“Very” Exotic Analyses: Long-lived Searches at the CMS and ATLAS Experiments

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‘A First Glance Beyond the Energy Frontier’

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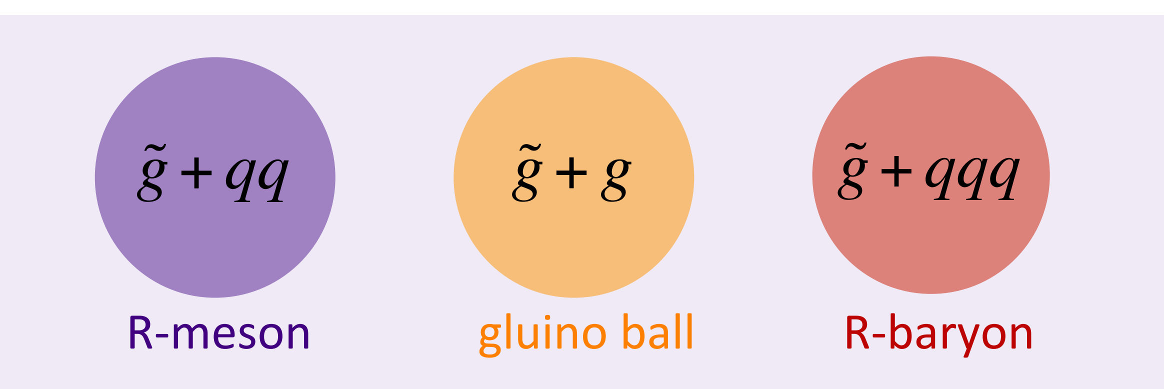
Outline

1. Considerations for Long-lived Analyses
2. **CMS** Summary of Long-lived Searches
3. **ATLAS** Summary of Long Lived Searches
4. Where is analysis coverage needed?
5. Organizational Structure of Future Searches
6. Conclusions

Long lived Particles: The "Very" Exotic

- Within exotics, the 'very' exotic analyses generally include particles with long lifetimes $c\tau_0 > 1$ mm.
- The manifestation of where the long-lived particle enters into the model can generate a **rich variety of signatures.**

"Hey…"
"we have needs too…"

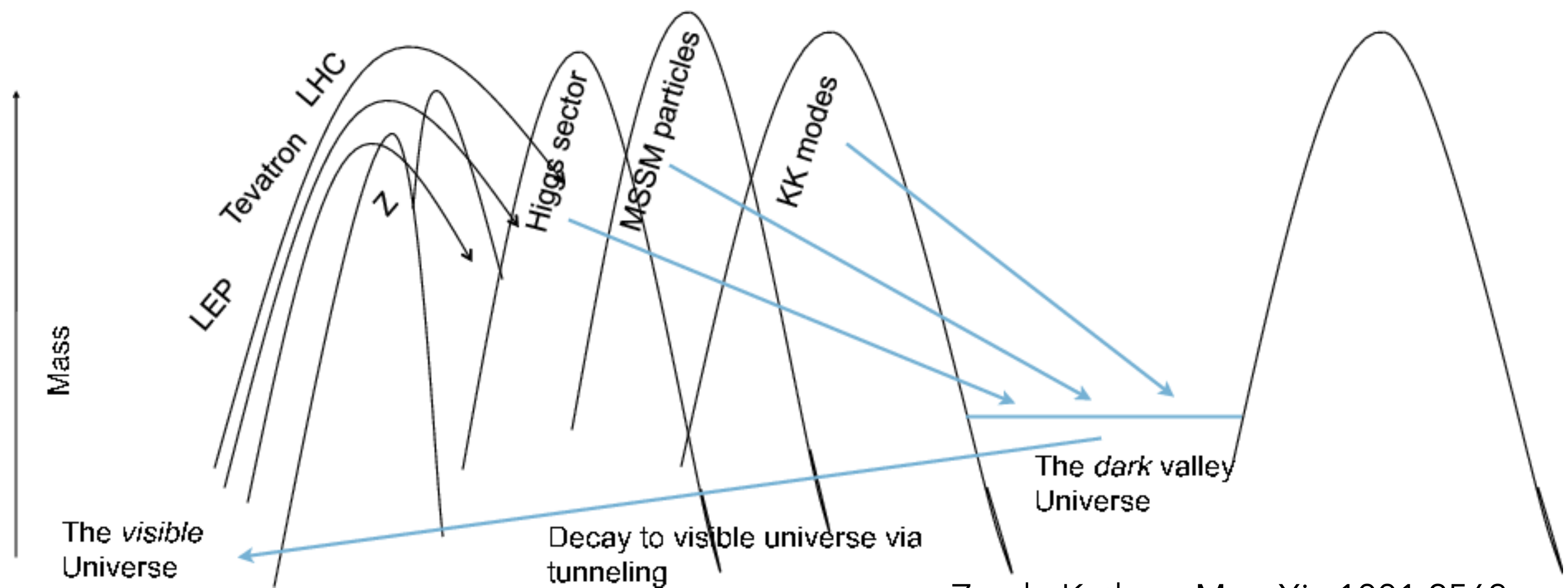


- **Individual needs are generally not met** by what are otherwise 'standard' prompt analysis procedures and large coordinated effort .
- What makes these analyses challenging, also makes them powerful and **important to undertake 'beyond the energy frontier'**

Long-lived Theoretical Motivations

Including but not limited to:

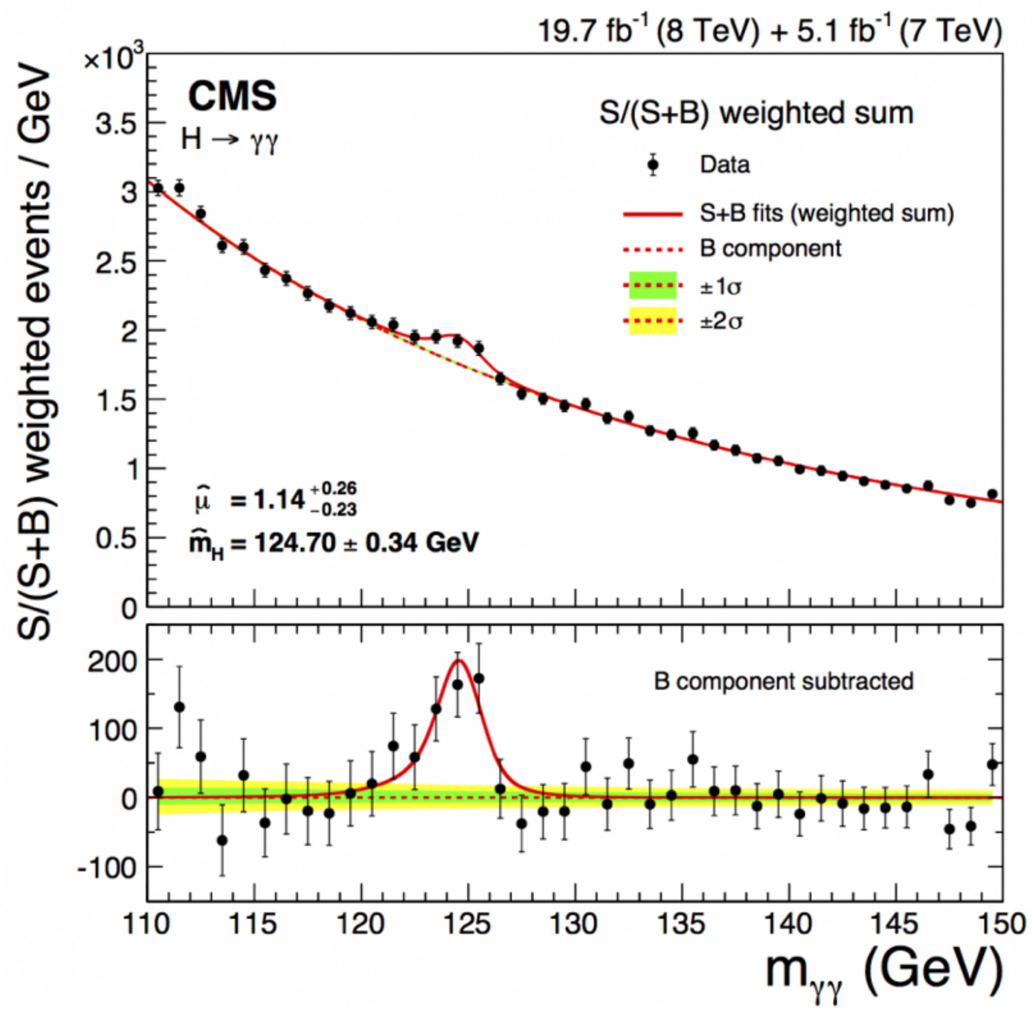
- Split SUSY
- Baryogenesis
- Twin Higgs
- RPV SUSY
- Emerging Jets
- Semi-visible Jets
- Dark Photons
- GMSB
- Hidden Valley Models

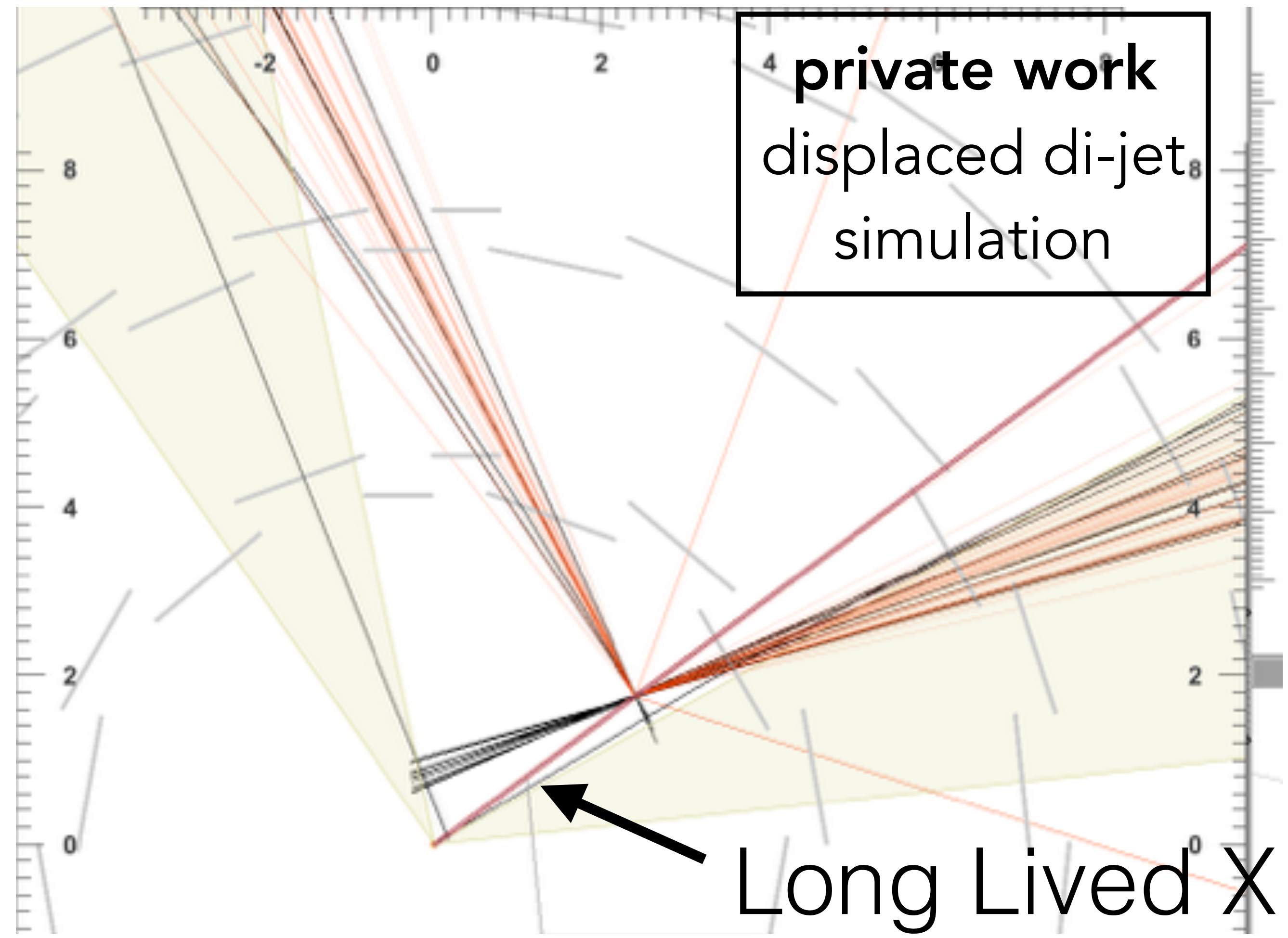


Zurek, Kathryn M. arXiv:1001.2563

As purely kinematics gains from the LHC diminish exotic decays **continue to indirectly probe higher energy scales**

Convincing Discoveries



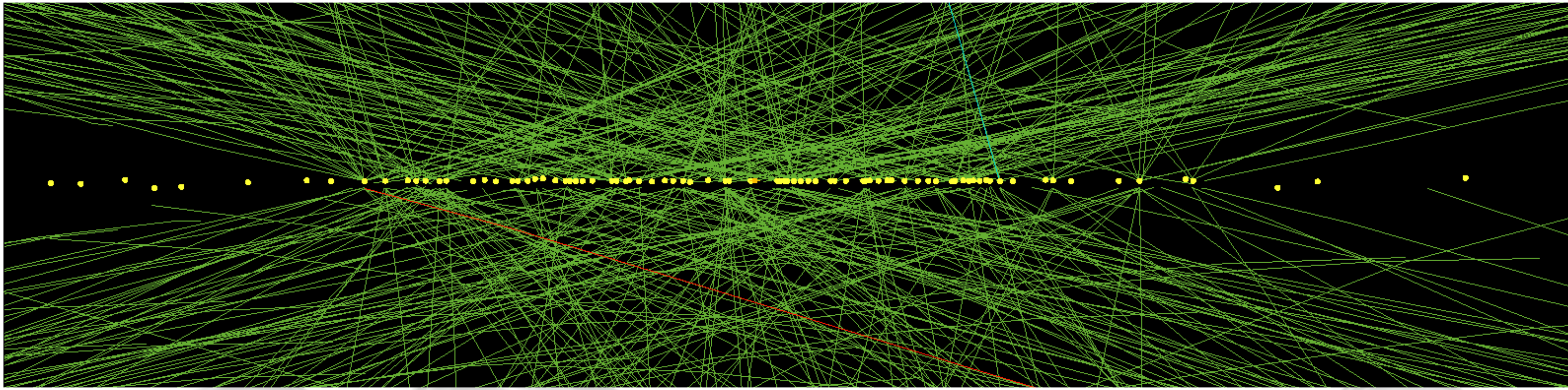


- We like results we can geometrically see, generally this is the shape of a resonance, but displaced vertices can be similarly striking.
- In depth tracking analysis of **a single event could be a very convincing** sign of new physics.

Considerations in 'Very' Exotic Analyses

- Non-standard physics **objects can break** in prompt analyses
- It can be difficult to determine signal systematics with **no 'precise' control samples** in Data. Heavy reliance on detector simulation of displaced objects (besides muons).
- Most analyses, are intimately tied to the **edges of tracking performance**. Analyses wait for final alignment.

Considerations in ‘Very’ Exotic Analyses

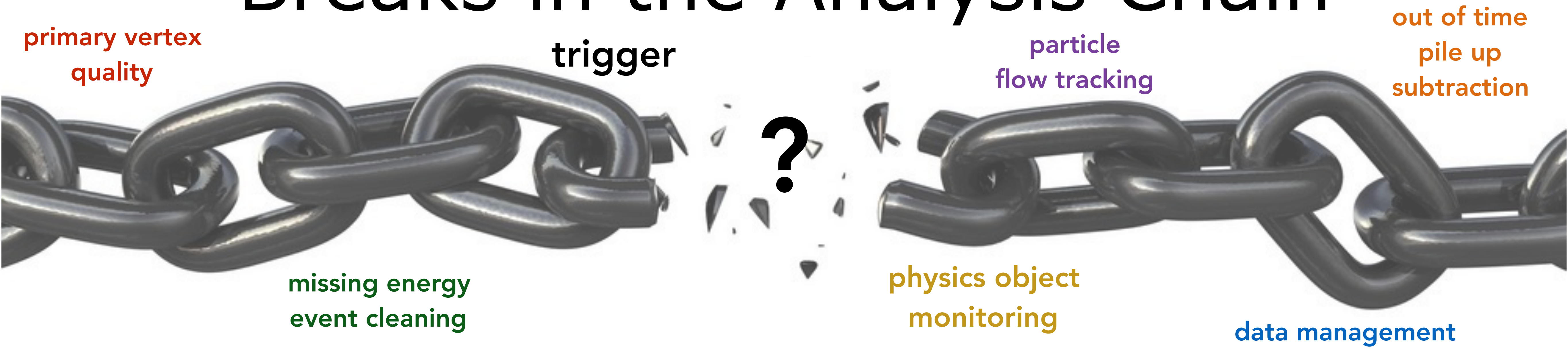


- Track reconstruction is becoming more **challenging with increasing PU**. Prompt lepton reconstruction is the top priority, and this (with good reason) generally **comes at the expense of displaced tracks.**
- Future analysis could require dedicated tracking (as ATLAS already performs) a CPU intensive task that competes for resources.
- Analyses are often **trigger efficiency limited**, or require specialized triggers that require **significant overhead** in manpower/ development which competes for bandwidth.

Breaks in the Analysis Chain

- We have to be very careful we are not throwing out 'very' exotic events. **Especially,** at early stages of data processing.
- Simple quality requirements for prompt searches when applied to displaced signatures can have dramatic effects.
- Decays in calorimetry look like **electronics noise.**
  - Magnetic Monopoles are limited by low level trigger spike cleaning in the ECAL.
  - Decays in the **CMS HCAL** look like a common CMS electronics issue that usually generates fake missing energy.
- Primary Vertex selection (quality in prompt analyses and selection in displaced analyses)

Breaks in the Analysis Chain



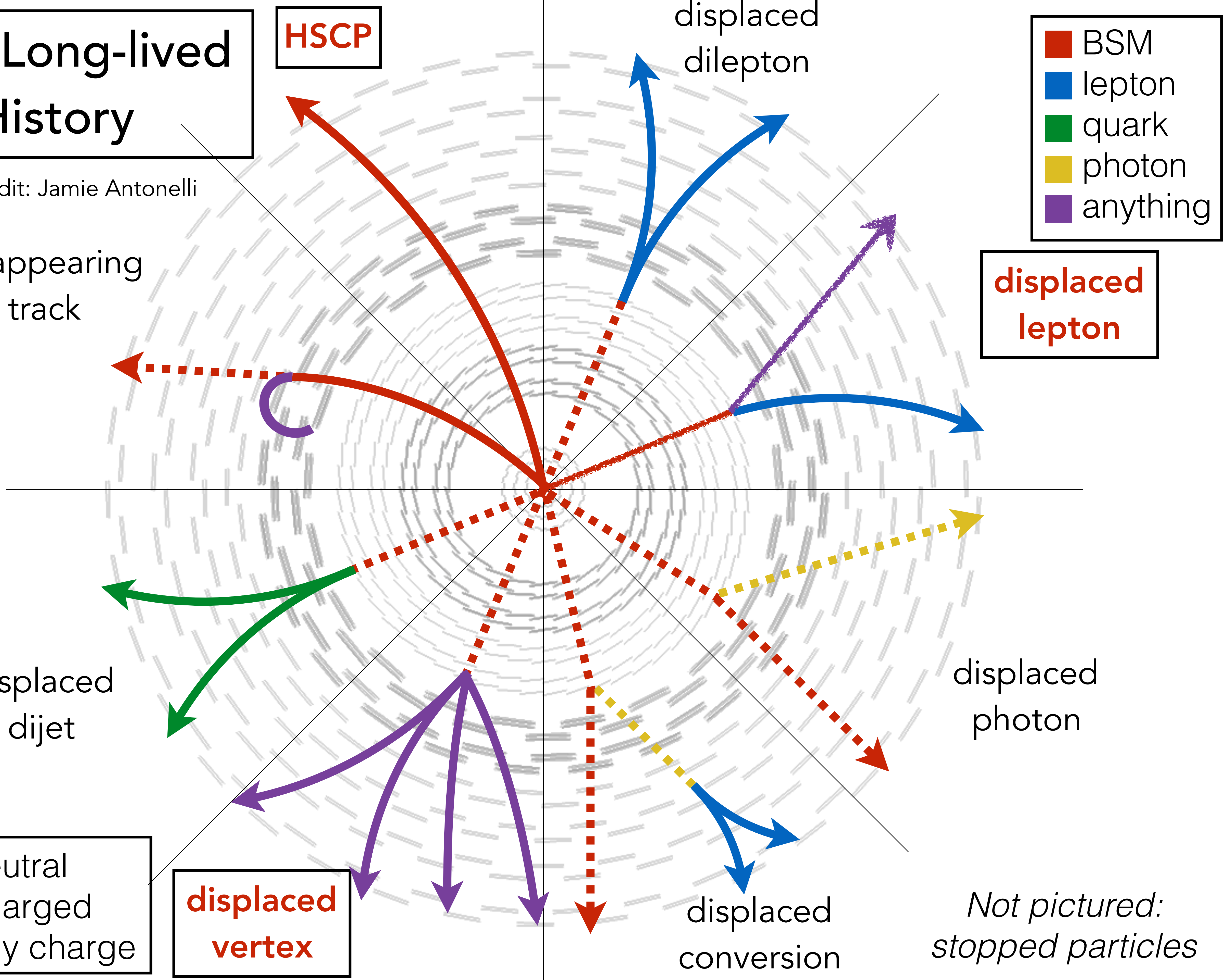
- Do **Particle Flow Jets** work for tracks we've never seen before? Very few analyses use calorimeter jets.
- **B tagging performance** drops exponentially beyond ~1 cm (upper cuts on displacement to eliminate fakes)
- Data formats for analysis are being more centralized and **very Exotic analyses need information that most people do not use** (ex. timing, dE/dx, and tracking information). These datasets are much larger and first to be deleted.
- With small teams **it is harder for long-lived teams to investigate detector issues**, which do not have central 'physics' object groups nor physics objects to monitor quality

CMS Exotic Long Lived From 7 to 13 TeV

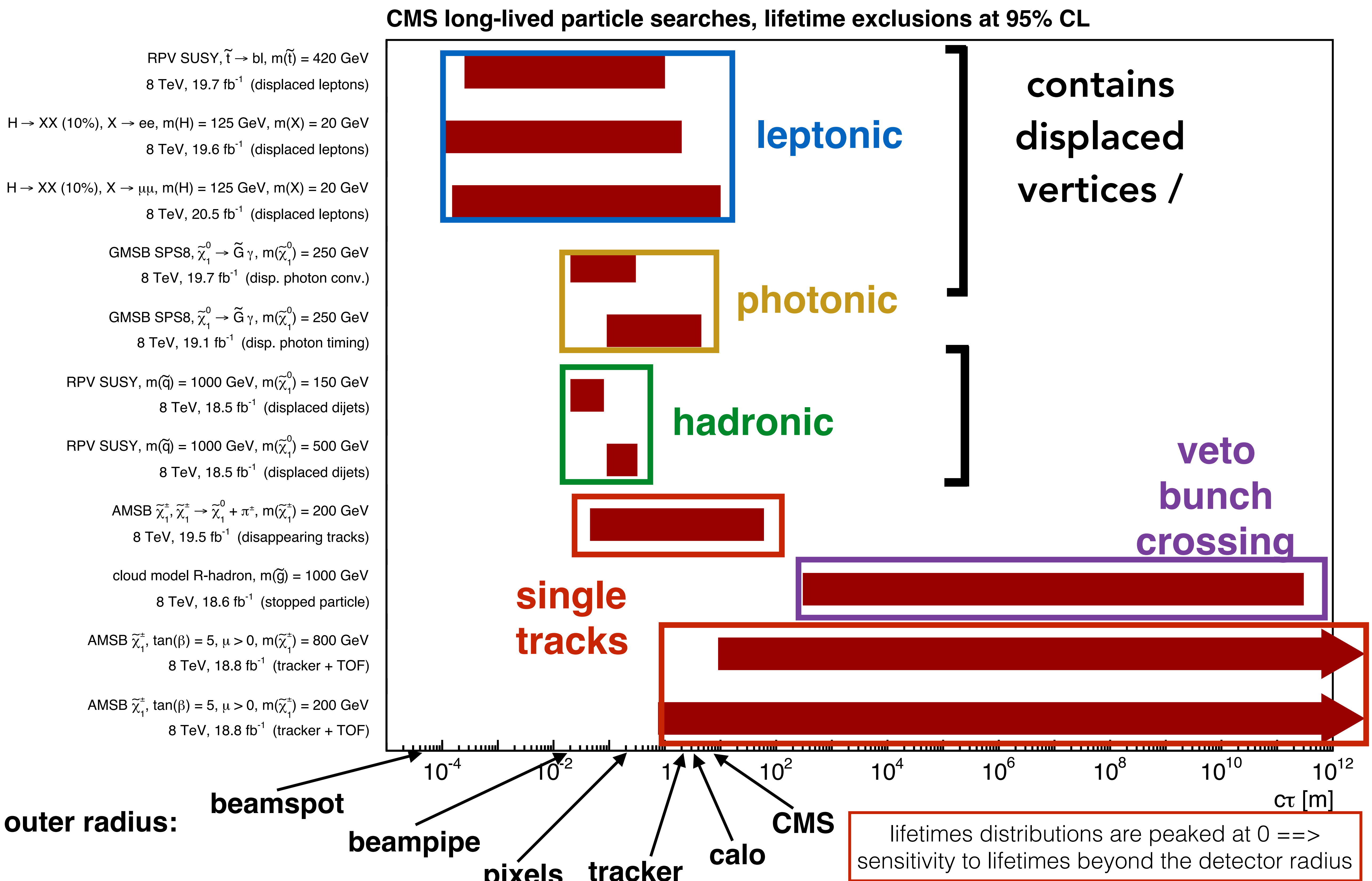
Group	#	Final state targeted	7 TeV	8 TeV	13 TeV
contains displaced vertices; leptonic	1	displaced e-e/μ-μ pairs	1211.2472	1411.6977	
	2	displaced μ-μ pairs in muon system		2005761	
	3	displaced e-μ events		1409.4789	**2205146**
	4	displaced μ-μ pairs (dark photons)		1506.00424	
hadronic	5	displaced vertices		**2160356**	
	6	displaced dijets		1411.6530	
photonic	7	displaced photons using conversions	1207.0627	2019862	**still many 13 TeV analyses to look forward to**
	8	displaced photons using ECAL timing	1212.1838	2063495	
single tracks	9	short, highly ionizing disappearing tracks		thesis	
	10	disappearing tracks		1411.6006	
	11	kinked tracks		thesis	
	12	fractionally charged particles	1210.2311	1305.0491	
	13	heavy stable charged particles (HSCP)	1205.0272	1305.0491	2114818 (2015) **2205281** (2016)
veto bunch crossing	14	stopped particles	1207.0106	1501.05603	
	15	out of time muons		thesis	

CMS Long-lived History

Graphic Credit: Jamie Antonelli

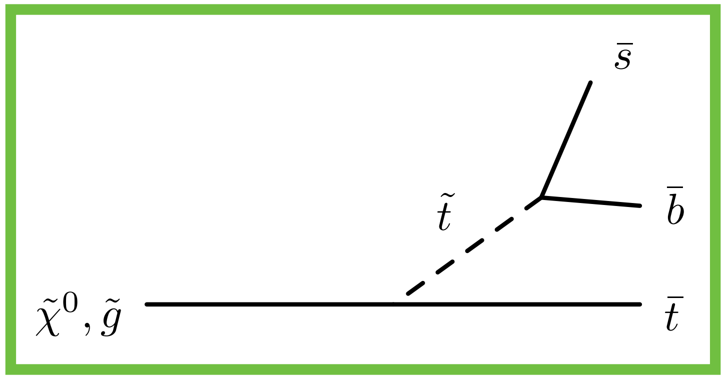


CMS Lifetime Exclusion Space

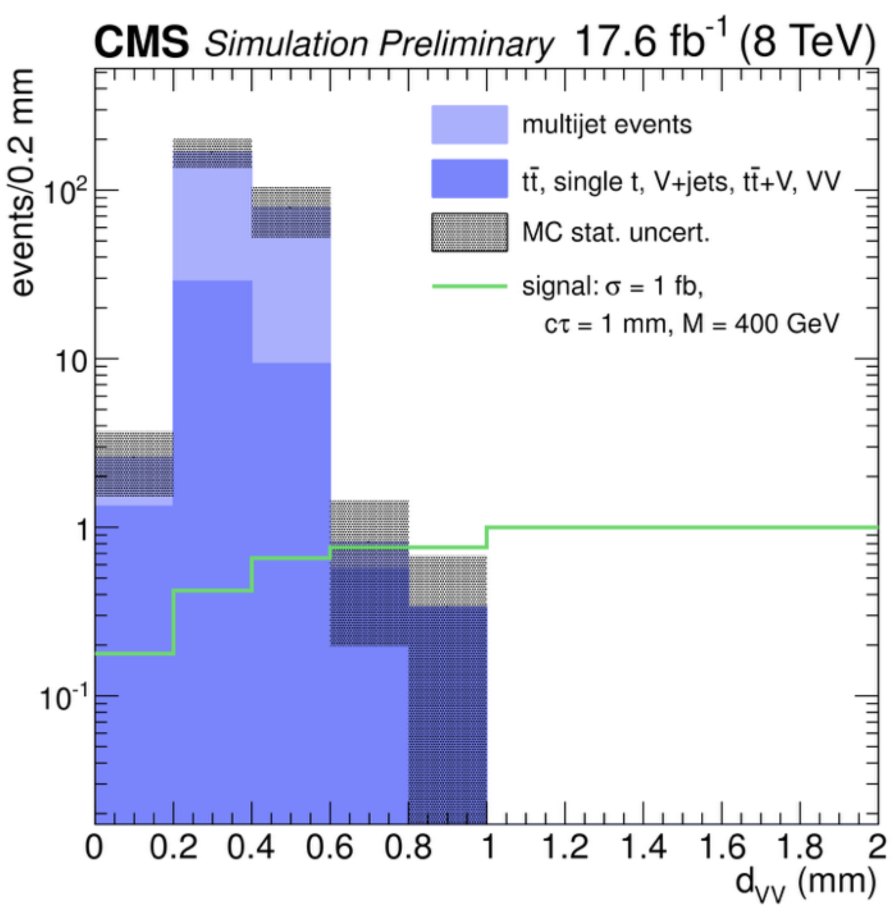


Displaced Vertex Analysis

- New **8 TeV Analysis** targeting RPV pair-produced displaced decays with a final state of **top+bottom+strange**



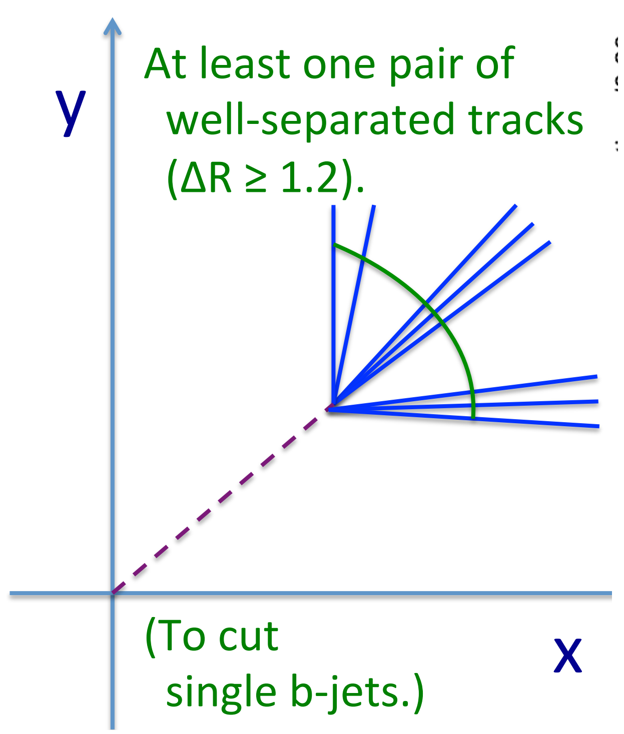
final search distribution

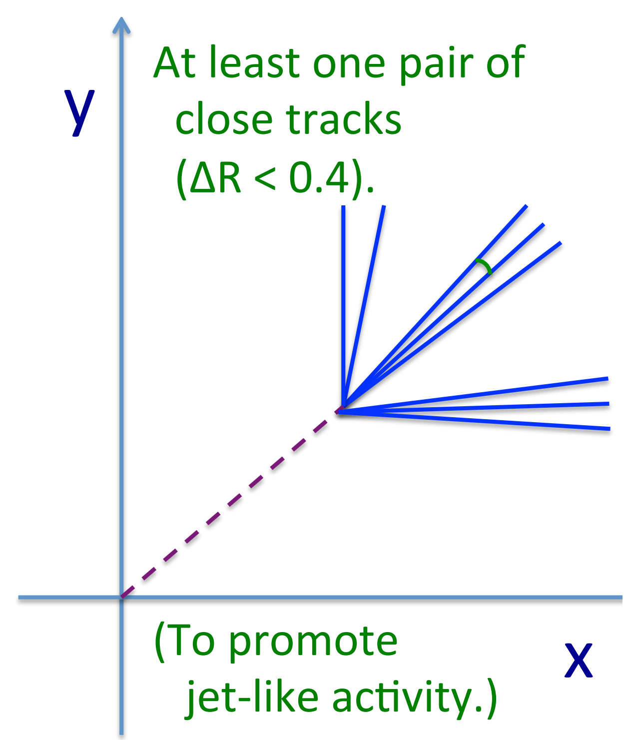


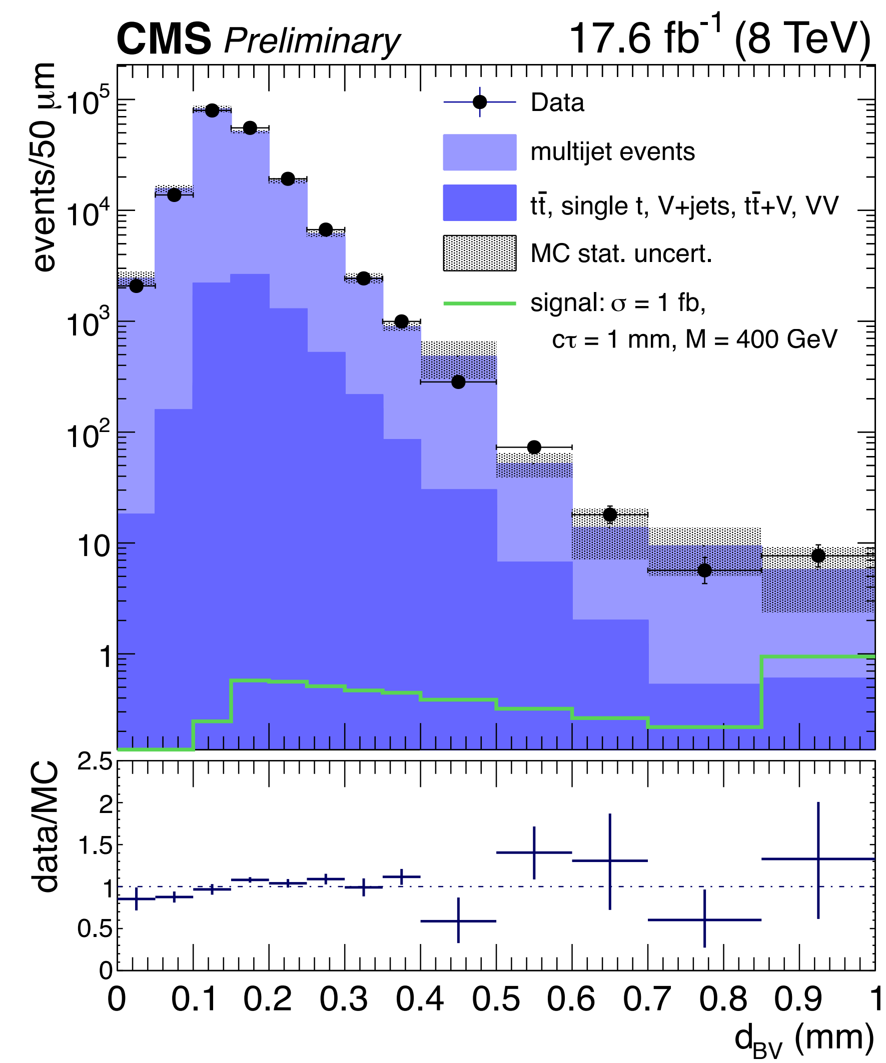
- Considers **'intermediate' lifetimes** between prompt and most displaced searches well within the beam pipe (signal region bins as low as 0.2 mm)
- Discriminating variable is the **distance between the two reconstructed vertices in the transverse plane (d_{vv})**
- Trigger strategy: H_T, with no additional requirements

https://cds.cern.ch/record/2160356

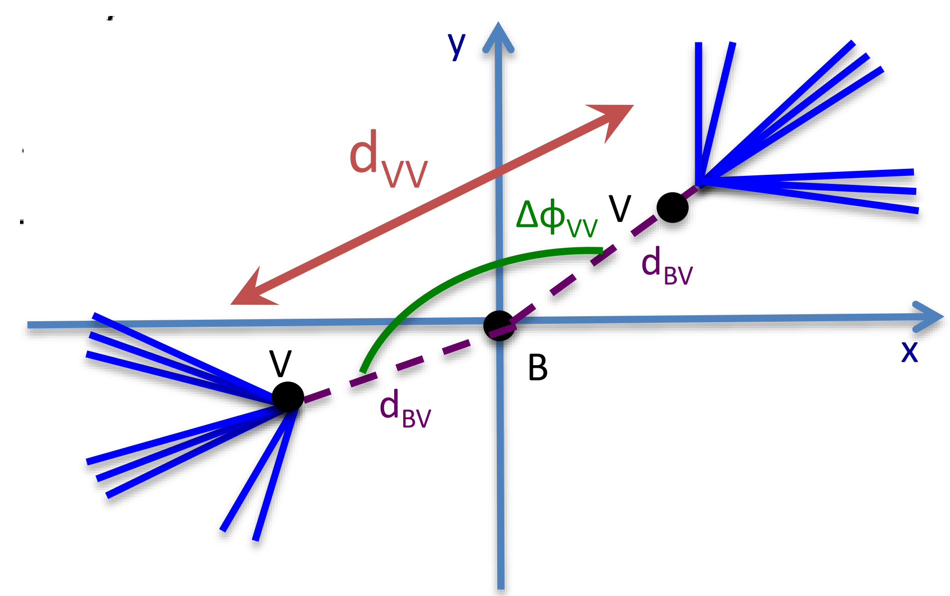
Background Estimation





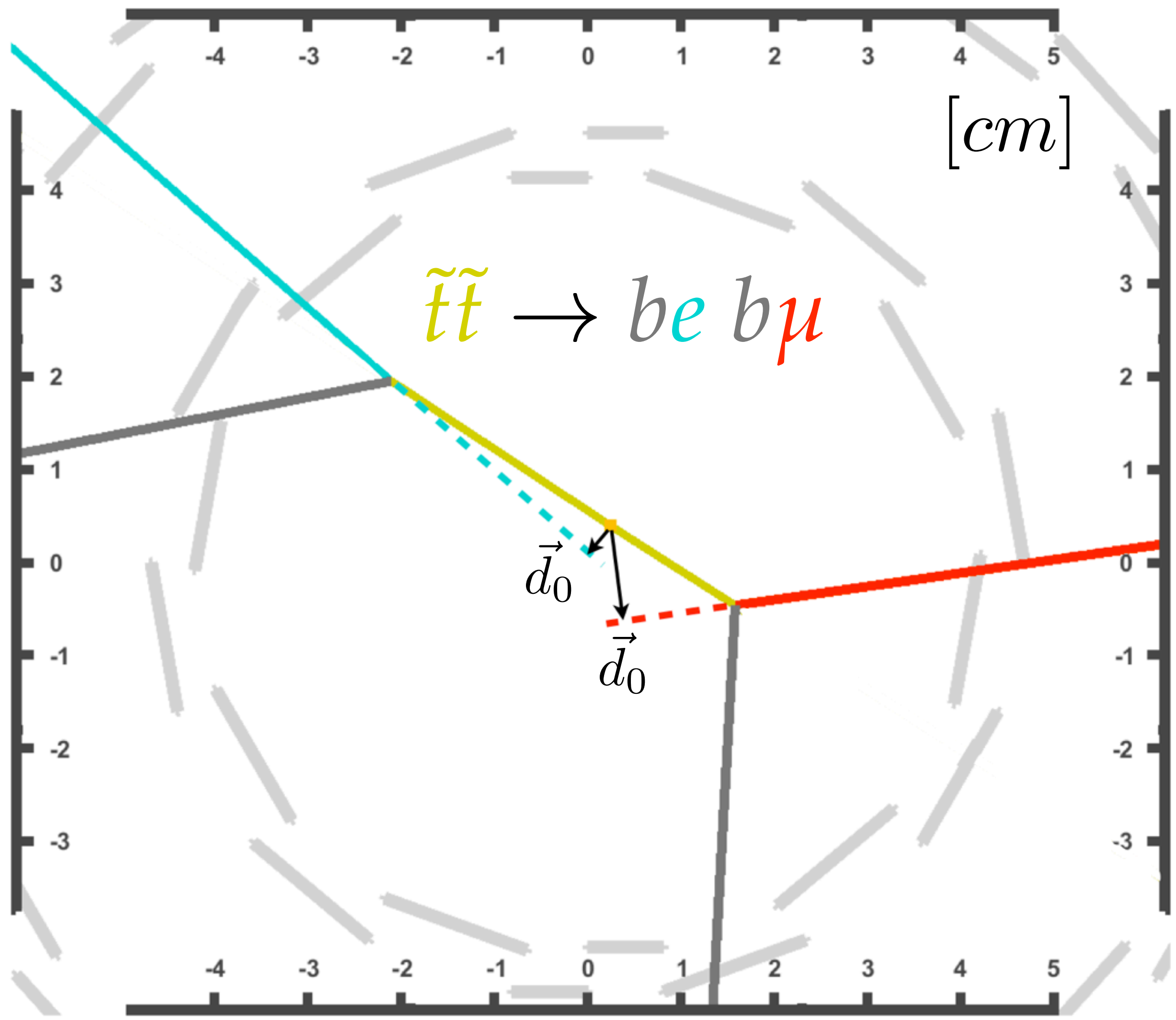


- Require at least 3 tracks per vertex with through two dR requirements
- Require separation ΔΦ between the two vertices
- The d_{VV} distribution is generated from the shape of d_{BV} for both vertices



13 TeV Displaced Lepton Analysis

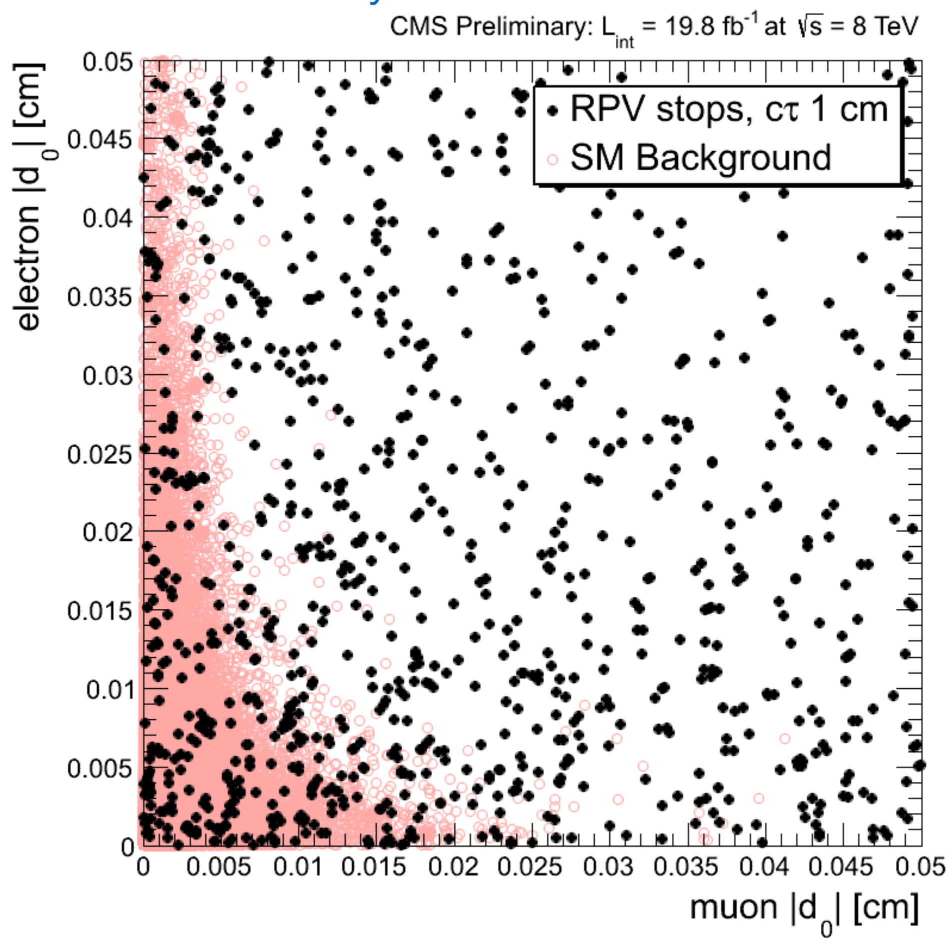
- Benchmark model of pair produced stops decaying to b+l with equal lepton branching fractions (tau, e, mu)
- Utilize $|d_0|$, the **transverse impact parameter** to separate signal from background
- No secondary vertexing increases inclusivity
- Dedicated displaced lepton triggers



cds.cern.ch/record/2205146?ln=en

Displaced Lepton Analysis

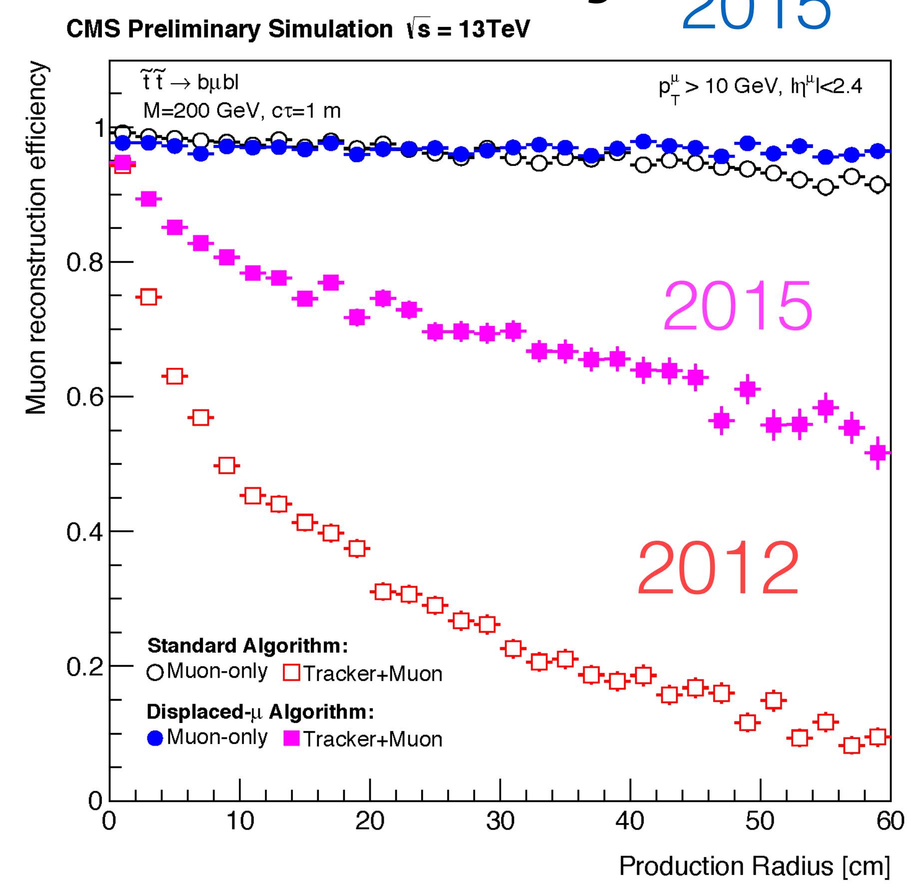
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G12024



- Analysis performed in the 2D plane of muon and electron $|d_0|$ (left)
- Three independent signal regions in regions of $|d_0|$ > 0.2 mm to $|d_0|$ >1 mm

offline reco efficiency

2015



https://cds.cern.ch/record/2037372?ln=en

- Run 2 analysis greatly **improved displaced muon reconstruction**, limiting factor in 2012
- Improved displaced muon triggering, with **dedicated displaced muon paths**

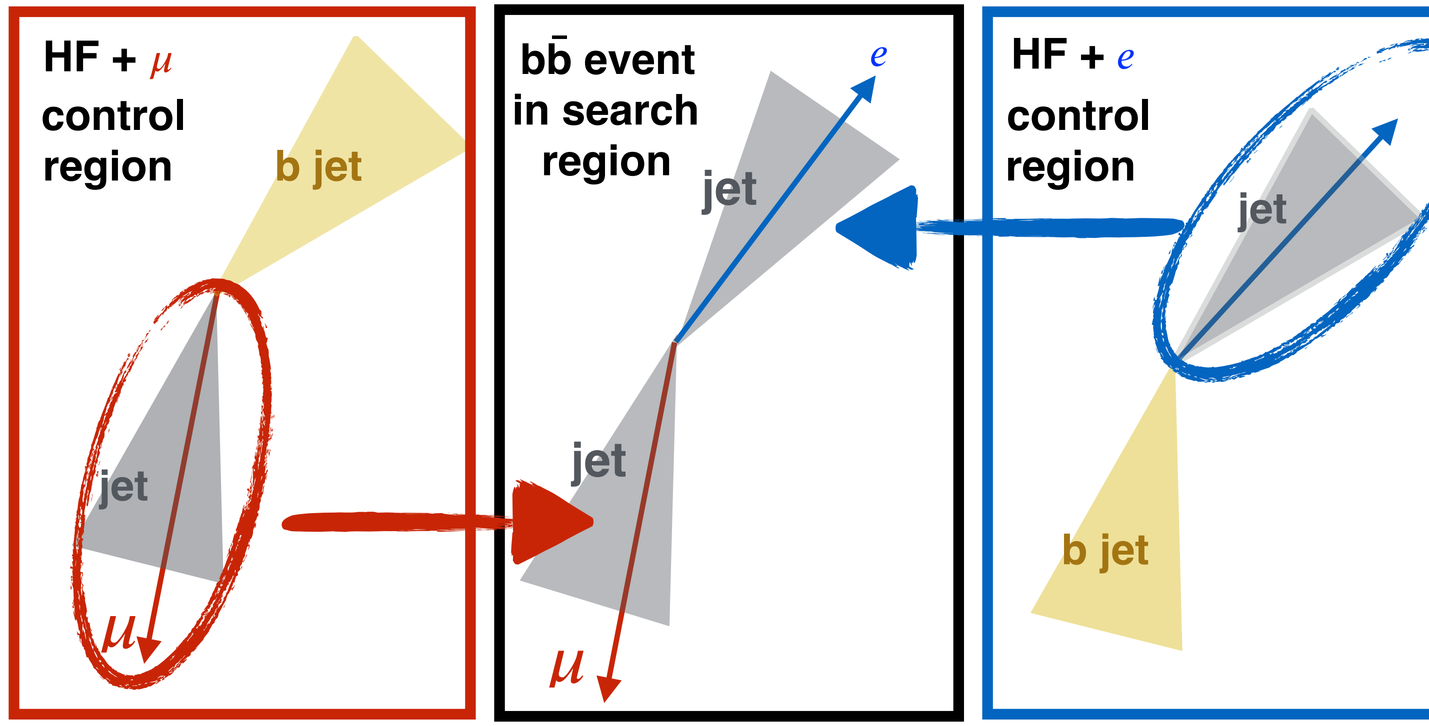
Dominant Background Prediction

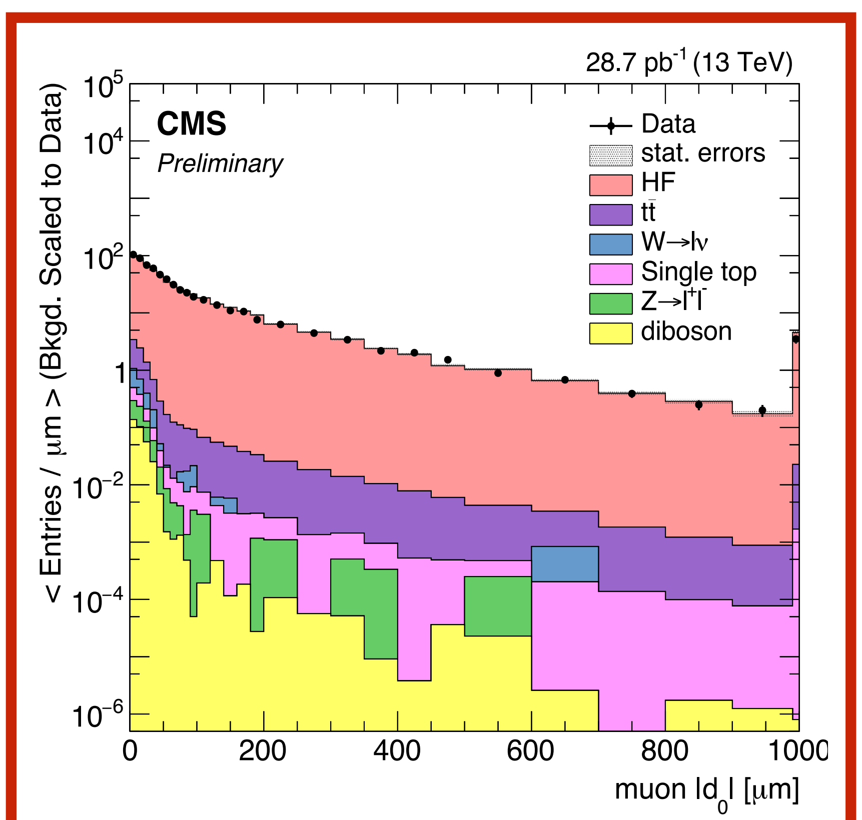
HF + μ/e control regions

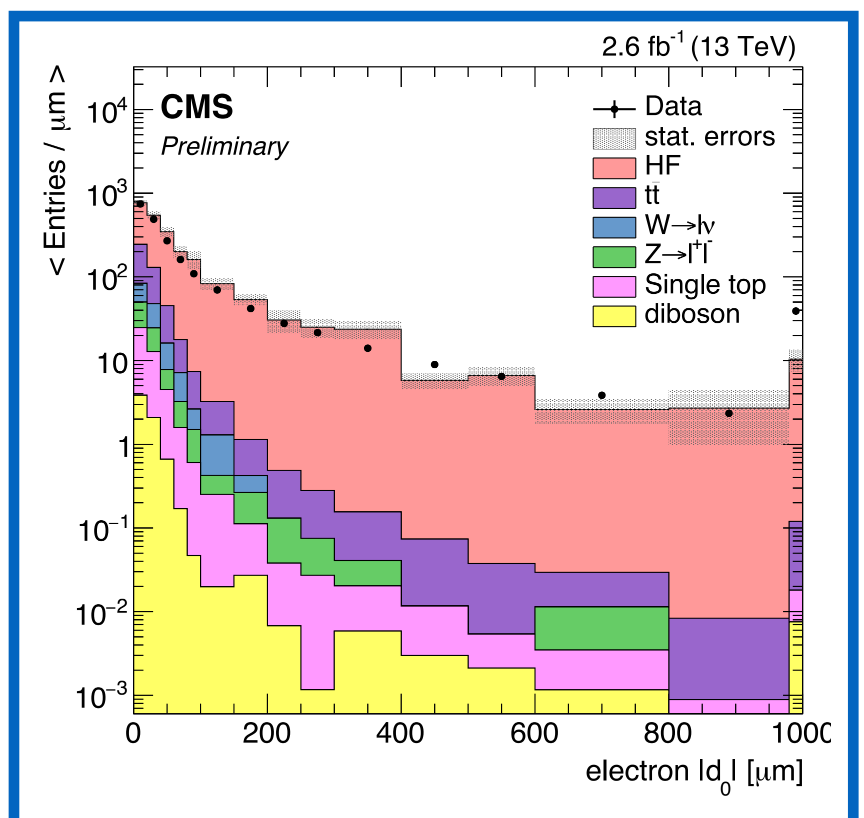
- b-tagged jet
- back-to-back jet with nearby lepton

Large, pure sample of HF events

Construct d_0 templates from data in these control regions

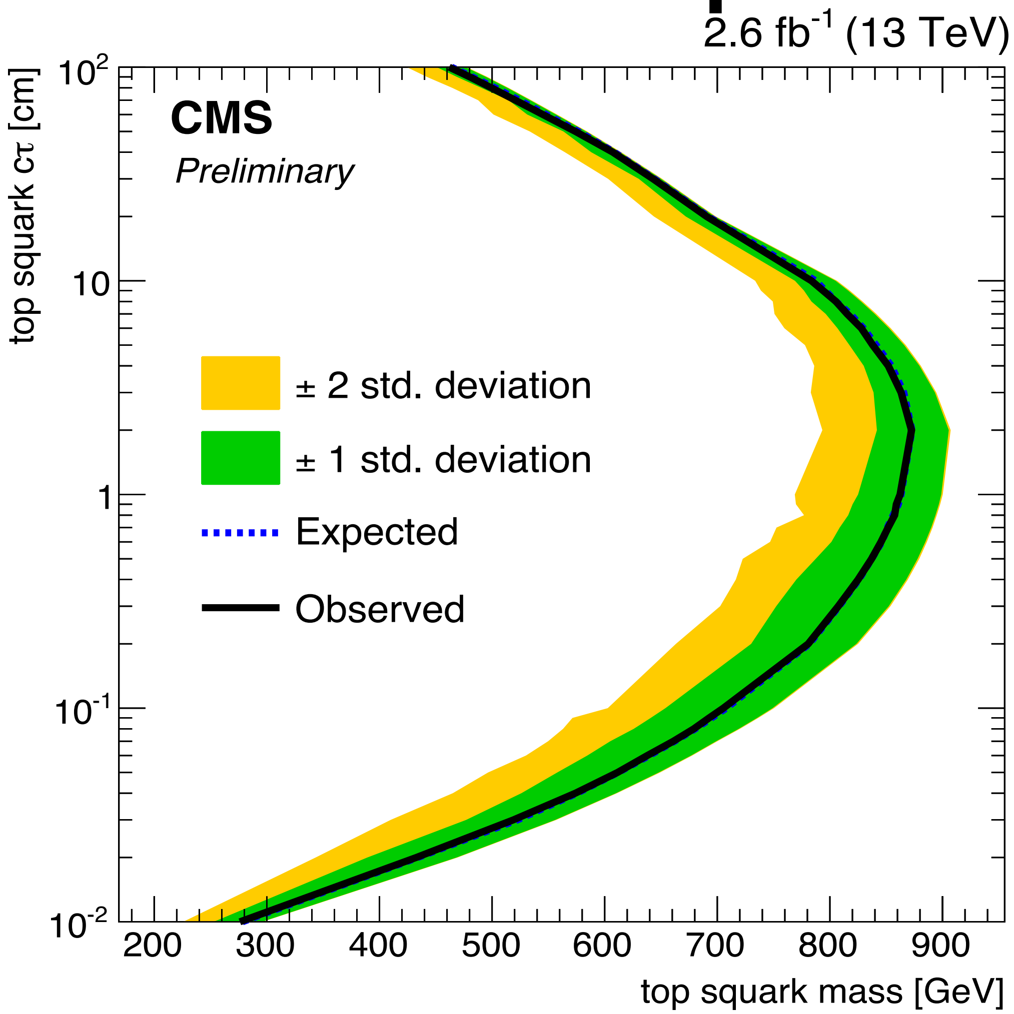






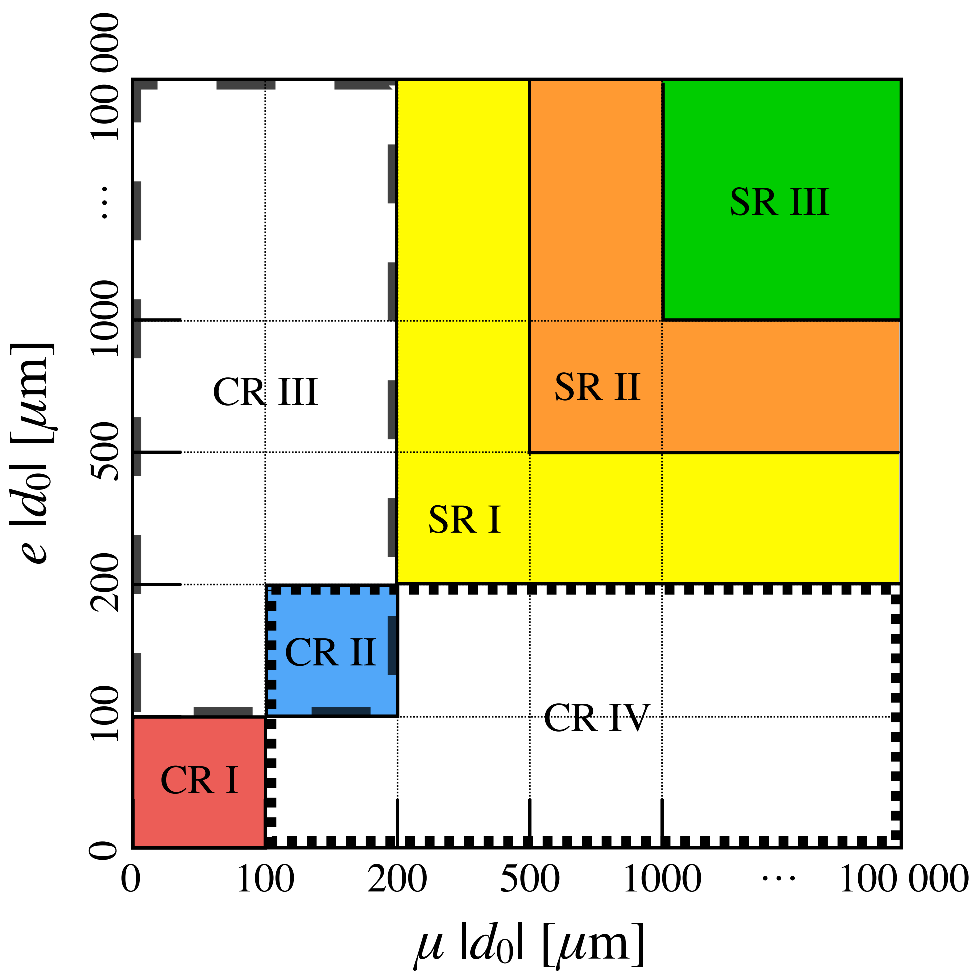
Calculate transfer factors from low d_0 sideband to high d_0 search regions

Displaced Leptons Result



- Best limit at about 2 cm, the stop mass is excluded up to 870 GeV
- Good agreement between observation and prediction within the three signal regions

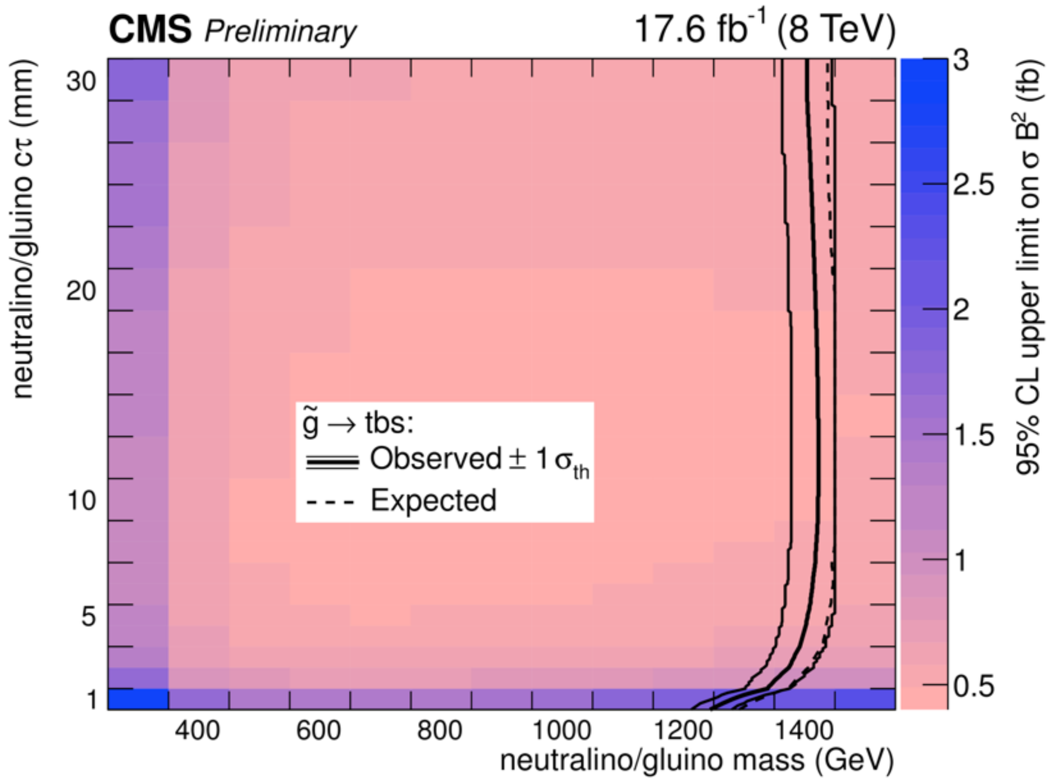
Approved by CMS:
Link to public page
Presented in ICHEP:
Link to the talk

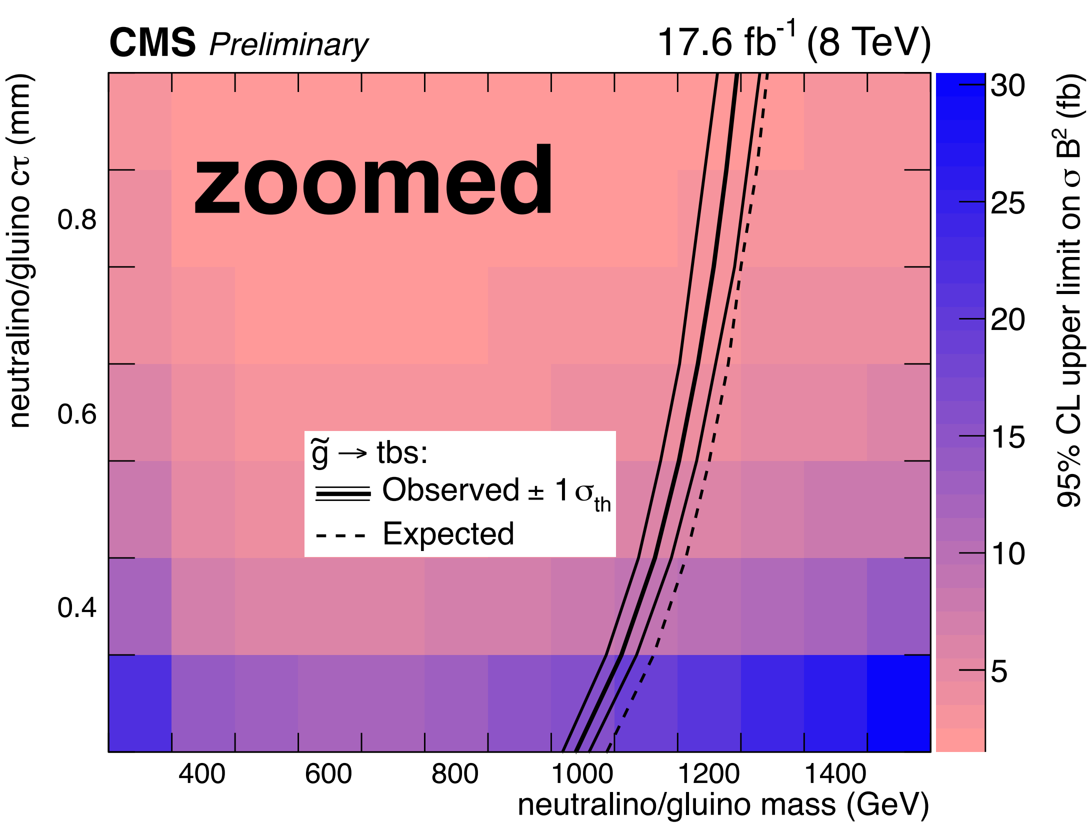


Event Source	Search Region I	Search Region II	Search Region III
non-HF sum	$(203 \pm 26) \times 10^{-3}$	$(410 \pm 170) \times 10^{-5}$	$(82 \pm 71) \times 10^{-5}$
data-driven HF	< 3.0	< 0.50	< 0.019
total background	< 3.2	< 0.50	< 0.020
observation	1	0	0
$pp \to \tilde{t}_1\tilde{t}_1^* (M_{\tilde{t}_1} = 700\,\text{GeV})$			
$c\tau = 0.1$ cm	3.8 ± 0.2	0.94 ± 0.06	0.16 ± 0.02
$c\tau = 1$ cm	5.2 ± 0.4	4.1 ± 0.3	7.0 ± 0.3
$c\tau = 10$ cm	0.8 ± 0.1	1.0 ± 0.1	5.8 ± 0.2
$c\tau = 100$ cm	0.009 ± 0.005	0.03 ± 0.01	0.27 ± 0.03

http://cds.cern.ch/record/2205146?ln=en

Displaced Vertex Results





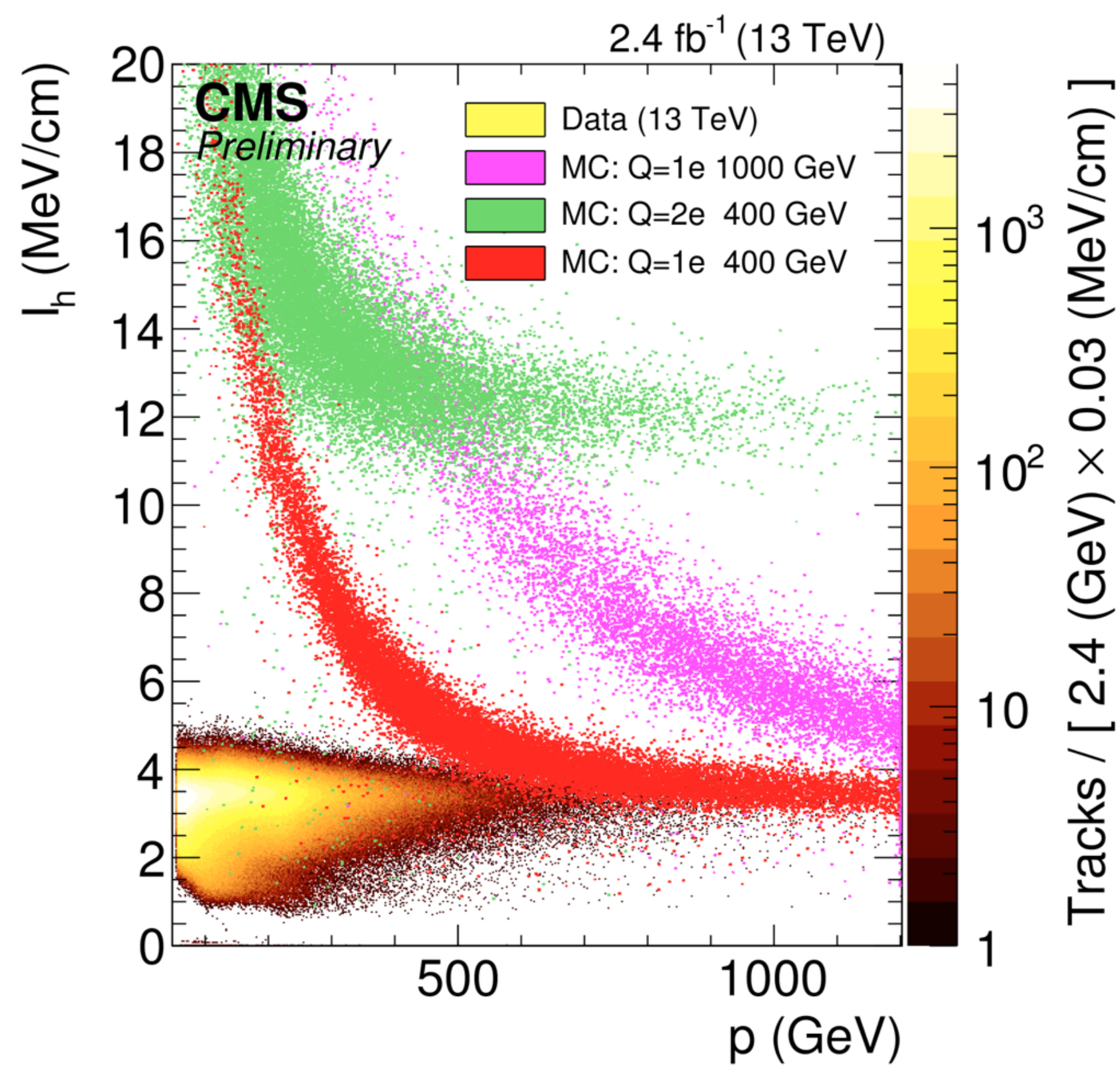
- Very small excess for $d_{vv} > 0.6$ with 7 events observed and 4.2 expected.
- Overall, observation agrees with prediction.
- Kinematic cuts limit analysis sensitivity below $m_g < 400$ GeV.
- Past the kinematic cuts signal efficiency is **as high as 60%.**
- **Excludes beyond 1 TeV gluino SMS xsec for all bins**, and beyond ~1400 GeV beyond a few millimeters.

Bin i	d_{VV} range	Observed n_i	Mean expected count
1	0.0–0.2 mm	6	6.2 ± 1.0
2	0.2–0.4 mm	193	192.2 ± 3.9
3	0.4–0.6 mm	45	48.0 ± 3.8
4	0.6–0.8 mm	5	3.5 ± 1.4
5	0.8–1.0 mm	1	0.3 ± 0.1
6	1.0–50 mm	1	0.3 ± 0.1

CMS: Heavy Stable Charged Particle (HSCP)

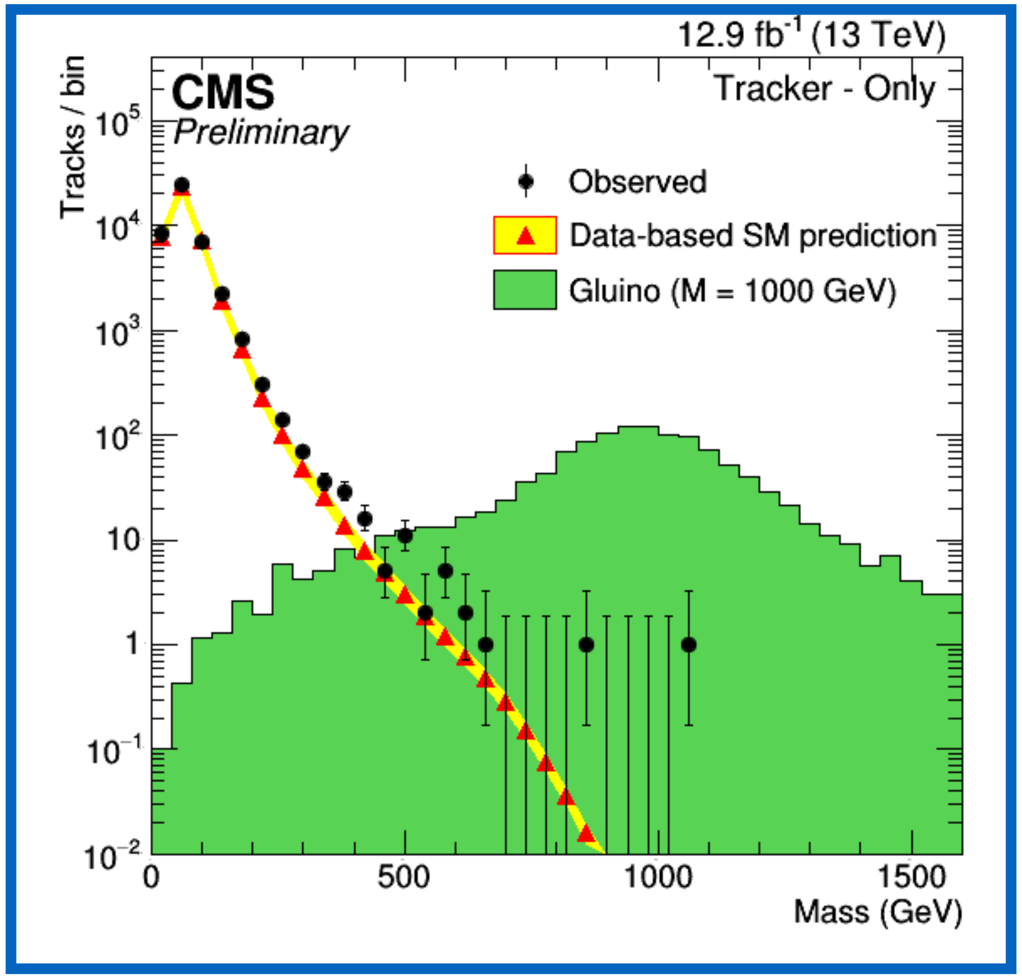
- Search for long-lived (stable on detector scales) charged R-Hadrons.
- Most mature analysis for CMS long-lived subgroup with 7,8, and 13 TeV results.
- Two main discriminating variables:
  - **dE/dx (I_h)**: energy loss in tracker.
  - $1/\beta$: time of flight to muon chambers.
- Trigger using a Muon or Missing Energy as leptonic-like HSCPs are generally reconstructed as muons.

cds.cern.ch/record/2114818



$$I_h = K\frac{m^2}{p^2} + C$$

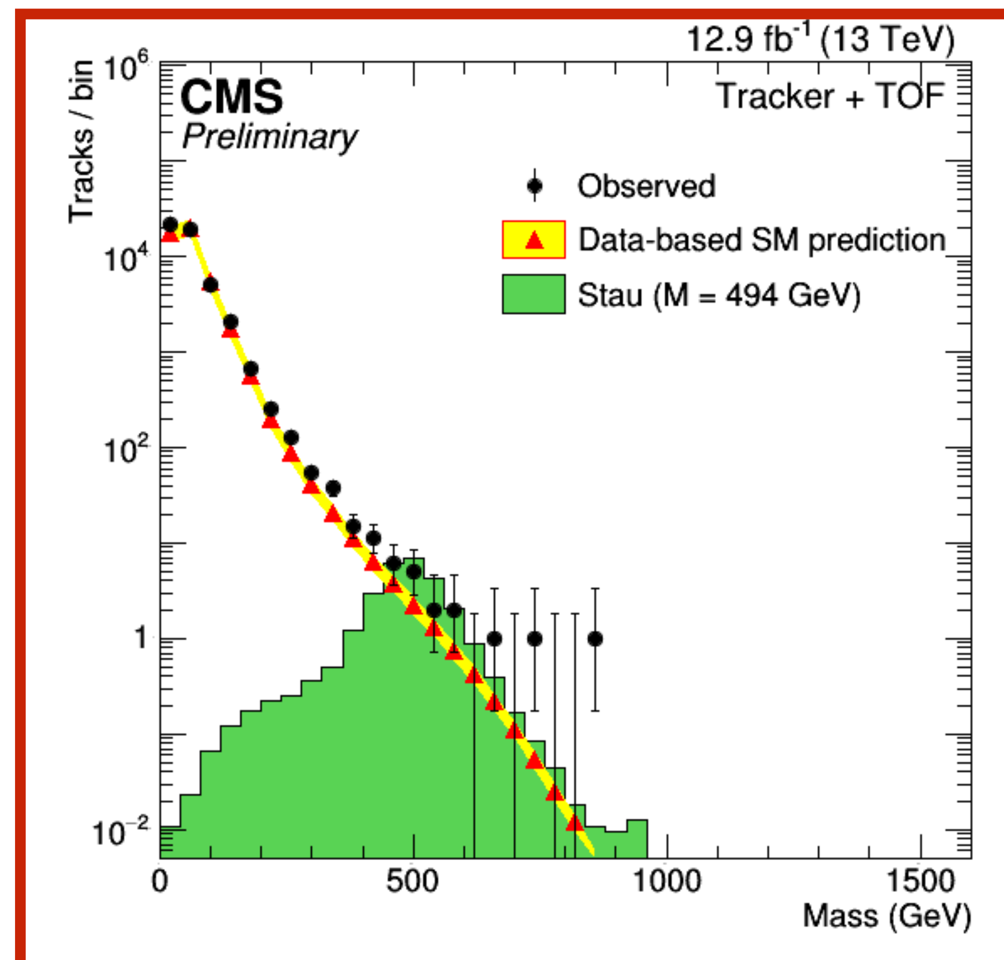
Background Estimation



- dE/dx measurement can be inverted into a mass measurement
- **This inversion** has constants K and C calibrated using low momentum protons (HIP)

$$I_h = K\frac{m^2}{p^2} + C$$

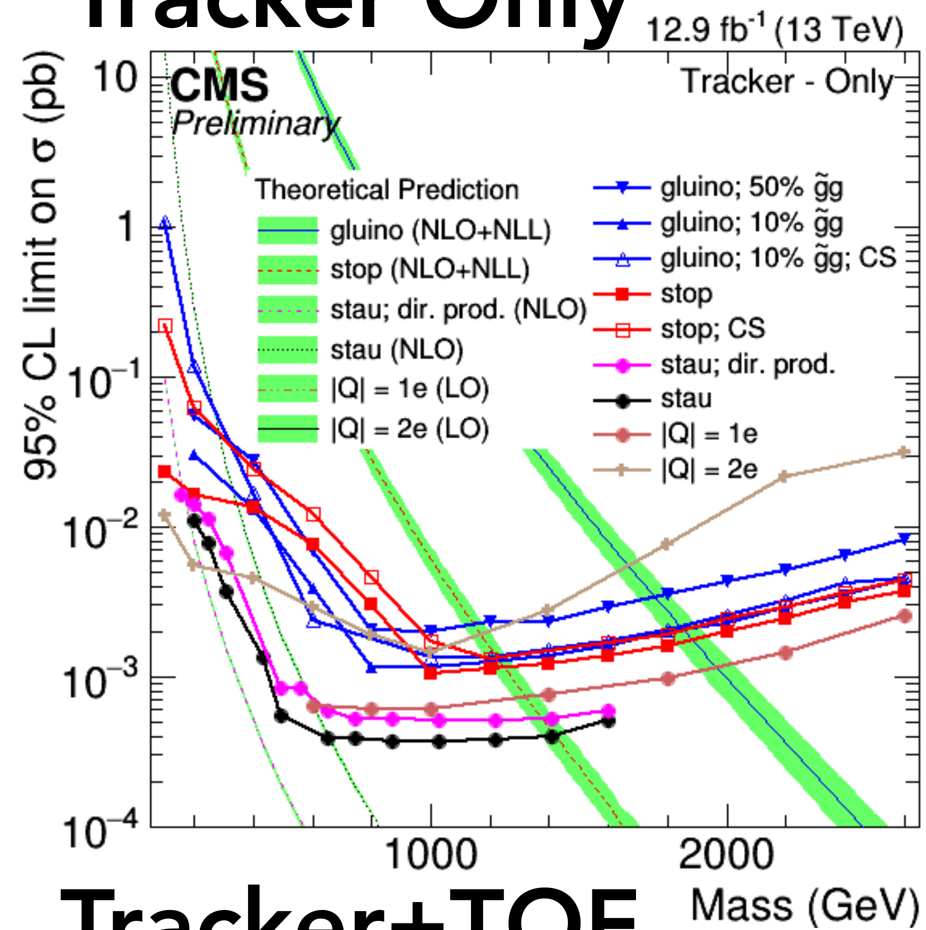
- Separate **Tracker Only** and **Tracker + TOF** searches are performed
- Background estimation is validated in loose regions of dE/dx and 1/beta



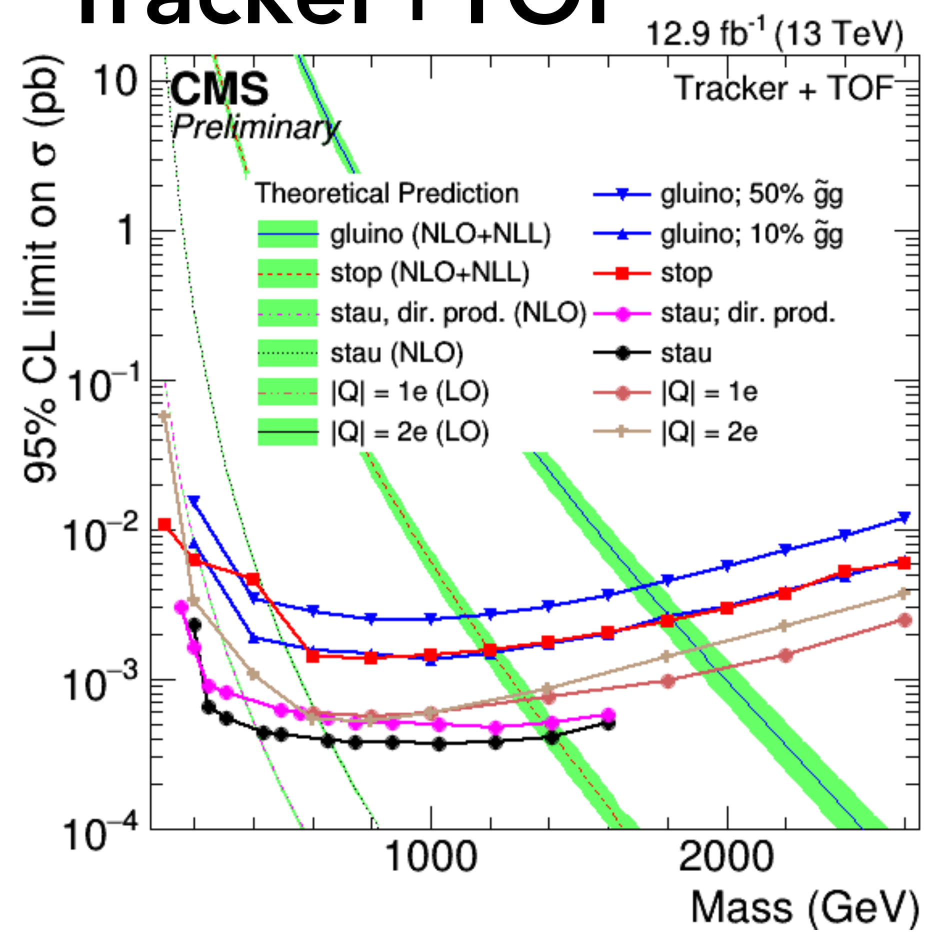
HSCP Results

- Numerous interpretations. Including stop, gluinos, staus, and Q=2 models
- Limits are placed up to 1.8 TeV (1-10 fb)
- A strict cross-section exclusion with no sensitivity lost to the branching fraction.

Tracker Only



Tracker+TOF



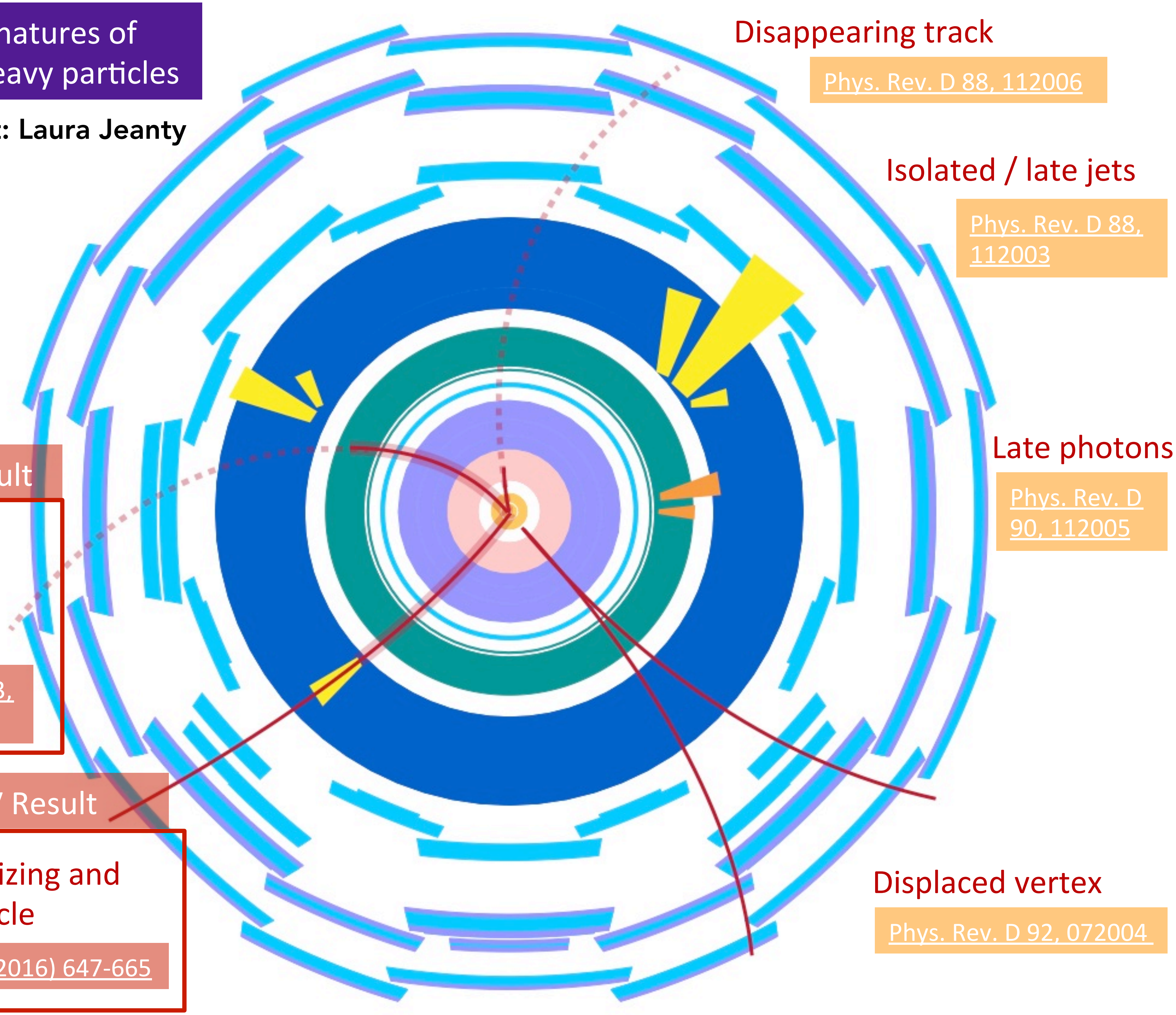
	Selection cuts				Numbers of events 2016	
	p_T (GeV)	I_{as}	$1/\beta$	Mass (GeV)	Pred.	Obs.
Trk-only	> 65	> 0.3	-	> 0	92.4 ± 18.9	94
				> 100	43.2 ± 8.9	46
				> 200	4.3 ± 0.9	7
				> 300	0.86 ± 0.18	0
				> 400	0.25 ± 0.05	0
Trk+TOF	> 65	> 0.175	> 1.250	> 0	53.1 ± 10.6	50
				> 100	7.7 ± 1.5	8
				> 200	0.82 ± 0.17	2
				> 300	0.15 ± 0.03	1
				> 400	0.04 ± 0.01	1

ATLAS Summary Signatures

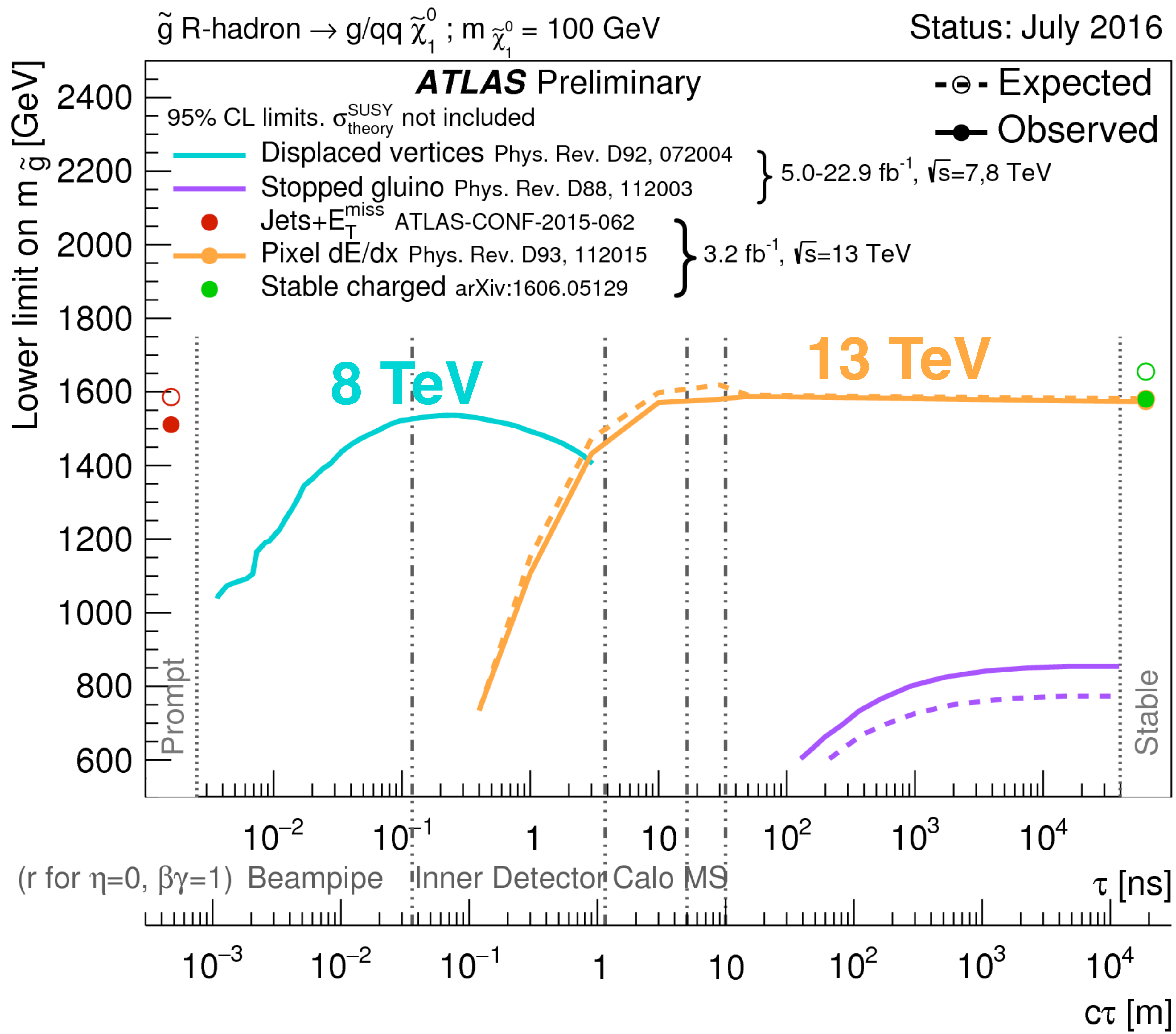
Detector signatures of long-lived heavy particles

Graphic Credit: Laura Jeanty

not shown: lepton jets



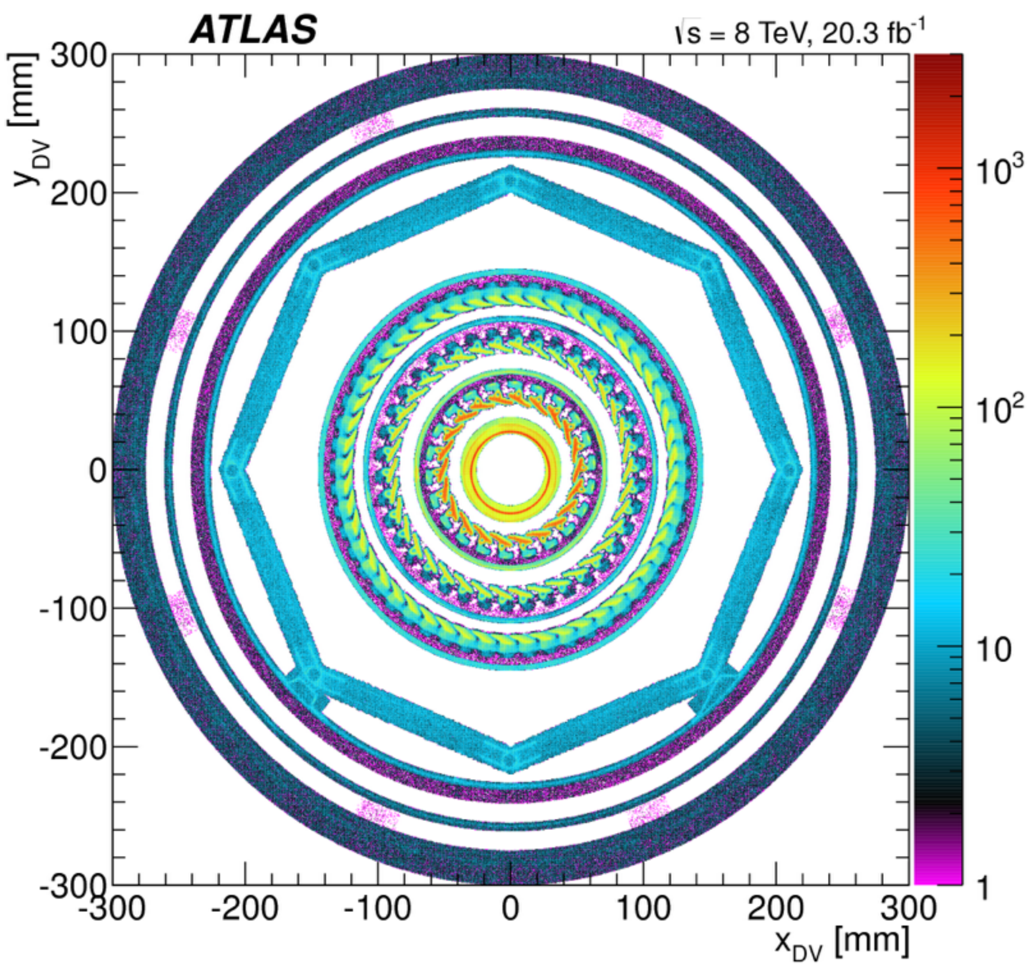
ATLAS Long-lived History



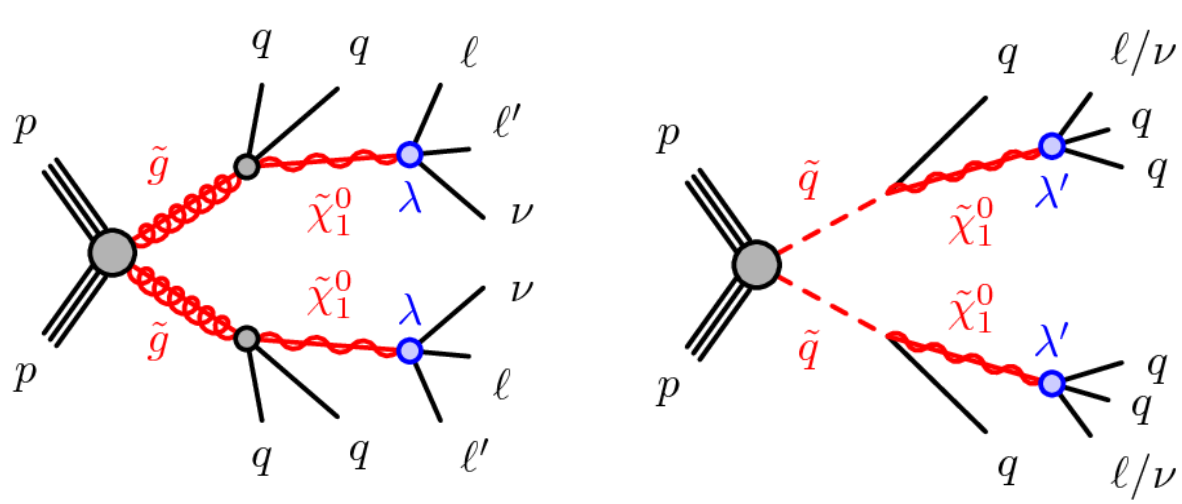
ATLAS Displaced Vertex/Dileptons (8 TeV)

Phys. Rev. D 92, 072004

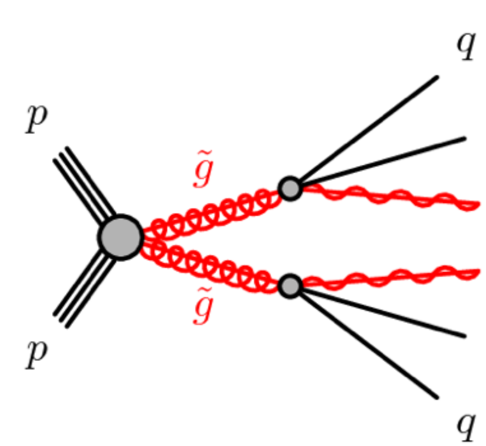
material vertex veto



- Very Inclusive Trigger Strategy (Vertex + X):
  - Muon p_t >50
  - 1 Photon p_t > 120 **or** 2 Photon p_t > 40
  - 4 Jets p_t > 40 **or** 5 Jets p_t > 55 **or** 6 Jets p_t > 45
  - ME_T > 80 GeV
- Reconstruct a secondary vertex and **veto vertices that are reconstructed within the detector material.**
- Require at least 5 tracks per vertex **or** two OS leptons.



rpv



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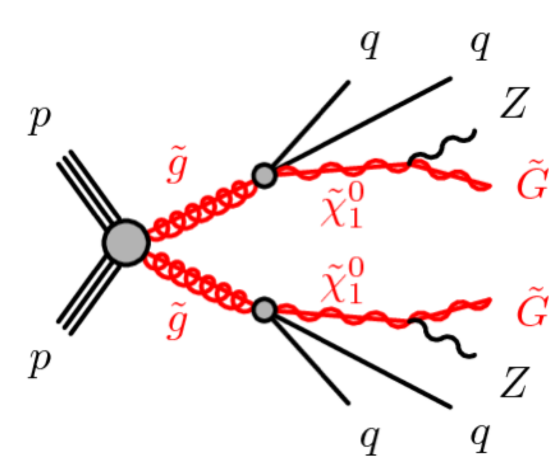


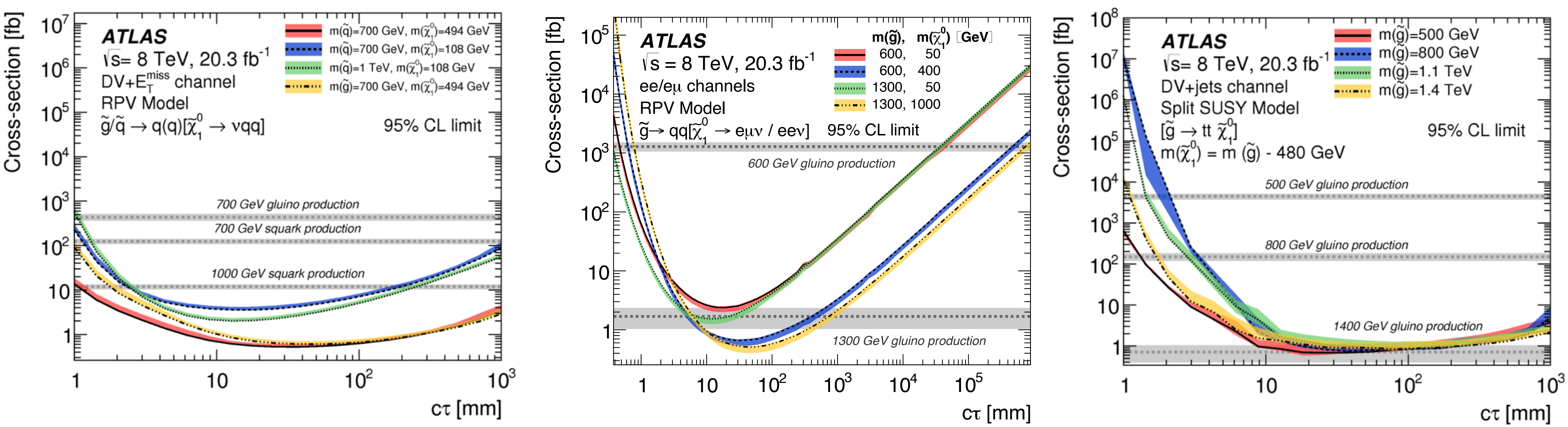
gmsb

Displaced Vertex/Di-lepton Results

- Large number of interpretations. Too many to list here.
- Background free signal region sets strong limits.
- No displaced vertex events are observed in all channels.

Channel	No. of background vertices $(\times 10^{-3})$
DV+jet	$410 \pm 7 \pm 60$
DV+E_T^{miss}	$10.9 \pm 0.2 \pm 1.5$
DV+muon	$1.5 \pm 0.1 \pm 0.2$
DV+electron	$207 \pm 9 \pm 29$

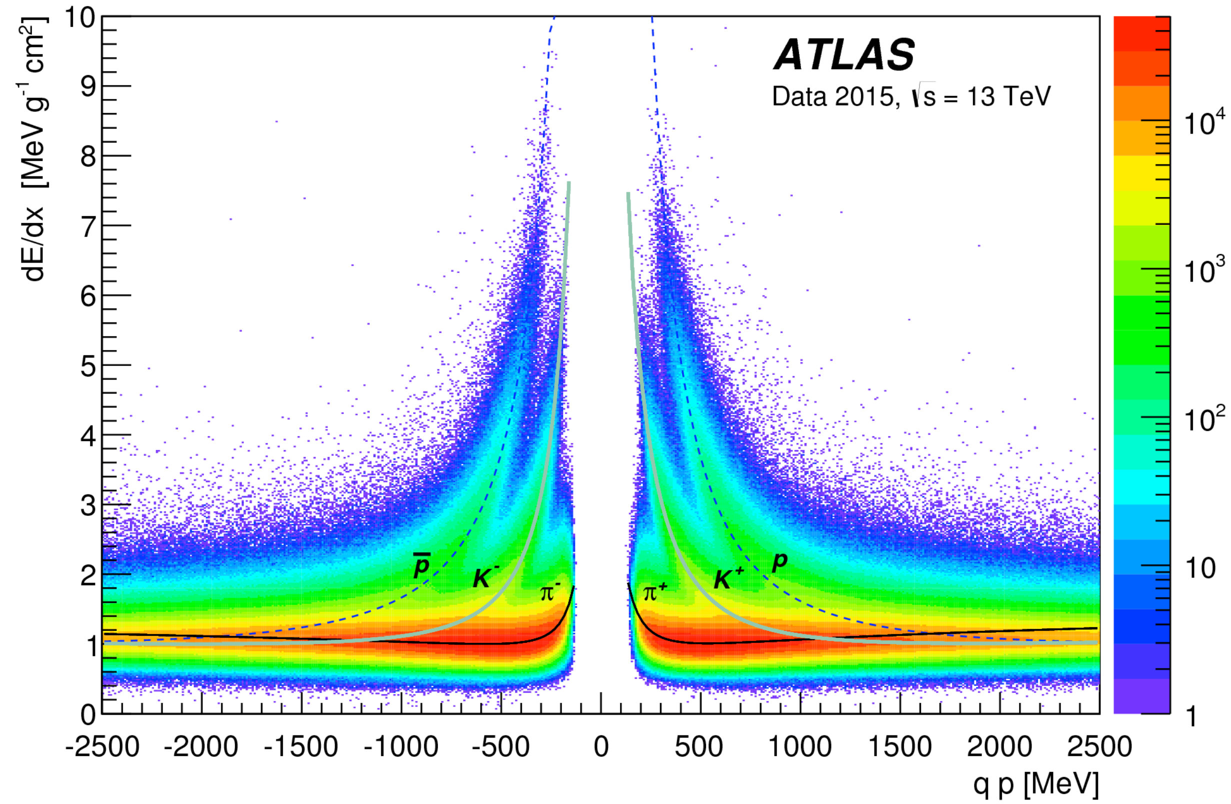
Channel	No. of background vertices $(\times 10^{-3})$
e^+e^-	$1.0 \pm 0.2 \ ^{+0.3}_{-0.6}$
$e^\pm\mu^\mp$	$2.4 \pm 0.9 \ ^{+0.8}_{-1.5}$
$\mu^+\mu^-$	$2.0 \pm 0.5 \ ^{+0.3}_{-1.4}$

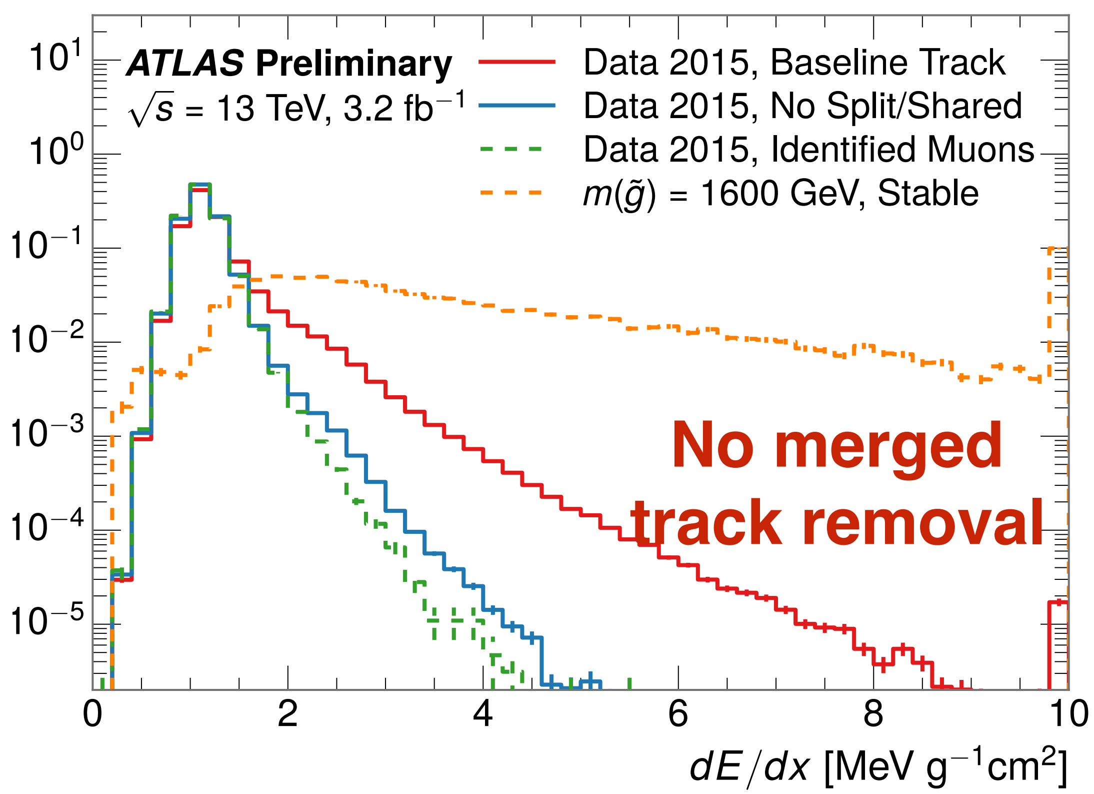


ATLAS Search for Meta-stable R-Hadrons

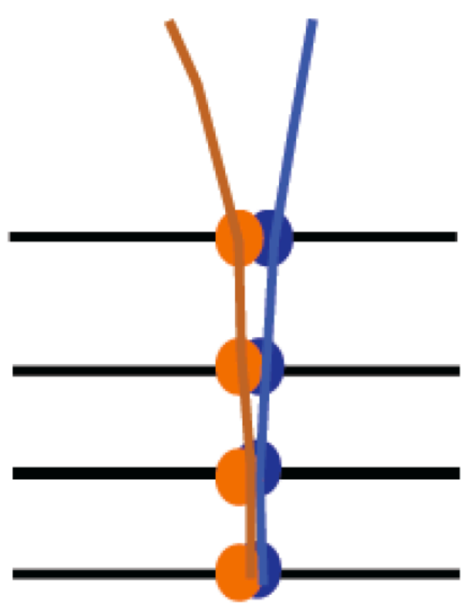
Phys. Rev. D 93, 112015

- Uses dE/dx to look at lifetimes >12cm
- Triggers on missing energy caused by recoiling ISR from heavy pair production.
- Large background tail in dE/dx due to merged tracks of charged particles.
- Neural net performed at track reconstruction removes merged tracks.

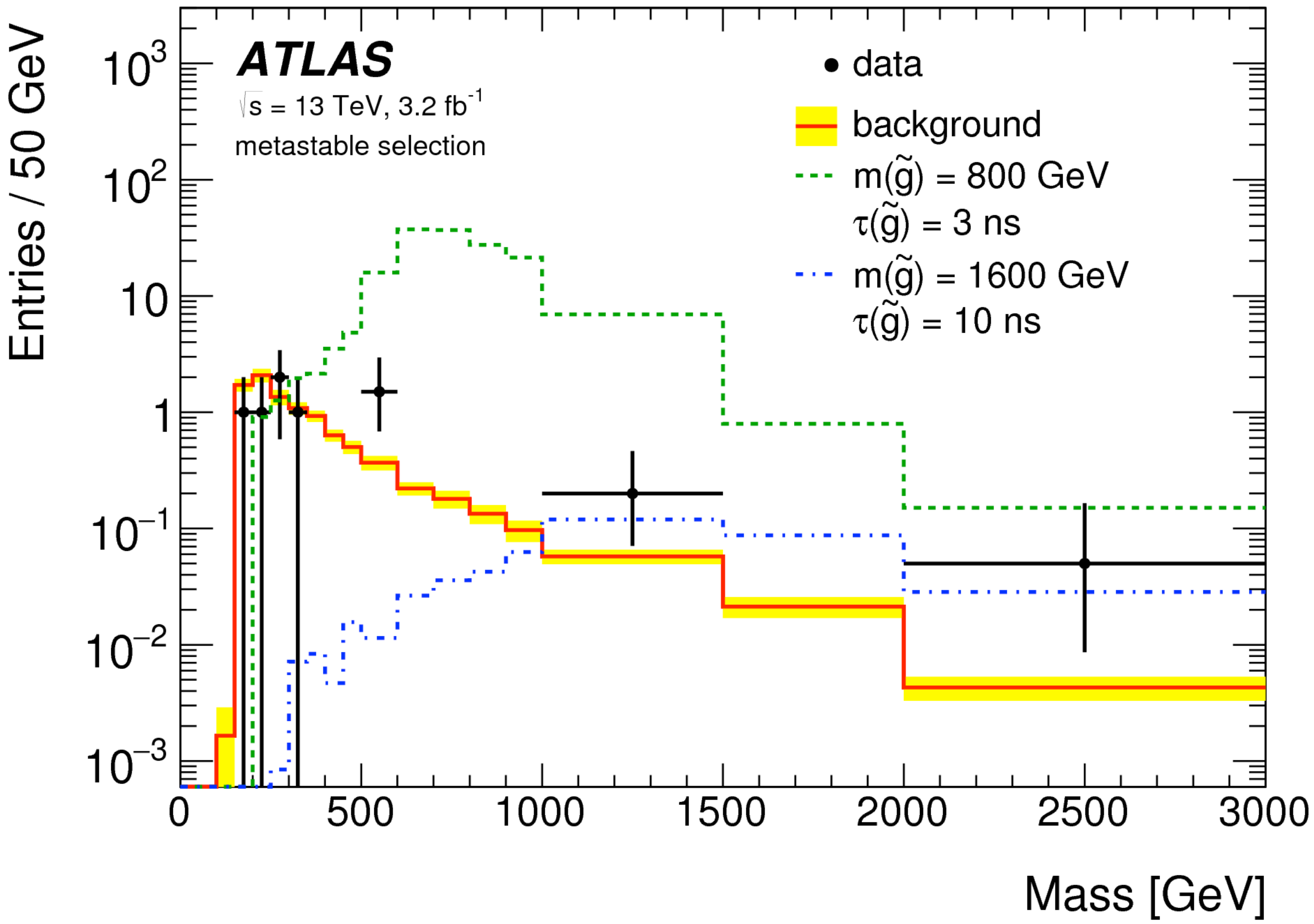


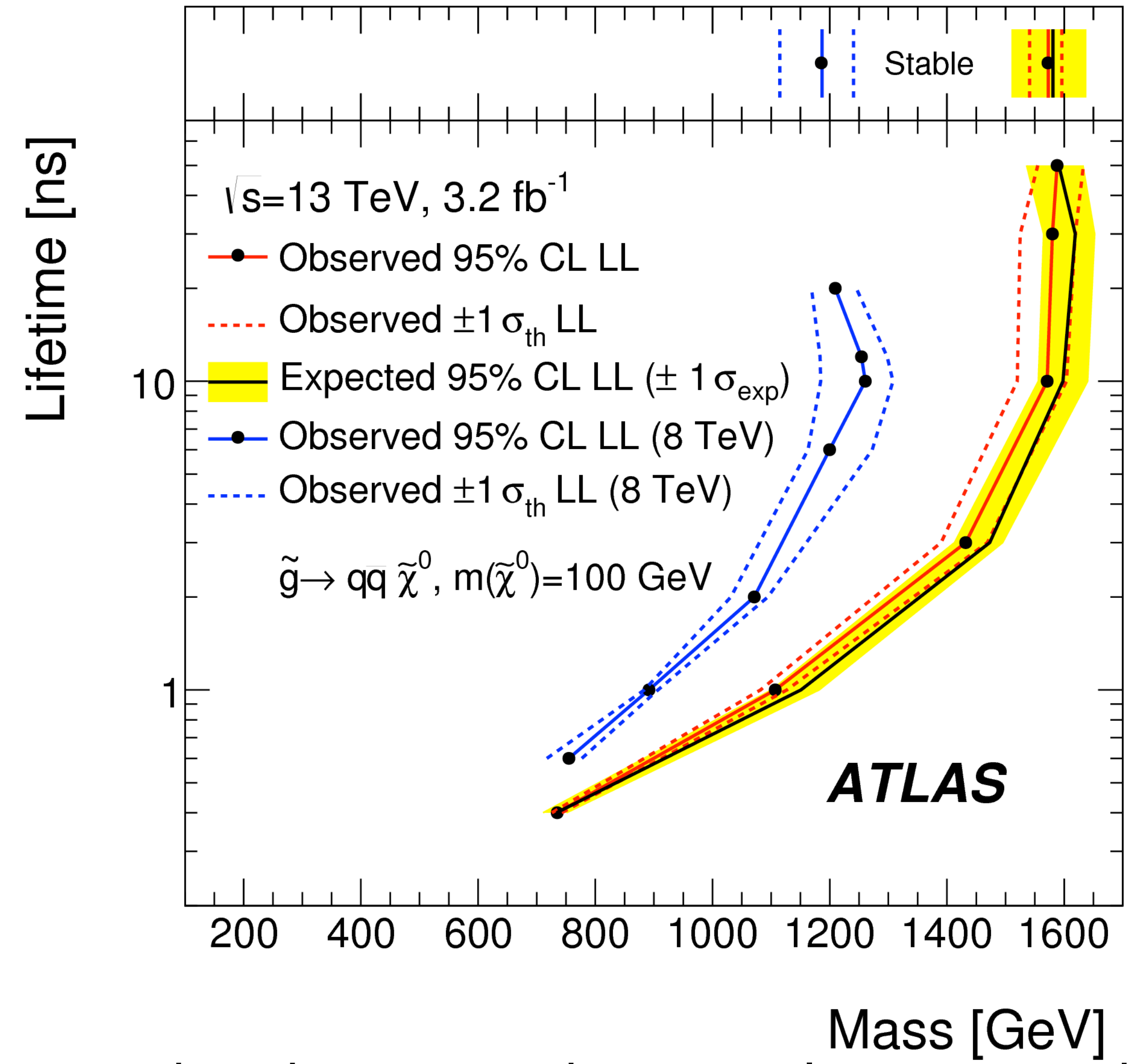


- New inner barrel layer (IBL) improves dE/dx resolution.
- Tail in dE/dx suppressed by 50%.



Meta-Stable R-hadrons Result

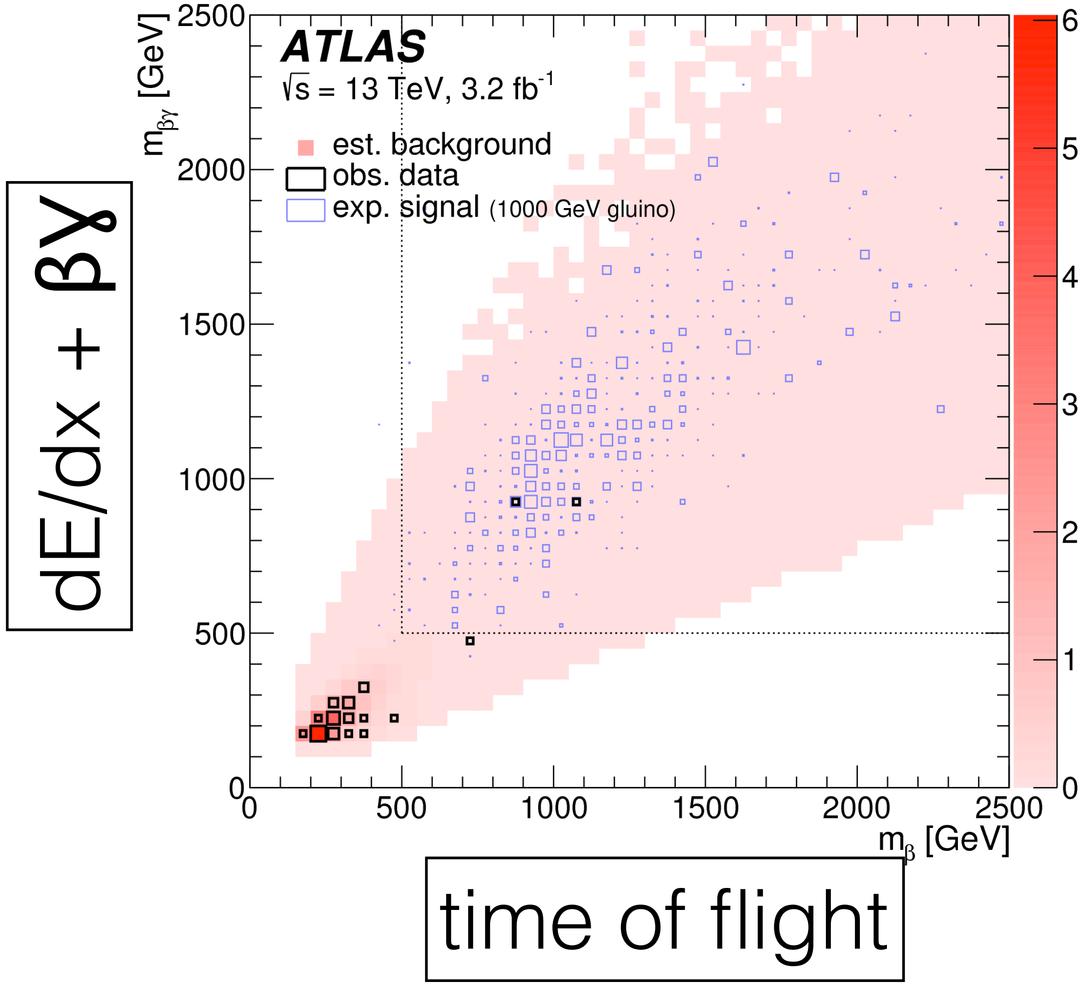


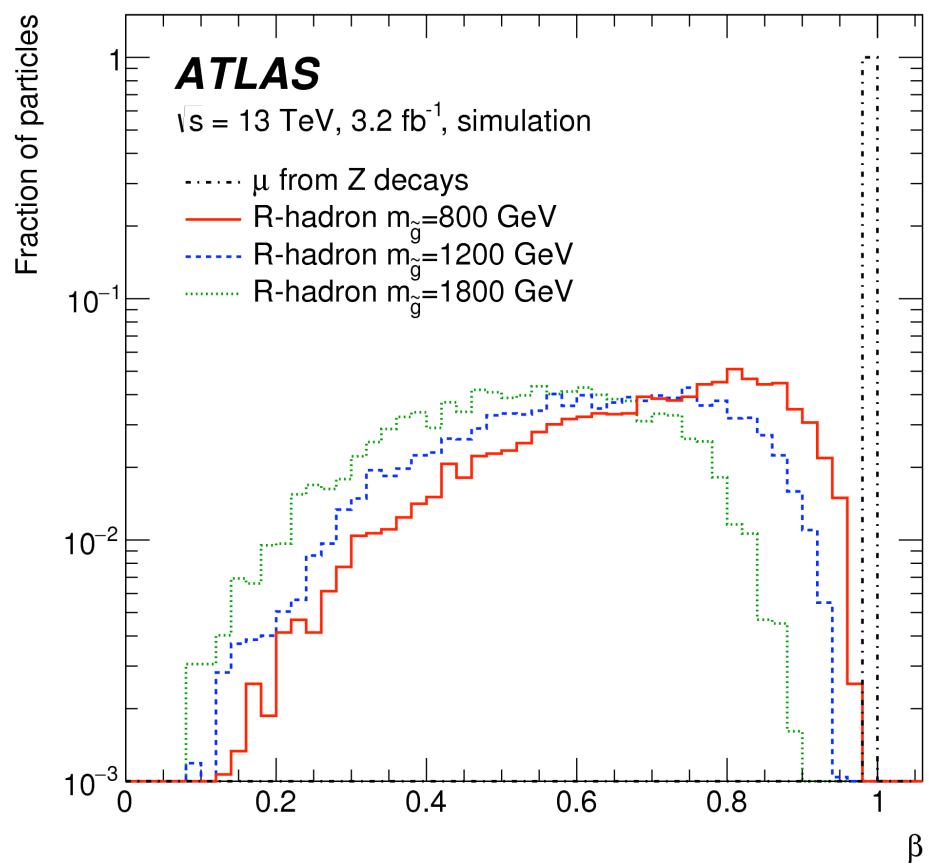


- The reconstructed mass distribution from dE/dx is used to set limits on the mass of the R-hadron.
- R-hadron decay to qq+neutralino with fixed $m_{neutralino}$ = 100 GeV.
- R-hadrons are excluded between 740 and 1590 GeV for lifetimes of 12 cm to stable.

ATLAS: Search for stable R-hadrons

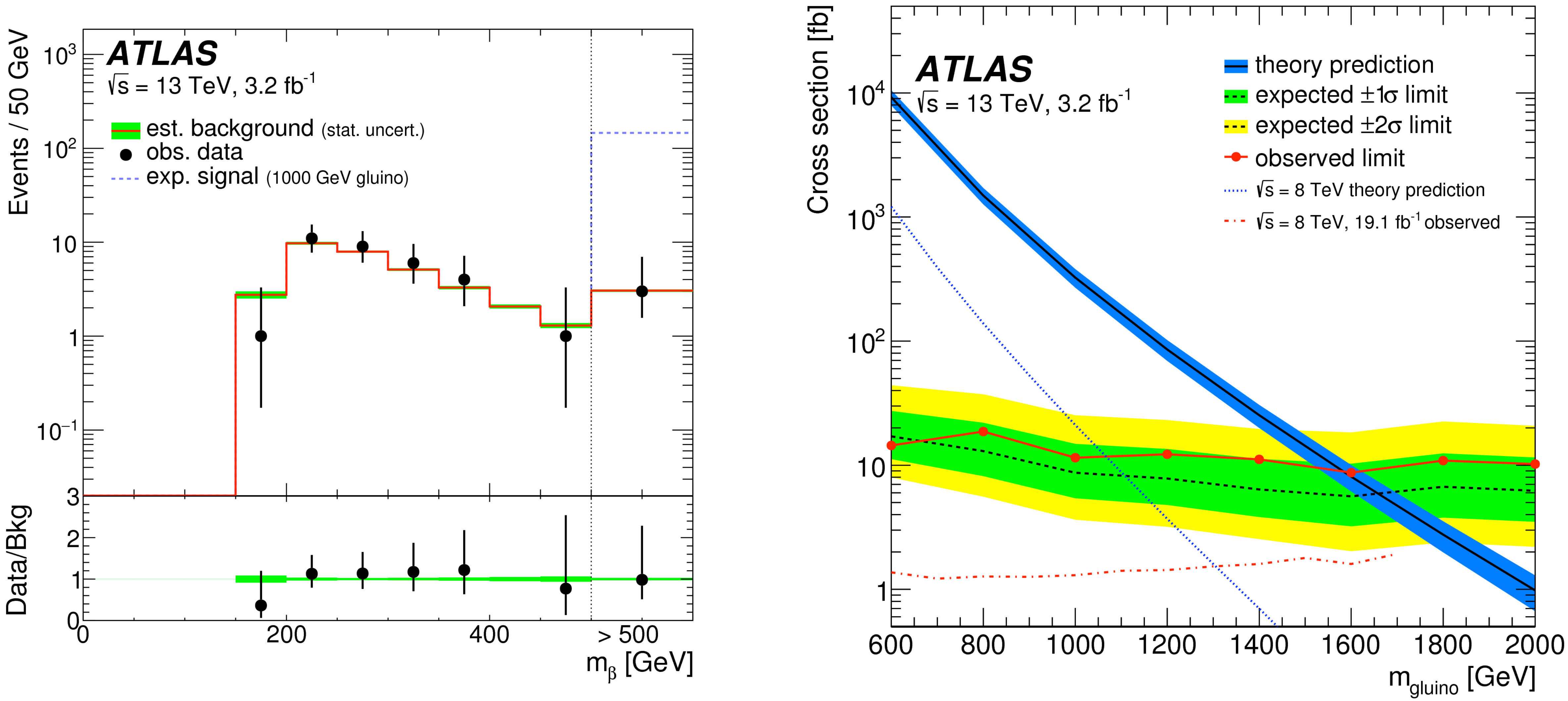
- Analysis formed in the plane of two mass estimations:
  - dE/dx and track βγ.
  - Calorimeter time of flight.
- Estimate background using sidebands of track momentum, β and βγ.





- Trigger using Missing Energy
- Sidebands yield background pdfs, which are used to estimate the background in the signal region

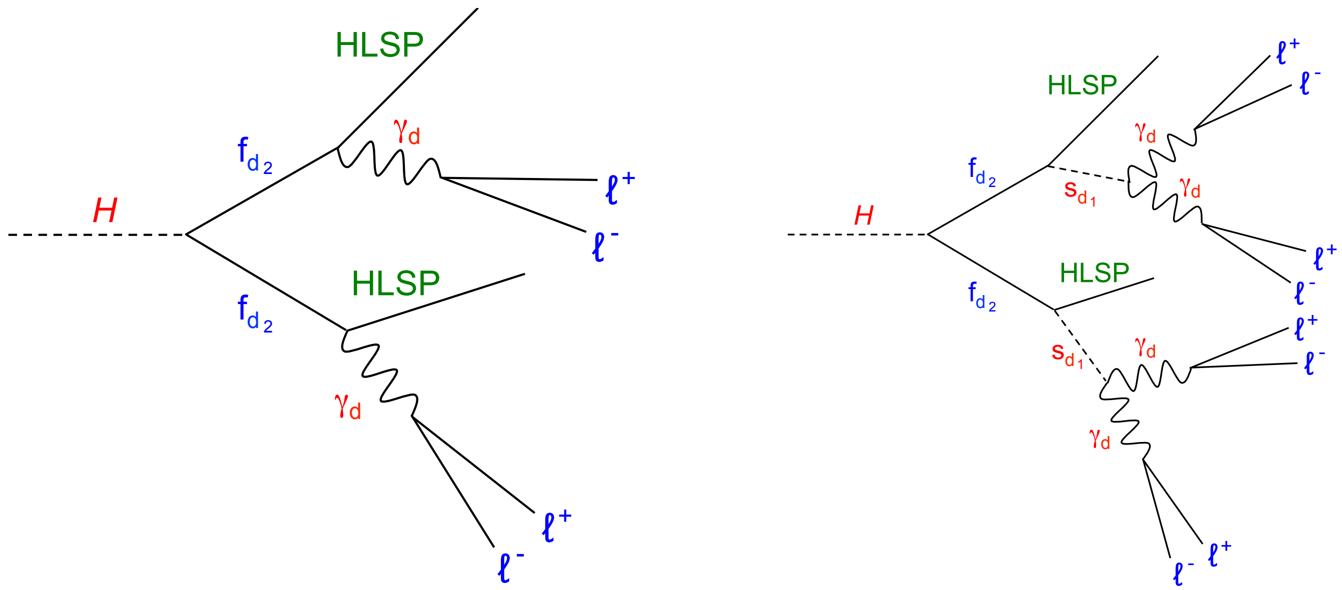
Stable R-hadron Result



Limit on production cross section set based on events with predicted mass above a given value (varies by the signal model). 95% confidence upper limits:

- gluinos: 1580 GeV
- stop: 890 GeV
- sbottoms: 805 GeV

ATLAS: Displaced Lepton Jets



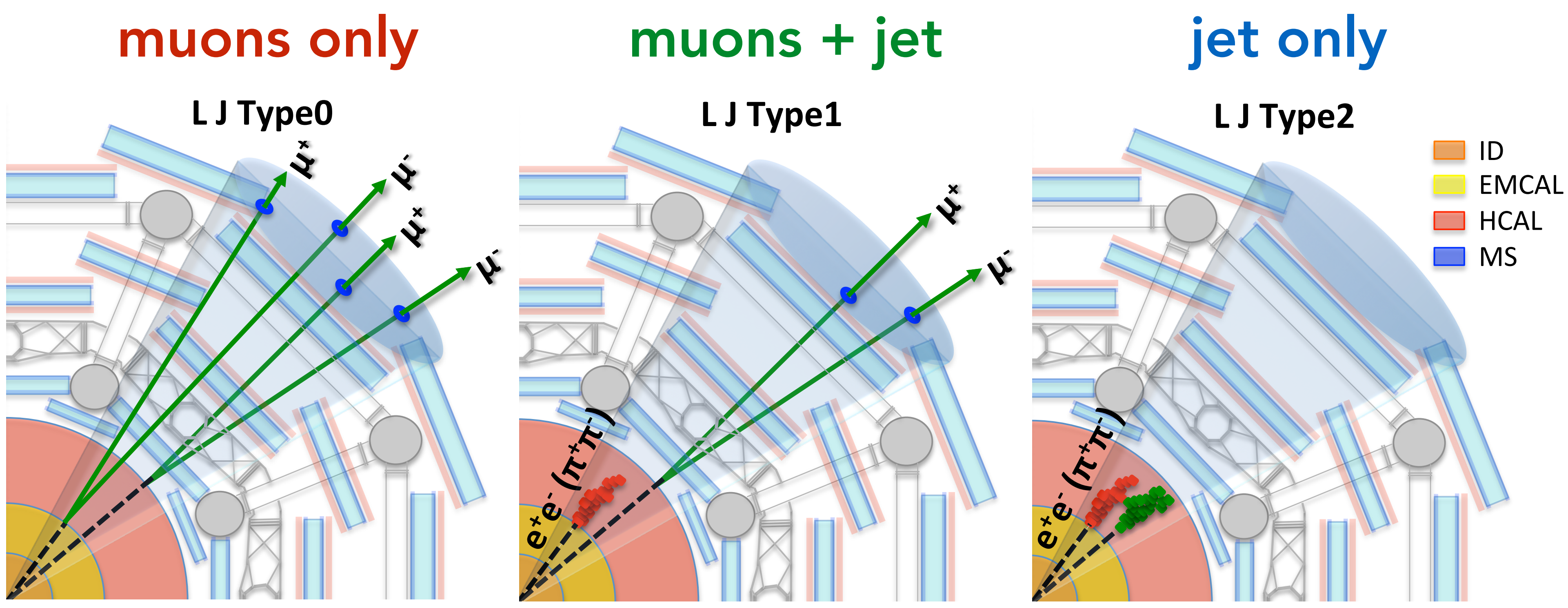
dark photon is very light <1 GeV

- New result since ICHEP: **ATLAS-CONF-2016-042**
- Search for highly collimated jets lepton jets produced by a 125 GeV Higgs
- Robust displaced trigger strategy. Three specialized triggers
  - Narrow Scan: 1 soft muon $p_t > 6$ in a cone near a harder muon $p_t > 20$ GeV
  - Tri-muon MS: 3 Muons $p_t > 6$ only within the muon spectrometer
  - Calo Ratio: Single Isolated jet with small EM fraction

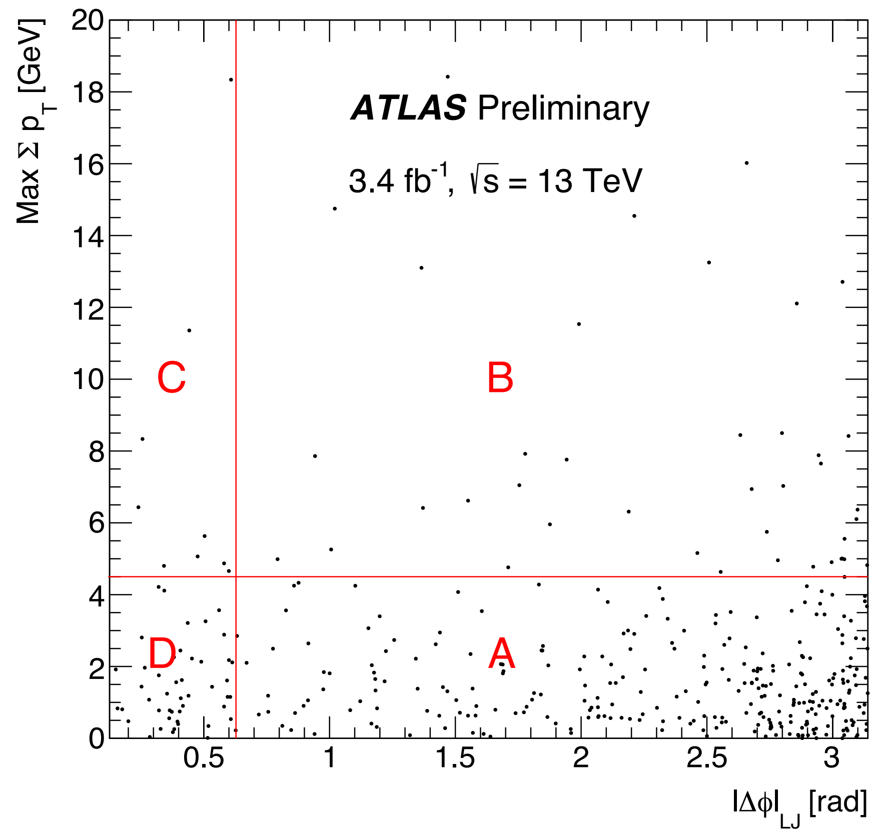
acceptance x efficiency

Trigger	Higgs $\rightarrow 2\gamma_d + X$ $m_H = 125$ GeV	Higgs $\rightarrow 2\gamma_d + X$ $m_H = 800$ GeV	Higgs $\rightarrow 4\gamma_d + X$ $m_H = 125$ GeV	Higgs $\rightarrow 4\gamma_d + X$ $m_H = 800$ GeV
Tri-muon MS-only	2.0	2.4	4.9	7.8
Narrow-Scan	10.6	23.0	8.3	38.4
CalRatio	0.3	9.7	0.1	7.4
OR of all	11.9	32.0	11.8	44.8

ATLAS: Lepton Jet Analysis

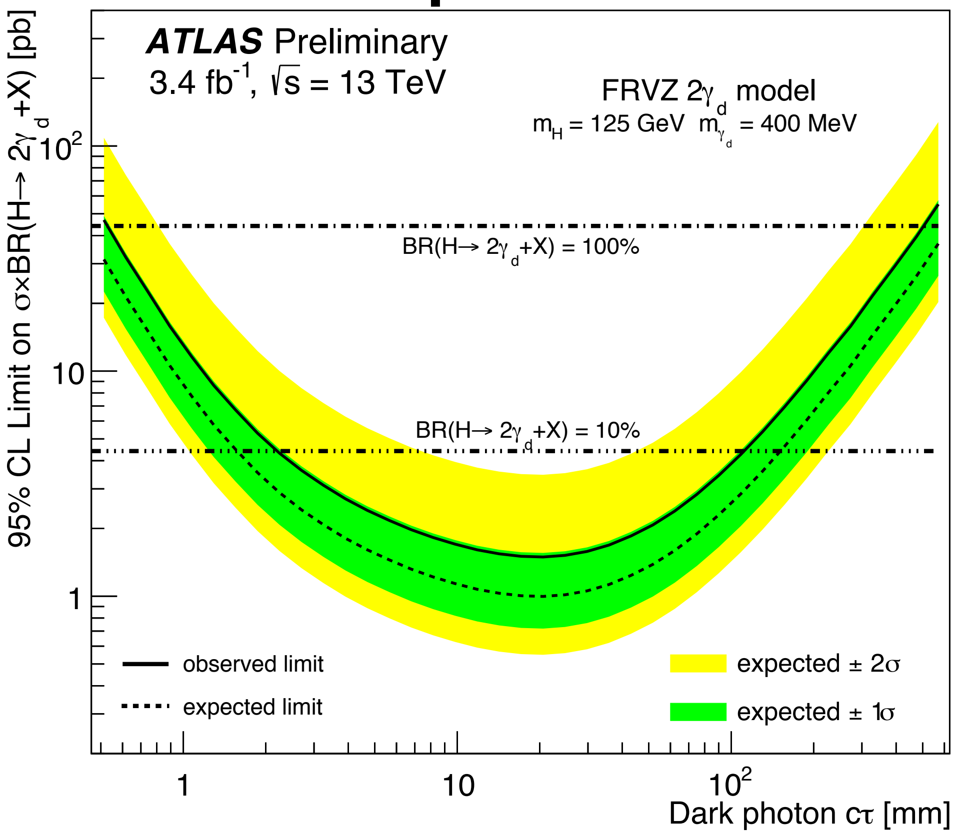


- Background prediction is data driven using ABCD method of uncorrelated variables
  - ΔΦ between the two lepton jets.
  - lepton jet in event with the highest sum track p_t
- Analysis gains inclusivity splitting jets into 3 types (above)



Lepton Jets Results

two dark photon



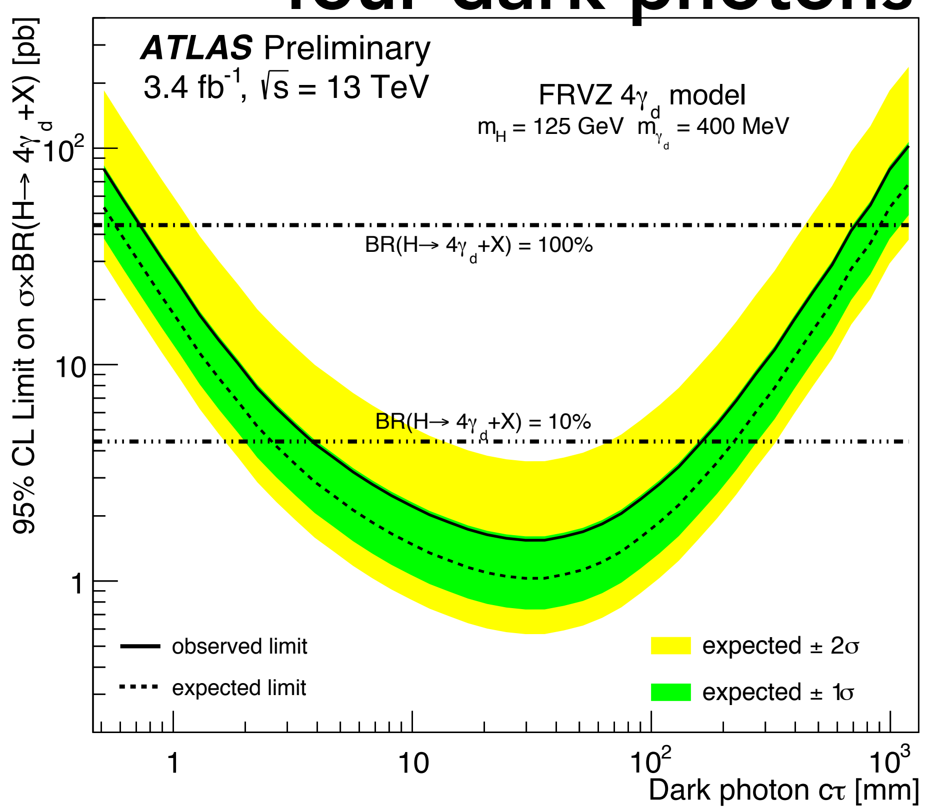
final yields

Category	Observed events	Expected background
All events	285	231 ± 12 (stat) ± 62 (syst)
Type2–Type2 excluded	46	31.8 ± 3.8 (stat) ± 8.6 (syst)
Type2–Type2 only	239	241 ± 41(stat) ± 65(syst)

- Good agreement between observed and expected with and without Type II jets
- Limits for the 4 and 2 dark photon final states

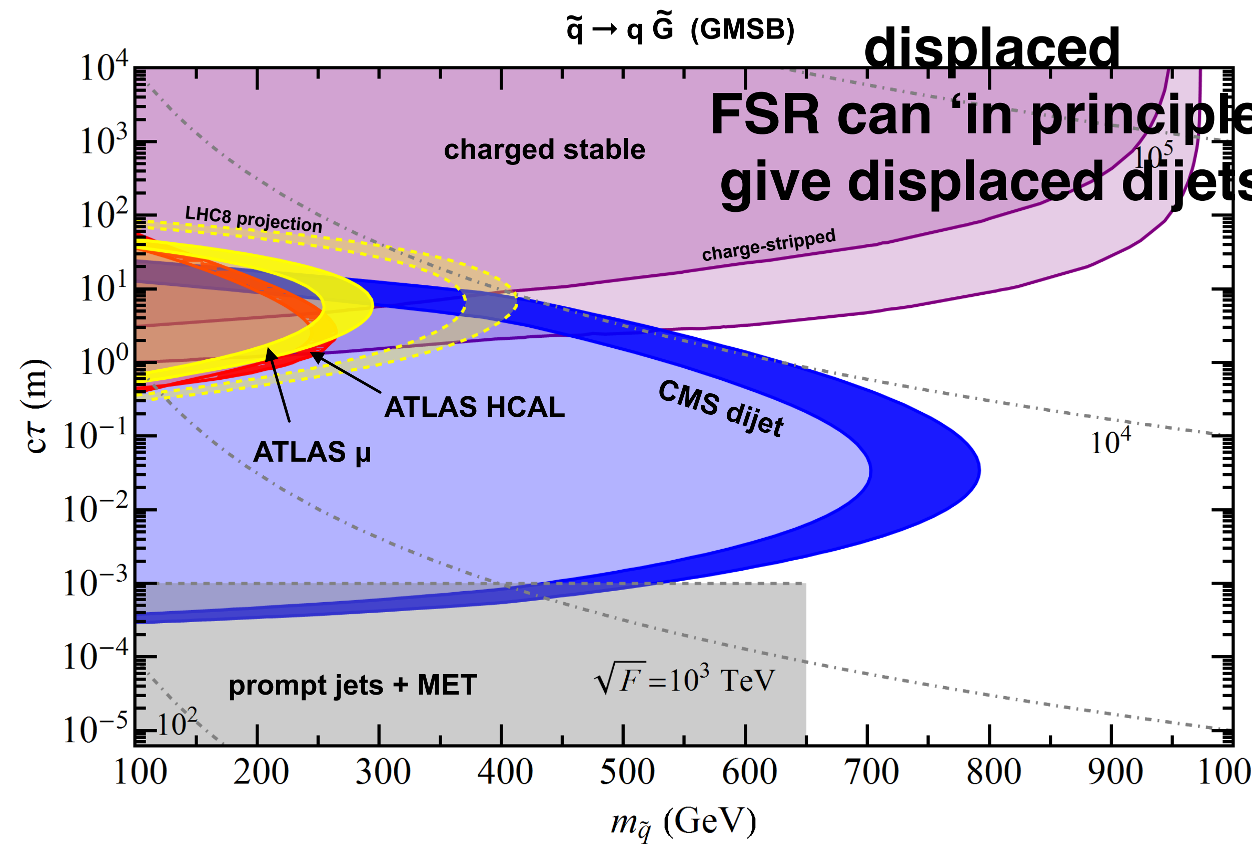
- Excludes a SM Higgs branching ratio of 10% between a few [mm] up to 10's of [cm]. Exclusions as low as ~1 pb
- Heavy higgs signatures are also investigated with m_H = 800 GeV as low as ~.6 pb

four dark photons



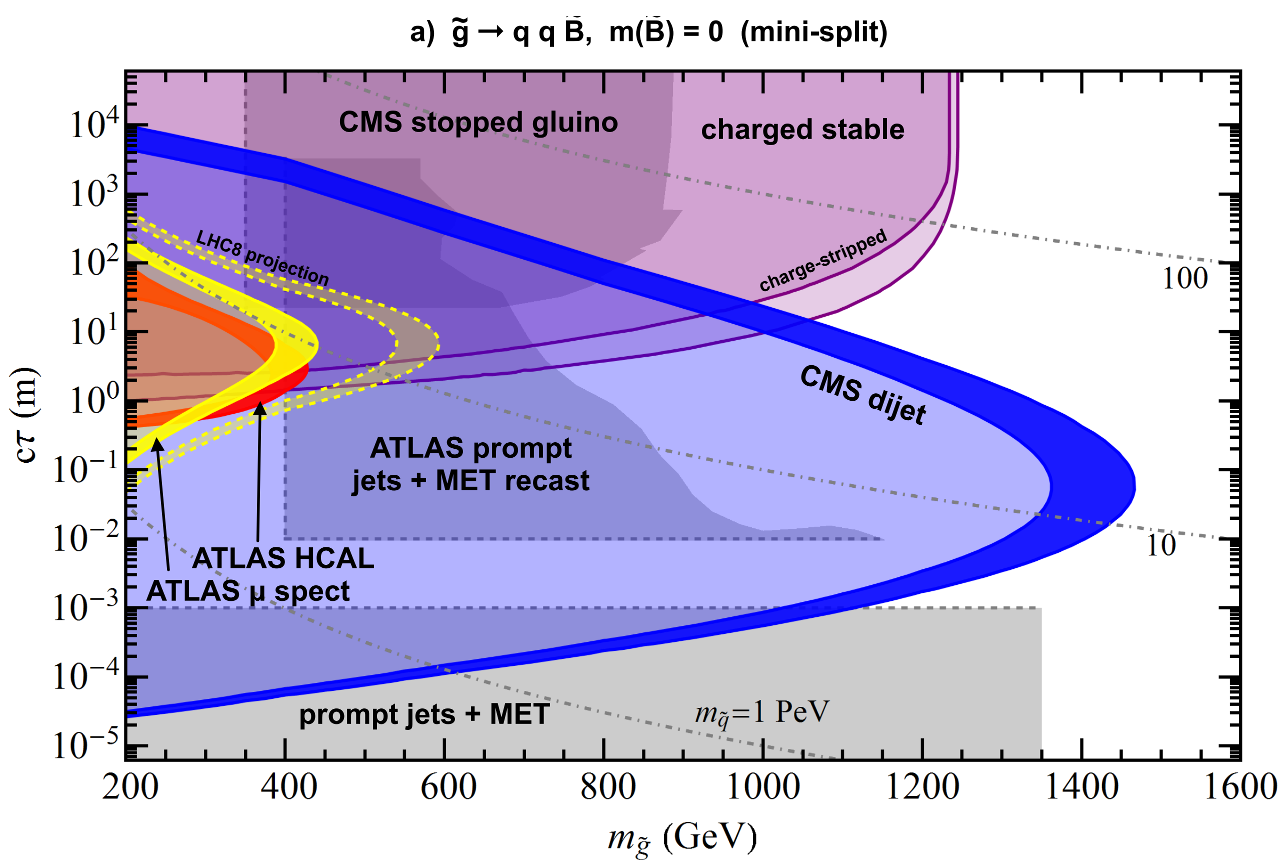
Future Benchmarks and Recasting

- Many analyses **are more sensitive/inclusive than they appear**, as we have seen through re-castings of existing searches
- Often models are excluded with no gaps in lifetime, from prompt to stable.
- Re-casts give a good idea of which analysis strategies can, given re-casting assumptions, cover the most ground.



displaced FSR can 'in principle' give displaced dijets

Z. Liu B. Tweedie arXiv:1503.05923

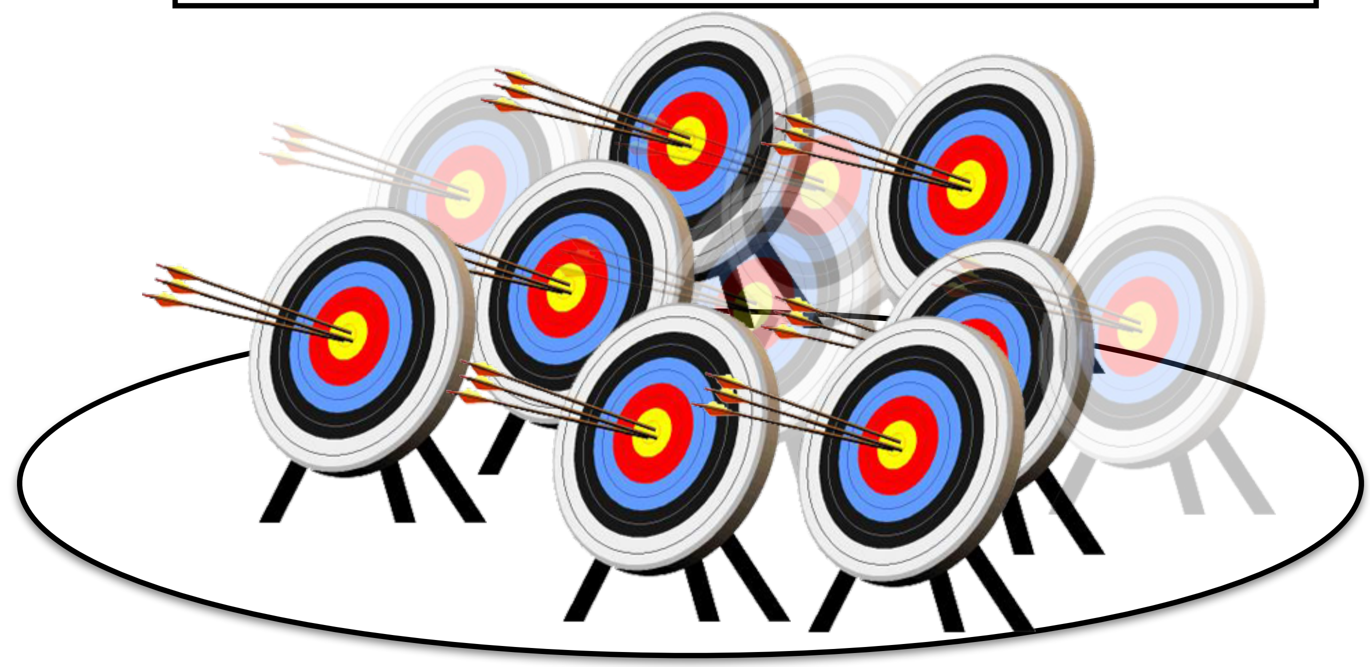


- However, these are and cannot account for **nefarious detector effects** or **regions of displaced tracking we may not yet understand**
- Track based analyses are still learning about the basis of sensitivity to analysis variables (boost, flavor, side-ways approaches, track matching to energy deposits,…)

Benchmarks and Re-interpretation

- Of course, **no group of simplified models can fully capture the enormous space** of long-lived analyses.
- A well selected set can, however, streamline MC generation and cross checking re-interpretations. This very helpful when small teams devise new analyses

Are we hitting targets we didn't aim for?
I certainly hope so….but bizarre tracking signatures should be simulated/studied.



With a small number of highly inclusive displaced analyses. We either need to understand the inclusivity or find more man power for dedicated searches

- A consolidated set of models can encourage corresponding prompt analyses to perform re-interpretations
- We need to **perform searches for missing coverage**. This is mostly organizational and not incredibly labor intensive

Very Inclusive Analyses

Displaced Vertex / Dileptons + X [ATLAS 8 TeV]

- Trigger on 'everything': ME_T, Jets, Muons, Electrons (as photons)
- Construct a secondary vertex and veto the detector material
- limitations: 3,4 track vertices and lighter states

Displaced Di-jet [CMS 8 TeV]

- Specialized Trigger, two energy deposit with small energy from prompt tracks
- Sensitivity to electrons, taus, jets, and muons
- Limited by signatures that do not have di-jet vertices X->MET+jet, L1 thresholds for H_T

dE/dx R-hadron Searches [CMS & ATLAS 13 TeV]

- Inclusive to all final states, limits are placed on xsec not xsec*BR
- Very mature analyses and continuity between datasets
- Limited by level 1 to have dedicated trigger

All Mono-X Analyses [CMS and ATLAS]

- Working points where the particles generally leave the detector are generally not generated to be re-interpreted by mono searches

So Where Are the Holes in Coverage?

Throughout Run 2 the long-lived community has elicited and received significant feedback on where we can improve:

General Summary of Suggestions

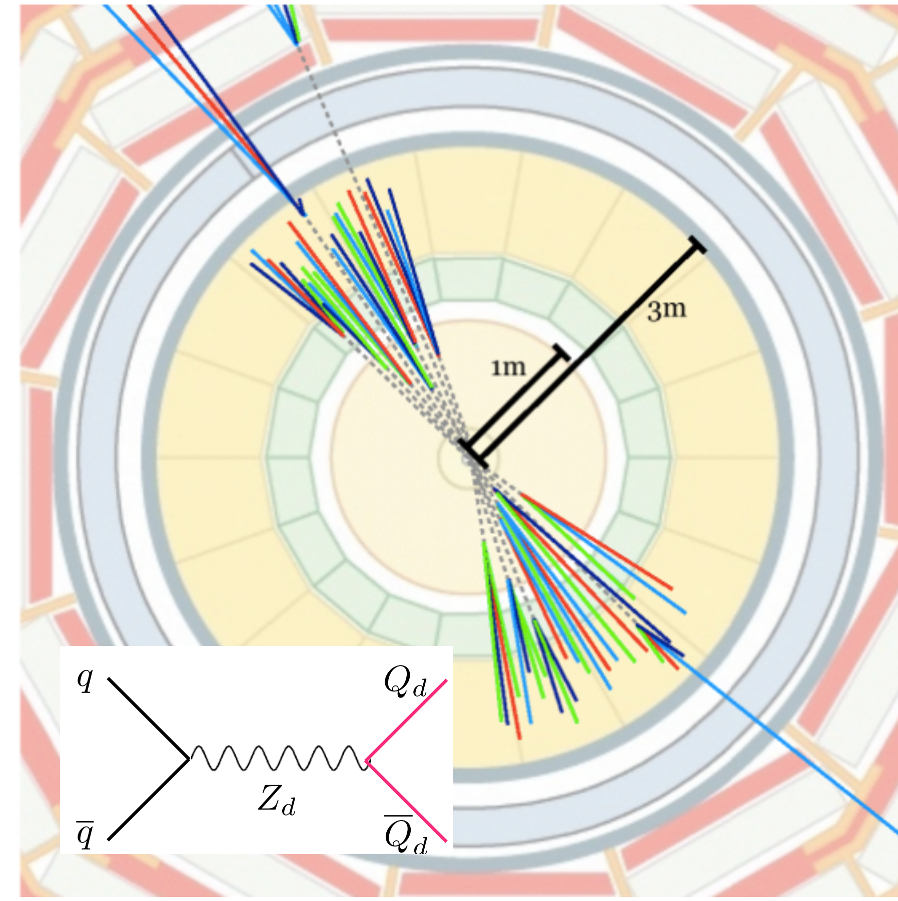
- More inclusive triggering strategies
- Softer hadronic signatures (Higgs portal / twin Higgs)
- Higher and lower mass working points
- No analysis explicitly investigating long lived decays to taus
- Explicit checks of prompt analyses performance on shorter lifetime signatures

Lets go into some detail on specific models not explicitly within our current coverage…

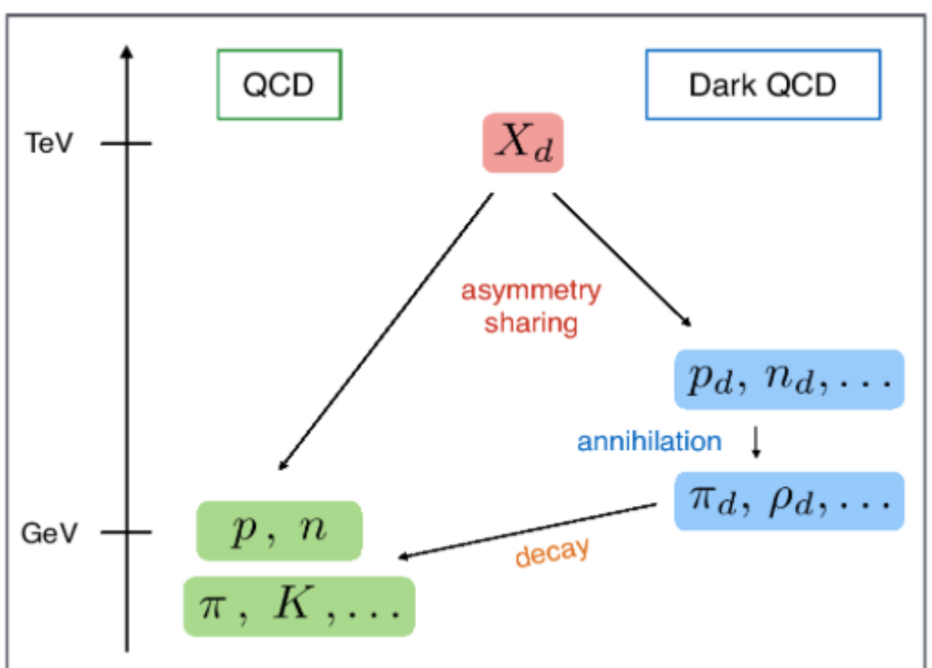
Emerging Jets

P. Schwaller, D. Stolarksi, A. Weiler. 'Emerging Jets' arXiv:1502.05409

- Class of BSM models with a new SU(N_{dark}) gauge symmetry with a new dark QCD scale ~TeV
- Dark hadrons are light and must decay through a heavy mediator, leading to displaced decays.
- Produces striking signatures with **<u>multiple displaced vertices within each jet</u>**



Field	$SU(3) \times SU(2) \times U(1)$	$SU(3)_{\text{dark}}$	Mass	Spin
Q_d	$(1, 1, 0)$	(3)	m_d $\mathcal{O}$(GeV)	Dirac Fermion
X_d	$(3, 1, \frac{1}{3})$	(3)	M_{X_d} $\mathcal{O}$(TeV)	Complex Scalar
Z_d	$(1, 1, 0)$	(1)	M_{Z_d} $\mathcal{O}$(TeV)	Vector Boson

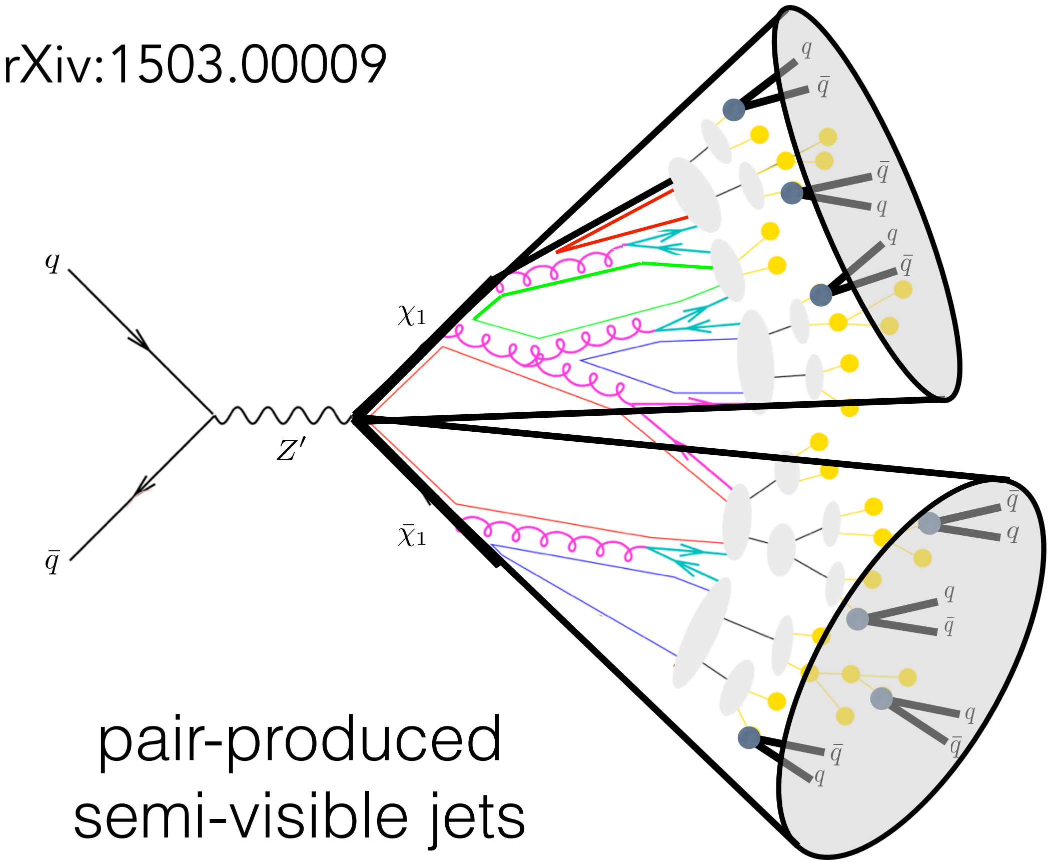


- Relevant mass scales determined by requiring the dark baryon to be a viable DM candidate
- No dedicated search yet performed, not obvious if <u>secondary vertexing</u> in past hadronic analyses will work…

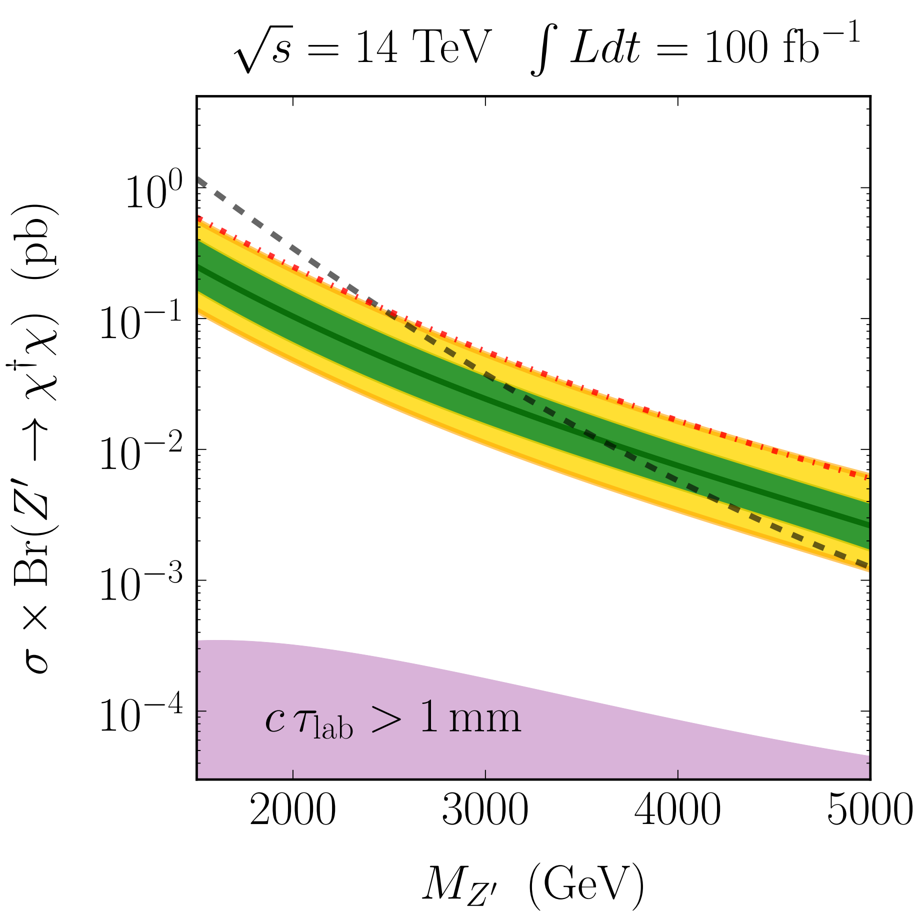
Semi-Visible Jets

T. Cohen, M. Lisanti H.K. Lou — arXiv:1503.00009

- Complicated final states containing jets that are visible hadronic states + stable neutral particles.
- **Missing energy is aligned with the jet direction**, usually selected against to suppress QCD.
- When these particles are long lived the signature is two large jets (recommended DR=1.1) with no common vertex.



pair-produced
semi-visible jets

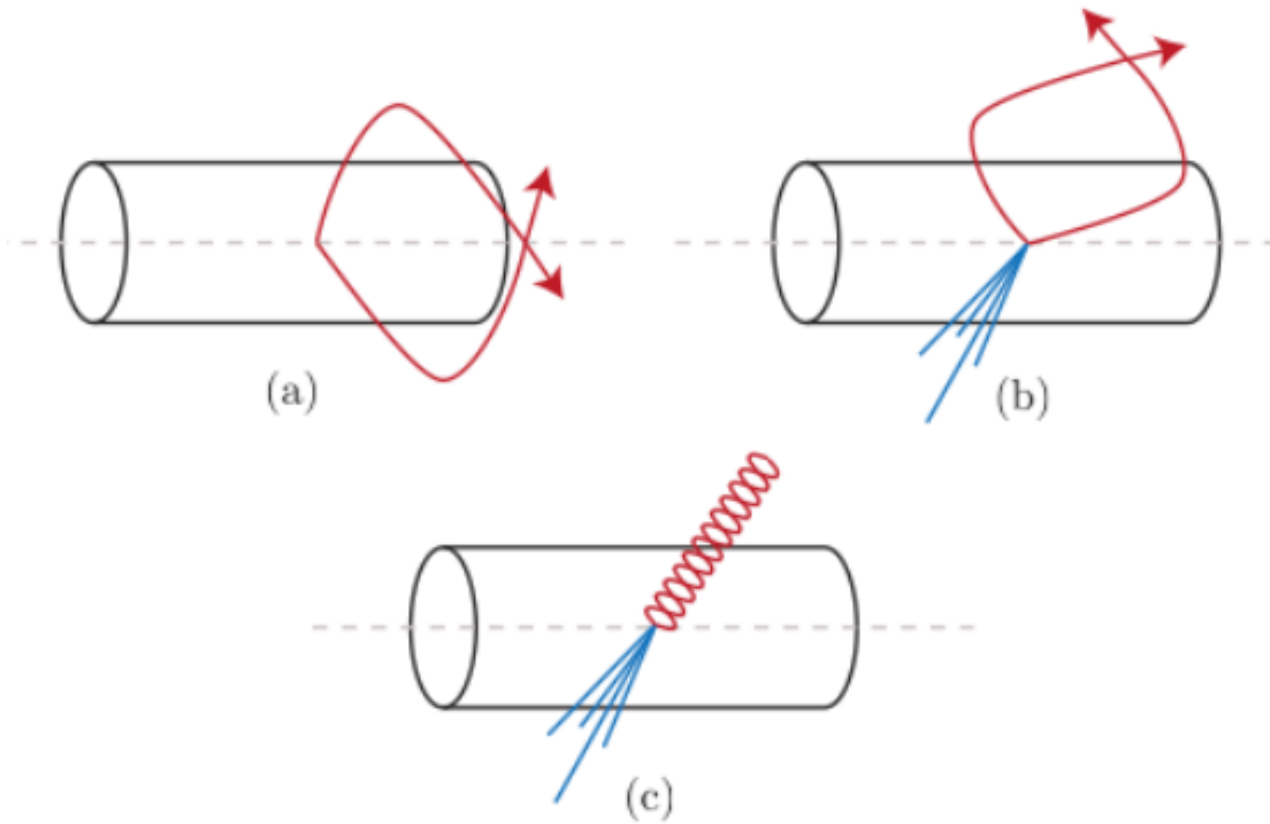


- Displaced di-jet analyses unlikely to have sensitivity without a common two jet vertex
- Possible sensitivity in ATLAS's Displaced Vertex + X search.
- Need to pro-actively generate benchmarks to check sensitivity.

Strange Track Signatures

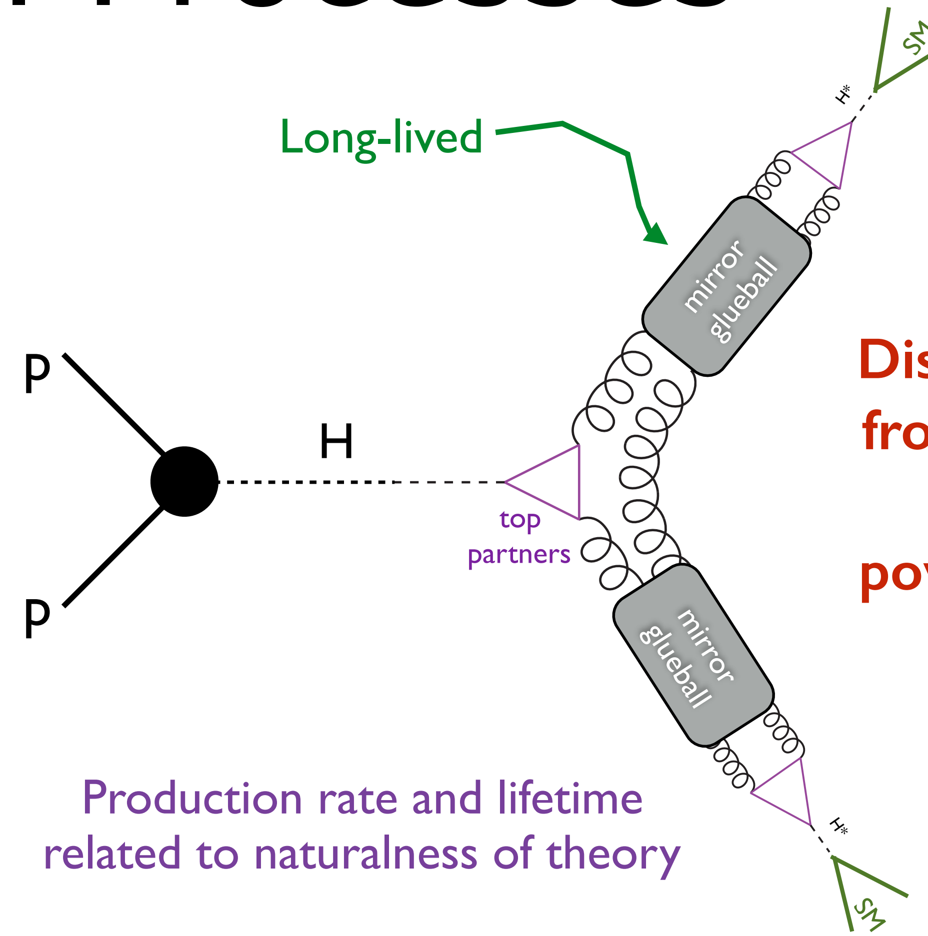
- **Kinked/Disappearing Tracks** : long lived particles with lifetimes on the scale of detector they undergo a decay within the tracker.
- **Quirks**: Anomalous track shapes. Dedicated track reconstruction?
- ‘**Exploding’ Tracks**: Benchmarks are needed for charged R-hadrons that decay within the tracker. Not clear how this affects analyses that use neutral benchmarks

quirk anomalous track bending



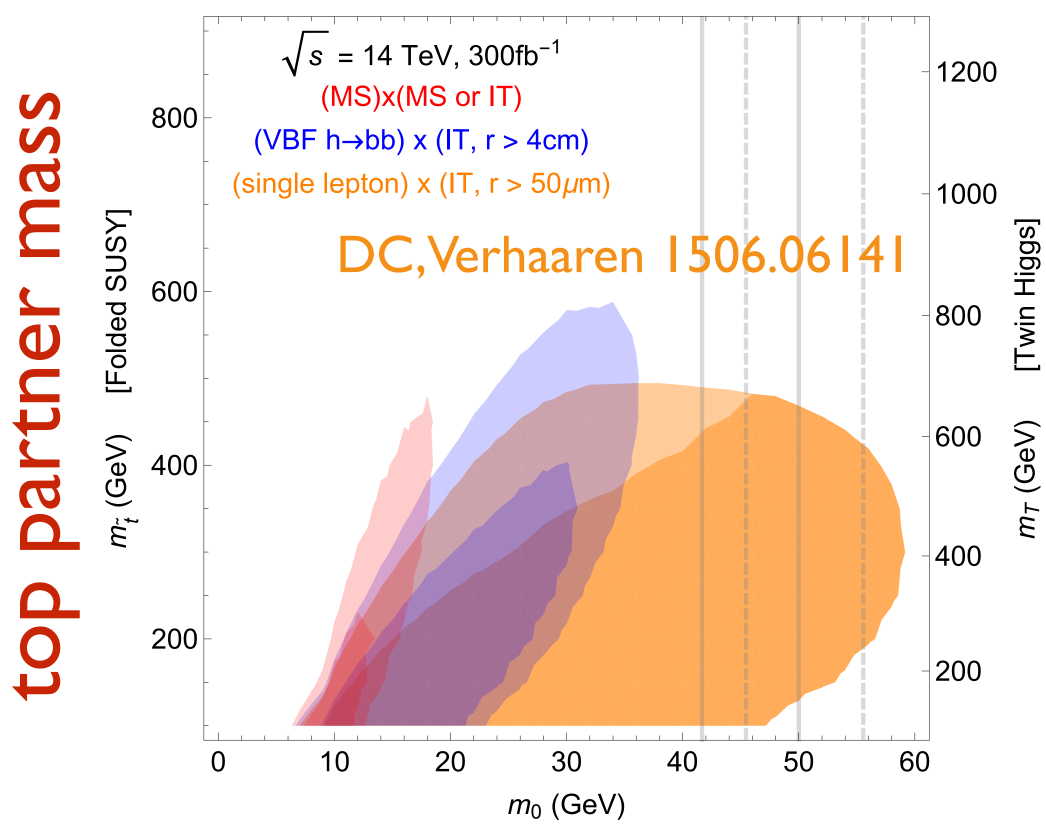
Higgs Portal Processes

- Need coverage of 125 GeV higgs decaying to displaced light mass X's 10-60 GeV in hadronic final states
- Gives neutral naturalness motivations for long-lived particles.
- Gives motivations for high lumi analyses, many higgs produced to probe low BR.



d. curtin

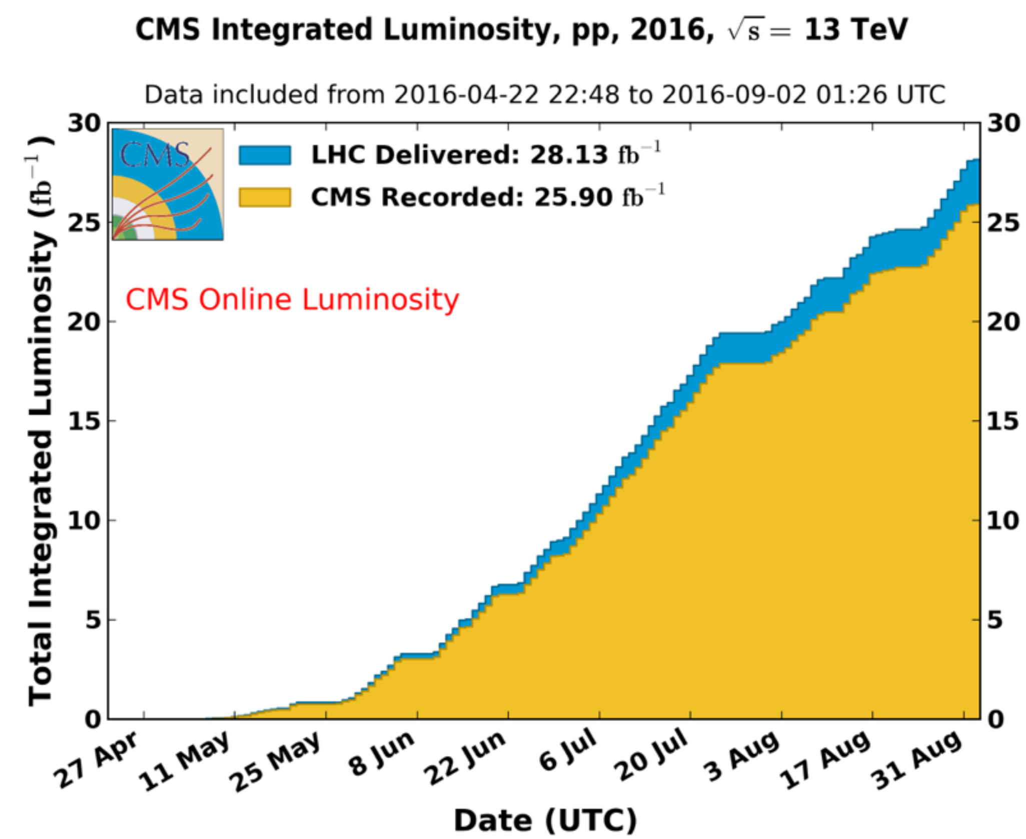
Displaced Vertices from exotic Higgs decays are a powerful probe of Naturalness!

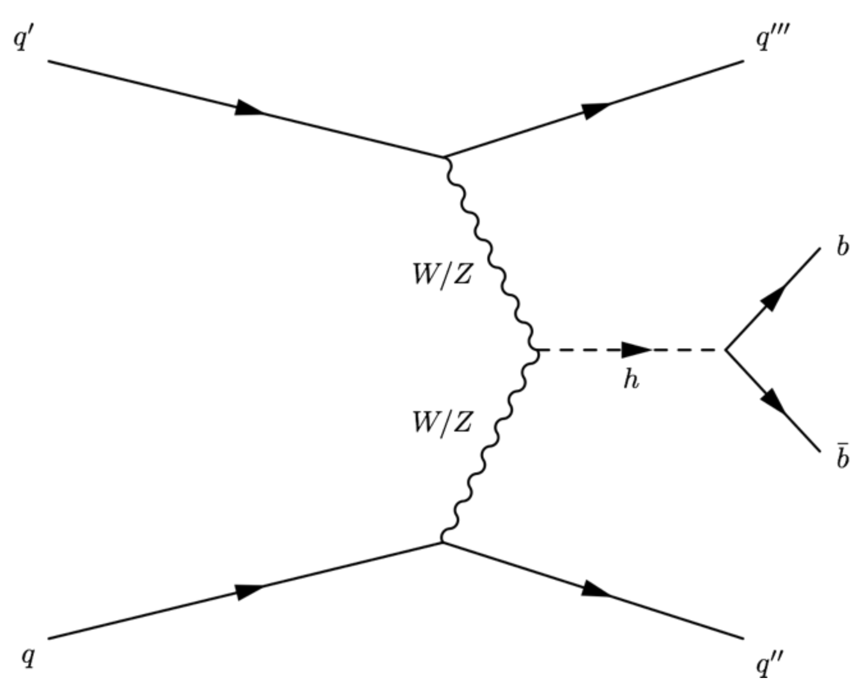


- **Very challenging signature**, from both the triggering perspective and analysis of very soft jets.
- Long lived glue-balls typically decay hadronically: b's, taus, and light flavor.

Triggering In The Intensity Frontier

- With the LHC strong performance **new luminosities and PU will continue to raise trigger thresholds** to stay within bandwidth constraints.
- This issue is particularly acute at the first trigger level (L1 for CMS) where tracking is not available until future upgrades.





- Creativity is necessary at the higher trigger levels to keep the thresholds as low as the L1.
- Upgrades to tracking and fast timing open new opportunities for triggering as well as analysis.

Known Triggering Strategies

Specialized Displaced Triggers

- **Displaced-dijet**: "prompt" energy fraction, no vertexing, sensitivity to leptons
- **Displaced Muon**: specialized tracking online
- **Calorimeter Ratio**: decays inside of calorimetry.
- **Muon Chamber Only Trigger:** lepton jets, MS activity
- **Out of time Decays**: veto bunch crossing and look for jets/muons

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Associated Production "prompt" Triggers

- VBF without b-tags. low level triggering is limiting until upgrades.
- leptons (can also be used for charged particle analyses)

Tracking Blind Inclusive Triggers:

- dijets, single jet, photons
- Missing Energy, H_T

Simplest solution…but also the most affected thresholds by increased luminosity

Conclusions

- Long-lived analyses from the experimental perspective have **very special needs and smaller teams** than prompt analyses.
- Analyses easily achieve background free signal regions with high efficiency. When the space is large it is **better to improve our coverage than marginal improvements** in dedicated searches.

- Increase inclusivity of final states [tau's, no secondary vertices]
- Softer hadronic kinematics [twin higgs]
- Improve trigger strategies in the face of ramping luminosity.

- We need to check that analyses can be as inclusive as we might believe. A structure of benchmarks/SMS's can be very helpful organizationally
- Many first 13 TeV long lived results are on the way!

Important Sources for this Talk

- **Long Lived Particle Mini-Workshop**. CERN 2016. https://indico.cern.ch/event/517268/
- **Jamie Antonelli**, "Searches for Long-lived Particles at CMS." CMS ICHEP 2016. http://indico.cern.ch/event/432527/contributions/1072042/
- **Laura Jeanty.** "Searches for long lived SUSY particles." ATLAS. ICHEP 2016. http://indico.cern.ch/event/432527/contributions/2219937/