Making Sense of Jet Radiation

A Series of Great Lessons

Tilman Plehn

Universität Heidelberg

IPMU 3/2015

WBF Higgs production

Higgs production with jets [w/ Rainwater, Zeppenfeld (1998)]

– the Pheno team (1997)

–

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– first paper to use WBF forward jets for light Higgs [ask Dieter and Dave how it all happened]

Searching for $H \to \tau\tau$ in weak boson fusion at the LHC

D. Rainwater and D. Zeppenfeld

Department of Physics, University of Wisconsin, Madison, WI 53706

K. Hagiwara

Theory Group, KEK, Tsukuba, Ibaraki 305-0801, Japan

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- detector simulations by hand [correct is what experimentalists can reproduce]
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We would like to thank Tao Han for useful discussions and use of his programs for b decay simulations. This research was supported in part by the University of Wisconsin Research

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What to do with jets

- background control makes the difference
- tagging jets

as compared to the Higgs signal: Z and γ bremsstrahlung occur at small angles with respect to the parent quarks, producing τ's forward of the jets. Thus, at the second level of cuts we require both τ's to lie between the jets with a separation in pseudorapidity $\Delta\eta_{j,\tau} > 0.7$, and the jets to occupy opposite hemispheres:

$$\eta_{j,min} + 0.7 < \eta_{\tau_{1,2}} < \eta_{j,max} - 0.7\,, \qquad \eta_{j_1} \cdot \eta_{j_2} < 0 \tag{17}$$

At the third level of cuts, which is also the starting point for our consideration of the various backgrounds, a wide separation in pseudorapidity is required between the two forward tagging jets,

$$\Delta\eta_{tags} = |\eta_{j_1} - \eta_{j_2}| \geq 4.4\,, \tag{18}$$

leaving a gap of at least 3 units of pseudorapidity in which the τ's can be observed. This technique

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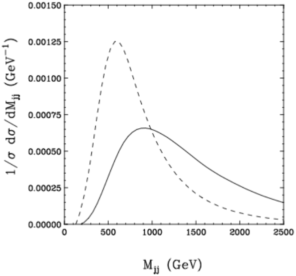

Invariant mass distribution of the two tagging jets for the Hjj signal

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	Hjj	QCD Zjj	EW Zjj	$Wj+jj$	$b\bar{b}jj$	σ_{Gauss}
P_{surv}	0.71	0.14	0.48	0.15	0.15	
no. events	10.4	0.61	0.46	0.11	0.24	5.2

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$\Rightarrow$ Jets are your friends

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B.16 $u\bar{u}$ processes

$\mathbf{u\bar{u} \to X}$						
Final state	MADGRAPH/HELAS 0.5 TeV	2 TeV	O'MEGA/WHIZARD 0.5 TeV	2 TeV	AMEGIC++/SHERPA 0.5 TeV	2 TeV
$\tilde{g}\tilde{g}$	—	1.1377(2)e3	—	1.1378(2)e3	—	1.1377(1)e3
$\tilde{e}_L\tilde{e}_L^*$	5.169(1)	1.5467(3)	5.1698(9)	1.5469(2)	5.1700(3)	1.54698(8)
$\tilde{e}_R\tilde{e}_R^*$	6.538(1)	0.7318(1)	6.538(1)	0.7318(1)	6.5379(3)	0.73179(4)
$\tilde{\mu}_L\tilde{\mu}_L^*$	5.169(1)	1.5467(3)	5.1687(9)	1.5466(3)	5.1693(3)	1.54679(8)
$\tilde{\mu}_R\tilde{\mu}_R^*$	6.538(1)	0.7318(1)	6.536(1)	0.7316(1)	6.5387(3)	0.73189(4)
$\tilde{\tau}_1\tilde{\tau}_1^*$	6.993(1)	0.7195(1)	6.992(1)	0.7194(1)	6.9935(3)	0.71949(4)
$\tilde{\tau}_2\tilde{\tau}_2^*$	4.1263(7)	1.3962(2)	4.1246(7)	1.3957(2)	4.1269(2)	1.39617(7)
$\tilde{\tau}_1\tilde{\tau}_2^*$	0.5420(1)	0.08218(1)	0.54193(9)	0.08217(1)	0.54199(3)	0.082184(4)
$\tilde{\nu}_e\tilde{\nu}_e^*$	5.7063(5)	1.1222(2)	5.706(1)	1.1222(2)	5.7064(3)	1.12224(6)
$\tilde{\nu}_\mu\tilde{\nu}_\mu^*$	5.7063(5)	1.1222(2)	5.704(1)	1.1217(2)	5.7070(3)	1.12237(6)
$\tilde{\nu}_\tau\tilde{\nu}_\tau^*$	5.812(1)	1.1228(2)	5.813(1)	1.1229(2)	5.8126(3)	1.12282(6)
$\tilde{u}_L\tilde{u}_L^*$	—	799.6(1)	—	799.6(1)	—	799.63(4)
$\tilde{u}_R\tilde{u}_R^*$	—	879.7(1)	—	879.7(1)	—	879.75(4)
$\tilde{u}_L\tilde{u}_R^*$	—	784.1(2)	—	784.16(3)	—	784.15(4)
$\tilde{c}_L\tilde{c}_L^*$	—	178.39(1)	—	178.39(2)	—	178.398(9)
$\tilde{c}_R\tilde{c}_R^*$	—	185.63(2)	—	185.62(2)	—	185.655(9)
$\tilde{t}_1\tilde{t}_1^*$	—	245.12(2)	—	245.11(3)	—	245.10(1)
$\tilde{t}_2\tilde{t}_2^*$	—	169.22(1)	—	169.22(2)	—	169.223(8)
$\tilde{t}_1\tilde{t}_2^*$	—	0.47708(4)	—	0.47714(8)	—	0.47712(2)
$\tilde{d}_L\tilde{d}_L^*$	—	166.63(2)	—	166.60(2)	—	166.621(8)
$\tilde{d}_R\tilde{d}_R^*$	—	185.58(2)	—	185.56(3)	—	185.60(1)
$\tilde{s}_L\tilde{s}_L^*$	—	175.69(1)	—	175.68(2)	—	175.686(9)
$\tilde{s}_R\tilde{s}_R^*$	—	185.58(2)	—	185.58(2)	—	185.578(9)
$\tilde{b}_1\tilde{b}_1^*$	—	200.37(2)	—	200.364(8)	—	200.38(1)
$\tilde{b}_2\tilde{b}_2^*$	—	186.50(2)	—	186.500(7)	—	186.51(1)
$\tilde{b}_1\tilde{b}_2^*$	—	0.19827(2)	—	0.198272(8)	—	0.19827(1)
$\tilde{\chi}_1^0\tilde{\chi}_1^0$	2.2483(1)	1.2164(1)	2.24829(2)	1.2165(1)	2.2483(1)	1.2165(2)
$\tilde{\chi}_1^0\tilde{\chi}_2^0$	0.053855(3)	0.10850(1)	0.0538560(9)	0.10850(1)	0.053855(3)	0.108493(5)
$\tilde{\chi}_1^0\tilde{\chi}_3^0$	0.524518(4)	0.096758(1)	0.524526(3)	0.096752(5)	0.52450(3)	0.096763(5)
$\tilde{\chi}_1^0\tilde{\chi}_4^0$	9.8233(3)e-3	0.067303(3)	9.82339(8)e-3	0.067293(6)	9.8238(5)e-3	0.067308(3)
$\tilde{\chi}_2^0\tilde{\chi}_2^0$	3.66463(5)	4.2298(3)	3.66472(3)	4.2296(4)	3.6646(2)	4.2298(3)
$\tilde{\chi}_2^0\tilde{\chi}_3^0$	—	0.21148(3)	—	0.211458(8)	—	0.21147(1)
$\tilde{\chi}_2^0\tilde{\chi}_4^0$	—	0.55025(5)	—	0.55025(8)	—	0.55028(3)
$\tilde{\chi}_3^0\tilde{\chi}_3^0$	—	3.3843(1)e-4	—	3.3843(1)e-4	—	3.3844(2)e-4
$\tilde{\chi}_3^0\tilde{\chi}_4^0$	—	4.4435(3)	—	4.4433(2)	—	4.4436(2)
$\tilde{\chi}_4^0\tilde{\chi}_4^0$	—	0.016385(3)	—	0.016389(3)	—	0.016386(1)
$\tilde{\chi}_1^+\tilde{\chi}_1^-$	153.97(2)	10.732(5)	153.977(2)	10.734(2)	153.964(8)	10.7329(5)
$\tilde{\chi}_2^+\tilde{\chi}_2^-$	—	5.0402(5)	—	5.0401(2)	—	5.0400(3)
$\tilde{\chi}_1^+\tilde{\chi}_2^-$	—	1.5363(2)	—	1.5362(2)	—	1.5363(1)
Zh^0	22.795(2)	1.1958(1)	22.797(2)	1.1960(2)	22.798(1)	1.19582(6)
ZH^0	2.37220(1)e-4	2.1138(2)e-4	2.37224(1)e-4	2.1142(4)e-4	2.3723(1)e-4	2.1141(1)e-4

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SPS	1a	1b	2	3	4	5	6	7	8	9
$\chi_1^0\chi_1^0$	0.003	0	0	0	0	0.001	0	0.001	0	0.46
$\chi_1^0\chi_2^0$	0.018	0.001	0.002	0.001	0.004	0.003	0.003	0.008	0.003	0
$\chi_1^0\chi_3^0$	0.002	0	0	0	0.001	0	0.001	0.003	0.001	0.002
$\chi_1^0\chi_4^0$	0.002	0	0	0	0.001	0	0.001	0.001	0.001	0.002
$\chi_2^0\chi_2^0$	0.52	0.10	0.24	0.10	0.26	0.29	0.039	0.057	0.15	0
$\chi_2^0\chi_2^0$	0.049	0.008	0.009	0.008	0.026	0.008	0.009	0.017	0.016	0
$\chi_2^0\chi_4^0$	0.065	0.011	0.011	0.011	0.034	0.009	0.023	0.045	0.022	0
$\chi_3^0\chi_3^0$	0.006	0.001	0.001	0.001	0.004	0.001	0.004	0.009	0.003	0
$\chi_3^0\chi_4^0$	0.008	0.001	0.001	0.001	0.004	0.001	0.005	0.013	0.003	0
$\chi_4^0\chi_4^0$	0.007	0.001	0.001	0.001	0.004	0.001	0.008	0.020	0.003	0

TABLE I: Cross sections [fb] for WBF neutralino pair production at LHC, for all MSSM benchmark SPS points, using the kinematic cuts of Eqs. (14) and (15). Cross sections are shown to two

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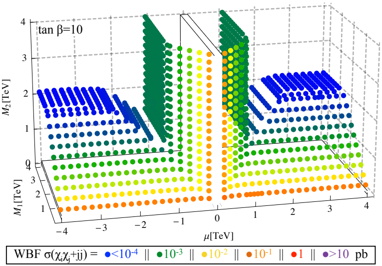
- at 100 TeV? [Takeuchi etal, Wang etal]



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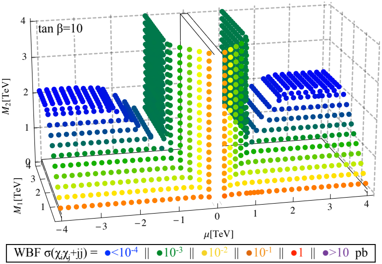
$\Rightarrow$ Attobarn is a unit for LHC rates



Tagging jet correlations

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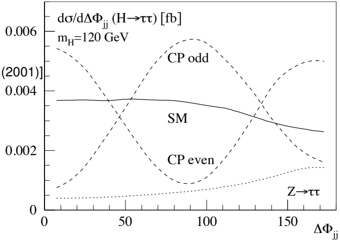

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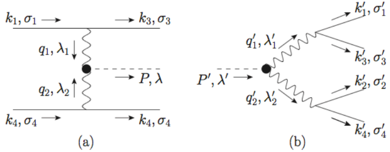

Figure 2: Schematic view of the subprocesses for (a) the X production with 2 jets via VBF, and (b) the X decay to 4 jets via a vector-boson pair. The four-momentum and the helicity of each particle are shown. The solid lines show either fermions or gluons.

The helicity amplitudes for the VBF processes (2.1) can generally be expressed as

$$\mathcal{M}^{\lambda}_{\sigma_1\sigma_3,\sigma_2\sigma_4} = \sum_{V_{1,2}} J^{\mu_1'}_{V_1 a_1 a_3}(k_1, k_3; \sigma_1, \sigma_3)\, J^{\mu_2'}_{V_2 a_2 a_4}(k_2, k_4; \sigma_2, \sigma_4) \times D^{V_1}_{\mu_1'\mu_1}(q_1)\, D^{V_2}_{\mu_2'\mu_2}(q_2)\, \Gamma^{\mu_1\mu_2}_{XV_1V_2}(q_1, q_2; \lambda)^*, \quad (2.3)$$

where $J^{\mu}_{V_1 a_1 a_3}$ and $J^{\mu}_{V_2 a_2 a_4}$ are the external fermion or gluon currents, and the vector-boson propagators are

$$D^{V_i}_{\mu'\mu}(q_i) = \begin{cases} \left(-g_{\mu'\mu} + \frac{q_{i\mu'} q_{i\mu}}{m^2_{V_i}}\right) D_{V_i}(q_i^2) & \text{for } V_i = W, Z, \\ -g_{\mu'\mu} D_{V_i}(q_i^2) & \text{for } V_i = \gamma, g, \end{cases} \quad (2.4)$$

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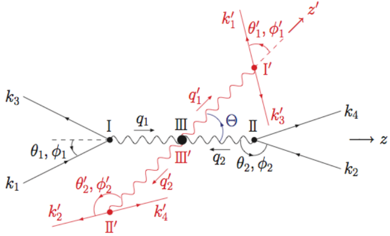

Figure 3: The momentum and angular configuration of the particles in the q_1 and q_2 Breit frame, (I) and (II), and the VBF frame (III) for the production; in the q_1' and q_2' rest frame, (I′) and (II′), and the X rest frame (III′) for the decay.

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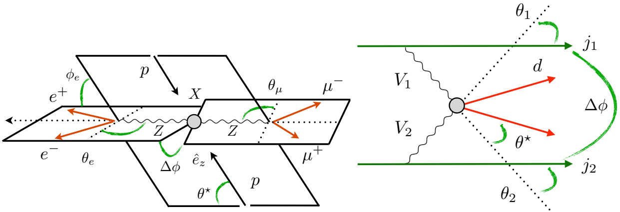
– step back: it's just Cabibbo angles



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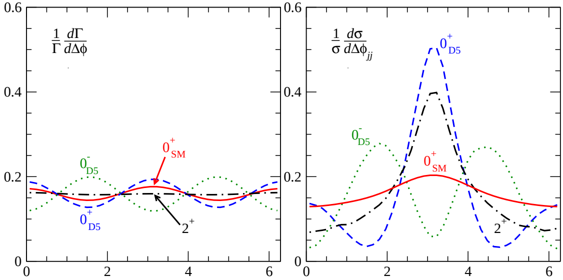

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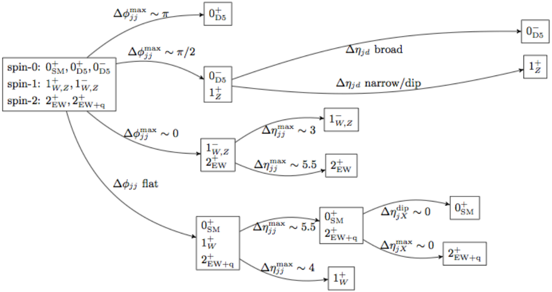
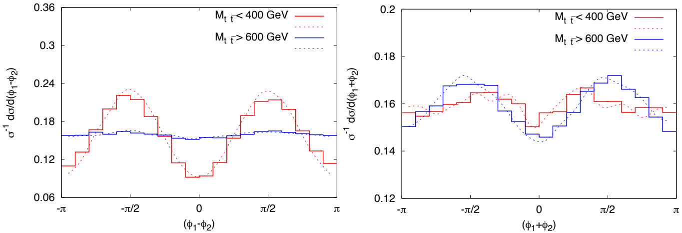
- few observables key...



Tops plus jets

Heavy quarks plus jets [w/ Mukhopadhyay (2013)]

- $t\bar{t}$ and $b\bar{b}$ + 2 QCD jets
- threshold production necessary



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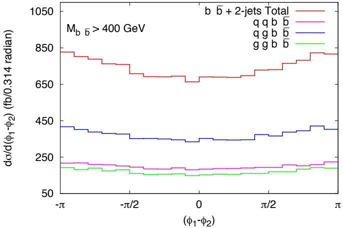
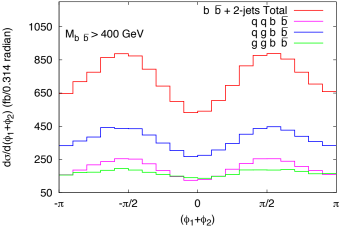
– $t\bar{t}$ and $b\bar{b}$ + 2 QCD jets

– threshold production necessary





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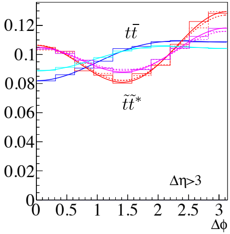
- series in $\Delta\phi$ truncated by available helicities [Buckley, TP, Ramsey-Musolf]

$$\frac{d\sigma}{d\Delta\phi} = A_0 + A_1 \cos\Delta\phi + A_2 \cos(2\Delta\phi)$$

- sign of A_2 set by spin of (s)tops
- 3-jet merged stronger correlated than 2-jets exclusive

$\Rightarrow$ The fun will start with Run2



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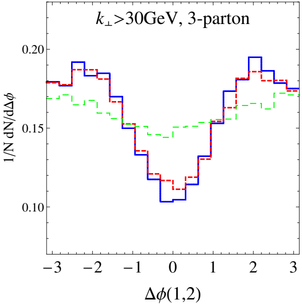
- CKKW-L merging up to 3 jets [MLM too time consuming]
- comparison of 1,2,3 hard jets



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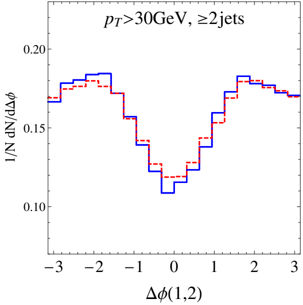

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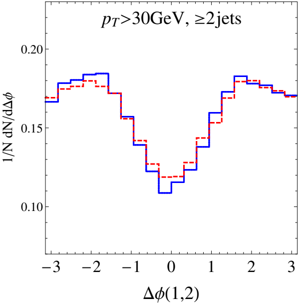

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Outlook

Thank you, Kaoru!

Great LHC ideas also beed hard work

Jets are your friends

BSM physics deserves proper simulation

Attobarn is a unit for LHC rates

I am too stupid for this paper

The fun will start with Run2

It helps to get your LHC tools right