河南师范大学
HENAN NORMAL UNIVERSITY

明德　正学　倡和　出新

LHT模型中顶夸克伴子的寻找

杨炳方

合作者：刘宁、武雷、张孟超、侯镖锋、张华莹

(arXiv:1508.07116, Phys. Lett. B 753 (2016) 664–669;
arXiv:1807.01607, Chin. Phys. C 42(10), (2018) 103102;
arXiv:1904.07434, accepted by Phys. Rev. D)

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报告内容

1、LHT模型中的顶夸克伴子

Littlest Higgs Model with T-parity（**LHT**）

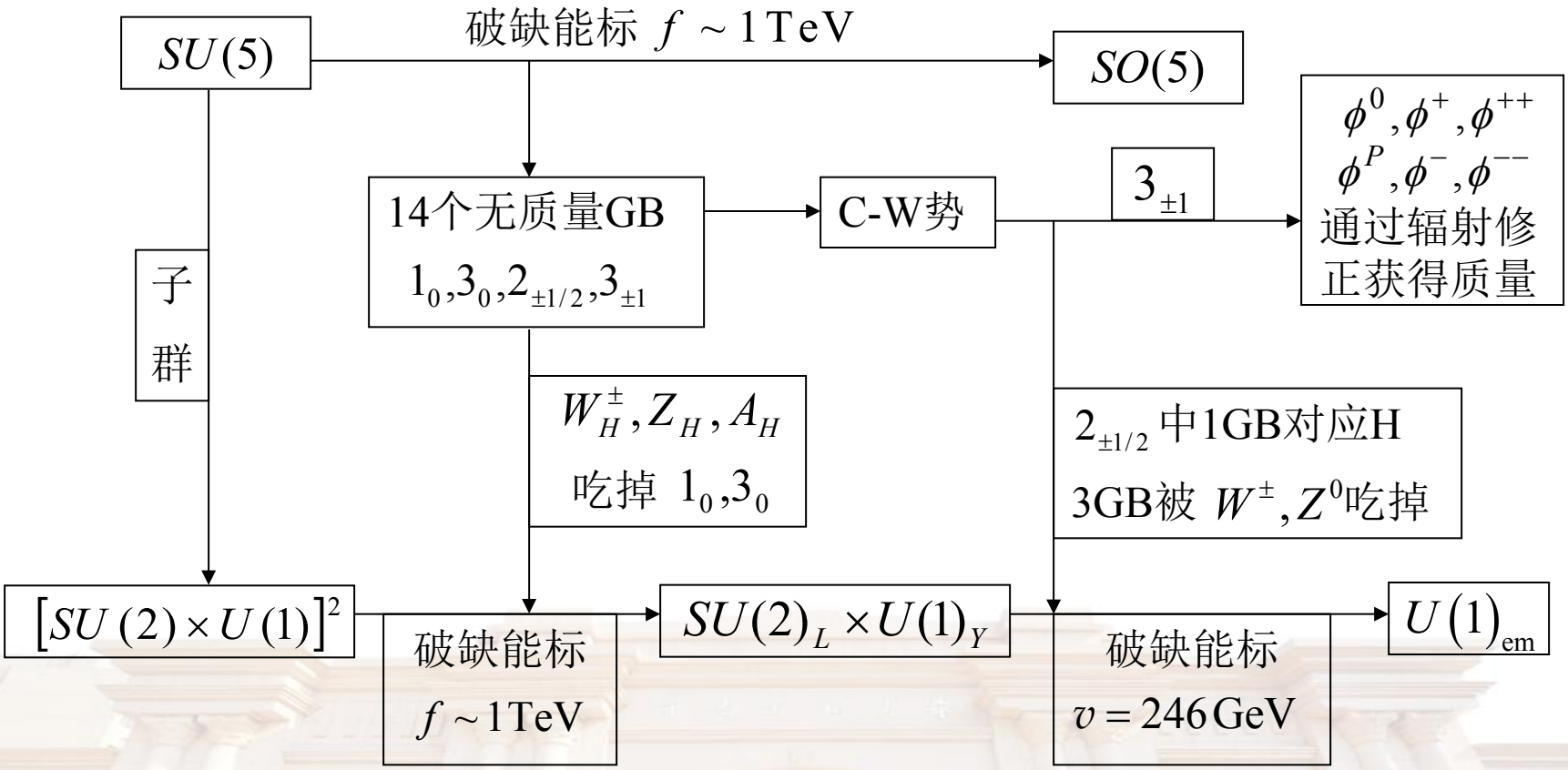
Little Higgs**理论引进“协同对称破缺”机制把Higgs粒子构造成** pseudo-Goldstone。

$$\mathcal{L} = \mathcal{L}_0 + \varepsilon_1 \mathcal{L}_1 + \varepsilon_2 \mathcal{L} \longrightarrow \delta m_h^2 \sim \frac{\varepsilon_1^2}{16\pi^2} \frac{\varepsilon_2^2}{16\pi^2} \Lambda^2$$

在TeV能区引入相同自旋的新粒子（重规范玻色子、重标量粒子和顶夸克伴子）抵消SM中相应粒子（规范玻色子、标量粒子和顶夸克）对Higgs质量所带来的单圈二次发散，从而稳定了Higgs粒子的质量。Littlest Higgs**(LH)是**Little Higgs**理论的最简单实现，为了避免来自电弱精确测量的限制，在LH模型中引入T宇称，一定程度上解决了规范等级问题和精细调节问题。

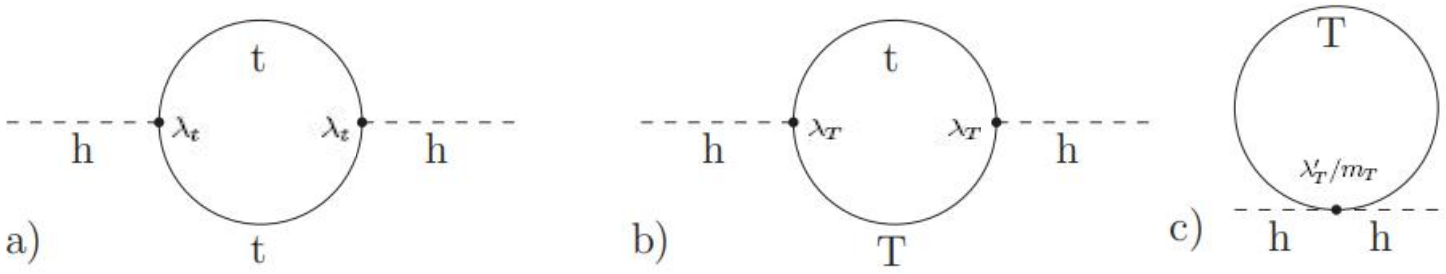
LHT模型中的顶夸克伴子

LH模型的结构



LHT模型中的顶夸克伴子

顶夸克对Higgs质量单圈二次发散的抵消



三个图对Higgs质量的贡献分别为

$$\begin{cases} \text{a)} = -6\lambda_t^2 \int \dfrac{d^4k}{(2\pi)^4}\dfrac{1}{k^2}, \\ \text{b)} = -6\lambda_T^2 \int \dfrac{d^4k}{(2\pi)^4}\dfrac{1}{k^2-M_T^2}, \\ \text{c)} = +6\lambda'_T \int \dfrac{d^4k}{(2\pi)^4}\dfrac{1}{k^2-M_T^2}, \end{cases}$$

$$\lambda_t = \frac{\sqrt{2}\lambda_1\lambda_2}{\sqrt{\lambda_1^2+\lambda_2^2}}, \quad \lambda_T = \frac{\sqrt{2}\lambda_1^2}{\sqrt{\lambda_1^2+\lambda_2^2}},$$
$$m_T = \sqrt{\lambda_1^2+\lambda_2^2}f, \ \lambda'_T = 2\lambda_1^2.$$

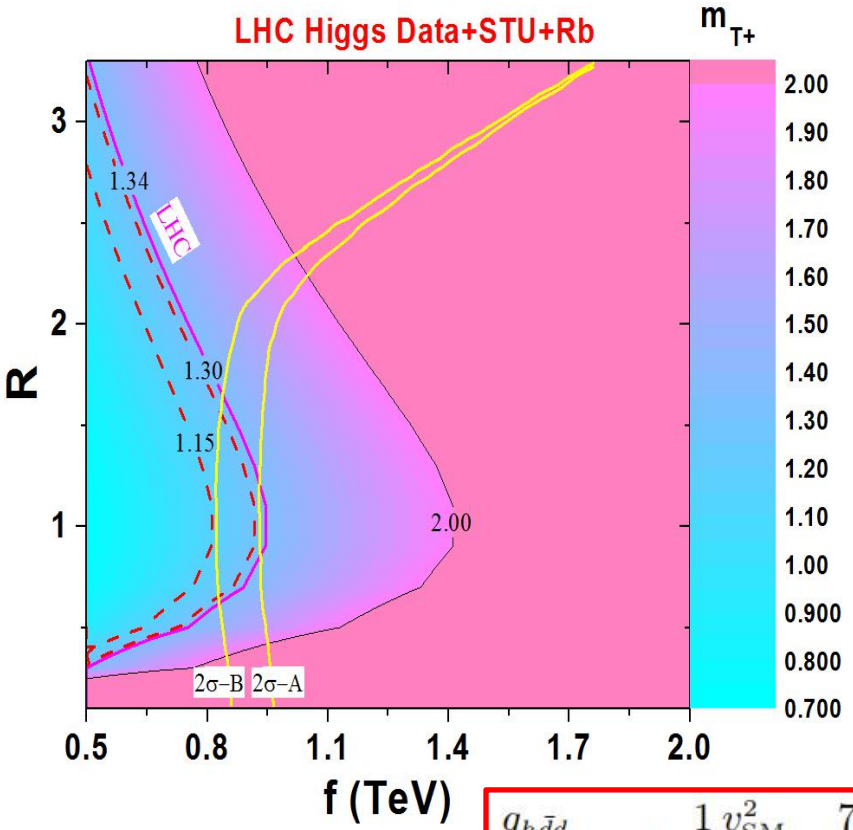
$\Rightarrow$ $\lambda'_T = \lambda_t^2 + \lambda_T^2$ 发散完全抵消

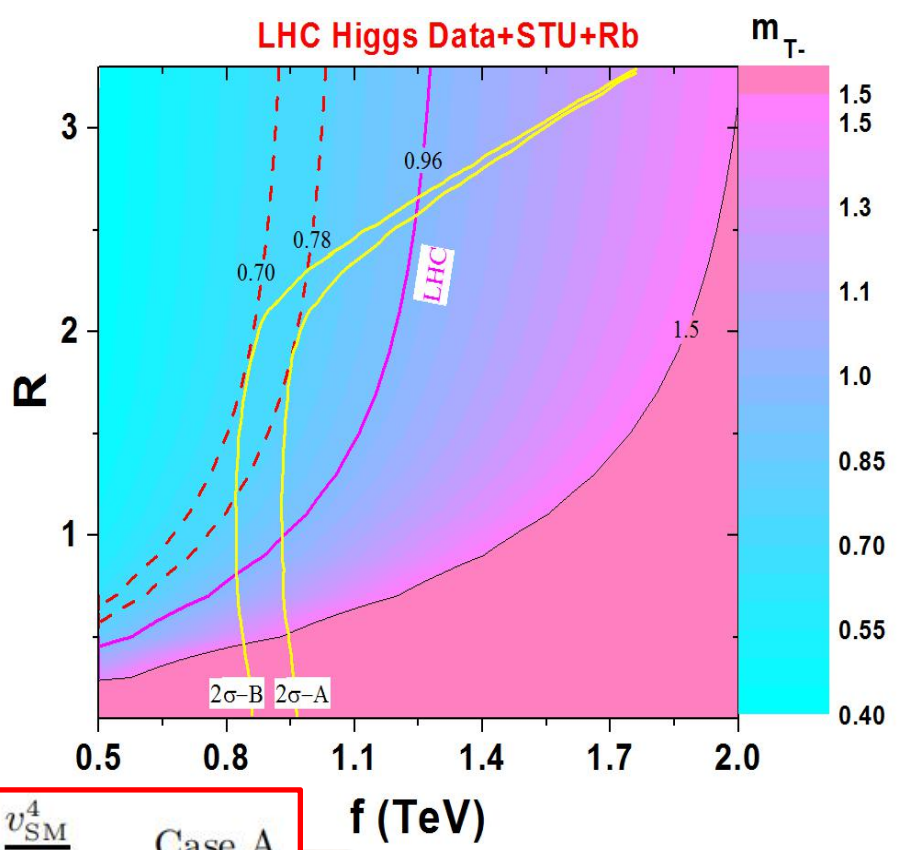
LHT模型中的顶夸克伴子

LHT模型预言的新粒子		SM
重规范玻色子：	$W_H^{\pm}, Z_H, A_H$	$W^{\pm}, Z, \gamma$
镜像费米子：	$u_H^i, d_H^i, l_H^i, \nu_H^i$	u^i, d^i, l^i, ν^i
重标量粒子：	$\Phi(\phi^{\pm}, \phi^{\pm\pm}, \phi^0, \phi^P)$	H
顶夸克伴子：	T_+, T_-	t

SM中的所有粒子是T-even的，新粒子（除T_+外）是T-odd的， T-odd的新粒子只能成对产生。最轻的T-odd粒子A_H，可作为暗物质的侯选者。

LHT模型中的顶夸克伴子–现有实验限制





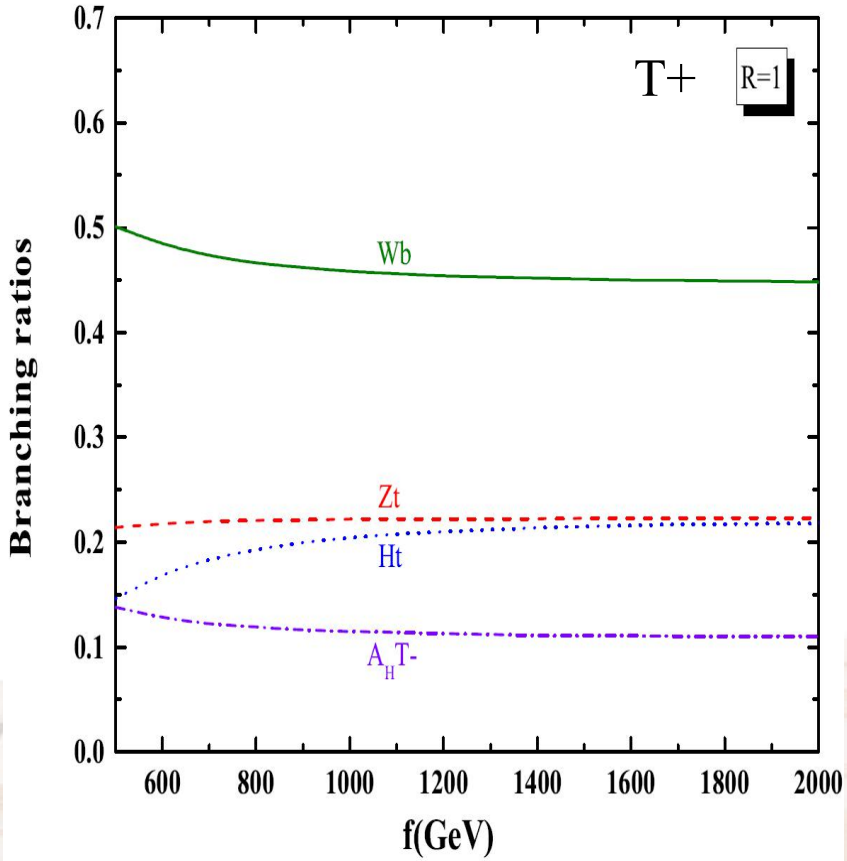
$$\frac{g_{h\bar{d}d}}{g_{h\bar{d}d}^{\rm SM}} = 1-\frac{1}{4}\frac{v_{\rm SM}^2}{f^2}+\frac{7}{32}\frac{v_{\rm SM}^4}{f^4} \qquad \text{Case A}$$

$$\frac{g_{h\bar{d}d}}{g_{h\bar{d}d}^{\rm SM}} = 1-\frac{5}{4}\frac{v_{\rm SM}^2}{f^2}-\frac{17}{32}\frac{v_{\rm SM}^4}{f^4} \qquad \text{Case B}$$

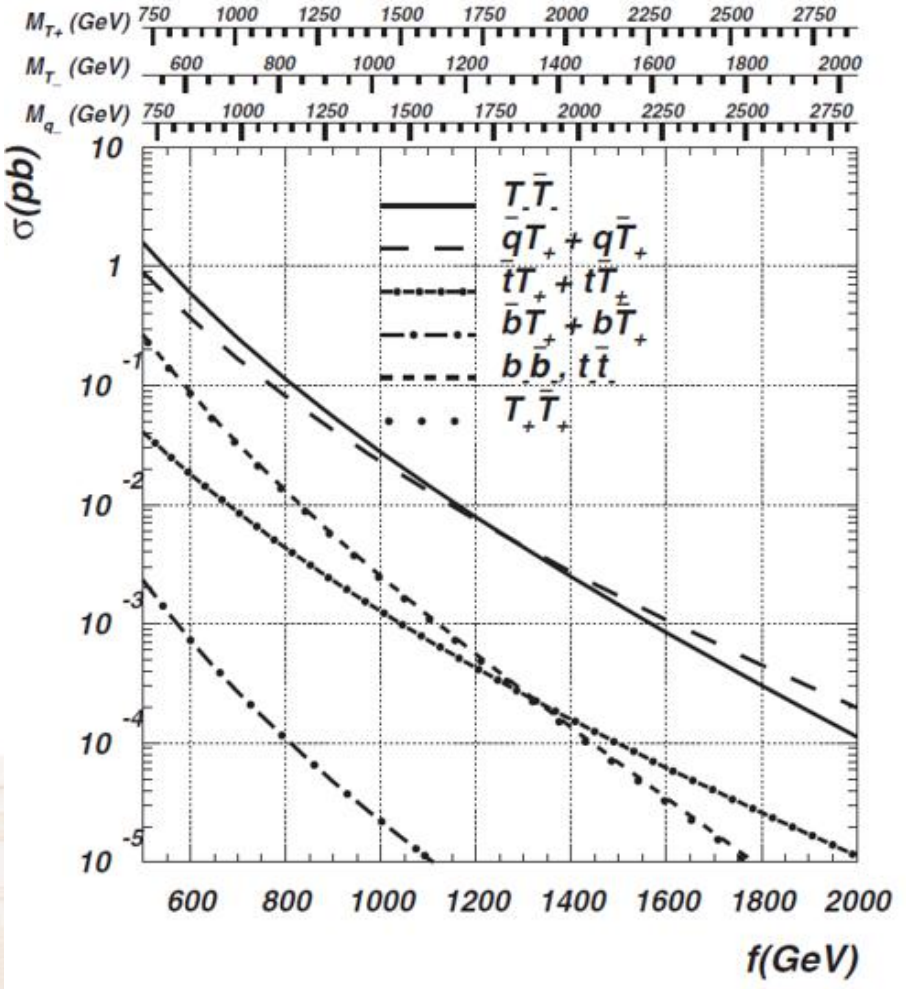
LHC限制: D. Dercks, G. Moortgat-Pick, J. Reuter, S. Y. Shim, JHEP 1805 (2018) 049

LHT模型中的顶夸克伴子分支比与LHC上的产生

$T- \rightarrow A_H t(100\%)$



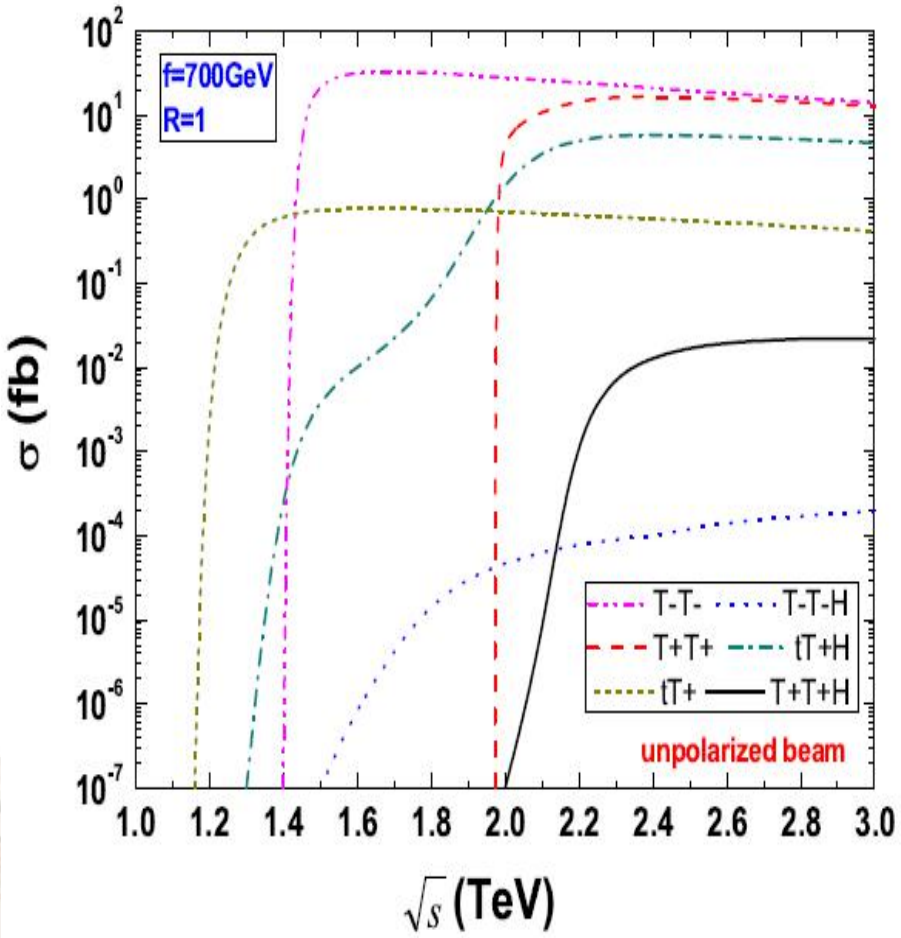
右图：A. Belyaev, C.-R. Chen, K. Tobe, C.-P. Yuan, Phys. Rev. D74(2006)115020

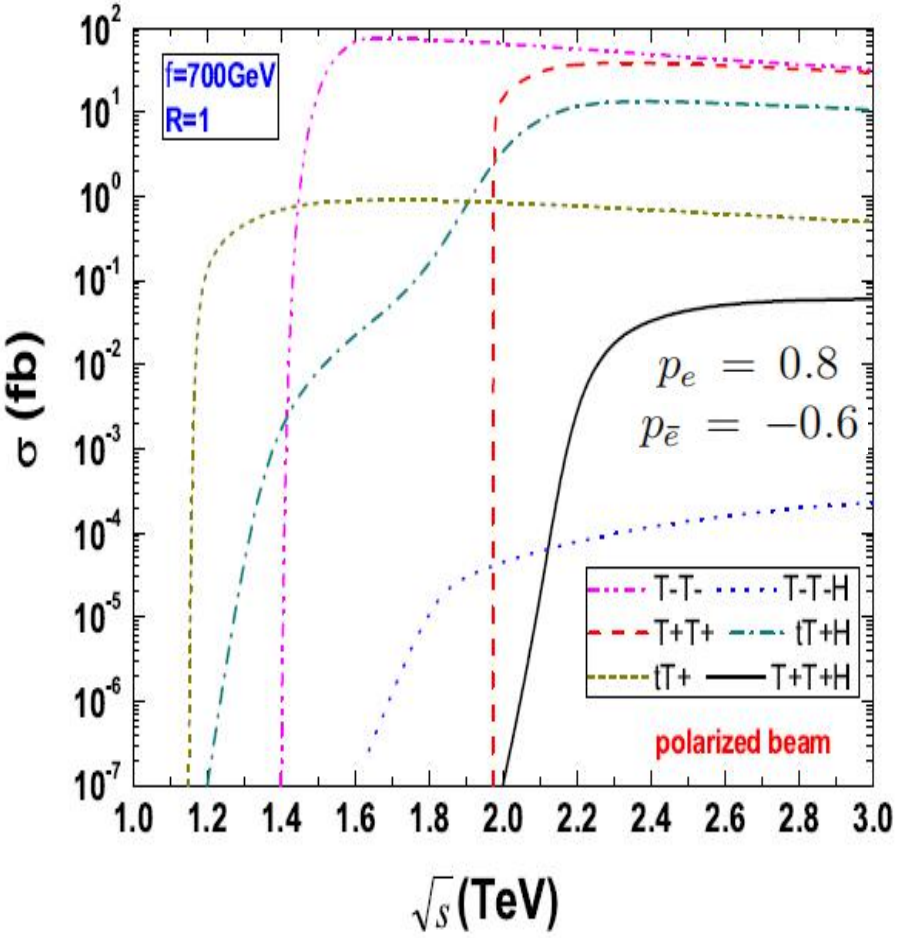


LHT模型中的顶夸克伴子

e^+e^-对撞机上的产生

H.Y. Wang and **B.F. Yang**, Adv. High Energy Phys. 2017 (2017) 5463128





LHT模型中的顶夸克伴子–相关文献(举例)

1、H.-C. Cheng, I. Low, L.-T. Wang,Top Partners in Little Higgs Theories with T-parity, Phys.Rev. D74 (2006) 055001;

2、S. Matsumoto, M. M. Nojiri, D. Nomura, Hunting for the Top Partner in the Littlest Higgs Model with T-parity at the LHC, Phys.Rev. D75 (2007) 055006;

3、S. Matsumoto, T. Moroi, K. Tobe,Testing the Littlest Higgs Model with T-parity at the Large Hadron Collider, Phys.Rev. D78 (2008) 055018;

4、Q.-H. Cao, C. S. Li, C.-P. Yuan, Impact of Single-Top Measurement to Littlest Higgs Model with T-Parity, Phys.Lett. B668 (2008) 24-27;

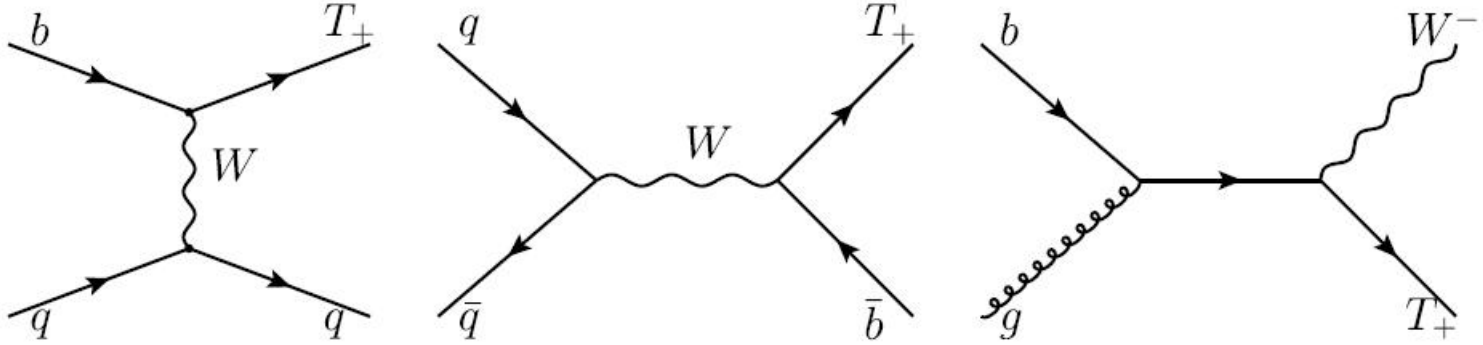
5、N. Vignaroli, Early discovery of top partners and test of the Higgs nature, Phys. Rev. D 86 (2012) 075017;

6、O. Matsedonskyi, G. Panico, A. Wulzer, On the Interpretation of Top Partners Searches, JHEP12(2014)097;

7、J. Reuter and M.Tonini,Top Partner Discovery in the T → tZ channel at the LHC, JHEP 1501 (2015) 088;

8、M. Chala, Direct bounds on heavy toplike quarks with standard and exotic decays, Phys. Rev. D 96 (2017) 015028.

2、LHC上T-even顶夸克伴子的寻找-th道



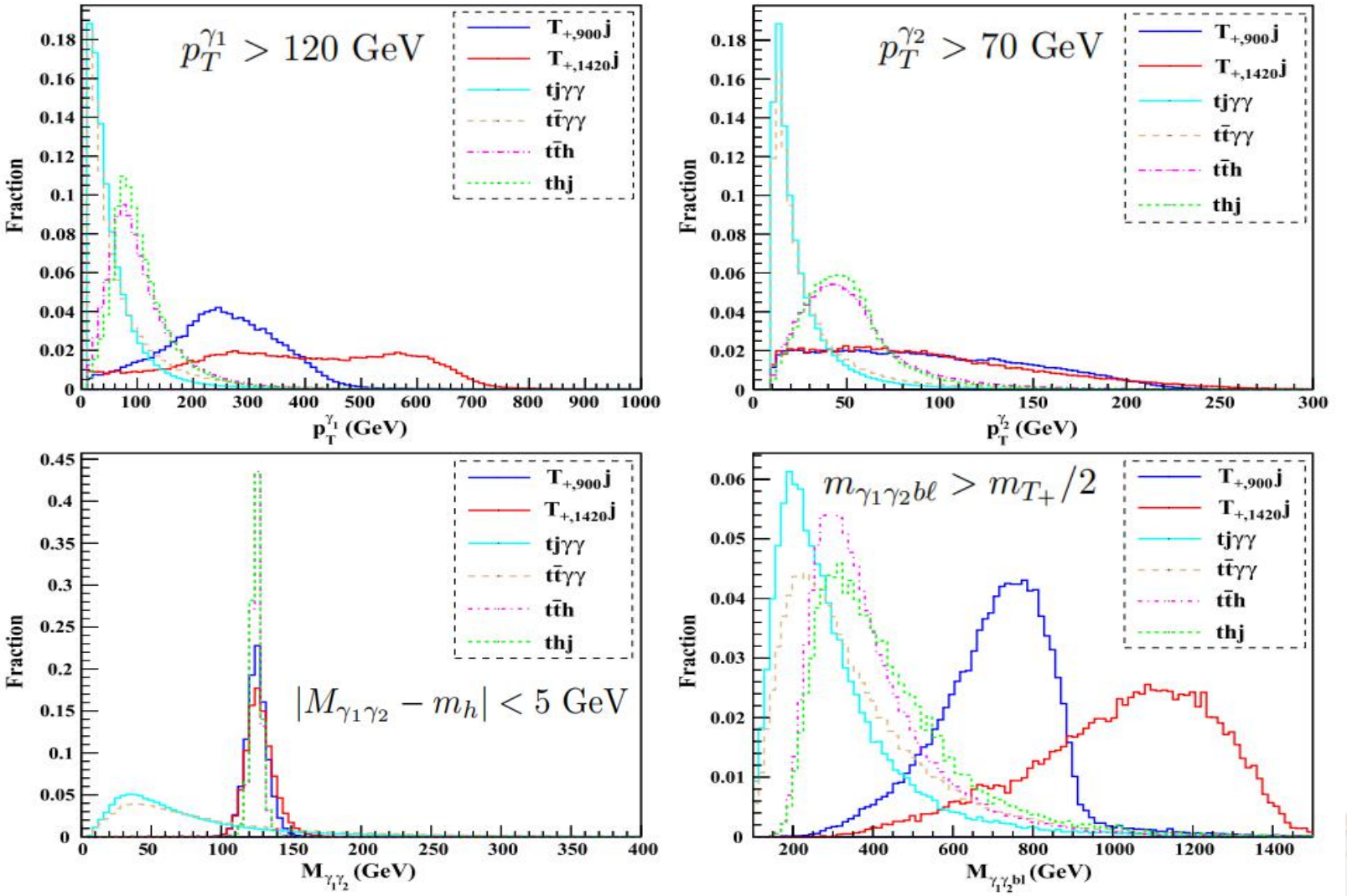
信号 $pp \to T_+(\to th)j \to t(\to b\ell^+\nu_\ell)h(\to \gamma\gamma)j$

主要背景 $pp \to tj\gamma\gamma,\ tt\gamma\gamma,\ t\bar{t}h,\ thj$

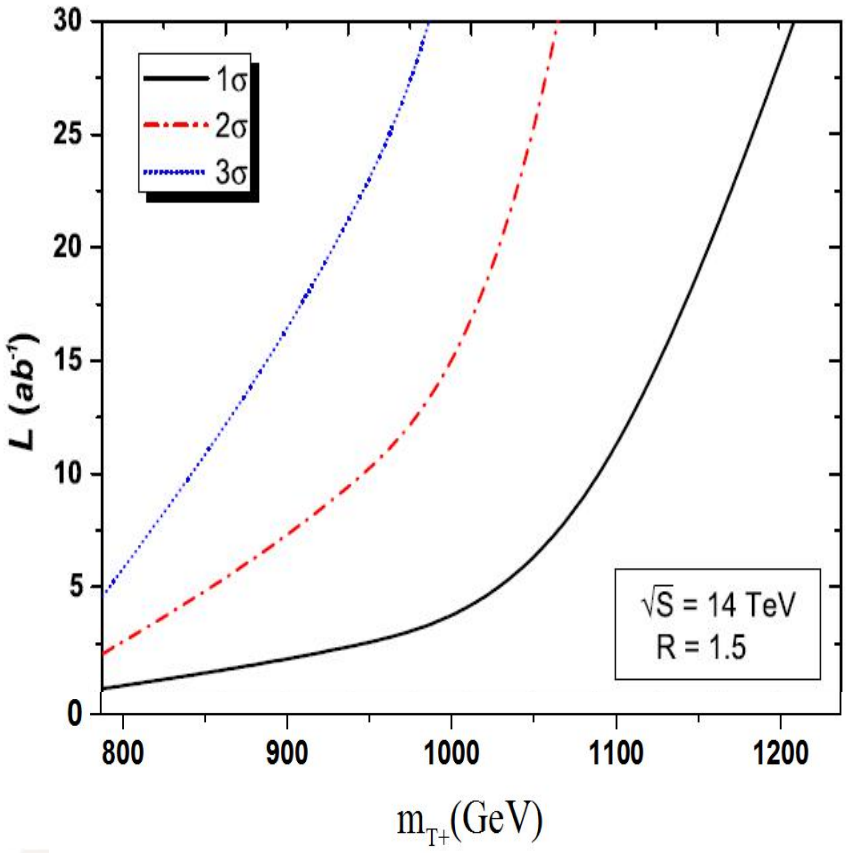
N. Liu, L. Wu, **B.F. Yang**, M.C. Zhang, Phys. Lett. B 753 (2016) 664–669

LHC上T-even顶夸克伴子的寻找

f=500GeV, R=0.5(m_{T+}=900GeV);
f=800GeV, R=0.5(m_{T+}=1420GeV)

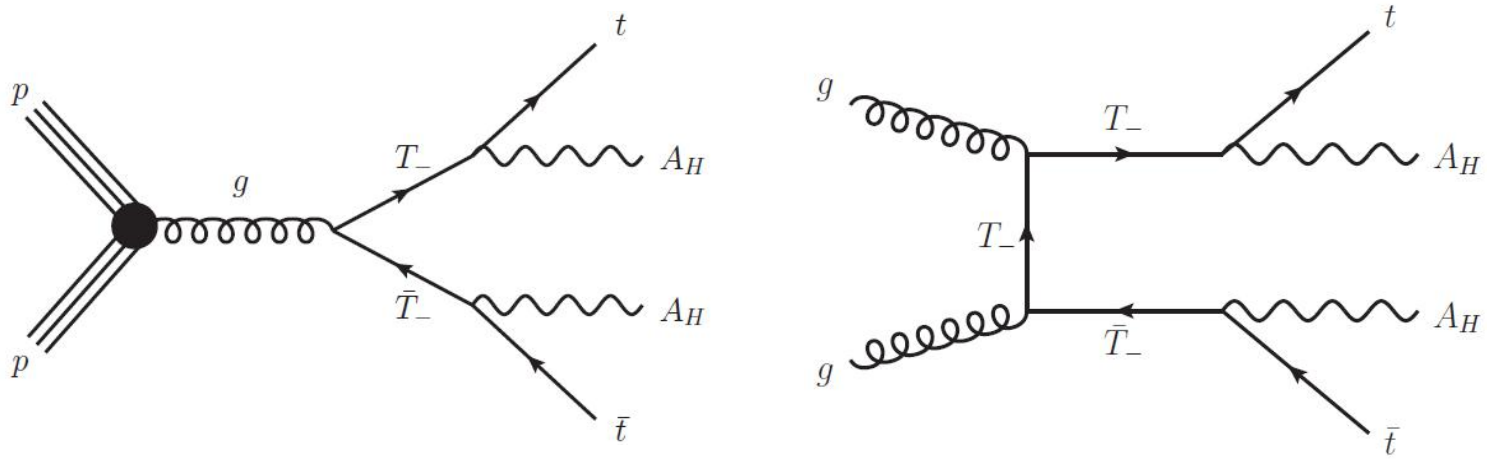


LHC上T-even顶夸克伴子的寻找



在高亮度LHC（14TeV+3000fb^{-1}）上T_+的质量在2σ水平可以被排除到800GeV。

3、LHC上T-odd顶夸克伴子的寻找-双轻子道

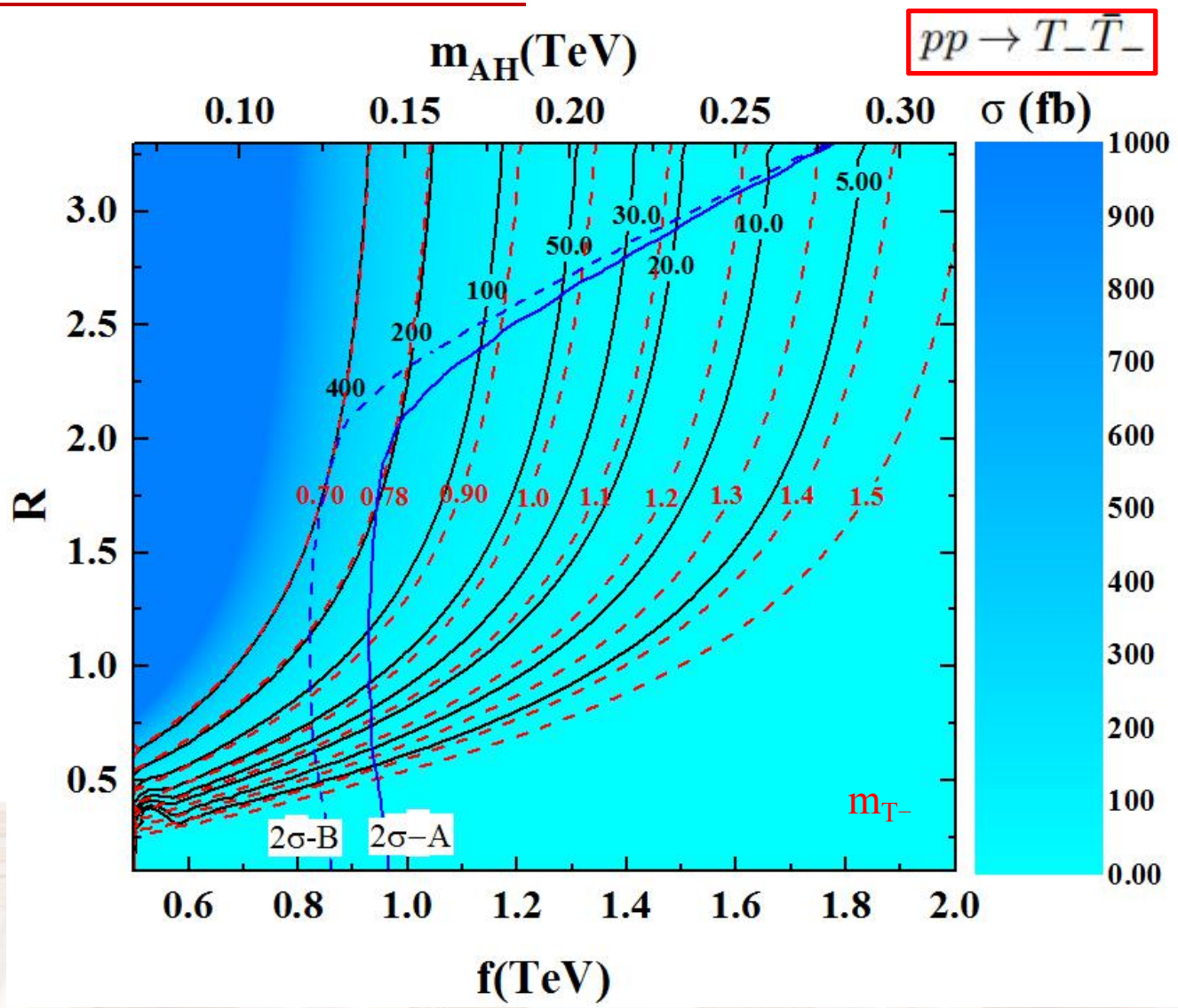


信号 $pp \to T_-\bar{T}_- \to t(\to l^+\nu_l b)\bar{t}(\to l^-\bar{\nu}_l\bar{b})A_H A_H \to l^+l^- + 2b + \not{E}_T$

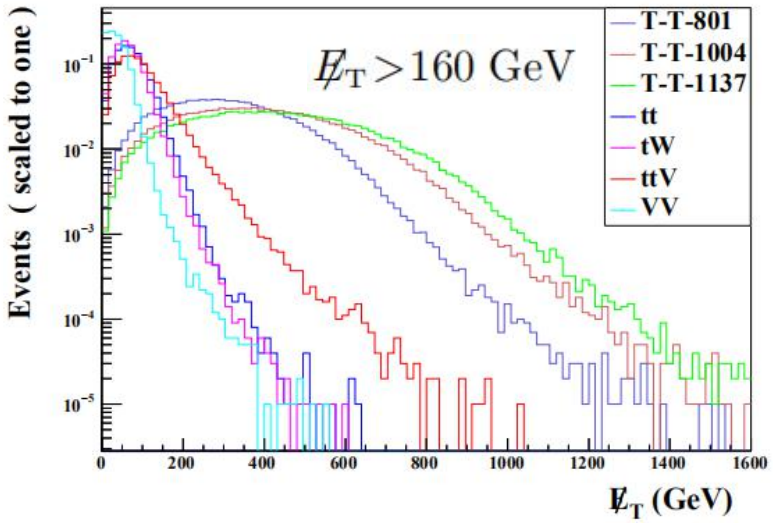
主要背景 $pp \to t\bar{t}\ ,\ tW,\ t\bar{t}V(V = W,Z),\ VV(WW,WZ,ZZ)$

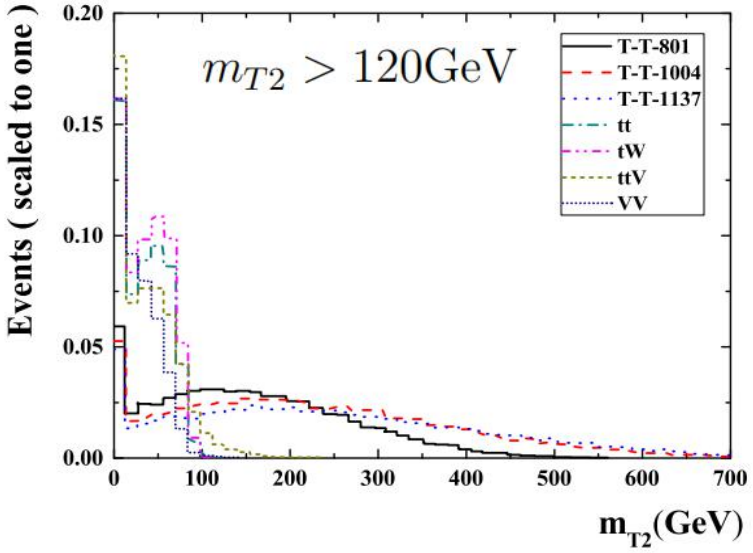
B.F. Yang, H.Y. Zhang, B.F. Hou, N. Liu, Chin. Phys. C 42(10), (2018) 103102

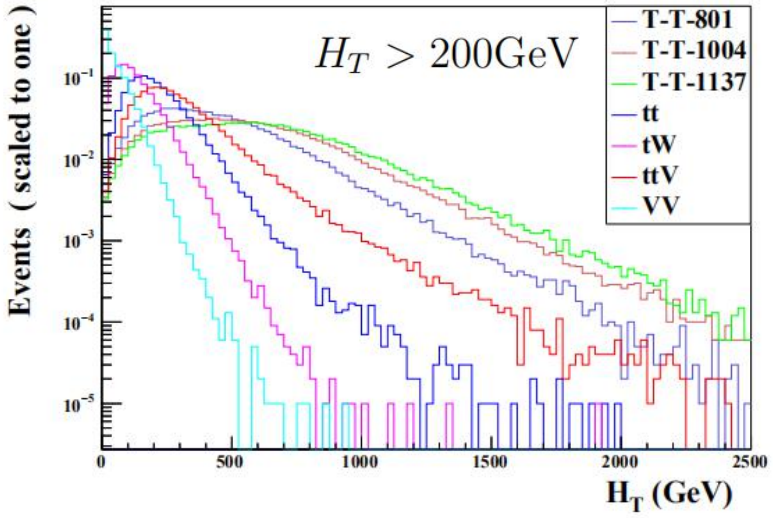
LHC上T-odd顶夸克伴子的寻找



LHC上T-odd顶夸克伴子的寻找

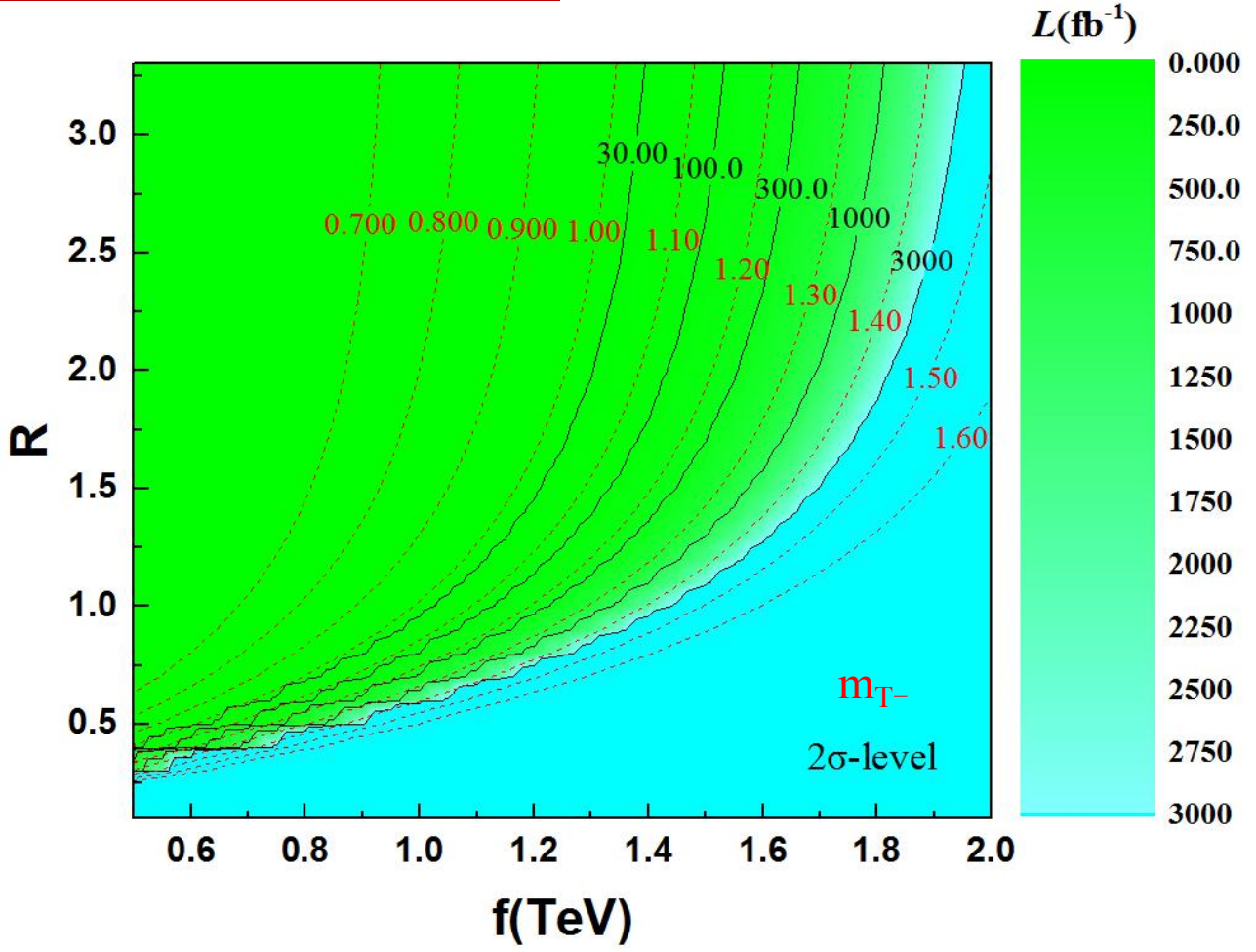






f=1000GeV, R=2 (m_{T_1}=801GeV);
f=1000GeV, R=1 (m_{T_1}=1004GeV);
f=1000GeV, R=0.8 (m_{T_1}=1137GeV)

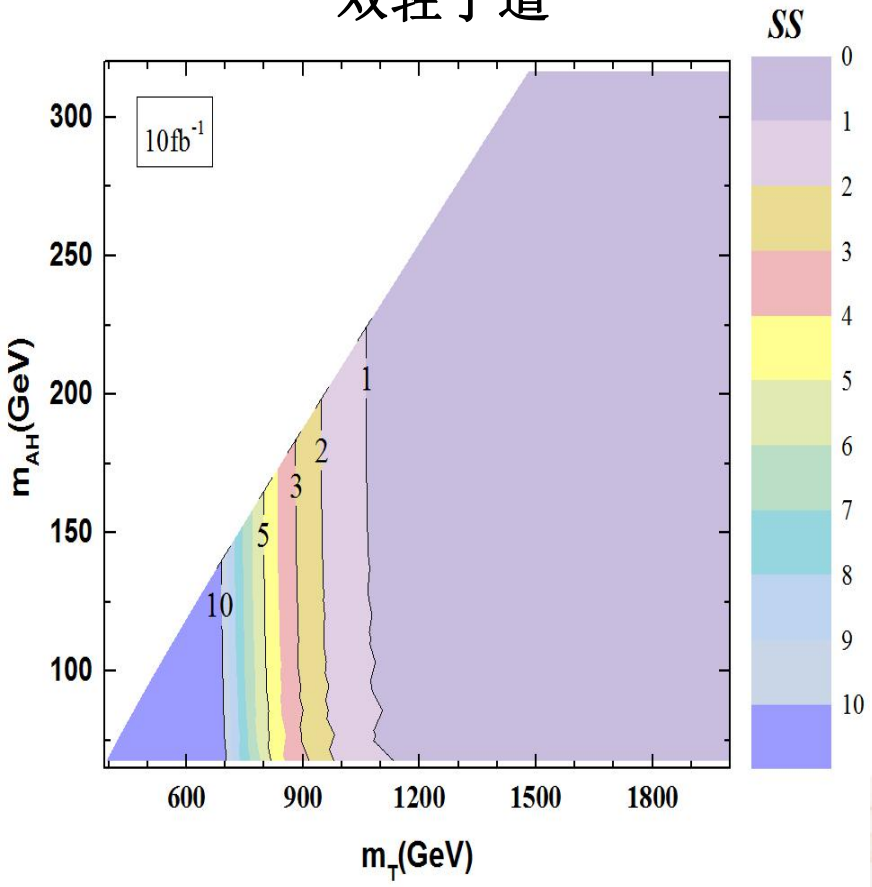
LHC上T-odd顶夸克伴子的寻找



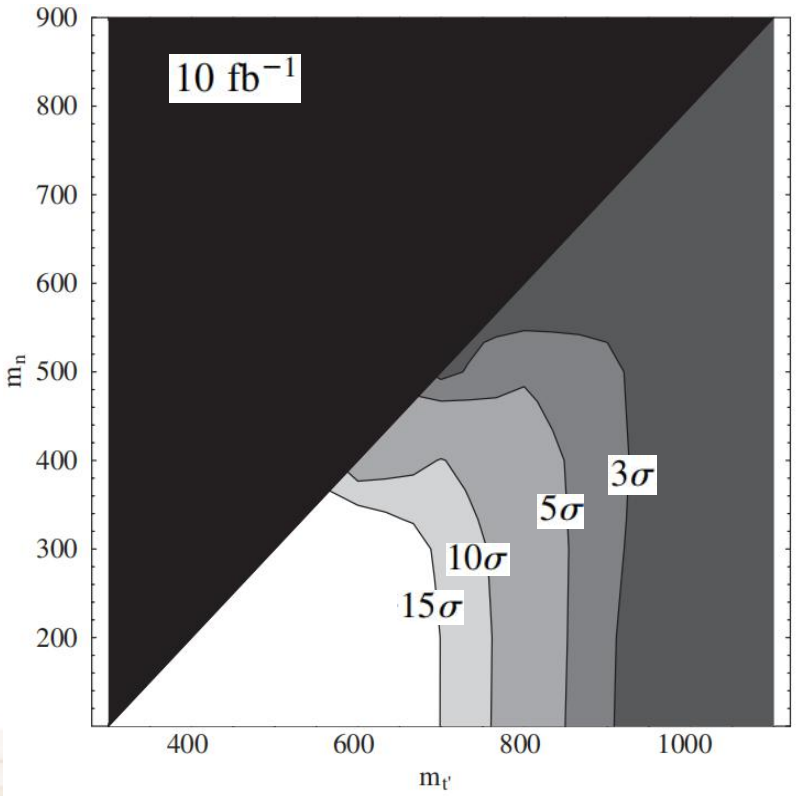
在高亮度LHC上T-的质量在2σ水平可以被排除到1440GeV。

LHC上T-odd顶夸克伴子的寻找

双轻子道



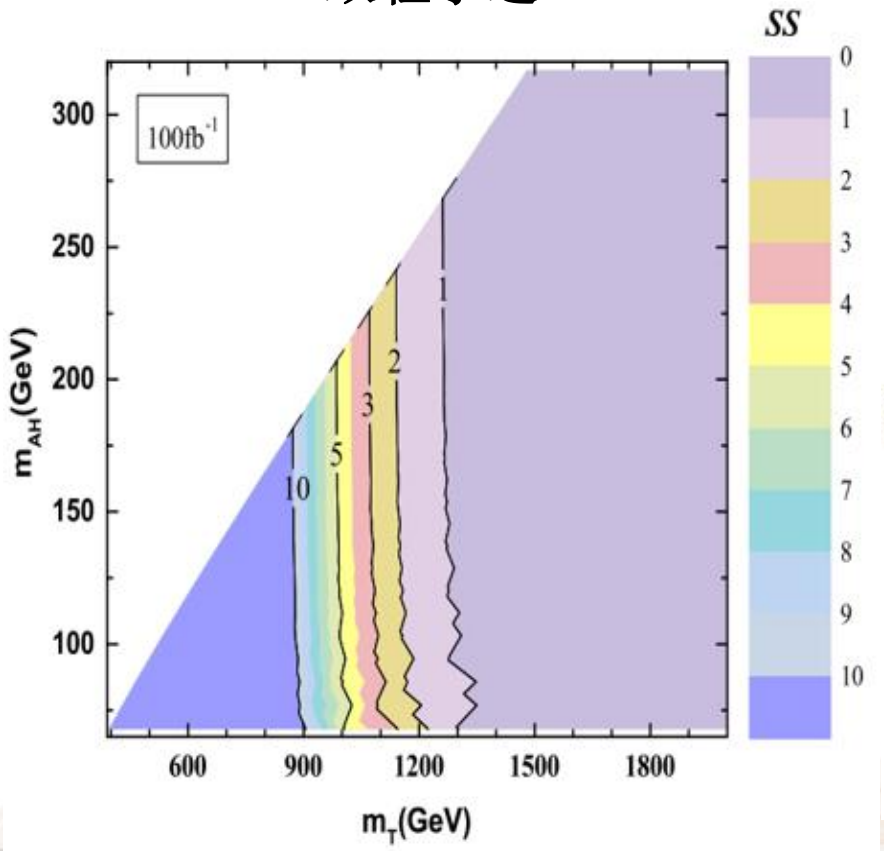
全强子道



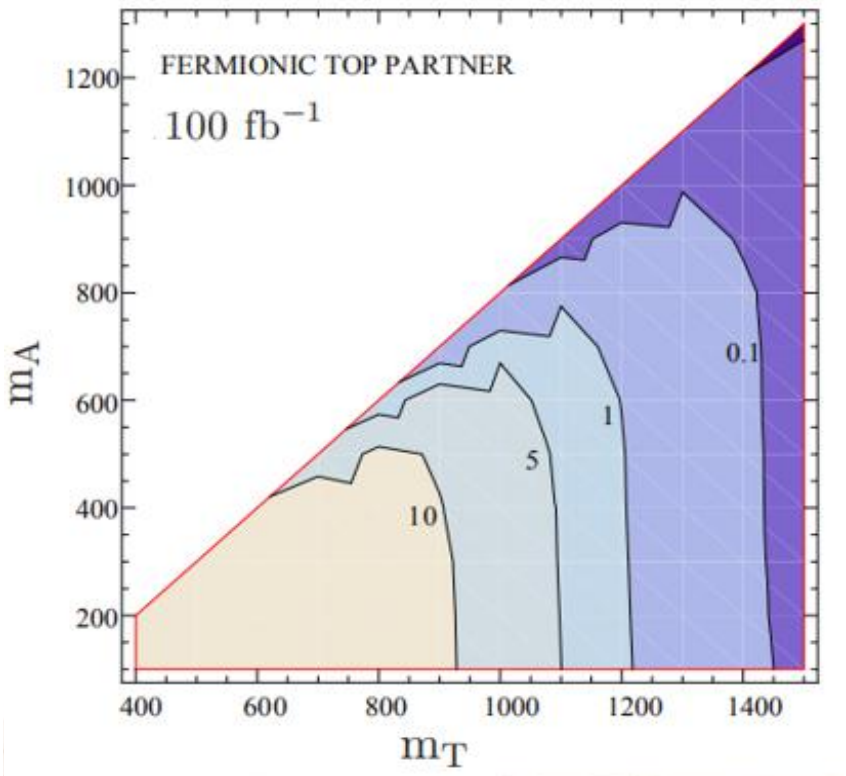
右图：P. Meade and M. Reece, Phys. Rev. D 74 (2006) 015010

LHC上T-odd顶夸克伴子的寻找

双轻子道

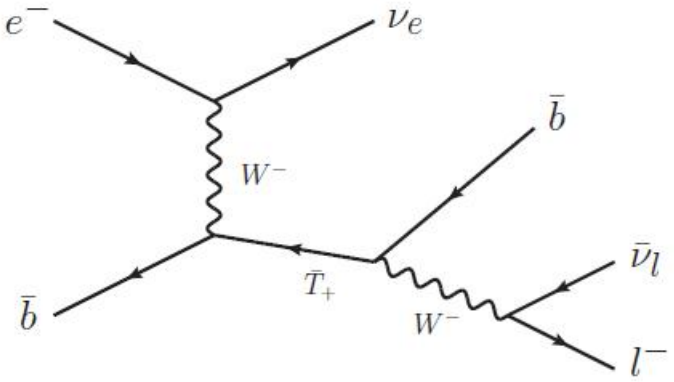


半轻子道



右图：T. Han, R. Mahbubani, D. G. E. Walker, L.-T. Wang, JHEP05(2009)117

4、高能ep对撞机上T-even顶夸克伴子的寻找



信号

$$e^- \; p \to \nu_e \; \bar{T}_+ (\to \bar{b} \; W^-) \to \nu_e (\bar{b} \; \nu_l \; l^-) \to l^- + \bar{b} + \not{E}_T$$

主要背景

$t\nu$: $e^- \; p \to \bar{t} \; (\to \bar{b} \; W^-) \nu_e \to l^- + \bar{b} + \not{E}_T$

$Wb\nu$: $e^- \; p \to \; W^- (\to l^- \; \bar{\nu}_l) \; \bar{b} \nu_e \to l^- + \bar{b} + \not{E}_T$

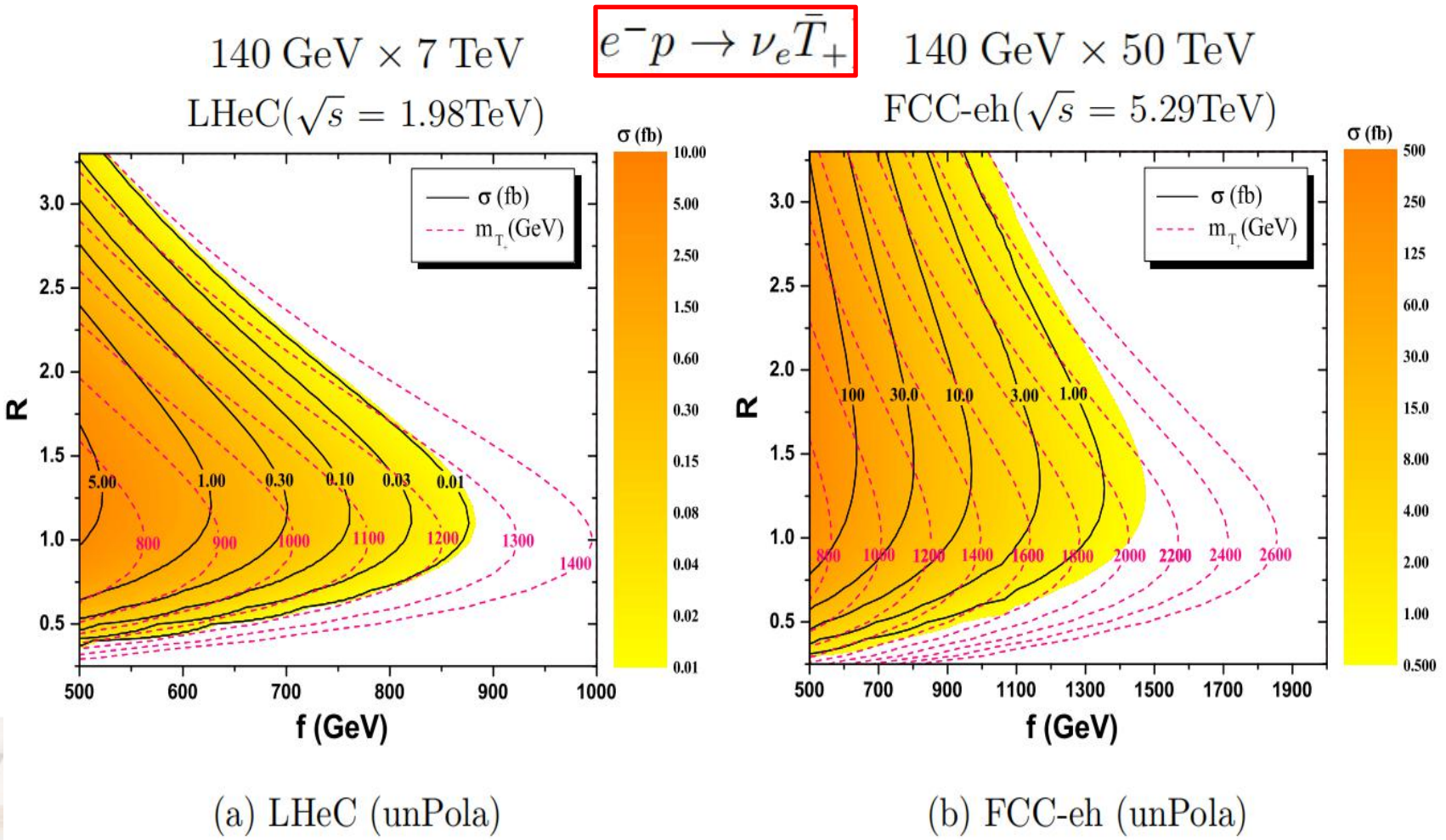
eZb: $e^- \; p \to e^- \; Z (\to \nu_l \; \bar{\nu}_l) \; b(\bar{b}) \; \to e^- + b(\bar{b}) + \not{E}_T$

$tZ\nu$: $e^- \; p \to \; \bar{t} \; (\to \bar{b} \; l^- \; \bar{\nu}_l) \; Z (\to \nu_l \; \bar{\nu}_l) \; \nu_l \to l^- + \bar{b} + \not{E}_T$

B.F. Yang,B.F. Hou,H.Y. Zhang,N. Liu, accepted by Phys. Rev. D

LHeC和FCC-eh上T-even顶夸克伴子的寻找

$e^- p \to \nu_e \bar{T}_+$

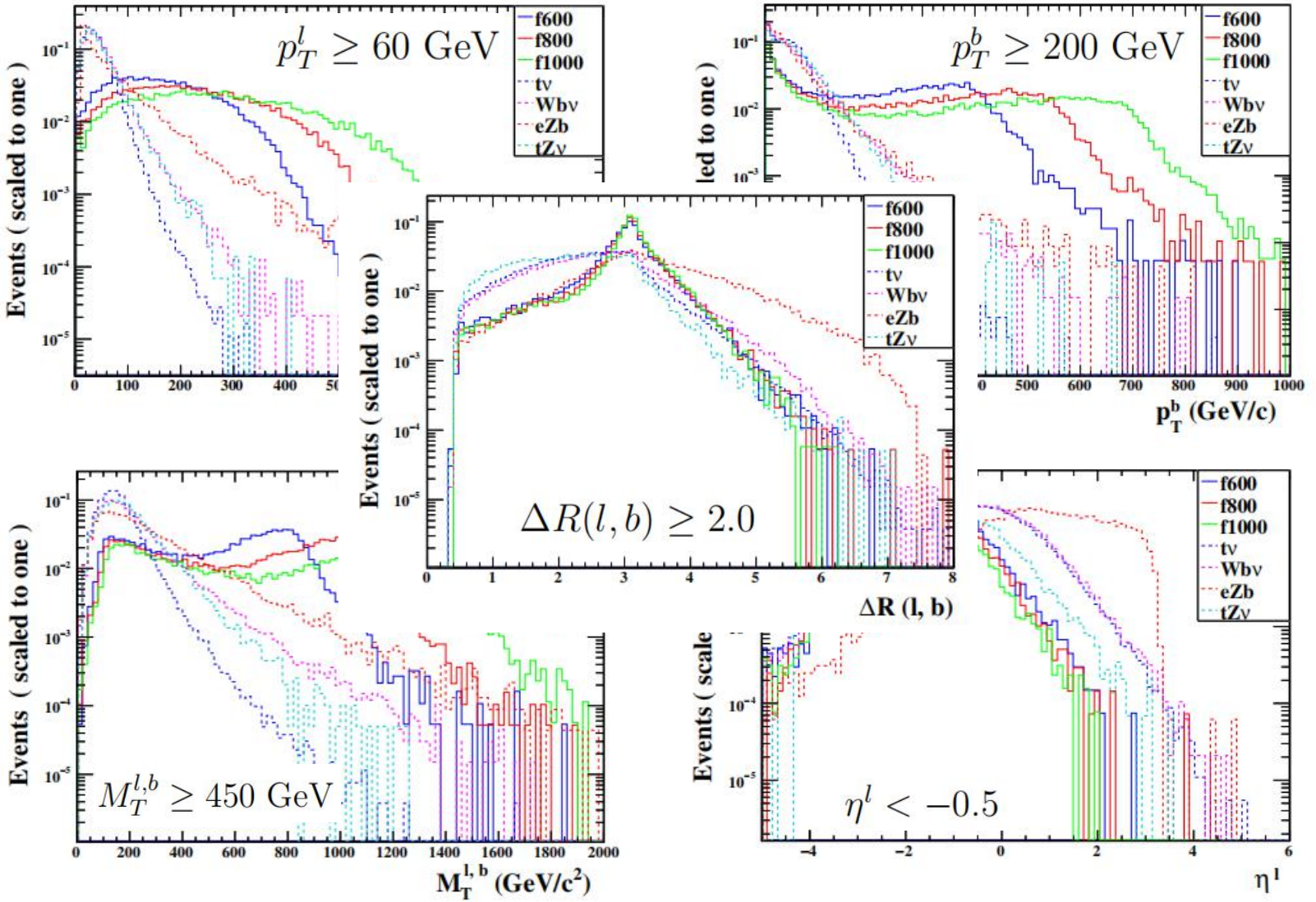


(a) LHeC (unPola)

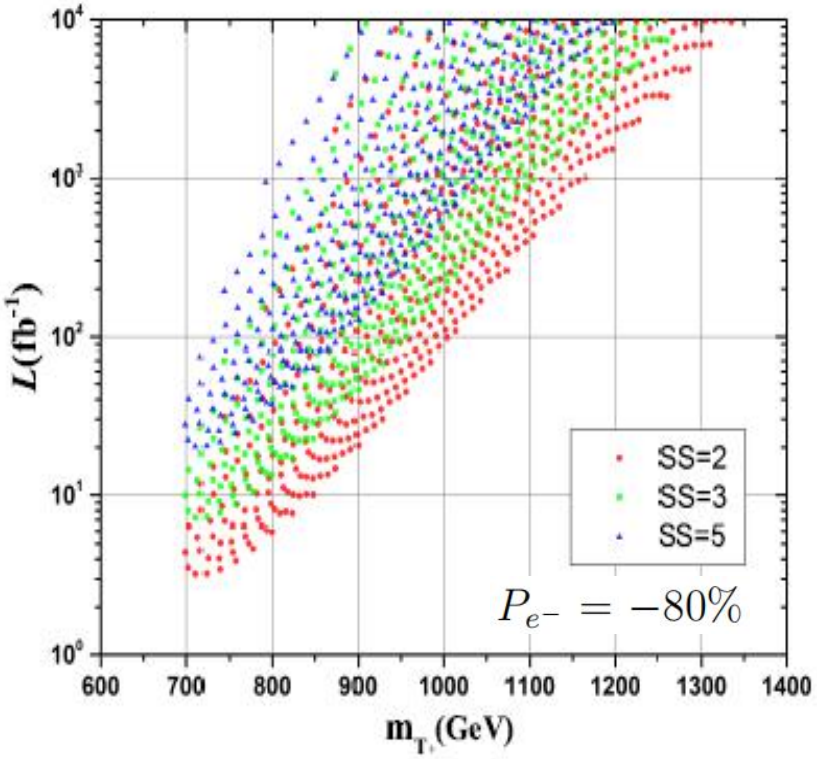
(b) FCC-eh (unPola)

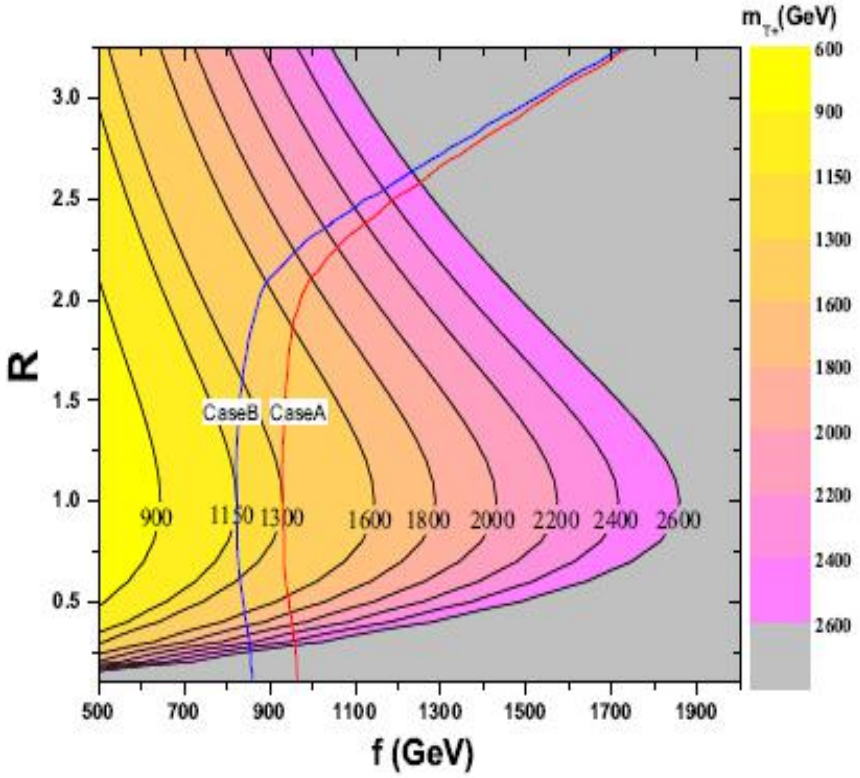
LHeC和FCC-eh上T-even顶夸克伴子的寻找

R=1,m_{T+}=840GeV, 1120GeV,1400GeV



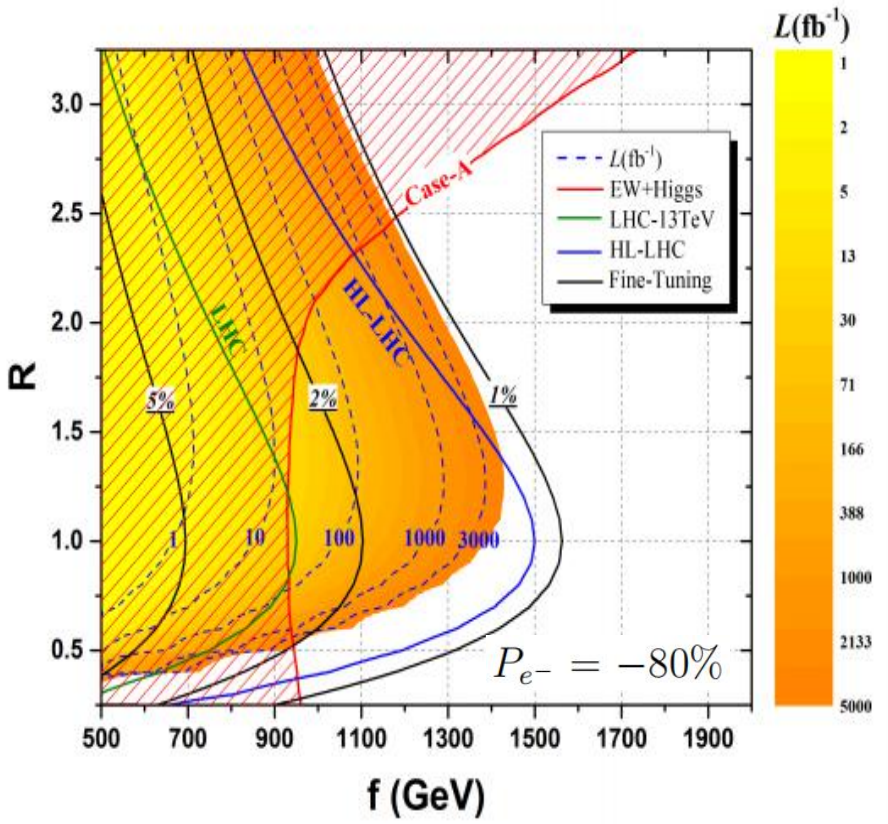
LHeC上T-even顶夸克伴子的寻找

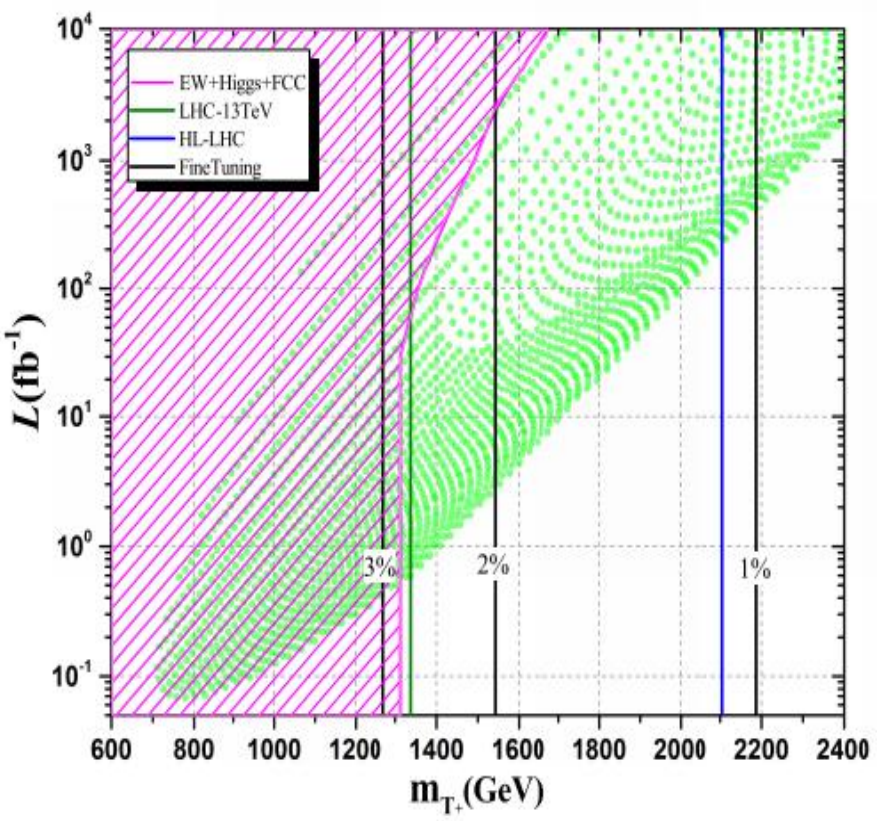




极化LHeC（3000fb^{-1}）对T_+质量的排除能力弱于电弱精确测量和Higgs数据整体拟合的限制。

FCC-eh上T-even顶夸克伴子的寻找





$$\Delta = \frac{\mu^2_{obs}}{|\delta\mu^2|}, \qquad \delta\mu^2 = -\frac{3\lambda_t m^2_{T_+}}{8\pi^2}\log\frac{\Lambda}{m^2_{T_+}}$$

极化FCC-eh（3000fb^{-1}）能将T_+的质量排除到1565GeV。

5、总结

1、LHC上T-even顶夸克伴子的寻找：在高亮度LHC上T-even顶夸克伴子的质量可以被排除到800GeV;

2、LHC上T-odd顶夸克伴子的寻找：在高亮度LHC上T-odd顶夸克伴子的质量可以被排除到1440GeV;

3、高能ep对撞机上T-even顶夸克伴子的寻找：LHeC（3000fb^{-1}）对顶夸克伴子质量的排除能力弱于电弱和Higgs数据的限制，极化FCC-eh（3000fb^{-1}）能将顶夸克伴子的质量排除到1565GeV;

4、尽管LHT模型受到LHC和FCC-eh实验的严格限制，仍然保持自然。

河南师范大学
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谢谢大家！