Probing hidden sectors at e^+e^- colliders via two-particle angular correlations

Vasiliki A. Mitsou

In collaboration with E. Musumeci, A. Irles, R. Pérez-Ramos, I. Corredoira, E. Sarkisyan-Grinbaum, M.A. Sanchis-Lozano

arXiv:2312.06526 [hep-ph]

24th HELLENIC SCHOOL AND WORKSHOPS ON ELEMENTARY PARTICLE PHYSICS AND GRAVITY

Workshop on the Standard Model and Beyond

August 25 – September 4, 2024, Corfu, Greece

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:

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

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

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

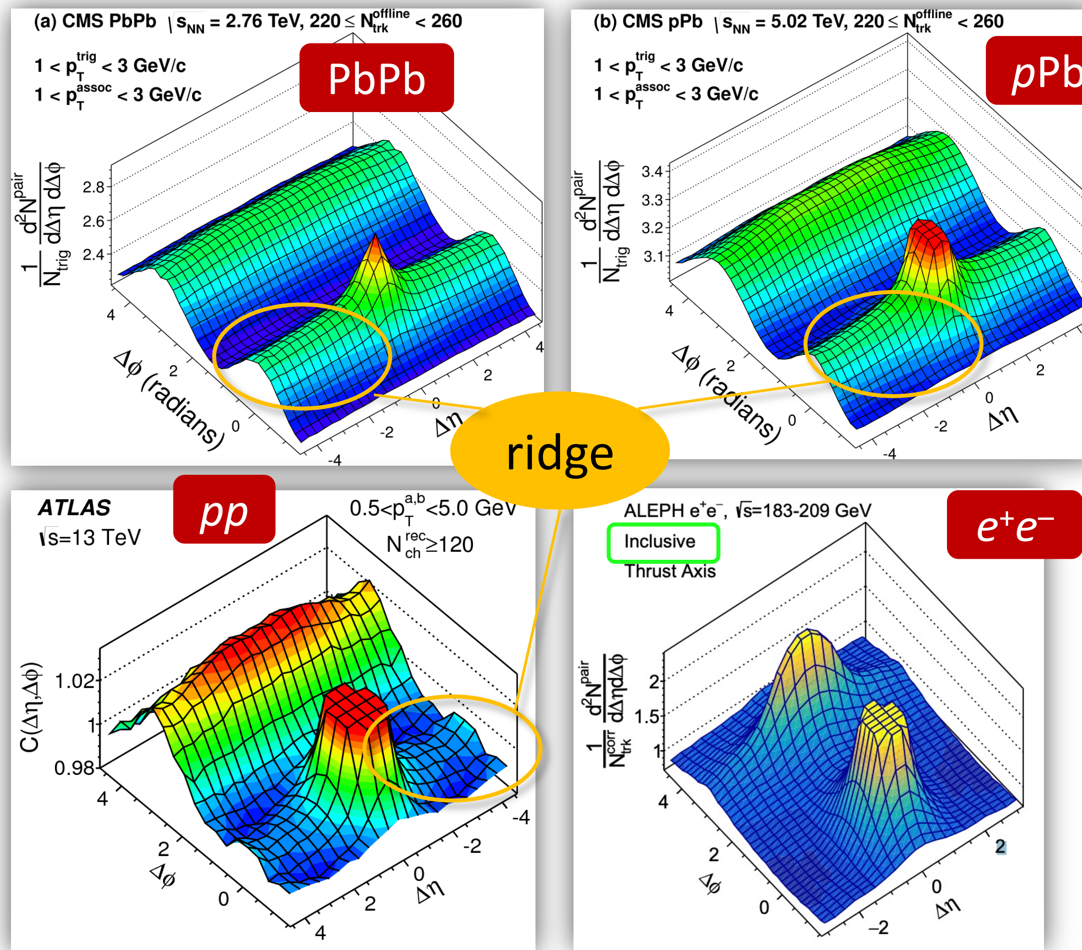
$$B(\Delta y, \Delta\phi) = \frac{1}{N_{mix}} \frac{d^2N^{mix}}{d\Delta y \Delta\phi}$$

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

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



Phys.Lett.B 724 (2013) 213

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Chen et al, Phys. Lett. B 856 (2024) 138957

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)

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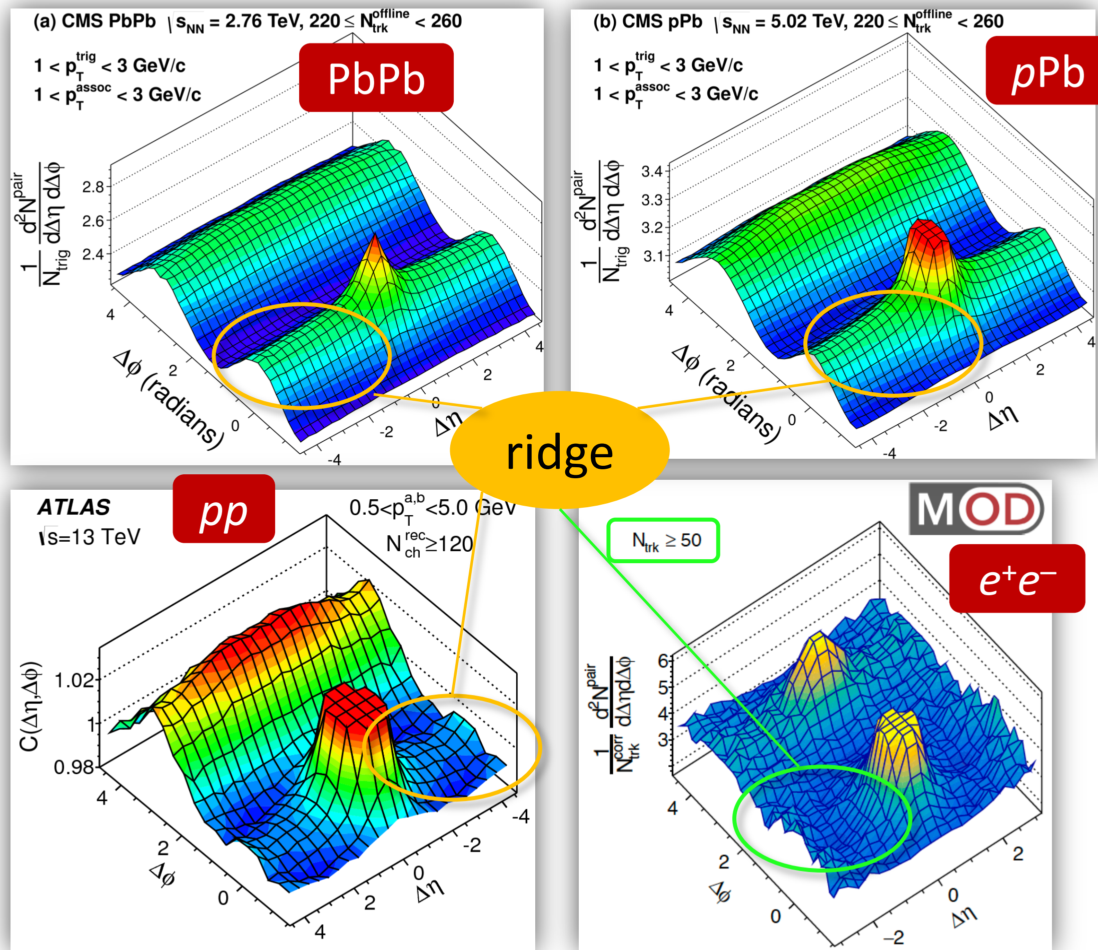

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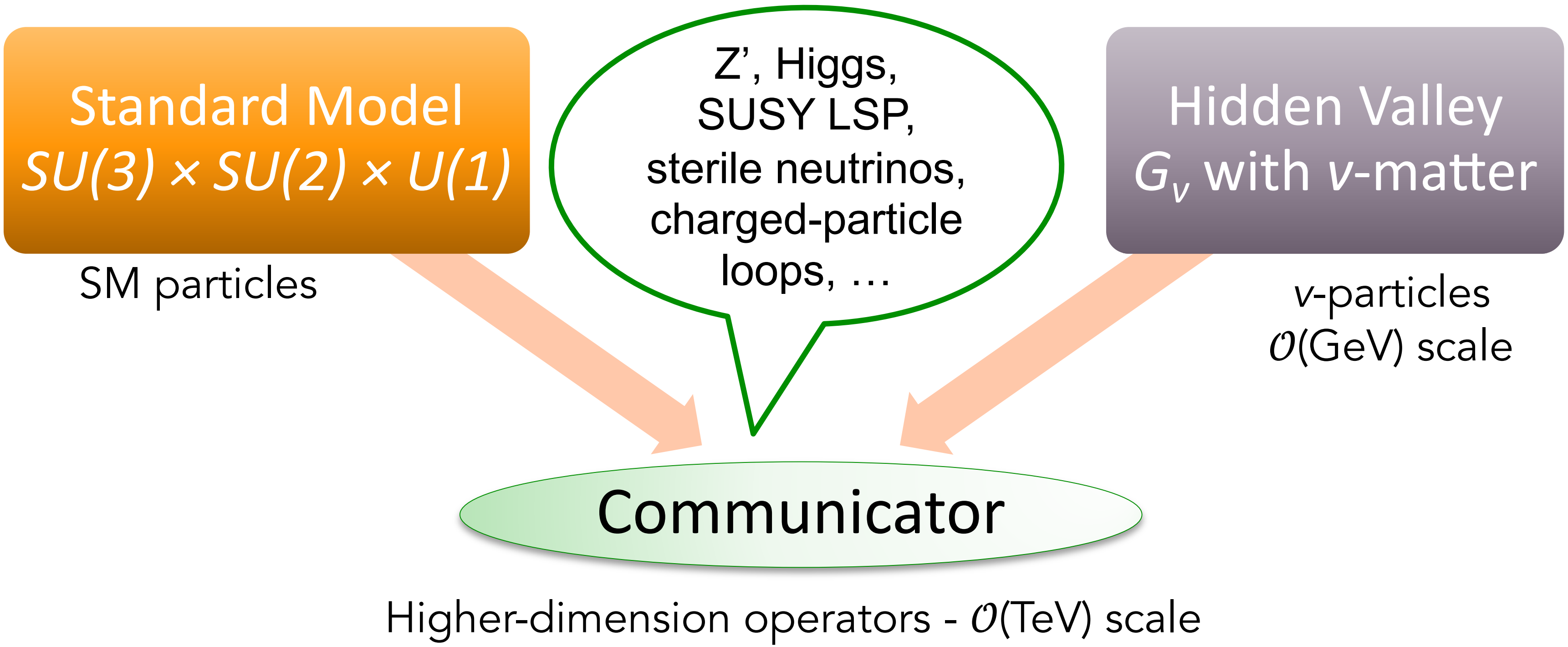
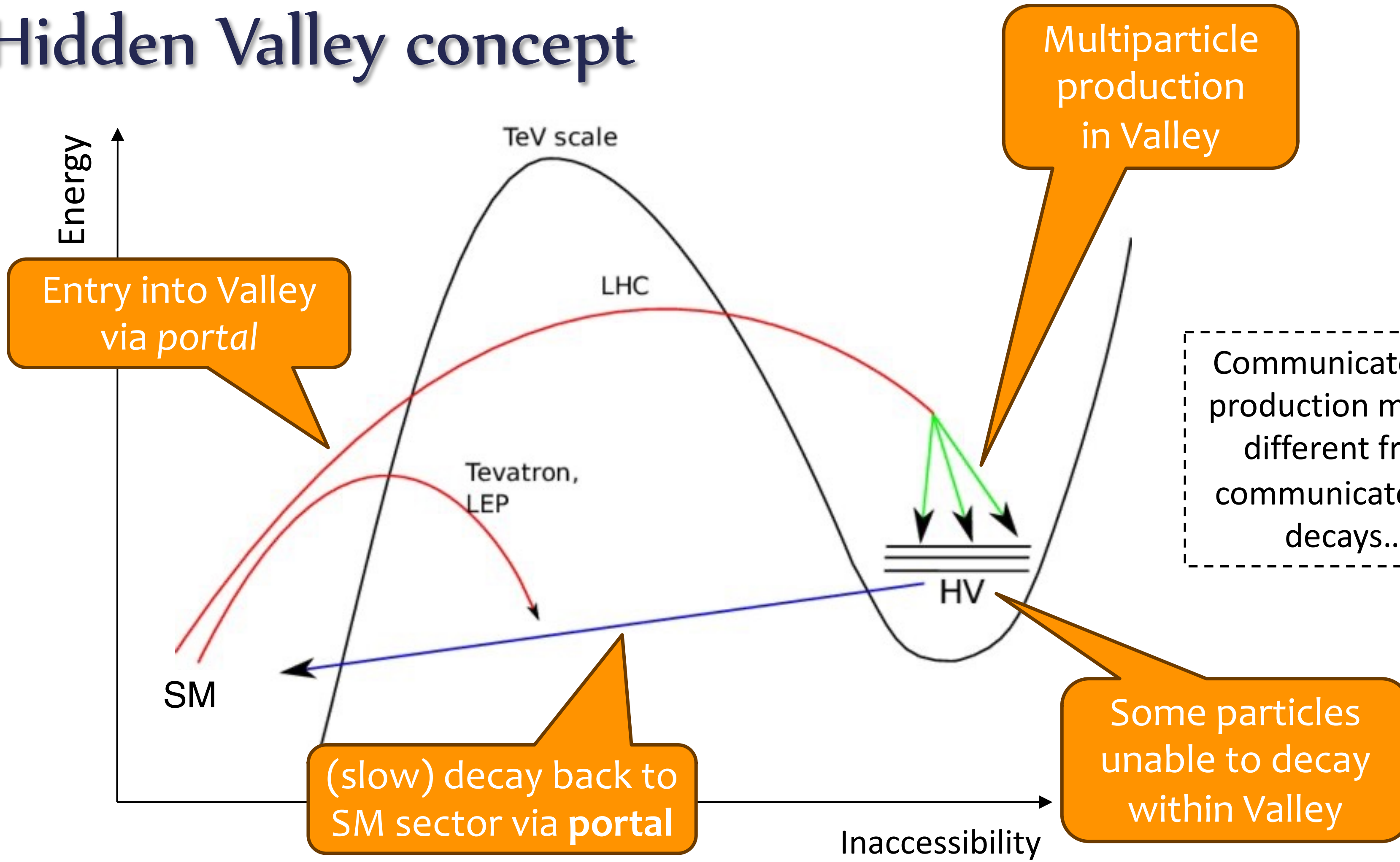
Hidden Valley (HV)

"Meta-model": large class of theoretical scenarios



Strassler & Zurek, Phys.Lett.B 651 (2007) 374

Hidden Valley concept



Communicator for production may be different from communicator for decays…

Why HV? How to probe them?

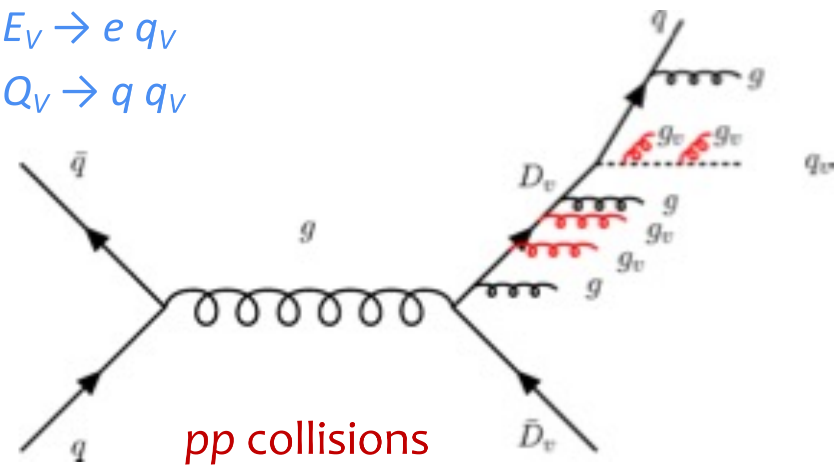
- Why Hidden Valley scenarios?
  - extra sectors common in string theory, SUSY breaking, extra dimensions, etc.
  - incredibly exciting if found: new particles, forces, dynamics
  - can drastically change phenomenology of SUSY/extra dims/etc.
  - implications for dark matter, early universe cosmology,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

QCD-like HV scenario

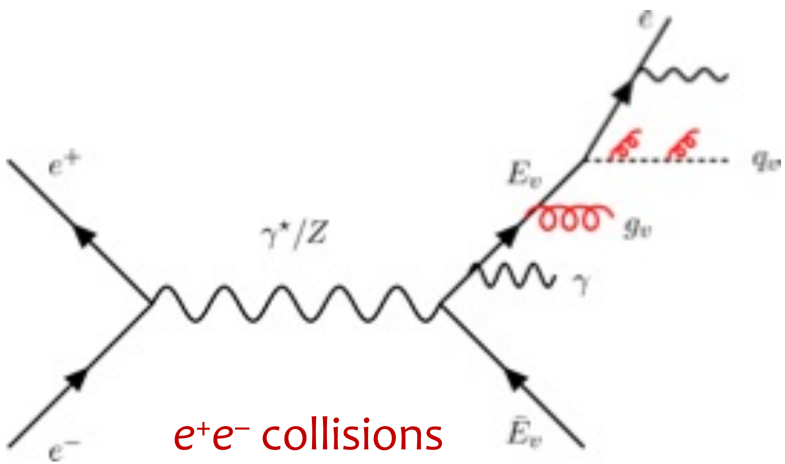
- Communicator: F_V
- Charged under G_{SM} and G_V
- Pair-produced in collisions
- v-quarks, q_V, and v-gluons, g_V
- Prompt decays
  - $F_V \rightarrow f\, q_V \longrightarrow$ hadrons
  - $E_V \rightarrow e\, q_V$
  - $Q_V \rightarrow q\, q_V$

Signature

Perturbation
in conventional QCD cascade
and final hadronisation
⇩
anomalies in angular correlations
e.g. *ridge*-like structures



pp collisions



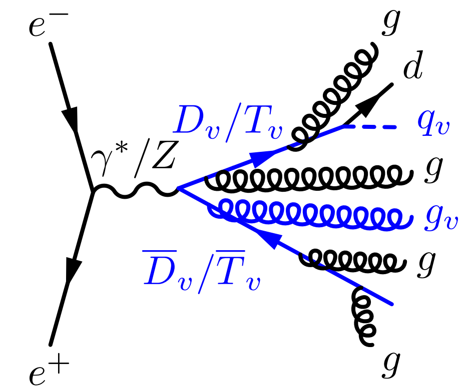
e^+e^- collisions

Carloni & Sjöstrand, JHEP 09 (2010) 105

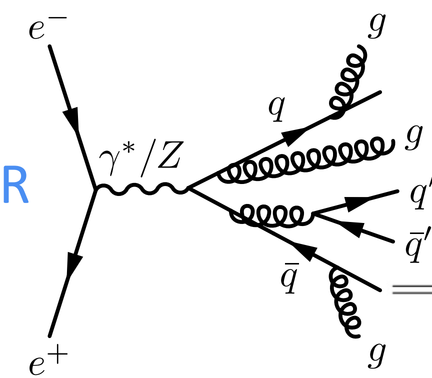
Signal and background processes

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

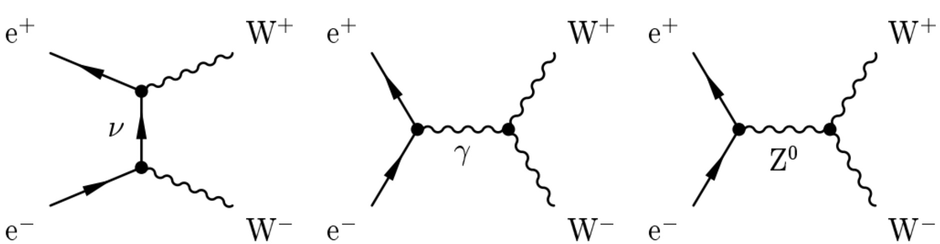
$m(D_V)$ = 125 GeV
α_V = 0.1
no long-lived particles



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



√s = 250 GeV
No polarised beam



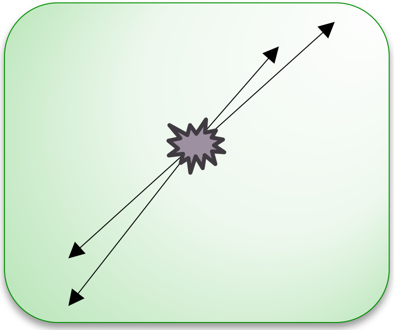
Process	σ_{PYTHIA8} [pb]	Efficiency [%]	$< N_{\text{ch}} >$
$e^+e^- \rightarrow D_v\bar{D}_v$			
m_{q_v} = 0.1 GeV	0.13	36	12.4 ± 3.7
m_{q_v} = 10 GeV	0.12	36	12.4 ± 3.7
m_{q_v} = 50 GeV	0.12	42	11.4 ± 3.5
m_{q_v} = 100 GeV	0.12	42	6.5 ± 2.1
$e^+e^- \rightarrow q\bar{q}$ with ISR	48	$\lesssim 0.01$	9.9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

Correlation-related variables

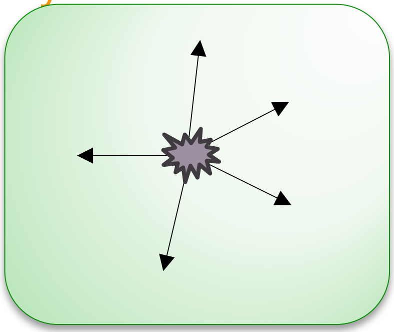
- Angular correlations → event shape
- *y*, *φ* coordinates defined w.r.t. thrust axis

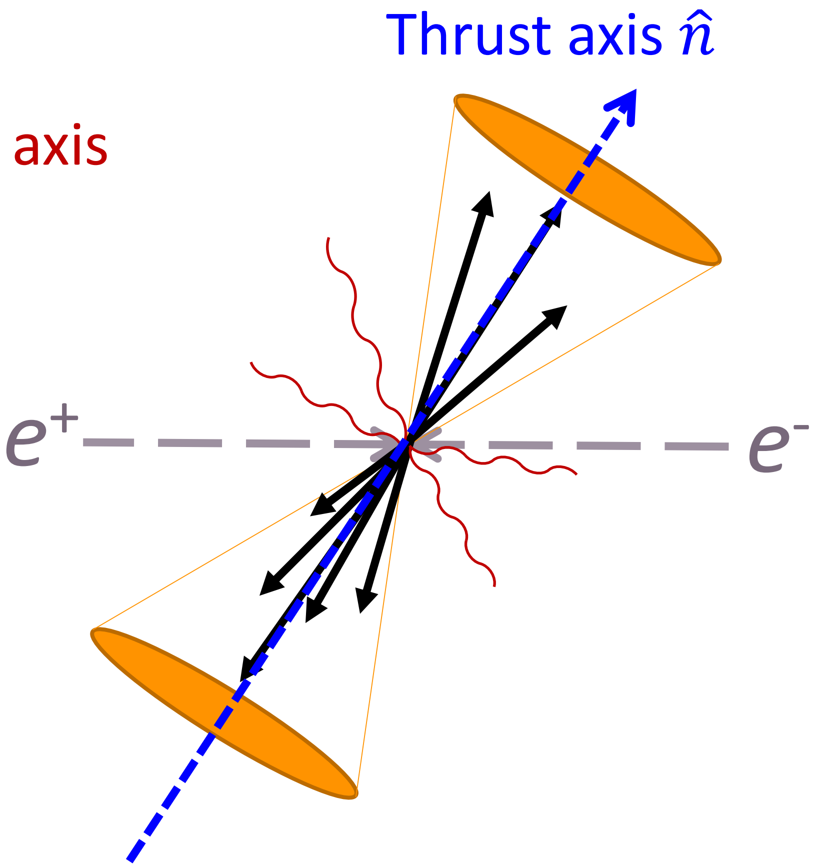
$$T = \max_{\vec{n}} \frac{\sum_i |\vec{p_i} \cdot \hat{n}|}{\sum_i |\vec{p_i}|}$$

T = 1
"pencil"-like event



T = 0.5
spherically
symmetric event





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}

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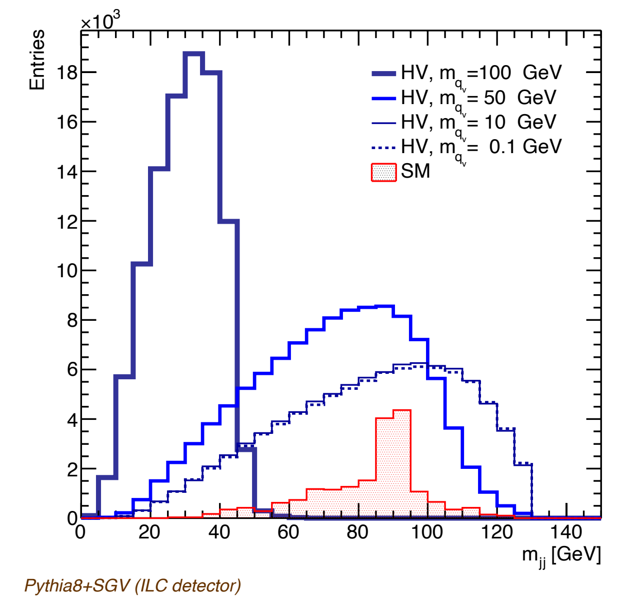


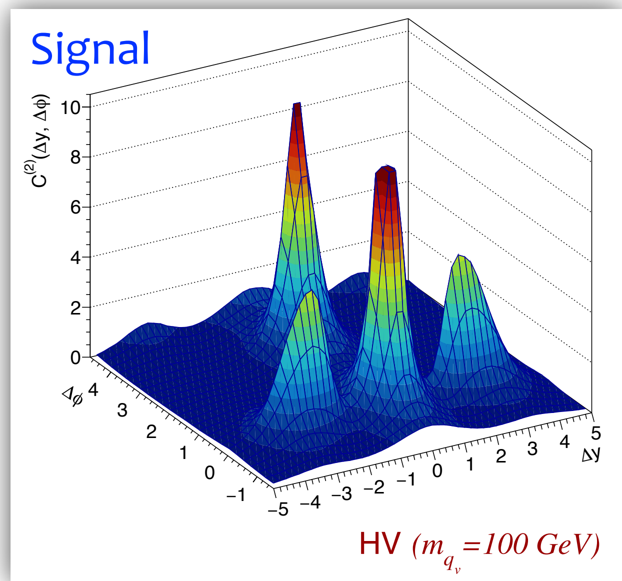
Simulation tools

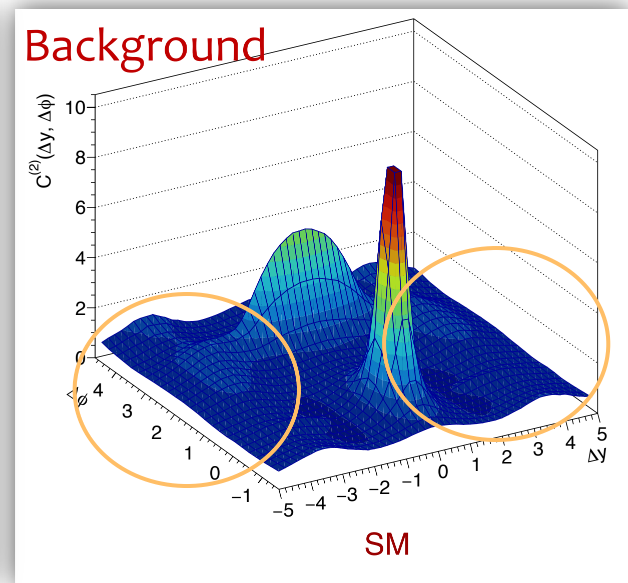
- Monte Carlo event generator: Pythia8
- Fast detector simulation
  - SGV 3.0 with ILD geometry
- Analysis: ILCSoft

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

Angular correlations

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





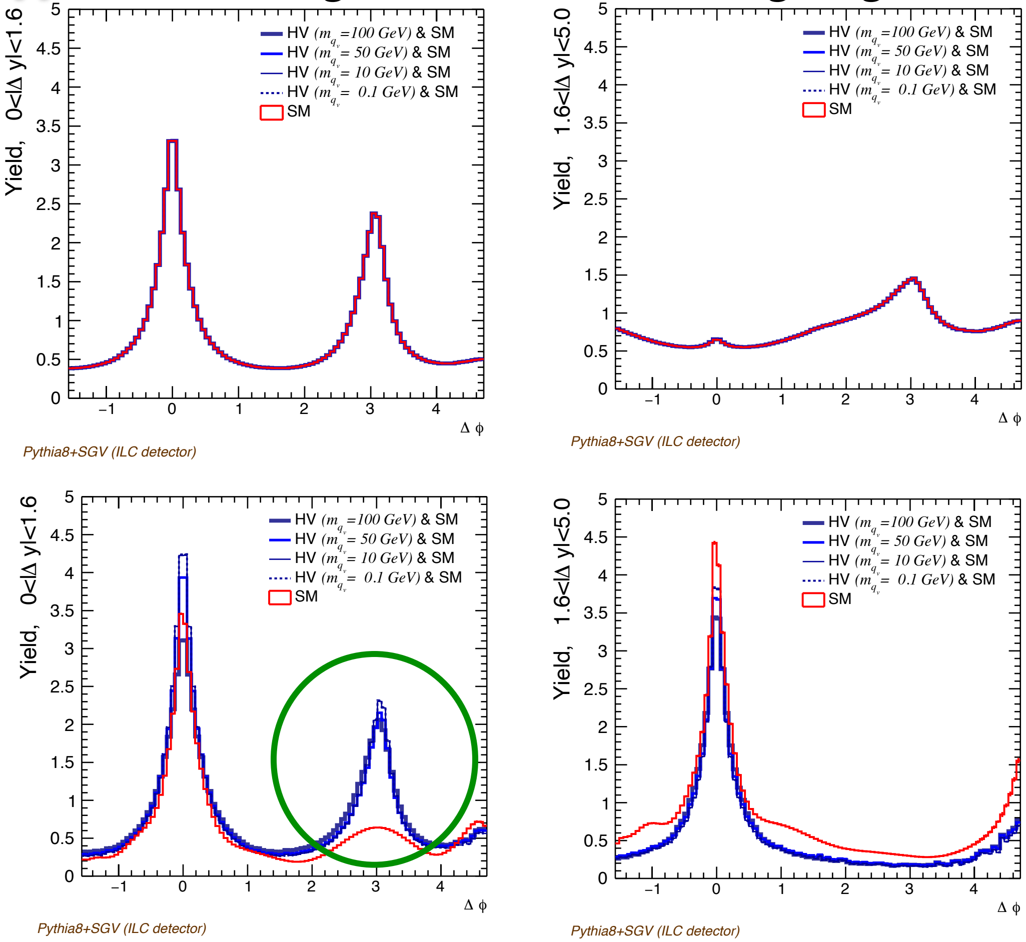
Effect of event selection

- 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**

short range **long range**

before cuts

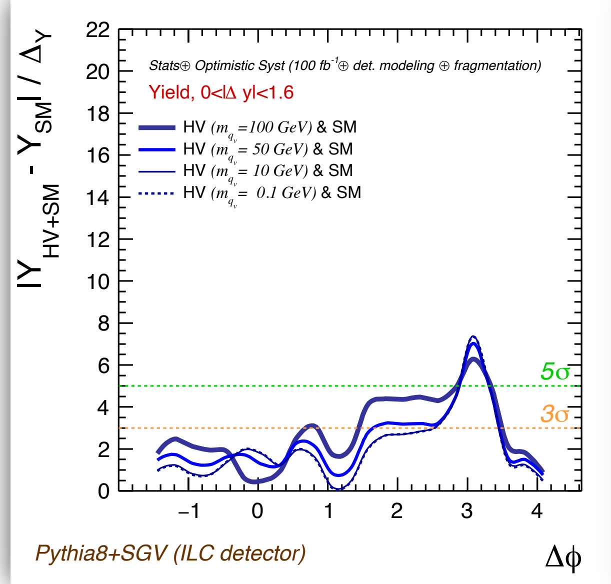
after cuts

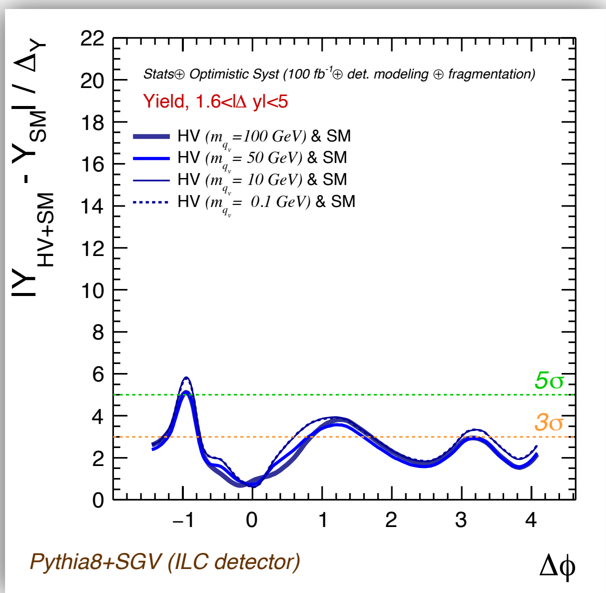


$$Y(\Delta\phi) = \frac{\int_{1.6\leq|\Delta y|\leq 3} S(\Delta y, \Delta\phi)\mathrm{d}y}{\int_{1.6\leq|\Delta y|\leq 3} B(\Delta y, \Delta\phi)\mathrm{d}y}$$

Uncertainties and sensitivity

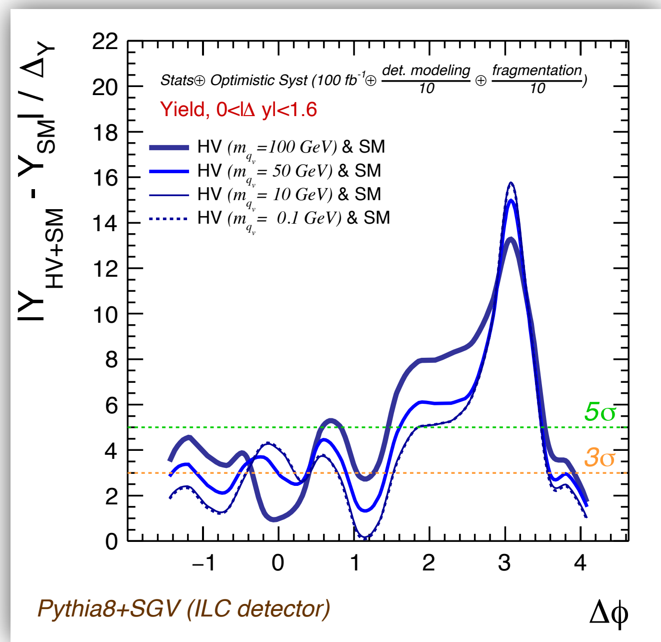
- Uncertainties
  - statistical from luminosity: 100 fb^{-1} (first year)
  - parton shower, fragmentation and hadronisation: HERWIG7.3 vs PYTHIA8
  - detector modelling: partially or totally cancelled in two-particle correlation
    - conservative uncertainty added: particle- versus detector-level
- Sensitivity
  - > 5σ in far peak

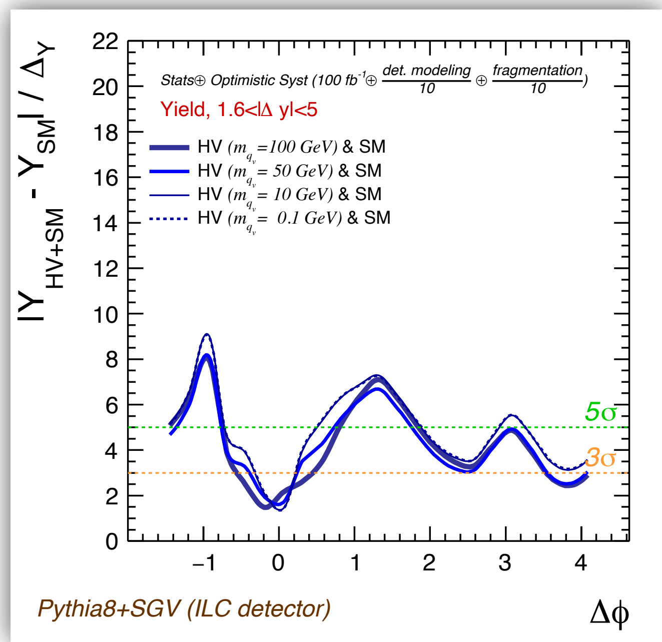




Sensitivity improvements

- 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





Higher energies

- In the HV sector, $T_v T_v$ channel appears
- tt(bar) production appears in the SM background
- Contribution from SM decreases with the energy

Process	$\sigma_{\sqrt{s}=500\text{GeV}}$ [pb]	$\sigma_{\sqrt{s}=1\text{TeV}}$ [pb]
	$m_{D_v} = 250$ GeV	$m_{D_v} = 500$ GeV
$e^+e^- \to D_v \bar{D}_v$	2.4×10^{-2}	4.4×10^{-3}
	$m_{T_v} = 250$ GeV	$m_{T_v} = 500$ GeV
$e^+e^- \to T_v \bar{T}_v$	9.5×10^{-2}	1.8×10^{-2}
$e^+e^- \to q\bar{q}$ with ISR	11	2.9
$e^+e^- \to t\bar{t}$	0.59	0.19
$WW \to 4q$	3.4	1.3

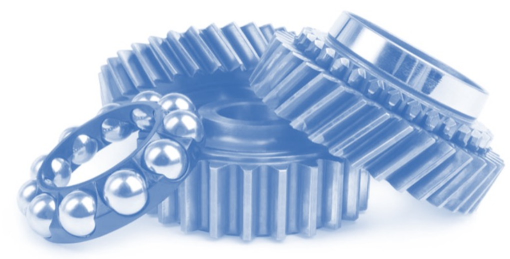
Conclusions

- **Two-particle angular correlations** in a e^+e^- factory can become a useful tool to discover New Physics
  - e.g. Hidden Valley scenarios
- Such searches are **complementary** to more conventional searches, thus increasing the discovery potential
- With conservative systematic uncertainties, sensitivity of > 5σ
- Future work
  - longitudinally polarised beams
  - FCC-specific detector

– E. Musumeci *et al*, "Two-particle angular correlations in the search for new physics at future *e*+*e*– colliders," Proc. LCWS2023, eConf C2305153 (2023), arXiv:2307.14734 [hep-ph] ← particle level
– E. Musumeci, A. Irles, R. Perez-Ramos, I. Corredoira, E. Sarkisyan-Grinbaum, VAM, M.A. Sanchis Lozano, "Exploring hidden sectors with two-particle angular correlations at future e^+e^- colliders," arXiv:2312.06526 [hep-ph]

Thank you for your attention!

Spares



PYTHIA HV codes

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			

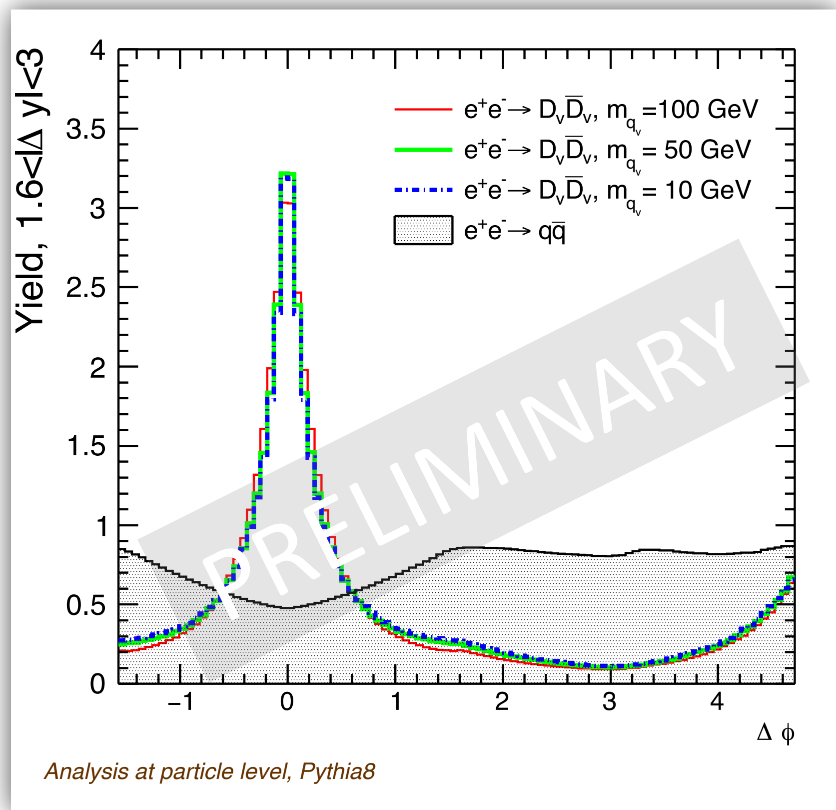
Carloni & Sjöstrand, JHEP 09 (2010) 105

Azimuthal yield *Y(Δφ)*

- Correlation-function projection for 1.6 < |Δy| < 3 (long range)

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

- Two completely different behaviours between signal and background
- Δϕ ~ 0
  - bump for the HV case
  - valley in the SM expectation
- Δϕ ~ π
  - valley (i.e. no contribution) for HV
  - SM contribution remains ~constant



Distribution shapes

- Pre-selection (w.r.t. beam axis)
  - final-state particles with transverse momentum $p_T > 0.5$ GeV
  - $|\cos\vartheta| \leq 0.99$ for detector acceptance
- Charged-particle multiplicity and di-jet invariant mass different between signal and background
- q_V-dependent cut