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

Emanuela Musumeci (IFIC, Valencia)

in collaboration with

A. Irles, R. Pérez-Ramos, I. Corredoira ,

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based on [2312.06526](2312.06526)

20/12/2023

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:

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

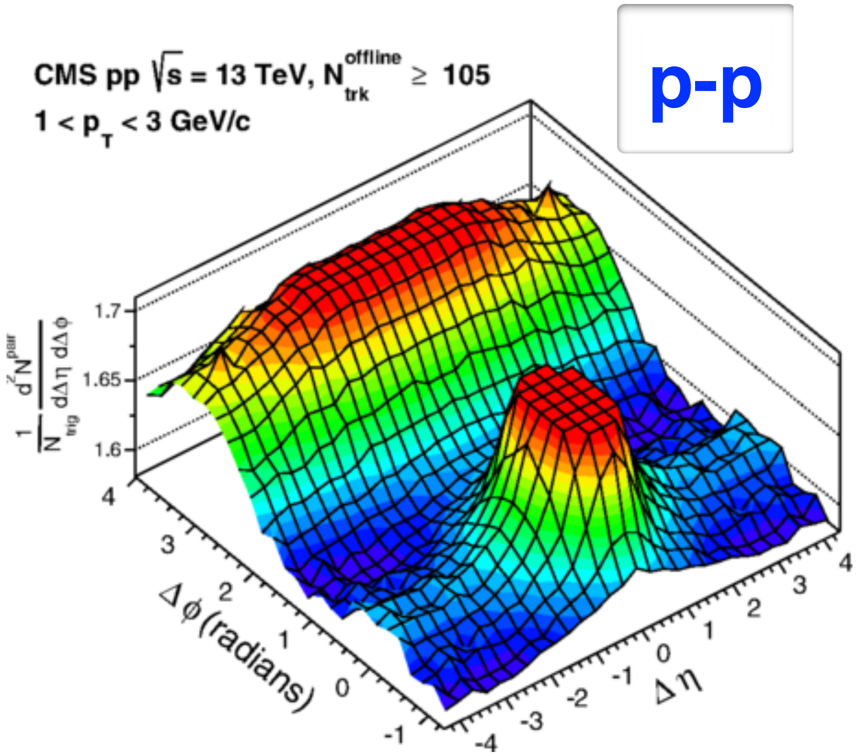
$$N_{pairs} = \int\int \frac{d^2N^{same}}{d\Delta y d\Delta\phi} d\Delta y d\Delta\phi$$

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

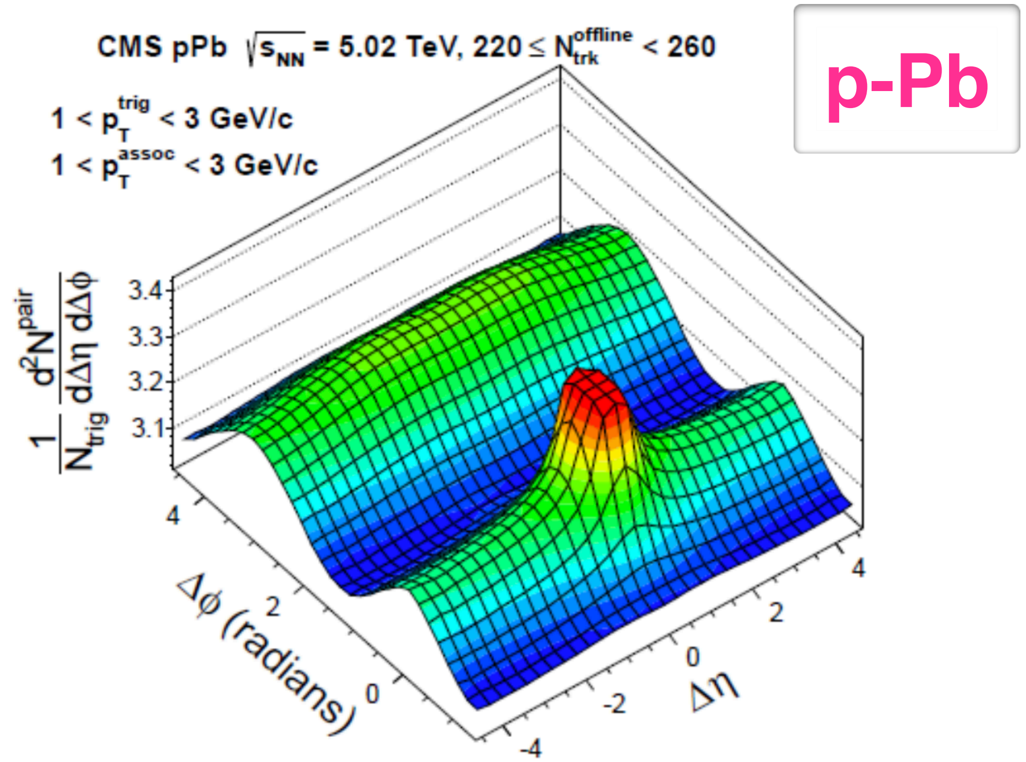
$$B(\Delta y, \Delta\phi) = \frac{1}{N_{mix}} \frac{d^2N^{mix}}{d\Delta y \Delta\phi}$$

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

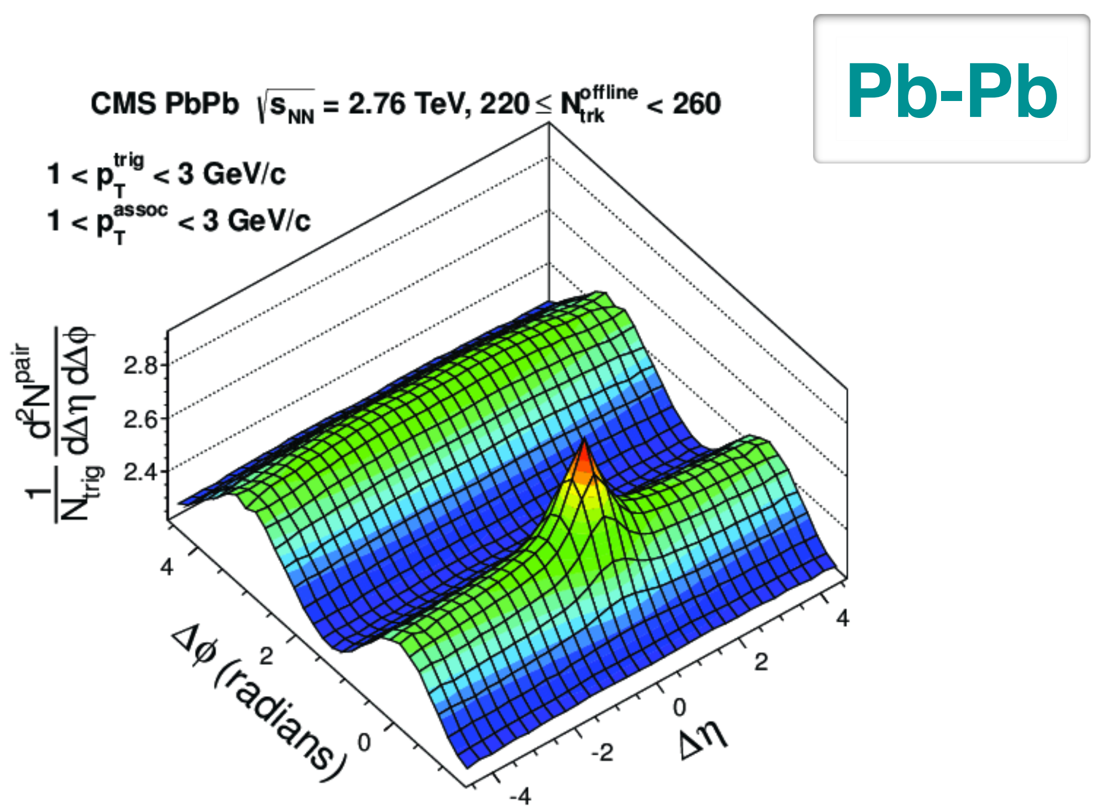
TWO-PARTICLE ANGULAR CORRELATIONS



Physical Review Letters 116(17)



Physics Letters B B724(4)



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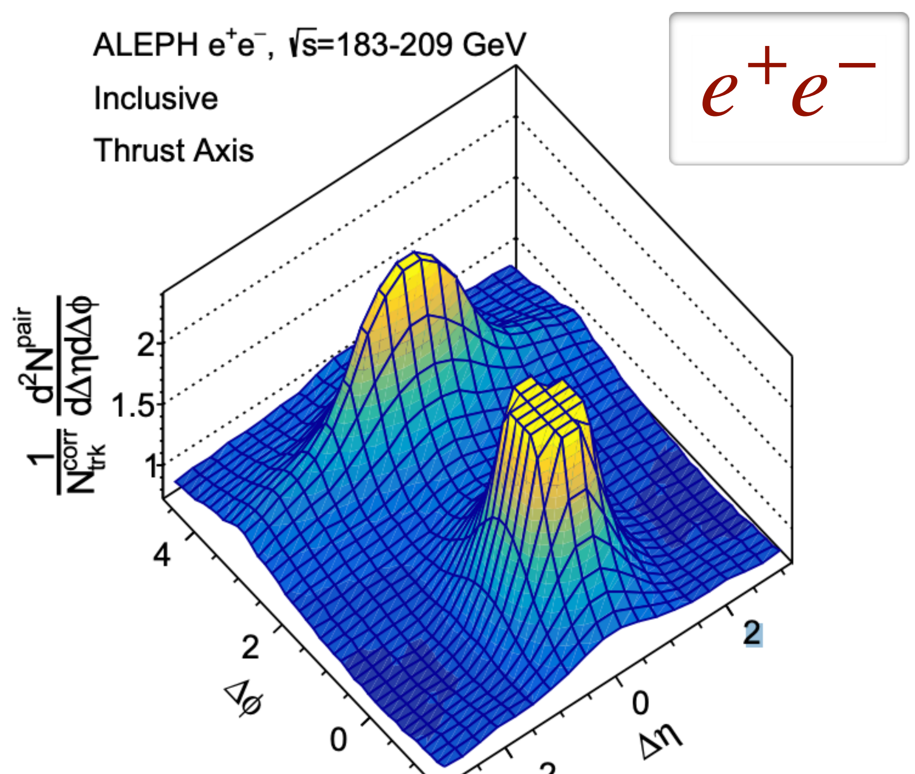
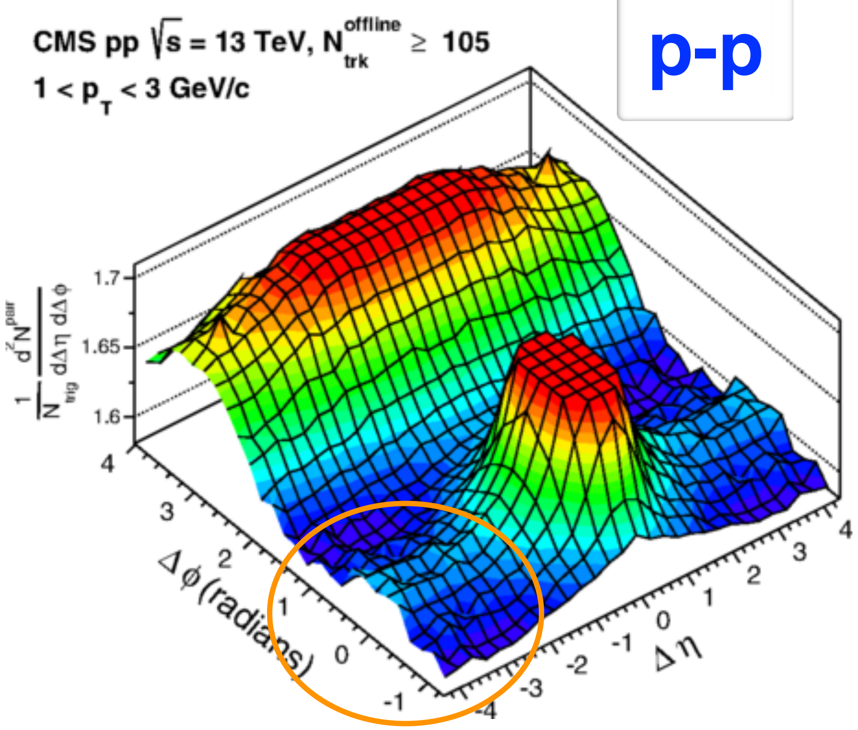


2312.05084

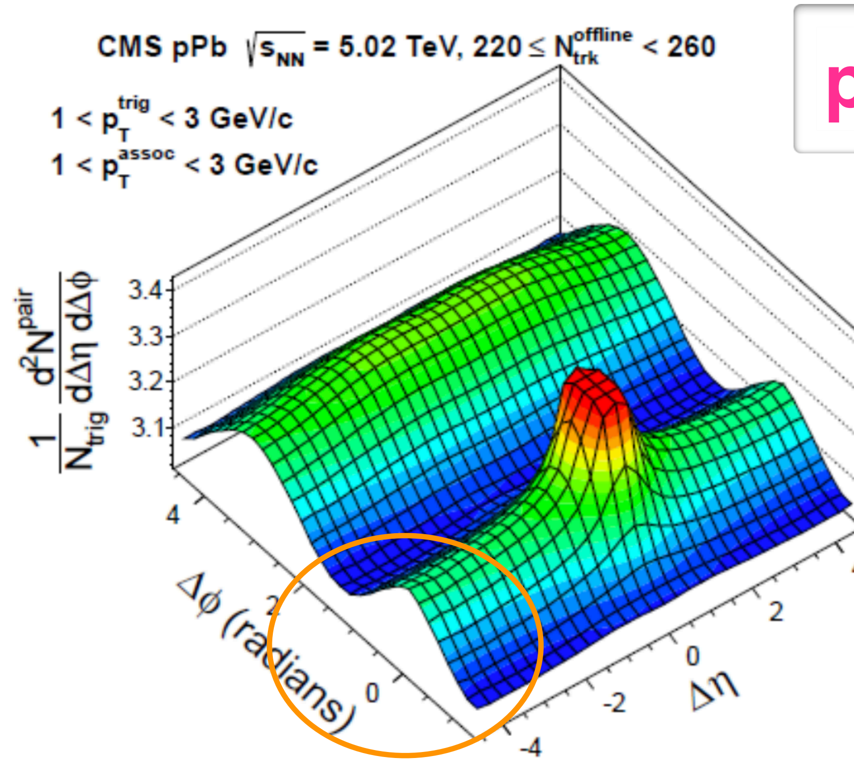
TWO-PARTICLE ANGULAR CORRELATIONS

p-p



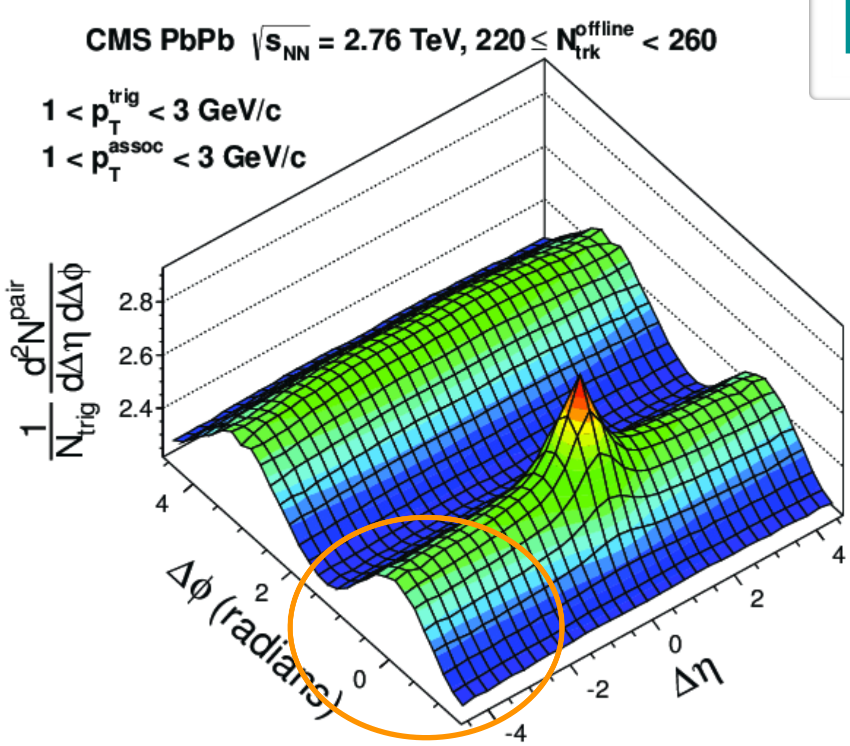
Physical Review Letters 116(17)

p-Pb



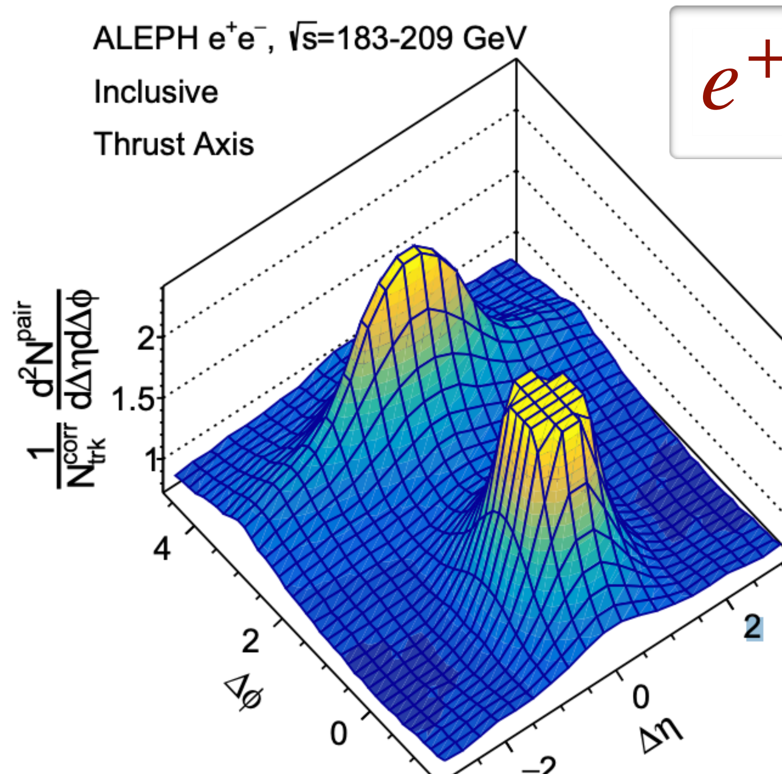
Physics Letters B B724(4)

Pb-Pb



Physics Letters B B724(4)

e^+e^-



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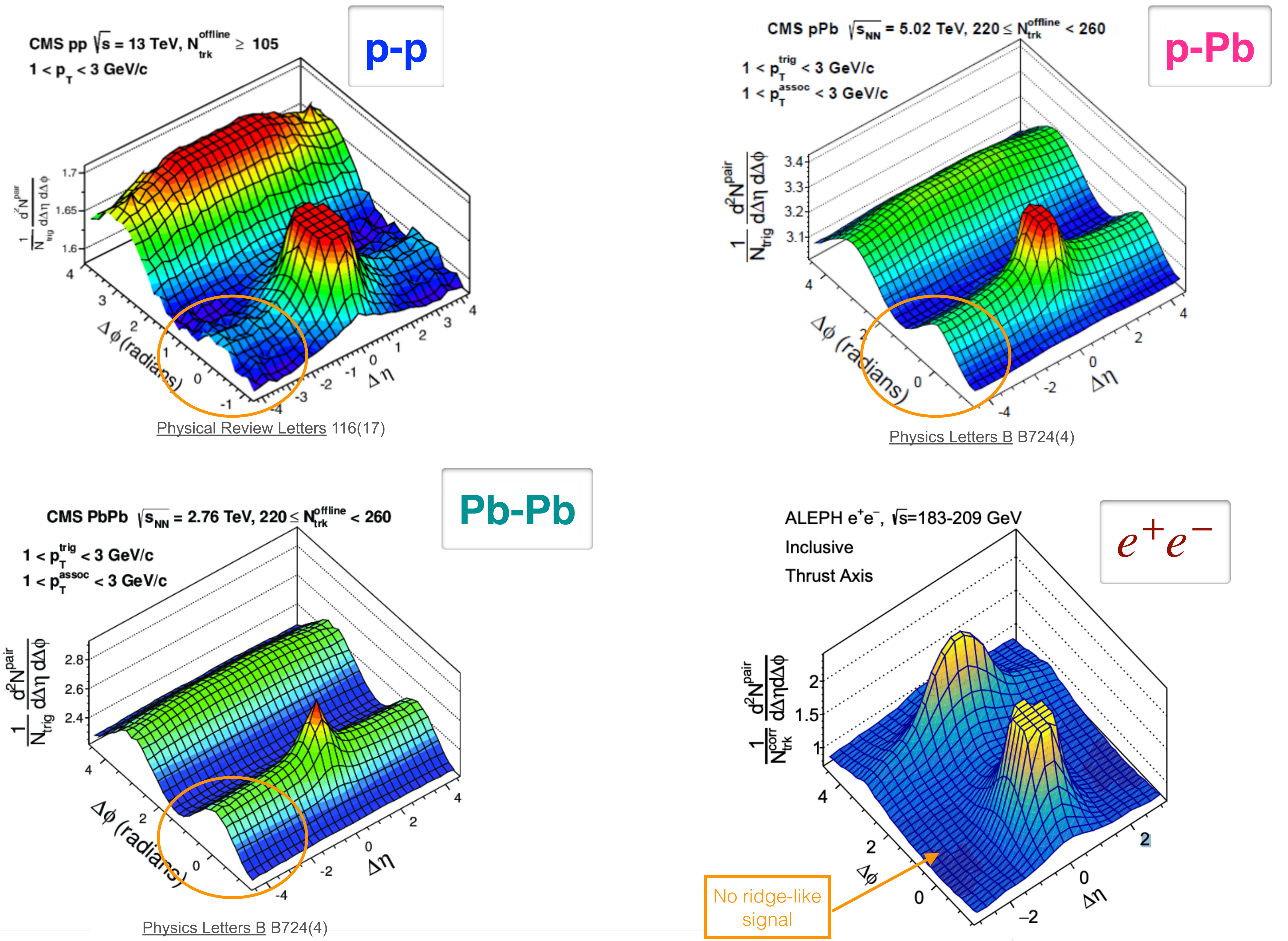
TWO-PARTICLE ANGULAR CORRELATIONS



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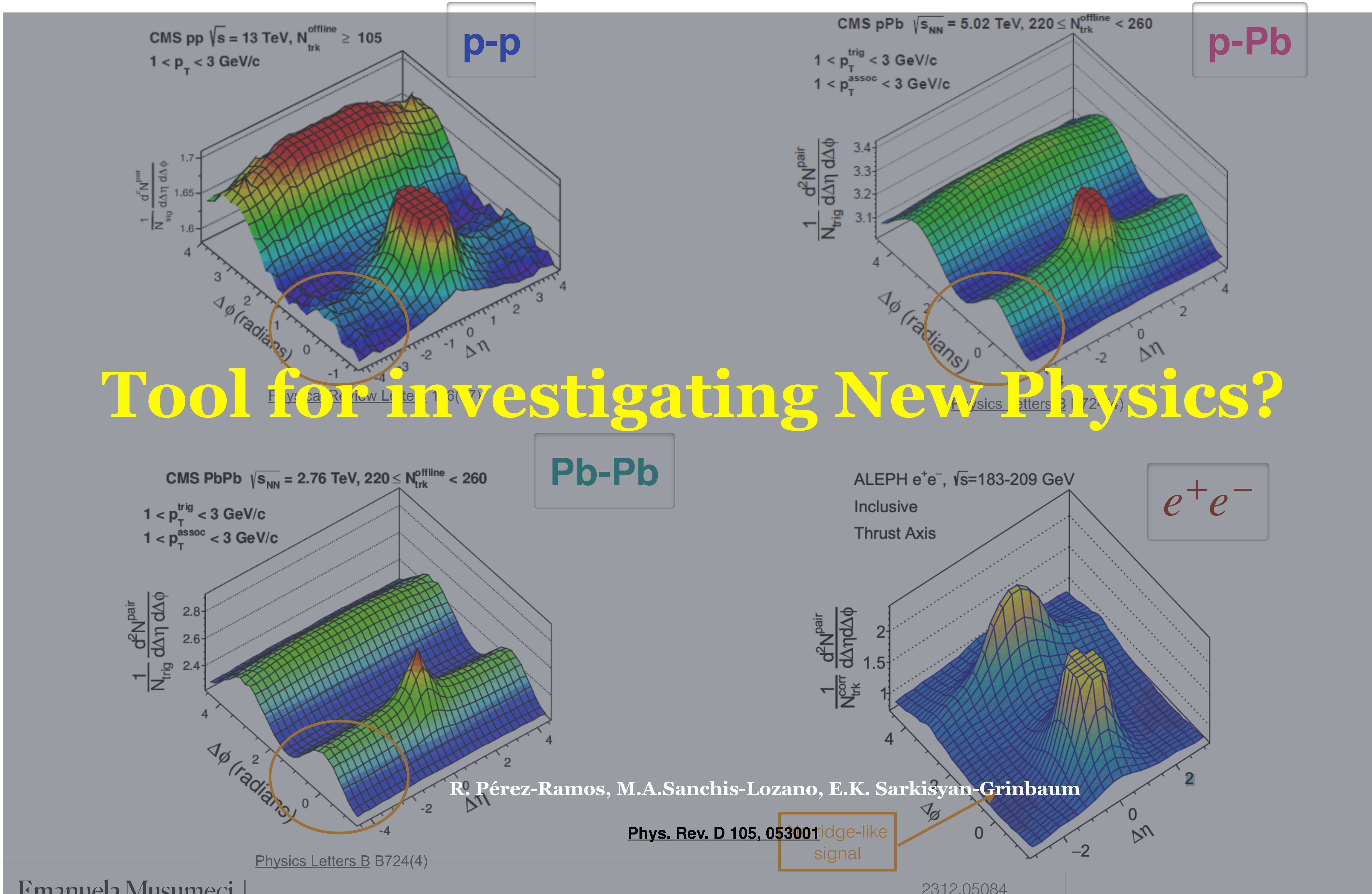
2312.05084

TWO-PARTICLE ANGULAR CORRELATIONS



Tool for investigating New Physics?

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

Phys. Rev. D 105, 053001

HIDDEN VALLEY PHENOMENOLOGY

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

G_{SM}

$SU(3)_C \times SU(2)_L \times U(1)_Y$

SM particles

G_V

v-particles

($\mathcal{O}$(GeV) scale)

HIDDEN VALLEY PHENOMENOLOGY

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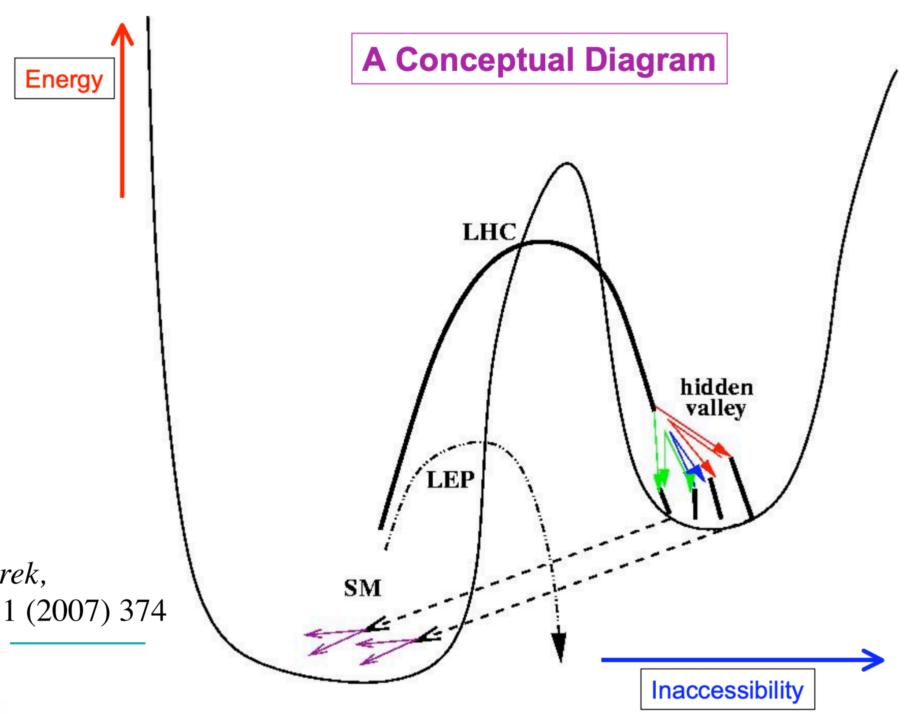
SM particles

G_V

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

Communicator

Higher-dimension operators
($\mathcal{O}$(TeV) scale)



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

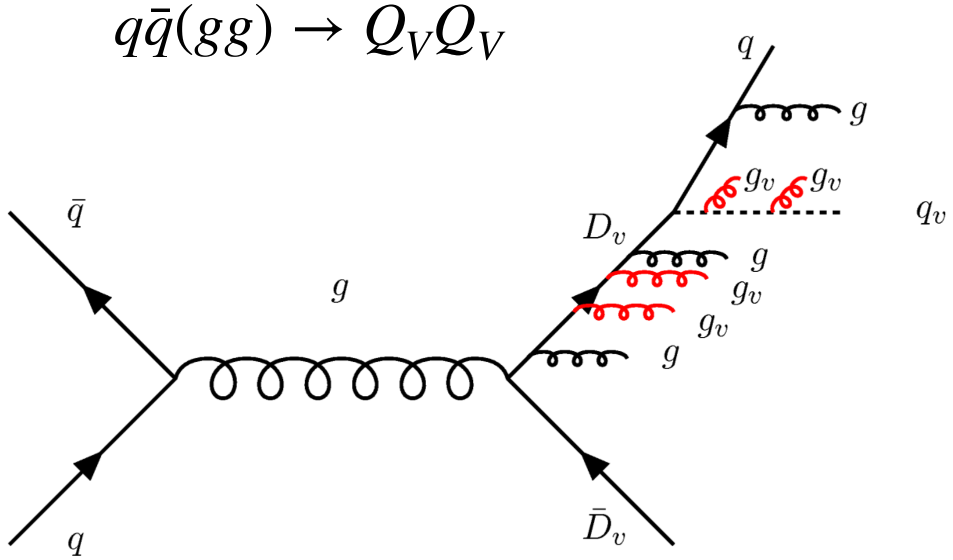
QCD-like scenario

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
  - $E_V \to e q_V$
  - $Q_V \to q q_V$

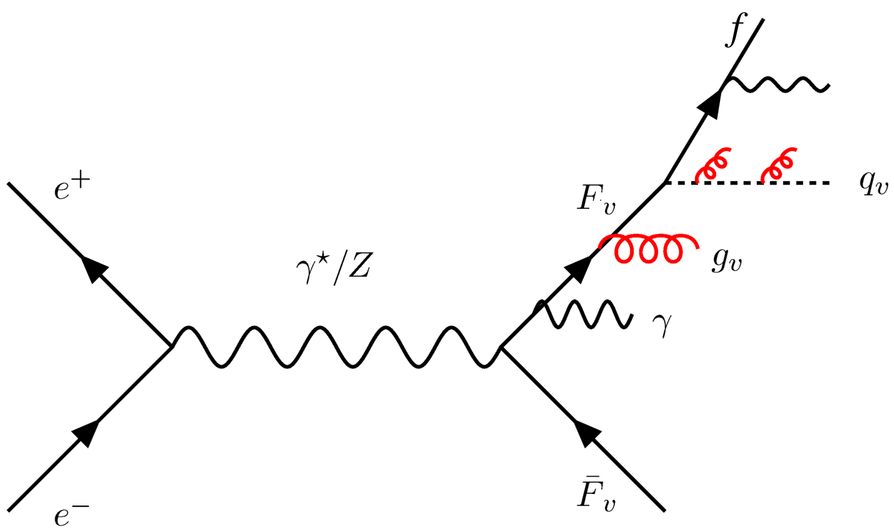
pp collisions

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



e^+e^- collisions

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



JHEP 1009:105,2010
L Carloni, T Sjöstrand

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: $F_V \to fq_V \longrightarrow$ hadrons
  - $E_V \to eq_V$
  - $Q_V \to qq_V$

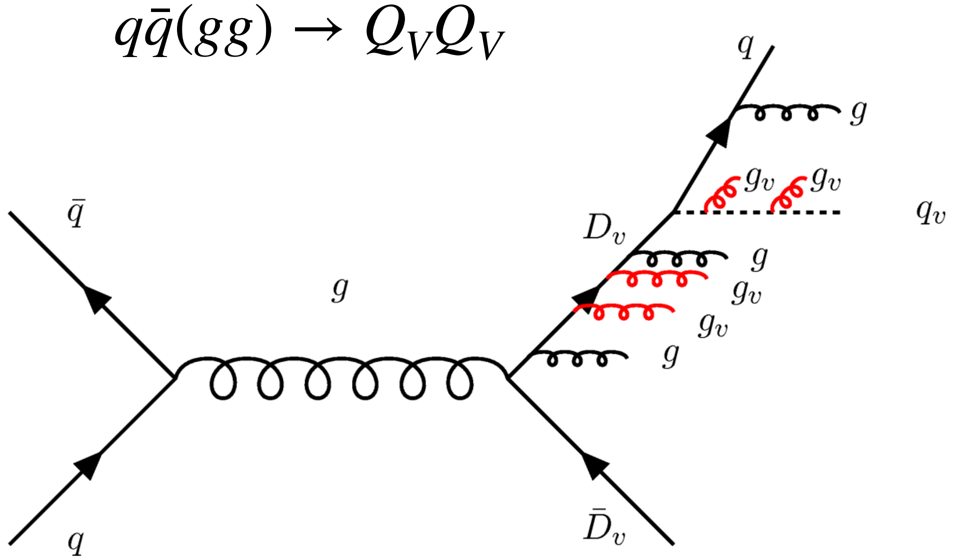
Signature

Perturbation in conventional QCD cascade and final hadronisation

anomalies in angular correlations

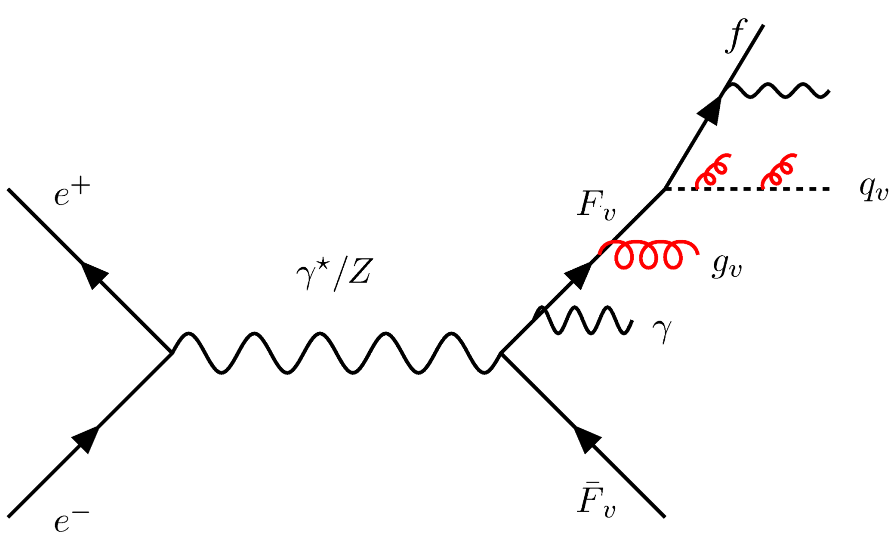
pp collisions

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



e^+e^- collisions

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



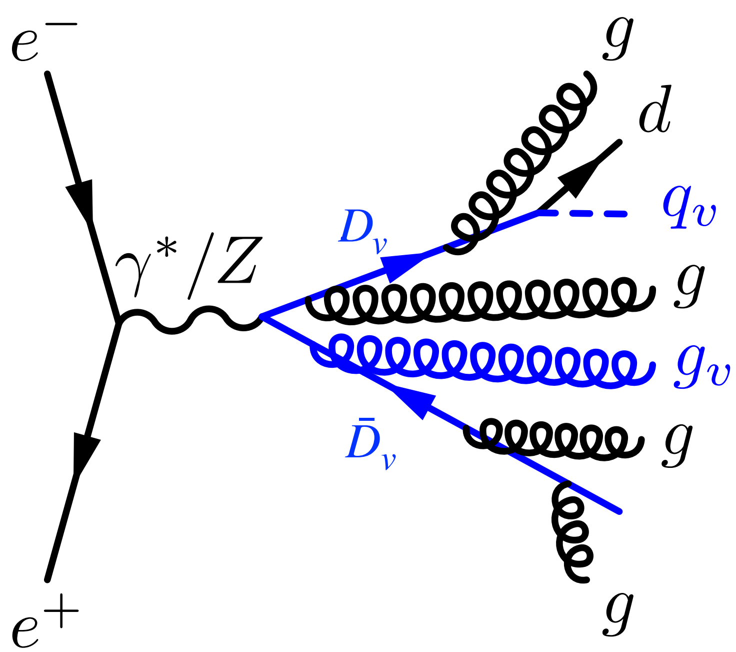
JHEP 1009:105,2010
L Carloni, T Sjöstrand

SIGNAL VS BACKGROUND

$\sqrt{s} = 250$ GeV

SIGNAL

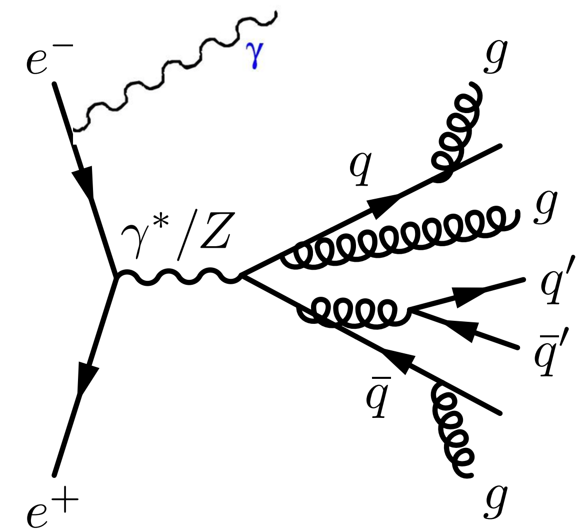
$e^+e^- \to \gamma^*/Z^0 \to D_V\bar{D}_V \to$ hadrons



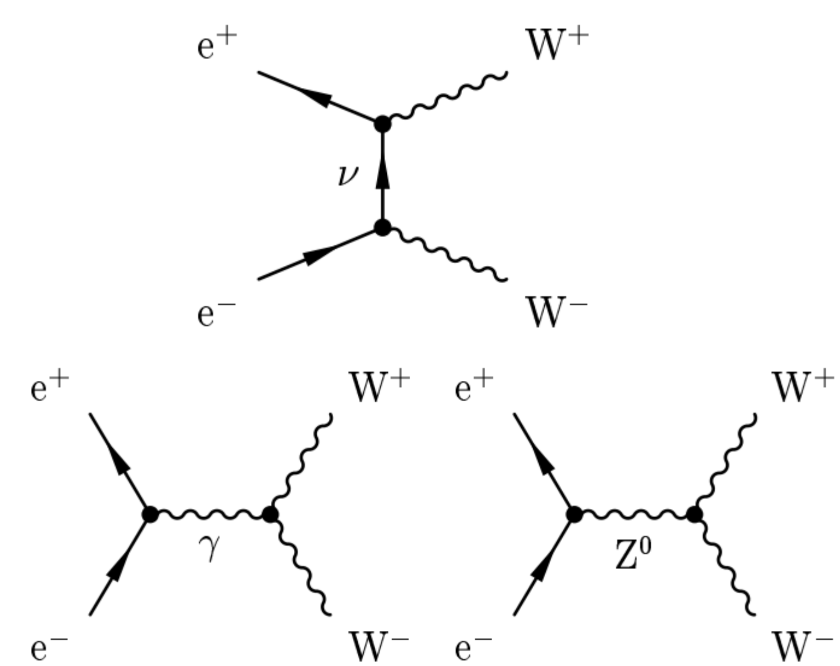
m_{D_V} = 125 GeV

BACKGROUND

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



ii) WW —> 4q



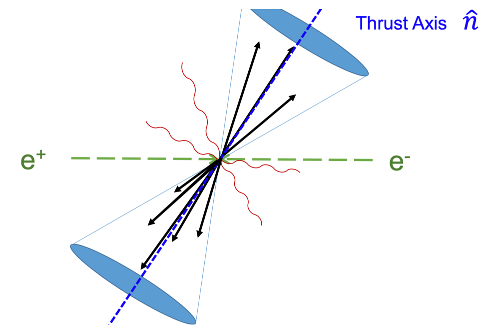
No polarised beam

Process	σ_{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

ANALYSIS AT DETECTOR LEVEL

$\sqrt{s} = 250$ GeV

Thrust Axis:



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

TOOLS

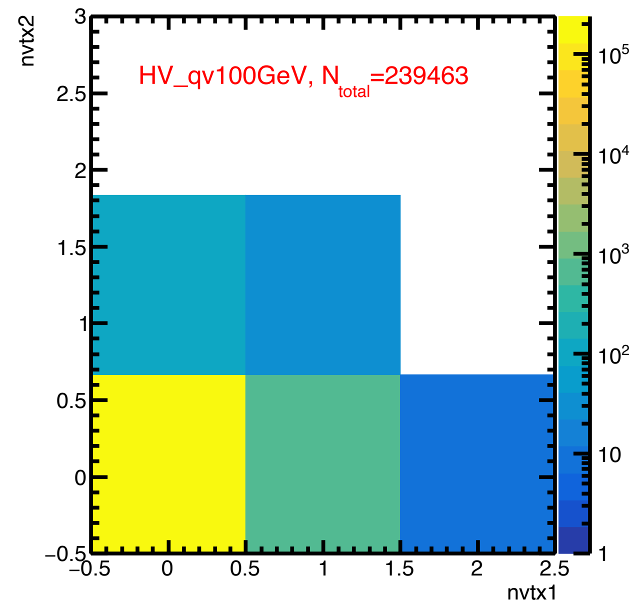
- Monte Carlo event generator:
  - ➡Pythia8
    - HepMC output
- Fast detector simulation
  - ➡ SGV
    - From HepMC files —> LCIO-DST (ILD geometry)
- Analysis
  - ➡ ILCSoft (https://github.com/QQbarAnalysis/QQbarAnalysis)
  - ➡ ROOT (https://github.com/airqui/AFBhq2021)

ANALYSIS AT DETECTOR LEVEL

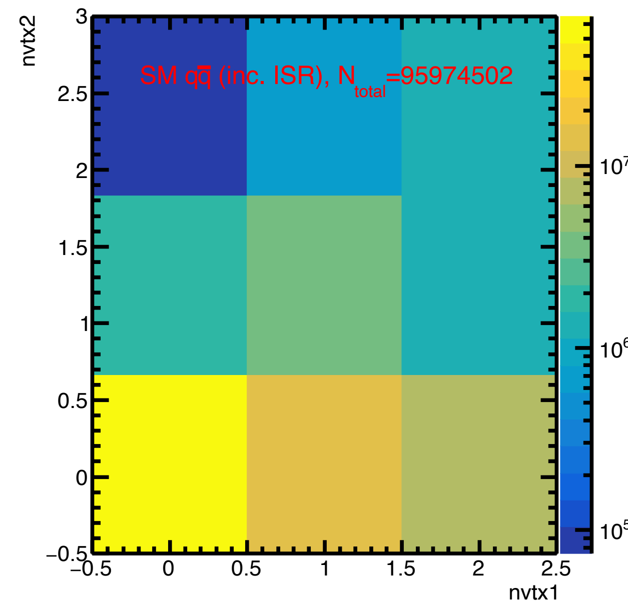
$\sqrt{s} = 250$ GeV, $\mathscr{L} = 2$ ab^{-1}

CUTS

- No secondary vertices



Analysis at detector level, Pythia8+SGV



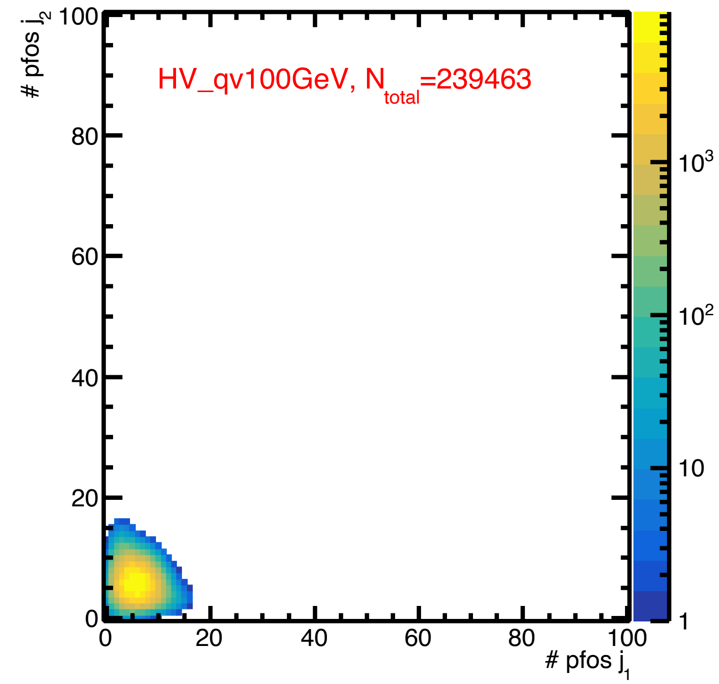
Analysis at detector level, Pythia8+SGV

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



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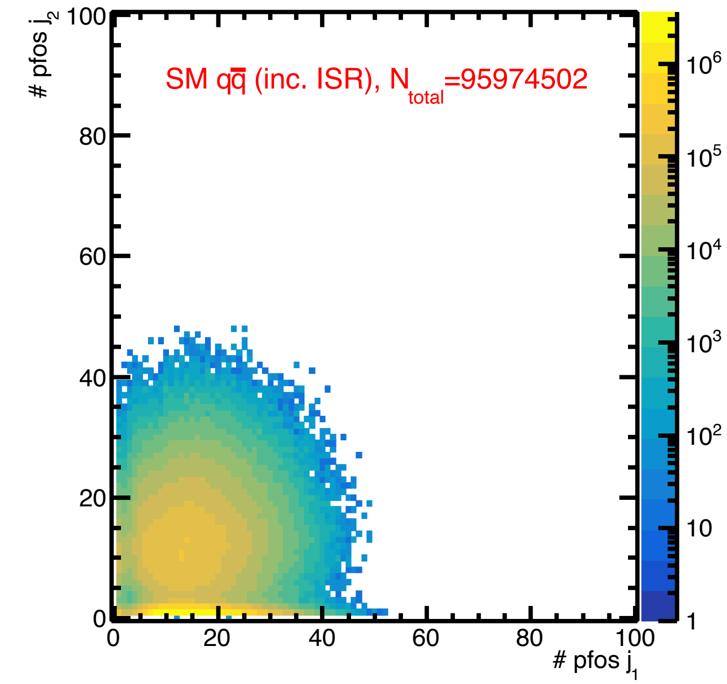

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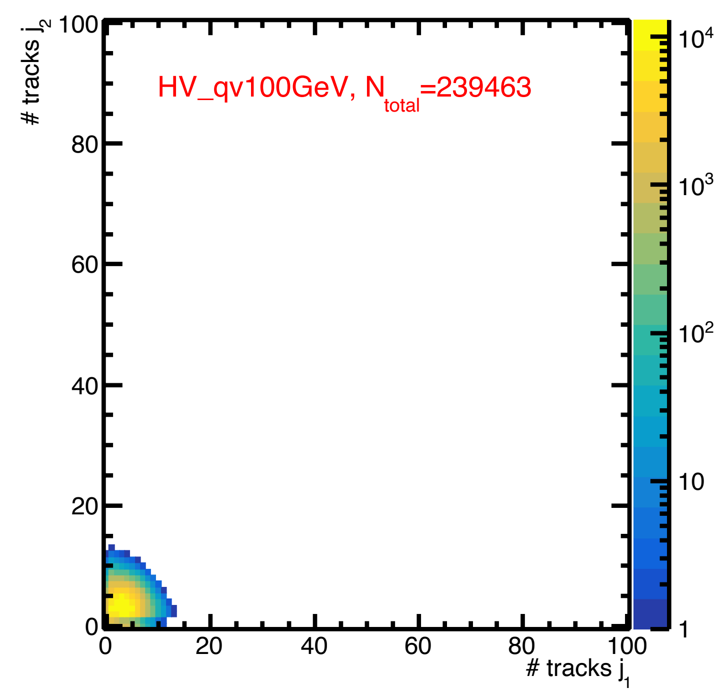
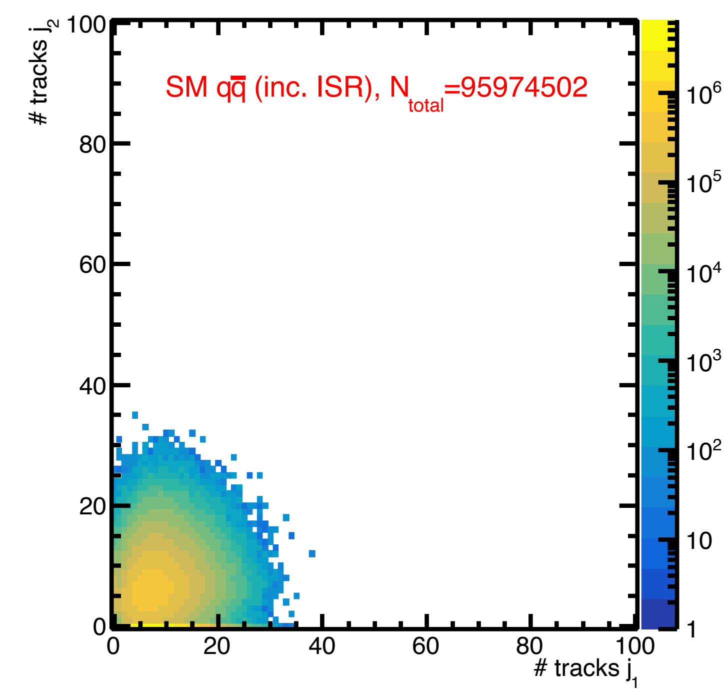


Analysis at detector level, Pythia8+SGV



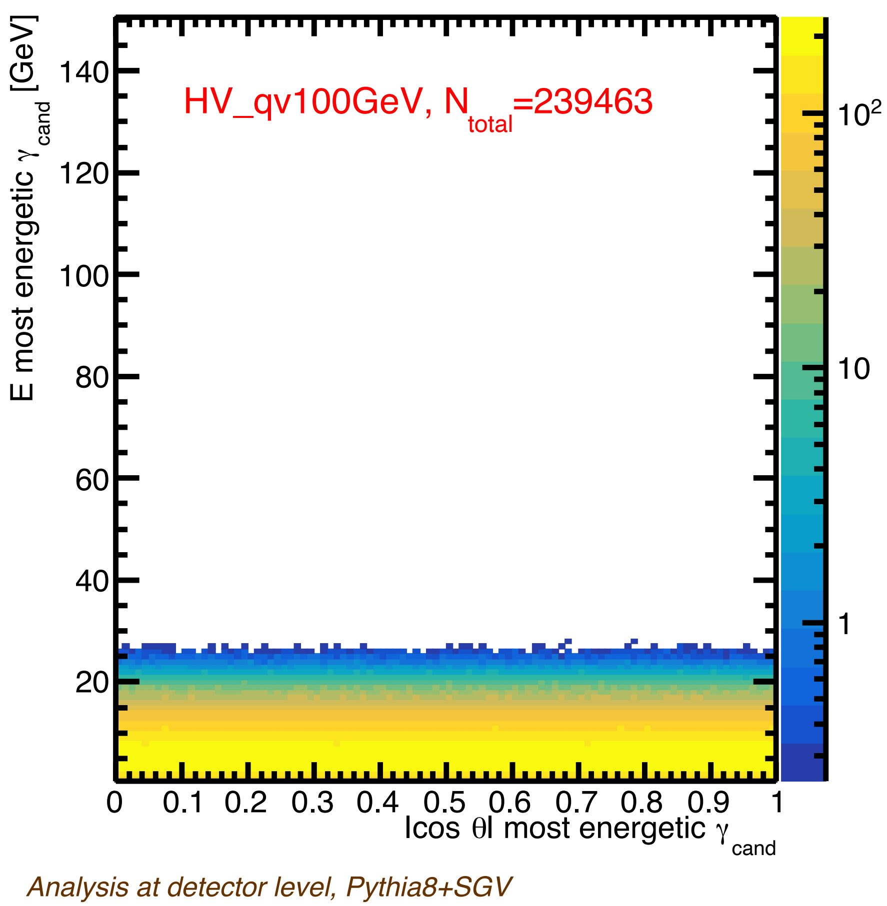
Analysis at detector level, Pythia8+SGV

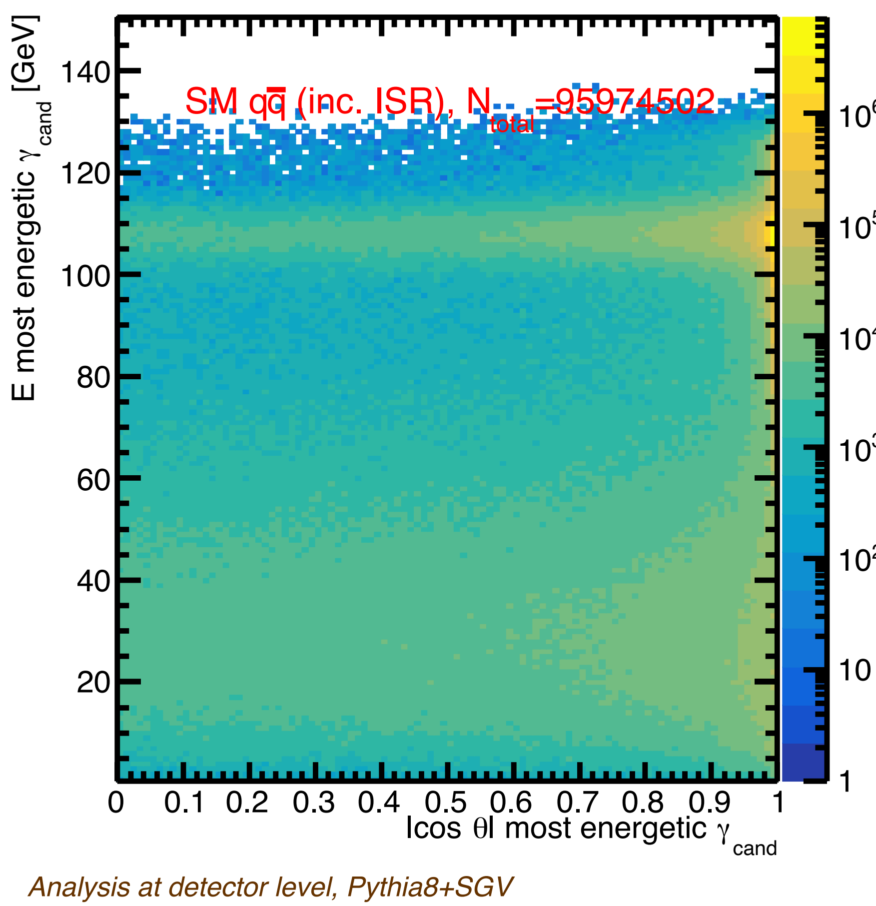
ANALYSIS AT DETECTOR LEVEL

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

CUTS

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



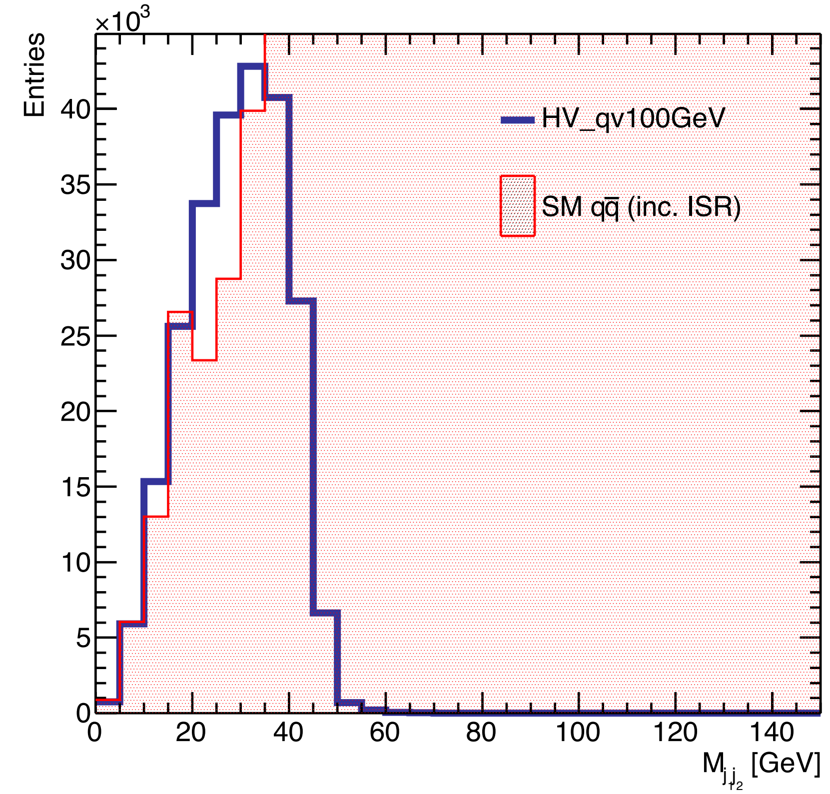


ANALYSIS AT DETECTOR LEVEL

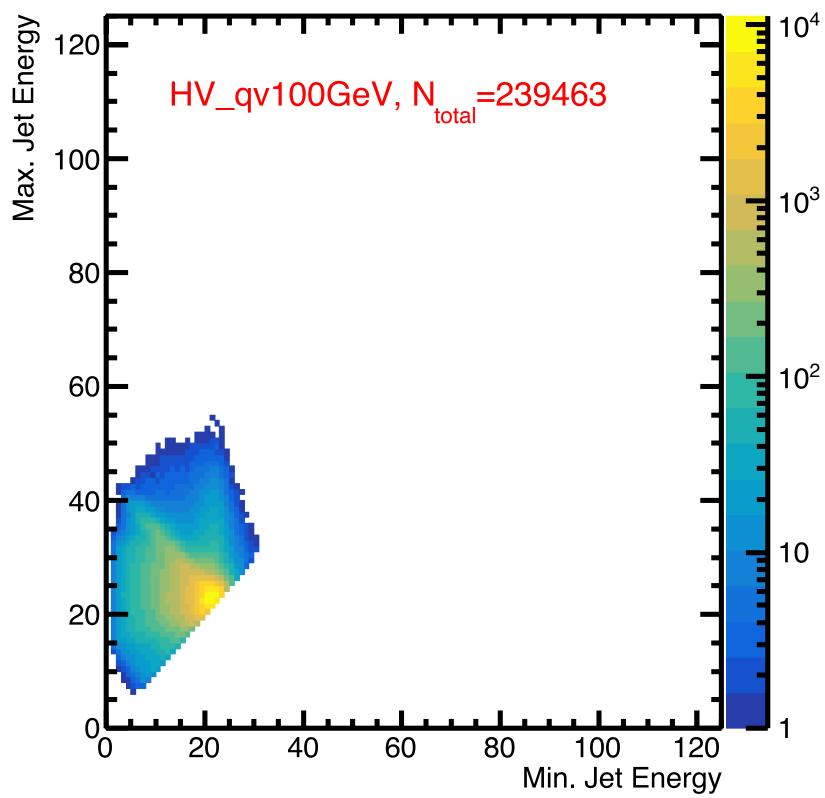
$\sqrt{s} = 250$ GeV, $\mathscr{L} = 2$ ab^{-1}

CUTS

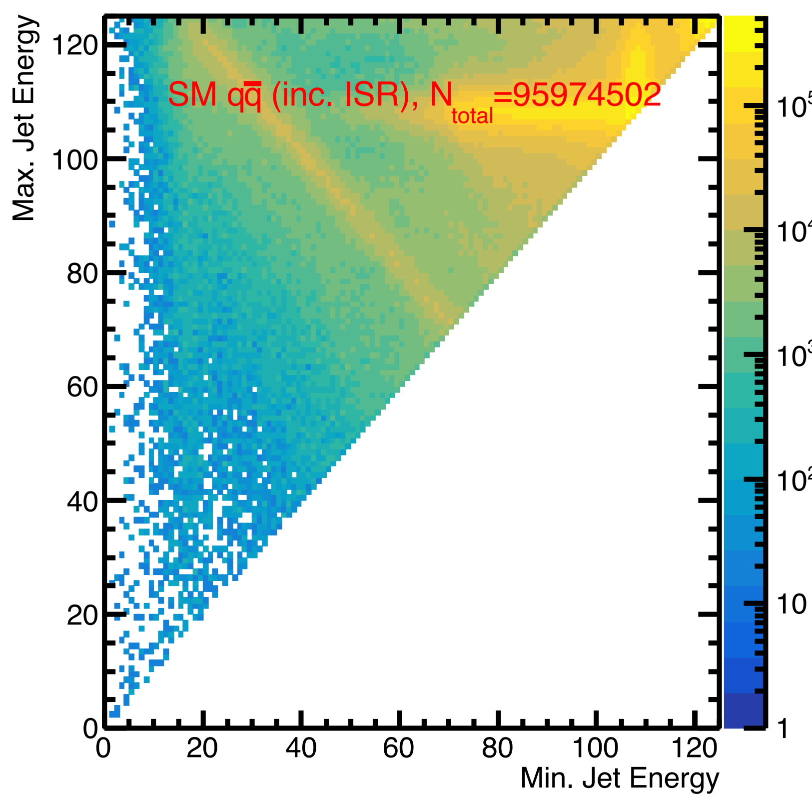
- No secondary vertices
- neutral PFOs ≤ 22 and charged PFOs ≤ 15
- $|\cos\theta_{\gamma_{ISR}}| < 0.5$
- $E_{\gamma_{ISR}}$ <40 GeV
- $m_{jj} < 130$ GeV
- $E_{jet} < 80$ GeV



Pythia8+SGV (ILC detector)



Analysis at detector level, Pythia8+SGV



Analysis at detector level, Pythia8+SGV

ANALYSIS AT DETECTOR LEVEL

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

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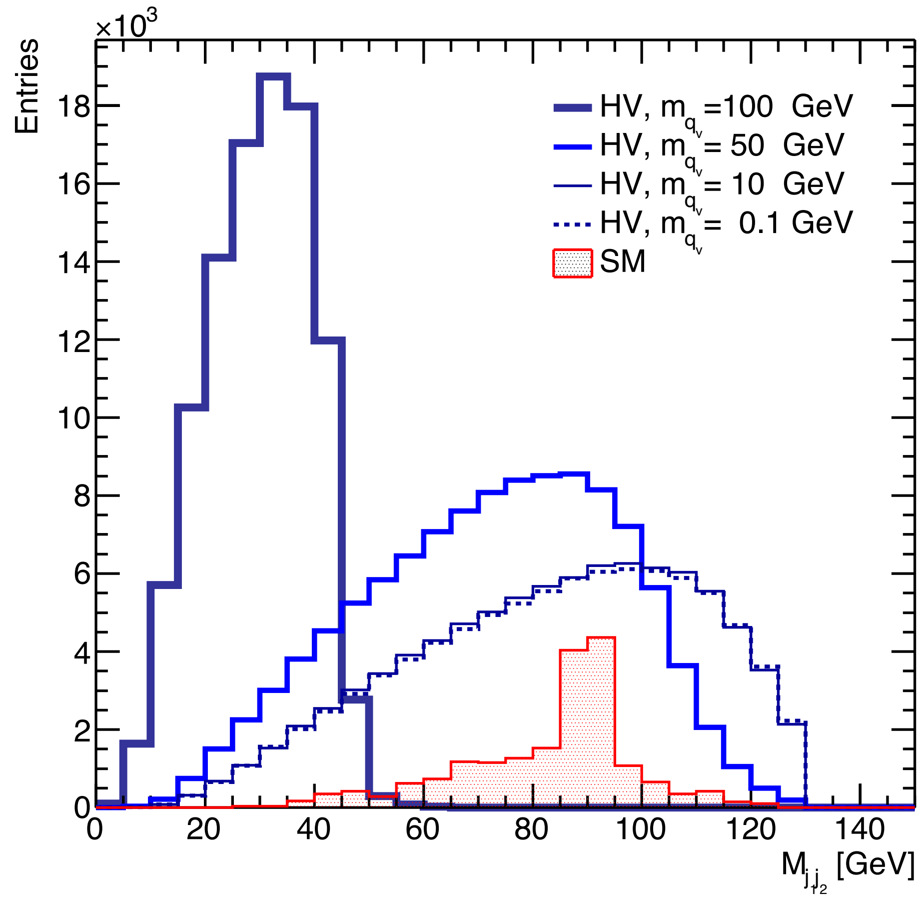
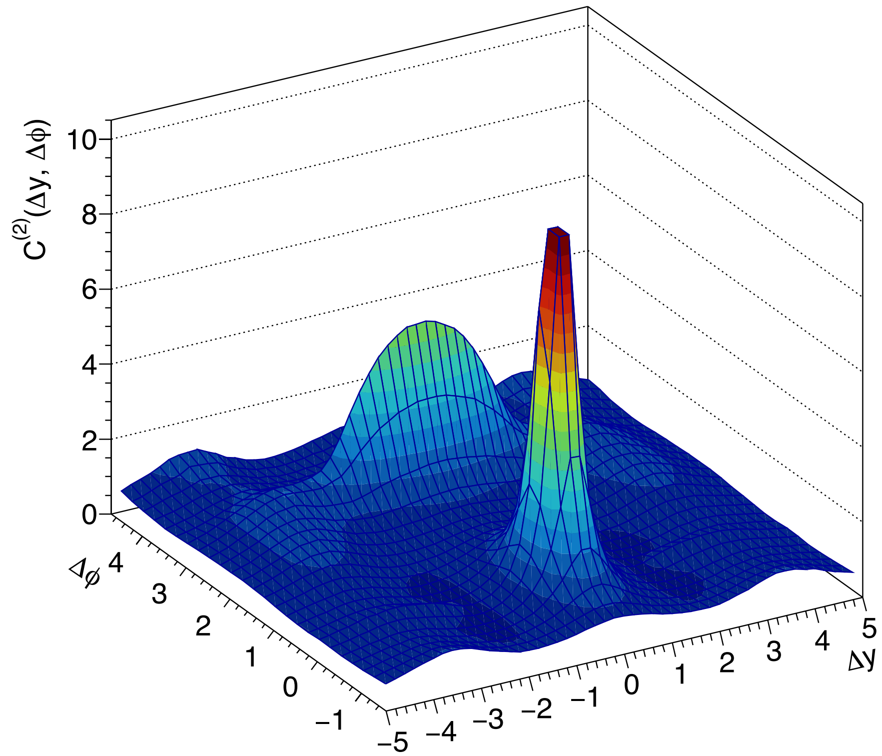


Pythia8+SGV (ILC detector)

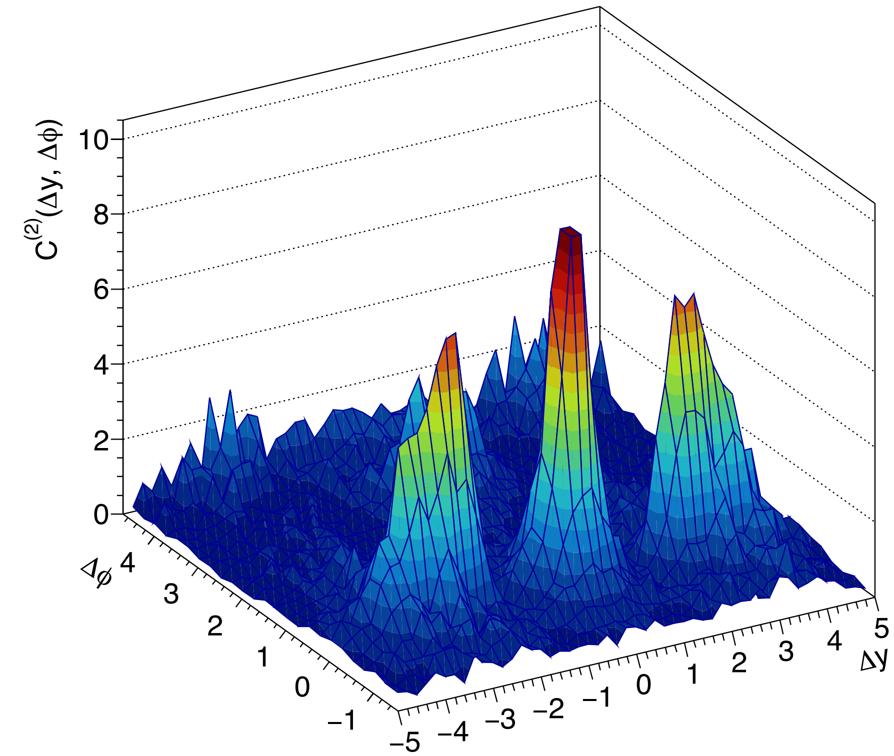
Process	σ_{PYTHIA8} [pb]	Efficiency [%]	$< N_{\text{ch}} >$
$e^+e^- \to D_v\bar{D}_v$			
$m_{q_v} = 0.1$ GeV	0.13	36	12.4 ± 3.7
$m_{q_v} = 10$ GeV	0.12	36	12.4 ± 3.7
$m_{q_v} = 50$ GeV	0.12	42	11.4 ± 3.5
$m_{q_v} = 100$ GeV	0.12	42	6.5 ± 2.1
$e^+e^- \to q\bar{q}$ with ISR	48	$\lesssim 0.01$	9.9 ± 3.4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

ANALYSIS AT DETECTOR LEVEL

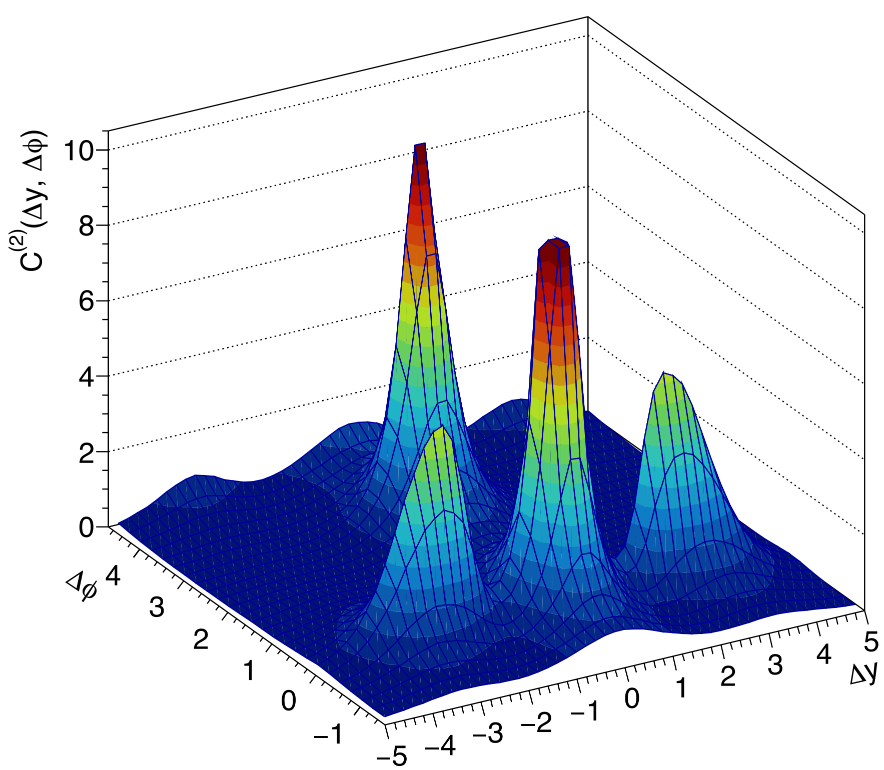
NO CUTS $\sqrt{s} = 250\ \mathrm{GeV}, \mathscr{L} = 2\ \mathrm{ab}^{-1}$ **CUTS**



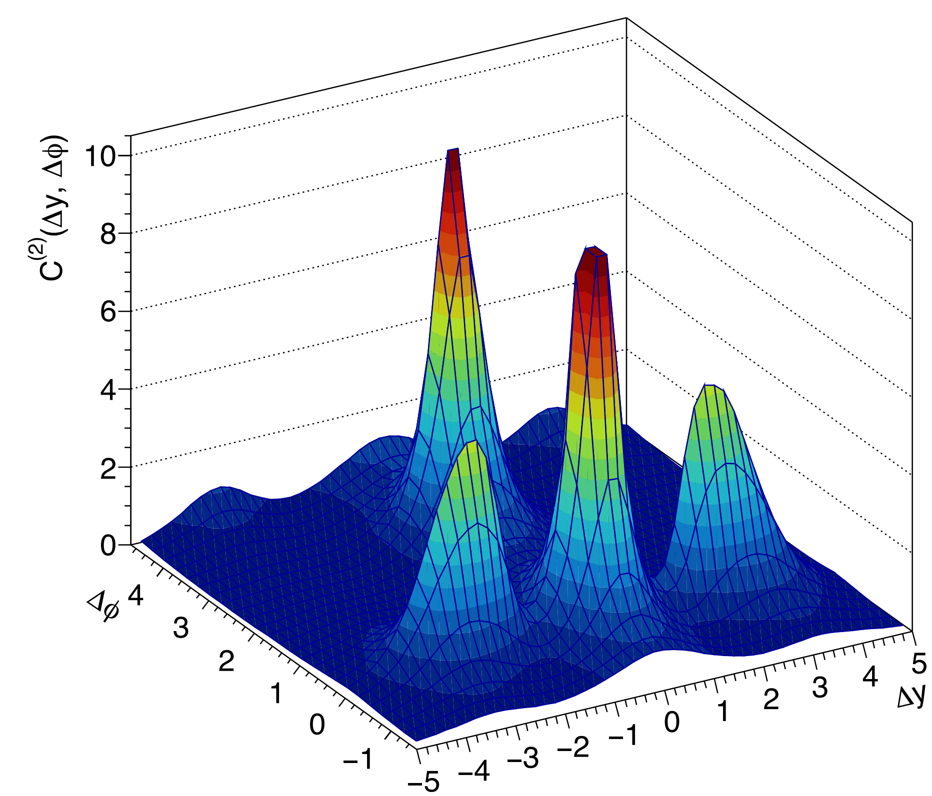
SM



SM



HV (m_{q_v}=100 GeV)



HV (m_{q_v}=100 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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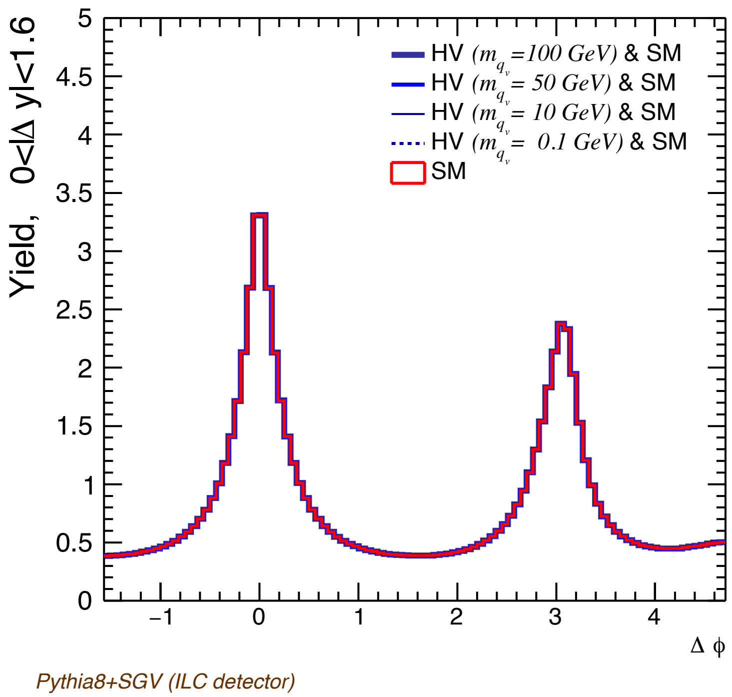
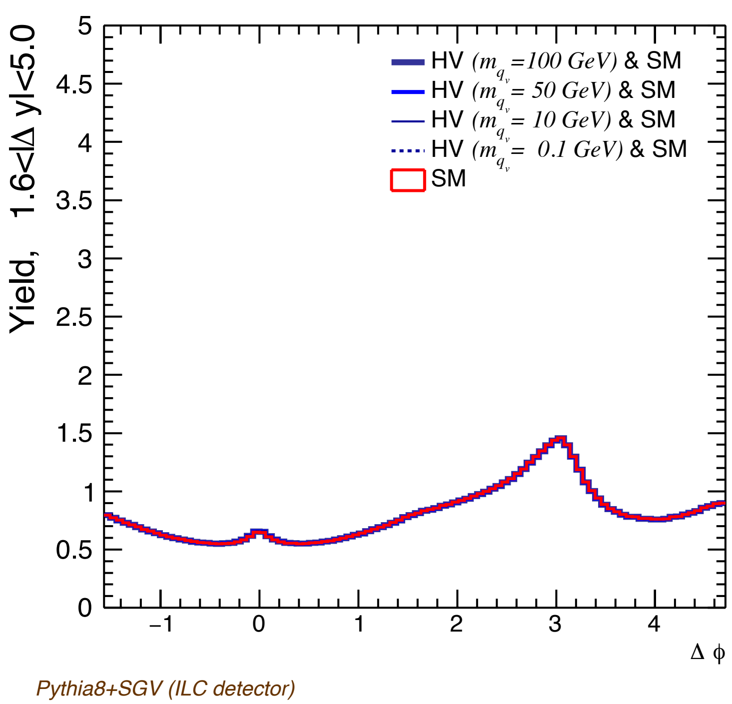
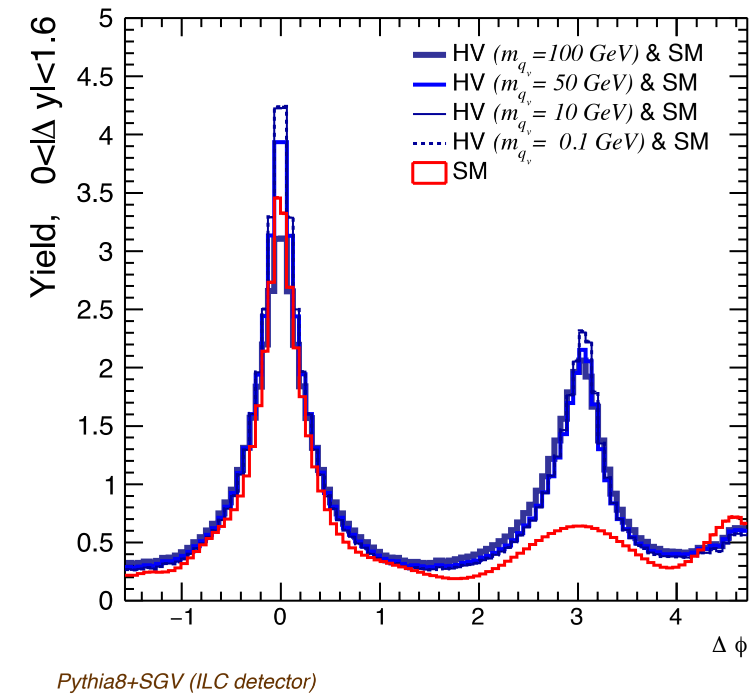
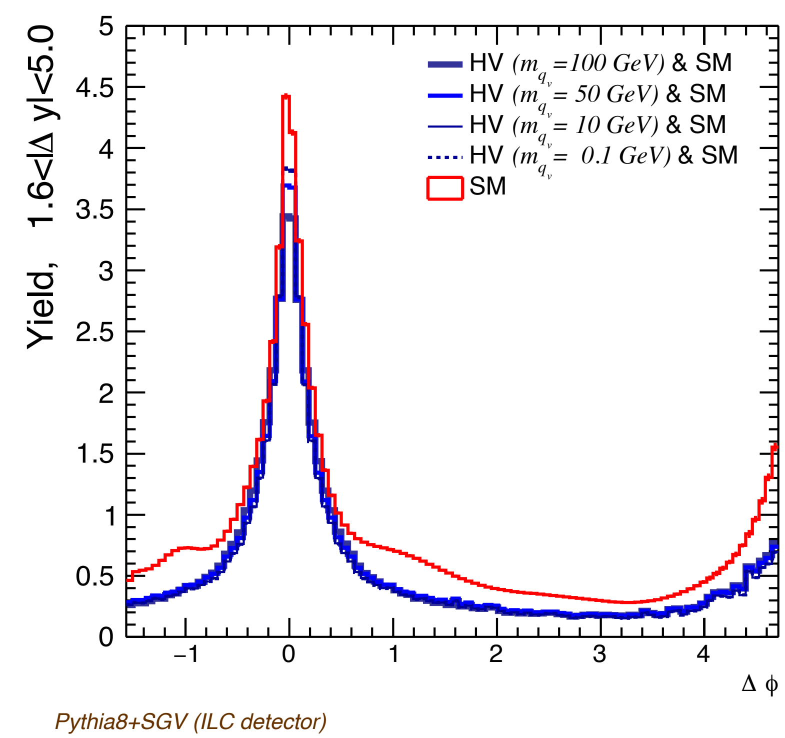
NO CUTS





CUTS



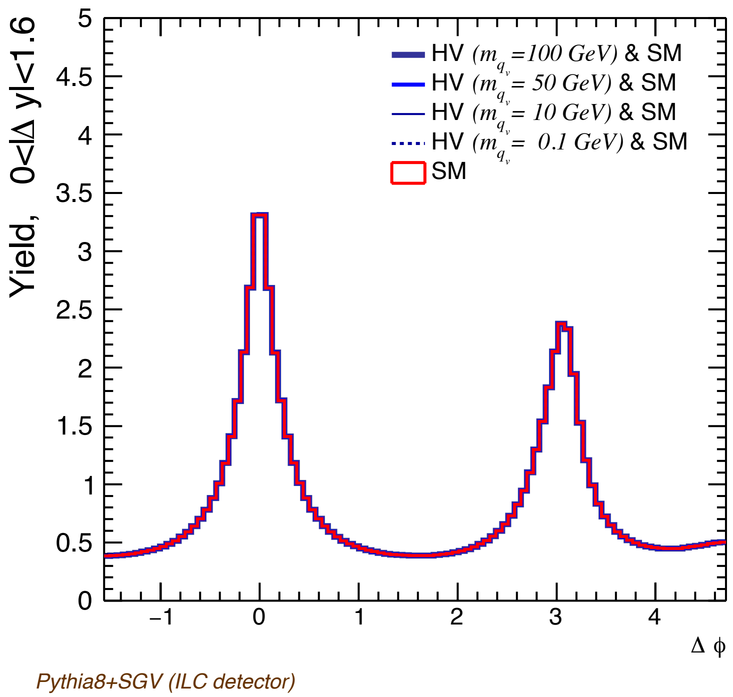


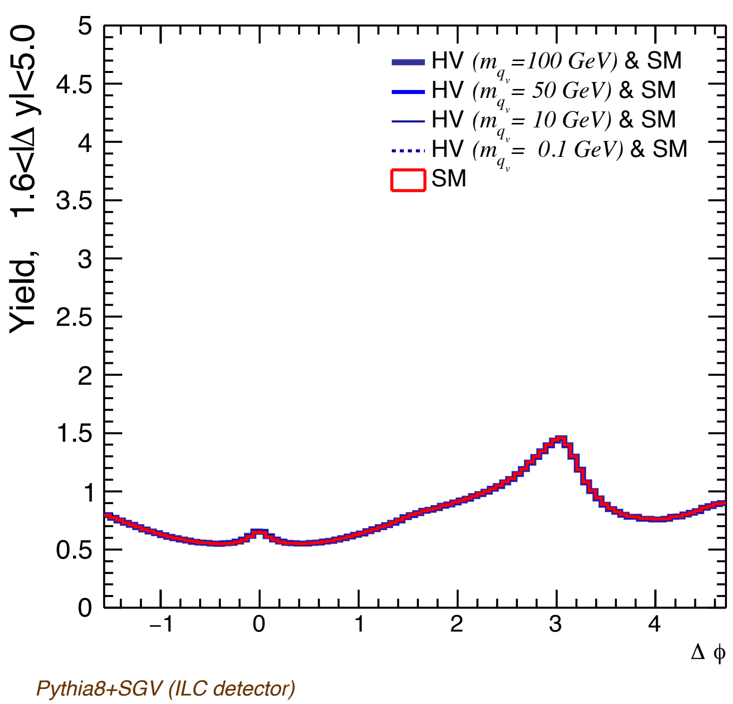
ANALYSIS AT DETECTOR LEVEL

Yield

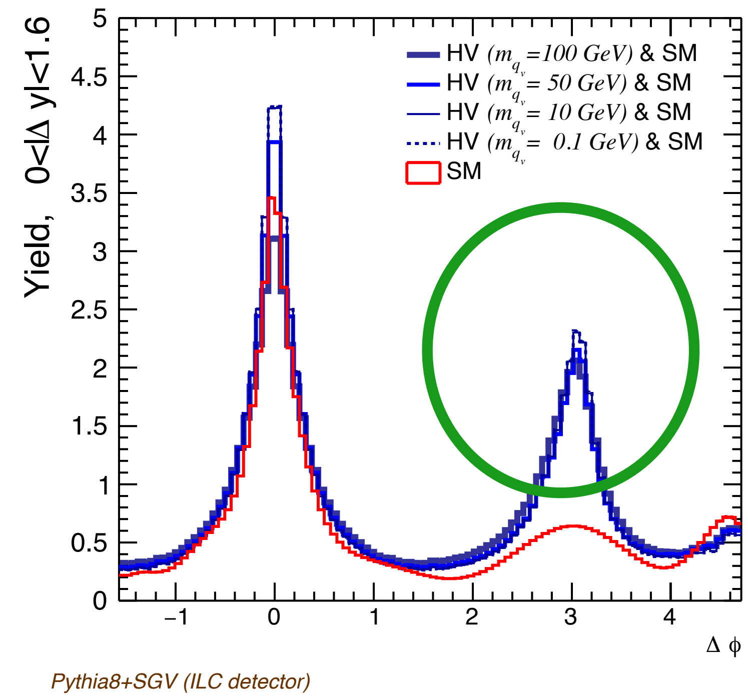
$$Y(\Delta\phi) = \frac{\int_{y_{\text{inf}} \leq |\Delta y| \leq y_{\text{sup}}} S(\Delta y, \Delta\phi) dy}{\int_{y_{\text{inf}} \leq |\Delta y| \leq y_{\text{sup}}} B(\Delta y, \Delta\phi) dy}$$

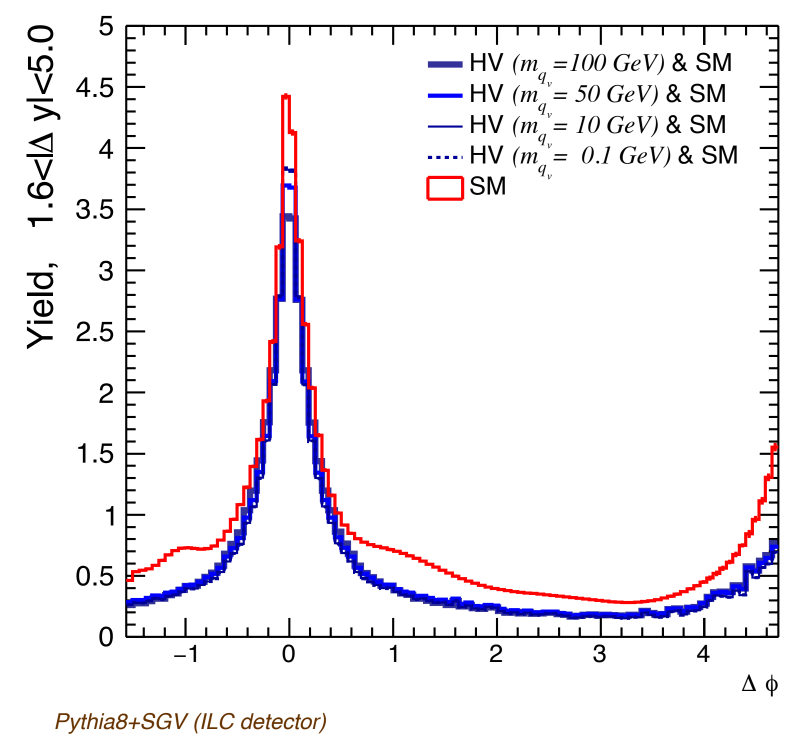
NO CUTS





CUTS

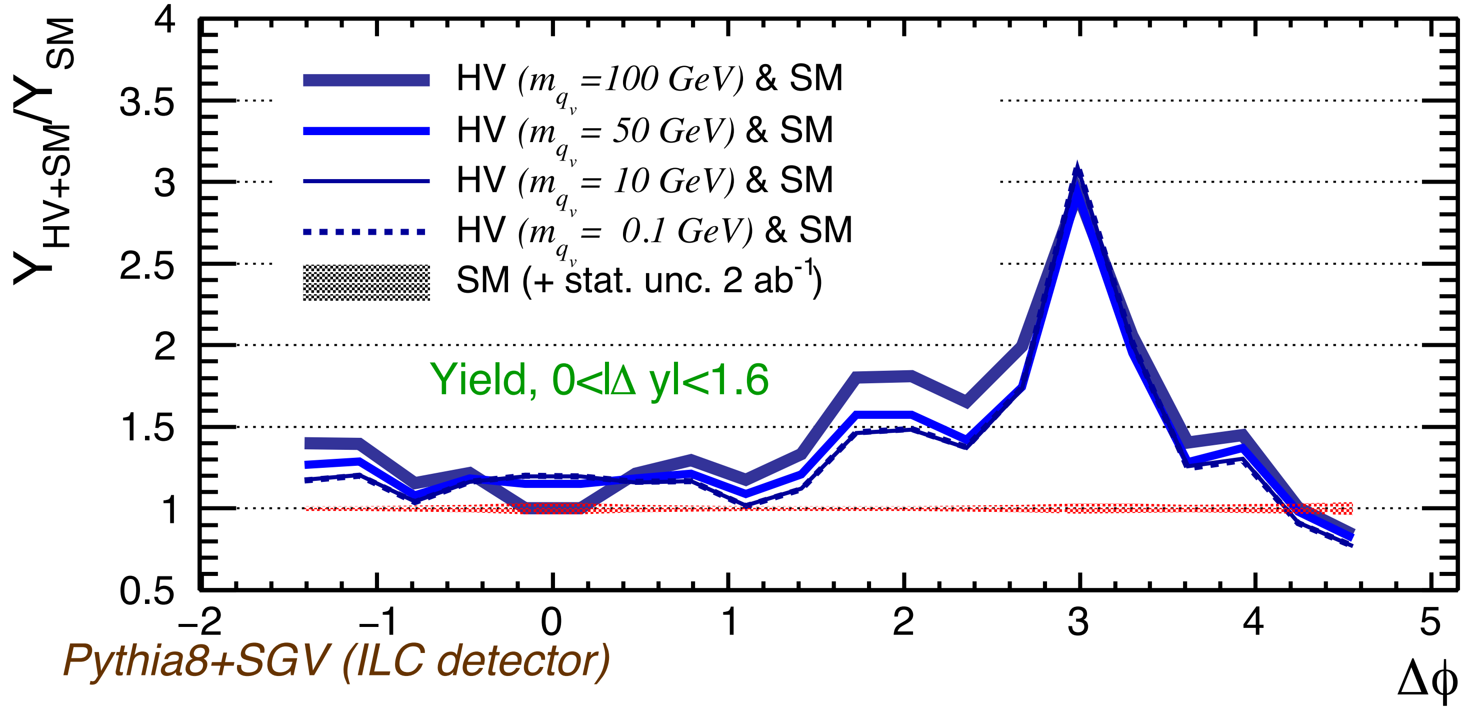


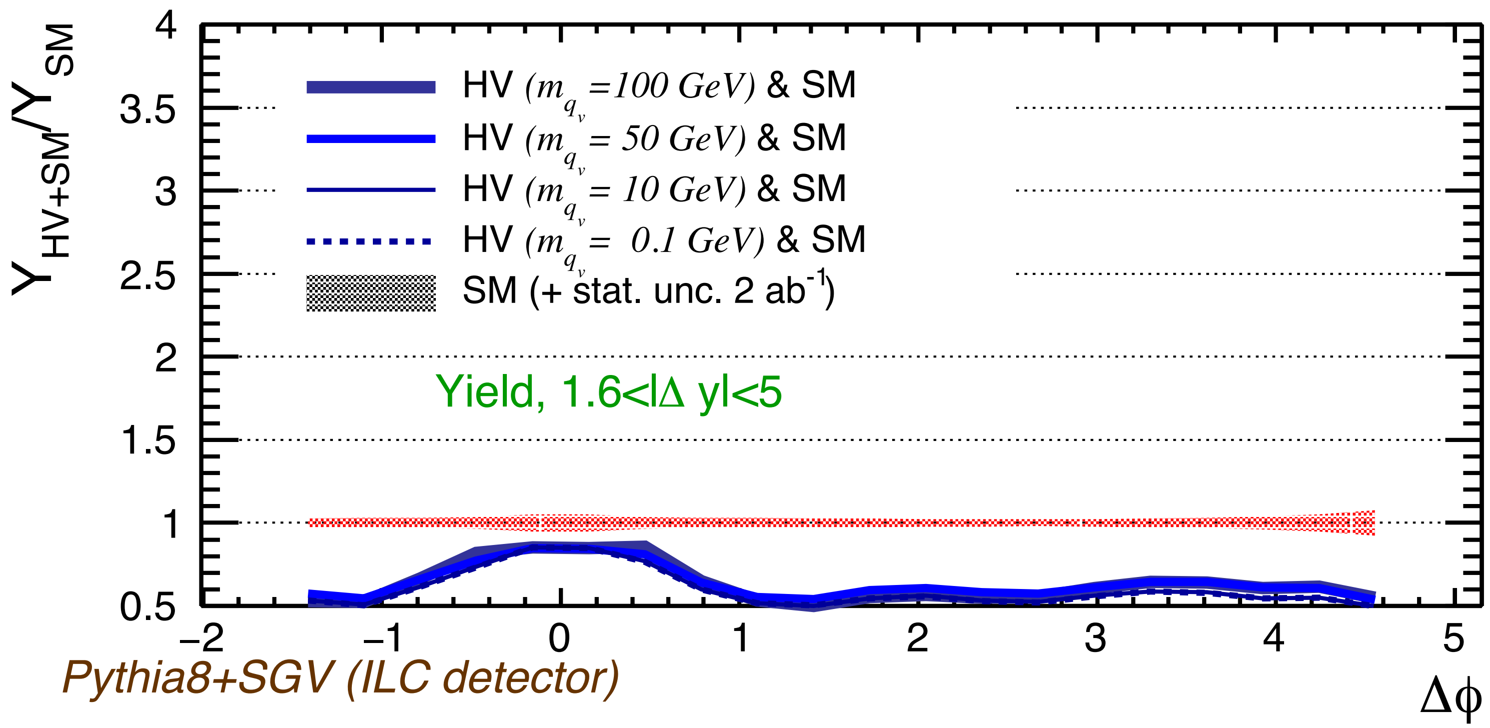


ANALYSIS AT DETECTOR LEVEL

$\sqrt{s} = 250$ GeV, $\mathscr{L} = 2$ 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
$e^+e^- \to D_v\bar{D}_v$	2.4×10^{-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 fusion	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!