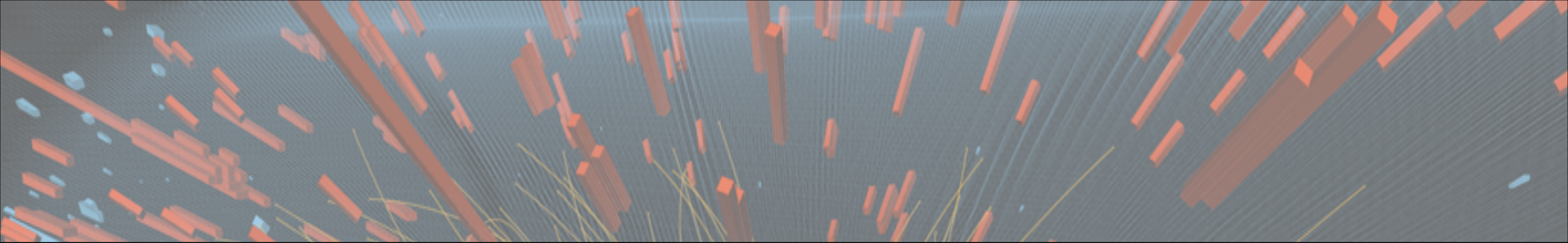
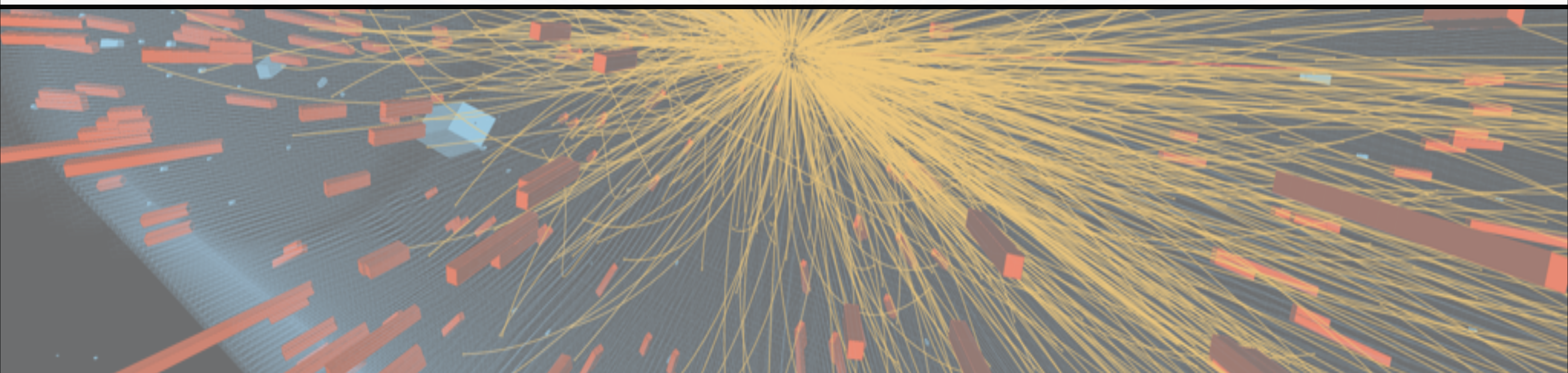


An Inclusive, Discovery Motivated Search For Long-Lived Beyond the Standard Model Physics



CMS Fundamental Physics Scholarship

Joshua Hardenbrook (Princeton University)

Advisor: Professor Christopher Tully

Outline

1. Displaced events are a **powerful** signature and **well motivated** for beyond the standard model physics at 13 TeV

2. The displaced parameter space covered by current CMS analyses leaves **room for interesting new work**

3. There are many ancillary benefits of supporting this project from both a **practical and collaborative** perspective

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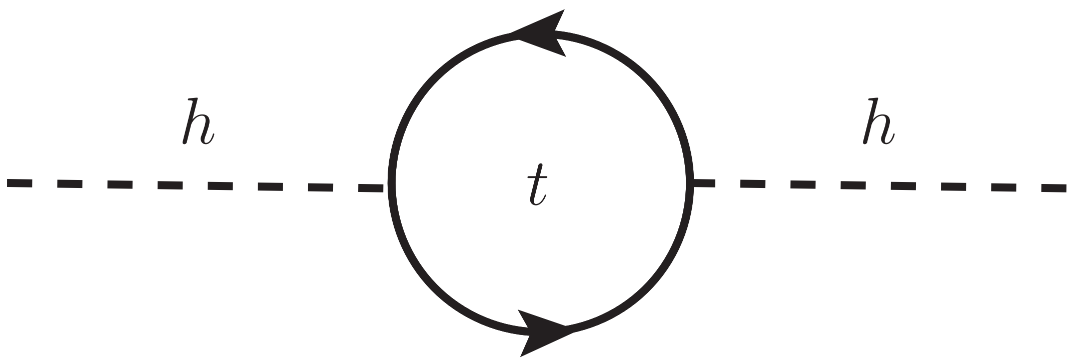
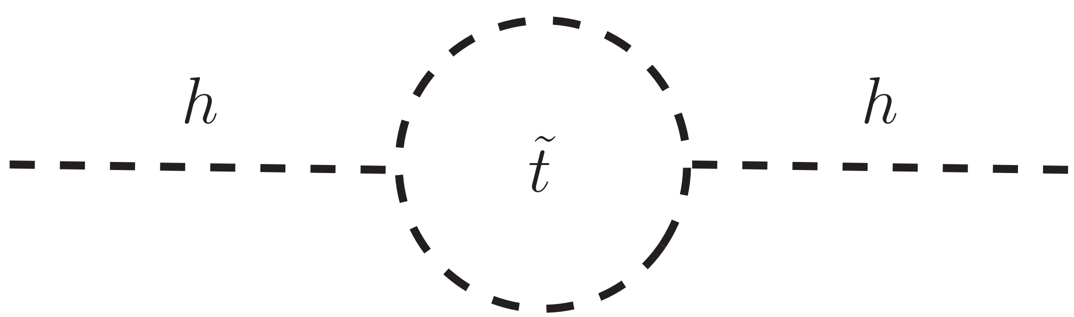
Naturalness At the LHC





- Motivations for finding SUSY at the LHC have been largely motivated by naturalness
- Quadratic divergences in the one loop corrections to the Higgs mass can be stabilized by new scalar particles, particularly (in SUSY) light stops

$$O(\text{Fine Tuning}) \approx M_{EW}^2 / M_{SUSY}^2$$

$$M_{SUSY} \approx M_{EW} \implies M_{SUSY} \leq 1 \text{ TeV}$$

- We expect that $M_{SUSY} \leq 1$ TeV to keep the tuning of our theory m_{EW}^2 / m_{SUSY}^2 close to unity…. new scalars are yet to been seen….

Naturalness and Split-SUSY

- We should remember this is not the worst tuning problem in physics…
- Using the M_{SUSY} assumed from the previous calculation, we have a fine tuning problem of order 10^{60}

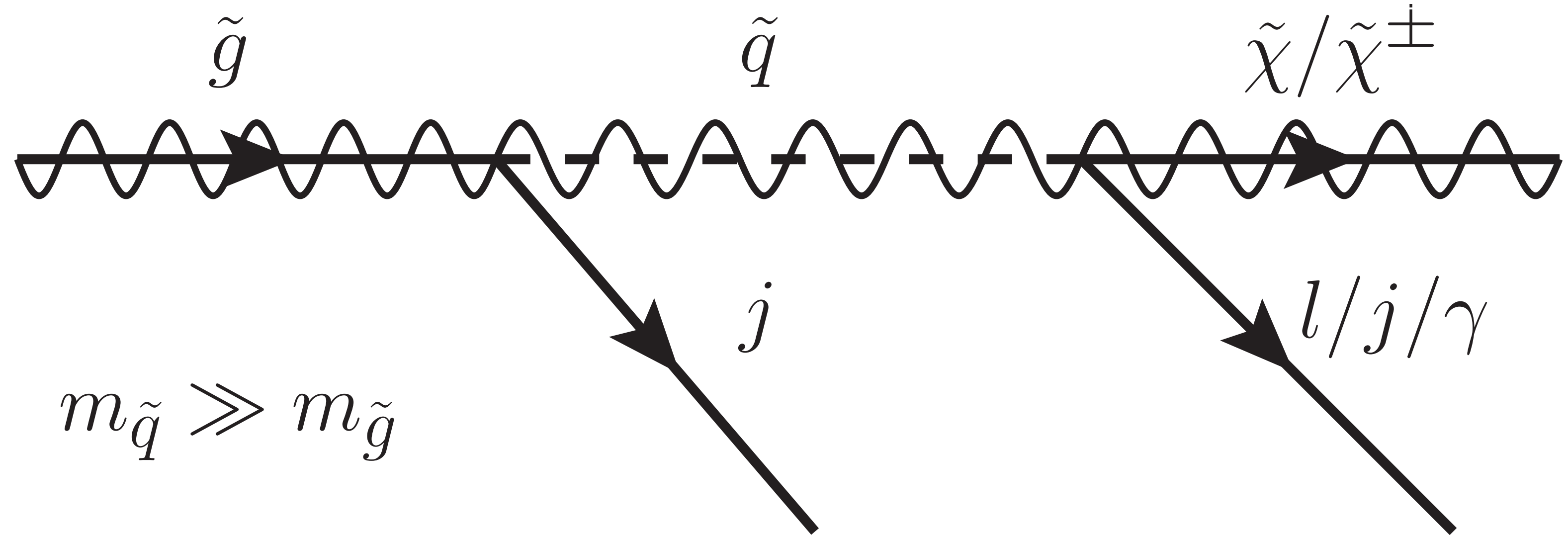
$$\Lambda_{CC} \geq M_{SUSY}^4 \qquad \Lambda_{CC} = 10^{-59}\mathrm{TeV}^4$$

- As the SUSY scalar space gets smaller our fine tuning problem becomes worse. Fine-tuning may have a role to play in BSM physics
- Split SUSY considers $M_{SUSY} > 1000$ TeV where scalars become prohibitively heavy for the LHC, but new fermions remain light by requiring neutralinos to be a good dark matter candidate

Split Supersymmetry

Suppressed decay

$$c\tau_{\tilde{g}} \approx 10^{-5} m \left(\frac{m_{\tilde{q}}}{\mathrm{PeV}}\right)^4 \left(\frac{\mathrm{TeV}}{m_{\tilde{g}}}\right)^5$$

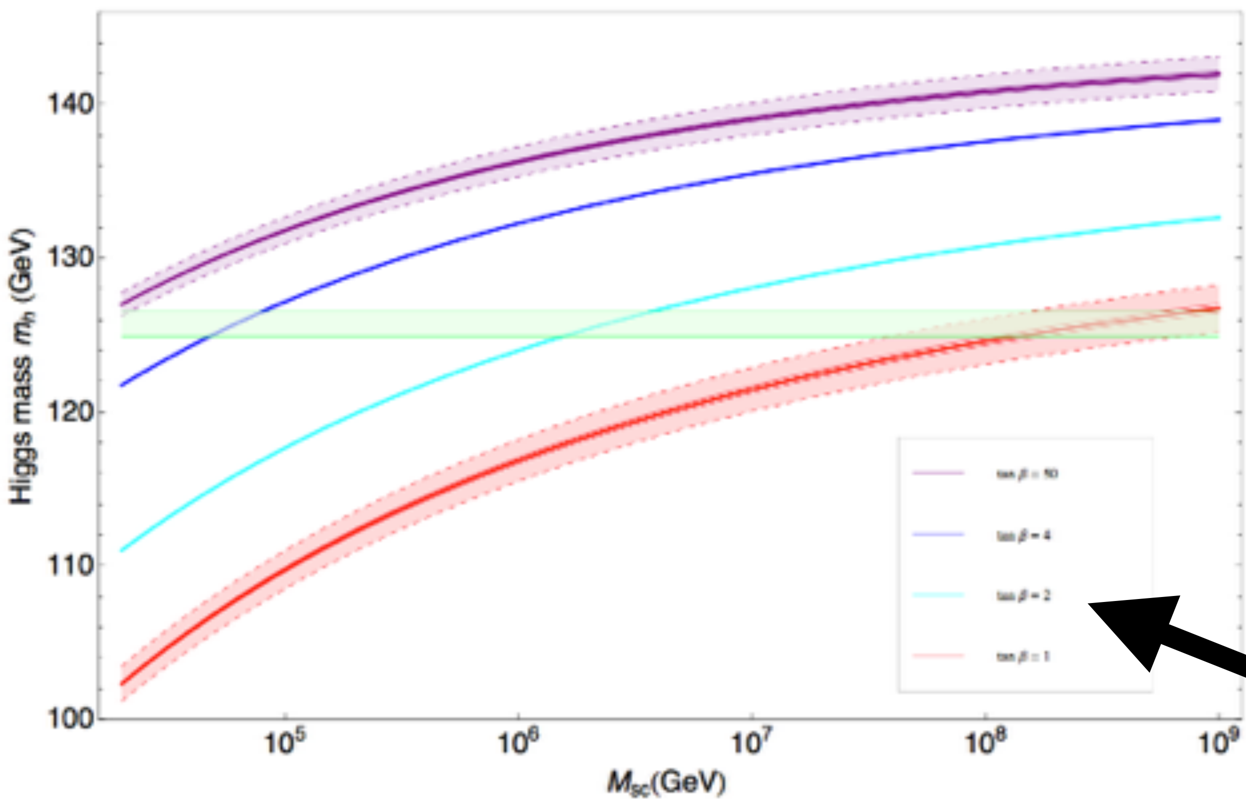


$$m_{\tilde{q}} \gg m_{\tilde{g}}$$

- The amplitude of the gluino decay through a squark propagator is suppressed by the high scalar mass and once produced will travel a measurably long distance before decaying
- Split-SUSY final states typically contain displaced vertices, missing energy, and heavy jet flavors
- A measurement of the displaced vertex lifetime and gluino mass would give us information about the scale of the new physics!

Split Supersymmetry Post-Higgs

Higgs mass vs. M_{scalar} ($\tan(\beta)$ contours)



"Supersymmetric Unification Without Low Energy Supersymmetry and Signatures for fine tuning at the LHC"
N. Arkani-Hamed, S. Dimopoulos
`arXiv:0405159v2`

"Aspects of Split Supersymmetry"
N. Arkani-Hamed, S. Dimopoulos, G. Guidice, A. Romanino,
`arXiv:0409232v2`

"Simply Unnatural Supersymmetry"
N. Arkani-Hamed, A. Gupta, N. Weiner, T. Zowarski
`arXiv:1212.6971v1`

$$c\tau_{\tilde{g}} \approx 10^{-5} m \left(\frac{m_{\tilde{q}}}{\text{PeV}}\right)^4 \left(\frac{\text{TeV}}{m_{\tilde{g}}}\right)^5$$

- After the higgs discovery Arkani-Hamed and Dimopoulos investigated the possible scalar mass scales for m_H=125 as a function of $\tan(\beta)$
- For m_{gluino} < 4 TeV we can probe up to scales of 10^4 TeV if the gluino decays within the tracker

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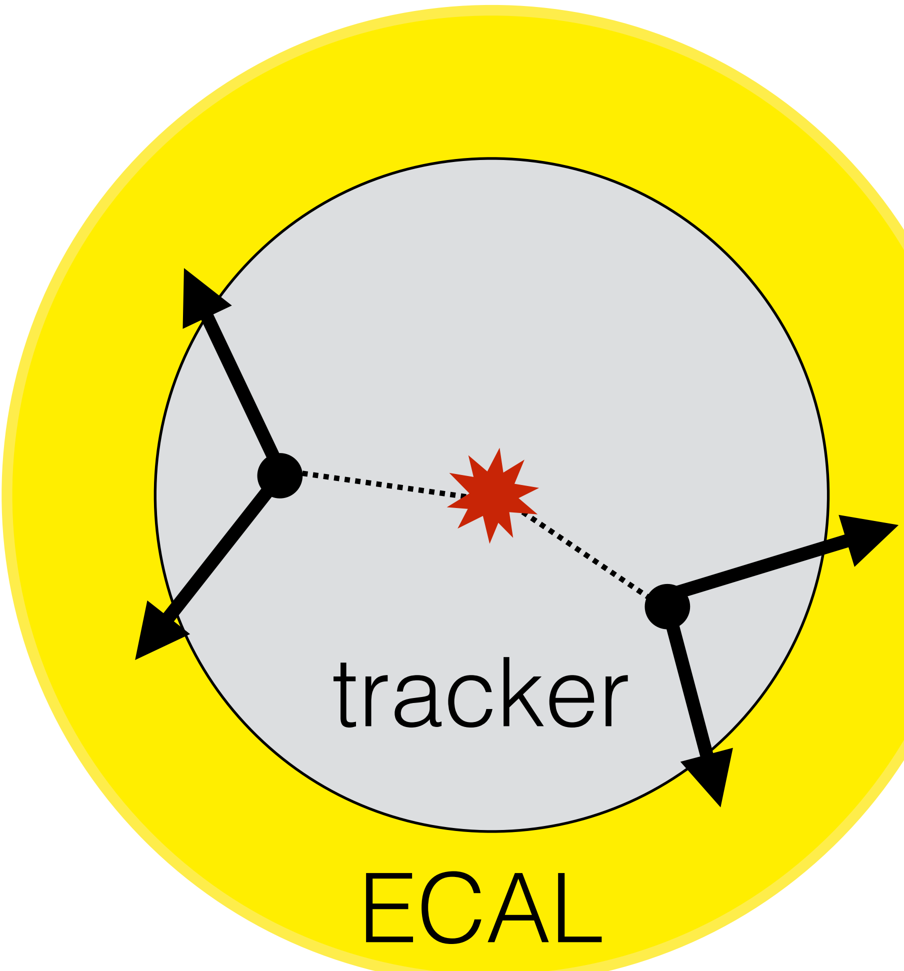
Displaced events

Displaced events would be a sign of new physics

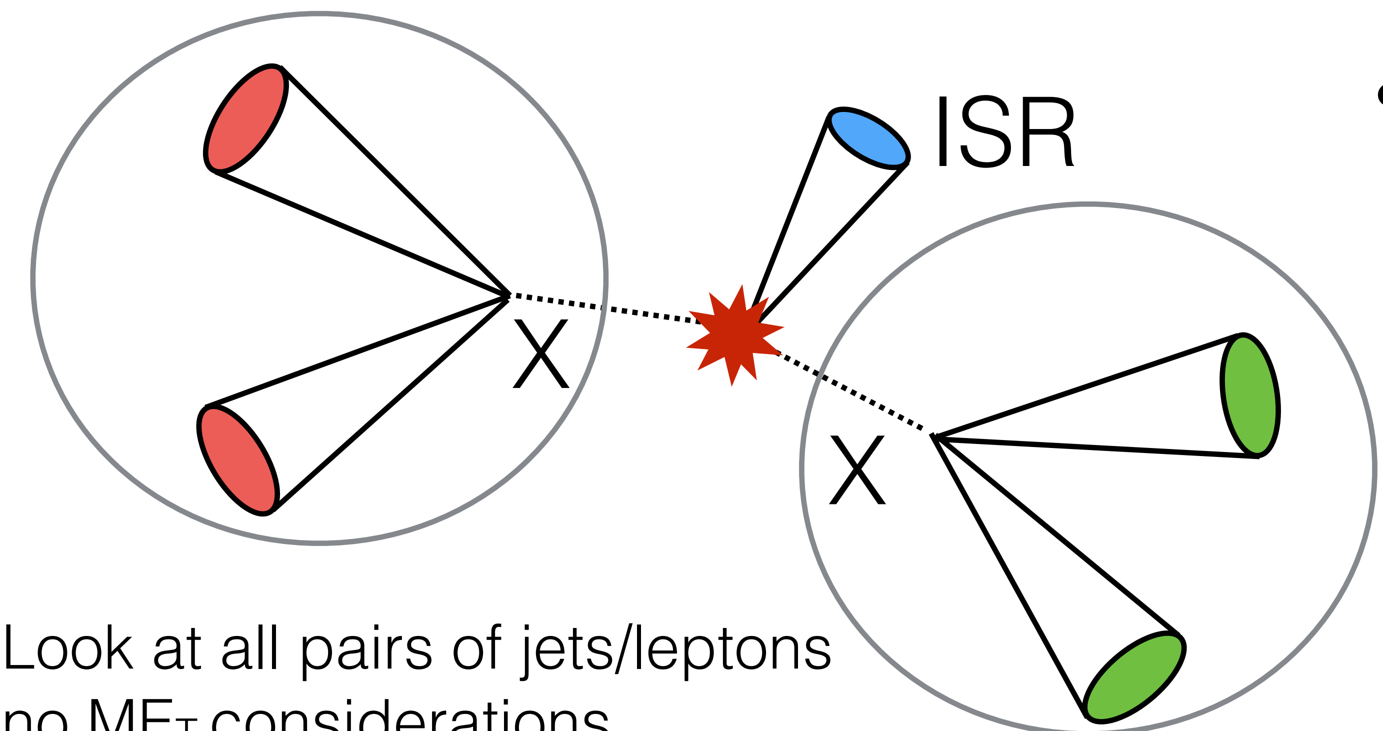


- Displaced events are events where a long-lived particle travels a measurable distance from the interaction point point before decaying.
- Asking for 2 displacements > .01 cm (the b lifetime) has heavily suppressed standard model background.
- We are motivated by Split SUSY's long lived gluinos, but other models such as hidden valley, RPV SUSY, and others predict long lived particles

CMS Lepton and Jet Searches

Di-jets and Di-leptons

$$pp \to \chi^0\chi^0 \to (qq)(qq) \text{ or } (ll)(ll)$$



Look at all pairs of jets/leptons
no ME_T considerations

Utilize dedicated triggers for displacement.

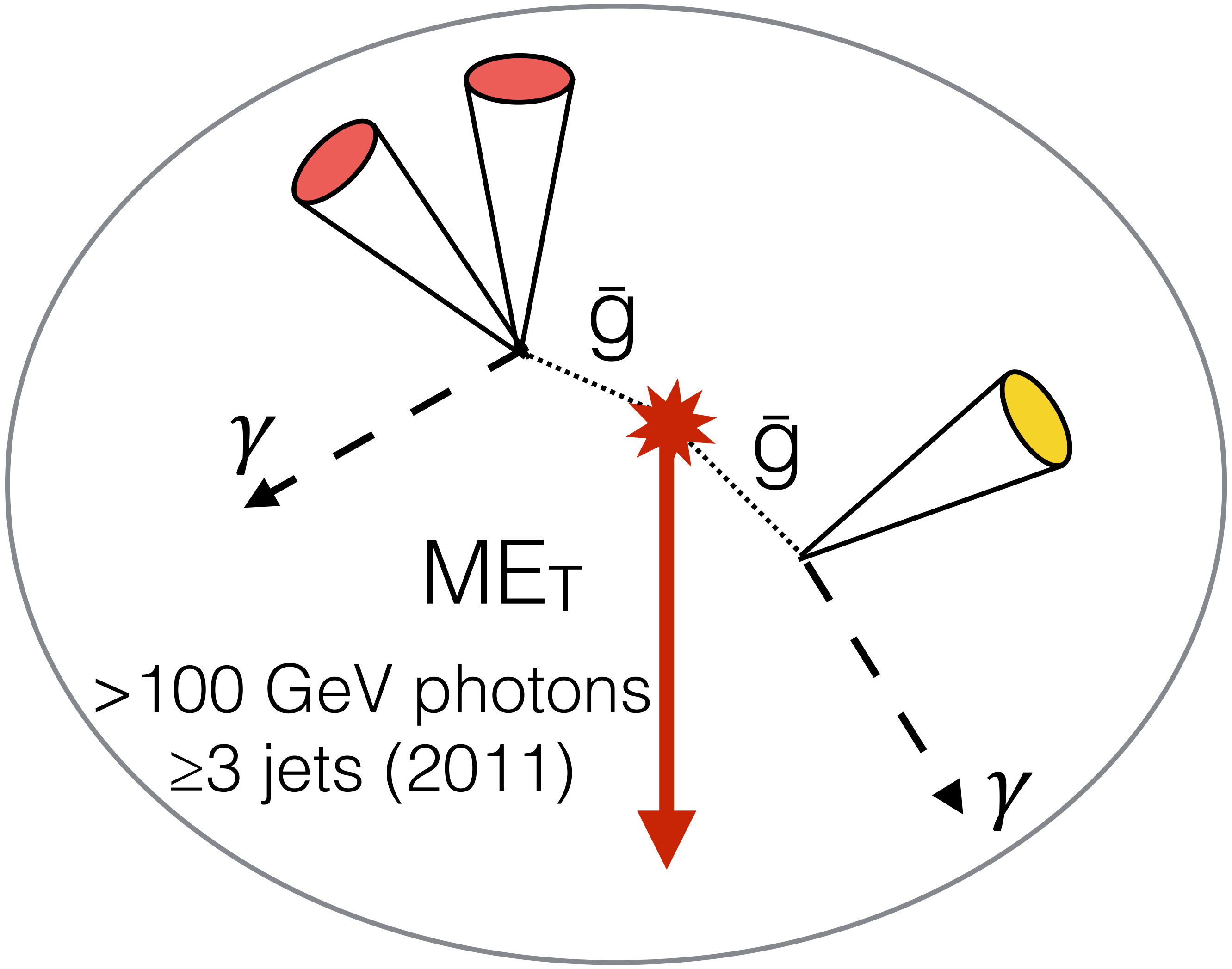
- Very targeted signal selection. Only 1 or 2 events pass the selection criteria. Selecting for events with high significance
- Searching for <u>individual instances of displacement</u> by looking at all possible pairs of leptons and jets with a secondary vertex (candidate basis)
- Very general results for theorist interpretation, but leaves a lot on the table to search with

CMS Photon Searches

- Use ECAL timing and photon conversions to find displaced vertices
- 2012 analysis exists, but no documentation available
- Targeted specifically for GMSB with long lived gluinos and many jets
- Incorporates missing energy distribution

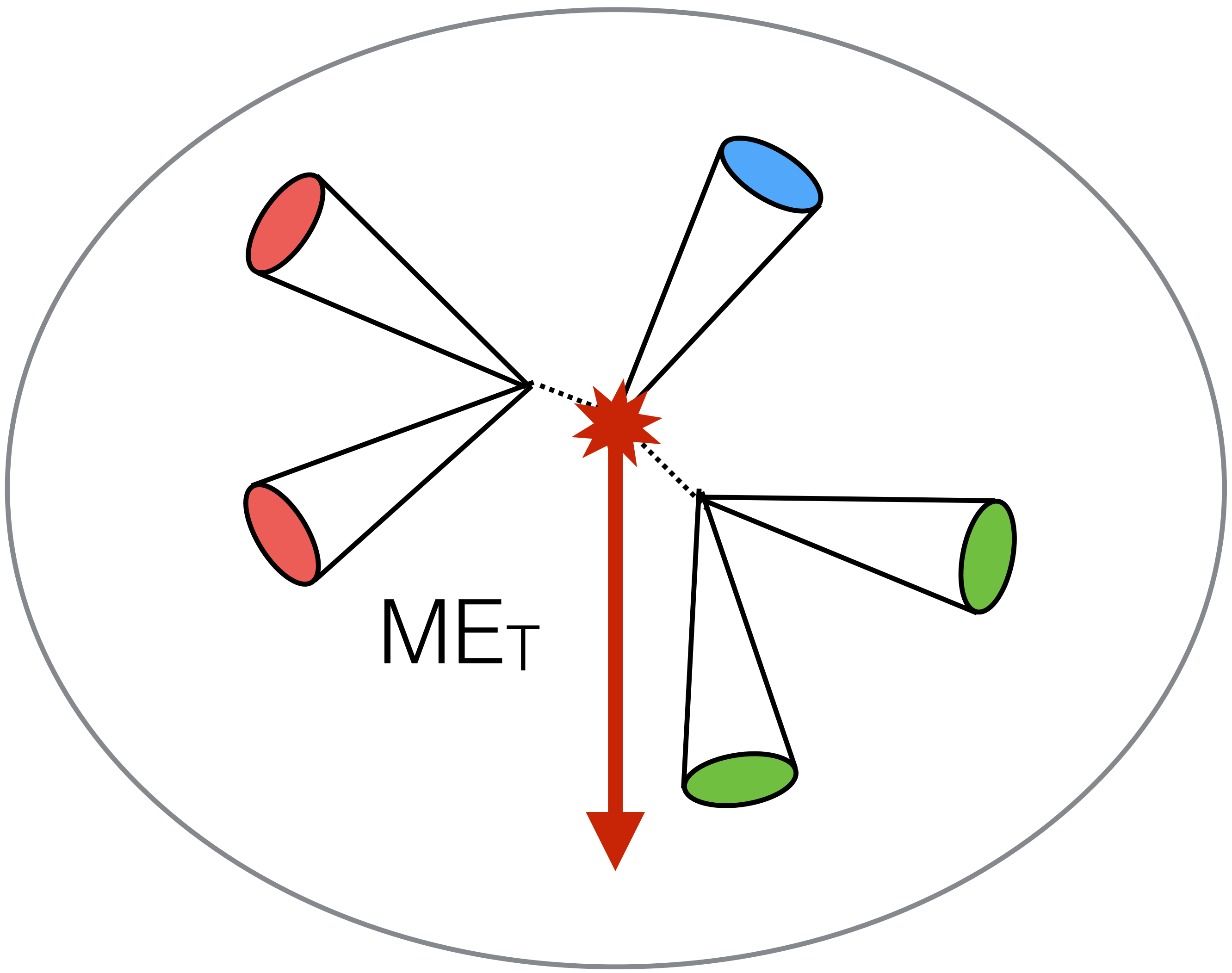
ex. GMSB Displaced Photon

$$pp \to \tilde{g}\tilde{g} \to (\gamma jj + \tilde{G})(\gamma j + \tilde{G})$$



Guiding Principles to this Study

Use full event w/ minimal req.



Tag as containing "loosely" displaced objects, reconstruct full event with kinematic variables

1. Investigate the **kinematic relationships** of the displaced objects to the rest of the event: (pair production, mass splittings, jet angles,jet mass)
2. Develop **"loose" displacement tags** to tag events containing loosely displaced objects (similar to b-tagging)
3. Perform the analysis as **inclusive** as possible (jets, leptons, photons)
4. Incorporate the **missing energy** distribution (split-susy)

Kinematic Variables w/ Categories

MET?	**Final State?**	**Pair Produced?**	**Displacement?**
• Yes • No	• Photons • Jets • Leptons	• Yes • No	• Short • Long

- By retaining events after selection we can use other general predictions of displaced events to look for new physics
- Event variables such as Razor allow us to compare events with different final states on equal footing. Razor would work out of the box, but other variables should be looked at.
- Analyze each category with a common method while optimizing each category to its own strengths

Outline

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Goals

1. **Improve Signal MC of displaced events**

Current signal samples require FULL-SIM, extend implementation to FAST-SIM displaced events

2. **Develop *reusable* loose displacement tags**

Investigate categories of jets, leptons, photons using tracker, photon conversions, dE/dx, and ECAL timing. Since the tags are loose, they can be reused by other analyses.

3. **Incorporate kinematic variables in an inclusive way**

Categorize events with and without ME_T and optimize kinematic variables such as the razor to the given categories

4. **Be discovery ready for 2015 data taking**

Start work in January 2014 to begin preparations

Collaboration

Current Displaced Analyses

Princeton: Di-leptons and Dijet

Inclusive Kinematic Variables

Caltech, Northeastern, Cornell, Princeton, CERN (Razor Analysis Framework)

New Jersey Area Theorists and Phenomenologists:

Institute for Advanced Study, Rutgers, and Princeton

Numerous CMS Groups:

HCAL, ECAL, Tracking, Trigger Development, MC Generators, EXO and SUSY

Conclusion

- Displaced physics has a number of motivations for beyond the standard model physics especially if Natural SUSY is not found at 13 TeV
- This project aims to improve MC simulation for displaced events, develop loose displacement tags, and utilize kinematic variables in an inclusive environment
- I am well suited for combining the inclusive strategies of the Razor analysis to the displaced analyses from Princeton
- Endorsement of the project would encourage support between theorist, phenomenologist communities outside of CERN
- **Special thanks to the committee for your time and effort with the application process!**

References from Proposal

[1] S. Dimopoulos, G. Giudice. Naturalness constraints in supersymmetric theories with non-universal soft terms, Phys. Lett. B357 (1995), no. 4, 573,

[2] N. Arkani-Hamed and Savas Dimopoulos. Supersymmetric Unification Without Low Energy Supersymmetry And Signatures for Fine-Tuning at the LHC. `arXiv:hep-th/0405159v2`

[3] G. Giudice, A. Romanino. Split Supersymmetry. `arXiv:hep-ph/0406088v2`

[4] N. Arkani-Hamed, S. Dimopolous, G.F. Giudice, A. Romanino. Aspects of Split Supersymmetry. `arXiv:hep-ph/0409232v2`

[5] N. Arkani-Hamed, A. Gupta, D. Kaplan, Neal Weiner, Tom Zowarski. Simply Unnatural Supersymmetry. `arXiv:1212.6971v1`

[6] J. Hewett, B. Lillie, M. Masip, and T. Rizzo, Signatures of long-lived gluinos in split supersymmetry. `arXiv:hep-ph/0408248v1`

[7] The CMS Collaboration. `EXO-12-037`. Search in leptonic channels for heavy resonances decaying to long-lived neutral particles.

[8] The CMS Collaboration. `EXO-12-026`. Searches for Long-lived Charged particles in pp Collisions at $\sqrt{s} = 7$ and 8 TeV.

[9] The CMS Collaboration. `EXO-12-038`. Search for long-lived neutral particles decaying to dijets.

[10] The CMS Collaboration. `EXO-11-035`. Search for long-lived particles in events with photons and missing energy in proton-proton collisions at $\sqrt{s} = 7$ TeV.

[11] The CMS Collaboration. `EXO-11-067`. Search for new physics with long-lived particles decaying to photons and missing energy in pp collisions at $\sqrt{s} = 7$ TeV

[12] The CMS Collaboration. `EXO-12-048`. Search for new physics in monojet events in pp collisions at $\sqrt{s} = 8$ TeV

[13] The CMS Collaboration. `SUS-12-001`. Search for Supersymmetry in Events with Photons and Missing Transverse Energy.

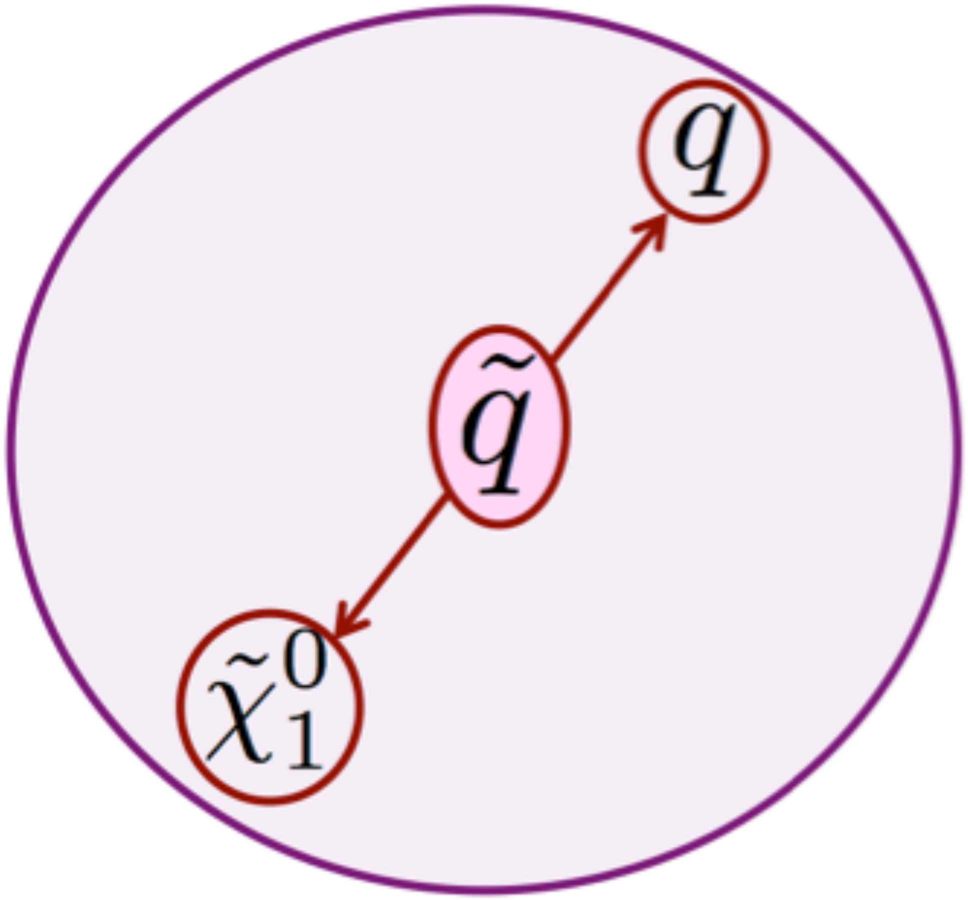
[14] The CMS Collaboration. `SUS-12-005`. Search for supersymmetry with the razor variables.

[15] The CMS Collaboration. `SUS-12-009`. A search for the decays of a new heavy particle in multijet events with the razor variables at CMS in pp collisions at $\sqrt{s} = 7$ TeV

BACKUP

Razor Kinematic Variables

Squark Rest Frame



- Examining the squarks rest frame the LSP and jet have equal momentum
- From this frame we see that the quark momentum is a measure of the scale of the new physics M_Δ

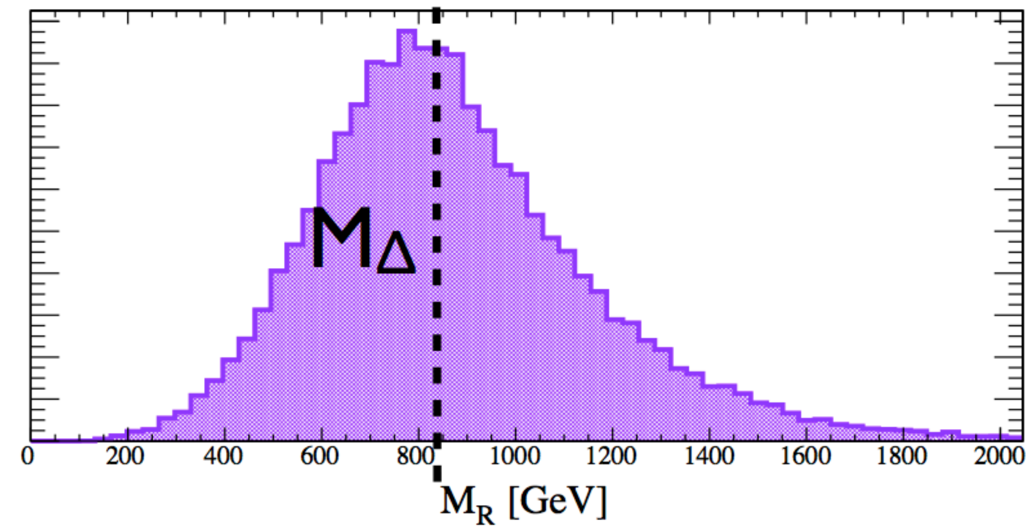
$$|\vec{P}_{jet}| = M_\Delta/2 = \frac{M_{\tilde{q}}^2 - M_{\tilde{\chi}}^2}{2M_{\tilde{q}}}$$

- The Razor makes a series of approximations to reach this frame and evaluates the jet momentum

Razor Kinematic Variables

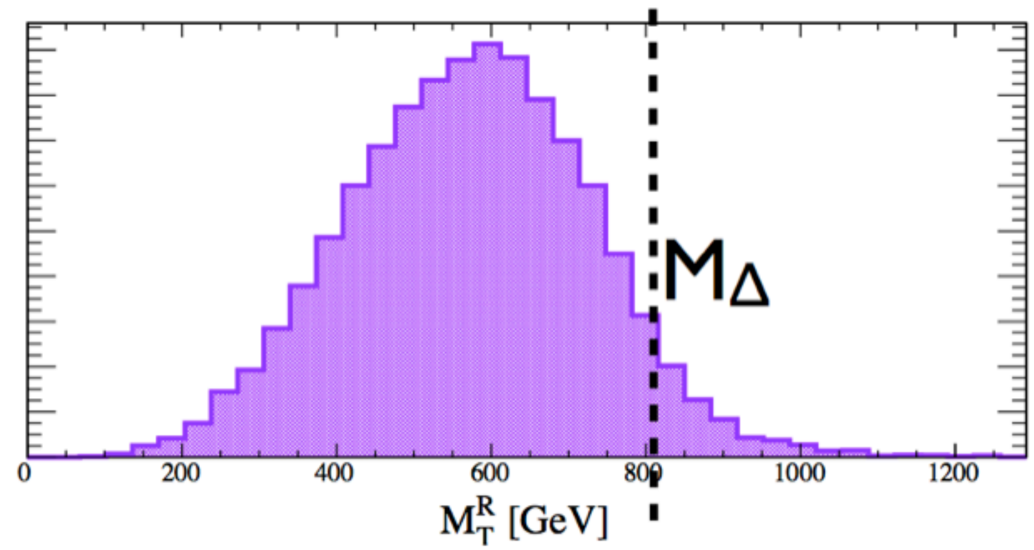
- M_R peaks at the mass scale M_Δ:

$$M_R = \sqrt{(|\vec{p}_{j_1}| + |\vec{p}_{j_2}|)^2 - (p_z^{j_1} + p_z^{j_2})^2}$$



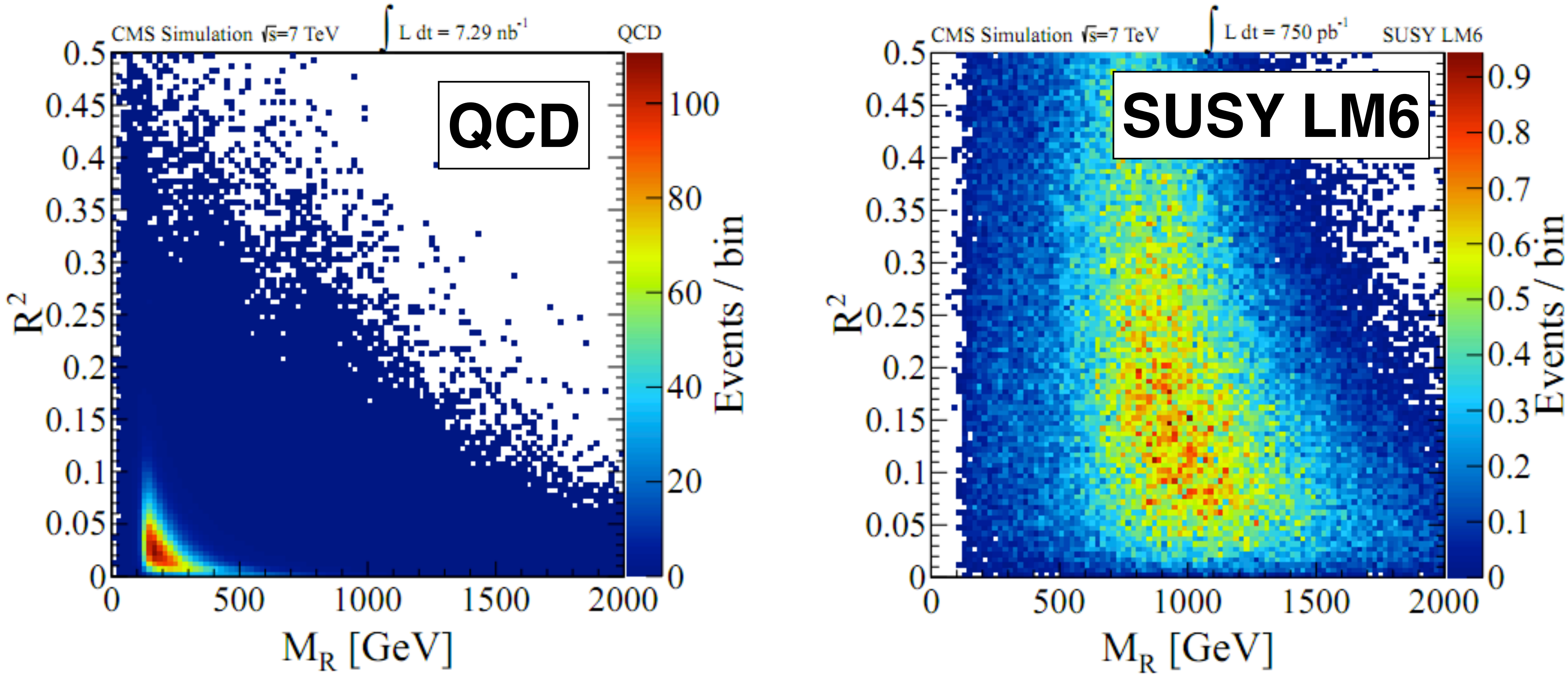
- M_T^R is related to the missing energy and approximates M_Δ as an edge:

$$M_T^R = \sqrt{\frac{E_T^{miss}(p_T^{j_1} + p_T^{j_2}) - \vec{E}_T^{miss} \cdot (\vec{p}_T^{j_1} + \vec{p}_T^{j_2})}{2}}$$



- R is their ratio: $R = \dfrac{M_T^R}{M_R}$

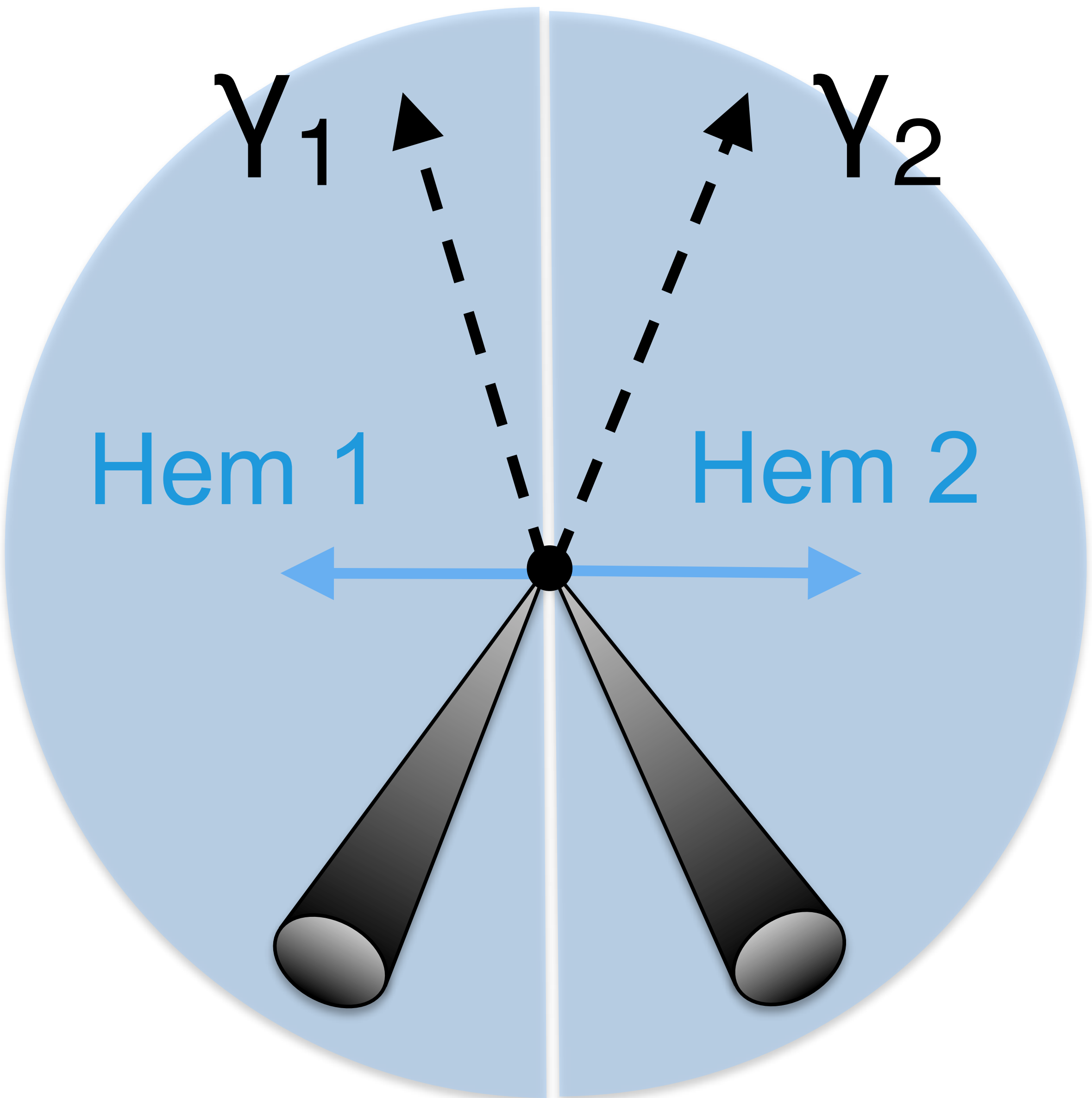
Razor Kinematic Variables



- Comparing SUSY events to QCD we see strong discrimination
- Background QCD is concentrated low in M_R and R^2

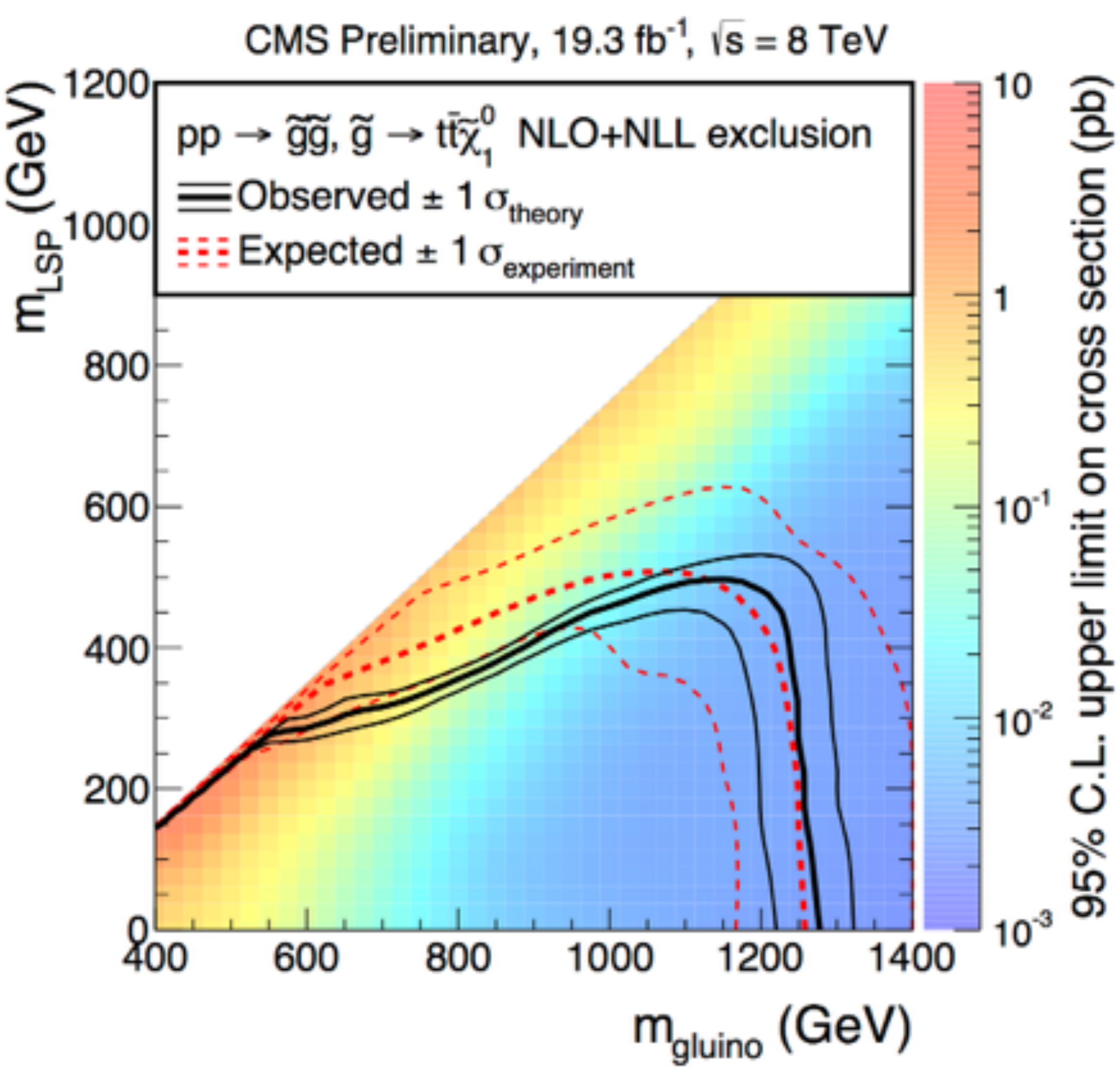
Hemisphere Formation

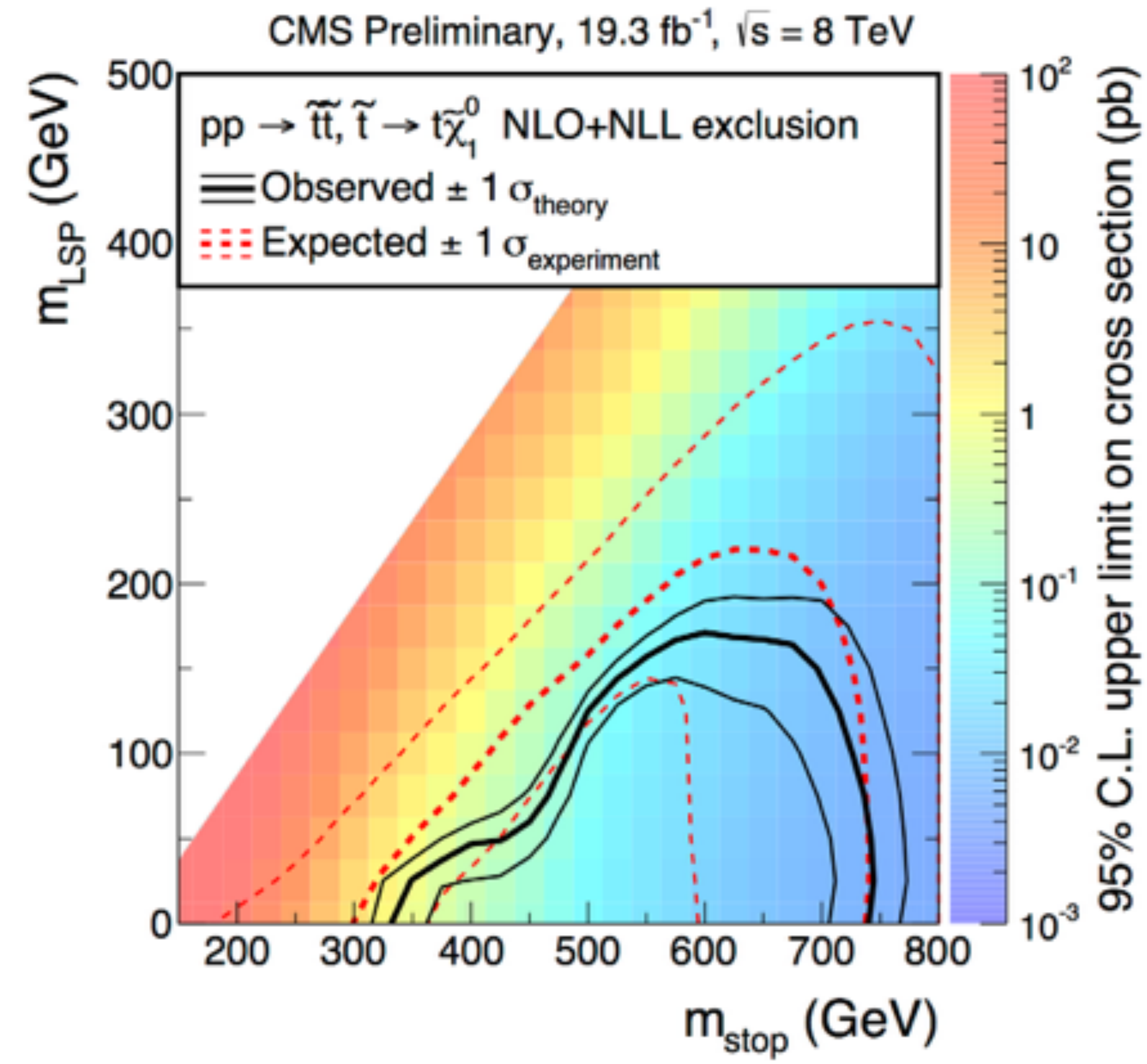
- Since there are usually more than 2 objects in an event we must force a dijet topology to evaluate the razor variables
- The collection of objects are added to two hemispheres such that the sum of the two hemisphere's invariant mass is minimized
- This allows the kinematic variables to be calculated for any pair produced topology with a visible final state

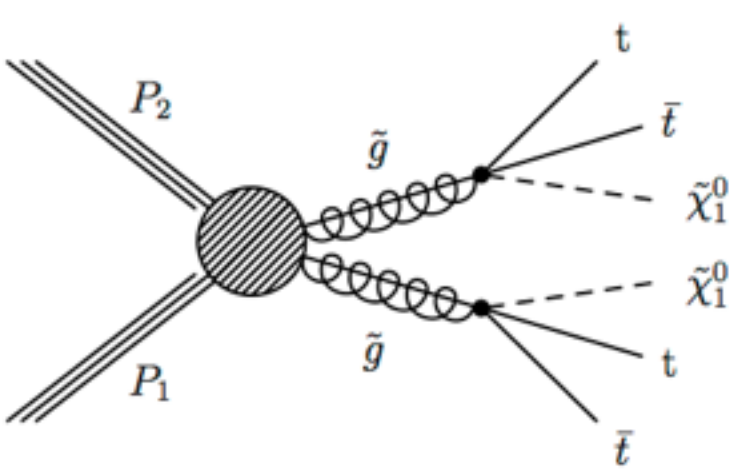


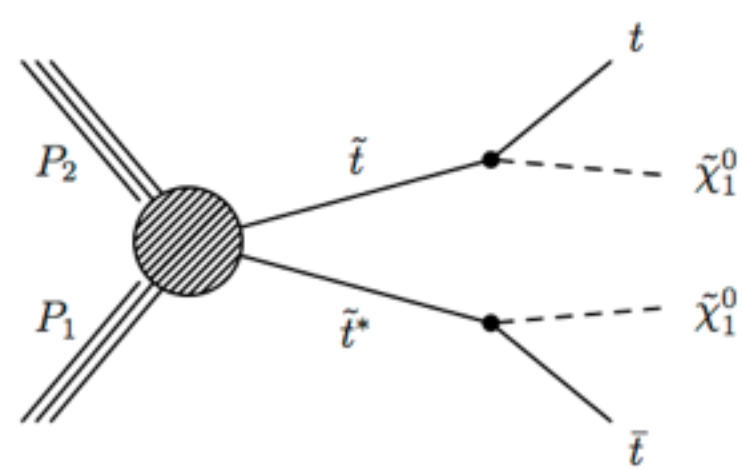
Minimal Invariant Mass Pairing

Razor (SUS-13-004) Limits





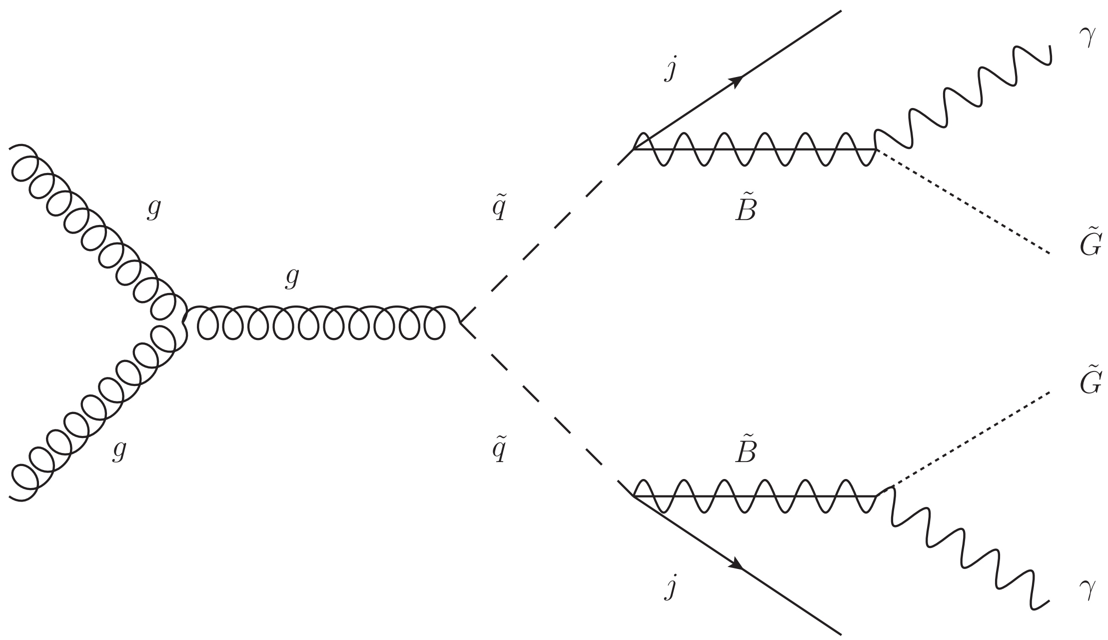


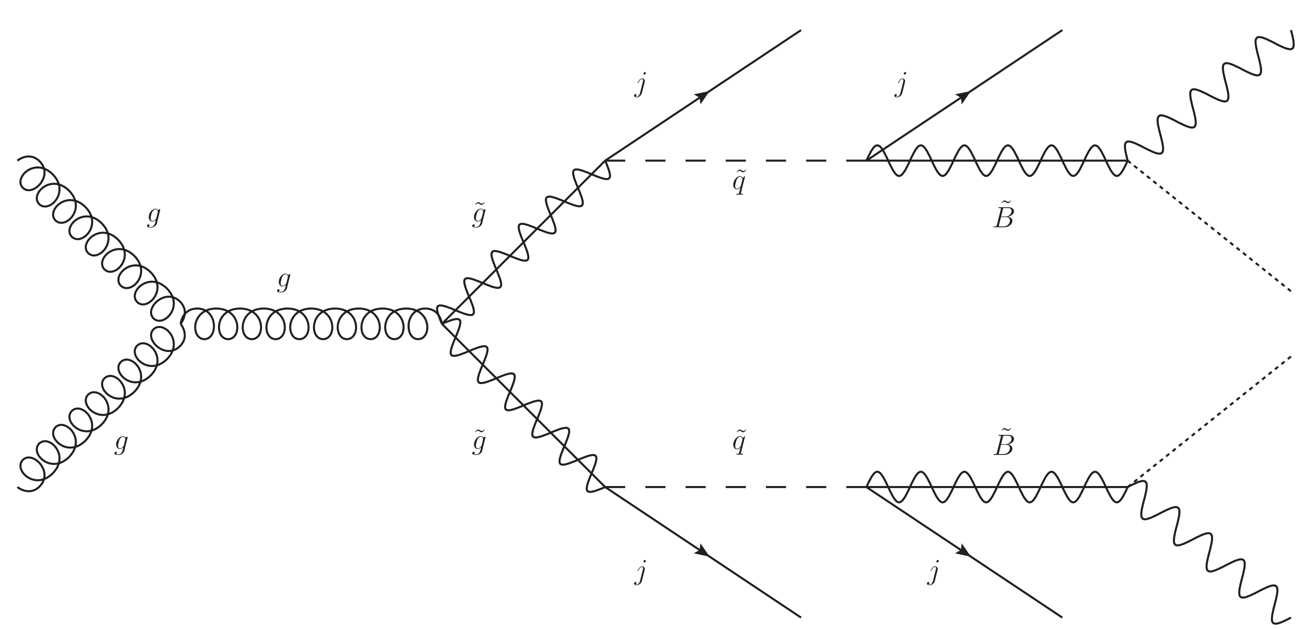


Razor Inclusive (SUS-13-001)

Requirements				
Box	lepton	b-tag	kinematic	jet
Dilepton Boxes				
MuEle	≥ 1 tight electron and ≥ 1 loose muon	≥ 1 b-tag	($M_R > 300$ GeV and $R^2 > 0.15$) and ($M_R > 450$ GeV or $R^2 > 0.2$)	≥ 2 jets
MuMu	≥ 1 tight muon and ≥ 1 loose muon	≥ 1 b-tag	($M_R > 300$ GeV and $R^2 > 0.15$) and ($M_R > 450$ GeV or $R^2 > 0.2$)	≥ 2 jets
EleEle	≥ 1 tight electron and ≥ 1 loose electron	≥ 1 b-tag	($M_R > 300$ GeV and $R^2 > 0.15$) and ($M_R > 450$ GeV or $R^2 > 0.2$)	≥ 2 jets
Single Lepton Boxes				
MuMultiJet	≥ 1 tight muon	≥ 1 b-tag	($M_R > 300$ GeV and $R^2 > 0.15$) and ($M_R > 450$ GeV or $R^2 > 0.2$)	≥ 4 jets
MuJet	≥ 1 tight muon	≥ 1 b-tag	($M_R > 300$ GeV and $R^2 > 0.15$) and ($M_R > 450$ GeV or $R^2 > 0.2$)	2 or 3 jets
EleMultiJet	≥ 1 tight electron	≥ 1 b-tag	($M_R > 300$ GeV and $R^2 > 0.15$) and ($M_R > 450$ GeV or $R^2 > 0.2$)	≥ 4 jets
EleJet	≥ 1 tight electron	≥ 1 b-tag	($M_R > 300$ GeV and $R^2 > 0.15$) and ($M_R > 450$ GeV or $R^2 > 0.2$)	2 or 3 jets
Hadronic Boxes				
MultiJet	none	≥ 1 b-tag	($M_R > 400$ GeV and $R^2 > 0.25$) and ($M_R > 550$ GeV or $R^2 > 0.3$)	≥ 4 jets
2b-Jet	none	≥ 2 b-tag	($M_R > 400$ GeV and $R^2 > 0.25$) and ($M_R > 550$ GeV or $R^2 > 0.3$)	2 or 3 jets

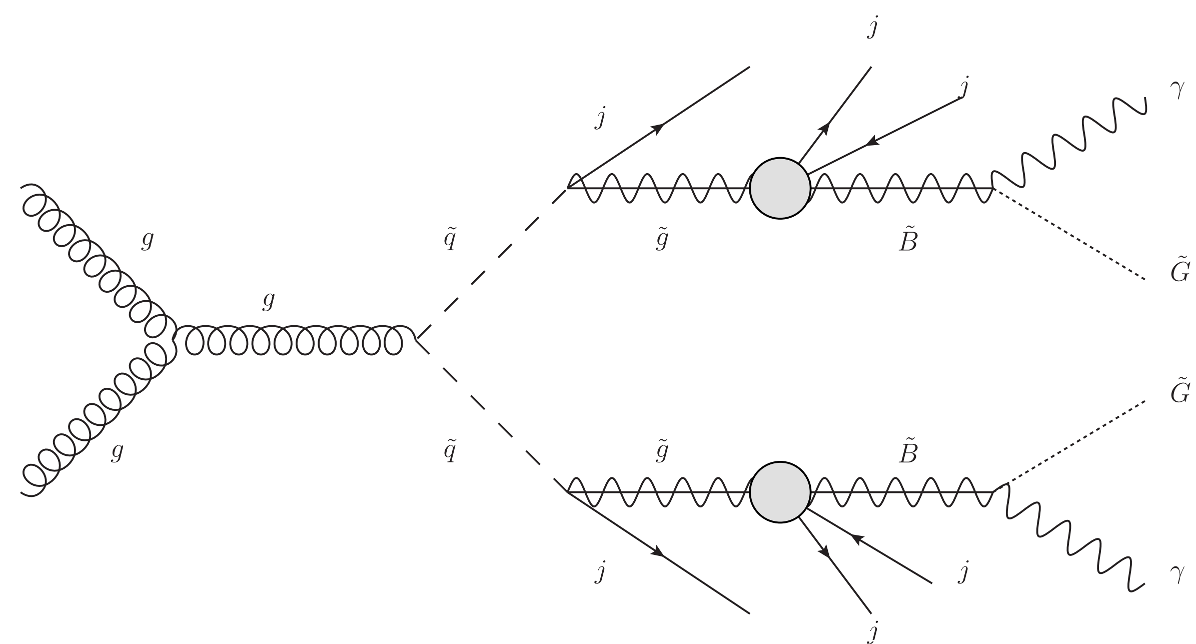
Razor Diphoton Search



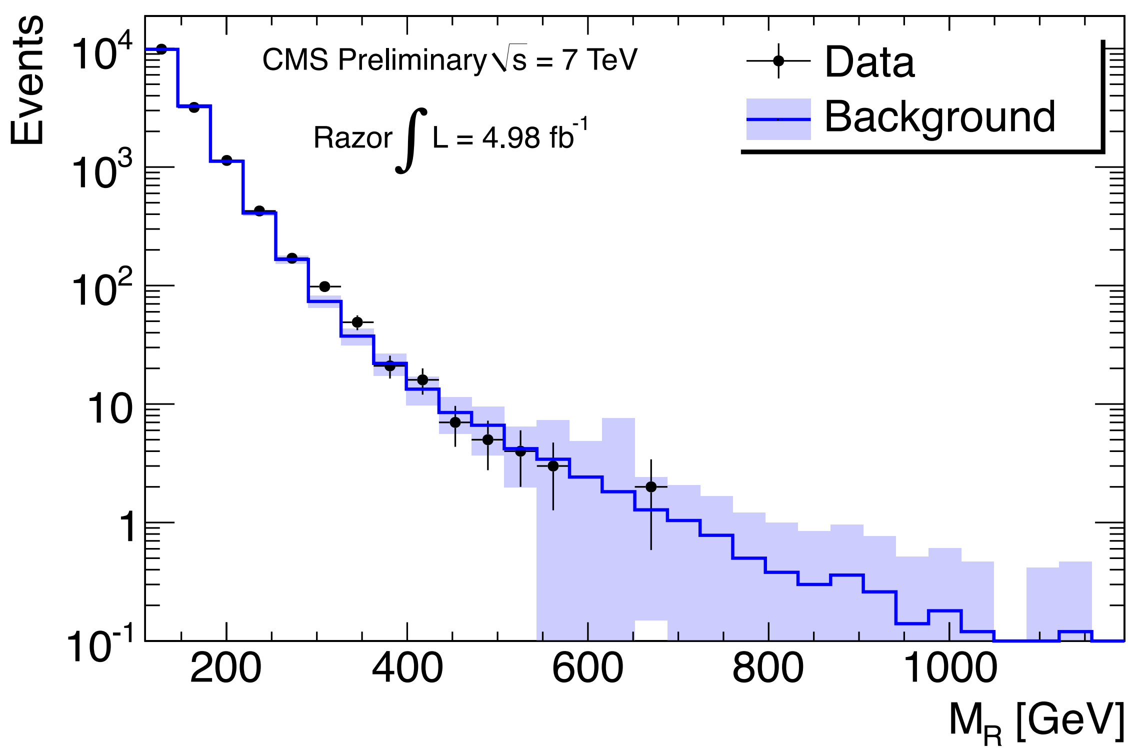


The standard GMSB signal is an admixture of cascading decays from gluinos, squarks, and binos (NLSP). The bino like NLSP decays to Graivitino (LSP) + photon

The Gravitino escapes detection and is detected as MET

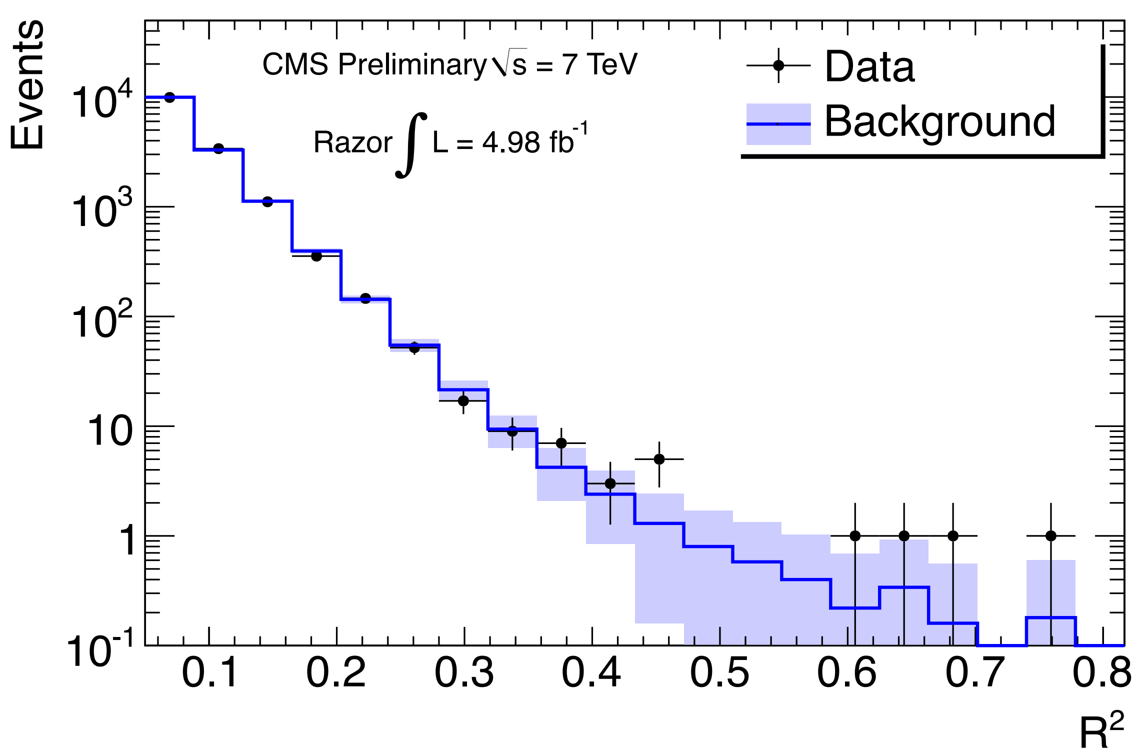


7 TeV Razor Diphoton Result (Unapproved)

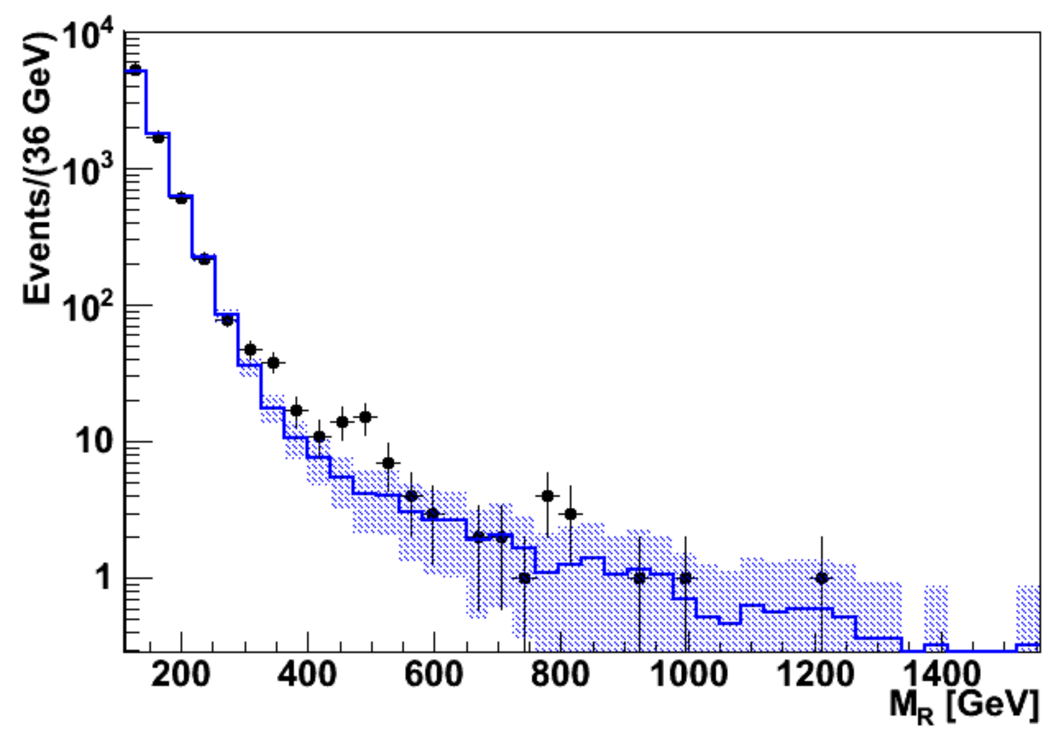


Two dimensional fit function

$$\left[b(x-x_0)^{\frac{1}{n}}(y-y_0)^{\frac{1}{n}}-n\right]e^{-b(x-x_0)^{\frac{1}{n}}(y-y_0)^{\frac{1}{n}}}$$



Signal Injection Tests



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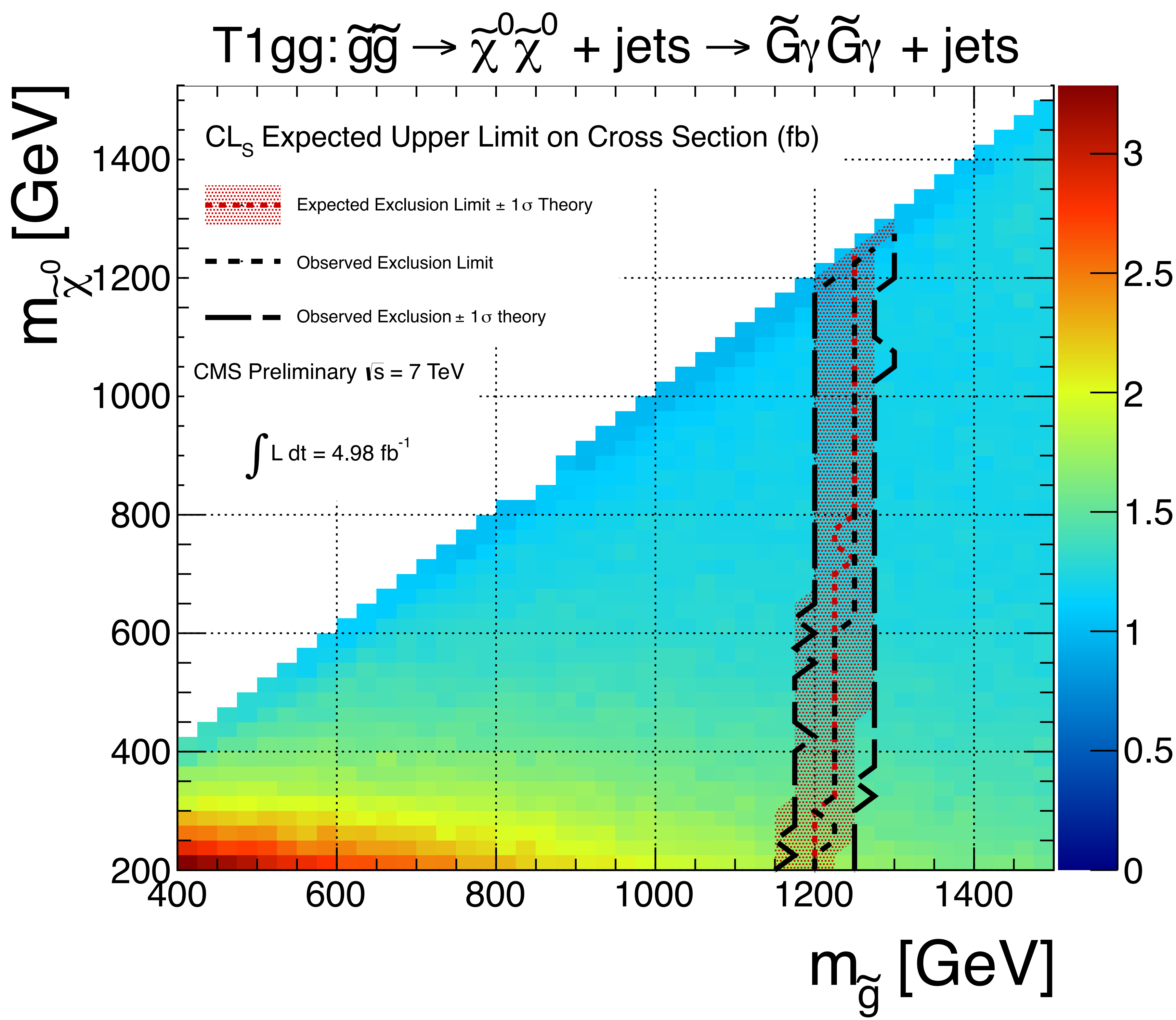
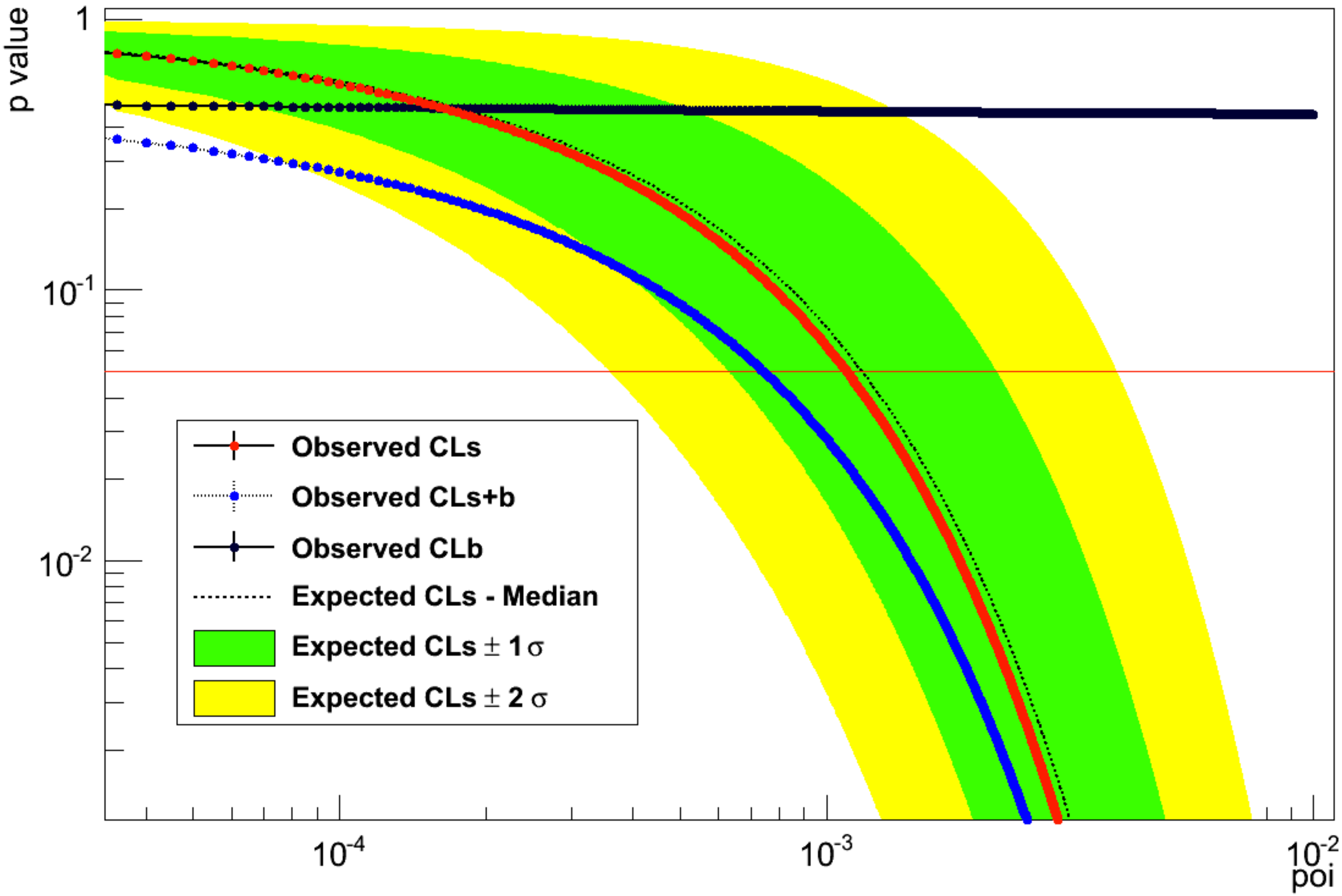


Single Point m_0=1200 $m_{1/2}$=1000

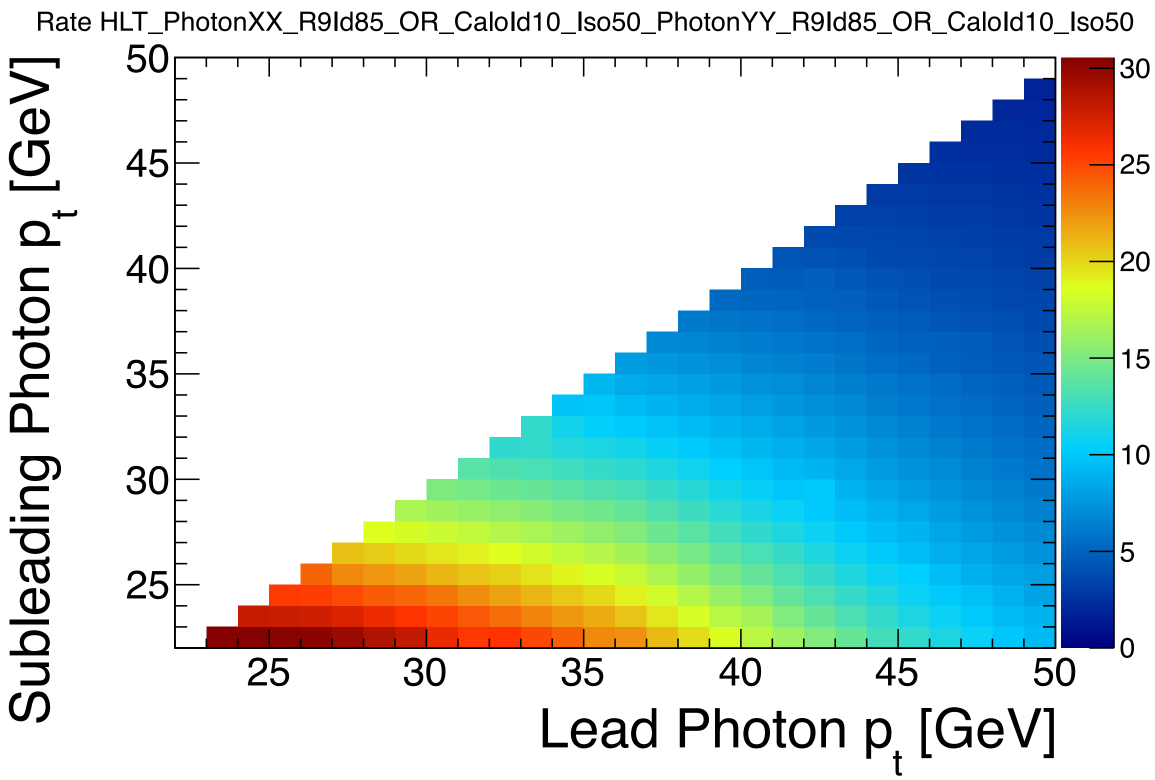


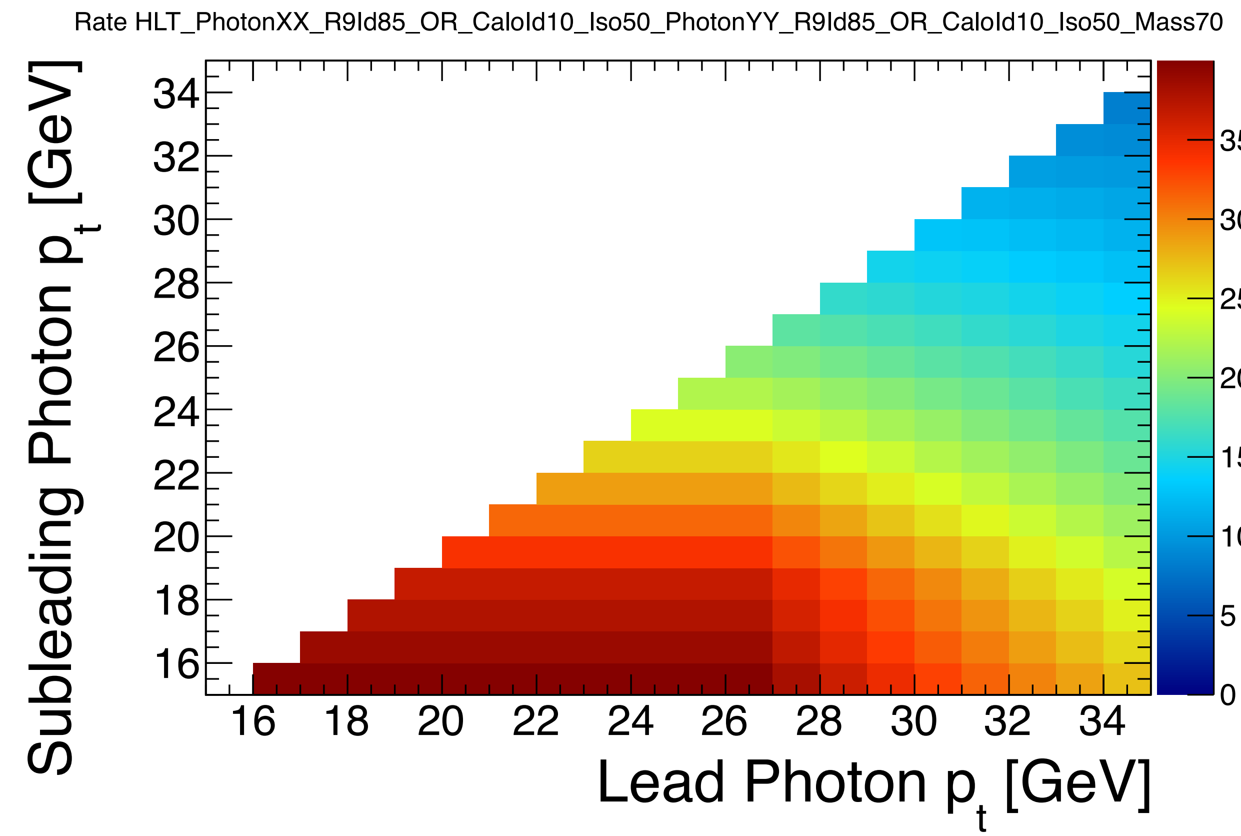
$H \rightarrow \gamma\gamma$ Trigger Definitions

Because of the large number of identification criteria, the triggers have long names, but are referred to by the cuts on the leading and sub-leading photon p_t and the mass cut on $m_{\gamma\gamma}$

1. 26/18 with a 70 GeV mass cut seeded by `L1_DoubleEG_13_7`:
   `HLT_Photon26_R9Id85_OR_CaloId10_Iso50_Photon18_R9Id85_OR_CaloId10_Iso50_Mass70_v2`
2. 36/22 with no mass cut seeded by `L1_SingleEG_22`:
   `HLT_Photon36_R9Id85_OR_CaloId10_Iso50_Photon22_R9Id85_OR_CaloId10_Iso50_v6`
3. 36/10 with an 80 GeV mass cut seeded by `L1_SingleEG_22`:
   `HLT_Photon36_R9Id85_OR_CaloId10_Iso50_Photon10_R9Id85_OR_CaloId10_Iso50_Mass80_v1`

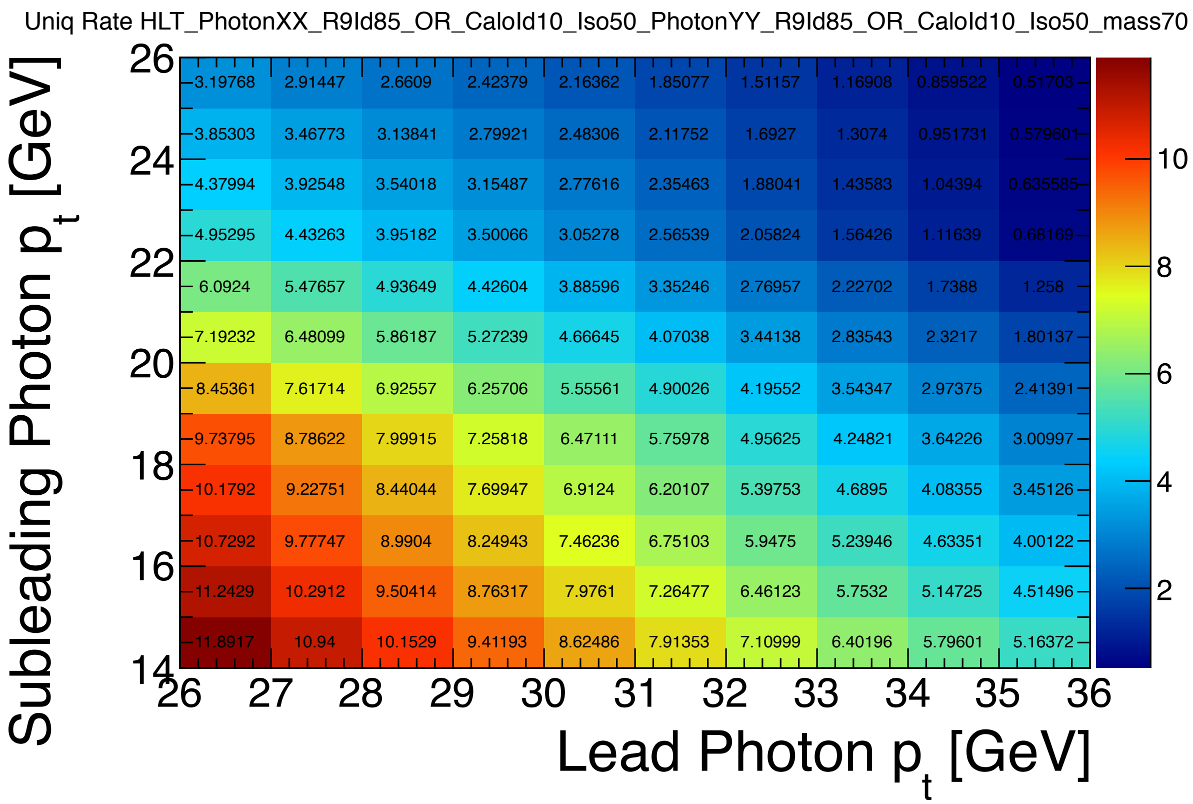
Raw Trigger Scans

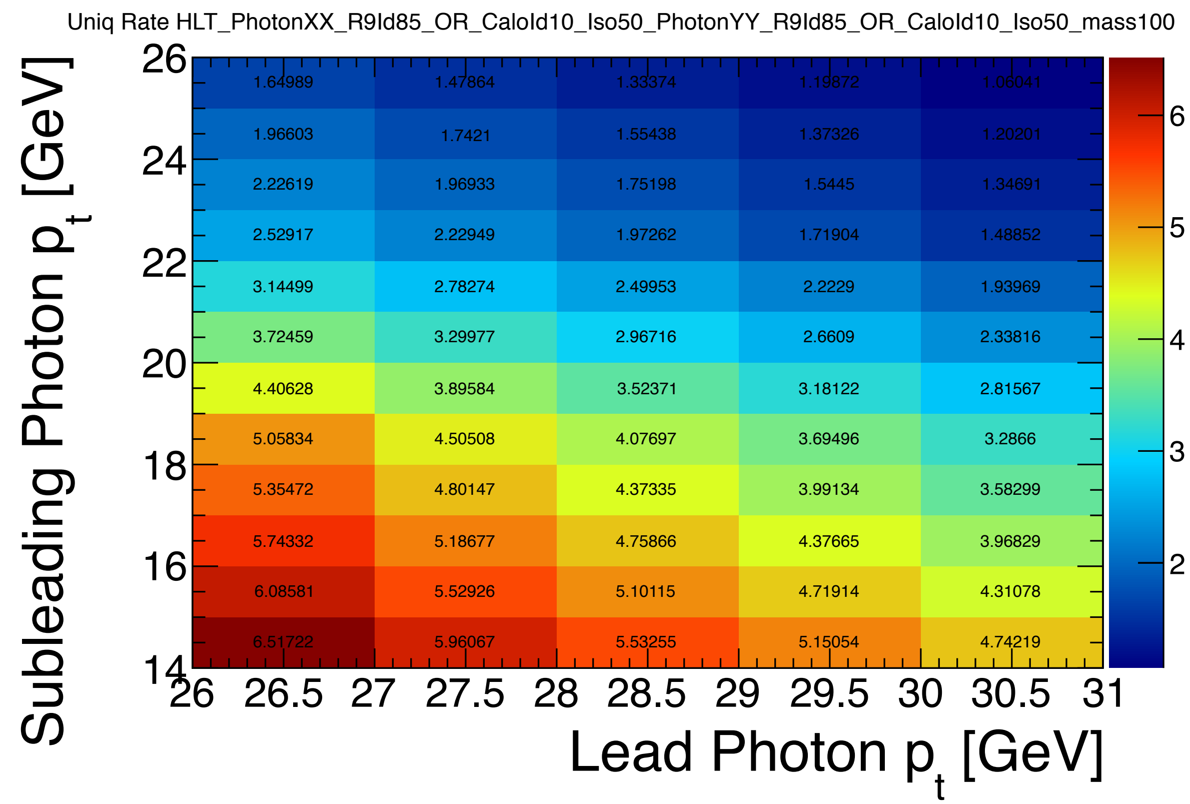




- Each individual trigger (p_{t1}, p_{t2}) is simulated on the RAW (pre-reconstruction) data using a trigger analysis package known as openHLT
- The RAW trigger rate corresponding to all events in which the trigger fired irregardless of the other triggers in the suite
- We scan the parameter space in the leading and subleasing p_t of the two photons

Unique Rate Trigger Scans





- The scan is also performed for the unique rate, which must be perform for EACH combination of possible triggers
- In these plots the 36/22 no mass cut trigger is held fixed and the massive trigger is probed in the 2 dimensional space of photon p_t
- We have included a luminosity factor of 2 to account for the next increase of luminosity for 13 TeV collisions in 2015.