CP-Violating Top Yukawa Coupling at the Future Muon Collider

Yanzhe Zhang

Morgan Cassidy, Zhongtian Dong, KC Kong, Ian Lewis, Ya-Juan Zheng

Outlines

- CPV Model
- Muon Collider
- Research
  - Signals & Backgrounds
  - Kinematic Distribution
  - Cut-Flow Table
- Take-Away

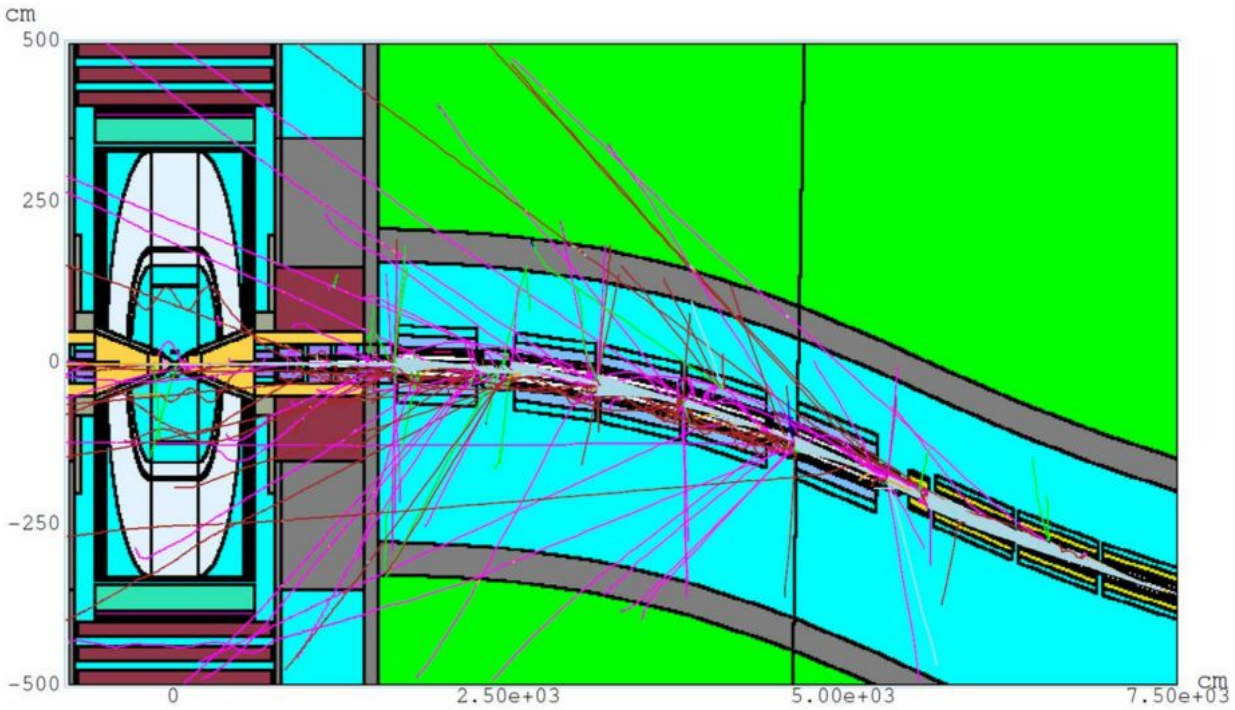
CPV Model

- Limitations of SM
  - Matter-antimatter asymmetry
- Top & Higgs
  - The heaviest two
  - Not yet very well constraint
  - Lagrangian

$$\bar{t}(\cos\alpha + i\gamma^5 \sin\alpha)th$$

Muon Colliders – Design

Shielding nozzles



Detector and Physics Performance at a Muon Collider, Nazar Bartosik et. al, https://arxiv.org/abs/2001.04431

Muon Colliders – Pros & Cons

	proton-proton	electron-positron	muon-muon
Clean collision environment	Fundamental particles		
High energy	Generate massive particles: top-quark and Higgs boson		
Less energy loss	Synchrotron radiation		$P \propto \frac{1}{R^2}\left(\frac{E}{m}\right)^4$
Stability	Decay or not decay		
Collimation		Forming beams	

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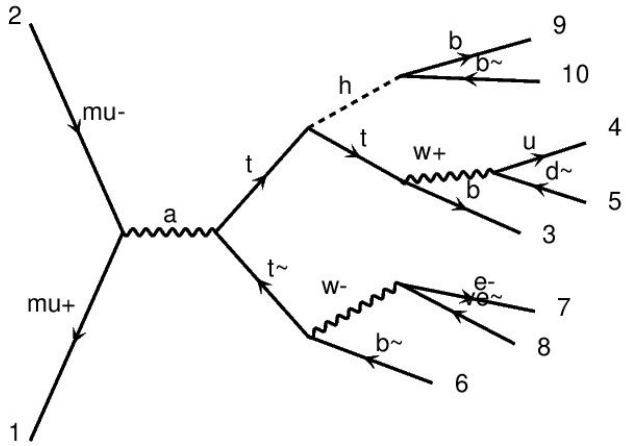
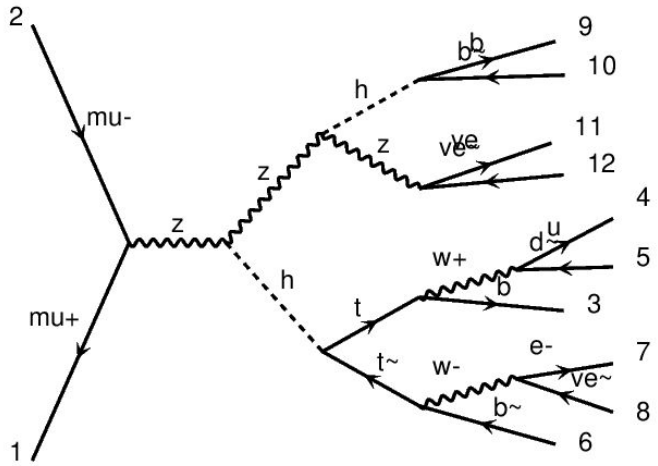
Research

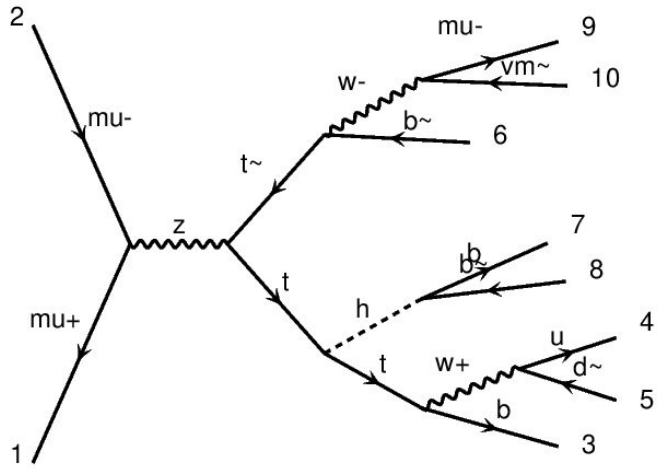
Signals & Backgrounds



$$\mu^+\mu^- \to t\bar{t}h$$



$$\mu^+\mu^- \to t\bar{t}h\nu\bar{\nu}$$



$$\mu^+\mu^- \to t\bar{b}h\mu^-\bar{\nu}$$

$$t \to bW^+, W^+ \to jj$$
$$\bar{t} \to \bar{b}W^-, W^- \to \ell^-\bar{\nu}_\ell$$

$$h \to b\bar{b}$$

Signals & Backgrounds

Backgrounds

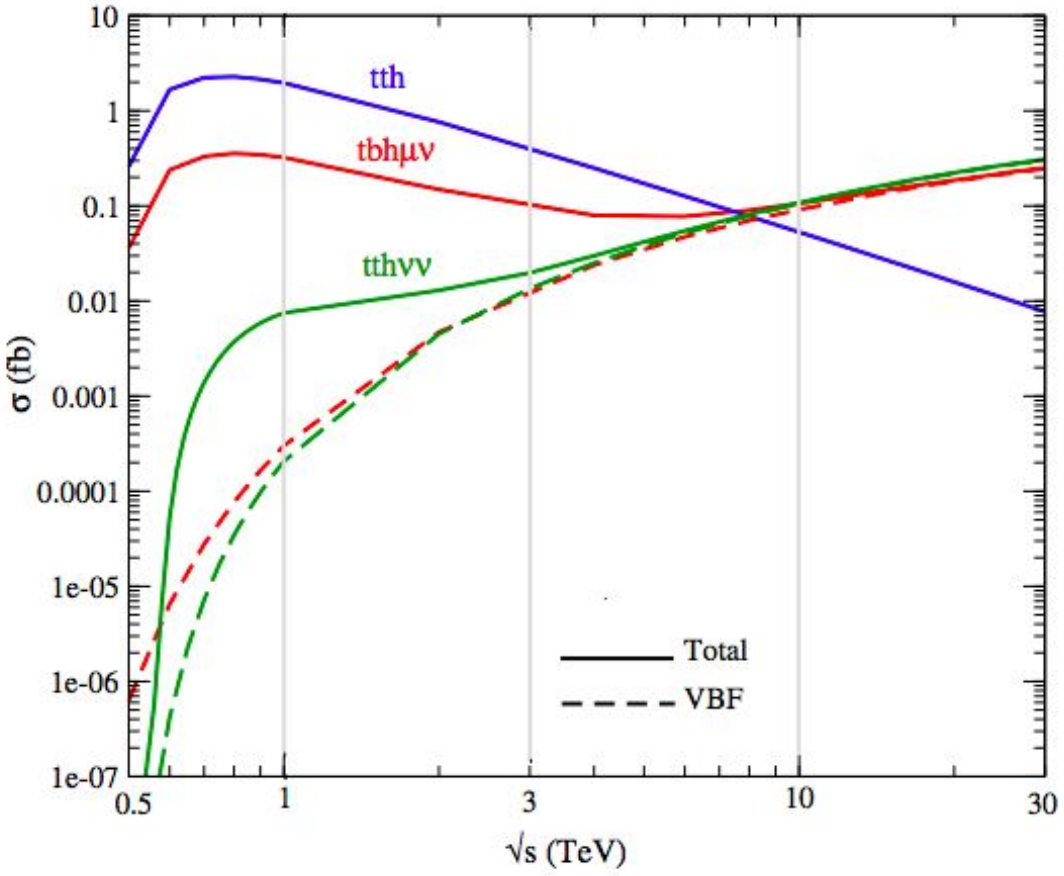
$$\mu^+\mu^- \to 4bjj\ell + \not{E}_T$$

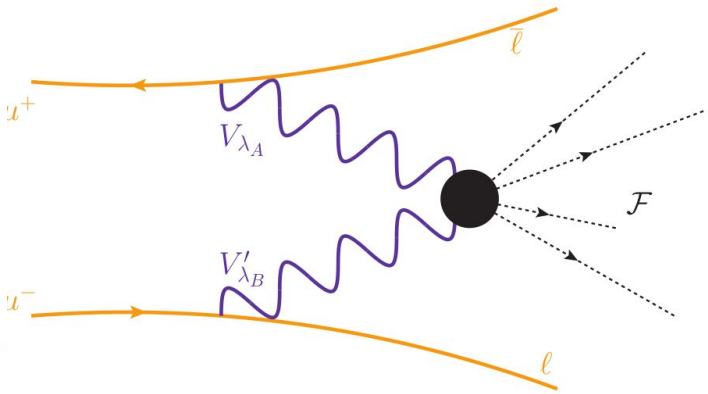
$$\mu^+\mu^- \to t\bar{t}b\bar{b}$$
$$\mu^+\mu^- \to t\bar{t}b\bar{b}\nu\bar{\nu}$$
$$\mu^+\mu^- \to t\bar{t}Z/\gamma, Z/\gamma \to b\bar{b}$$
$$\mu^+\mu^- \to W^+W^-, W^+W^- \to t\bar{t}b\bar{b}$$

$$t \to bW^+, W^+ \to jj$$
$$\bar{t} \to \bar{b}W^-, W^- \to \ell^-\bar{\nu}_\ell$$

$$h \to b\bar{b}$$

Energy Picking



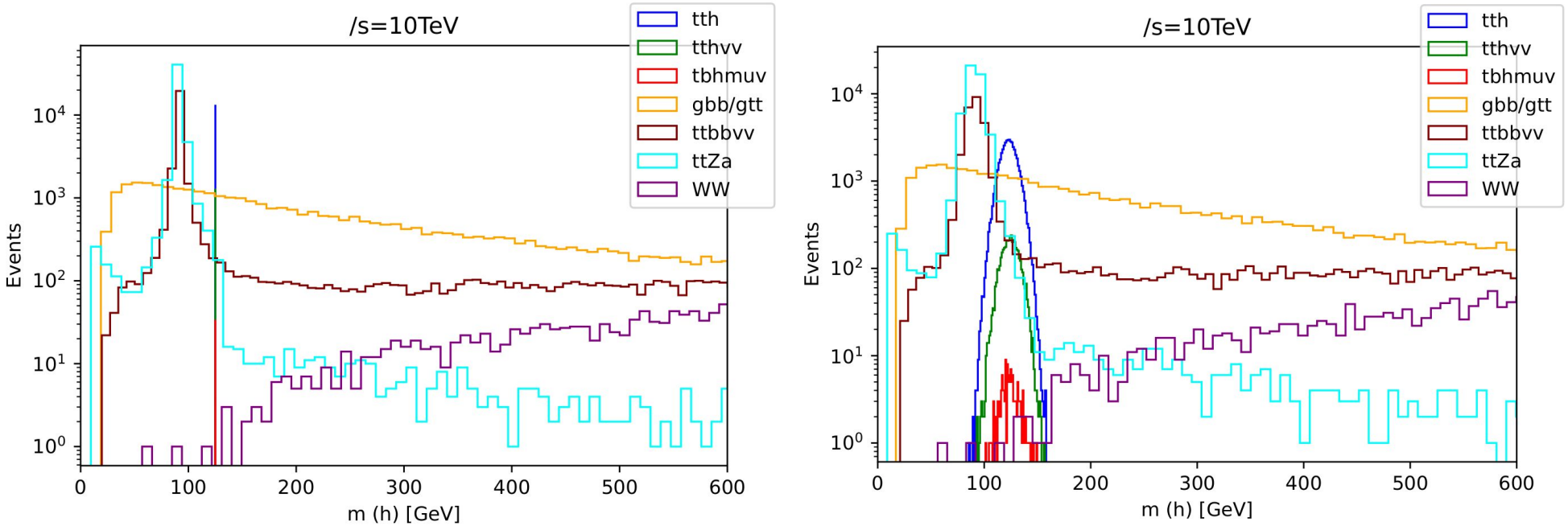


The Effective Vector Boson Approximation in High-Energy Muon Collisions, Richard Ruiz et al., https://arxiv.org/abs/2111.02442

Detector Effect

Gaussian distribution $\frac{\sigma_E}{E} = 0.1$

Fig
“Higgs” before and after smearing at 10 TeV



Kinematic Distribution – η

$$\eta = \frac{1}{2} ln \left(\frac{|\mathbf{p}| + p_L}{|\mathbf{p}| - p_L} \right) \quad |\mathbf{p}| >> m \longrightarrow \quad y = \frac{1}{2} ln \left(\frac{E + p_L}{E - p_L} \right)$$

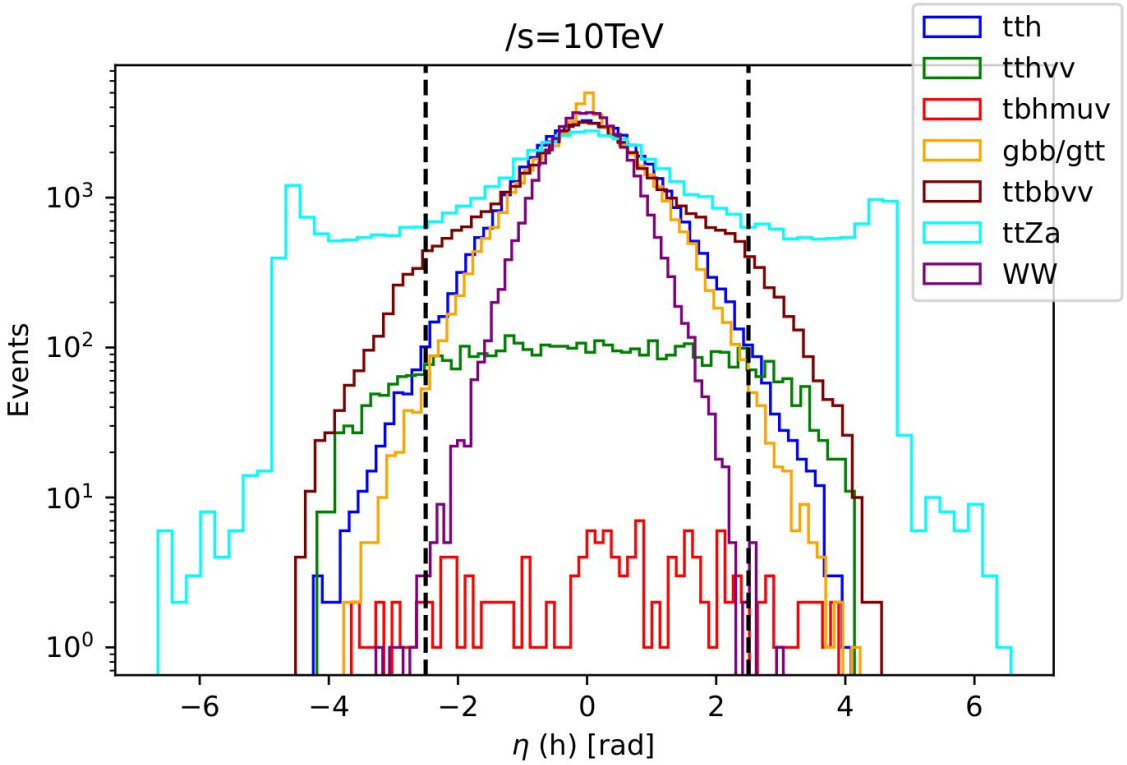


Fig
"Higgs" pseudorapidity

|η| < 2.5
Detector requirement

Kinematic Distribution – ΔR

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} \qquad \cos\Delta\phi = \frac{p_{1x}p_{2x} + p_{1y}p_{2y}}{\sqrt{(p_{1x}^2 + p_{1y}^2)(p_{2x}^2 + p_{2y}^2)}}$$

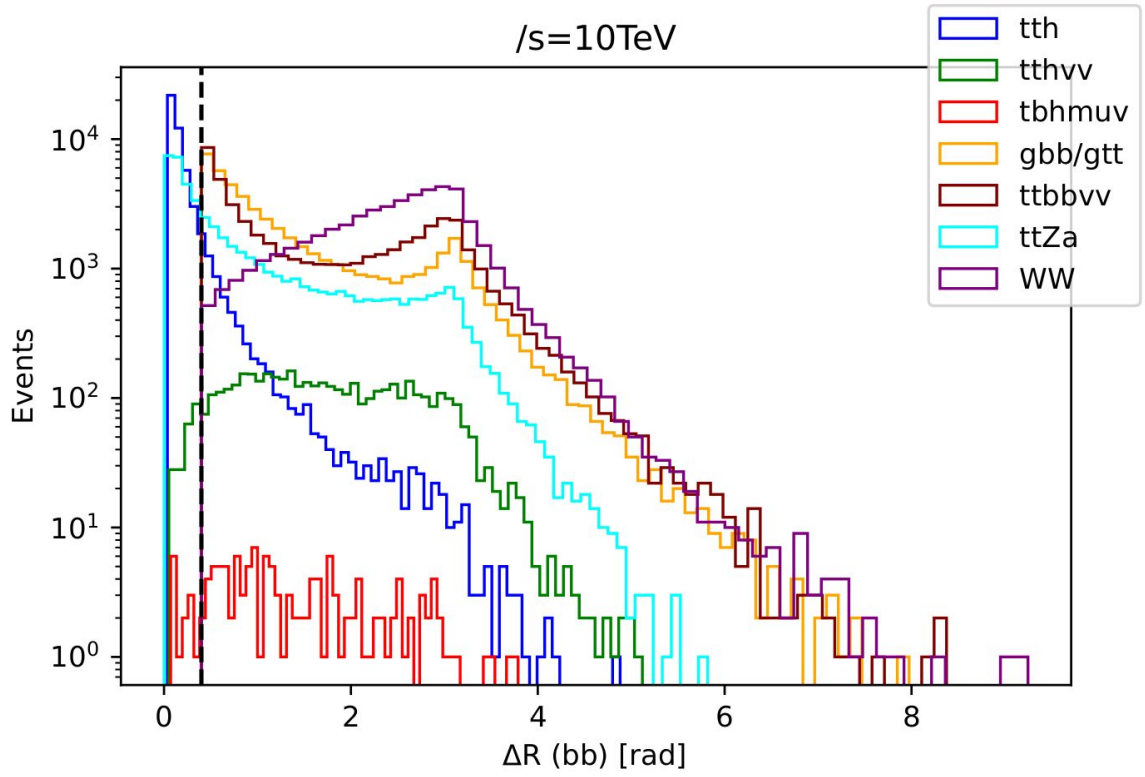


Fig
Angular separation between two bottoms decayed from “Higgs”

ΔR > 0.4
Minimum cut

Kinematic Distribution – pT

$$p_T = \sqrt{p_x^2 + p_y^2}$$

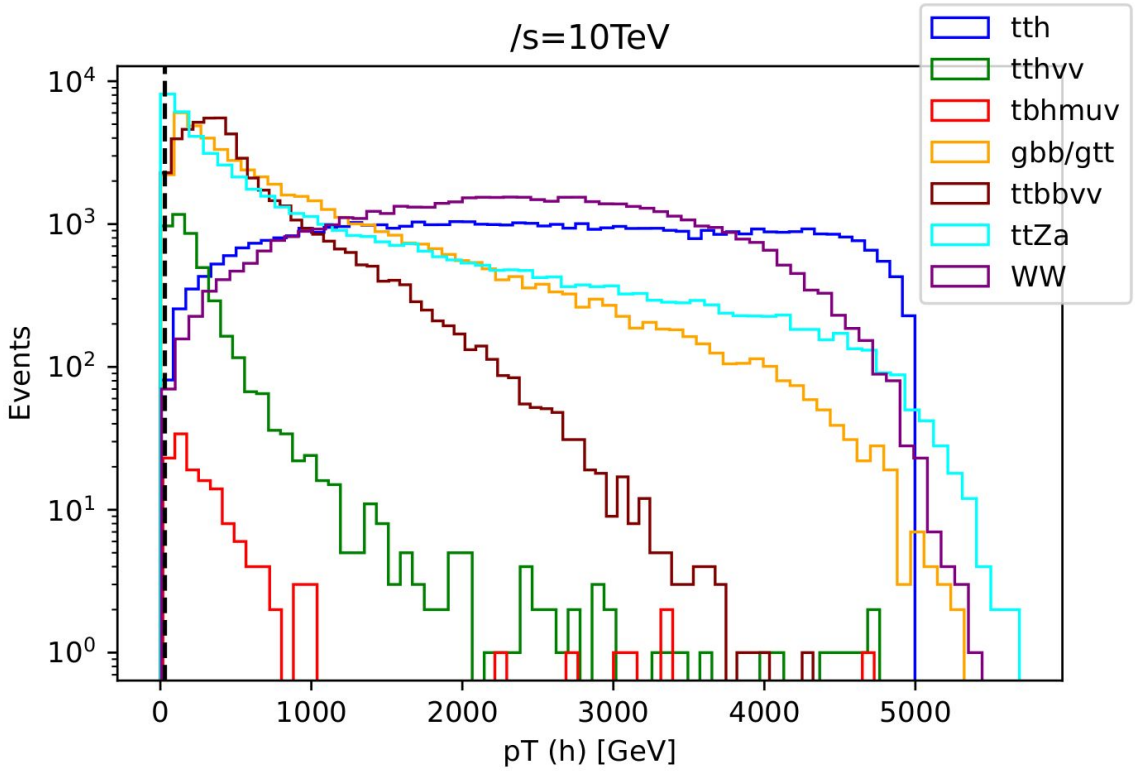


Fig
"Higgs" transverse momentum

pT > 30 GeV
Acceptance cut

Kinematic Distribution – Invariant Mass

$$M^2 = m_1^2 + m_2^2 + 2(E_1 E_2 - \mathbf{p}_1 \cdot \mathbf{p}_2)$$

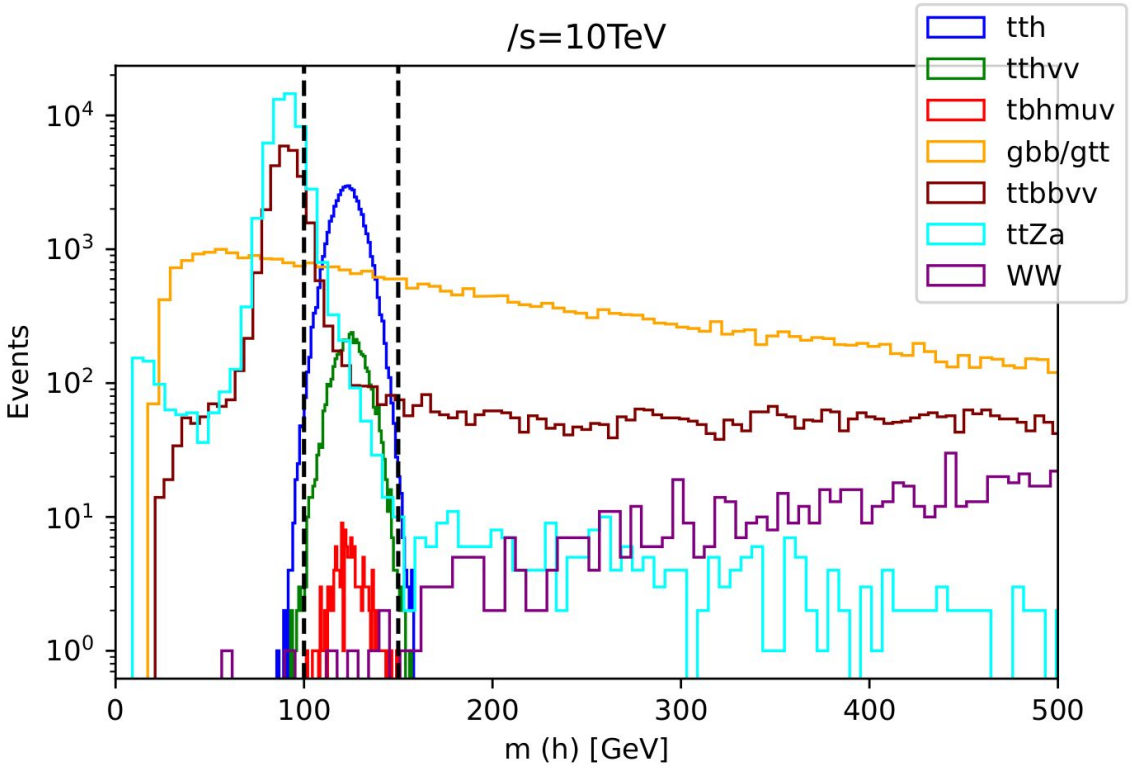


Fig
“Higgs” invariant mass

100 GeV < M < 150 GeV

Overall Cut-Off

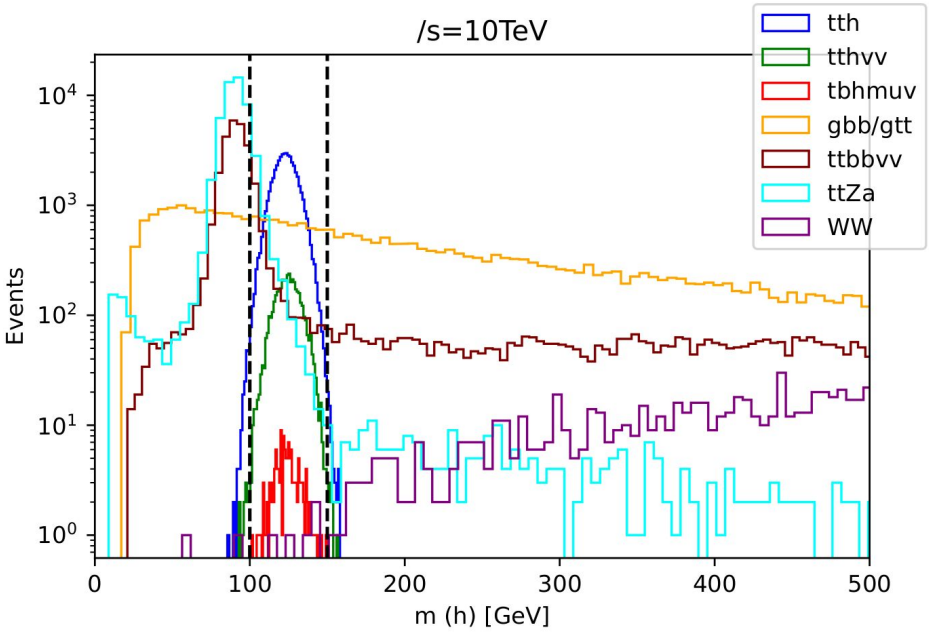
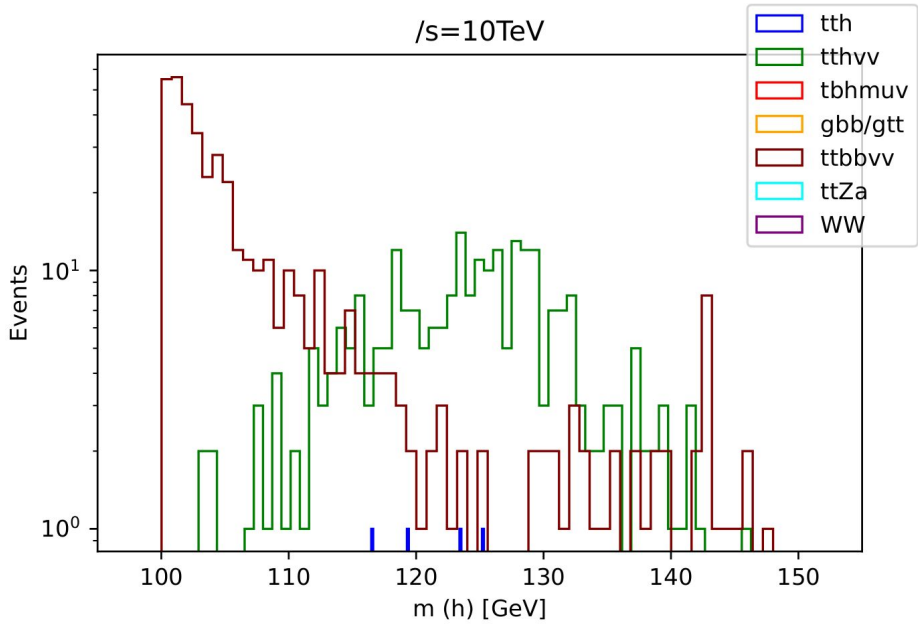


Fig
"Higgs" invariant mass, before and after cuts, at 10 TeV

|η| < 2.5
ΔR > 0.4
pT > 30 GeV
100 GeV < M < 150 GeV



Cut-Flow Table

$S/\sqrt{S+B}$

/s [TeV]	Cuts	tth [fb]	tthvv [fb]	tbhmuv [fb]	bkg [fb]	sig	bkg	Significance
1	Generation cuts	0.28	0.0011	0.096	0.24	37.71	23.95	4.8
L = 100 [1/fb]	η+pT+ΔR	0.0499	0.000146	0.0253	0.039	7.54	3.9	2.23
	η+pT+ΔR+M	0.0497	0.000146	0.0253	0.0053	7.52	0.53	2.65
10	Generation cuts	0.0076	0.015	0.028	0.72	511	7162	5.8
L = 10000 [1/fb]	η+pT+ΔR	6e-7	0.00092	–	0.023	9.24	229	0.6
	η+pT+ΔR+M	6e-7	0.00092	–	0.002	9.24	20.2	1.7
30	Generation cuts	0.001	0.044	0.032	4.02	778	40224	3.8
L = 10000 [1/fb]	η+pT+ΔR	–	0.00145	6.9e-6	0.084	14.6	837	0.5
	η+pT+ΔR+M	–	0.0014	6.9e-6	0.0084	14.1	83.7	1.43

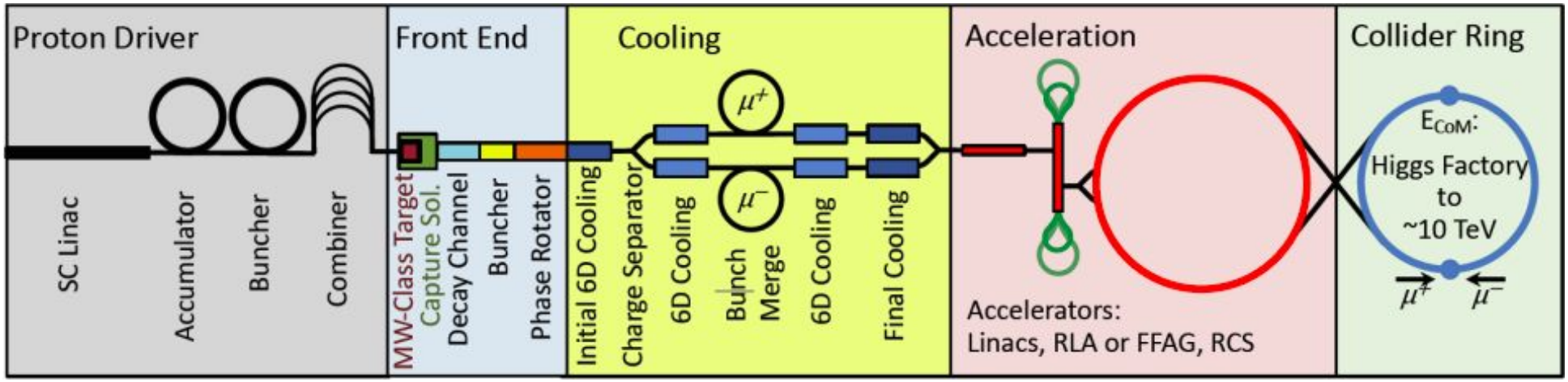
Take-Away

- CPV
- Advantages of a muon collider
- Future improvements
  - New energy picking: with 3 TeV
  - Scanning over CP-phases

Questions?

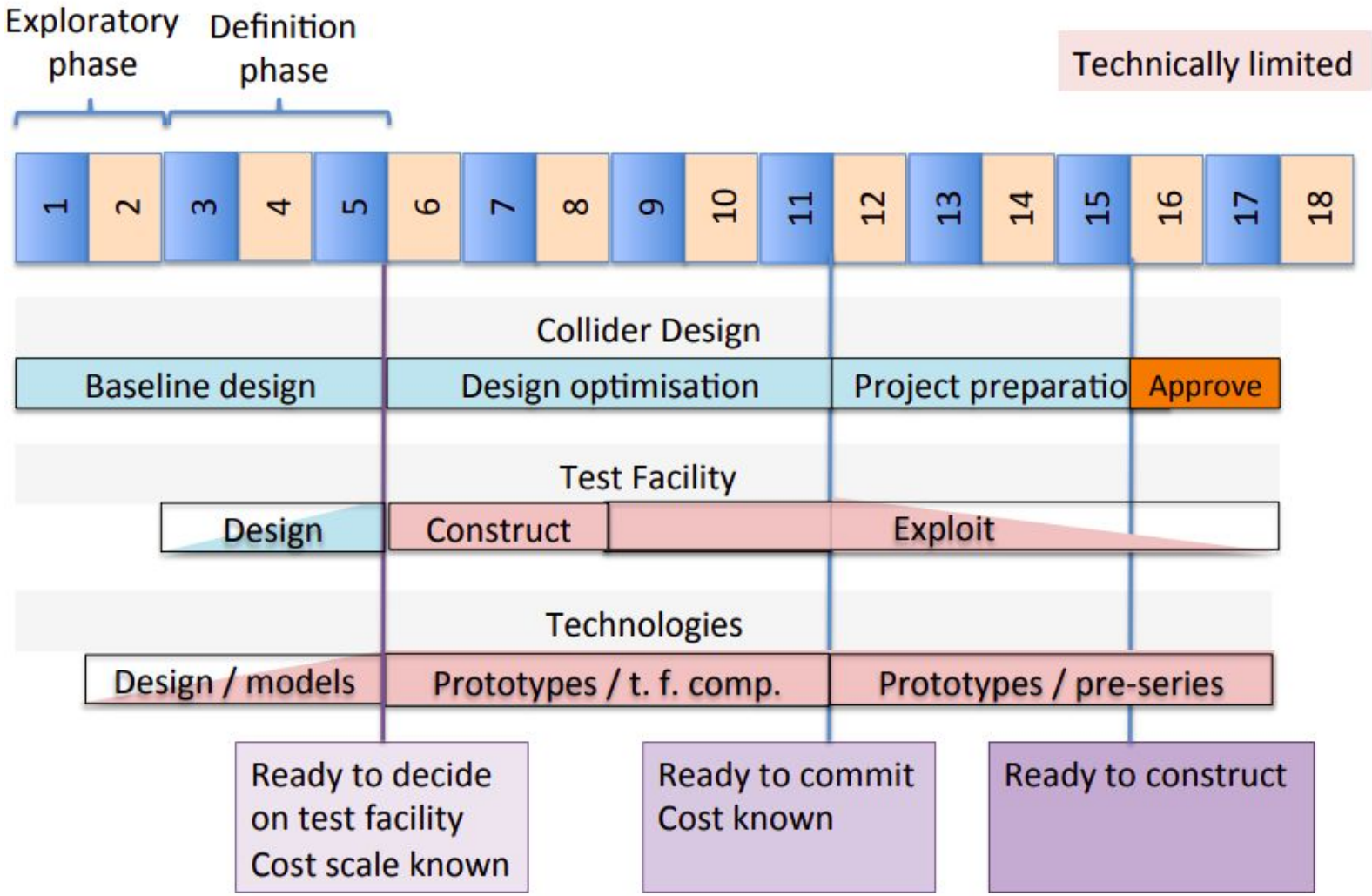
Muon Colliders – Design

Proton-driven muon collider concept



The Muon Collider, Daniel Schulte,
https://indico.cern.ch/event/1056654/attachments/2276509/3867446/Japan.pdf

Muon Colliders – Timeline



Muon Collider for HEP, Daniel Schulte for the forming international muon collider collaboration, https://indico.fnal.gov/event/48462/contributions/211682/attachments/141874/178911/APS_Daniel_Schulte.pdf

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