



Investigating hidden sectors at future e^+e^- colliders through two-particle angular correlations

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in collaboration with

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based on [2312.06526](#)
(Submitted to PRD)

TWO-PARTICLE ANGULAR CORRELATIONS

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

❖ Difference in Rapidity

$$\Delta y = y_2 - y_1$$

❖ Difference in Azimuthal angle:

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

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

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

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

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

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

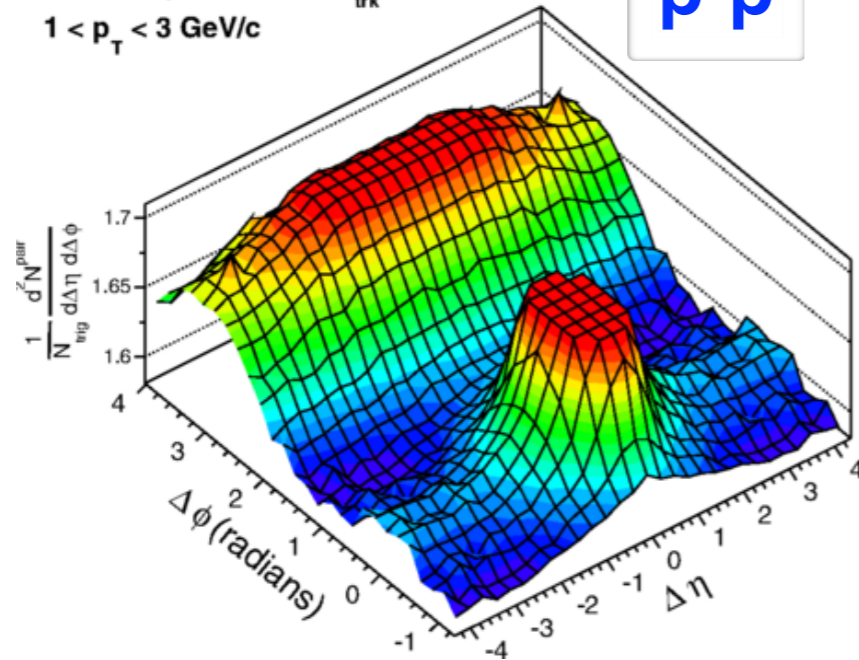
$$B(\Delta y, \Delta\phi) = \frac{1}{N_{mix}} \frac{d^2 N^{mix}}{d\Delta y d\Delta\phi}$$

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

TWO-PARTICLE ANGULAR CORRELATIONS

CMS pp $\sqrt{s} = 13$ TeV, $N_{\text{trk}}^{\text{offline}} \geq 105$
 $1 < p_T < 3$ GeV/c

p-p

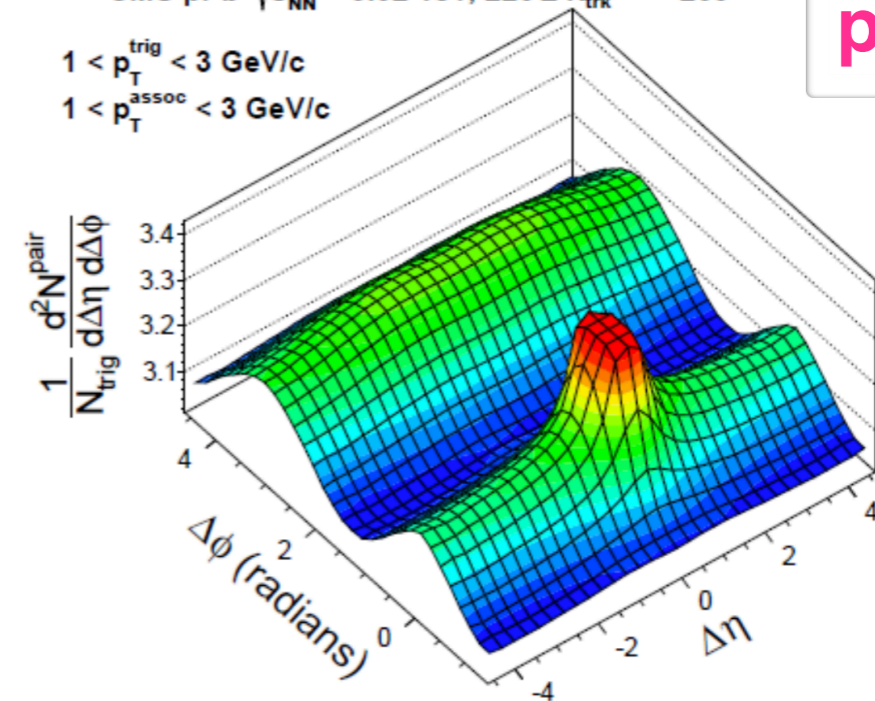


Phys. Rev. Lett. 116, 172302

CMS pPb $\sqrt{s_{\text{NN}}} = 5.02$ TeV, $220 \leq N_{\text{trk}}^{\text{offline}} < 260$

$1 < p_T^{\text{trig}} < 3$ GeV/c
 $1 < p_T^{\text{assoc}} < 3$ GeV/c

p-Pb

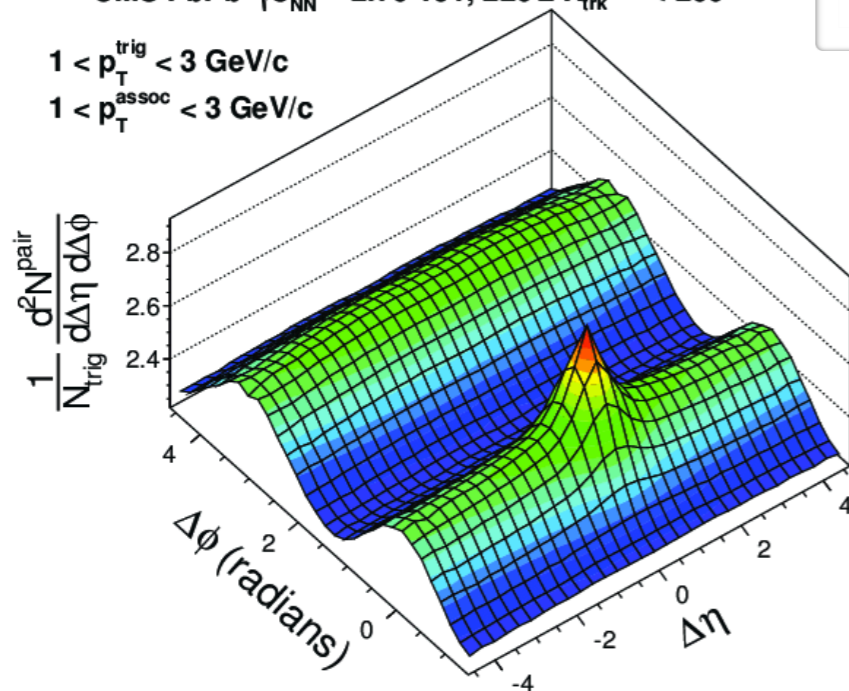


Physics Letters B B724(4)

CMS PbPb $\sqrt{s_{\text{NN}}} = 2.76$ TeV, $220 \leq N_{\text{trk}}^{\text{offline}} < 260$

$1 < p_T^{\text{trig}} < 3$ GeV/c
 $1 < p_T^{\text{assoc}} < 3$ GeV/c

Pb-Pb

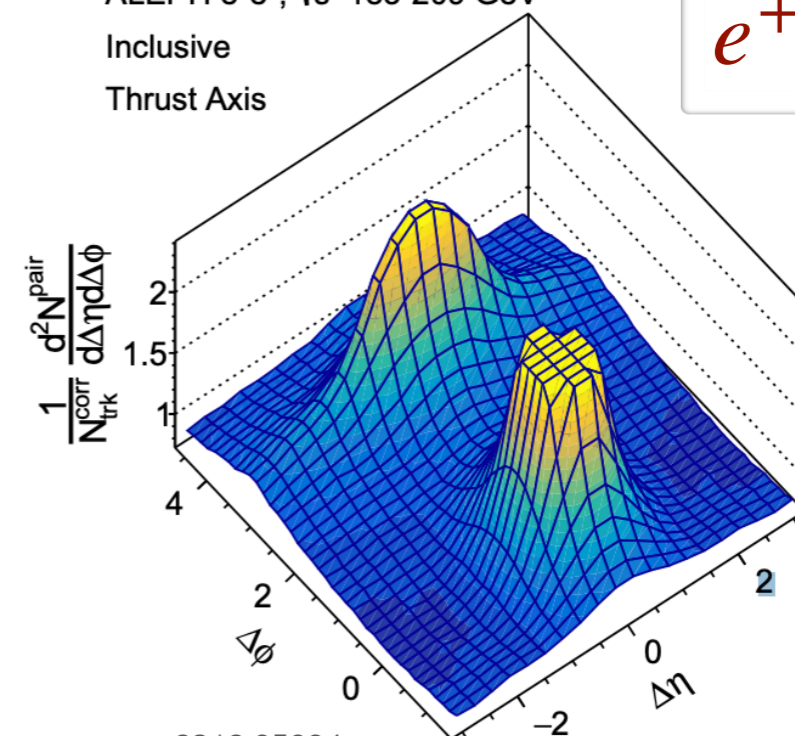


Physics Letters B B724(4)

ALEPH e^+e^- , $\sqrt{s} = 183-209$ GeV

Inclusive
 Thrust Axis

e^+e^-

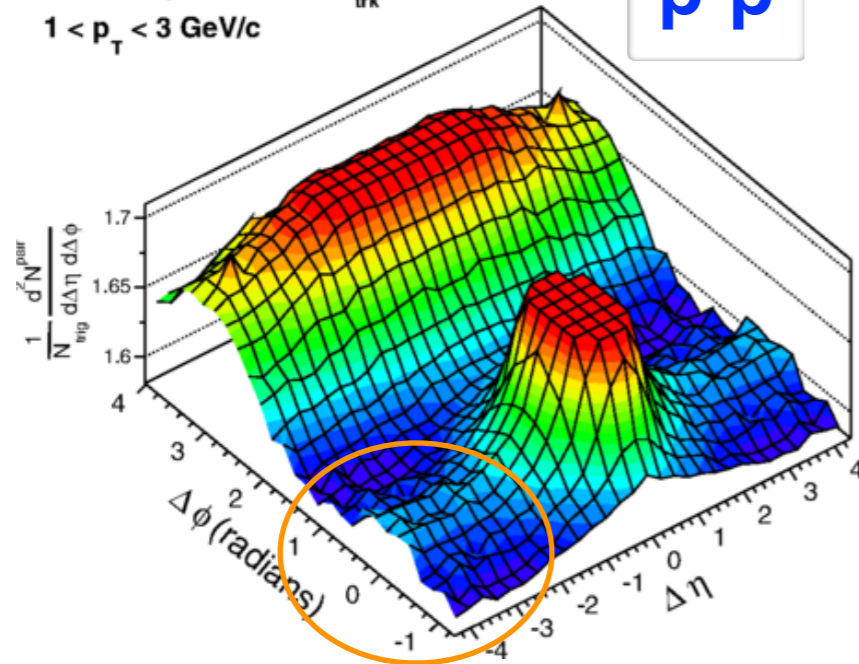


2312.05084

TWO-PARTICLE ANGULAR CORRELATIONS

CMS pp $\sqrt{s} = 13$ TeV, $N_{\text{trk}}^{\text{offline}} \geq 105$
 $1 < p_T < 3$ GeV/c

p-p

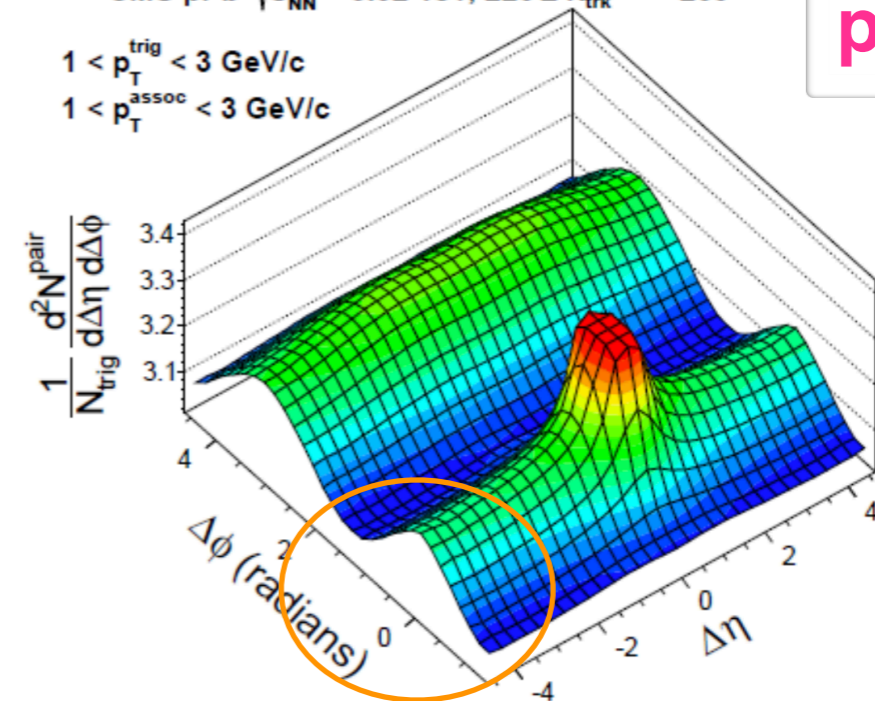


Phys. Rev. Lett. 116, 172302

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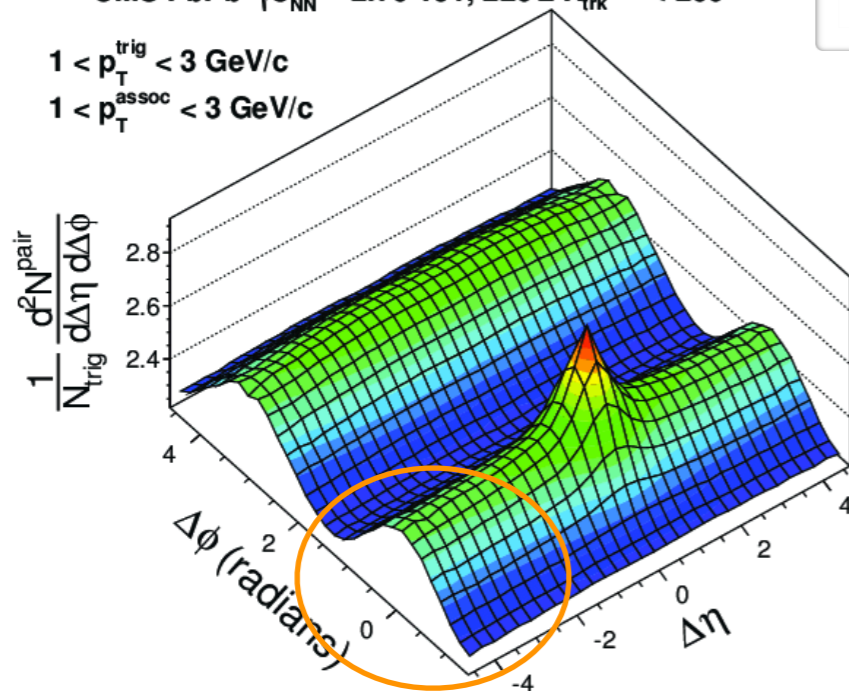


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Pb-Pb

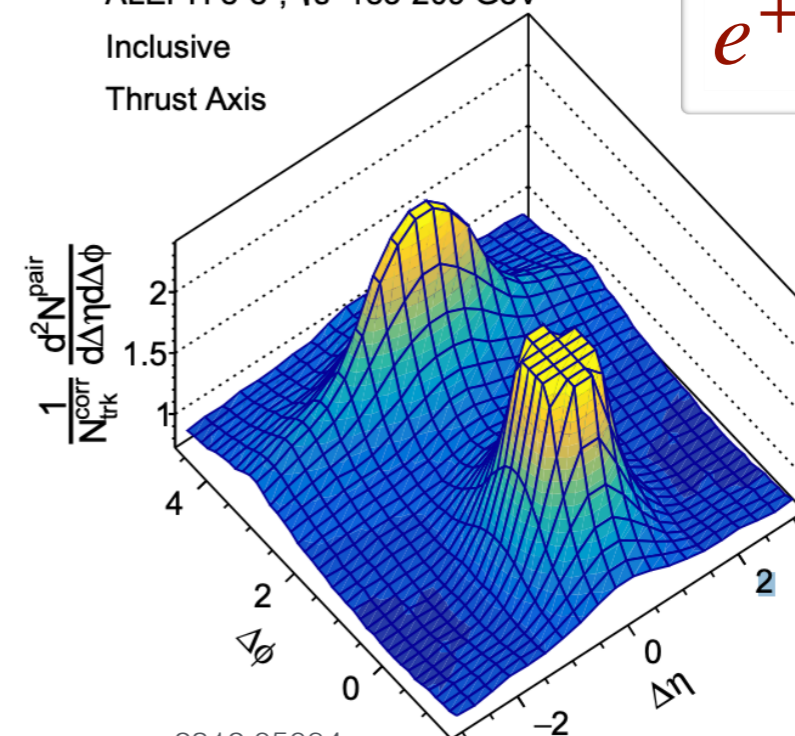


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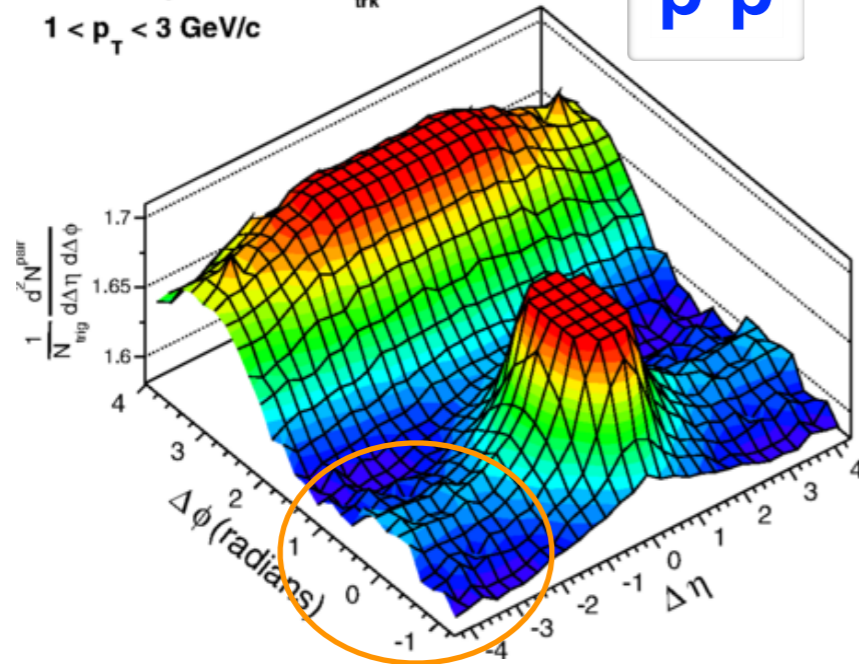


2312.05084

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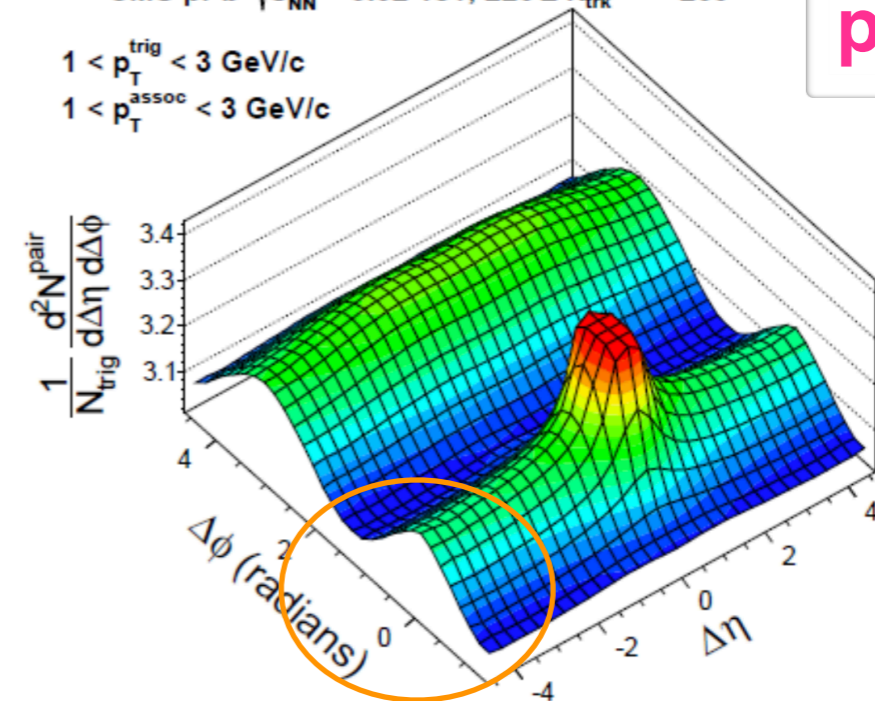


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p-Pb

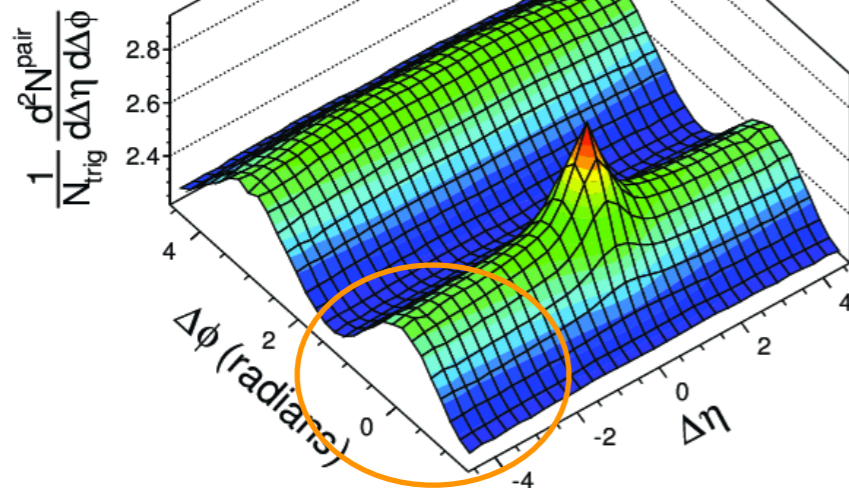


Physics Letters B B724(4)

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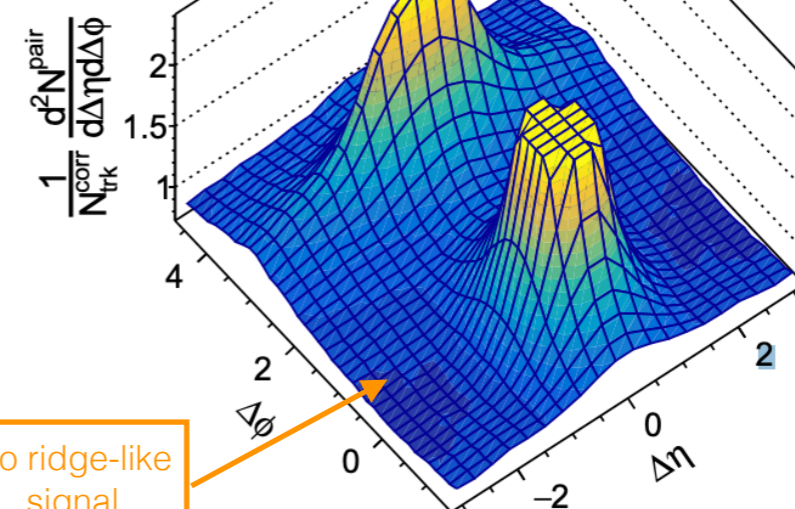


Physics Letters B B724(4)

ALEPH e^+e^- , $\sqrt{s} = 183-209$ GeV

Inclusive
 Thrust Axis

e^+e^-



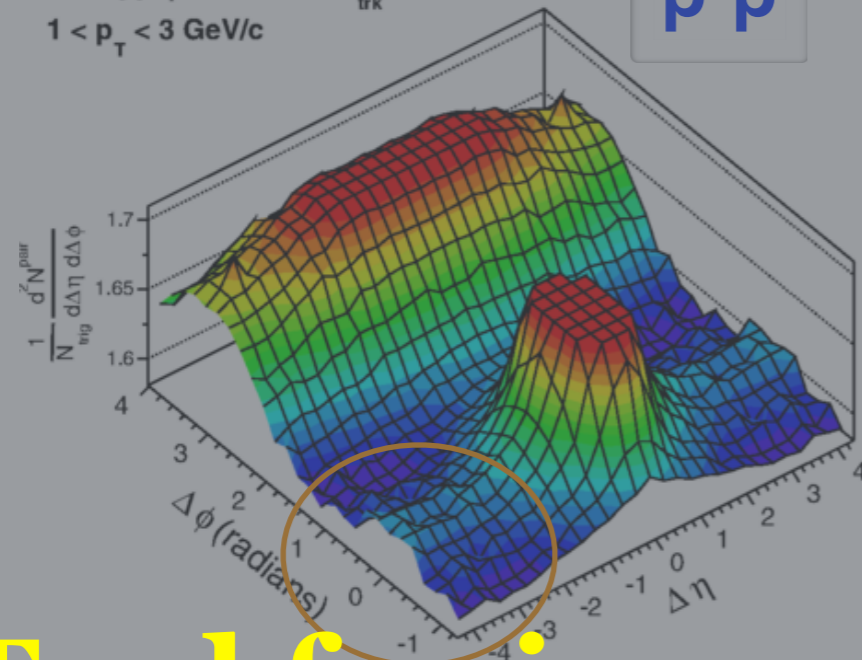
No ridge-like
 signal

2312.05084

TWO-PARTICLE ANGULAR CORRELATIONS

CMS pp $\sqrt{s} = 13$ TeV, $N_{\text{trk}}^{\text{offline}} \geq 105$
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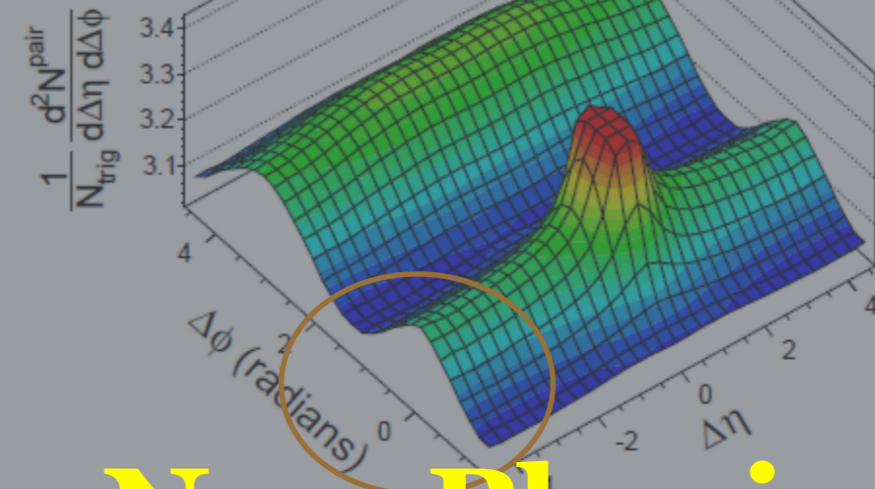
p-p



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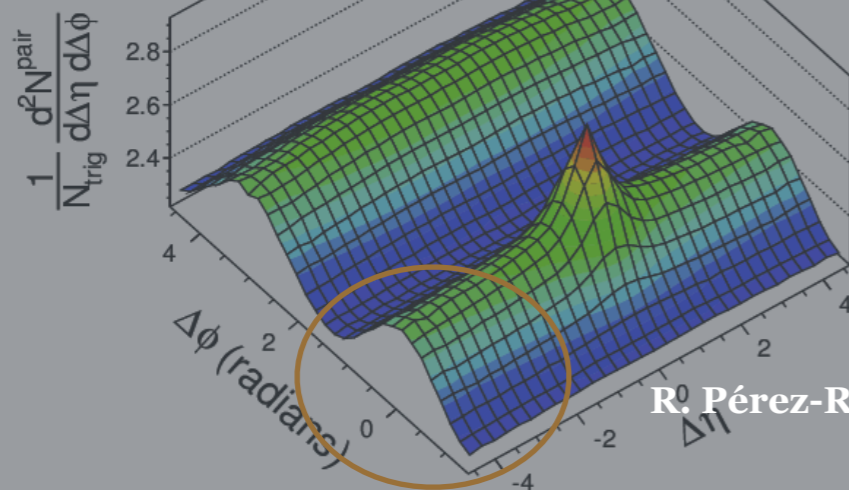


Tool for investigating New Physics?

CMS PbPb $\sqrt{s_{\text{NN}}} = 2.76$ TeV, $220 \leq N_{\text{trk}}^{\text{offline}} < 260$

$1 < p_T^{\text{trig}} < 3$ GeV/c
 $1 < p_T^{\text{assoc}} < 3$ GeV/c

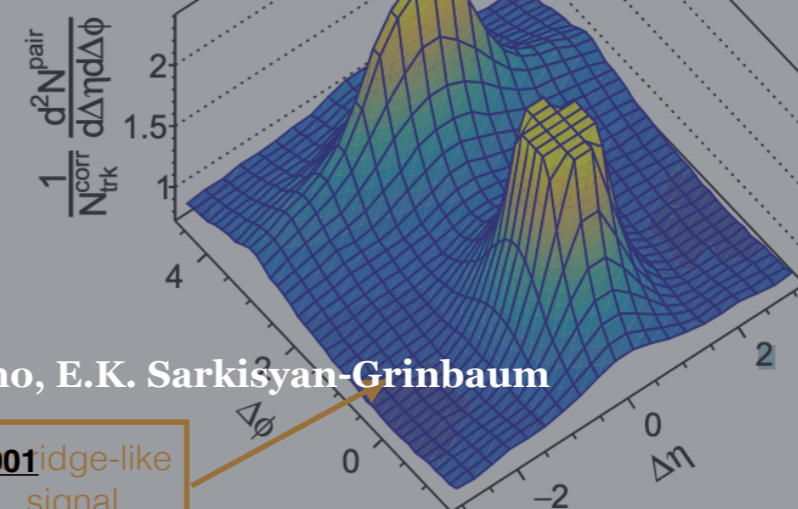
Pb-Pb



ALEPH e^+e^- , $\sqrt{s} = 183-209$ GeV

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 Thrust Axis

e^+e^-



R. Pérez-Ramos, M.A.Sanchis-Lozano, E.K. Sarkisyan-Grinbaum

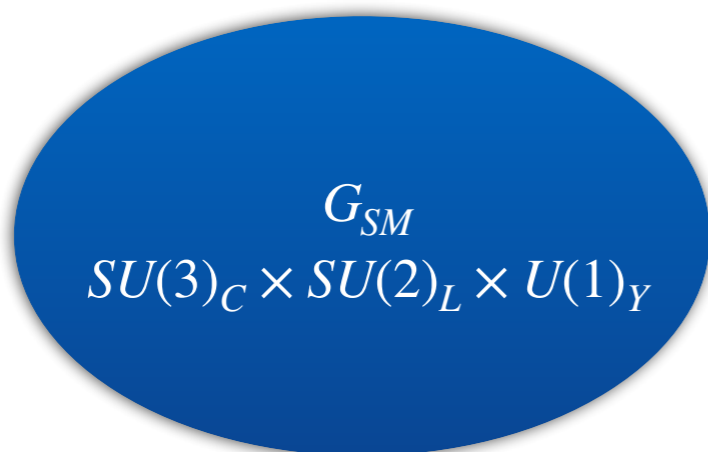
Phys. Rev. D 105, 053001
 ridge-like signal

Physics Letters B B724(4)

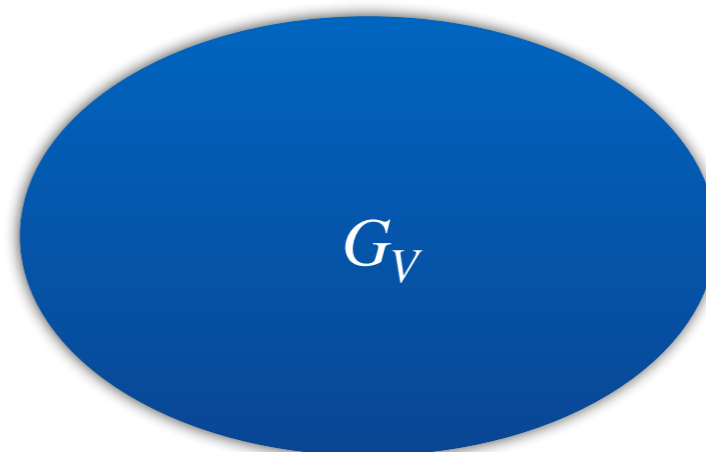
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HIDDEN VALLEY PHENOMENOLOGY

The term *Hidden Valley* refers to a wide class of models



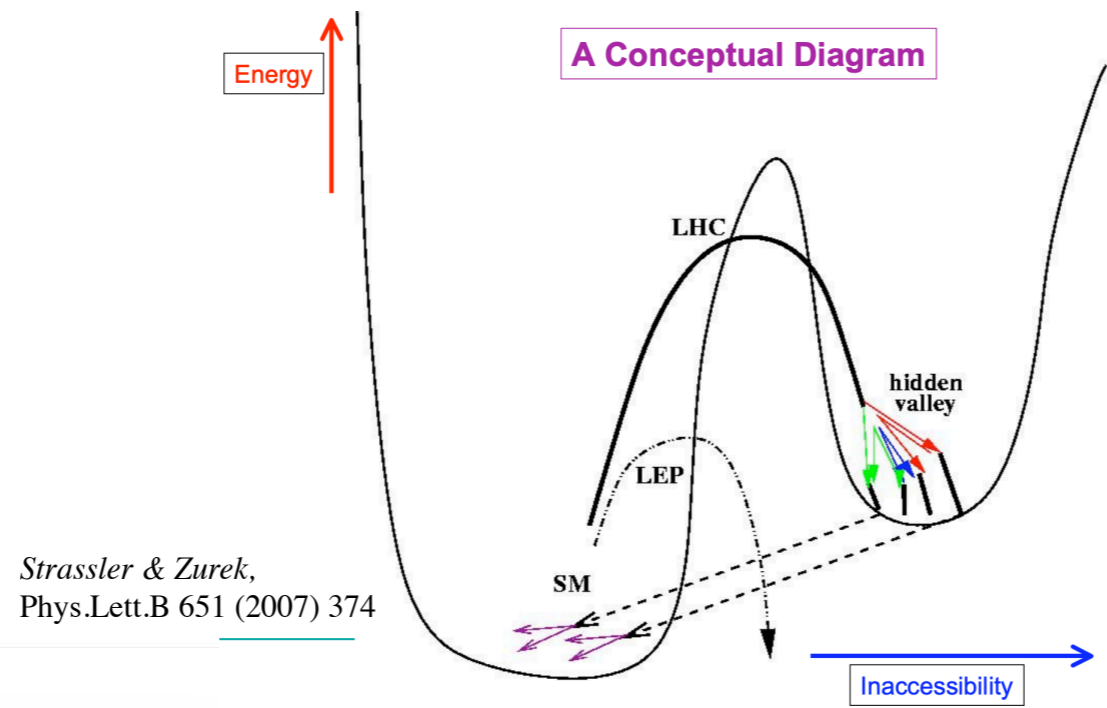
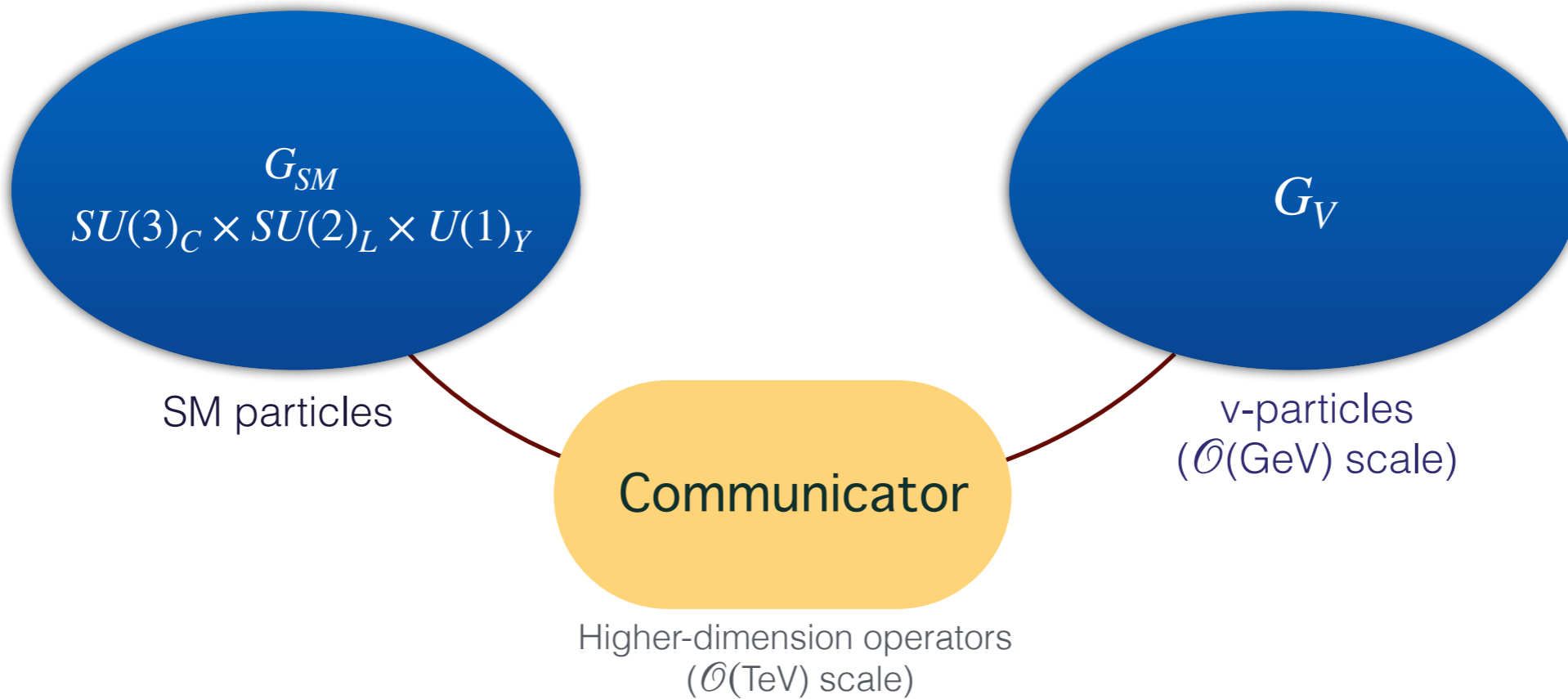
SM particles



v-particles
($\mathcal{O}(\text{GeV})$ scale)

HIDDEN VALLEY PHENOMENOLOGY

The term *Hidden Valley* refers to a wide class of models



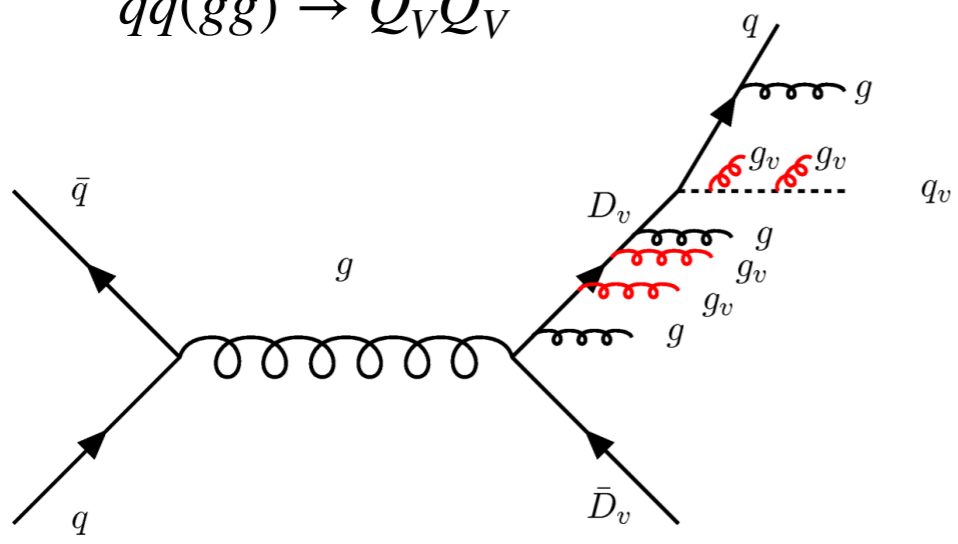
QCD-like scenario

Communicator: F_V

- mirror partner of the SM charged quarks and leptons
- Charged under G_{SM} and G_V
- Pair-produced
- (Prompt) decays: $F_V \rightarrow fq_V \longrightarrow$ hadrons
 - $\ni E_V \rightarrow eq_V$
 - $\ni Q_V \rightarrow qq_V$

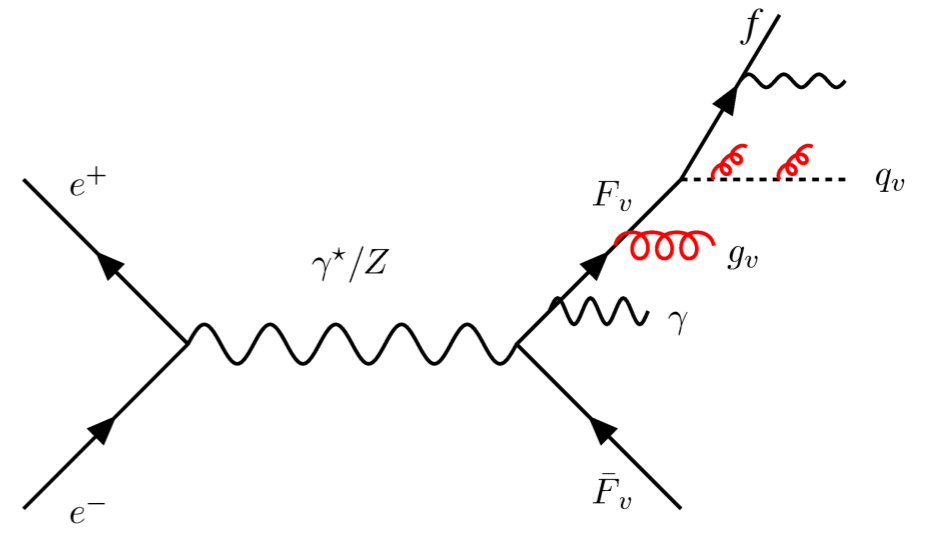
pp collisions

$$q\bar{q}(gg) \rightarrow Q_V\bar{Q}_V$$



e^+e^- collisions

$$e^+e^- \rightarrow \gamma^*/Z^0 \rightarrow F_V\bar{F}_V$$



QCD-like scenario

Communicator: F_V

- mirror partner of the SM charged quarks and leptons
- Charged under G_{SM} and G_V
- Pair-produced
- (Prompt) decays: $F_V \rightarrow fq_V \longrightarrow$ hadrons
 - $E_V \rightarrow eq_V$
 - $Q_V \rightarrow qq_V$

Signature

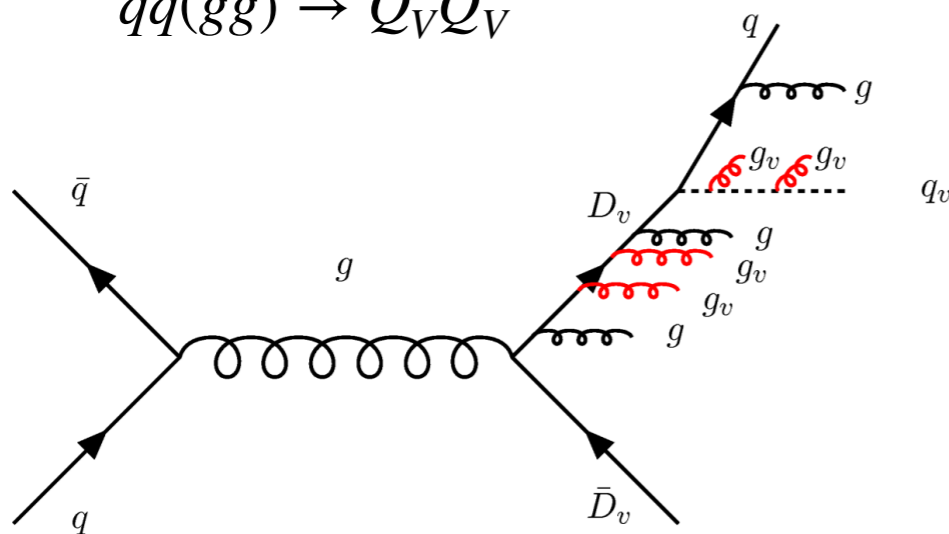
Perturbation in
conventional QCD
cascade and final
hadronisation



anomalies in angular
correlations

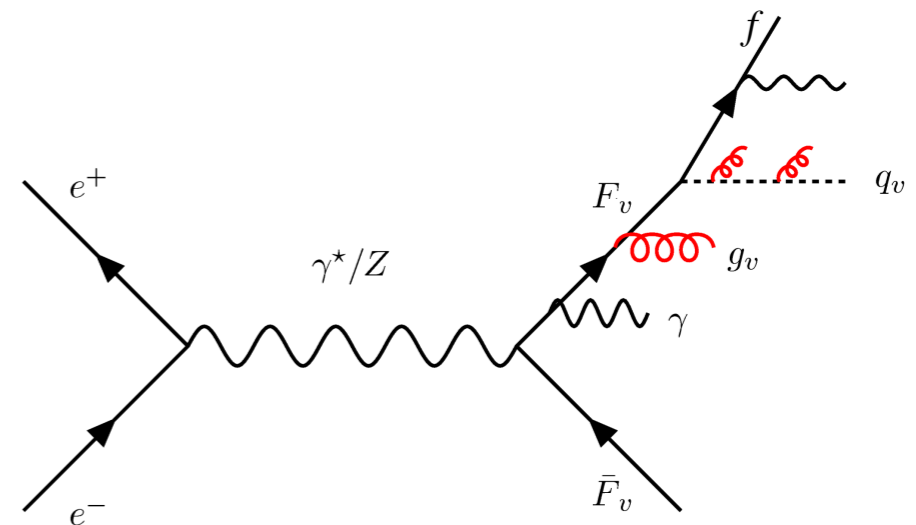
pp collisions

$$q\bar{q}(gg) \rightarrow Q_V\bar{Q}_V$$



e^+e^- collisions

$$e^+e^- \rightarrow \gamma^*/Z^0 \rightarrow F_V\bar{F}_V$$

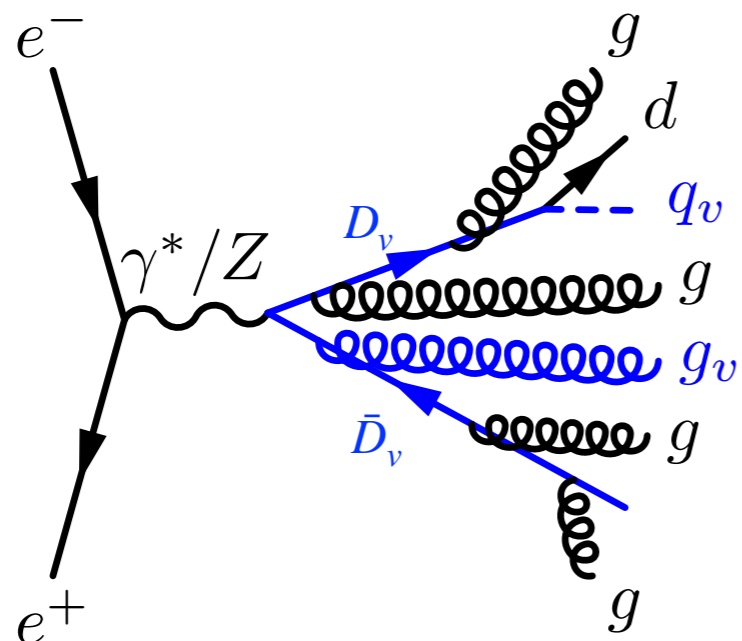


SIGNAL VS BACKGROUND

$$\sqrt{s} = 250 \text{ GeV}$$

SIGNAL

$$e^+e^- \rightarrow \gamma^*/Z^0 \rightarrow D_V \bar{D}_V \rightarrow \text{hadrons}$$



$$m_{D_V} = 125 \text{ GeV}$$

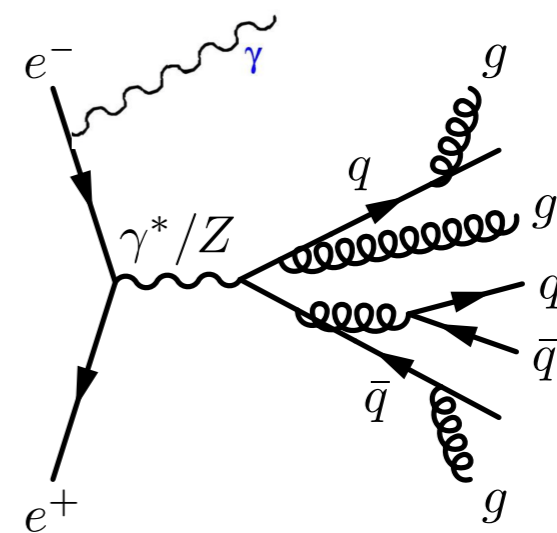
$$\alpha_V = 0.1$$

No polarised beam

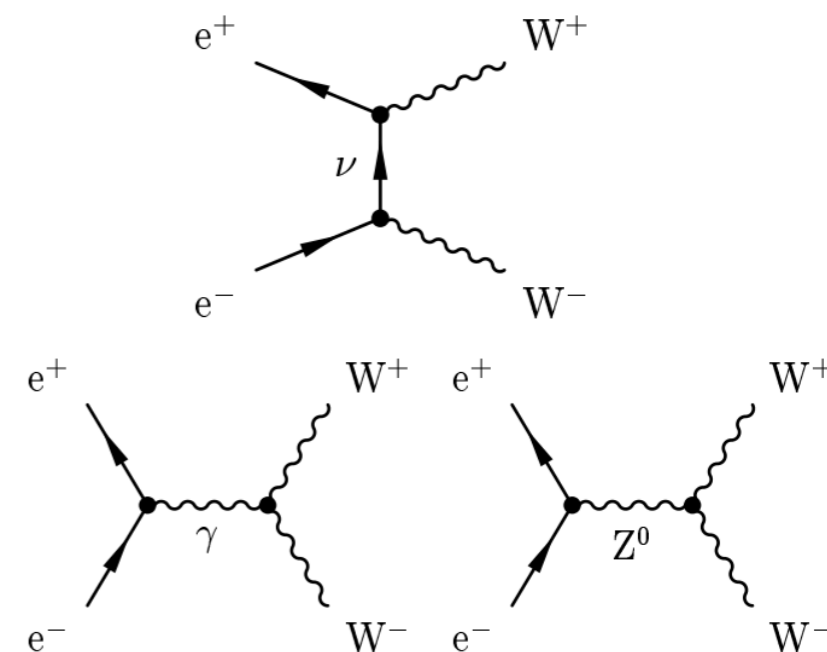
Process	σ_{PYTHIA8} [pb]
$e^+e^- \rightarrow D_V \bar{D}_V$	
$m_{q_v} = 0.1 \text{ GeV}$	0.13
$m_{q_v} = 10 \text{ GeV}$	0.12
$m_{q_v} = 50 \text{ GeV}$	0.12
$m_{q_v} = 100 \text{ GeV}$	0.12
$e^+e^- \rightarrow q\bar{q}$ with ISR	48
$WW \rightarrow 4q$	7.4

BACKGROUND

i) $q\bar{q}$ production with ISR



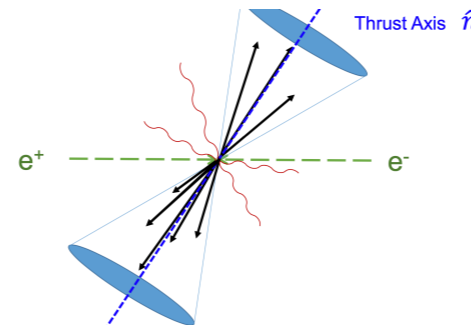
ii) $WW \rightarrow 4q$



ANALYSIS AT DETECTOR LEVEL

$$\sqrt{s} = 250 \text{ GeV}$$

Thrust Axis:



$$T = \max_{\vec{n}} \frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum_i |\vec{p}_i|}$$

TOOLS

- Monte Carlo event generator:

- ➔ Pythia8

- HepMC output

- Fast detector simulation

- ➔ SGV 3.0

- From HepMC files → LCIO-DST

- ILD geometry

- Analysis

- ➔ ILCSoft (<https://github.com/qqbaranalysis/qqbaranalysis>)

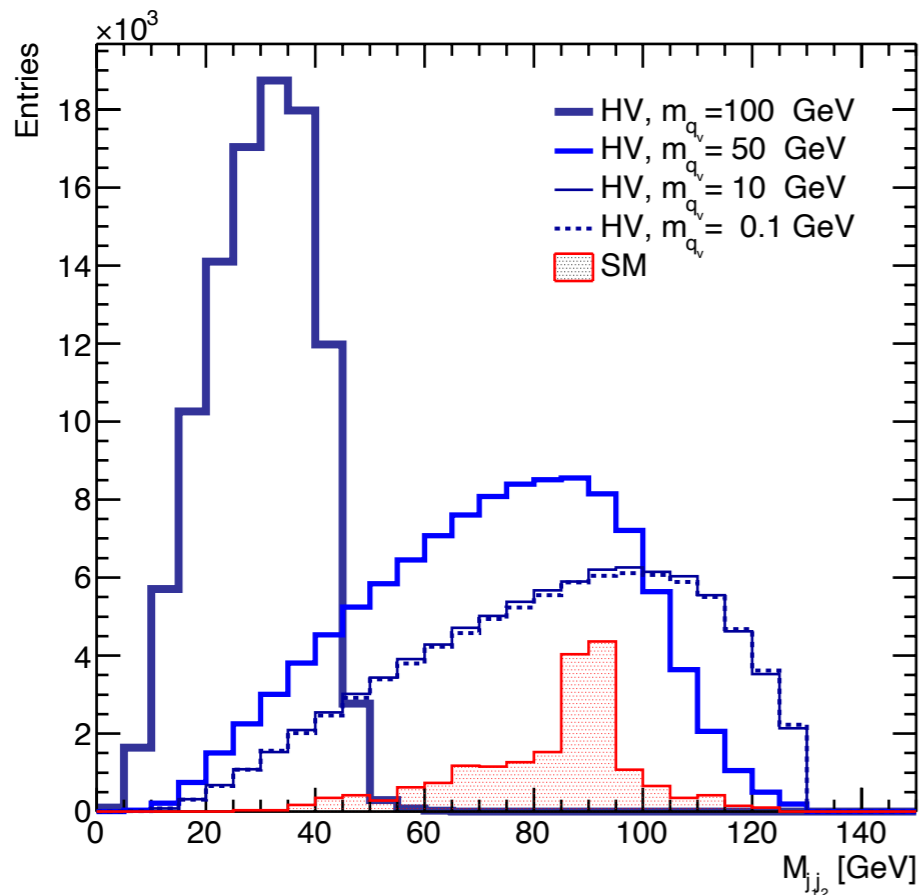
- ➔ ROOT (<https://github.com/airqui/AFBhq2021>)

ANALYSIS AT DETECTOR LEVEL

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

CUTS

- ❖ No secondary vertices
- ❖ neutral PFOs ≤ 22 and charged PFOs ≤ 15
- ❖ $|\cos \theta_{\text{ISR}}| < 0.5$
- ❖ $E_{\text{ISR}} < 40 \text{ GeV}$
- ❖ $m_{jj} < 130 \text{ GeV}$
- ❖ $E_{\text{jet}} < 80 \text{ GeV}$



Pythia8+SGV (ILC detector)

Process	σ_{PYTHIA8} [pb]	Efficiency [%]	$\langle N_{\text{ch}} \rangle$
$e^+e^- \rightarrow D_v \bar{D}_v$			
$m_{qv} = 0.1 \text{ GeV}$	0.13	36	12.4 ± 3.7
$m_{qv} = 10 \text{ GeV}$	0.12	36	12.4 ± 3.7
$m_{qv} = 50 \text{ GeV}$	0.12	42	11.4 ± 3.5
$m_{qv} = 100 \text{ GeV}$	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	$\lesssim 0.001$	-

ANALYSIS AT DETECTOR LEVEL

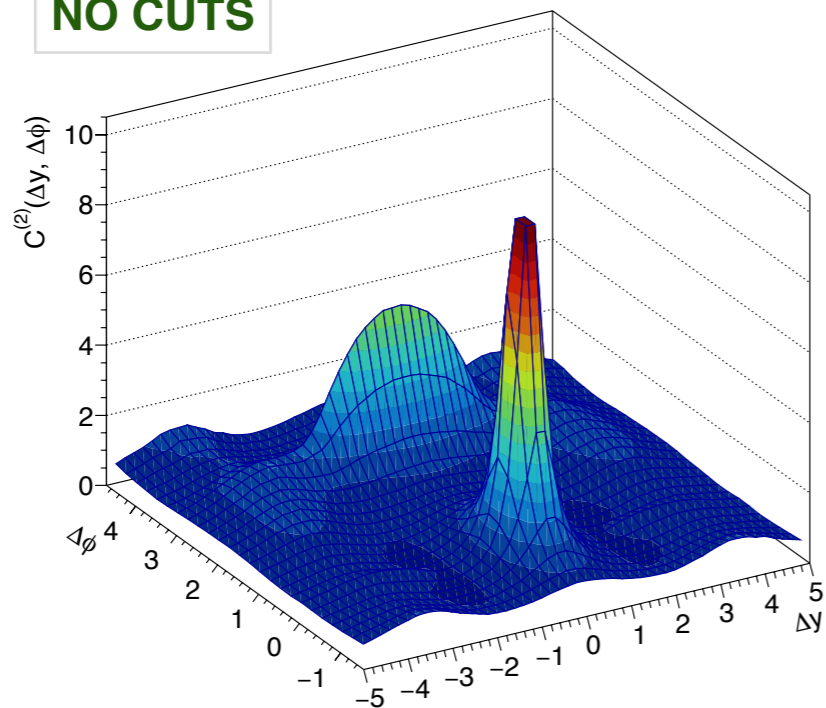
$$\sqrt{s} = 250 \text{ GeV}, \mathcal{L} = 2 \text{ ab}^{-1}$$

BACKGROUND

SIGNAL

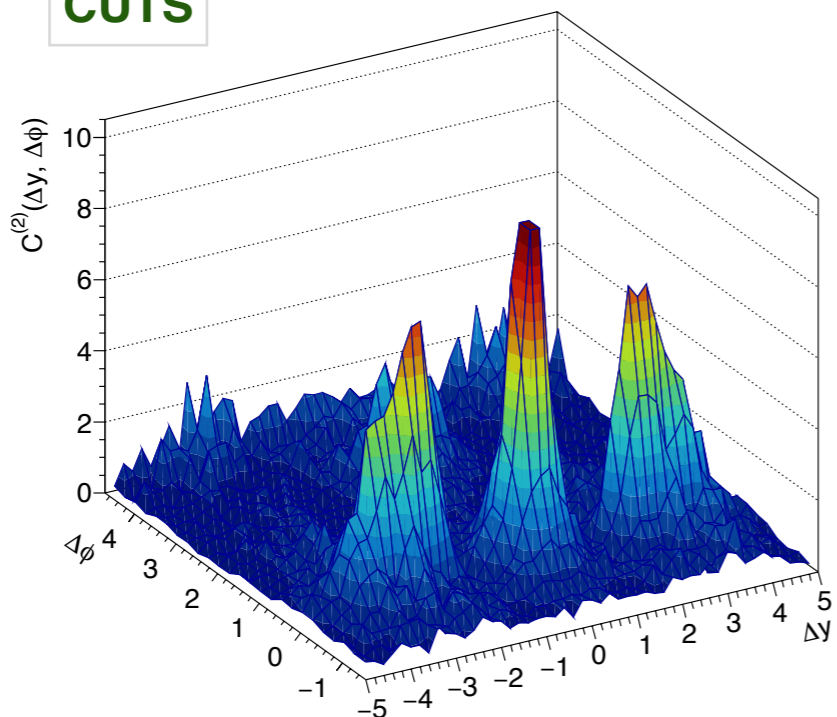
Thrust axis

NO CUTS



SM

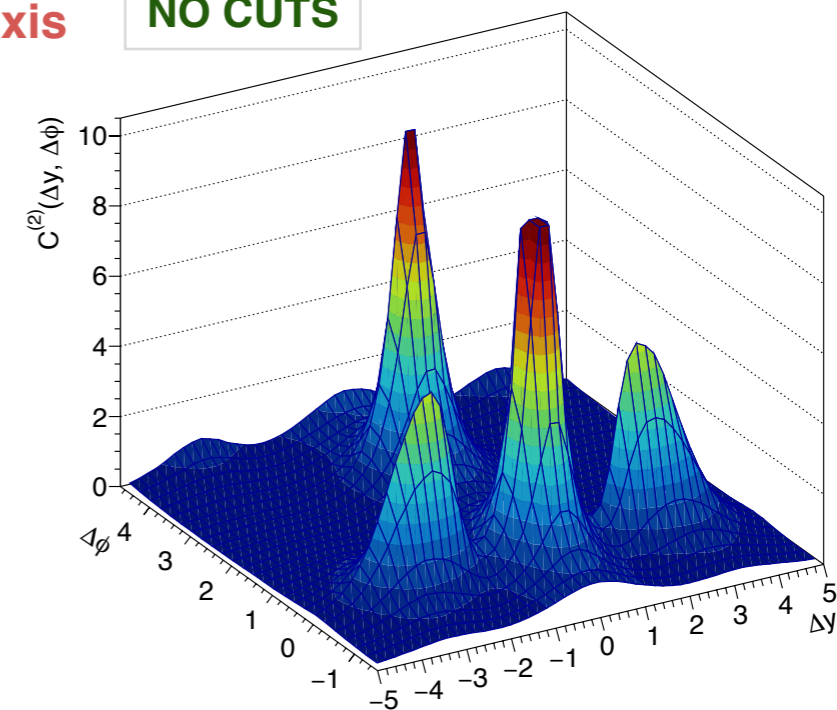
CUTS



SM

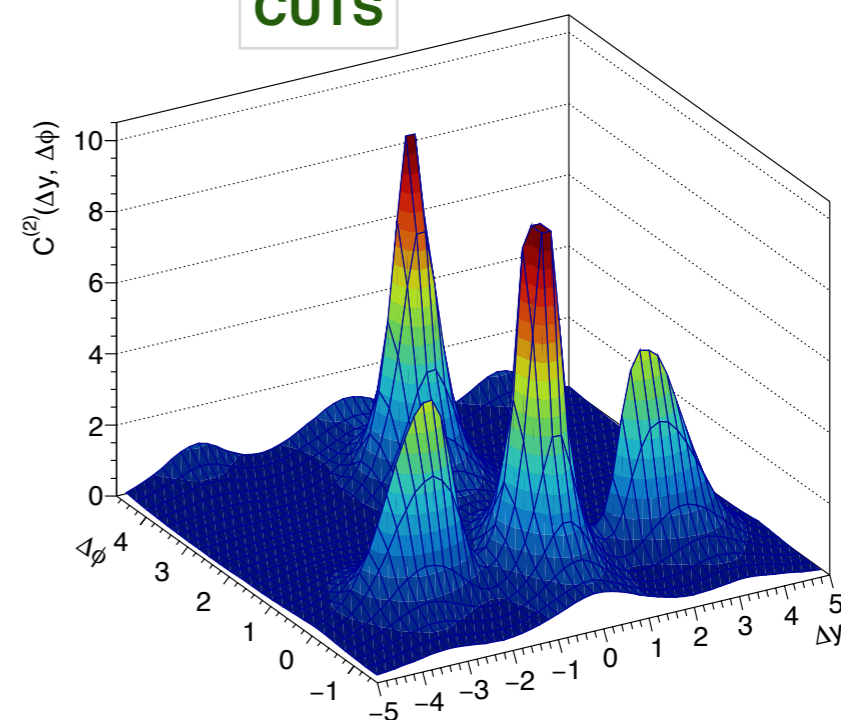
Thrust axis

NO CUTS



HV ($m_{q_v} = 100 \text{ GeV}$)

CUTS



HV ($m_{q_v} = 100 \text{ GeV}$)

ANALYSIS AT DETECTOR LEVEL

Yield

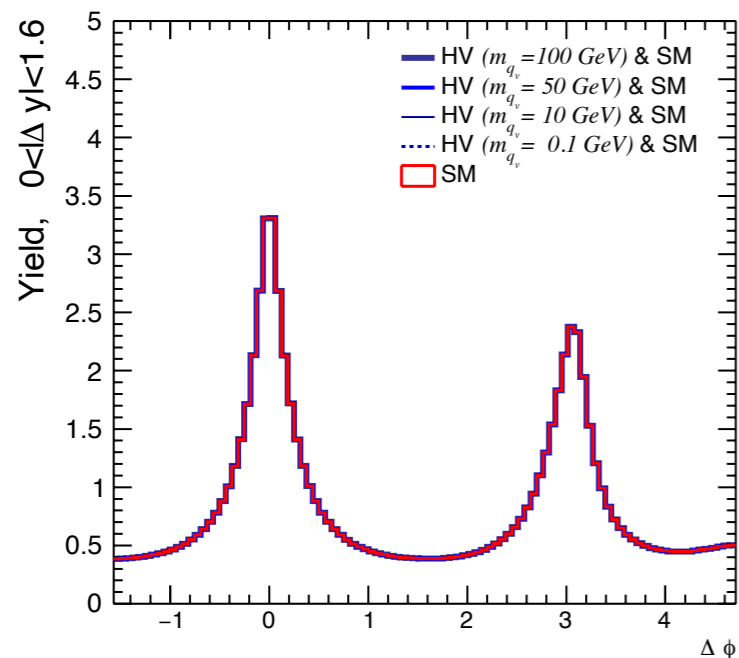
$$Y(\Delta\phi) = \frac{\int_{y_{\text{inf}} \leq |\Delta y| \leq y_{\text{sup}}} S(\Delta y, \Delta\phi) dy}{\int_{y_{\text{inf}} \leq |\Delta y| \leq y_{\text{sup}}} B(\Delta y, \Delta\phi) dy}$$

ANALYSIS AT DETECTOR LEVEL

Yield

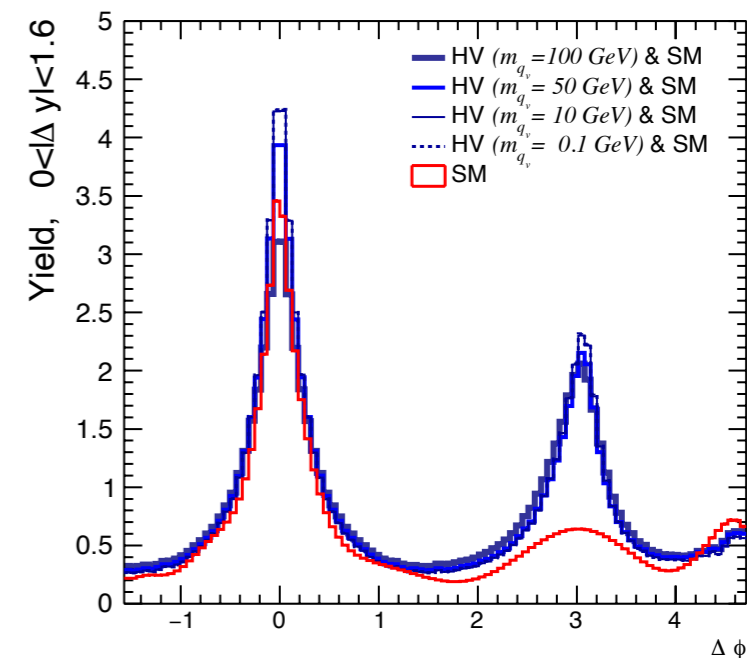
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NO CUTS

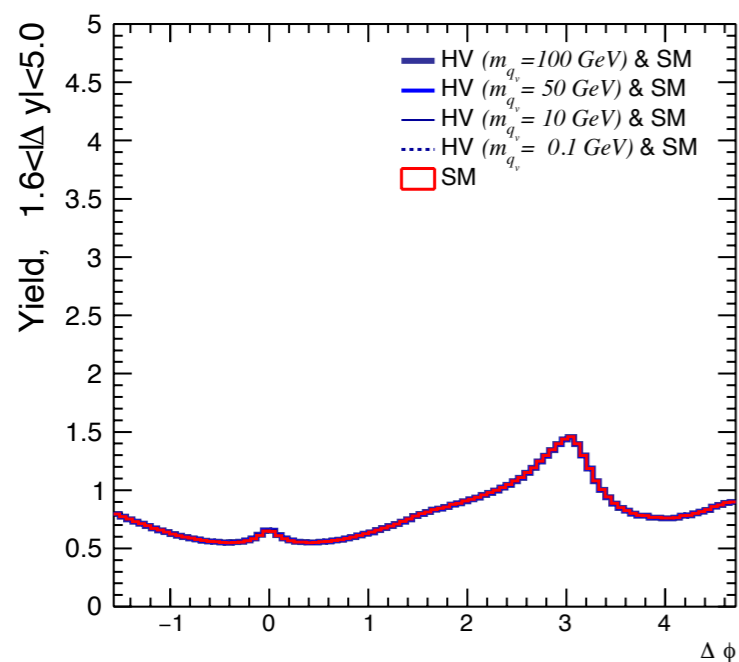


Pythia8+SGV (ILC detector)

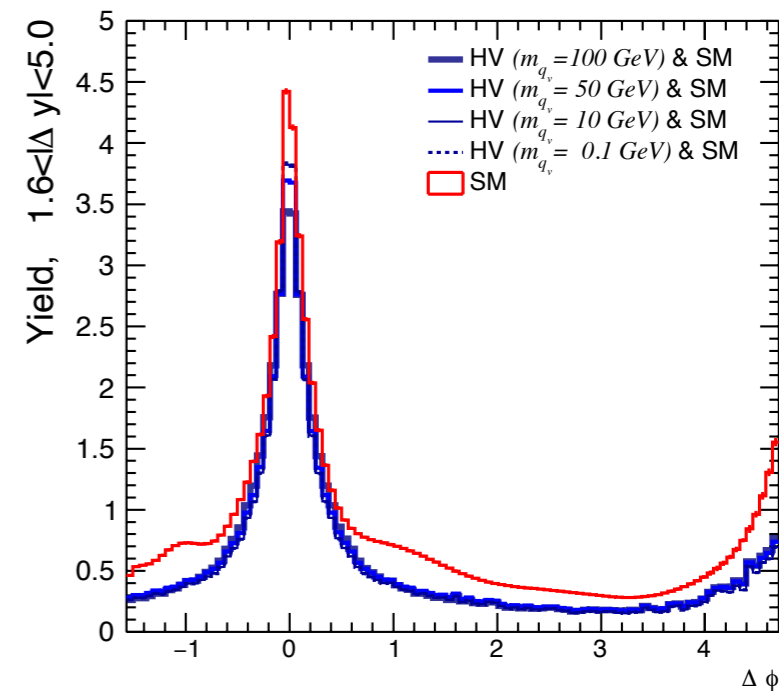
CUTS



Pythia8+SGV (ILC detector)



Pythia8+SGV (ILC detector)



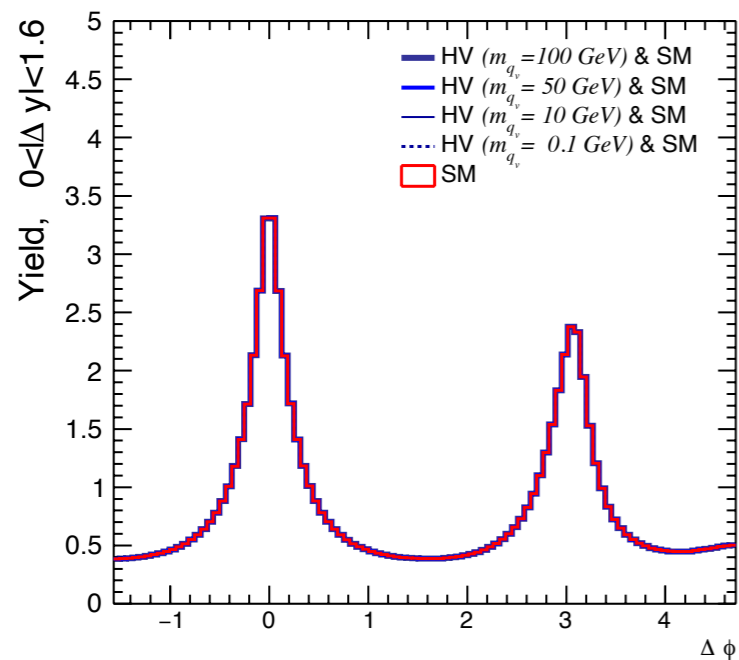
Pythia8+SGV (ILC detector)

ANALYSIS AT DETECTOR LEVEL

Yield

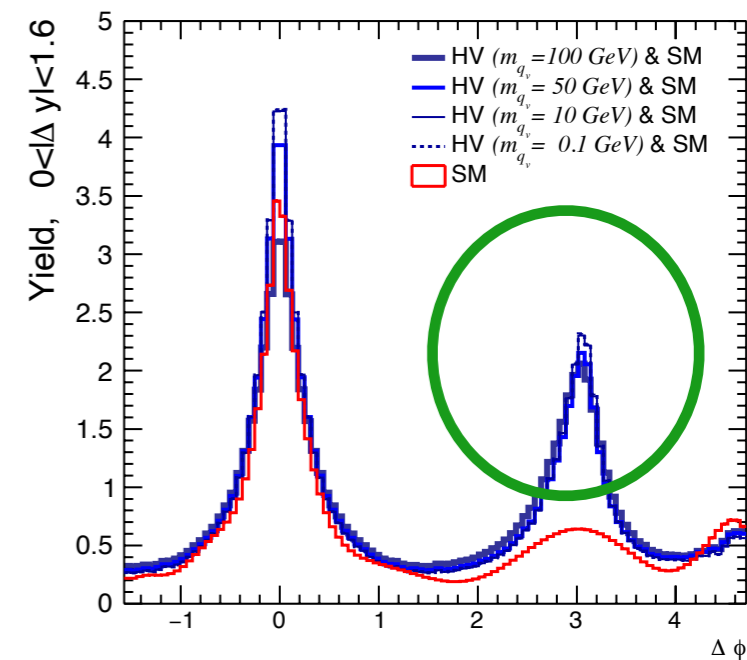
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NO CUTS

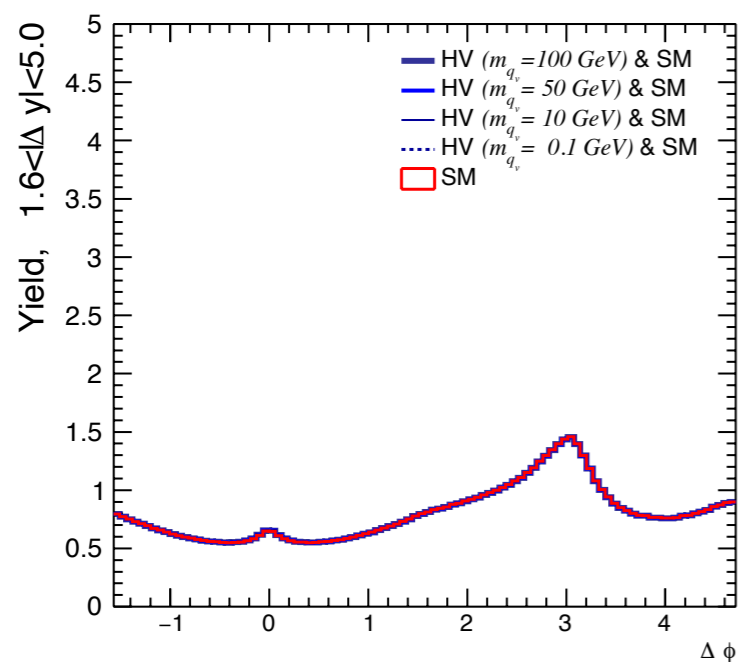


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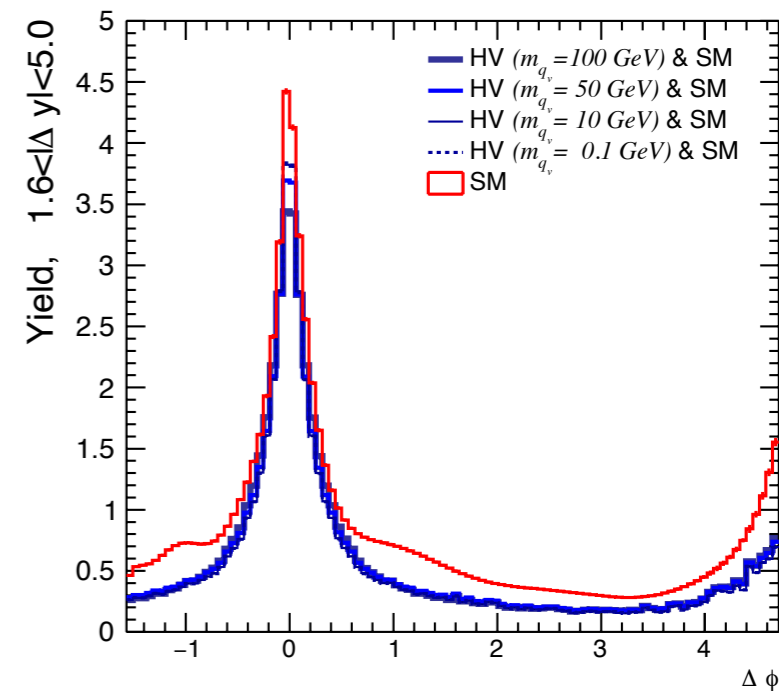
CUTS



Pythia8+SGV (ILC detector)



Pythia8+SGV (ILC detector)



Pythia8+SGV (ILC detector)

ANALYSIS AT DETECTOR LEVEL

Uncertainties

Statistical :
Collected Luminosity
 $\mathcal{L} = 100 \text{ fb}^{-1}$

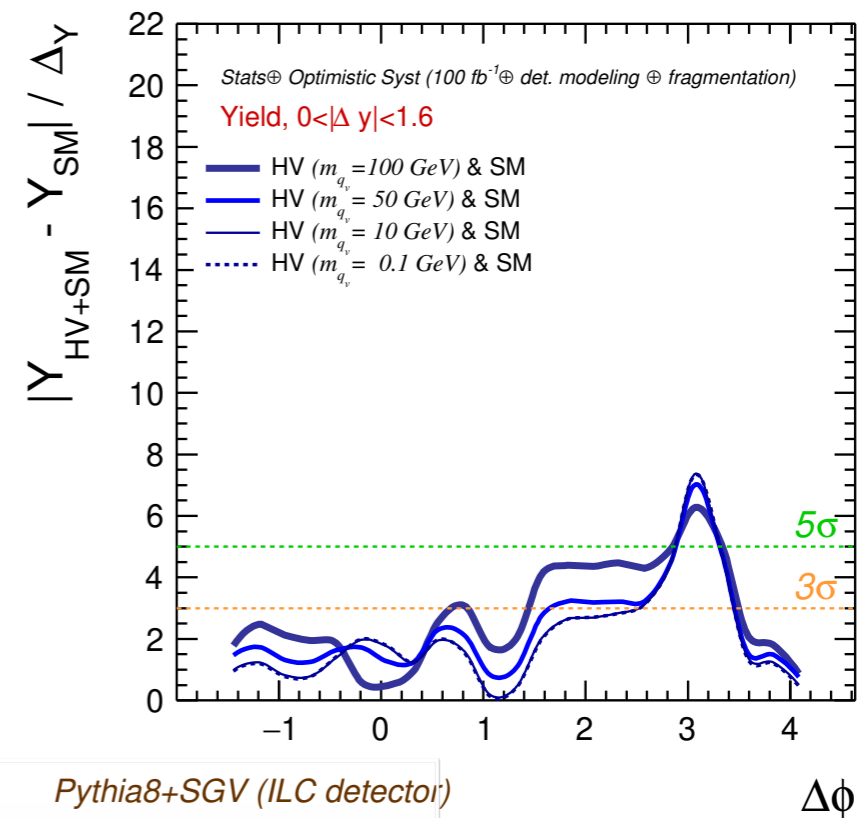
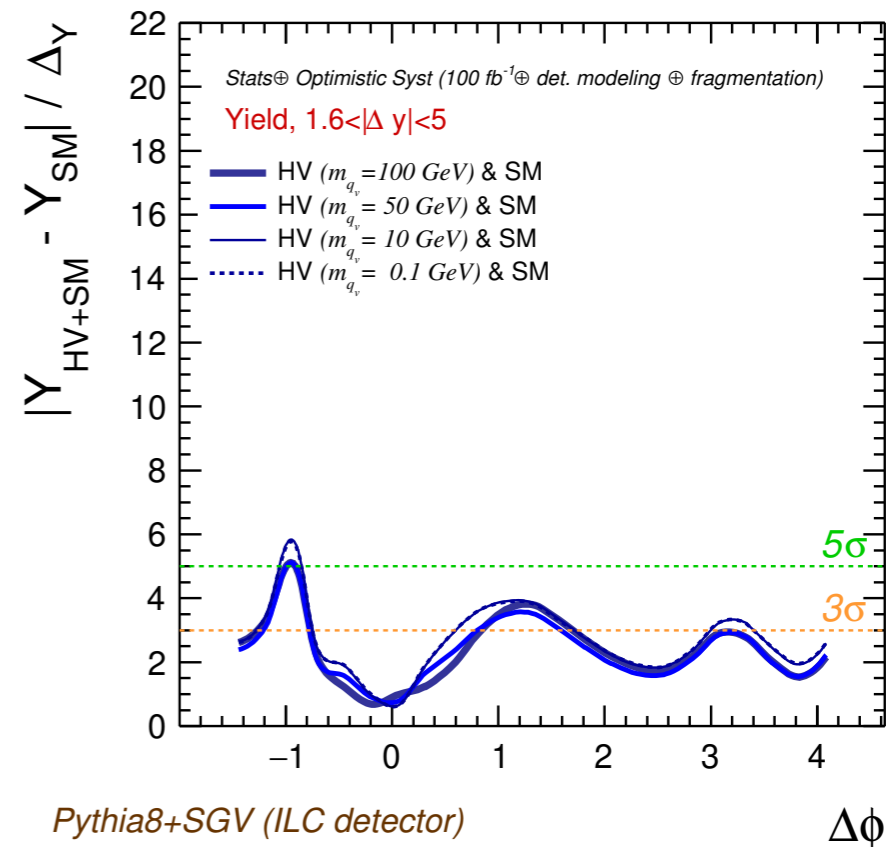


Systematic:

- **Detector modeling**
 - Bin by Bin comparison
- **Fragmentation, Hadronisation**
 - Pythia8 VS Herwig

The total uncertainty is composed of the addition in quadrature of :

- the statistical uncertainty for the expected number of events
- the systematic uncertainties of Y_{SM}



OUTLOOK AT HIGHER ENERGIES

@ Particle Level

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

SUMMARY

- ❖ The analysis of the long-range angular particle correlations can provide valuable insights into the initial state of matter on top of QCD partonic shower
- ❖ We investigate the *observability of hidden sectors* at future e^+e^- colliders with two-particle angular correlations at $\sqrt{s} = 250$ GeV
- ❖ Our results indicate that the study of angular correlations in multiparticle production could *be useful to uncover* the existence of New Physics
- ❖ An outlook at $\sqrt{s} = 500$ GeV and $\sqrt{s} = 1$ TeV was performed



Thanks for your attention!