Hadron correlations on the search of new physics beyond the SM in the $e^+e^- - annihilation$

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Outline

- Motivation and Introduction
- Monte Carlo Tools in PYTHIA 8
- Two Particle correlations
- Experimental Overview on Two Particle Correlations
- Results on Two Particle Correlations
- Three Particle Correlations
- Results on Three Particle Correlations
- Conclusions
- Back-up Slides

Part I

Motivation and Introduction

Motivation and Introduction

Some references:

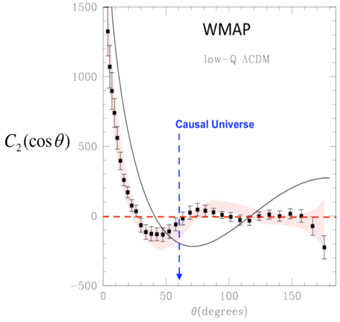
- M. A. Sanchis-Lozano, *Prospects of searching for (un)particles from Hidden Sectors using rapidity correlations in multiparticle production at the LHC*, **Int. J. Mod. Phys. A 24, 4529-4572 (2009)**
- M. A. Sanchis-Lozano and E. K. Sarkisyan-Grinbaum, *Searching for new physics with three-particle correlations in pp collisions at the LHC*, **Phys. Lett. B 781, 505-509 (2018)**
- R. Pérez-Ramos, M. A. Sanchis-Lozano and E. K. Sarkisyan-Grinbaum, *Searching for hidden matter with long-range angular correlations at e^+e^- colliders*, **arXiv:2110.05900**

Why may one search for hidden matter from particle correlations?

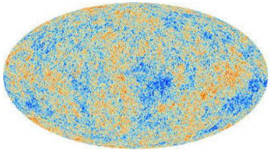
Courtesy: M. A. Sanchis-Lozano's talk at ILC "kick-off":

Angular correlations in Cosmology

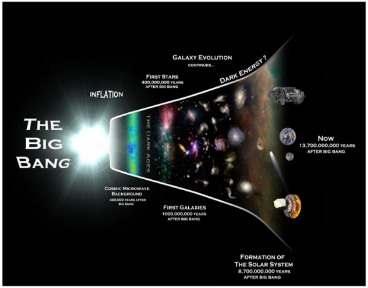
$$C_2(\cos\theta) \equiv \langle \delta T(\vec{n}_1)\, \delta T(\vec{n}_2) \rangle = \frac{1}{4\pi} \sum_{\ell=2}^{\infty} (2\ell+1)\; C_\ell\; P_\ell(\cos\theta)$$



Max angle ≈ 60 º



Inflation is required to explain the amazing homogeneity of the CMB across the sky (10^{-5} K)



Inflation (initial source) $\Leftrightarrow$ HV particle pairs (NP) produced in hard scatt. processes at the LHC and future ILC!

Part II

Monte Carlo Tools in PYTHIA 8

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, $f\bar{f} \to \gamma^*/Z^0 \to F_v \bar{F}_v$ for all states
3. Further decays: $F_v \to f\ q_v \to$ hadrons

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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Monte Carlo Tools in Pythia 8

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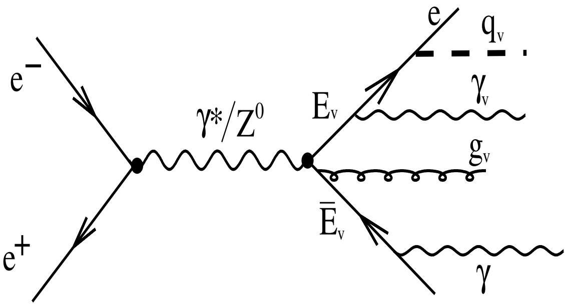

Monte Carlo Tools in Pythia 8

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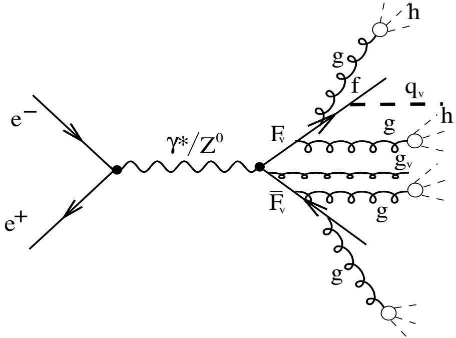

Monte Carlo Tools in Pythia 8

Production Process

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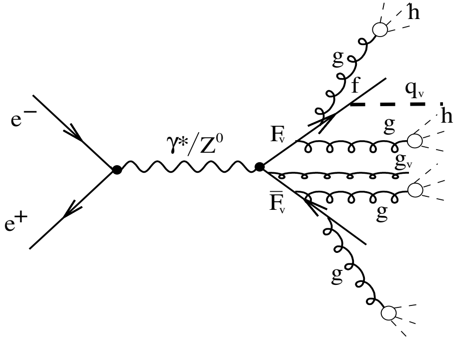
2. EW-like in e^+e^--annihilation, $f\bar{f} \to \gamma^*/Z^0 \to F_v \overline{F}_v$ for all states
3. $g_v \to g_v g_v$, $g_v \to q_v \bar{q}_v$ & $\gamma_v \to q_v \bar{q}_v \sim$ SM processes



Part III

Event shapes

Sphericity

Momentum energy tensor

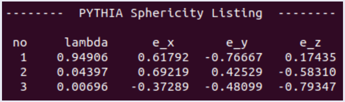
$$S^{\alpha,\beta} = \sum_i p_i^\alpha p_i^\beta / \sum_i p_i^2$$

- p_i: final state particle momenta with components $(\alpha, \beta) = 1, 2, 3$
- Sphericity axis: eigenvector corresponding to the maximum eigenvalue: $\lambda_1 > \lambda_2 > \lambda_3$
- Transverse momentum p_t: lies on the event transverse plane
- Azimuthal angle ϕ: calculated with respect to the eigenvector of the momentum tensor having the smallest eigenvalue (i.e. λ_3) (lies on the event transverse plane)

- This choice of axis is especially suitable in e^+e^- colliders.

Sphericity

Momentum energy tensor



-------- PYTHIA Sphericity Listing --------

no	lambda	e_x	e_y	e_z
1	0.94906	0.61792	-0.76667	0.17435
2	0.04397	0.69219	0.42529	-0.58310
3	0.00696	-0.37289	-0.48099	-0.79347

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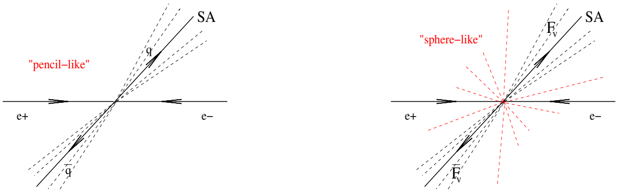
Sphericity



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- This choice of axis is especially suitable in e^+e^- colliders.

Part IV

Kinematics, variables & hadron distributions

Kinematics and variables & hadron distributions

Rapidity versus pseudo-rapidity

Rapidity:

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right),$$

p_z is the longitudinal momentum defined w.r.t. the sphericity axis.

Kinematics and variables & hadron distributions

Rapidity versus pseudo-rapidity

Pseudo-rapidity:

$$\eta = -\ln\left(\tan\frac{\Theta}{2}\right),$$

Θ is the angle between the particle momentum and the sphericity axis.

Kinematics and variables & hadron distributions

Rapidity versus pseudo-rapidity

In the massless limit:

$$y \approx \eta - \frac{m^2}{4p^2}\left(\tan^{-2}\frac{\Theta}{2} - \tan^2\frac{\Theta}{2}\right) + \mathcal{O}\left(\frac{m^2}{E^2}\right),$$

Θ is the angle between the particle momentum and the sphericity axis.

Kinematics and variables & hadron distributions

Rapidity versus pseudo-rapidity

In the massless limit:

$$y \approx \eta - \frac{m^2}{2p^2}\sinh(2\eta) + \mathcal{O}\left(\frac{m^2}{E^2}\right) \Rightarrow y \approx \eta$$

Kinematics and variables & hadron distributions

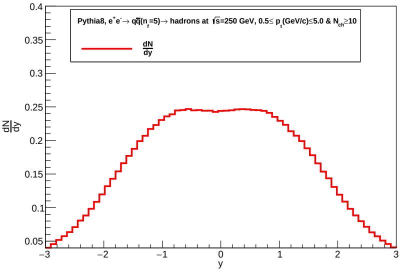
Rapidity versus pseudo-rapidity differences

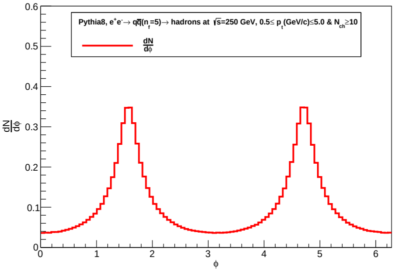
In the massless limit ($\Delta y = y_2 - y_1$ & $\Delta\eta = \eta_2 - \eta_1$):

$$\Delta y - \Delta\eta \approx \frac{m_1^2}{2p_1^2}\sinh(2\eta_1) - \frac{m_2^2}{2p_2^2}\sinh(2\eta_2) \Rightarrow \Delta y \approx \Delta\eta$$

Distributions (sphericity axis)

Rapidity and azimuthal distributions for the e^+e^--annihilation into hadrons via SM quark pairs.



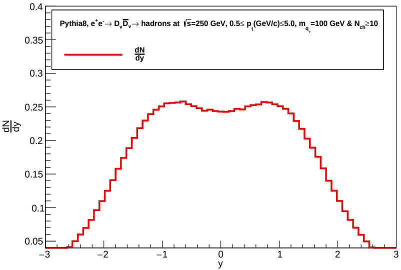


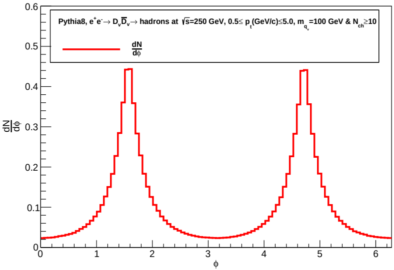
Consistency check

Used as input for two- and three-particle correlation functions!

Distributions (sphericity axis)

Rapidity and azimuthal distributions for the e^+e^--annihilation into hadrons via HV Dv quark anti-quark pairs.





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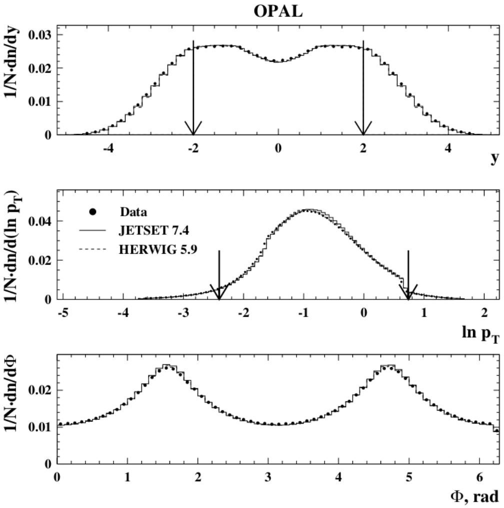
Used as input for two- and three-particle correlation functions!

Kinematics and variables & hadron distributions



Part V

Two-particle Correlations

Two-particle Correlations

Definitions

- Rapidity difference:

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

- Angular difference:

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

Two-particle Correlations

- Density of particle pairs produced within the same event:

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

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

- Density of particle pairs from different (mix) events:

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

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

Two-particle Correlations

Two-particle correlation function (rapidity, azimuth)

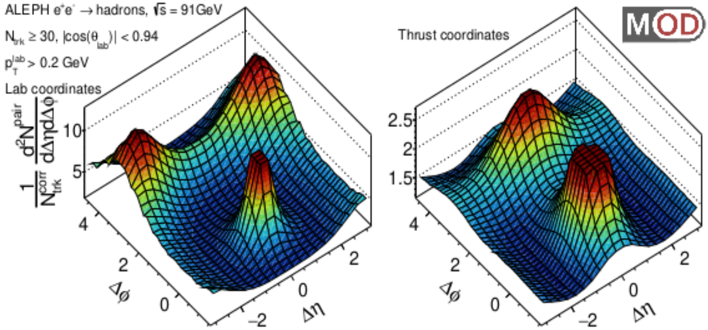
$$\mathcal{C}_2(\Delta y, \Delta\phi) = \frac{S(\Delta y, \Delta\phi)}{B(\Delta y, \Delta\phi)}$$

Two-particle Correlations

Two particle correlation function (pseudo-rapidity,azimuth)

$$\mathcal{C}_2(\Delta\eta, \Delta\phi) = \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)}$$

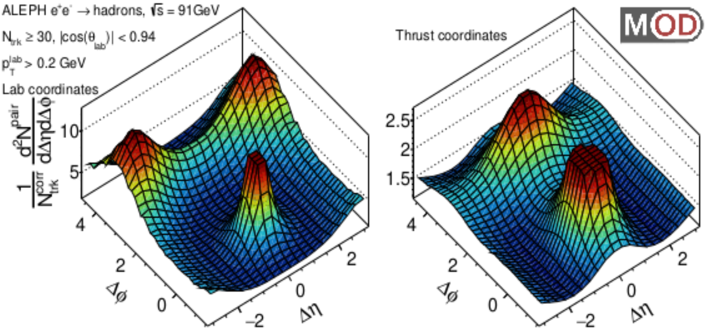
Experimental Overview on Two Particle Correlations



PRL ref

Two-particle correlation functions for events with the number of charged particle tracks in the event $N_{trk} \geq 30$ in the lab coordinates (left) and thrust coordinates (right) analyses.

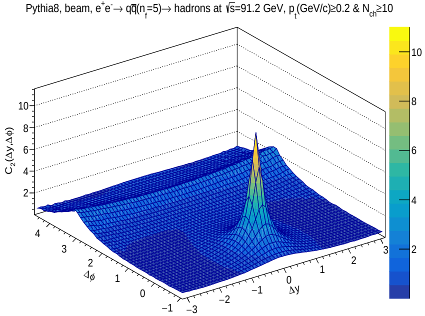
Experimental Overview on Two Particle Correlations

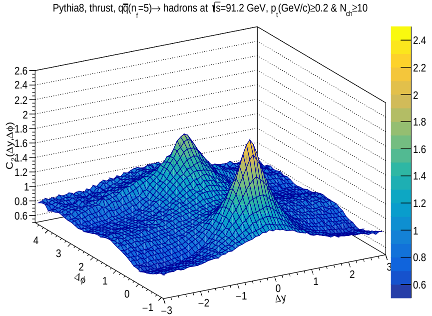


PRL ref

The analysis shows shape sensitivity with respect to the chosen frame of reference: e.g. in the beam frame, the away side ridge exhibits stronger and longer correlations in $\Delta\eta$ over the full $\Delta\phi = \pi$ range.

Experimental Overview on Two Particle Correlations

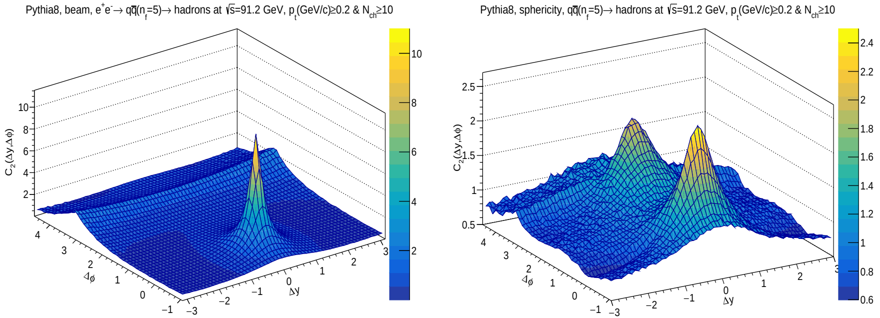




Two-particle correlations (Pythia8)

Two-particle correlations in the beam axis (left panel) and the thrust axis (right panel). MC reproduces the general trends of the ALEPH results.

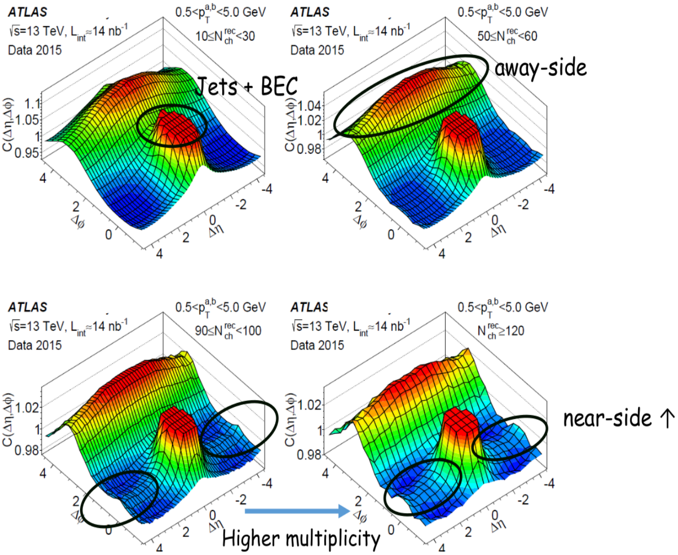
Experimental Overview on Two Particle Correlations



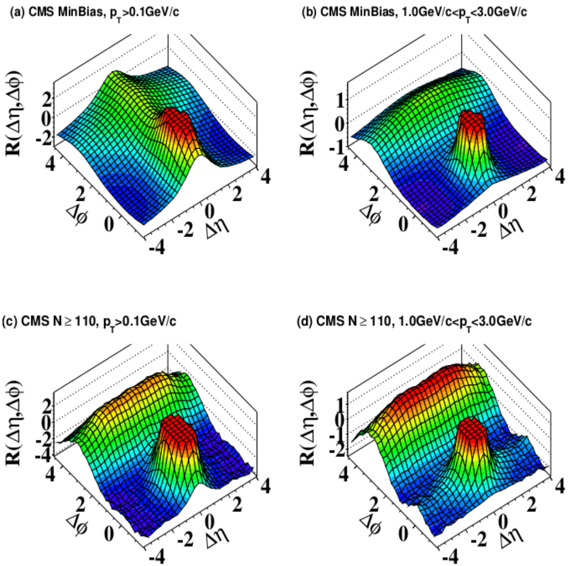
Two-particle correlations (Pythia8)

Two-particle correlations in the beam axis (left panel) and the sphericity axis (right panel). MC follows the general trends of the ALEPH results.

Experimental Overview on Two Particle Correlations

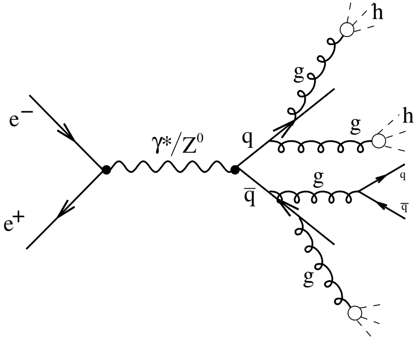


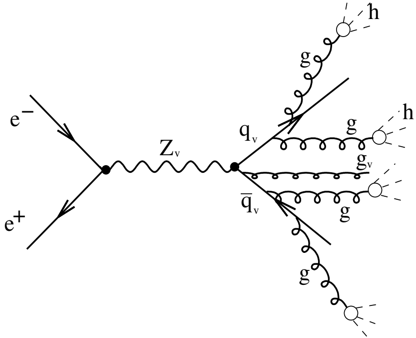
Experimental Overview on Two Particle Correlations



Results on Two Particle Correlations

Standard Model versus Hidden Valley parton cascade:





The q_v-mass (4900101) can be changed: 10-100 GeV!

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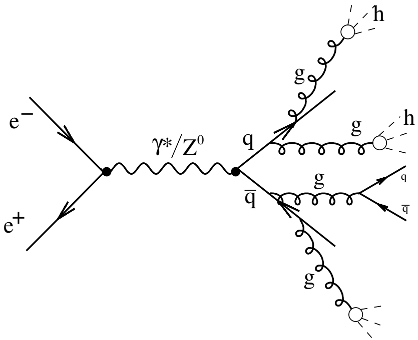
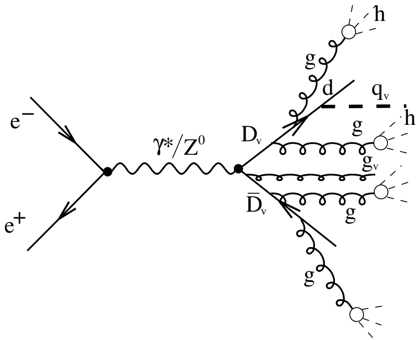
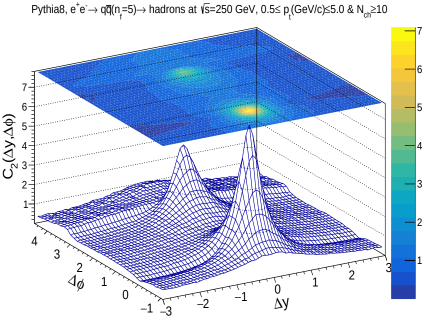
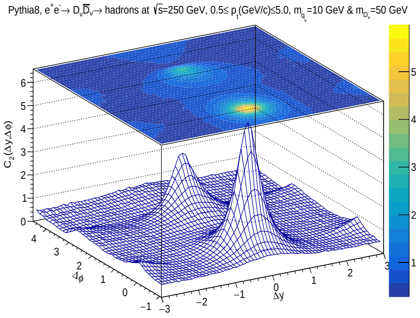




The D_v-mass (4900001) can be changed: 50-($\sqrt{s}/2$) GeV!

Results on Two Particle Correlations

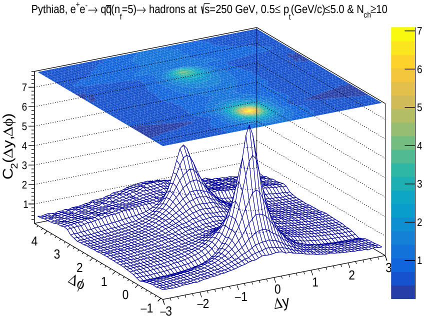


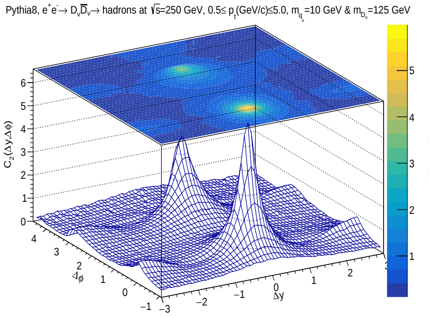


Two-particle correlation:

$C_2(\Delta y, \Delta\phi)$ in the SM (left panel) and the HV with the v-quark mass $m_{q_v} = 10$ GeV & $m_{D_v} = 50$ GeV (right panel) in the e^+e^- annihilation generated with PYTHIA8 at $\sqrt{s} = 250$ GeV.

Results on Two Particle Correlations

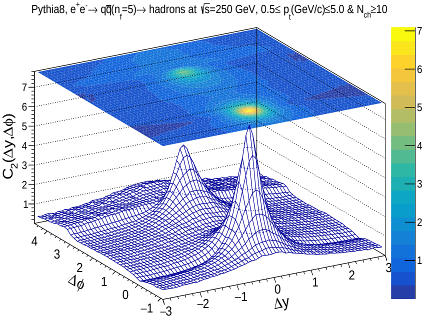


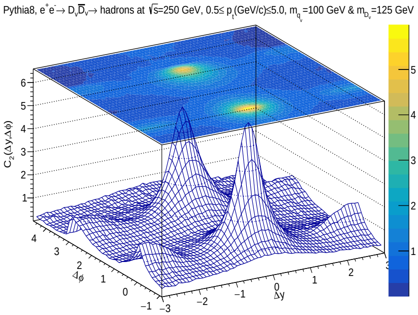


Two-particle correlation:

$C_2(\Delta y, \Delta\phi)$ in the SM (left panel) the HV with the v-quark mass $m_{q_v} = 10$ GeV & $m_{D_v} = 125$ GeV (right panel) in the e^+e^- annihilation generated with PYTHIA8 at $\sqrt{s} = 250$ GeV.

Results on Two Particle Correlations

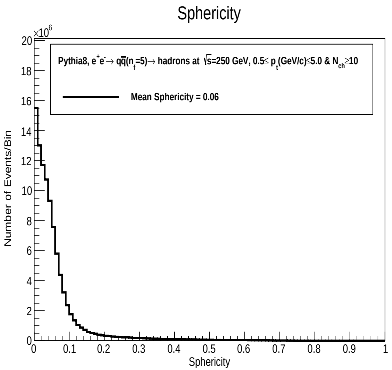


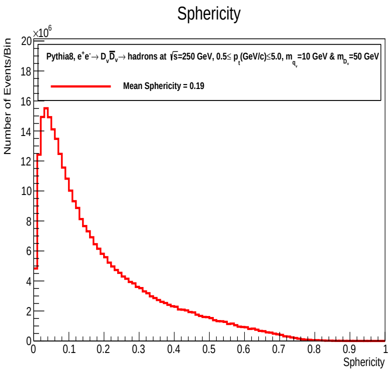


Two-particle correlation:

$C_2(\Delta y, \Delta\phi)$ in the SM (left panel) the HV with the v-quark mass $m_{q_v} = 100$ GeV & $m_{D_v} = 125$ GeV (right panel) in the e^+e^- annihilation generated with PYTHIA8 at $\sqrt{s} = 250$ GeV.

Results on Two Particle Correlations

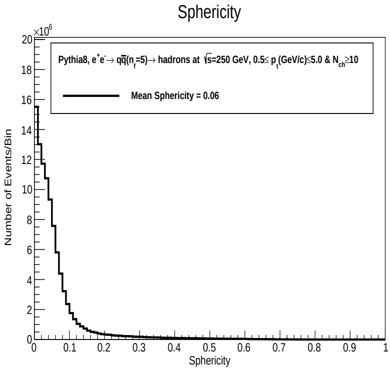


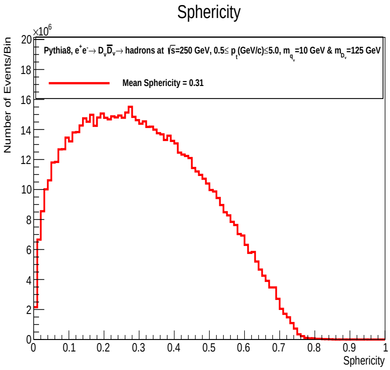


Sphericity:

The light quark events ("pencil-like") exhibit a much lower mean sphericity than the HV events ("sphere-like")!

Results on Two Particle Correlations

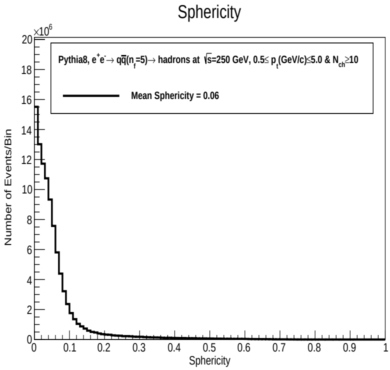


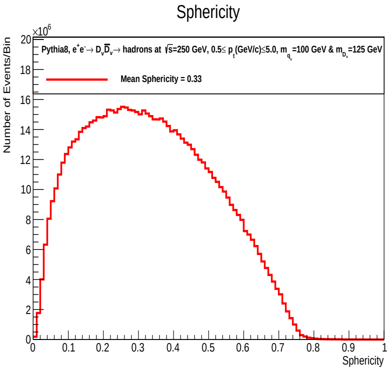


Sphericity:

The mean sphericity mainly increases as the mass of the Dv-quark is increased from 50-125 GeV!

Results on Two Particle Correlations





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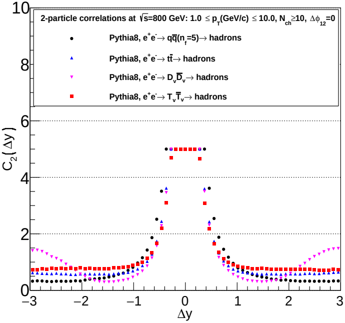
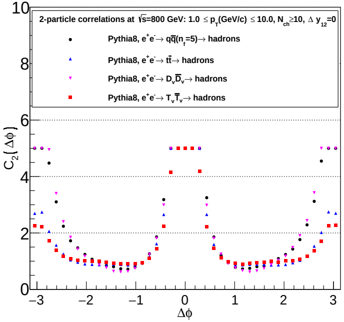
Results on Two Particle Correlations

Cuts on the rapidity-y and angular-ϕ planes

Examples of 2-particle correlations in the e^+e^--annihilation into hadrons at $\sqrt{s} = 800$ GeV. From top to bottom: 1) SM light quark pairs, 2) SM top quark pairs, 3) HV Dv quark pairs, 4) HV Tv quark pairs with default $\alpha_v = 0.1$ (highest energy threshold).

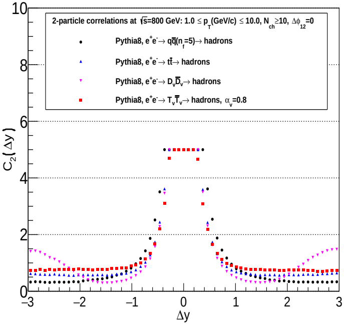


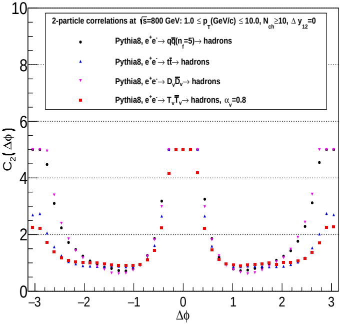


Results on Two Particle Correlations

Cuts on the rapidity-y and angular-ϕ planes

Examples of 2-particle correlations in the e^+e^--annihilation into hadrons at $\sqrt{s} = 800$ GeV. From top to bottom: 1) SM light quark pairs, 2) SM top quark pairs, 3) HV Dv quark pairs, 4) HV Tv quark pairs $\alpha_v = 0.8$ (highest energy threshold).





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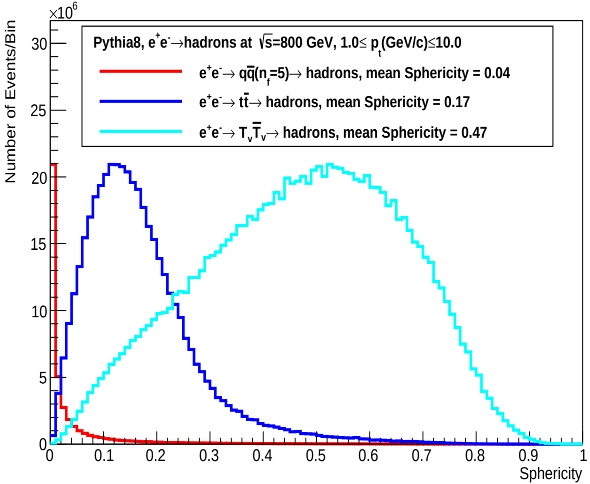


Part VI

Three-particle correlations

Three particle Correlations

Definitions

- Rapidity differences:

$$\Delta y_{12} = y_2 - y_1, \quad \Delta y_{13} = y_3 - y_1$$

- Angular differences:

$$\Delta\phi_{12} = \phi_2 - \phi_1, \quad \Delta\phi_{13} = \phi_3 - \phi_1,$$

Three particle Correlations

- Density of particle triplets produced within the same event for $\Delta y_{12} = \Delta y_{13} = 0$:

$$S(\Delta\phi_{12}, \Delta\phi_{13}) = \frac{1}{N_{triplets}} \frac{d^2 N^{\text{same}}}{d\Delta\phi_{12} d\Delta\phi_{13}}$$

$$N_{triplets} = \iint \frac{d^2 N^{\text{same}}}{d\Delta\phi_{12} d\Delta\phi_{12}} d\Delta\phi_{13}$$

- Density of particle triplets from different (mix) events:

$$B(\Delta\phi_{12}, \Delta\phi_{13}) = \frac{1}{N_{mix}} \frac{d^2 N^{\text{mix}}}{d\Delta\phi_{12} d\Delta\phi_{13}}$$

$$N_{mix} = \iint \frac{d^2 N^{\text{mix}}}{d\Delta\phi_{12} d\Delta\phi_{13}} d\Delta\phi_{12} d\Delta\phi_{13}$$

Three particle Correlations

Three particle correlation function (pseudo-rapidity)

$$\mathcal{C}_3(\Delta\phi_{12}, \Delta\phi_{13}) = \frac{S(\Delta\phi_{12}, \Delta\phi_{13})}{B(\Delta\phi_{12}, \Delta\phi_{13})}\Bigg|_{\Delta y_{12}=\Delta y_{13}=0}$$

for particles moving with similar longitudinal momentum (along the SA event-by-event)

Three particle Correlations

Courtesy M. A. Sanchis-Lozano & E. K. Sarkisyan-Grinbaum:

Some theory

Dominant long-range correlation term in $C_3\,(\Delta\phi_{12}, \Delta\phi_{13})$

$$h^{(3)}(\Delta\phi_{12}, \Delta\phi_{13}) \;\sim\; \exp\left[-\frac{(\Delta\phi_{12})^2 + (\Delta\phi_{13})^2 - \Delta\phi_{12}\Delta\phi_{13}}{3\delta_{\mathrm{h}\phi}^2 + \delta_{\mathrm{h}\phi}^2}\right]$$

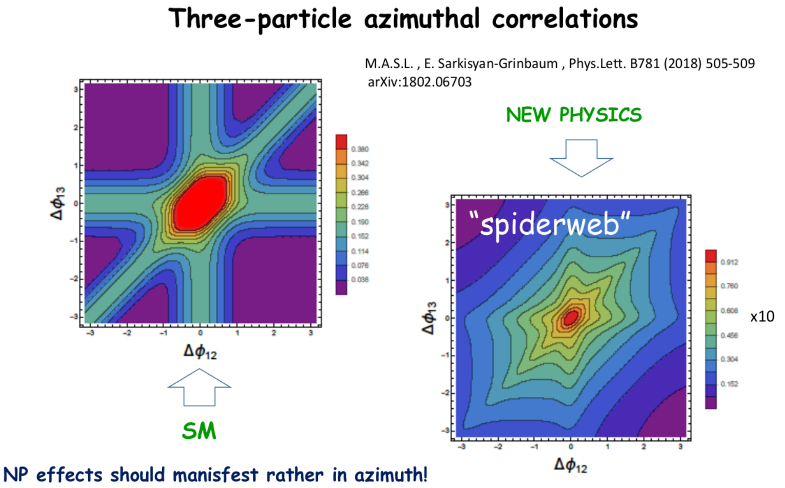
$$+\;\exp\left[-\frac{(\Delta\phi_{12})^2}{2(2\delta_{\mathrm{c}\phi}^2 + \delta_{\mathrm{h}\phi}^2)}\right] + \exp\left[-\frac{(\Delta\phi_{13})^2}{2(2\delta_{\mathrm{c}\phi}^2 + \delta_{\mathrm{h}\phi}^2)}\right] + \exp\left[-\frac{(\Delta\phi_{12})^2 + (\Delta\phi_{13})^2 - 2\Delta\phi_{12}\Delta\phi_{13}}{2(2\delta_{\mathrm{c}\phi}^2 + \delta_{\mathrm{h}\phi}^2)}\right].$$

Here, $\delta_{\mathrm{h}\phi}$ and $\delta_{\mathrm{c}\phi}$ represent the expected correlation length due to the first and second steps in the evolution of the parton cascade using a simplified model. In turn, correlations of particles from clusters are parametrized by δ_{ϕ}, which can be referred to as the cluster decay width in the transverse plane (see [7,29]). The full set of expressions for the 3-particle correlation function $C_3(\Delta\phi_{12}, \Delta\phi_{13})$ in a 3-step cascade process can be found in [7].

M.A.S.L. , E. Sarkisyan-Grinbaum , Phys .Lett. B781 (2018) 505-509
arXiv:1802.06703

Three particle Correlations

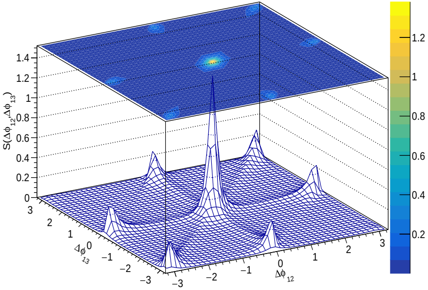
Courtesy M. A. Sanchis-Lozano & E. K. Sarkisyan-Grinbaum:

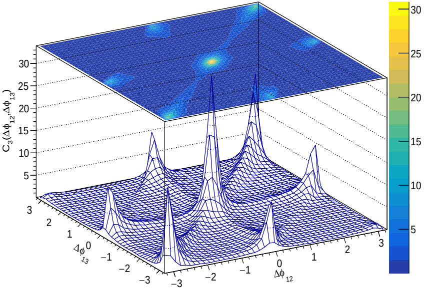


Three particle Correlations

3D-Plots

Density of particle triplets: $S(\Delta\phi_{12}, \Delta\phi_{13})$ (left panel) and three-particle correlations $\mathcal{C}_3(\Delta\phi_{12}, \Delta\phi_{13})$ (right panel).

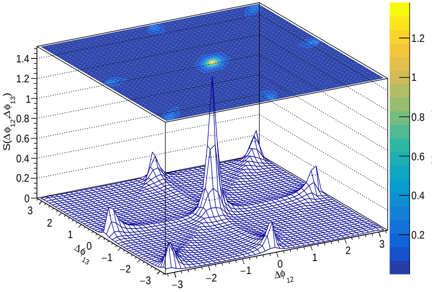


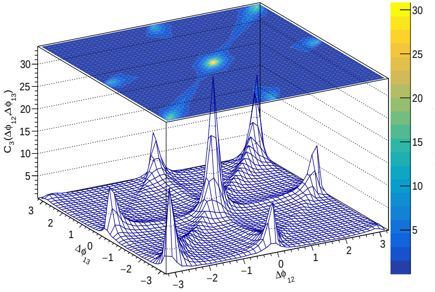


Three particle Correlations

3D-Plots (SM quarks)

- Central peak at $(0,0)$ shows three strongly correlated particles
- Satellite peaks at $(0,-\pi)$, $(0,\pi)$, (π,π) etc show correlations from two particles and one opposite back-to-back particle.



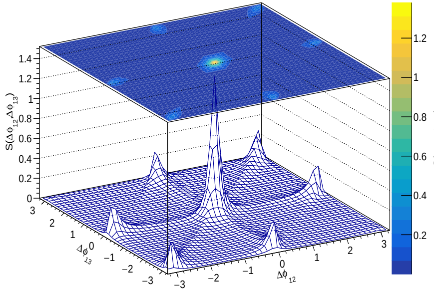


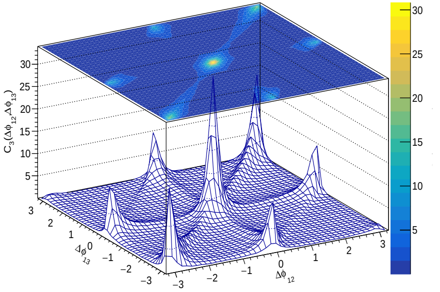
Three particle Correlations

3D-Plots (SM quarks)

The analysis is performed from:

- contour plots (“spiderweb”),
- on-diagonal cut: $\Delta\phi_{12} = \Delta\phi_{13}$, off-diagonal cut: $\Delta\phi_{12} = -\Delta\phi_{13}$.



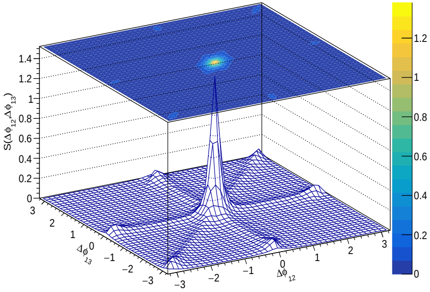


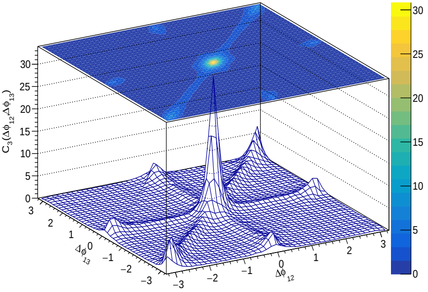
Three particle Correlations

3D-Plots (top quark)

The analysis is performed from:

- contour plots ("spiderweb"),
- on-diagonal cut: $\Delta\phi_{12} = \Delta\phi_{13}$, off-diagonal cut: $\Delta\phi_{12} = -\Delta\phi_{13}$.





Three particle Correlations

3D-Plots (HV Tv quark)

The analysis is performed from:

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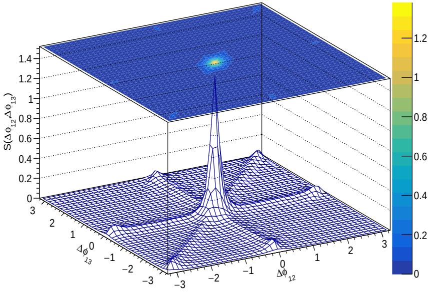
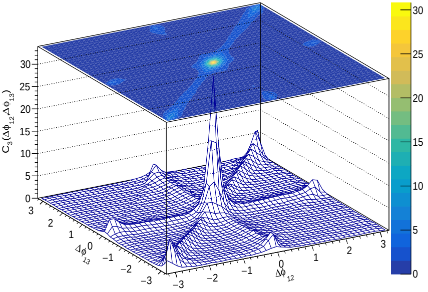




Three particle Correlations

Analysis for on- & off-diagonal correlations:

Fits are made using three Gaussian functions with widths δ_s, δ_m & δ_l for:

- short-range correlations mainly due to resonance decays,
- middle-range correlations mainly due to the QCD parton shower,
- and long-range correlations, attributed to the HV sector on top of the conventional cascade.

Three particle Correlations

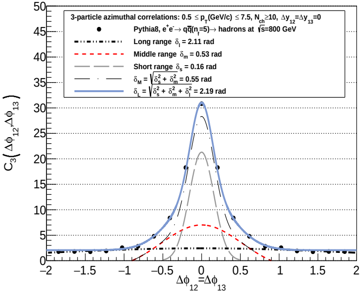
Analysis for on- & off-diagonal correlations:

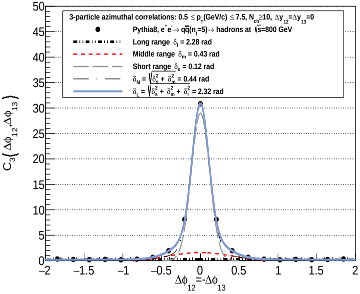
In order to disentangle the possible existence of a hidden sector, more general widths can be defined:

- $\delta_M = \sqrt{\delta_s^2 + \delta_m^2}$ for "pure" QCD correlations,
- $\delta_L = \sqrt{\delta_s^2 + \delta_m^2 + \delta_l^2}$ for all QCD and HV correlations.

Three-particle correlations

(v)-quark species:	light quarks	$t\bar{t}$	$T_v \overline{T}_v$
δ_L(on-diagonal)	2.11	3.89	6.16
δ_M(on-diagonal)	0.55	0.59	0.64
δ_M(off-diagonal)	0.44	0.53	0.53
mean sphericity	0.04	0.17	0.47





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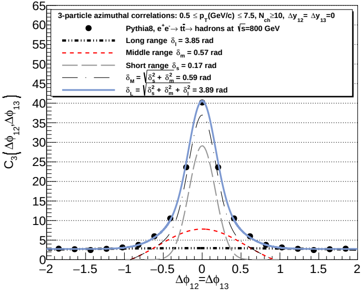

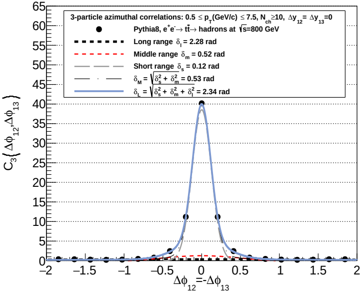

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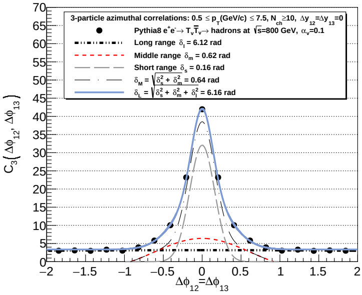

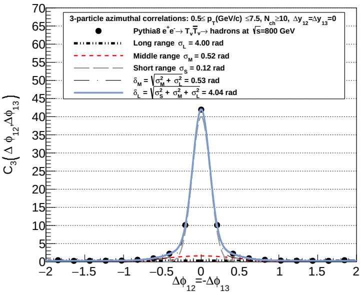

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Contour plot analysis:

- Outer ellipse: minor/major axes $= \delta_M(\text{off-})/\delta_L(\text{on-})$. Major axis includes HV correlations.
- Inner ellipse: minor/major axes $= \delta_M(\text{off-})/\delta_M(\text{on-})$. Major axis does not include HV correlations.

Three-particle correlations

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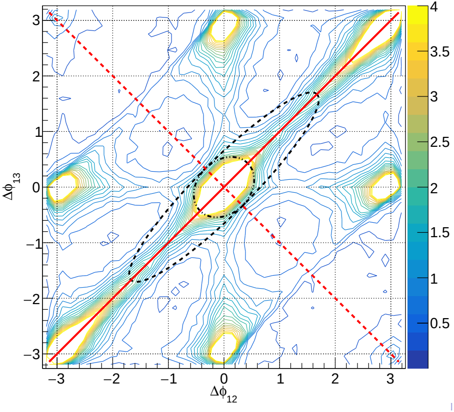

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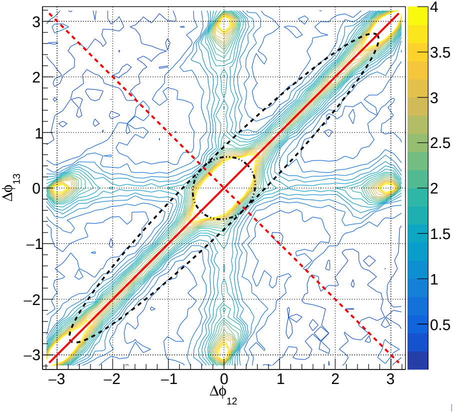

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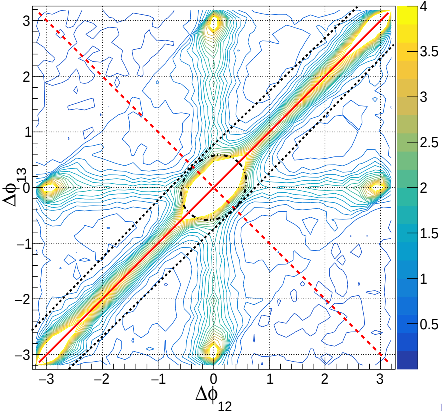


Part VII

Conclusions

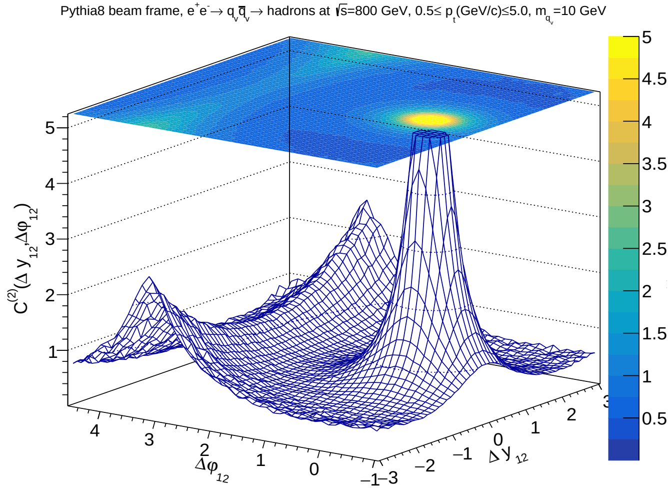
Conclusions

- Near-side ridge in two-particle correlations (in sphericity) mainly coming from mass asymmetries in HV scenarios.
- Models exhibit increasing sphericity from SM to SM TOP and HV scenarios: HV events are "fatter".
- Long range three-particle correlations in HV scenario (Tv) compared to SM following the hierarchy $\delta_L(HV) > \delta_L(TOP) > \delta_L(q\bar{q})$.
- The hierarchy matches the highest mean sphericity for HV events.
- Complementary tools can be developed in order to further contribute to the potential discovery of HV sectors and high luminosity runs at the LHC and at future e^+e^- colliders.

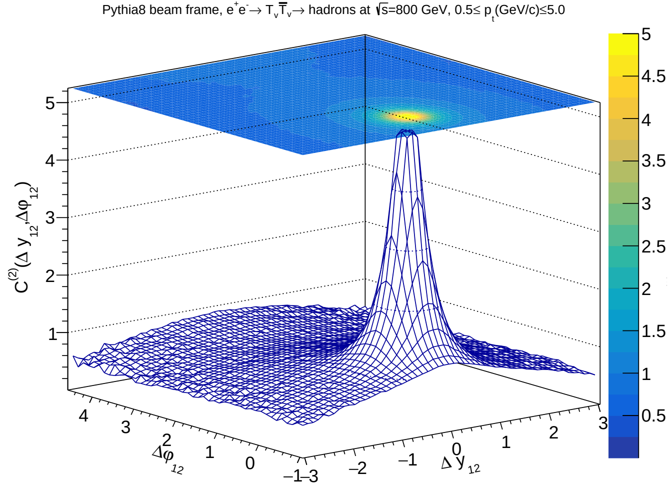
Part VIII

Back-up Slides

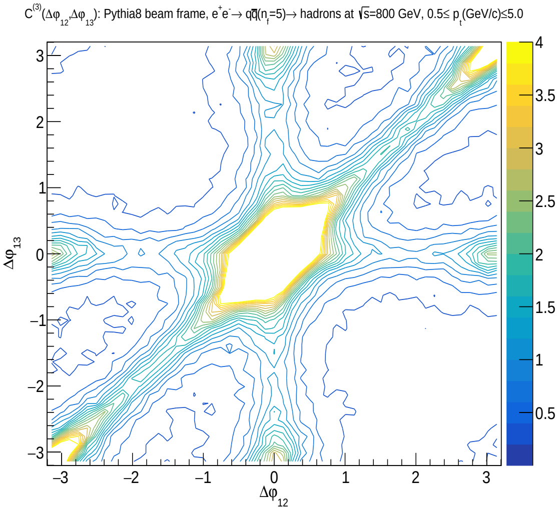
2- & 3-particle correlations



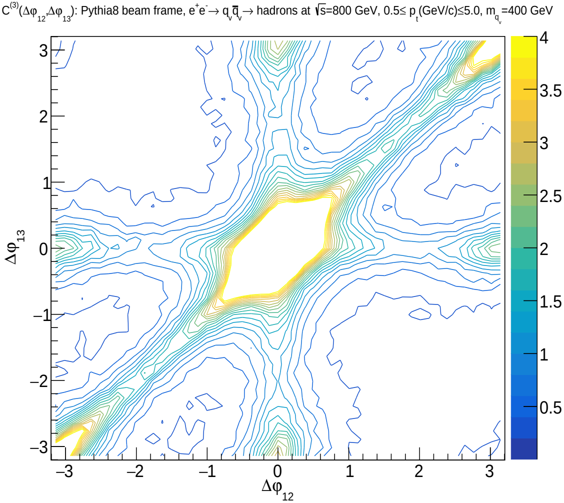
2- & 3-particle correlations



2- & 3-particle correlations



2- & 3-particle correlations



2- & 3-particle correlations