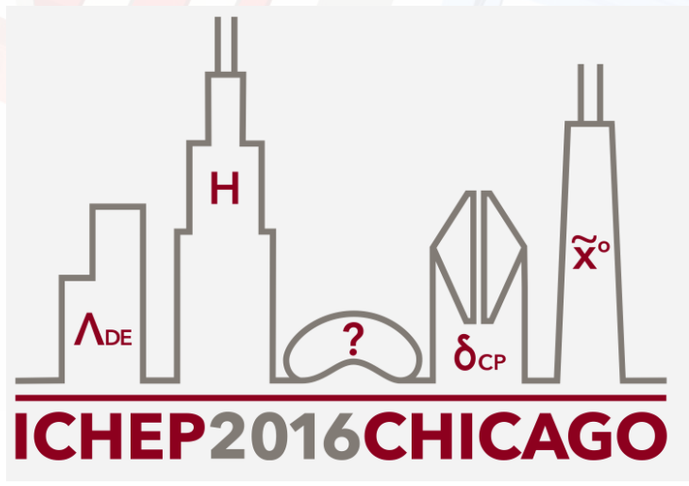
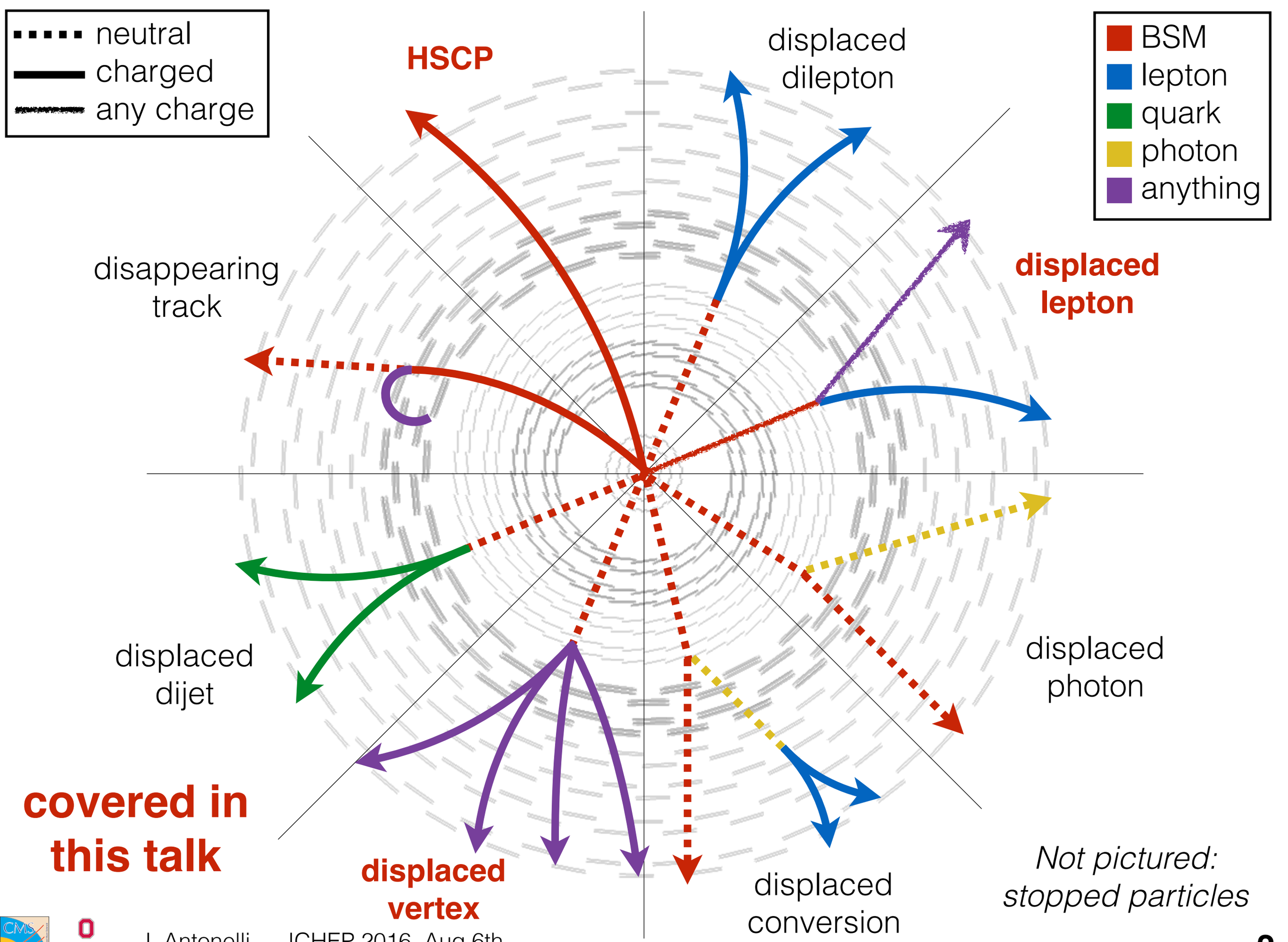
# Searches for long-lived particles (LLPs) at CMS

J. Antonelli

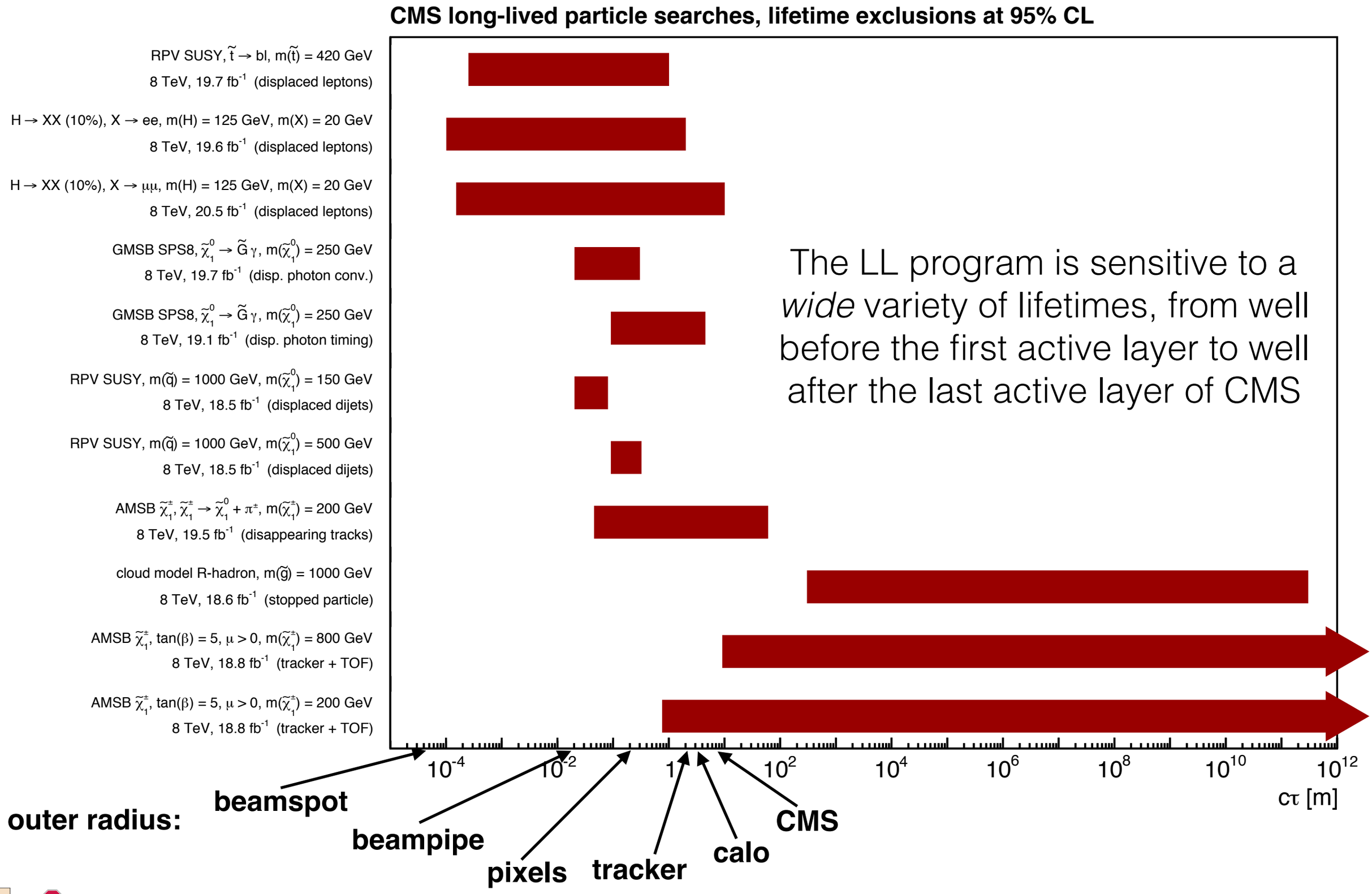
on behalf of the CMS collaboration

THE OHIO STATE UNIVERSITY




neutral
charged
any charge
BSM
lepton
quark
photon
anything
HSCP
displaced dilepton
disappearing track
displaced lepton
displaced dijet
displaced photon
displaced vertex
displaced conversion
covered in this talk
Not pictured: stopped particles

# CMS program covers a broad lifetime range



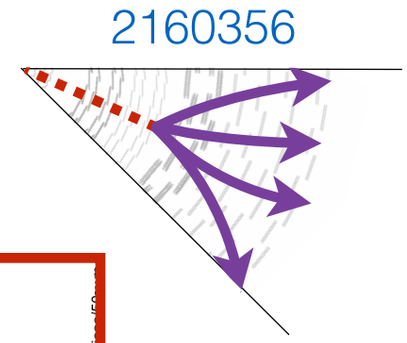

The LL program is sensitive to a *wide* variety of lifetimes, from well before the first active layer to well after the last active layer of CMS

# Many public 7/8 TeV searches (and two at 13 TeV)

| | Final state targeted | 7 TeV | 8 TeV | 13 TeV |
|---|---|---|---|---|
| 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 | |
| 5 | displaced photons using ECAL timing | 1212.1838 | 2063495 | |
| 6 | displaced photons using conversions | 1207.0627 | 2019862 | |
| 7 | displaced vertices | | **2160356** | |
| 8 | displaced dijets | | 1411.6530 | |
| 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)<br>**2205281** (2016) |
| 14 | stopped particles | 1207.0106 | 1501.05603 | |
| 15 | out of time muons | | thesis | |

**covered in this talk**

# Displaced vertex search




***First of its kind on CMS*** (8 TeV)

Targets **SUSY RPV → tbs**
- small couplings → long lifetimes

Short-ish lifetimes (inside beampipe)

**Reconstruct displaced vertices**
- using tracks with $d_0 > 100$ μm

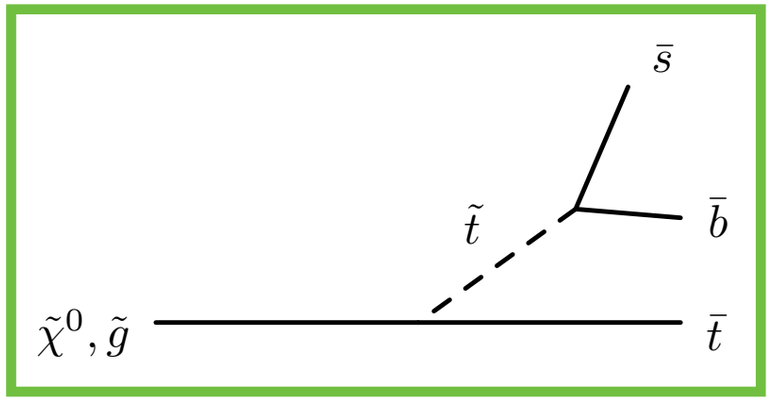
**Vertex selection**:
- ≥ 5 tracks, ≥ 3 with $p_T > 3$ GeV
- well measured vertex position
- ≥ 1 track matched to jet
- "substructure lite":

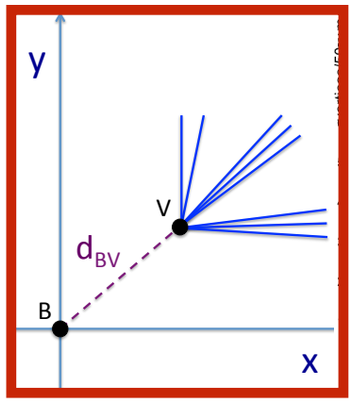
  0 track pairs with $\Delta R > 4$

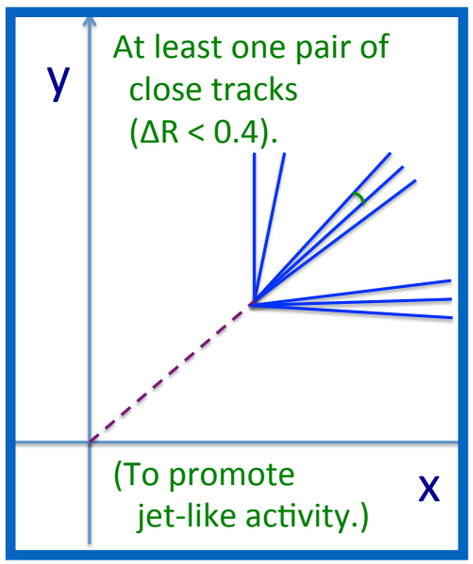
  **≥ 1 track pair with $\Delta R < 0.4$**

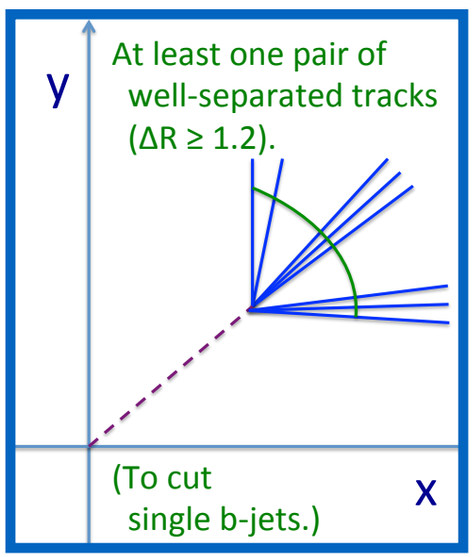
  **≥ 1 track pair with $\Delta R > 1.2$**

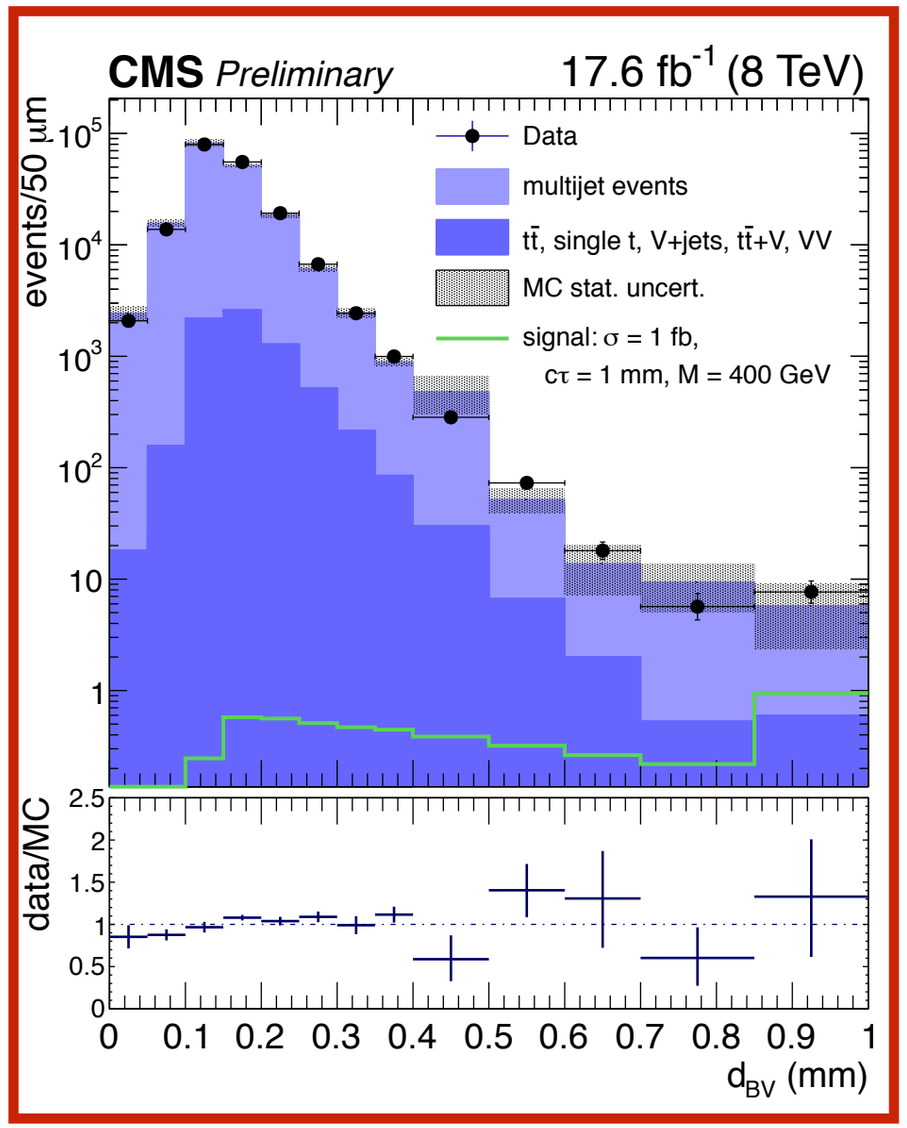
Create sample of **1-vertex events**



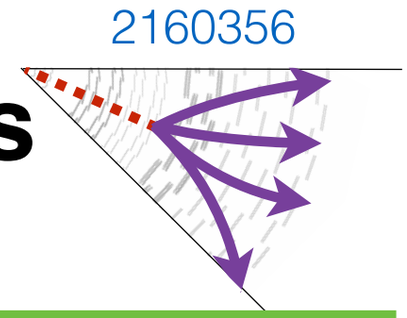



# Background taken from 1-vertex data events



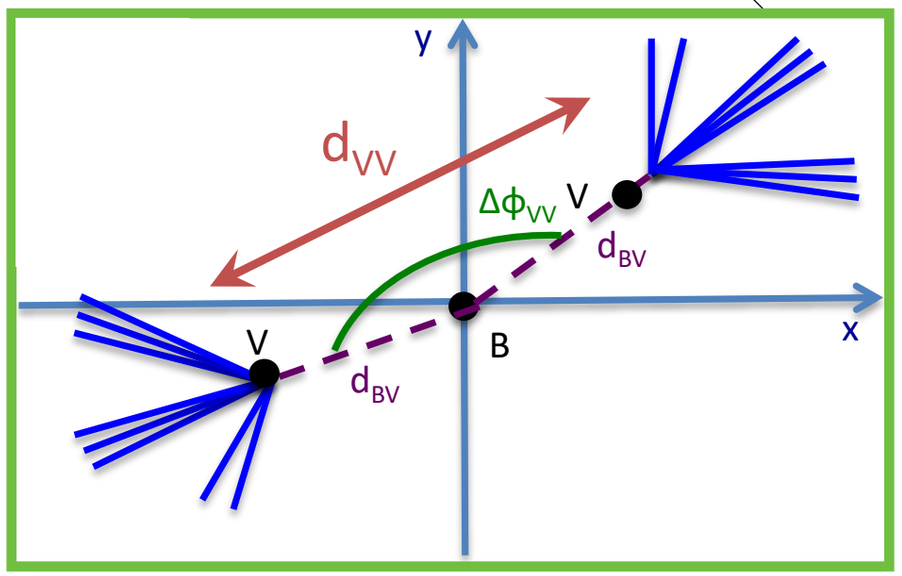

## Signal expected in 2-vertex events

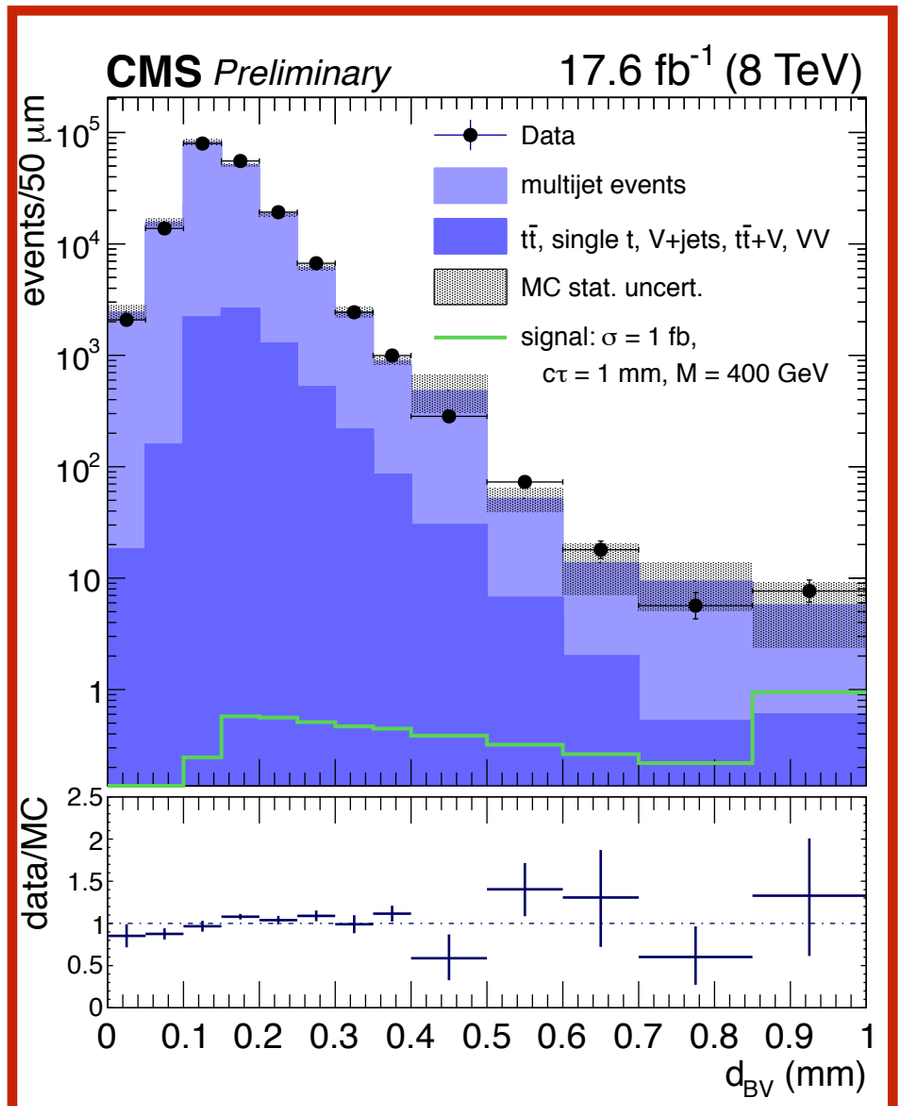
$d_{VV}$: distance between vertices in transverse plane

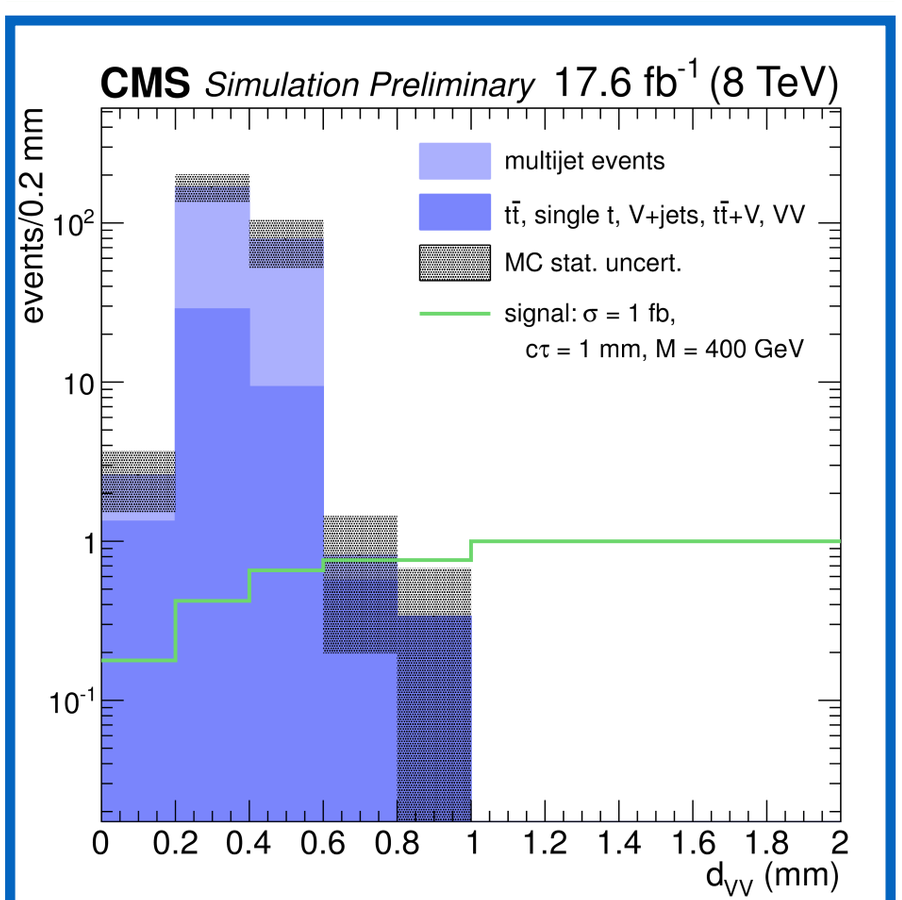
**High discrimination power expected from $d_{VV}$**

Taking two events from **1-vertex data**:
$d_{BV}$: vertex displacement
$\Delta\phi_{VV}$: angular separation

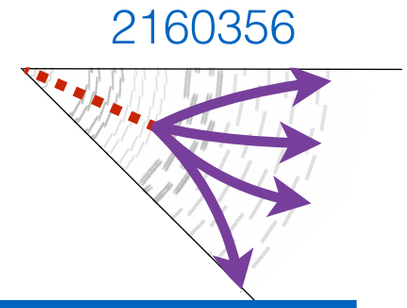
**Create expected $d_{VV}$ shape in background**



# Exclusions at the fb scale




Signal extracted using $d_{VV}$ distribution

**Observation agrees well with background expectation**

- slight excess for $d_{VV}$ > 0.6 mm

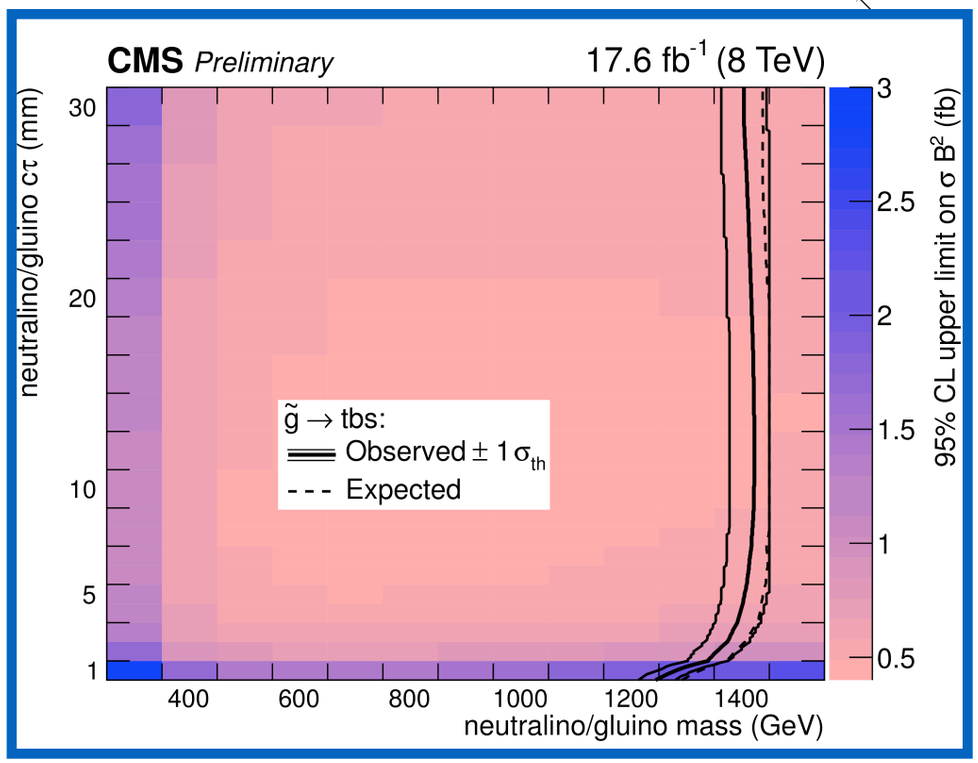
**$\chi_0/\tilde{g}$ models excluded beyond 1 TeV**

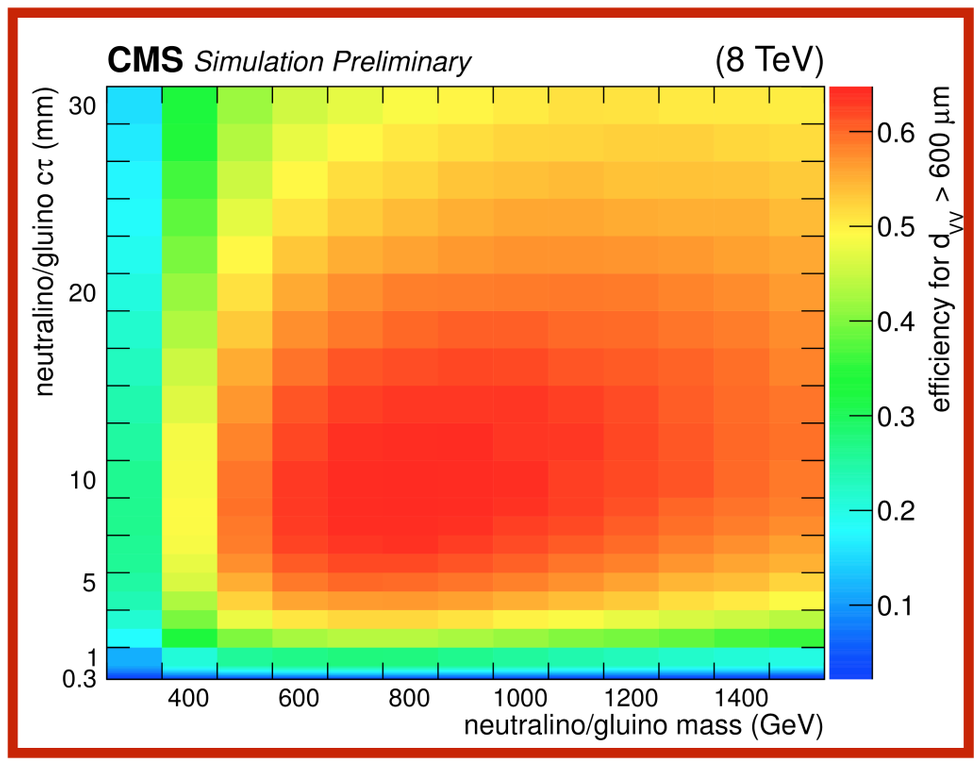
**Signal efficiency as high as 60%**

Signal efficiency limited by:

- kinematic cuts at low $\chi_0/\tilde{g}$ mass
- $d_0$ > 100 μm cut at low lifetime

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



# Displaced eμ search

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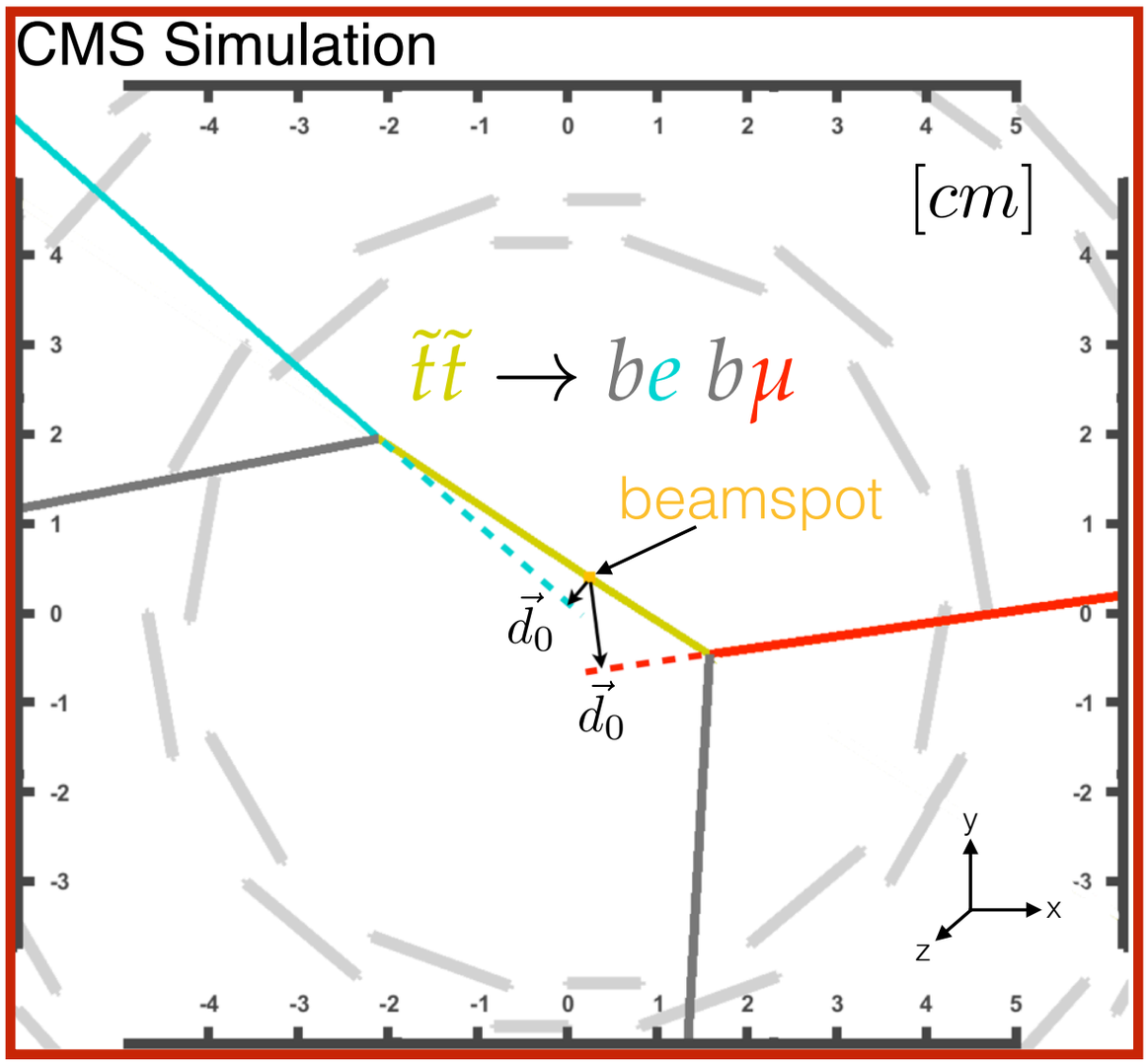



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G12024

*Update of 8 TeV search*

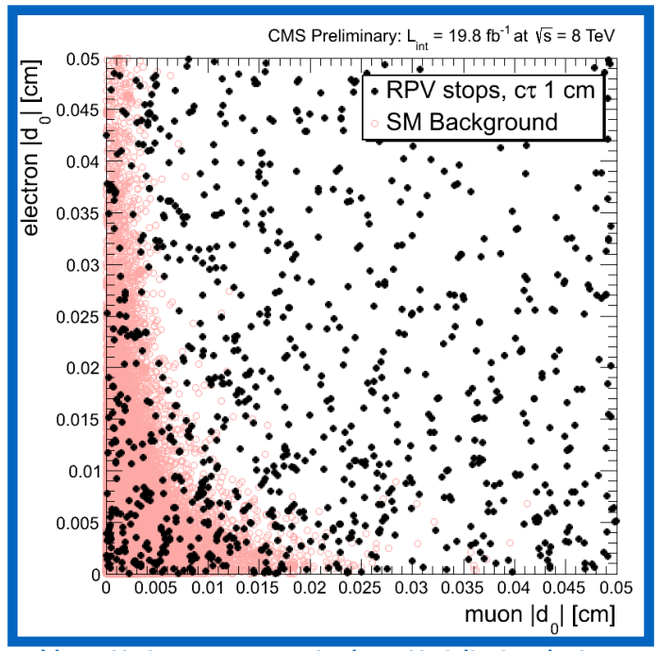
**Targets RPV $\tilde{t} \rightarrow bl^{\pm}$ in eμ final state**

**Lepton $d_0$ used as discriminating variable**

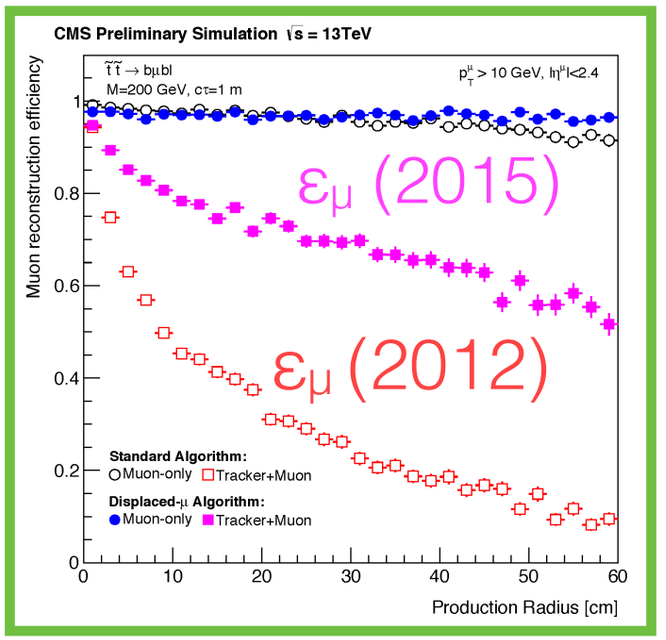
**Improved displaced muon acceptance**

Constrain search to decays within pixel detector (R < 10 cm)

**Select events with one OS eμ pair**




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




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

# Main background: Heavy Flavor QCD (HF)

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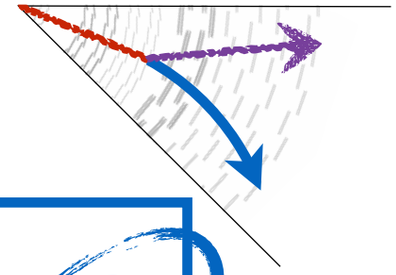
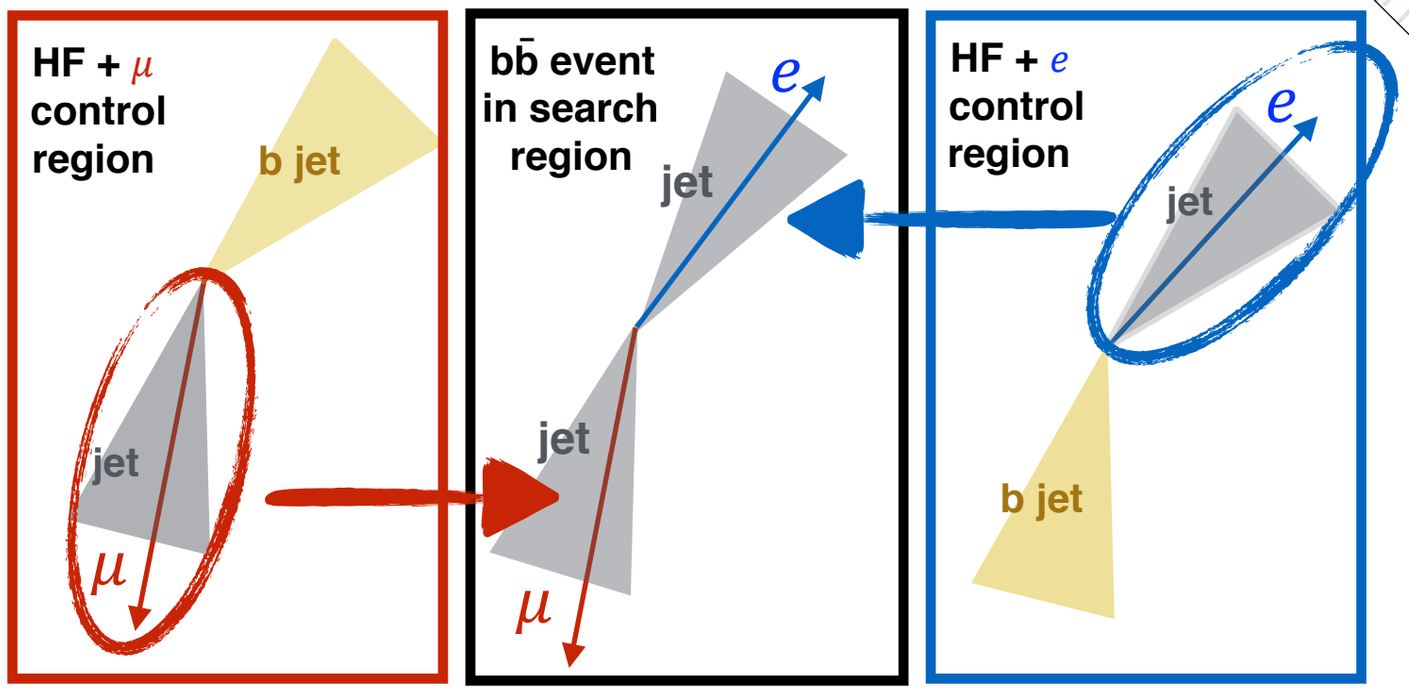


**HF + μ/e control regions**

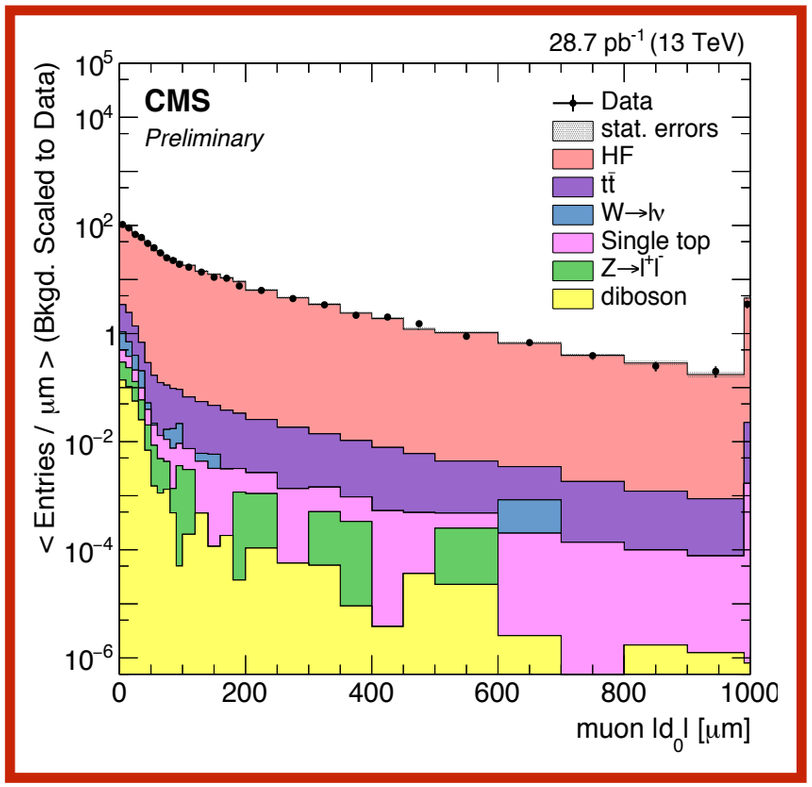
- b-tagged jet
- back-to-back jet with nearby lepton

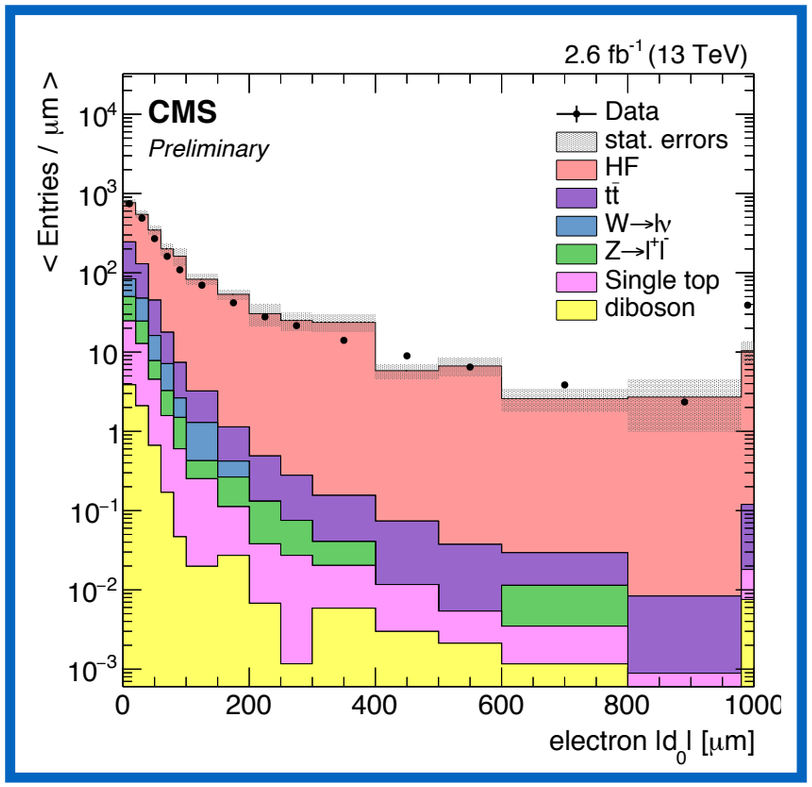
Large, pure sample of HF events

**Construct $d_0$ templates from data in these control regions**




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



# Limits placed over 4 decades in cτ

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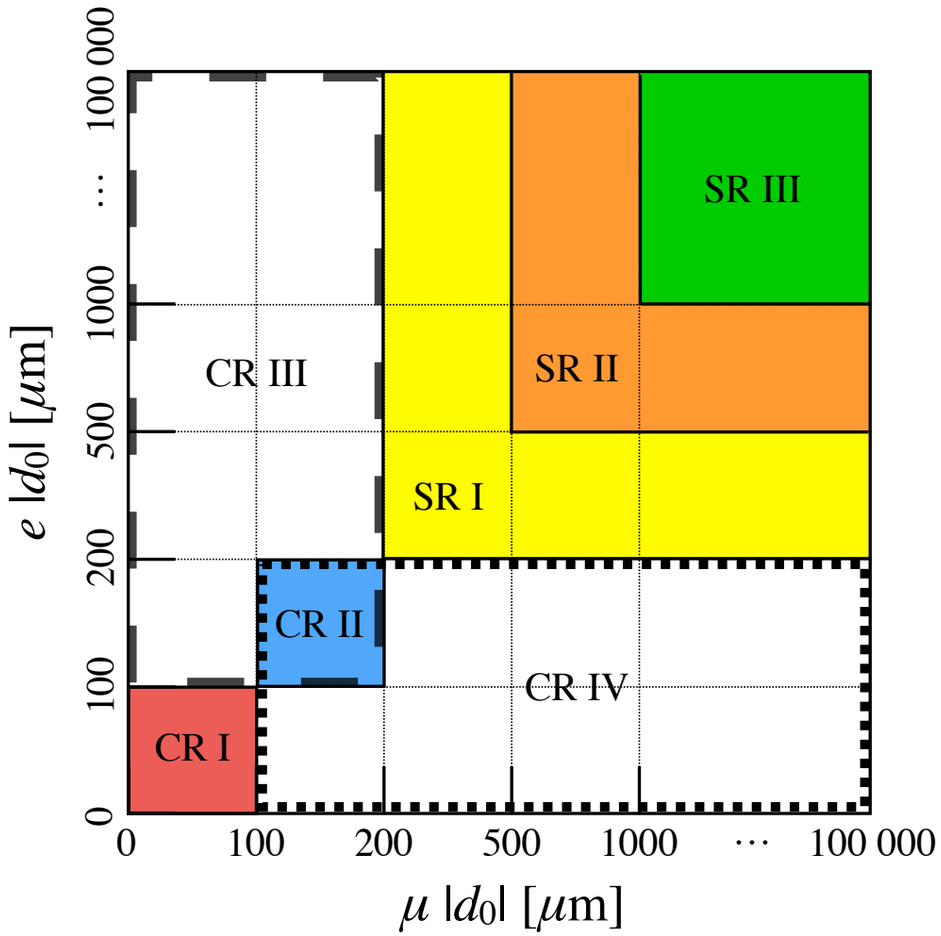
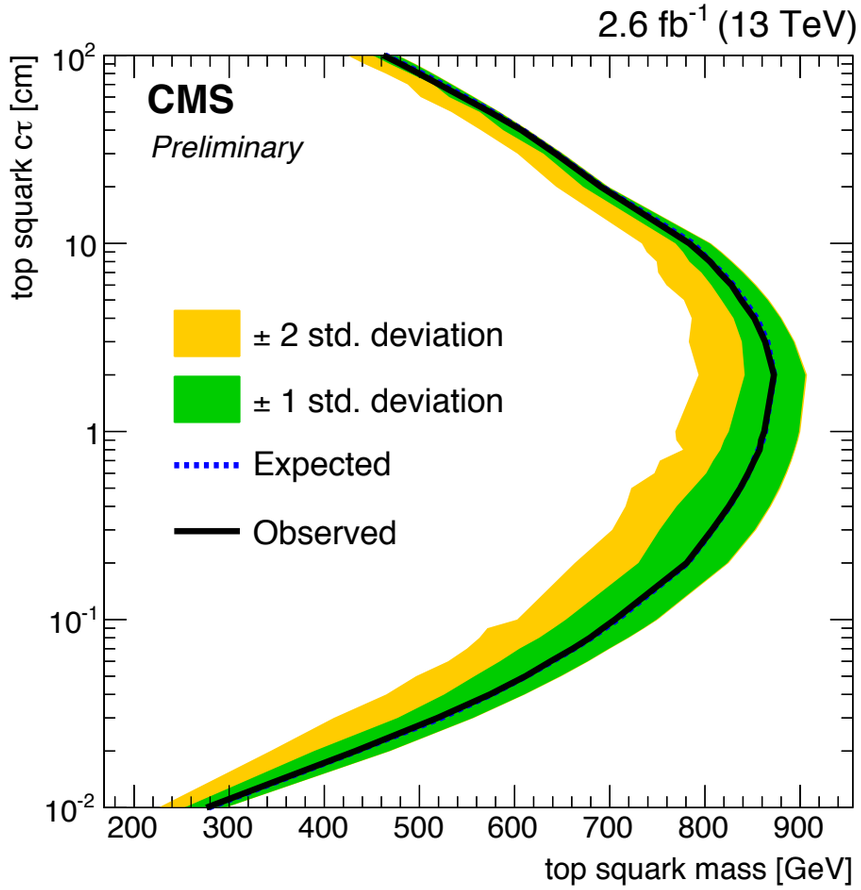



Three orthogonal search regions: 200 μm < $d_0$ < 10 cm

Observation consistent with
(very small) background expectation

Sensitivity limited by:
- $d_0$ > 200 μm cut at small cτ
- lepton reconstruction efficiencies at large cτ

| 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 |
| $pp \to \tilde{t}_1\tilde{t}_1^*(M_{\tilde{t}_1} = 700\,\text{GeV})$ | | | |
| $c\tau = 0.1\,\text{cm}$ | $3.8 \pm 0.2$ | $0.94 \pm 0.06$ | $0.16 \pm 0.02$ |
| $c\tau = 1\,\text{cm}$ | $5.2 \pm 0.4$ | $4.1 \pm 0.3$ | $7.0 \pm 0.3$ |
| $c\tau = 10\,\text{cm}$ | $0.8 \pm 0.1$ | $1.0 \pm 0.1$ | $5.8 \pm 0.2$ |
| $c\tau = 100\,\text{cm}$ | $0.009 \pm 0.005$ | $0.03 \pm 0.01$ | $0.27 \pm 0.03$ |



# Heavy Stable Charged Particle (HSCP) search

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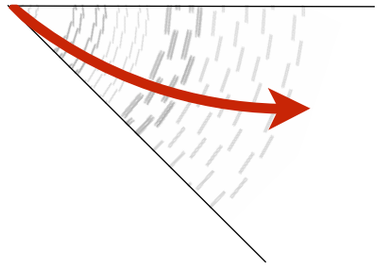
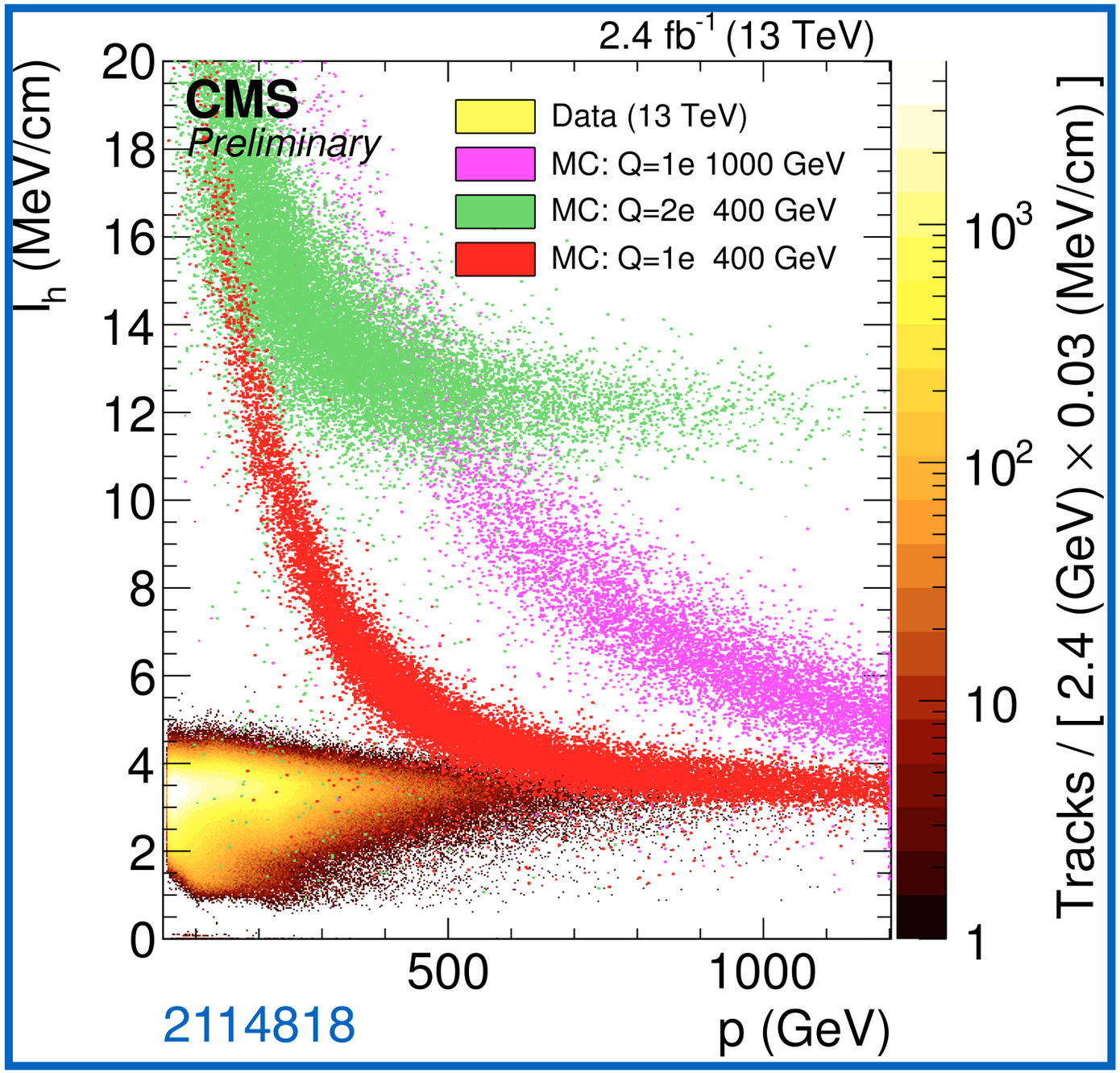


*Most mature long-lived search on CMS*
- done at 7/8/13 TeV

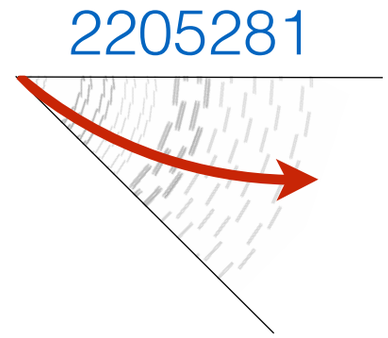
**H**eavy → slow
**S**table → interacts with detector
**C**harged → tracker + muon system
**P**article

Two discriminating variables:
- **dE/dx**: energy loss in tracker
- $\beta^{-1}$: time of flight to muon chambers

Since R-Hadron HSCPs can become neutral via detector interactions, **Tracker Only** and **Tracker + TOF** searches are performed



# Background taken from data sidebands



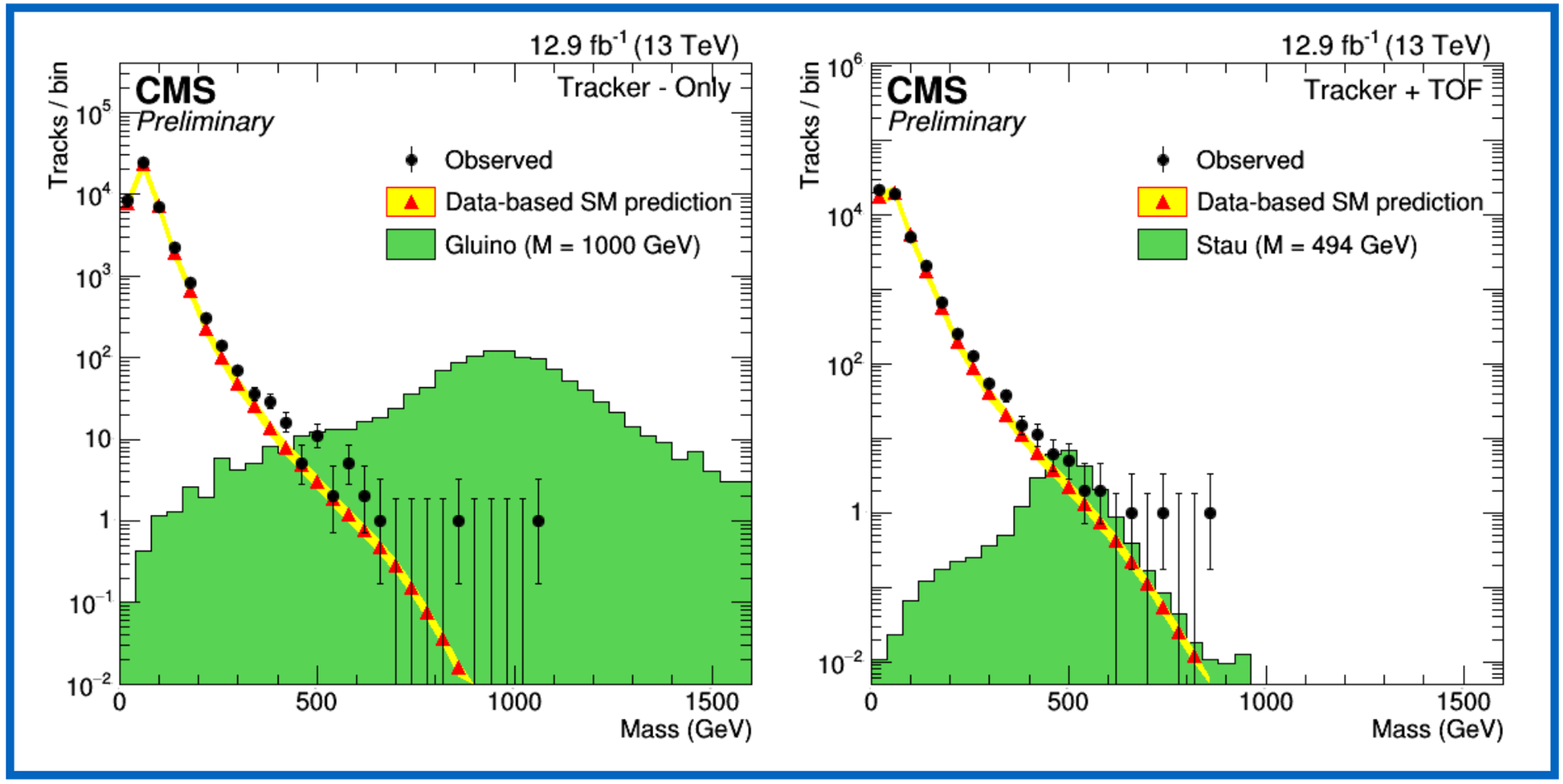

**dE/dx estimator ($I_h$) can be converted into rough mass estimate**

**K,C** constants calibrated using low momentum proton data

Background mass shape and normalization taken from low p, low dE/dX sidebands

**Loose dE/dx and $\beta^{-1}$ selections applied to validate background estimate**

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



# Limits set on a variety of models

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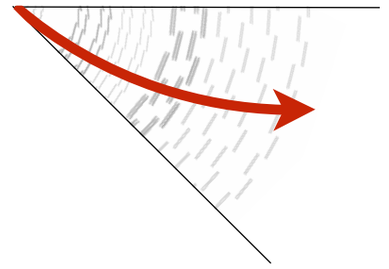


After final selection:

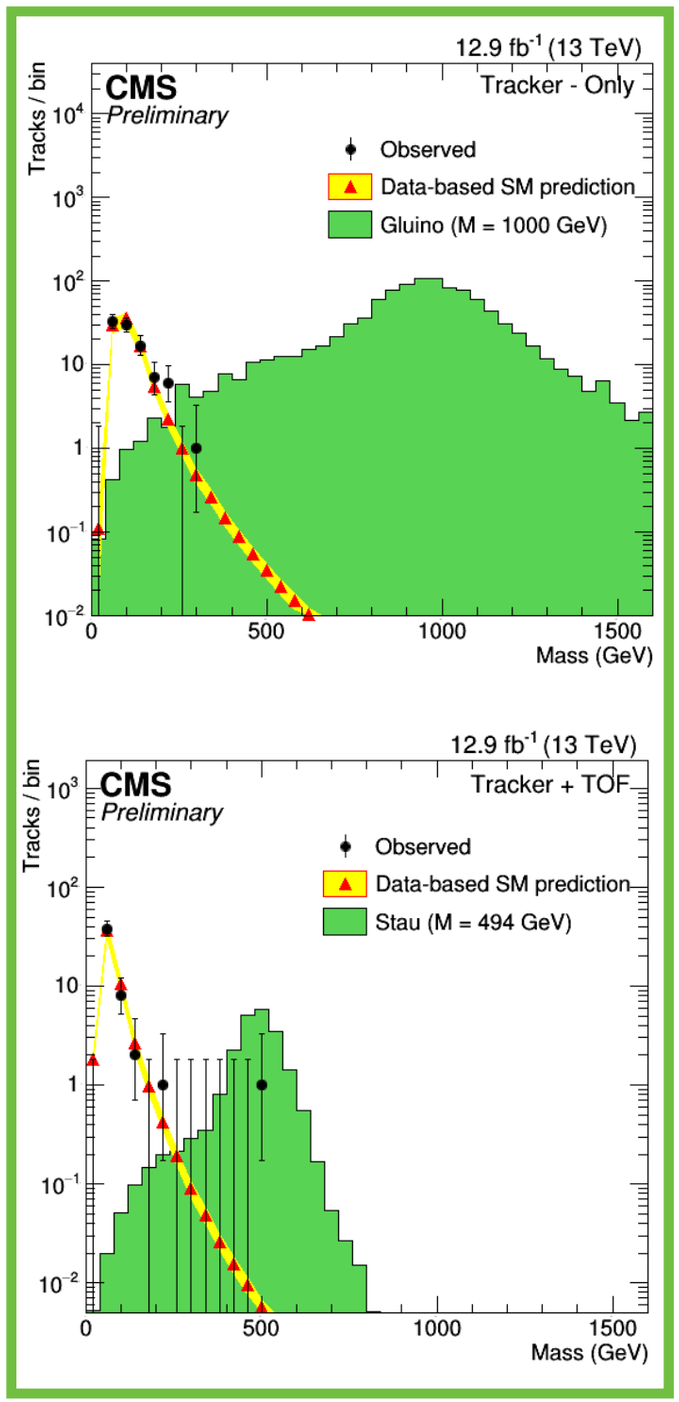
**no large excess at high mass**

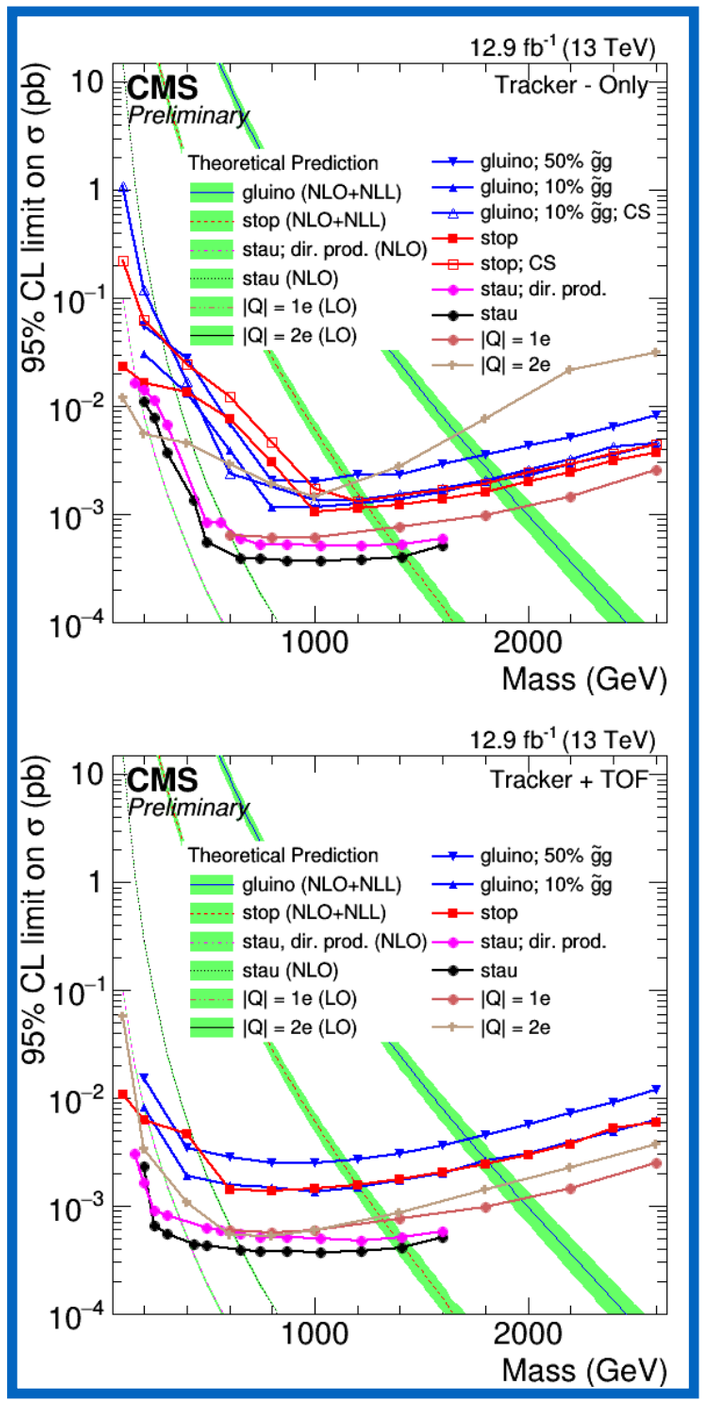
**Cross section limits on the 1-10 fb scale**

**Mass limits up to 1.8 TeV**

No loss from branching fractions!

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



# There's a lot to look forward to!

| | Final state targeted | 13 TeV |
|---|---|---|
| 1 | displaced e-e/μ-μ pairs | |
| 2 | displaced μ-μ pairs in muon system | |
| 3 | displaced e-μ events | 2205146 |
| 4 | displaced μ-μ pairs (dark photons) | |
| 5 | displaced photons using ECAL timing | |
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| 12 | fractionally charged particles | |
| 13 | heavy stable charged particles (HSCP) | 2114818 (2015)<br>2205281 (2016) |
| 14 | stopped particles | |
| 15 | out of time muons | |
| 16 | top secret new searches | |

**This are tricky analyses:**

- Very sensitive to detector performance
- generally wait for final calibration/alignments

**Updates to existing searches:**

- **8→13 TeV boost** gives dramatic improvement for high mass searches
- Most searches are very **statistics limited** - and the LHC is killing it right now

**Brand new searches:**

- No spoilers here…
- ***LLP landscape is very sparsely covered by existing searches!***

*Fin*

# Direct and indirect searches are complimentary

## Direct searches

- observe BSM particle passing through detector
- better for **long lifetimes**
- good for **charged LLPs**

## Indirect searches

- detect LLP decay products
- better for **short lifetimes**
- good for **neural LLPs**

Shaded area: range of lifetimes for which half of the particles are within the acceptance