SEARCHES @ CMS

SEARCHES FOR SUPERSYMMETRY USING RAZOR VARIABLES AT CMS

SUSY 2016

THE UNIVERSITY OF MELBOURNE

MELBOURNE, AUSTRALIA

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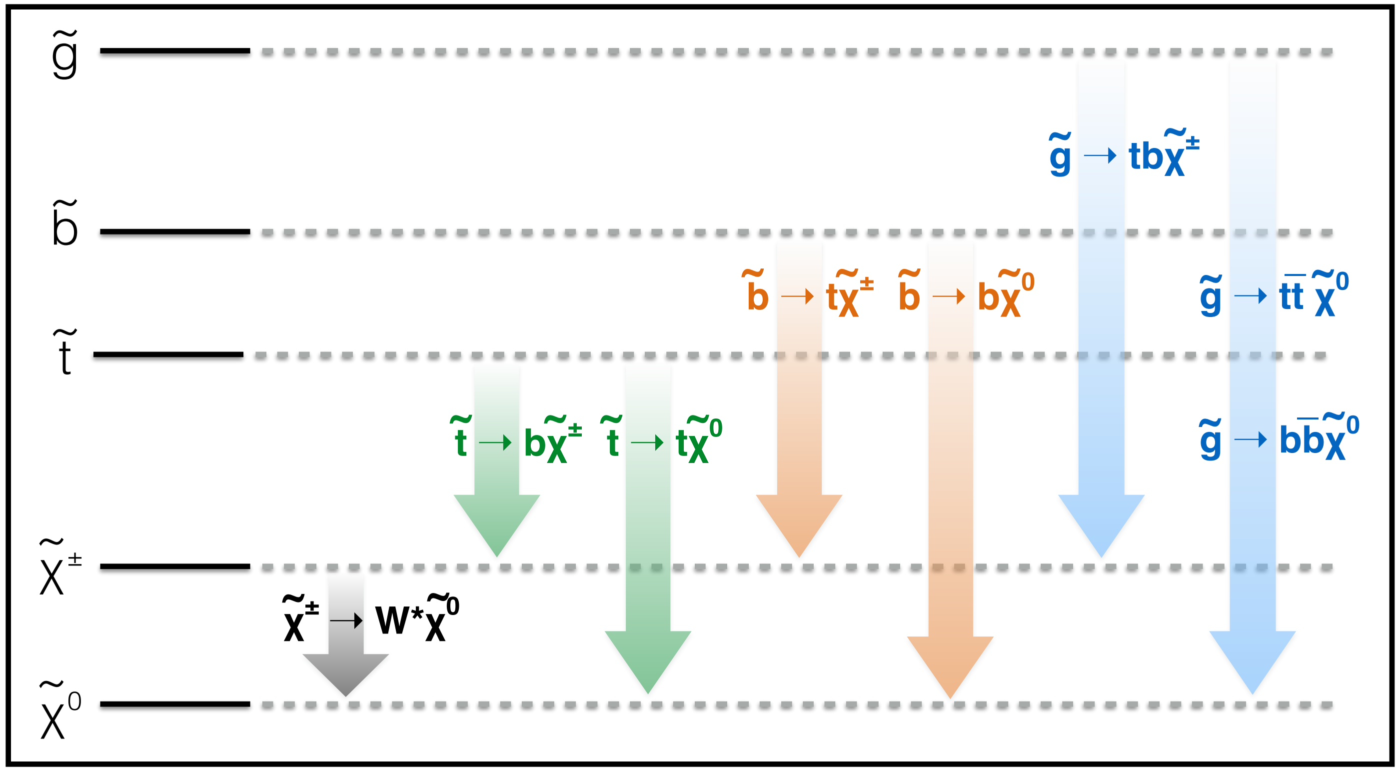
OUTLINE

- Motivation: expanded natural SUSY
- Why razor variables?
- Searches
  - Inclusive search for squarks and gluinos
  - Exclusive search for anomalous $H \rightarrow \gamma\gamma$ production
- New topological triggers
- Outlook

NATURAL SUSY

- Lightest Higgs boson mass is connected with
  - Higgsino masses (tree level)
  - stop/sbottom masses (1 loop)
  - gluino mass (2 loop)
- Naturalness = all contributions are of the same order as the physical Higgs mass (no fine-tuning)
- "Acceptable" fine-tuning implies
  Higgsinos lighter than ~300 GeV
  stops lighter than ~700 GeV
  gluinos lighter than ~1.5 TeV[1]
- Possible spectrum:

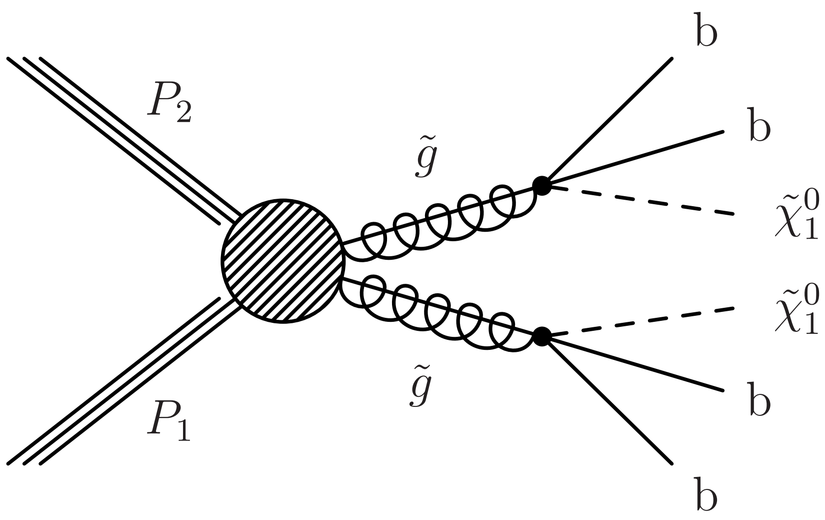


1. M. Papucci, et al. JHEP 1209 (2012) 035

SUSY SIMPLIFIED MODELS

- One heavy particle (gluino), one invisible particle (neutralino), one possible decay channel (bb)

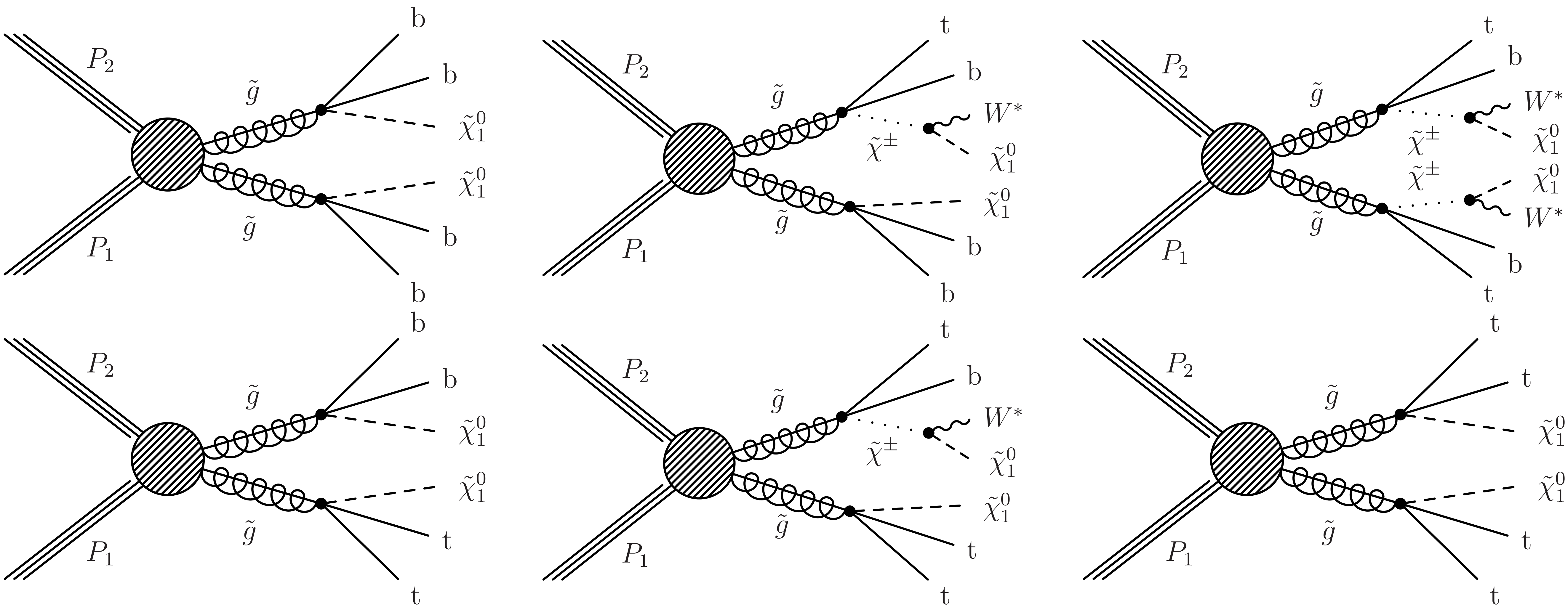
$$100\% \quad = \quad \mathrm{BR}(\tilde{g} \to b\bar{b}\tilde{\chi}_1^0)$$



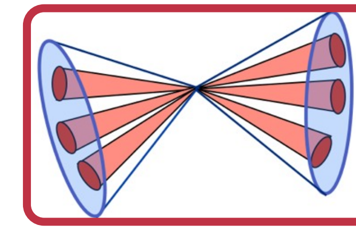
NATURAL SUSY SIMPLIFIED MODELS

- Extended "natural" spectrum: allow multiple decay channels to see how it impacts our sensitivity
- Possible gluino decay topologies (depending on branching ratios *x*, *y*, *z*)

$$
\begin{aligned}
x &= \mathrm{BR}(\tilde{g} \to b\bar{b}\tilde{\chi}_1^0) \\
y &= \mathrm{BR}(\tilde{g} \to t\bar{t}\tilde{\chi}_1^0) \\
z &= \mathrm{BR}(\tilde{g} \to tb\tilde{\chi}_1^\pm)
\end{aligned}
$$



INCLUSIVE RAZOR

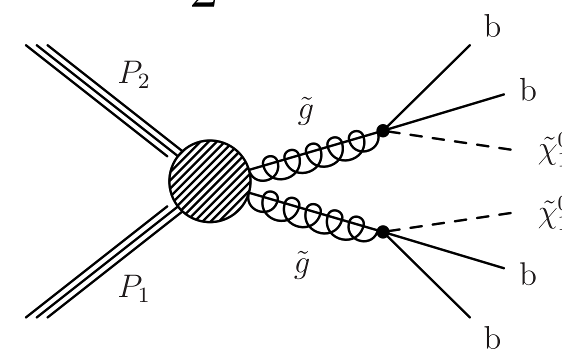


- Treat all events as "dijets + MET" by clustering particles into two pseudo-jets, called megajets

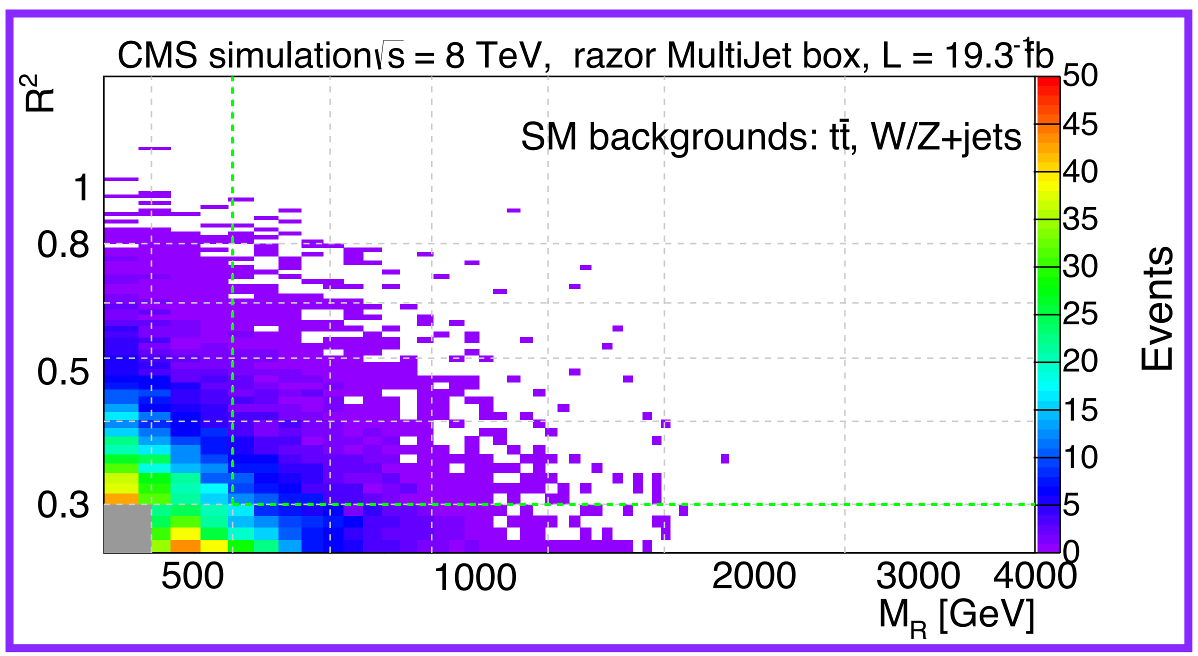
$$M_R = \sqrt{(|\vec{p}_{j1}| + |\vec{p}_{j2}|)^2 - (p_z^{j1} + p_z^{j2})^2}$$

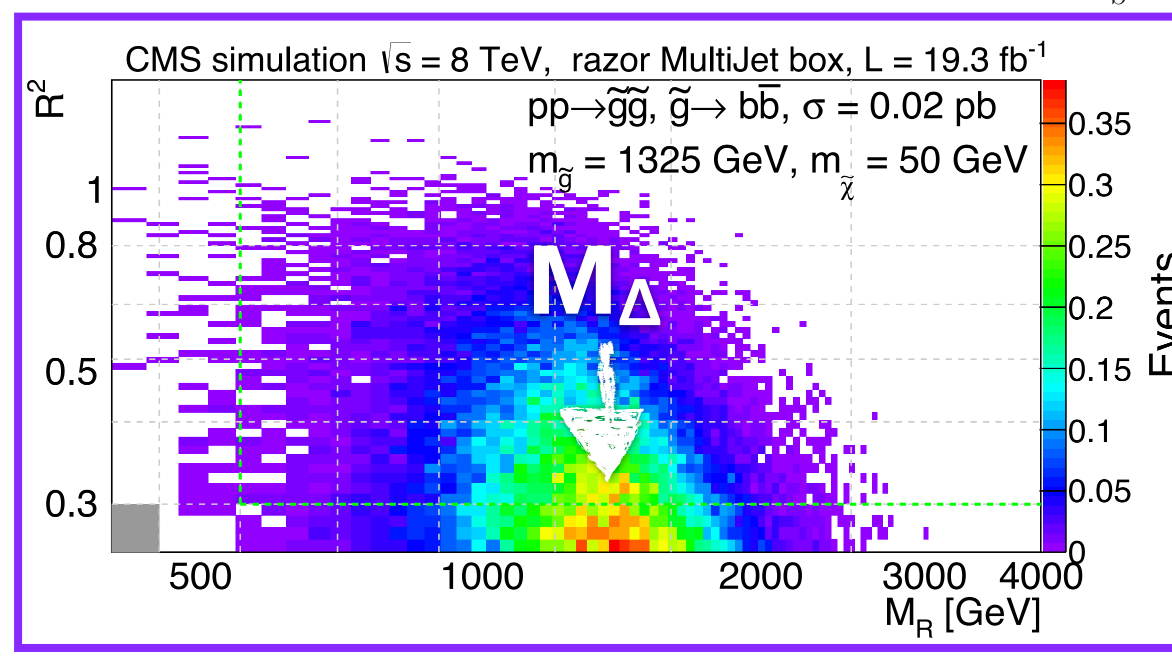
$$R \equiv \frac{M_T^R}{M_R} \qquad M_T^R \equiv \sqrt{\frac{E_T^{\text{miss}}(p_T^{j1} + p_T^{j2}) - \vec{E}_T^{\text{miss}} \cdot (\vec{p}_T^{j1} + \vec{p}_T^{j2})}{2}}$$

- Gluino signal events well-separated from SM background events



R^2 related to MET

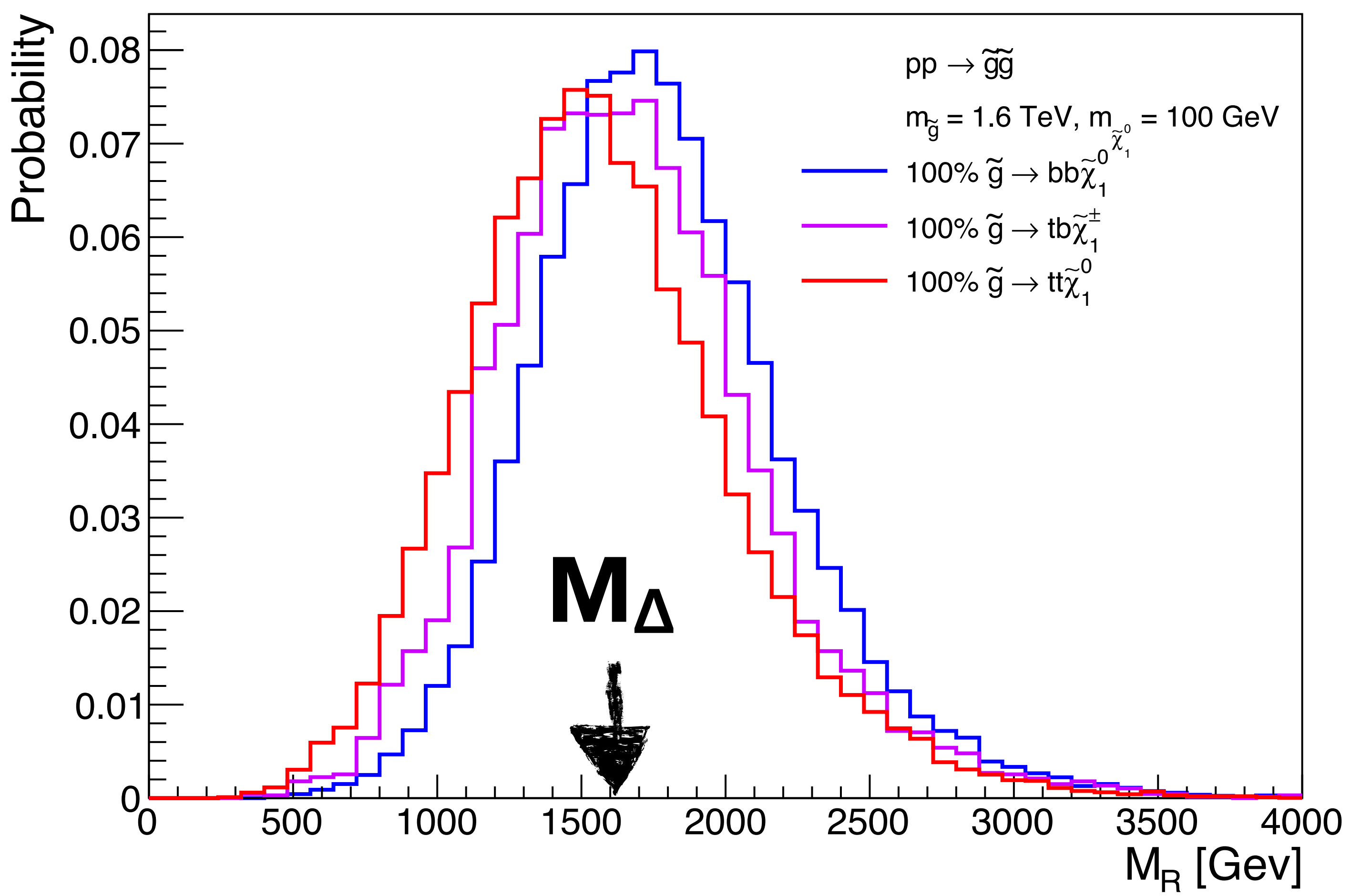




M_R peaks at char. mass scale **M_Δ** $= \frac{m_{\tilde{g}}^2 - m_{\tilde{\chi}_1^0}^2}{m_{\tilde{g}}}$

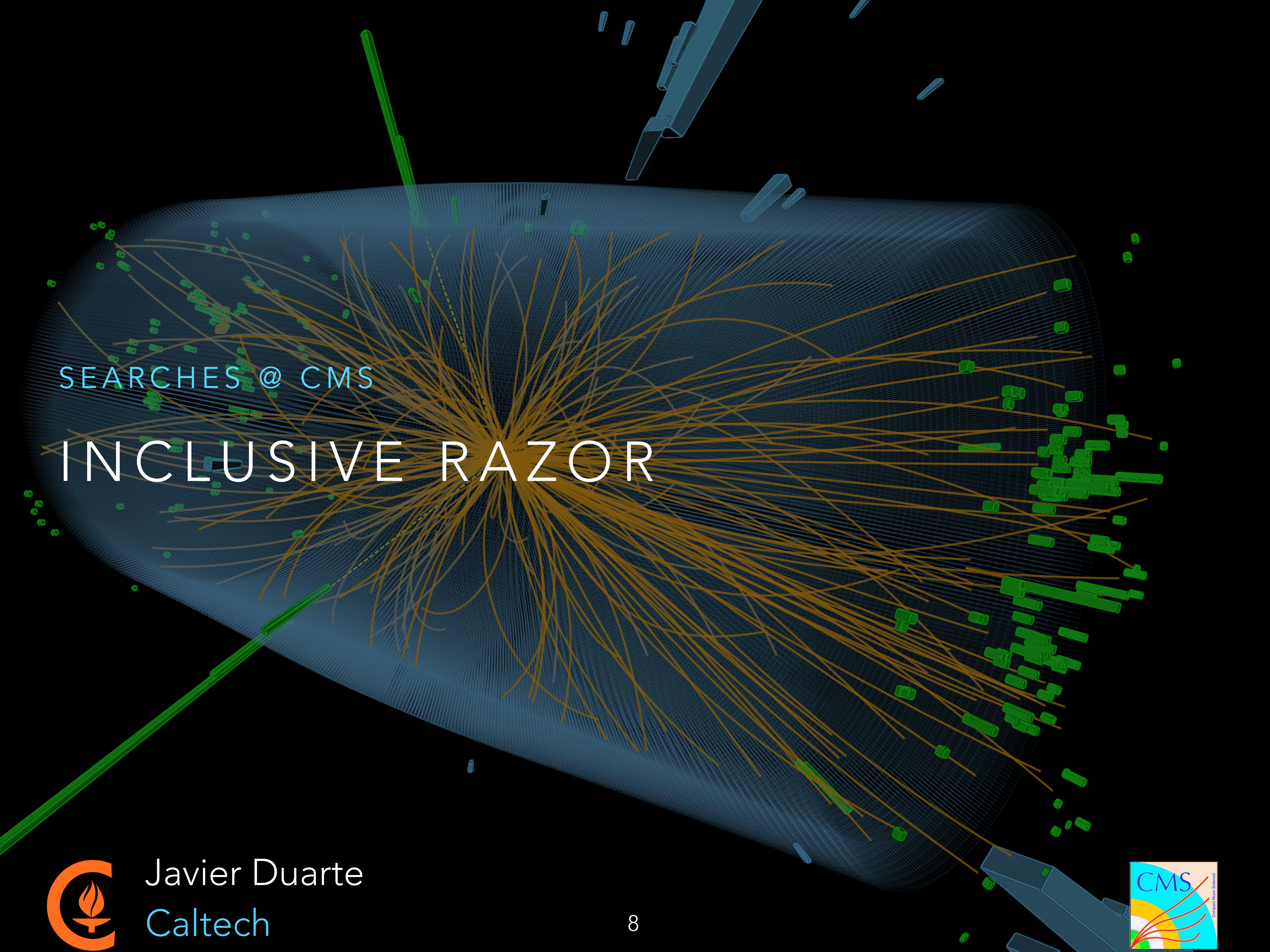
WHY RAZOR FOR NATURAL SUSY?

- Behavior of razor variables largely invariant under different gluino decay modes
  - Slight dependence on the presence of top quarks: More tops → lower M_R response, larger M_R resolution



neglecting mass of bb, tt, tbW* systems,

$$M_\Delta = \frac{m_{\tilde{g}}^2 - m_{\tilde{\chi}_1^0}^2}{m_{\tilde{g}}}$$



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INCLUSIVE RAZOR

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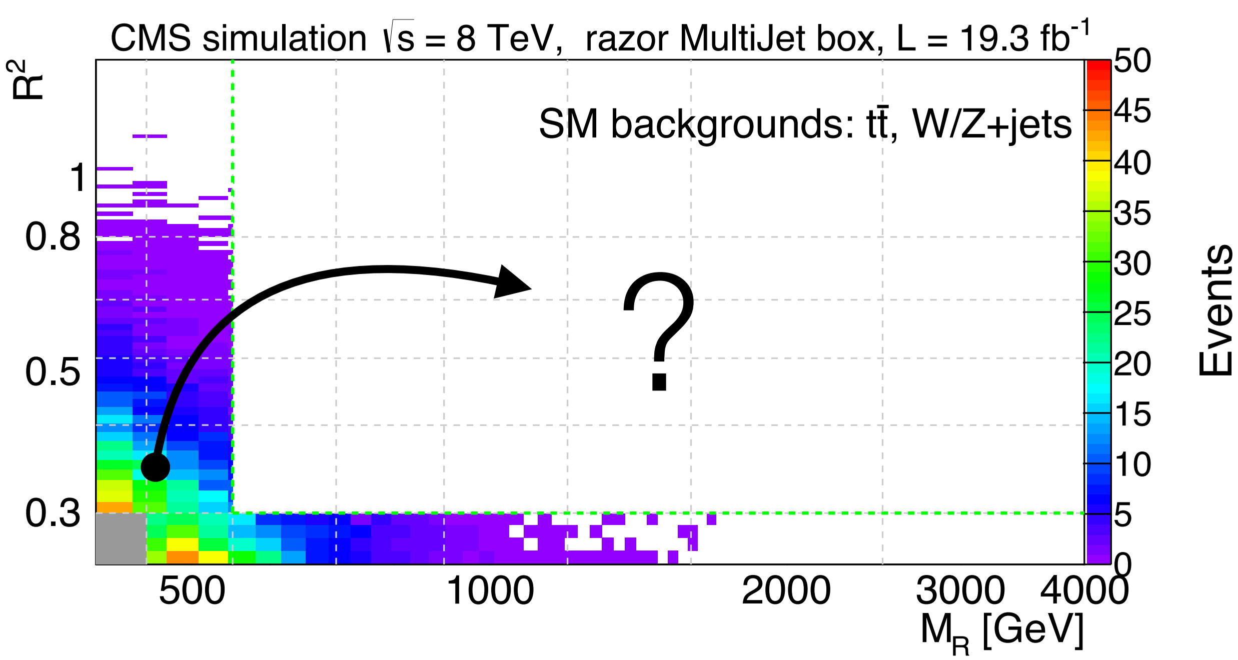
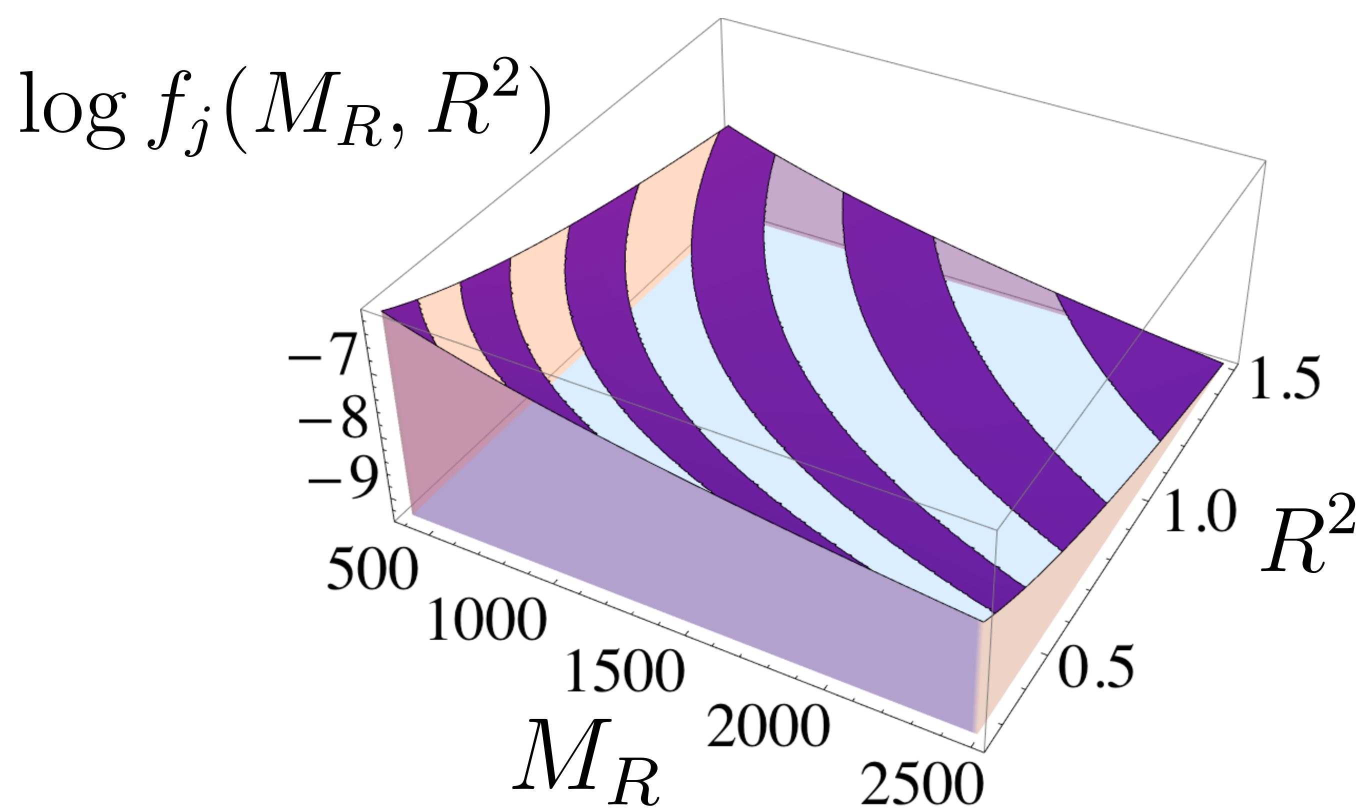
DATA-DRIVEN BACKGROUND PREDICTION

$$f_{\text{Razor}}(x,y) \propto \left(b[(x-x_0)(y-y_0)]^{1/n} - 1\right) \text{Exp}\{-bn[(x-x_0)(y-y_0)]^{1/n}\}$$

- Fit the 2D distribution of data with an empirical function in a background-enriched sideband, and extrapolate to the signal-sensitive region
- Extensive validation of functional form performed on 2010-2015 data and MC





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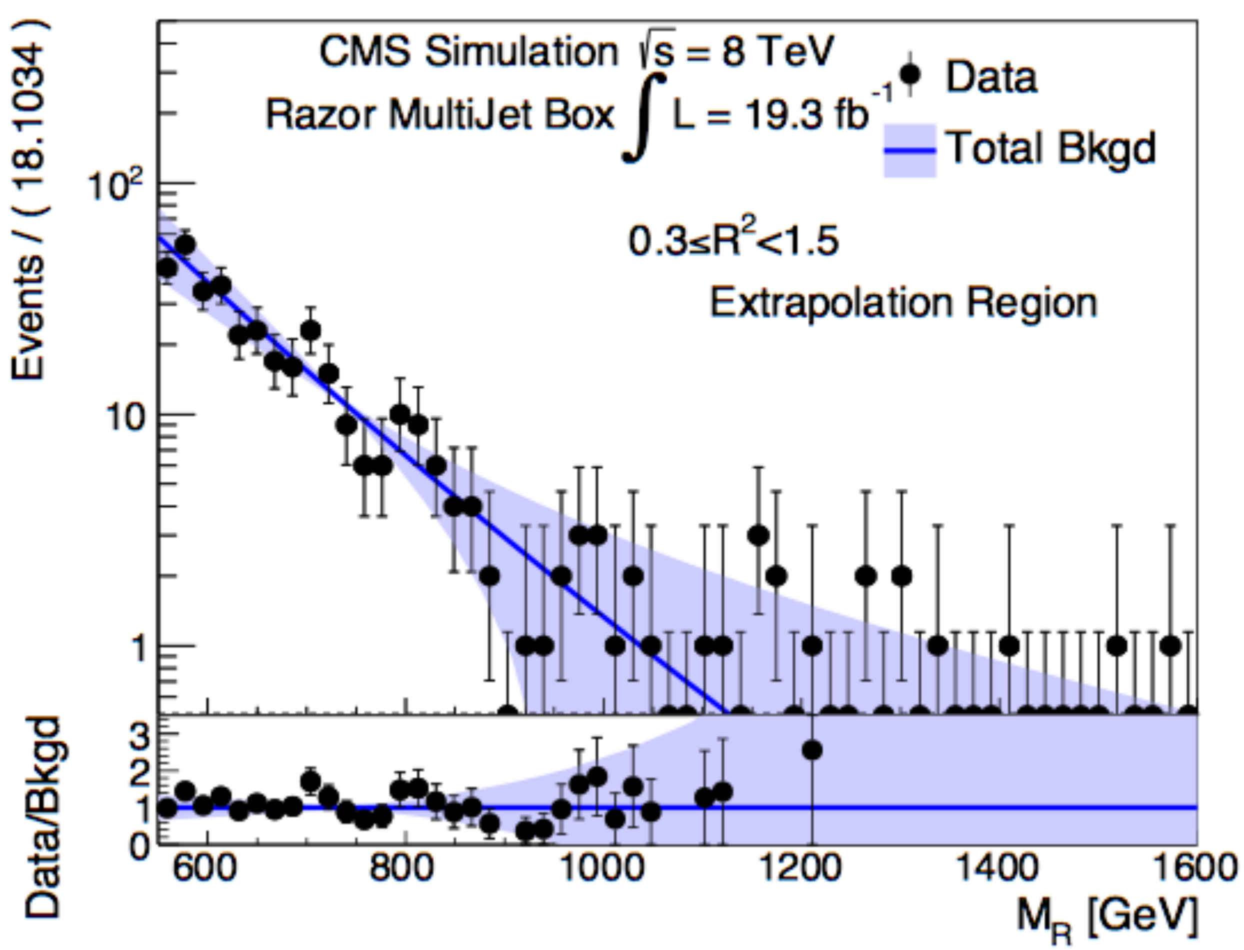
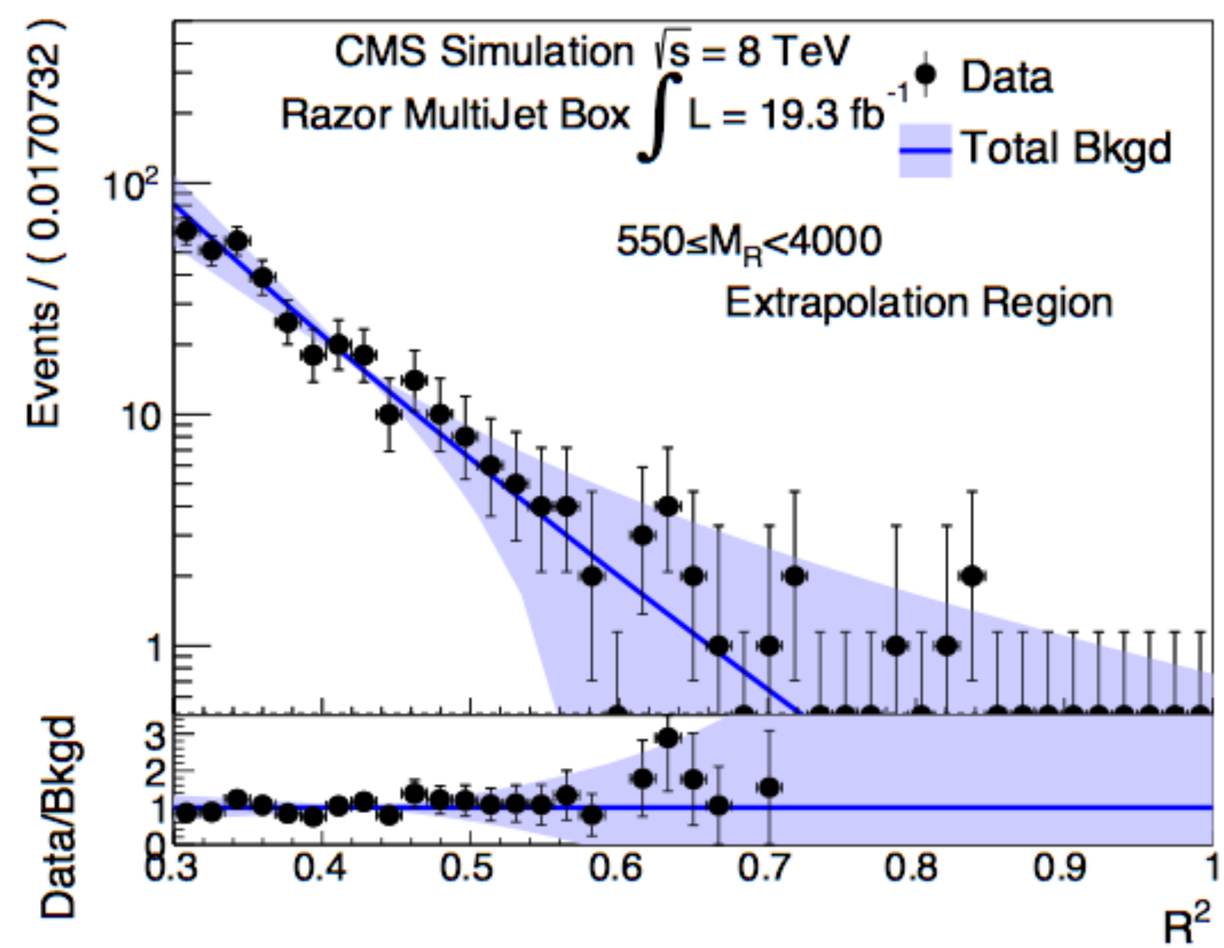
FIT SYSTEMATIC UNCERTAINTIES

- Size of background systematic uncertainty in signal-sensitive region varies between ~40%-100%
- Example from 8 TeV fit shows how variation of shape parameters affects background prediction





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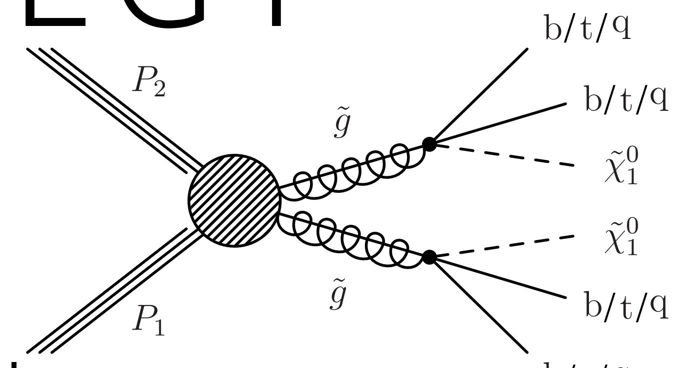
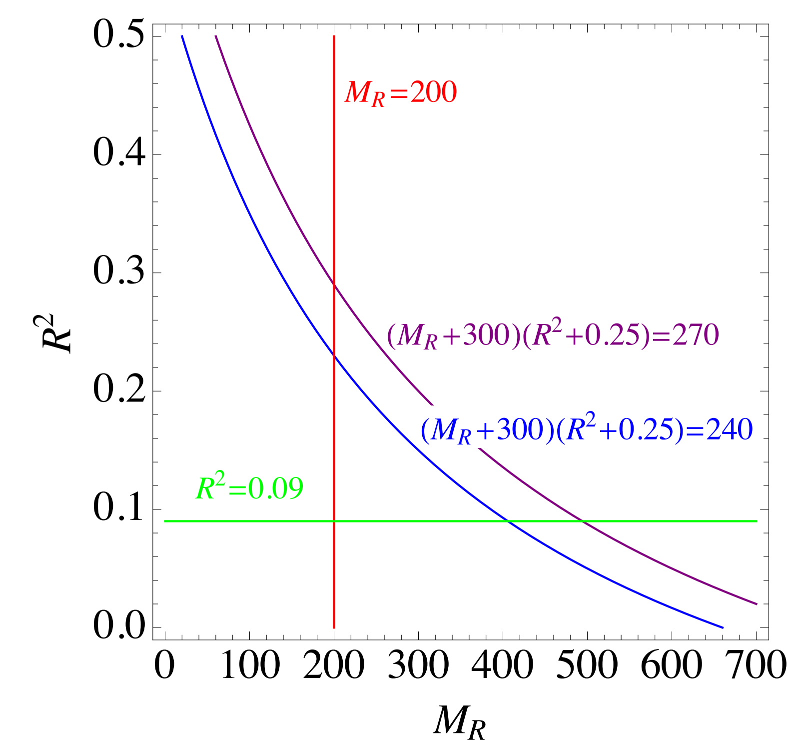
TARGET AND STRATEGY



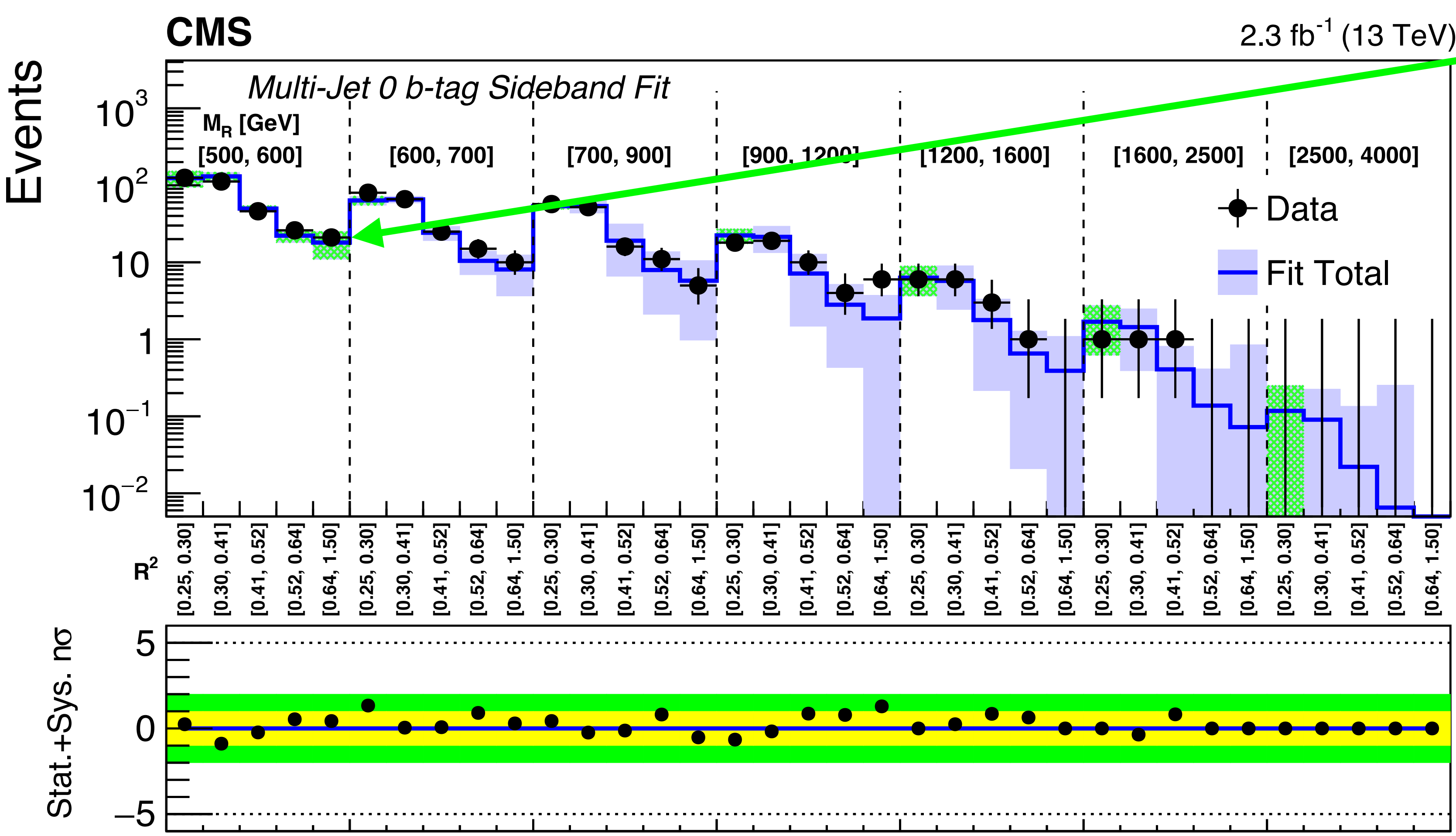
- Same basic strategy as in Run 1 with short-term target of gluino-mediated signal models
- Select and categorize events based on jets and leptons
  - Perform maximum likelihood fit in a **sideband** of R^2 and M_R and quantify agreement between SM backgrounds and data
- All-hadronic channel (MultiJet) uses custom **razor trigger**

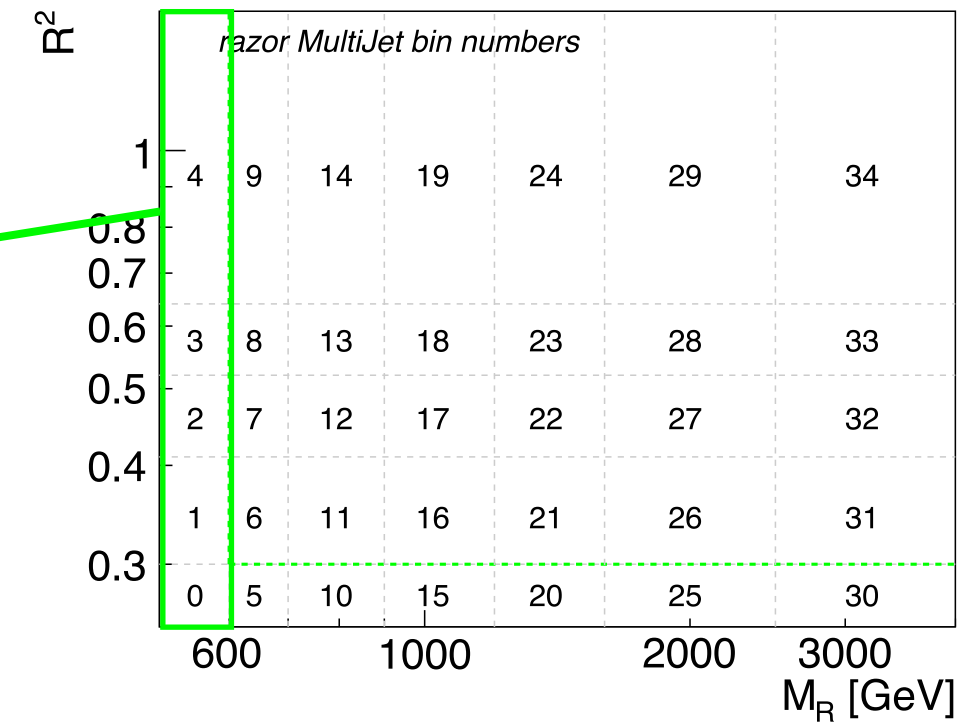


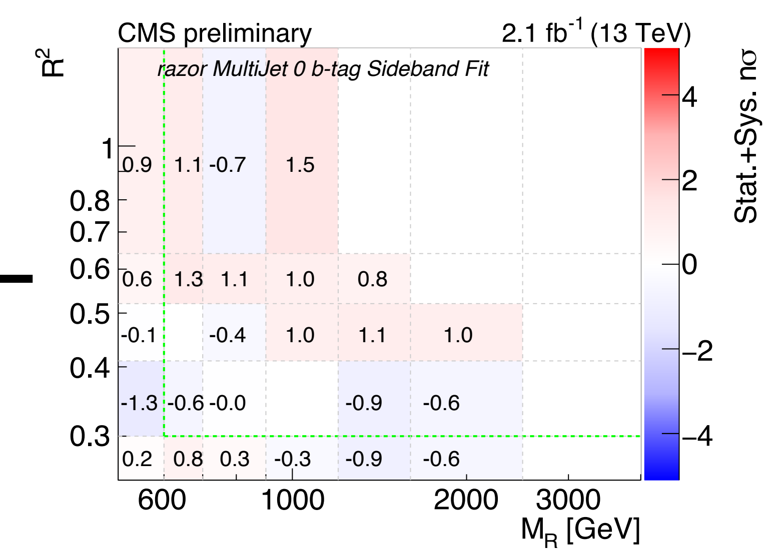
SUS-15-004

2D FIT PROJECTION

- Alternate representation of the data, fit prediction, and their agreement provides greater density of information
- **Green** illustrates sideband bins







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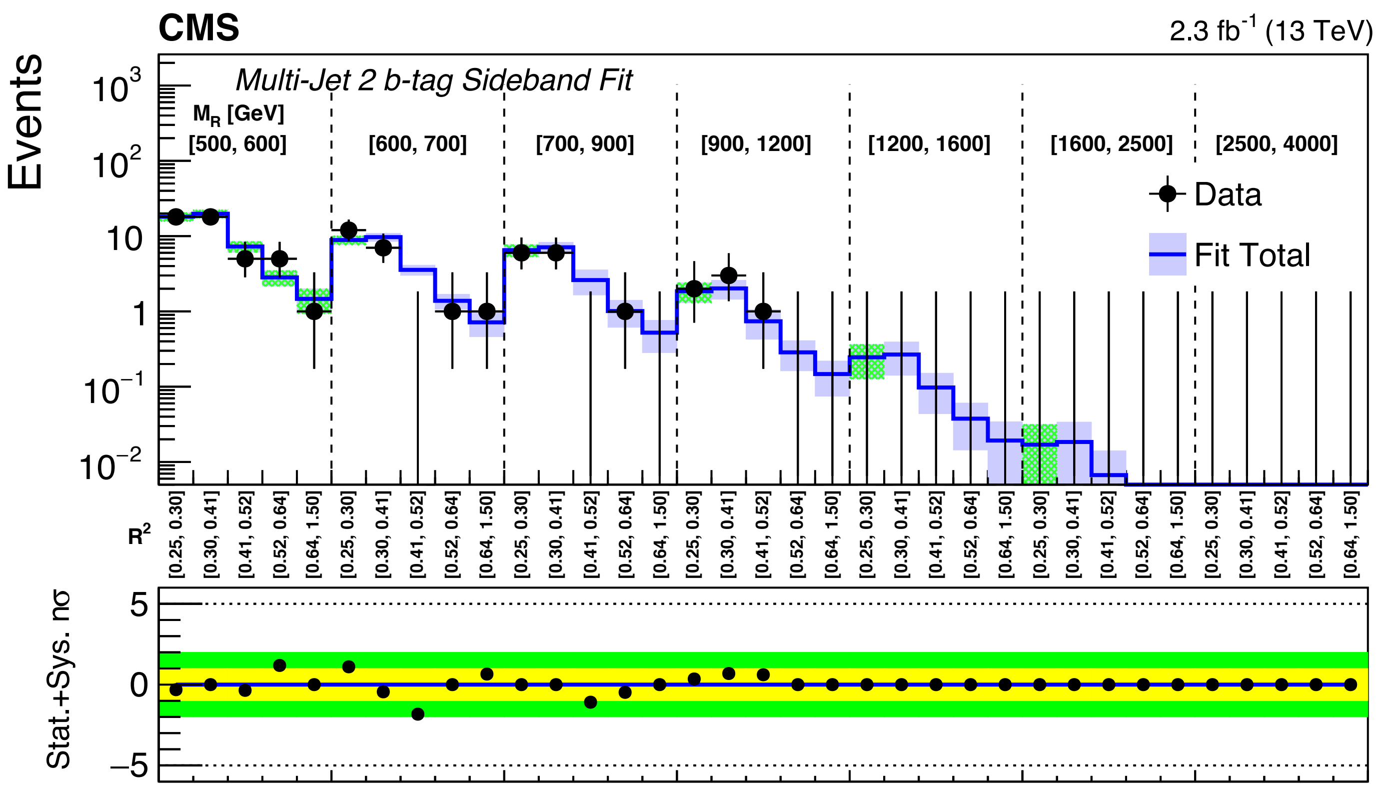
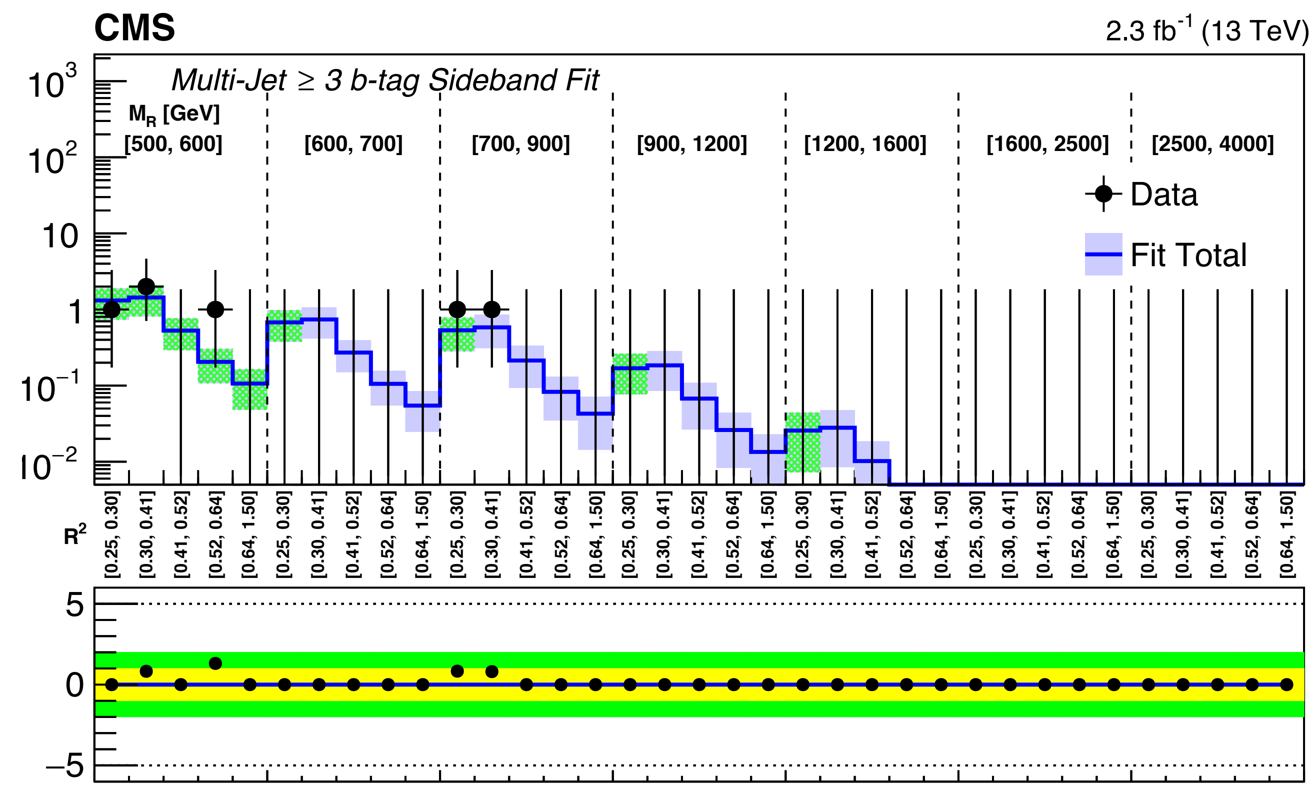
SUS-15-004 SELECTED RESULTS IN DATA

- No significant deviation observed in any data category
- Scattered ~2σ "local" deviations consistent with fluctuations

P-VALUE= 34%

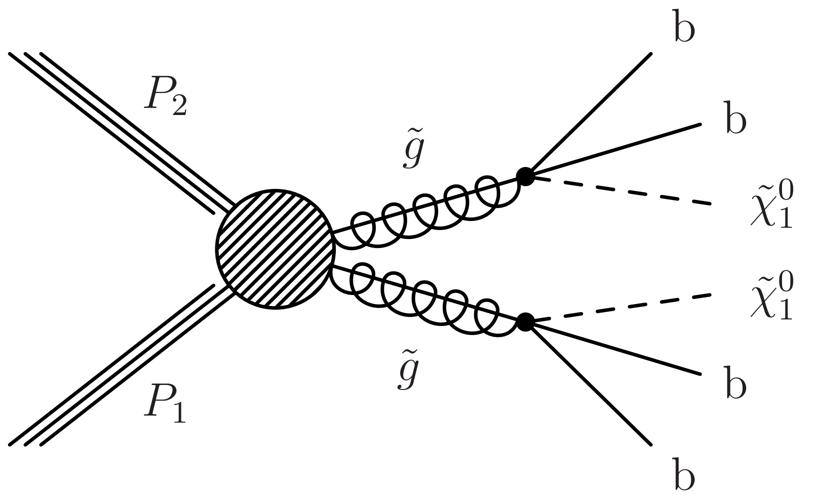


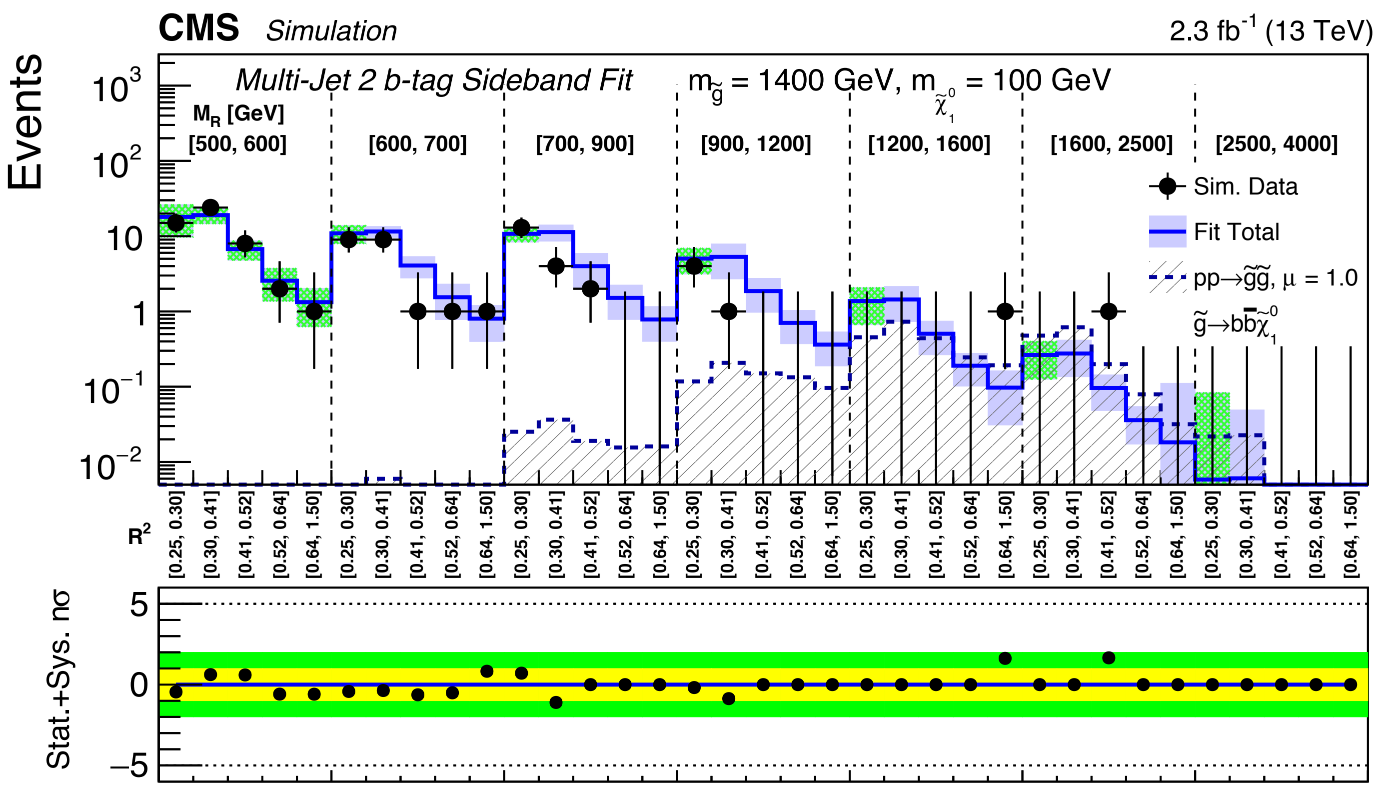
P-VALUE= 85%

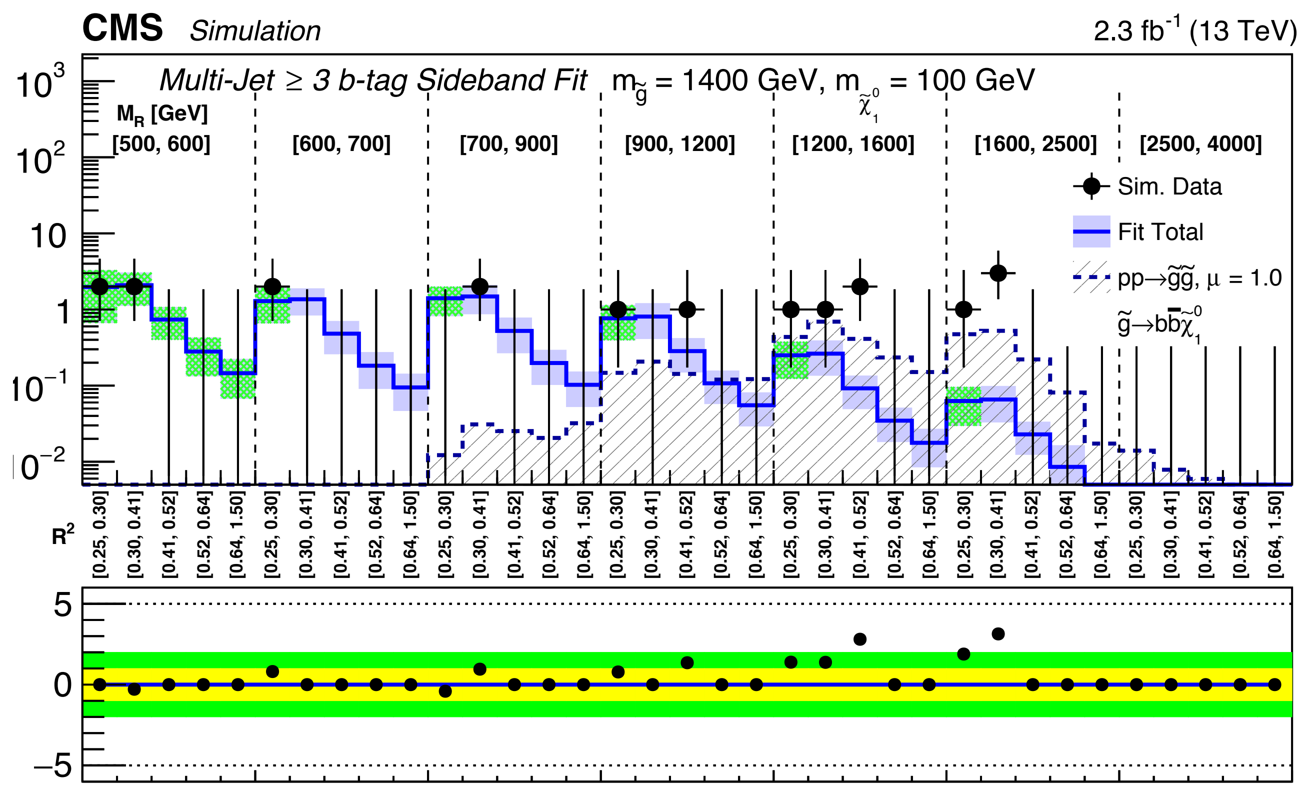


SIGNAL INJECTION

- Simulated signal injection for $m_{\tilde{g}}$ = 1400 GeV, $m_{\tilde{\chi}_1^0}$ = 100 GeV illustrates how an excess consistent with SUSY would appear

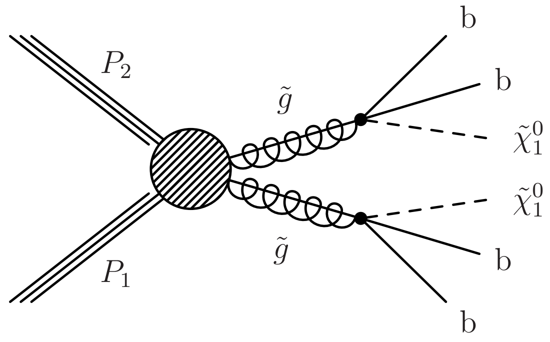




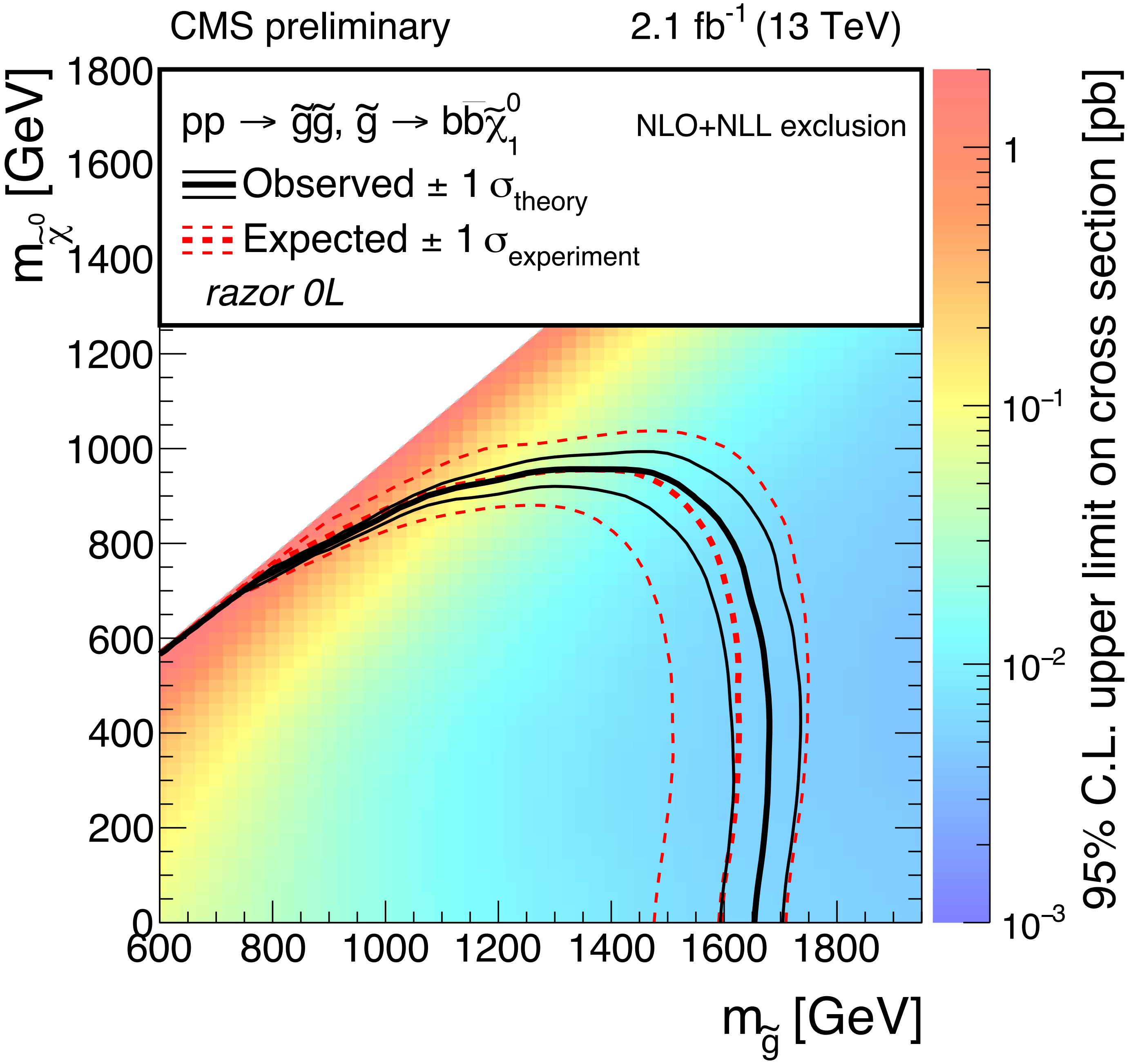


[SUS-15-004]

RUN 2 LIMITS

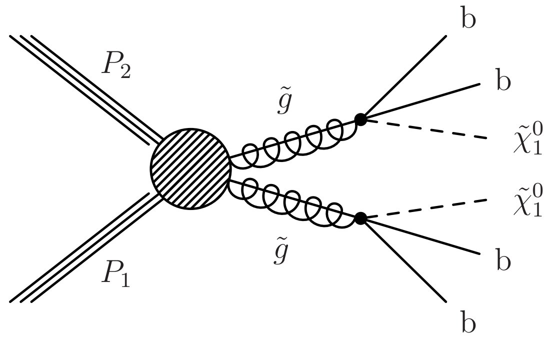


- For a massless LSP, gluino is excluded below **1650 GeV** with 2.1 fb^{-1} at 13 TeV in four-bottom-quark final state



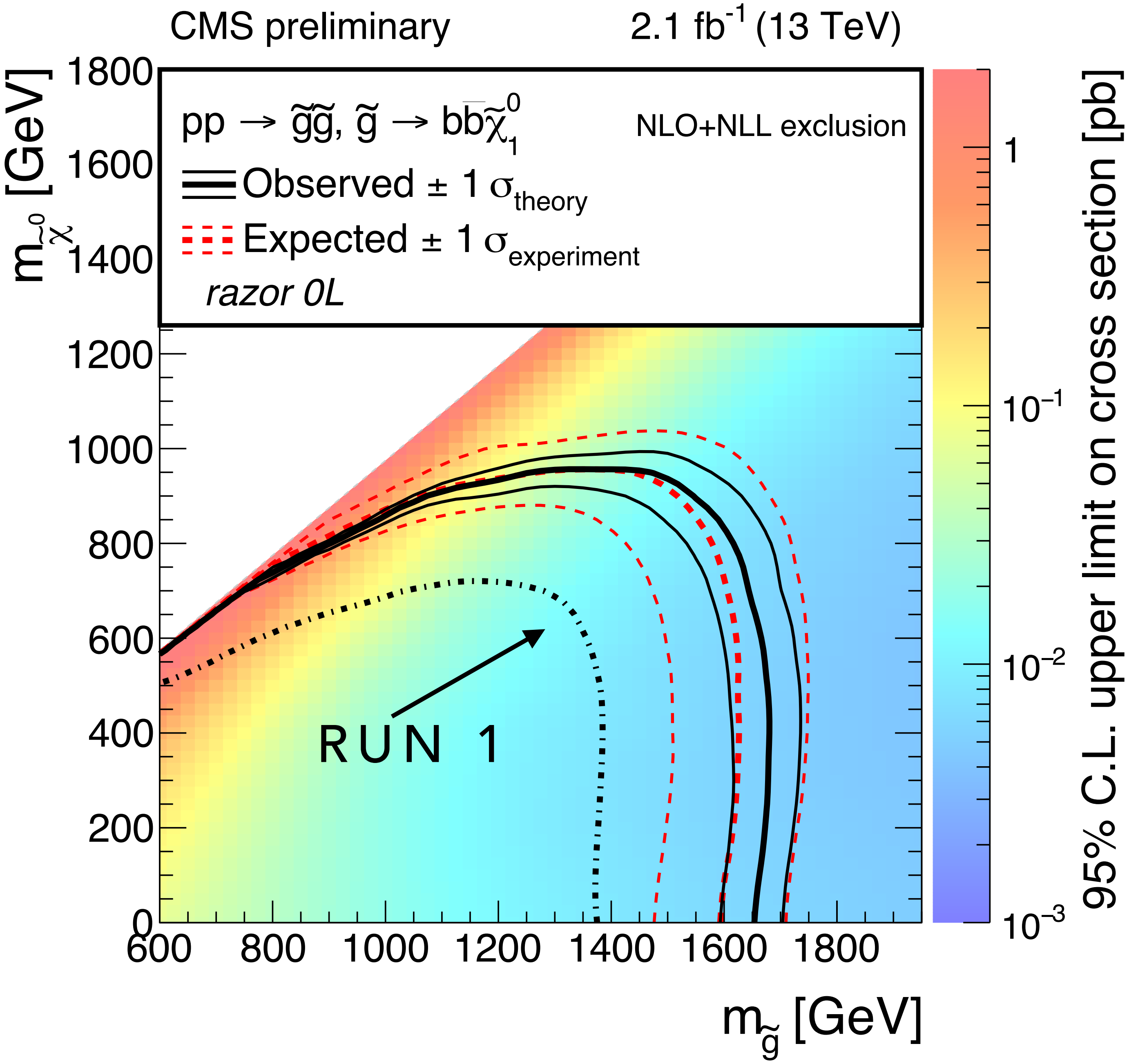
[SUS-15-004]

RUN 2 LIMITS



- For a massless LSP, gluino is excluded below **1650 GeV** with 2.1 fb^{-1} at 13 TeV in four-bottom-quark final state

- Compare with Run 1 limit **1400 GeV** with 19.3 fb^{-1} at 8 TeV



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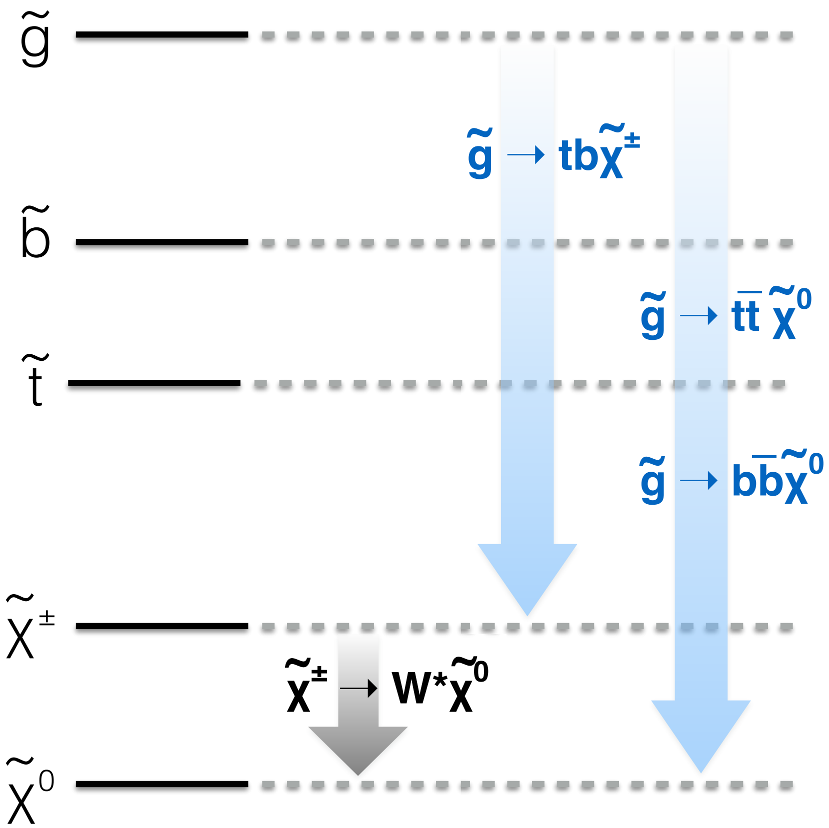
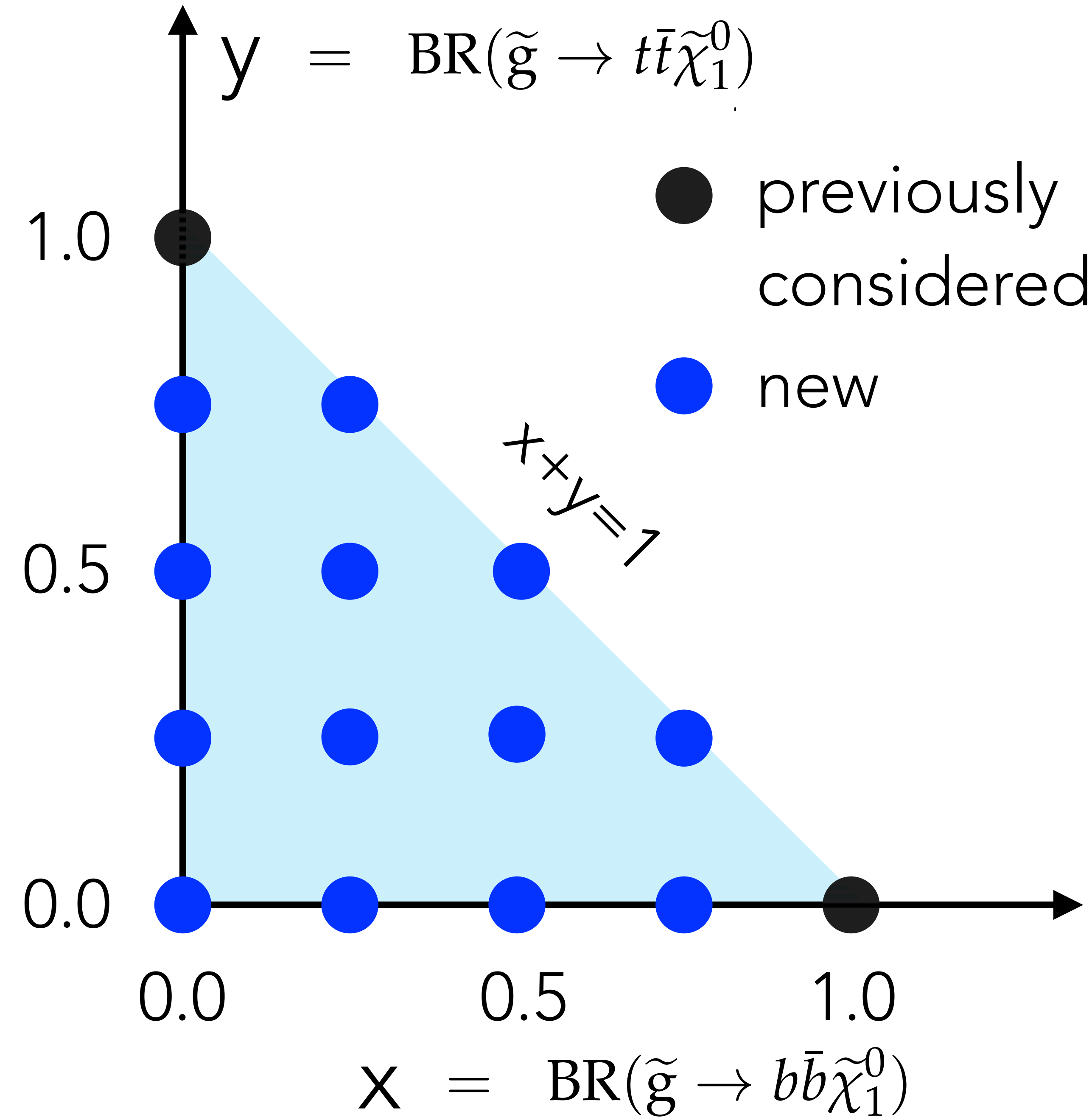
BRANCHING RATIOS

- Scan the triangular branching ratio phase space in (x,y)

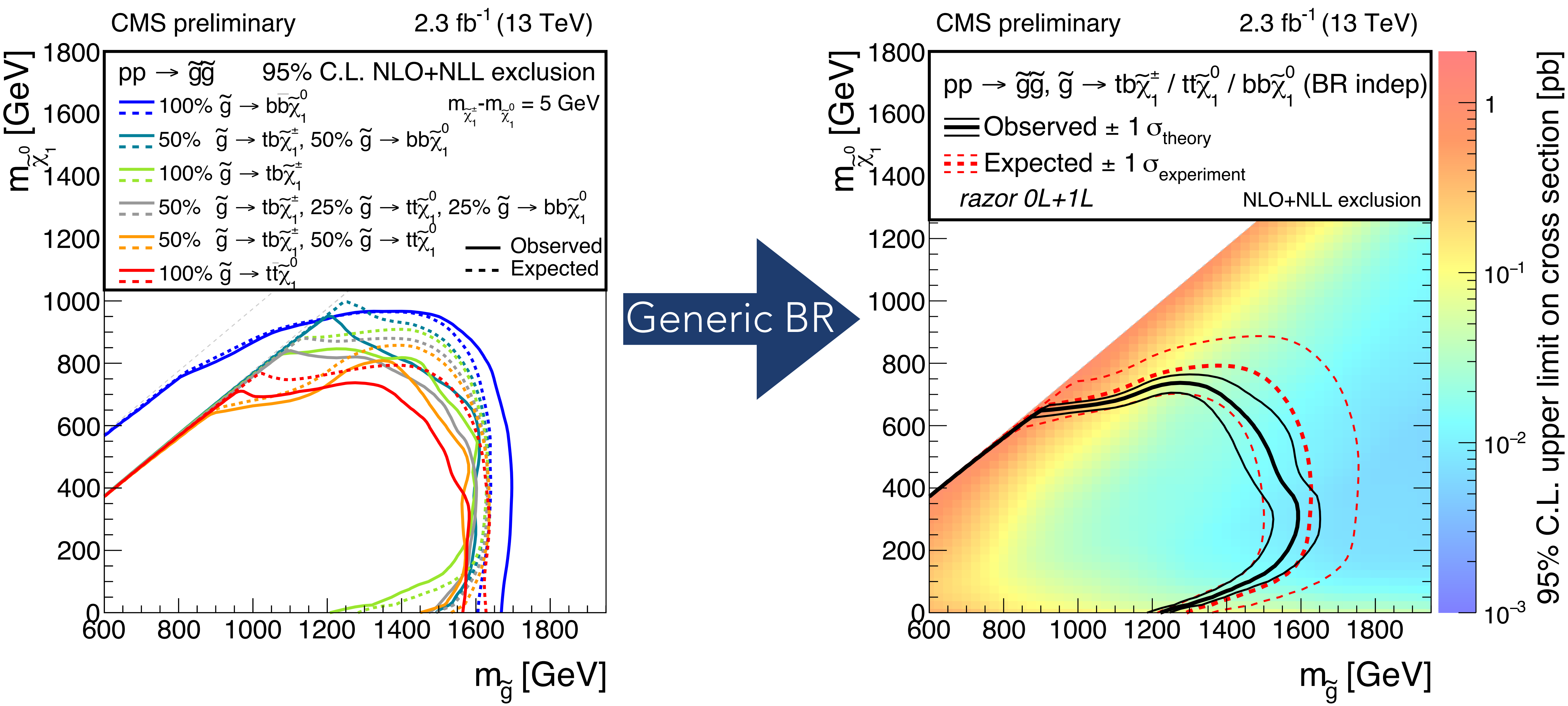
$$x = \mathrm{BR}(\tilde{g} \to b\bar{b}\tilde{\chi}_1^0)$$
$$y = \mathrm{BR}(\tilde{g} \to t\bar{t}\tilde{\chi}_1^0)$$
$$z = \mathrm{BR}(\tilde{g} \to tb\tilde{\chi}_1^{\pm})$$





[SUS-16-004](#) SUMMARY OF RUN 2 LIMITS

- For generic branching ratio, gluino is excluded below **~1600 GeV**
- **First branching-ratio independent gluino limit from LHC!**



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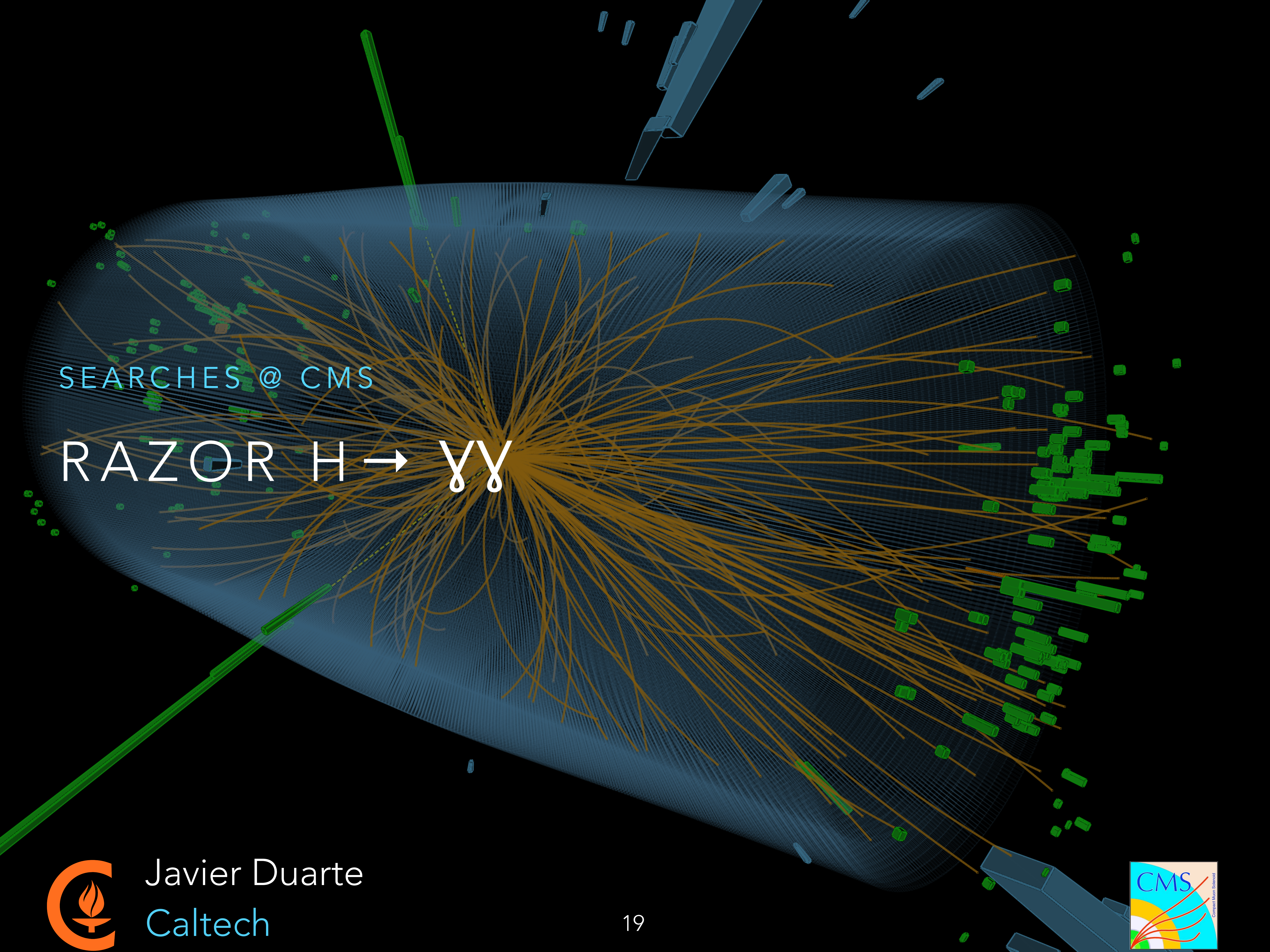
RAZOR H→ γγ



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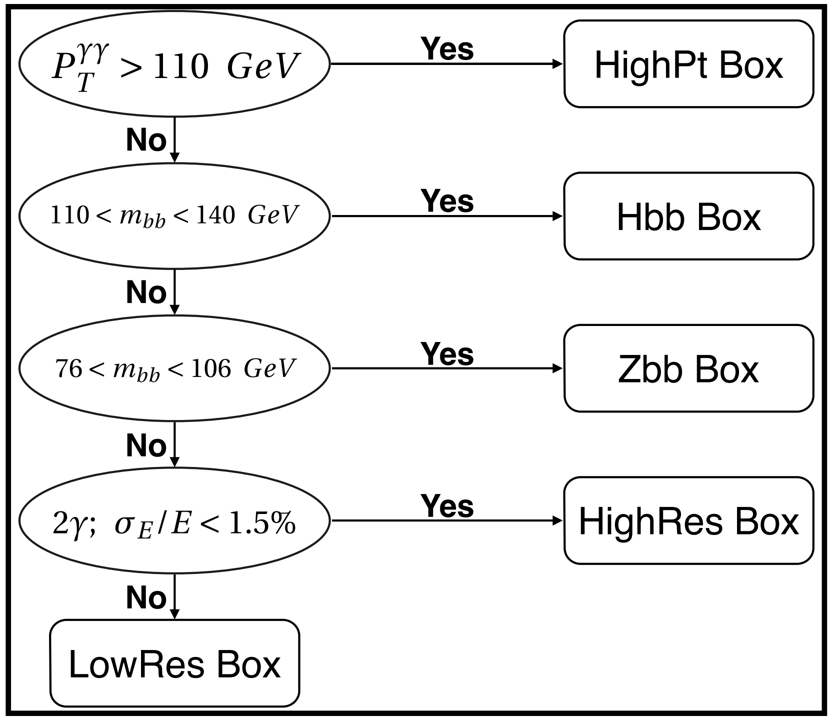
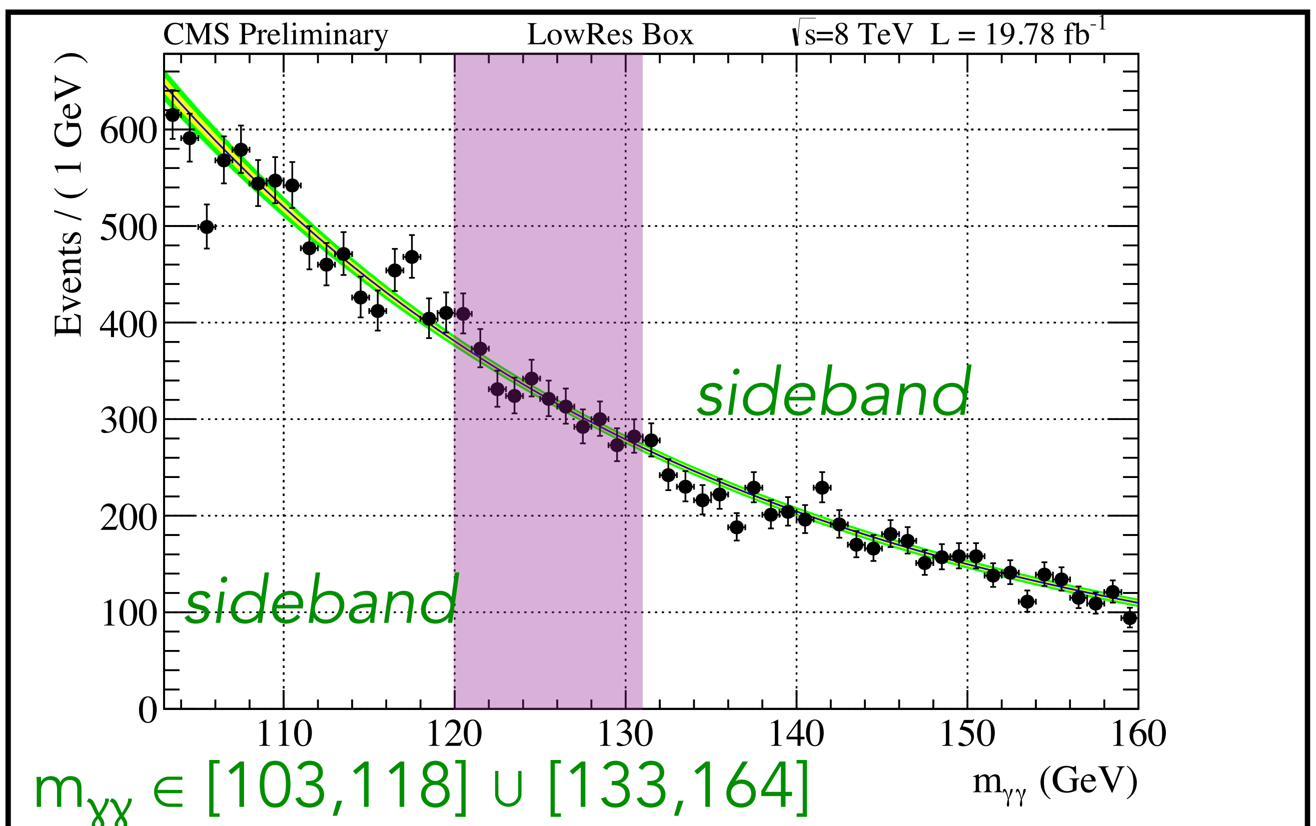
RAZOR $H \to \gamma\gamma$ SEARCH





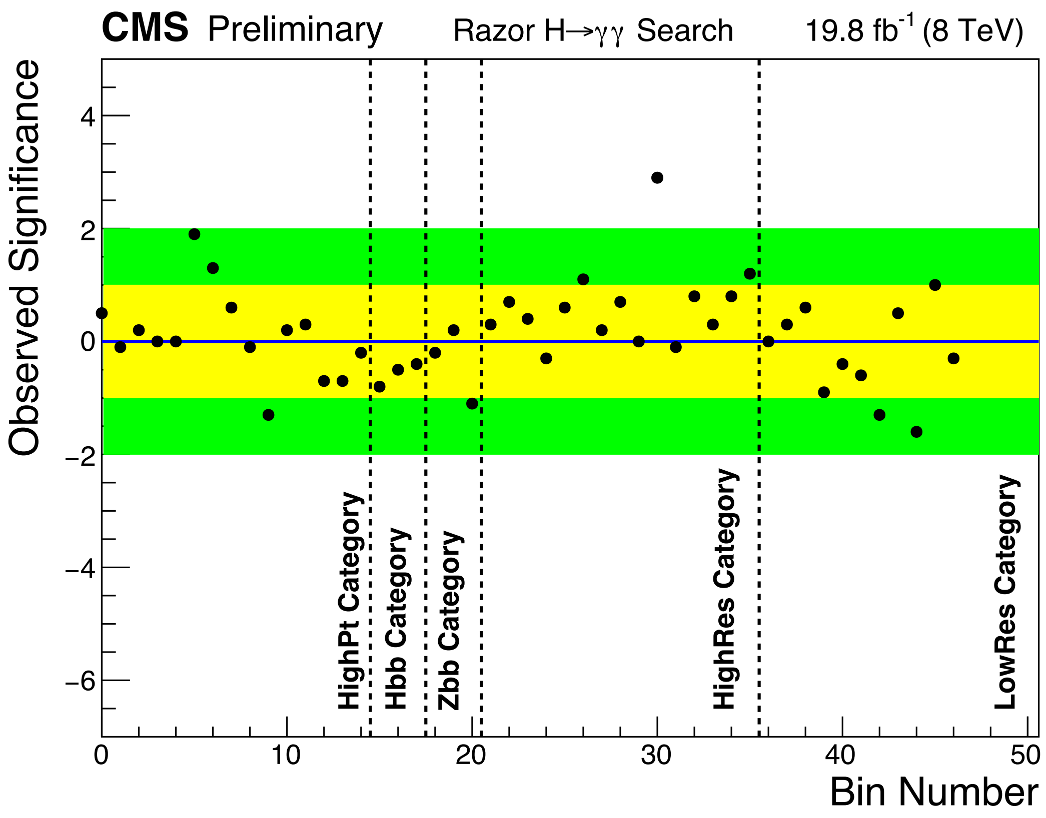
- Search for electroweak SUSY production (Higgsinos, Winos, Binos)
- Selection:
  - Tag events using $H \to \gamma\gamma$
  - Categorize using Higgs p_T and photon resolution
- Discriminating variables M_R and R^2
- Background prediction in R^2-M_R plane by interpolating from $m_{\gamma\gamma}$ sidebands
- Look bin-by-bin in R^2-M_R plane for an excess

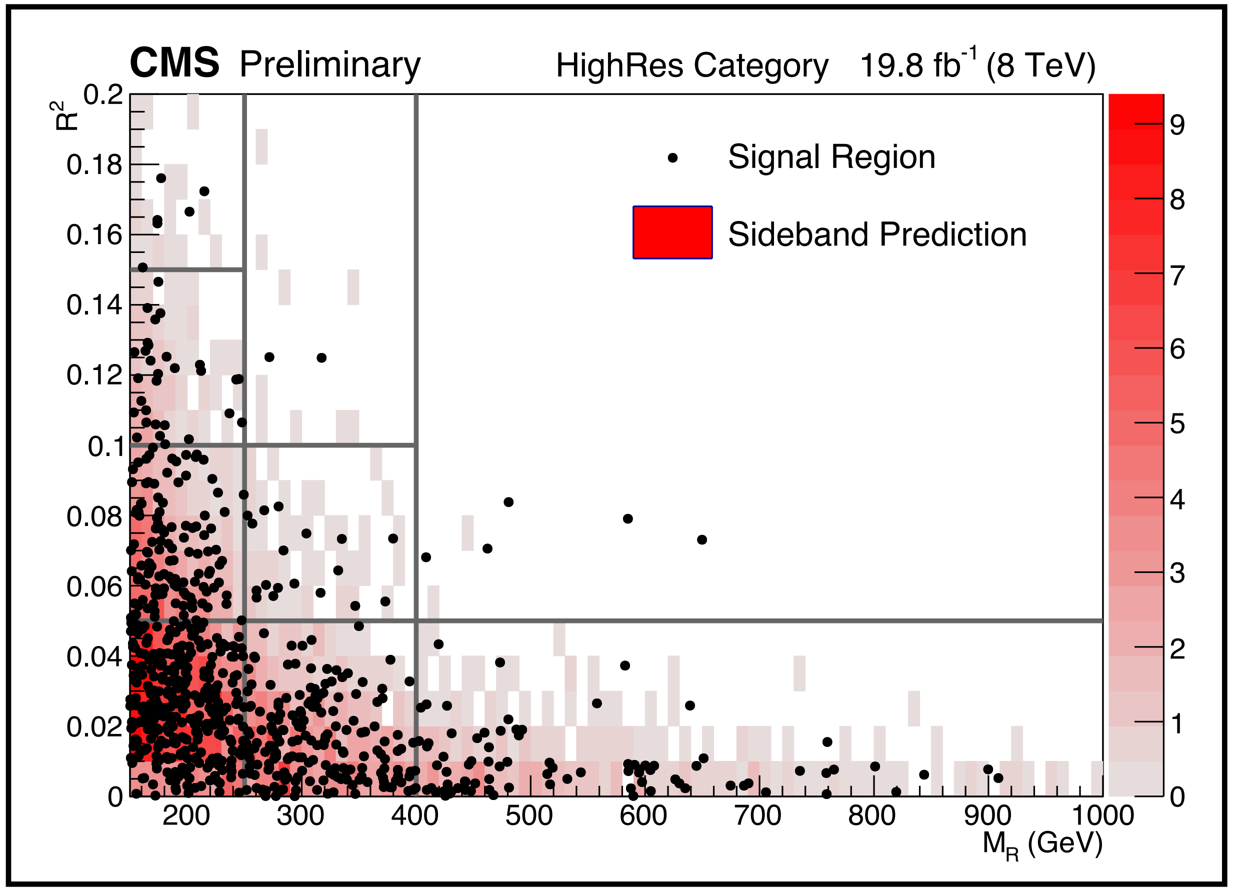
SUS-14-017

HIGH RES CATEGORY

M_R region	R^2 region	observed events	expected background	p-value	significance (σ)
150 - 250	0.00 - 0.05	363	$357.6^{+9.6}_{-9.4}$(syst.)	0.40	0.3
150 - 250	0.05 - 0.10	149	$139.4^{+5.6}_{-5.4}$(syst.)	0.23	0.7
150 - 250	0.10 - 0.15	35	$32.5^{+3.4}_{-3.1}$(syst.)	0.34	0.4
150 - 250	0.15 - 1.00	7	$8.0^{+1.7}_{-1.4}$(syst.)	0.40	-0.3
250 - 400	0.00 - 0.05	218	$207.9^{+7.0}_{-6.8}$(syst.)	0.27	0.6
250 - 400	0.05 - 0.10	20	$14.7^{+2.5}_{-2.1}$(syst.)	0.13	1.1
250 - 400	0.10 - 1.00	3	$2.7^{+0.8}_{-0.6}$(syst.)	0.43	0.2
400 - 1400	0.00 - 0.05	109	$101.6^{+5.0}_{-4.8}$(syst.)	0.26	0.7
400 - 1400	0.05 - 1.00	5	$0.5^{+0.4}_{-0.2}$(syst.)	0.002	2.9
1400 - 3000	0.00 - 1.00	0	$0.9^{+0.5}_{-0.3}$(syst.)	0.44	-0.1

2.9σ local excess
is 1.6σ after
look-elsewhere effect

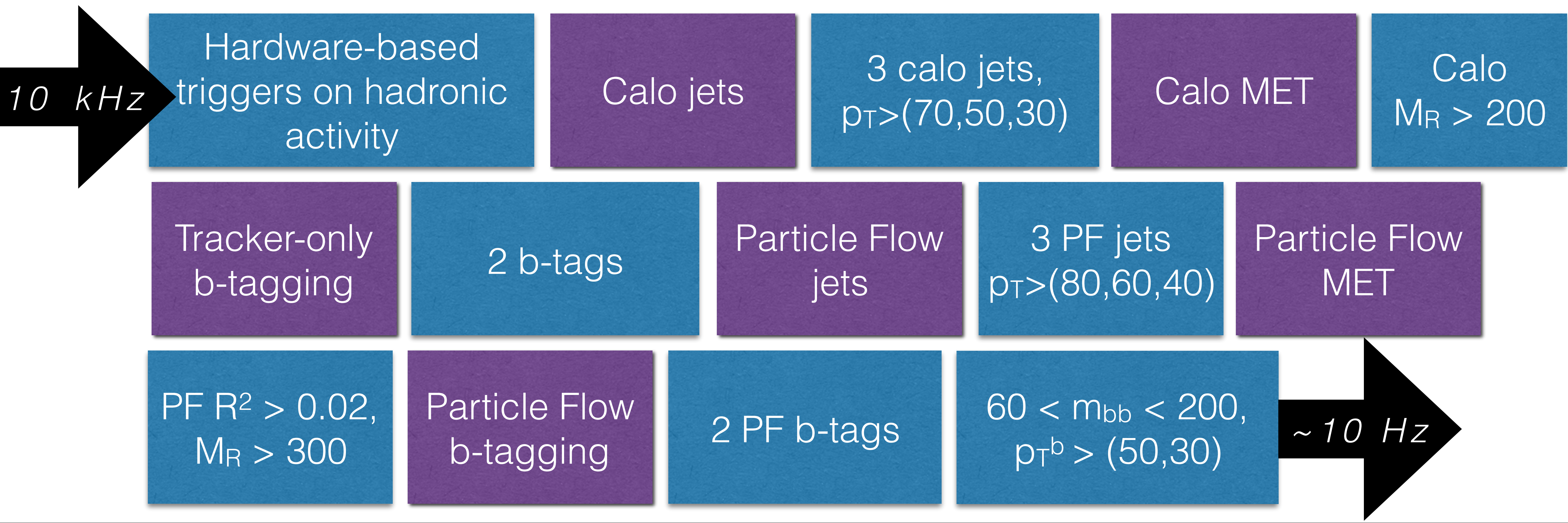




→ **excess not consistent with standard EWK SUSY models**

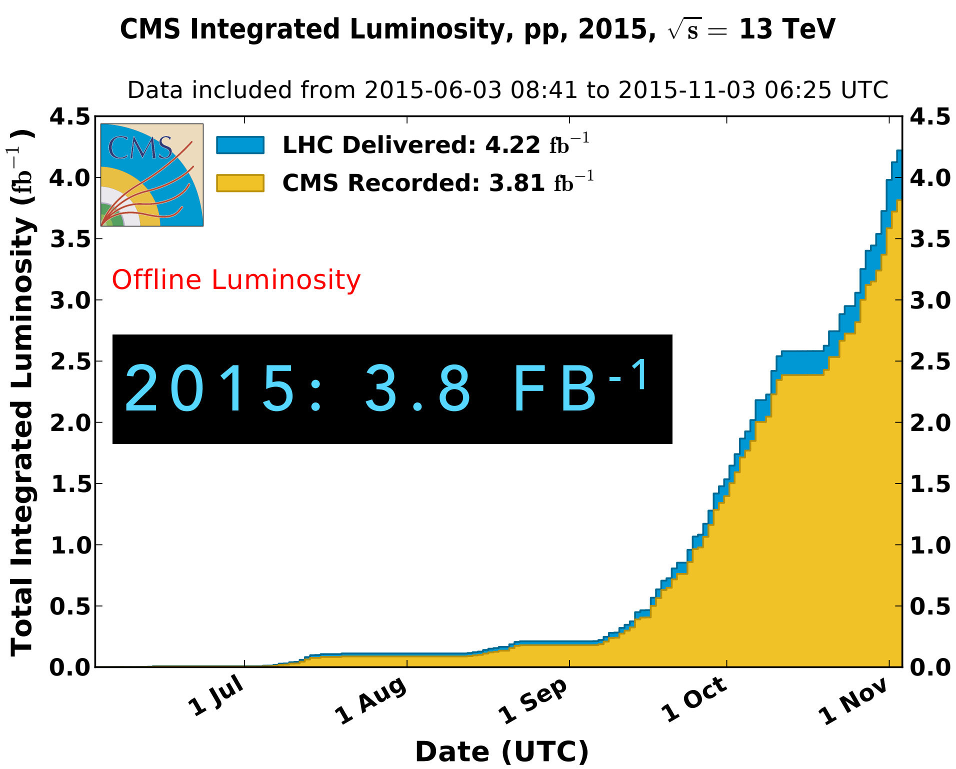
RAZOR TRIGGERS

- 4 triggers designed for different aspects of SUSY/DM/Higgs phase space
  - Dijet trigger (squark pair production)
  - Quadjet trigger (gluino pair production)
  - R^2 trigger (DM direct production / large transverse imbalance)
  - $H \rightarrow bb$ trigger (Higgs-aware SUSY à la $H \rightarrow \gamma\gamma$ 8 TeV excess)



SUMMARY AND OUTLOOK

- The CMS SUSY search program at 13 TeV has produced stringent limits on many natural SUSY scenarios
    - gluinos excluded below ~1600 GeV for generic BR
- Interesting excess seen in razor H→γγ analysis, so we developed a trigger to search in the H→bb channel
- Forthcoming razor H→γγ analysis of 2015+2016 13 TeV data as well as inclusive razor analysis of 2016 13 TeV data: **stay tuned!**



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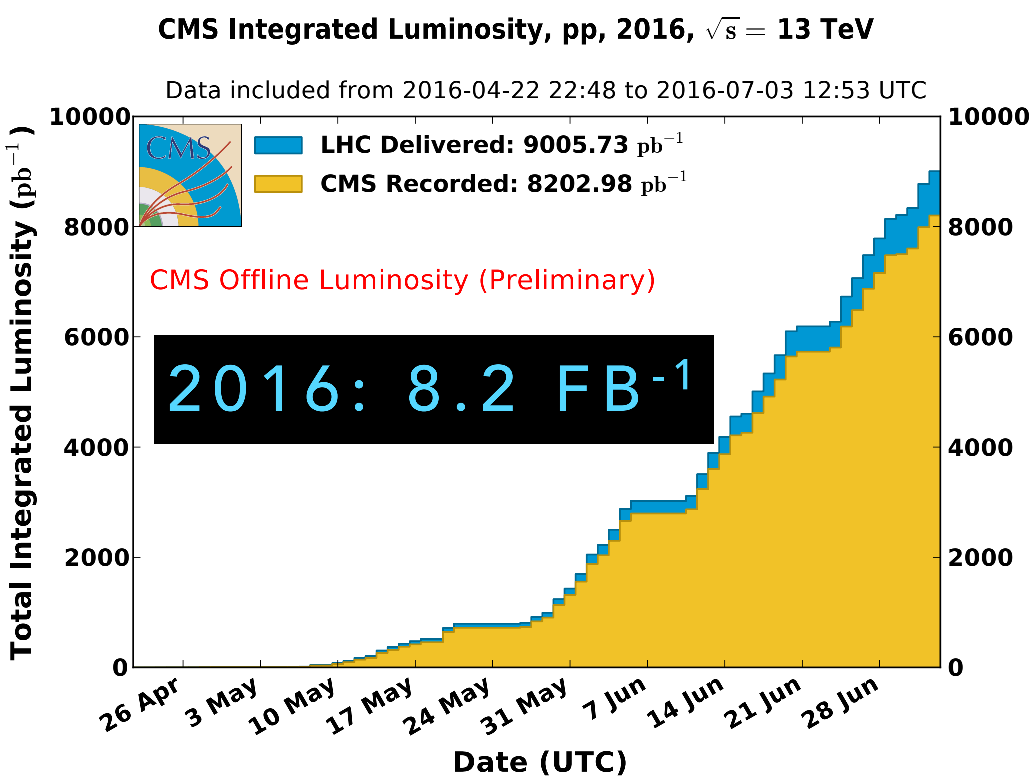

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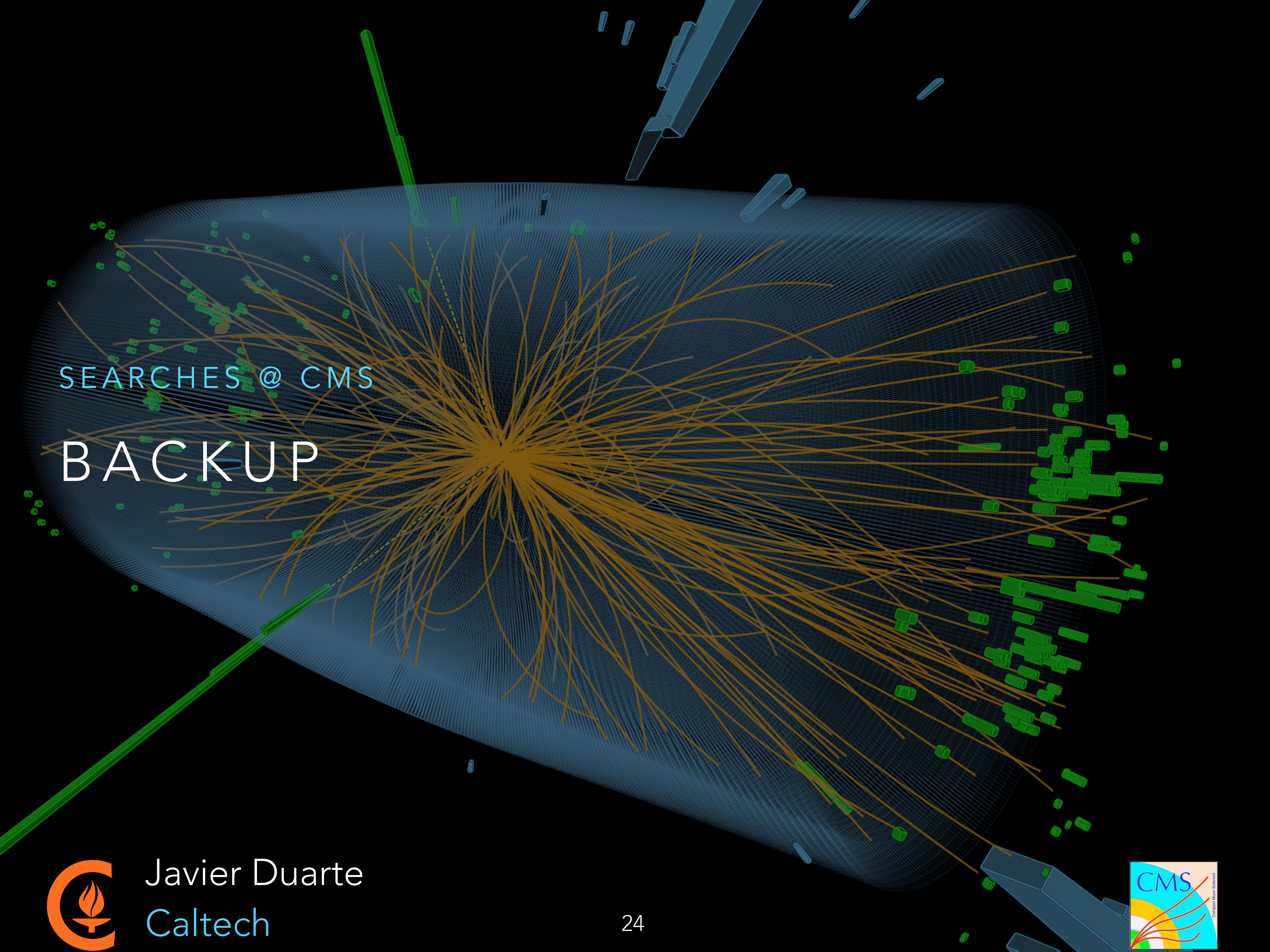
BACKUP



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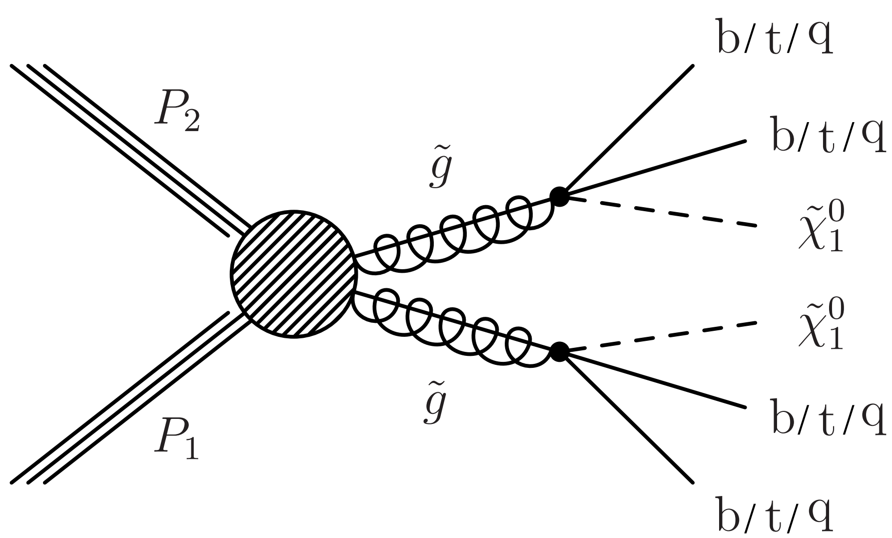
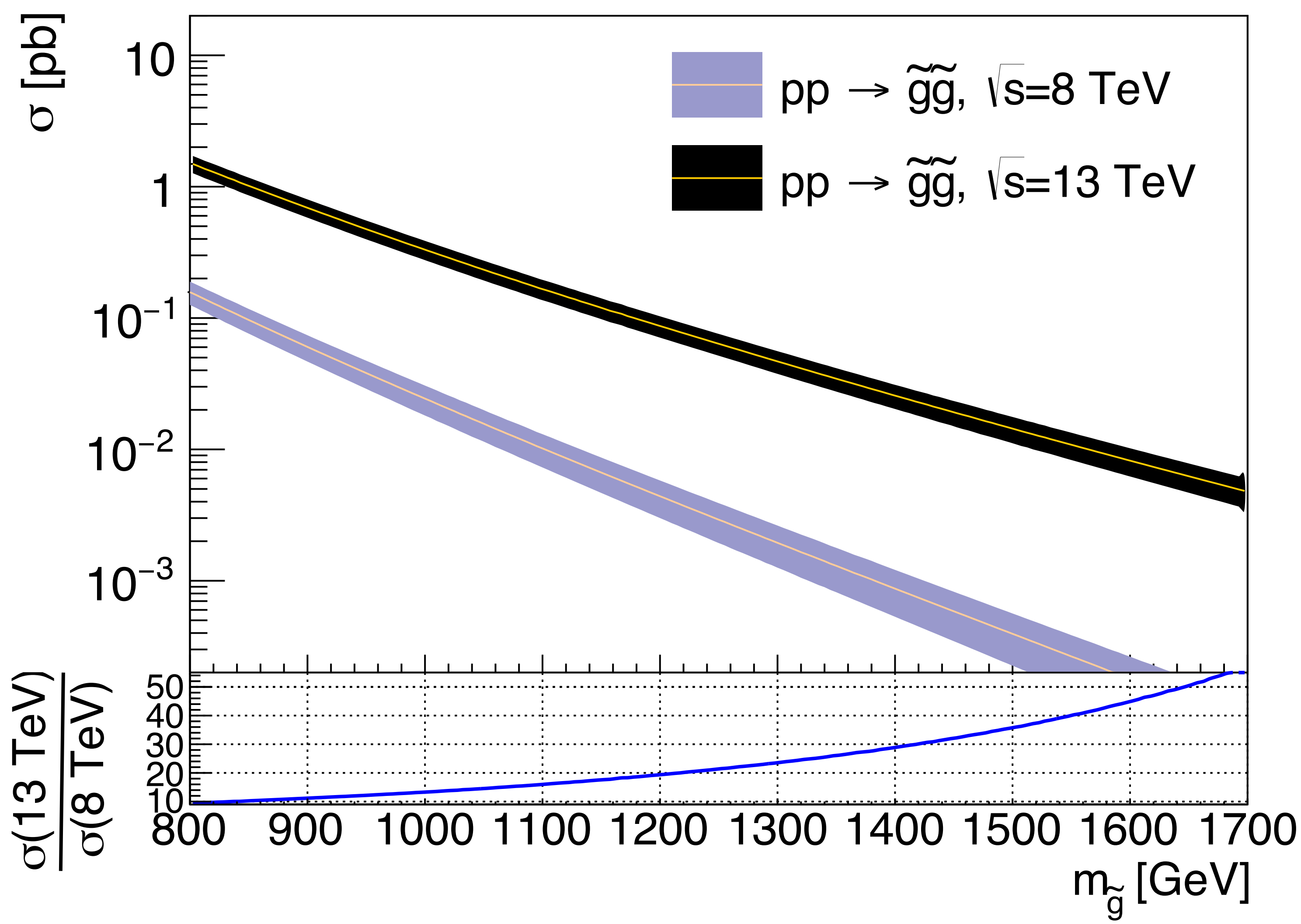
GLUINO PAIR PRODUCTION

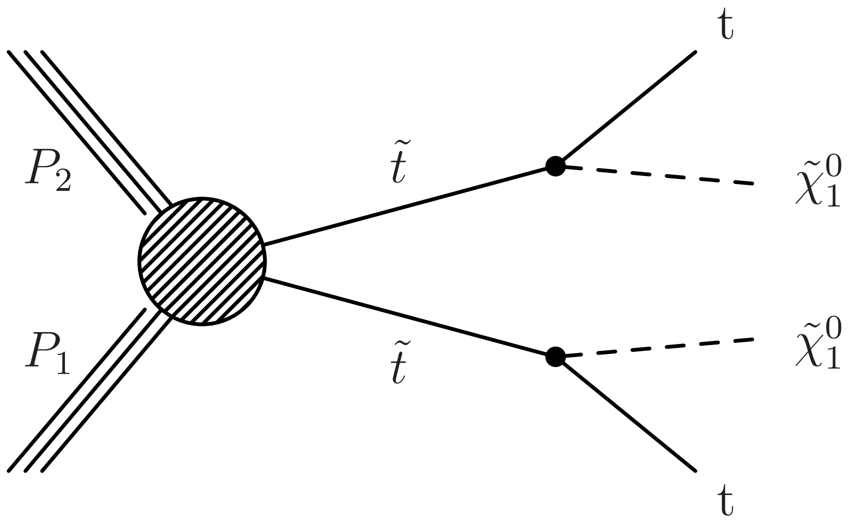
- Gluino pair production cross section at the 13 TeV LHC is **10x-50x** greater than 8 TeV in the accessible phase space

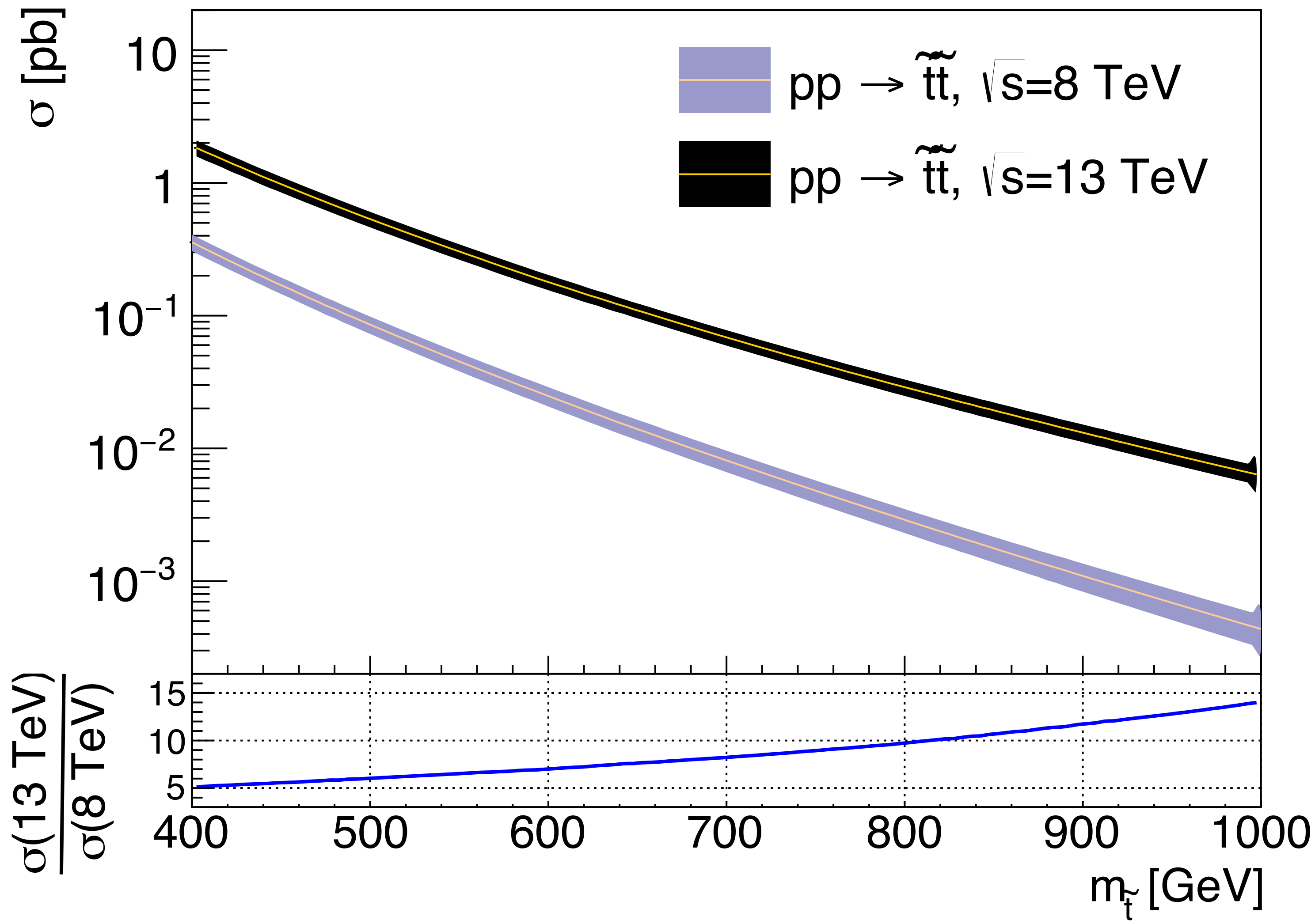




STOP PAIR PRODUCTION

- Stop pair production cross section at the 13 TeV LHC is **5x-15x** greater than 8 TeV in the accessible phase space

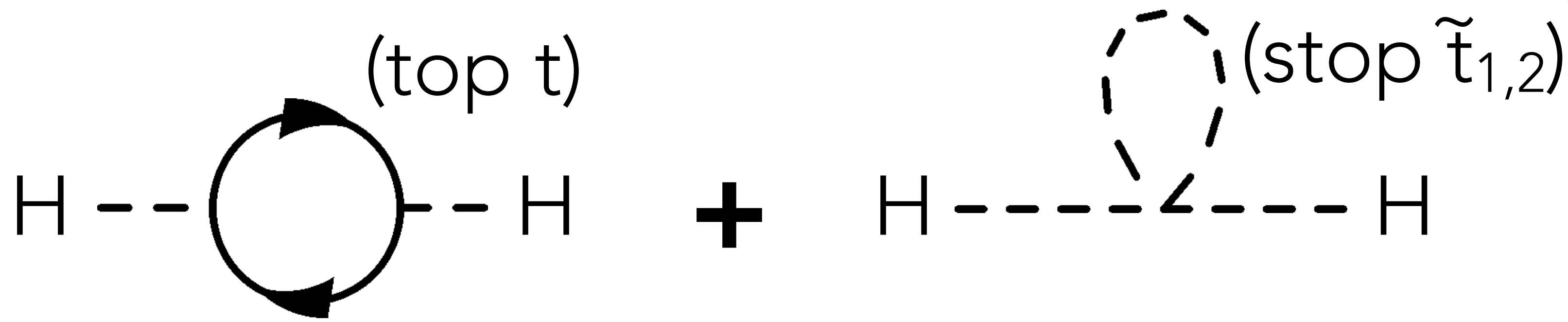




HIGGS AND NATURALNESS

- Without SUSY, the Higgs mass would "naturally" be enormous, unless certain parameters are delicately fine-tuned to **1 part in 10,000,000,000,000,000**
- With SUSY, the Higgs mass matches what we see without excessive fine tuning

SUSY ⇒ $|\lambda_f|^2 = \lambda_S$



problematic

unless cancelled

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\rm UV}^2 + \cdots \qquad \Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\Lambda_{\rm UV}^2 + \cdots$$

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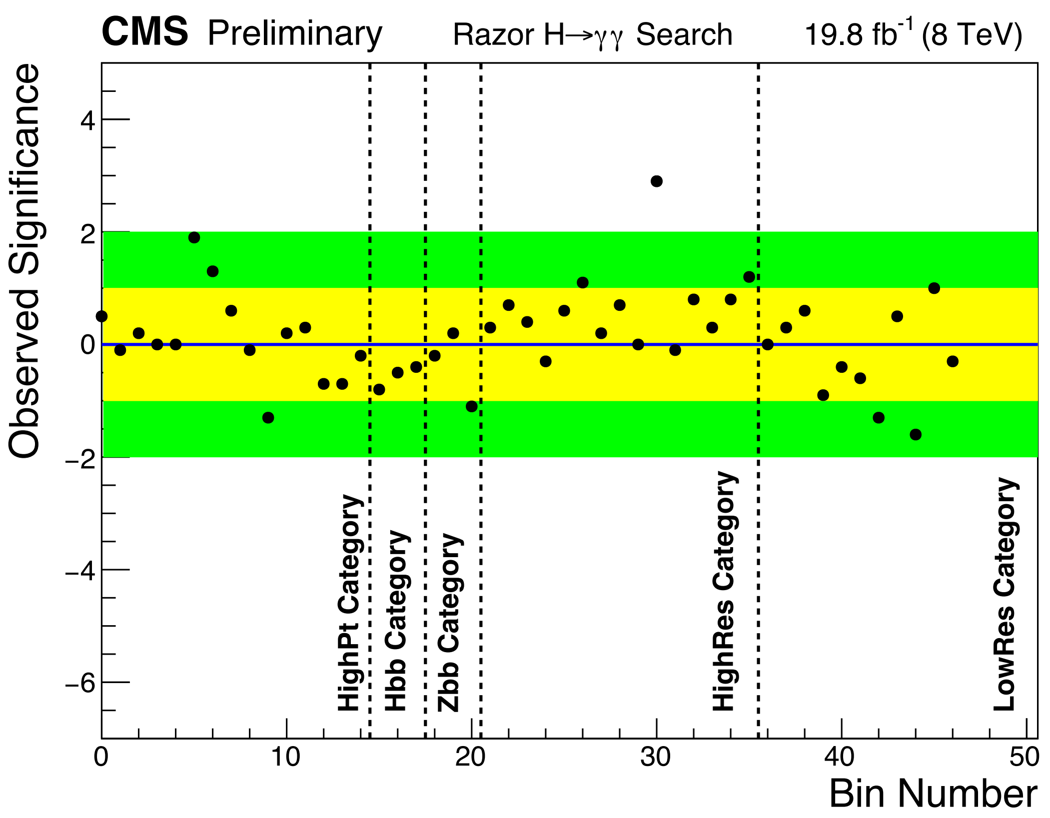

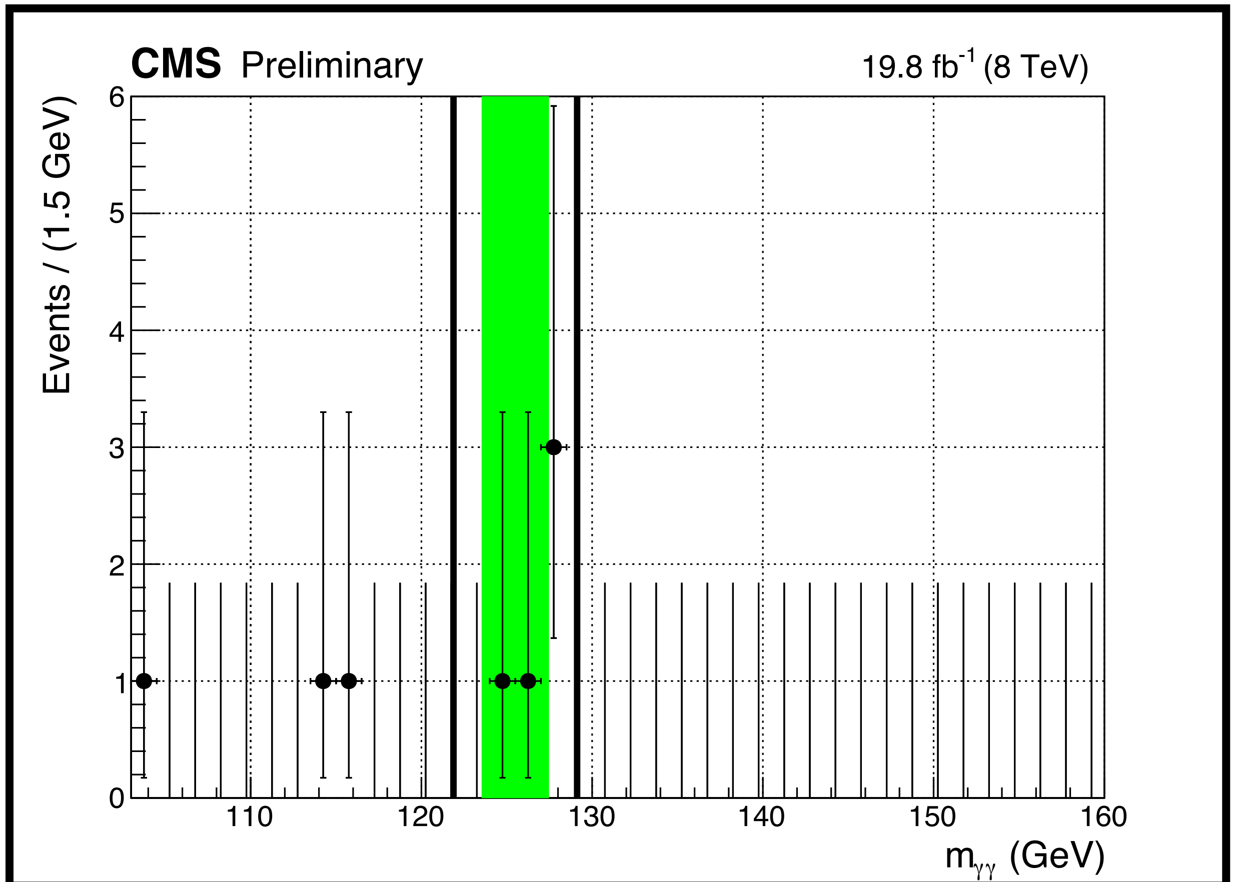

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RUN 2 SIGNAL SYSTEMATICS

- Updated Run 2 signal systematic uncertainties

SYSTEMATIC UNCERTAINTIES	
LEPTON SELECTION EFFICIENCY	2%
LEPTON TRIGGER EFFICIENCY	3%
LUMINOSITY	4.6%
JET ENERGY SCALE	15-30%, VARIES WITH ENERGY & ETA
B-TAGGING EFFICIENCY	5-15%
FASTSIM LEPTON EFFICIENCY	0-10%, VARIES WITH ENERGY & ETA
FASTSIM B-TAGGING EFFICIENCY	0-10%
ISR	UP TO 30%
PARTON DENSITY FUNCTIONS	10%
REN. AND FAC. SCALES	3-5%
PILEUP REWEIGHTING	<1%
MC STATISTICS	POISSON

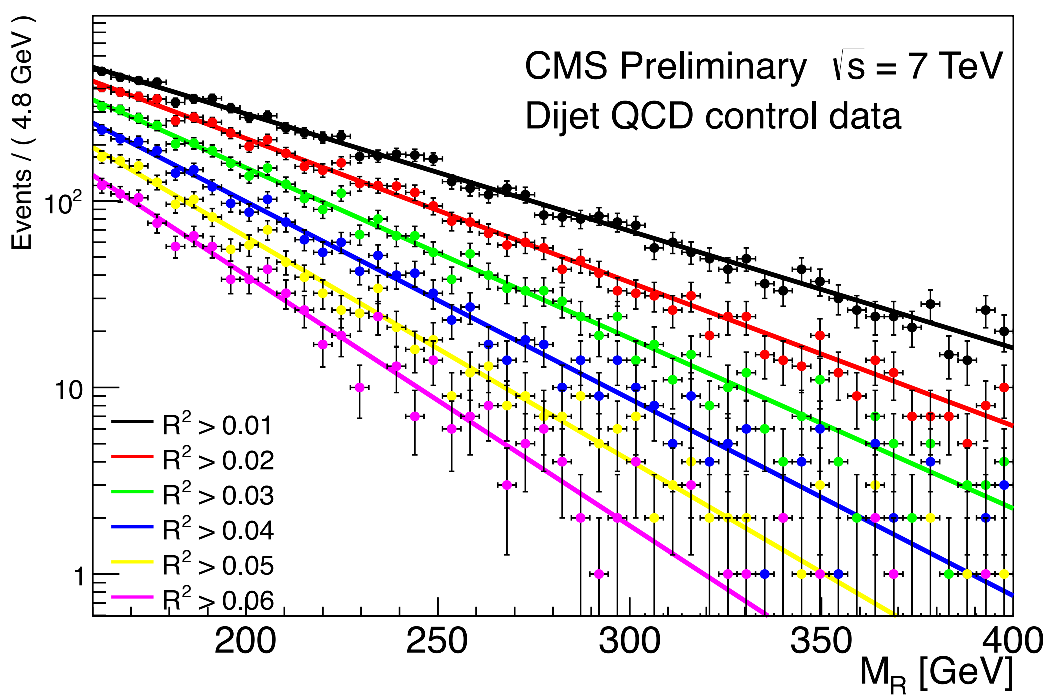
BASELINE SELECTION

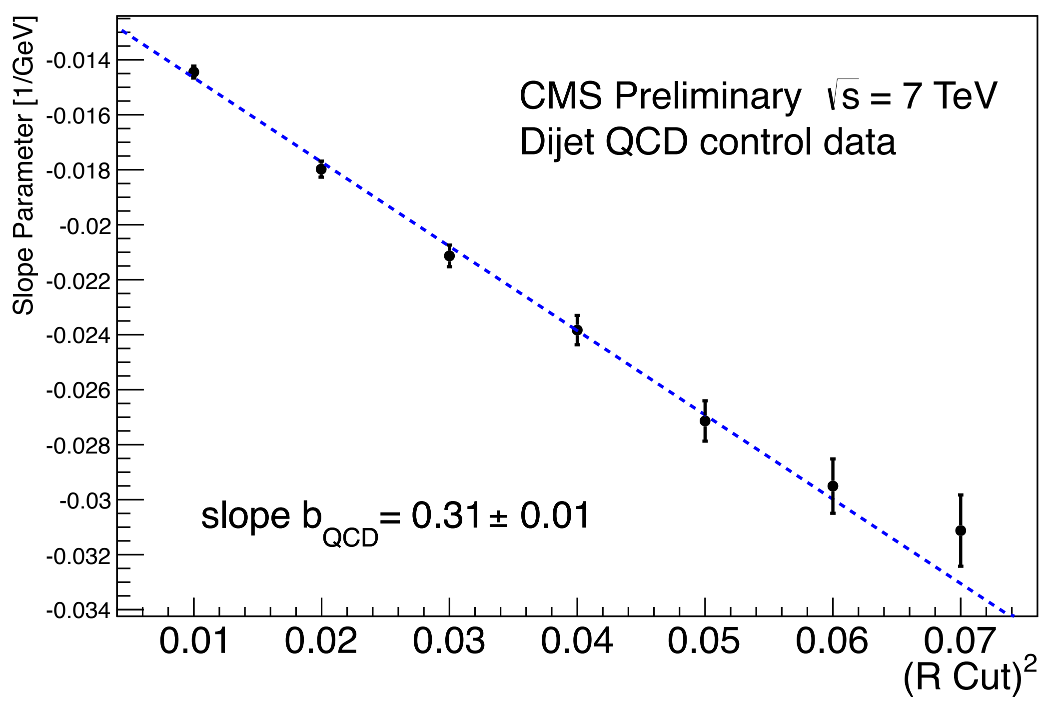
- For all boxes, we select events that have at least four jets with p_T > 40 GeV and |η|<3
  - In the MultiJet box, we also require at least two jets with p_T > 80 GeV and |η|<3
  - Within each box, we categorize events which have 0, 1, 2, ≥3 b-tags

Event category	B-Tag bins	Selection cuts
Electron + Multijet	0 b-tag, 1 b-tag, 2 b-tag, 3 or more b-tags	single electron triggered events, one tight electron, $p_T(e) > 25$ GeV, $M_T > 120$ GeV, $\geq$4 jets with $p_T > 40$ GeV, $M_R > 400$ GeV, $R^2 > 0.15$
Muon + Multijet	0 b-tag, 1 b-tag, 2 b-tag, 3 or more b-tags	single muon triggered events, one tight muon, $p_T(\mu) > 20$ GeV, $M_T > 120$ GeV, $\geq$4 jets with $p_T > 40$ GeV, $M_R > 400$ GeV, $R^2 > 0.15$
Multijet	0 b-tag, 1 b-tag, 2 b-tag, 3 or more b-tags	hadronic razor triggered events, $\Delta\phi < 2.8$, no veto electrons or muons, $\geq$4 jets with $p_T > 40$ GeV, $\geq$2 jets with $p_T > 80$ GeV, $M_R > 500$ GeV, $R^2 > 0.25$

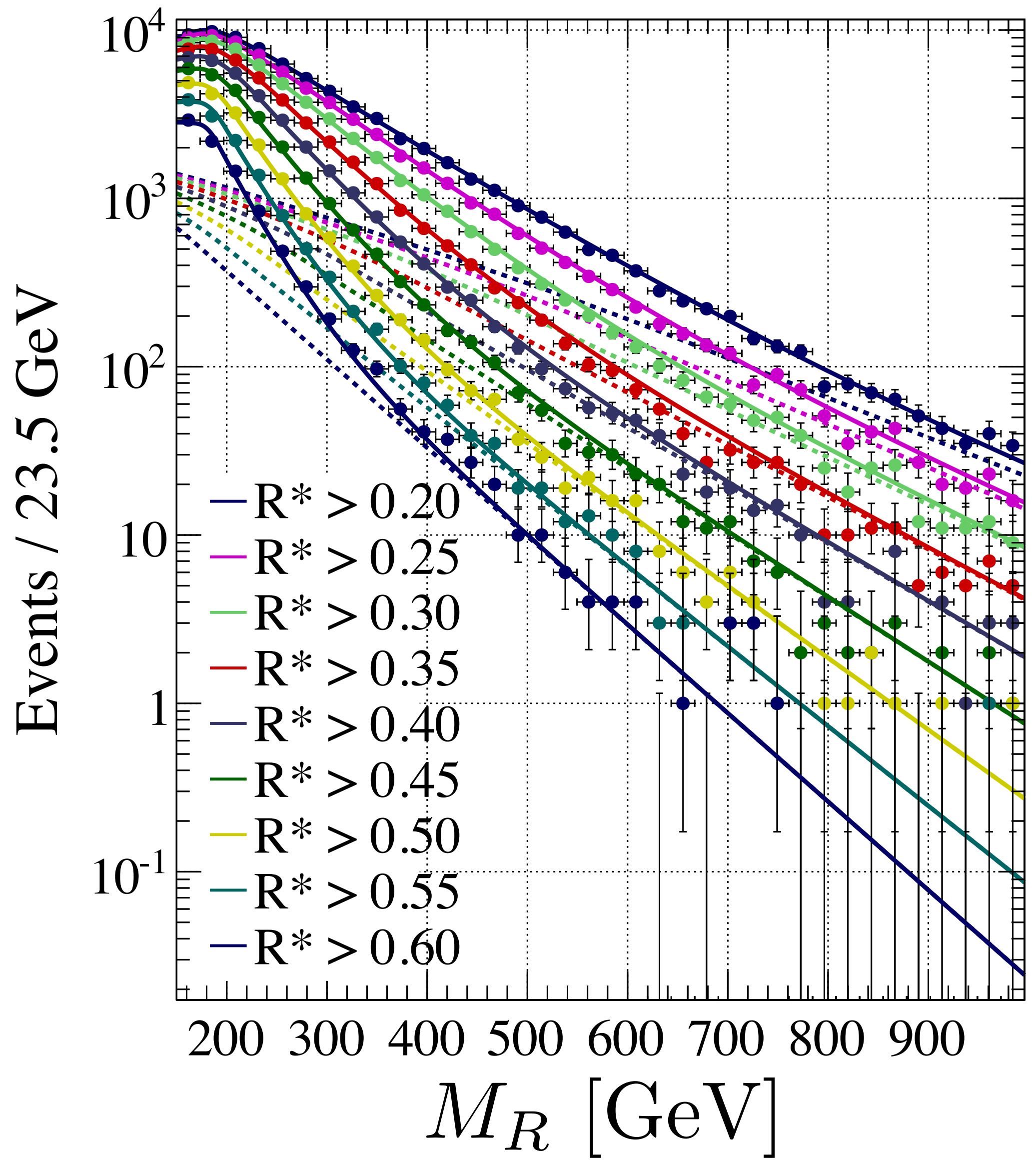
RAZOR VARIABLES (SCALING)

- Empirically we found that, for each background, the tail of the MR distribution is well-modeled by a falling exponential for different R cuts
- The exponents follow a linear relation with respect to the cut position, allowing for an analytic description of the tail





MOTIVATION FOR 2D RAZOR PDF



- As you increase the cut on R2, the exponential slope on MR becomes steeper
  - Exp. slope increases linearly with the R2 cut
- Same thing for MR $\longleftrightarrow$ R2

$$(1) \int_{y_{\rm min}}^{\infty} dy f(x,y) \propto e^{-kx}, \qquad k = by_{\rm min} + c$$

$$(2) \int_{x_{\rm min}}^{\infty} dx f(x,y) \propto e^{-ky}, \qquad k = bx_{\rm min} + c$$

Function satisfying (1) and (2) is:

$$f_{\rm th}(x,y) = (b(x-x_0)(y-y_0)-1)e^{-b(x-x_0)(y-y_0)}$$

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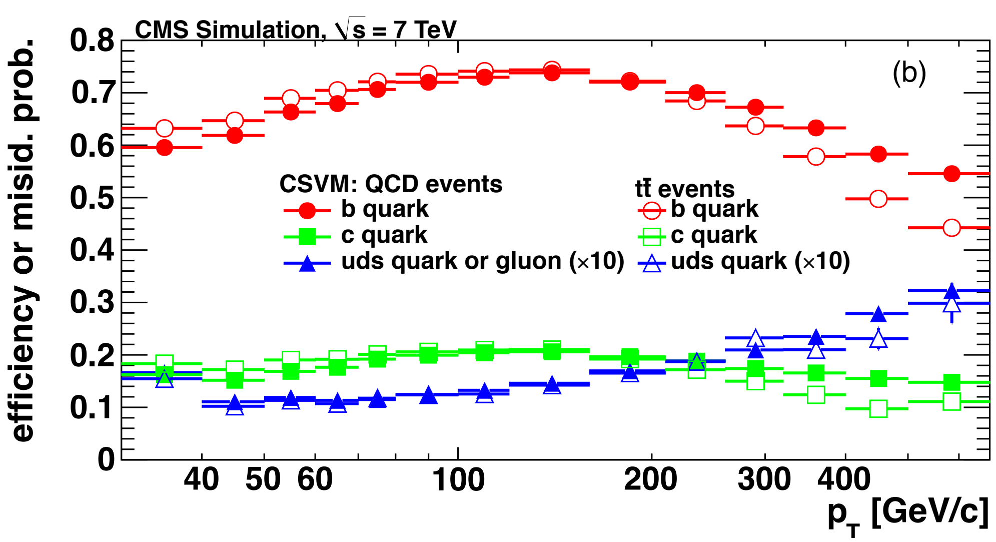
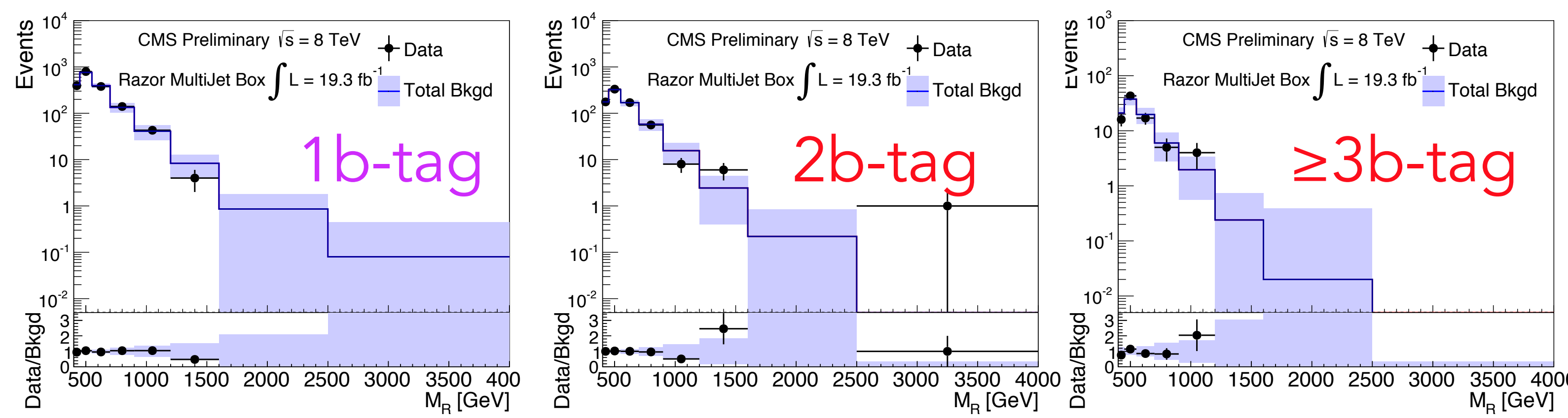
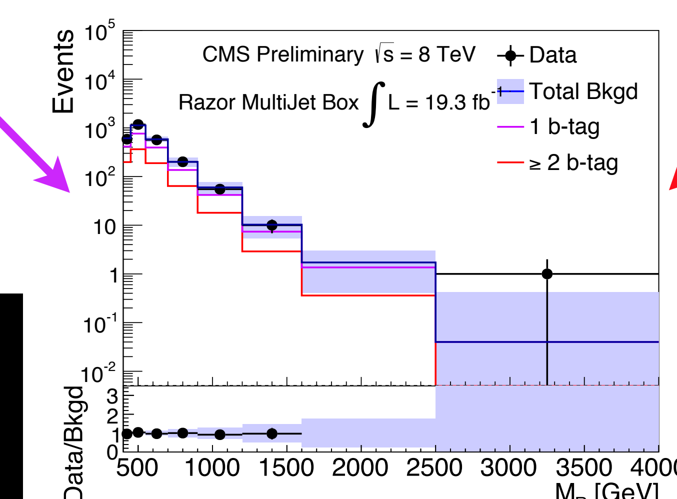
SENSITIVITY WITH B-TAGGING

- For 8 TeV, majority of background is tt+jets, which populates 1b-tag and 2b-tag
- b-tagging based on "combined secondary vertex" algorithm
- The large mass, relatively long lifetimes and hard daughters of bottom hadrons can be used to identify the hadronic jets into which the b quarks fragment
- Discriminator uses secondary vertex and the kinematic variables associated with this vertex, such as flight distance and direction
- b-tagging has dependence on pT, so we expect the MR shape to have some dependence on the b-tag bin (so we allow the ≥2b-tag shape to differ from the 1b-tag shape)







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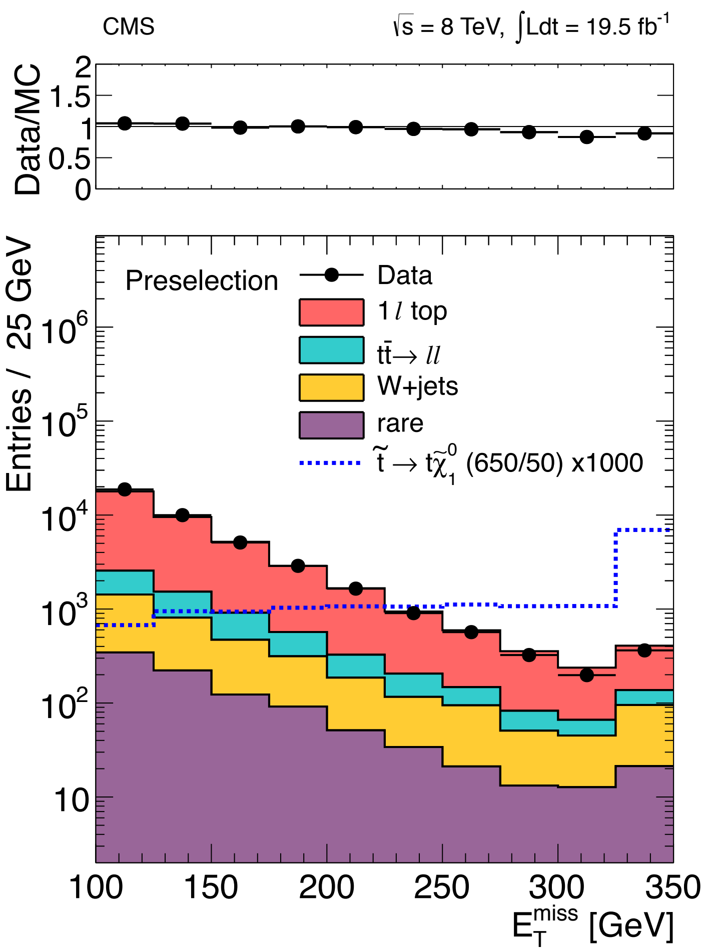
SUS-13-011

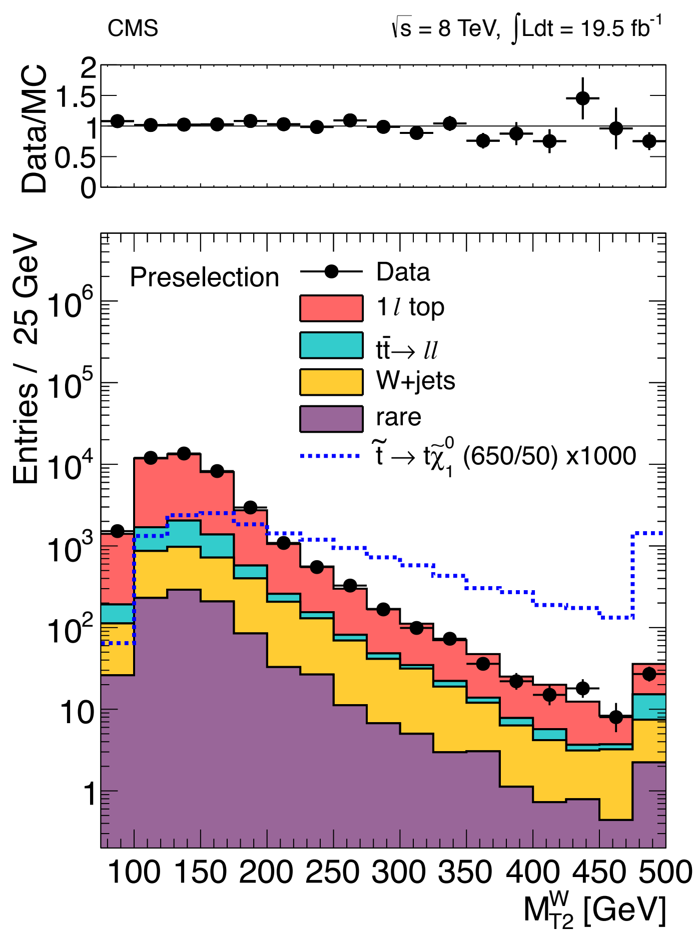
EPJC 73 (2013) 2677

1 LEPTON BDT

- After tight single lepton selection, optimize different multivariate boosted decision trees (BDTs) for different regions of phase space based on signal-sensitive observables

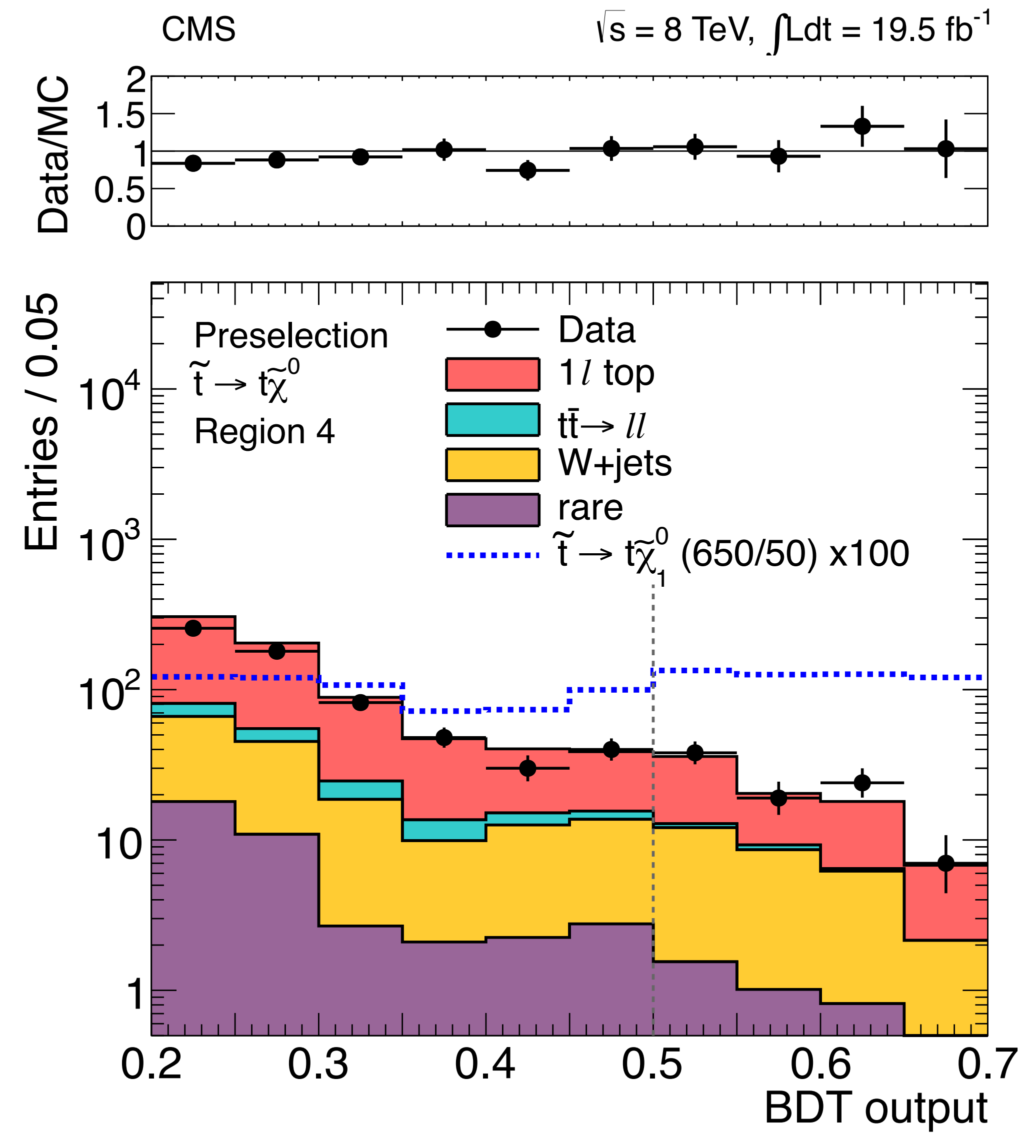
example inputs:



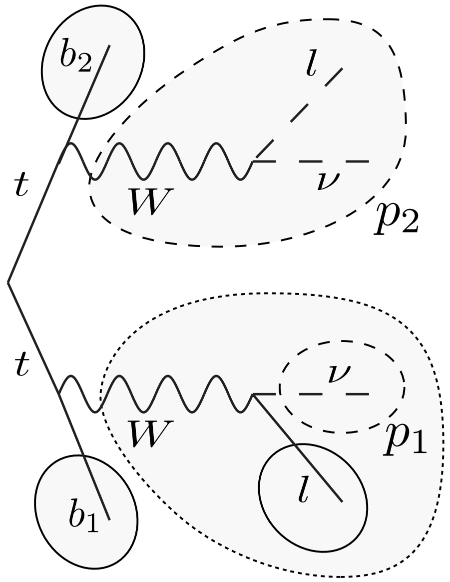


output:

→

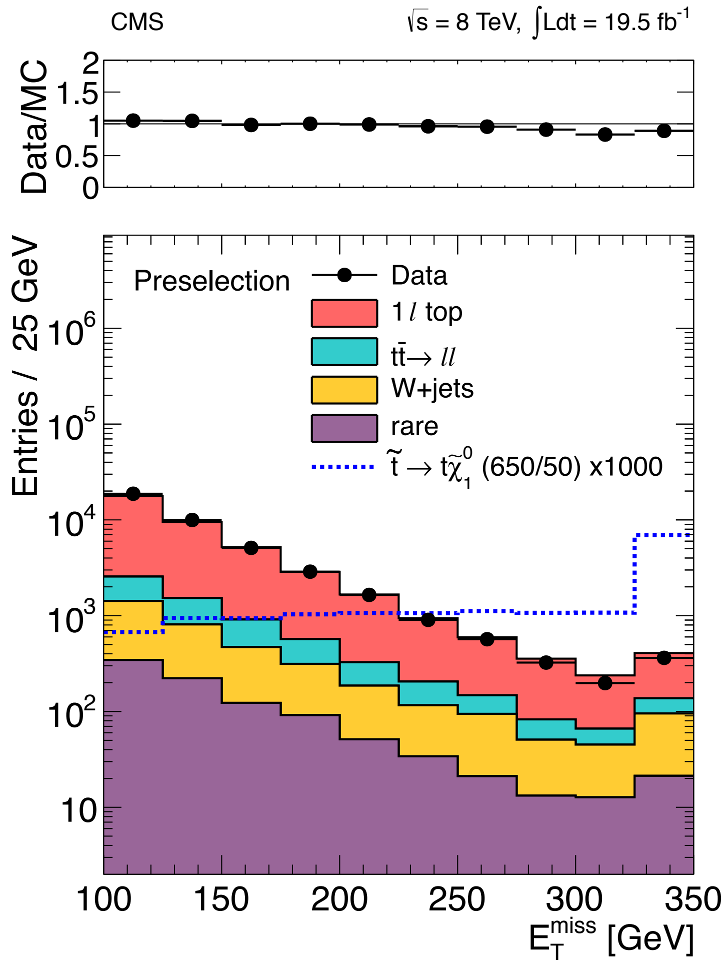


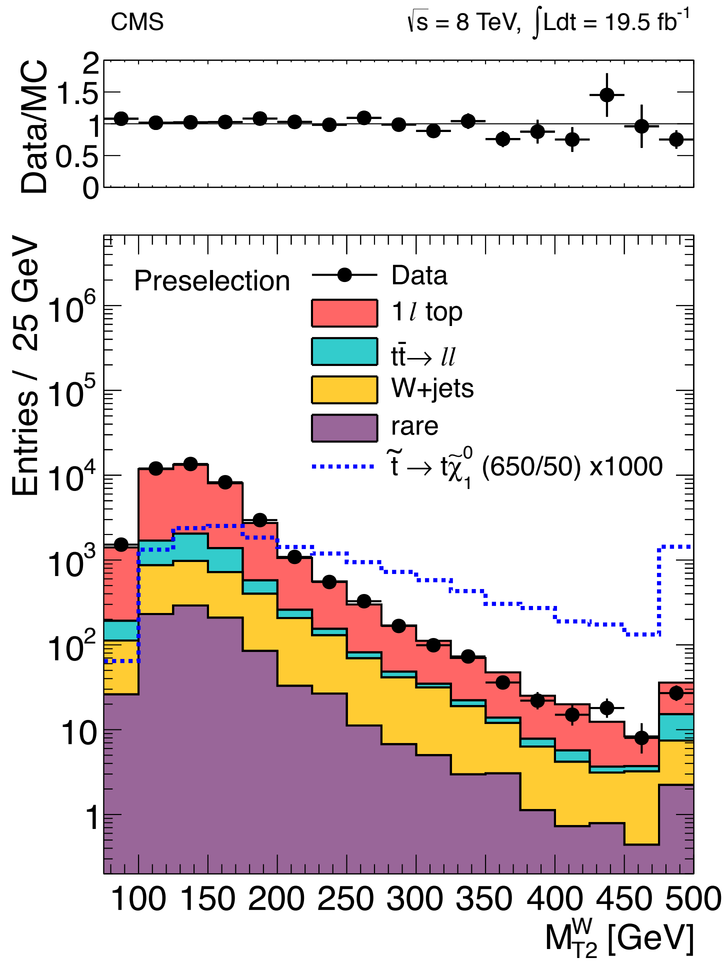
1 LEPTON DETAILS



- Define a multivariate boosted decision tree (BDT) based on several signal sensitive observables, e.g. $E_T^{\rm miss}$, M_{T2}^W
- M_{T2}^W= minimum mother particle mass consistent with observed and assumed kinematic constraints

$$M_{T2}^W = \min\left\{m_y \text{ consistent with: } \begin{bmatrix} \vec{p}_1^T + \vec{p}_2^T = \vec{E}_T^{\rm miss},\; p_1^2 = 0,\; (p_1+p_\ell)^2 = p_2^2 = M_W^2, \\ (p_1 + p_\ell + p_{b_1})^2 = (p_2 + p_{b_2})^2 = m_y^2 \end{bmatrix}\right\}$$





LHC CL$_S$ LIMIT SETTING

LHC CL$_s$

$$\mathcal{L}(\text{data}|\sigma,\hat{\theta}_\sigma)\pi(\hat{\theta}_\sigma) \geq \mathcal{L}(\text{data}|\sigma,\theta)\pi(\theta) \quad \forall\,\theta,\ \text{fixed}\ \sigma$$

$$\mathcal{L}(\text{data}|\hat{\hat{\sigma}},\hat{\hat{\theta}})\pi(\hat{\hat{\theta}}) \geq \mathcal{L}(\text{data}|\sigma,\theta)\pi(\theta) \quad \forall\,\theta,\sigma$$

$$\tilde{q}_\sigma = -2\log\left(\frac{\mathcal{L}(\text{data}|\sigma,\theta_\sigma)}{\mathcal{L}(\text{data}|\hat{\hat{\sigma}},\hat{\hat{\theta}})}\right), \quad 0 \leq \hat{\hat{\sigma}} \leq \sigma$$

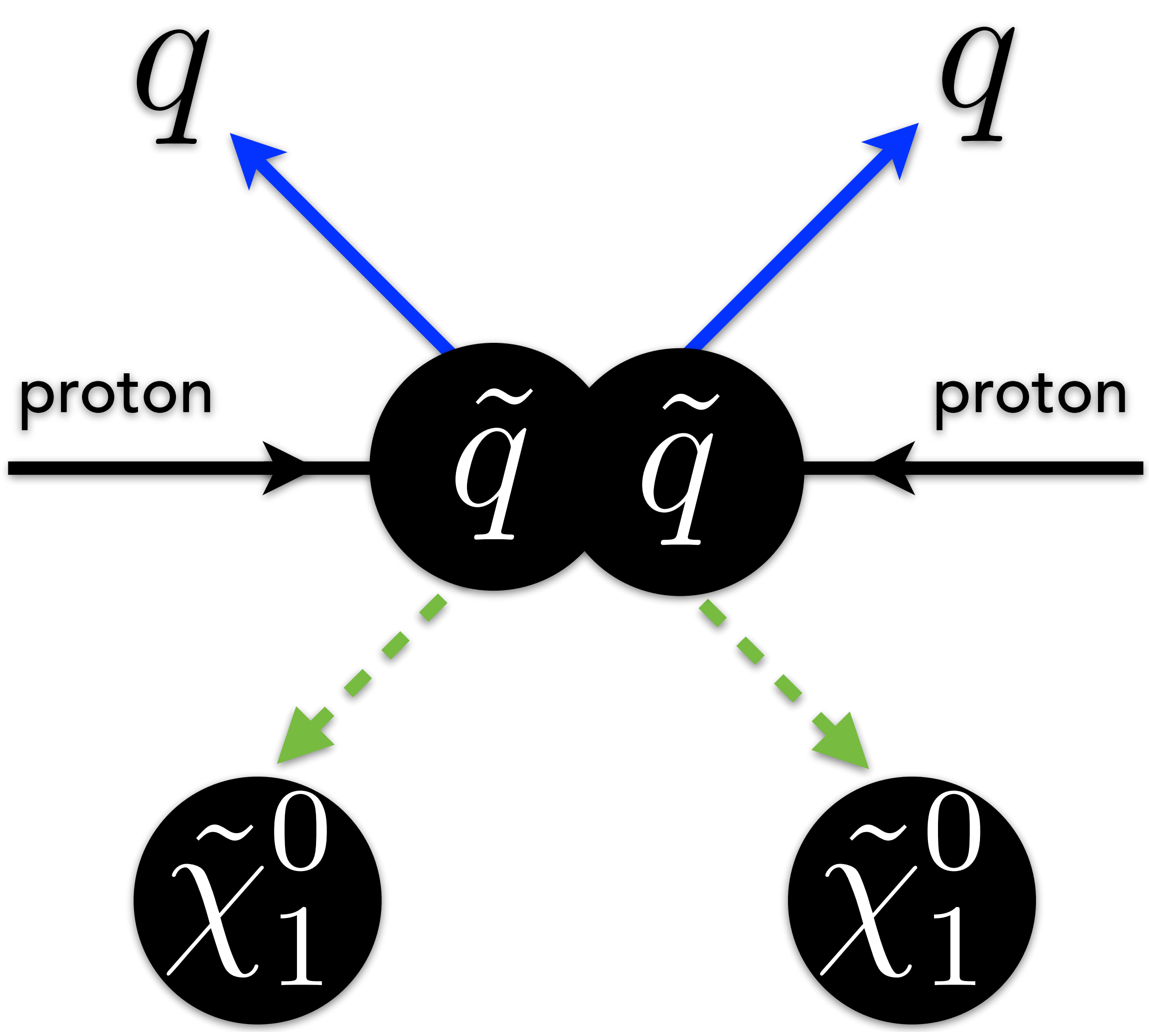
$$\text{CL}_{\text{s+b}}(\sigma) = \int_{\tilde{q}_\sigma^{\text{obs}}}^{\infty} d\tilde{q}_\sigma\ f(\tilde{q}_\sigma|\sigma,\hat{\theta}_\sigma^{\text{obs}})$$

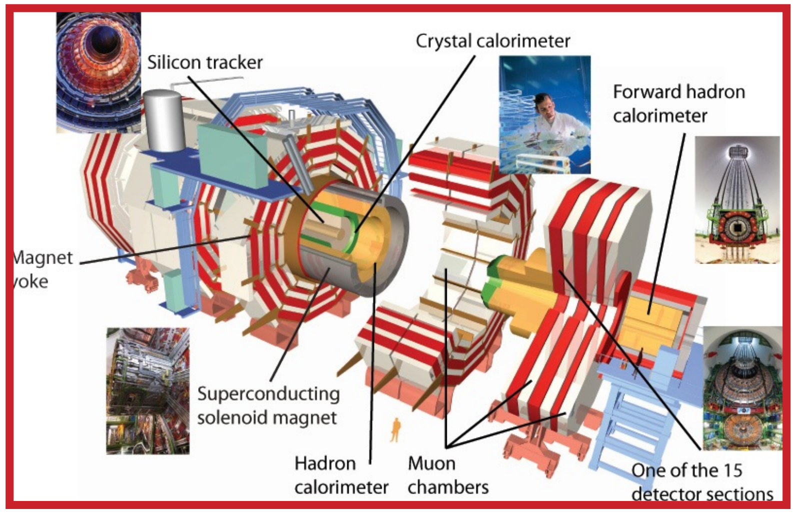
$$\text{CL}_{\text{b}} = \int_{\tilde{q}_\sigma^{\text{obs}}}^{\infty} d\tilde{q}_\sigma\ f(\tilde{q}_\sigma|\sigma,\hat{\theta}_0^{\text{obs}})$$

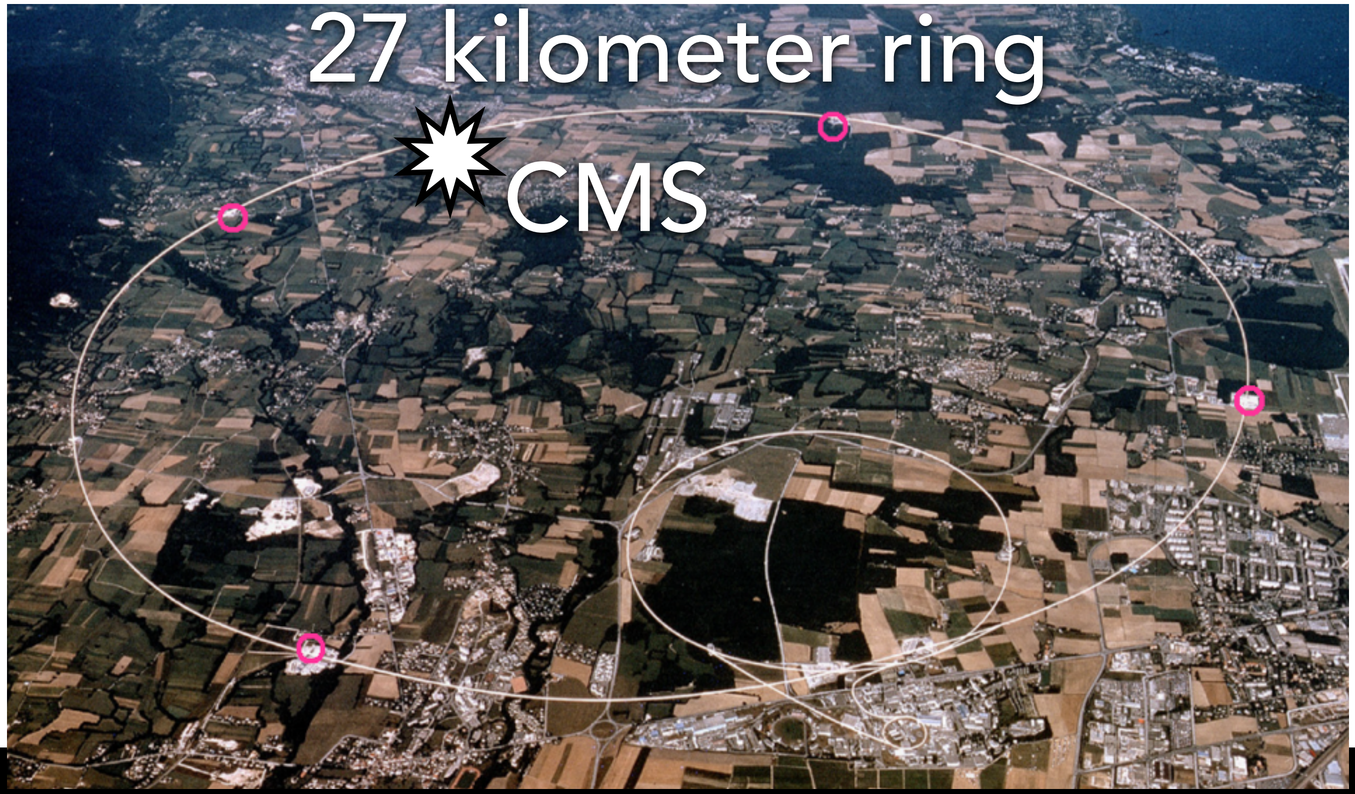
- b-only (s+b) full fit on data => best fit for b-only (s+b) nuisance parameters
- All nuisances fixed to ML estimators at toy generation
- Profile Likelihood ratio (s+b vs. best-fit s+b) test statistic re-fit in the full region

SUSY PRODUCTION AT THE LHC

- Protons collide, producing **two squarks**, which then decay to **two quarks** and **two invisible particles**







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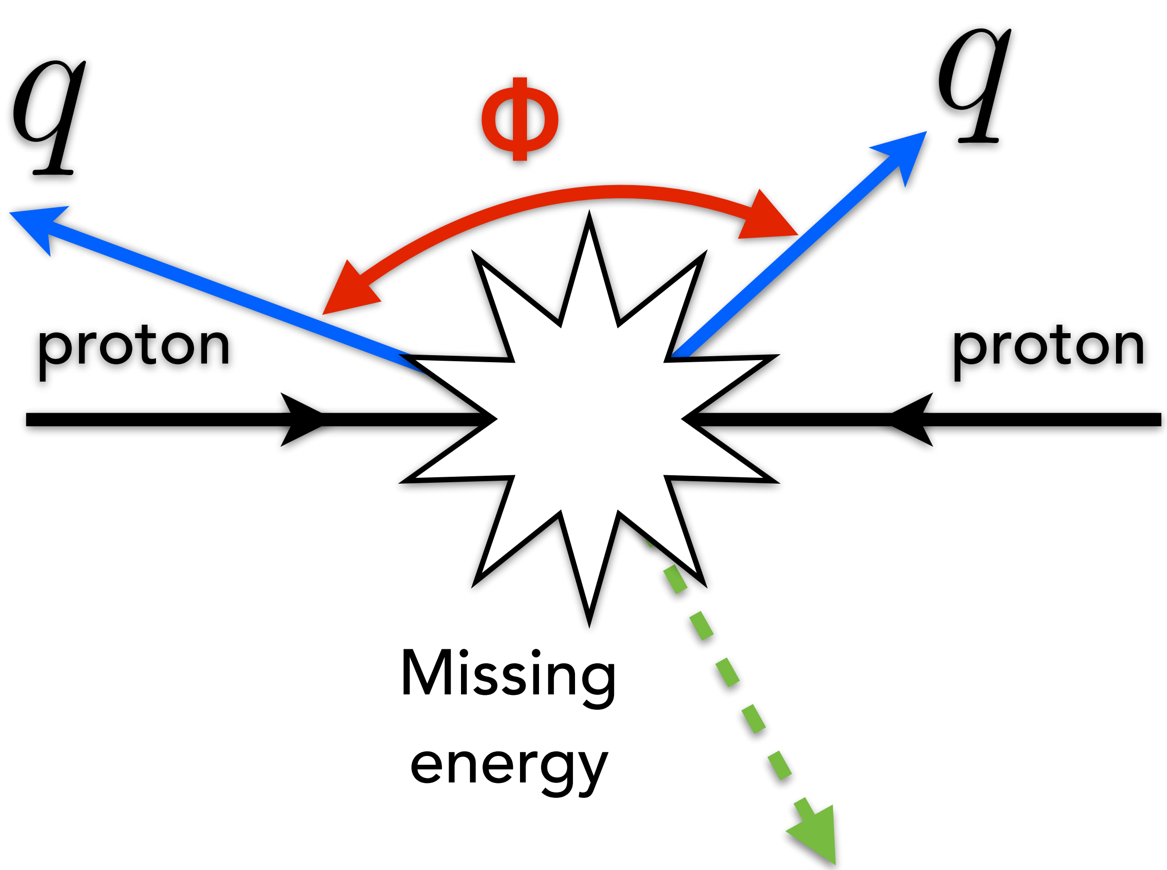
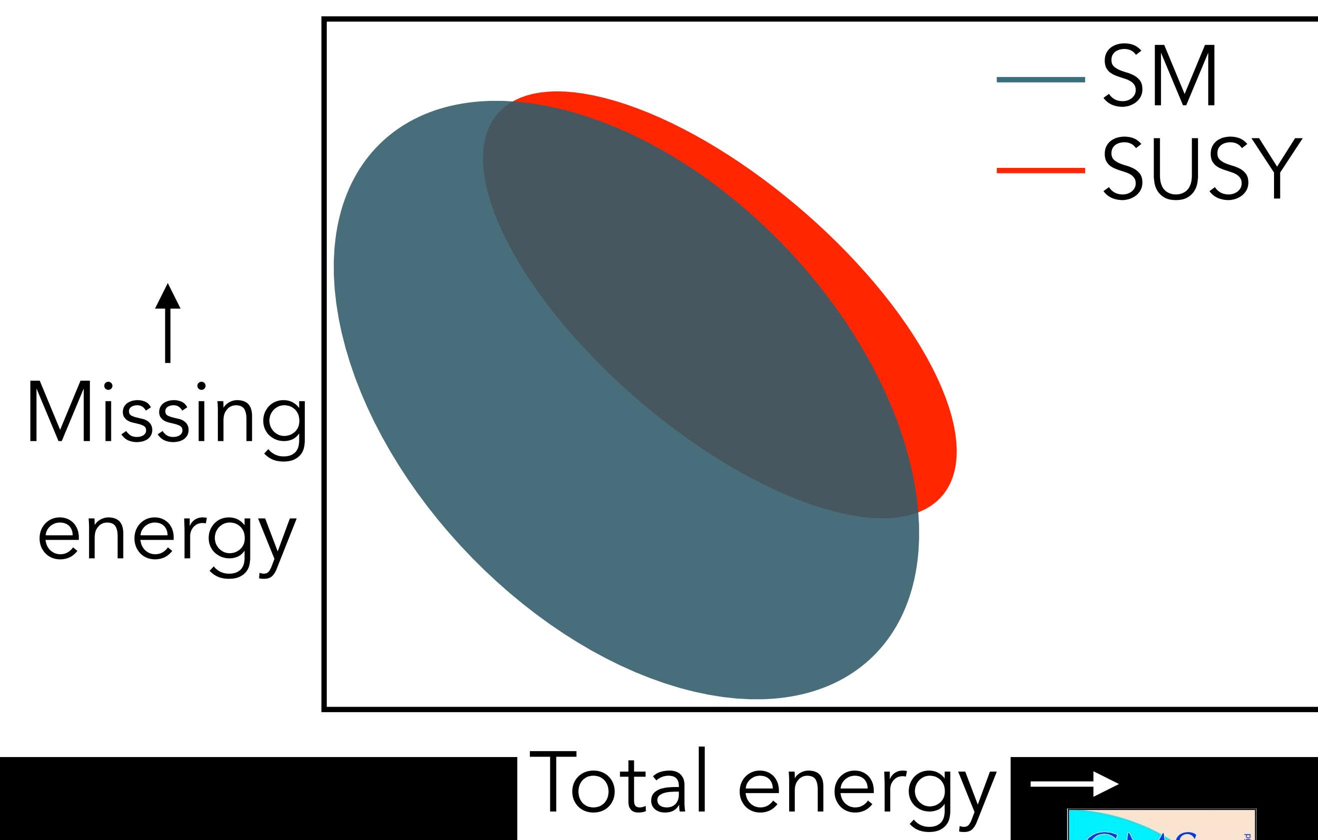
WHAT WE SEE

- We can't directly observe the invisible particles, but we observe **missing transverse momentum**

How can discriminate signal from background?



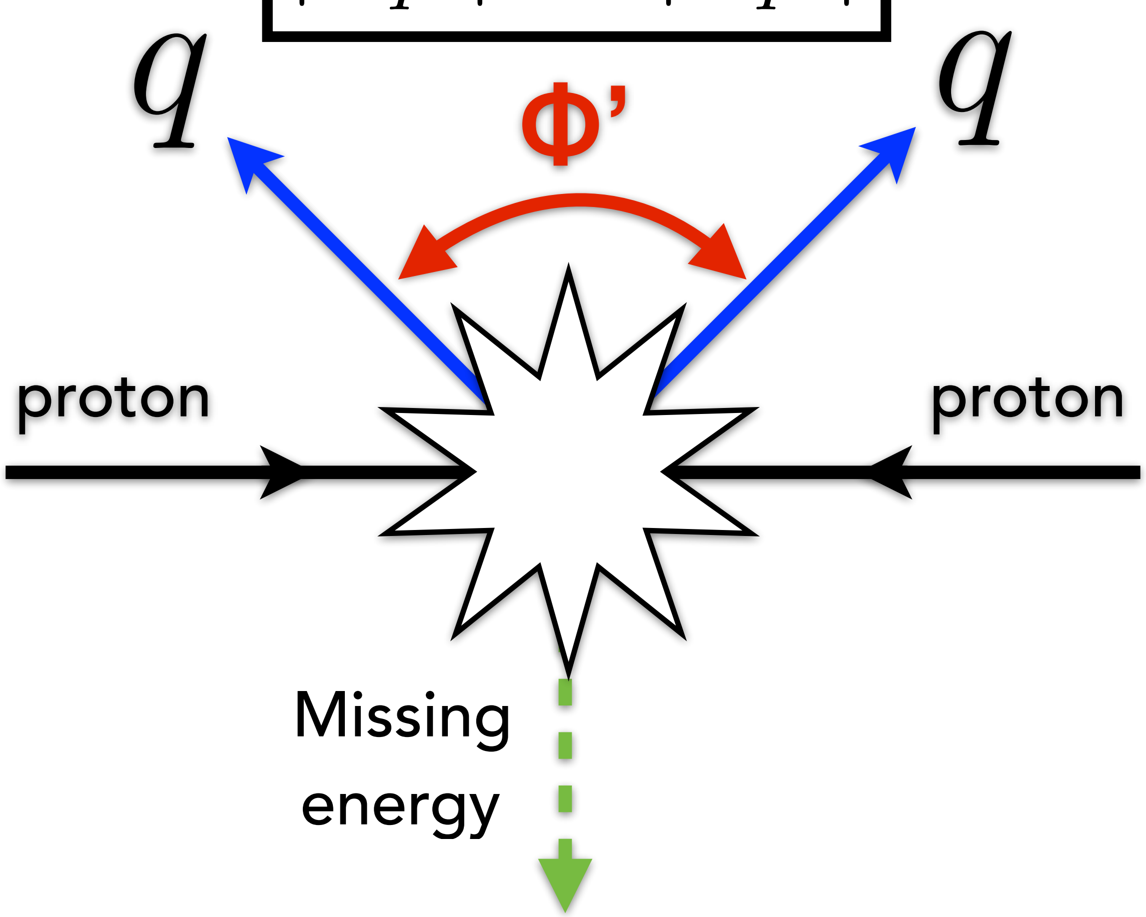
How can we estimate the hidden masses of the super particles?



RAZOR VARIABLES

Transform to a more symmetric frame where the visible momenta are equal

$$|\vec{p}_{q1}| = |\vec{p}_{q2}|$$

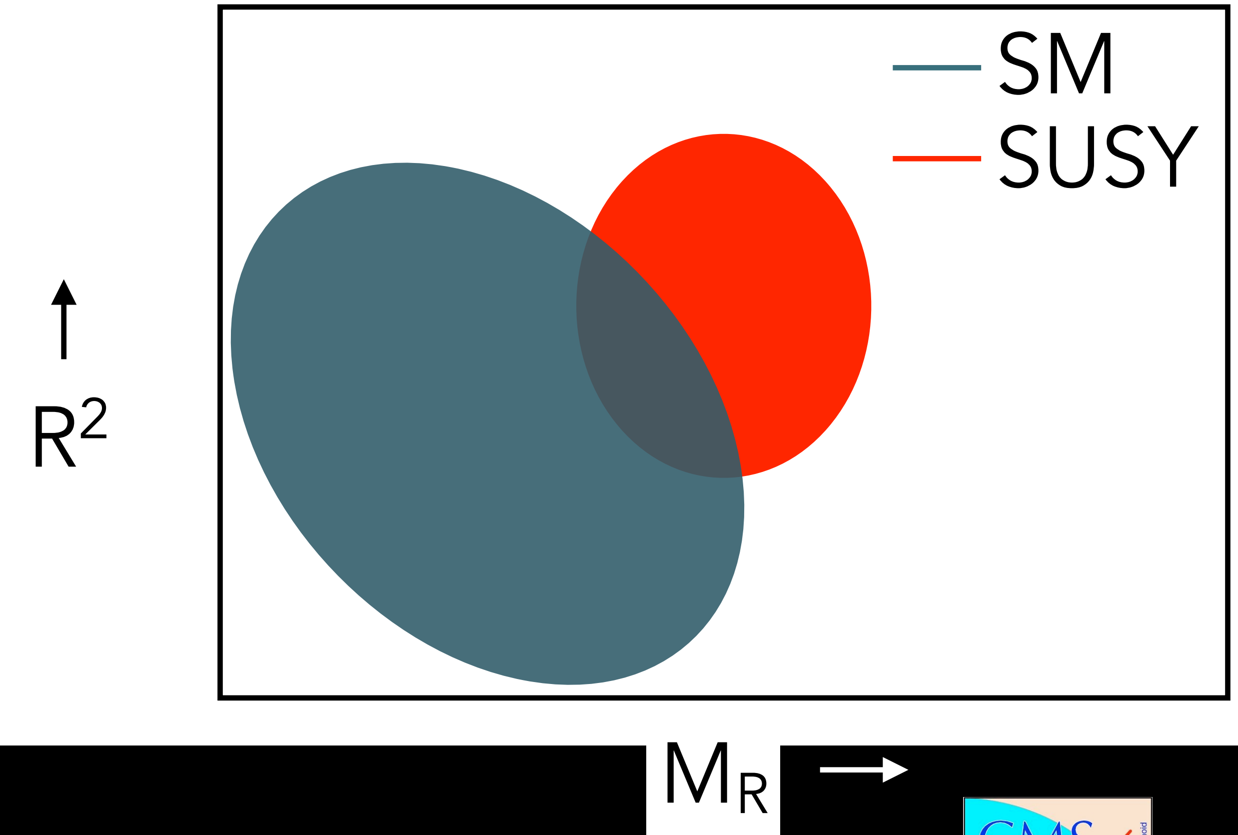


In this frame, we compute the **razor variables**, functions of the visible and missing momenta

$$M_R \equiv 2|\vec{p}_{q1}|$$

$$R \equiv \frac{M_T^R}{M_R}$$

$$M_T^R \equiv \sqrt{\frac{E_T^{\text{miss}}(p_T^{q1} + p_T^{q2}) - \vec{E}_T^{\text{miss}} \cdot (\vec{p}_T^{\,q1} + \vec{p}_T^{\,q2})}{2}}$$



SLHA FOR NATURAL SUSY

- SLHA file can be found at:

https://github.com/CMS-SUS-XPAG/GenLHEfiles/blob/master/slha/T2tb.slha

- Chargino decay branching fractions are:

```
#          BR          NDA      ID1        ID2        ID3
     3.51024479E-01    3     1000022         2         -1   # BR(~chi_1+ -> ~chi_10 u    db)
     3.51024479E-01    3     1000022         4         -3   # BR(~chi_1+ -> ~chi_10 c    sb)
     1.17008160E-01    3     1000022       -11         12   # BR(~chi_1+ -> ~chi_10 e+   nu_e)
     1.17008160E-01    3     1000022       -13         14   # BR(~chi_1+ -> ~chi_10 mu+  nu_mu)
     6.39347234E-02    3     1000022       -15         16   # BR(~chi_1+ -> ~chi_10 tau+ nu_tau)
```