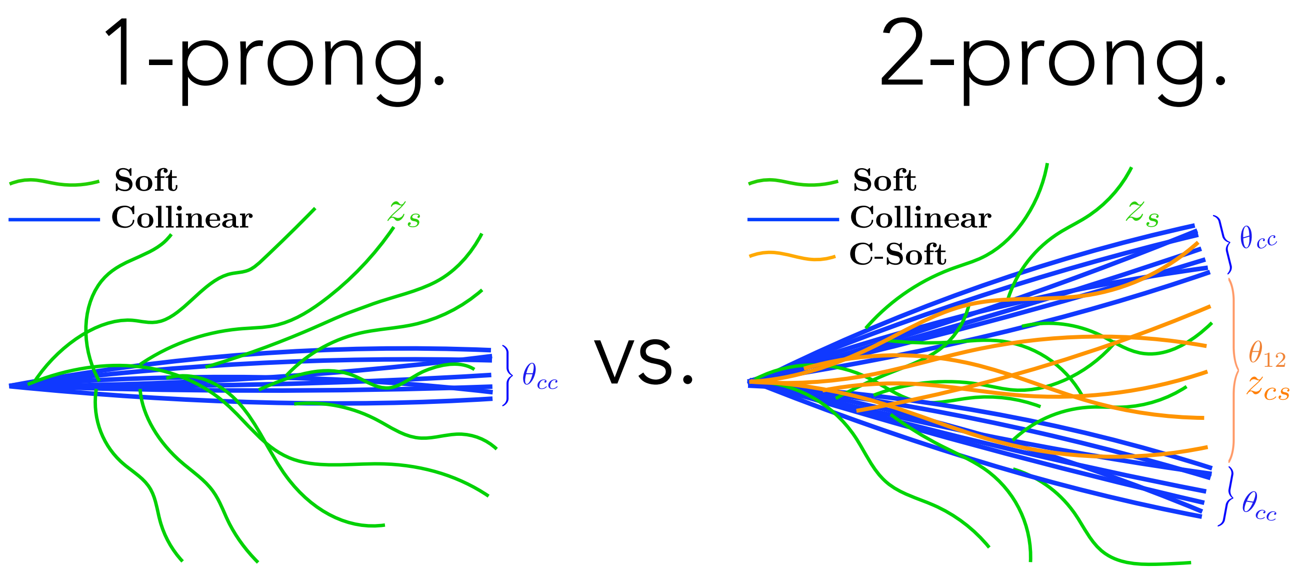




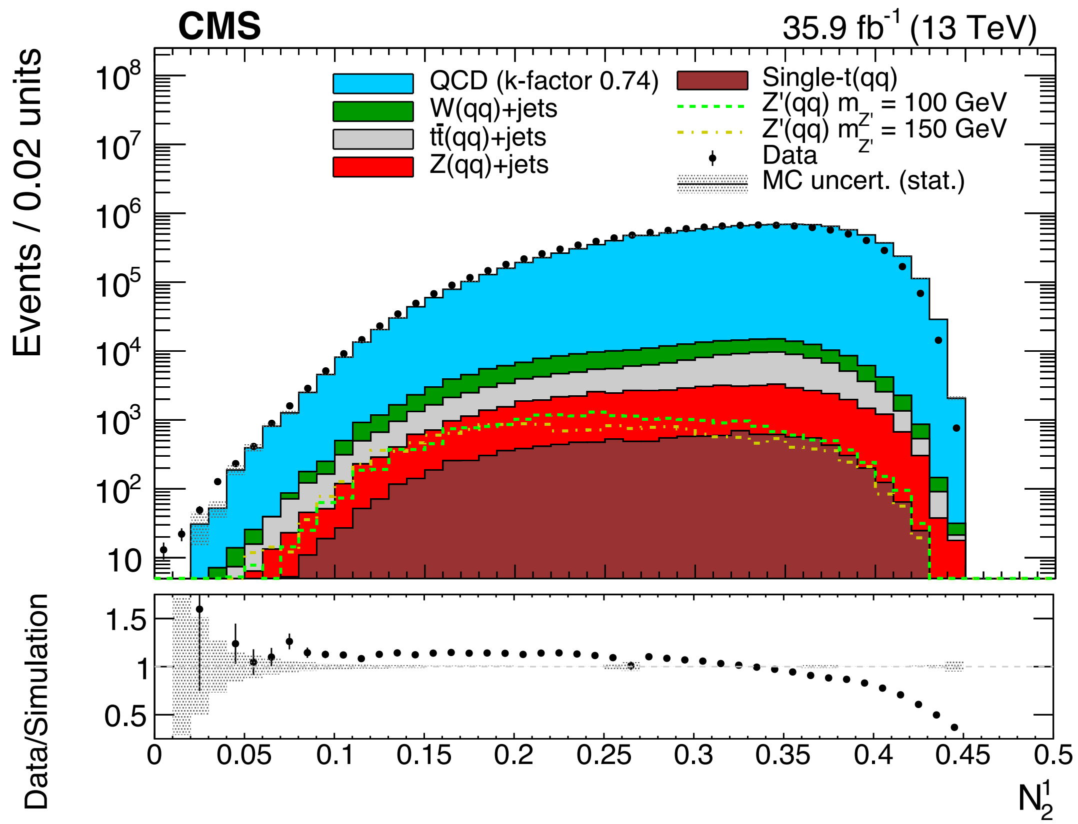
smaller QCD background too!

EXECUTIVE SUMMARY

- Online selection:
    - jet p_T > 360 GeV (m > 30 GeV) or H_T > 900 GeV
- Offline selection:
    - jet p_T > 500 GeV, $|\eta|$ < 2.5
- Substructure selection:
    - Soft drop jet mass > 40 GeV
    - $\mathbf{N^1_2{}^{DDT}}$ (5% QCD eff. WP)
- Backgrounds:
    - QCD
    - **SM Candles**: W/Z + jets



arXiv:1609.07483



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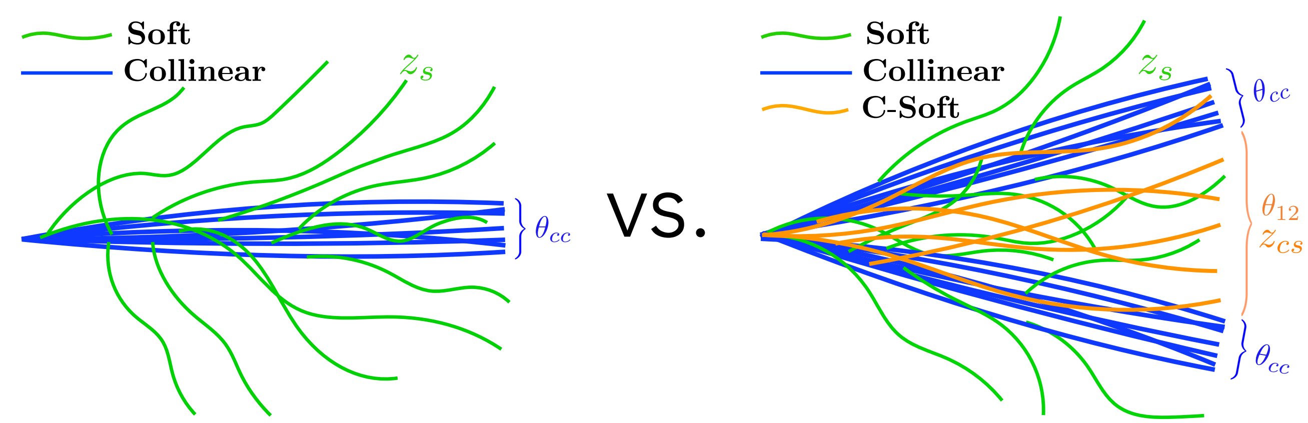
1-prong. 2-prong.



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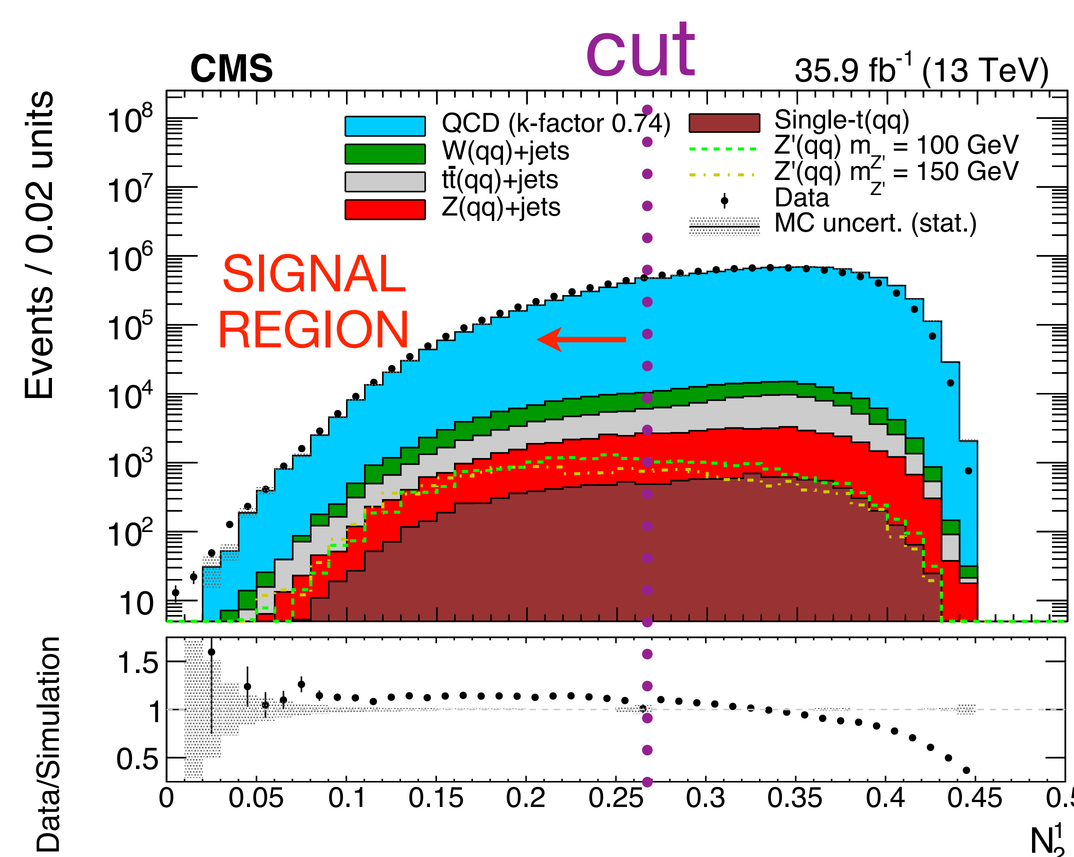
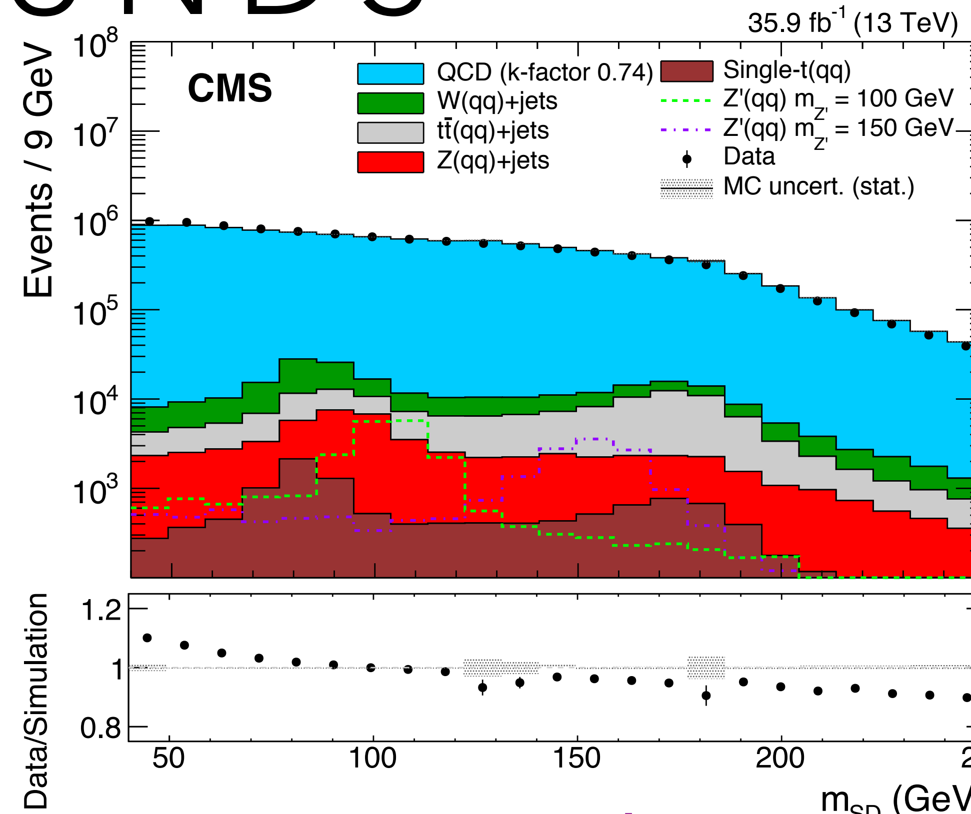
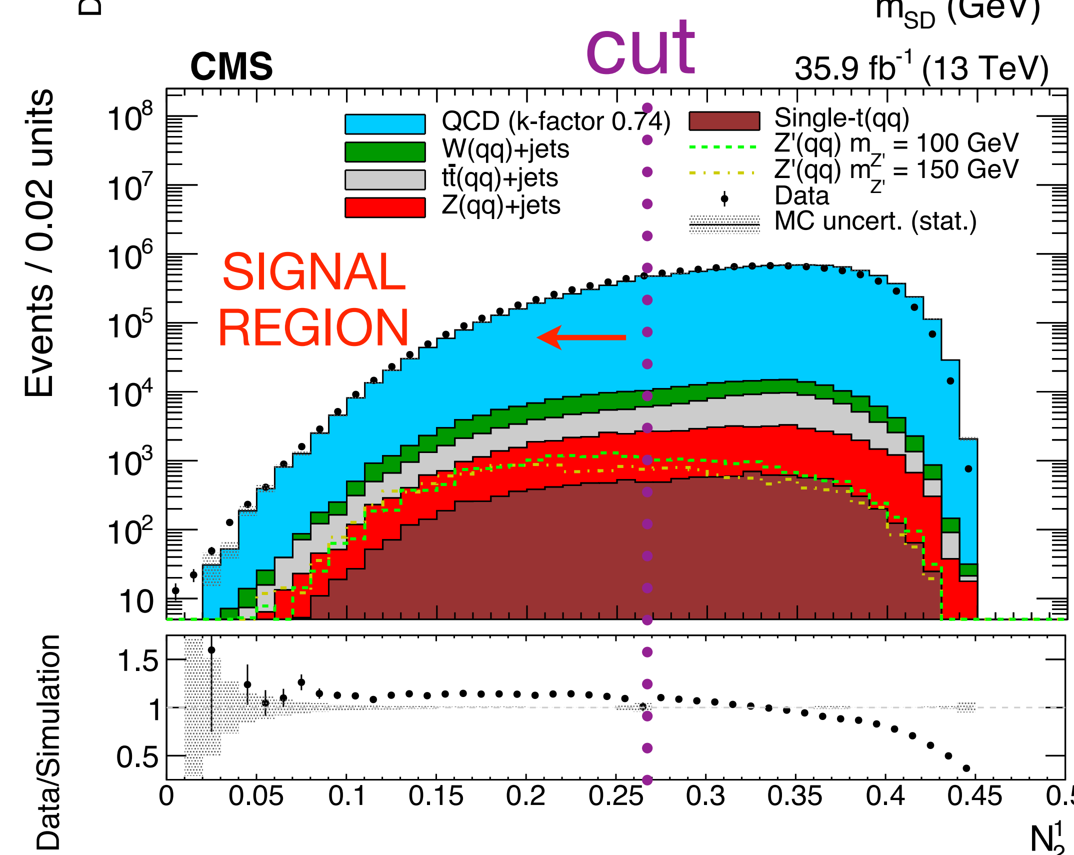


[PRL 119, 111802 (2017)](https://doi.org/10.1103/PhysRevLett.119.111802)

BACKGROUNDS

- QCD jet mass spectrum prediction methods:
  - Monte Carlo simulation (can we trust it?)
  - Pure parametric fit (large uncertainties)
  - **Data-driven sideband prediction**





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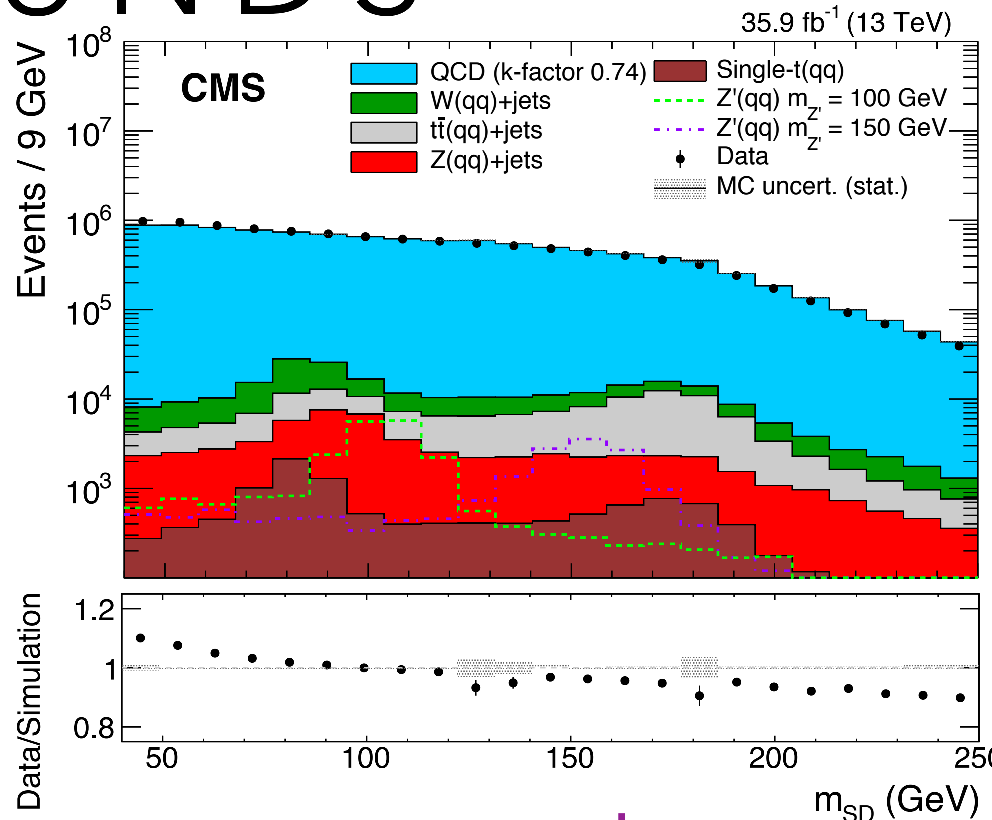
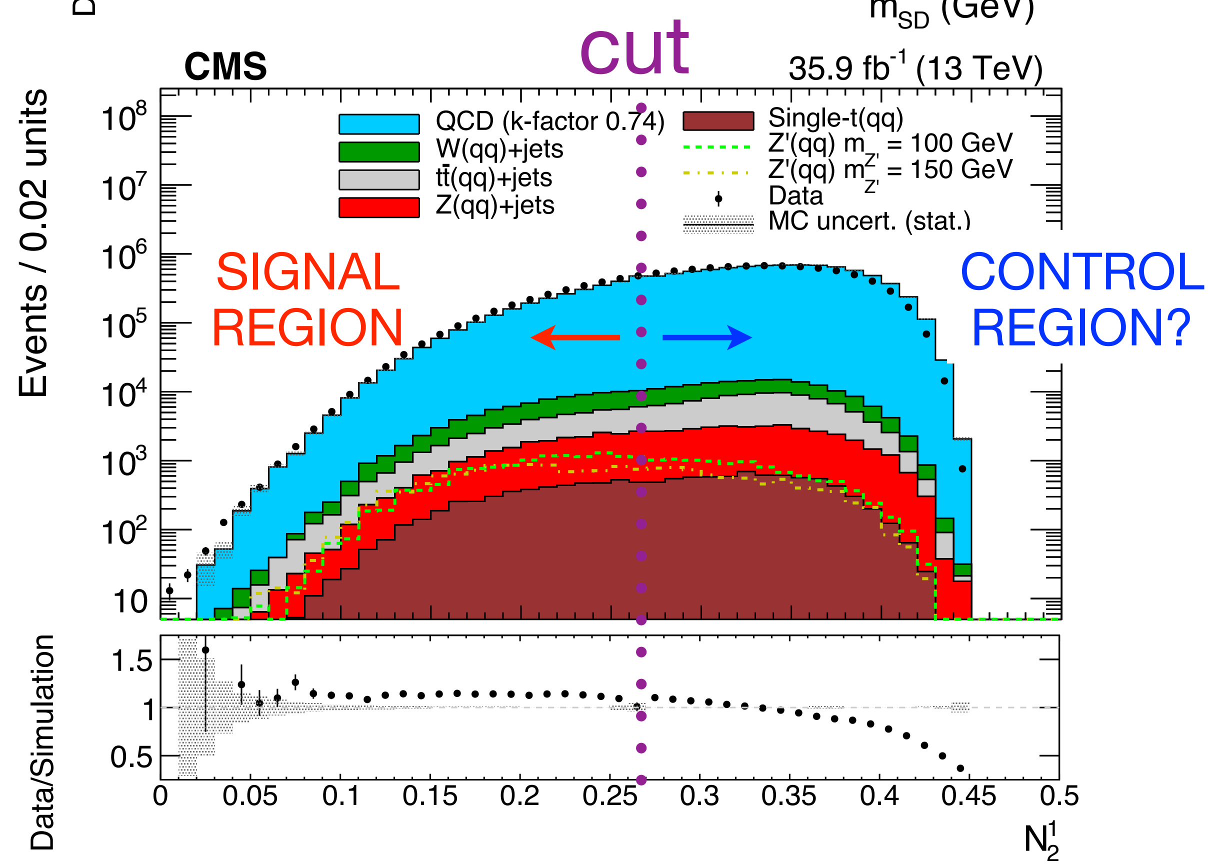
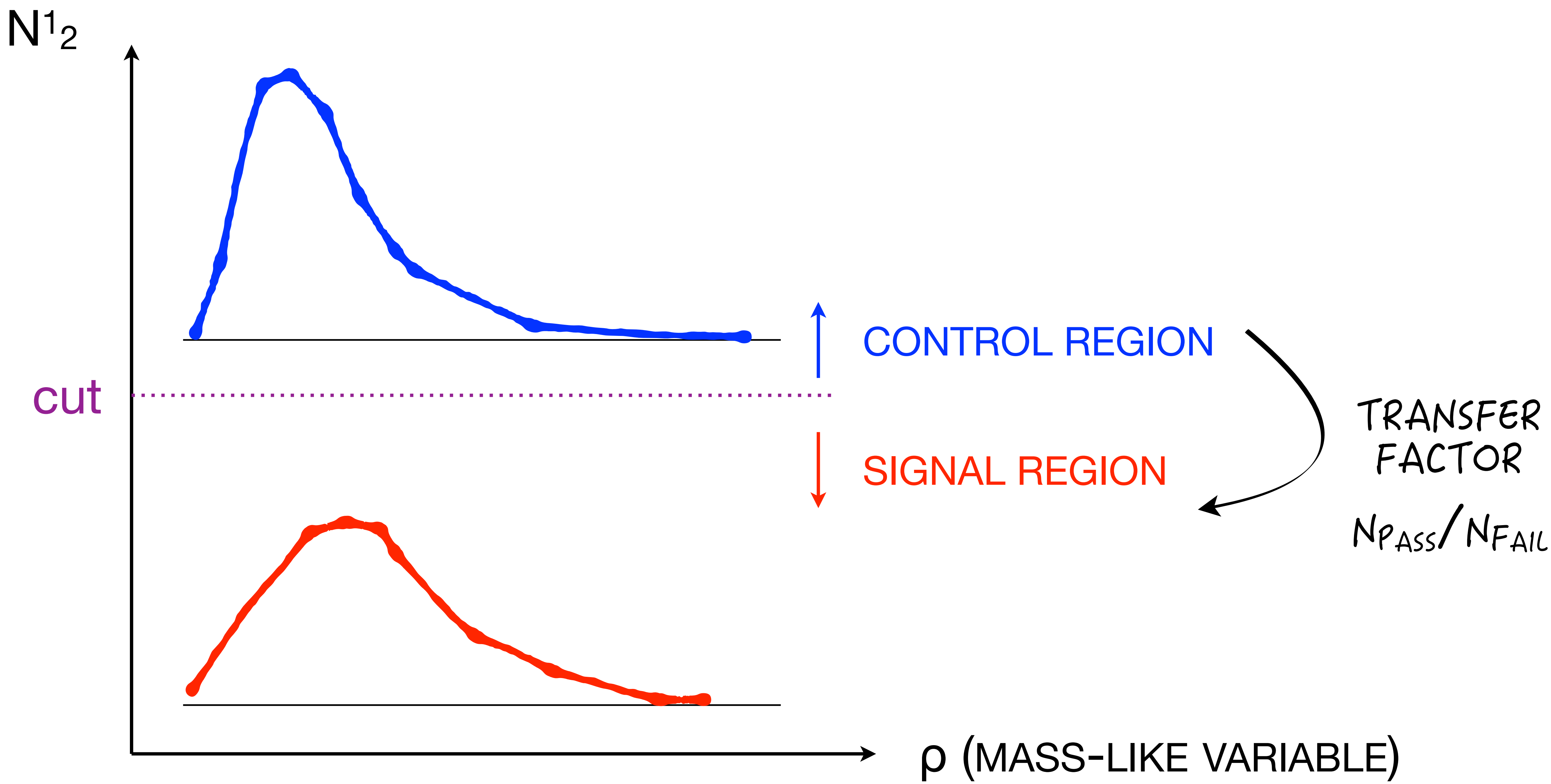




SIDEBAND QCD PREDICTION

- Core idea: predict QCD jet mass distribution from failing region
- Problem: cut on N^1_2 sculpts jet mass distribution!



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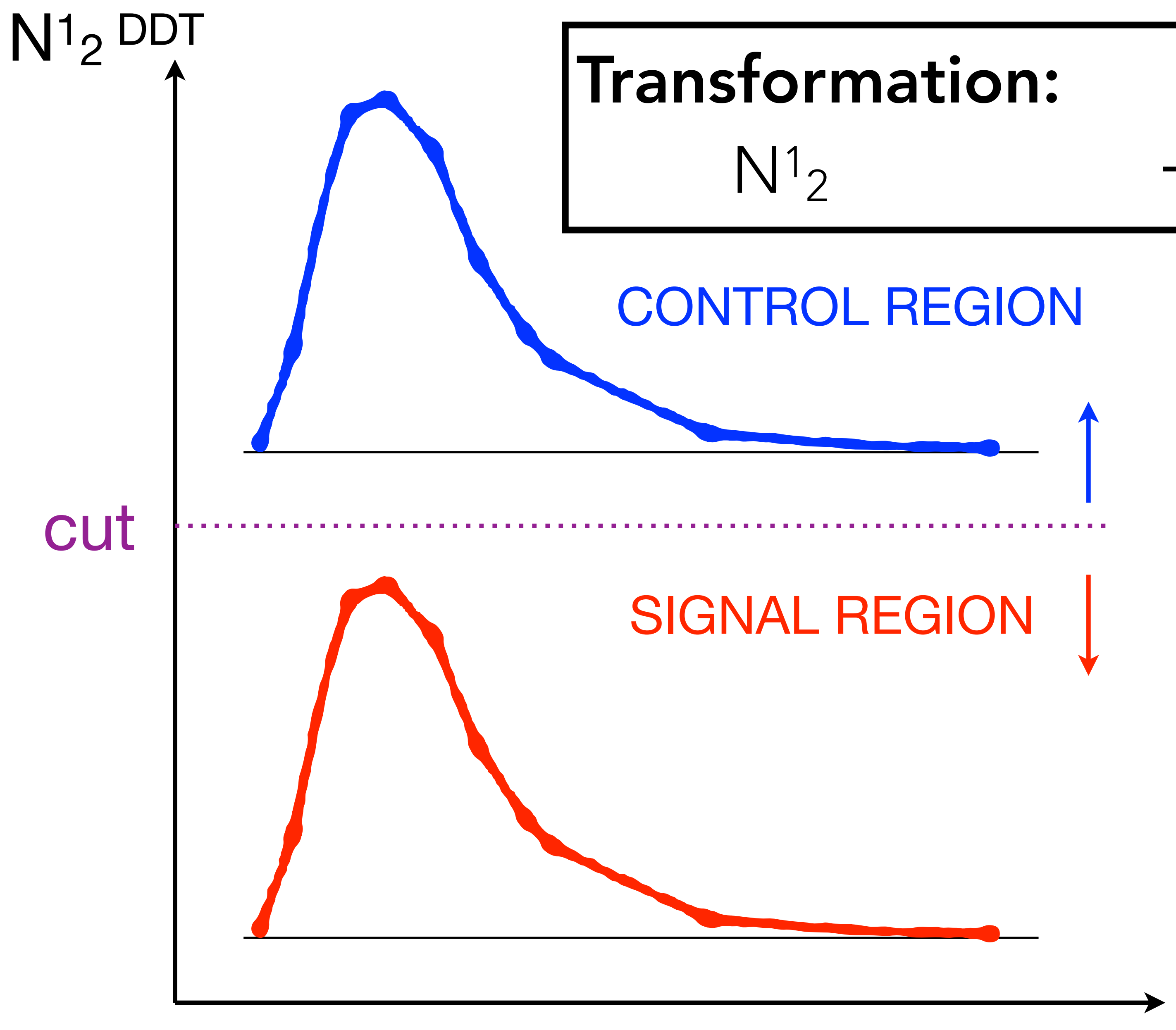
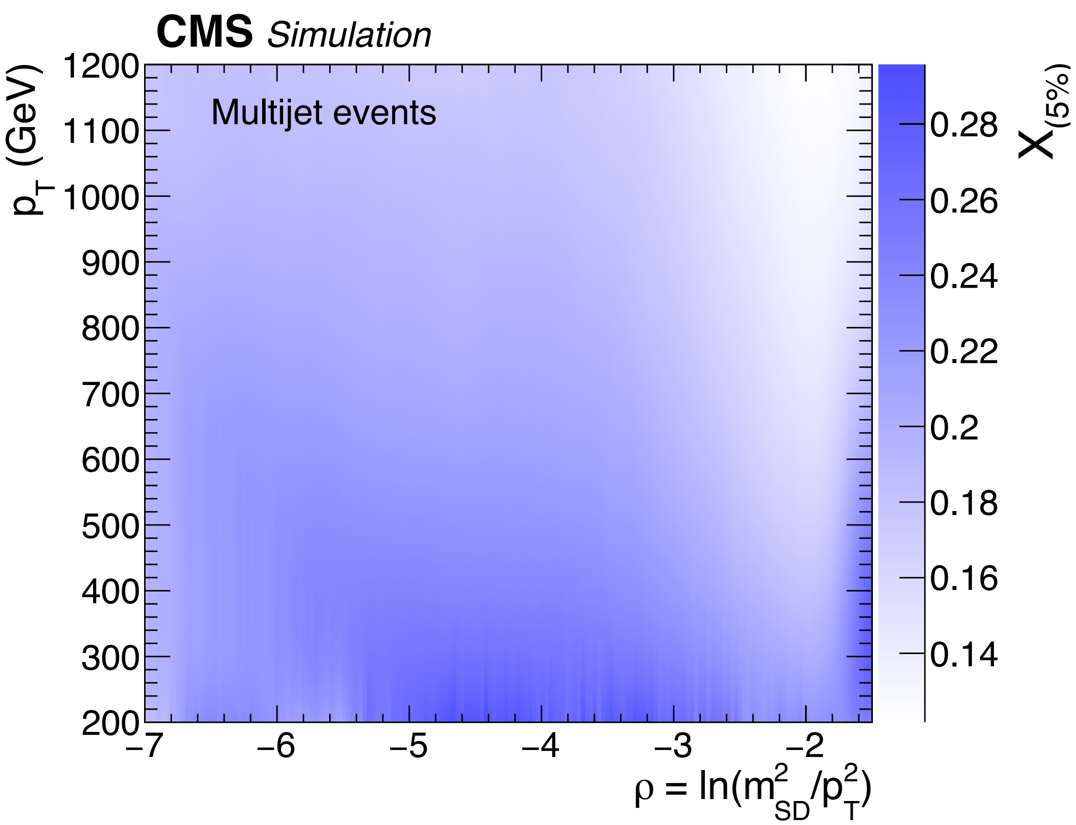
SIDEBAND QCD PREDICTION

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

Transformation:

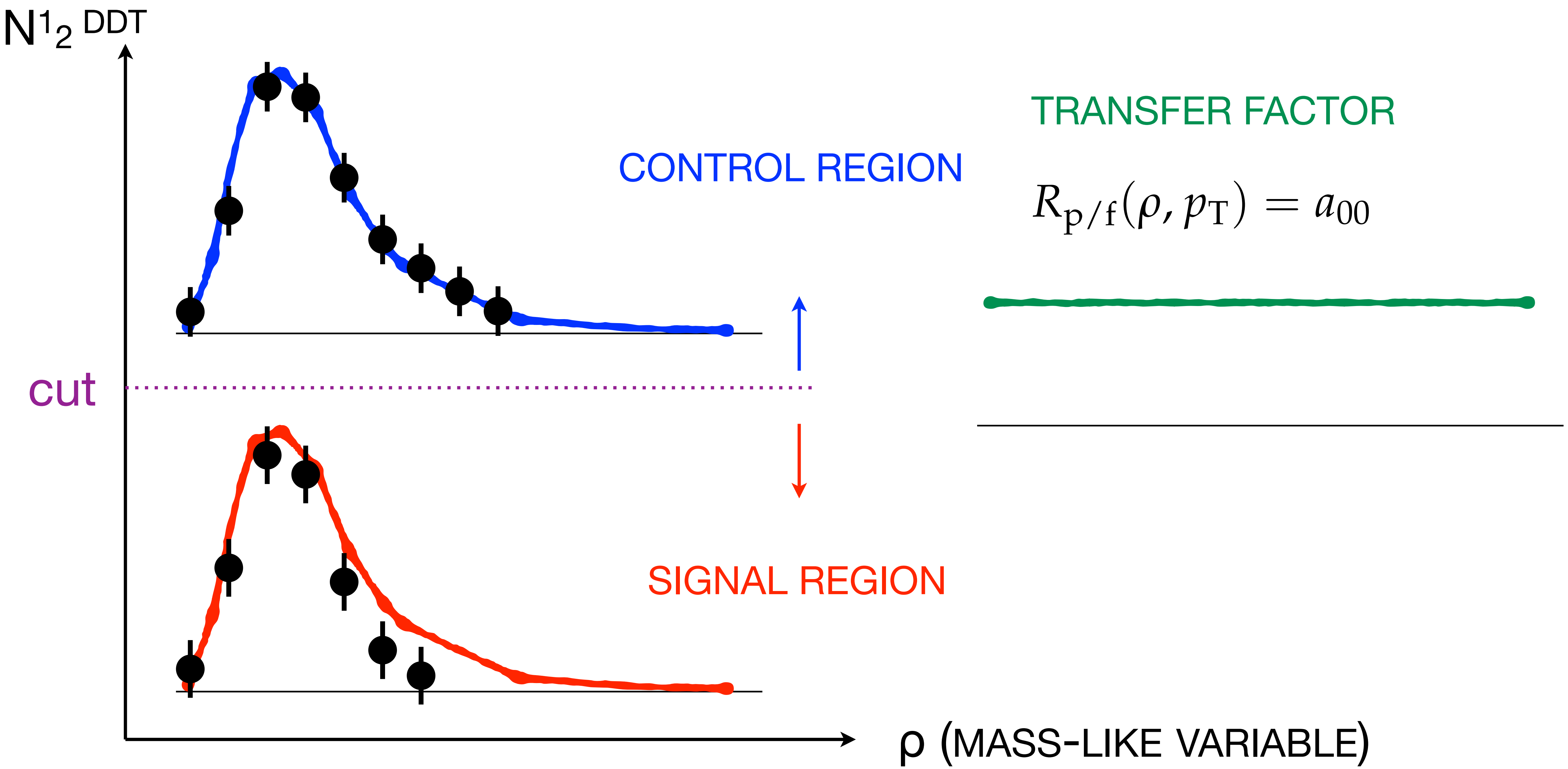
$$N^1_2 \rightarrow N^1_2{}^{DDT} = N^1_2 - X_{(5\%)}$$





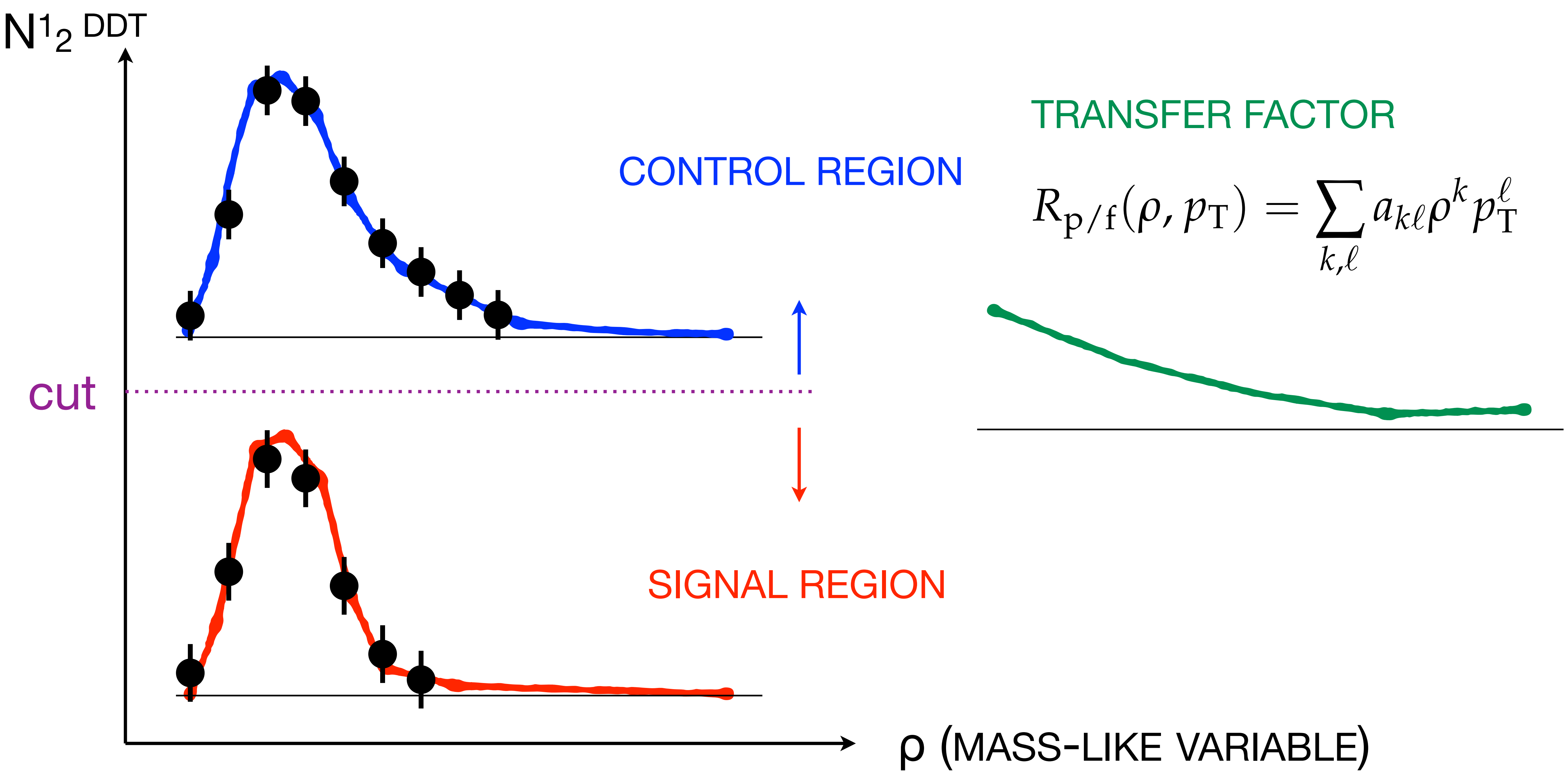
MORE REALISTIC

- In real data, signal region and control region have slightly different shapes



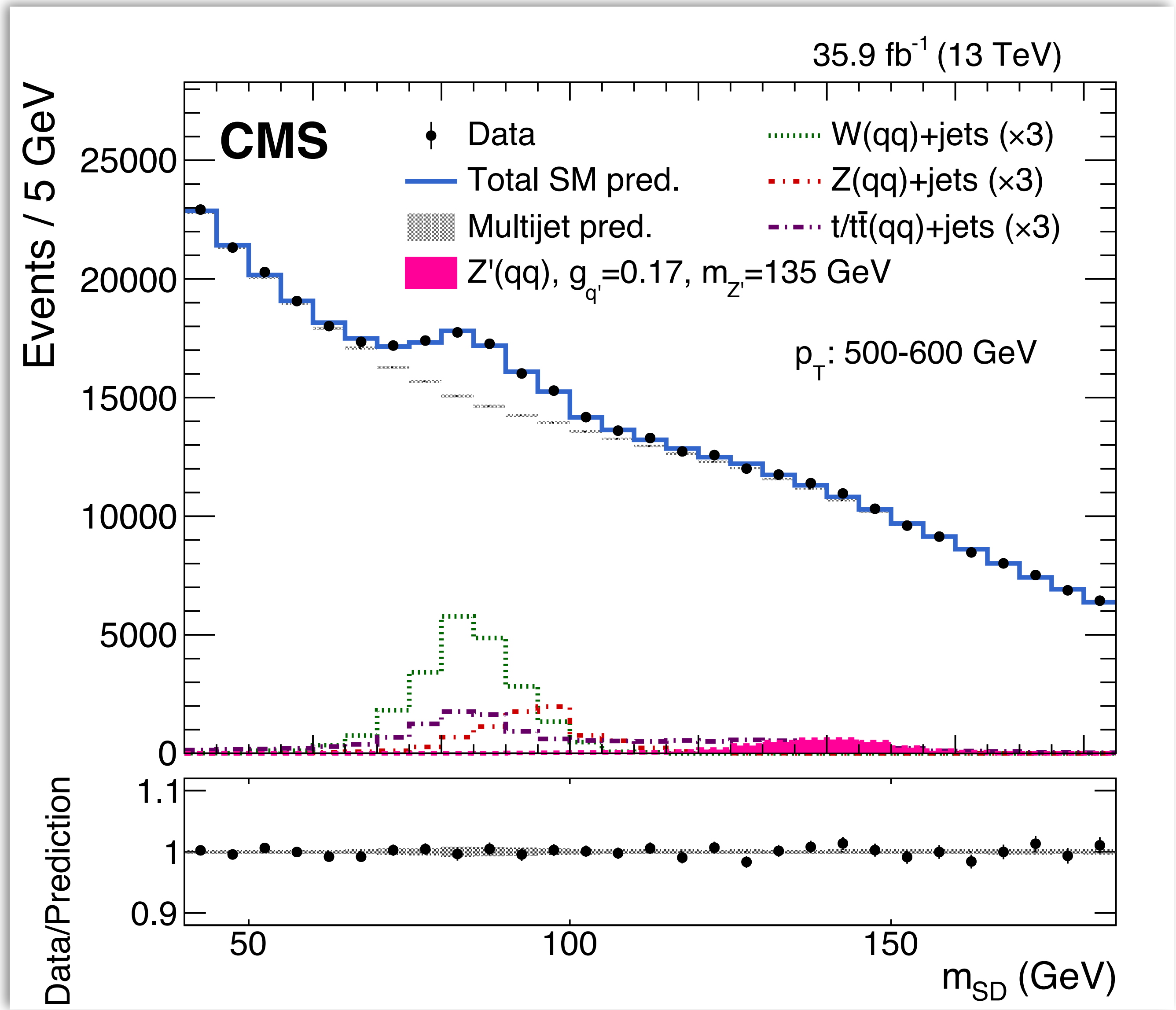
FITTING TRANSFER FACTOR

- Fit directly for a parametrized transfer factor



BOOSTED DIJET FIT

- Fit results per p_T bin



JHEP 01 (2018) 097

QCD multijet background from control region failing substructure

×

transfer factor $R_{p/f}(\rho, p_T)$

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

BOOSTED DIJET FIT

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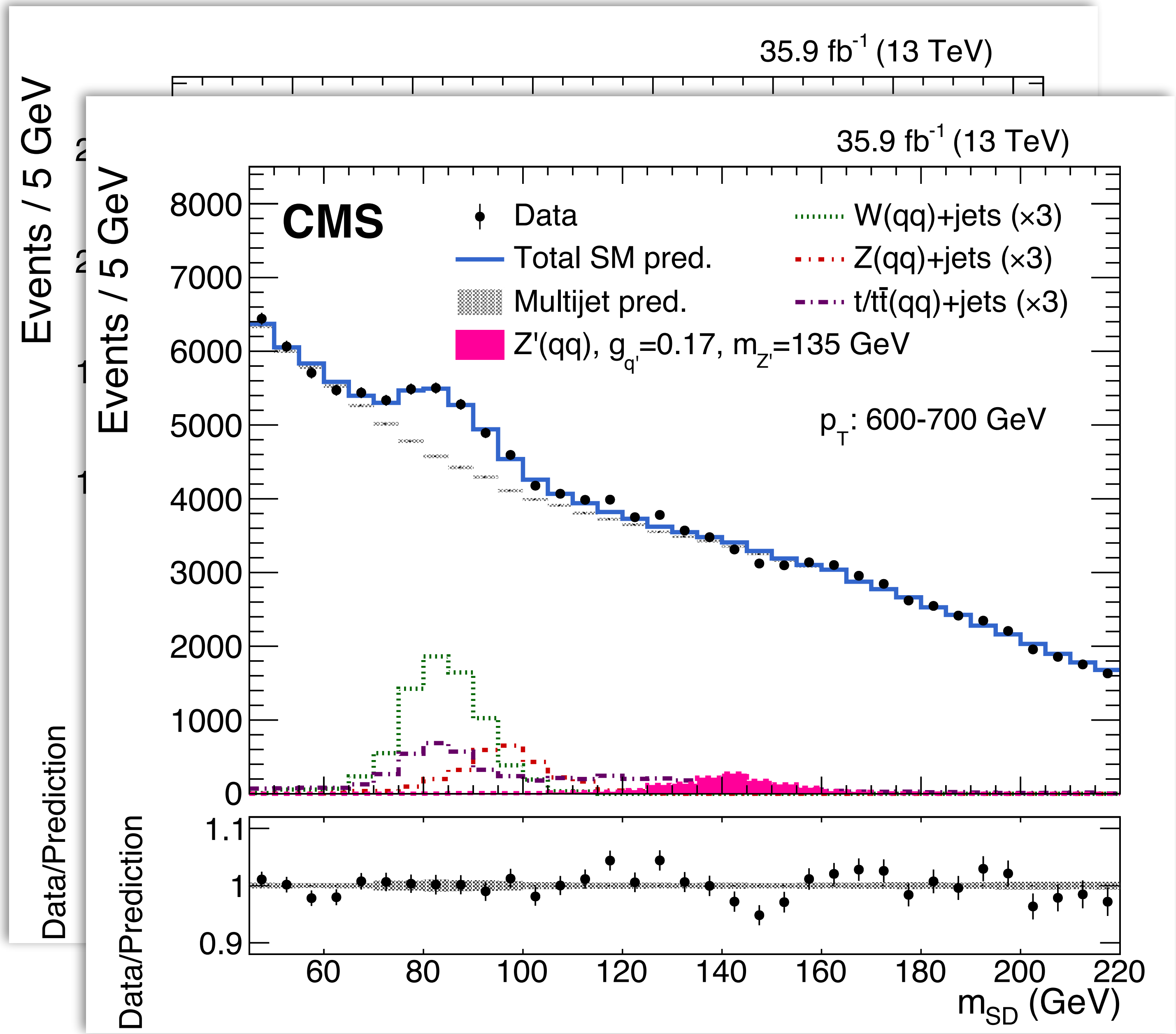

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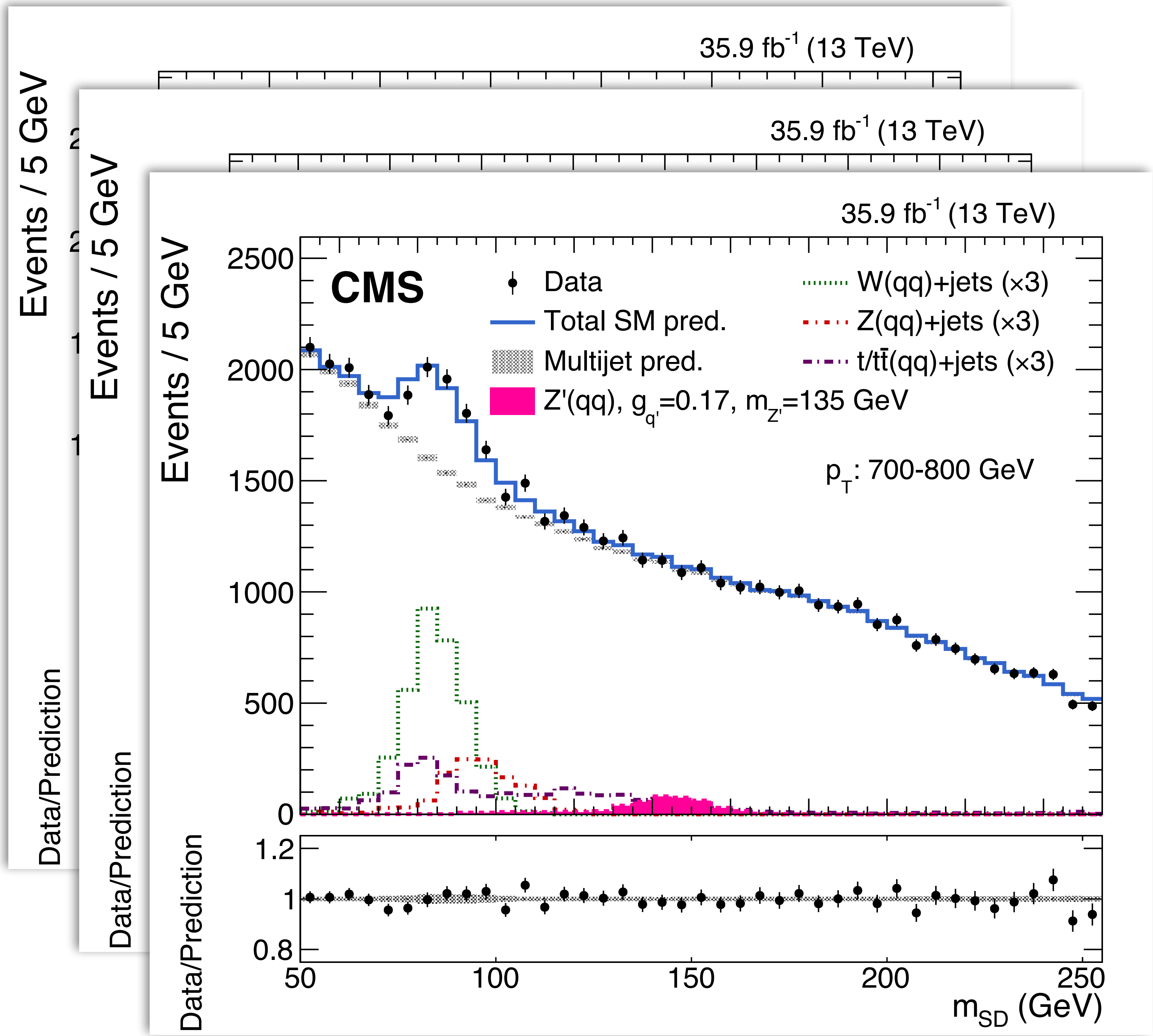

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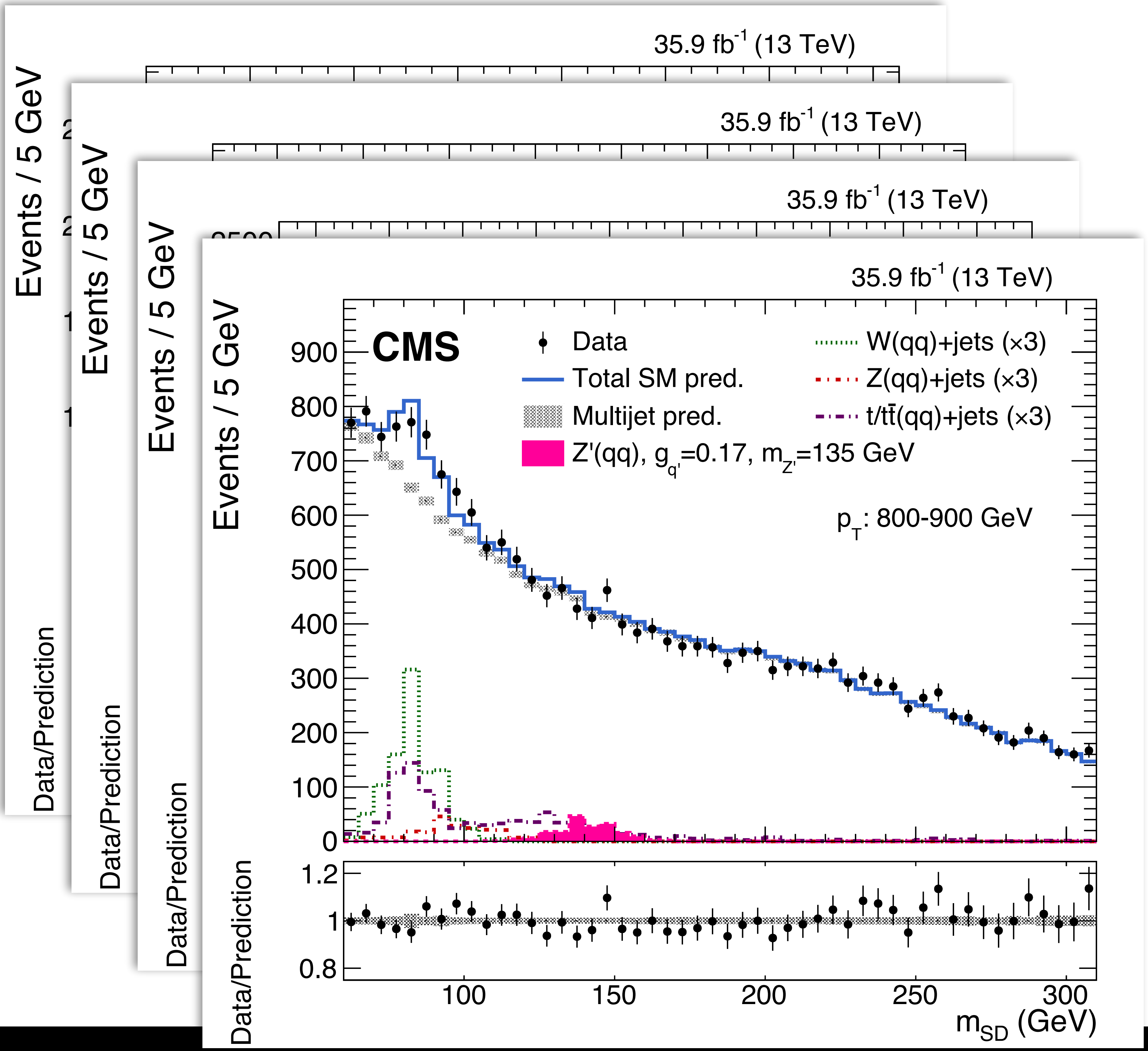

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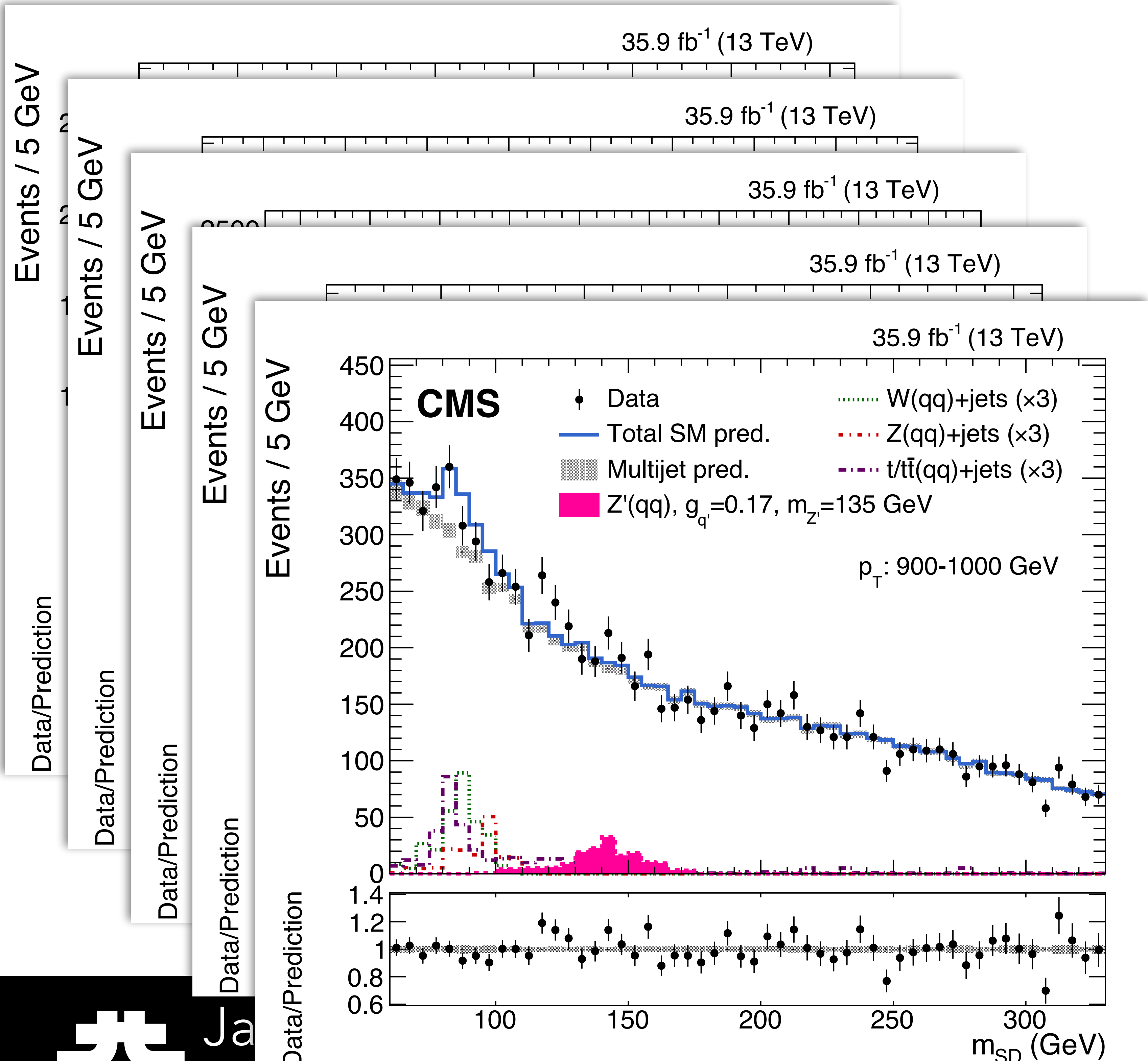

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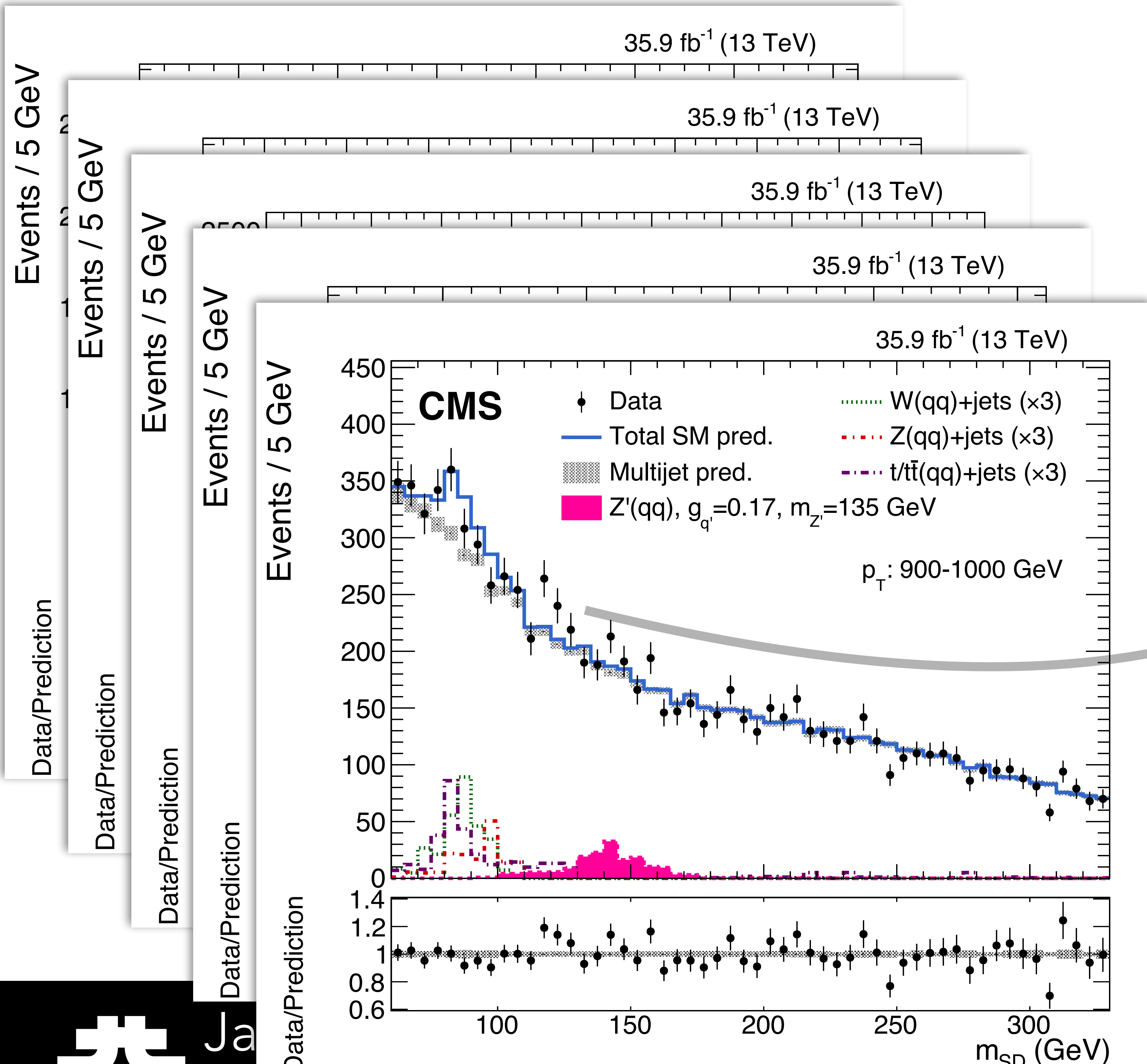

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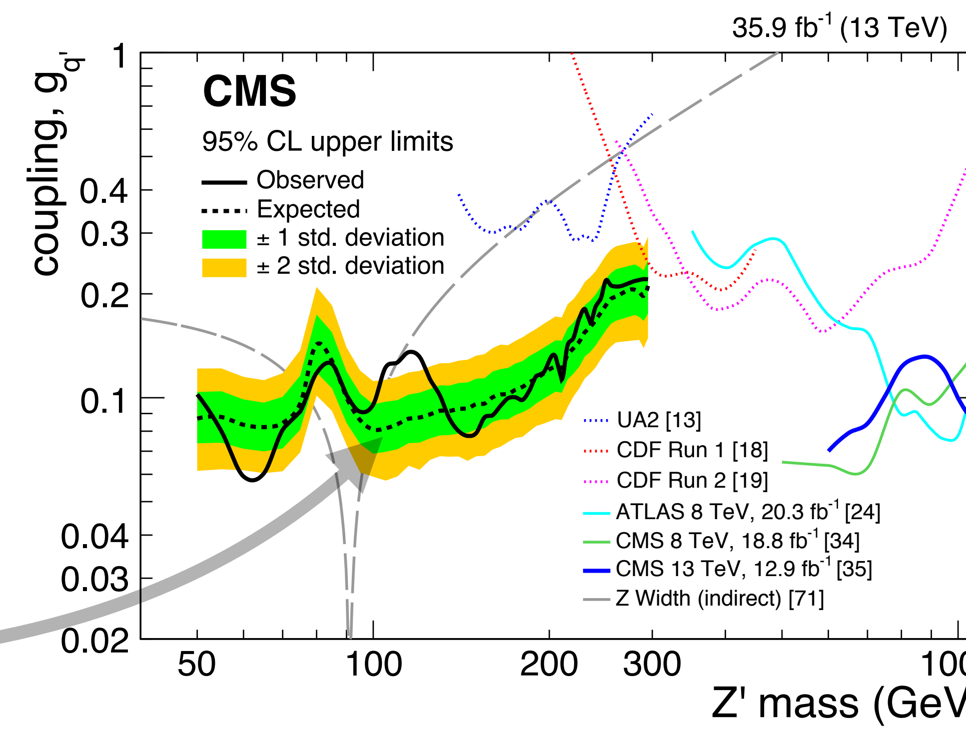
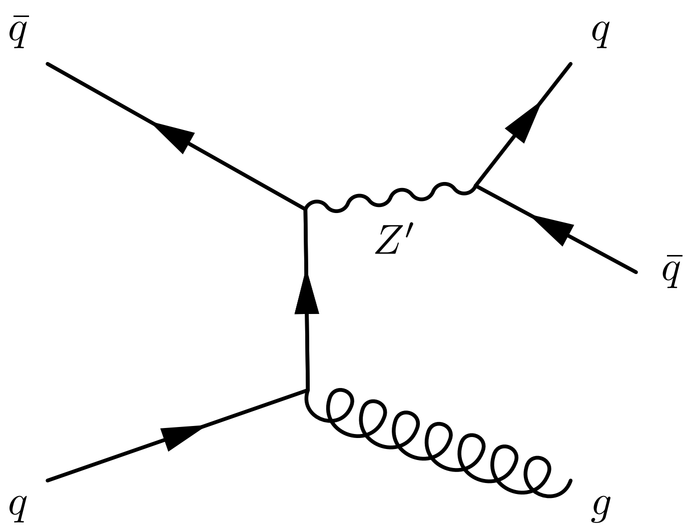


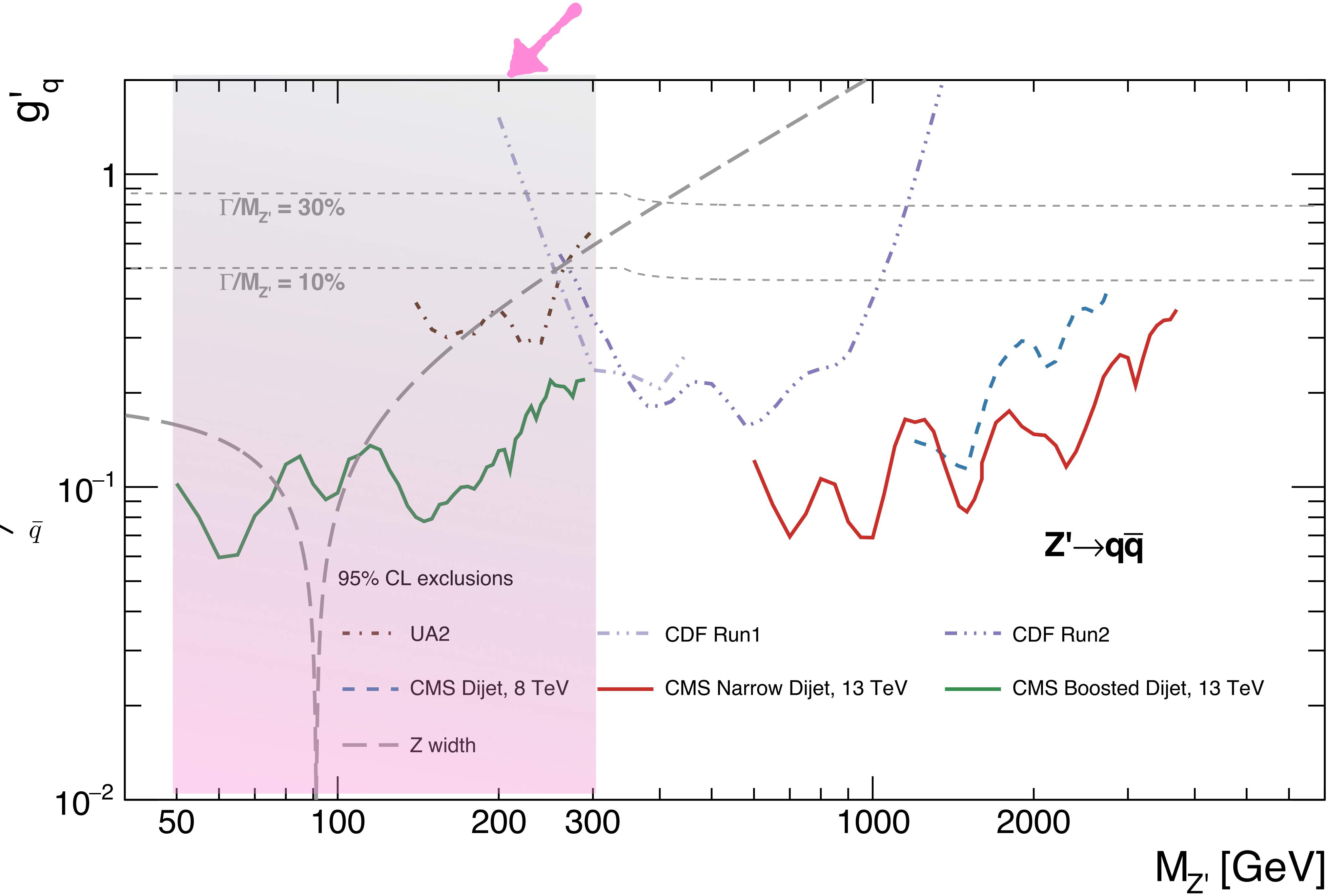
SM candles: W/Z(qq) peak provides in-situ constraint of Z′(qq) signal systematics

BOOSTED DIJET

JHEP 01 (2018) 097

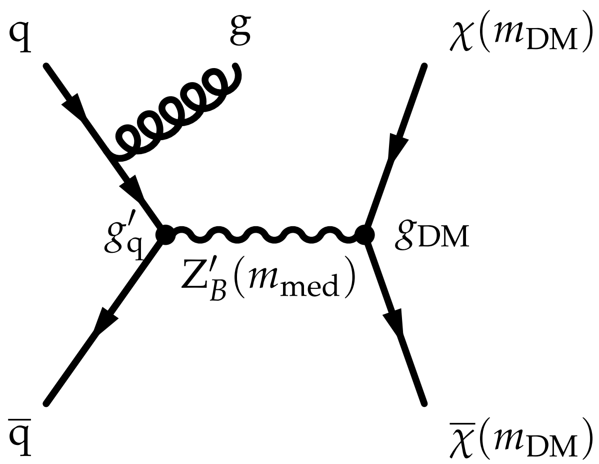
- Expanded CMS reach down to 50 GeV



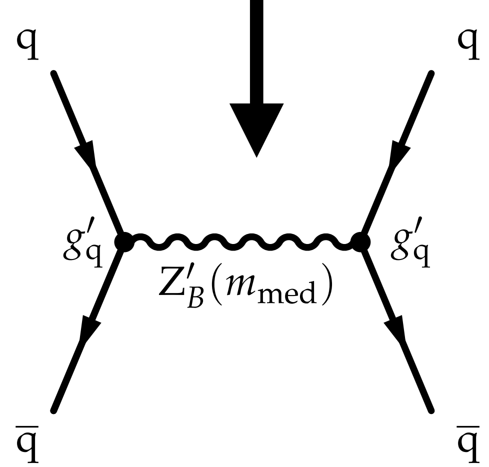


SENSITIVITY TO DARK MATTER

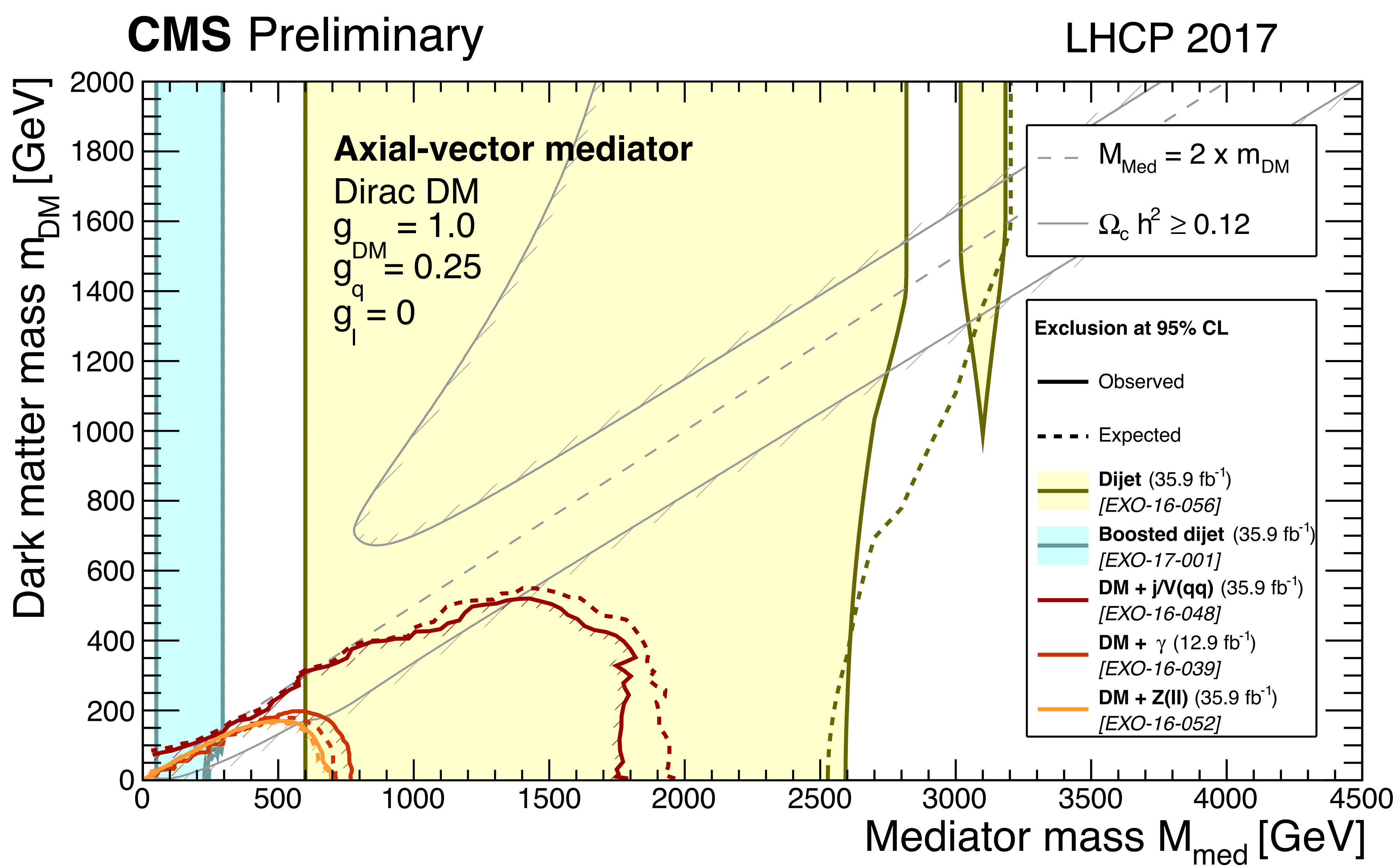
- Sensitive to large range of ***dark matter*** parameter space by looking directly for resonant production of the ***mediator***



MET+X

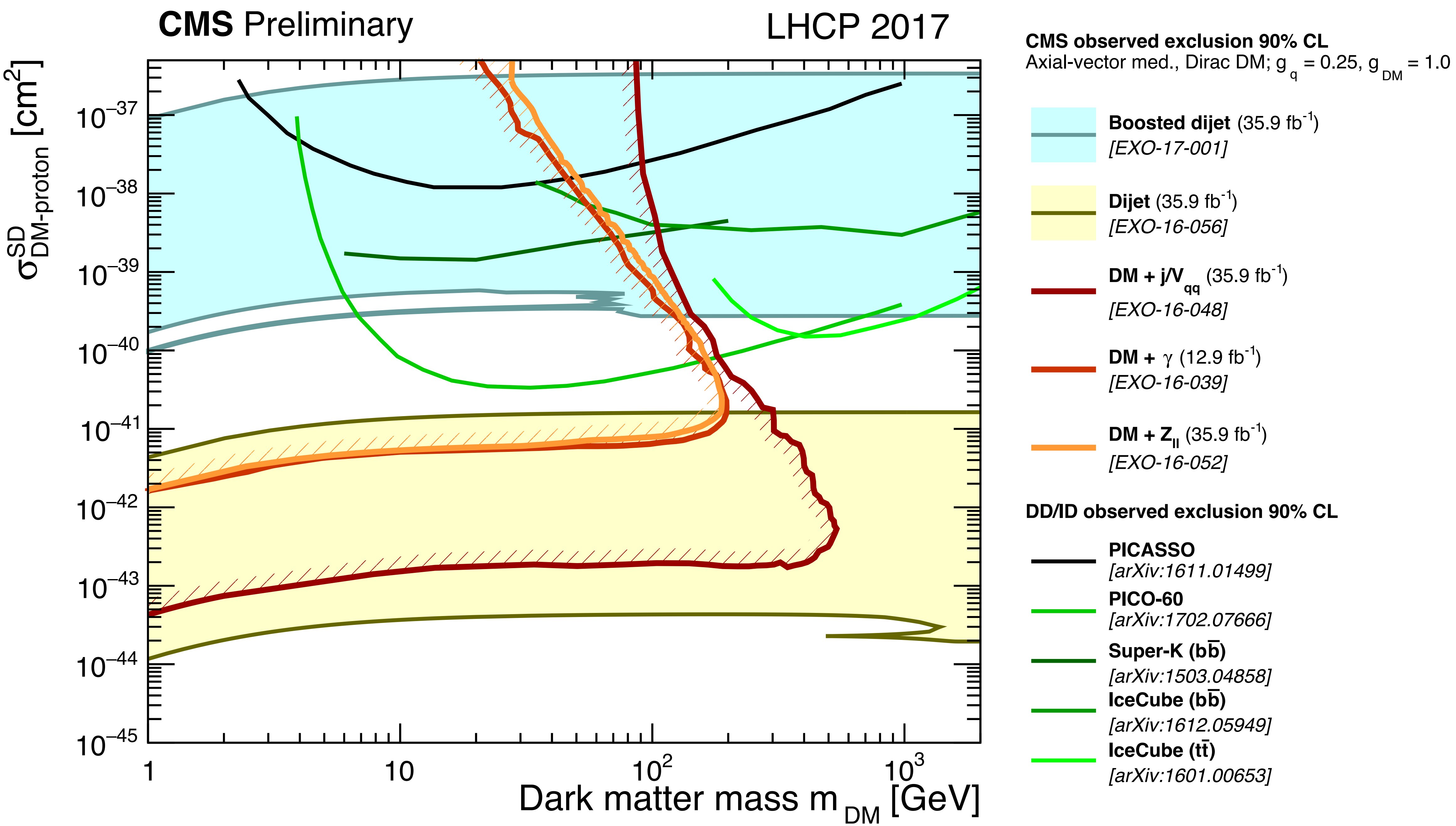


DIJET

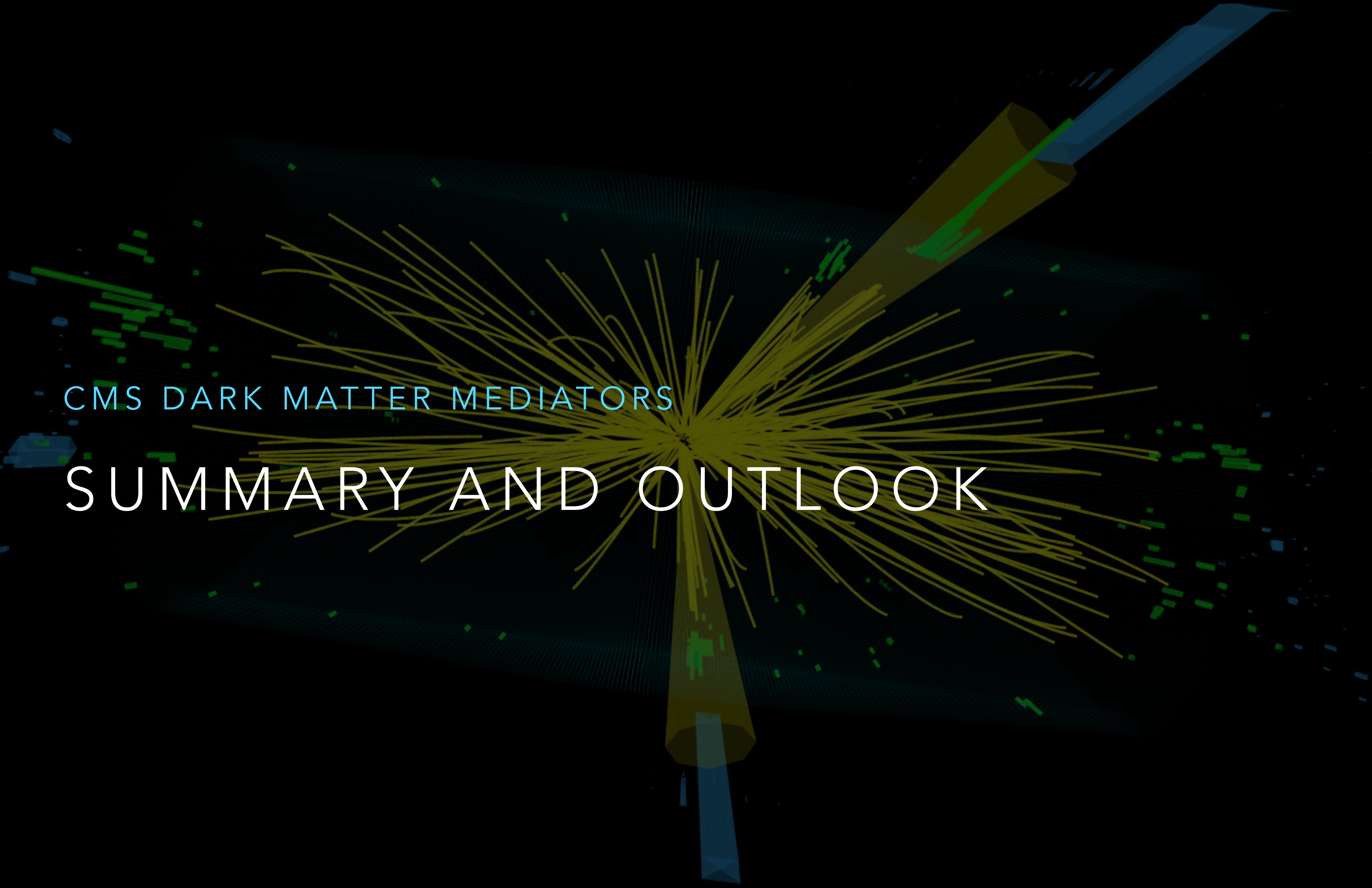


SENSITIVITY TO DARK MATTER

- Converted to plane of nucleon-dark matter cross section versus dark matter mass



NOTE: MODEL DEPENDENT



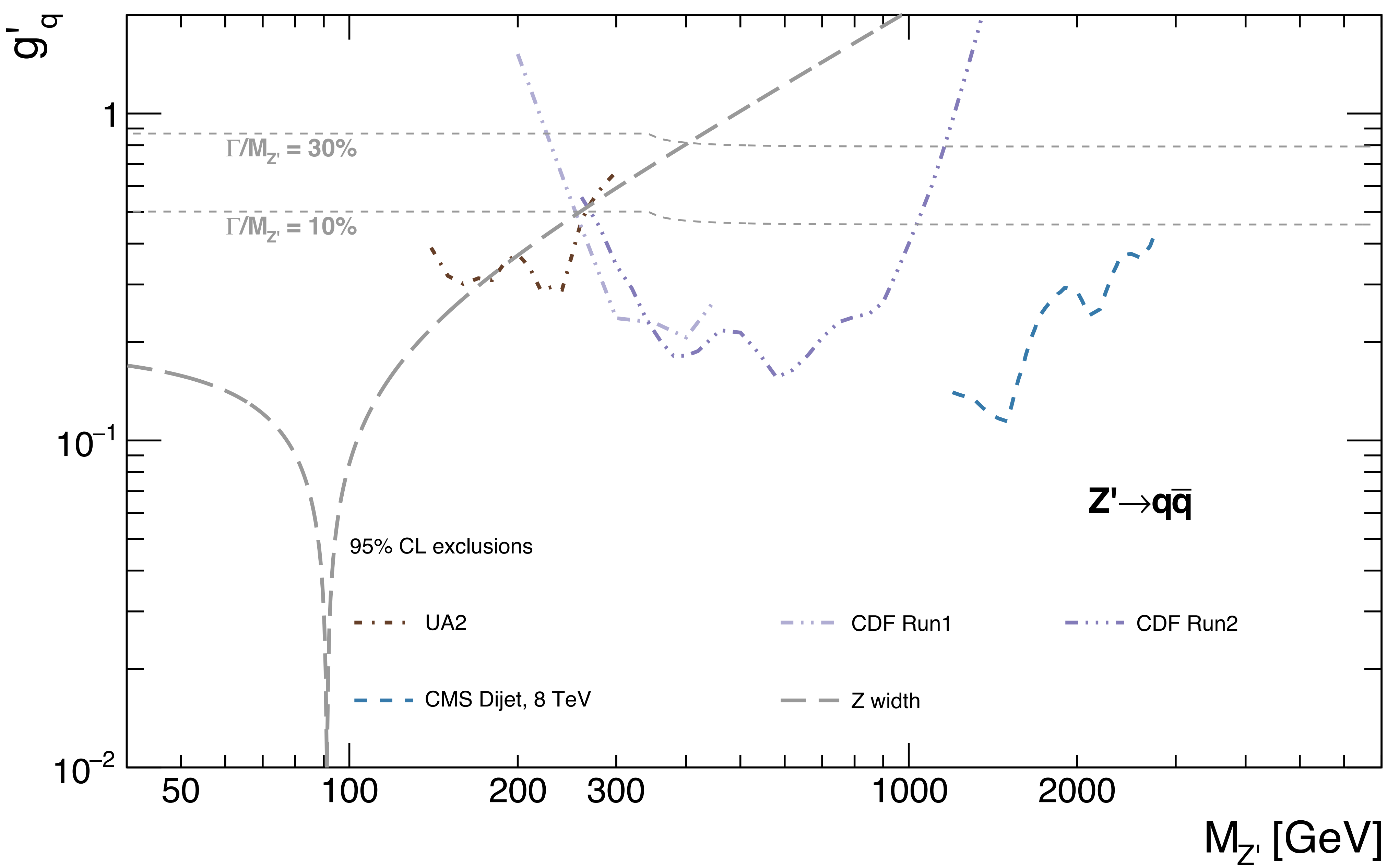
CMS DARK MATTER MEDIATORS

SUMMARY AND OUTLOOK

Javier Duarte
Fermilab

SUMMARY AND OUTLOOK

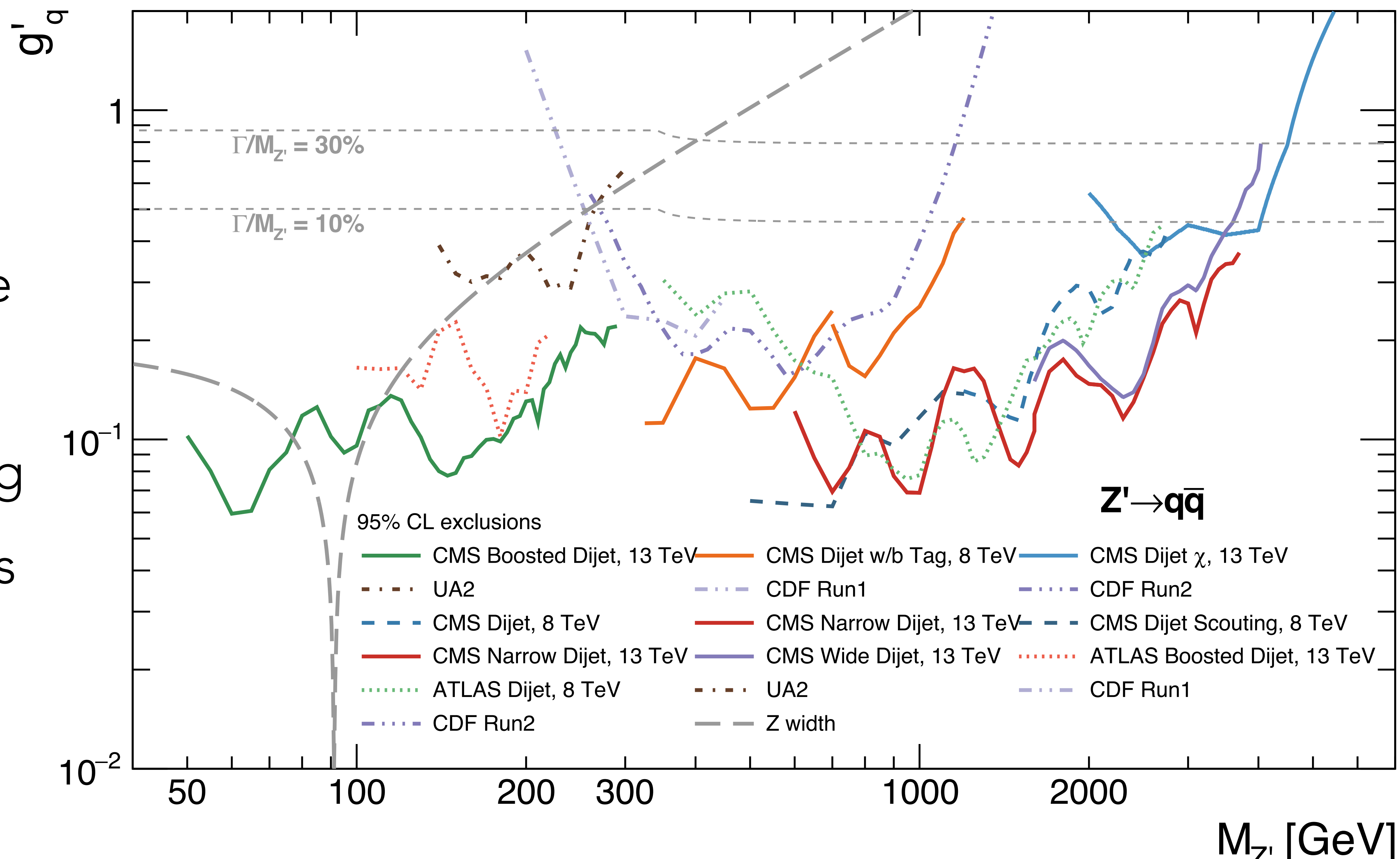
- More to dijets than meets the eye



SUMMARY AND OUTLOOK

- More to dijets than meets the eye

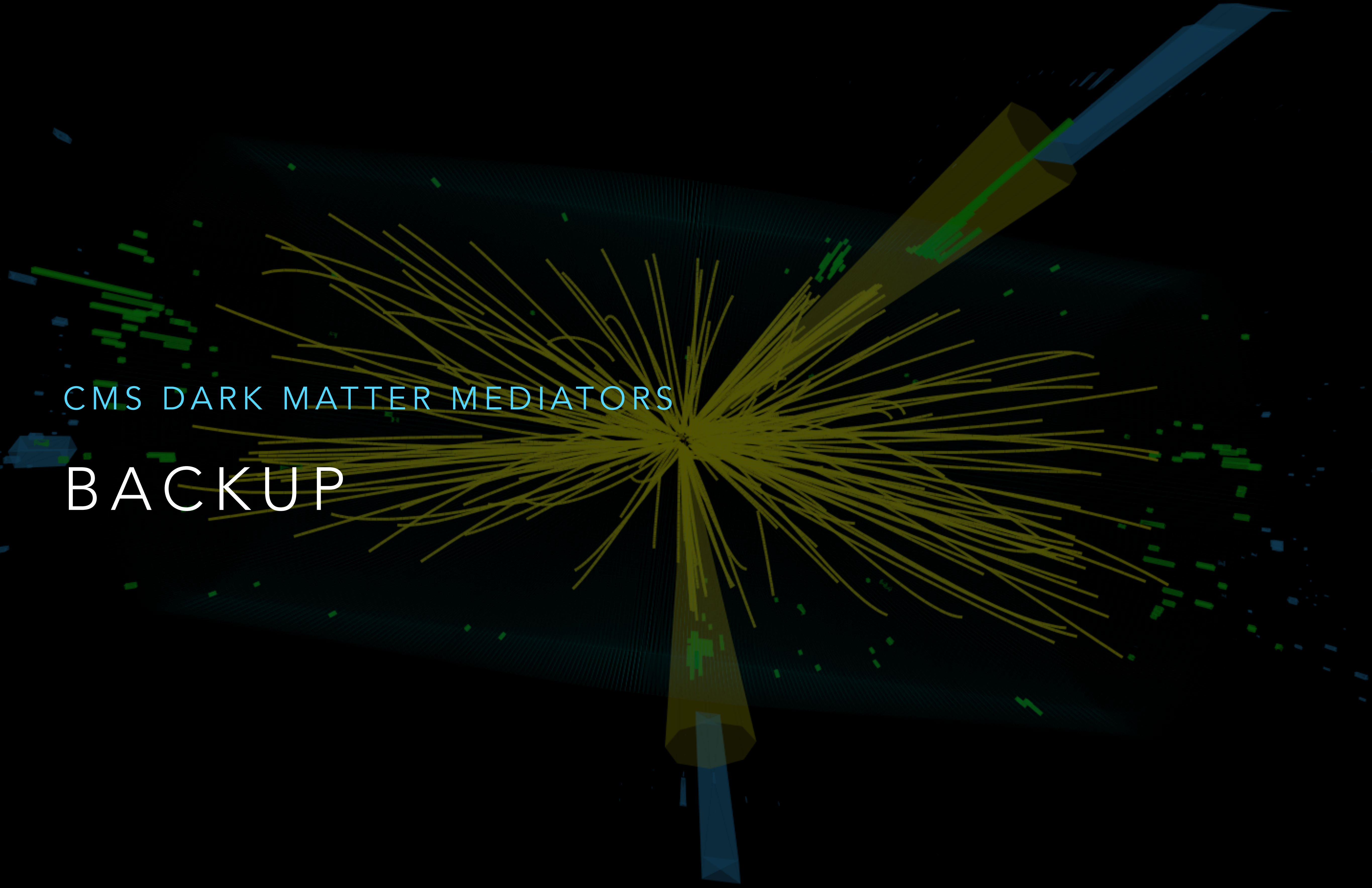
- Dark matter
- Data scouting
- Jet substructure
- b-tagging
- Machine leaning
- Higgs couplings
- New triggers
- and more…



- Looking forward to the rest of Run 2 and Run 3!

CMS DARK MATTER MEDIATORS

BACKUP



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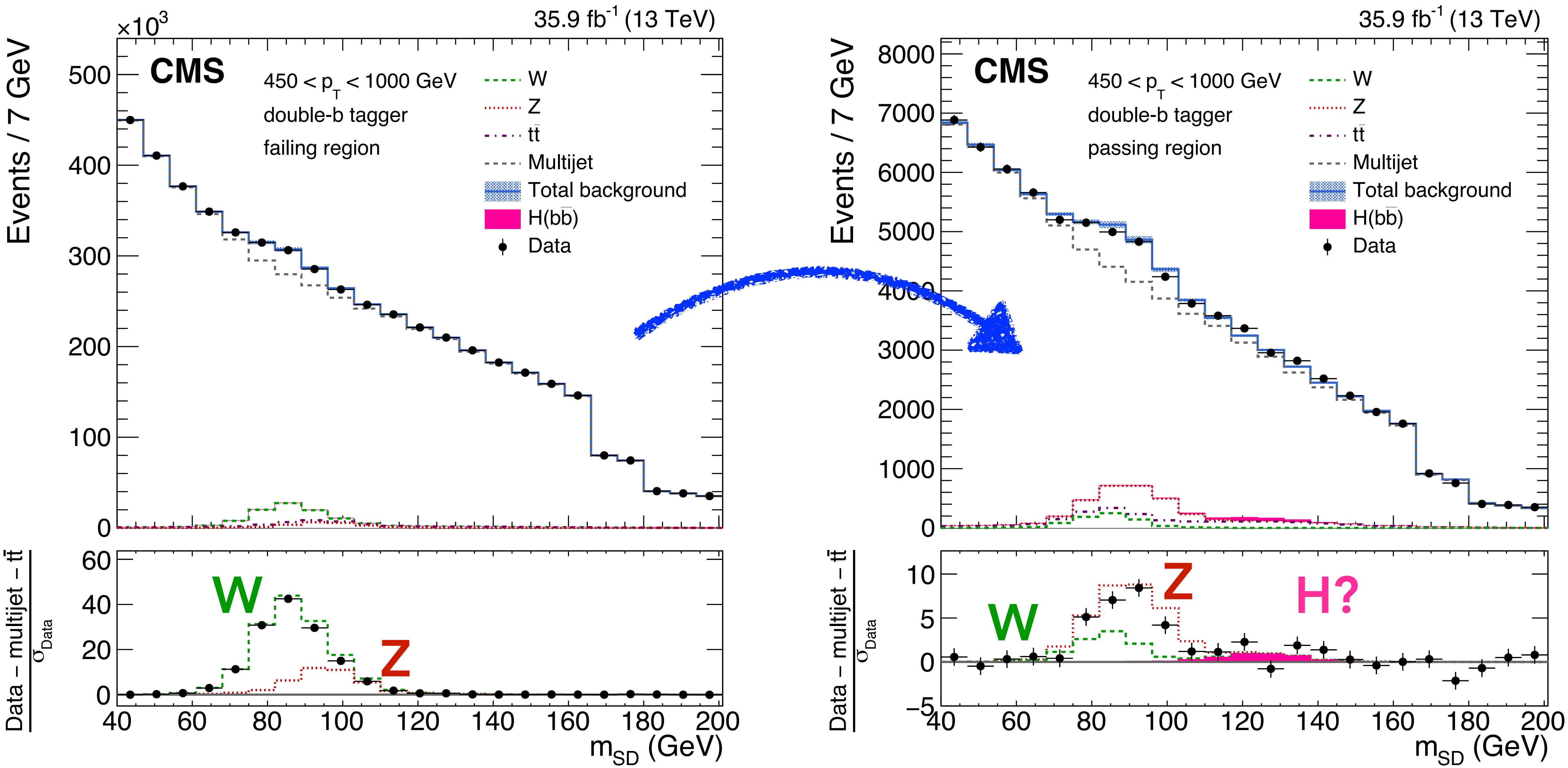
Fermilab

[PRL 120, 071802 (2018)](https://example.com)

BOOSTED H→BB

- Simultaneous search for Z(bb) and H(bb)

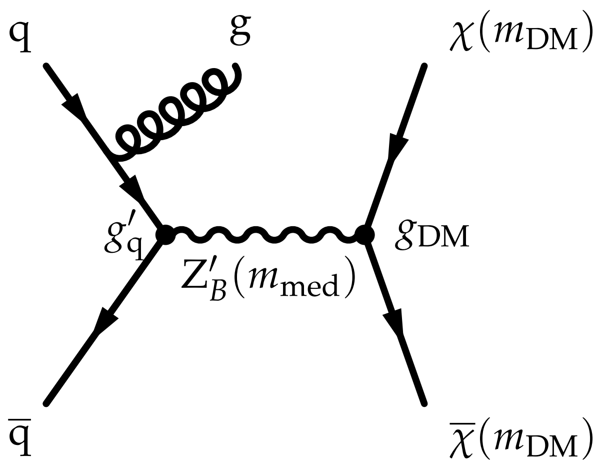


observed H(bb) significance:

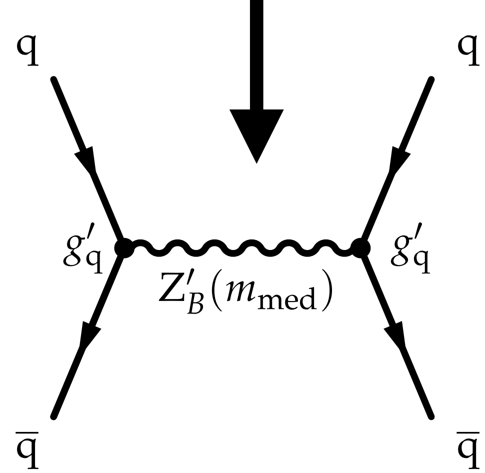
1.5σ, $\mu_H = 2.3^{+1.8}_{-1.6}$

SENSITIVITY TO DARK MATTER

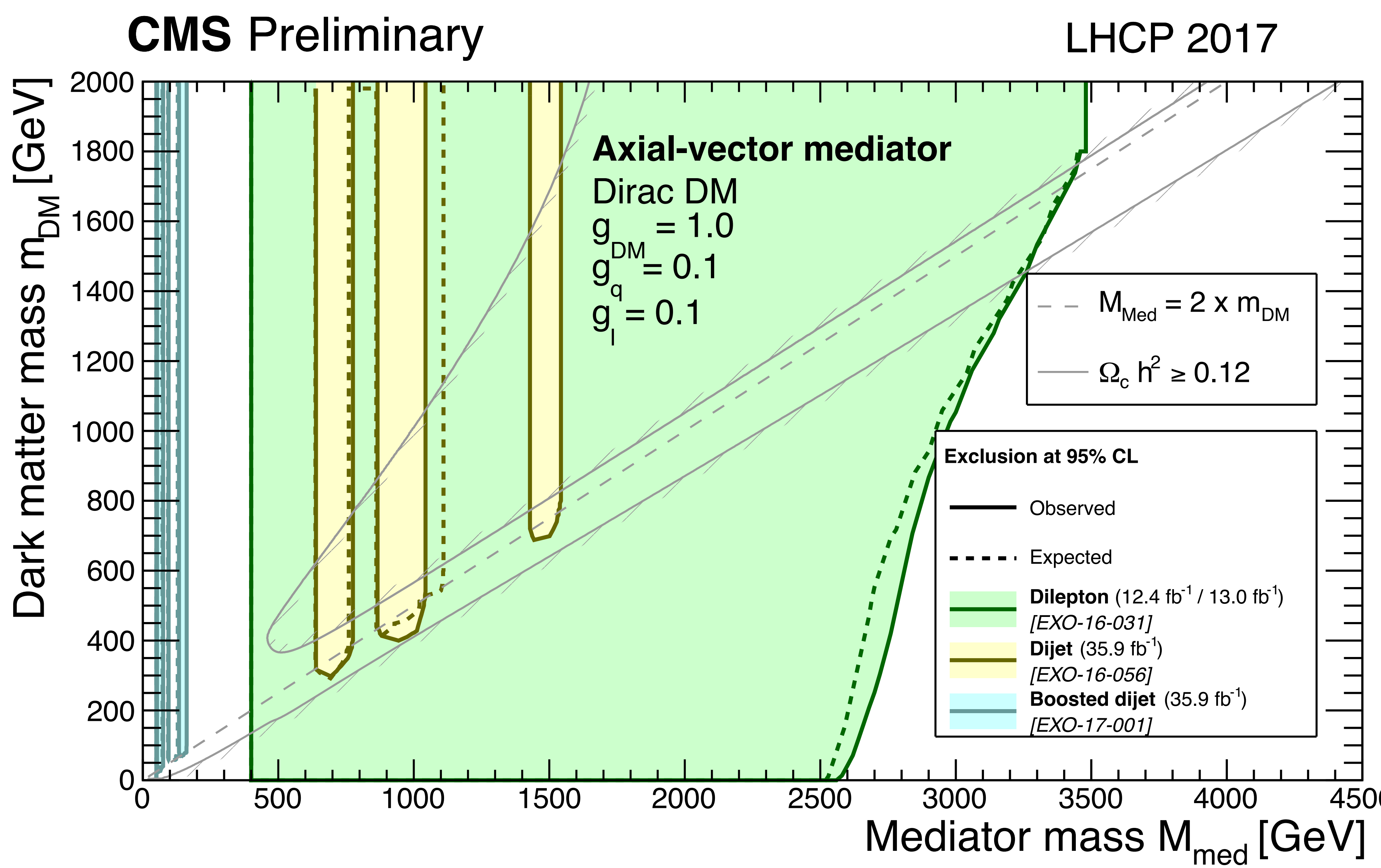
- Sensitive to large range of ***dark matter*** parameter space by looking directly for resonant production of the ***mediator***



MET+X



DIJET



SENSITIVITY TO DARK MATTER

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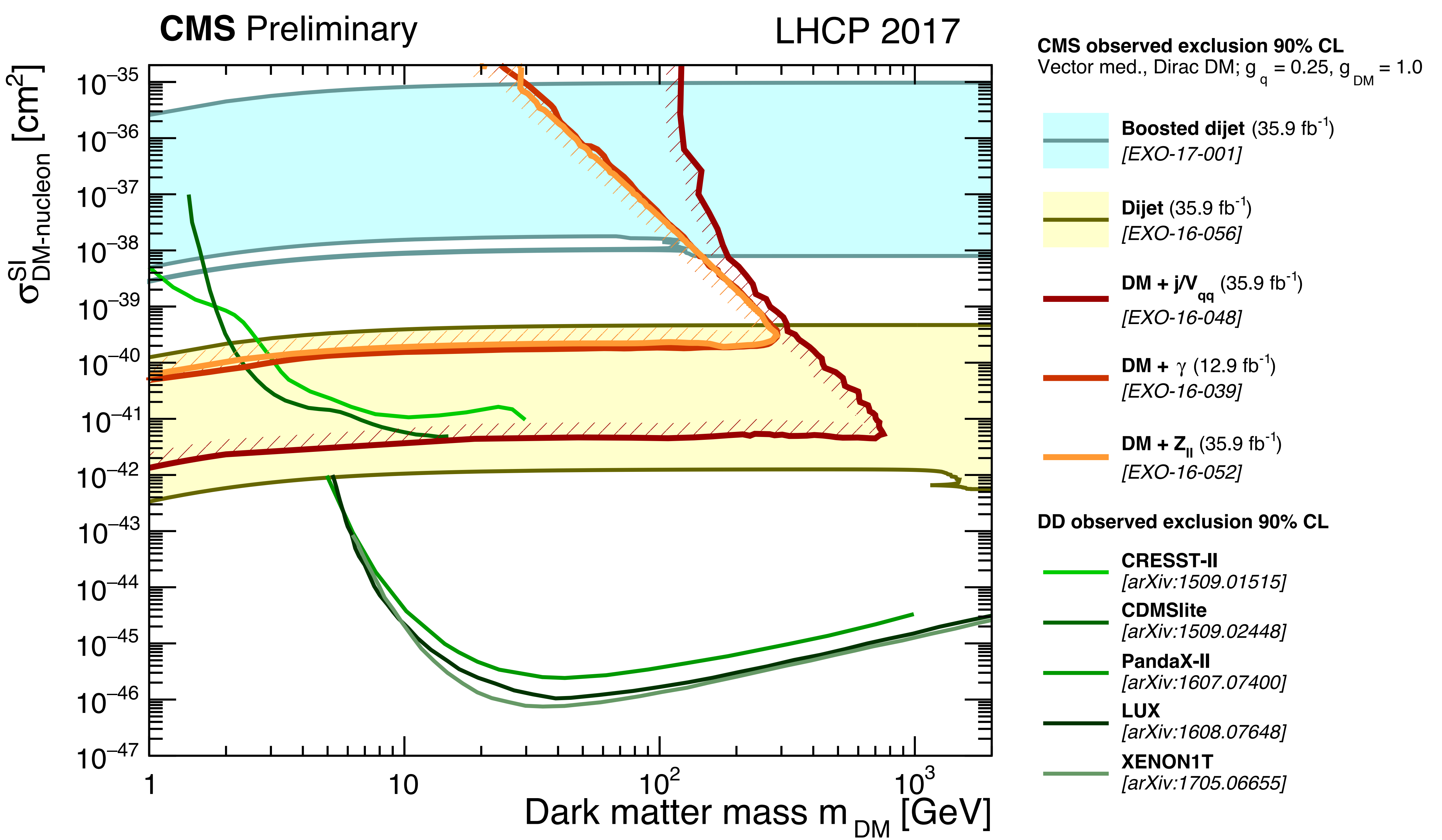


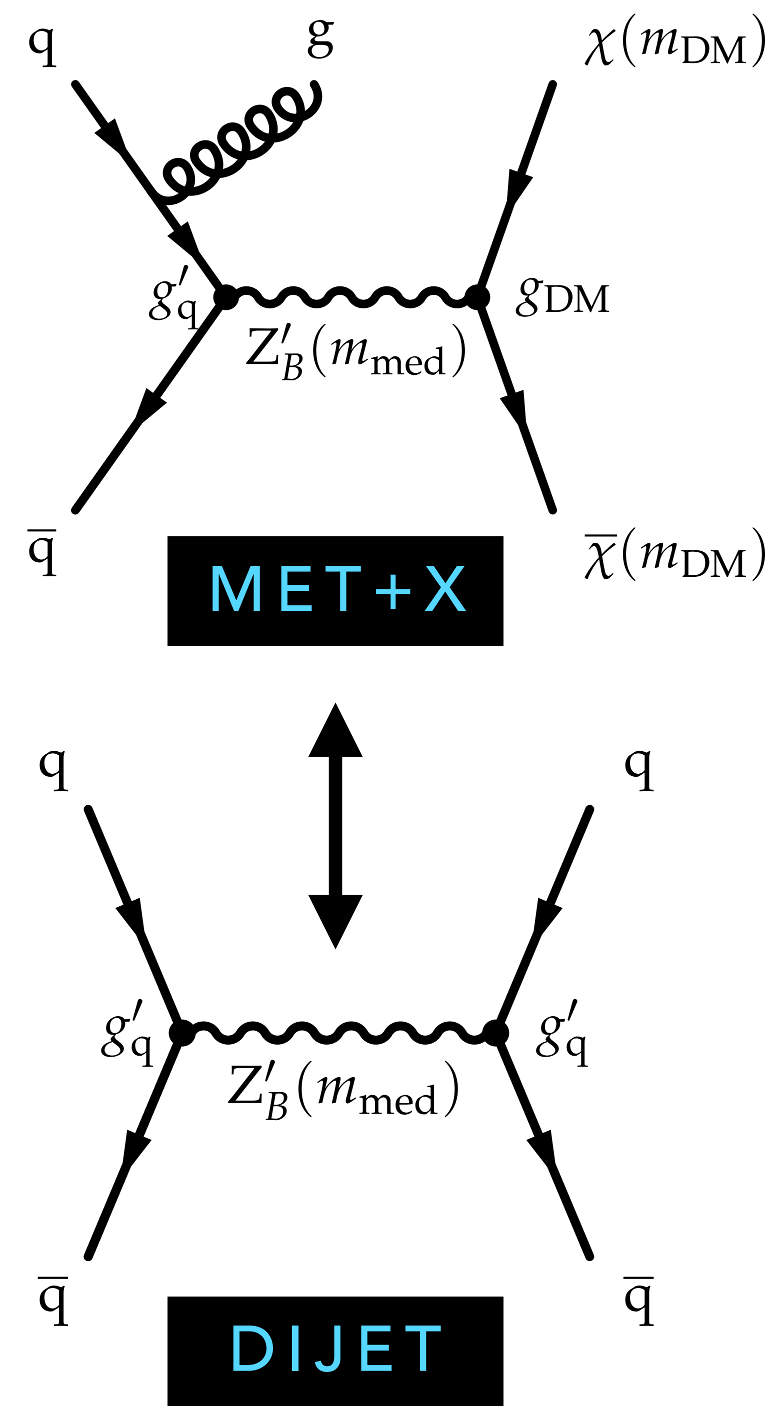
NOTE: MODEL DEPENDENT

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 $\mathbf{g_{DM}} > 0$ and $\mathbf{m_{DM}} < m_M/2$?

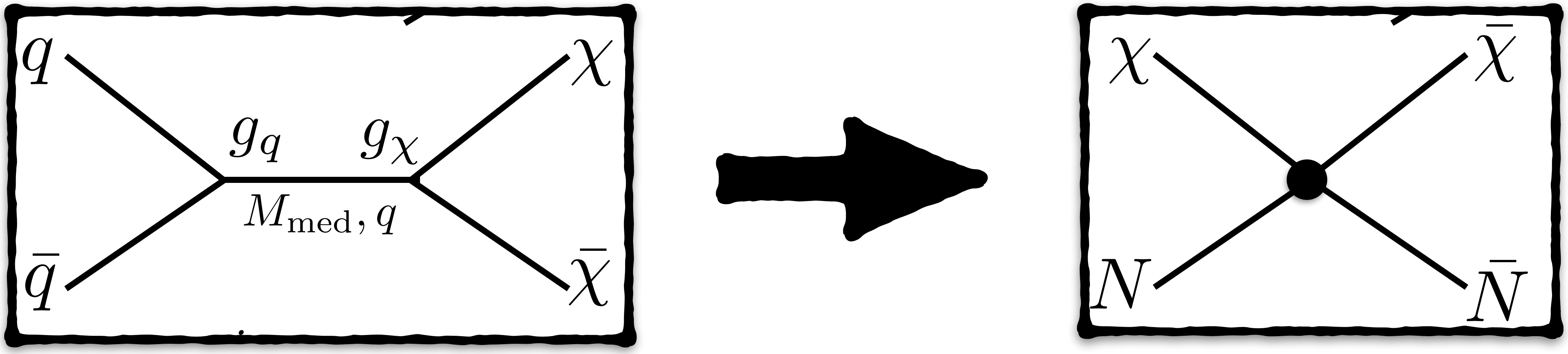
$$\mathcal{L}_{\mathrm{V}} = -g_{\mathrm{DM}} Z'_{B\mu}\bar{\chi}\gamma^{\mu}\chi - g'_{\mathrm{q}}\sum_{\mathrm{q}} Z'_{B\mu}\bar{q}\gamma^{\mu}q$$

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



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

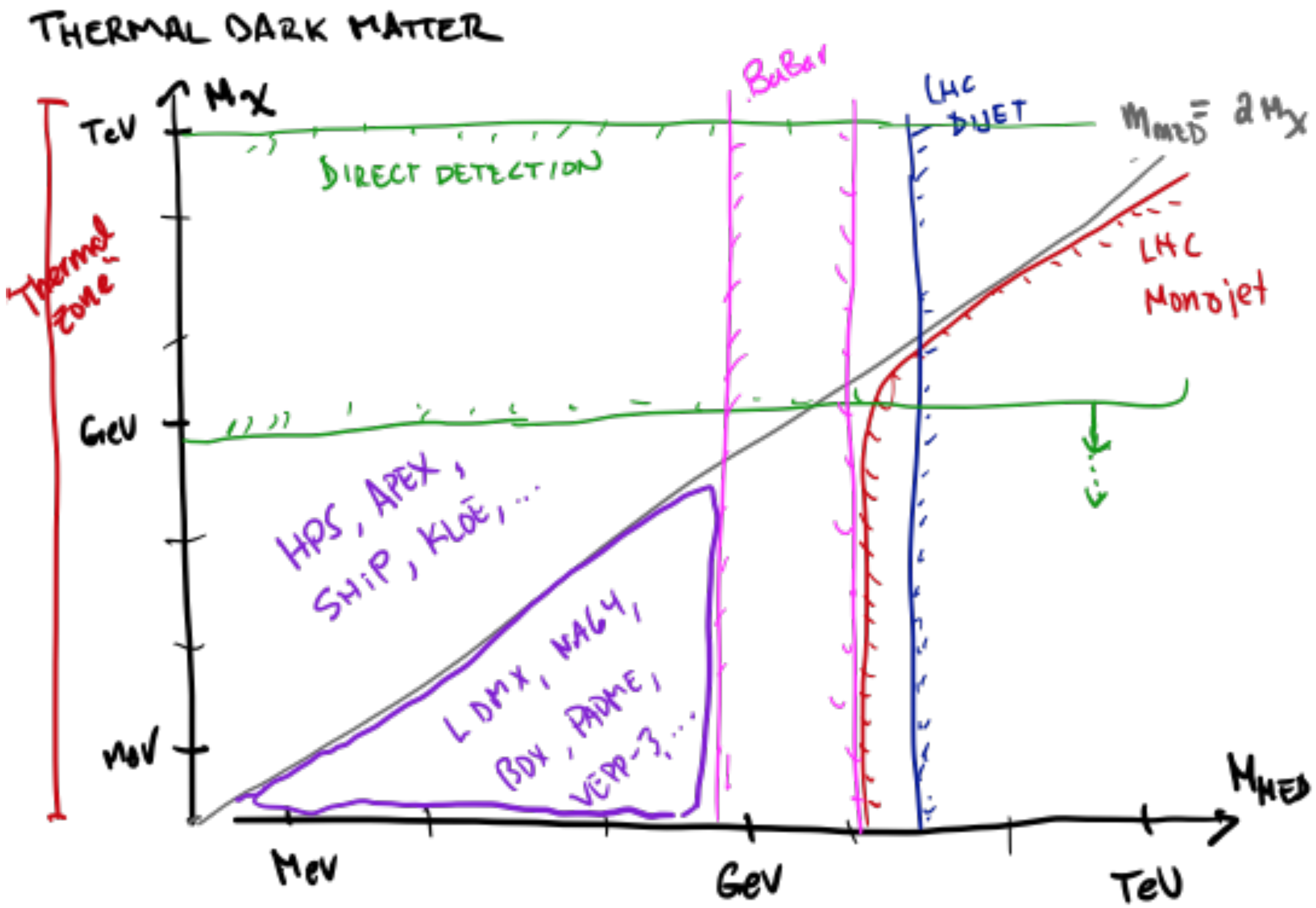
$$f^{\rm p} = f^{\rm n} = 0.32 g'_{\rm q}.$$

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

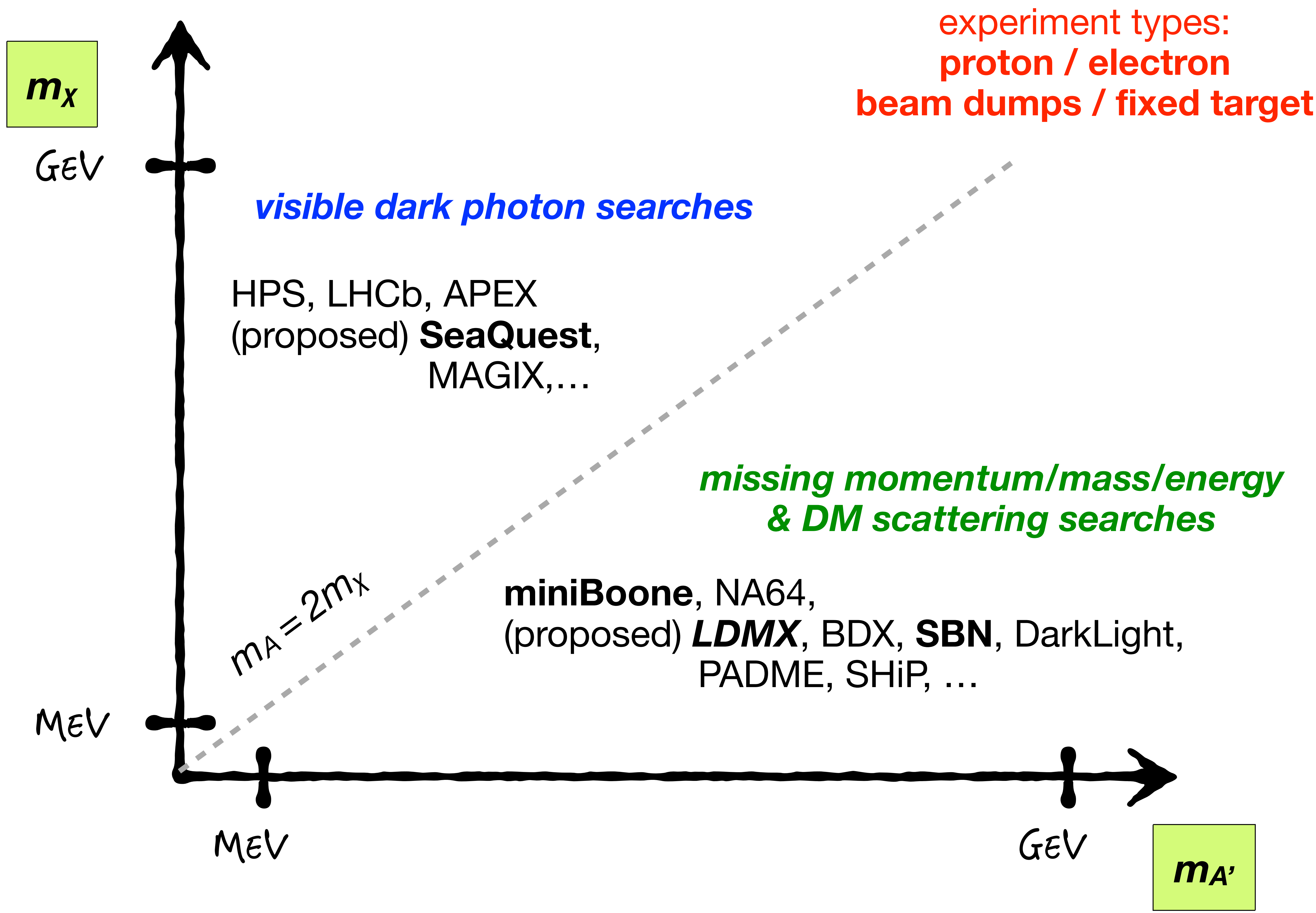
$$\simeq 2.4 \times 10^{-42}\,{\rm cm}^2 \cdot \left(\frac{g'_{\rm q} g_{\rm DM}}{0.25}\right)^2 \left(\frac{1\,{\rm TeV}}{m_{\rm med}}\right)^4 \left(\frac{\mu_{\rm N\chi}}{1\,{\rm GeV}}\right)^2,$$

arXiv:1603.04156

DM COMPLEMENTARITY



DM COMPLEMENTARITY



QCD TRANSFER FACTOR

- If tagger were completely uncorrelated from jet mass and p_T in data, the transfer factor would be flat

$$N^{\mathrm{QCD}}_{\mathrm{pass}}(m_{\mathrm{SD}}, p_{\mathrm{T}}) = R_{\mathrm{p/f}}(\rho, p_{\mathrm{T}}) \cdot N^{\mathrm{QCD}}_{\mathrm{fail}}(m_{\mathrm{SD}}, p_{\mathrm{T}})$$

$$N^{\mathrm{QCD}}_{\mathrm{pass}}(m_{\mathrm{SD}i}, p_{\mathrm{T}j}) = \boxed{a_{00}} \cdot N^{\mathrm{QCD}}_{\mathrm{fail}}(m_{\mathrm{SD}i}, p_{\mathrm{T}j})$$

QCD TRANSFER FACTOR

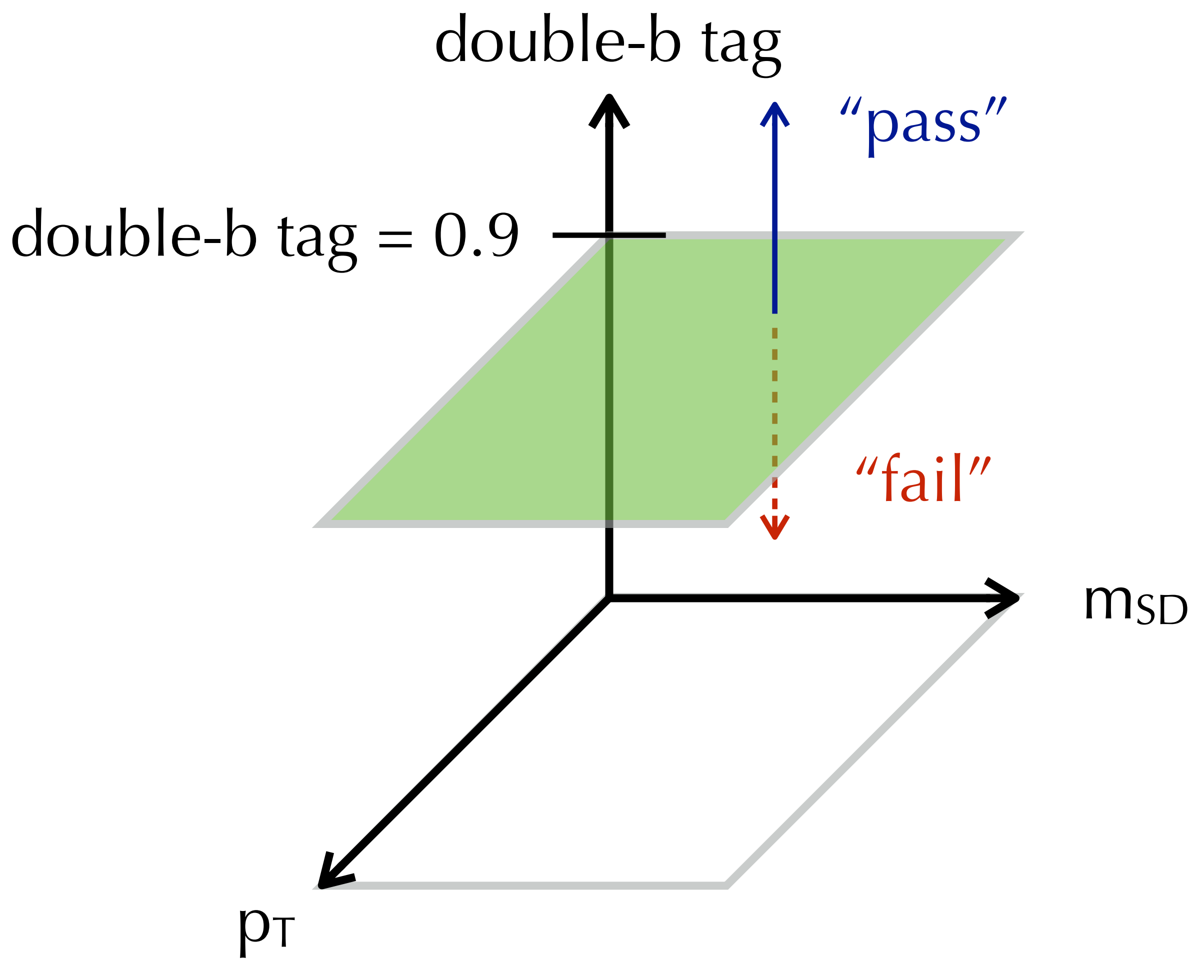
- If tagger were completely uncorrelated from jet mass and p_T in data, the transfer factor would be flat
- **Taylor expand** as a polynomial in ρ and p_T to parameterize any small correlations
- Fisher F-test to determine order of polynomial needed to fit the ratio: 2rd order in ρ and 1st order in p_T is sufficient

$$N^{\mathrm{QCD}}_{\mathrm{pass}}(m_{\mathrm{SD}}, p_{\mathrm{T}}) = R_{\mathrm{p/f}}(\rho, p_{\mathrm{T}}) \cdot N^{\mathrm{QCD}}_{\mathrm{fail}}(m_{\mathrm{SD}}, p_{\mathrm{T}})$$

$$N^{\mathrm{QCD}}_{\mathrm{pass}}(m_{\mathrm{SD}i}, p_{\mathrm{T}j}) = \left(\sum_{k,\ell} a_{k\ell}\rho^k_{ij} p_{\mathrm{T}}{}^{\ell}_{j}\right) \cdot N^{\mathrm{QCD}}_{\mathrm{fail}}(m_{\mathrm{SD}i}, p_{\mathrm{T}j})$$

BACKGROUND STRATEGY

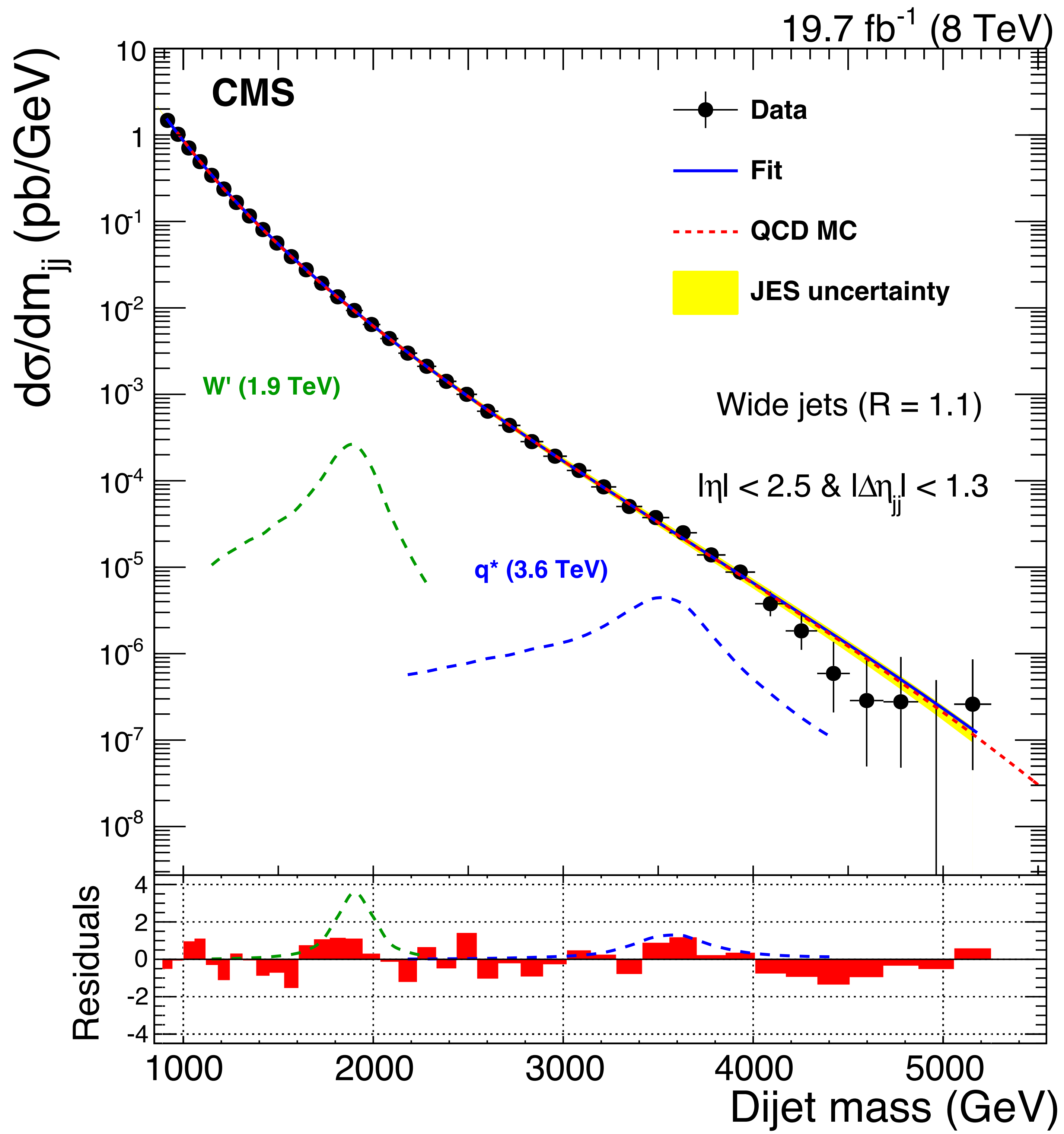
- Backgrounds estimated from data
  - QCD (90%): from failing double b-tag × **transfer factor**
  - tt+jets (3%): from 1μ control region
- Backgrounds estimated from corrected simulation:
  - W/Z+jets (5%)
  - single-t, VV (<1%)



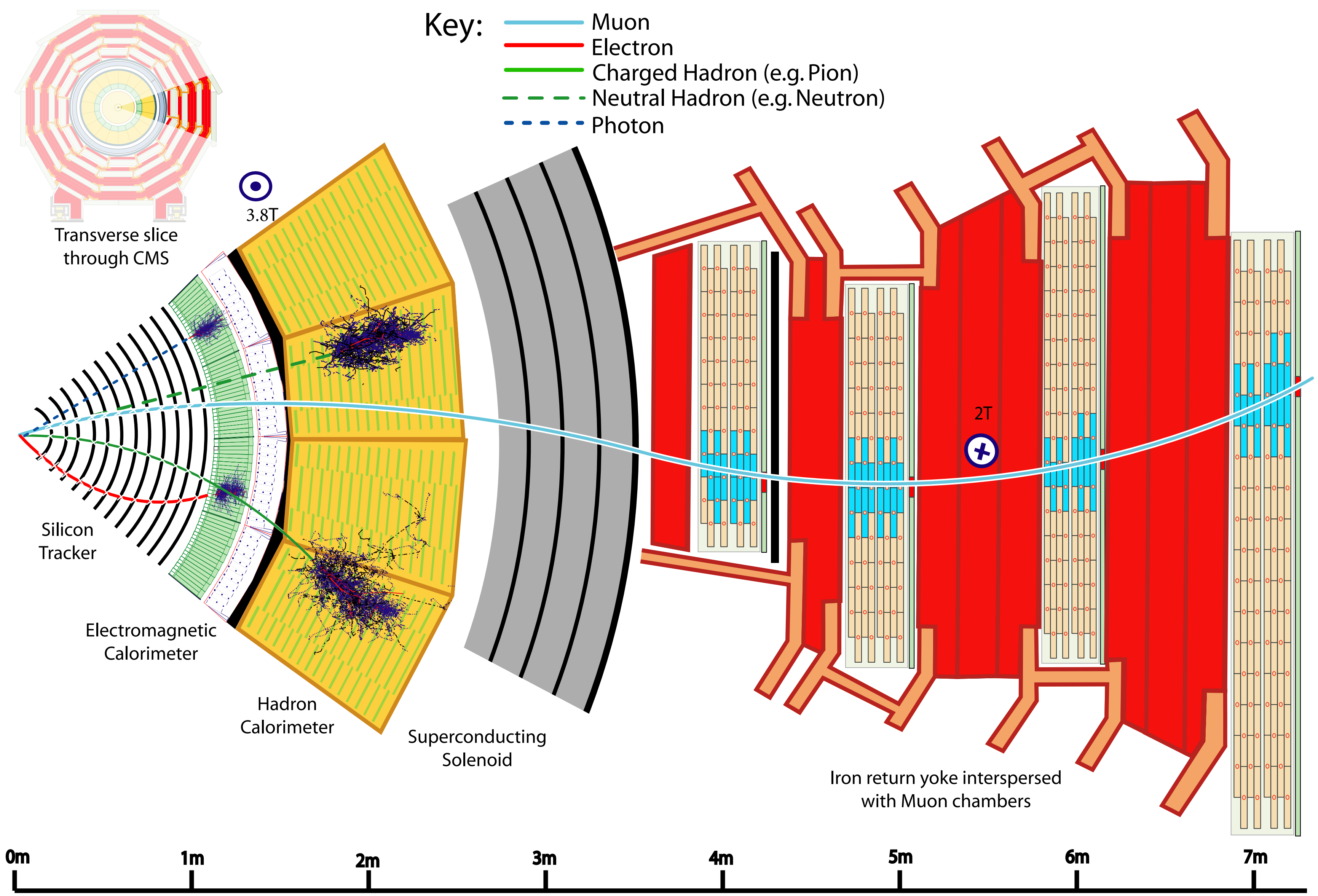
arXiv:1501.04198

CLASSIC DIJET

- Classic dijet search @ LHC (CMS, 8 TeV)



CMS DETECTOR

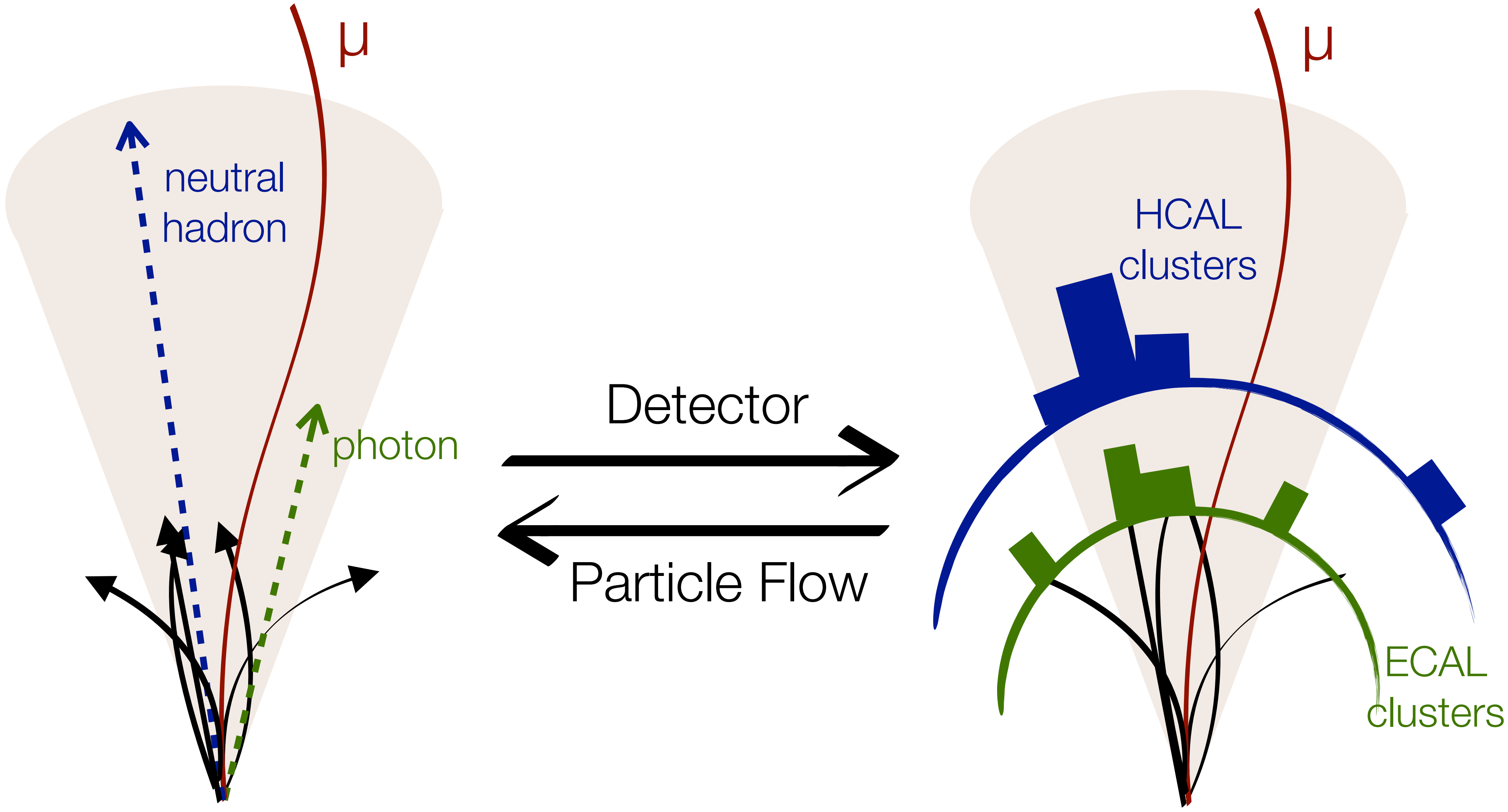


Detector	p_T-resolution	η/Φ-segmentation
Tracker	0.6% (0.2 GeV) – 5% (500 GeV)	0.002 x 0.003 (first pixel layer)
ECAL	1% (20 GeV) – 0.4% (500 GeV)	0.017 x 0.017 (barrel)
HCAL	30% (30 GeV) – 5% (500 GeV)	0.087 x 0.087 (barrel)

arXiv:1706.04965

PARTICLE FLOW

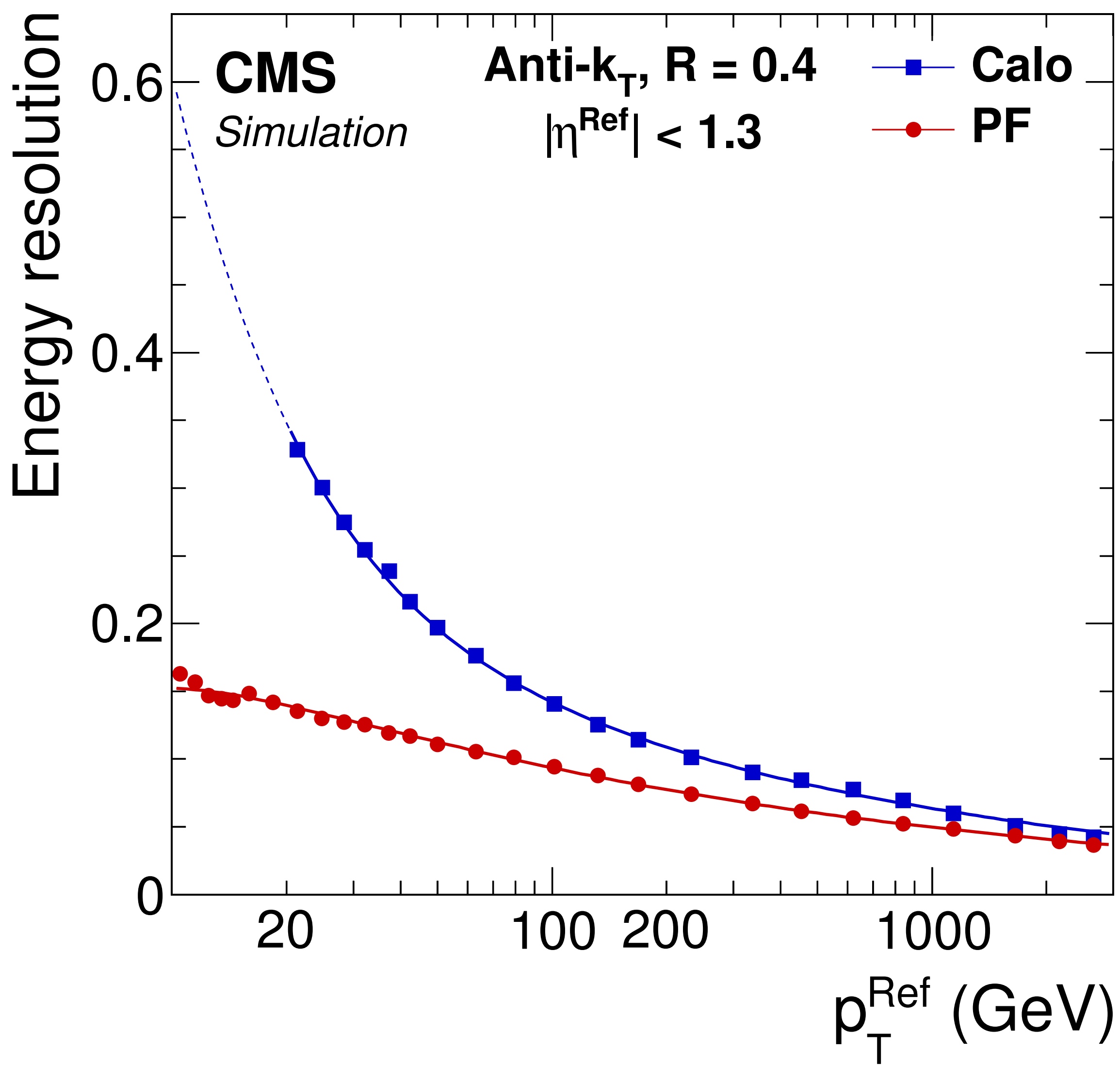
- Efficient combination of complementary detector subsystems

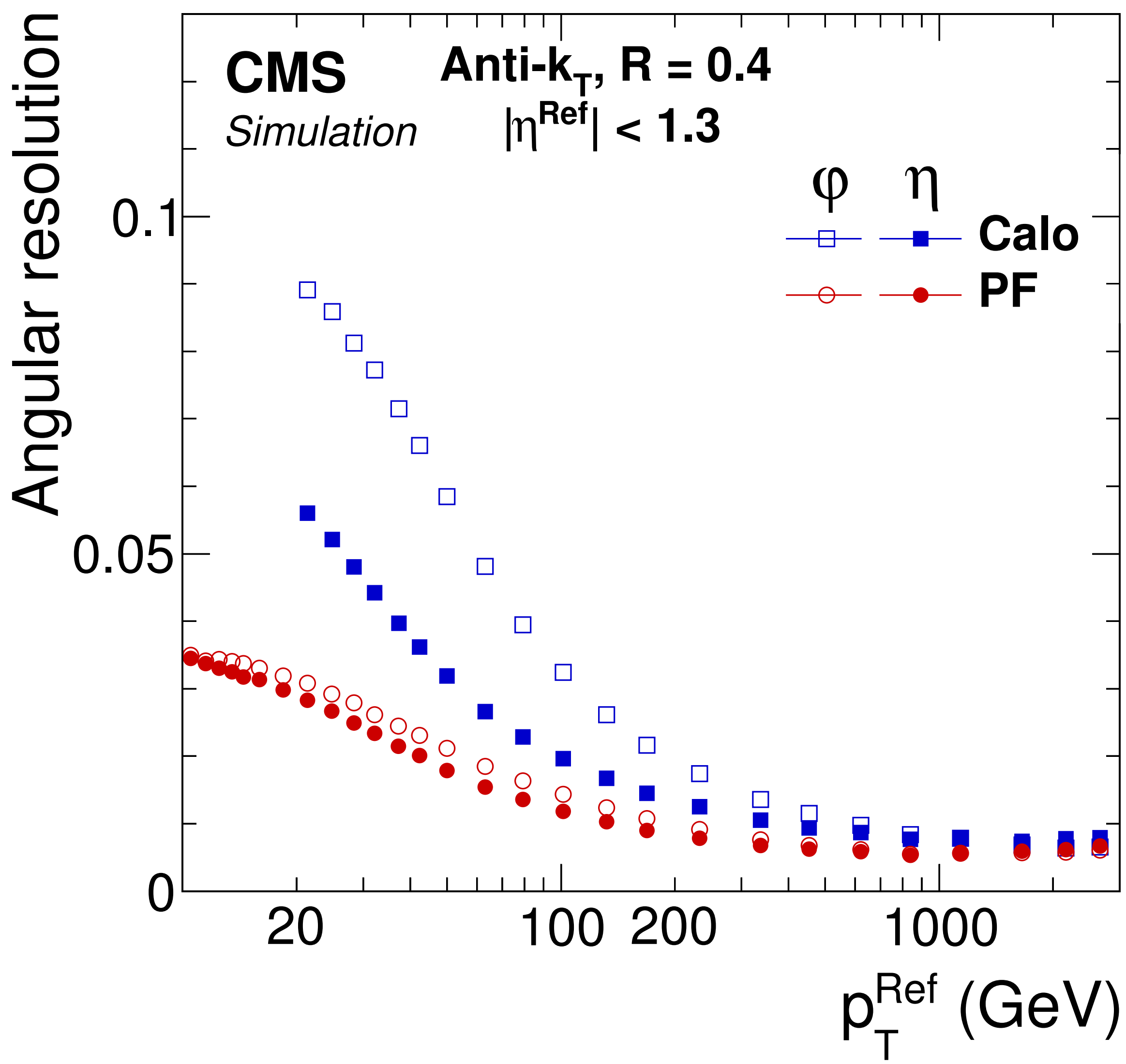


[arXiv:1706.04965](https://arxiv.org/abs/1706.04965)

PARTICLE FLOW

- Efficient combination of complementary detector subsystems
- Holistic particle interpretation of the event improves energy/spatial resolution for jets, among many other things…

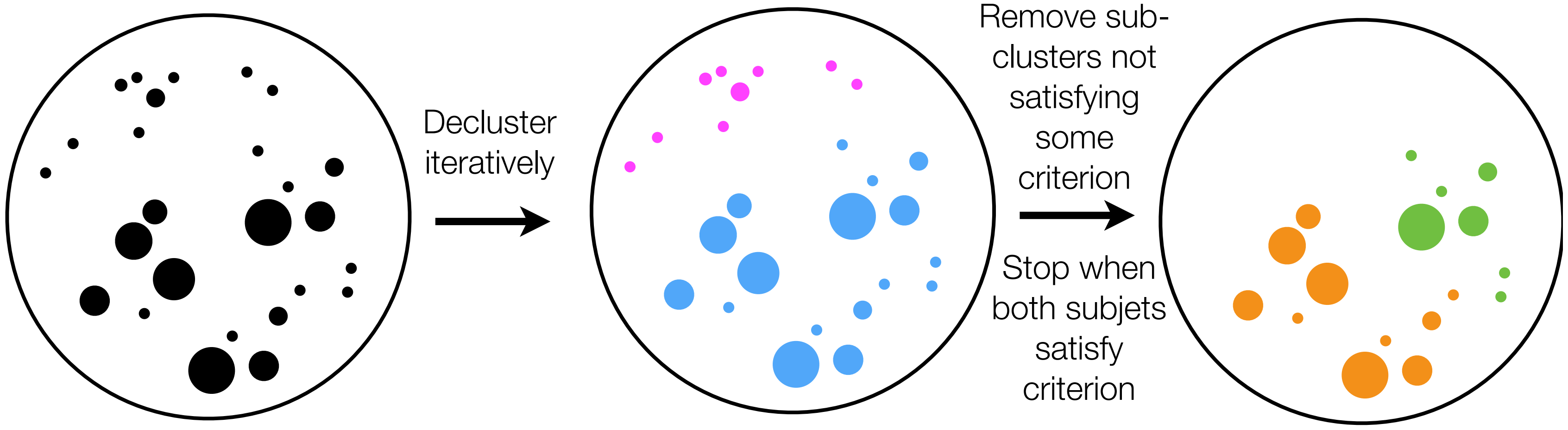




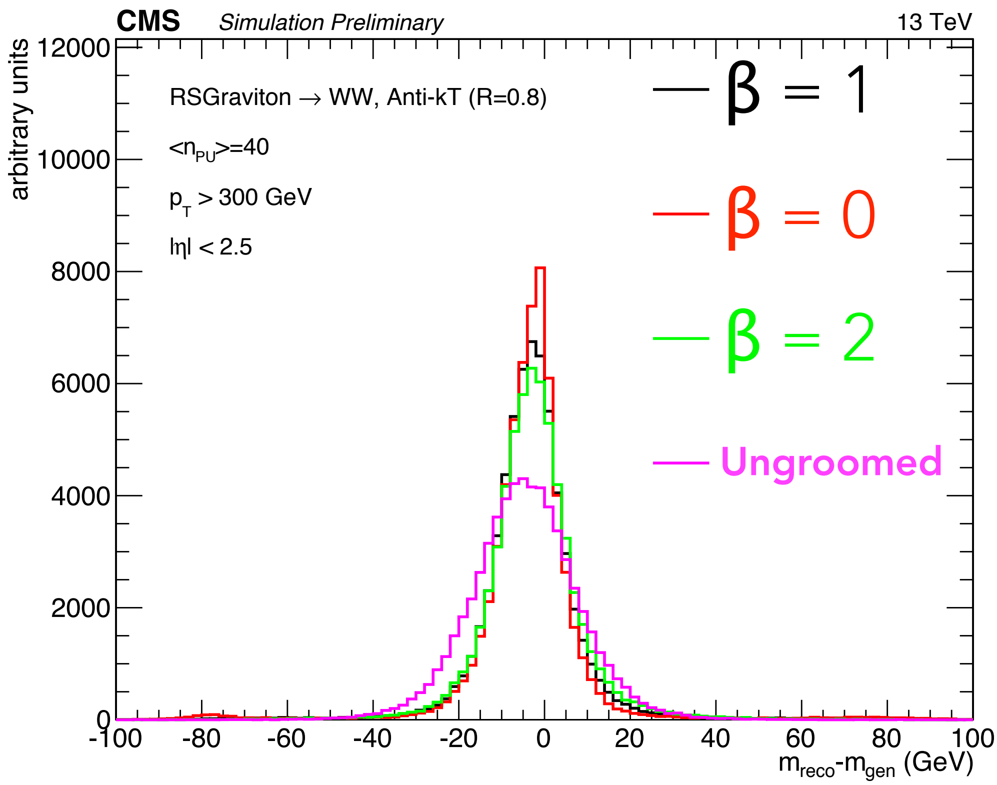
arXiv:1307.0007
arXiv:1402.2657

JET MASS

- Provides good separation between W/Z/H-jets and q/g jets
- Grooming removes soft and wide-angle radiation (soft drop / modified mass drop tagger)



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



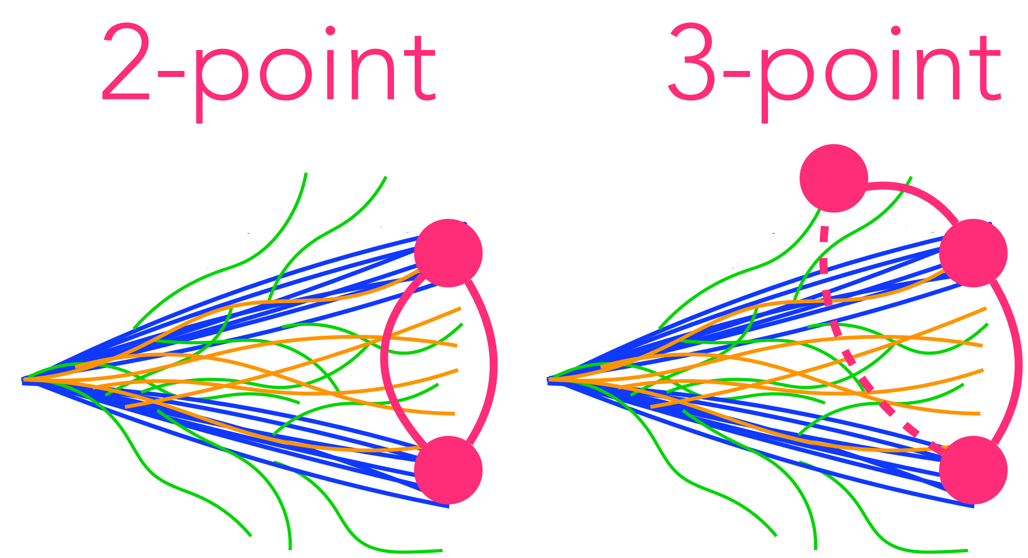
CMS: $z_{cut} = 0.1$, $\beta = 0$

arXiv:1609.07483

JET SUBSTRUCTURE

- How many "prongs" are in the jet?
- Generalized energy correlation functions are sensitive to N-point correlations within a jet
  - Two-pronged jets have ${}_2e_3 \ll ({}_1e_2)^2$
- Stable under grooming

$$N_2^\beta = \frac{{}_2e_3^\beta}{({}_1e_2^\beta)^2} \quad \beta = 1$$



$${}_1e_2^\beta = \frac{1}{p_{\mathrm{T}J}^2} \sum_{1 \le i < j \le n_J} p_{\mathrm{T}i} p_{\mathrm{T}j} \Delta R_{ij}^\beta$$

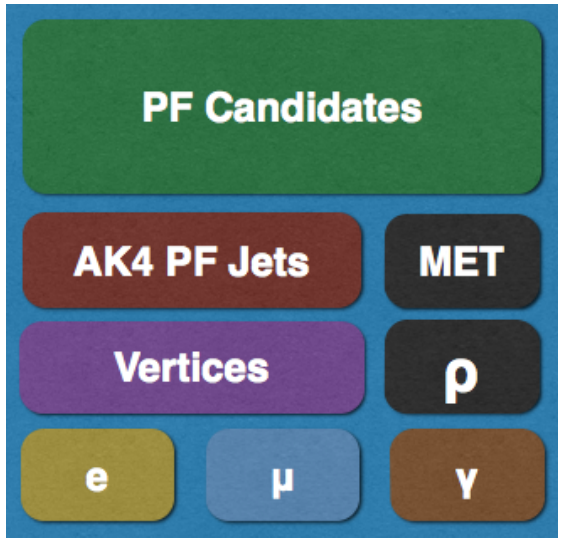
$${}_2e_3^\beta = \frac{1}{p_{\mathrm{T}J}^3} \sum_{1 \le i < j < k \le n_J} p_{\mathrm{T}i} p_{\mathrm{T}j} p_{\mathrm{T}k} \min\{\Delta R_{ij}^\beta \Delta R_{ik}^\beta, \Delta R_{ij}^\beta \Delta R_{jk}^\beta, \Delta R_{ik}^\beta \Delta R_{jk}^\beta\}$$

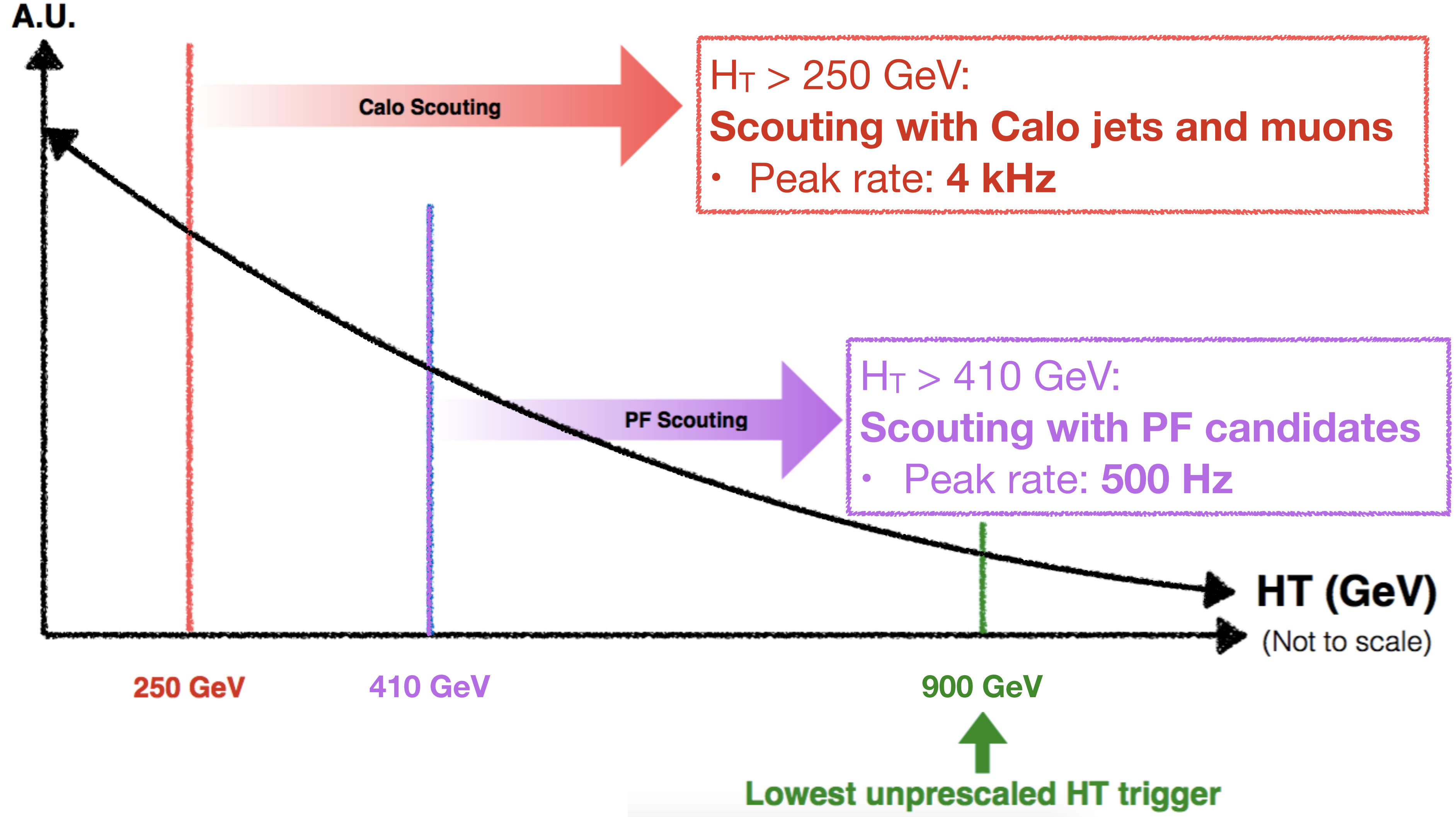
D. Anderson "Data Scouting at CMS" 2015 IEEE NSS/MIC

DATA SCOUTING

- How can we trigger below H_T = 900 GeV?
- ***Reconstruct/save*** only necessary information to perform analysis → record more events
- "**PF Scouting**" is more flexible but limited by **timing** @ HLT (tracking)

PF Scouting
500 Hz × 15 kB



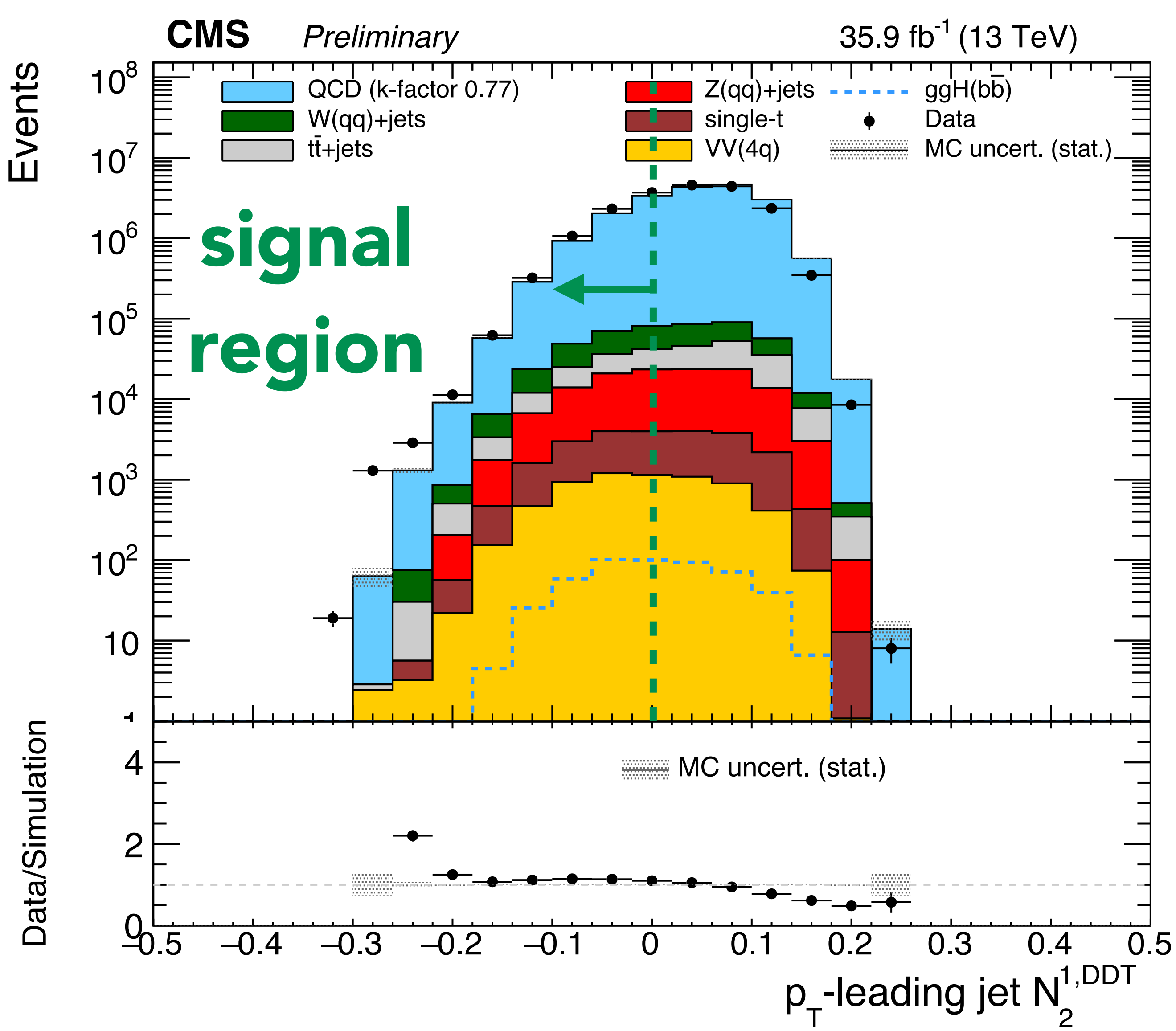


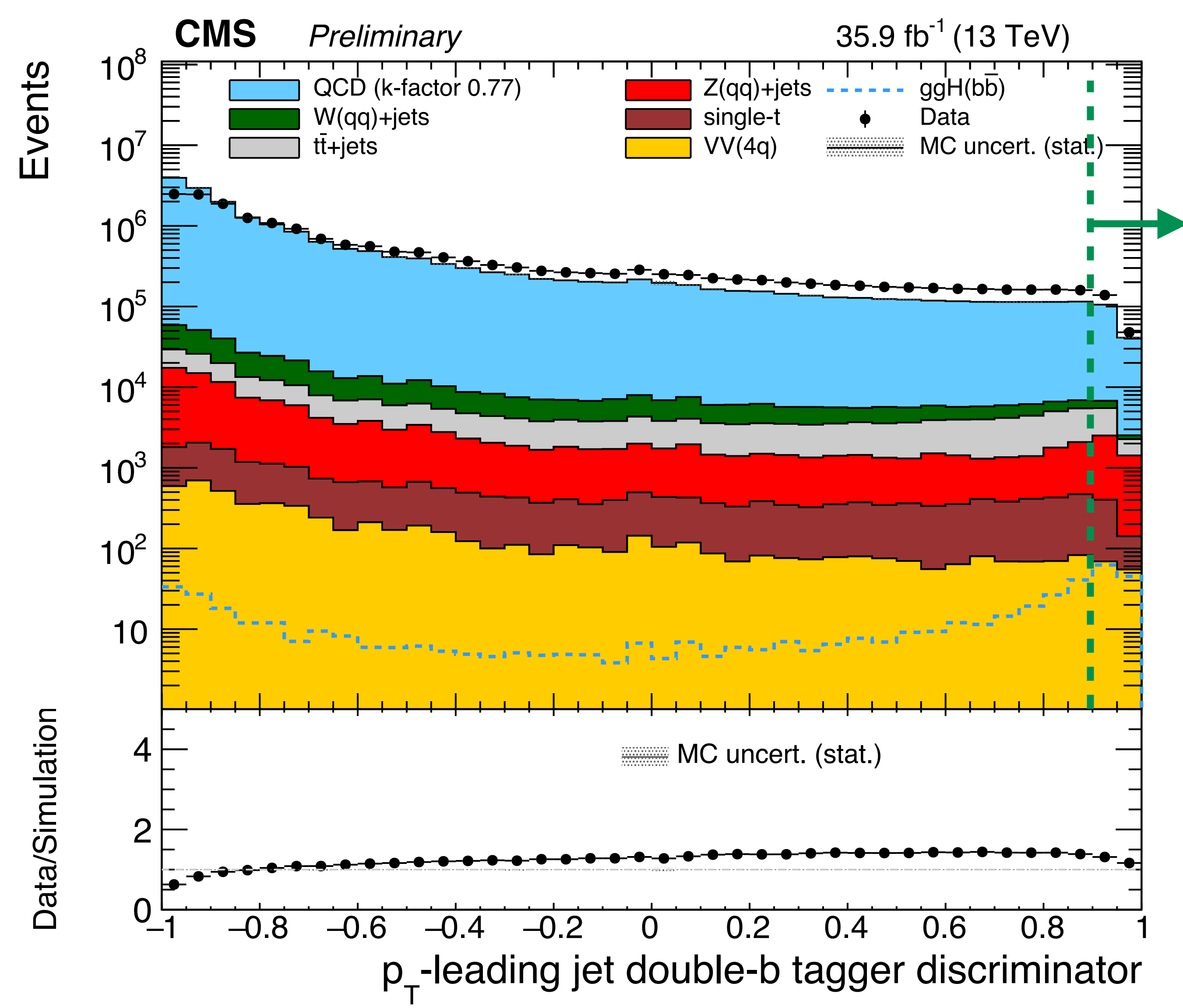
PRL 120, 071802 (2018)

ANALYSIS SELECTION

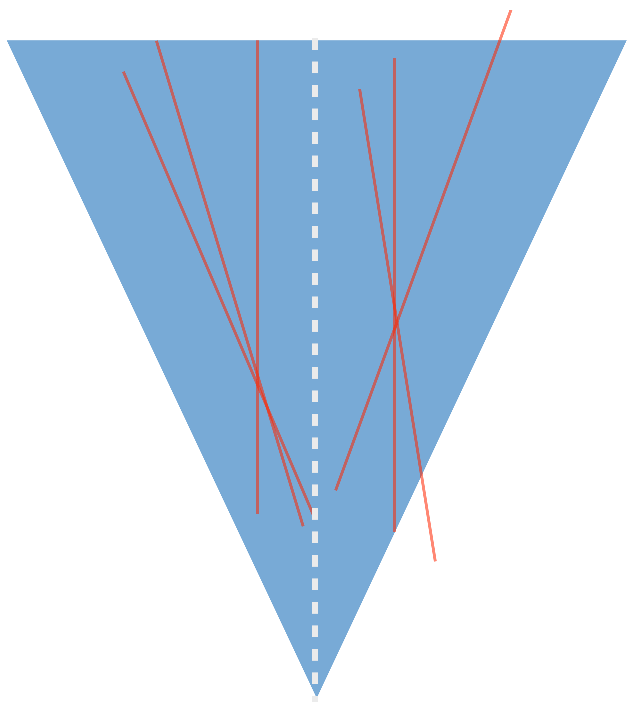
Substructure: two prong discrimination, 50% sig. efficiency, 26% bkg. efficiency

Double-b tagger: 30% sig. efficiency, 1% bkg. efficiency (tight working point)

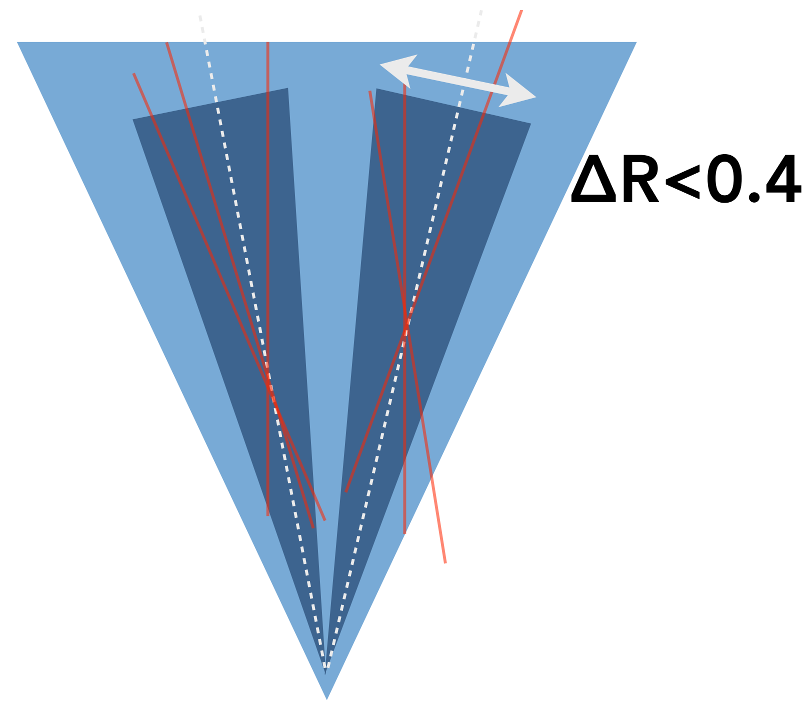




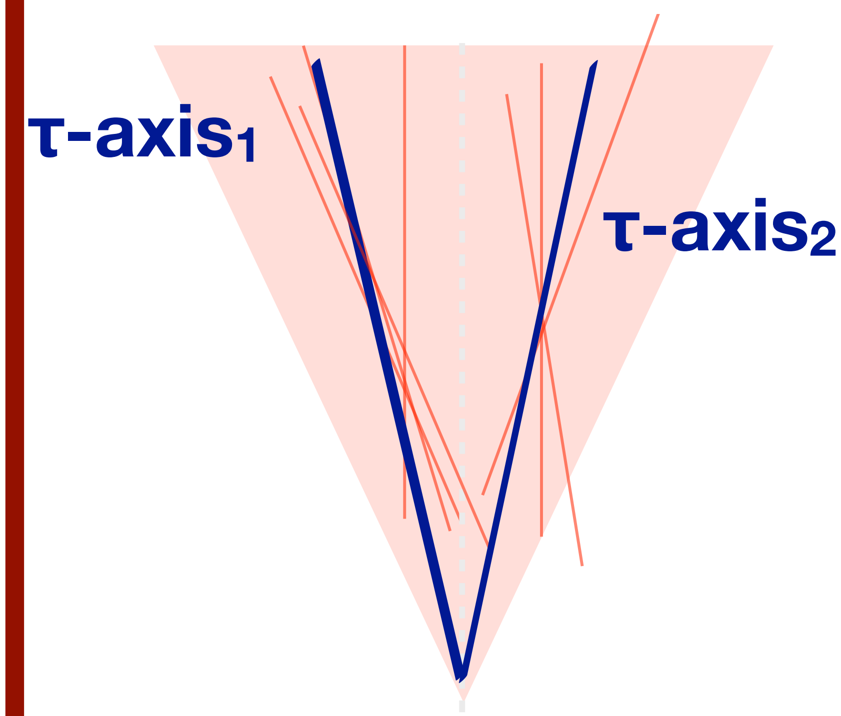
MULTIPLE APPROACHES



fatjet



subjets



double-b

- Based on standard b-tagging algorithm
- Not designed for two b's in the same jet

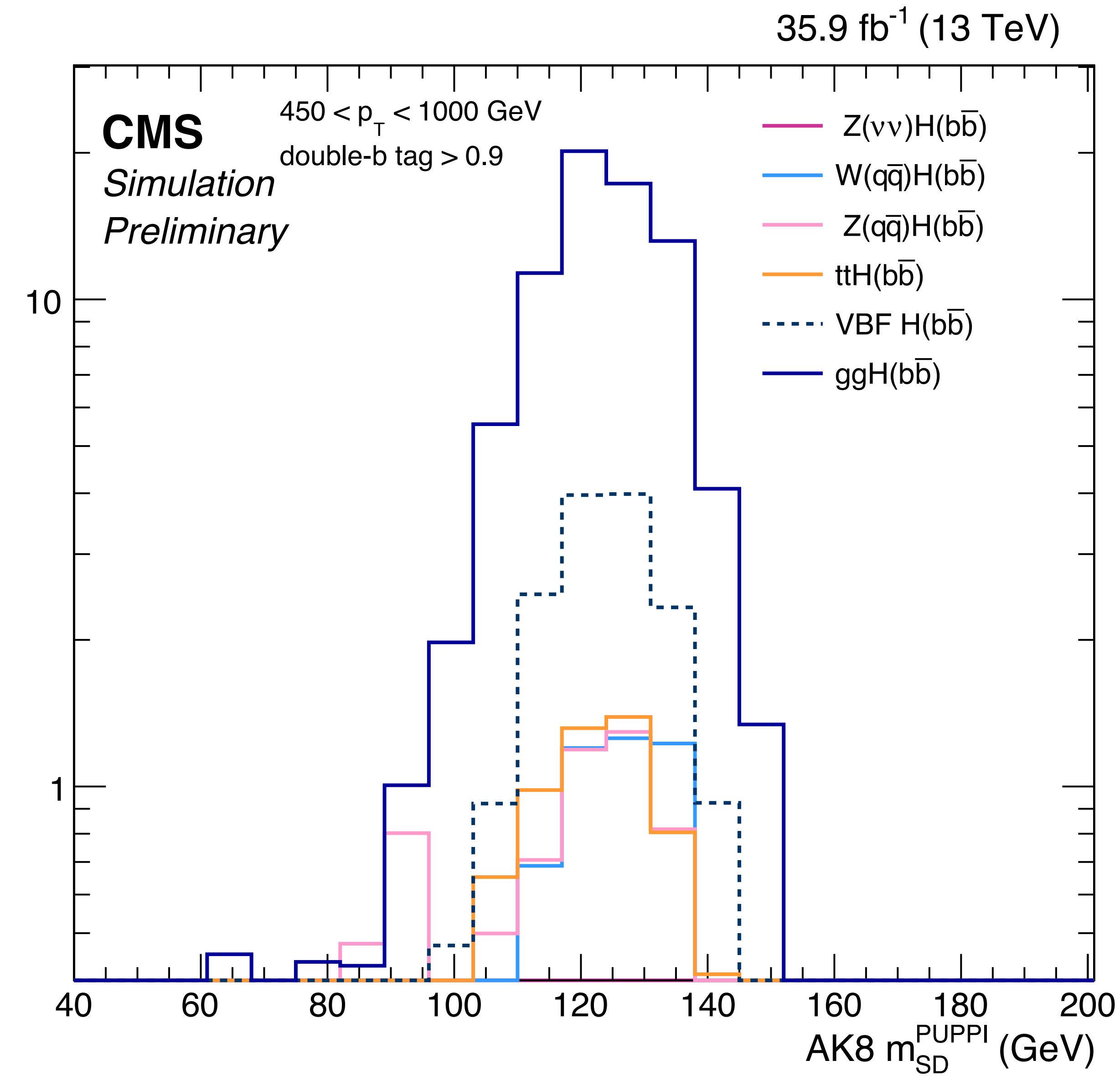
- Defines sub-jets
- Standard b-tagging applied to each subject

- Identifies two b hadron decay chains in the same fat jet
- Does not define subjects, but uses N-subjettiness axes

HIG-17-010

SIGNAL COMPOSITION

- Analysis is inclusive in Higgs production mode
- Dominant contribution is ggF (74%)
  - 12% VBF
  - 8% VH
  - 6% ttH



arXiv:1407.6013

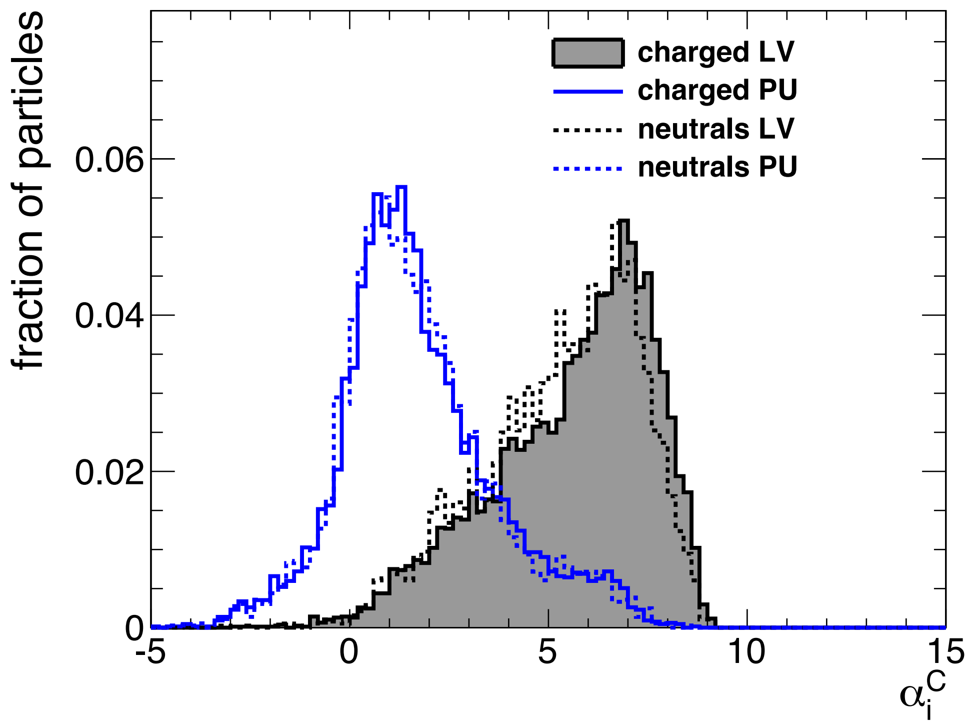
PUPPI

- **PUPPI** (**P**ile**U**p **P**er **P**article **I**d): general framework that determines, per particle, a weight for **how likely** a particle is from PU
- **Key insight**: using QCD ansatz to infer neutral pileup contribution

[1] define a local discriminant, α, between pileup (PU) and leading vertex (LV)

$$\alpha_i^C = \log \left[\sum_{j \in \mathrm{Ch,LV}} \frac{p_{T,j}}{\Delta R_{ij}} \Theta(R_0 - \Delta R_{ij}) \right]$$

[2] get data-driven α distribution for PU using charged PU tracks



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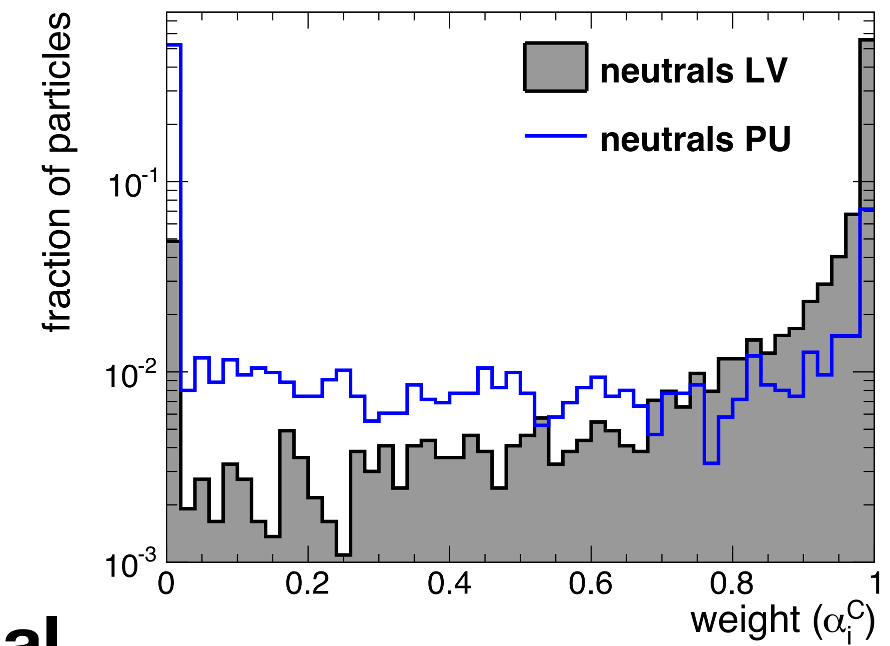
[2] get data-driven α distribution for PU using charged PU tracks

[3] for the neutrals, ask "how un-PU-like is α for this particle?", compute a weight



[4] reweight the four-vector of the particle by this weight, then proceed to interpret the event as usual

arXiv:1407.6013

PUPPI

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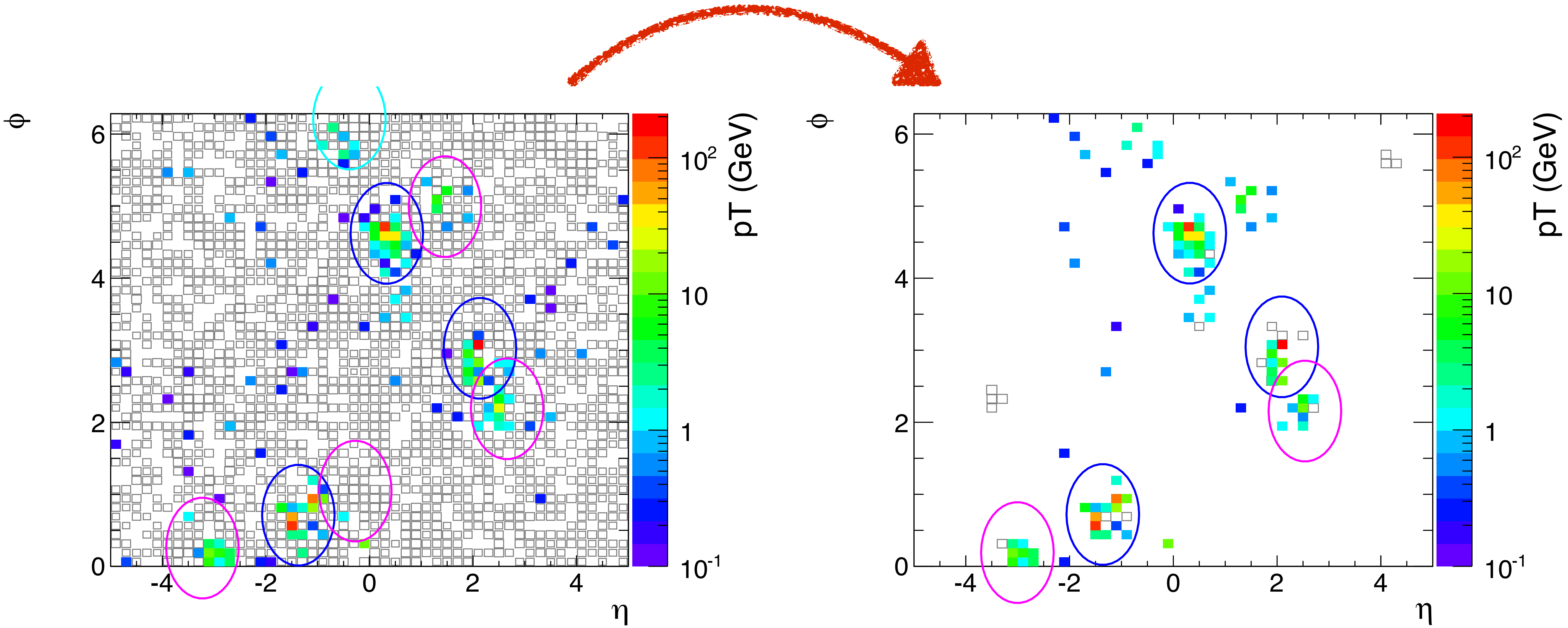
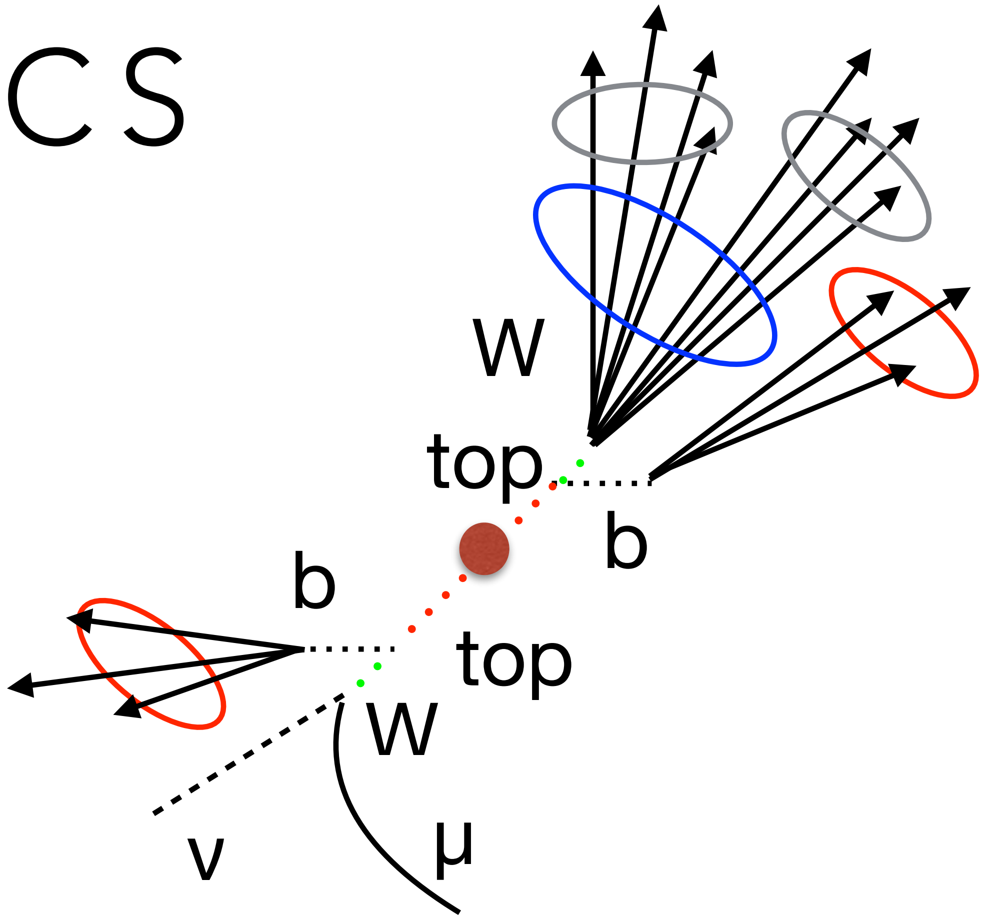
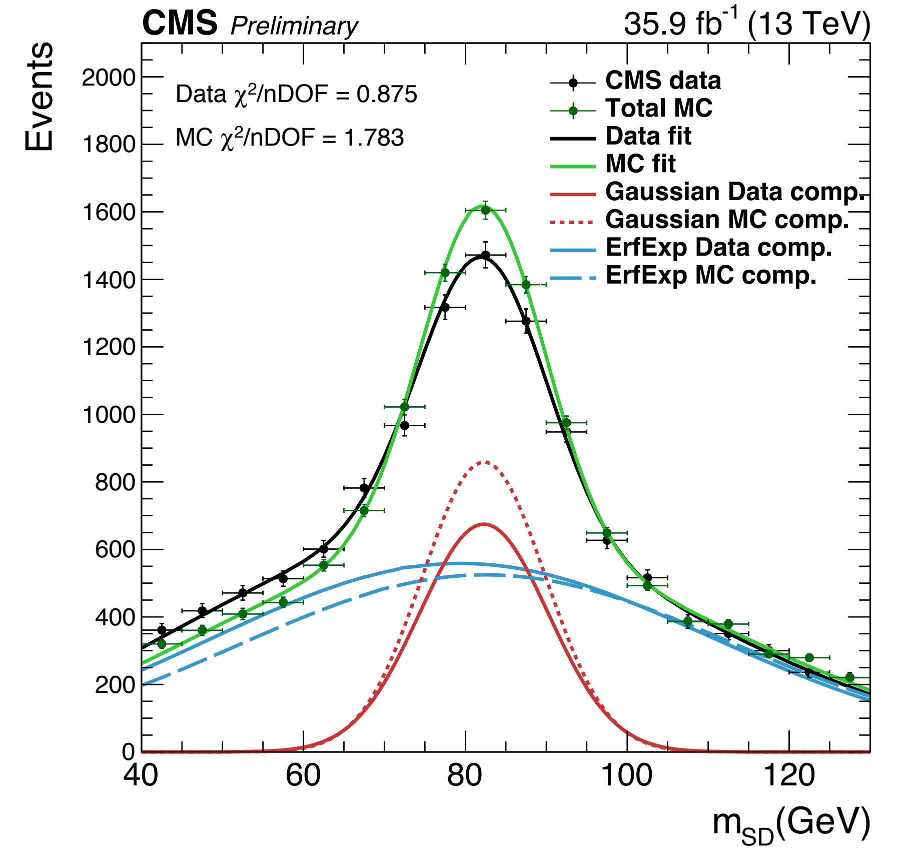


SYSTEMATICS

Systematic uncertainty source	Type (shape or normalization)	Relative size (or description)
QCD transfer factor	both	profile $a_{k\ell}$ and QCD normalization
Luminosity	normalization	2.5%
V-tag ($N_2^{1,DDT}$) efficiency	normalization	4.3%
Muon veto efficiency	normalization	0.5%
Electron veto efficiency	normalization	0.5%
Trigger efficiency	normalization	4%
Muon ID efficiency	shape	up to 0.2%
Muon isolation efficiency	shape	up to 0.1%
Muon trigger efficiency	shape	up to 8%
$t\bar{t}$ normalization SF	normalization	from 1μ CR: 8%
$t\bar{t}$ double-b mis-tag SF	normalization	from 1μ CR: 15%
W/Z NLO QCD corrections	normalization	10%
W/Z NLO EWK corrections	normalization	15% – 35%
W/Z NLO EWK ratio decorrelation	normalization	5% – 15%
double-b tagging efficiency	normalization	4%
Jet energy scale	normalization	up to 10%
Jet energy resolution	normalization	up to 15%
Jet mass scale	shape	shift m_{SD} peak by $\pm$0.4%
Jet mass resolution	shape	smear m_{SD} distribution by $\pm$9%
Jet mass scale p_T	normalization	0.4%/100 GeV (p_T)
Monte Carlo statistics	normalization	-
H p_T correction (gluon fusion)	both	30%



- Signal systematic uncertainties from merged W sample in semi-leptonic ttbar events (external constraint)
- SM candles: presence of W/Z(bb) in final jet mass distribution provides in-situ constraint
- Higgs p_T correction uncertainty of 30%



DATA RATES, SIZES, AND TIMING

	Event Rate [Hz]	CPU Timing [ms]	File Size [kB]
Calo Scouting	4000	10	3
PF Scouting	500	25	15
Standard	1000	240	1000

LONG HISTORY OF DIJET SEARCHES

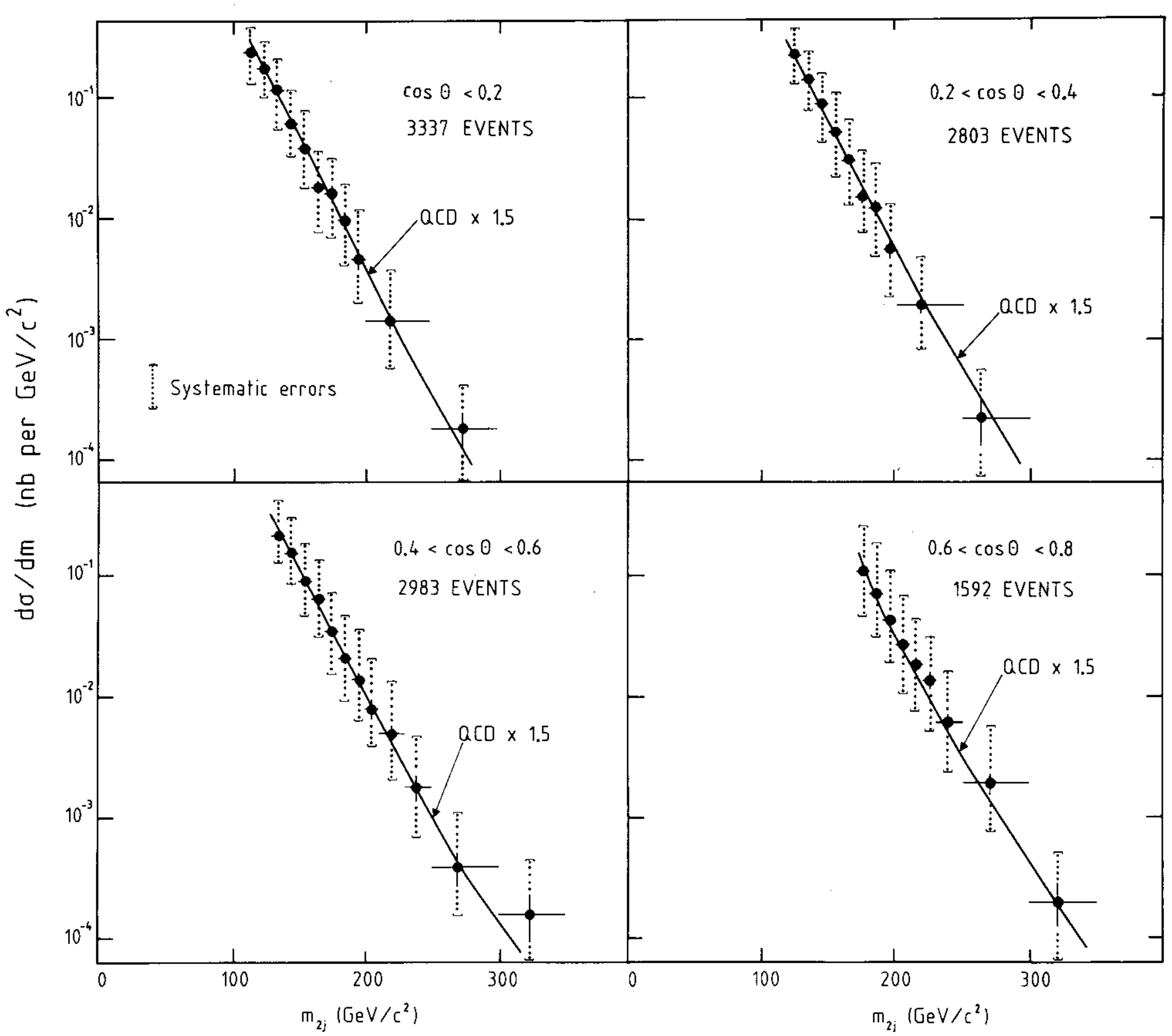
- Dijet resonance searches are fundamental discovery probes at hadron colliders
- What kind of physics can we do?

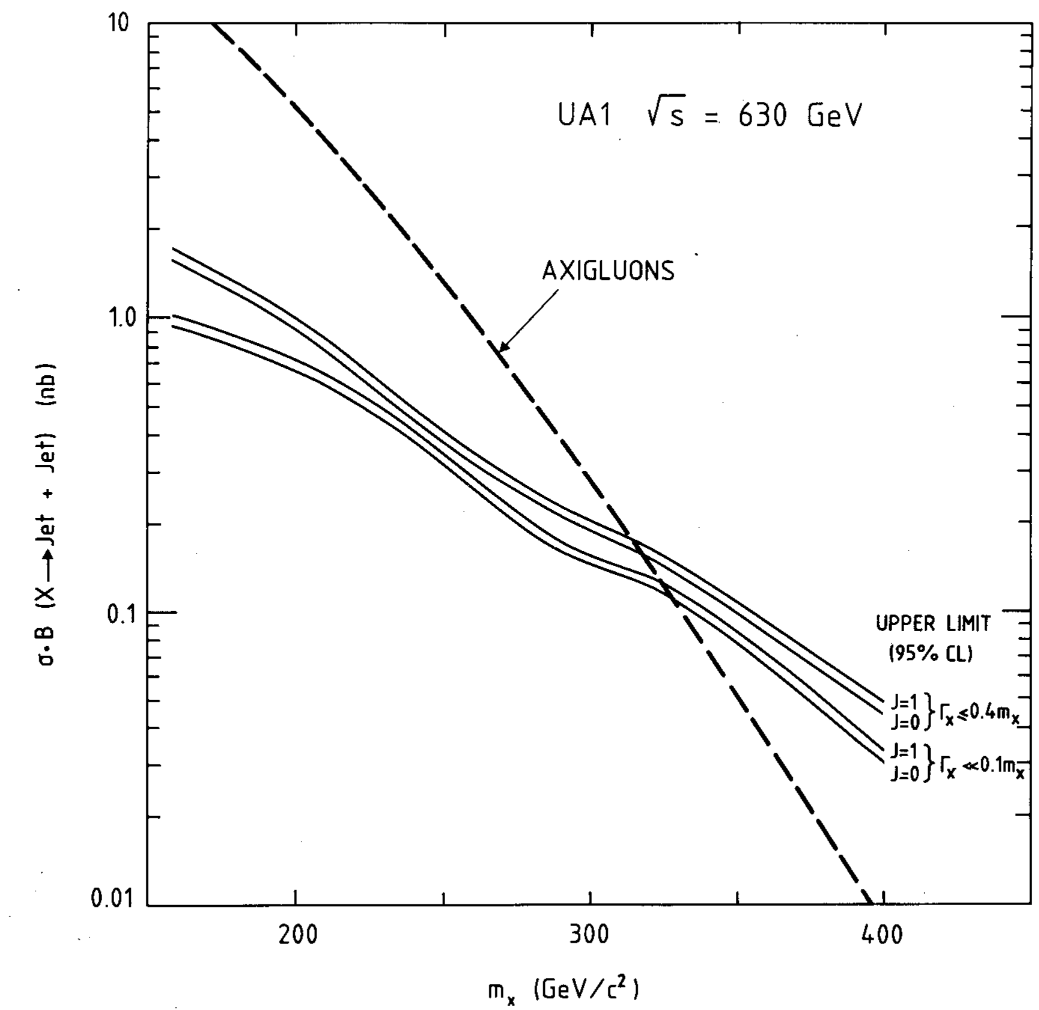
EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH

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

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

UA1 Collaboration, CERN, Geneva, Switzerland

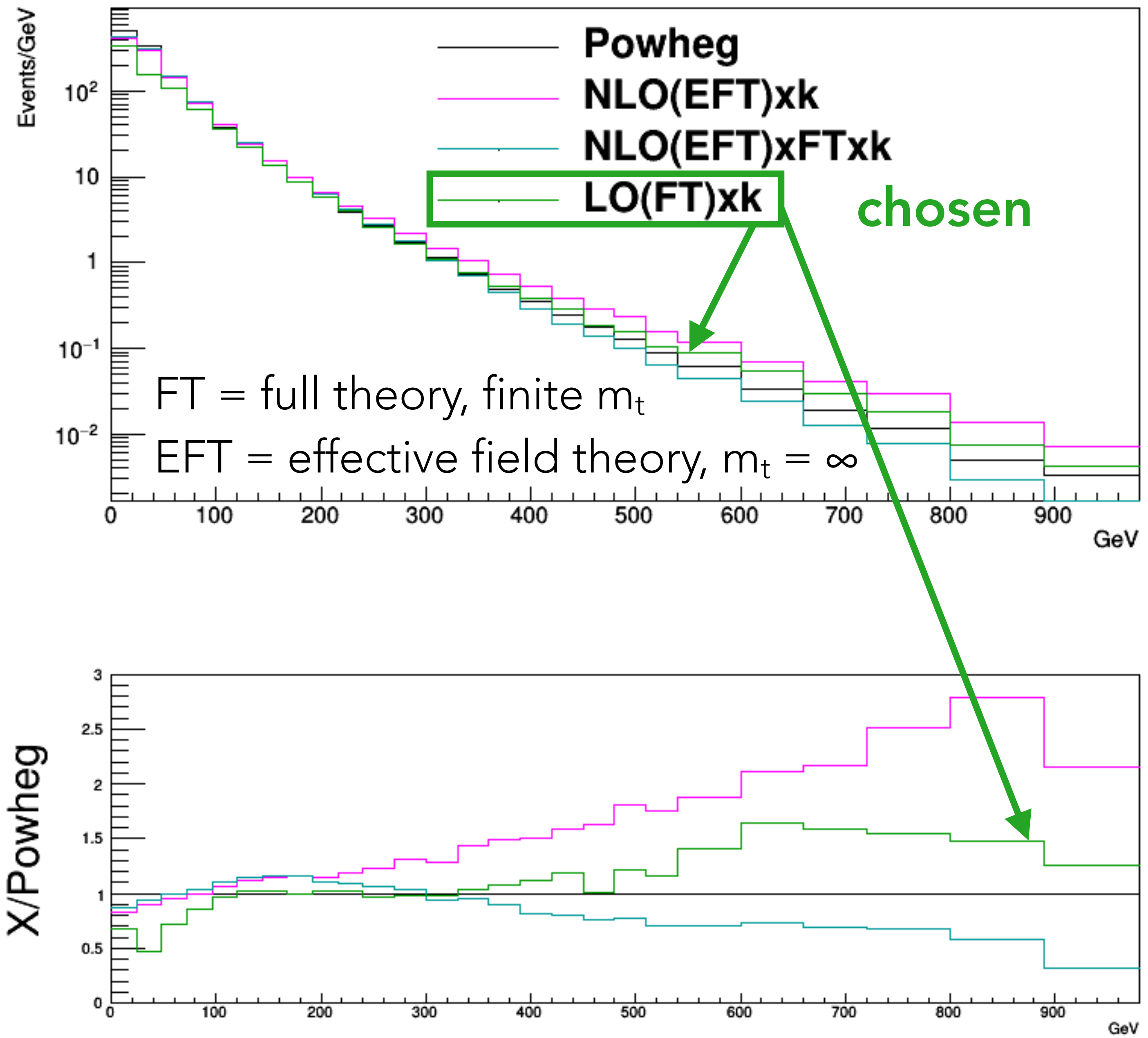




HIG-17-010

HIGGS P_T MODELING

- LO H+0–2jet Pythia CKKW-L merged, finite m_t
- NLO H+1jet finite m_t up to $1/m_t^4$ expansion: arXiv:1609.00367
- NNLO H+1jet, $m_t = \infty$, p_T^H up to ~200 GeV arXiv:1508.02684
- Two factorized systematic uncertainties:
  - 30% overall normalization
  - 30% linear change in slope (no effect on overall norm.)

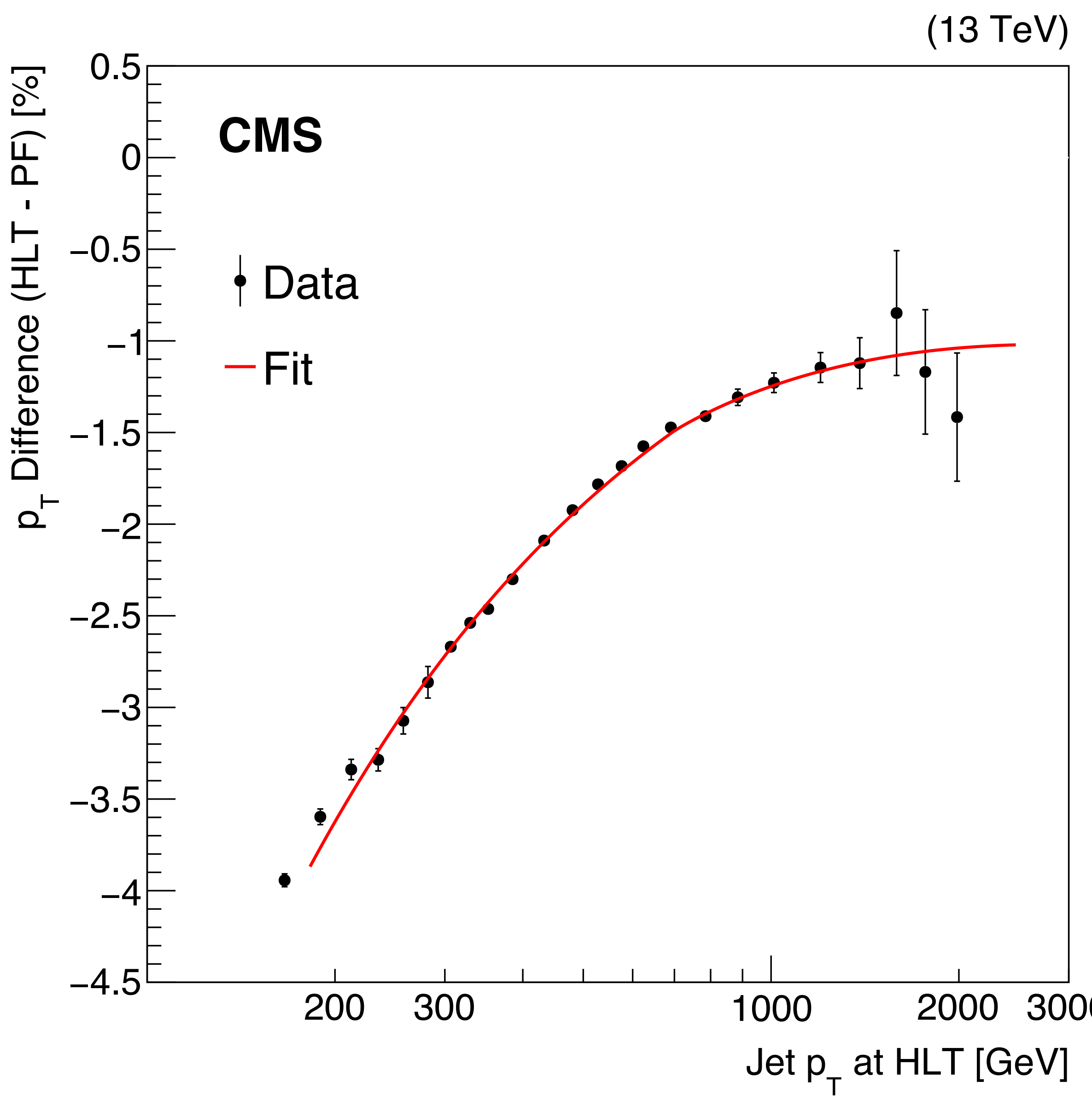


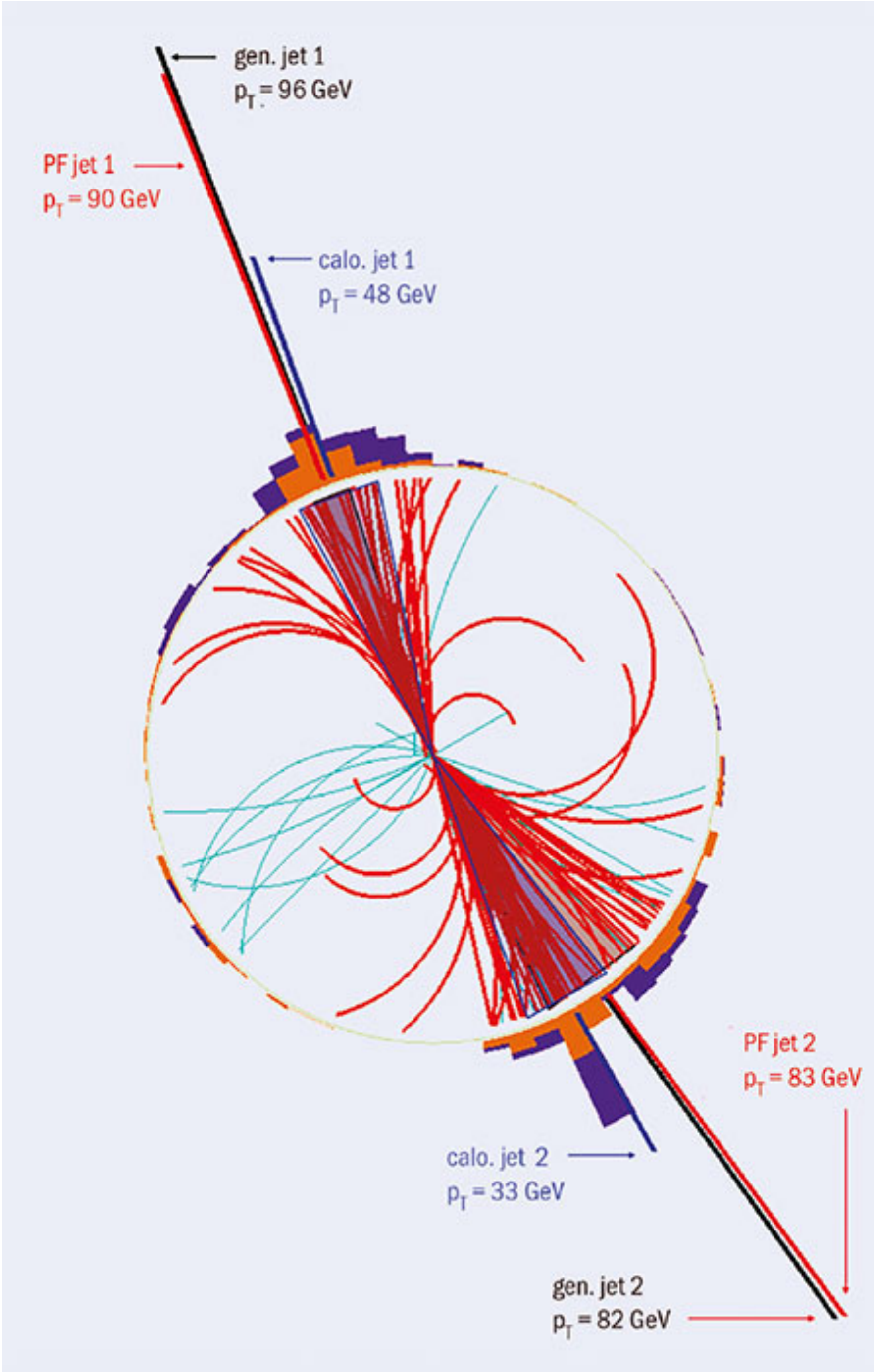
$$\text{GF H(NNLO} + m_t) = (1 \text{ jet } m_t \to \infty) \times \frac{\text{MG LO } 0-2 \text{ jet } m_t}{(1 \text{ jet } m_t \to \infty)} \times \frac{\text{NLO 1 jet } m_t}{\text{LO 1 jet } m_t} \times \frac{\text{NNLO 1 jet } m_t \to \infty}{\text{NLO 1 jet } m_t \to \infty}$$

CKKW merged — factor of 2 — factor of 1.25

ONLINE CALO M_{JJ} CALIBRATION

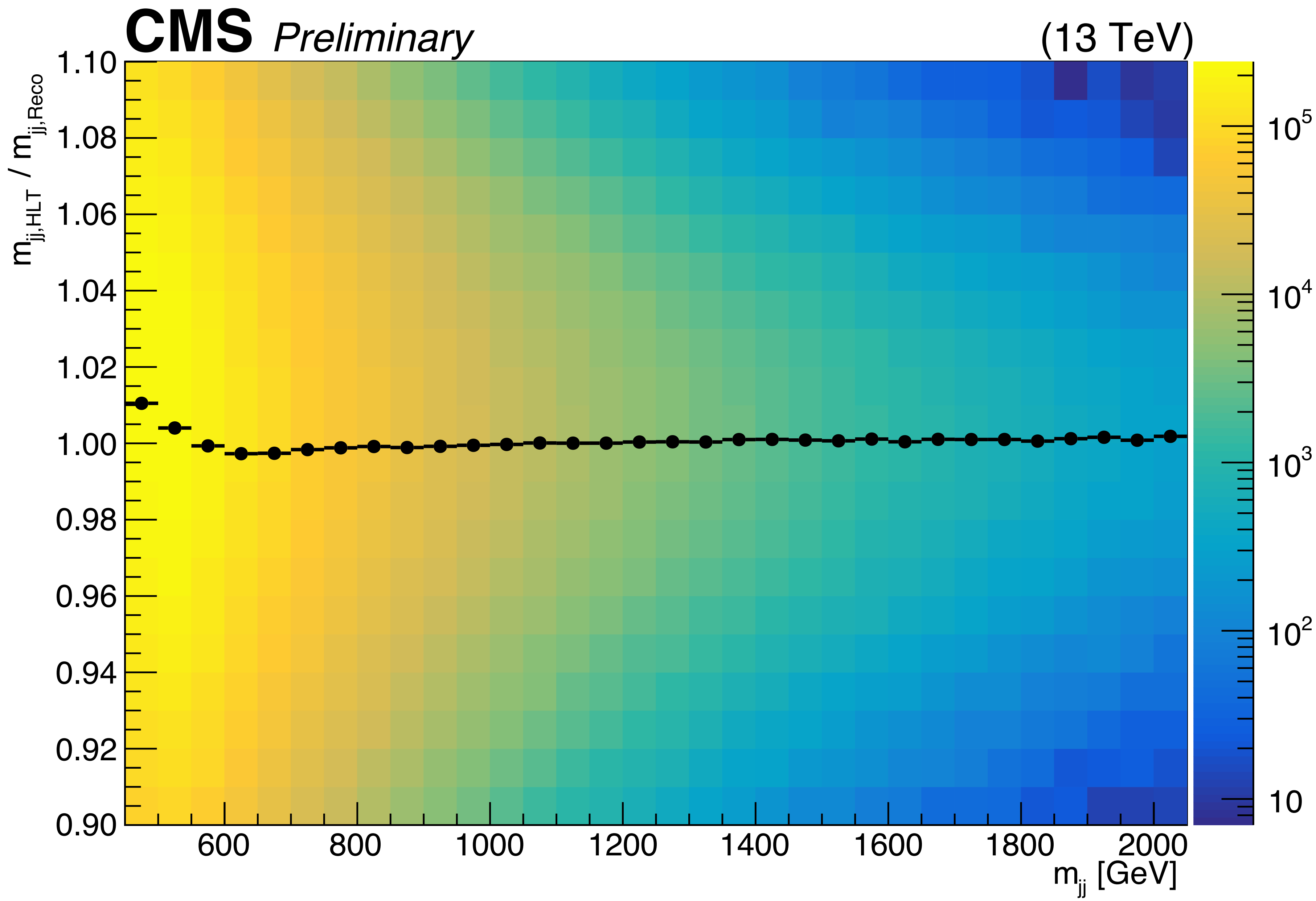
- Fit to correct Online Calo jet p_T

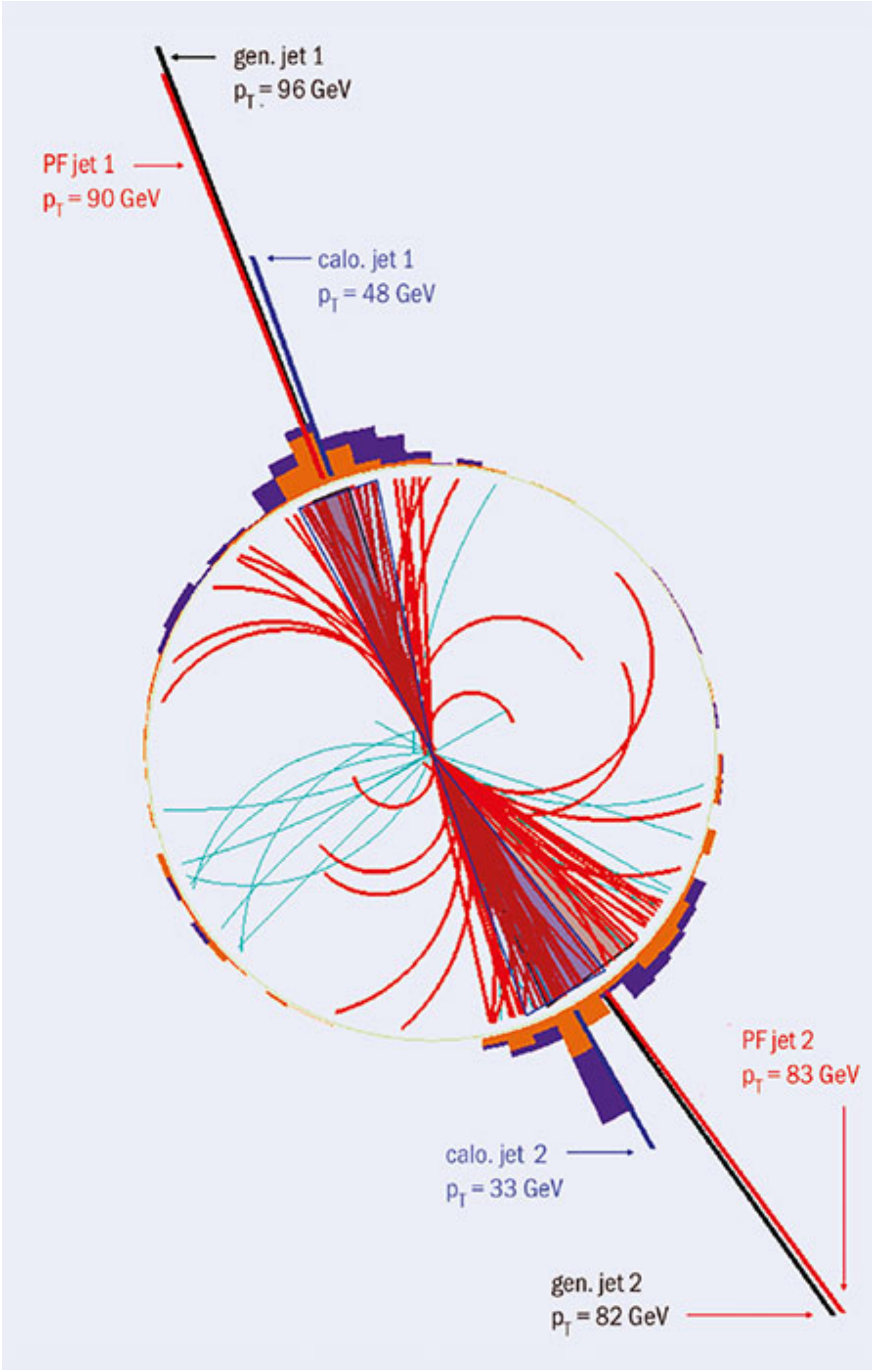




ONLINE CALO M_{JJ} CALIBRATION

- Ratio of Online Calo m_{jj} to Offline PF m_{jj}





DARK MATTER MEDIATOR

- m_{DM} and g_{DM} affect mediator decay branching ratios
  - Smaller $m_{DM} < m_M/2$ and larger $g_{DM} > 0$ gives
    - larger BR(Z′ → χχ)
    - smaller BR(Z′ → qq)
- Same dijet cross section upper limit at $g_{DM} = 0$ translates into weaker coupling limit at $g_{DM} > 0$ (smaller branching to dijets)

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

$$\Gamma_{\mathrm{V}}^{\mathrm{q}\bar{\mathrm{q}}} = \frac{(g_{\mathrm{q}}')^2 m_{\mathrm{med}}}{4\pi}\left(1-4\frac{m_{\mathrm{q}}^2}{m_{\mathrm{med}}^2}\right)^{1/2}\left(1+2\frac{m_{\mathrm{q}}^2}{m_{\mathrm{med}}^2}\right)$$

$$\sigma[\mathrm{Z}_{\mathrm{B}}' \to \mathrm{q}\bar{\mathrm{q}} | g_{\mathrm{B}}', g_{\mathrm{DM}}] = \sigma(\mathrm{Z}_{\mathrm{B}}' \to \mathrm{q}\bar{\mathrm{q}} | g_{\mathrm{B}}, g_{\mathrm{DM}} = 0)$$

$$\Rightarrow \quad \frac{(g_{\mathrm{B}}')^4}{\Gamma^{\mathrm{q}\bar{\mathrm{q}}}(g_{\mathrm{B}}') + \Gamma^{\chi\bar{\chi}}} = \frac{g_{\mathrm{B}}^4}{\Gamma^{\mathrm{q}\bar{\mathrm{q}}}(g_{\mathrm{B}})}$$

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

SENSITIVITY TO DARK MATTER

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

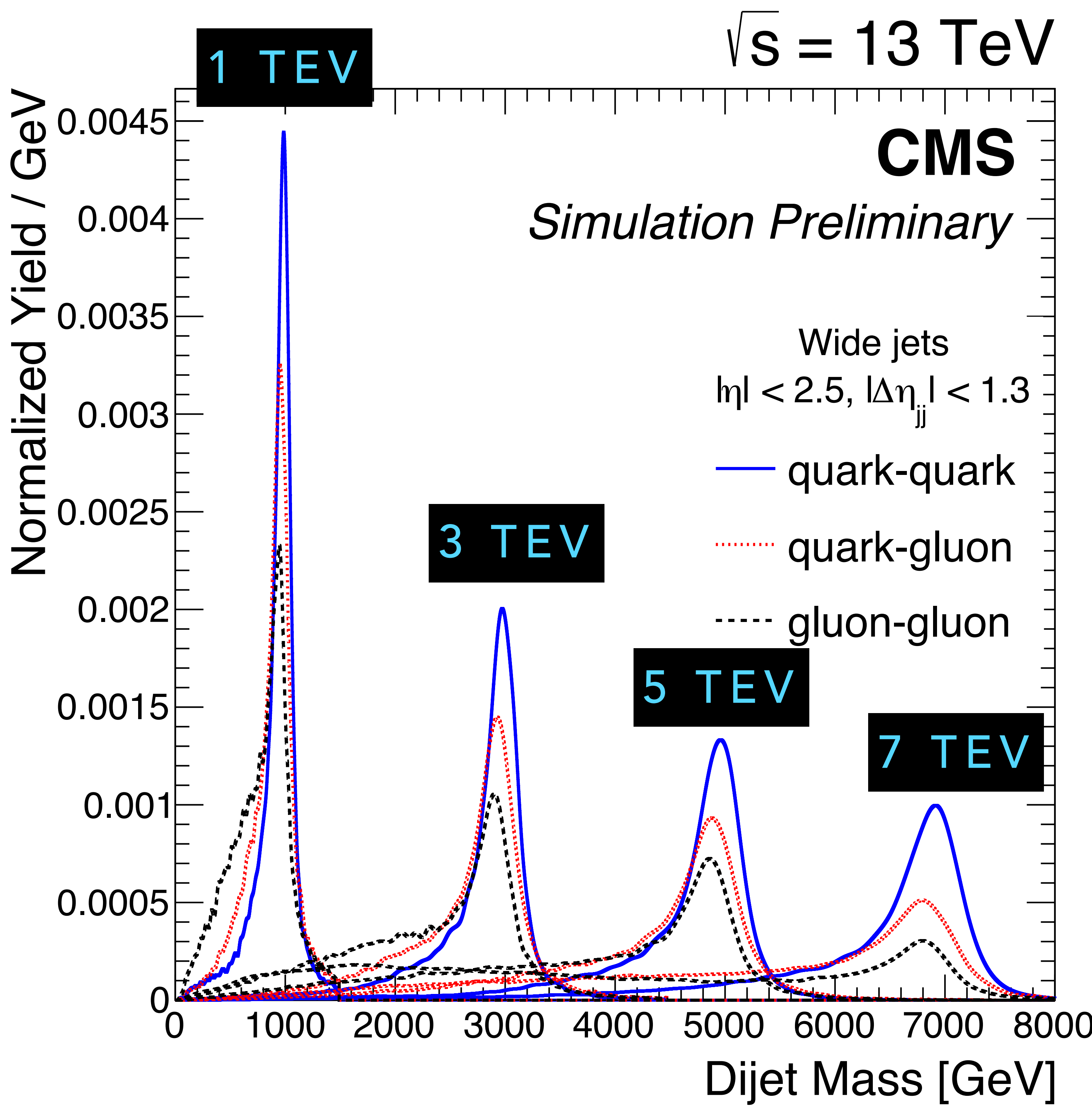
$$\begin{aligned} C_p &= (C_u - \eta)\Delta u + (C_d - \eta z)\Delta d + (C_s - \eta w)\Delta s\,, \\ C_n &= (C_u - \eta)\Delta d + (C_d - \eta z)\Delta u + (C_s - \eta w)\Delta s\,. \end{aligned} \tag{9}$$

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.

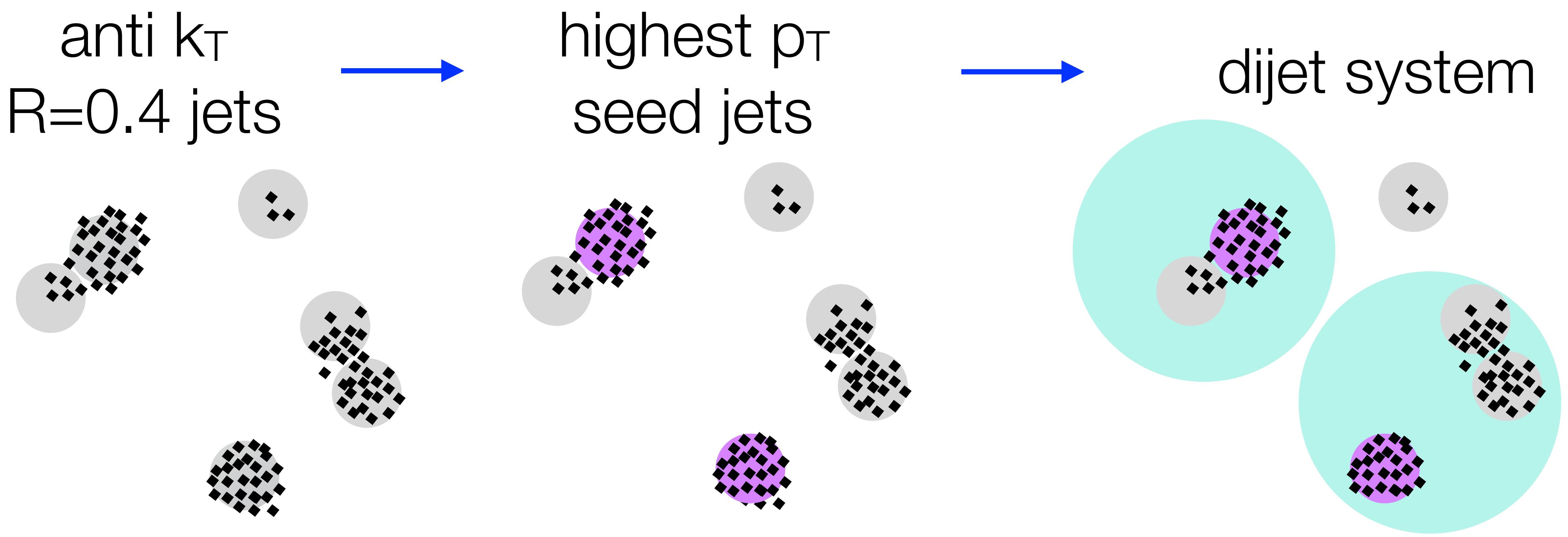
MANY SIGNAL MODELS

- 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, …



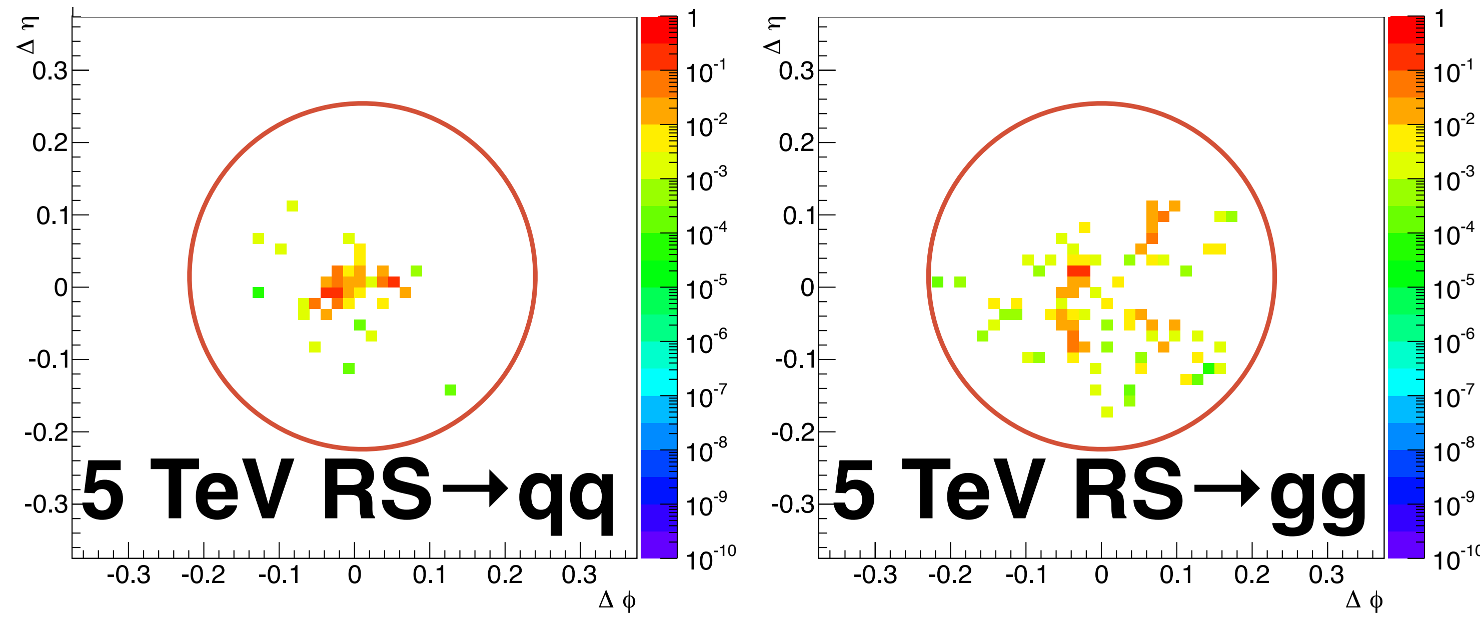
WIDE JETS

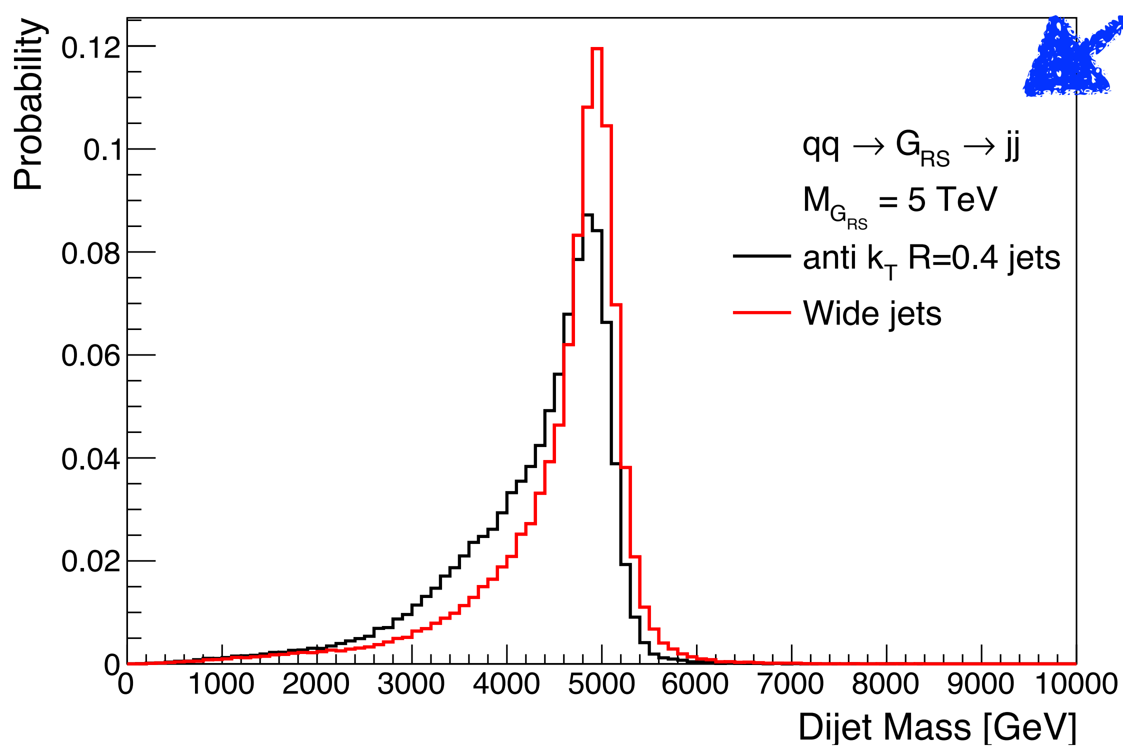
- Jets initially reconstructed with anti-k_T algorithm with R=0.4
- "Wide jet" algorithm uses two leading jets as seeds
  - Adds neighboring jets to nearest leading jet if within $\Delta R < 1.1$
  - Recover loss in mass response due to radiation

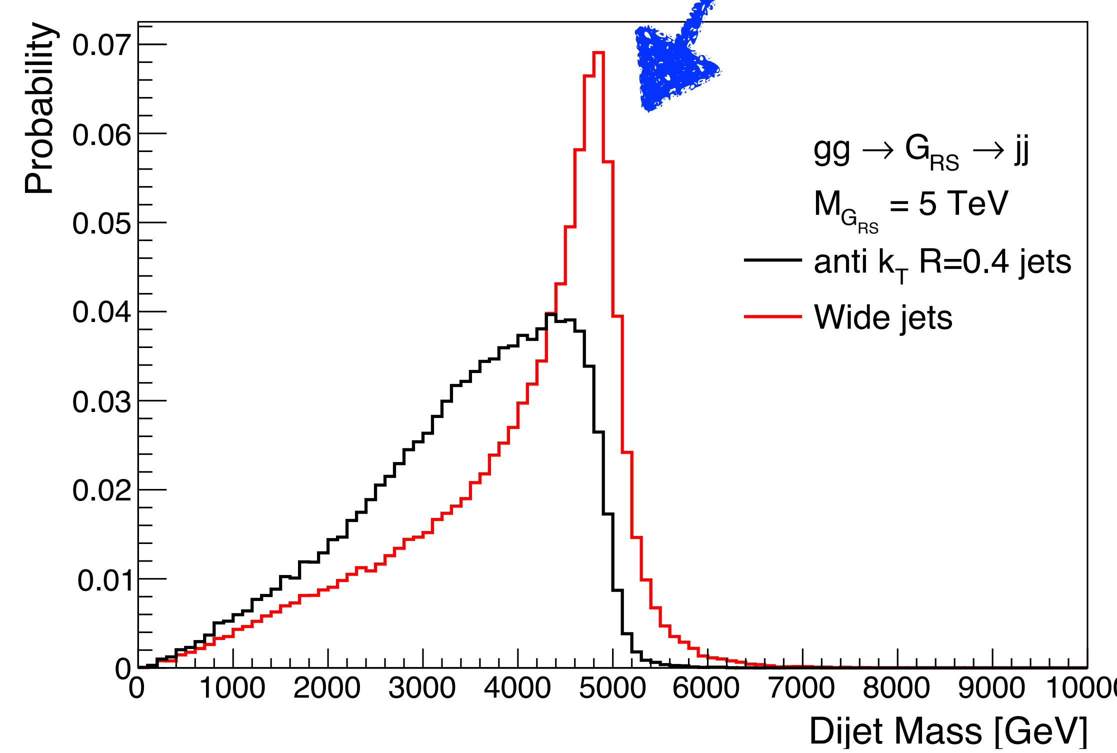


WIDE JETS

- 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

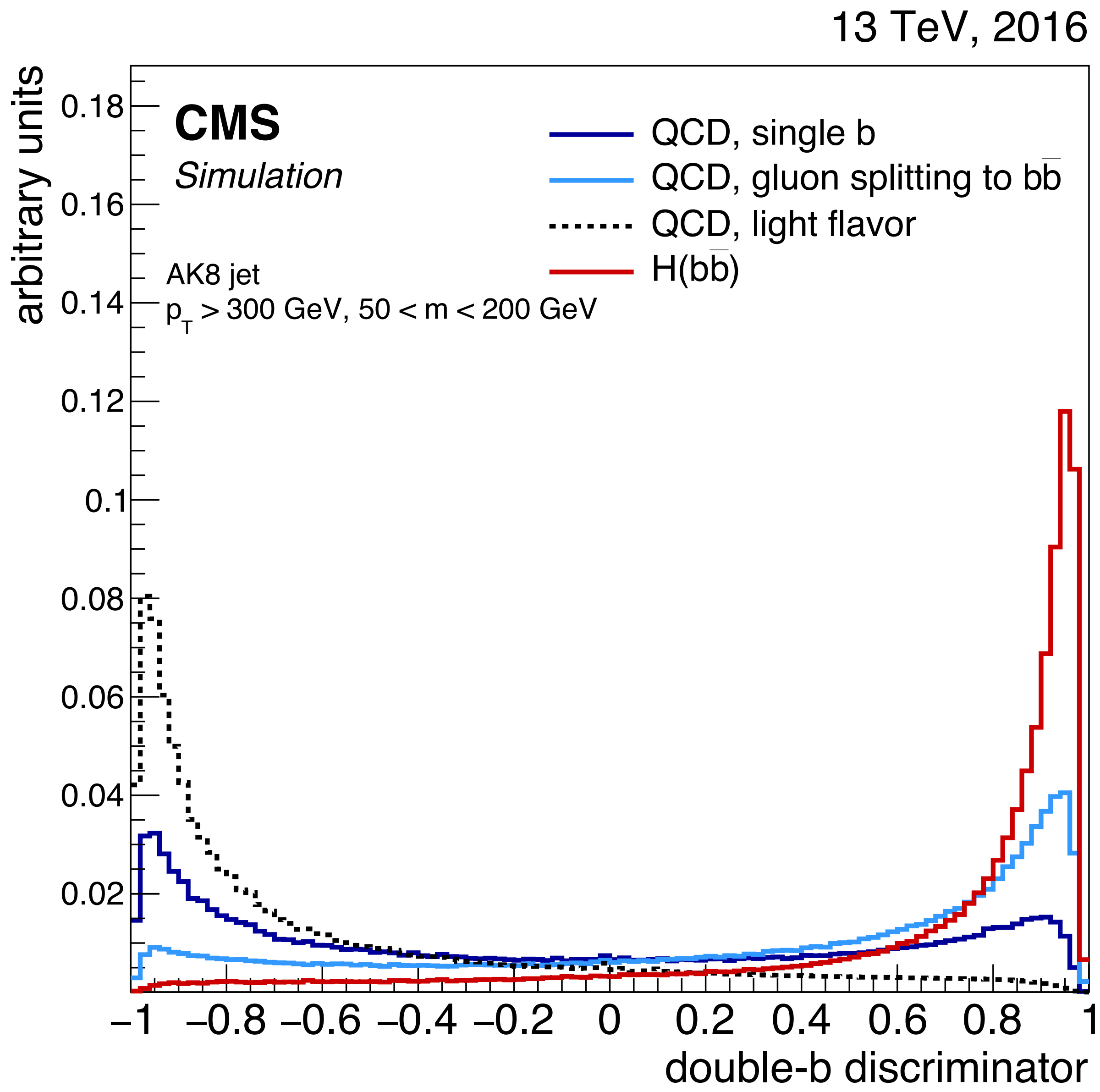






DOUBLE-B TAGGER

- Combines tracking and vertexing information in a multivariate classifier with 27 observables
- Targets the bb signal with additional aims:
  - jet mass and p_T independent
  - cover a very wide p_T range
  - inputs are chosen to avoid p_T correlation
    - e.g. no ΔR-like variables, no substructure info

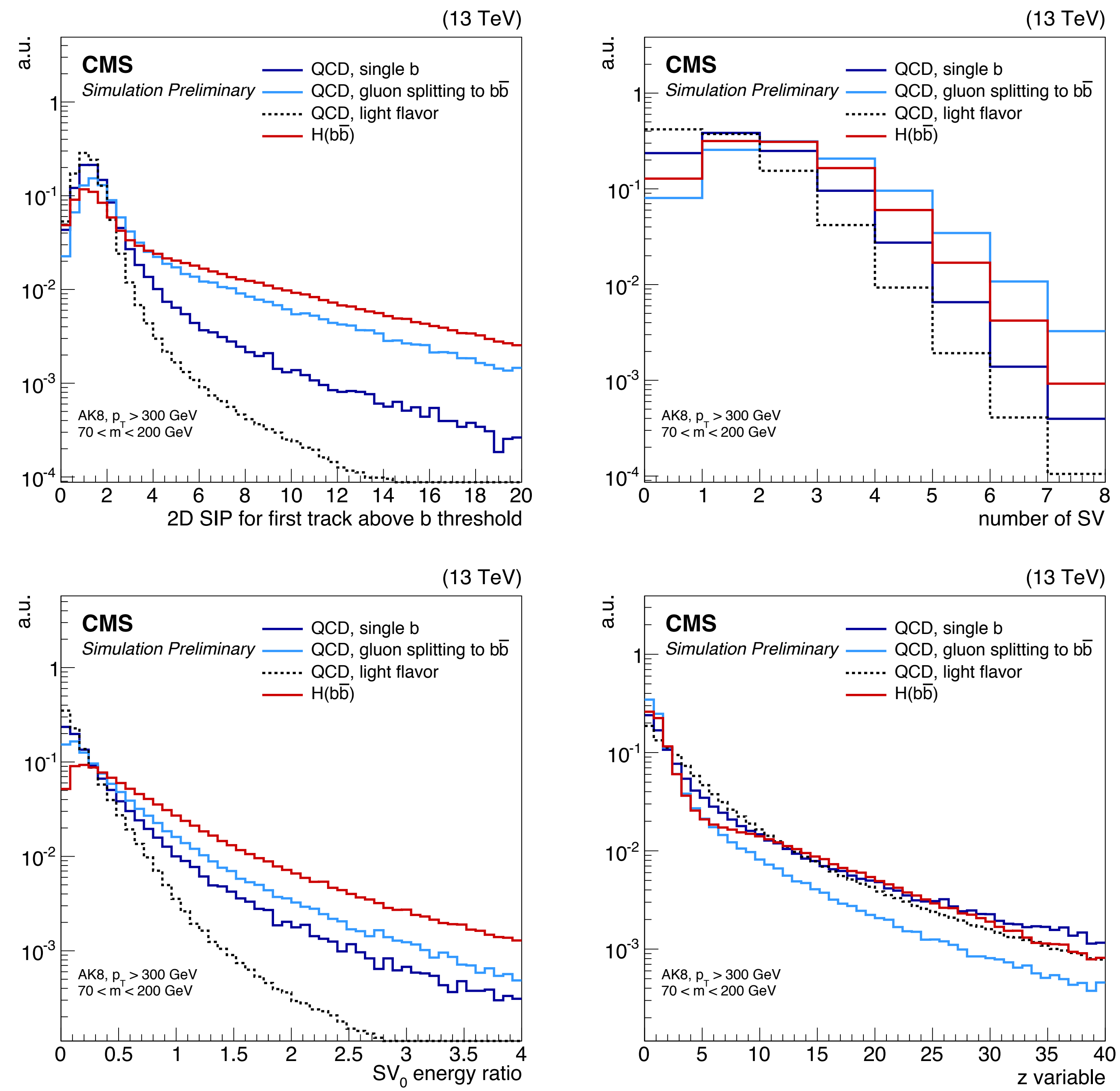


DOUBLE-B TAGGER INPUTS

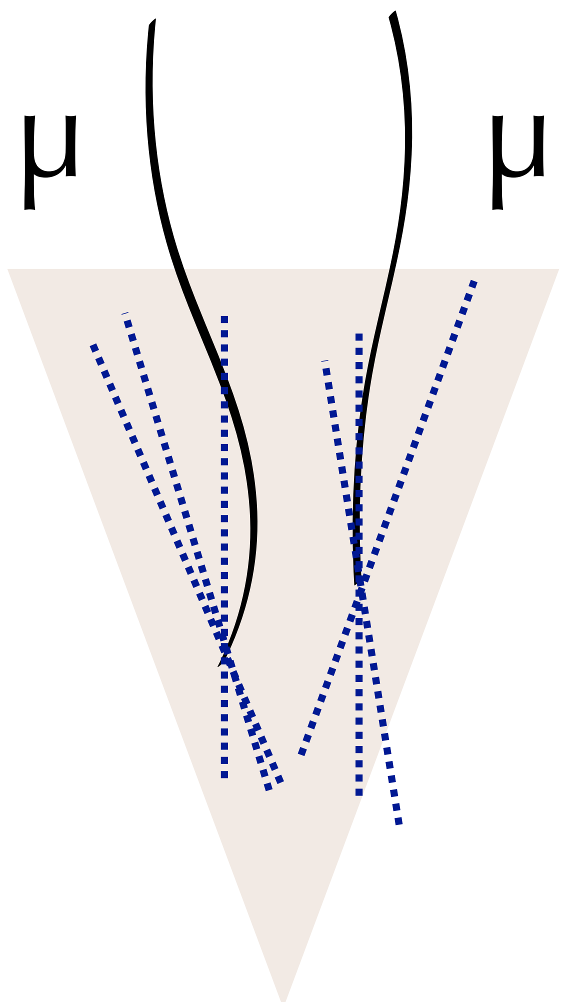
- The first four SIP values for selected tracks ordered in decreasing SIP;
- For each τ-axis we consider the first two SIP values for their respective associated tracks ordered in decreasing SIP, to further discriminate against single b quark and light flavor jets from QCD when one or both SV are not reconstructed due to IVF inefficiencies;
- The measured IP significance in the plane transverse to the beam axis, 2D SIP, of the first two tracks (first track) that raises the SV invariant mass above the bottom (charm) threshold of 5.2 (1.5) GeV;
- The number of SV associated to the jet;
- The significance of the 2D distance between the primary vertex and the secondary vertex, flight distance, for the SV with the smallest 3D flight distance uncertainty, for each of the two τ-axes;
- The ΔR between the SVs with the smallest 3D flight distance uncertainty and its τ-axis, for each of the two τ-axes;
- The relative pseudorapidity, $\eta_{\rm rel}$, of the tracks from all SVs with respect to their τ-axis for the three leading tracks ordered in increasing $\eta_{\rm rel}$, for each of the two τ-axes;
- The total SV mass, defined as the total mass of all SVs associated to a given τ-axis, for each of the two τ-axes;
- The ratio of the total SV energy, defined as the total energy of all SVs associated to a given τ-axis, and the total energy of all the tracks associated to the fat jet that are consistent with the primary vertex, for each of the two τ-axes;
- The information related to the two-SV system, the z variable, defined as:

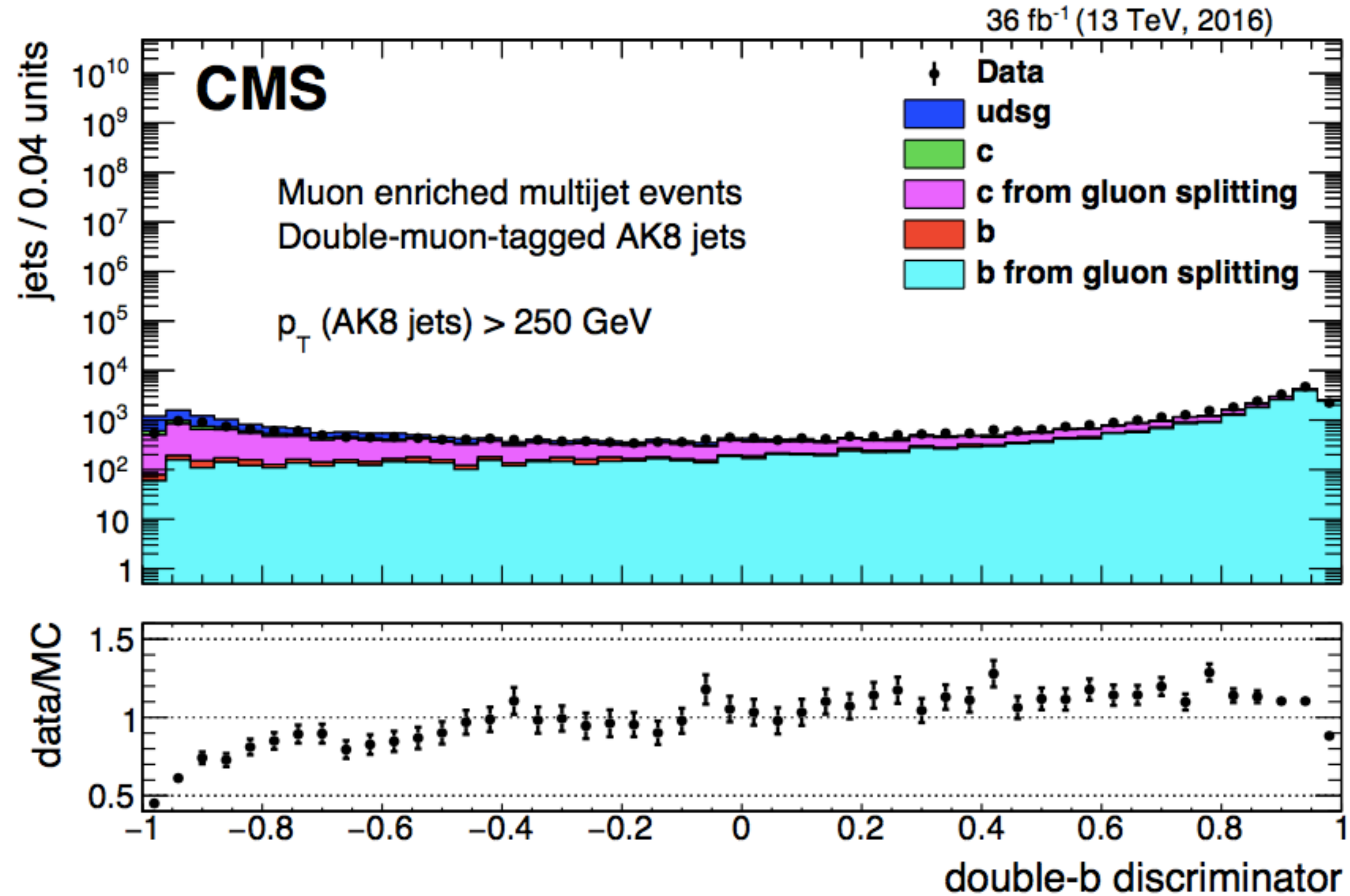
$$z = \Delta R(\mathrm{SV}_0, \mathrm{SV}_1) \cdot \frac{p_{\mathrm{T,SV}_1}}{m(\mathrm{SV}_0, \mathrm{SV}_1)} \quad (2)$$

where SV_0 and SV_1 are SVs with the smallest 3D flight distance uncertainty. The z variable helps rejecting the $\mathrm{b\bar{b}}$ background from gluon splitting relying on the different kinematic properties compared to the $\mathrm{b\bar{b}}$ pair from the decay of a massive resonance.



EFFICIENCY IN DATA

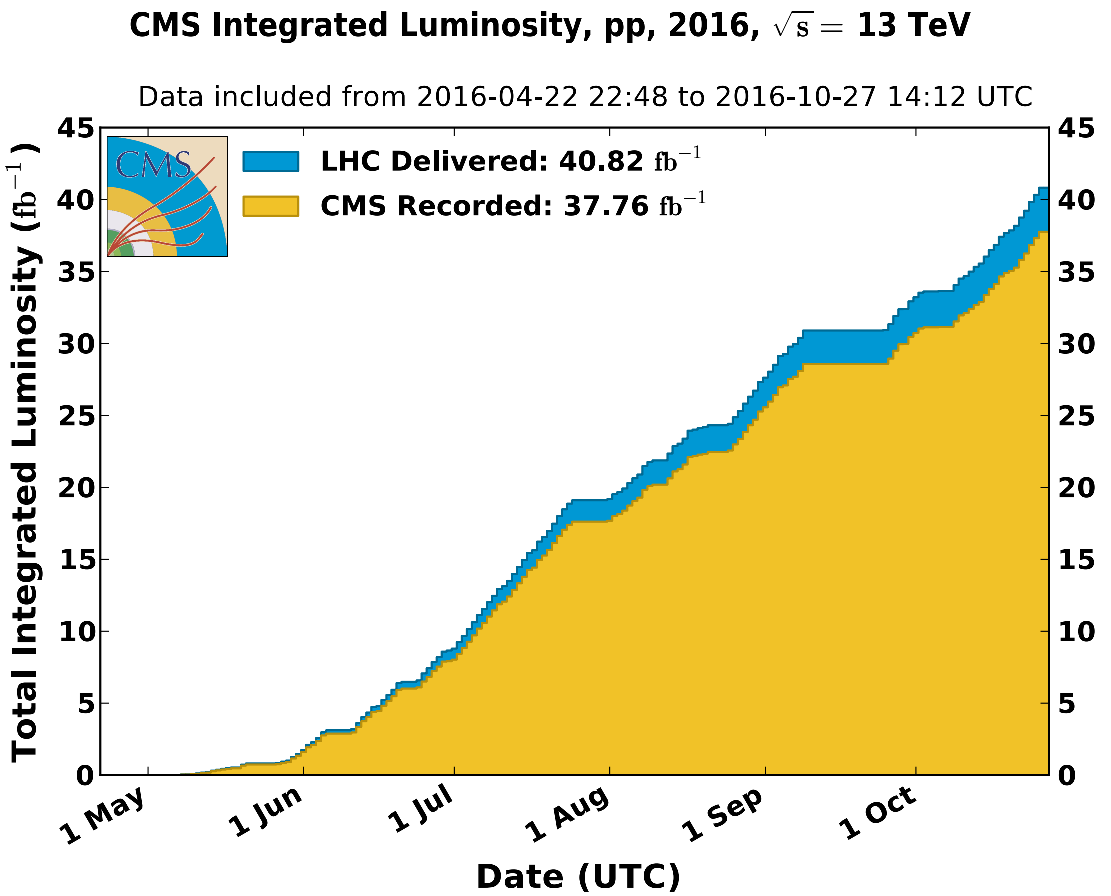


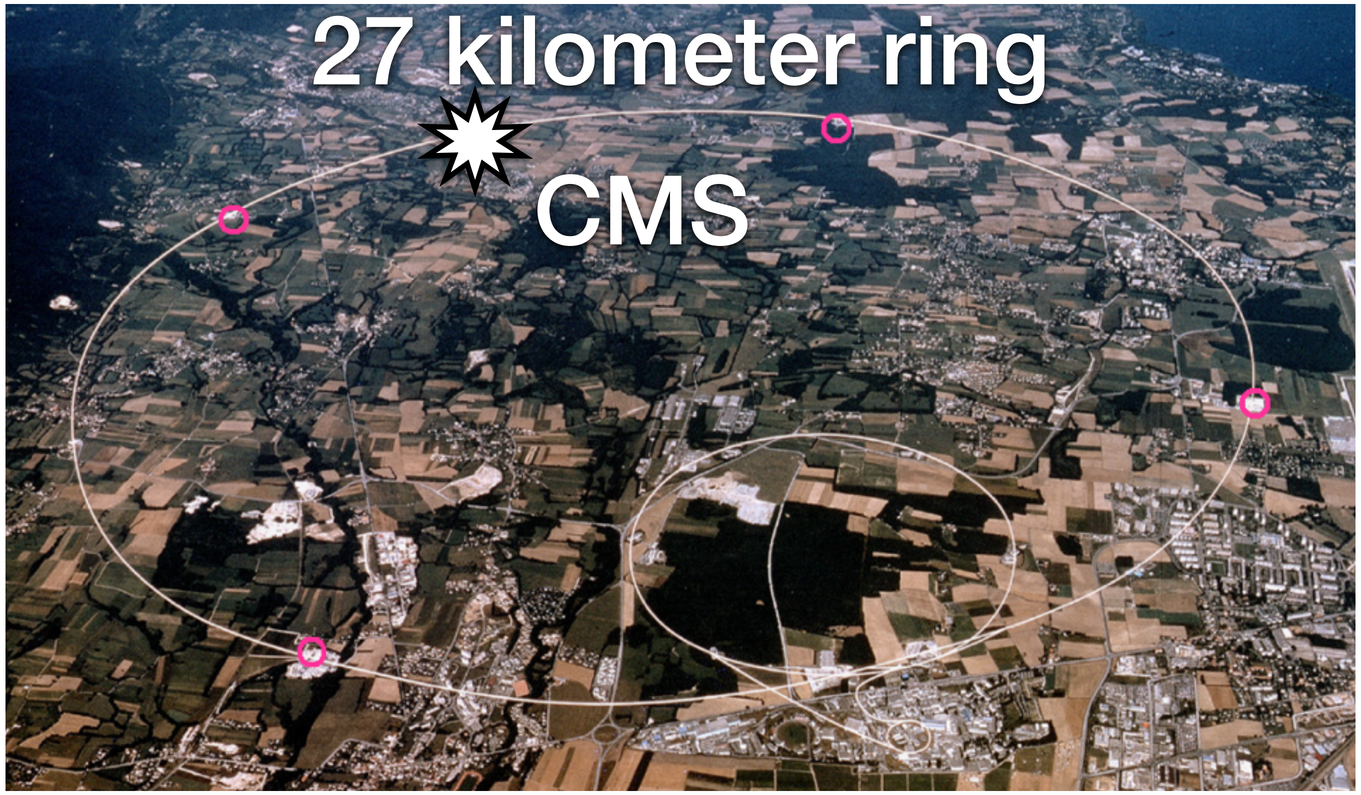


- Using g(bb) jet as proxy in double muon tagged jet sample
- Associated data/MC uncertainty 3-5%

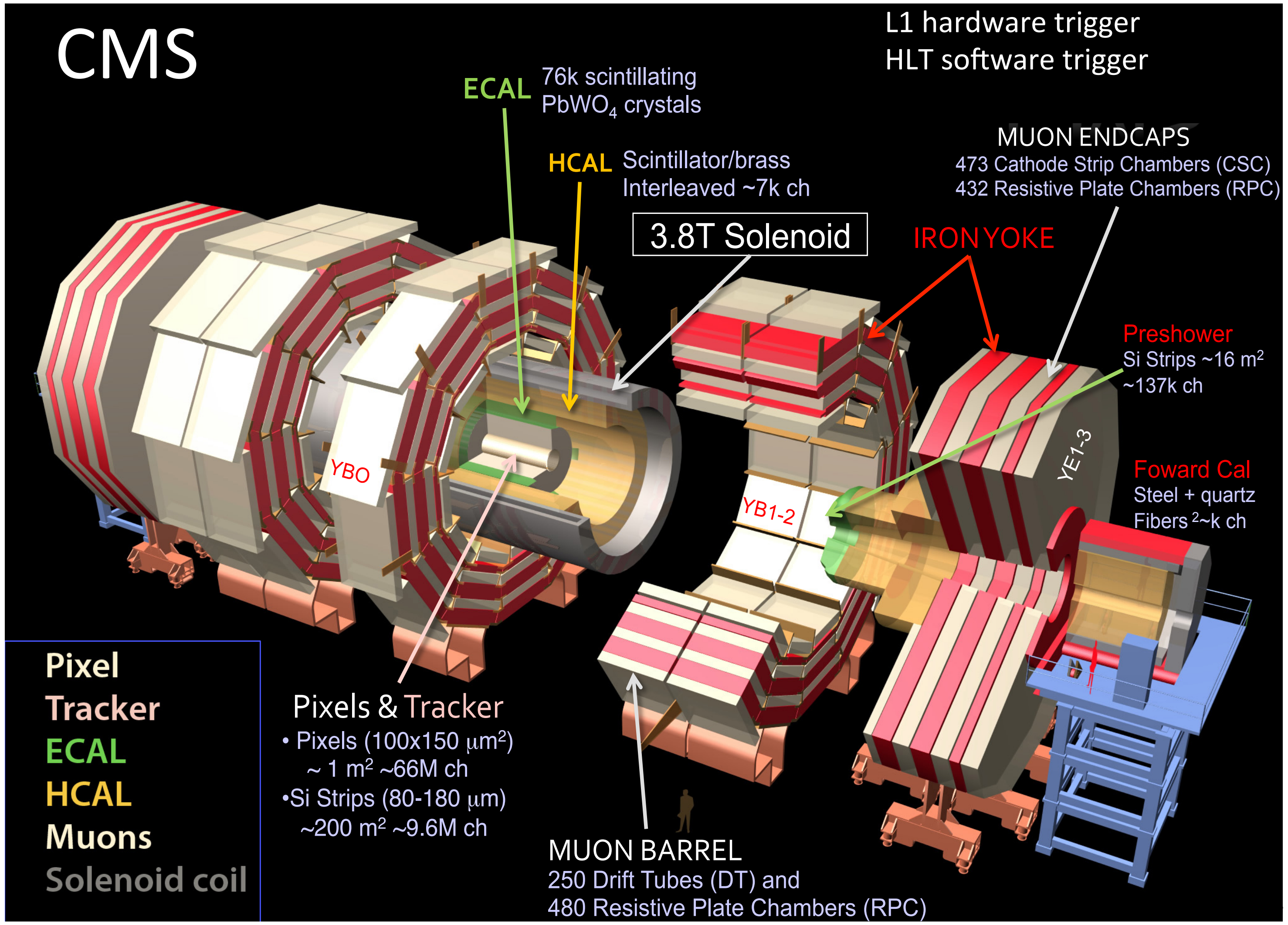
LARGE HADRON COLLIDER

- Proton-proton collisions at 13 TeV in 2016





COMPACT MUON SOLENOID



- 3.8 T magnetic field bends particle trajectories allowing for excellent tracking
- ECAL: $PbWO_4$ crystals (high density, short radiation length and Molière radius)
- HCAL: plastic scintillator and brass absorber interleaved
- Muon system: drift tubes (DT), resistive plate chambers (RPC), and cathode strip chambers (CSC)