Progress of the SM Working Group

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On behalf of Qing-Hong Cao, Chong Sheng Li,
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2nd CFHEP Symposium on circular collider physics

Not too much

Contents

Many pieces missing!
Some studies in progress…
Man-power needed!

The Standard Model

- Our best theory about the subatomic world
- Definitely should be examined with higher precision and at higher energy
- Foundation to go “beyond the standard model”

Things to measure/test

- Fundamental parameters: 18(+1)
- Properties of the Higgs boson
- Properties of fermions
- Properties of gauge bosons

Knowledges needed for going beyond

- Precision calculations for SM/BSM processes
- Parton distribution functions
- Understanding boosted objects

EFT framework

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{n,i} \frac{C_{n,i}}{\Lambda^{4+n}} O_{n,i}$$

18(+1) parameters

Deviations from the SM

Good approximation @ CEPC

Possibly (at least we hope) not valid @ SPPC

Parameters/observables

Examples:

	Current	ILC	TLEP
m_Z	0.0023%	0.0018%	0.0001%
m_W	0.02%	0.004%	0.0006%
m_t	0.5%	0.02%	0.01%
α_s	0.5%	0.4%	0.08%

	Current	ILC	TLEP
Γ_Z	0.09%	0.03%	0.004%
$\sin^2\theta^l_{\rm eff}$	0.07%	0.004%	0.0004%
R_b	0.3%	0.06%	0.02%
N_ν	0.27%	0.13%	0.03%

Studies dedicated to CEPC required!
(e.g.: work of Liantao Wang *et al.* presented yesterday)

Interesting examples of higher dimensional operators

Triple and quartic gauge boson couplings

$$\mathcal{L}_{\rm EFT} \supset \sum_i \frac{c_i}{\Lambda^2} O_i + \sum_{j=1,2} \frac{f_{S,j}}{\Lambda^4} O_{S,j} + \sum_{j=0,\ldots,9} \frac{f_{T,j}}{\Lambda^4} O_{T,j} + \sum_{j=0,\ldots,7} \frac{f_{M,j}}{\Lambda^4} O_{M,j}$$

Top quark flavor-changing neutral interactions

$$\begin{aligned}\mathcal{L}_{\rm EFT} \supset & \frac{\alpha_{uG\phi}^{ij}}{\Lambda^2}\, \bar{q}_L^i \lambda^a \sigma^{\mu\nu} u_R^j\, \tilde{\phi}\, G_{\mu\nu}^a + \frac{\alpha_{uB\phi}^{ij}}{\Lambda^2}\, \bar{q}_L^i \sigma^{\mu\nu} u_R^j\, \tilde{\phi}\, B_{\mu\nu} + \frac{\alpha_{uW\phi}^{ij}}{\Lambda^2}\, \bar{q}_L^i \tau_I \sigma^{\mu\nu} u_R^j\, \tilde{\phi}\, W_{\mu\nu}^I \\ & + \frac{\alpha_{\phi q}^{1,ij}}{\Lambda^2}\, i(\phi^\dagger D_\mu \phi)(\bar{q}_L^i \gamma^\mu q_L^j) + \frac{\alpha_{\phi q}^{3,ij}}{\Lambda^2}\, i(\phi^\dagger \tau_I D_\mu \phi)(\bar{q}_L^i \gamma^\mu \tau_I q_L^j) \\ & + \frac{\alpha_{\phi u}^{ij}}{\Lambda^2}\, i(\phi^\dagger D_\mu \phi)(\bar{u}_R^i \gamma^\mu u_R^j) + \frac{\alpha_{u\phi}^{ij}}{\Lambda^2}\, (\phi^\dagger \phi)(\bar{q}_L^i u_R^j \tilde{\phi}) + \mathcal{L}_{4f}\,,\end{aligned}$$

Challenges for theorists

- Complicated perturbative calculations, typically:
  - NNNLO QCD + NNLO EW @ CEPC
  - NNLO QCD + NLO EW @ SPPC
  - Resummation of various large logarithms
- Improving our knowledges about PDFs and jets

SM @ CEPC

Weak gauge coupling of the bottom quark

Long-standing puzzle about the forward-backward asymmetry

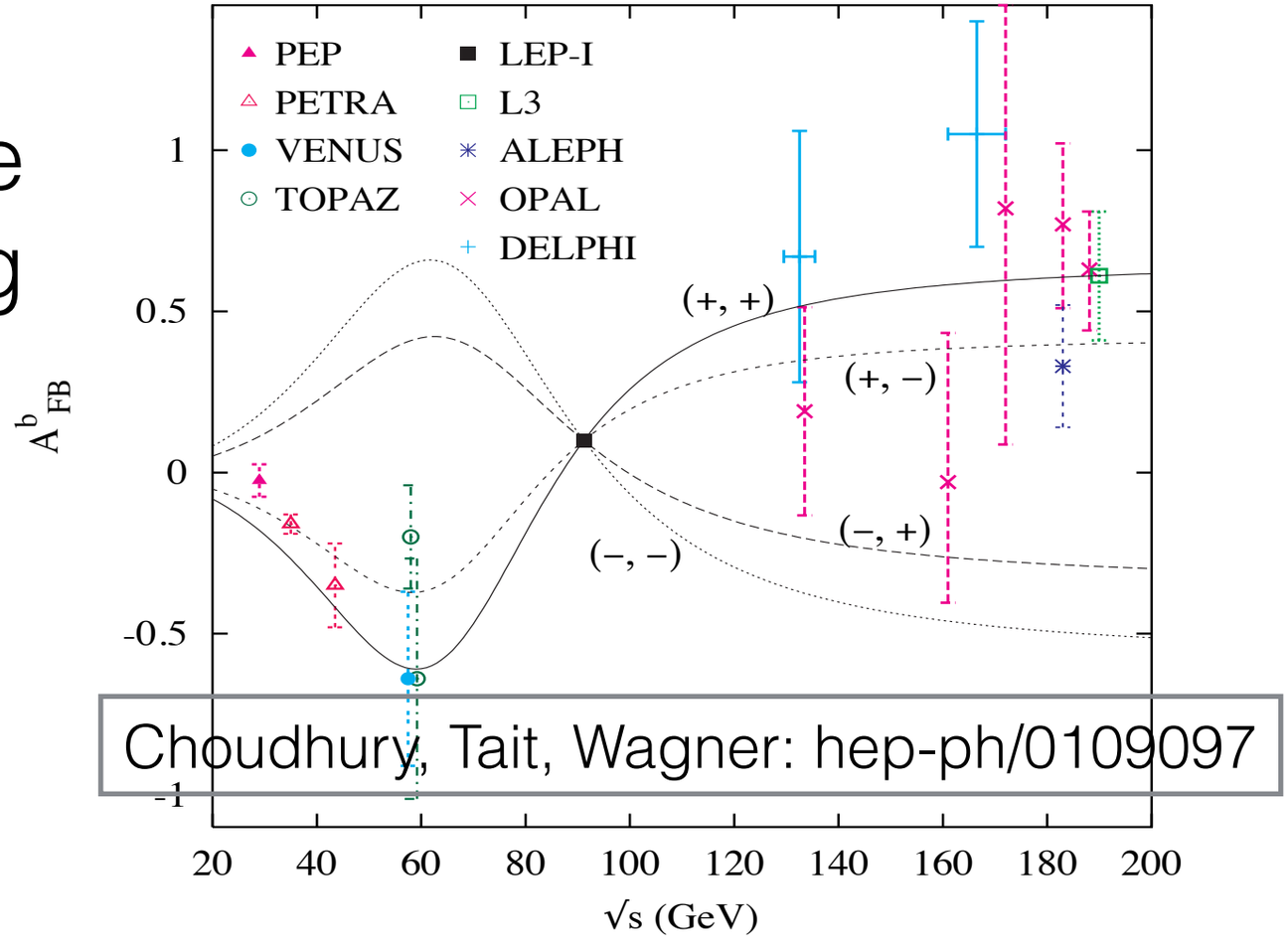
$A_{FB}^{(0,b)}$

LEP1	Theory
0.0992 ± 0.0016	0.1034 ± 0.0007

Also a sign ambiguity for the right-handed *Z-b-b* coupling

CEPC can help to resolve both issues

Systematic uncertainties?



Choudhury, Tait, Wagner: hep-ph/0109097

Weak gauge coupling of the top quark

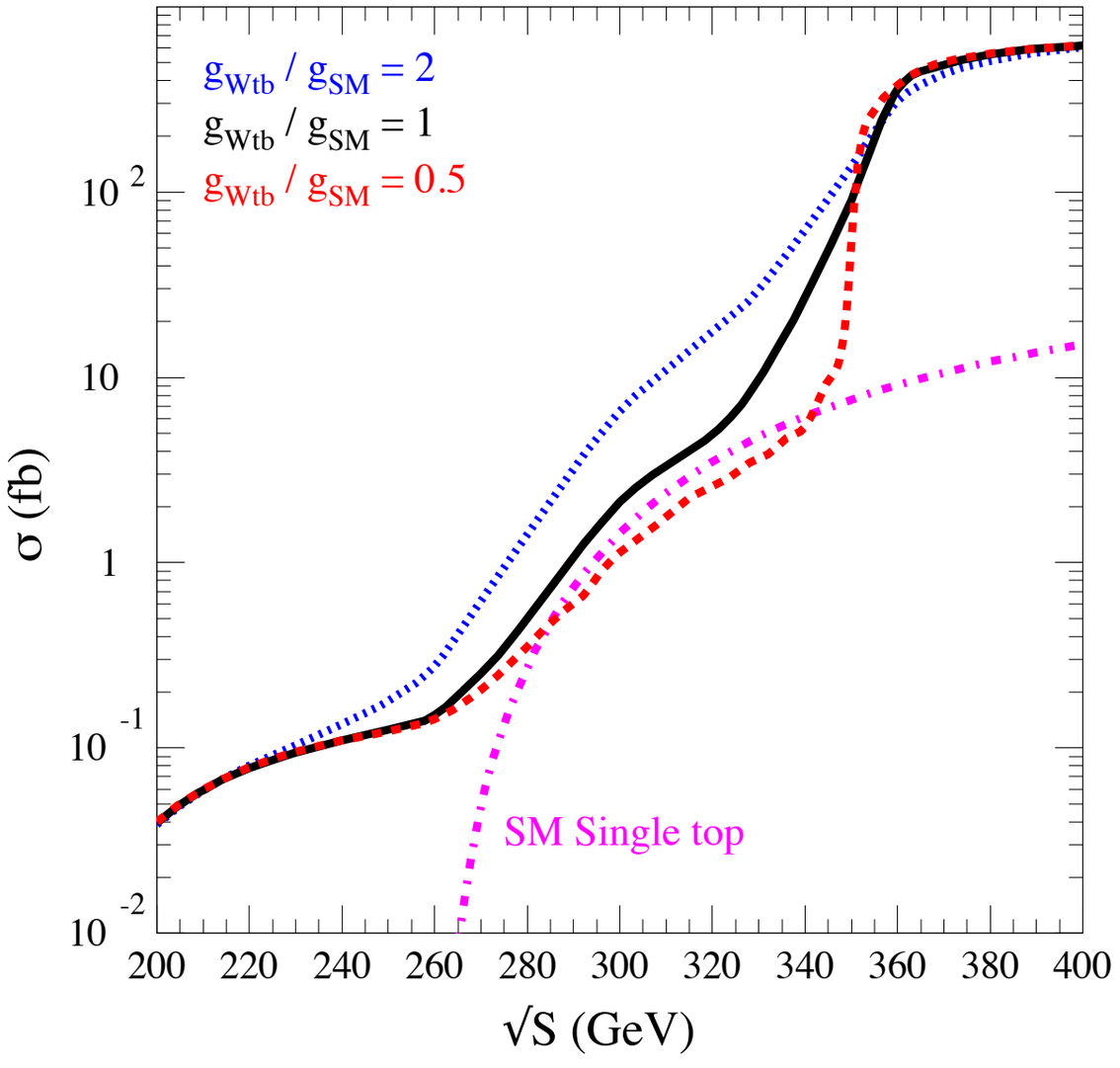
Energy not enough to produce a pair of on-shell top quarks

One on-shell and one off-shell possible:

$$e^+e^- \to \gamma/Z \to t\bar{t}^* \to b\bar{b}W^+W^-$$

Low cross section, but could be feasible with high luminosity

Systematic uncertainties?



Batra, Tait: hep-ph/0606068

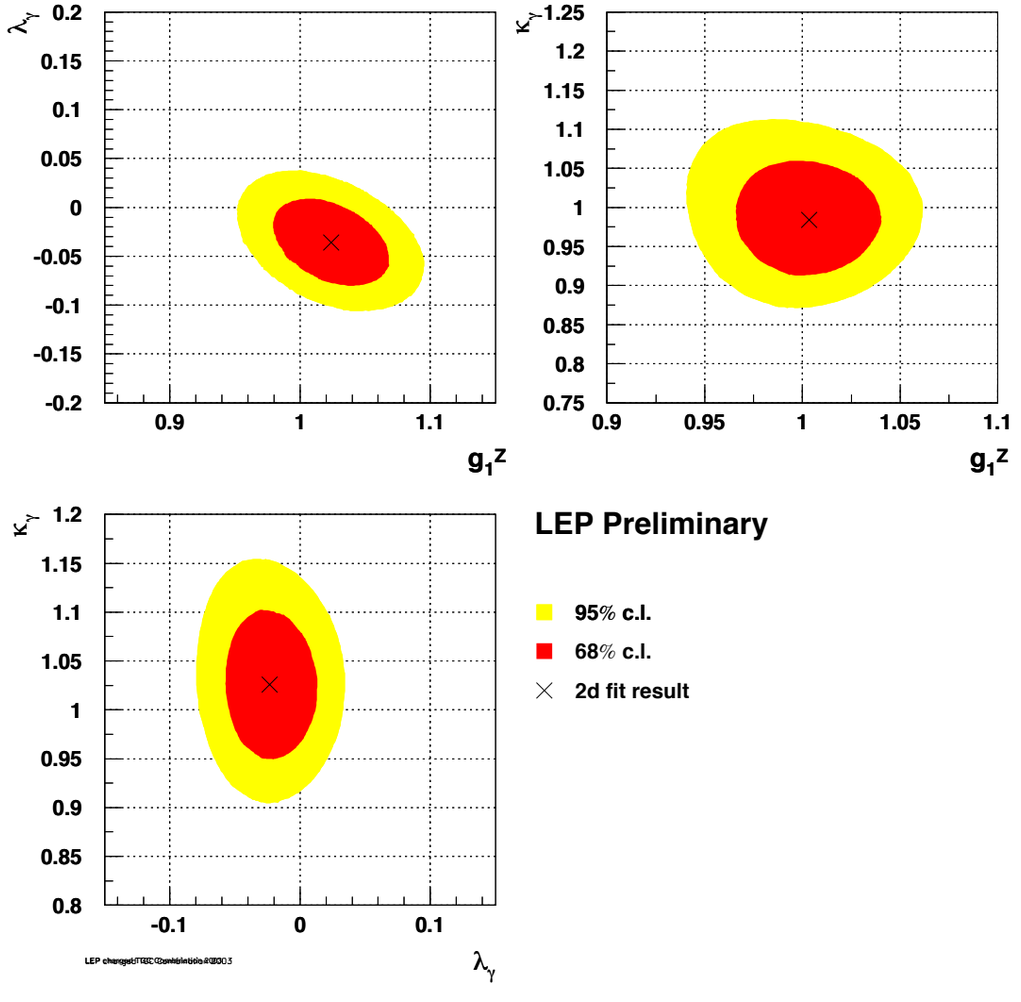
Triple and quartic gauge boson couplings

W^+W^- & single W → *WWA* & *WWZ* couplings

$W^+W^-\gamma$ & $Z\gamma\gamma$ → *WWAA*, *WWZA*, *ZZAA* couplings

Unfortunately no *WWZ* production, hence no sensitivity to *WWZZ* coupling

TODOs:
Assess improvements over LEP
Electroweak corrections



Single Top @ CEPC

$$e^+e^- \to \gamma/Z \to t\bar{c}$$

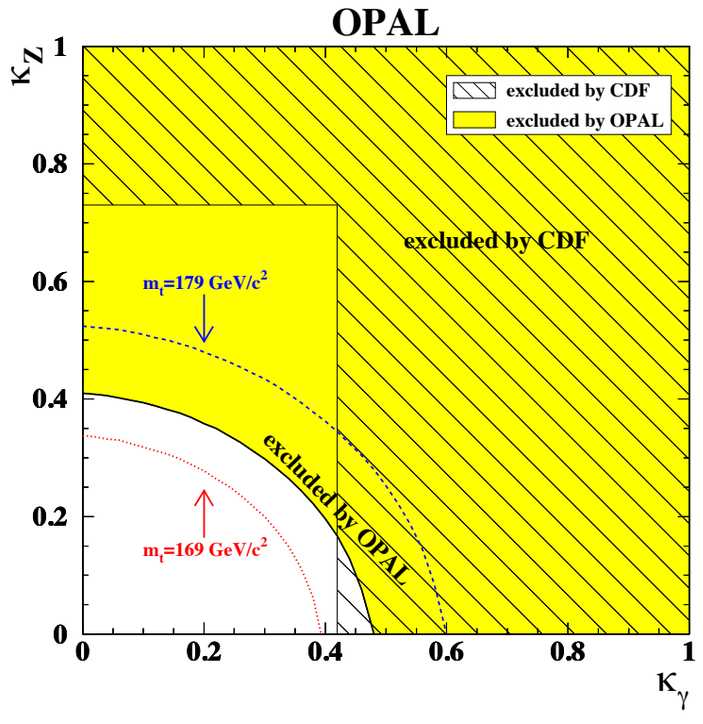
Probes flavor-changing neutral interactions of the top quark

Early theoretical studies:

Han, Hewett: hep-ph/9811237
Huang, Wu, Zhu: hep-ph/9901369
Bar-Shalom, Wudka: hep-ph/9905407
Aguila-Saavedra, Riemann: hep-ph/0102197
Cao, Liu, Yang: hep-ph/0311166

LEP studies:

OPAL: hep-ex/0110009
ALEPH: hep-ex/0206070



In progress: new analysis @ CEPC with QCD effects (Gao and LLY)

SM @ SPPC

Triple and quartic gauge boson couplings

The SPPC can explore all double and triple gauge boson production processes

Needs to understand boosted gauge bosons (see later)

Initial study on the *WWW* production and QGCs:

Wen, Qu, Yang, Yan, Li, Mao: 1407.4922

	No form factor		$\Lambda = 1$ TeV, n=2		$\Lambda = 0.5$ TeV, n=2	
	lower limit	upper limit	lower limit	upper limit	lower limit	upper limit
$\frac{f_{S0}}{\Lambda^4}$	-2.93×10^{-12}	3.04×10^{-12}	-1.65×10^{-9}	1.50×10^{-9}	-2.06×10^{-8}	2.15×10^{-8}
$\frac{f_{S1}}{\Lambda^4}$	-1.30×10^{-12}	1.16×10^{-12}	-1.87×10^{-9}	2.37×10^{-9}	-2.75×10^{-8}	2.84×10^{-8}
$\frac{f_{T0}}{\Lambda^4}$	-3.69×10^{-15}	2.97×10^{-15}	-9.18×10^{-12}	6.76×10^{-12}	-9.90×10^{-11}	7.30×10^{-11}

Table 13. Constraints on anomalous quartic couplings parameters f_{S0}/Λ^4, f_{S1}/Λ^4 and f_{T0}/Λ^4 at 100 TeV future proton proton collider via WWW production pure leptonic decay channel with integrated luminosity of 3000 fb^{-1}. Units are in GeV^{-4}.

More studies needed!

Top quark properties

- Mass and width
- Total and differential cross sections, asymmetries
- *Z-t-t* and *W-t-b* gauge couplings
- *H-t-t* Yukawa coupling
- Anomalous productions and decays

Production and decay

Current status:

- NNLO QCD for total cross section

Czakon, Fiedler, Mitov:1303.6254

- NLO+NNLL QCD for various distributions

Many references! Sorry…

- NLO EW; mixed EW-QCD

- NNLO QCD for fully differential decay

Gao, Li, Zhu: 1210.2808

Desired: fully differential production+decay with
NNLO QCD + NLO EW + resummation

Issue: boosted top quarks (see later)

Charge asymmetry

Unresolved puzzle @ Tevatron

Several proposals to look @ LHC

Antunano, Kuhn, Rodrigo: 0709.1652
Wang, Xiao, Zhu: 1011.1428
Xiao, Wang, Zhou, Zhu: 1101.2507
Kuhn, Rodrigo: 1109.6830

Can SPPC say something about it?

Top FCNC

Many studies on the productions and decays
for the LHC incorporating QCD effects

Hosch, Whisnant, Young: hep-ph/9703450
Han, Hosch, Whisnant, Young, Zhang: hep-ph/9806486
Liu, Li, **LLY**, Jin: hep-ph/0508016
Zhang, Li, Gao, Zhang, Li: 0810.3889
Gao, Li, Zhang, Zhu: 0910.4349
Zhang, Li, Gao, Zhu, Yuan: 1004.0898
Zhang, Li, Li, Gao, Zhu: 1101.5346
Li, Zhang, Li, Gao, Zhu: 1103.5122
Gao, Li, **LLY**, Zhang: 1104.4945

TODO: carry over analyses to the SPPC

PDFs

- Error from the PDFs has become one of the major sources to the systematic uncertainties of many measurements

- Need to be improved for the SPPC, especially the gluon PDF and the small-*x* region

- Recent proposals from Chinese Lattice QCD community may help

Ji: 1305.1539
Ma, Qiu: 1404.6860

See also talk by Jianhui Zhang

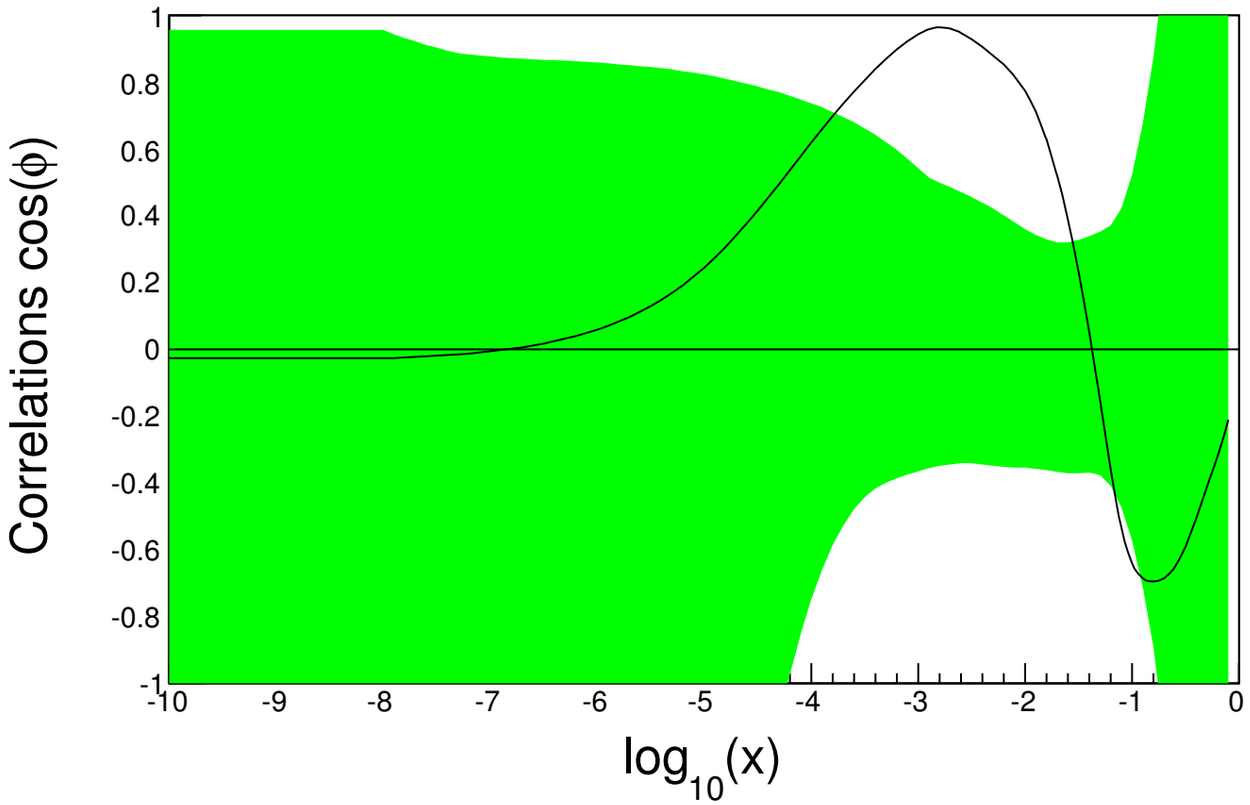
- PDFs for top, *W*, *Z*; EW correction/evolution

Gluon PDF

Can be constrained using Higgs production, top quark pair production and di-photon production

Di-photon @ 14 TeV

Di-photon @ 50 TeV



Plots from Zhao Li

Boosted objects @ SPPC

- Identification (jet substructures)
- Theoretical calculation (large logarithms)
  - Mass logarithms
  - Electroweak Sudakov double logarithms

Jet substructures

- Hadronically decaying high-p_T Higgs bosons, top quarks, W and Z bosons lead to "fat jets"

- Could be distinguished from QCD jets by studying their internal structures

- Many proposed methods for the LHC; should be revalidated for the SPPC

Two ways toward jet substructures

- Early investigations: purely numeric, based on Monte-Carlo event generators
- Analytic approaches based on QCD calculations
  - Jet mass / jet energy profile Li, Li, Yuan: 1107.4535, 1206.1344
  - Jet mass Kelly, Schwartz, Zhu: 1102.0561, 1112.3343
  - Mass-drop, trimming, pruning Dasgupta, Fregoso, Marzani, Salam: 1307.0007

Fat jets?

- The typical size of, e.g., the Higgs jet behaves like

$$R \sim \frac{2m_H}{p_T}$$

- People usually talk about Higgs jets with $p_T \sim 200$ GeV, which means $R \sim 1.25$

- What about Higgs jets with $p_T \sim 1$ TeV at the SPPC?

  - $R \sim 0.25$ similar to the typical size of QCD jets

Not fat anymore?

Mass logarithms

Example: top quarks produced with very high energies (not necessarily high p_T)

$$\ln(m_t/E)$$

Resummation: parton distribution functions, fragmentation functions and jet functions for the top quark

High-p_T boosted tops

Large logarithms resummed into top FFs/JFs

Resummation framework:

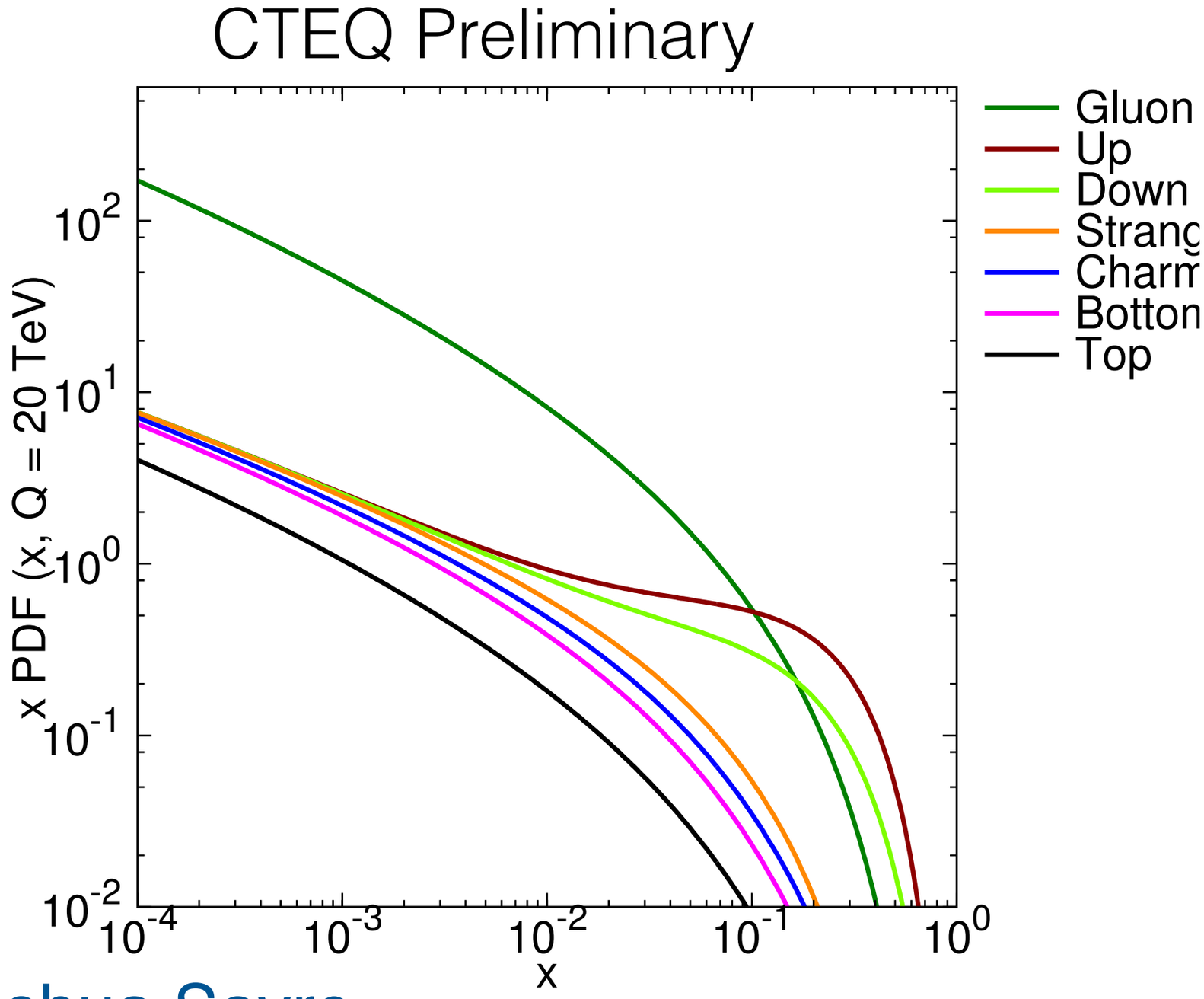
Ferroglia, Pecjak, **LLY**: 1205.3662, 1207.4798, 1306.1537; +Marzani: 1310.3836

$$C_{ij}(z, M, m_t, \cos\theta, \mu_f) = C_D^2(m_t, \mu_f)\,\mathrm{Tr}\left[\boldsymbol{H}_{ij}(M, t_1, \mu_f)\,\boldsymbol{S}_{ij}(\sqrt{\hat{s}}(1-z), t_1, \mu_f)\right]$$
$$\otimes C_{ff}^{ij}(z, m_t, \mu_f) \otimes C_{t/t}(z, m_t, \mu_f) \otimes C_{t/t}(z, m_t, \mu_f)$$
$$\otimes S_D(m_t(1-z), \mu_f) \otimes S_D(m_t(1-z), \mu_f) + \mathcal{O}(1-z) + \mathcal{O}\left(\frac{m_t}{M}\right)$$

In progress: numerical studies for the SPPC

Low-p_T boosted tops

Large logarithms resummed into top PDFs



See also talk by Joshua Sayre

Electroweak Sudakov

- At high energies, the *W and Z* bosons are effectively massless
- Soft/collinear → Sudakov double logarithms
- Resummation framework

Chiu, Golf, Kelley, Manohar:
0709.2377, 0712.0396

- A few studies for the LHC; effects should be more important for the SPPC

Investigations needed

SM processes @ 100 TeV

Wish-list from 1405.1067

Process	State of the Art	Desired
H	$d\sigma$ @ NNLO QCD (expansion in $1/m_t$) full m_t/m_b dependence @ NLO QCD and @ NLO EW NNLO+PS, in the $m_t \to \infty$ limit	$d\sigma$ @ NNNLO QCD (infinite-m_t limit) full m_t/m_b dependence @ NNLO QCD and @ NNLO QCD+EW NNLO+PS with finite top quark mass effects
H + j	$d\sigma$ @ NNLO QCD (g only) and finite-quark-mass effects @ LO QCD and LO EW	$d\sigma$ @ NNLO QCD (infinite-m_t limit) and finite-quark-mass effects @ NLO QCD and NLO EW
H + 2j	σ_{tot}(VBF) @ NNLO(DIS) QCD $d\sigma$(VBF) @ NLO EW $d\sigma$(gg) @ NLO QCD (infinite-m_t limit) and finite-quark-mass effects @ LO QCD	$d\sigma$(VBF) @ NNLO QCD + NLO EW $d\sigma$(gg) @ NNLO QCD (infinite-m_t limit) and finite-quark-mass effects @ NLO QCD and NLO EW
H + V	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW σ_{tot}(gg) @ NLO QCD (infinite-m_t limit)	with H $\to b\bar{b}$ @ same accuracy $d\sigma$(gg) @ NLO QCD with full m_t/m_b dependence
tH and $\bar{t}$H	$d\sigma$(stable top) @ LO QCD	$d\sigma$(top decays) @ NLO QCD and NLO EW
t$\bar{t}$H	$d\sigma$(stable tops) @ NLO QCD	$d\sigma$(top decays) @ NLO QCD and NLO EW
gg $\to$ HH	$d\sigma$ @ NLO QCD (leading m_t dependence) $d\sigma$ @ NNLO QCD (infinite-m_t limit)	$d\sigma$ @ NLO QCD with full m_t/m_b dependence

SM processes @ 100 TeV

Wish-list from 1405.1067

Process	State of the Art	Desired
$t\bar{t}$	$\sigma_{\rm tot}$(stable tops) @ NNLO QCD dσ(top decays) @ NLO QCD dσ(stable tops) @ NLO EW	dσ(top decays) @ NNLO QCD + NLO EW
$t\bar{t}$ + j(j)	dσ(NWA top decays) @ NLO QCD	dσ(NWA top decays) @ NNLO QCD + NLO EW
$t\bar{t}$ + Z	dσ(stable tops) @ NLO QCD	dσ(top decays) @ NLO QCD + NLO EW
single-top	dσ(NWA top decays) @ NLO QCD	dσ(NWA top decays) @ NNLO QCD + NLO EW
dijet	dσ @ NNLO QCD (g only) dσ @ NLO EW (weak)	dσ @ NNLO QCD + NLO EW
3j	dσ @ NLO QCD	dσ @ NNLO QCD + NLO EW
γ + j	dσ @ NLO QCD dσ @ NLO EW	dσ @ NNLO QCD + NLO EW

SM processes @ 100 TeV

Wish-list from 1405.1067

Process	State of the Art	Desired
V	$d\sigma$(lept. V decay) @ NNLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNNLO QCD and @ NNLO QCD+EW NNLO+PS
V + j(j)	$d\sigma$(lept. V decay) @ NLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW
VV′	$d\sigma$(V decays) @ NLO QCD $d\sigma$(on-shell V decays) @ NLO EW	$d\sigma$(decaying off-shell V) @ NNLO QCD + NLO EW
gg → VV	$d\sigma$(V decays) @ LO QCD	$d\sigma$(V decays) @ NLO QCD
Vγ	$d\sigma$(V decay) @ NLO QCD $d\sigma$(PA, V decay) @ NLO EW	$d\sigma$(V decay) @ NNLO QCD + NLO EW
$Vb\bar{b}$	$d\sigma$(lept. V decay) @ NLO QCD massive b	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW, massless b
VV′γ	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW
VV′V″	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW
VV′ + j	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW
VV′ + jj	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW
γγ	$d\sigma$ @ NNLO QCD + NLO EW	q_T resummation at NNLL matched to NNLO

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Thank you and contributions appreciated!