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Future e^+e^- colliders as probes of hidden sectors via particle angular correlations

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AITANA

SECOND • ECFA • WORKSHOP
on e^+e^- Higgs / Electroweak / Top Factories

11-13 October 2023
Paestum / Salerno / Italy

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:

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

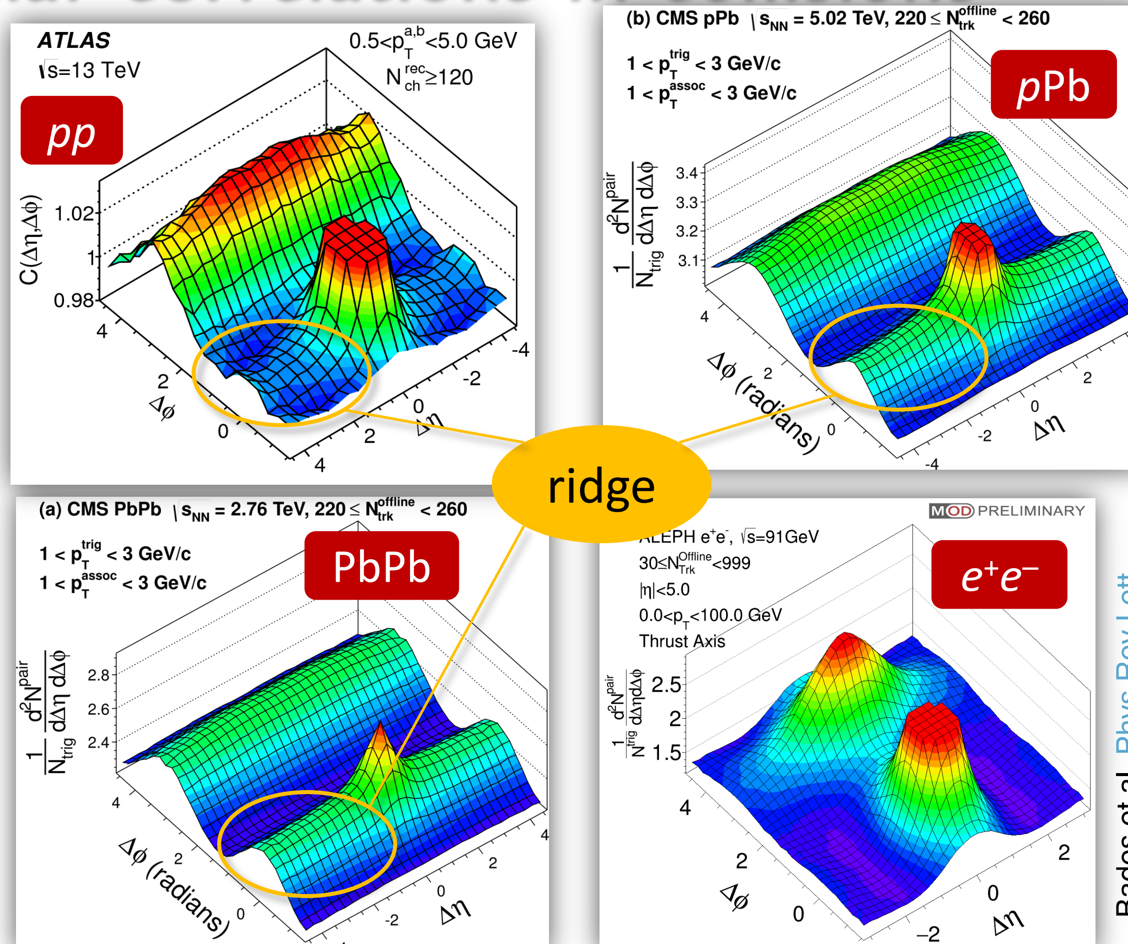
$$N_{mix} = \iint \frac{d^2N^{mix}}{d\Delta y d\Delta\phi} d\Delta y d\Delta\phi$$

y: rapidity
φ: azimuthal angle

Two-particle angular correlations in collisions

- Interesting features depending on colliding particles and track multiplicities
- Also relevant for heavy-ion physics in the quest for a new state of matter

Phys. Rev. Lett. 116 (2016) 172301



Phys.Lett.B 724 (2013) 213

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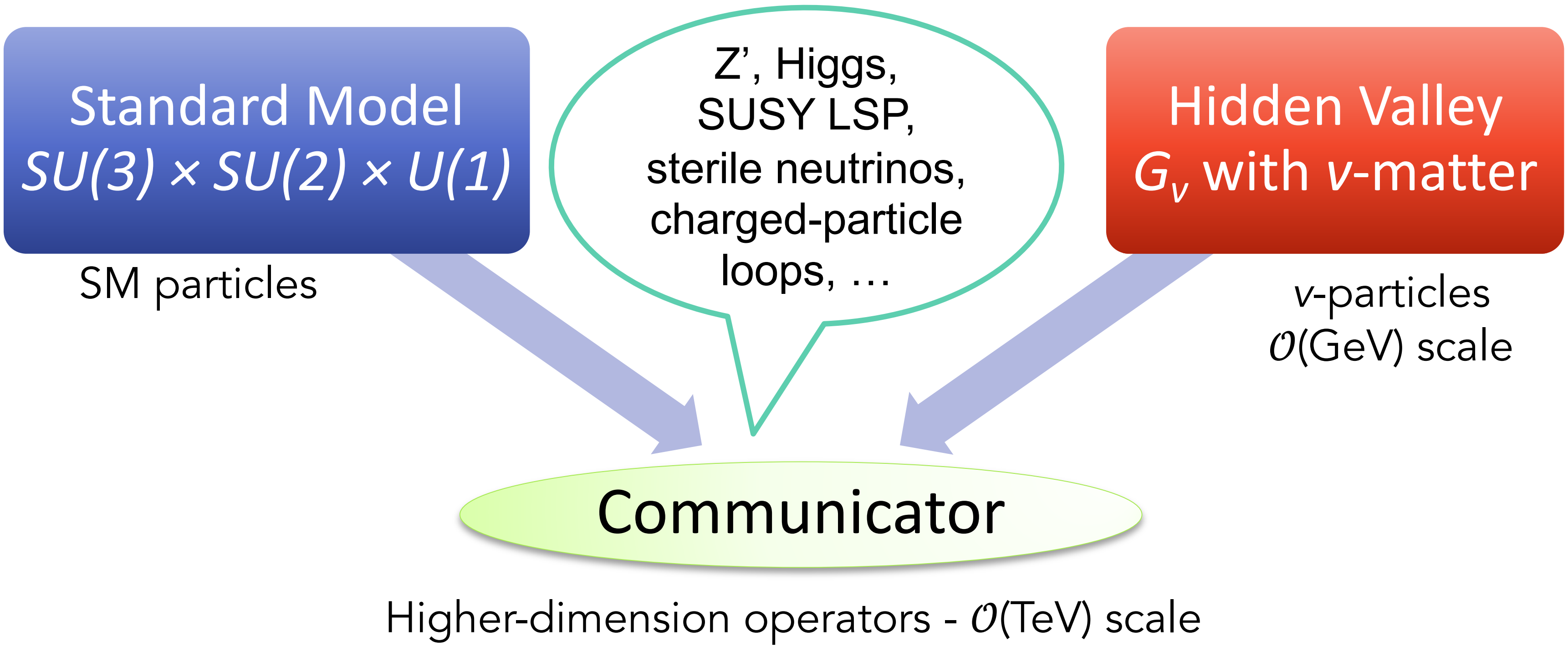
Bades et al, Phys.Rev.Lett. 123 (2019) 212002

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)

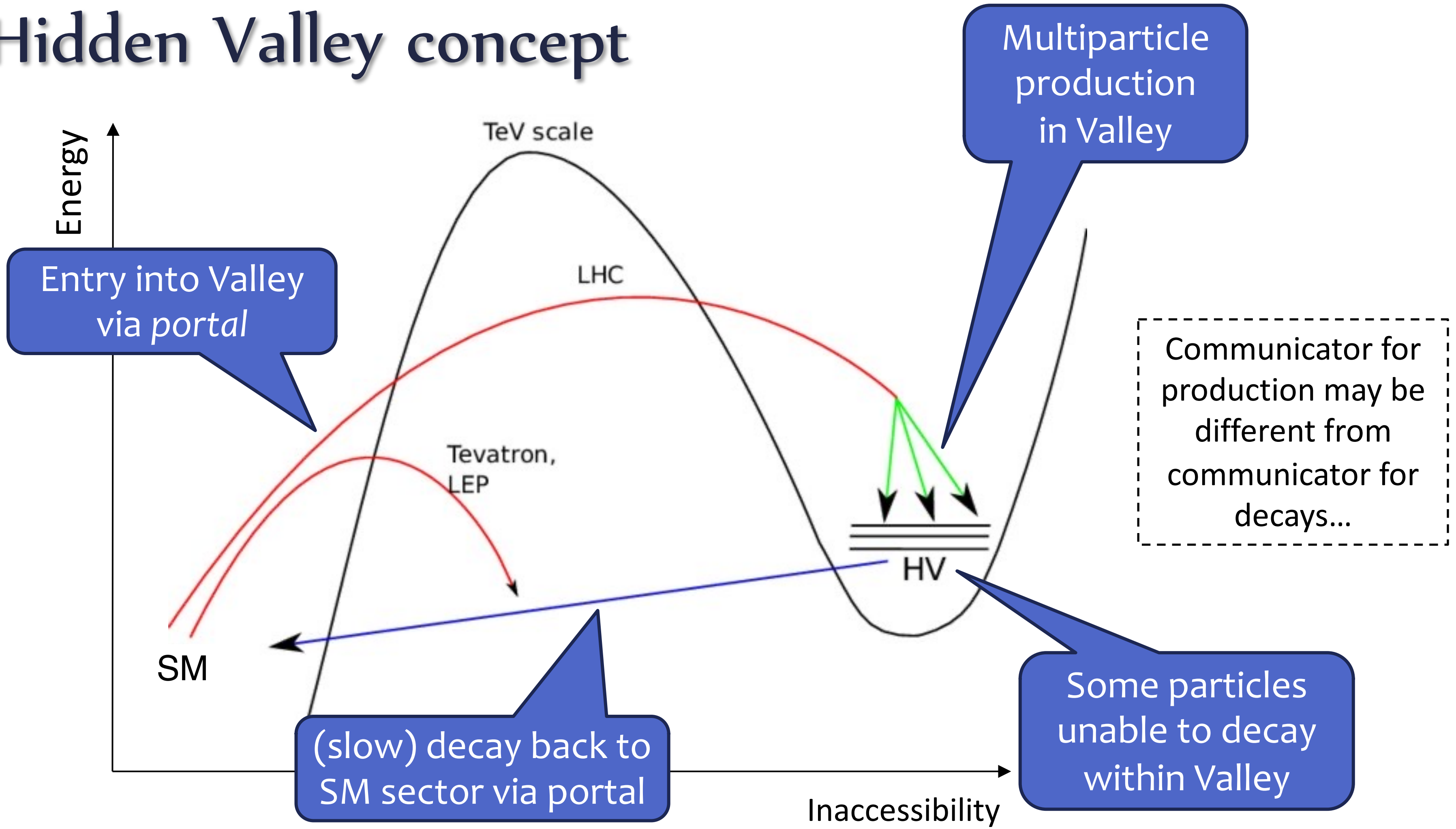
Hidden Valley (HV)

"Meta-model": large class of theoretical scenarios



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

Hidden Valley concept



Why HV? How to probe it?

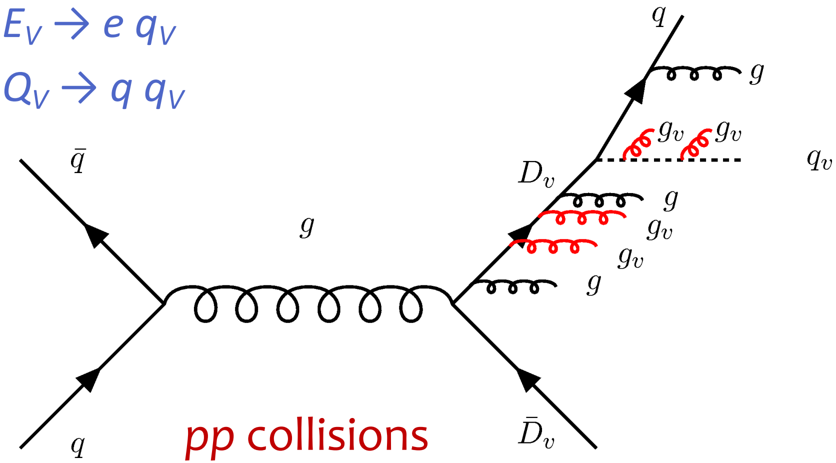
- Why Hidden Valley scenario?
  - extra sectors common in string theory, SUSY breaking, extra dimensions, etc.
  - incredibly exciting if found: new particles, forces, dynamics
  - can drastically change phenomenology of SUSY/extra dims/etc.
  - implications for dark matter, early universe cosmology,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

QCD-like HV scenario

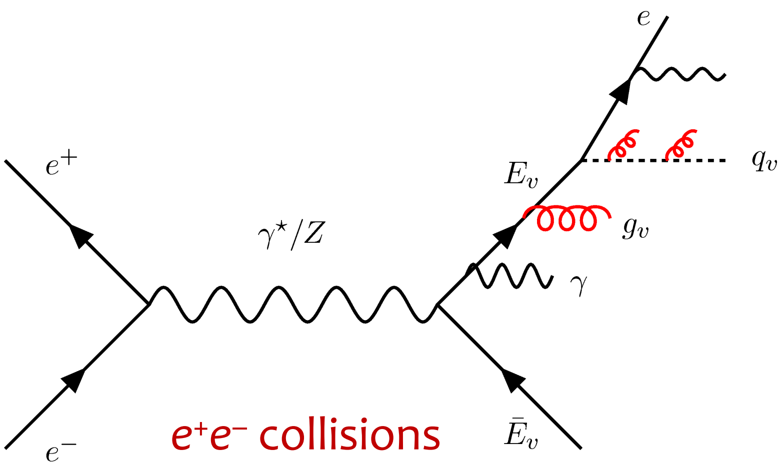
- Communicator: F_V
- Charged under G_{SM} and G_V
- Pair-produced in collisions
- v-quarks, q_V, and v-gluons, g_V
- Prompt decays
  - $F_V \to f\, q_V \longrightarrow$ hadrons
  - $E_V \to e\, q_V$
  - $Q_V \to q\, q_V$

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

Production at e^+e^- colliders

$\sqrt{s}$ = 250 GeV

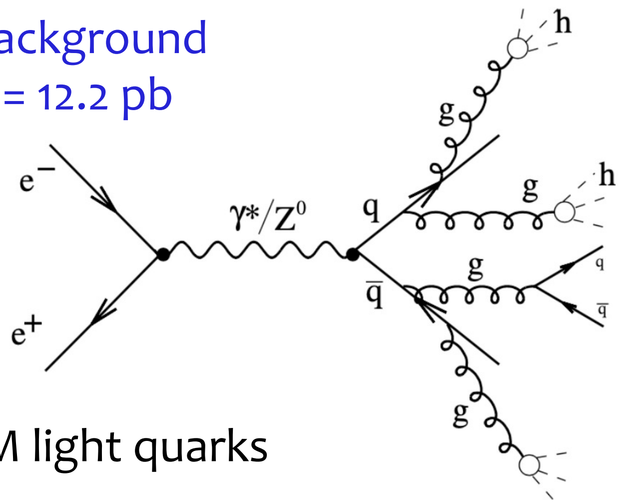
- Simulation
  - PYTHIA8
  - FastJet, `ee_genkt_algorithm` for jet reconstruction
- Analysis
  - ROOT

➔ Particle-level analysis presented here

➔ Detector-level analysis ongoing

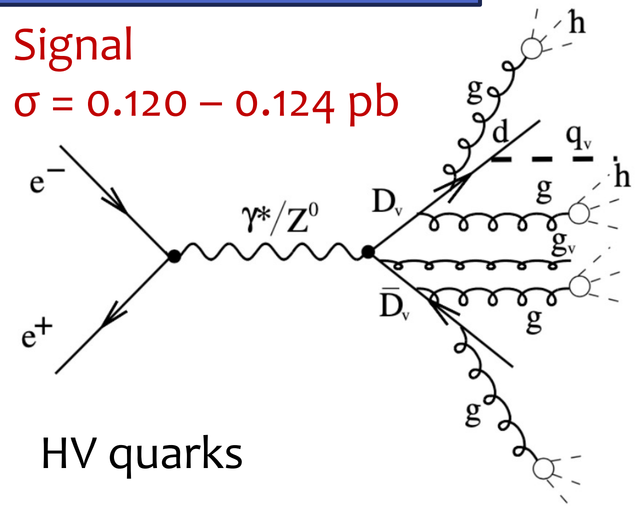
- $m(D_V)$ = 125 GeV
- α_V = 0.1
- $m(q_V)$ = 10, 50, 100 GeV

Background
σ = 12.2 pb



SM light quarks

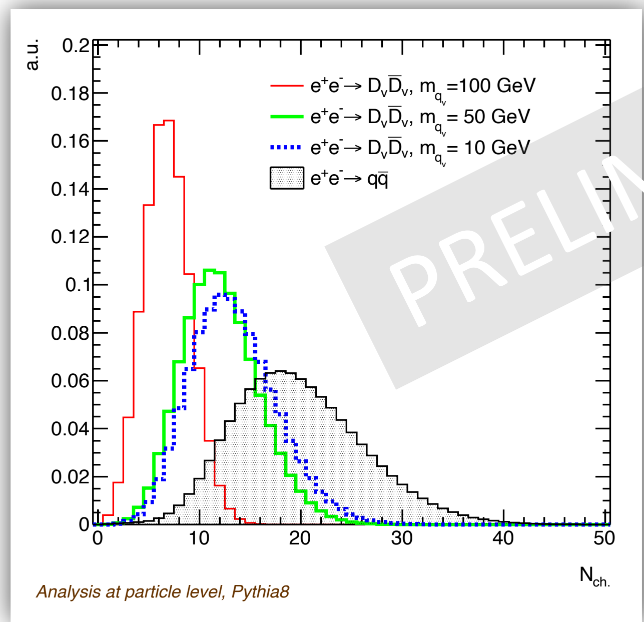
Signal
σ = 0.120 – 0.124 pb

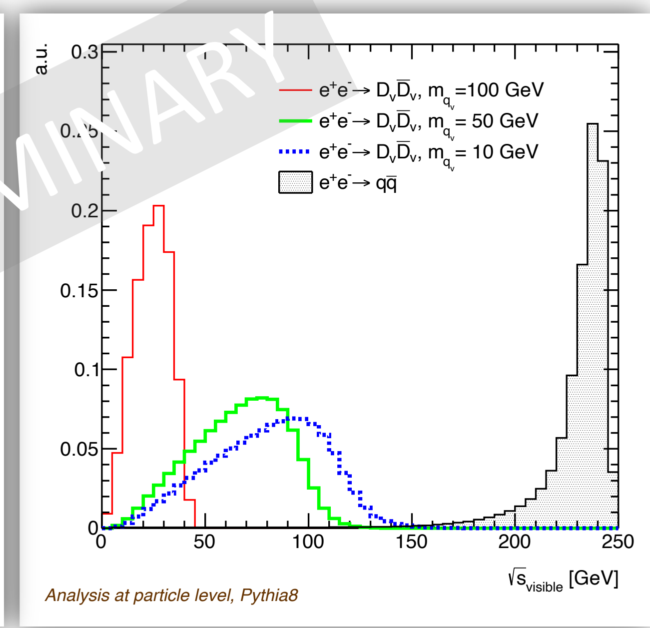


HV quarks

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



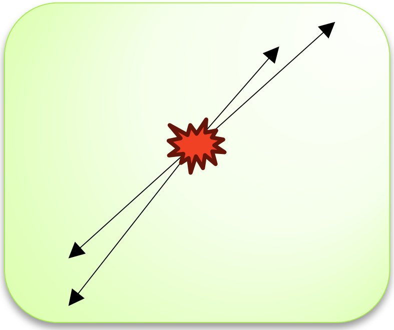


Correlation-related variables

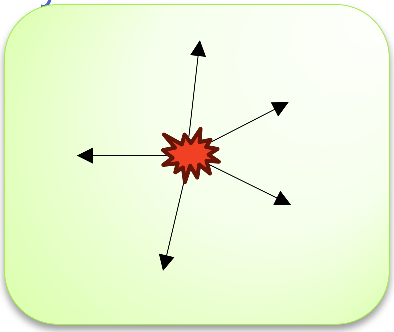
- Angular correlations → event shape
- *y*, *φ* coordinates defined w.r.t. thrust axis

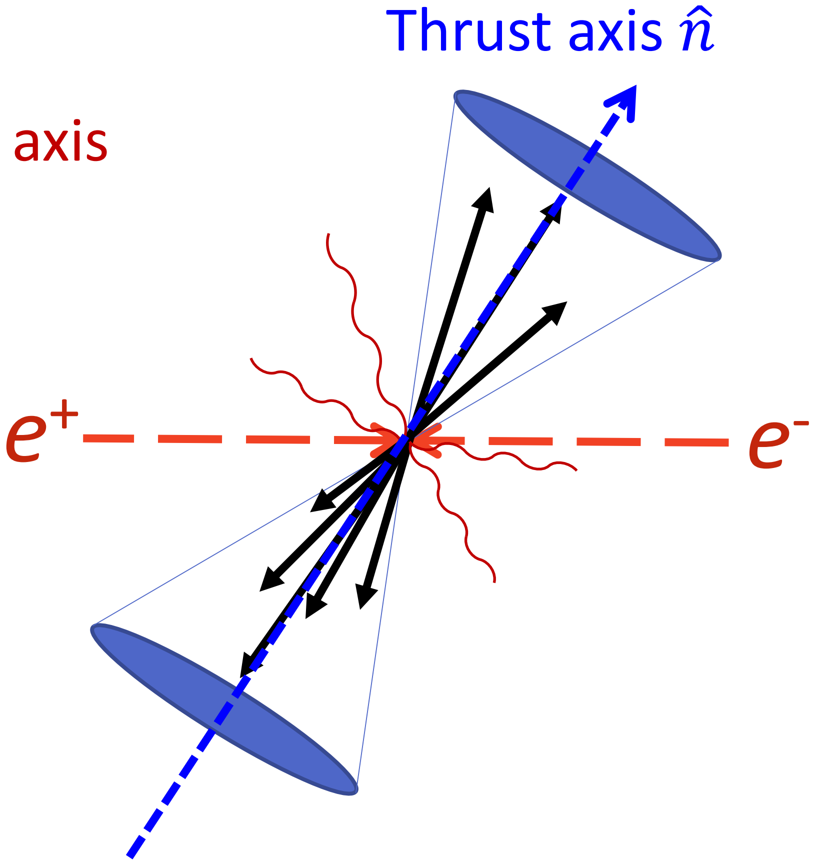
$$T = \max_{\vec{n}} \frac{\sum_i |\vec{p_i} \cdot \hat{n}|}{\sum_i |\vec{p_i}|}$$

T = 1
"pencil"-like event



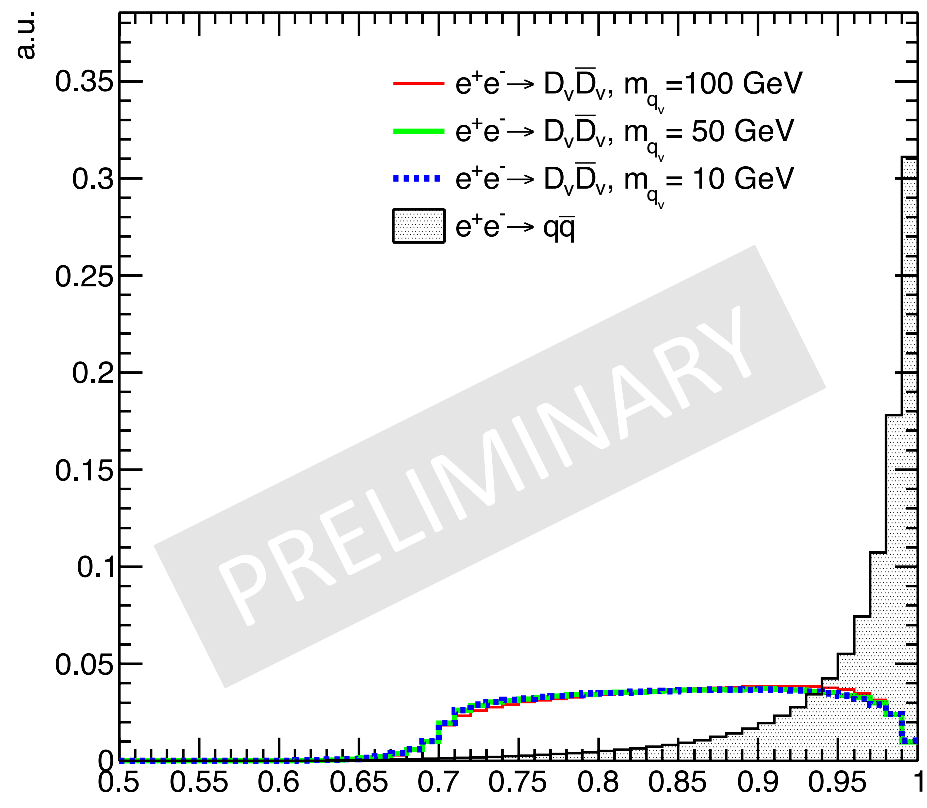
T = 0.5
spherically
symmetric event





Thrust

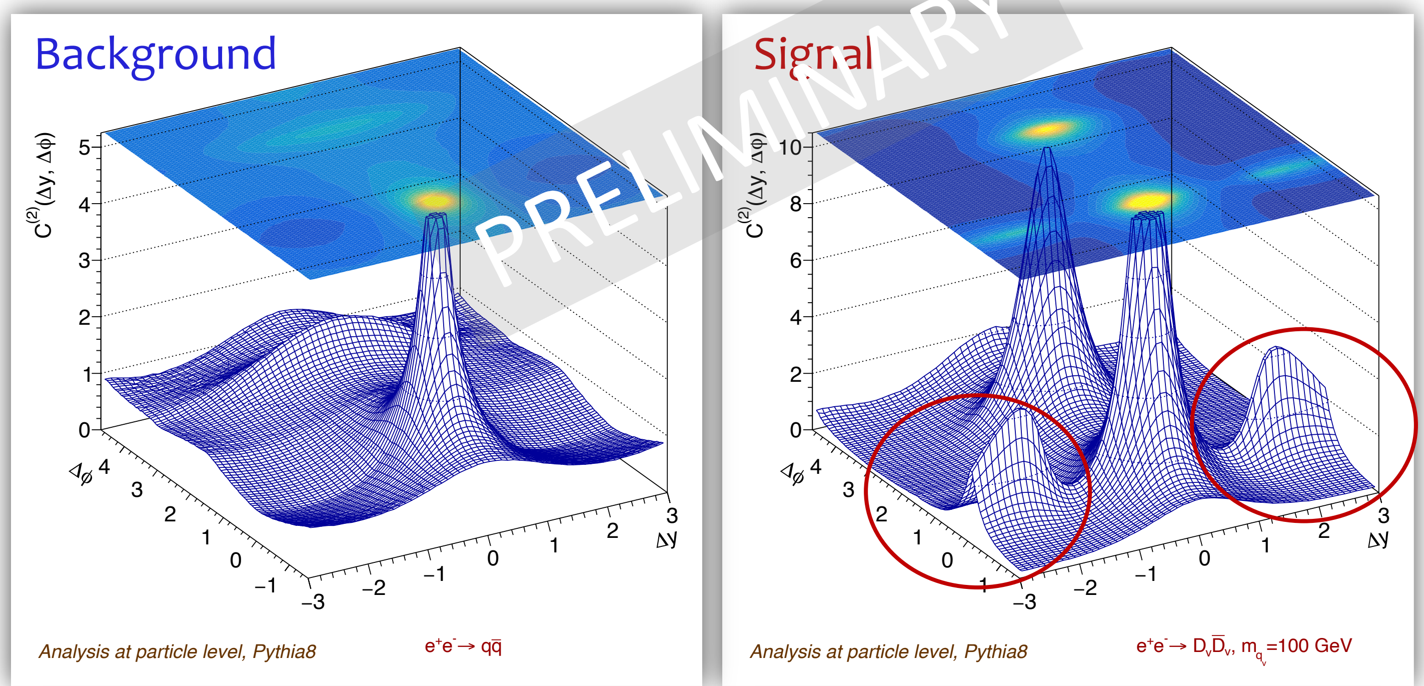
- Light quark production (background) leads mostly to pencil-like events
- HV production (signal) yields sphere-like events on average
- q_V-independent cut on thrust itself



Analysis at particle level, Pythia8

Angular correlations

- Decay $D_v \rightarrow d\, q_v$ 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
- Different shape of distribution could be interpreted as a **hint of New Physics**

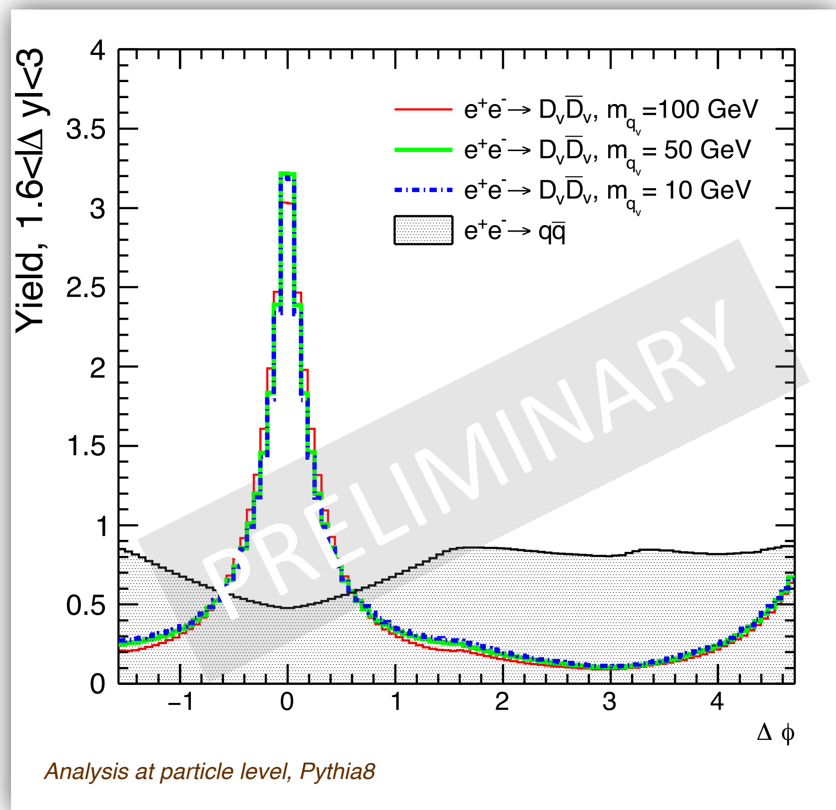


Azimuthal yield $Y(\Delta\varphi)$

- 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



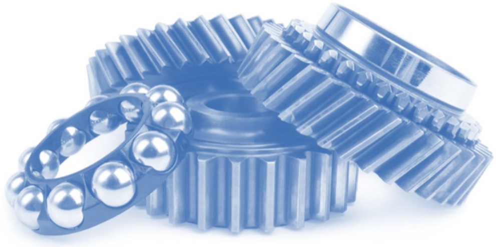
Conclusions

- **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
- Ongoing work
  - detector effects
  - inclusion of ISR and VBF as backgrounds
  - higher energy options: $\sqrt{s}$ = 500 GeV – 1 TeV

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

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			

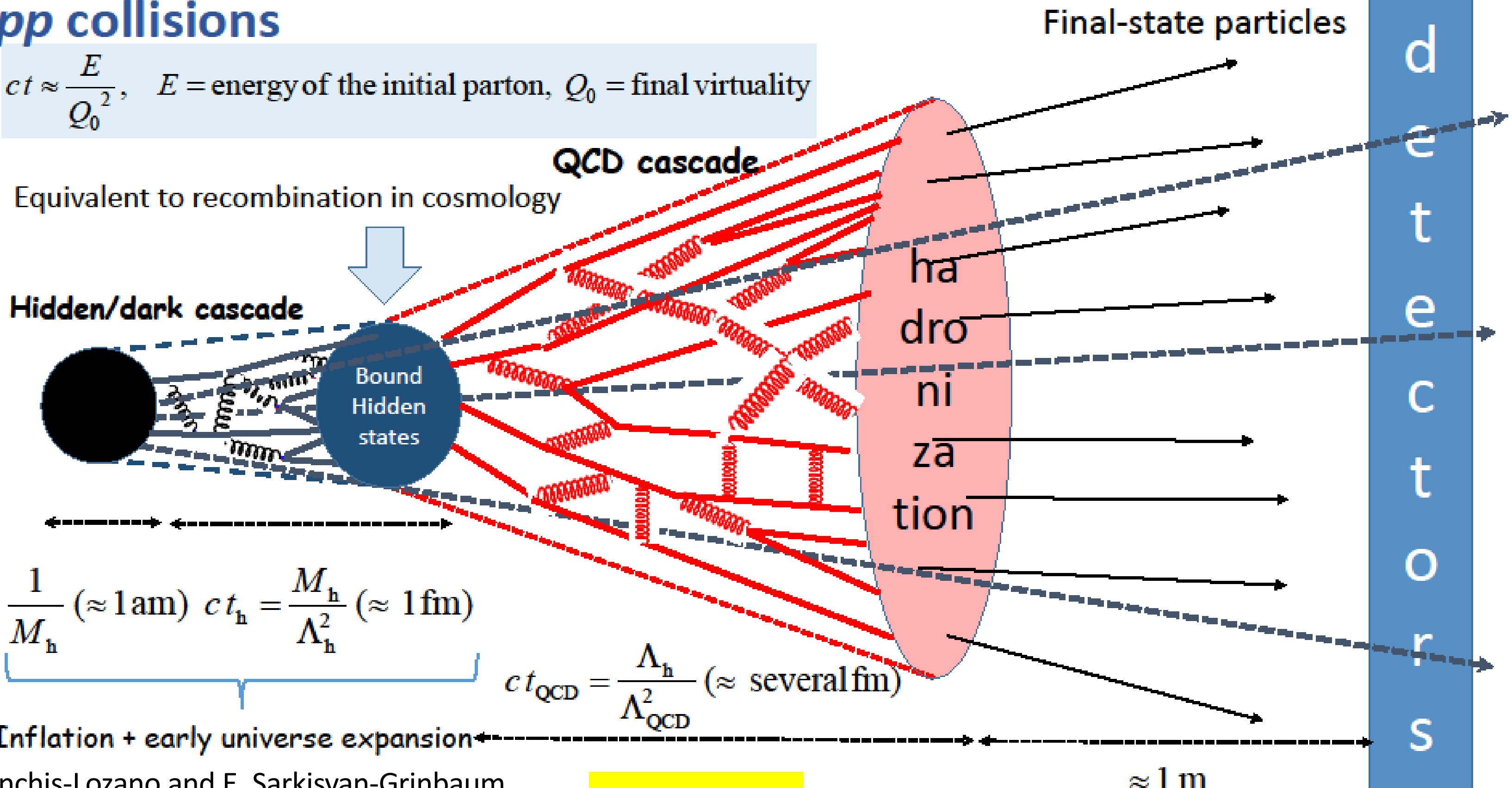
Carloni & Sjöstrand, JHEP 09 (2010) 105

M.A. Sanchis-Lozano, Valencia U, 2021

Analogy with high-energy collisions

pp collisions

$$ct \approx \frac{E}{Q_0^2}, \quad E = \text{energy of the initial parton}, \ Q_0 = \text{final virtuality}$$



M.A.Sanchis-Lozano and E. Sarkisyan-Grinbaum
Phys.Rev.D 102 (2020) 3, 035013 arXiv:2006.06569

Not at scale