The generalised spectral structure of QFT correlators

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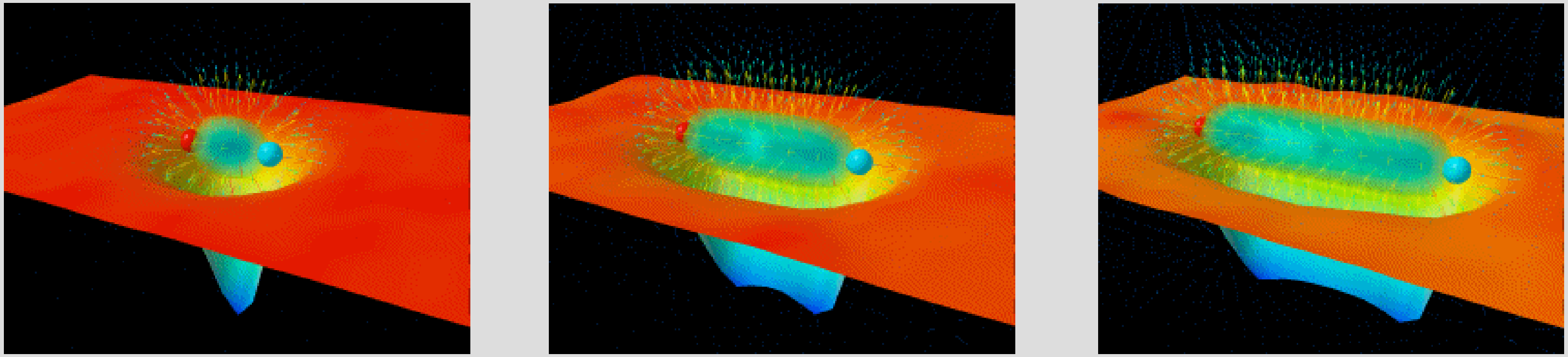
Outline

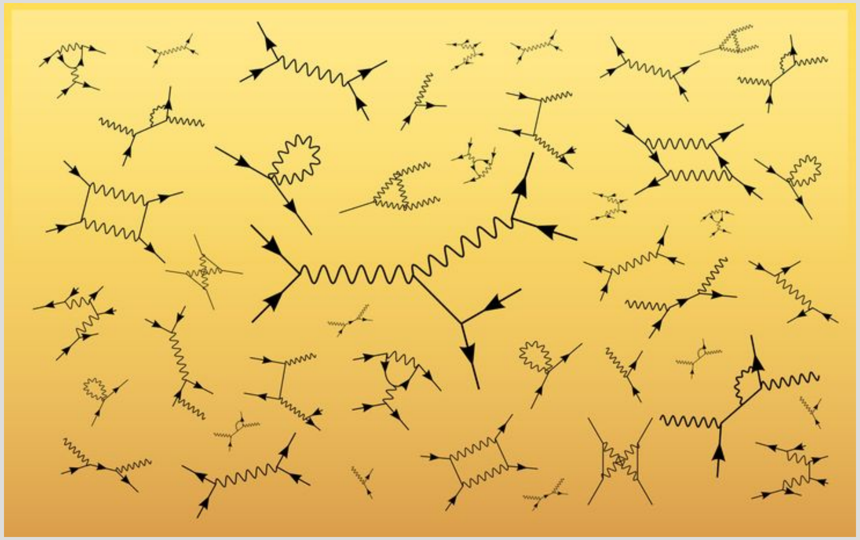
1. Local QFT: an axiomatic approach
2. Correlation functions in local QFT
3. Confinement and the CDP
4. The gluon propagator
5. Summary and outlook



[The University of Adelaide (2015)]

1. Local QFT: an axiomatic approach

- Perturbation theory has proven to be an extremely successful tool for investigating problems in particle physics



But by definition this procedure is only valid in a ***weakly interacting regime***

$\rightarrow$ Form factors?

$\rightarrow$ Parton distribution functions?

$\rightarrow$ Convergence of perturbative series?

- This emphasises the need for a non-perturbative approach!

$\rightarrow$ **Local QFT** is one such approach

1. Local QFT: an axiomatic approach

- Local QFT approaches are defined by a core set of axioms:

Axiom 1 (Hilbert space structure). *The states of the theory are rays in a Hilbert space $\mathcal{H}$ which possesses a continuous unitary representation $U(a,\alpha)$ of the Poincaré spinor group $\overline{\mathscr{P}_+^\uparrow}$.*

Axiom 2 (Spectral condition). *The spectrum of the energy-momentum operator P^μ is confined to the closed forward light cone $\overline{V}^+ = \{p^\mu \mid p^2 \geq 0,\, p^0 \geq 0\}$, where $U(a,1) = e^{iP^\mu a_\mu}$.*

Axiom 3 (Uniqueness of the vacuum). *There exists a unit state vector $|0\rangle$ (the vacuum state) which is a unique translationally invariant state in $\mathcal{H}$.*

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$$U(a,\alpha)\varphi_i^{(\kappa)}(x)U(a,\alpha)^{-1} = S_{ij}^{(\kappa)}(\alpha^{-1})\varphi_j^{(\kappa)}(\Lambda(\alpha)x + a)$$

where $S(\alpha)$ is a finite dimensional matrix representation of the Lorentz spinor group $\overline{\mathscr{L}_+^\uparrow}$, and $\Lambda(\alpha)$ is the Lorentz transformation corresponding to $\alpha \in \overline{\mathscr{L}_+^\uparrow}$.

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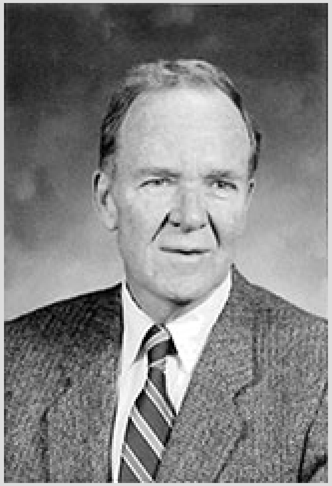
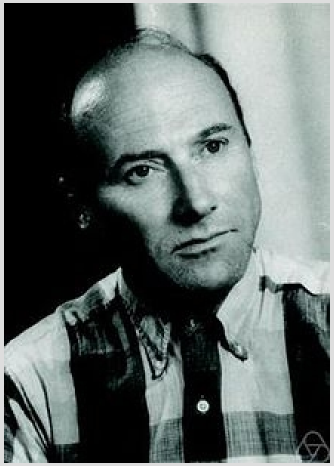


A. Wightman

[R. F. Streater and A. S. Wightman, *PCT, Spin and Statistics, and all that* (1964).]



R. Haag

[R. Haag, *Local Quantum Physics*, Springer-Verlag (1996).]

1. Local QFT: an axiomatic approach

- The central idea with Local QFT is that these axioms are <u>physically motivated</u>

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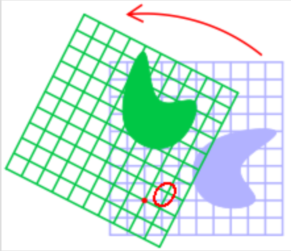
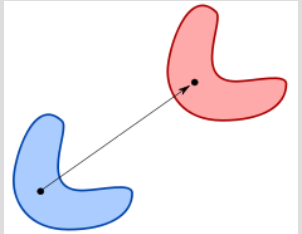
when applied to any state in $\mathcal{H}$, *for any fields* $\varphi_l^{(\kappa)}, \varphi_m^{(\kappa')}$.

"The theory is invariant under Poincaré transformations"





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when applied to any state in $\mathcal{H}$, for any fields $\varphi^{(\kappa)}_l, \varphi^{(\kappa')}_m$.

"Energy is bounded from below – the theory is stable"

1. Local QFT: an axiomatic approach

- The central idea with Local QFT is that these axioms are physically motivated

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Axiom 3 (**Uniqueness of the vacuum**). *There exists a unit state vector $|0\rangle$ (the vacuum state) which is a unique translationally invariant state in $\mathcal{H}$.*

“The vacuum state is unique and looks the same to all observers”

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"Quantum fields φ are operator-valued distributions"

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"Connect the permitted physical states with the field degrees of freedom"

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"Causality!"

2. Correlation functions in local QFT

- Despite their simplicity, the axioms of local QFT have many important consequences:

  $\rightarrow$ Correlation functions $\boxed{\langle 0|\varphi^{(\kappa_1)}_{l_1}(x_1)\cdots\varphi^{(\kappa_n)}_{l_n}(x_n)|0\rangle}$ are distributions

  $\rightarrow$ ***Reconstruction Theorem*** – a QFT can be reconstructed from knowledge of *all* the correlators

  $\rightarrow$ Spin-statistics theorem, *CPT* theorem, connection of Minkowski and Euclidean QFTs, existence of scattering states, ...

- Things become more complicated in gauge theories!

"Local Gauss law"

$$\boxed{\partial^{\nu} G^{a}_{\mu\nu} = J^{a}_{\mu}}$$

(i) *Preserve positivity, lose locality (e.g. Coulomb gauge QED)*

(ii) *Preserve locality, lose positivity (e.g. Landau gauge QCD)*

2. Correlation functions in local QFT

- For the remainder of this talk we will focus on option (ii)
- The local Gauss law implies that all charged fields are *non-local*

  $\rightarrow$ To recover locality one modifies this equation, lifting this restriction, but maintains the constraint for **physical** states

$$\boxed{\langle \mathrm{phys}|\partial^{\nu}G^{a}_{\mu\nu} - J^{a}_{\mu}|\mathrm{phys}\rangle = 0}$$

$$\boxed{\partial^{\mu}A^{(+)}_{\mu}|\mathrm{phys}\rangle = 0}$$ ***Gupta-Bleuler (QED)***

$$\boxed{Q_B|\mathrm{phys}\rangle = 0}$$ ***BRST (QCD)***

- This procedure necessarily introduces both zero and negative norm (ghost) states into the theory!
- Modifies QFT axioms $\rightarrow$ ***Pseudo-Wightman*** approach [Bogolubov et al.]

[N. N. Bogolubov, A. A. Logunov, A. I. Oksak and I. T. Todorov, General Principles of Quantum Field Theory, (1990).]

2. Correlation functions in local QFT

- In the Pseudo-Wightman approach many of the previous axioms are maintained, except now the full space of states is not positive-definite
- Determining the effect that this change has on the characteristics of QFTs is essential for unravelling the dynamics of gauge theories
- In particular, this can help in understanding the *non-perturbative* structure of QCD correlators

QCD correlators

- Dyson-Schwinger, Bethe-Salpeter equations, FRGEs
- Enter into the calculation of bound-state observables; meson spectra, decay constants, glueball masses,…
- QCD phase diagram: effects of finite temperature and density
- Confinement

2. Correlation functions in local QFT

→ ***What is the general structure of a Pseudo-Wightman correlation function?***

- Due to the Lorentz transformation property of the fields the Fourier transform of any field correlator can be written

$$\boxed{\widehat{T}_{(1,2)}(p) = \mathcal{F}\left[\langle 0|\phi_1(x)\phi_2(y)|0\rangle\right] = \sum_{\alpha=1}^{\mathcal{N}} Q_\alpha(p)\,\widehat{T}_{\alpha(1,2)}(p)}$$

Lorentz covariant polynomial

Lorentz invariant component

- The spectral condition implies that the Lorentz invariant components must *vanish* outside the (closed) forward light cone ($p^2 \geq 0$, $p^0 \geq 0$)

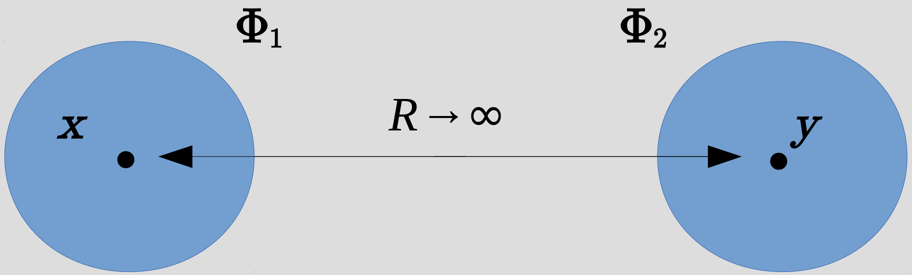
$$\boxed{\widehat{T}_{\alpha(1,2)}(p) = P(\partial^2)\delta(p) + \int_0^\infty ds\,\theta(p^0)\delta(p^2 - s)\rho_\alpha(s)}$$

Purely singular component

Spectral function

3. Confinement and the CDP

- For non-gauge theories satisfying the standard local QFT axioms, the correlation strength between clusters of fields always **decreases** with space-like separation $R = -(x\text{-}y)^2$ [Araki; Araki, Hepp, Ruelle]



$\rightarrow$ *This is called the* ***cluster decomposition property*** *(CDP)*

$$\boxed{|\langle 0|\Phi_1(x)\Phi_2(y)|0\rangle - \langle\Phi_1(x)\rangle\langle\Phi_2(y)\rangle| \xrightarrow{R\to\infty} 0}$$

- States therefore become increasingly decorrelated the further apart they are separated!

[H. Araki, *Ann. Phys.* **11**, 260 (1960).]
[H. Araki, K. Hepp and D. Ruelle, *Helv. Phys. Acta* **35**, 164 (1962).]

3. Confinement and the CDP

- But what about QCD? If the CDP held this would allow one to pull apart coloured states!

- It turns out though that the CDP **can be violated** in QFTs satisfying the Pseudo-Wightman axioms [Strocchi 1976]:

Theorem (Cluster Decomposition).

$$\left|\langle 0|\mathcal{B}_1(x_1)\mathcal{B}_2(x_2)|0\rangle^T\right| \leq \begin{cases} C_{1,2}[\xi]^{2N-\frac{3}{2}}e^{-M[\xi]}\left(1+\frac{|\xi_0|}{[\xi]}\right), & \textit{with a mass gap } (0,M) \textit{ in } \mathcal{V} \\ \widetilde{C}_{1,2}[\xi]^{2N-2}\left(1+\frac{|\xi_0|}{[\xi]^2}\right), & \textit{without a mass gap in } \mathcal{V} \end{cases}$$

where: $\langle 0|\mathcal{B}_1(x_1)\mathcal{B}_2(x_2)|0\rangle^T = \langle 0|\mathcal{B}_1(x_1)\mathcal{B}_2(x_2)|0\rangle - \langle 0|\mathcal{B}_1(x_1)|0\rangle\langle 0|\mathcal{B}_2(x_2)|0\rangle$, $N \in \mathbb{Z}_{\geq 0}$, $\xi = x_1 - x_2$ *is large and space-like, and* $C_{1,2}, \widetilde{C}_{1,2}$ *are constants independent of* ξ *and* N.

- Depends on whether the theory has a mass gap, and the value of the positive integer parameter N

  $\rightarrow$ *for the CDP to be violated it is necessary that* $\boldsymbol{N > 0}$

- N is related to the boundedness properties of the corresponding momentum space correlator [PL, 1511.02780]

[F. Strocchi, *Phys. Lett.* B **62**, 60 (1976).]

3. Confinement and the CDP

- Any correlation function is determined by its spectral functions ρ

  $\rightarrow$ The value of N must therefore be related to the type of components appearing in ρ

- Besides ordinary massive poles $\delta(s\text{-}m^2)$ and continuum contributions, spectral functions can have more singular properties in the *Pseudo-Wightman* case

- In particular, $\rho(s)$ can possess **generalised pole** terms of the form:

$$\boxed{\delta^{(n)}(s - m_n^2) = \left(\tfrac{d}{ds}\right)^n \delta(s - m_n^2), \qquad (n \geq 1)}$$

- These components lead to a stronger IR singular behaviour

- The existence of these delta-derivative components is sufficient to prove that $N > 0$ [PL, 1511.02780]

  $\rightarrow$ **Are these components present in QCD correlators?**

4. The gluon propagator

- A QCD correlation function of particular interest is the *gluon propagator*
- Taking into account general QFT and model-dependent constraints one can write [PL, 1702.02954; 1801.09337]:

$$\boxed{\widehat{D}^{ab\,F}_{\mu\nu}(p) = i\int_0^\infty \frac{ds}{2\pi}\frac{\left[g_{\mu\nu}\rho_1^{ab}(s) + p_\mu p_\nu \rho_2^{ab}(s)\right]}{p^2 - s + i\epsilon} + \sum_{n=0}^{N}\left[c_n^{ab}\, g_{\mu\nu}(\partial^2)^n + d_n^{ab}\partial_\mu\partial_\nu(\partial^2)^{n-1}\right]\delta(p)}$$

Taking trace, in Landau gauge

$$\boxed{D(p) = 3i\int_0^\infty \frac{ds}{2\pi}\frac{\rho_1(s)}{p^2 - s + i\epsilon} + \sum_{n=0}^{N+1} g_n(\partial^2)^n\delta(p)}$$

- Can now use numerical data to test different propagator ansätze

Euclidean generalisation is needed to test lattice data

$$\boxed{D(p) = 3\int_0^\infty \frac{ds}{2\pi}\frac{\rho_1(s)}{p^2 + s} + \sum_{n=0}^{N+1} g_n(-\nabla^2)^n\delta(p)}$$

4. The gluon propagator

- Using the high precision Landau gauge lattice data from [Dudal, Oliveira, Silva 1803.02281] the strategy was to perform fits of various generalised pole terms up to some IR cutoff [Li, PL, Oliveira, Silva, 1907.10073]

- Started with the simplest possible one-pole components

$$\boxed{D_0(p) = \frac{Z_0}{p^2 + m_0^2}, \qquad D_1(p) = \frac{Z_1}{(p^2 + m_1^2)^2}, \qquad D_2(p) = \frac{Z_2}{(p^2 + m_2^2)^3}.}$$

- Also tested the various two-term combinations $\rightarrow$ fits performed with different choices of (increasingly conservative) systematics

- <u>**Results:**</u> found that the data was consistent with the appearance of a generalised mass pole in the spectral function of the form:

$$\boxed{\mathcal{Z}_1 \delta'(s - m_1^2), \qquad \left[m_1 = 0.89^{+0.09}_{-0.06} \text{ GeV}, \quad Z_1 = 52^{+8}_{-6} \text{ GeV}^2\right]}$$

4. The gluon propagator

→ ***How does one interpret such a spectral component?***

Spectral function **components** ⟷ **States** in the spectrum

On-shell state with mass m_0

- *$Z_0>0$, positive norm (physical)*
- *$Z_0<0$, negative norm (unphysical)*

Continuum contribution, contains information about composite states

$$\rho(s) \sim \mathcal{Z}_0\delta(s-m_0^2) + \mathcal{Z}_1\delta'(s-m_1^2) + \mathcal{Z}_2\delta''(s-m_2^2) + \cdots + \rho_c(s)$$

*Massive on-shell states with **zero** norm*

4. The gluon propagator

- A $\delta'(s\text{-}m_1^2)$ component in the gluon spectral function implies the existence of a **massive on-shell zero-norm state in the spectrum**

  $\rightarrow$ State dominates the *IR* behaviour of the propagator

- One has $N > 0$, but non-vanishing m_1 suggestions that that component is not singular enough at $p^2 = 0$ to violate the CDP

  $\rightarrow$ Results in an *exponential* fall-off for $R \rightarrow \infty$

- Clustered states created from *single* gluon fields do not appear to decorrelate the further apart they are separated

  $\rightarrow$ *Gluon propagator not gauge-invariant though, so doesn't contradict the expectation that asymptotic coloured states are absent from the spectrum!*

5. Summary and outlook

- Local QFT is a framework which can be used to better understand the non-perturbative characteristics of QFTs
- Due to the complications that arise in gauge theories, QCD correlators can potentially contain more singular *generalised pole* components

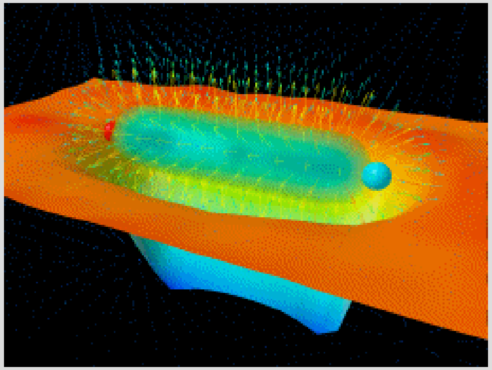
  $\rightarrow$ Important for understanding the asymptotic behaviour of correlators (*confinement*)

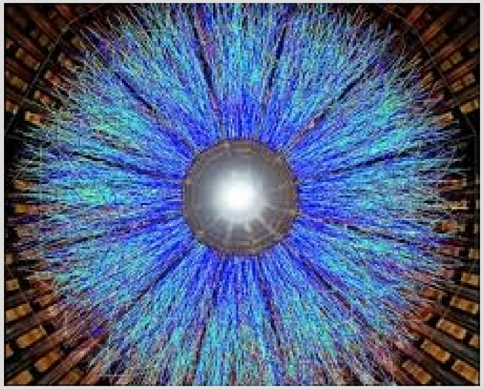
  $\rightarrow$ Constrains the spectrum of the theory (*zero-norm states*)
- Fits of generalised pole terms to infrared gluon propagator lattice data suggest that the data is compatible with the existence of these type of components

  $\rightarrow$ ***Opens a new direction for understanding QCD correlators***

Outlook

- *Are generalised pole terms relevant for hadron phenomenology?*
- *Can purely singular terms play a role in the CDP?*
- *What happens at finite temperature and density?*
- *What about gauge-invariant correlators?*





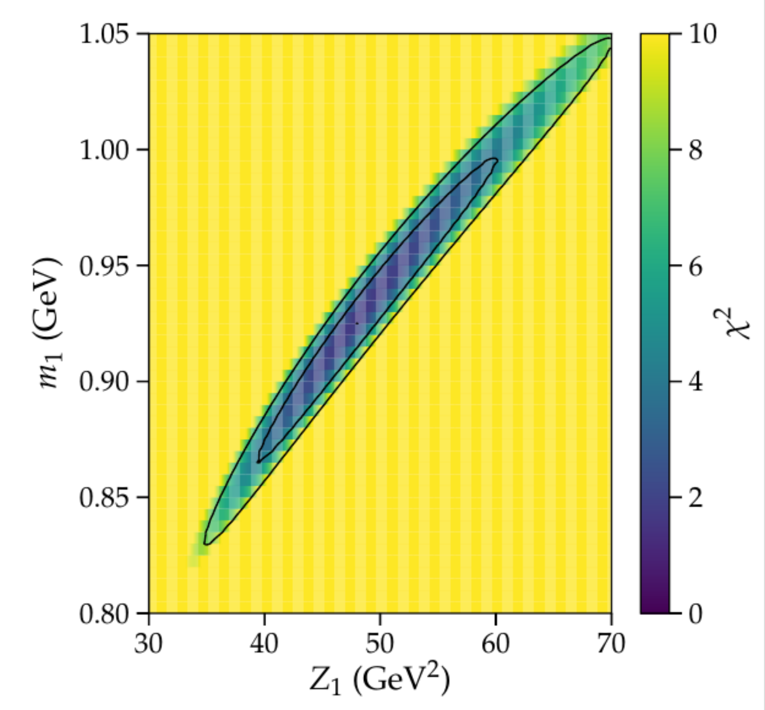
[Brookhaven National Lab]

Backup

Fit results for [Li, PL, Oliveira, Silva, 1907.10073]

- Performed fits using both 64^4 and 80^4 lattice data samples from [Dudal, Oliveira, Silva 1803.02281] to check for volume-dependent effects
- Found that single delta-derivative provided a good fit alone, and its inclusion in other fit ansätze resulted in an improvement of those fits

$\rightarrow$ Chi-squared map for the 80^4 $D_1(p)$ fit with statistical & polynomial shape uncertainty



Backup

Chi-squared definitions used in fits

(1) Statistical errors only:

$$\chi_1^2 = (\boldsymbol{G} - \boldsymbol{D})^{\mathrm{T}} \boldsymbol{C}^{-1} (\boldsymbol{G} - \boldsymbol{D}),$$

(2) Statistical + shape systematics:

$$f_i(p_i, a, b) = \frac{a + p_i^2}{ab + p_i^2},$$

$$\chi_2^2 = (\boldsymbol{G} \cdot \boldsymbol{f} - \boldsymbol{D})^T \boldsymbol{C}^{-1} (\boldsymbol{G} \cdot \boldsymbol{f} - \boldsymbol{D}) + \frac{(a-\alpha)^2}{\sigma_a^2} + \frac{(b-\beta)^2}{\sigma_b^2},$$

(3) Statistical + poly. shape:

$$\chi_3^2 = (\boldsymbol{G} \cdot \boldsymbol{g} - \boldsymbol{D})^T \boldsymbol{C}^{-1} (\boldsymbol{G} \cdot \boldsymbol{g} - \boldsymbol{D}) + \frac{|\boldsymbol{g} - \gamma|^2}{\sigma_g^2},$$

Backup

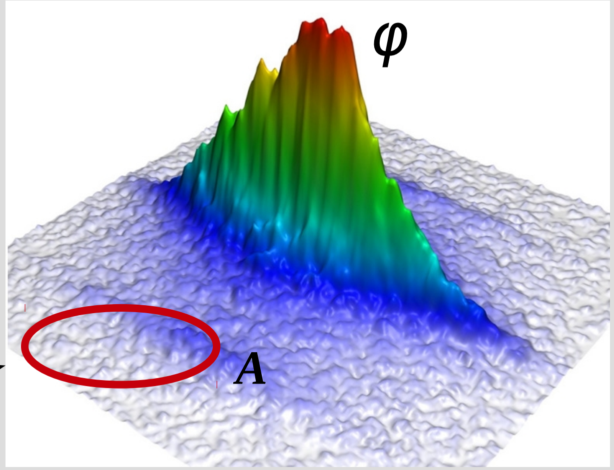
- Quantum fields $\varphi(x)$ are distributions – *what difference does this make?*

  $\rightarrow$ This means that they cannot be evaluated at a single point (e.g. Dirac delta $\delta(x)$ at $x{=}0$)

  $\rightarrow$ Need to 'average them out' over some spacetime region ***A***

$$\boxed{\mathcal{M}_\varphi := \int_A d^4x\, \varphi(x) f(x)}$$

Can think of this as the performance of a measurement M_φ in the region ***A*** where $f(x)$ is non-zero



[MPI Munich (2004)]

- But why? – Heisenberg: $\boxed{\Delta x \Delta p \sim \frac{\hbar}{2}}$