Demystifying Multivariate Searches and the Hunt for the Higgs

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Harvard University

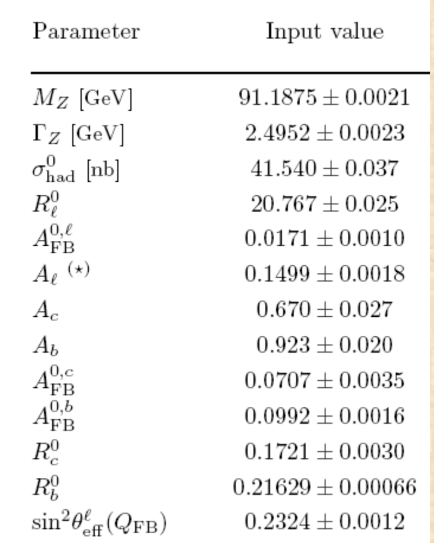
Work down with Jason Gallicchio,
PRL, 105:022001,2010
and with Gallicchio, Tweedie, Huth, Kagan and Black
... *in preparation*

Johns Hopkins University
September 20, 2010

Part 1:

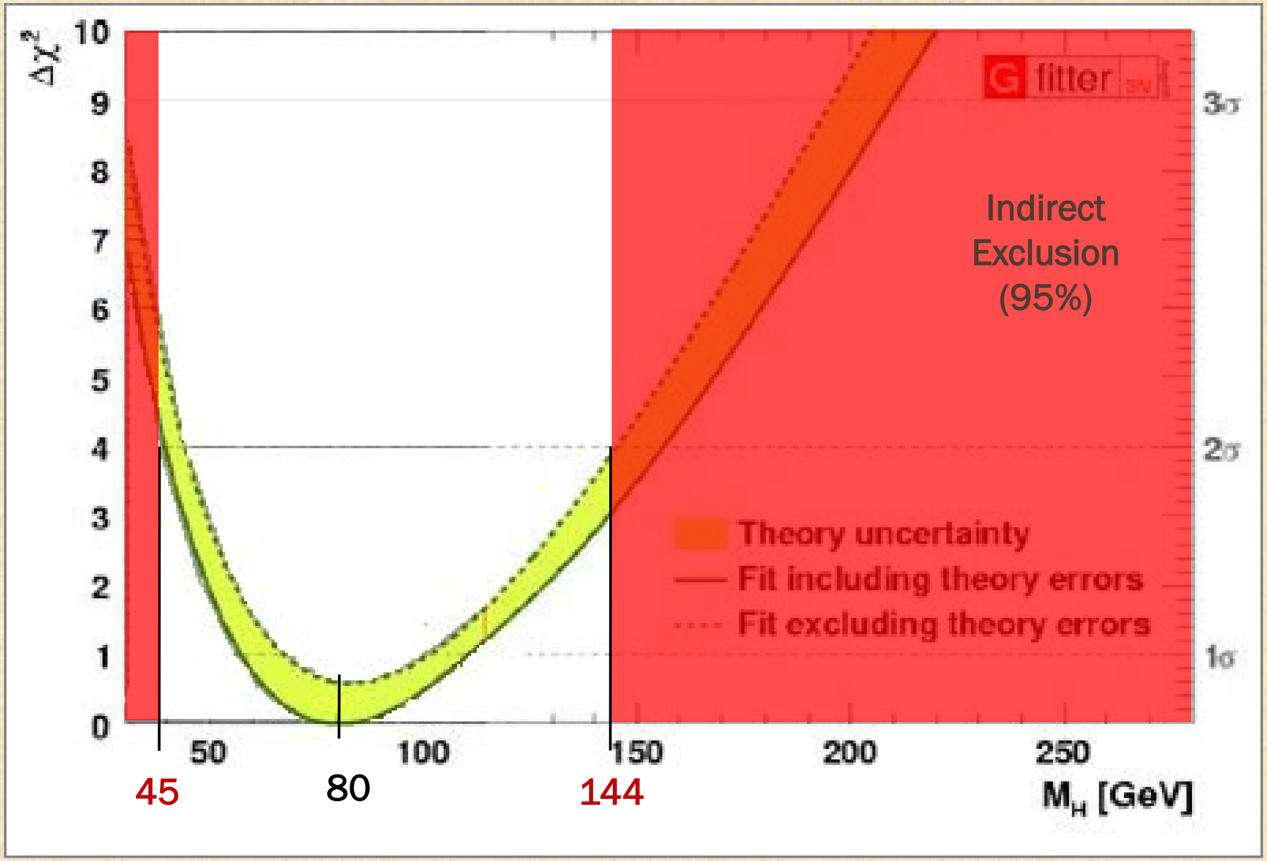
Motivation

WHERE IS THE HIGGS?



Parameter	Input value
M_Z [GeV]	91.1875 ± 0.0021
Γ_Z [GeV]	2.4952 ± 0.0023
σ^0_{had} [nb]	41.540 ± 0.037
R^0_ℓ	20.767 ± 0.025
$A^{0,\ell}_{\text{FB}}$	0.0171 ± 0.0010
A_ℓ $^{(\star)}$	0.1499 ± 0.0018
A_c	0.670 ± 0.027
A_b	0.923 ± 0.020
$A^{0,c}_{\text{FB}}$	0.0707 ± 0.0035
$A^{0,b}_{\text{FB}}$	0.0992 ± 0.0016
R^0_c	0.1721 ± 0.0030
R^0_b	0.21629 ± 0.00066
$\sin^2\theta^\ell_{\text{eff}}(Q_{\text{FB}})$	0.2324 ± 0.0012

Combine many observables to constrain Higgs mass



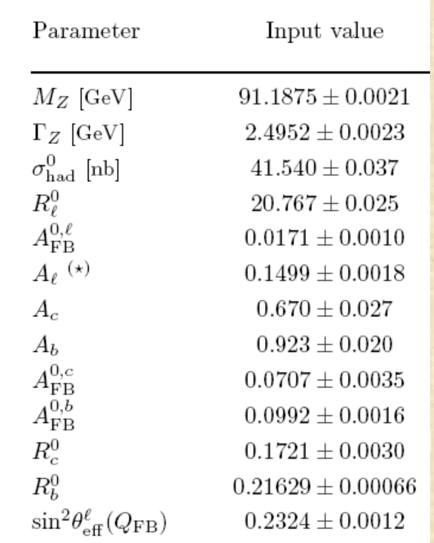
Indirect Exclusion (95%)

45

80

144

WHERE IS THE HIGGS?



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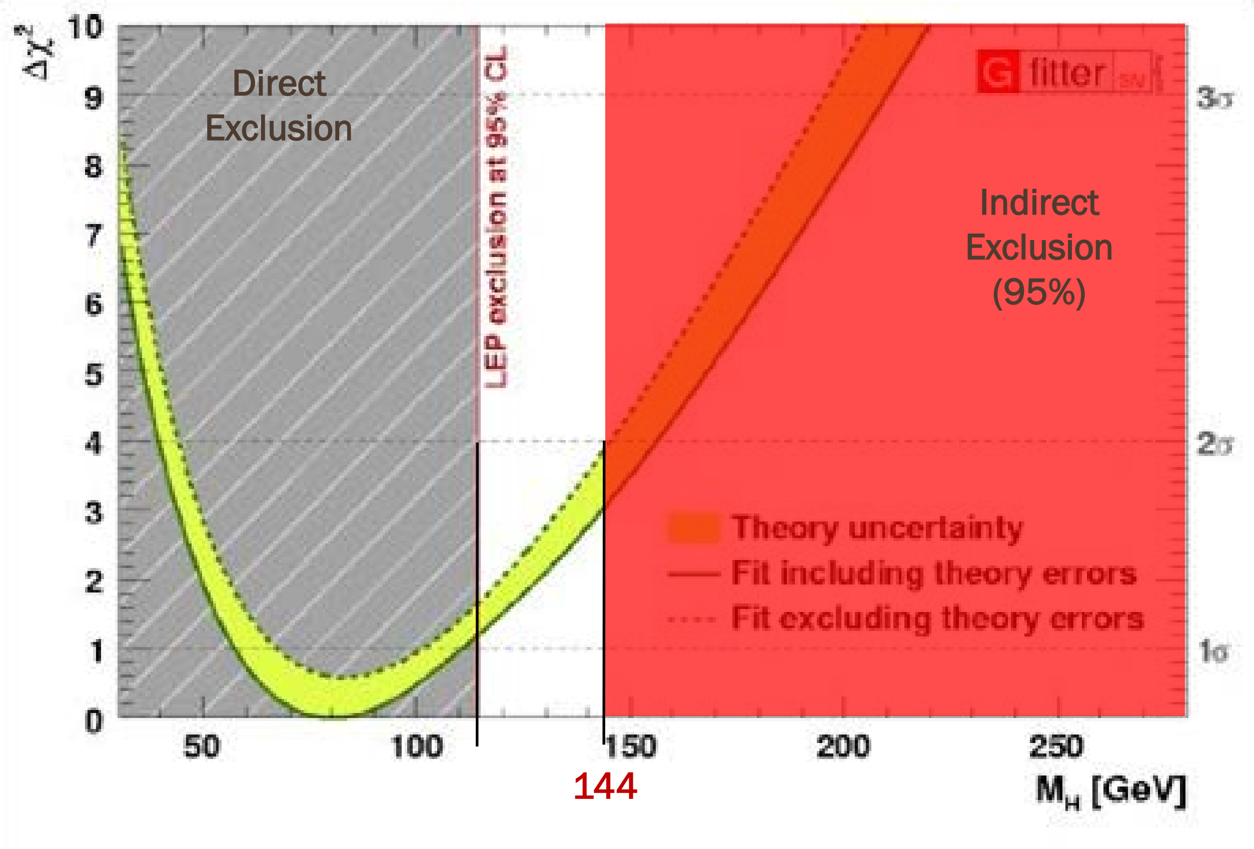

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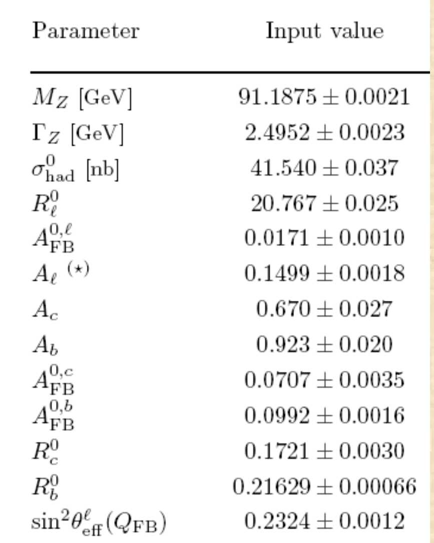

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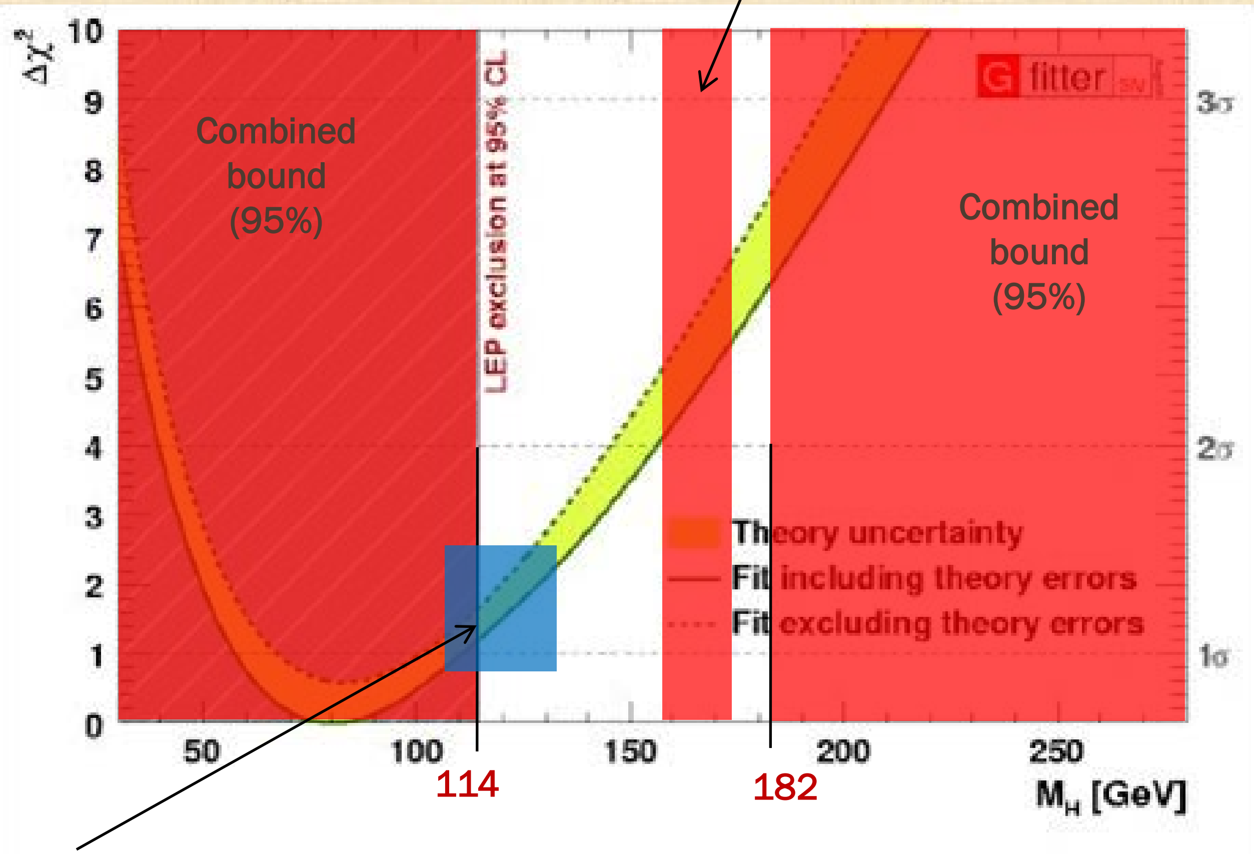
Combine many observables to constrain Higgs mass

Recent Tevatron exclusion (158-175 GeV)

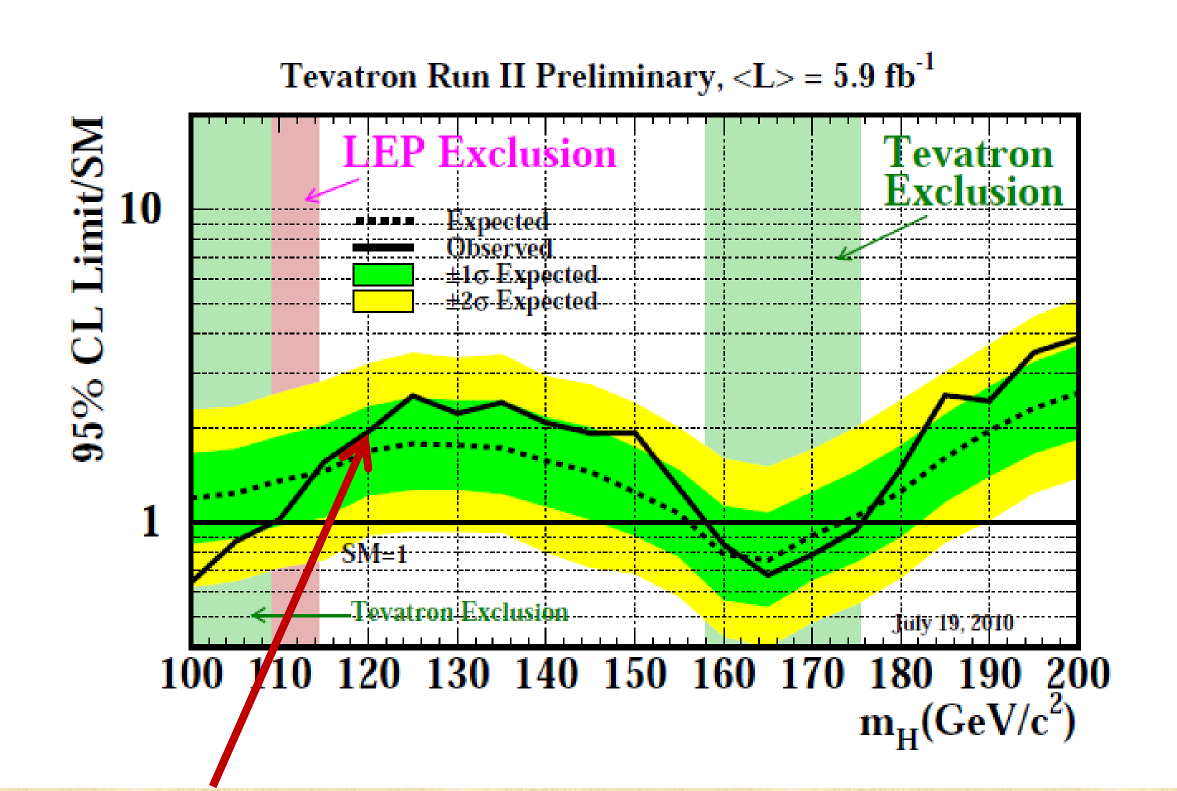
CDF+D0
arXiv: 1007.4587



If it exists, Higgs is most likely light

HOW DO WE FIND A LIGHT HIGGS?

Tevatron



- Need a factor of 2 improvement in significance for m_H=120
- Double statistics gives √2, where will the other √2 come from?

LHC

- Important search channel is

  pp → W/Z + H

  H → bb

- Abandoned by ATLAS and CMS

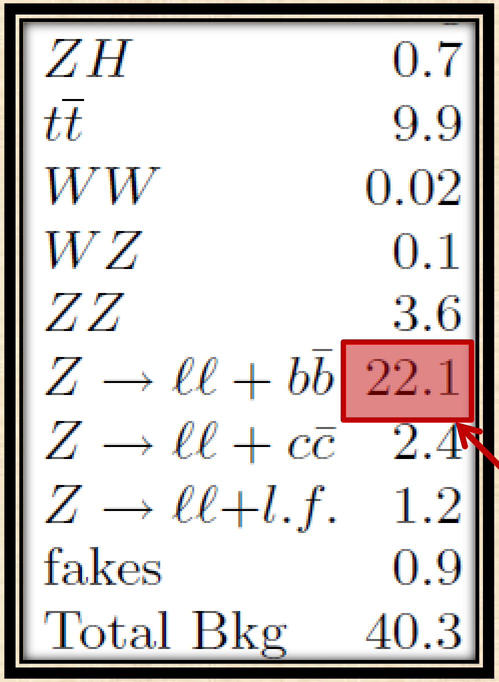
  too much background

- Recently high P_T W/Z + H revived,
  - Requires P_T > 200
  - Lose 95% of signal

How good can we do in W/Z + (H → bb)?

FOCUS ON $pp \to HZ \to b\bar{b}l^+l^-$

CDF note 10235 (summer 2010)



ZH	0.7
$t\bar{t}$	9.9
WW	0.02
WZ	0.1
ZZ	3.6
$Z \to \ell\ell + b\bar{b}$	22.1
$Z \to \ell\ell + c\bar{c}$	2.4
$Z \to \ell\ell + l.f.$	1.2
fakes	0.9
Total Bkg	40.3

Dominant background is the irreducible one

CDF employs multivariate approach

Inputs to the neural net are

- Missing transverse energy
- Dijet mass
- tt matrix element output
- ZH matrix element output
- Sum of leading jet Pt's
- number of jets

Parton-level kinematics

Questions:

- Are there smarter more comprehensive inputs?
- Can we trust the multivariate approach?

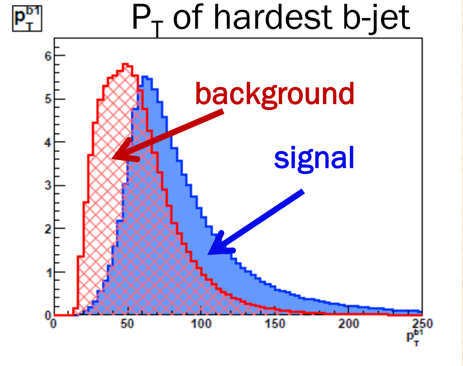
Part 2:

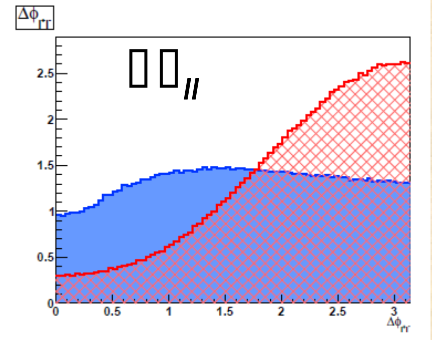
The Inputs

KINEMATIC VARIABLES

Standard Stuff

- P_T's of b's and the leptons
- □ □□□□ □□ for the b jets and the leptons
- □R of the b's and the leptons
- P_T of the reconstructed Z
- P_T of the reconstructed Higgs
- $m_{bb:}$ invariant mass of the b's



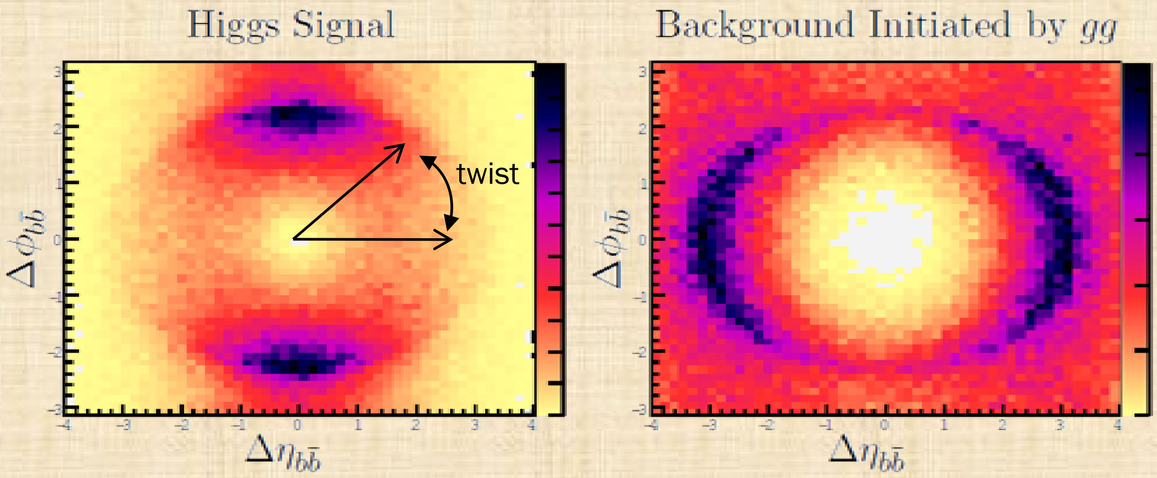


Less Standard Stuff

- acoplanarity of the b's: $2\pi - \Delta\theta_{b\bar{b}} - \Sigma\theta_{b\bar{b}}$
- acoplanarity of the leptons
- transverse mass of the bb system $m_T^{b\bar{b}} = m^2 + p_x^2 + p_y^2$
- transverse mass of the lepton system
- invariant mass of 2 leptons and 1 b or 2 b's and 1 lepton

TWIST

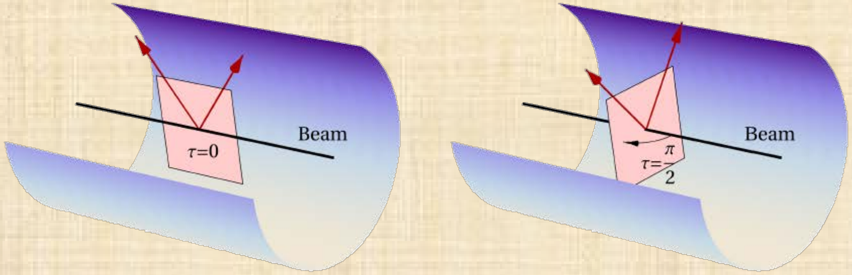
Look at 2D distribution in □□ □□space:



It seems that neither □ nor □ nor R holds the right information

Introducing **twist** = polar angle in this plane

Background has pole for
zero twist
(t-channel singularity)

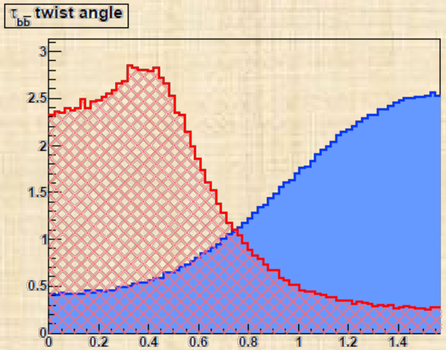


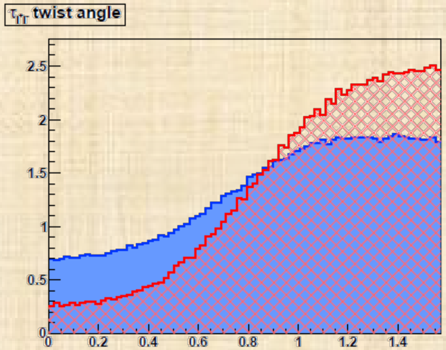
TWIST

b-jet twist

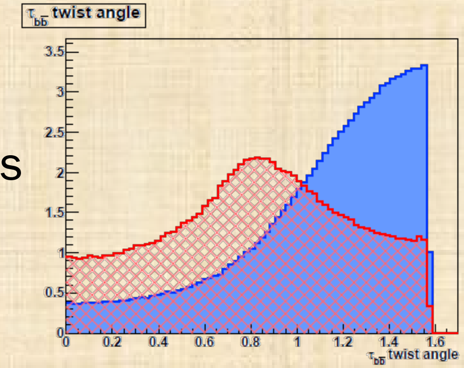
lepton twist

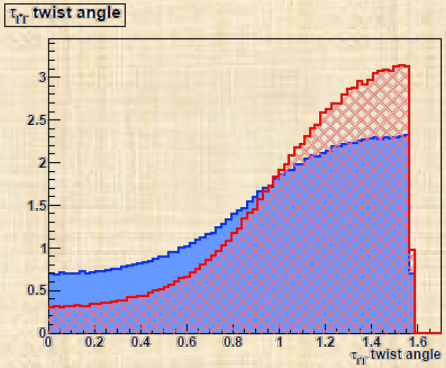
Parton level – no cuts





Jet level with detector cuts

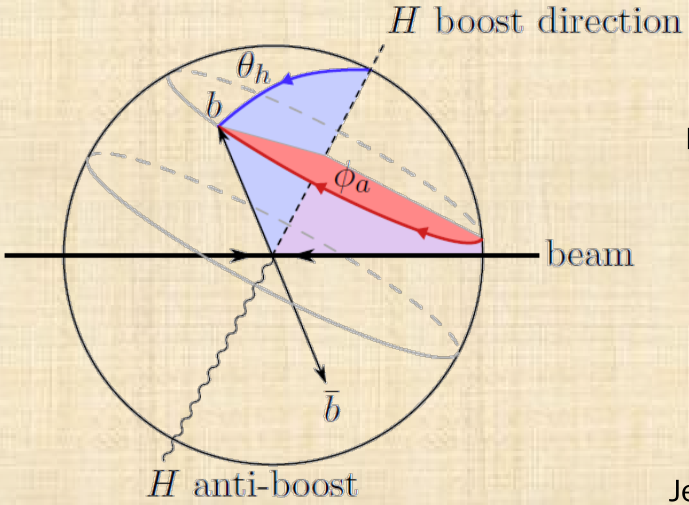




Could be more generally useful....

HELICITY AND AZILICITY ANGLES

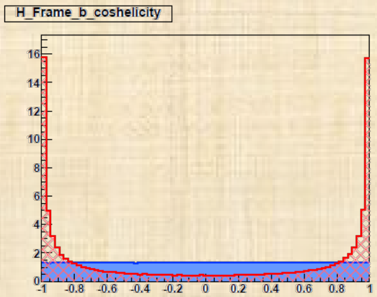
Angles in Higgs rest frame
relative to H boost direction

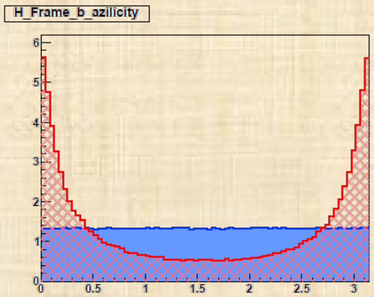


helicity angle

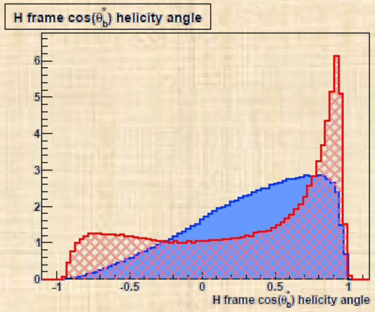
azilicity angle

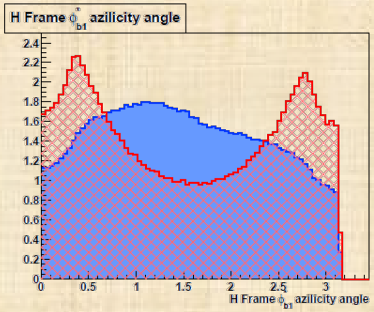
Parton level
– no cuts





Jet level
with detector cuts





Signal is on-shell

- angles meaningful

Background is not a resonance

- Angles meaningless
- Expect peaked due to collinear singularities

CHINESE MENU METHOD

- Pick a particle: high-p_T b-jet, low-p_T b-jet, high-p_T lepton, low-p_T lepton, Higgs, Z
- Optionally transform to a boosted frame: Higgs, Z, Center of Mass (CM)
- Optionally rotate the polar axis to point along the initial direction of the particle whose frame you're in (for Helicity and Azilicity Angles).
- Pick a kinematic property: p_T, η, ϕ, $\cos(\theta)$, etc.
- Optionally pick a second particle to form a sum or difference, sometimes with a coordinate transformation as in ΔR and twist τ, and sometimes with a more complicated combination as in invariant-mass.
- For vector quantities optionally take the magnitude of vector sums, $|\vec{p_1} \pm \vec{p_2}|$ or scalar sums, $|\vec{p_1}| \pm |\vec{p_2}|$.

- $\Delta y_{H,b1}$ and $\Delta y_{H,b2}$: Difference in rapidity between Higgs and higher-p_T or lower-p_T b-jet
- $\cos(\theta^*_{b2})$: Center of Mass frame $\cos(\theta)$ of the lower-p_T b-jet. Same for higher-p_T b-jet.
- $\Delta p_T^{Z,l1}$: Difference in p_T between the reconstructed Z and the higher-p_T lepton
- $\Delta p_T^{b1,l2}$: Difference in p_T between the higher-p_T b-jet and the lower-p_T lepton
- $\Sigma p_T^{b1,l2}$: Sum of p_T's of the higher-p_T b-jet and the lower-p_T lepton
- $\Delta \eta_{b1,l2}$: Difference in η between the higher-p_T b-jet and the lower-p_T lepton

EVENT SHAPE VARIABLES

Nothing to do with the particular signal or background

- H_T = Scalar sum of all E_T
- Σp_T = Scalar sum of all p_T (which differs from H_T for massive jets)
- H_z = Boost of the center-of-mass system along the beam
- E_{vis} = Scalar sum of all visible energy
- $\hat{s}$ = CM energy for hard collision, or invariant mass of the reconstructed Higgs and Z.
- Centrality
- Aplanarity and Aplanority
- Sphericity and Spherocity
- DShape and Yvariable (related to the eigenvalues that go into defining the above)
- Fox-Wolfram Moments

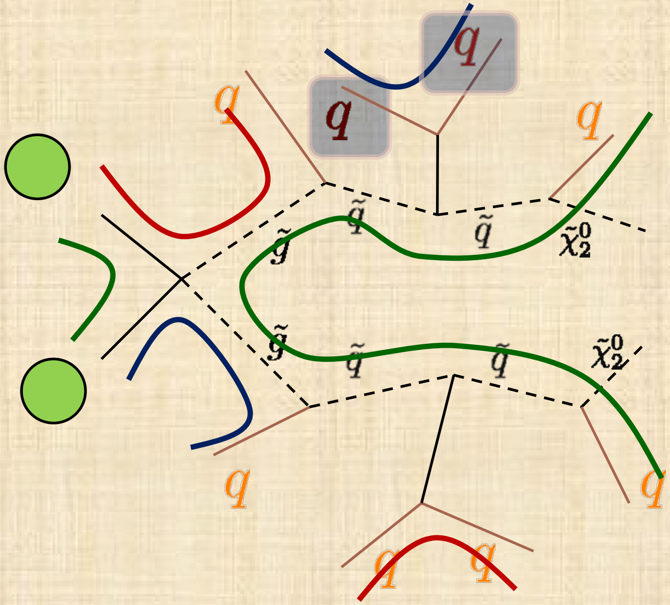
JET SUPERSTRUCTURE

What is not in the parton-level kinematics?

- Global information
  - Event shapes

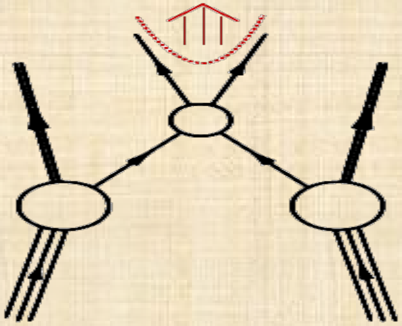
- Color:
  - Color charge: Quark vs. Gluon jets
  - Color connections

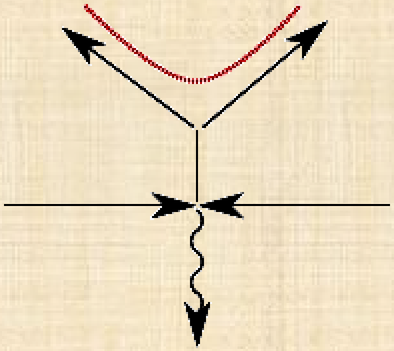
$$\mathrm{Tr}[T^A T^B] \propto \delta^{AB}$$



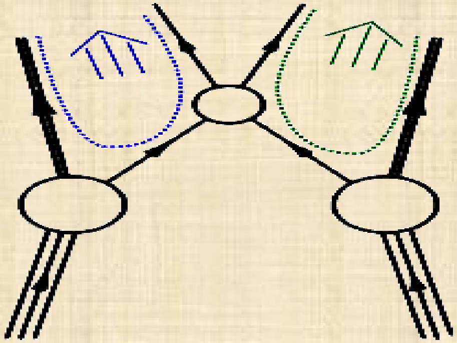
COLOR CONNECTIONS

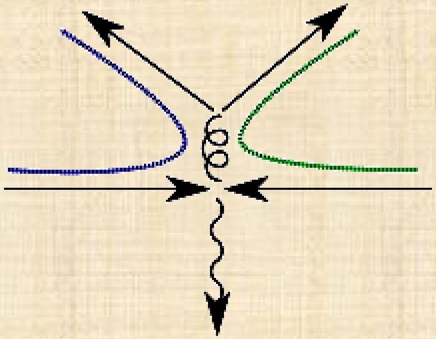
Signal



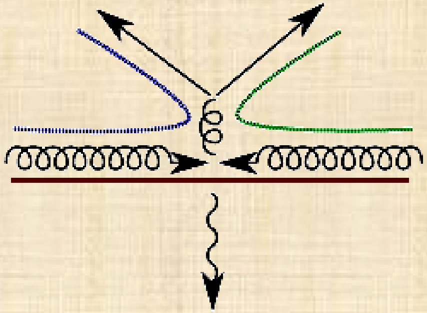


Background





$q\bar{q} \rightarrow Zb\bar{b}$

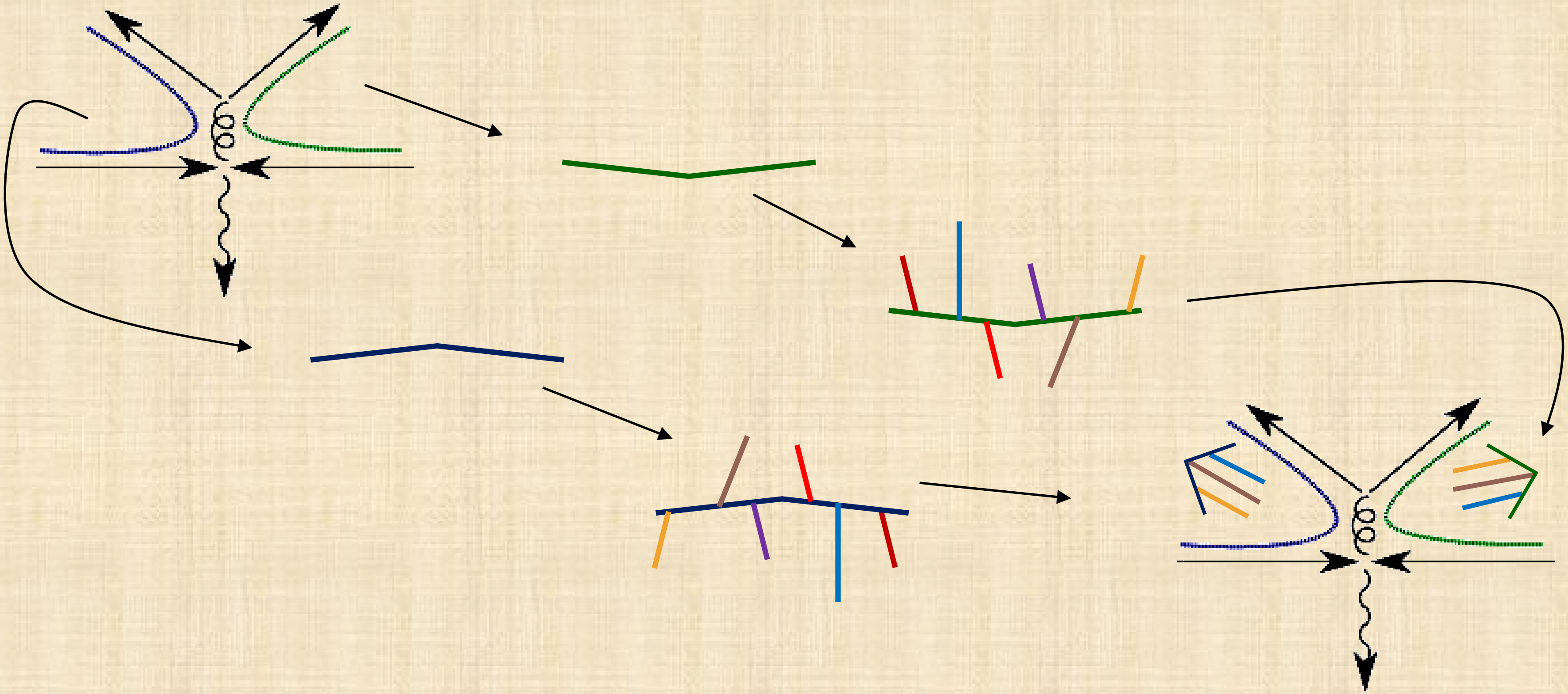


$gg \rightarrow Zb\bar{b}$

HOW DO THEY SHOW UP?

Monte Carlo simulation

- Color coherence (angular ordering, e.g. Herwig)
- Color string showers in its rest frame (pt ordering, e.g. Pythia)
  - Boost → string showers in string-momentum direction



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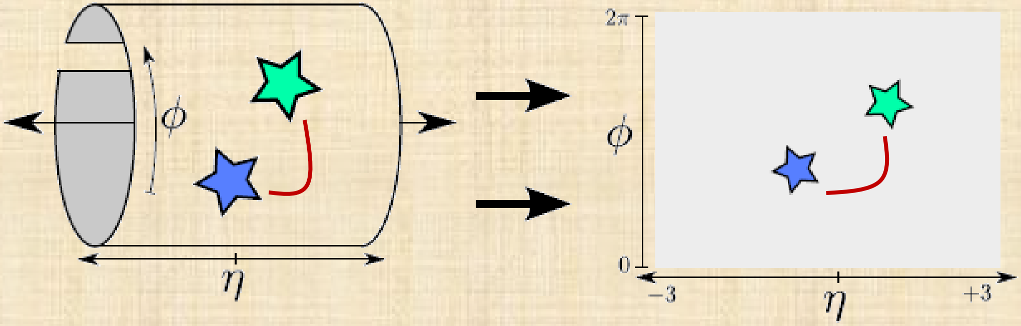
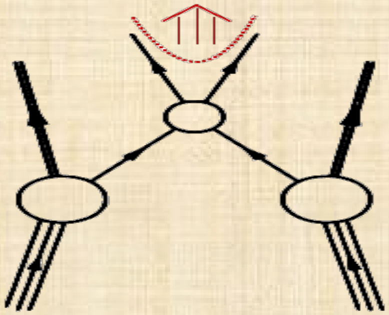


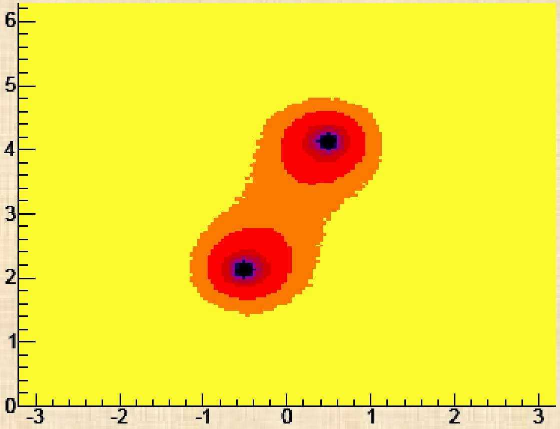


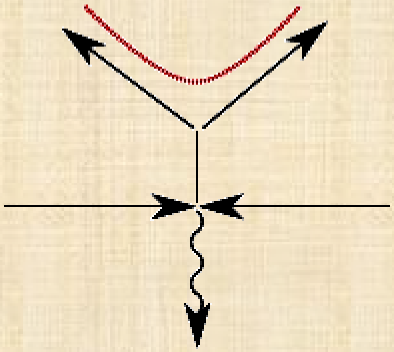
Shower same event *millions* of times

Higgs:

$$\Delta\eta_{b\bar{b}} = 1$$
$$\Delta\phi_{b\bar{b}} = 2$$

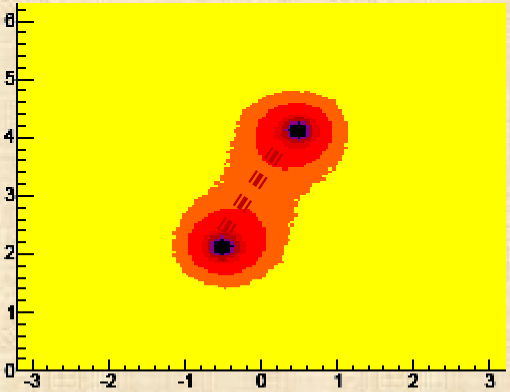
Add up E_T in each cell:

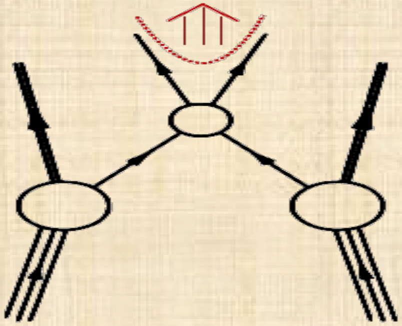


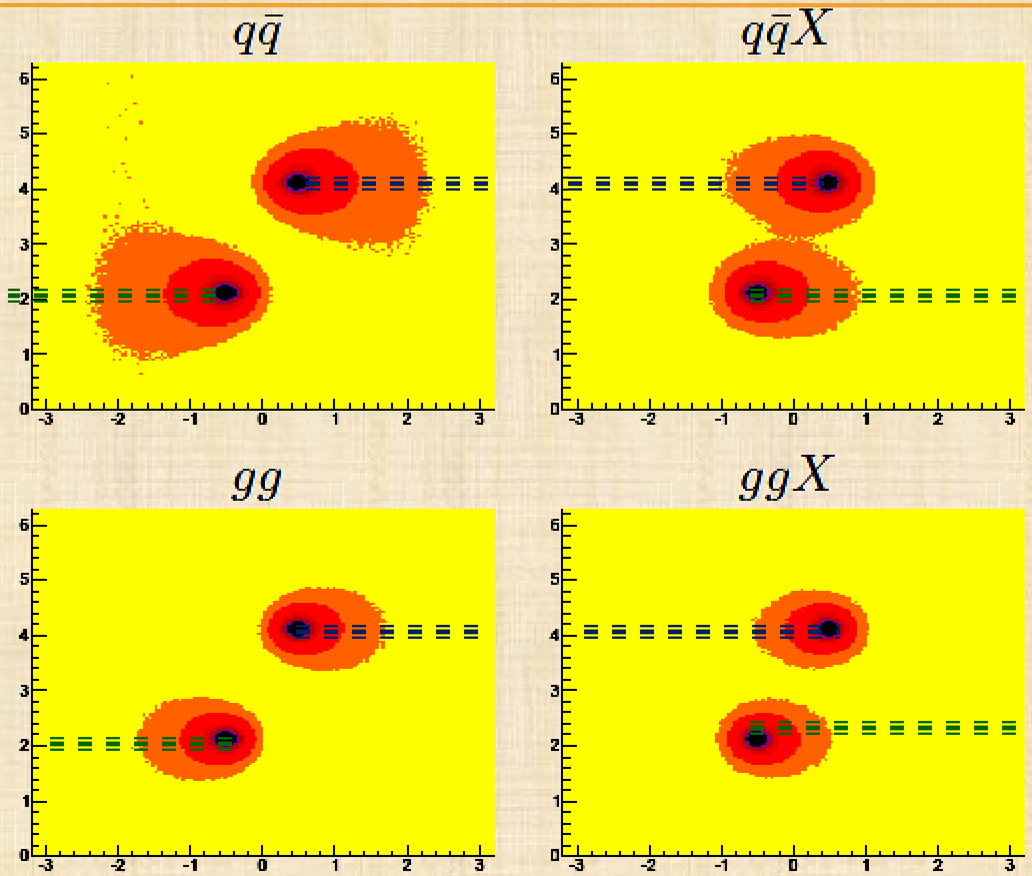


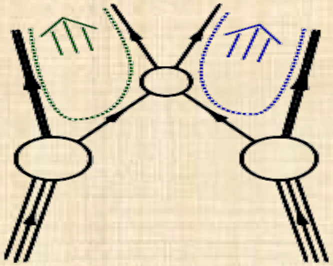
SIGNAL VS BACKGROUND

Higgs:



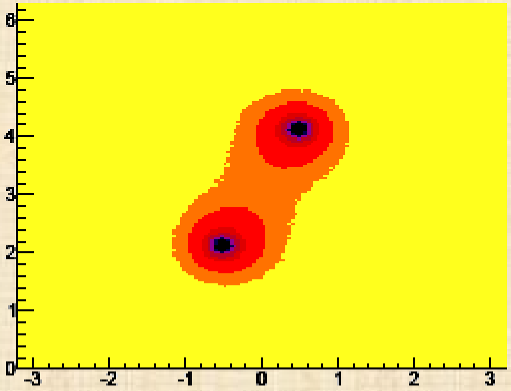




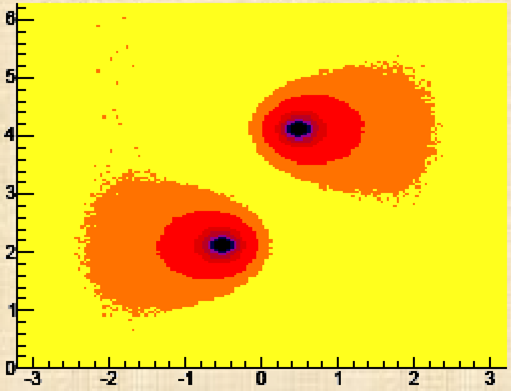


HOW CAN WE USE IT?

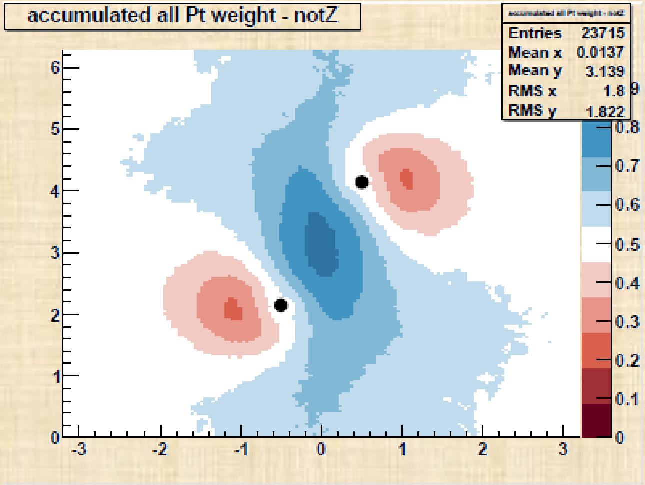
Higgs:



$q\bar{q}$

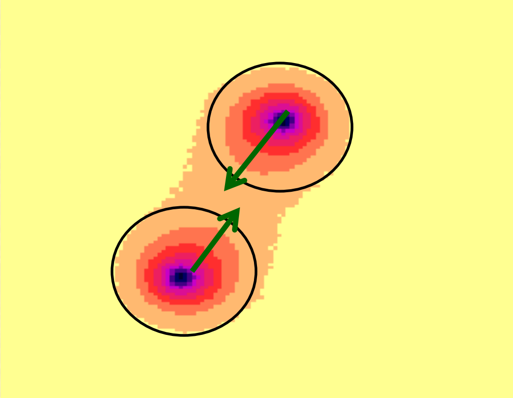


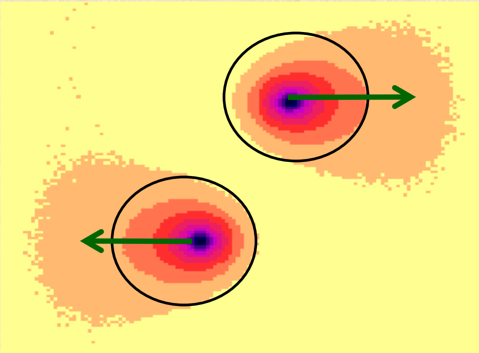
Baysean **probability** that each bit of radiation is **signal**

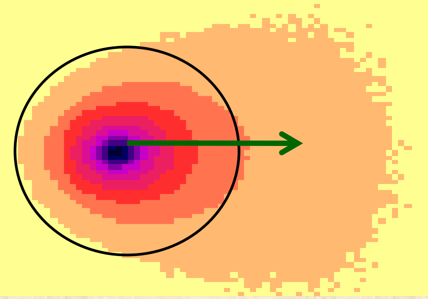


- Most useful radiation is R = 0.5 – 1.5 away
- Pattern depends strongly on **kinematics**
- Can we find a ***simpler*** or more ***universal*** discriminant?

PULL

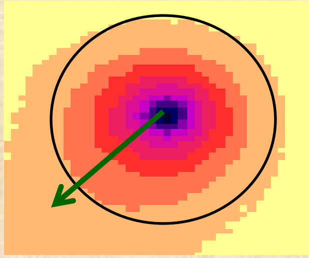






- Find **jets** (e.g. anti-k_T)
- Construct **pull vector** (~ dipole moment)
  on radiation in **jet**

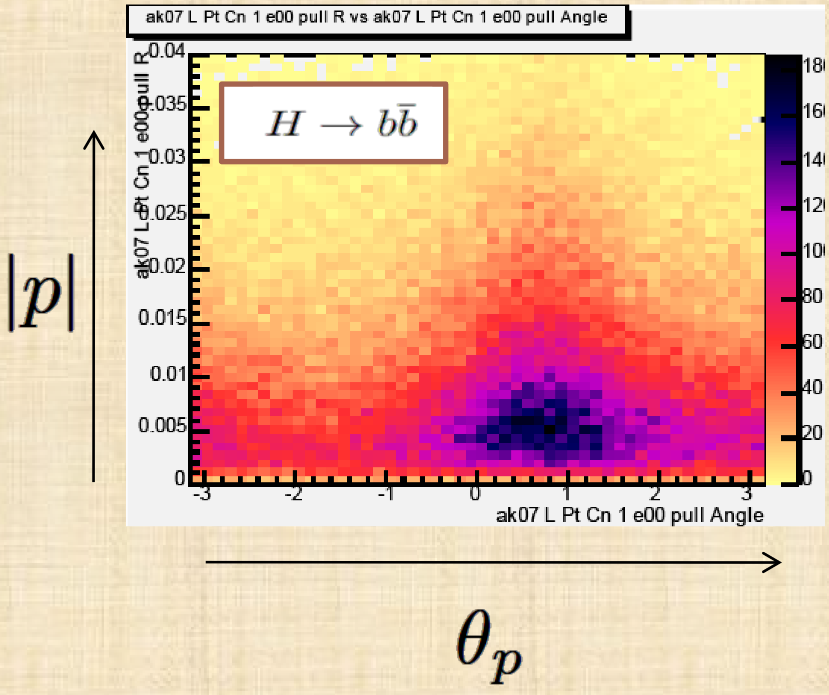
$$\vec{p} = \sum_i \frac{E_T^i \, |r_i|}{E_T^{jet}} \, \vec{r}_i$$

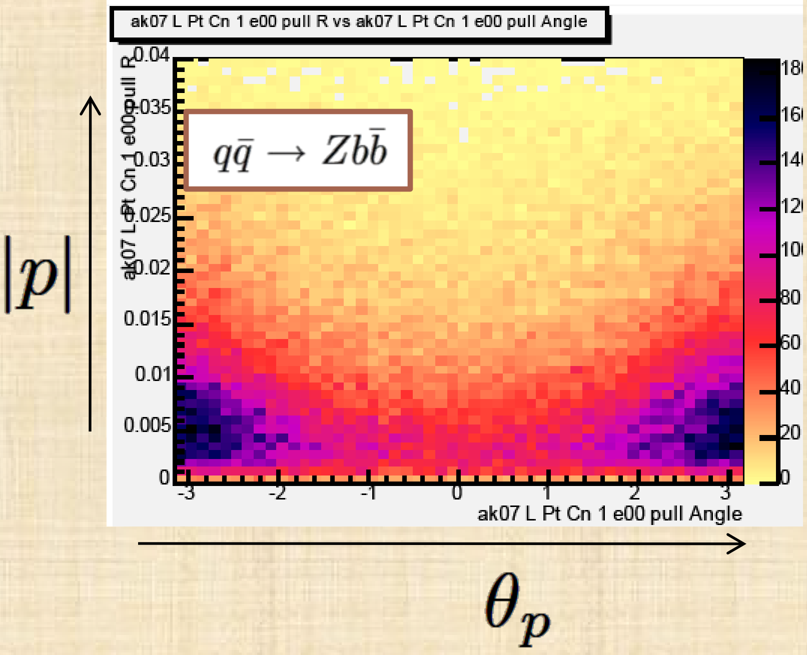


- Can use bigger jets for pull, but R = 0.7 seems optimal

PULL VECTOR IN RADIAL COORDS

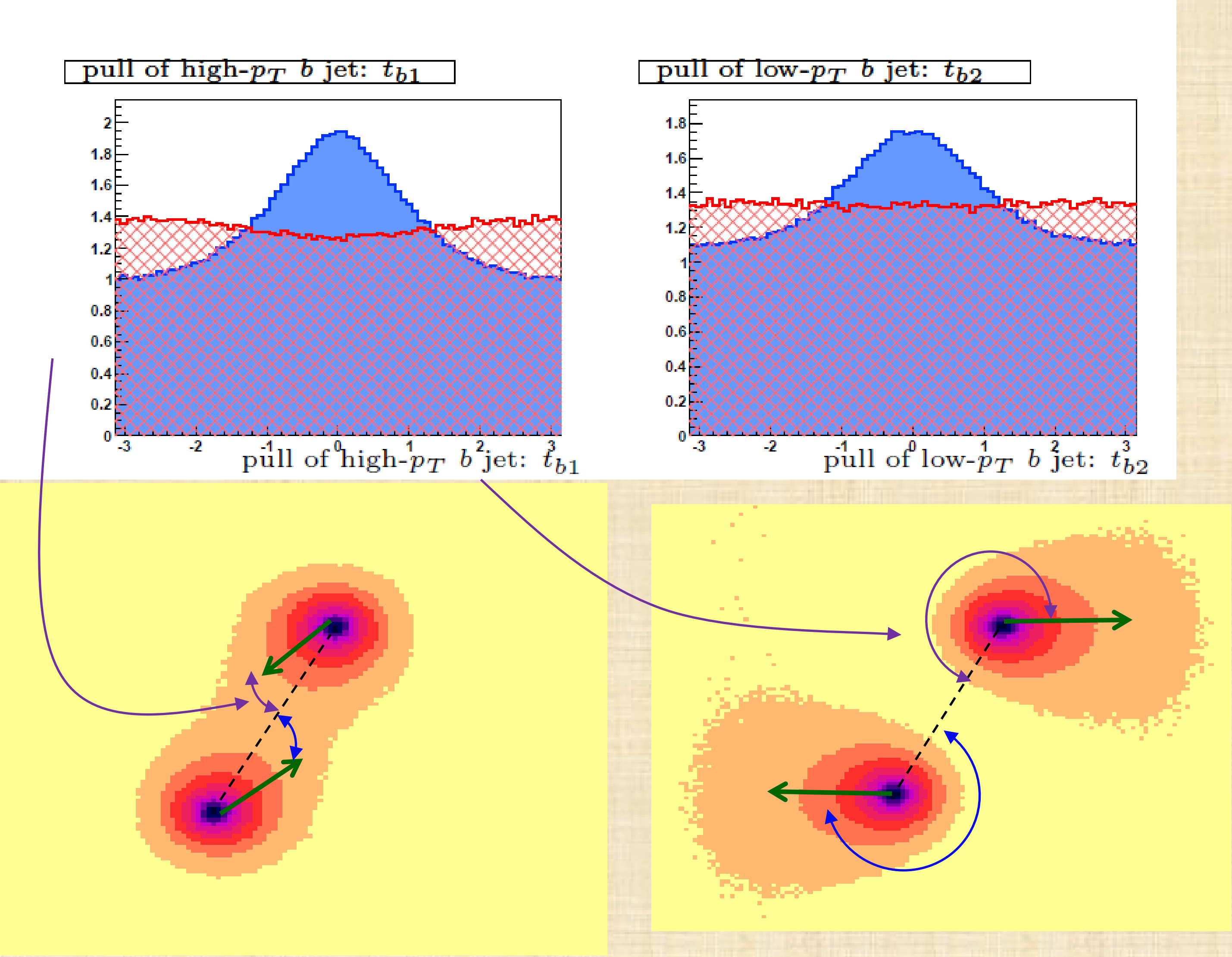
$$\vec{p} = \sum_i \frac{E_T^i \, |r_i|}{E_T^{jet}} \vec{r}_i$$





- Angle much more important than length
- Look at radial pull angle (like for twist)

SIGNAL VS BACKGROUND



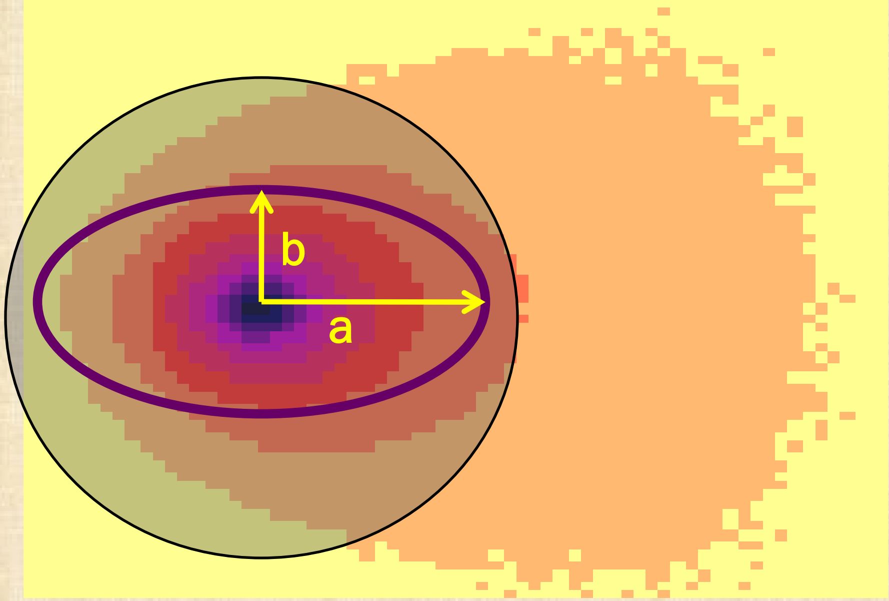
SECOND MOMENTS

What about **higher moments**?

$$\mathbf{I} = \sum_i \frac{E_T^i |r_i|}{E_T^{jet}} \begin{pmatrix} \Delta\phi_i^2 & -\Delta\phi_i \, \Delta\eta_i \\ -\Delta\eta_i \, \Delta\phi_i & \Delta\eta_i^2 \end{pmatrix} \longrightarrow$$

Eigenvalues
a and b

JET



Eccentricity

$$e = \sqrt{\frac{a^2 - b^2}{a^2}}$$

Girth

$$g = \sqrt{a^2 + b^2}$$

OTHER "SHOWERED" VARIABLES

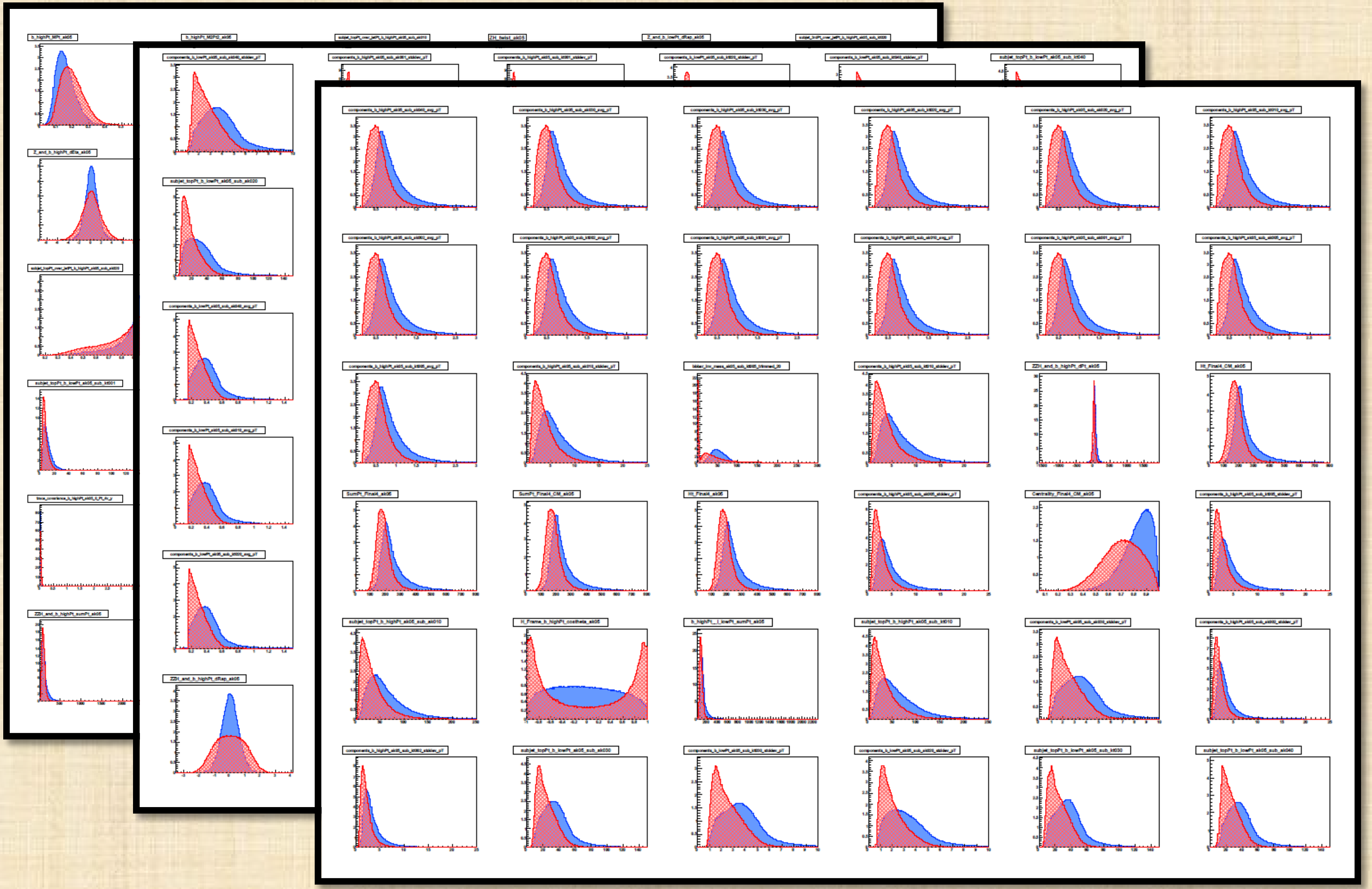
Many variables vanish at the parton level

- Do not enter the matrix element method
- Complimentary and uncorrelated with kinematic variables

- Mass of each b-jet and the jet mass to p_T ratio
- Rapidity y in addition to pseudorapidity η of each massive b-jet
- Subjet multiplicity for each b-jet
- Average p_T of the small subjets within each b-jet
- p_T of hardest, 2nd hardest, and 3rd hardest subjets within each b-jet
- Radial moments ("girth") of each b-jet: $g = \sum_i \frac{p_T^i |r_i|}{p_T^{jet}}$
- Angularity: $\tau_a = \frac{1}{m_{jet}} \sum_i E_i \sin^a\left(\frac{\pi\theta_i}{2R}\right)\left[1 - \cos\left(\frac{\pi\theta_i}{2R}\right)\right]^{1-a}$ for $-1 < a < 1$

SUMMARY

- We looked at ~ 900 discriminents!



Part 3:

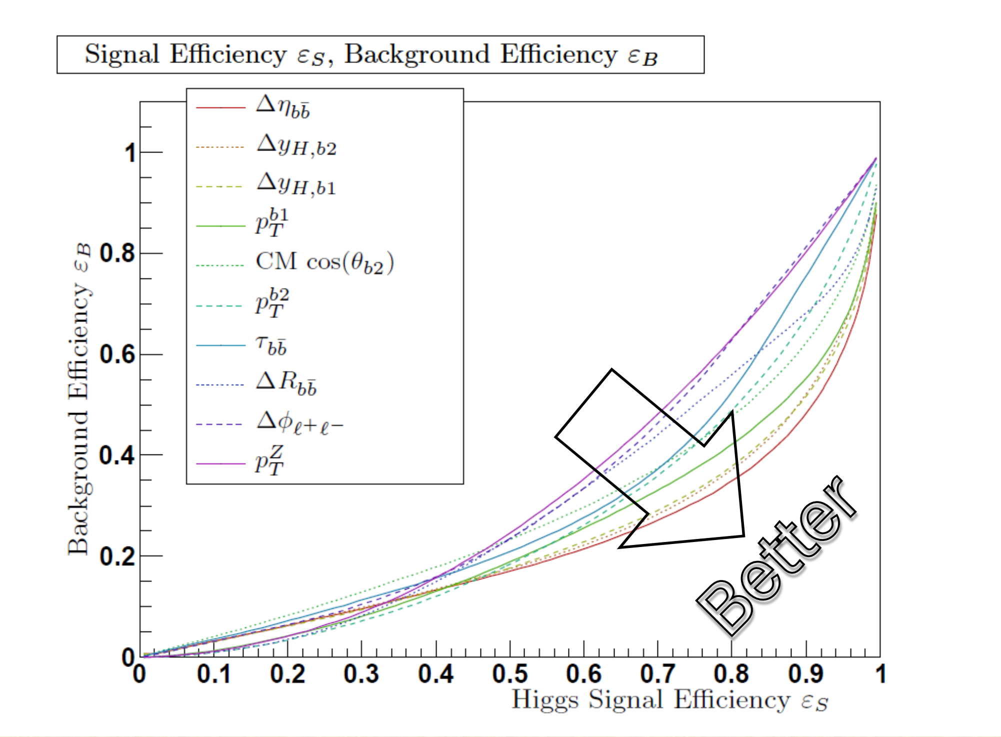
The Output

EFFICIENCIES

ROC curve:

Background efficiency as a function of signal efficiency

Receiver
Operator
Characteristic

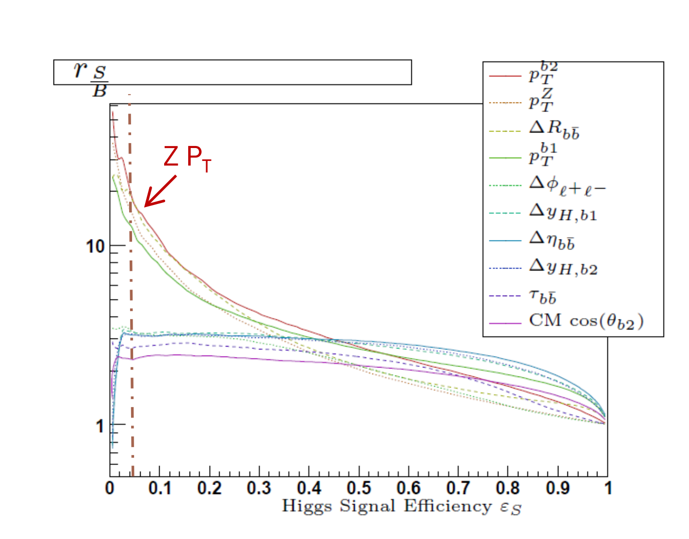


Which variable is best?

OTHER VISUALIZATIONS

$$\frac{S}{B} \xrightarrow{\text{cut}} \frac{\varepsilon_S S}{\varepsilon_S B} = \left(\frac{\varepsilon_S}{\varepsilon_B}\right)\frac{S}{B}$$

$$r_{\frac{S}{B}} \equiv \frac{\varepsilon_S}{\varepsilon_B}$$



Butterworth et al.
arXiv:0802.2470

$$p_T^Z > 200 \text{ GeV}$$

□S= 1/20

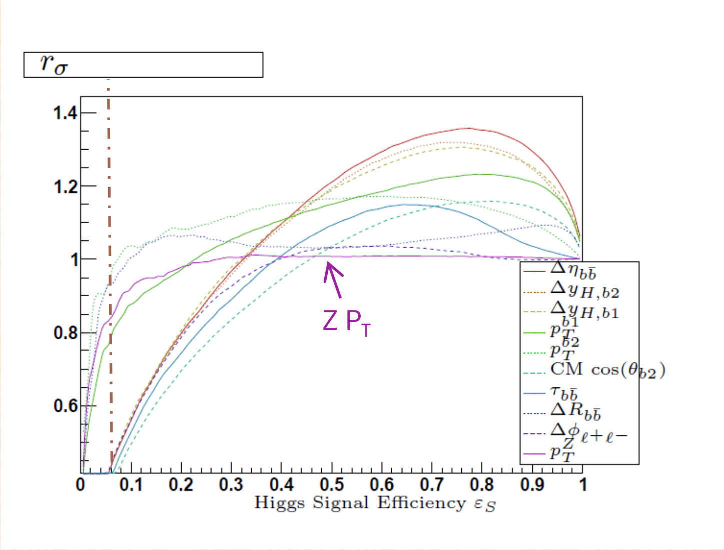
□B= 1/360

$\frac{□_S}{□_B}$ =18

Significance
Improvement
Characteristic

$$\sigma \equiv \frac{S}{\sqrt{B}} \xrightarrow{\text{cut}} \frac{\varepsilon_S S}{\sqrt{\varepsilon_B B}} = \left(\frac{\varepsilon_S}{\sqrt{\varepsilon_B}}\right)\sigma$$

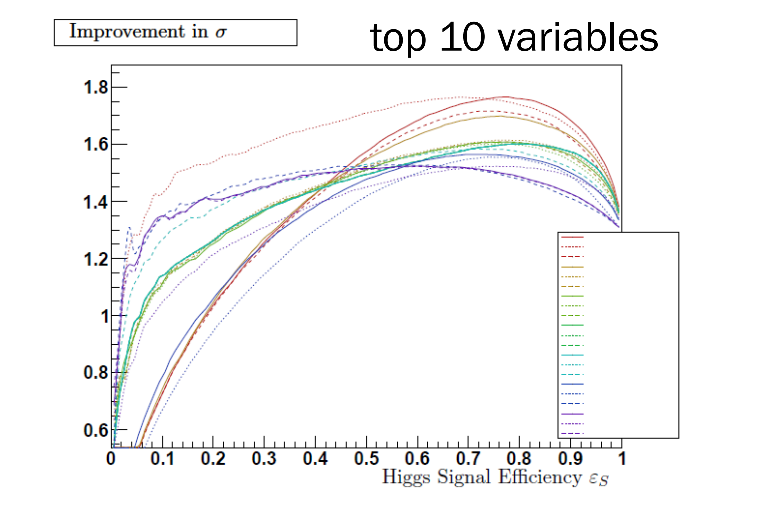
$$r_\sigma \equiv \frac{\varepsilon_S}{\sqrt{\varepsilon_B}}$$



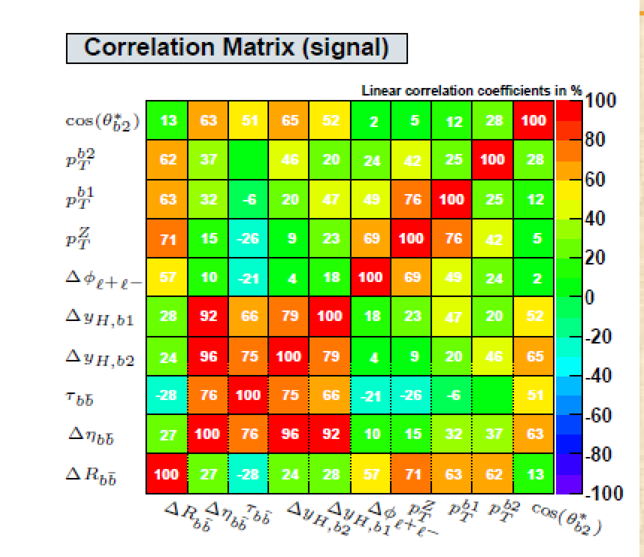
$\frac{\varepsilon_S}{\sqrt{\varepsilon_B}}$=0.94

- Has maximum
- Maximum r□ can rank variables
- Effective visualization
  - Contains lots of information

TOP VARIABLES



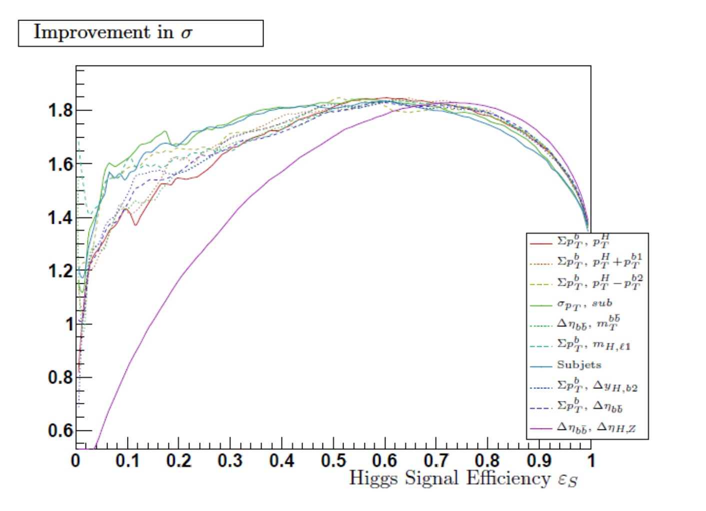
top 10 variables

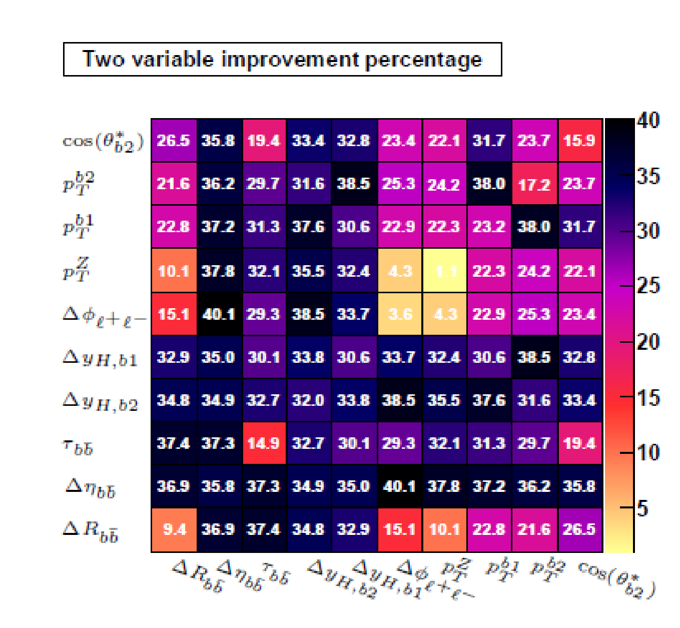


Correlation Matrix (signal)

	$\Delta R_{b\bar{b}}$	$\Delta\eta_{b\bar{b}}$	$\tau_{b\bar{b}}$	$\Delta y_{H,b2}$	$\Delta y_{H,b1}$	$\Delta\phi_{\ell+\ell-}$	p_T^Z	p_T^{b1}	p_T^{b2}	$\cos(\theta^*_{b2})$
$\cos(\theta^*_{b2})$	13	63	51	65	52	2	5	12	28	100
p_T^{b2}	62	37		46	20	24	42	25	100	28
p_T^{b1}	63	32	-6	20	47	49	76	100	25	12
p_T^Z	71	15	-26	9	23	69	100	76	42	5
$\Delta\phi_{\ell+\ell-}$	57	10	-21	4	18	100	69	49	24	2
$\Delta y_{H,b1}$	28	92	66	79	100	18	23	47	20	52
$\Delta y_{H,b2}$	24	96	75	100	79	4	9	20	46	65
$\tau_{b\bar{b}}$	-28	76	100	75	66	-21	-26	-6		51
$\Delta\eta_{b\bar{b}}$	27	100	76	96	92	10	15	32	37	63
$\Delta R_{b\bar{b}}$	100	27	-28	24	28	57	71	63	62	13

top 10 pairs, with boosted decision trees





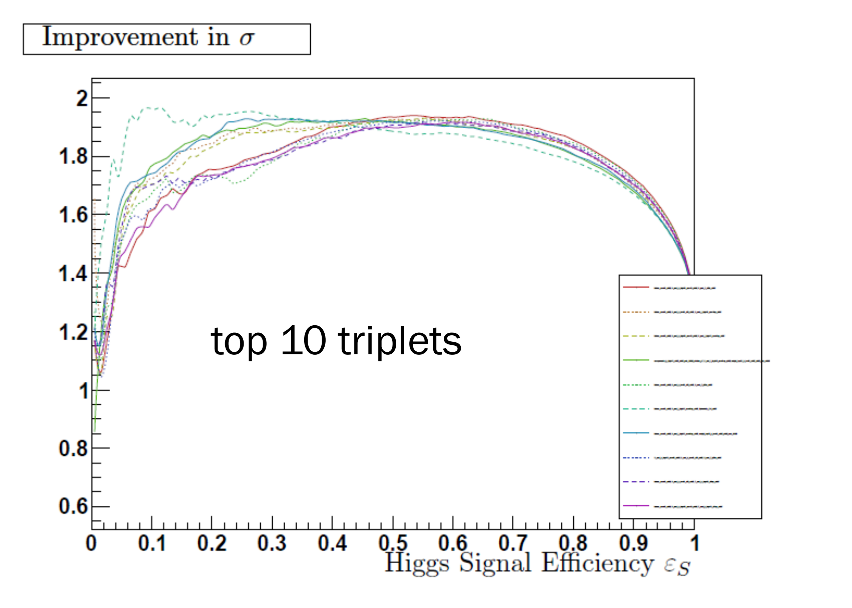
Two variable improvement percentage

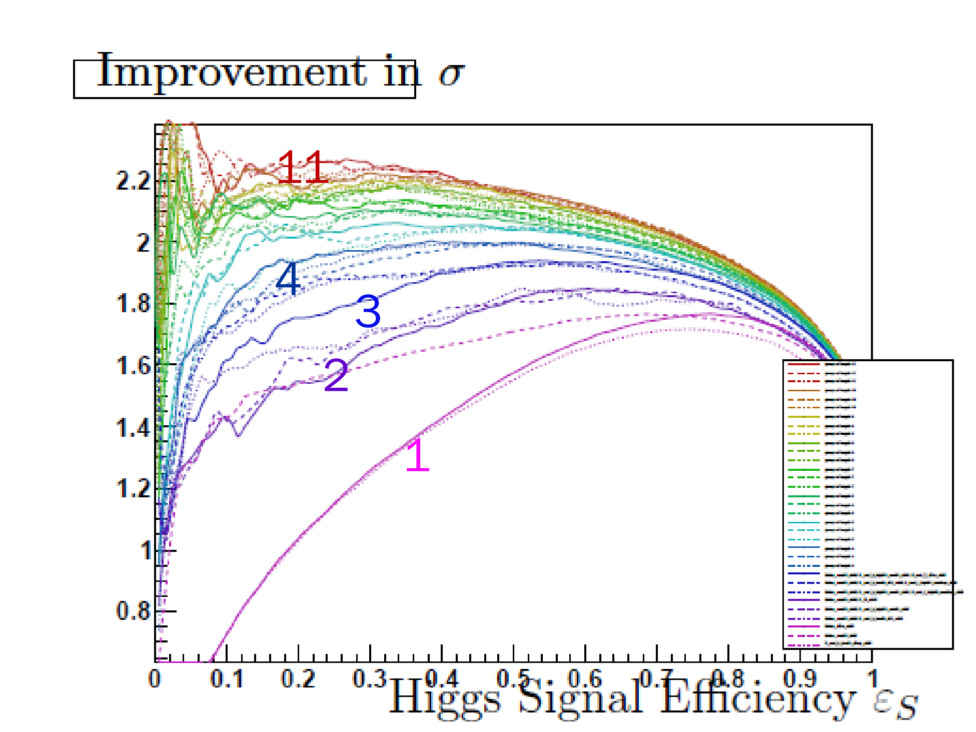
	$\Delta R_{b\bar{b}}$	$\Delta\eta_{b\bar{b}}$	$\tau_{b\bar{b}}$	$\Delta y_{H,b2}$	$\Delta y_{H,b1}$	$\Delta\phi_{\ell+\ell-}$	p_T^Z	p_T^{b1}	p_T^{b2}	$\cos(\theta^*_{b2})$
$\cos(\theta^*_{b2})$	26.5	35.8	19.4	33.4	32.8	23.4	22.1	31.7	23.7	15.9
p_T^{b2}	21.6	36.2	29.7	31.6	38.5	25.3	24.2	38.0	17.2	23.7
p_T^{b1}	22.8	37.2	31.3	37.6	30.6	22.9	22.3	23.2	38.0	31.7
p_T^Z	10.1	37.8	32.1	35.5	32.4	4.3	1.1	22.3	24.2	22.1
$\Delta\phi_{\ell+\ell-}$	15.1	40.1	29.3	38.5	33.7	3.6	4.3	22.9	25.3	23.4
$\Delta y_{H,b1}$	32.9	35.0	30.1	33.8	30.6	33.7	32.4	30.6	38.5	32.8
$\Delta y_{H,b2}$	34.8	34.9	32.7	32.0	33.8	38.5	35.5	37.6	31.6	33.4
$\tau_{b\bar{b}}$	37.4	37.3	14.9	32.7	30.1	29.3	32.1	31.3	29.7	19.4
$\Delta\eta_{b\bar{b}}$	36.9	35.8	37.3	34.9	35.0	40.1	37.8	37.2	36.2	35.8
$\Delta R_{b\bar{b}}$	9.4	36.9	37.4	34.8	32.9	15.1	10.1	22.8	21.6	26.5

ADDING MORE

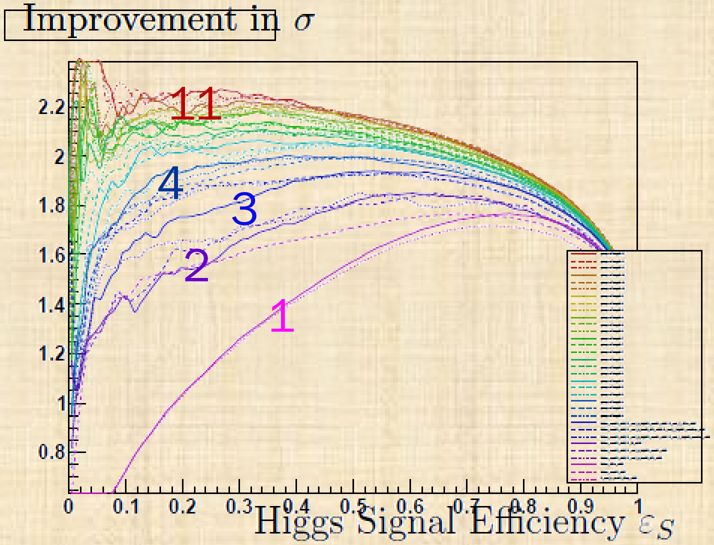
Sequential variable addition

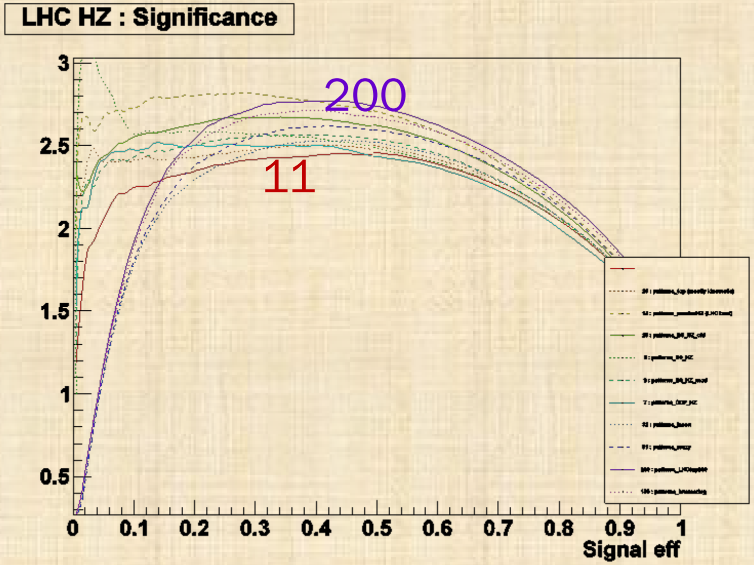
- Take top 3 sets of n variables
- Add any of original 900
- Take top 3 sets of n+1 variables





OBSERVATIONS





- Converges slowly
- Sensitivity to statistics apparent
  - $r_{\square} = 2$ $\square_S = 0.05$ gives $\square_B = 1/1600$
  - 1 million events down to 600

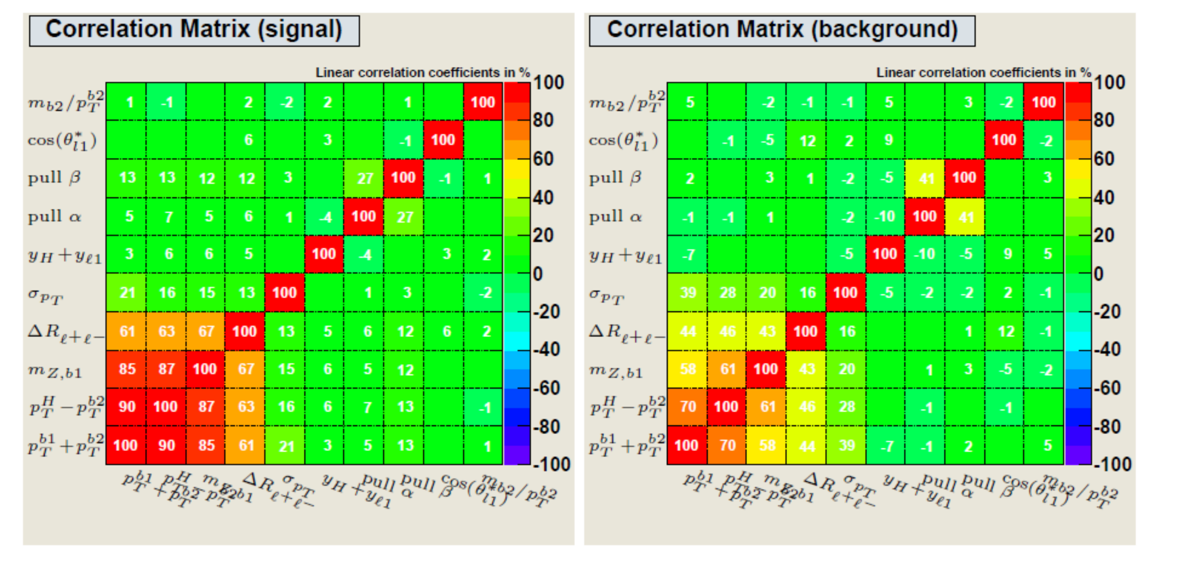
- Some variables very poor by themselves, but show up as 5th or 6th variable

Top 10 include

- Higgs p_T
- $\square R_{ZH}$
- Pull
- Twist y (twist with y not $\square$)
- Event shape D
- Determinant of covariance matrix for radiation in low p_T b jet
- Scalar sum of the b jet p_Ts

CORRELATIONS OF GOOD 10 COMBO

Best 10 combo



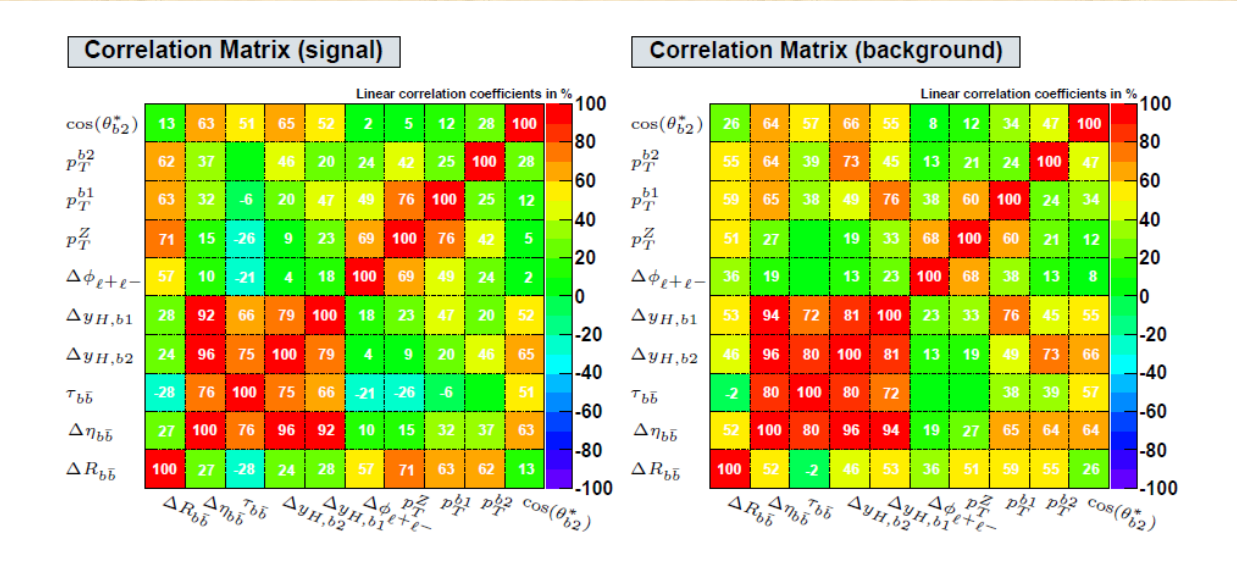
Correlation Matrix (signal)

	$p_T^{b1}+p_T^{b2}$	$p_T^H-p_T^{b2}$	$m_{Z,b1}$	$\Delta R_{\ell+\ell-}$	σ_{p_T}	$y_H+y_{\ell 1}$	pull α	pull β	$\cos(\theta^*_{l1})$	m_{b2}/p_T^{b2}
m_{b2}/p_T^{b2}	1	-1		2	-2	2		1		100
$\cos(\theta^*_{l1})$				6		3		-1	100	
pull β	13	13	12	12	3		27	100	-1	1
pull α	5	7	5	6	1	-4	100	27		
$y_H+y_{\ell 1}$	3	6	6	5		100	-4		3	2
σ_{p_T}	21	16	15	13	100		1	3		-2
$\Delta R_{\ell+\ell-}$	61	63	67	100	13	5	6	12	6	2
$m_{Z,b1}$	85	87	100	67	15	6	5	12		
$p_T^H-p_T^{b2}$	90	100	87	63	16	6	7	13		-1
$p_T^{b1}+p_T^{b2}$	100	90	85	61	21	3	5	13		1

Correlation Matrix (background)

	$p_T^{b1}+p_T^{b2}$	$p_T^H-p_T^{b2}$	$m_{Z,b1}$	$\Delta R_{\ell+\ell-}$	σ_{p_T}	$y_H+y_{\ell 1}$	pull α	pull β	$\cos(\theta^*_{l1})$	m_{b2}/p_T^{b2}
m_{b2}/p_T^{b2}	5		-2	-1	-1	5		3	-2	100
$\cos(\theta^*_{l1})$		-1	-5	12	2	9			100	-2
pull β	2		3	1	-2	-5	41	100		3
pull α	-1	-1	1		-2	-10	100	41		
$y_H+y_{\ell 1}$	-7				-5	100	-10	-5	9	5
σ_{p_T}	39	28	20	16	100	-5	-2	-2	2	-1
$\Delta R_{\ell+\ell-}$	44	46	43	100	16			1	12	-1
$m_{Z,b1}$	58	61	100	43	20		1	3	-5	-2
$p_T^H-p_T^{b2}$	70	100	61	46	28		-1		-1	
$p_T^{b1}+p_T^{b2}$	100	70	58	44	39	-7	-1	2		5

Best 10 individuals



Correlation Matrix (signal)

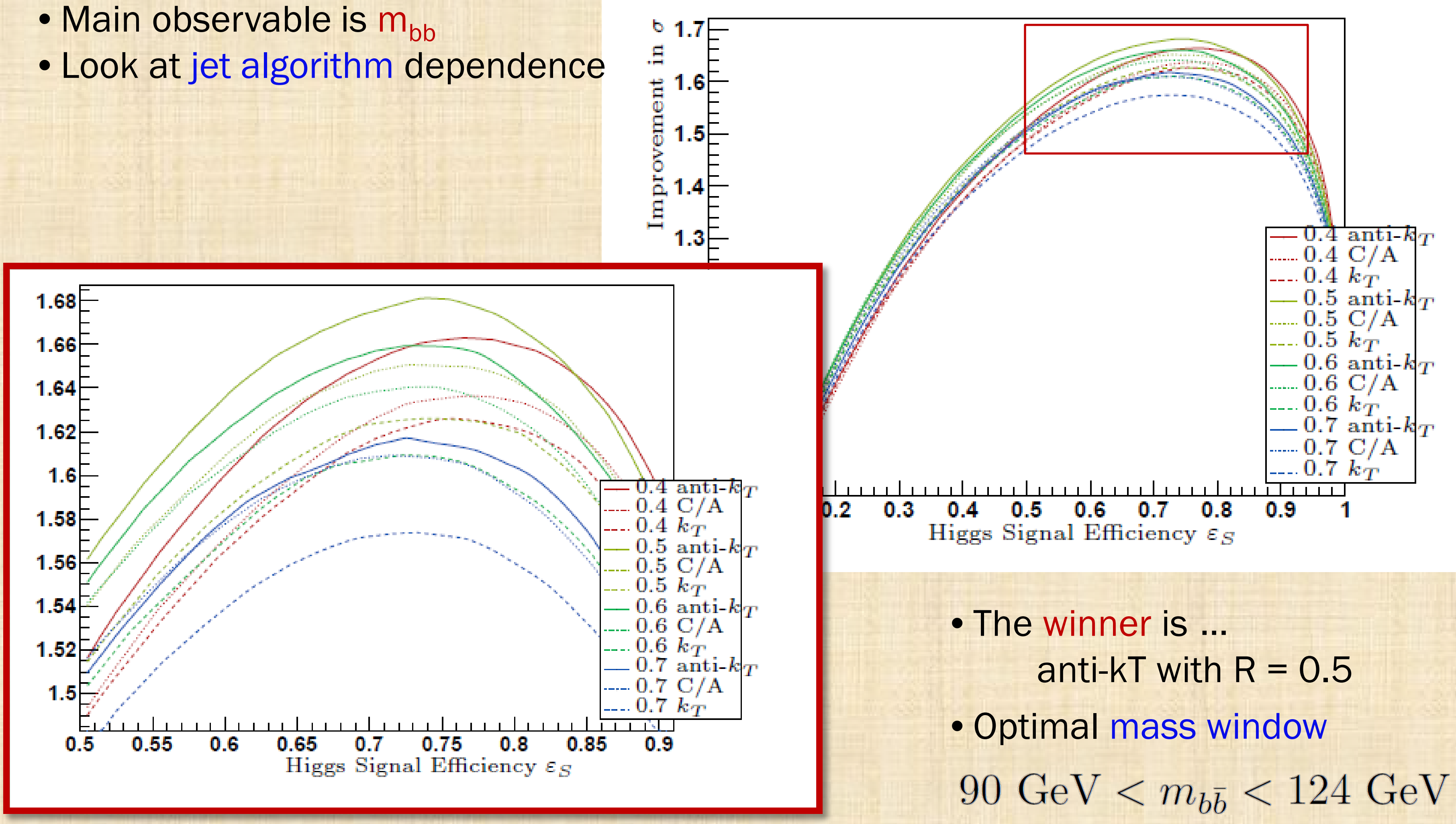
	$\Delta R_{b\bar{b}}$	$\Delta\eta_{b\bar{b}}$	$\tau_{b\bar{b}}$	$\Delta y_{H,b2}$	$\Delta y_{H,b1}$	$\Delta\phi_{\ell+\ell-}$	p_T^Z	p_T^{b1}	p_T^{b2}	$\cos(\theta^*_{b2})$
$\cos(\theta^*_{b2})$	13	63	51	65	52	2	5	12	28	100
p_T^{b2}	62	37		46	20	24	42	25	100	28
p_T^{b1}	63	32	-6	20	47	49	76	100	25	12
p_T^Z	71	15	-26	9	23	69	100	76	42	5
$\Delta\phi_{\ell+\ell-}$	57	10	-21	4	18	100	69	49	24	2
$\Delta y_{H,b1}$	28	92	66	79	100	18	23	47	20	52
$\Delta y_{H,b2}$	24	96	75	100	79	4	9	20	46	65
$\tau_{b\bar{b}}$	-28	76	100	75	66	-21	-26	-6		51
$\Delta\eta_{b\bar{b}}$	27	100	76	96	92	10	15	32	37	63
$\Delta R_{b\bar{b}}$	100	27	-28	24	28	57	71	63	62	13

Correlation Matrix (background)

	$\Delta R_{b\bar{b}}$	$\Delta\eta_{b\bar{b}}$	$\tau_{b\bar{b}}$	$\Delta y_{H,b2}$	$\Delta y_{H,b1}$	$\Delta\phi_{\ell+\ell-}$	p_T^Z	p_T^{b1}	p_T^{b2}	$\cos(\theta^*_{b2})$
$\cos(\theta^*_{b2})$	26	64	57	66	55	8	12	34	47	100
p_T^{b2}	55	64	39	73	45	13	21	24	100	47
p_T^{b1}	59	65	38	49	76	38	60	100	24	34
p_T^Z	51	27		19	33	68	100	60	21	12
$\Delta\phi_{\ell+\ell-}$	36	19		13	23	100	68	38	13	8
$\Delta y_{H,b1}$	53	94	72	81	100	23	33	76	45	55
$\Delta y_{H,b2}$	46	96	80	100	81	13	19	49	73	66
$\tau_{b\bar{b}}$	-2	80	100	80	72			38	39	57
$\Delta\eta_{b\bar{b}}$	52	100	80	96	94	19	27	65	64	64
$\Delta R_{b\bar{b}}$	100	52	-2	46	53	36	51	59	55	26

JET ALGORITHMS

- Main observable is m_{bb}
- Look at jet algorithm dependence



- The winner is …
  anti-kT with R = 0.5
- Optimal mass window

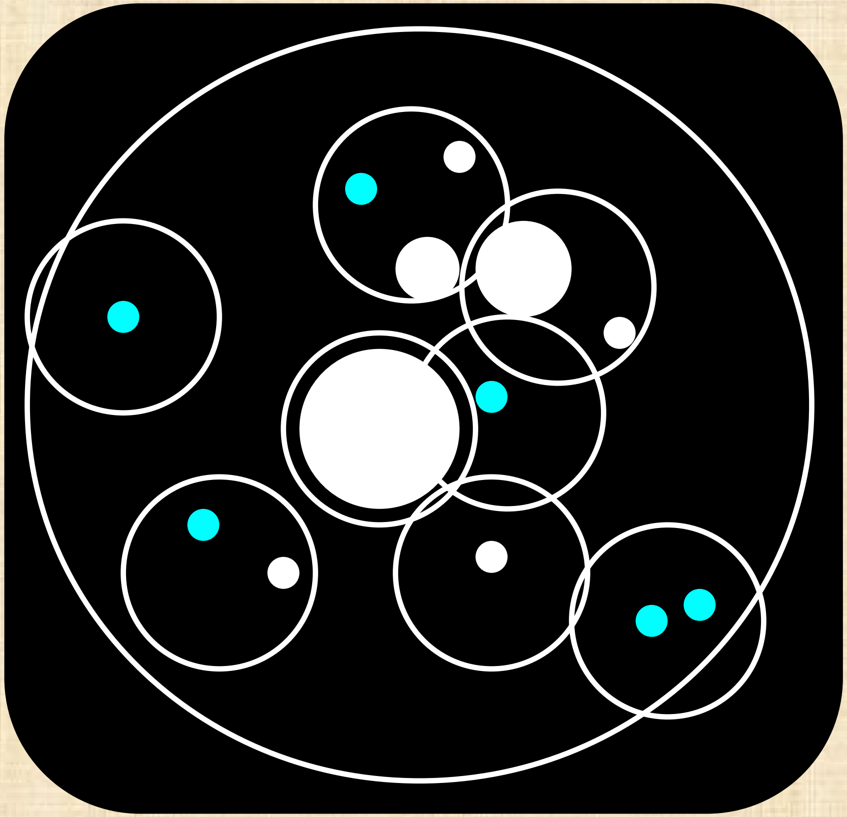
$$90\ \text{GeV} < m_{b\bar{b}} < 124\ \text{GeV}$$

(slides stolen from Brock)

TRIMMING

Krohn, Thaler, Wang

1. Reclustering jet constituents into *very* thin jets

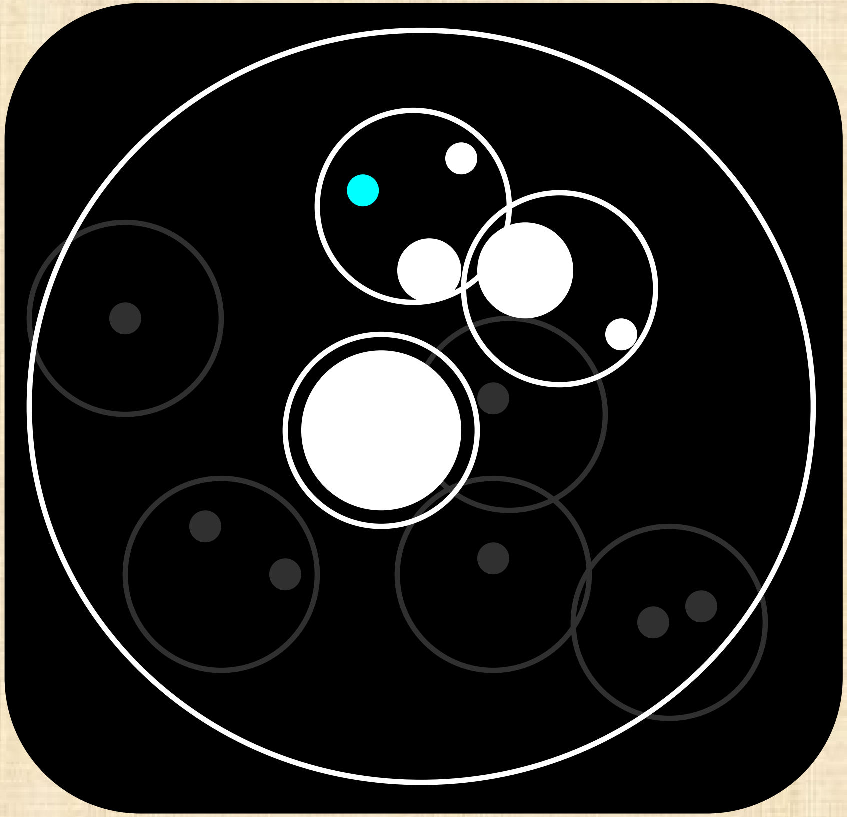


(slides stolen from Brock)

TRIMMING

Krohn, Thaler, Wang

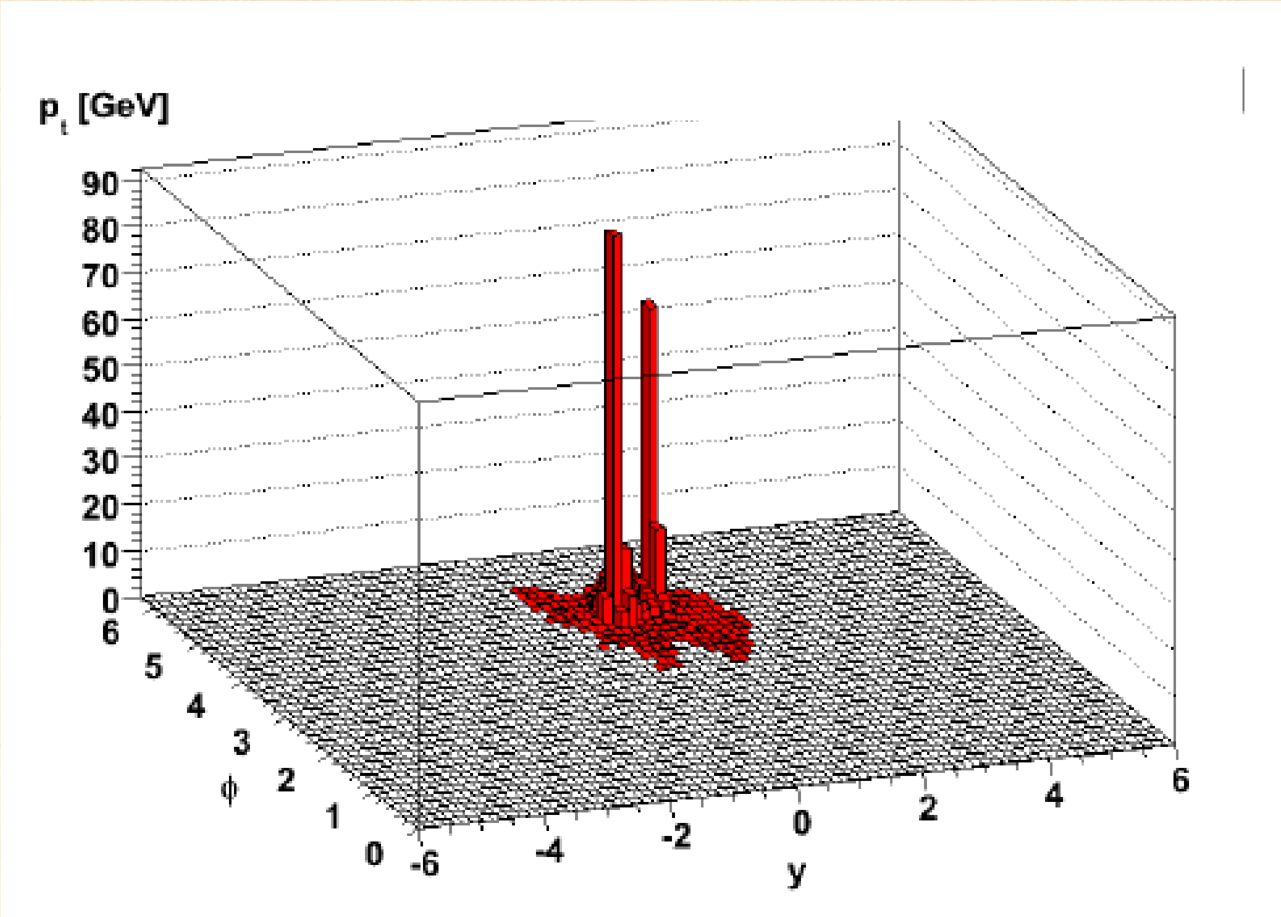
1. Reclluster jet constituents into *very* thin jets

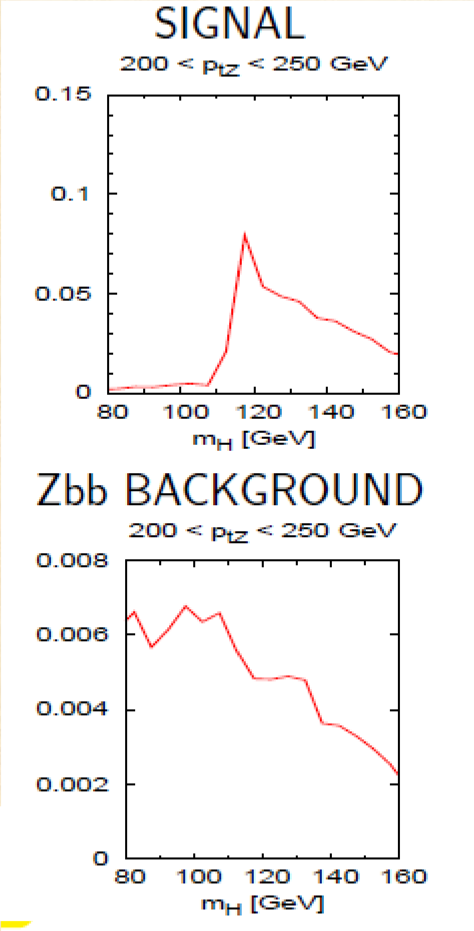


2. Throw away thin jets that are too soft

(slides from Gavin Salam)

TRIMMING Boosted H ⟶ bb



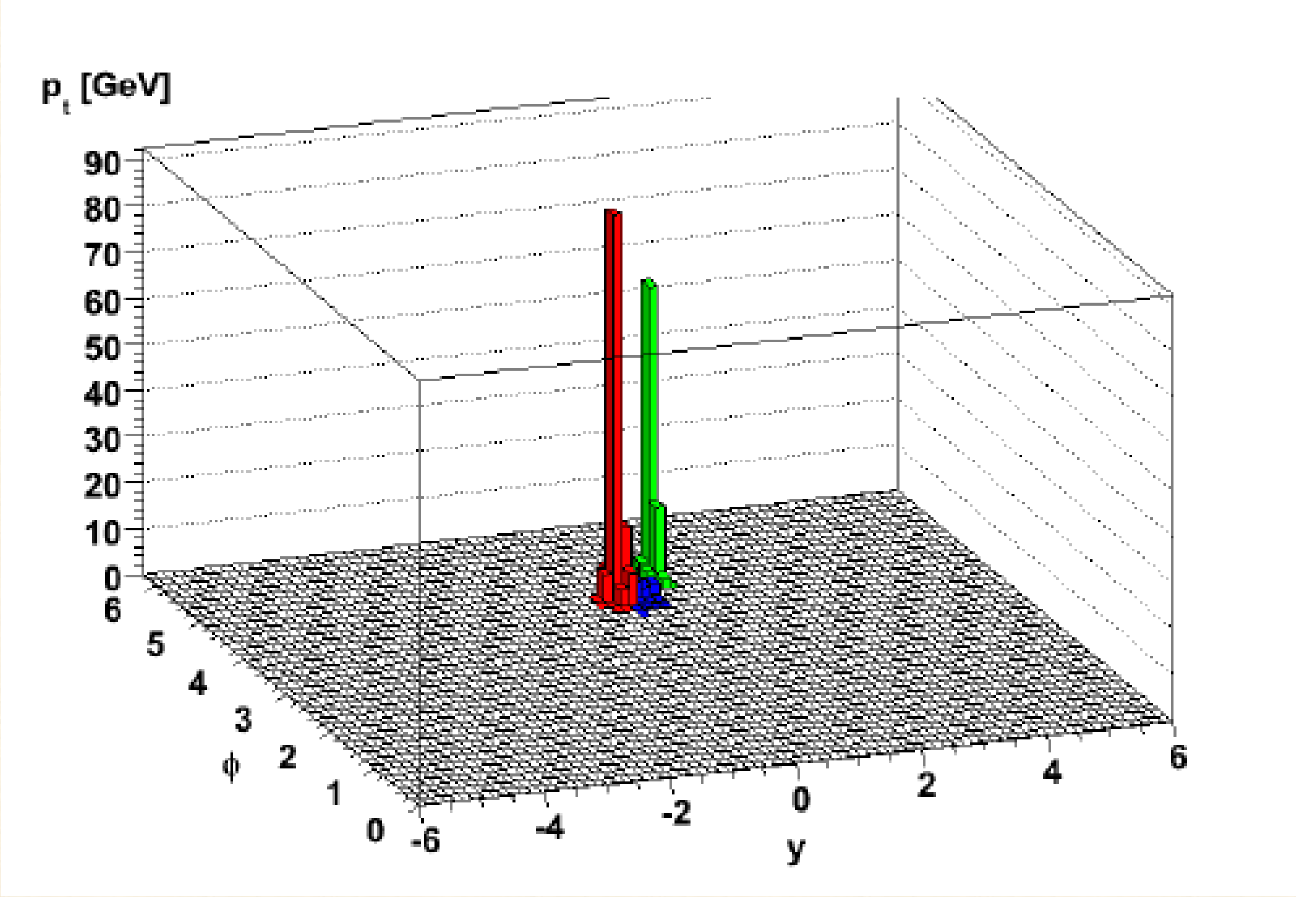

SIGNAL

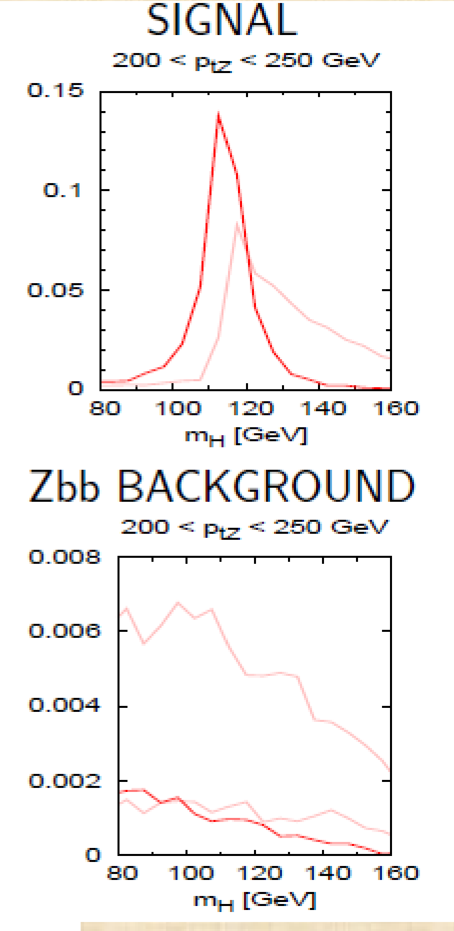
Zbb BACKGROUND

(slides from Gavin Salam)

TRIMMING

Boosted H ⟶ bb

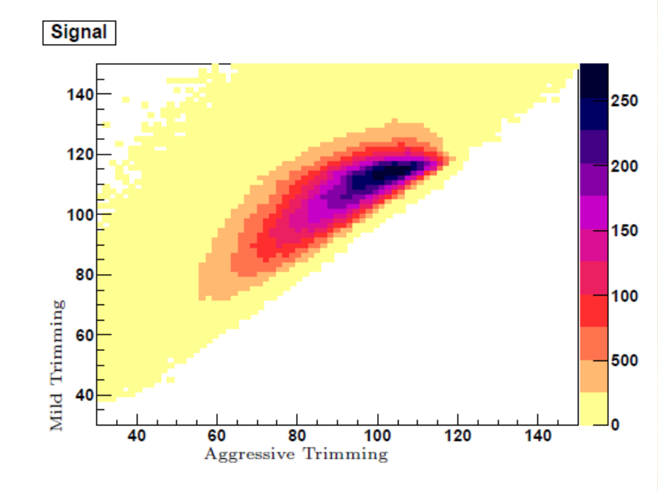


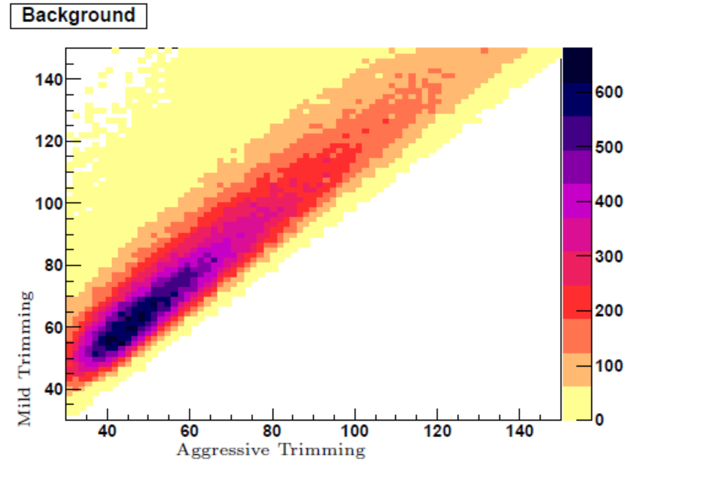

SIGNAL

Zbb BACKGROUND

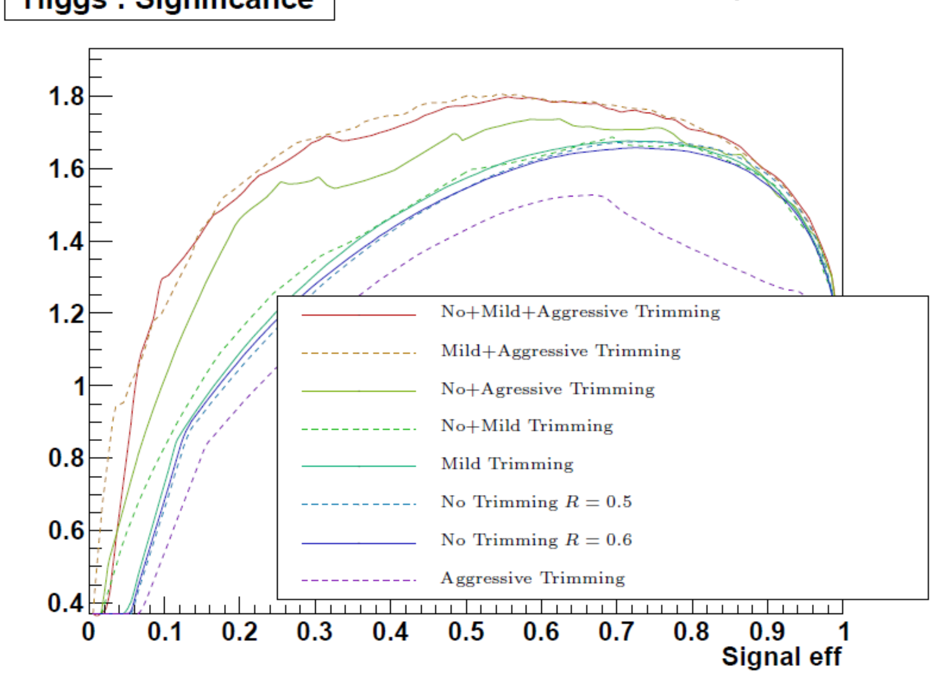
MULTIPLE TRIMMINGS

Trimming does not seem to help much in our case…





Multiple trimmings do help!



(inspired by Soper and Spannowsky)

CONCLUSIONS

- Final efficiencies still under construction
- Looks like we can help the Tevatron searches
    - around 10% with variables (relative to the ones they use)
    - around 10% with masses (assuming they can trim)
- W/Z + H is totally feasible at the LHC
    - Do not need large p_T
    - Discovery potential with 30 fb^{-1}

General Observations

- SIC curves provide a useful visualization
    - demonstrate instabilities
    - show covergance
    - visually compare variables' performance
- Uncorrelated variables helpful after kinematics exhausted
- Multiple mass measures useful

Future

- Compare boosted decision trees, random forest, neural networks, etc.
- Compare different generators (Herwig/Pythia)
- Study reducible backgrounds