Top and Higgs Tagging

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Bonn 06/2012

Fat jets

Boosted particles at the LHC

1994 boosted $W \to 2$ jets from heavy Higgs [Seymour]

1994 boosted $t \to 3$ jets [Seymour]

2002 boosted $W \to 2$ jets from strongly interacting WW [YSplitter: Butterworth, Cox, Forshaw]

2006 boosted $t \to 3$ jets from heavy resonances [Agashe, Belyaev, Krupovnickas, Perez, Virzi]

2008 boosted $H \to b\bar{b}$ [Butterworth, Davison, Rubin, Salam]

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2009 boosted $t \to 3$ jets in Higgs production [TP, Salam, Spannowsky]

2010 boosted $t \to 3$ jets from top partners [HEPTopTagger: TP, Spannowsky, Takeuchi, Zerwas]

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2012 stop searches at 8 TeV [HEPTopTagger]

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Jet Algorithms

Definition of jets

– jet–parton duality $\Leftrightarrow$ what are partons in detector?

– need algorithm to reconstruct what was one parton [IR save recombination algos]

– crucial for any LHC analysis

Different measures [FASTJET: Cacciari, Salam, Soyez]

– define jet–jet and jet–beam distance [and resolution y_{cut}]

$$\begin{aligned}
&k_T && y_{ij} = \frac{\Delta R_{ij}}{D} \min\left(p_{T,i}, p_{T,j}\right) && y_{iB} = p_{T,i} \\
&\text{C/A} && y_{ij} = \frac{\Delta R_{ij}}{D} && y_{iB} = 1 \\
&\text{anti-}k_T && y_{ij} = \frac{\Delta R_{ij}}{D} \min\left(p_{T,i}^{-1}, p_{T,j}^{-1}\right) && y_{iB} = p_{T,i}^{-1} \; .
\end{aligned}$$

– (1) find minimum $y_{\text{min}} = \min_{kl}(y_{kl}, y_{kB})$
(2a) if $y_{\text{min}} = y_{kl} < y_{\text{cut}}$ combine k and l, go to (1)
(2b) if $y_{\text{min}} = y_{kB} < y_{\text{cut}}$ remove k, go to (1)
(2c) if $y_{\text{min}} > y_{\text{cut}}$, done

– theoretical and experimental trade-off decisions

– fat jets: use clustering history

Analysis 1: $VH, H \to b\bar{b}$

New strategy for $H \to bb$ [Butterworth, Davison, Rubin, Salam]

- desperately needed [2/3 of all light Higgses; impact SFitter-Higgs]
  but killed by continuum $Vb\bar{b}$ background
- S: large m_{bb}, boost-dependent R_{bb}
  B: large m_{bb} only for large R_{bb}
  S/B: go for large m_{bb} and small R_{bb}, so boost Higgs
- fat Higgs jet $R_{bb} \sim 2m_H/p_T \sim 0.8$ [like b tag for now]
- $q\bar{q} \to V_\ell H_b$ sizeable in boosted regime [$p_T \gtrsim 300$ GeV, few % of total rate]

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$\Rightarrow$ best performance: C/A algorithm

jet definition	σ_S/fb	σ_B/fb	$S/\sqrt{B}_{30}$
C/A, $R = 1.2$	0.57	0.51	4.4
$k_\perp$, $R = 1.0$	0.19	0.74	1.2
SISCone, $R = 0.8$	0.49	1.33	2.3

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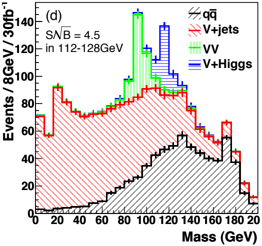
Bottom line, details later

- combined channels $V \to \ell\ell, \nu\nu, \ell\nu$
- NLO rates [bbV notorious, not from data alone]
- Z peak as sanity check
- checked by Freiburg [Piquadio]
  subjet b tag excellent [70%/1%]
  charm rejection challenging
  $m_H \pm 8$ GeV tough



Analysis 2: $t\bar{t}H, H \to b\bar{b}$

Sad story of $t\bar{t}H, H \to b\bar{b}$ [Atlas-Bonn study, CMS-TDR even worse]

– trigger: $t \to bW^+ \to b\ell^+\nu$
  reconstruction and rate: $\bar{t} \to \bar{b}W^- \to \bar{b}jj$

– continuum background $t\bar{t}b\bar{b}, t\bar{t}jj$ [weighted by b-tag]

– not a chance:
  1– combinatorics: m_H in $pp \to 4b_{tag}\ 2j\ \ell\nu$
  2– kinematics: peak-on-peak
  3– systematics: $S/B \sim 1/9$

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Fat jets idea [TP, Salam, Spannowsky]

- S/B: $R_{bb} < 1.2$; $b\bar{b}$ pair boosted [solves 1]
- boosted regime different for S and B [solves 2]
- see how far we get... [watch S/B for 3]
- cool: fat Higgs jet + fat top jet

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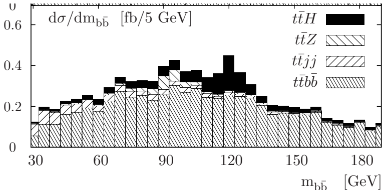
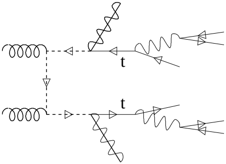
Bottom line, details later

- require tagged top and Higgs
  trigger on lepton
- remove 'Higgs' as $t_\ell \to b$ plus QCD
  3rd b tag in continuum [costing $S/\sqrt{B}$]
  only continuum $t\bar{t}b\bar{b}$ left



per 1 fb	signal	$t\bar{t}Z$	$t\bar{t}b\bar{b}$	$t\bar{t}$+jets
after acceptance	24.1	6.9	191	4160
one top tag	10.2	2.9	70.4	1457
m_{bb} window	2.9	0.44	12.6	116
two subjet b tags	1.0	0.08	2.3	1.4
third b tag	0.48	0.03	1.09	0.06

Analysis 3: stop pairs



Stop pairs including reconstruction [TP, Spannowsky, Takeuchi, Zerwas]

– stop crucial for hierarchy problem
  comparison to other top partners [Meade & Reece]

– hadronic: $\tilde{t}\tilde{t}^* \to t\tilde{\chi}_1^0 \; \bar{t}\tilde{\chi}_1^0$ [CMS: leptons as spontaneous life guards]

per 1 fb	$\tilde{t}_1\tilde{t}_1^*$						$t\bar{t}$	QCD	W+jets	Z+jets	S/B	$S/\sqrt{B}_{10\ \text{fb}^{-1}}$
$m_{\tilde{t}}$[GeV]	340	390	440	490	540	640					340	
$p_{T,j} > 200$ GeV, ℓ veto	728	447	292	187	124	46	87850	$2.4 \cdot 10^7$	$1.6 \cdot 10^5$	n/a	$3.0 \cdot 10^{-5}$	
$\not{E}_T > 150$ GeV	283	234	184	133	93	35	2245	$2.4 \cdot 10^5$	1710	2240	$1.2 \cdot 10^{-3}$	
first top tag	100	91	75	57	42	15	743	7590	90	114	$1.2 \cdot 10^{-2}$	
second top tag	15	12.4	11	8.4	6.3	2.3	32	129	5.7	1.4	$8.3 \cdot 10^{-2}$	
b tag	8.7	7.4	6.3	5.0	3.8	1.4	19	2.6	$\lesssim 0.2$	$\lesssim 0.05$	0.40	5.9
$m_{T2} > 250$ GeV	4.3	5.0	4.9	4.2	3.2	1.2	4.2	$\lesssim 0.6$	$\lesssim 0.1$	$\lesssim 0.03$	0.88	6.1

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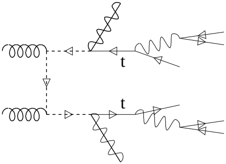

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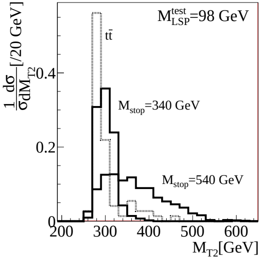
- stop mass from m_{T2} endpoint [like sleptons or sbottoms]

$$m_{T2}(\hat{m}_\chi) = \min_{\not{p}_T = q_1 + q_2} \left[\max_j \; m_{T,j}(q_j; \hat{m}_\chi) \right] \stackrel{!}{<} m_{\tilde{t}}$$

⇒ hadronic search as easy as $b\bar{b} + \not{E}_T$



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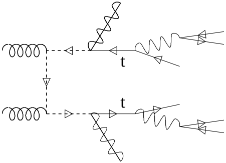

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Stop searches in 2012 [TP, Spannowsky, Takeuchi; Chicago, Hopkins,...]

1– two top tags: rate limited, really only for 14 TeV

2– top tag plus on bottom tag: better, but still no 5σ for 2012

3– top tag plus lepton: even better, maybe 5σ in 2012

per 1 fb	$\tilde{t}\tilde{t}^*$				$t\bar{t}$	$t\bar{t}Z$	W+jets	S/B	$S/\sqrt{B}_{10\text{fb}^{-1}}$
$m_{\tilde{t}}$	350	400	450	500				400	
ℓ and fat jet	145	76.5	40.6	22.1	$2.4 \cdot 10^4$	3.21	$3.7 \cdot 10^4$		
$\vec{\not{p}}_T > 100$ GeV	104	61.5	34.8	19.5	5631	2.20	8547		
$n_{\text{tag}} = 1$	13.1	9.02	5.80	3.60	789	0.33	80.5	0.01	1.0
$m_T > 150$ GeV	4.63	4.27	3.25	2.19	3.28	0.10	0.99	1.0	6.5

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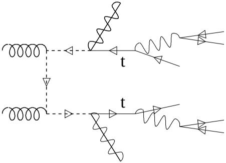

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$m_{\tilde{t}}$	350	400	450	500			400	
$n_\ell = 2$	31.0	14.3	7.07	3.58	7651	n.a.		
$\vec{\not{p}}_T > 100$ GeV	19.0	9.99	5.40	2.94	1313	0.35		
$m_{T2}^{\ell\ell} > 100$ GeV	6.05	4.30	2.70	1.65	0.65	0.09	5.8	15.8

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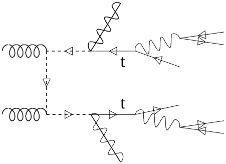

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$\Rightarrow$ there is hope!

Higgs tagger

Higgs tag for busy QCD environment [BDRS; TP, Salam, Spannowsky]

– uncluster one-by-one: $j \to j_1 + j_2$
  1– unbalanced $m_{j_1} > 0.8 m_j$ means QCD; discard j_2
  2– soft $m_{j_1} < 30$ GeV means QCD; keep j_1
– double b tag [possibly add balance criterion]
  three leading $J = p_{T,1} p_{T,2} (\Delta R_{12})^4$ vs m_{bb}
– no mass constraint — side bin
  typical mis-tag probability $< 10^{-5}$
– underlying event and pileup deadly
  filter reconstruction jets [Butterworth–Salam, cf pruning, trimming]
  zoomed-in C/A analysis with $R_\text{filt} = \min(0.3, R_{bb}/2)$
– reconstruct m_H w/ one QCD jet

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Better than traditional b jets

- no combinatorial choices
- more soft partons included in m_H
- b tagging easier than in continuum
- QCD features useful [Soper & Spannowsky]

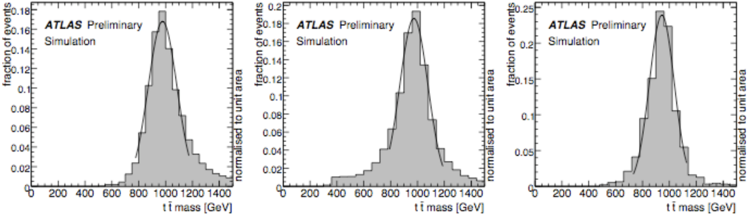
  ...

Top tagger

Highly boosted top quarks [Kaplan, Rehermann, Schwartz, Tweedie; Princeton, Seattle...]

– identify hadronic tops with $p_T \gtrsim 800$ GeV
  isolation and b tagging challenging

– ATLAS studies for semileptonic top pairs [adapted Y-splitter, full sim, ATLAS-2010-008]



(a) minimal (b) full reconstruction (c) mono-jet

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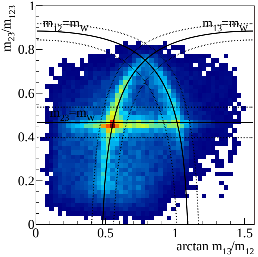
1– reconstruct $m_W = 60...95$ GeV
reconstruct $m_t = 150...200$ GeV
helicity angle $\cos\theta_{t,j_1} > 0.7$
no b tag needed

2– HEPTopTagger for $t\bar{t}$ [TP, Salam, Spannowsky, Takeuchi]
kinematic selection: $m_{jjj}, m_{jj}^{(1)}, m_{jj}^{(2)}$



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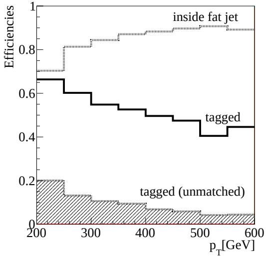

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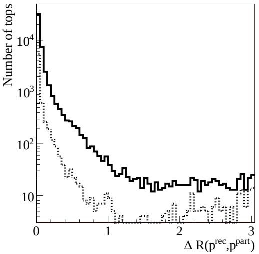

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1– reconstruct $m_W = 60...95$ GeV
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helicity angle $\cos\theta_{t,j_1} > 0.7$
no b tag needed

2– HEPTopTagger for $t\bar{t}$ [TP, Salam, Spannowsky, Takeuchi]
kinematic selection: $m_{jjj}, m_{jj}^{(1)}, m_{jj}^{(2)}$

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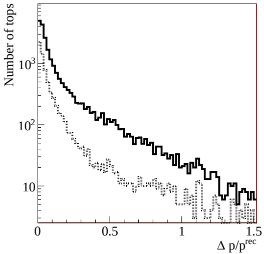

Top tagger

Highly boosted top quarks [Kaplan, Rehermann, Schwartz, Tweedie; Princeton, Seattle...]

- identify hadronic tops with $p_T \gtrsim 800$ GeV
  isolation and b tagging challenging
- ATLAS studies for semileptonic top pairs [adapted Y-splitter, full sim, ATLAS-2010-008]

BDRS-inspired top tagger [TP, Salam, Spannowsky, Takeuchi; Johns Hopkins]

- start with C/A jet [$R = 1.5$]
- uncluster one-by-one: $j \to j_1 + j_2$
  1– unbalanced $m_{j_1} > 0.8 m_j$ means QCD; discard j_2
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$\Rightarrow$ hadronic top like tagged b [used by ATLAS-HD]

Higgs 2011 and beyond

Why a 125 GeV Higgs needs SFitter [Zeppenfeld et al; Dührssen et al; SFitter 2009 & 2012]

– many parameters: Higgs couplings to $W, Z, t, b, \tau + (g, \gamma)$ [SM-like operators]

$$g_{Hxx} \equiv g_x = g_x^{\text{SM}} \; (1 + \Delta_x)$$

– many measurements: $GF : H \to ZZ, WW, \gamma\gamma$ [already 2011]
$WBF : H \to ZZ, WW, \gamma\gamma, \tau\tau$ [mostly 2012]
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Global view of 2011 data [Klute, Lafaye, TP, Rauch, Zerwas, Dührssen]

– is there a SM-like solution?
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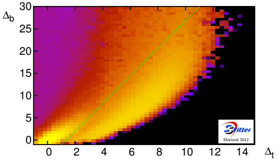

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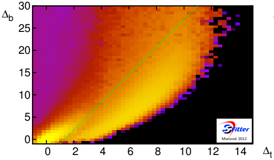
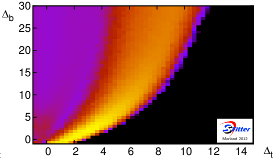
(2) measured 2011: measured central values and error bars

– solutions overlapping



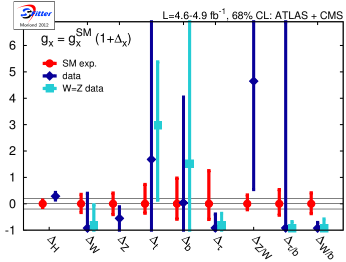


Higgs 2011 and beyond

Local view of 2011 data [Klute, Lafaye, TP, Rauch, Zerwas, Dührssen]

- focus on SM solution where possible
- five couplings from data

  $g_W \sim 0$ while $g_Z > 0$
  g_b through total width
  g_b and g_t hurt by secondary solution
  g_τ inconclusive
  g_g and g_γ requiring $t\bar{t}H$ analysis
- poor man's analysis great: $\Delta_j \equiv \Delta_H$



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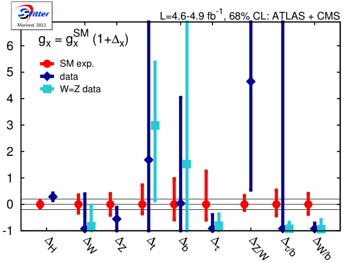


2012, 2014, etc

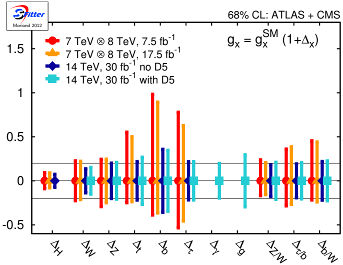
– specifially Higgs:

dark side of the Higgs portal?
new states in effective couplings?

– 2012: meaningful WBF measurements
g_W and g_τ accessible

– 2014: $t\bar{t}H$ and $H \to b\bar{b}$ measurements
g_g and g_γ accessible

⇒ exciting prospects!



Outlook

Fat jets — the most QCD fun in a long time

- VH: bringing back 2/3 of light Higgses
- $t\bar{t}H$: curing combinatorics and backgrounds
- impact on Higgs coupling analysis obvious [SFitter]

- $\tilde{t}\tilde{t}^*$: curing backgrounds
- Z': improving mass resolution ...

- HEPTopTagger code as FASTJET add-on [www.thphys.uni-heidelberg.de/˜plehn/HEPTopTagger] implemented and tested by ATLAS, improvements welcome

Notes on LHC physics: Springer and arXiv:0910.4182

Some of this work was funded by the BMBF Theorie-Verbund which is great for LHC phenomenology

Bundesministerium für Bildung und Forschung

Crucial: dealing with pileup

Filtering [BDRS, also used in HEPTopTagger]

- designed for C/A algorithm
- reduce effective fat-jet area
  zoom in on relevant final subjets
- number of jets and size negotiable

Pruning [Ellis, Vermillion, Walsh]

- designed for k_T algorithm
- extract relevant collinear splittings in splitting history
- soft/collinearity condition negotiable

Trimming [Krohn, Thaler, Wang]

- designed for anti-k_T algorithm
- remove soft fat jet regions [inverse to filtering]
  slightly different interpretation for k_T algo

- filtering + pruning useful [Spannowsky & Soper]
- should we use more/less of the clustering history?
- and can we do this with pileup?

Leptonic top tag

Leptonic tag [Thaler & Wang; Rehermann & Tweedie; TP, Spannowsky, Takeuchi]

– known: masses of top decay products
  unknown: 3-momentum of neutrino
  measured: $E_b, E_\ell, m_{b\ell}$ [rest frame]

– W and t mass constraints
  third parameter elsewhere
  do not use measured $\not{p}_T$ vector

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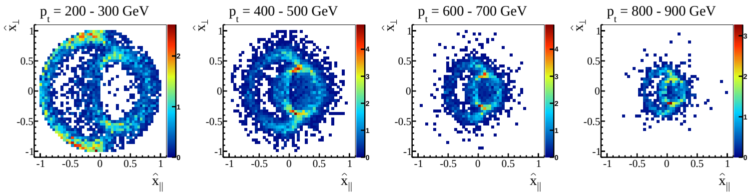
– neutrino coordinates
  leading in $b - \ell$ direction
  sub-leading in $b - \ell$ decay plane [orthogonal approx $p_\nu^{||} = 0$]
  sub-leading orthogonal to decay plane [decay plance approx $p_\nu^{\perp} = 0$]

  components $(p_\nu^{||}, p_\nu^{\perp})$



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– semileptonic top partners at LHC:

  'At the LHC, combinatorics make it unlikely that we will be able to observe stop pair production with a decay to a semileptonic top pair and missing energy.'

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  wrong!

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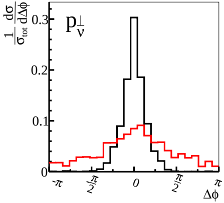

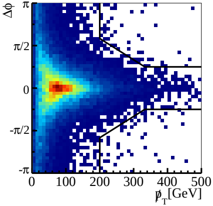

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– top partner decays observable

	orthogonal approximation							decay plane approximation						
	$\tilde{t}_1 \tilde{t}_1^*$				$t\bar{t}$	W+jets	S/B	$\tilde{t}_1 \tilde{t}_1^*$				$t\bar{t}$	W+jets	S/B
$m_{\tilde{t}}$[GeV]	340	440	540	640			440	340	440	540	640			440
1.-5. base cuts	27.38	13.71	6.33	2.89	642.72	2.63	0.021							
6. approximation	14.81	7.69	3.61	1.66	285.16	1.41	0.027	27.33	13.67	6.31	2.89	642.37	2.63	0.021
7. $p_T^{est} > 200$GeV	8.61	4.53	2.41	1.24	215.62	0.60	0.021	9.13	5.16	2.87	1.61	242.21	0.54	0.021
8. $\not{p}_T$ vs. $\Delta\phi$ cut	0.97	1.52	1.23	0.76	0.72	0.02	2.06	1.22	1.82	1.53	1.02	1.31	0.06	1.33

SFitter: Error analysis

Sources of uncertainty

- statistical error: Poisson
  systematic error: Gaussian, if measured
  theory error: not Gaussian
- simple argument
  LHC rate 10% off: no problem
  LHC rate 30% off: no problem
  LHC rate 300% off: Standard Model wrong
- theory likelihood flat centrally and zero far away
- profile likelihood construction: RFit [CKMFitter]

$$-2 \log \mathcal{L} = \chi^2 = \vec{\chi}_d^T \, C^{-1} \, \vec{\chi}_d$$

$$\chi_{d,i} = \begin{cases} 0 & |d_i - \bar{d}_i| < \sigma_i^{(\text{theo})} \\ \dfrac{|d_i - \bar{d}_i| - \sigma_i^{(\text{theo})}}{\sigma_i^{(\text{exp})}} & |d_i - \bar{d}_i| > \sigma_i^{(\text{theo})} \end{cases}$$

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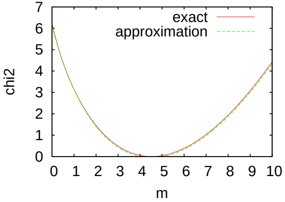
Combination of errors

– Gaussian $\otimes$ Gaussian: half width added in quadrature
  Gaussian/Poisson $\otimes$ flat: RFit scheme
  Gaussian $\otimes$ Poisson: ??

– approximate formula

$$\frac{1}{\log\mathcal{L}_{\text{comb}}} = \frac{1}{\log\mathcal{L}_{\text{Gauss}}} + \frac{1}{\log\mathcal{L}_{\text{Poisson}}}$$

– modified Minuit gradient fit last step



SFitter: Markov chains

Cooling Markov chains [Lafaye, TP, Rauch, Zerwas]

– zoom in on peak structures [inspired by simulated annealing]

– modified condition
Markov chain in 100 partitions, numbered by j

$$\frac{p(m')}{p(m)} > r^{\frac{100}{j\,c}} \qquad \text{with} \quad c \sim 10, \qquad r\epsilon[0,1] \quad \text{random number}$$

– check for parameter coverage with many Markov chains

⇒ exclusive likelihood map first result

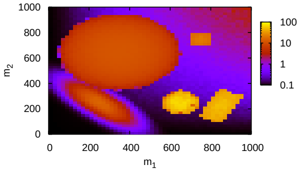
SFitter: Frequentist vs Bayesian

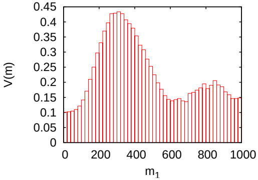
Getting rid of model parameters

– poorly constrained parameters
  uninteresting parameters
  unphysical parameters [JES part of m_t extraction]

– two ways to marginalize likelihood map

1– integrate over probabilities
  normalization etc mathematically correct
  integration measure unclear
  noise accumulation from irrelevant regions
  classical example: convolution of two Gaussians





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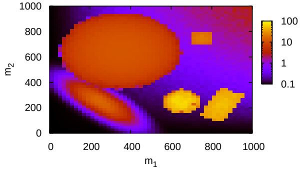
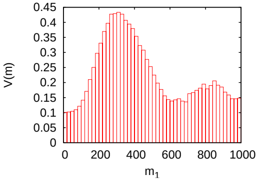
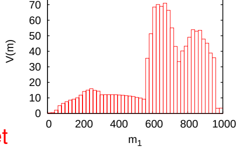




2– profile likelihood $\mathcal{L}(.., x_{j-1}, x_{j+1} \dots) \equiv \max_{x_j} \mathcal{L}(x_1, \dots, x_n)$
  no integration needed
  no noise accumulation
  not normalized, no comparison of structures
  classical example: best-fit point



– one-dimensional parameter distributions second target