

New Frontiers in TeV Physics: From Quantum Tomography to LLM Agents

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第二届TeV物理前沿专题研讨会暨第33届LHC Mini-Workshop

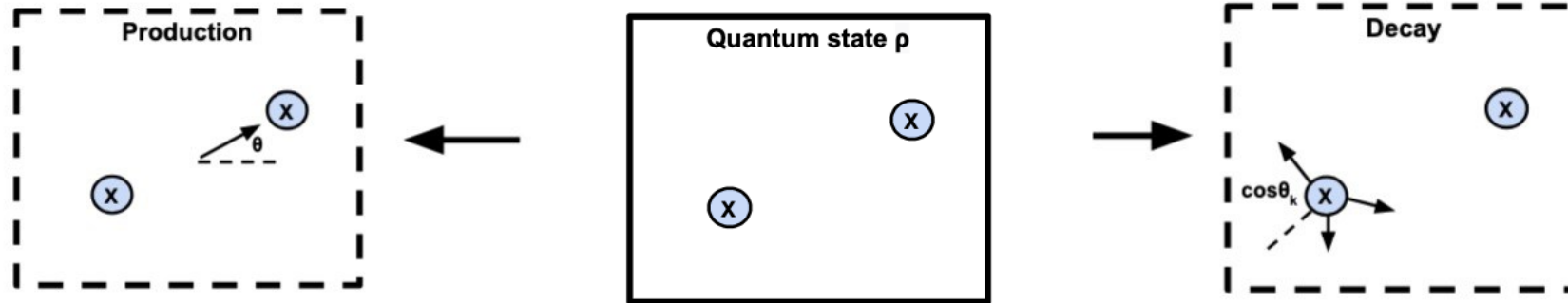
Beijing, Sep 20, 2026



Quantum Tomography @ Colliders

Two paths to proceed to quantum tomography

$$\rho = \frac{1}{4} \left(\mathbb{I}_2 \otimes \mathbb{I}_2 + \sum_i B_i^+ \sigma_i \otimes \mathbb{I}_2 + \sum_j B_j^- \mathbb{I}_2 \otimes \sigma_j + \sum_{ij} C_{ij} \sigma_i \otimes \sigma_j \right)$$



Kinematic Approach

Cheng, Han, Low [2410.08383](#)

- Theory input on the production
- Spin is related with scattering kinematic
- Initial states and scattering angle θ , speed of particle β
- Useful for stable particles

Decay Approach

Afik, de Nova. [2003.02280](#)

- Theory input on the decay
- Spin is related with decay distribution
- Angles in rest frames of decay products
- Useful for particles with tracked decay products

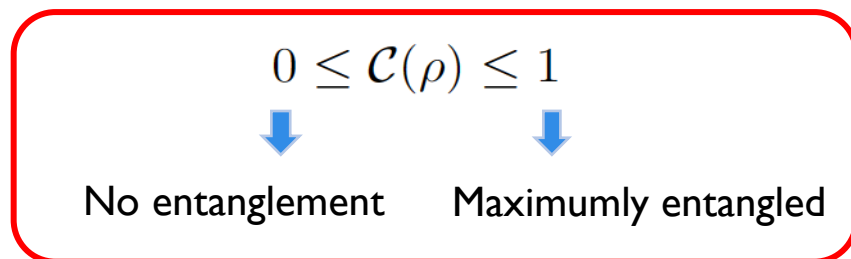
Both inherit the corresponding quantum information:

Interaction @ production $\leftarrow$ Theory $\rightarrow$ Interaction @ decays

Quantum Information Observables

Concurrence

$$\mathcal{C}(\rho) = \max(0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4)$$



λ_i is eigenvalues of $\sqrt{\sqrt{\rho}\tilde{\rho}\sqrt{\rho}}$,

$$\tilde{\rho} = (\sigma_2 \otimes \sigma_2)\rho^*(\sigma_2 \otimes \sigma_2)$$

Bell variable

- CHSH inequality $|E_{11} - E_{12} + E_{21} + E_{22}| \leq 2$

- Each term calculable from **measured density matrix**

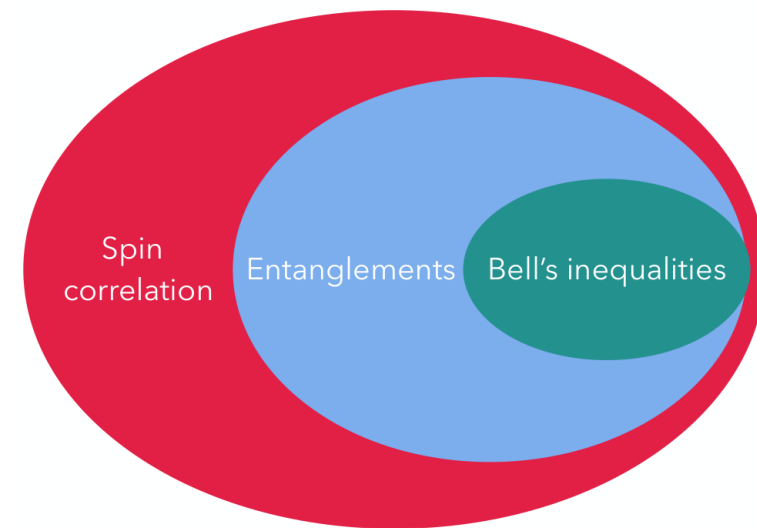
$$E_{11} = \vec{a}_1 \cdot C \cdot \vec{b}_1$$

Reference axis for qubit A

Reference axis for qubit B

- The violation of Bell's inequality

$$\mathcal{B} = \left| \vec{a}_1 \cdot C \cdot (\vec{b}_1 - \vec{b}_2) + \vec{a}_2 \cdot C \cdot (\vec{b}_1 + \vec{b}_2) \right| > 2$$



$$\mathcal{C} > 0 \text{ and } \mathcal{B} \geq 2$$

- conceptually different

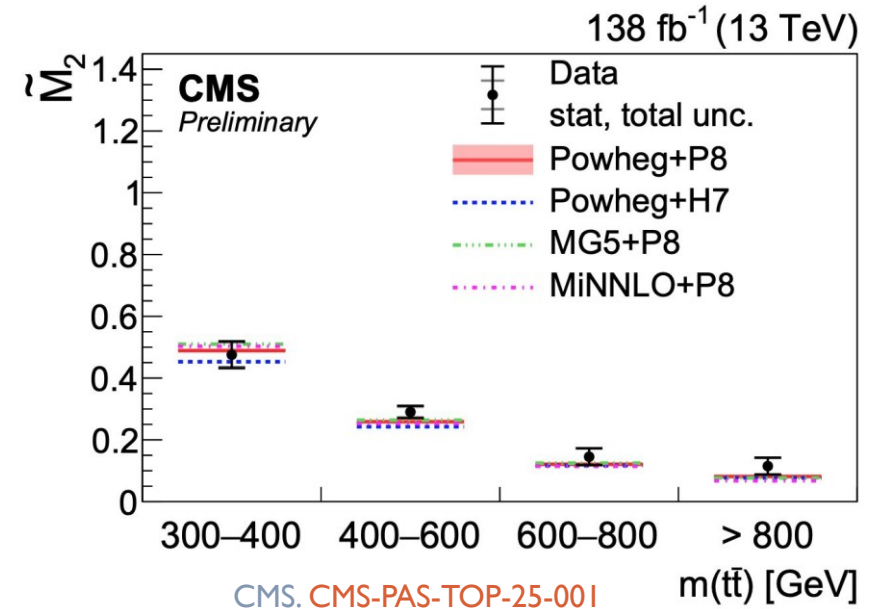
Quantum Magic

- **Stabilizer states** that can be efficiently simulated by a classical computer.
 - Entanglement is **not** enough to guarantee the advantage of quantum computing
 - **Bell states** have $C = 1$ but $M_2 = 0$!
- **Magic States**: A second layer of “**quantumness**” where quantum computing has advantages

$$\mathcal{M}_2 = -\log_2 \frac{1 + \sum_i (B_i^+)^4 + \sum_j (B_j^-)^4 + \sum_{ij} (C_{ij})^4}{1 + \sum_i (B_i^+)^2 + \sum_j (B_j^-)^2 + \sum_{ij} (C_{ij})^2}.$$

Stabilizer state $\mathcal{M}_2 = 0$

Magic state $0 < \mathcal{M}_2 \leq \log_2 \frac{16}{7} \approx 1.192$



Effects from Beam Polarizations of $e^+e^- \rightarrow f\bar{f}$

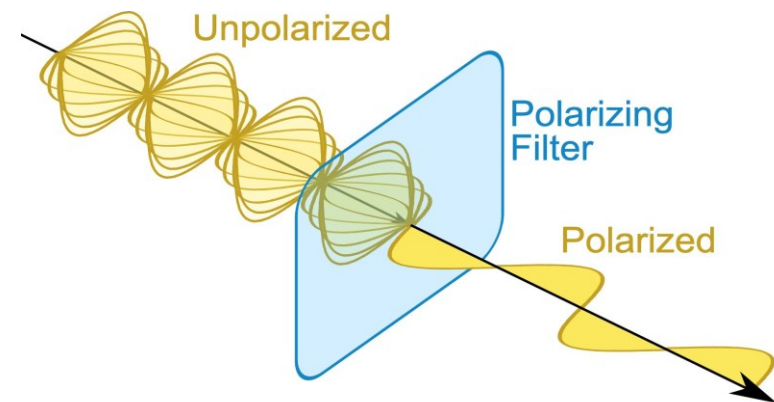
Y G, Tao Han, Matthew Low, Youle Su, arXiv: 2602.02719

- Simplest processes to explore / play
- High colliding energy & luminosity
- Control beam polarizations (60%-80%)
- Highly successful programs:

LEP1, LEP2, SLC, SuperKEKB, BEPC II, DAΦNE ...

- Next HEP collider: the Higgs factory

STCF, FCC-ee, CEPC, ILC, LCF ...



Recently Study of Polarization of QI:

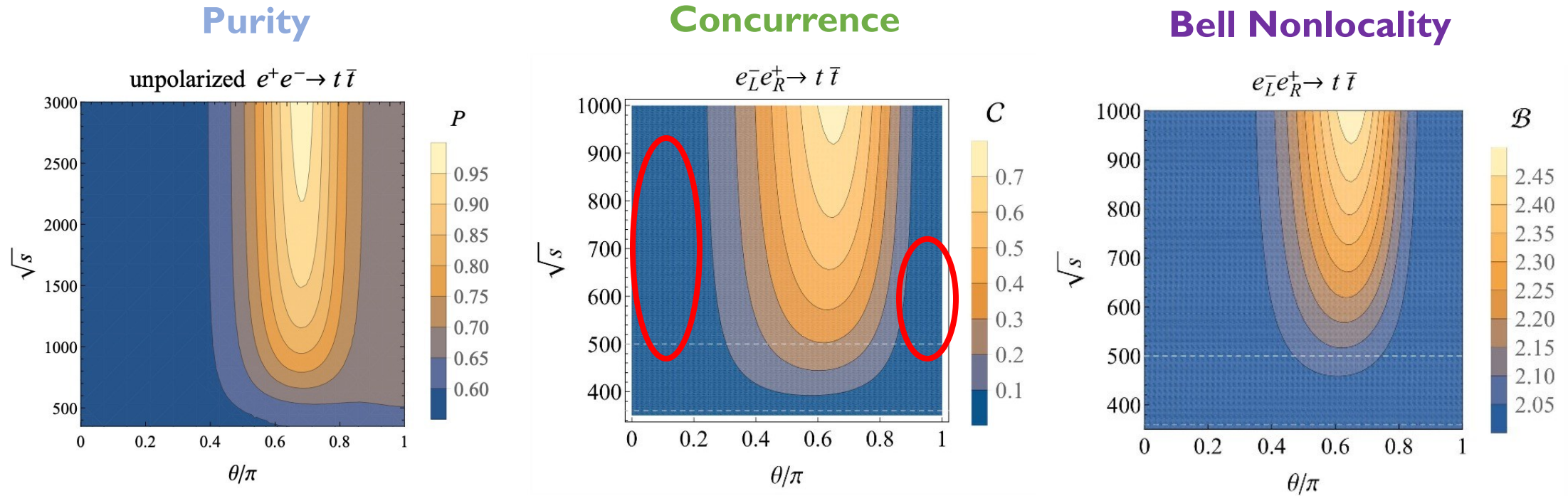
M. Altakach et al., 2601.09558;

Hong-Wei Zhang, Xu Cao, Tai-Fu Feng. 2602.10389;

Yi-Jing Fang, Kun Cheng, Tao Han, Yan-Dong Liu, Hao Zhang. 2604.11887;

Yu-Xuan Liu, Luo-Ting He, Bo-Wen Xiao. 2604.17756

(1) $e^+e^- \rightarrow t\bar{t}$ at the threshold & above



Radiative Correction:

Aoude, et al., [2604.16268](#)

- Strongly correlated with the state purity $P = \text{Tr}(\rho^2)$.
- TeV scale lepton collider can generate stronger entangled $t\bar{t}$ than that observed at the LHC
- No entanglement near threshold, nor in backward/forward scattering.
- Maximum at an angle $\cos \theta = \mp \beta f_A/f_V$ (with $f_A^R/f_V^R \approx 0.6$ and $f_A^L/f_V^L \approx -0.5$)

(1) $e^+e^- \rightarrow t\bar{t}$ the threshold & above

- At the high-energy ($\beta \rightarrow 1$) **Helicity basis**

$$|\psi\rangle \propto g_L d_{1,1}^1(\theta) |\uparrow\uparrow\rangle + g_R d_{-1,1}^1(\theta) |\downarrow\downarrow\rangle, \quad g_{L,R} = (f_V \pm f_A)/2.$$

$$|\psi\rangle = a|\uparrow\uparrow\rangle + b|\downarrow\downarrow\rangle + c|\uparrow\downarrow\rangle + d|\downarrow\uparrow\rangle, \text{ with } |a|^2 + |b|^2 + |c|^2 + |d|^2 = 1$$

$$a = e^2 (f_V^{R/L} + f_A^{R/L} \beta) (\cos \theta \pm 1),$$

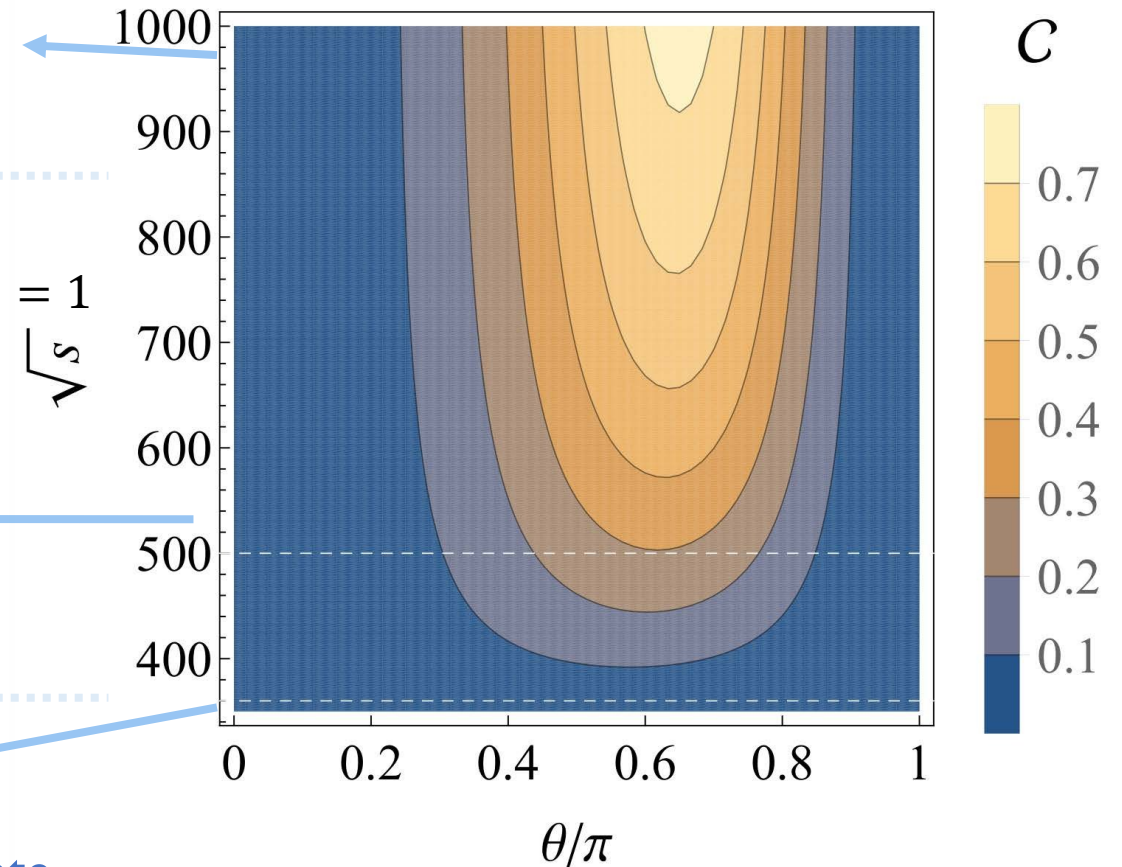
$$b = e^2 (f_V^{R/L} - f_A^{R/L} \beta) (\cos \theta \mp 1),$$

$$c = d = \mp e^2 f_V^{R/L} \sqrt{1 - \beta^2} \sin \theta, \quad c \propto m_t^2$$

- Near threshold ($\beta \rightarrow 0$) **Fixed beam basis**

$$\begin{array}{ll} t\bar{t} \text{ state} & |\psi_{\text{out}}\rangle = |\downarrow\downarrow\rangle \text{ or } |\uparrow\uparrow\rangle \text{ is separable state} \\ e^-e^+ \text{ beam} & |\psi_{\text{in}}\rangle = |LR\rangle \text{ or } |RL\rangle \end{array}$$

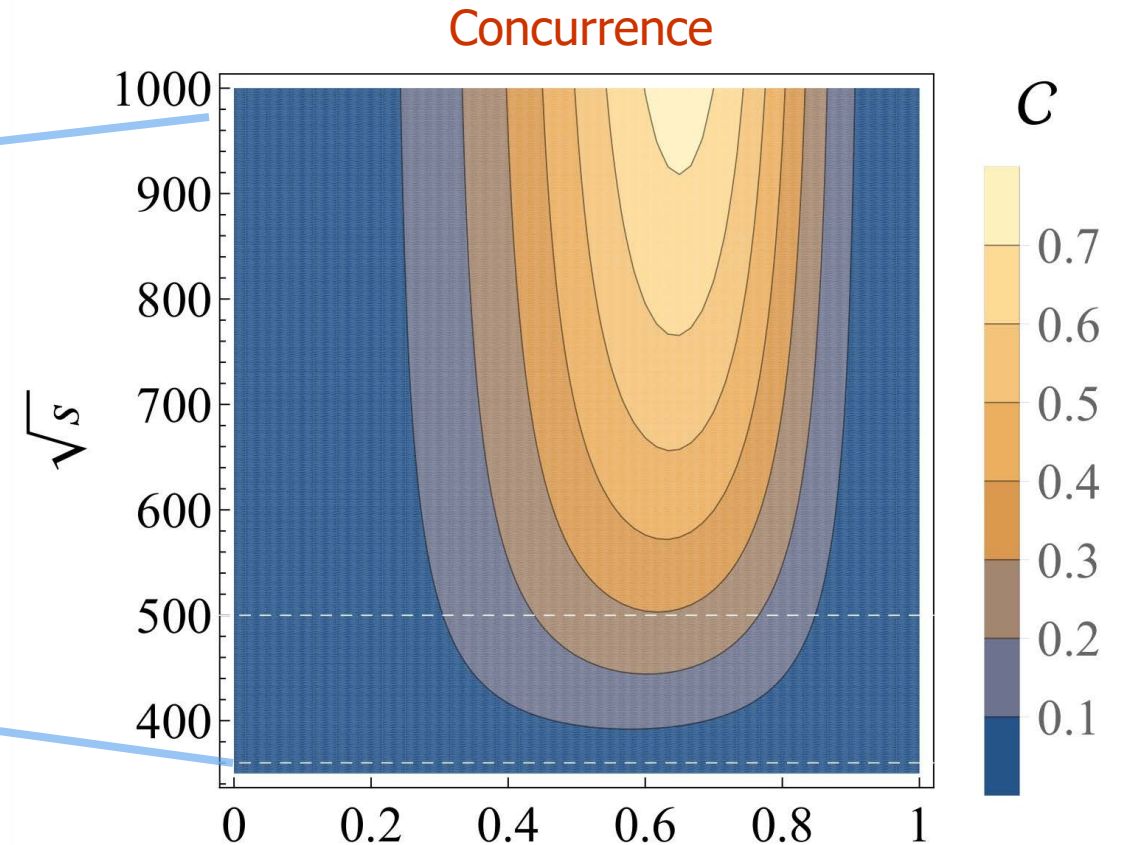
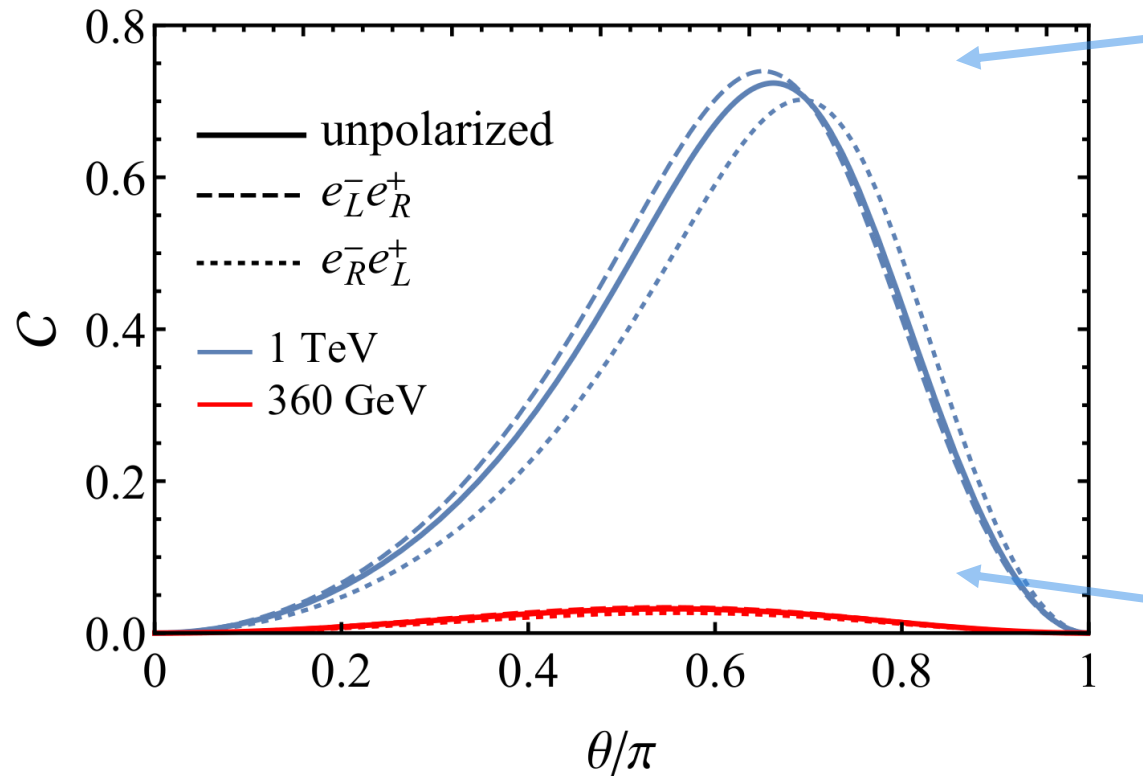
Concurrence



No entanglement at threshold,
nor in backward/forward scattering!

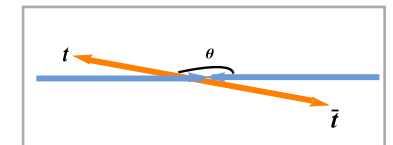
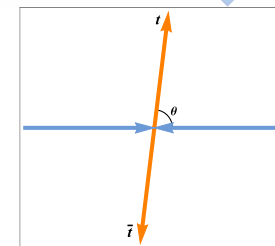
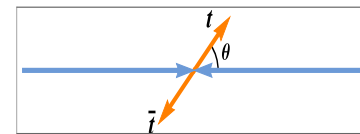
(1) $e^+e^- \rightarrow t\bar{t}$ at the threshold & above

$$|\psi\rangle \propto \frac{1}{\sqrt{2}} (|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle) + \epsilon \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle), \quad \epsilon \propto \frac{\sqrt{1-\beta^2}}{\sin \theta_{\max}}.$$



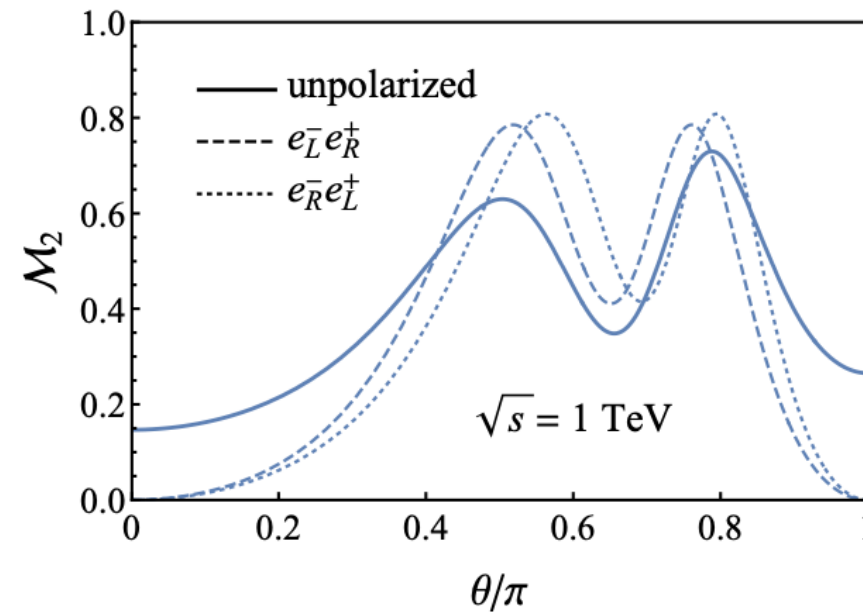
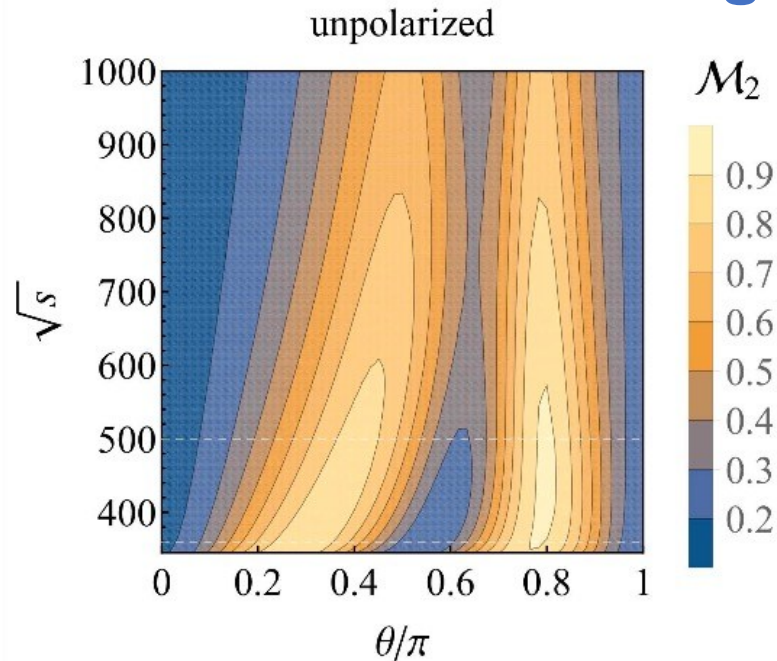
$\epsilon \rightarrow 0 \rightarrow$ **Bell triplet state** $\rightarrow \mathcal{C} \rightarrow 1$

$\theta_{\max}^{\text{LR}} < \theta_{\max}^{\text{RL}} \rightarrow |\epsilon_{\text{LR}}| < |\epsilon_{\text{RL}}| \rightarrow \mathcal{C}_{\max}^{\text{LR}} > \mathcal{C}_{\max}^{\text{RL}}$



(1) $e^+e^- \rightarrow t\bar{t}$ at the threshold & above

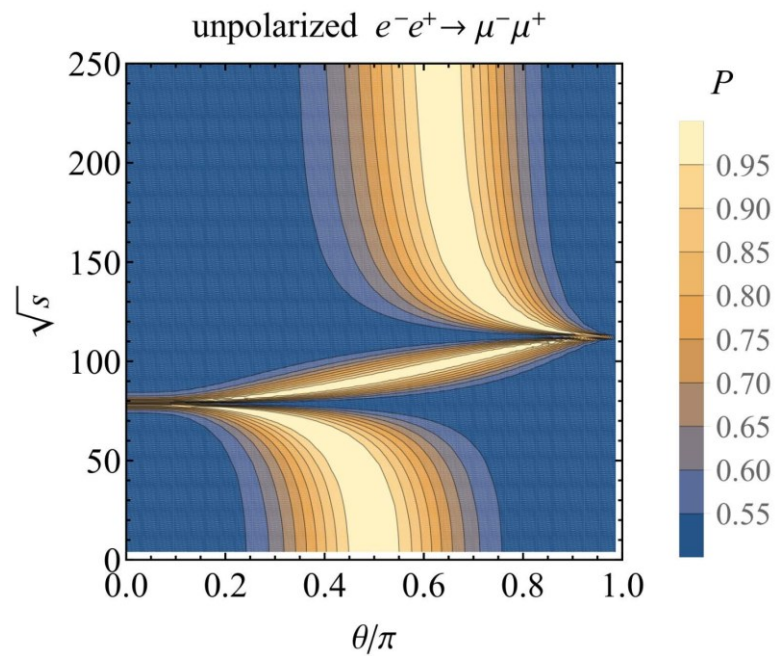
Magic: the quantum resource



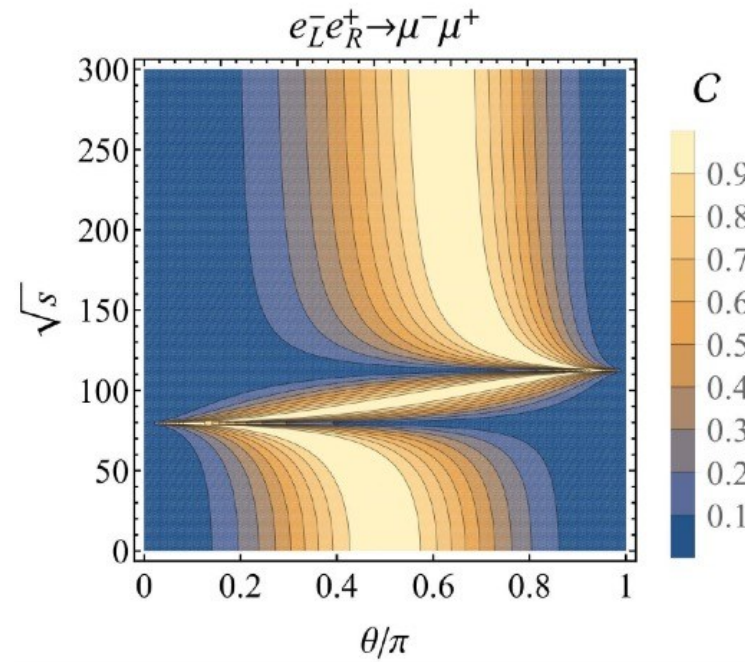
- Twin-peak of Magic
- Near Bell-state region $\Rightarrow$ Magic close to min!
- Zero entanglement may have non-zero magic!
- Polarization helps enhance magic!

(2) $e^+e^- \rightarrow \mu^+\mu^-/\tau^+\tau^-$ at the Z pole & beyond

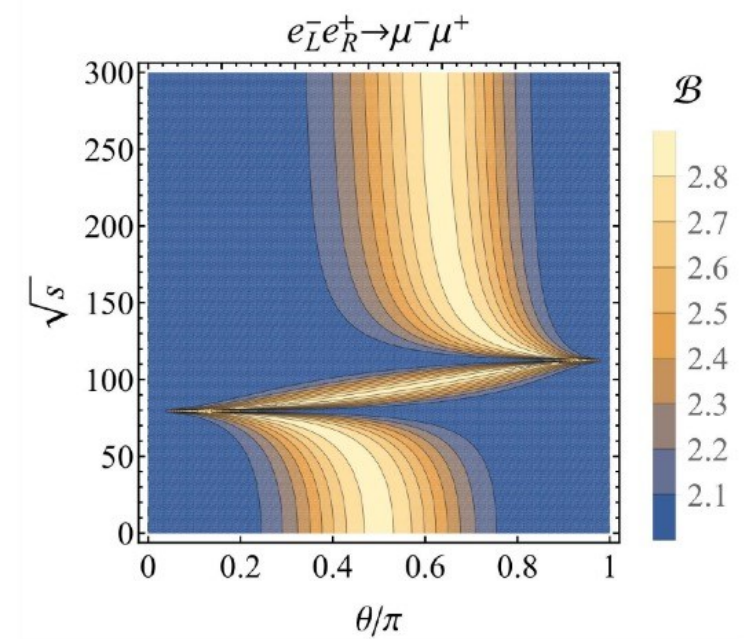
Purity



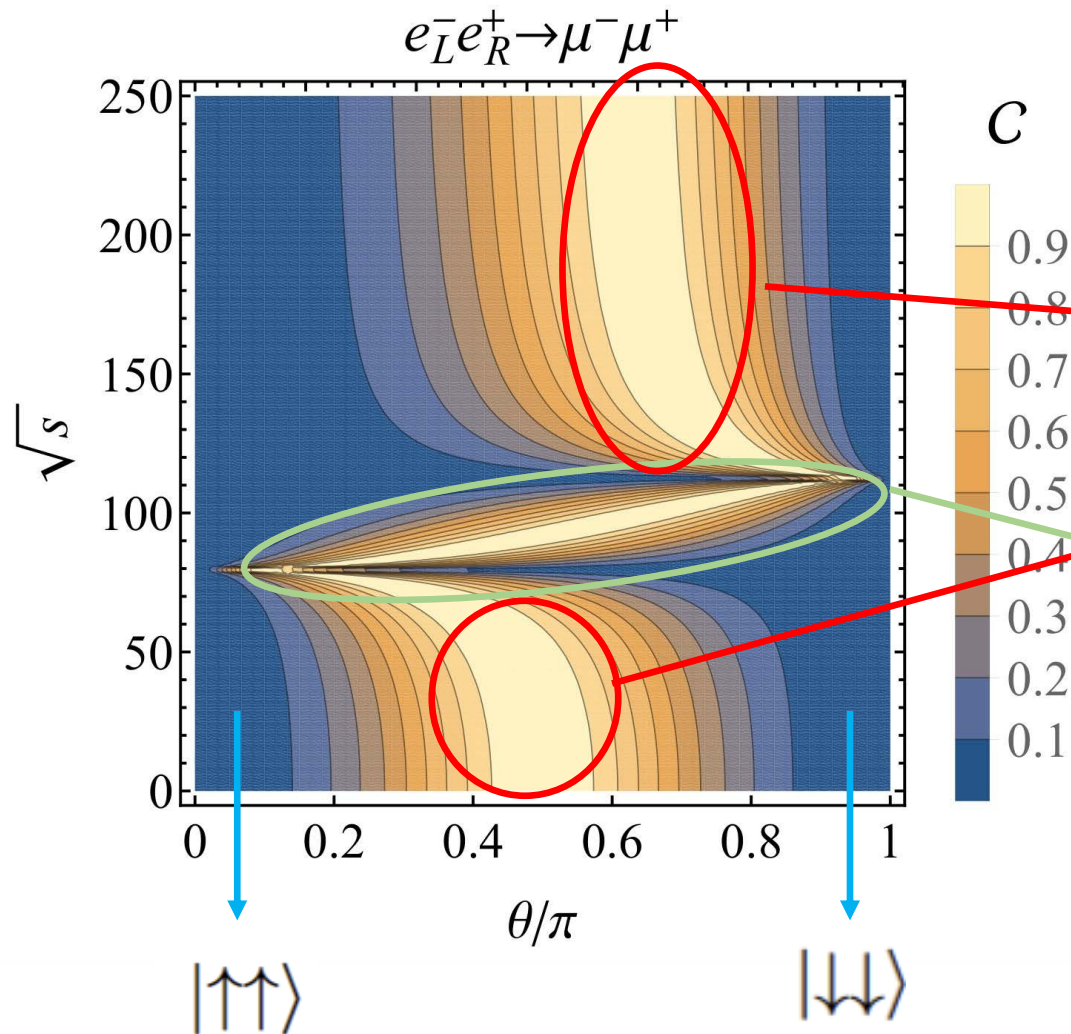
Concurrence



Bell Nonlocality



(2) $e^+e^- \rightarrow \mu^+\mu^-/\tau^+\tau^-$ at the Z pole & beyond



Different Bell state at different energy scales:
governed by the vector/axial vector couplings

Interference of
QED and EW

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}} (|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle)$$

QED symmetric

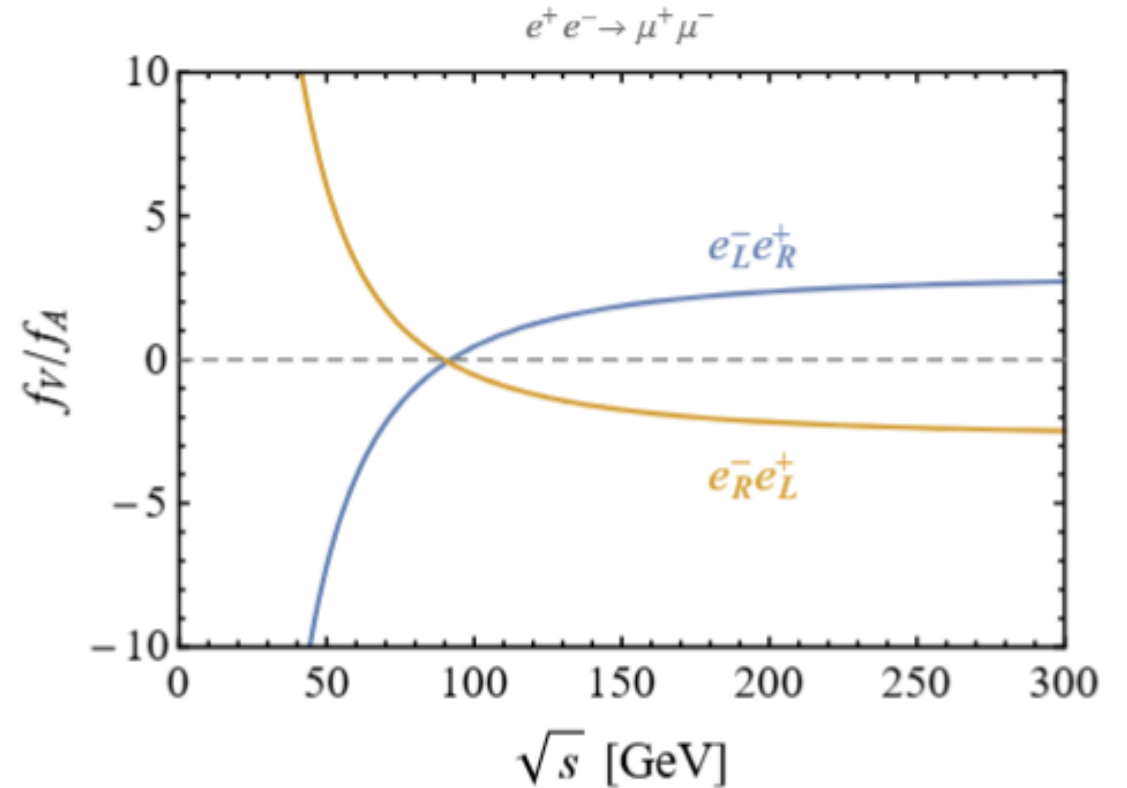
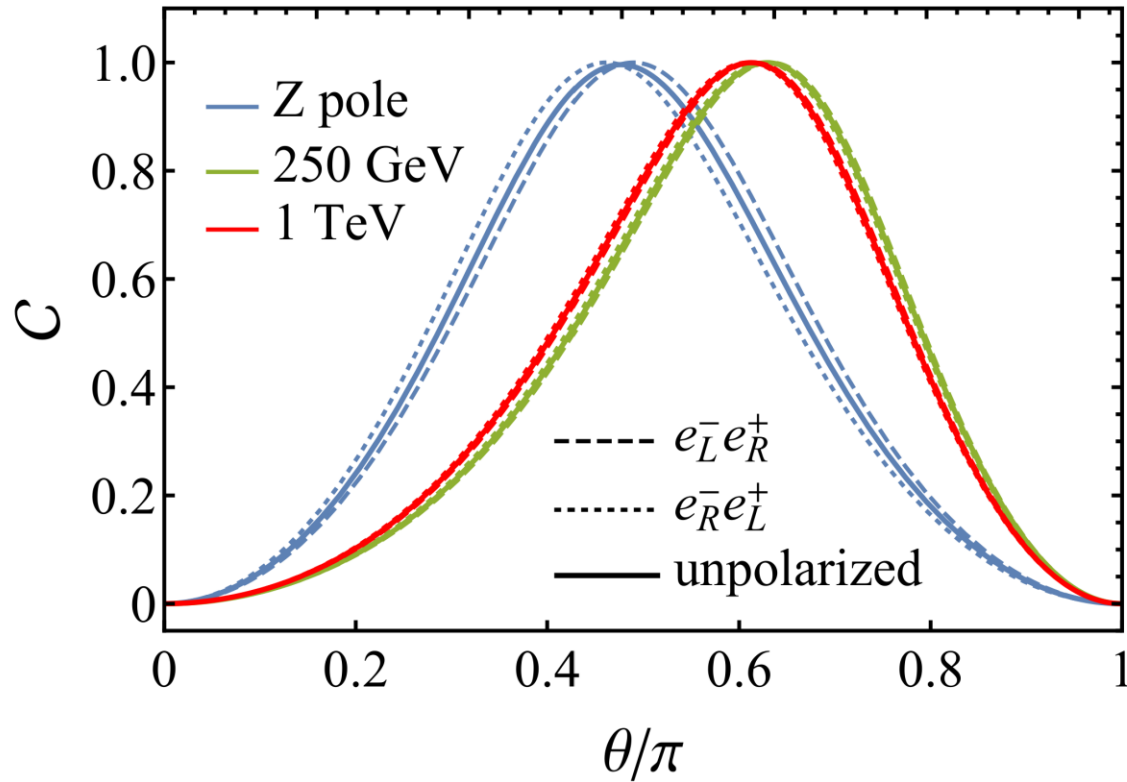
Weak chiral

$$|\Phi^-\rangle = \frac{1}{\sqrt{2}} (|\uparrow\uparrow\rangle - |\downarrow\downarrow\rangle)$$

Unpolarized Beam:

- Classical mixing of fully polarized case
- Max Entanglement close to pure state

(2) $e^+e^- \rightarrow \mu^+\mu^-/\tau^+\tau^-$ at the Z pole & beyond



LR similar to RL

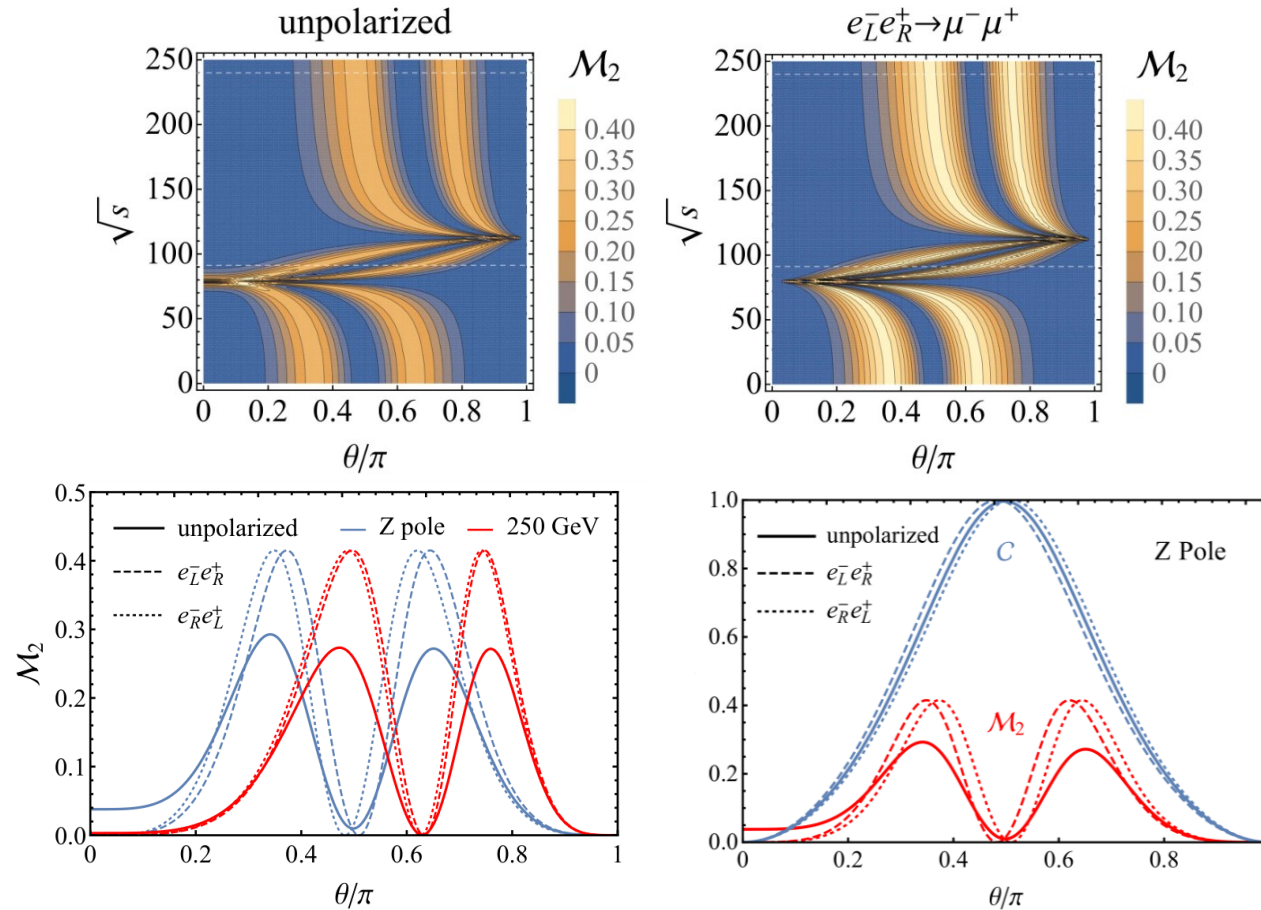


$$\frac{f_V^{RL}}{f_A^{RL}} \sim -\frac{f_V^{LR}}{f_A^{LR}}$$

Ratio between vector and axial coupling strength controls whether the state becomes **separable** or **entangled**

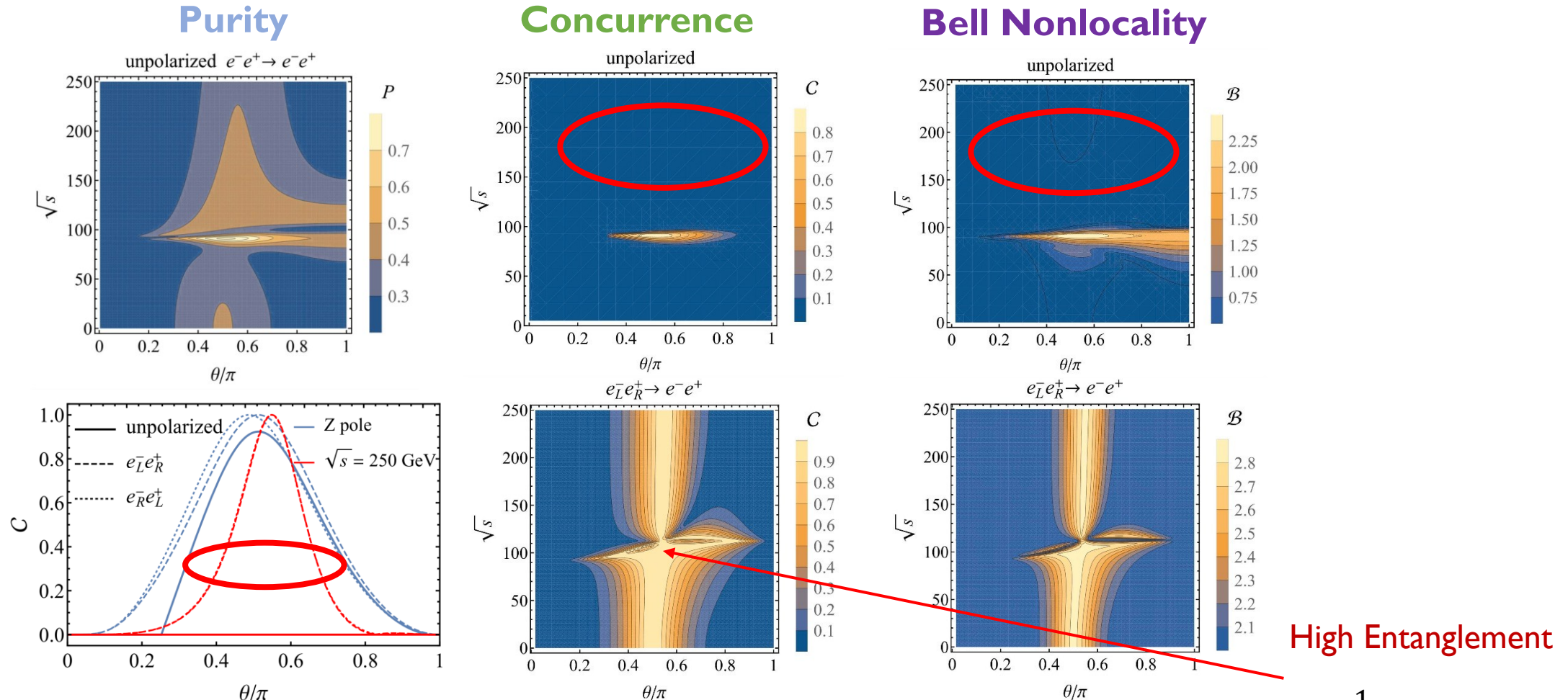
(2) $e^+e^- \rightarrow \mu^+\mu^-/\tau^+\tau^-$ at the Z pole & beyond

Magic



- Two Peaks of Magic & Max entanglement $\rightarrow$ low magic
- Magic is more sensitive to polarization

(3) Bhabha scattering & t-s interference



- Z-pole and RL, LR beams similar to $e^-e^+ \rightarrow \mu^-\mu^+$
- Unpolarized largely washed out by t-channel RR, LL
- Complete polarization will significantly enhance entanglement.

$$|\Phi^-\rangle = \frac{1}{\sqrt{2}}(|\uparrow\uparrow\rangle - |\downarrow\downarrow\rangle)$$

(3) Bhabha scattering & t-s interference

Bhabha scattering has both *s* and *t* channels

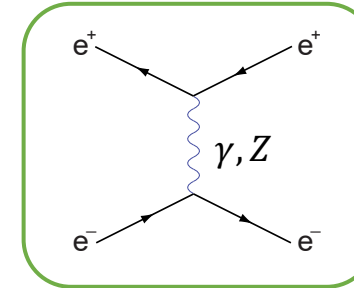
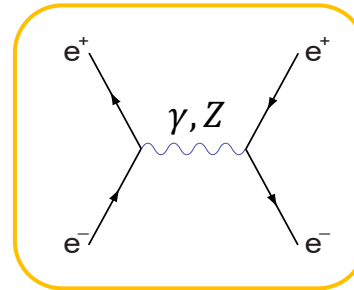
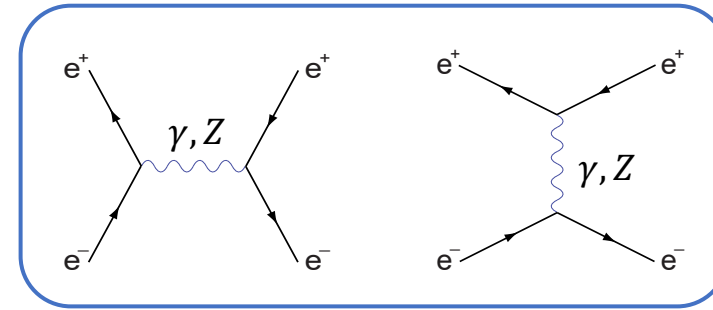
Helicity amplitudes separate into 3 categories:

- *s*+*t* interference: $M(LR, \downarrow\downarrow) = M(RL, \uparrow\uparrow)$
- *s*-channel only: $M(LR, \uparrow\uparrow)$ and $M(RL, \downarrow\downarrow)$
- *t*-channel only: $M(LL, \downarrow\uparrow) = M(RR, \uparrow\downarrow)$

□ How *t*-channel influences QI?

- ✓ Owing to the helicity conservation in massless scattering, *t*-channel results in separable states

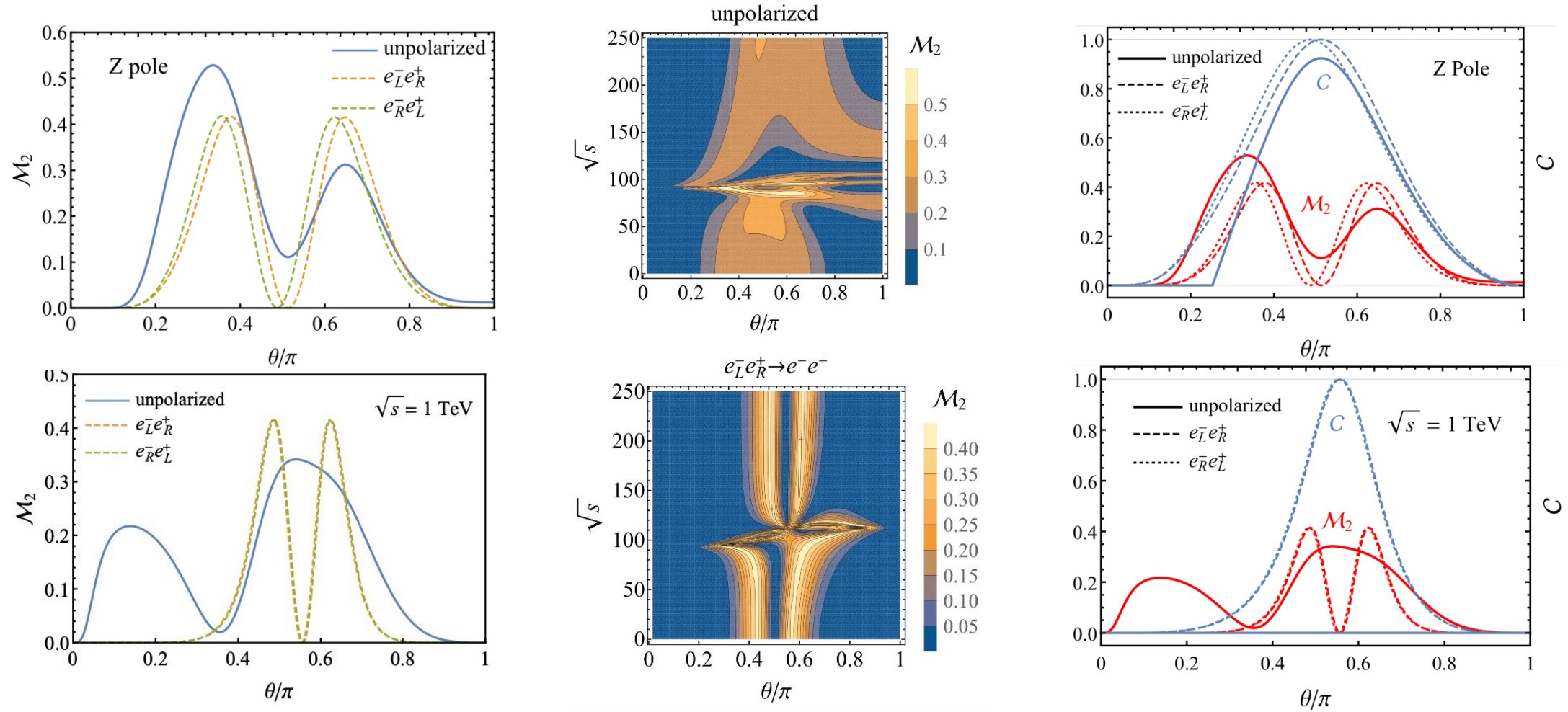
$$|\psi_{RR}\rangle = c_{RR} |\uparrow\downarrow\rangle, \quad |\psi_{LL}\rangle = d_{LL} |\downarrow\uparrow\rangle$$



Entangled State
 $|\psi\rangle = \alpha|\uparrow\uparrow\rangle + \beta|\downarrow\downarrow\rangle$

Separable State
 $|\uparrow\downarrow\rangle$ or $|\downarrow\uparrow\rangle$

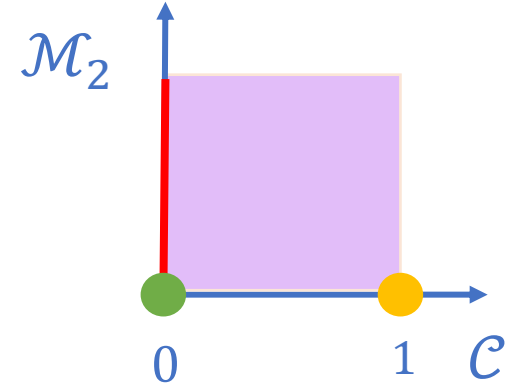
(3) Bhabha scattering & t-s interference



- Magic exhibits twin-peak structure
- Some interesting area: $C = 0$ but $M_2 > 0$;

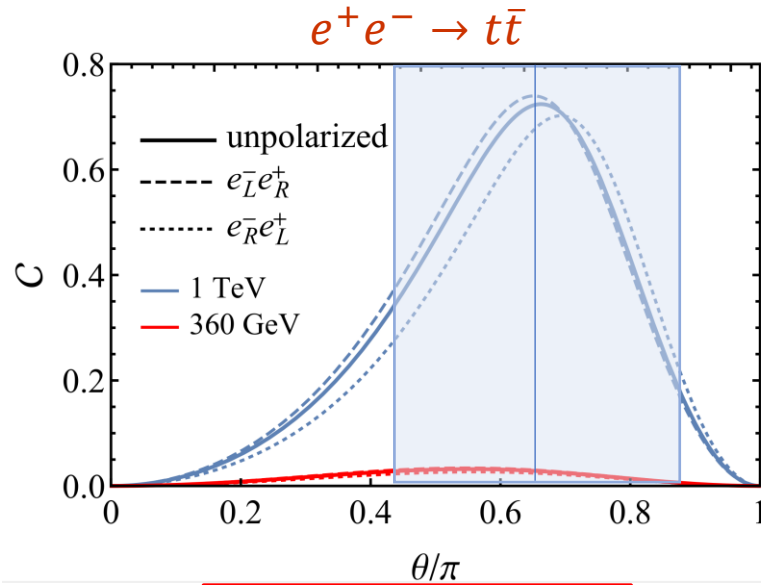
Entanglement vs. Magic in $f\bar{f}$ systems

- Magic is more polarization-tunable
- Parameter space can be classified into 4 regimes:



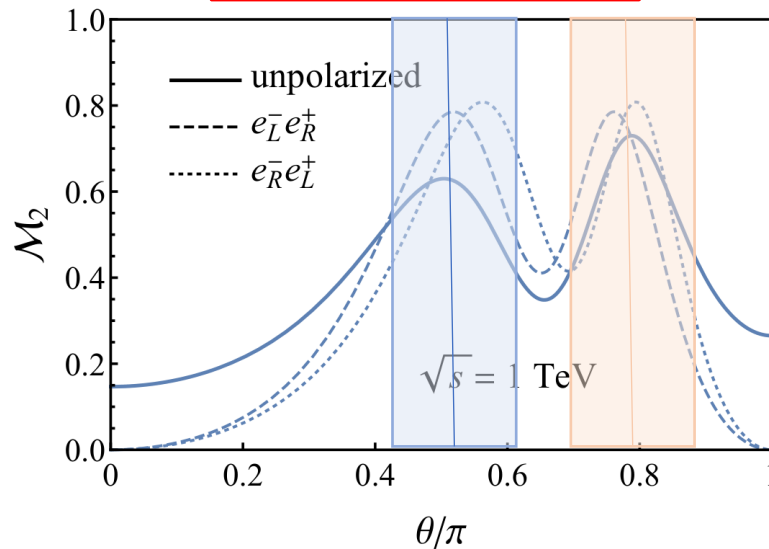
$\mathcal{C} \rightarrow 0$ $\mathcal{M}_2 \rightarrow 0$	$\mathcal{C} \rightarrow 1$ $\mathcal{M}_2 \rightarrow 0$	$0 < \mathcal{C} < 1$ $\mathcal{M}_2 > 0$	$\mathcal{C} = 0$ $\mathcal{M}_2 > 0$
Separable States + Stabilizer State	Maximally Entangled + Stabilizer State	Entangled + Non-stabilizer State	Separable States + Non-stabilizer State
polarized $\theta \rightarrow 0, \pi$	$\cos \theta \approx \mp \beta f_A / f_V$	twin-peak	1. unpolarized $\theta \rightarrow 0, \pi$ 2. s/t Interference dominate

QI Measurement at Colliders



$$\theta_c - \frac{\Delta\theta}{2} < \theta_t < \theta_c + \frac{\Delta\theta}{2}$$

Decay Approach
for comparison



$\sqrt{s} = 1 \text{ TeV}$		Entanglement Measure ($\mathcal{C}$)						Bell Nonlocality ($\mathcal{B} - 2$)					
(P_{e^-}, P_{e^+})	Δ_{sys}	$\mathcal{C}$	$\Delta_{\text{tot}}(\mathcal{C})$	S, S^{-1}	θ_c	$\Delta\theta$	$\mathcal{B} - 2$	$\Delta_{\text{tot}}(\mathcal{B})$	S, S^{-1}	θ_c	$\Delta\theta$		
(0, 0)	1%	0.49	0.022	$> 5\sigma, 4.5\%$	119°	92°	0.37	0.090	4.2σ	119°	37°		
	2%	0.55	0.035	$> 5\sigma, 6.4\%$	119°	75°	0.41	0.133	3.1σ	119°	29°		
(+0.8, -0.6)	1%	0.41	0.025	$> 5\sigma, 6.1\%$	124°	110°	0.34	0.10	3.3σ	124°	38°		
	1%	0.41	0.032	$> 5\sigma, 7.9\%$	124°	110°	0.37	0.14	2.6σ	124°	31°		
(-0.8, +0.6)	1%	0.49	0.020	$> 5\sigma, 4.2\%$	116°	101°	0.41	0.074	$> 5\sigma, 18\%$	116°	34°		
	2%	0.49	0.032	$> 5\sigma, 6.5\%$	116°	101°	0.45	0.12	3.7σ	116°	25°		

$\sqrt{s} = 1 \text{ TeV}$		Central Region						Backward Region					
(P_{e^-}, P_{e^+})	Δ_{sys}	$\mathcal{M}_2$	$\Delta_{\text{tot}}(\mathcal{M}_2)$	S, S^{-1}	θ_c	$\Delta\theta$	$\mathcal{M}_2$	$\Delta_{\text{tot}}(\mathcal{M}_2)$	S, S^{-1}	θ_c	$\Delta\theta$		
(0, 0)	1%	0.58	0.040	$> 5\sigma, 2.4\%$	91°	48°	0.66	0.058	$> 5\sigma, 3.0\%$	111°	48°		
	2%	0.60	0.061	$> 5\sigma, 3.5\%$	91°	35°	0.66	0.070	$> 5\sigma, 3.7\%$	141°	48°		
(+0.8, -0.6)	1%	0.81	0.035	$> 5\sigma, 1.5\%$	99°	48°	0.78	0.067	$> 5\sigma, 3.0\%$	145°	40°		
	2%	0.82	0.052	$> 5\sigma, 2.2\%$	99°	36°	0.78	0.077	$> 5\sigma, 3.4\%$	145°	40°		
(-0.8, +0.6)	1%	0.79	0.029	$> 5\sigma, 1.3\%$	92°	45°	0.77	0.039	$> 5\sigma, 1.7\%$	137°	40°		
	2%	0.79	0.049	$> 5\sigma, 2.1\%$	92°	34°	0.78	0.055	$> 5\sigma, 2.4\%$	137°	37°		

Summary: All Processes Exceed 5σ

Another New Frontiers in TeV Physics: AI Application in Physics

- Data Analysis (Dr.Sai, COLLIDER-BENCH, RooAgent ...)
- Collider Phenomenolog Study
(Collider Agent, DarkAgents, HEP-CoPilot, EasyScan_HEP 2...)
- More specialized Agents ... *Apologies to many recent works*
- AI-Driven Discovery (refer to the talks presented this morning)

We proposed a natural-language-driven agent for SMEFT phenomenology:

SMEFT-Pheno-Agent

Motivation of SMEFT-Pheno-Agent

Y G, Jie Wang , Ji-Chong Yang, arXiv: 2607.22331

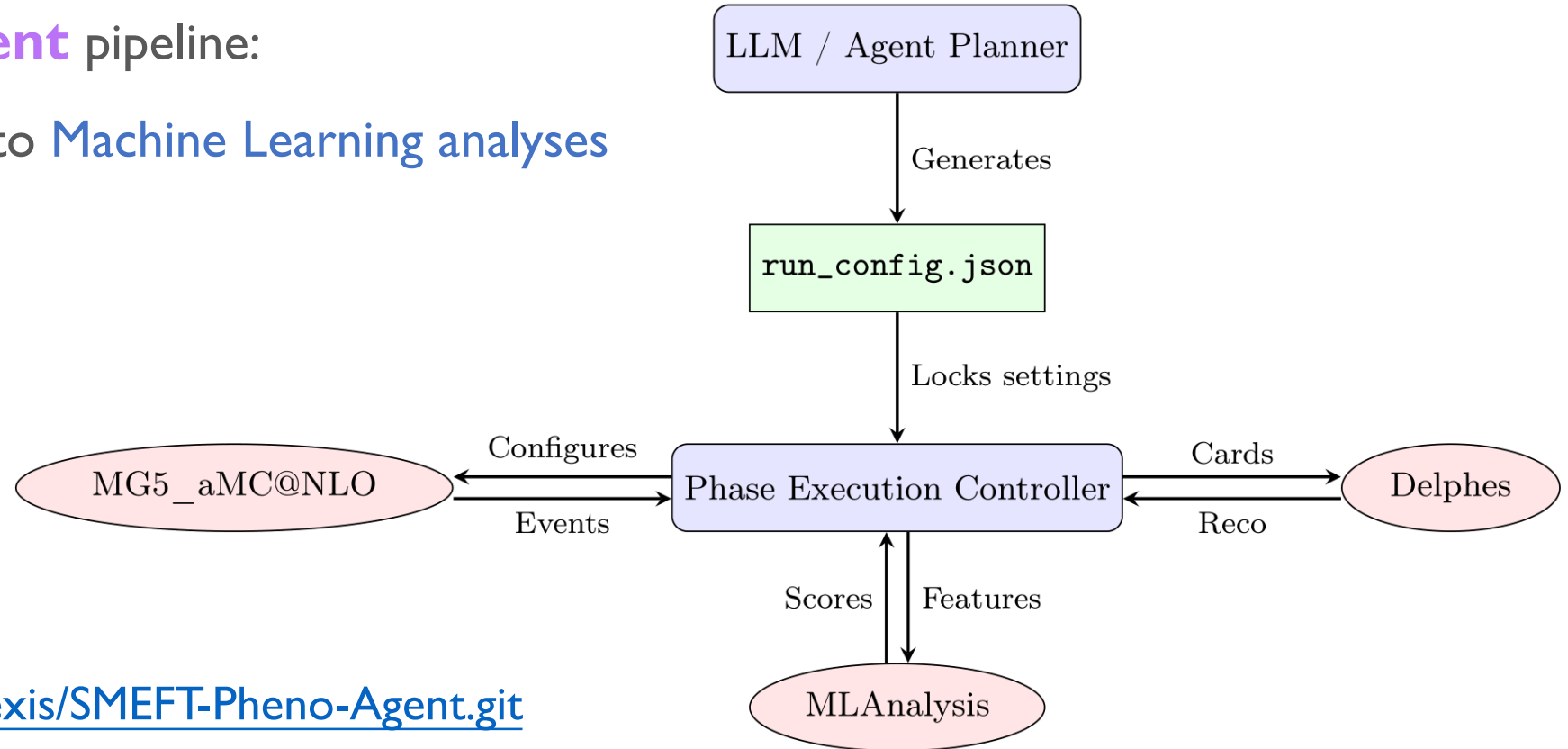
- Collider Data Analysis is a natural fit for Machine Learning
 - Rarer processes bring more final-state particles and more observables
 - ideal for ML in high dimensions
- The Gap of Real Automatic
 - ML-based new physics searches described as “automatic,”
 - but full automation remains far from achieved
- AI Agents are changing how we work



SMEFT-Pheno-Agent

SMEFT-Pheno-Agent pipeline:

from event simulation to Machine Learning analyses



The source code:

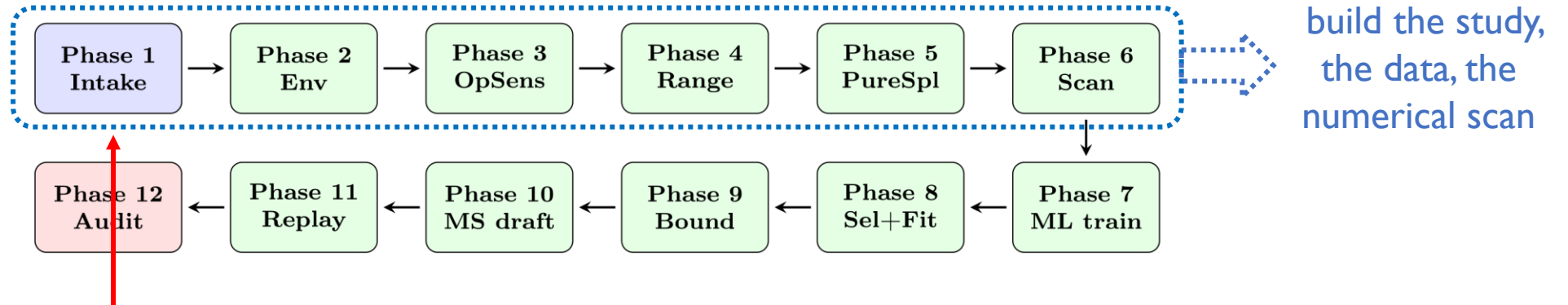
<https://github.com/NBAlexis/SMEFT-Pheno-Agent.git>

A gitee mirror:

<https://gitee.com/NBAlexis/automated-smeft-ml-pheno>

SMEFT-Pheno-Agent

Twelve-phase execution graph



- I found WSL2 with Ubuntu-24.04 available. Since this is native Windows, local mode is unavailable – you'll use `wsl2`, `ssh`, or `auto-install`.

[1/9] WSL2 distro Ubuntu-24.04 was found. What is the absolute MadGraph5 path inside WSL2? Provide `wsl2:/absolute/MG5/path`, `ssh user@host:/absolute/MG5/path`, or type `install` to auto-install on the selected target.

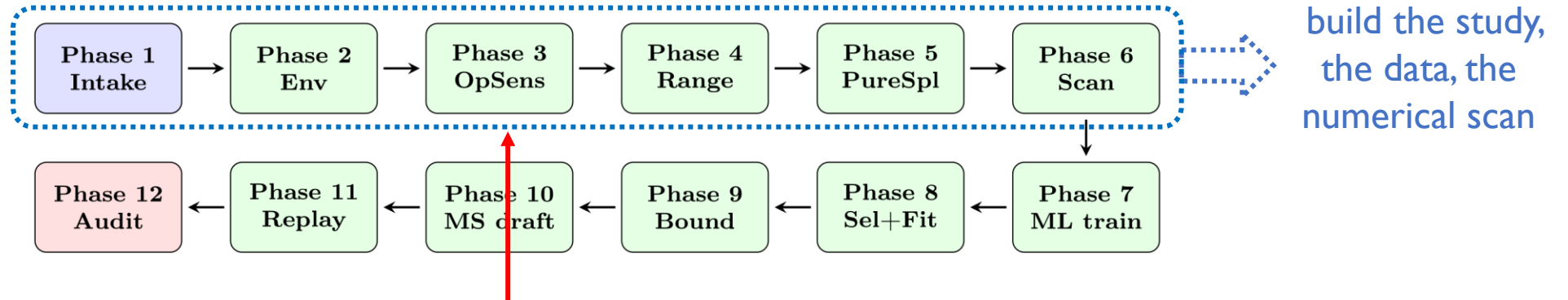
已找到 WSL2 发行版 Ubuntu-24.04。请提供 WSL2 内部的 MadGraph5 绝对路径，输入 `wsl2:/absolute/MG5/path`、`ssh user@host:/absolute/MG5/path`，或输入 `install` 在所选目标上自动安装。

* Baked for 47s

> `install`

SMEFT-Pheno-Agent

Twelve-phase execution graph



```
---  
[3/9] What collider process should be studied? Provide one physics process, or a  
bracketed list such as [mu+ mu- > l+ vl j j, mu+ mu- > l- vl~ j j]. Do not add  
quotes and do not include NP=, QED=, or QCD= suffixes.  
要研究哪个对撞过程？请提供一个物理过程，或一个方括号列表，例如 [mu+ mu- > l+ vl  
j j, mu+ mu- > l- vl~ j j]。不要加引号，也不要包含 NP=、QED= 或 QCD= 后缀。
```

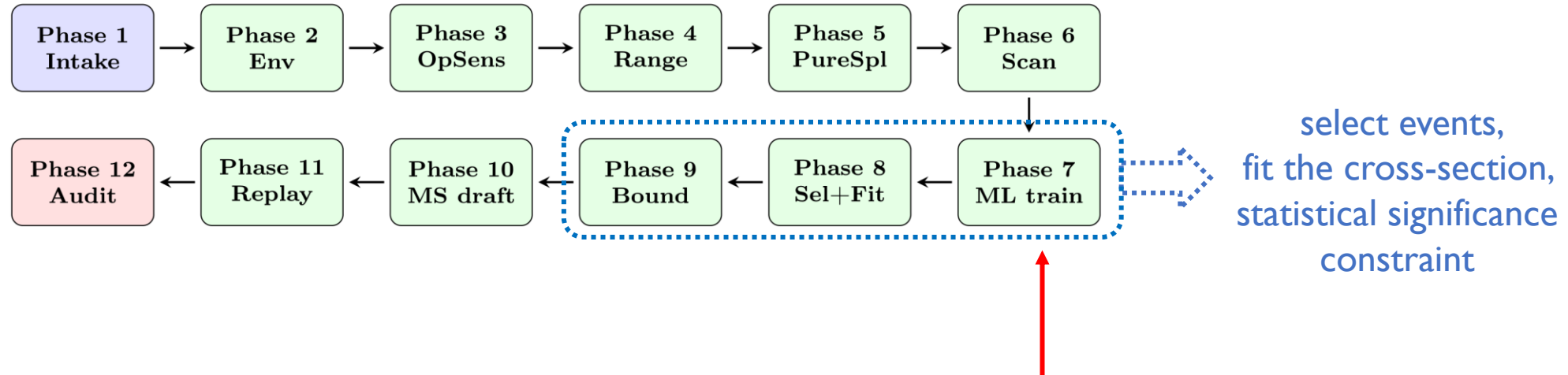
* Crunched for 18s

```
> mu+ mu- > a j j
```

P3: operator sensitivity validation; P4: SM baseline and coefficient range
P5: pure event samples (an SM event and one NP event with coefficient)
P6: coefficient scan

SMEFT-Pheno-Agent

Twelve-phase execution graph



```
---
[7/9] Do you already have CutExperiment installed on the selected execution
target? No default path was found. Provide a path, or type clone to clone it
from https://gitee.com/NBAlexis/CutExperiment.git.
所选执行目标上是否已经安装 CutExperiment? 未找到默认路径。请提供路径，或输入
clone 从 https://gitee.com/NBAlexis/CutExperiment.git 克隆。

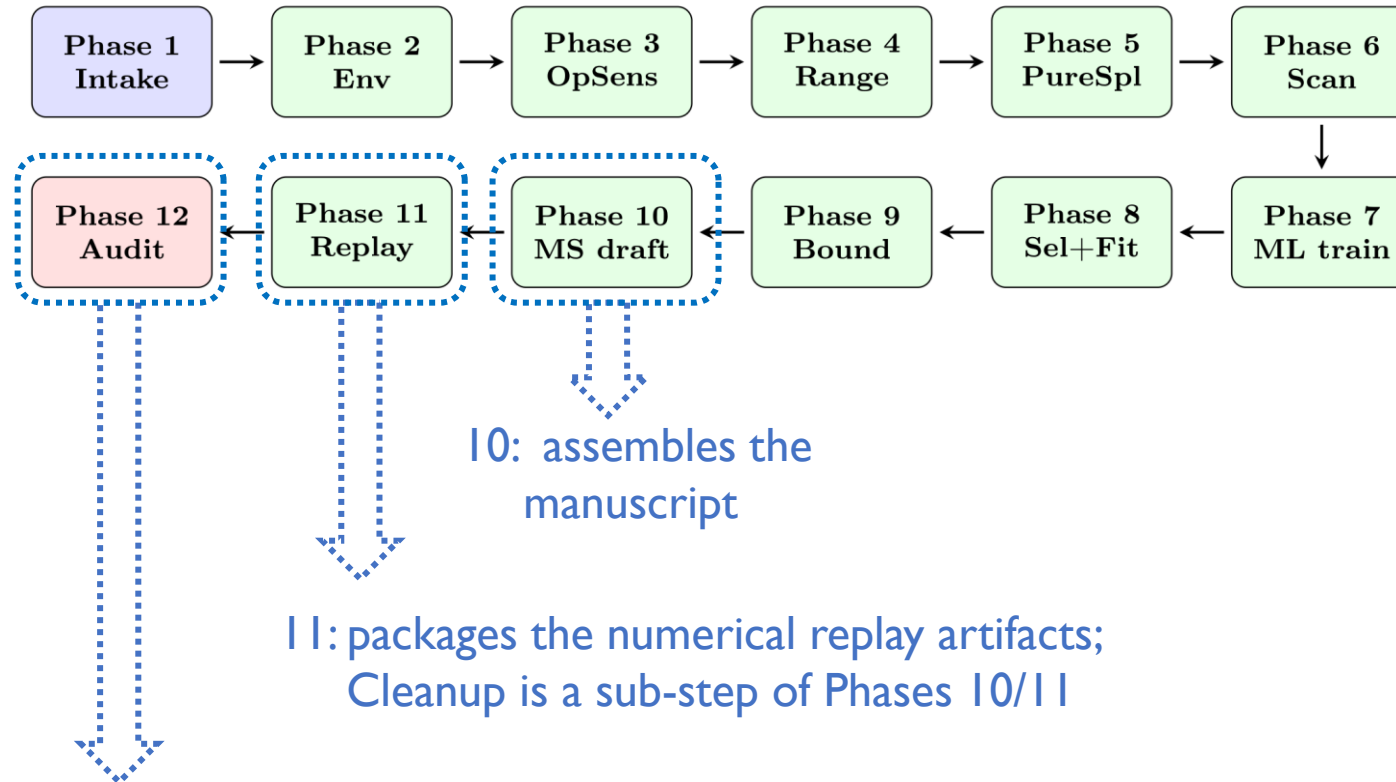
* Churned for 6s

> clone
```

P7: MLAnalysis → Machine Learning analysis

SMEFT-Pheno-Agent

Twelve-phase execution graph



10: assembles the manuscript

11: packages the numerical replay artifacts;
Cleanup is a sub-step of Phases 10/11

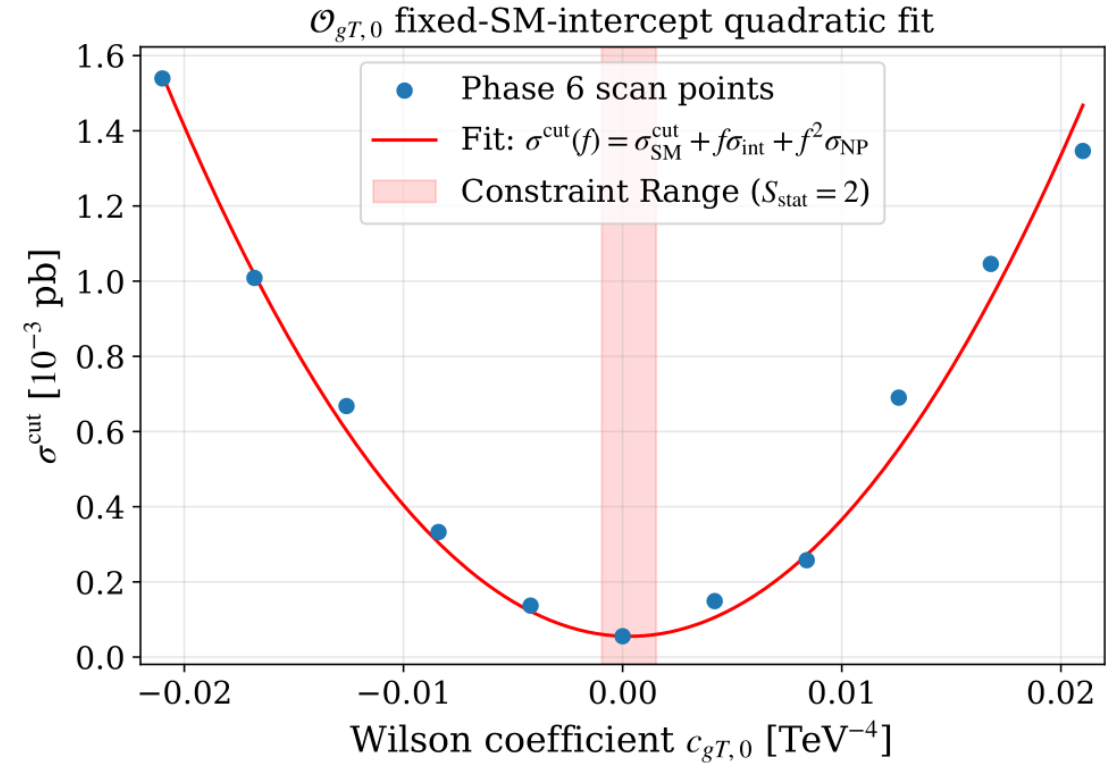
12: re-reads the declared artifacts
for cross-phase self-consistency

Example:

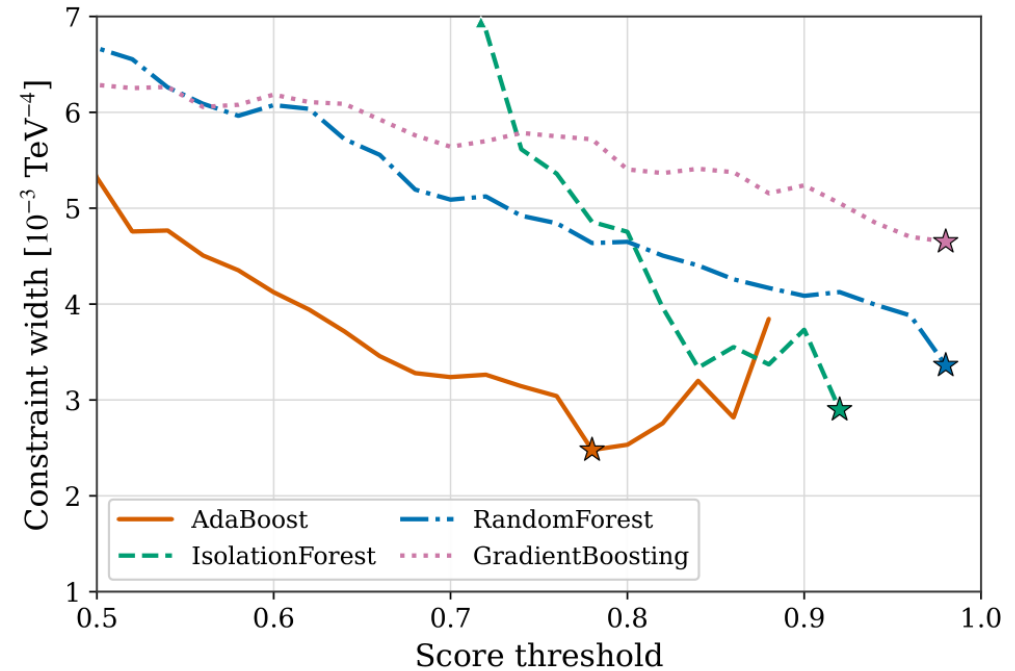
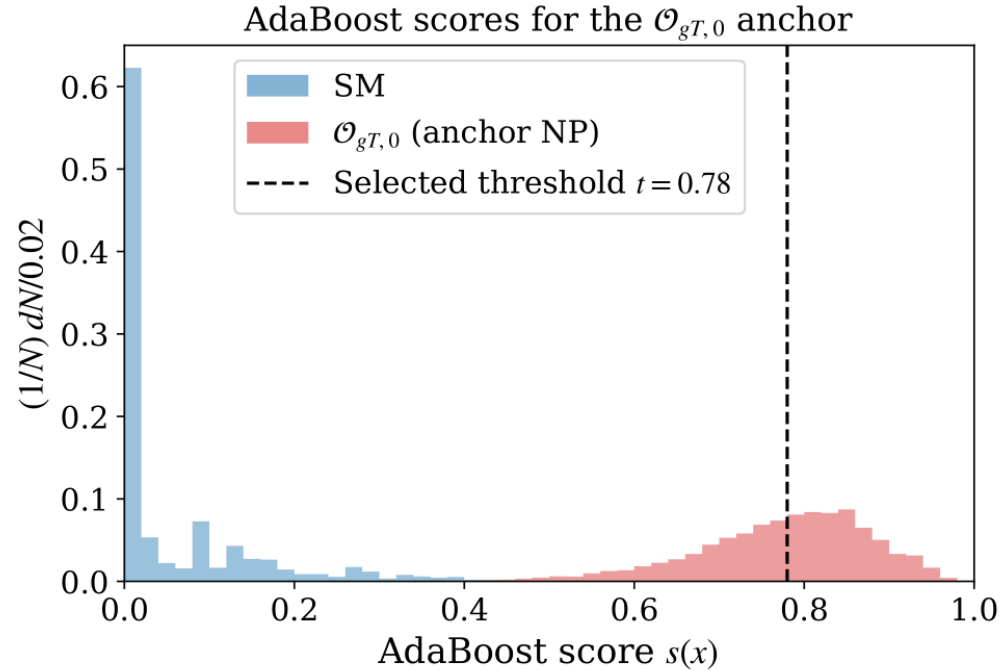
TABLE I. Phase 1 configuration excerpt for the reference run.

Quantity	Locked value
Process	$\mu^+\mu^- \rightarrow \nu_\mu \bar{\nu}_\mu jj$
Centre-of-mass energy	$\sqrt{s} = 10 \text{ TeV}$
Integrated luminosity	10 ab^{-1}
Configured polarisation tuple	$(-1, +1)$
Model	gQGC_UF0
Detector simulation	delphes_card_MuonColliderDet.tcl
Final-state requirement	$N_{\text{jet}} \geq 2$
Locked event budgets (events)	$N_{\text{SM}} = 1 \times 10^6, N_{\text{NP}} = 10^5, N_{\text{scan}} = 10^6$

S_{stat}	$c_{gT,0} (10^{-3} \text{ TeV}^{-4})$
2	$[-0.948, 1.531]$
3	$[-1.218, 1.800]$
5	$[-1.655, 2.237]$



SMEFT-Pheno-Agent



Algorithm	Optimal threshold	Constraint width (10^{-3} TeV^{-4})	Selected
AdaBoost	0.78	2.479	✓
Isolation Forest	0.92	2.899	
Random Forest	0.98	3.361	
Gradient Boosting	0.98	4.651	

Welcome to try our skills !

Summary

- **QIS** @ colliders: New observables & rich physics! ➡ **New Pheno!**
- e^+e^- collisions: high energy, high luminosity, beam polarizations
⇒ good control of quantum states
- Longitudinal/Transverse beam polarization
- **LLM Agent** for HEP: changing how we work ! ➡ **New method !**

We're just at the beginning of the journey!



Back up | 2026 >

$$|P(a,b) - P(a,b')| + |P(a',b) + P(a',b')| \leq 2 \cdot \epsilon_m$$



Welcome to the Quantum Year!
Celebrating entanglement

Bienvenue dans l'année quantique !
Fêtons l'intrication



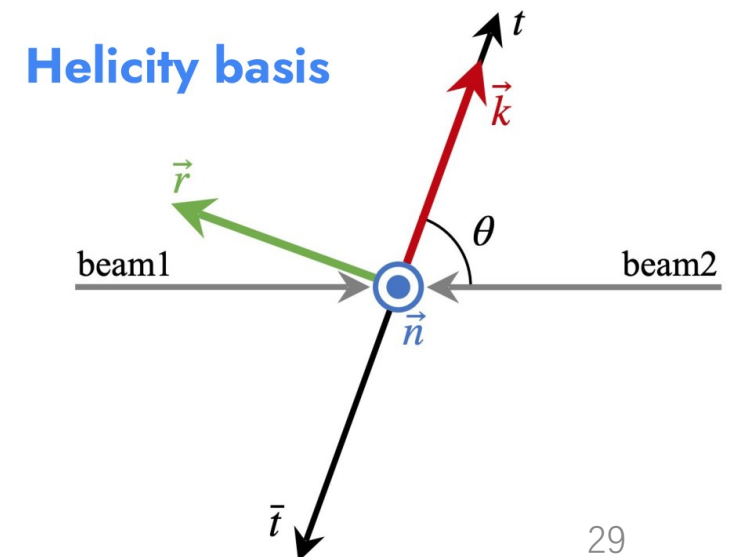
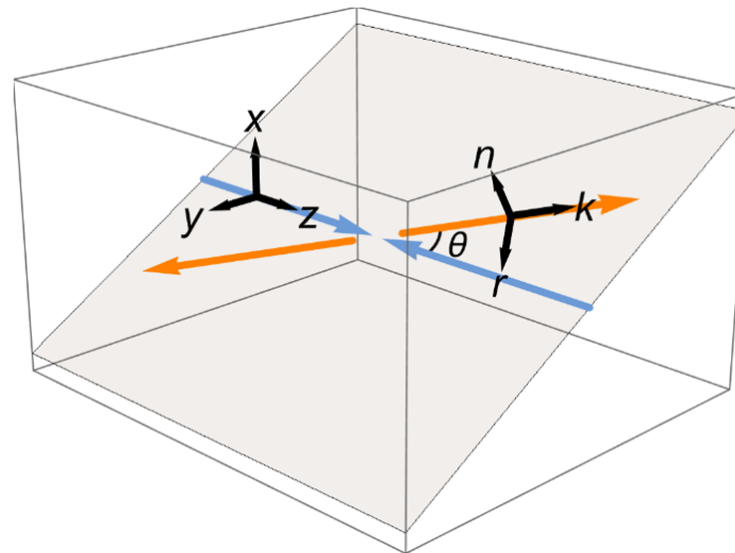
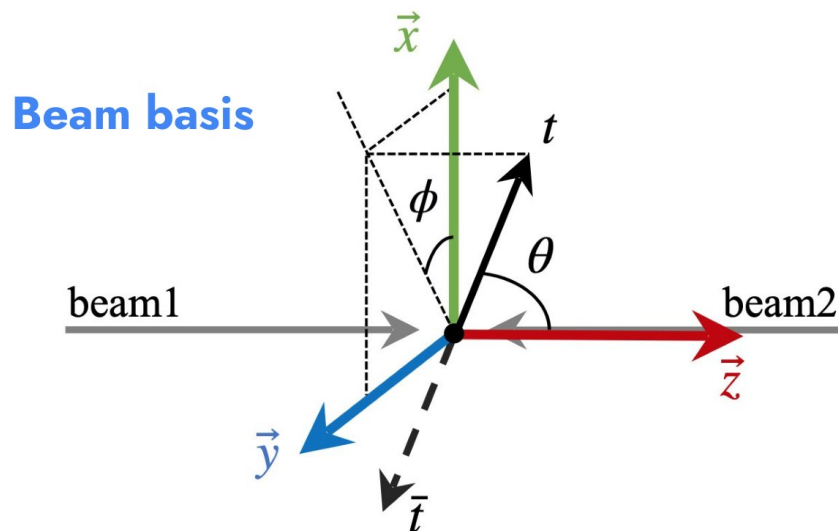
Quantum Tomography @ Colliders

Cheng, Han, Low [2311.09166](#)
Cheng, Fang, Han, Low [2502.14065](#)

Choice of **Basis**

- Equivalent to **axes** for spin measurement
- Beam basis $\{x,y,z\}$: cancellation leads to null result
- Helicity basis $\{r,k,n\}$: entanglement with no cancellations after averaging over phase space

Chirality $\approx$ helicity at high energy, simplifies physical interpretation



Quantum Tomography of $e^+e^- \rightarrow f\bar{f}$

- For the fully-polarized LR ($e_L^- e_R^+$) or RL ($e_R^- e_L^+$) the final state $|f\bar{f}\rangle$ is a pure two-qubit state

- Full tomography

$$B_k^\pm = \frac{2(f_V \pm f_A c_\theta)(f_A \pm f_V c_\theta)}{(f_V^2 + f_A^2)(1 + c_\theta^2) \pm 4f_V f_A c_\theta},$$

$$C_{ij} = \frac{1}{\mathcal{D}} \begin{pmatrix} s_\theta^2 (f_V^2 (2 - \beta^2) - f_A^2 \beta^2) & 0 & -2(f_V^2 c_\theta \pm f_V f_A \beta) s_\theta \sqrt{1 - \beta^2} \\ 0 & (f_A^2 - f_V^2) \beta^2 s_\theta^2 & 0 \\ -2(f_V^2 c_\theta \pm f_V f_A \beta) s_\theta \sqrt{1 - \beta^2} & 0 & f_V^2 (2c_\theta^2 + \beta^2 s_\theta^2) + f_A^2 \beta^2 (1 + c_\theta^2) \pm 4f_V f_A \beta \end{pmatrix}$$

with normalization factor $\mathcal{D} = f_V^2 (2 - \beta^2 s_\theta^2) \pm 4\beta f_V f_A c_\theta + \beta^2 f_A^2 (1 + c_\theta^2)$

- Effective chiral couplings:
(**BSM** will modify them!)

$$f_V^L = Q_e Q_f + \frac{g_L^e (g_L^f + g_R^f)}{2c_W^2 s_W^2} \frac{s}{s - m_Z^2 + i\Gamma_Z m_Z},$$

$$f_A^L = -\frac{g_L^e (g_L^f - g_R^f)}{2c_W^2 s_W^2} \frac{s}{s - m_Z^2 + i\Gamma_Z m_Z},$$

$$f_V^R = Q_e Q_f + \frac{g_R^e (g_L^f + g_R^f)}{2c_W^2 s_W^2} \frac{s}{s - m_Z^2 + i\Gamma_Z m_Z},$$

$$f_A^R = -\frac{g_R^e (g_L^f - g_R^f)}{2c_W^2 s_W^2} \frac{s}{s - m_Z^2 + i\Gamma_Z m_Z},$$

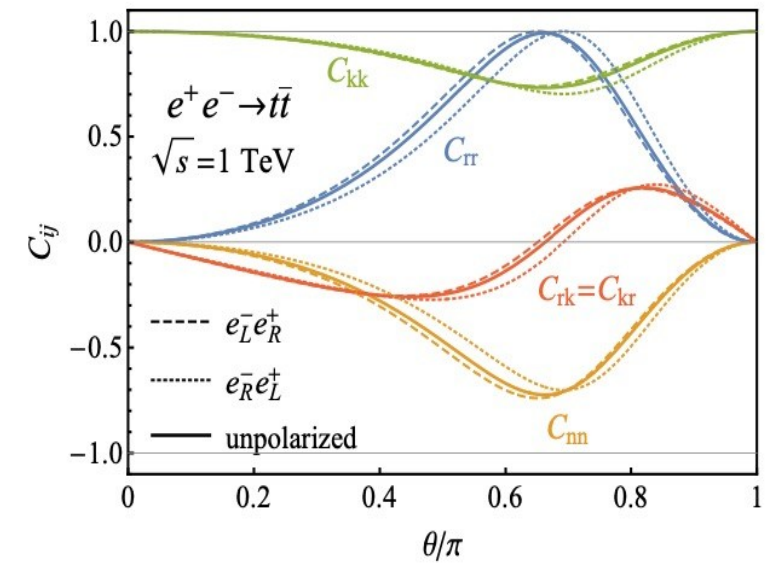
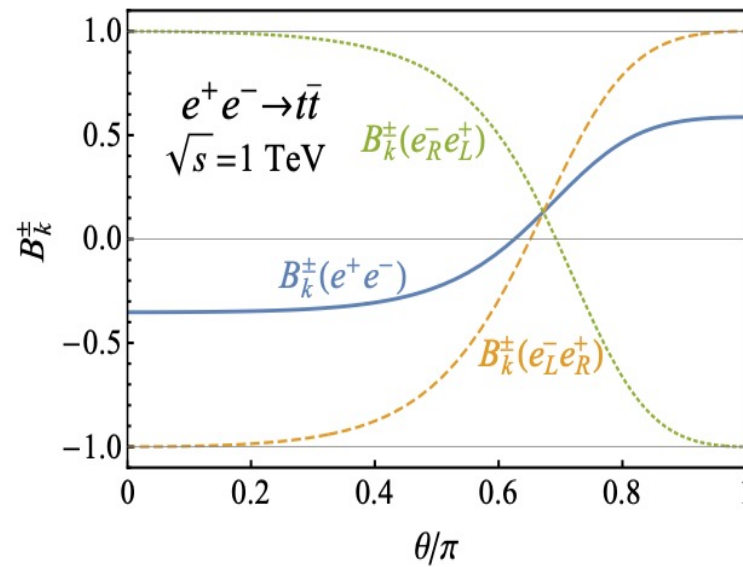
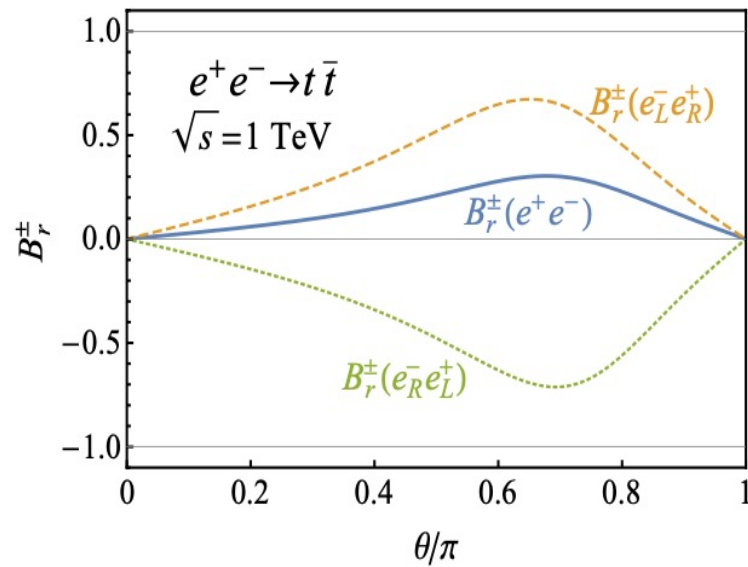
- Concurrence:** $\mathcal{C} = \frac{\beta^2 s_\theta^2 (f_V^2 - f_A^2)}{\mathcal{D}}$ **& Bell:** $\mathcal{B} = 2\sqrt{1 + \mathcal{C}^2}$.

reaching the maximum $\mathcal{C} \rightarrow 1$, $\mathcal{B} \rightarrow 2\sqrt{2}$ at $\cos \theta = \mp f_A / f_V$.

Applicable to $f\bar{f}$ with / without decay!

(1) $e^+e^- \rightarrow t\bar{t}$ at the threshold & above

- Fano coefficients of $e^-e^+ \rightarrow t\bar{t}$



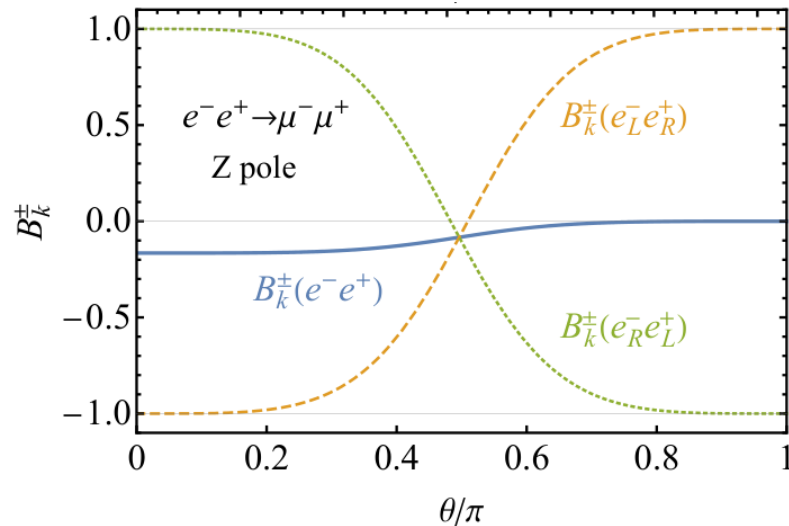
RL $\Leftrightarrow$ LR flip single-particle polarization vectors B_i ; spin-correlation matrix C_{ij} insensitive to polarization

(2) $e^+e^- \rightarrow \mu^+\mu^-/\tau^+\tau^-$ at the Z pole & beyond

- Quantum states for $e^-e^+ \rightarrow \mu^-\mu^+$

$|\psi\rangle = a|\uparrow\uparrow\rangle + b|\downarrow\downarrow\rangle$, with a and b for polarization RL (LR)

$$a \propto \left(1 + \frac{f_A^{R/L}}{f_V^{R/L}}\right) (1 \pm \cos\theta), \quad b \propto \left(1 - \frac{f_A^{R/L}}{f_V^{R/L}}\right) (1 \mp \cos\theta),$$

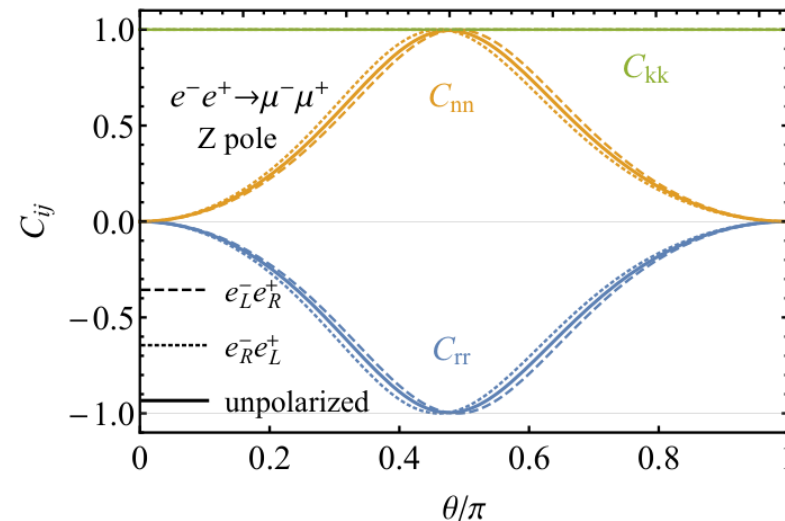


RL $\Leftrightarrow$ LR flip f-polarization B_i ;

- Density matrix

The unpolarized process is a mixture of polarized processes.

$$\rho_{\text{mixed}} = \begin{pmatrix} \rho_{\uparrow\uparrow}^{\uparrow\uparrow} & 0 & 0 & \rho_{\downarrow\downarrow}^{\uparrow\uparrow} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \rho_{\downarrow\downarrow}^{\downarrow\downarrow} & 0 & 0 & \rho_{\uparrow\uparrow}^{\downarrow\downarrow} \end{pmatrix}.$$

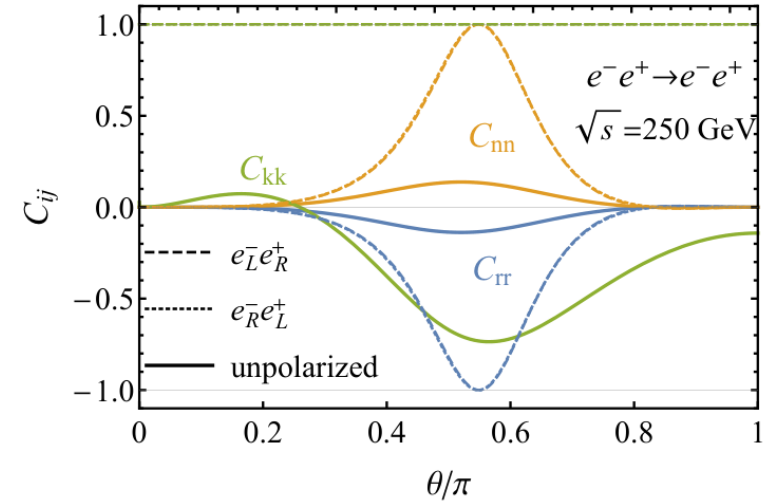
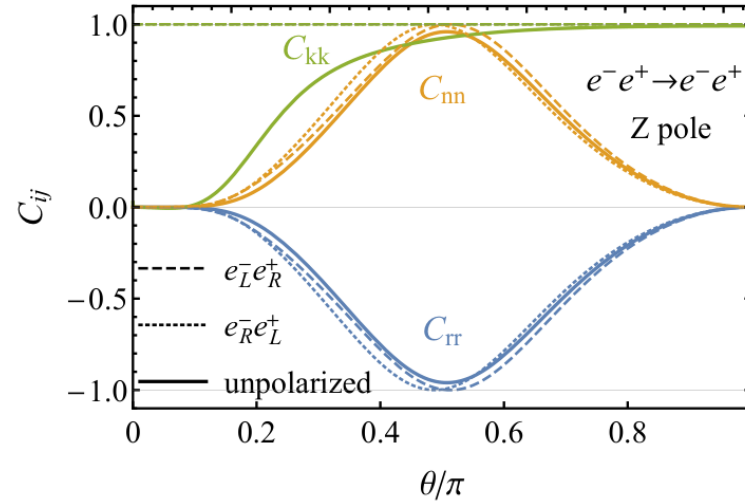


C_{ij} insensitive to polarization

(3) Bhabha scattering & t-s interference

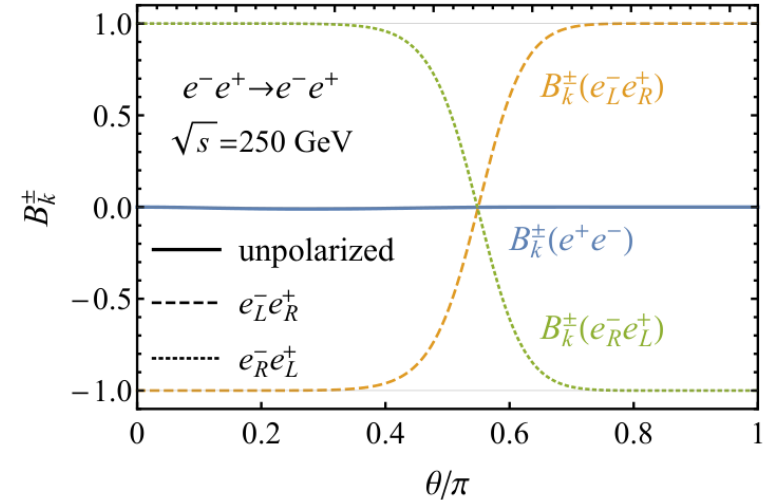
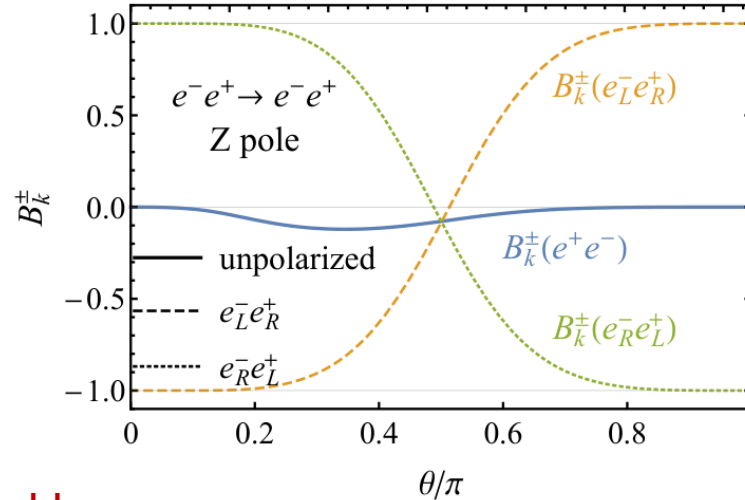
- unpolarized e^+e^- system

$$\rho_{\text{mixed}} = \begin{pmatrix} \rho_{\uparrow\uparrow,\uparrow\uparrow} & 0 & 0 & \rho_{\uparrow\uparrow,\downarrow\downarrow} \\ 0 & \rho_{\uparrow\downarrow,\uparrow\downarrow} & 0 & 0 \\ 0 & 0 & \rho_{\downarrow\uparrow,\downarrow\uparrow} & 0 \\ \rho_{\downarrow\downarrow,\uparrow\uparrow} & 0 & 0 & \rho_{\downarrow\downarrow,\downarrow\downarrow} \end{pmatrix}$$



- Fano coefficients of $e^-e^+ \rightarrow e^-e^+$

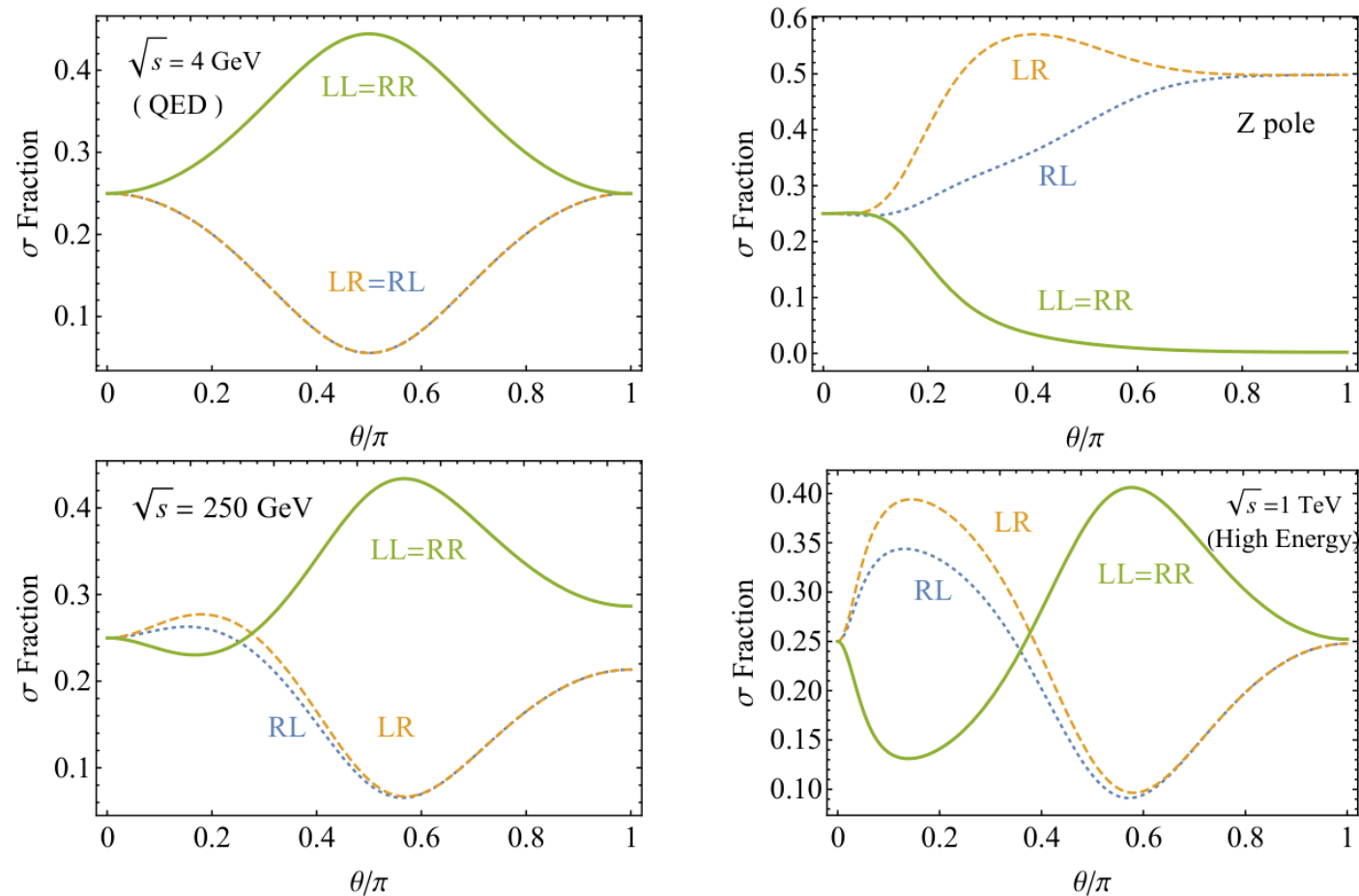
$$C_{ij} = \begin{pmatrix} C_{rr} & 0 & 0 \\ 0 & C_{nn} & 0 \\ 0 & 0 & C_{kk} \end{pmatrix}, \quad B_i^\pm = \begin{pmatrix} 0 \\ 0 \\ B_k \end{pmatrix}$$



Key difference from s-channel-only :

C_{ij} itself changes with polarization in Bhabha,
polarization reweights s vs t channel contributions.

Bhabha scattering & t-s interference



- QED and 250 GeV: t-channel dominates forward region.
- Z-pole: s-channel dominates similar with only s-channel process