Experimental prospects on quantum decoherence in fermion-pair production + FSR.

Tomography & Quantum Discord

Quantum Decoherence Meeting

22th of June, 2026, 10:00 AM CERN time

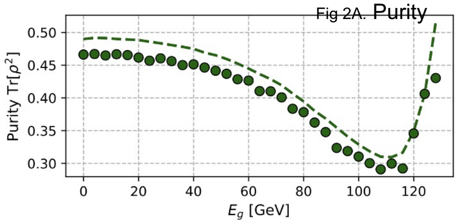
Guillermo García-Mir, José Manuel Camacho, Marcel Vos, María Moreno Llácer

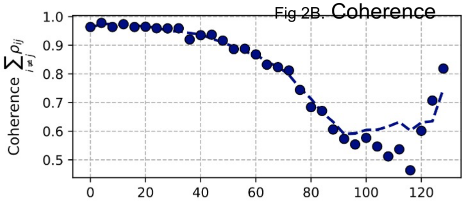
Motivations

In the last two meetings → Most of the discussions centered around two main topics

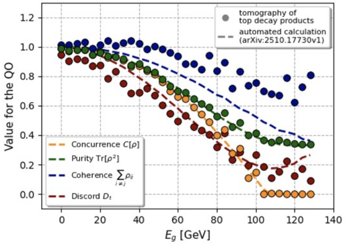
1. Results for some observables disagree between analytical/automated and tomography methods.

$e^+e^- \rightarrow tt + g$ events





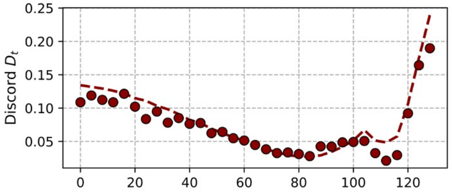
H → tt + g events

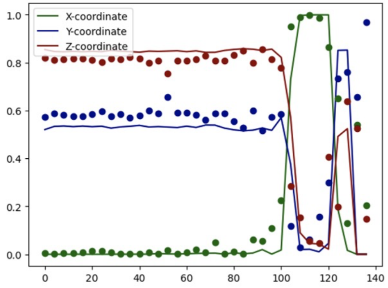


We have traced the error to a particular definition of an axis in tomography, and think we have solved the issue.

1. Several discord routines have been tested.

$e^+e^- \rightarrow tt + g$ events





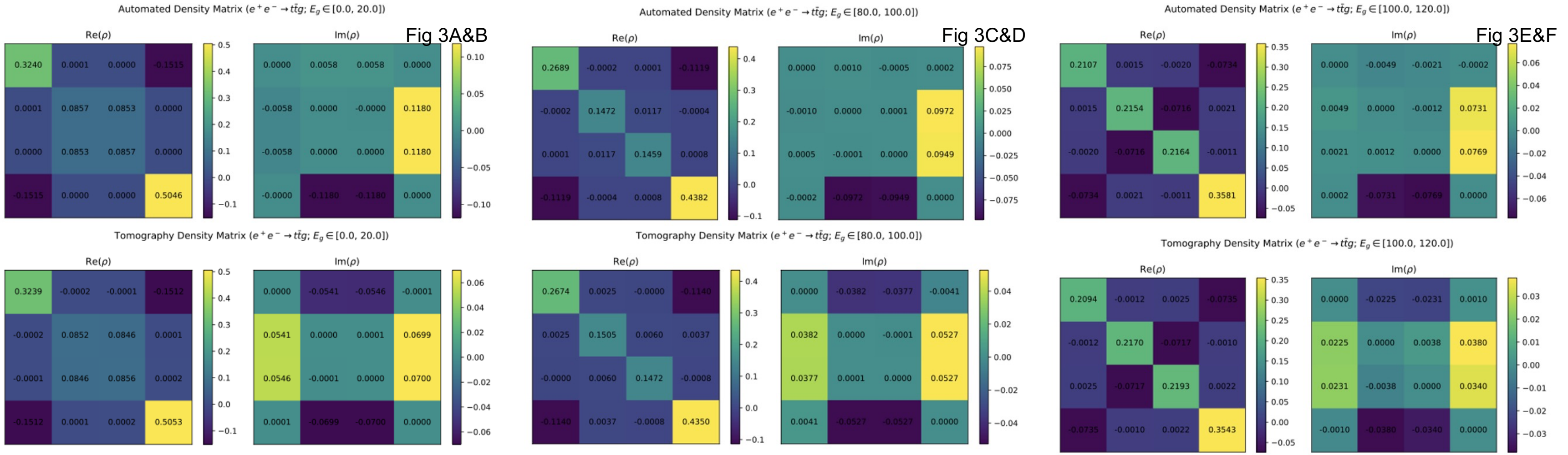
We have found an algorithm that improves the results we get.

“Tracing” the path to analytical/automated and tomography discrepancies

Mismatch present in Purity → Surprised it was not present in Concurrence (which mostly depends on C_{ii}).

A. The “shape” of the density matrices

As pointed out last meeting — and thanks to Valentin and Leonardo’s help –, we found the construction of the density matrices is different between the automated and tomography methods



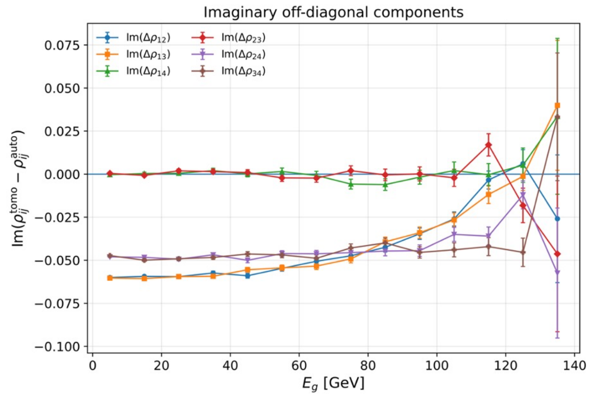
Some things to point from these graphs: [1.] The real parts are consistent between methods, so the issue is isolated to the imaginary part. [2.] The real part of figures C to F is almost diagonal, contrary to figures A and B → Purity minimum.

“Tracing” the path to analytical/automated and tomography discrepancies

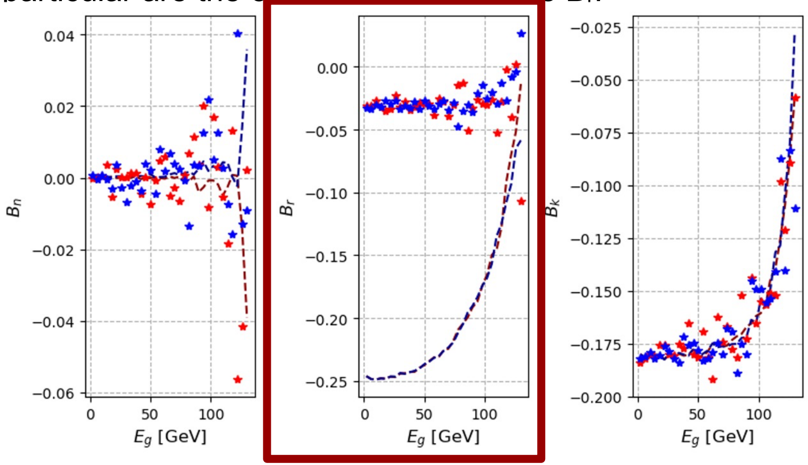
A. The “shape” of the density matrices

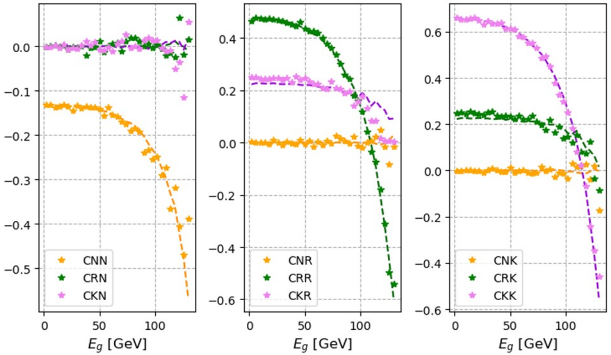
The discrepancies are isolated to the imaginary parts of the off diagonal [(1, 2), (1, 3), (4, 2), (4, 3)] elements →

$$\rho = \frac{1}{4}\begin{bmatrix} 1 + B_3^+ + B_3^- + C_{33} & B_1^- + C_{31} - i(\boxed{B_2^-} + C_{32}) & B_1^+ + C_{13} - i(\boxed{B_2^+} + C_{23}) & C_{11} - C_{22} - i(C_{12} + C_{21}) \\ B_1^- + C_{31} + i(\boxed{B_2^-} + C_{32}) & 1 + B_3^+ - B_3^- - C_{33} & C_{11} + C_{22} + i(C_{12} - C_{21}) & B_1^+ - C_{13} - i(\boxed{B_2^+} - C_{23}) \\ B_1^+ + C_{13} + i(\boxed{B_2^+} + C_{23}) & C_{11} + C_{22} - i(C_{12} - C_{21}) & 1 - B_3^+ + B_3^- - C_{33} & B_1^- - C_{31} - i(\boxed{B_2^-} - C_{32}) \\ C_{11} - C_{22} + i(C_{12} + C_{21}) & B_1^+ - C_{13} + i(\boxed{B_2^+} - C_{23}) & B_1^- - C_{31} + i(\boxed{B_2^-} - C_{32}) & 1 - B_3^+ - B_3^- + C_{33} \end{bmatrix}$$



Inspecting the density matrix structure, we note how these terms in particular are the only ones that involve B_r:





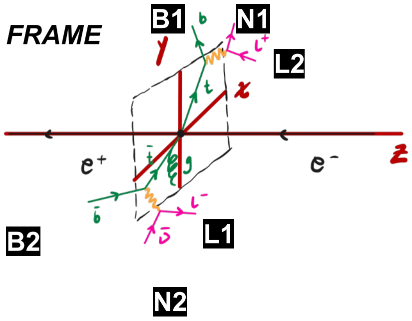
Is strange that this issue does not clearly propagate to the C matrix —note the perfect agreement of C_{RR}—

“Tracing” the path to analytical/automated and tomography discrepancies

B. The definition of $\cos\theta_r^{t/\tilde{t}}$ in tomography:

Based on W. Bernreuter et. al. (JHEP12026, 2015)

1. LAB FRAME



T1 = B1 + N1 + L2
T2 = B2 + N2 + L1

TT = T1 + T2

2. BOOST TO THE TT RF

```
newL1 = L1; newL2 = L2;
newL1.Boost(-TTBAR.BoostVector());
newL2.Boost(-TTBAR.BoostVector());
```

3. BOOTS TO THE PARENT FERMION

```
newL1.Boost(-newT2.BoostVector());
newL2.Boost(-newT1.BoostVector());
```

$$\hat{p}_e = (0,0,1), \quad y_p = \hat{k}\cdot\hat{p}_e, \quad r_p = \sqrt{1-y_p^2} \qquad \hat{k} = \frac{\vec{p}_t}{|\vec{p}_t|}$$

$$\hat{r} = \mathrm{sign}(y_p)\frac{\hat{p}_e - y_p\,\hat{k}}{r_p} \qquad \hat{n} = sign(y_p)\hat{k}\times\hat{r}$$

```
if (y1 > 0) n1_vector *= 1.;
if (y1 < 0) n1_vector *= -1.;
t[41] = newL2.Vect().Unit().Dot(n1_vector);
```

	label	$\hat{\mathbf{a}}$	$\hat{\mathbf{b}}$
transverse	n	$\mathrm{sign}(y_p)\,\hat{\mathbf{n}}_p$	$-\mathrm{sign}(y_p)\,\hat{\mathbf{n}}_p$
r axis	r	$\mathrm{sign}(y_p)\,\hat{\mathbf{r}}_p$	$-\mathrm{sign}(y_p)\,\hat{\mathbf{r}}_p$
helicity	k	$\hat{\mathbf{k}}$	$-\hat{\mathbf{k}}$

“The factors $\mathrm{sign}(y_p)$ are required because of the Bose symmetry of the initial gg state” (Bernreuter, 2015, page 16).

The imaginary part comes from the y component. The problem may arise from an improper definition of the “*Oxy”* plane and rotation to r.

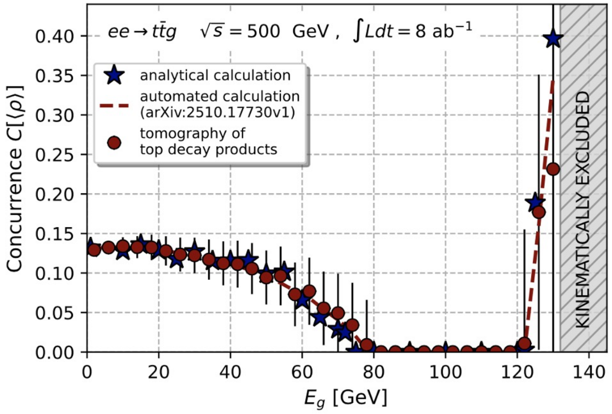
Outlook → We will be studying **eliminating the sign(y_p) corrections for e^+e^-, keeping this for pp**. Would it be possible for you to help us also producing some qq/gg → tt+g preditions using the analytical/automated methods.

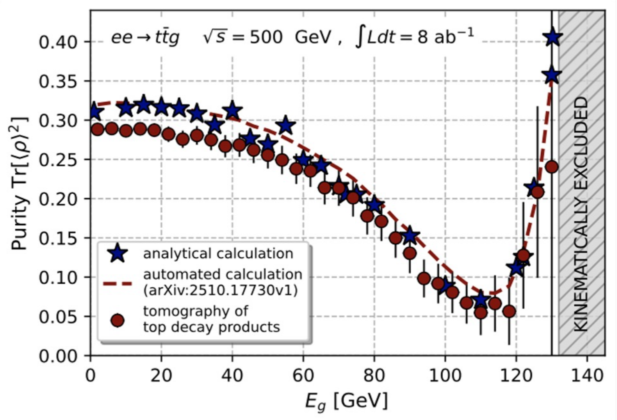
Updated combination C[ρ] and Tr[ρ²] results

A. Final Concurrence & Purity combination graphs

Many thanks to Leonardo for the updated results! We now have a concurrence and purity distributions almost perfectly mapped in all gluon energy spectrum.

Without introducing any changes in the tomography algorithm, the purity distribution still shows the tension between the automated/analytical and the tomography approaches.





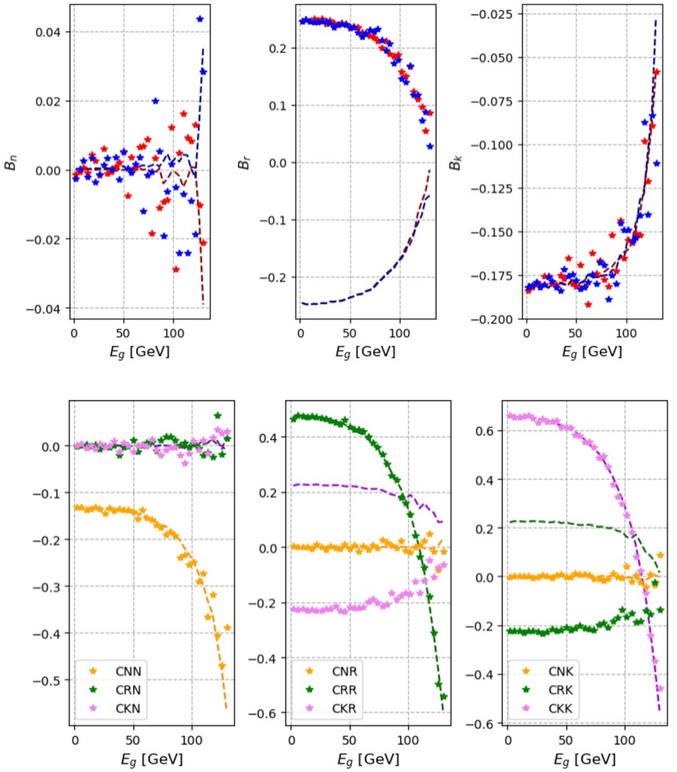
Updated combination C[ρ] and Tr[ρ²] results

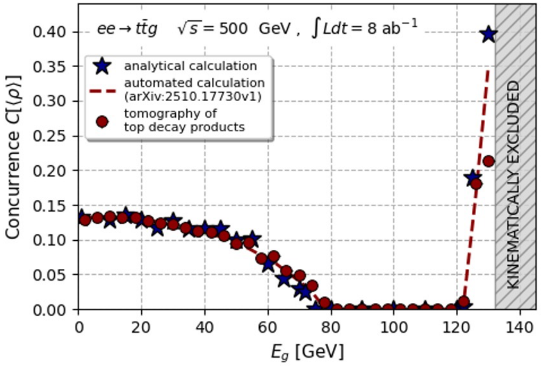
B. **Concurrence and Purity results without the `*sign($y_p$)*` rotation.**

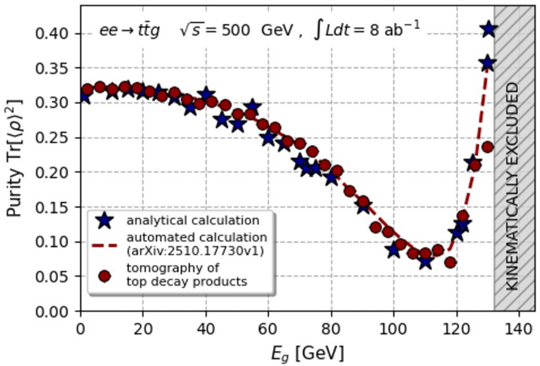
$ee \to Z^*/\gamma^* \to t\bar{t}g \quad \sqrt{s} = 500$ GeV , $\int Ldt = 8$ ab^{-1}

-- Automated calculation (arXiv:2510.17730v1)

⋆ Tomography calculation







After eliminating the Bernreuther sign flip, both Concurrence and Purity now show perfect match for all the methods.

The sign of a small set of B and C coefficients still does not match —ongoing work—.

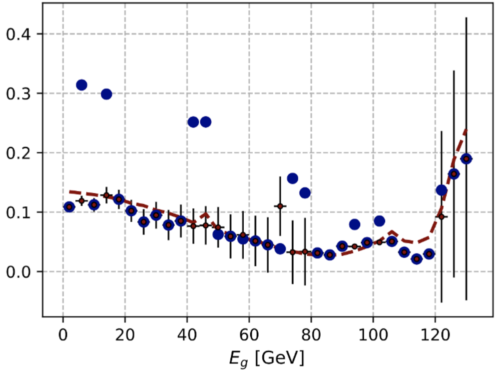
Progress in the discord calculation and minimization tensions

A. Discord results for different minimization algorithms:

I will be limiting to three algorithms, we can discuss this in the future, if we need to optimize this further:

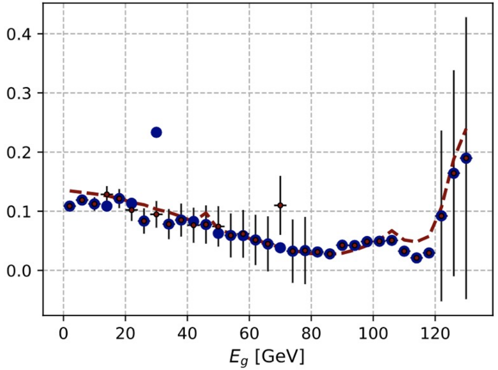
scipy "*minimize*" optimizer angular coordinates

Time for 35 bins : ~0.30 s



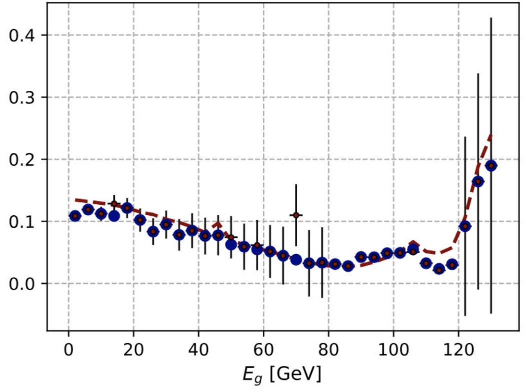
scipy "*minimize*" optimizer 3D cartesian coordinates (Valentin)

Time for 35 bins : ~ 2.00 s



scipy "*global - basinhoppin*" optimizer (link) - 2D cartesian coordinates

Time for 35 bins : ~ 20.0 s



The main conclusion is → Global minimizer ar extremely effective (even with few iterations) but are slower → We will not be using them for uncertainty calculation, for example.