First CFHEP Symposium on Circular Collider Physics

Standard Model Tests

Qing-Hong Cao

Peking University

On behalf of the SM Working Group

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Some recent theoretical progress in Higgs boson and top quark physics at hadron colliders

arXiv: 1401.1101

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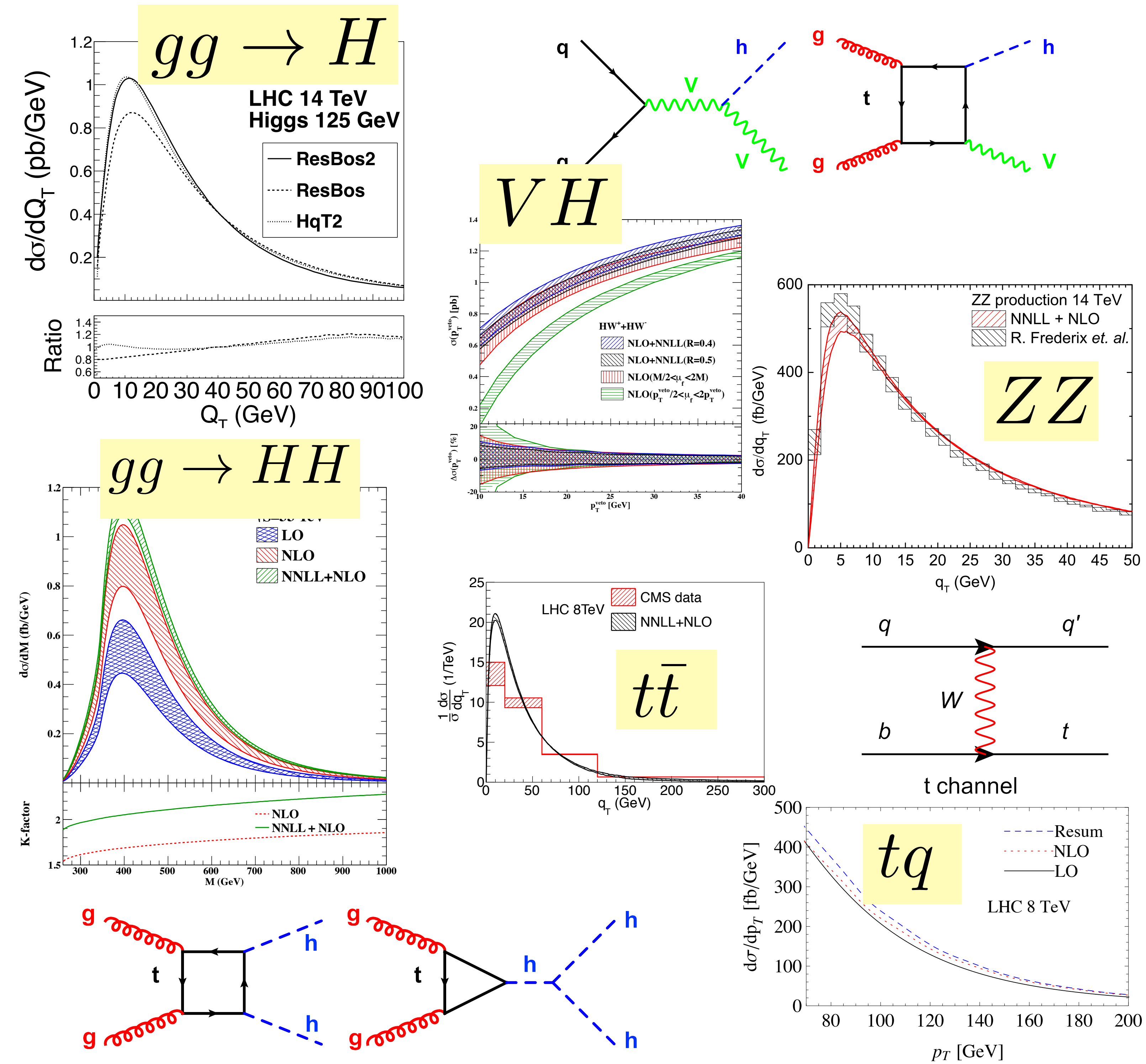
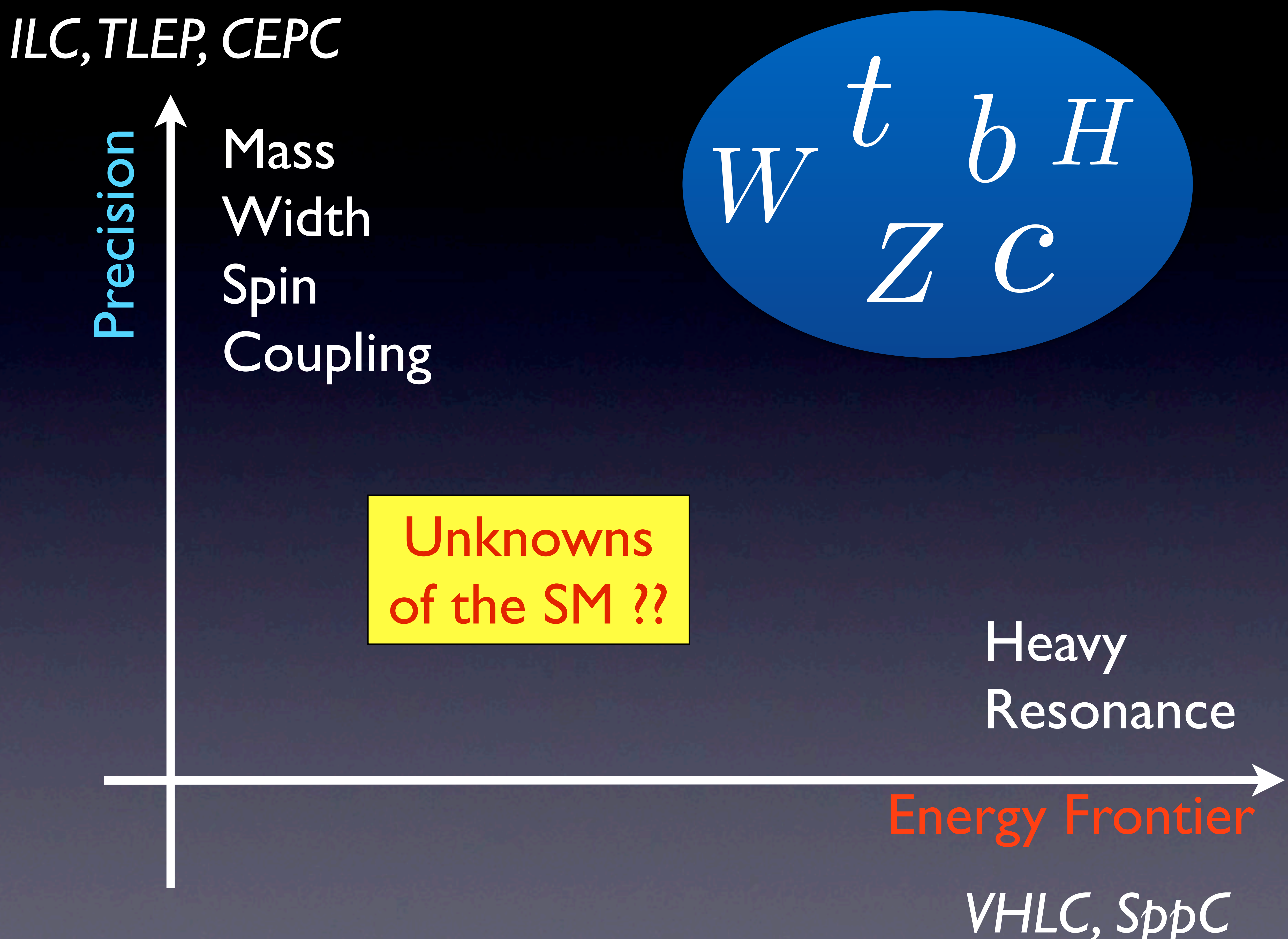
(Dated: January 9, 2014)

In this review we briefly summarize some recent theoretical progress in Higgs boson and top quark physics, especially the fixed-order and resummation predictions in QCD at both the Tevatron and the LHC.

CONTENTS





ILC, TLEP, CEPC
Precision
Mass
Width
Spin
Coupling
W
t
b
H
Z
c
Unknowns
of the SM ??
Heavy
Resonance
Energy Frontier
VHLC, SppC

SM Physics Precision

Precision measurements

Mass: W-boson, Top-quark, Higgs-boson

Width: W-boson, Top-quark, Higgs-boson

Spin: Higgs-boson, Top-quark spin correlation

CP: Higgs-boson

see Z. G. Si's talk

Indirect searches

Anomalous couplings and rare decay

(Effective field theory)

Untested Aspects of the SM

Higgs electroweak couplings

See Higgs Working-Group's report

Higgs boson self-coupling

Boosted object techniques

Triple-gauge-coupling / Quartic-gauge-coupling

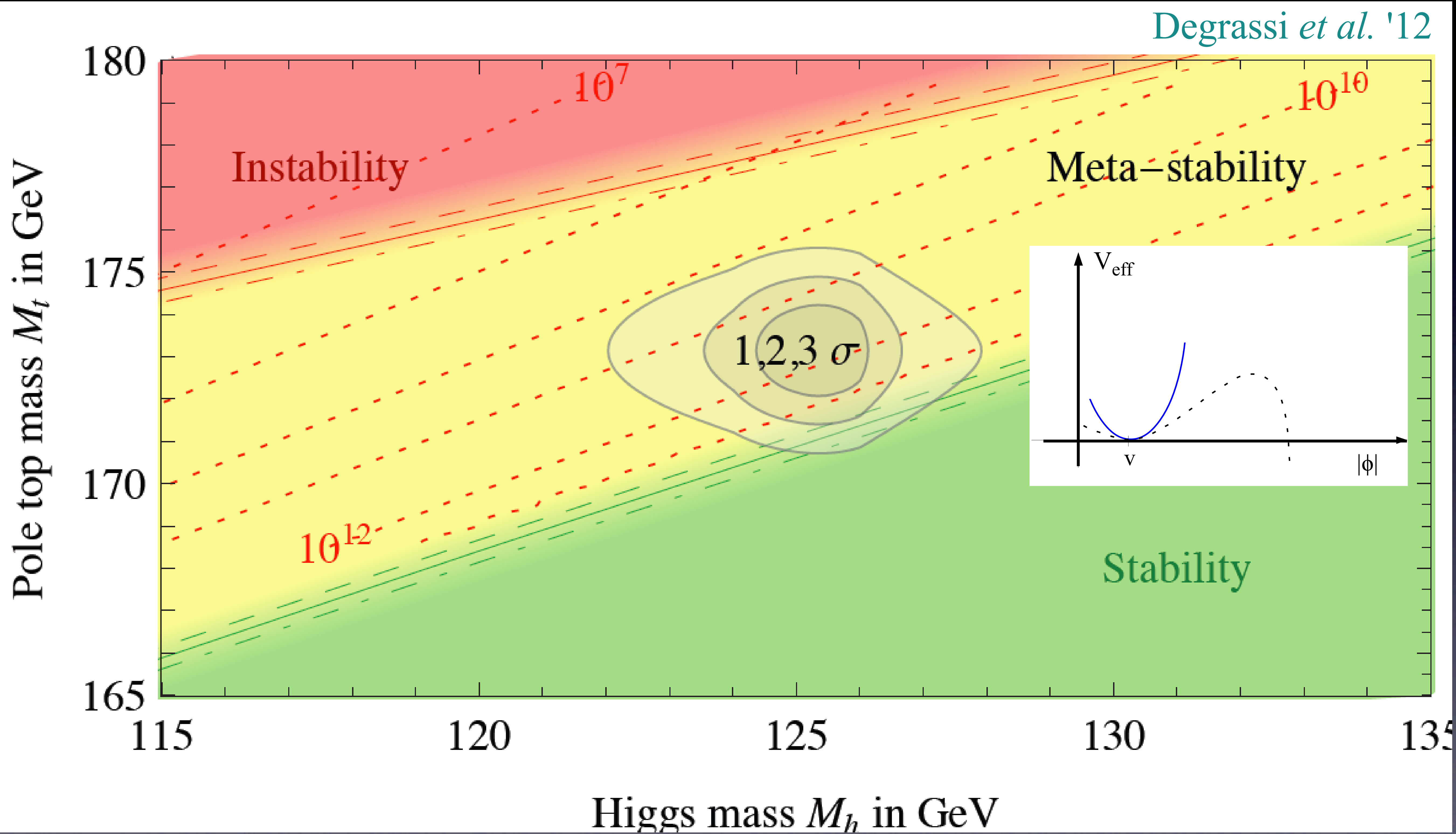
Dim-6 and Dim-8 operators in linear realization

Weak interaction of the 3rd generation quarks

Fully understanding top- and bottom-quark chirality structure of couplings, Vtb=1? ...

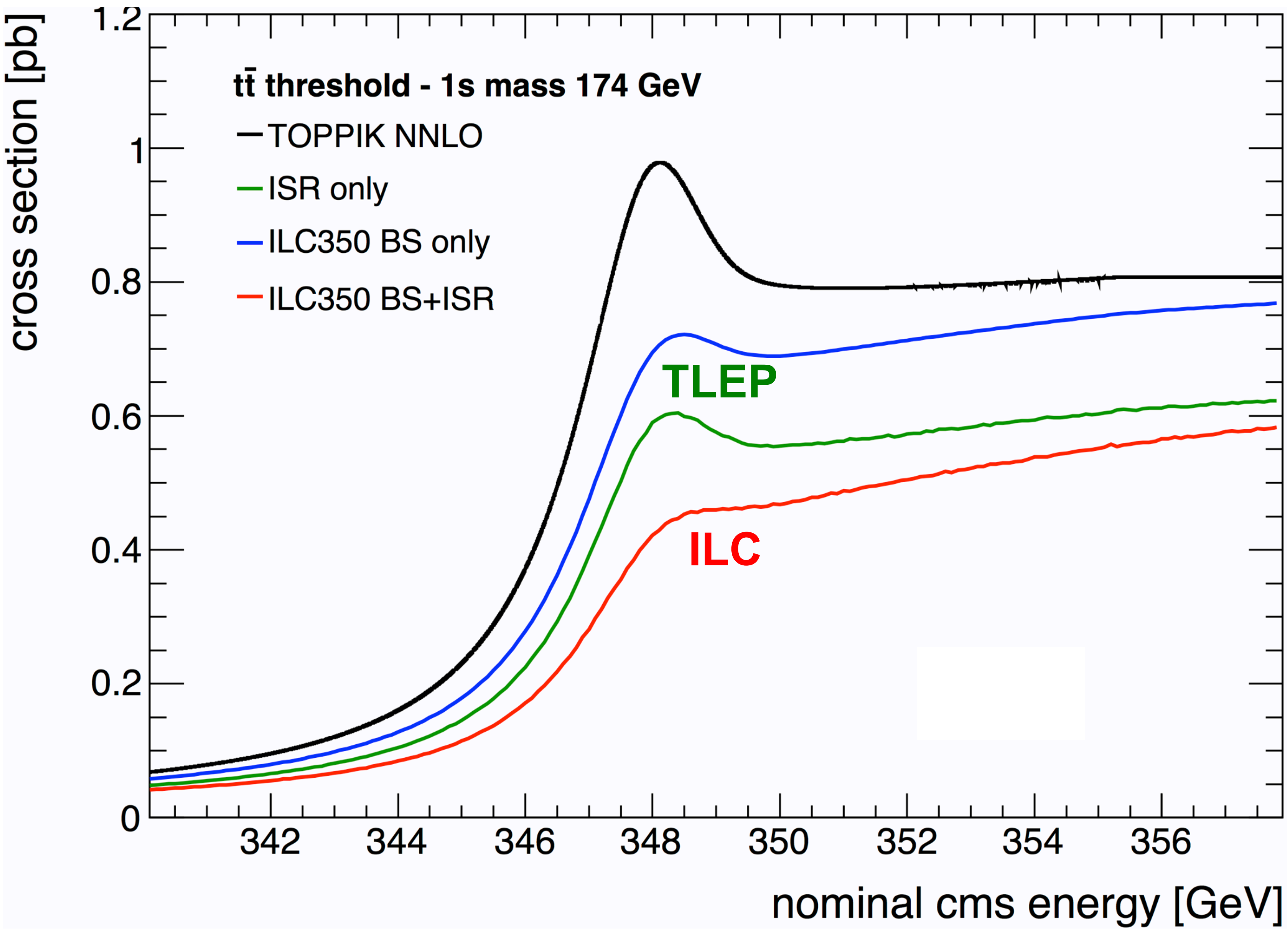
Mass Precision

Top-Quark Mass vs Higgs-Boson Mass



Top-Quark Mass at ILC and TLEP

Collider	TLEP 350	ILC 350
Total Integrated Luminosity (ab^{-1})	**2.6**	0.35
Number of $t\bar{t}$ pairs	**1,000,000**	100,000



$m_t = 174$ GeV

Peak ~ 346 GeV

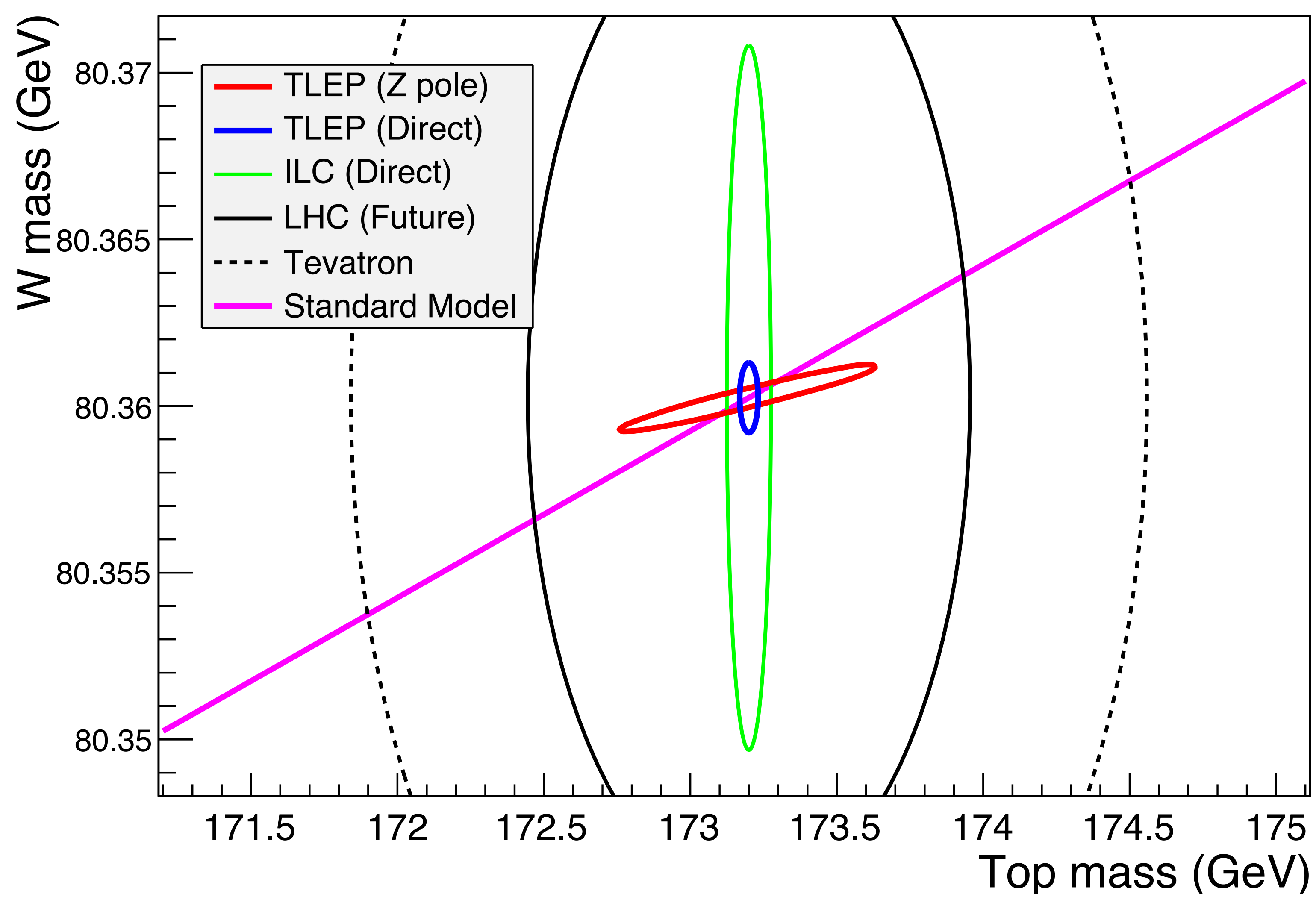
$m_t = 173$ GeV

Peak ~ 348 GeV

Top Precision at ILC and TLEP

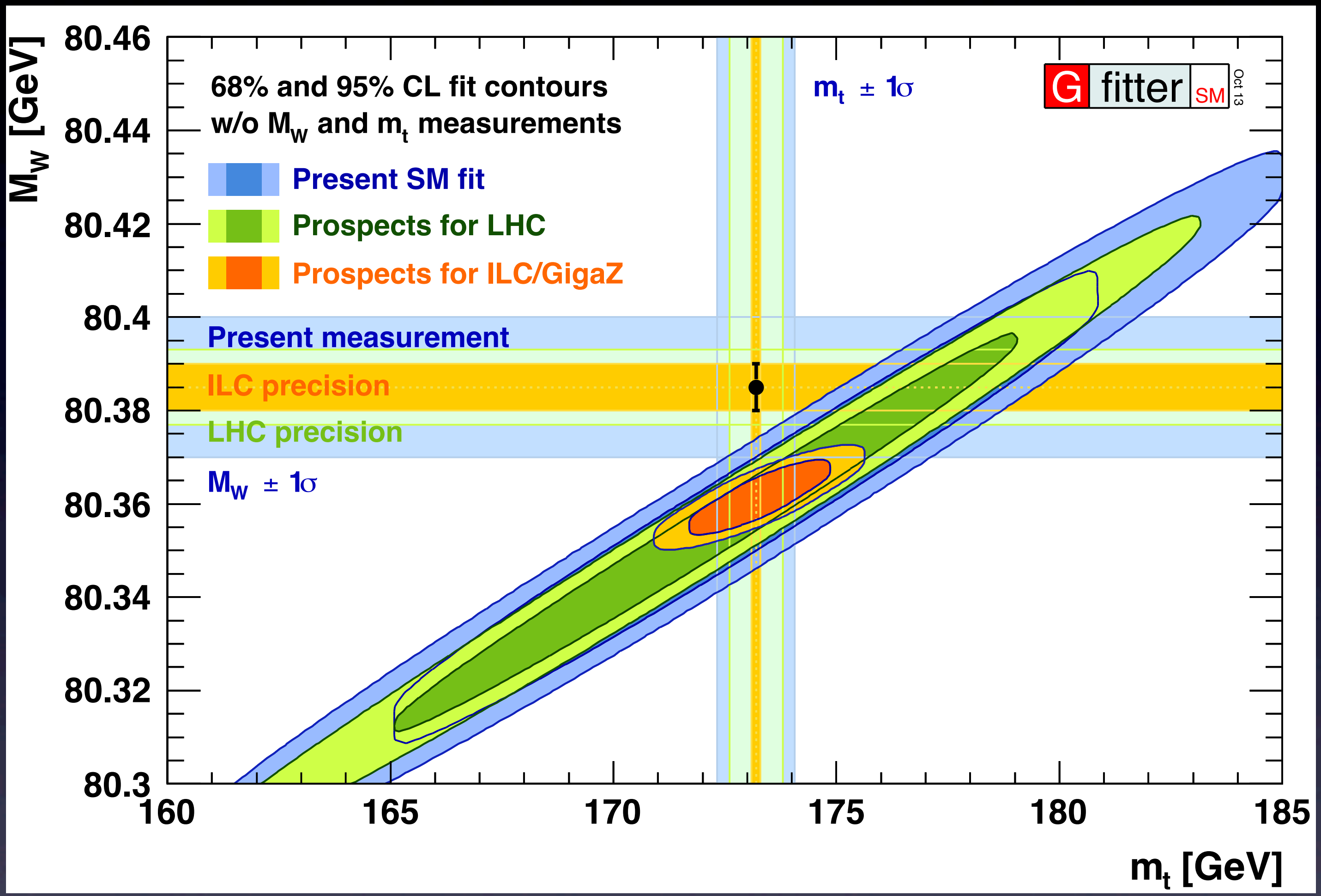
5 years scan

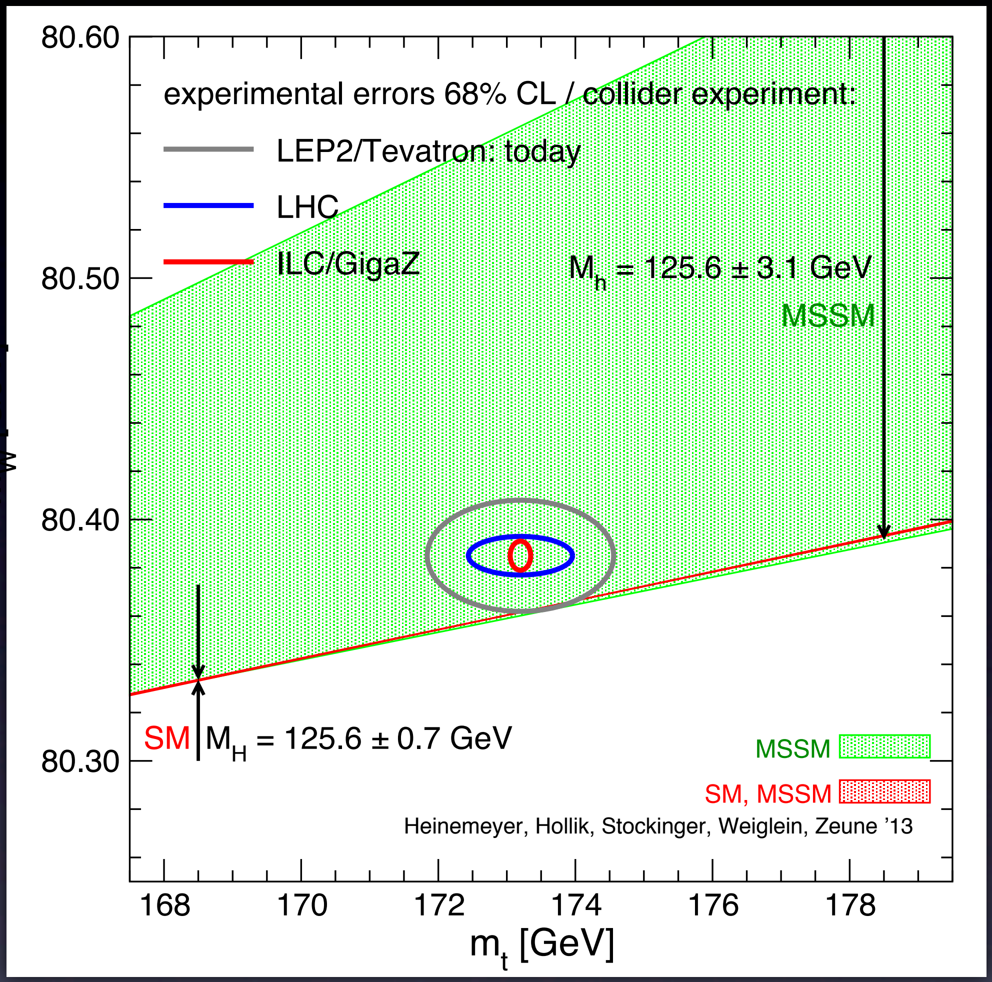
Parameter	m_{top}	Γ_{top}	λ_{top}
TLEP	**10 MeV/c^2**	**11 MeV**	$\pm$**13**%
ILC	31 MeV/c^2	34 MeV	$\pm 40\%$



Mass Precision

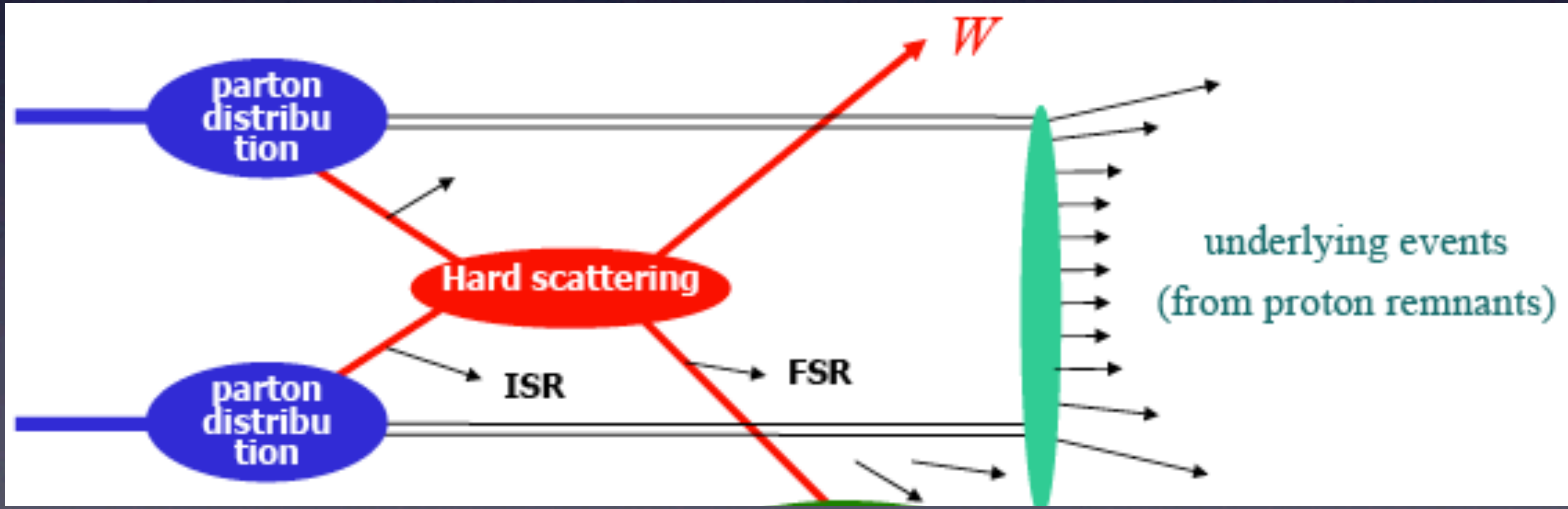
Top-quark, W-boson and Higgs boson





	LHC	LHC	ILC/GigaZ	ILC	ILC	ILC	TLEP	SM prediction
$\sqrt{s}$ [TeV]	14	14	0.091	0.161	0.161	0.250	0.161	-
$\mathcal{L}[\text{fb}^{-1}]$	300	3000		100	480	500	3000×4	-
ΔM_W [MeV]	8	5	-	4.1-4.5	2.3-2.9	2.8	< 1.2	4.2(3.0)
$\Delta \sin^2 \theta^\ell_{\text{eff}}$ $[10^{-5}]$	36	21	1.3	-	-	-	0.3	3.0(2.6)

Parton Distribution Functions



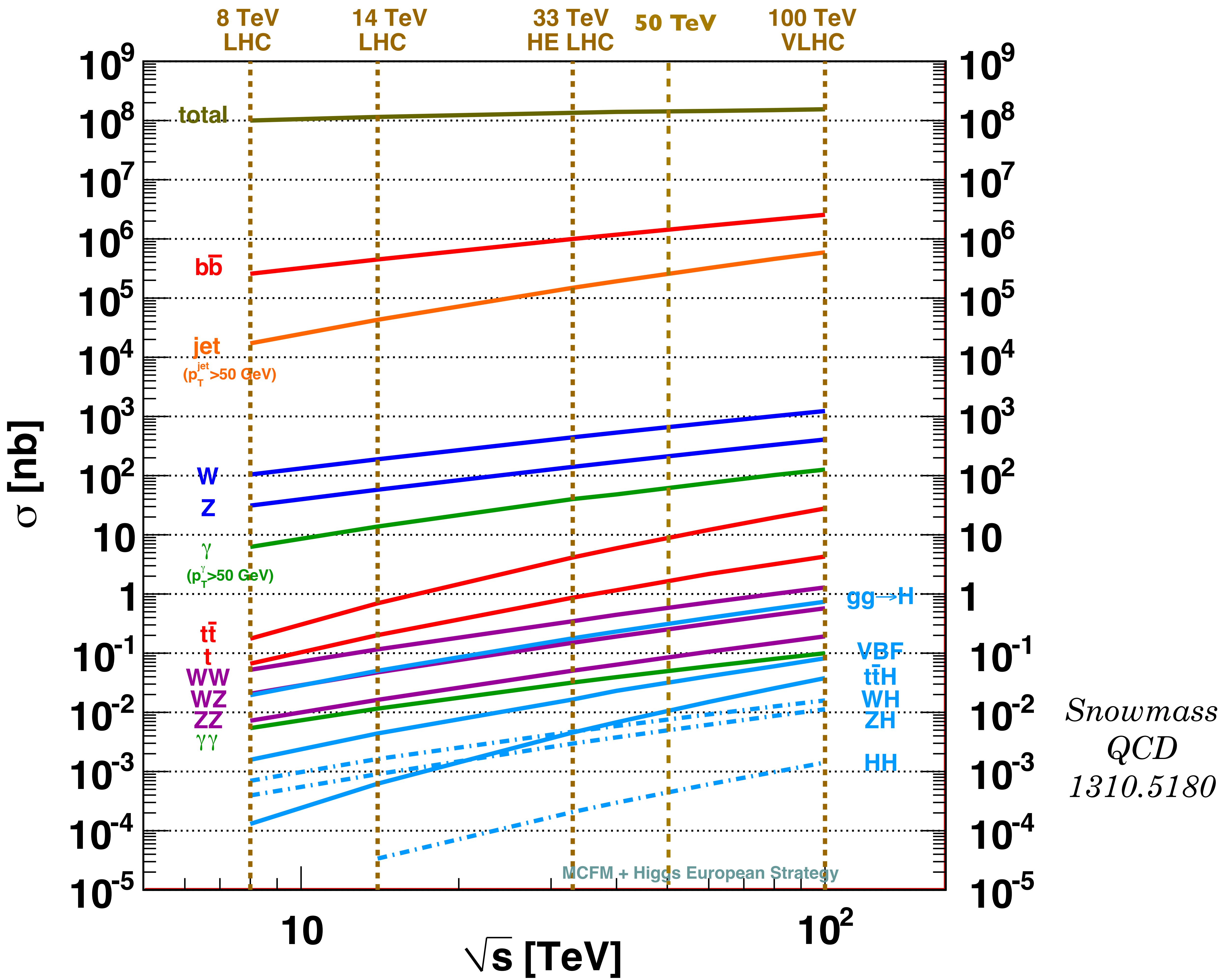
Parton Distribution Functions

Groups providing NNLO PDFs based on non-LHC data

NNLO	CTEQ	MRST/MSTW	NNPDF	ABKM/ABM	HERA	JR
Since	2012	2004	2011	2009	2011	2008
Latest	CT10	MSTW08/CPd	NNPDF2.3	ABM11/12	HERA15	JR09
Error	50	40	100	28	28	26

PDFs at the LHC are aiming at high accuracies and with great diversities (NNLO in QCD + NLO in EW)

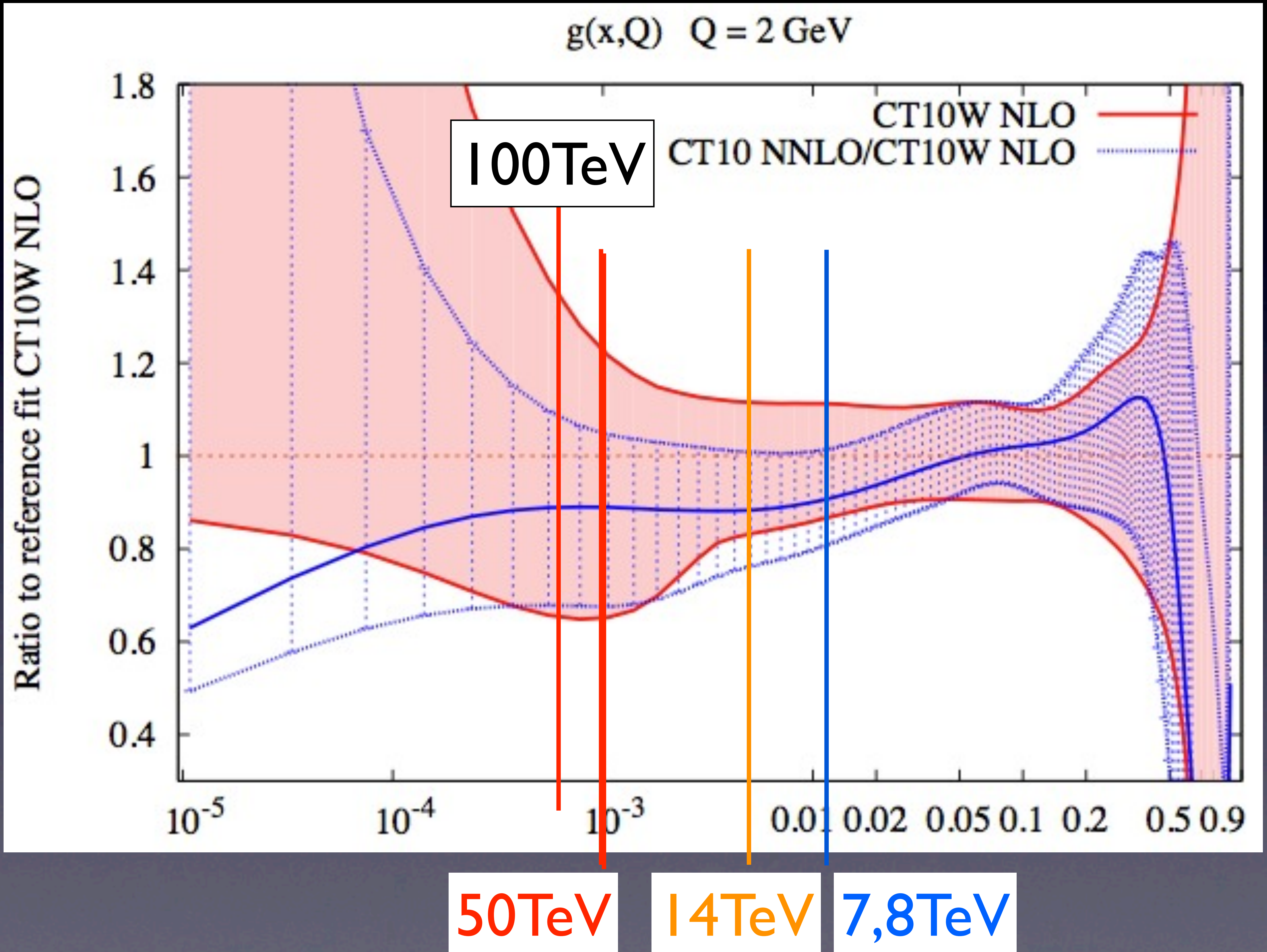
PDF uncertainties
NNLO PDF + EW correction
Variable-Flavor-Number scheme (top-quark PDF?)



8 TeV LHC
14 TeV LHC
33 TeV HE LHC
50 TeV
100 TeV VLHC
total
bb̄
jet
(p_T^jet>50 GeV)
W
Z
γ
(p_T^γ>50 GeV)
tt̄
t
WW
WZ
ZZ
γγ
gg→H
VBF
tt̄H
WH
ZH
HH
MCFM + Higgs European Strategy
σ [nb]
√s [TeV]
Snowmass QCD 1310.5180

Gluon PDFs

$$\langle x \rangle \approx \frac{50\ \mathrm{GeV}}{E_{\mathrm{cm}}}$$



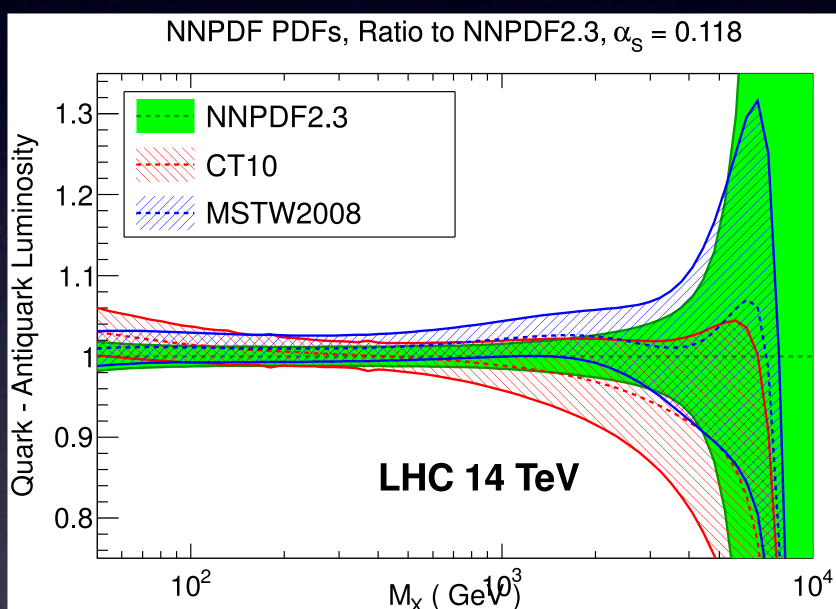
Luminosities and Uncertainties for 14, 100 TeV

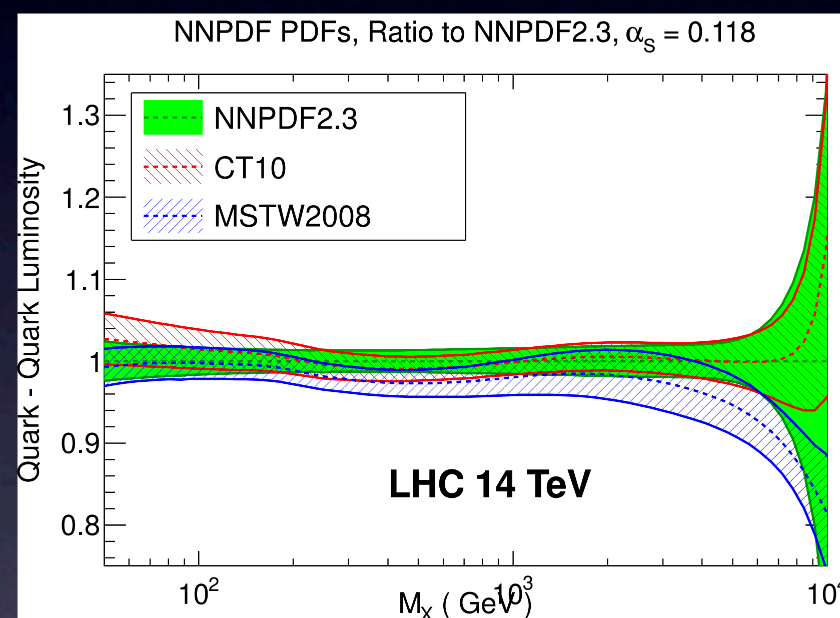
Normalized to NNPDF central

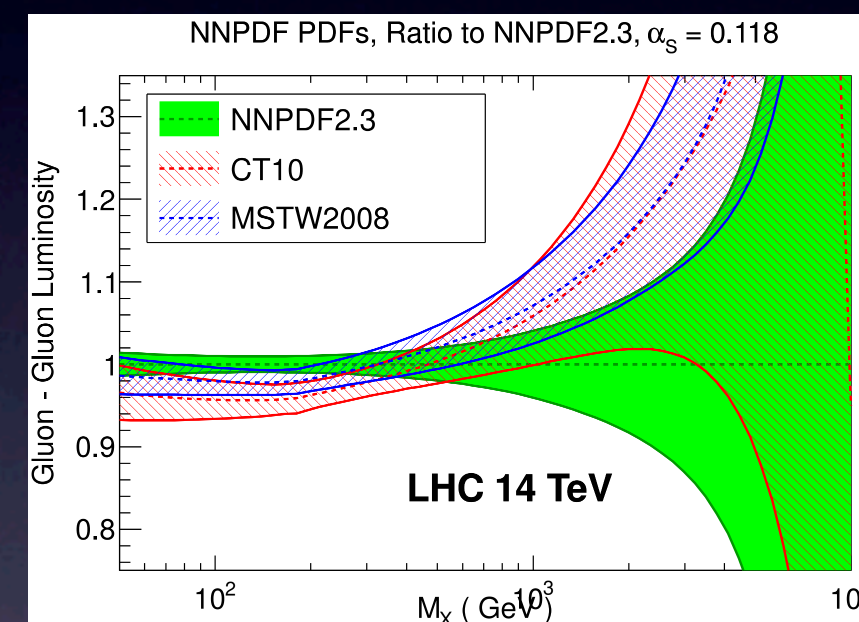
$$\Phi_{ij}\left(M_X^2\right) = \frac{1}{s}\int_\tau^1 \frac{dx_1}{x_1} f_i\left(x_1, M_X^2\right) f_j\left(\tau/x_1, M_X^2\right)$$

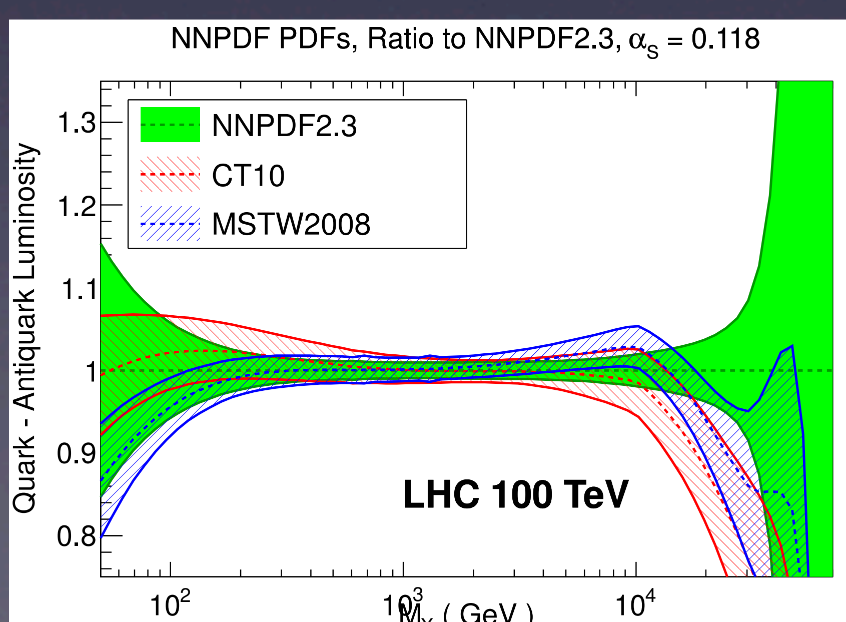
Snowmass report:
QCD 1310.5180

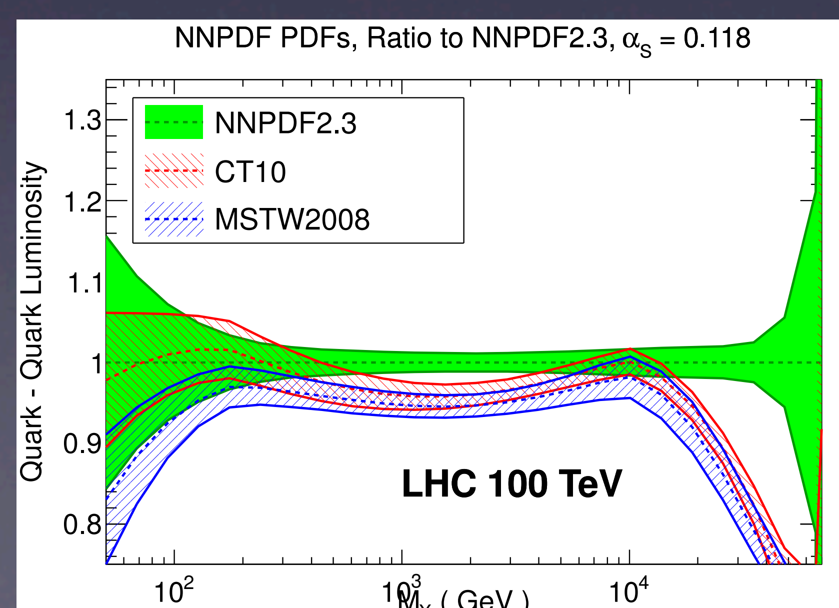
$q\bar{q}$ qq gg

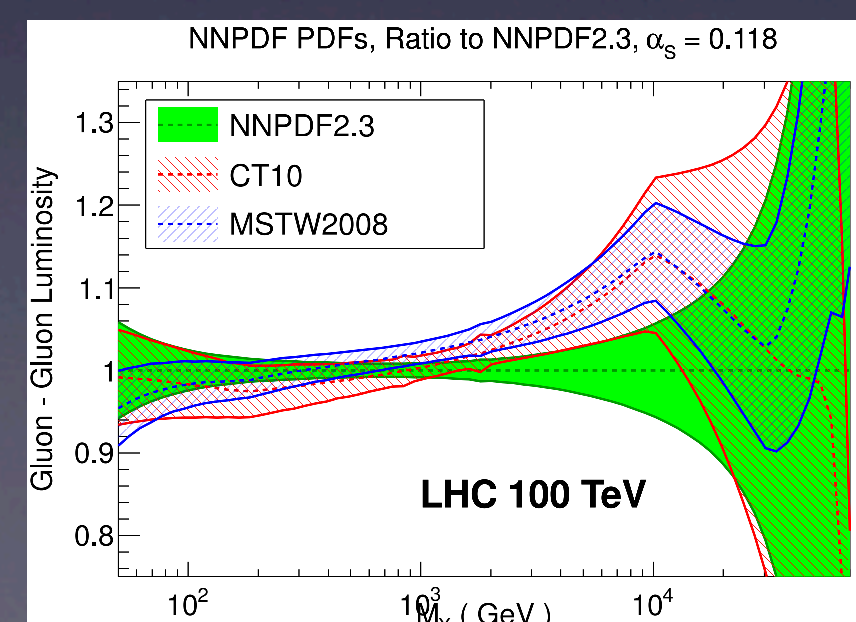






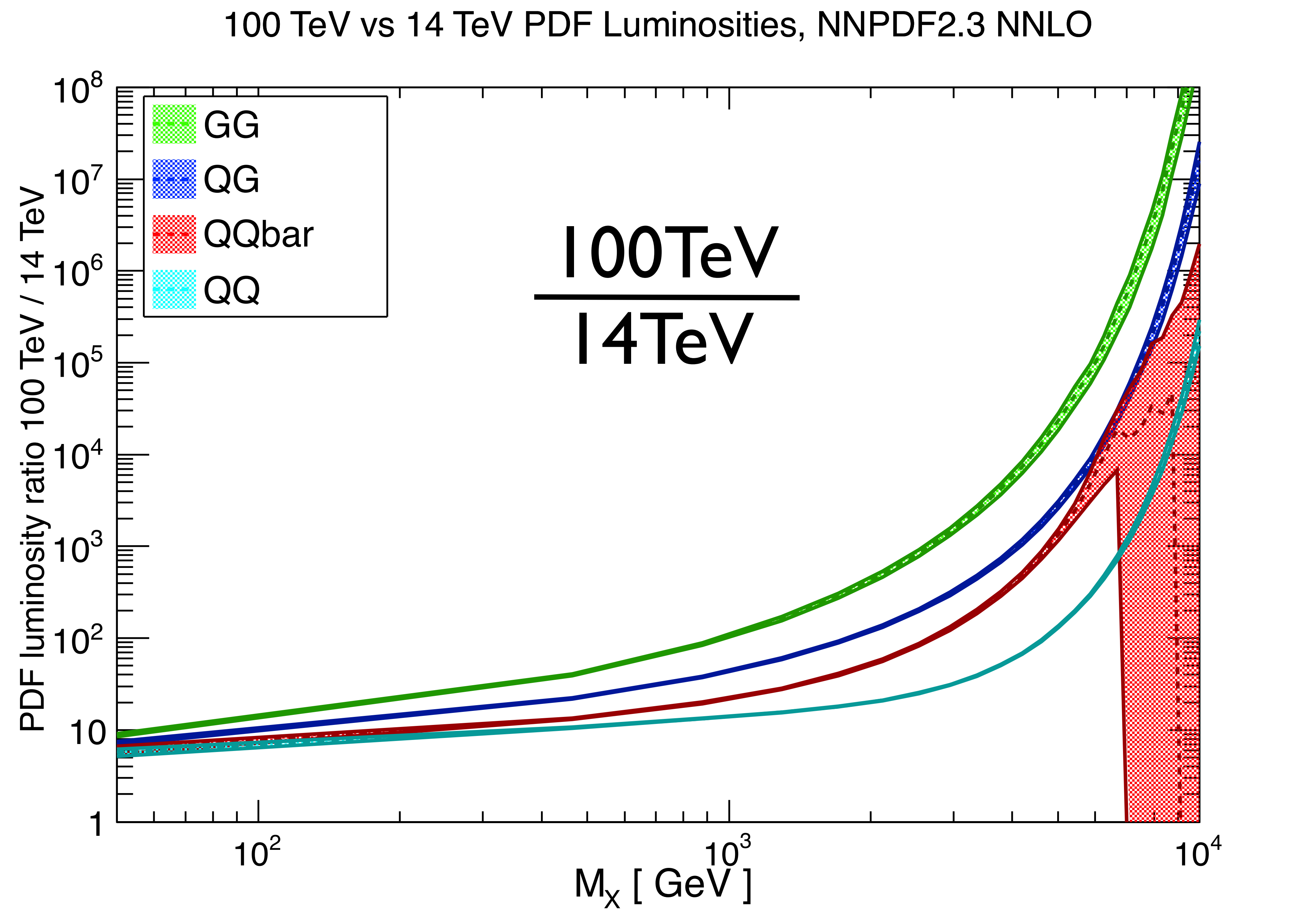






PDF Luminosities

$$\Phi_{ij}\left(M_X^2\right) = \frac{1}{s}\int_\tau^1 \frac{dx_1}{x_1} f_i\left(x_1, M_X^2\right) f_j\left(\tau/x_1, M_X^2\right)$$



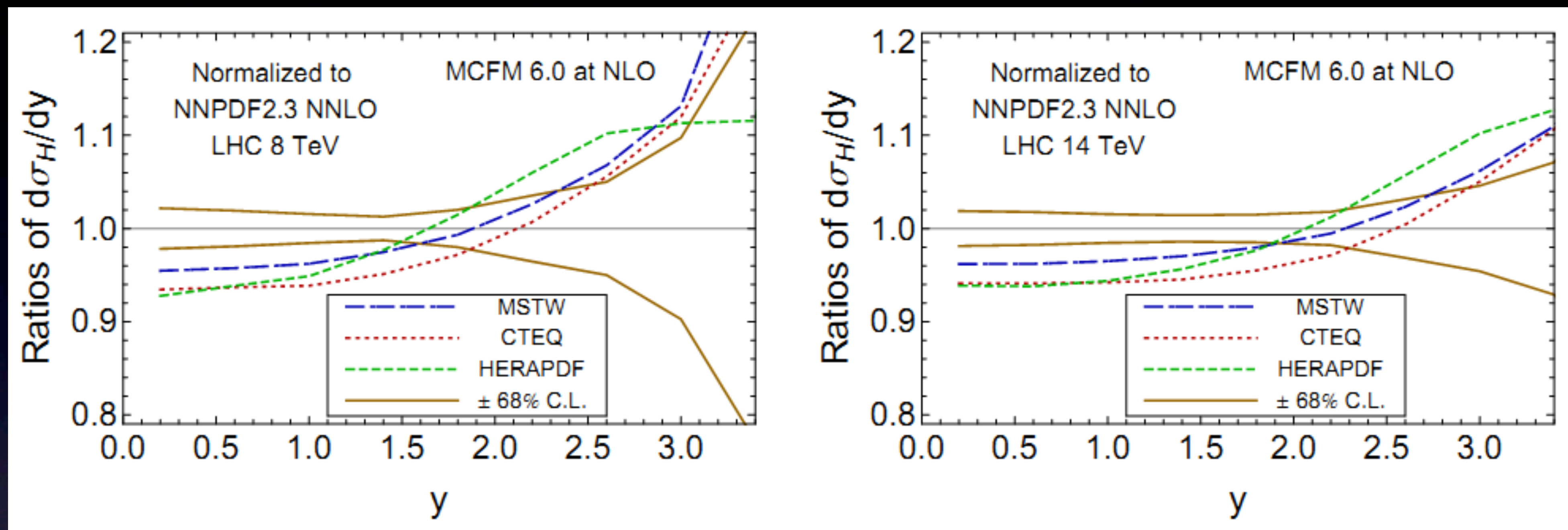
Juan Rojo, FCCK metting

Standard Candle of Gluon PDF

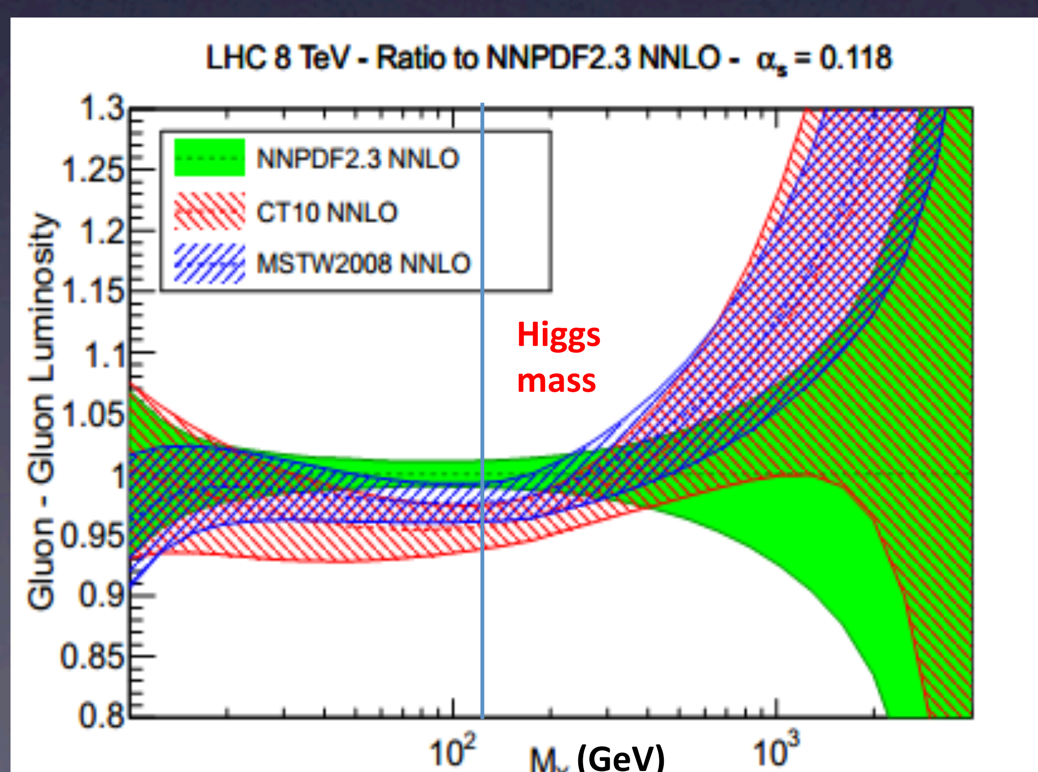
(Higgs production + Top-pair production)

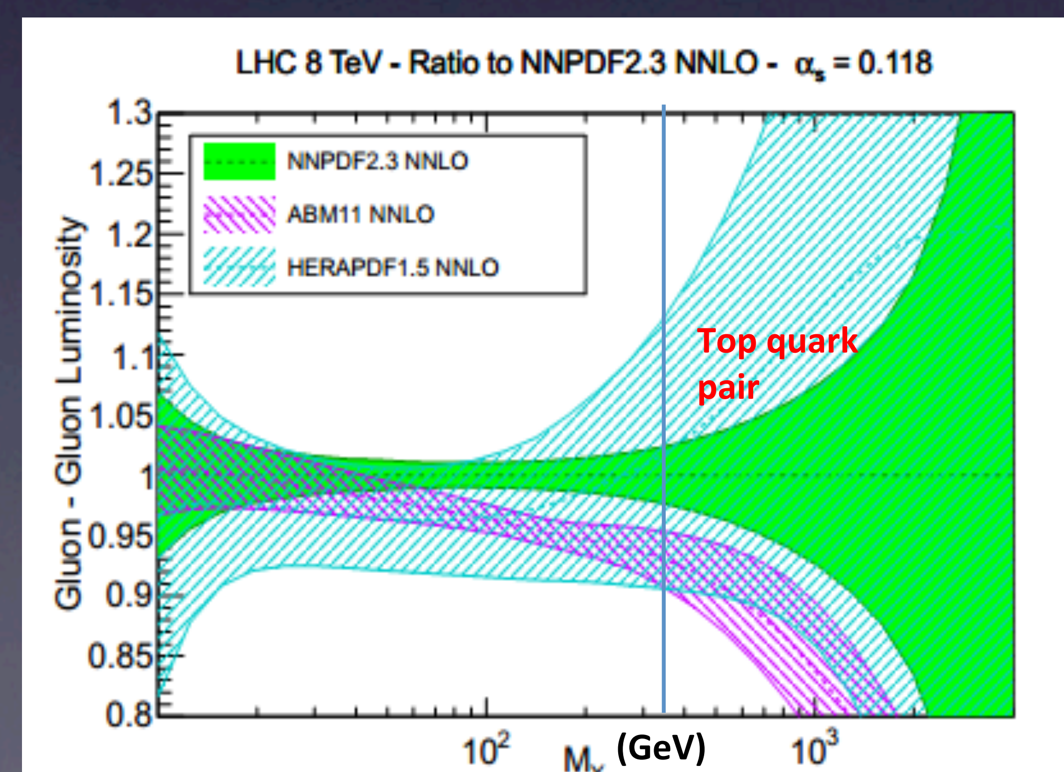
Rapidity distribution

PDF benchmkaring, Gao et al, 1211.5142



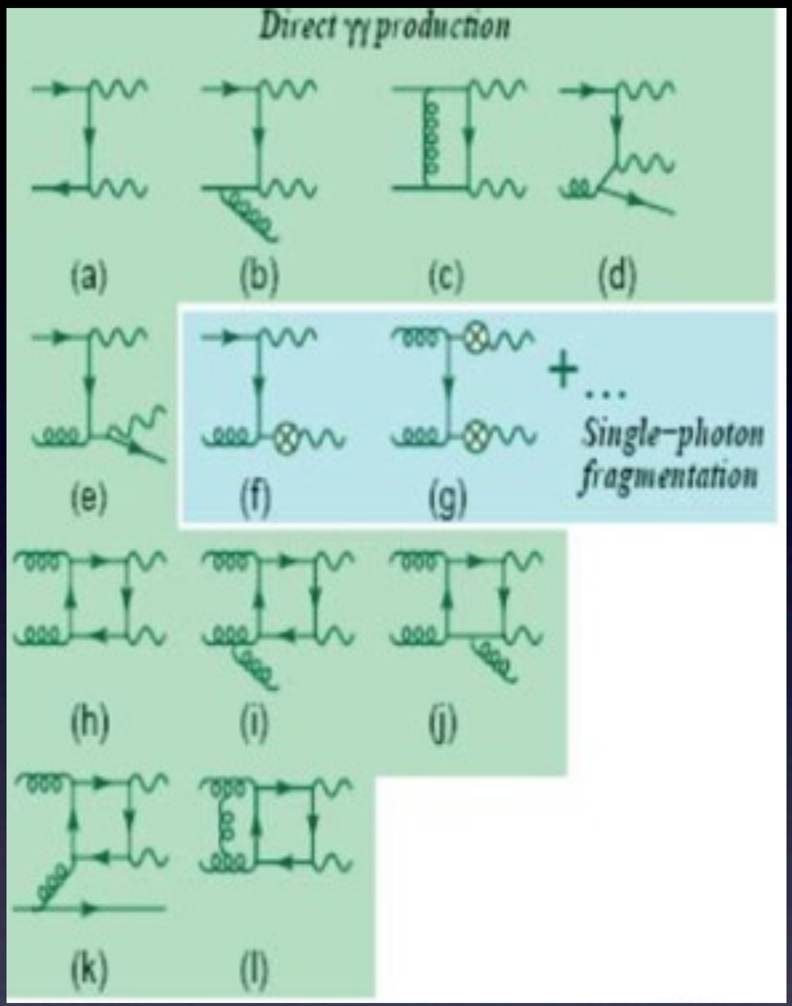
Gluon-Gluon parton luminosity at 8 TeV





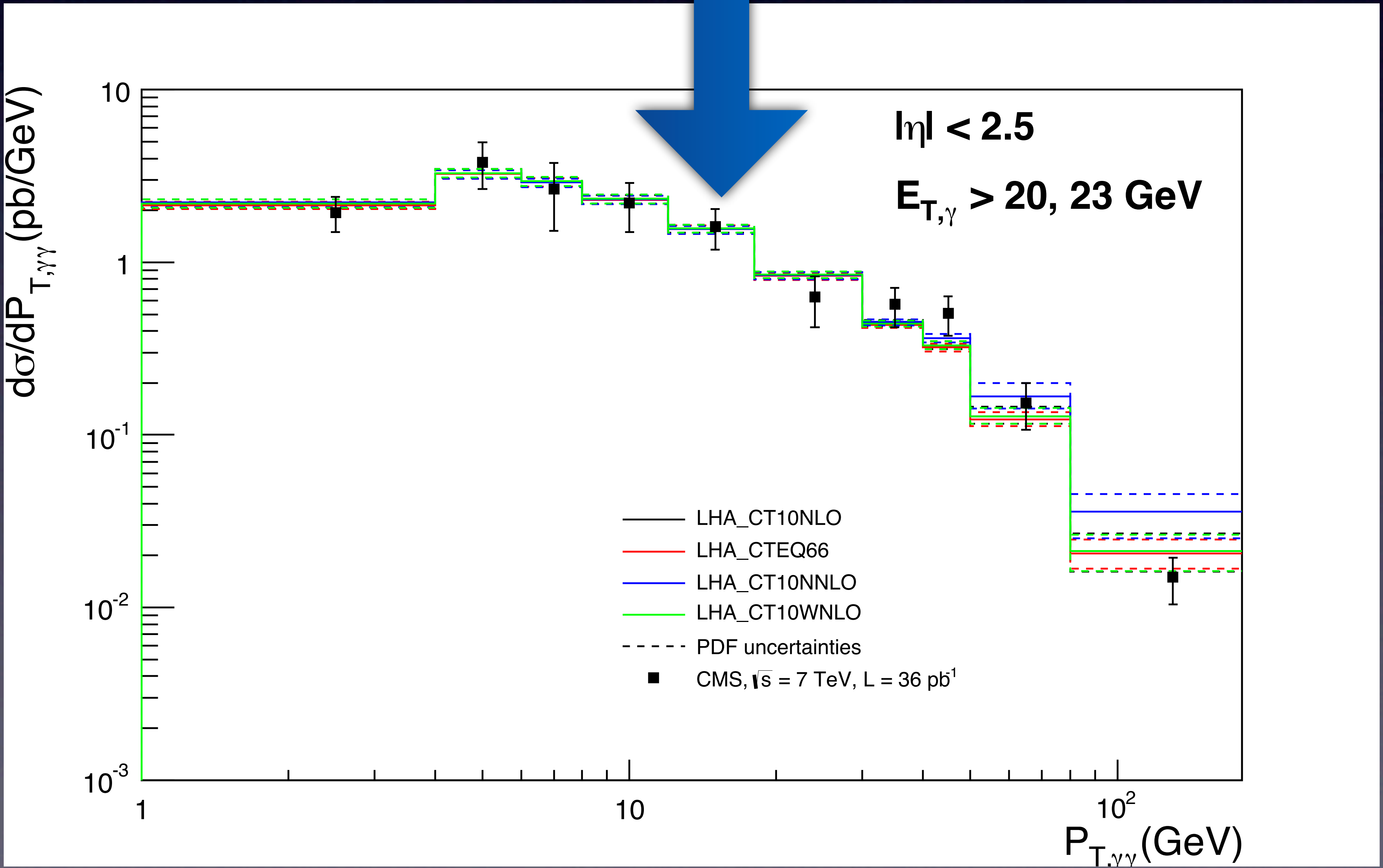
Di-photon Production and Gluon PDF

Zhao Li

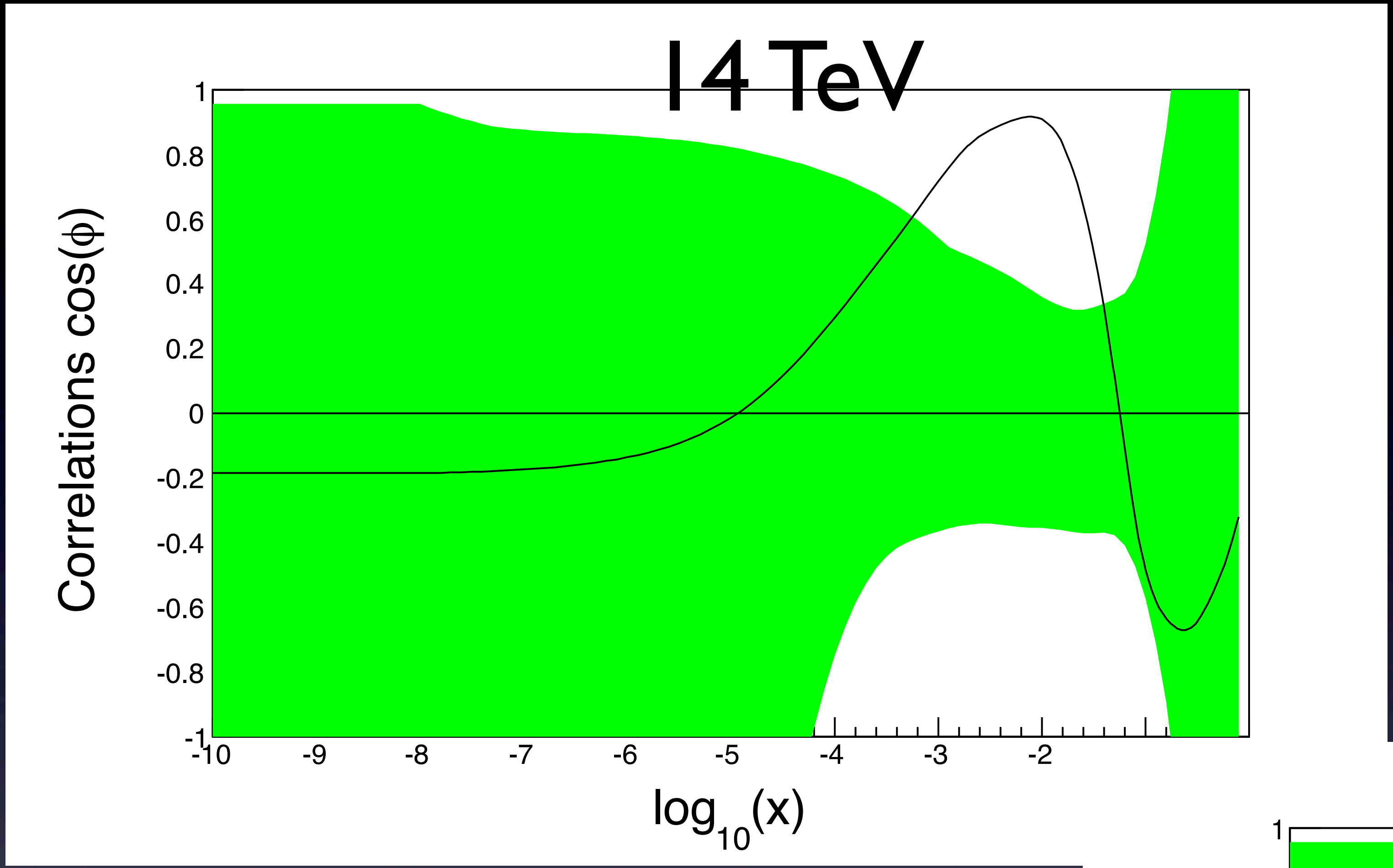


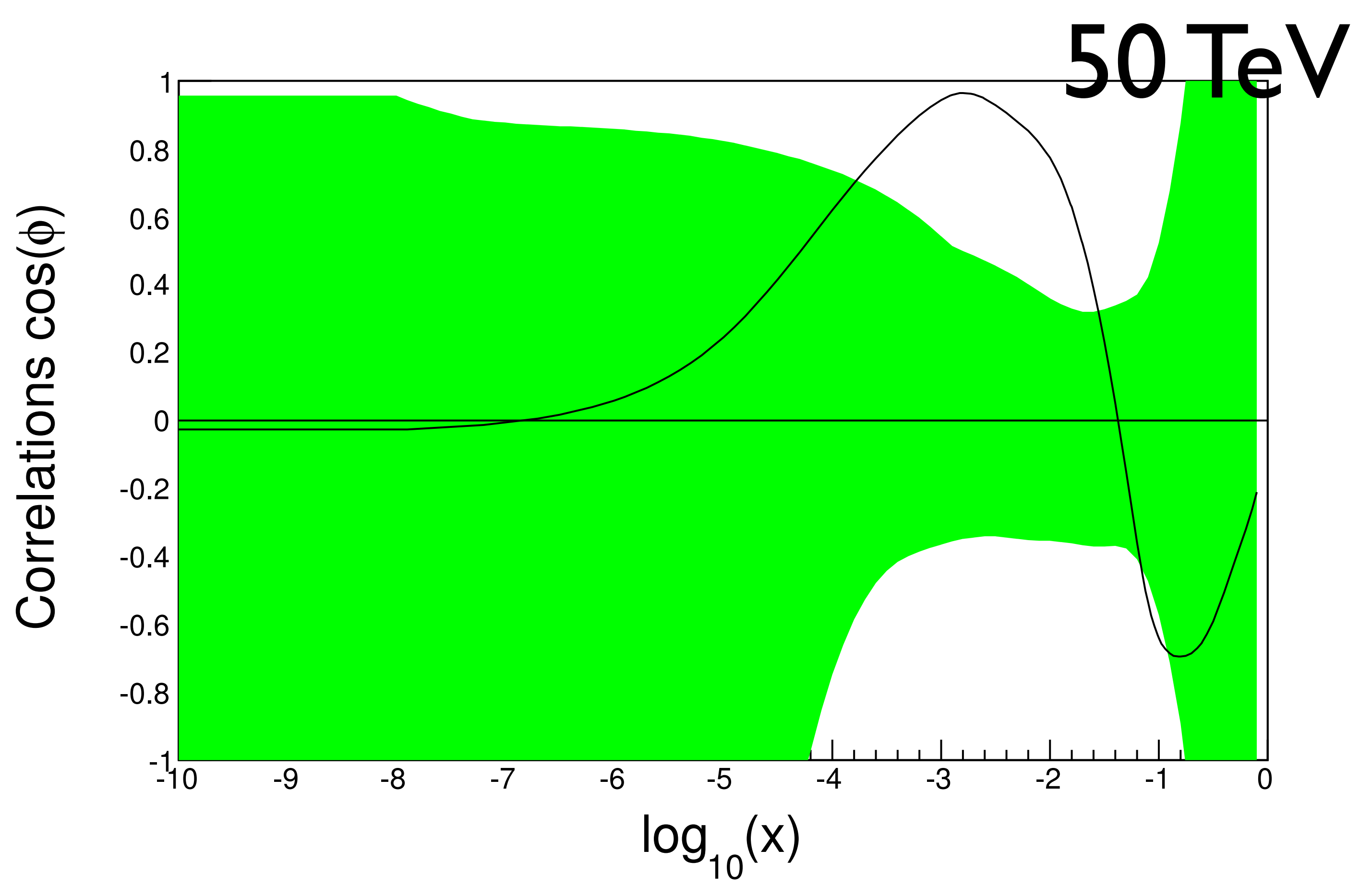
CSS qT resummation

$p_T(\gamma\gamma) = 15\ \mathrm{GeV}$



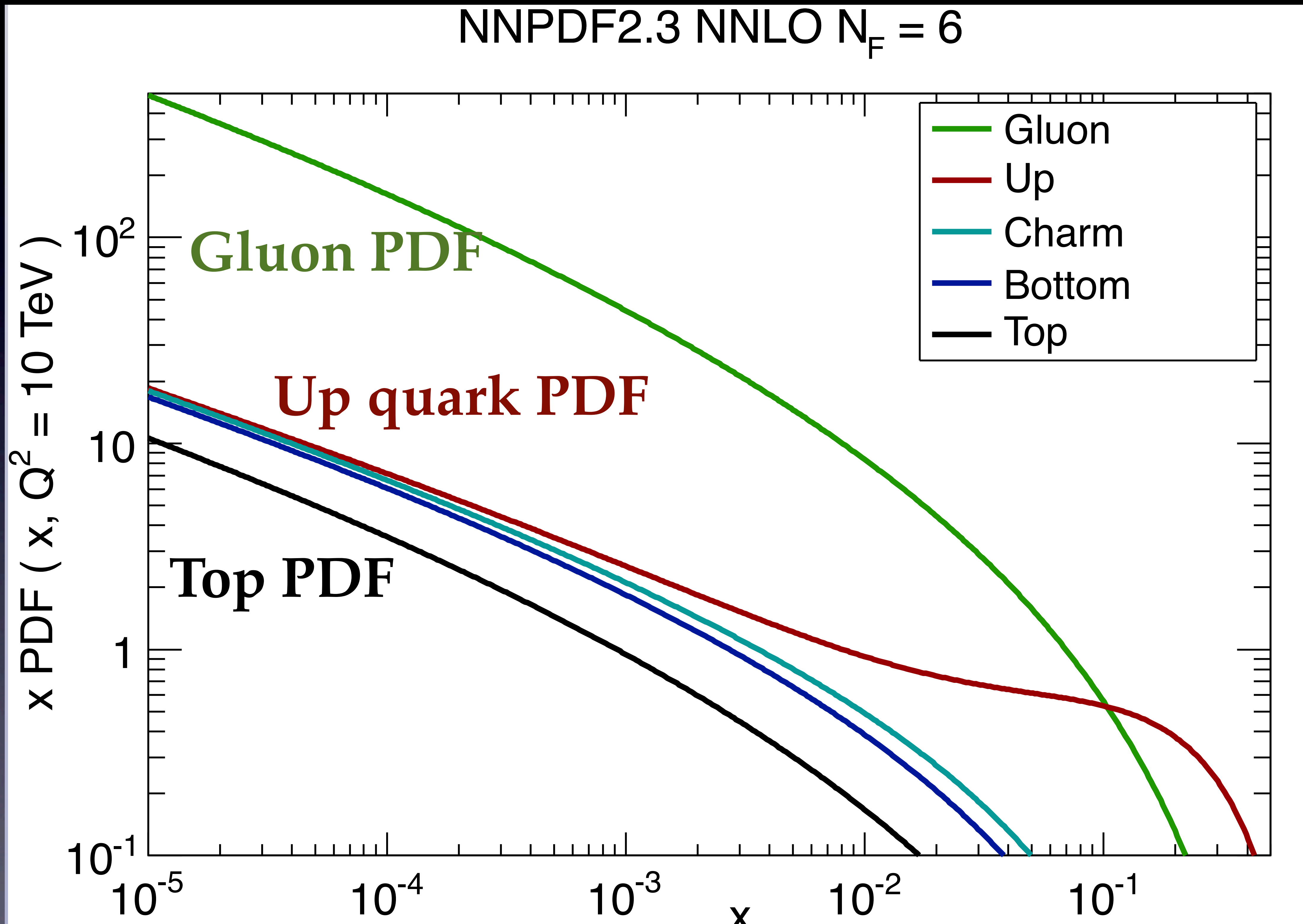
Di-photon Production and Gluon PDF





Differential x-section versus PDF (mainly gluon) correlation

Top-Quark PDFs

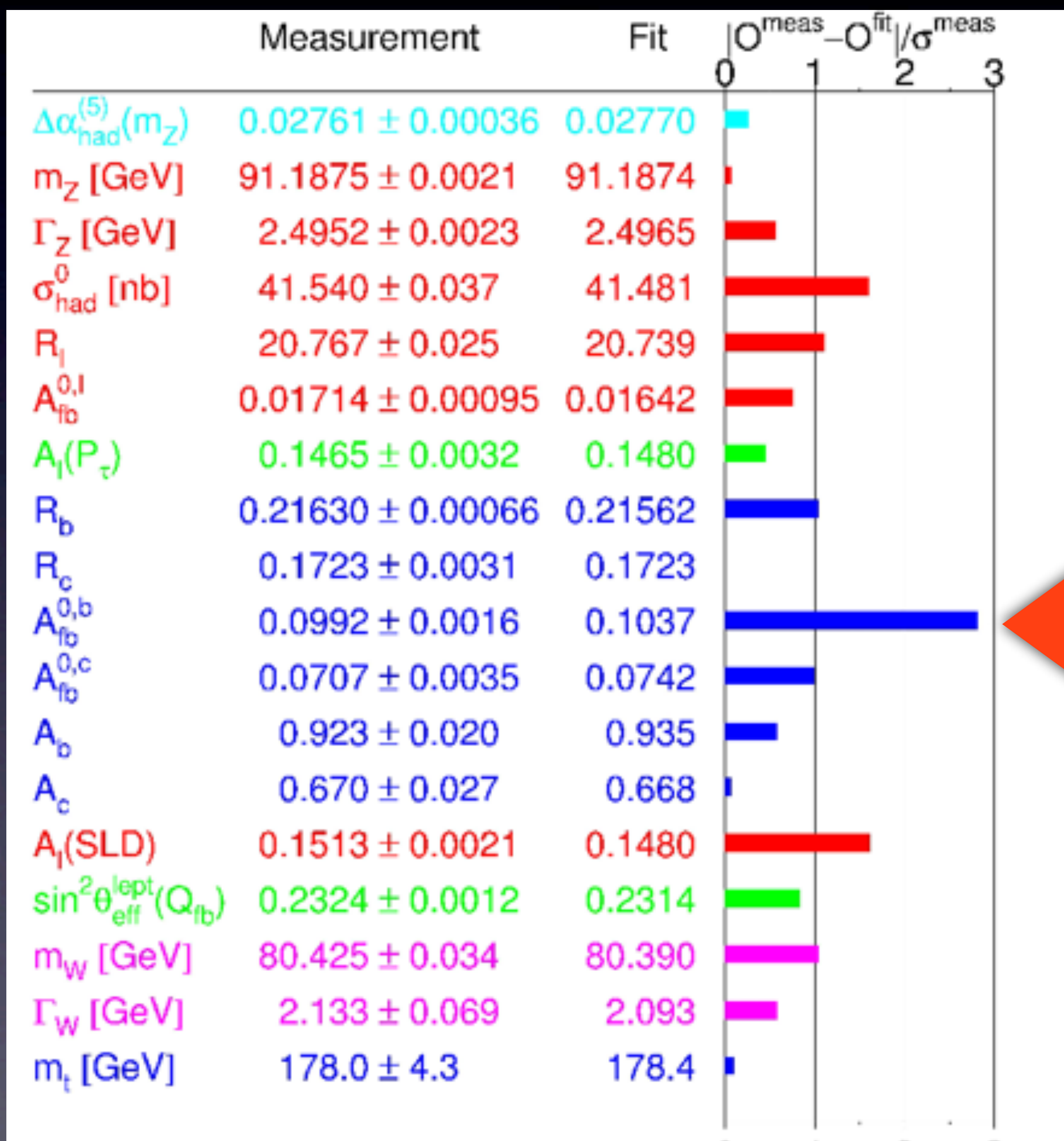


Juan Rojo, FCCK metting

Third Generation Quarks

Weak Couplings of 3rd Generation

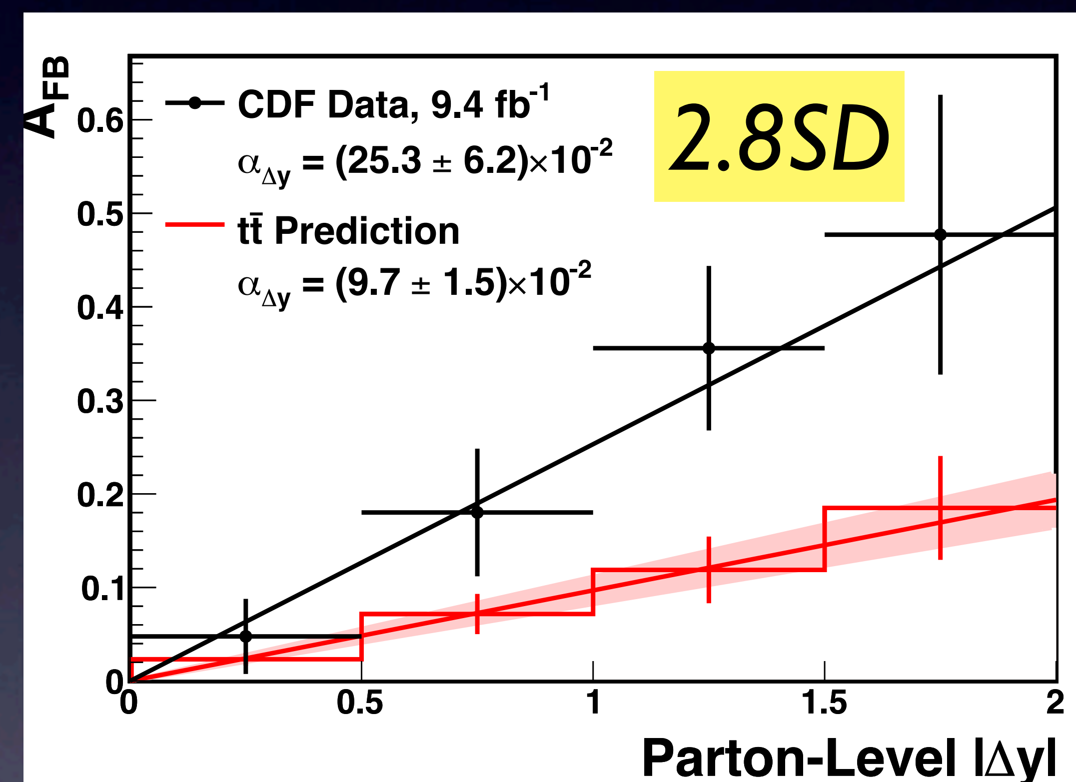
Something is rotten in the 3rd generation quarks



AFB(b) at LEP

Top charge asymmetry
at the Tevatron

see Z. G. Si's talk



Measurement		Measured Value, %	Theoretical Expectation [1], %
CDF	$9.4\ fb^{-1}$	16.4 ± 4.7	8.8 ± 0.6
D0	$5.4\ fb^{-1}$	19.6 ± 6.5	

Bernreuther and Z. G. Si, 1205.6580

$\mathrm{A_{FB}}(b)$ and $R(b)$

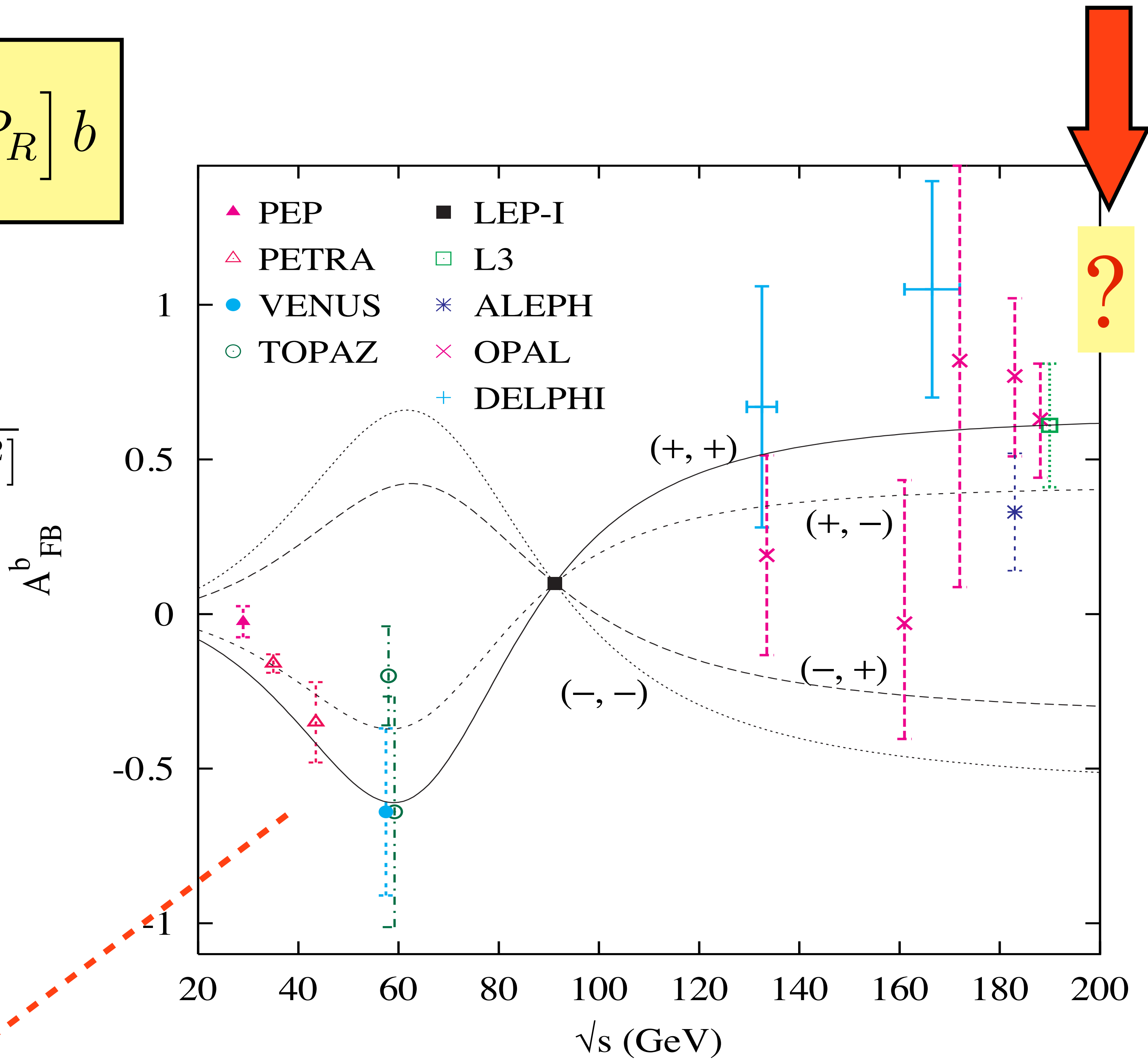
CEPC

$$\mathcal{L}_{Zb\bar{b}} = \frac{-e}{s_W c_W} Z_\mu \bar{b}\gamma^\mu \left[\bar{g}_L^b P_L + \bar{g}_R^b P_R\right] b$$

$$R_b \equiv \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to \text{hadrons})} \simeq \frac{(\bar{g}_L^b)^2 + (\bar{g}_R^b)^2}{\sum_q \left[(\bar{g}_L^q)^2 + (\bar{g}_R^q)^2\right]}$$

$$A_{FB}^b|_{\sqrt{s}\simeq m_Z} = \frac{3}{4} A_\ell \, A_b$$

$$A_b \simeq \frac{(\bar{g}_L^b)^2 - (\bar{g}_R^b)^2}{(\bar{g}_L^b)^2 + (\bar{g}_R^b)^2}$$



+

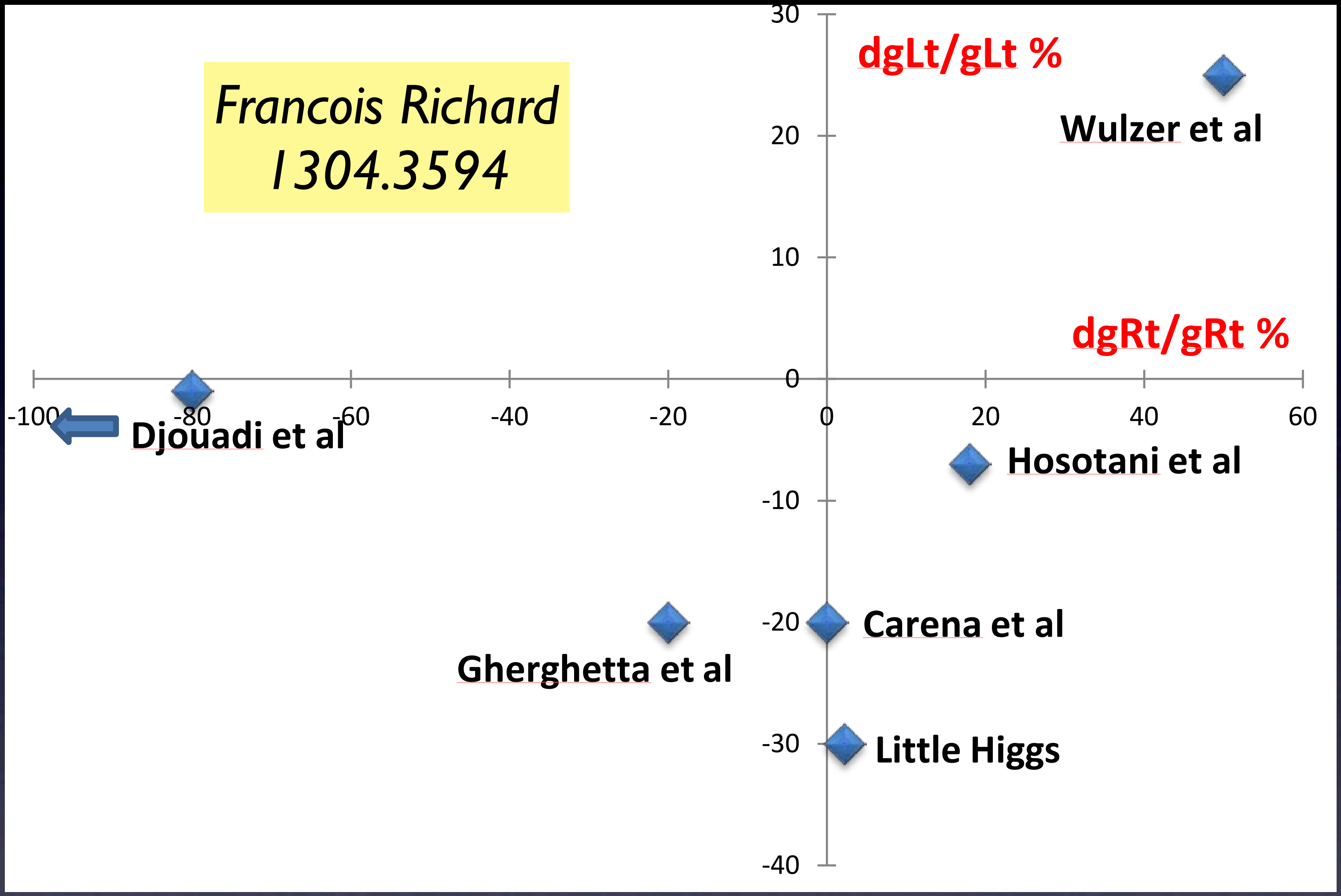
$$(\bar{g}_L^b, \bar{g}_R^b) \approx (\pm 0.992 g_L^b(SM), \pm 1.26 g_R^b(SM))$$

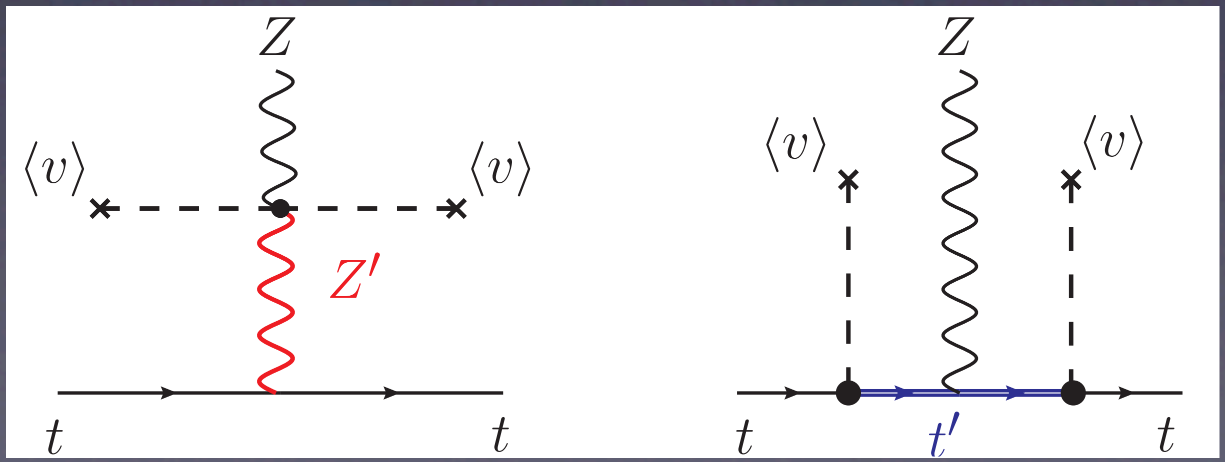
Weak Couplings of 3rd Generation Quarks

Z-t-t coupling

$$
\begin{aligned}
\mathcal{O}^{(1)}_{\phi q} &= i\left(\phi^\dagger D_\mu \phi\right)\left(\bar{q}\gamma^\mu q\right), \\
\mathcal{O}^{(3)}_{\phi q} &= i\left(\phi^\dagger \tau^I D_\mu \phi\right)\left(\bar{q}\gamma^\mu \tau^I q\right), \\
\mathcal{O}_{\phi t} &= i\left(\phi^\dagger D_\mu \phi\right)\left(\bar{t}_R\gamma^\mu t_R\right), \\
\mathcal{O}_{\phi b} &= i\left(\phi^\dagger D_\mu \phi\right)\left(\bar{b}_R\gamma^\mu b_R\right), \\
\mathcal{O}_{\phi \phi} &= \left(\phi^\dagger \epsilon D_\mu \phi\right)\left(\bar{t}_R\gamma^\mu b_R\right),
\end{aligned}
$$

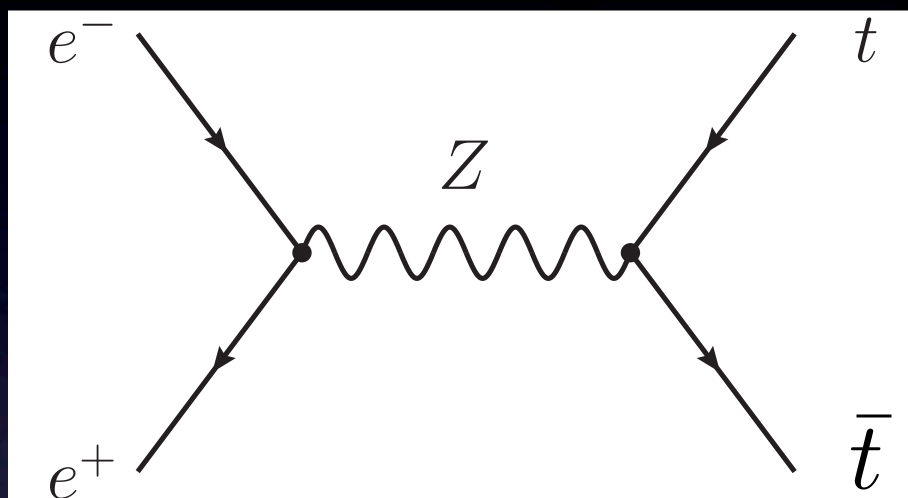
Berger, QHC, Low,
Phys.Rev.D80:074020(2009)
0907.2191



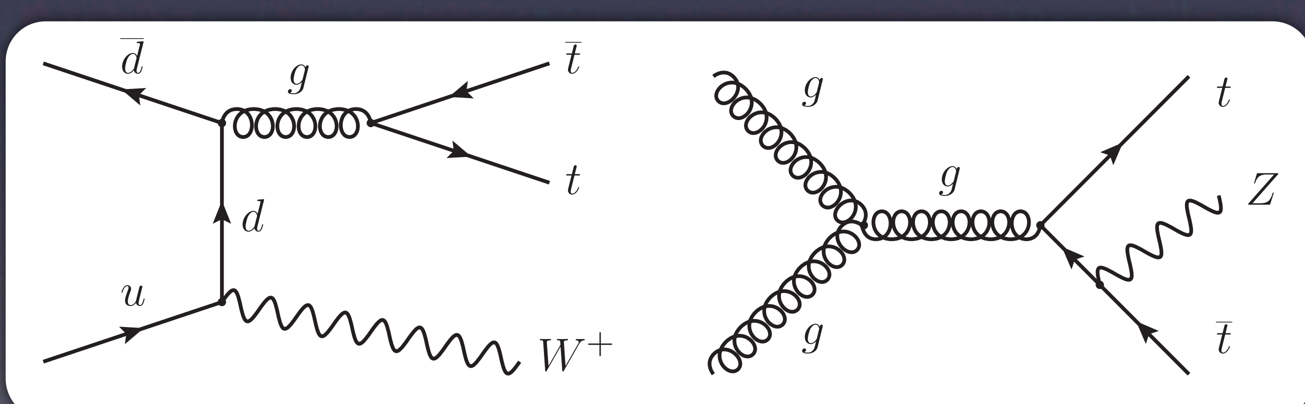


Z-*t*-*t* Coupling Measurements

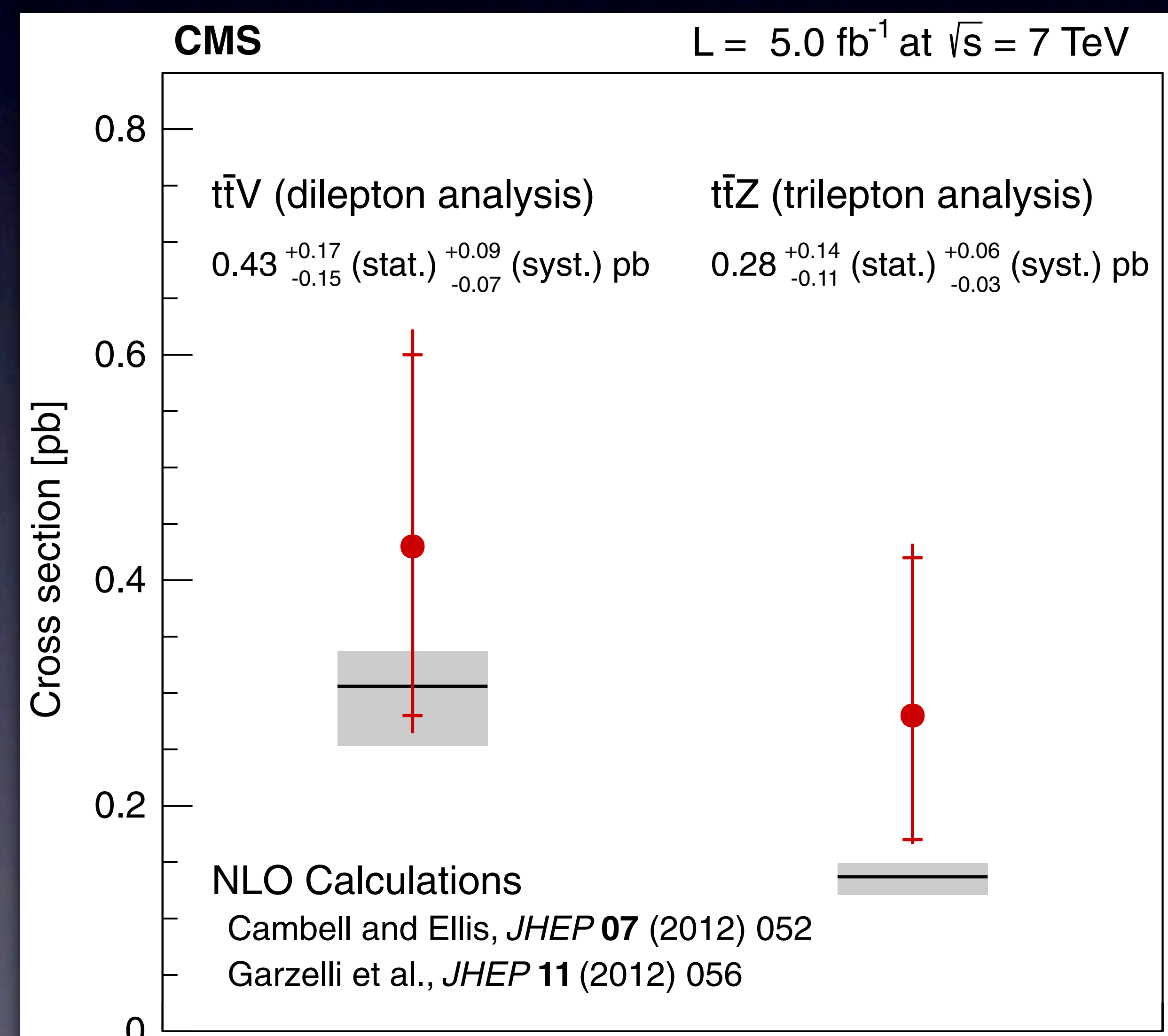
Precision Machine



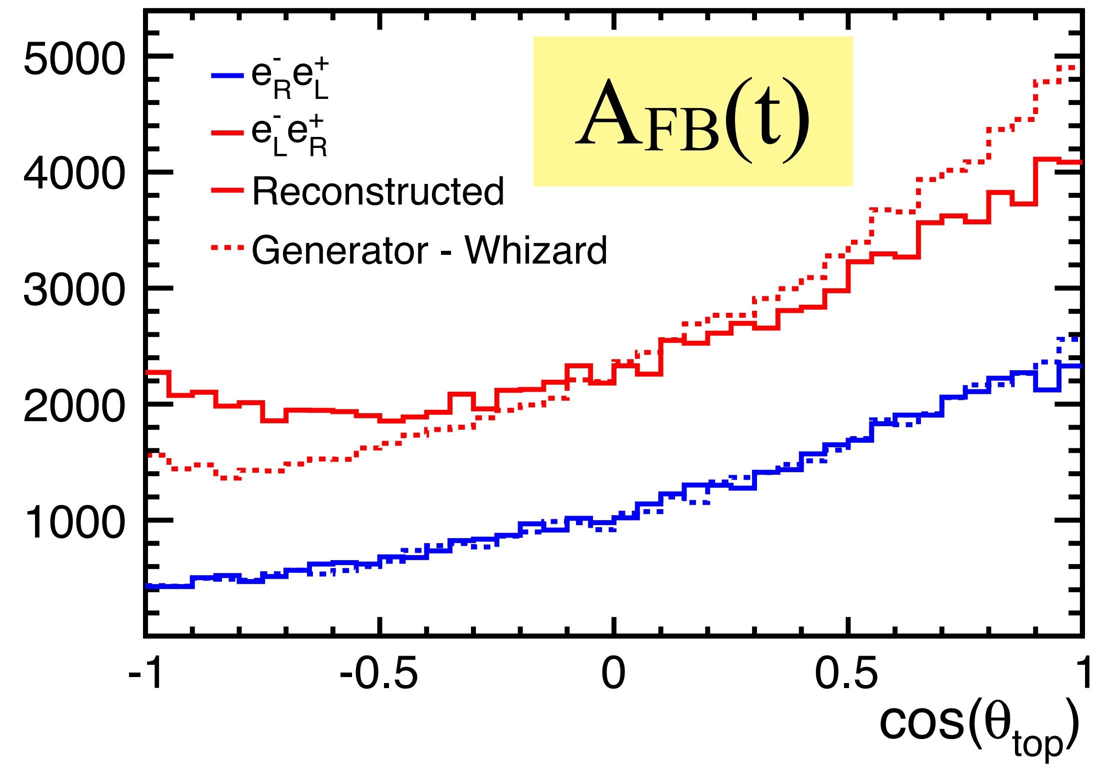
Energy Frontier

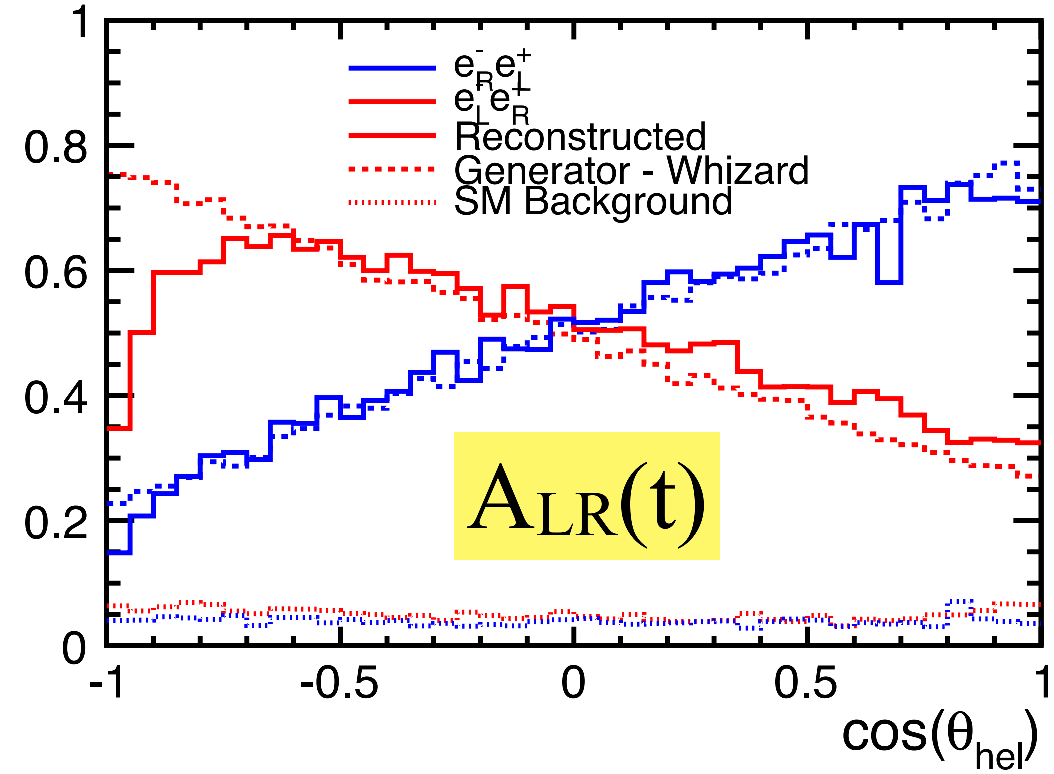


CMS, *PRL 110, 172002 (2013)*

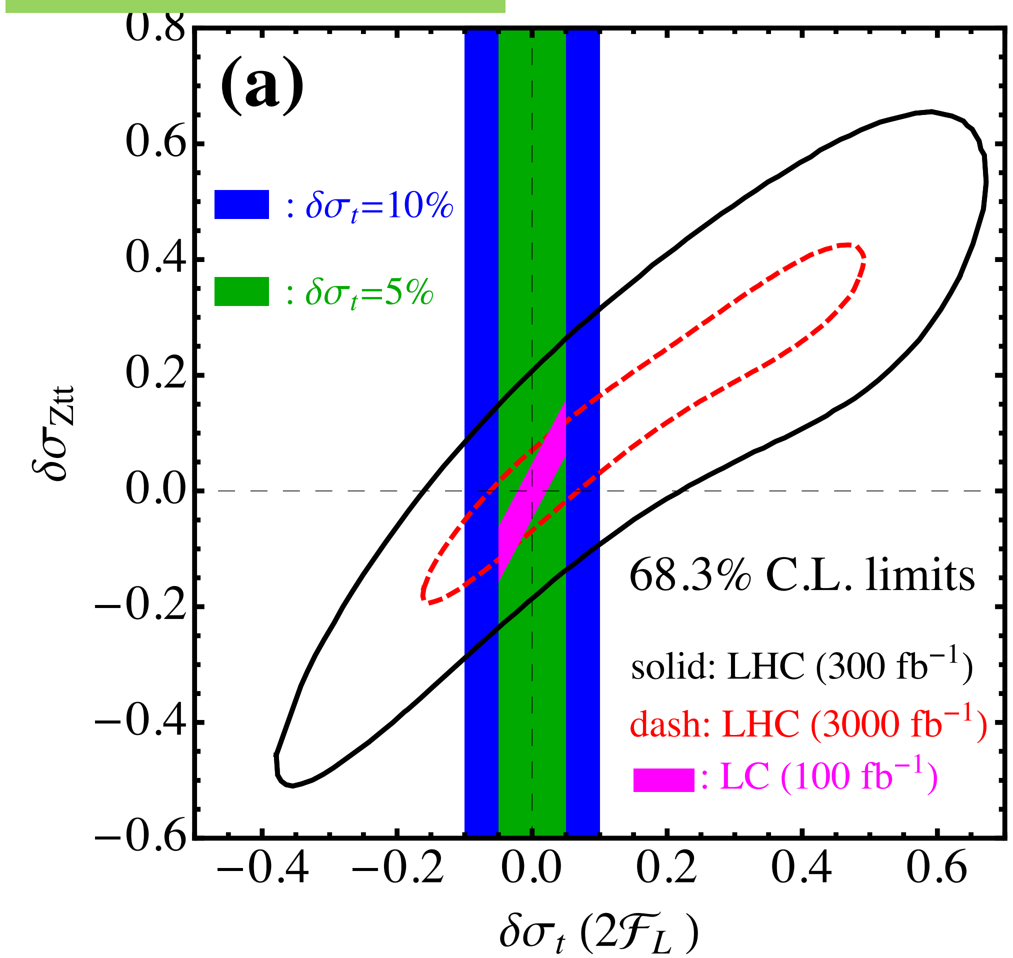


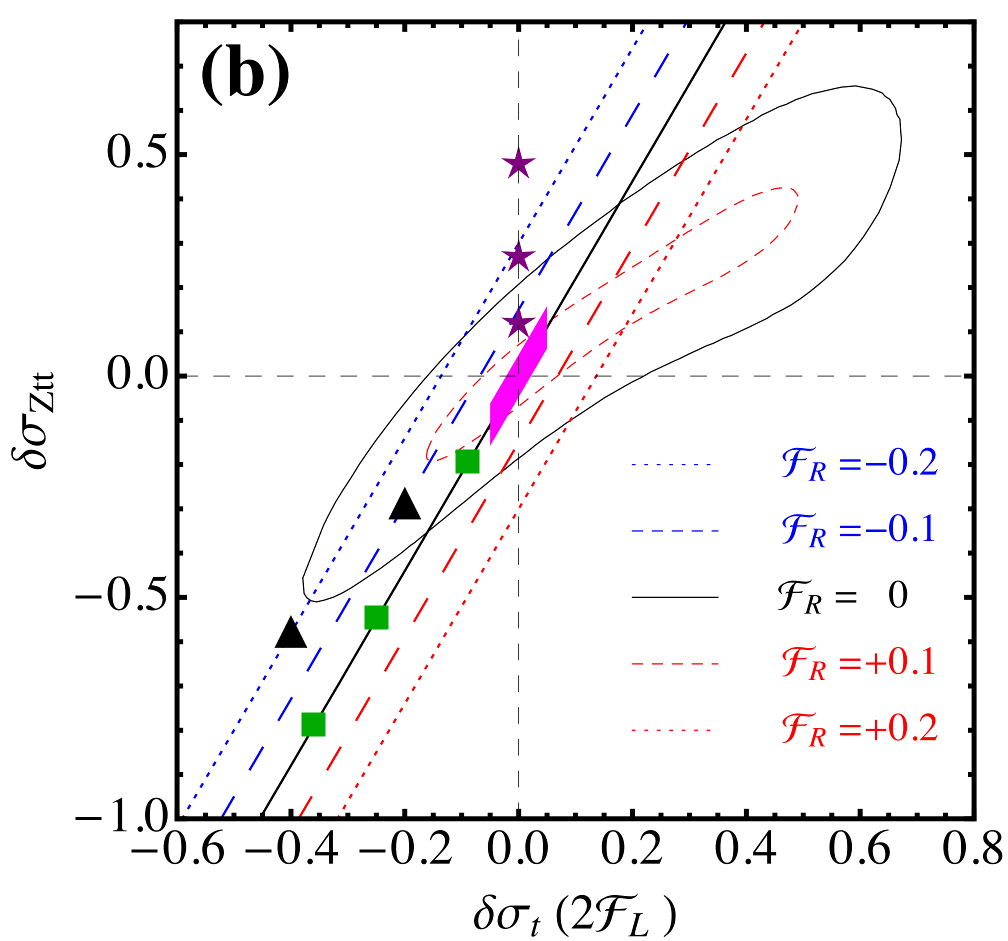
500GeV ILC, 250 fb^{-1}





LHC 14TeV





■ : *left-handed t-prime*

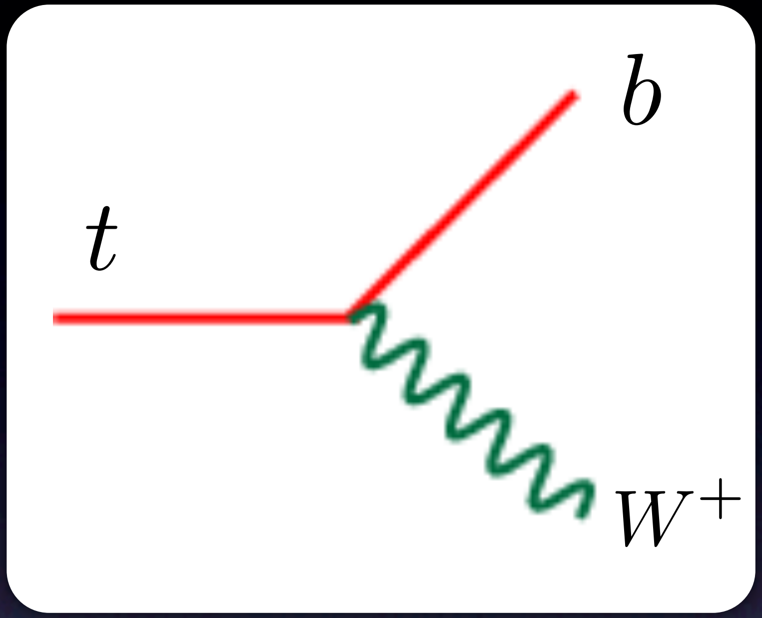
★ : *right-handed t-prime*

▲: *chiral 4th generation*

Berger, QHC, Low, 0907.2191

W-*t*-*b* Coupling

Have we measured *Wtb* coupling already? No!



$$i\frac{g}{\sqrt{2}}V_{tb}\gamma^{\mu}P_L$$

Vtb measurement from Top-quark decay

$$R = \frac{\mathrm{Br}(t \to Wb)}{\mathrm{Br}(t \to Wq)} = \frac{|V_{tb}|^2}{\sum_q |V_{tq}|^2} = |V_{tb}|^2$$

Unitarity Assumption

How can one measure V_{tb} without assuming CKM unitarity (three generations) or the SM electroweak coupling?

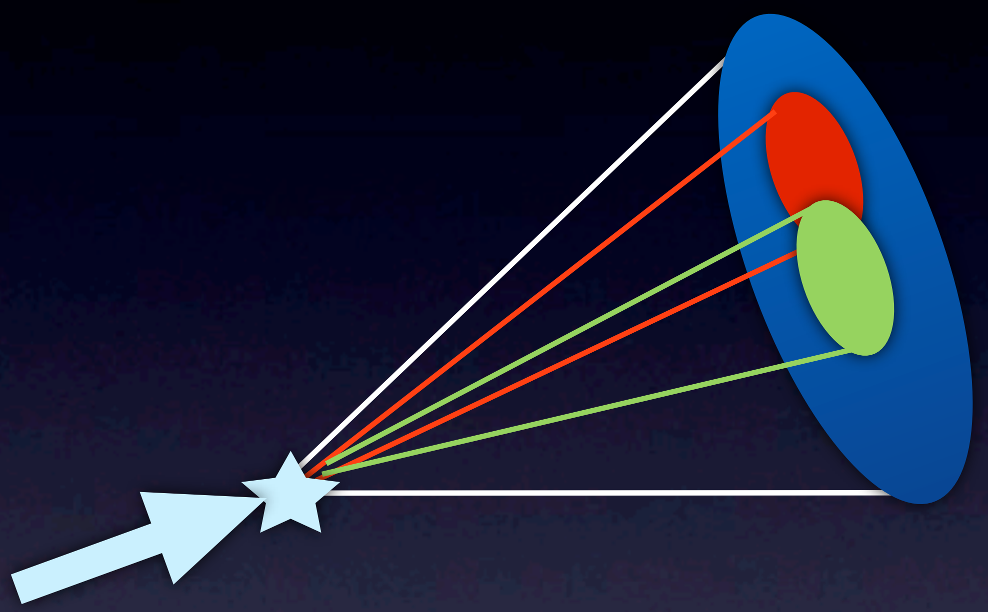
Boosted Physics

New kinematics at a 100 TeV machine

Boosted Physics

New physics often occurs in the tail of high PT region.

- T-prime, B-prime
- W-prime, Z-prime
- Heavy scalar

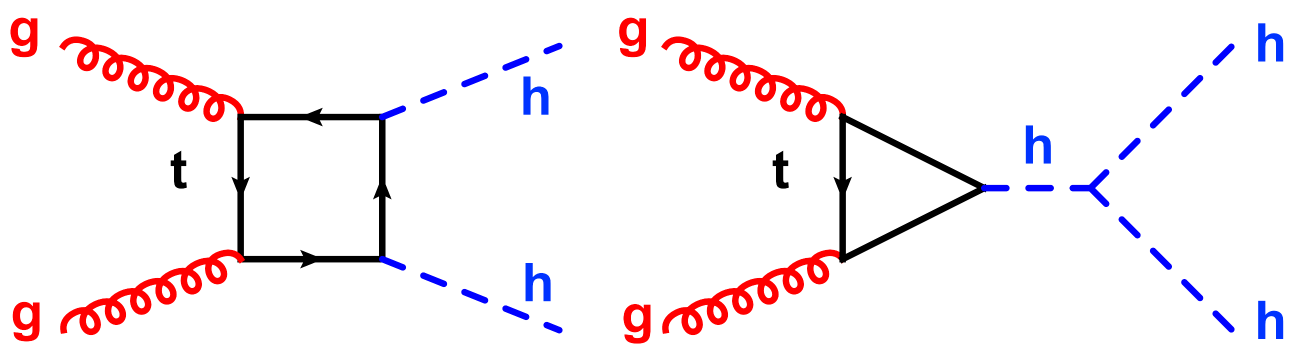


SM processes in large invariant mass range are bootcamp for all boost techniques

- Higgs-boson pair production
- Vector-boson pair production

Higgs Self-coupling Measurement

$$V(H) = \frac{1}{2}M_H^2 H^2 + \lambda_{HHH} v H^3 + \frac{1}{4}\lambda_{HHHH} H^4$$



Li Lin Yang

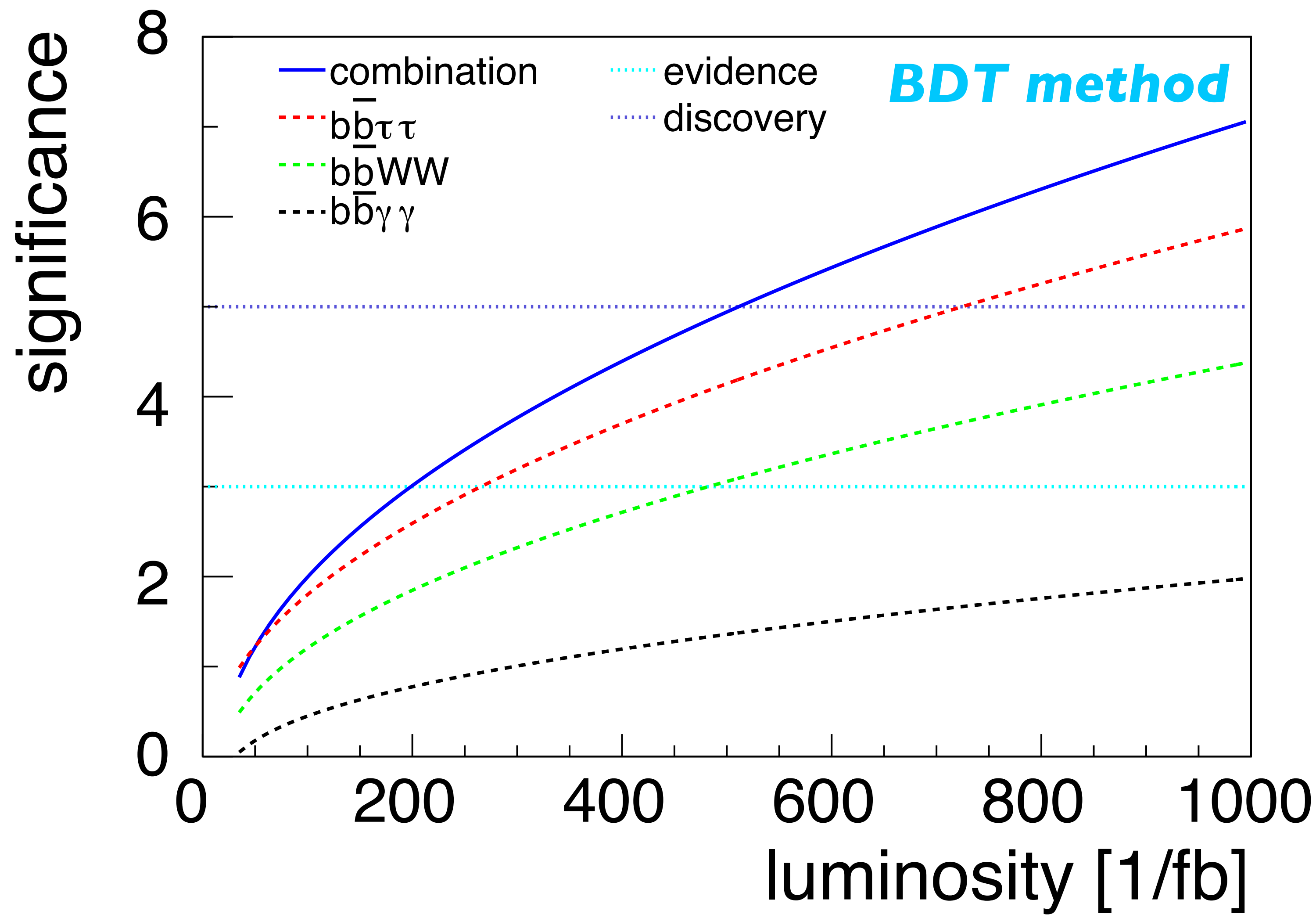
$p_T^H \geq 200$ GeV

Signal X-section

$\sqrt{s}$ [TeV]	14	33	50	100
σ_{NLO} [fb]	33.9	208	446	1419
σ_{NNLO} [fb]	41.1	249	530	1672

Signal vs Background

14TeV	S (600 fb^{-1})	B (600 fb^{-1})
$b\bar{b}\tau^+\tau^-$	50	104
$b\bar{b}W^+W^-$	11.2	7.4
$b\bar{b}\gamma\gamma$	6	12.5

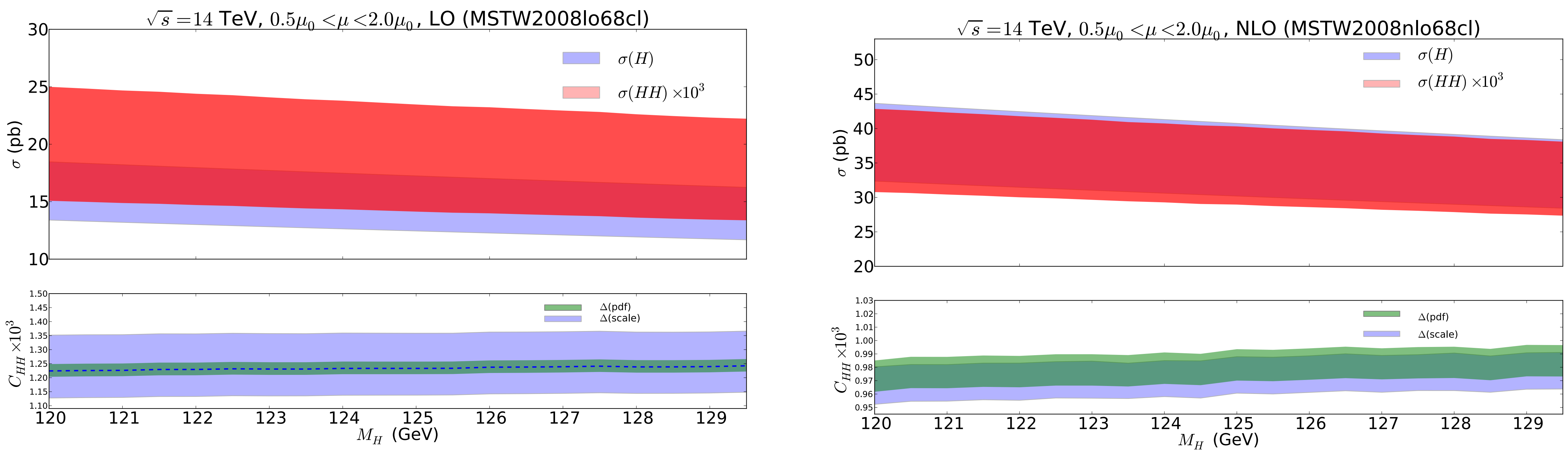


Higgs Self-coupling

Li Lin Yang

$$C_{HH} = \frac{\sigma(pp \to HH)}{\sigma(pp \to H)}$$

$\frac{2}{1}$ method



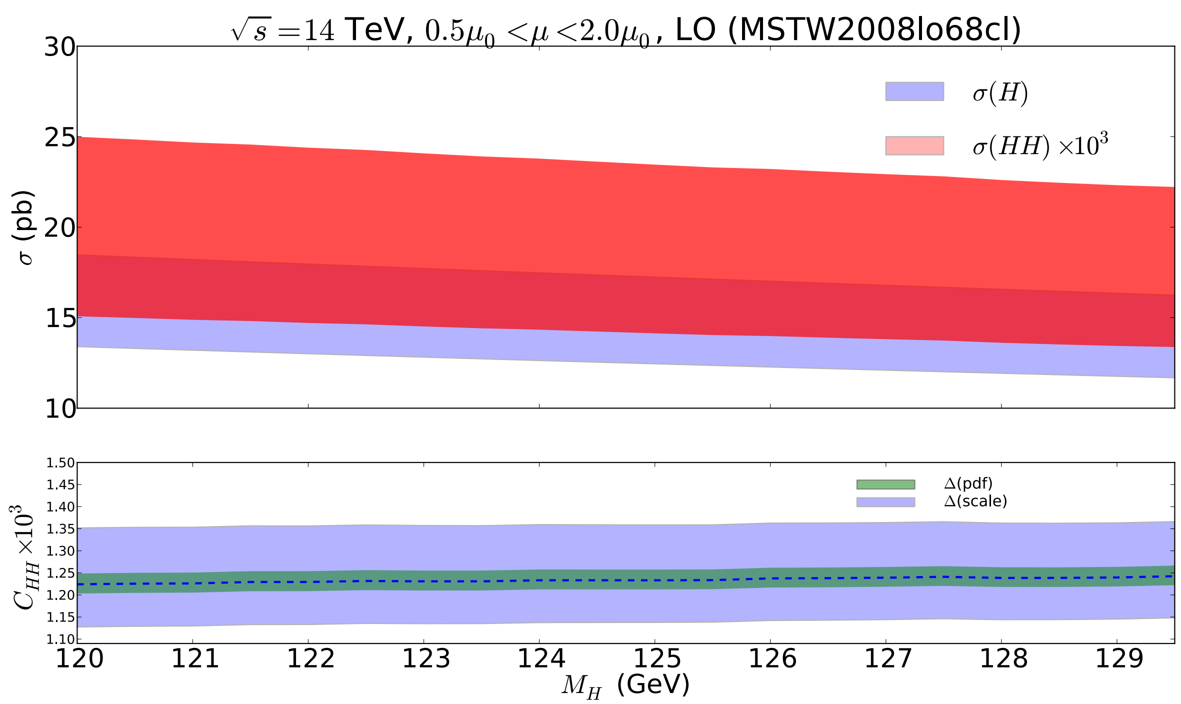
Channel	S/B (600 fb^{-1})	$\Delta C_{HH}/C_{HH}$ (600 fb^{-1})	$\Delta C_{HH}/C_{HH}$ (3000 fb^{-1})
$b\bar{b}\tau^+\tau^-$	50/104	0.400	0.279
$b\bar{b}W^+W^-$	11.2/7.4	0.513	0.314
$b\bar{b}\gamma\gamma$	6/12.5	0.964	0.490

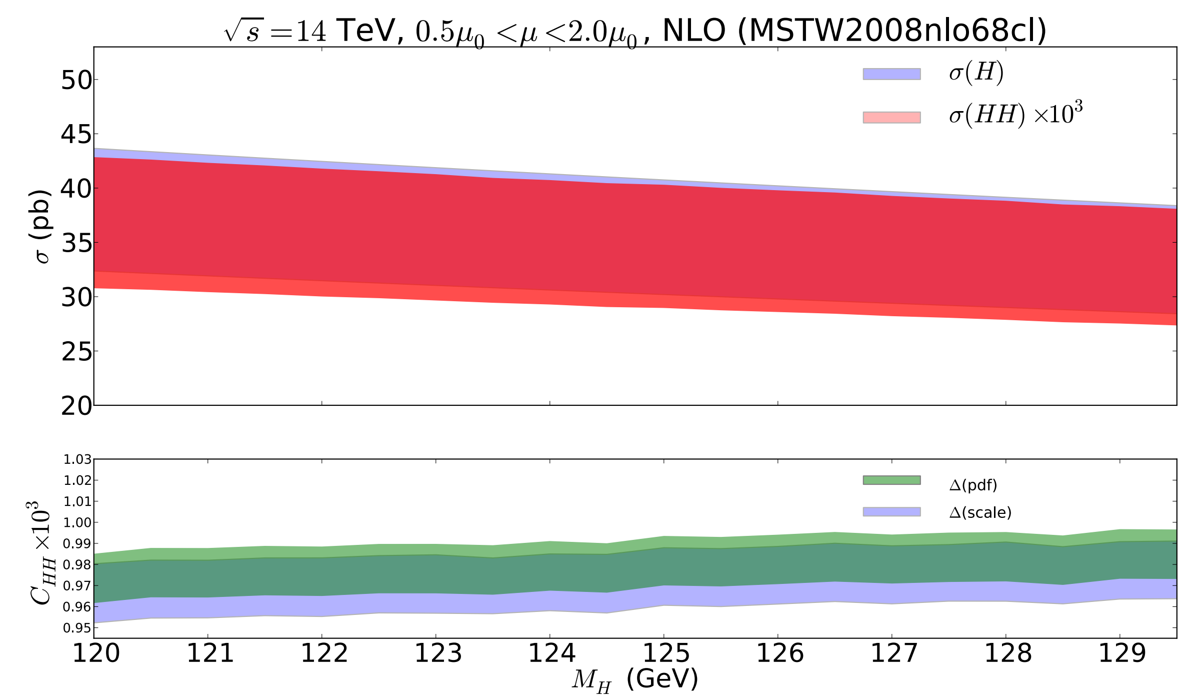
Higgs Self-coupling

Li Lin Yang

$$C_{HH} = \frac{\sigma(pp \to HH)}{\sigma(pp \to H)}$$

$\frac{2}{1}$ method





14TeV $y_t = y_t^{\rm SM}$

Channel	600 fb^{-1} (2σ)	600 fb^{-1} (1σ)	3000 fb^{-1} (2σ)	3000 fb^{-1} (1σ)
$b\bar{b}\tau^+\tau^-$	$(0.22, 4.70)$	$(0.57, 1.64)$	$(0.42, 2.13)$	$(0.69, 1.40)$
$b\bar{b}W^+W^-$	$(0.04, 4.88)$	$(0.46, 1.95)$	$(0.36, 4.56)$	$(0.65, 1.46)$
$b\bar{b}\gamma\gamma$	$(-0.56, 5.48)$	$(0.09, 4.83)$	$(0.08, 4.84)$	$(0.48, 1.87)$

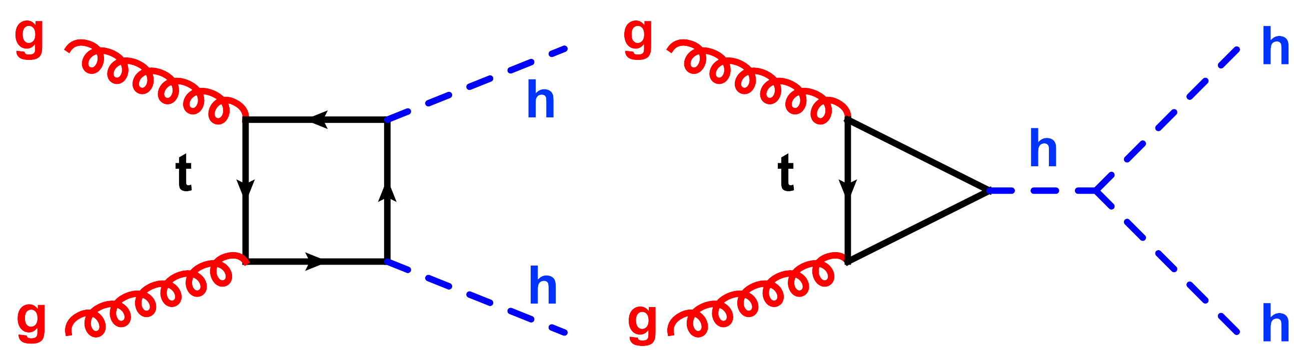
To achieve same sensitivity

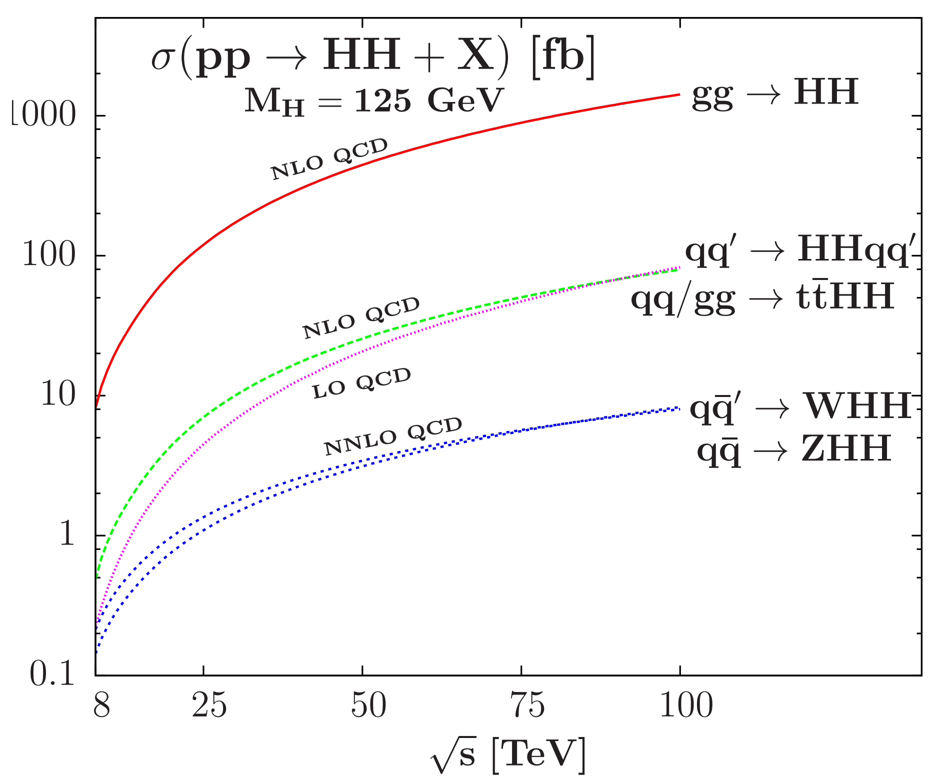
L/3.4 (50TeV)

L/5.8 (100TeV)

Higgs Self-coupling

$$V(H) = \frac{1}{2}M_H^2 H^2 + \lambda_{HHH} v H^3 + \frac{1}{4}\lambda_{HHHH} H^4$$





Baglio, Djouadi et al, 1212.5581

E_{cm}	8 TeV	14 TeV	33 TeV	100 TeV
$\sigma_{\rm NNLO}$	9.76 fb	40.2 fb	243 fb	1638 fb
Scale [%]	$+9.0-9.8$	$+8.0-8.7$	$+7.0-7.4$	$+5.9-5.8$
PDF [%]	$+6.0-6.1$	$+4.0-4.0$	$+2.5-2.6$	$+2.3-2.6$
PDF+α_s [%]	$+9.3-8.8$	$+7.2-7.1$	$+6.0-6.0$	$+5.8-6.0$

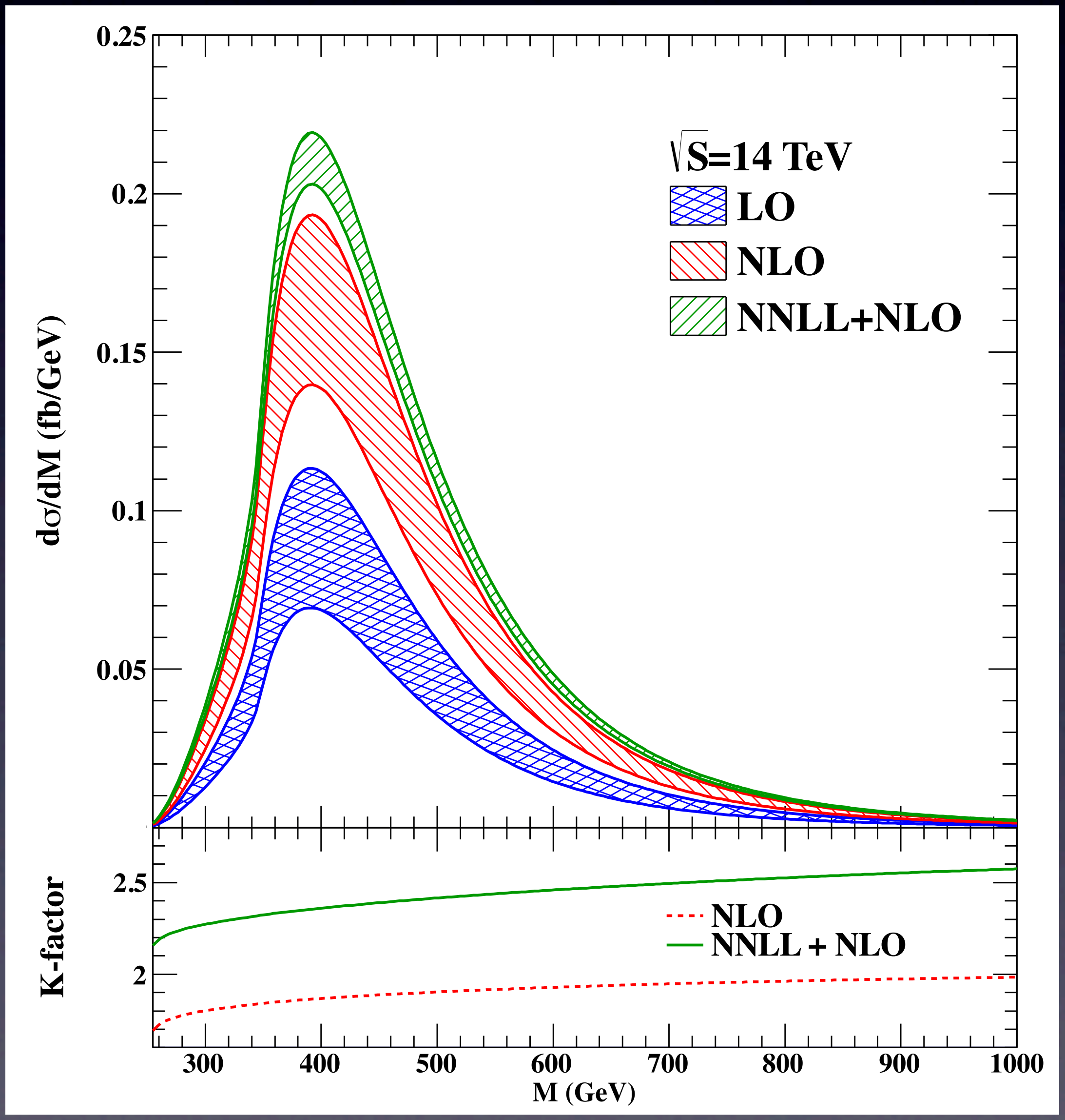
Daniel de Florian, Javier Mazzitelli 1309.6594

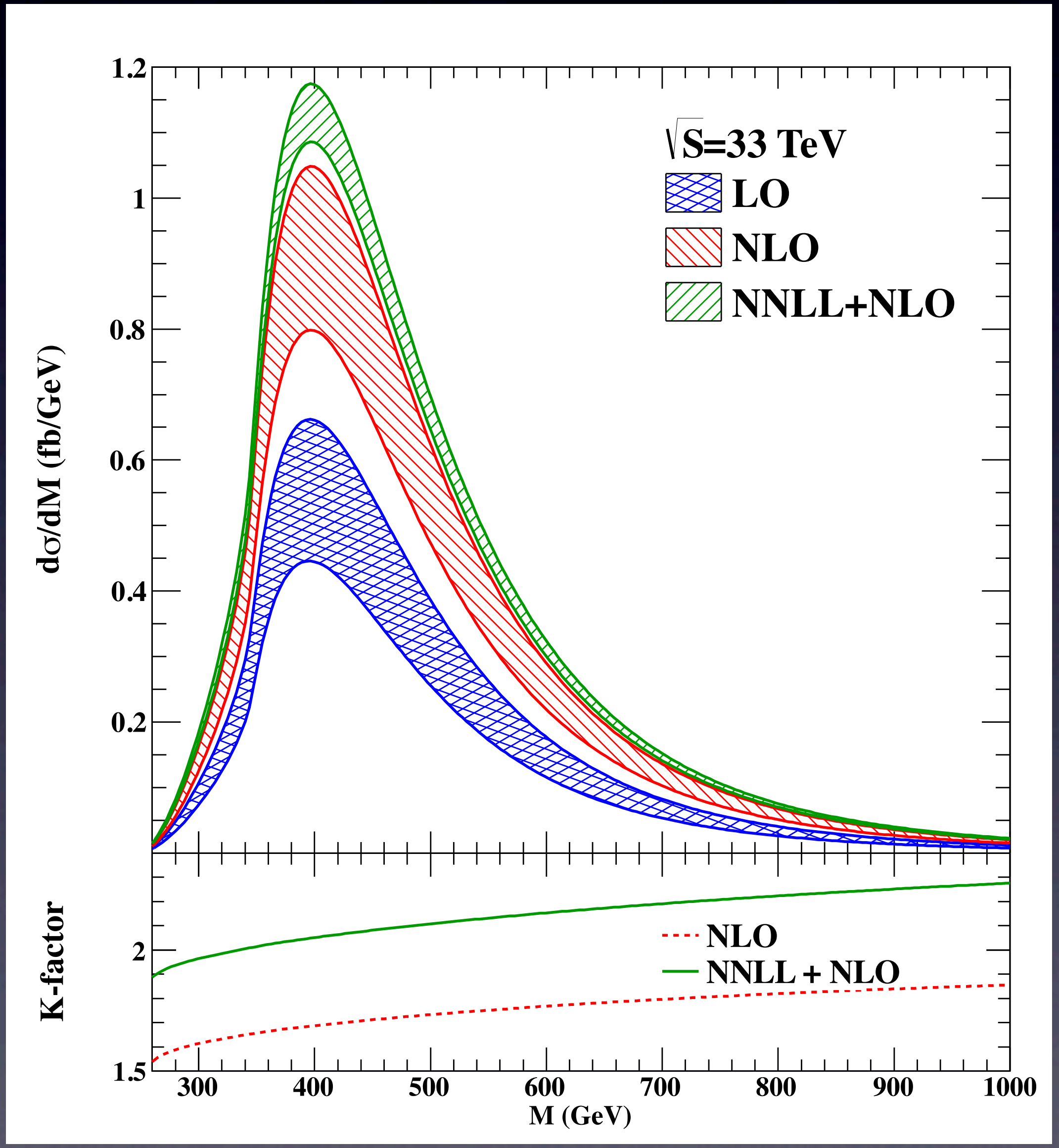
Higgs Self-coupling

Threshold resummation effects at the NNLL

Ding Yu Shao, Chong Sheng Li, Hai Tao Li, Jian Wang, JHEP07(2013)169

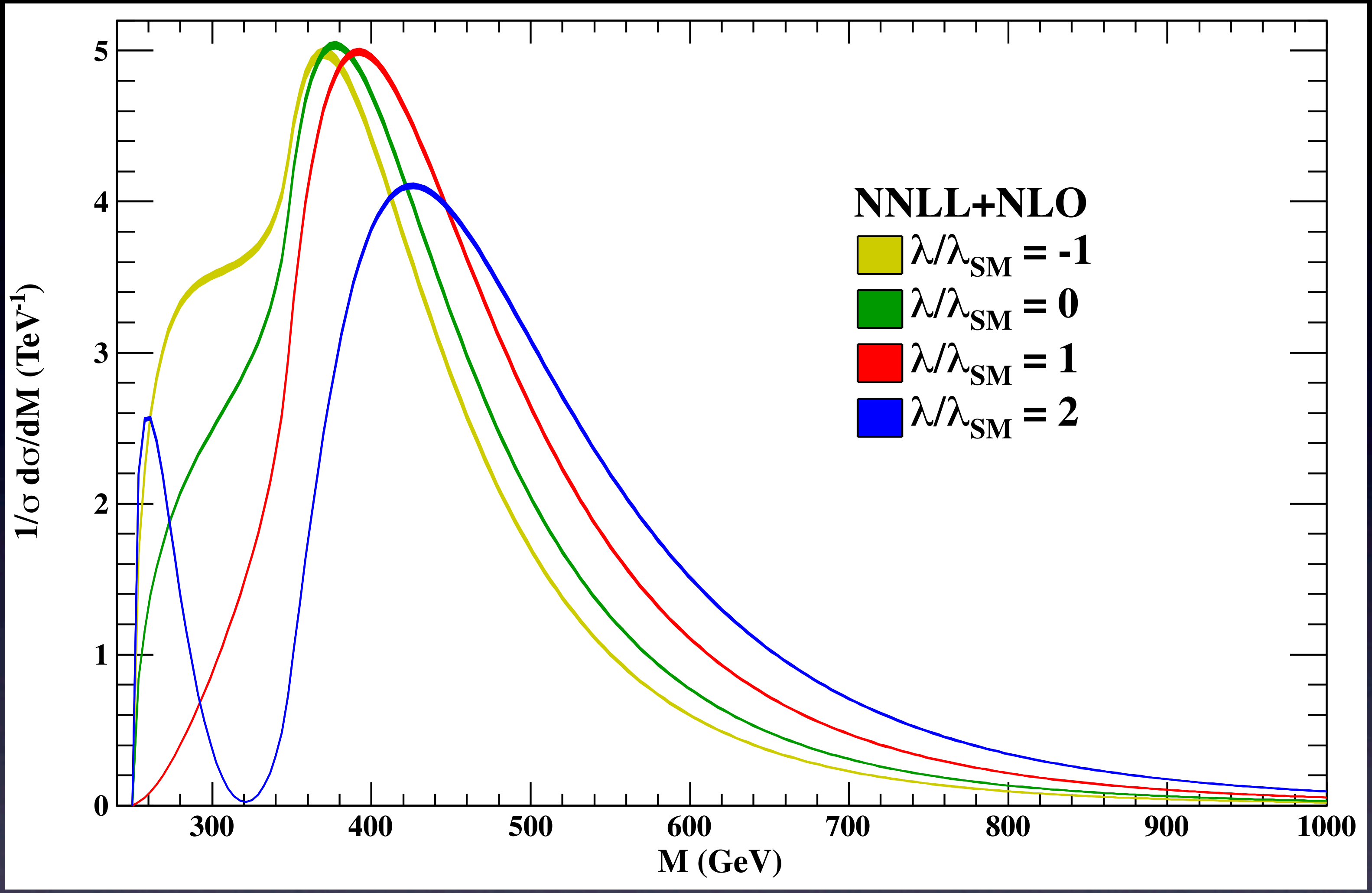
Also see 1401.1101



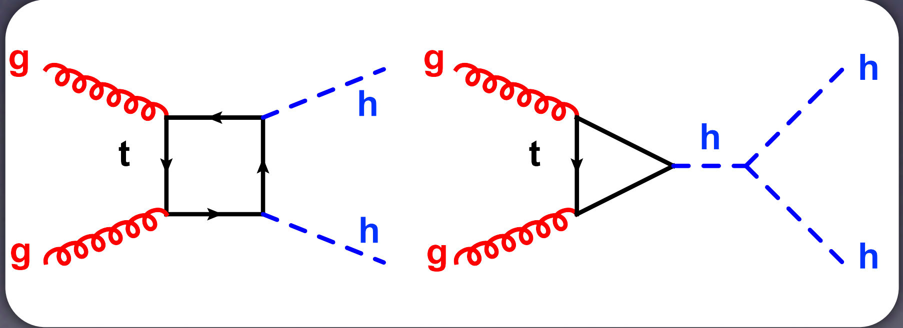


Scale Error ~ 8%,   PDF + alphas Error ~10%

Invariant Mass of Higgs-Boson Pair



$$\mathcal{L}_{\text{eff}} = \frac{\alpha_s(\mu^2)}{12\pi v} C_t(\mu^2) G^a_{\mu\nu} G^{a\ \mu\nu} h - \frac{\alpha_s(\mu^2)}{24\pi v^2} C_t(\mu^2) G^a_{\mu\nu} G^{a\ \mu\nu} h^2$$

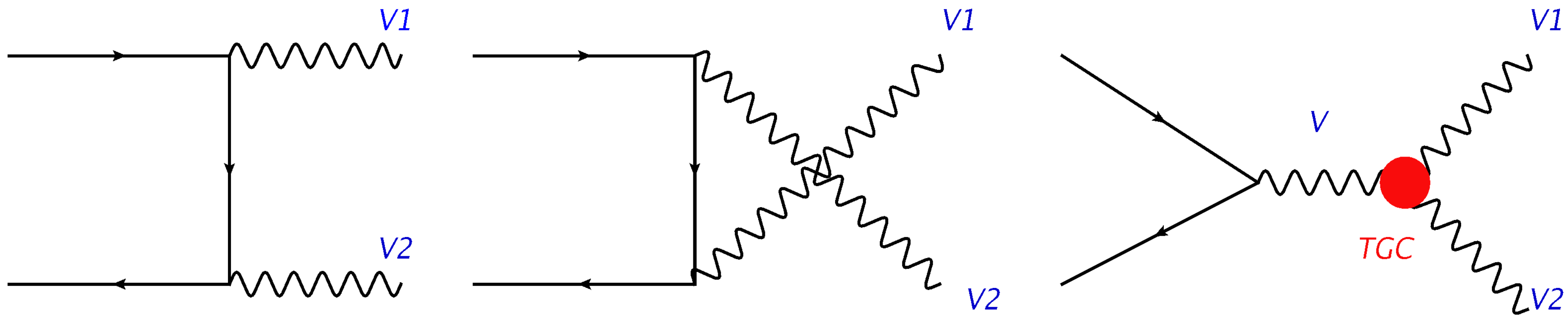


$\lambda/\lambda_{\text{SM}}$	$\sqrt{S} = 14$ TeV NLO [fb]	NLO + NNLL [fb]	K-factor
-1	$127.9^{+23.1+8.7\,(+3.8)}_{-18.8-7.7\,(-3.3)}$	$161.6^{+9.8+12.0\,(+6.0)}_{-3.1-11.4\,(-4.9)}$	1.26
0	$71.1^{+12.8+4.8\,(+2.1)}_{-10.5-4.3\,(-1.8)}$	$90.0^{+5.4+6.8\,(+3.3)}_{-1.7-6.4\,(-2.8)}$	1.27
1	$33.9^{+6.1+2.3\,(+1.0)}_{-5.0-2.0\,(-0.9)}$	$42.9^{+2.6+3.3\,(+1.6)}_{-0.8-3.1\,(-1.3)}$	1.27
2	$16.1^{+2.9+1.1\,(+0.5)}_{-2.4-1.0\,(-0.4)}$	$20.4^{+1.2+1.6\,(+0.8)}_{-0.4-1.5\,(-0.7)}$	1.27

Quartic Gauge Coupling
and
Triple Gauge Coupling

(Important for testing the SM)

Triple Gauge Coupling



	ZWW	AWW	HWW	HZZ	HZA	HAA	WWWW	ZZWW	ZAWW	AAWW
$\mathcal{O}_{WWW}$	X	X					X	X	X	X
$\mathcal{O}_{W}$	X	X	X	X	X		X	X	X	
$\mathcal{O}_{B}$	X	X		X	X					
$\mathcal{O}_{\Phi d}$			X	X						
$\mathcal{O}_{\Phi W}$			X	X	X	X				
$\mathcal{O}_{\Phi B}$				X	X	X				
$\mathcal{O}_{\tilde{W}WW}$	X	X					X	X	X	X
$\mathcal{O}_{\tilde{W}}$	X	X	X	X	X					
$\mathcal{O}_{\tilde{W}W}$			X	X	X	X				
$\mathcal{O}_{\tilde{B}B}$				X	X	X				

$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_{\rho}^{\mu}]$$
$$\mathcal{O}_{W} = (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi)$$
$$\mathcal{O}_{B} = (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi),$$
$$\mathcal{O}_{\Phi d} = \partial_\mu\left(\Phi^\dagger\Phi\right)\partial^\mu\left(\Phi^\dagger\Phi\right)$$
$$\mathcal{O}_{\Phi W} = \left(\Phi^\dagger\Phi\right)\mathrm{Tr}[W^{\mu\nu}W_{\mu\nu}]$$
$$\mathcal{O}_{\Phi B} = \left(\Phi^\dagger\Phi\right)B^{\mu\nu}B_{\mu\nu}$$

$$\mathcal{O}_{\tilde{W}WW} = \mathrm{Tr}[\tilde{W}_{\mu\nu}W^{\nu\rho}W_{\rho}^{\mu}]$$
$$\mathcal{O}_{\tilde{W}} = (D_\mu\Phi)^\dagger \tilde{W}^{\mu\nu}(D_\nu\Phi)$$
$$\mathcal{O}_{\tilde{W}W} = \Phi^\dagger\tilde{W}_{\mu\nu}W^{\mu\nu}\Phi$$
$$\mathcal{O}_{\tilde{B}B} = \Phi^\dagger\tilde{B}_{\mu\nu}B^{\mu\nu}\Phi$$

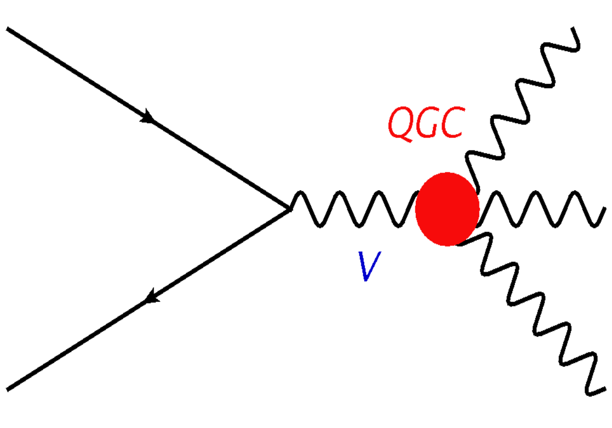
Snowmass EW 1310.6708

Quartic Gauge Coupling

Important for testing the SM

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	X	X	X						
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$,$\mathcal{O}_{M,6}$,$\mathcal{O}_{M,7}$	X	X	X	X	X	X	X		
$\mathcal{O}_{M,2}$,$\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$,$\mathcal{O}_{M,5}$		X	X	X	X	X	X		
$\mathcal{O}_{T,0}$,$\mathcal{O}_{T,1}$,$\mathcal{O}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{O}_{T,5}$,$\mathcal{O}_{T,6}$,$\mathcal{O}_{T,7}$		X	X	X	X	X	X	X	X
$\mathcal{O}_{T,8}$,$\mathcal{O}_{T,9}$			X			X	X	X	X

$$\mathcal{O}_{T,0} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times \mathrm{Tr}\left[W_{\alpha\beta}W^{\alpha\beta}\right] ,$$
$$\mathcal{O}_{T,1} = \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \times \mathrm{Tr}\left[W_{\mu\beta}W^{\alpha\nu}\right] ,$$
$$\mathcal{O}_{T,2} = \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right] \times \mathrm{Tr}\left[W_{\beta\nu}W^{\nu\alpha}\right] ,$$
$$\mathcal{O}_{T,5} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta} ,$$
$$\mathcal{O}_{T,6} = \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu} ,$$
$$\mathcal{O}_{T,7} = \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha} ,$$
$$\mathcal{O}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{O}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha} .$$



Snowmass
EW
1310.6708

Rare Decays

Top-Quark Rare Decay

expectations from theory

Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

current limits

Process	Br Limit	Search	Dataset	Reference
$t \to Zq$	7×10^{-4}	CMS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	19.5 fb^{-1}, 8 TeV	[130]
$t \to Zq$	7.3×10^{-3}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	2.1 fb^{-1}, 7 TeV	[137]
$t \to gu$	3.1×10^{-5}	ATLAS $qg \to t \to Wb$	14.2 fb^{-1}, 8 TeV	[131]
$t \to gc$	1.6×10^{-4}	ATLAS $qg \to t \to Wb$	14.2 fb^{-1}, 8 TeV	[131]
$t \to \gamma u$	6.4×10^{-3}	ZEUS $e^{\pm}p \to (t \text{ or } \bar{t}) + X$	474 pb^{-1}, 300 GeV	[134]
$t \to \gamma q$	3.2×10^{-2}	CDF $t\bar{t} \to Wb + \gamma q$	110 pb^{-1}, 1.8 TeV	[132]
$t \to hq$	8.3×10^{-3}	ATLAS $t\bar{t} \to Wb + hq \to \ell\nu b + \gamma\gamma q$	20 fb^{-1}, 8 TeV	[135]
$t \to hq$	2.7×10^{-2}	CMS* $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	5 fb^{-1}, 7 TeV	[136]
$t \to$ invis.	9×10^{-2}	CDF $t\bar{t} \to Wb$	1.9 fb^{-1}, 1.96 TeV	[133]

extrapolations

t->Zq, γq, Zc

Process	Br Limit	Search	Dataset	Reference
$t \to Zq$	2.2×10^{-4}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	300 fb^{-1}, 14 TeV	[140]
$t \to Zq$	7×10^{-5}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	3000 fb^{-1}, 14 TeV	[140]
$t \to Zq$	$5\,(2) \times 10^{-4}$	ILC single top, γ_μ $(\sigma_{\mu\nu})$	500 fb^{-1}, 250 GeV	Extrap.
$t \to Zq$	$1.5\,(1.1) \times 10^{-4\,(-5)}$	ILC single top, γ_μ $(\sigma_{\mu\nu})$	500 fb^{-1}, 500 GeV	[141]
$t \to Zq$	$1.6\,(1.7) \times 10^{-3}$	ILC $t\bar{t}$, γ_μ $(\sigma_{\mu\nu})$	500 fb^{-1}, 500 GeV	[141]
$t \to \gamma q$	8×10^{-5}	ATLAS $t\bar{t} \to Wb + \gamma q$	300 fb^{-1}, 14 TeV	[140]
$t \to \gamma q$	2.5×10^{-5}	ATLAS $t\bar{t} \to Wb + \gamma q$	3000 fb^{-1}, 14 TeV	[140]
$t \to \gamma q$	6×10^{-5}	ILC single top	500 fb^{-1}, 250 GeV	Extrap.
$t \to \gamma q$	6.4×10^{-6}	ILC single top	500 fb^{-1}, 500 GeV	[141]
$t \to \gamma q$	1.0×10^{-4}	ILC $t\bar{t}$	500 fb^{-1}, 500 GeV	[141]
$t \to gu$	4×10^{-6}	ATLAS $qg \to t \to Wb$	300 fb^{-1}, 14 TeV	Extrap.
$t \to gu$	1×10^{-6}	ATLAS $qg \to t \to Wb$	3000 fb^{-1}, 14 TeV	Extrap.
$t \to gc$	1×10^{-5}	ATLAS $qg \to t \to Wb$	300 fb^{-1}, 14 TeV	Extrap.
$t \to gc$	4×10^{-6}	ATLAS $qg \to t \to Wb$	3000 fb^{-1}, 14 TeV	Extrap.
$t \to hq$	2×10^{-3}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	300 fb^{-1}, 14 TeV	Extrap.
$t \to hq$	5×10^{-4}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	3000 fb^{-1}, 14 TeV	Extrap.
$t \to hq$	5×10^{-4}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \gamma\gamma q$	300 fb^{-1}, 14 TeV	Extrap.
$t \to hq$	2×10^{-4}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \gamma\gamma q$	3000 fb^{-1}, 14 TeV	Extrap.

so many possibilities for the large integrated lumi and clean environment of FCCee

Patrizia Azzi's talk

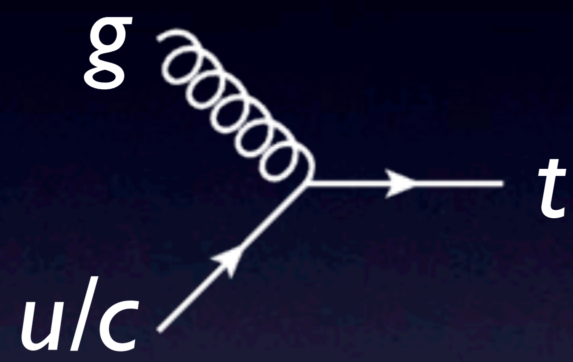
Top-Rare-decay and Direct Top-Production

- Anomalous g-q-t FCNC coupling

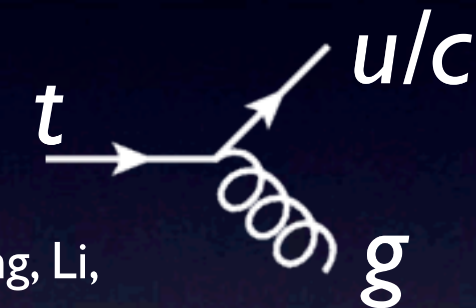
$$\mathcal{L} = g_s \sum_{q=u,c} \frac{\kappa_{tqg}}{\Lambda} \bar{t} \sigma^{\mu\nu} T^a (f_q^L P_L + f_q^R P_R) q G^a_{\mu\nu} + h.c.$$

★ NLO K_F ~1.3-1.5
★ promising at the LHC

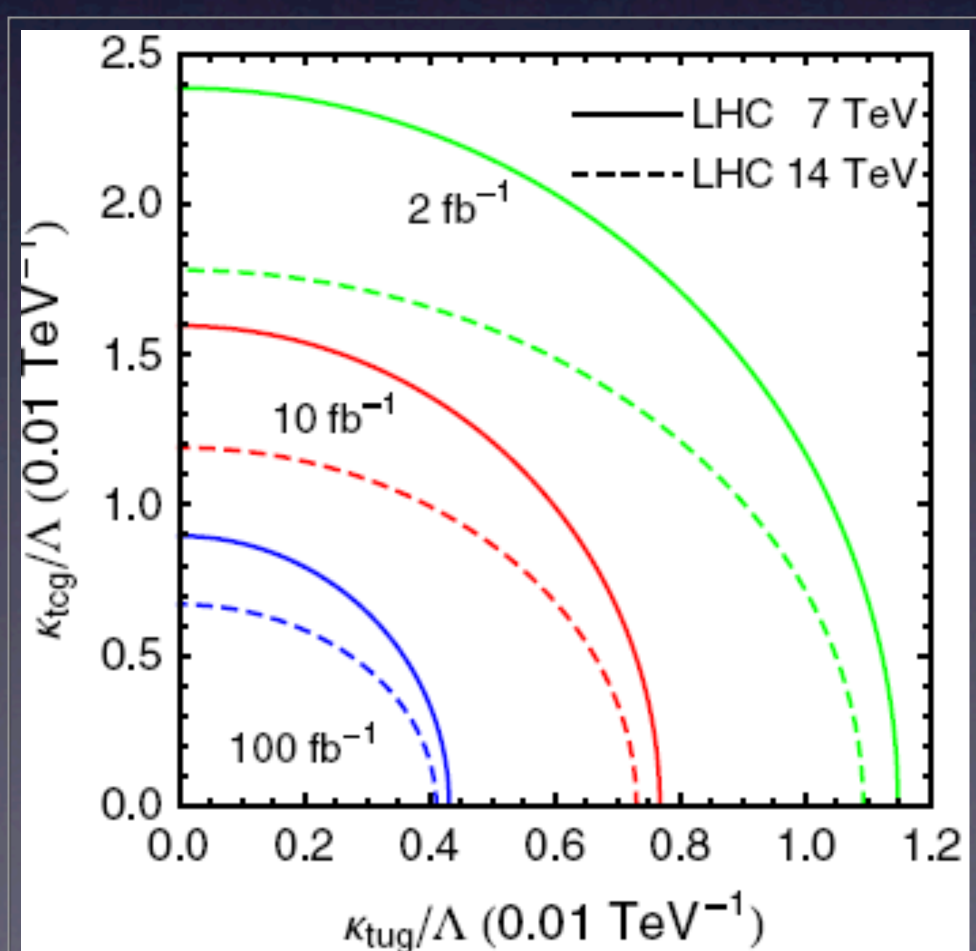
Gao, C. S. Li, Yang, Zhang,
PRL 107 (2011) 092002

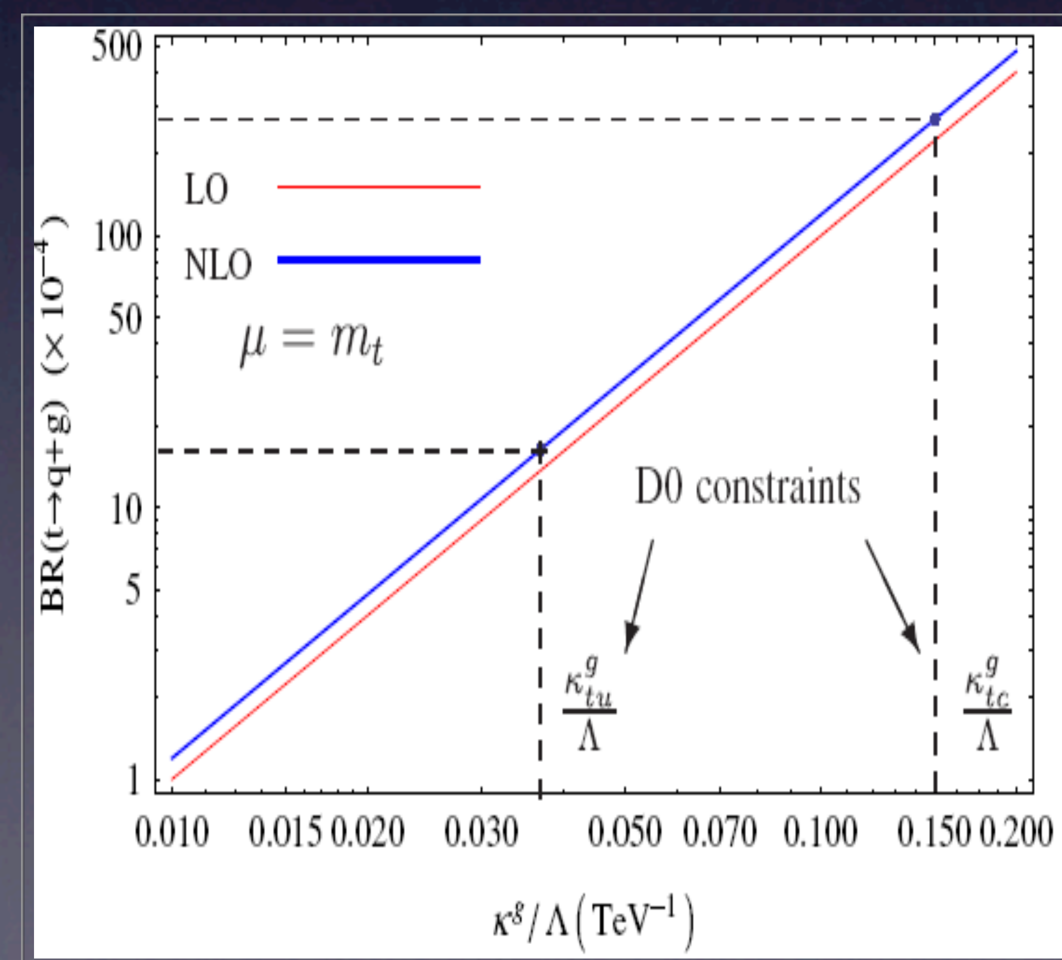


★ NLO K_F ~1.2



Zhang, C. S. Li, Gao, Zhang, Li,
PRL 102 (2009) 072001





Summary

Untested Aspects of the SM

Higgs electroweak couplings

SM Higgs?

Higgs boson self-coupling

Boosted object techniques

Triple-gauge-coupling / Quartic-gauge-coupling

Dim-6 and Dim-8 operators in linear realization

Weak interaction of the 3rd generation quarks

Fully understanding top- and bottom-quark chirality structure of couplings, Vtb=1? ...