Search for New Physics with Multiparticle Correlations and Cosmological Analogies

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Two-particle rapidity correlations

$$C_2(y_1, y_2) = \rho(y_1, y_2) - \rho(y_1)\rho(y_2)$$

← 2-particle rapidity correlation function

$$\rho(y) = \frac{1}{\sigma_{in}} \frac{d\sigma_{in}}{dy}, \ \rho_2(y_1, y_2) = \frac{1}{\sigma_{in}} \frac{d^2\sigma_{in}}{dy_1 dy_2}$$

one- and two-particle densities

$$\int dy_1 dy_2 \, C(y_1, y_2) = D^2 - < n >$$

(= 0 for *independent* emission)

$$K_2(y_1, y_2) = \frac{C_2(y_1, y_2)}{\rho(y_1)\rho(y_2)} = \frac{1}{\sigma_{in}} \frac{d^2\sigma_{in}}{dy_1 dy_2} / \frac{1}{\sigma_{in}{}^2} \frac{d\sigma_{in}}{dy_1} \frac{d\sigma_{in}}{dy_2} - 1$$

$$F_2 = \frac{< n(n-1) >}{< n >^2} = \frac{D^2}{< n >^2} - \frac{1}{< n >} + 1, \quad D^2 = < n^2 > - < n >^2$$

Scaled factorial moment

Generalization to *higher-orders* is straightforward:

I.M.Dremin and W.J.Gary, Phys. Rept.349 (2001) 301

E.A. De Wolf, I.M. Dremin, W. Kittel, Phys. Rep. 270 (1996) 1

2-particle azimuthal and (pseudo)rapitity correlations

$$R(\Delta\eta,\Delta\phi)=\frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}$$

$$\Delta\eta=\eta_1-\eta_2 \quad ; \quad \Delta\phi=\phi_1-\phi_2$$

$S(\Delta\eta, \Delta\phi)$: particle pair distribution from ***the same*** event

$B(\Delta\eta, \Delta\phi)$: particle pair distribution from ***different*** events

Complex structure of 2-dimensional plot in pp, pA and AA collisions

seen by ALICE, ATLAS, and CMS at the LHC

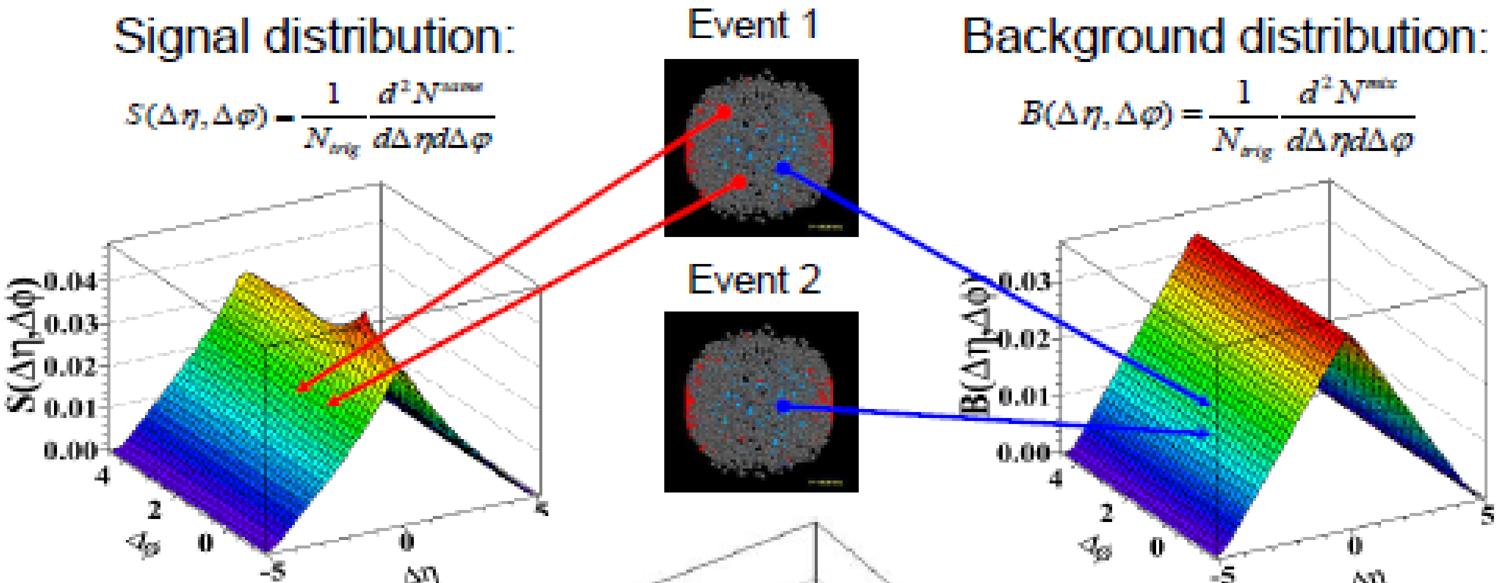
2-particle azimuthal and (pseudo)rapitity correlations

Signal distribution:

$$S(\Delta\eta,\Delta\varphi) = \frac{1}{N_{trig}}\frac{d^2N^{same}}{d\Delta\eta d\Delta\varphi}$$

Background distribution:

$$B(\Delta\eta,\Delta\varphi) = \frac{1}{N_{trig}}\frac{d^2N^{mix}}{d\Delta\eta d\Delta\varphi}$$

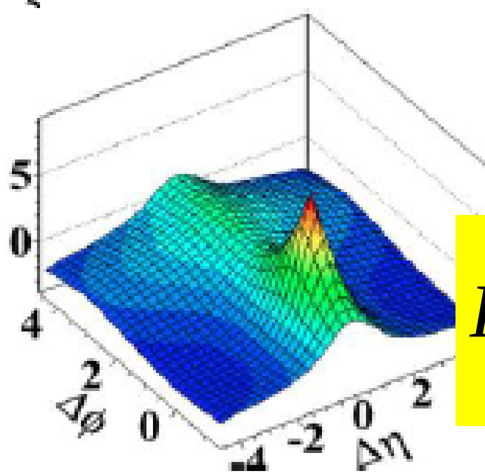


same event pairs

mixed event pairs

$$\Delta\eta = \eta^{assoc} - \eta^{trig}$$

$$\Delta\varphi = \varphi^{assoc} - \varphi^{trig}$$



$$R(\Delta\eta,\Delta\phi) = \frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}$$

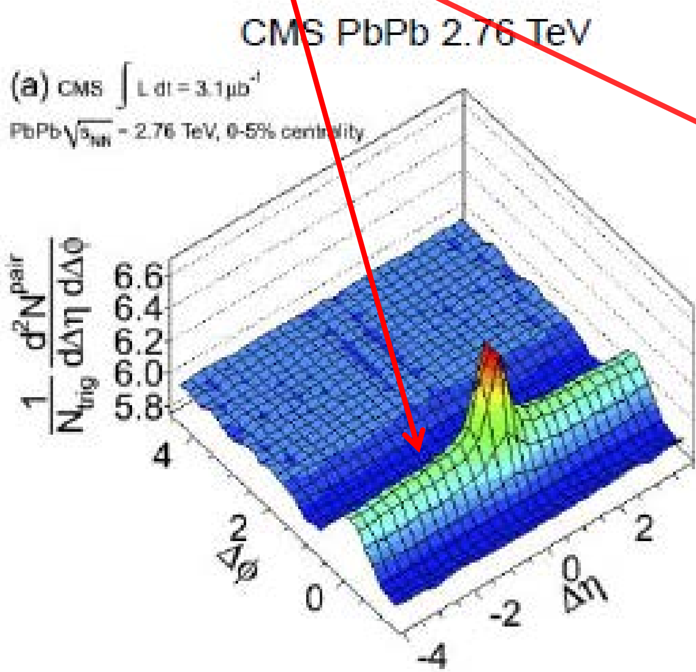
Divide signal by background

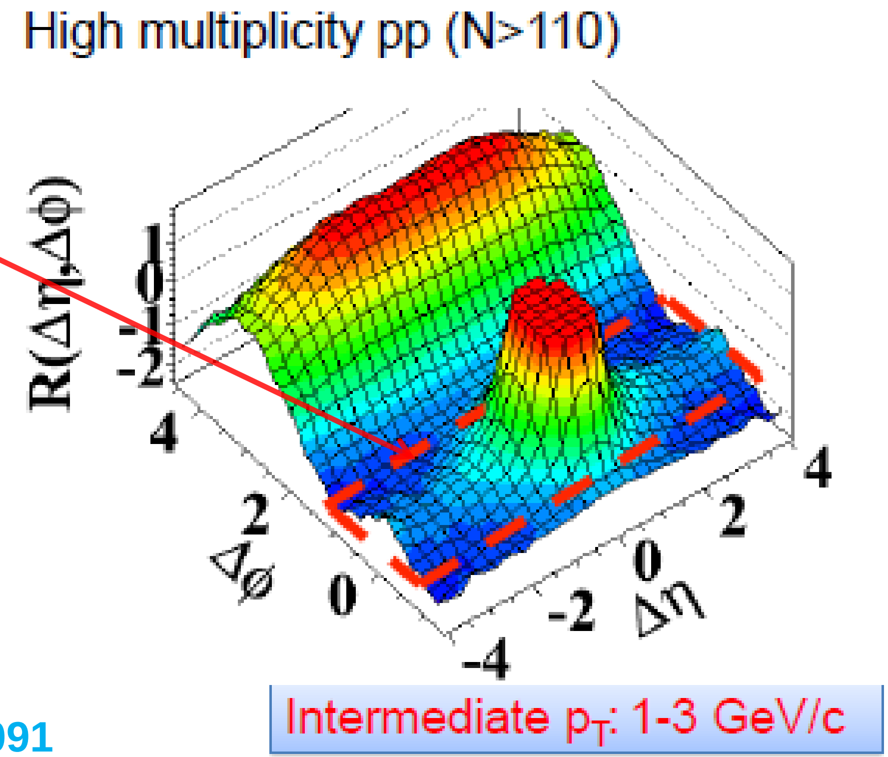
S(Δη, Δϕ): particle pair ***signal*** distribution from ***the same*** event

B(Δη, Δϕ) : particle pair ***background*** distribution from ***different*** events

Ridge structure

``Ridge" structure ***extending over Δη at Δϕ = 0***



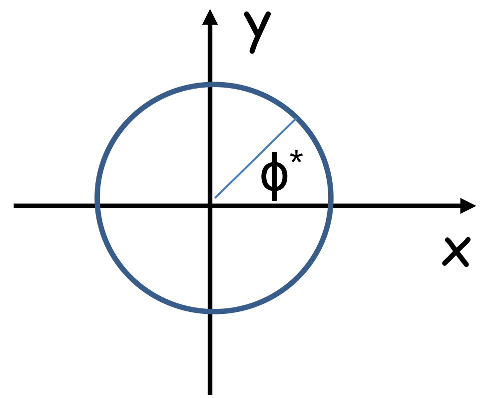


CMS Collab. J. High Energy Phys. 1009 (2010) 091

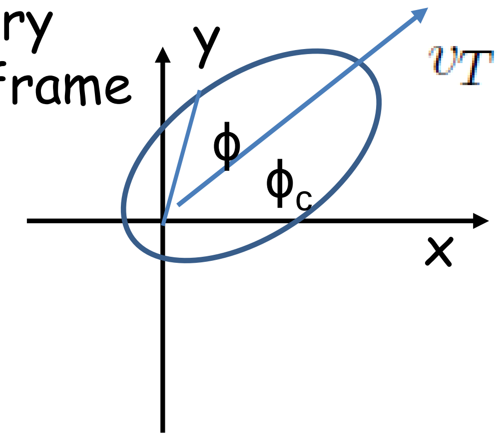
- **Expected in heavy-ion collisions (*hydro, high density*)**
- **Unexpected in pp (and pA) interactions**
- **Similarity in pp *and* heavy-ion collisons!**
- ***No explanation* so far, while many models proposed**

Correlated-cluster model

cluster
reference frame



laboratory
reference frame



Lorentz boost γ_T

- Azimuthal dependence

1) ***Isotropic* cluster emission**

2) ***Isotropic* particle emission in clusters:** $w^*(\phi^*)$ = constant

- **Gaussians** for *cluster and particle* distributions inside clusters

$$\rho^{(c)}(y_c,\phi_c)\ \sim\ \exp\left[-\frac{y_c^2}{2\delta_{cy}^2}\right],\ \rho^{(1)}(y,\phi;y_c,\phi_c)\ \sim\ \exp\left[-\frac{(y-y_c)^2}{2\delta_y^2}\right]\ \exp\left[-\frac{(\phi-\phi_c)^2}{2\delta_\phi^2}\right]$$

The cluster correlation length $\delta_{cy}^2 \gtrsim \delta_y^2 \lesssim 1$ the cluster decay "width",

and the cluster azimuthal decay "width" $\boxed{\delta_\phi\ \sim\ \dfrac{1}{v_T\ \gamma_T}}$

M.-A .Sanchis-Lozano, ESG, Phys. Lett. B 766 (2017) 170

Correlated-cluster model

$$R(\Delta y,\Delta\phi) = \frac{s(\Delta y,\Delta\phi)}{b(\Delta y,\Delta\phi)}$$

$$= \frac{s^{\rm SR}(\Delta y,\Delta\phi) + s^{\rm LR}(\Delta y,\Delta\phi)}{b(\Delta y,\Delta\phi)} = 1 + \frac{h^{\rm SR}(\Delta y,\Delta\phi)}{\langle N_{\rm c}\rangle} + \frac{\langle N_{\rm c}(N_{\rm c}-1)\rangle}{\langle N_{\rm c}\rangle^2}\, h^{\rm LR}(\Delta\phi)$$

Reduces at large $\langle N_c \rangle$

Short-range contribution:

$$h^{\rm SR}(\Delta y,\Delta\phi) = \frac{e_{\rm s}^{\rm SR}(\Delta y,\Delta\phi)}{e_{\rm b}(\Delta y,\Delta\phi)} = \exp\left[-\frac{(\Delta y)^2}{4\delta_y^2}\right]\exp\left[-\frac{(\Delta\phi)^2}{4\delta_\phi^2}\right]$$

Long-range contribution:

$$h^{\rm LR}(\Delta y,\Delta\phi) = \frac{e_{\rm s}^{\rm LR}(\Delta y,\Delta\phi)}{e_{\rm b}(\Delta y,\Delta\phi)} \simeq \cancel{\exp\left[-\frac{(\Delta y)^2}{4(\delta_y^2+\delta_{cy}^2)}\right]}\exp\left[-\frac{(\Delta\phi)^2}{2(2\delta_\phi^2+\delta_{c\phi}^2)}\right]$$

near-side ridge

For $\delta^2_{cy} \gg \delta^2_y$

≈ 0.1 radians ($p_T \approx 1$ GeV)

MAIN RESULT: **The *ridge* effect of 2-particle *correlations at small Δφ over a wide (pseudo)rapidity range* is naturally explained within a model of clusters *correlated in the transverse plane***

M.-A .Sanchis-Lozano, ESG, Phys. Lett. B 766 (2017) 170

3-particle correlations

$$C_3(1,2,3) = \rho_3(1,2,3) + 2\rho(1)\rho(2)\rho(3) - \rho_2(1,2)\rho(3) - \rho_2(2,3)\rho(1) - \rho_2(1,3)\rho(2)$$

$$\rho_3(y_1, y_2, y_3, \phi_1, \phi_2, \phi_3) \;=\; \frac{1}{\sigma_{\rm in}} \, \frac{d^6\sigma}{dy_1 dy_2 dy_3 d\phi_1 d\phi_2 d\phi_3} \, .$$

3-partice density

Correlation function ratio:

$$c_3(\vec{\Delta y}, \vec{\Delta\phi}) = \frac{s_3 + 2b_3 - s_{123} - s_{231} - s_{132}}{b_3} \, ,$$

$\vec{\Delta y}, \vec{\Delta\phi}$ for $\Delta y_{ij}, \Delta\phi_{ij}$

, $\vec{y} = (y_1, y_2, y_3)$, $\vec{\phi} = (\phi_1, \phi_2, \phi_3)$

Signal (*s*):

$$s_3(\vec{\Delta y}, \vec{\Delta\phi}) \;=\; \int d\vec{y}\; d\vec{\phi}\; \vec{\delta}(\Delta y)\; \vec{\delta}(\Delta\phi)\; \rho_3(\vec{y}, \vec{\phi})$$

$$d\vec{y}\; d\vec{\phi} \;= dy_1 dy_2 dy_2\; d\phi_1 d\phi_2 d\phi_3$$

$$\vec{\delta}(\Delta y) = \delta(\Delta y_{12} - y_1 + y_2)\; \delta(\Delta y_{13} - y_1 + y_3)$$

Background (*b*):

$$b_3(\vec{\Delta y}, \vec{\Delta\phi}) \;=\; \int d\vec{y}\; d\vec{\phi}\; \vec{\delta}(\Delta y)\; \vec{\delta}(\Delta\phi)\; \rho(y_1, \phi_1)\; \rho(y_2, \phi_2)\; \rho(y_3, \phi_3)$$

$$s_{123}(\vec{\Delta y}, \vec{\Delta\phi}) \;=\; \int d\vec{y}\; d\vec{\phi}\; \vec{\delta}(\Delta y)\; \vec{\delta}(\Delta\phi)\; \rho(y_1, \phi_1)\; \rho_2(y_2, \phi_2, y_3, \phi_3)$$

+ permutations

M.-A .Sanchis-Lozano, ESG,
Phys. Rev. D 96 (2017) 074012

Correlated-cluster model: 3 clusters

$$c_3(\vec{\Delta y},\vec{\Delta\phi}) = \frac{s_3^{(1)}(\vec{\Delta y},\vec{\Delta\phi}) + s_3^{(2)}(\vec{\Delta y},\vec{\Delta\phi}) + s_3^{(3)}(\vec{\Delta y},\vec{\Delta\phi})}{b_3(\vec{\Delta y},\vec{\Delta\phi})}$$

$$= \frac{1}{\langle N_c\rangle^2} h^{(1)}(\vec{\Delta y},\vec{\Delta\phi}) + \frac{\langle N_c(N_c-1)\rangle}{\langle N_c\rangle^3} h^{(2)}(\vec{\Delta y},\vec{\Delta\phi}) + \frac{\langle N_c(N_c-1)(N_c-2)\rangle}{\langle N_c\rangle^3} h^{(3)}(\vec{\Delta y},\vec{\Delta\phi})$$

Reducing at large ‹Nc›

ridge effect

Three-particle three-cluster contribution

for $\delta^2_{cy} >> \delta^2_y$ and $\delta^2_{c\Phi} >> \delta^2_\Phi$

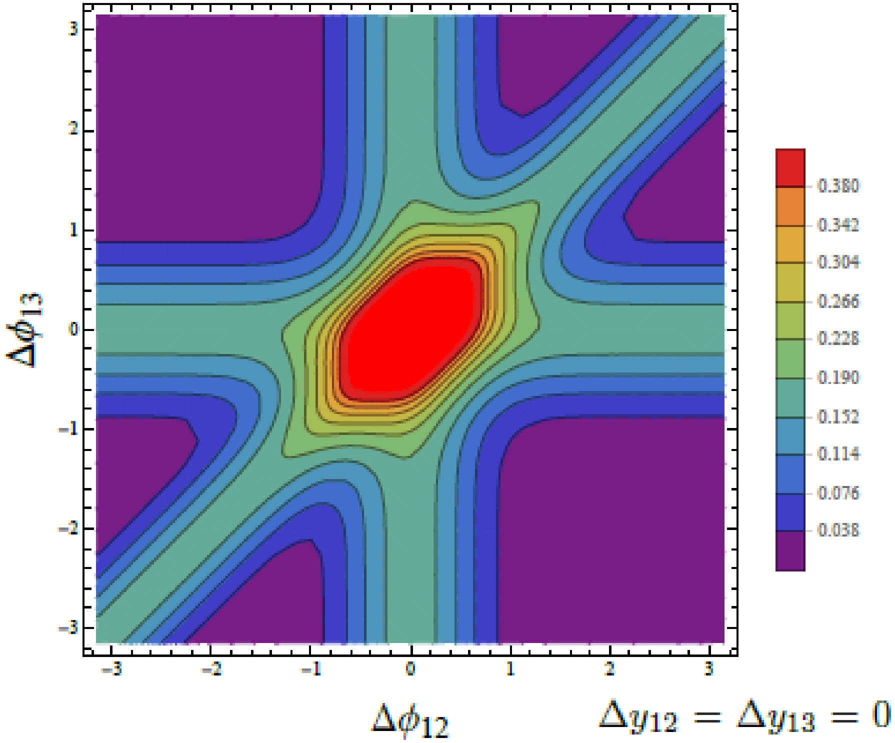
$$h^{(3)}(\Delta y_{12},\Delta y_{13},\Delta\phi_{12},\Delta\phi_{13}) \sim \exp\left[\frac{(\Delta y_{12})^2 + (\Delta y_{13})^2 + -(\Delta y_{12})(\Delta y_{13})}{3\delta^2_{cy}}\right]$$

$$\times\left(\exp\left[-\frac{(\Delta\phi_{12})^2 + (\Delta\phi_{13})^2 - \Delta\phi_{12}\Delta\phi_{13}}{\delta^2_{c\phi}}\right] + \exp\left[-\frac{(\Delta\phi_{12})^2}{2\delta^2_{c\phi}}\right] + \exp\left[-\frac{(\Delta\phi_{13})^2}{2\delta^2_{c\phi}}\right] + \exp\left[-\frac{(\Delta\phi_{12})^2 + (\Delta\phi_{13})^2 - 2\Delta\phi_{12}\Delta\phi_{13}}{2\delta^2_{c\phi}}\right]\right)$$

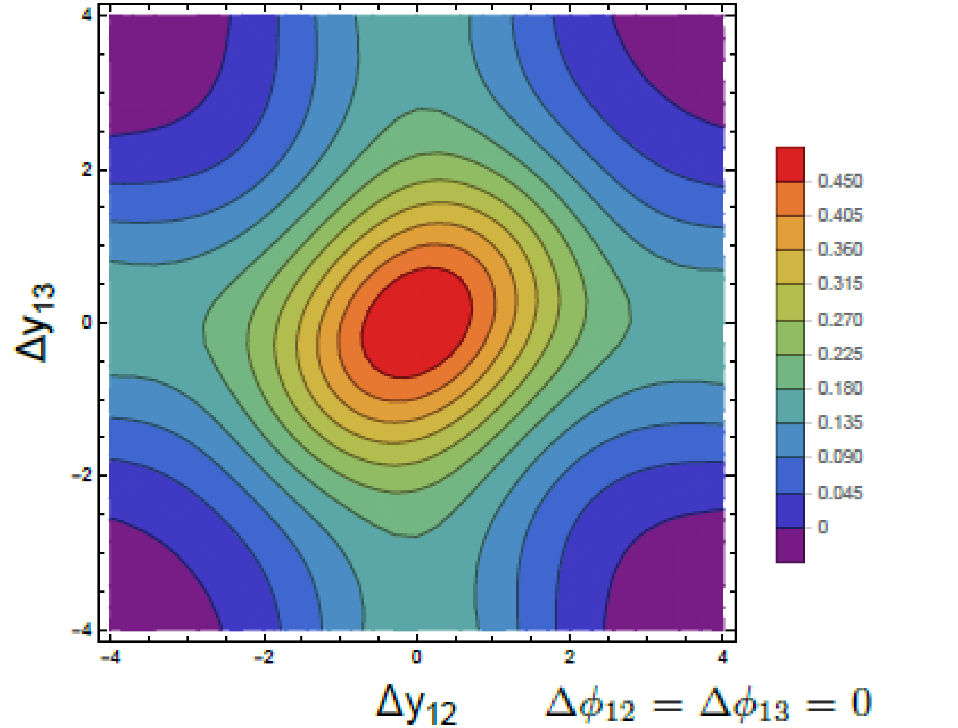
MAIN RESULT: The *ridge effect* of 3-particle *correlations at small Δφ over a wide (pseudo)rapidity range* is natural and to be observed as predicted in *model of clusters correlated in the transverse plane*

M.-A .Sanchis-Lozano, ESG, Phys. Rev. D 96 (2017) 074012

Correlated clusters: 3-part. contour plots



$\Delta y_{12} = \Delta y_{13} = 0$



$\Delta\phi_{12} = \Delta\phi_{13} = 0$

$\delta_y = 0.9,\ \delta_{cy} = 4,\ \delta_\phi = 0.14,\ \delta_{c\phi} = 0.5,$

Left panel: ***structured asymmetric*** **two-dimensional plot, results from the** ***two correlation scales*** **–** ***a short-range*** **azimuthal correlation scale set by** ***single cluster decay*** **vs.** ***long-range*** **correlation length** ***from*** $h^{(3)}$ ***term of three cluster formation*****, the** ***ridge effect due to transversly correlated-cluster emission***

Right panel: **rather** ***structureless*** **plot dominating by** ***sinlge cluster decay*** **short-range correlation scale**

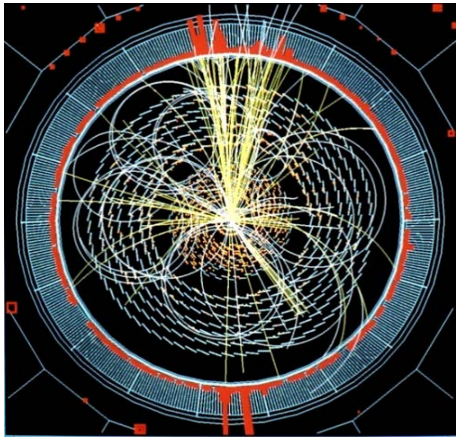
M.-A .Sanchis-Lozano, ESG, Phys. Rev. D 96 (2017) 074012

Usually expected signatures of New Physics @ LHC

Mainly on the <u>transverse plane</u>:

> Lower background

> Expected signatures such as
- high-p_T jets, leptons or photons
- missing transverse energy/momentum
- displaced vertices …
- mass peaks



LHC potential must be fully used

***Novel* signals should not be overlooked however, e.g.**

- related to multiparticle production (***soft*** physics)
- **but *tagged by hard signals***

diffuse signal

May be helpful for ***discovery*** of a new stage of matter (**Hidden/Dark Sector**) manifesting in the parton cascade of high-energy pp collisions.

Not an easy task!

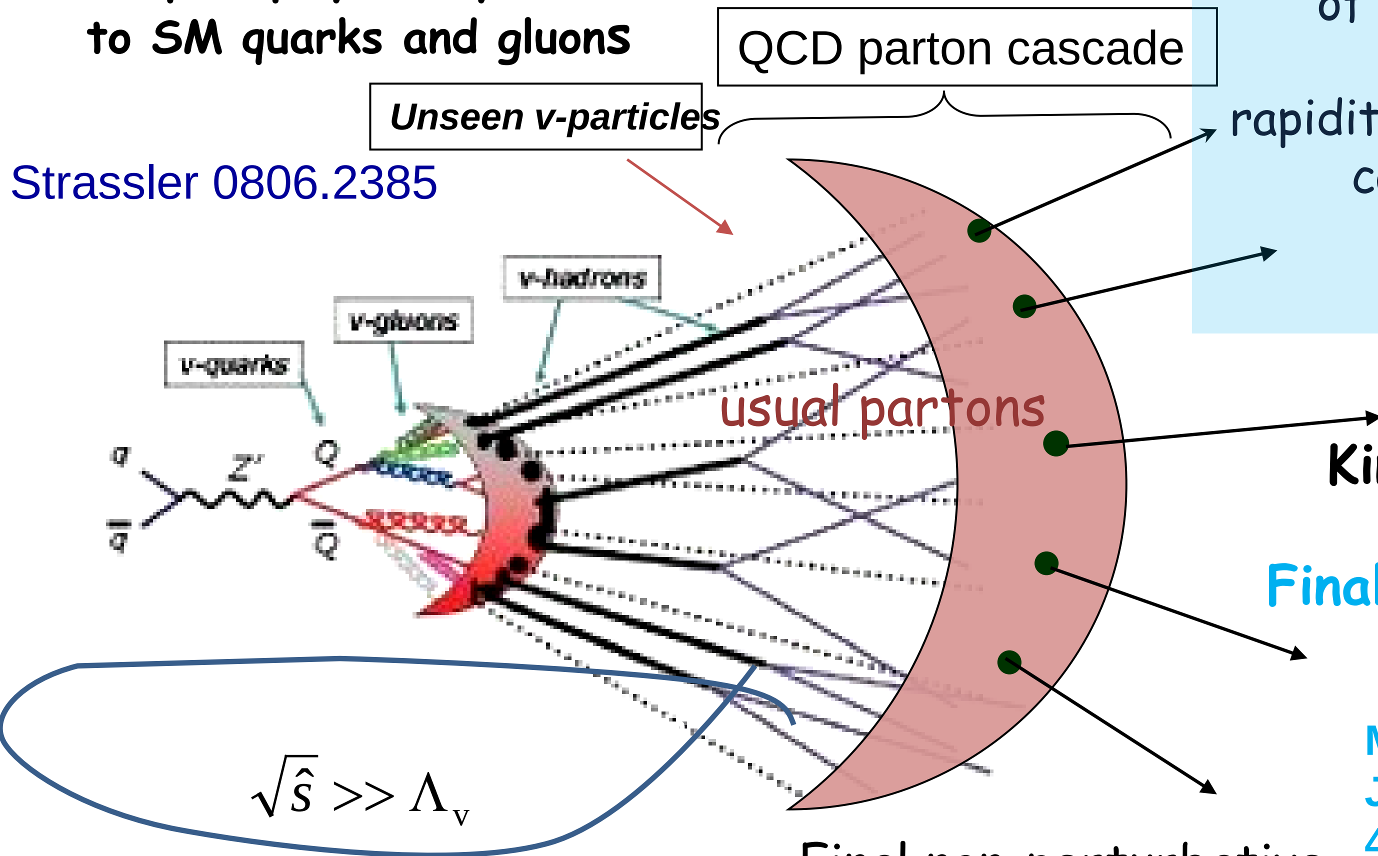
Techniques related to the quest for QGP in heavy-ion collisions

Hidden Valley + SM shower

Depending on the model parameters

Some v-particles can be stable, decay outside the detectors, **or promptly decay back to SM quarks and gluons**

Strassler 0806.2385



Final non-perturbative hadronization

Multiplicity distributions of final state particles and rapidity/azimuthal correlations can be affected by the extra step in the cascade

Kind of diffuse signal

Final state SM particles

M.-A .Sanchis-Lozano, Int. J. Mod Phys. A24 (2009) 4529

One more (and different) step than in conventional QCD-parton showers

Estimates

$$M_h \approx 350-1000\,\text{TeV}, \quad \Lambda_h \approx 10-100\,\text{GeV}$$

M.-A .Sanchis-Lozano, ESG,
Phys. Rev. D 102 (2020) 035013

$$t_h = \frac{M_h}{\Lambda_h^2} (\approx 1\,fm) \qquad t_f = \frac{\Lambda_h}{\Lambda_{QCD}^2} + \frac{M_h}{\Lambda_h^{\,2}} \approx 5-10\,fm$$

$$\phi_0 = \frac{2\pi}{\ln\left(t_f / t_h\right)} \approx \pi \text{ radians} = 180^0$$

Very long range azimuthal correlations can be expected!

Maximum angle (causality) in a linearly expanding universe

Such long range azimuthal correlations suggest uncovering the existence of a hidden/dark matter stage on top of the QCD parton cascade

M.-A .Sanchis-Lozano, ESG,
MDPI Physics 1 (2019) 84

Effect of NP contribution in 3-step cascade

Two-particle density $$\frac{1}{\sigma_{\rm in}}\frac{d^2\sigma}{d\phi_1 d\phi_2} = \int d\phi_{\rm s}\ \rho^{\rm (s)}(\phi_{\rm s})$$

$$\times \left[\int d\phi_{\rm c}\ \rho^{\rm (c)}(\phi_{\rm c};\phi_{\rm s})\ \rho_2^{(1)}(\phi_1,\phi_2;\phi_{\rm c}) + \int d\phi_{\rm c1}d\phi_{\rm c2}\ \rho_2^{\rm (c)}(\phi_{\rm c1},\phi_{\rm c2};\phi_{\rm s})\ \rho^{(1)}(\phi_1;\phi_{\rm c1})\rho^{(1)}(\phi_2;\phi_{\rm c2})\right]$$

$$+ \int d\phi_{\rm s1}d\phi_{\rm s2}\ \rho_2^{\rm (s)}(\phi_{\rm s1},\phi_{\rm s2})$$

$$\rho_2^{\rm (s)}(\phi_{\rm s1},\phi_{\rm s2}) \approx e^{-\frac{(\phi_{s1}-\phi_{s2})^2}{2\delta_{s\phi}^2}}$$

$$\times \int d\phi_{\rm c1}d\phi_{\rm c2}\ \rho^{\rm (c)}(\phi_{\rm c1};\phi_{\rm s1})\ \rho^{\rm (c)}(\phi_{\rm c2};\phi_{\rm s2})\ \rho^{(1)}(\phi_1,\phi_{\rm c1})\ \rho_1^{(1)}(\phi_2;\phi_{\rm c2})$$

We use again Gaussians to parametrize the effect of a hidden/dark sector

$$C(\Delta\phi) \approx \exp\left[-\frac{(\Delta\phi)^2}{2\underbrace{(\delta_{s\phi}{}^2 + 2\delta_{c\phi}^2 + 2\delta_{\phi}^2)}_{\delta_{s\phi}^2}}\right] \quad , \quad \delta_{s\phi}{}^2 >> \delta_{c\phi}{}^2 >> \delta_{\phi}{}^2$$

M.-A .Sanchis-Lozano, ESG, Phys. Lett. B 781 (2018) 505

3-particle correlations in 3-step cascade

Focusing on azimuthal variable

$$\frac{1}{\sigma_{\rm in}}\frac{d^3\sigma}{d\phi_1 d\phi_2 d\phi_3} = \int d\phi_s\, \rho^{(\rm s)}(\phi_s)$$

$$\times \Big[\rho^{(\rm c)}(\phi_c;\phi_s)\ \rho_3^{(1)}(\phi_1,\phi_2,\phi_3;\phi_c) + \rho_2^{(\rm c)}(\phi_{c1},\phi_{c2};\phi_s)\ \rho^{(1)}(\phi_1;\phi_{c1})\rho_2^{(1)}(\phi_2,\phi_3;\phi_{c2})$$

$$+ \rho_3^{(\rm c)}(\phi_{c1},\phi_{c2},\phi_{c3};\phi_s)\ \rho^{(1)}(\phi_1;\phi_{c1})\rho^{(1)}(\phi_2;\phi_{c2})\rho^{(1)}(\phi_3;\phi_{c3})\Big] + \int d\phi_{s1} d\phi_{s2}\ \rho_2^{(\rm s)}(\phi_{s1},\phi_{s2})$$

$$\times \Big\{\Big[\rho^{(\rm c)}(\phi_{c1};\phi_{s1})\ \rho^{(\rm c)}(\phi_{c2};\phi_{s2})\ \rho^{(1)}(\phi_1,\phi_{c1})\ \rho_2^{(1)}(\phi_2,\phi_3;\phi_{c2},\phi_{c3}) + \ \text{combinations}\Big]$$

$$\Big[+\ \rho^{(\rm c)}(\phi_{c1};\phi_{s1})\ \rho_2^{(\rm c)}(\phi_{c2},\phi_{c3};\phi_{s2})\ \rho^{(1)}(\phi_1;\phi_{c1})\ \rho^{(1)}(\phi_2;\phi_{c2})\ \rho^{(1)}(\phi_3;\phi_{c3}) + \ \text{combinations}\Big]\Big\}$$

$$+ \int d\phi_{s1} d\phi_{s2} d\phi_{s3}\ \rho_3^{(\rm s)}(\phi_{s1},\phi_{s2},\phi_{s3})$$

$$\times \Big[\rho^{(\rm c)}(\phi_{c1};\phi_{s1})\ \rho^{(\rm c)}(\phi_{c2};\phi_{s2})\ \rho^{(\rm c)}(\phi_{c3};\phi_{s3})\ \rho^{(1)}(\phi_1;\phi_{c1})\ \rho^{(1)}(\phi_2;\phi_{c2})\ \rho^{(1)}(\phi_3;\phi_{c3})\Big]$$

$$\Delta y_{12} = y_1 - y_2 \quad , \quad \Delta y_{12} = y_1 - y_2, \quad \Delta\phi_{12} = \phi_1 - \phi_2 \quad , \quad \Delta\phi_{13} = \phi_1 - \phi_3$$

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3-particle correlations from three hidden sources

$$c_3(\Delta\phi_{12},\Delta\phi_{13}) = \frac{1}{\langle N_s\rangle^2} h^{(1)}(\Delta\phi_{12},\Delta\phi_{13}) + \frac{1}{\langle N_s\rangle} h^{(2)}(\Delta\phi_{12},\Delta\phi_{13}) + h^{(3)}(\Delta\phi_{12},\Delta\phi_{13})$$

Reducing at large $\langle N_c \rangle$

Three-particle contribution from three hidden sources

for $\delta^2_{s\Phi} >> \delta^2_{c\Phi} >> \delta^2_{\Phi}$

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

$$+\;\exp\left[-\frac{(\Delta\phi_{12})^2}{2(2\delta^2_{c\phi}+\delta^2_{s\phi})}\right] + \exp\left[-\frac{(\Delta\phi_{13})^2}{2(2\delta^2_{c\phi}+\delta^2_{s\phi})}\right] + \exp\left[-\frac{(\Delta\phi_{12})^2+(\Delta\phi_{13})^2-2\Delta\phi_{12}\Delta\phi_{13}}{2(2\delta^2_{c\phi}+\delta^2_{s\phi})}\right]$$

MAIN RESULT: The *effect of NP to be observed* in the three-particle correlations on top of the ridge phenomenon is predicted in the model of clusters *correlated in the transverse plane*

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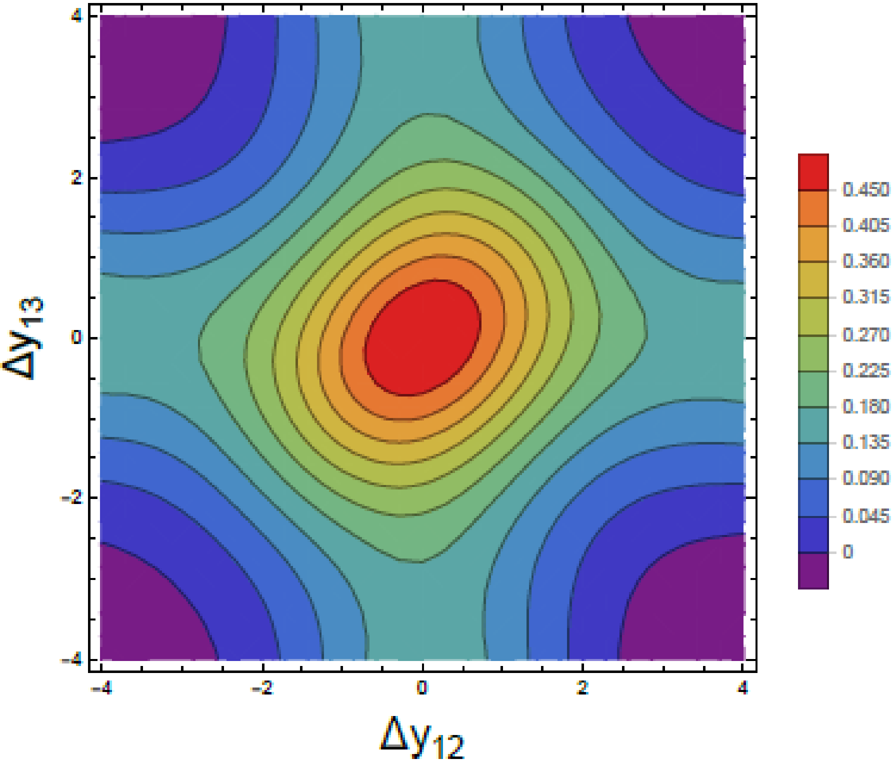
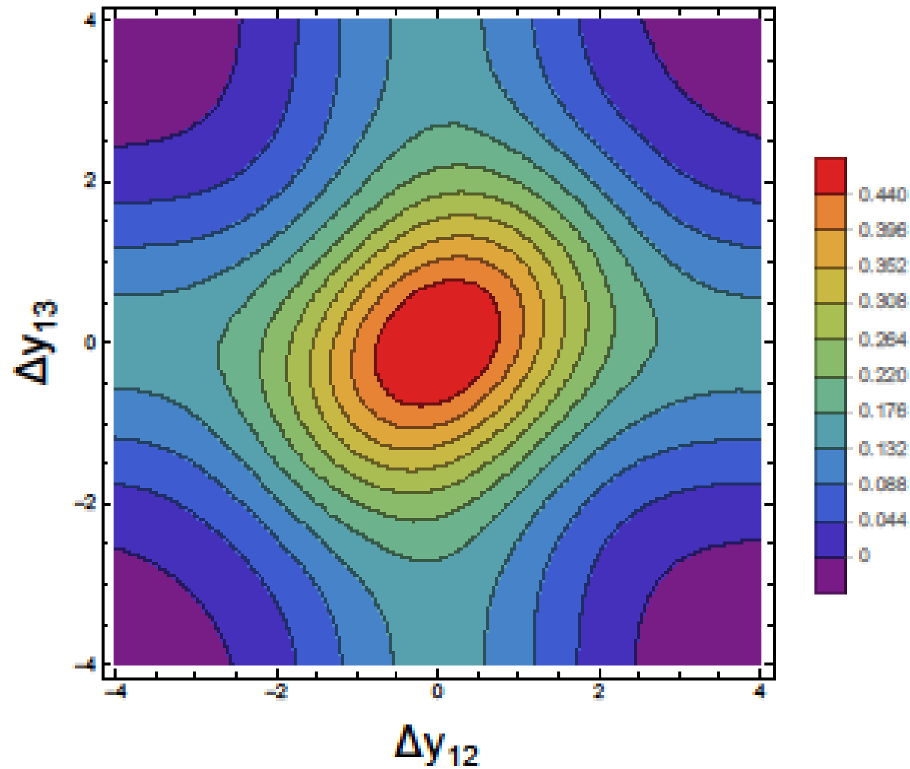
Three-particle pseudorapidity correlations



Almost no difference

NEW PHYSICS



SM

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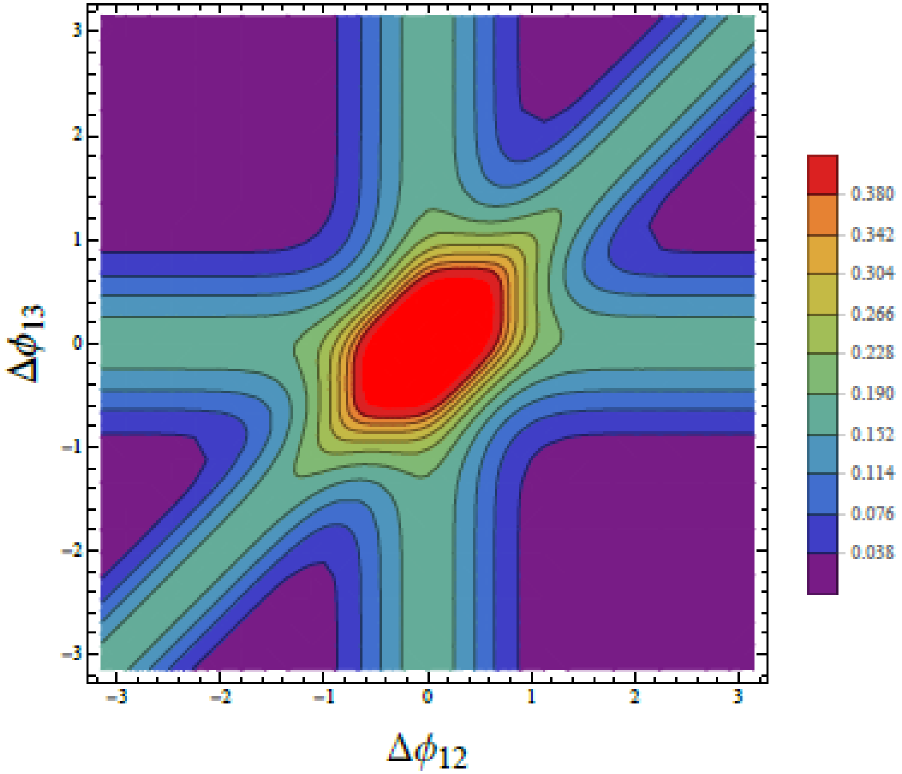
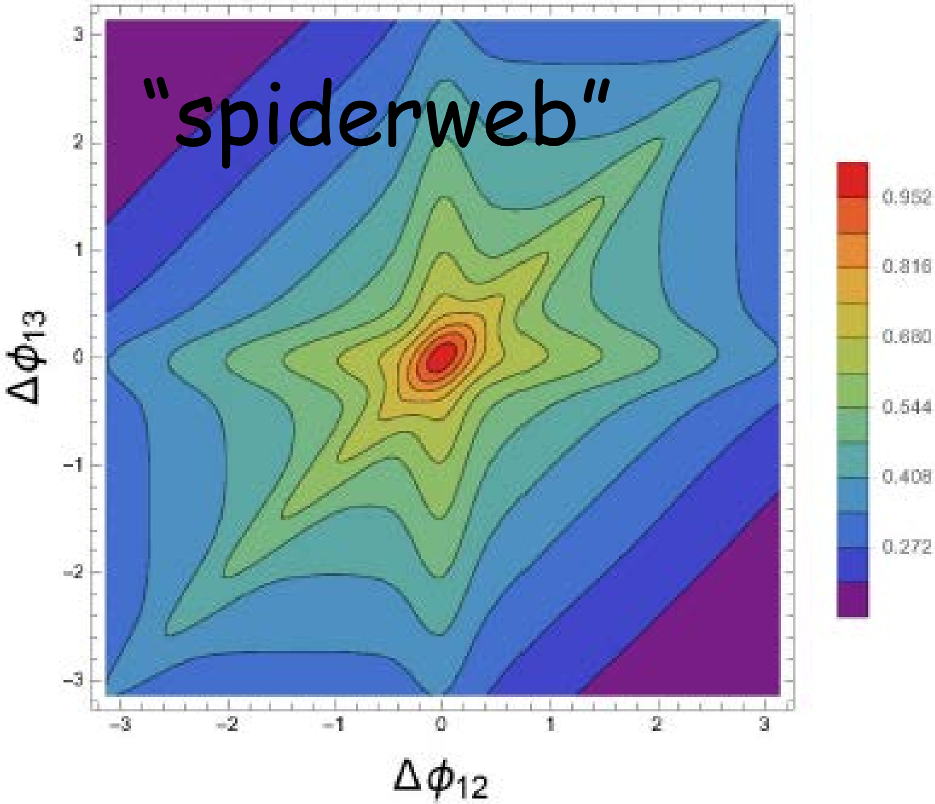
Three-particle azimuthal correlations



NEW PHYSICS



SM

NP effects should rather manisfest in azimuth!

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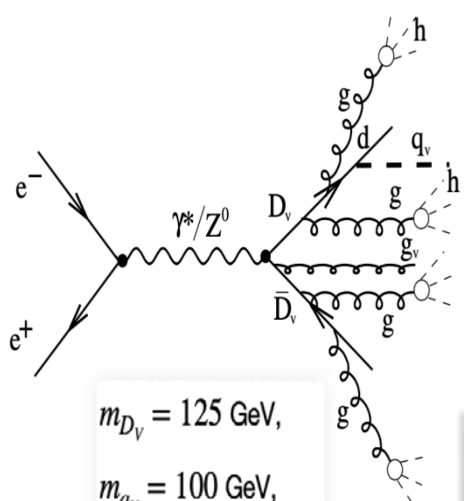
Signal vs background

QCD-like scenario

The HV particles have to be pair-produced

SIGNAL

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



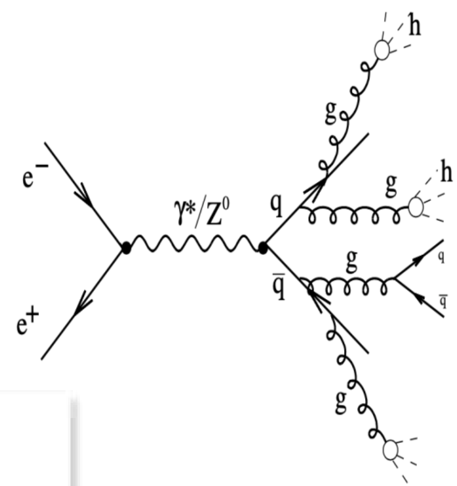
$m_{D_V} = 125$ GeV,

$m_{q_V} = 100$ GeV,

$\alpha_V = 0.1$

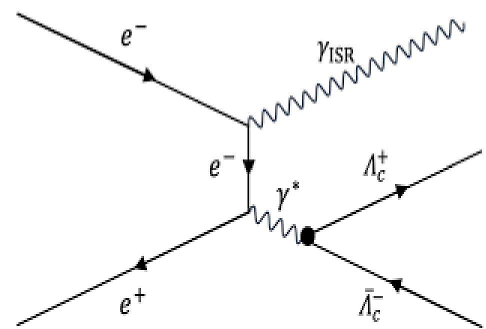
BACKGROUND

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



TOOLS:
- Pythia8
- FastJet
- ROOT

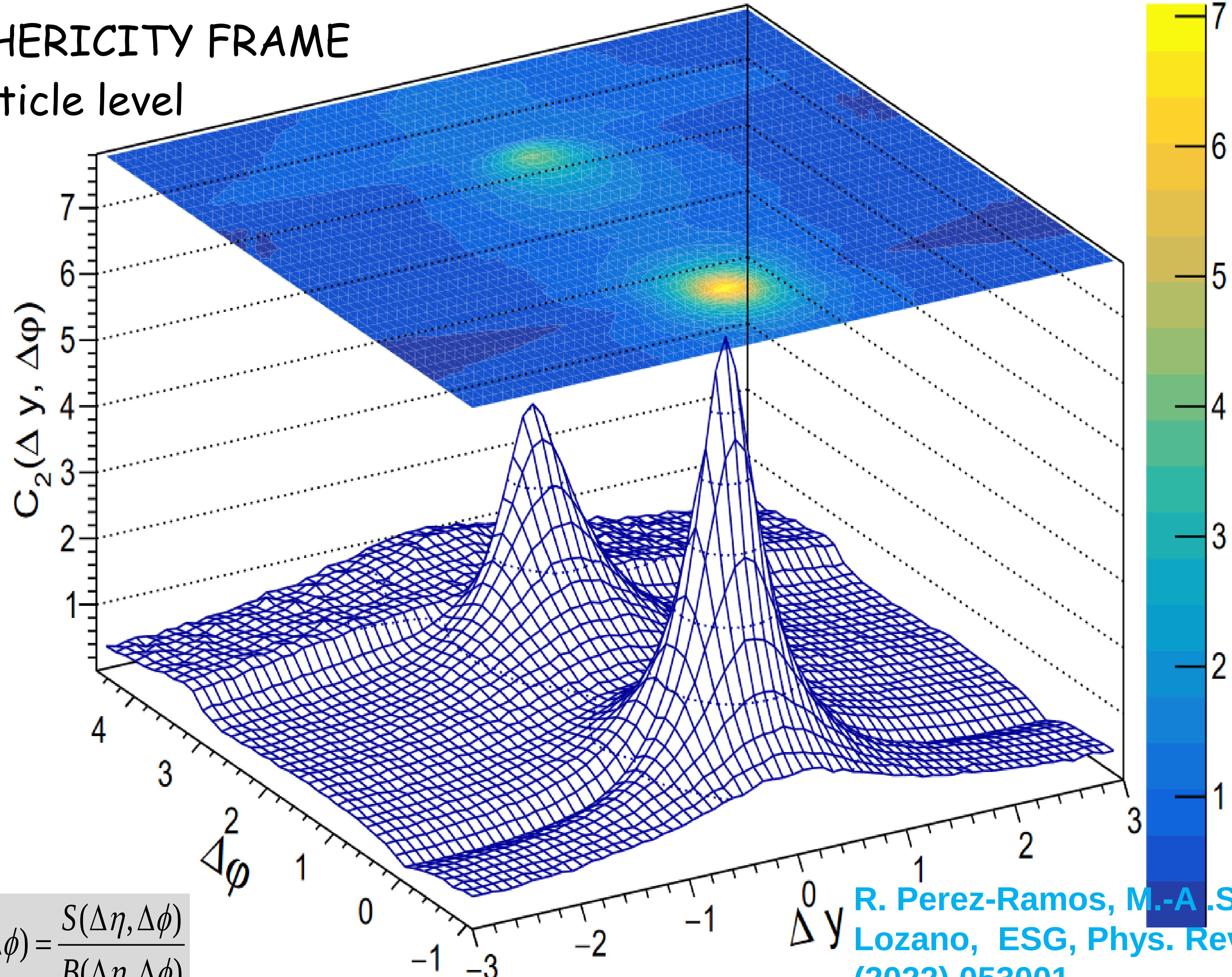
We take into account the ISR contribution



Pythia8, $e^+e^- \to q\bar{q}(n_f=5) \to$ hadrons at $\sqrt{s}=250$ GeV, $0.5 \le p_t(\mathrm{GeV}/c) \le 5.0$ & $N_{ch} \ge 10$

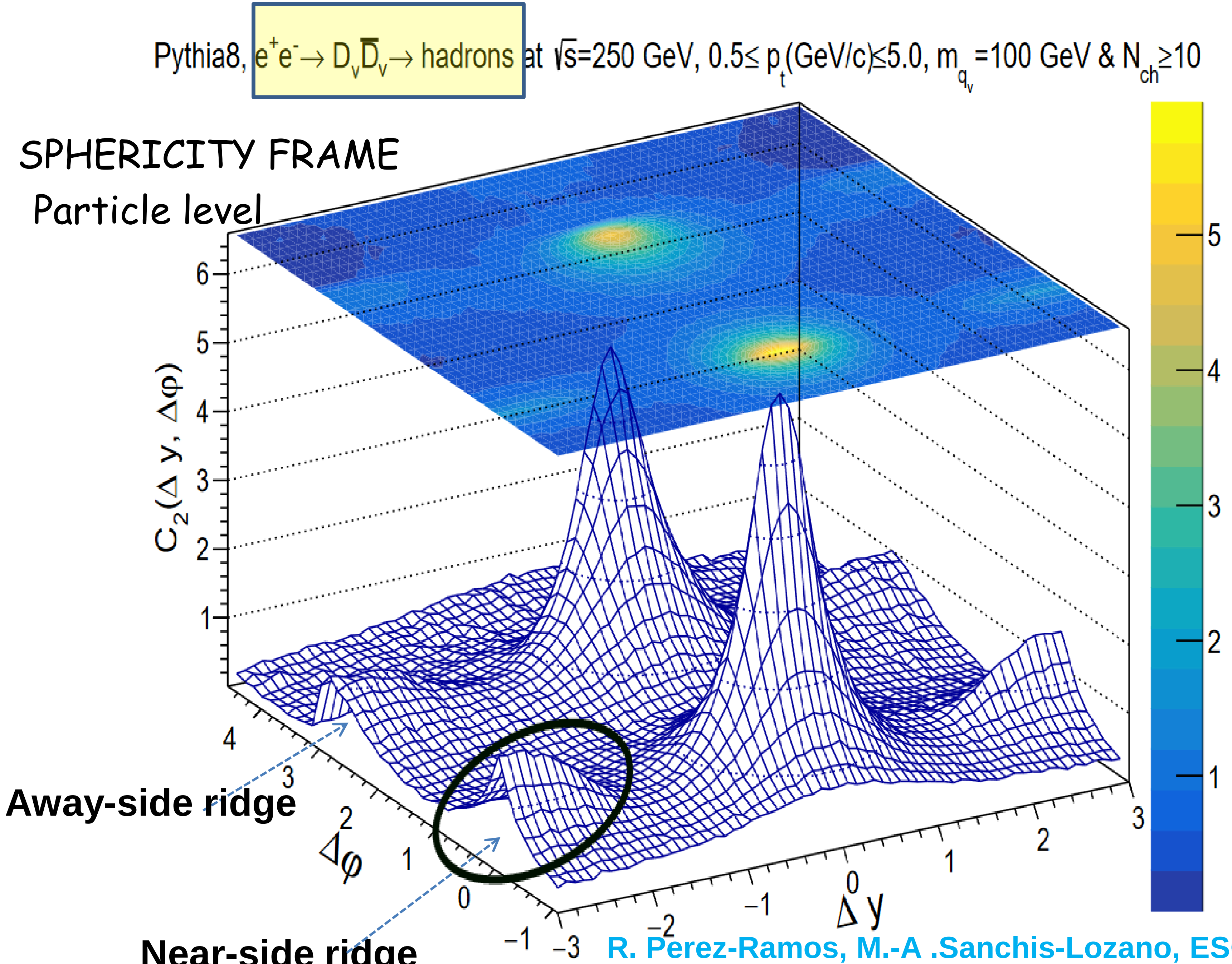
SPHERICITY FRAME

Particle level



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

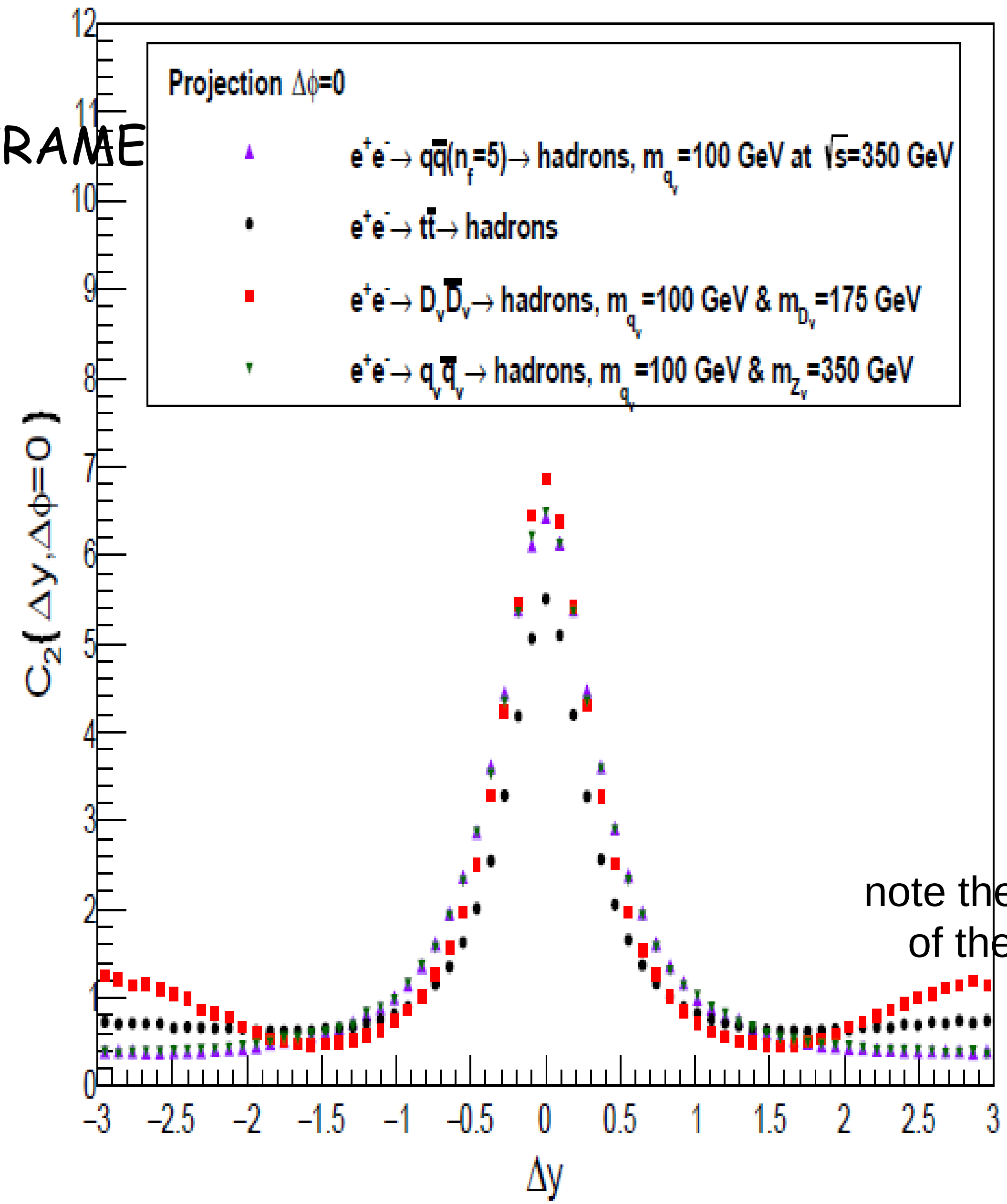
R. Perez-Ramos, M.-A .Sanchis-Lozano, ESG, Phys. Rev. D 105 (2022) 053001



R. Perez-Ramos, M.-A .Sanchis-Lozano, ESG,
Phys. Rev. D 105 (2022) 053001

SPHERICITY FRAME

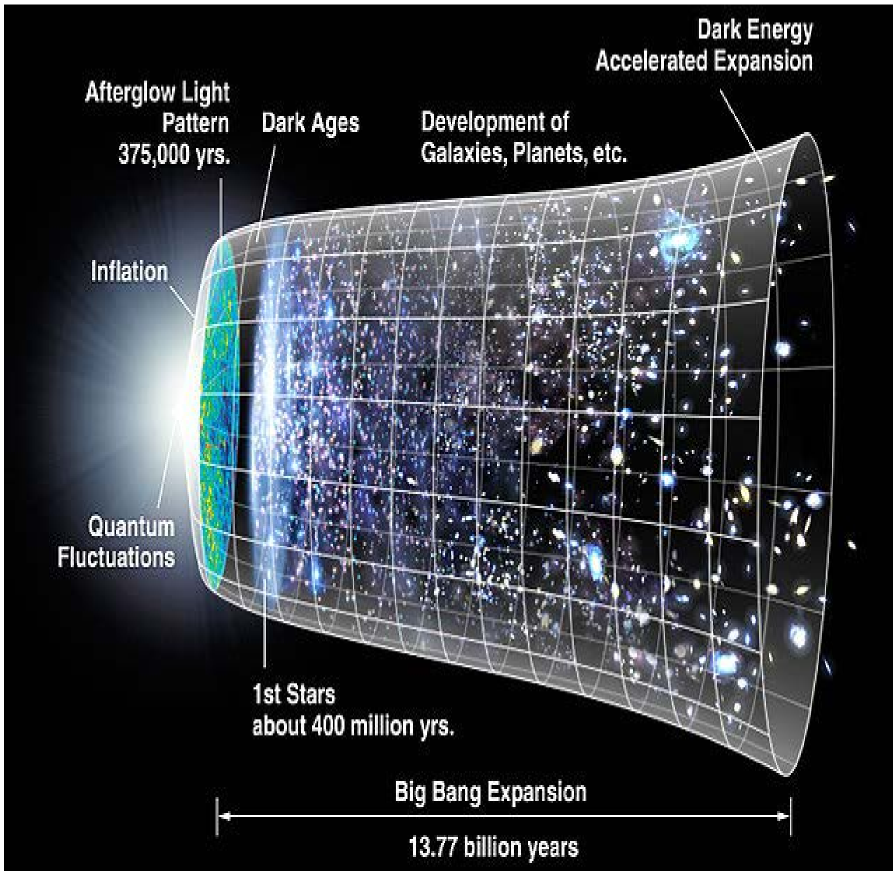
Particle level

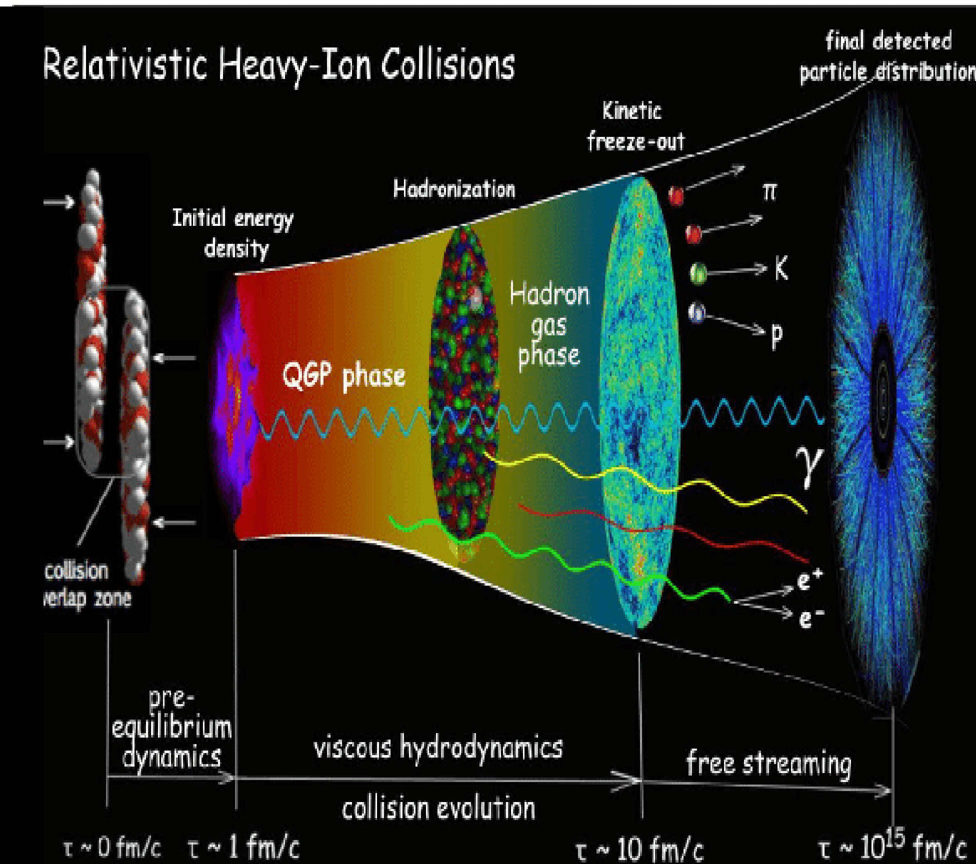


note the interpolating position of the top-antitop channel

R. Perez-Ramos, M.-A .Sanchis-Lozano, ESG,
Phys. Rev. D 105 (2022) 053001

Heavy-ion collision analogy with universe evolution

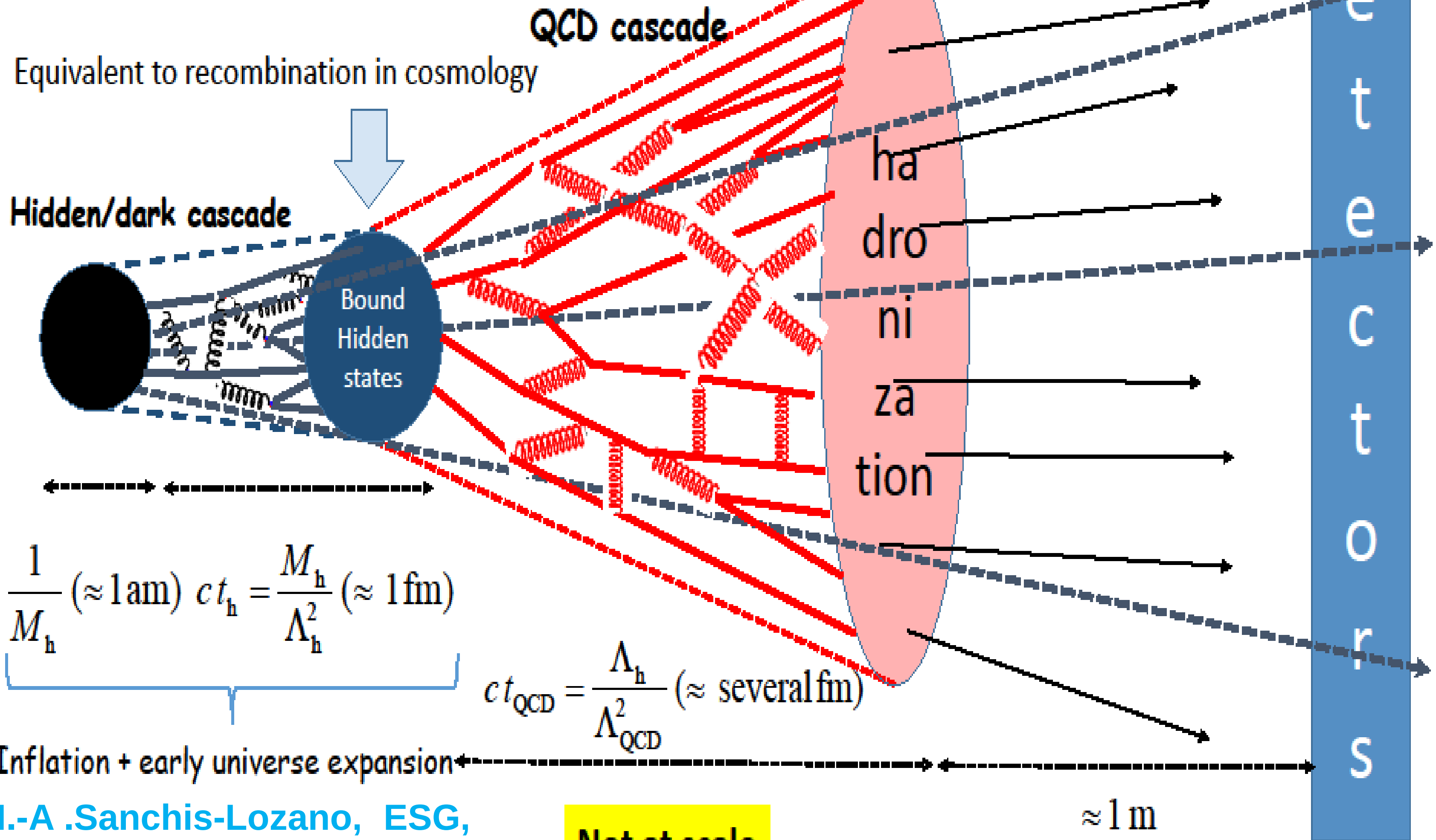




Analogy with high-energy collisions

High-energy collisions

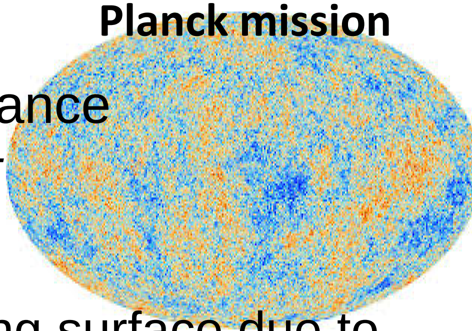
$$ct \approx \frac{E}{Q_0^{\,2}}, \quad E = \text{energy of the initial parton}, \; Q_0 = \text{final virtuality}$$



M.-A .Sanchis-Lozano, ESG,
Phys. Rev. D 102 (2020) 035013

Not at scale

Cosmic analogy of pp collisions



Maximum fluctuation distance at any cosmic time t

$$C(\cos\theta) \equiv \langle T(\hat{\mathbf{n}}_1)T(\hat{\mathbf{n}}_2)\rangle = \frac{1}{4\pi}\sum_l (2l+1)C_l P_l(\cos\theta)\,.$$

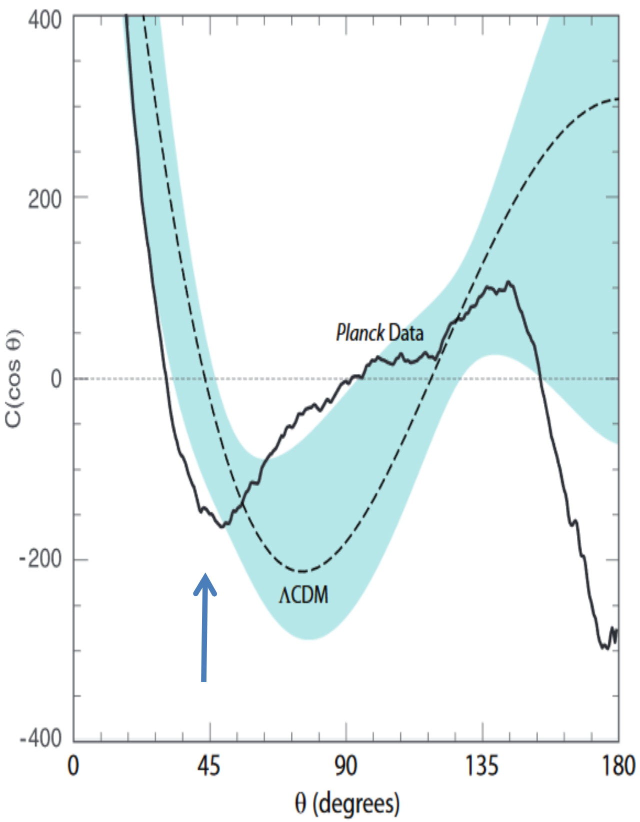
$$\lambda_{\max}(t) = 2\,\pi\,R(t)$$

$$R_h = c\,t \;\text{ universe}$$

F. Melia, arXiv:1207.0015 [astro-ph.CO]

The distance to the last scattering surface due to the expansion is given by

$$\text{Linear}: \; a(t) = \frac{t_f}{t} \qquad r_{rec} = c\int_{t_{rec}}^{t_f}\frac{dt'}{a(t')} = ct_f\int_{t_{rec}}^{t_f}\frac{dt'}{t'} = ct_f\ln\left(\frac{t_f}{t_{rec}}\right)$$



The maximum angular size of any fluctuation associated to the last scattering surface should be of order

$$\theta_{\max} = \frac{\lambda_{\max}(t_{rec})}{R(t_{rec})}$$

where the proper distance to the last scattering surface is

$$R(t_{rec}) = a(t_{rec})\,r_{rec} = a(t_{rec})\,c\,t_f\ln\left(\frac{t_f}{t_{rec}}\right) = c\,t_{rec}\ln\left(\frac{t_f}{t_{rec}}\right)$$

$$\boxed{\theta_0 = \frac{2\pi}{\ln\left(t_f/t_{rec}\right)} \approx \frac{\pi}{4}\,\text{rad} \approx 45^0}$$

$$t_{rec} = 380000 \text{ years}$$

$$t_f = 1.38 \text{ Gyears}$$

Conclusions

- **A model of the clusters correlated in the transverse plane provides an explanation of the two-particle *ridge* effect and predicts the ridge phenomenon to hold in three particle correlations**

- **New physics (hidden/dark sector) signatures are shown to be directly tested by experiments using (multi)particle correlations (with the selection cuts *to enhance* NP effect)**

- **An intriguing common explanation is proposed upon the assumption of an unconventional early state: an expanding universe before recombination/decoupling up to present days vs formation of hidden/dark states in high energy collisions followed by QCD cascade to hadrons**

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THANK YOU!

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