Vector-Like Quarks:

NLO QCD corrections and di-Higgs production

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LPTHE

Based On work with
Cacciapaglia, Cai, Carvalho, Deandrea, Flacke, Fuks, Majumder

ERC LHCtheory Workshop
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WHY VECTOR-LIKE QUARKS

✦ What is vector-like quarks ?

✤ Quarks whose left-handed and right-handed components lie in the same representation of SM gauge group

✦ Why are vector-like quarks interesting ?

✤ Vector-like quarks are common predictions of many new physics models (e.g. extra dimension/composite models)

✤ Strong scrutiny for searches performed at the LHC *also see E.Vryonidou's talk on Higgs prod.*

✦ Model independent description of vector-like quarks

VLQ	Charge
T	+2/3
B	-1/3
X	+5/3
Y	-4/3

$$\mathcal{L}_{\rm VLQ} = i\bar{Y}\not{D}Y - m_Y\bar{Y}Y + i\bar{B}\not{D}B - m_B\bar{B}B + i\bar{T}\not{D}T - m_T\bar{T}T + i\bar{X}\not{D}X - m_X\bar{X}X$$

$$- h\left[\bar{B}\left(\hat{\kappa}^B_L P_L + \hat{\kappa}^B_R P_R\right)q_d + \text{h.c.}\right] - h\left[\bar{T}\left(\hat{\kappa}^T_L P_L + \hat{\kappa}^T_R P_R\right)q_u + \text{h.c.}\right] \quad \textbf{VLQ-Higgs}$$

$$+ \frac{g}{2c_W}\left[\bar{B}\not{Z}\left(\tilde{\kappa}^B_L P_L + \tilde{\kappa}^B_R P_R\right)q_d + \text{h.c.}\right] + \frac{g}{2c_W}\left[\bar{T}\not{Z}\left(\tilde{\kappa}^T_L P_L + \tilde{\kappa}^T_R P_R\right)q_u + \text{h.c.}\right] \quad \textbf{VLQ-Z}$$

$$+ \frac{\sqrt{2}g}{2}\left[\bar{Y}\not{W}\left(\kappa^Y_L P_L + \kappa^Y_R P_R\right)q_d + \text{h.c.}\right] + \frac{\sqrt{2}g}{2}\left[\bar{B}\not{W}\left(\kappa^B_L P_L + \kappa^B_R P_R\right)q_u + \text{h.c.}\right]$$

$$+ \frac{\sqrt{2}g}{2}\left[\bar{T}\not{W}\left(\kappa^T_L P_L + \kappa^T_R P_R\right)q_d + \text{h.c.}\right] + \frac{\sqrt{2}g}{2}\left[\bar{X}\not{W}\left(\kappa^X_L P_L + \kappa^X_R P_R\right)q_u + \text{h.c.}\right] \quad \textbf{VLQ-W}$$

CONSTRAINTS

✦ Searches at the LHC and phenomenological constraints

- ✤ Vector-like quark pair-production and single-production impose on the masses of > 750-1500 GeV
- ✤ Cares must be paid to the interpretation of these limits (under simplifying assumptions):
  - ✤ assume 100% branching ratio of VLQ decaying into third-generation SM quarks
  - ✤ Decaying into first two-generation SM quarks are less explored
  - ✤ Sizeable couplings to the first two generations are still allowed only by indirect constraints
- ✤ The couplings are not fully independent **[Buchkremer, Cacciapaglia, Deandrea & Panizzi (NPB'13)]**

$$(\hat{\kappa}^Q_{L,R})_f = \frac{\kappa_Q m_Q}{v}\sqrt{\frac{\zeta^f_{L,R}\,\xi^Q_H}{\Gamma^Q_H}} \qquad (\tilde{\kappa}^Q_{L,R})_f = \kappa_Q\sqrt{\frac{\zeta^f_{L,R}\,\xi^Q_Z}{\Gamma^Q_Z}} \qquad (\kappa^Q_{L,R})_f = \kappa_Q\sqrt{\frac{\zeta^f_{L,R}\,\xi^Q_W}{\Gamma^Q_W}}$$

mixing between VLQ and SM quarks

determine BRs

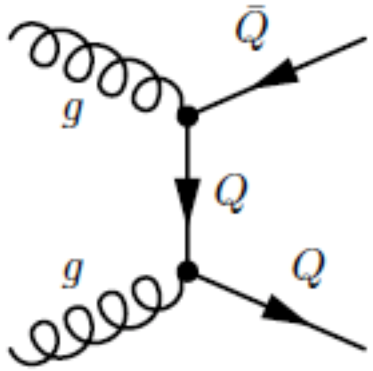
- ✤ Phenomenological constraints (FCNC, LEP data and atomic parity violation)
  - ✤ Sizeable mixing with all three generations are only allowed kappaQ < 1e-2 to 1e-3
  - ✤ The bounds are relaxed to (0.07,0.2,0.1) with one generation mixings
- ✤ It can be applicable to any process in the model, where we exhausted VLQ pair, single VLQ, VLQ+H/Z/W and diboson productions.

NLO QCD CORRECTIONS

Fuks, HSS (EPJC'17)

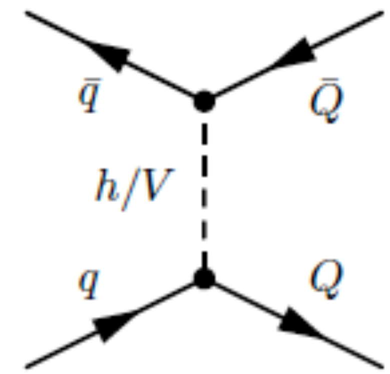
✦ VLQ pair production as an example with MG5aMC

$\mathcal{A}_{\mathrm{QCD}} =$



$\sim \alpha_S$

$\mathcal{A}_{\mathrm{NP}} =$



$\sim \alpha_{\mathrm{NP}}$

$\mathcal{A}_{\mathrm{QCD}} \gg \mathcal{A}_{\mathrm{NP}}$ when $m_Q \sim m_{H/V}$

$\mathcal{A}_{\mathrm{QCD}} < \mathcal{A}_{\mathrm{NP}}$ when $m_Q \gg m_{H/V}$

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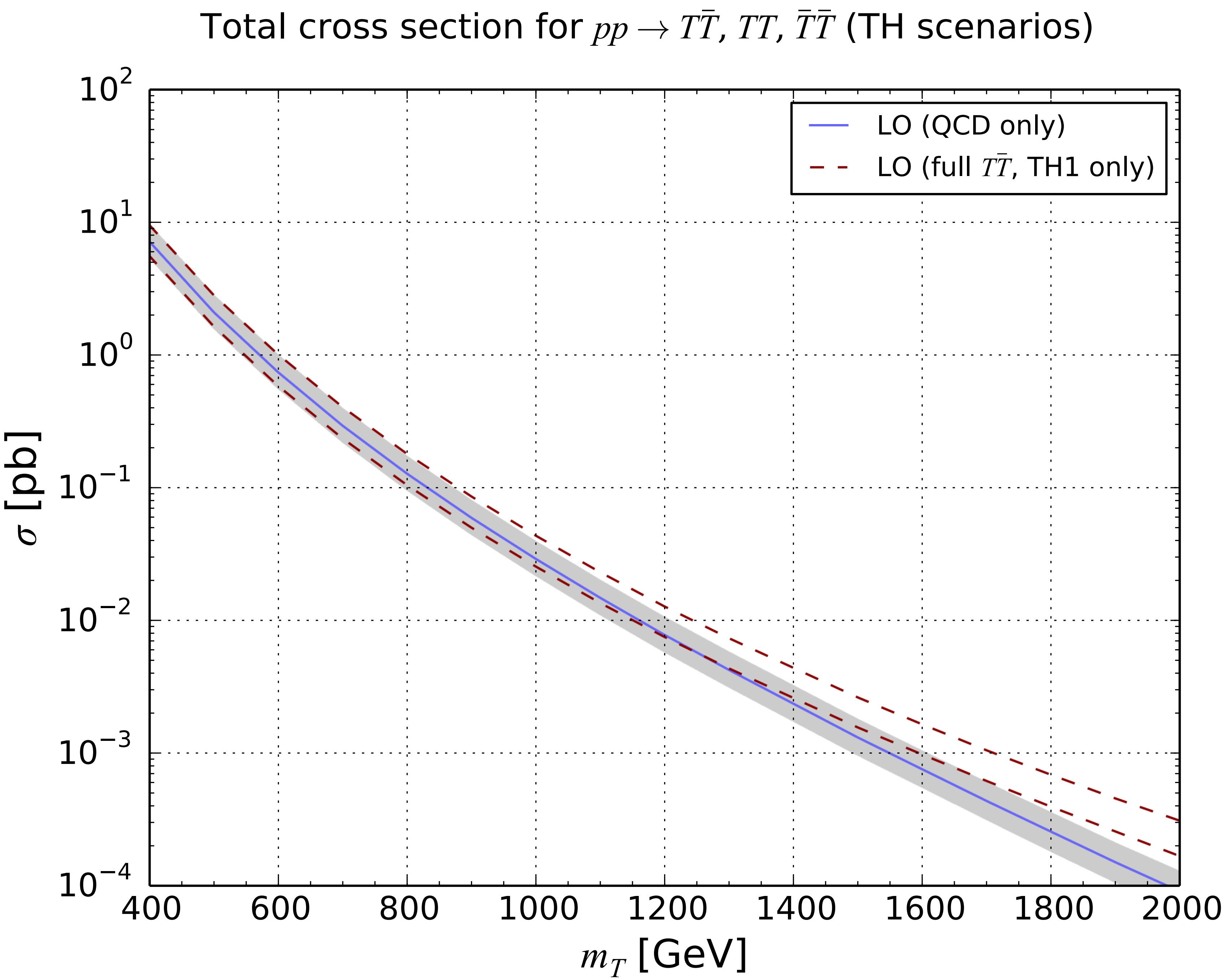

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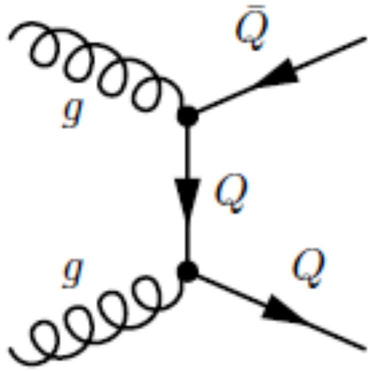
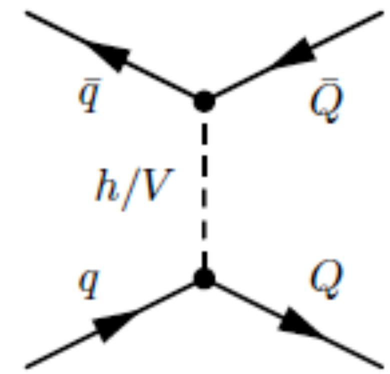
$\mathcal{A}_{\rm QCD} =$ 

$\sim \alpha_S$ $\quad \mathcal{A}_{\rm NP} =$ 

$\sim \alpha_{\rm NP}$

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$$\mathcal{A}_{\rm QCD} < \mathcal{A}_{\rm NP} \quad \text{when} \quad m_Q \gg m_{H/V}$$

LO: $\mathcal{O}(\alpha_S^2)$ $\quad \mathcal{O}(\alpha_S\alpha_{\rm NP})$ $\quad \mathcal{O}(\alpha_{\rm NP}^2)$

NLO QCD $\quad$ NLO QCD $\quad$ NLO QCD

NLO: $\mathcal{O}(\alpha_S^3)$ $\quad \mathcal{O}(\alpha_S^2\alpha_{\rm NP})$ $\quad \mathcal{O}(\alpha_S\alpha_{\rm NP}^2)$ $\quad \mathcal{O}(\alpha_{\rm NP}^3)$

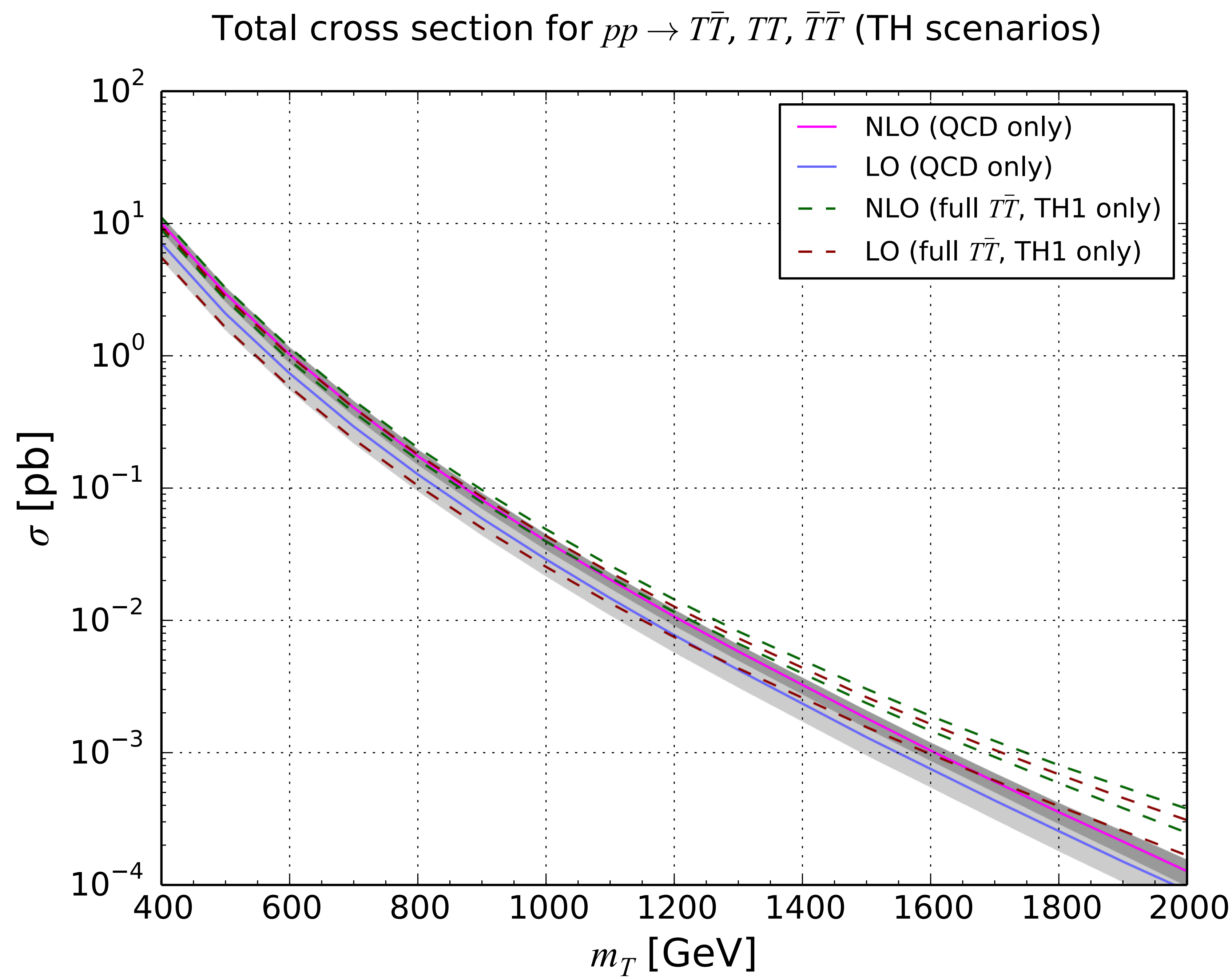
NLO QCD CORRECTIONS

Fuks, HSS (EPJC'17)

- VLQ pair production as an example with MG5aMC

$\mathcal{A}_{\mathrm{QC}}$

$\sim \alpha_{\mathrm{NP}}$



I/V

I/V

LO

NLC

$\alpha^2_{\mathrm{NP}})$

NLO

$\mathcal{O}(\alpha^3_{\mathrm{NP}})$

Friday, March 24, 17

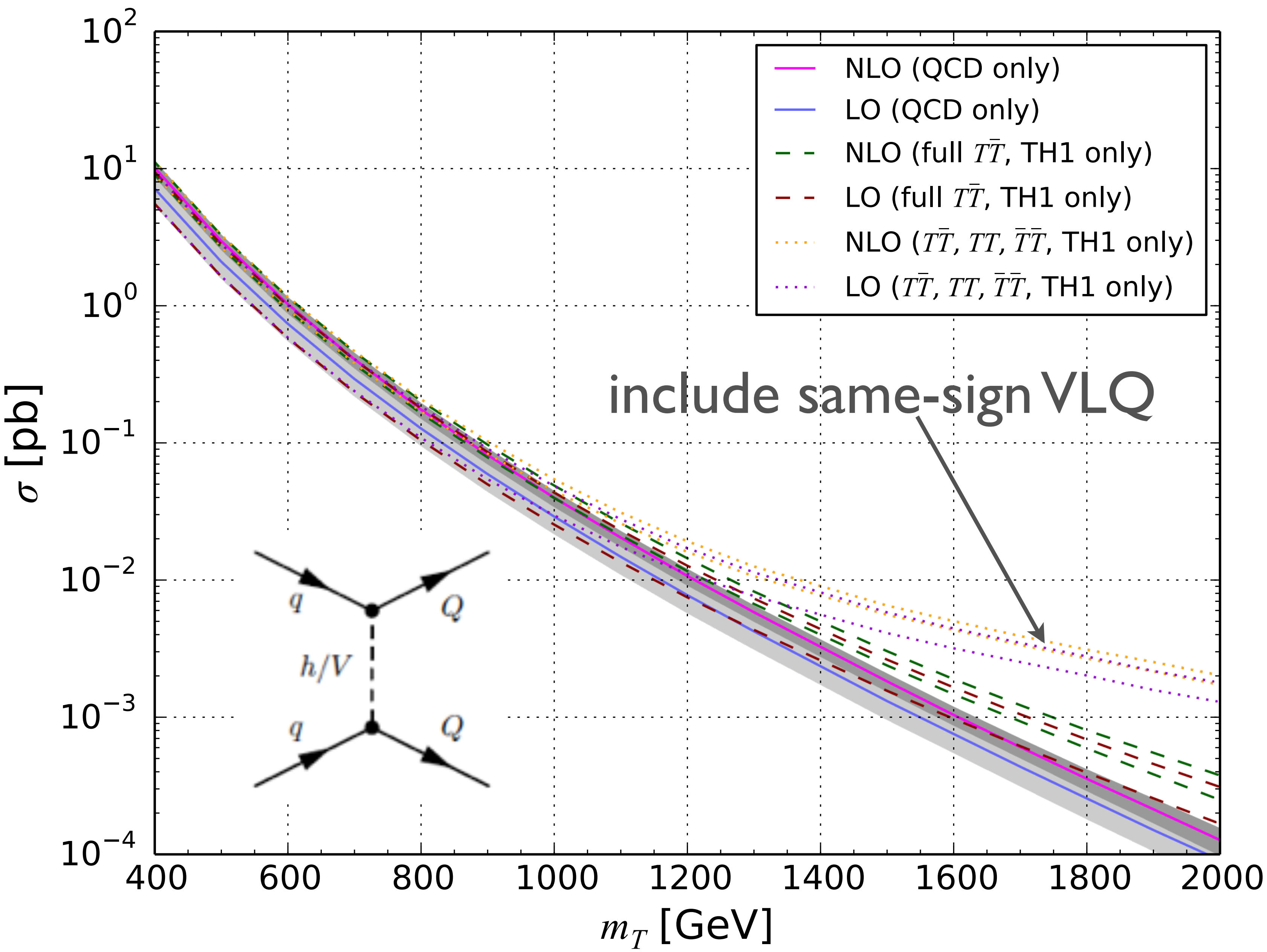
NLO QCD CORRECTIONS

Fuks, HSS (EPJC'17)

✦ VLQ pair production as an example with MG5aMC

Total cross section for $pp \to T\bar{T}$, TT, $\bar{T}\bar{T}$ (TH scenarios)

$\mathcal{A}_{\rm QC}$ $\sim \alpha_{\rm NP}$



$/V$

$/V$

LO

NLC

$\iota^2_{\rm NP})$

NLO

$\mathcal{O}(\alpha^3_{\rm NP})$

NLO QCD CORRECTIONS

Fuks, HSS (EPJC'17)

✦ VLQ pair production as an example with MG5aMC

$\mathcal{A}_{\rm QC}$ $\sim \alpha_{\rm NP}$

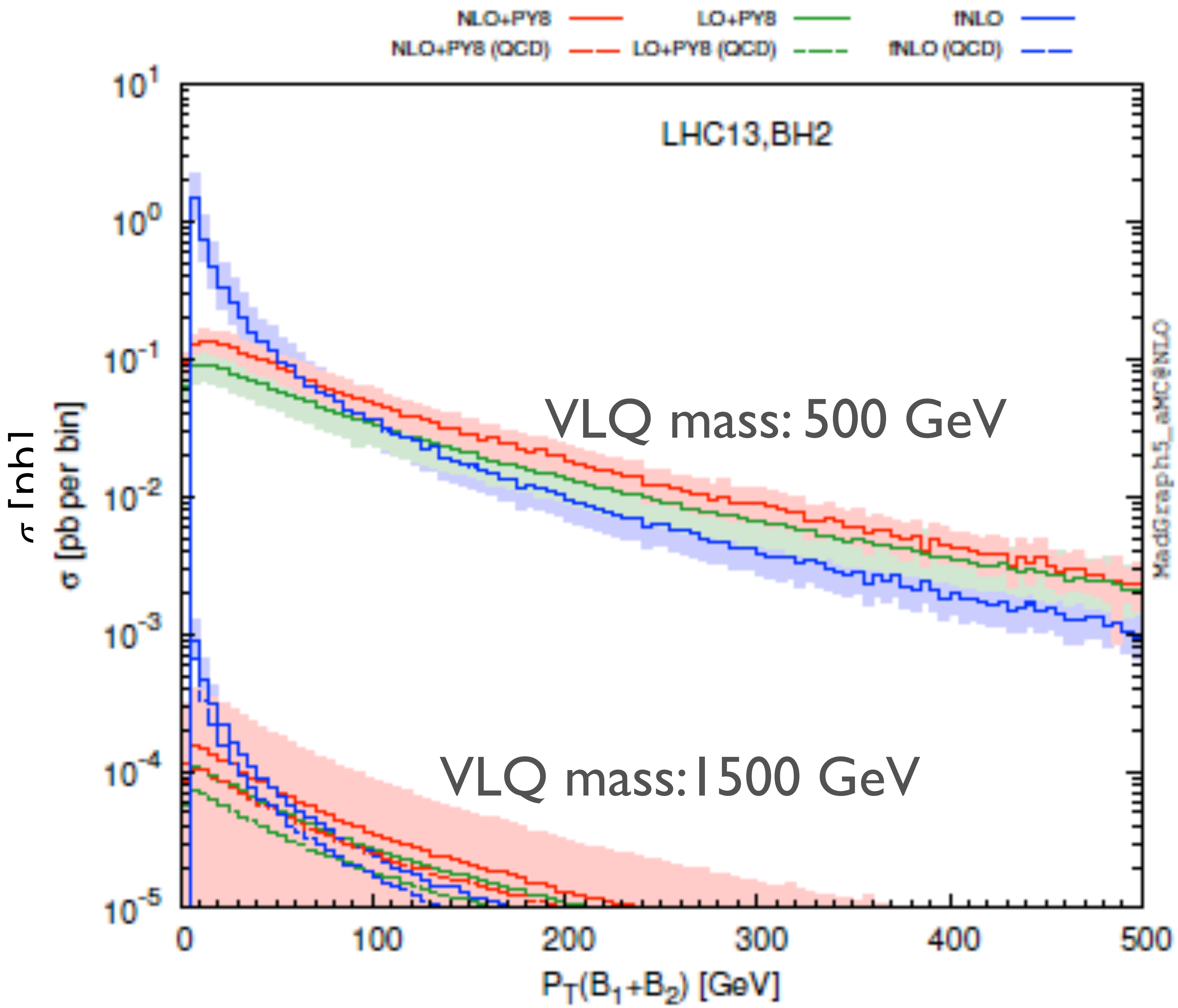
$/V$

$/V$

LO $\alpha^2_{\rm NP})$

NLC

NLO $\mathcal{O}(\alpha^3_{\rm NP})$



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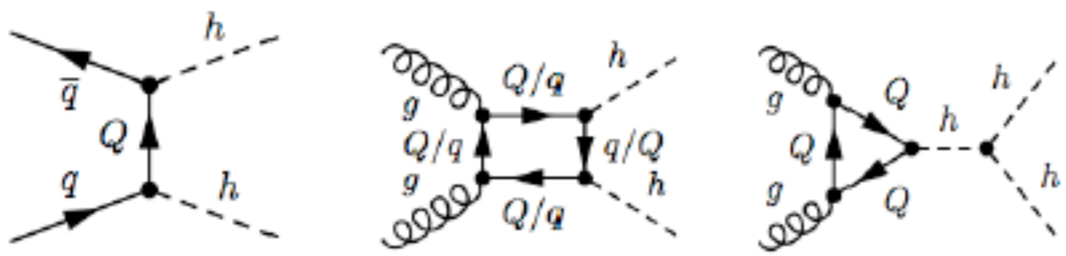
DIHIGGS PRODUCTION

Caccipagalia, Cai, Carvalho, Deandrea, Flacke, Fuks, Majumder, HSS (in prep.)

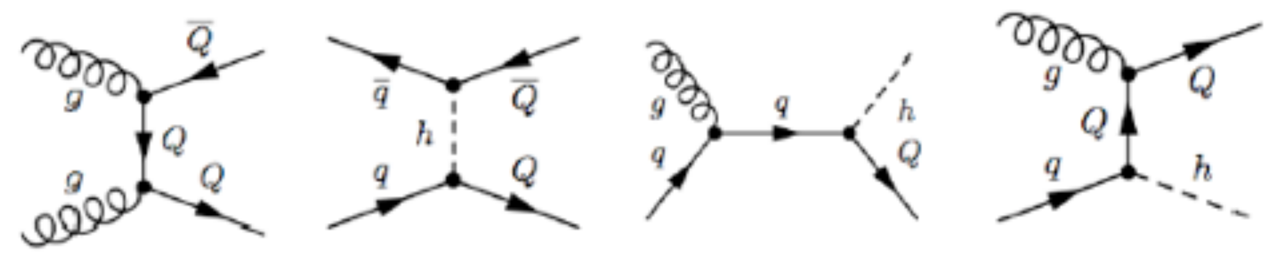
✦ Nonresonance di-Higgs production from VLQ: phenomenology at NLO+Pythia8

see S. Borowka's talk on SM calculations

Direct production

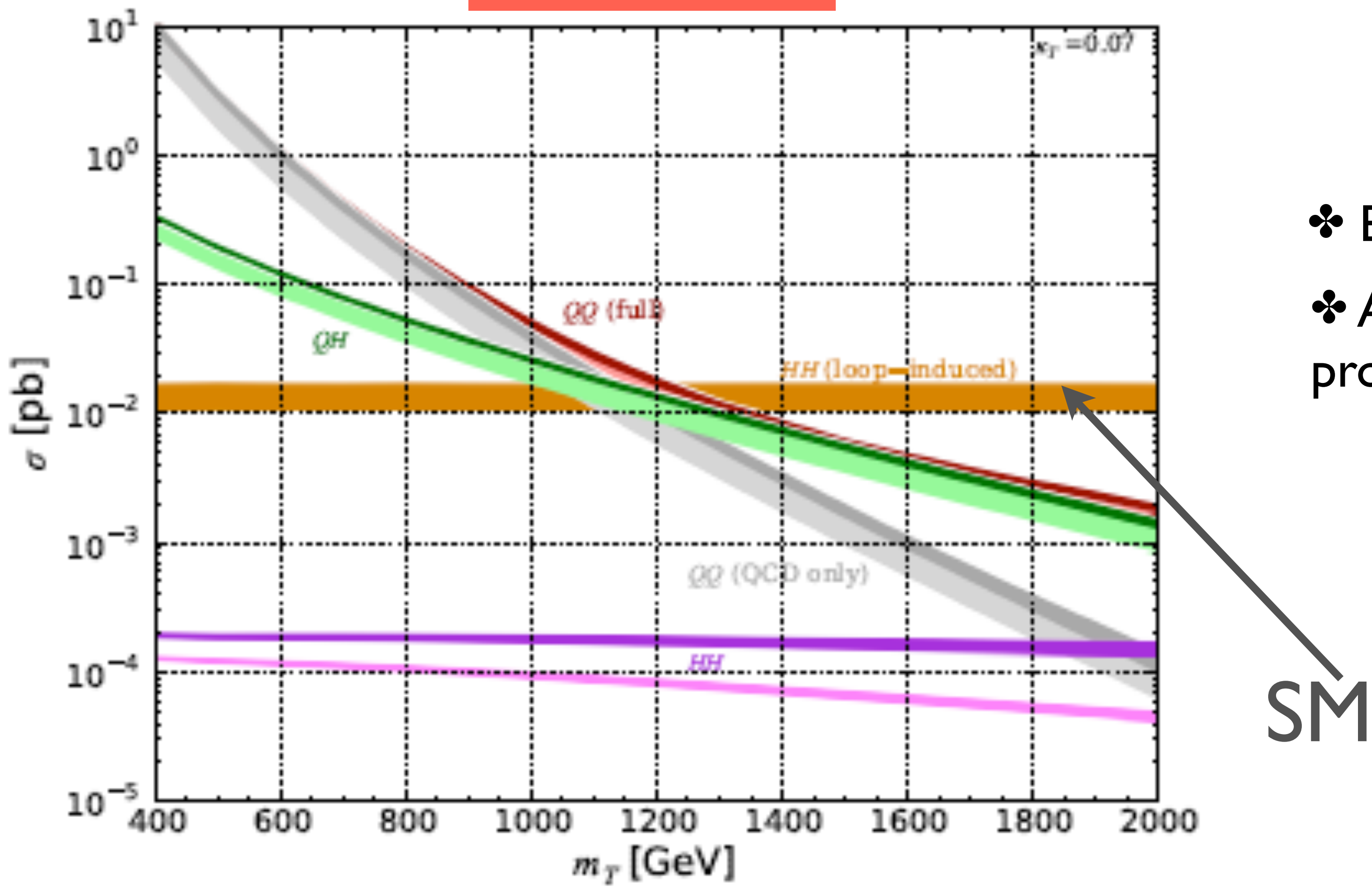


Feeddown production



$$\otimes Q(\bar{Q}) \rightarrow H + q(\bar{q})$$

Non-boosted



Boosted

- ✤ Enhance the total cross section at mass < 1 TeV
- ✤ Above 1.2 TeV, enhance the boosted Higgs production cross section

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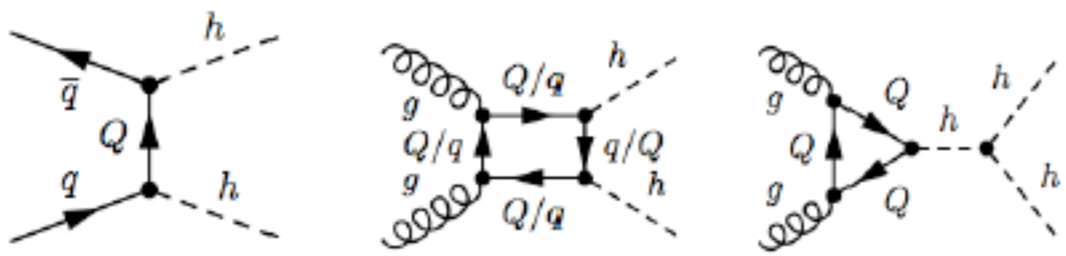

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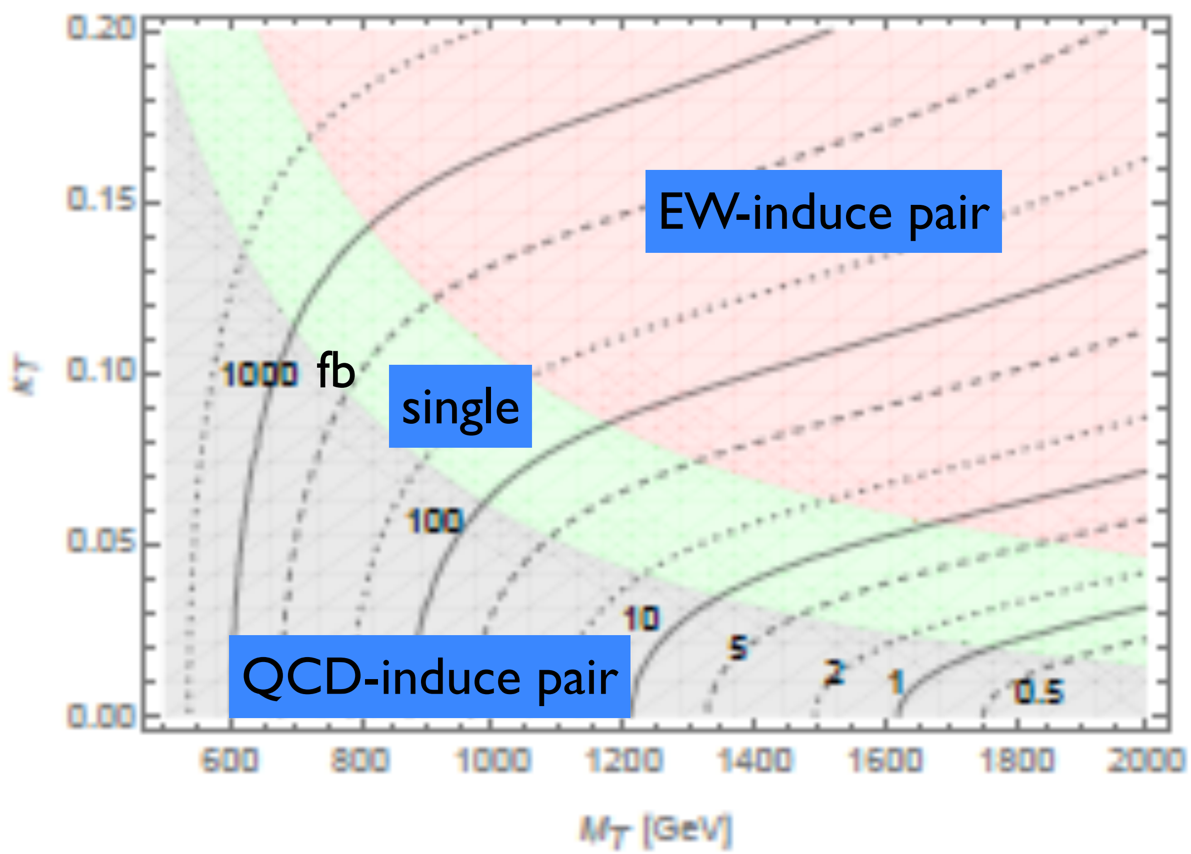

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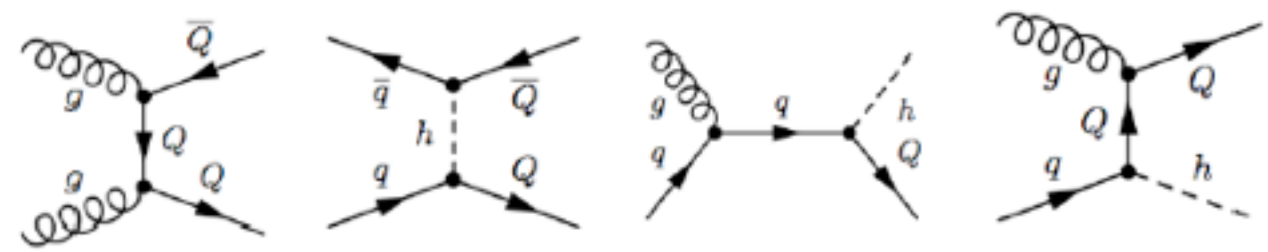

$$\otimes Q(\bar{Q}) \to H + q(\bar{q})$$

Boosted

- ✤ Enhance the total cross section at mass < 1 TeV
- ✤ Above 1.2 TeV, enhance the boosted Higgs production cross section
- ✤ Dominant contributions in (mass, coupling) plane

LHC SEARCHES: SIMULATIONS

Caccipagalia, Cai, Carvalho, Deandrea, Flacke, Fuks, Majumder, HSS (in prep.)

✦ Many LHC searches for di-Higgs production are present:

$H(\to b\bar{b})H(\to b\bar{b})$	ATLAS (PRD'16); CMS-PAS-HIG-16-026, CMS-PAS-HIG-16-002, CMS-PAS-B2G-16-008
$H(\to b\bar{b})H(\to \tau^+\tau^-)$	CMS-PAS-HIG-16-029, CMS-PAS-HIG-16-028
$H(\to b\bar{b})H(\to \gamma\gamma)$	ATLAS-CONF-2016-004, CMS-PAS-HIG-16-032
$H(\to b\bar{b})H(\to W^+W^-)$	CMS-PAS-HIG-16-024
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- Categories of analysis:
  - Resolved analyses

    resolved jets: $R=0.4,\ \text{anti k}_\text{T}, p_T^j > 20\ \text{GeV}, |\eta^j| < 2.5$

    b-jet tagging: efficiency from CMS map (1211.4462) $\begin{cases} p_T^b > 40\ \text{GeV}\ \ (\text{ATLAS}) \\ p_T^b > 30\ \text{GeV}\ \ (\text{CMS}) \end{cases}$

    requires at least 4 resolved b-tagged jets and two pairs $\Delta R(b,b) < 1.5$

    + other CMS and ATLAS selection rules to select Higgs candidate
  - Boosted analyses

    N-subjetiness tau21 to tag a Higgs jet
    b-tagging and b-tagged fat jet = two b-tagged subjets
    + other CMS and ATLAS selection rules to select Higgs candidate

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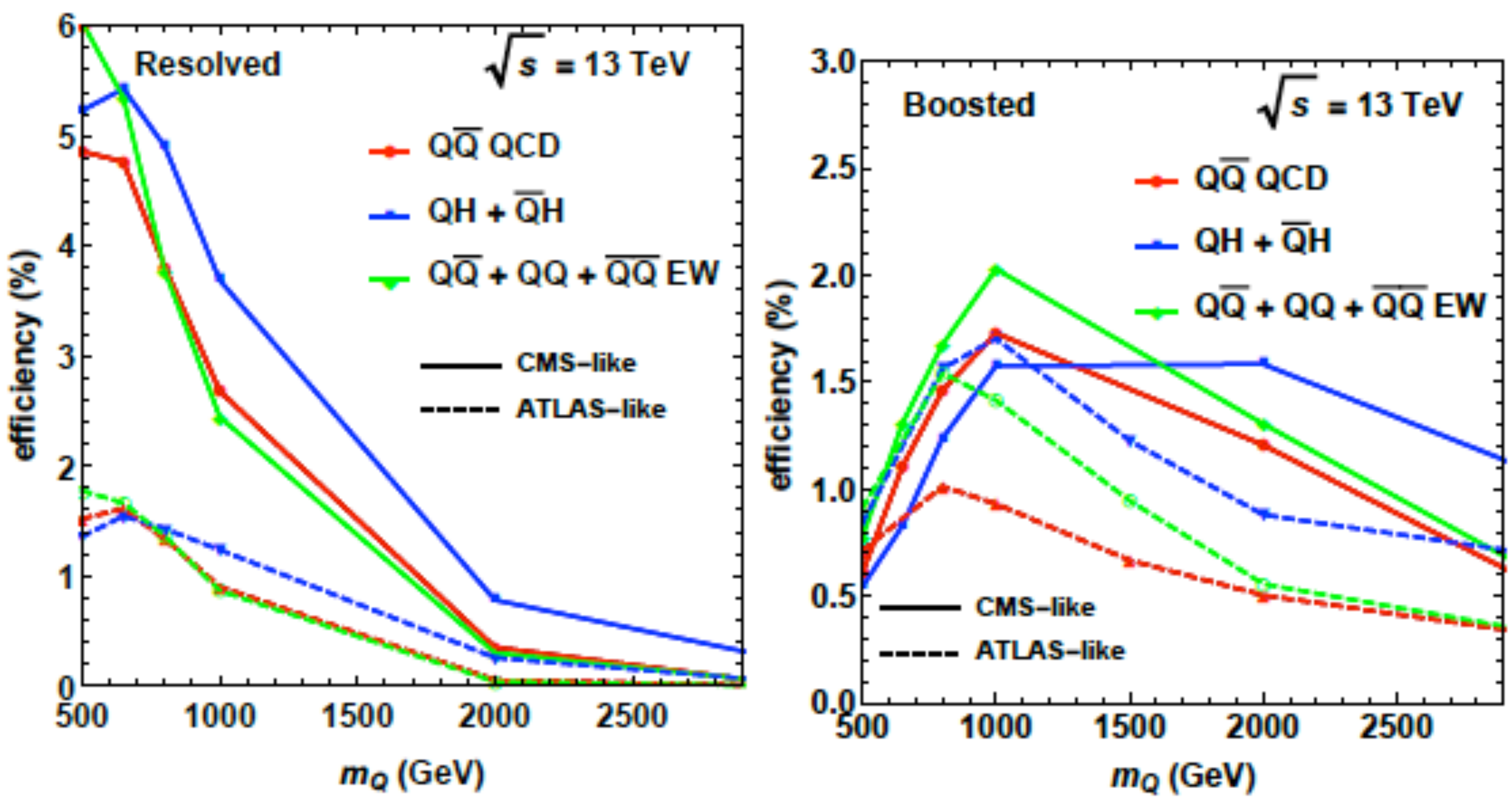

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✦ The number of events at 13 TeV (kappaT=0.05)

Recast	Int. lumi (fb^{-1})	Events				
		Data	Signal, M_Q in GeV			
			500	800	1000	2000
ATLAS-like resolved [32]	3.2	46	140	9.92	5.84	-
ATLAS-like boosted [32]	3.2	20	68.6	6.91	1.92	0.029
CMS-like resolved [34]	2.3	797	415	25.3	5.84	-
CMS-like boosted [35]	2.7	15	52.3	8.88	3.28	0.123

help to improve S/B

✦ Unlike the resonance di-Higgs production, we have actually three configurations:

- ✦ Resolved analyses
  - ✤ Four well-separated b-jets are reconstructed (small radius parameter)
  - ✤ Compatible with the decay of two Higgs bosons
- ✦ Boosted analyses
  - ✤ Two well-separated fat b-jets are reconstructed (large radius parameter)
  - ✤ Compatible with the boosted decays of two Higgs bosons
- ✦ Semi-boosted analyses
  - ✤ One fat b-jet is reconstructed (large radius), as well as two extra b-jets (small radius)
  - ✤ Compatible with the decays of one boosted Higgs boson, and one non-boosted one

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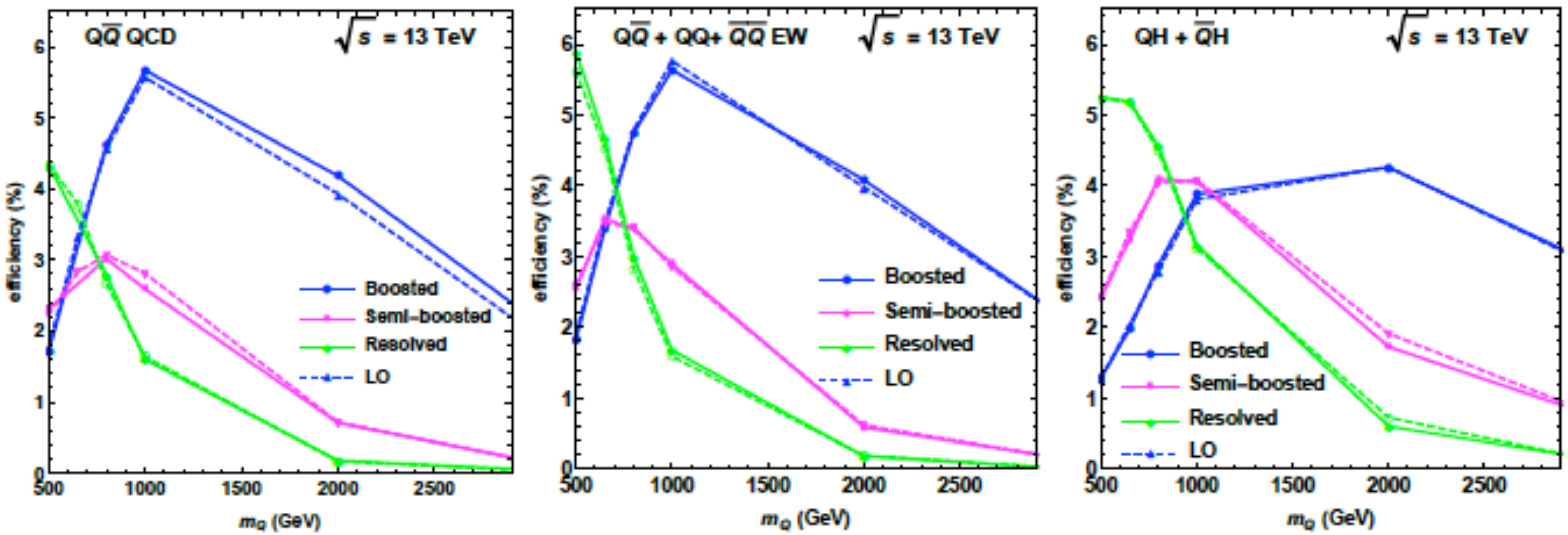
new

LHC SEARCHES: SIMULATIONS

✦ Efficiencies of analyses inspired by typical ATLAS/CMS 13 TeV searches



- Boosted analyses are important when mass > 1 TeV
  - Same selection efficiencies regardless of the production mode
  - Region where EW production and single production dominant
- Semi-boosted analyses may help in the intermediate region, especially for single prod.
- Efficiency of resolved analyses is improved at low mass by EW pair production
- NLO QCD effects are mild (largest in QCD pair production)

✦ Bottom line: there is an opportunity of improvement with respect to the present bounds on VLQ diHiggs channels

THANK YOU FOR YOUR ATTENTION !

Backup Slides

CONCRETE EXAMPLES

✦A first model example:

Atre, Chala and Santiago (JHEP'13);
Atre, Carena, Han and Santiago et al. (PRD'09, JHEP'11);

$$-\mathcal{L} \supset M_1\ \bar{U}_{1L}U_{1R} + M_2\ \bar{U}_{2L}U_{2R} + \left(1+\frac{h}{v_{\rm SM}}\right)\left(y_1\bar{U}_{1L}+y_2\bar{U}_{2L}\right)\tilde{u}_R$$

	$U(1)_Y$	$SU(2)_W$
Q_1	1/3	$\begin{pmatrix} U_1 \\ D_1 \end{pmatrix}$
Q_2	7/3	$\begin{pmatrix} X_2 \\ U_2 \end{pmatrix}$

✤ A symmetric case is motivated by relaxing experimental constraints

$M_1 = M_2 = M$ and $y_1 = y_2 = y$

✤ The new physics contributions will cancel in Zqq coupling and in EW precision obs.

✤ The mass eigenstates are:

states	mass
T	$\frac{M}{\cos\phi_R}$
T'	M
u	0

$$\tan\phi_R = \frac{\sqrt{2}y}{M}$$

✦A second model example: Composite Higgs with partial compositeness and extended custodial sym.

Agashe, Contino, Da Rold and Pomarol (PLB'06)