BSM Likelihoods in CMS 100 150 200 250 300 350 400 *mass.* Right*: excluded regions in the (m^t* \overline{C} $\frac{1}{2}$ and the signal-background hypothesis can be written by written by written by written by written by written by

Likelihoods for the LHC Searches, CERN in the two boxes as follows: all the *Z*(⌫⌫)+jets background to the Had box; 8% (92%) of January, 23, 2013 $\frac{1000}{M_{\odot}}$ $\frac{1500}{2500}$ $\frac{1}{2500}$ $\frac{0.2}{2500}$ which produce at least one muon in 50 by the 2D Razor Function *f^j* (*MR, R*² log *f^j* (*MR, R*² *f^j* (*MR, R*²

q
H

[~]*^j*²)² (*p^j*¹

^z + *p^j*²

January 21, 2013

 $t = t$

^T + *p^j*²

*j*2SM

⁰*,j*) 1]

Overview

- Likelihoods in BSM searches at CMS
	- Binned Cut and Count (Poisson)
	- Unbinned Shape Analysis (Analytic function)
	- Binned Cut and Count (Multinomial)
- Approximating the likelihood for reinterpretation
	- Simplify as binned cut and count (Poisson)
- Tools to help and future efforts

Public Likelihoods in CMS

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CMS SUSY Public Likelihoods

Canonical Use of Likelihoods

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Canonical Use

Use your favorite generator, Pythia8, MadGraph5, etc. for your BSM model

Apply cuts, efficiencies and **2** smear with detector response

Reinterpret results for your BSM **3** 110 model with the likelihood $\bigcap_{\mathbf{A}}$ $\zeta \searrow$ IV Λ \sim \sim \sim \sim \sim

> 100 150 200 250 300 350 400 is a Bayesian Analysis... One possible simple application

Bayesian Application of Likelihood *•* Tight muon (*p^T >* 15*, |*⌘*| <* 2*.*1), Loose muon (*p^T >* 10*, |*⌘*| <* 2*.*1) ari Application or Linching *^p*(*s, b|N*) = *^L*(*N|s, b*)⇡(*s, b*)

Recall from G. Cowan's talk *θ, evalued from G. Cowan's talk*

Bayes' theorem only needs $L(x|\theta)$ evaluated with a given data set (the 'likelihood principle'). *•* Cover bear
• Mumumum: only needs $L(x|\theta)$ evaluated with a given eorem only needs $L(x|\theta)$ e

likelihood and mean $s+b$ (model) F sum over thing oxponsion. is enough. Single bin counting experiment Observe *N* events (data) Interested in a signal, with Poisson counting experiment *•* Events (data)
• Controllectronic mode of the Tight electronic energy electronic energy electronic mode of the Ma *Frances*
• All mean s+b (model

 $\mathcal{L}(N|s,b) = \frac{(s+b)^N e^{-(s+b)}}{N!}$ *N*!

^R *^L*(*N|s, b*)⇡(*s, b*)*dbds*

L(*N|s, b*)⇡(*s*)⇡(*b*)*db*

 $p(s, b|N) = \frac{\mathcal{L}(N|s, b)\pi(s, b)}{\int L(N|s, b)\pi(s, b)}$ $\int L(N|s,b)\pi(s,b)dbds$ normalization in CMS Update our priors in light of data with Bayes' rule model space

Bayesian Application of Likelihood *•* Mu: one Tight muon an Applicatio $U \cap U \cap U$ $\overline{\mathcal{L}}$ *L*(*N|s, b*)⇡*s*(*s*)⇡*b*(*b*)*db*

• play different roles Parameters play different roles

s - signal yield, parameter-of-interest

 p **ce** parameter
 $\pi(s, b) = \pi_s(s)\pi_b(b)$ *b* - background yield, nuisance parameter

Usually only interested in signal yield, so we marginalize nuisance parameter $p(s|N) \propto$ z
Z $\mathcal{L}(N|s,b)\pi_s(s)\pi_b(b)db$ informative *^L*(*N|s, b*) = (*^s* ⁺ *^b*)*^N ^e*(*s*+*b*)

Compute 95% credibility intervals or whatever we want

 $\pi(s, b) = \pi_s(s)\pi_b(b)$

 \sum_{λ}

non-informative

^R *^L*(*N|s, b*)⇡(*s, b*)*dbds*

Example: cut and count

Wednesday, January 23, 13 99 and 200 a

SS Dilepton **55 Background Estimation**

[arXiv:1104.3168](http://arxiv.org/abs/1104.3168) JHEP 1106:077 (2011)

7 TeV/8 TeV Updates arXiv:1205.3933 arXiv:1212.6194

After selection, estimate backgrounds $\overline{\mathbf{B}}$ **5** $\overline{\mathbf{B}}$ **5 \overline{\mathbf{B}}** $\text{C} \cdot \text{C}$

 \bullet 2 reconstructed jets, $p_T > 30$ GeV (from Λ Ω) • Rare SM processes | $($ from MC $)$ e.g. $q\bar{q} \rightarrow WZ$ and ZZ \bullet $E_T^{\text{miss}} > 30$ GeV (ee and $\mu\mu$) $qq \rightarrow q'q'W^{\pm}W^{\pm}$ or $E_T^{\text{miss}} > 20$ GeV $(e\mu)$ $2 \times (q\overline{q} \rightarrow W^{\pm})$, tt̄W, and WWW \bullet 1 or 2 fake leptons \bullet charge mis-reconstruction $p = \frac{p}{2}$ contributions are very small, $p = \frac{p}{2}$ **5 Background Estimation** $\begin{pmatrix} \text{II}\text{OII}\text{II}\text{III}\text{IVIV} \end{pmatrix}$ with $\begin{pmatrix} \text{I}\text{III}\text{III}\text{III}\text{IVIV} \end{pmatrix}$ $O(\frac{\log \log \log n}{\log \log n})$ structed as leptons, or jet fluctuations leading to hadronic *t* signatures. We will refer to all of $\mathbf v$, dilu VVVVV, i.e., i.e., i.e., i.e., the signal we are searching for $\mathbf v$, the signal we are searching for $\mathbf v$, the signal we are searching for $\mathbf v$, the signal we are searching for $\mathbf v$, i.e., $\mathbf v$, \math

 (011) Search in SS dilepton + jets + MET ates final states in several signal regions $S_{\rm s}$ sources of same-sign dilepton events with both leptons with both leptons $S_{\rm s}$ \overline{C} a with a blatter in boyona bignan ogiono more than a few percent of the total background of the total background

- *•* 2 isolated leptons, first lepton *p^T >* 20 GeV, Δ fter selection second lepton $p_T > 10$ GeV $\frac{1}{4}$ and $\frac{1}{2}$ and $\frac{1}{2}$ is a theory functional states $\frac{1}{2}$ and $\frac{1}{2}$ \sim 2 isolated reprofision correction $p_T > 20$ Oe ℓ , ClION, second reprofit $p_T > 10$ Second contribution from pp \mathbf{r}
	- λ grounds e RelIso < 0.1 for $p_T > 20$ GeV and IsoSum < 2 GeV for $p_T < 20$ GeV righted to and IsoSum simulation and $\frac{1}{2}$ for $n_T < 20$ GeV
	- $\sum_{i=1}^{\infty}$ secondition group $\sum_{i=1}^{\infty}$ of $\sum_{i=1}^{\infty}$
	- $E_T^{\text{miss}} > 30 \text{ GeV}$ (*ee* and $\mu\mu$) or $E_T^{\text{miss}} > 20 \text{ GeV}$ (*e* μ) $e\mu$ ₎ 1 external candidates can be $F_{\text{cm}}^{\text{miss}} > 30$ GeV (ee and $\mu \mu$) f_{at} and f_{at} or $F_{\text{at}}^{\text{miss}} > 20 \text{ GeV} (\text{e} \mu)$
- simulation, assigning a 50% systematic uncertainty. The background contribution from pp ! W*g*, where the W decays leptonically and the photon converts in the detector material giving (data-driven) e.g. semi-leptonic tt $\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ is the background from position from pp to the contribution from pp $\begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$ simulation, assigning a 50% systematic uncertainty. The background contribution from pp ! The dominant background contribution is from events with one lepton, jets, and *E*miss (data-driven) eptons (Charge mis-reconstruction) $t\bar{t}$ with one lepton from the α

SS Dilepton Results

\blacksquare dominates all search regions. The low-*pT*-lepton analysis has a small, but non-negligible, back- \mathcal{L}_{c} with the stress with two face leptons. Estimates for backgrounds due to to backgrounds due to to the total stress of \mathcal{L}_{c} Data: No excess

Set Bayesian 95% credibility limits

Additional Information for Gen-level Study

Parametrized curve describes analysis efficiency to canonical signal model **at gen-level**

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Validation - SS Dilepton

Using simple efficiency model of CMS detector, the 95% C.L. limits are reproduced

Model Publication - SS Dilepton

[arXiv:1104.3168](http://arxiv.org/abs/1104.3168) JHEP 1106:077 (2011)

clearly specified selection

- 2 isolated leptons, first lepton $p_T > 20$ GeV, second lepton $p_T > 10$ GeV
- Rellso < 0.1 for $p_T > 20$ GeV and IsoSum $<$ 2GeV for $p_T < 20$ GeV
- 2 reconstructed jets, $p_T > 30$ GeV
- $E_T^{\text{miss}} > 30 \text{ GeV}$ (*ee* and $\mu\mu$) or $E_T^{\text{miss}} > 20 \text{ GeV}$ (*e* μ)

object efficiencies for a canonical signal model

17 dicted BG" refer to the sum of the data-driven estimates of the fake lepton contributions, and the residual contributions predicted by the simulations predicted by the simulation. The rows in the rows in t background as predicted from the simulation alone. Rows labeled "**observed**" show the actual observed yields predicted background and

simulation samples described in Section 4 are represented. Figure 8 summarizes the signal region die paradis and background composition in all four search in all four search in the search regions present \Box lepton plus jets background where the second lepton second lept reproducibility of limits

Reinterpreting a shape analysis in a new BSM model Example: 2011 Razor analysis

Wednesday, January 23, 13 15

y

Razor Variables Motivation

Approximate the squark rest frame by boosting to the frame where $|p^R_{j1}| = |p^R_{j2}|$ *L*
L
*D B*_{*-}</sub> <i>l D R*₋*l***</sub>**

Transformed momentum defines razor variable **MR** *p*(*s|N*)*ds* = 0*.*95 rans

Estimates the momentum in *f* **Estimates the momentum in the true squark rest frame**

$$
|\vec{p}_{j1}|=\frac{M_{\tilde{q}}^2-M_{\tilde{\chi}}^2}{2M_{\tilde{q}}}
$$

M^R and *R*². The full likelihood for the background-only hypothesis can be written, exp[^P *^j*2SM *N^j*] Y cut 290 as shown in the exponential fit is found to be a linear function of *R*2 fitting *S* in the form *S* = *a* + *bR*² cut determines the values of *a* and *b*. cut 200 as shown in Fig. 2 (right); in Fig. 2 (righ Modeling the Backgroun

*R*² ²⁸⁹ to extract the coefficient in the exponent, denoted by *S*. The value of *S* that maximizes the

*R*² ²⁸⁹ to extract the coefficient in the exponent, denoted by *S*. The value of *S* that maximizes the

threshold for events in data selected in the QCD control box. (Bottom left) The exponential Wednesday, January 23, 13 19

N! $\frac{1}{2}$ Razor Shape Analysis *Razor Shape Ar*
Events are classified in 6 disjoint boxes *N*_{*N*} (*i*) + *N*_{*l*} (*i*) + *N*_{*l*} (*i*) + *N*_{*l*} (*i*) + *R₂* \/ *Njf^j* (*MR*(*i*)*, R*² (*i*)) azor Shar *Njf^j* (*MR*(*i*)*, R*² (*i*))

Ls+*^b* = **based on lepton content** *In each box, each SI i*₁ In each box, for each box, for each background, the probability density is regiverite properting definity is
adeled by 1 or 2 instances of Dackground probability density ⇥ exp[*k^j* (*M^R ^M*⁰ *F*
ts are ck bac
mc Γ exp[*N^s* ^P *N*! *N* ²
ach
2010 In each box, each SM background probability density is IN EXECUTE BOX, FOR EACH BACKGROUND, THE PROBABILITY OF \mathcal{P}_max modeled by 1 or 2 instances of

L^b =

Njf^j (*MR*(*i*)*, R*²

(*i*))

$$
f_j(M_R, R^2) = [k_j(M_R - M_{R,j}^0)(R^2 - R_{0,j}^2) - 1]
$$

^z + *p^j*²

2

^z)² *M^R*

^T ⌘

$$
\times \exp[-k_j(M_R - M_{R,j}^0)(R^2 - R_{0,j}^2)]
$$

*^j*2SM *N^j*]

N!

*^j*2SM *N^j*]

 \mathbb{P}^{\mathbb

M^R and *R*². The full likelihood for the background-only hypothesis can be written,

*^j*2SM *N^j*]

Y

f^j (*MR, R*²

by the 2D Razor Function

*^j*2SM *N^j*]

N! *i*=1. Razor Shape Analysis *N*_{*N*} (*i*) + *N*_{*l*} (*i*) + *N*_{*l*} (*i*) + *N*_{*l*} (*i*) + *R₂* \/ *Njf^j* (*MR*(*i*)*, R*² (*i*)) azor Shar $\bigcap_{n\geq0}$ *N*! and the signal terms of the signal terms o *N*! *i*=1^X *j*2SM and the signal terms of the si

L^b =

*^j*2SM *N^j*]

N!

*^j*2SM *N^j*]

 \mathbb{P}^{\mathbb

M^R and *R*². The full likelihood for the background-only hypothesis can be written,

L^b =

L^b =

*^j*2SM *N^j*]

Y

Njf^j (*MR*(*i*)*, R*²

(*i*))

(*i*))

Njf^j (*MR*(*i*)*, R*²

Njf^j (*MR*(*i*)*, R*²

(*i*))

!

Njf^j (*MR*(*i*)*, R*² (*i*)) azor Shar $\bigcap_{n \geq 0} \bigcup_{i=1}^n A_{i,n} = 1$ *N*! *i*=1^X Razor Shape Analysis *N*_{*N*} (*i*) + *N*_{*l*} (*i*) + *N*_{*l*} (*i*) + *N*_{*l*} (*i*) + *R₂* \/ January 21, 2013 January 21, 2013 January 21, 2013

The Restriction Computer Duarte Caltech *|p* ~*j*1*|* = *|p F*
ts are ck and the signal based on *^j*2SM *N^j*] NC
J bac
mc *n*_g₁ Currently definity is
a *i* deled by 1 or 2 instances of $f_j(M_R, R^2) = (k_j)M_R - (M_{R,j}^0)(R^2 - R_0^2)$ \sim even density density \sim $\begin{array}{c|c} -5 \\ -10 \end{array}$ *R,j*)(*R*² *^R*² $\sum_{0.5}$ -20
 500 $\frac{1}{2}$ $\frac{1}{2}$ R^2 log *f^j* (*MR, R*² M_B 2500 the momenta of the second was carefully Γ exp[*N^s* ^P *i*n ead *N*! *sea* or abod on repton bontont
each box, each SM
und probability density is $\frac{1}{2}$ box, each SM *Njf^j* (*MR i, R*² *i*) 1-1 IN EXECUTE BOX, for each background, the probability may be approximated by the probability of $\mathbb{R}^{n\times n}$ by the 2D Razor Function $\left| \log f_j(M_R, R^2) \right|$ *R,j*)(*R*² *^R*² ⁰*,j*) 1] ⇥ exp[*k^j* (*M^R ^M*⁰ *R,j*)(*R*² *^R*² θ ,g. j = ttbar, W/Z+jets, etc. 500 ^R $\overline{)000}$ $\frac{1}{200}$ $\frac{1}{200}$ $\frac{1}{200}$ $\frac{1}{200}$ $\frac{1}{200}$ $M_{\rm B}$ 2000 2500 $^{10.2}$ μ _{*f}* ^{14}R , 11 10 , 11 10 10 11 10 11 10 11 10 11 10 11 10 11 10 11 10 11 10 11 10 11 $\frac{1}{\sqrt{10}}$ **based on lepton content** *N*! $\overline{1}$ $\frac{1}{2}$ *j*2SM *Njf^j* (*MR i, R*² background probability density is **will-ELE** modeled by 1 or 2 instances of $-1]$ $\times \exp[\frac{1}{k_j} (M_R - M_{R,j}^0)(R^2 - (R_{0,j}^2))]$ \sqrt{a} \int *j* $\frac{1}{2}$ $\left| \frac{R_{0,j}^2}{2} \right|$ $\left[\frac{R}{R,j} \right]$ $\left[\frac{R_{0,j}^2}{R_{0,j}} \right]$ fit parameters of bkgd model *M^R* = (*|p* ~*^j*¹*|* + *|p* [~]*^j*²)² (*p^j*¹ *^z* + *p^j*² *^z*)² *M^R ^T* ⌘ *^T* (*p^j*¹ $f(x) = f(x)$ *^T*) *E* MU-ELE MU-MU)<mark>(ELE-ELE</mark> MU | ELE **HAD** Razor Shape Analysis
Events are classified in 6 disjoint boxes In each box, each SM *f^j* (*MR, R*² Dackground probability density ⇥ exp[*k^j* (*M^R ^M*⁰) *M^R R*² -5 $\begin{bmatrix} -10 \\ -15 \\ -20 \end{bmatrix}$ 500 ₁₀₀₀ $\frac{1}{2}$ *j*2*|* [~]*^j*²)² (*p^j*¹ \mathbb{Z} \mathbb{Z} ² \mathbb{Z} Caltech *^T* ⌘ 2 *R* ⌘ **M**
Representation of *T M^R* j indexes the SM background, $\begin{array}{|c|c|c|c|c|}\hline & & & & \\\hline & & & & \\\hline & & & & & \\\hline & & & & & & \\\hline & & & & & & & \\\hline & & & & & & & & \\\hline & & & & & & & & \\\hline \end{array}$ *n* replure content
N replure can *^j*2SM *N^j*] UU|
'''' II
tv is *Njf^j* (*MR*(*i*)*, R*² (*i*)) **1** \mathbf{r} \mathbf{p}^2 *^j*2SM *N^j*] *N*! *i*=1 $\times \exp[\frac{-k_j}{M_R} - \frac{M_{R,j}^{\circ}}{M_R}] (R^2 - R_{0,j}^2)$ *i*) $\begin{array}{c|c} -10 & \diagup 15 & \diagdown 0.5 \end{array}$ $\begin{array}{c} -20 \ \end{array}$ *f*_{*z*000} $\overline{}$ $\begin{bmatrix} k_j \end{bmatrix} \frac{M_R^0}{M_R^0}$ $\sqrt{2}$ log *f^j* (*MR, R*²) *M^R R*² *l*_b λ exp[^P *^j*2SM *N^j*] Y *N*! *i*ontent
SM
density i: *Njf^j* (*MR*(*i*)*, R*² (*i*)) . . .
!! !! $\int (M - D^2)$ *^j*2SM *N^j*] *N*! $\overline{}$ *i*=1 *Nsfs*(*MR*(*i*)*, R*² $\overline{R^2}$ In each box, for each background, the probability density may be approximated $\begin{array}{c} -20 \\ 500 \end{array}$ $\frac{1500}{20}$ $\frac{1}{2500}$ (0.2) $\frac{k}{2500}$ $\left| k_j \right| \left| M_{R,j}^0 \right| \left| R_0^2 \right|$ log *f^j* (*MR, R*²) *M^R R*² 20X, run cun
2006 CN *^j*2SM *N^j*] *N*! *Njf^j* (*MR*(*i*)*, R*² (*i*)) |
E M_R, R^2 \sqrt{N} *^j*2SM *N^j*] *N*! \times exp $\left[$ $\frac{K_j}{M_R} - \frac{M_{R,j}^2}{M_{R,j}}(K - \frac{K_{0,j}^2}{M})\right]$ In each box, for each background, the probability density may be approximated $\begin{array}{c} -20 \\ 500 \end{array}$ *f*_{$\frac{1}{2500}$ (0.2)} $\left| k_j \right|{M}_{R,j}^0 \left| {R}_{0,k}^2 \right|$ **R,j** (*R*2 *R*2 *R2 R2 R2* ⁰*,j*)] log *f^j* (*MR, R*²) *M^R R*²

M^R and *R*². The full likelihood for the background-only hypothesis can be written,

*^j*2SM *N^j*]

Y

L^b =

*^j*2SM *N^j*]

*^j*2SM *N^j*]

 \mathbb{P}^{\mathbb

N!

Njf^j (*MR*(*i*)*, R*²

(*i*))

California Institute of Technology JI UTIVITIU Razor Unbinned Likelihood

The Razor 2010 likelihood is an analytic function in the Razor 2010 in the Razor and Arthur Mathematical *M^R* and *R*². The full likelihood for the background-only hypothesis can be written, An unbinned, extended maximum likelihood fit is performed in a sideband fit region, and extrapolated

R,j)(*R*² *^R*²

$$
\mathcal{L}_b = \frac{\exp[-\sum_{j \in \text{SM}} N_j]}{N!} \prod_{i=1}^N \left(\sum_{j \in \text{SM}} N_j f_j(M_{R(i)}, R_{(i)}^2) \right)
$$

i indexes an event in the dataset

 $\Delta t = \frac{1}{2} \pi r^2$ $f_j = \text{prob. density } p$ *N*! f_j = prob. density per SM bkgd. y per
vent o *Nsfs*(*MR*(*i*)*, R*² *N* = total number of events *N_j* = expected yield per SM bkgd R^2 _(i), $M_{R(i)}$ = per-event observables

⁰*,j*) 1]

Razor Fit Results significant discrepancy is observed between the data and the fit model in any of the six boxes

 E vents/ (0.013)

Figure 1: Projection of the 2D fit result of the 2D fit results of the MR (1) and *R*₂ (right) for the Had box. The box. histogram is the total standard model prediction as obtained from a single pseudo-experiment backgrounds described by sum of $\mathcal S$ PDFs of the form Sum of W/Z+jets and tt+jets exp[*N^s* ^P $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ *M*_{*S*} *M*_{*z*} *I*_{*r*} *M*_{*R*} *I*_{*r*} *I*_{*r}* $\overline{2}$ by the 2D Razor Function

$$
f_j(M_R, R^2) = [k_j(M_R - M_{R,j}^0)(R^2 - R_{0,j}^2) - 1] \n\begin{array}{c|c}\n\text{HAD} & 68\% \text{ range} & \text{mode} & \text{median} & \text{observed} & \text{p-value} \\
\hline\n\text{SR1} & (0, 0.7) & 0.5 & 0.5 & 0 & 0.99 \\
\text{SR2} & (0, 0.7) & 0.5 & 0.5 & 0 & 0.99 \\
\hline\n\text{SR2} & (0, 0.7) & 0.5 & 0.5 & 0 & 0.99 \\
\hline\n\text{SR3} & (45, 86) & 73 & 69 & 74 & 0.68 \\
\hline\n\text{SR4} & (4, 15) & 9.5 & 10.5 & 20 & 0.12\n\end{array}
$$

Figure 2: The p-values corresponding to the observed number of events in the HAD box signals in the HAD bo

regions (SRI<u>). The green region indicates the fit region indicates the fit region (FR) in the HAD box.</u> Similar results are such as the fit region of $\sqrt{2}$

predictions is drawn in these projections.

Signal + Background Likelihood *L^b* = + Backgrd rour *Njf^j* (*MR*(*i*)*, R*² (*i*)) $\sqrt{ }$ *California Institute of Technology* J ian \top Do \Box $\mathcal P$ is an analytic function in the Razor $\mathcal P$

M^R and *R*². The full likelihood for the background-only hypothesis can be written,

 h the ckaround hypothesis is formed f An unbinned, extended likelihood for the signal +background hypothesis is formed from the sum *M^R* and *R*². The full likelihood for the background-only hypothesis can be written, *^j*2SM *N^j*] *M^R* and *R*². The full likelihood for the background-only hypothesis can be written, ba expression is the set of \mathcal{P} *N*! \sqrt{r} *NUMBER SERVISOR in*
ypoth *Njf^j* (*MR*(*i*)*, R*² (*i*))

Department of Physics

$$
\mathcal{L}_{s+b} = \frac{\exp[-N_s - \sum_{j \in \text{SM}} N_j]}{N!} \prod_{i=1}^N \left(N_s f_s(M_{R(i)}, R_{(i)}^2) + \sum_{j \in \text{SM}} N_j f_j(M_{R(i)}, R_i^2) \right)
$$

signal
signal
+
background

$$
\sum_{\substack{0.5 \text{odd } n_1 \text{ odd } n_2 \text{ odd } n_3 \text{ odd } n_4}}^{0} \left(N_s f_s(M_{R(i)}, R_{(i)}^2) + \sum_{j \in \text{SM}} N_j f_j(M_{R(i)}, R_i^2) \right)
$$

$$
\sum_{\substack{n_1 \text{odd } n_2 \text{ odd } n_3 \text{ odd } n_4 \text{ odd } n_5 \text{ odd } n_5 \text{ odd } n_6 \text{ odd } n_7 \text{ odd } n_8 \text{ odd } n_9 \text{ odd } n_9 \text{ odd } n_9 \text{ odd } n_1 \text{ odd } n_1 \text{ odd } n_2 \text{ odd } n_3 \text{ odd } n_4 \text{ odd } n_5 \text{ odd } n_6 \text{ odd } n_7 \text{ odd } n_8 \text{ odd } n_9 \text{ odd } n
$$

|p

^T ⌘

~*j*1*|* = *|p*

~*j*2*|*

^T) *^E*[~] miss

^T ·(*p*~*^j*¹

R ⌘

M^R

q

Caltech

^z + *p^j*²

^z)² *M^R*

Limit Setting The Razor 2D likelihood is an analytic function in the Razor \mathcal{L} is an analytic function in the Razor kinematic variables in the Razor kinematic variables in the Razor kinematic variables in the Razor kinematic varia *M^R* and *R*². The full likelihood for the background-only hypothesis can be written, *N* ! Marginalized limit C and the signal-background hypothesis can be written by written \Box (*i*)) Limit Sett atting
ands as *limit N*
 N Iikelihod *Njf^j* (*MR*(*i*)*, R*² *<u>jmit Setting</u> I* I:1.

i=1

We use the ratio of *marginal* likelihoods as the test statistic, evaluated on data in the signal region \overline{C} *N*! **i**
margir *Njf^j* (*MR*(*i*)*, R*² (*i*)) *l* We use the ratio of *r* We use the ratio of *marginal* likelihoods as the test $\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 &$ $\frac{d}{dx}$ *K z s i* (*i*) $\frac{d}{dx}$ *f* (*i*) $\frac{d}{dx}$ (*i*) $\frac{d}{dx}$ *f* (*n*) $\frac{d}{dx}$ L *L We use the ratio of marginal* likelihoods as the test \log $\left(\frac{1}{2} \right)$ $\overline{}$ s $\overline{}$ s $\overline{}$ *N*! *lihoc* $\frac{1}{1}$ as the test e tes

Njf^j (*MR*(*i*)*, R*²

$$
\mathcal{L}_{s+b} = \frac{\exp[-N_s - \sum_{j \in \text{SM}} N_j]}{N!} \prod_{i=1}^N \left(N_s f_s(M_{R(i)}, R_{(i)}^2) + \sum_{j \in \text{SM}} N_j f_j(M_{R(i)}, R_i^2) \right) \bigg|_{\text{as}}^{\text{as}} \bigg|
$$

$$
\mathcal{L}_{s+b}^{(m)} = \int \mathcal{L}_{s+b} d\nu_b d\nu_s
$$

Done *numerically*, by varying the distributions of the signal and background in pseudo-experiments according to the nuisance parameter priors* $\int f(x) \, dx$ ⇥ exp[*k^j* (*M^R ^M*⁰ *R,j*)(*R*² *^R*² ⁰*,j*)] *r*ound signal and background in pseudo-experiments \mathcal{L} and \mathcal{L} and \mathcal{L} and \mathcal{L} and \mathcal{L} and \mathcal{L} and \mathcal{L} k . Λ the dis according to the nuisar $\frac{1}{2}$

 \tilde{C} $\frac{1}{\sqrt{2}}$ blod fit parameter \bullet *D* \bullet DNgu in parameters \prime ⁰ j \prime \cdot \prime R , j \prime \cdot \cdot \cdot \cdot \cdot according to the nuisance parameter priors*
 ν_b bkgd fit parameters k_j $M^0_{R,j}$ $R^2_{0,j}$ etc. ν_{s} bkgd fit parameters ν_{s} *jet energy scale L*(*m*) $\boldsymbol{\nu}_{\boldsymbol{b}}$ bkgd fit parameters $\;k_j\;\;M^0_{R,j}\;\;R^2_{0,j}\;$ etc. bkgd fit parameters k_j $M_{R,j}^{\circ}$ $R_{0,j}^2$ etc.

log *f^j* (*MR, R*²

 ν_s a in parameters $v_j - k_j$ $v_{0,j}$ ord.
Phergy scale, PDFs, etc. \overline{b} *L*(*m*) jet energy scale, PDFs, etc.

*More on

*r*₂, etc. $\frac{1}{2}$ *More on this procedure later

⁰*,j*)]

R,j)(*R*² *^R*²

) *M^R R*²

) *M^R R*²

log *f^j* (*MR, R*²

 \ldots called and \ldots

i=1

and the signal-background hypothesis can be written by α background hypothesis can be written by α

i=1^X

*j*2SM

R,j)(*R*² *^R*²

*j*2SM

⁰*,j*) 1]

*^j*2SM *N^j*]

⁰*,j*) 1]

) *M^R R*²

R,j)(*R*² *^R*²

R,j)(*R*² *^R*²

⇥ exp[*k^j* (*M^R ^M*⁰

2011 Razor Limits \overline{A} relevant SM backgrounds as a function of *R*² ⁴⁶¹ and *MR*. This function is proved to model the correlation between *R*² ⁴⁶² and *MR* in the region under study to a good precision in the Monte ⁴⁶³ Carlo, much higher than the precision of the fit used to predict the shape of the backgrounds

20 11 Summary

from data. Assuming the modeling of the *R*² ⁴⁶⁴ vs *MR* implied by the 2D function is correct, a 2D

p
*p*₂
z p^{*i*}*n*² **7** T *^T* (*p^j*¹ *^T* + *p^j*² **Razor Binned Likelihood** *zor* Binned Likelihoo \overline{OC}

*E*miss

Since CMS data is not public, unbinned likelihood is of limited use \vert Instead, one can construct an binned likelihood as the product of \vert many independent poisson likelihoods data is not public, unbinned likelinood is of limited use one can construct an binne

$$
\mathcal{L}_{s+b}^{(m)} = \prod_{\text{bin }i} \int \text{Poisson}(n_i|s_i, b_i) \pi(b_i|\bar{b}_i, \delta b_i) db_i
$$

⇡ = Gamma*,* Gaussian*,* LogNormal*,* etc. your choice of prior \sim œ 0.45 0.5 Mean expected background count is marginalized with Gamma, Gaussian, LogNormal, etc. $\frac{10 \text{ m}}{4 \text{ s}}$

^T) *E*

s

 \sim mission is a mission of \sim

^T ·(*p*

^T + *p^j*²

(*|p*

~*^j*¹*|* + *|p*

Additional Information - Razor Analysis arXiv:1202.1503 twiki.cern.ch/twiki/bin/viewauth/CMSPublic/RazorLikelihoodHowTo and IsoSum*<* 2GeV for *p^T <* 20 GeV *•* 2 reconstructed jets, *p^T >* 30 GeV $\frac{7}{1202}$ 1503 or *E*miss *^T >* 20 GeV (*eµ*) M

˜ *< m*˜ + *m^t*

mt

Ω Ω Ω ¹ Ω ¹ *Mq*˜ *• R*² *>* 0.18, *M^R >* 400 GeV (Had) ˜ *< m*˜ + *m^t*

- 2, jets with $p_T > 60$ GeV, cluster all jets ($p_T > 40$, $|\eta| < 3.0$) into megajets
- $R^2 > 0.18$, $M_R > 400$ GeV (Had)

• Electronic Electronic

 700

600

500

400

300

200

 100

 $\mathbf{M}_{1/2}$ [GeV]

second lepton *p^T >* 10 GeV

- Tight electron ($p_T > 20$, $|\eta| < 2.5$), Loose electron ($p_T > 10$, $|\eta| < 2.5$)
- Tight muon ($p_T > 15$, $|\eta| < 2.1$), Loose muon ($p_T > 10$, $|\eta| < 2.1$)

 $Cies$ f

sel. efficiencies for CMSSM

1500

2000

1000

 M_0 [GeV]

- MuEle: one Tight electron, one Tight muon
- *•* MuMu: one Tight muon, one Loose muon

CMSSM tan_{ß=10} HAD Box

• Ele: one Tight electron

• Mu: one Tight muon

 $\frac{1}{2}$ -20 $\frac{1}{2}$ -20 $\frac{1}{2}$

 $CMSSM$

• EleEle: one Tight electron, one Loose electron *•* Had: all other events

clearly specified selection
and observed violds and observed yields *•* 2, jets with *p^T >* 60 GeV, cluster all jets (*p^T >* 40*, |*⌘*| <* 3*.*0) into megajets *•* Tight electron (*p^T >* 20*, |*⌘*| <* 2*.*5), Loose electron (*p^T >* 10*, |*⌘*| <* 2*.*5)

F $\sum_{\substack{a \text{ s} \ \text{ s} \ \text{ s}}}$ is a set of a binned error into a binned error into account the predicted error of $\sum_{\substack{a \ \text{ s} \ \text{ s} \ \text{ s} \ \text{ s}}}$ likelihood function

 $\mathcal{L}^{(m)}_{s+b} = \prod$ bin *i* z
Z $\text{Poisson}(n_i|s_i, b_i) \pi(b_i|\bar{b}_i, \delta b_i)db_i$

500

Validation and Combination of Razor Binned Likelihood ⁷

FR Reinterpretation for light stops for dark matter (DM), and *(iv)* give observable signals at LHC14. In this special window, t_{max} supersymmetric mass $\sum_{i=1}^{n}$ is $\sum_{i=1}^{n}$ ˜ ! `⌫`*bN decays and ^m^t* ˜ *M*DM = 30 *GeV. Even if this case is the most favorable for the selection of leptonic final states, the hadronic* ˜ *M*DM*.* nents as well as the total, the event yield, and the observed 95% confidence level upper limit on the number of non-SM events (*NUL*) calculated under three different assumptions for the event efficiency uncertainty (see the number of the number of the number of the \mathbf{N} line of the table includes both tagged and untagged jets. ntarnratation for light stops to. These considerations suggest that the Had box is the only relevant sample to consider in the only relevant sample posterior is obtained as the product of the posteriors in each of the bins provided in [34]. two analyses. The 95%-probability limit is obtained integrating the posterior from 0 up to

arXiv:1212.6847 No. of b-tags 2 2 2 2 2 2 2 3 2

m

Dr $\overline{3}$ \sim \sim $\frac{1}{2}$ \sim Search for right-handed stop with Charge-flip BG 1.4 *±* 0.3 1.1 *±* 0.2 0.5 *±* 0.1 0.05 *±* 0.01 0.3 *±* 0.1 0.12 *±* 0.03 0.03 *±* 0.01 0.008 *±* 0.004 0.20 *±* 0.05

 \mathbf{C} \overrightarrow{C} V $\begin{array}{ccc} m_{\tilde{t}} & m_{\tilde{t}} \end{array}$ $m_{\tilde{t}_1} = 200–400\,{\rm GeV}$ $\frac{100.7}{100}$ 1.0 ∴ **±** 1.0 **±** 1.0 **±** 1.5 *±* 1.0 0.6 $\frac{1}{2}$ 1.5 *±* 1.4 $\frac{1}{2}$ $m_{\tilde{\ell}} = 211111172$ N_{11} $-$ 200 100 00 $\sqrt{ }$ $\frac{1}{2}$

> Motivated by LHC data and flavor constraints, RG equations, and thermal abundance for DM $\begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$ $\begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$ equations, and thermal abundance for DM ciency uncertainty is discussed in Section 6. This uncertainty is discussed in Section 6. The section 6. The s

Table 1: A summary of this search. For each signal region (SR), we show its most most most most most most most

1

(i) are well consistent with all collider data and flavor constraints, *(ii)* naturally emerge

produced stop events as a function of the stop mass, for t

box is the most populated due to the small value of m^t

10
10
10 **• The mostly department of the stop has a much larger mass (in the 1–2 TeV range), stop in the 1–2 TeV range), stop** $\overline{\mathbf{r}}$ **ranged mass (in the 1–2 TeV range), stop** $\overline{\mathbf{r}}$ **ranged mass (in the 1–2 TeV range), stop 100** Generated pair-produced stops with $\frac{z}{100}$ and $\frac{z}{20}$ and $\frac{z}{20}$ our analy implemented and razor and razor and leptons. Based on generator-level jets and leptons. Based on generator-lev **6** Generated pair-produced stops with $\mathbb{E}[\mathbf{e}_1, \mathbf{e}_2, \mathbf{e}_3]$ are collected with distribution triggers. The effective is mea- \blacktriangledown • Pythia 8, clustered into jets with FastJet

$$
\tilde{t} \rightarrow \ell \nu_{\ell} b N.
$$

3

2 Applied lepton efficiencies and the mission of the miss \mathbf{A} is also well requirement on leptons in Z events in Z events is also well reproduced by the simulation. However, \mathbf{A} $\mathcal{S}(\mathcal{S})$ events with hadronic case than in Z events. To account for this variation, we take a set of this variation, we take a set of the **From SS Dilepton** in the acceptance of signal events.

from RG evolution of simple UV completions, *(iii)* predict the correct thermal abundance

the signal cross section and is the signal cross section. In the case of the razor analysis, the actual cross section. In the actual cross section, the actual cross section. In the actual cross section, the actual cross

production cross section much larger than for Dark Matter direct detection. At the same

(2012) **Contract Contract Derived posterior probability on** extends both the 1D and 2D and 2D

$$
\begin{array}{cc}\n\cdot & \scriptscriptstyle \text{electrons} \\
\cdot & \scriptscriptstyle \text{muons} \\
\hline\n\text{no no 120 140 160 180 200}\n\end{array}\n\quad\n\begin{array}{c}\n\bar{P}(\sigma) = \int_0^\infty db \int_0^1 d\epsilon \frac{(b + L\sigma\epsilon)^n e^{-b - L\sigma\epsilon}}{n!} \text{Ln}(\epsilon|\bar{\epsilon}, \delta_\epsilon) \text{Ln}(b|\bar{b}, \delta_b)\n\end{array}
$$

Recap of Uses $\overline{}$

150

 \mathbf{G} │
│ arXiv[,] 1206.0 **T** $\left| \begin{array}{c} \n\text{or} \\ \n\text{or} \\ \n\end{array} \right|$ arXiv:1206.0264

150

• 2 reconstructed jets, *p^T >* 30 GeV

BayesFITS combination of Razor with Higgs, $B_s \rightarrow \mu\mu$, etc. to derive posterior probabilities in CMSSM I *ton* $T \cap \mathsf{C}$ \sum_{α} 200 n *n* ith \cup $n \, dr$

Reinterp. for very light stops* 150 150 *M^R* ⇠ *Mq*˜

 \overline{C} 300 *Used a coarser binned likelihood

50 Wednesday, January 23, 13 33

(a) (b) (b) (b) (b) (b) (b) Figure 2: Marginalized posterior pdf in (a) the (*m*0, *m*1*/*2) plane and (b) the (*A*0, tan) plane of the CMSSM, constrained in Table II. The experiments listed in Table II. \sim abyorder in the \sim ~ degen. with neutralino aintarn : Reinterp. for light stops,

 $\mathcal{L}^{\mathcal{L}}(\mathcal{L}^{\mathcal{L}})$ is a subset of $\mathcal{L}^{\mathcal{L}}$

bound.

Example: Search for contact interactions in jet pT spectrum

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Contact Interactions The experimental results are interpreted in terms of a CI model described by the effective Lawhere \sim 1 or 1 \sim 1 or 1 \sim 0 \sim 0 \sim constructively or const **Let us amplitude for interactions** contact interactions ^L² (*q*¯*Lg^µqL*)(*q*¯*LgµqL*), (1) \sim \sim \pm C ^{*l*} Interactions $h \rightarrow h \rightarrow h$ \overline{a} t Interactions

²⁹ **2 Theoretical models** m ass scale Λ New quark-gluon physics at a high mass scale Λ $\frac{1}{2}$ *interaction* where $\frac{1}{2}$ denotes a left-handed and $\frac{1}{2}$ mass scale Λ where *quark-gluon physics at a high* and α = α interfering and an projective array. interfering are in production and amplitude for an amplitude for $\log n$

→ effective 4-fermion interaction and Reparametrize *a* \blacksquare *l**n* \blacksquare \blacksquare \blacksquare **⇒** effective 4-fermion interaction

-1

$$
L = \zeta \frac{2\pi}{\Lambda^2} (\bar{q}_L \gamma^\mu q_L) (\bar{q}_L \gamma_\mu q_L) \qquad \lambda = 1/\Lambda^2
$$

 α Reparametrize Reparametrize *a* = *a*SM + *l a*CI

destructive constructive $u = u_{\rm SM} + \lambda u_{\rm CL}$ age *s^k* = *ck* + *bk l* + *ak l*² *s^k* = *ck* + *bk l* + *ak l*²

 α proportional to cross section proportional to $\Rightarrow \sigma_k = c_k + b_k \lambda + a_k \lambda^2$ squared amplitude $\sigma_k =$

$$
+1
$$

factor of the probability

cross section proportional to
\nsquared amplitude
\n
$$
\sigma_k = c_k + b_k \lambda + a_k \lambda^2
$$
\n
$$
QCD_{\rm NLO}
$$
\n
$$
CI(\Lambda)
$$

+1

 $\begin{array}{ccc} & & L \\ & & \end{array}$

²⁹ **2 Theoretical models**

 $g_{\rm 3, 17}$ (3, 17) $g_{\rm 3, 17}$ (3, 17) $g_{\rm 3, 17}$ (3, 17) $g_{\rm 3, 17}$

, (2)

, and the set of $\mathcal{L}(\mathcal{L})$, and the set of $\mathcal{L}(\mathcal{L})$, and the set of $\mathcal{L}(\mathcal{L})$

Statistical Model simultaneously to four PYTATISTICAL INTO THE 19 \bigcup this manner in order the four the four cross section ratios. See \bigcup $\overline{\mathbf{A}}$ \mathbf{A} \mathbf{A} \mathbf{A} 1111 Statistical Model ¹⁰⁶ In the search region, the inclusive jet spectrum has a range of five orders of magnitude, which ¹¹¹ we achieve by using a multinomial distribution, which is the probability to observe *K* counts, ¹¹⁰ to sidestep the issue of normalization by considering only the shape of the jet *p*^T spectrum. This ¹¹¹ we achieve by using a multinomial distribution, which is the probability to observe *K* counts,

(right).

 1099 ± 0.000 to change by as 50 ± 0.000 to change of computing limits, we have chosen of computing limits, we have chosen \sim

 1099 ± 0.000 to change by as 50 ± 0.000 to change of computing limits, we have chosen of computing limits, we have chosen \sim

Handling Nuisances ³¹⁹ QCDNLO as described in Section 5.1 to obtain parameter values for *p*1, *p*2, *p*3, and *p*4. Five hun-³²⁰ dred sets of these parameters are generated, constituting a discrete approximation to the prior ⁸⁹ In Figure 4 we compare the observed inclusive jet *p*^T spectrum with the NLO QCD jet *p*^T spec- S o trum, which is non-malized total observed in the search region using the search region using the S ization factor 4.007 *[±]* 0.009 (stat.) fb¹ ⁹¹ (Section 5). The normalization is the ratio of the observed \mathcal{S} is the predicted cross section in the search region. The prediction are in the prediction are in the prediction are in the prediction \mathcal{S}

³²¹ *p*(*w*) ⌘ *p*(*p*1, *p*2, *p*3, *p*4). of **correlated** background and signal spectra, in which parameters vary randomly a method of the state of the Likelihood is marginalized discretely by creating ensemble Pr(KS) of 0.66 and the *c*² ⁹⁴ per number of degrees of freedom (NDF) of 23.5/19. Table 2 lists ekarouna and signal spectra. In which contains with destructive interference. Figure 6 ⁹⁷ compares the data with models with constructive interference.

> PDFs factorization scale Ω $\overline{}$

⁸⁸ **4 Results**

323 unit below the position of $p(D|\lambda)$ Refit resulting distributions 500 times, arrive at a discrete approximation of marginal model $p(D|\lambda) = \int p(D|\lambda, \omega) \pi(\omega) d\omega$, $^! \cap$ $\overline{}$ Figure 4: The observed jet *p*^T spectrum compared with the NLO QCD jet *p*^T spectrum (left). The

 318.818 randomly. The ansatz in Eq. (4) is the ansatz in Eq. (4) is the quartet of ratios α

model
$$
p(D|\lambda) = \int p(D|\lambda, \omega) \pi(\omega) d\omega,
$$

$$
\approx \frac{1}{M} \sum_{m=1}^{M} p(D|\lambda, \omega_m),
$$

Results

Set 95% lower limits of 9.9 TeV $\int_{\mathcal{D}} |v(x)|^2 dx$ OET 3.3 IGM and the central values of all nuisance parameters. The solid curve is the likelihood (destructive) and 14.3 TeV (constructive) $-2\log\left(\frac{p(x|\lambda)}{p(x|0)}\right)$
preing ratio of marginal model and CL₂ using ratio of marginal model and CL_s

Summary and Outlook

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Summary and Outlook

- CMS BSM searches use a variety of likelihoods and handle nuisances / compute limits in different ways
	- Bayesian (Marginalize), Frequentist (Profile), Hybrid
- Several analyses provide public likelihoods and details for generator-level study of your own BSM model
- Even in cases where full model are not provided, one can derive an approximate likelihood
- Working to provide public likelihoods in future CMS BSM analyses
	- Razor Analysis will provide full details and code to implement binned likelihood in python

