

Review on exotic physics in CMS

... and Run 3 perspectives

COMPOSE-IT

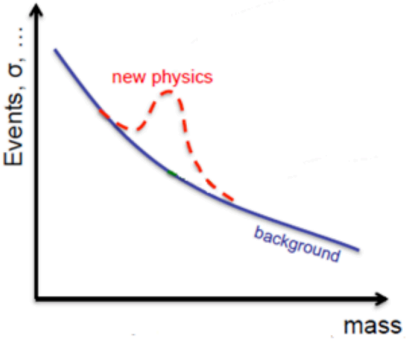
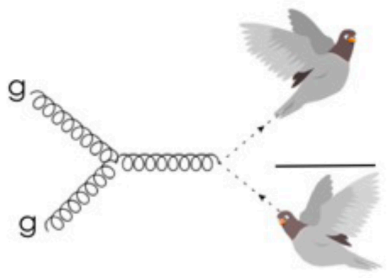
Unitarity for composite models
and beyond in the HL-LHC era

27 - 28 January 2020 - Perugia - Italy

Livia Soffi



- **Run2 searches as starting point for Run3 developments**
- Exploit **detector capabilities and novel experimental techniques** to identify unconventional signatures

<p>RESONANCES</p> 	<p>Di-jet:</p>	<p>Boosted + ISR - EXO-18-012 Scouting + ISR - EXO-16-056 High Mass - EXO-19-012 Angular - EXO-16-046</p>
	<p>Di-lepton:</p>	<p>Z' - EXO-19-019 Dark Photons - EXO-19-018</p>
<p>UNUSUAL SIGNATURES</p> 	<p>Leptons(*):</p>	<p>Multilepton - EXO-19-002 Leptoquark - EXO-19-016 Excited (gll) - EXO-18-004 Excited (lljj) - EXO-18-013 Heavy Neutrinos - EXO-16-026</p>
	<p>Long-lived Particles:</p>	<p>Delayed Jets - EXO-19-001 Delayed Photons - EXO-19-005 NN tagger (ML) - EXO-19-011</p>

Non Conventional Signatures

**Dedicated
trigger
algorithms**

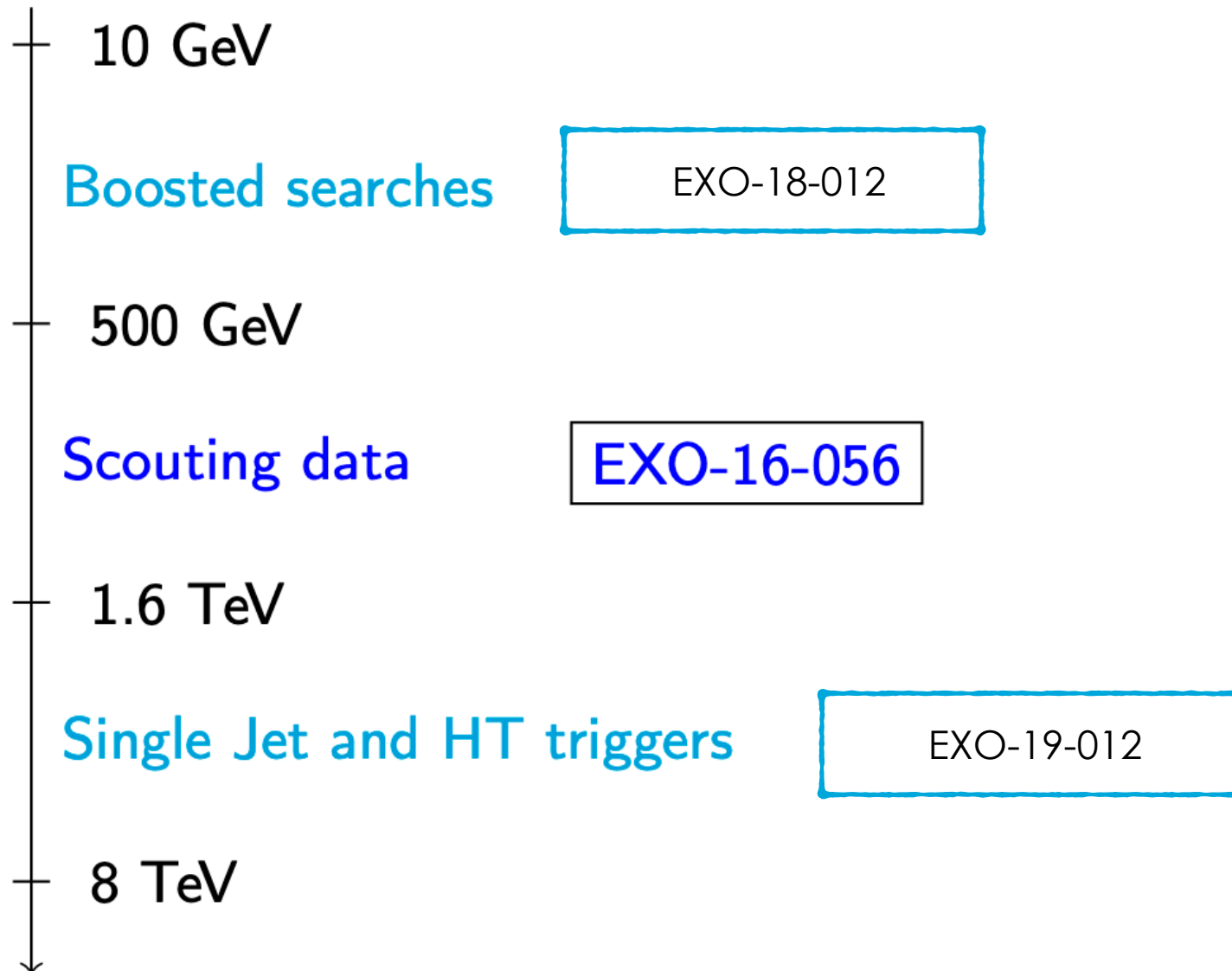
**Unique object
reconstruction,
discriminating
variables, or data
processing**

**Re-defined
analyses strategies
w/ atypical
backgrounds**

tify

DiJet Searches at CMS

- New resonances in qq , qg , gg final states in **~ 10 GeV to ~ 8 TeV**.
- **Different trigger strategies** for different mass ranges.



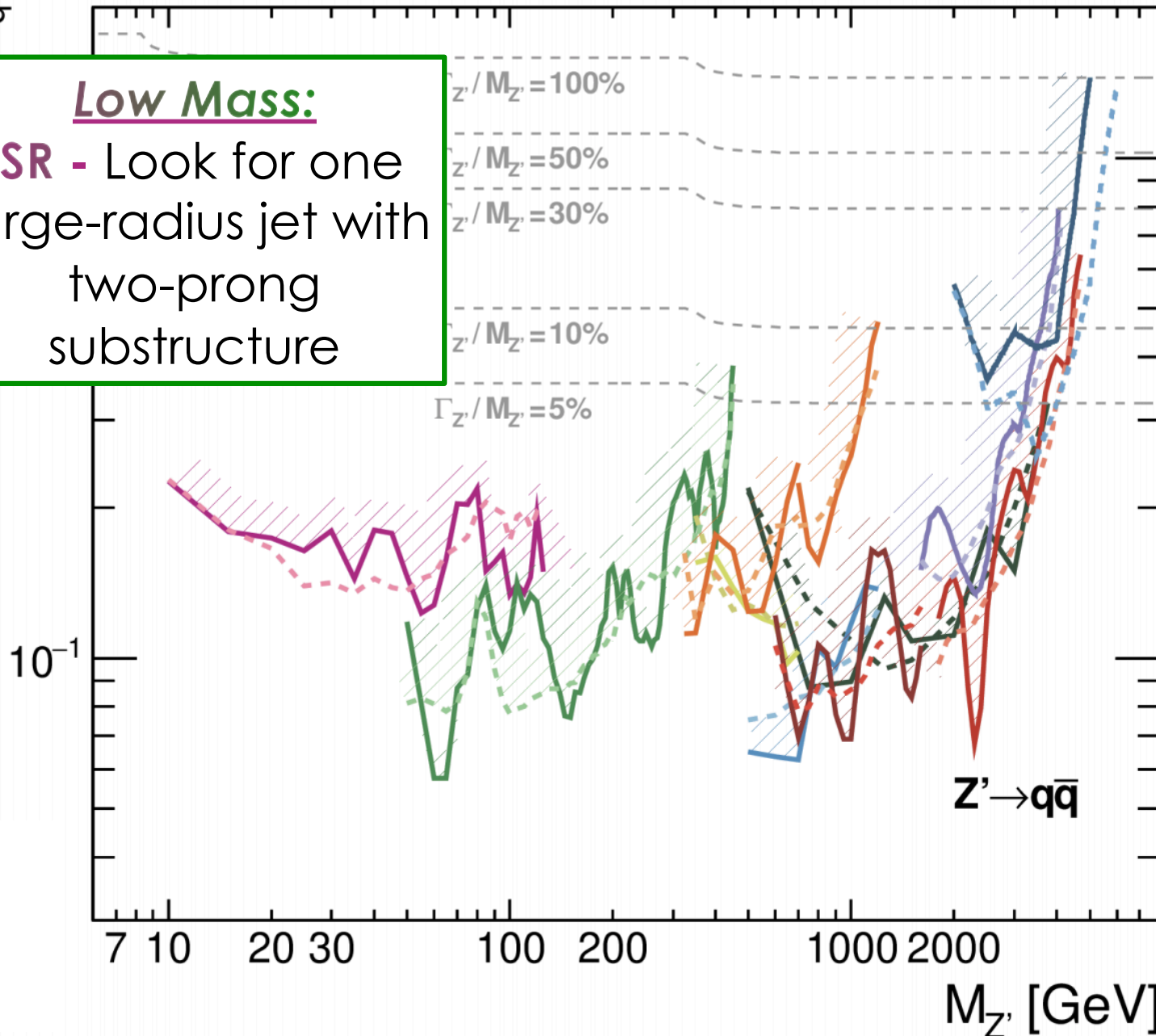
[Reference](#)

DiJet Searches at CMS

CMS Internal

31/10/19

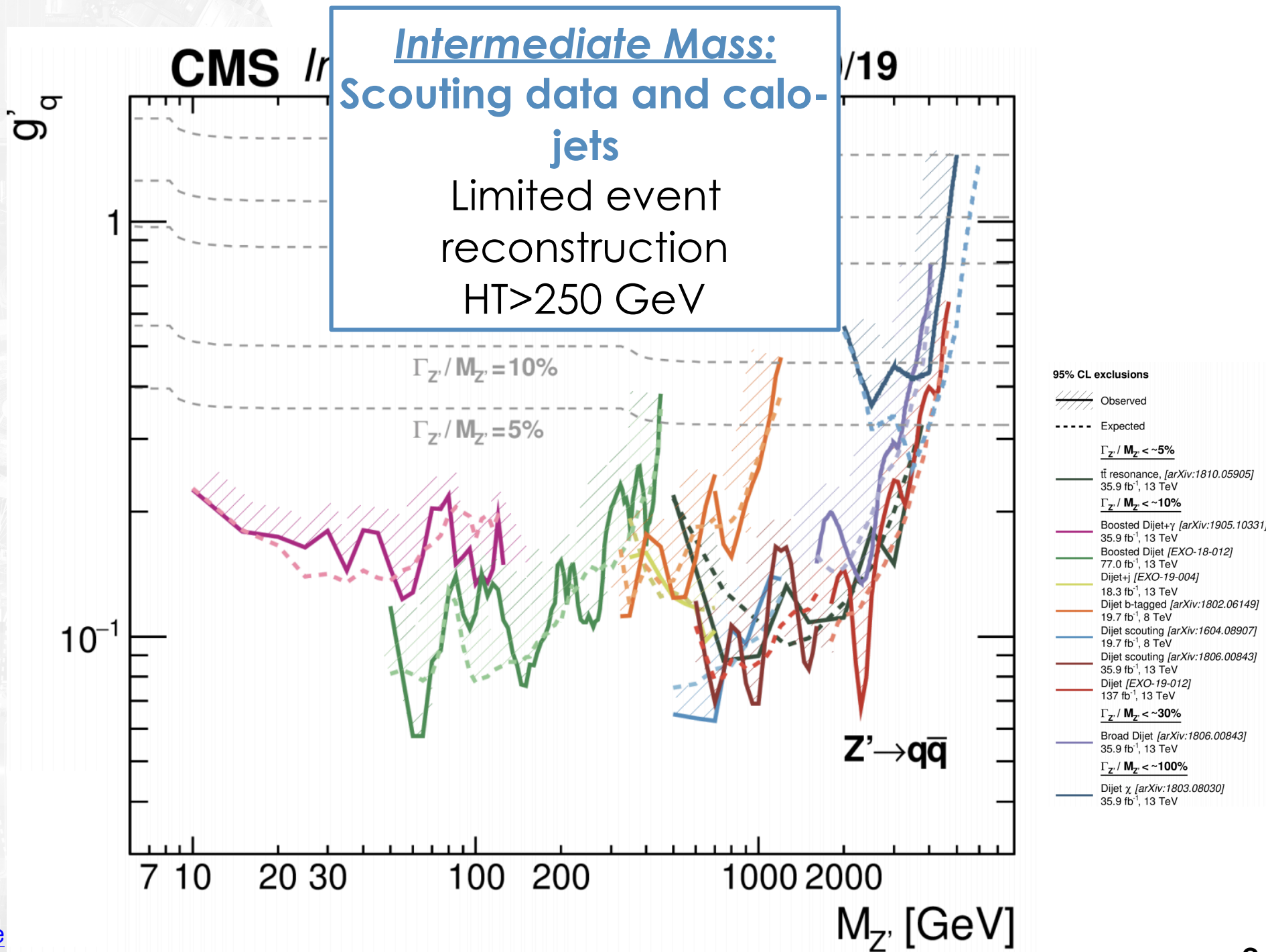
Low Mass:
ISR - Look for one large-radius jet with two-prong substructure



- 95% CL exclusions**
- Observed
 - Expected
 - $\Gamma_{Z'}/M_{Z'} < \sim 5\%$
 - $t\bar{t}$ resonance, [arXiv:1810.05905]
35.9 fb⁻¹, 13 TeV
 - $\Gamma_{Z'}/M_{Z'} < \sim 10\%$
 - Boosted Dijet+ γ [arXiv:1905.10331]
35.9 fb⁻¹, 13 TeV
 - Boosted Dijet [EXO-18-012]
77.0 fb⁻¹, 13 TeV
 - Dijet+j [EXO-19-004]
18.3 fb⁻¹, 13 TeV
 - Dijet b-tagged [arXiv:1802.06149]
19.7 fb⁻¹, 8 TeV
 - Dijet scouting [arXiv:1604.08907]
19.7 fb⁻¹, 8 TeV
 - Dijet scouting [arXiv:1806.00843]
35.9 fb⁻¹, 13 TeV
 - Dijet [EXO-19-012]
137 fb⁻¹, 13 TeV
 - $\Gamma_{Z'}/M_{Z'} < \sim 30\%$
 - Broad Dijet [arXiv:1806.00843]
35.9 fb⁻¹, 13 TeV
 - $\Gamma_{Z'}/M_{Z'} < \sim 100\%$
 - Dijet χ [arXiv:1803.08030]
35.9 fb⁻¹, 13 TeV

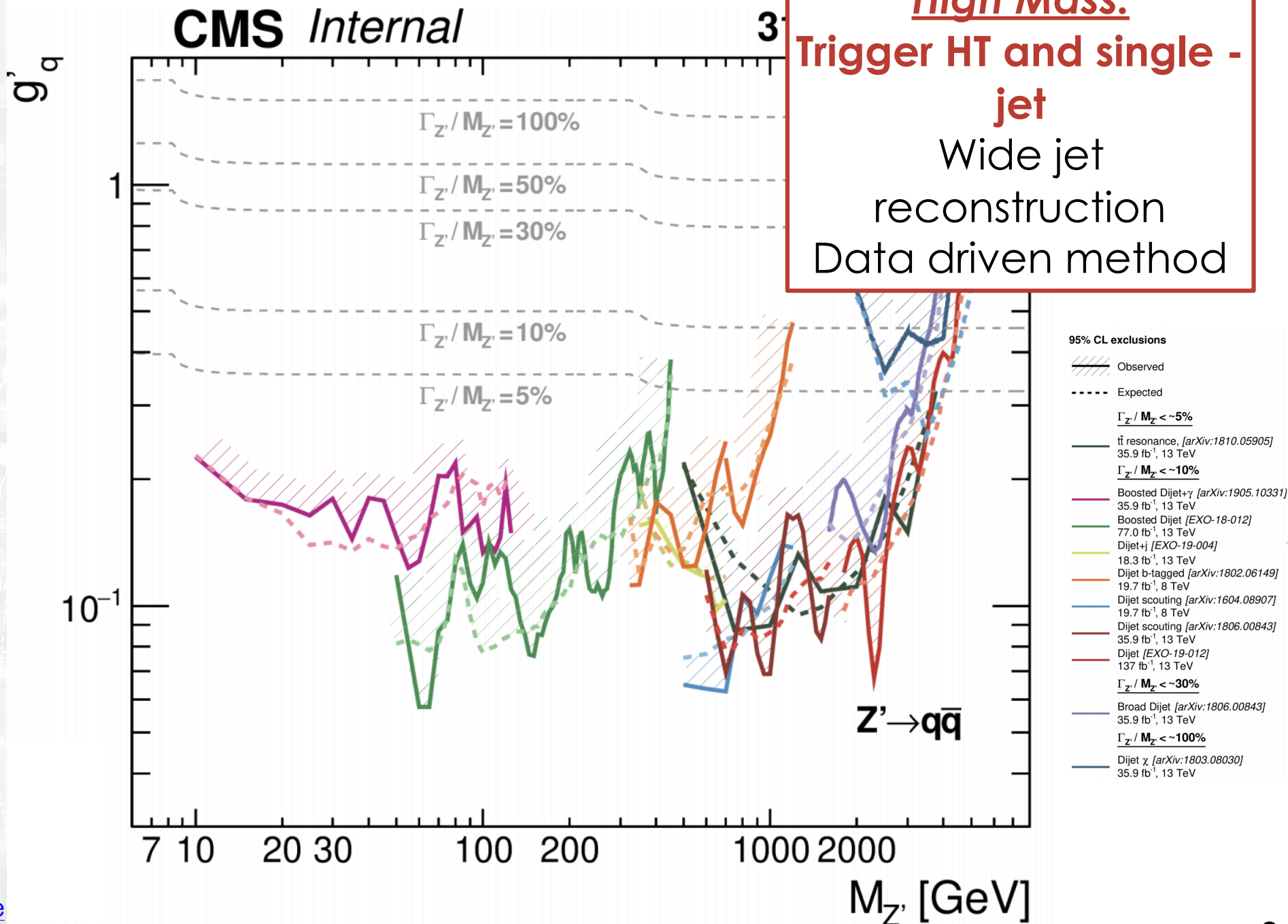
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DiJet Searches at CMS

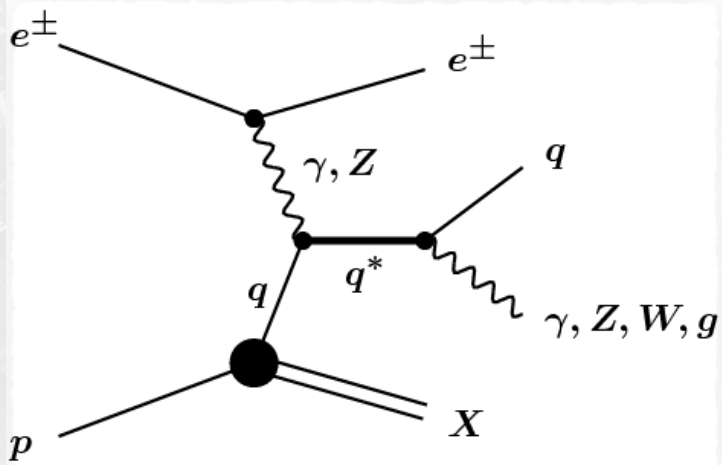


[Reference](#)

DiJet Searches at CMS



Excited Quarks in Hadronic Channels

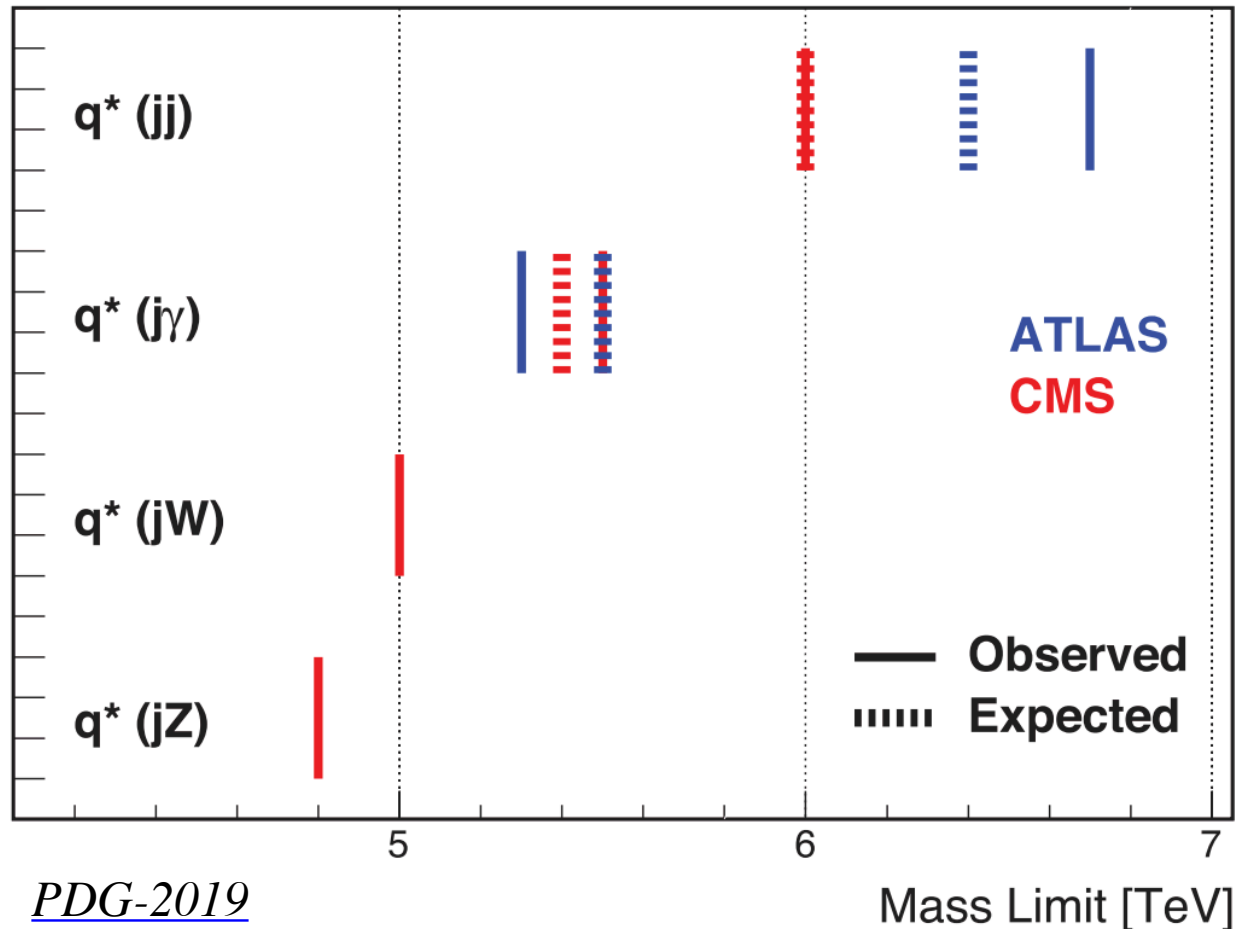


CMS-PAS-EXO-17-026

Phys. Lett. B 781 (2018) 390

PHYSICAL REVIEW D 97, 072006 (2018)

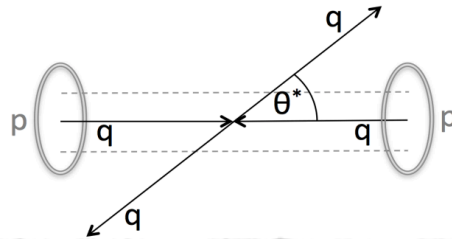
PHYSICAL REVIEW D 97, 072006 (2018)



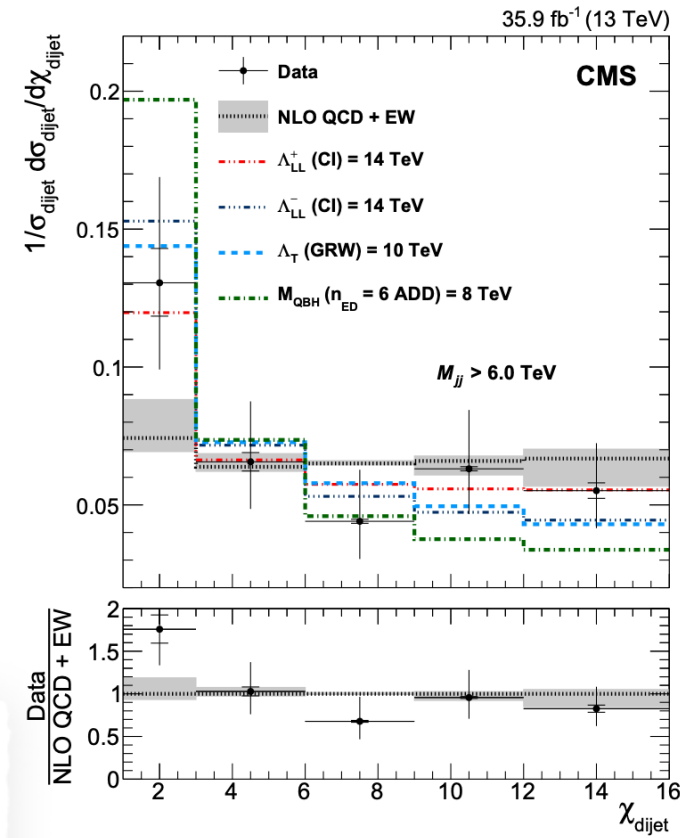
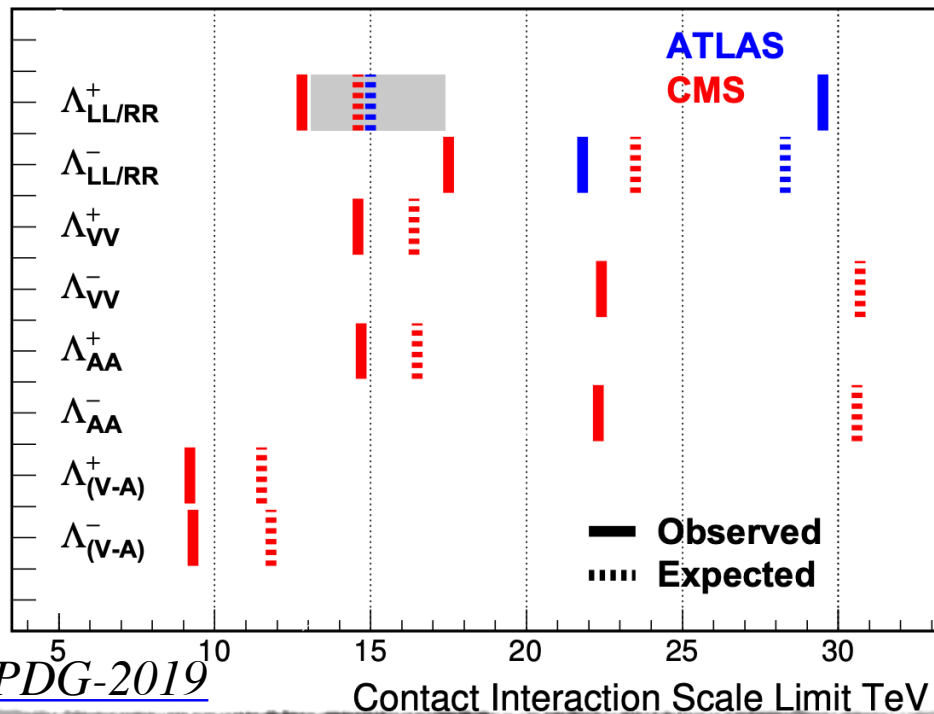
Composite Quarks in Hadronic channel

- **Dijet angular distributions** probe parton parton scattering angle

$$\chi_{\text{dijet}} = e^{|y_1 - y_2|} \sim \frac{1 + |\cos \theta^*|}{1 - |\cos \theta^*|}$$

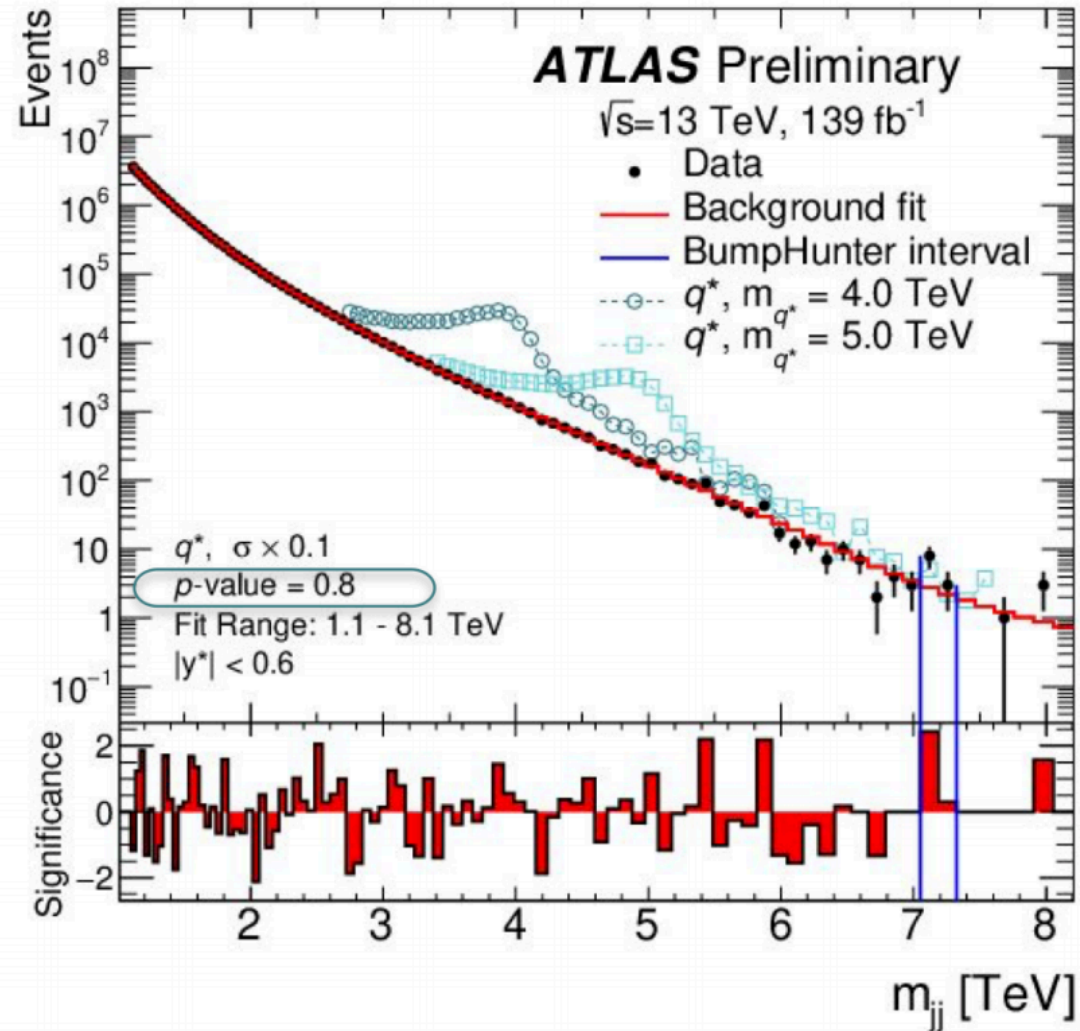
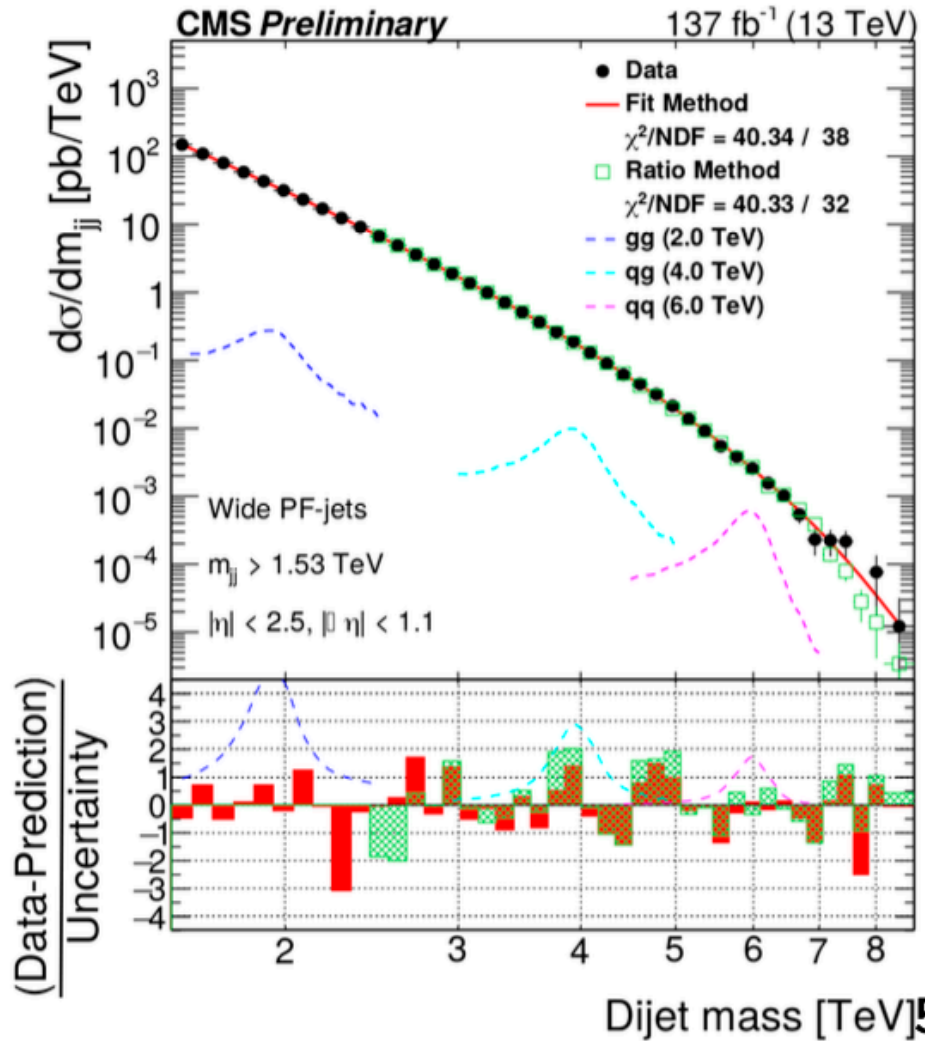


- New Physics will change the χ_{dijet} distribution at low χ_{dijet} at high M_{jj}



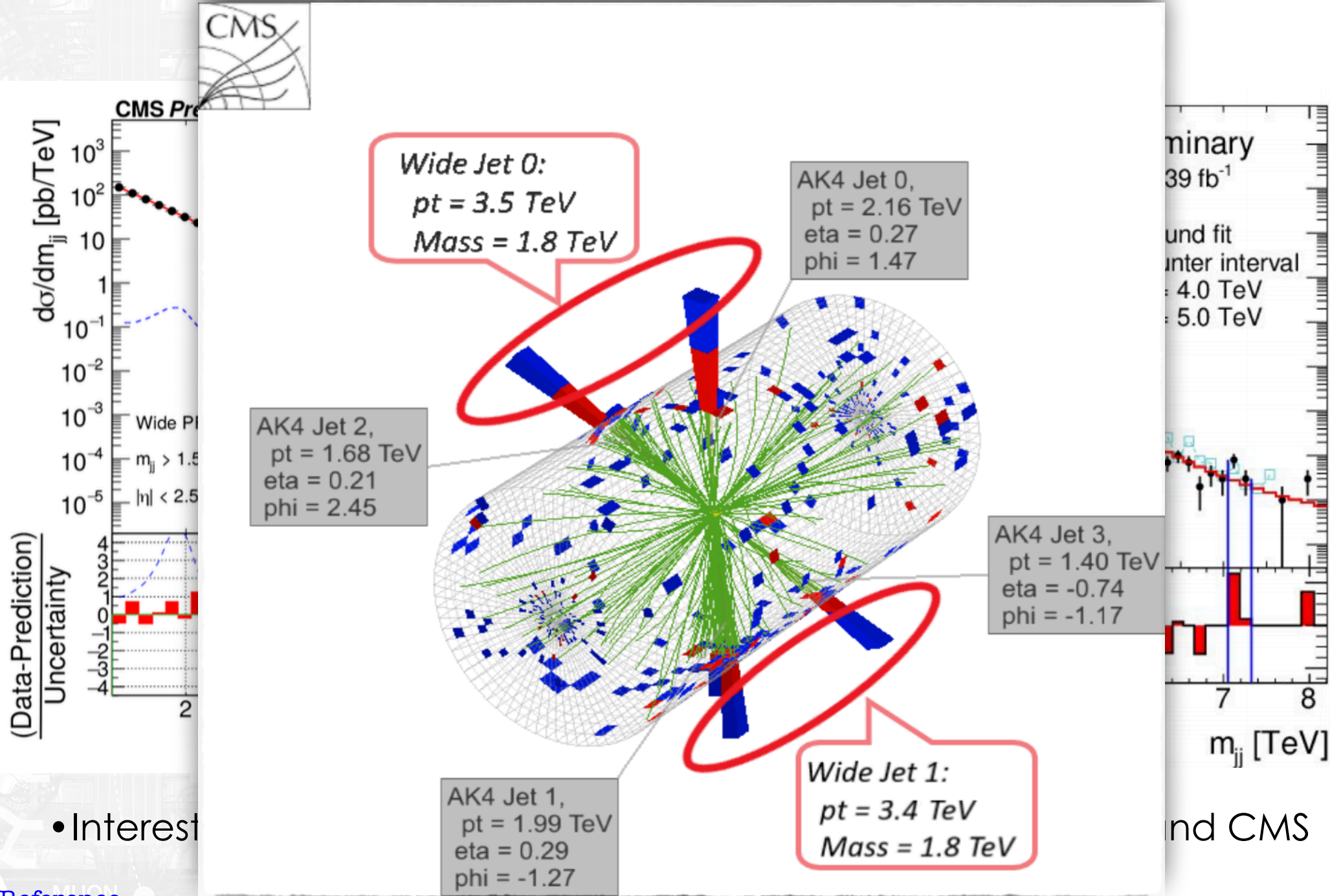
Eur. Phys. J. C 78 (2018) 789

DiJet Searches at LHC



- Interesting clustering of **events at 8 TeV** seen by both ATLAS and CMS

DiJet Searches at LHC

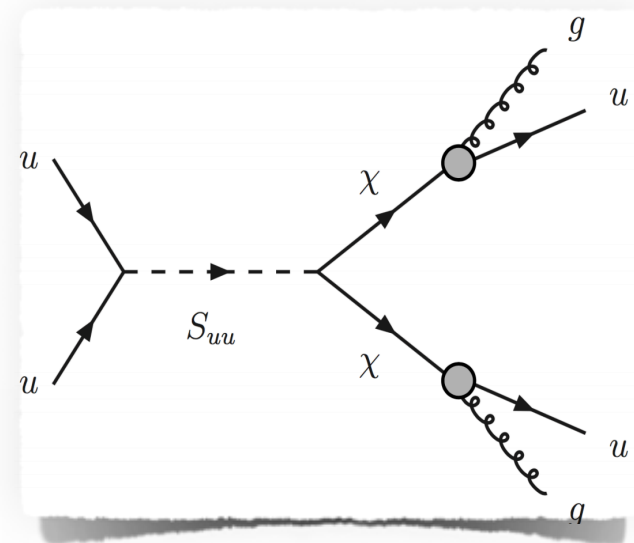


• Interest

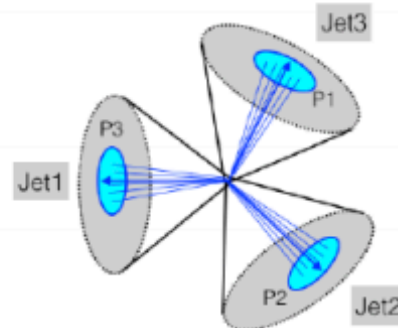
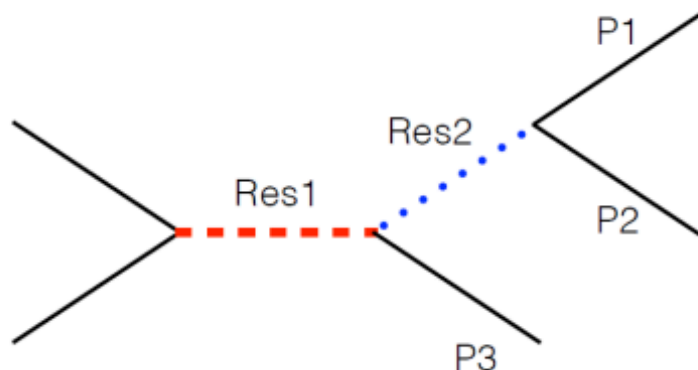
[Reference](#)

Dijet novelties towards Run 3

- **B-tagged analysis** @ Summer20
- Dijet **Angular analysis** @Fall 2020
- **Paired dijet search** w/ multiple signals @Winter20



- **Tri-Jet final states:** BSM Theories w/ extradimensions: [arXiv:1612.00047](https://arxiv.org/abs/1612.00047)



Excited Leptons - Phenomenology

- Motivated by compositeness models (ref [\[1\]](#) [\[2\]](#) [\[3\]](#) [\[4\]](#))
 - Quarks and leptons might consist of sub-particles bounded by a new gauge interaction of scale Λ
 - Their excited states, excited fermions, could be produced via 4-fermion contact interaction

Contact Interaction (CI)

$$\mathcal{L}_{\text{CI}} = \frac{g_*^2}{2\Lambda^2} \frac{1}{2} j^\mu j_\mu$$

Gauge Interaction (GI)

$$\mathcal{L}_{\text{GI}} = \frac{1}{2\Lambda} \bar{f}_R^* \sigma^{\mu\nu} \left(gf \frac{\boldsymbol{\tau}}{2} \cdot \mathbf{W}_\mu + g' f' \frac{Y}{2} B_{\mu\nu} \right) f_L + \text{h.c.},$$

- ▶ 4 important parameters:
 - ▶ Mass
 - ▶ Λ - Compositeness scale
 - ▶ f, f' - Couplings rescaling Λ

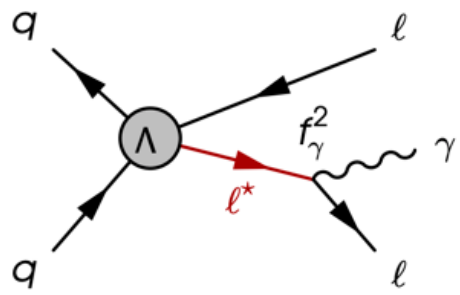
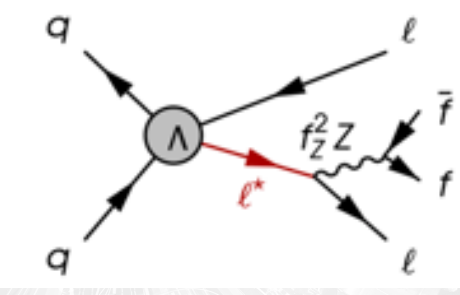
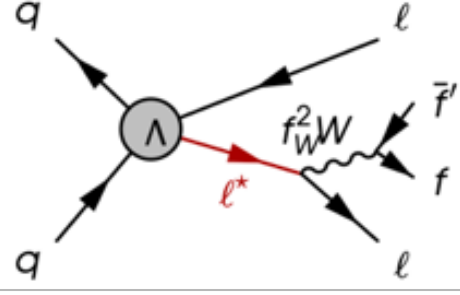
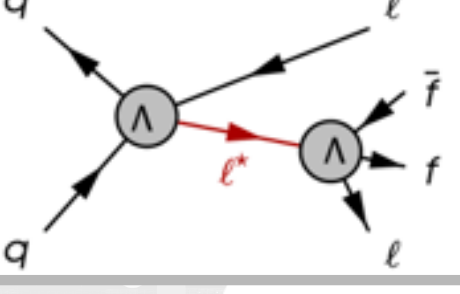
[1] J. C. Pati, A. Salam, and J. A. Strathdee, "Are quarks composite?", Phys. Lett. B 59 (1975) 265

[2] H. Terazawa, M. Yasue, K. Akama, and M. Hayshi, "Observable effects of the possible substructure of leptons and quarks", Phys. Lett. B 112 (1982) 387

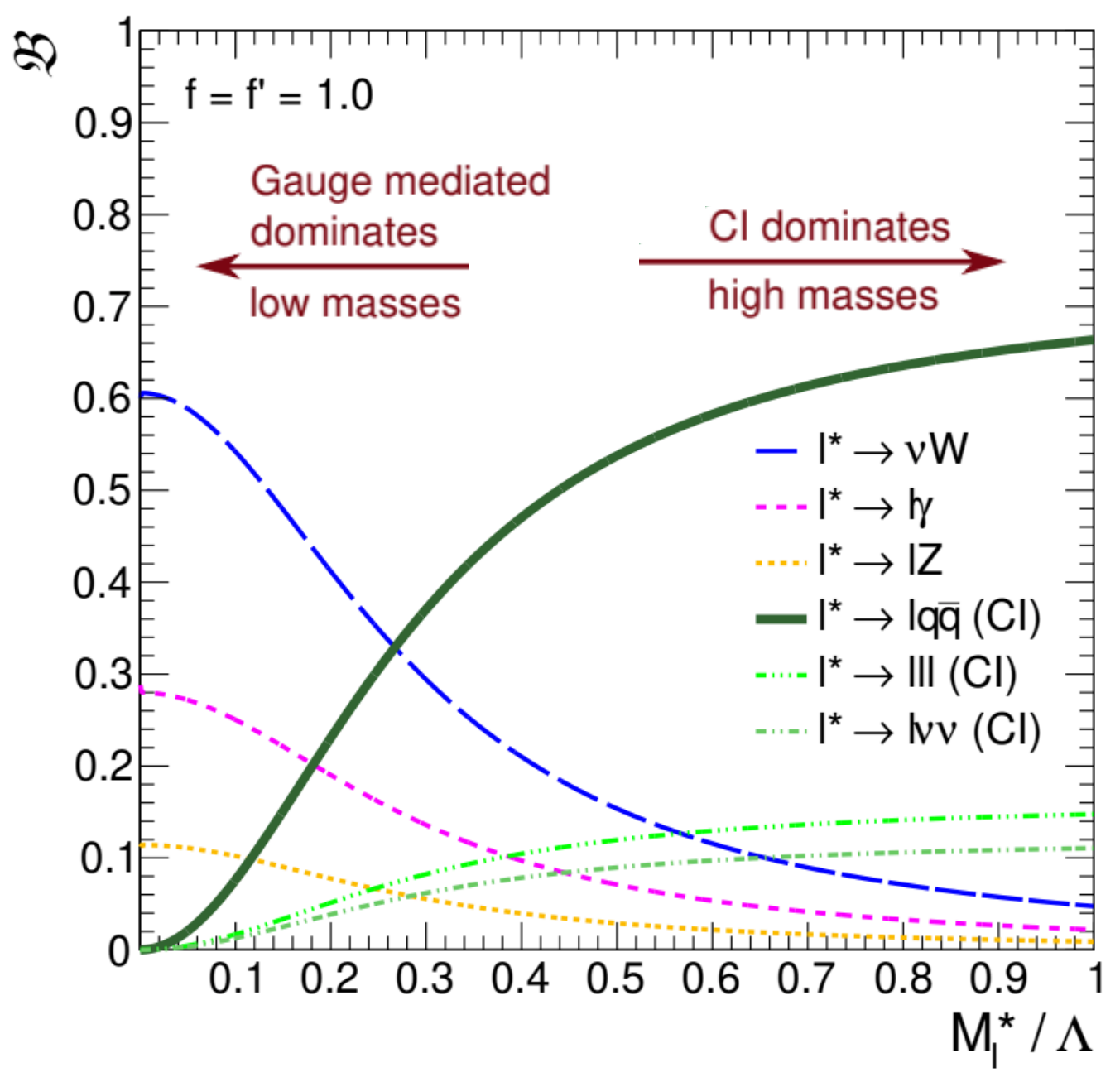
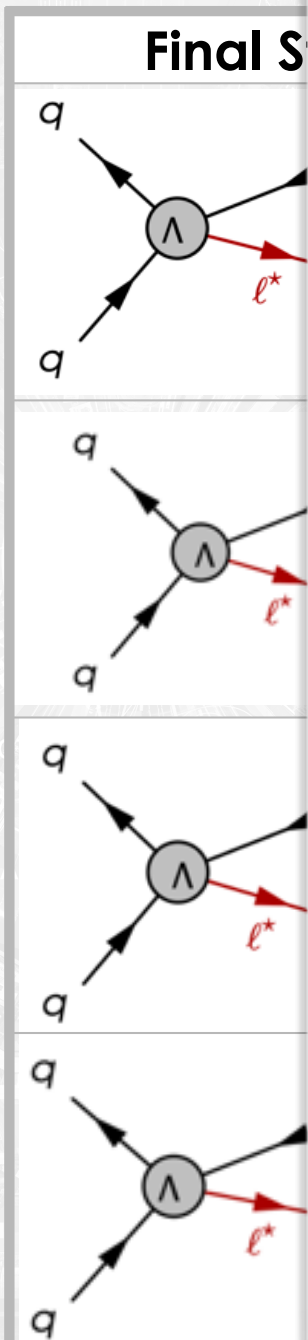
[3] E. Eichten, K. D. Lane, and M. E. Peskin, "New Tests for Quark and Lepton Substructure", Phys. Rev. Lett. 50 (1983) 811

[4] U. Baur, M. Spira, and P. M. Zerwas, "Excited quark and lepton production at hadron colliders", Phys. Rev. D 42 (1990) 815

Excited Leptons - Overview

Final State	Pros	Cons	Status at CMS
 <p>A Feynman diagram showing two incoming quarks (q) merging at a vertex (Λ) to produce two outgoing leptons (l) and a photon (γ). A red arrow labeled l^* represents the excited lepton propagator. The coupling to the photon is labeled f_γ^2.</p>	Very Clean	Forbidden for $f=-f'$	2016 public 2017/18 ongoing <u>1811.03052</u>
 <p>A Feynman diagram showing two incoming quarks (q) merging at a vertex (Λ) to produce two outgoing leptons (l) and a fermion-antifermion pair ($f \bar{f}$). A red arrow labeled l^* represents the excited lepton propagator. The coupling to a Z boson is labeled f_Z^2.</p>	Sensitive to $f=-f'$	Low eff and worse resolution	Ongoing
 <p>A Feynman diagram showing two incoming quarks (q) merging at a vertex (Λ) to produce two outgoing leptons (l) and a fermion-antifermion pair ($f \bar{f}'$). A red arrow labeled l^* represents the excited lepton propagator. The coupling to a W boson is labeled f_{WW}^2.</p>	Highest BR for GI	Large background	Ongoing
 <p>A Feynman diagram showing two incoming quarks (q) merging at a vertex (Λ) to produce two outgoing leptons (l) and a fermion-antifermion pair ($f \bar{f}$). A red arrow labeled l^* represents the excited lepton propagator between two vertices (Λ).</p>	Sensitive at high mass - NOT PERFORMED AT RUN 1	None	2016/17 public 2018 ongoing <u>2001.04521</u>

Excited Leptons - Overview



at CMS

public
ongoing

[v.org/abs/1811.03052](https://arxiv.org/abs/1811.03052)

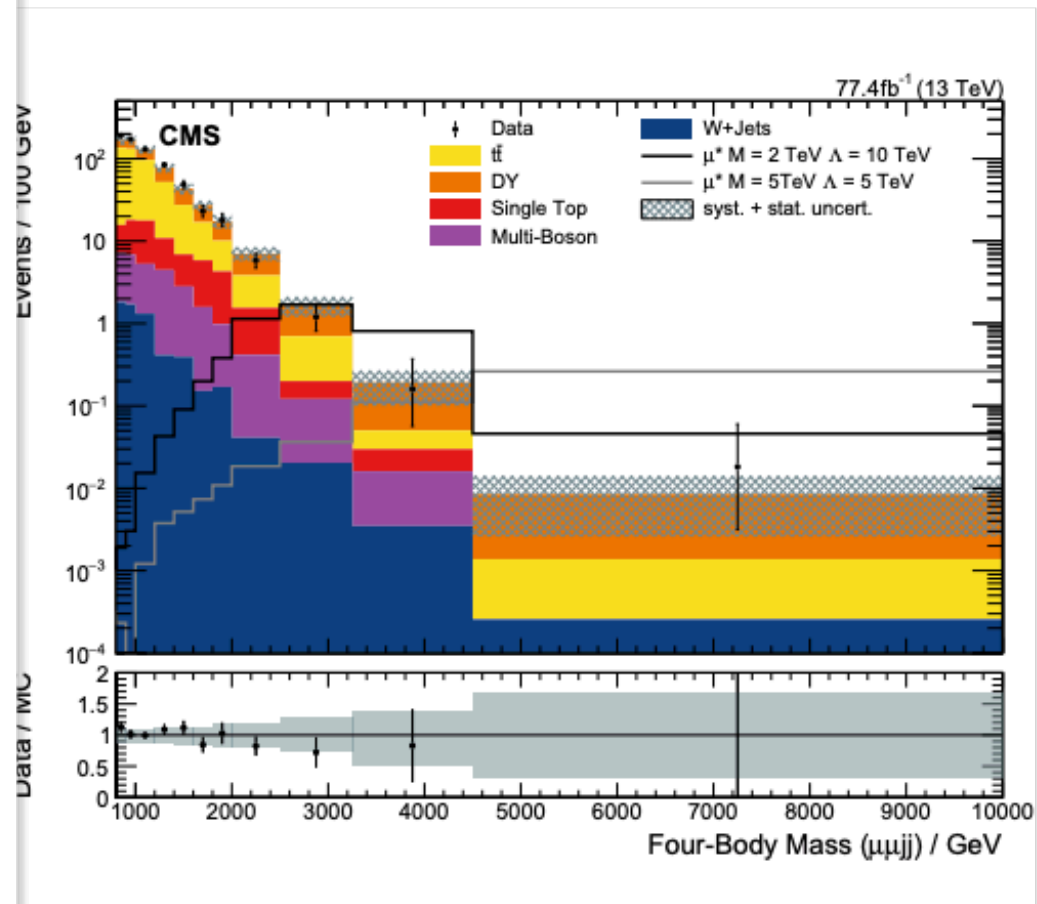
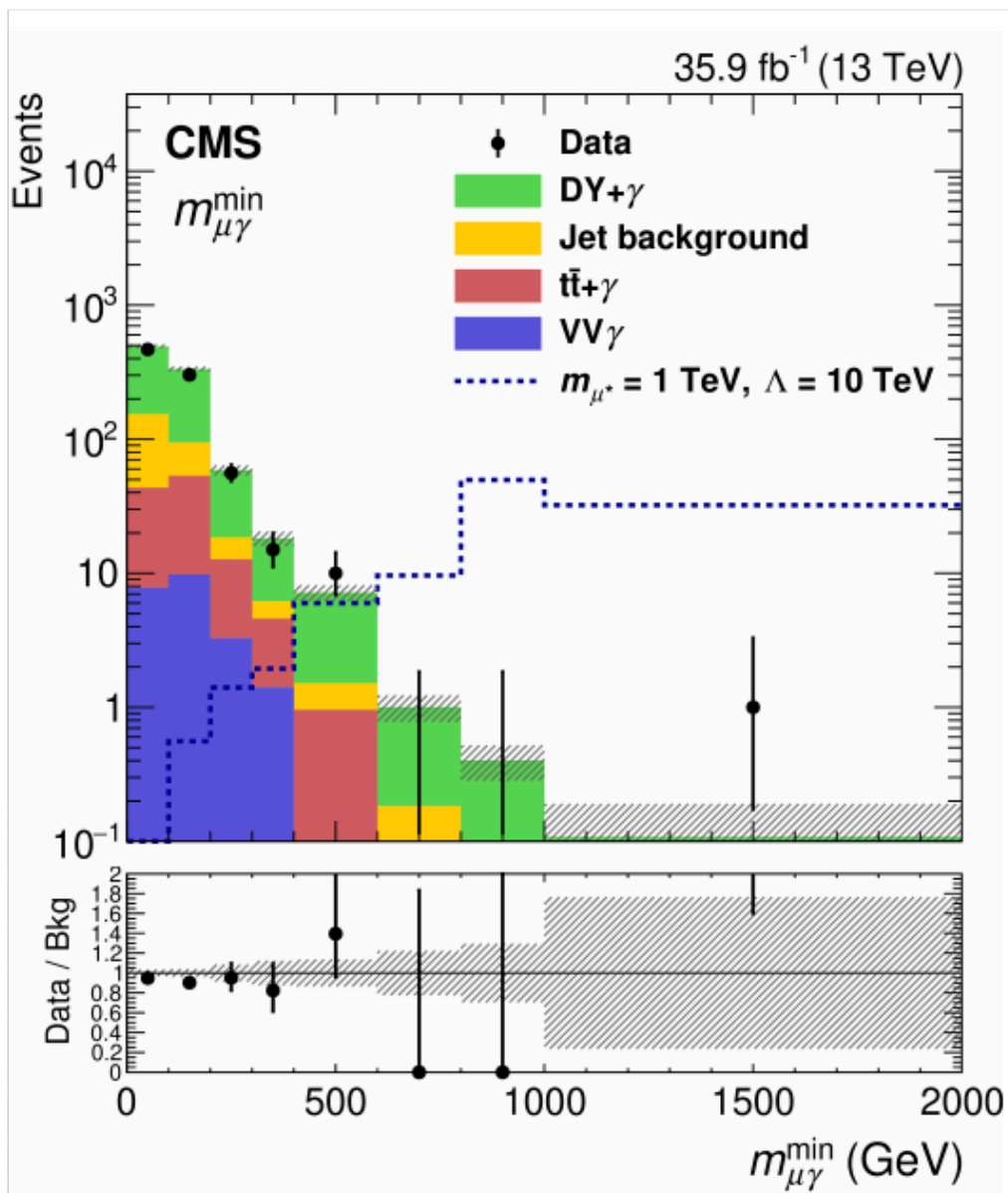
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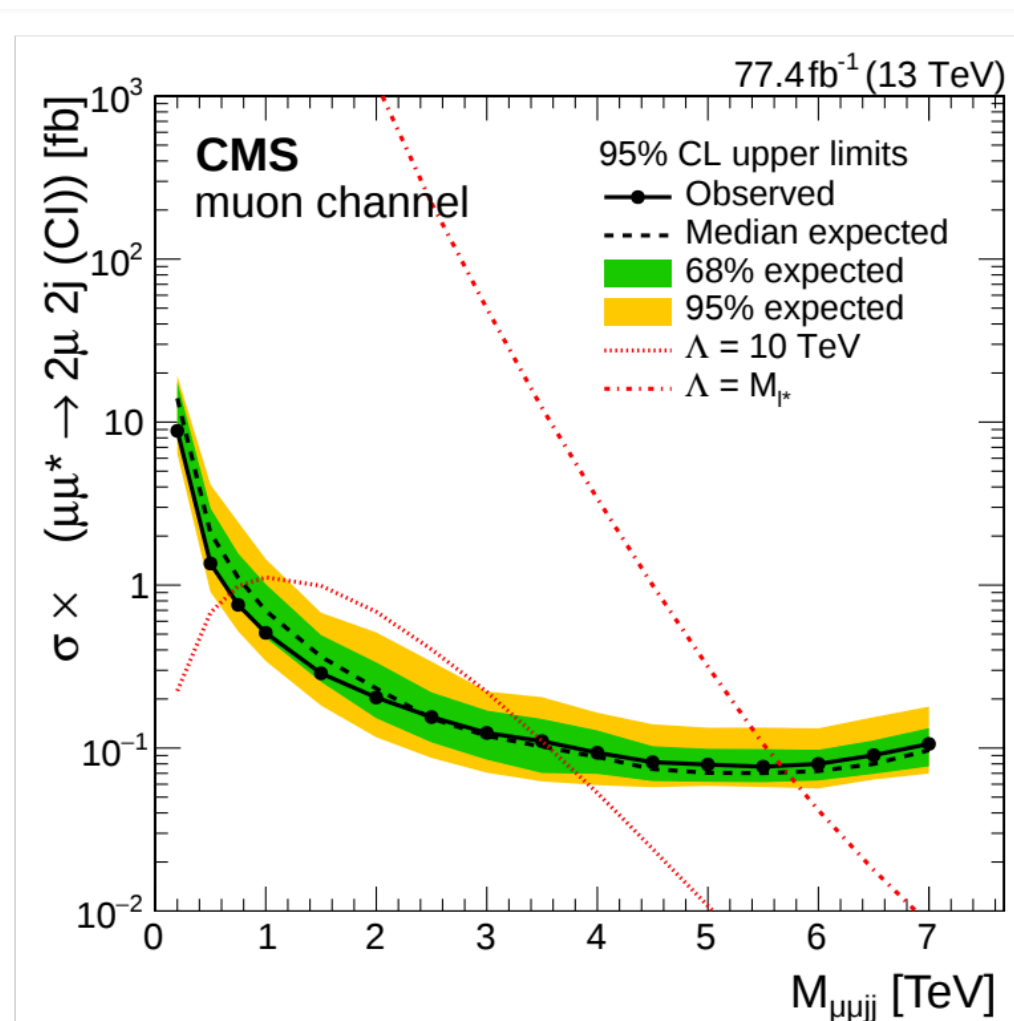
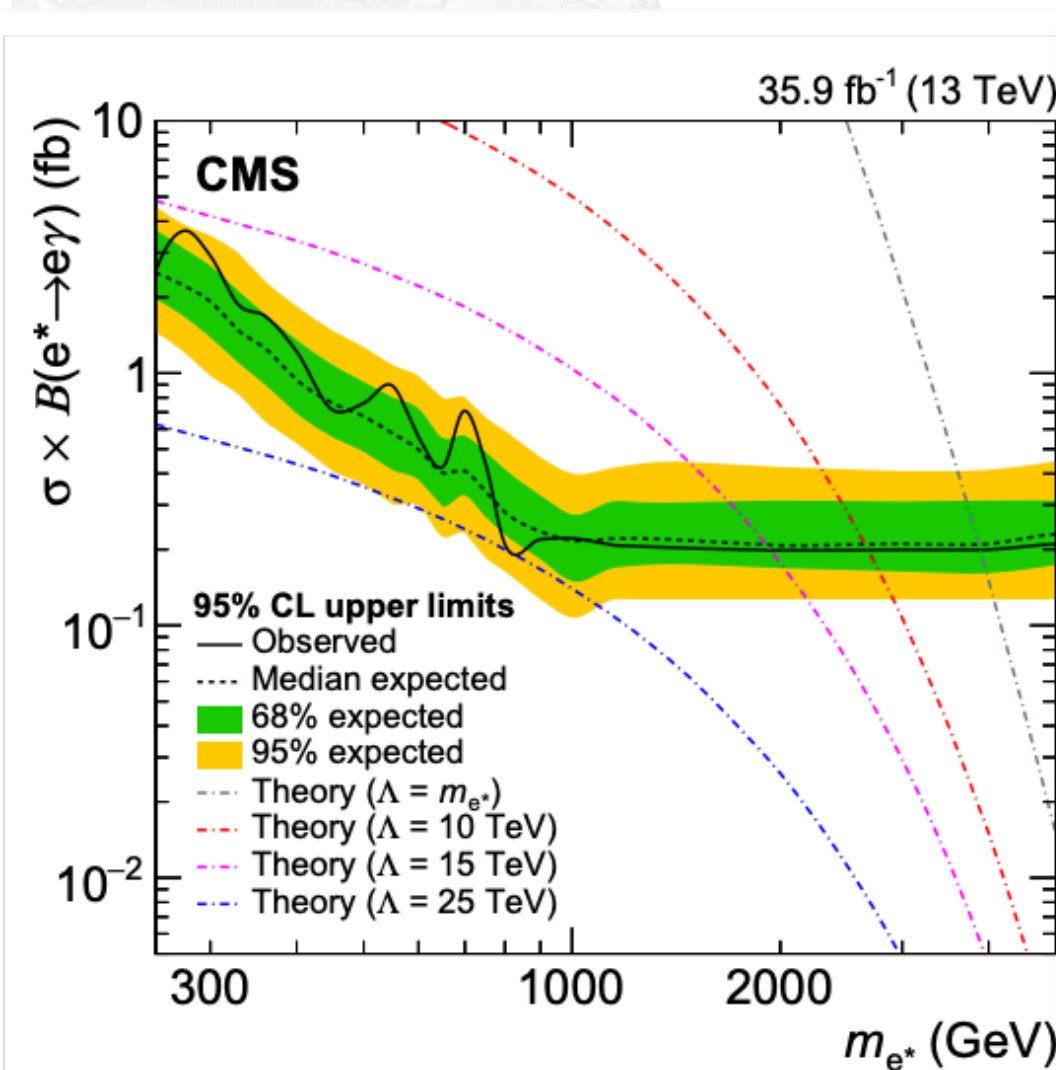
7 public
going

3

Excited Leptons - Public Results @ 13 TeV



Excited Leptons - Public Results @ 13 TeV



Excited Leptons - Run 2/3 plans

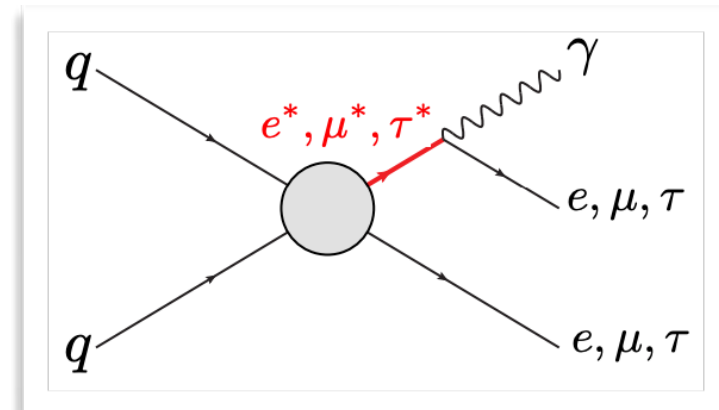
- **Run 2 Legacy:** publish full results w/ different values of couplings in interpretations

- **Run 3 planning**

- @14 TeV: expect factor 2 more cross section
- Investigate W channel
- Go to lower masses

- Include **tau channel:**

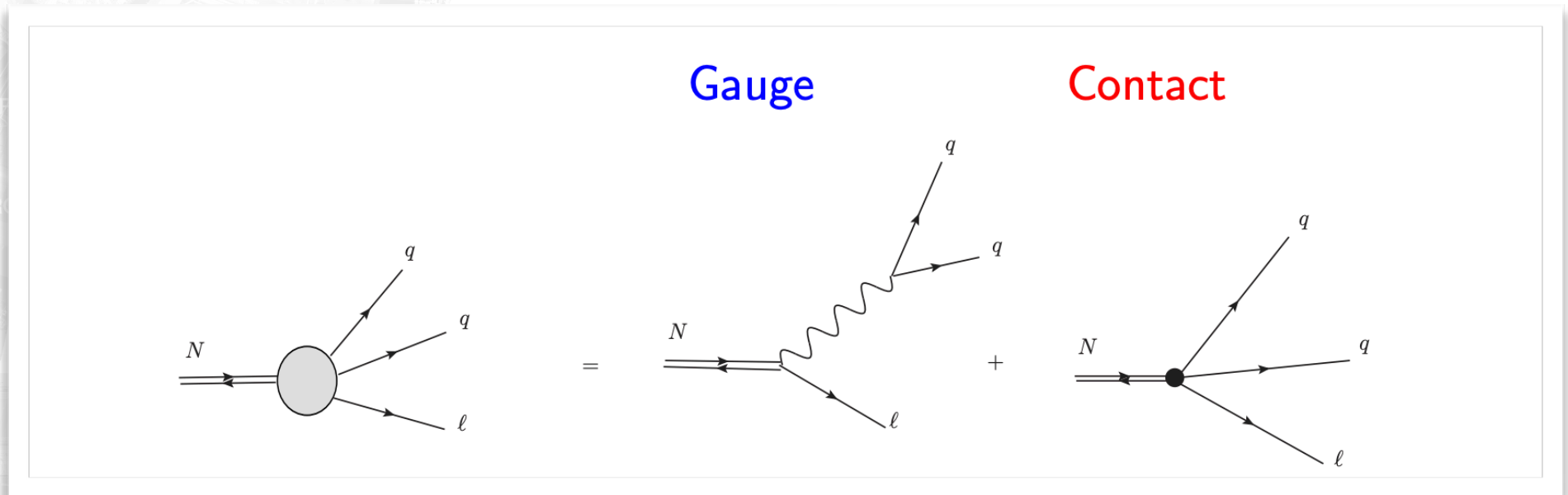
- No CMS analyses to-date have looked for an excited τ
- Include $\tau e + \tau h$, $\tau \mu + \tau h$, $\tau h + \tau h$ final states.
- Reconstruct the $\tau + \gamma$ mass resonance



target summer 2020

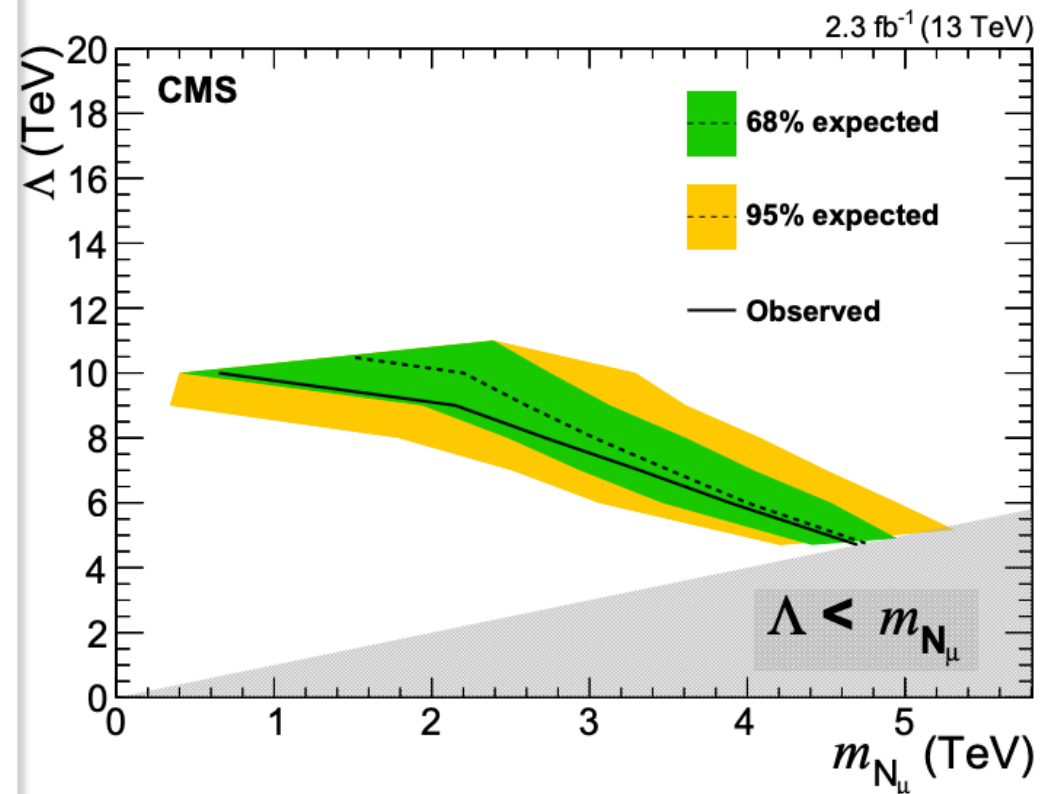
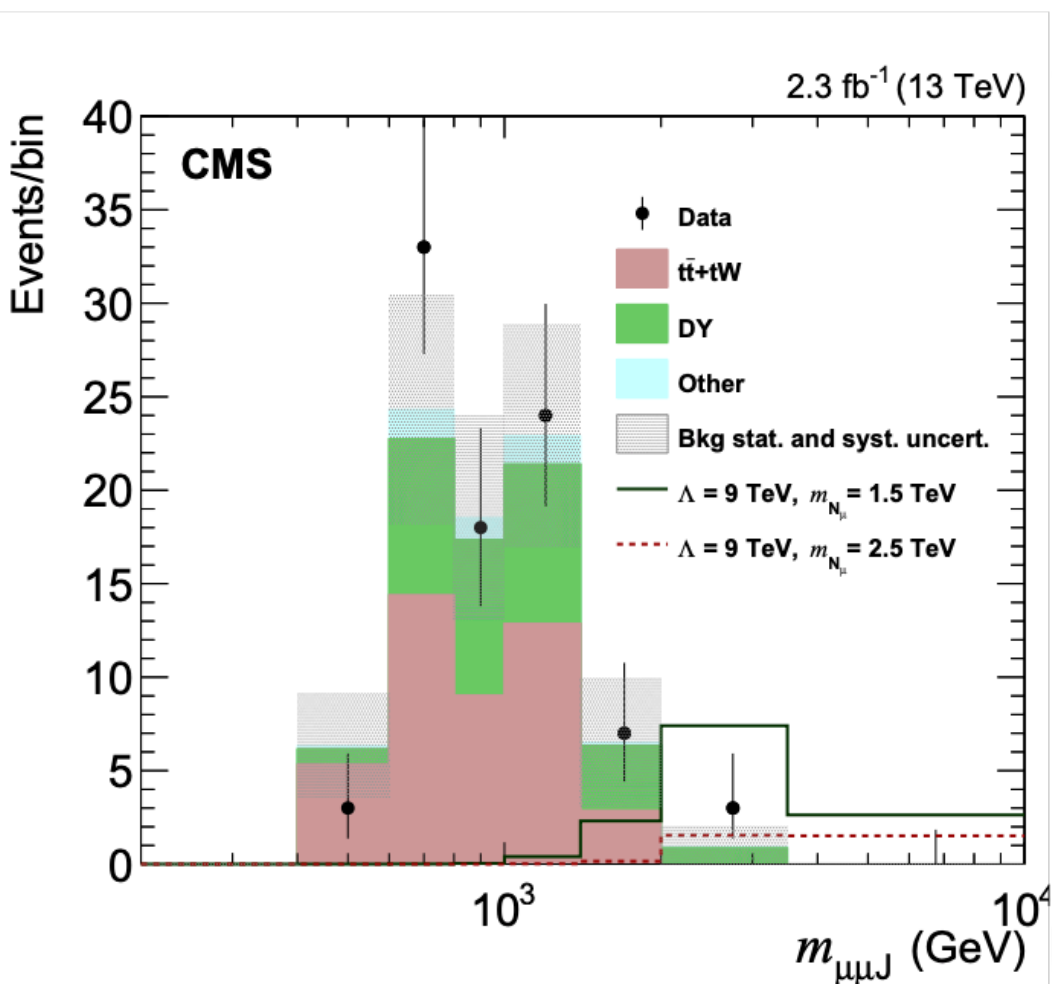
Heavy Composite Neutrinos

- Take in to account the HN **eejj Run1 excess** via the production of a heavy composite (excited) neutrino.
- Both production and decay can happen via **Gauge** or **Contact** interaction
 - **CI dominates in production**
 - Decay: one fat jet (GI) vs **CI two well separated jets (CI)**



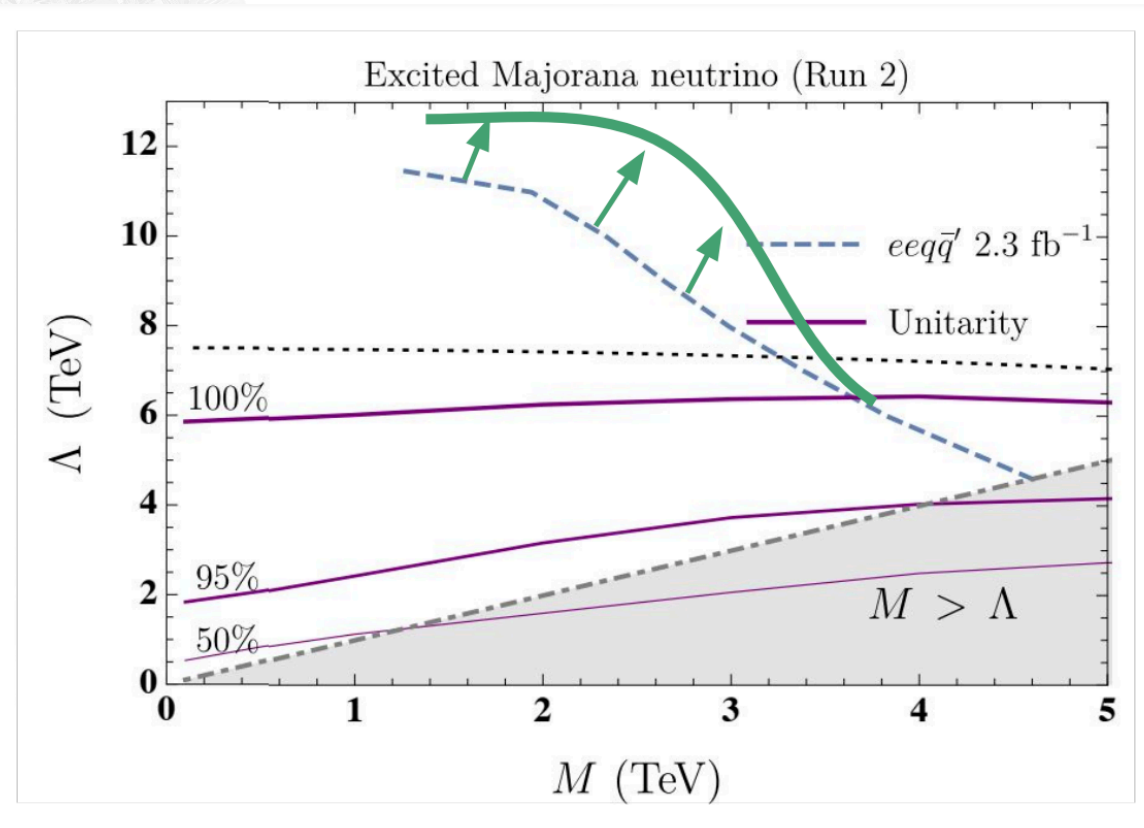
Heavy Composite Neutrinos - Public Results @13 TeV

- Take in to account the HN **eejj Run1 excess** via the production of a heavy composite (excited) neutrino.
- Both production and decay can happen via **Gauge** or **Contact** interaction



Heavy Composite Neutrinos - Novelties

- Present goal: analysis **re-optimization and extension** to the full Run 2
- Recent pheno paper on unitary bounds of EFT composite models: [1903.12285](https://arxiv.org/abs/1903.12285)

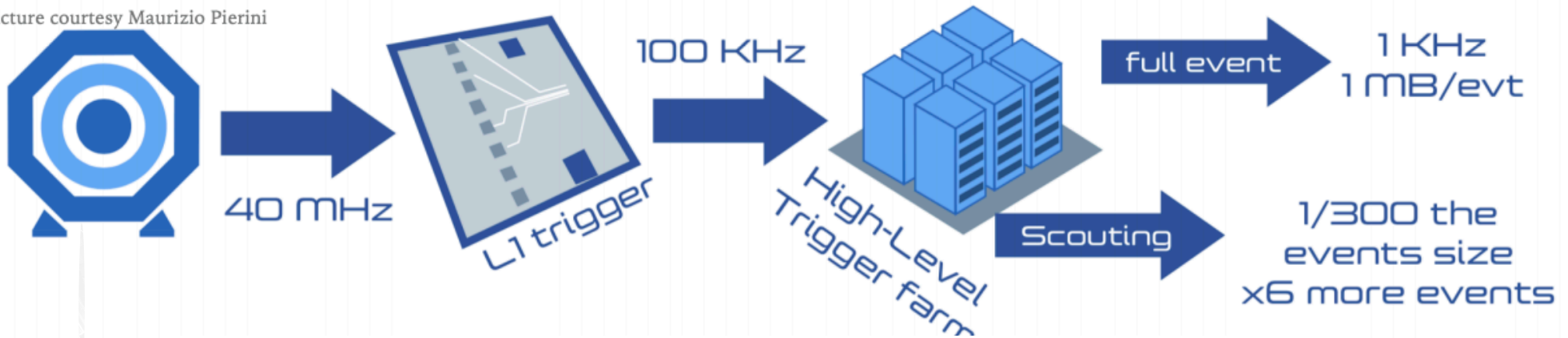


- **Shape of parameter space defined by Unitarity** bound motivates re-optimization of signal region

target 2020

Exploring the low mass regions

Picture courtesy Maurizio Pierini



$$\text{Trigger Bandwidth} = \text{Event Rate} \times \text{Event Size}$$

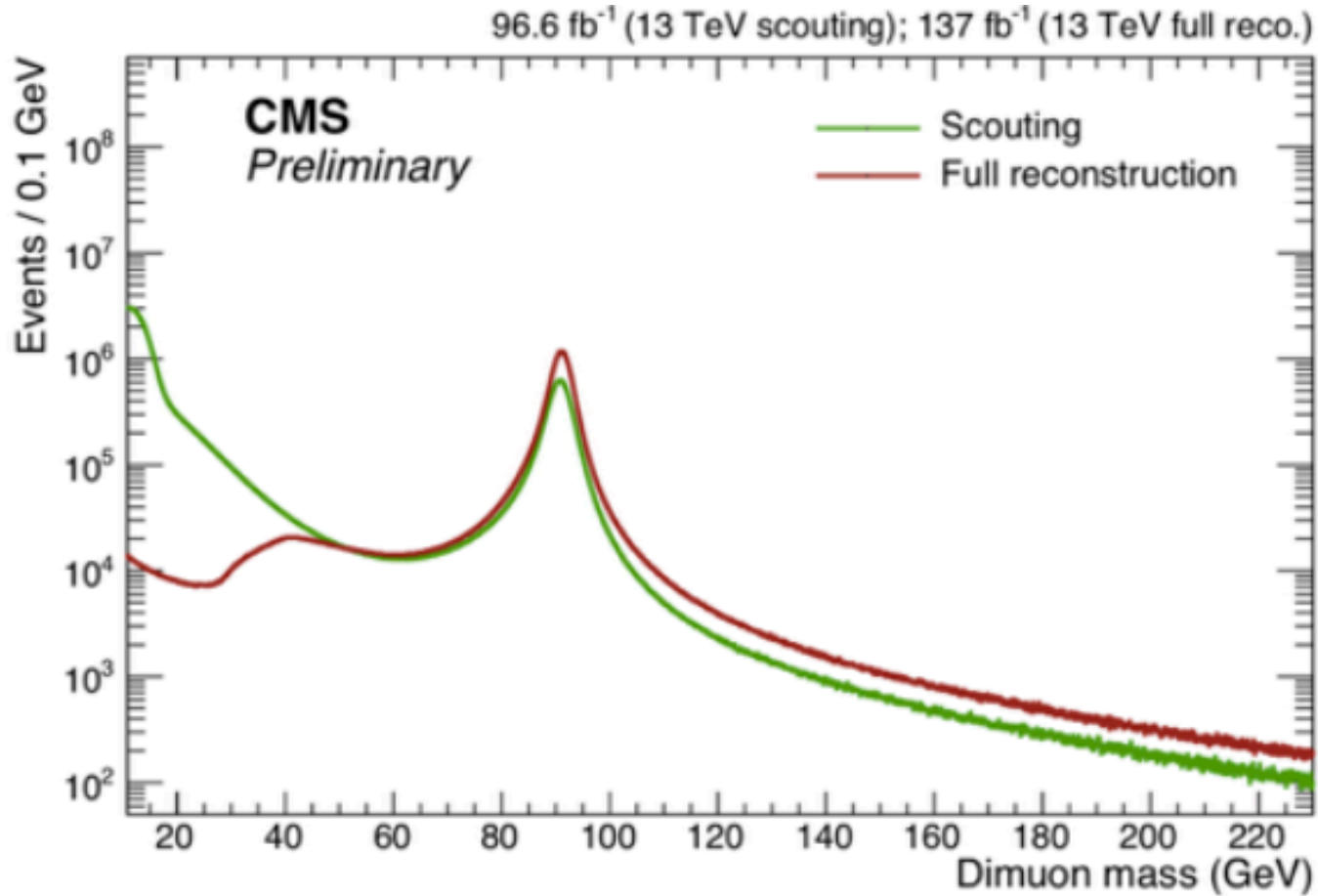
~1 kHz × **~1 MB**

If we want to **increase** rate We need to **decrease** event size

- **Hadronic Scouting** (since 2011) objects are HLT objects w/o offline reconstruction and calibration-> worse resolution
- Going beyond hadronic scouting: **Di-muon scouting** trigger (since 2015)

Exploring the low mass regions

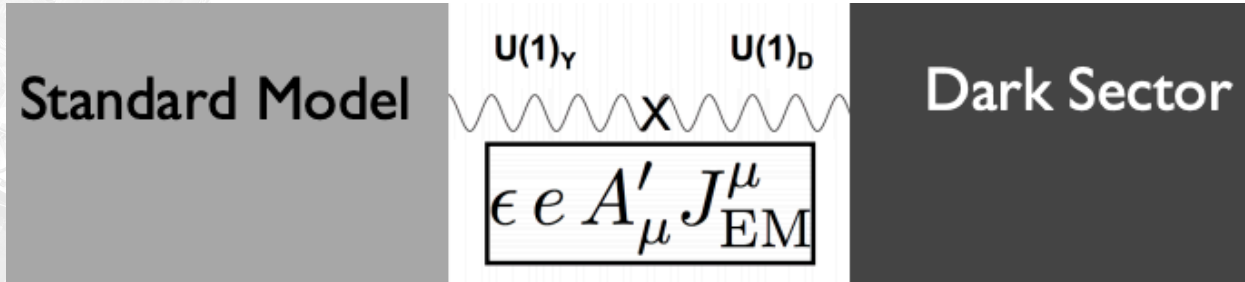
Picture courtesy Maurizio Pierini



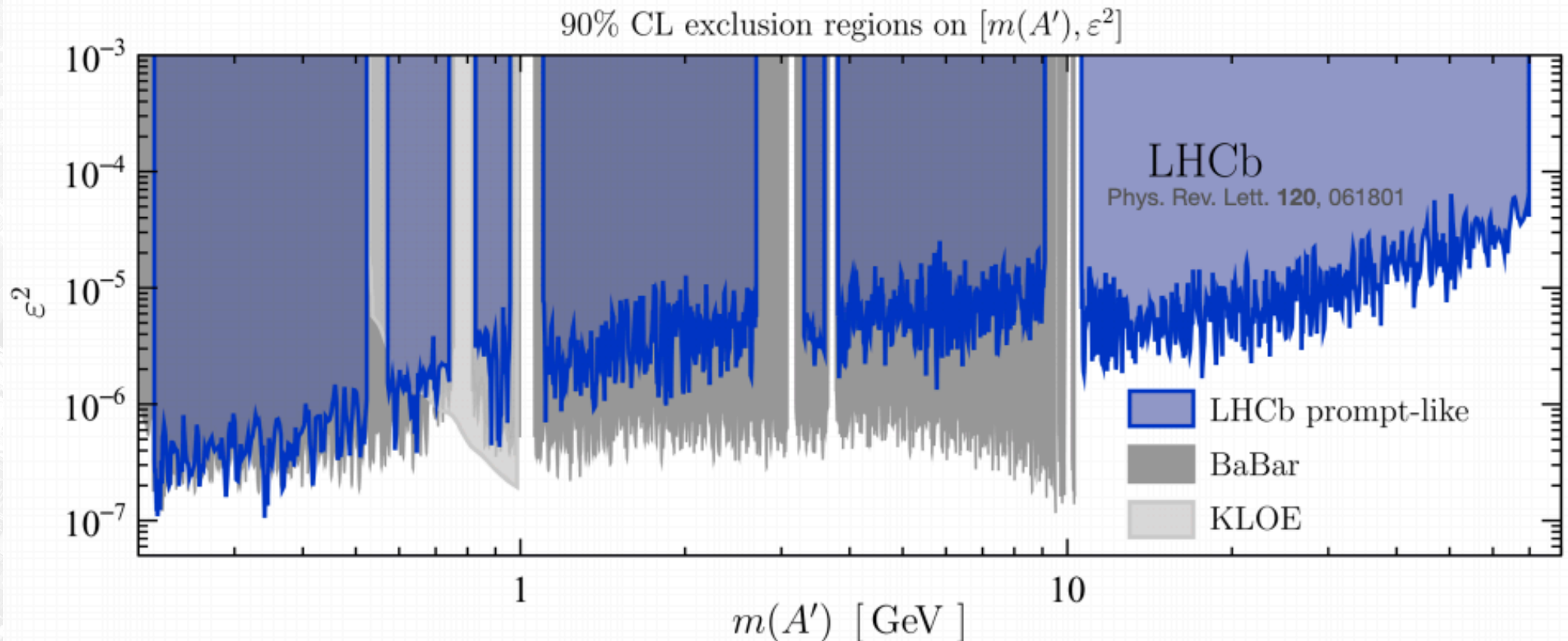
- **Hadronic** offline

- Going beyond hadronic scouting: **Di-muon scouting** trigger (since 2015)

Low mass Dielectron Resonances



- If $\epsilon < 10^{-5}$ A' **can be longlived**

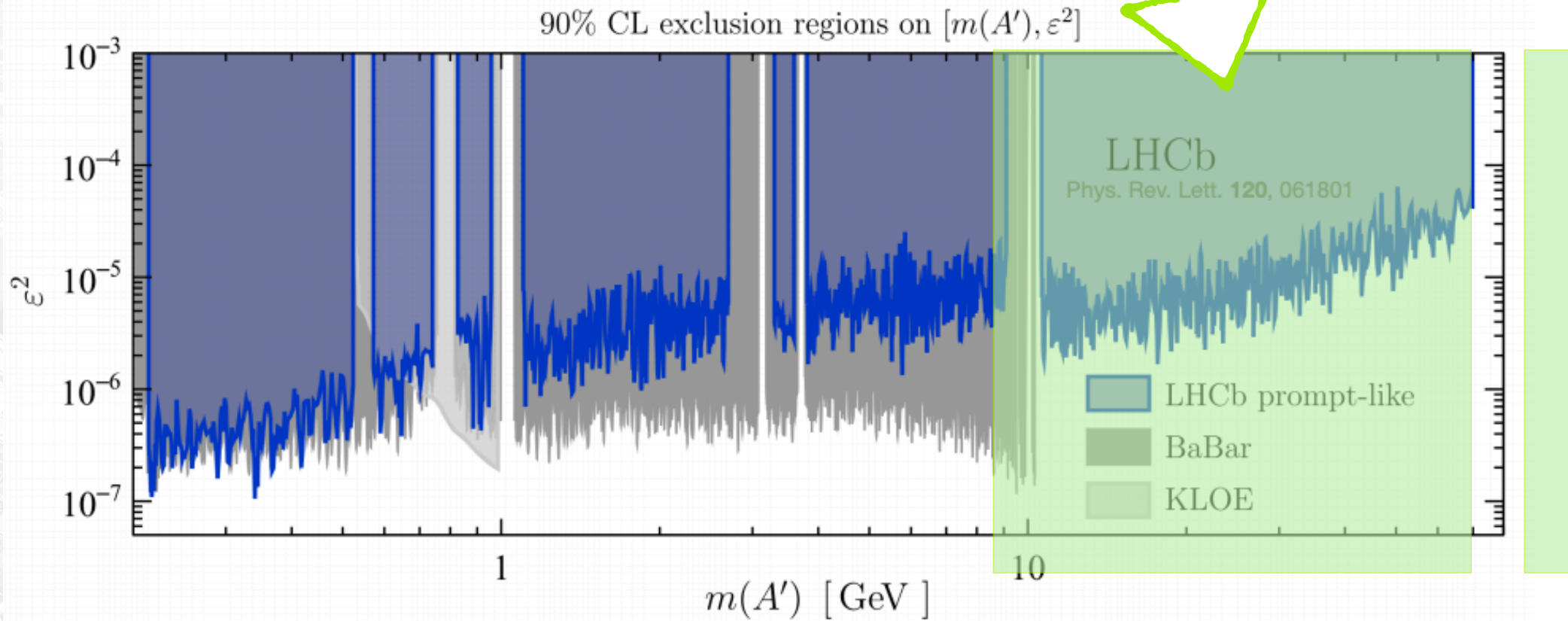


Low mass Dielectron Resonances

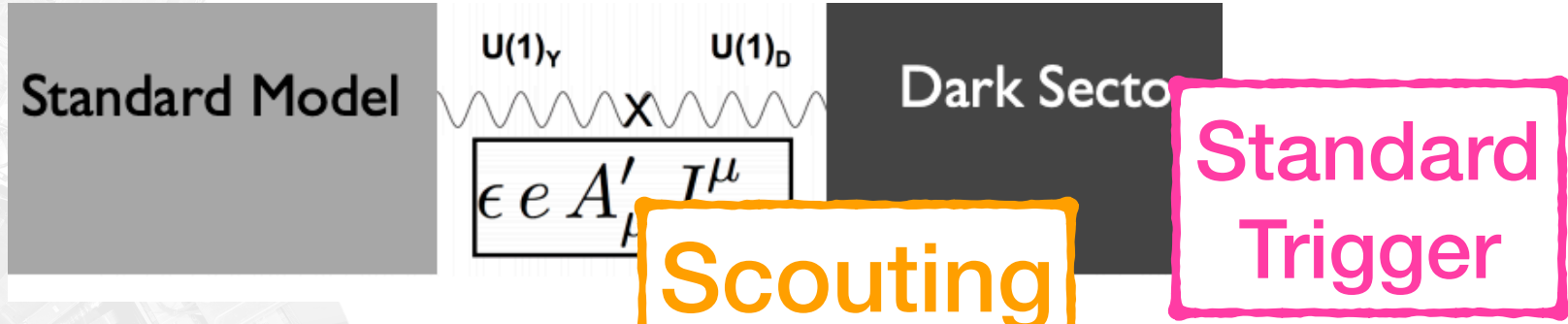


**CMS is searching in this region.
Might go even lower in mass.**

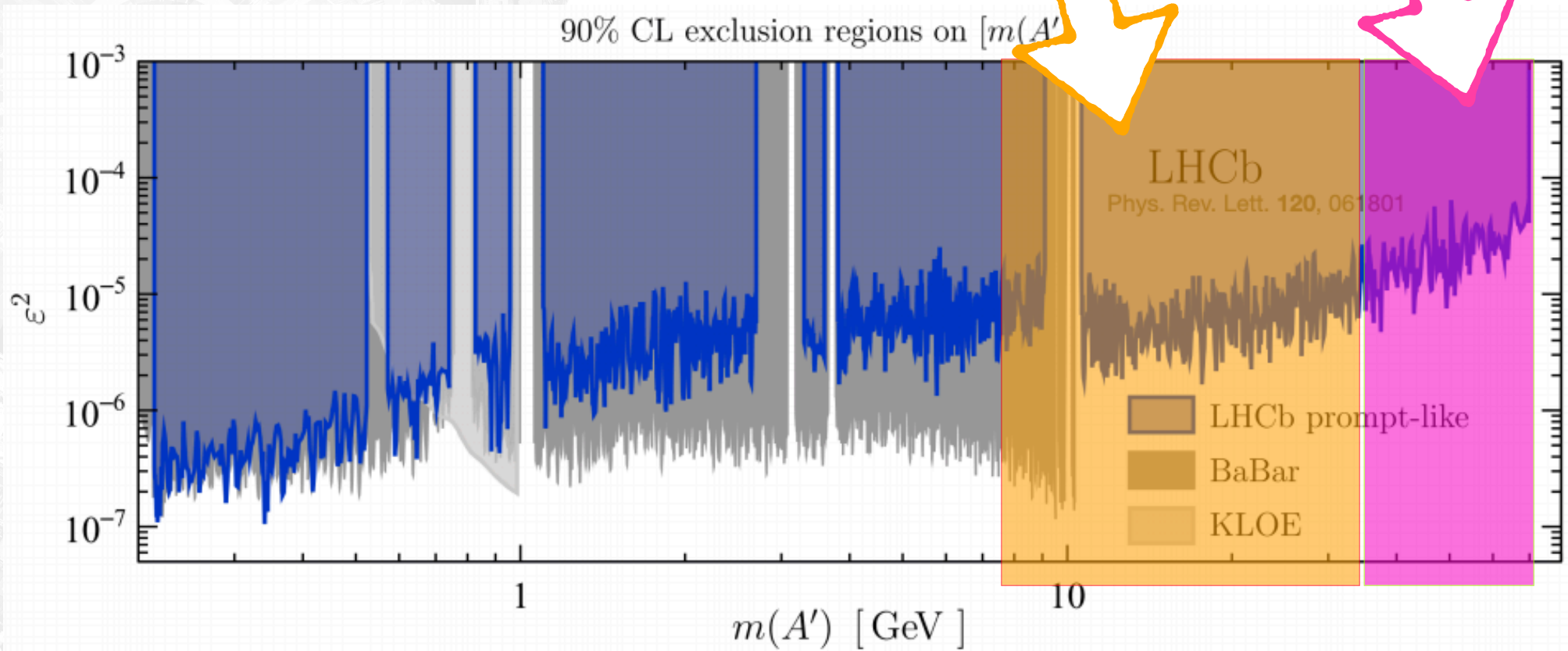
- If $\epsilon < 10^{-7}$ A' can be long-lived



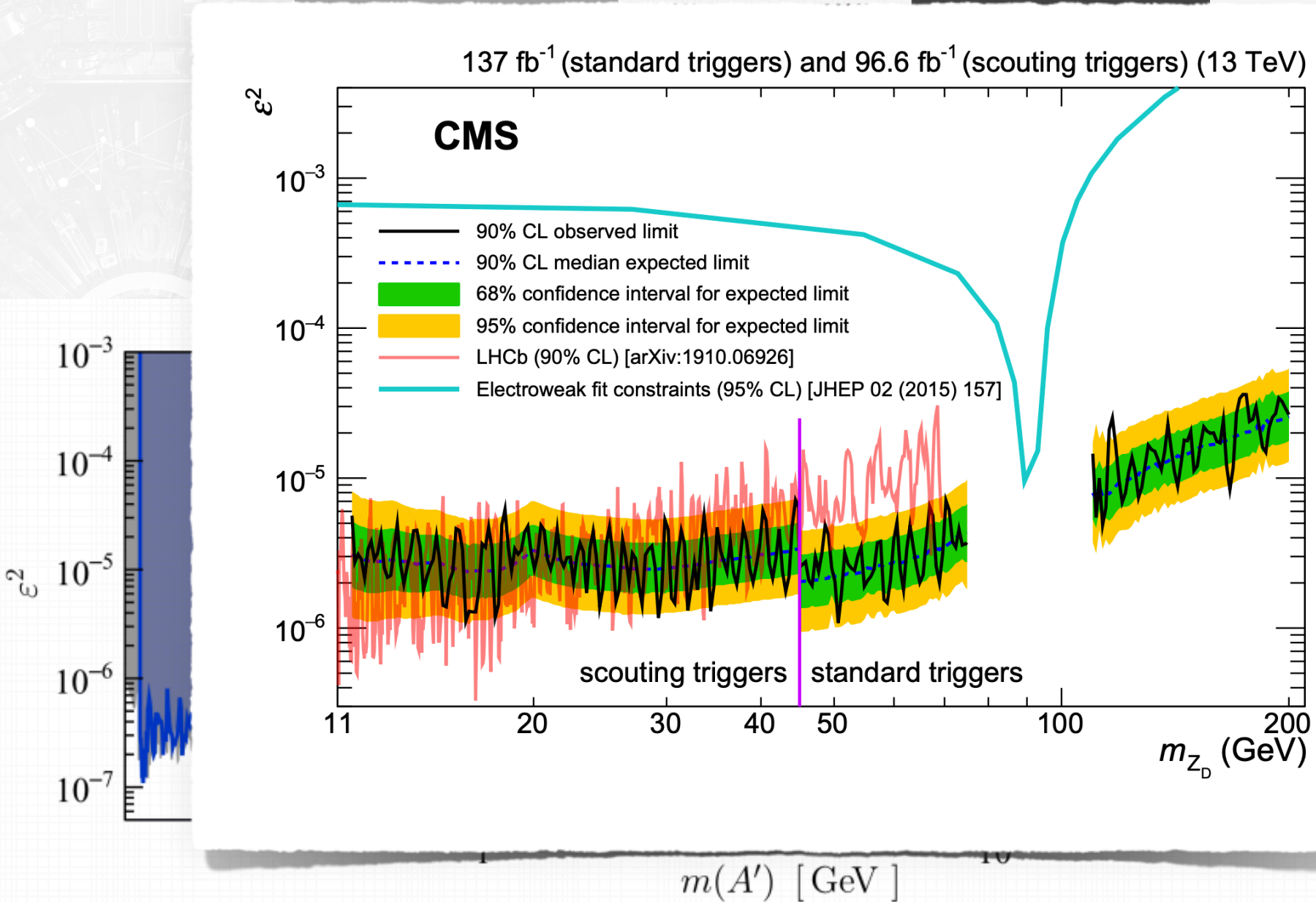
Low mass Dielectron Resonances



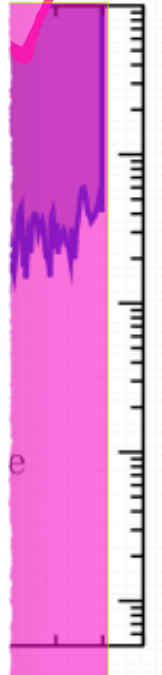
- If epsilon < 10⁻⁵ A' can be long-lived



Low mass Dilepton Resonances



ard
er



Scouting planning towards Run 3

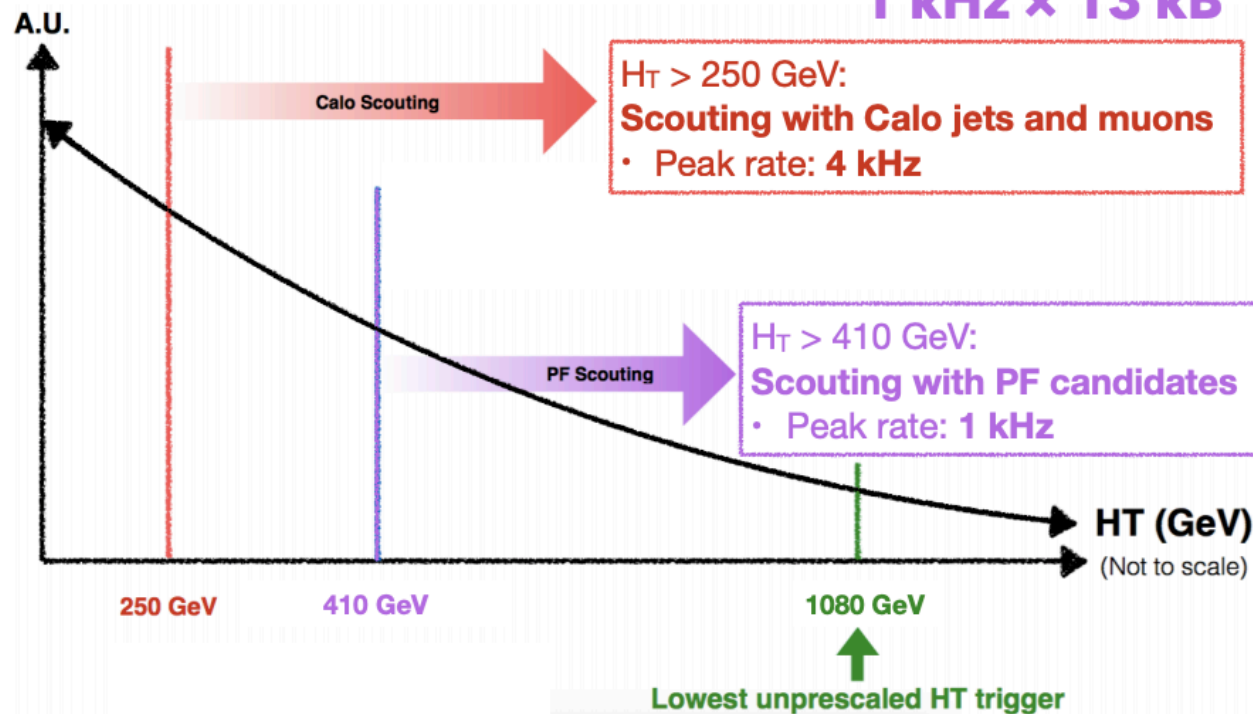
- Going **lower in energy** exploring different approaches:



Calo Scouting
4 kHz \times 7 kB



PF Scouting
1 kHz \times 13 kB



Scouting planning towards Run 3

- Going **lower in energy** exploring different approaches:



Calo Scouting
4 kHz \times 7 kB

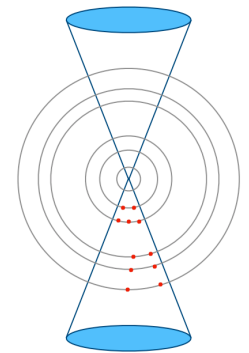


PF Scouting
1 kHz \times 13 kB

A.U.

- **EGamma Scouting**: store all the info to re-do calibrations. Physics motivations: **Axions (gg)** and **Dark Photons in electrons**

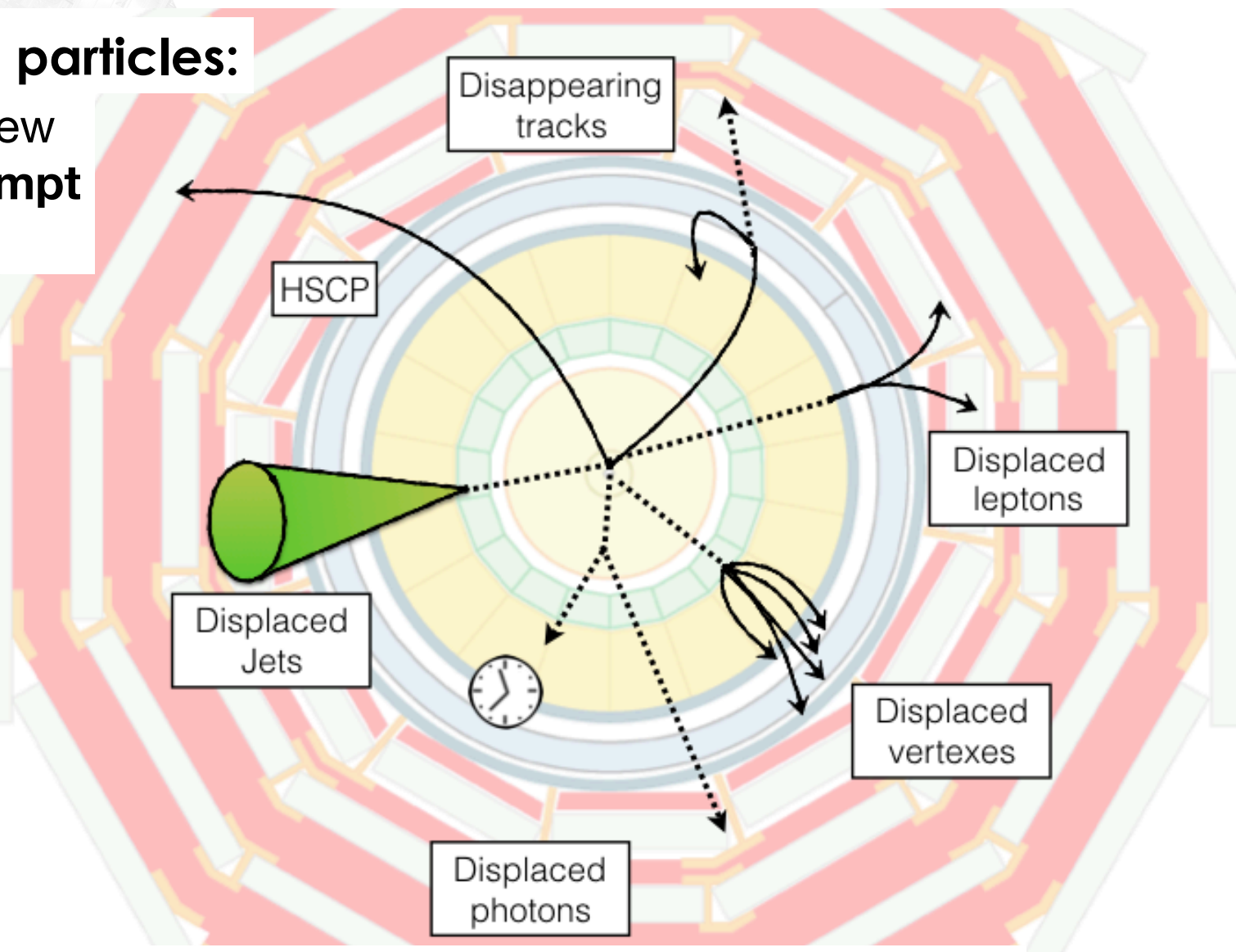
- **Inclusive scouting stream for LLP**: single-jet L1 + store all info for the region opposite to the jet in ϕ



More exotic signatures at LHC

- **Long-lived particles:**

- No hints of new physics in **prompt searches**



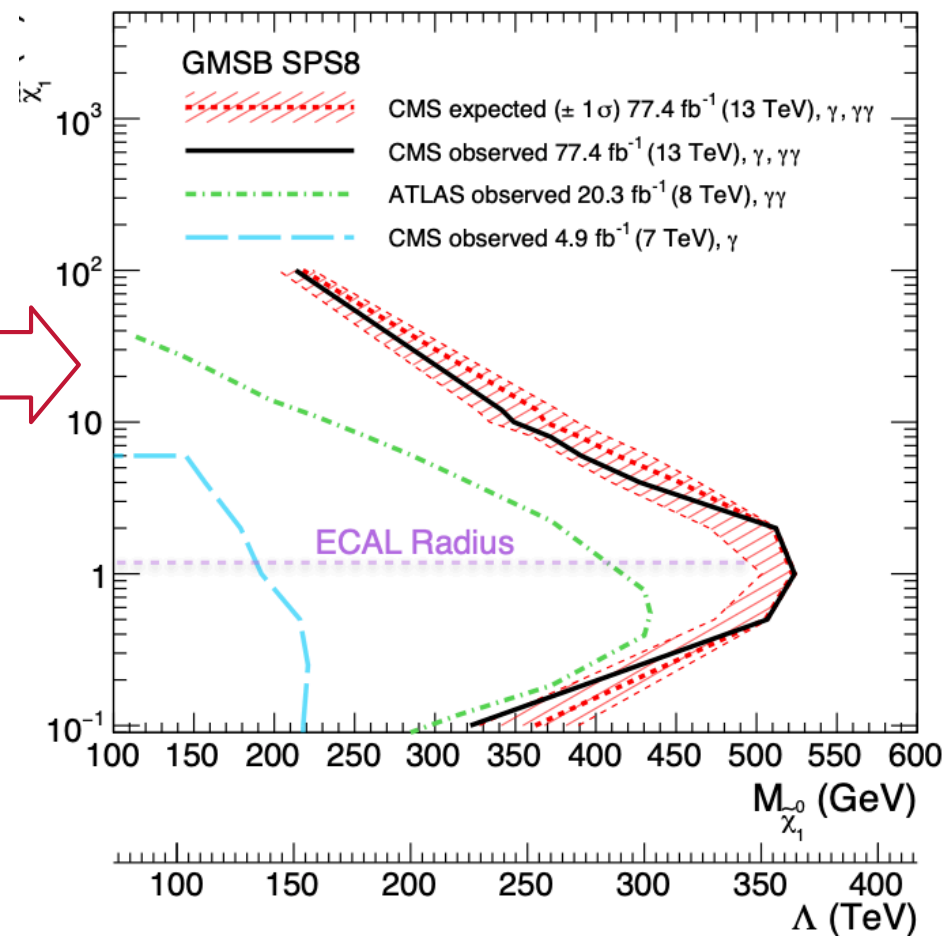
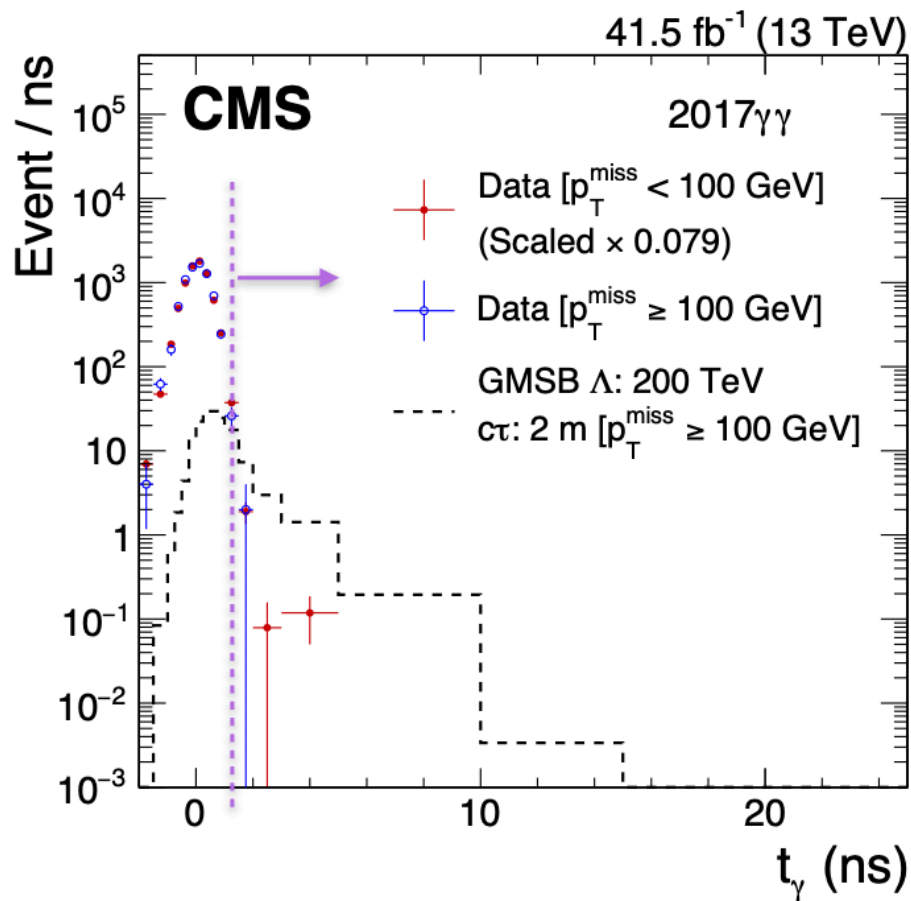
- **Extend the coverage & reach !**

Explore **more final states**

More **luminosity & better detector**

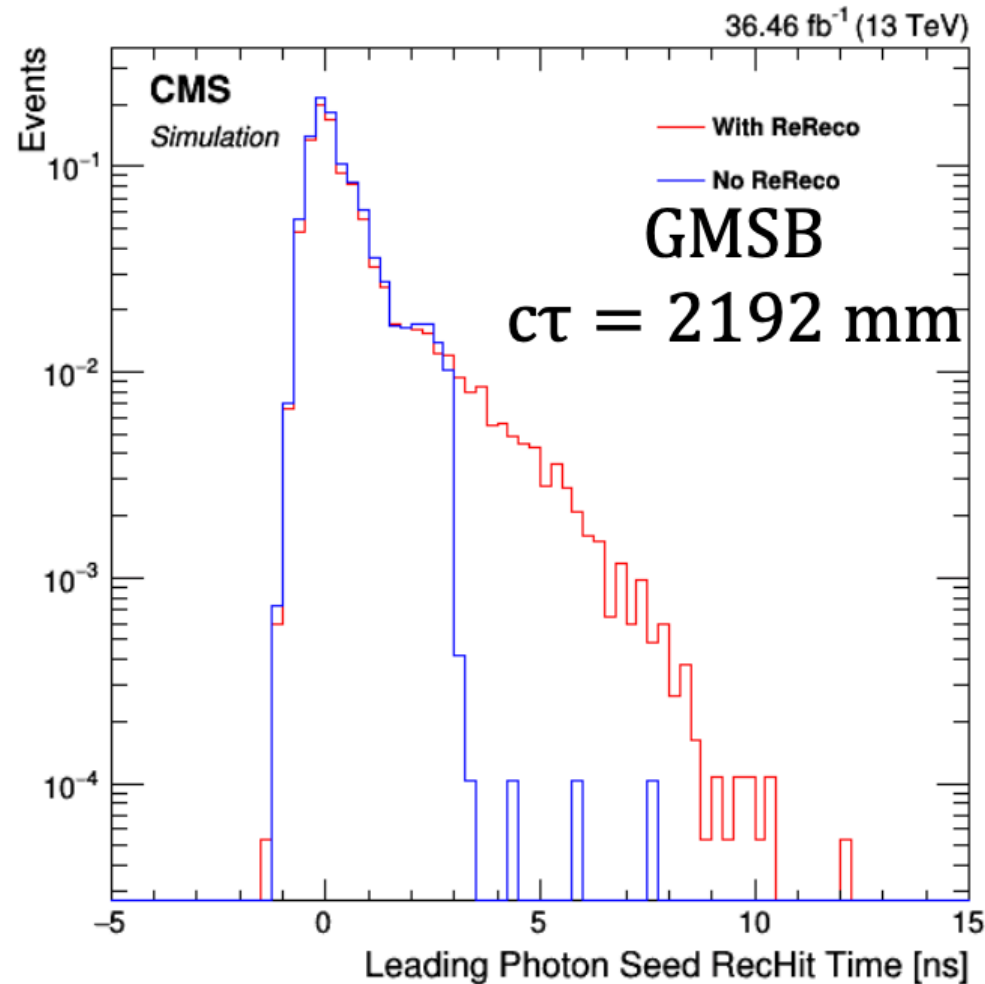
Displaced Photons

- Search for **delayed photons** in SUSY events



Pushing detector performances

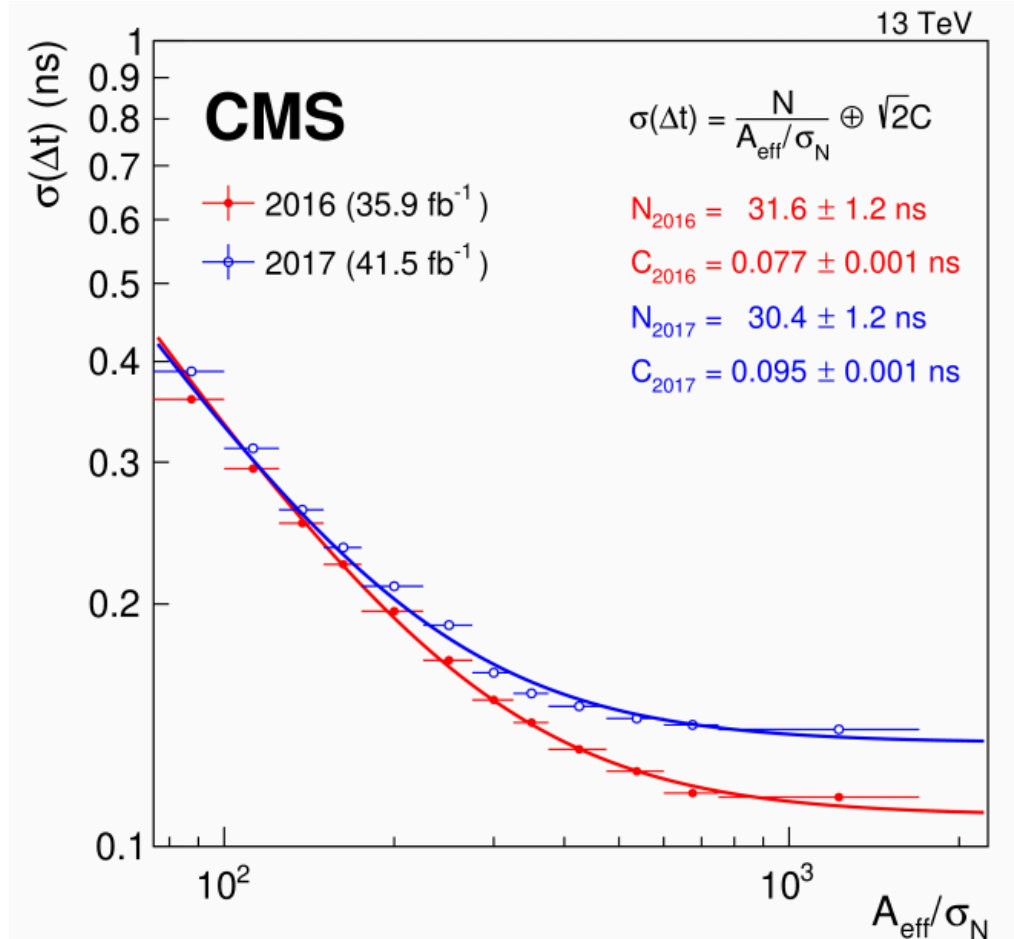
- Unique **Reconstruction** Sequence



Ad hoc **Particle Flow reconstruction** for rechits above a few GeV flagged as out-of-timewhen forming superclusters

Pushing detector performances

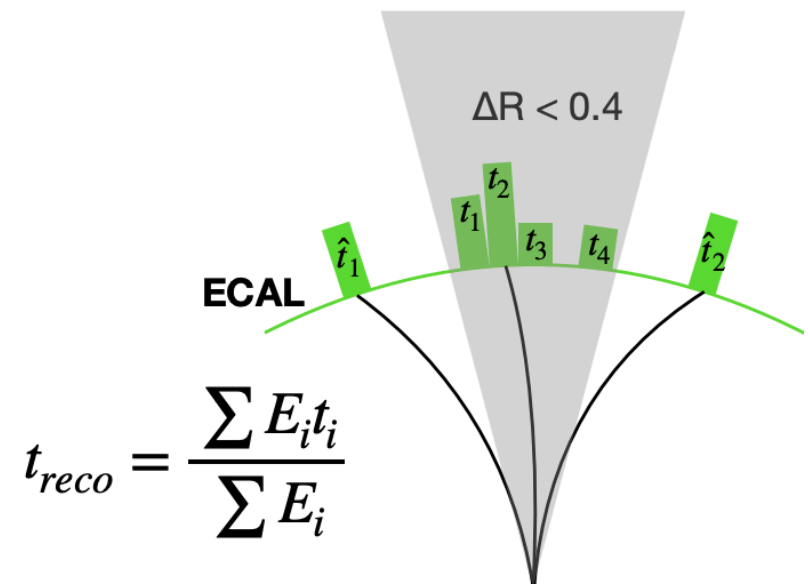
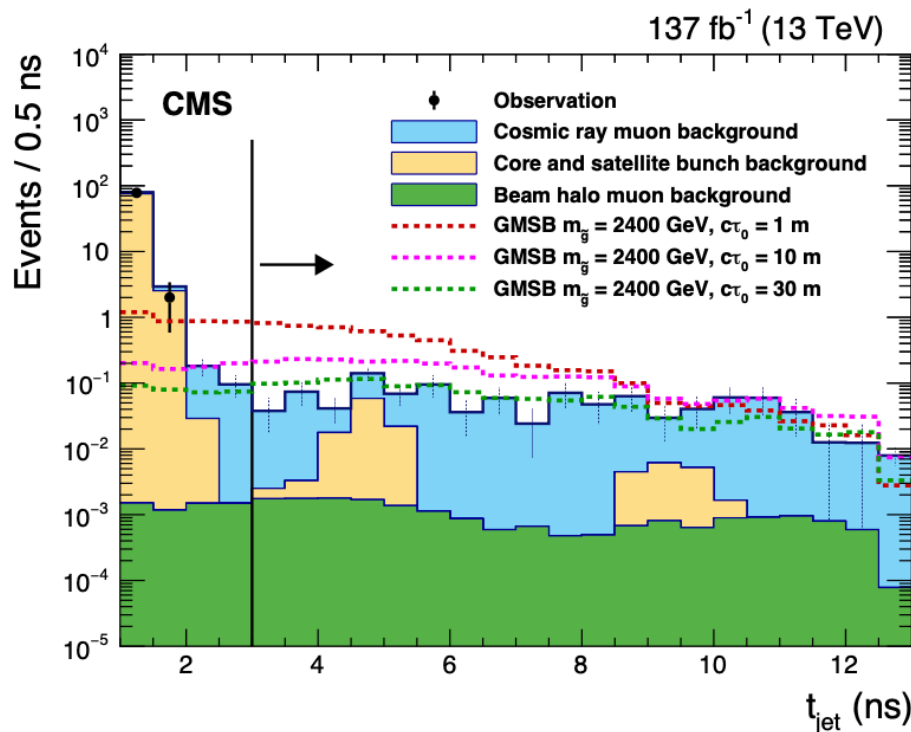
- Atypical use of the **detector**



Resolution of time difference between the two most energetic neighbouring crystals of an ECAL cluster for 2016 and 2017 data.

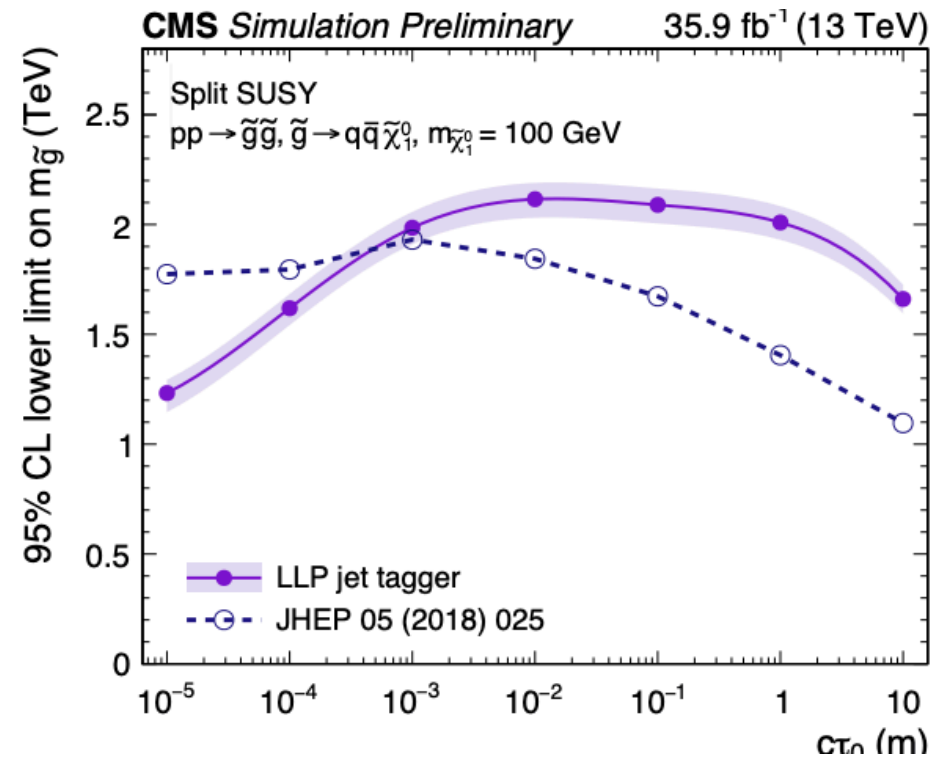
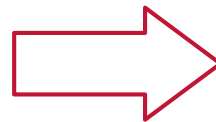
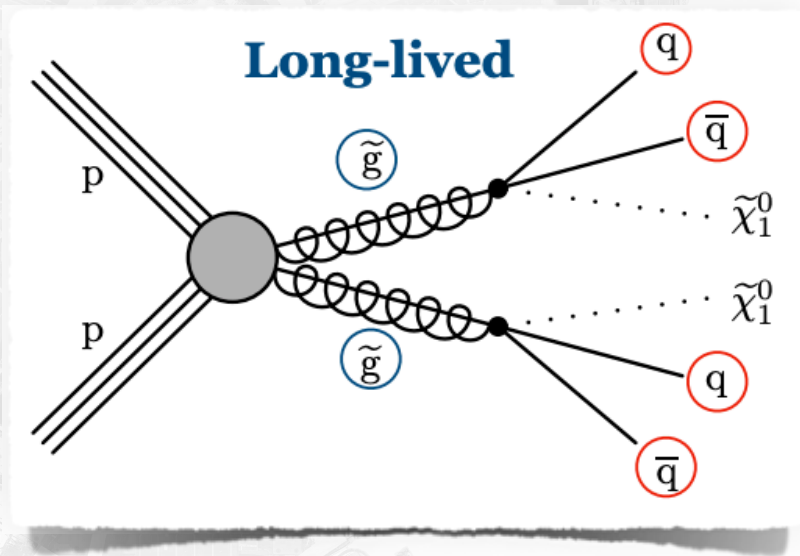
Displaced Jets

- Long-lived gluinos give rise to **jets from displaced vertex**
- Use time from **ECAL cells to match the calo-jets**
- LLP decays **beyond the tracker**, complementary to tracker-based analysis [EXO-17-018] (> 100 cm)
- **Non Collision Backgrounds**



Exploring Machine Learning for Run 3

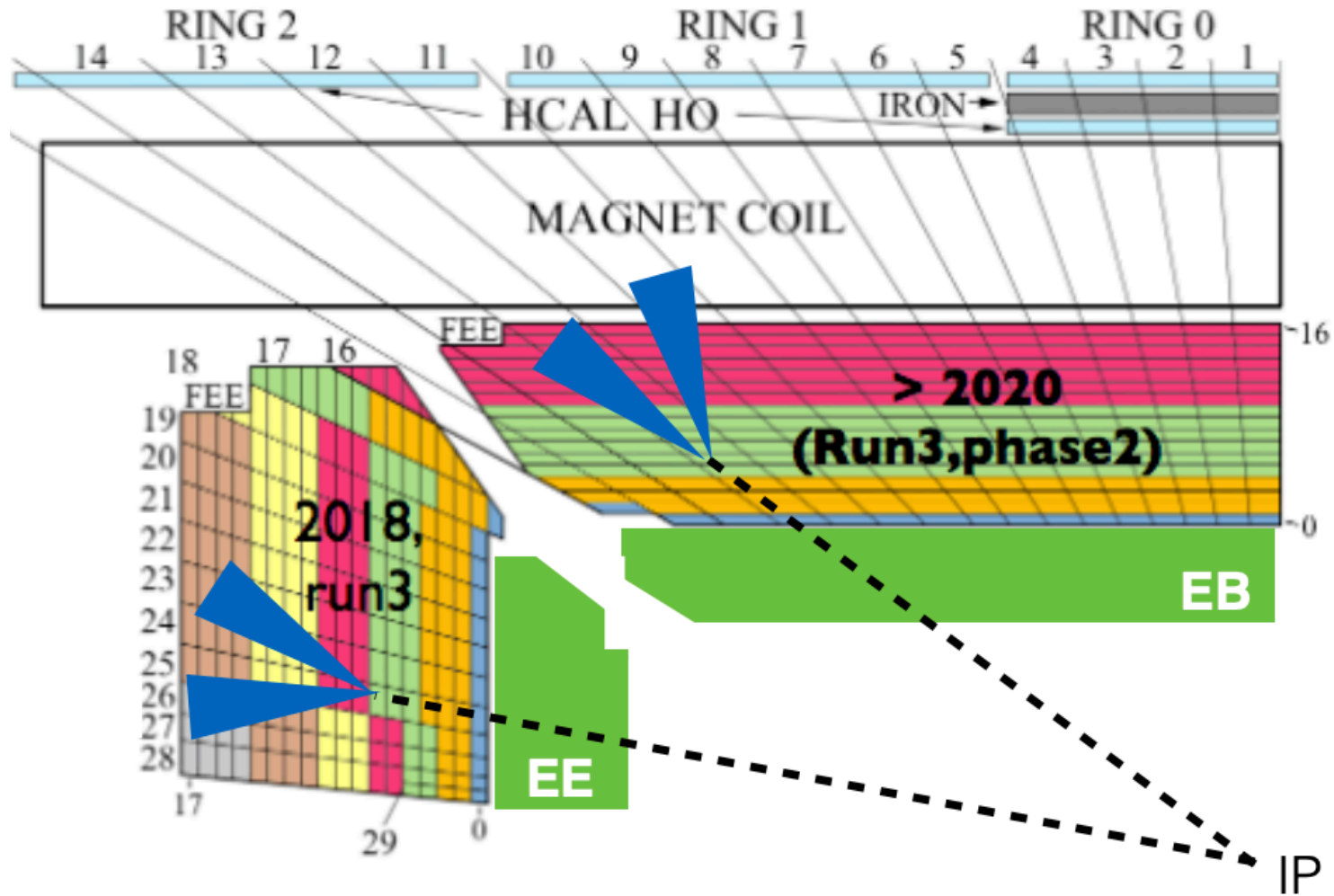
- Use full power of multiple variables and reduce need for manual tuning
- Development of a **generic displaced jet tagger w/ ML algorithm** validated with 2016 data



- Still room for **improvement for soft jets and model dependence**
- Add **displaced jet flavor tagging**

New strategies for Run 3 Trigger and ID

e.g. Possible HCAL handles: - High EHCAL/EECAL, - Depth and/or shower shape - Timing



Outlook and Planning for Run 3

Run III will significantly **increase the discovery potential** of EXO analyses

**Non
Conventional
Signatures**

```
graph LR; A[Non Conventional Signatures] --> B[Dedicated trigger algorithms]; A --> C[Unique object reconstruction, discriminating variables, or data]; A --> D[Re-defined analyses strategies w/];
```

**Dedicated
trigger
algorithms**

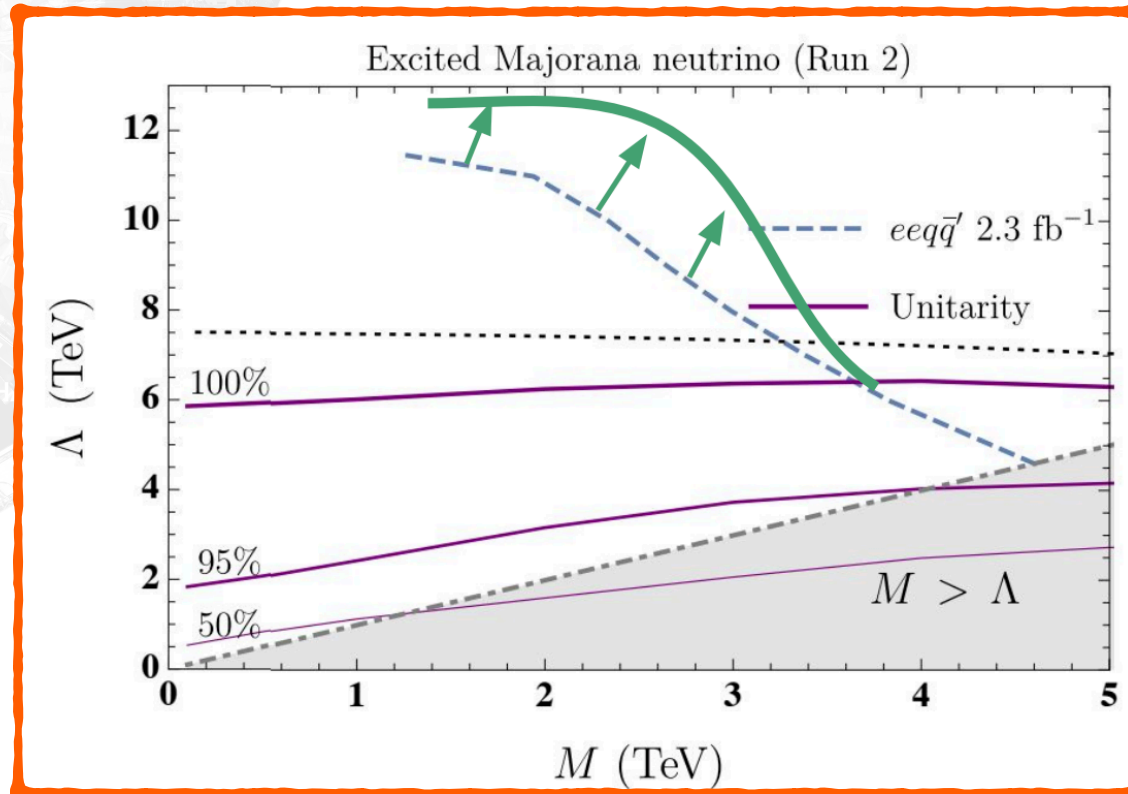
**Unique object
reconstruction,
discriminating
variables, or data**

**Re-defined
analyses
strategies w/**

Outlook and Planning for Run 3

Run III will significantly **increase the discovery potential** of EXO analyses

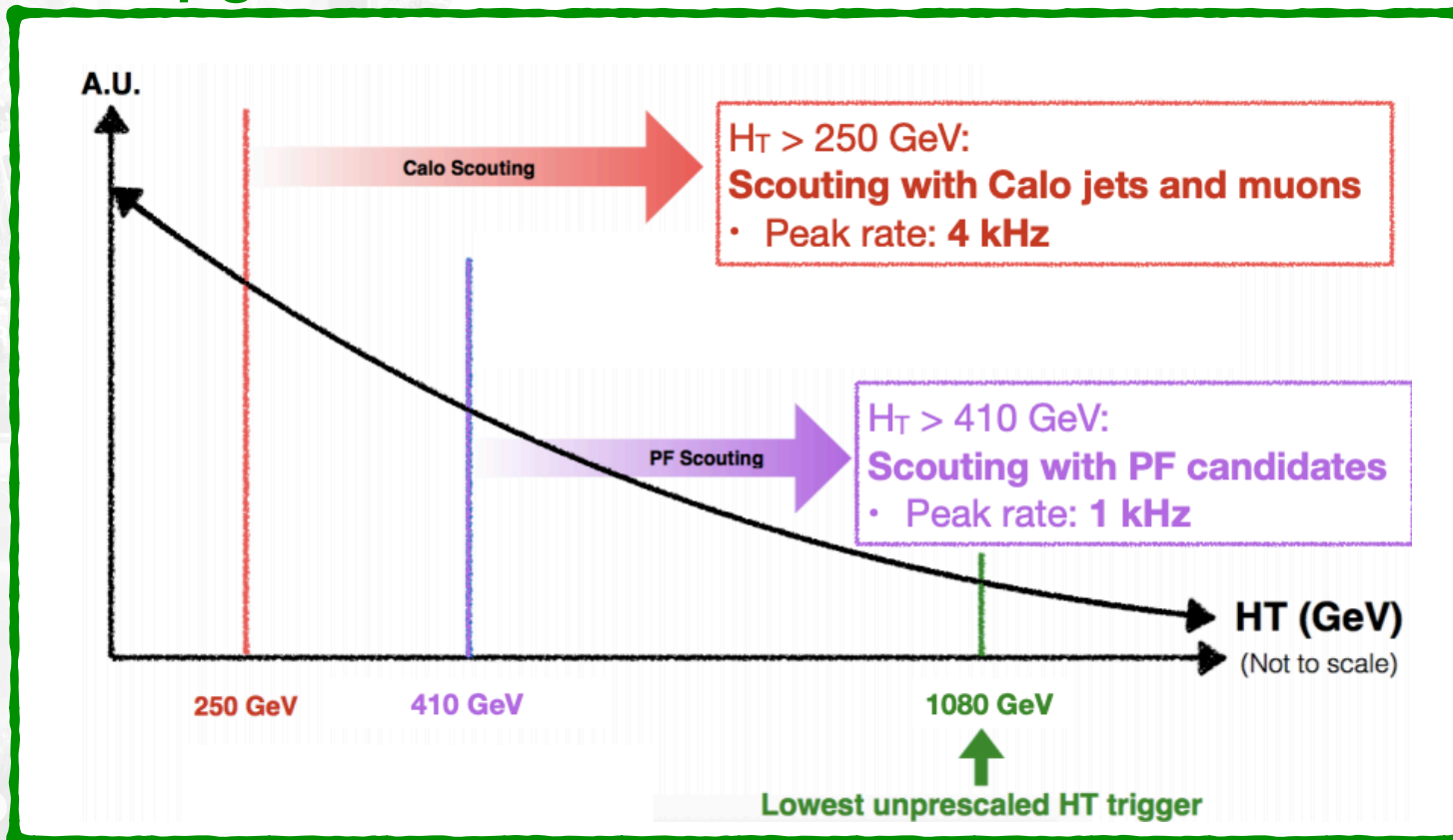
- **Improving and expanding upon completed, or ongoing, Run II analyses**



Outlook and Planning for Run 3

Run III will significantly **increase the discovery potential** of EXO analyses

- **Improving and expanding** upon **completed, or ongoing, Run II** analyses
- Designing **new trigger approaches** exploiting at best the new **detector upgrades**



Outlook and Planning for Run 3

Run III will significantly **increase the discovery potential** of EXO analyses

- **Improving and expanding** upon **completed, or ongoing, Run II** analyses
- Designing **new trigger approaches** exploiting at best the new **detector upgrades**
- Exploring **new final states**

