# Pairwise States vs. Dressed States and the Geometric Phase for Monopoles

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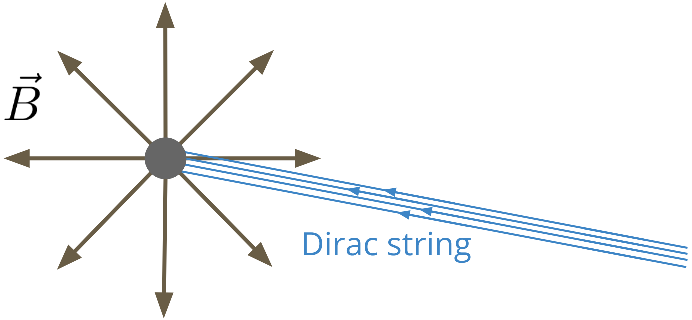
# Magnetic Monopoles

Sources of U(1) field with non-trivial winding number $\pi_1[\mathrm{U}(1)] = \mathbb{Z}$

$$\vec{B} = \frac{g}{4\pi r^2}\hat{r}$$




At $r \gg m^{-1}$ effectively abelian

Maxwell's eqs → Need Dirac string* Dirac '31

String unobservable → Dirac quantization Dirac '31, Wu & Yang '76

* Or nontrivial gauge bundle

# Magnetic Monopoles

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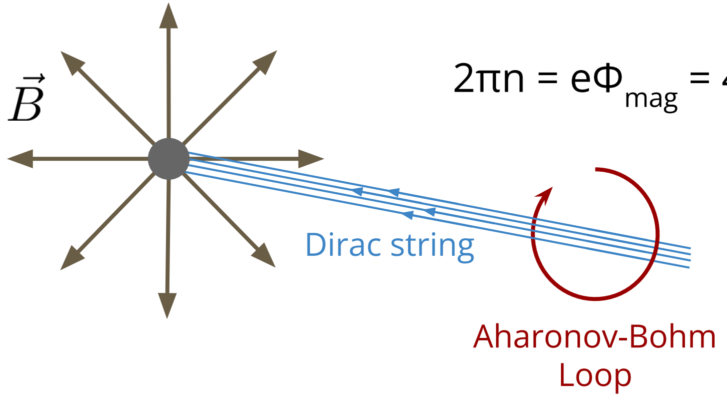


$2\pi n = e\Phi_{mag} = 4\pi q$ $\quad q \equiv eg/4\pi$

$$\downarrow$$

$$\boxed{q=n/2}$$

At $r \gg m^{-1}$ effectively abelian

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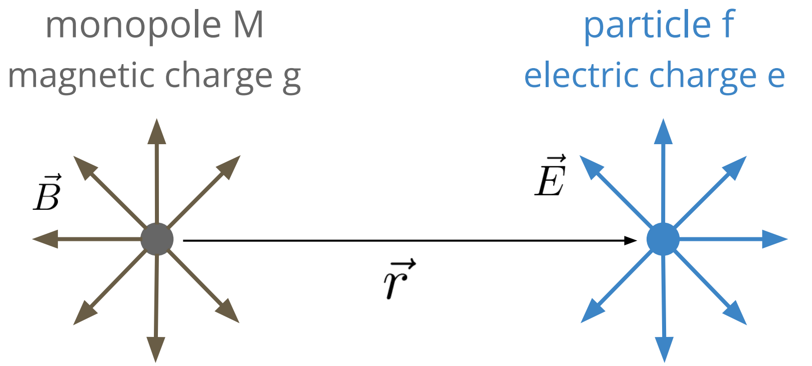
# Monopoles and Charges: Angular Momentum in EM Field

Thomson 1904




$$\vec{J}_{\text{field}} = \frac{1}{4\pi} \int \vec{r}\,' \times \left(\vec{E} \times \vec{B}\right) d^3r\,' = -\frac{g}{4\pi} \int \left(\vec{\nabla}\,' \cdot \vec{E}\right) \hat{r}\,' \, d^3r' = -eg\hat{r}$$

Distance independent!

# Some Overarching Themes and Questions

What is the action for electrodynamics + Monopoles ? How do we quantize it?

Weinberg ‘65; Schwinger ‘66; Zwanziger ‘71

What is the space of quantum multiparticle states with charges and monopoles?

Where does the extra angular momentum enter in the quantum (field) theory?

What is the role of Dirac quantization in the quantum field theory?

What is the role of the Dirac String in the quantum field theory?

Zwanziger ‘72; Csaki, Hong, Shirman, Terning, OT, Waterbury ‘20

Csaki, Hong, Shirman, Terning, OT ‘21 (PRL); Csaki, Shirman, Terning, OT ‘21; This work

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But also

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# What Are the Quantum Multiparticle States for Charges and Monopoles?

Extra angular momentum in EM field, sourced by all *pairs* of charges and monopoles

$$\longrightarrow \quad |\text{charge, monopole}\rangle \neq |\text{charge}\rangle \otimes |\text{monopole}\rangle$$

Charges-monopole multiparticle states don't live in a *Fock Space*

How do we define charge-monopole multiparticle states?

The definition should reflect extra EM angular momentum in the EM field

# Electric-Magnetic "Pairwise" States

Zwanziger '72

Csaki, Hong, Shirman, Terning, OT, Waterbury '20

Csaki, Hong, Shirman, Terning, OT, PRL '21

*Electric-magnetic* multiparticle states $\big|\underbrace{p_1, \ldots, p_n}_{\text{momenta}};\ \underbrace{\sigma_1, \ldots, \sigma_n}_{\text{spins / helicities}};\ \underbrace{q_{12},\, q_{13}, \ldots, q_{n-1,n}}_{\text{pairwise helicities}}\big\rangle$

The pairwise helicities are the Dirac-quantized $q_{ij} = \dfrac{e_i g_j - e_j g_i}{4\pi}$

They are the S-matrix manifestation of the extra angular momentum

$$\Delta \vec{J}_{ij} = -q_{ij} \hat{r}_{ij}$$

carried by the electromagnetic field that's sourced by the dyon (or charge-monopole) pair (i,j)

# Electric-Magnetic "Pairwise" States

Zwanziger '72

Csaki, Hong, Shirman, Terning, OT, Waterbury '20

Csaki, Hong, Shirman, Terning, OT, PRL '21

Under a Lorentz transformation, transform with an extra pairwise Little Group phase:

$$U(\Lambda)\left|p_1,\ldots,p_n;\sigma_1,\ldots,\sigma_n;q_{12},q_{13},\ldots q_{f-1,f}\right\rangle =$$

$$\underbrace{e^{i\Phi_{LG}}}_{\text{pairwise phase}}\prod_{i=1}^{f}\mathcal{D}^{i}_{\sigma_i'\sigma_i}\left|\Lambda p_1,\ldots,\Lambda p_f;\sigma_1',\ldots,\sigma_f';q_{12},q_{13},\ldots,q_{f-1,f}\right\rangle$$

The pairwise phase $\Phi_{LG}\equiv-\sum_{l<m}q_{lm}\varphi_{LG}\left(p_l,p_m,\Lambda\right)$ leads to modified angular-momentum selection rules in the scattering of charges, monopoles and dyons

# The Pairwise Little Group; A Short Dive-In

Consider the charge-monopole state $|p_1, p_2; q_{12}\rangle$

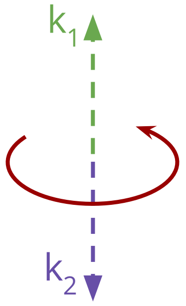
How does it transform under Lorentz?

1. Define the COM momenta $k^{\mu}_{1,2} = \left(E^c_{1,2}, 0, 0, \pm p_c\right)$

2. The pairwise Little Group (LG) is the subgroup of Lorentz which keeps $k_1$, $k_2$ invariant, i.e. U(1) rotations around the z-axis

3. The pairwise helicities $q_{ij}$ label representations of each $U(1)_{ij}$

$$U\left[R_z(\varphi)\right]|k_1, k_2; q_{12}\rangle = e^{iq_{12}\varphi}\,|k_1, k_2; q_{12}\rangle$$




Pairwise Little Group = z-rotations

$$p_c = \sqrt{\frac{(p_1 \cdot p_2)^2 - m_1^2 m_2^2}{s}}$$

$$E^c_i = \sqrt{m_i^2 + p_c^2}$$

# The Pairwise Little Group; A Short Dive-In

Zwanziger '72

Consider the charge-monopole state $|p_1, p_2; q_{12}\rangle$

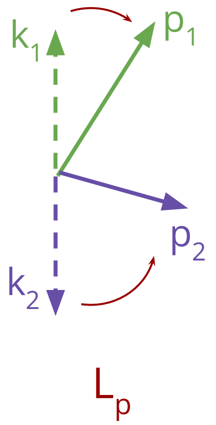
How does it transform under Lorentz?

4. Define $L_p$ so that $p^{\mu}_{1,2} = [L_p]^{\mu}{}_{\nu}\, k^{\nu}_{1,2}$

5. Under any Lorentz transformation $\Lambda$

$$U[\Lambda]\,|p_1, p_2; q_{12}\rangle = e^{iq_{12}\varphi_{LG}(p_1,p_2,\Lambda)}\,|\Lambda p_1, \Lambda p_2; q_{12}\rangle$$

where $R_z\left[\varphi_{LG}\left(p_i, p_j, \Lambda\right)\right] = L^{-1}_{\Lambda p}\Lambda L_p$

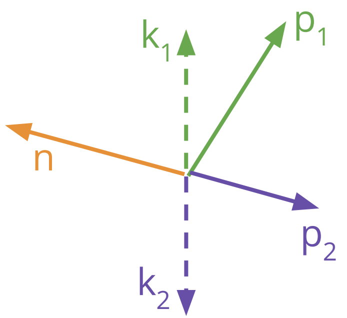


# $\varphi_{LG}(p_1, p_2, \Lambda)$, Explicitly

Zwanziger '72

We fix the freedom in $L_p$ by choosing arbitrary vector $n^\mu$ and let

$$[L_p]^\mu{}_2 = \hat{\epsilon}^\mu(p_1, p_2, n)$$




The pairwise phase is then

$$\boxed{\cos\left[\varphi_{LG}\left(p_1, p_2, \Lambda\right)\right] = \hat{\epsilon}\left(p_1, p_2, \Lambda^{-1} n\right) \cdot \hat{\epsilon}\left(p_1, p_2, n\right)}$$

$n^\mu$ is the pairwise LG analog of the Dirac string for the monopole

$$\hat{\epsilon}^\mu(abc) \equiv \frac{\epsilon^{\mu\nu\rho\sigma} a_\nu b_\rho c_\sigma}{|\epsilon^{\mu\nu\rho\sigma} a_\nu b_\rho c_\sigma|}$$

# Pairwise States: Results

- Derived all 3pt amplitudes involving charges, monopoles, and dyons
- Reproduced the forced chirality flip in the lowest PW for fermion-monopole scattering
- Reconstructed monopole spherical harmonics from pairwise spinor-helicity variables

Csaki, Hong, Shirman, Terning, OT, Waterbury '20

- Derived geodesics in Taub-NUT background as the classical limit of "pairwise" amplitudes

Kol, O'Connell, OT, '21

- Defined pairwise states for mutually-non-local branes

Csaki, Terning, OT, upcoming

- Proposed an on-shell derivation for monopole catalysis of nucleon decay (the Rubakov-Callan effect)

Csaki, Shirman, Terning, OT, '21

# A Lingering Question and Its Straightforward Answer

What is the actual origin of the "pairwise" charge-monopole states?

How does QED+monopoles "know" to create such complicated multiparticle states?

Today - a straightforward answer

$$|p_1, \ldots, p_f\,;\, q_{12}, q_{13}, \ldots, q_{n-1n}\rangle = |p_1, \ldots, p_f\rangle\!\rangle$$

pairwise
states

IR-dressed
charge-monopole states
of monopole-QED (QEMD)

# Dressed States in QED

The QED S-matrix is IR-finite when taken between asymptotic states “dressed” by soft photons

$$S_{\mathrm{QED,finite}} = \langle\!\langle p_1^{out}, \ldots, p_m^{in} | p_1^{in}, \ldots, p_n^{in} \rangle\!\rangle$$

Faddeev-Kulish: $$|p_1, \ldots, p_n\rangle\!\rangle = \exp\left[\mathcal{T}\int_{-\infty}^{\infty} dt\, V_I^{as}(t)\right] |p_1, \ldots, p_n\rangle$$

IR-dressed state

“bare” state

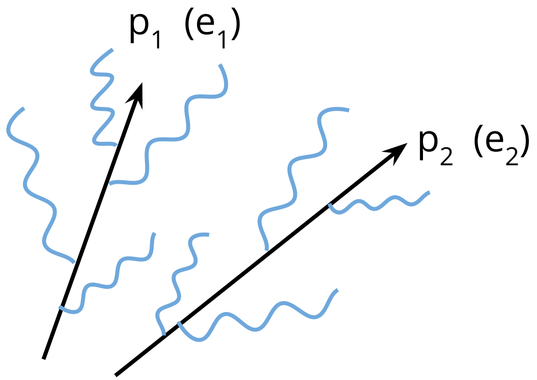
$$V_I^{as}(t) = -\lim_{t\to\pm\infty}\int d^3x\,[j^\mu A_\mu]$$

asymptotic potential:

generates retarded/advanced EM field associated with the charges moving with momenta $p_1, \ldots, p_n$

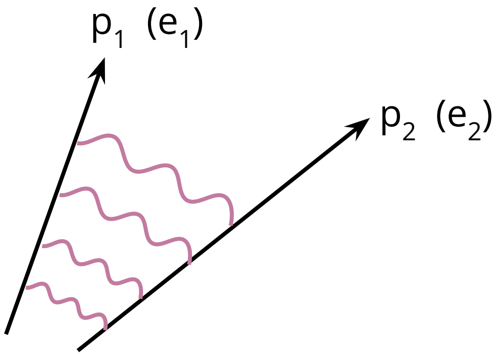
# Dressed States in QED

$$\exp\left[\mathcal{T}\int_{-\infty}^{\infty} dt\, V_I^{as}(t)\right] = e^{R_{FK}}\, e^{i\Phi_{FK}}$$




$$R_{FK} = -i\int_{-\infty}^{\infty} dt\ V_I^{as}(t)$$

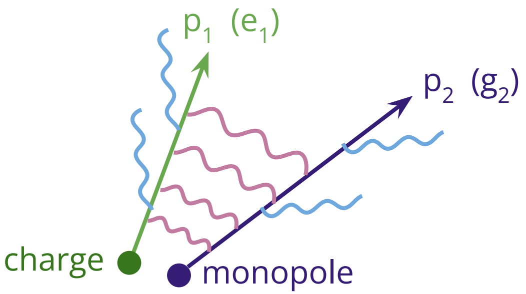
Real part of dressing (~soft photon creation operators)




$$\Phi_{FK} = \frac{i}{2}\int_{-\infty}^{\infty} dt_1 \int_{-\infty}^{t_1} dt_2\ \left[V_I^{as}(t_1)\,, V_I^{as}(t_2)\right]$$

Imaginary part of dressing (virtual photon exchange)

# Dressed States in Monopole-QED (QEMD)




Add dual interaction: $V_{as}^{I}(t) = -\lim_{|t|\to\infty}\int d^3x \left[ j_e^\mu A_\mu + j_g^\mu \widetilde{A}_\mu \right]$

$j_e^\mu$ electric current density

$j_g^\mu$ magnetic current density

Gauge field $$A_\mu(x) = \sum_{a=\pm}\int \frac{d^3k}{(2\pi)^3}\frac{1}{2\omega_k}\left[\varepsilon_\mu^{*a}(\vec{k})a_a(\vec{k})e^{ik\cdot x} + \varepsilon_\mu^{a}(\vec{k})a_a^\dagger(\vec{k})e^{-ik\cdot x}\right]$$

Dual gauge field $$\widetilde{A}_\mu(x) = \sum_{a=\pm}\int \frac{d^3k}{(2\pi)^3}\frac{1}{2\omega_k}\underbrace{\left[\widetilde{\varepsilon}_\mu^{*a}(\vec{k})a_a(\vec{k})e^{ik\cdot x} + \widetilde{\varepsilon}_\mu^{a}(\vec{k})a_a^\dagger(\vec{k})e^{-ik\cdot x}\right]}_{\text{same creation/annihilation ops.}}$$

“One photon, two descriptions”

# QEMD Dressed States = Pairwise States?

We want to show that the dressed state transforms the same as the pairwise state

$$U\left[\Lambda\right]|p_1,\ldots,p_f\rangle\!\rangle = e^{i\Phi_{LG}}\,|\Lambda p_1,\ldots,\Lambda p_f\rangle\!\rangle$$

For an infinitesimal $\Lambda^{\mu}_{\nu} = \exp\left(\delta\tau\omega^{\mu}_{\nu}\right)$ we have $U[\Lambda] = \exp\left[\frac{i}{2}\delta\tau M^{\mu\nu}\omega_{\nu\mu}\right]$

Where $M_{\mu\nu}$ is the Noether generator for Lorentz transformations in QEMD

From the definition of the dressed states:

$$\exp\left[\frac{i}{2}\delta\tau M^{\mu\nu}\omega_{\nu\mu}\right]e^{R_{FK}}e^{i\Phi_{FK}}\,|p_1,\ldots,p_f\rangle = e^{i\Phi_{LG}}e^{R_{FK}}e^{i\Phi_{FK}}\,|\Lambda p_1,\ldots,\Lambda p_f\rangle$$

# QEMD Dressed States = Pairwise States?

Using Baker-Campbell-Hausdorff, we need to show that

$$\Big\{ \underbrace{[M^{\mu\nu}, R_{FK}] + \frac{1}{2}\left[[M^{\mu\nu}, R_{FK}], R_{FK}\right]}_{\text{QEMD Lorentz generator acting on the real soft-photon cloud}} - \underbrace{\Delta\Phi^{\mu\nu}_{FK}}_{\text{shift of virtual soft photon phase under Lorentz}} \Big\} |p_1, \ldots, p_f\rangle = \underbrace{\Phi^{\mu\nu}_{LG}}_{\text{infinitesimal pairwise phase}} |p_1, \ldots, p_f\rangle$$

$$\Phi_{FK}\,|_{\Lambda p} - \Phi_{FK}\big|_p \equiv \frac{\delta\tau}{2}\omega_{\mu\nu}\Delta\Phi^{\mu\nu}_{FK} + \mathcal{O}\left(\delta\tau^2\right)$$

$$\Phi_{LG} \equiv \frac{\delta\tau}{2}\omega_{\mu\nu}\varphi^{\mu\nu}_{LG} + \mathcal{O}\left(\delta\tau^2\right)$$

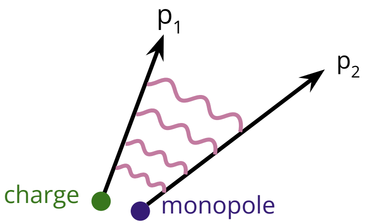
$$\Phi^{\mu\nu}_{LG} = -\sum_{l<m} q_{lm}\varphi^{\mu\nu}_{LG;lm}$$

$$\varphi^{\mu\nu}_{LG;lm} = \frac{\tau_{lm}}{\epsilon^2\left(p_l, p_m, n\right)} n^{[\mu}\epsilon^{\nu]}\left(p_l, p_m, n\right)$$

$$\tau_{lm} \equiv \sqrt{\left(p_l \cdot p_m\right)^2 - m_l^2 m_m^2}$$

we prove this via direct calculation

# Calculating $\Phi_{FK}$ in QEMD




$$\Phi_{FK} \sim \frac{i}{2}\int_0^{\infty} dt_1 \int_0^{t_1} dt_2 \left[V_I^{as}(t_1), V_I^{as}(t_2)\right] - (t_1, t_2 \leftrightarrow -t_1, -t_2)$$

this has

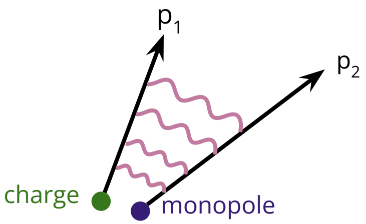
$$e\left[p_1 \cdot \varepsilon^{*a}(\vec{k})\right] a_a(\vec{k}) + \ldots$$

this has

$$g\left[p_2 \cdot \widetilde{\varepsilon}^{a}(\vec{k})\right] a_a^{\dagger}(\vec{k}) + \ldots$$

$$\Phi_{FK} \sim \int d^3k \left[p_1 \cdot \varepsilon^{a}(\vec{k})\right]\left[p_2 \cdot \widetilde{\varepsilon}^{a}(\vec{k})\right] \sim \underbrace{\int d^3k \frac{\epsilon(p_1, p_2, n, k)}{n \cdot k + i\epsilon} + cc.}_{\text{Integral over all soft photon exchanges between charge \& monopole}}$$

# Calculating $\Phi_{FK}$ in QEMD

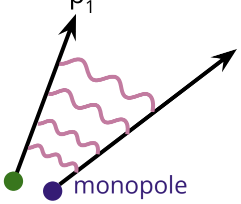



$$\Phi_{FK} = \sum_{l<m} q_{lm} \iint D_l p_a D_m p_b \left[\varphi_{FK}\left(p_a, p_b, n\right)\right]$$

$$\varphi_{FK}\left(p_1, p_2, p_3\right) = 4\pi\, \mathrm{Im}\left[\mathcal{I}\left(p_1, p_2, p_3\right) - \mathcal{I}\left(-p_1, p_2, p_3\right) - \mathcal{I}\left(p_1, -p_2, p_3\right) + \mathcal{I}\left(-p_1, -p_2, p_3\right)\right] \qquad p_3 \equiv n$$

$D_l p \equiv d^3 p \left[b_l(\vec{p}) b_l^\dagger(\vec{p}) - d_l^\dagger(\vec{p}) d_l(\vec{p})\right] / \left[2\omega_l \cdot (2\pi)^3\right]$

# Calculating $\Phi_{FK}$ in QEMD

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where

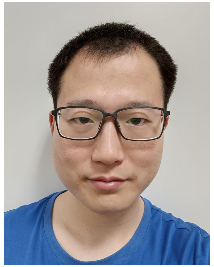
$$\mathcal{I}\left(p_1, p_2, p_3\right) = \int \frac{d^4k}{(2\pi)^4} \frac{i\epsilon\left(p_1, p_2, p_3, k\right)}{\left(k^2 + i\epsilon\right)\left(p_1 \cdot k - i\epsilon\right)\left(p_2 \cdot k + i\epsilon\right)\left(p_3 \cdot k + i\epsilon\right)}$$

All that remains is to calculate this Feynman integral

Alas! This integral is 0/0 and needs regularization...

$D_l p \equiv d^3 p \left[b_l(\vec{p}) b_l^\dagger(\vec{p}) - d_l^\dagger(\vec{p}) d_l(\vec{p})\right] / \left[2\omega_l \cdot (2\pi)^3\right]$

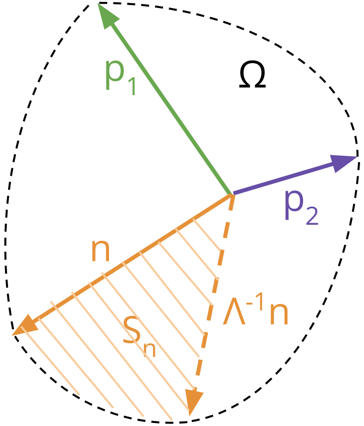
# A Slick Trick




While $\mathcal{I}$ is ill-defined, what we need is actually $\Delta\Phi_{FK} \sim \Delta\mathcal{I}$

$$\Delta\mathcal{I} = \mathcal{I}\left(\Lambda p_1, \Lambda p_2, n\right) - \mathcal{I}\left(p_1, p_2, n\right)$$
$$= \mathcal{I}\left(p_1, p_2, \Lambda^{-1} n\right) - \mathcal{I}\left(p_1, p_2, n\right)$$

which *is* well defined as can be shown in position space via Stokes' theorem




In momentum space, we showed using Schwinger parameters that

$$\Delta\mathcal{I} = -\frac{i}{2\pi}\Omega\left(-p_1, p_2, n, \Lambda^{-1} n\right)$$

So the integral really computes the 4D solid angle between $-p_1$, $p_2$, $n$, and $\Lambda^{-1}n$

# Final Result for $\Delta\Phi_{FK}$

Substituting in $\varphi_{FK}(p_1, p_2, p_3) = 4\pi\,\mathrm{Im}\left[\mathcal{I}(p_1, p_2, p_3) - \mathcal{I}(-p_1, p_2, p_3) - \mathcal{I}(p_1, -p_2, p_3) + \mathcal{I}(-p_1, -p_2, p_3)\right]$

The 4D solid angle degenerates to a dihedral angle

$$\Delta\varphi_{FK}(p_1, p_2, n) = 2\arccos\left[\hat{\epsilon}\left(p_1, p_2, \Lambda^{-1}n\right) \cdot \hat{\epsilon}(p_1, p_2, n)\right] = -2\Phi_{LG}$$

shift in soft photon phase = -2 pairwise Little Group phase

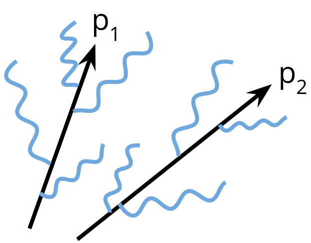
what about the contribution from real photons?

# QEMD Dressed States = Pairwise States?

Using Baker-Campbell-Hausdorff, we need to show that

$$\left\{ \underbrace{\left[M^{\mu\nu}, R_{FK}\right] + \frac{1}{2}\left[\left[M^{\mu\nu}, R_{FK}\right], R_{FK}\right]}_{\substack{\text{QEMD Lorentz generator acting} \\ \text{on the real soft-photon cloud} \\ \downarrow \\ ?}} - \underbrace{\Delta\Phi^{\mu\nu}_{FK}}_{\substack{\text{shift of virtual soft photon} \\ \text{phase under Lorentz} \\ \downarrow \\ 2\Phi^{\mu\nu}_{LG}}} \right\} |p_1, \ldots, p_f\rangle = \underbrace{\Phi^{\mu\nu}_{LG}}_{\substack{\text{infinitesimal} \\ \text{pairwise phase}}} |p_1, \ldots, p_f\rangle$$

# Real Photon Contribution



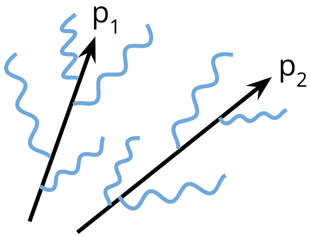

QEMD Energy-Momentum tensor: $\theta^{\mu\nu} = \theta^{\mu\nu}_{EM} + \theta^{\mu\nu}_{\varphi,A} + \theta^{\mu\nu}_{\varphi,B} + \dots$

$$\theta^{\mu\nu}_{EM} = \frac{1}{2}\left(F^{\mu}{}_{\alpha}F^{\alpha\nu} + \widetilde{F}^{\mu}_{\alpha}\widetilde{F}^{\alpha\nu}\right) \qquad \theta^{\mu\nu}_{\varphi,V} = \sum_l \frac{1}{2}\left(D^{\{\mu}_{V,l}\phi_l\right)\left(D^{\nu\}}_{V,l}\phi_l\right)^* - \frac{1}{2}\eta^{\mu\nu}\left[\eta_{\alpha\beta}\left(D^{\alpha}_{V,l}\phi_l\right)\left(D^{\beta}_{V,l}\phi_l\right)^* - m_l^2\phi_l\phi_l^*\right]$$

Noether generator for Lorentz: $M^{\mu\nu} \equiv M^{\mu\nu}_{EM} + M^{\mu\nu}_{\varphi,A} + M^{\mu\nu}_{\varphi,B}$ $\qquad M^{\mu\nu}_i = \int d^3x\, x^{[\mu}\theta^{0\nu]}_i$

commutators with $R_{FK}$ $\longleftrightarrow$ substituting “retarded EM field” in $M_{\mu\nu}$

# Real Photon Contribution




Contribution from covariant derivative

$$[M_A^{\mu\nu} + M_B^{\mu\nu}, R_{FK}] = \sum_{l<m} q_{lm} \iint D_l p_a D_m p_b \left\{ \frac{\tau_{ab}\, n^{[\mu}\epsilon^{\nu]}\left(p_a, p_b, n\right)}{\epsilon^2\left(p_a, p_b, n\right)} - \frac{\epsilon^{\mu\nu}\left(p_a, p_b\right)}{\tau_{ab}} \right\}$$

Contribution from EM kinetic term

$$\frac{1}{2}\left[\left[M_{EM}^{\mu\nu}, R_{FK}\right], R_{FK}\right] = \sum_{l<m} q_{lm} \iint D_l p_a D_m p_b \left[ \frac{\epsilon^{\mu\nu}\left(p_a, p_b\right)}{\tau_{ab}} \right]$$

Total contribution:

$$\left\{ [M^{\mu\nu}, R_{FK}] + \frac{1}{2}\left[\left[M^{\mu\nu}, R_{FK}\right], R_{FK}\right] \right\} |p_1, \ldots, p_f\rangle = -\Phi_{LG}^{\mu\nu} |p_1, \ldots, p_f\rangle$$

# QEMD Dressed States = Pairwise States!

Using Baker-Campbell-Hausdorff, we need to show that

$$\left\{\underbrace{[M^{\mu\nu}, R_{FK}] + \frac{1}{2}\left[[M^{\mu\nu}, R_{FK}], R_{FK}\right]}_{\substack{\text{QEMD Lorentz generator acting} \\ \text{on the real soft-photon cloud} \\ \downarrow \\ -\Phi^{\mu\nu}_{LG}}} - \underbrace{\Delta\Phi^{\mu\nu}_{FK}}_{\substack{\text{shift of virtual soft photon} \\ \text{phase under Lorentz} \\ \downarrow \\ 2\Phi^{\mu\nu}_{LG}}}\right\} |p_1, \ldots, p_f\rangle = \underbrace{\Phi^{\mu\nu}_{LG}}_{\substack{\text{infinitesimal} \\ \text{pairwise phase}}} |p_1, \ldots, p_f\rangle$$

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$$U[\Lambda] \, |p_1, \ldots, p_f\rangle\!\rangle = e^{i\Phi_{LG}} \, |\Lambda p_1, \ldots, \Lambda p_f\rangle\!\rangle$$

dressed states = pairwise states ✓

# Bonus: A Nontrivial Geometric (Berry) Phase

We showed that the dressed states of monopole-QED transform as:

$$U[\Lambda]\,|p_1,\ldots,p_f\rangle\!\rangle = e^{i\Phi_{LG}}\,|\Lambda p_1,\ldots,\Lambda p_f\rangle\!\rangle$$

What happens if Λ is a 2π rotation?

$$\gamma_{\text{Berry}} \equiv \Phi_{FK}(2\pi\,\text{rotation}) = \pm 2\pi \sum_{l<m} q_{lm}$$

Allowing only fermionic or bosonic statistics, we have a fully relativistic derivation of Dirac quantization

If $\Sigma q_{lm}$ is a half-integer, we get a *minus sign* for a 2π rotation - like a fermion

For half-integer pairwise helicity, we can make fermions out of bosons! ✓

# Conclusions

The multiparticle quantum states for charges and monopoles are not a Fock space;

They have pairwise helicities $q_{ij}$ and transform with pairwise LG phases $\varphi_{LG}(p_i, p_j, \Lambda)$

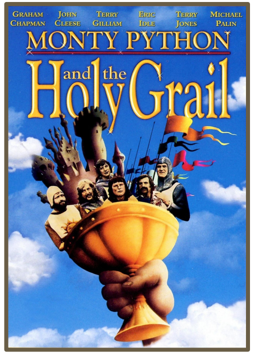
The pairwise LG provides modified angular momentum selection rules constraining the scattering amplitudes of monopoles and charges

The pairwise states are equivalent to the soft-photon dressed states of monopole-QED

The pairwise LG phase $\varphi_{LG}$ is the shift of the soft photon phase $\varphi_{FK}$ under a Lorentz transformation

The pairwise/dressed states have a geometric phase that can make fermions out of bosons!

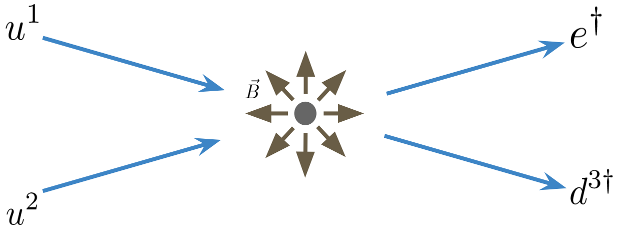
# Future Directions



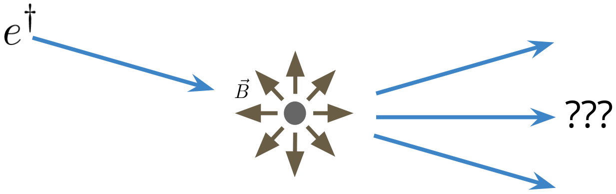

The holy grail:

A full 4D derivation of monopole catalysis of proton decay

And a solution to the monopole unitarity puzzle




monopole catalysis




monopole unitarity puzzle

We conjecture that the EM field sourced by monopoles and charges creates a (never before encountered) abelian instanton. This would-be instanton mediates proton decay at strong interaction rates.

# Bonus: Topology!

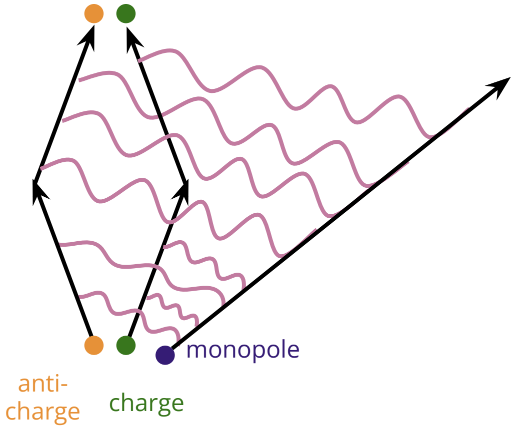
Terning, Verhaaren '18

The soft photon phase $\varphi_{FK}$ depends on the unphysical Dirac string

Can we measure it in an interference experiment?

For a closed path, we can apply Stokes' theorem

directly for $\varphi_{FK}$ and not just $\Delta\varphi_{FK}$




However, the result is an unobservable $2\pi q_{12}$ x integer !

In fact, the $\varphi_{FK}$ integral computes the topological linking number

between the charge worldline and the Dirac string worldsheet in 4D

This is the QFT generalization of the original Dirac quantization argument