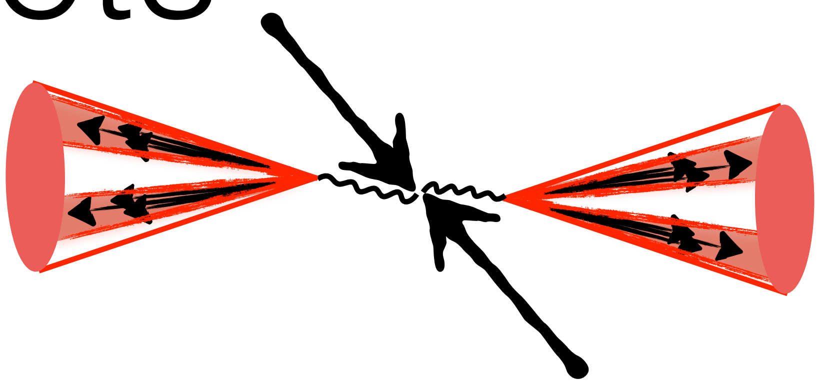
Diboson Interference Resurrection at LHC via subjets



Rafael Aoude and William Shepherd

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to be publish soon..

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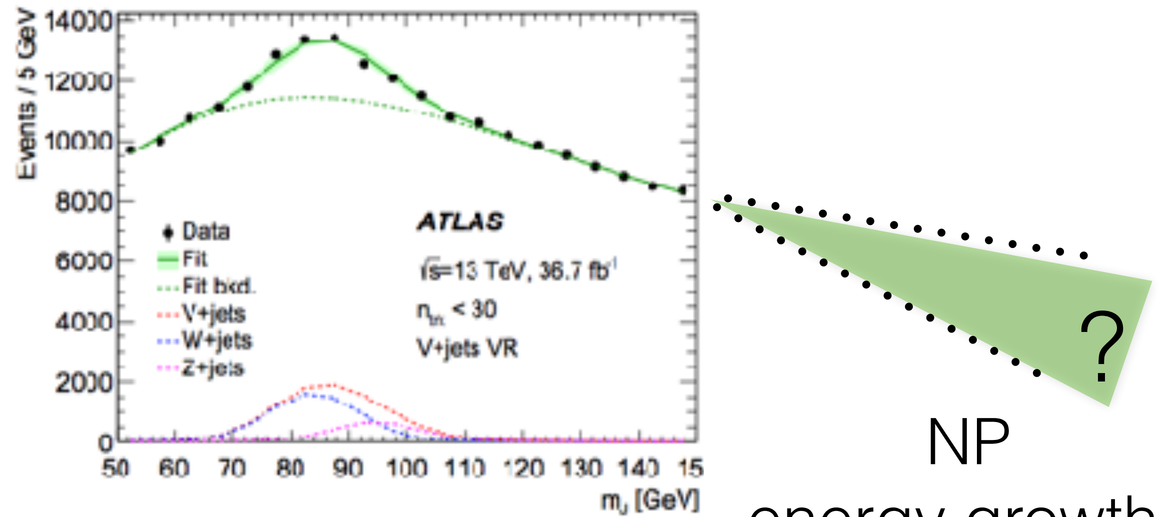
focusing on distribution tails of WW/WZ production at LHC …

new physics
via **anomalous Triple Gauge coupling**



NP
energy growth?

$$\sigma_{\text{int}} \sim A^{\text{SM}}(A^{\text{BSM}})^*$$

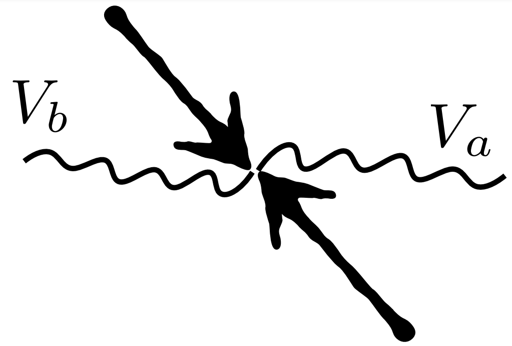
for some ops: 2 → 2 don't interfere

…but the actual process 2 → 4 does

requires unfolding
angular distribution !

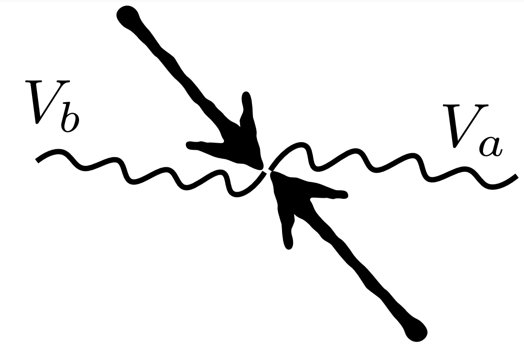
jet substructure
techniques

WZ/WW production at LHC



$$\mathcal{L}_{\mathrm{SM}} \supset -i g_{WWV} \left(\underbrace{g_{1,V}}_{=1} (W^{+\mu\nu} W^{-}_{\mu} V_{\nu} - W^{-\mu\nu} W^{-}_{\mu} V_{\nu}) + \underbrace{\kappa^{V}}_{=1} W^{+}_{\mu} W^{-}_{\nu} V^{\mu\nu} \right)$$

WZ/WW production at LHC



$$\mathcal{L}_{\rm SM} \supset -ig_{WWV}\left(\underset{=1}{g_{1,V}}(W^{+\mu\nu}W^-_\mu V_\nu - W^{-\mu\nu}W^-_\mu V_\nu) + \underset{=1}{\kappa^V} W^+_\mu W^-_\nu V^{\mu\nu}\right)$$

deviations from SM

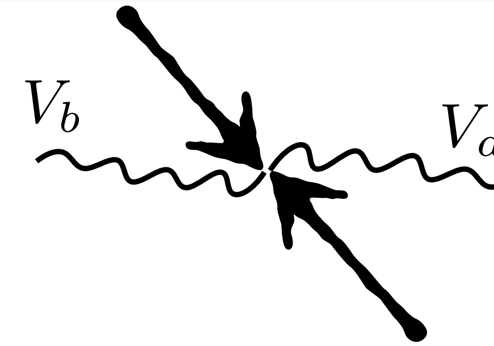
$$\mathcal{L}_{\rm BSM,1} = ig\, c_W\, \delta g_{1,Z}\, Z_\nu W^{+\mu\nu}W^-_\mu + {\rm h.c.} + ig(c_W\, \delta\kappa_Z Z^{\mu\nu} + s_W\, \delta\kappa_\gamma A^{\mu\nu})W^+_\mu W^-_\nu$$

gauge invariance

$$\delta g_{1,\gamma} = 0$$

$$\delta\kappa_Z = \delta g_{1,z} - s^2_W/c^2_W \delta\kappa_\gamma$$

WZ/WW production at LHC



$$\mathcal{L}_{\mathrm{SM}} \supset -ig_{WWV}\left(\underset{=1}{g_{1,V}}(W^{+\mu\nu}W^{-}_{\mu}V_{\nu} - W^{-\mu\nu}W^{-}_{\mu}V_{\nu}) + \underset{=1}{\kappa^{V}}W^{+}_{\mu}W^{-}_{\nu}V^{\mu\nu}\right)$$

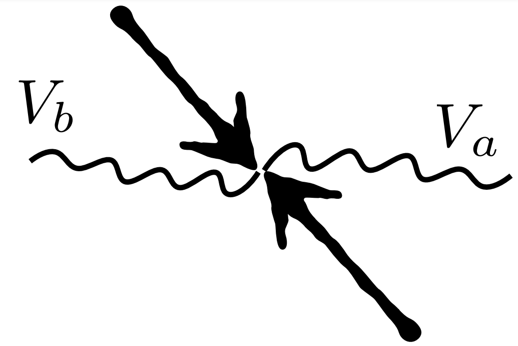
deviations from SM

$$\mathcal{L}_{\mathrm{BSM},1} = ig\,c_W\,\delta g_{1,Z}\,Z_{\nu}W^{+\mu\nu}W^{-}_{\mu} + \mathrm{h.c.} + ig(c_W\,\delta\kappa_Z Z^{\mu\nu} + s_W\,\delta\kappa_{\gamma}A^{\mu\nu})W^{+}_{\mu}W^{-}_{\nu}$$

new op.

$$\mathcal{L}_{\mathrm{BSM},2} = \frac{ig\,\lambda_Z}{M_W^2}W^{+\nu}_{\mu}W^{-\rho}_{\nu}W^{3\mu}_{\rho}$$

WZ/WW production at LHC



$$\mathcal{L}_{\rm SM} \supset -i g_{WWV} \left(\underbrace{g_{1,V}}_{=1} (W^{+\mu\nu} W^-_\mu V_\nu - W^{-\mu\nu} W^-_\mu V_\nu) + \underbrace{\kappa^V}_{=1} W^+_\mu W^-_\nu V^{\mu\nu} \right)$$

deviations from SM

$$\mathcal{L}_{\rm BSM,1} = i g\, c_W\, \delta g_{1,Z} Z_\nu W^{+\mu\nu} W^-_\mu + \text{h.c.} + i g (c_W\, \delta\kappa_Z Z^{\mu\nu} + s_W\, \delta\kappa_\gamma A^{\mu\nu}) W^+_\mu W^-_\nu$$

same helicities as SM

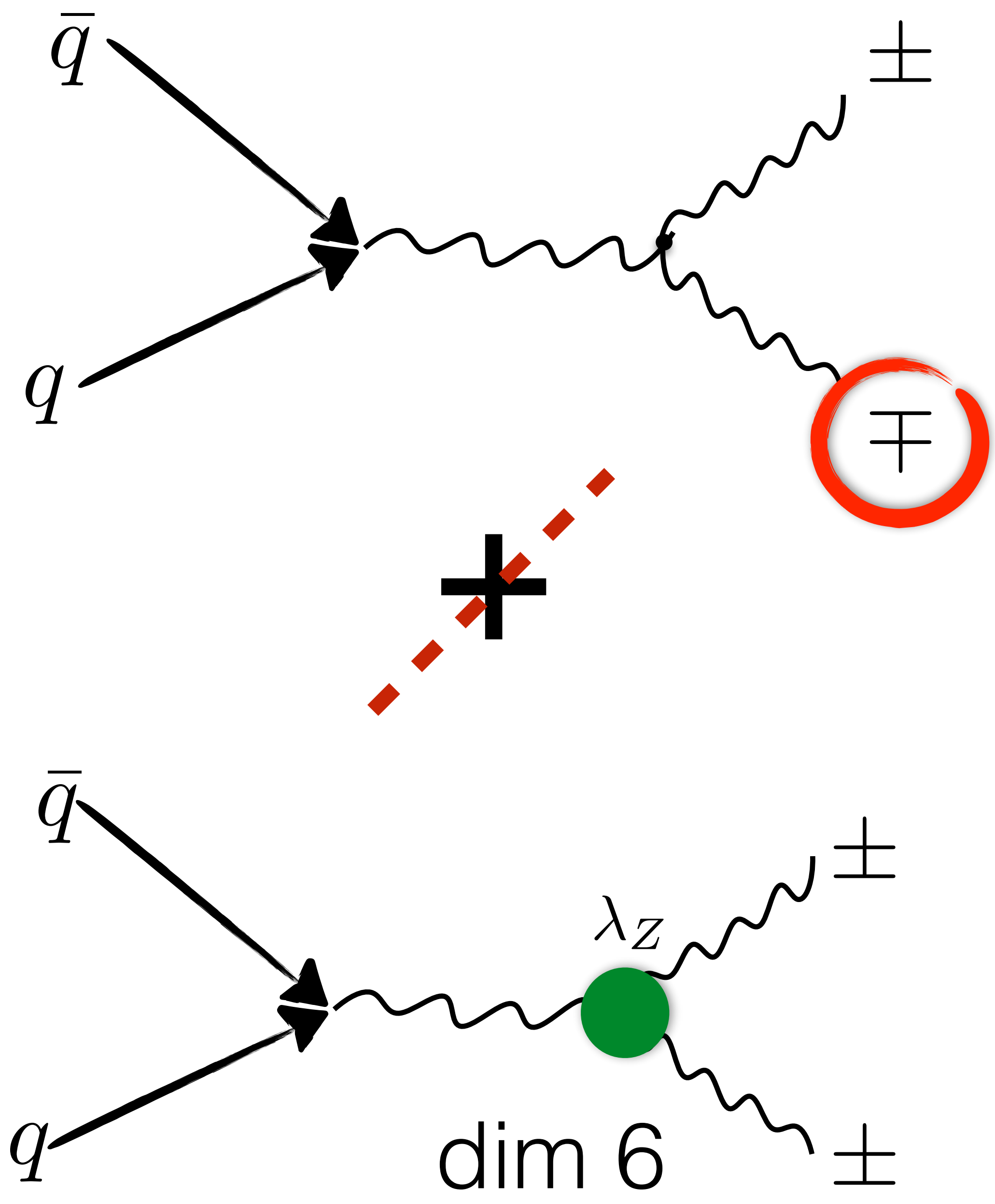
new op.

$$\mathcal{L}_{\rm BSM,2} = \frac{i g\, \lambda_Z}{M_W^2} W^{+\nu}_\mu W^{-\rho}_\nu W^{3\mu}_\rho$$

different helicities

$2 \to 2$
suppressed
operator

Diboson non-interference λ_Z



$$\mathcal{A}^{\rm SM}(q\bar{q} \to V_T W_T^{\pm}) \sim E^0$$

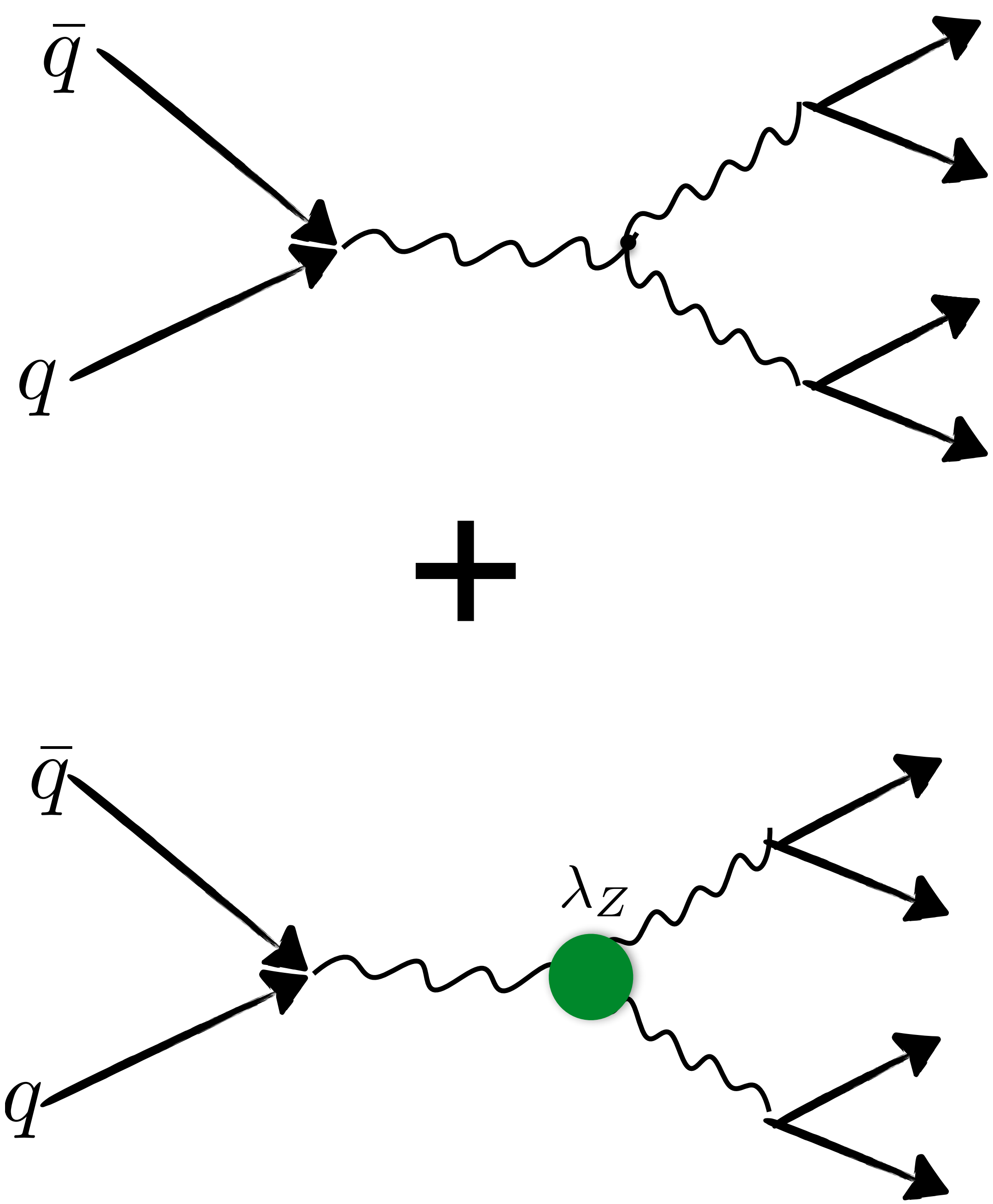
$$\mathcal{A}^{BSM,\lambda_Z}(q\bar{q} \to V_T W_T^{\pm}) \sim \frac{E^2}{m_W^2}\lambda_Z$$

2 → 2 scattering amplitudes don't interfere!!

[Dixon and Shadmi, 94]

[Azatov, Contino, Machado and Riva, 16]

Diboson Ressurection! λ_Z



$2 \rightarrow 4$ scattering amplitudes interfere!!

unfold angular distributions

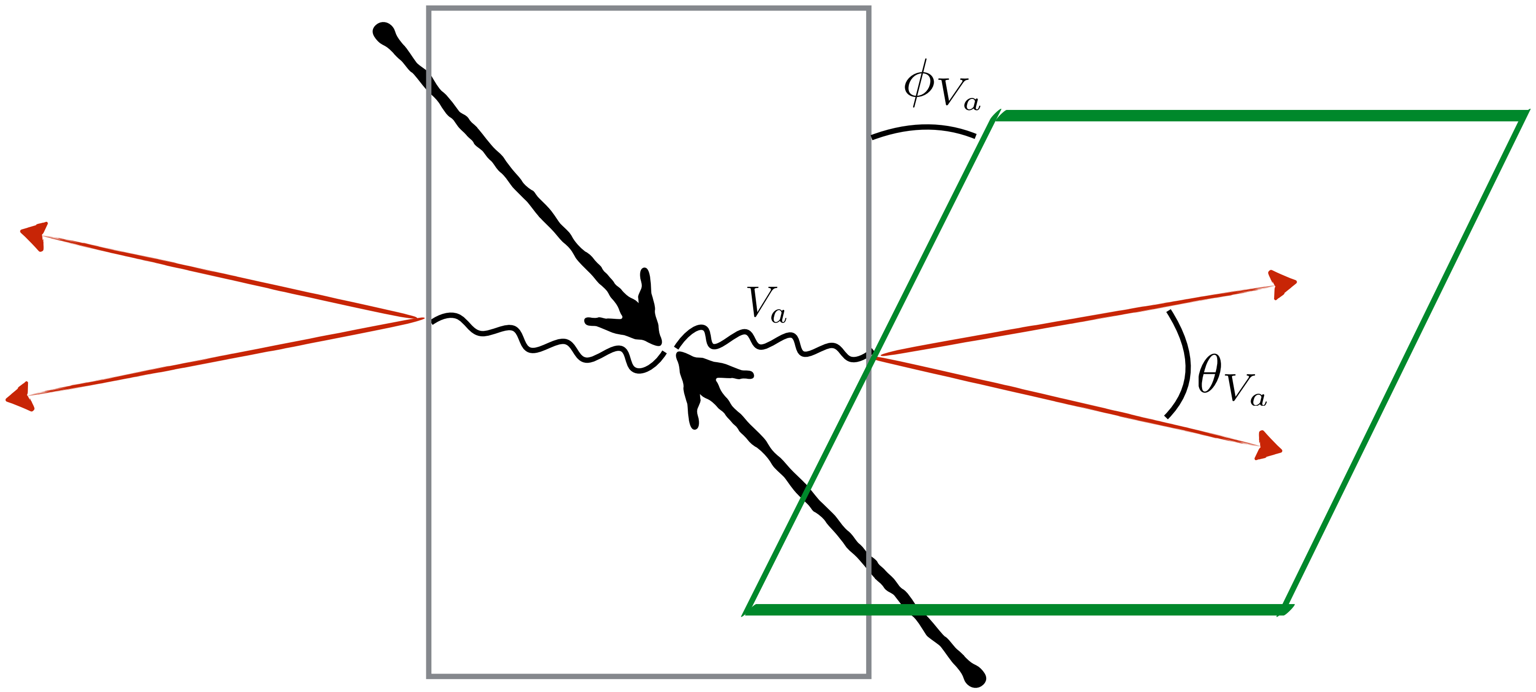
Azimuthal angles are important !

Diboson interference resurrection

only $\frac{ig\,\lambda_Z}{M_W^2} W_\mu^{+\nu} W_\nu^{-\rho} W_\rho^{3\mu}$

Unfold angular distributions

$$\frac{d\sigma_{\rm int}(q\bar{q} \to V_a V_b \to 4\psi)}{d\phi_{V_a} d\phi_{V_b}} \sim \cos 2\phi_{V_a} + \cos 2\phi_{V_b}$$

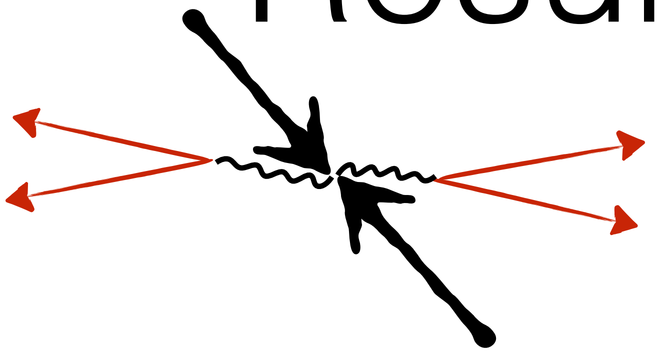


[Dixon and Shadmi, 94]

[Panico, Riva, and Wulzer, 17]

[Azatov, Elias-Miró, Reyimuaji and Venturini, 17]

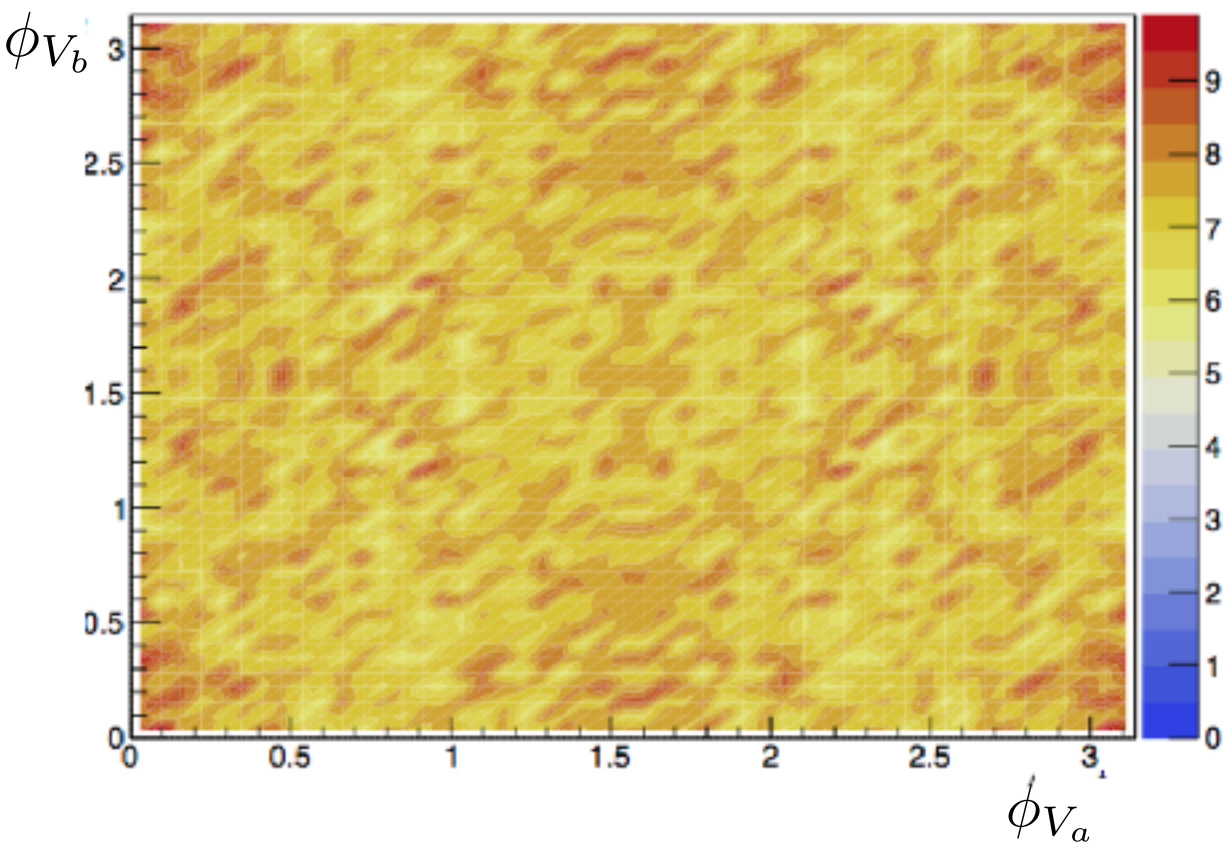
Resurrection at partonic level



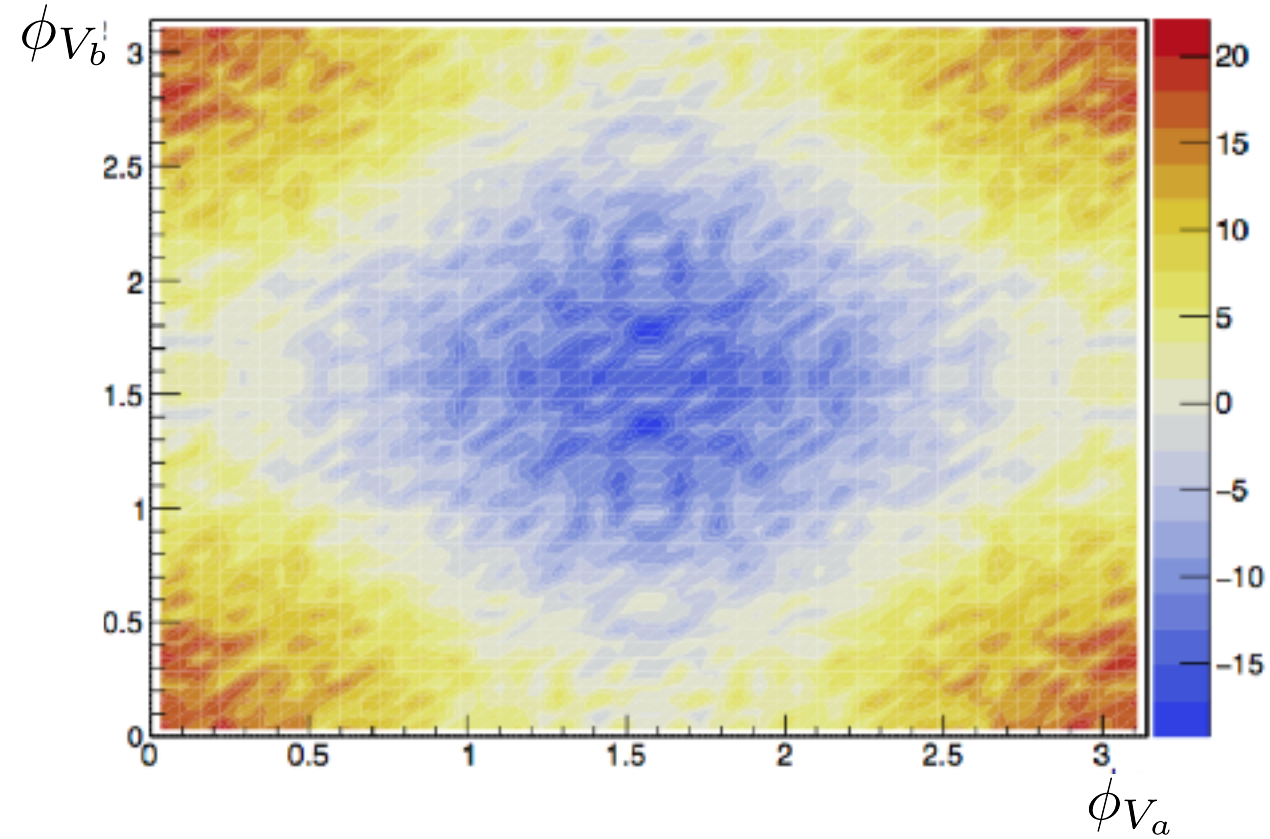
partonic case

$q\bar{q} \to W^+W^- \to 4q$

$\sigma_{\rm SM}$



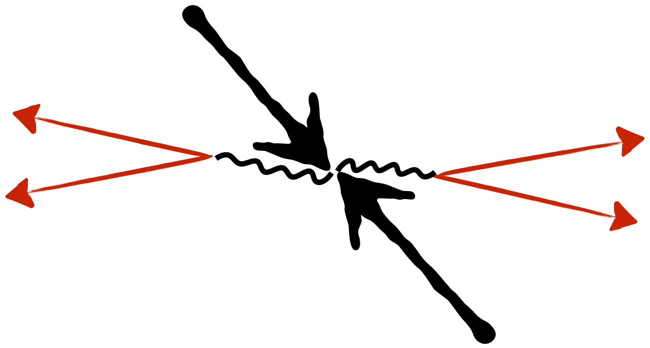
$\sigma_{\rm int}$



$700\text{GeV} \le m_{VV} \le 800\text{GeV}$

$$\frac{ig\,\lambda_Z}{M_W^2} W_\mu^{+\nu} W_\nu^{-\rho} W_\rho^{3\mu}$$

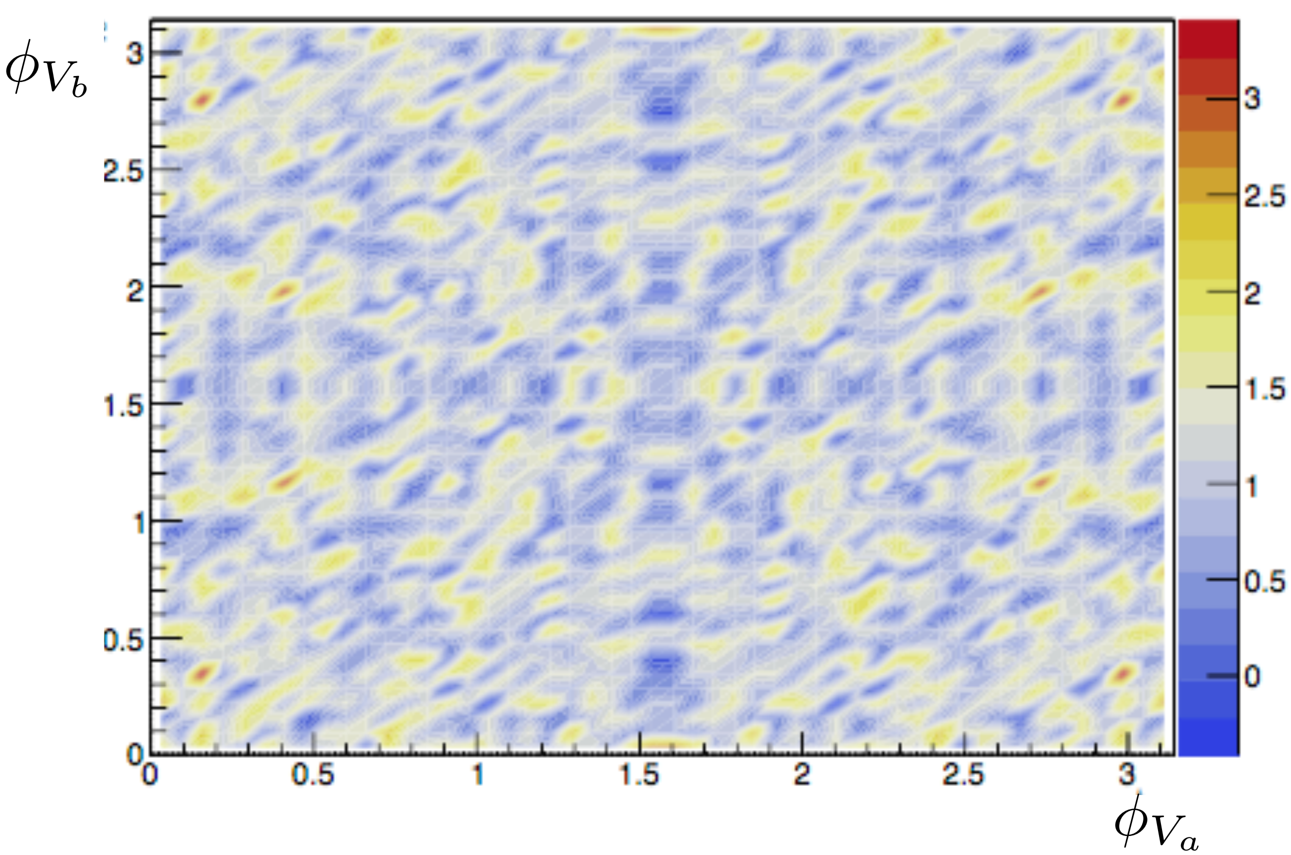
Can other dim-6 ops. produce this pattern?



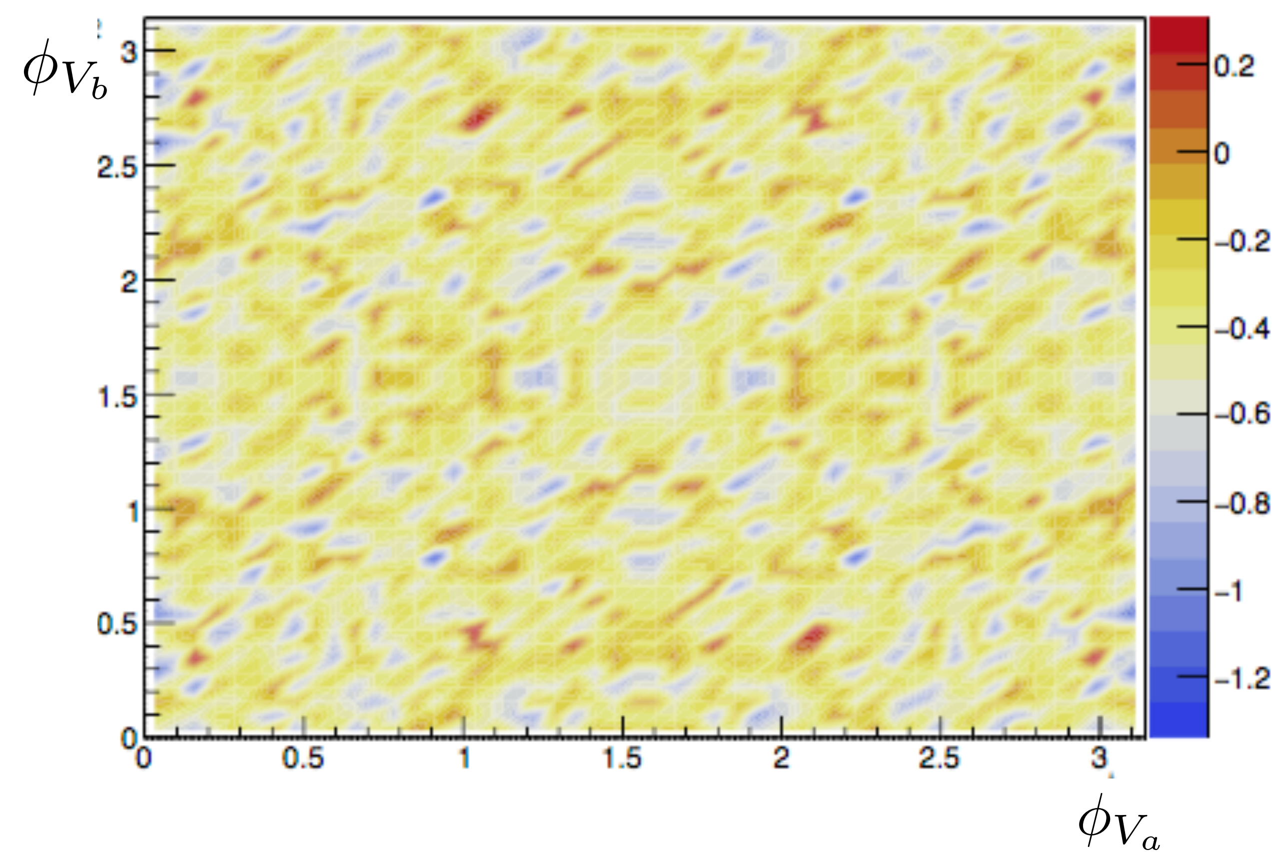
partonic case

$q\bar{q} \to W^+W^- \to 4q$

$ig\, c_W\, \delta g_{1,Z}\, Z_\nu W^{+\mu\nu} W^-_\mu$



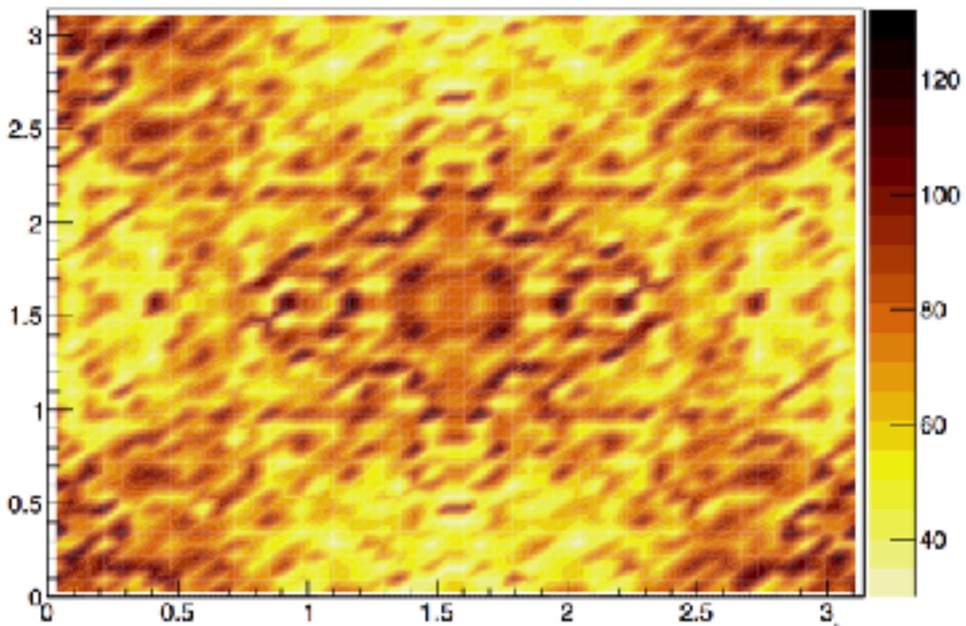
$igc_W \delta\kappa_Z\; Z^{\mu\nu} W^+_\mu W^-_\nu$



Can BSM^2 produce this pattern?

partonic case

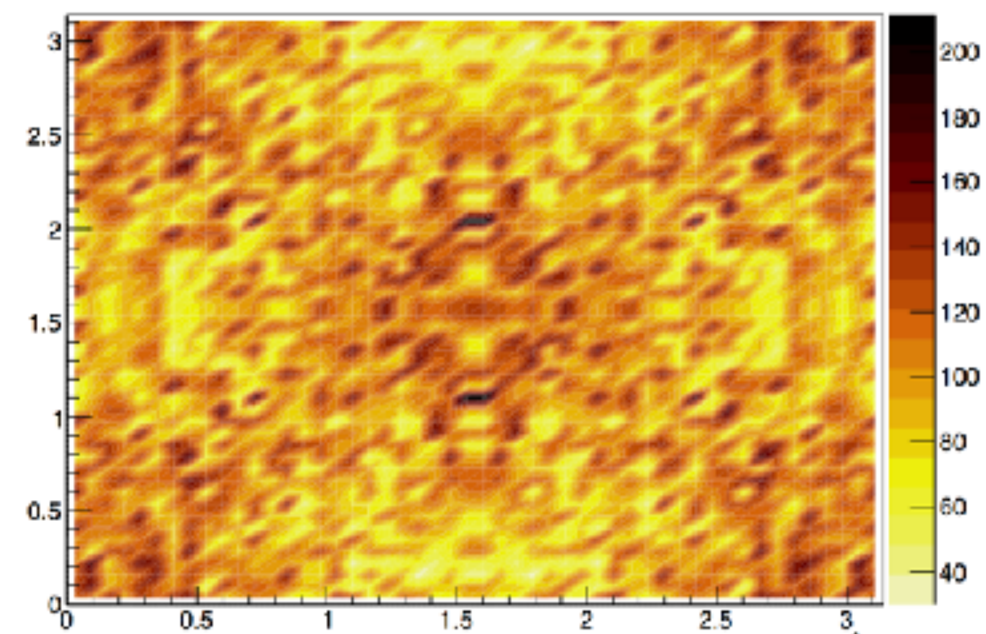
only λ_Z



some pattern but same sign

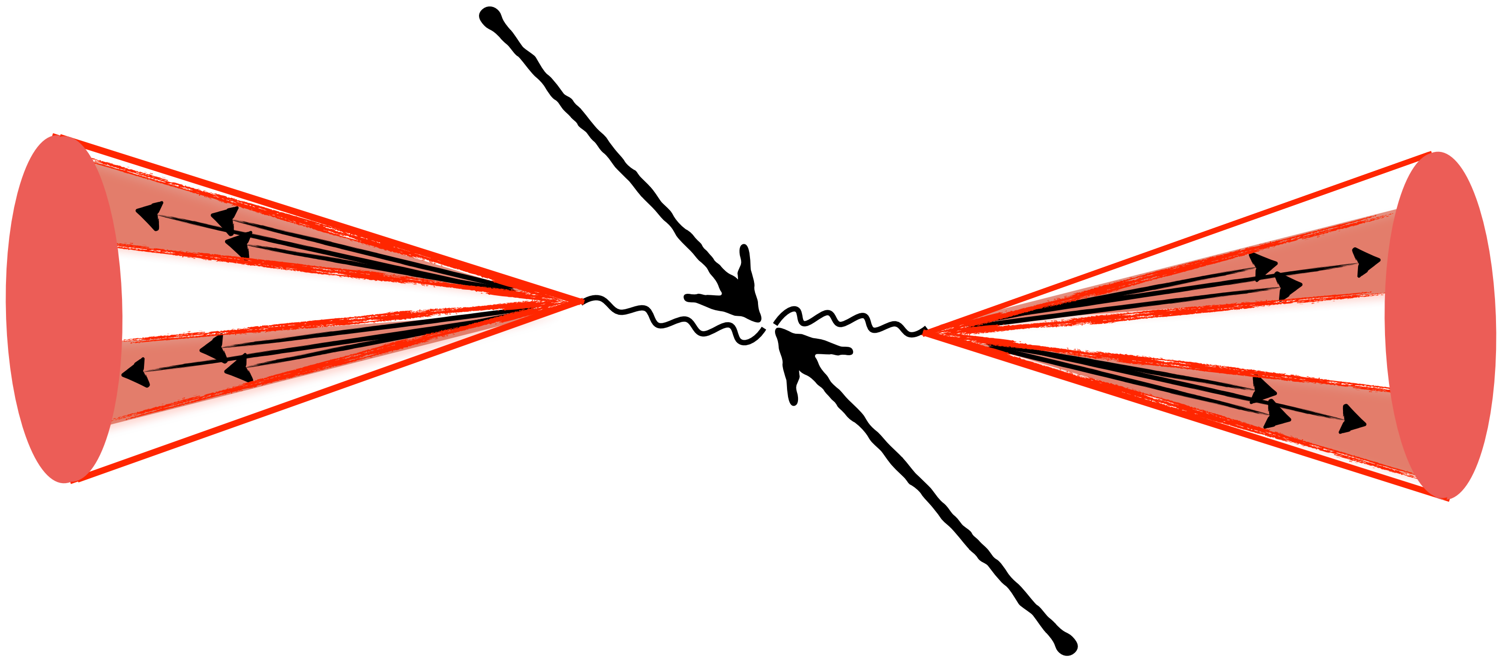
$$\text{const.} + A\cos[2\phi_{V_1} + 2\phi_{V_2}]$$

all ops.



BSM^2 ⟷ theory error

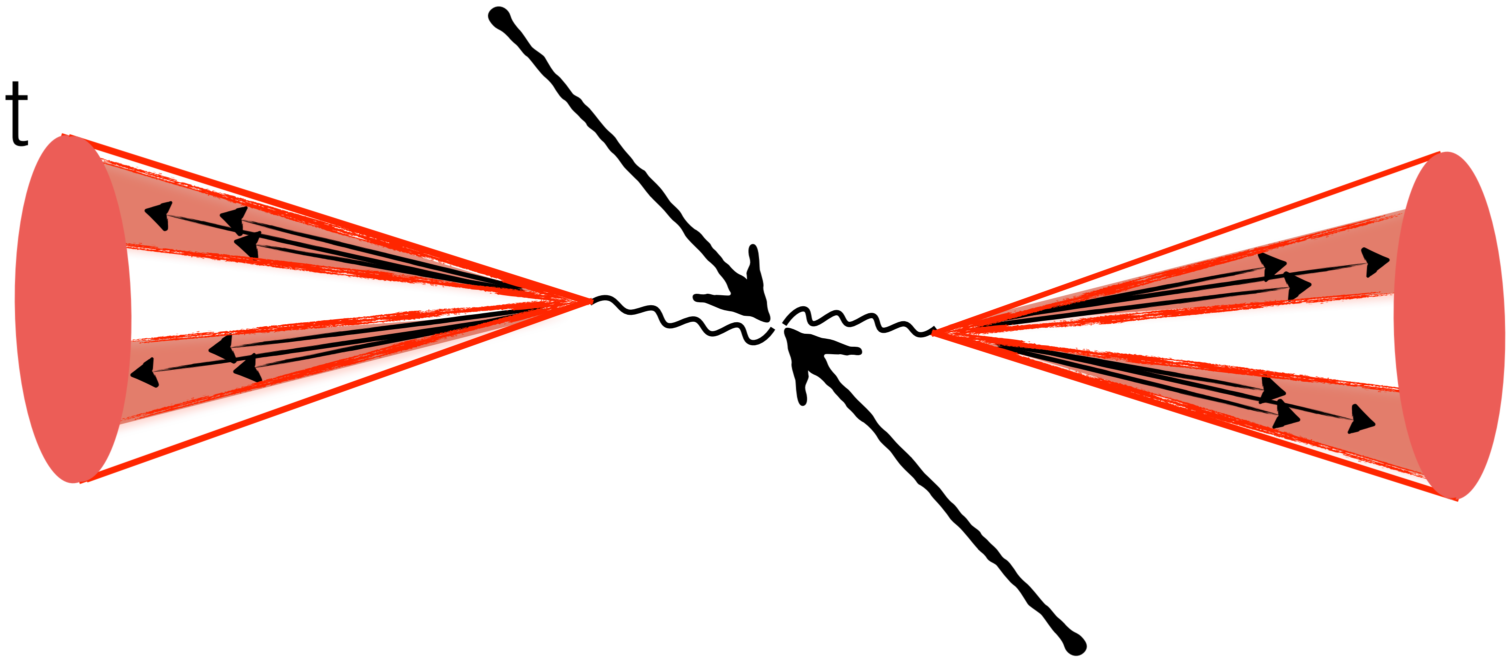
Resurrection at (sub)jet level



Resurrection at (sub)jet level

fat jets: anti-kt, R =1.0

harder jets clustered first



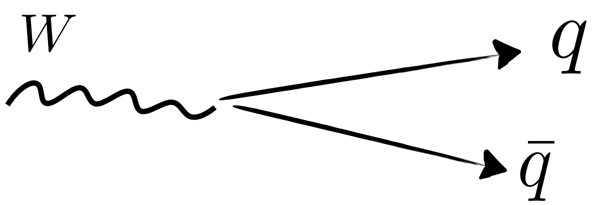
sub jets: N-subjettiness

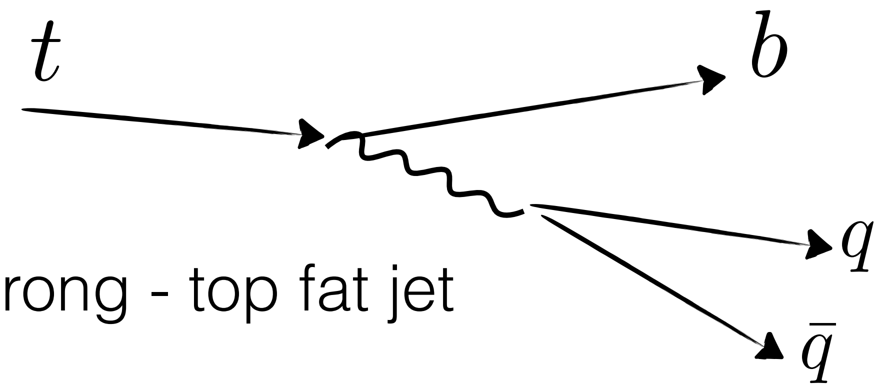
$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min\{\Delta R_{1,k}, \Delta R_{2,k}, ..., \Delta R_{N,k}\}$$

$\tau_N \to 0$ with N prong

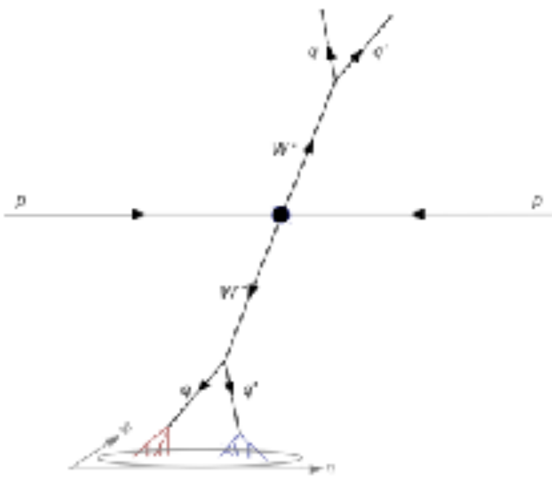
[Thaler and Van Tilburg, 11]

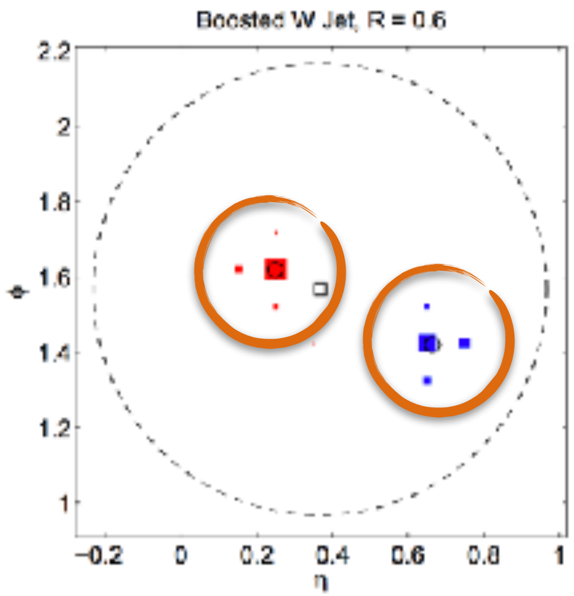
Resurrection at (sub)jet level

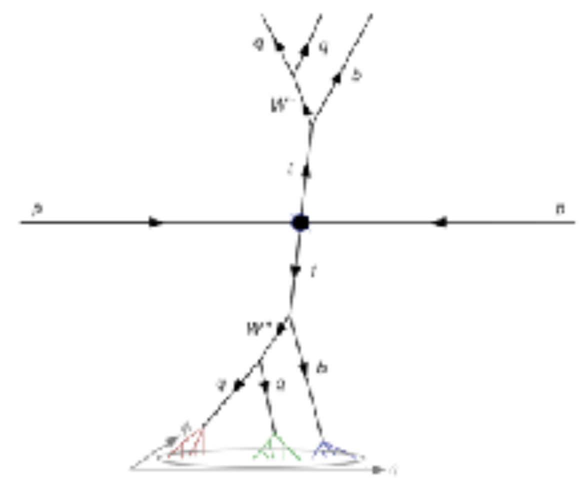


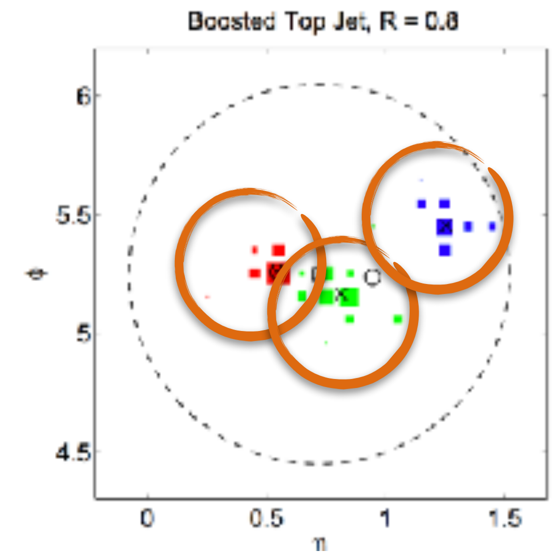


- 2 prong - W/Z/h fat jet
- 3 prong - top fat jet









$\tau_2/\tau_1 \to 0$ for 2 prong jet

$\tau_3/\tau_2 \to 0$ for 3 prong jet

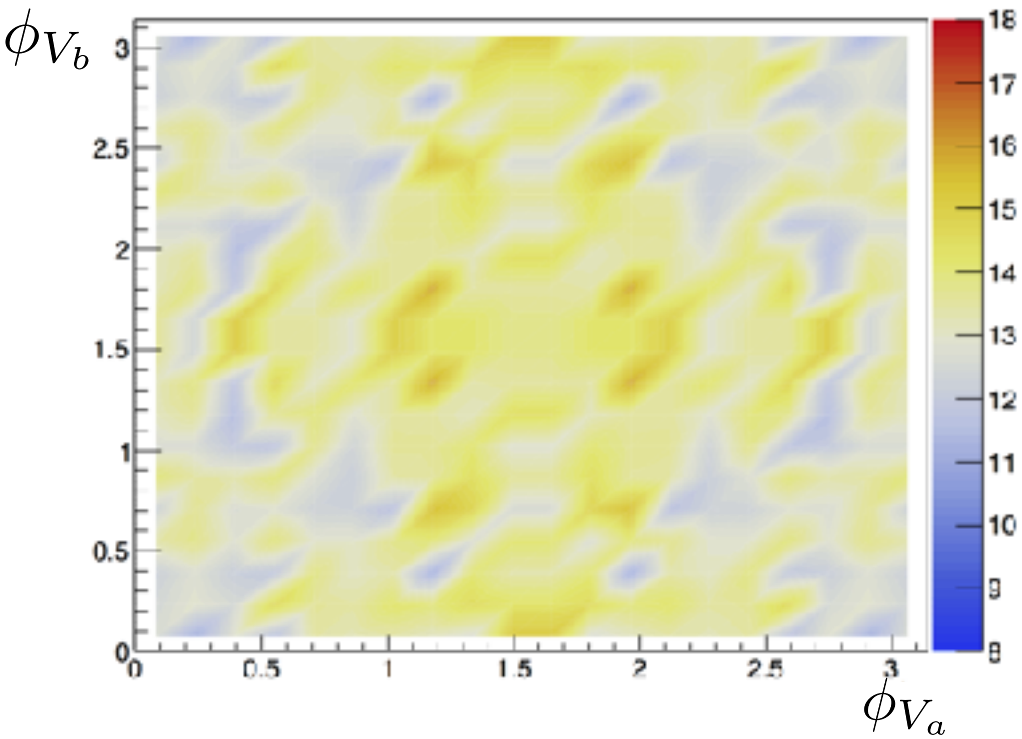
QCD: q/g → 1-prong jets

[Thaler and Van Tilburg, 11]

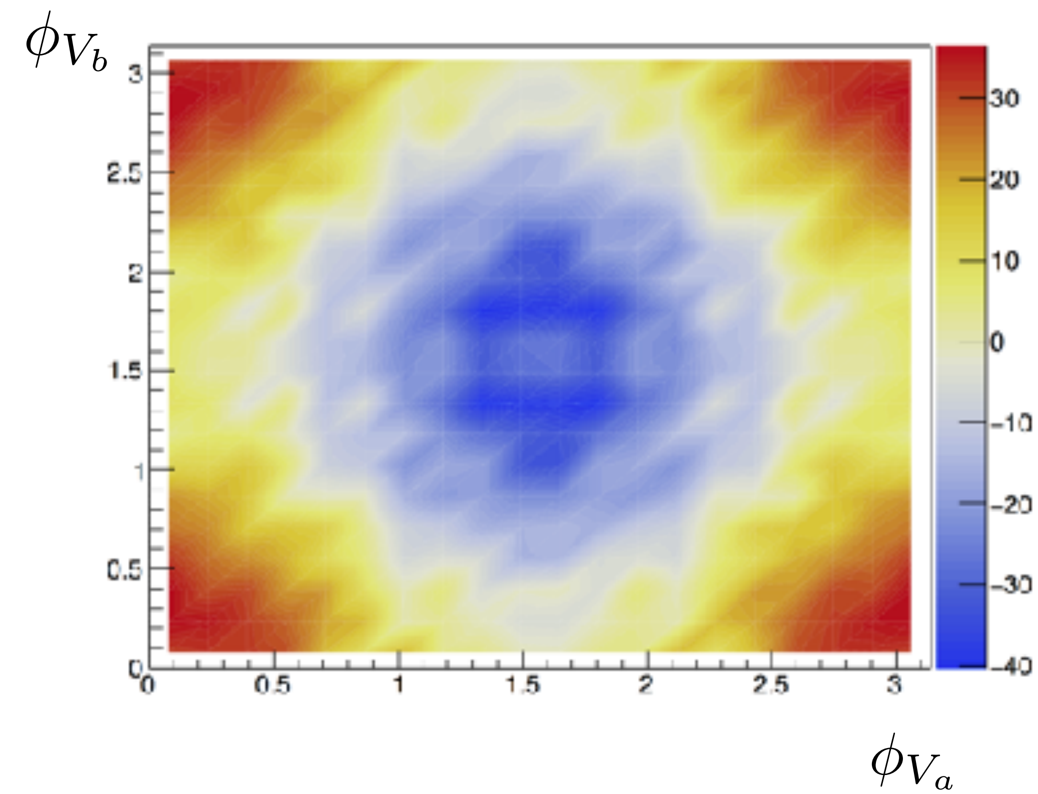
Resurrection at (sub)jet level

hadronic case

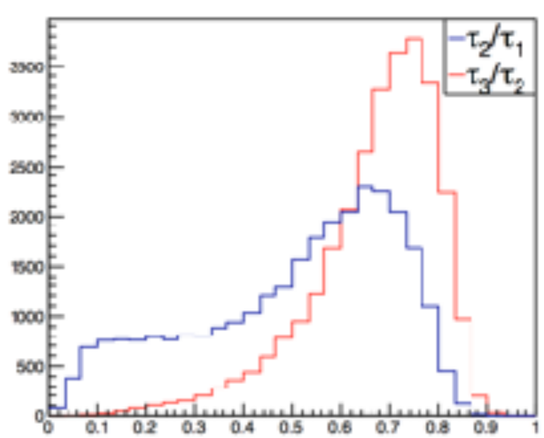
$\sigma_{\rm SM}$



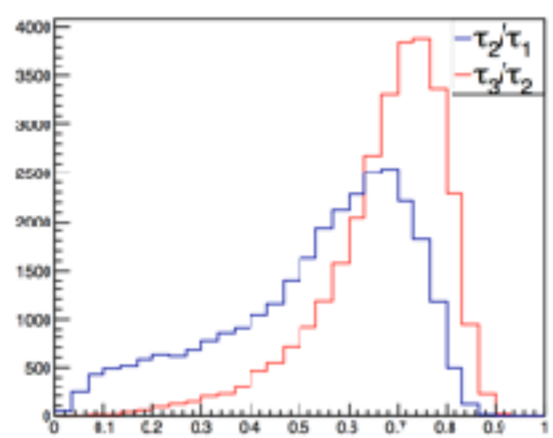
$\sigma_{\rm int}$



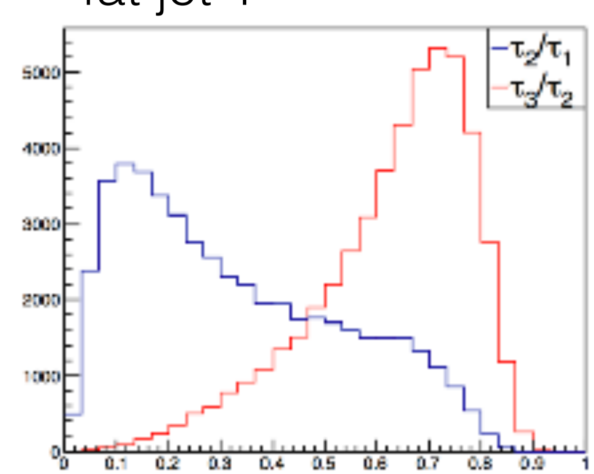
fat jet 1



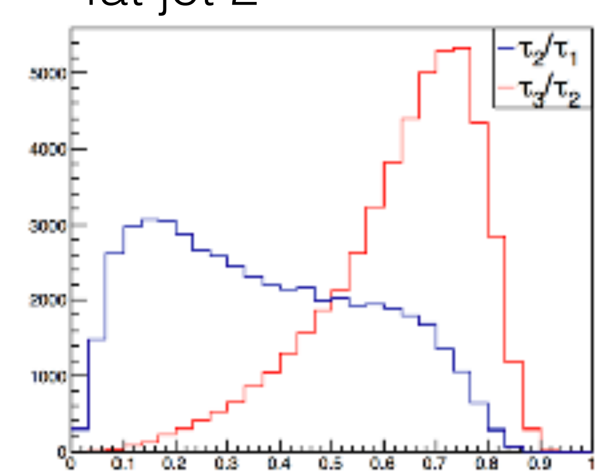
fat jet 2



fat jet 1



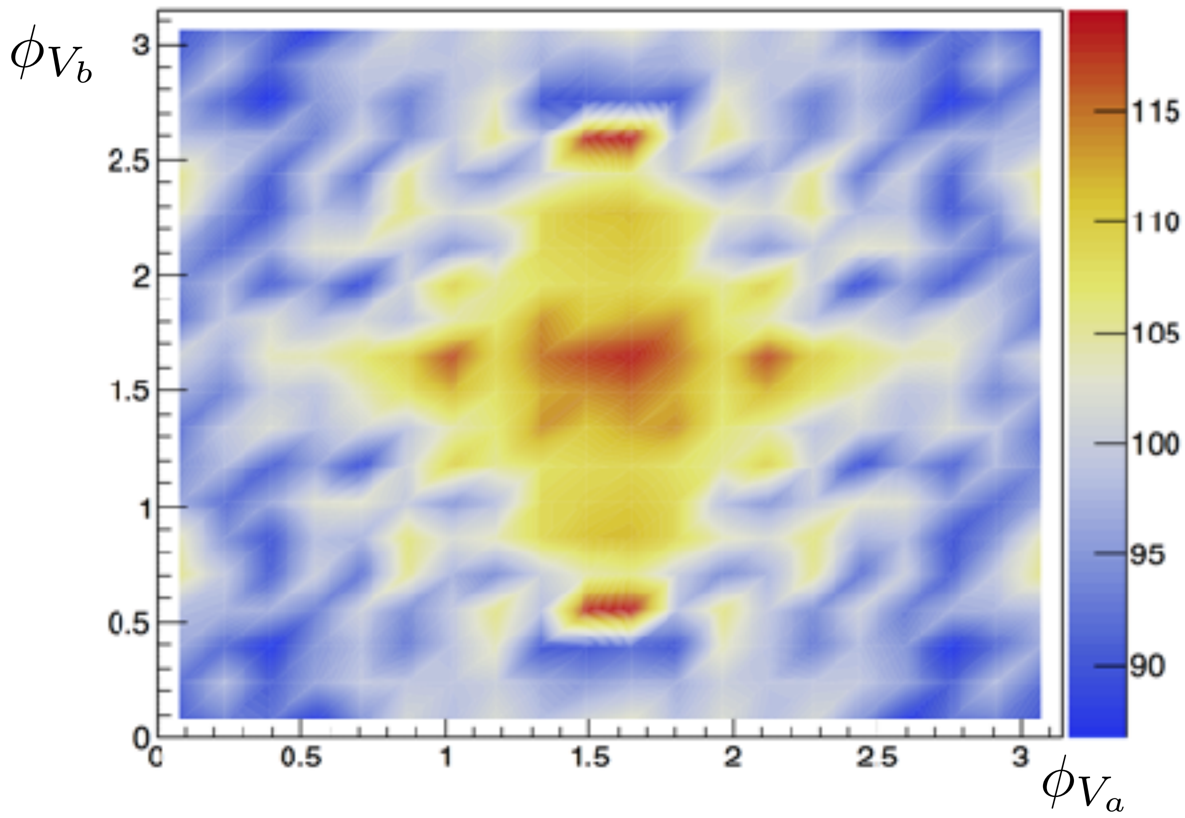
fat jet 2



Backgrounds

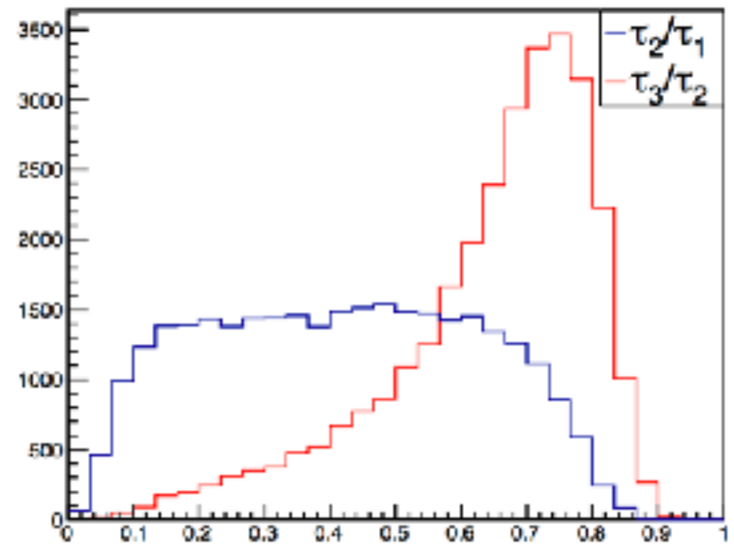
Background at (sub)jet level

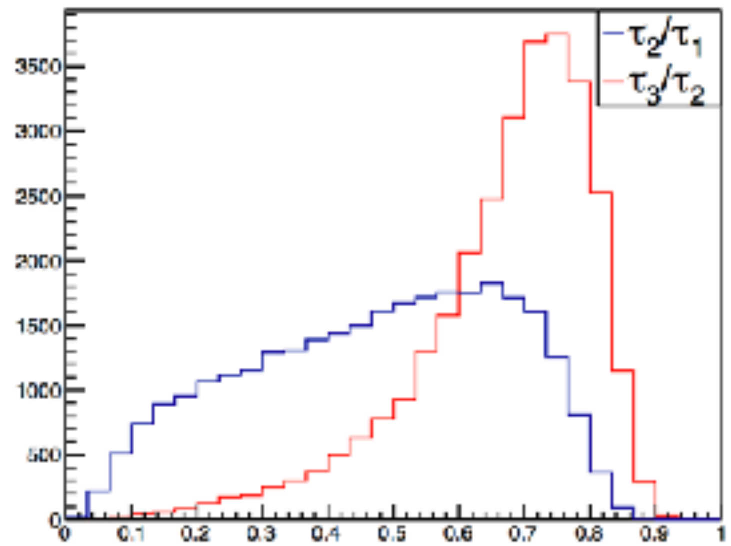
tt production



dangerous ⚠

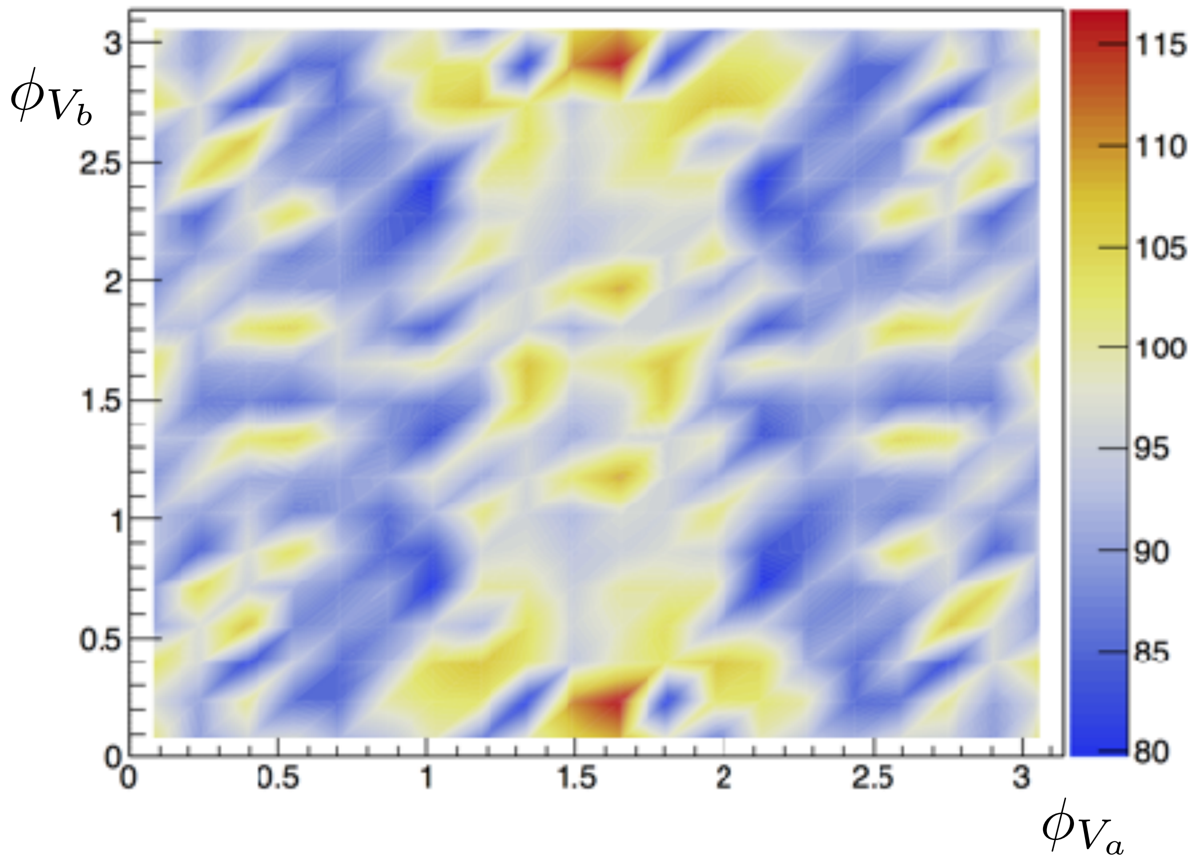
needs tagging and topology cuts



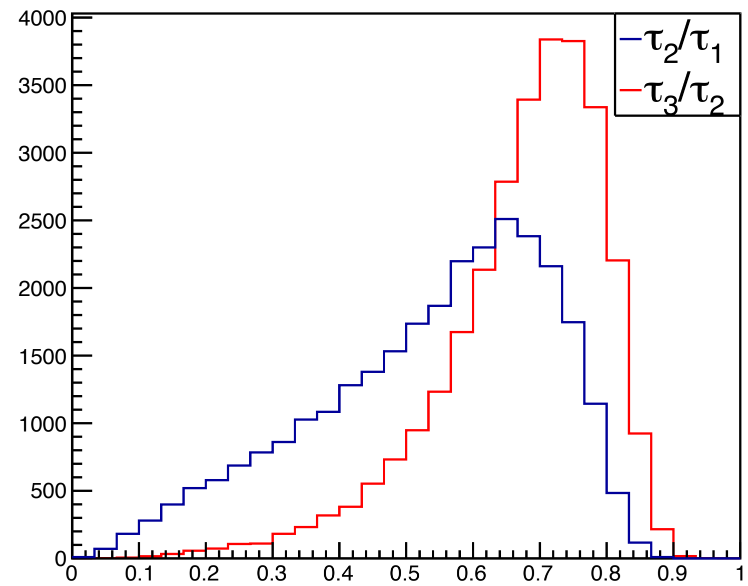


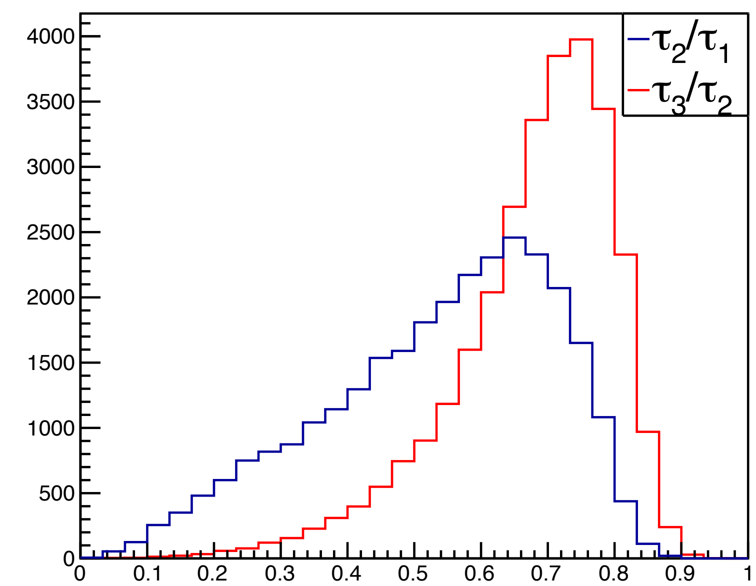
Background at (sub)jet level

jets



could be dangerous
but easily removed
with tagging





@ reconstruction level

Topology and tagging cuts

$$(p_{T1} - p_{T2})/(p_{T1} + p_{T2}) < 0.15$$

$$40 \text{ GeV} \leq \mathrm{m}_{j_1} \leq 100 \text{ GeV}$$

$$40 \text{ GeV} \leq \mathrm{m}_{j_2} \leq 100 \text{ GeV}$$

$$\tau_2/\tau_1 < 0.45$$

$$\tau_3/\tau_2 > 0.45$$

$$\text{acoplanarity} < 0.5$$

→

channel	efficiency
signal λ_Z	~ 15%
SM	~ 5%
jets	~0.002% ⚠
t t̃	~0.3% ⚠
V+jets	~0.4%
t+W	~1%

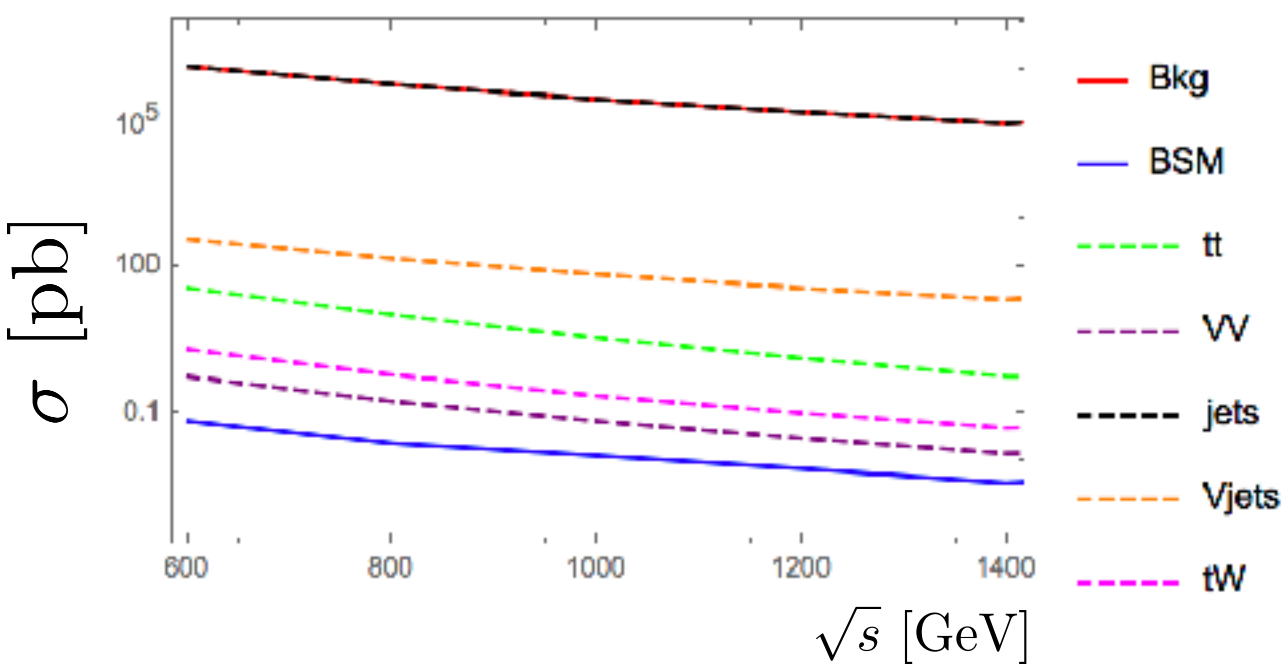
Calorimeter granularization

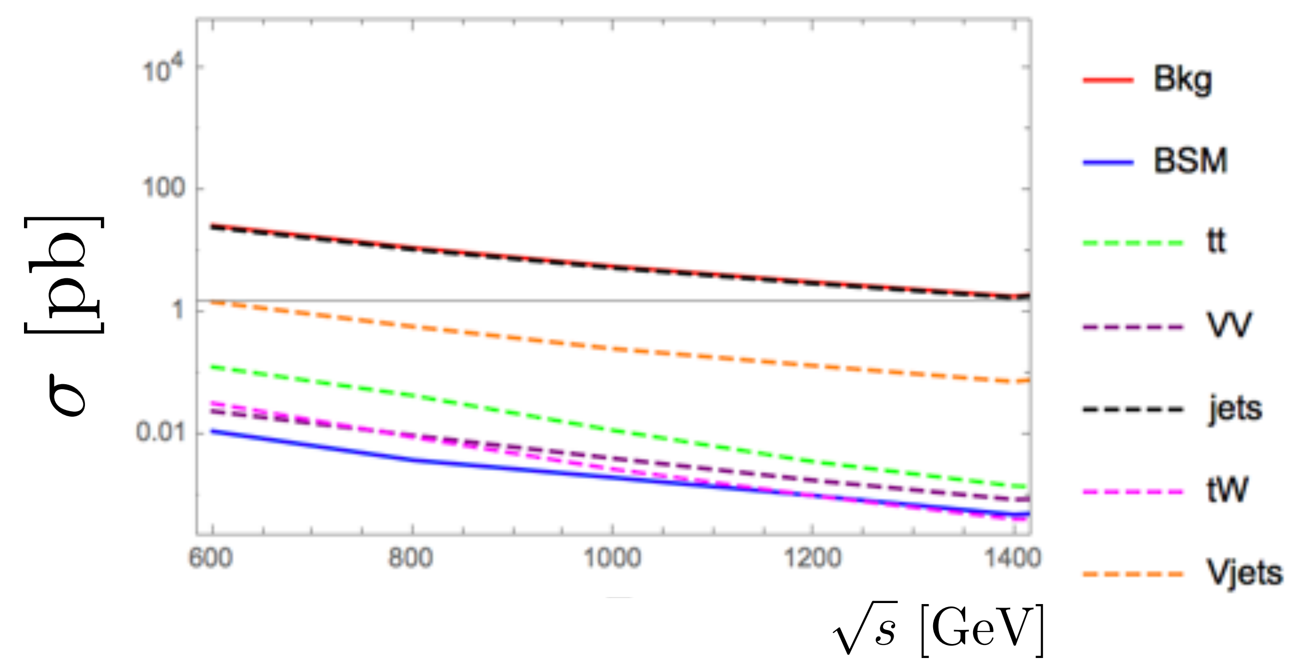
cannot resolve tracks in the same cell (0.1 × 0.1 in ϕ × η)

and does not trigger soft jets (pT < 0.5)

@ reconstruction level

after reco cuts

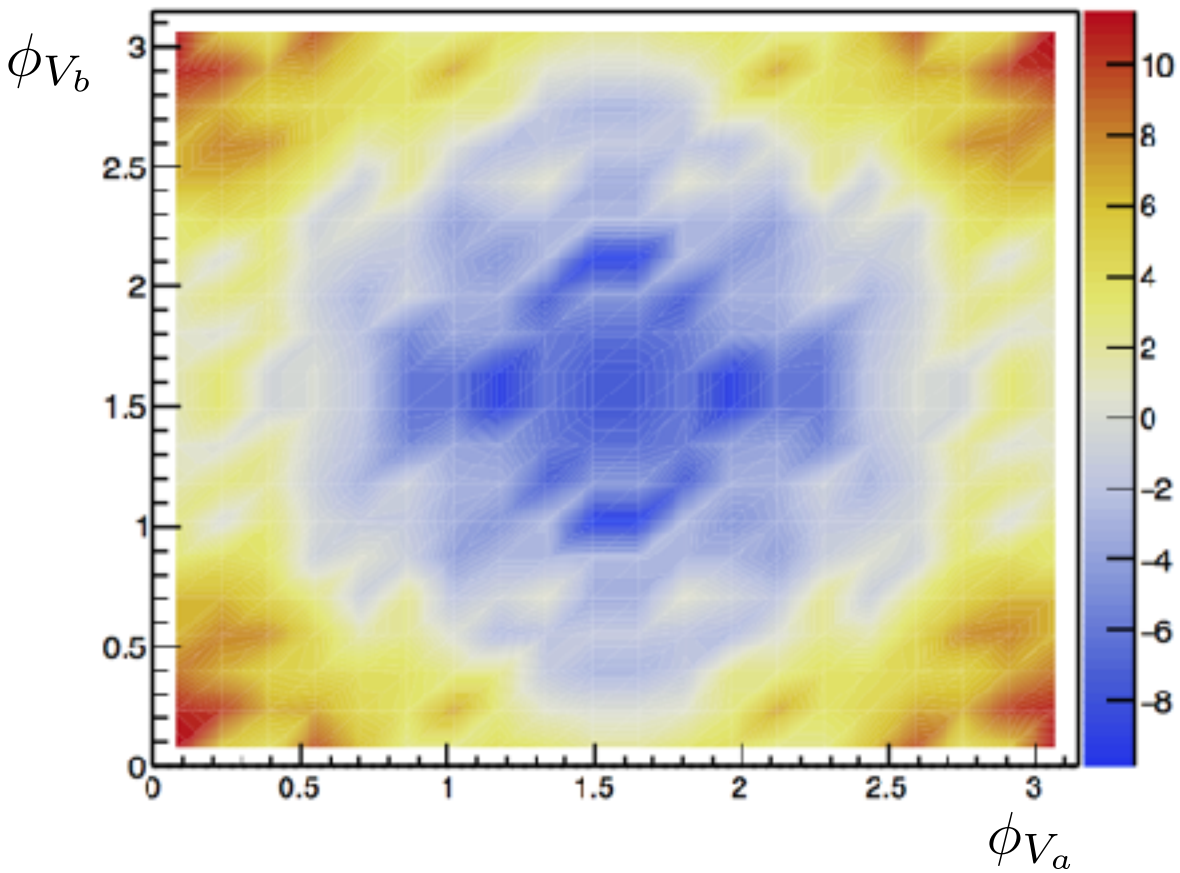




jets still dominate
bkg !

… after reconstruction cuts

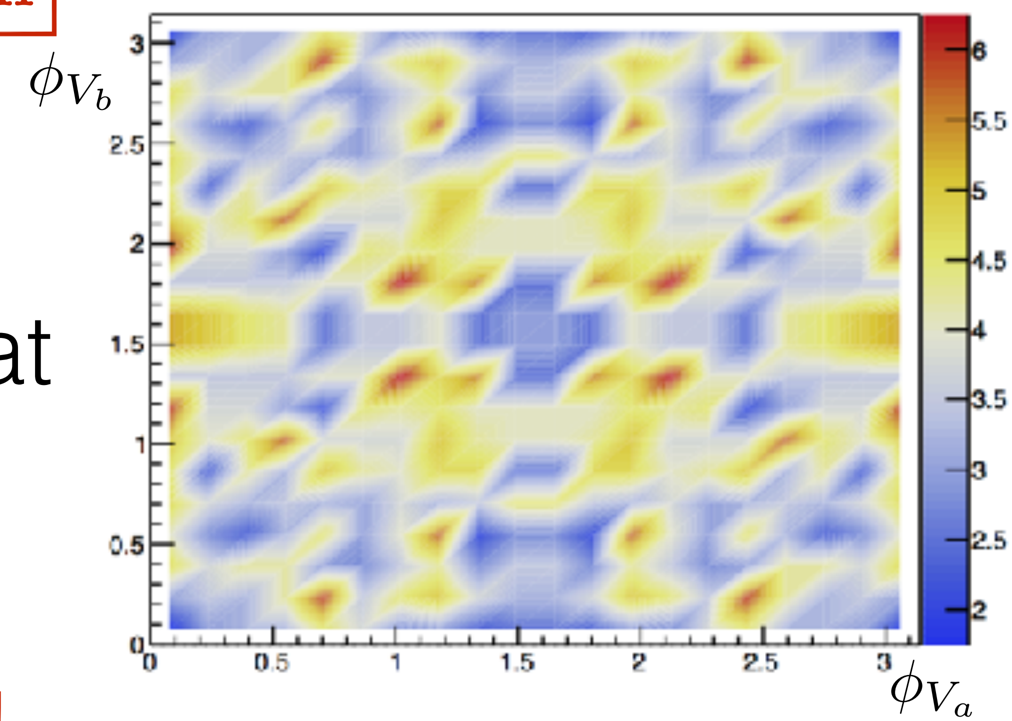
Hadronic case



keeps the angular distribution

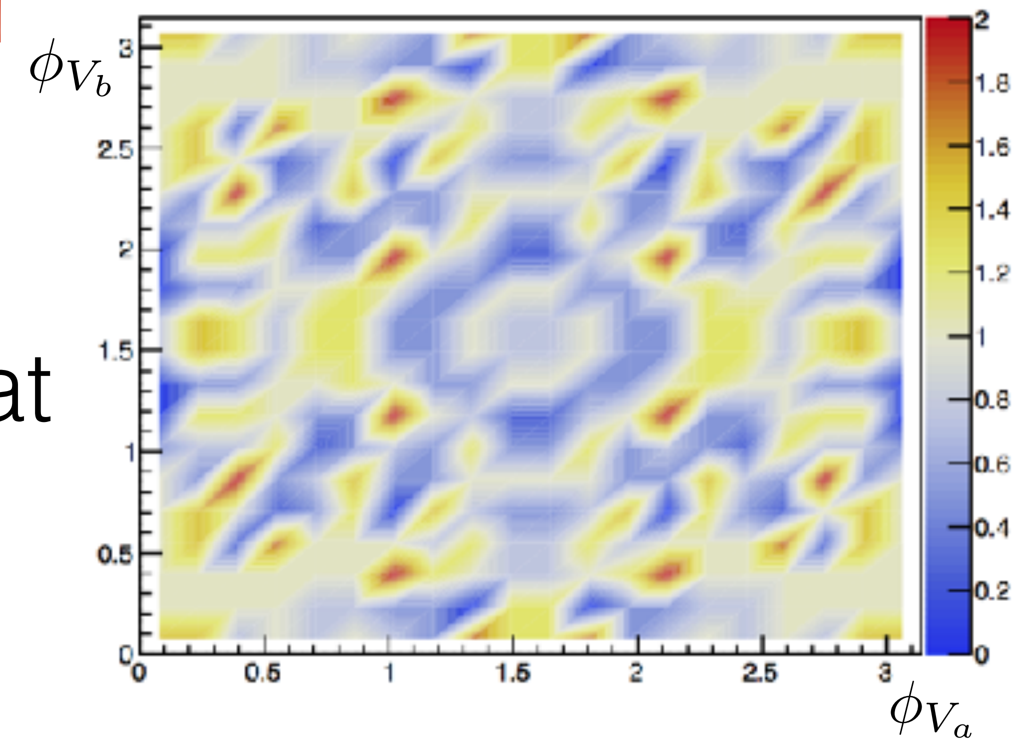
tt production

~ flat

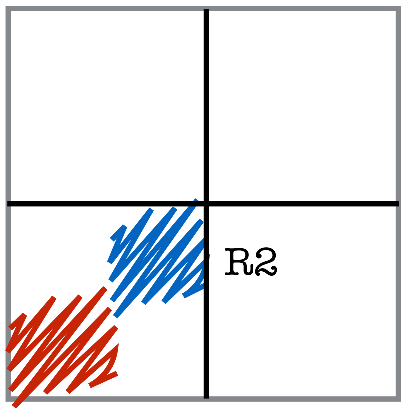


jets

~ flat

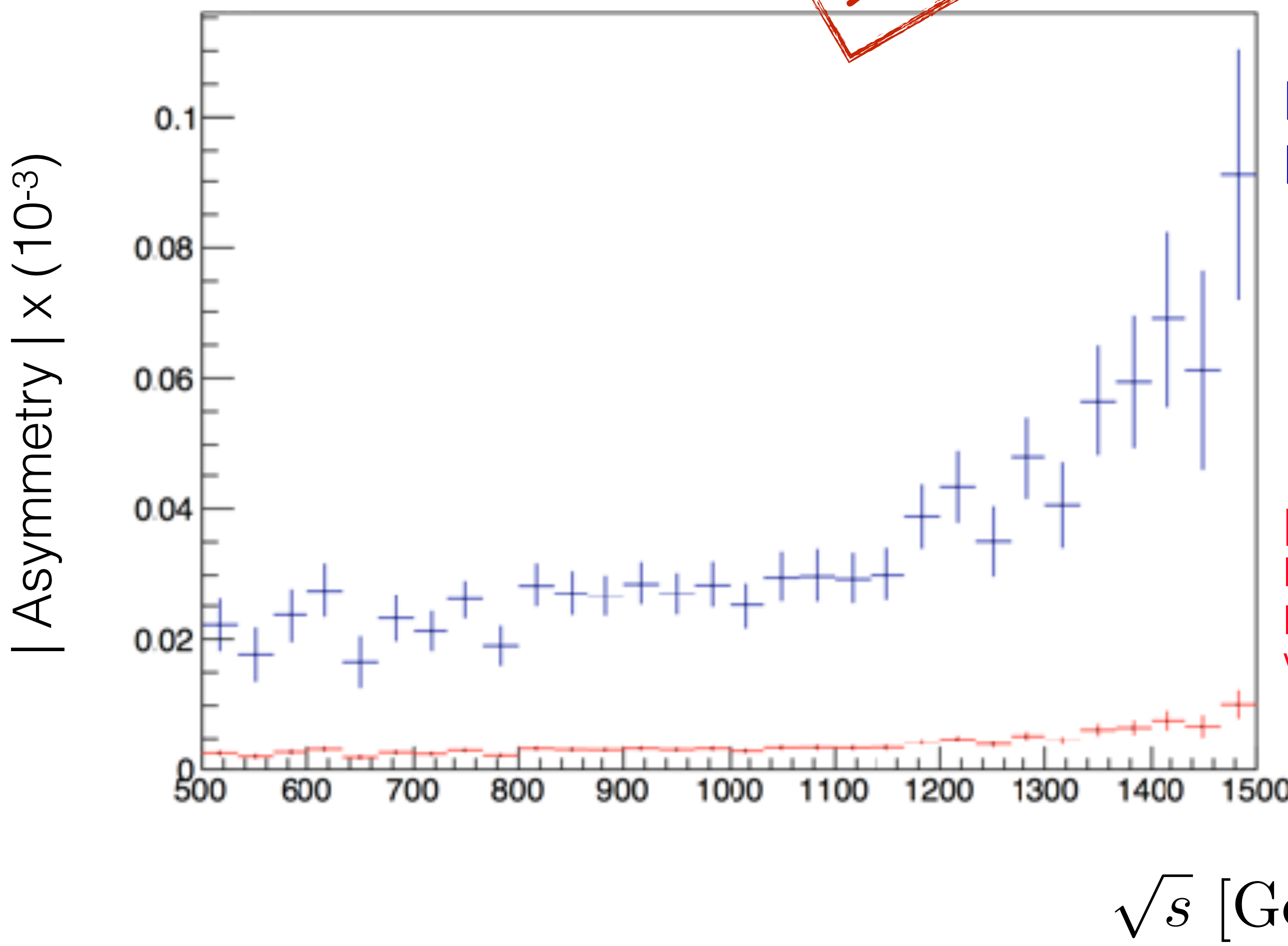


Asymmetry



$\texttt{R1} : \phi_{V_{a,b}} \in [0, \pi/4]$

$\texttt{R2} : \phi_{V_{a,b}} \in [3\pi/4, \pi/2]$



$$\mathcal{A} \equiv \frac{\texttt{R1} - \texttt{R2}}{\texttt{R1} + \texttt{R2}} \sim \frac{(\sigma_{SM} + \lambda_Z \sigma_{\text{int}}) - (\sigma_{SM} - \lambda_Z \sigma_{\text{int}})}{(\sigma_{SM} + \lambda_Z \sigma_{\text{int}}) + (\sigma_{SM} - \lambda_Z \sigma_{\text{int}})} \sim \frac{\lambda_Z \sigma_{\text{int}}}{\sigma_{SM}} \sim \lambda_Z E^2$$

basically jets

Conclusions

unfolding angular distributions with subjet → energy growth of suppressed ops

Asymmetry can probe λ_Z at high energies

sensitive to only one dim-6 op.

BKG

jet contaminates but vanishes in asymmetry

ttbar loses angular dependence

*semileptonic case not shown

Backup slides

Helicity structures

W decay amplitudes

	V_1	V_2
0	no ϕ_{V_1}	no ϕ_{V_2}
$+$	$\sim e^{+i\phi_{V_1}}$	$\sim e^{-i\phi_{V_2}}$
$-$	$\sim e^{-i\phi_{V_1}}$	$\sim e^{+i\phi_{V_2}}$

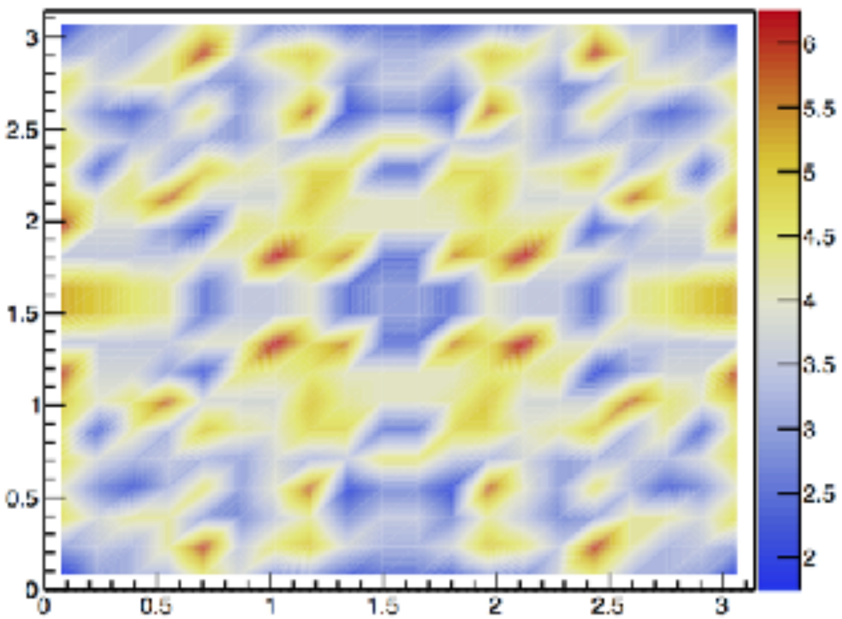
$$\sigma_{\rm int} \sim 2\, \mathfrak{Re}[\mathcal{A}_{\rm SM}\mathcal{A}^*_{\rm BSM}]$$

$$\mathcal{A}_{\rm SM} \sim \mathcal{A}_{\rm SM}^{q\bar{q}\to V_1 V_2}\mathcal{M}^{V_1}\mathcal{M}^{V_2}$$

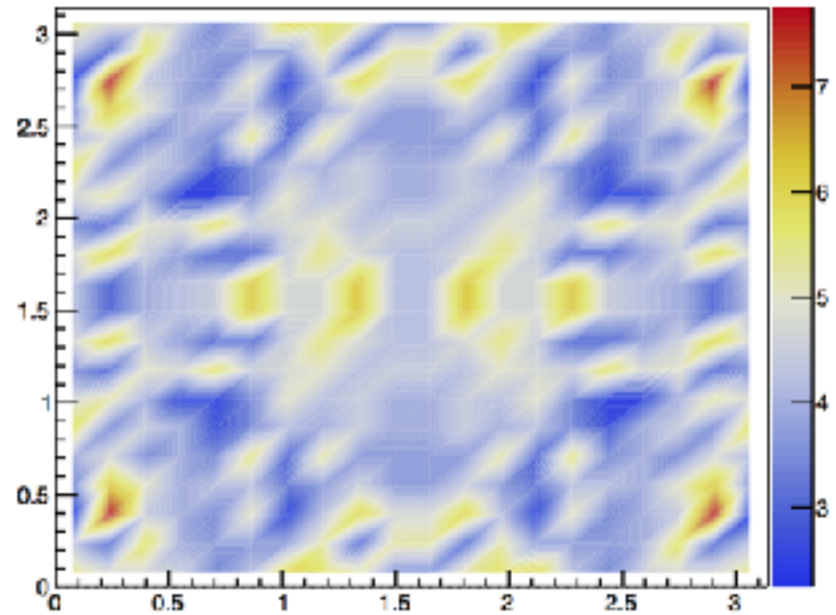
$$\mathcal{A}_{\rm BSM} \sim \mathcal{A}_{\rm BSM}^{q\bar{q}\to V_1 V_2}\mathcal{M}^{V_1}\mathcal{M}^{V_2}$$

“flatness” of backgrounds

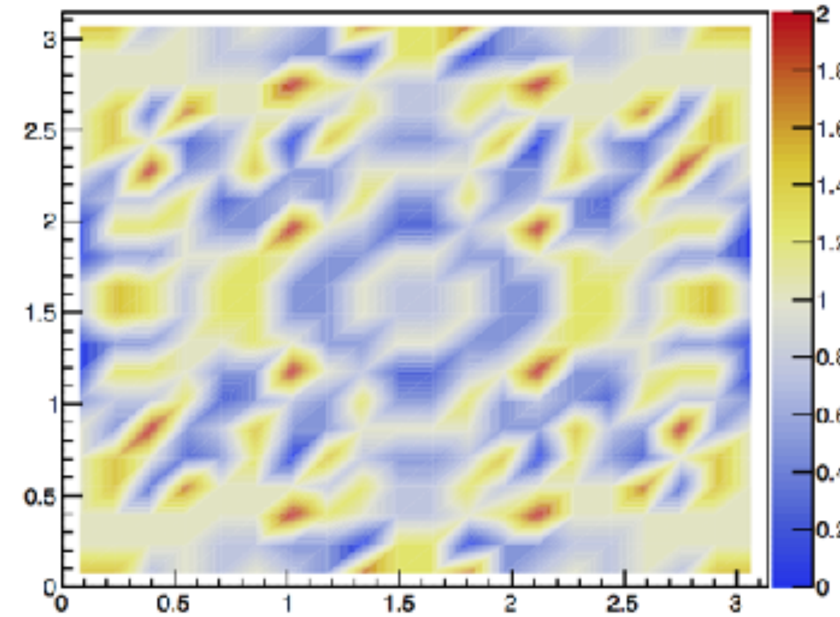
t t̃



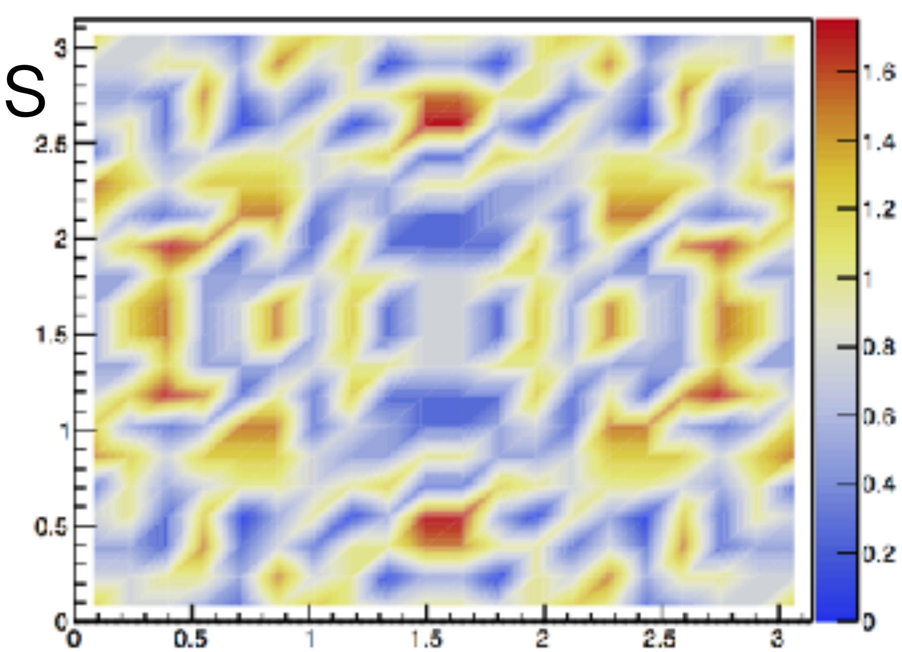
t+W

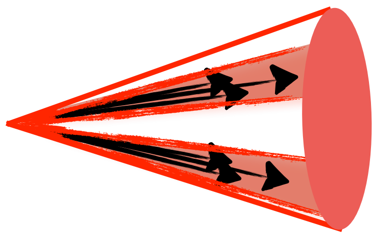


jets

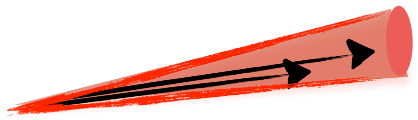


V+jets





Recombination scheme



subjet - WTA scheme

WTA scheme

sum of pT: $p_{Tr} = p_{T1} + p_{T2},$

direction of hardest pseudo-jet: $\hat{n}_r = \begin{cases} \hat{n}_1 & \text{if } p_{T1} > p_{T2}, \\ \hat{n}_2 & \text{if } p_{T2} > p_{T1}. \end{cases}$

[Bertolini, Chan, and Thaler,14]

Disobon non Interference Resurrection via subjets

- high-energy limit
- tree level
- at least one transversely-polarized vector boson

SM and BSM appear in different helicity

2 → 2 scattering amplitudes don't interfere

A_4	$\|h(A_4^{SM})\|$	$\|h(A_4^{BSM})\|$
$VVVV$	0	4,2
$VV\phi\phi$	0	2
$VV\psi\psi$	0	2
$V\psi\psi\phi$	0	2
$\psi\psi\psi\psi$	2,0	2,0
$\psi\psi\phi\phi$	0	0
$\phi\phi\phi\phi$	0	0

[Azatov, Contino, Machado and Riva, 16]

Disobon ~~non~~ Interference Resurrection via subjets

SM and BSM appear in different helicity

2 → 2 scattering amplitudes don't interfere

$$\mathrm{SM}: \quad q\bar{q} \to V_{T_\pm} V_{T_\mp}$$

$$\mathcal{O}_{3\mathrm{W}}: \quad q\bar{q} \to V_{T_\pm} V_{T_\pm}$$

A_4	$\lvert h(A_4^{\mathrm{SM}})\rvert$	$\lvert h(A_4^{\mathrm{BSM}})\rvert$
$VVVV$	0	4,2
$VV\phi\phi$	0	2
$VV\psi\psi$	0	2
$V\psi\psi\phi$	0	2
$\psi\psi\psi\psi$	2,0	2,0
$\psi\psi\phi\phi$	0	0
$\phi\phi\phi\phi$	0	0

[Azatov, Contino, Machado and Riva, 16]

… but 2 → 4 can interfere

For a n-point amplitude: $|h(A^{SM}_{n\geq 5})| \leq n-4$

$$h(A_6^{SM}) = 0, \pm 2$$

dim-6 op.

$\mathcal{O}_i$	$h^{\mathcal{O}}_{min}$	$h^{\mathcal{O}}_{max}$
F^3	$6-n$	n
$F^2\phi^2,\ F\psi^2\phi,\ \psi^4$	$6-n$	$n-2$
$\psi^2\bar{\psi}^2,\ \psi\bar{\psi}\phi^2 D,\ \phi^4 D^2$	0	$n-4$
$\psi^2\phi^3$	$6-n$	$n-4$
ϕ^6	0	$n-6$

[Azatov, Contino, Machado and Riva, 16]

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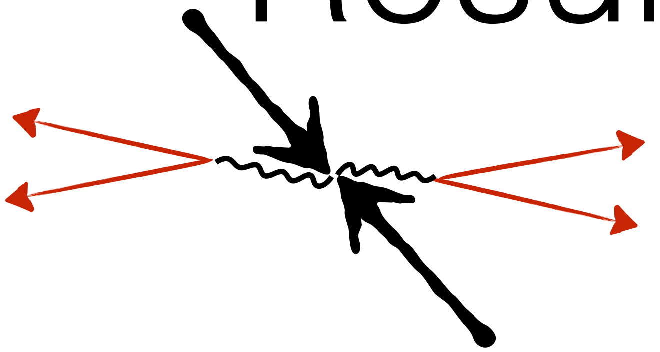
$\mathcal{O}_i$	$h^{\mathcal{O}}_{min}$	$h^{\mathcal{O}}_{max}$
F^3	$6-n$	n
$F^2\phi^2$, $F\psi^2\phi$, ψ^4	$6-n$	$n-2$
$\psi^2\bar{\psi}^2$, $\psi\bar{\psi}\phi^2 D$, $\phi^4 D^2$	0	$n-4$
$\psi^2\phi^3$	$6-n$	$n-4$
ϕ^6	0	$n-6$

$$2 \leq h(A_6^{\mathcal{O}}) \leq 4$$

[Azatov, Contino, Machado and Riva, 16]

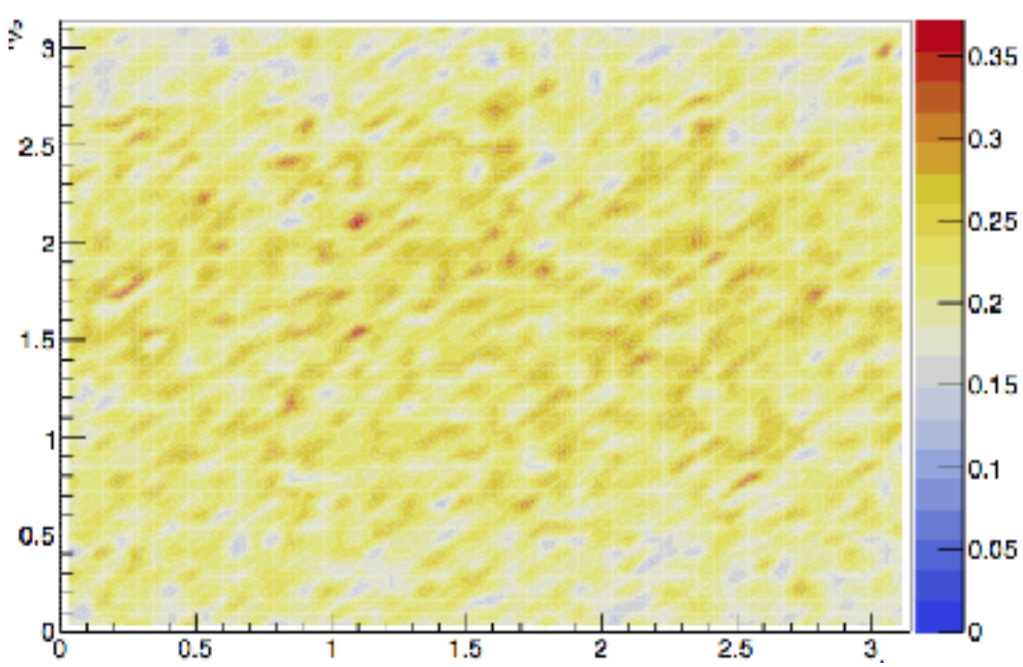
Resurrection at partonic level



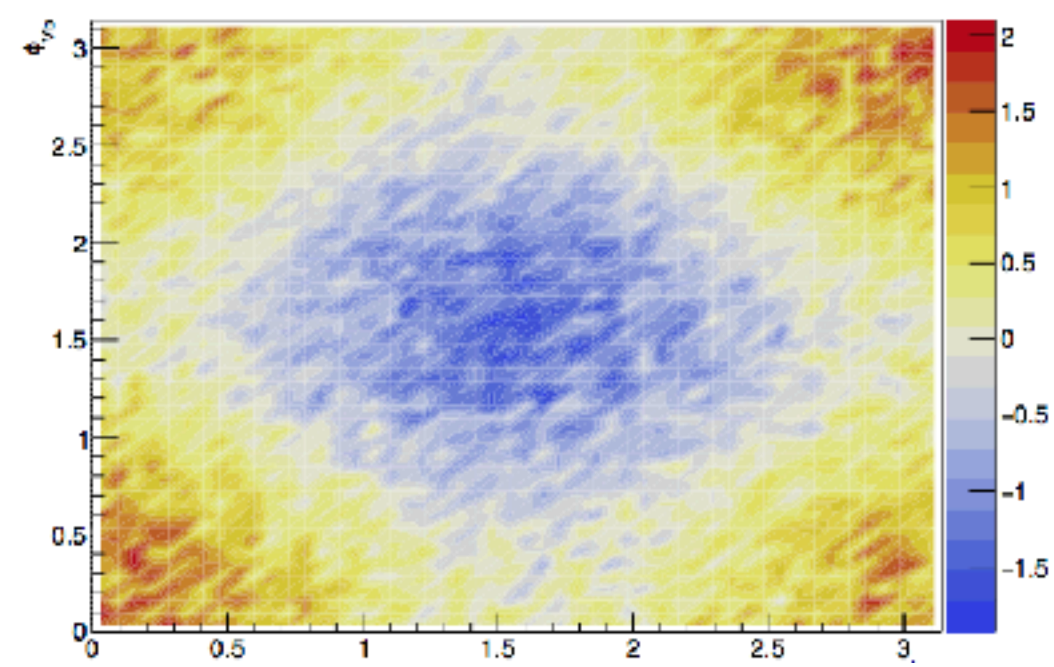
Semileptonic case

$$q\bar{q} \to W^+ Z \to jjl^+l^-$$

$\sigma_{\rm SM}$



$\sigma_{\rm int}$



$$700\text{GeV} \leq m_{VV} \leq 800\text{GeV}$$

$$\frac{ig\,\lambda_Z}{M_W^2} W_\mu^{+\nu} W_\nu^{-\rho} W_\rho^{3\mu}$$

Resurrection at (sub)jet level

Semileptonic case