# Exploring hidden sectors at future $e^+e^-$ colliders with two angular particle correlations

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in collaboration with

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V. A. Mitsou, E. Sarkisyan-Grinbaum, M.A. Sanchis-Lozano

based on 2312.06526

**ILD MEETING**

16/01/2024

UNIÓN EUROPEA
Fondo Europeo de Desarrollo Regional

# 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:

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

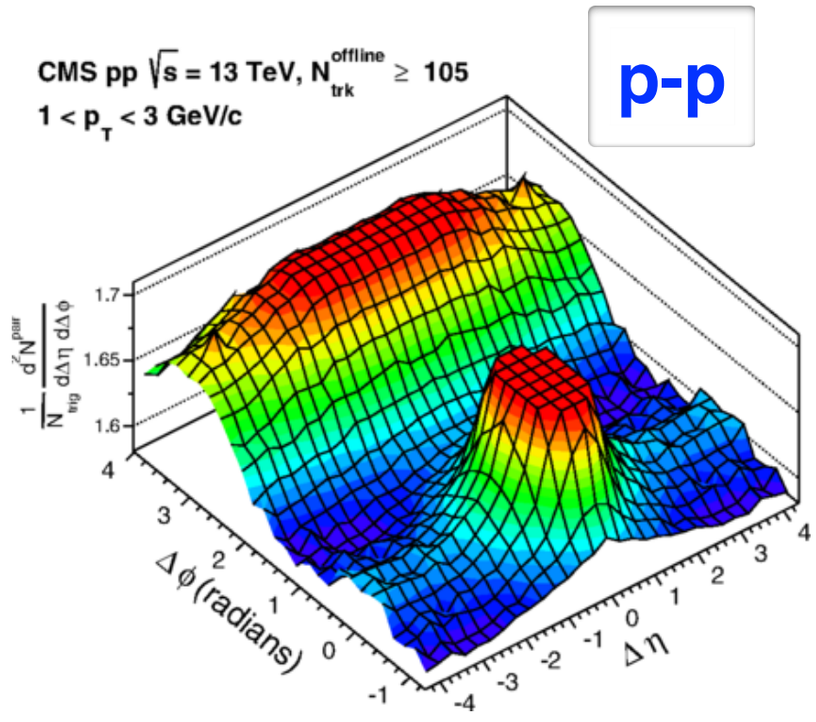
$$N_{pairs} = \int\int \frac{d^2N^{same}}{d\Delta y d\Delta\phi} d\Delta y d\Delta\phi$$

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

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

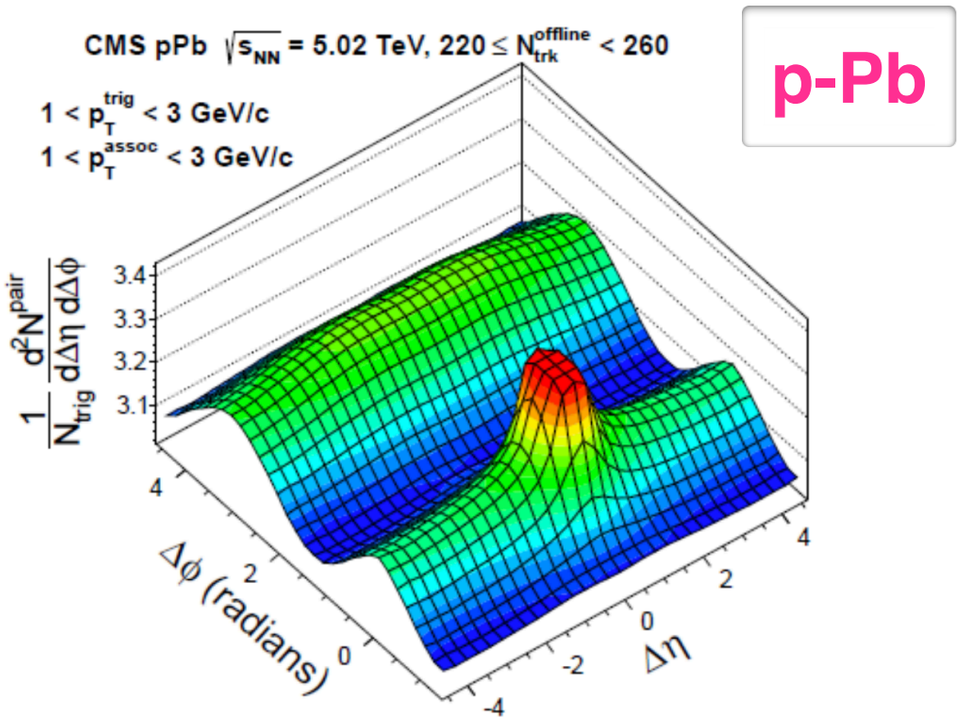
$$N_{mix} = \int\int \frac{d^2N^{mix}}{d\Delta y d\Delta\phi} d\Delta y d\Delta\phi$$

# TWO-PARTICLE ANGULAR CORRELATIONS



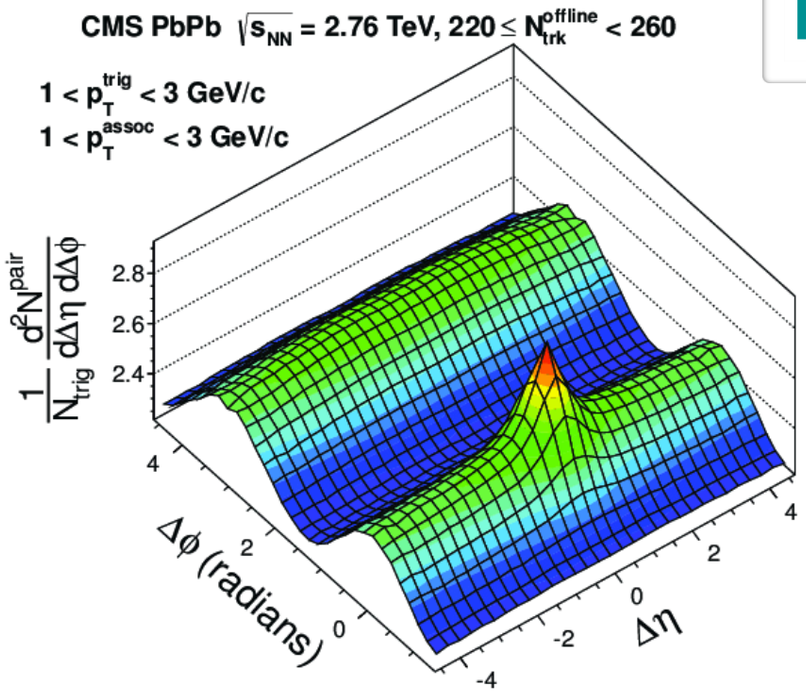

**p-p**

Phys. Rev. Lett. **116**, 172302



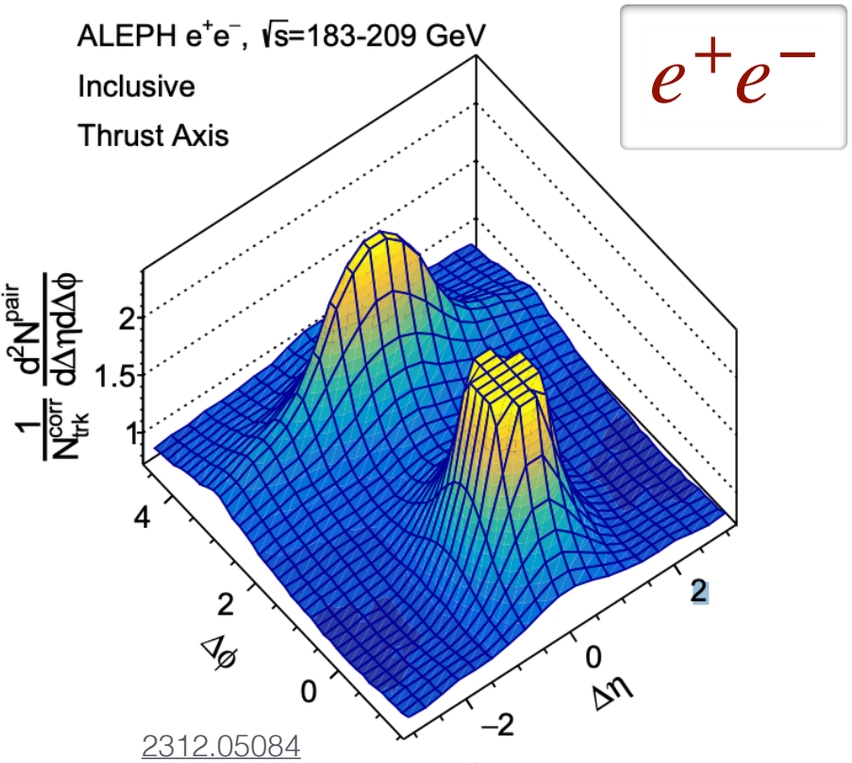

**p-Pb**

Physics Letters B B724(4)




**Pb-Pb**

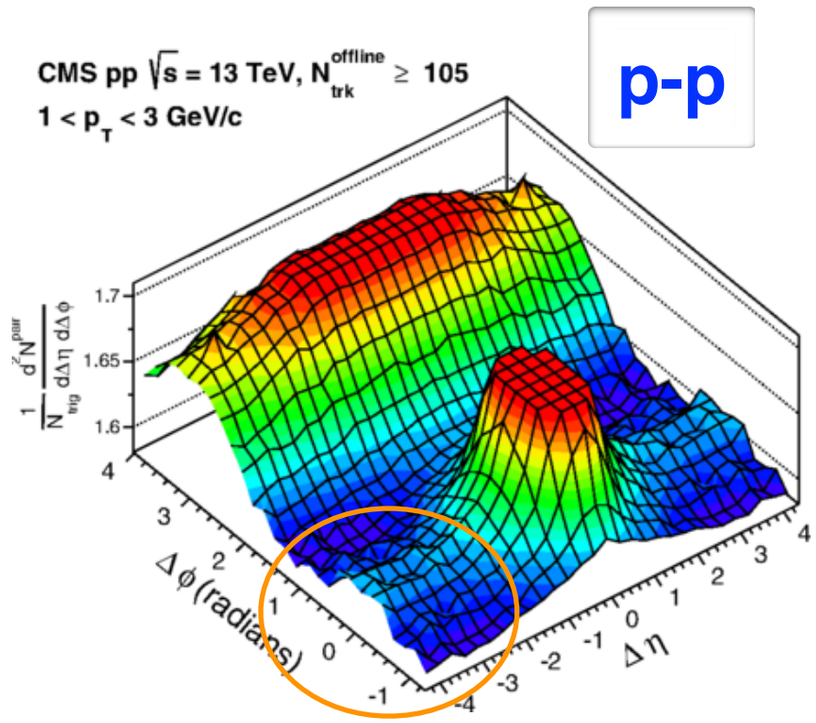
Physics Letters B B724(4)




**$e^+e^-$**

2312.05084

# TWO-PARTICLE ANGULAR CORRELATIONS




p-p

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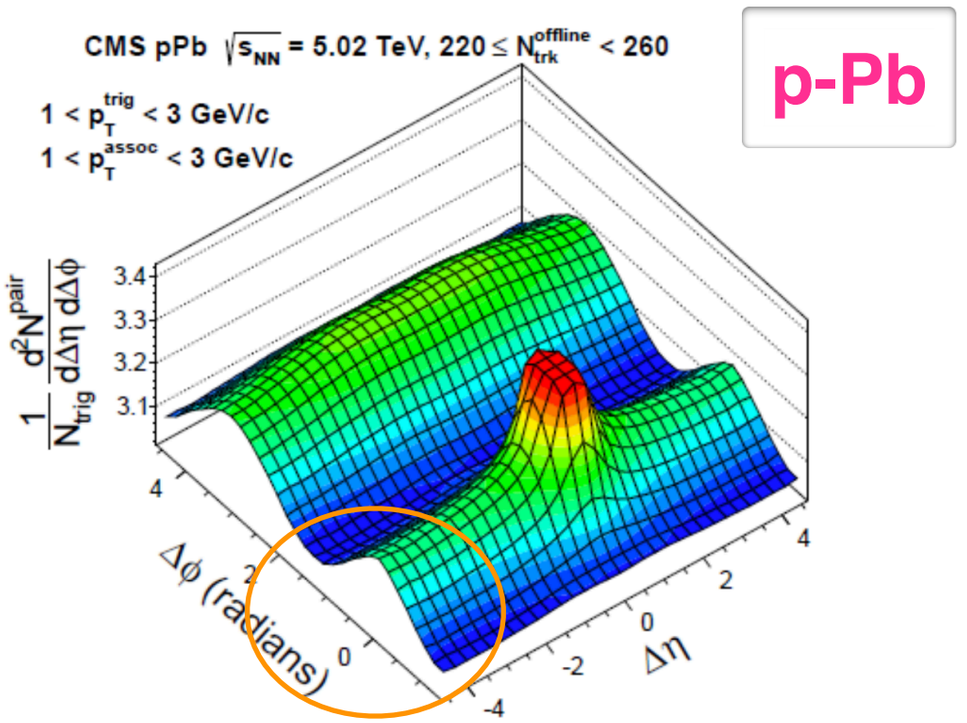


p-Pb

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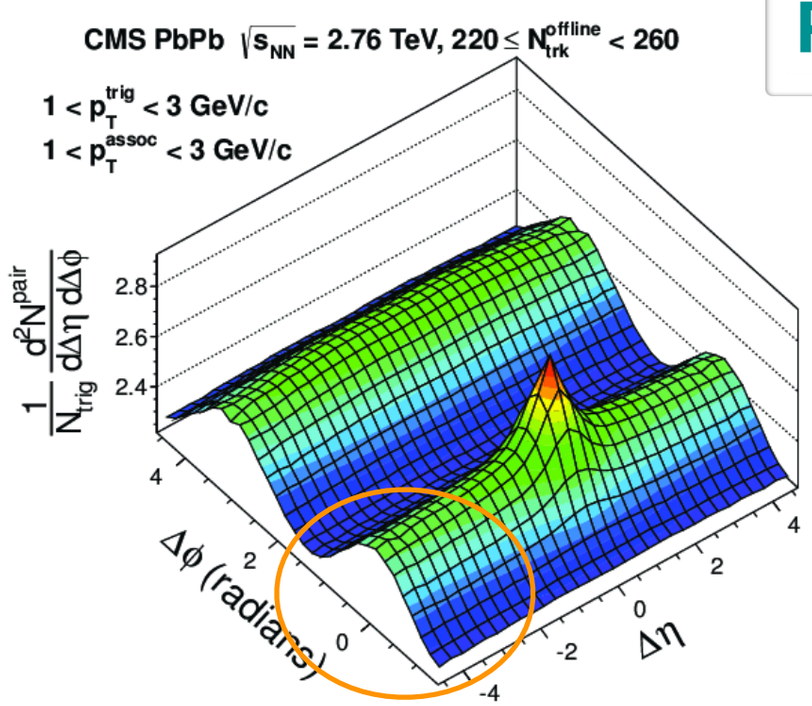
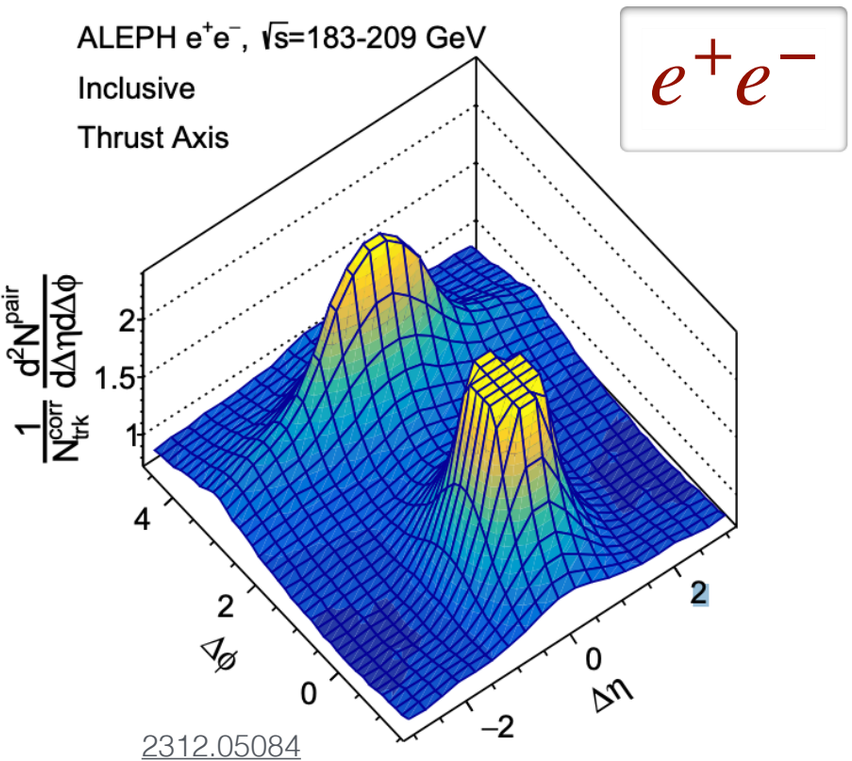



Pb-Pb

Physics Letters B B724(4)




$e^+e^-$

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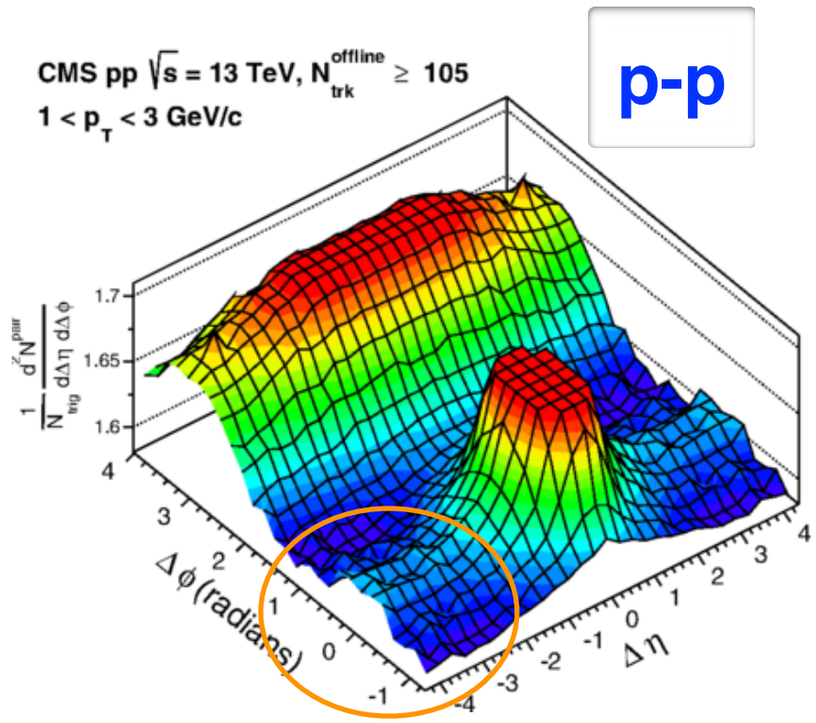


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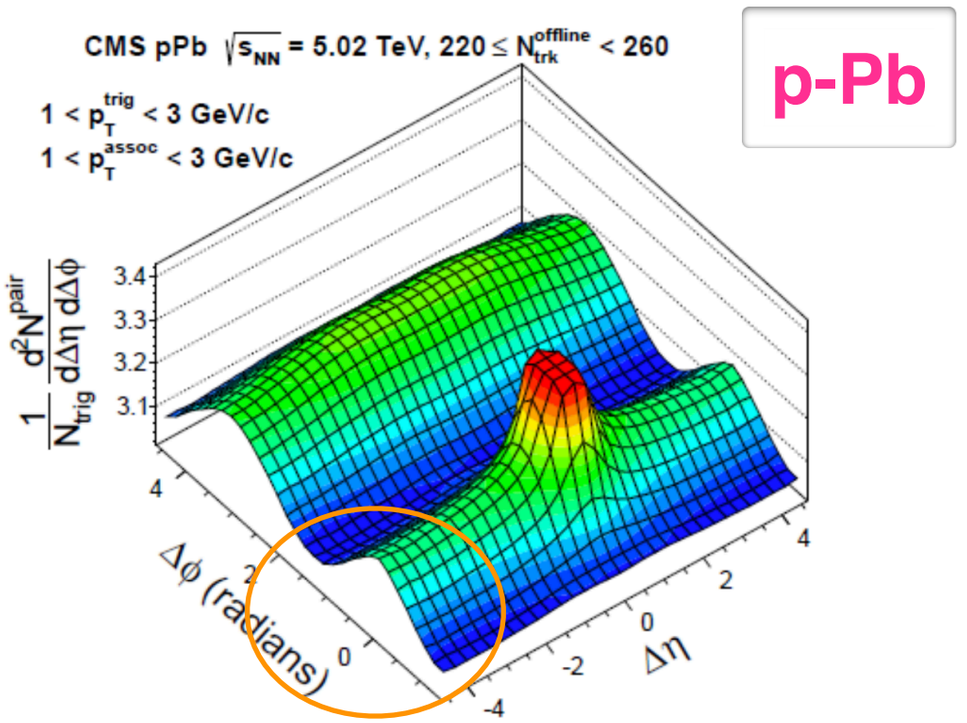


p-Pb

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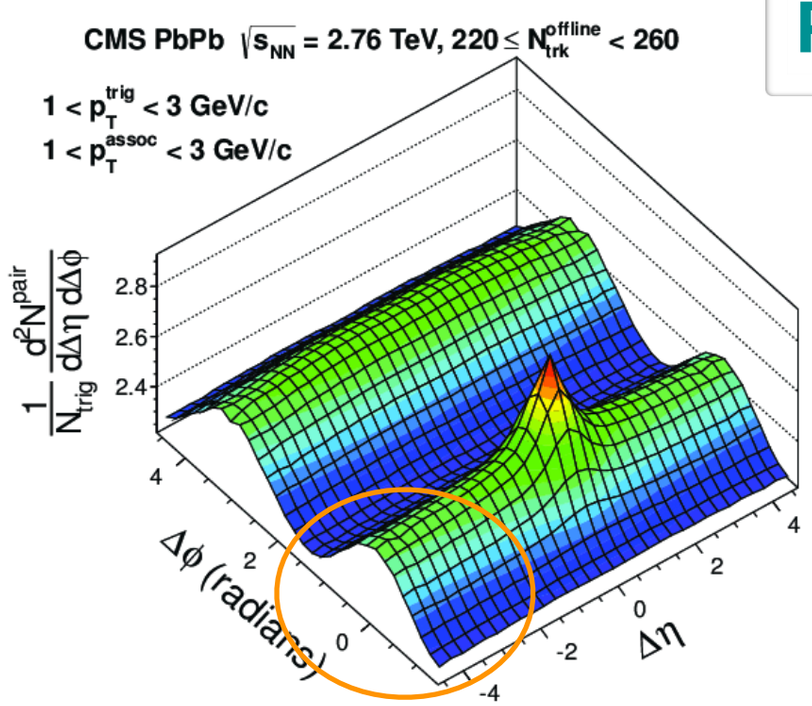


Pb-Pb

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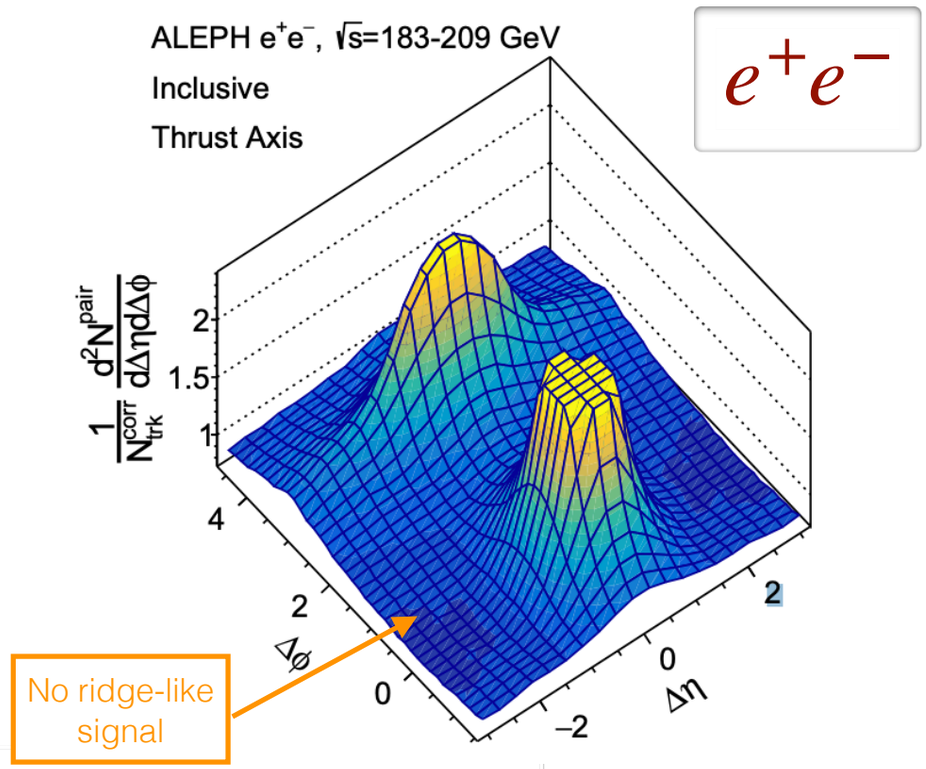
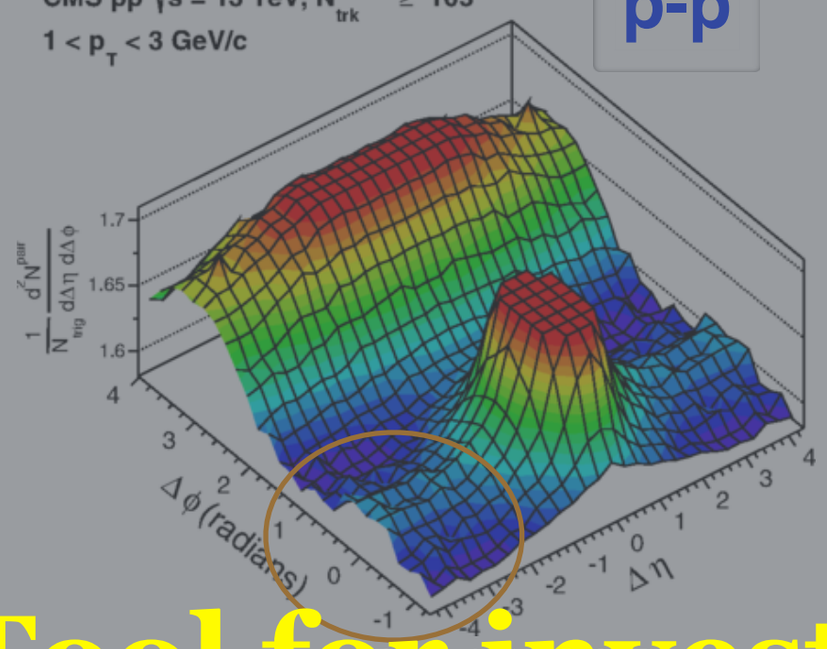



$e^+e^-$

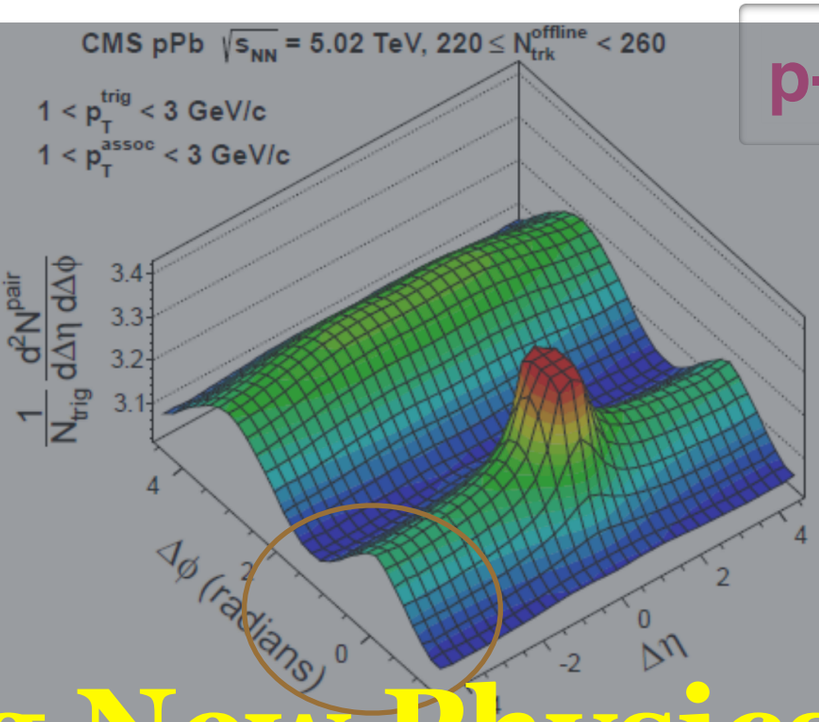
2312.05084

# TWO-PARTICLE ANGULAR CORRELATIONS

p-p




p-Pb

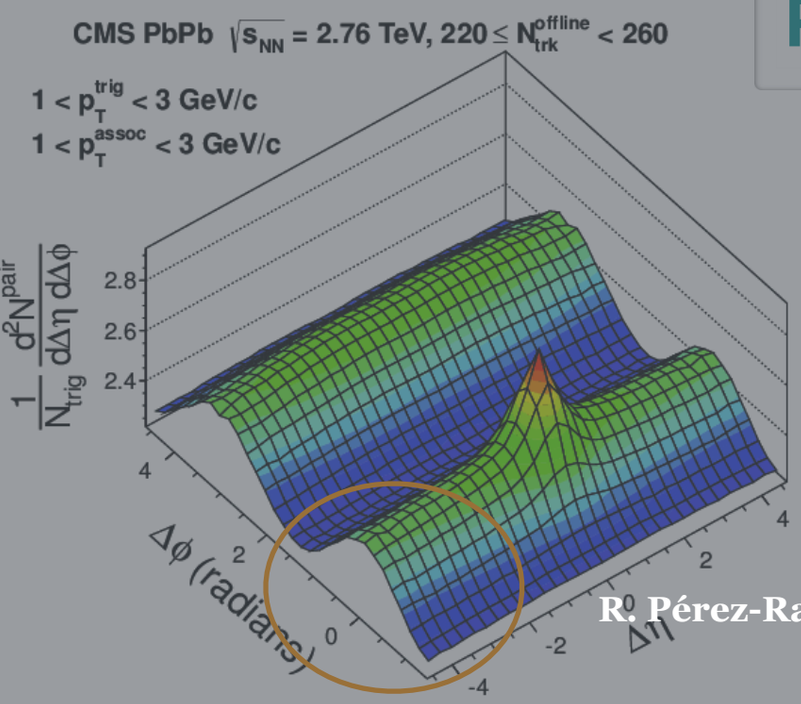



Physical Review Letters 116(7)

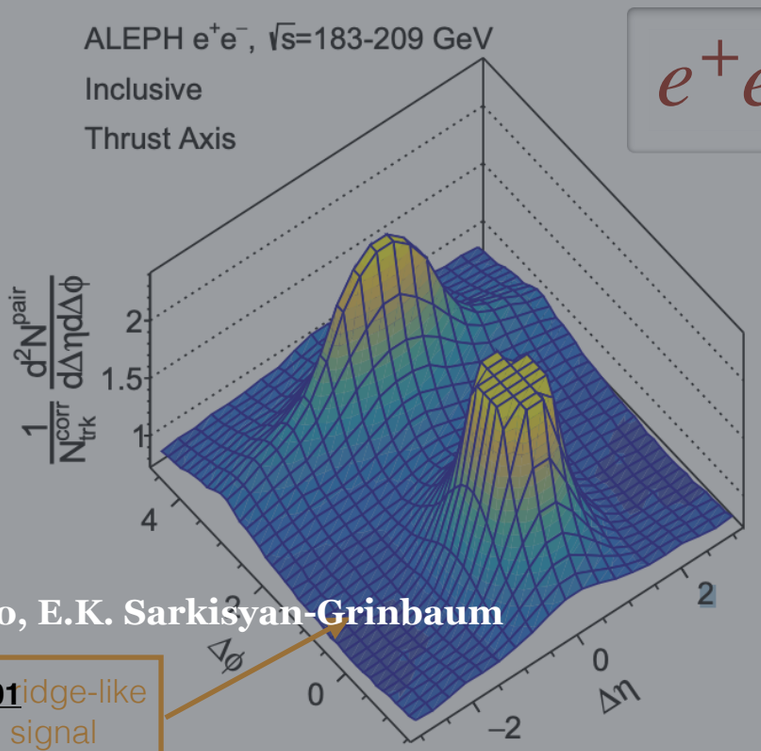
Physics Letters B 724(4)

# Tool for investigating New Physics?

Pb-Pb




$e^+e^-$

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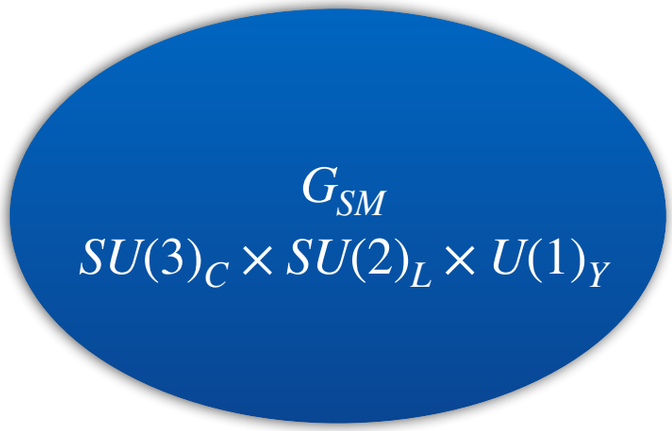
Phys. Rev. D 105, 053001

ridge-like signal

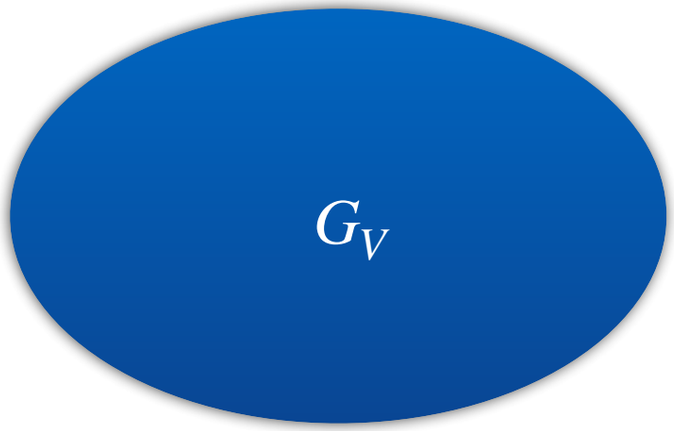
2312.05084

# HIDDEN VALLEY PHENOMENOLOGY

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




SM particles




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

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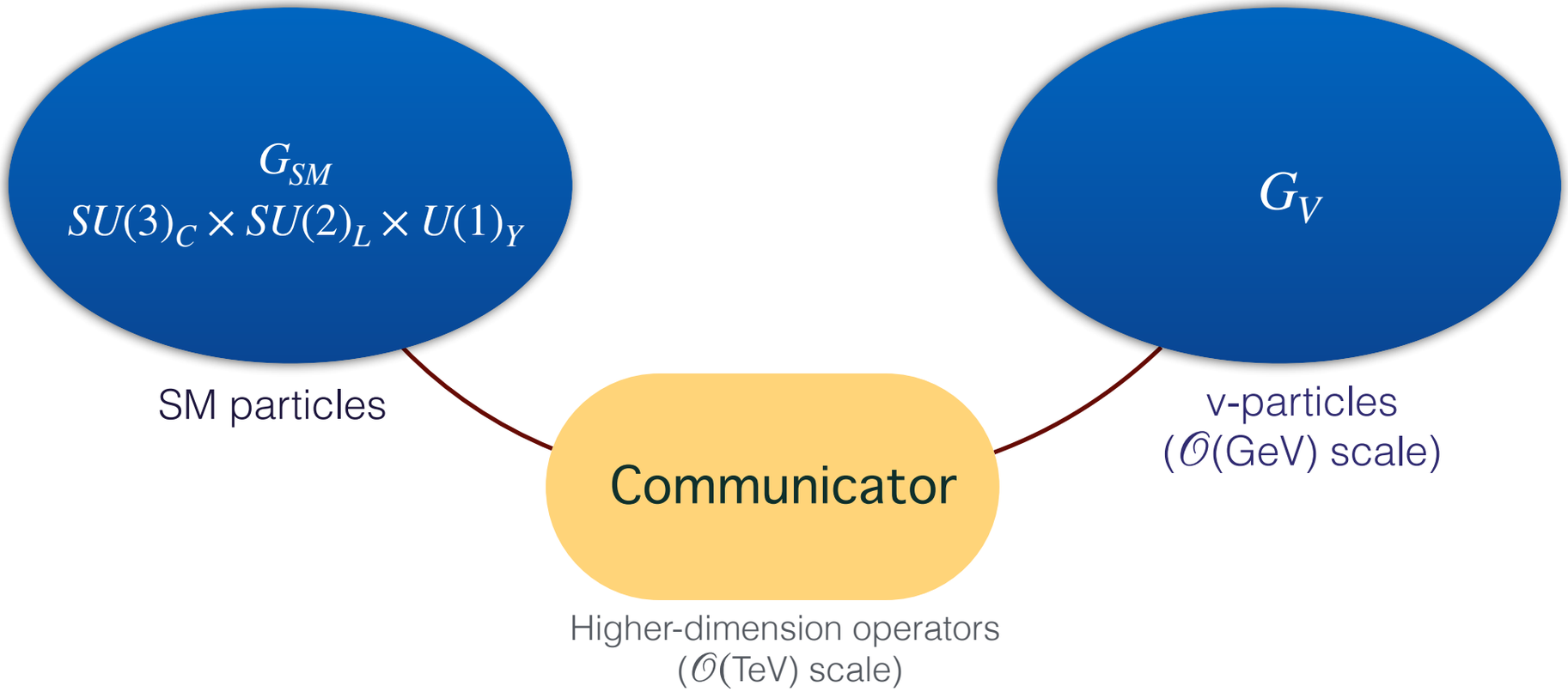
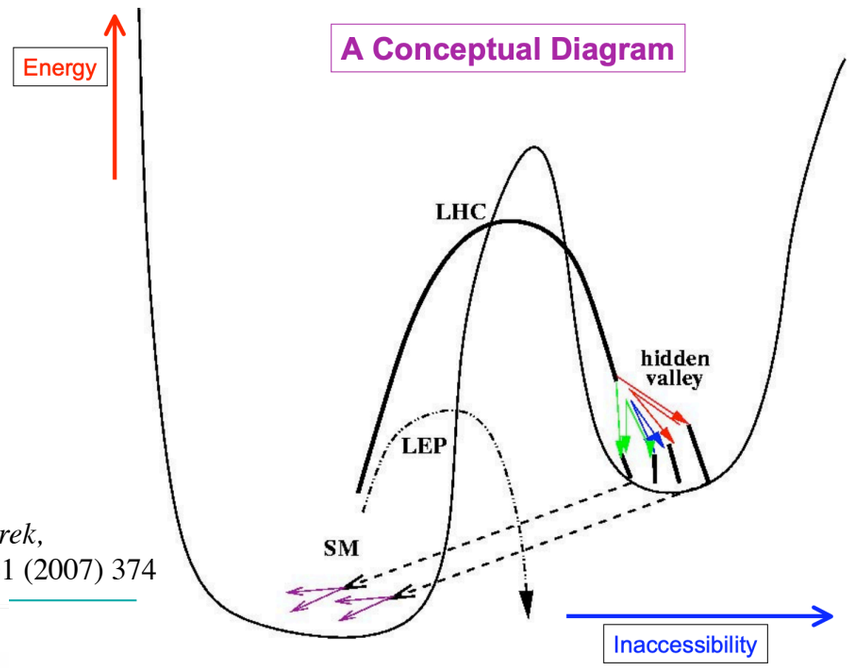



*Strassler & Zurek,*
Phys.Lett.B 651 (2007) 374

# HIDDEN VALLEY PHENOMENOLOGY

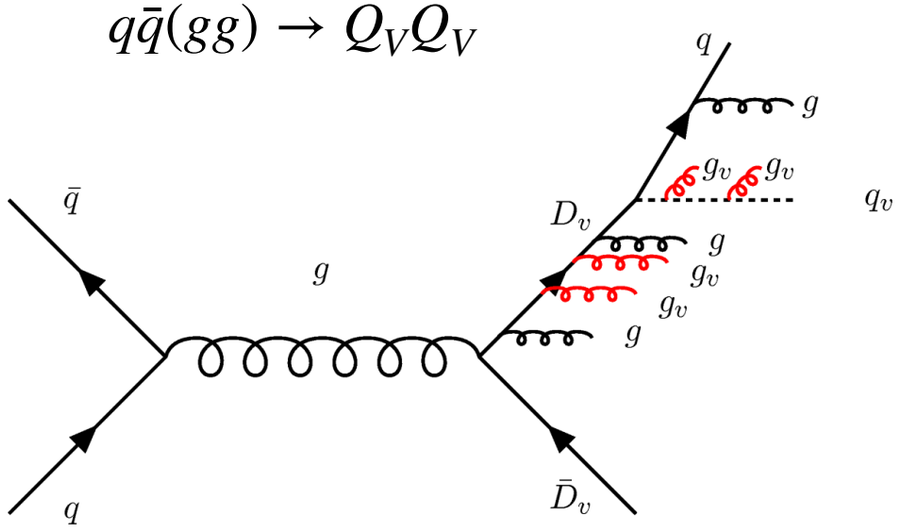
## QCD-like scenario

Communicator: $F_V$

- mirror partner of the SM charged quarks and leptons
- Charged under $G_{SM}$ and $G_V$
- Pair-produced
- (Prompt) decays: $F_V \to f q_V \longrightarrow$ hadrons
  - $E_V \to e q_V$
  - $Q_V \to q q_V$

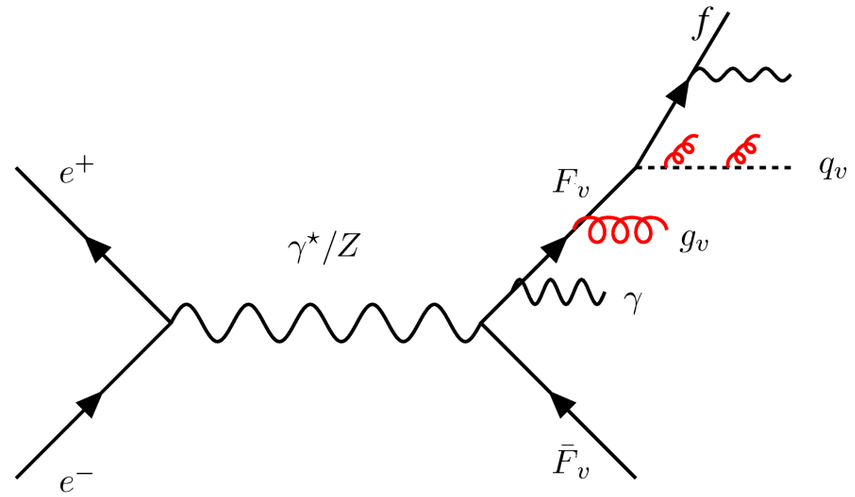
### pp collisions

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




### $e^+e^-$ collisions

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




JHEP 1009:105,2010
L Carloni, T Sjöstrand

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  - $Q_V \to q q_V$

**Signature**

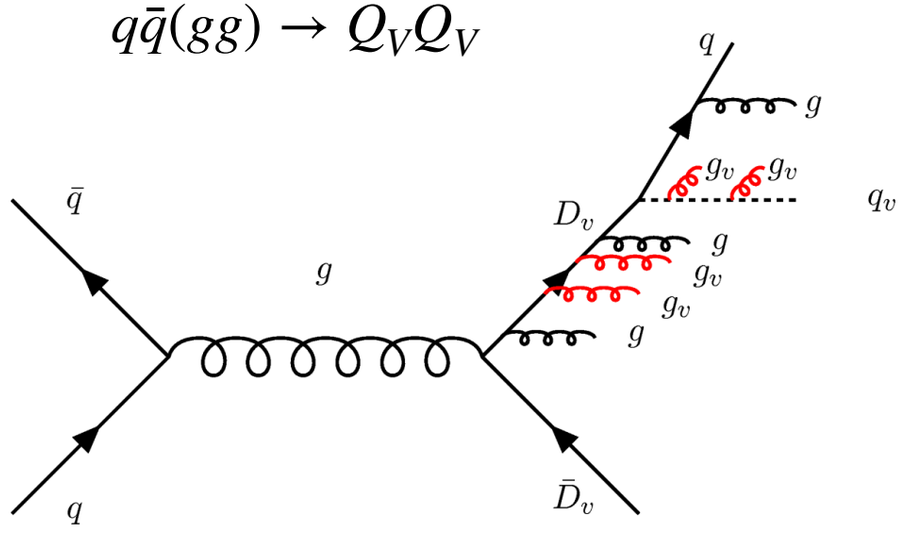
Perturbation in conventional QCD cascade and final hadronisation

↓

anomalies in angular correlations

### pp collisions

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

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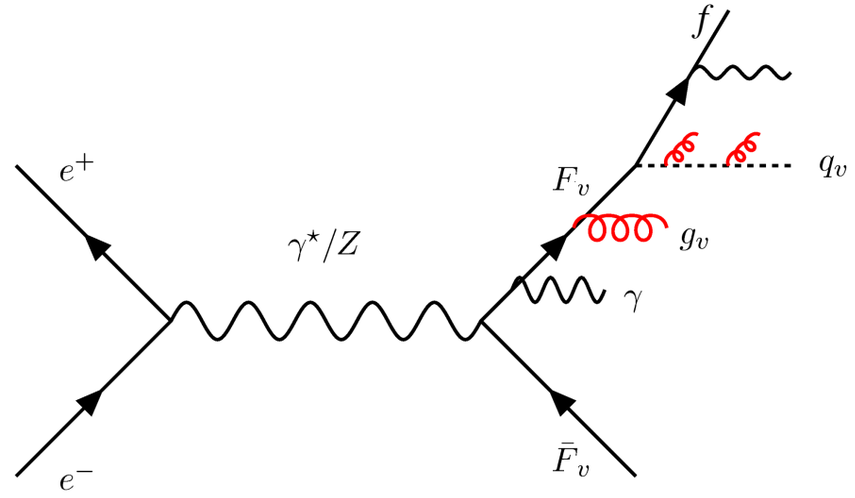


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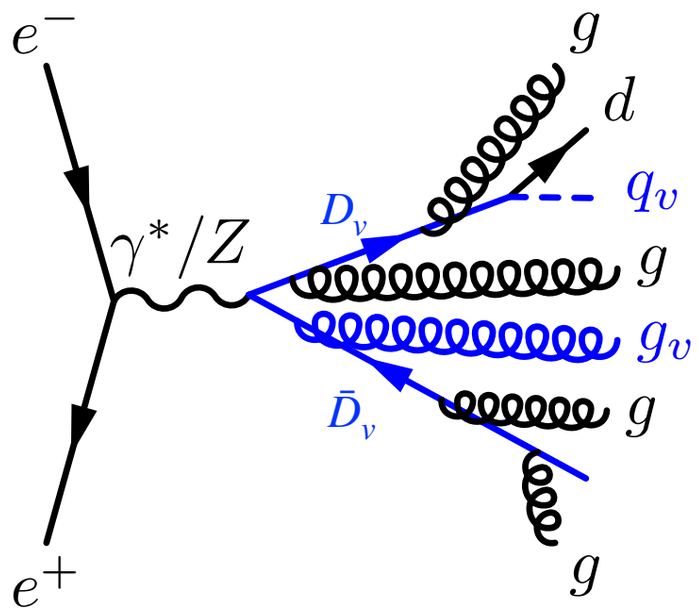
# SIGNAL VS BACKGROUND

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

## SIGNAL

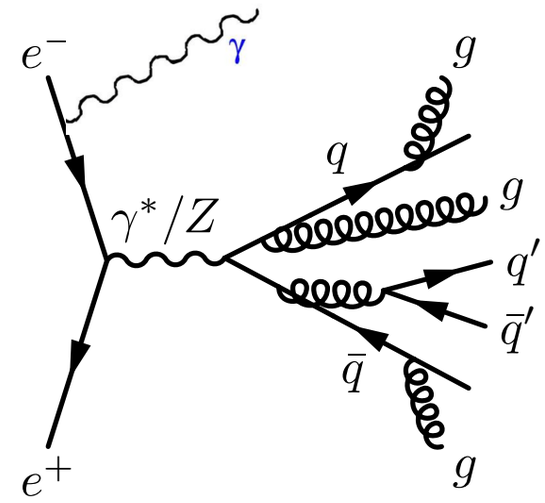
$e^+e^- \to \gamma^*/Z^0 \to D_V\bar{D}_V \to$ hadrons




$m_{D_V}$ = 125 GeV
$\alpha_v = 0.1$

## BACKGROUND

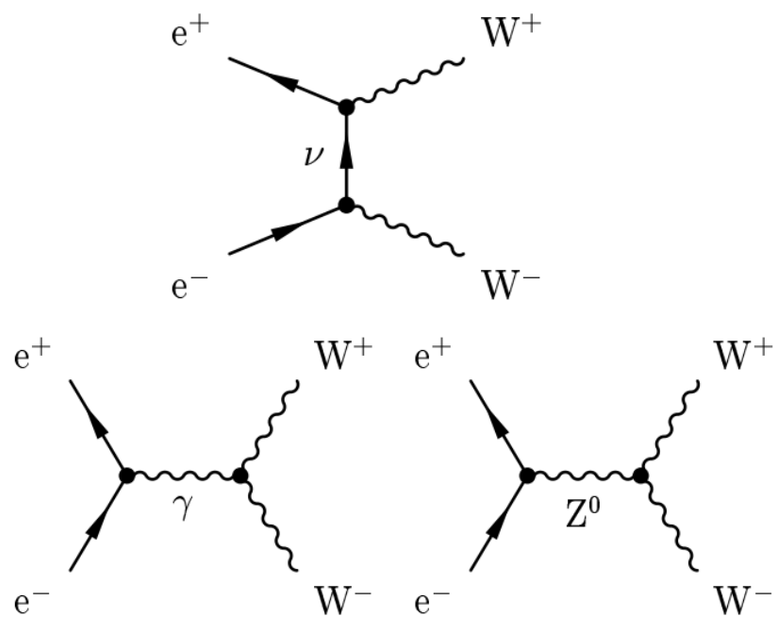
i) $q\bar{q}$ production with ISR




**No polarised beam**

| Process | $\sigma_{\text{PYTHIA8}}$ [pb] |
|---|---|
| $e^+e^- \to D_v\bar{D}_v$ | |
| $m_{q_v} = 0.1$ GeV | 0.13 |
| $m_{q_v} = 10$ GeV | 0.12 |
| $m_{q_v} = 50$ GeV | 0.12 |
| $m_{q_v} = 100$ GeV | 0.12 |
| $e^+e^- \to q\bar{q}$ with ISR | 48 |
| $WW \to 4q$ | 7.4 |

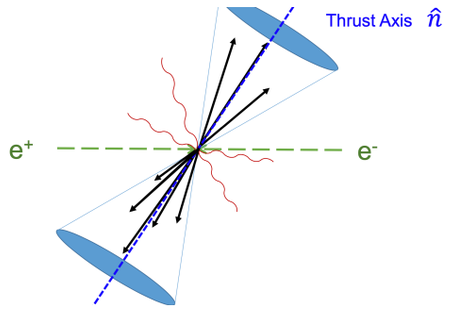
ii) WW —> 4q



# 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

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

## CUTS

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

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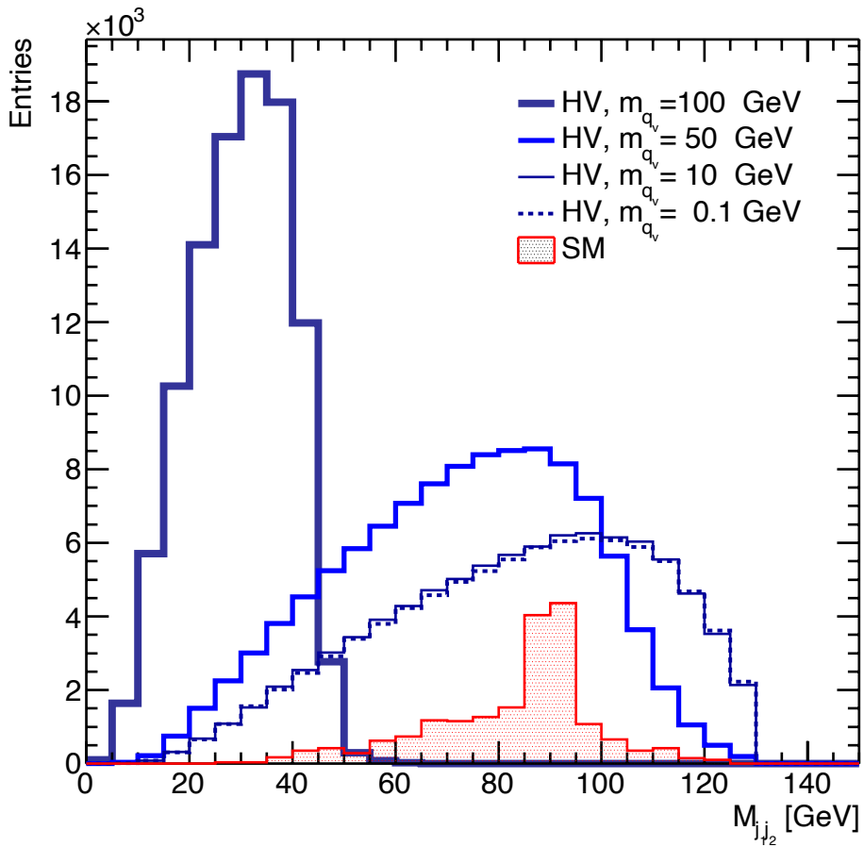



*Pythia8+SGV (ILC detector)*

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

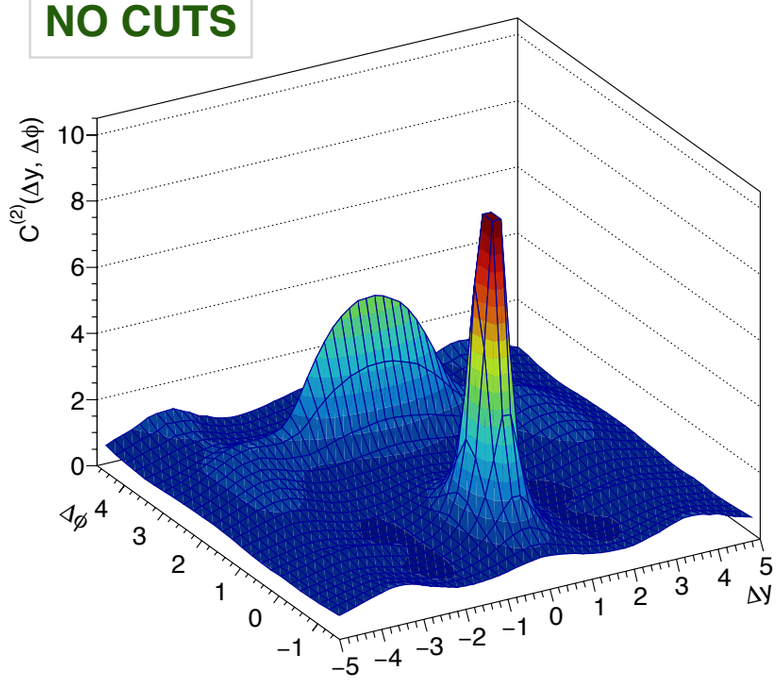
# ANALYSIS AT DETECTOR LEVEL

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

## BACKGROUND

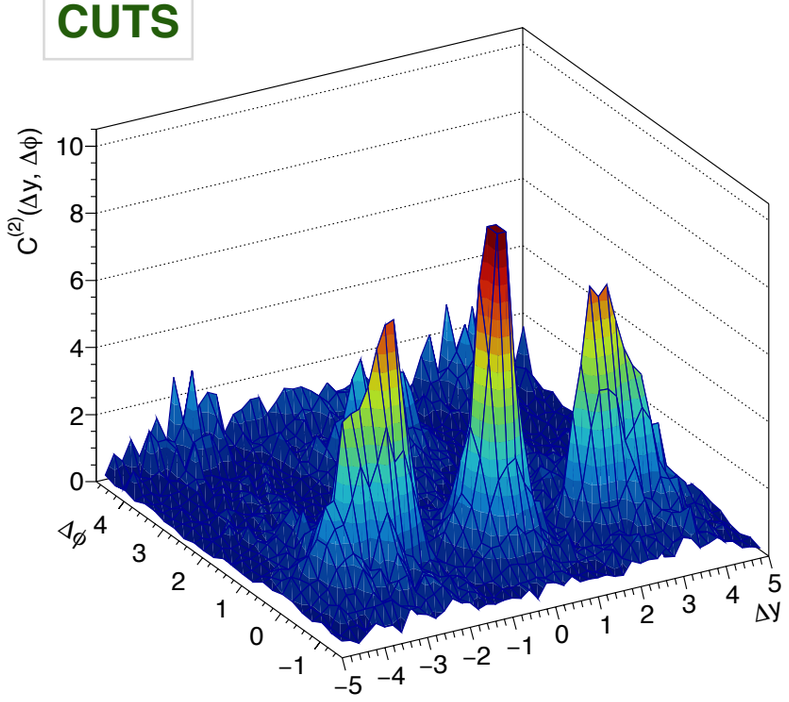
Thrust axis

NO CUTS




SM

CUTS

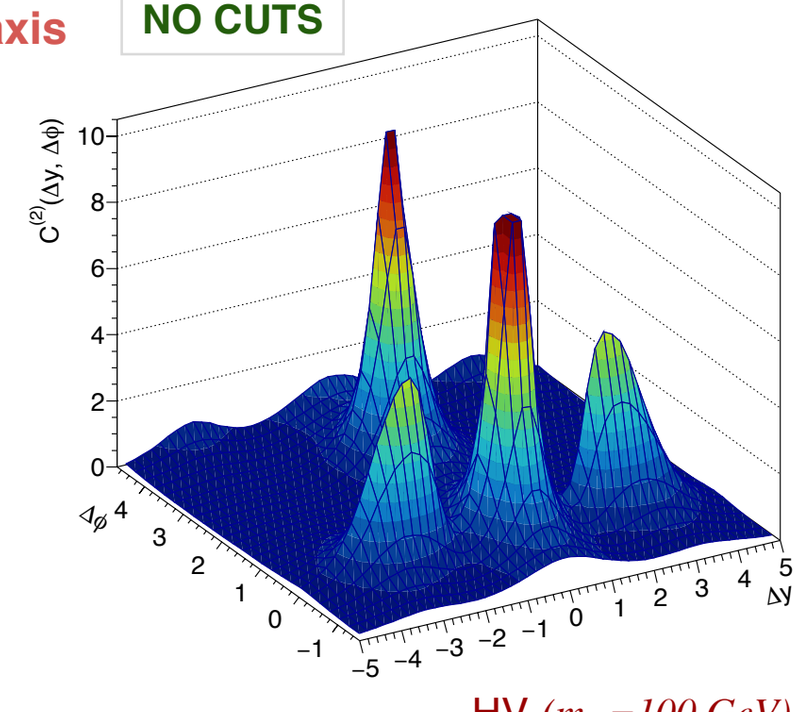



SM

## SIGNAL

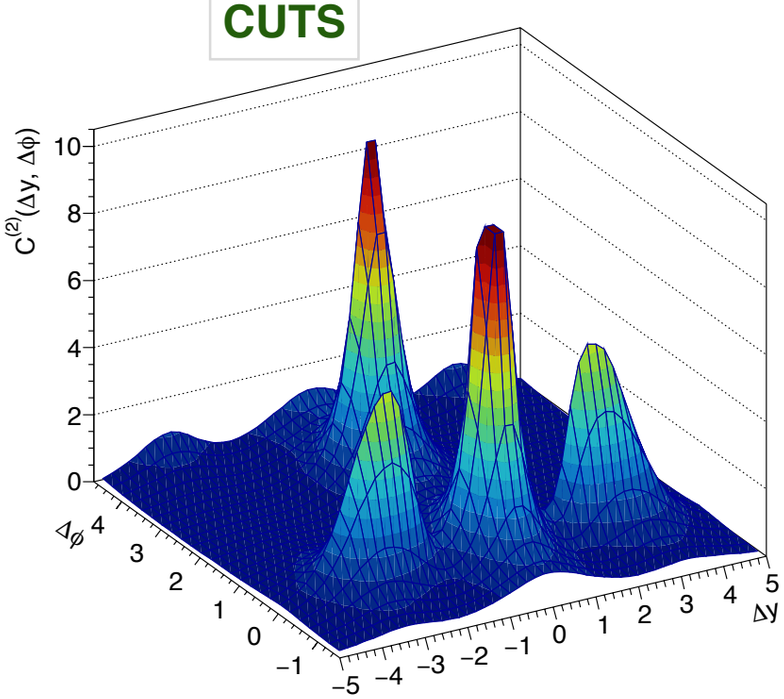
Thrust axis

NO CUTS




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

CUTS




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

# ANALYSIS AT DETECTOR LEVEL

## Yield

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

# ANALYSIS AT DETECTOR LEVEL

## Yield

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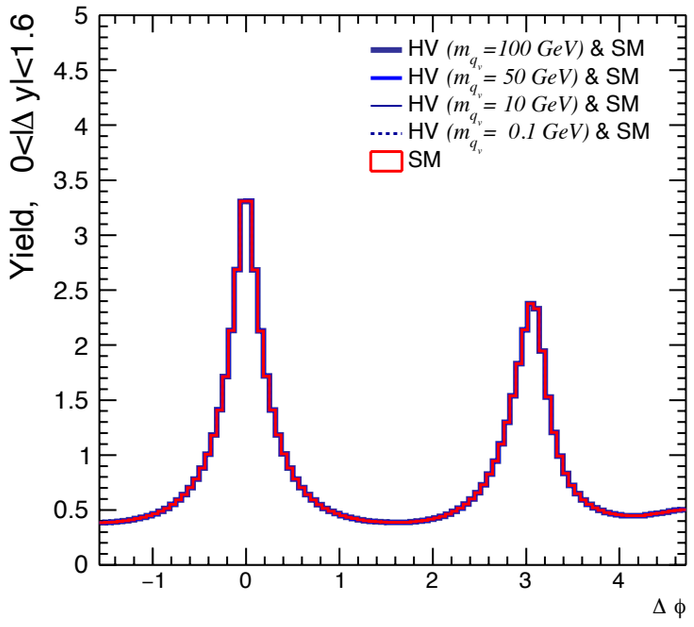
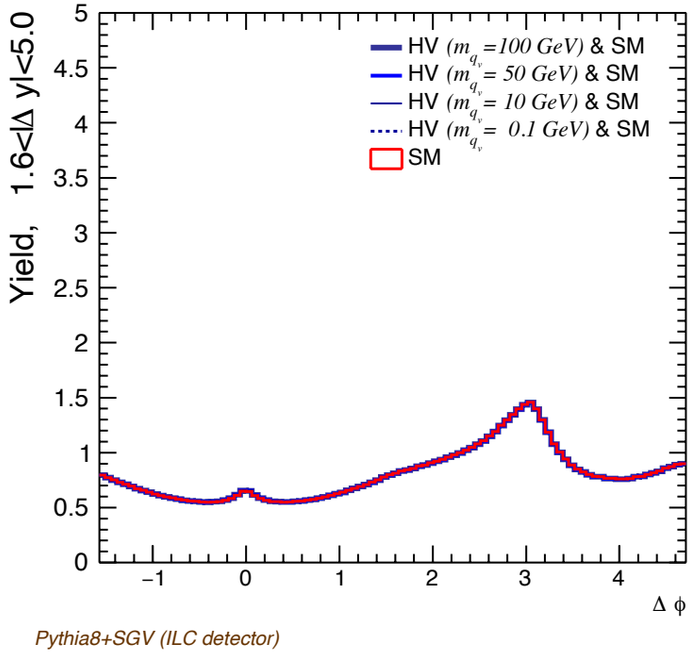
### NO CUTS




*Pythia8+SGV (ILC detector)*

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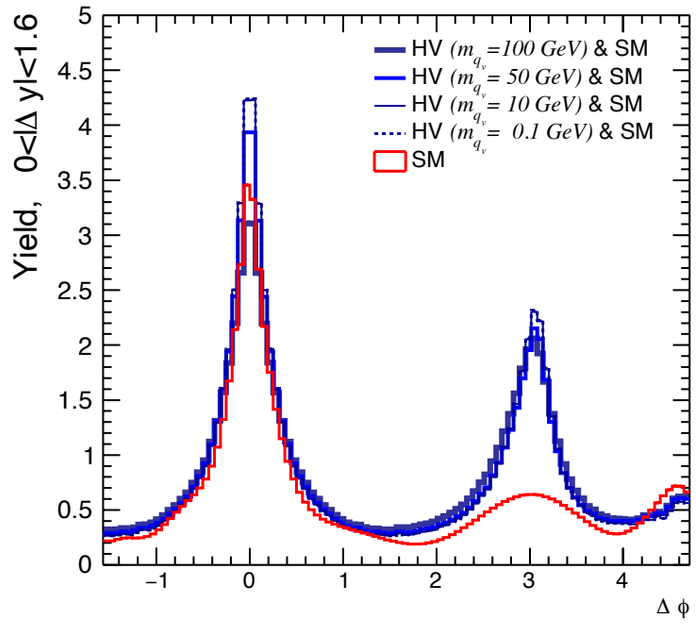
### CUTS

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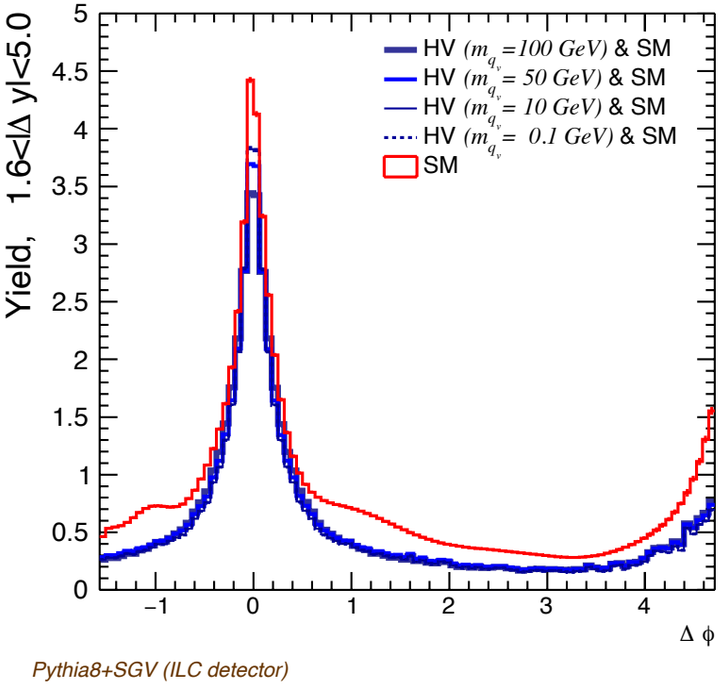


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# ANALYSIS AT DETECTOR LEVEL

## Yield

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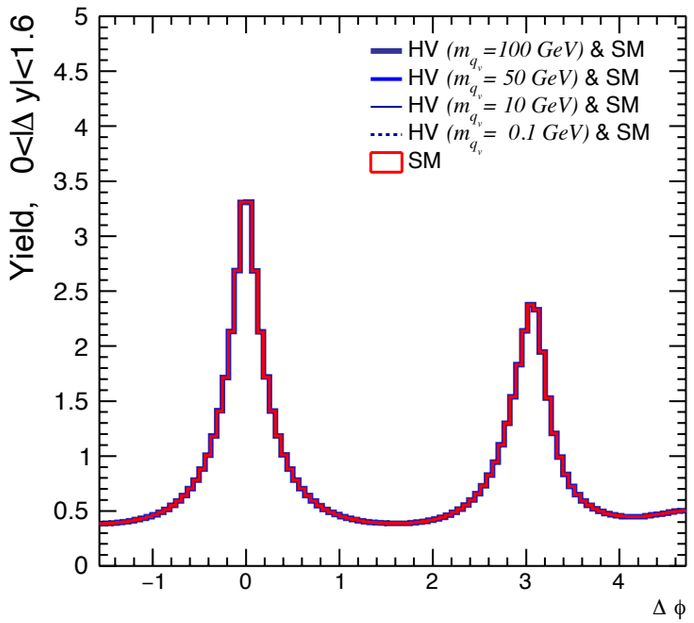


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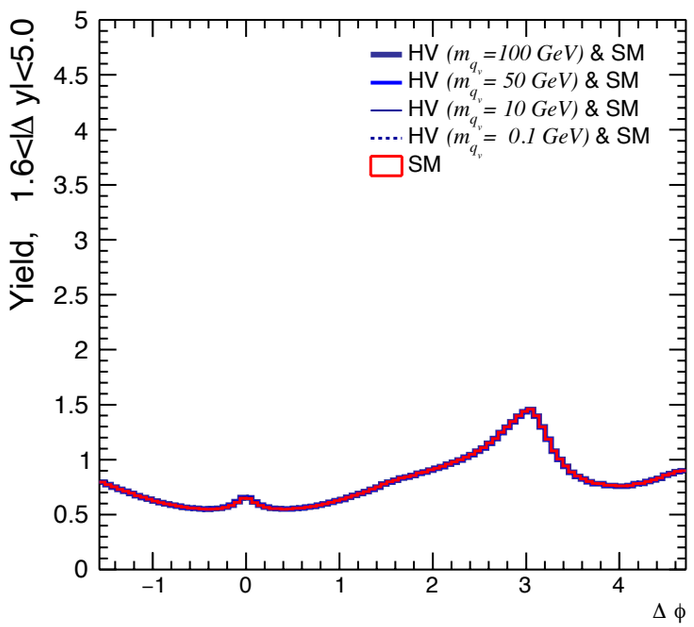


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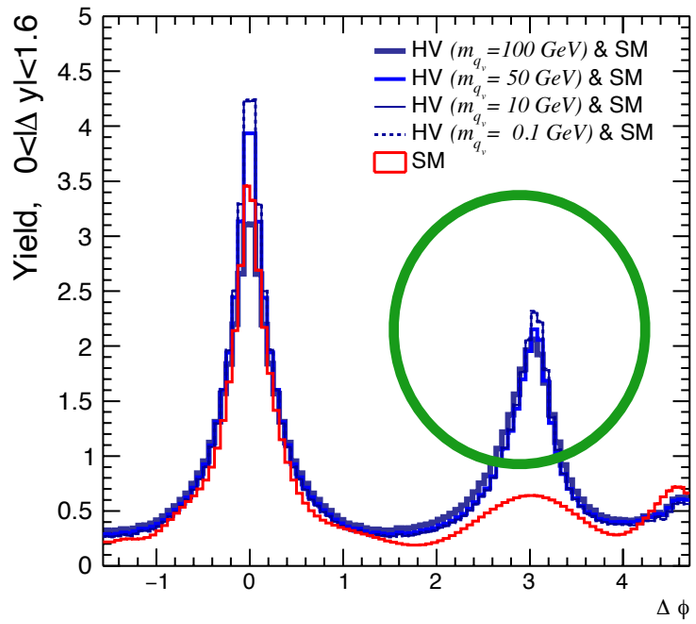
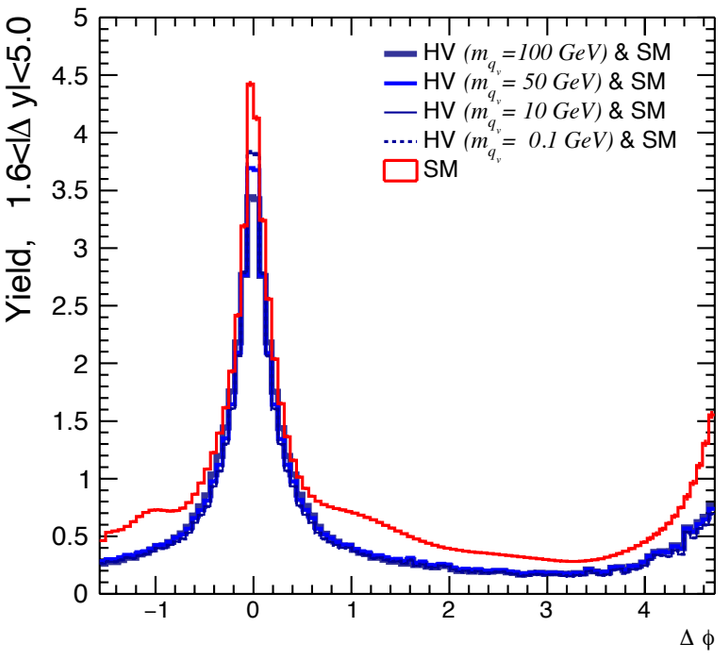



*Pythia8+SGV (ILC detector)*

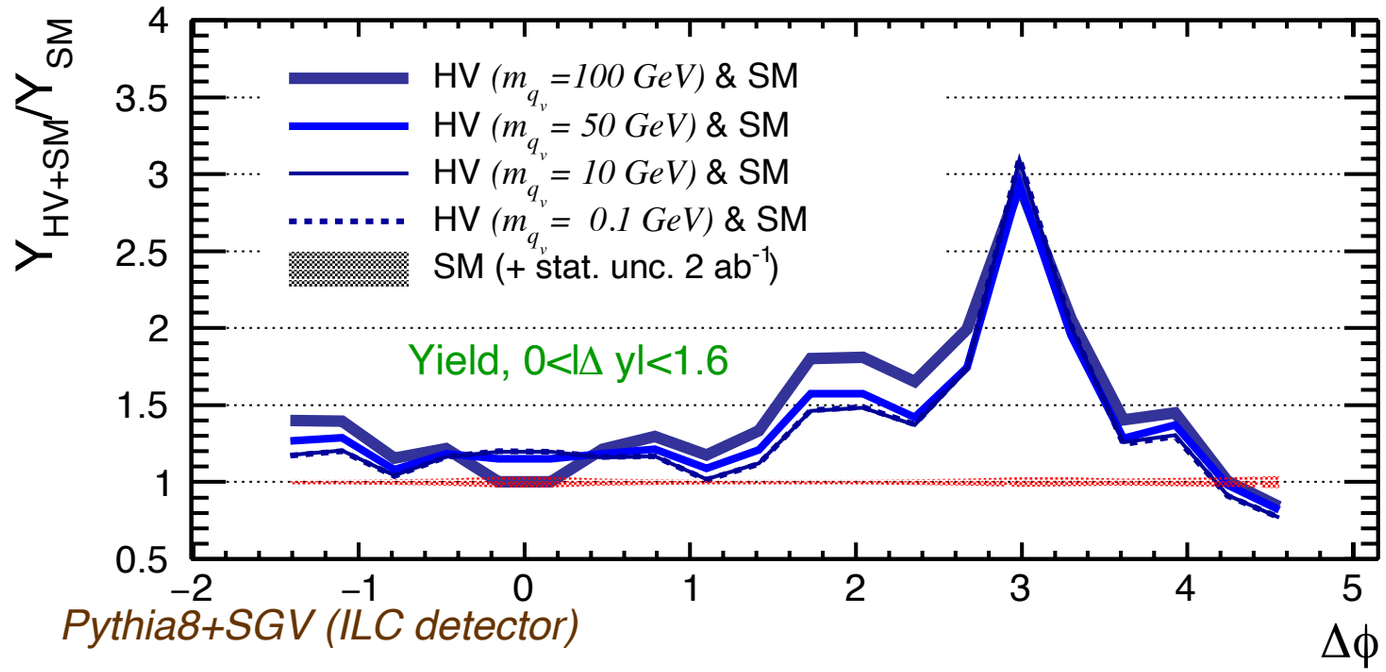


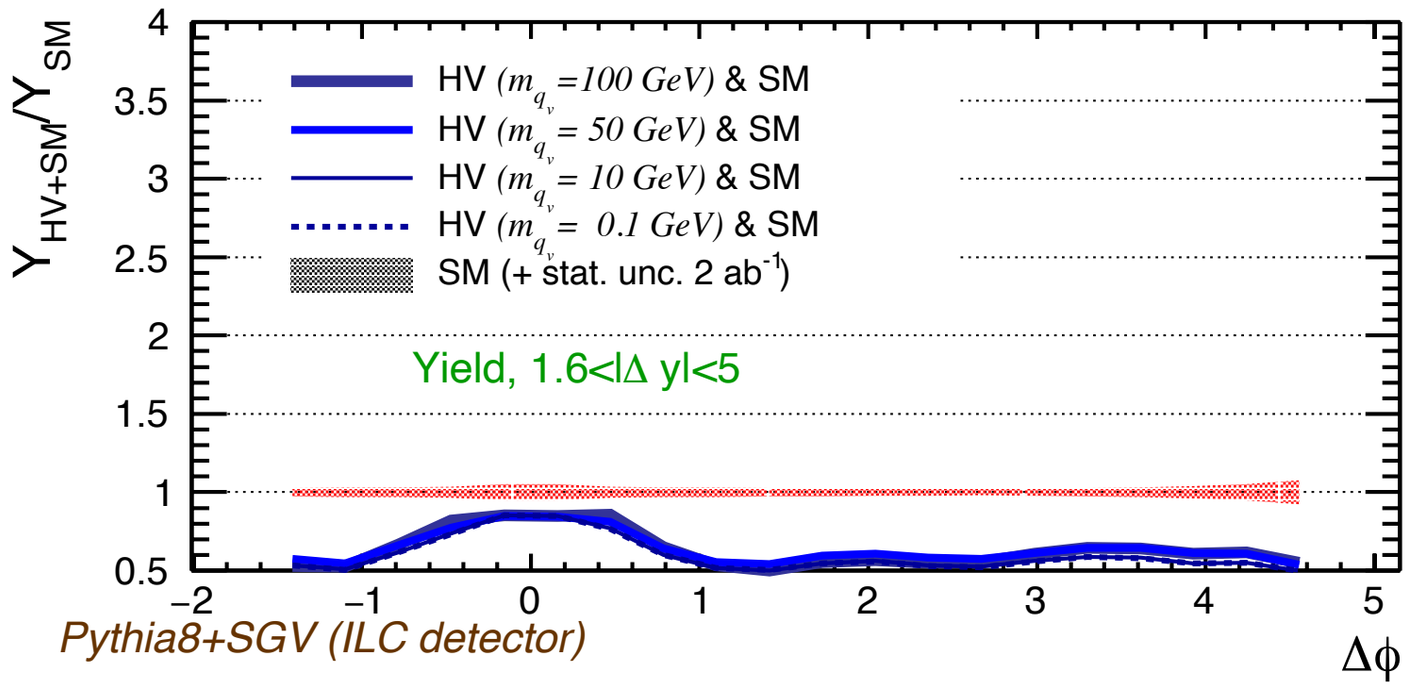

*Pythia8+SGV (ILC detector)*

# ANALYSIS AT DETECTOR LEVEL

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

Ratio of yield distributions



# OUTLOOK AT HIGHER ENERGIES

| 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 |
| $e^+e^- \to D_v\bar{D}_v$ | $2.4 \times 10^{-2}$ | $4.4 \times 10^{-3}$ |
| | $m_{T_v} = 250$ GeV | $m_{T_v} = 500$ GeV |
| $e^+e^- \to T_v\bar{T}_v$ | $9.5 \times 10^{-2}$ | $1.8 \times 10^{-2}$ |
| $e^+e^- \to q\bar{q}$ with ISR | 11 | 2.9 |
| $e^+e^- \to t\bar{t}$ | 0.59 | 0.19 |
| $WW \to 4q$ | 3.4 | 1.3 |

# 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!

# Back-up slides

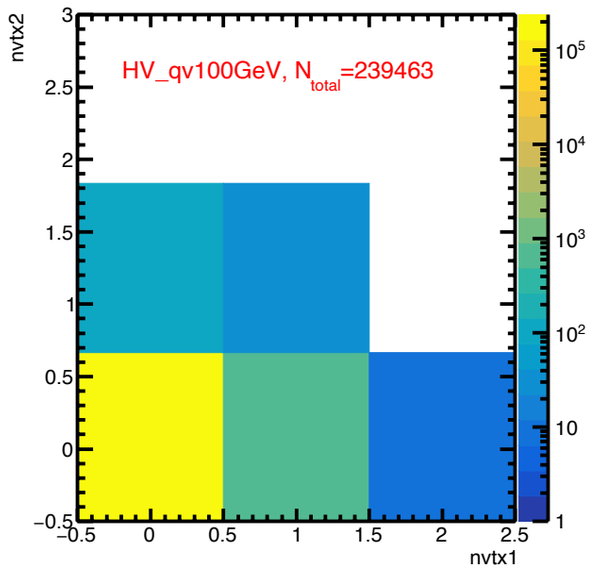
# ANALYSIS AT DETECTOR LEVEL

## Thrust Axis

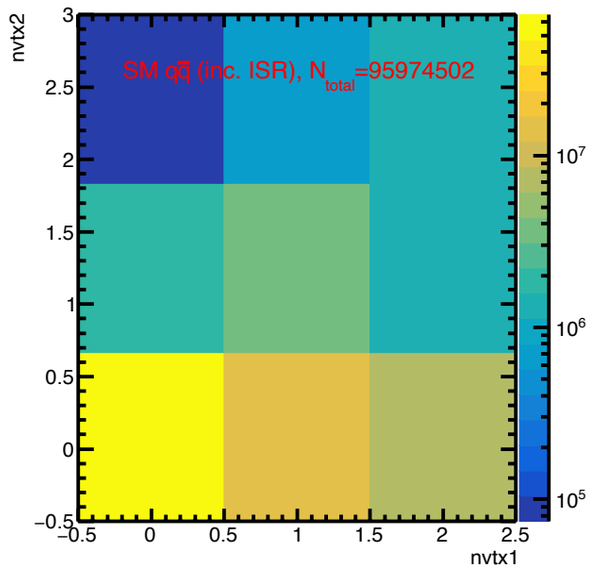
$$\sqrt{s} = 250\ \text{GeV}, \mathscr{L} = 2\ \text{ab}^{-1}$$

**CUTS**

- No secondary vertices




*Analysis at detector level, Pythia8+SGV*



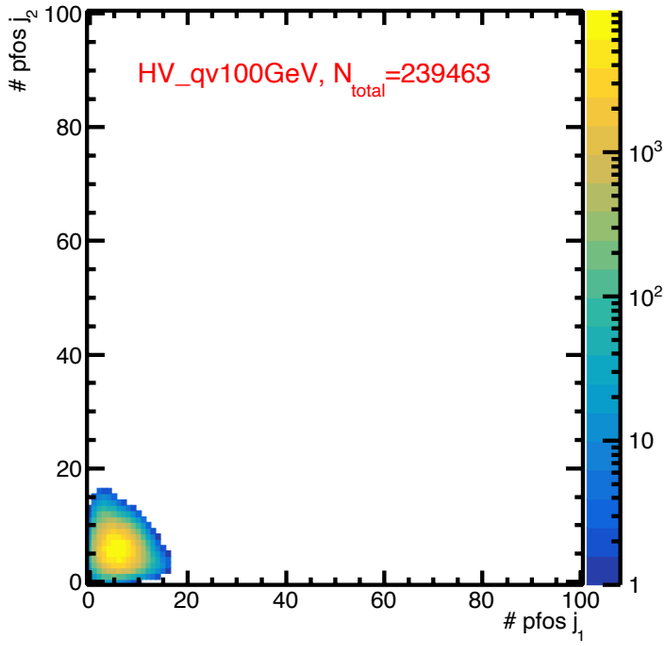

*Analysis at detector level, Pythia8+SGV*

# ANALYSIS AT DETECTOR LEVEL

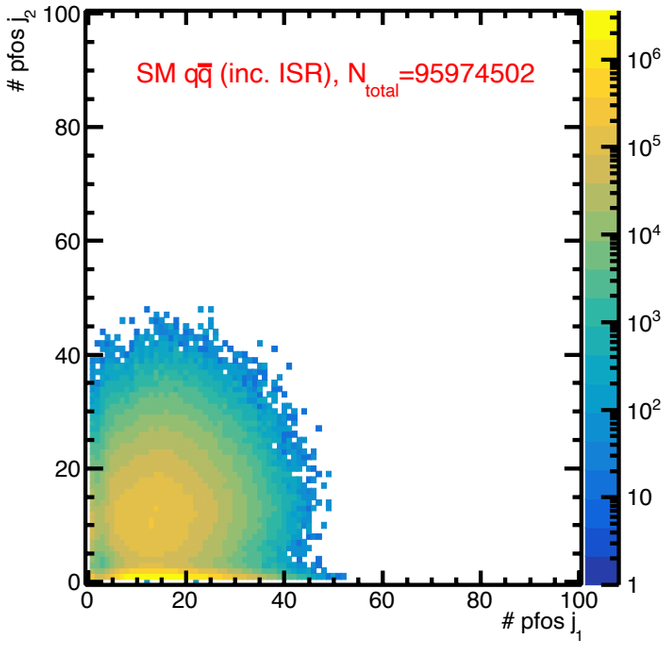
$\sqrt{s} = 250\ \text{GeV}, \mathscr{L} = 2\ \text{ab}^{-1}$

## CUTS

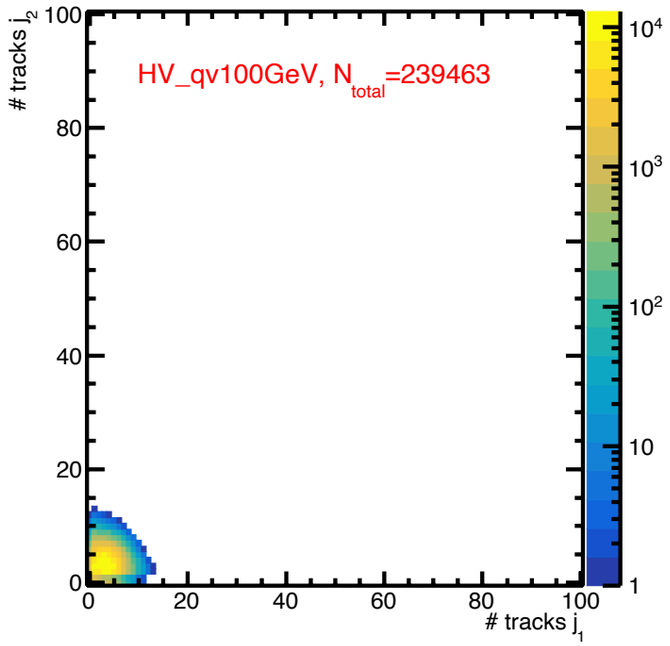
- No secondary vertices
- neutral PFOs ≤ 22 and charged PFOs ≤ 15



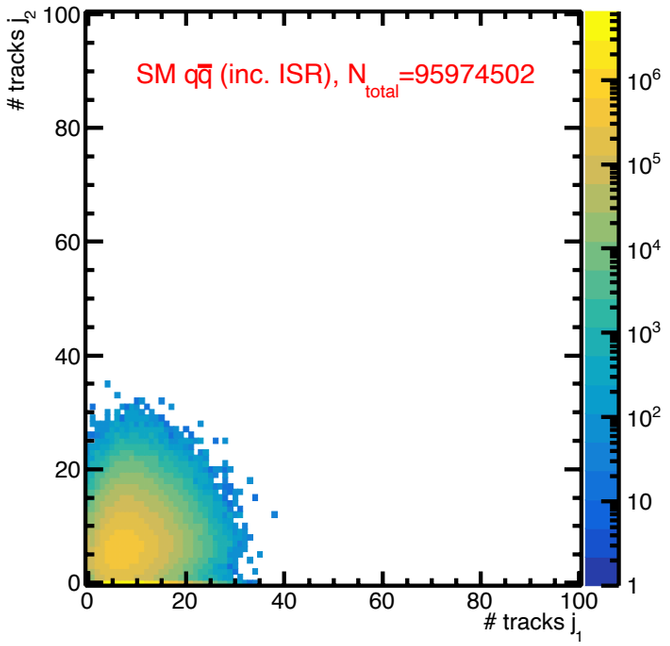

*Analysis at detector level, Pythia8+SGV*




*Analysis at detector level, Pythia8+SGV*




*Analysis at detector level, Pythia8+SGV*



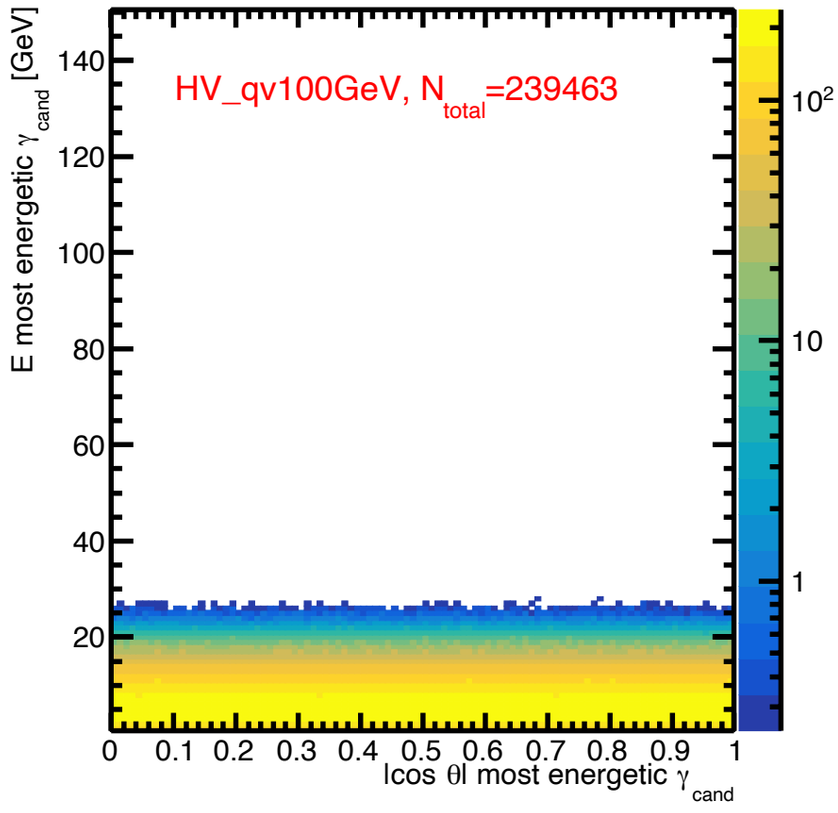

*Analysis at detector level, Pythia8+SGV*

# ANALYSIS AT DETECTOR LEVEL

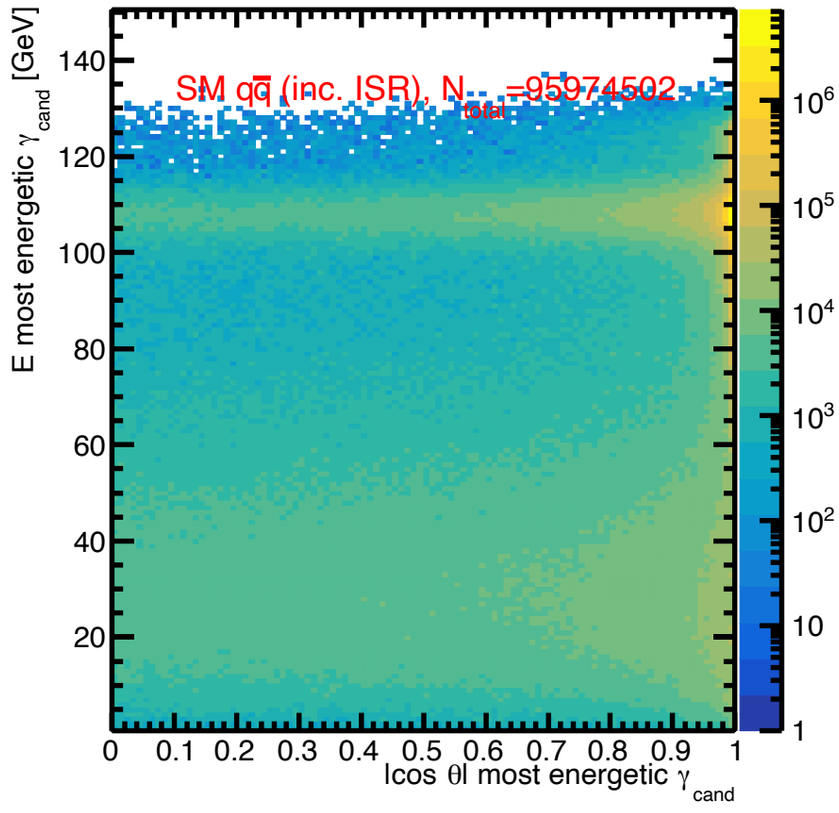
$$\sqrt{s} = 250\ \text{GeV}, \mathscr{L} = 2\ \text{ab}^{-1}$$

## CUTS

- No secondary vertices
- neutral PFOs ≤ 22 and charged PFOs ≤ 15
- $|\cos\theta_{\gamma_{ISR}}| < 0.5$
- $E_{\gamma_{ISR}} < 40$ GeV




*Analysis at detector level, Pythia8+SGV*



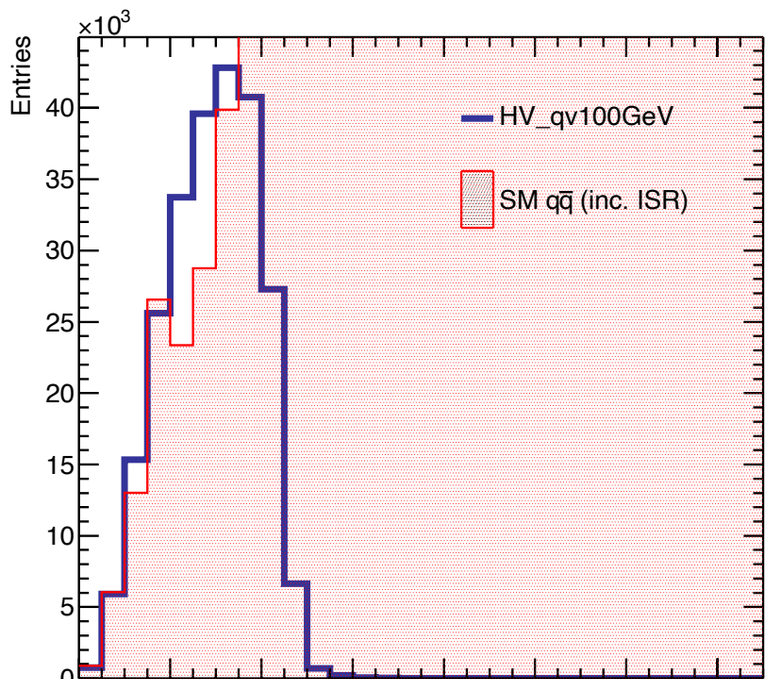

*Analysis at detector level, Pythia8+SGV*

# ANALYSIS AT DETECTOR LEVEL

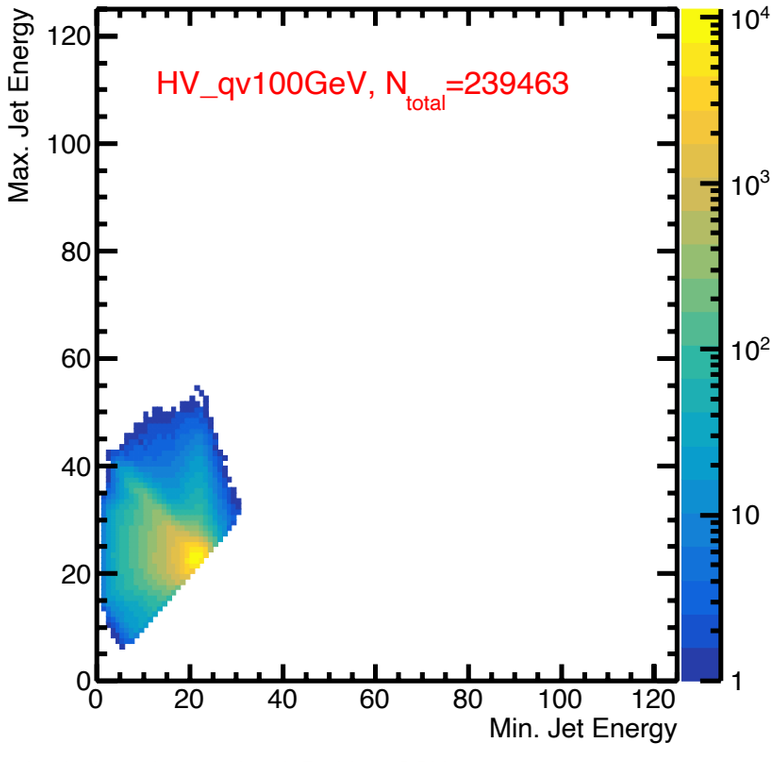
$$\sqrt{s} = 250\ \text{GeV}, \mathscr{L} = 2\ \text{ab}^{-1}$$

## CUTS

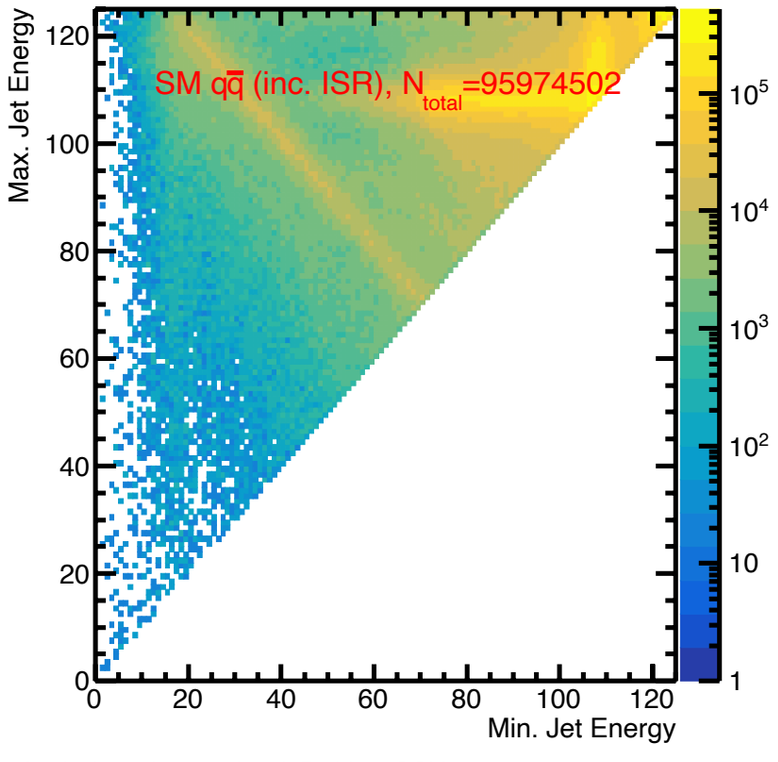
- No secondary vertices
- neutral PFOs ≤ 22 and charged PFOs ≤ 15
- $|\cos\theta_{\gamma_{ISR}}| < 0.5$
- $E_{\gamma_{ISR}}$ <40 GeV
- $m_{jj} < 130$ GeV
- $E_{jet} < 80$ GeV




*Pythia8+SGV (ILC detector)*




*Analysis at detector level, Pythia8+SGV*




*Analysis at detector level, Pythia8+SGV*