Quantum Observables for Collider Physics

Experimental perspective on the future of quantum information in collider physics

- A very difficult task!
- Current status
- Mixture of
 - Prospects at various future colliders
 - Which machines ? ... future R&D (biased view's)
- Conclusion

Andy Jung

Workshop on Quantum Observables for Collider Physics





Nov 10th, 2023

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Workshop on Quantum Observables for Collider Physics

Hope for next iteration in 2024...

Some slide content taken from:



Nov 10th, 2023

Entanglement is there...

Slide by M.Vos

Quantum entanglement in top quark pair production



Read more about this!

https://atlas.cern/Updates/Briefing/Top-Entanglement

D < -1/3: top quarks are "entangled" This is new and exciting! Collect top quark data, separate in three regions, measure "entangled-o-meter" D

 $D \neq 0$: top quark spins are correlated. Confirms something we have known since 2012.



- Updates / News on Theory prediction
- Systematic uncertainties ?
- Need complete picture at LHC
 - \rightarrow stay tuned

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Q: Tell me about the quantum entanglement of top quarks

A: It's important to note that the behavior of particles on the quantum level is not always intuitive, and while **entanglement is a fascinating and well-studied phenomenon**, its application and relevance depend on the specific characteristics of the particles involved.

At the current state of knowledge up to my last training cut-off in January 2022, discussions of quantum entanglement with top quarks were not a common topic in the scientific literature.

If there have been significant developments or new insights in this area beyond 2022, I recommend checking more recent sources for the latest information.

Entanglement prospects

Studied extensively theoreticaly.

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- Measured by the D0, CDF, ATLAS and CMS collaborations.
- No link between spin-correlations and quantum entanglement so far.
- Spin-Correlations not Quantum **Entanglement!**
- However, Quantum Entanglement ⊂ Spin-Correlations.



Y. Afik & J. de Nova







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 $\frac{2\Theta}{\pi}$

Experimental perspectives on the future of QI in collider physics 5

0.8

0.7

0.4

0.3

0.2

Future collider landscape

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Hard Groundwork

 LHCtopWG effort from both sides: joined ATLAS + CMS effort

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 Enormous amount of person power also in understanding of systematic uncertainties across both experiments



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- Facilitate future combinations, studies on systematic uncertainties, etc.
- Vital and critical for success of Run 3 (and beyond)
 Many details, please check:

[LHCtopWG: Common samples]

Towards common MC settings in ATLAS & CMS: ATL-PHYS-PUB-2021-016 & CMS NOTE-2021/005 **Prospects at the HL-LHC**

Double diff. xsec

$$\frac{1}{\sigma} \frac{d^2 \sigma}{d \cos \theta^a_+ d \cos \theta^b_-} = \frac{1}{4} (1 + \frac{B^a_+}{B^a_+} \cos \theta^a_+ + \frac{B^b_-}{B^b_-} \cos \theta^b_- - \frac{C(a, b)}{C(a, b)} \cos \theta^a_+ \cos \theta^b_-)$$



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- Using conservation of 4-momentum (with the mass of the top and W boson assumed)
- The measured b and I momenta together help constrain the neutrino momentum to an ellipse.
- For the double neutrino case, an additional MET constraint is imposed.

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| Cut | SUSY | $t\bar{t}$ | Single Top | Diboson |
|----------------------------------|------------|------------|------------|-----------|
| 2 leptons | 3180752 | 46942286 | 6291825 | 875681 |
| $\epsilon_{tot},\epsilon_{cut}$ | 14 %, 14 % | 14 %, 14 % | 2 %, 2 % | 9%,9% |
| 2 jets | 2230452 | 34109607 | 3035953 | 123486 |
| $\epsilon_{tot}, \epsilon_{cut}$ | 10 %, 70 % | 10 %, 73 % | 1 %, 48 % | 1 %, 14 % |
| MET | 1867103 | 27796121 | 2462018 | 112145 |
| $\epsilon_{tot}, \epsilon_{cut}$ | 8 %, 84 % | 8 %, 81 % | 1~%, 81~% | 1 %, 91 % |
| b-tag | 1812201 | 27133968 | 2204553 | 49470 |
| $\epsilon_{tot}, \epsilon_{cut}$ | 8 %, 97 % | 8 %, 98 % | 1 %, 90 % | 1 %, 44 % |
| | | | | |

Table 3: Summary of flat systematic uncertainties.

| Systematic Uncertainty | Yellow Report Recommendation |
|------------------------|---------------------------------------|
| Muon ID | 0.5 % |
| Electron ID | 1 % |
| Luminosity | 1 % |
| b-tagging | 1 % |
| Pile Up | 2 % |
| Theoretical | 50 % of current 14 TeV cross-sections |

Table 4: Summary of shape-based systematic uncertainties.

| Systematic Uncertainty | Yellow Report Recommendation |
|---|------------------------------|
| PDF | M_x based look-up table |
| top p_T | 33% of Run2 |
| Jet Energy Scale | from shape |
| Jet Energy Resolution | from shape |
| Renormalization and Factorization Scale | 50 % of Run2 |



Prospects at the HL-LHC



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Prospects at the HL-LHC

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Side track: What to measure...





Bin of normalized differential cross section

Correlation are non-trivial and only experiments can determine!

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Future colliders (FCC like)

| Proposal Name | Proposal Name CM energy Lum./IP | | Years of | Years to | Construction | Est. operating |
|---------------------------|---------------------------------|---|-------------|------------------------|----------------|----------------|
| | nom. (range) | | pre-project | first | cost range | electric power |
| | [TeV] | $[10^{34} \text{ cm}^{-2} \text{s}^{-1}]$ | R&D | physics | $[2021 \ B\$]$ | [MW] |
| $FCC-ee^{1,2}$ | 0.24 | 7.7(28.9) | 0-2 | 13-18 | 12-18 | 290 |
| | (0.09-0.37) | | | | | |
| $CEPC^{1,2}$ | 0.24 | 8.3(16.6) | 0-2 | 13-18 | 12-18 | 340 |
| | (0.09-0.37) | | | | | |
| ILC ³ - Higgs | 0.25 | 2.7 | 0-2 | $<\!\!12$ | 7-12 | 140 |
| factory | (0.09-1) | | | | | |
| CLIC ³ - Higgs | 0.38 | 2.3 | 0-2 | 13-18 | 7-12 | 110 |
| factory | (0.09-1) | | | | | |
| $\rm CCC^3$ (Cool | 0.25 | 1.3 | 3-5 | 13-18 | 7-12 | 150 |
| Copper Collider) | (0.25 - 0.55) | | | | | |
| High Energy ILC | 3 | 6.1 | 5-10 | 19-24 | 18-30 | $\sim \! 400$ |
| | (1-3) | | | | | |
| High Energy CLIC | 3 | 5.9 | 3-5 | 19-24 | 18-30 | ~ 550 |
| | (1.5-3) | | | | | |
| High Energy CCC | 3 | 6.0 | 3-5 | 19-24 | 12-18 | ~ 700 |
| | (1-3) | | | | | |

- A very interesting perspective is provided by future colliders, where ttbar pairs are expected to be produced from e+e- collisions, such as the FCC-ee
- Channel: In particular, in future linear e+e- colliders

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FCC ee – Prospects

 Ultimate precision for top quark properties: mass, width, and Yukawa coupling

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- Can use measurement of cross section shape around threshold to extract m_t , Γ_t , y_t and α_s
- $m_t \otimes \Gamma_t$ simultaneous fit expected δ_{stat} : ±17 MeV (m_t) , ±45 MeV (Γ_t)
- δ_{syst} dominated by theory, e.g. $m_t \sim 45$ MeV!
- Current top mass average (LHC + Tevatron): 172.69±0.3 GeV
- Entanglement prospects: Prepare initial state!
- HERA demonstrated polarization is possible but challenging and timedependent!
- EIC will have improved methods...

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- Ultimate precision for top quark properties: mass, width, and Yukawa coupling
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- $m_t \otimes \Gamma_t$ simultaneous fit expected δ_{stat} : ±17 MeV (m_t), ±45 MeV (Γ_t)
- δ_{syst} dominated by theory, e.g. $m_t \sim 45 \text{ MeV}!$
- Current top mass average (LHC + Tevatron): 172.69±0.3 GeV
- Entanglement prospects: Prepare initial state!
- Entanglement proxy matters...

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[arXiv:2309.08103]

e+e- \rightarrow Zh, h \rightarrow tau tau:

| Channels | Obs. | $\mathbf{Q}\mathbf{M}$ | Clas. | Exp. @CEPC |
|---------------------------------|-------------|------------------------|----------|-----------------|
| 7 . 00 | ${\cal A}$ | 0.164 | 0.119 | 0.155 ± 0.287 |
| $\Sigma \rightarrow \ell \ell$ | $m_1 + m_2$ | > 1 | ≤ 1 | 2.12 ± 1.11 |
| 7 | ${\cal A}$ | 0.164 | 0.119 | 0.140 ± 0.098 |
| $ m Z ightarrow \jmath \jmath$ | $m_1 + m_2$ | > 1 | ≤ 1 | 1.20 ± 0.37 |





FCC ee – Timeline



Belle II – Prospects

 Circular colliders pushing the frontier on EW precision e.g. FCC-ee at Z-pole, 5x10¹² compared to Z_{ee} ~ LEP x 10⁵

| Particle production (10^9) | $B^0 \ / \ \overline{B}^0$ | B^+ / B^- | $B^0_s \ / \ \overline{B}^0_s$ | $\Lambda_b \ / \ \overline{\Lambda}_b$ | $c\overline{c}$ | τ^-/τ^+ |
|------------------------------|----------------------------|---------------|--------------------------------|--|-----------------|-----------------|
| Belle II | 27.5 | 27.5 | n/a | n/a | 65 | 45 |
| FCC-ee | 300 | 300 | 80 | 80 | 600 | 150 |

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| | Quantity | current | ILC250 | ILC-GigaZ | FCC-ee | CEPC | CLIC380 |
|--|--------------------------------------|------------|------------|------------|--------------------|------------------|-----------|
| Flavor physics with | $\Delta lpha(m_Z)^{-1}~(imes 10^3)$ | 17.8^{*} | 17.8^{*} | | 3.8(1.2) | 17.8^{*} | |
| riavor physics with | $\Delta m_W ~({ m MeV})$ | 12* | 0.5~(2.4) | | $0.25\ (0.3)$ | 0.35~(0.3) | |
| ~10 ¹² bb. cc (CKM. CP | $\Delta m_Z ~({ m MeV})$ | 2.1^{*} | 0.7~(0.2) | 0.2 | 0.004~(0.1) | 0.005~(0.1) | 2.1^{*} |
| | $\Delta m_H~({ m MeV})$ | 170* | 14 | | 2.5~(2) | 5.9 | 78 |
| violation in neutral B | $\Delta\Gamma_W ~({ m MeV})$ | 42* | 2 | | 1.2 (0.3) | 1.8 (0.9) | |
| mesons,) | $\Delta\Gamma_Z$ (MeV) | 2.3^{*} | 1.5~(0.2) | 0.12 | 0.004 (0.025) | $0.005\ (0.025)$ | 2.3^{*} |
| · • | $\Delta A_e~(imes 10^5)$ | 190* | 14 (4.5) | 1.5(8) | 0.7~(2) | 1.5(2) | 60 (15) |
| Tau physics program | $\Delta A_{\mu}~(imes 10^5)$ | 1500^{*} | 82 (4.5) | 3(8) | 2.3~(2.2) | 3.0(1.8) | 390 (14) |
| (1, 1) | $\Delta A_{	au}~(imes 10^5)$ | 400* | 86(4.5) | 3(8) | 0.5~(20) | 1.2(20) | 550(14) |
| with $\sim 2 \times 10^{-1} \tau \tau$ (lepton | $\Delta A_b \; (imes 10^5)$ | 2000^{*} | 53 (35) | 9~(50) | 2.4(21) | 3(21) | 360 (92) |
| universality,) | $\Delta A_c~(imes 10^5)$ | 2700* | 140(25) | 20 (37) | 20 (15) | 6 (30) | 190 (67) |
| | $\Delta \sigma_{ m had}^0~({ m pb})$ | 37* | | | 0.035~(4) | 0.05~(2) | 37* |
| QCD at the Z (coupling, | $\delta R_e~(imes 10^3)$ | 2.4^{*} | 0.5~(1.0) | 0.2 (0.5) | 0.004~(0.3) | 0.003~(0.2) | 2.5(1.0) |
| fragmentation) | $\delta R_{\mu}~(imes 10^3)$ | 1.6^{*} | 0.5(1.0) | 0.2~(0.2) | $0.003\ (0.05)$ | 0.003~(0.1) | 2.5(1.0) |
| nagmentation) | $\delta R_{	au}~(imes 10^3)$ | 2.2^{*} | 0.6(1.0) | 0.2~(0.4) | 0.003~(0.1) | 0.003~(0.1) | 3.3(5.0) |
| and much more | $\delta R_b~(imes 10^3)$ | 3.1^{*} | 0.4(1.0) | 0.04~(0.7) | $0.0014 \ (< 0.3)$ | 0.005~(0.2) | 1.5(1.0) |
| | $\delta R_c(imes 10^3)$ | 17* | 0.6(5.0) | 0.2(3.0) | $0.015\ (1.5)$ | 0.02(1) | 2.4(5.0) |



"signal" region for observing Bell inequality violation

1.5

0.5

-1.0

concurrence

Belle II – Prospects



- Y(4S)(b b) decays to B0 + B0, where we have |B0> = | bd>, | B0> = |b d>.
- We get an entangled state:
 - 1√2 (|B0⟩| B0⟩ − | B0⟩|B0⟩).



solid lines: SM expectation

0.5

Horodecki observable

"signal" region for observing entang

1.0

 $\mathfrak{m}_{12}[C]$

| | Collider | Type | \sqrt{s} | $\mathcal{P}[\%]$ | $\mathcal{L}_{\mathrm{int}}$ | | |
|-------|---------------------------------|----------|--------------------|---------------------------|-----------------------------------|--|--|
|)(b | | | | e^-/e^+ | $ \mathrm{ab}^{-1}/\mathrm{IP} $ | | |
| | HL-LHC | pp | 14 TeV | | 3 | | |
| | ILC and C^3 | ee | $250~{ m GeV}$ | $\pm 80/\pm 30$ | 2 | | |
| ve | c.o.m almost | | $350 { m GeV}$ | $\pm 80/\pm 30$ | 0.2 | | |
| | similar | | $500^* { m GeV}$ | $\pm 80/\pm 30$ | 4 $ $ | | |
| | | | $1 { m TeV}$ | $\pm 80/\pm 20$ | 8 | | |
| | CLIC | ee | $380 {\rm GeV}$ | $\pm 80/0$ | 1 | | |
| | CEPC | ee | M_Z | | 60 | | |
| | | | $ 2M_W$ | | 3.6 $ $ | | |
| | | | $240 \mathrm{GeV}$ | | 20 | | |
| | | | $360 { m GeV}$ | | 1 | | |
| | FCC-ee | ee | M_Z | | 150 | | |
| | | | $2M_W$ | | 10 | | |
| | | | $240 \mathrm{GeV}$ | | 5 | | |
| | | | $2 M_{top}$ | | 1.5 | | |
| | muon-collider (higgs) | $\mu\mu$ | 125 GeV | | 0.02 | | |
| | | | $\neg \frown$ | | | | |
| | Assume the s | ame | | olarizat | ion not | | |
| | physics reach f | or IL | | in hee | alina | | |
| | and newly pror | noser | 4 | in pas | enne | | |
| | | | * (| design for C ³ | | | |
| | | | | | | | |
| ement | | | | | | | |
| | С |)ther | techno | logical | solution | | |
| | (in alua | | | | orizodi | | |
| | (Including HELEN) summarized in | | | | | | |

https://arxiv.org/pdf/2209.14136.pdf

By Christian Veelken

-0.5

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0.0



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...even further into the Future

| Proposal Name | CM energy | Lum./IP | Years of | Years to | Construction | Est. operating |
|---------------|----------------|---|-------------|------------------------|--------------|----------------|
| | nom. $(range)$ | @ nom. CME | pre-project | first | cost range | electric power |
| | [TeV] | $[10^{34} \text{ cm}^{-2} \text{s}^{-1}]$ | R&D | physics | [2021 B\$] | [MW] |
| Muon Collider | 10 | 20 (40) | > 10 | > 25 | 12-18 | ~ 300 |
| | (1.5-14) | | | | | |
| FCC-hh | 100 | 30(60) | >10 | > 25 | 30-50 | $\sim \! 560$ |
| | | | | | | |
| SPPS | 125 | 13(26) | > 10 | $>\!25$ | 30-80 | $\sim \! 400$ |
| | (75-125) | | | | | |



...even further into the Future

FCC timeline

Quantum Observables

for Collider Physics

FUTURE

CIRCULAR

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→ Essentially need to start R&D on detector (& accelerator) now-ish!

US perspective: Snowmass

| Proton Driver | Front End | Cooling | ς μ+ | | | Accelerati | ion | | Colli | der Ring E _{COM} : | | | |
|--|---|---|-------------------|------------|---------------|----------------------------|---------------|--|-------|--------------------------------|-----------|-----------|--------|
| SC Linac Accumulator Buncher Combiner | MW-Class Target Capture Sol. I Decay Channel Buncher | Phase Rotator Initial 6D Cooling Charge Separator 6D Cooling | Bunch Merge | 6D Cooling | Final Cooling | Accelerator Linacs, RLA | rs: or FFA | AG, RCS | | to 10 TeV | | | |
| Short, intense proton bunch | | Ionisation muon in i | n cooli matter | ng of | | Accelerat energy | tion to | collision | Col | lision | | | |
| Protor decay muons | s produce p into muons are capture | ions which ed | | | | | 500 | | | · · · · · | • • • • • | · · · · · | |
| Parameter | Symbol | unit | | | | | | | | | | | |
| Centre-of-mass energy | E_{cm} | TeV | 3 | 10 | 14 | | 200 | | | | | | |
| Luminosity | \mathcal{L} | $10^{34} {\rm cm}^{-2} {\rm s}$ | 1.8 | 20 | 40 | Te/ | 200 | ļ | | | | | 1 |
| Collider circumference | C_{coll} | km | 4.5 | 10 | 14 | | 100 | | | | | | |
| Average field | $\langle B \rangle$ | Т | 7 | 10.5 | 10.5 | s | 100 | a service a serv | | | | | |
| Muons/bunch | N | 10^{12} | 2.2 | 1.8 | 1.8 | | 50 | / / | | | | | |
| Repetition rate | f_r | $_{\rm Hz}$ | 5 | 5 | 5 | | | | | | | | 1 |
| Beam power | P_{coll} | MW | 5.3 | 14.4 | 20 | | | | | | | | 1 |
| Longitudinal emittance | ϵ_L | MeVm | 7.5 | 7.5 | 7.5 | | 20 | 5 | 10 | 15 | 20 | 25 | 3(|
| Transverse emittance | ϵ | $\mu { m m}$ | 25 | 25 | 25 | | | 5 | 10 | 15 | 20 | 25 | 50 |
| IP bunch length | σ_z | $\mathbf{m}\mathbf{m}$ | 5 | 1.5 | 1.07 | | | | | $\sqrt{s_{II}}$ [T | eV∣ | | |
| IP betafunction | β | mm | 5 | 1.5 | 1.07 | | | | | | | | |
| IP beam size | σ | $\mu { m m}$ | 3 | 0.9 | 0.63 | | | | | | | | |

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Quantum Observables for Collider Physics



- Significant R&D is required to demonstrate MuC elements (Cooling, Fast ramping magnets, Target, Neutrino Flux, Beam Induced Background,...)
 - Renewed interest in the U.S. and Europe
 - Formal collaboration formed





• Exciting new opportunities...

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 \rightarrow Essentially need to start R&D on detector (& accelerator) now-ish!



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US Snowmass perspective

| | LHC | Higgs Factory | Multi TeV Colliders |
|------------|--|--|--|
| 2025-2030 | Prioritize LHC and aux. experiments | Establish a targeted e⁺e⁻ Higgs factory detector R&D program. | Develop an initial design for a first stage TeV-scale Muon Collider in the US. Support critical detector R&D towards EF multi-TeV colliders. |
| 2030-2035 | Continue strong support for the HL-LHC physics program. | Support construction of an e⁺e⁻ Higgs factory. | 1. Demonstrate principal risk mitigation for a first stage TeV-scale Muon Collider. |
| After 2035 | Continuing support of the HL-LHC physics program to the conclusion of archival measurements | Support completing construction and establishing the physics program of the Higgs factory. | Demonstrate readiness to construct a first-stage TeV-scale Muon Collider. Ramp up funding support for detector R&D for energy frontier multi-TeV colliders. |

"The US EF community has also expressed renewed interest and ambition to bring back energy-frontier collider physics to the US soil while maintaining its international collaborative partnerships and obligations."

Other opportunities: EIC

- → Will be the 2^{nd} ep/lon collider after 1^{st} HERA ep collider @DESY
- \rightarrow Probes of Entanglement ?

Key facts

Quantum Observables

for Collider Physics

- The Electron-Ion Collider User Group *(EICUG)* consists of more than **1200 physicists** from over 250 laboratories and universities from around the world
- 2.4 miles long accelerator

Project Design Goals

- High Luminosity: L= 10³³ 10³⁴ cm⁻²sec⁻¹, 10 100 fb-1/year
- Highly Polarized Beams: 70%

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- Large Center of Mass Energy Range: $E_{cm} = 20 140$ GeV
- Large Ion Species Range: protons Uranium
- Accommodate a Second Interaction Region (IR) with a 2nd detector

Physics goals: Understand origin of mass & spin of the nucleon structure / proton





Ep/ion: Entanglement Entropy

- Entanglement entropy based on number of charged particles
- Always very hard to model accurately

$$S = -\operatorname{tr} \rho \ln \rho = -\sum_{n} p_{n} \ln p_{n}$$
$$S = \ln[xG(x)]$$



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Initial State: Polarization of e-beam

- HERA demonstrated polarization is possible but challenging and timedependent!
- EIC will have improved methods...but
- Need high polarization for hadrons and electrons of > 70%

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- Need both polarization directions present in the same fill to suppress systematics
- Spin need to be longitudinal in the IP
- Electron spin need to be vertical in the arcs

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 Systematic uncertainties for entanglement proxies ?







Lots of opportunities ahead...

- ECFA (European Committee for Future Accelerators) matrix of experiment/detector" mapped to technologies / R&D (DRD)
- ECFA Detector R&D roadmap: https://cds.cern.ch/record/2784893

R&D collaborations

<u>US CPAD RDC's</u>

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- Europe CERN DRD's
- → Just few examples, Get involved!

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Personal bias...

 R&D efforts on low-mass support structures with integrated services for silicon detector systems





Basic Research Needs for High Energy Physics Detector Research & Development





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ominal therm

Through-plane thermal conductivity of layer [W/mK

- Multi-functional composite structure
- Integration of cooling and other services into the support structures to reduce mass further
- Novel approach to mechanics design from inception phase of the detector
- Need to start early/ier with R&D...

Future Mechanics and R&D:

- "BlueSky Mechanics" for detectors at future Colliders (FCC, muon, LC, etc.) <u>https://arxiv.org/abs/2203.14347</u>
- 2. "CalVision" project for mechanics of dual readout calorimetry <u>https://arxiv.org/abs/2203.04312</u>



Want great physic's results – why should you care ?

- Future detectors are huge, "mechanics" is a significant fraction of material and also of the cost – serious risks related to raw and rare materials
- Substantial R&D in all areas to make FCC-ee/hh, muonC or others a reality
 - Interdisciplinary R&D can realize additional synergistic activities

Quantum Observables for Collider Physics

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Lowest mass yet stiff and conductive (thermally and electrically) requires new approaches



https://arxiv.org/abs/2203.14347

Can improve b-ID efficiencies by ~2% per b-jet and high b-jet multiplicity ~10% (absolut!)
Significant improvement by novel approach, b-ID relevant for top & Higgs physics

Conclusions & Outlook

- Quantum entanglement/tomography (at high energy colliders)
 - New and exciting field of Quantum Information in HEP
 - New approach to test & challenge the SM

Quantum Observables

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- Very interesting workshops (Oxford, $1/\sqrt{3}$ Purdue, Florencia)
- LHC: ATLAS measurement of entanglement in top quark events, non-trivial, complex "mixed-state" production
- Future e⁺e⁻ machines: carefully prepared initial state (including tunable beam polarization, except C³)
- e+e- seems promising scenarios to study QI problems



