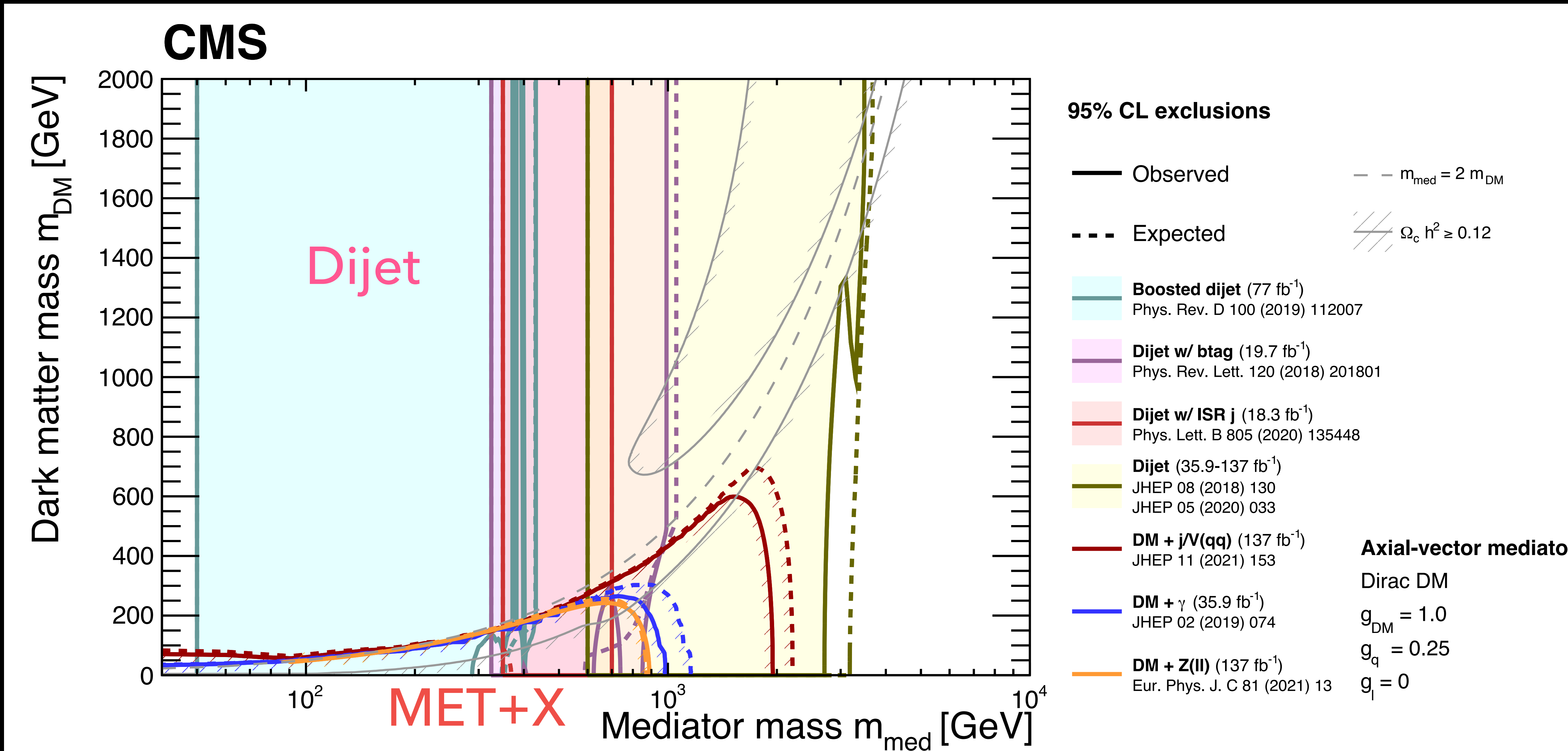
Future directions for s-channel searches

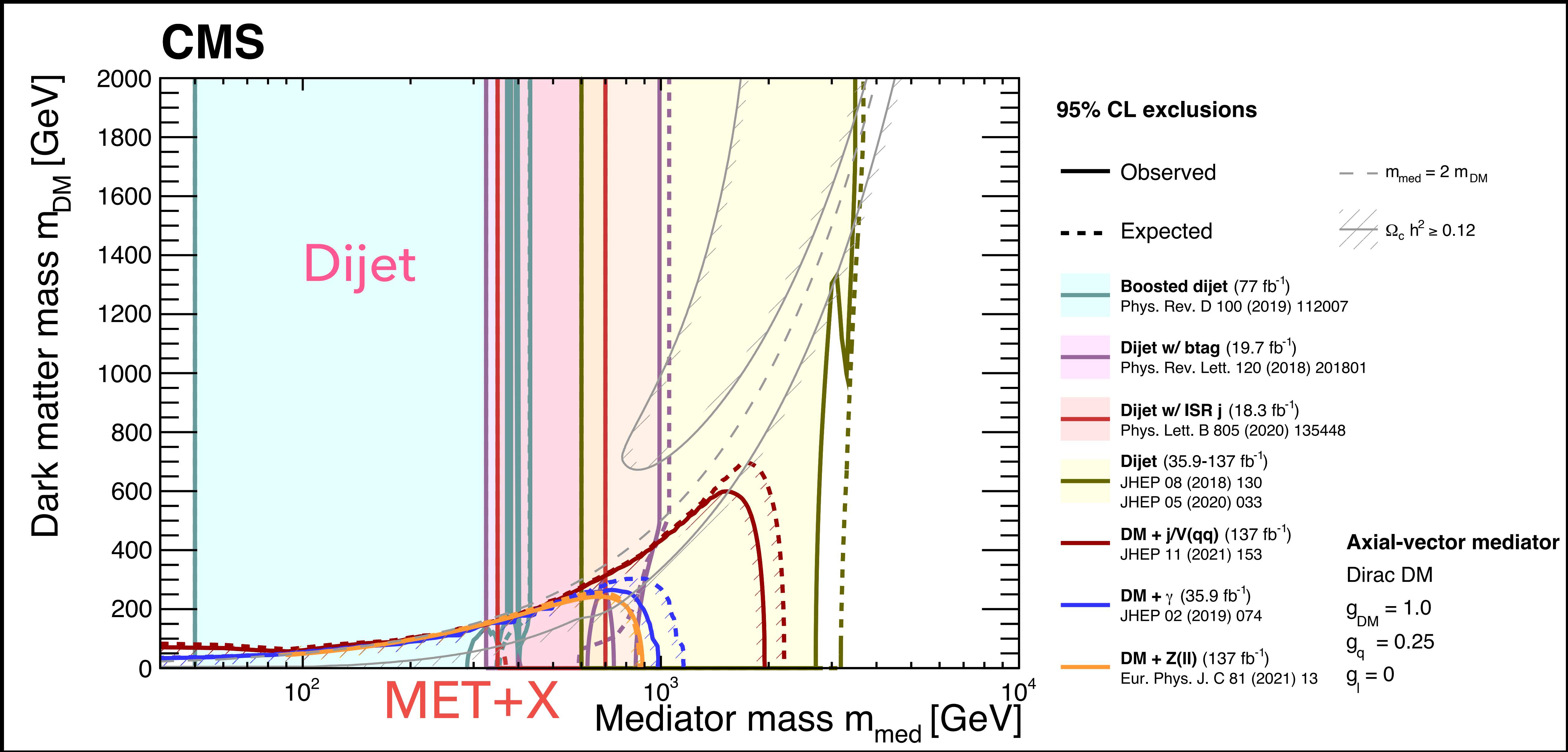
David Yu

May 14, 2024

S-CHANNEL TODAY

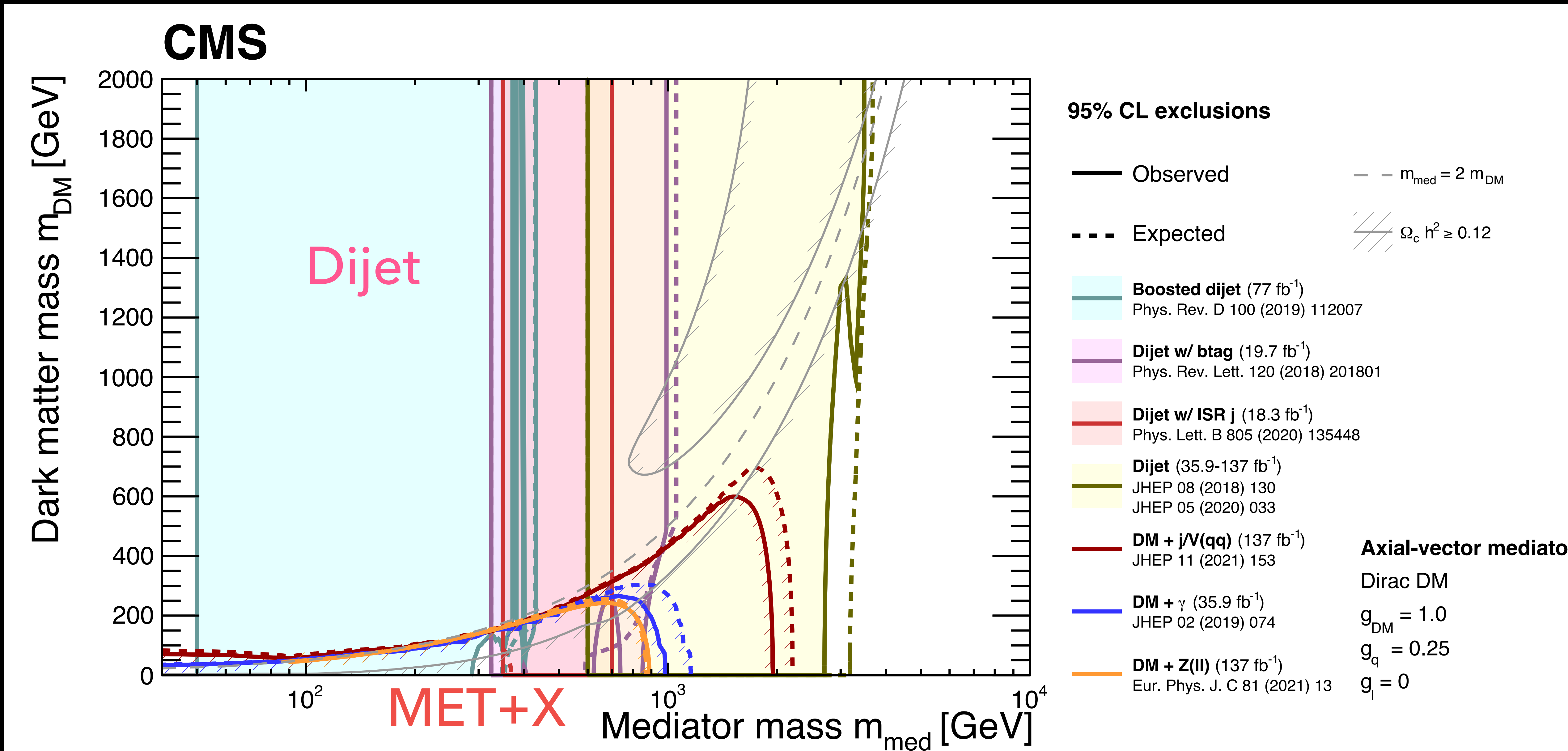


S-CHANNEL TODAY



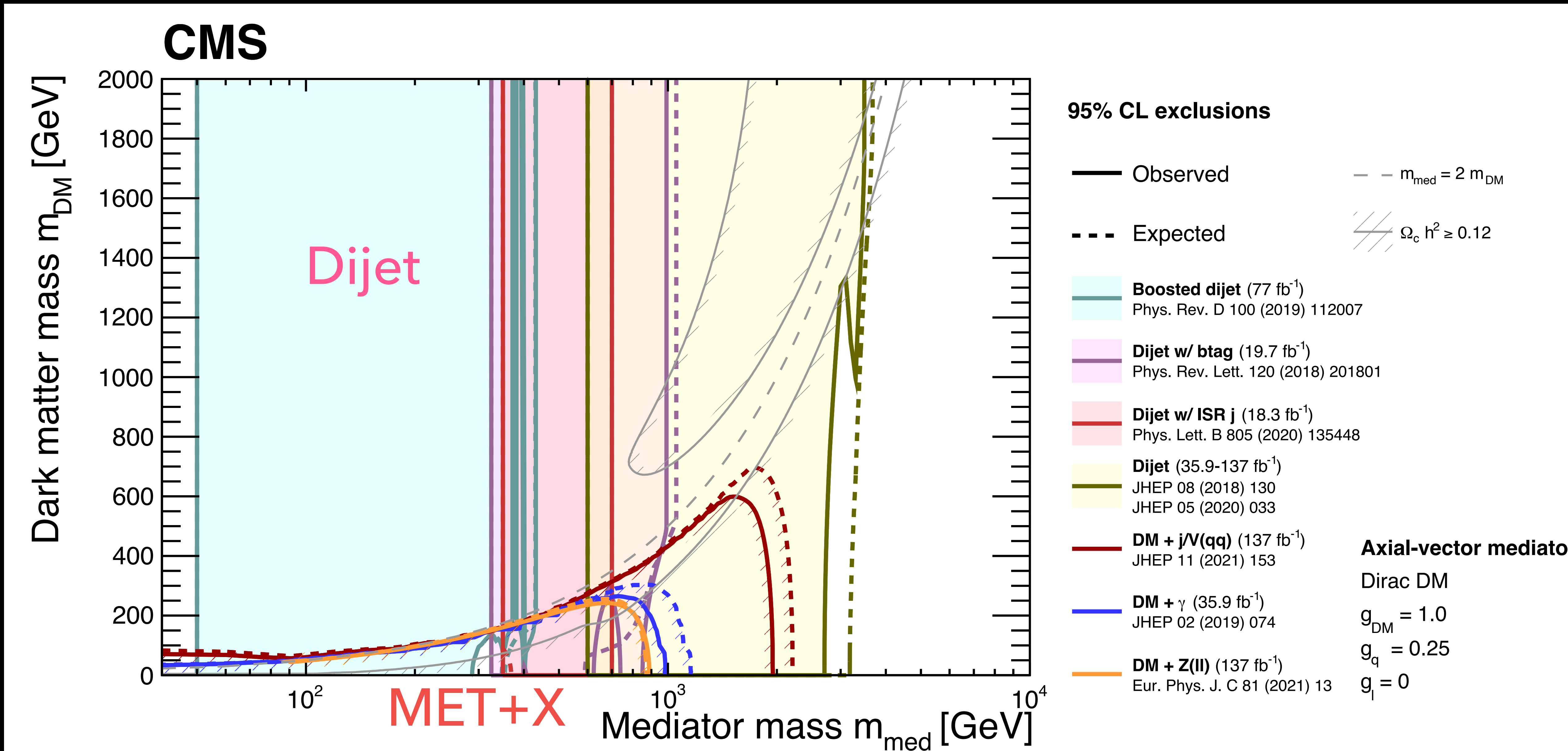
- Present LHC data have thoroughly tested DMWG Run 2 s-channel benchmark models.

S-CHANNEL TODAY



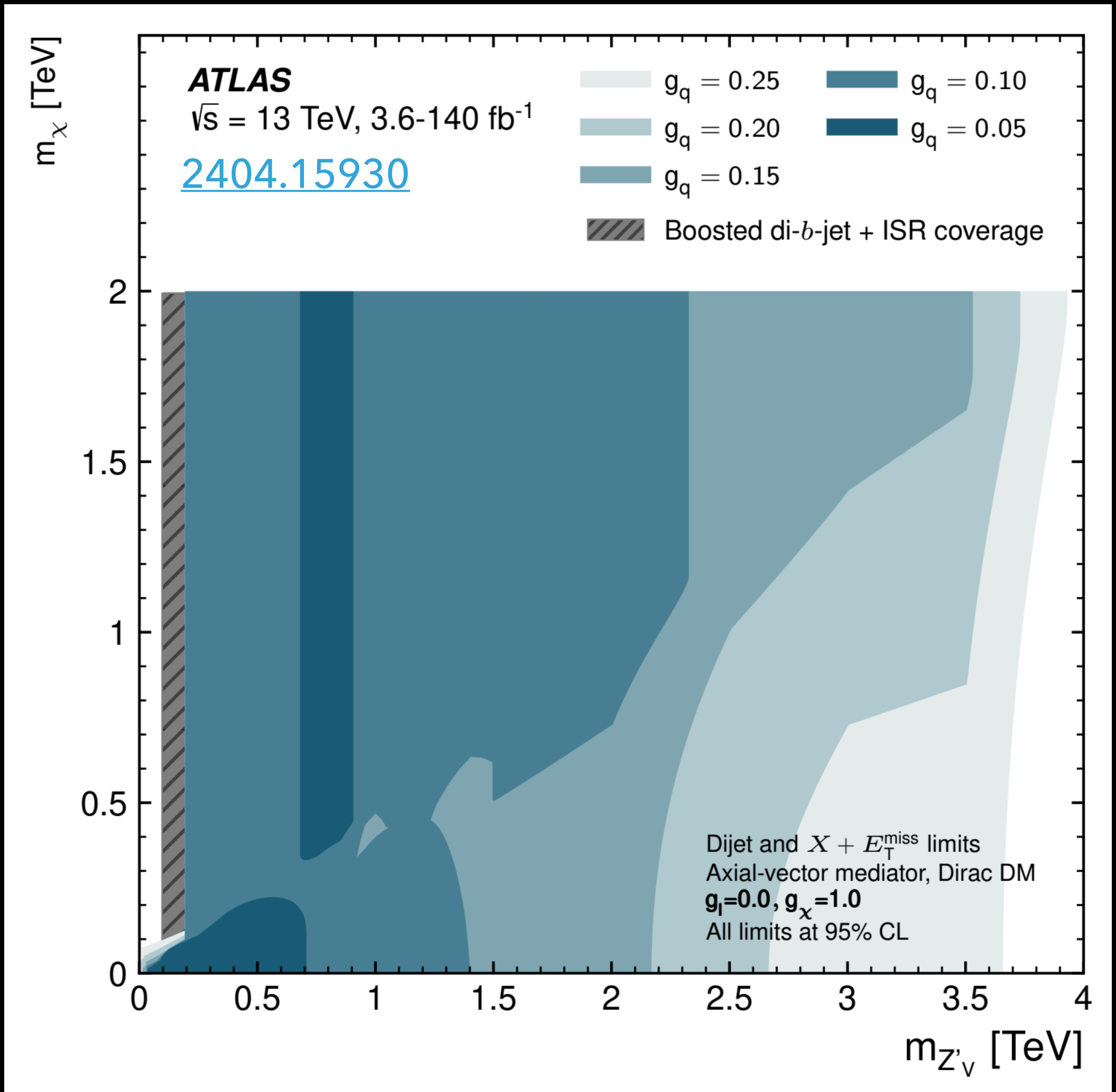
- Present LHC data have thoroughly tested DMWG Run 2 s-channel benchmark models.
  - For chosen couplings, sensitive to $M(Z') \sim$ few TeV

S-CHANNEL TODAY



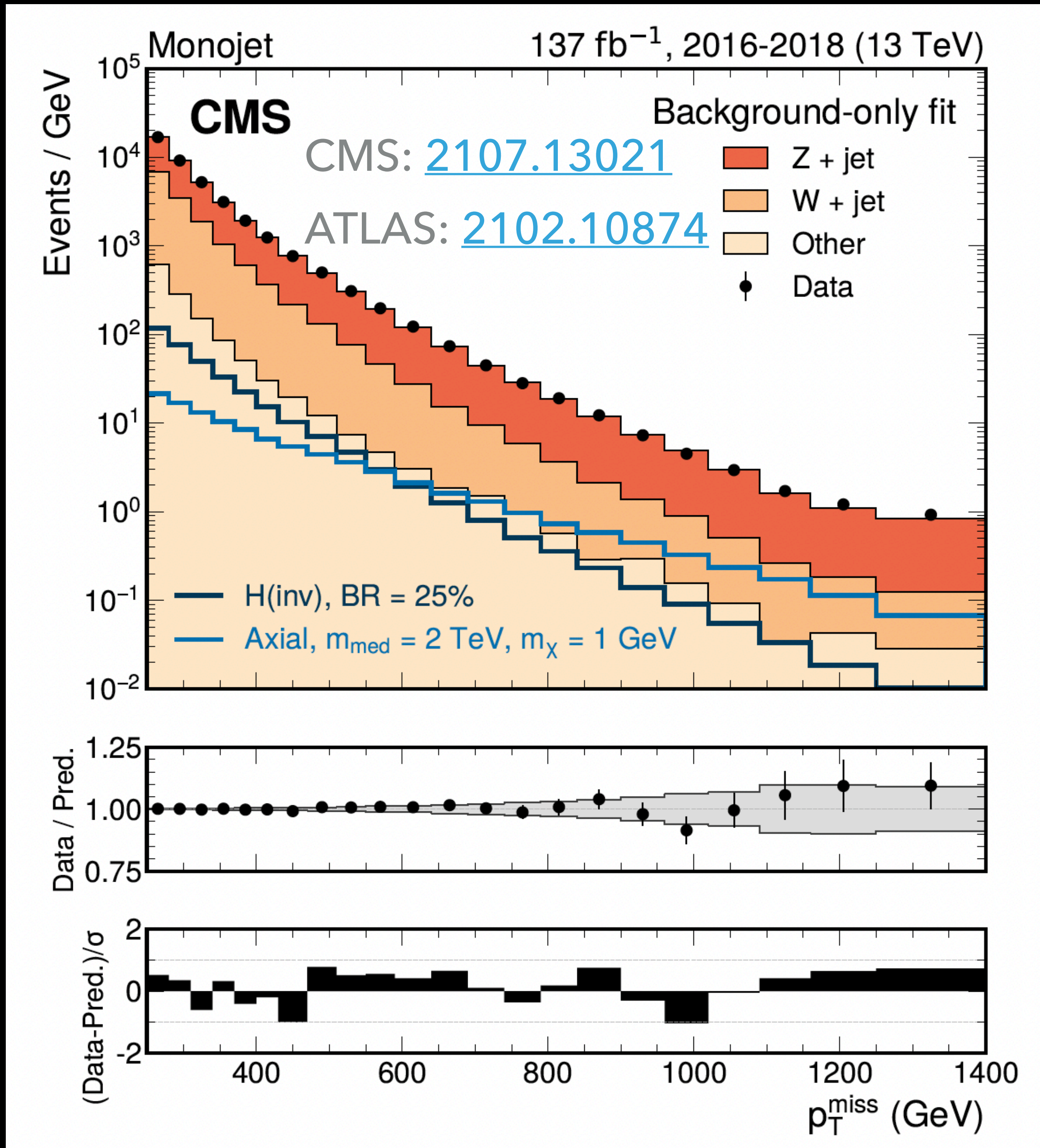
- Present LHC data have thoroughly tested DMWG Run 2 s-channel benchmark models.
  - For chosen couplings, sensitive to $M(Z') \sim$ few TeV
- Complementarity coverage from invisible (MET+X) and visible (dijet, dilepton) final states.

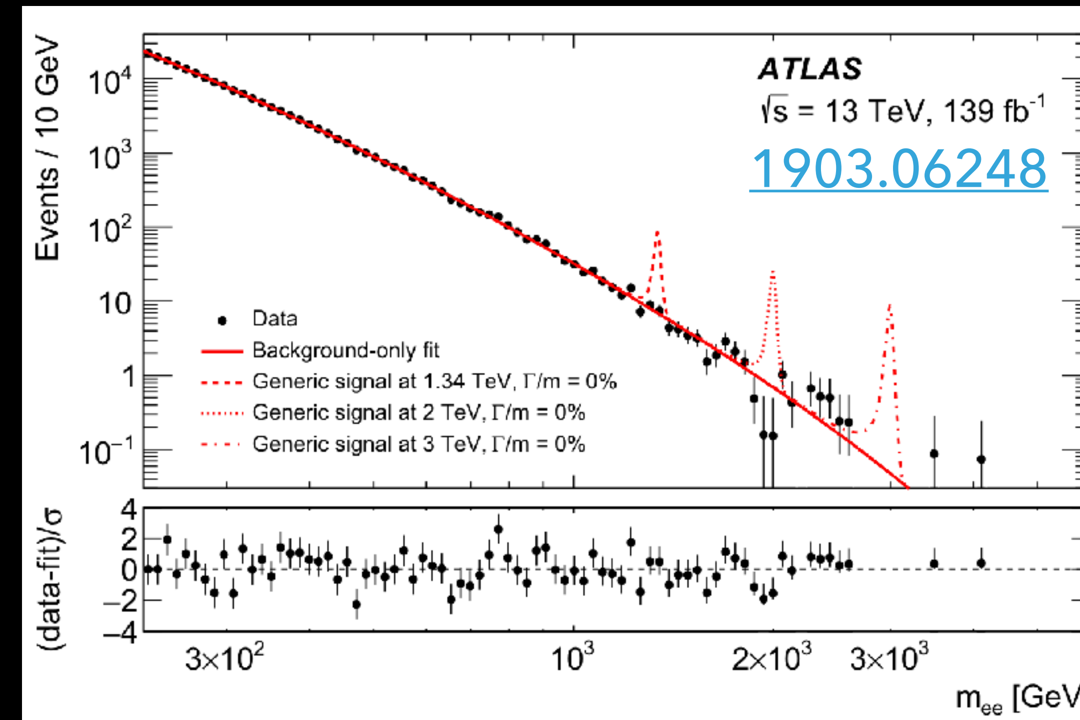
S-CHANNEL TOMORROW

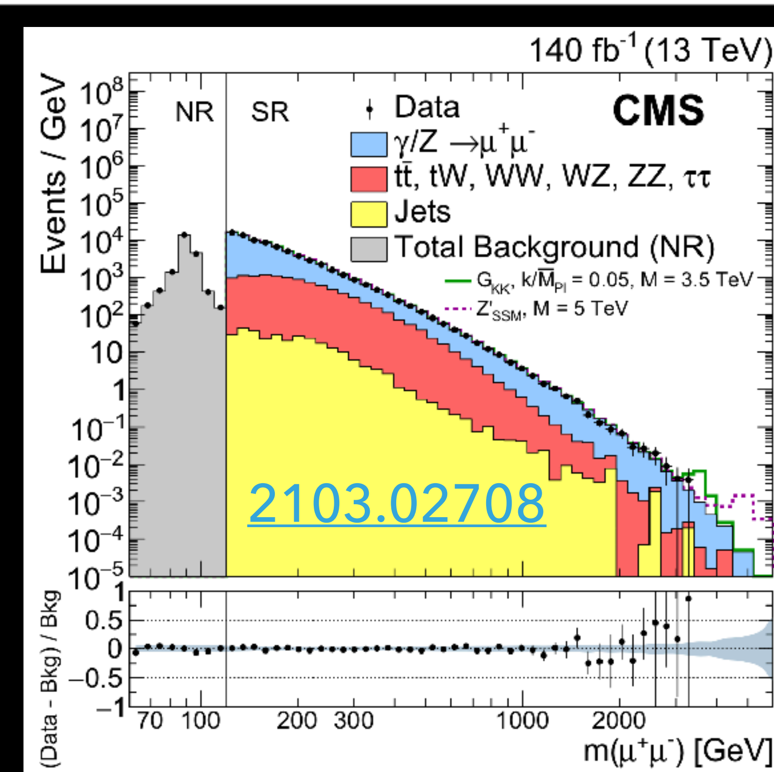


- Next generations of s-channel searches: probe smaller couplings.
  - $g_\mathrm{q} \sim \sigma^{1/2} \sim \mathscr{L}^{1/4}$

RUN 2 RESULTS: MET+X, DILEPTON

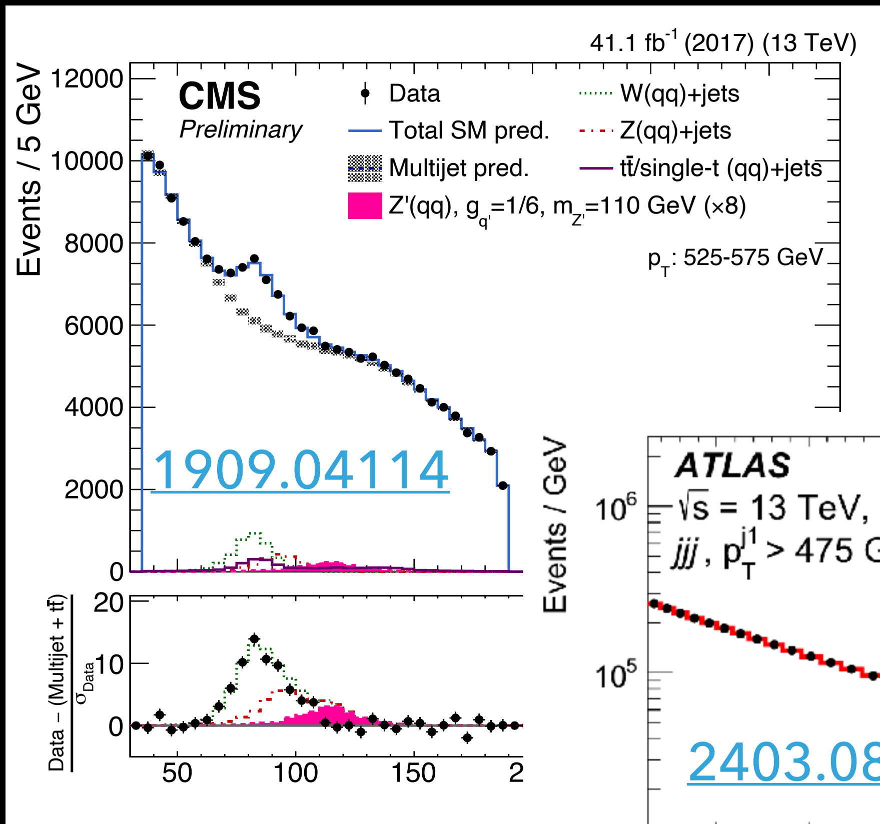


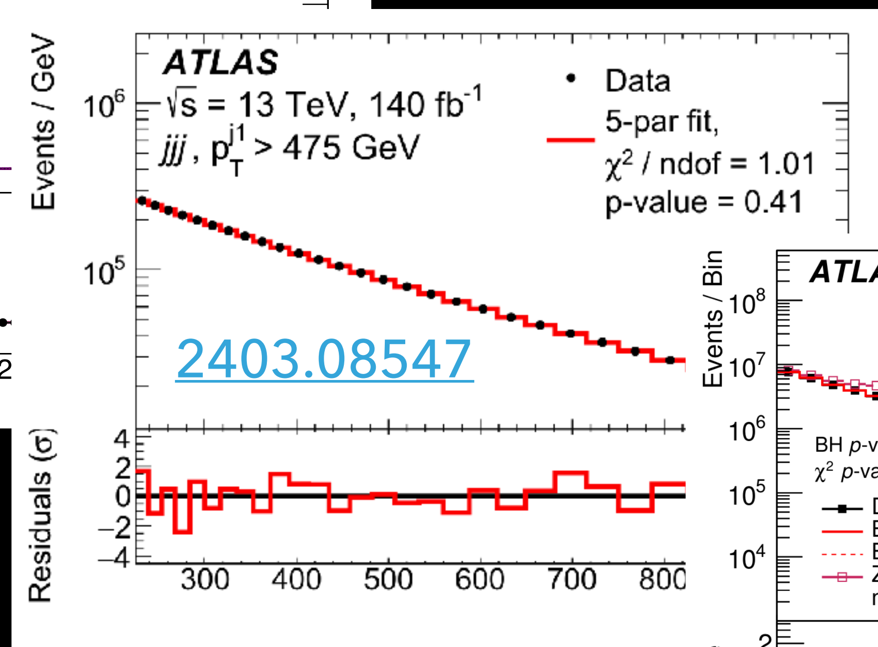


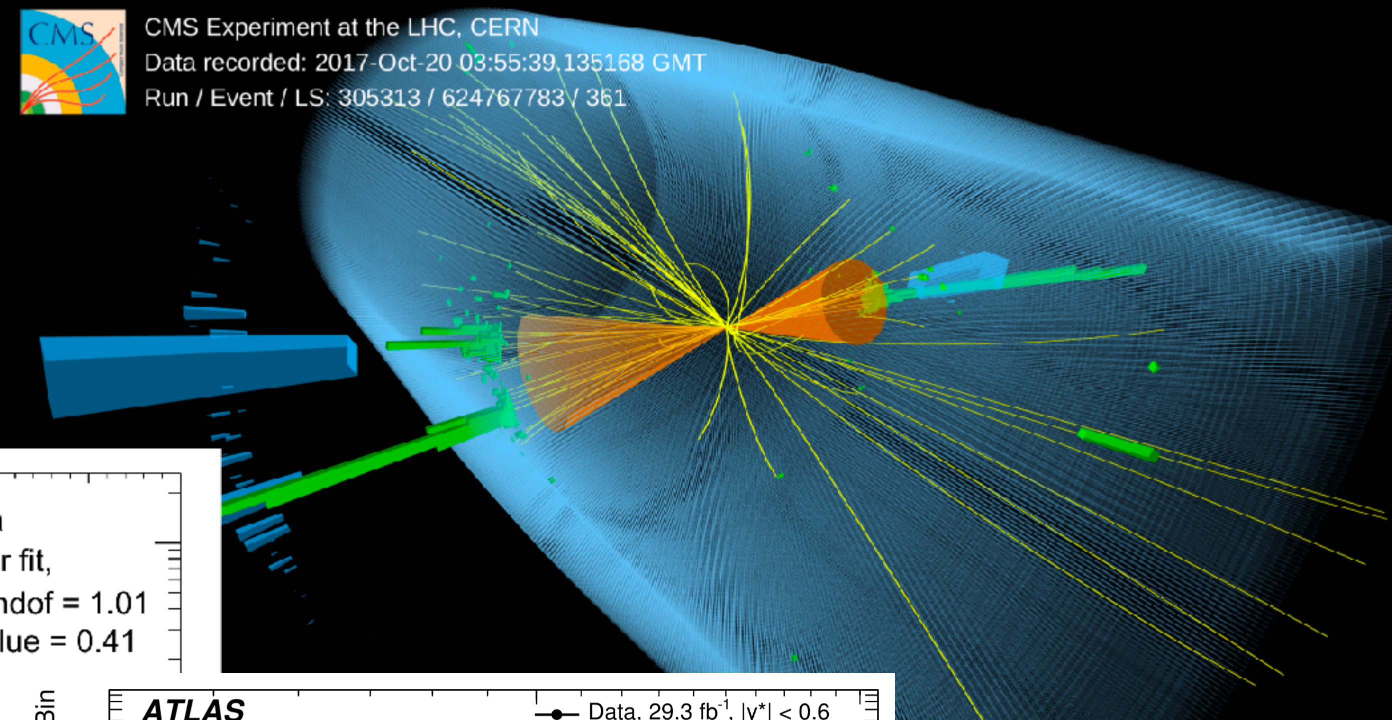


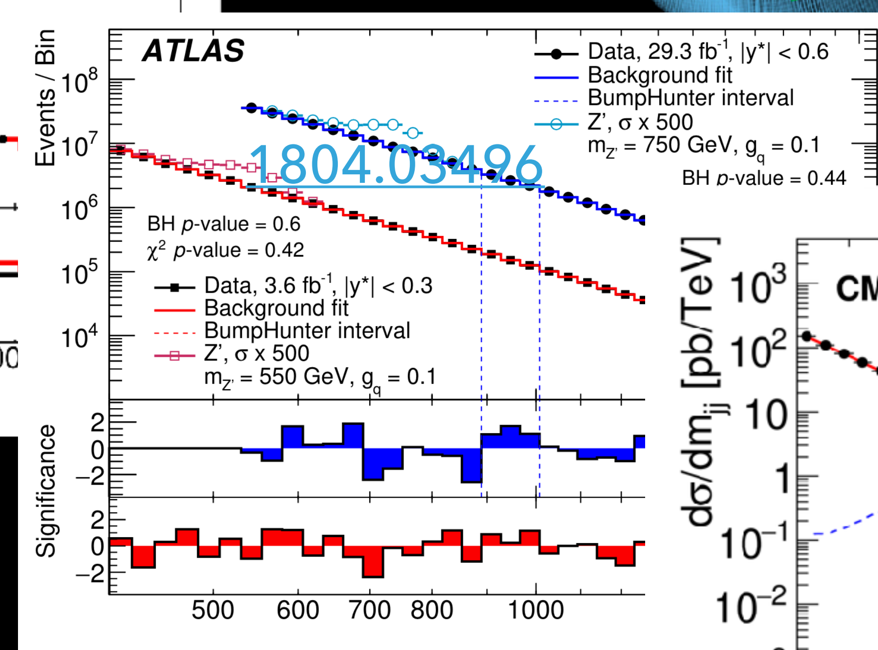
- MET+X: governed by irreducible $Z(\nu\nu)$ +jets background.
  - Multi-CR fit constrains systematics, scales well w/$\mathscr{L}$
- Dilepton: see dark photon session :)

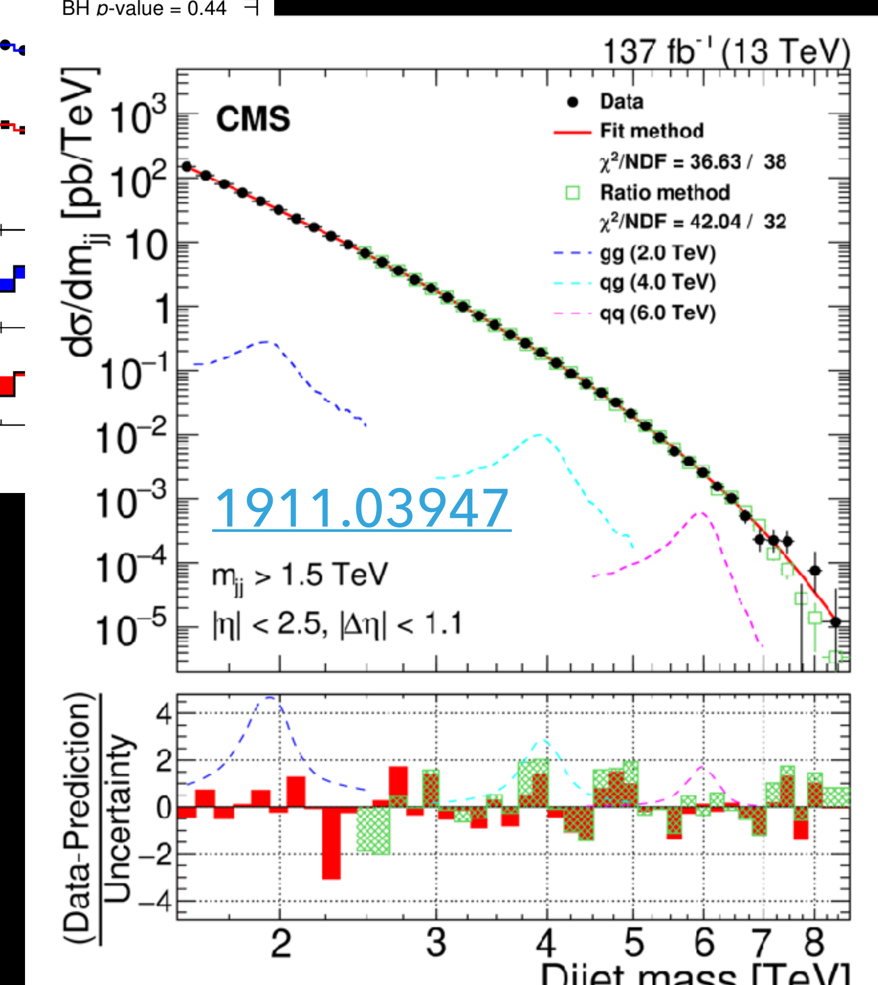
RUN 2 RESULTS: DIJET





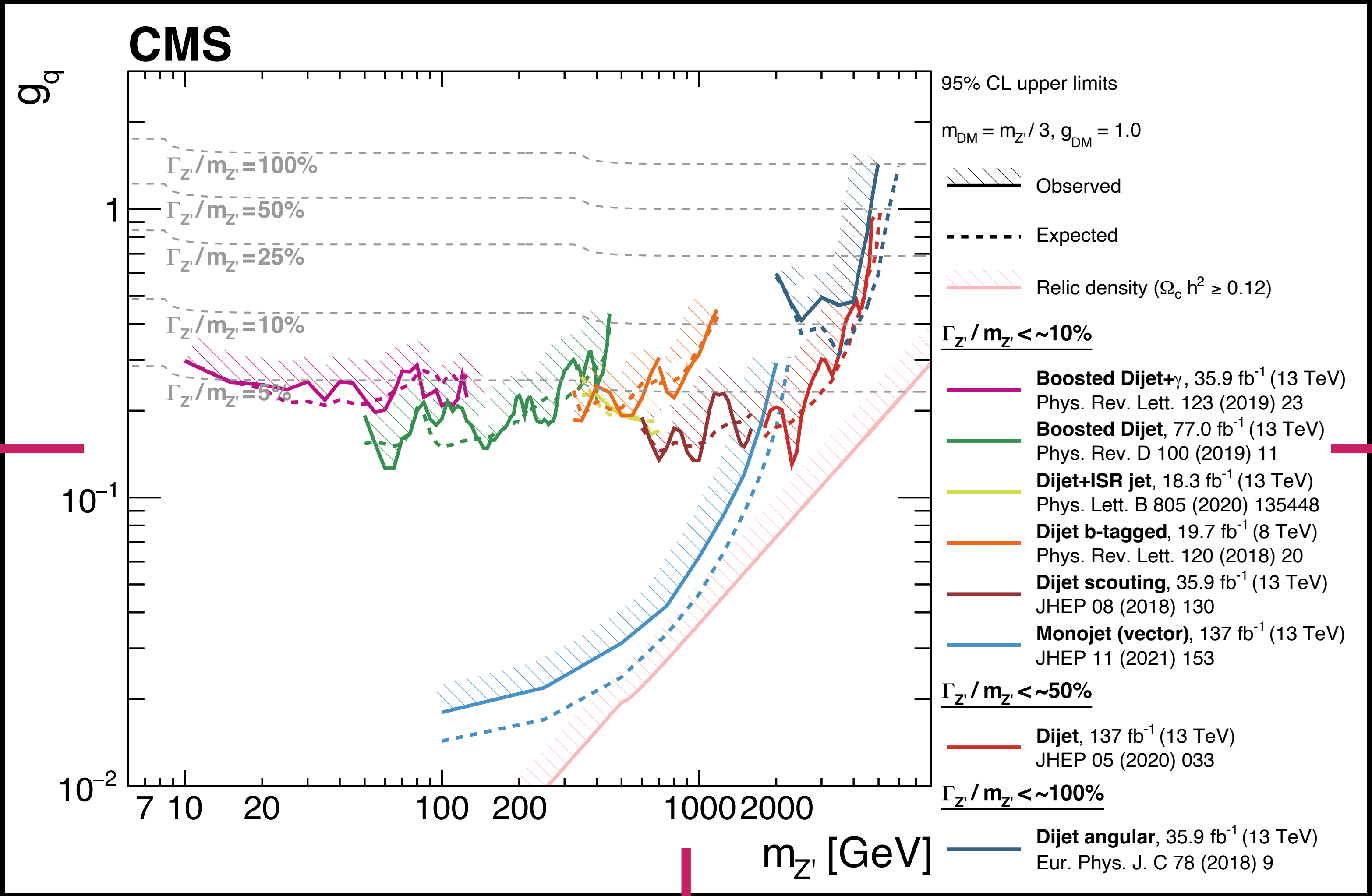






- Dijet: huge QCD background governs both sensitivity and phase space coverage.
- Diverse array of techniques invented in Run 2 to cover phase space.
- Further room for improvements from innovation.

DIJET ROADMAP



Low mass strategies ←

- Scouting/trigger-level analysis

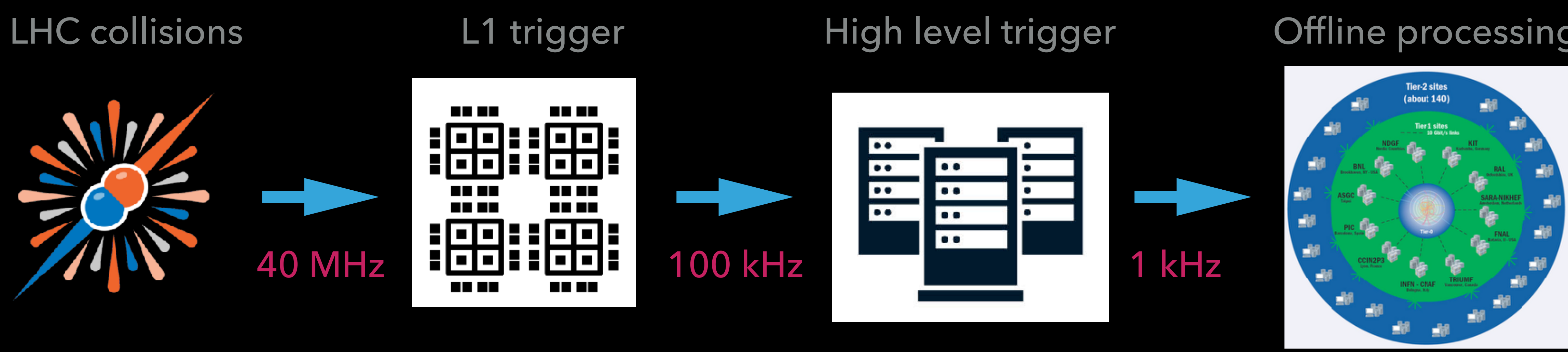
→ $\sqrt{s}, \mathscr{L}$

↓

Better methods, $(\mathscr{L}^{1/4})$

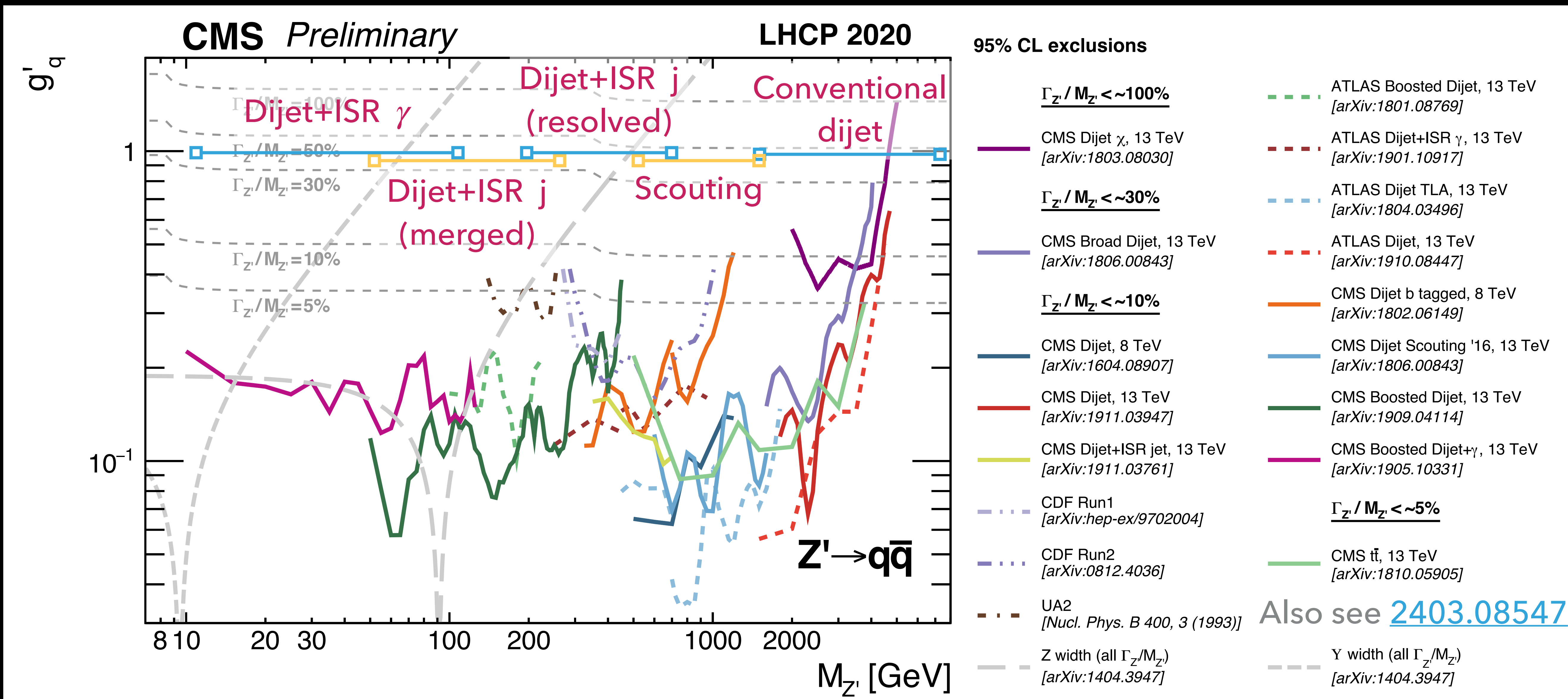
- Jet and event tagging
- Background modeling
- Resonance mass reconstruction

LOW MASS LIMITATIONS



- Traditional dijet method is limited by **trigger bandwidth**
  - In Run 2, triggers limited to ~1 kHz (Run 3 ~ 1.5 kHz)
  - Main dijet trigger: save events with $H_\mathrm{T} \equiv \sum p_\mathrm{T}(j) \gtrsim 1\,\mathrm{TeV}$
- ⇒ **Looking below 1.5 TeV requires a different trigger strategy**
- How can we probe lower masses? Three main methods:
  - **Scouting/TLA/turbo:** read out HLT jets/partial events to save bandwidth
  - **ISR:** resonances produced w/large jet or photon ISR
  - HLT b tagging

LOW MASS STRATEGIES






RUN 2 SCOUTING

- What are the constraints on our data acquisition?
  - **DAQ bandwidth** from P5 to T0: **3-5 GB/s**
  - **Prompt reconstruction**: process raw data within ~48 hours
  - HLT latency: decision within ~400 ms
  - Storage space (tape and disk)
- There is **no hard DAQ limit** on the **HLT event rate**, but rather the **HLT bandwidth**
  - 1 kHz × 1 MB/event = 1 GB/s
- Scouting: record trigger-level objects instead of full raw data
  - Calo jets (HT>250 GeV) and **particle flow jets (PF) (HT>410 (HLT), 360 (L1) GeV)**

Stream	Rate (Hz)	Event size (kB)	Bandwidth (MB/s)
Muons	420	860	360
Hadrons/Taus	345	870	300
Scouting (calo)	4580	8.9	40
Scouting (PF)	1380	14.8	20

Mukherjee 2019

RUN 3 SCOUTING

Type	L1 threshold	HLT threshold (**2023**)
e/γ	$1\ e/\gamma$, $p_T > 30\,\mathrm{GeV}$, $\|\eta\| < 2.1$	1 SC (loose), $p_T > 30\,\mathrm{GeV}$
	$2\ e/\gamma$, $p_T > 18/12\,\mathrm{GeV}$, $\|\eta\| < 1.5$	2 SC (loose), $p_T > 12\,\mathrm{GeV}$
μ	2μ, $p_T > 15/7\,\mathrm{GeV}$	2μ, $p_T > 3\,\mathrm{GeV}$
	2μ, OS, $p_T > 4.5\,\mathrm{GeV}$, $\|\eta\| < 2$, $m_{\mu\mu} > 7\,\mathrm{GeV}$	
	2μ, OS, $p_T > 4\,\mathrm{GeV}$, $\|\eta\| < 2.5$, $\Delta R < 1.2$	
	2μ, OS, $p_T > 0\,\mathrm{GeV}$, $\|\eta\| < 1.5$, $\Delta R < 1.4$ (**2023**)	
	3μ, $p_T > 5/3/3\,\mathrm{GeV}$	
Jets/H_T	$H_T > 280$ (**2023**), 360 (**2022**) GeV	
	1 jet, $p_T > 180\,\mathrm{GeV}$	
	2 jets, $p_T > 30\,\mathrm{GeV}$, $\|\eta\| < 2.5$, $\Delta\eta < 1.5$, $m_{jj} > 250$ (**2023**), 300 (**2022**) GeV	

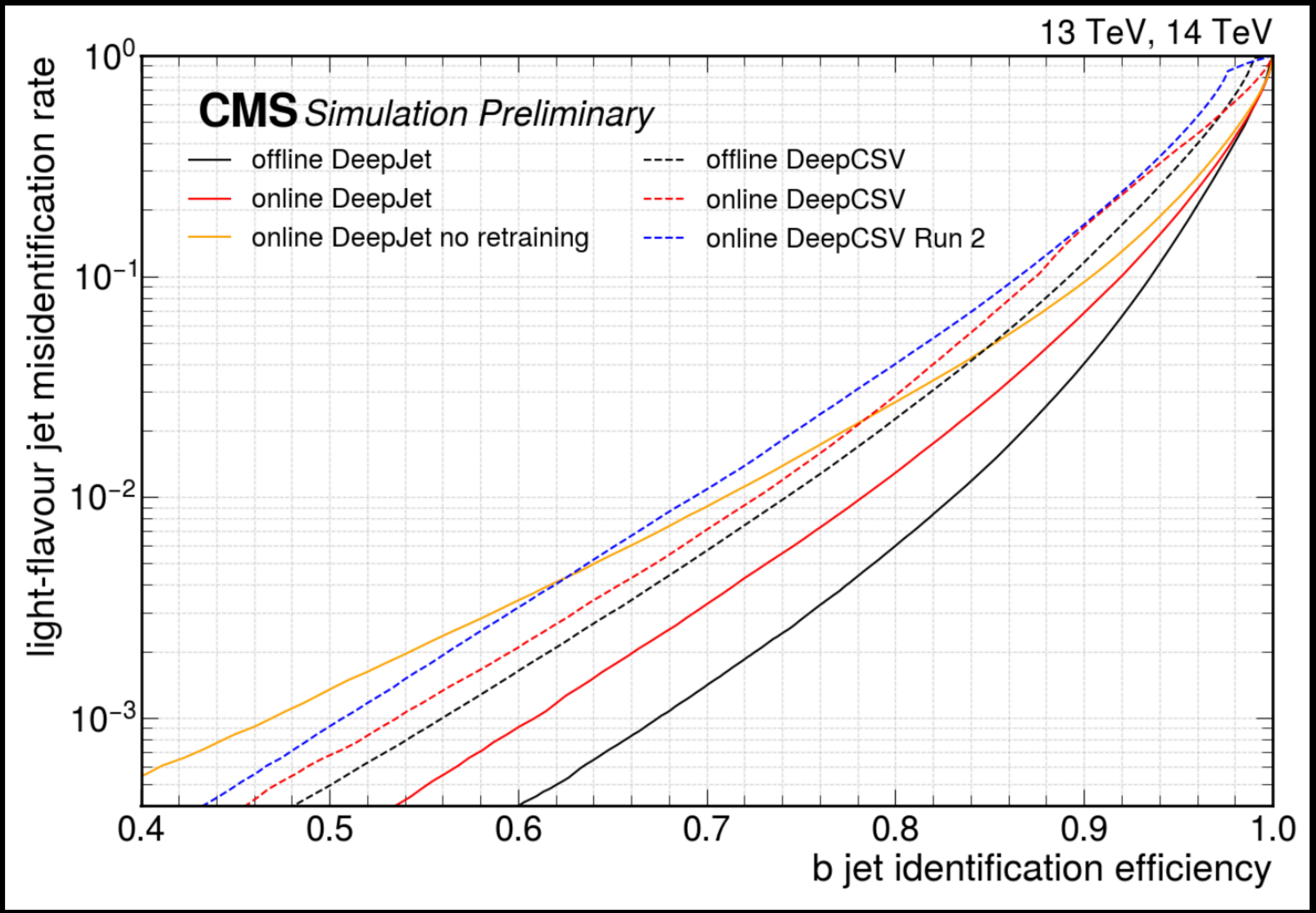
- Lots of new toys in Run 3: lower thresholds (e.g. HT 410→280 GeV), add e/γ
- Key tech: GPUs @HLT (~35% reduced processing time; higher L1 input rate).
  - Room to improve: lower track ϵ and $\sigma(p_T)$ ⇒ degraded b tagging.
- More interest! Personpower for better calibrations, algorithms.

- See recent review paper at 2403.16134!

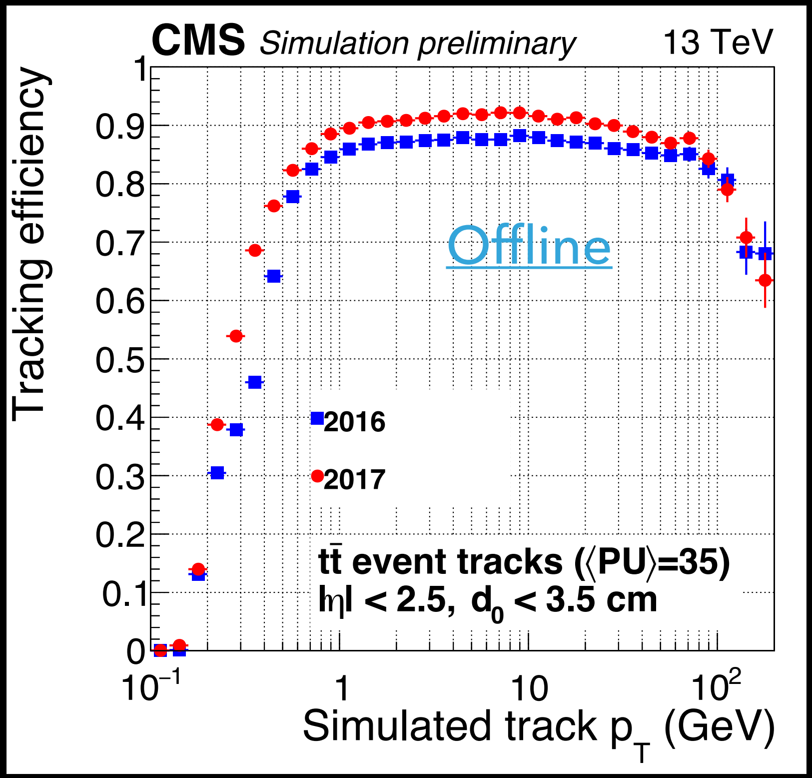
Year	$\mathcal{L}_{inst}$ [cm^{-2}s^{-1}]	PU	Standard rate [Hz]	Parking rate [Hz]	Scouting rate [Hz]
2018	1.2×10^{34}	38	1000	3000	5000
2022	1.5×10^{34}	46	1800	2440	22000
2023	1.7×10^{34}	48	1700	2660	17000

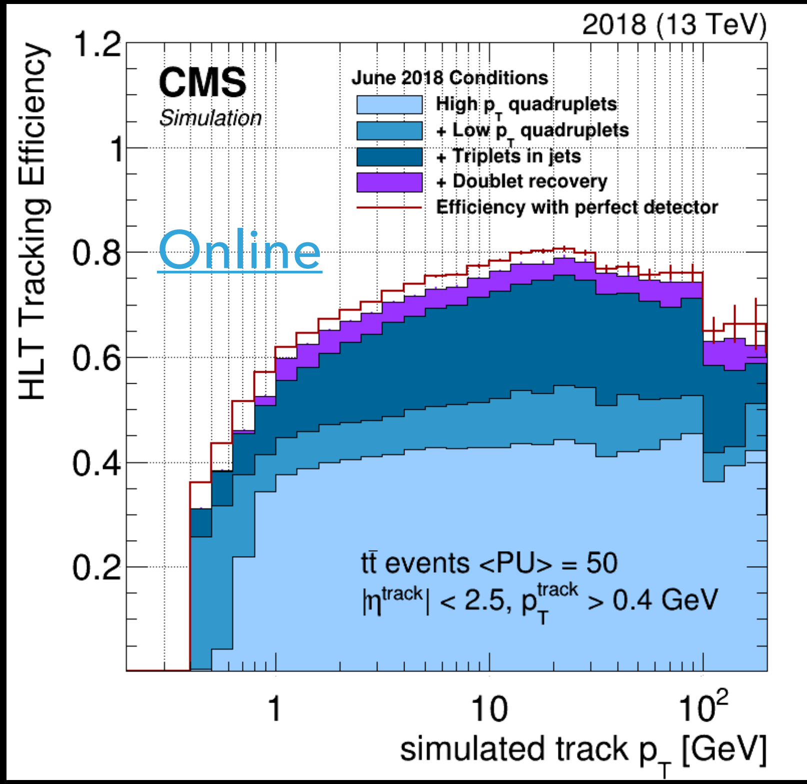
SCOUTING * TAGGING

- Lesson from Run 2: retrain online tagging algorithms on HLT inputs.
  - For example, tracking efficiency takes a ~10% hit (worse for displaced tracks).
- For Run 3, ParticleNet @HLT achieves online b tagging within a few percent of offline.



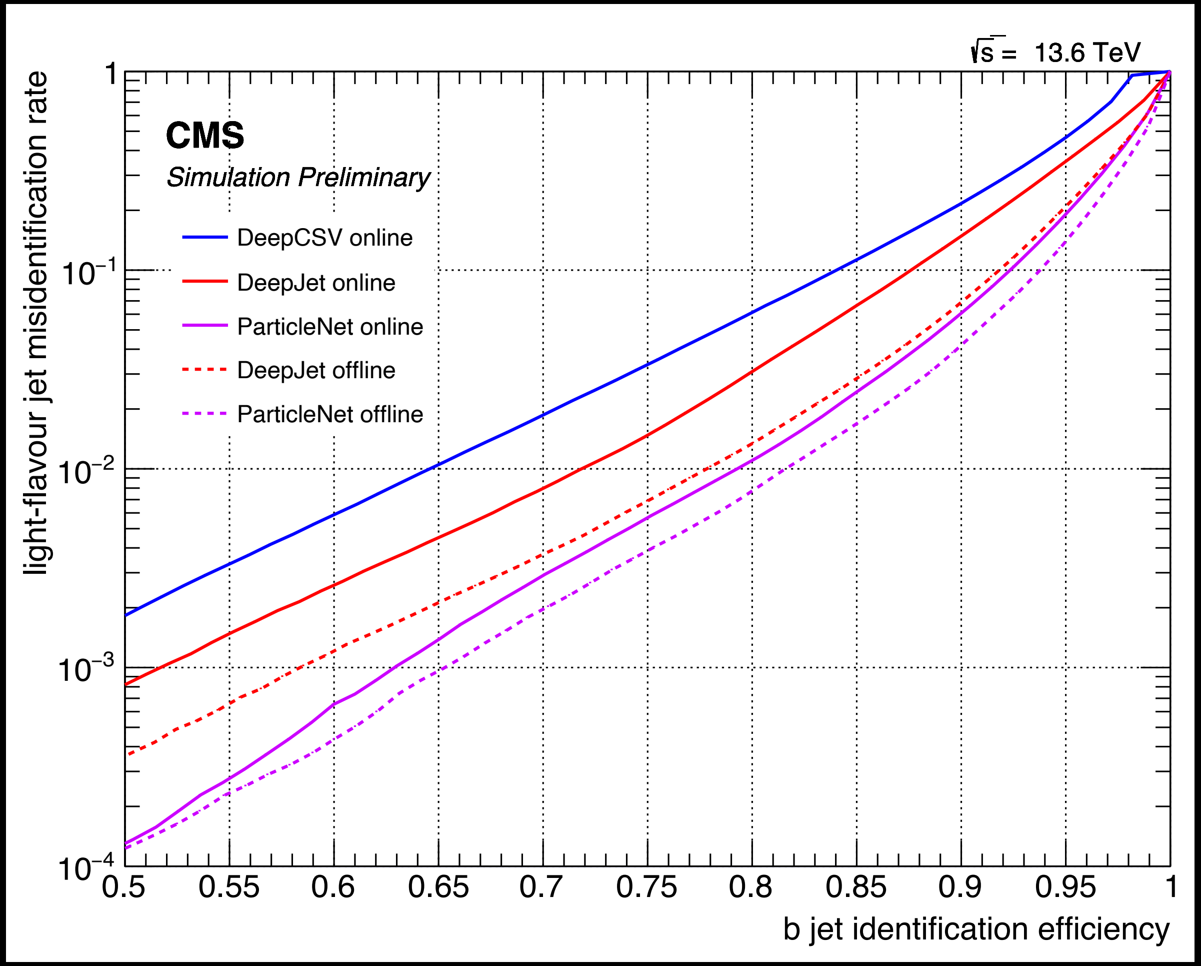
CMS-DP-2022-030, CMS-DP-2023-021



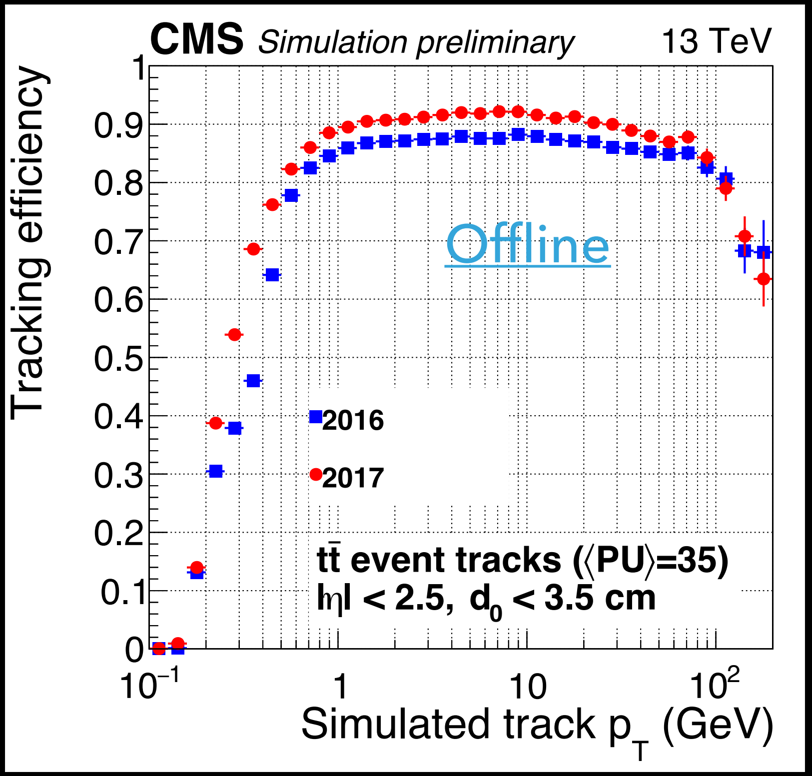


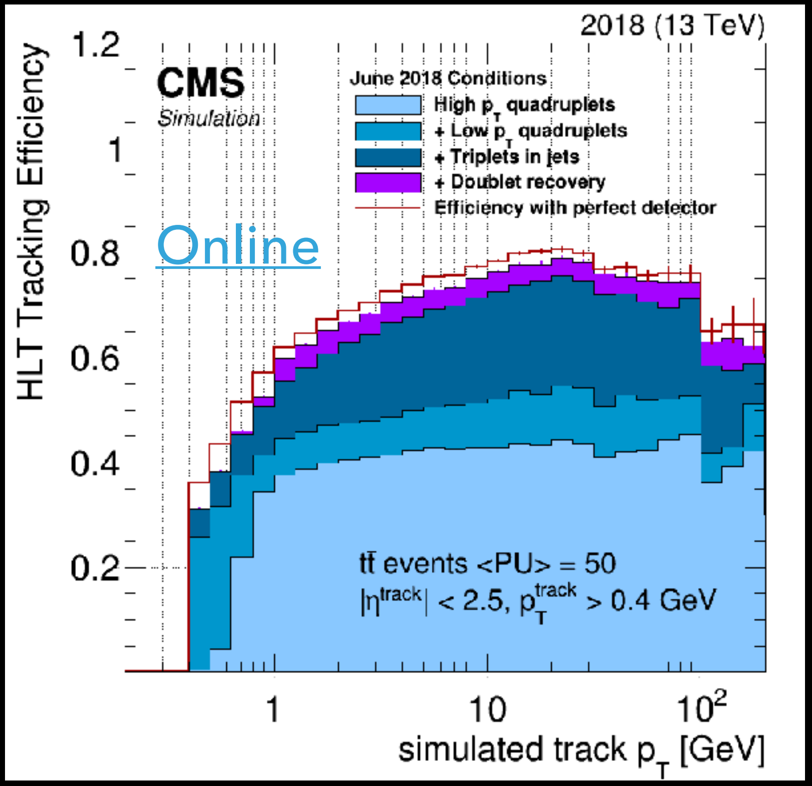
SCOUTING * TAGGING

- Lesson from Run 2: retrain online tagging algorithms on HLT inputs.
  - For example, tracking efficiency takes a ~10% hit (worse for displaced tracks).
- For Run 3, ParticleNet @HLT achieves online b tagging within a few percent of offline.

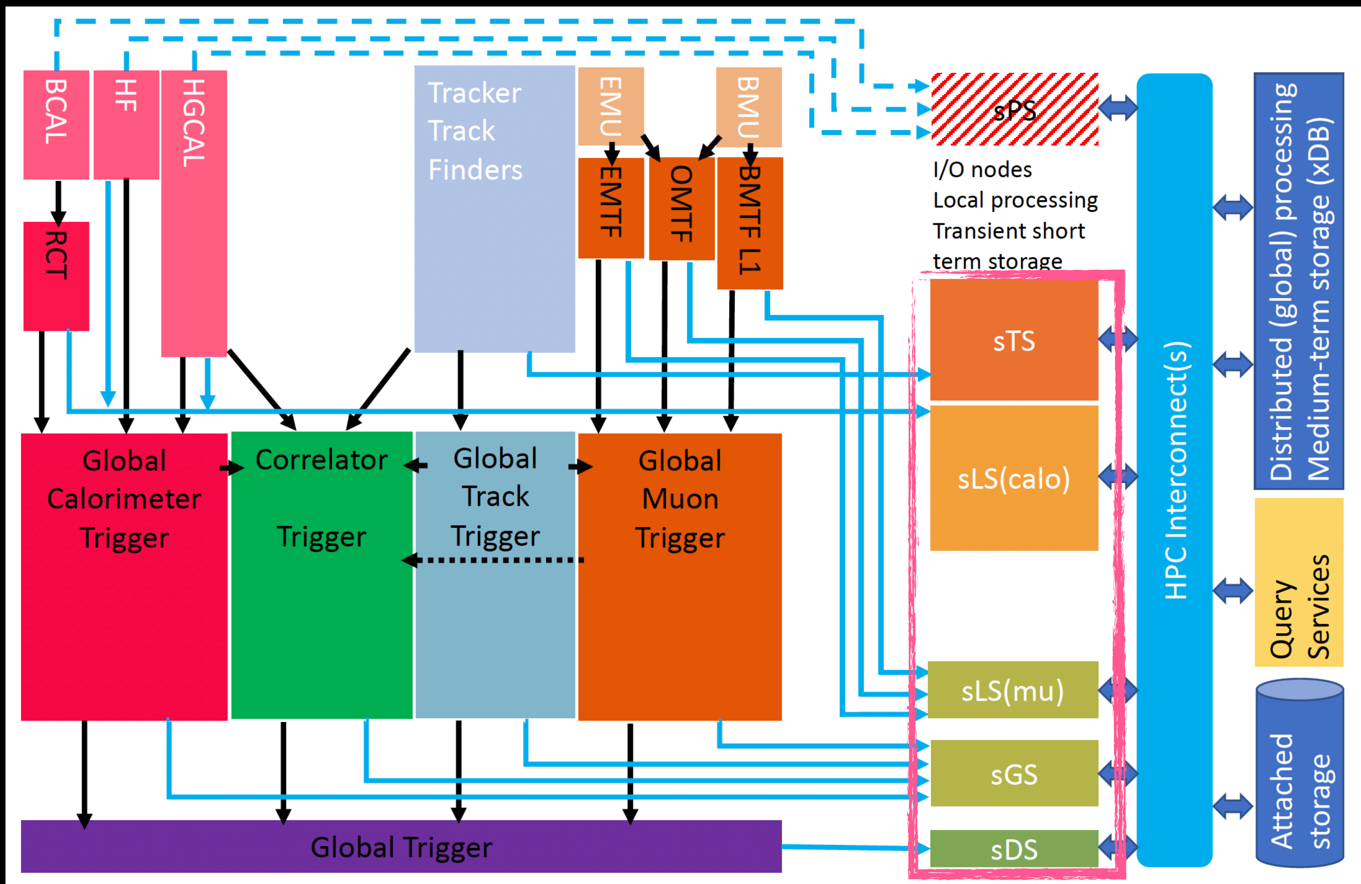


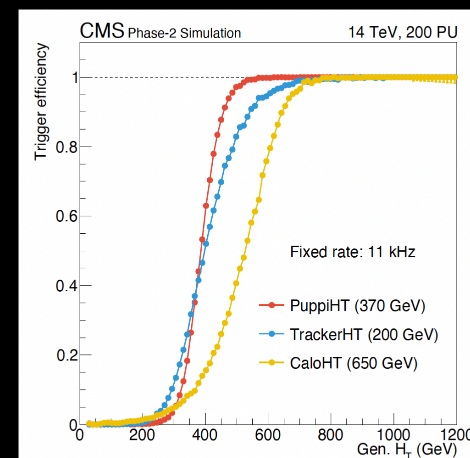
CMS-DP-2022-030, CMS-DP-2023-021





HL-LHC SCOUTING





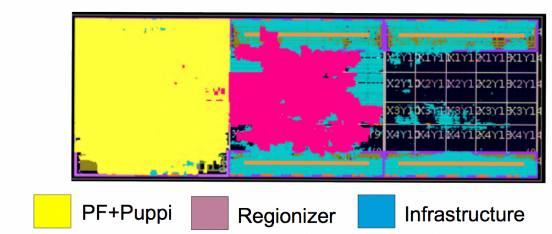


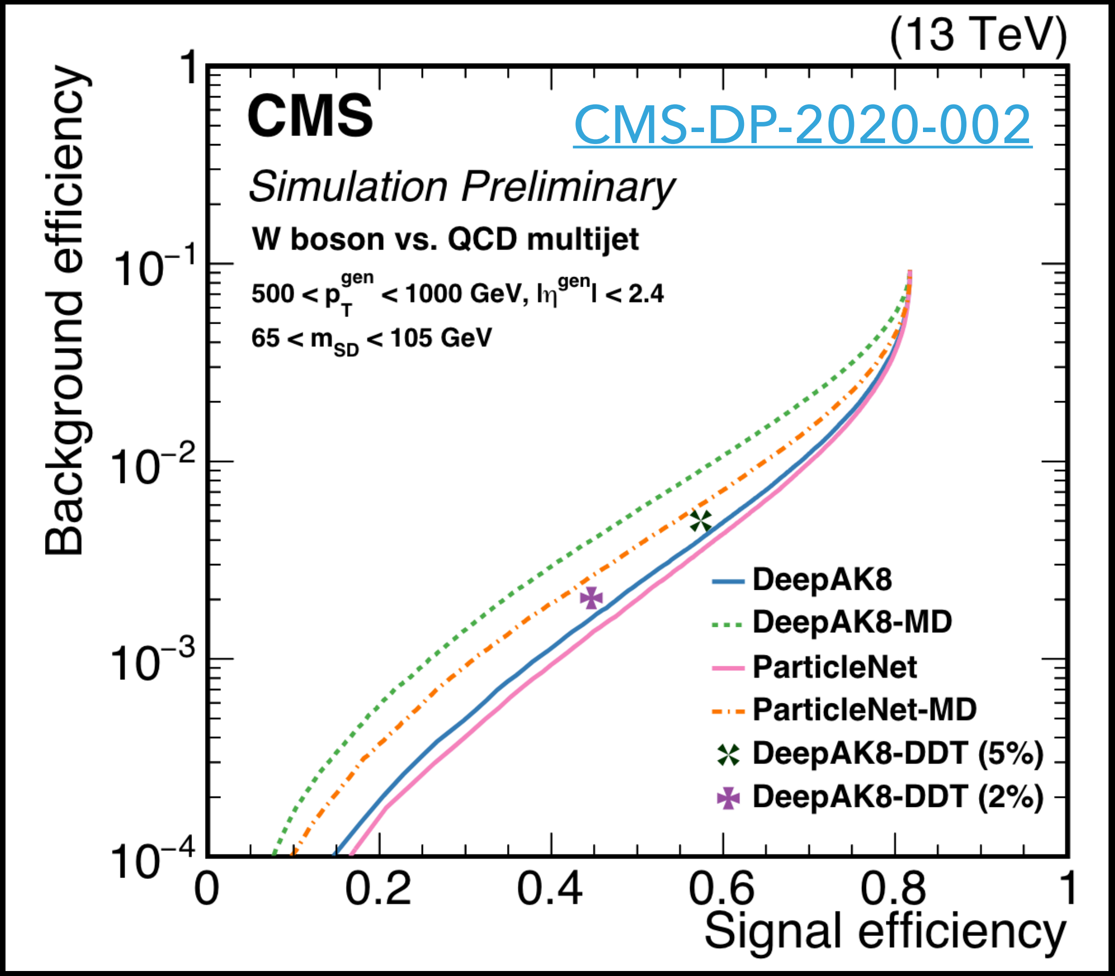
Figure 3. Left: The signal efficiency is shown for $t\bar{t}$ events selected by H_T triggers utilizing different sets of inputs at a fixed trigger rate of 10.5 kHz. The performance of the H_T trigger quantity computed with PUPPI jets, tracker-only jets and calorimeter jets are compared. Top: The FPGA floorplan for the prototype particle-flow algorithm, showing how the elements of the algorithm have been placed in the FPGA fabric (Xilinx Virtex (VU9P)).

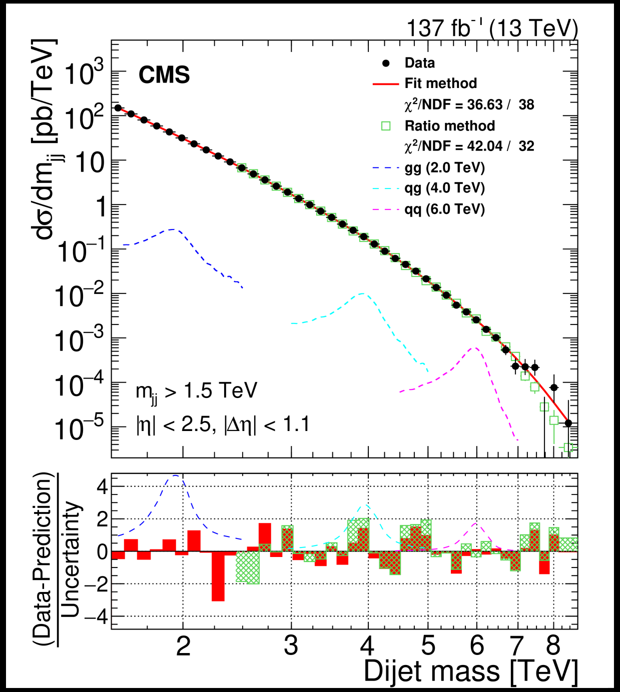
Zabi 2022

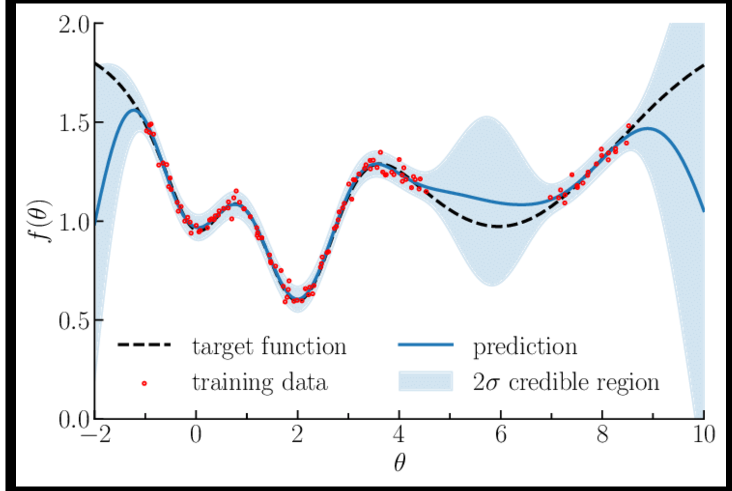
- HL-LHC triggering is a whole new ballgame: 750 kHz accept rate, tracking, HGCAL, ML on FPGAs.
  - Dreaming big: particle flow, PUPPI, b tagging, tau tagging.
- Nominal design includes modular 40 MHz scouting system.
  - Baseline scouting global system (sGS): triggerless dijet search w/performance similar to current HLT scouting?

METHOD IMPROVEMENTS

- Better separate dijets from QCD:
  - Resonance mass (e.g. $M(\vec{j}_1 + \vec{j}_2), m_{\mathrm{SD}}$)
  - Event/jet info ($\Delta\eta_{jj} < 1.1$, τ_{21}/N_2^1)
  - Flavor tagging
- New ways to estimate QCD backgrounds:
  - High-$\Delta\eta_{jj}$ sideband vs. empirical function: rigidity improves uncertainties.
  - Non-parametric methods: Gaussian process regression (2202.05856).

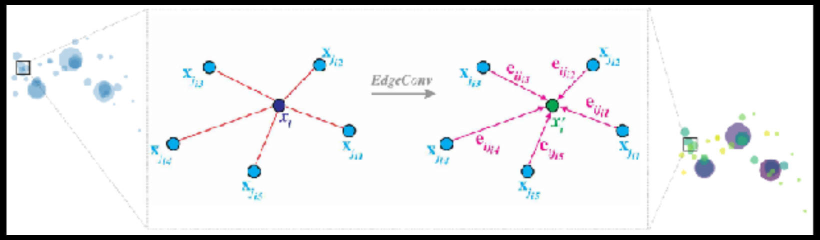


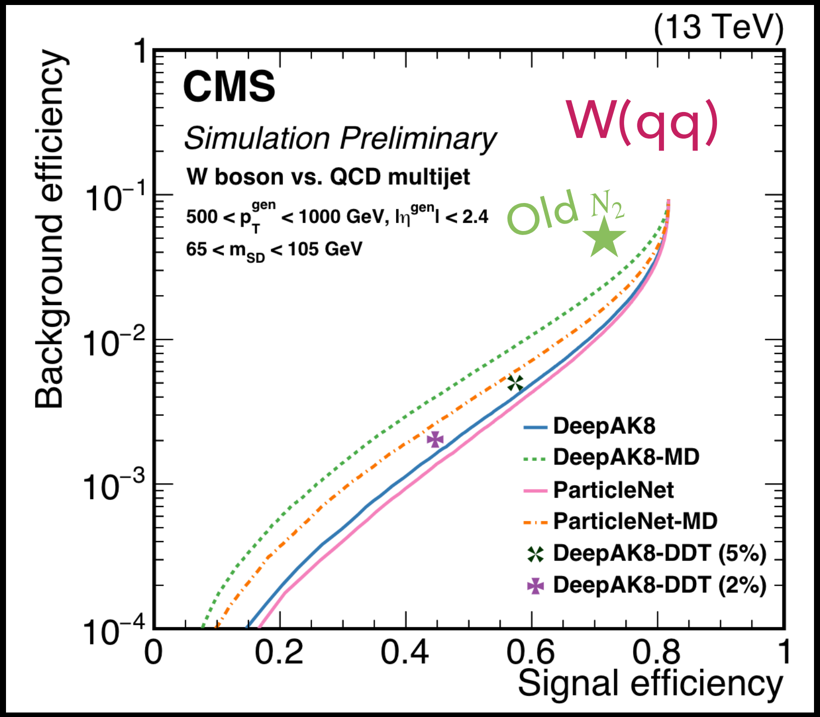


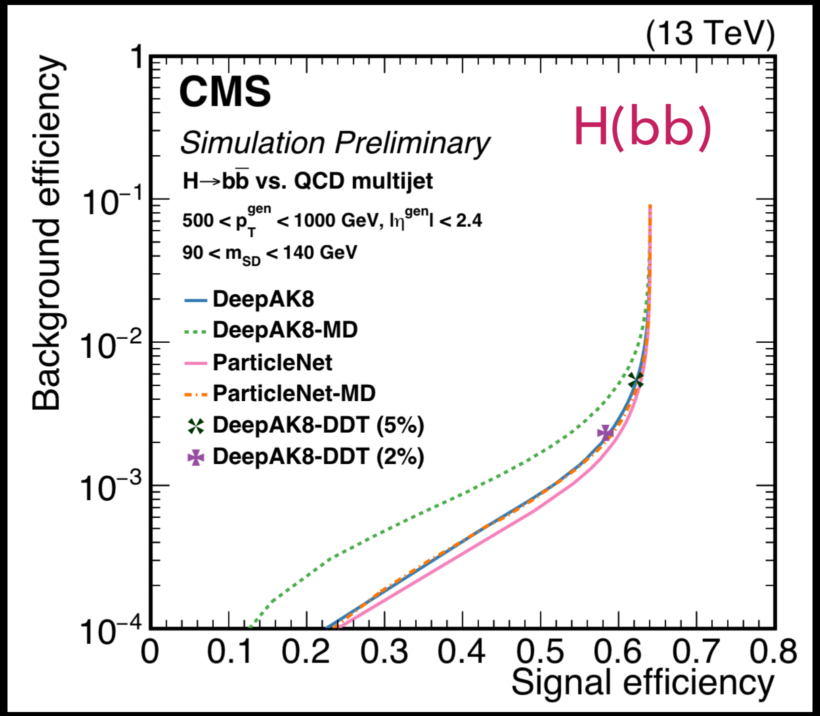


TWO-PRONGED JET TAGGING

- For boosted dijet searches, key handle is **2-pronged jet tagging**.
- Past searches used analytical variables, e.g., τ_{21}, N_2^1 (*DDT).
- Large potential gains from NN-based taggers , e.g., CMS ParticleNet, ParT.
  - Graph NNs trained on jet particle constituents.
  - Multi-class taggers: QCD, qq, cc, bb, t, …
  - Mass-decorrelated using a wide grid of signal masses.
- Target heavy-flavor resonances as well, e.g. scalar mediator w/MFV or more exotic scenarios (cc, $\tau\tau$, bq?…)

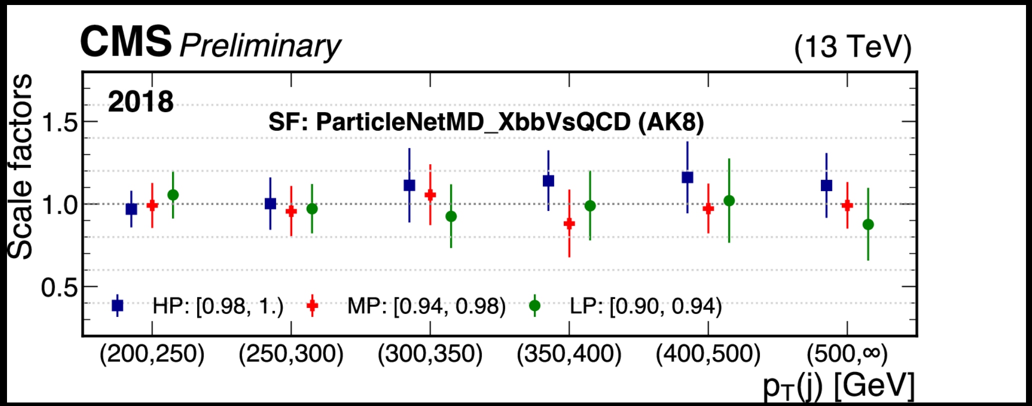




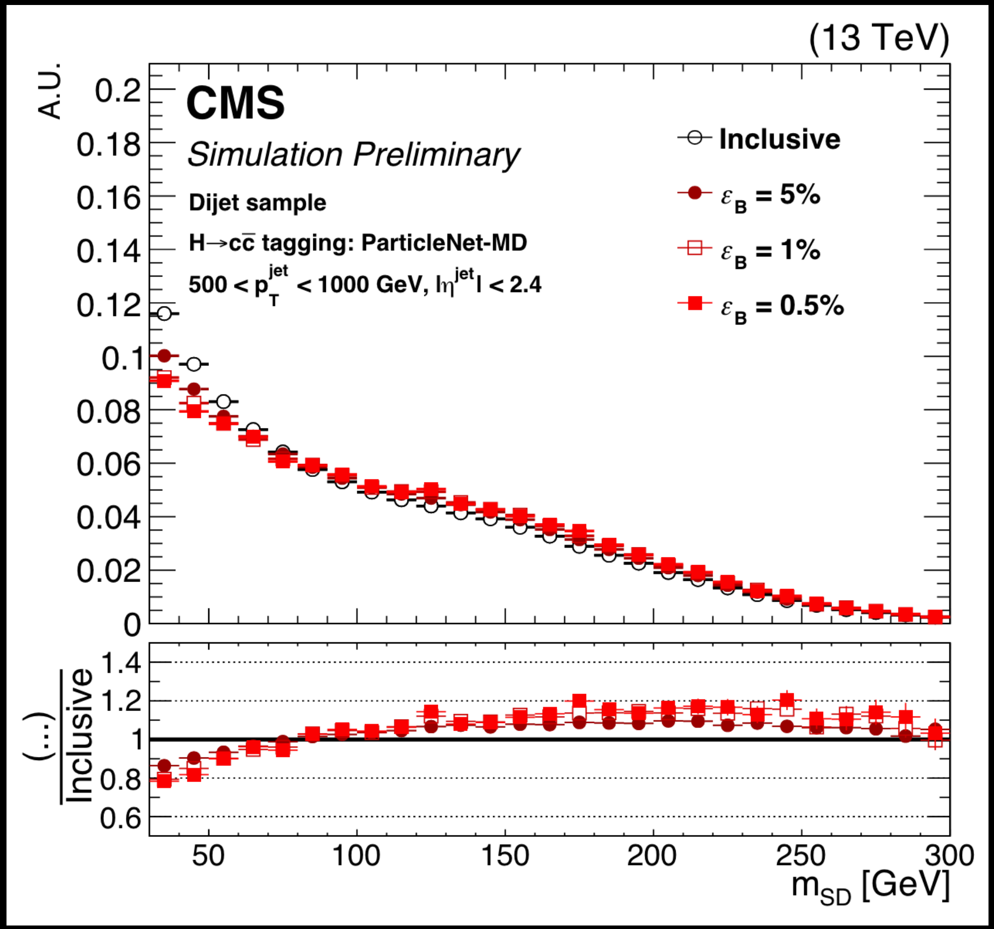


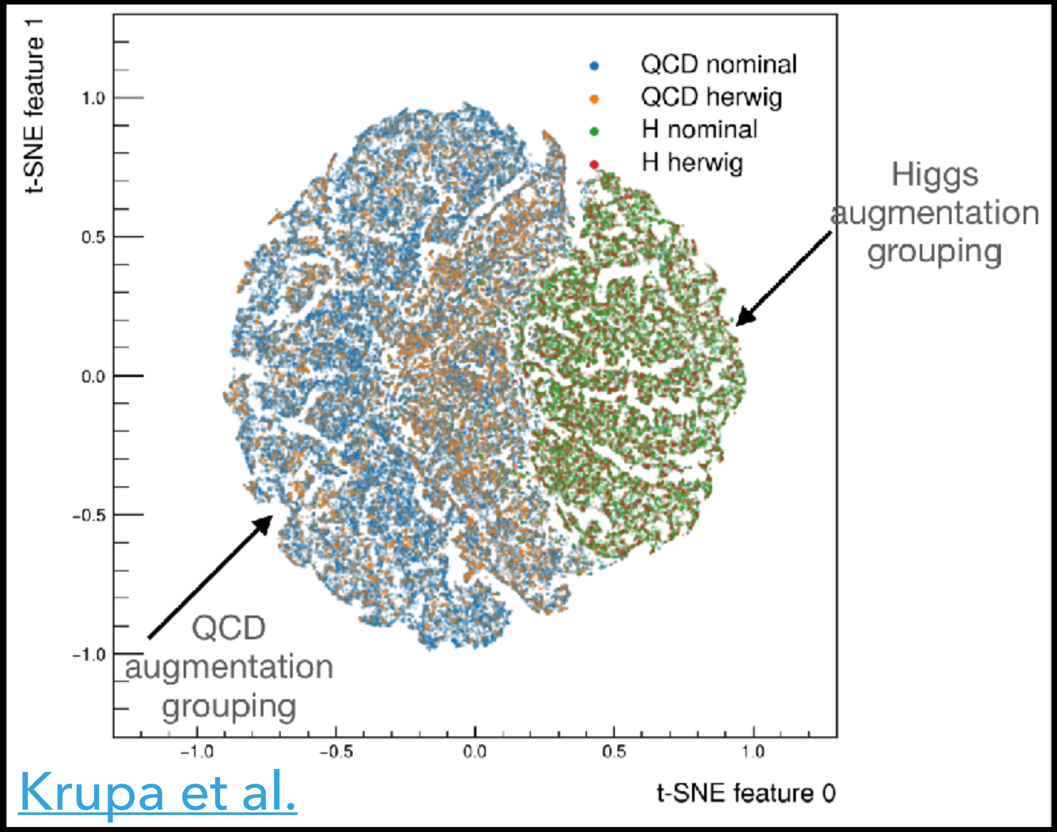
FOCUS ON SYSTEMATICS

CMS-DP-2022-005



- Early generations of taggers exhibited large data-MC scale factors (~30%).
- Situation is somewhat better recently; increasing focus on robustness as well as performance.

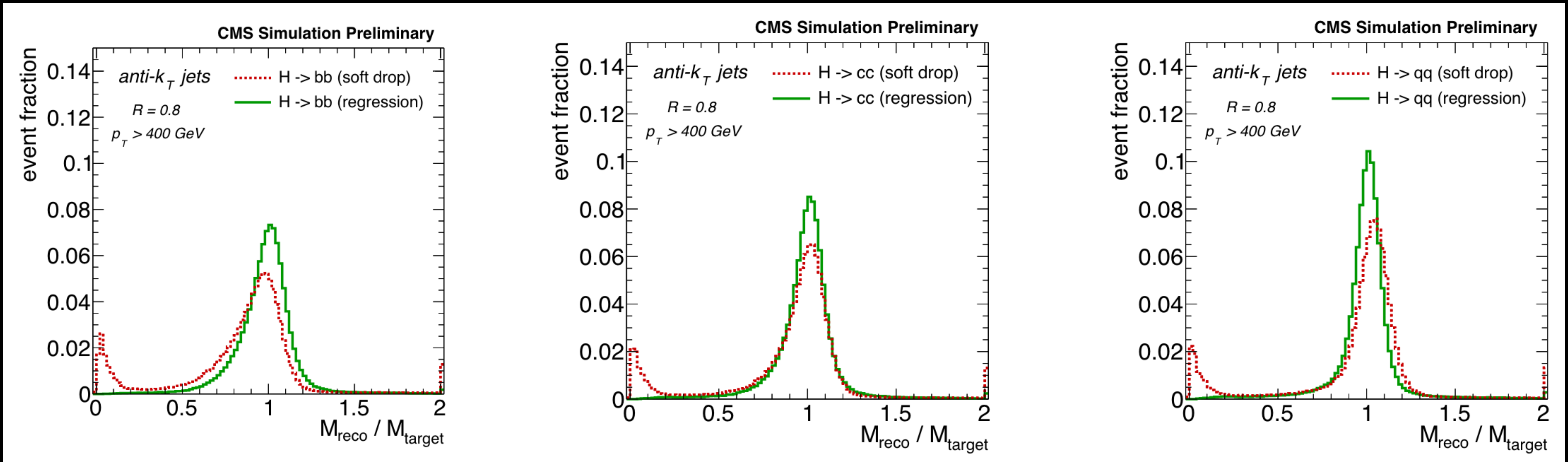




- Mass decorrelation: train using wide set (or continuous distribution) of signal masses. Critical for bump hunts and calibrating on standard candles (e.g. W(qq)).

- Tagger resilience against data/MC mismodeling:
  - Enforce invariance under known parton shower uncertainties (contrastive learning).
  - Reweight/morph MC to match data.

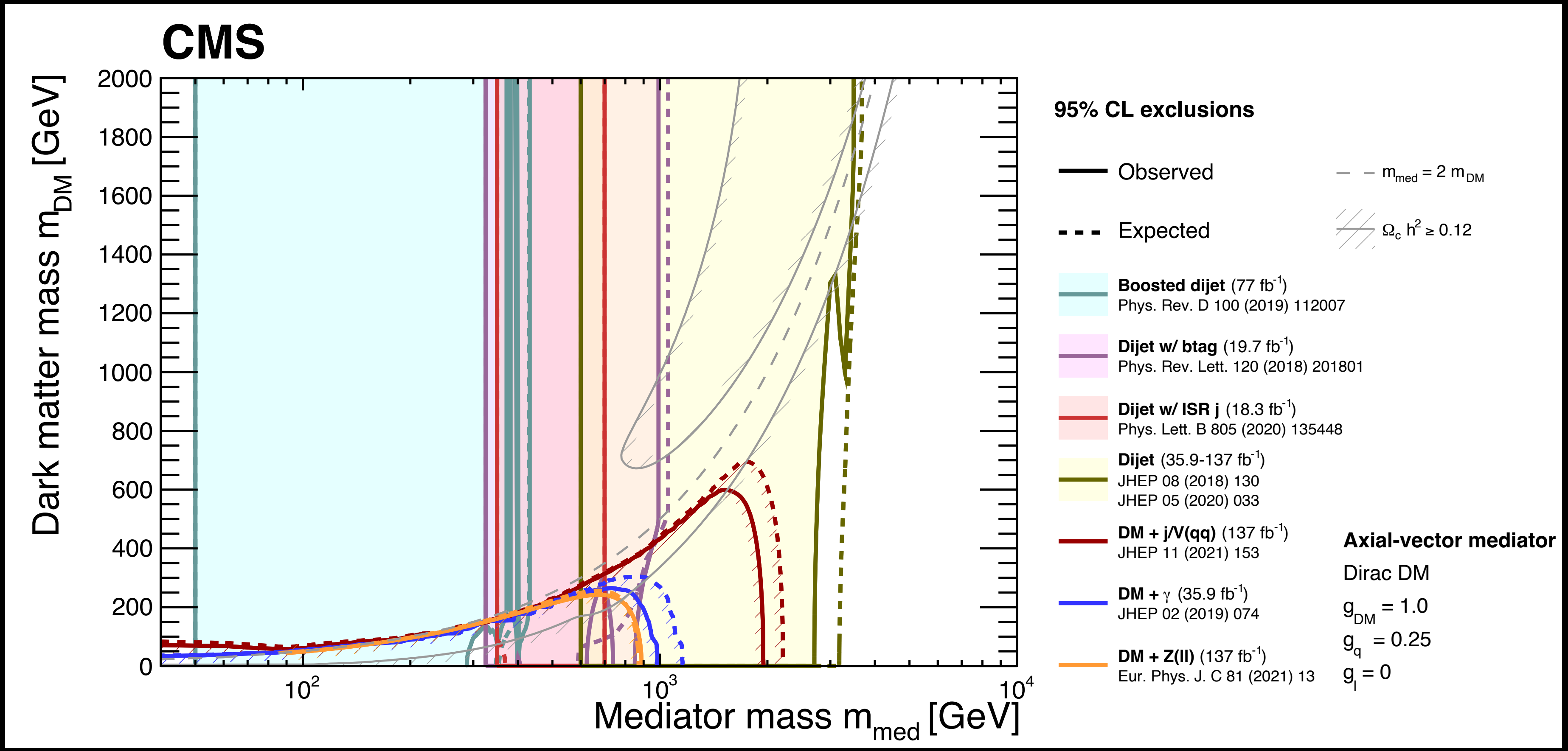
MASS REGRESSION



CMS-DP-2021-017

- Mass resolution is (clearly) a key parameter of bump hunts.
  - Pileup suppression (track-vertex association, PUPPI)
  - CMS high-mass dijet has a FSR recovery algorithm, adding nearby AK4 jets ($\Delta R < 1.1$) to m_{jj}.
  - Boosted dijet searches rely on pileup rejection and groomed mass (soft drop).
- Latest ML taggers show good potential for mass regression.
  - Especially for heavy flavor and $\tau\tau$ resonances.

CONCLUSION



- s-channel benchmark models thoroughly tested with LHC Run 2 data; future searches will go beyond benchmarks to (much) smaller couplings.
- Dijet searches in particular have potential beyond luminosity scaling:
  - Better signal identification and QCD rejection, better QCD modeling.
  - Low mass methods, esp. scouting/TLA (HLT and L1; dilepton too).
- We should see all of this in Run 3!

- Further reading: ATLAS/CMS review papers

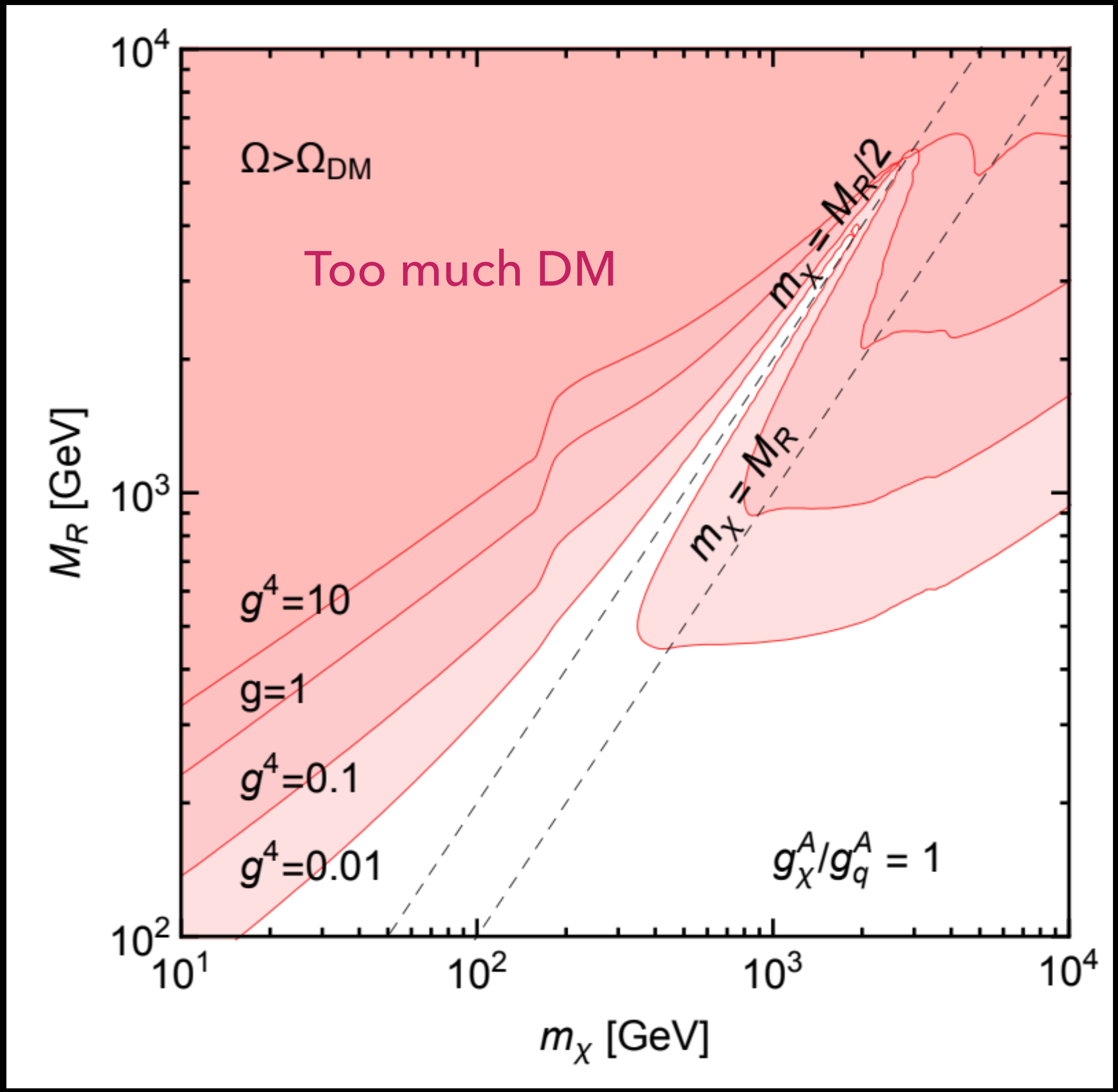
Thanks for listening!

Any questions?

Backup slides

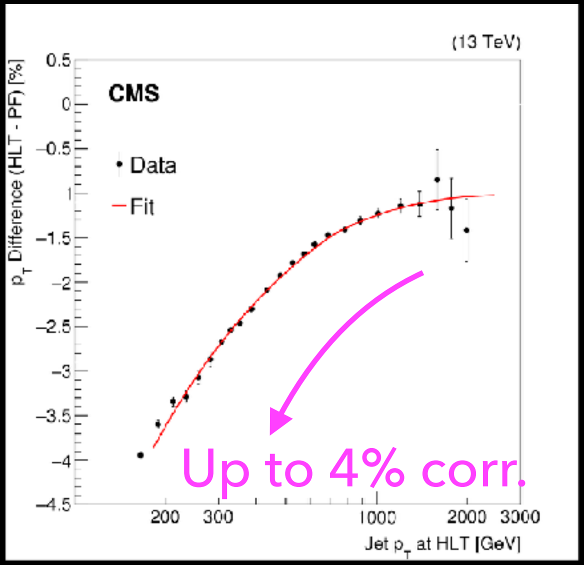
LOW MASS IS WELL MOTIVATED

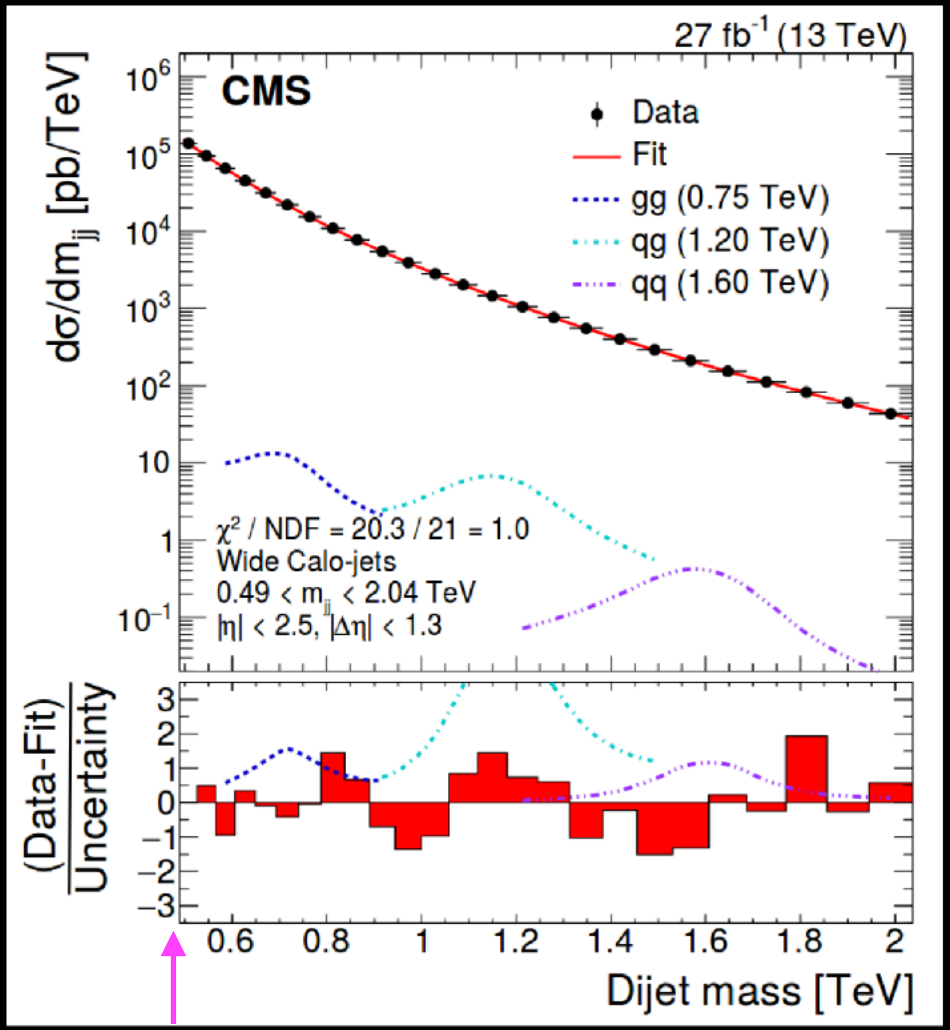
- With a lower threshold of 1.5 TeV, the traditional dijet search leaves significant phase space uncovered
- The DM simplified model directly motivates low Z' masses!

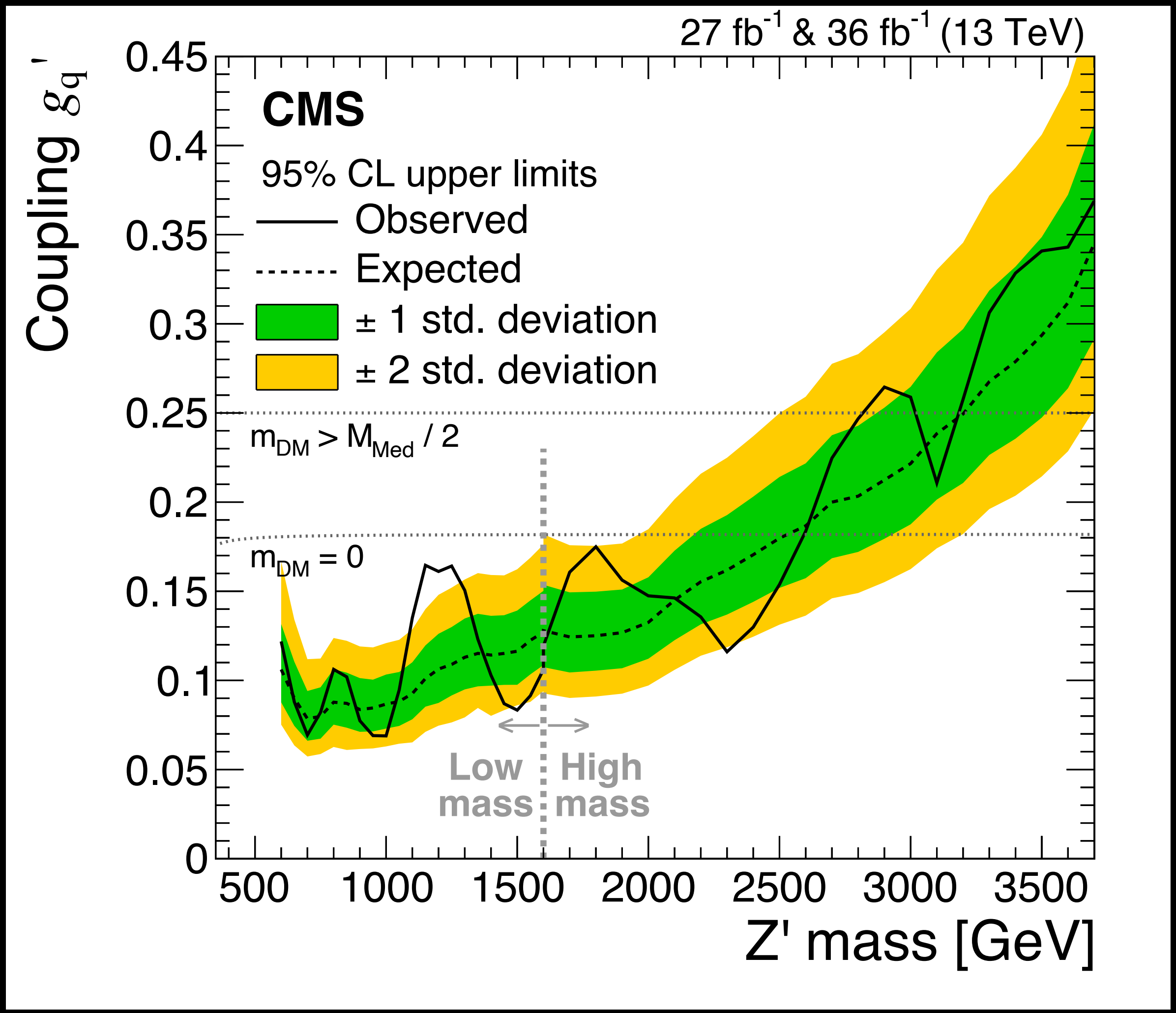


DIJET SCOUTING

- **Calibrate** CaloJets to offline PF jets (using prescaled data)
- Scouting probes Z's down to $m_{Z'} = 600$ GeV
  - Lower limit actually due to L1 trigger (H_T>175 GeV)



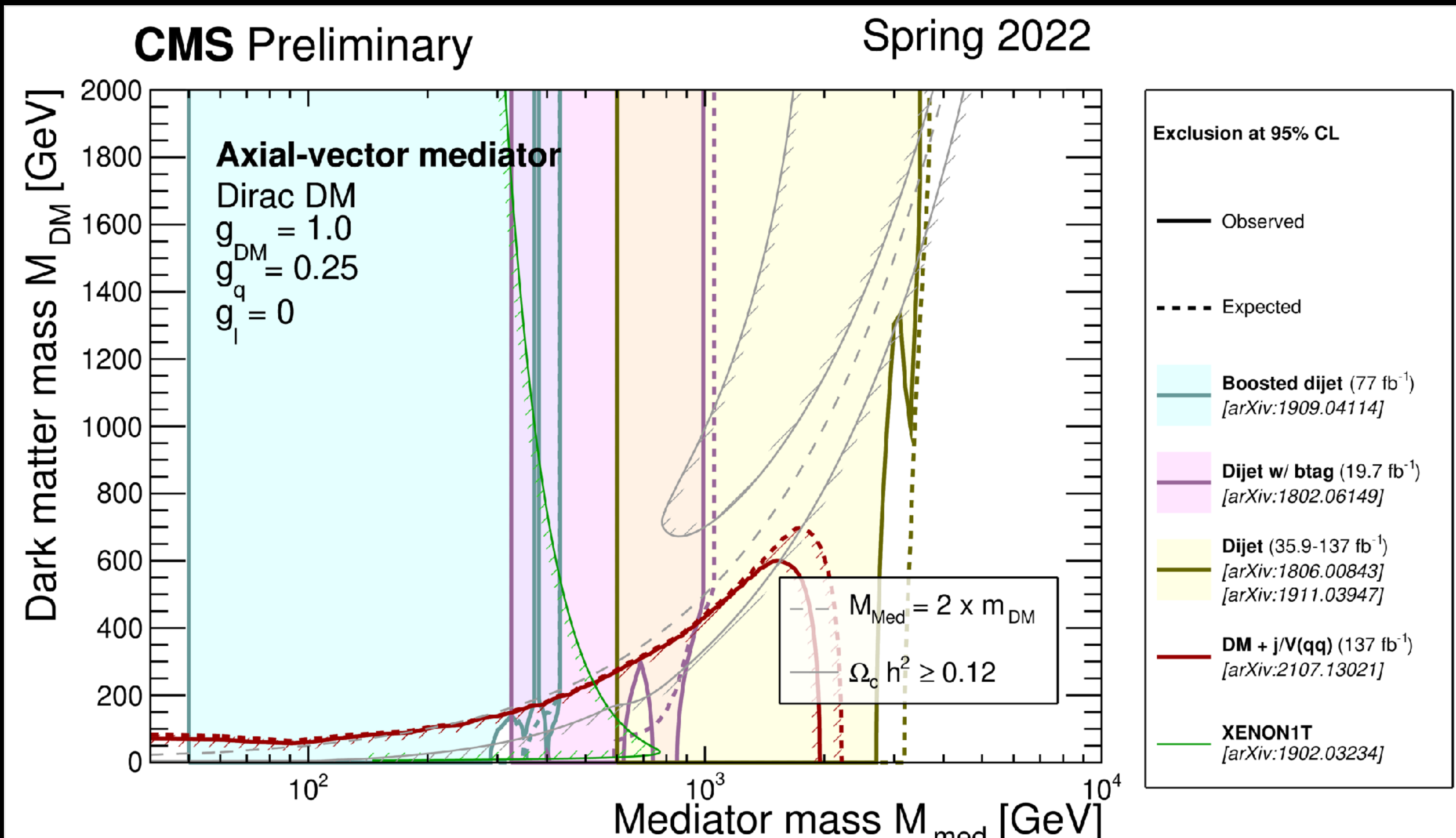




Starts at 500 GeV, rather than 1500 GeV!

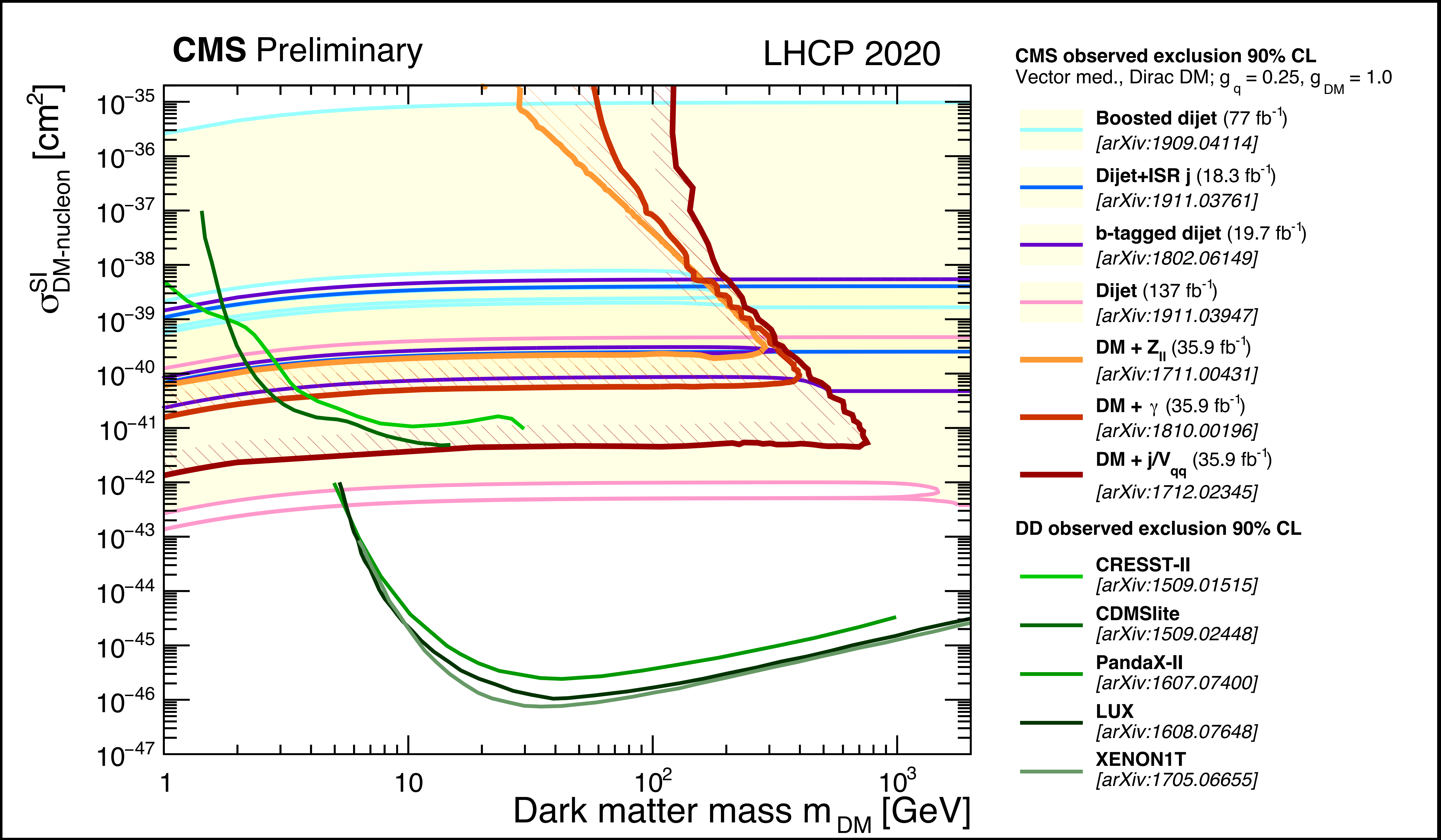
DARK MATTER INTERPRETATIONS

- For chosen couplings, mono-X and dijet cover similar range of $m(Z')$



DARK MATTER INTERPRETATIONS

- Converting to DM-nucleon cross section, collider searches complement direct detection experiments



DARK MATTER INTERPRETATIONS

- Turn on DM couplings ⇒ nice complementarity w/"mono-X" searches
- Turn on lepton couplings ⇒ demonstrates relative strength of channels