Is there still room for Naturalness?
An answer from the SMEFT

based on
2108.01094 with I. Brivio, E. Geoffray, W. Killian, M. Krämer
M. Luchmann, T. Plehn, B. Summ
2101.07273 with R. Schäfer, S. Westhoff and D. van Dyk
1910.03606 with I. Brivio, F. Maltoni, R. Moutafis,
T. Plehn, E. Vryonidou, S. Westhoff and C. Zhang

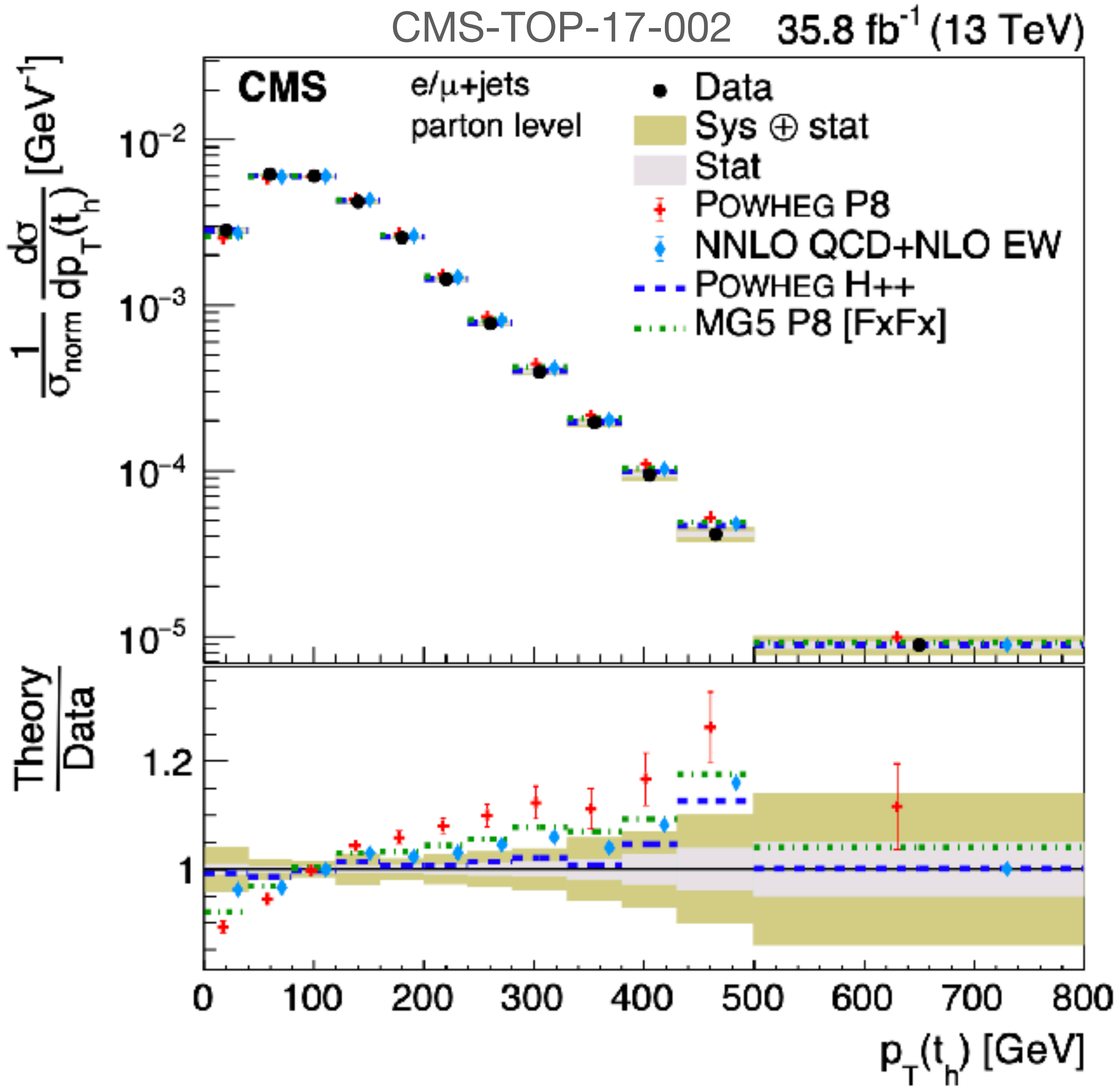
UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

NORDITA:
Is there still room for Naturalness?
25.04.22

Sebastian Bruggisser

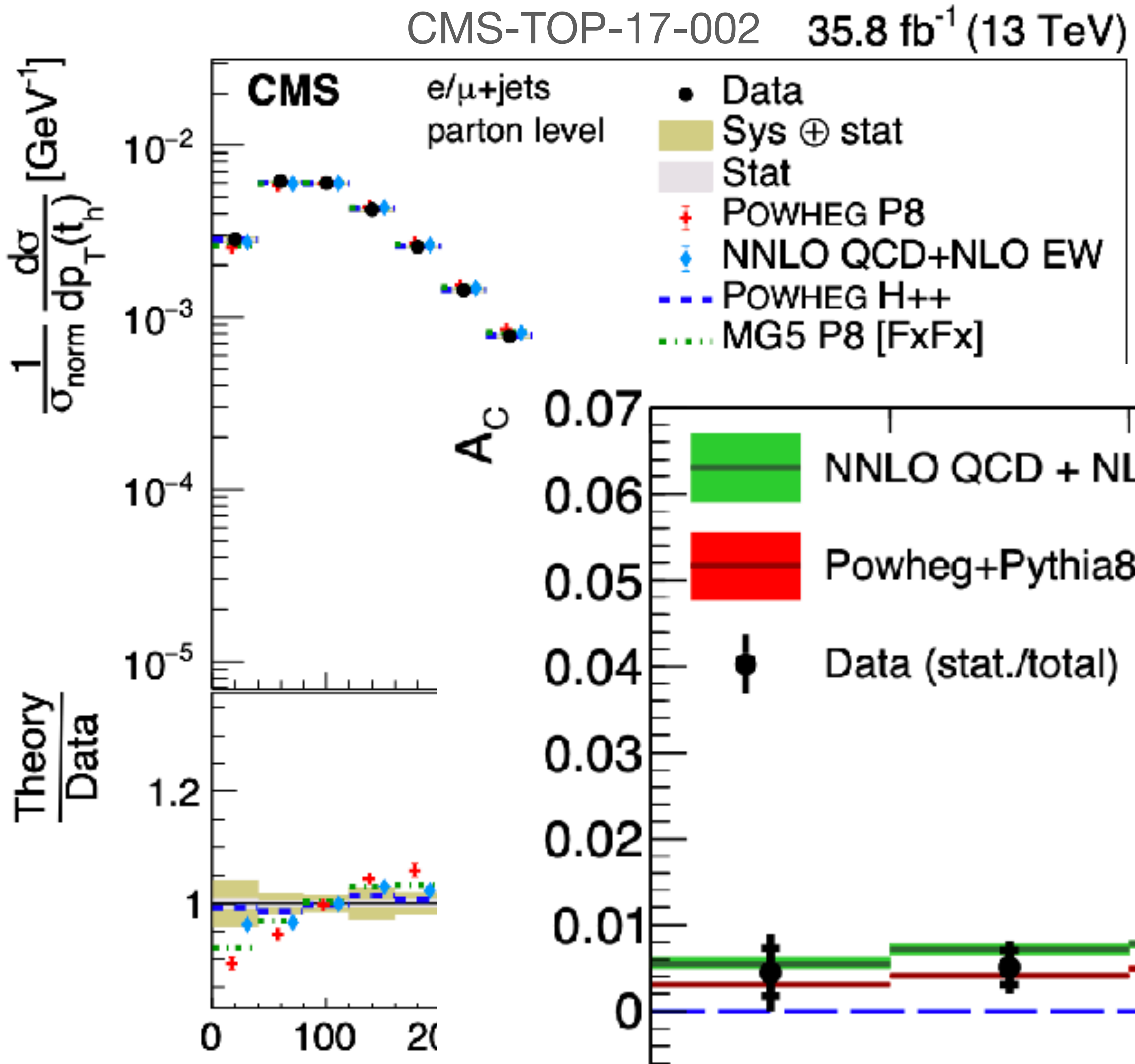
Motivation

Motivation



CMS-TOP-17-002
35.8 fb^{-1} (13 TeV)
CMS
e/μ+jets
parton level
Data
Sys ⊕ stat
Stat
POWHEG P8
NNLO QCD+NLO EW
POWHEG H++
MG5 P8 [FxFx]
$\frac{1}{\sigma_{norm}} \frac{d\sigma}{dp_T(t_h)}$ [GeV^{-1}]
Theory / Data
$p_T(t_h)$ [GeV]

Motivation


CMS-TOP-17-002
35.8 fb-1 (13 TeV)
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e/μ+jets
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Data
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POWHEG P8
NNLO QCD+NLO EW
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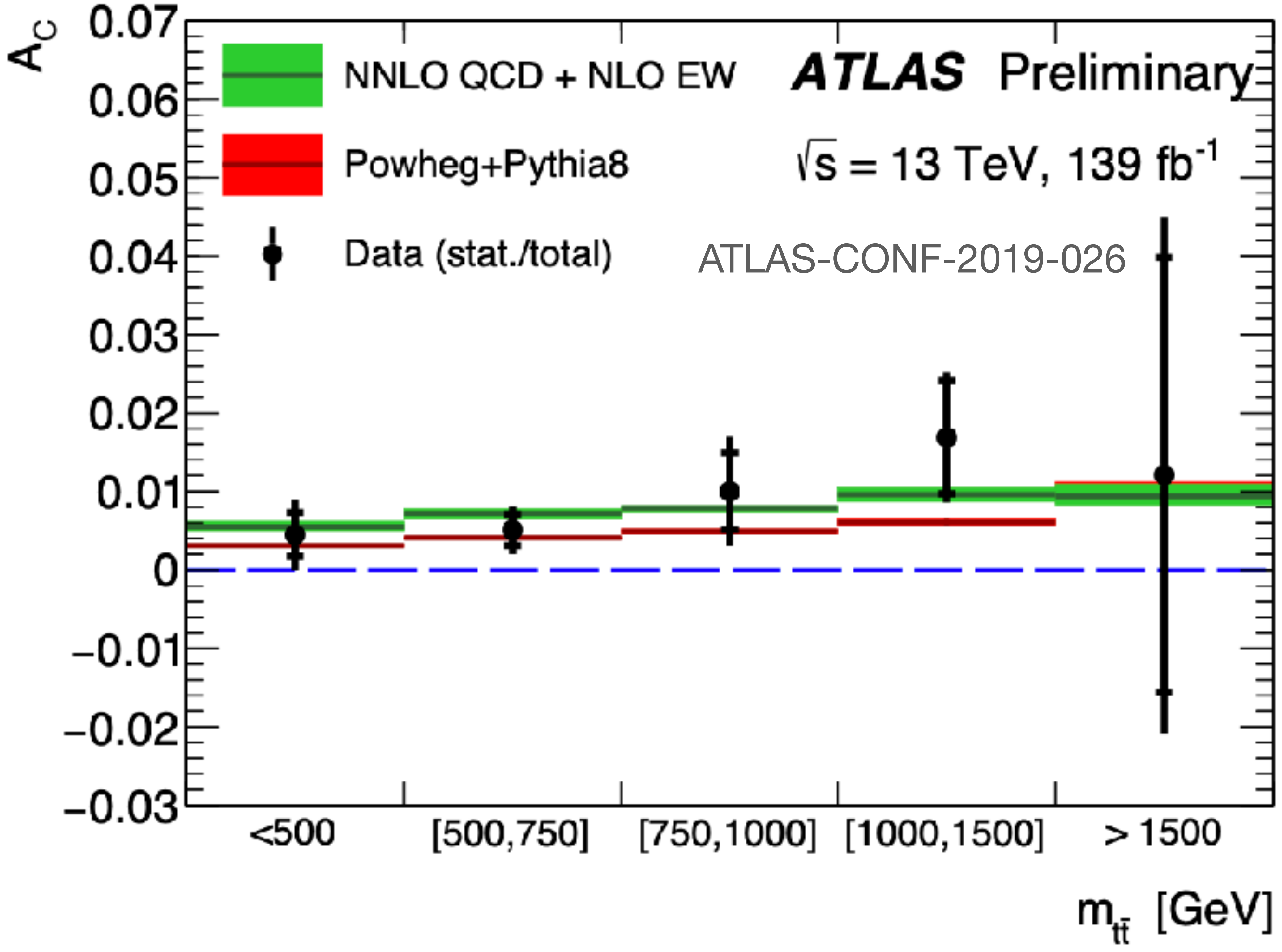
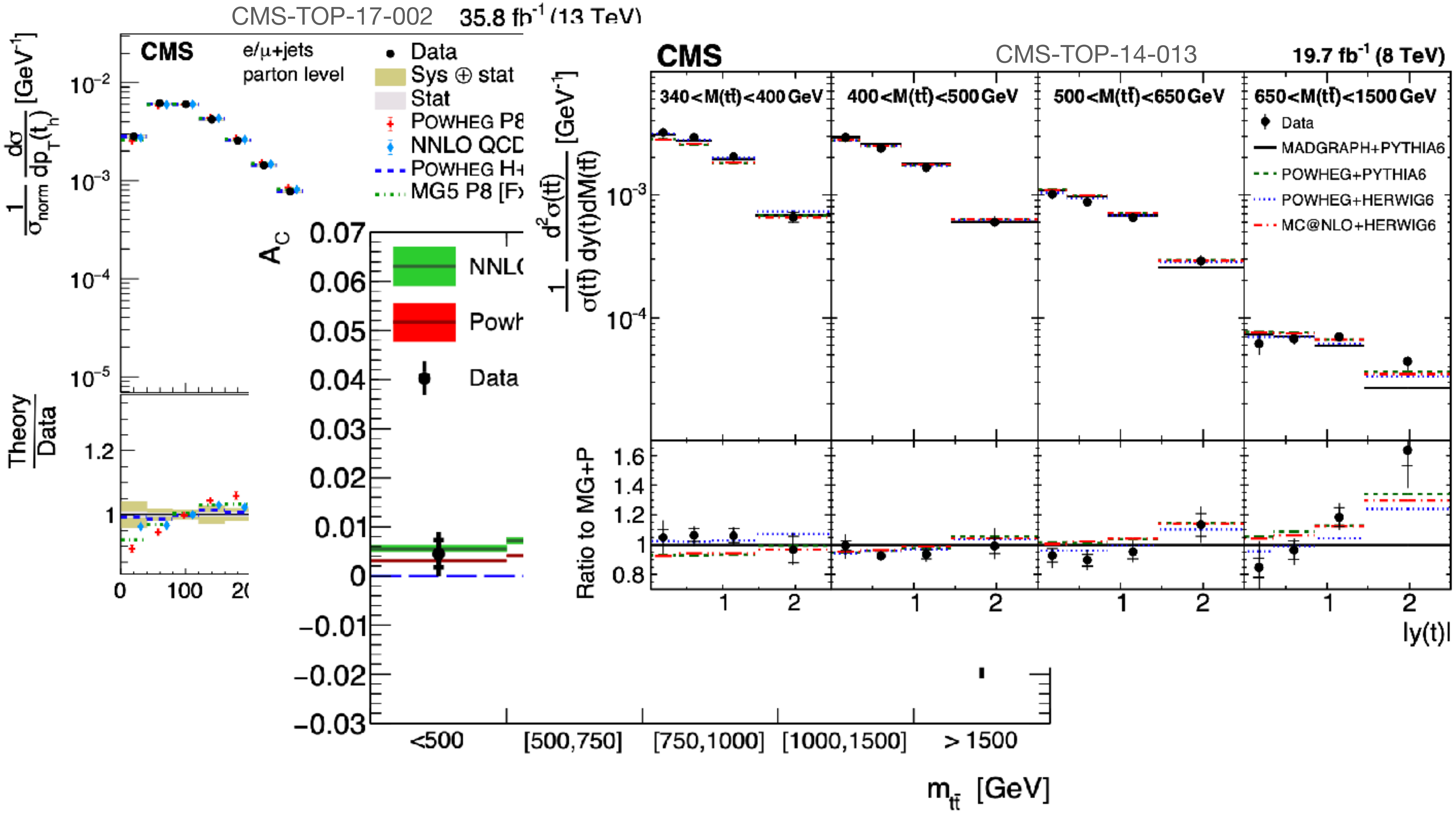
Theory / Data

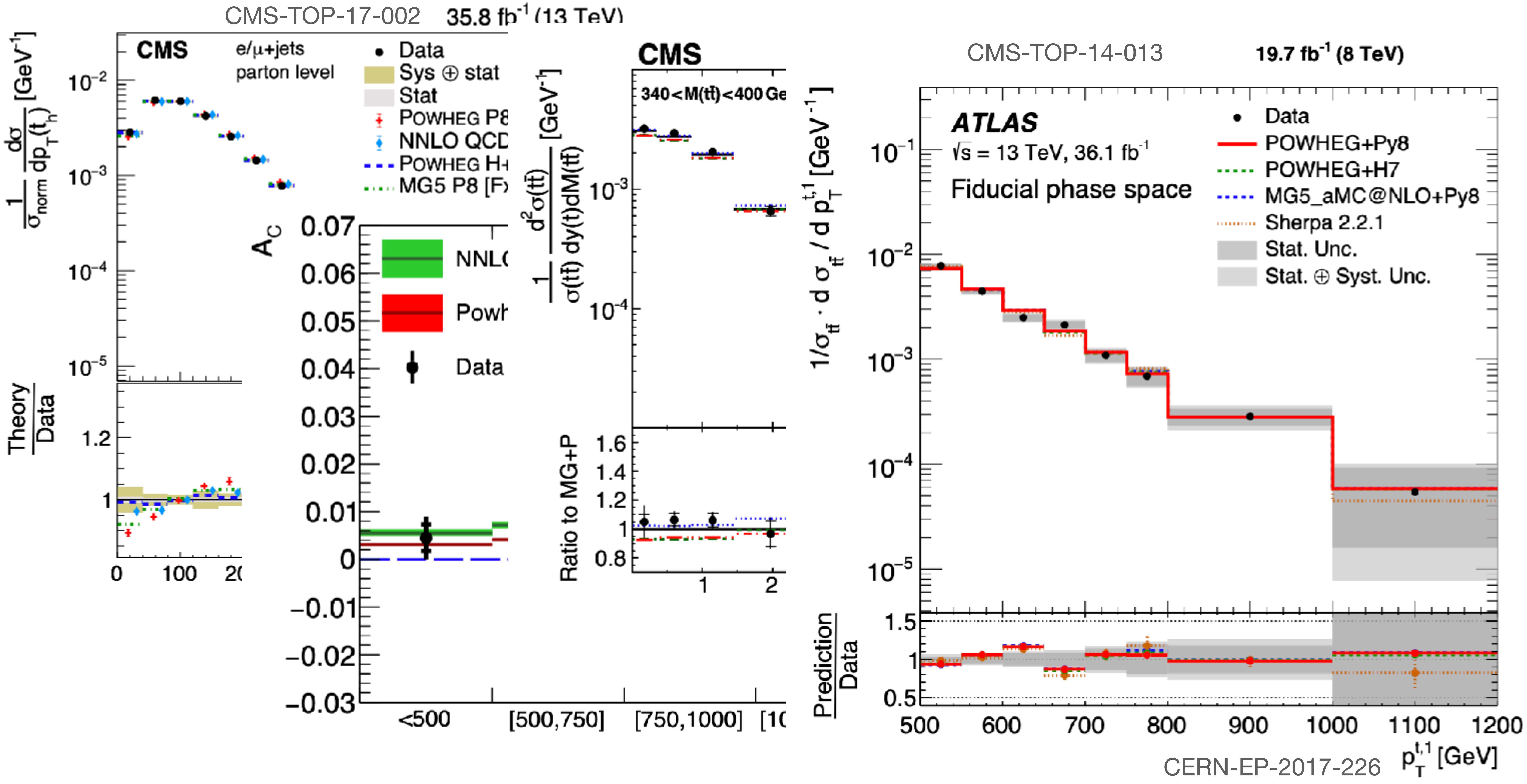

ATLAS Preliminary
√s = 13 TeV, 139 fb-1
NNLO QCD + NLO EW
Powheg+Pythia8
Data (stat./total)
ATLAS-CONF-2019-026
A_C
<500
[500,750]
[750,1000]
[1000,1500]
> 1500
m_tt̄ [GeV]

Motivation



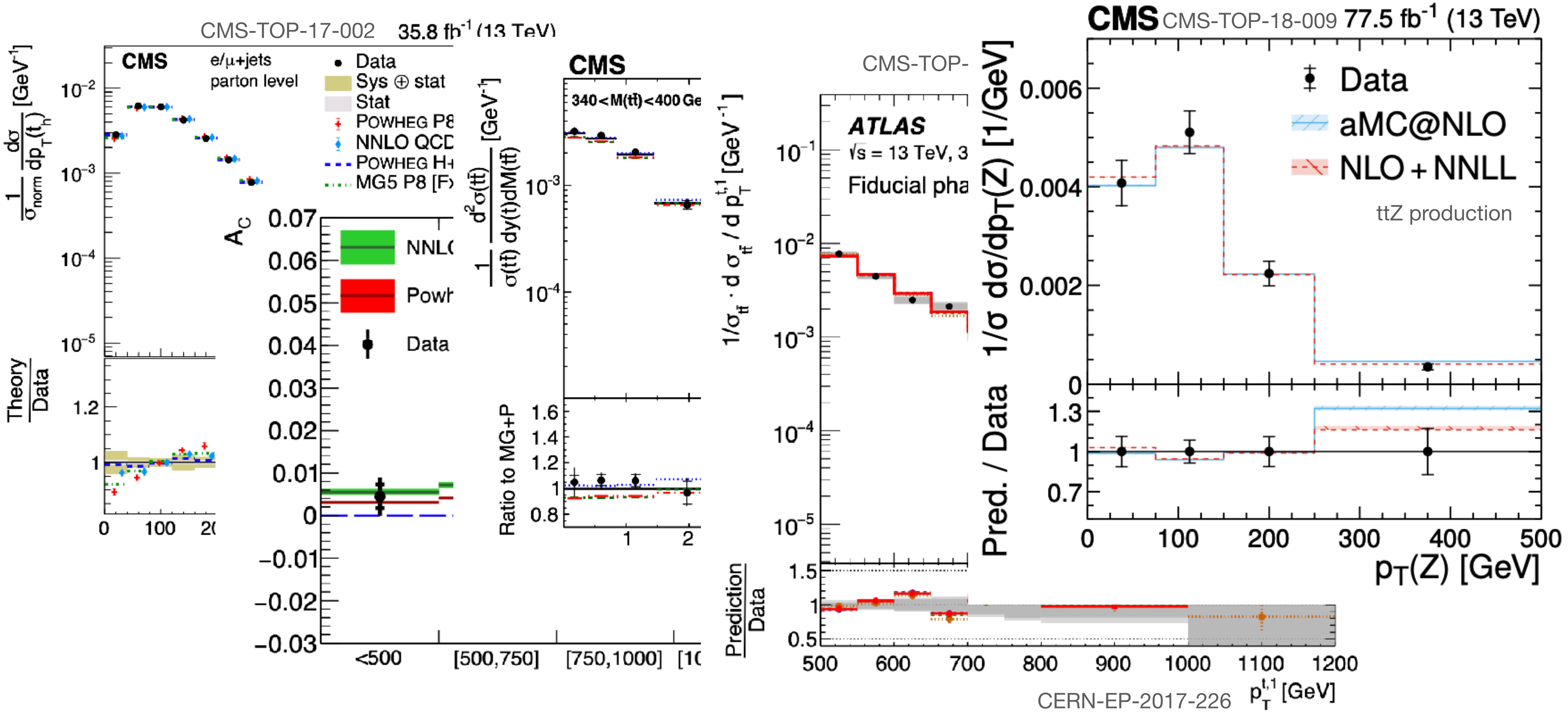
CMS-TOP-17-002
35.8 fb-1 (13 TeV)
CMS
e/μ+jets
parton level
Data
Sys ⊕ stat
Stat
POWHEG P8
NNLO QCD
POWHEG H
MG5 P8 [F
Theory / Data
A_C
NNL
Powh
Data
m_tt̄ [GeV]
<500
[500,750]
[750,1000]
[1000,1500]
> 1500
CMS
CMS-TOP-14-013
19.7 fb-1 (8 TeV)
340<M(tt̄)<400 GeV
400<M(tt̄)<500 GeV
500<M(tt̄)<650 GeV
650<M(tt̄)<1500 GeV
Data
MADGRAPH+PYTHIA6
POWHEG+PYTHIA6
POWHEG+HERWIG6
MC@NLO+HERWIG6
Ratio to MG+P
|y(t)|

Motivation



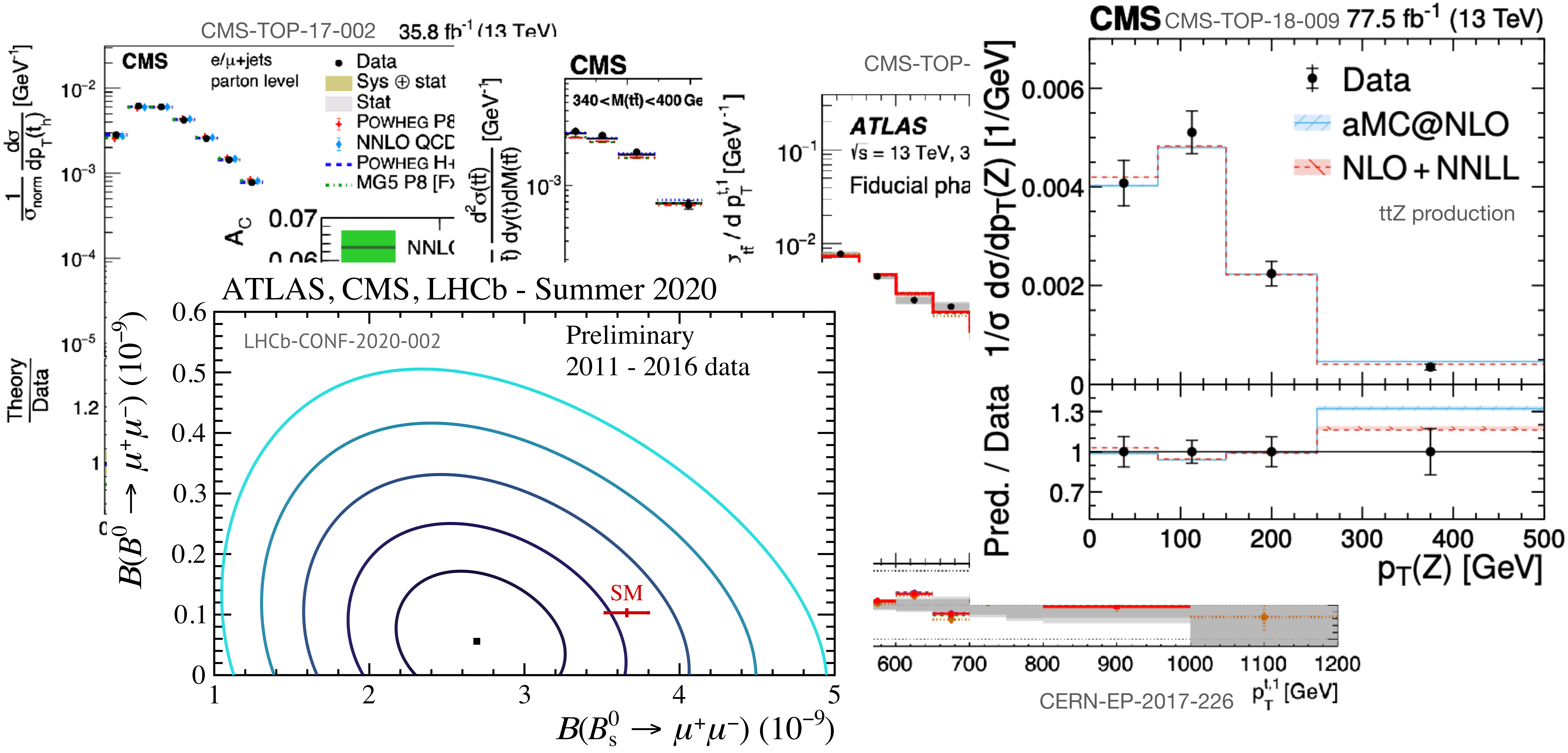
CMS-TOP-17-002
35.8 fb-1 (13 TeV)
CMS
e/μ+jets
parton level
Data
Sys ⊕ stat
Stat
POWHEG P8
NNLO QCD
POWHEG H
MG5 P8 [F
Theory / Data
A_C
NNLO
Powh
Data
<500
[500,750]
[750,1000]
340<M(tt̄)<400 Ge
Ratio to MG+P
CMS-TOP-14-013
19.7 fb-1 (8 TeV)
ATLAS
√s = 13 TeV, 36.1 fb-1
Fiducial phase space
Data
POWHEG+Py8
POWHEG+H7
MG5_aMC@NLO+Py8
Sherpa 2.2.1
Stat. Unc.
Stat. ⊕ Syst. Unc.
Prediction / Data
p_T^{t,1} [GeV]
CERN-EP-2017-226

Motivation



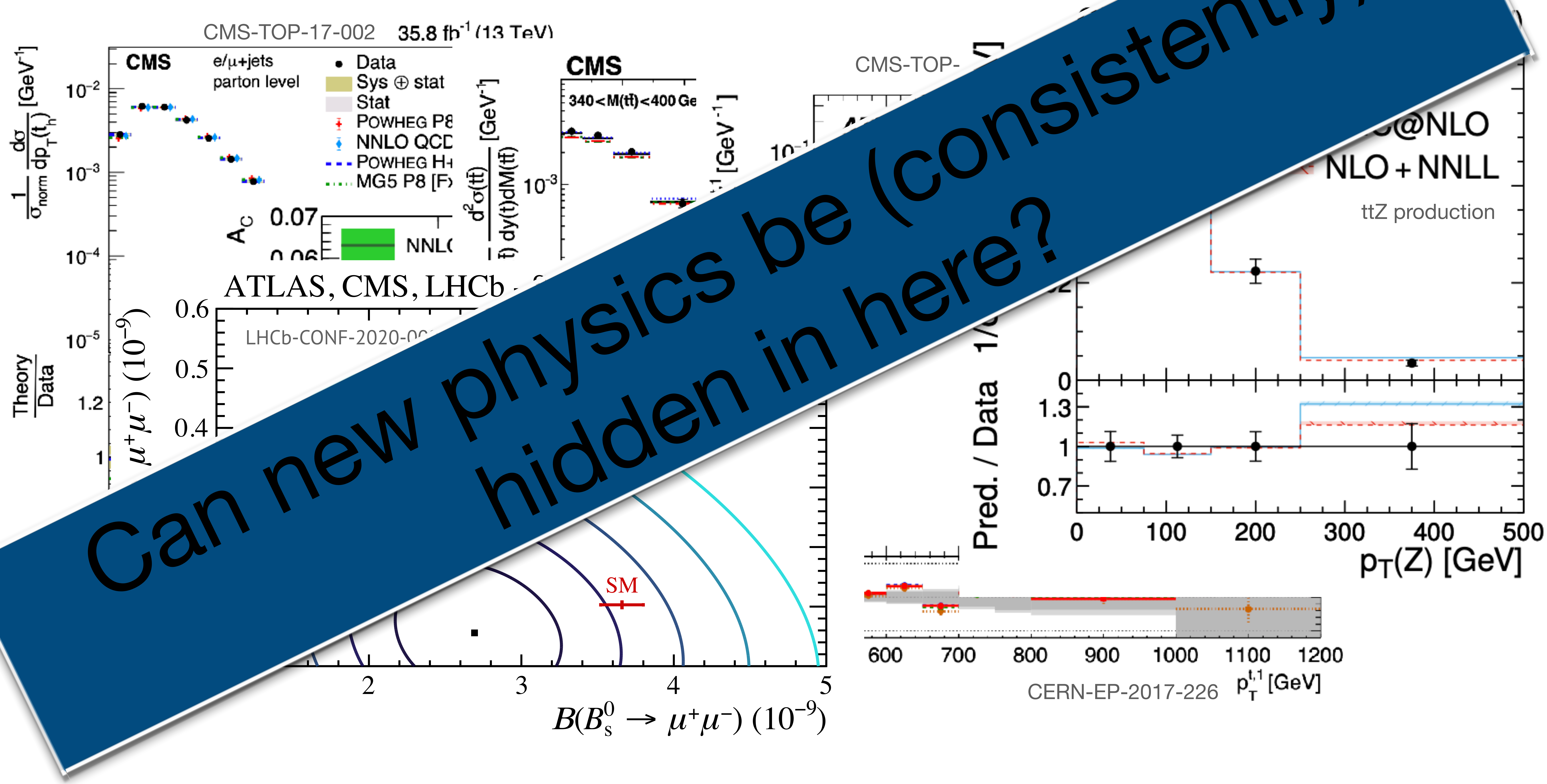
CMS-TOP-17-002
35.8 fb⁻¹ (13 TeV)
CMS
e/μ+jets
parton level
Data
Sys ⊕ stat
Stat
POWHEG P8
NNLO QCD
POWHEG H
MG5 P8
Theory / Data
A_C
NNLO
Powh
Data
<500
[500,750]
[750,1000]
CMS
340<M(tt̄)<400 Ge
Ratio to MG+P
CMS-TOP-
ATLAS
√s = 13 TeV, 3
Fiducial pha
Prediction / Data
$p_T^{t,1}$ [GeV]
CERN-EP-2017-226
CMS CMS-TOP-18-009 77.5 fb⁻¹ (13 TeV)
Data
aMC@NLO
NLO + NNLL
ttZ production
1/σ dσ/dp_T(Z) [1/GeV]
Pred. / Data
p_T(Z) [GeV]

Motivation



CMS-TOP-17-002
35.8 fb^{-1} (13 TeV)
CMS
e/μ+jets
parton level
Data
Sys ⊕ stat
Stat
CMS
340<M(tt̄)<400 GeV
CMS-TOP-
ATLAS
√s = 13 TeV
Fiducial pha
ATLAS, CMS, LHCb - Summer 2020
LHCb-CONF-2020-002
Preliminary
2011 - 2016 data
SM
$B(B^0 \to \mu^+\mu^-)$ (10^{-9})
$B(B_s^0 \to \mu^+\mu^-)$ (10^{-9})
CMS CMS-TOP-18-009 77.5 fb^{-1} (13 TeV)
Data
aMC@NLO
NLO + NNLL
ttZ production
1/σ dσ/dp$_T$(Z) [1/GeV]
Pred. / Data
p$_T$(Z) [GeV]
CERN-EP-2017-226

Motivation



Can new physics be (consistently) hidden in here?

Motivation

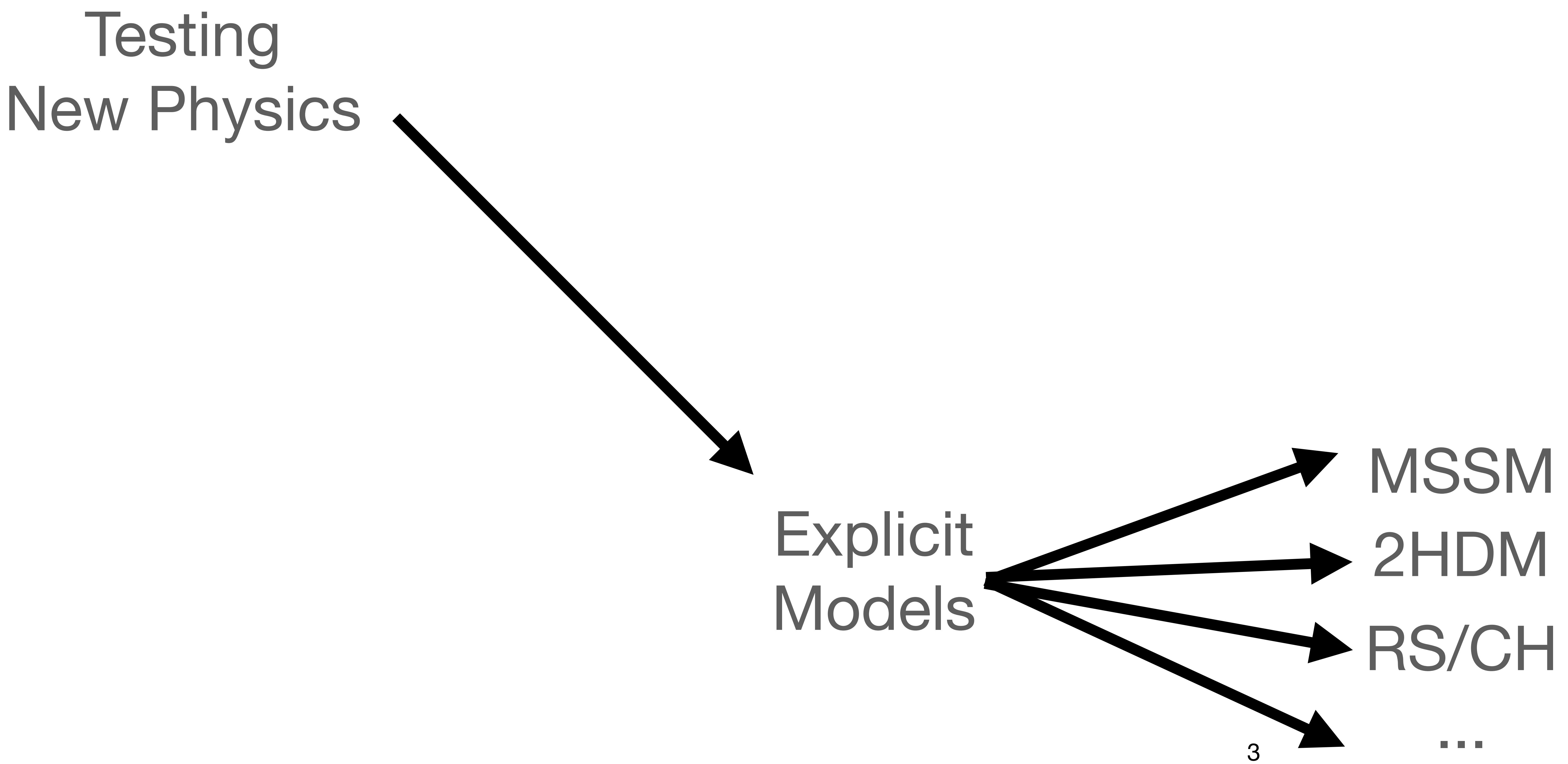
Testing
New Physics

Motivation

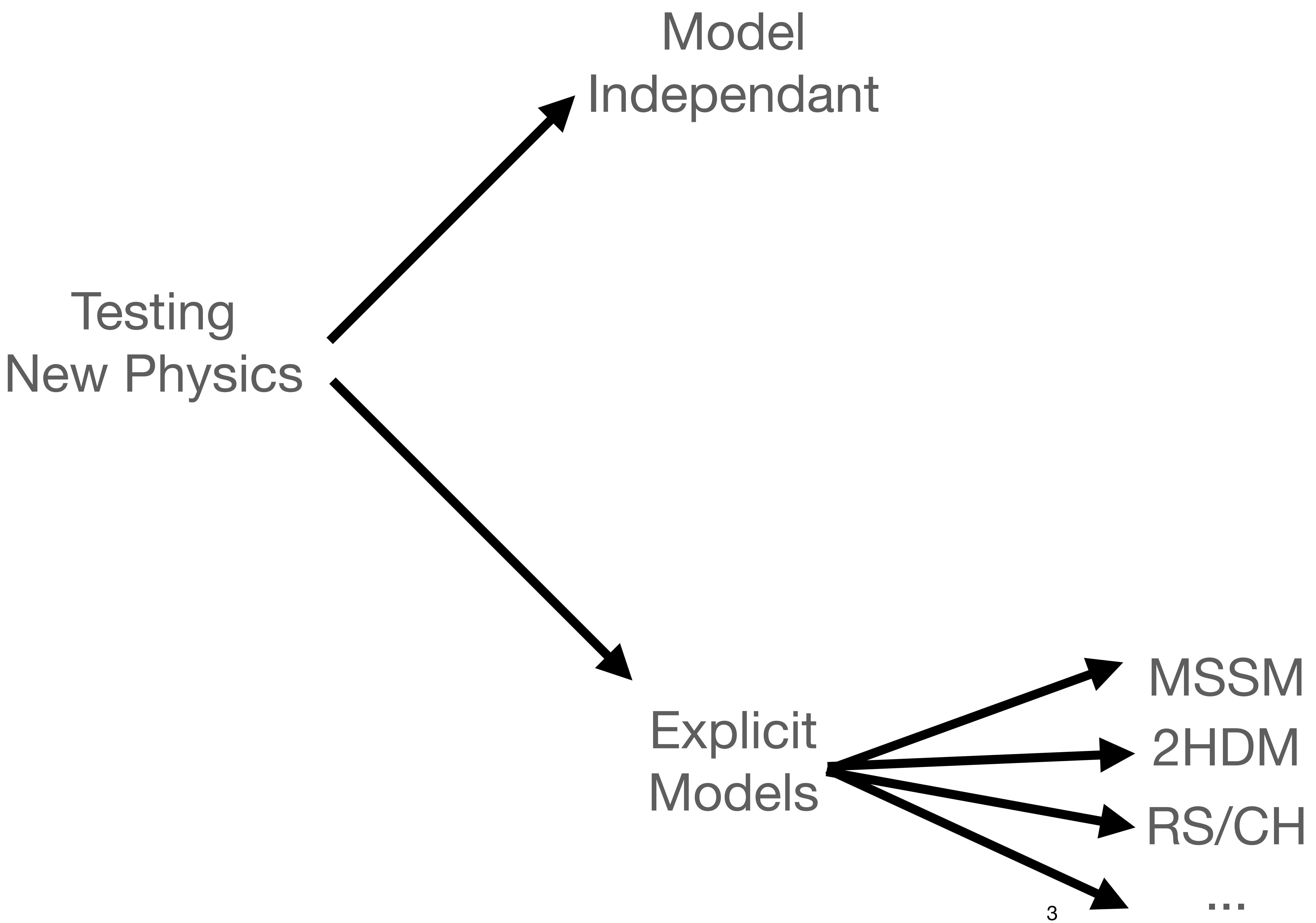
Testing
New Physics

Explicit
Models

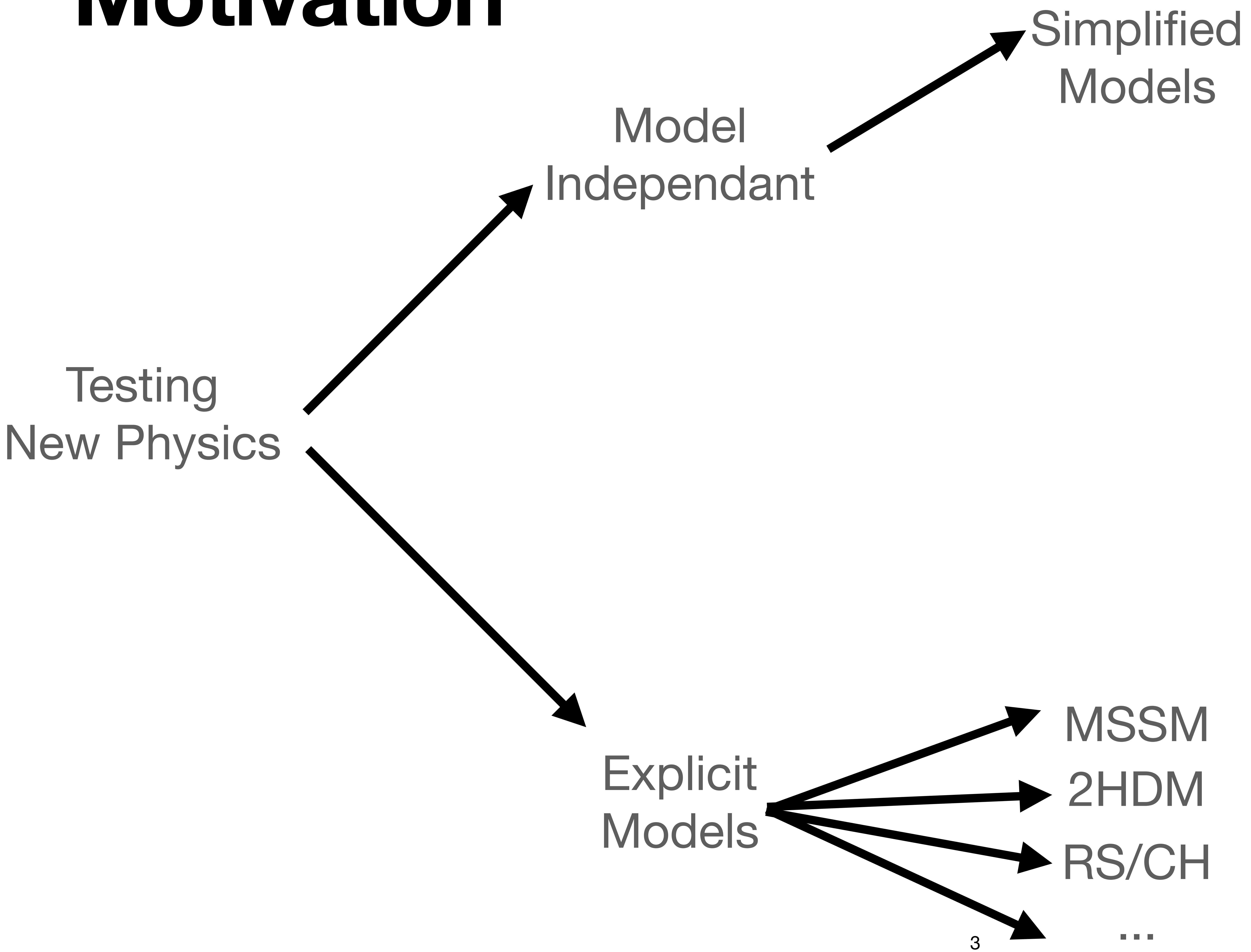
Motivation



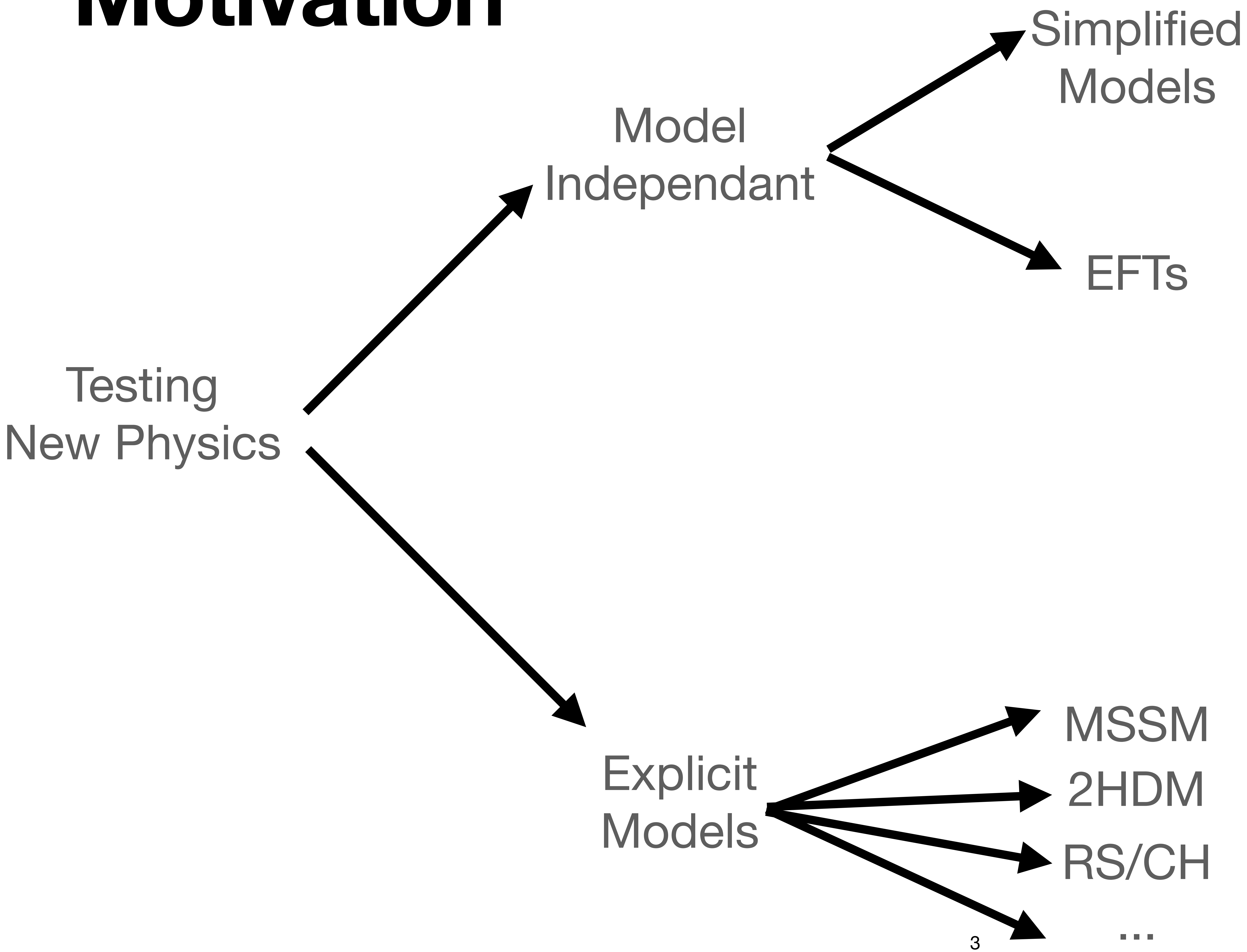
Motivation


Model
Independant
Testing
New Physics
Explicit
Models
MSSM
2HDM
RS/CH
...

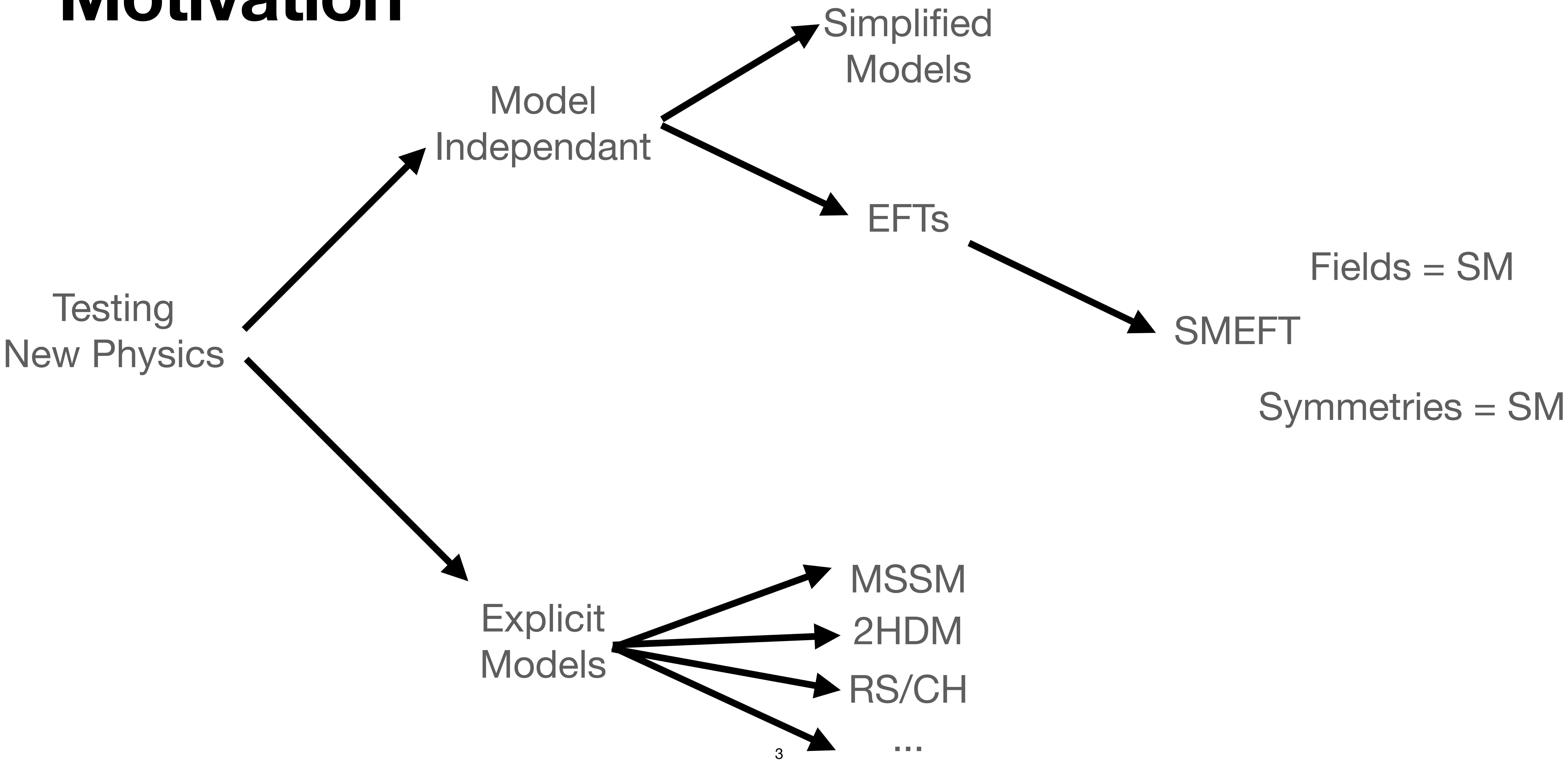
Motivation


Simplified
Models
Model
Independant
Testing
New Physics
Explicit
Models
MSSM
2HDM
RS/CH
...

Motivation


Testing
New Physics
Model
Independant
Simplified
Models
EFTs
Explicit
Models
MSSM
2HDM
RS/CH
...

Motivation


Testing
New Physics
Model
Independant
Simplified
Models
EFTs
SMEFT
Fields = SM
Symmetries = SM
Explicit
Models
MSSM
2HDM
RS/CH
...

SMEFT

Fields = SM Symmetries = SM

e.g. 1008.4884/1312.2014

SMEFT

Fields = SM

Symmetries = SM

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{\mathcal{C}_i}{\Lambda^{d_i-4}} \mathcal{O}_i$$

e.g. 1008.4884/1312.2014

SMEFT

Fields = SM Symmetries = SM

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{\mathcal{C}_i}{\Lambda^{d_i-4}} \mathcal{O}_i = \mathcal{L}_{SM} + \frac{\mathcal{C}_i}{\Lambda} \mathcal{O}_i^{d=5} + \frac{\mathcal{C}_i}{\Lambda^2} \mathcal{O}_i^{d=6} + \mathcal{O}(\Lambda^{-3})$$

e.g. 1008.4884/1312.2014

SMEFT

Fields = SM

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$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{\mathcal{C}_i}{\Lambda^{d_i-4}}\mathcal{O}_i = \mathcal{L}_{SM} + \frac{\mathcal{C}_i}{\Lambda}\mathcal{O}_i^{d=5} + \frac{\mathcal{C}_i}{\Lambda^2}\mathcal{O}_i^{d=6} + \mathcal{O}(\Lambda^{-3})$$

L violating
irrelevant for us

e.g. 1008.4884/1312.2014

SMEFT

Fields = SM

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$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{\mathcal{C}_i}{\Lambda^{d_i-4}}\mathcal{O}_i = \mathcal{L}_{SM} + \frac{\mathcal{C}_i}{\Lambda}\mathcal{O}_i^{d=5} + \frac{\mathcal{C}_i}{\Lambda^2}\mathcal{O}_i^{d=6} + \mathcal{O}(\Lambda^{-3})$$

L violating
irrelevant for us

$$\frac{E^2}{\Lambda^2}$$

e.g. 1008.4884/1312.2014

SMEFT

Fields = SM

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$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{\mathcal{C}_i}{\Lambda^{d_i-4}}\mathcal{O}_i = \mathcal{L}_{SM} + \frac{\mathcal{C}_i}{\Lambda}\mathcal{O}_i^{d=5} + \frac{\mathcal{C}_i}{\Lambda^2}\mathcal{O}_i^{d=6} + \mathcal{O}(\Lambda^{-3})$$

L violating
irrelevant for us

$\{s, v^2, m_t^2, \dots\}$

$$\frac{E^2}{\Lambda^2}$$

e.g. 1008.4884/1312.2014

SMEFT

Fields = SM Symmetries = SM

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{\mathcal{C}_i}{\Lambda^{d_i - 4}} \mathcal{O}_i = \mathcal{L}_{SM} + \frac{\mathcal{C}_i}{\Lambda} \mathcal{O}_i^{d=5} + \frac{\mathcal{C}_i}{\Lambda^2} \mathcal{O}_i^{d=6} + \mathcal{O}(\Lambda^{-3})$$

e.g. 1008.4884/1312.2014

SMEFT

Fields = SM

Symmetries = SM

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{\mathcal{C}_i}{\Lambda^{d_i-4}}\mathcal{O}_i = \mathcal{L}_{SM} + \frac{\mathcal{C}_i}{\Lambda}\mathcal{O}_i^{d=5} + \frac{\mathcal{C}_i}{\Lambda^2}\mathcal{O}_i^{d=6} + \mathcal{O}(\Lambda^{-3})$$

O(20) coeffs.

e.g. 1008.4884/1312.2014

SMEFT

Fields = SM   Symmetries = SM

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{\mathcal{C}_i}{\Lambda^{d_i - 4}}\mathcal{O}_i = \mathcal{L}_{SM} + \frac{\mathcal{C}_i}{\Lambda}\mathcal{O}_i^{d=5} + \frac{\mathcal{C}_i}{\Lambda^2}\mathcal{O}_i^{d=6} + \mathcal{O}(\Lambda^{-3})$$

O(20) coeffs.   O(10) coeffs.

e.g. 1008.4884/1312.2014

SMEFT

Fields = SM Symmetries = SM

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{\mathcal{C}_i}{\Lambda^{d_i-4}}\mathcal{O}_i = \mathcal{L}_{SM} + \frac{\mathcal{C}_i}{\Lambda}\mathcal{O}_i^{d=5} + \frac{\mathcal{C}_i}{\Lambda^2}\mathcal{O}_i^{d=6} + \mathcal{O}(\Lambda^{-3})$$

O(20) coeffs. O(10) coeffs. 2499 coeffs.

e.g. 1008.4884/1312.2014

SMEFT

"Warsaw" basis
1008.4884

$1: X^3$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^*\left(H^\dagger D_\mu H\right)$

$5: \psi^2H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4: X^2H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

$6: \psi^2XH + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{H}\, G_{\mu\nu}^A$
Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I \widetilde{H}\, W_{\mu\nu}^I$
Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)H\, G_{\mu\nu}^A$
Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I H\, W_{\mu\nu}^I$
Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$

$7: \psi^2H^2D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}_p\tau^I\gamma^\mu l_r)$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(q_p\tau^I\gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p\gamma^\mu d_r)$

$8: (\bar{L}L)(\bar{L}L)$	
$Q_{\ell\ell}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$
$Q_{\ell q}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{\ell q}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$

$8: (\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8: (\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(q_p\gamma_\mu T^A q_r)(u_s\gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8: (\bar{L}R)(\bar{R}L) + \text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8: (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$

$8: (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

Table from
Brivio, Trott 1706.08945

SMEFT

"Warsaw" basis
1008.4884

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I H W^I_{\mu\nu}$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G^A_{\mu\nu}$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W^I_{\mu\nu}$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I H\, W^I_{\mu\nu}$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
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$8: (\bar{L}L)(\bar{L}L)$	
$Q_{\ell\ell}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
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$8: (\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
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Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I H W^I_{\mu\nu}$
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Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde H\, W^I_{\mu\nu}$
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Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

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$Q^{(1)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar l_p \gamma^\mu l_r)$
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$8: (\bar L L)(\bar L L)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$
$Q^{(1)}_{qq}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$
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$Q^{(1)}_{lq}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$
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Organization in fundamental physics: Symmetries

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Global $\quad B - L, \quad CP, \quad \dots$

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Gauge Structure

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SU(2) Singlet
Sensitive to u+d initial state

Gauge Structure

$$O_{Qq}^{1,8} = C_{Qq}^{1,8}(\bar{q}_3\gamma^\mu T^A q_3)(\bar{q}_i\gamma_\mu T^A q_i) \qquad O_{Qq}^{3,8} = C_{Qq}^{3,8}(\bar{q}_3\gamma^\mu T^A \tau^I q_3)(\bar{q}_i\gamma_\mu T^A \tau^I q_i)$$

SU(2) Tripplet
Sensitive to u-d initial state

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Valence quark maximum

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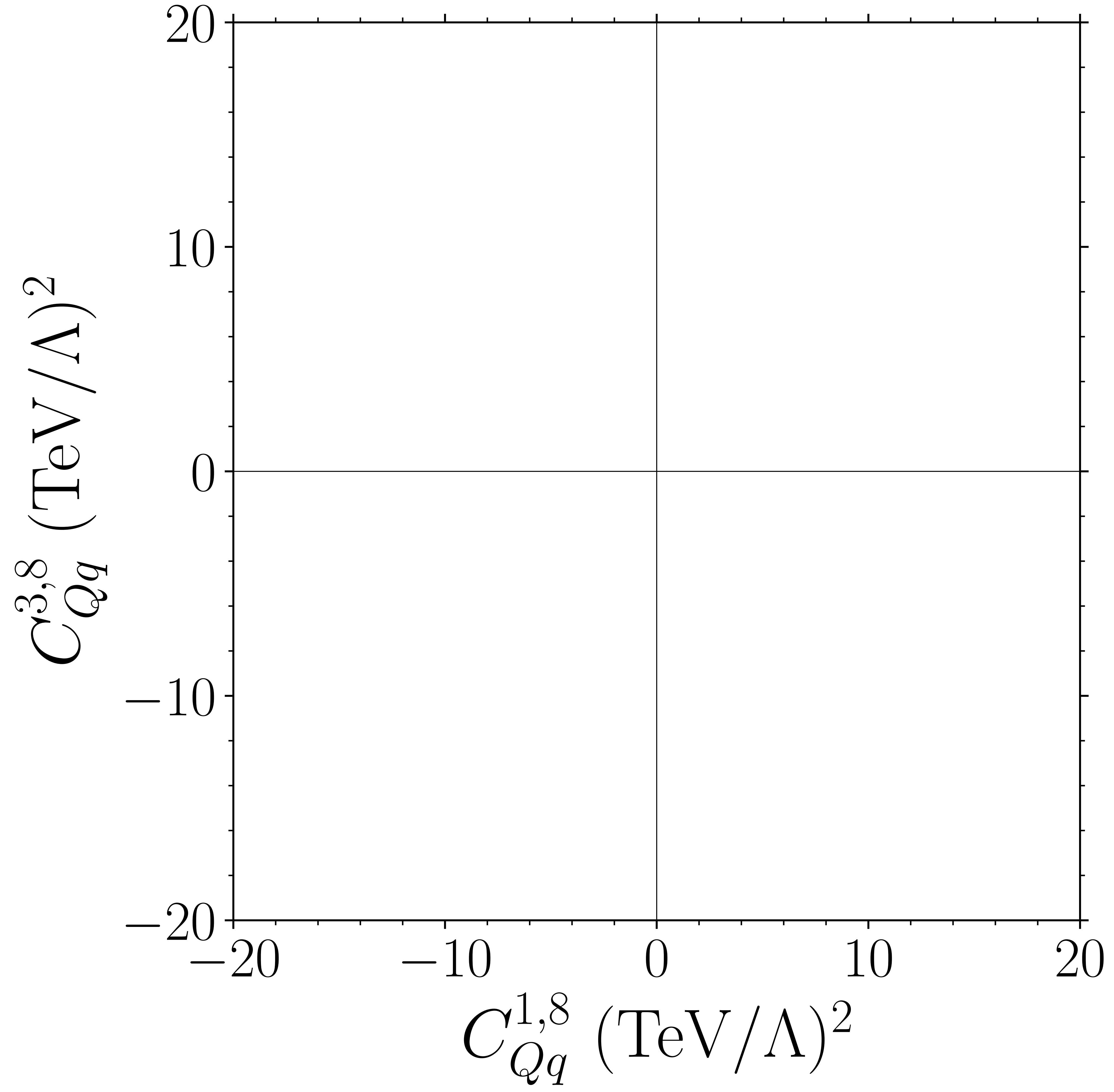

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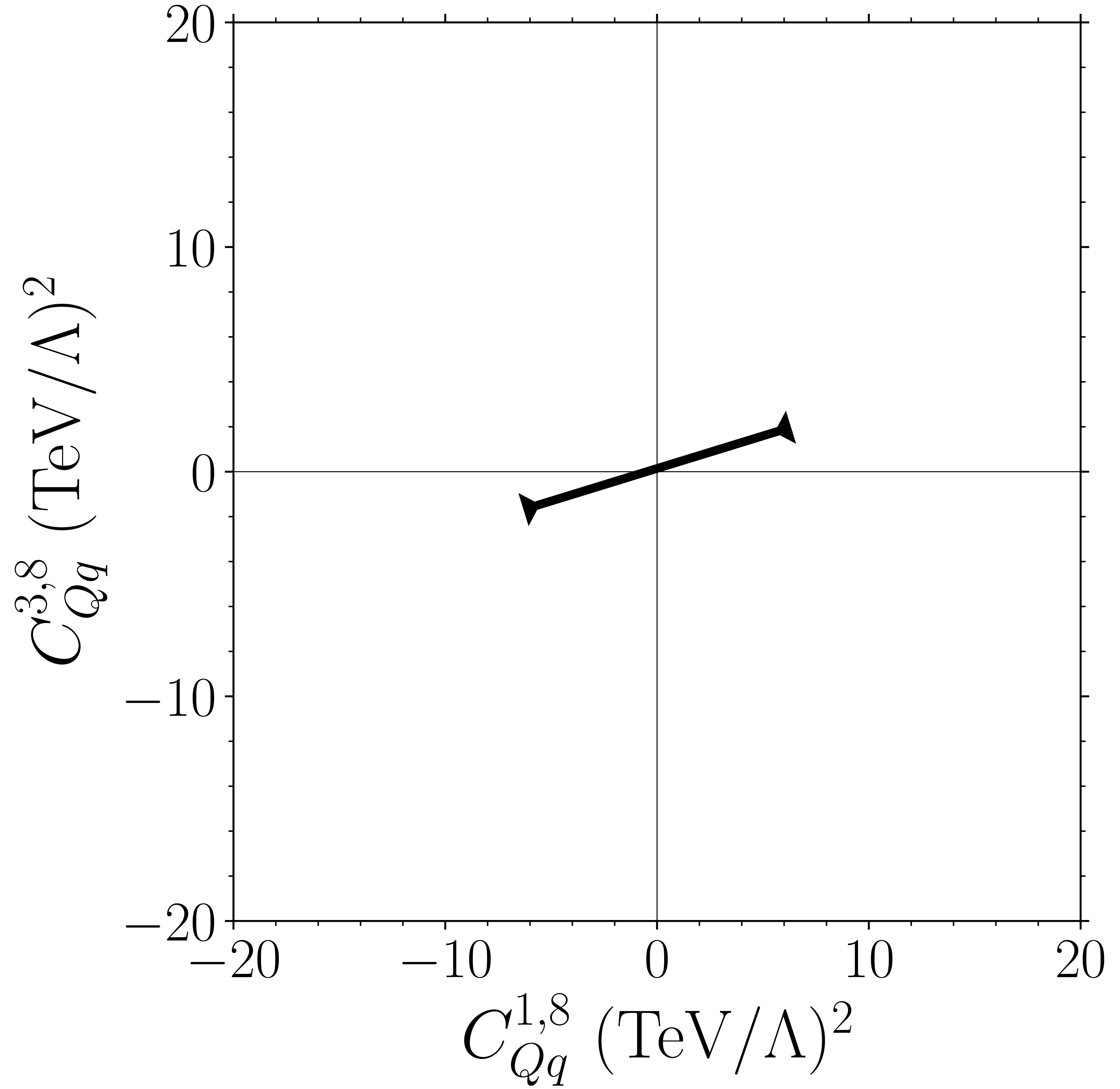

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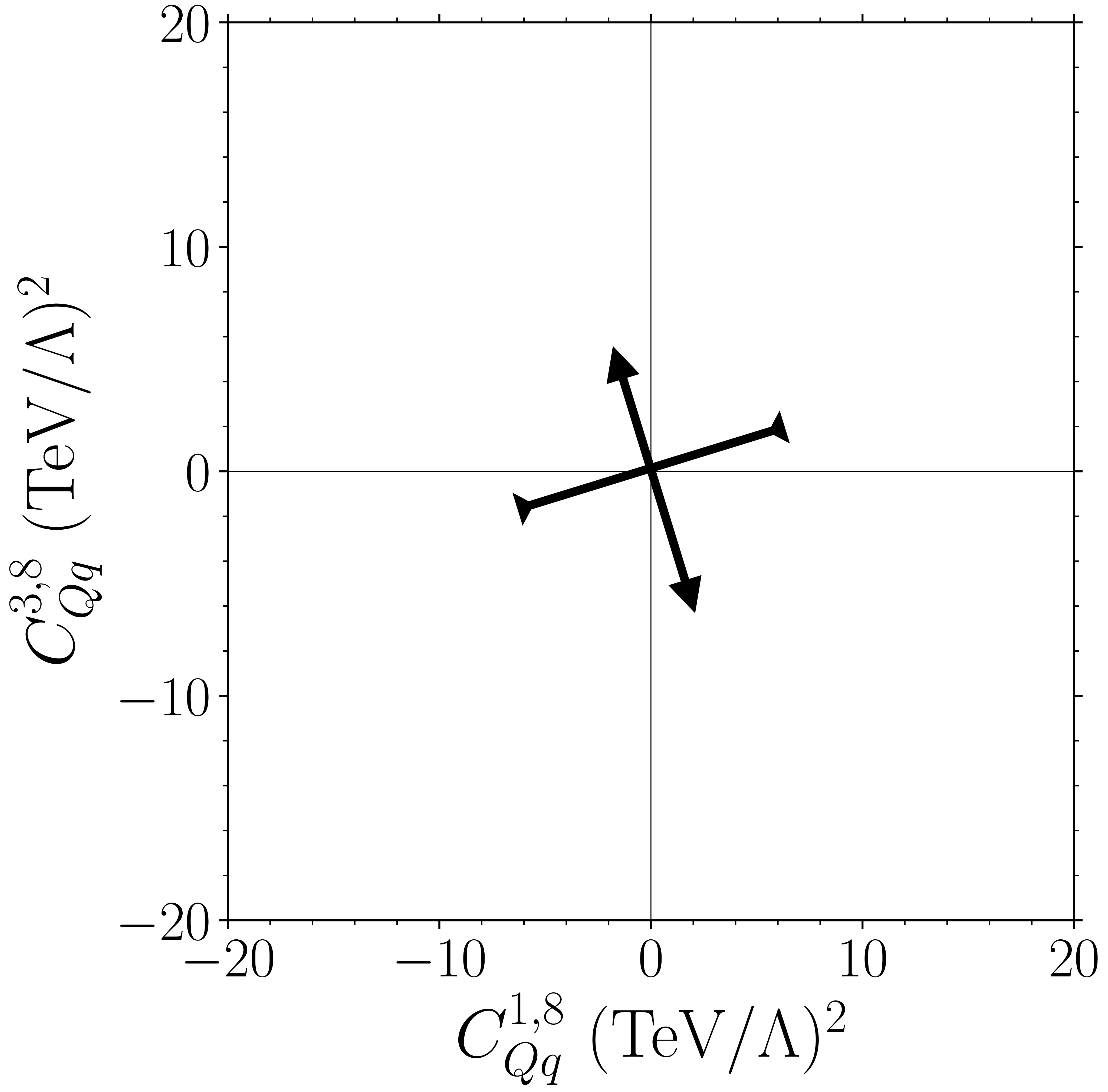

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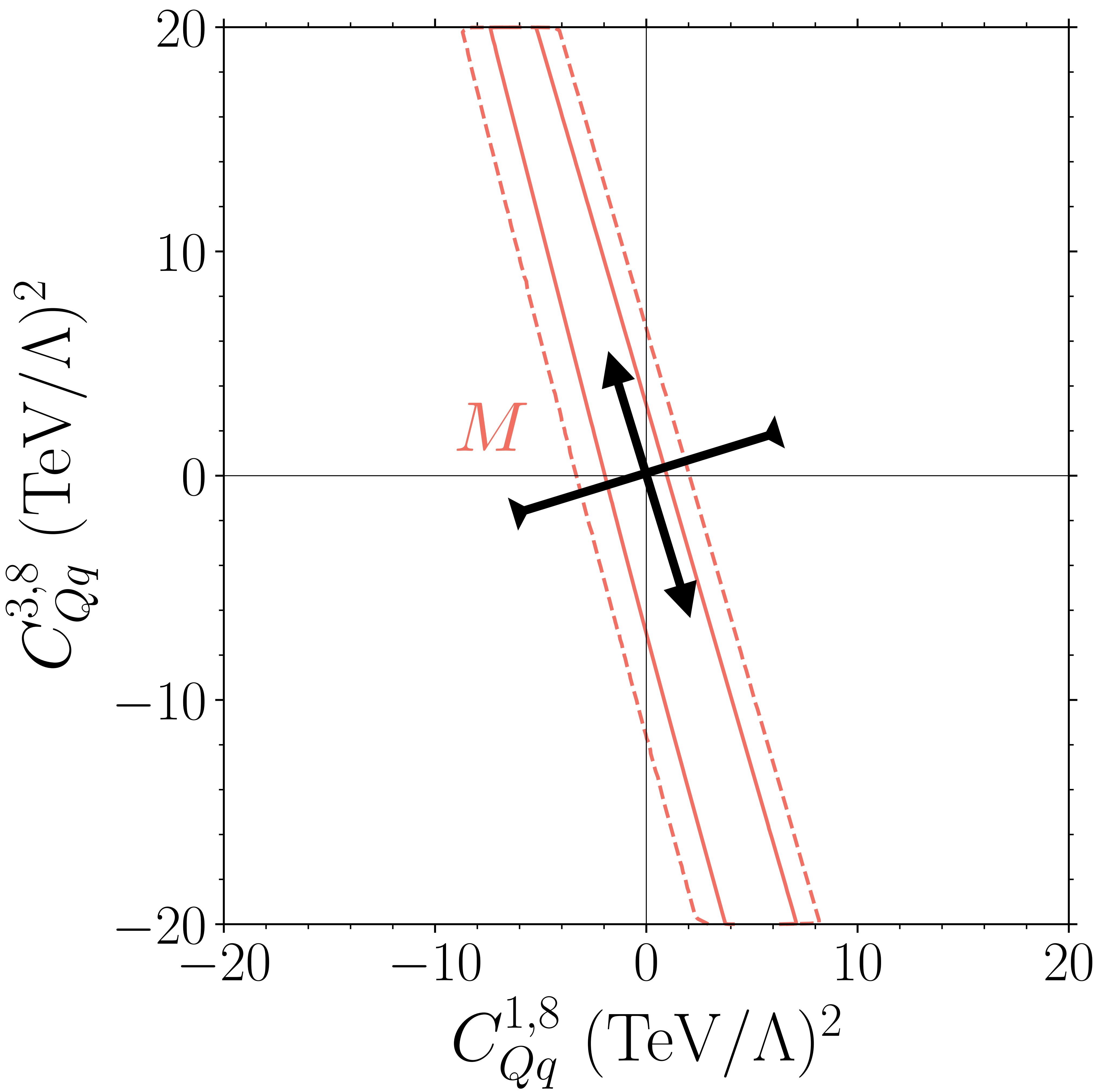

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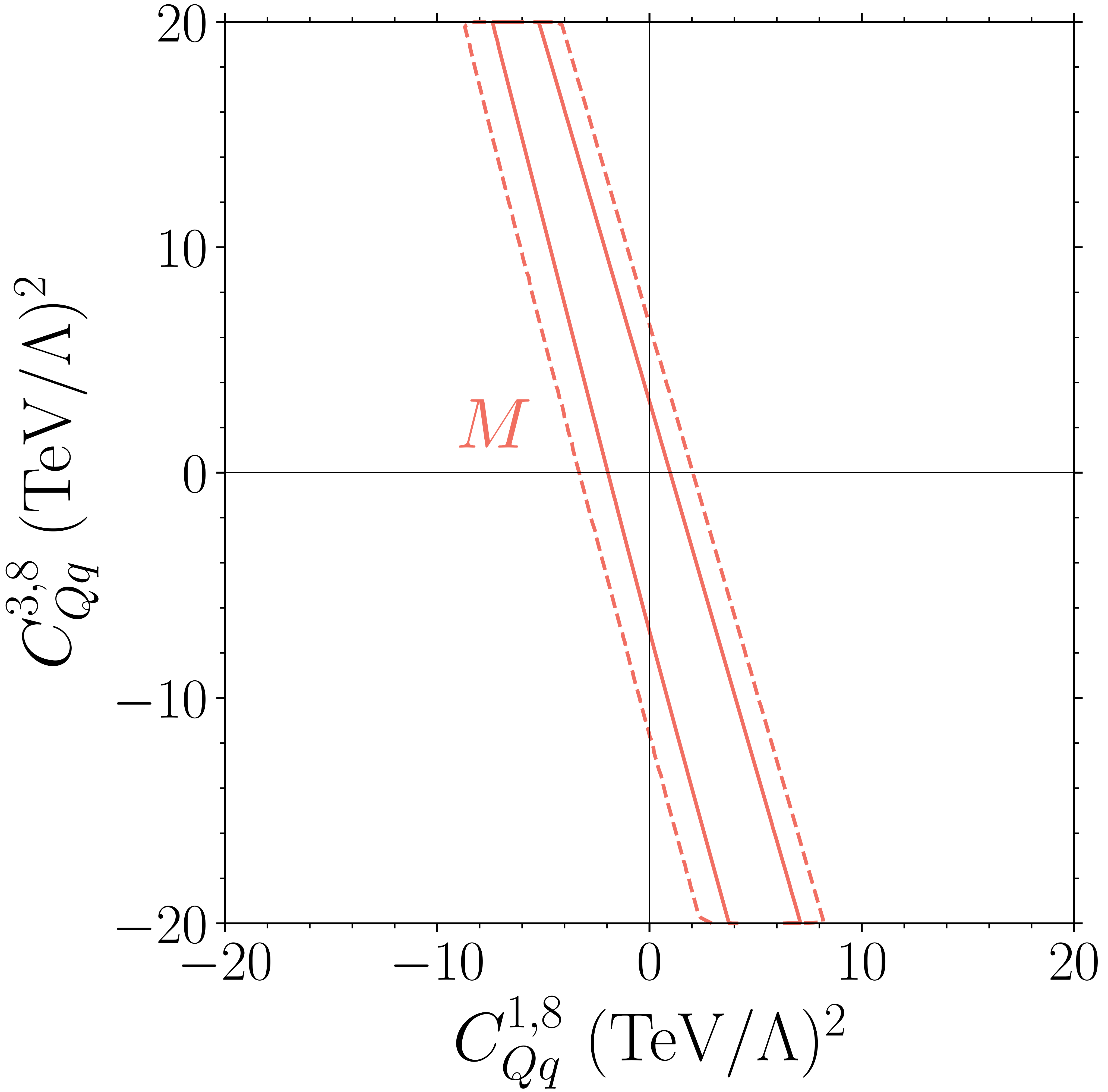
Probe different r(x) in boosted regime



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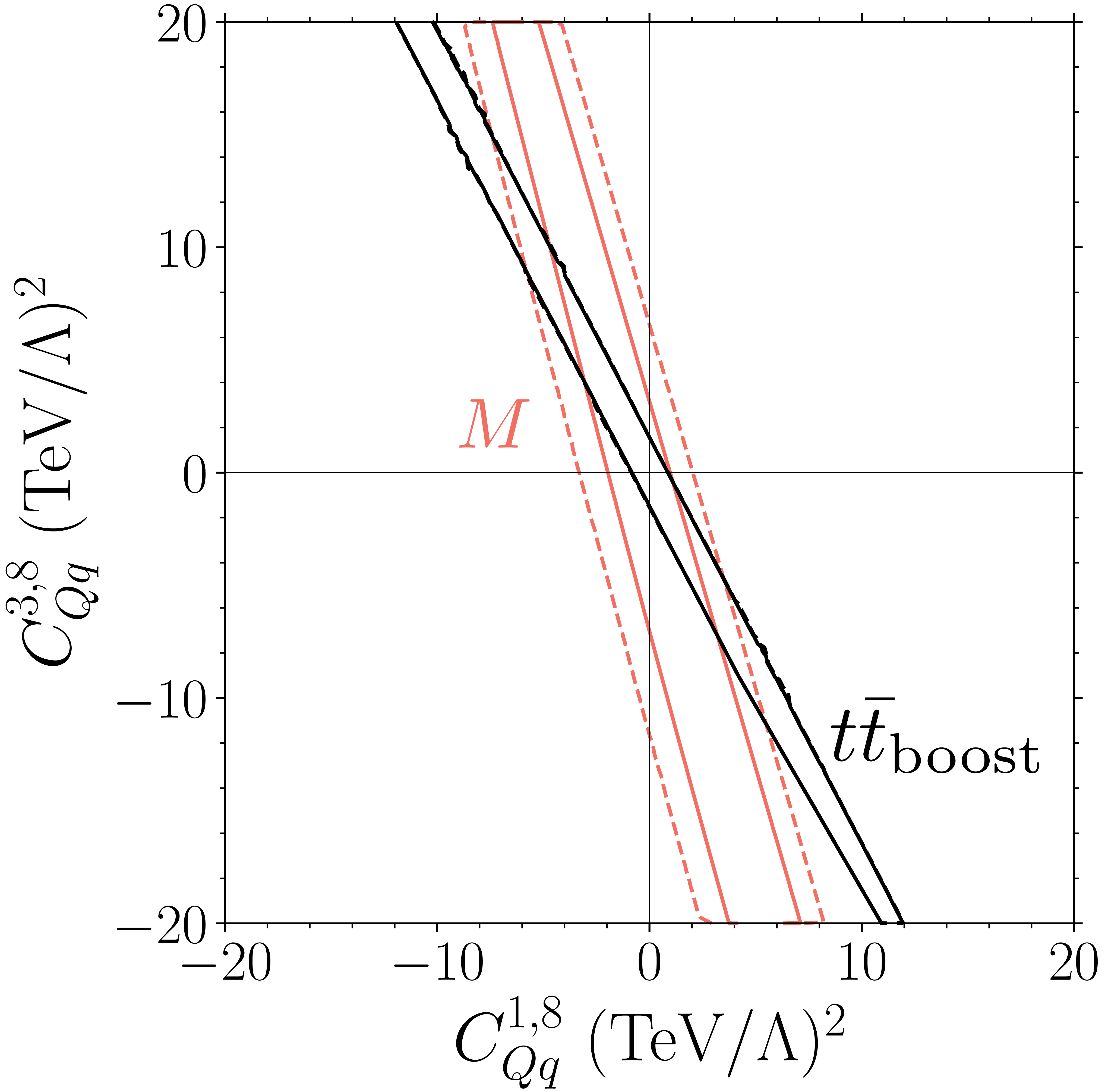

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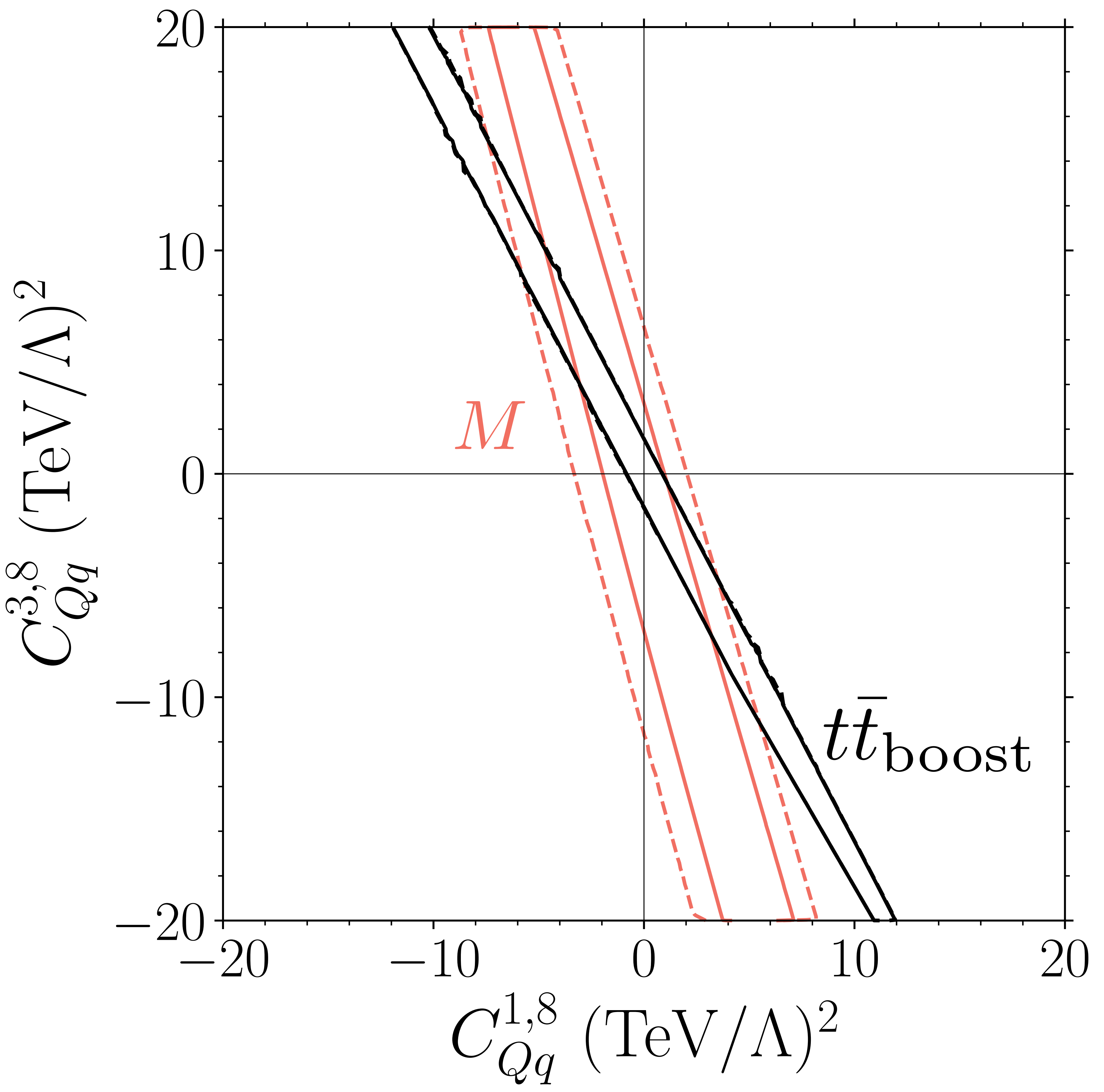

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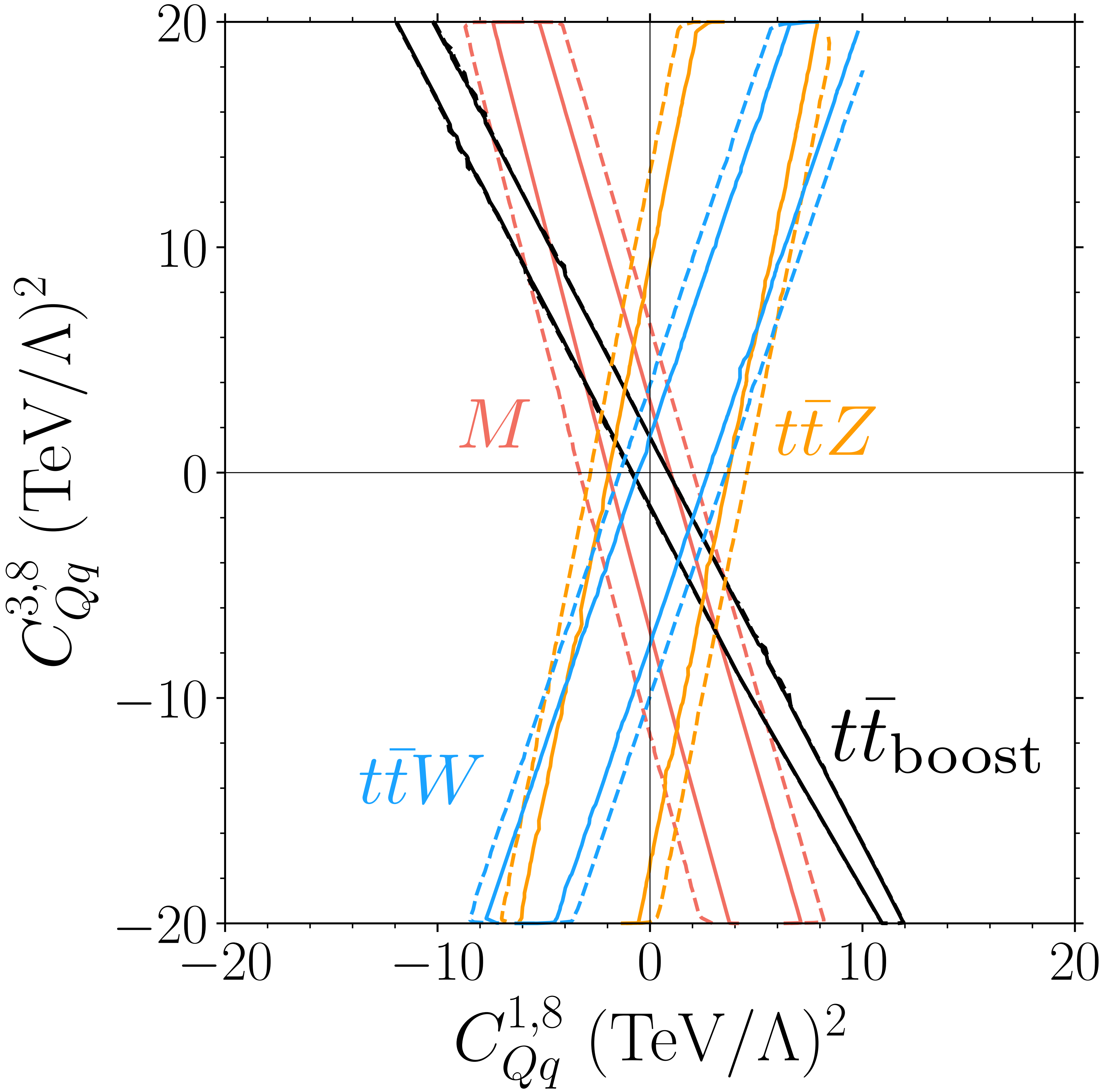

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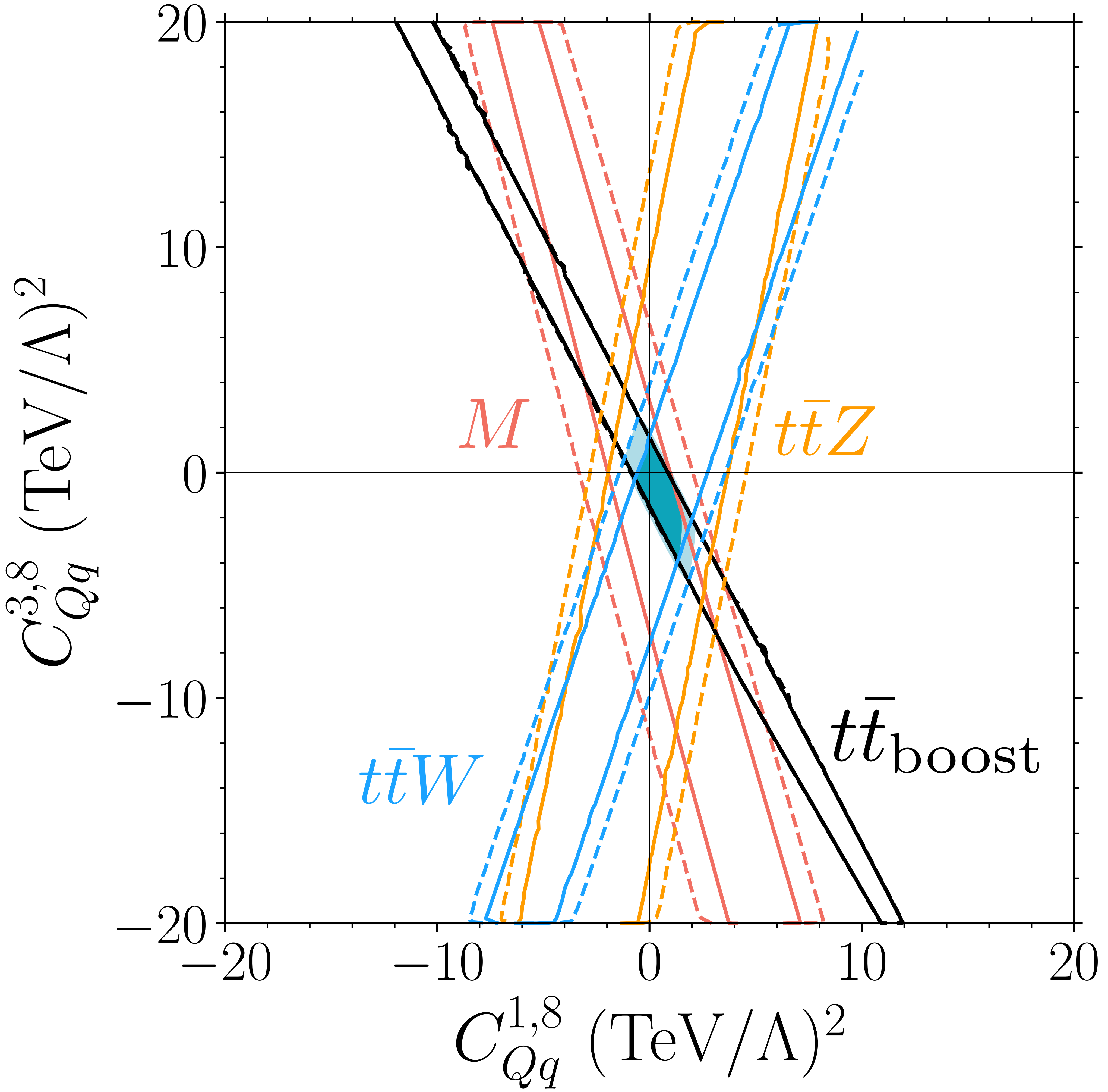

Organization in fundamental physics: Symmetries

Lorentz $(\bar{\psi}\Gamma\psi) \quad : \quad \Gamma = 1, \gamma^5, \gamma^\mu, \gamma^\mu\gamma^5, \sigma^{\mu\nu}$

High Energy

Gauge $SU(3)_C \times SU(2)_L \times U(1)_Y$

Global $B-L, \quad CP, \quad \ldots$

Flavour $U(3)_Q \times U(3)_u \times U(3)_d \times U(3)_L \times U(3)_e$ High-Low connection

Bißmann, Grunwald, Hiller, Kröninger
2012.10456
Aoude, Hurth, Renner, Shepherd
2003.05432

Flavour

a long story

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a long story

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- Here: Subset of operators in MFV as a proof of principle

The Setup

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The Measurements

- T Tbar (87 + 5A)
- Single T (13)
- TTZ / TTW (4)
- TZ / TW (7)
- Top Decay (8)

Old but reinterpreted in MFV

- $B_S \to \mu^+\mu^-$
- $B \to X_s\gamma$

New

MFV

$$U(3)_Q \times U(3)_u \times U(3)_d$$

$$Y_u \sim (3, \bar{3}, 1) \qquad\qquad Y_d \sim (3, 1, \bar{3})$$

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Flavour breaking

	$C_{\phi q}^{(1)}$	$C_{\phi q}^{(3)}$	$C_{\phi u}$	$C_{\phi d}$	$C_{\phi ud}$	C_{uX}	C_{dX}
ii	a	a	a	a	0	0	0
33	$a + by_t^2$	$a + by_t^2$	$a + by_t^2$	a	$(a + by_t^2)y_b y_t V_{tb}$	$(a + by_t^2)y_t$	$(a + by_t^2)y_b V_{tb}$
ki	$cy_b^2 V_{kb} V_{ib}^*$	$cy_b^2 V_{kb} V_{ib}^*$	0	0	0	0	0
$i3$	$cy_b^2 V_{ib} V_{tb}^*$	$cy_b^2 V_{ib} V_{tb}^*$	0	0	0	$cy_b^2 y_t V_{ib} V_{tb}^*$	$ay_b V_{ib}$
#	3	3	2	1	1	2	2

MFV

$$\Big[(A_Q)_{kl}(A_Q)_{mn} + (\tilde{A}_Q)_{kn}(\tilde{A}_Q)_{ml}\Big]\,(\bar{Q}^k\gamma^\mu Q^l)(\bar{Q}^m\gamma^\mu Q^n)$$

	$C_{qq}^{(1)}$, $C_{qq}^{(3)}$	C_{uu}	C_{dd}
$iiii$	$(aa)+(\widetilde{aa})$	$(aa)+(\widetilde{aa})$	$(aa)+(\widetilde{aa})$
$iijj$	(aa)	(aa)	(aa)
$ijji$	$(\widetilde{aa})$	$(\widetilde{aa})$	$(\widetilde{aa})$
$33ii$	$(aa)+(ba)y_t^2$	$(aa)+(ba)y_t^2$	(aa)
$3ii3$	$(\widetilde{aa})+(\widetilde{ba})y_t^2$	$(\widetilde{aa})+(\widetilde{ba})y_t^2$	$(\widetilde{aa})$
3333	$(aa)+(\widetilde{aa})+2((ba)+(\widetilde{ba}))y_t^2+\mathcal{O}(y_t^4)$	$(aa)+(\widetilde{aa})+2((ba)+(\widetilde{ba}))y_t^2+\mathcal{O}(y_t^4)$	$(aa)+(\widetilde{aa})$
$iikl$	$(ac)y_b^2 V_{kb}V_{lb}^*$	0	0
$ilki$	$(\widetilde{ac})y_b^2 V_{kb}V_{lb}^*$	0	0
$33kl$	$((ac)+(bc)y_t^2)y_b^2 V_{kb}V_{lb}^*$	0	0
$3lk3$	$((\widetilde{ac})+(\widetilde{bc})y_t^2)y_b^2 V_{kb}V_{lb}^*$	0	0
$\#$	9	5	2

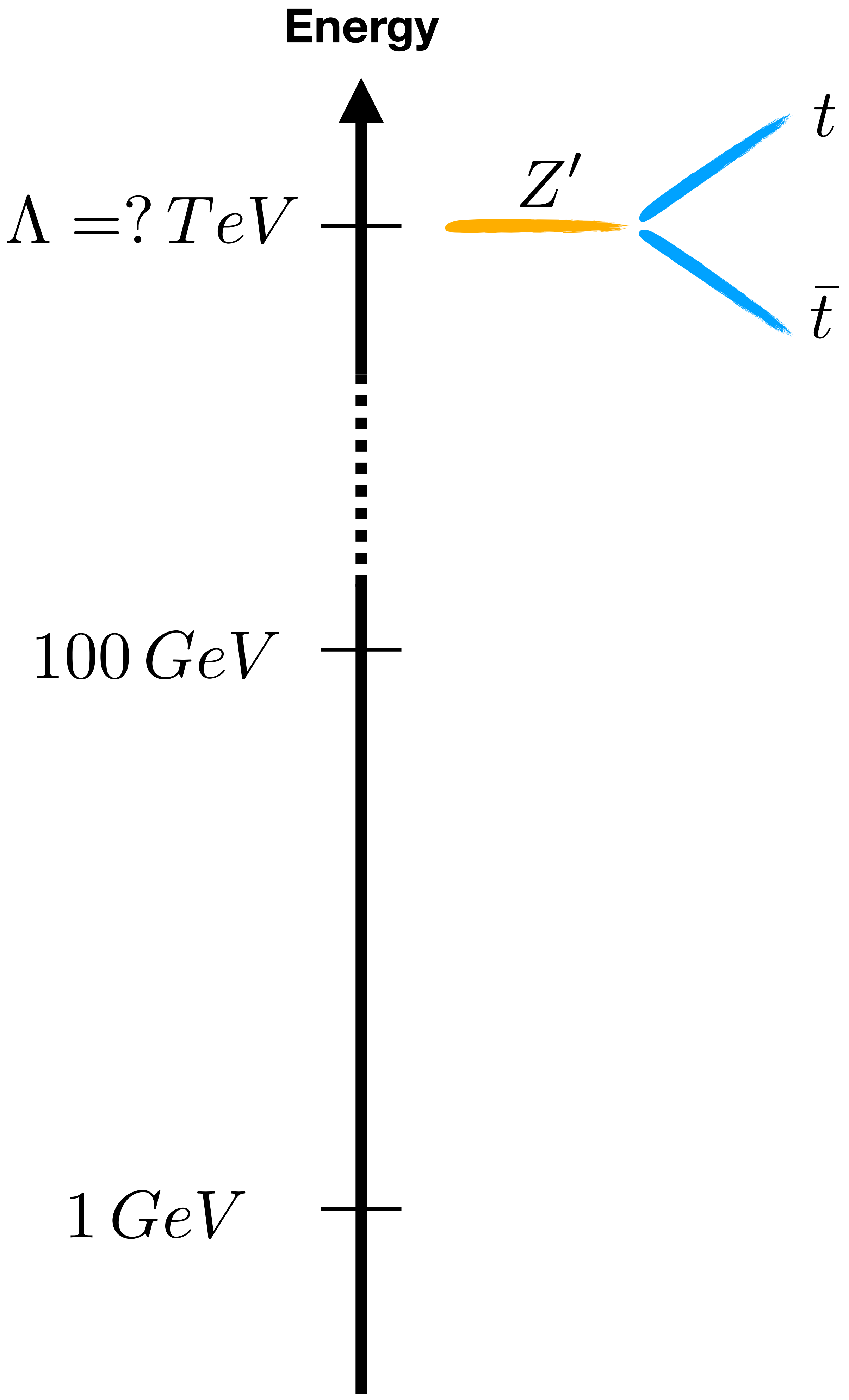
Top-Down

Aebischer, Crivelin, Fael, Greub 1512.02830 & 1606.02588

Dekens, Stoffer 1908.05295

Jenkins, Manohar, Stoffer 1709.04486

Hurth, Renner, Shepherd 1903.00500



Full model

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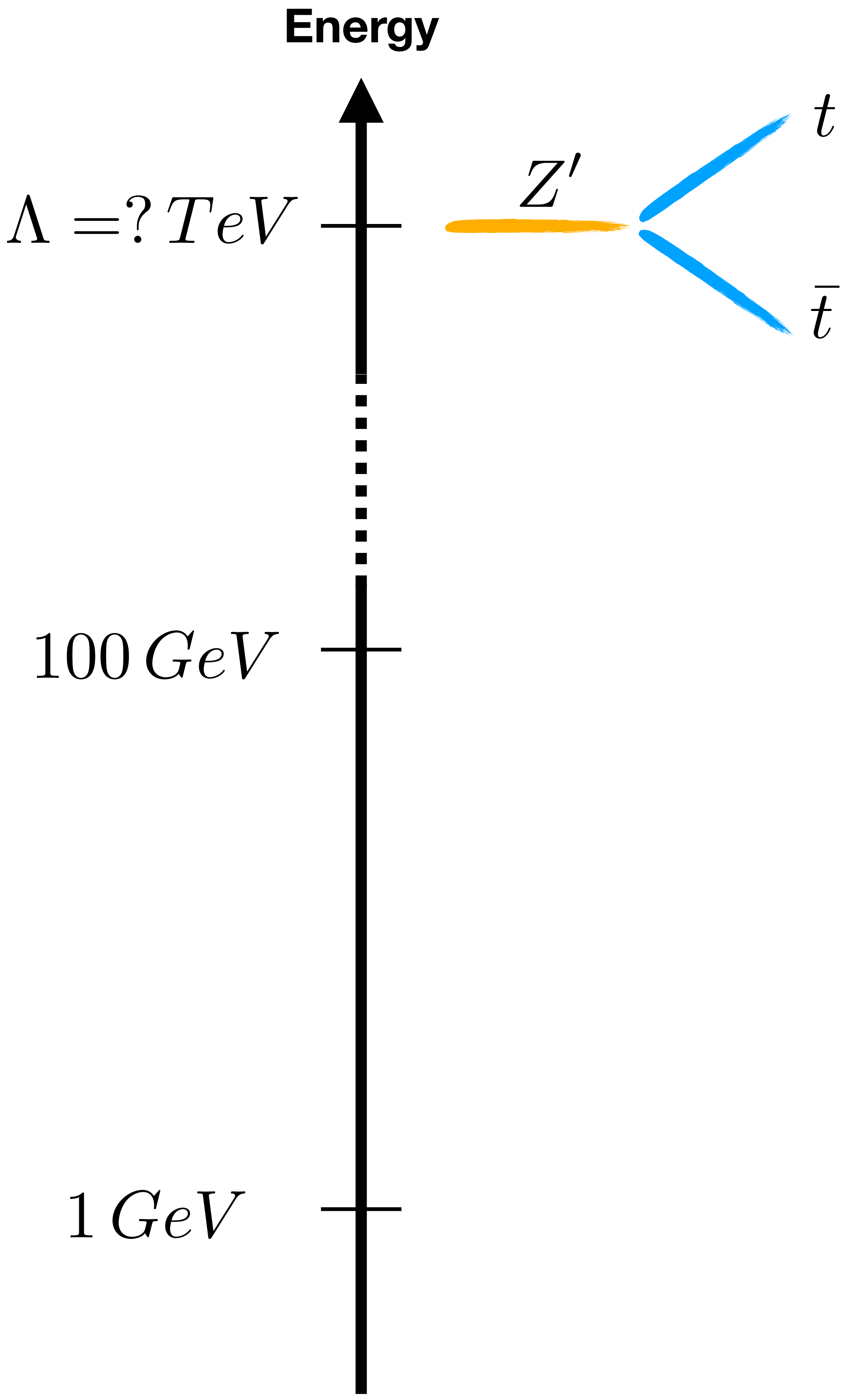

Full model

SMEFT

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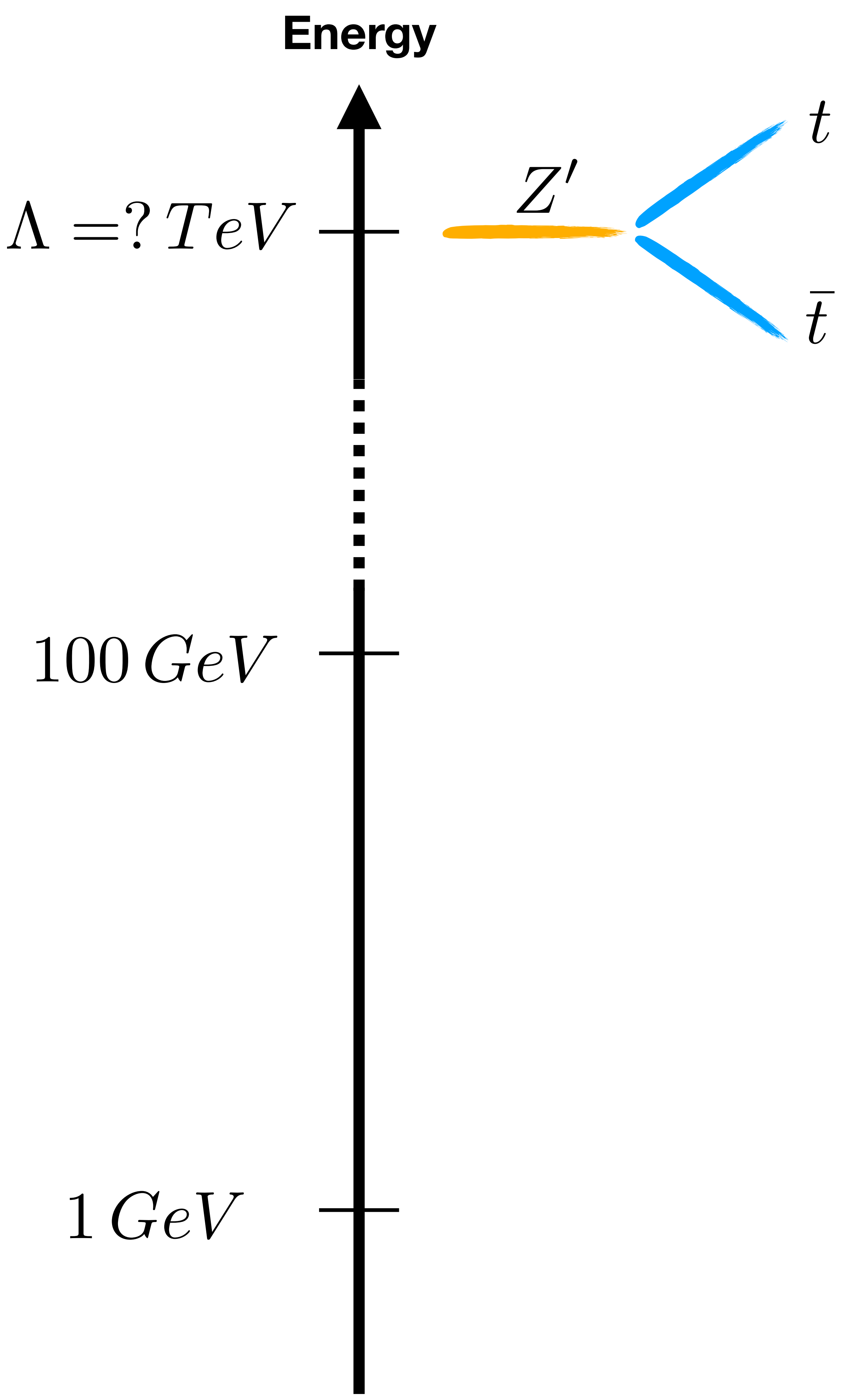

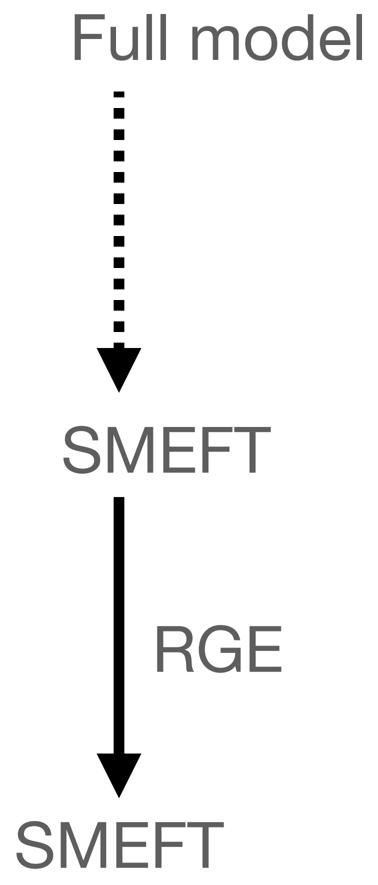

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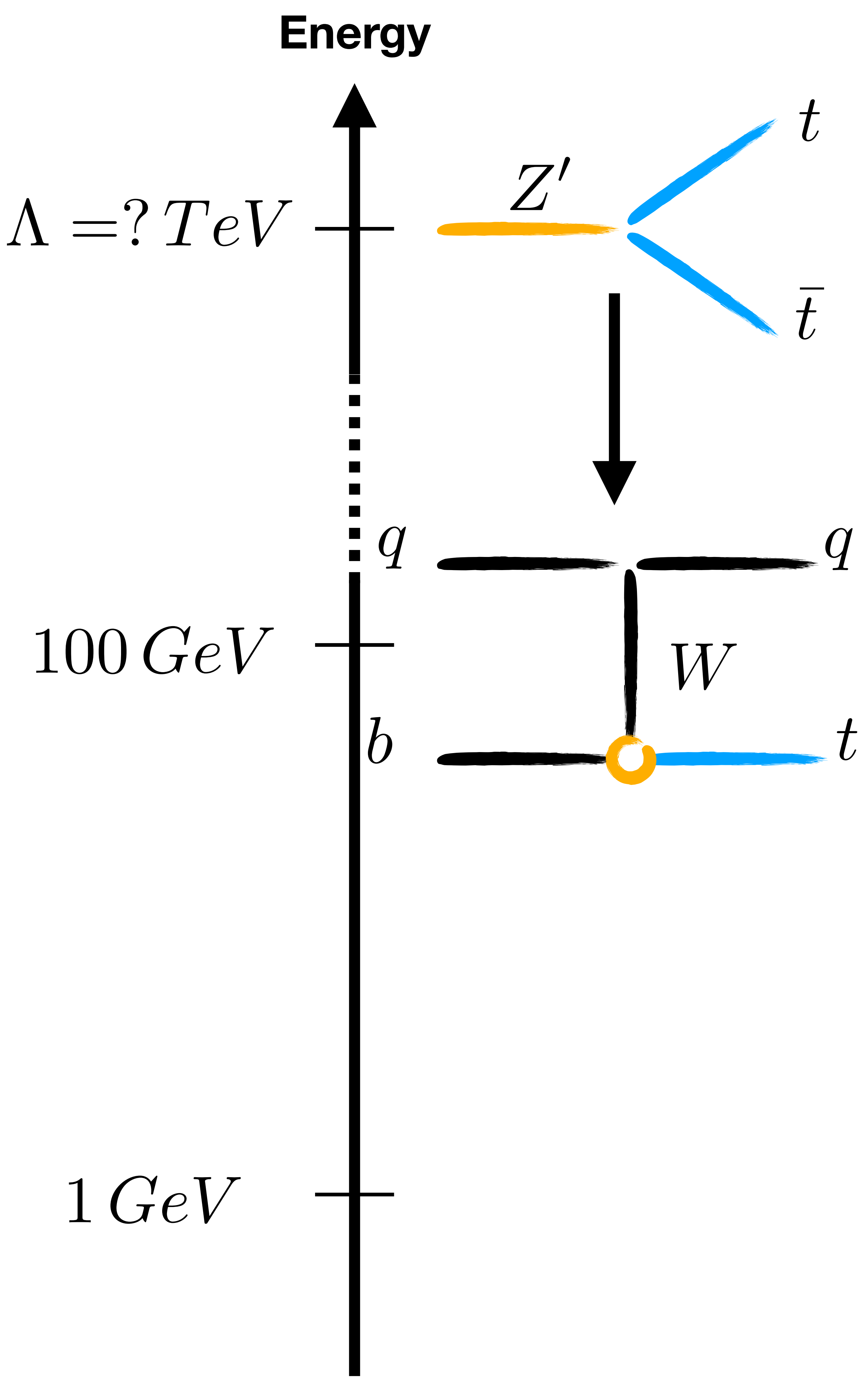

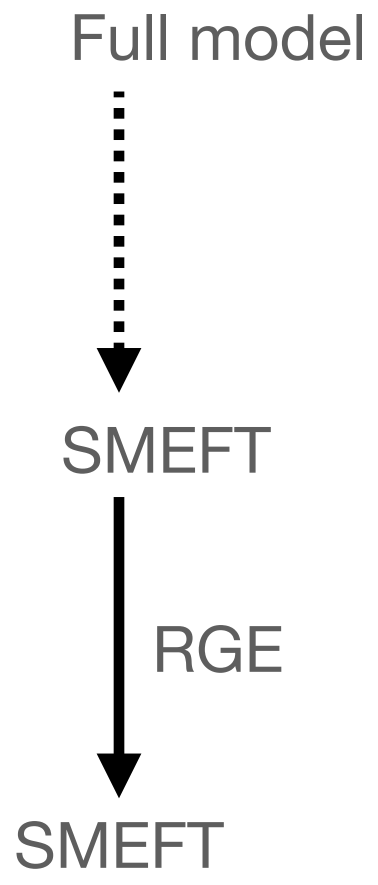

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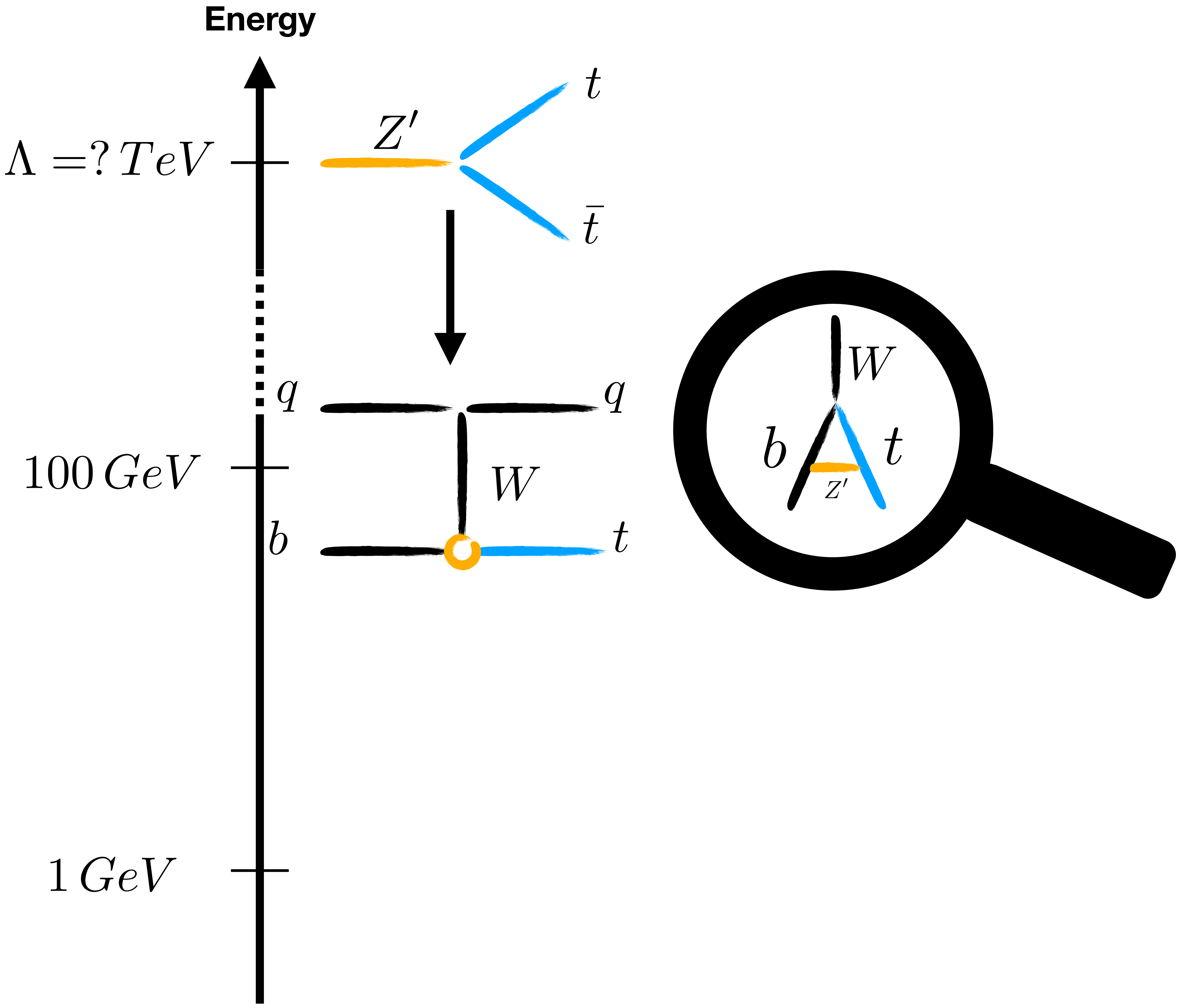

Full model

$\downarrow$

SMEFT

$\downarrow$ RGE

SMEFT

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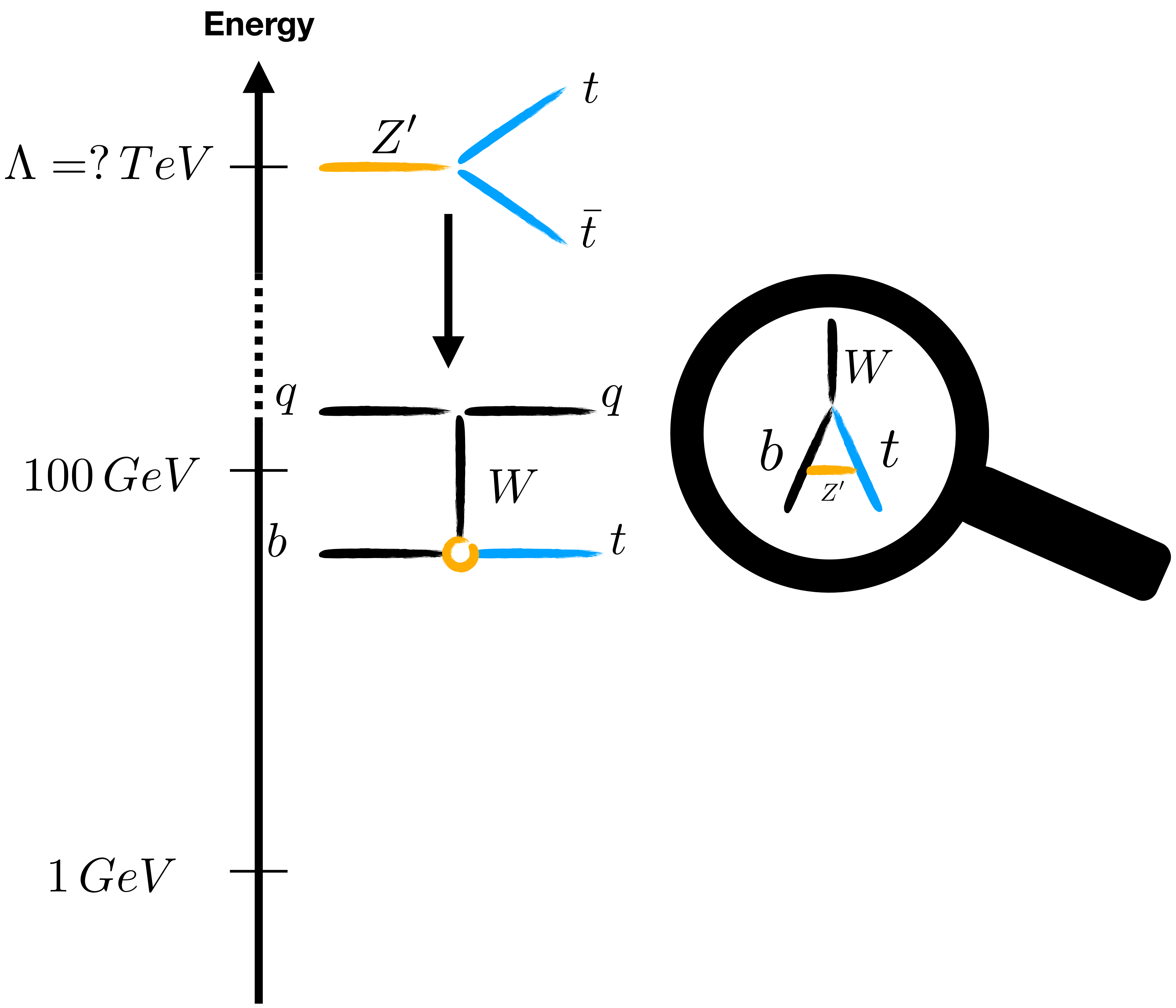

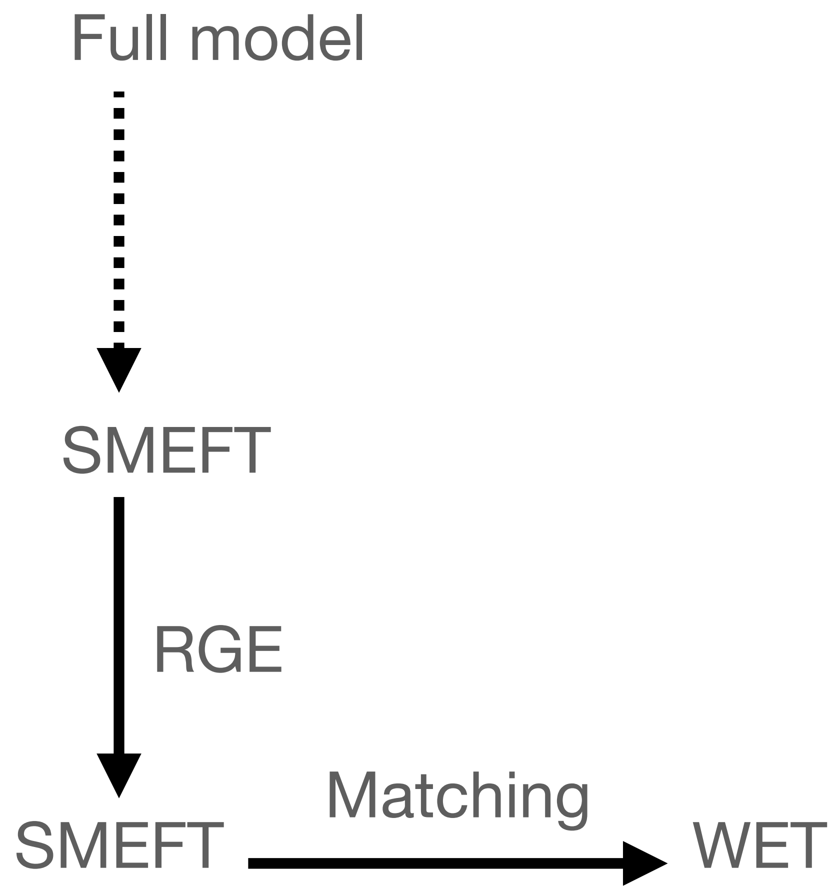

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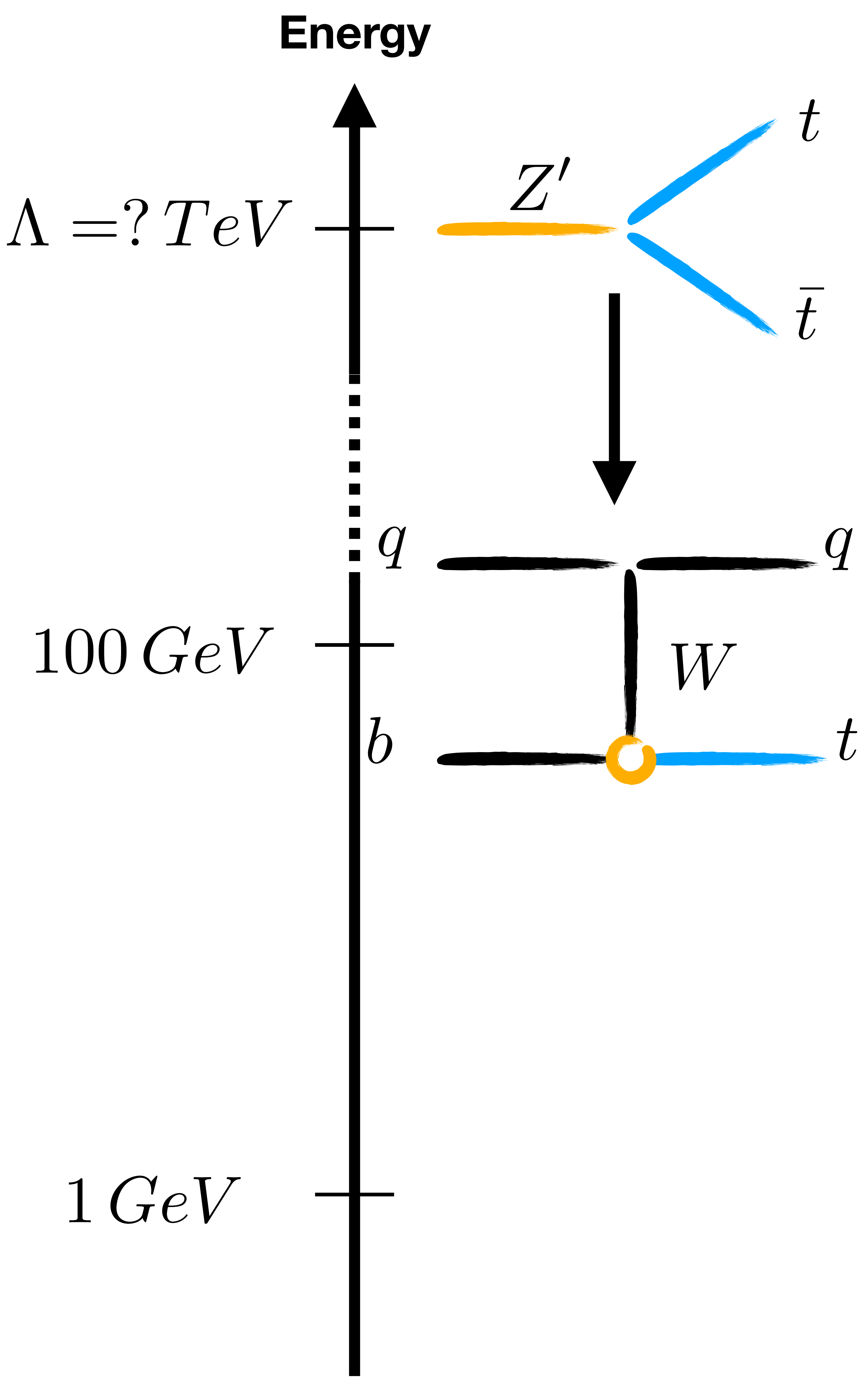
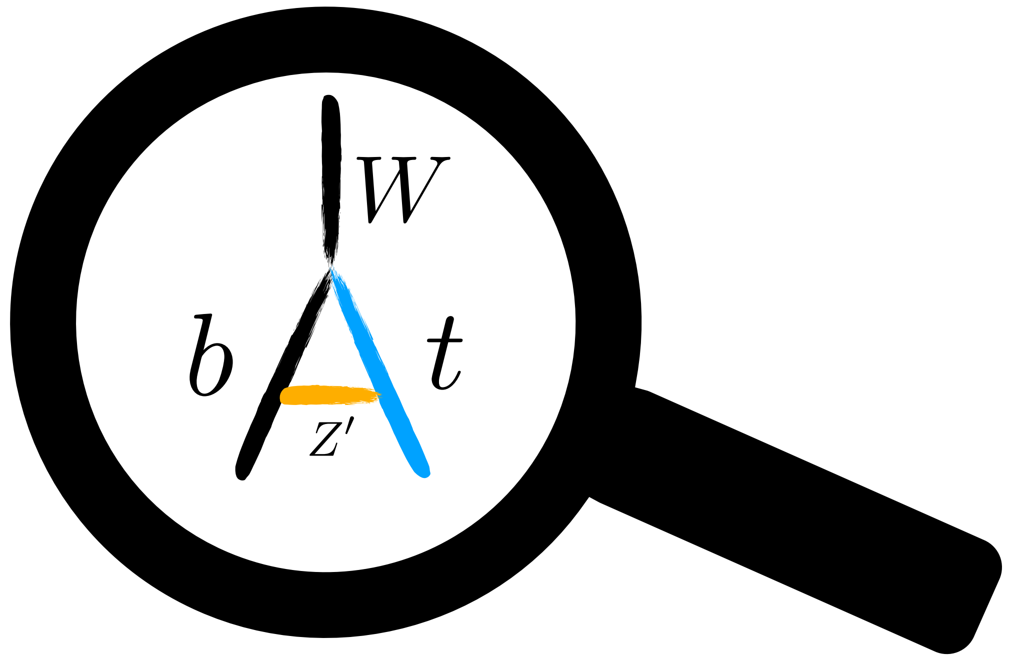
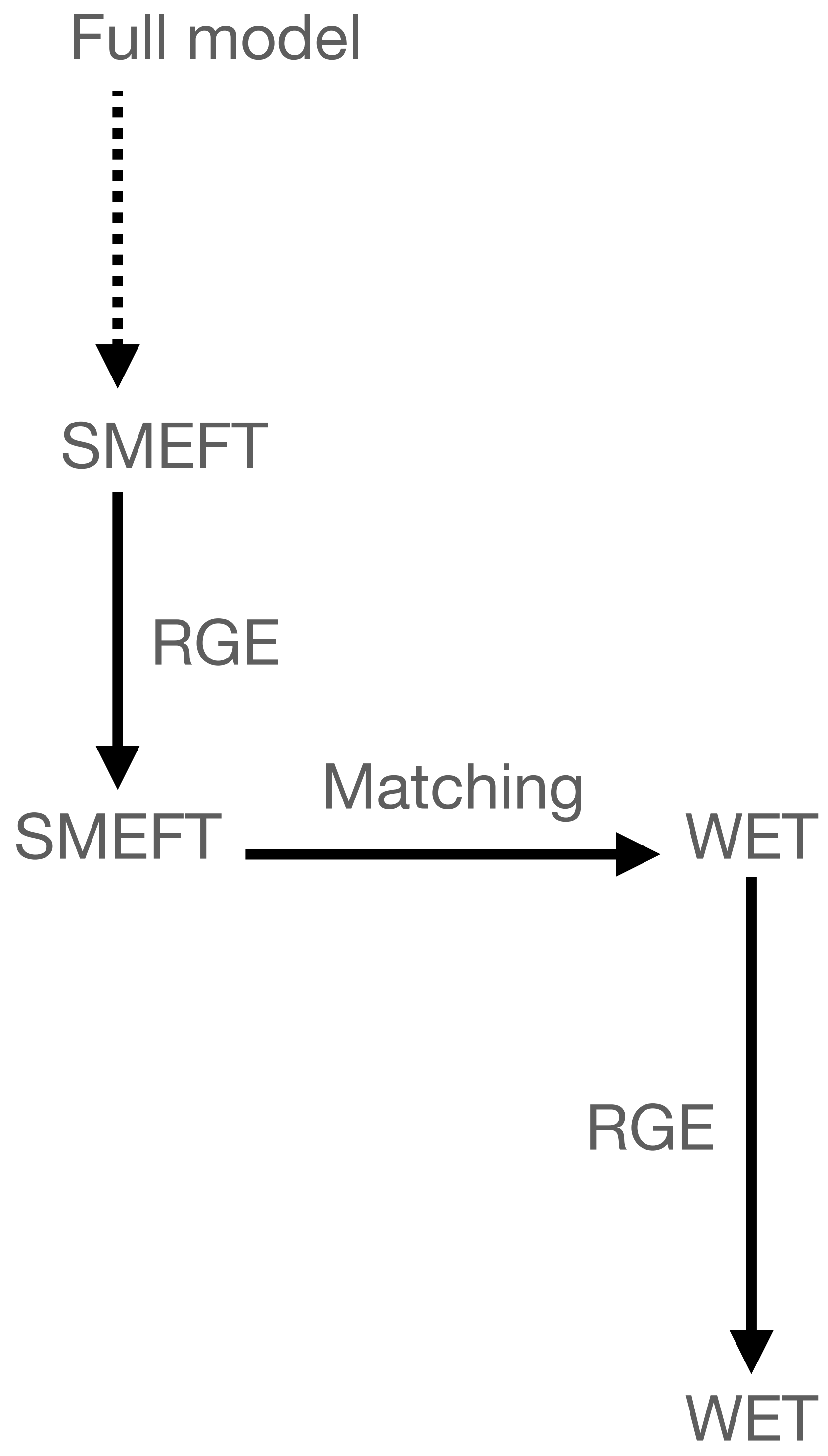






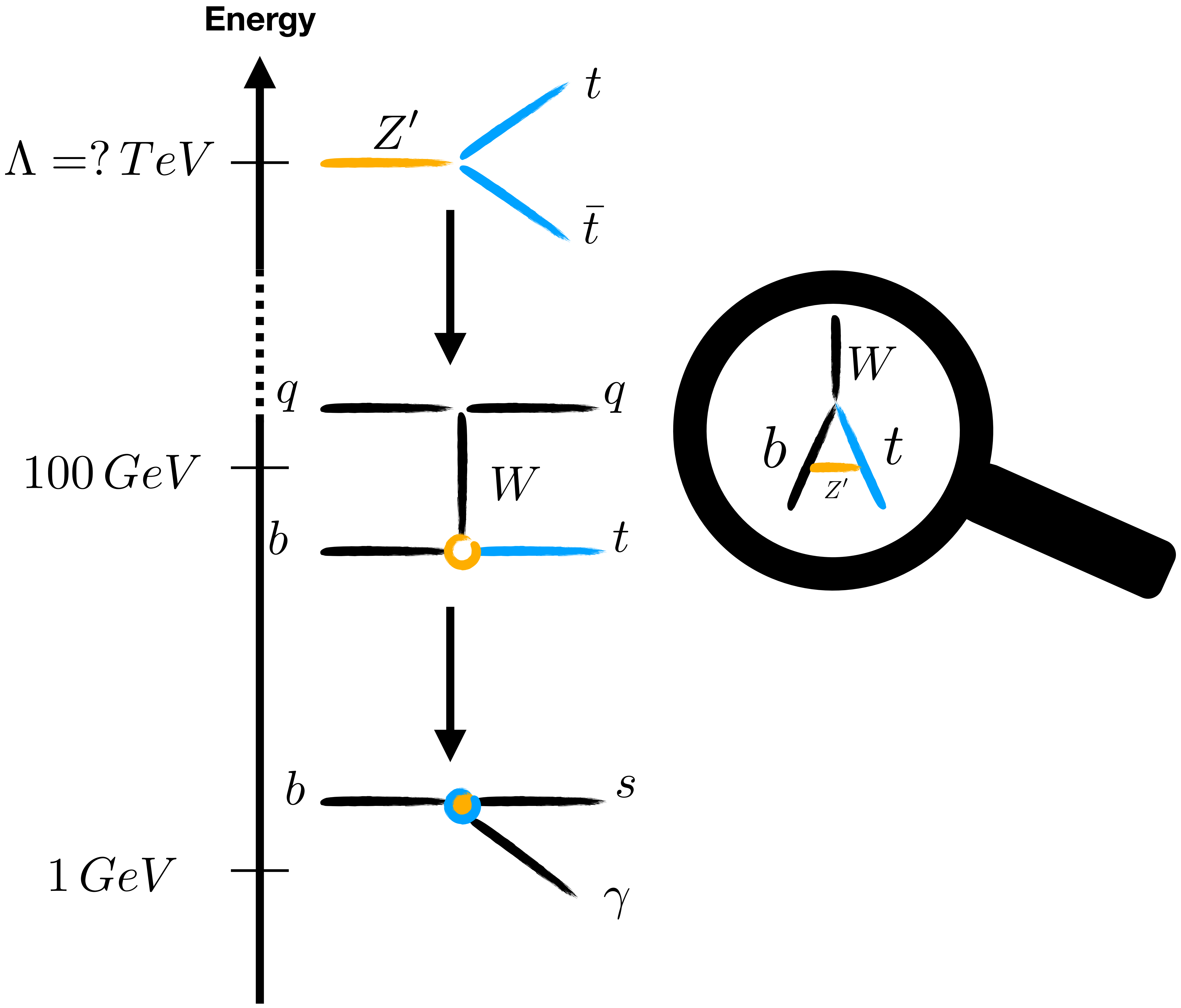
Top-Down

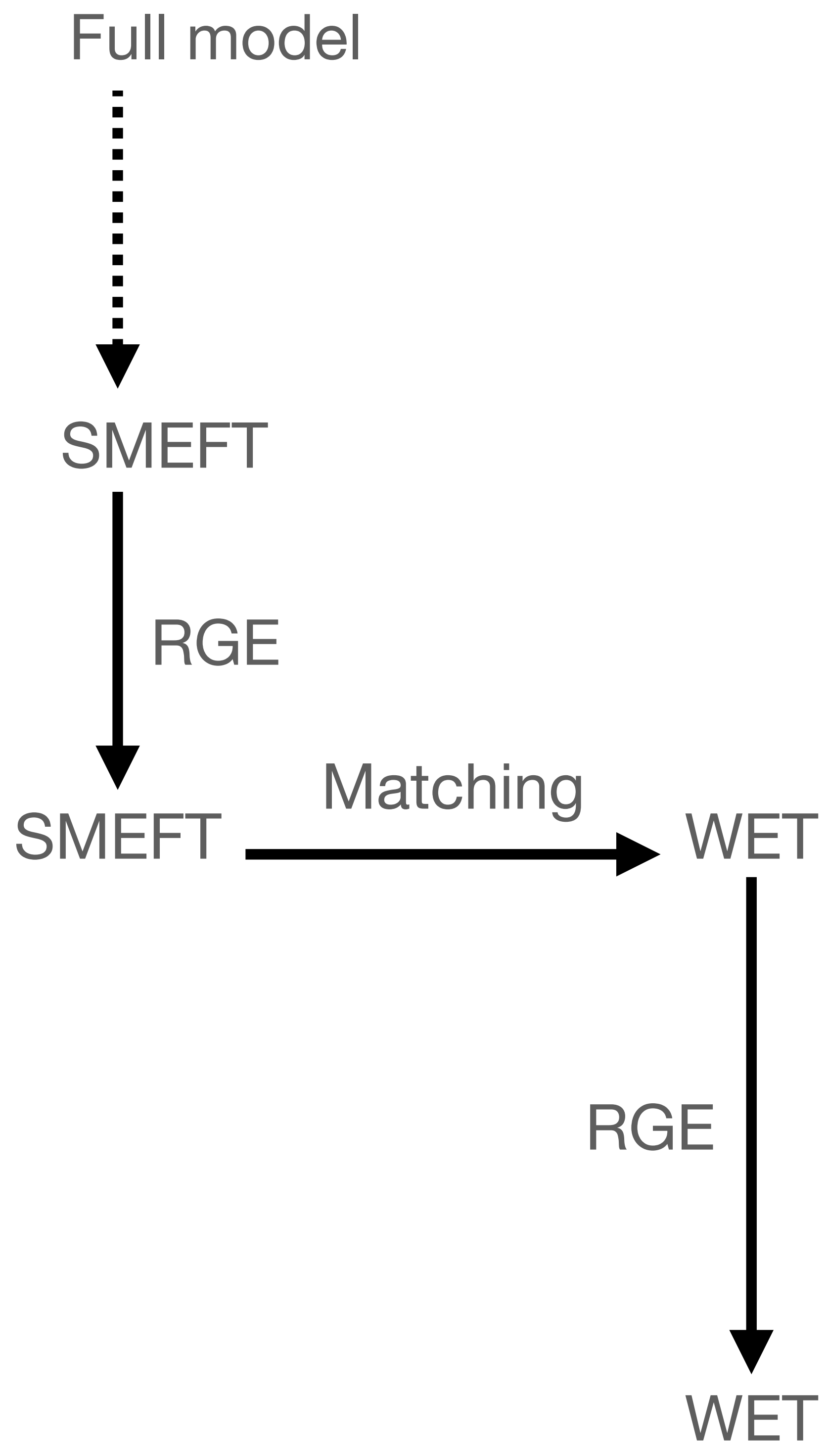
Aebischer, Crivelin, Fael, Greub 1512.02830 & 1606.02588

Dekens, Stoffer 1908.05295

Jenkins, Manohar, Stoffer 1709.04486

Hurth, Renner, Shepherd 1903.00500





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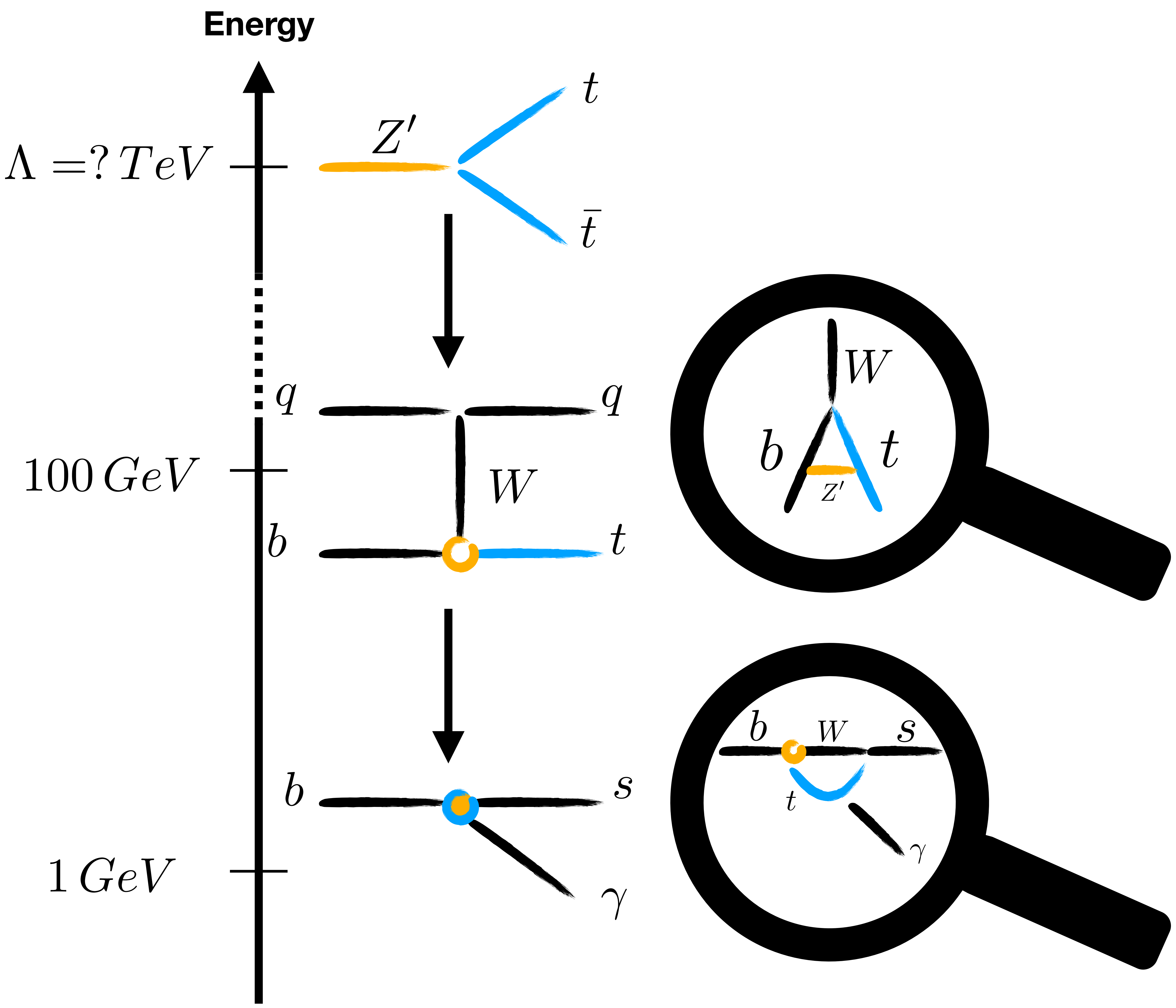

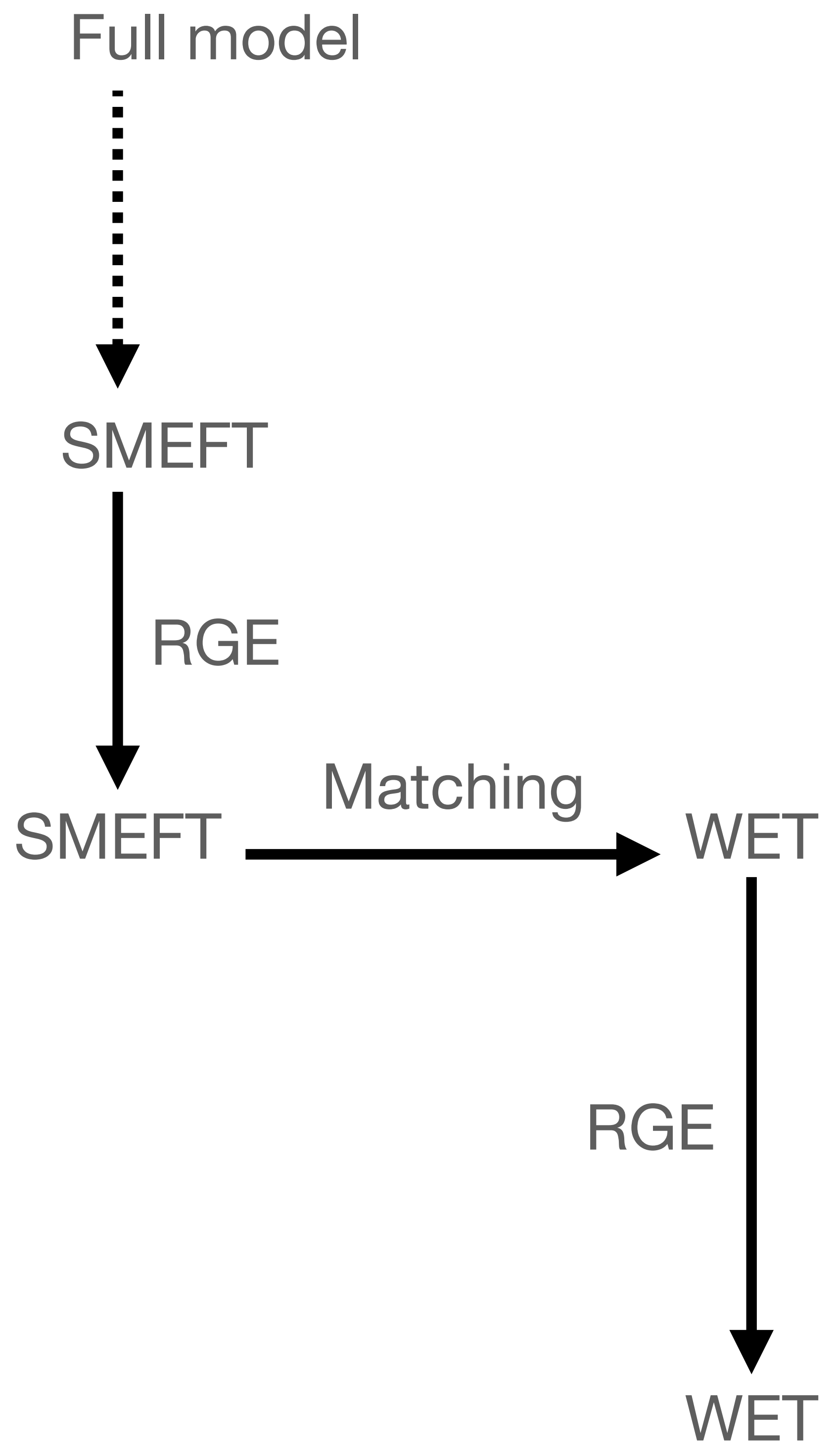

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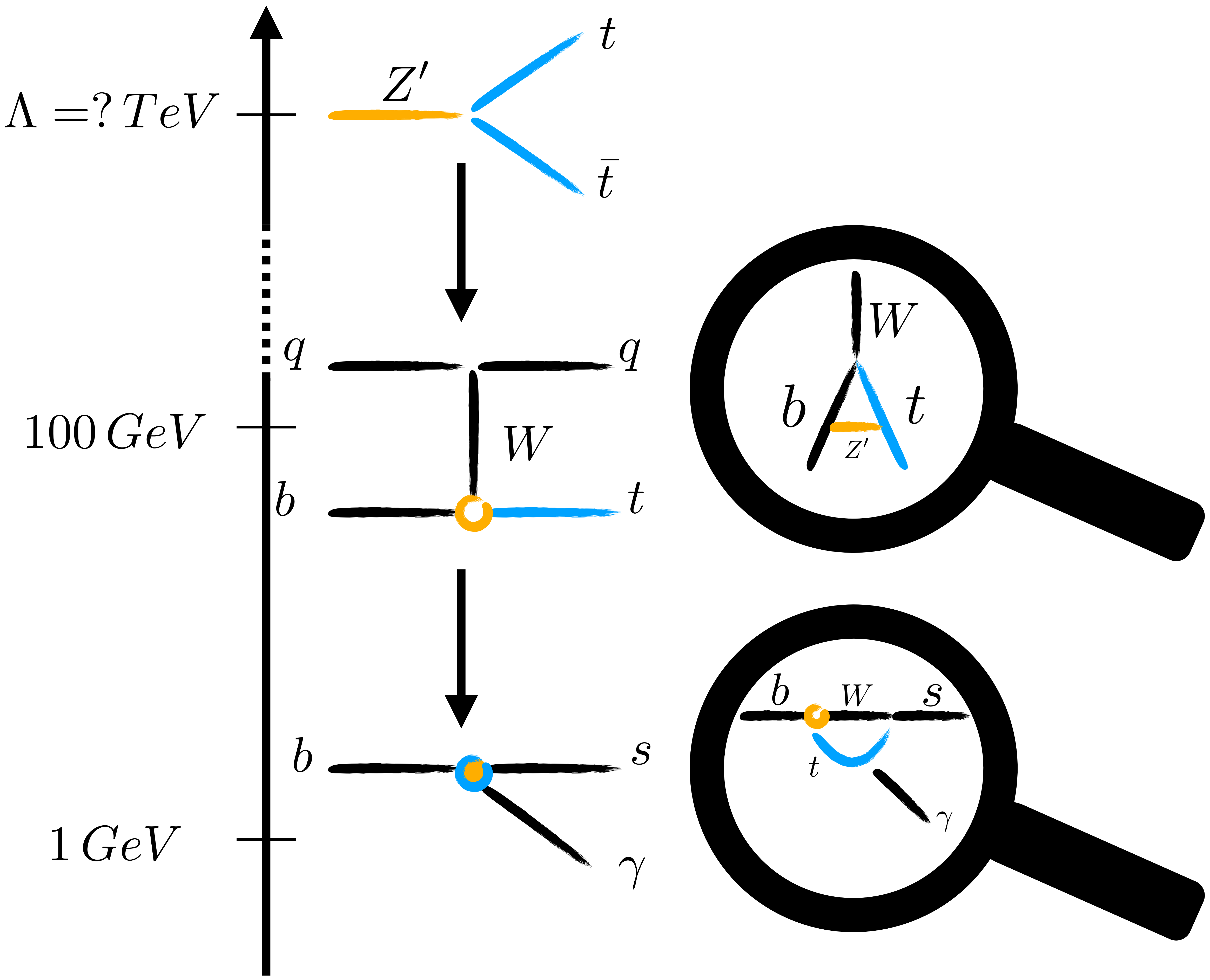

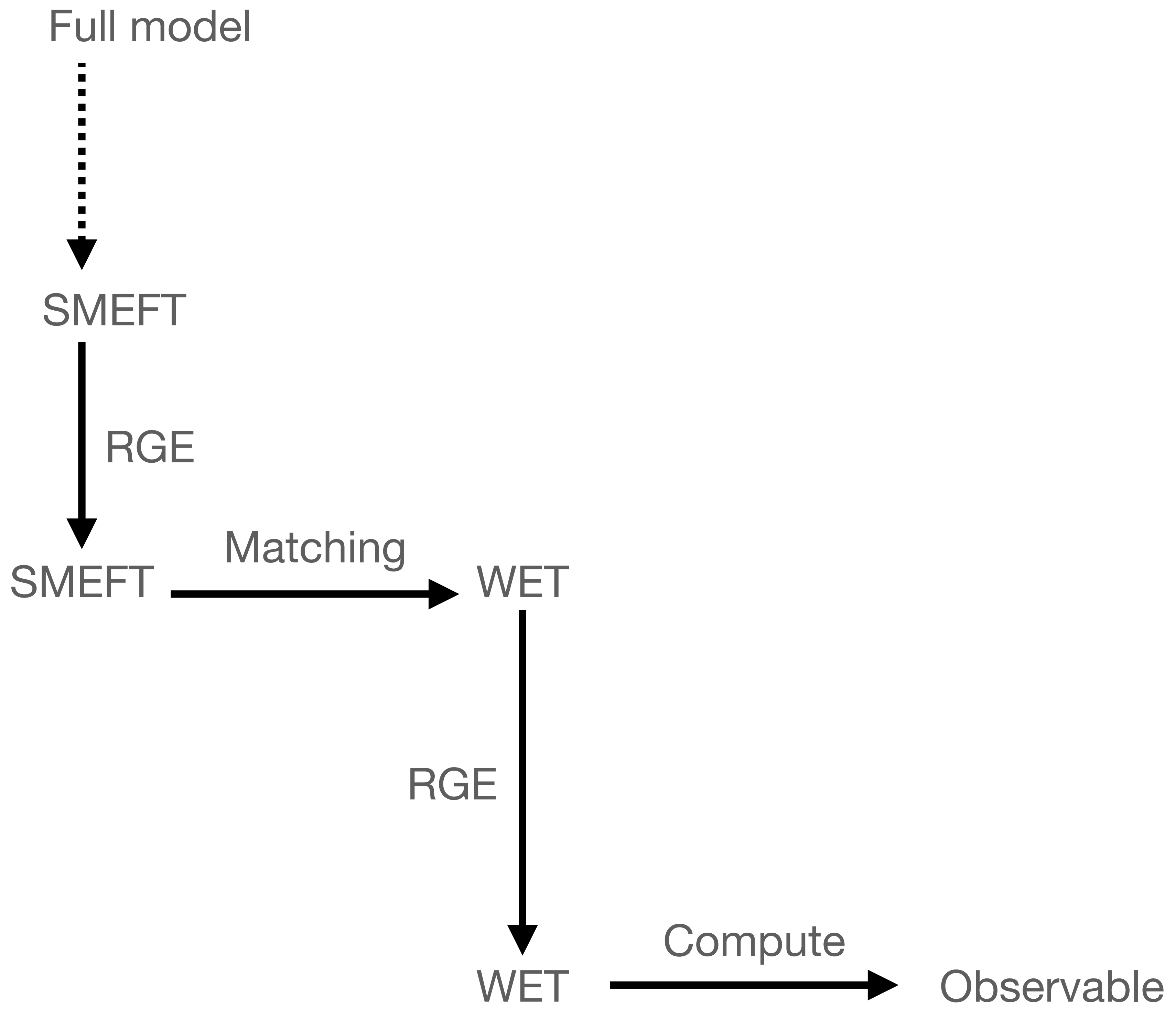

Top-Down

Aebischer, Crivelin, Fael, Greub 1512.02830 & 1606.02588

Dekens, Stoffer 1908.05295

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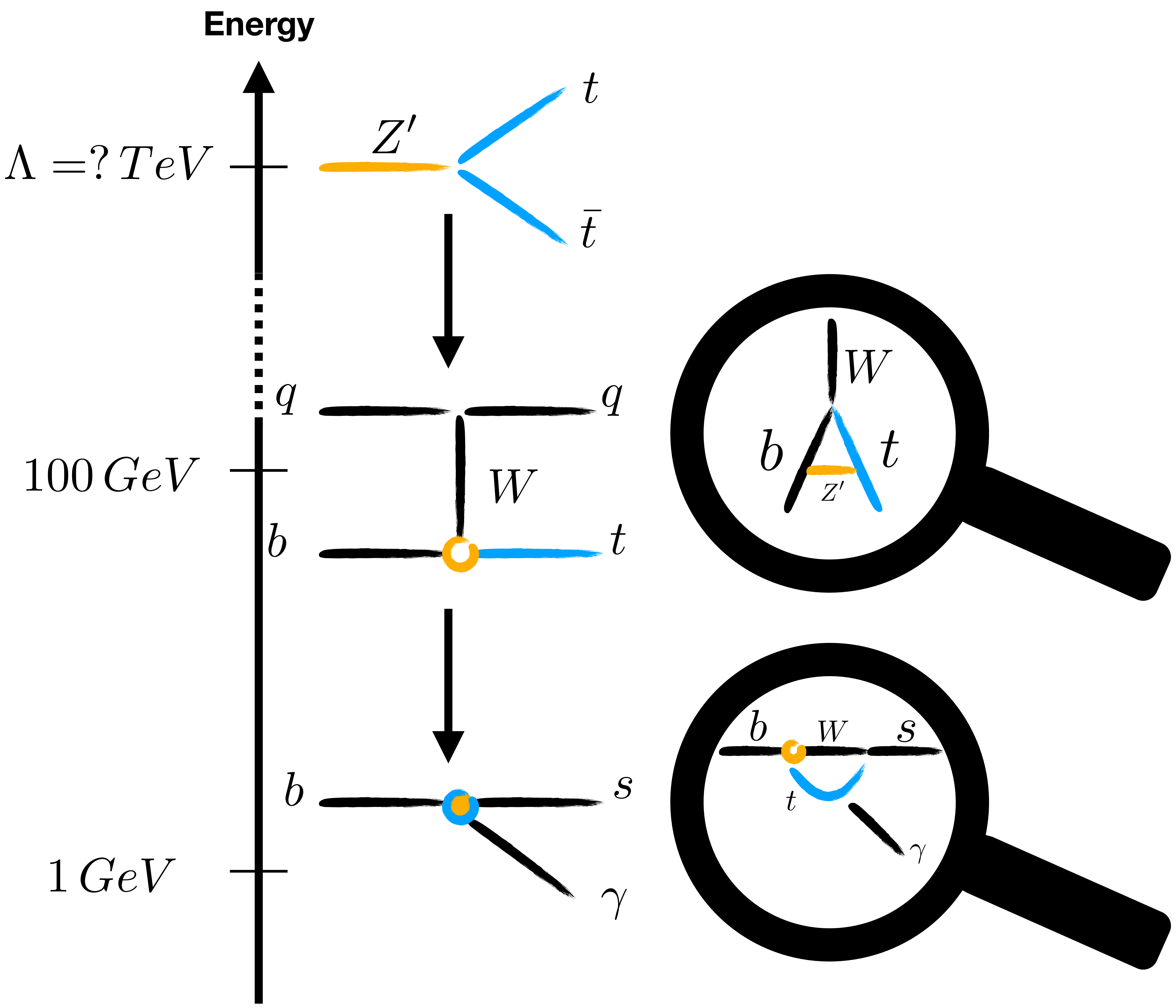
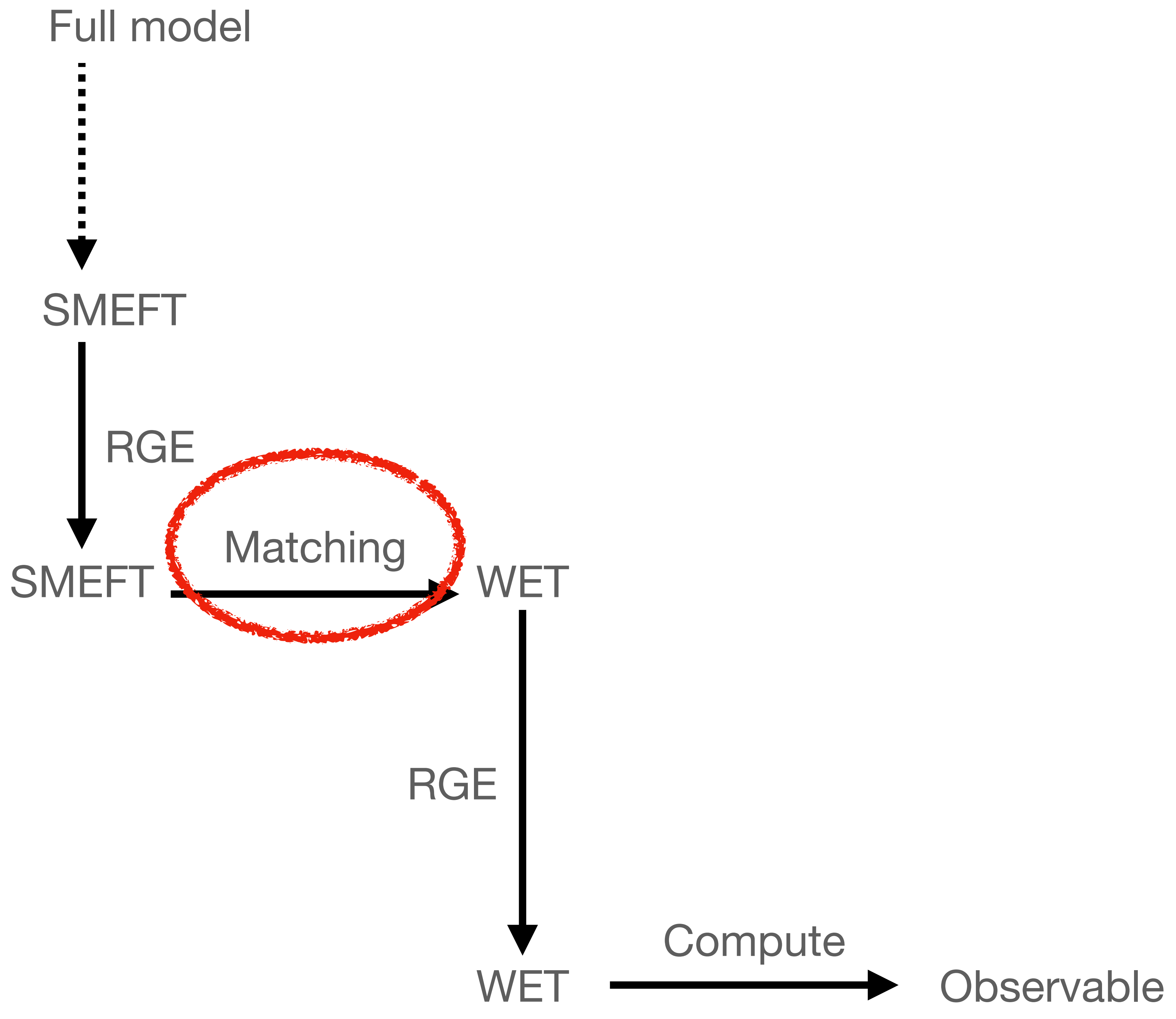
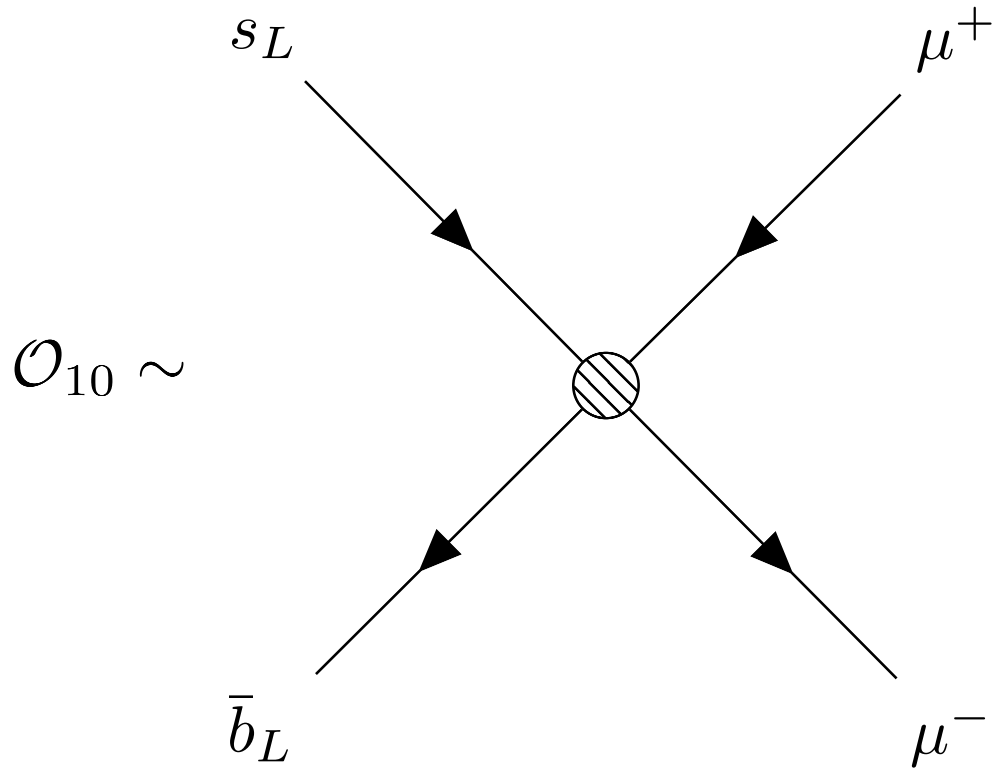


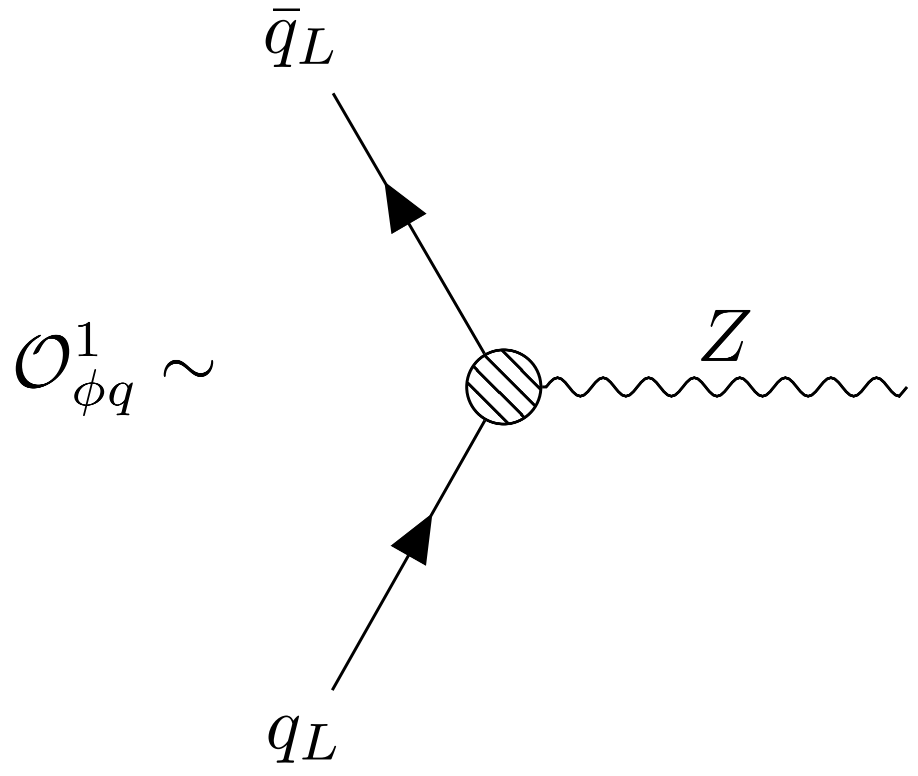


Top-Down

WET

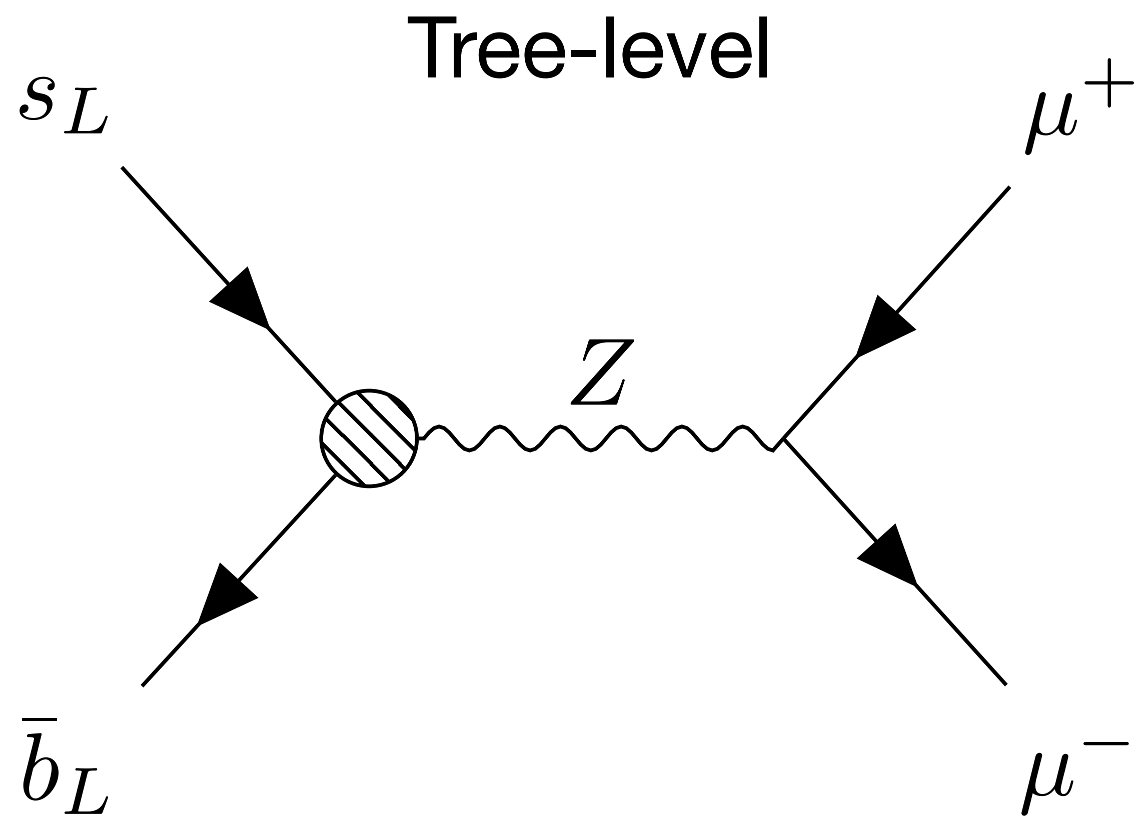


SMEFT

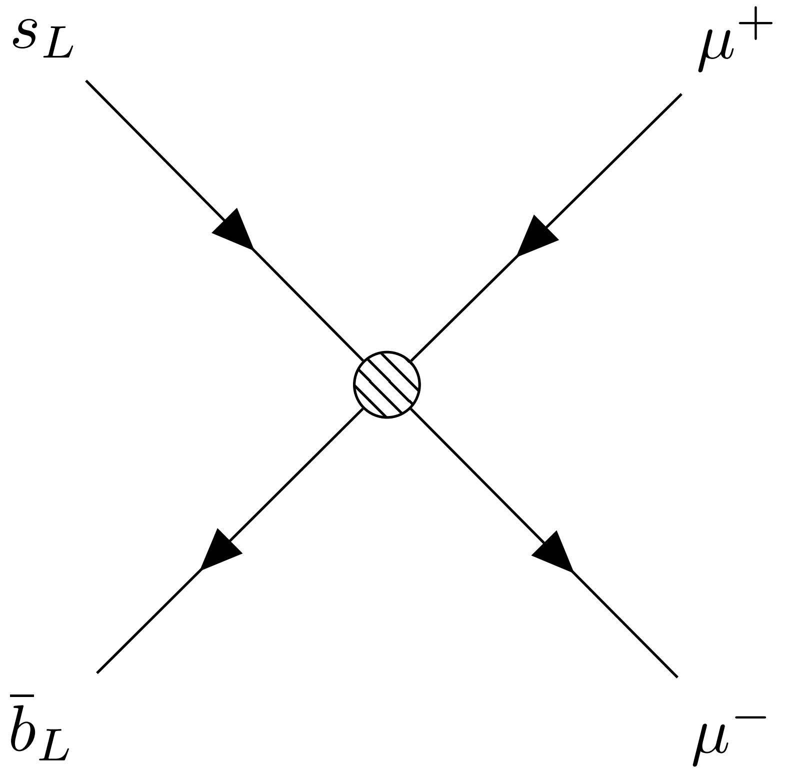


MFV	$\mathcal{C}^1_{\phi q}$
ii	a
33	$a + y_t^2 b$

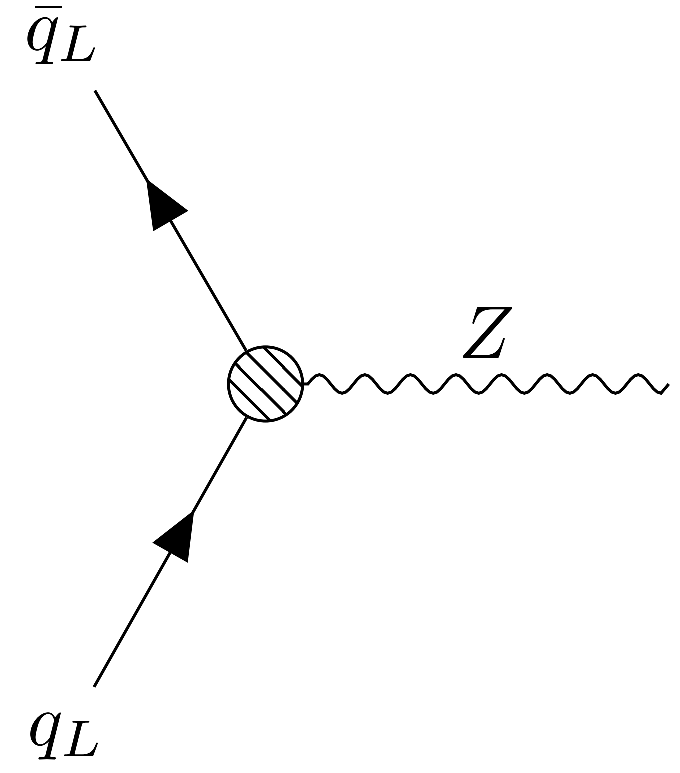
Top-Down



WET

$\mathcal{O}_{10} \sim$ 

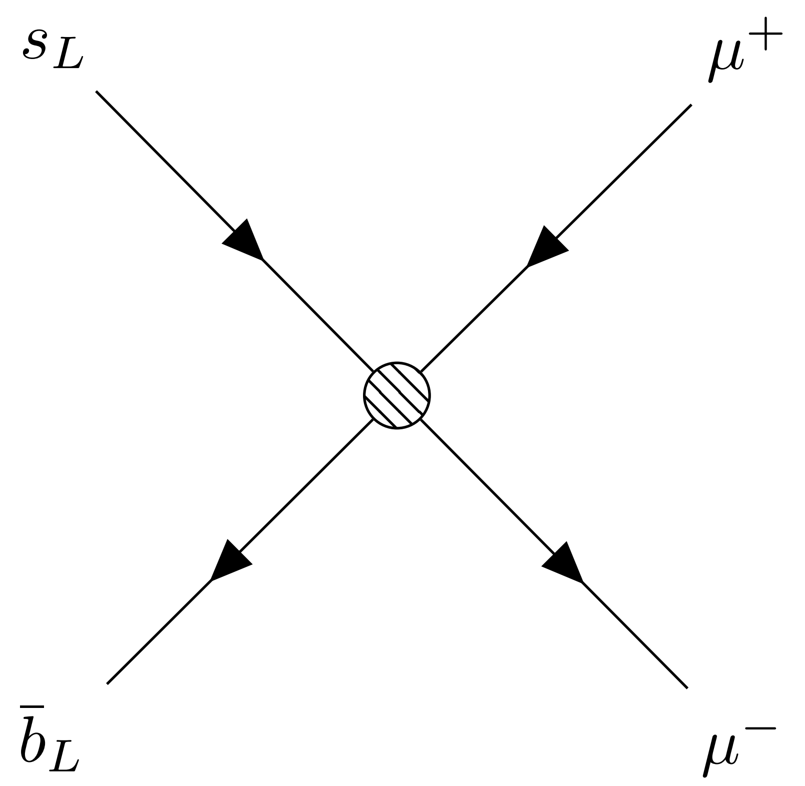
SMEFT

$\mathcal{O}^1_{\phi q} \sim$ 

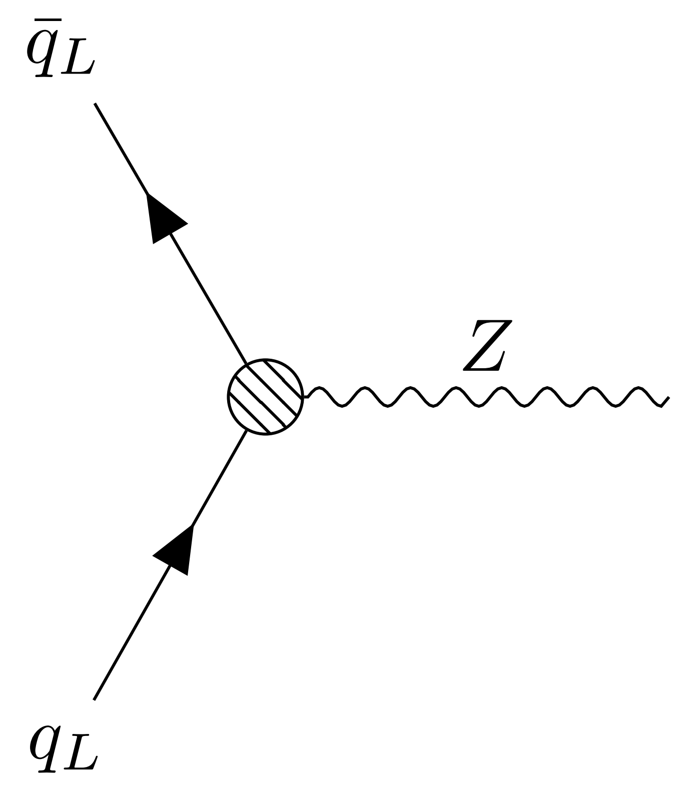
MFV	$\mathcal{C}^1_{\phi q}$
ii	a
33	$a + y_t^2 b$

Top-Down

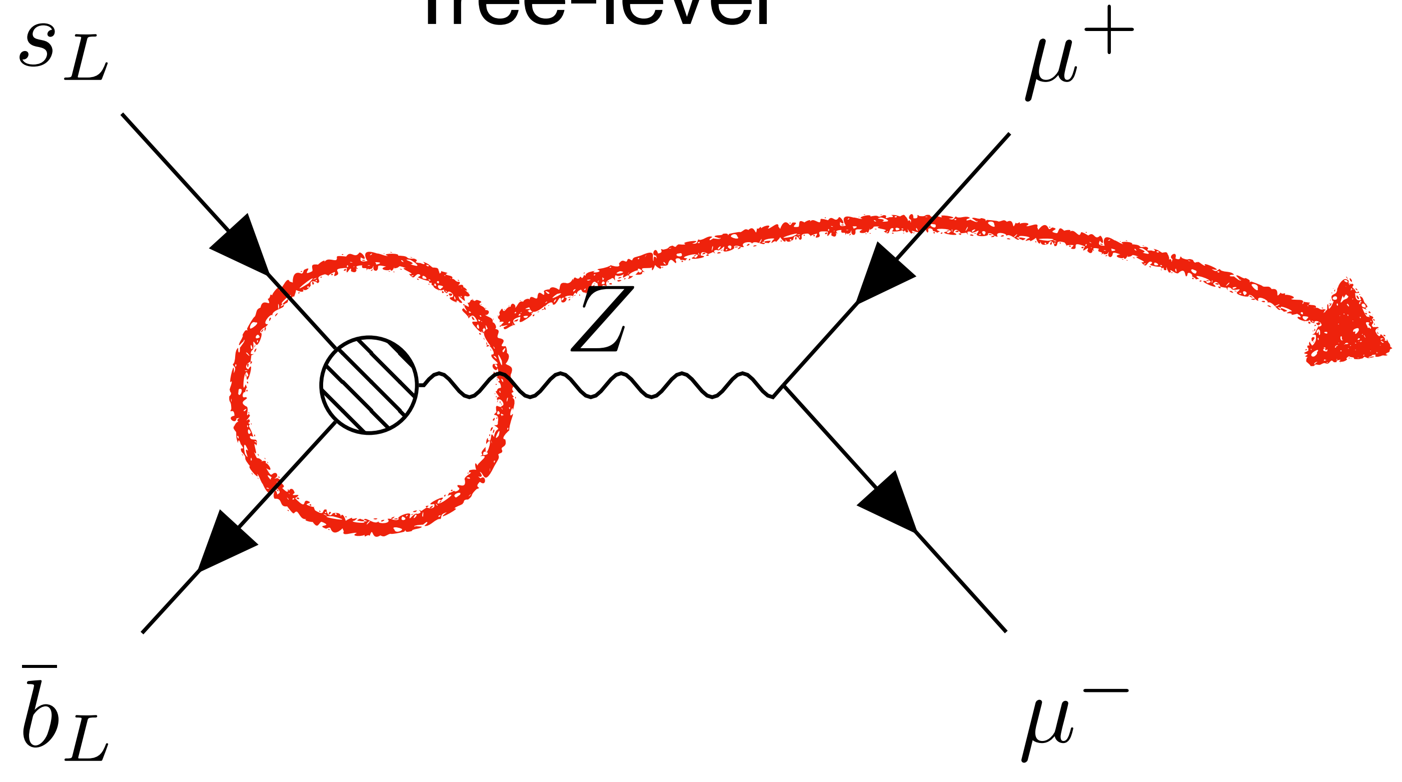
WET

$\mathcal{O}_{10} \sim$ 

SMEFT

$\mathcal{O}^1_{\phi q} \sim$ 

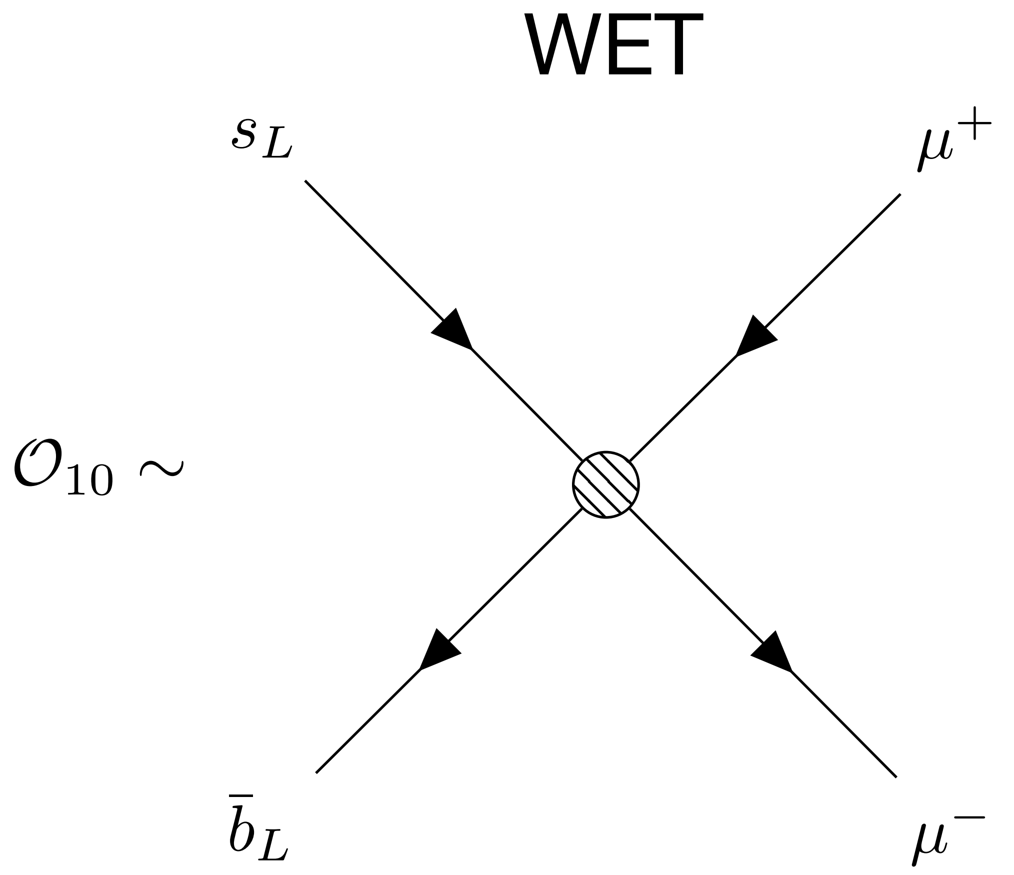
Tree-level

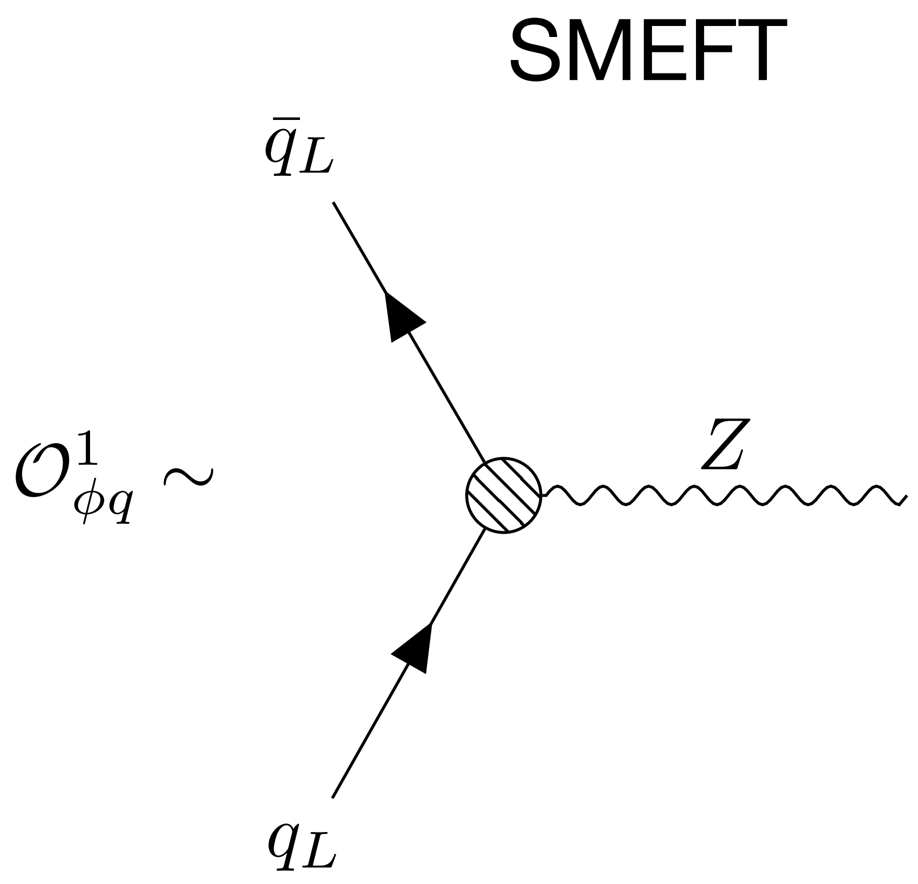


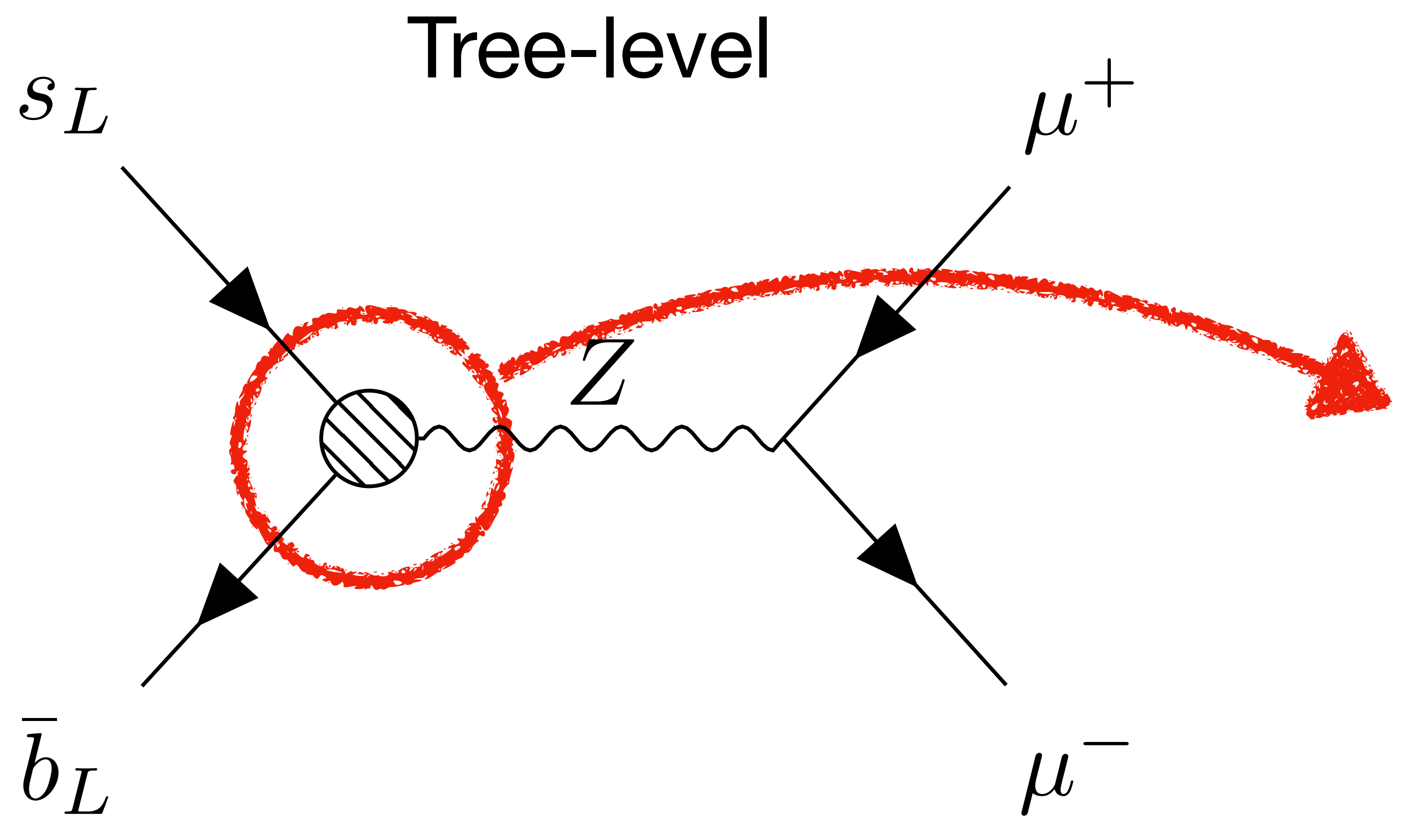
$$\sim \left[\mathcal{C}^1_{\phi q}\right]_{ij} V^*_{is} V_{jb} \left(\bar{s}_L \gamma_\mu b_L\right) Z^\mu$$

MFV	$\mathcal{C}^1_{\phi q}$
ii	a
33	$a + y_t^2 b$

Top-Down





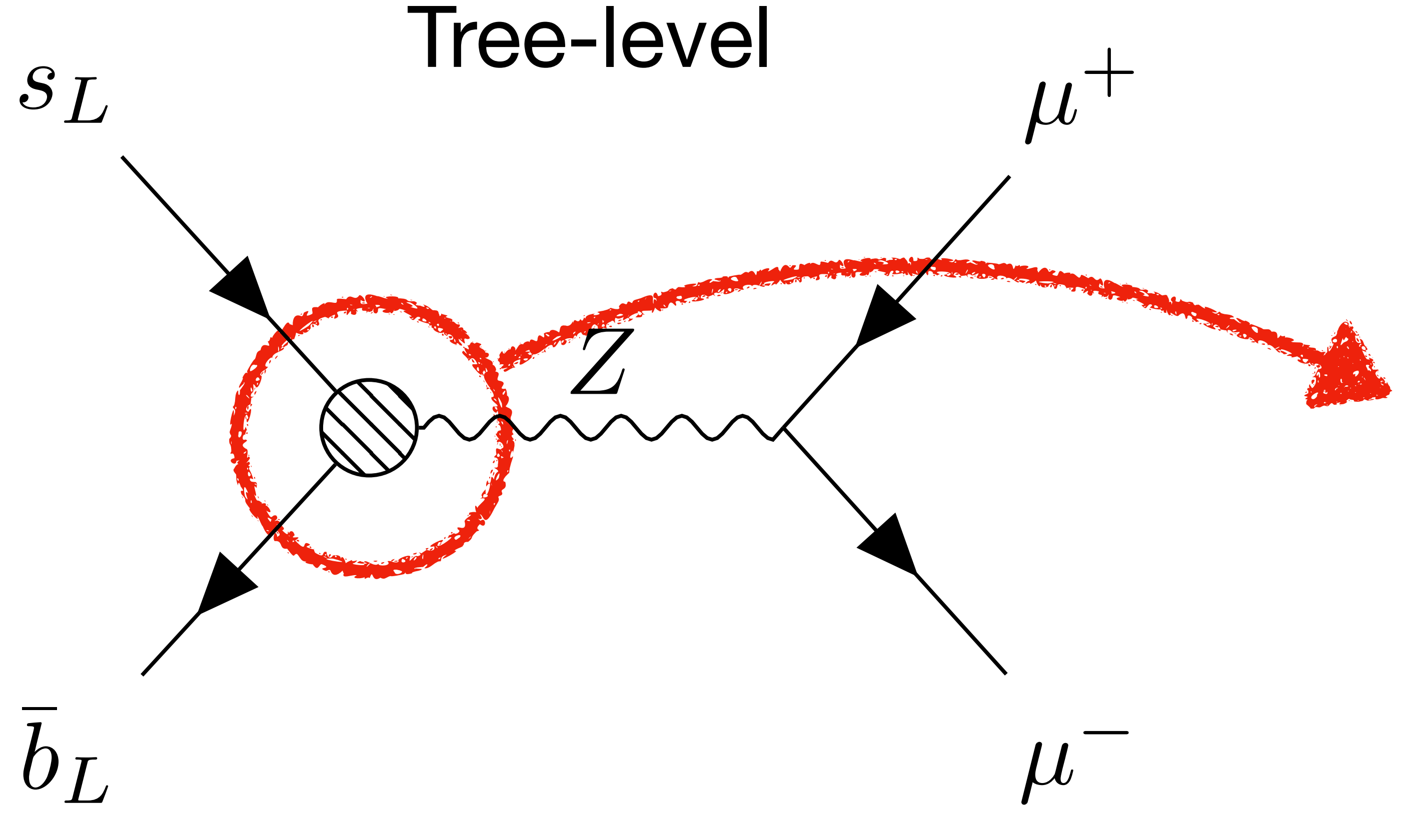


$$\sim \left[\mathcal{C}^1_{\phi q}\right]_{ij} V^*_{is} V_{jb} \left(\bar{s}_L \gamma_\mu b_L\right) Z^\mu$$

MFV	$\mathcal{C}^1_{\phi q}$
ii	a
33	$a + y_t^2 b$

Top-Down

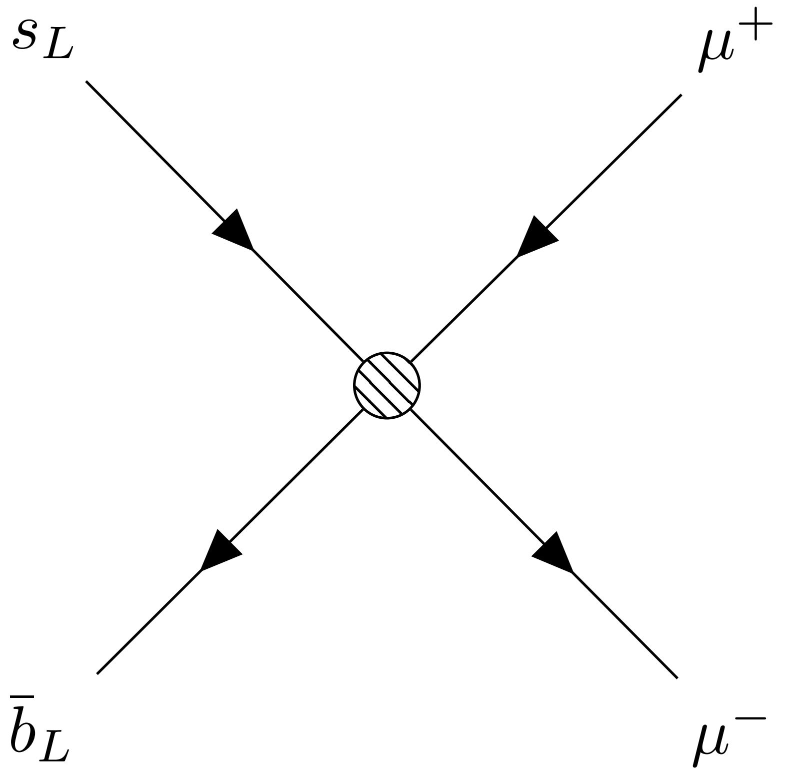
Tree-level



$$\sim \left[\mathcal{C}^1_{\phi q}\right]_{ij} V^*_{is} V_{jb} \left(\bar{s}_L \gamma_\mu b_L\right) Z^\mu$$

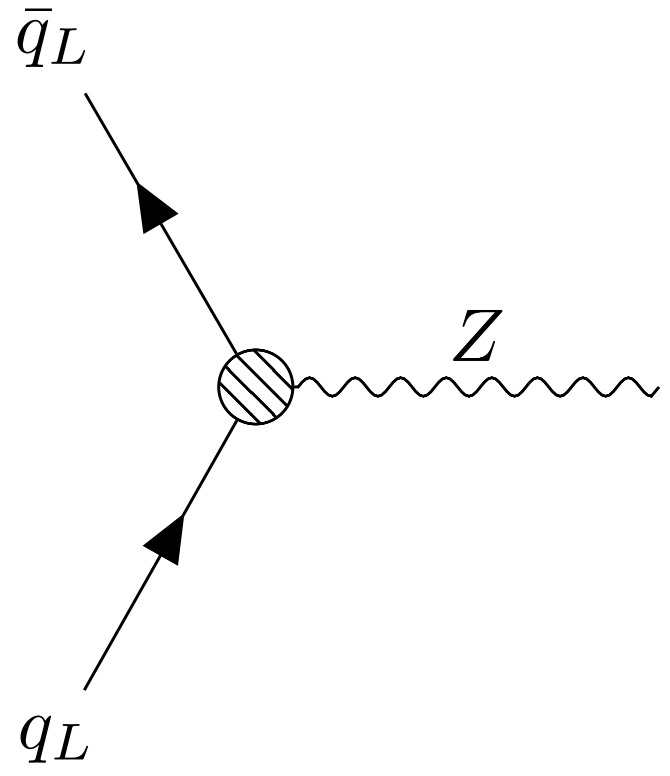
WET

$\mathcal{O}_{10} \sim$



SMEFT

$\mathcal{O}^1_{\phi q} \sim$



$$\mathcal{C}_{10}$$

$$\mathcal{C}^1_{\phi q} \begin{cases} \text{Tree-level} \\ \text{Loop-level} \end{cases}$$

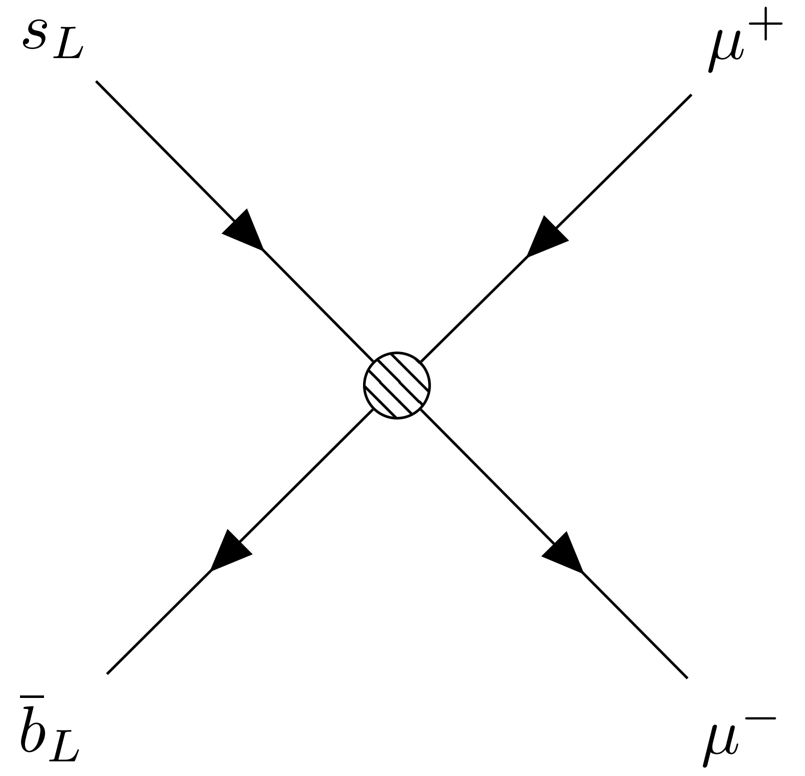
$$b$$

MFV	$\mathcal{C}^1_{\phi q}$
ii	a
33	$a + y_t^2 b$

Top-Down

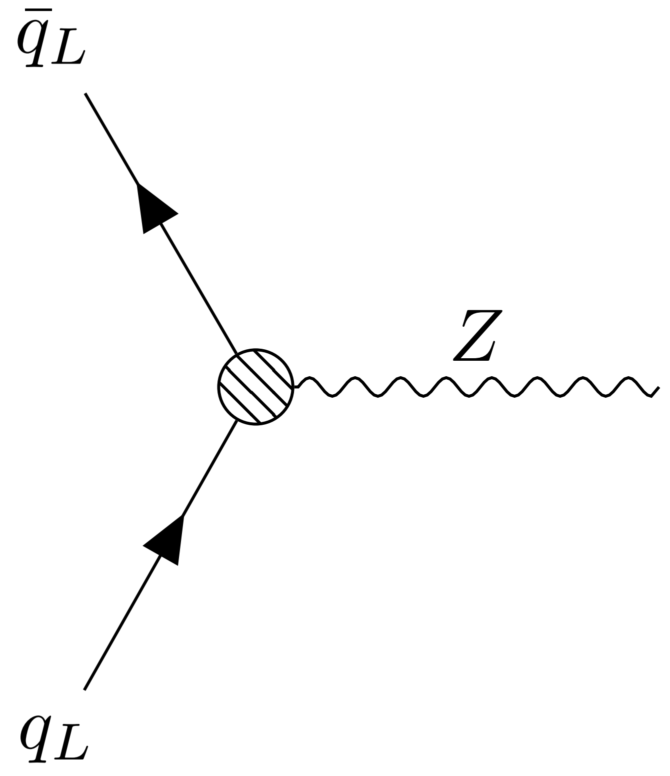
WET

$\mathcal{O}_{10} \sim$

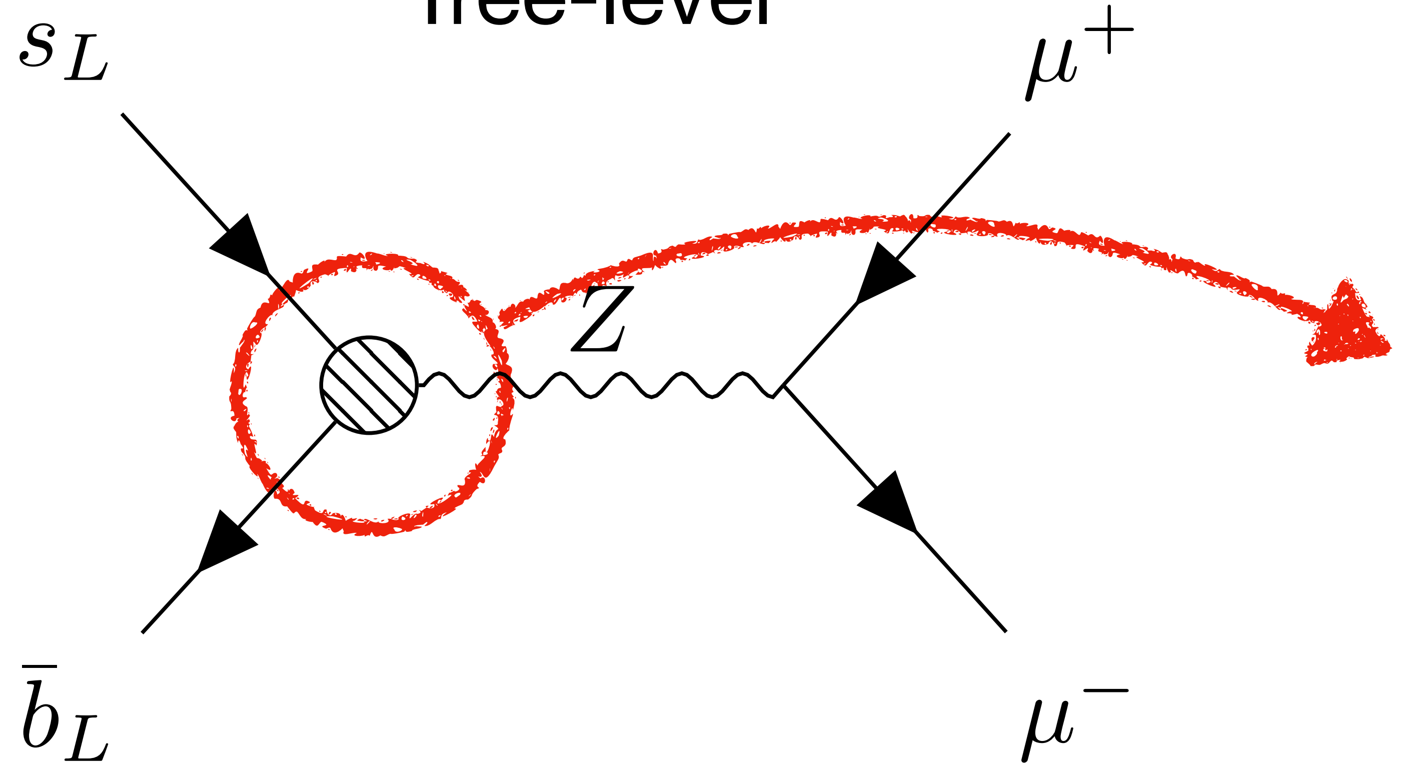


SMEFT

$\mathcal{O}^1_{\phi q} \sim$



Tree-level



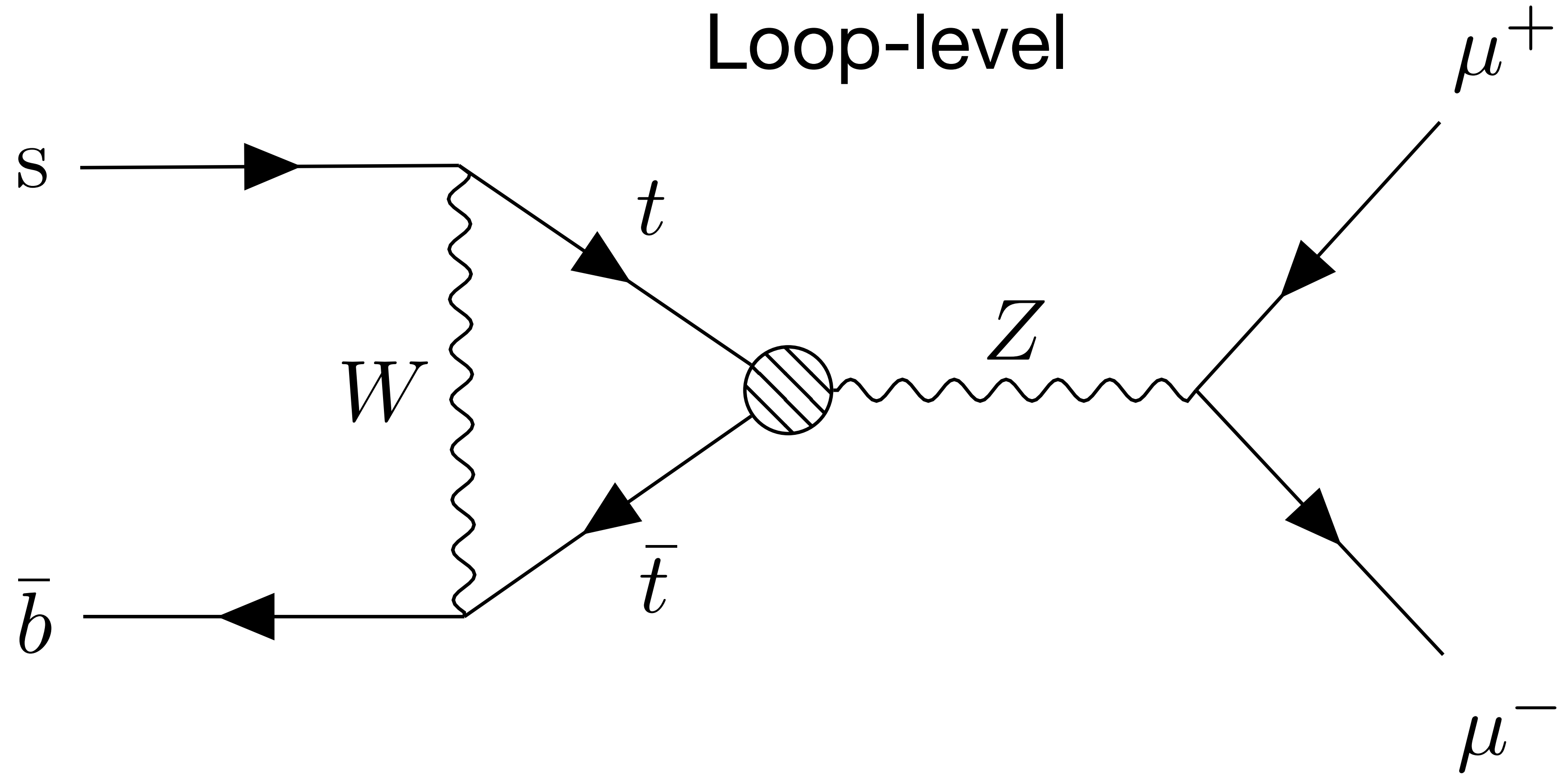
$$\sim \left[\mathcal{C}^1_{\phi q}\right]_{ij} V^*_{is} V_{jb} \left(\bar{s}_L \gamma_\mu b_L\right) Z^\mu$$

$\mathcal{C}_{10}$

b

$$\mathcal{C}^1_{\phi q} \begin{cases} \text{Tree-level} \\ \text{Loop-level} \end{cases}$$

Loop-level

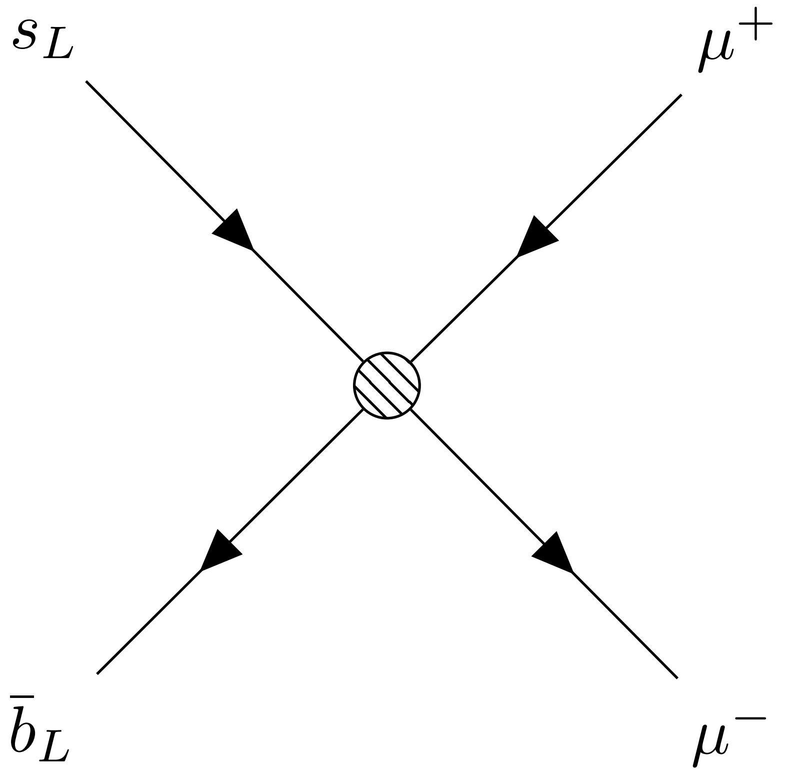


MFV	$\mathcal{C}^1_{\phi q}$
ii	a
33	$a + y_t^2 b$

Top-Down

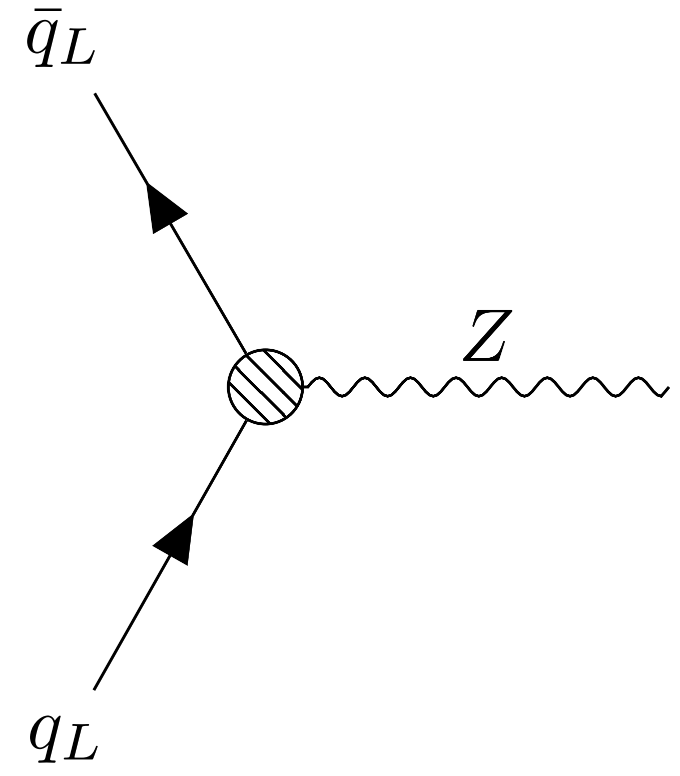
WET

$\mathcal{O}_{10} \sim$

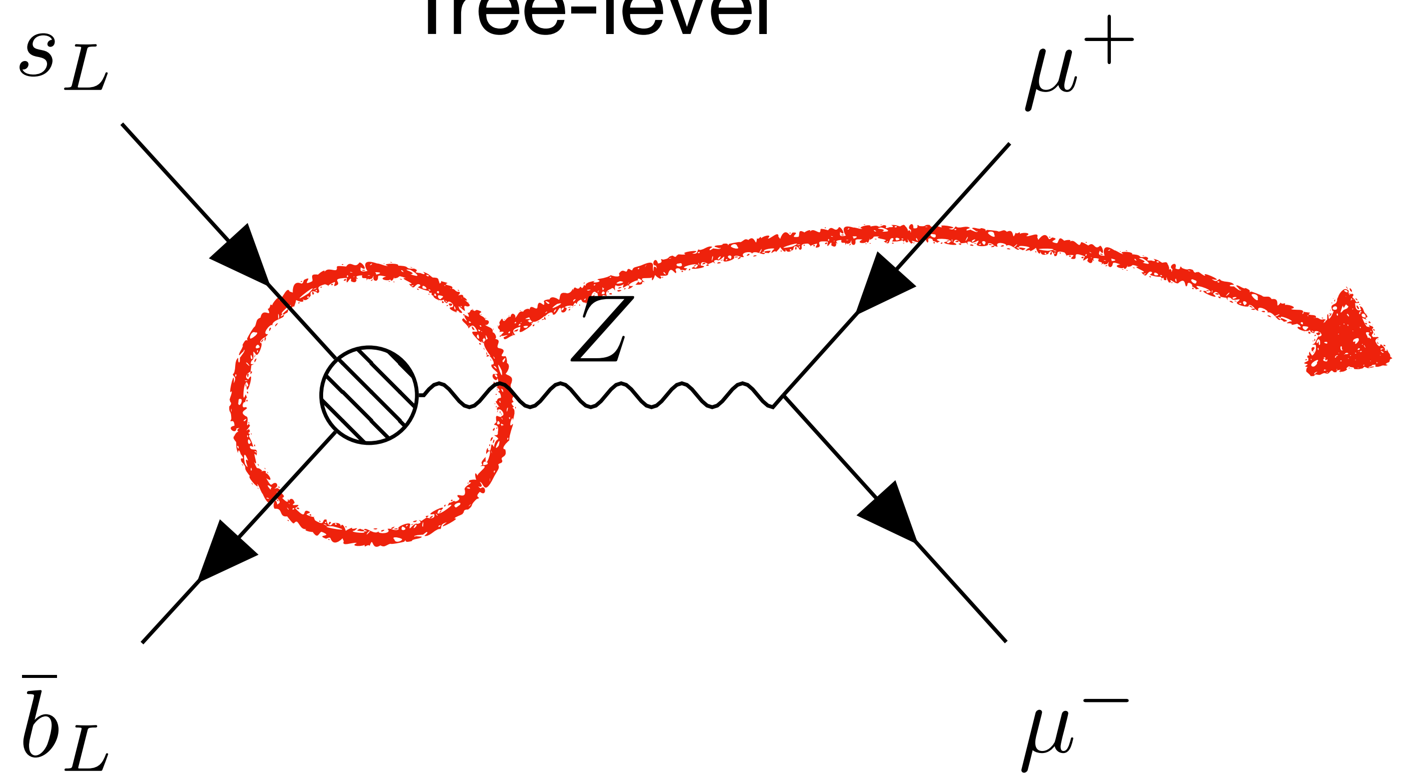


SMEFT

$\mathcal{O}^1_{\phi q} \sim$



Tree-level



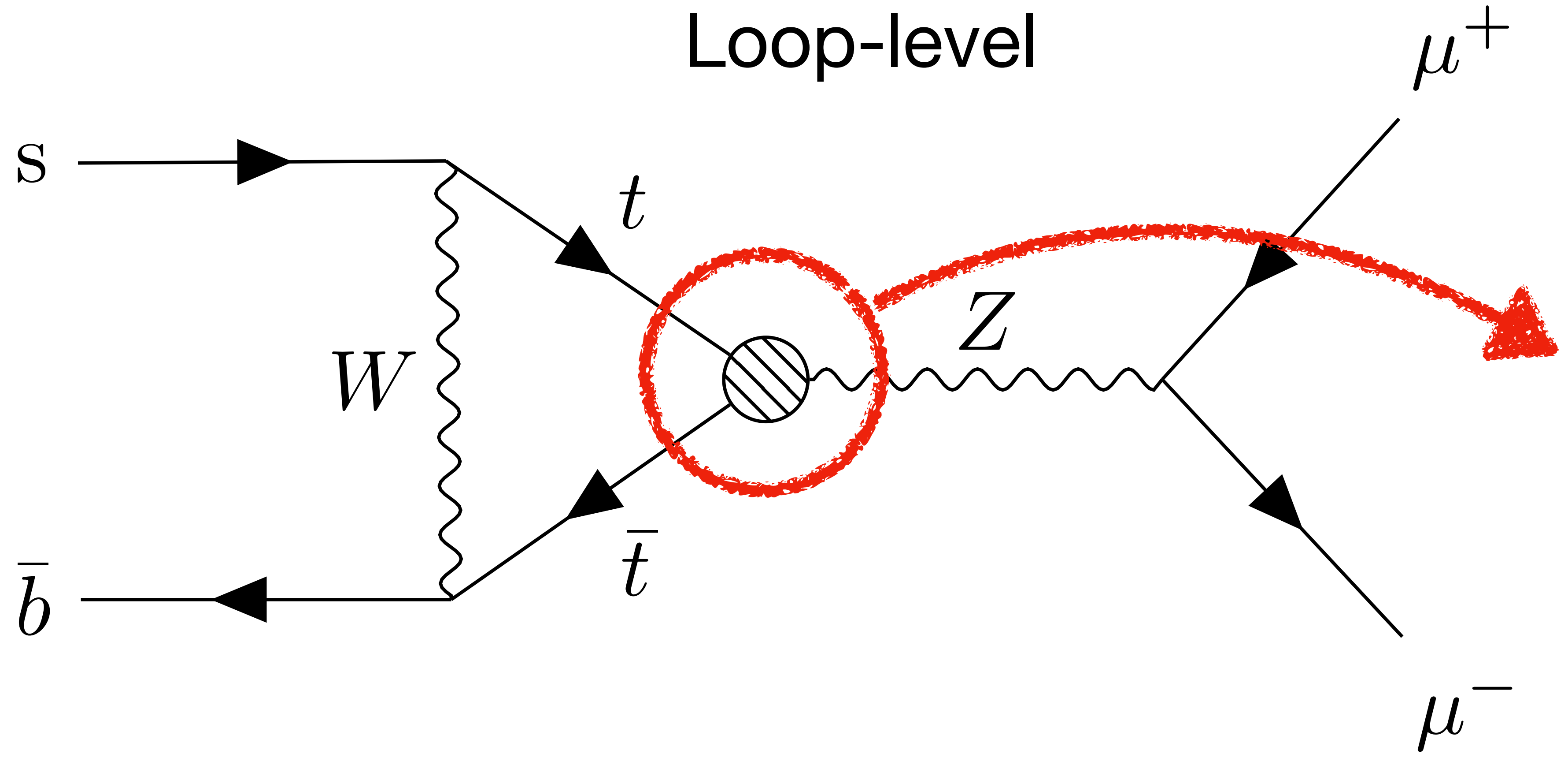
$$\sim \left[\mathcal{C}^1_{\phi q}\right]_{ij} V^*_{is} V_{jb} \left(\bar{s}_L \gamma_\mu b_L\right) Z^\mu$$

$\mathcal{C}_{10}$

b

$$\mathcal{C}^1_{\phi q} \begin{cases} \text{Tree-level} \\ \text{Loop-level} \end{cases}$$

Loop-level



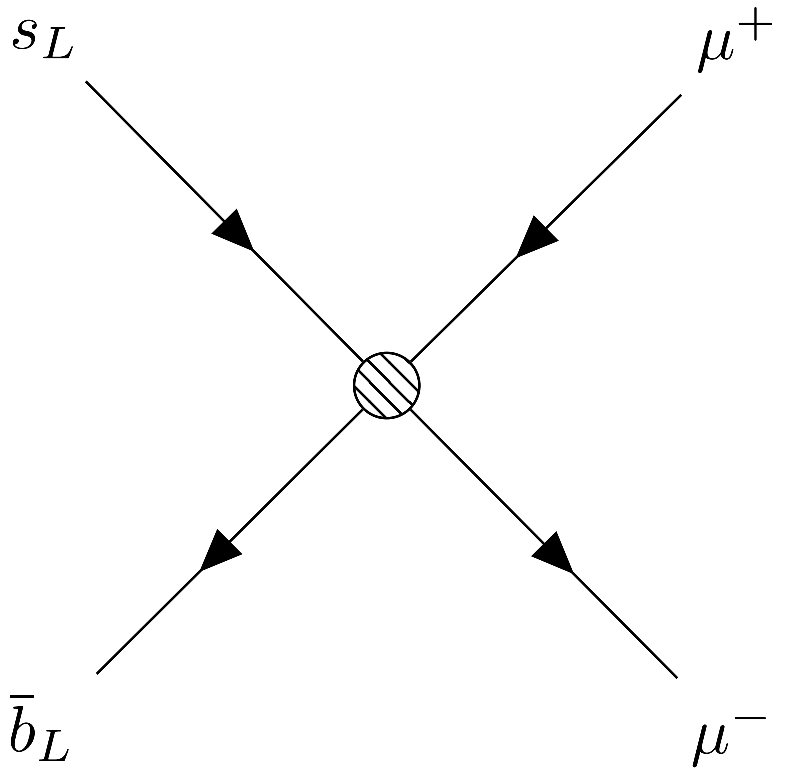
$$\sim \left[\mathcal{C}^1_{\phi q}\right]_{33} V^*_{ts} V_{tb} \left(\bar{t}_L \gamma_\mu t_L\right) Z^\mu$$

MFV	$\mathcal{C}^1_{\phi q}$
ii	a
33	$a + y_t^2 b$

Top-Down

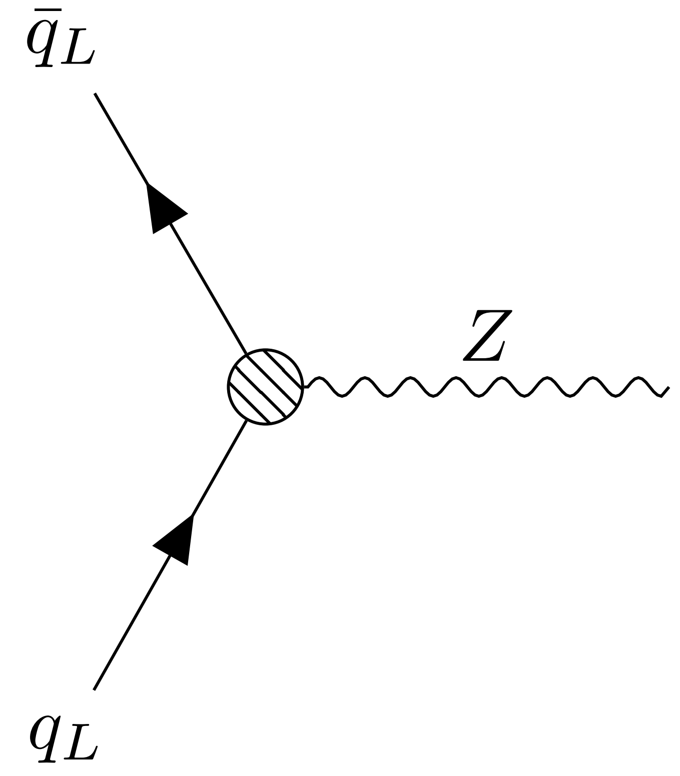
WET

$\mathcal{O}_{10} \sim$

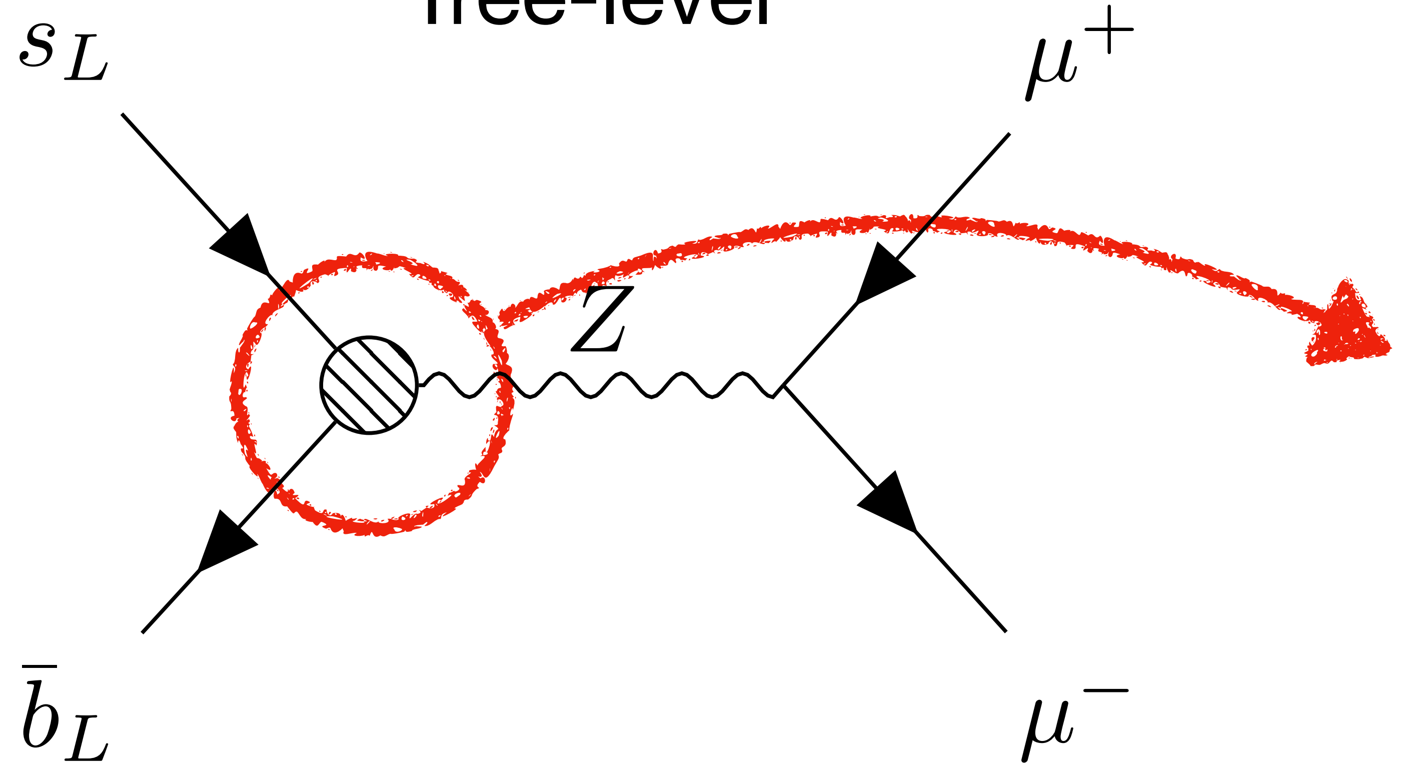


SMEFT

$\mathcal{O}^1_{\phi q} \sim$

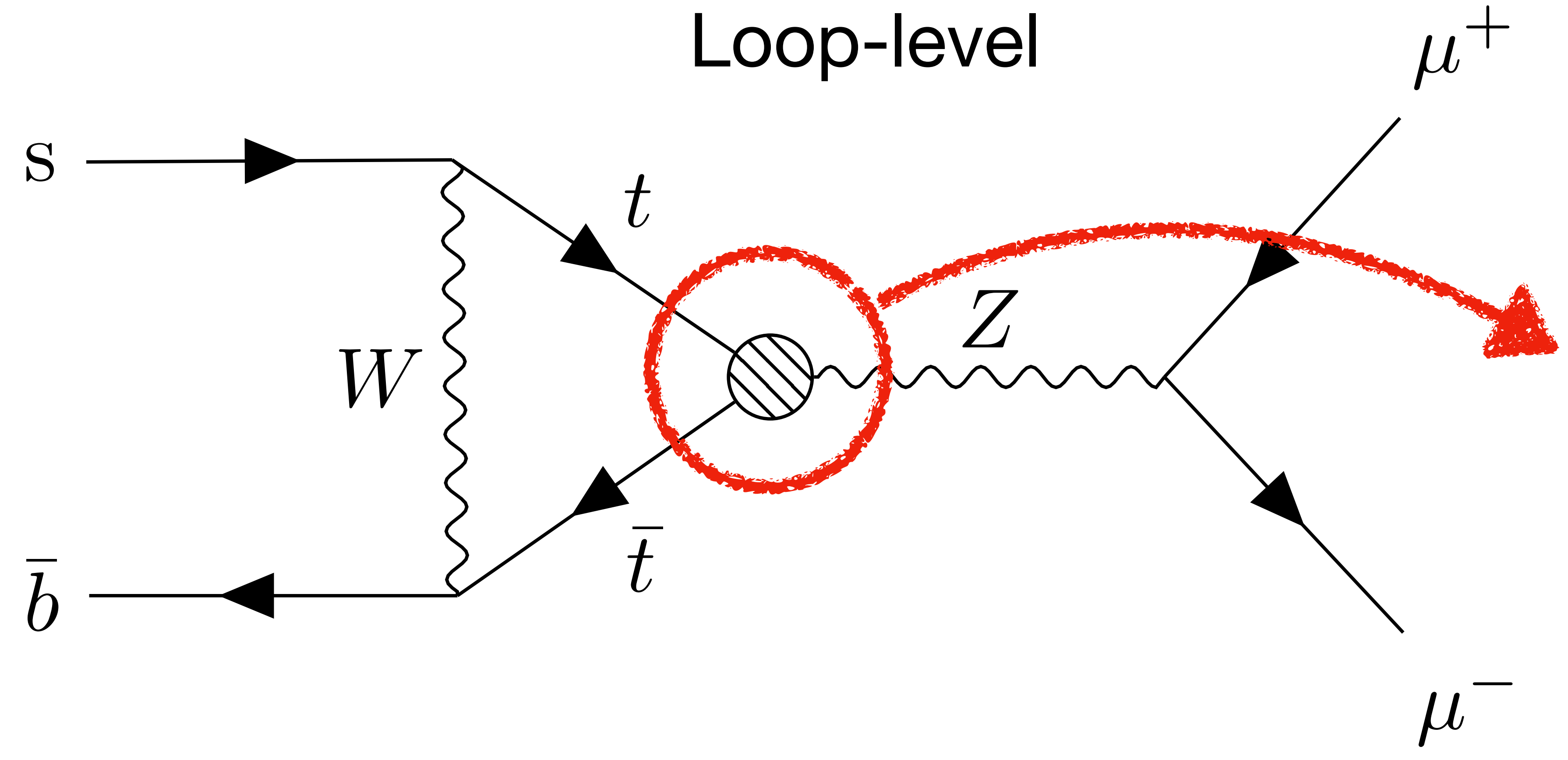


Tree-level



$$\sim \left[\mathcal{C}^1_{\phi q}\right]_{ij} V^*_{is} V_{jb} \left(\bar{s}_L \gamma_\mu b_L\right) Z^\mu$$

Loop-level



$$\sim \left[\mathcal{C}^1_{\phi q}\right]_{33} V^*_{ts} V_{tb} \left(\bar{t}_L \gamma_\mu t_L\right) Z^\mu$$

$$\mathcal{C}_{10}$$

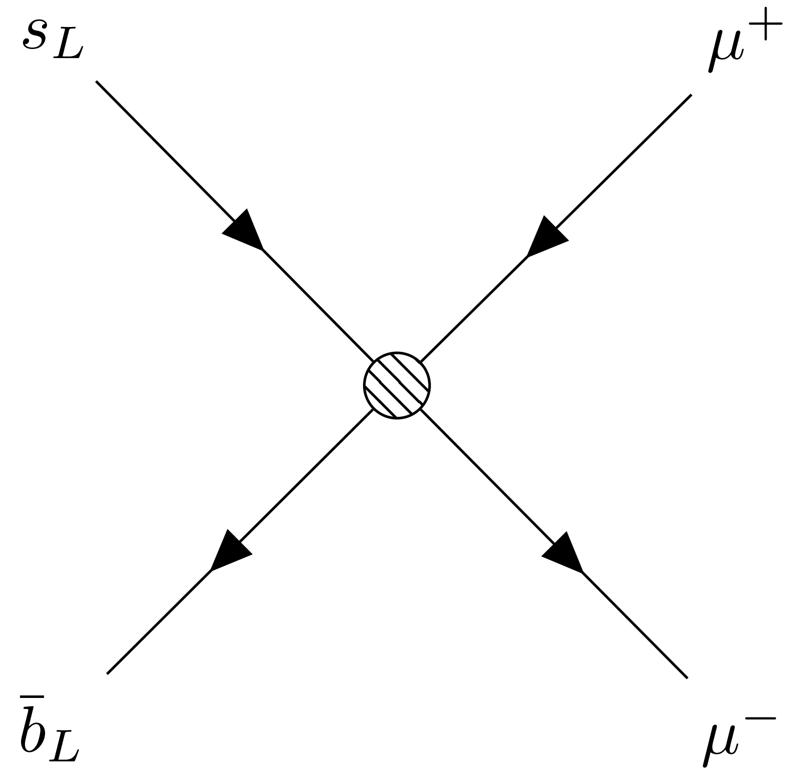
$$\mathcal{C}^1_{\phi q} \begin{cases} \text{Tree-level} & b \\ \text{Loop-level} & a + y_t^2 b \end{cases}$$

MFV	$\mathcal{C}^1_{\phi q}$
ii	a
33	$a + y_t^2 b$

Top-Down

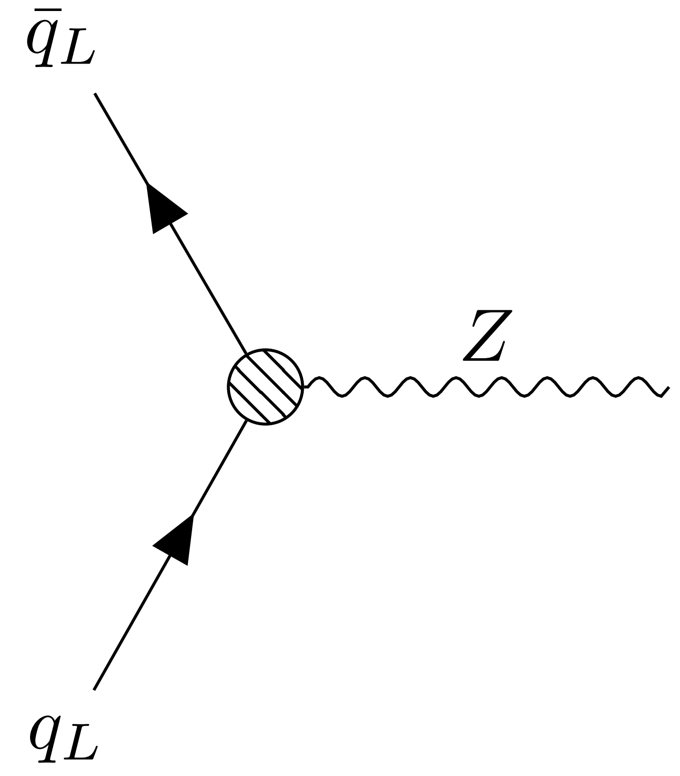
WET

$\mathcal{O}_{10} \sim$

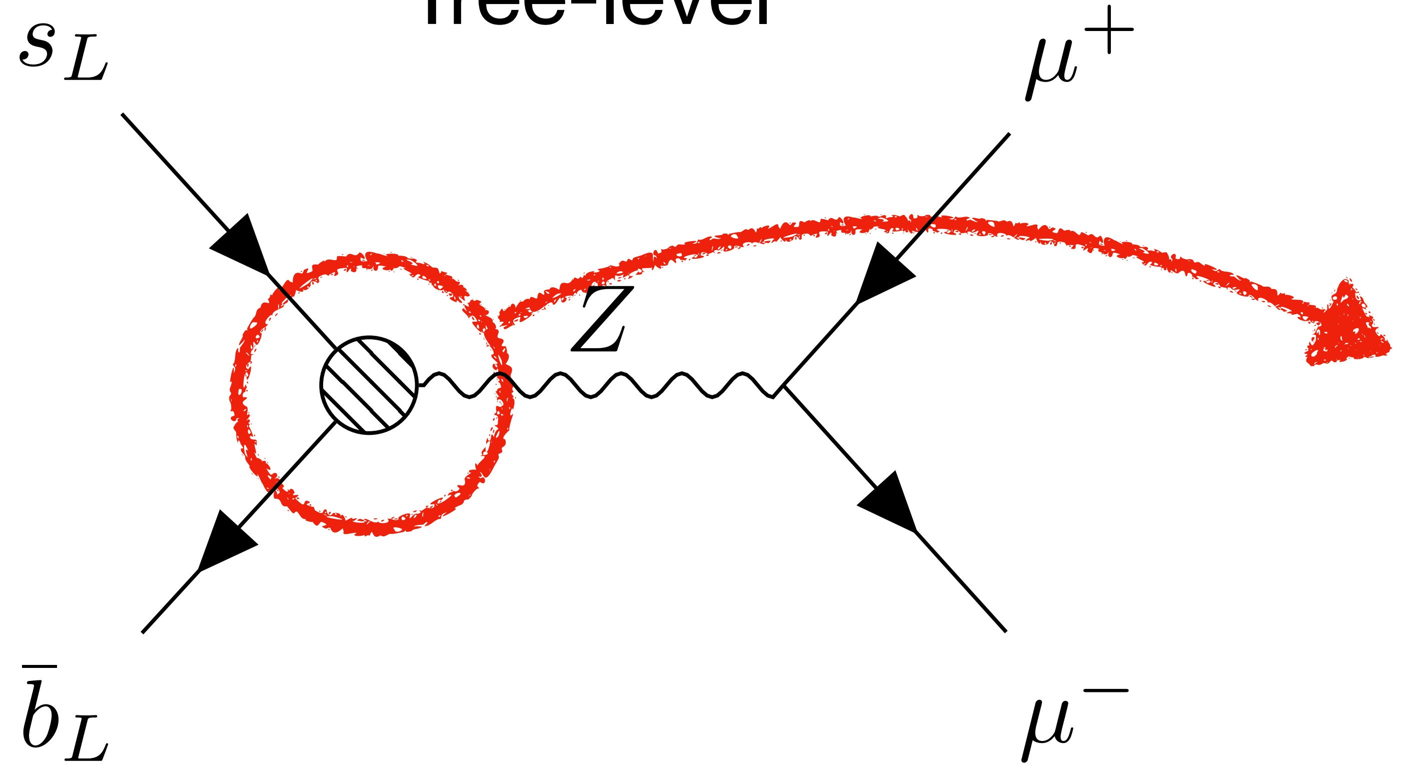


SMEFT

$\mathcal{O}^1_{\phi q} \sim$

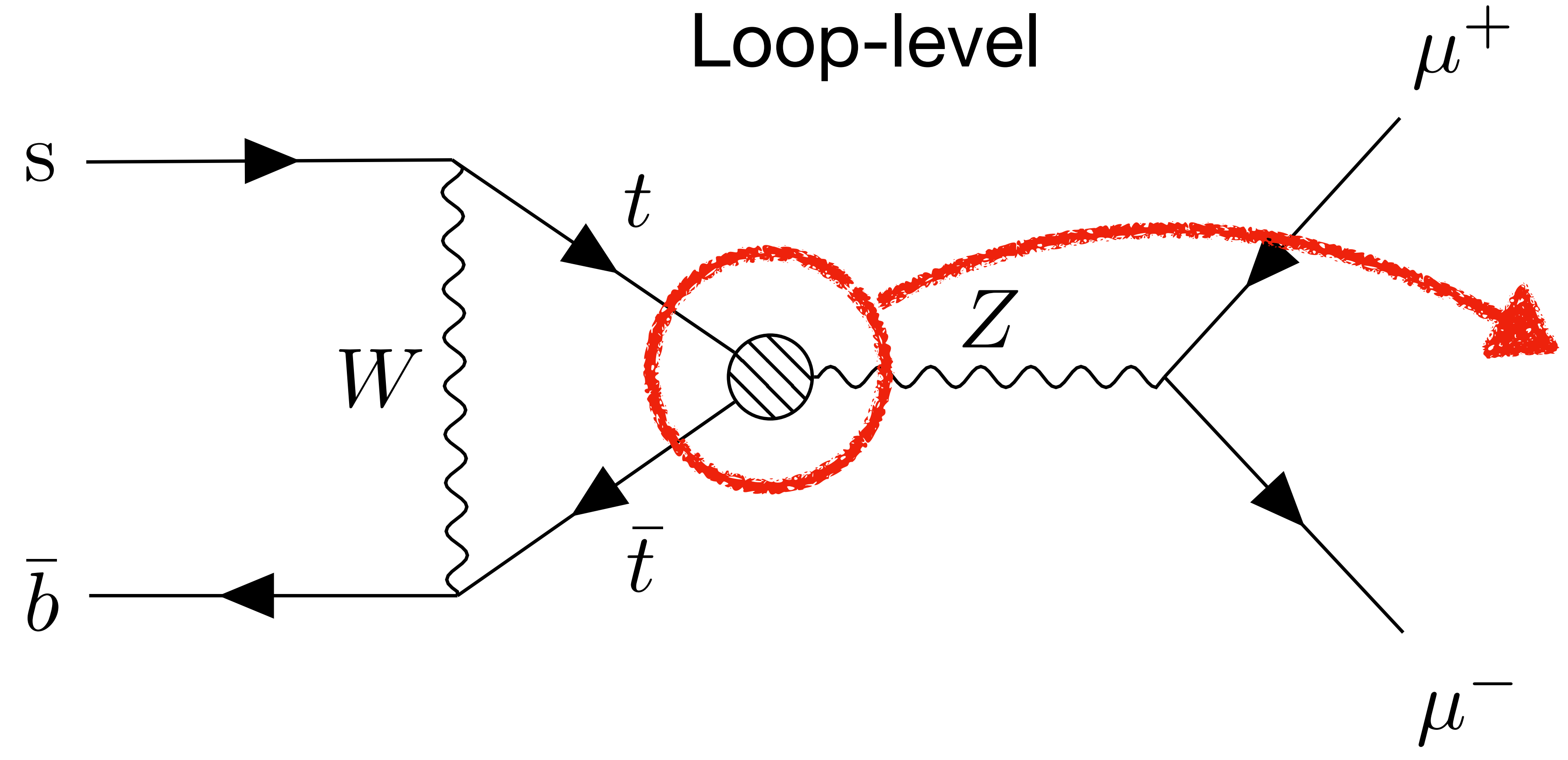


Tree-level



$$\sim \left[\mathcal{C}^1_{\phi q}\right]_{ij} V^*_{is} V_{jb} \left(\bar{s}_L \gamma_\mu b_L\right) Z^\mu$$

Loop-level



$$\sim \left[\mathcal{C}^1_{\phi q}\right]_{33} V^*_{ts} V_{tb} \left(\bar{t}_L \gamma_\mu t_L\right) Z^\mu$$

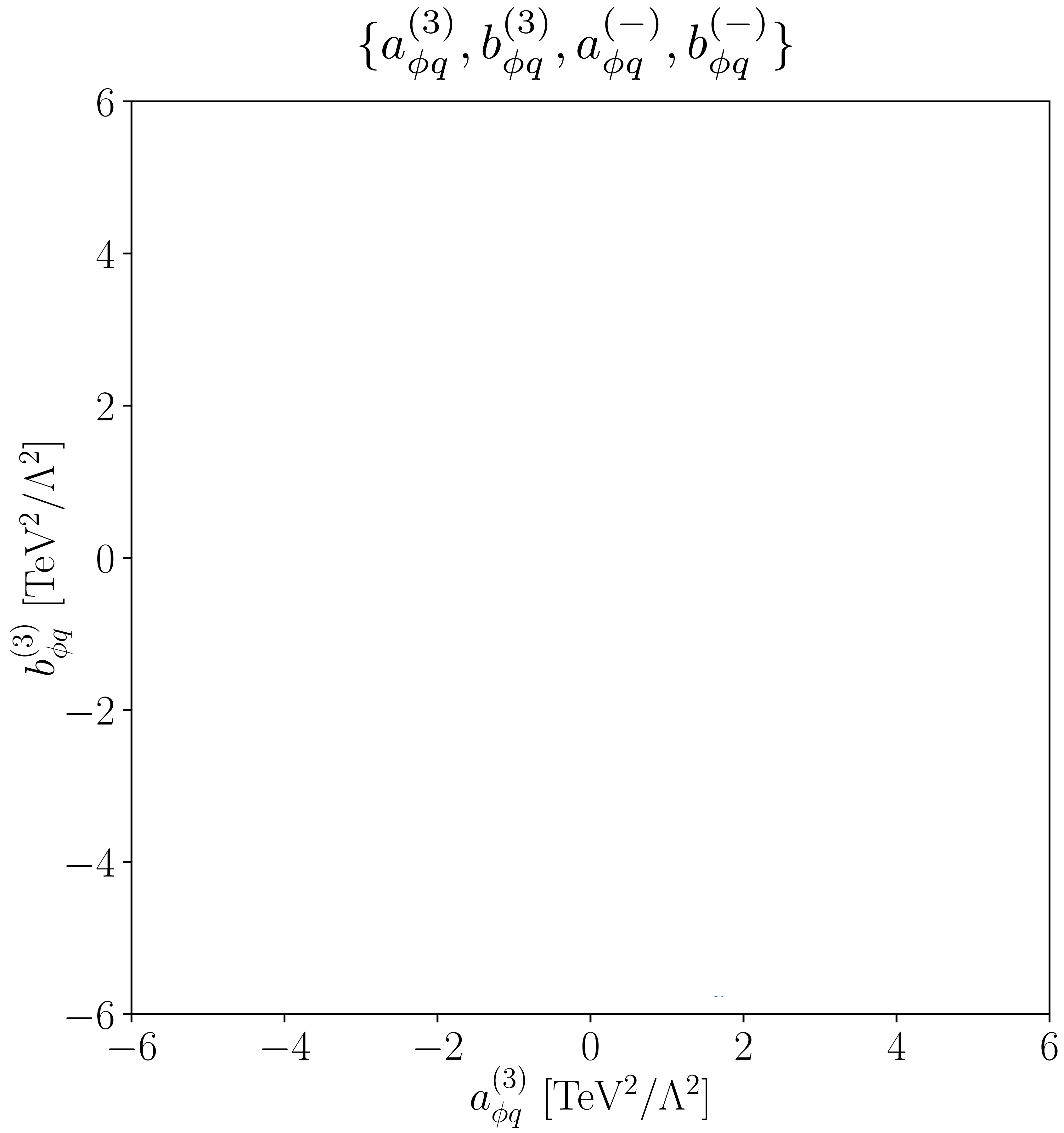
Matching & Running	$\mathcal{C}_{10}$
$a^1_{\phi q}$	0.1
$b^1_{\phi q}$	24.73

An Example: $C^1_{\phi Q}$ & $C^3_{\phi Q}$

Combined fit to top data

$$C^{(-)}_{\phi Q} = C^1_{\phi Q} - C^3_{\phi Q}$$

$$C^{(+)}_{\phi Q} = C^1_{\phi Q} + C^3_{\phi Q}$$

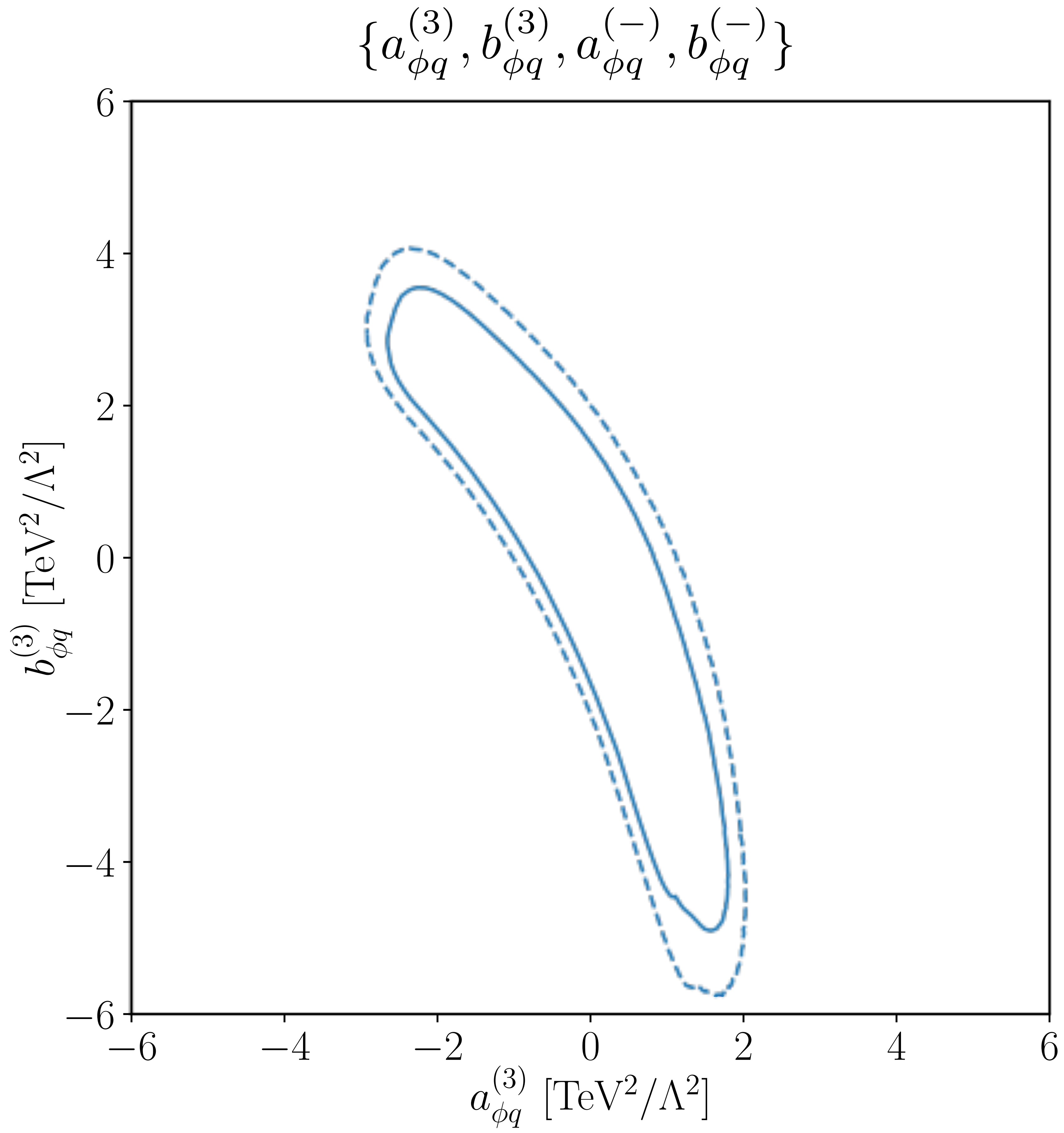


An Example: $C^1_{\phi Q}$ & $C^3_{\phi Q}$

$$C^{(-)}_{\phi Q} = C^1_{\phi Q} - C^3_{\phi Q}$$

Combined fit to top data

$$C^{(+)}_{\phi Q} = C^1_{\phi Q} + C^3_{\phi Q}$$



An Example: $C^1_{\phi Q}$ & $C^3_{\phi Q}$

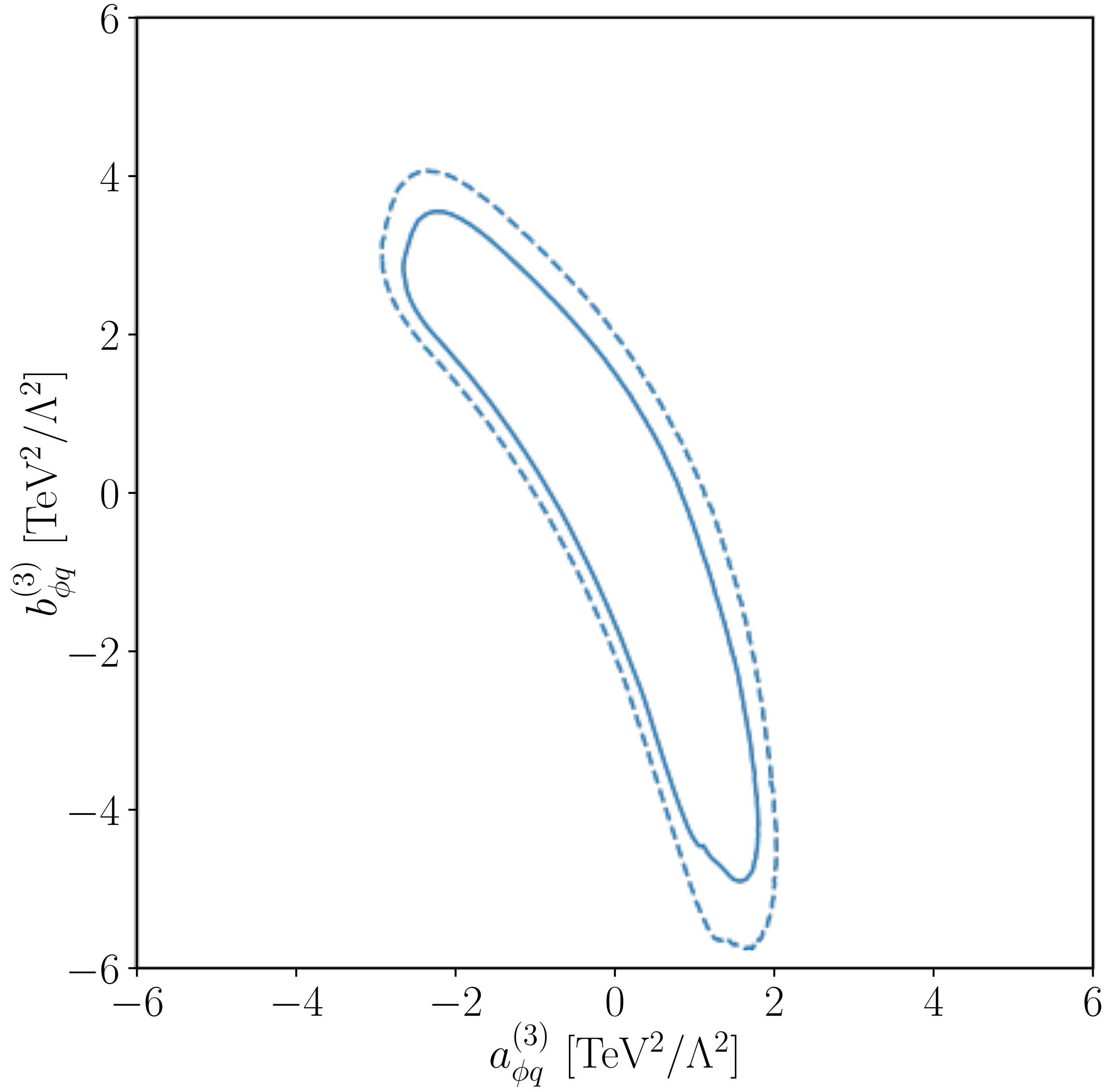
$$C^{(-)}_{\phi Q} = C^1_{\phi Q} - C^3_{\phi Q}$$

Combined fit to top data

$$C^{(+)}_{\phi Q} = C^1_{\phi Q} + C^3_{\phi Q}$$

$\{a^{(3)}_{\phi q}, b^{(3)}_{\phi q}, a^{(-)}_{\phi q}, b^{(-)}_{\phi q}\}$

$$\boxed{\mathcal{B}(B_s \to \mu^+\mu^-) \times 10^9 = 3.57 - 41.0\, b^{(+)}_{\phi q} + 117.8 (b^{(+)}_{\phi q})^2}$$



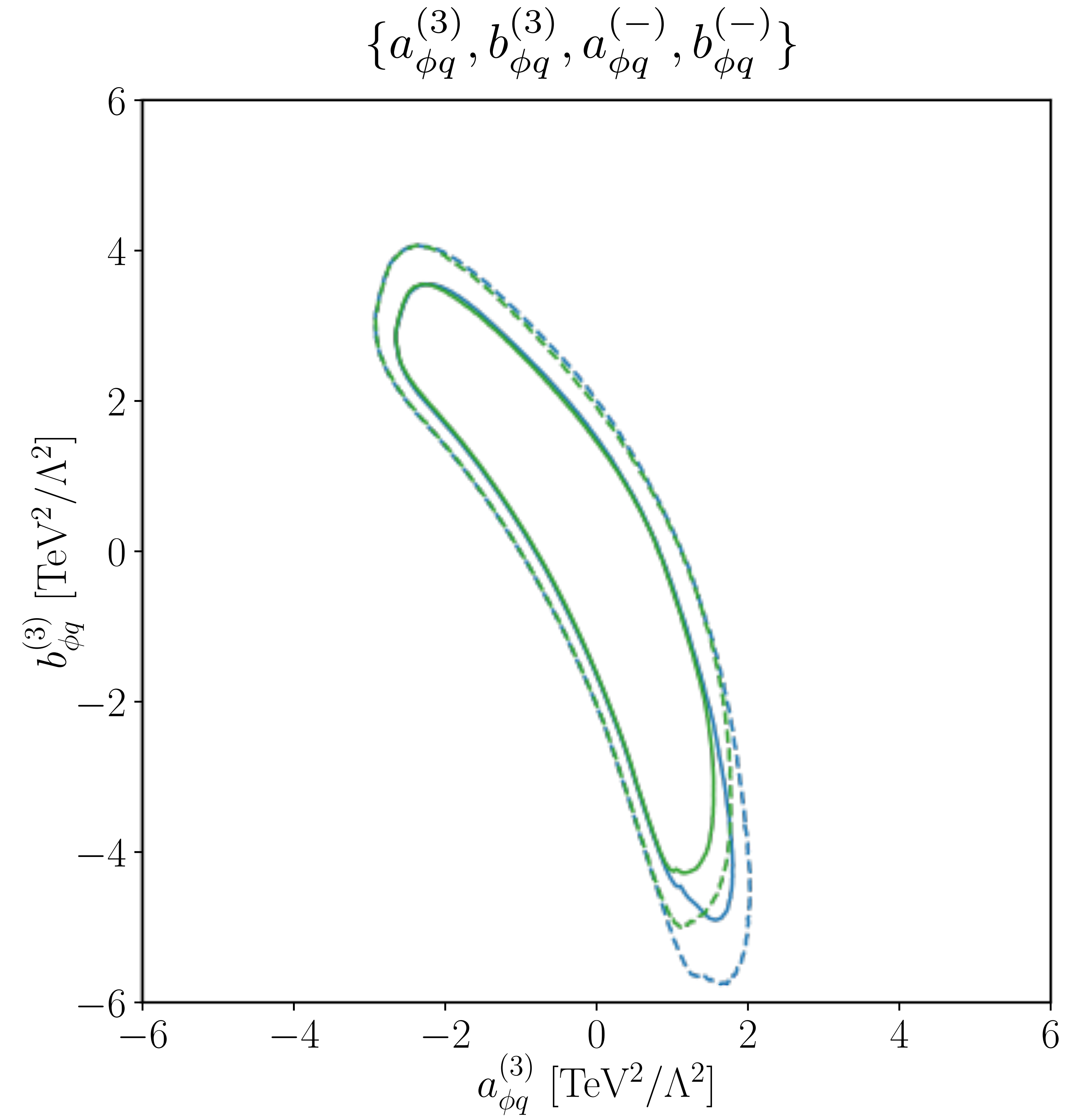
An Example: $C^1_{\phi Q}$ & $C^3_{\phi Q}$

$$C^{(-)}_{\phi Q} = C^1_{\phi Q} - C^3_{\phi Q}$$

$$C^{(+)}_{\phi Q} = C^1_{\phi Q} + C^3_{\phi Q}$$

Combined fit to top data & $\mathcal{B}(B_s \to \mu^+\mu^-)$

$$\boxed{\mathcal{B}(B_s \to \mu^+\mu^-) \times 10^9 = 3.57 - 41.0\, b^{(+)}_{\phi q} + 117.8 (b^{(+)}_{\phi q})^2}$$



An Example: $C^1_{\phi Q}$ & $C^3_{\phi Q}$

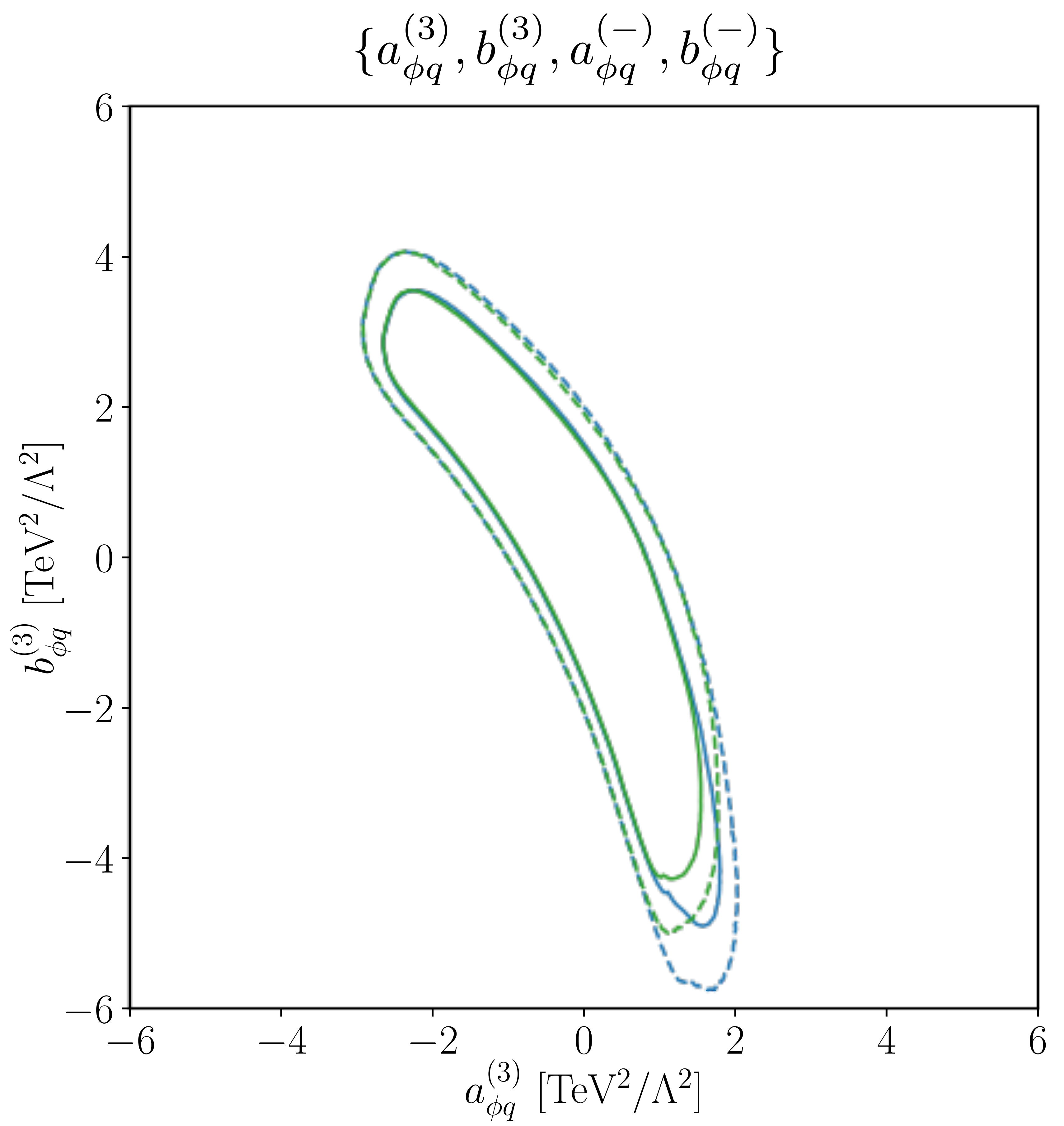
$$C^{(-)}_{\phi Q} = C^1_{\phi Q} - C^3_{\phi Q}$$

$$C^{(+)}_{\phi Q} = C^1_{\phi Q} + C^3_{\phi Q}$$

Combined fit to top data & $\mathcal{B}(B_s \to \mu^+\mu^-)$

$$\boxed{\mathcal{B}(B_s \to \mu^+\mu^-) \times 10^9 = 3.57 - 41.0\, b^{(+)}_{\phi q} + 117.8 (b^{(+)}_{\phi q})^2}$$

$$\boxed{\mathcal{B}(B \to X_s \gamma) \times 10^4 = 3.26 + 0.36\, a^{(3)}_{\phi q} - 0.76\, b^{(3)}_{\phi q}}$$



An Example: $C^1_{\phi Q}$ & $C^3_{\phi Q}$

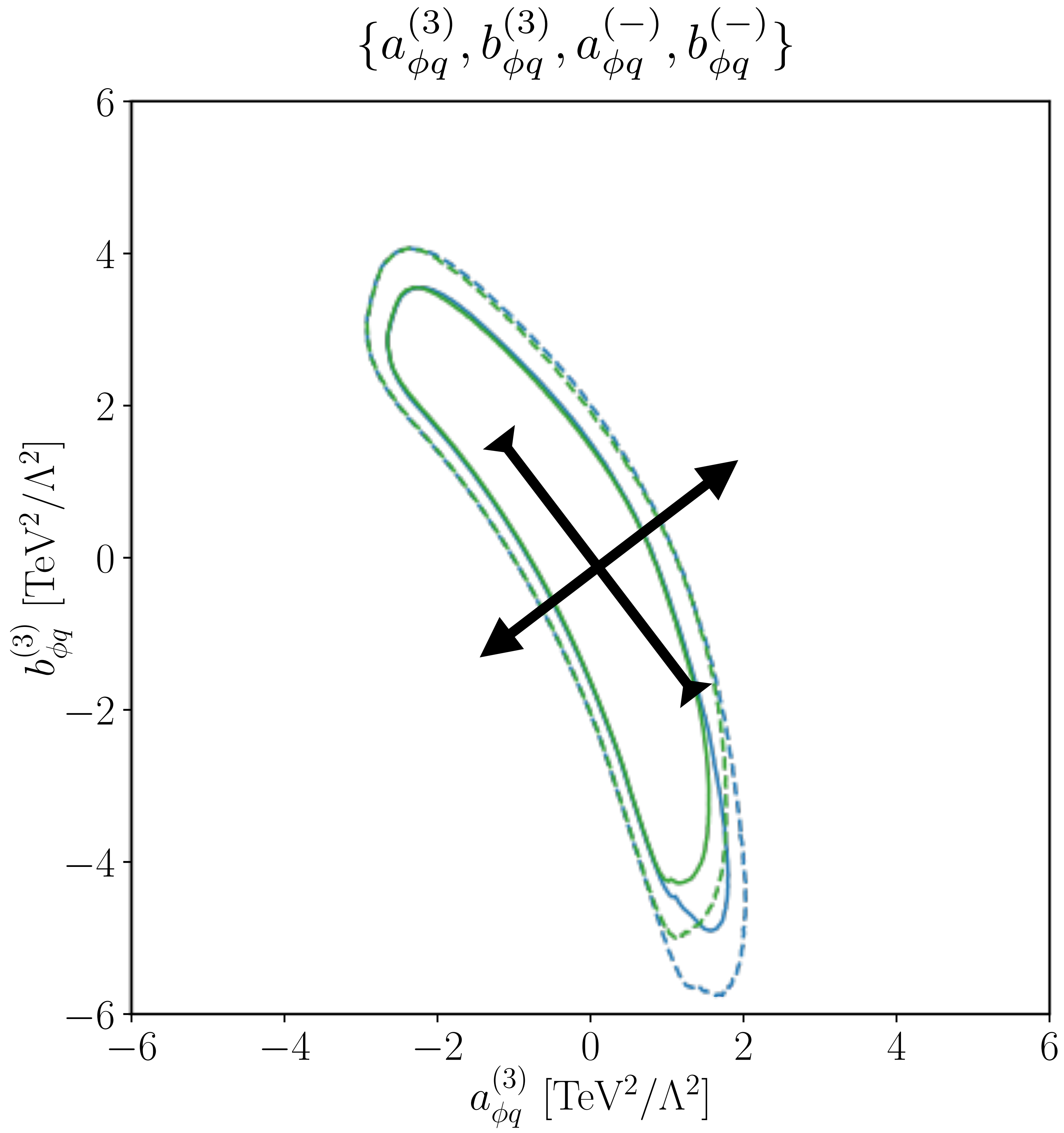
$C^{(-)}_{\phi Q} = C^1_{\phi Q} - C^3_{\phi Q}$

$C^{(+)}_{\phi Q} = C^1_{\phi Q} + C^3_{\phi Q}$

Combined fit to top data & $\mathcal{B}(B_s \to \mu^+\mu^-)$

$$\boxed{\mathcal{B}(B_s \to \mu^+\mu^-) \times 10^9 = 3.57 - 41.0\, b^{(+)}_{\phi q} + 117.8 (b^{(+)}_{\phi q})^2}$$

$$\boxed{\mathcal{B}(B \to X_s \gamma) \times 10^4 = 3.26 + 0.36\, a^{(3)}_{\phi q} - 0.76\, b^{(3)}_{\phi q}}$$



An Example: $C^1_{\phi Q}$ & $C^3_{\phi Q}$

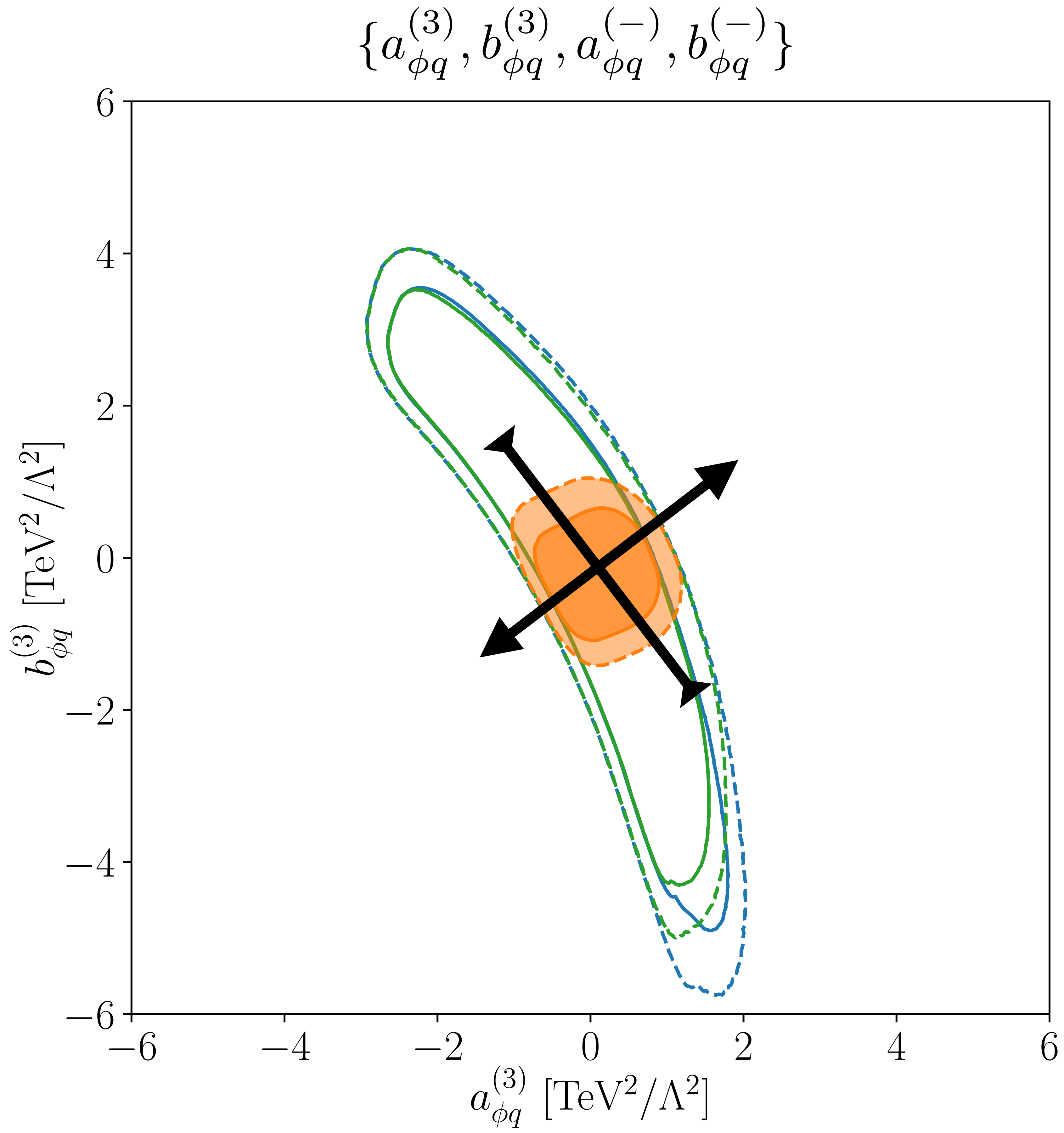
$$C^{(-)}_{\phi Q} = C^1_{\phi Q} - C^3_{\phi Q}$$

Combined fit to top data & $\mathcal{B}(B_s \to \mu^+\mu^-)$& $\mathcal{B}(B \to X_s\gamma)$

$$C^{(+)}_{\phi Q} = C^1_{\phi Q} + C^3_{\phi Q}$$

$$\boxed{\mathcal{B}(B_s \to \mu^+\mu^-) \times 10^9 = 3.57 - 41.0\, b^{(+)}_{\phi q} + 117.8(b^{(+)}_{\phi q})^2}$$

$$\boxed{\mathcal{B}(B \to X_s\gamma) \times 10^4 = 3.26 + 0.36\, a^{(3)}_{\phi q} - 0.76\, b^{(3)}_{\phi q}}$$



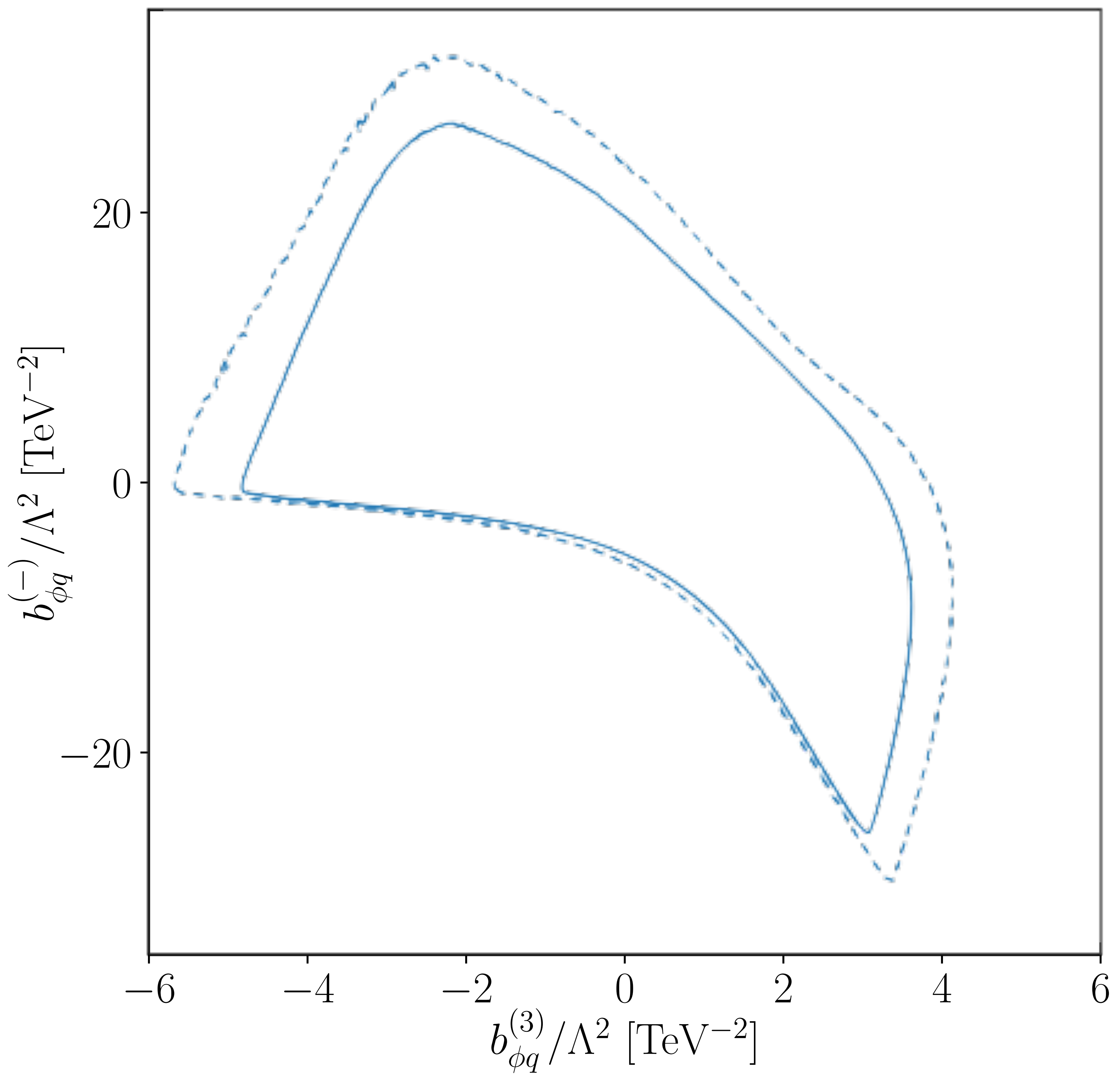
An Example: $C^1_{\phi Q}$ & $C^3_{\phi Q}$

$$C^{(-)}_{\phi Q} = C^1_{\phi Q} - C^3_{\phi Q}$$

$$C^{(+)}_{\phi Q} = C^1_{\phi Q} + C^3_{\phi Q}$$

Combined fit to top data

$\{a^{(3)}_{\phi q}, b^{(3)}_{\phi q}, a^{(-)}_{\phi q}, b^{(-)}_{\phi q}\}$



An Example: $C^1_{\phi Q}$ & $C^3_{\phi Q}$

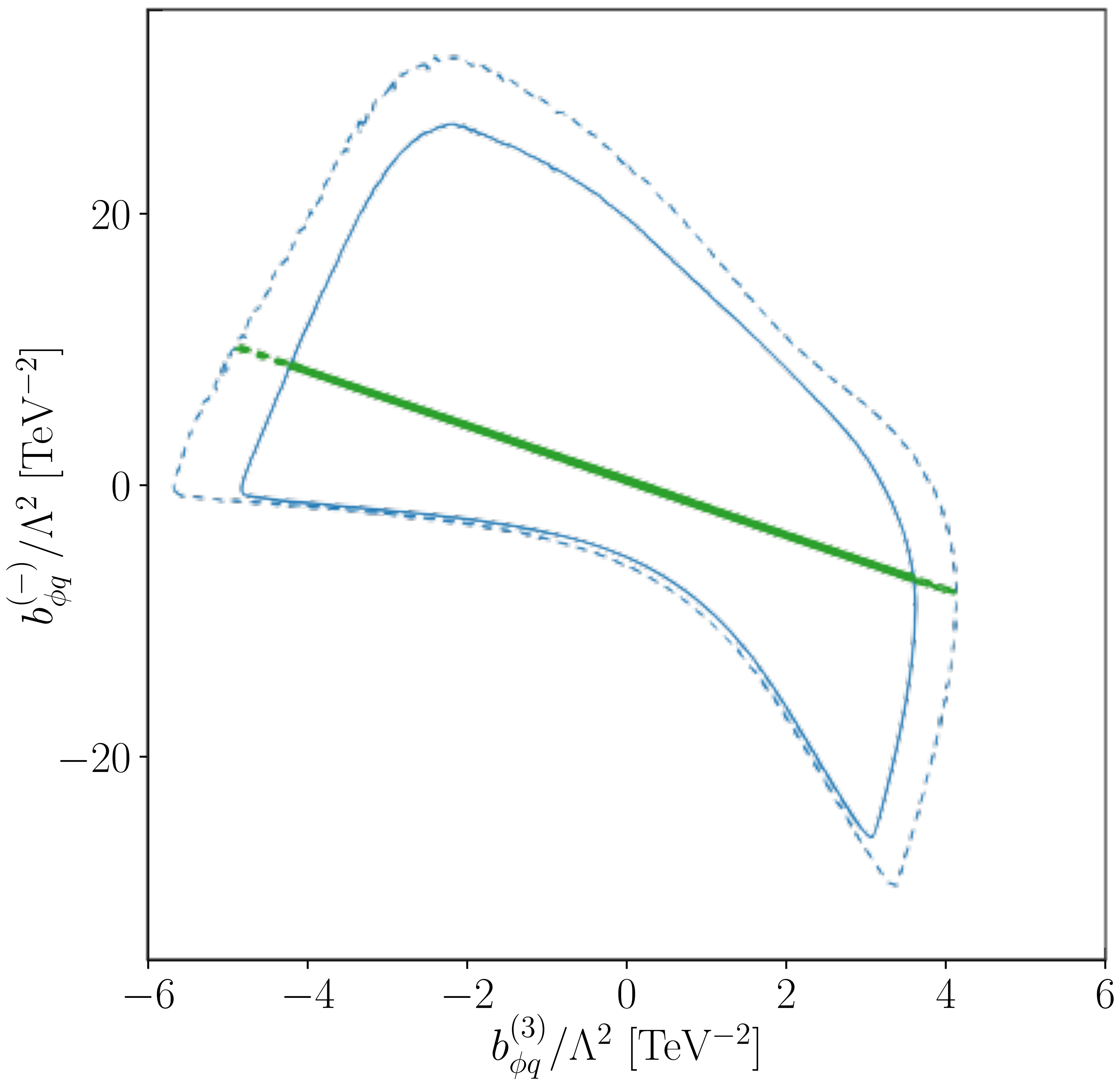
$$C^{(-)}_{\phi Q} = C^1_{\phi Q} - C^3_{\phi Q}$$

$$C^{(+)}_{\phi Q} = C^1_{\phi Q} + C^3_{\phi Q}$$

Combined fit to top data & $\mathcal{B}(B_s \to \mu^+\mu^-)$

$$\boxed{\mathcal{B}(B_s \to \mu^+\mu^-) \times 10^9 = 3.57 - 41.0\, b^{(+)}_{\phi q} + 117.8 (b^{(+)}_{\phi q})^2}$$

$\{a^{(3)}_{\phi q}, b^{(3)}_{\phi q}, a^{(-)}_{\phi q}, b^{(-)}_{\phi q}\}$



An Example: $C_{\phi Q}^{1}$ & $C_{\phi Q}^{3}$

$$C_{\phi Q}^{(-)} = C_{\phi Q}^{1} - C_{\phi Q}^{3}$$

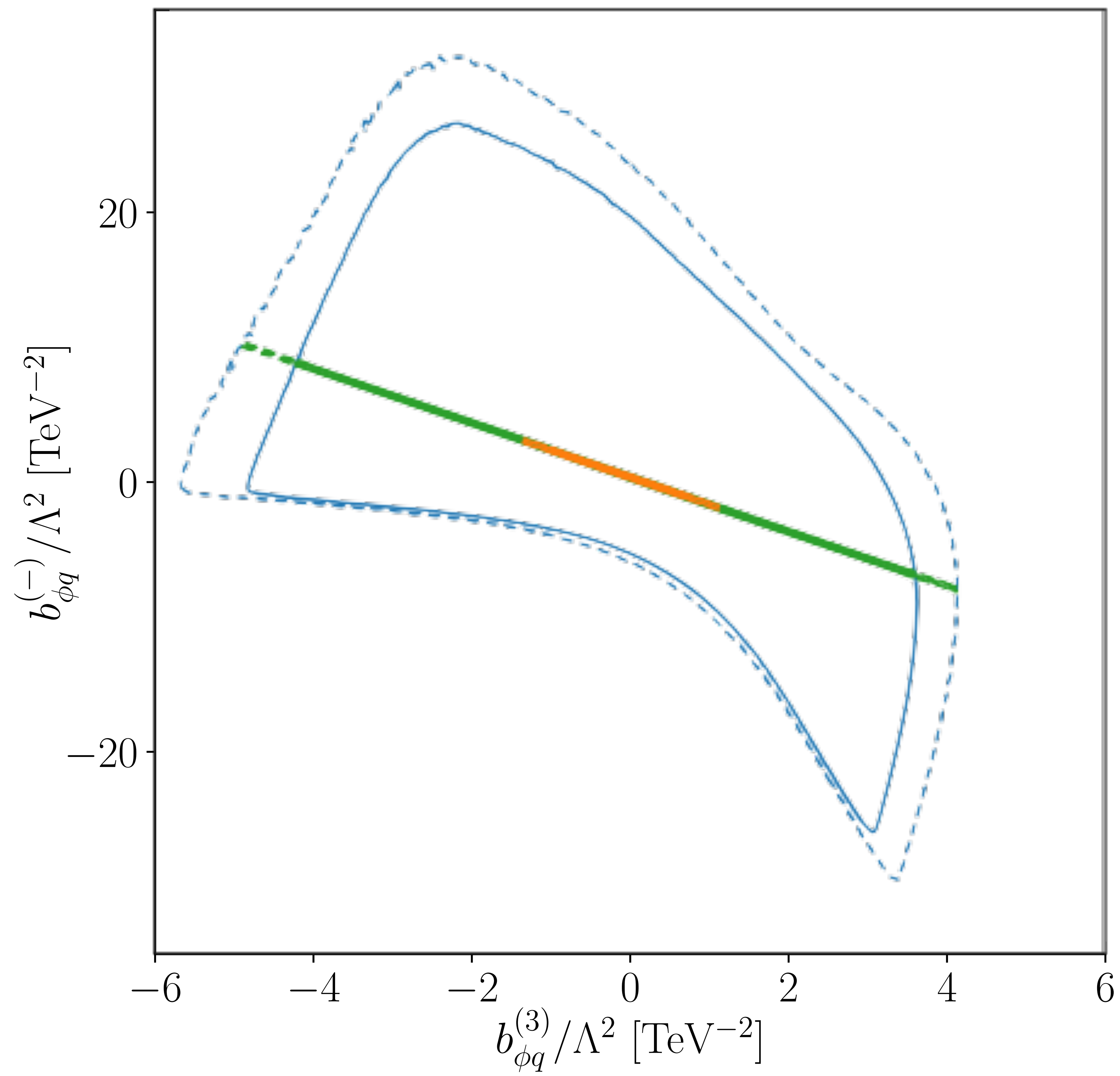
Combined fit to top data & $\mathcal{B}(B_s \to \mu^+\mu^-)$& $\mathcal{B}(B \to X_s\gamma)$

$$C_{\phi Q}^{(+)} = C_{\phi Q}^{1} + C_{\phi Q}^{3}$$

$$\boxed{\mathcal{B}(B_s \to \mu^+\mu^-) \times 10^9 = 3.57 - 41.0\, b_{\phi q}^{(+)} + 117.8(b_{\phi q}^{(+)})^2}$$

$$\boxed{\mathcal{B}(B \to X_s\gamma) \times 10^4 = 3.26 + 0.36\, a_{\phi q}^{(3)} - 0.76\, b_{\phi q}^{(3)}}$$

$\{a_{\phi q}^{(3)}, b_{\phi q}^{(3)}, a_{\phi q}^{(-)}, b_{\phi q}^{(-)}\}$



An Example: $C^1_{\phi Q}$ & $C^3_{\phi Q}$

$$C^{(-)}_{\phi Q} = C^1_{\phi Q} - C^3_{\phi Q}$$

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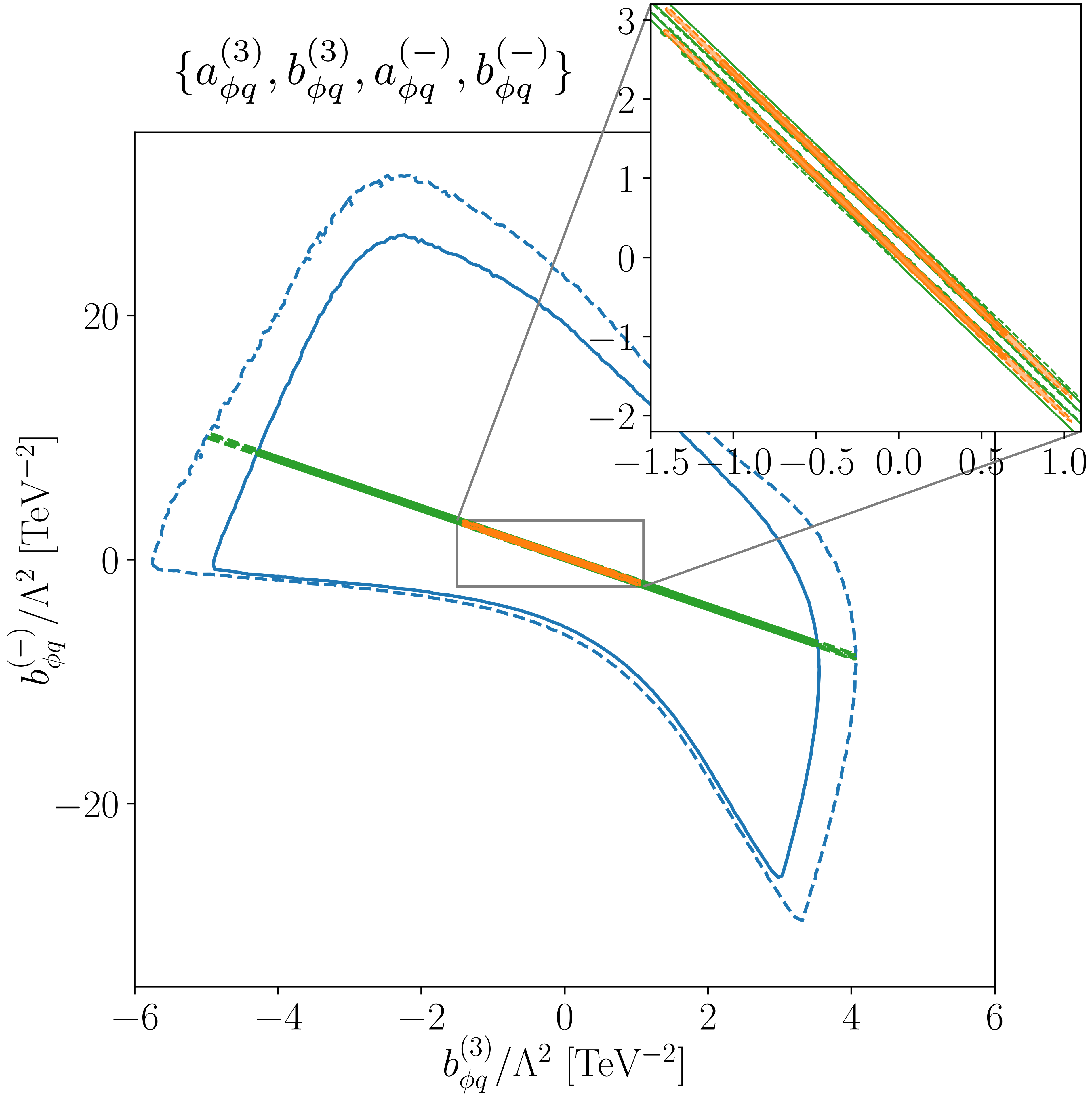

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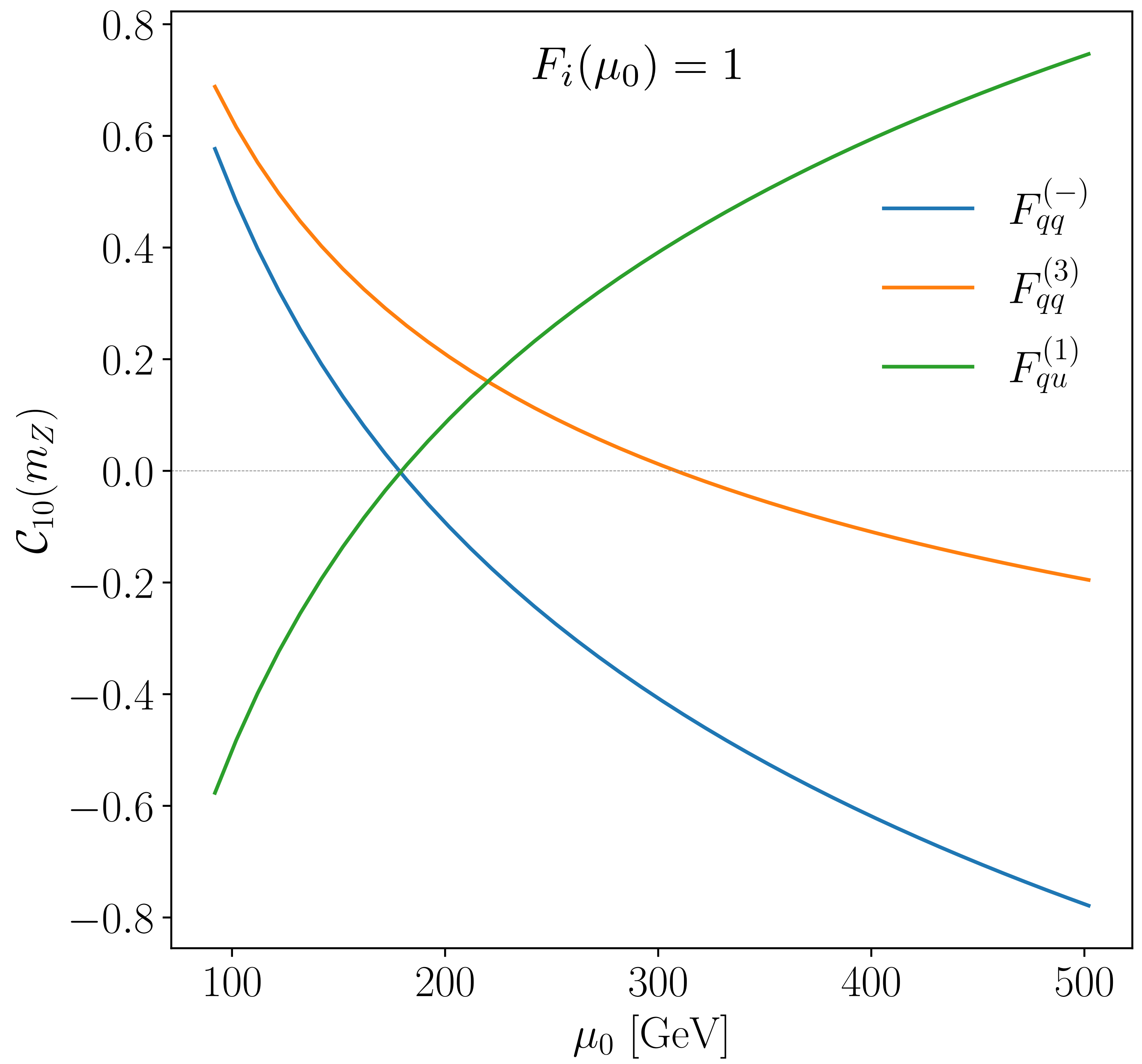

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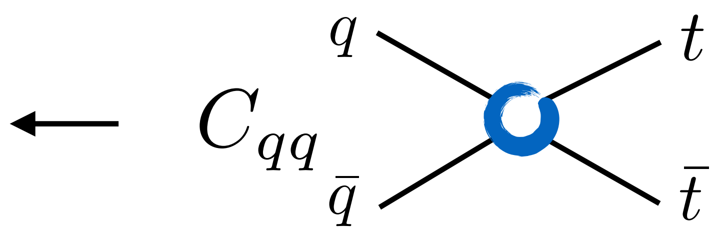

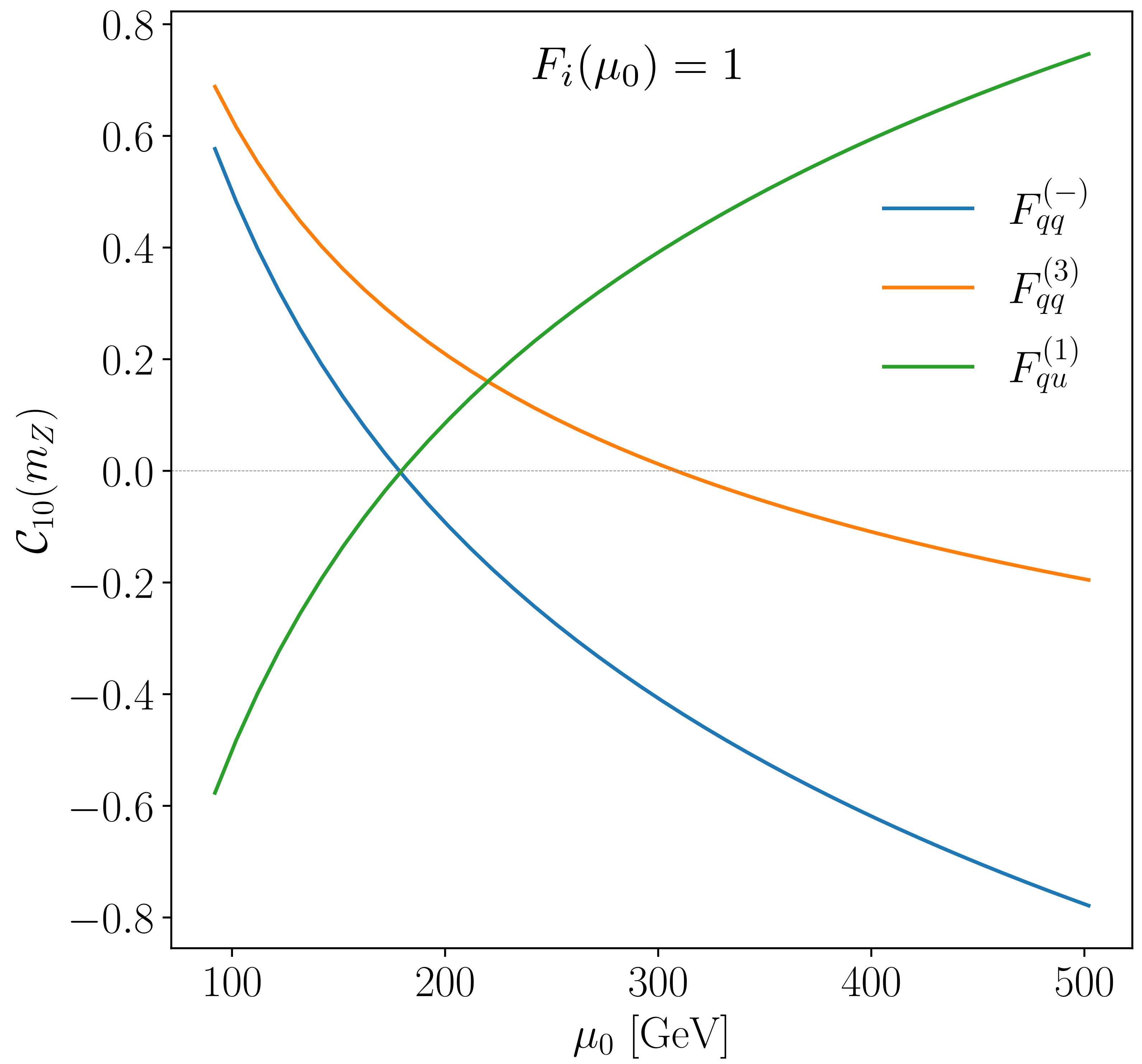

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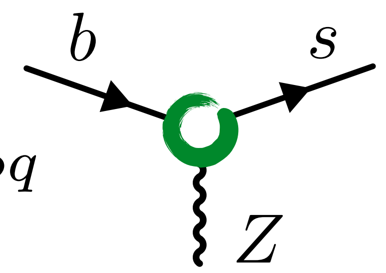
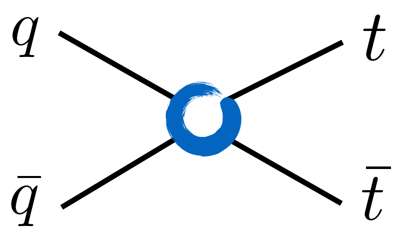
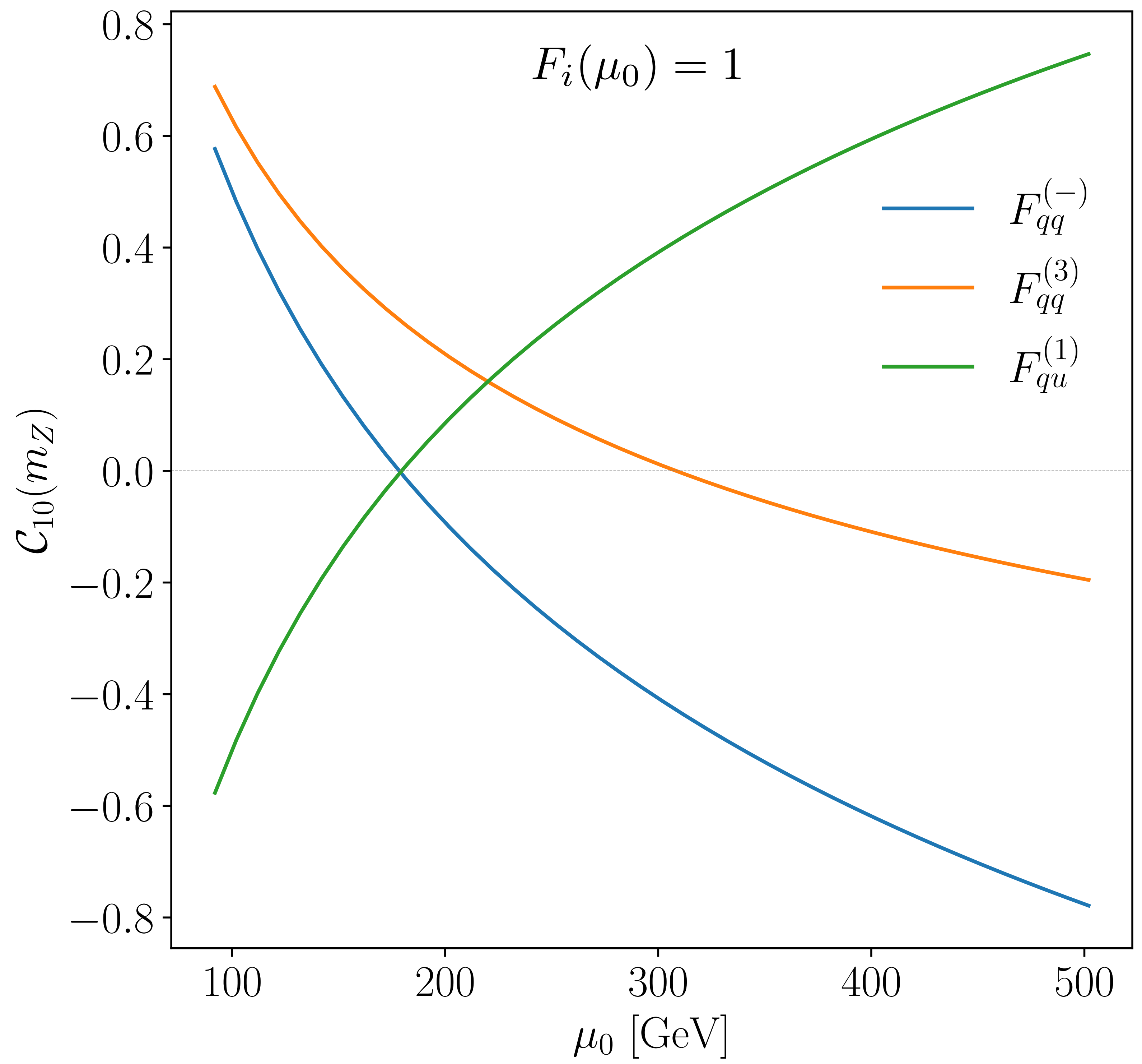
$\leftarrow$ $C_{\phi q}$  $\leftarrow$ C_{qq} 



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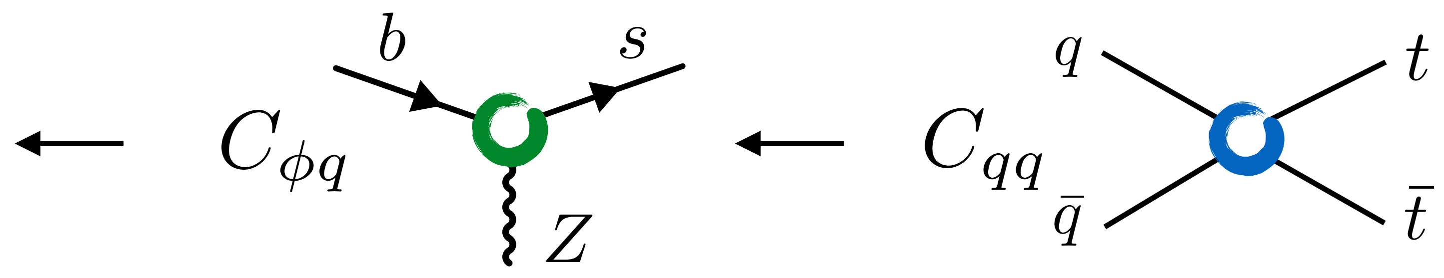

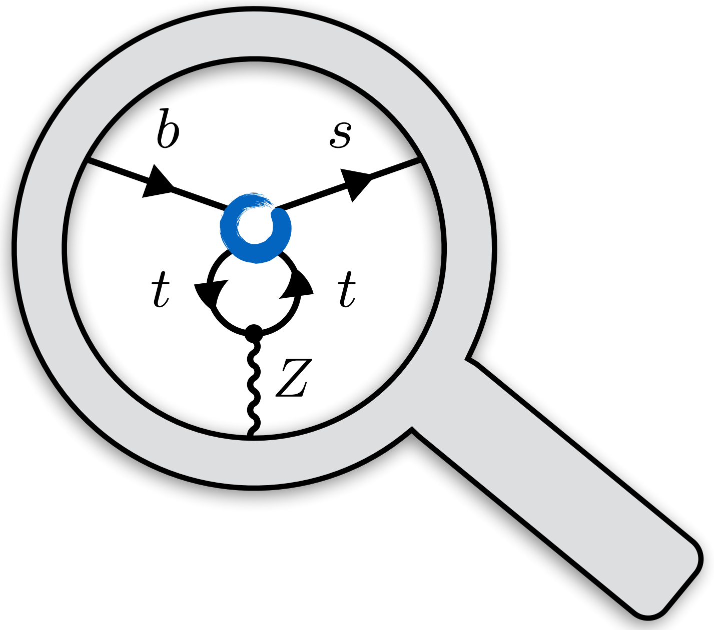

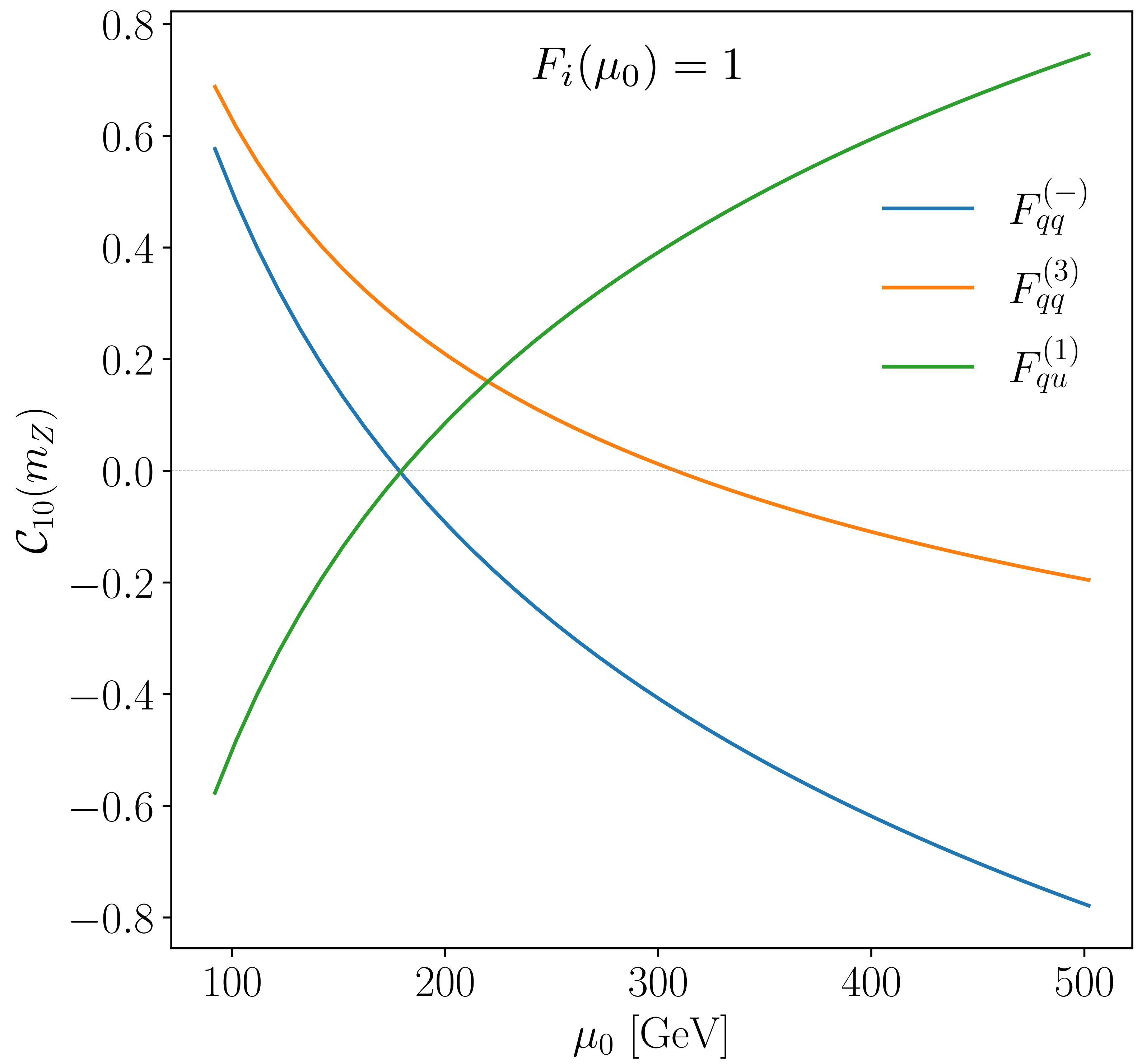

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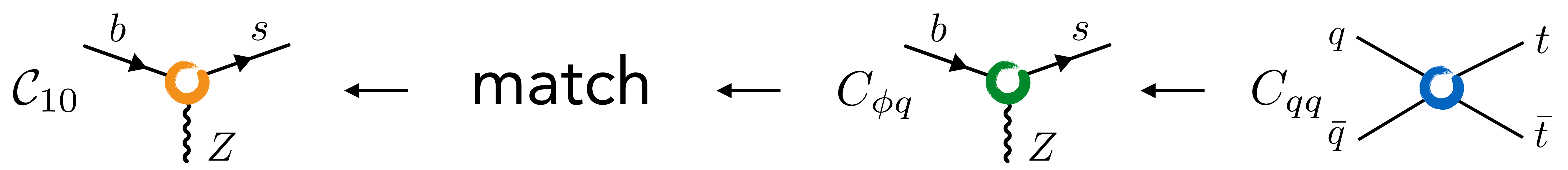

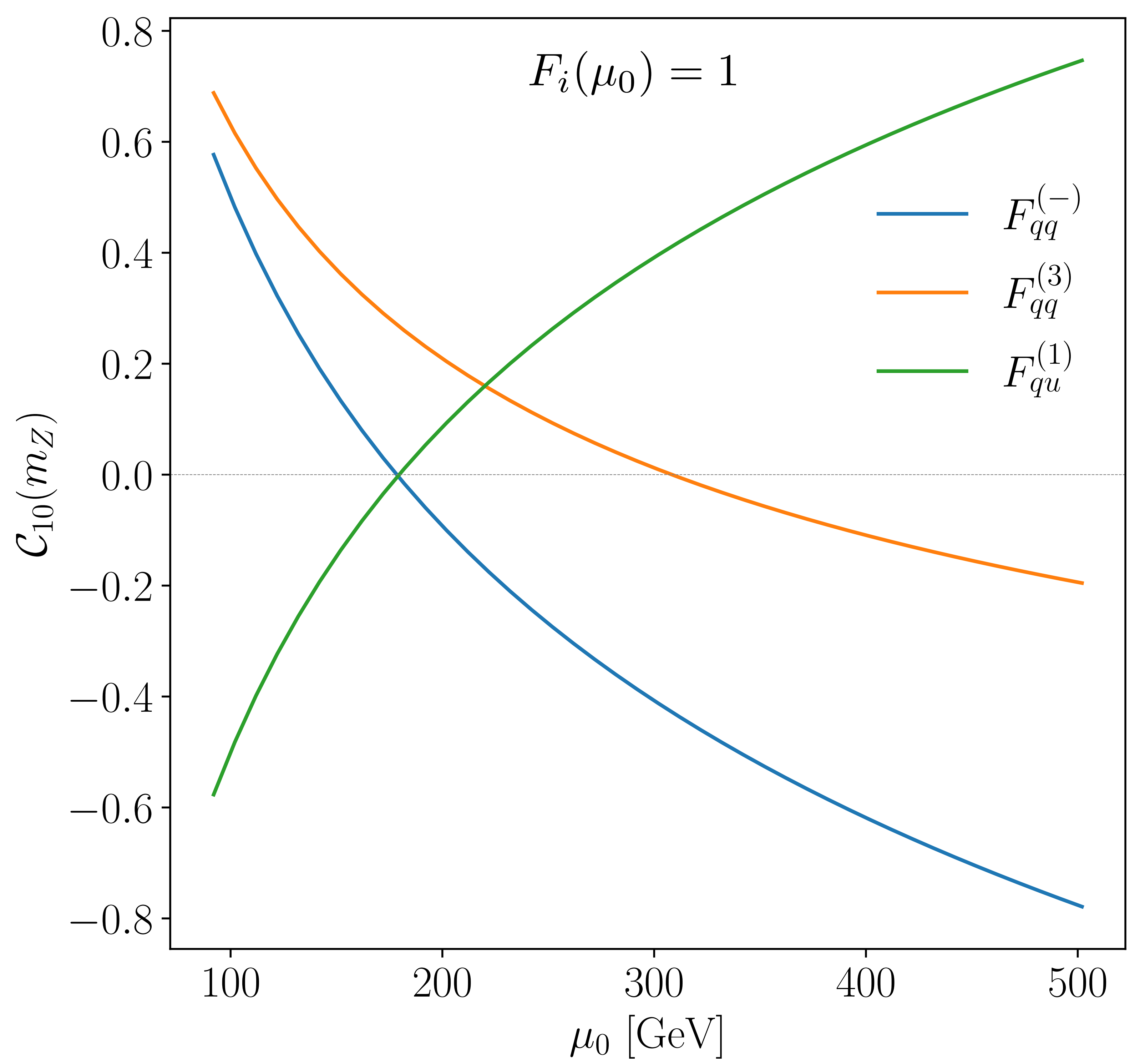

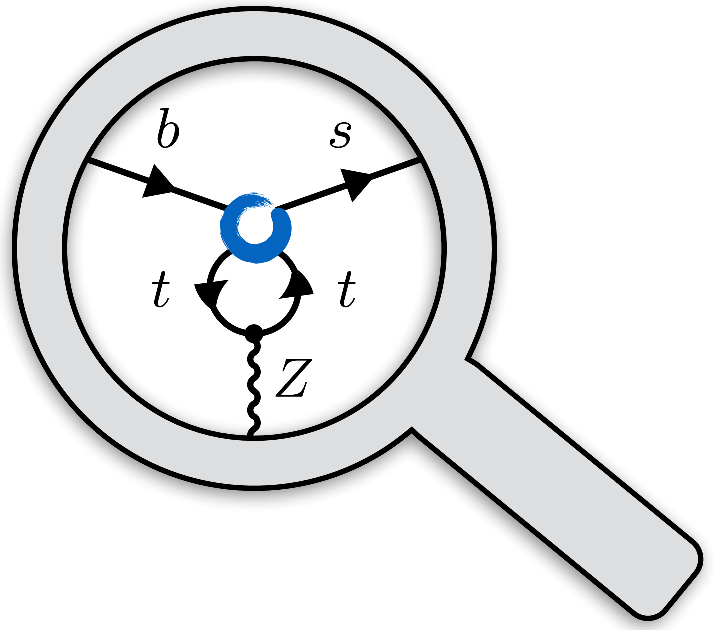

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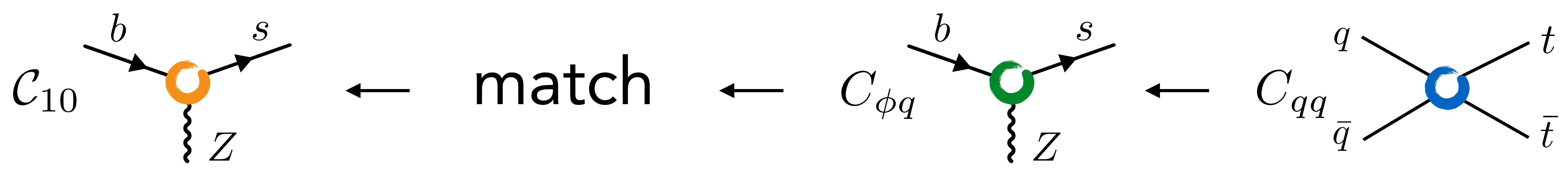

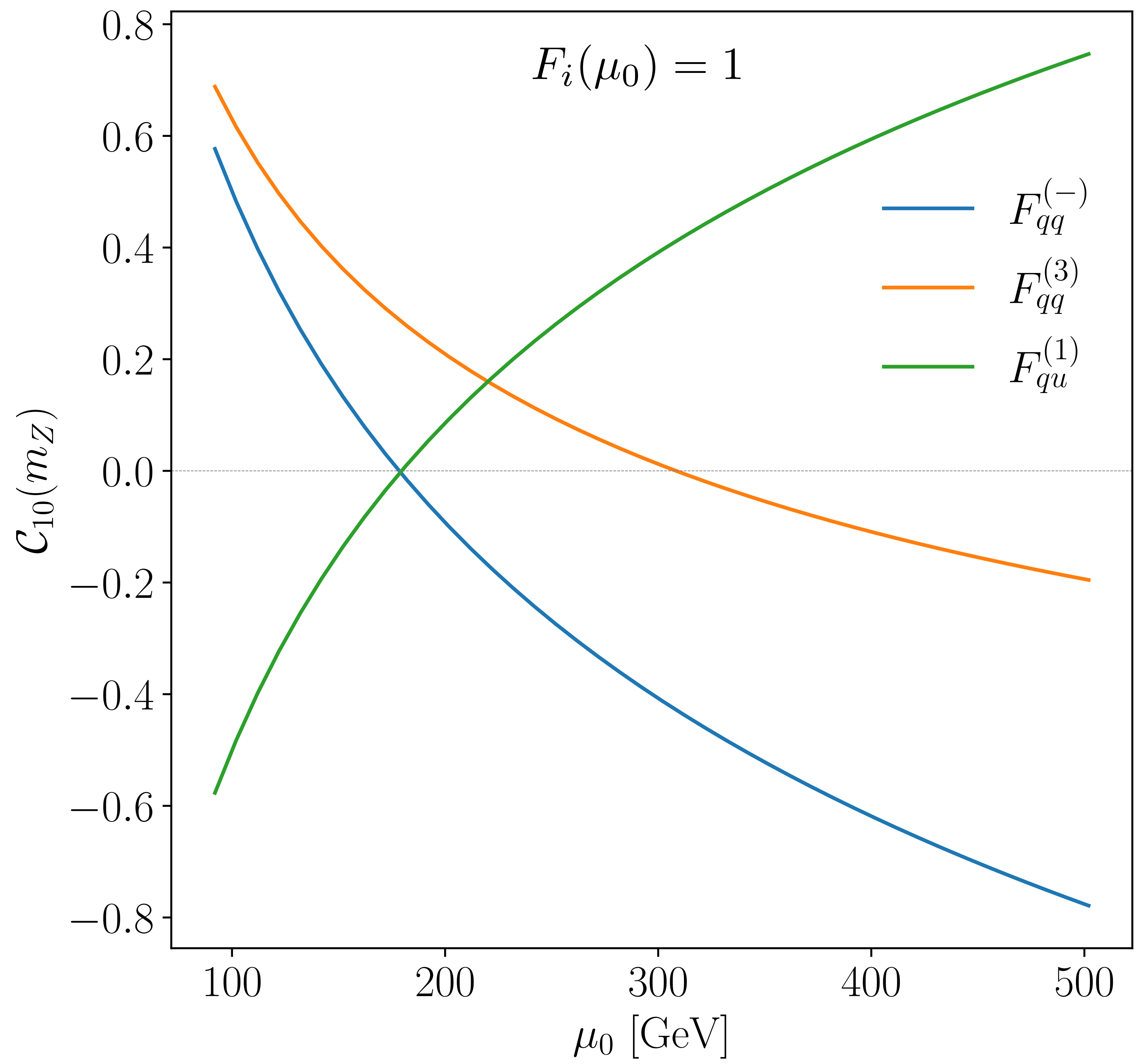

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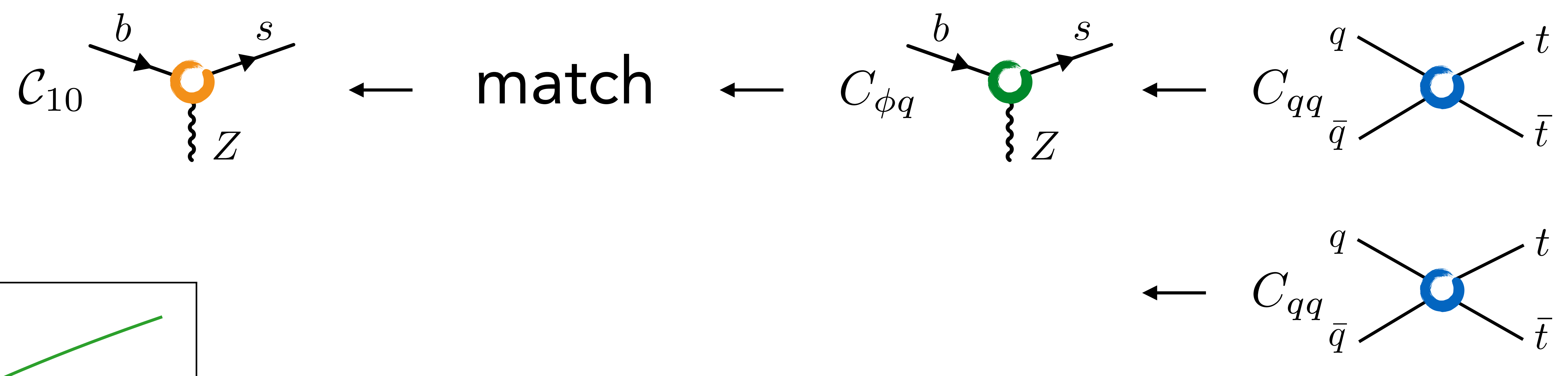

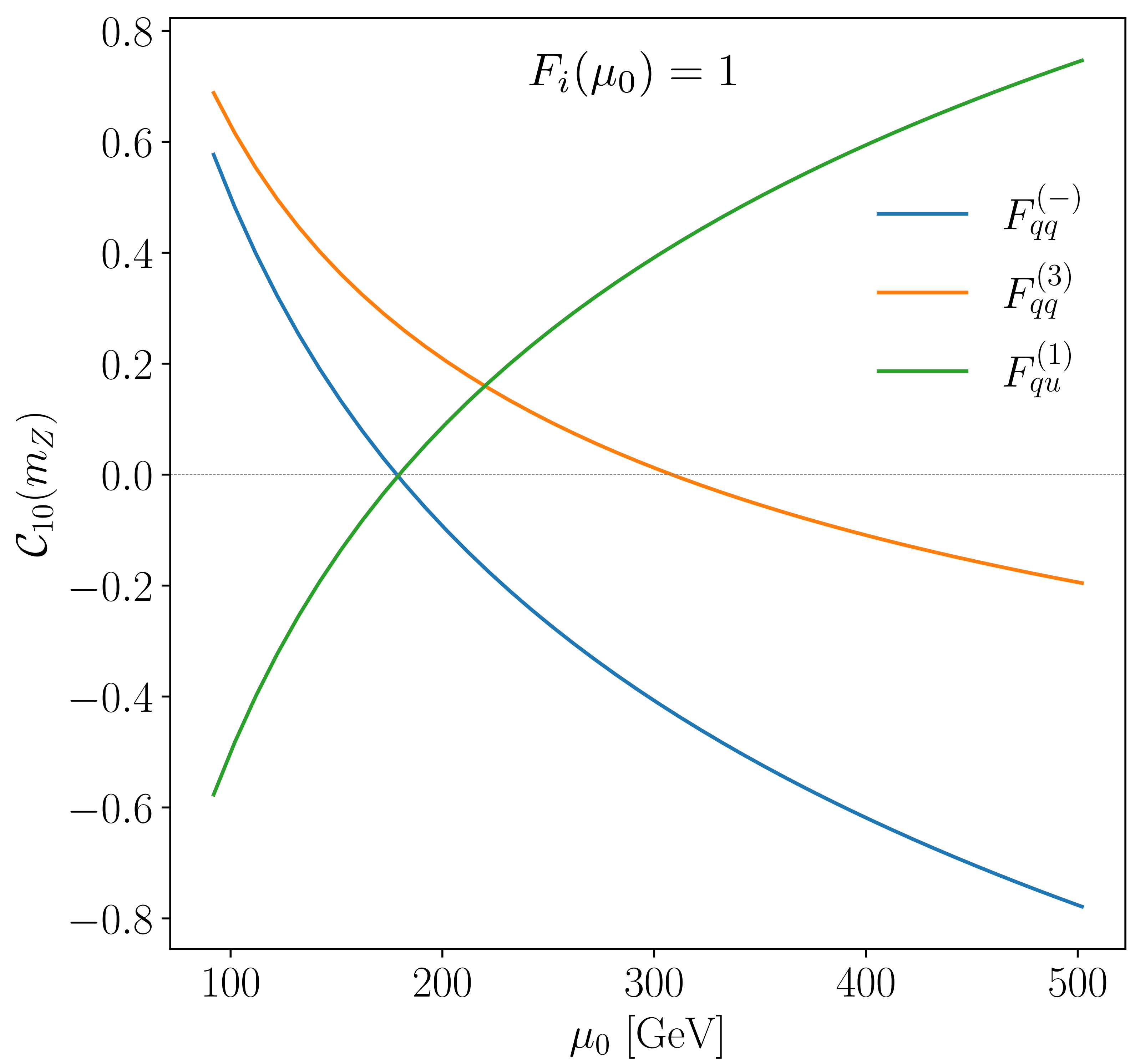

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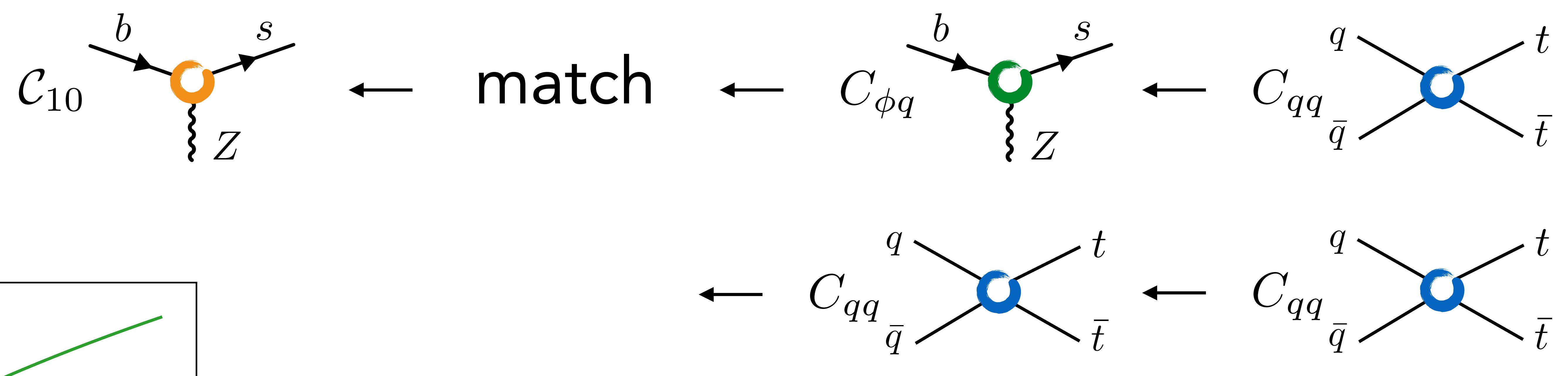

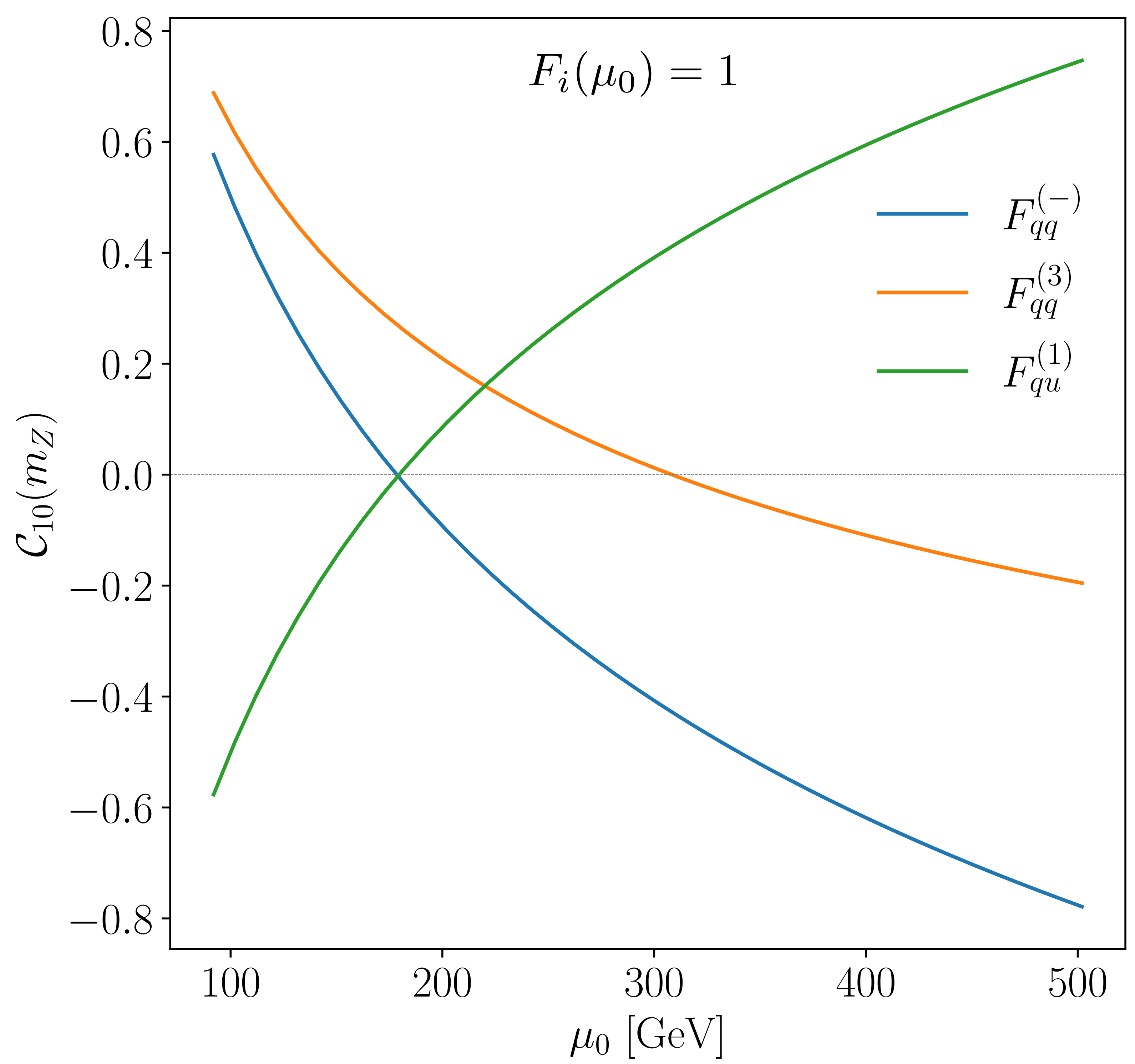

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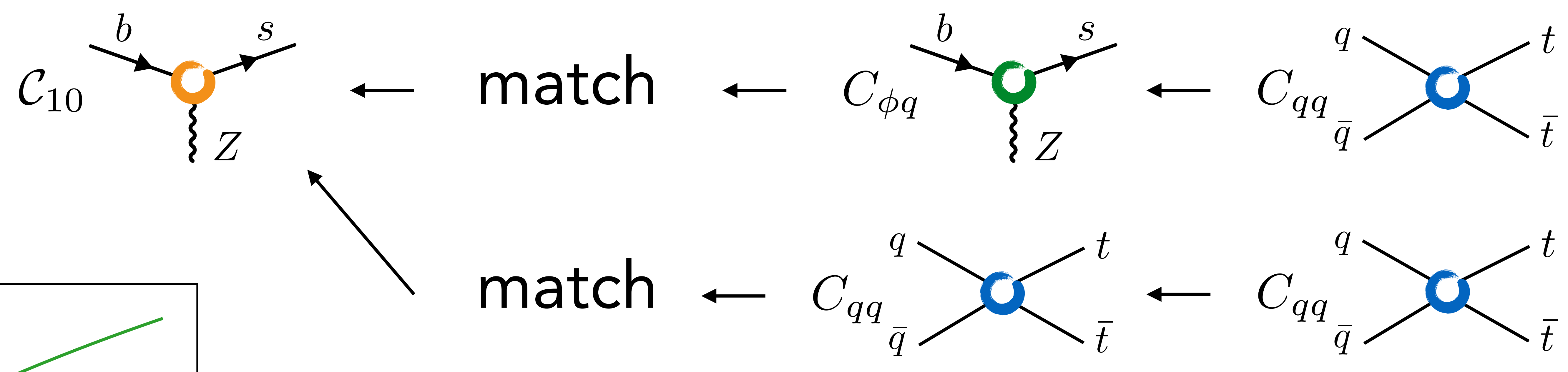

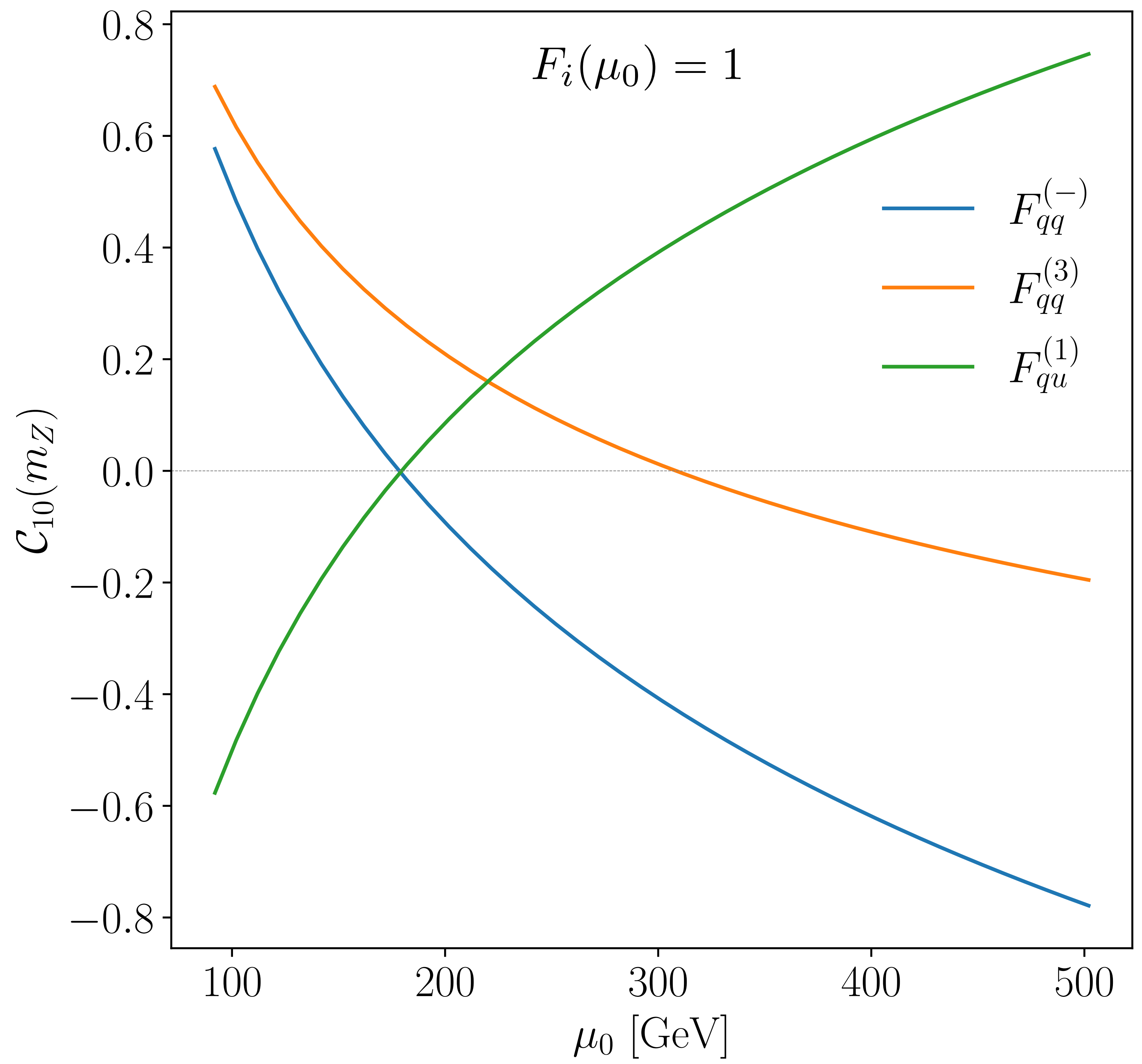

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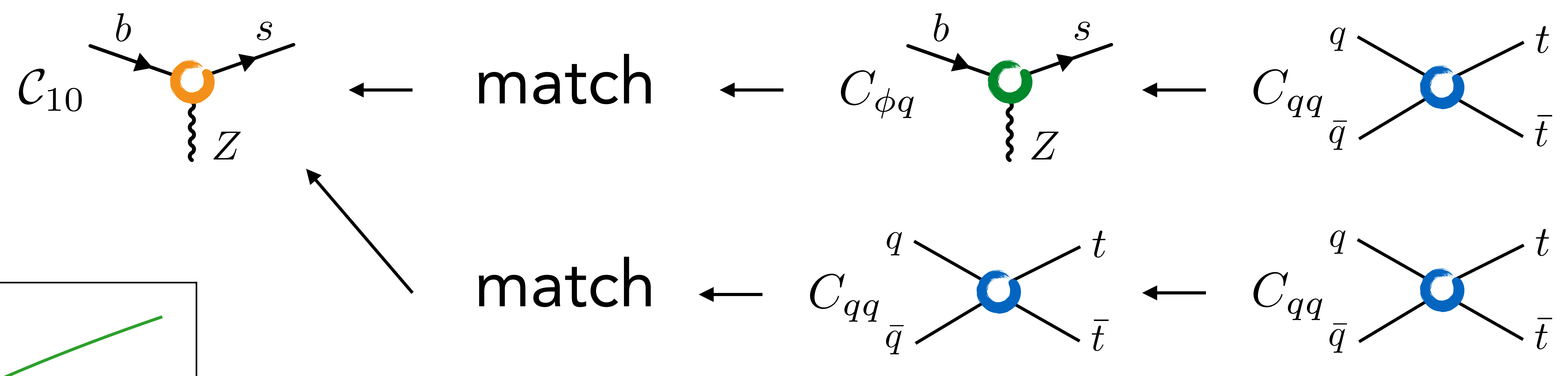

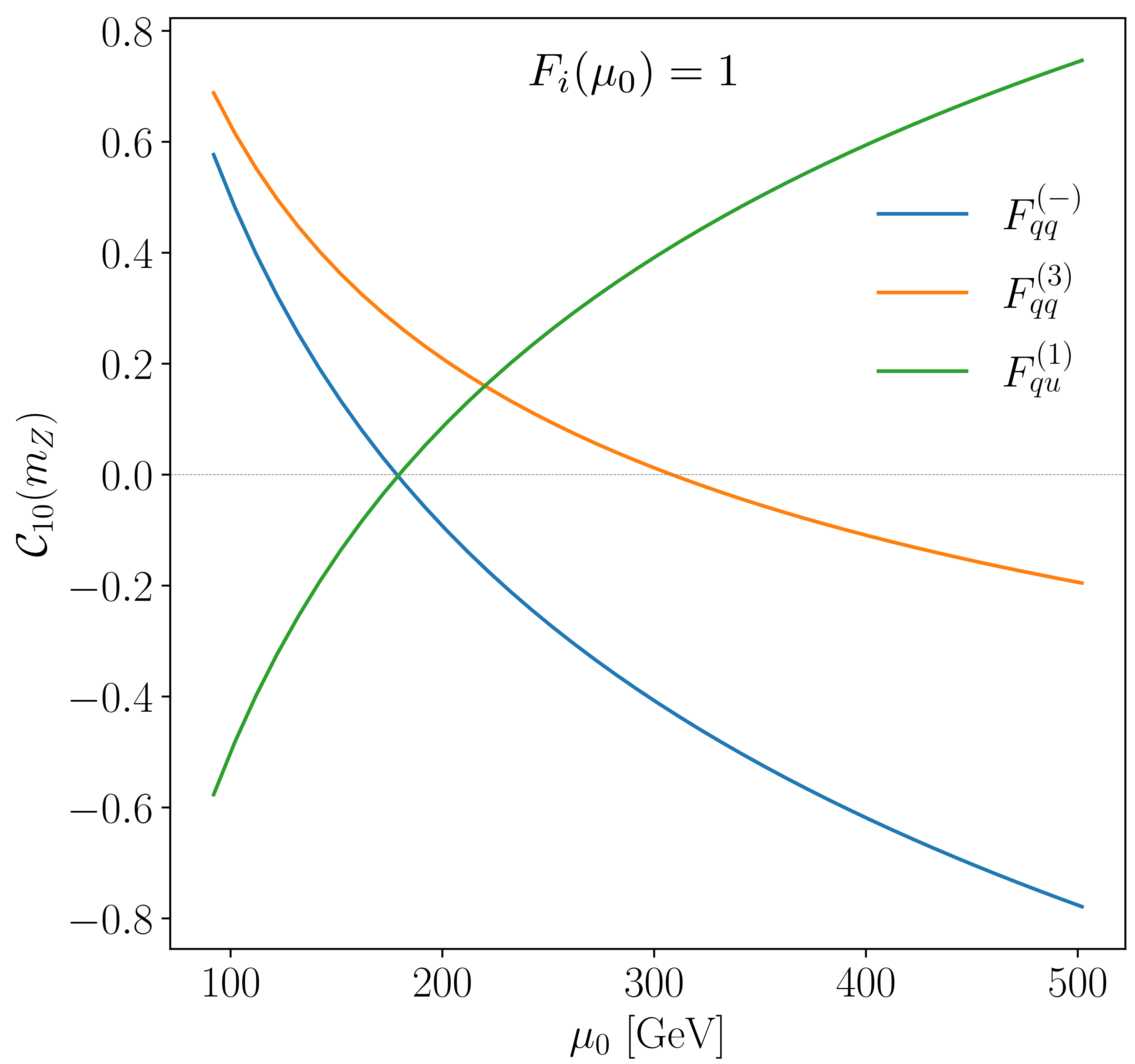

→ better to include complete set of operators in fit!

Slide adapted from Susanne Westhoff

What about concrete models?

Example: Gauge-Tripplet extension

$$
\begin{aligned}
\mathcal{L} =& \mathcal{L}_{SM} - \frac{1}{4}\widetilde{V}^{\mu\nu A}\widetilde{V}^{A}_{\mu\nu} - \frac{\tilde{g}_M}{2}\widetilde{V}^{\mu\nu A}\widetilde{W}^{A}_{\mu\nu} + \frac{\tilde{m}_V^2}{2}\widetilde{V}^{\mu A}\widetilde{V}^{A}_{\mu} \\
&+ \sum_f \tilde{g}_f \widetilde{V}^{\mu A} J^{fA}_{\mu} + \tilde{g}_H \widetilde{V}^{\mu A} J^{HA}_{\mu} + \frac{\tilde{g}_{VH}}{2}|\phi|^2 \widetilde{V}^{\mu A}\widetilde{V}^{A}_{\mu}
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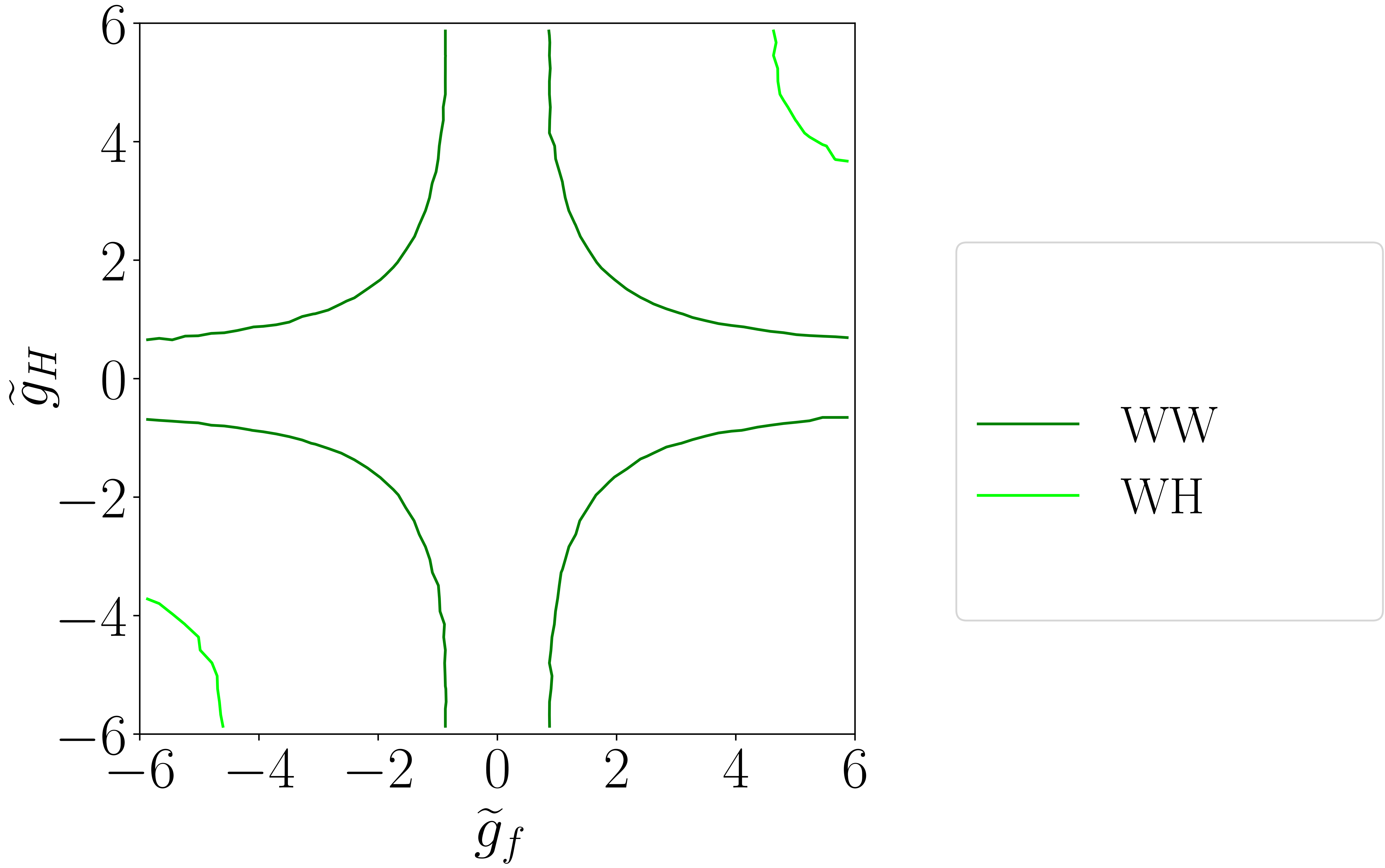
Example: Gauge-Tripplet extension

- m_V = 4 TeV
- *WW* and *WH* resonance searches up to 4 TeV
- 1-Loop matching



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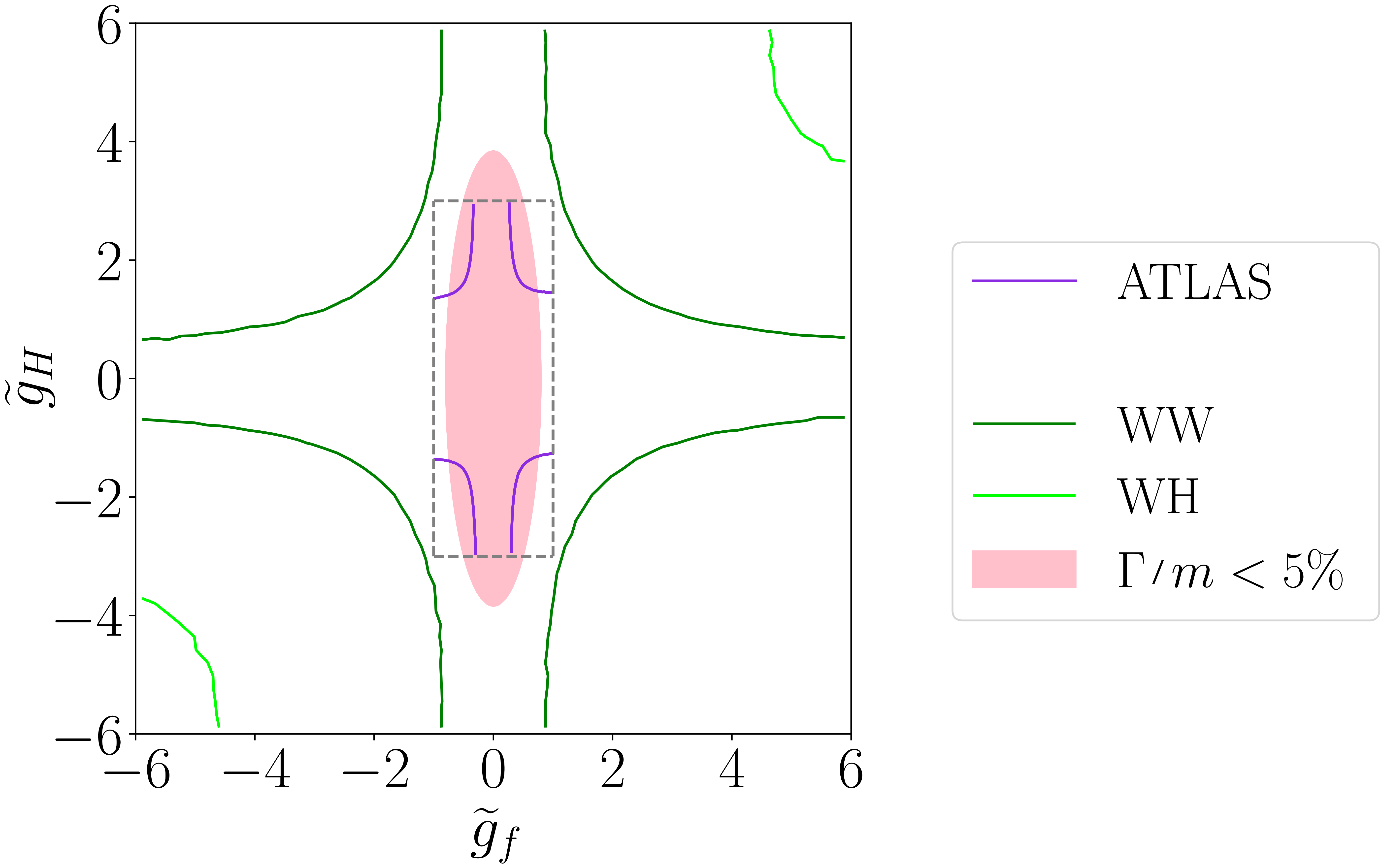

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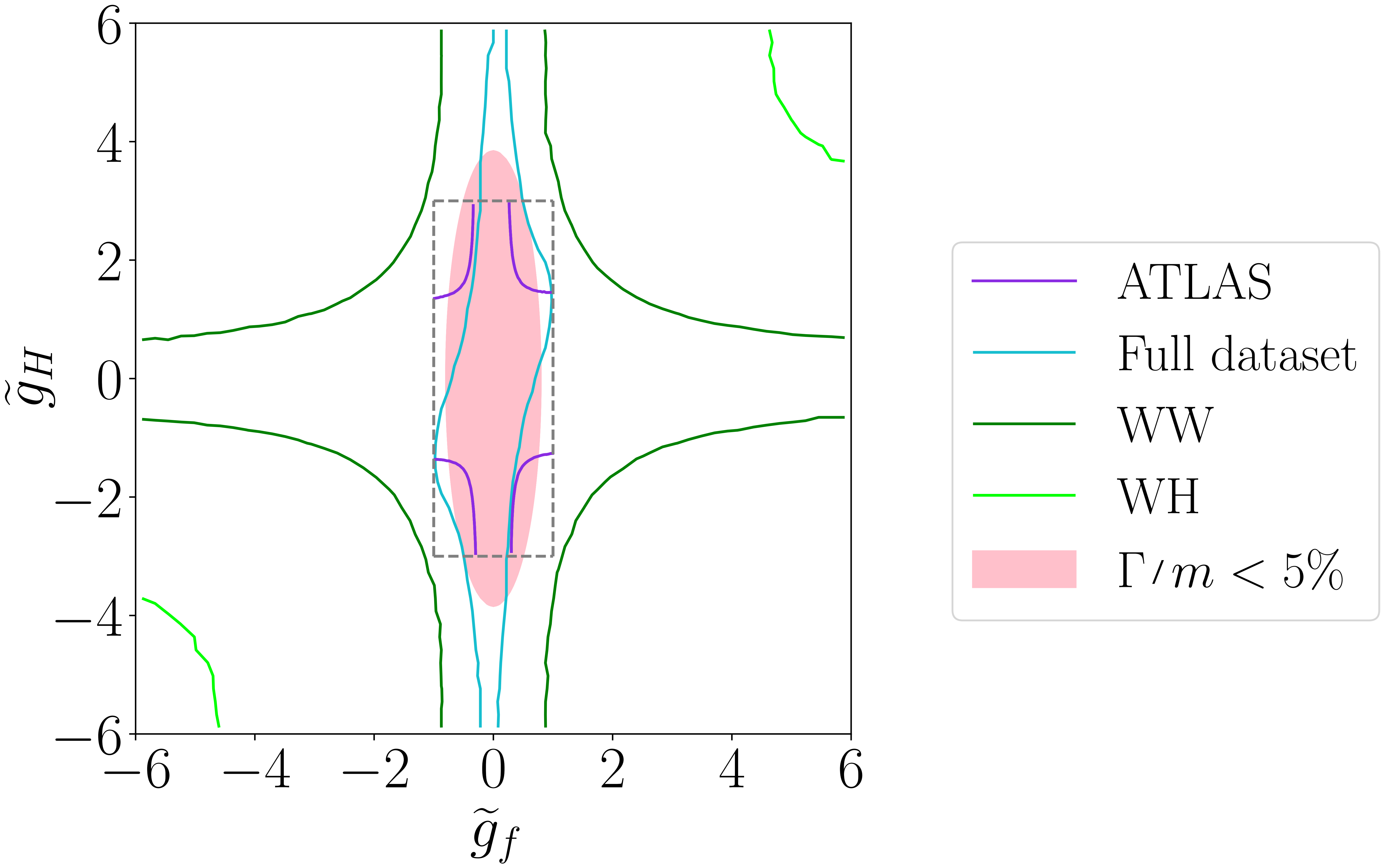

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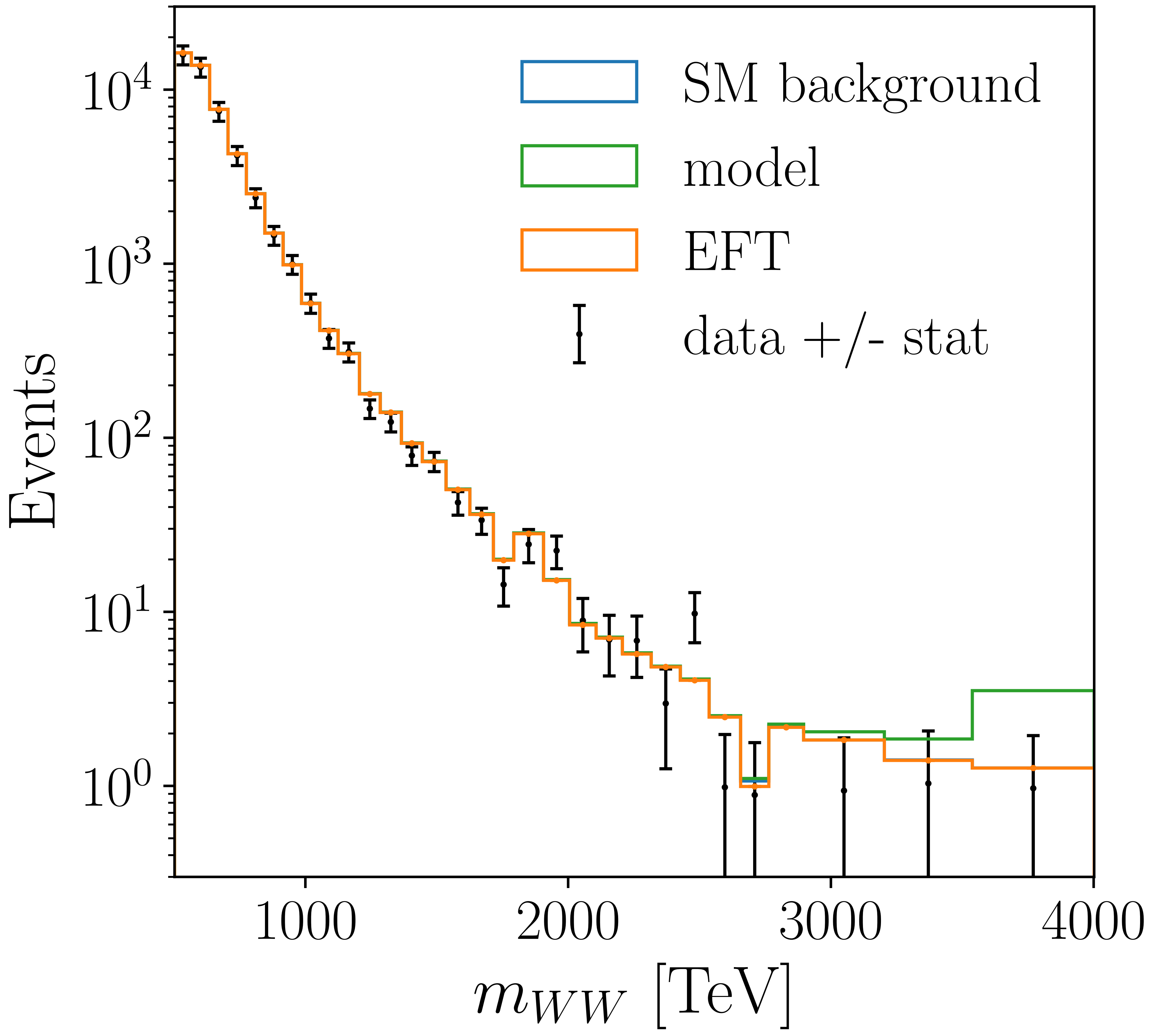

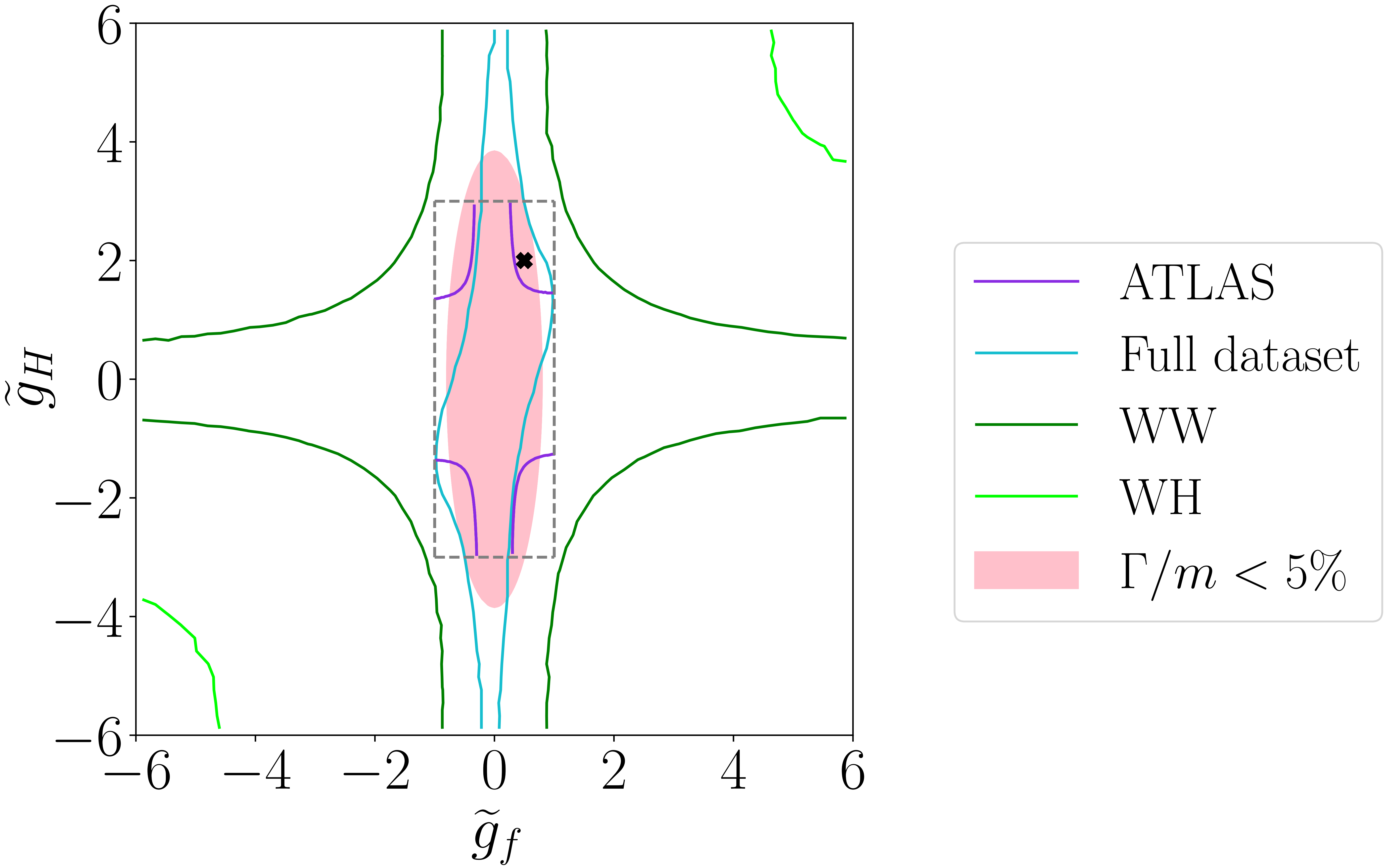

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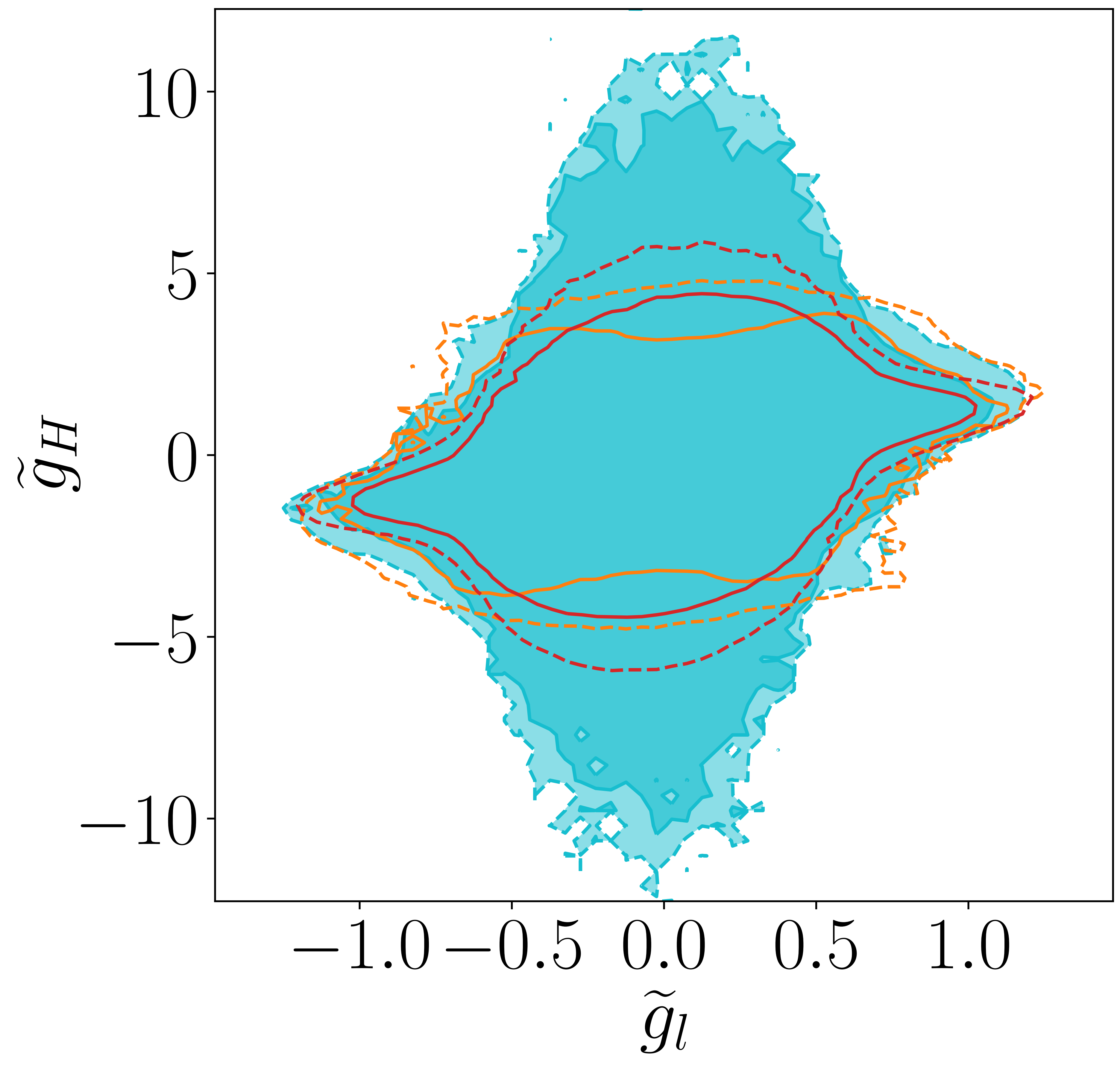
m_V = 4 TeV

5 Parameter Fit

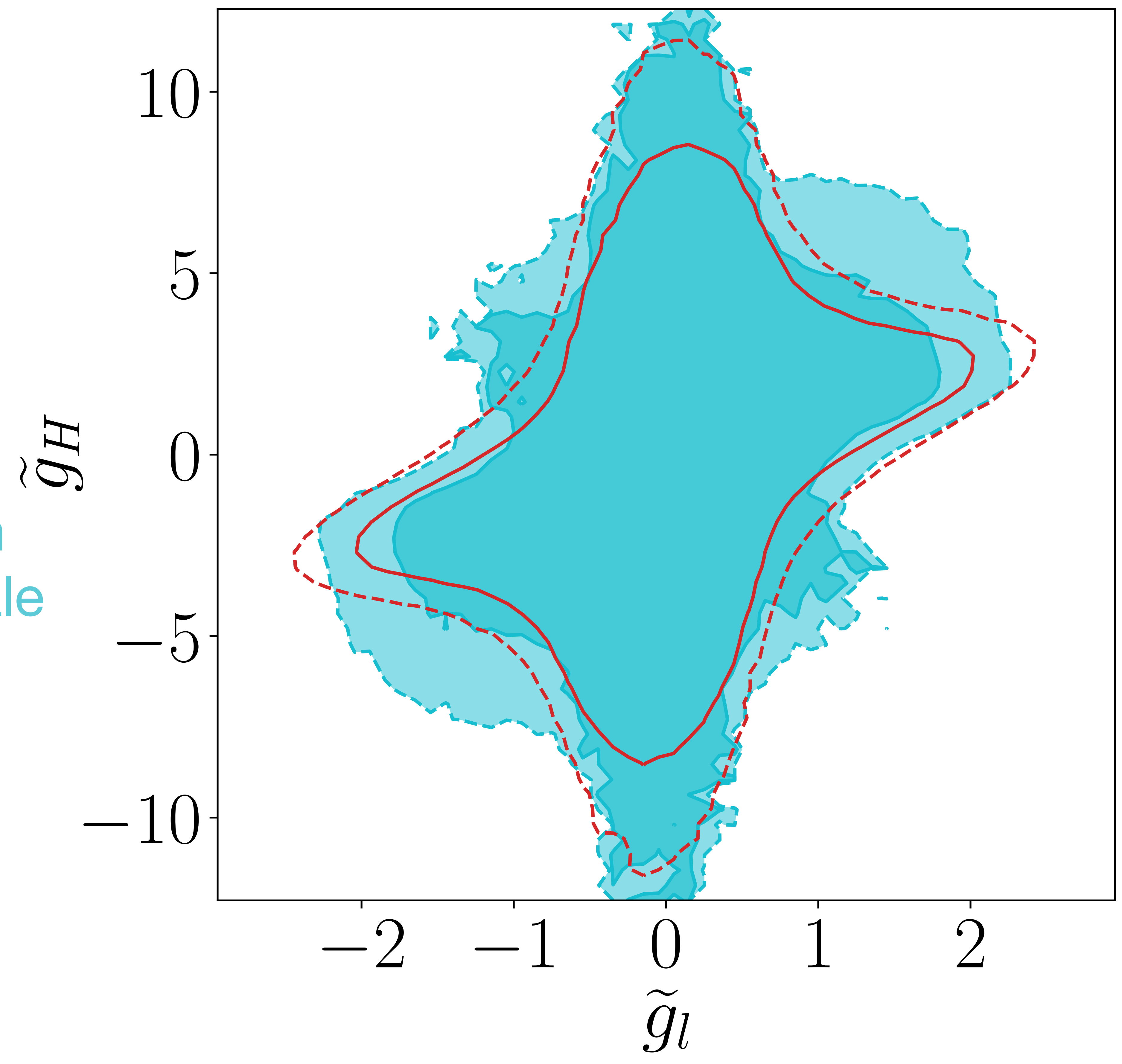
m_V = 8 TeV



Tree level

1-Loop

1-Loop with matching scale



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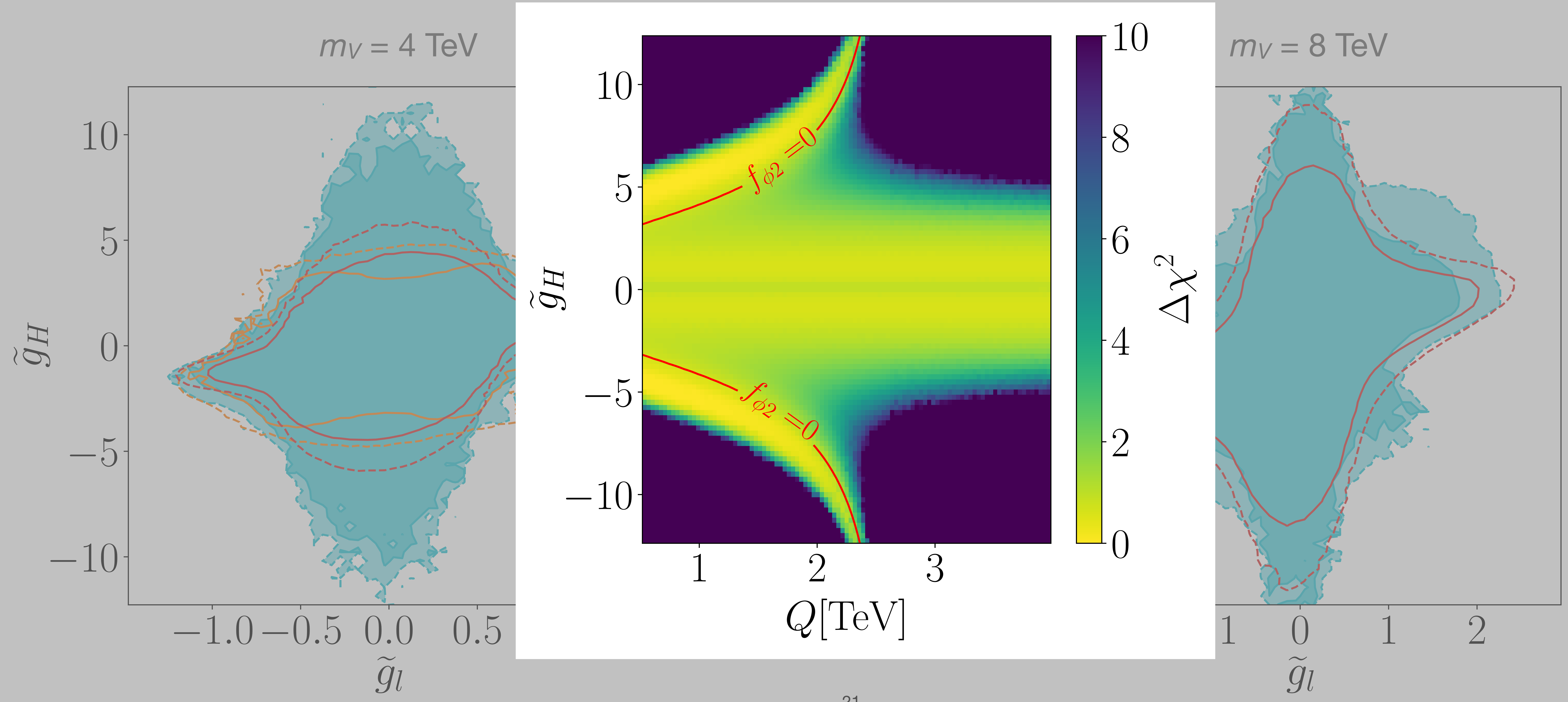

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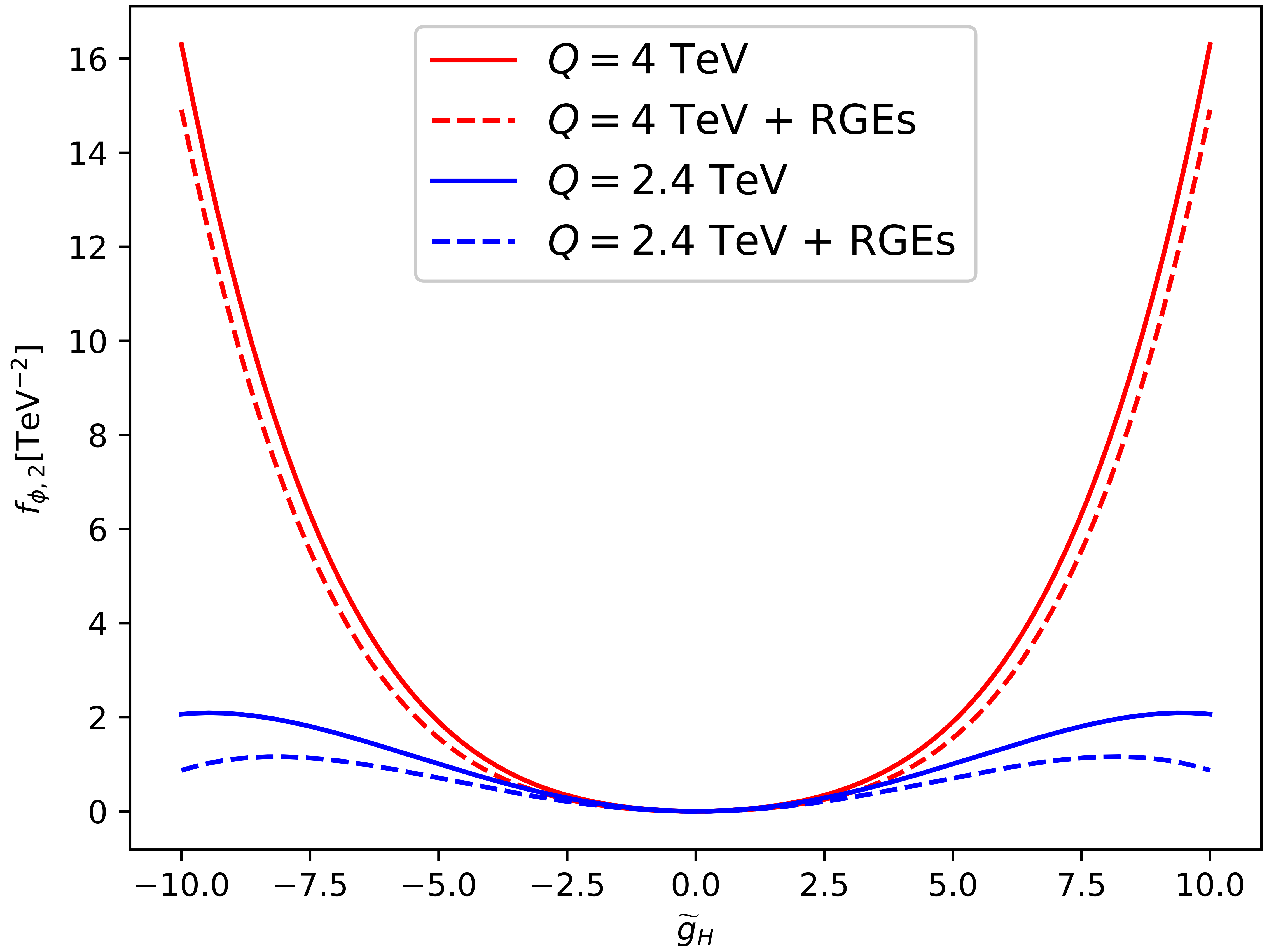
  - ...

Matching Scale



The Data

Where the sensitivity comes from

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$$O_{tG} = C_{tG}(\bar{q}_3\sigma^{\mu\nu}T^A u_3)\tilde{\phi}G^A_{\mu\nu}$$

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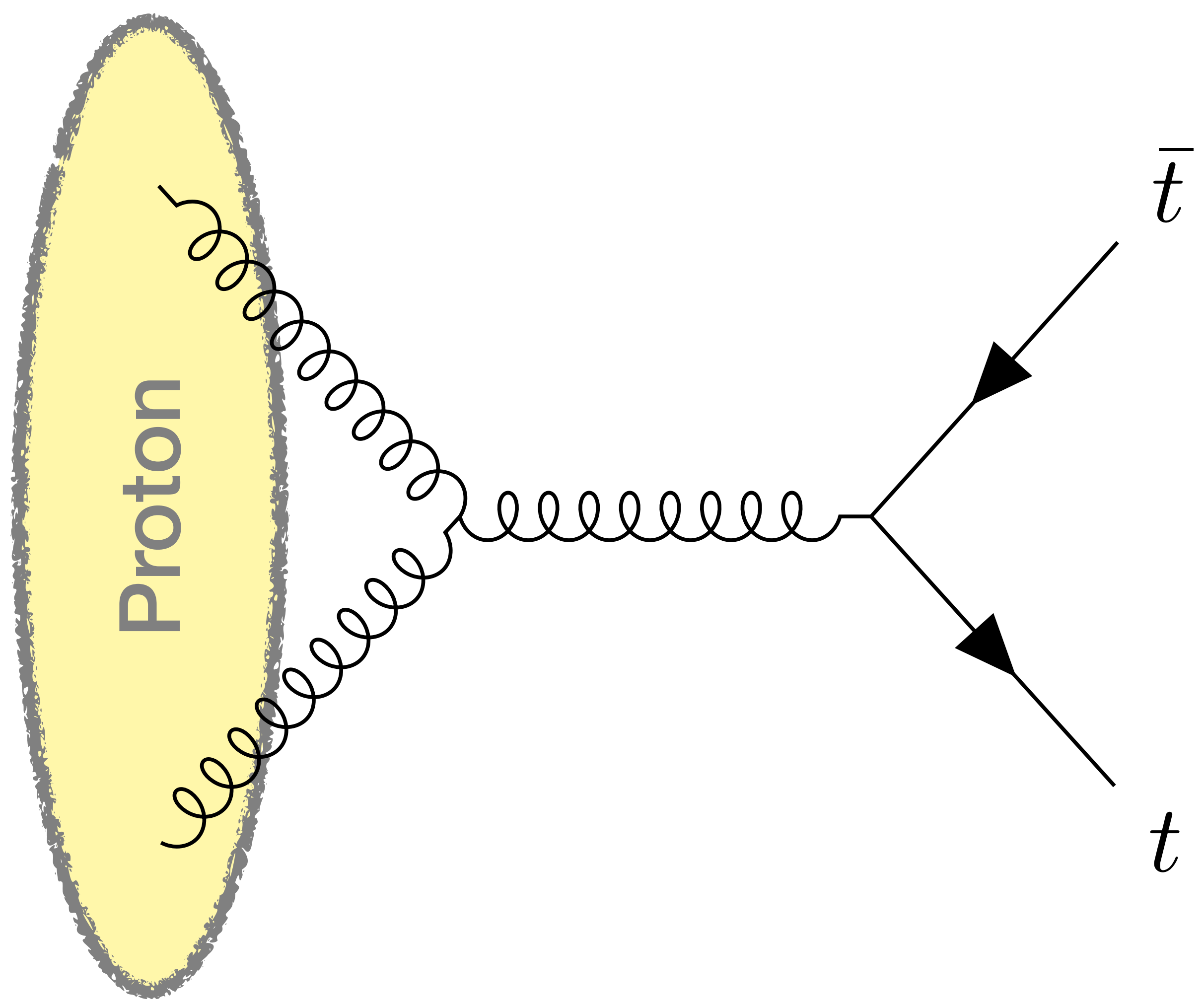

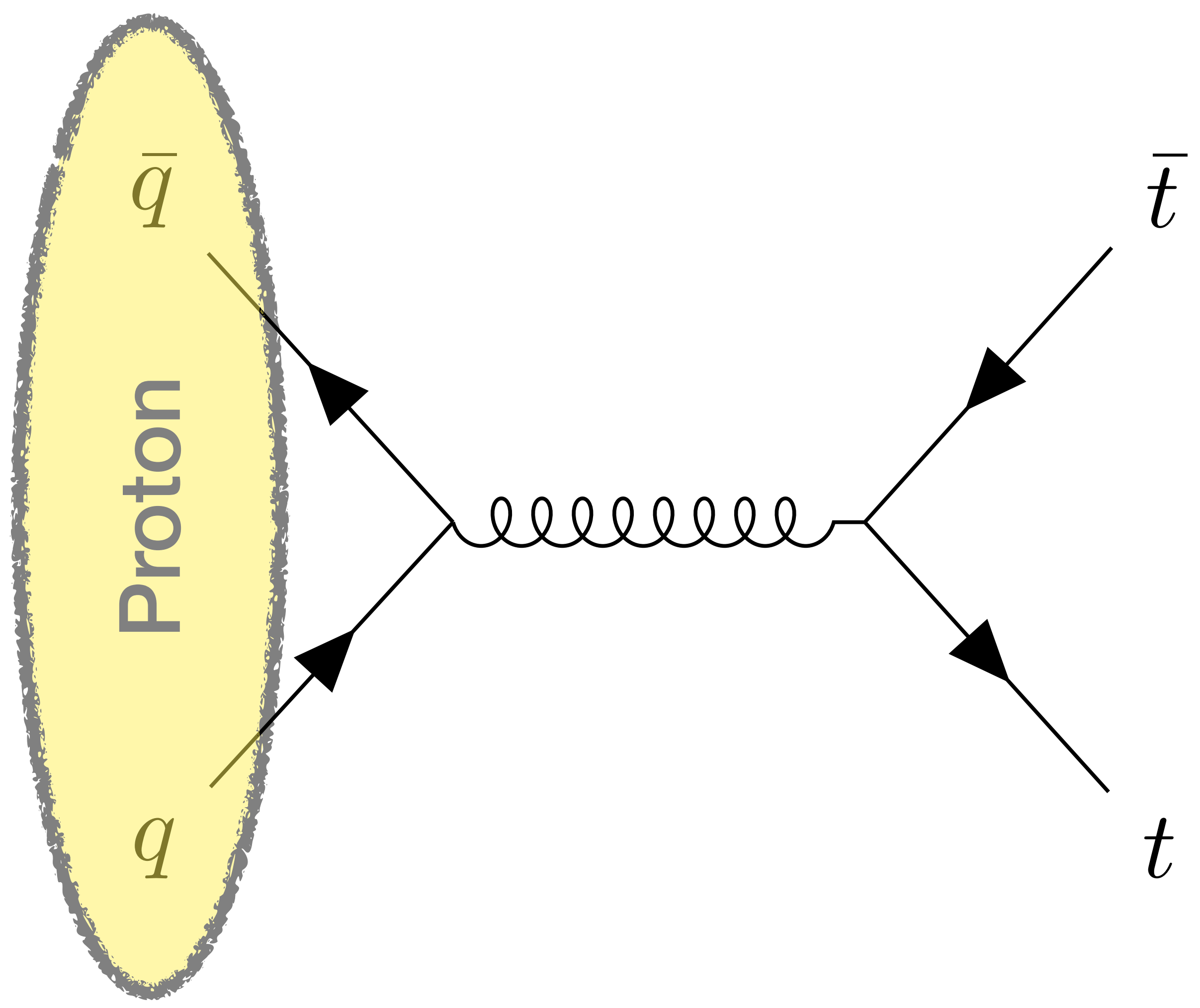

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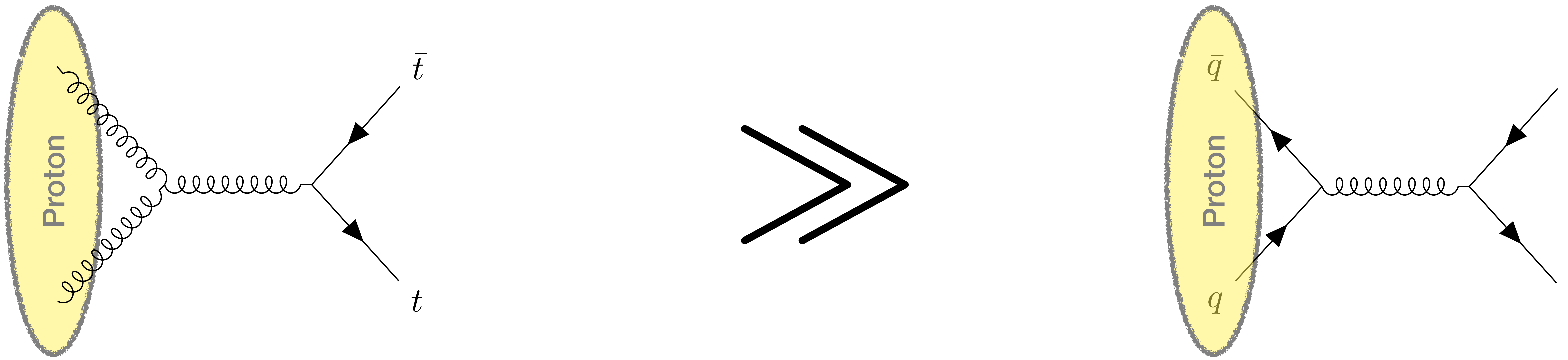
$$O^8_{tu} = C^8_{tu}(\bar{u}_3 \gamma^\mu T^A u_3)(\bar{u}_i \gamma_\mu T^A u_i)$$



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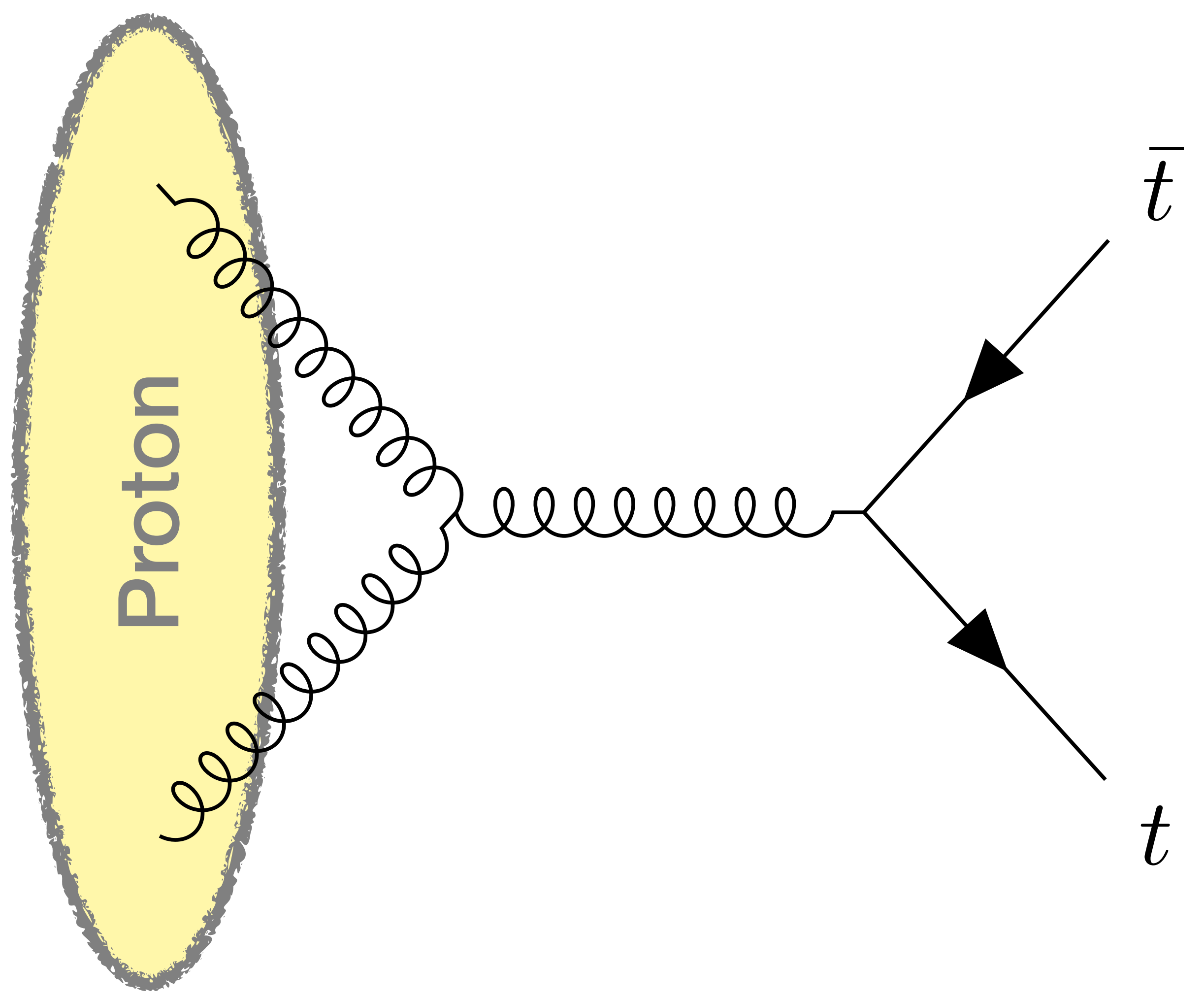
$$\frac{1}{\sigma}\frac{d\sigma}{dm_{t\bar{t}}} \approx \frac{\sigma_{SM}(m_{t\bar{t}})}{\sigma_{SM}(2m_t}\left(1 + \mathcal{O}(1)\frac{C_{tG}}{\Lambda^2} + \mathcal{O}(m^2_{t\bar{t}})\frac{C^8_{tu}}{\Lambda^2}\right)$$



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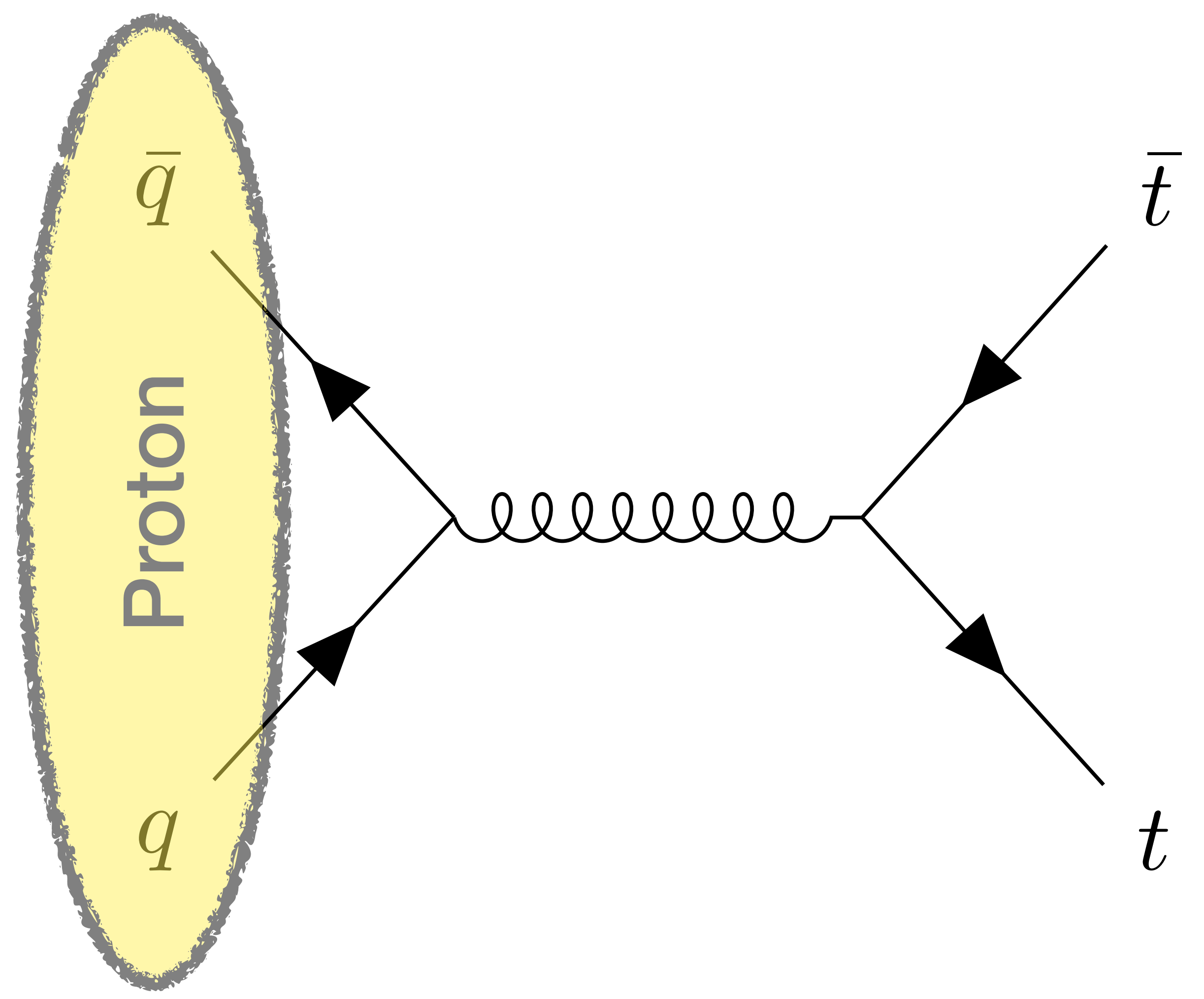

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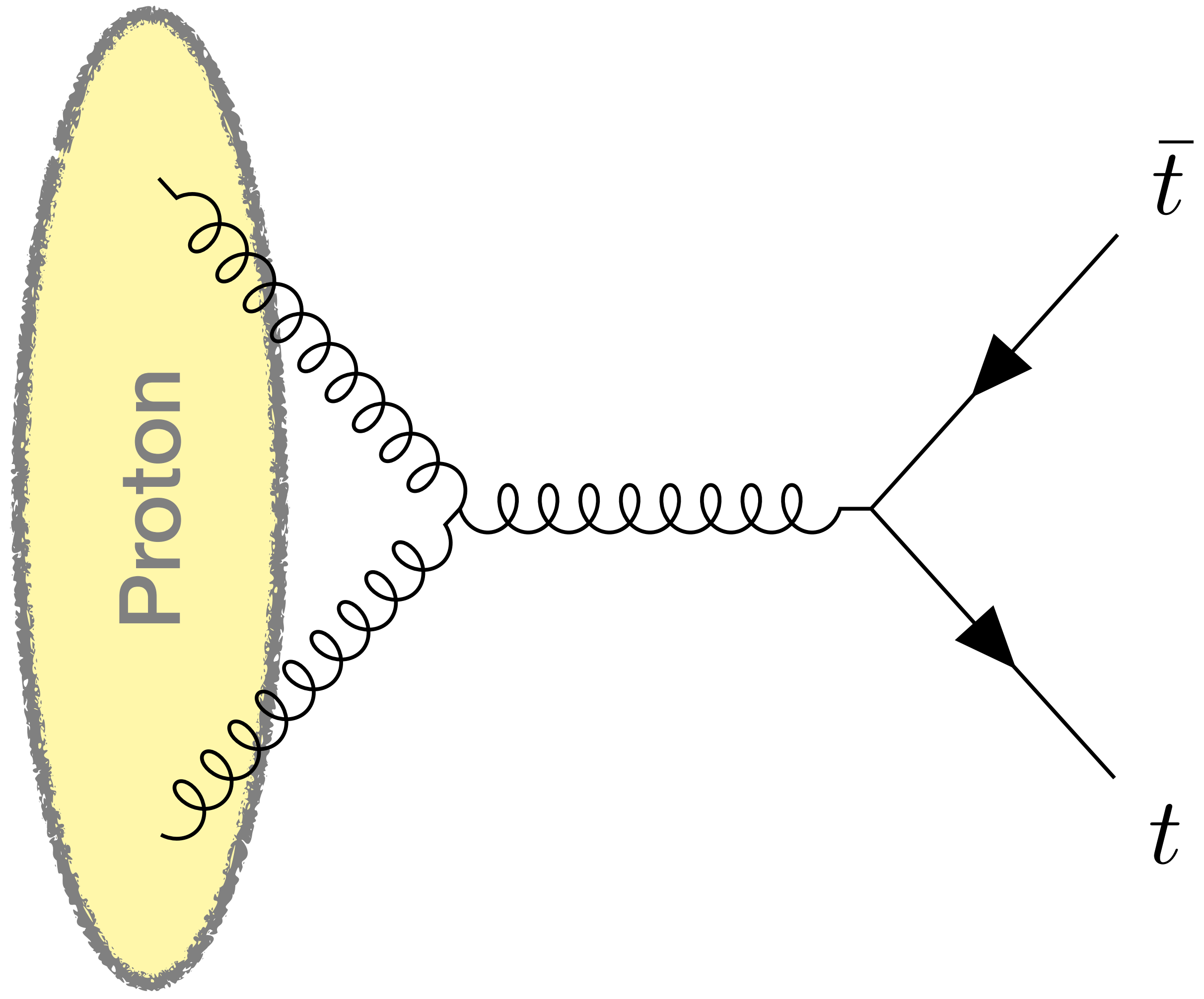

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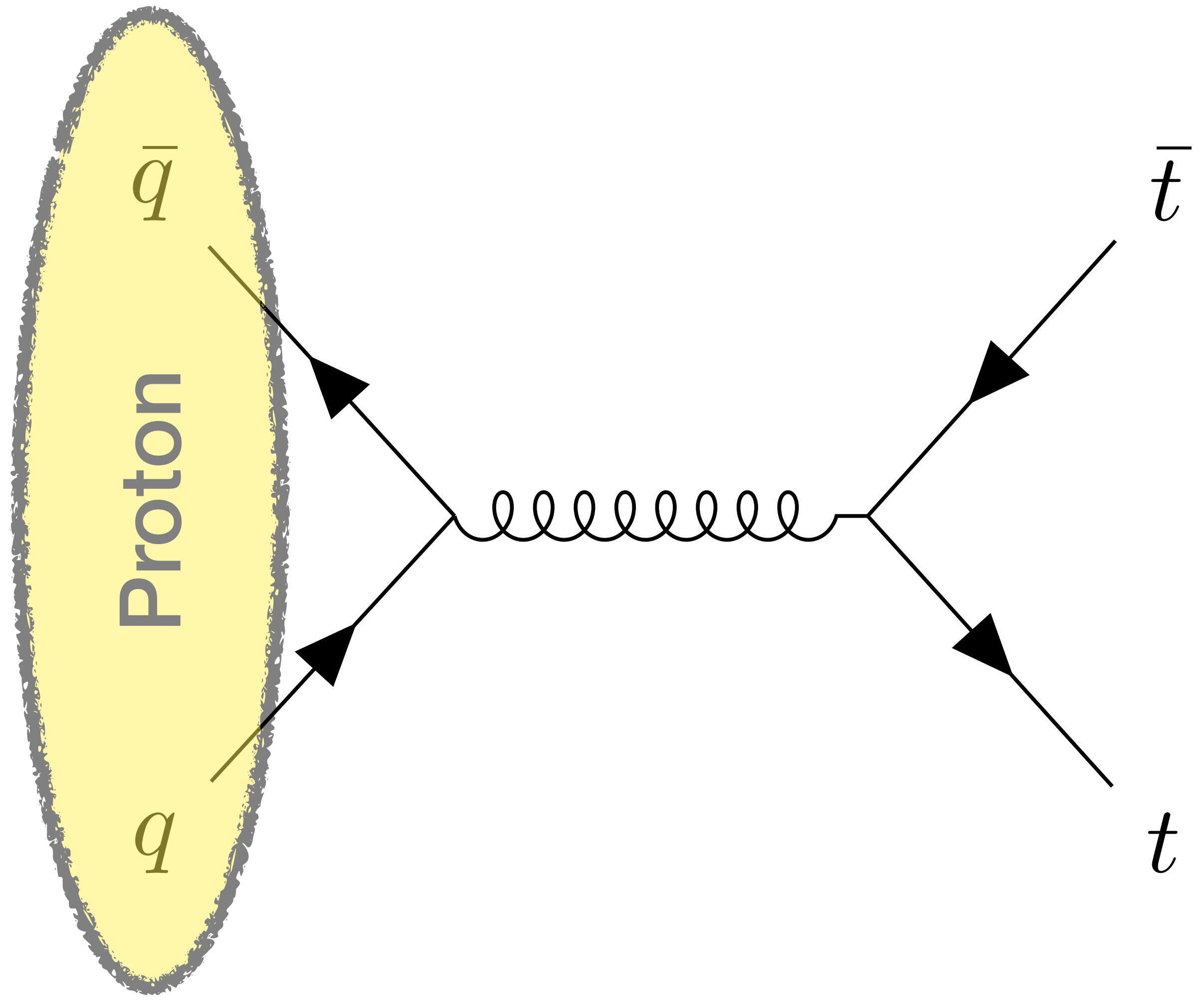

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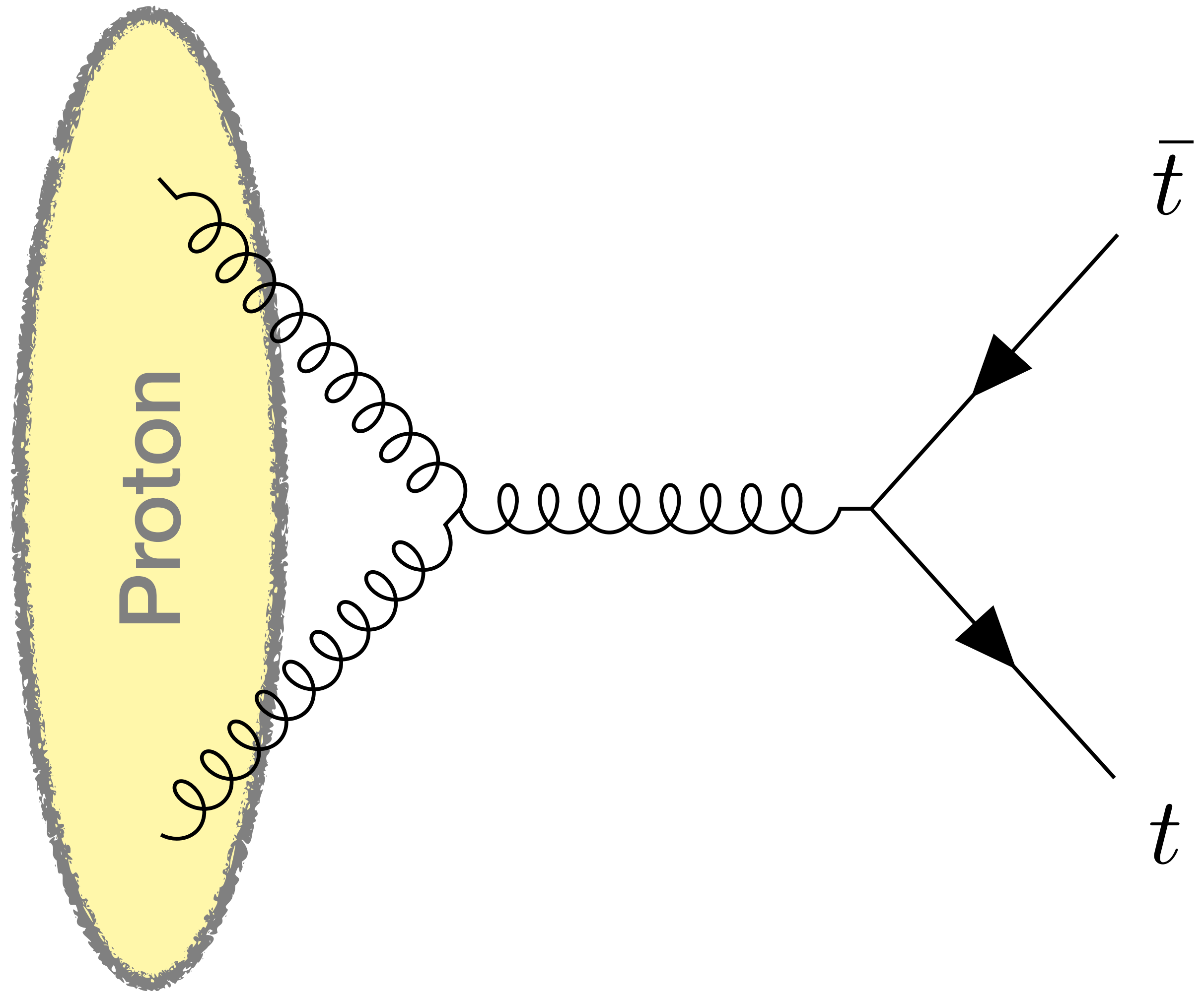
Stays small

Grows very large
for high bins



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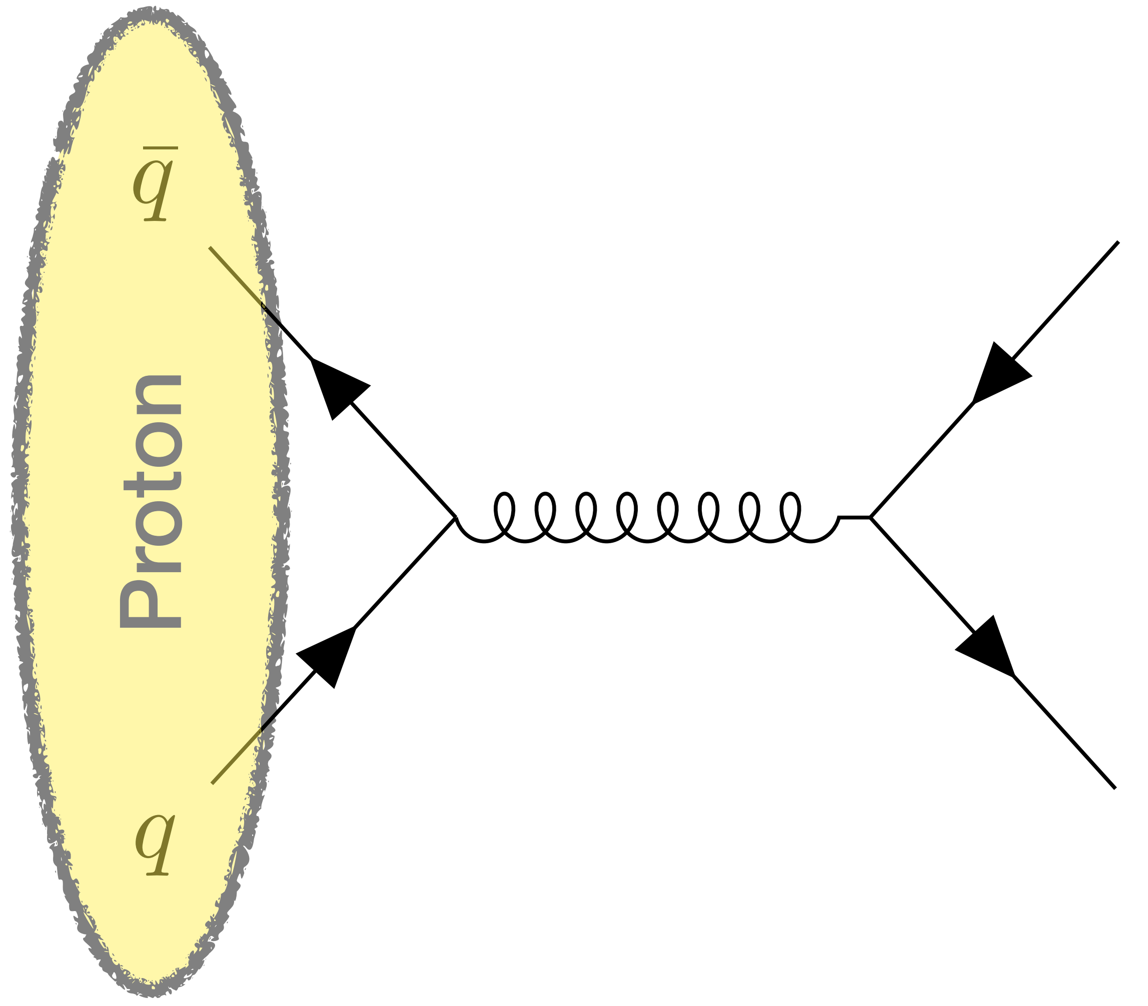

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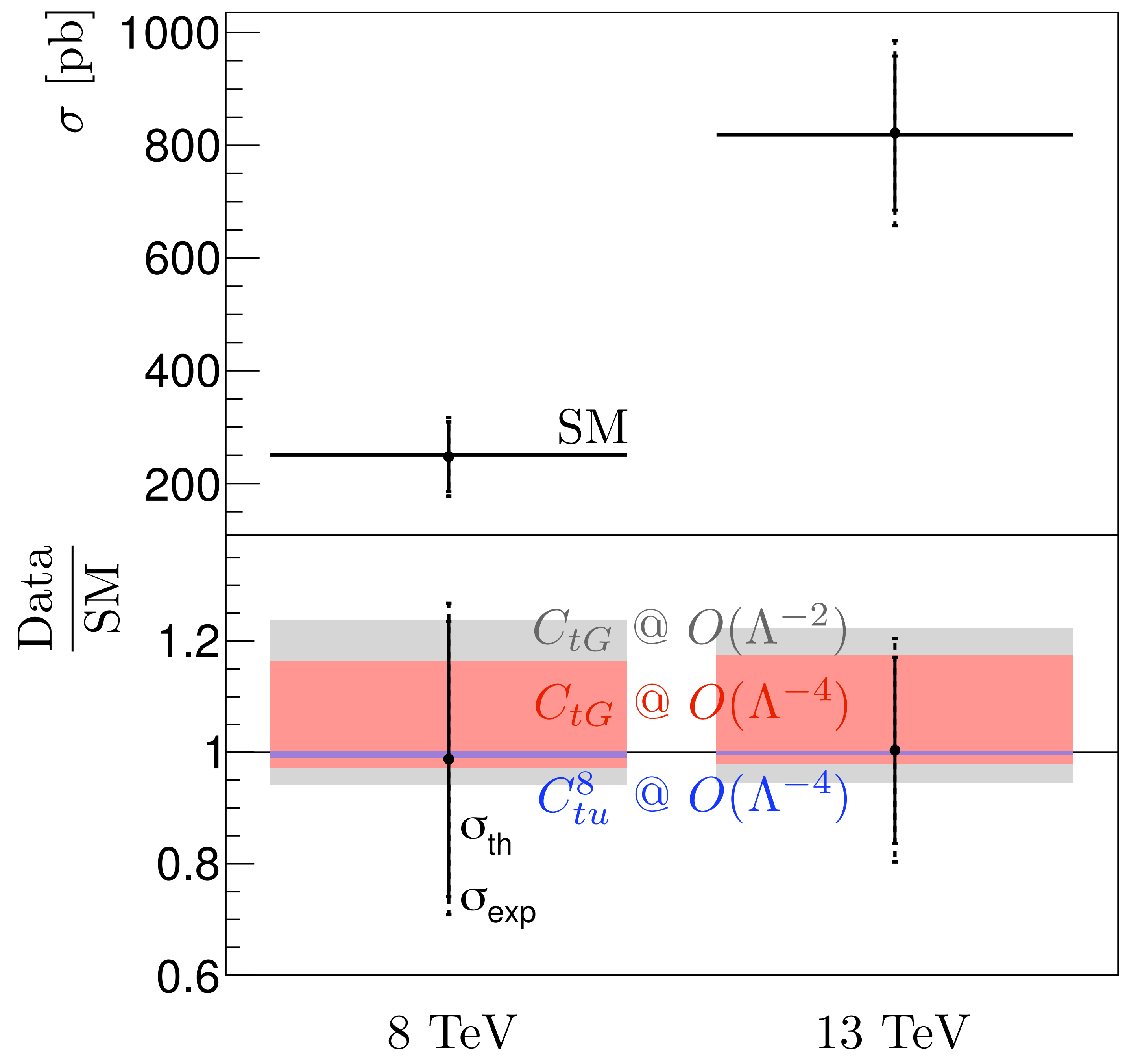

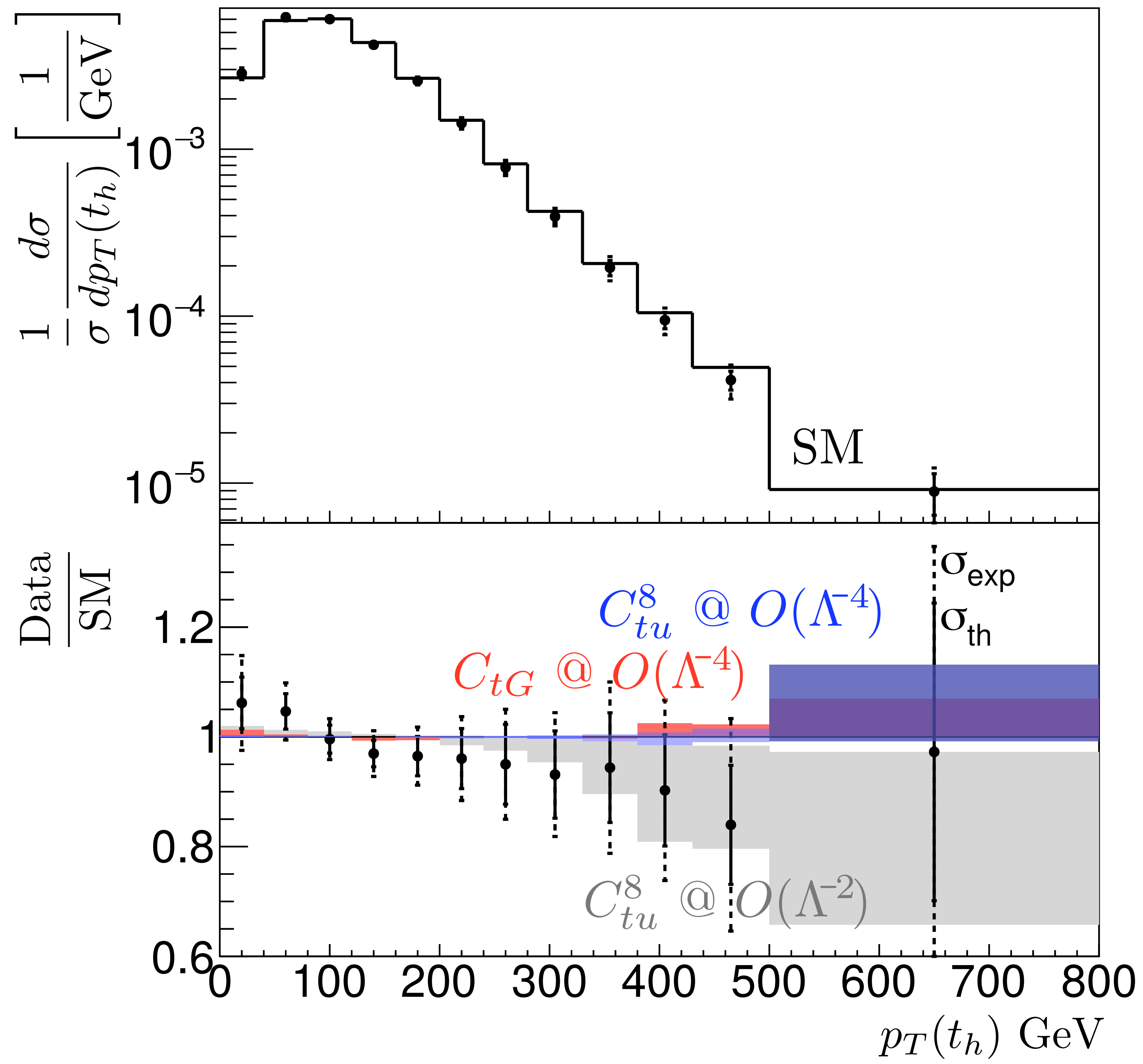

An Example: $C^1_{\phi Q}$ & $C^3_{\phi Q}$

$$[\mathcal{O}^1_{\phi q}]_{ij} = \left(\phi^\dagger\, i\, \overleftrightarrow{D}_\mu\, \phi\right)(\bar{q}_i \gamma^\mu q_j)$$

$$[\mathcal{O}^3_{\phi q}]_{ij} = \left(\phi^\dagger i \overleftrightarrow{D}^I_\mu \phi\right)(\bar{q}_i \gamma^\mu \tau^I q_j)$$

$$C^{(-)}_{\phi Q} = C^1_{\phi Q} - C^3_{\phi Q}$$

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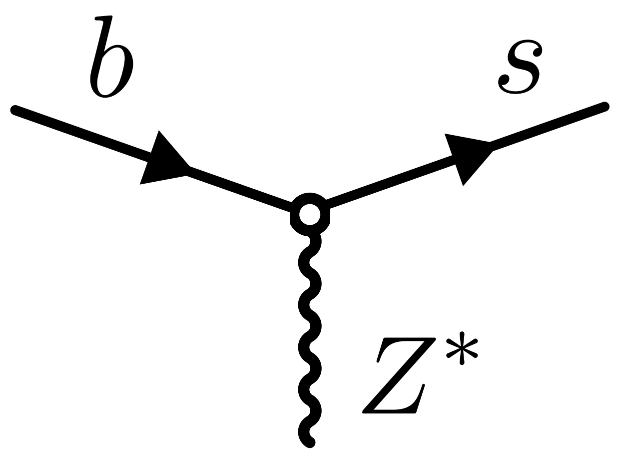
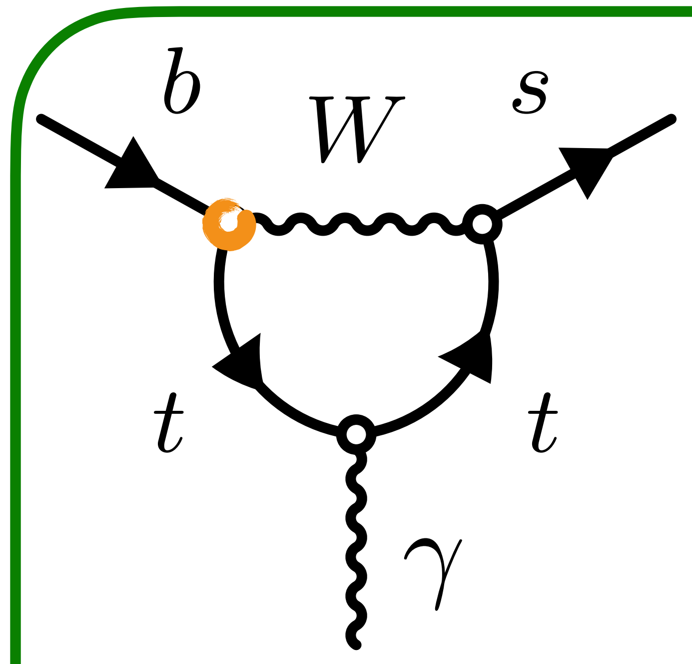
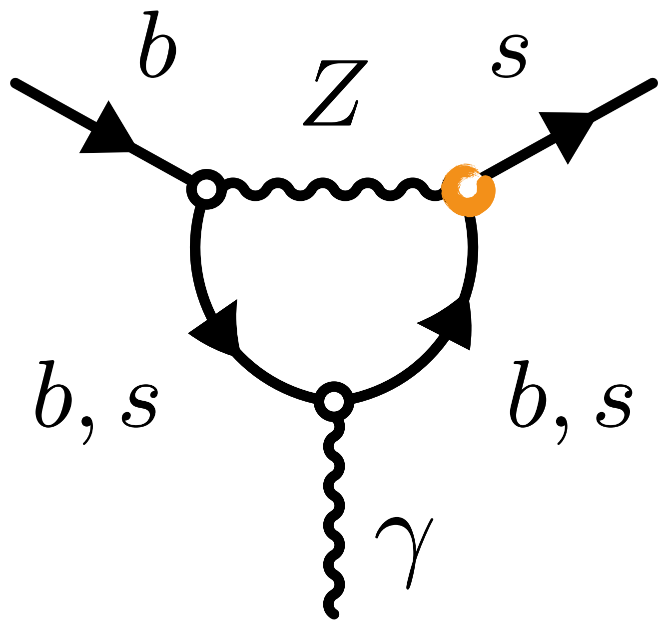


$b^{(+)}_{\phi q}\, y_t^2$

$$\mathcal{B}(B_s \to \mu^+\mu^-) \times 10^9 = 3.57 - 41.0\, b^{(+)}_{\phi q} + 117.8 (b^{(+)}_{\phi q})^2$$



$a^{(3)}_{\phi q} + b^{(3)}_{\phi q}\, y_t^2$



$b^{(3)}_{\phi q}$

$$\mathcal{B}(B \to X_s \gamma) \times 10^4 = 3.26 + 0.36\, a^{(3)}_{\phi q} - 0.76\, b^{(3)}_{\phi q}$$

An Example: $C^1_{\phi Q}$ & $C^3_{\phi Q}$

TTZ Production and EW effects

$$C^{(-)}_{\phi Q} = C^1_{\phi Q} - C^3_{\phi Q}$$

$$C^{(+)}_{\phi Q} = C^1_{\phi Q} + C^3_{\phi Q}$$

$$\{a^{(3)}_{\phi q}, b^{(3)}_{\phi q}, a^{(-)}_{\phi q}, b^{(-)}_{\phi q}\}$$

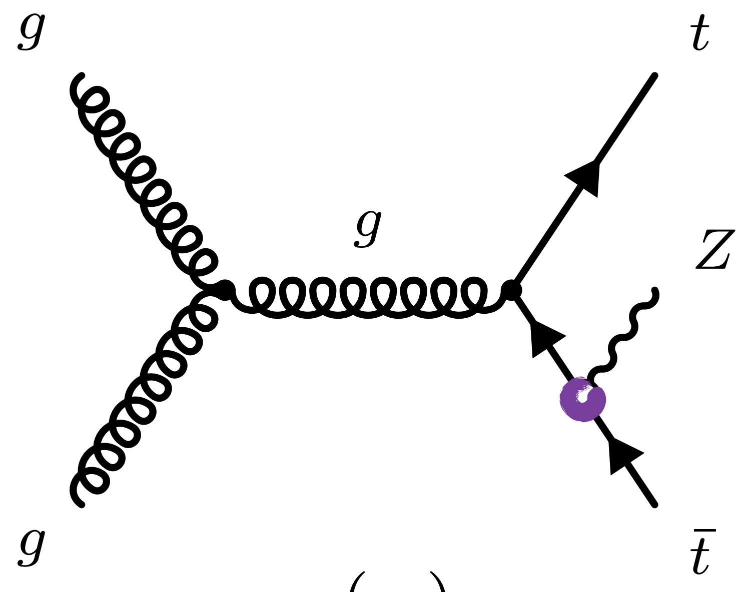
An Example: $C_{\phi Q}^{1}$ & $C_{\phi Q}^{3}$

TTZ Production and EW effects

$$C_{\phi Q}^{(-)} = C_{\phi Q}^{1} - C_{\phi Q}^{3}$$

$$C_{\phi Q}^{(+)} = C_{\phi Q}^{1} + C_{\phi Q}^{3}$$

$\{a_{\phi q}^{(3)}, b_{\phi q}^{(3)}, a_{\phi q}^{(-)}, b_{\phi q}^{(-)}\}$



$A_{\phi q}^{(-)}$

$A = a + y_t^2 b$

An Example: $C^1_{\phi Q}$ & $C^3_{\phi Q}$

TTZ Production and EW effects

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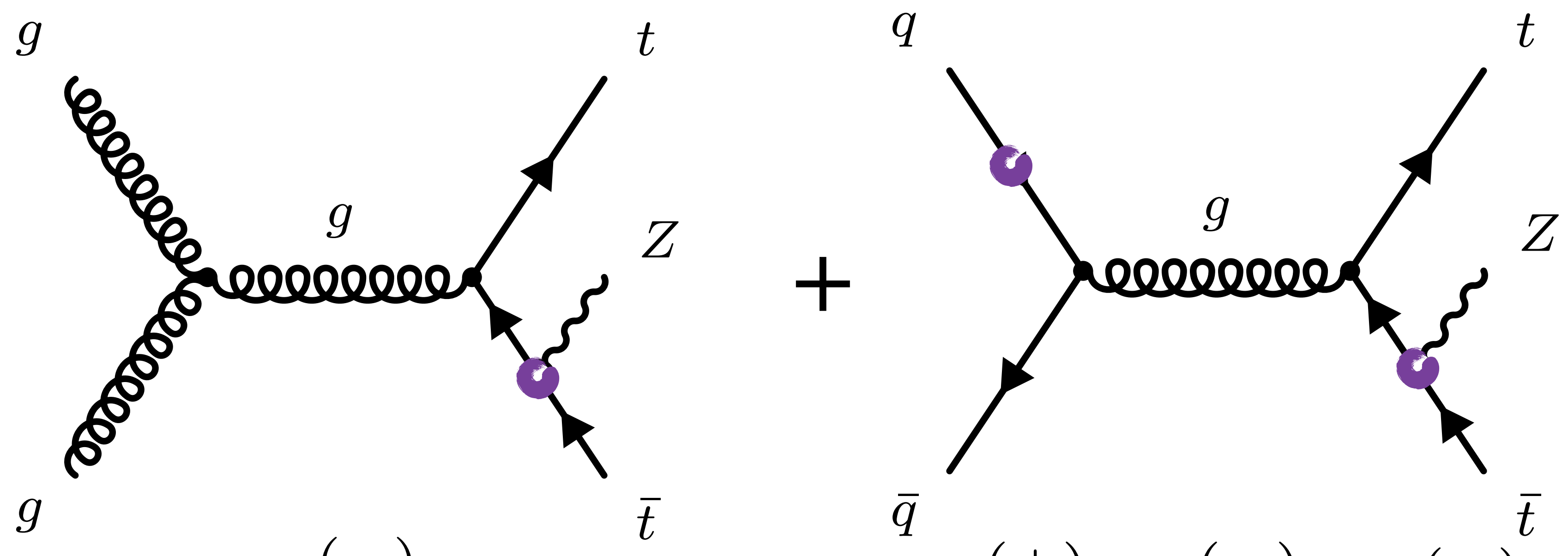

$A^{(-)}_{\phi q}$ $\quad$ $a^{(+)}_{\phi q}$, $a^{(-)}_{\phi q}$, $A^{(-)}_{\phi q}$

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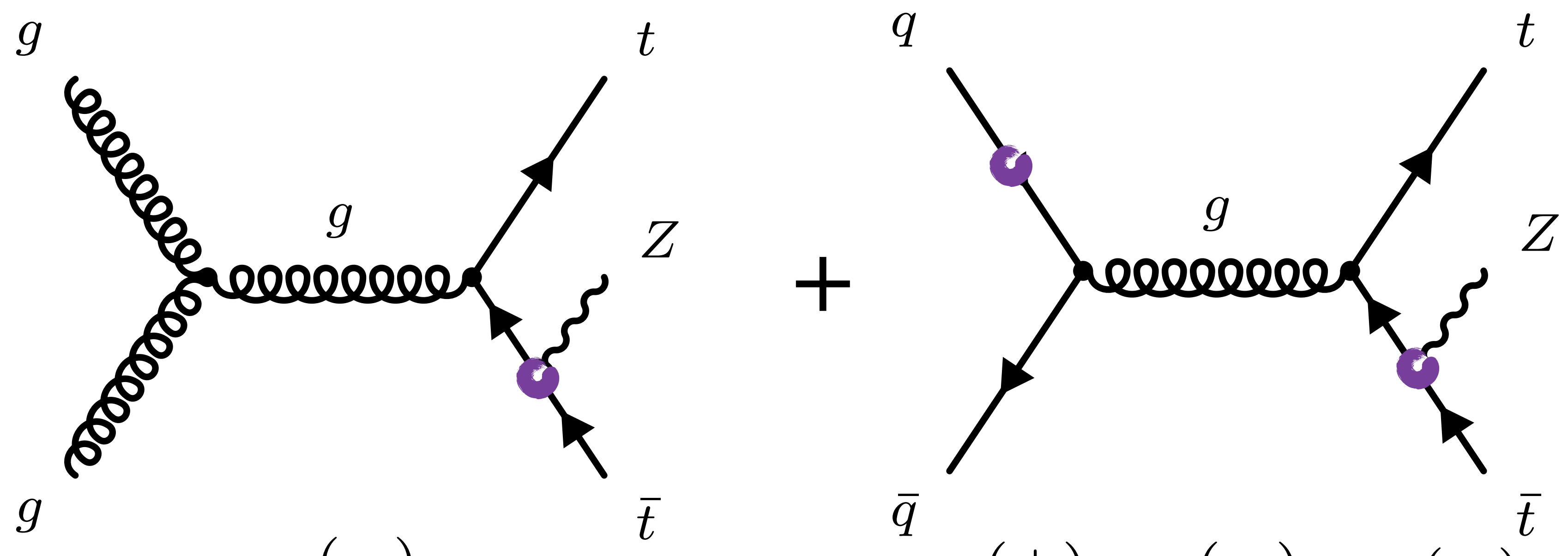

$A^{(-)}_{\phi q}$

$a^{(+)}_{\phi q}$, $a^{(-)}_{\phi q}$, $A^{(-)}_{\phi q}$

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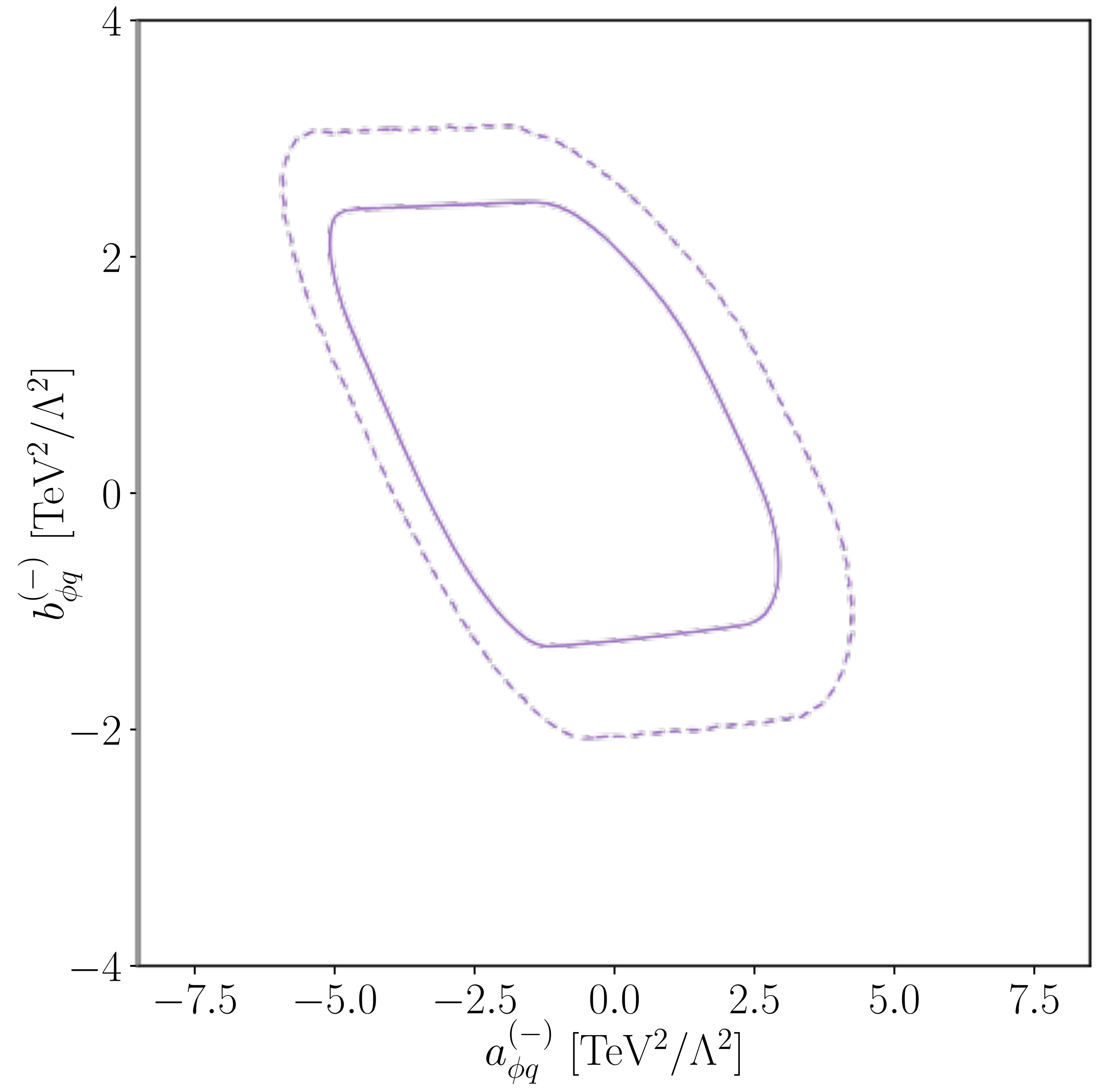

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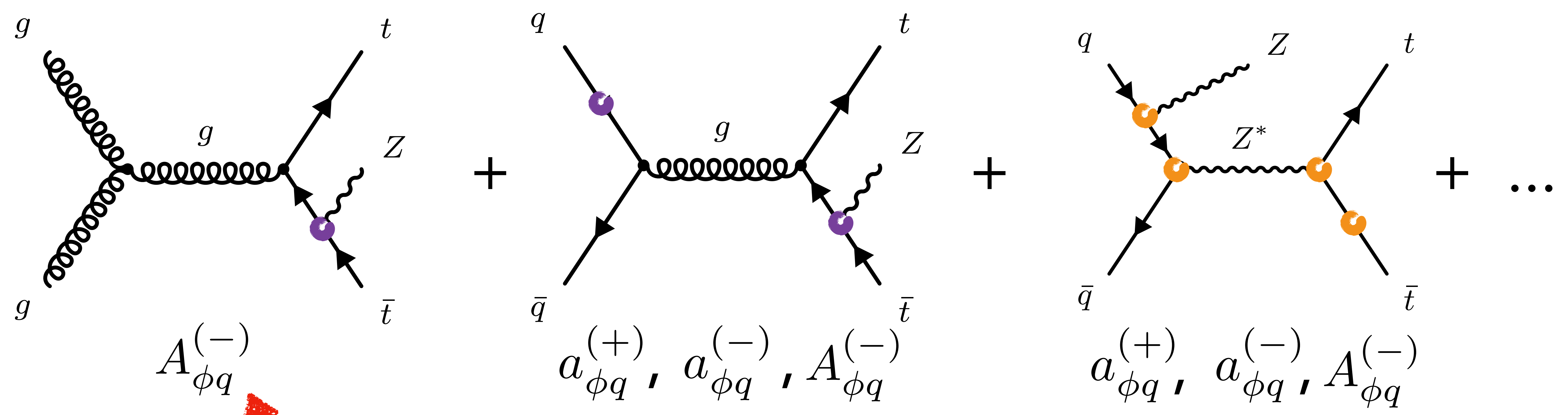

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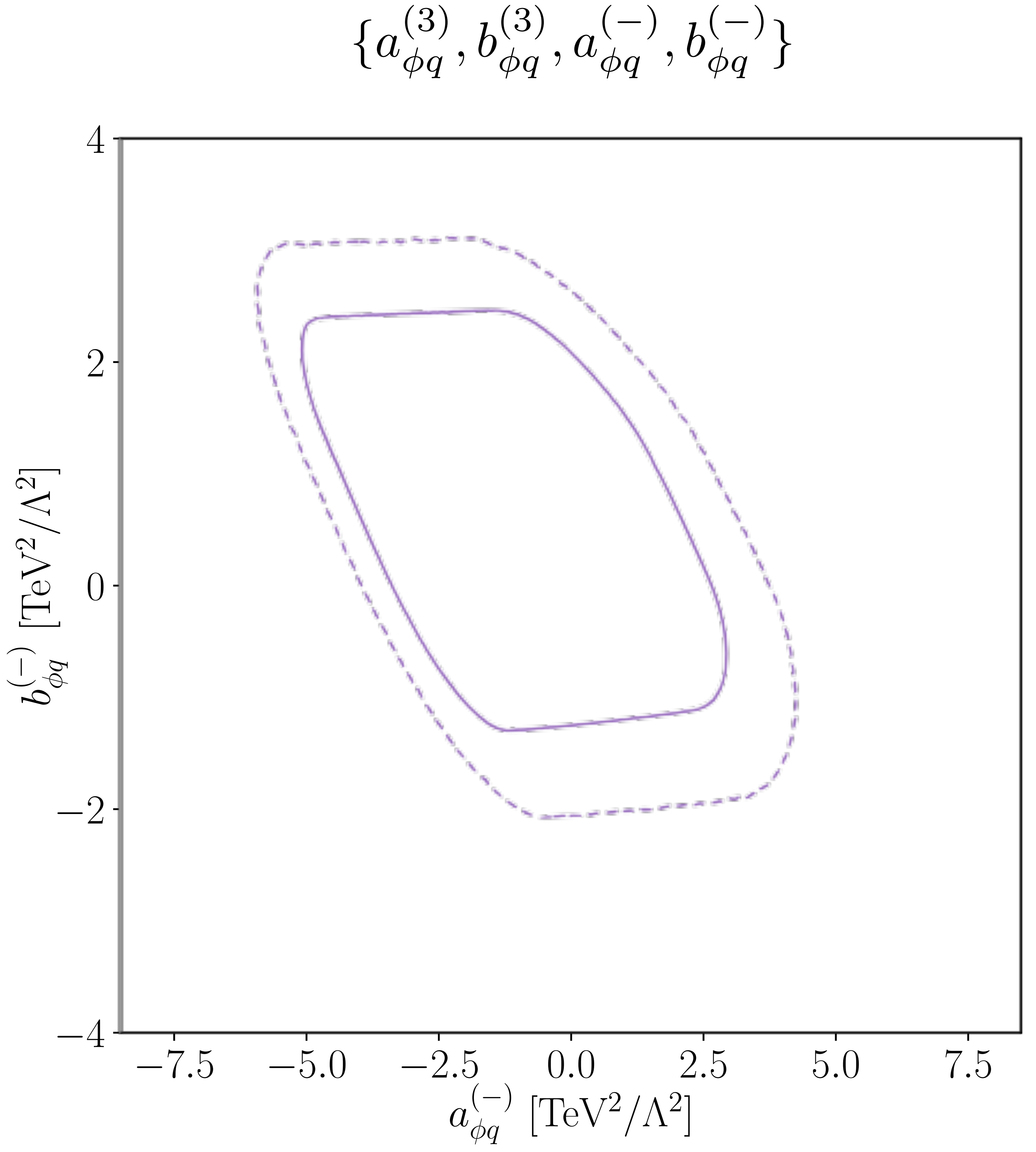

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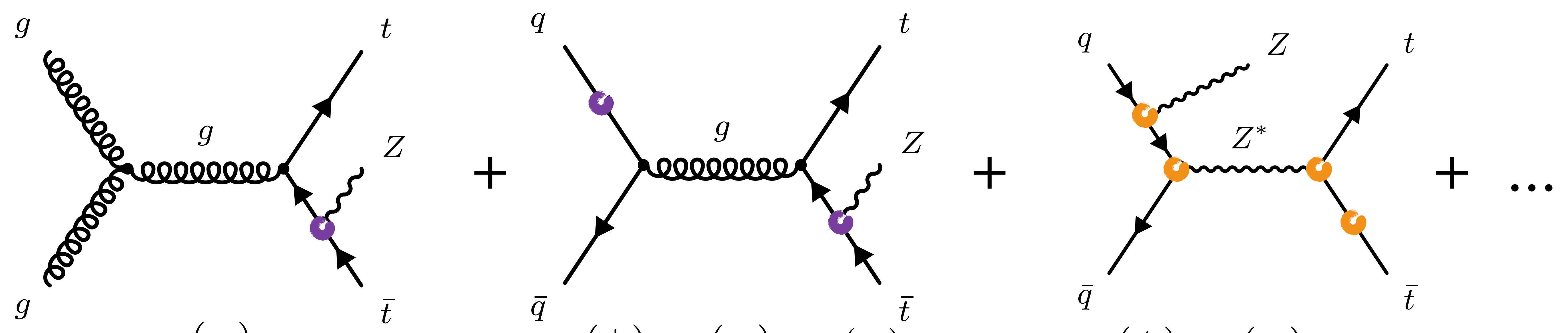
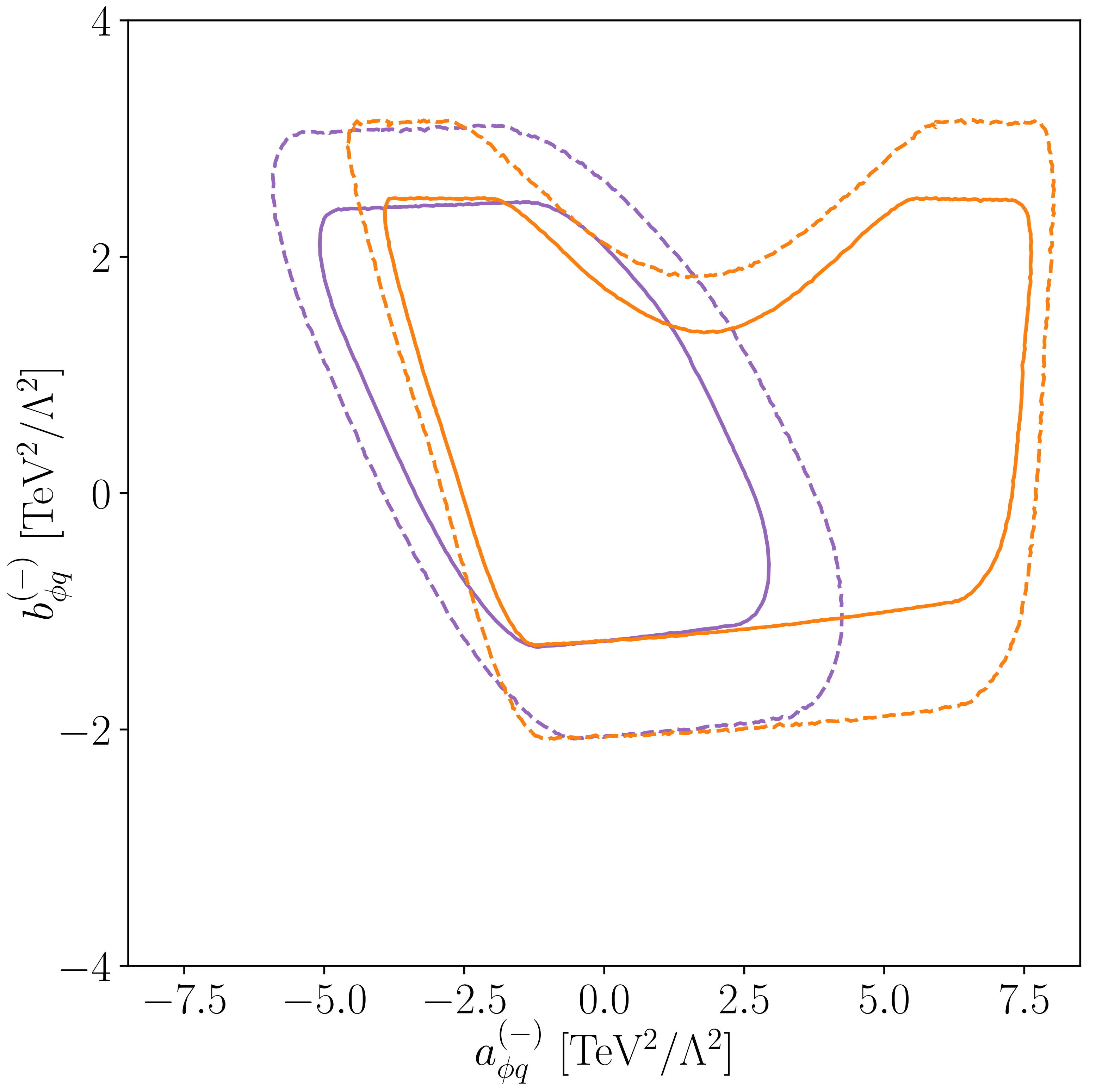


$A^{(-)}_{\phi q}$ $\quad a^{(+)}_{\phi q}, a^{(-)}_{\phi q}, A^{(-)}_{\phi q}$ $\quad a^{(+)}_{\phi q}, a^{(-)}_{\phi q}, A^{(-)}_{\phi q}$

$A = a + y_t^2 b$

$\{a^{(3)}_{\phi q}, b^{(3)}_{\phi q}, a^{(-)}_{\phi q}, b^{(-)}_{\phi q}\}$



How to do Global Fits?

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- Choose a model

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- Choose a model
  - SMEFT
    - Basis
    - Flavour
    - Order
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Construct Likelihood

- Toy Monte Carlo
- Markov Chains
- Analytical
- ...

Extract limits

Toy MC

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- Generate a random "toy"-measurement according to the uncertainties

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$$\mu_1 = 105 - 5(c_1 + c_2)$$

Predictions

$$\mu_2 = 93 + 3(c_1 - c_2)$$

$$\mu_{1/2}^{exp} = 100 \pm 10$$

Measurements

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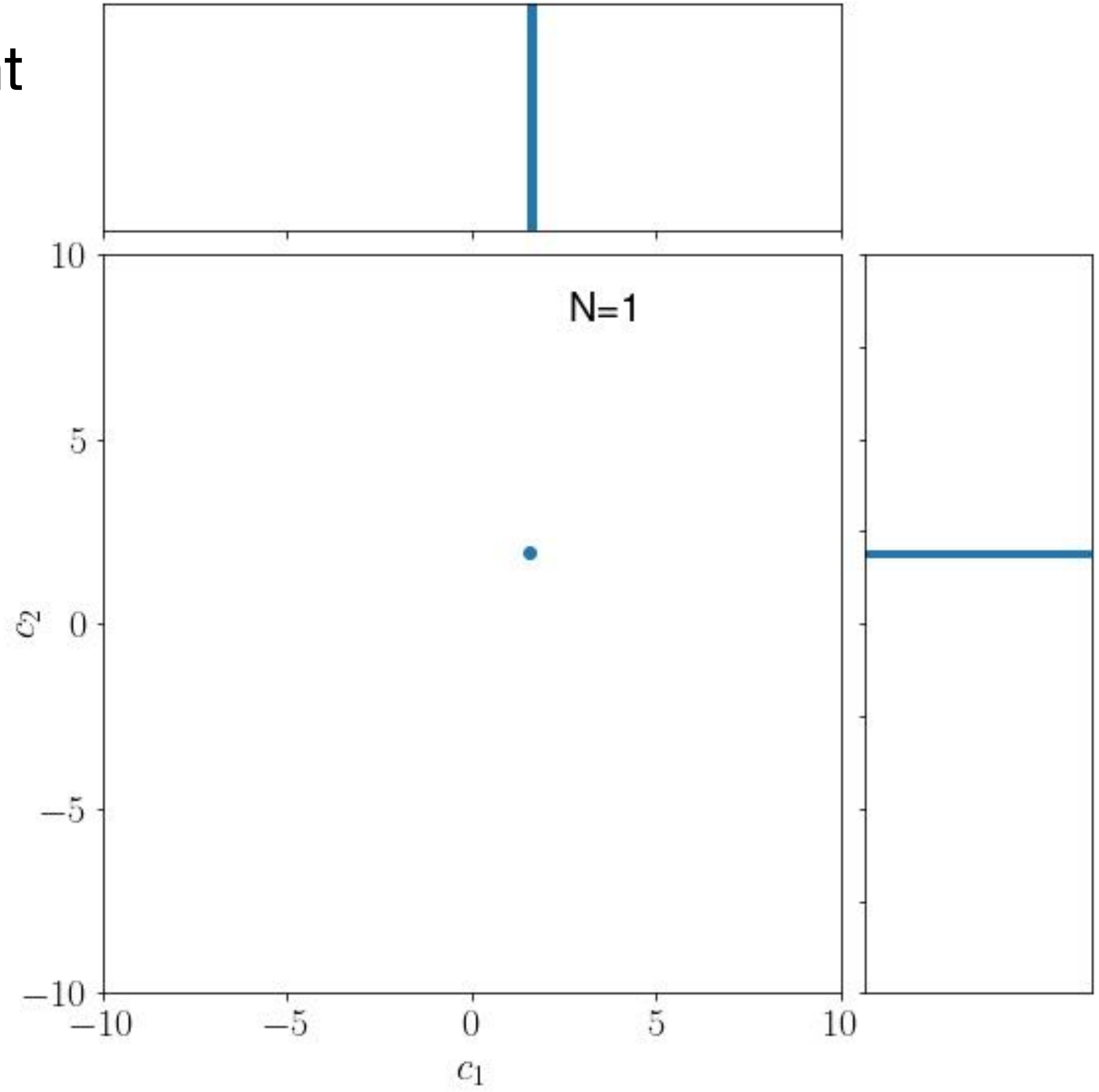

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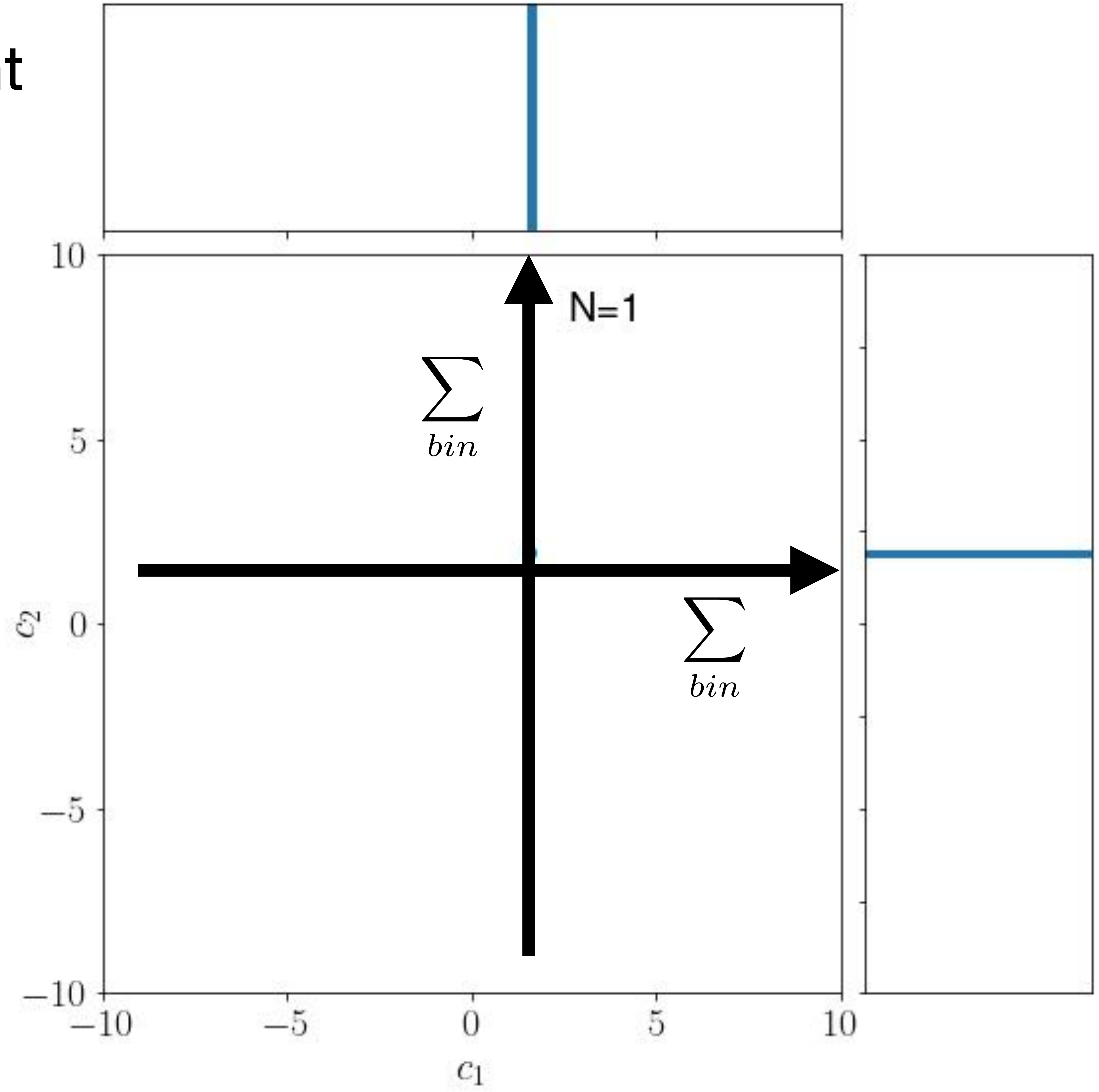

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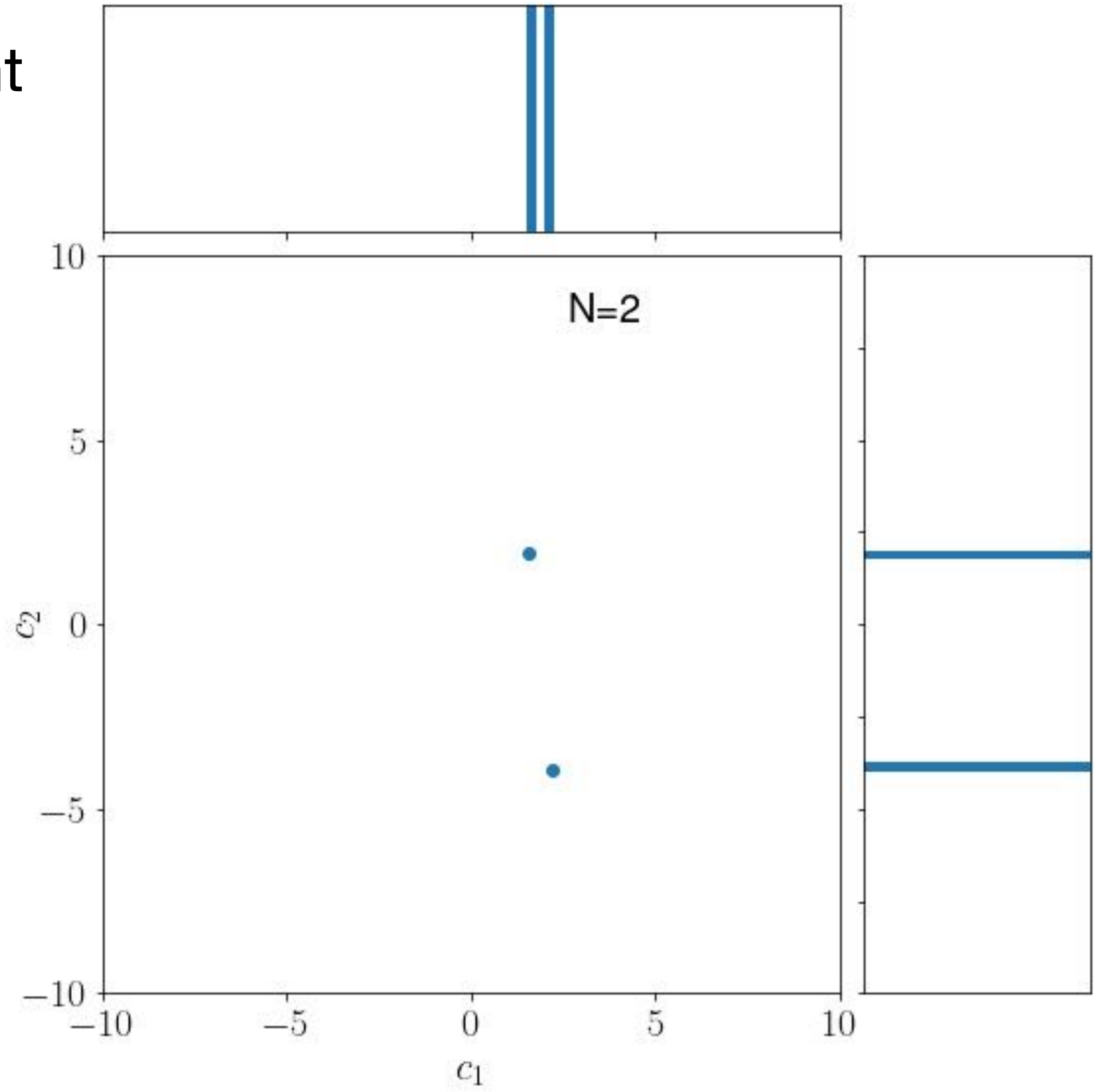

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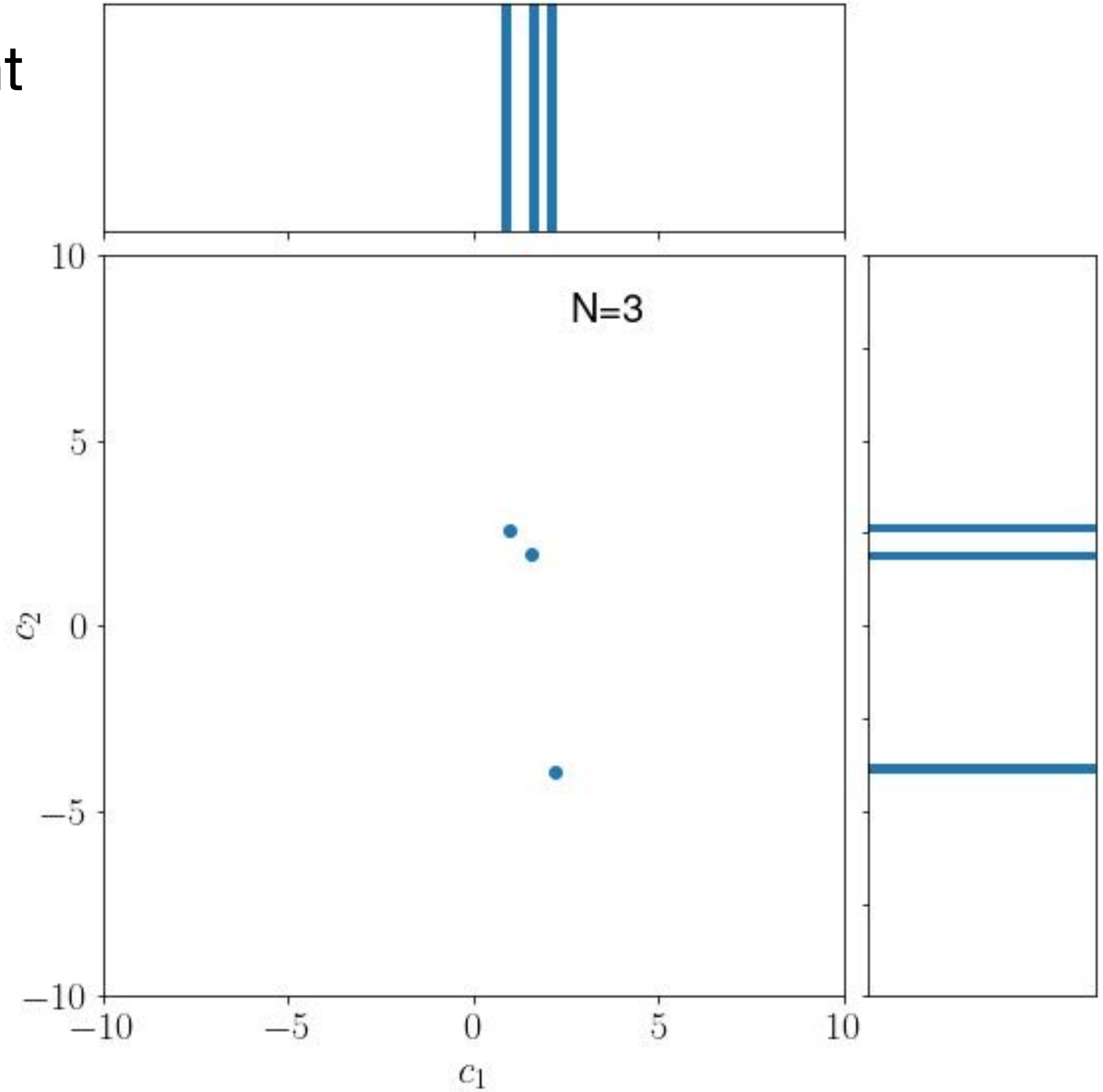

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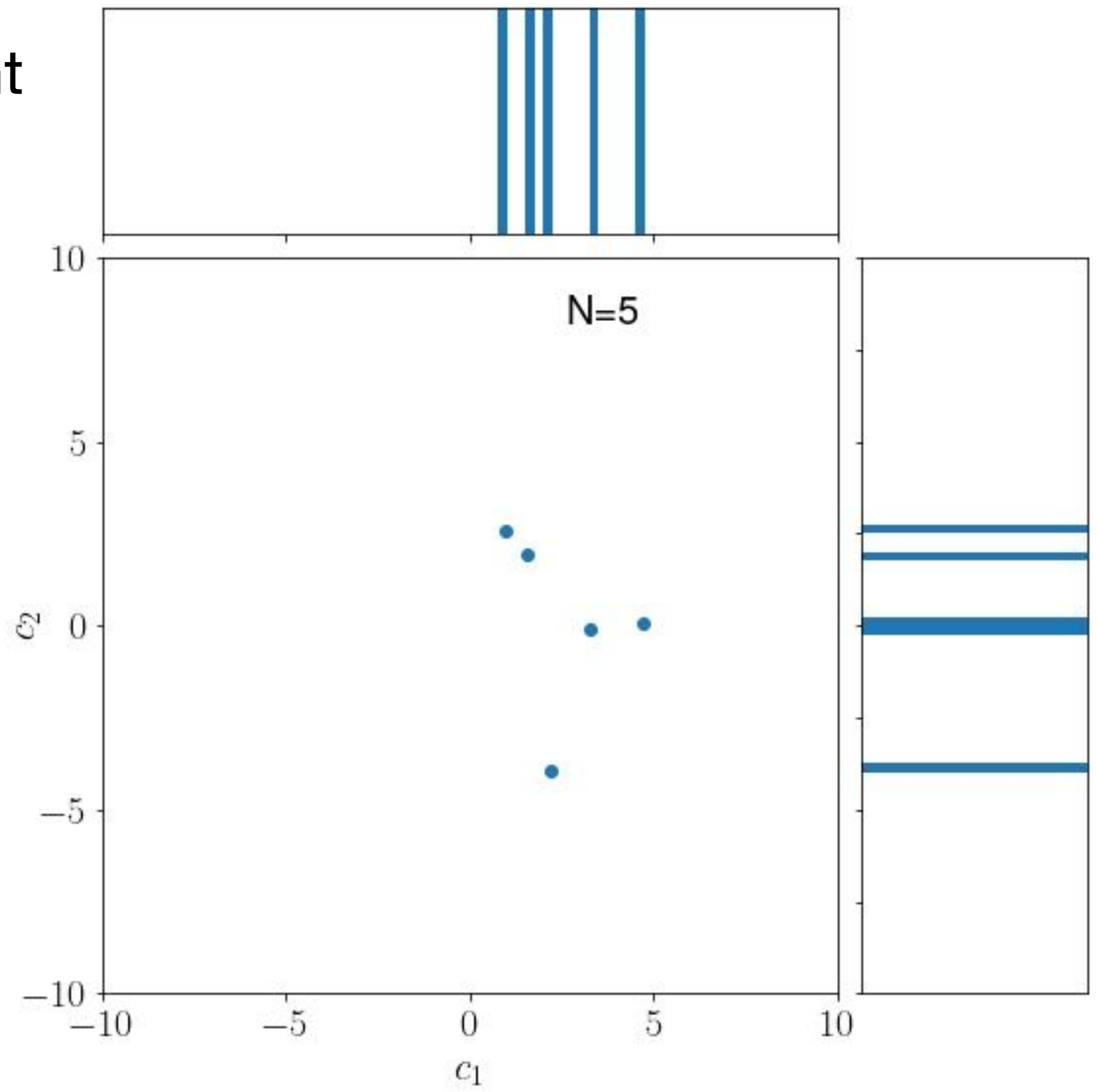

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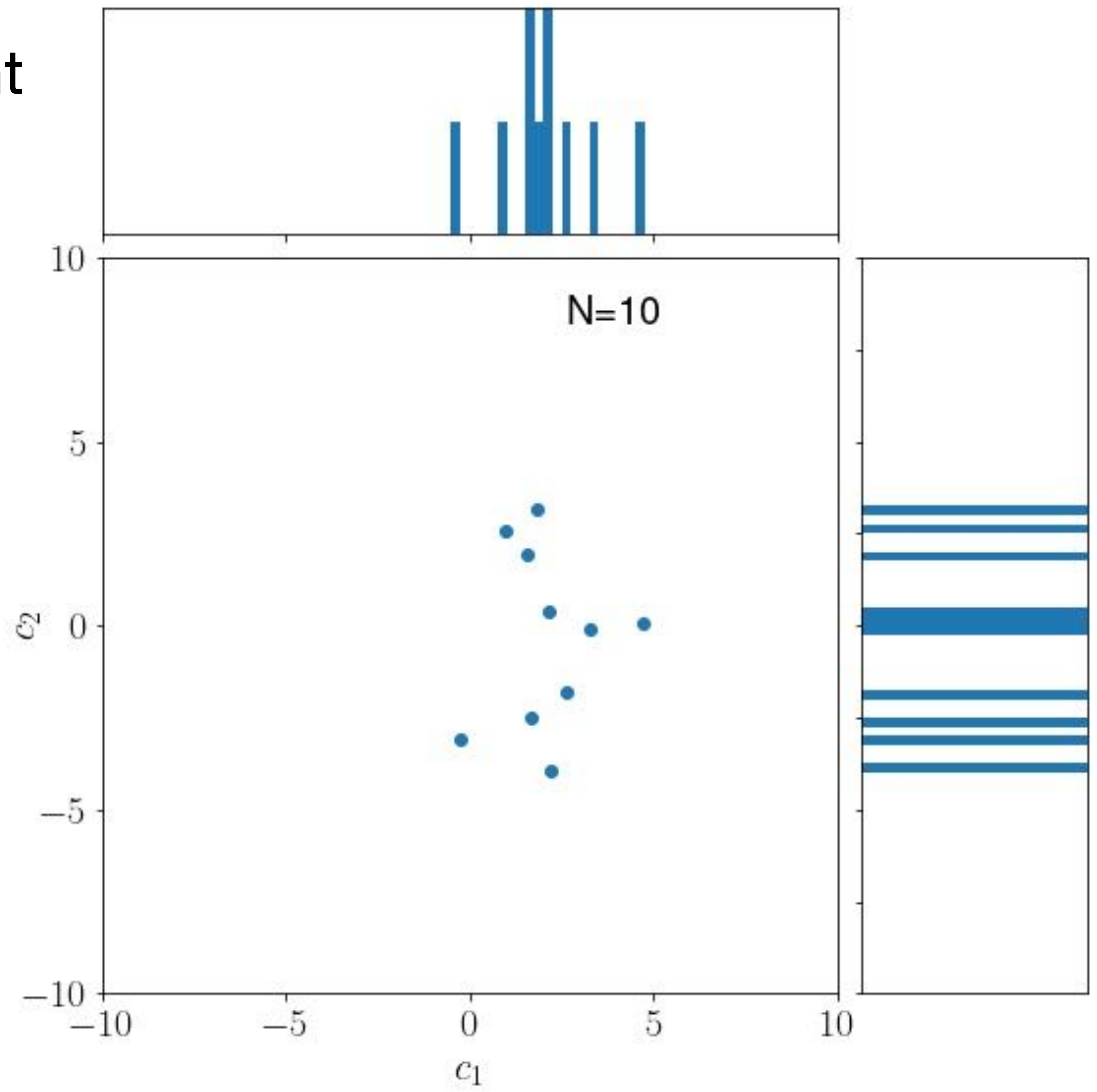

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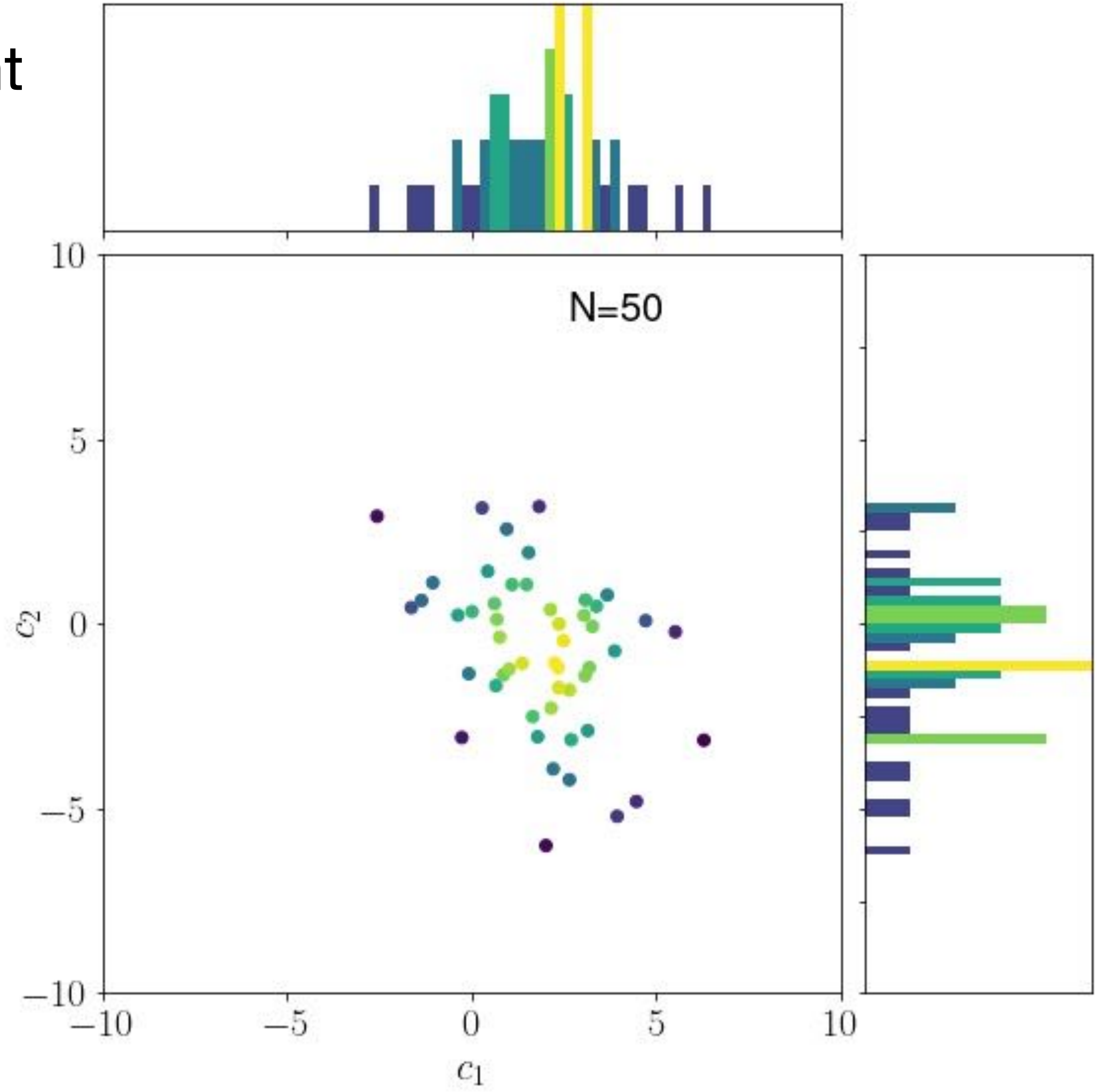

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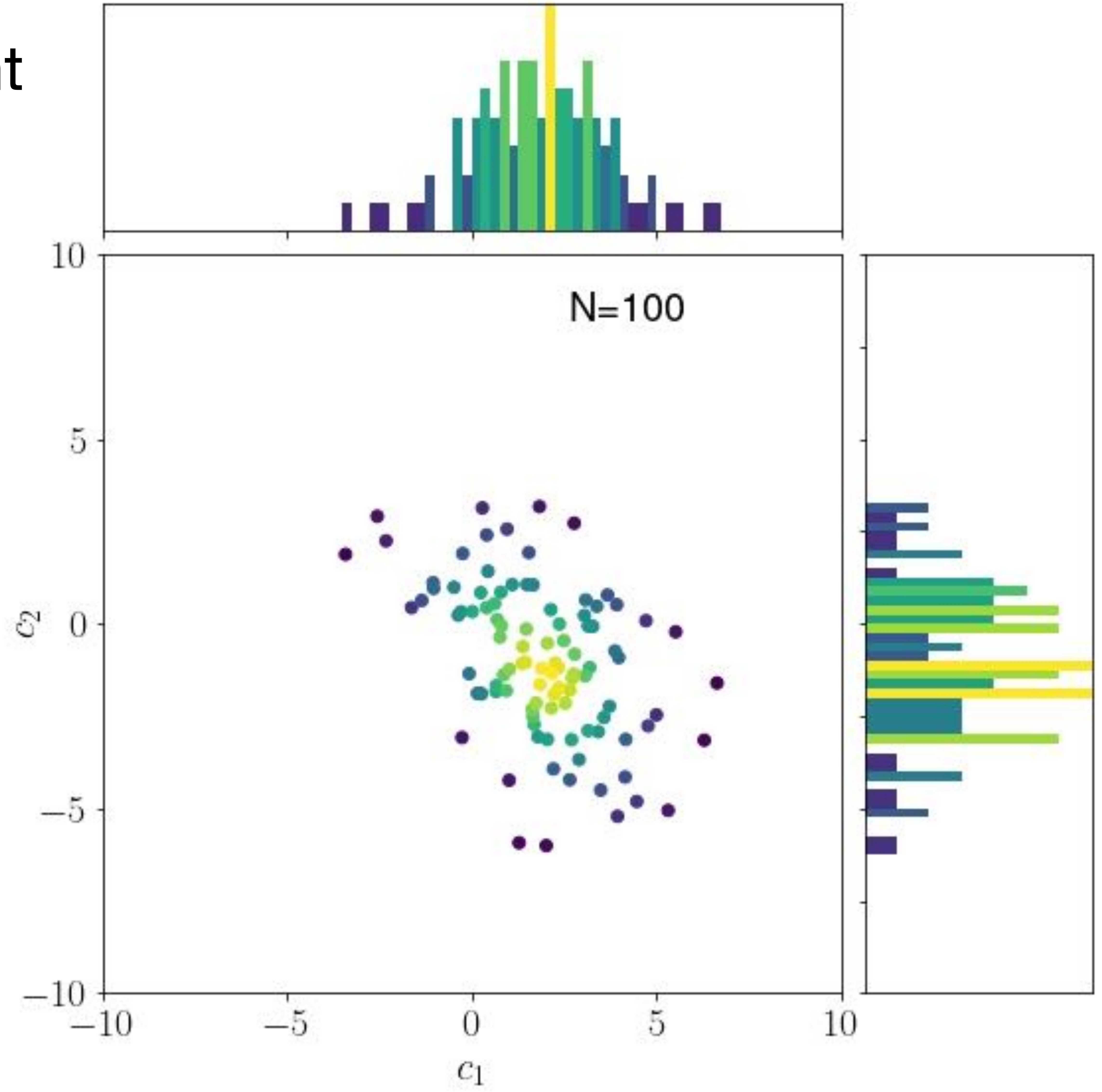

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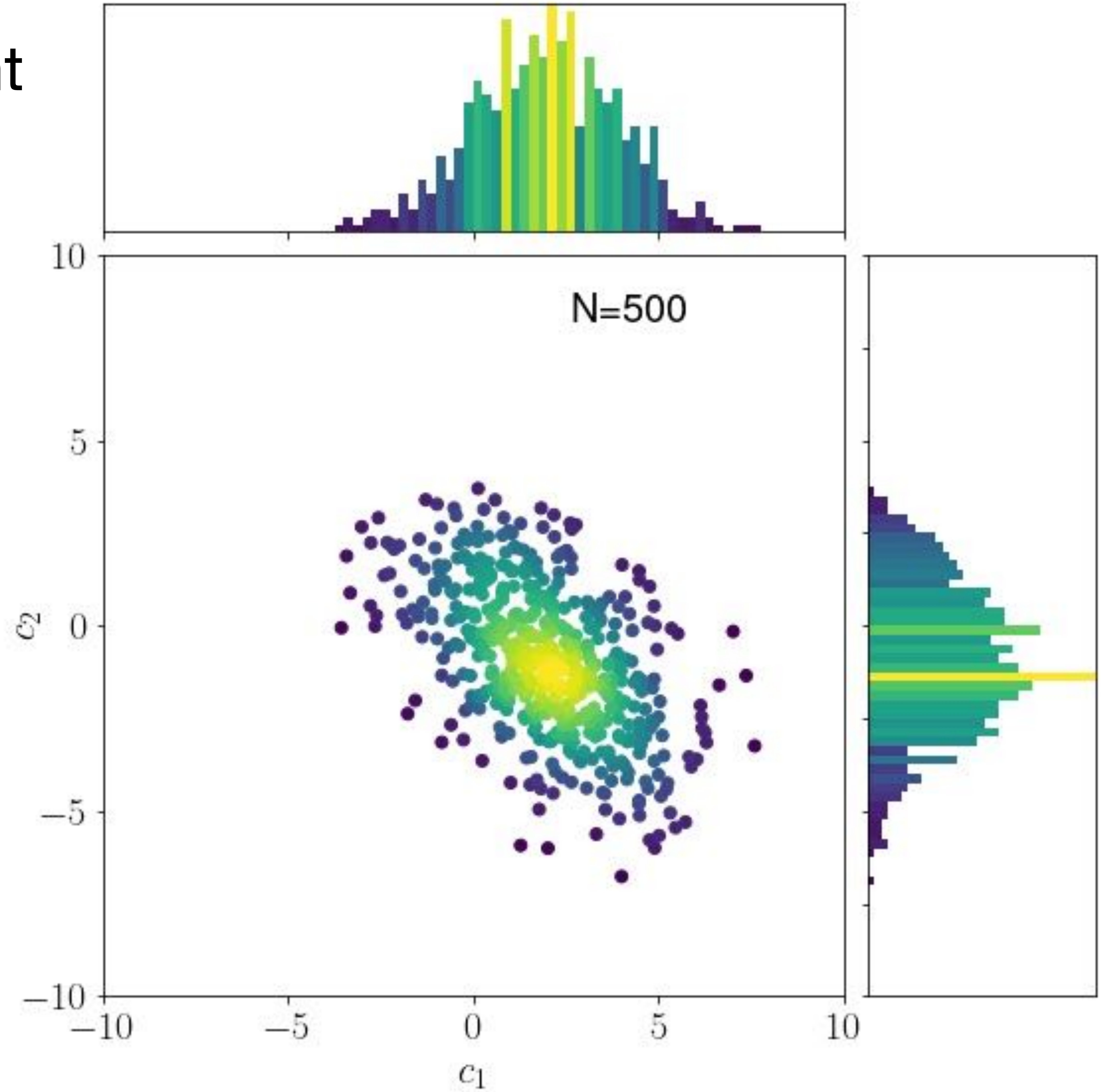

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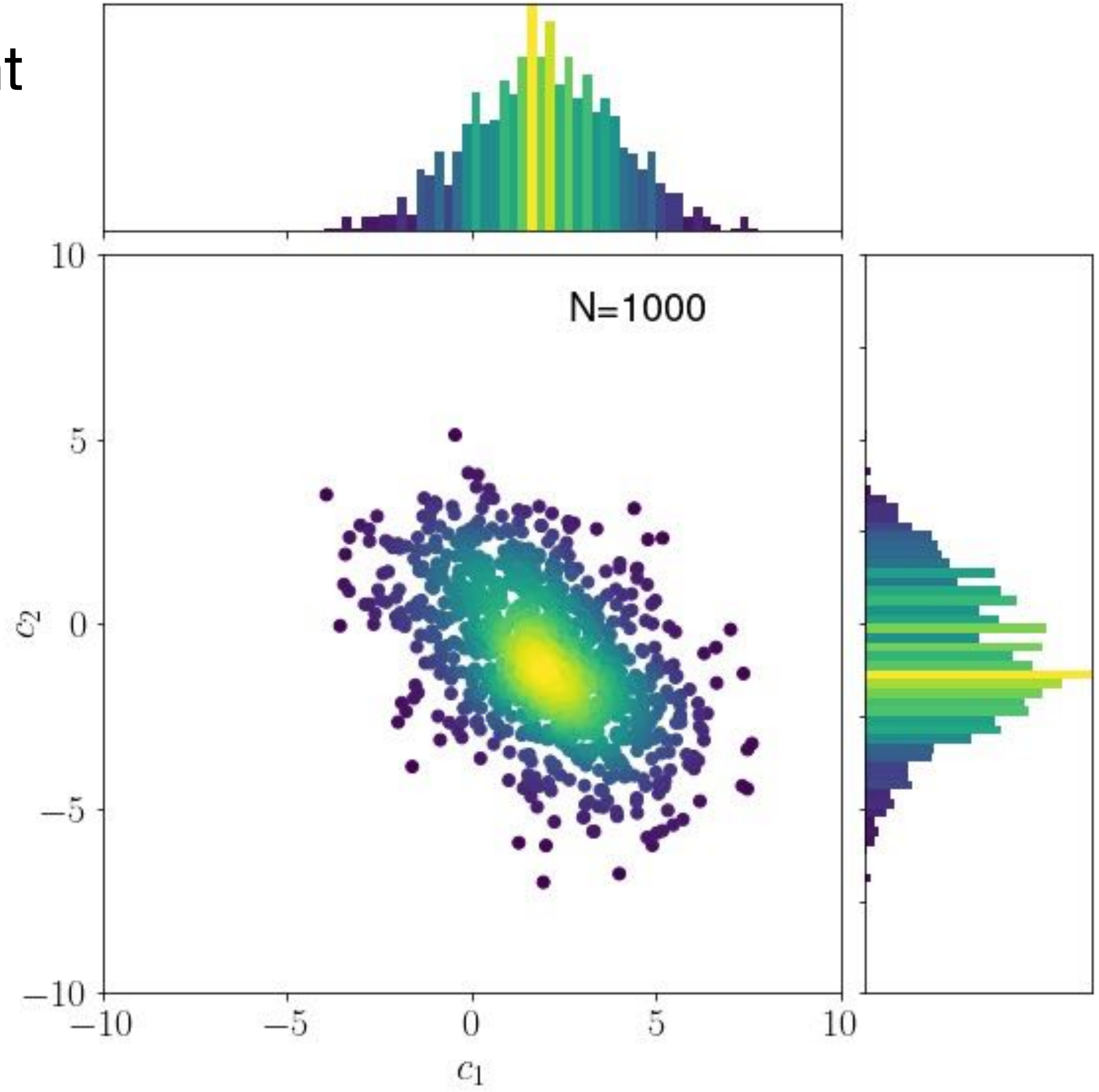

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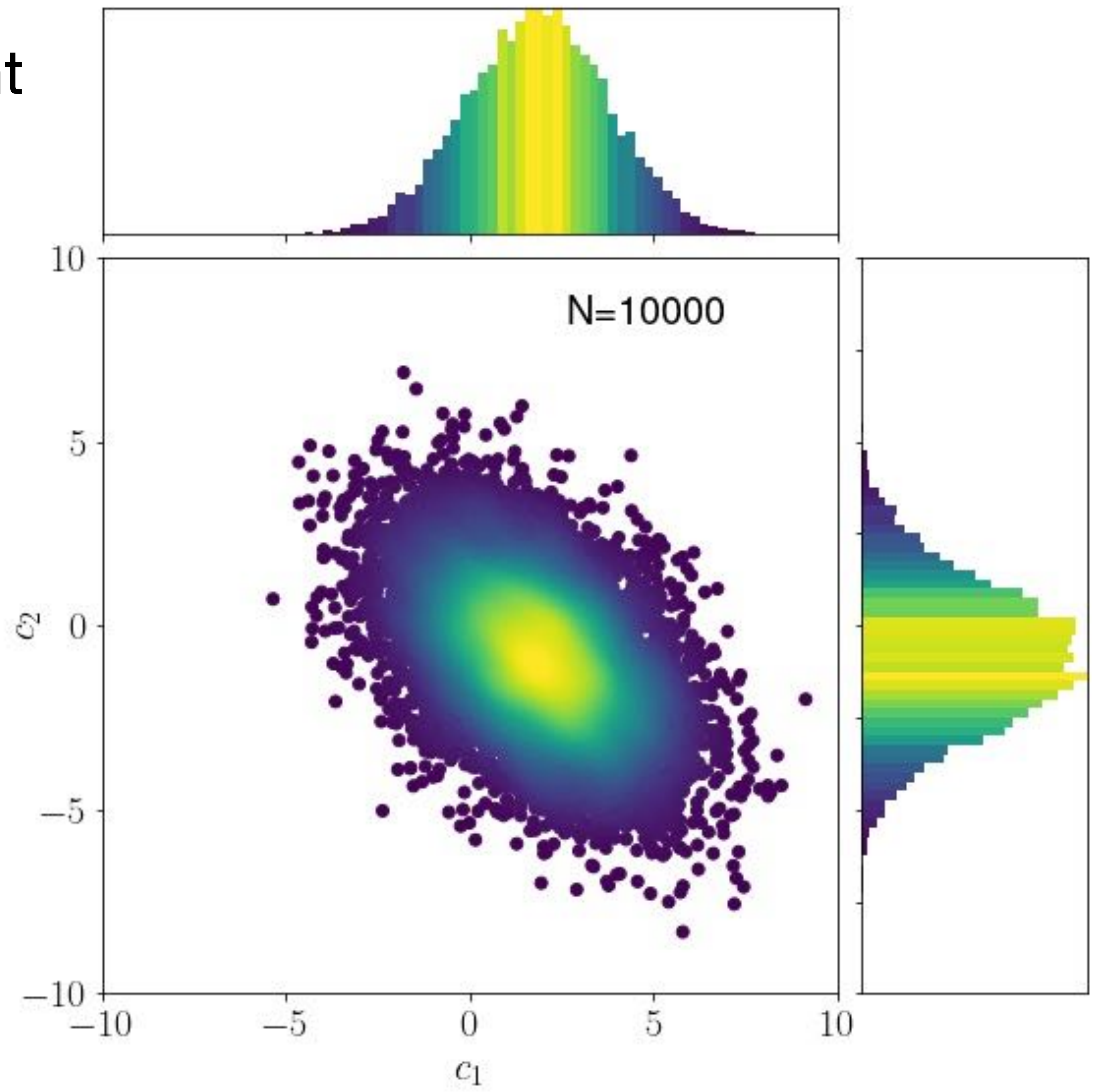

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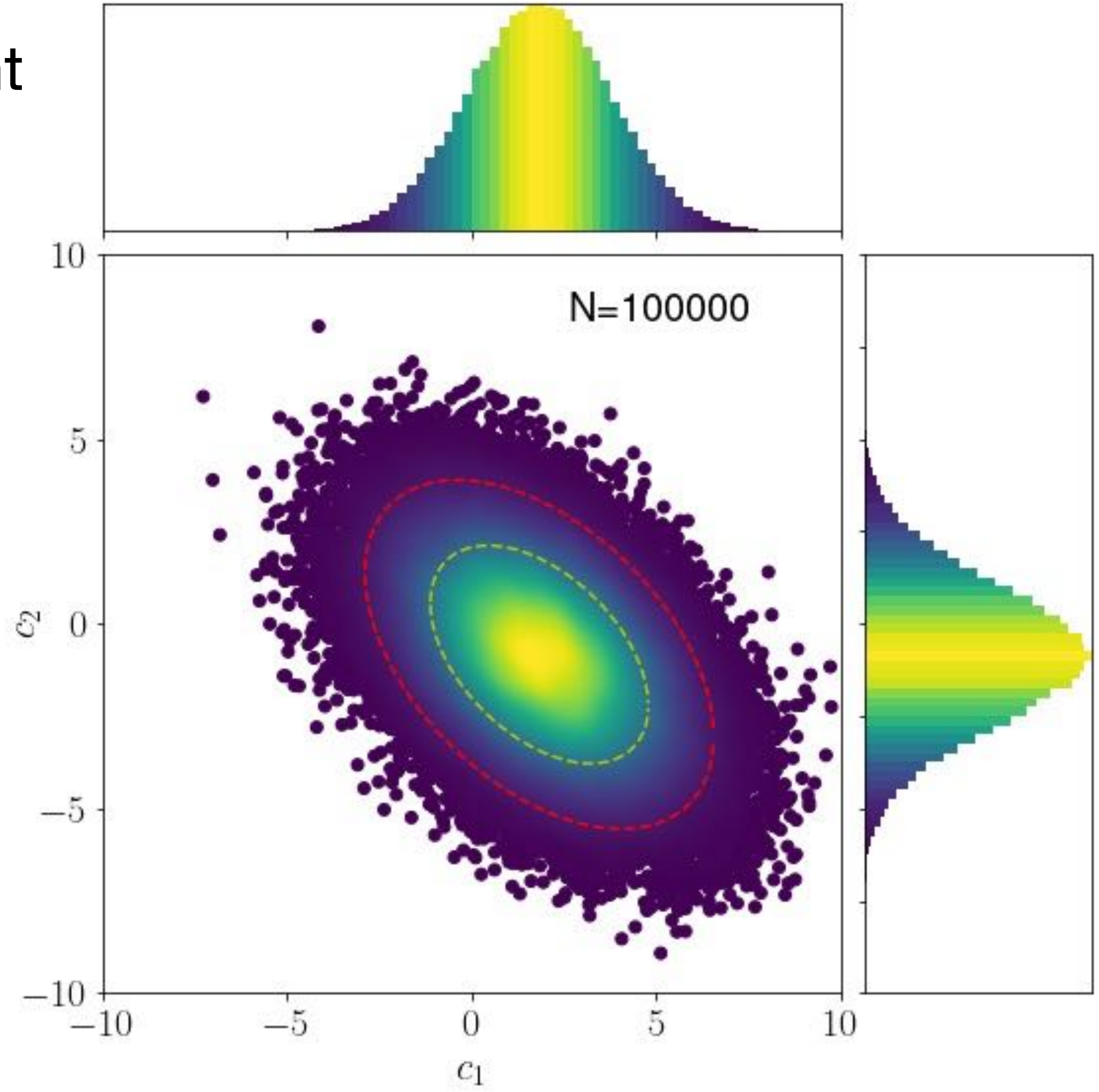

Markov Chains

Metropolis-Hastings

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- Start at random point x_i

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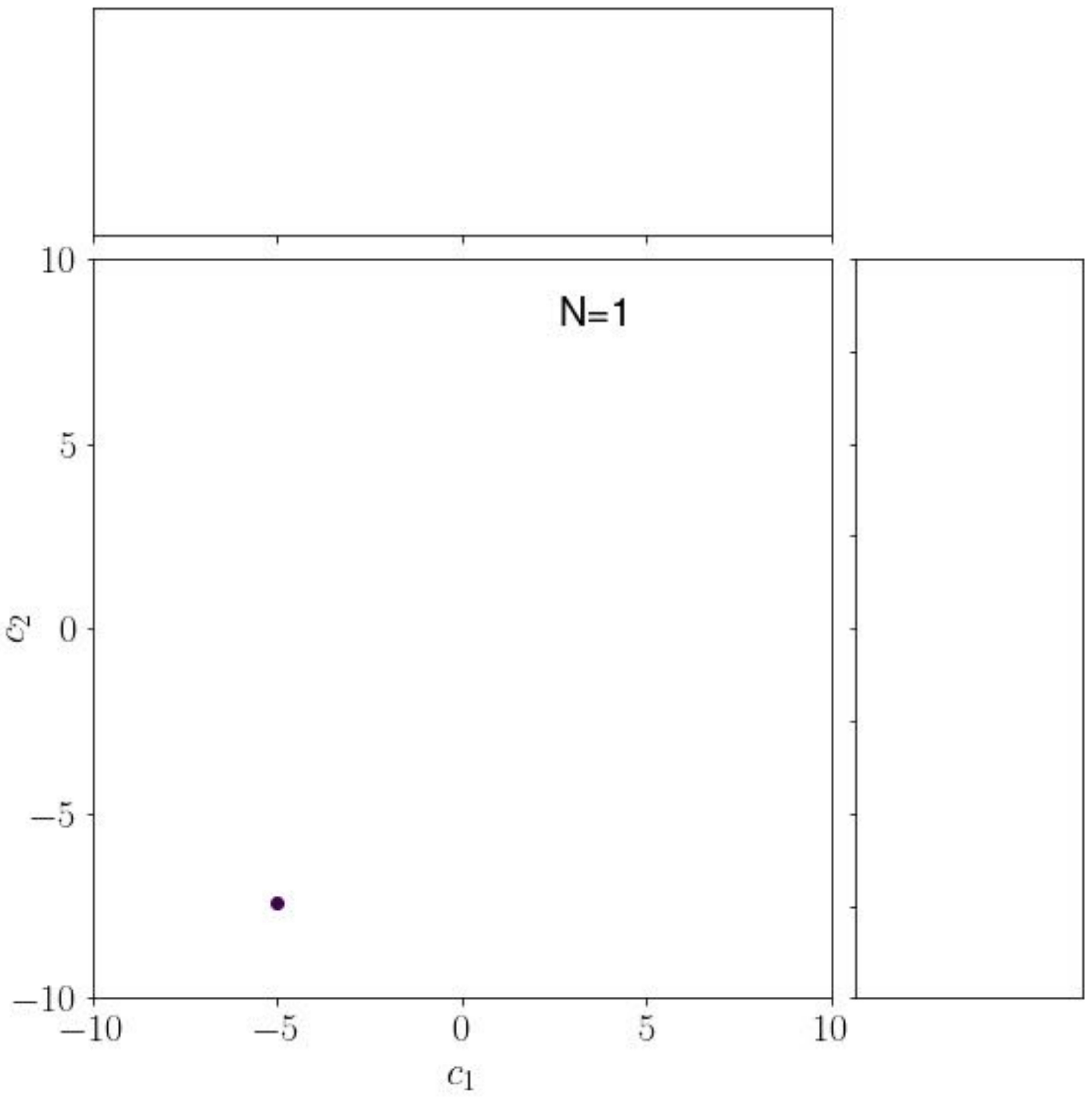

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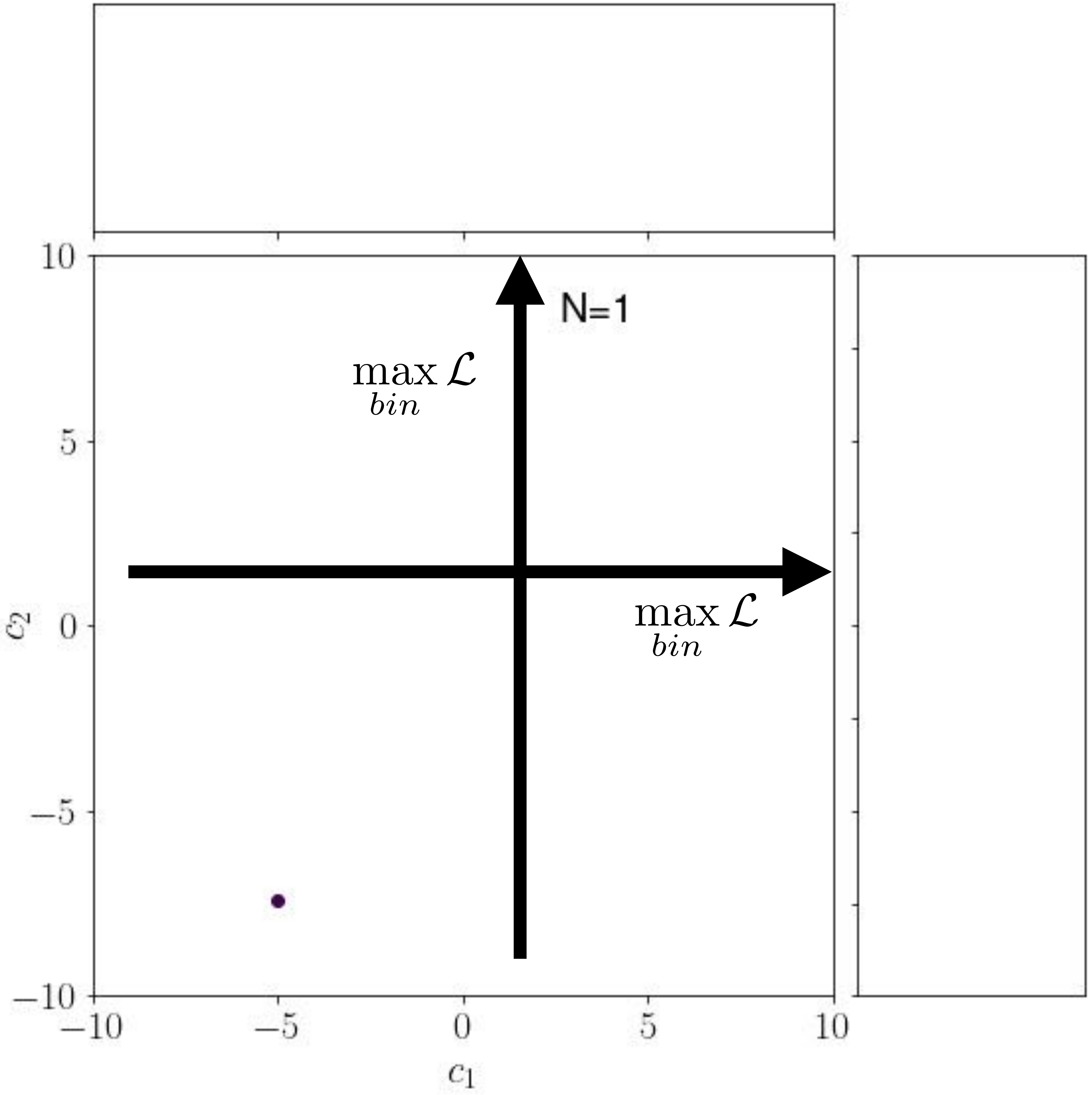

Markov Chains
Metropolis-Hastings

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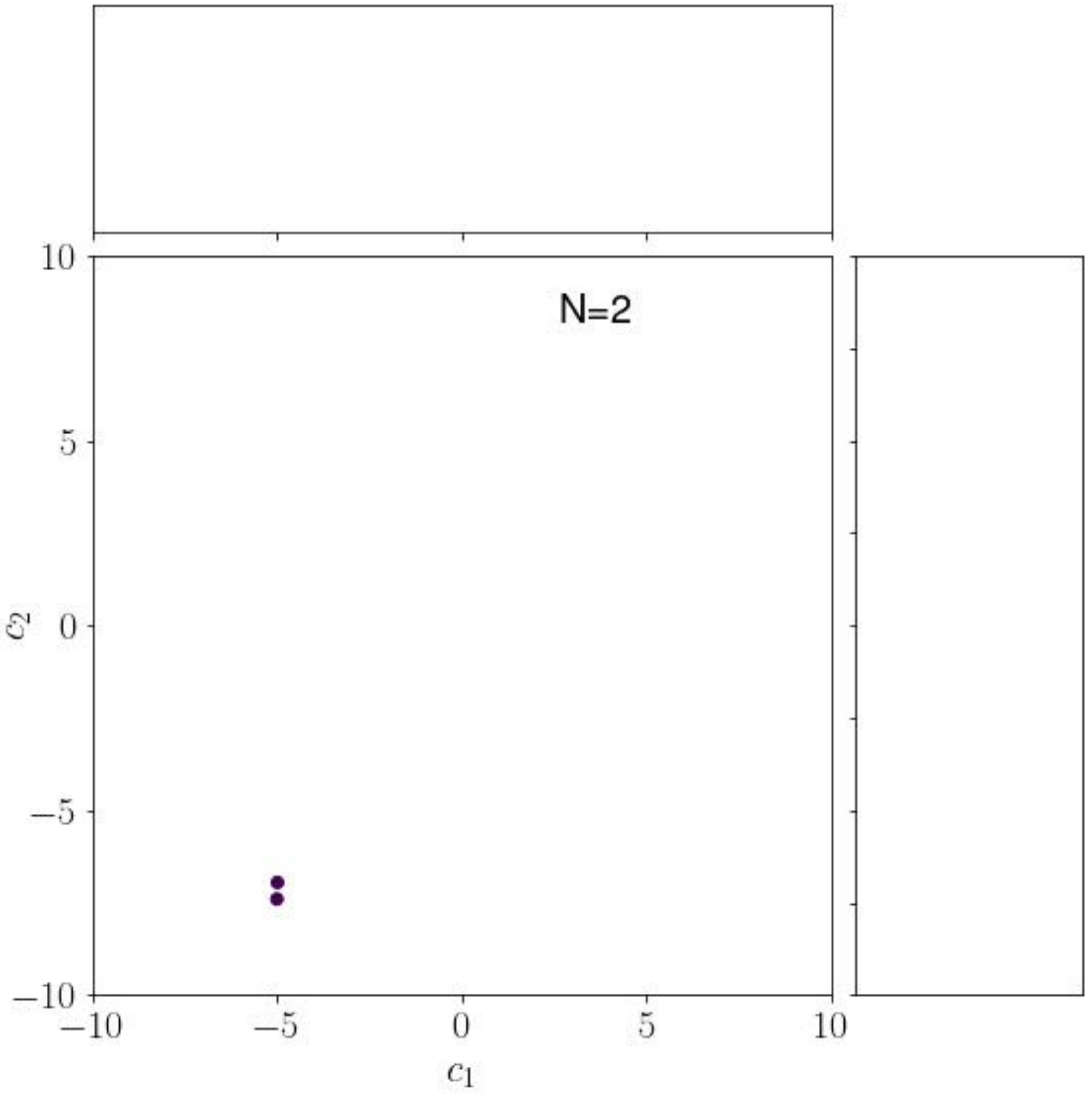

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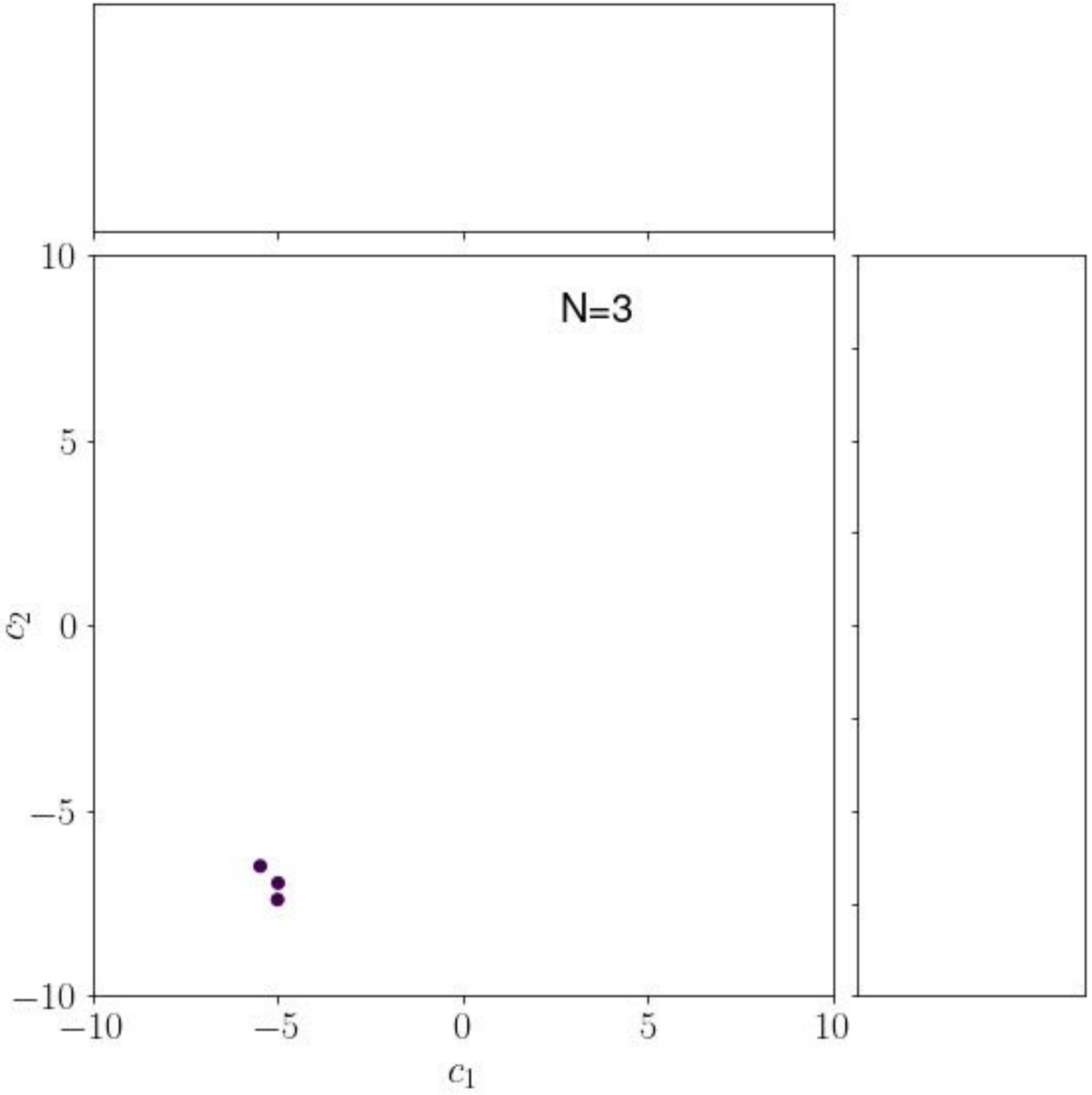

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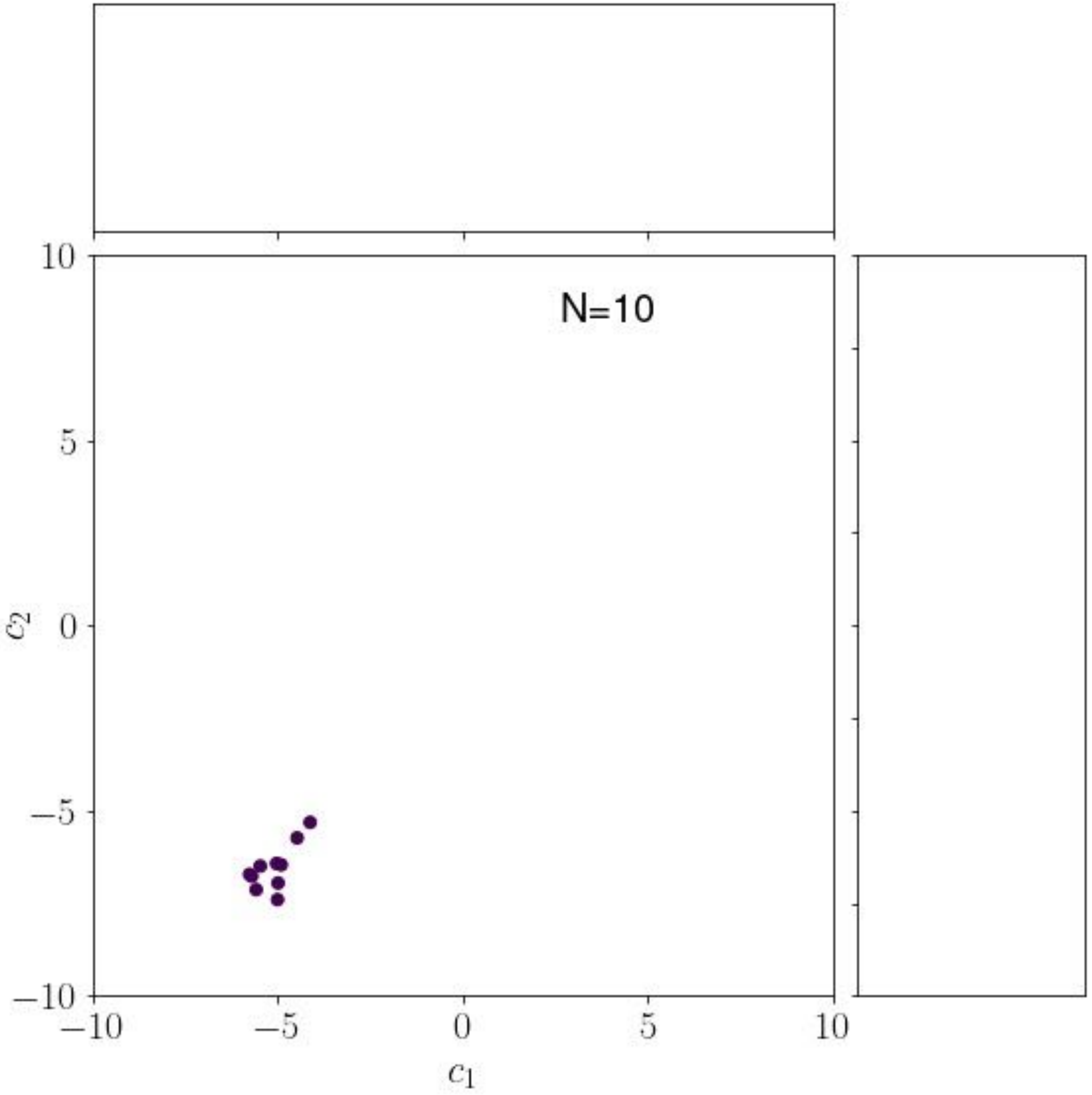

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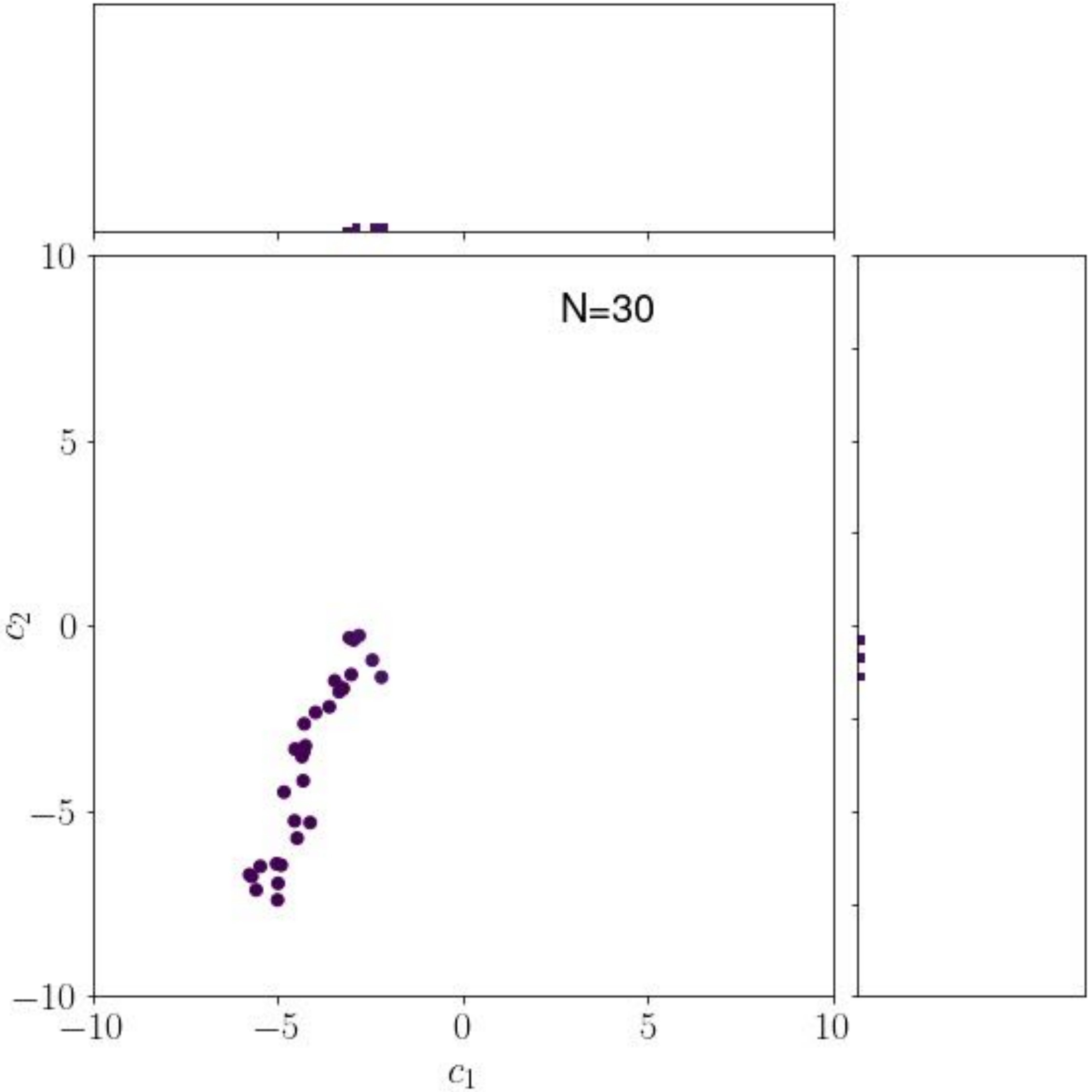

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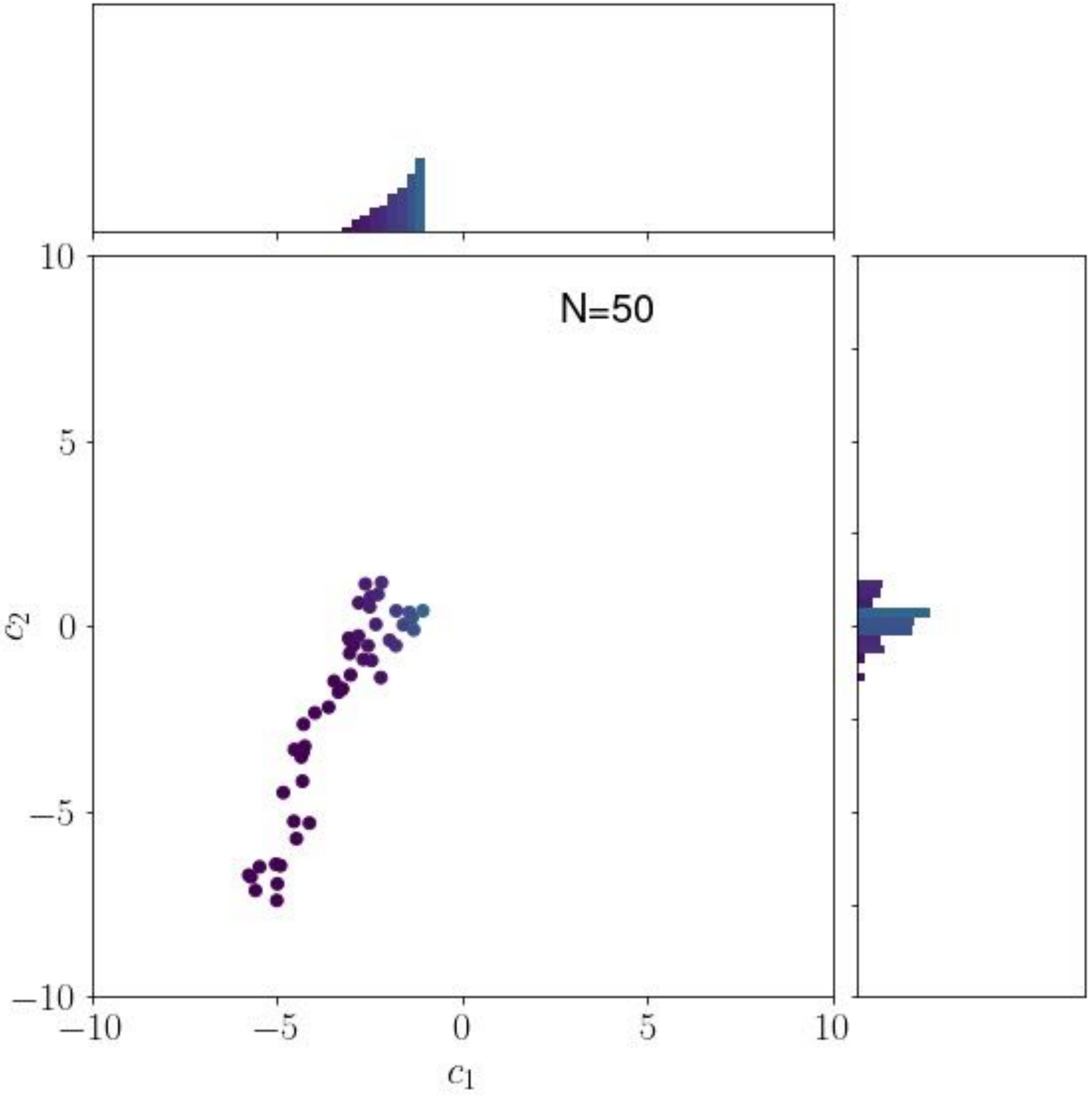

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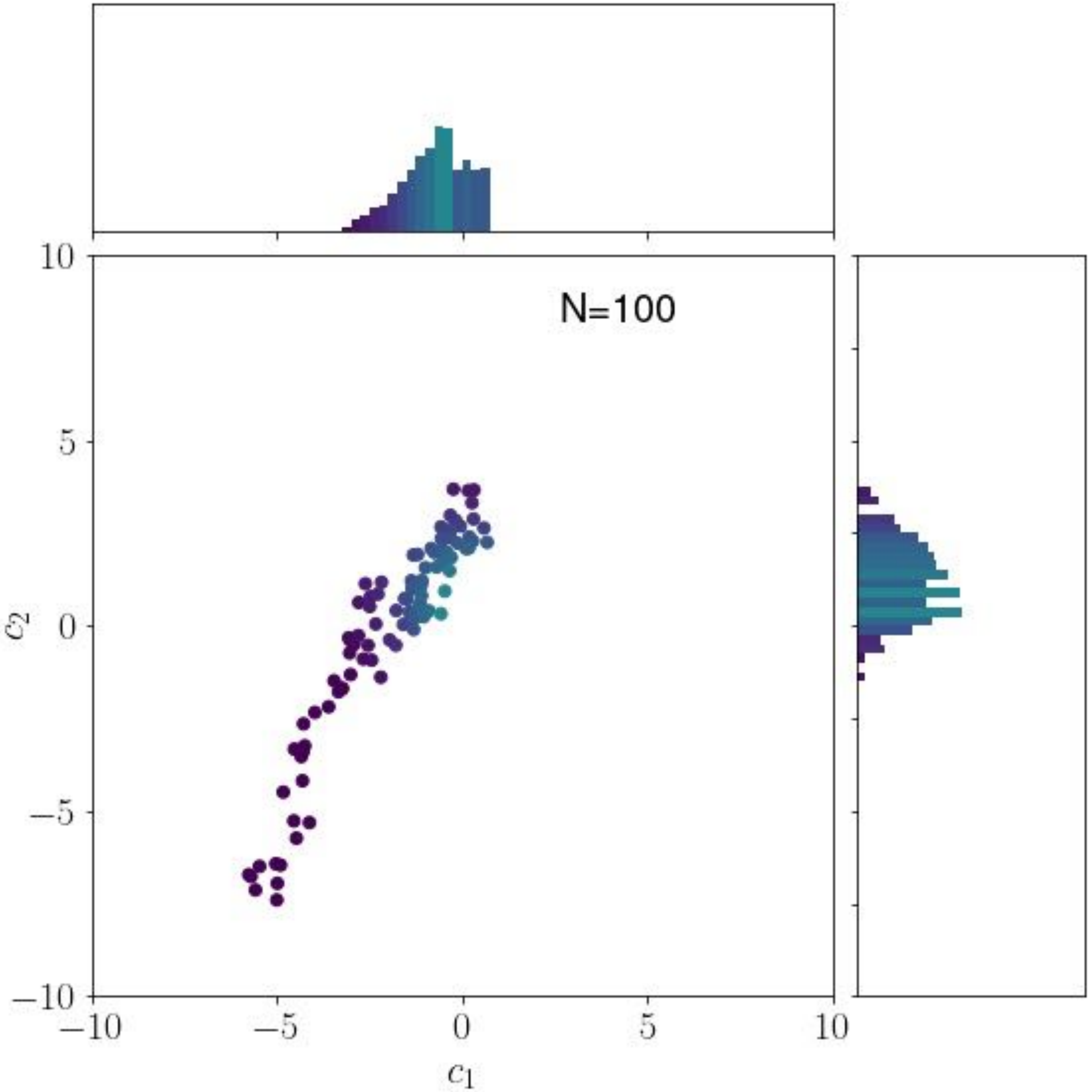

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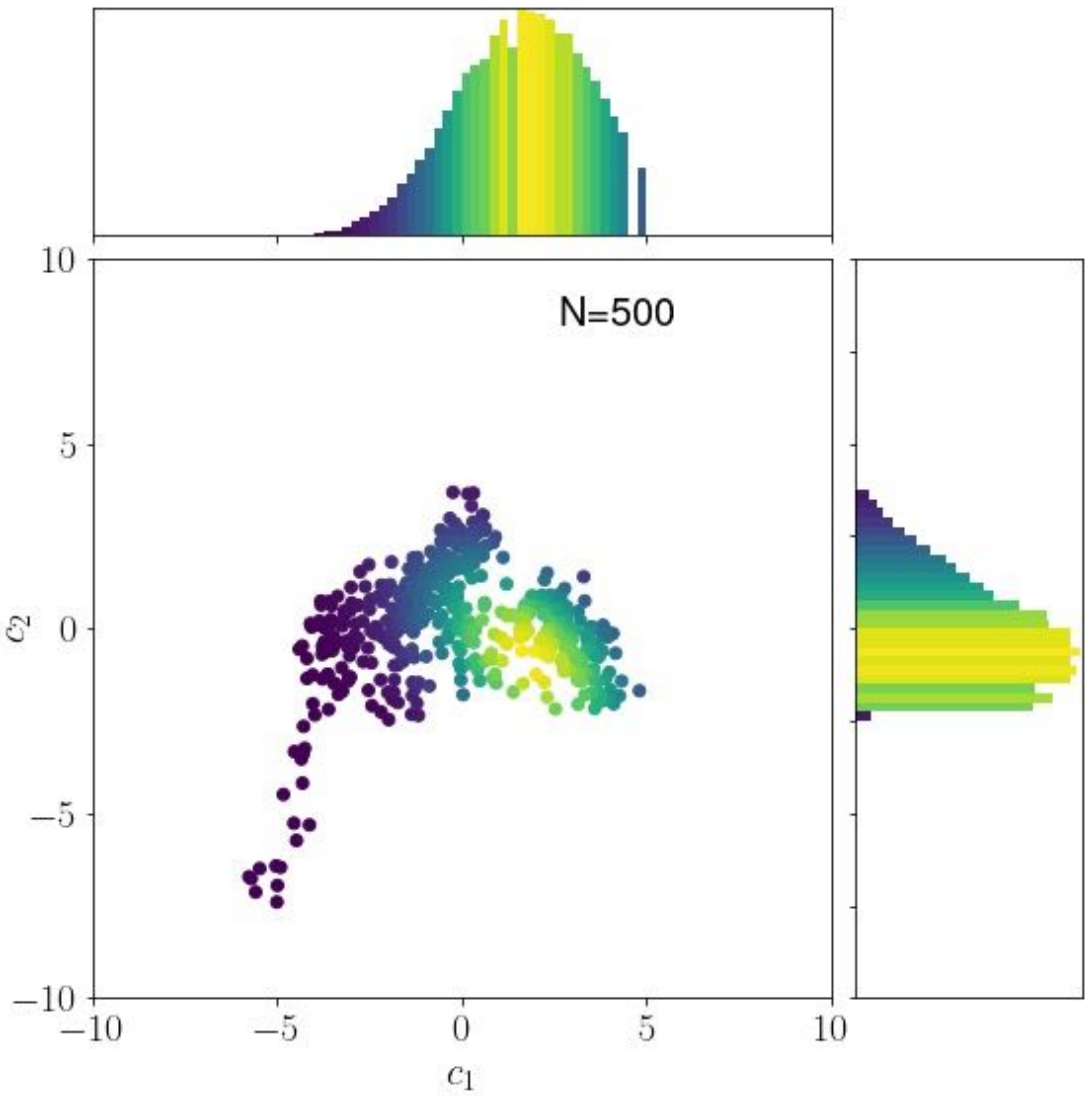

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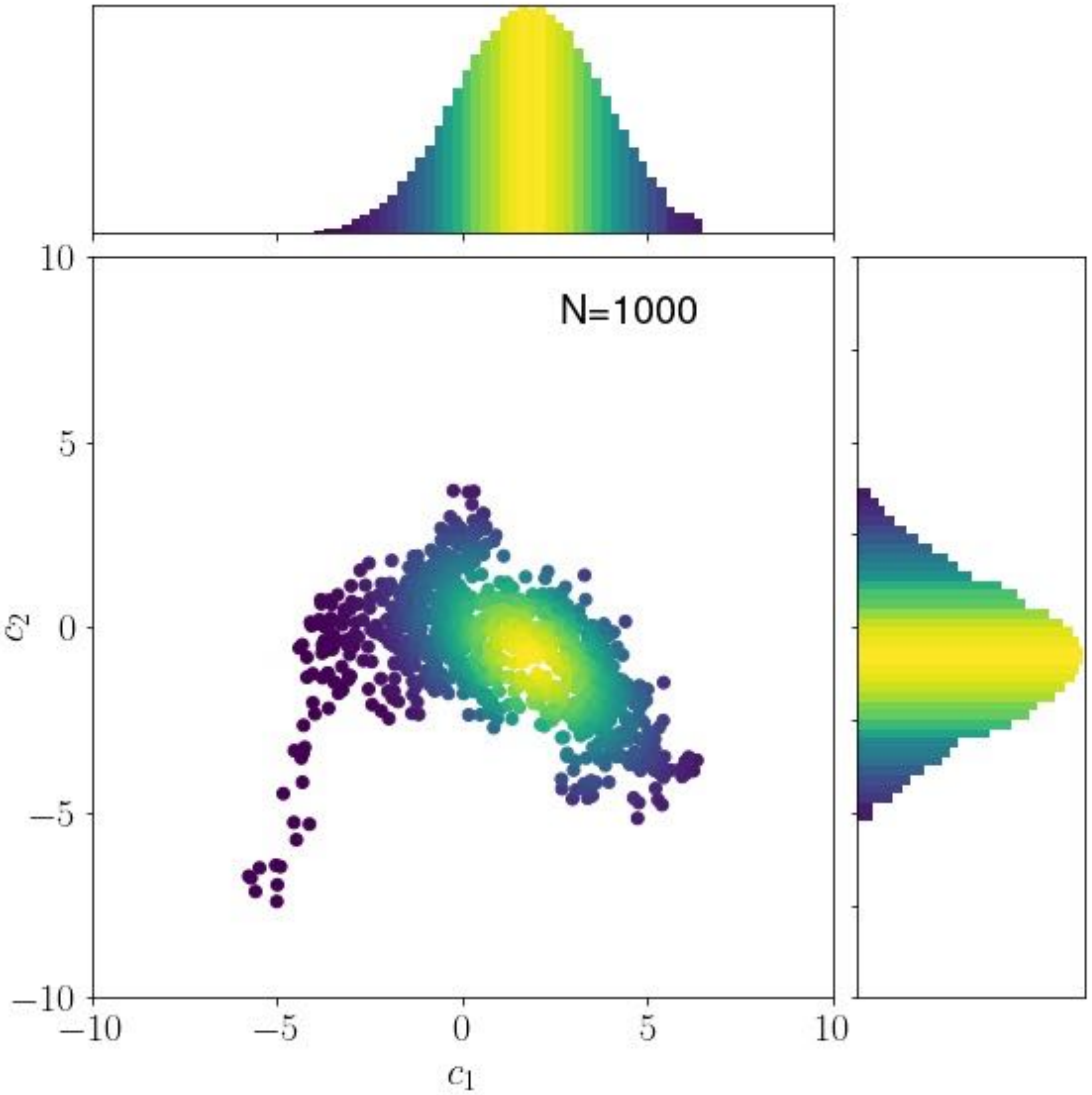

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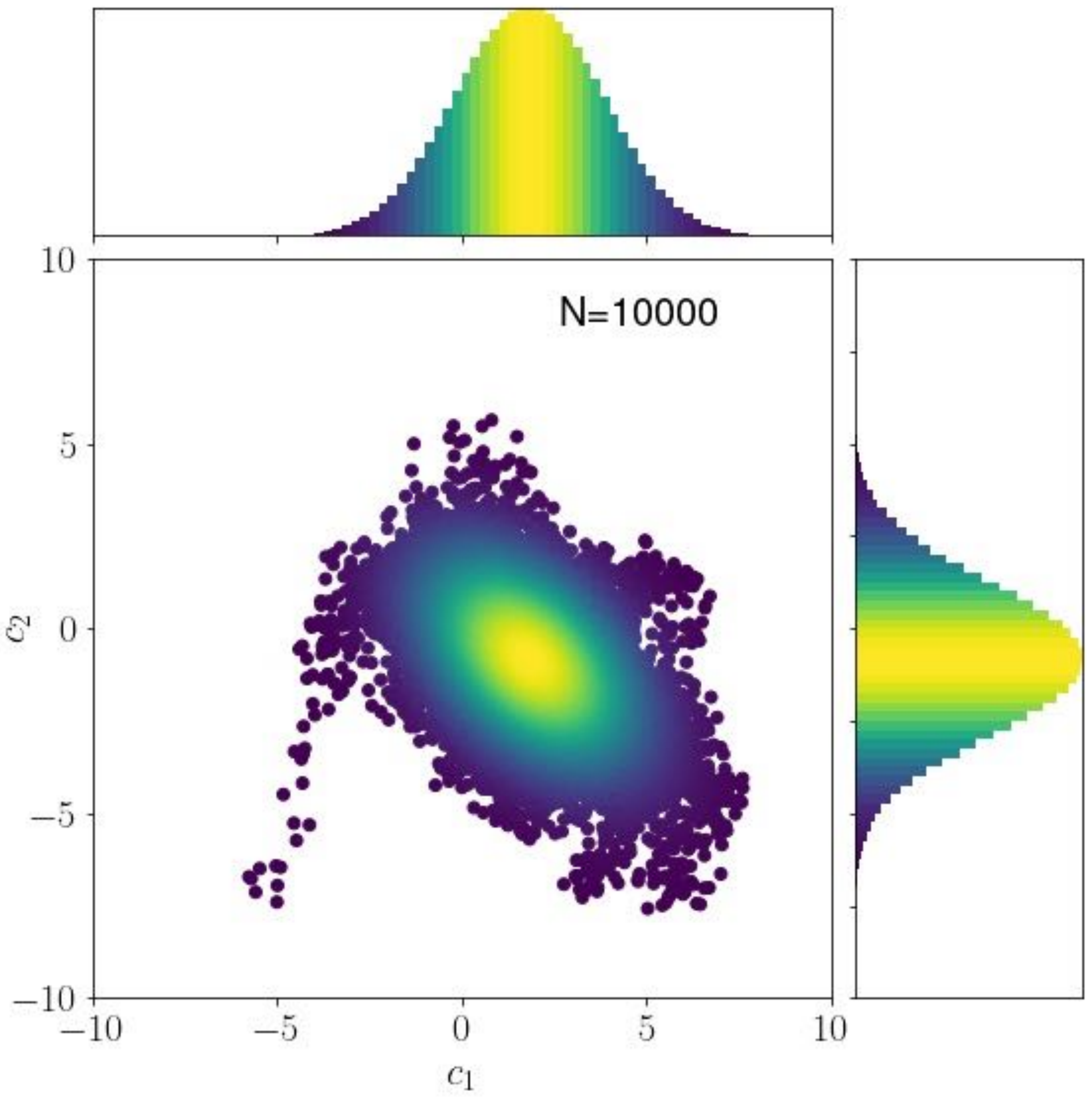

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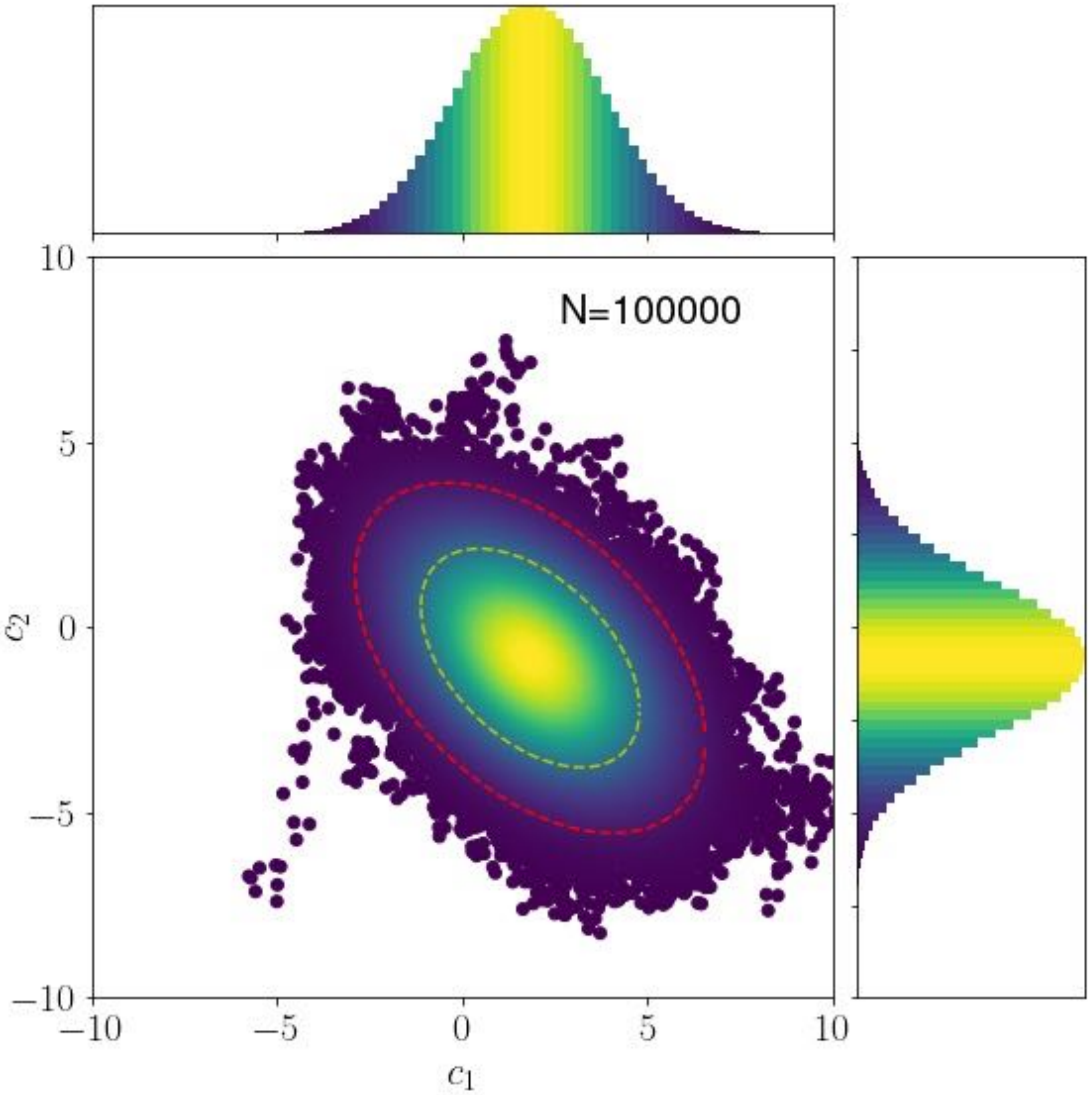
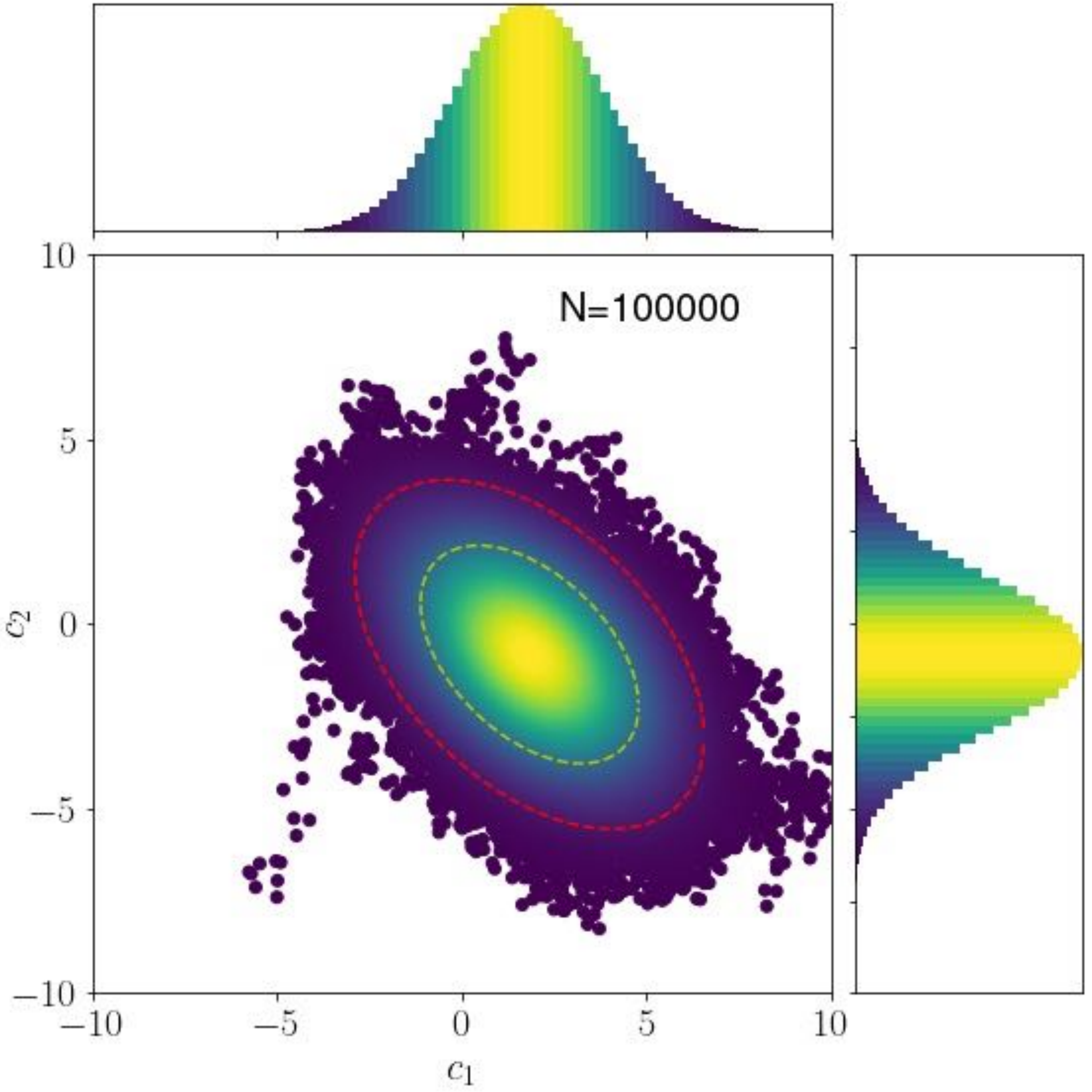


MC vs. Toys

Markov Chain

Toy Monte Carlo



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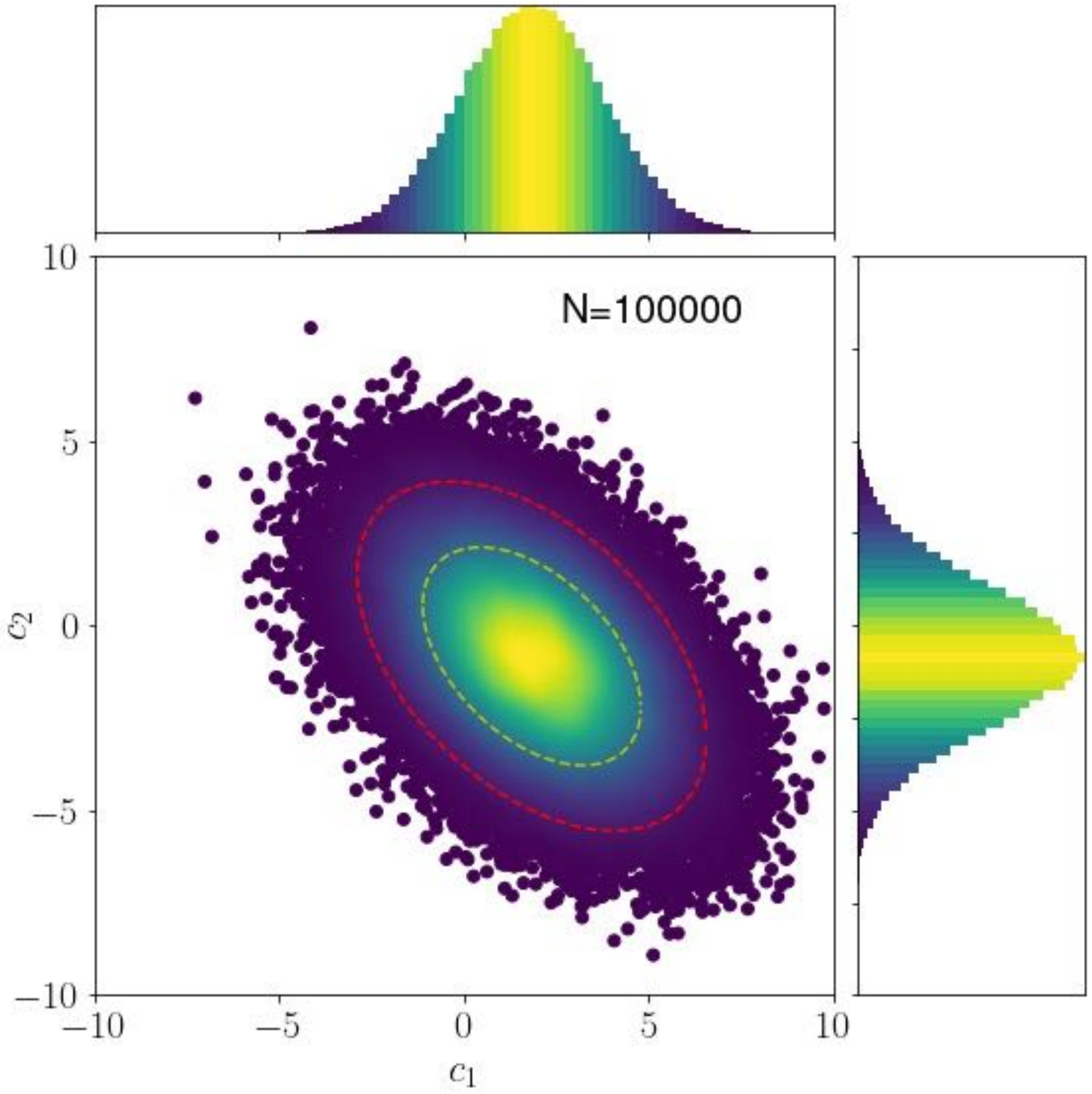

The Model

Linear vs. Quadratic

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$$\mathcal{A} = \mathcal{A}_{SM} + \frac{c_i}{\Lambda^2}\mathcal{A}_i$$

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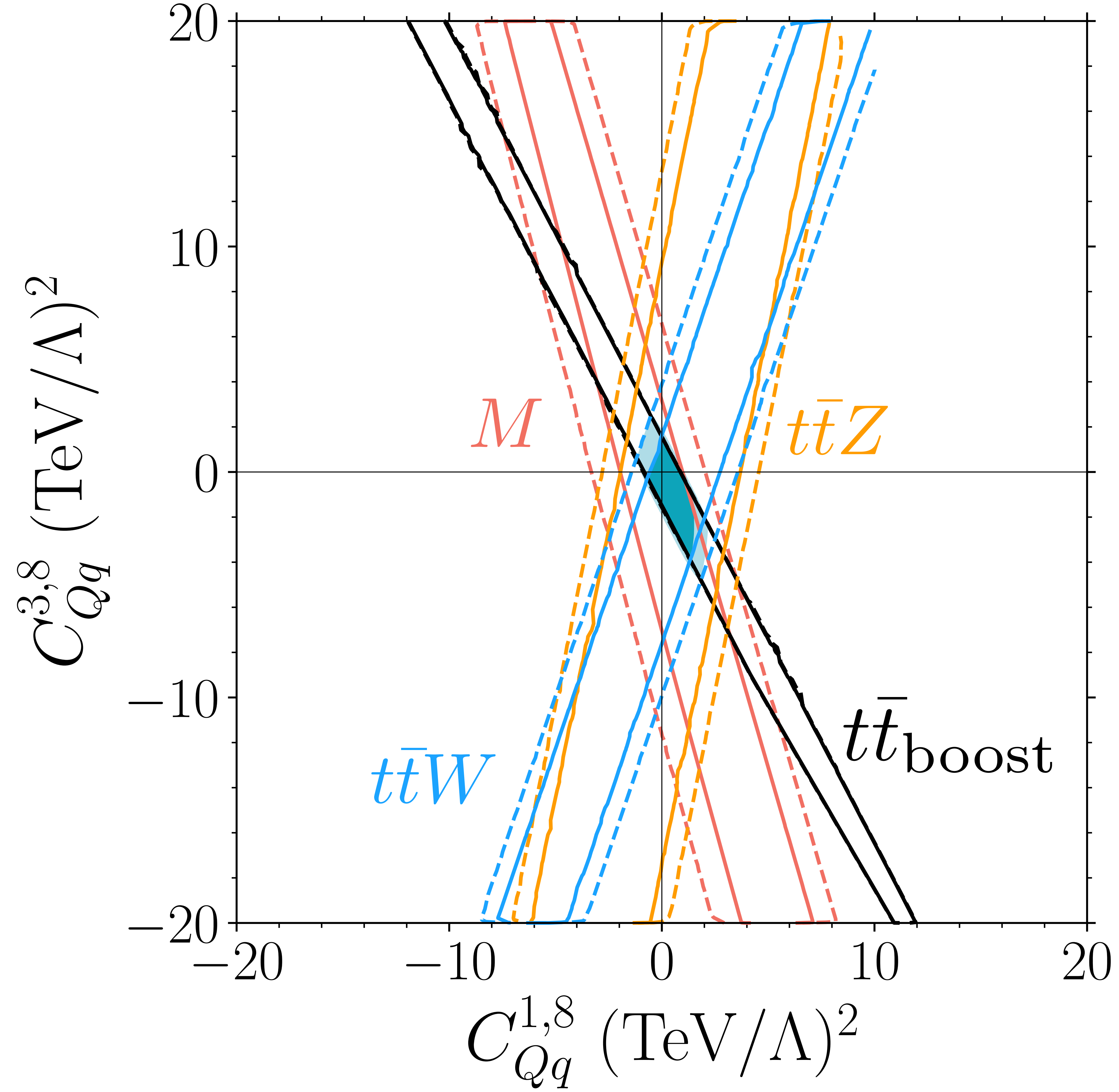

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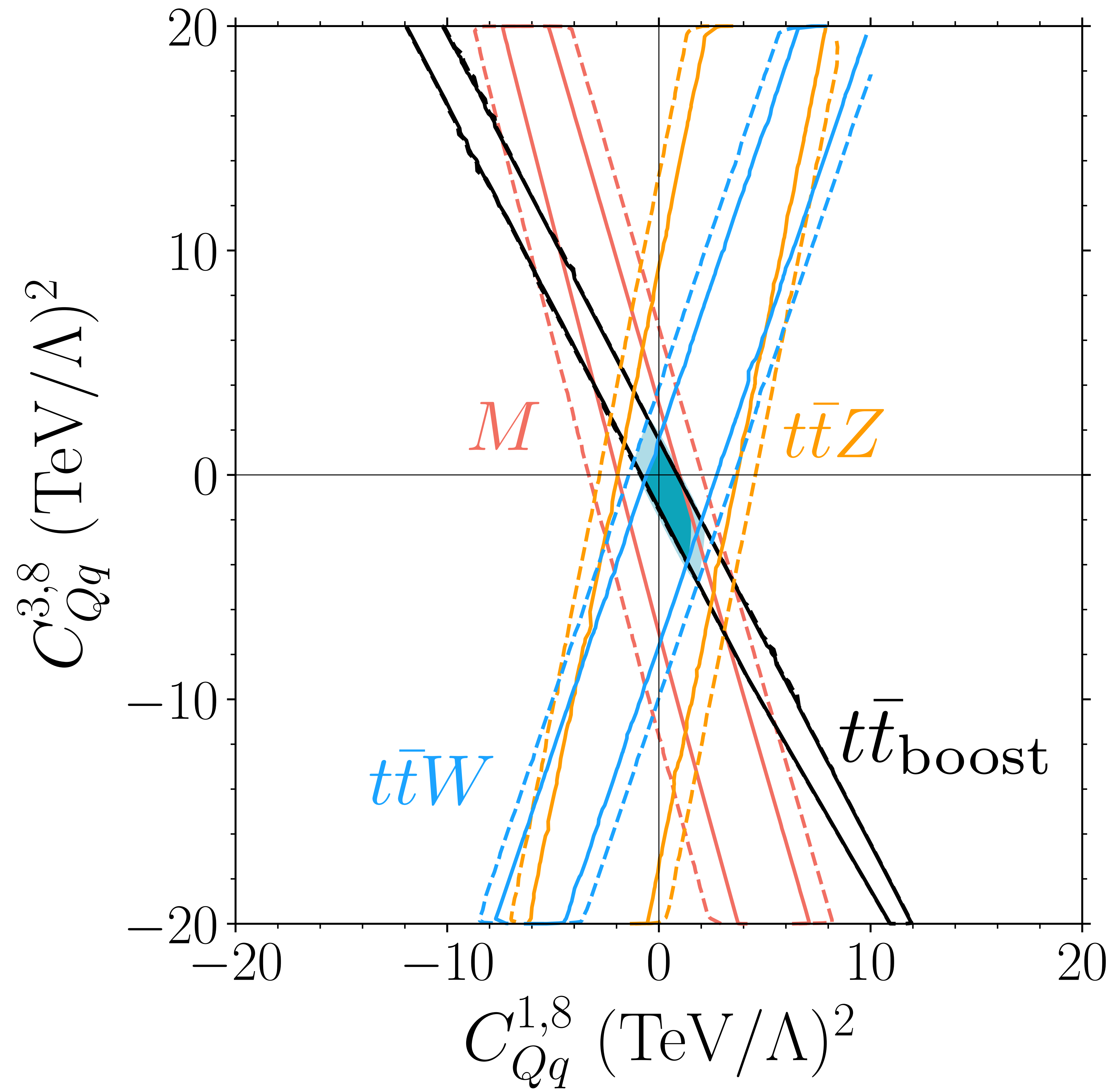

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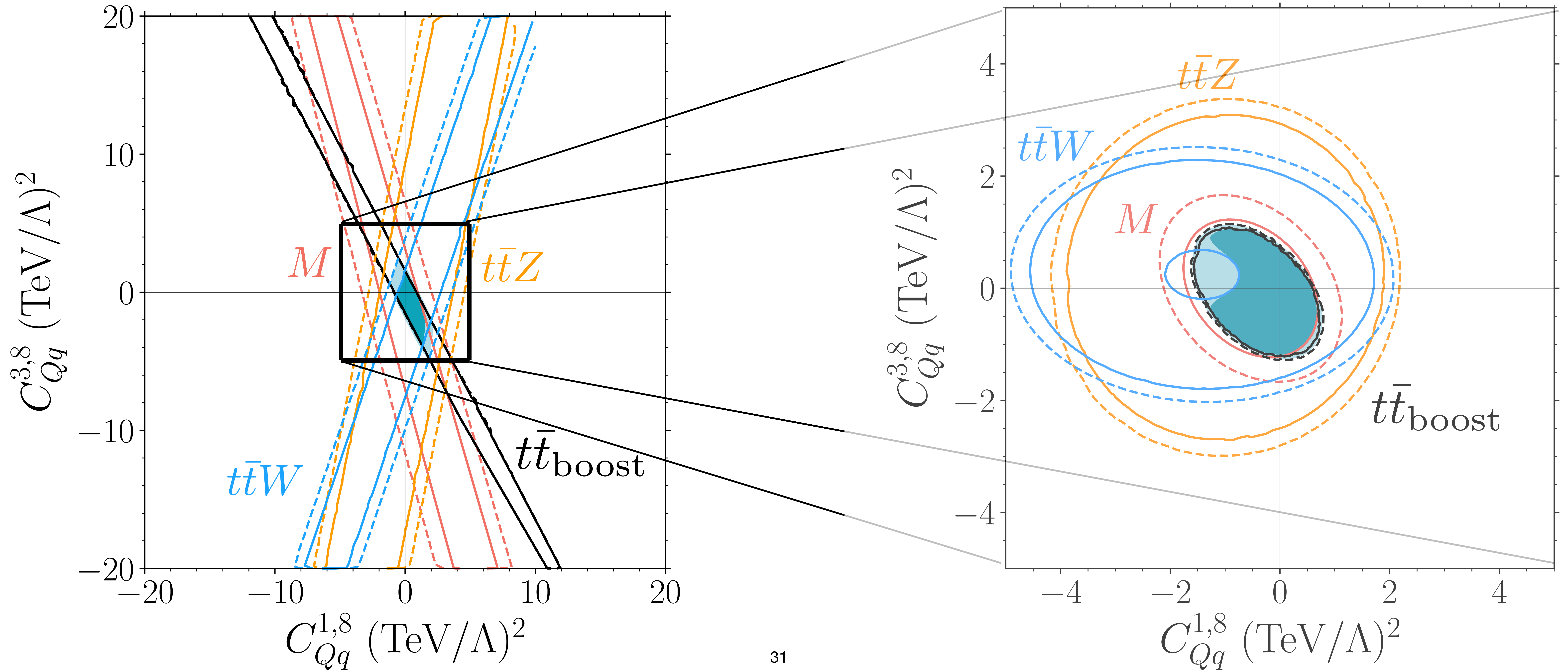

Uncertainties

What matters?

$$\mu_j = \underbrace{\bar{\mu}_j}_{\text{Central Value}} \pm \underbrace{\sigma_{\mathrm{pois},j}}_{\text{Statistical Uncertainty}} \pm \underbrace{\sigma_{\mathrm{gauss},j}}_{\text{Uncorrelated systematic Uncertainty}} \pm \underbrace{\sum_i \sigma_{\mathrm{syst},ij}}_{\text{Correlated systematics Uncertainty}} \pm \underbrace{\sigma_{\mathrm{theo},j}}_{\text{Flat Uncertainties}}$$

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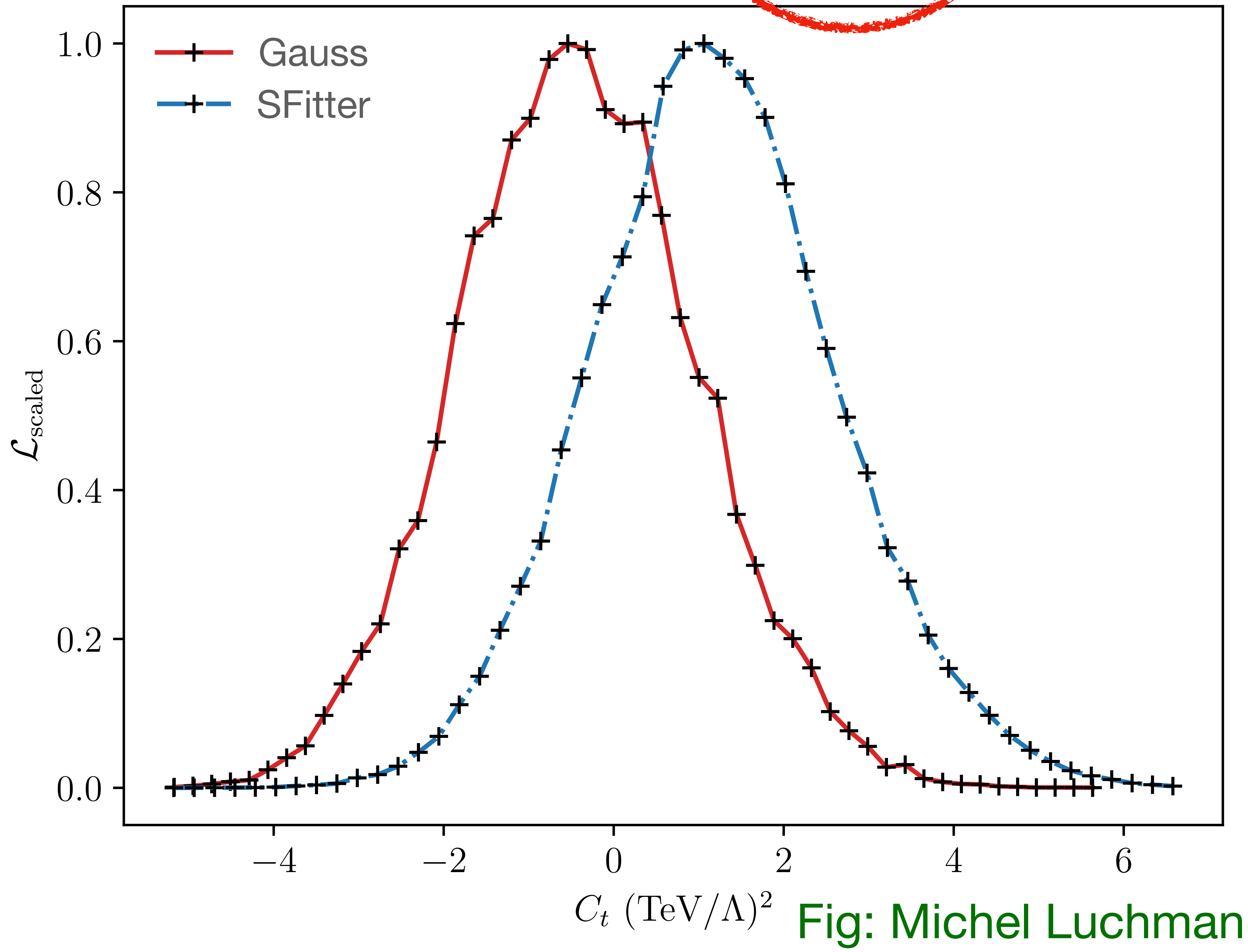

Fig: Michel Luchmann, 8D-Fit

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Full correlations known?

Yes

Full correlation matrix

No

Assume full (1) or no (0) correlation

Uncertainties

What matters?

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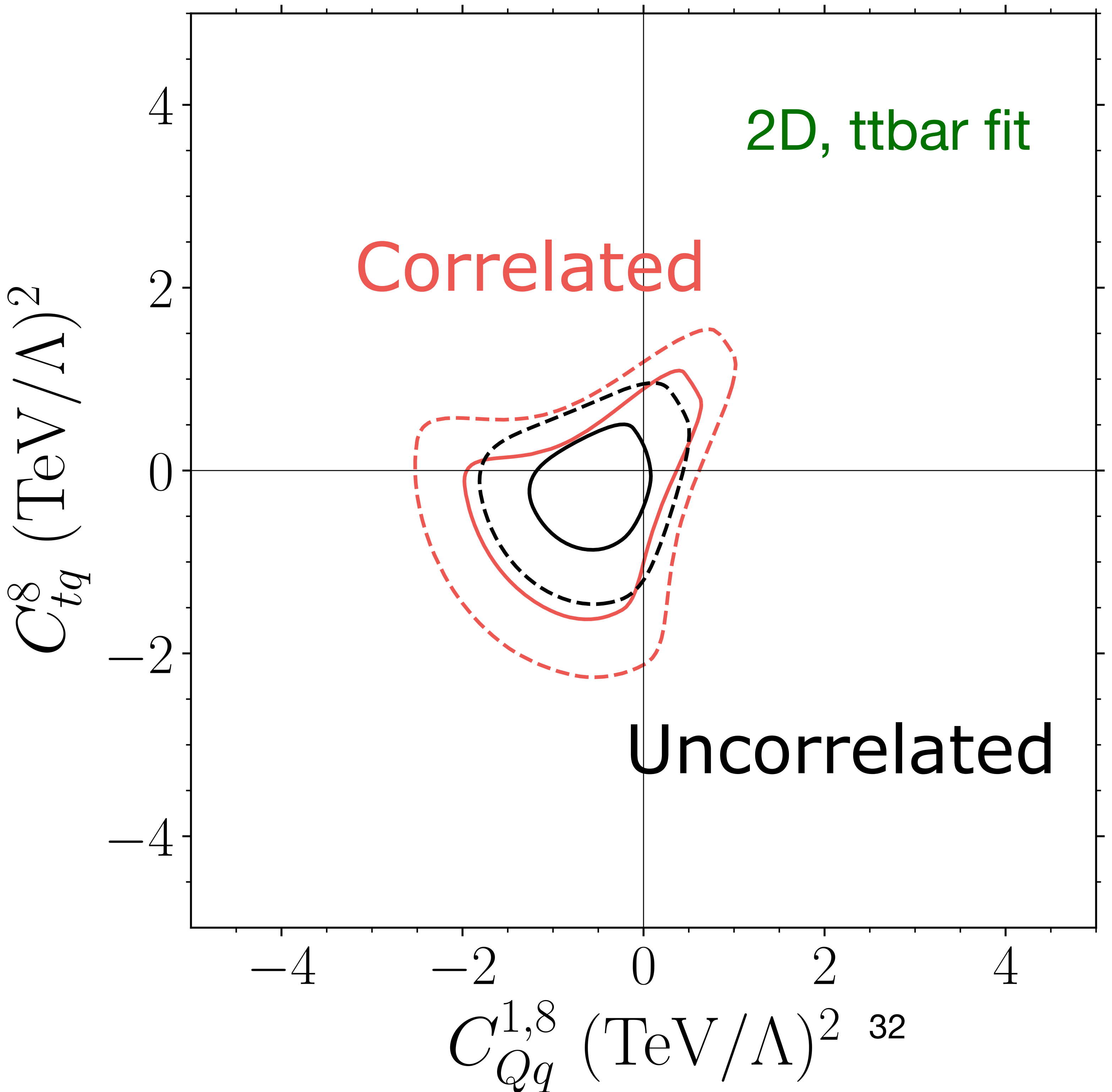

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Correlated?

Yes

Nuisance parameter

No

Add linearly

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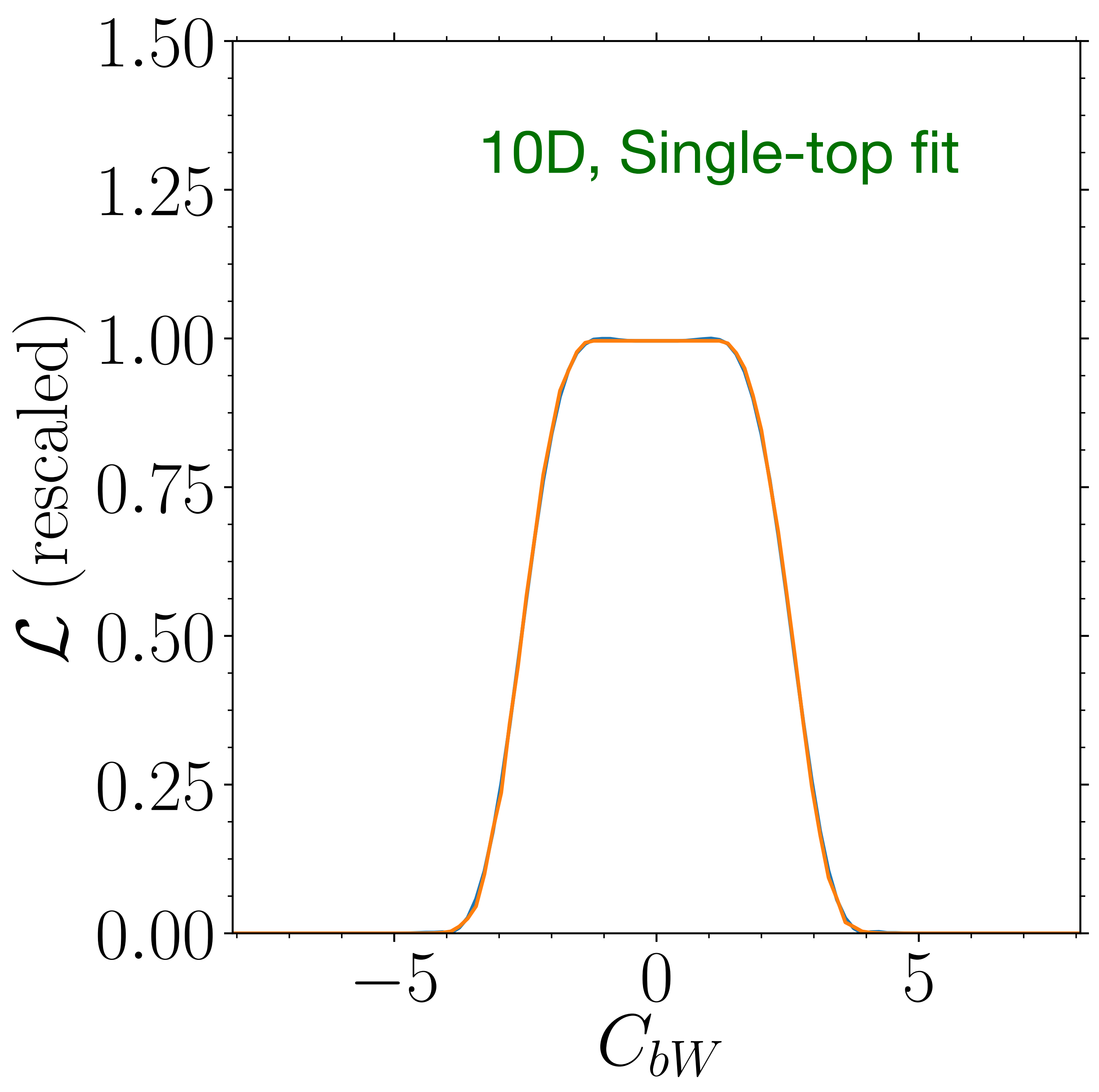

Correlated?

Yes → Nuisance parameter

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Correlated?

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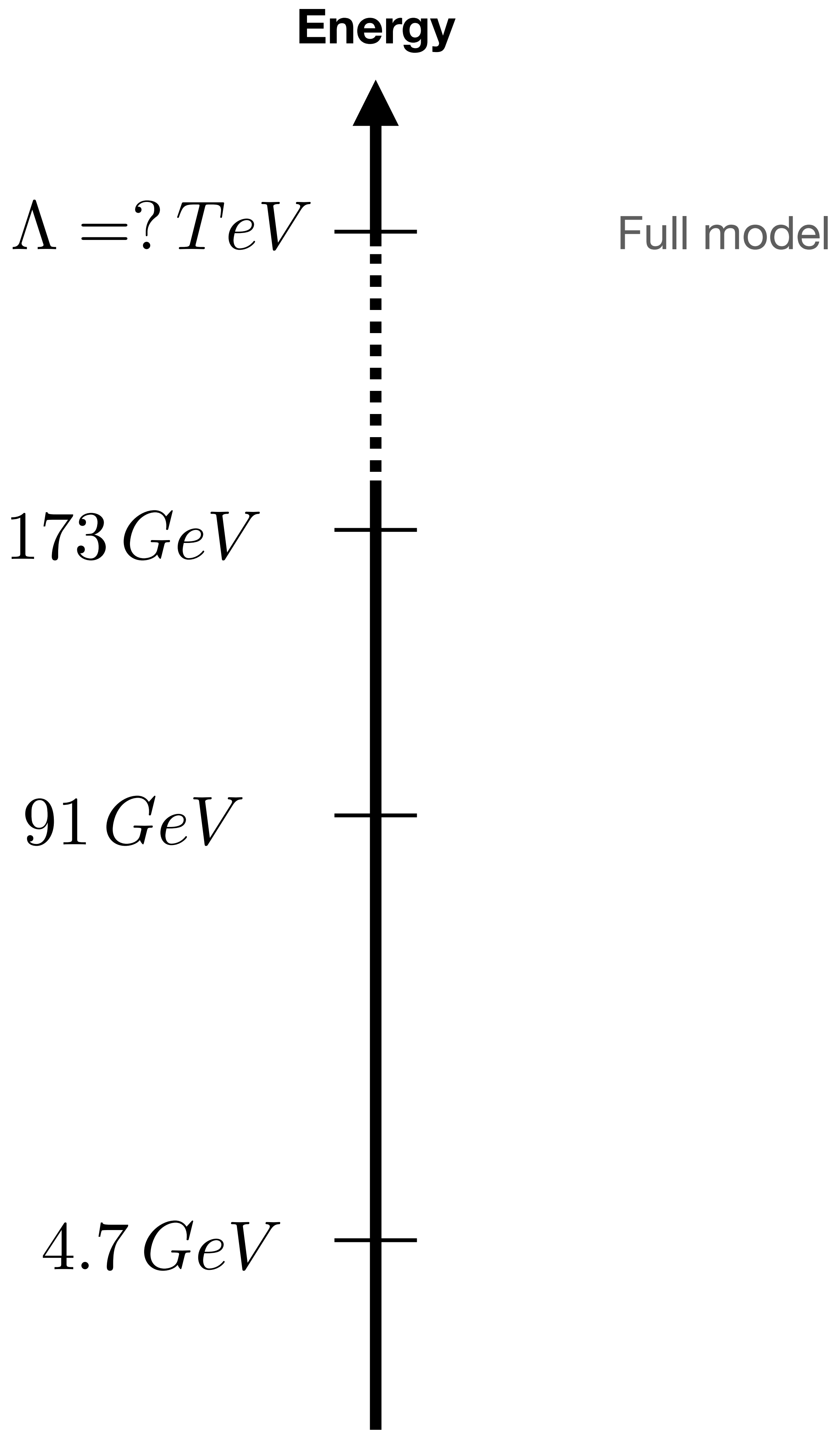
Nuisance parameter

No

Add linearly

- Conservative and ignorant
- Better: e.g. include as nuissance parameters

Top-Down



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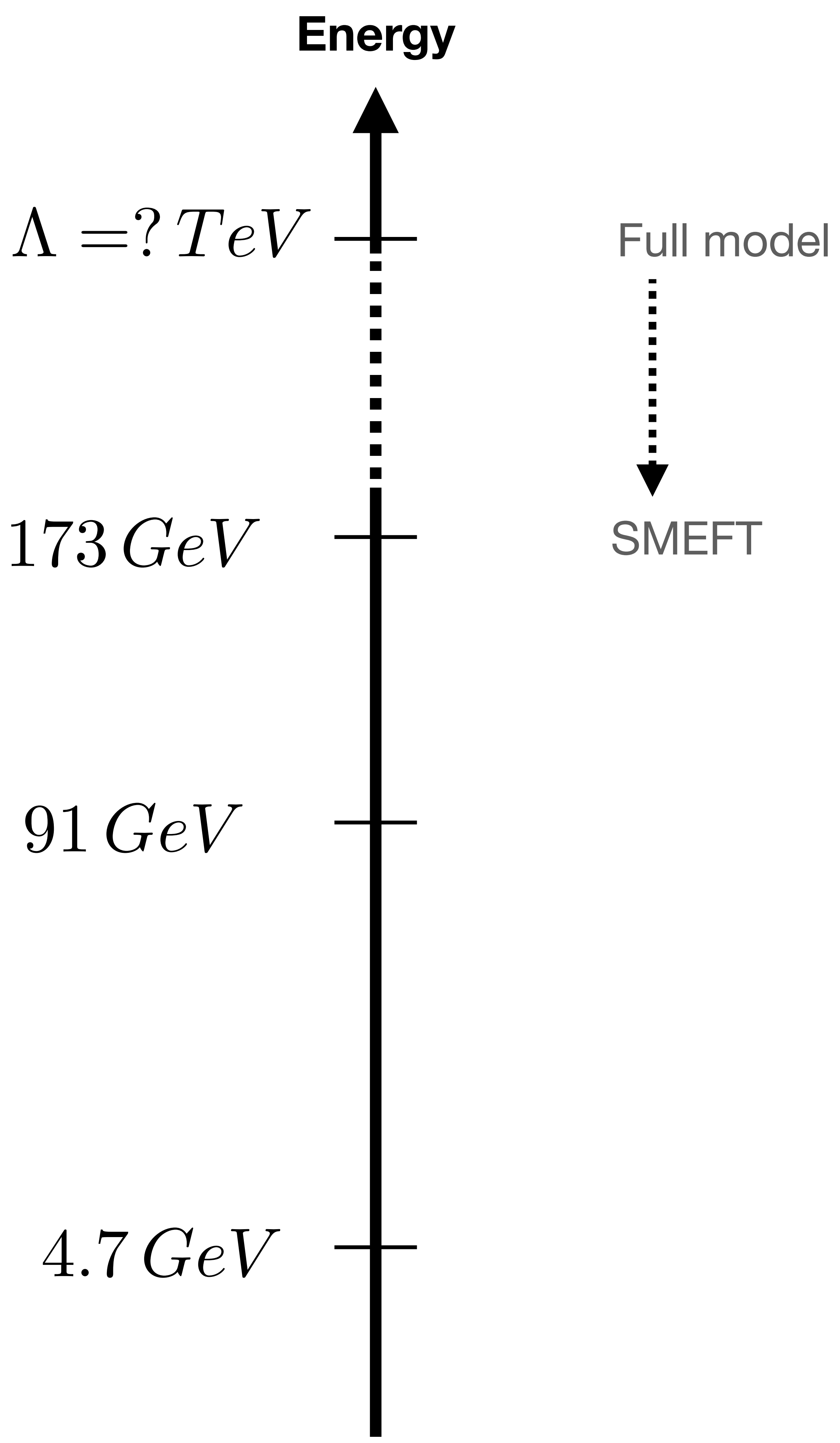

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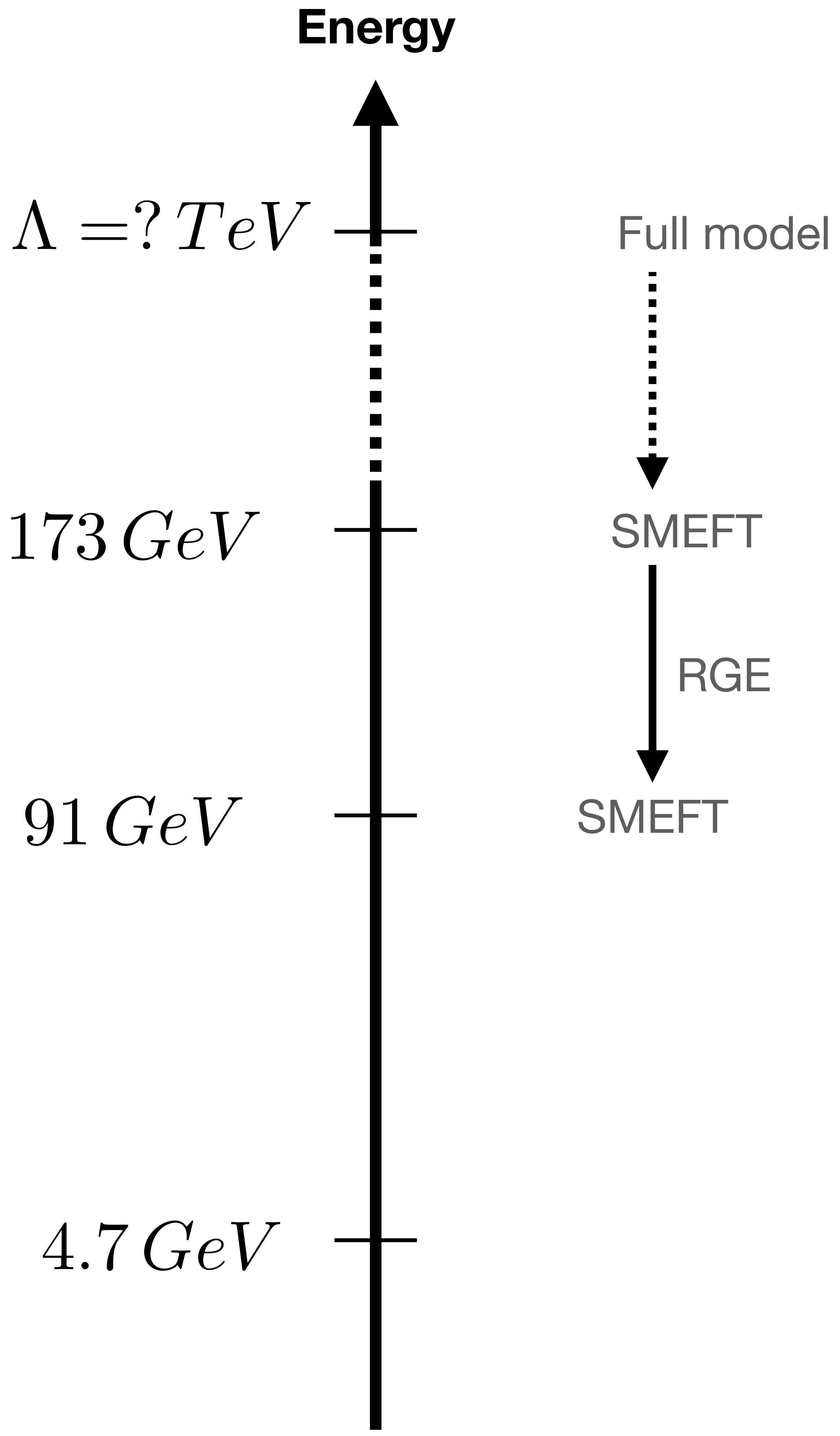
Energy
$\Lambda = ?\, TeV$
Full model
$173\, GeV$
SMEFT
RGE
$91\, GeV$
SMEFT
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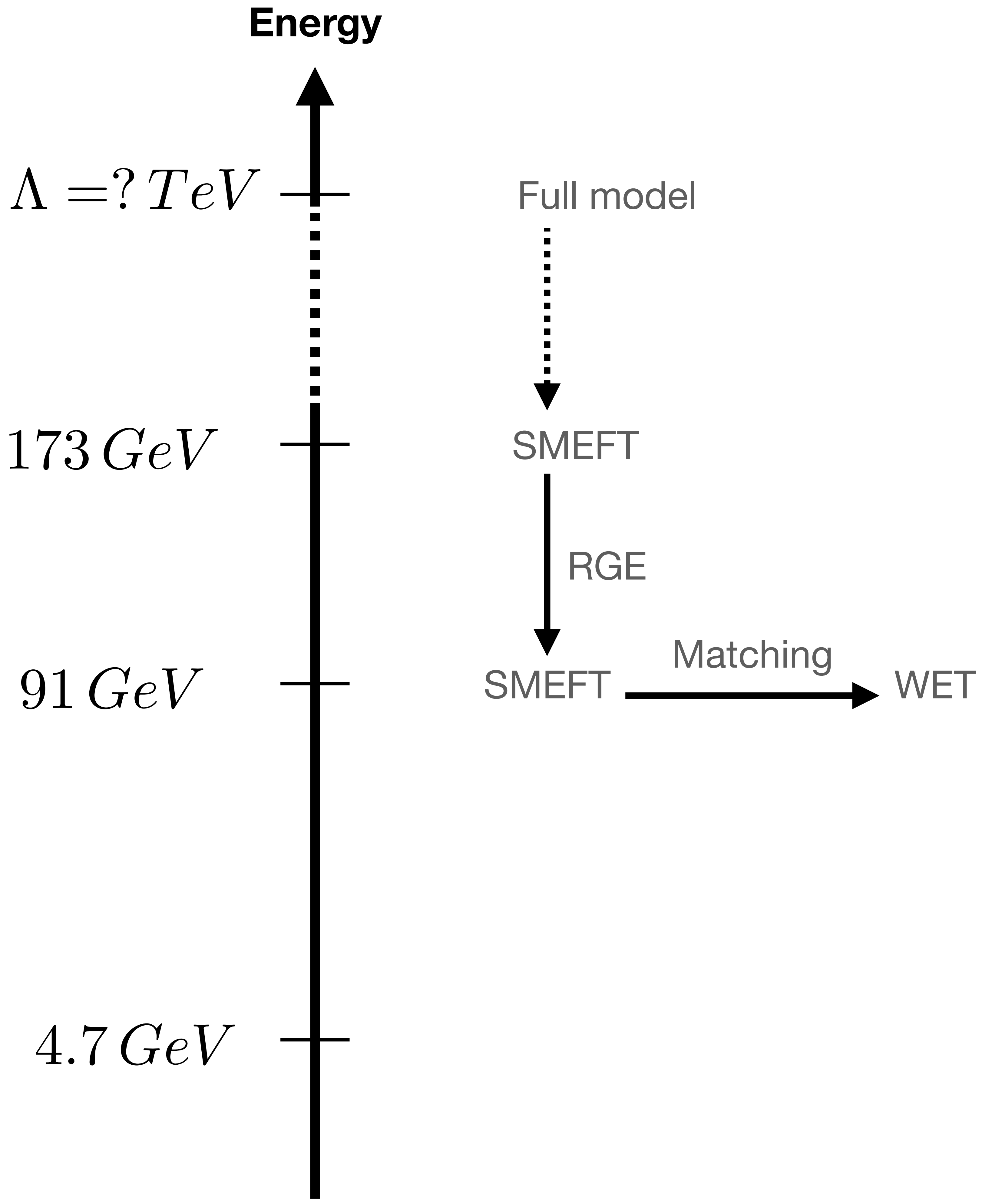
Top-Down



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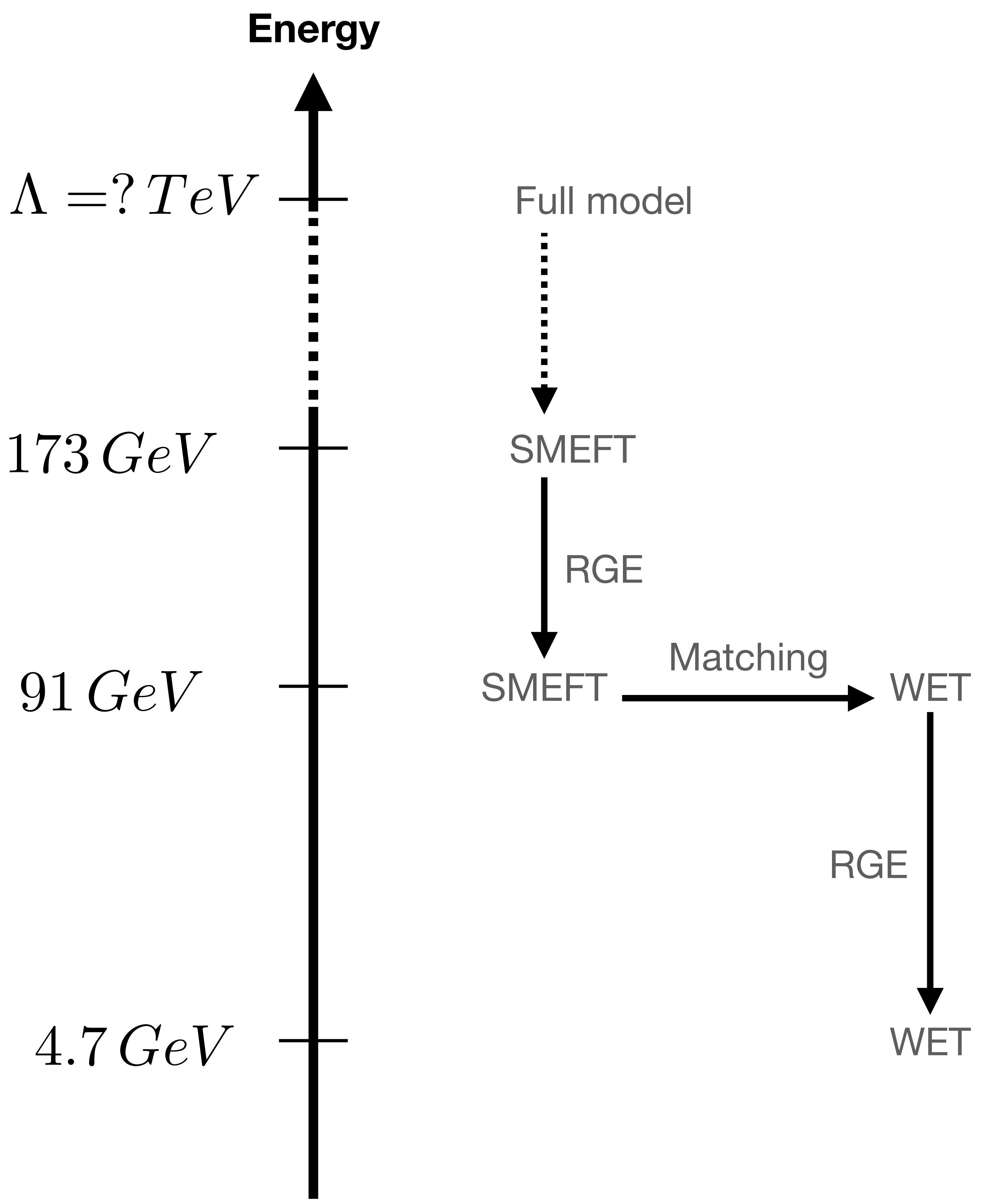

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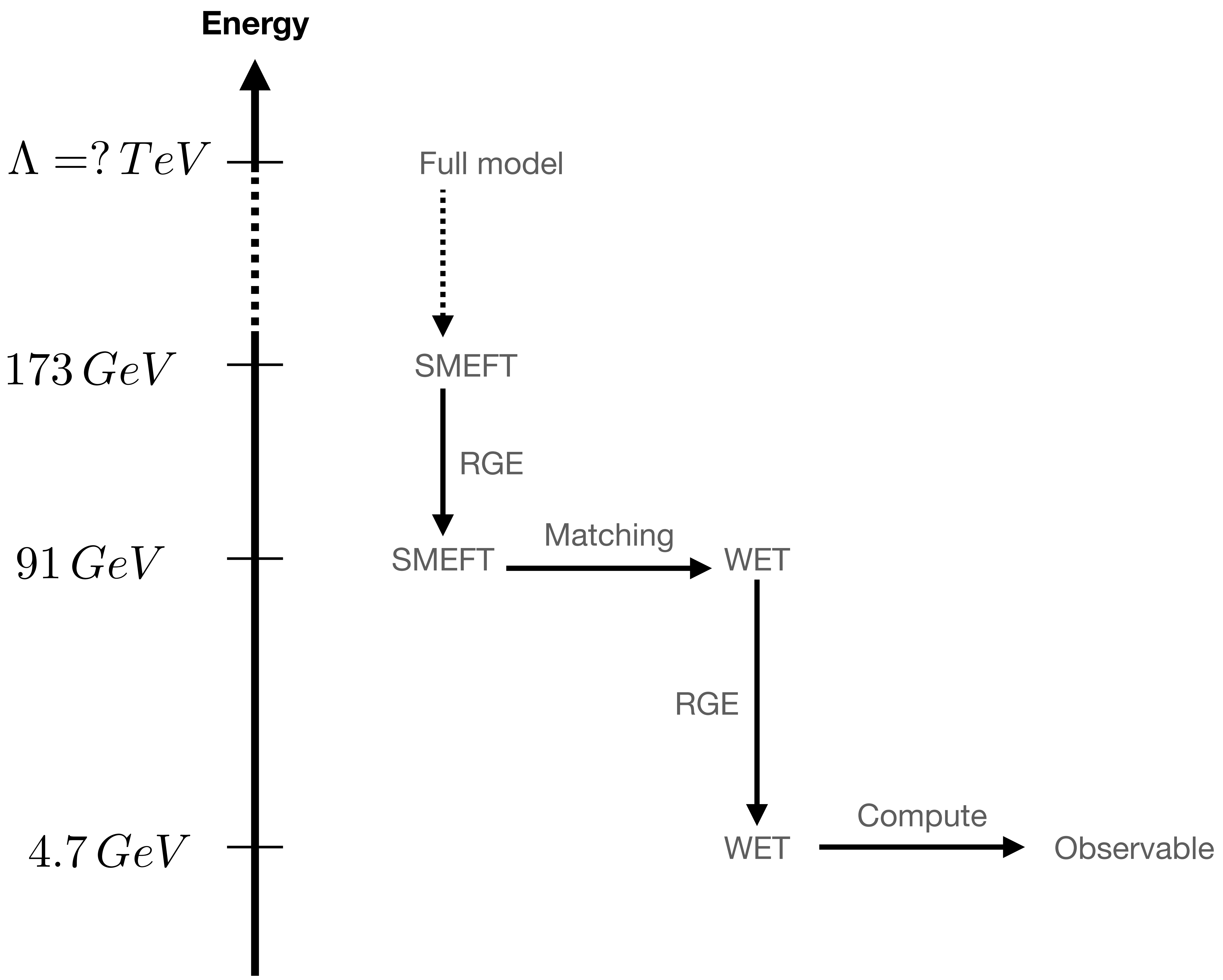

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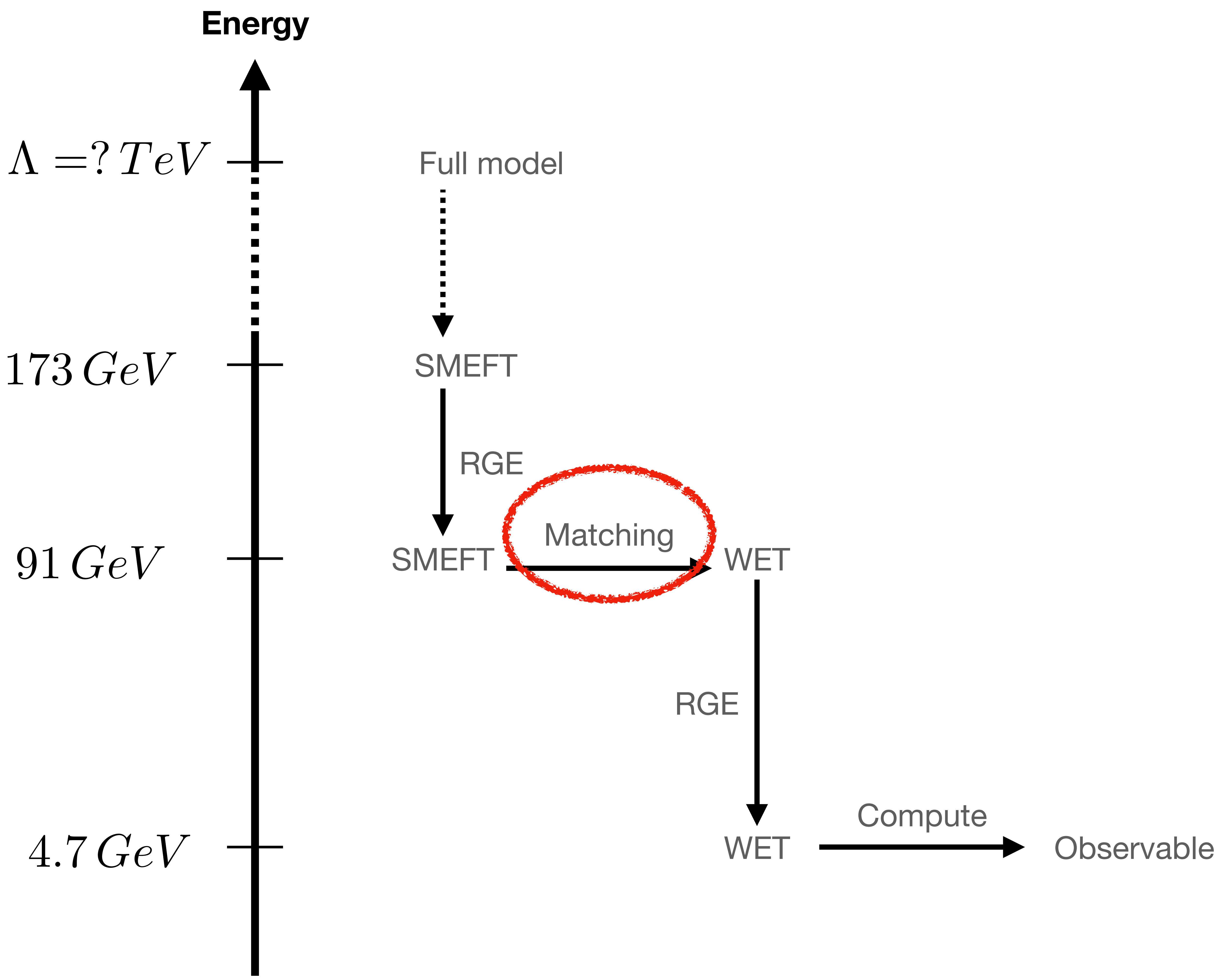

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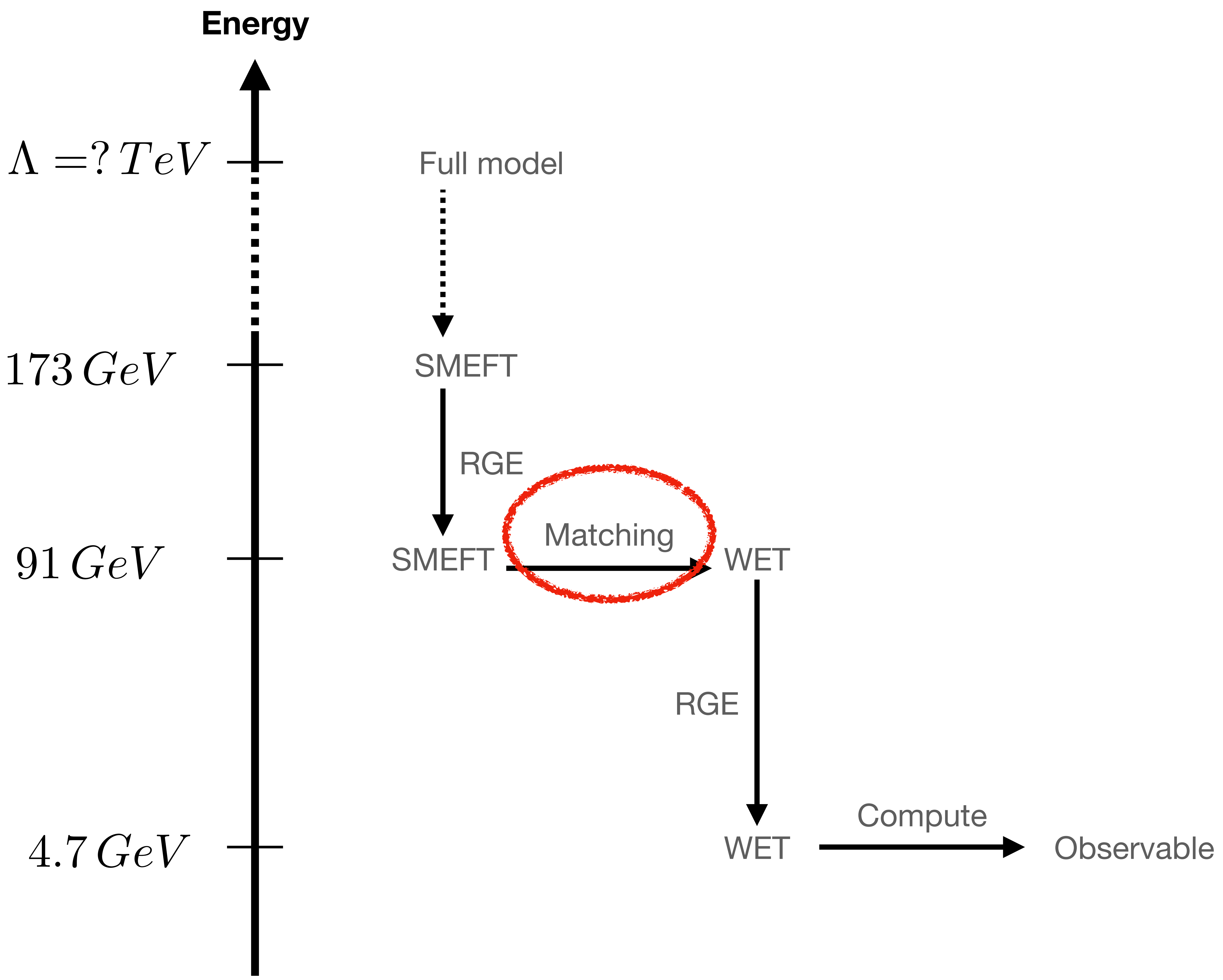
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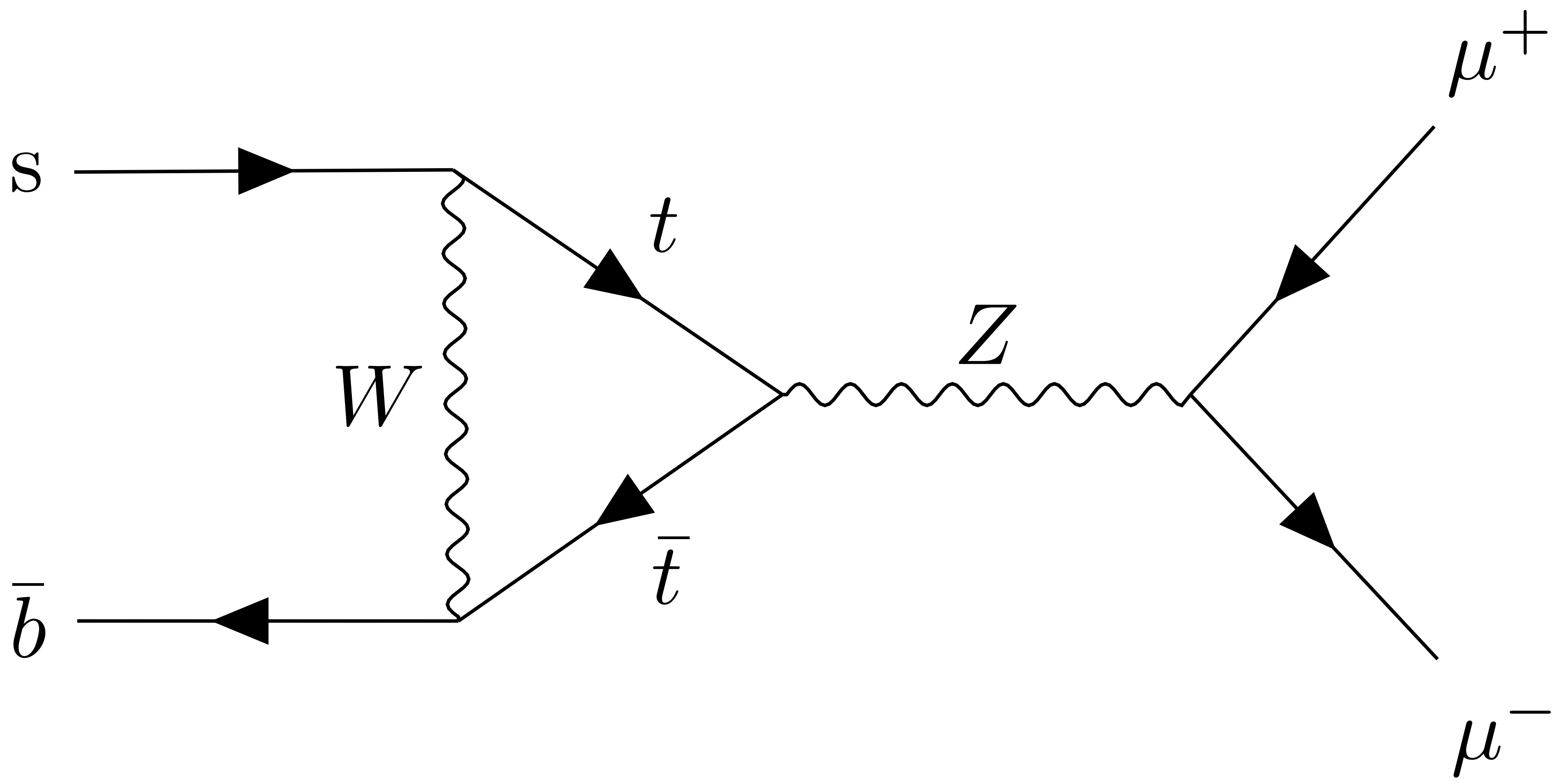
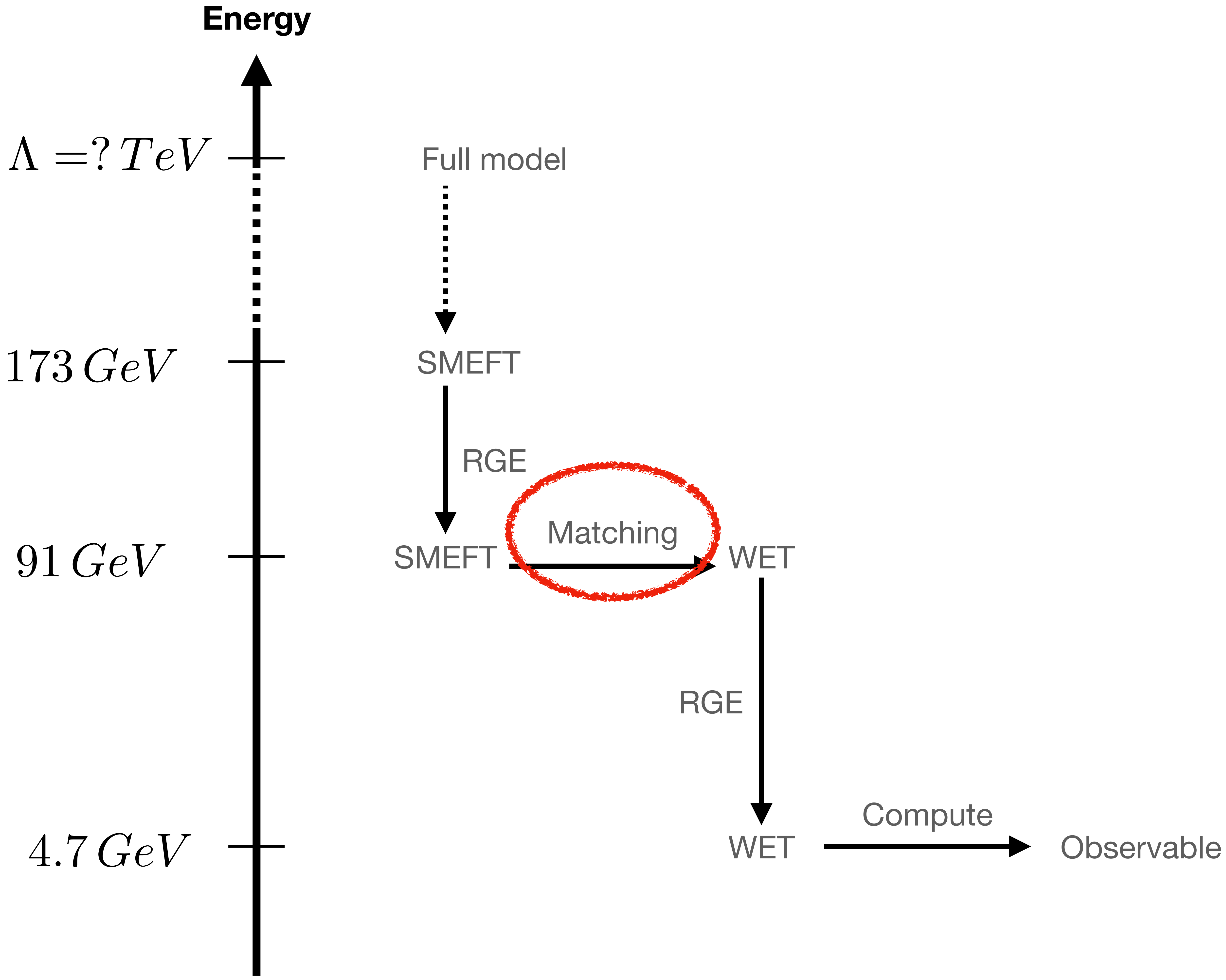
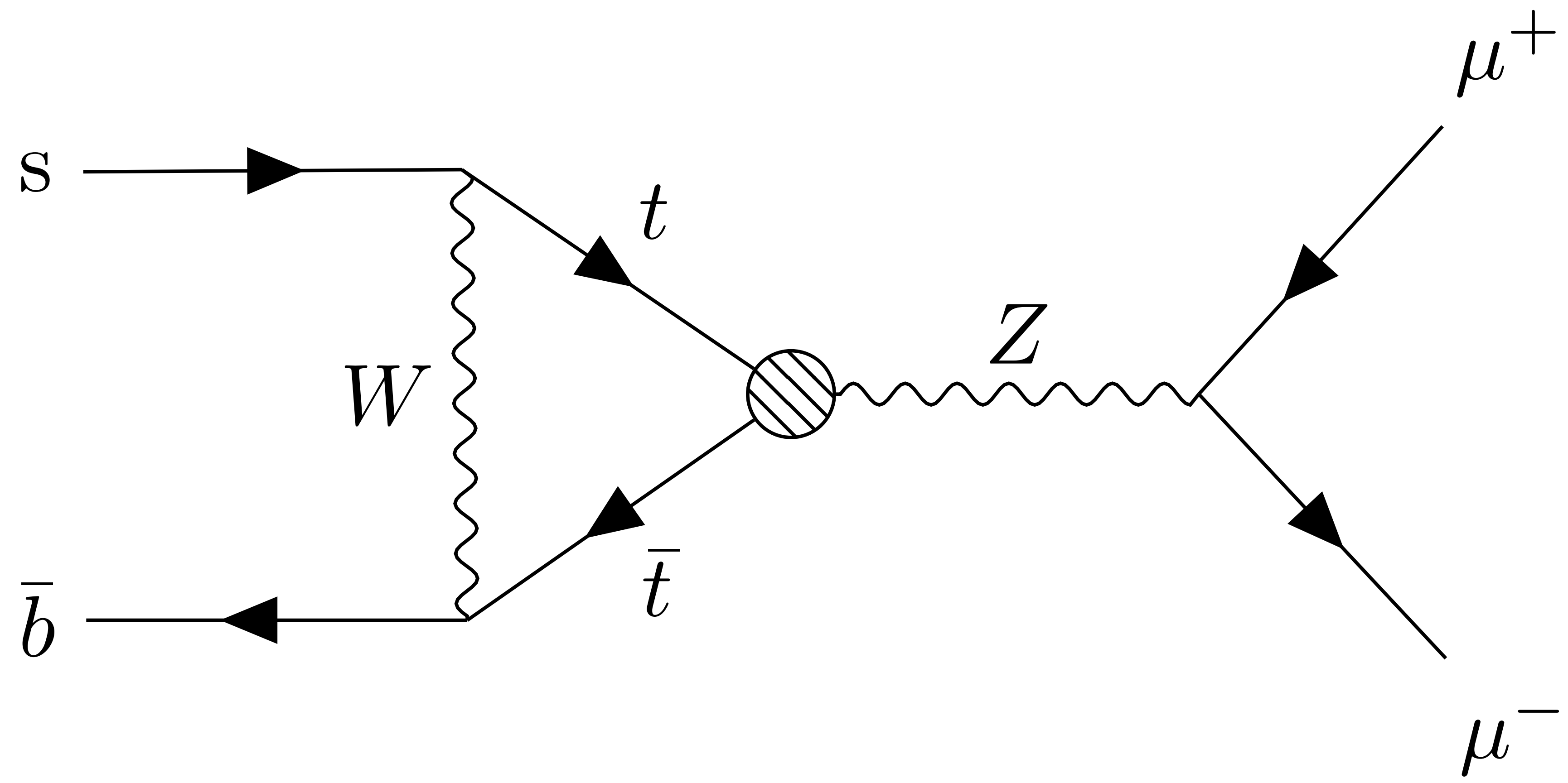

s
$\bar{b}$
W
t
$\bar{t}$
Z
μ^+
μ^-

Top-Down





$$\left[\mathcal{O}^{1}_{\phi q}\right]_{ij} = \left(\phi^\dagger\, i\, \overleftrightarrow{D}_\mu\, \phi\right)\left(\bar{q}_i \gamma^\mu q_j\right)$$

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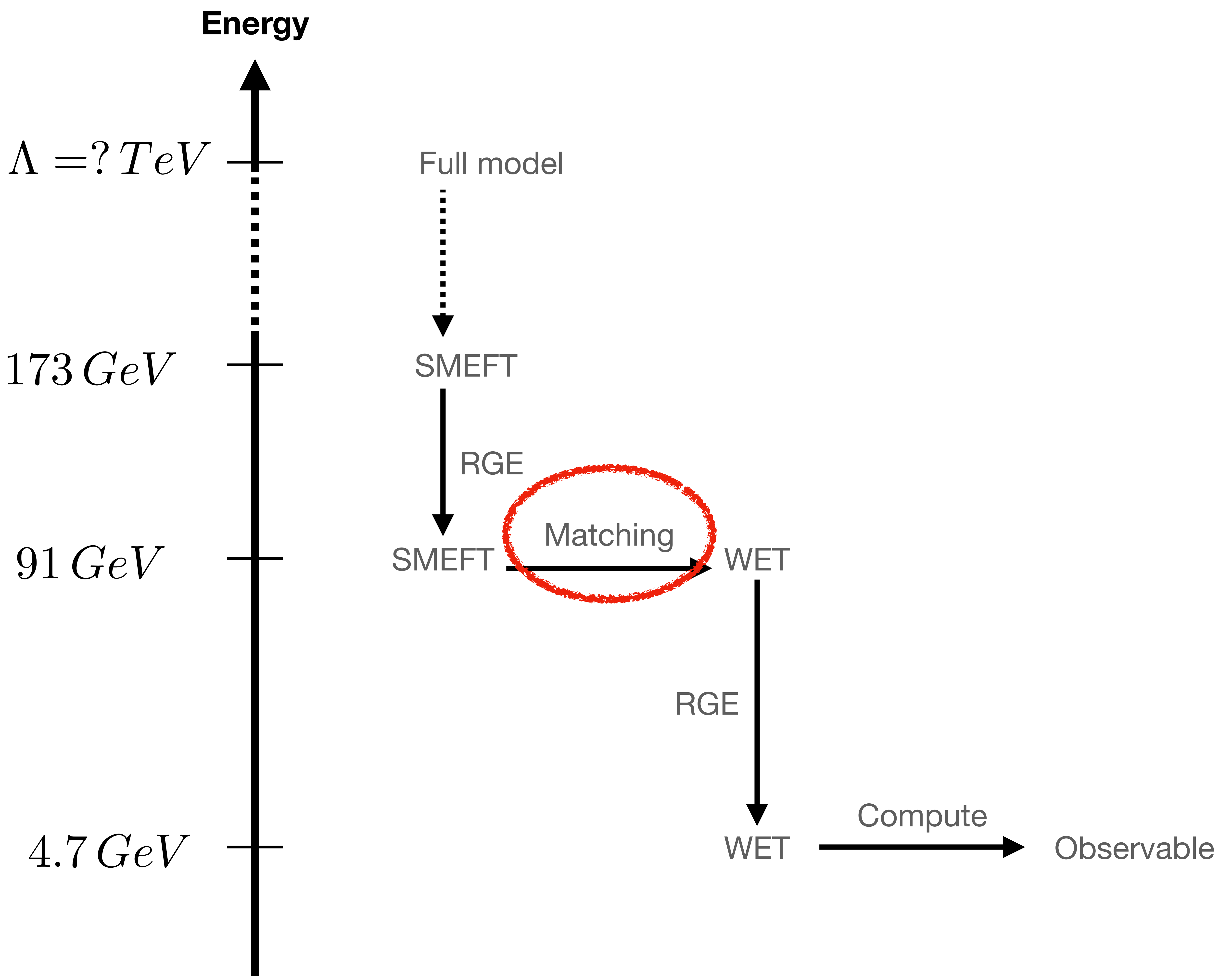

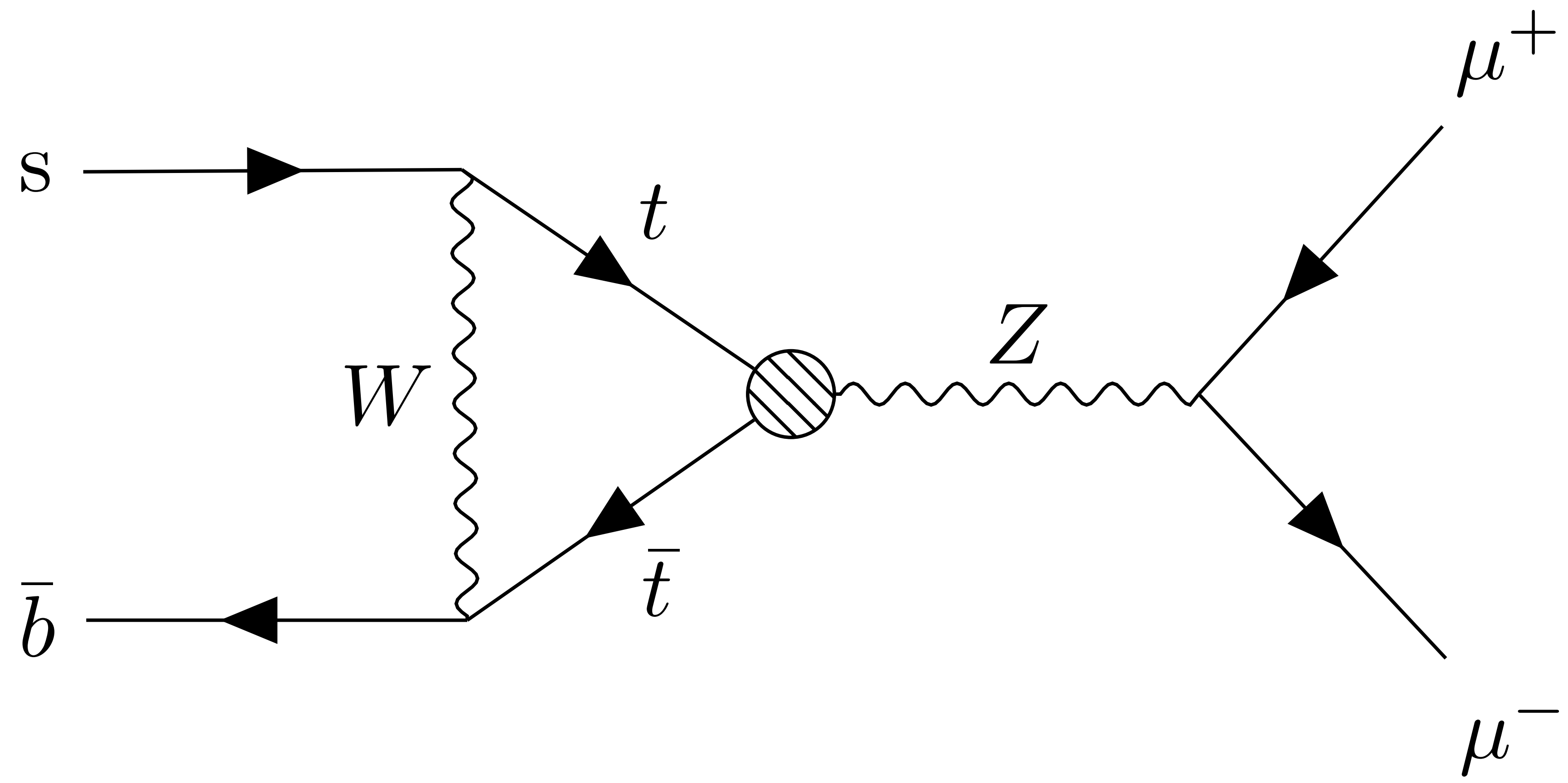

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MFV	$\mathcal{C}^1_{\phi q}$
ii	a
33	$(a + y_t^2 b) y_t$

Exampe: Four-quark couplings

$$O_{qq}^{(1)} = (\overline{Q}\gamma_\mu Q)(\overline{Q}\gamma^\mu Q)$$

$$O_{qq}^{(3)} = (\overline{Q}\gamma_\mu \tau^a Q)(\overline{Q}\gamma^\mu \tau^a Q)$$

$$(C_{qq})^{33ii} = A_{qq}$$

$$(C_{qq})^{3ii3} = \widetilde{A}_{qq}$$

$$(C_{qq})^{3333} = A_{qq} + \widetilde{A}_{qq} + B_{qq}$$

$$A_{qq} = (aa) + (ba)y_t^2$$

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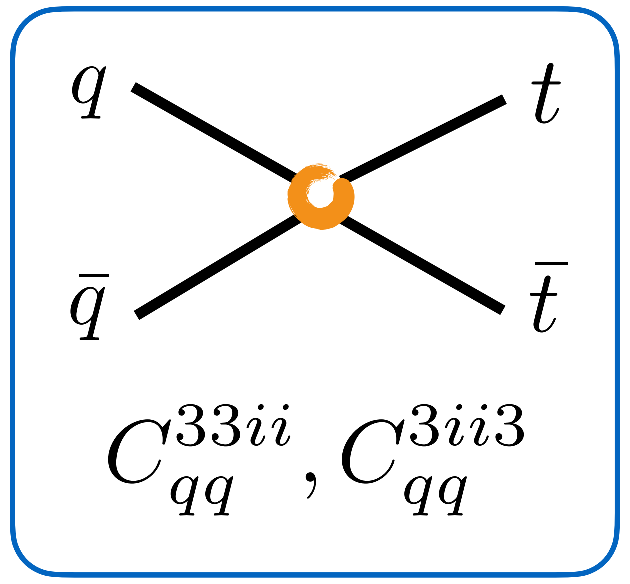

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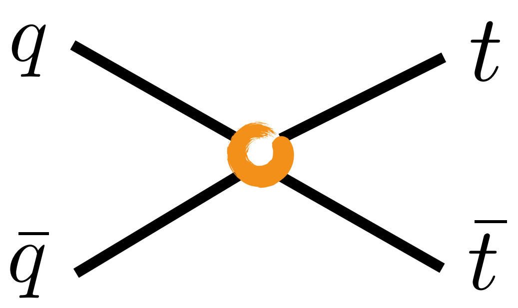
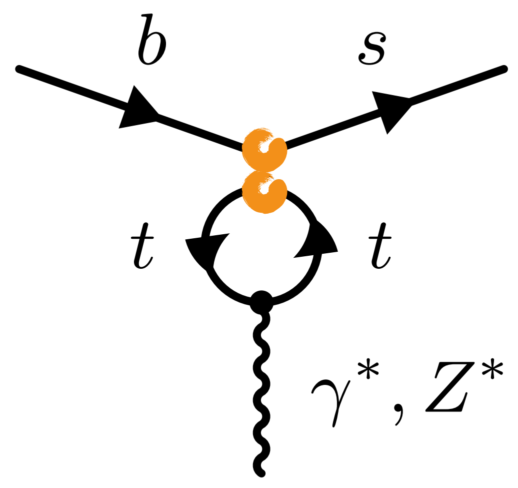
top



$C_{qq}^{33ii}, C_{qq}^{3ii3}$

bottom



$\sum_k C_{qq}^{(-),33kk}$

$$\mathcal{C}_{10} \sim \underbrace{\tilde{A}_{qq}^{(-)} + B_{qq}^{(-)} y_t^2}_{F_{qq}^{(-)}} \quad \& \quad \underbrace{A_{qq}^{(3)} + B_{qq}^{(3)} y_t^2}_{F_{qq}^{(3)}}$$

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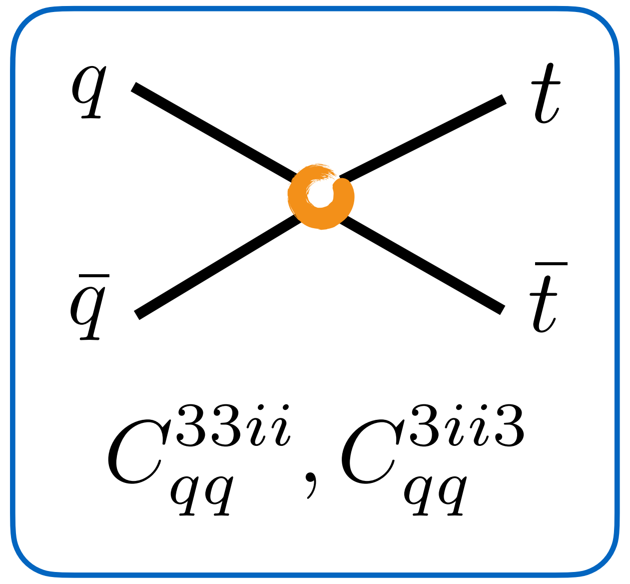
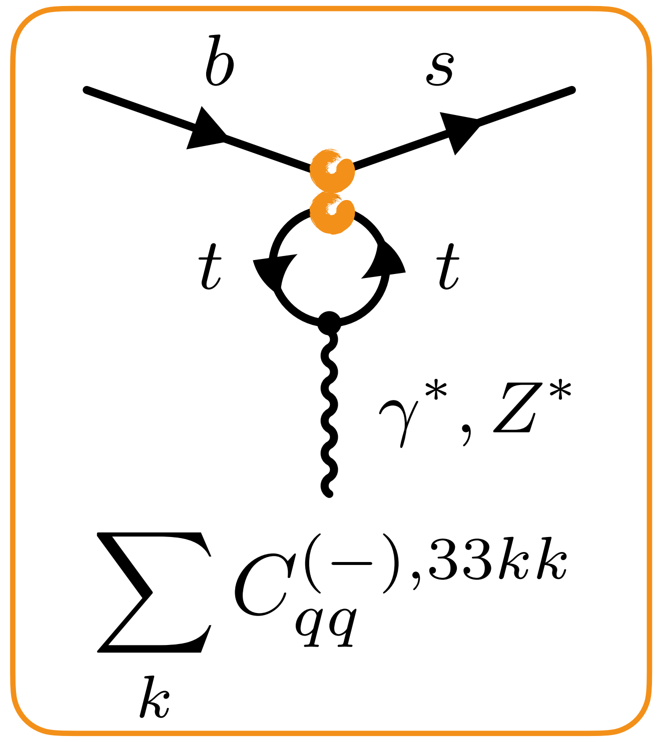


bottom



$$\mathcal{C}_{10} \sim \underbrace{\tilde{A}_{qq}^{(-)} + B_{qq}^{(-)} y_t^2}_{F_{qq}^{(-)}} \quad \& \quad \underbrace{A_{qq}^{(3)} + B_{qq}^{(3)} y_t^2}_{F_{qq}^{(3)}}$$

$$\{\widetilde{A}_{qq}^{(-)}, A_{qq}^{(3)}, B_{qq}\}$$