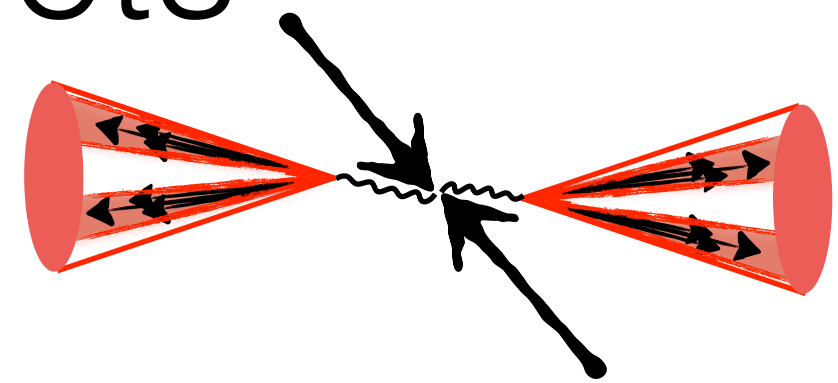
Diboson Interference Resurrection at LHC via subjets



Rafael Aoude

Higgs Effective Field Theory
Mainz, 2018

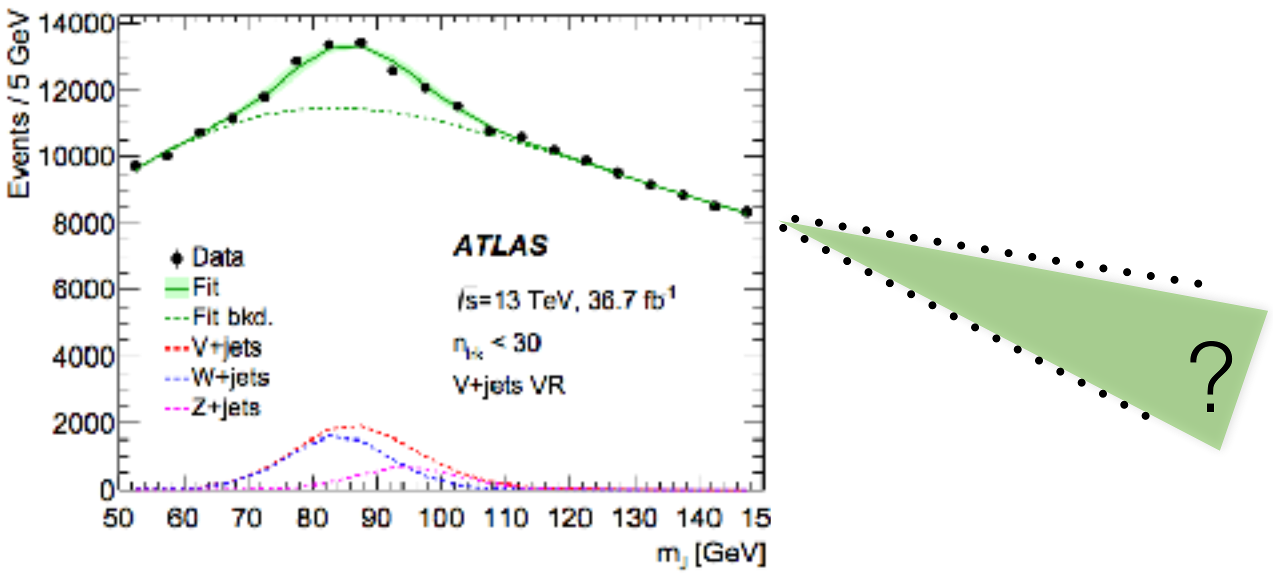
Unterstützt von / Supported by
Alexander von Humboldt
Stiftung / Foundation

based on work in progress with William Shepherd

JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

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

… add NP via aTGC



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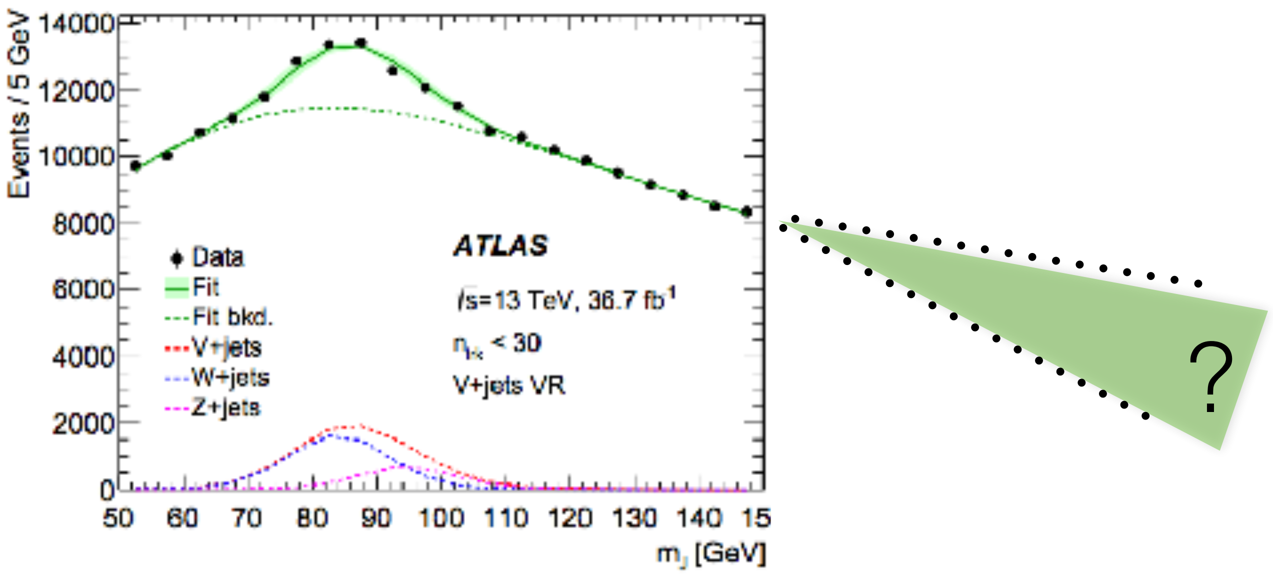

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$$\sigma_{\rm int} \sim A^{\rm SM}(A^{\rm BSM})^* + {\rm h.c.}$$ can probe NP at high E

for some ops $2 \to 2$ don't interfere…

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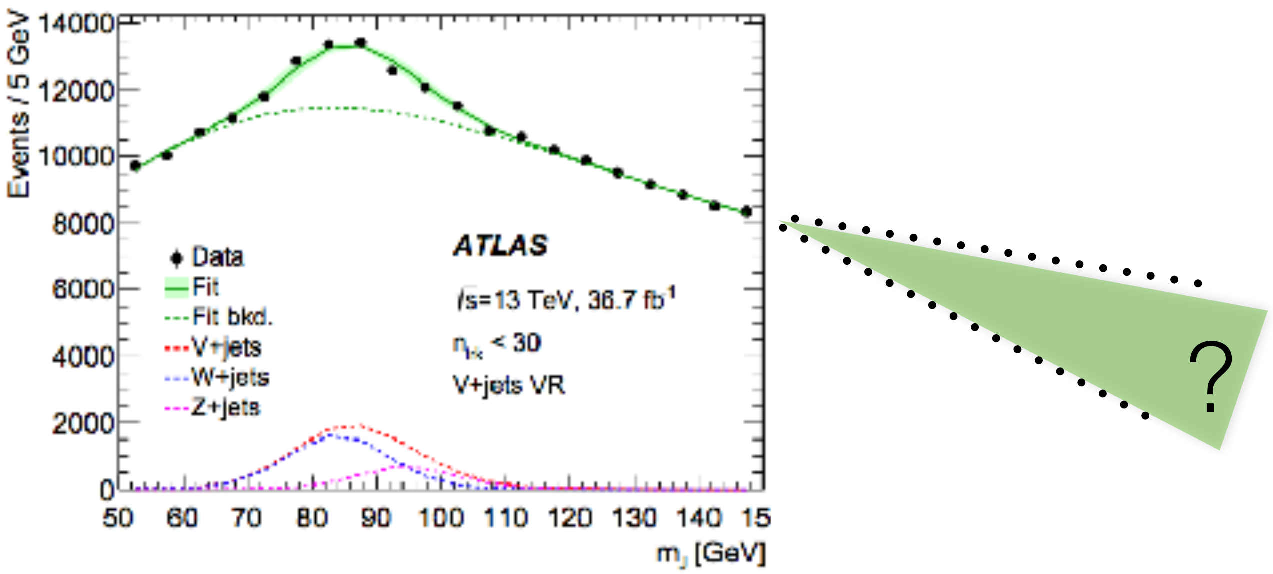

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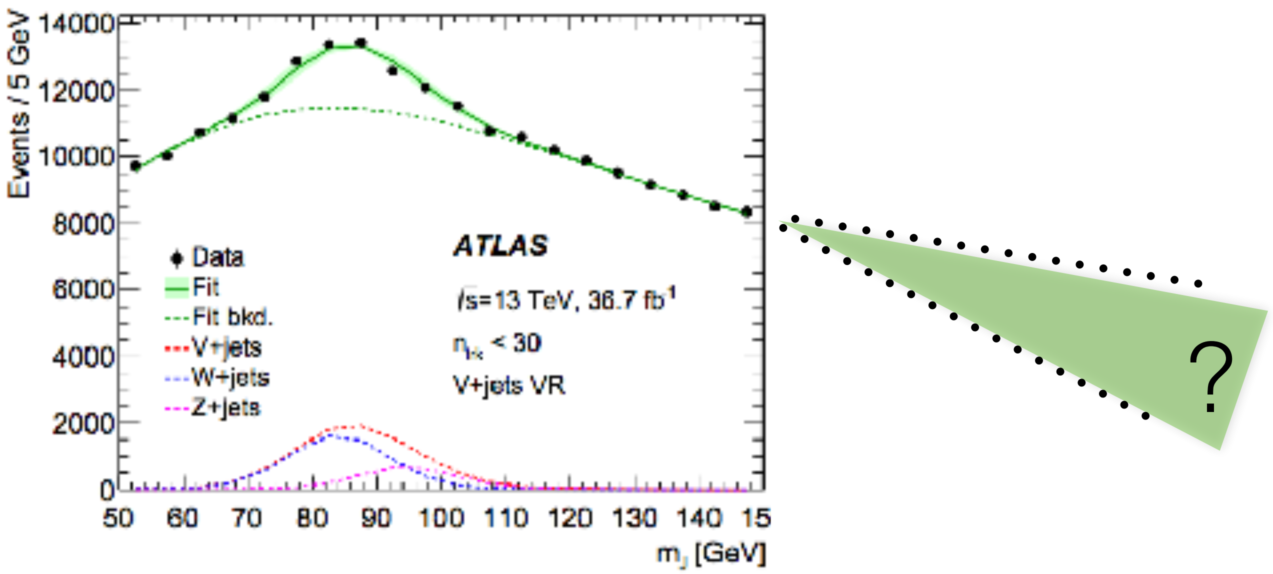

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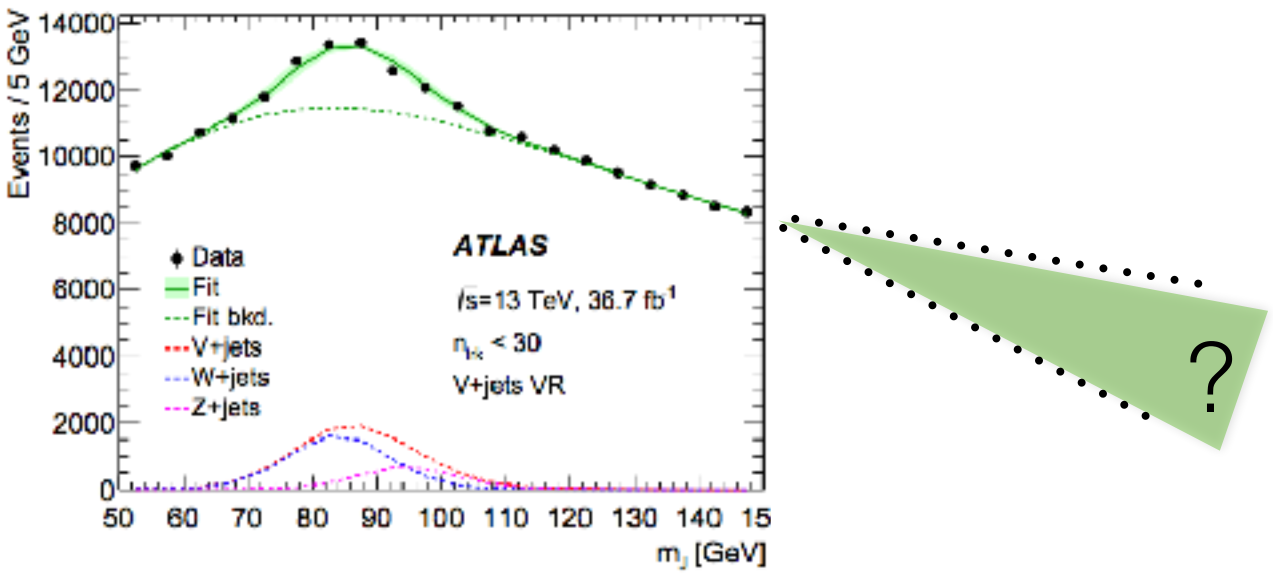

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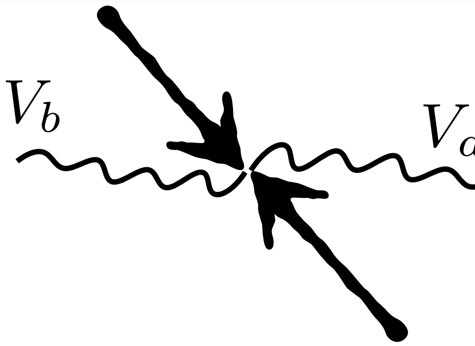
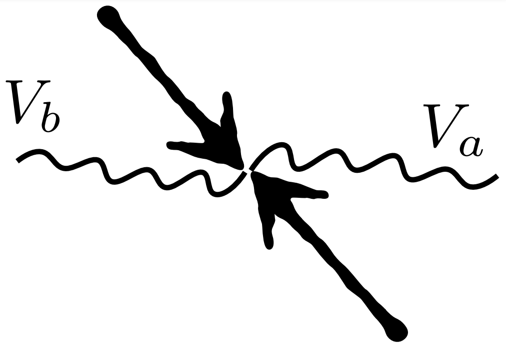
jet substructure techniques

WZ/WW production at LHC



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

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

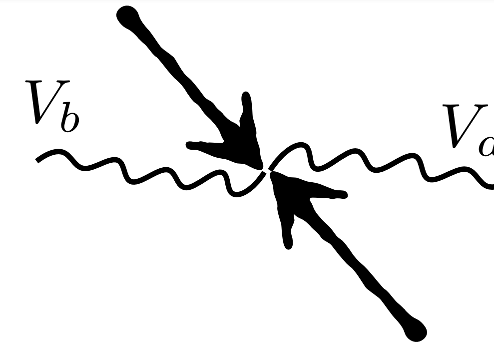
$$\mathcal{L}_{\rm BSM,1} = ig\, c_W\, \delta g_{1,Z}\, Z_\nu W^{+\mu\nu} W^-_\mu + {\rm h.c.} + ig(c_W\, \delta\kappa_Z Z^{\mu\nu} + s_W\, \delta\kappa_\gamma A^{\mu\nu})W^+_\mu W^-_\nu$$

gauge invariance

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

$$\delta\kappa_Z = \delta g_{1,z} - s_W^2/c_W^2 \delta\kappa_\gamma$$

WZ/WW production at LHC



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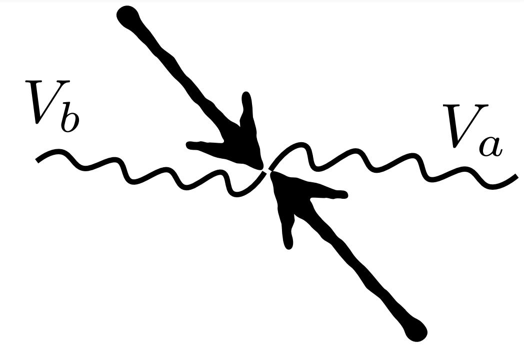
new op.

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

WZ/WW production at LHC



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

deviations from SM

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

same helictites as SM

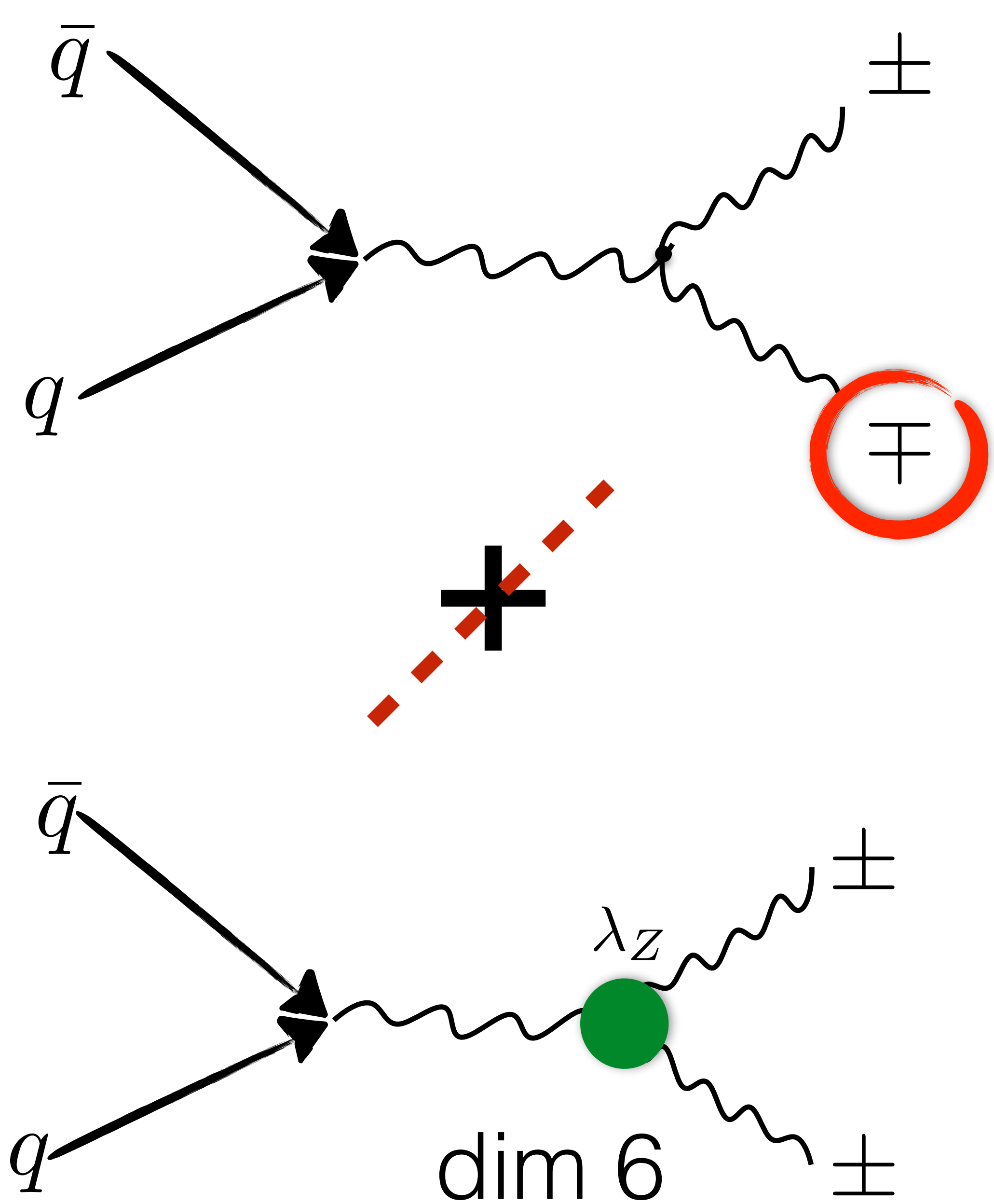
new op.

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

transverse bosons

does not interfere with SM (due to helicity selection rules)

Diboson non-interference λ_Z



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

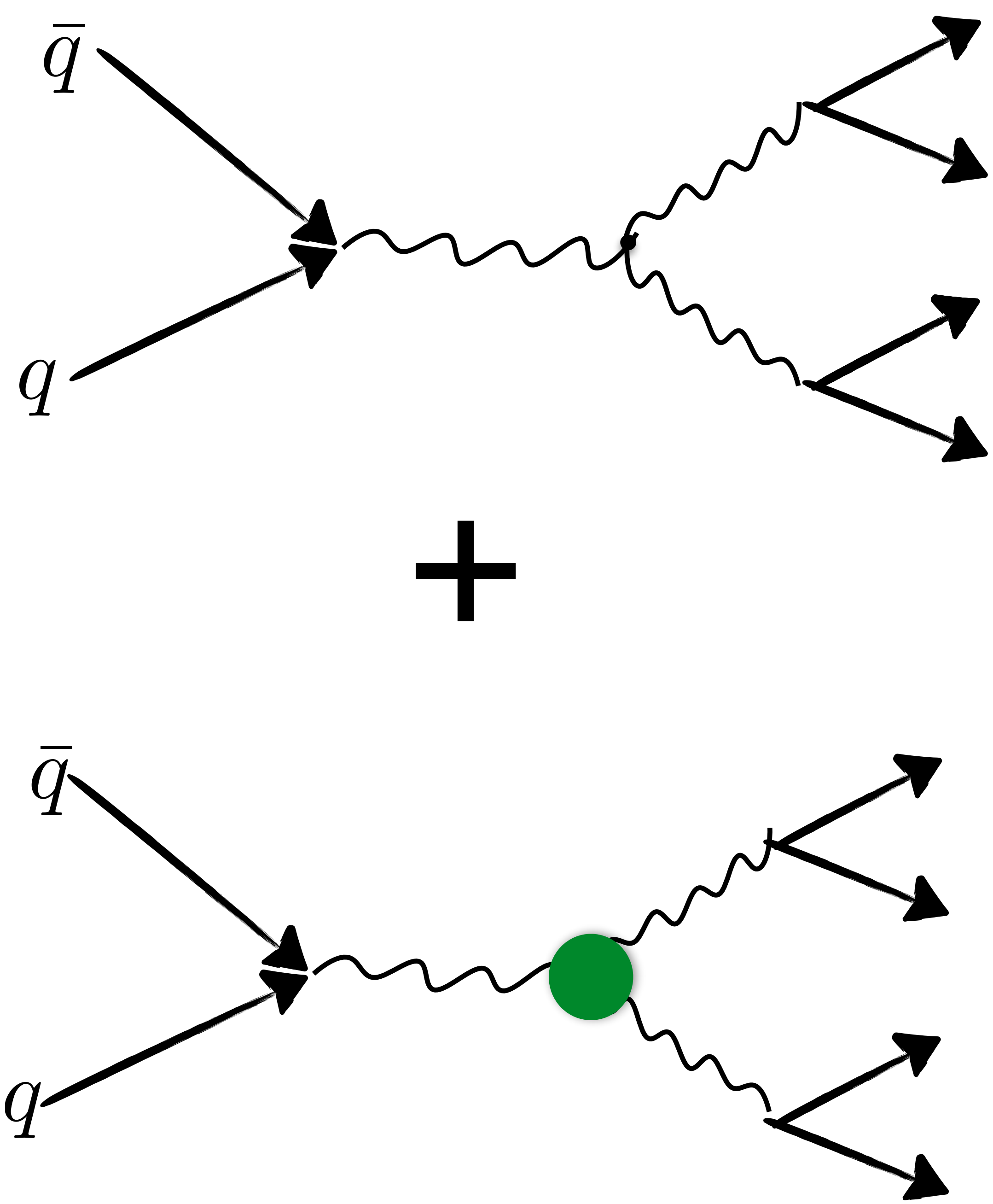
$$\mathcal{A}^{BSM,\lambda_Z}(q\bar{q} \to V_T W_T^{\pm}) \sim \frac{E^2}{m_W^2}\lambda_Z$$

2 → 2 scattering amplitudes don't interfere!!

[Dixon and Shadmi, 94]

[Azatov, Contino, Machado and Riva, 16]

Diboson Ressurection! λ_Z



2 → 4 scattering amplitudes interfere!!

↓

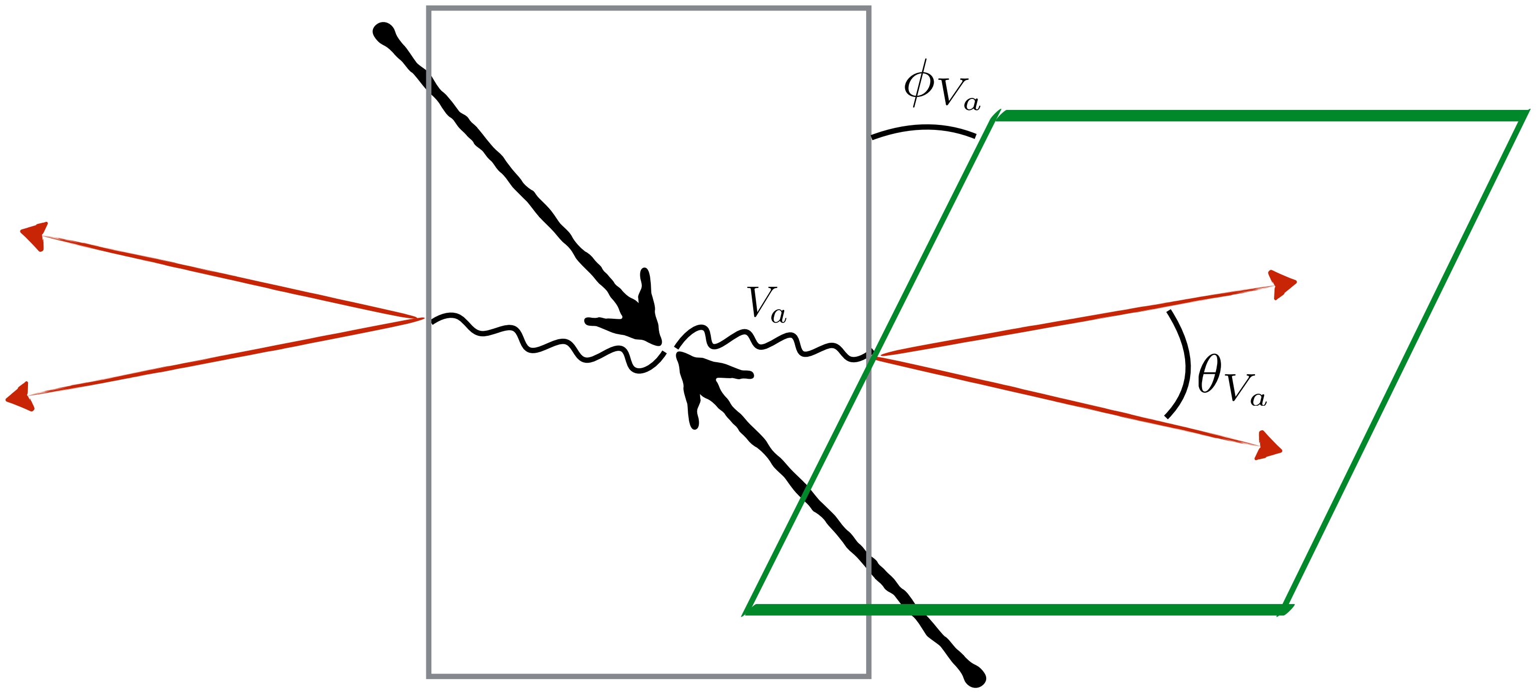
unfold angular distributions

Diboson interference resurrection

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

Unfold angular distributions

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

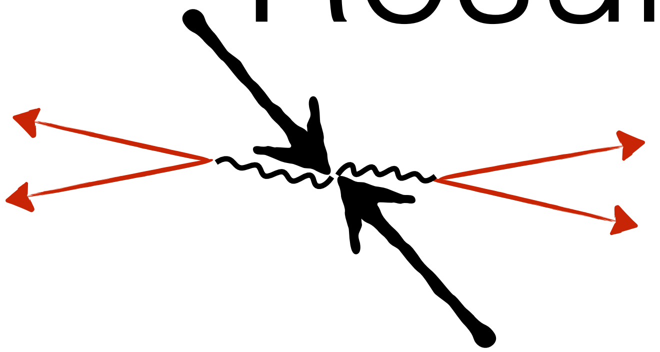


[Dixon and Shadmi, 94]

[Panico, Riva, and Wulzer, 17]

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

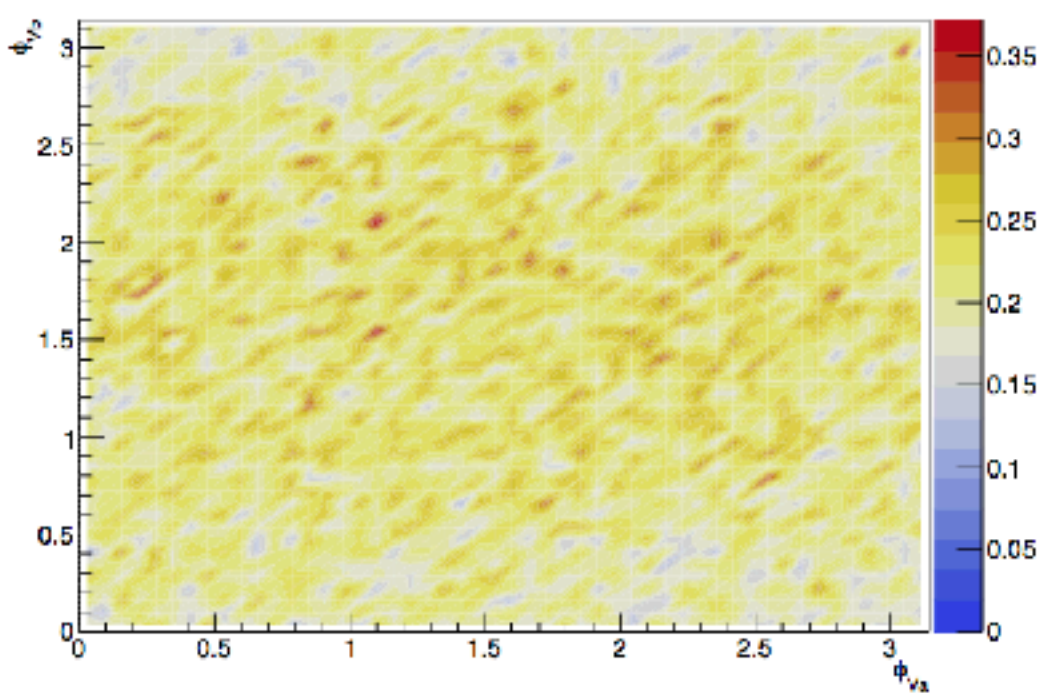
Resurrection at partonic level



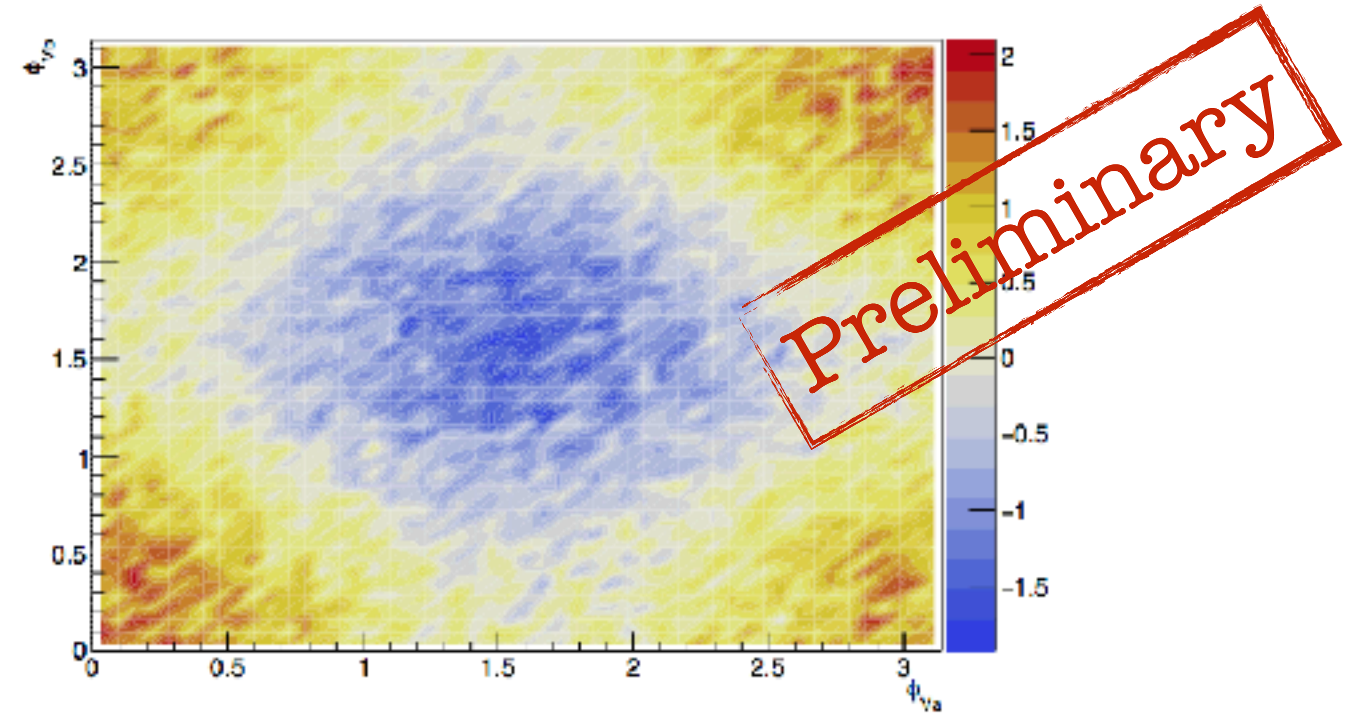
Semileptonic case

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

σ_{SM}



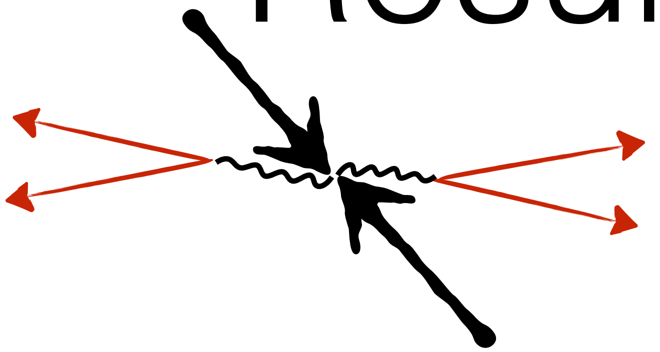
σ_{int}



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

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

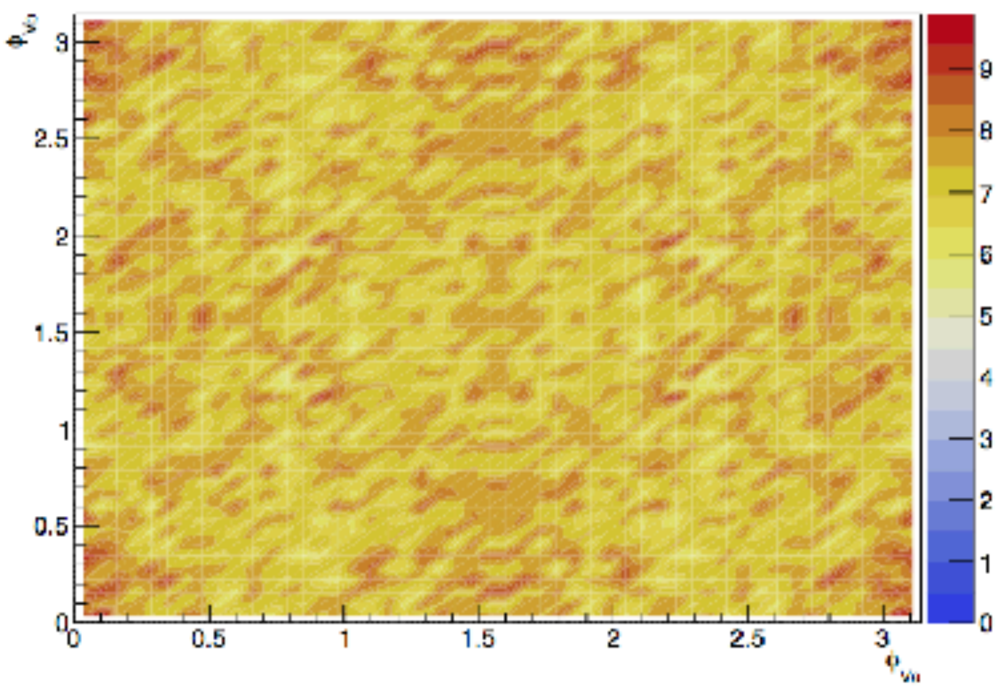
Resurrection at partonic level



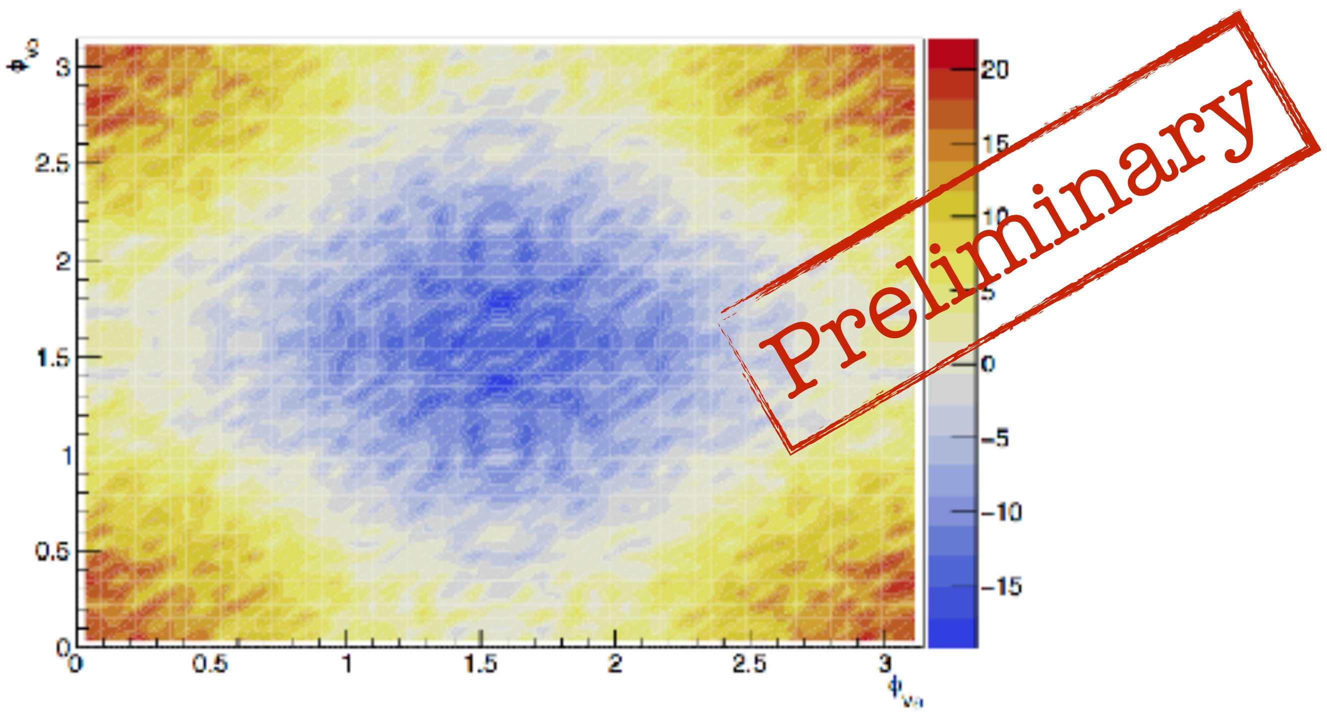
Hadronic case

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

σ_{SM}



σ_{int}

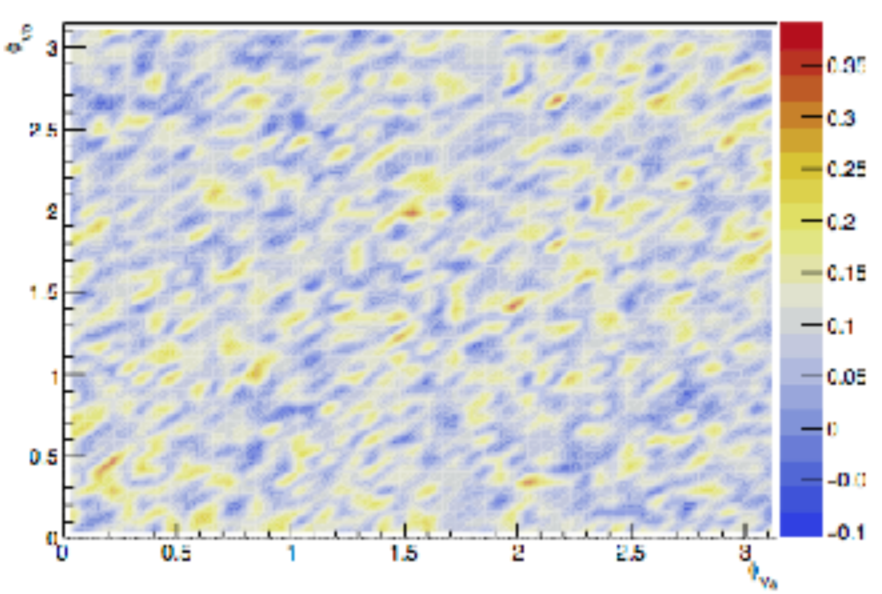


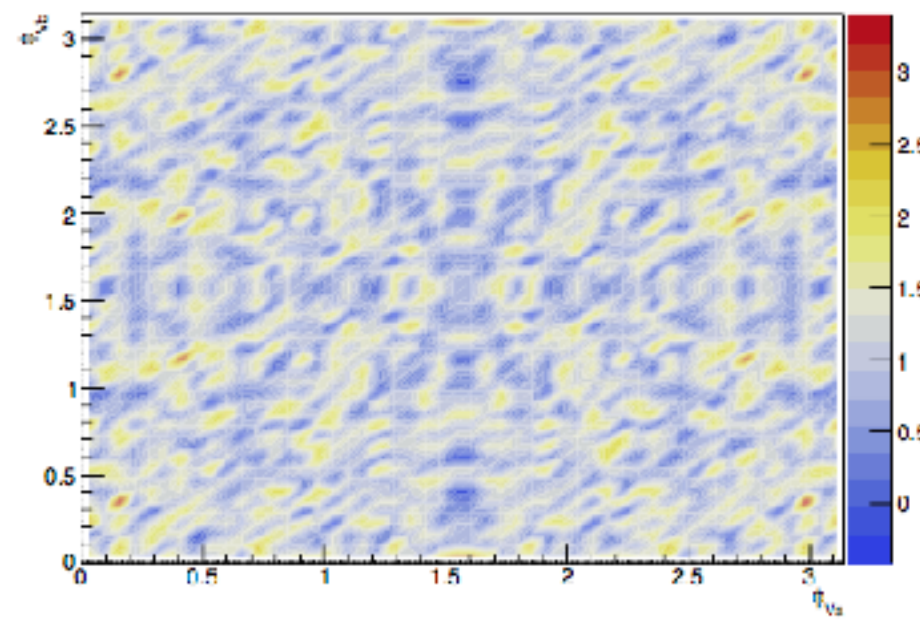
$700\mathrm{GeV} \leq m_{VV} \leq 800\mathrm{GeV}$

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

Can other dim-6 ops. produce this pattern?

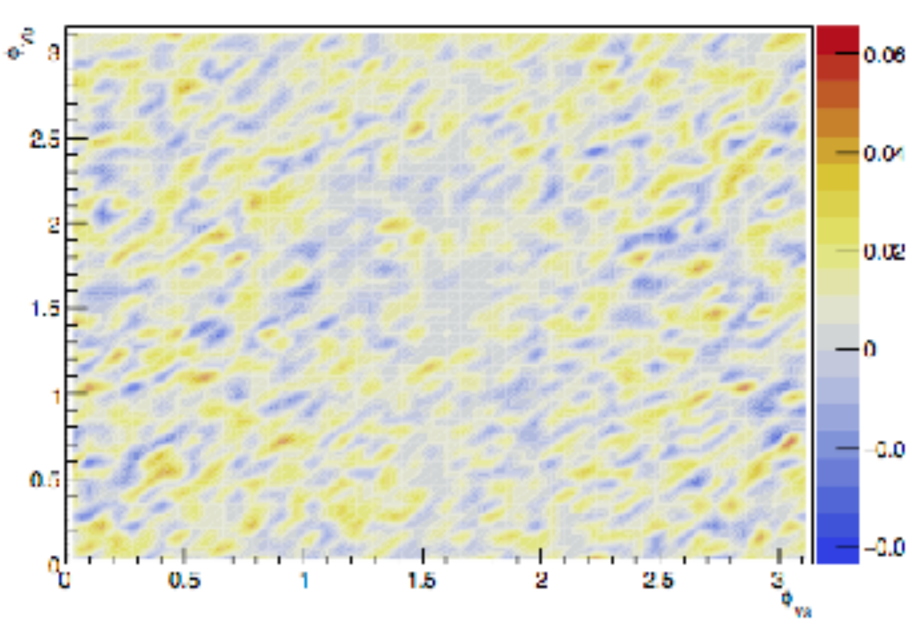
Semileptonic case | **Hadronic case**

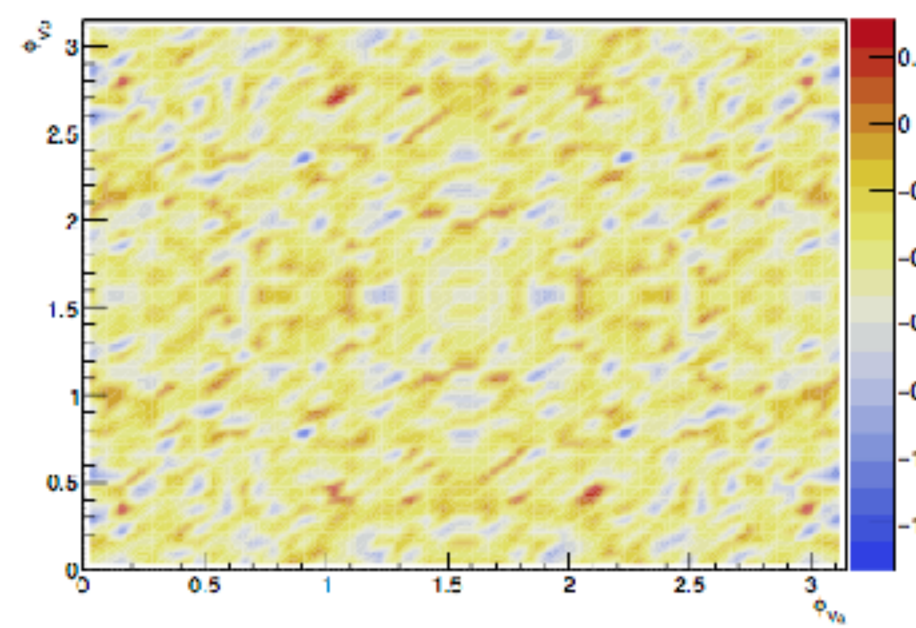




$$ig\, c_W\, \underline{\delta g_{1,Z}}\, Z_\nu W^{+\mu\nu} W^-_\mu$$

Preliminary



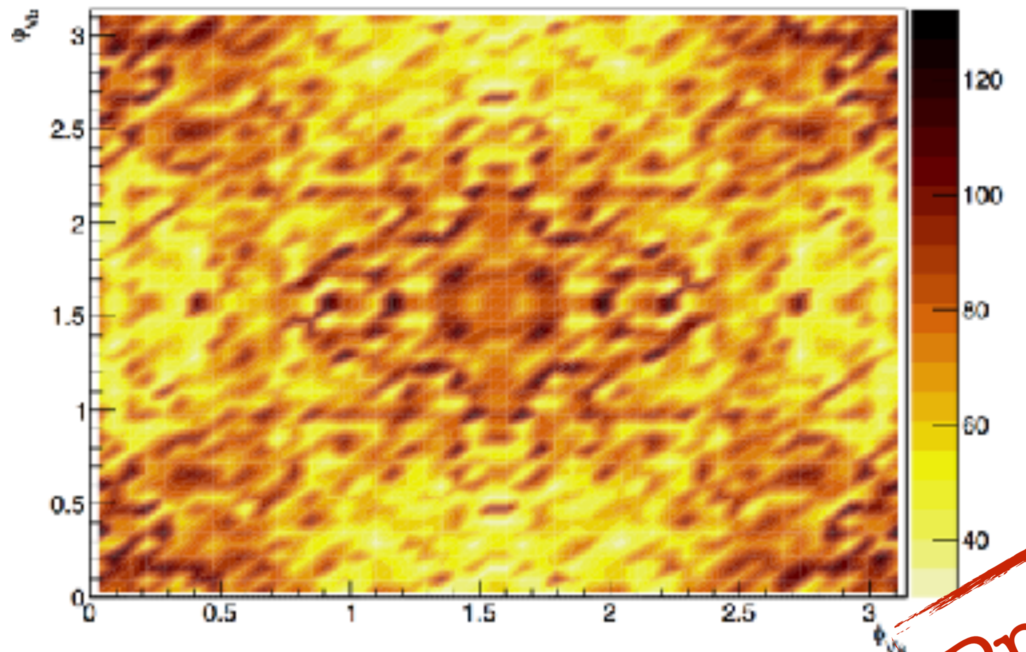


$$ig c_W \underline{\delta \kappa_Z}\, Z^{\mu\nu} W^+_\mu W^-_\nu$$

Can BSM^2 produce this pattern?

partonic case

only λ_Z

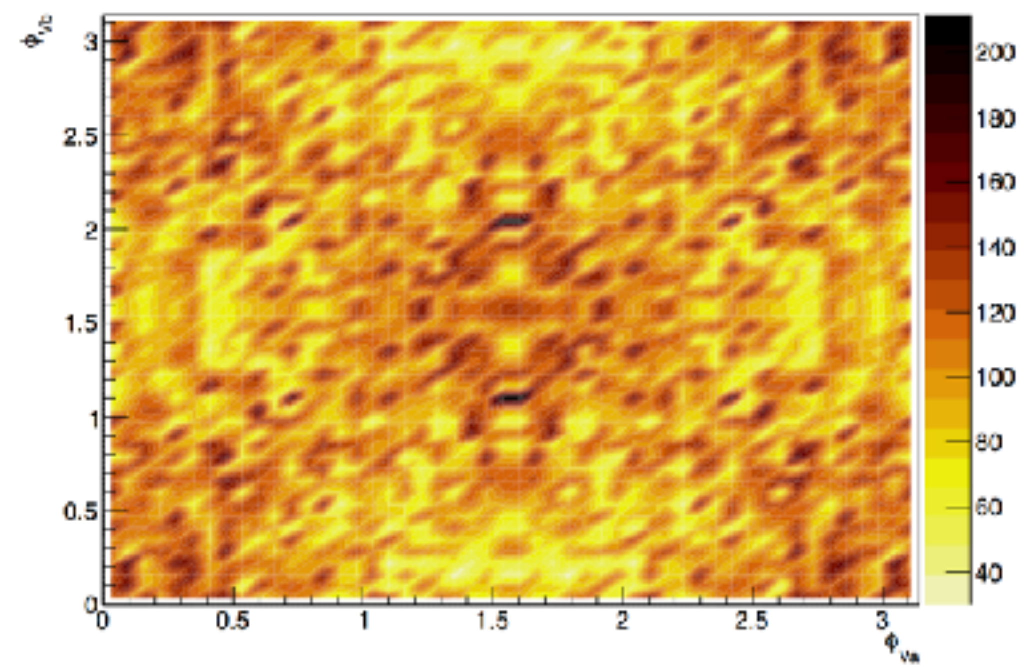


some pattern but same sign

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

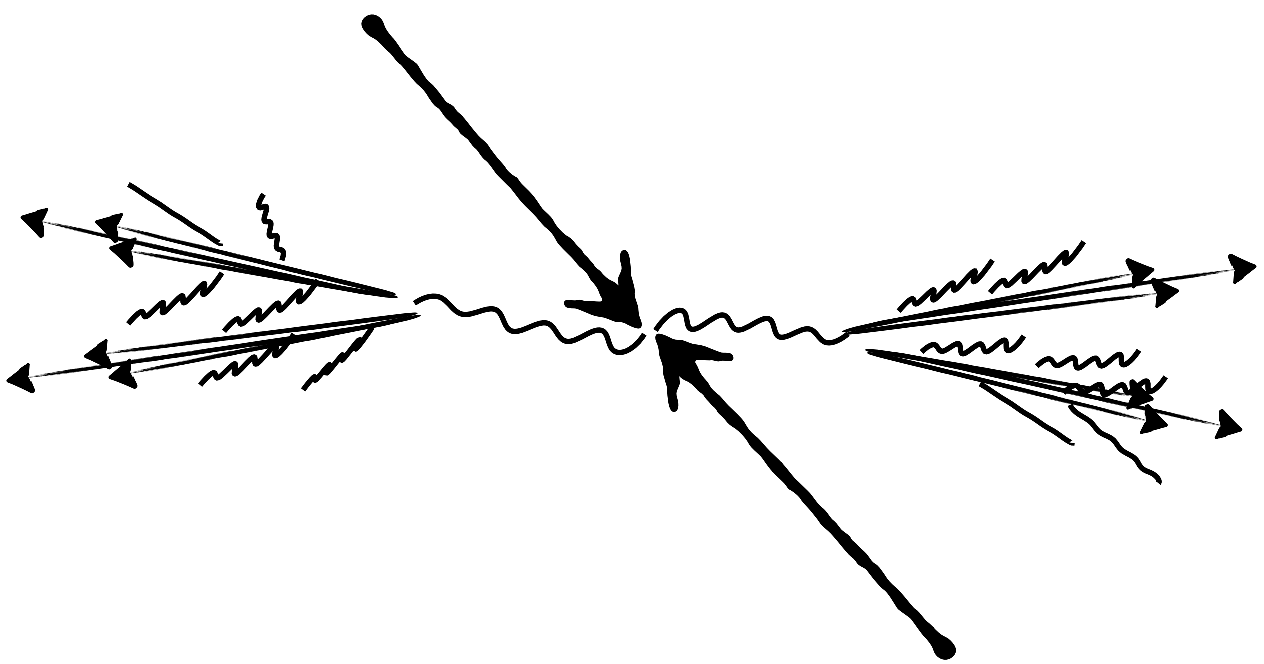
Preliminary

all ops.



$\mathrm{BSM}^2 \longleftrightarrow$ theory error

Resurrection at (sub)jet level

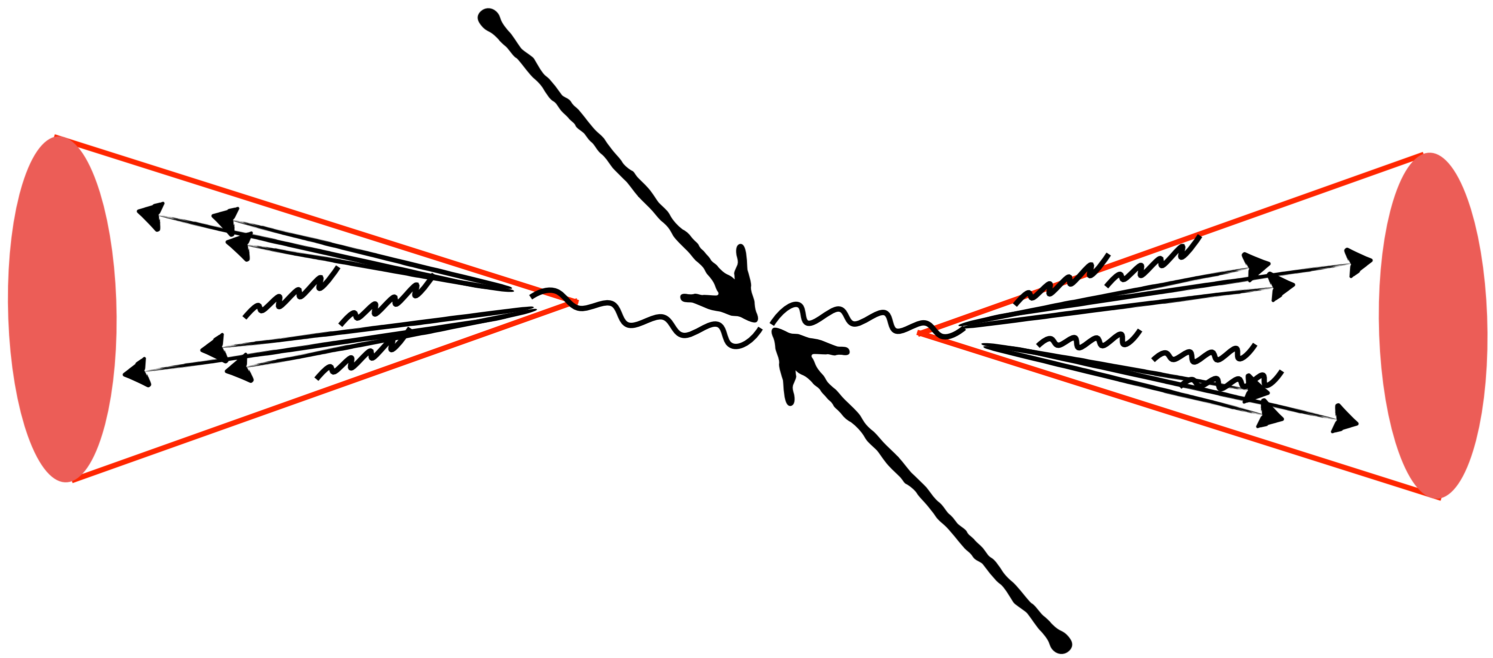


[Thaler and Van Tilburg, 11]

Resurrection at (sub)jet level

fat jets: anti-kt, R =1.0

harder jets
clustered first



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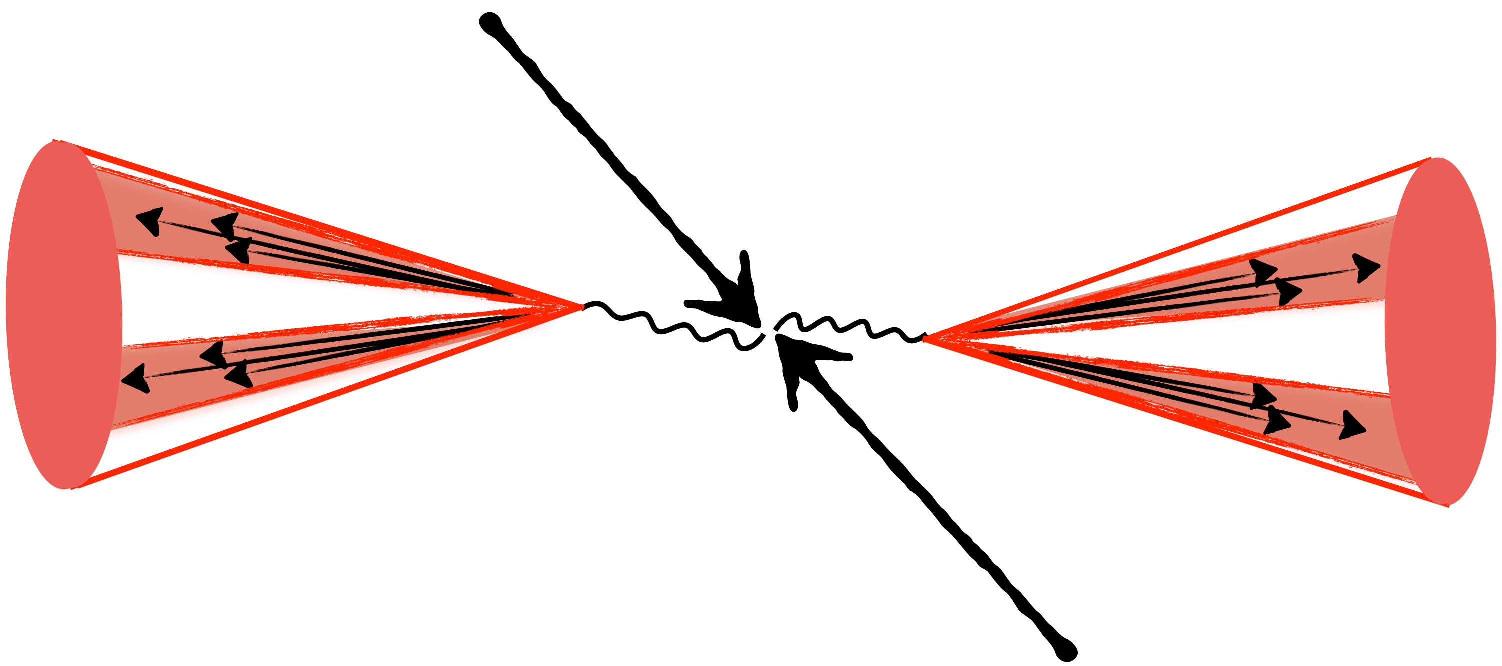


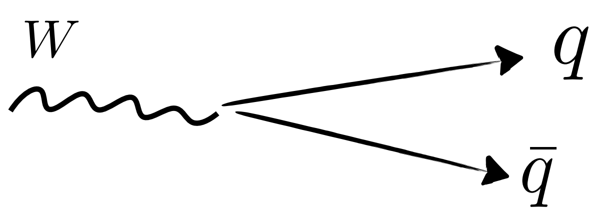
sub jets: N-subjettiness

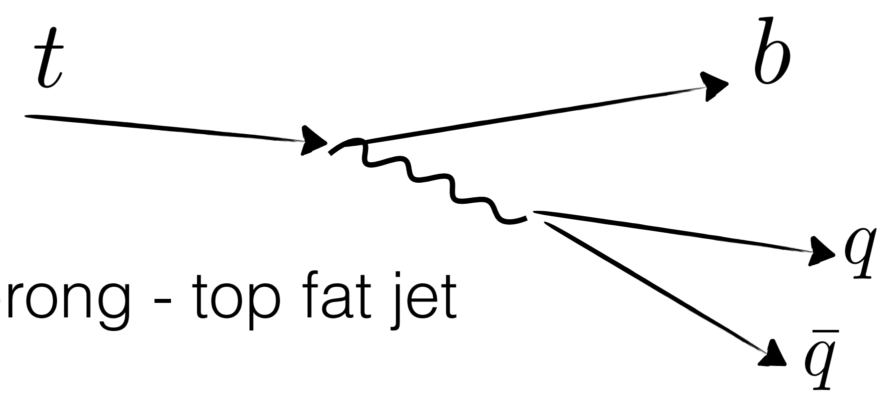
$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min\{\Delta R_{1,k}, \Delta R_{2,k}, ..., \Delta R_{N,k}\}$$

$\tau_N \to 0$ with N prong

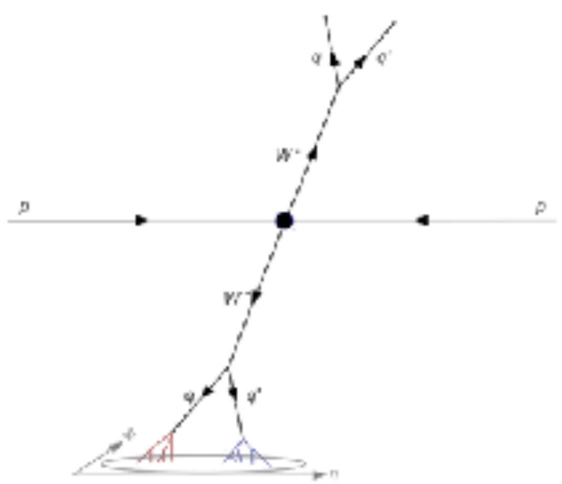
[Thaler and Van Tilburg, 11]

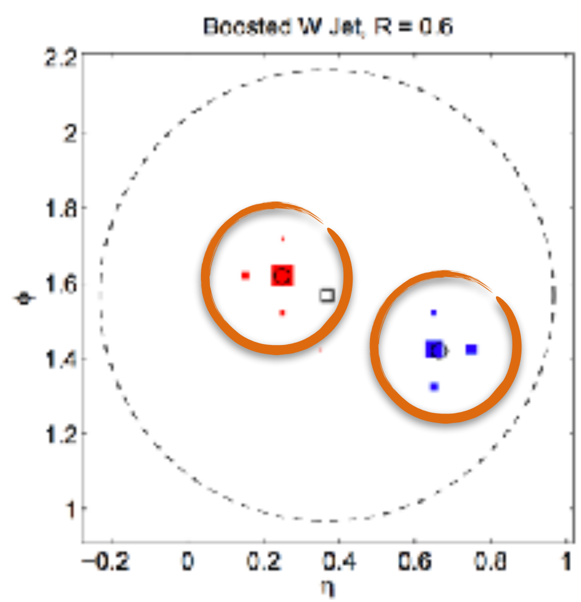
Resurrection at (sub)jet level

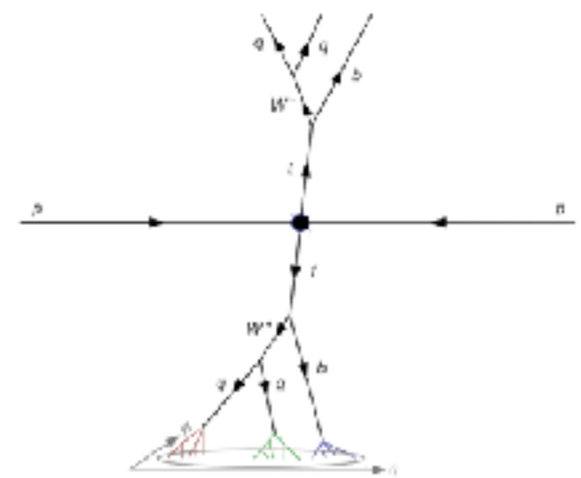


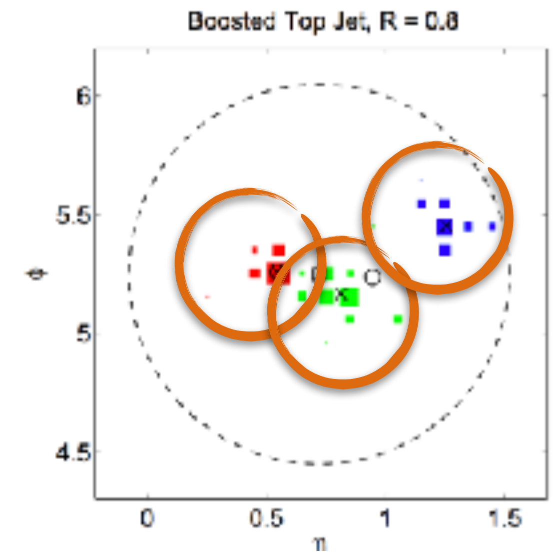


- 2 prong - W/Z/h fat jet
- 3 prong - top fat jet









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

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

QCD: q/g → 1-prong jets

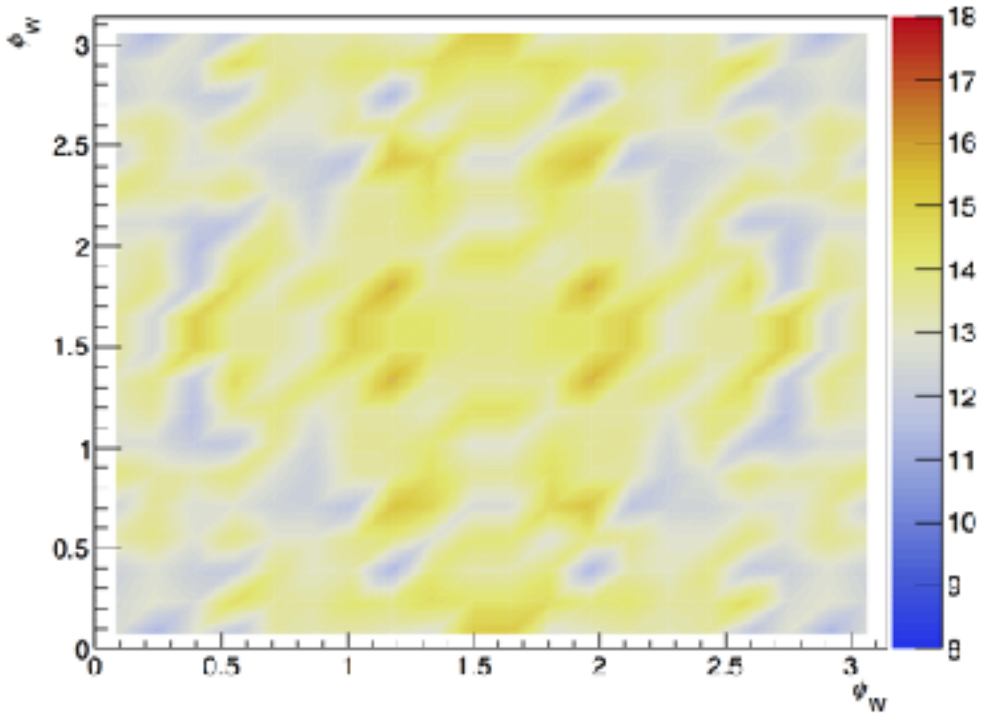
[Thaler and Van Tilburg, 11]

Very Preliminary

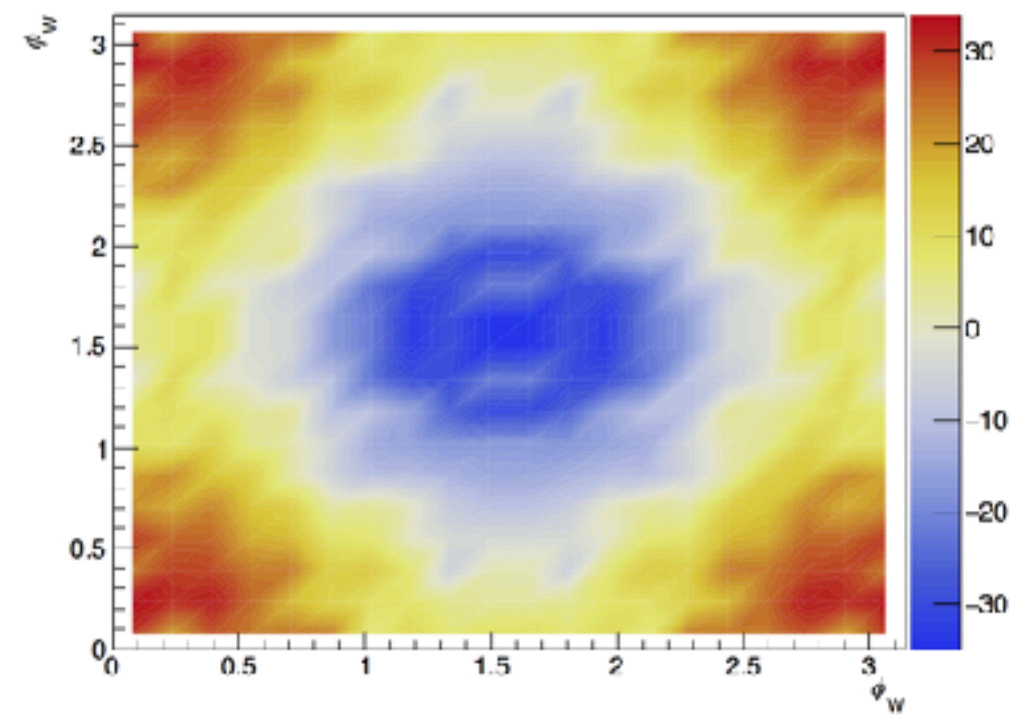
Resurrection at (sub)jet level

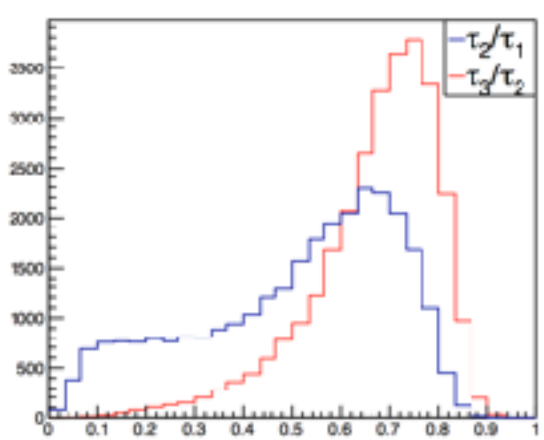
Hadronic case

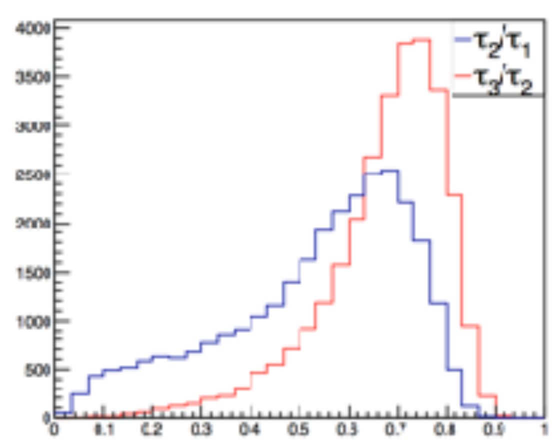
σ_{SM}

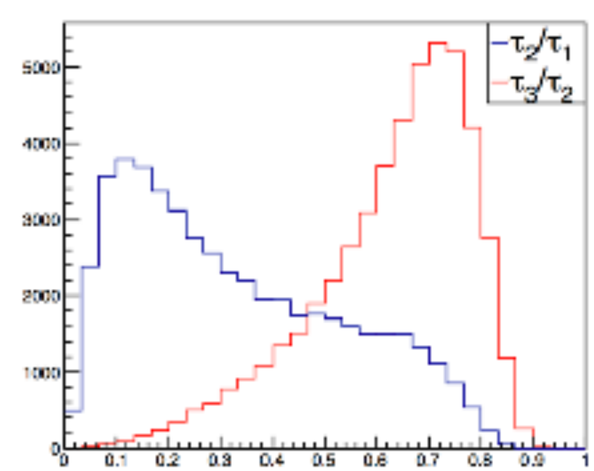


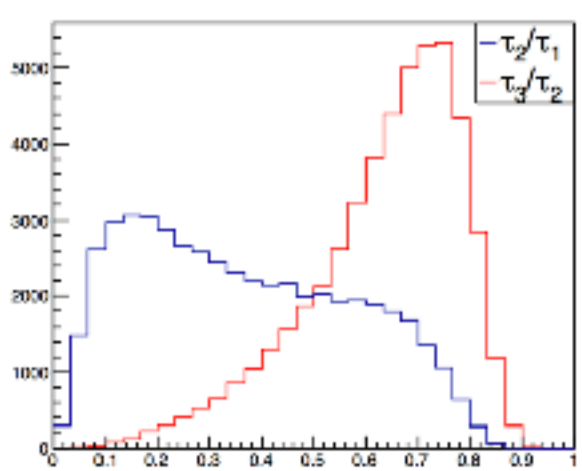
σ_{int}





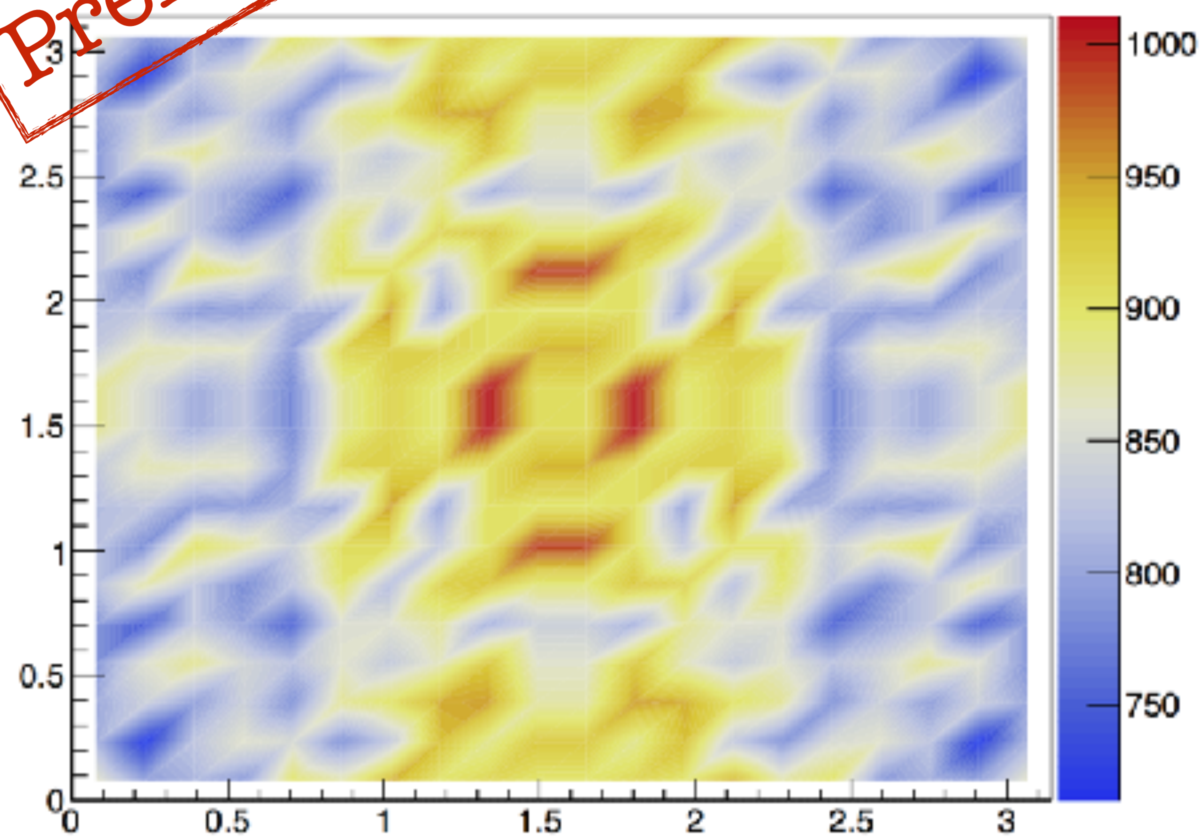






Very Preliminary

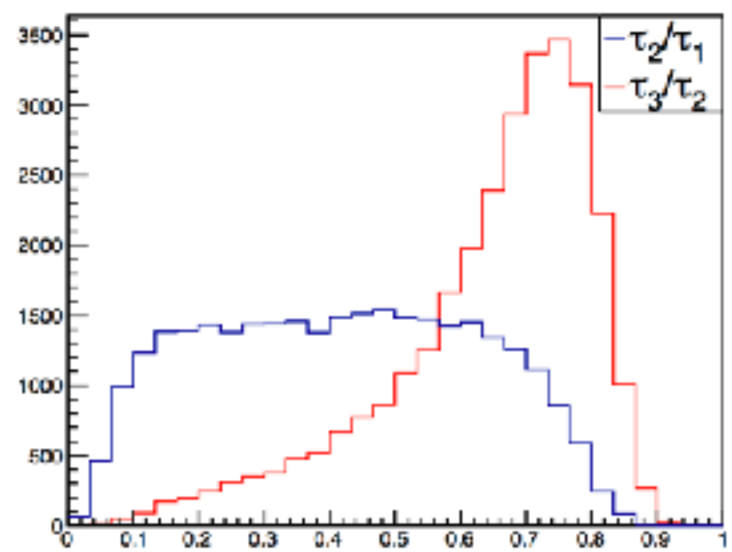
Resurrection at (sub)jet level

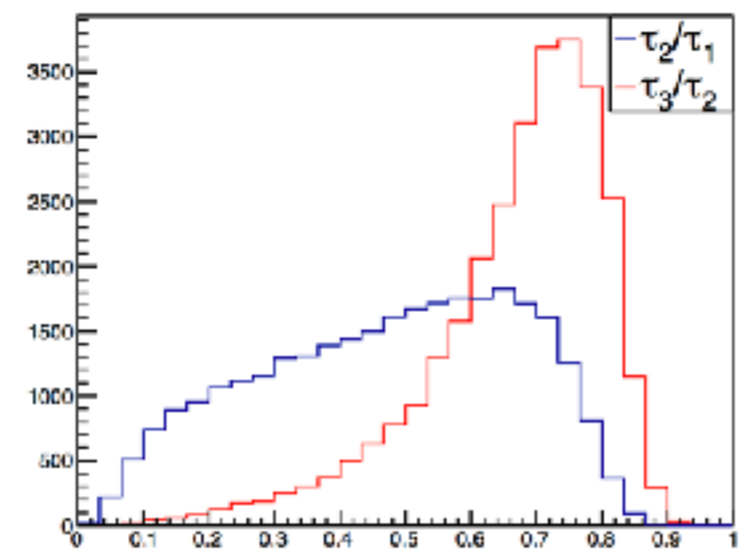


BACKGROUND - tt production

dangerous ⚠

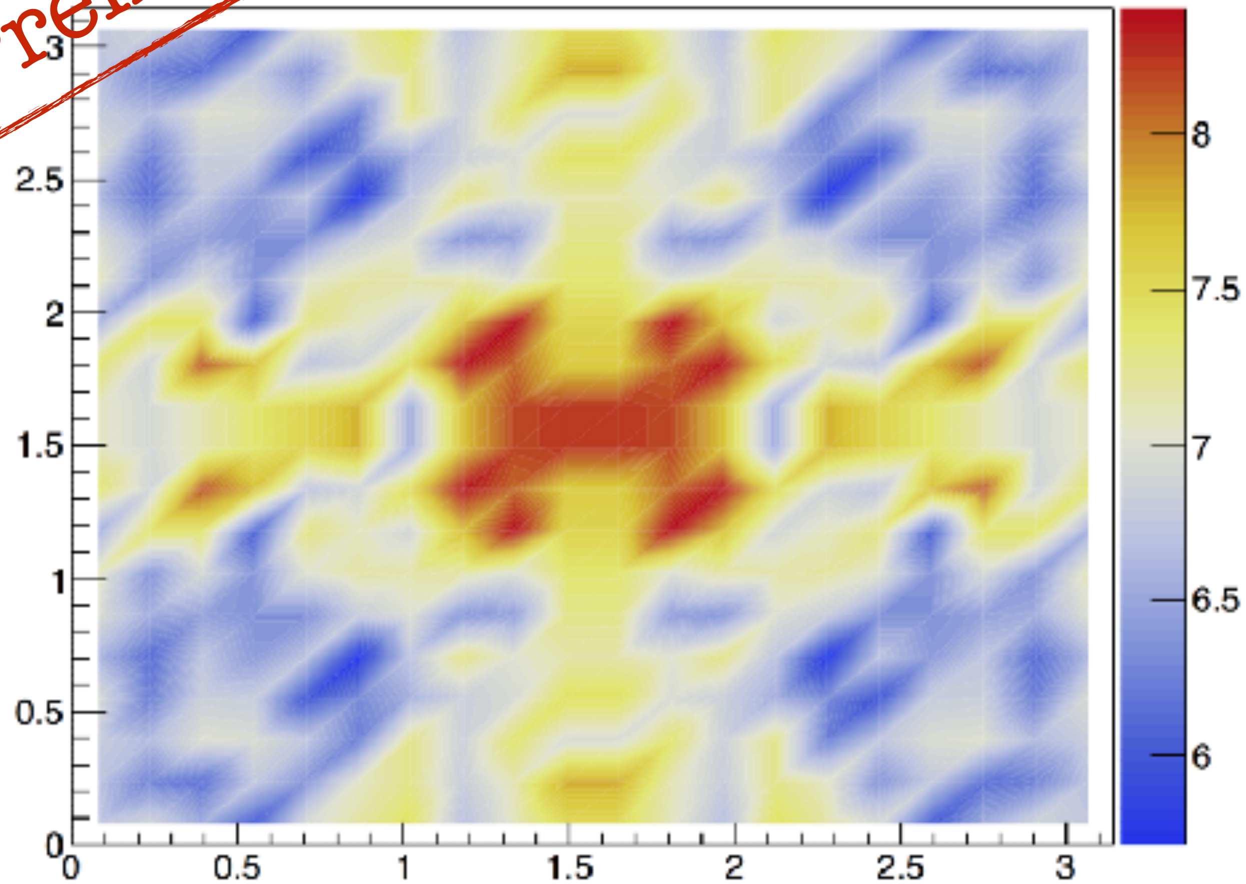
needs tagging and topology cuts



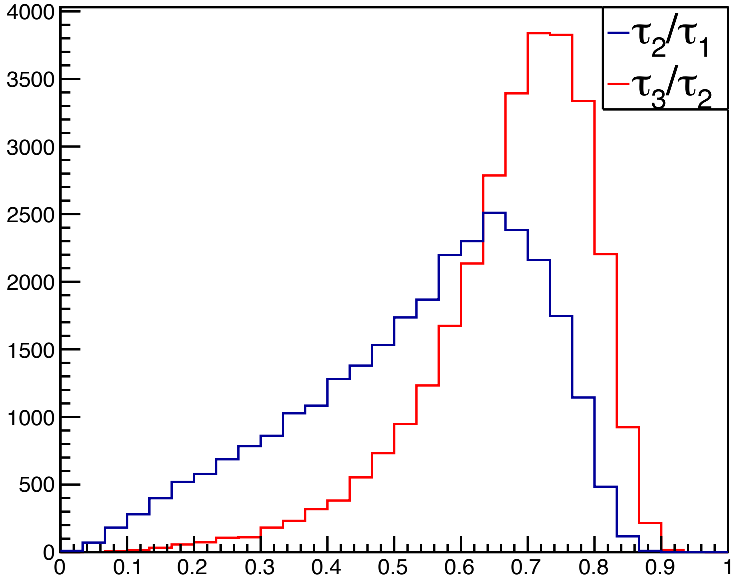


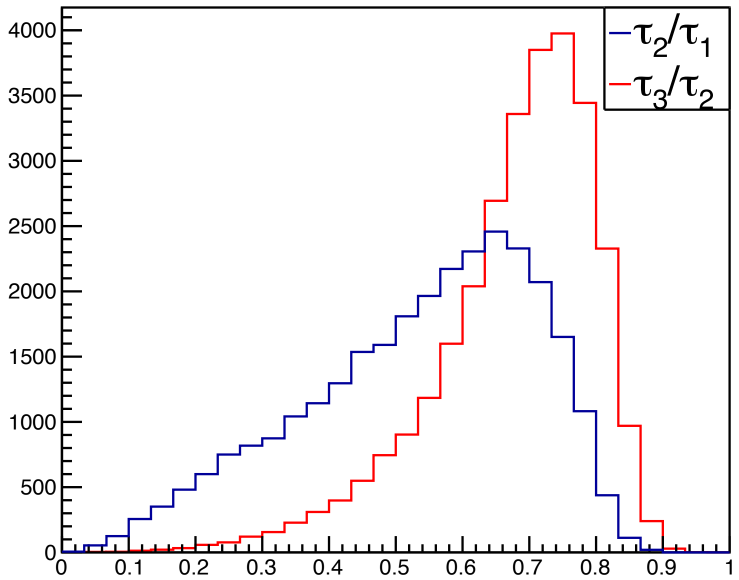
Resurrection background

dijets



could be dangerous
but easily removed
with tagging





@ reconstruction level

Topology and tagging cuts

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

$$\tau_2/\tau_1 < 0.45$$

$$40\ \mathrm{GeV} \leq \mathrm{m}_{j_1} \leq 100\ \mathrm{GeV}$$
$$40\ \mathrm{GeV} \leq \mathrm{m}_{j_2} \leq 100\ \mathrm{GeV}$$

→

channel	efficiency
signal λ_Z	~ 33%
SM	~ 8%
bkg - dijet	~1%
bkg - ttbar	~10% ⚠

Calorimeter granularization

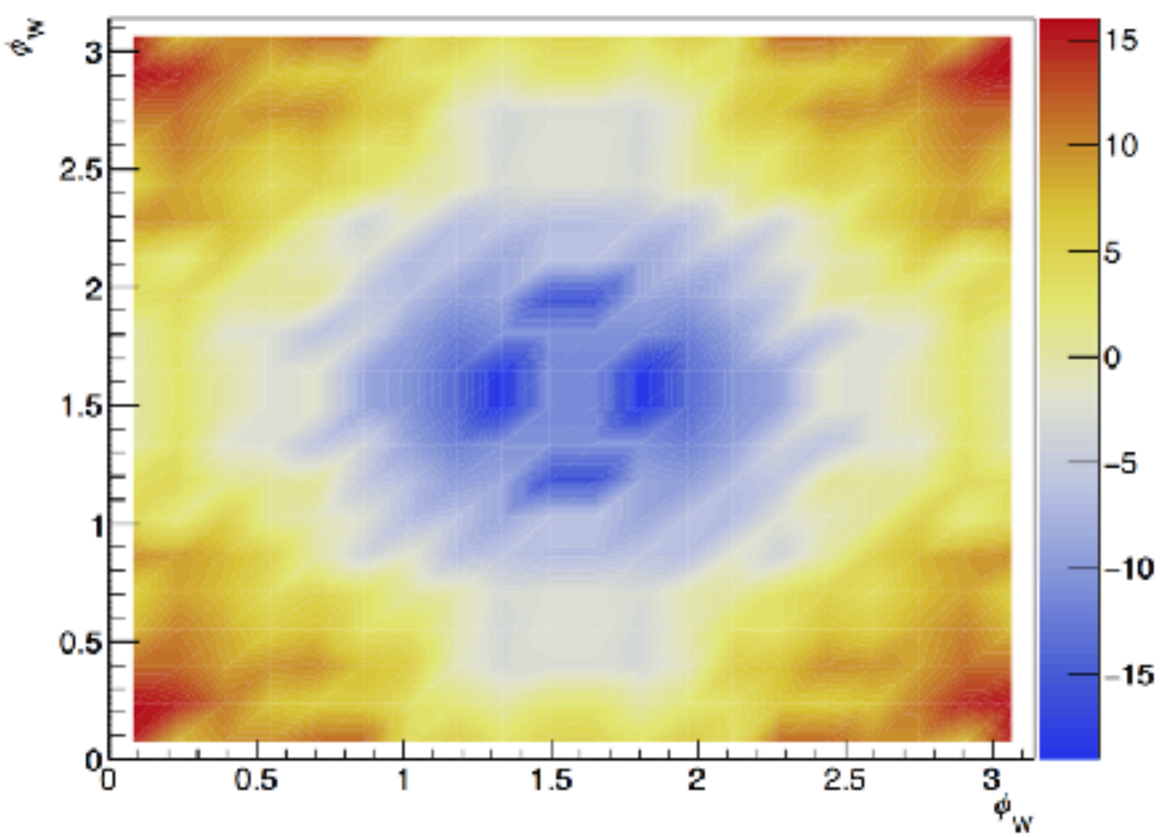
cannot resolve tracks in the same cell (0.1 × 0.1 in ϕ × η)

and does not trigger soft jets (pT < 0.5)

... after reconstruction cuts

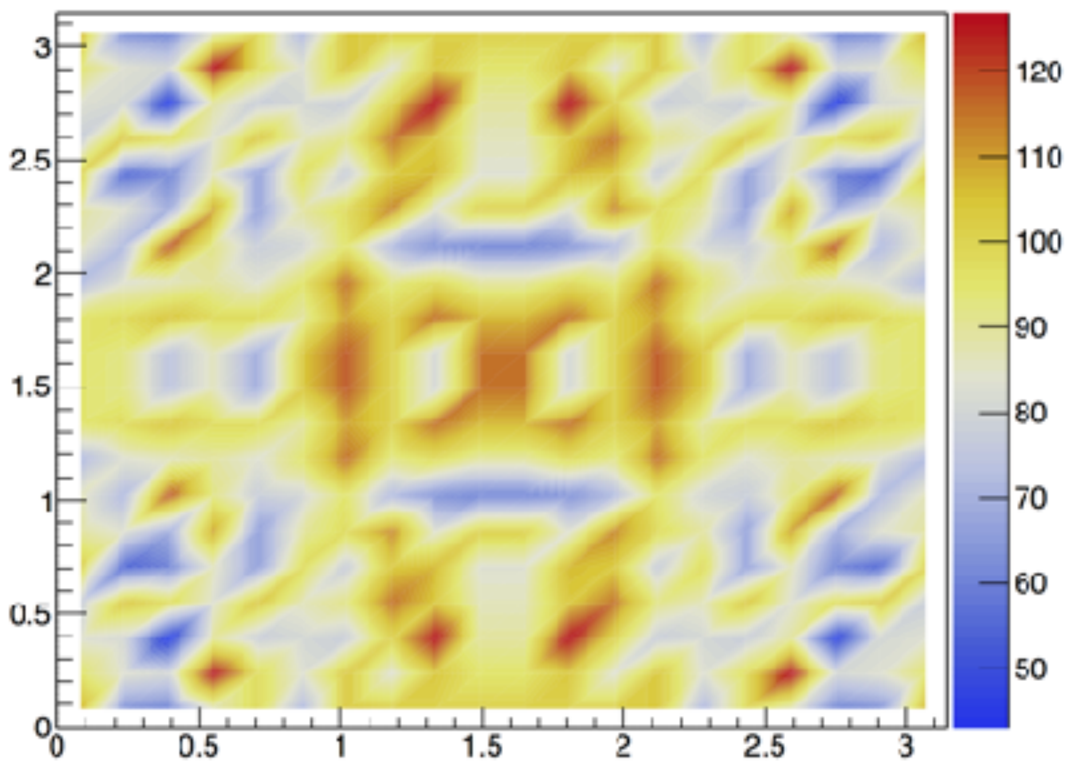
Very Preliminary

Hadronic case



keeps the angular distribution

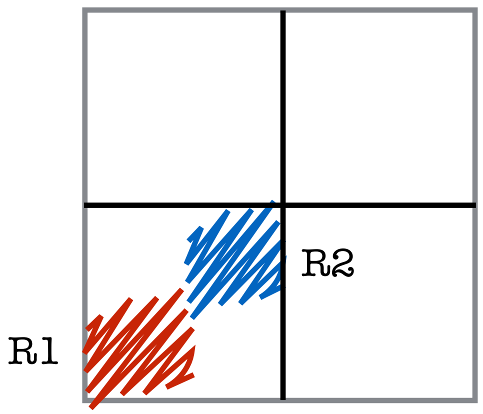
BACKGROUND - tt production



~ flat

Very Preliminary

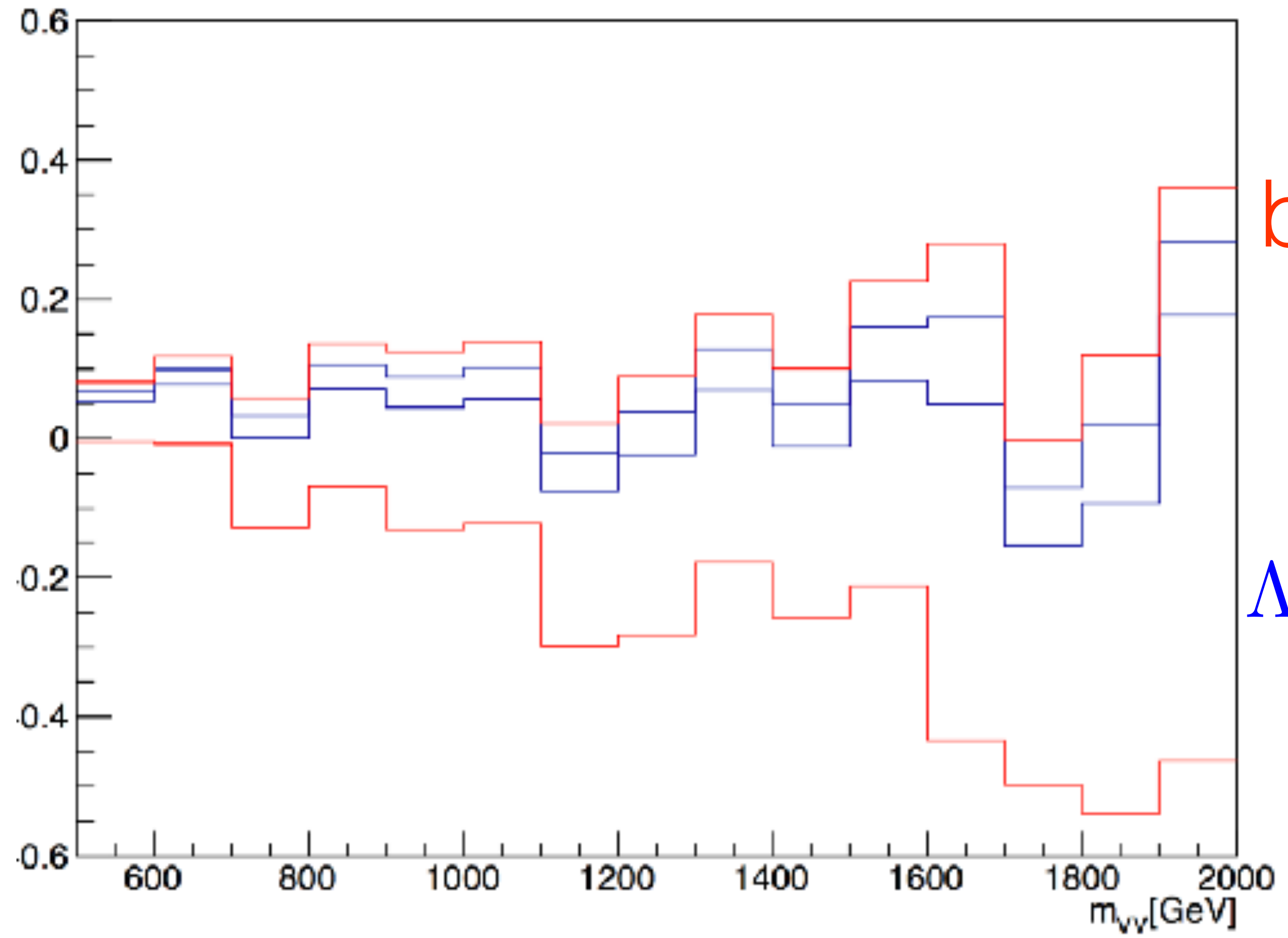
Asymmetry



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

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

jets



LEP bounds

$c \sim 1$

$\Lambda \sim 1\mathrm{TeV}$

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

Conclusions

unfolding angular distributions → energy growth of suppressed ops

Asymmetry can probe λ_Z at high energies

BKG

dijet bkg under control

ttbar is accepted but loses angular dependence

… still room for improvement

Backup slides

Helicity structures

W decay amplitudes

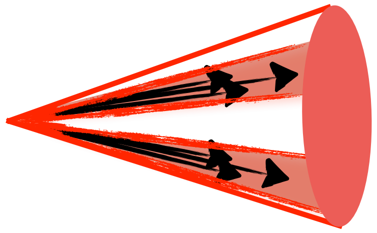
	V_1	V_2
0	no ϕ_{V_1}	no ϕ_{V_2}
$+$	$\sim e^{+i\phi_{V_1}}$	$\sim e^{-i\phi_{V_2}}$
$-$	$\sim e^{-i\phi_{V_1}}$	$\sim e^{+i\phi_{V_2}}$

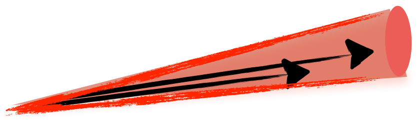
$$\sigma_{\text{int}} \sim 2\, \mathfrak{Re}[\mathcal{A}_{\text{SM}} \mathcal{A}^*_{\text{BSM}}]$$

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

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

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

SM and BSM appear in different helicity

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

2 → 2 scattering amplitudes don't interfere

A_4	$\lvert h(A_4^{\rm SM})\rvert$	$\lvert h(A_4^{\rm BSM})\rvert$
$VVVV$	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]

Disobon non Interference Resurrection via subjets

SM and BSM appear in different helicity

2 → 2 scattering amplitudes don't interfere

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

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

A_4	$\lvert h(A_4^{\text{SM}})\rvert$	$\lvert h(A_4^{\text{BSM}})\rvert$
$VVVV$	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: $|h(A_{n\geq 5}^{SM})| \leq n-4$

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

dim-6 op.

$\mathcal{O}_i$	$h_{min}^{\mathcal{O}}$	$h_{max}^{\mathcal{O}}$
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	$n-6$

[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.

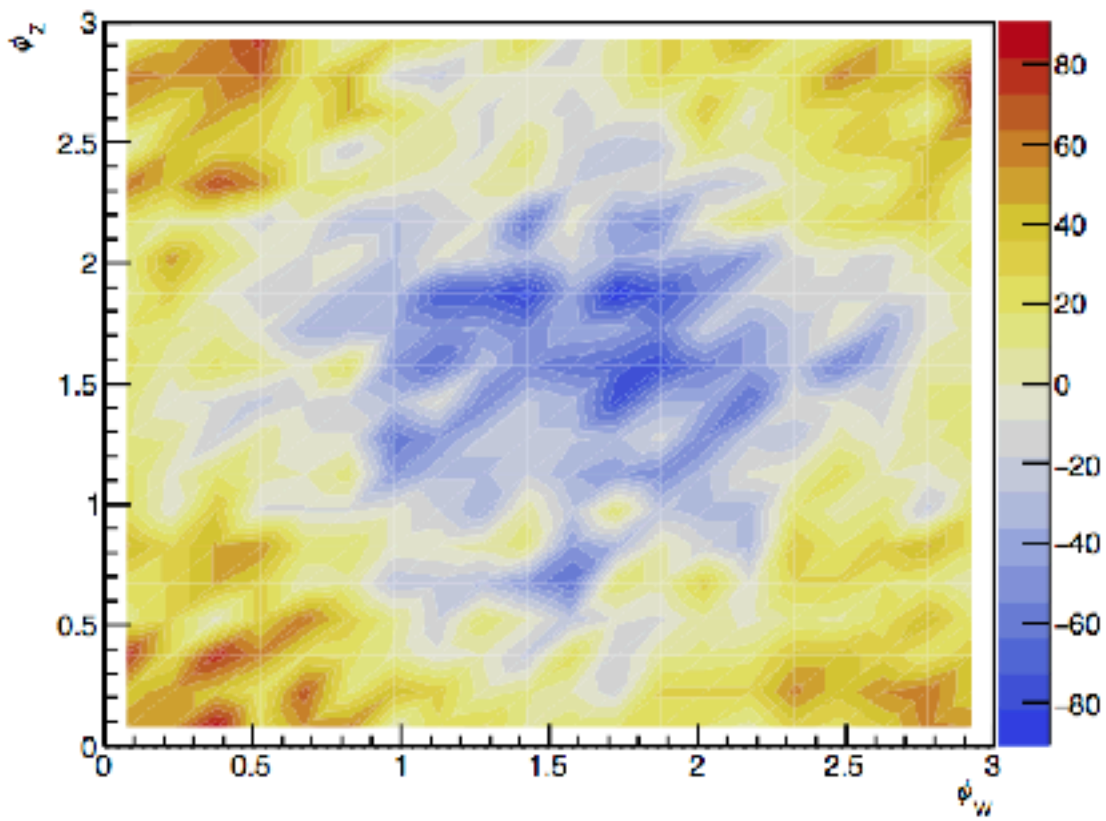
$\mathcal{O}_i$	$h^{\mathcal{O}}_{min}$	$h^{\mathcal{O}}_{max}$
F^3	$6-n$	n
$F^2\phi^2,\ F\psi^2\phi,\ \psi^4$	$6-n$	$n-2$
$\psi^2\bar{\psi}^2,\ \psi\bar{\psi}\phi^2 D,\ \phi^4 D^2$	0	$n-4$
$\psi^2\phi^3$	$6-n$	$n-4$
ϕ^6	0	$n-6$

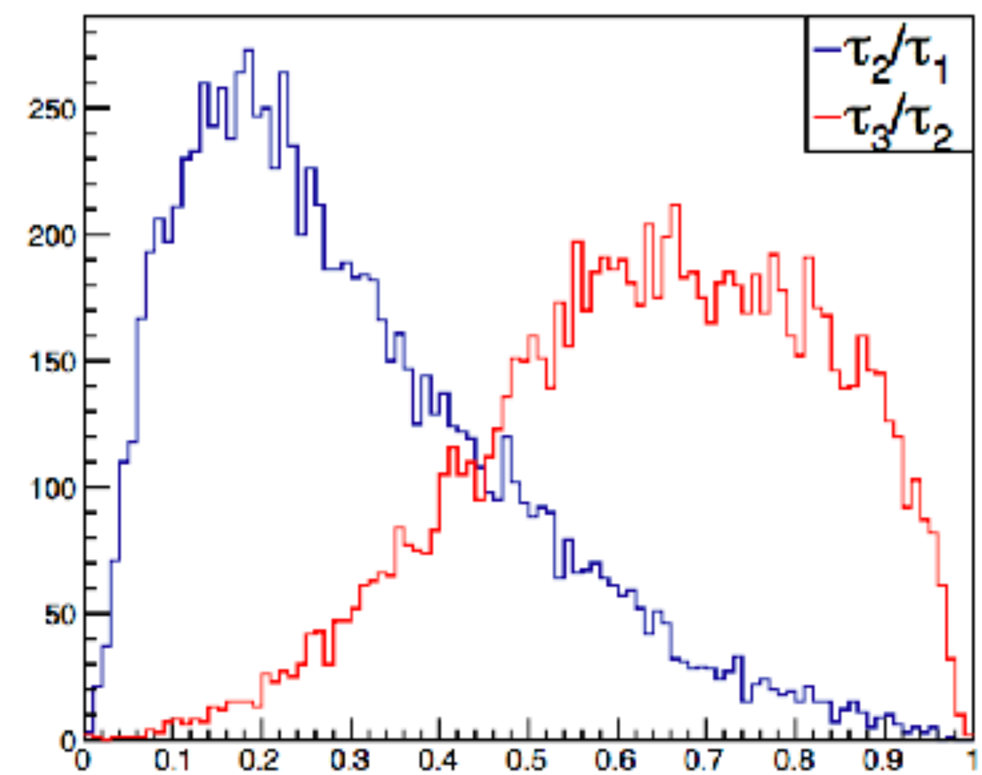
$$2 \leq h(A_6^{\mathcal{O}}) \leq 4$$

[Azatov, Contino, Machado and Riva, 16]

Resurrection at (sub)jet level

Semileptonic case





Preliminary