Probing New Physics at future e+e- colliders with two-particle angular correlations

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arXiv:2312.06526 [hep-ph]

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October 9, 2024

Outline

- Definiton of pertinent variables and two-particle correlation function
- Motivation for using two-particle correlations on the search of NP BSM
- Pythia8 implementation of HV scenarios within its PYSHOW algorithm
- Analysis at particle level including selection cuts and detector effects (ILD)
- Main results and estimation of uncertainties
- Conclusions

Two-particle correlations $(\Delta y, \Delta\phi)$

Definitions

- Rapidity difference:

$$\Delta y = y_1 - y_2,$$

- or pseudo-rapidity difference:

$$\Delta\eta = \eta_1 - \eta_2,$$

- Angular difference:

$$\Delta\phi = \phi_1 - \phi_2$$

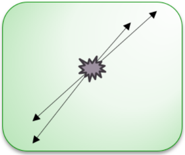
Two-particle correlations $(\Delta y, \Delta\phi)$

Correlation-related variables

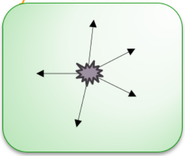
- Angular correlations → event shape
- *y*, *φ* coordinates defined w.r.t. thrust axis

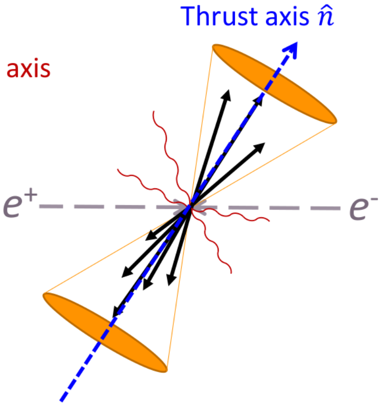
$$T = \max_{\vec{n}} \frac{\sum_i |\vec{p_i} \cdot \hat{n}|}{\sum_i |\vec{p_i}|}$$

T = 1
"pencil"-like event



T = 0.5
spherically symmetric event





Angular correlations

- Powerful method to study the underlying mechanisms of particle production
- Uncover possible collective effects resulting from high particle densities
- Two-particle correlation function C_2

$$C_2(\Delta y, \Delta\phi) = \frac{S(\Delta y, \Delta\phi)}{B(\Delta y, \Delta\phi)}$$

"B" does not stand for "background = SM processes". Expresses completely *uncorrelated* pairs (different events)

Density of particle pairs produced within the **same** event:

$$S(\Delta y, \Delta\phi) = \frac{1}{N_{pairs}} \frac{d^2 N^{same}}{d\Delta y \Delta\phi}$$

$$N_{pairs} = \iint \frac{d^2 N^{same}}{d\Delta y d\Delta\phi} d\Delta y d\Delta\phi$$

Density of particle pairs produced in the **different** events:

$$B(\Delta y, \Delta\phi) = \frac{1}{N_{mix}} \frac{d^2 N^{mix}}{d\Delta y \Delta\phi}$$

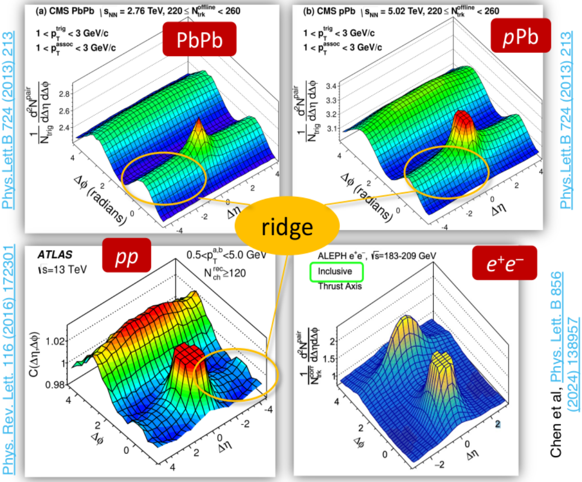
$$N_{mix} = \iint \frac{d^2 N^{mix}}{d\Delta y d\Delta\phi} d\Delta y d\Delta\phi$$

y: rapidity
φ: azimuthal angle

Two-particle angular correlations in collisions

- Interesting features depending on colliding particles and track multiplicities
- Heavy-ion collisions: ridge structure associated with fluctuating ion initial state

Sanchis-Lozano, Int.J.Mod.Phys.A 24, 4529 (2009)
Sanchis-Lozano & Sarkisyan-Grinbaum, Phys.Lett.B 781, 505 (2018)
Pérez-Ramos, Sanchis-Lozano, Sarkisyan-Grinbaum, Phys.Rev.D 105, 053001 (2022)



Two-particle angular correlations

Two-particle angular correlations in collisions

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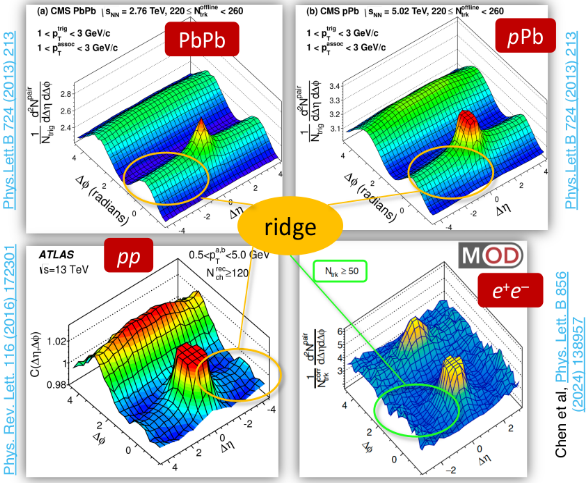

Why HV? How to probe them?

- Why Hidden Valley scenarios?
  - extra sectors common in string theory, SUSY breaking, extra dimensions, etc.
  - incredibly exciting if found: new particles, forces, dynamics
  - can drastically change phenomenology of SUSY/extra dims/etc
  - implications for dark matter, early universe cosmology, astrophysics,...
- Experimental probes
  - relatively weak experimental constraints!
  - vast array of possibilities
  - phenomenology challenging for hadron colliders.

PYSHOW algorithm

Based in the PYSHOW algorithm of transverse momentum i.e., $p_\perp$-ordered cascades in Pythia8, but for one detail: the normal time-like showering formalism was expanded with a third kind of radiation (HV), in addition to the QCD and QED ones.

$$\frac{d\mathcal{P}}{dp_\perp} = \left(\frac{d\mathcal{P}_{\mathrm{QCD}}}{dp_\perp} + \frac{d\mathcal{P}_{\mathrm{QED}}}{dp_\perp} + \frac{d\mathcal{P}_{\mathrm{HV}}}{dp_\perp}\right) \exp\left[-\int\left(\ldots + \frac{d\mathcal{P}_{\mathrm{HV}}}{dp_\perp}\right) dp'_\perp\right]$$

Production Process

The HV particles have to be pair-produced:

1. QCD-like in $pp(\bar{p})$ collisions, $gg \to Q_v \bar{Q}_v$ and $q\bar{q} \to Q_v \bar{Q}_v$
2. EW-like in e^+e^--annihilation, $f\bar{f} \to \gamma^*/Z^0 \to F_v \overline{F}_v$ for all states
3. Further decays: $F_v \to f\ q_v \to$ hadrons (i.e. $E_v \to e\ q_v$, $Q_v \to q\ q_v$)

name	partner	code	name	partner	code
D_v	d	4900001	E_v	e	4900011
U_v	u	4900002	ν_{Ev}	ν_e	4900012
S_v	s	4900003	MU_v	μ	4900013
C_v	c	4900004	ν_{MUv}	ν_μ	4900014
B_v	b	4900005	TAU_v	τ	4900015
T_v	t	4900006	ν_{TAUv}	ν_τ	4900016
g_v		4900021			
γ_v		4900022			
q_v		4900101			

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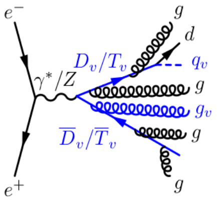
C_v	c	4900004	ν_{MUv}	ν_μ	4900014
B_v	b	4900005	TAU_v	τ	4900015
T_v	t	4900006	ν_{TAUv}	ν_τ	4900016
g_v		4900021			
γ_v		4900022			
q_v		4900101			

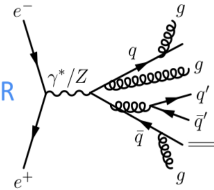
Signal and background processes

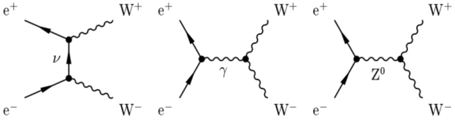


- Signal
  - $e^+e^- \to \gamma^*/Z \to \bar{D}_V\, D_V \to$ hadrons

$m(D_V)$ = 125 GeV
α_V = 0.1
no long-lived particles

- Background
  - $q\bar{q}$ production with ISR
  - $W^+W^- \to q\bar{q}q\bar{q}$





√s = 250 GeV
No polarised beam

Process	σ_{PYTHIA8} [pb]	Efficiency [%]	$< N_{\text{ch}} >$
$e^+e^- \to D_v\bar{D}_v$			
m_{q_v} = 0.1 GeV	0.13	36	12.4 ± 3.7
m_{q_v} = 10 GeV	0.12	36	12.4 ± 3.7
m_{q_v} = 50 GeV	0.12	42	11.4 ± 3.5
m_{q_v} = 100 GeV	0.12	42	6.5 ± 2.1
$e^+e^- \to q\bar{q}$ with ISR	48	$\lesssim 0.01$	9.9 ± 3.4
$WW \to 4q$	7.4	$\lesssim 0.001$	-

Analysis with detector effects

Analysis with detector effects

Event selection

- no secondary vertices
- neutral PFOs* ≤ 22 and charged PFOs ≤ 15
- reconstructed ISR photons
  - $|\cos\vartheta_{\gamma ISR}| < 0.5$
  - $E_{\gamma ISR} < 40$ GeV
- Di-jet invariant mass: $m_{jj} < 130$ GeV
- Leading jet invariant mass: $E_{jet} < 80$ GeV

$\sqrt{s} = 250$ GeV
$\mathcal{L} = 2$ ab^{-1}

Process	σ_{PYTHIA8} [pb]	Efficiency [%]	$< N_{\text{ch}} >$
$e^+e^- \to D_v \bar{D}_v$			
$m_{q_v} = 0.1$ GeV	0.13	36	12.4 ± 3.7
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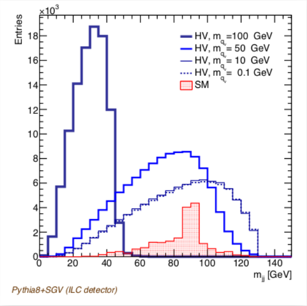


Simulation tools

- Monte Carlo event generator: Pythia8
- Fast detector simulation
  - SGV 3.0 with ILD geometry
- Analysis: ILCSoft

*PFOs: Particle Flow Objects. Detector level particle candidates in ILD

Analysis with detector effects

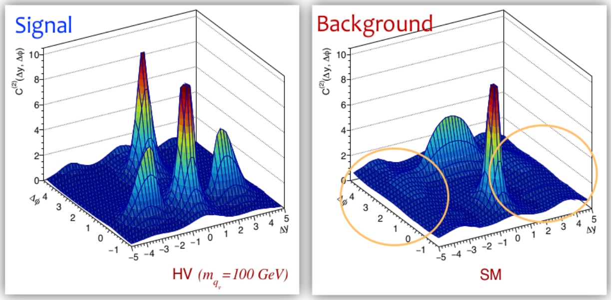
Main conclusion:

The selection cut efficiency shows a drastic reduction of the SM background while the HV signal is affected to a lesser extent!

Remark: For the computation of B, only a thrust value larger than 0.96 was imposed, keeping the same requirements on PFO multiplicities as for S!

Angular correlations

- Decay $D_v \to d\, q_v$ initiates a partonic (visible + invisible) shower
- Near-side peak at ($\Delta y \simeq 0$, $\Delta\phi \simeq 0$) mainly from track pairs within same jet
- Near-side ridge with two pronounced bumps at $1.6 < |\Delta y| < 3$, $\Delta\phi \simeq 0$, in HV scenario
  - absent in background
- Away-side correlation ridge around $\Delta\varphi \simeq \pi$ → back-to-back momentum balance



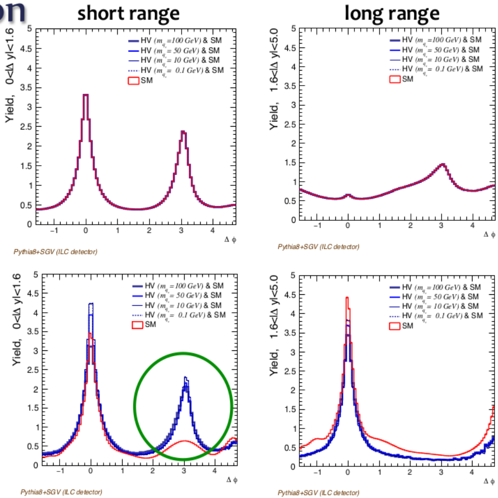
Analysis with detector effects: main results

Effect of event selection

- SM reduced while keeping HV
- Yield becomes observable for HV discovery
- Long-range, near-side ridge in SM due to ISR effect (resonant Z production)
- Different behaviour between signal and background
  → **hint of New Physics**

before cuts

after cuts



$$Y(\Delta\phi) = \frac{\int_{1.6\leq|\Delta y|\leq 3} S(\Delta y, \Delta\phi)\mathrm{d}y}{\int_{1.6\leq|\Delta y|\leq 3} B(\Delta y, \Delta\phi)\mathrm{d}y}$$

Analysis with detector effects: main results

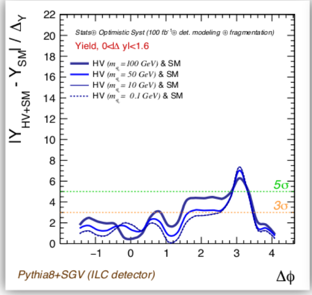
Main result

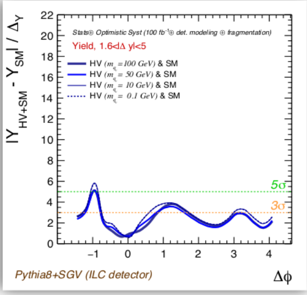
At short range after cuts, a sizable peak at $\Delta\phi \simeq \pi$ characterizes the HV scenario, unlike the pure SM case.

This difference would potentially serve as a valuable signature of a hidden sector, complementary to more conventional BSM searches!

Uncertainties and sensitivity

- Uncertainties
  - statistical from luminosity: 100 fb^{-1} (first year)
  - parton shower, fragmentation and hadronisation: HERWIG7.3 vs PYTHIA8
  - detector modelling: partially or totally cancelled in two-particle correlation
    - conservative uncertainty added: particle- versus detector-level



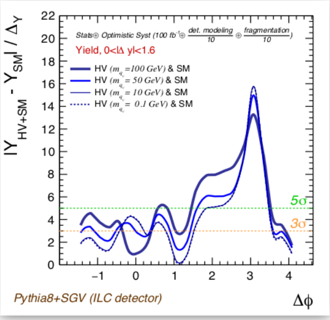


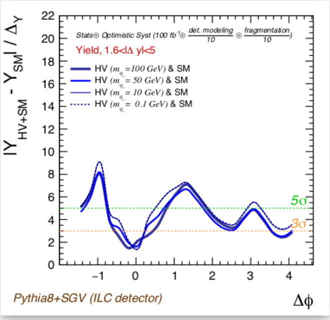
- Sensitivity
  - $> 5\sigma$ in far peak

Analysis with detector effects: main results

Sensitivity improvements

- Conservative uncertainty estimation → room for improvement
- Assuming that systematic uncertainties improve by an order of magnitude, much better prospects
- Different hidden-quark (q_v) masses affects the sensitivity





Conclusions

- Two-particle angular correlations in e+e- factories can become a useful toot to discover NP (e.g. Hidden Valley scenarios)
- Such searches are complementary to more conventional searches, thus increasing the discovry potential
- Sensitivity $> 5\sigma$ with convervative systematic uncertainties.
- Future work: longitudinally polarised beams and FCC-specific detector!