“粒子物理前沿卓越创新中心”

考评答辩

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一.
- W/Z physics

二.
- Higgs Physics

三.
- Bc meson and doubly heavy baryon

四.
- New Physics

1. W/Z physics

WWW	(PRD 95, 073005, 2017)
ZZγ	(JPG 44, 085002, 2017), (EPJC 76, 76, 2016)
ZZjet	(PRD 94, 013011, 2016)
ZZZ	(JPG 43, 115001, 2016)
Wwjet	(PRD 92, 033005, 2015)
WZZ	(JHEP 10, 186, 2015)
WWγ	(EPJC 74, 3166, 2014)
ZZW	(MPLA 31, 1450153, 2014)
Z γ γ	(EPJC 74, 2739, 2014)

LHC: Precision measurements will be possible in Run2

ZZ+jet: **A useful background process for Higgs-boson production.**

ZZ+ γ: **Help for the determination of quartic gauge boson coupling.**

Les Houches 2013: Physics at TeV Colliders
Standard Model Working Group Report

$VV'V''$	$d\sigma$(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
$\gamma\gamma$	$d\sigma$ @ NNLO QCD + NLO EW	q_T resummation at NNLL matched to NNLO

Wishlist part 3 – Electroweak Gauge Bosons (V = W, Z)

Les Houches 2015: Physics at TeV Colliders Standard Model Working Group Report

High-precision prediction !

$pp \to V + j$	$d\sigma$	N^2LO_{QCD}	$d\sigma$	$N^2LO_{QCD} + NLO_{EW}$+ decays
$pp \to V + 2j$	$d\sigma$ $d\sigma$	NLO_{QCD}+ decays NLO_{EW}+ decays	$d\sigma$	$N^2LO_{QCD} + NLO_{EW}$+ decays
$pp \to VV' + 1, 2j$	$d\sigma$ $d\sigma$	NLO_{QCD}+ decays NLO_{EW}	$d\sigma$	NLO_{QCD}+ NLO_{EW}+ decays
$pp \to VV'V''$	$d\sigma$ $d\sigma$	NLO_{QCD} NLO_{EW}	$d\sigma$	NLO_{QCD}+ NLO_{EW}+ decays
$pp \to \gamma\gamma$	$d\sigma$	N^2LO_{QCD}	$d\sigma$	$N^2LO_{QCD} + NLO_{EW}$
$pp \to \gamma\gamma + j$	$d\sigma$	NLO_{QCD}	$d\sigma$	$N^2LO_{QCD} + NLO_{EW}$

Precision wish list: vector boson final states. $V = W, Z$ and $V', V'' = W, Z, \gamma$.

- Corrections of NLO QCD could be large (typically at $\mathcal{O}(\mathbf{10\%})$) !
- Necessary to reduce the scale dependence !

$\mathcal{O}(\alpha_{\rm ew}) \sim \mathcal{O}(\alpha_s^2)$

The **NLO EW** correction becomes mandatory !

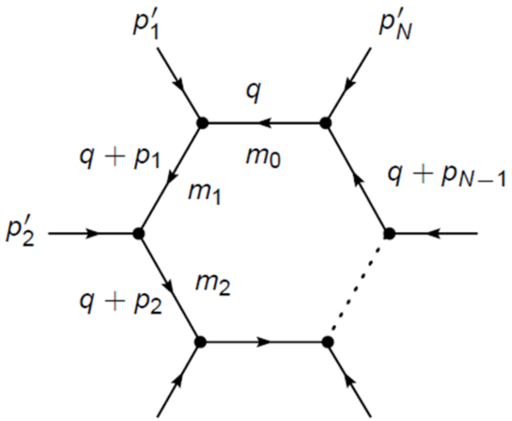
Integrated cross section:

$$\sigma^{LO}(pp\to ZZ + jet/\gamma)=\sum_{a,b}\int d\,x_1 \mathrm{d}x_2\, f_{a/p}(x_1) f_{b/p}(x_2)\hat{\sigma}^{LO}_{ab\to ZZ+jet/\gamma}$$

1. Phase space

Loop amplitudes tensor reduction:

$$T^{N}_{\mu_1\ldots\mu_M} = \frac{(2\pi\mu)^{4-D}}{i\pi^2}\int d^Dq\,\frac{q_{\mu_1}\cdots q_{\mu_M}}{D_1\cdots D_{N-1}} \quad \textbf{with } D_i = \left[(q+p_i)^2 - m_i^2\right]$$



N = 5: Reduced to 4-point integrals based on approach raised by Denner- Dittmaier.

N$\leqslant$4: Standered PV dimensional tensor reduction.

$$F^{N}_{j_1\ldots j_M} \sim \frac{N(p,m)}{(detG_N)^M}$$ → 0 : **Numerical Instability !**

$$G_N = \begin{pmatrix} 2p_1p_1 & \cdots & 2p_1p_{N-1} \\ \vdots & \ddots & \vdots \\ 2p_{N-1}p_1 & \cdots & 2p_{N-1}p_{N-1} \end{pmatrix}$$

In-house improved package

$$\frac{\det(G_3)}{(2p^2_{max})^3} < 10^{-5}?$$

YES, Quadruple arithmetic

NO, Double arithmetic

2. IR singularity

I. Two cutoff space slicing method(TCPSS)

soft region: $E_\gamma \leq \delta_s\sqrt{s}/2$ Soft IR poles exactly canceled with $d\sigma_{vir}$

hard region: $E_\gamma > \delta_s\sqrt{s}/2$

- **hard collinear region**: $\cos\theta_{\gamma q} \leq 1-\delta_c$
  canceled with $d\sigma_{vir}$ with PDFs redefiniton $d\sigma_{pdf}$.
- **hard non-collinear region**: $\cos\theta_{\gamma q} > 1-\delta_c$
  IR finite

☺ Clear physics picture
☹ Large number cancellation

II. Dipole subtraction method

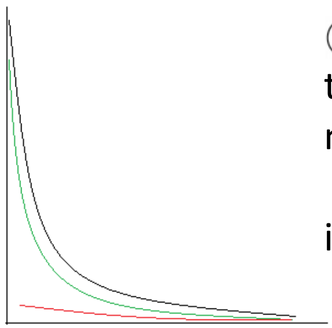
$$\sigma_{NLO} = \sigma_{LO} + \int_m \left[d\sigma_{virt} + \int_1 \boldsymbol{d\sigma_{dipole}}\right] + \int_{m+1} [d\sigma_{real} - \boldsymbol{d\sigma_{dipole}}]$$

IR divergence canceled

approximates the divergent behavior of $d\sigma_{real}$ in all soft/collinear regions

The dipole terms are only needed in the singular region

Parameter $\boldsymbol{\alpha}$:distinct regions neighboring a singularity and regions without need of a subtraction



☹ Mapping of momentum between the dipole terms and real emission matrix
☺ Higher stability of numerical integration

3. Fine structure constant scheme

$$\alpha(0) \rightarrow \alpha_{G_\mu} = \frac{\sqrt{2}}{\pi} G_\mu M_W^2 \sin^2\theta_W \,, \quad \delta z_e \rightarrow \delta z_e - \frac{1}{2}\Delta r$$

for collinear photon emission

$\alpha_{G_\mu} = \alpha_0(1 + \Delta r) + \Delta\alpha^3$

absorb high order universal effects due to Δr

	LO	NLO QCD	NLO EW
$pp \rightarrow ZZ + jet$	$\alpha_{G_\mu}^2 \alpha_s$	$\alpha_{G_\mu}^2 \alpha_s{}^2$	$\alpha_{G_\mu}^3 \alpha_s$
$pp \rightarrow ZZ + \gamma$	$\alpha_{G_\mu}^2 \alpha_0$	$\alpha_s \alpha_{G_\mu}^2 \alpha_0$	$\alpha_{G_\mu}^3 \alpha_0$

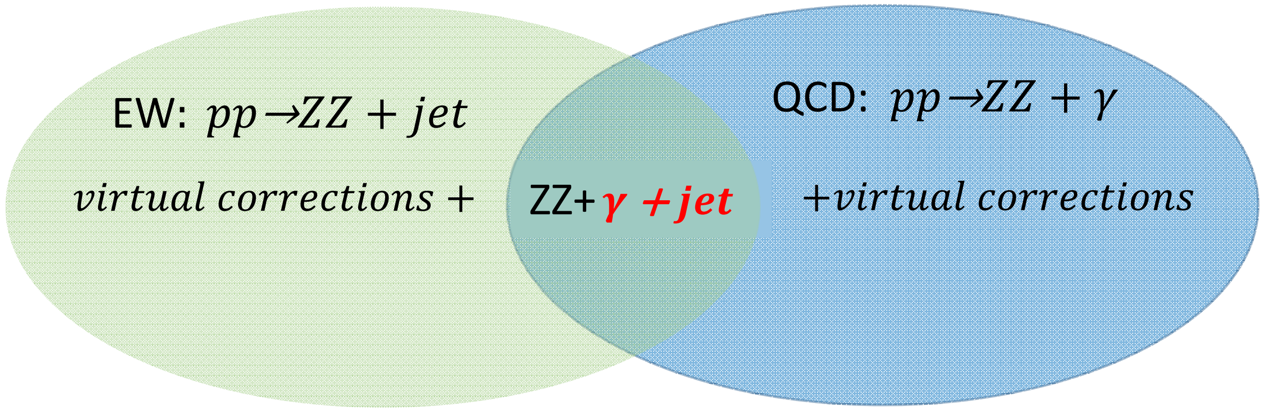
4. Event identification

QCD emission

$pp \to ZZ + jet \; + jet$ $\qquad$ $pp \to ZZ + \boldsymbol{\gamma} \; \boldsymbol{+ jet}$

EW emission

$pp \to ZZ + \boldsymbol{jet} \; \boldsymbol{+ \gamma}$ $\qquad$ $pp \to ZZ + \gamma + \gamma$



ZZ+ jet ? $\qquad$ ZZ+ γ ?

Method A:

$$p_{T,jet} > \chi(\delta), \qquad \chi(\delta)=E_{T,\gamma}\, \epsilon_\gamma \left(\frac{1-\cos(\delta)}{1-\cos(\delta_0)}\right)^n$$

S. Frixione, Phys. Lett. B 429 396 (1998)

Method B:

$$\mathcal{D}_{q\to\gamma}(z_\gamma) = -\frac{Q_q^2\alpha}{2\pi}\frac{1}{\epsilon}\frac{1}{\Gamma(1-\epsilon)}\left(\frac{4\pi\mu_r^2}{\delta_c\hat{s}}\right)^\epsilon [z_\gamma(1-z_\gamma)]^{-\epsilon}[P_{\gamma q}(z_\gamma)-\epsilon z_\gamma] + D^{\text{bare}}_{q\to\gamma}(z_\gamma).$$

$$D^{\text{bare}}_{q\to\gamma}(z_\gamma) = \frac{Q_q^2\alpha}{2\pi}\frac{1}{\epsilon}\frac{1}{\Gamma(1-\epsilon)}\left(\frac{4\pi\mu_r^2}{\mu_f^2}\right)^\epsilon P_{\gamma q}(z_\gamma) + D_{q\to\gamma}(z_\gamma, \mu_f)$$

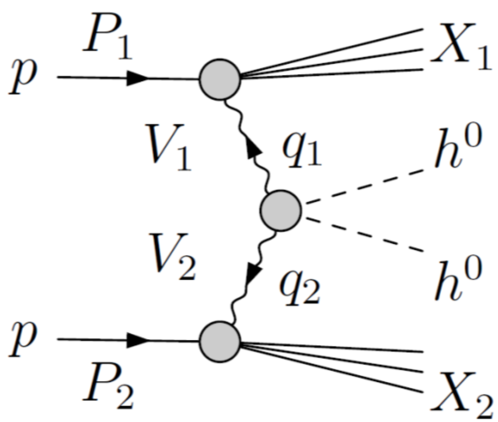
$$\frac{E_{jet}}{E_{jet}+E_\gamma} > 0.7$$

E.W.N. Glover and A.G. Morgan, Z. Phys. C 62. 311(1994)

2. Higgs Physics

VBF Higgs pair (PRD 96, 055006, 2017) (PRD 89, 075011, 2014) (PRD 89, 073001, 2014)
HZ in LHT at NLO+NLL accuracy (PRD 94, 074020, 2016)
HH in RS (PRD 92, 116005, 2015)
ttH (PLB 738, 1, 2014)
H5h in GM (submitted)

- Higgs production channel !
- Higgs self coupling !



Method A: Structure function

Method A: Effective theory

Structure function :

$$\begin{aligned} F_i^Z(x,Q^2) &= 2f_i(x)\int_0^1 dy \int_0^1 dz\delta(x-yz)\sum_{j=1}^{n_f}(v_j^2+a_j^2) \\ &\quad \times\Big[q^+_{\mathrm{ns},j}(y,\mu_f)C^+_{i,\mathrm{ns}}(z,Q,\mu_r,\mu_f)+q_{\mathrm{s}}(y,\mu_f)C_{i,\mathrm{q}}(z,Q,\mu_r,\mu_f)+g(y,\mu_f)C_{i,\mathrm{g}}(z,Q,\mu_r,\mu_f)\Big], \\ F_3^Z(x,Q^2) &= 2f_3(x)\int_0^1 dy \int_0^1 dz\delta(x-yz)\sum_{j=1}^{n_f}2v_j a_j \\ &\quad \times\Big[q^-_{\mathrm{ns},j}(y,\mu_f)C^-_{3,\mathrm{ns}}(z,Q,\mu_r,\mu_f)+q^{\mathrm{v}}_{\mathrm{ns}}(y,\mu_f)C^{\mathrm{v}}_{3,\mathrm{ns}}(z,Q,\mu_r,\mu_f)\Big], \end{aligned}$$

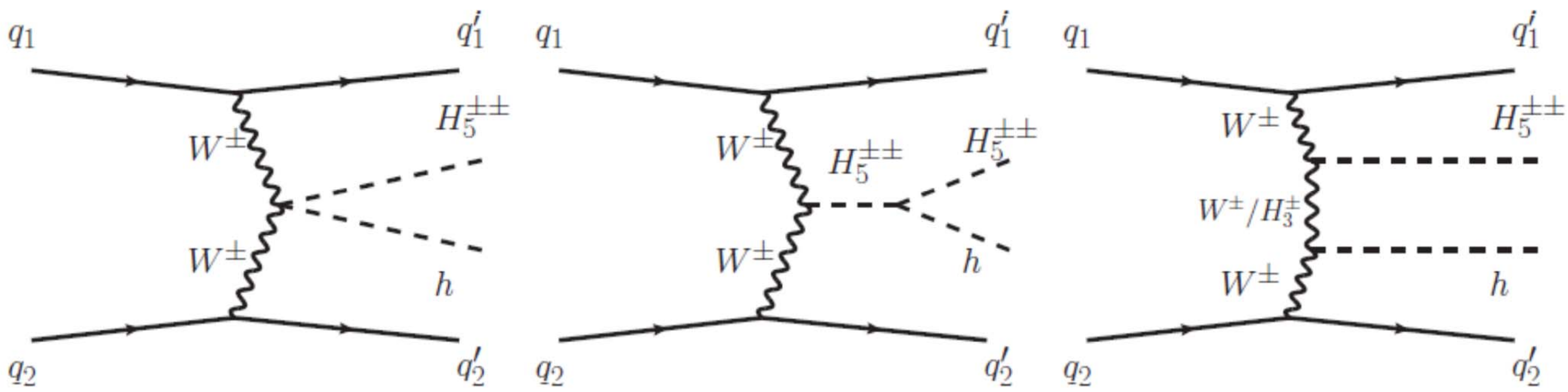
$$
\begin{aligned}
C_{i,\mathrm{ns}}^{\pm} &= \delta(1-x) + a_s\Big[c_{i,\mathrm{ns}}^{(1),\pm} + L_M P_{\mathrm{ns}}^{(0),\pm}\Big] \\
&+ a_s^2\Big[c_{i,\mathrm{ns}}^{(2),\pm} + L_M\Big(P_{\mathrm{ns}}^{(1),\pm} + c_{i,\mathrm{ns}}^{(1),\pm}\otimes(P_{\mathrm{ns}}^{(0),\pm}-\beta_0)\Big) + L_M^2\Big(\frac{1}{2}P_{\mathrm{ns}}^{(0),\pm}\otimes(P_{\mathrm{ns}}^{(0),\pm}-\beta_0)\Big) \\
&+ \beta_0 L_R\Big(c_{i,\mathrm{ns}}^{(1),\pm} + L_M P_{\mathrm{ns}}^{(0),\pm}\Big)\Big], \qquad (i=1,2,3),
\end{aligned}
$$

$$
\begin{aligned}
C_{i,\mathrm{q}} &= \delta(1-x) + a_s\Big[c_{i,\mathrm{q}}^{(1)} + L_M P_{\mathrm{qq}}^{(0)}\Big] \\
&+ a_s^2\Big[c_{i,\mathrm{q}}^{(2)} + L_M\Big(P_{\mathrm{qq}}^{(1)} + c_{i,\mathrm{q}}^{(1)}\otimes(P_{\mathrm{qq}}^{(0)}-\beta_0) + c_{i,\mathrm{g}}^{(1)}\otimes P_{\mathrm{gq}}^{(0)}\Big) \\
&+ L_M^2\Big(\frac{1}{2}P_{\mathrm{qq}}^{(0)}\otimes(P_{\mathrm{qq}}^{(0)}-\beta_0) + \frac{1}{2}P_{\mathrm{qg}}^{(0)}\otimes P_{\mathrm{gq}}^{(0)}\Big) \\
&+ \beta_0 L_R\Big(c_{i,\mathrm{q}}^{(1)} + L_M P_{\mathrm{qq}}^{(0)}\Big)\Big],
\end{aligned}
$$

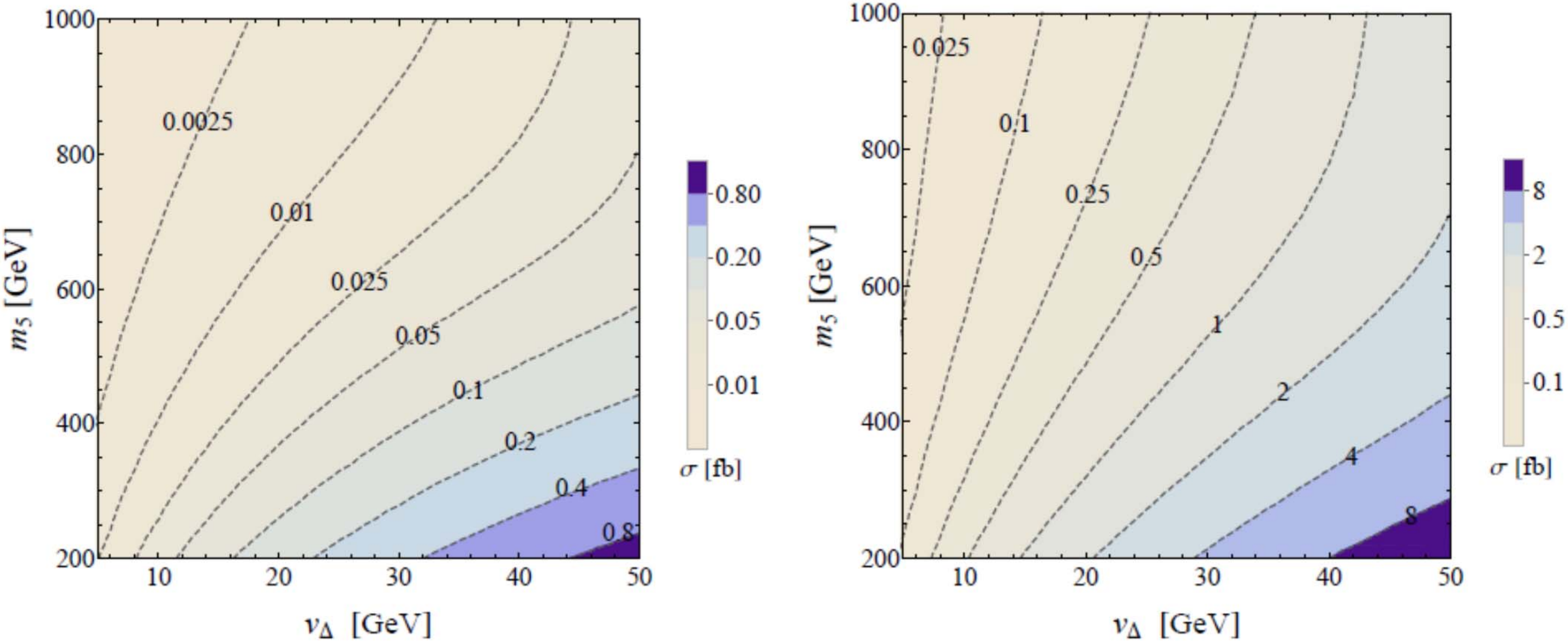
Wilson coefficients can be determined by the PDFs !

GM model: Higgs real triplet, complex triplet, doublet

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^{+} \\ -\phi^{+*} & \phi^{0} \end{pmatrix}, \qquad \Delta = \begin{pmatrix} \chi^{0*} & \xi^{+} & \chi^{++} \\ -\chi^{+*} & \xi^{0} & \chi^{+} \\ \chi^{++*} & -\xi^{+*} & \chi^{0} \end{pmatrix}$$



Cross section :



K factor :

benchmark point	A	B	C	D
(m_5, v_Δ) (GeV)	$(200, 24)$	$(200, 17)$	$(300, 24)$	$(300, 17)$

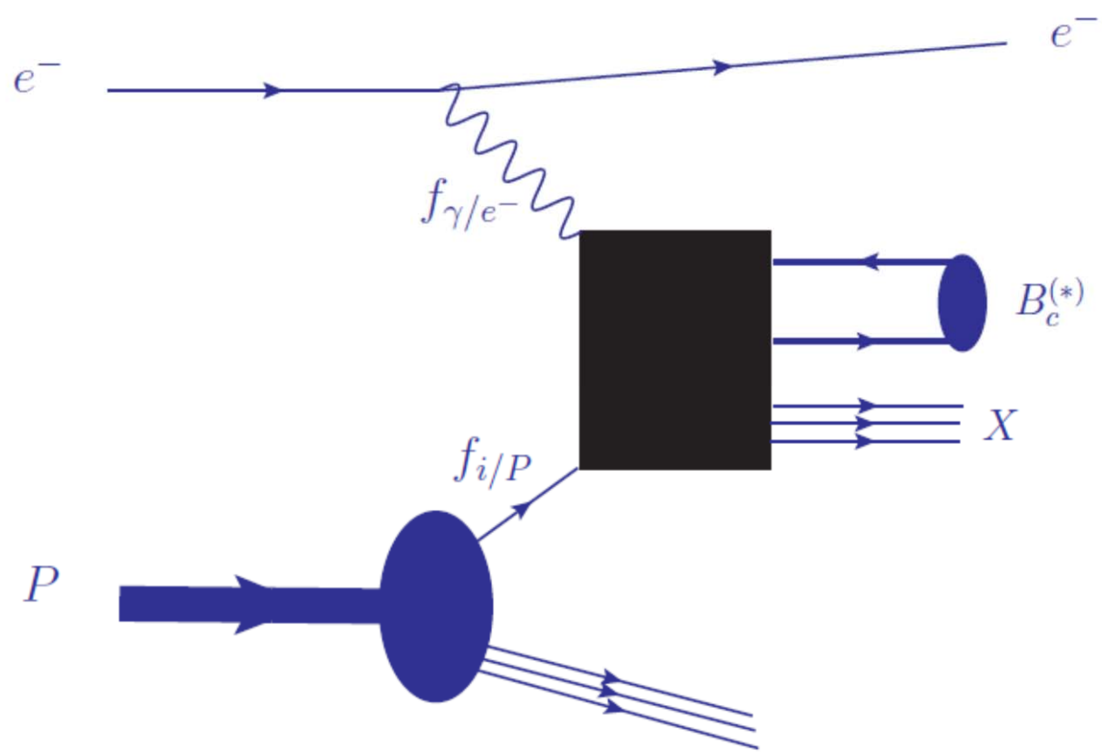
benchmark point	$\sqrt{S}$ (TeV)	LO (fb)	NLO QCD (fb)	K
A	14	$0.2208^{+6.5\%}_{-5.9\%}$	$0.2649^{+1.8\%}_{-2.1\%}$	1.20
	70	$2.726^{+0.3\%}_{-0.4\%}$	$2.803^{+3.2\%}_{-2.8\%}$	1.03
B	14	$0.1095^{+6.5\%}_{-6.0\%}$	$0.1320^{+1.7\%}_{-2.1\%}$	1.20
	70	$1.349^{+0.3\%}_{-0.4\%}$	$1.386^{+3.2\%}_{-2.8\%}$	1.03
C	14	$0.1105^{+7.1\%}_{-6.3\%}$	$0.1337^{+2.2\%}_{-2.4\%}$	1.21
	70	$1.593^{+0.2\%}_{-0.1\%}$	$1.672^{+3.1\%}_{-2.5\%}$	1.05
D	14	$0.05504^{+7.2\%}_{-6.4\%}$	$0.06675^{+2.2\%}_{-2.5\%}$	1.21
	70	$0.7900^{+0.23\%}_{-0.02\%}$	$0.8276^{+3.1\%}_{-2.6\%}$	1.05

3. Bc meson and doubly heavy baryon

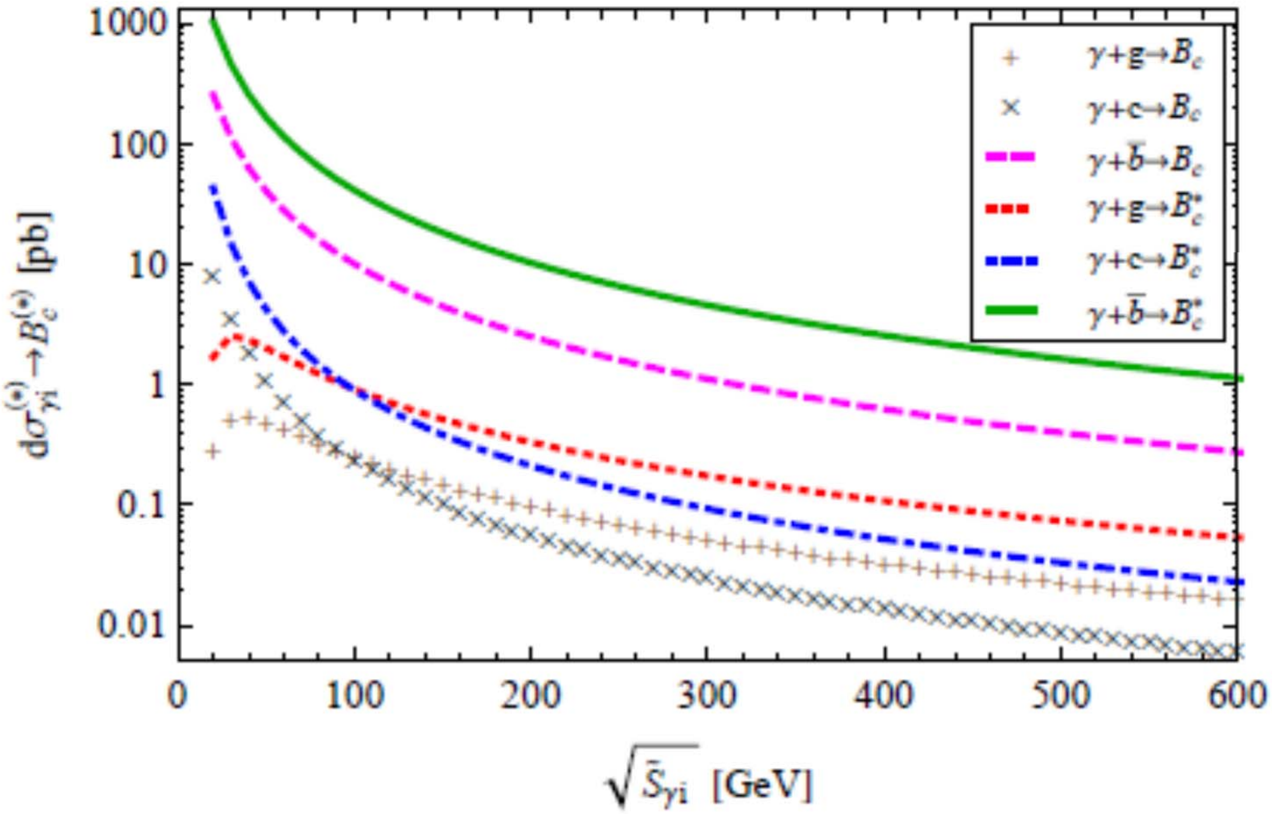
Bc* (PRD 95, 034019, 2017)

Bc** (arXiv:1710.11508)

doubly heavy baryon (PRD 95, 074020, 2017)



e^-
e^-
f_{γ/e^-}
$B_c^{(*)}$
X
$f_{i/P}$
P



10^5 events/year @ LHeC !

GM-VFN scheme ! PDF, b-quark mass and scale uncertainties.

4. New physics

Tau to muon+γ (EPJC 76, 421, 2016)

T-odd quark pair production (MPLA 25, 1550125, 2015)

DM+Z (EPJC 74, 3219, 2014)

DM+W (JHEP 09, 069, 2014)

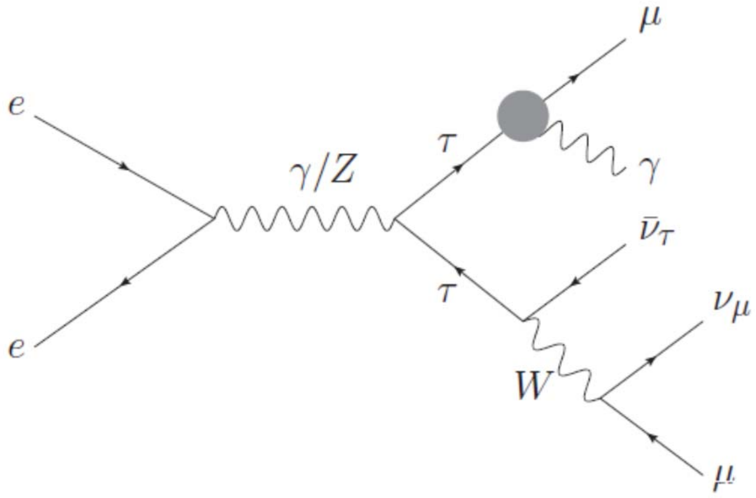
……

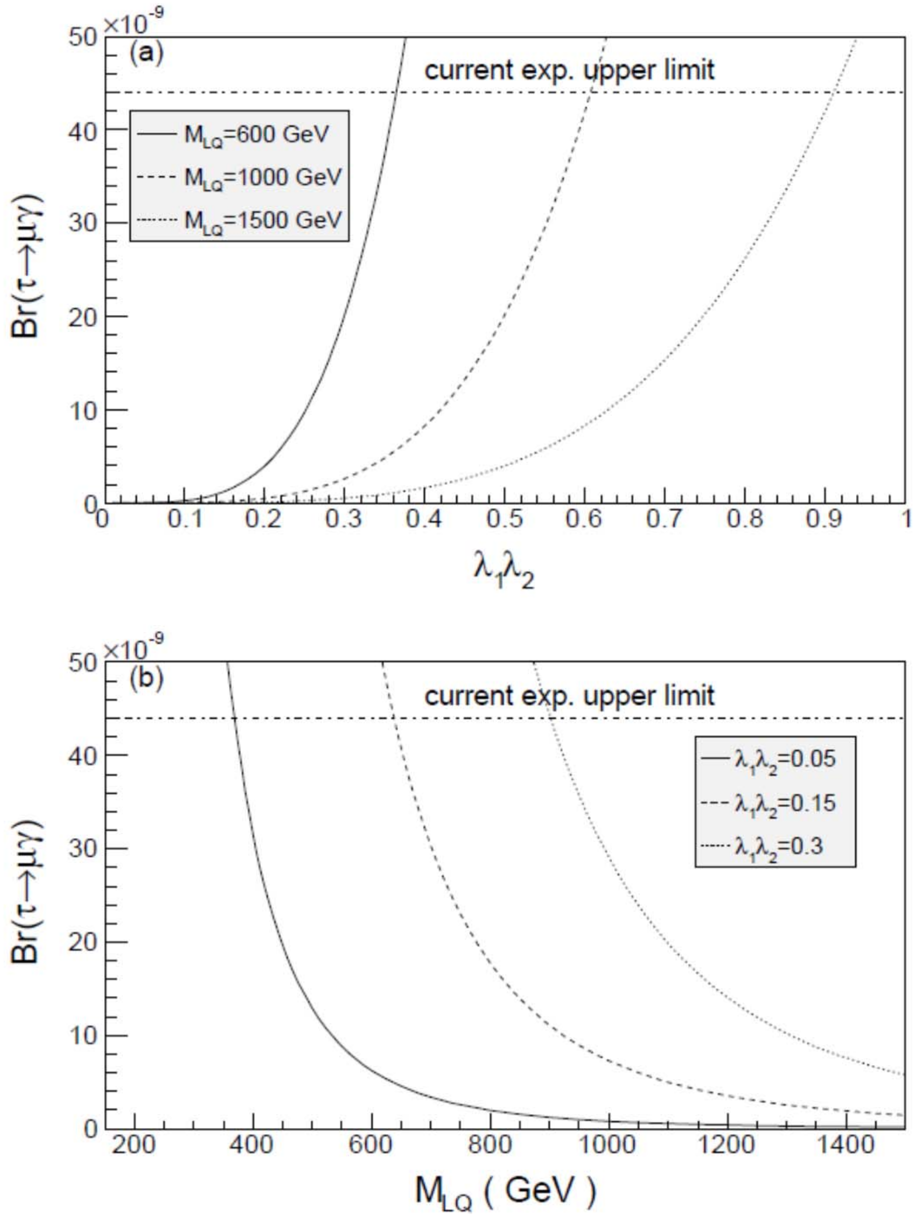
LHT model:

Precise calculation for heavy gauge boson production in the LHT model

Journal of Physics : Conference Series 523 (2014) 012054

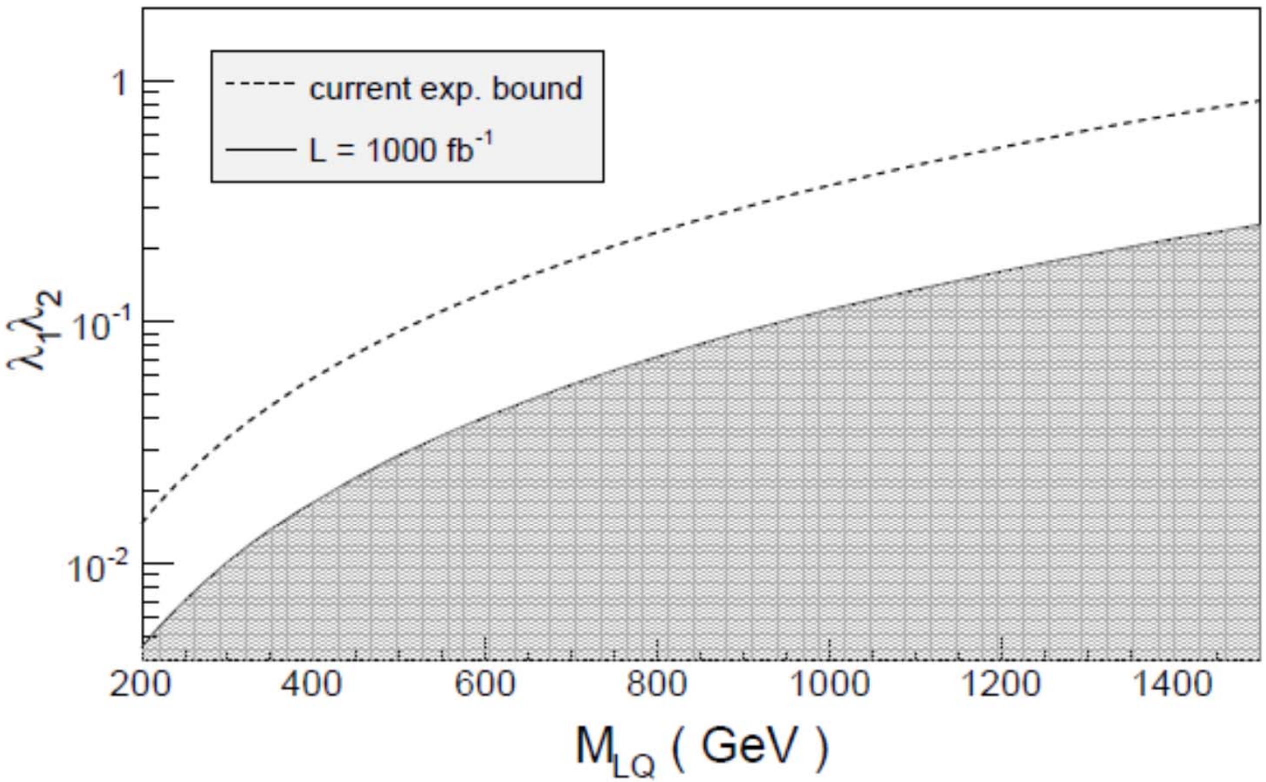
Tau to muon + photon:



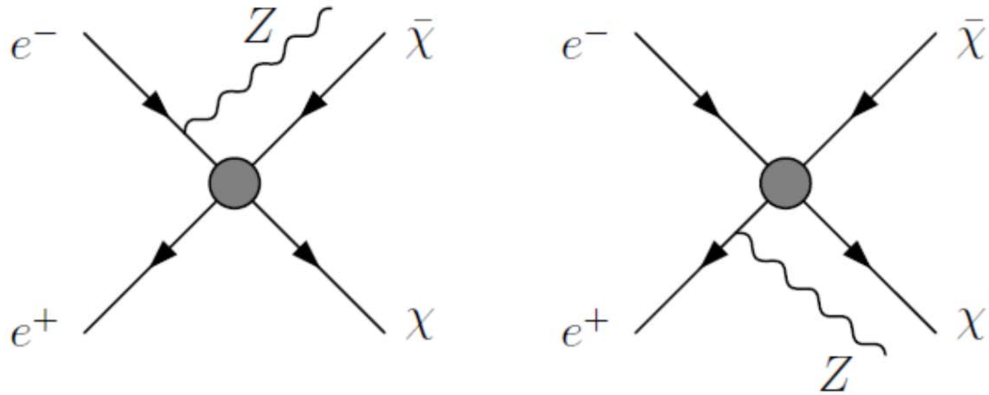


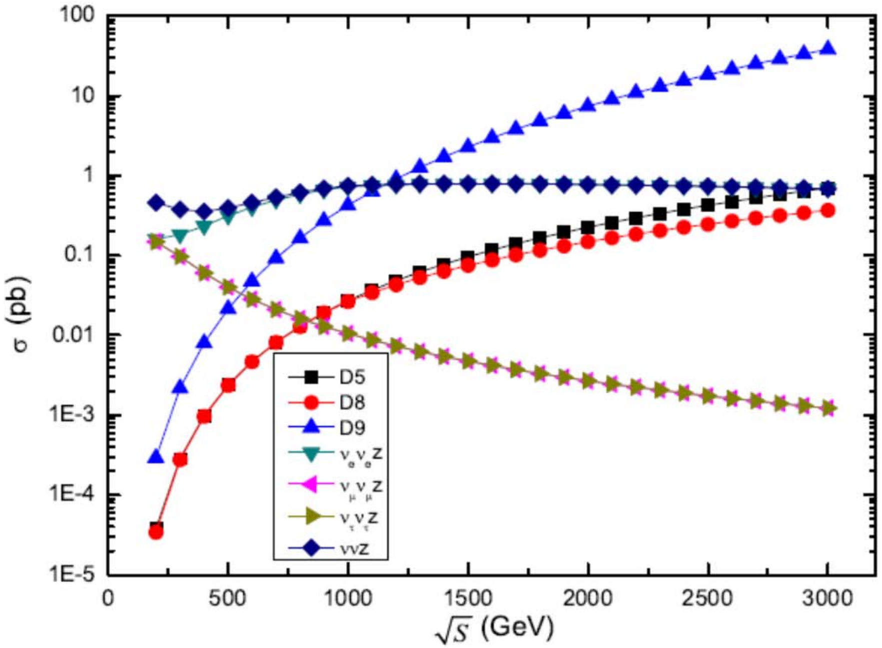
Constrains parameter space of leptoquark model:

Tau to muon + photon:



DM search at colliders :





目前在主持及参加的科研项目：

11375171，基金委面上项目：“**含奇异希格斯多重态的新物理理论的高精度现象学研究**”，**2014.1-2017.12**（主持）

11775211，基金委面上项目：“**标准模型希格斯粒子性质及TeV新物理理论中希格斯部分结构的唯象研究**”，**2018.1-2011.12**（主持）

11535002，基金委重点项目：“**标准模型及新物理中的精密计算**”，**2016.1-2020.12**（参加）

感谢各位！