HADRON COLLIDER PRODUCTION OF MASSIVE VECTOR COLOR-OCTET @ NLO
&
CONSTRAINTS ON THE PARAMETER SPACE

Arsham Farzinnia
Tsinghua University

August 1, 2013

OVERVIEW

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- **PART I:** Hadron Collider Production of Massive Color-Octet Vector Bosons at Next-to-Leading Order
  - The Coloron Model
  - NLO Formal Analysis
  - NLO Phenomenological Analysis

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- **PART II:** Constraints on the Scalar Sector of the Renormalizable Coloron Model
  - Theoretical Constraints
  - Experimental Constraints

PART I

HADRON COLLIDER PRODUCTION OF MASSIVE COLOR-OCTET VECTOR BOSONS AT NEXT-TO-LEADING ORDER

R.S. CHIVUKULA, A. F., R. FOADI, E.H. SIMMONS, PRD85 (2012) 054005 [ARXIV:1111.7261 [HEP-PH]]
R.S. CHIVUKULA, A. F., J. REN, E.H. SIMMONS, PRD87 (2013) 094011 [ARXIV:1303.1120 [HEP-PH]]

MOTIVATION

- Axigluon *[Frampton, Glashow (1987); Bagger, Schmidt, King (1988)]*
- Topcolor *[Hill (1991); Hill, Parke (1994); Popovic, Simmons (1998)]*
- Models with Colored Technifermion *[Chivukula et al. in *Barklow, T.L. (ed.) et al.*]*
- Coloron *[Chivukula et al. (1996); Simmons (1997); Martynov, Smirnov (2009)]*
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Phenomenology:

- Top Quark Forward-Backward Asymmetry *[Ferrario, Rodrigo (2009); Frampton, Shu, Wang (2010)]*

IN PART I..

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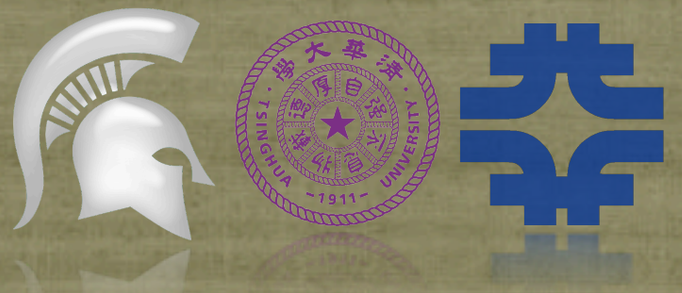

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- Quark-antiquark annihilation & gluon-fusion channels

COLORON THEORY

$$SU(3)_{1c} \times SU(3)_{2c}$$

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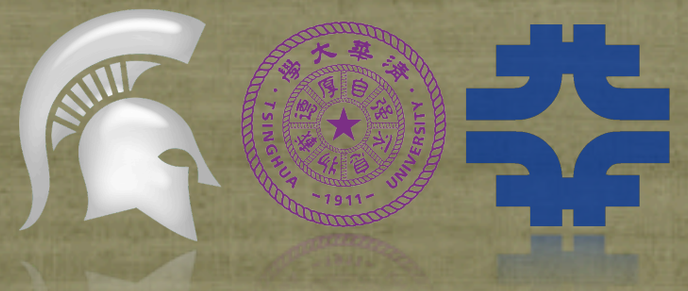

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- 8 massless gauge bosons (massless vector color-octet)
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FORMALISM: GAUGE SECTOR

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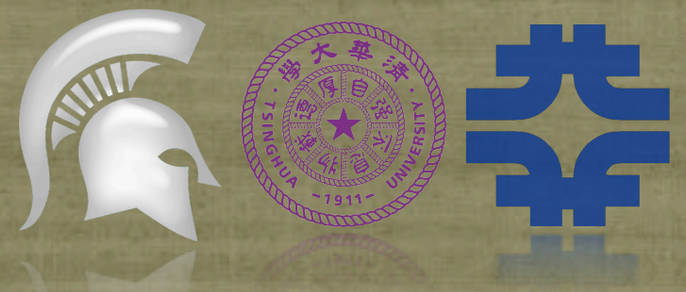

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g_{s_1} g_{s_2}

$\Big\downarrow\Big\downarrow$ v_s (VEV)

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QCD

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$$\sin\theta_c = \frac{g_{s_1}}{\sqrt{g_{s_1}^2 + g_{s_2}^2}}$$

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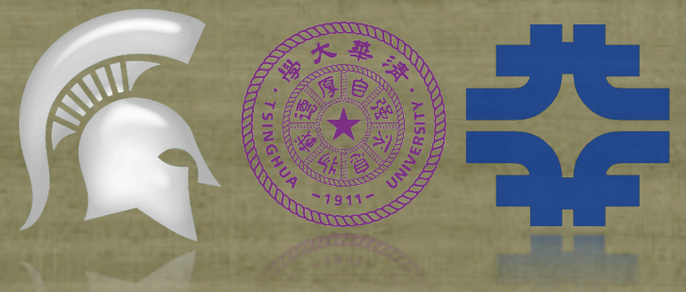

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$$g_s = g_{s_1}\cos\theta_c = g_{s_2}\sin\theta_c \qquad \left(\frac{1}{g_s^2} = \frac{1}{g_{s_1}^2} + \frac{1}{g_{s_2}^2}\right)$$

- 8 massless gluons
- 8 massive colorons $M_C \propto \dfrac{g_s\, v_s}{\sin 2\theta_c}$

FORMALISM: QUARK COUPLINGS

General chiral coupling of matter to the gauge bosons:

$$\mathcal{L}_{\text{quark}} = \bar{q}^i i \left[\not{\partial} - i g_s \not{G}^a t^a - i \not{C}^a t^a \left(g_L P_L + g_R P_R \right) \right] q_i$$

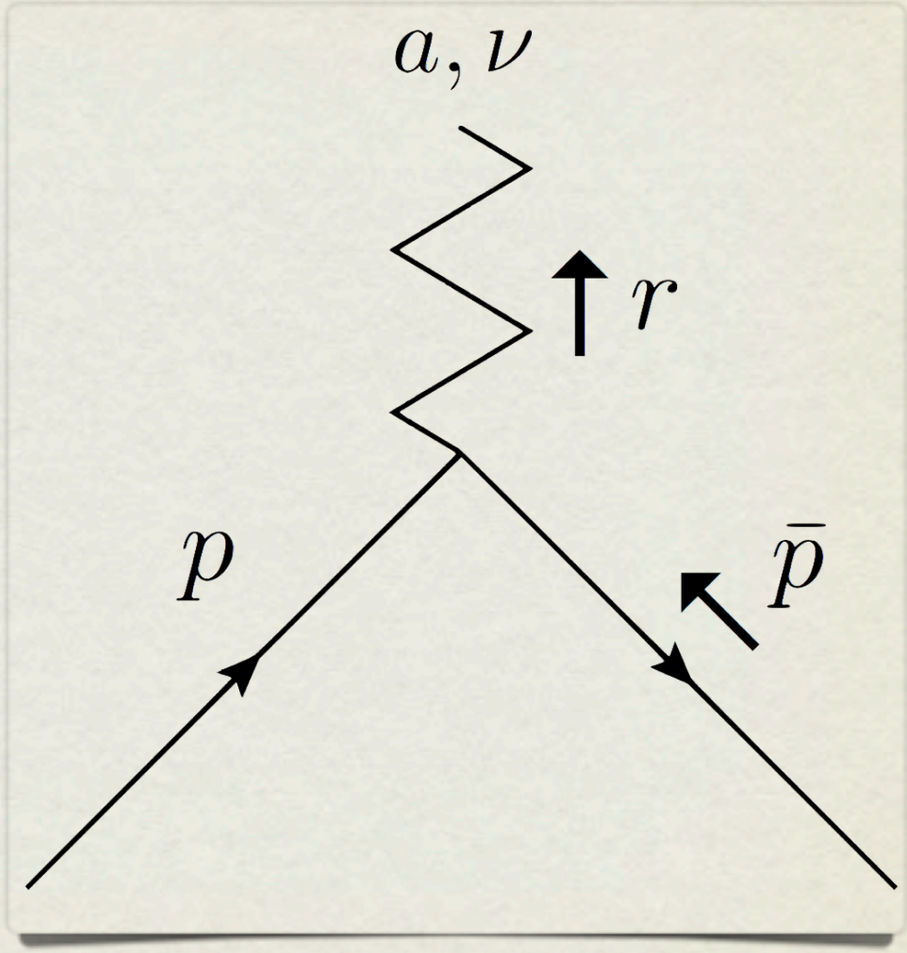
helicity projection operators: $P_{L,R} \equiv \frac{1 \mp \gamma_5}{2}$

Depending on how quarks transform under the original gauge group, choose:

$$g_L, g_R \in \{ -g_s \tan\theta_c, g_s \cot\theta_c \}$$

e.g. in Axigluon models $\theta_c = \pi/4$

COLORON PRODUCTION: TREE-LEVEL



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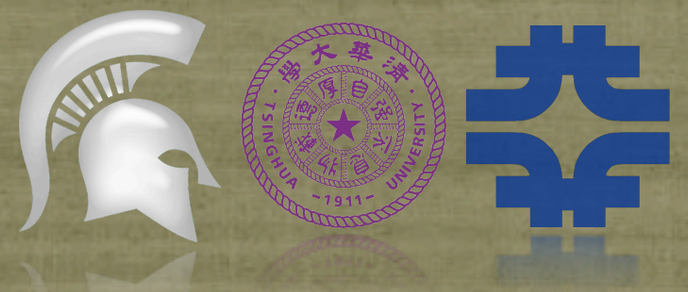
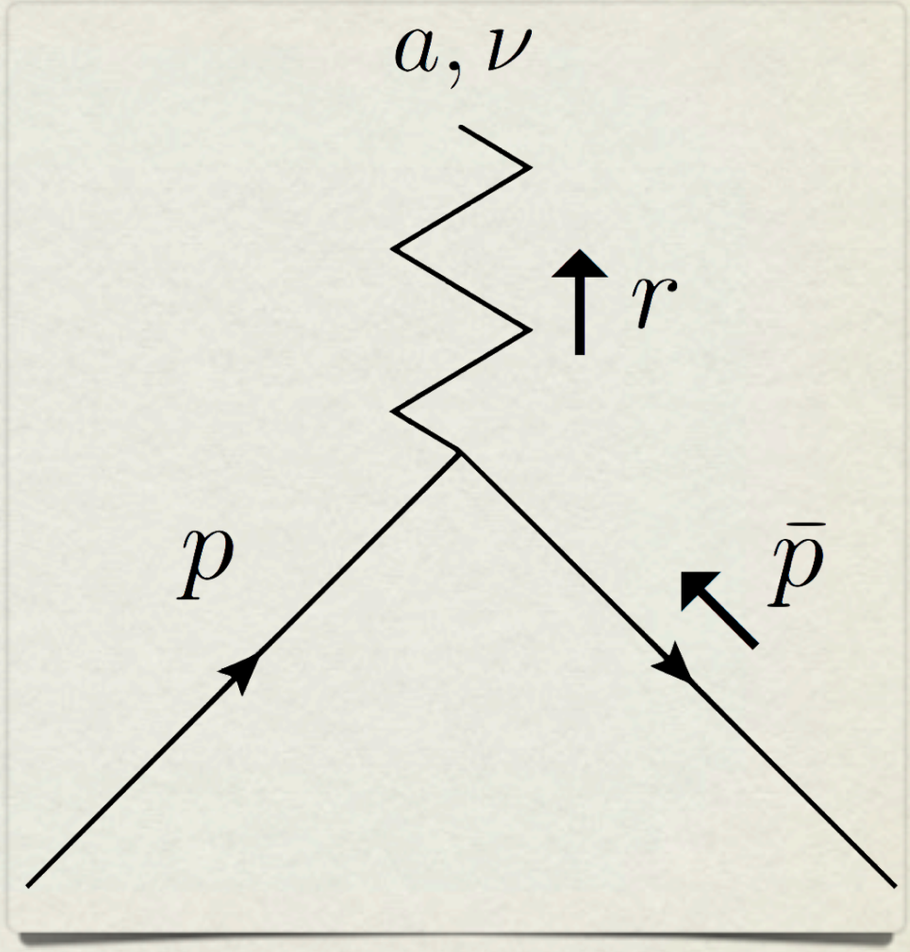


- Quark-antiquark annihilation



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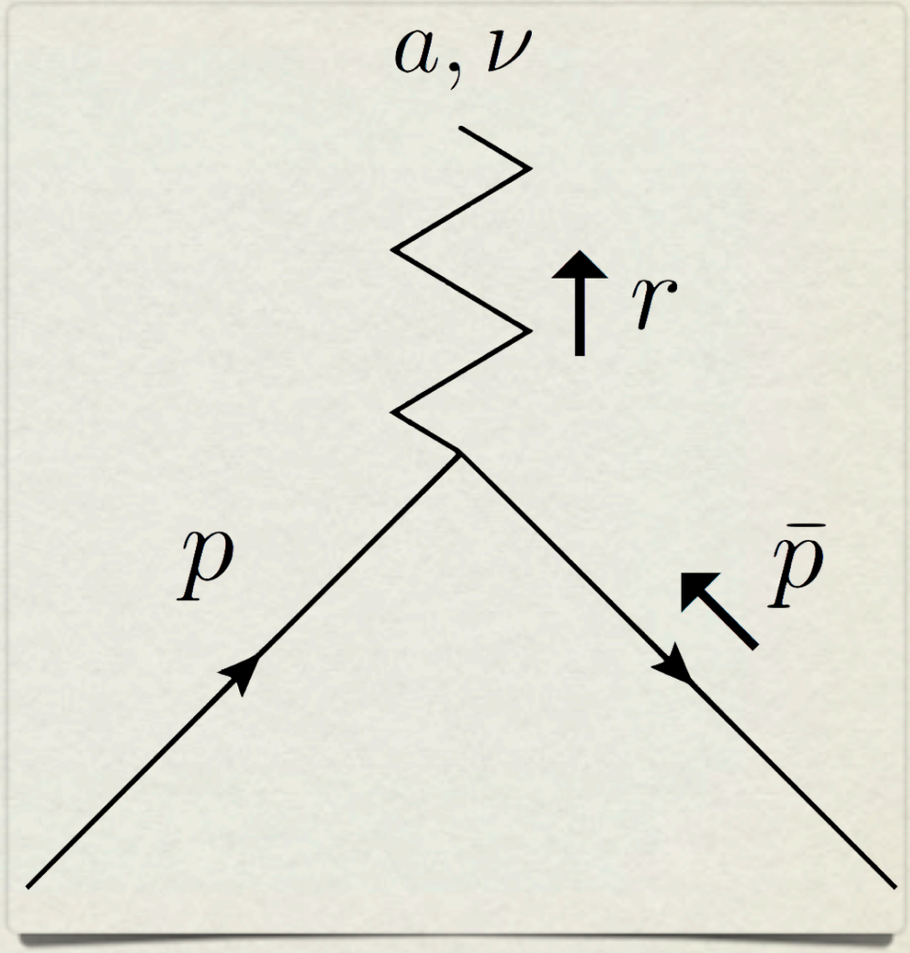
- Quark-antiquark annihilation
- No gluon-fusion at tree-level!! *[Chivukula, Grant, Simmons (2001)]*



COLORON PRODUCTION: TREE-LEVEL

- Quark-antiquark annihilation
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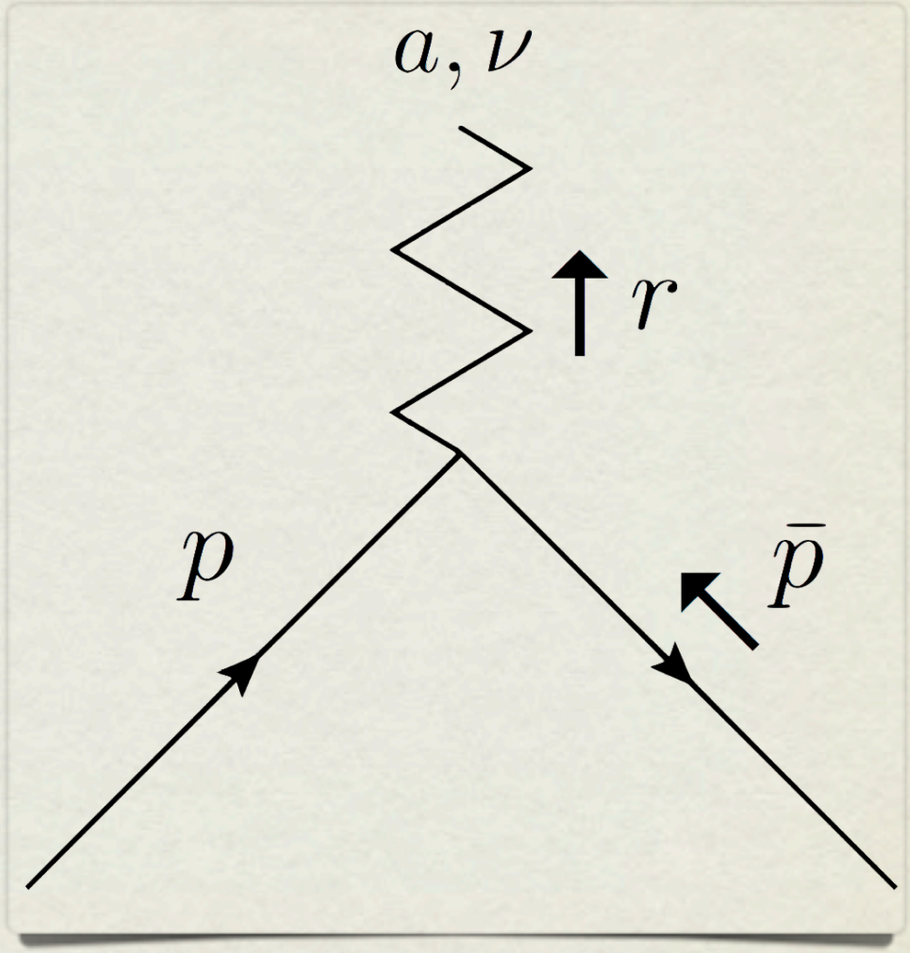
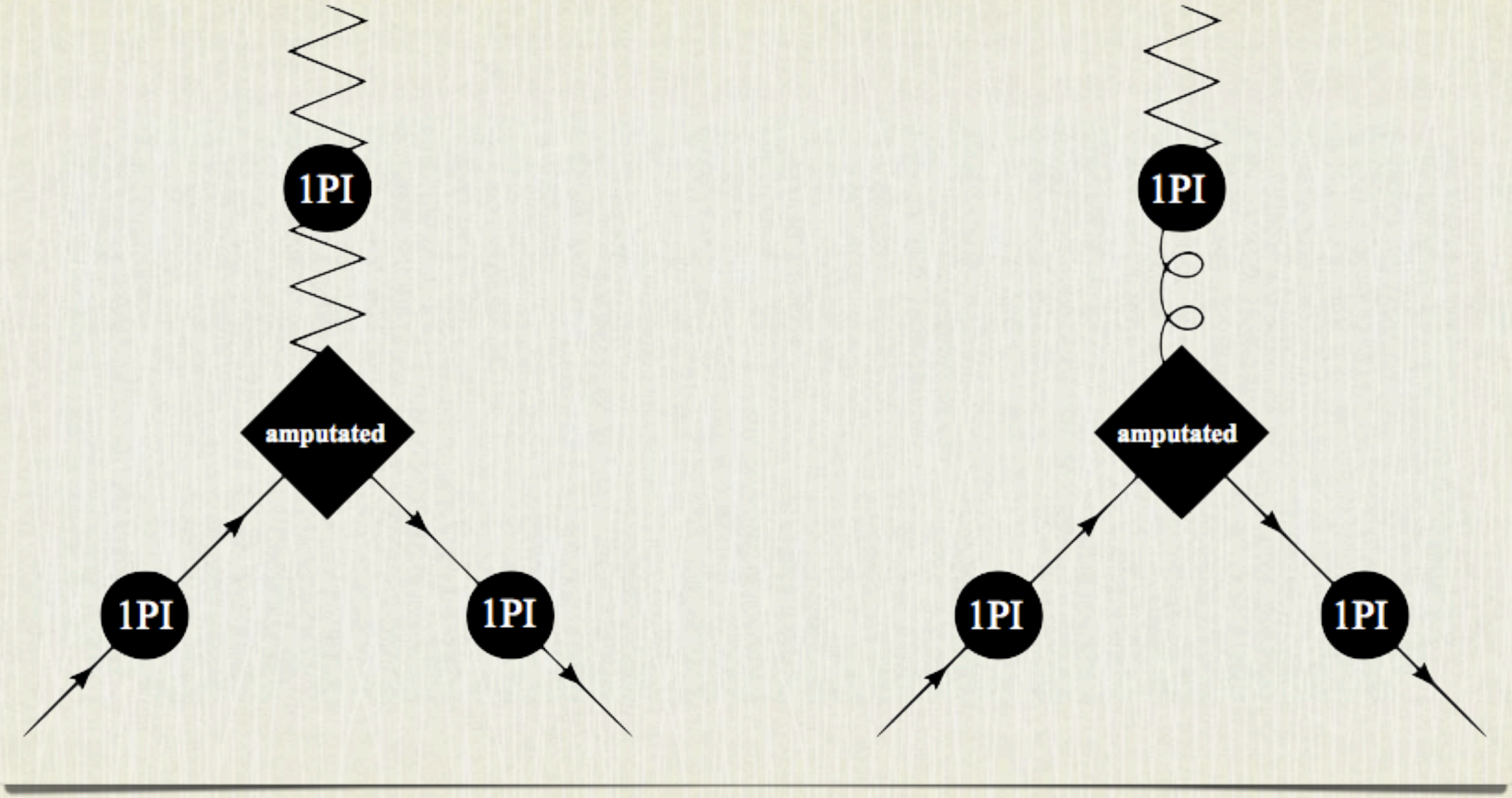
- General quark couplings

$$q\bar{q}C_\mu^a = i\gamma_\mu \left(g_L P_L + g_R P_R\right) t^a$$

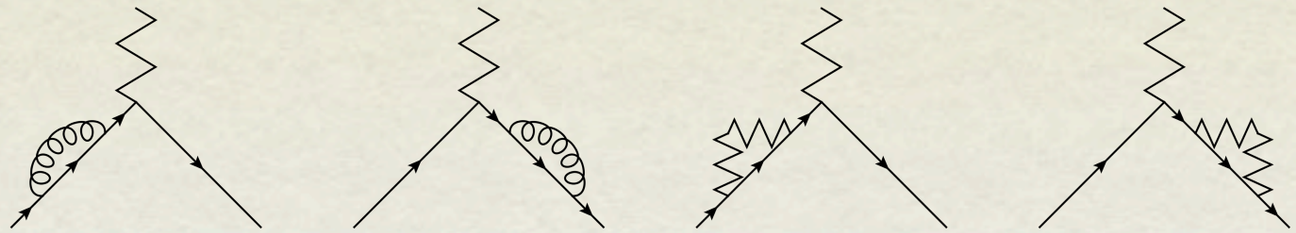




NLO PRODUCTION: VIRTUAL CORRECTIONS

VIRTUAL CORRECTION DIAGRAMS

Quark self-energy:



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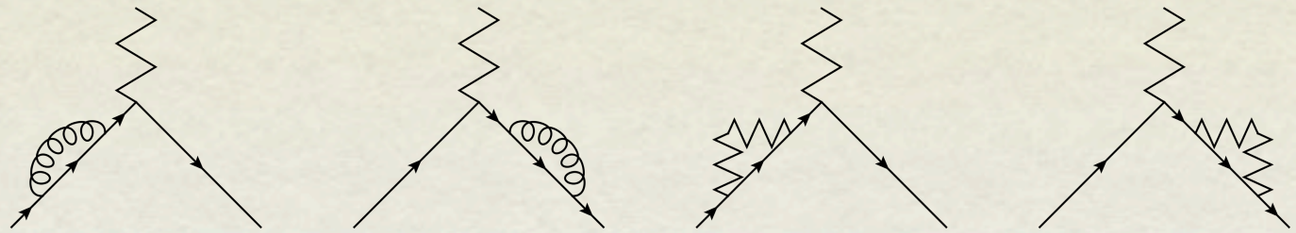
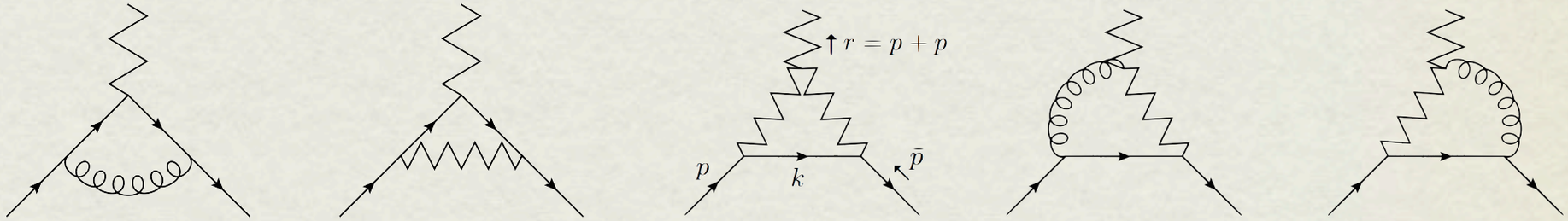


Abelian & non-Abelian vertices:



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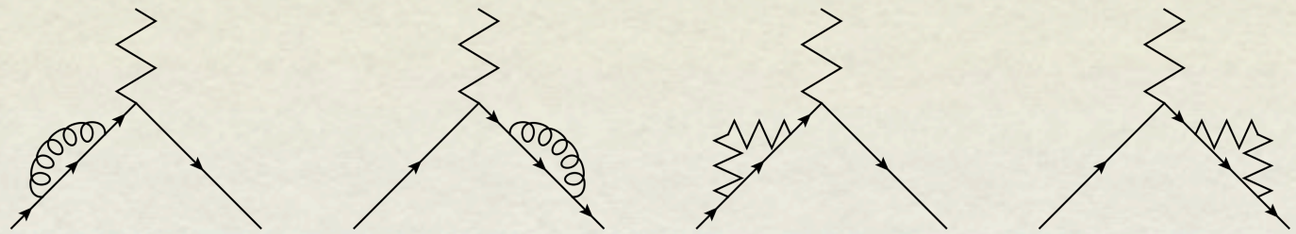

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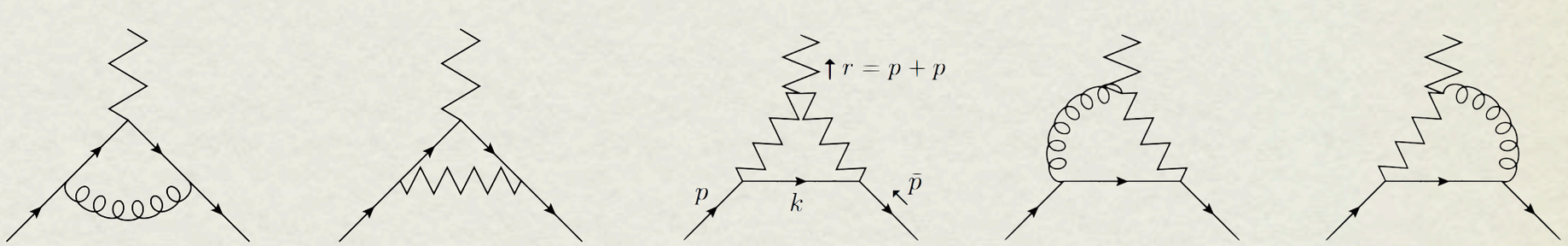
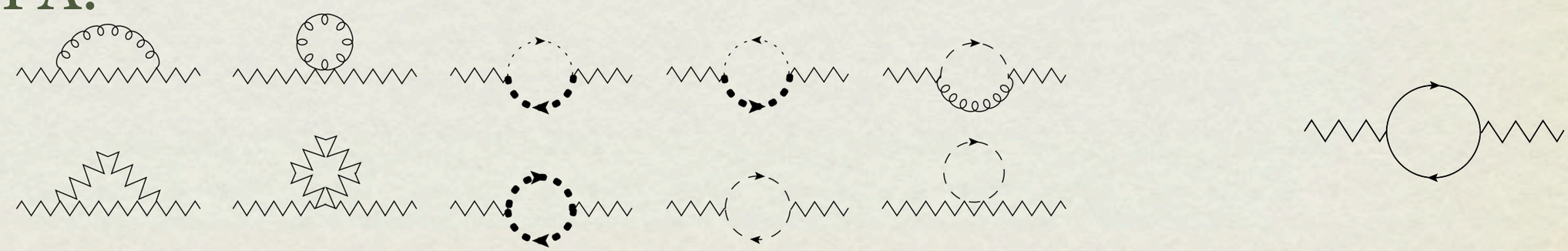


Coloron VPA:



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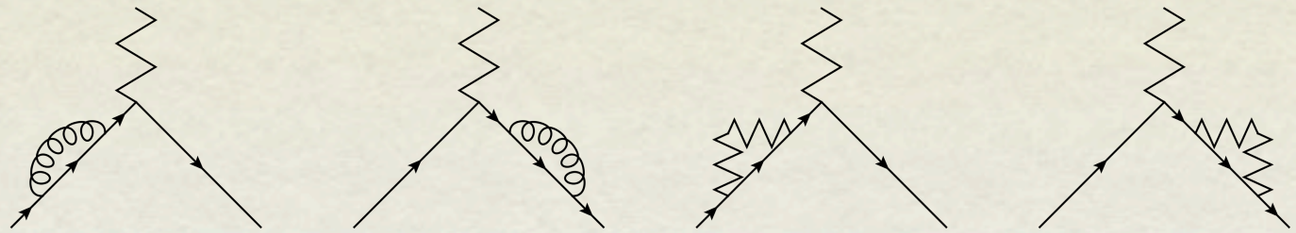

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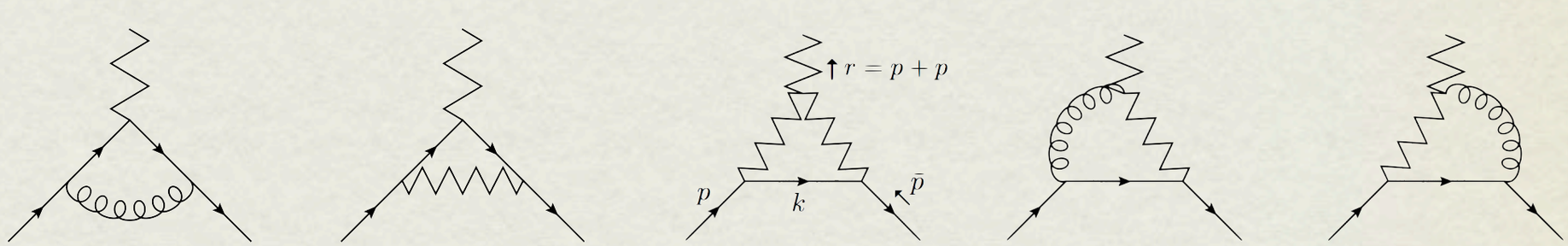

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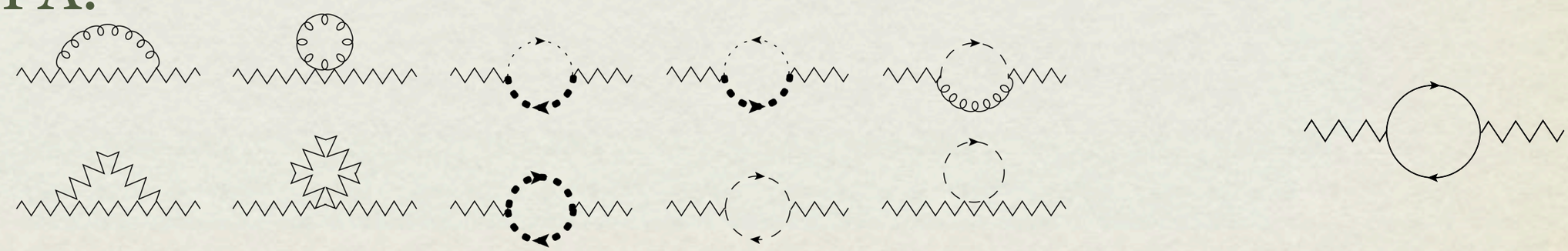
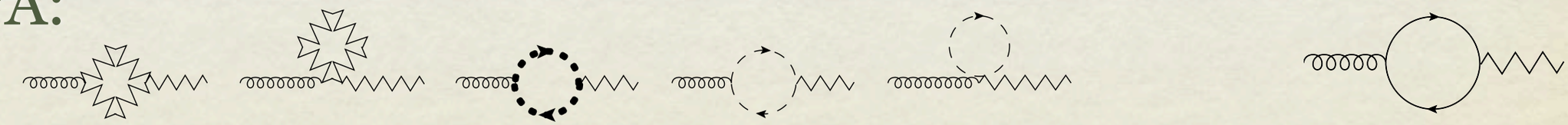


Mixed VPA:



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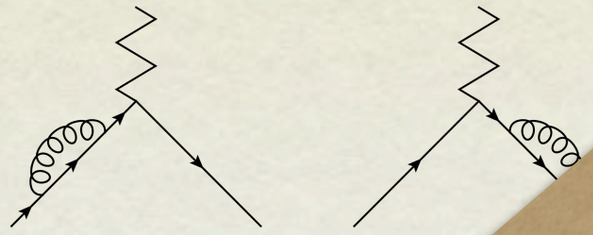

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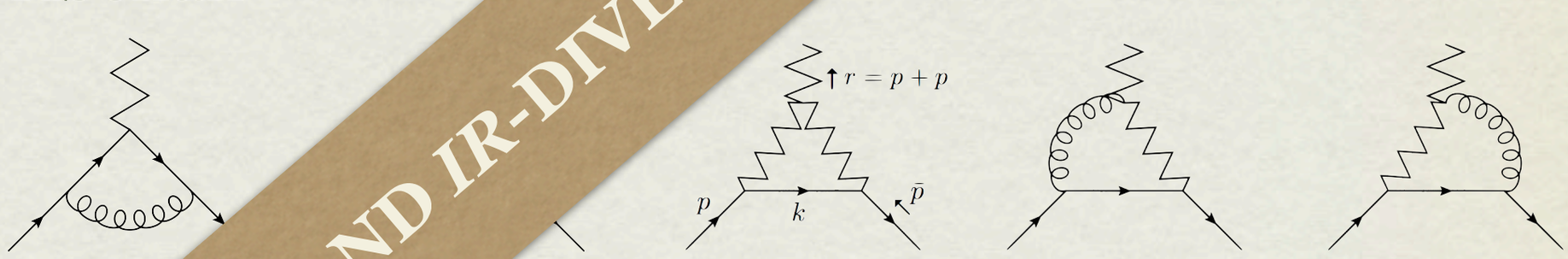

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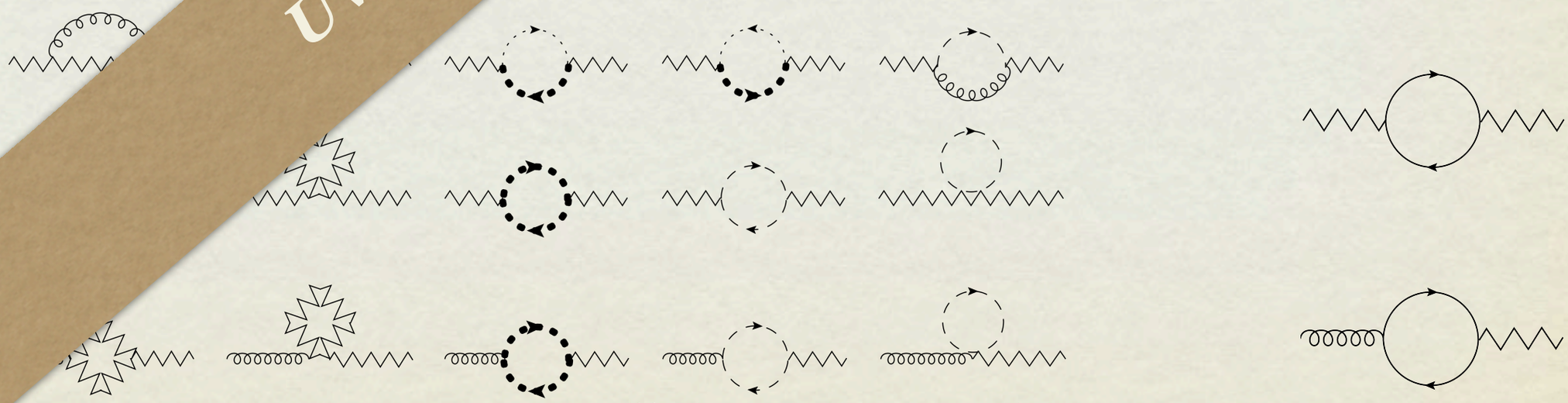
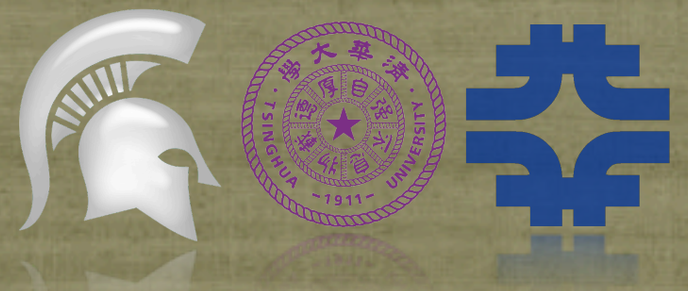


Mixed:

UV- AND *IR*-DIVERGENT!!

CURIOUS SUBTLETY..



QED Ward identity: $\partial^\mu j_\mu = 0$

☛ Cancellation of the *UV* divergence among vertex corrections and quark self-energy

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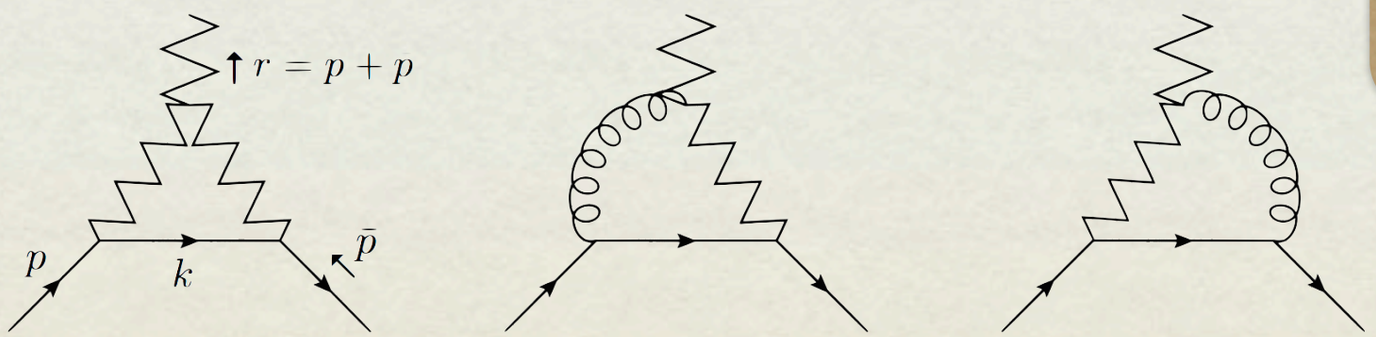
Non-Abelian gauge theory: $D^\mu j^a_\mu = 0$

☛ No such cancellation!!

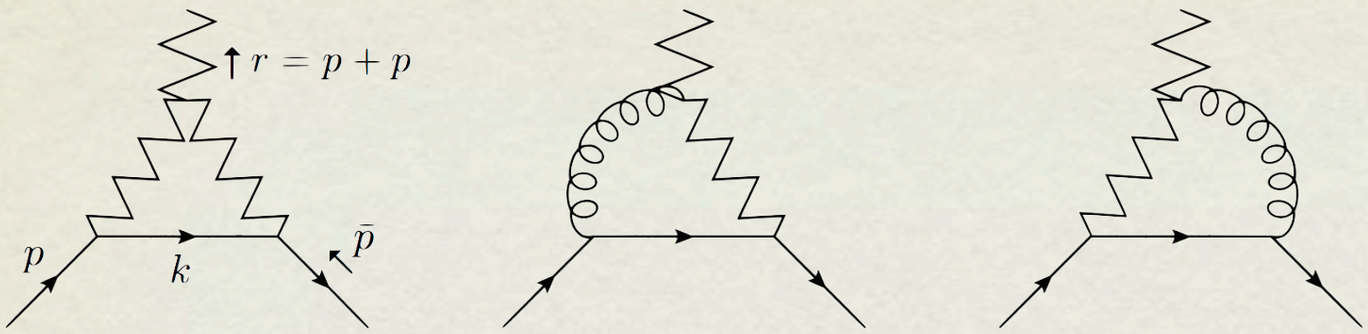
Need a consistent way of isolating *UV* from *IR*!!



REMEDY: USE PINCH TECHNIQUE

$$\Gamma^{\mu\nu\rho}(k,p,\bar{p}) = g^{\mu\nu}(-2p-\bar{p}+k)^{\rho} + g^{\nu\rho}(p-\bar{p}-2k)^{\mu} + g^{\rho\mu}(k+p+2\bar{p})^{\nu}$$

[Binosi, Papavassiliou (2009)]



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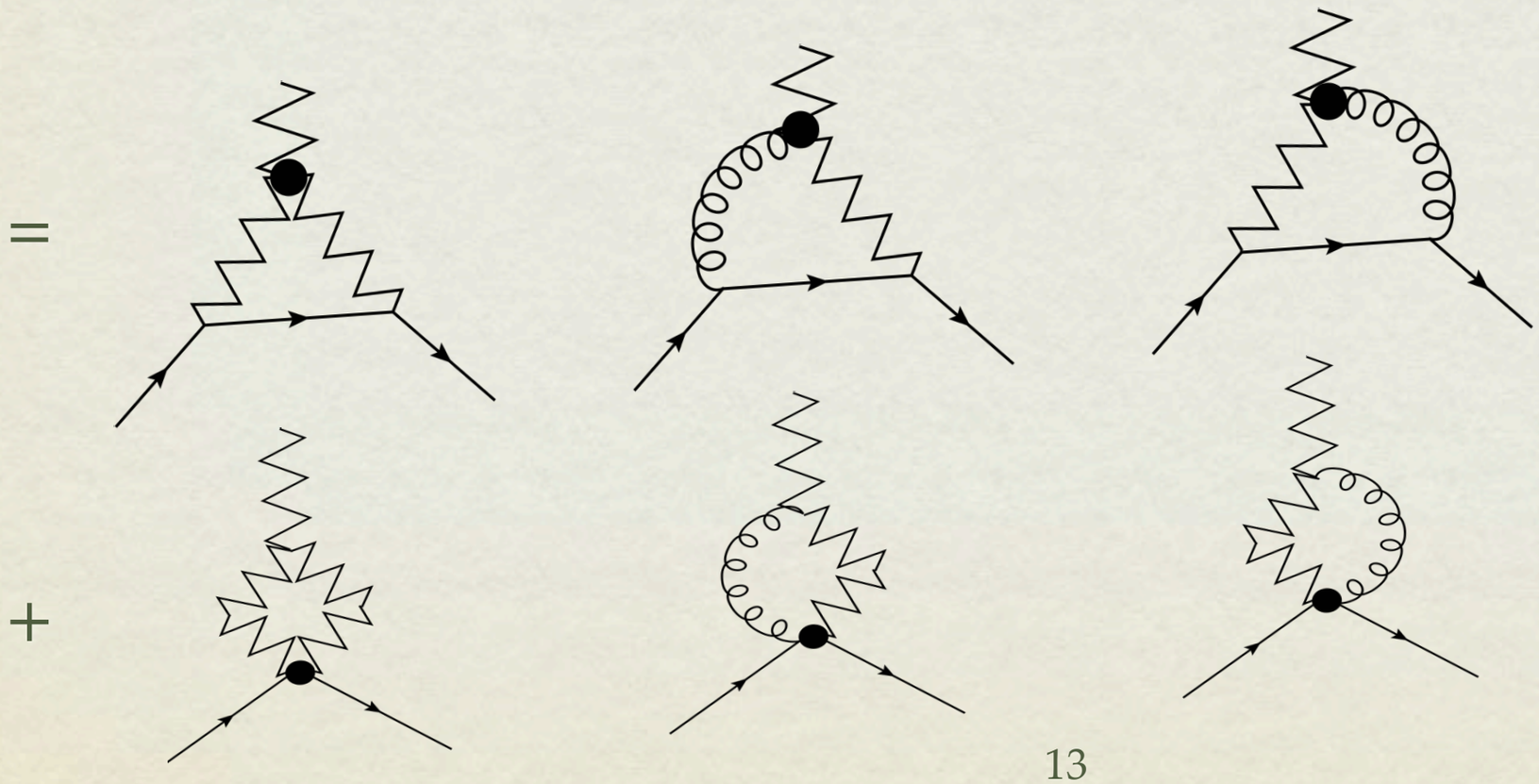

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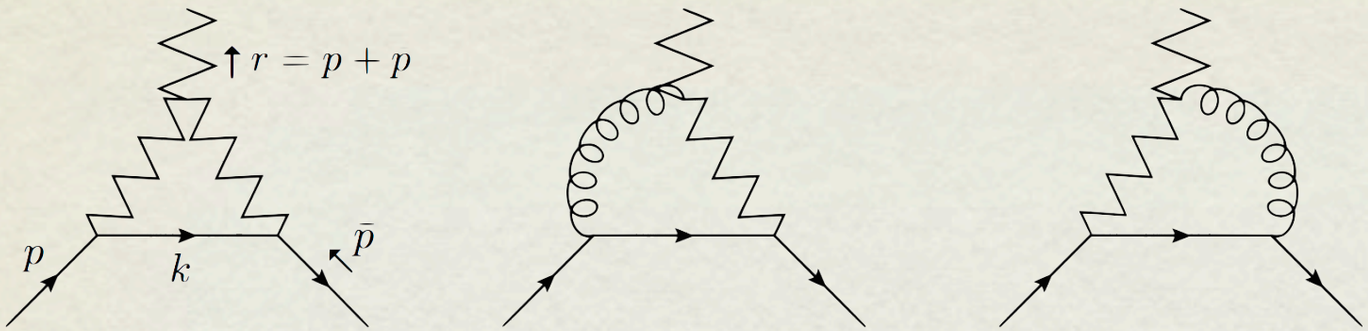

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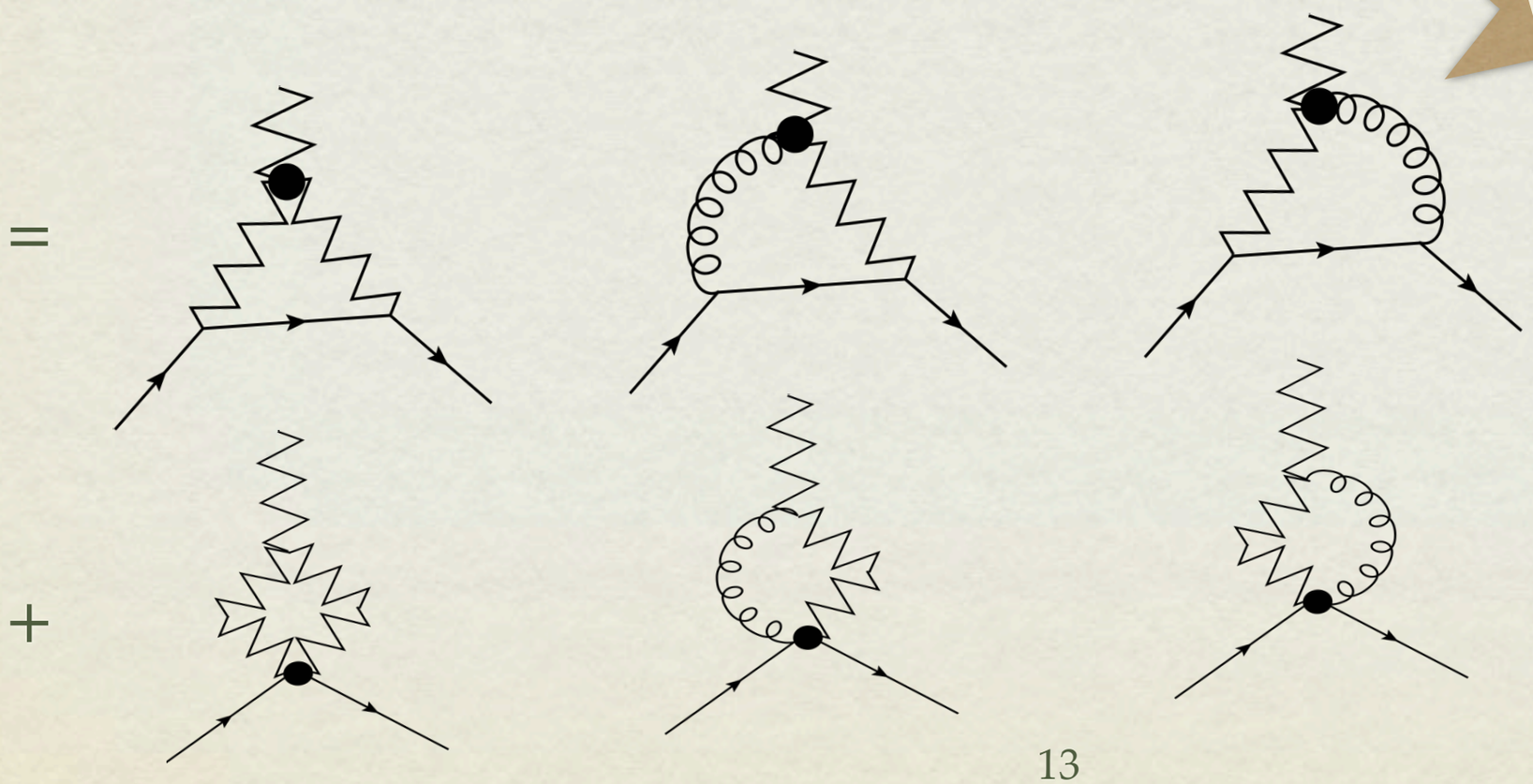
$$\Gamma^{\mu\nu\rho}_{P}(k,p,\bar{p}) = g^{\mu\nu}($$

"Unpinched": Satisfies QED-like Ward identity!!



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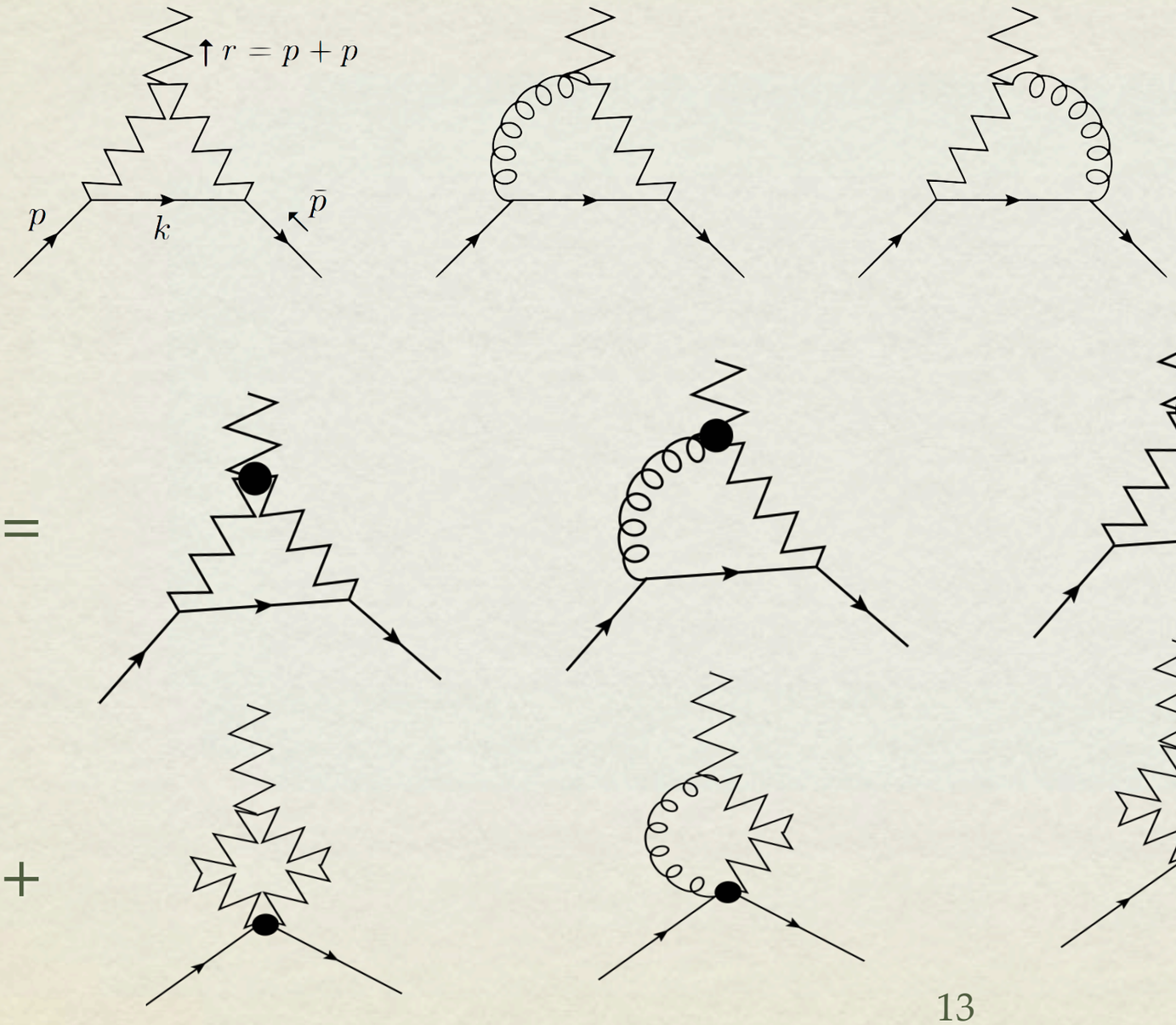

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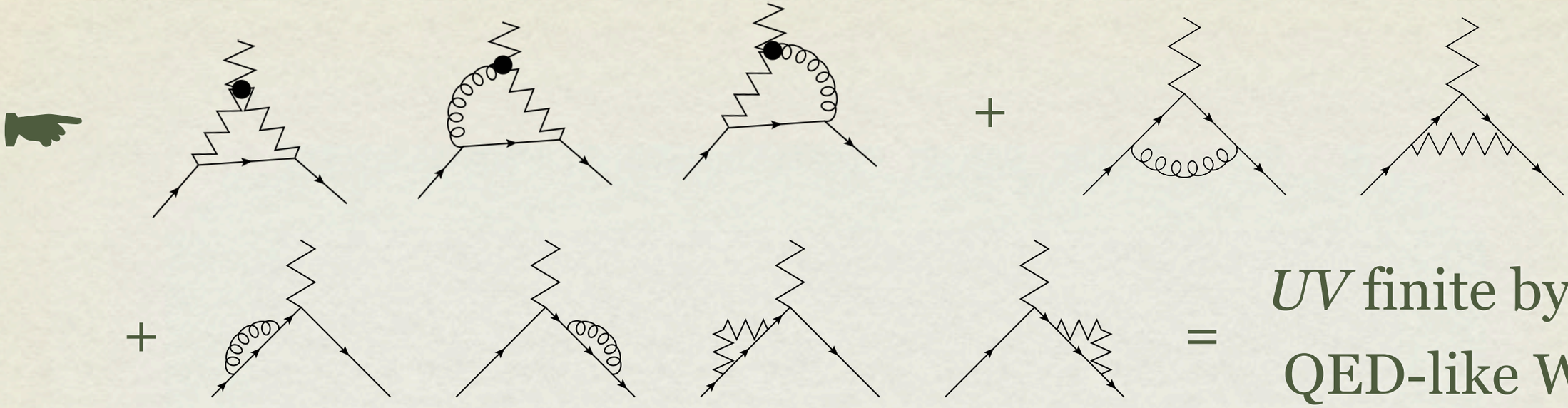
"Unpinched": Satisfies QED-like Ward identity!!

"Pinched": Looks like a propagator; reassign to the VPA!!

UV ISOLATION & CANCELLATION



UV finite by the QED-like WI!!

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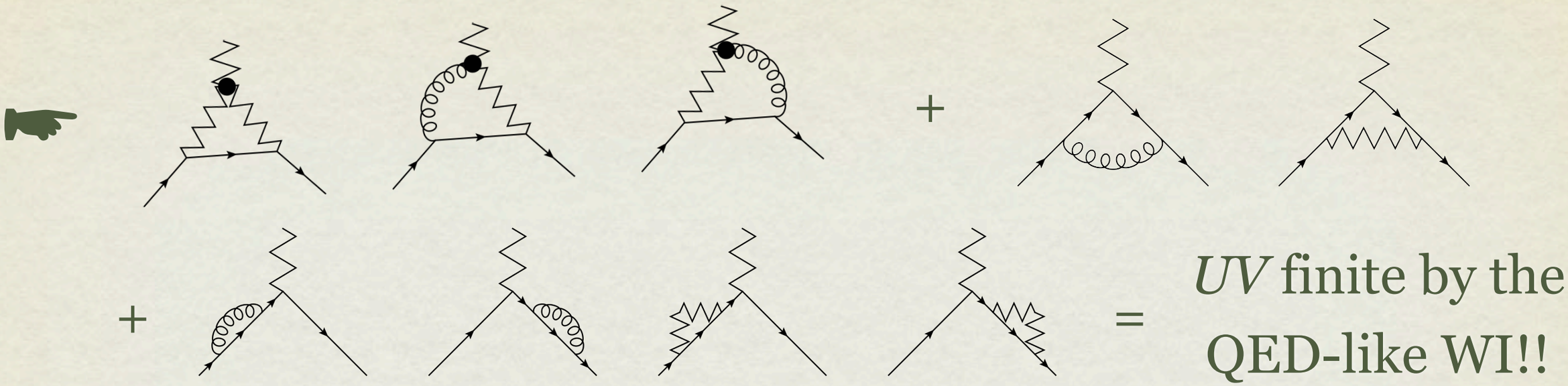

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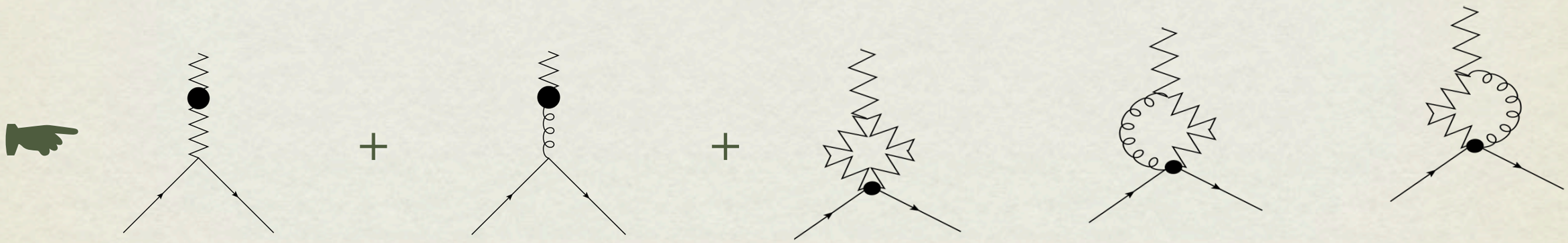
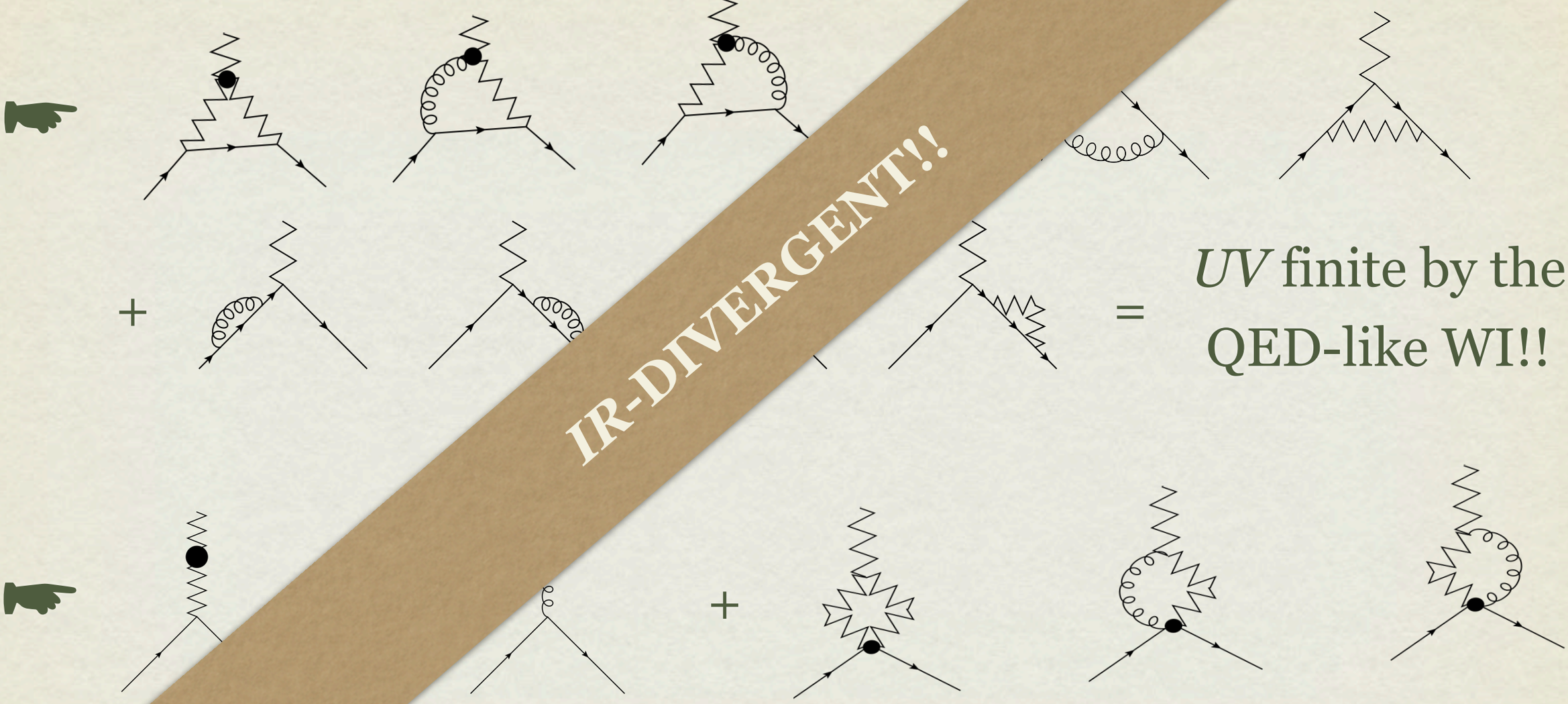


= Two gauge-invariant propagators (VPAs) ➙ cancel *UV* with the two available counterterms!!

UV ISOLATION & CANCELLATION



IR-DIVERGENT!!

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  ➙ no detection of "very low energy" (soft) and "very close together" (collinear) real particles

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- “Imperfect” detector with finite spatial and energy resolution ➞ no detection of “very low energy” (soft) and “very close together” (collinear) real particles

- Consists of real gluon and real (anti)quark emission

NLO PRODUCTION: REAL EMISSION CONTRIBUTIONS

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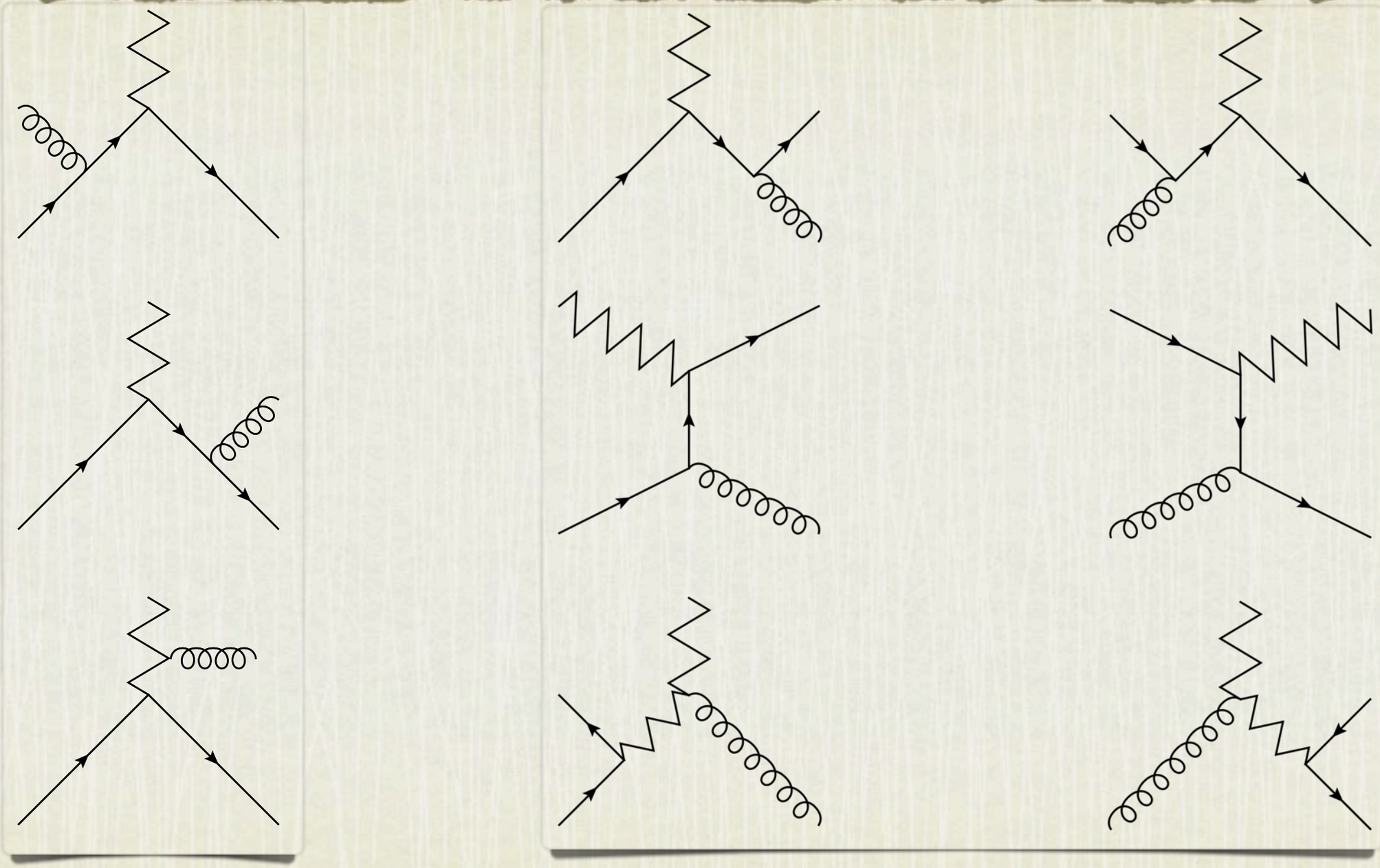
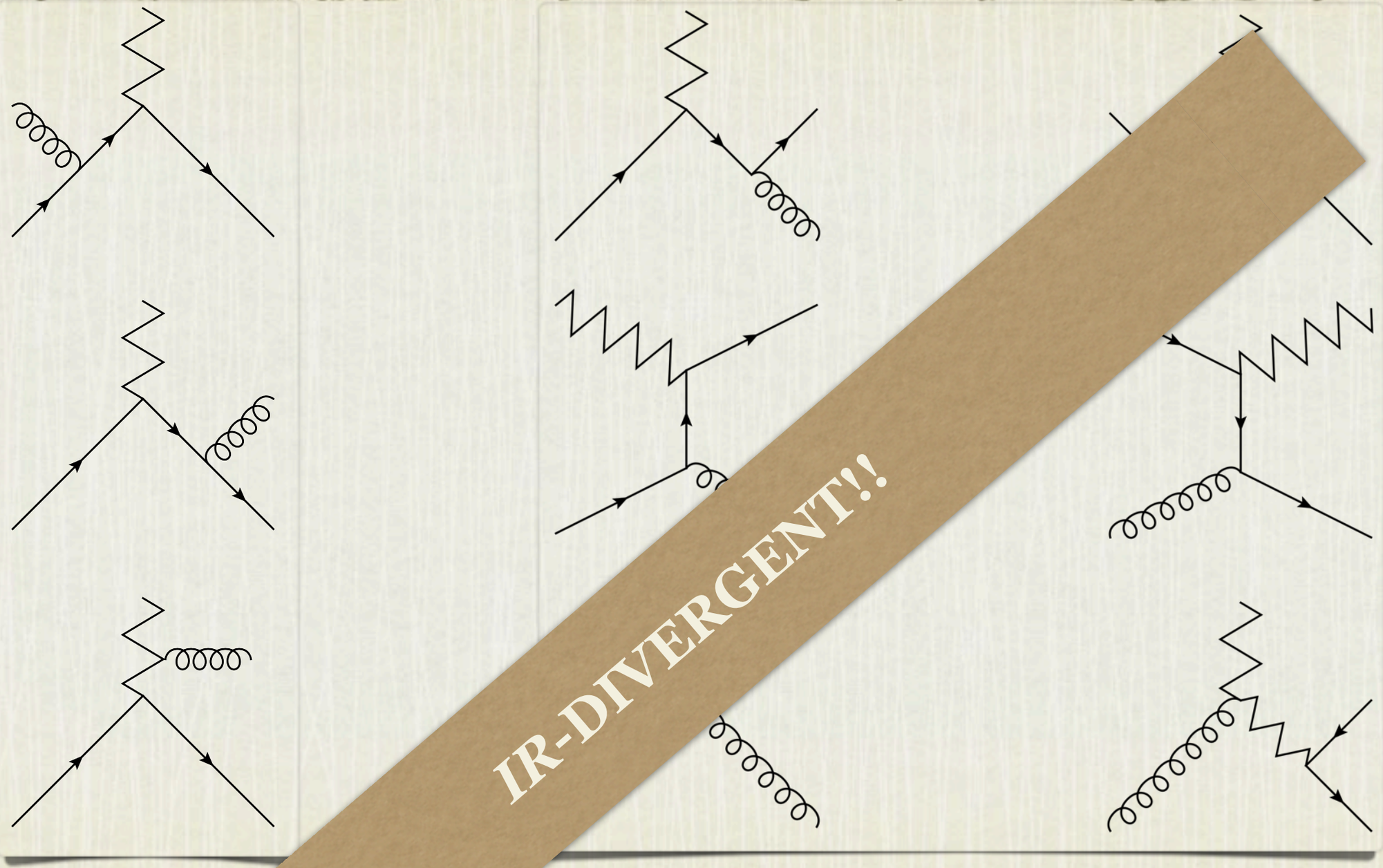
- These *IR* singularities must cancel against those in the virtual corrections!!



REAL EMISSION DIAGRAMS



IR-DIVERGENT!!

REAL EMISSION DIAGRAMS

NLO PRODUCTION CROSS SECTION

$$\sigma = \int dx_1 \int dx_2 \Bigg\{ \sum_q \Big[f_q^0(x_1) f_{\bar{q}}^0(x_2) + f_{\bar{q}}^0(x_1) f_q^0(x_2) \Big] \Big(\hat{\sigma}^{(0)}_{q\bar{q}\to C} + \hat{\sigma}^{(1)}_{q\bar{q}\to C} + \hat{\sigma}^{(1)}_{q\bar{q}\to gC} \Big)$$

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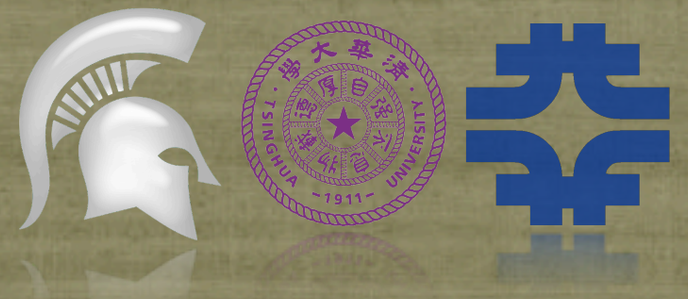

- Full hadron collider NLO production cross section:

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"bare" PDFs

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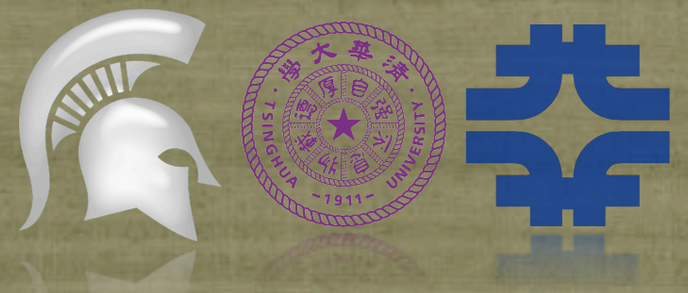

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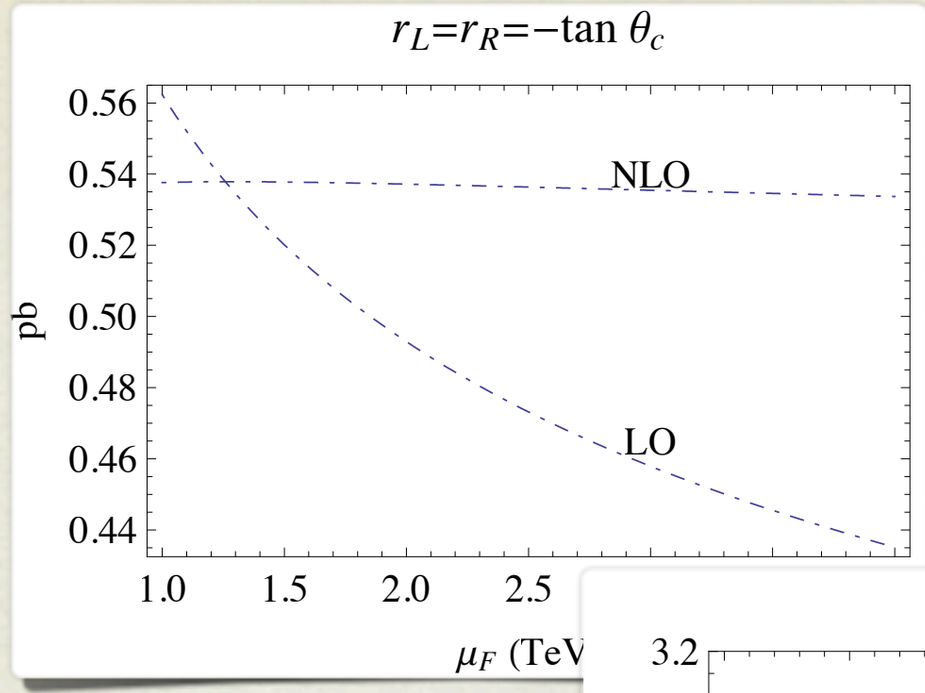
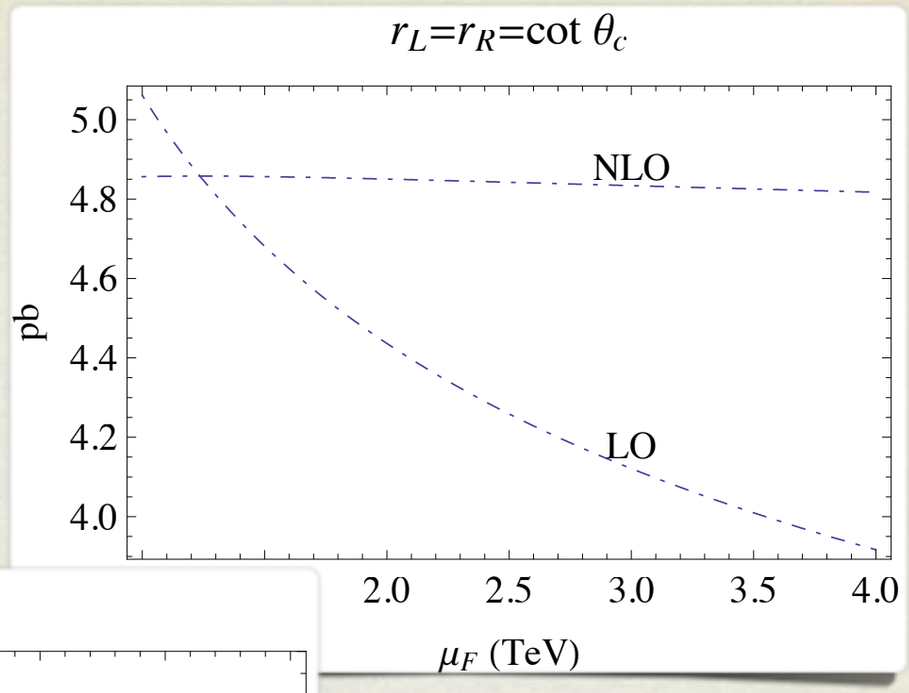
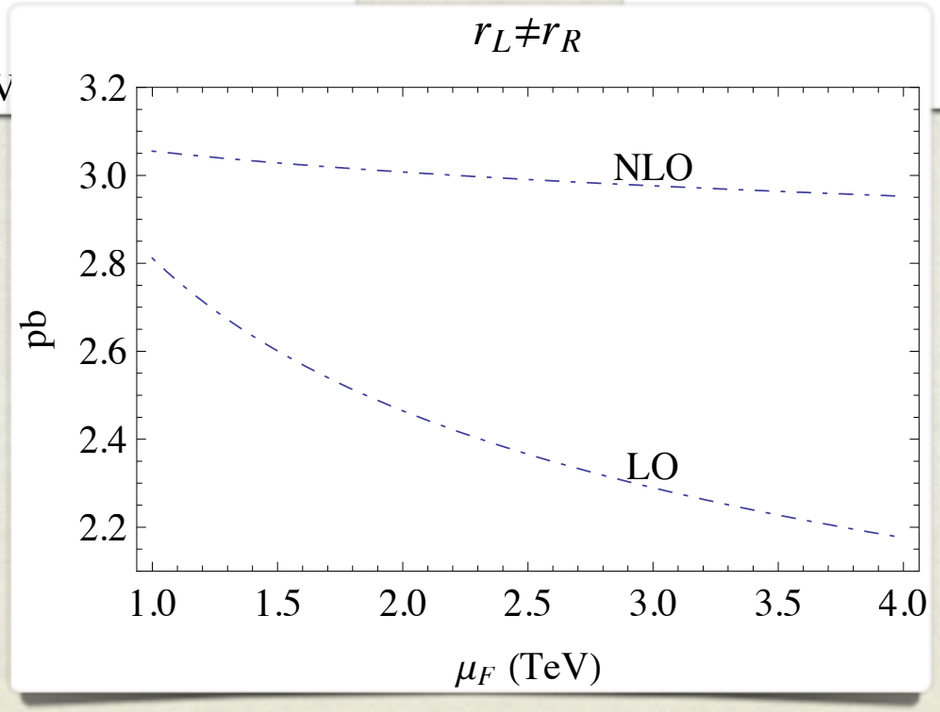
- Absorb them in "bare" PDFs ➙ PDF renormalization

FACTORIZATION-SCALE DEPENDENCE







$\sqrt{s} = 7\,\text{TeV}$

$\mu = M_C = 2.1\,\text{TeV}$

$\sin^2\theta_c = 0.25$

All-order result independent of μ_F

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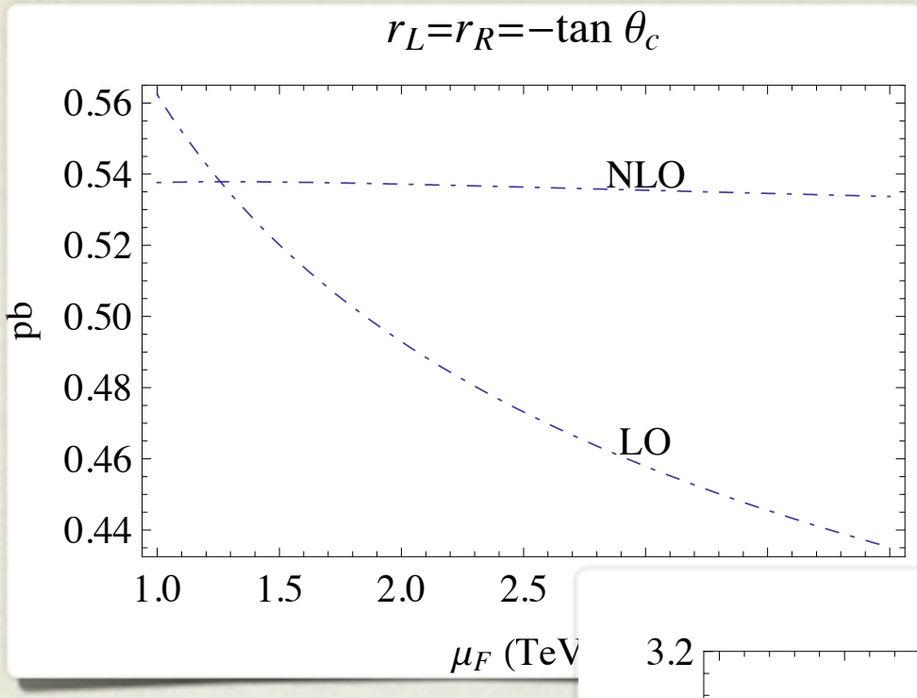

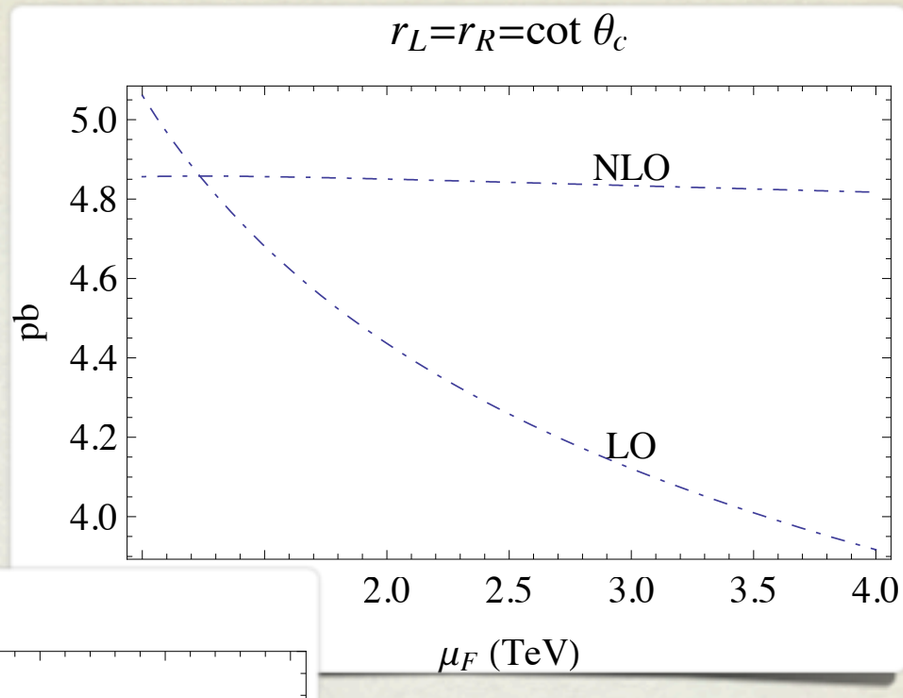

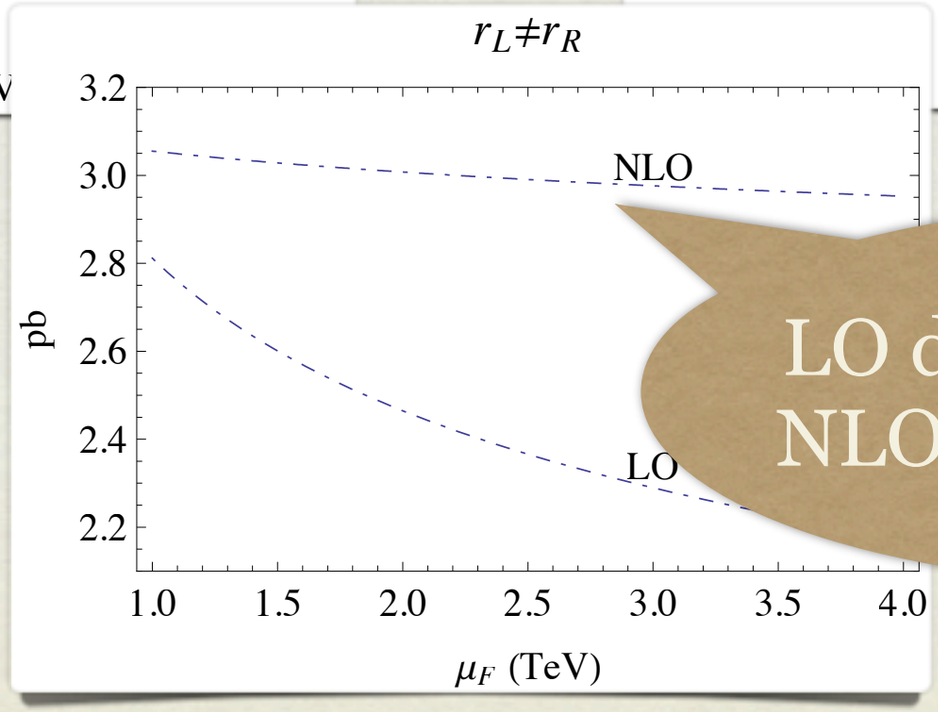

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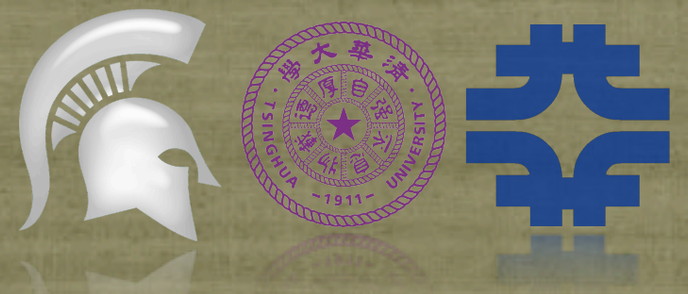
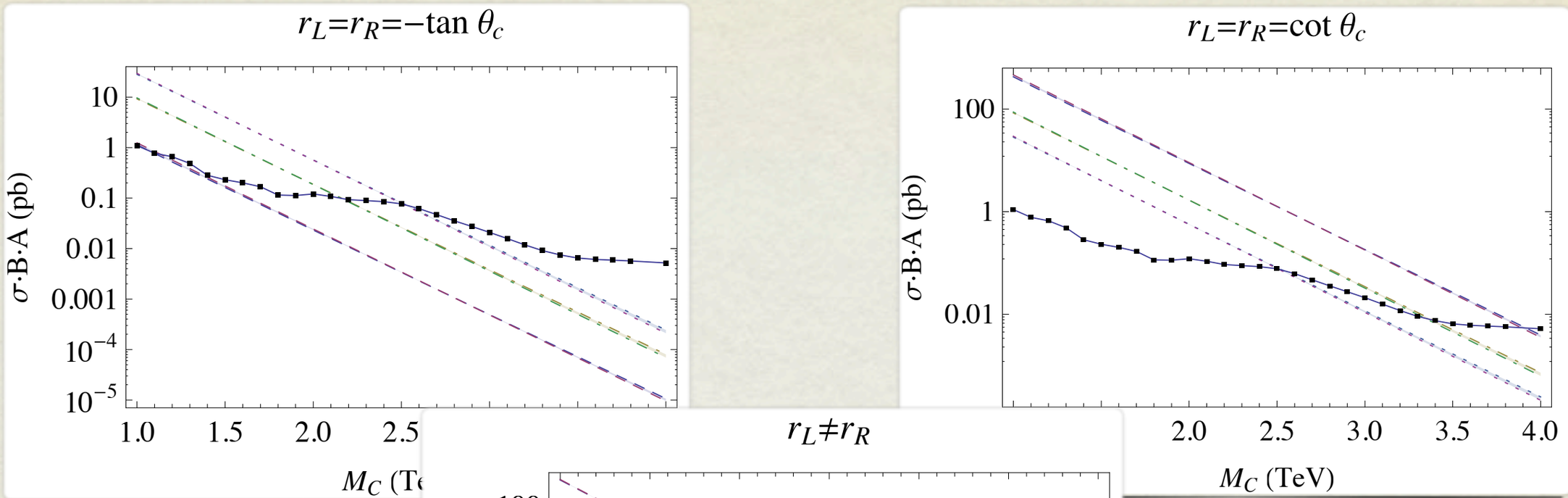
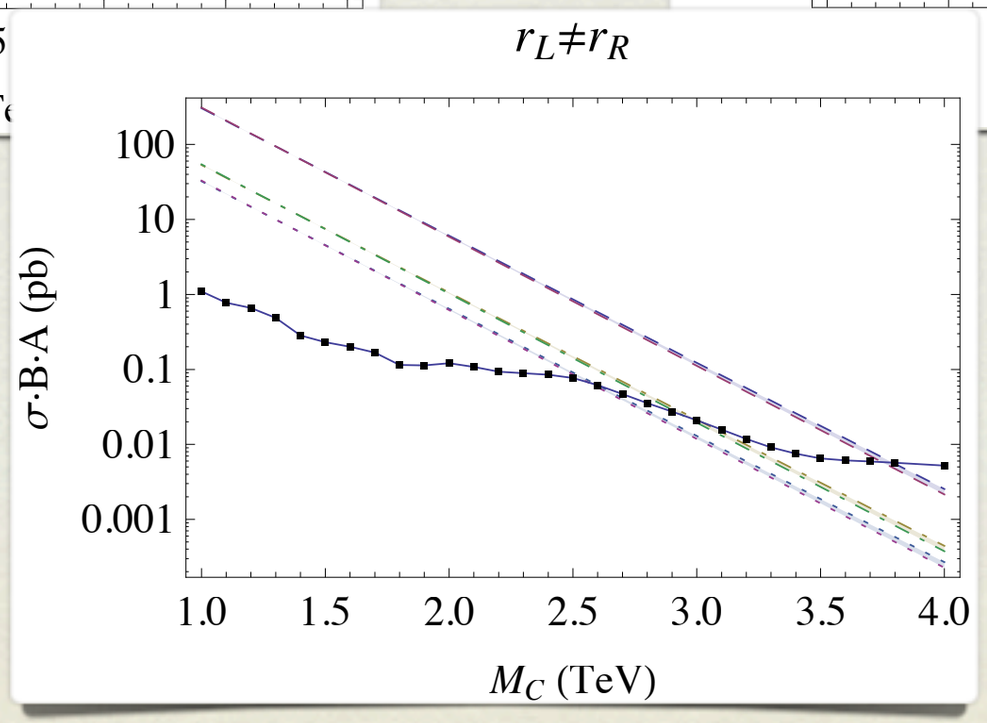
LO dependence: 30%
NLO dependence: 2%

NLO CROSS SECTION







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CMS upper bound (solid)

$\sin^2\theta_c = 0.05$ (dashed)

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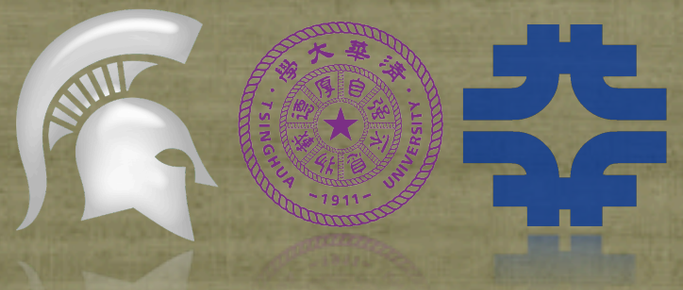
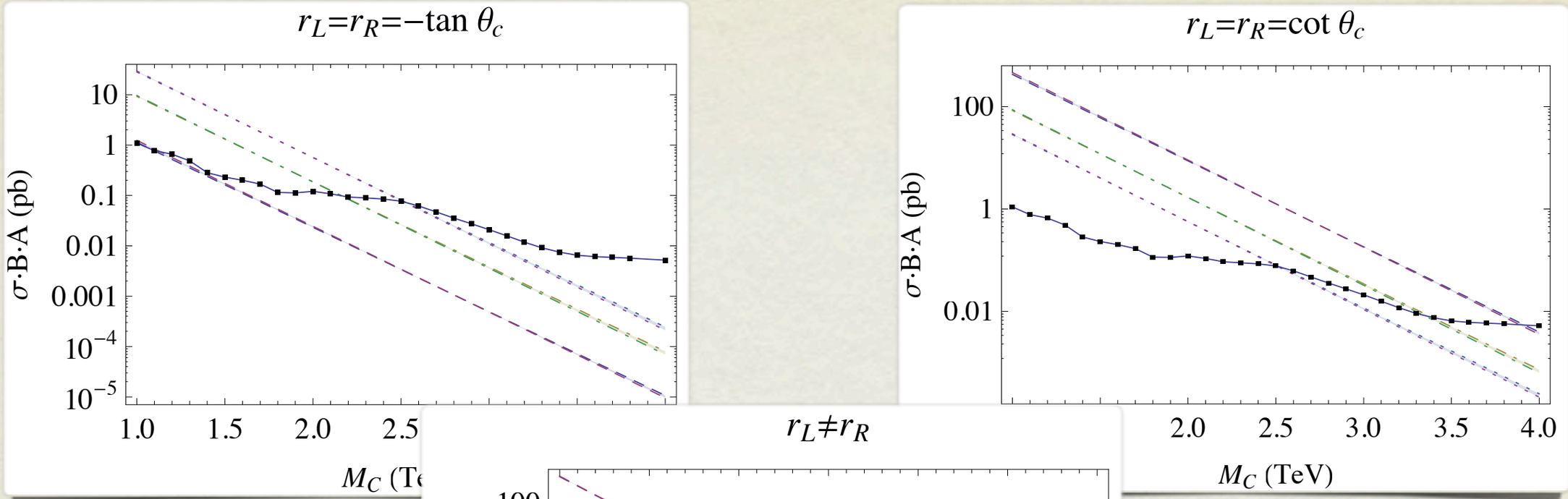
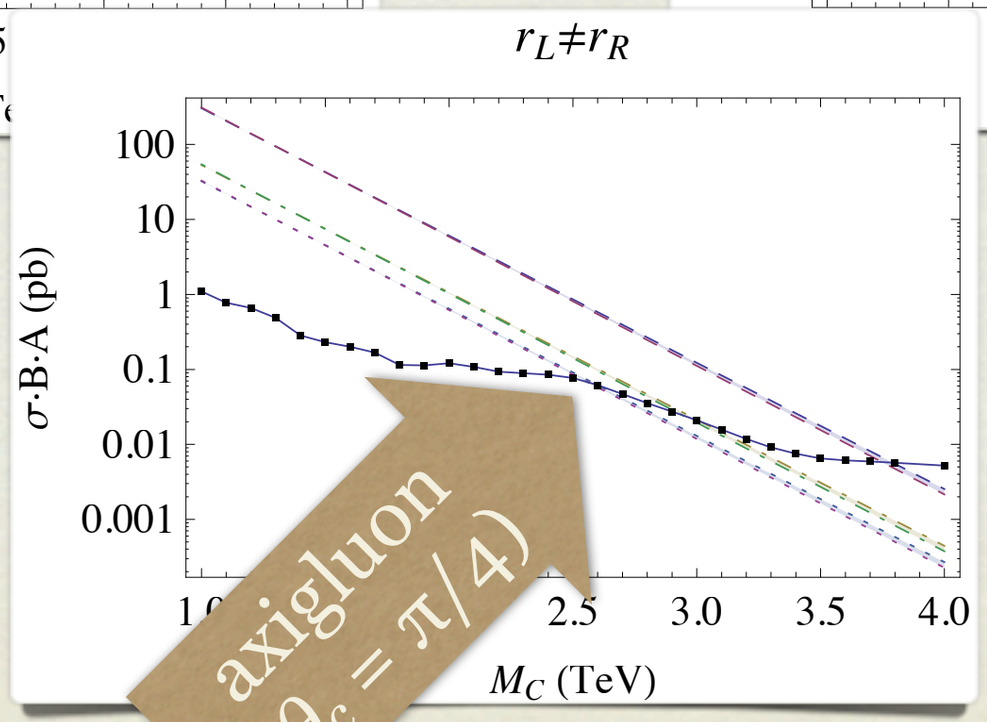
NLO CROSS SECTION







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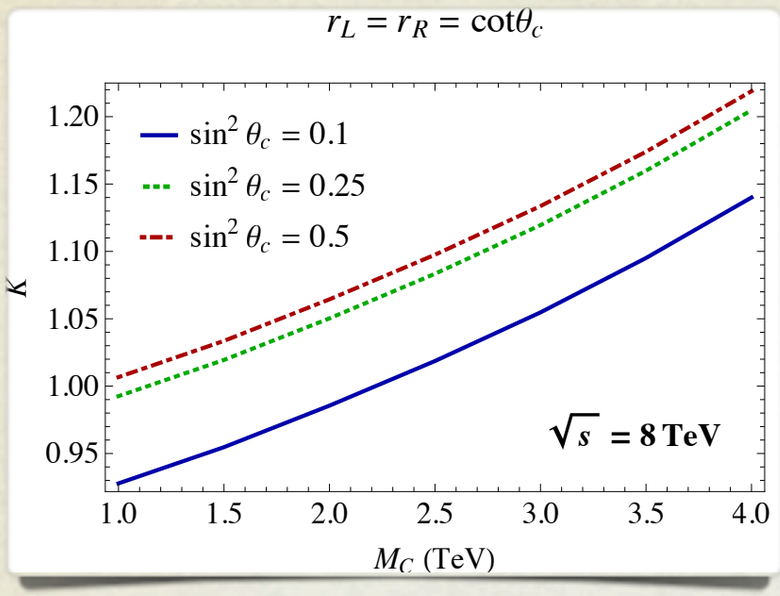

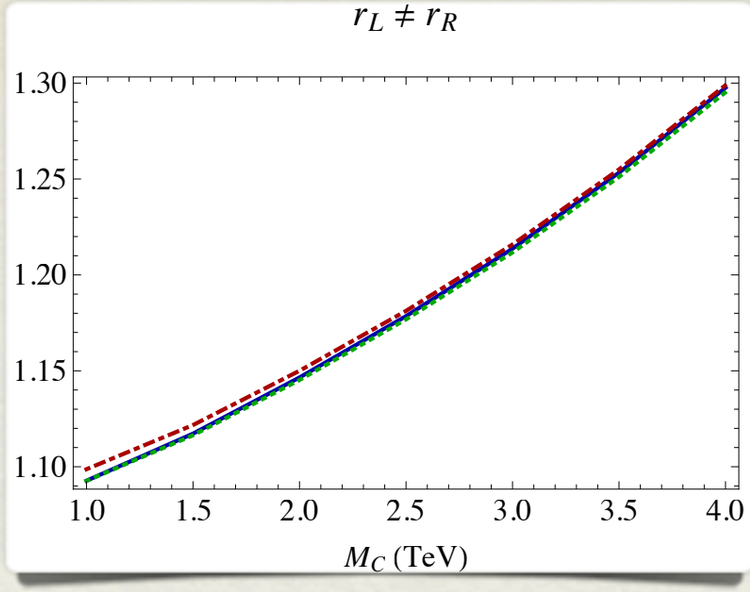

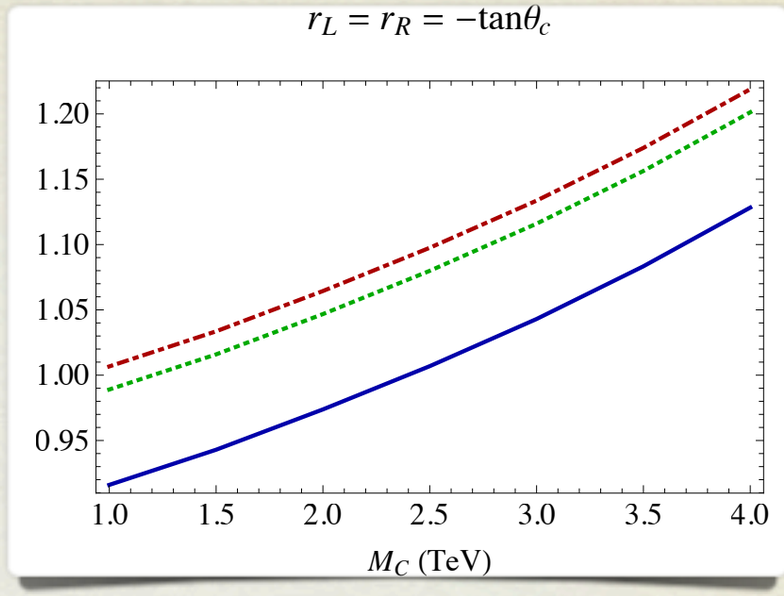

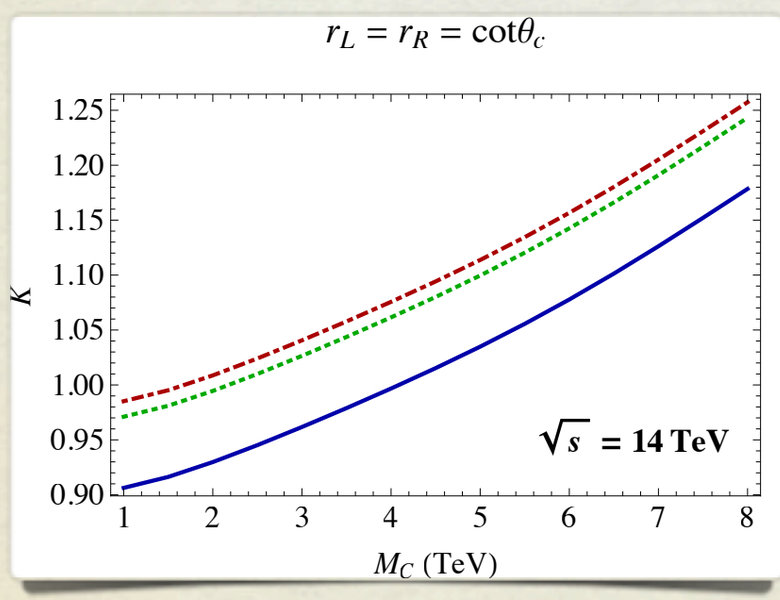

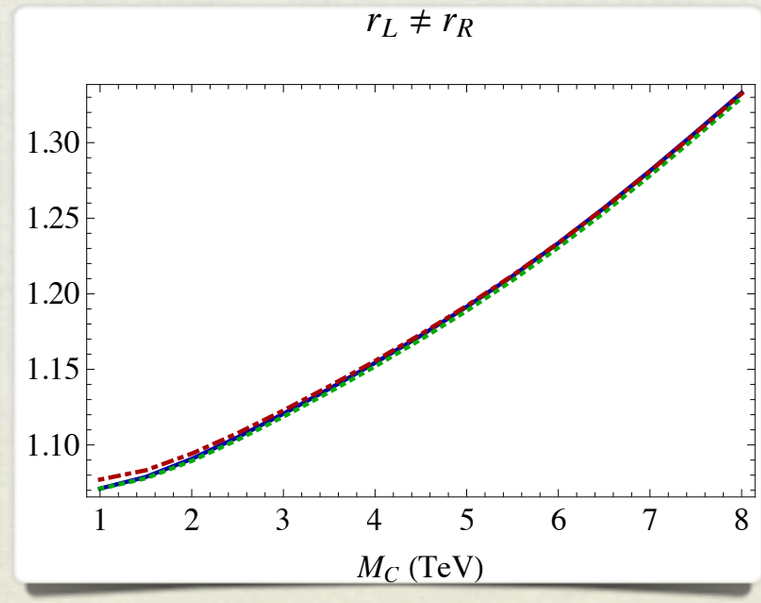

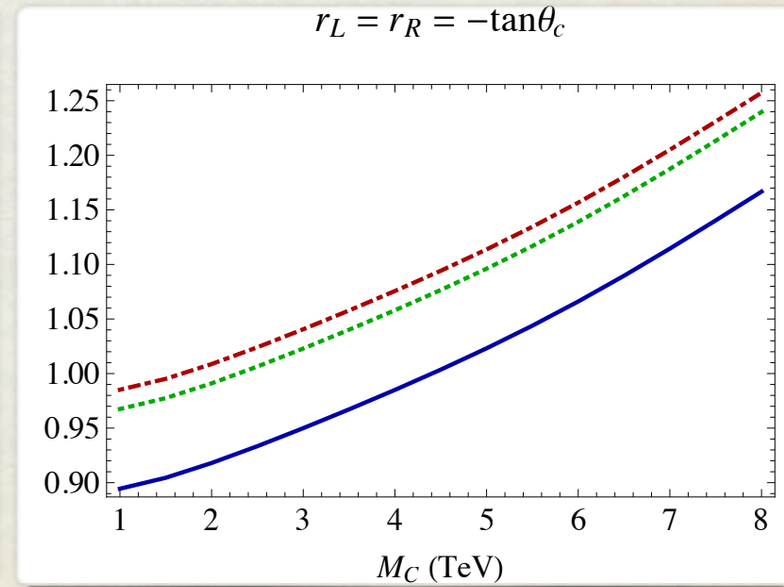

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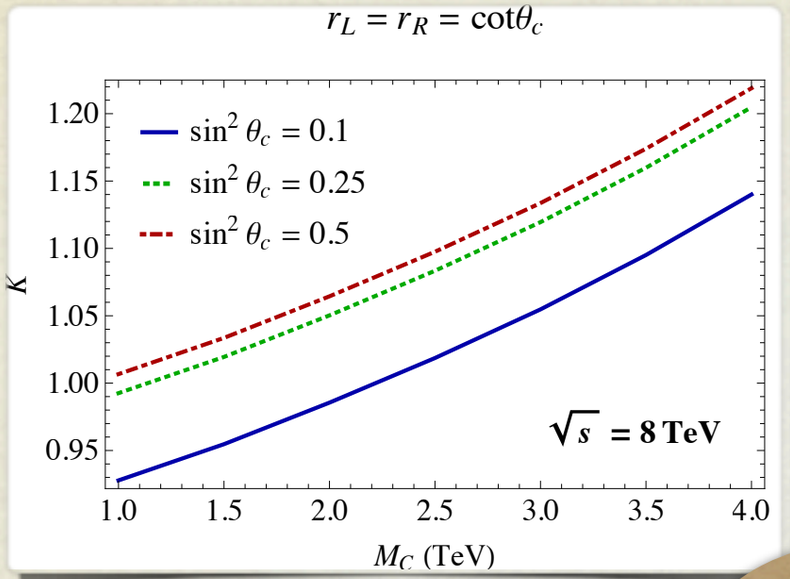

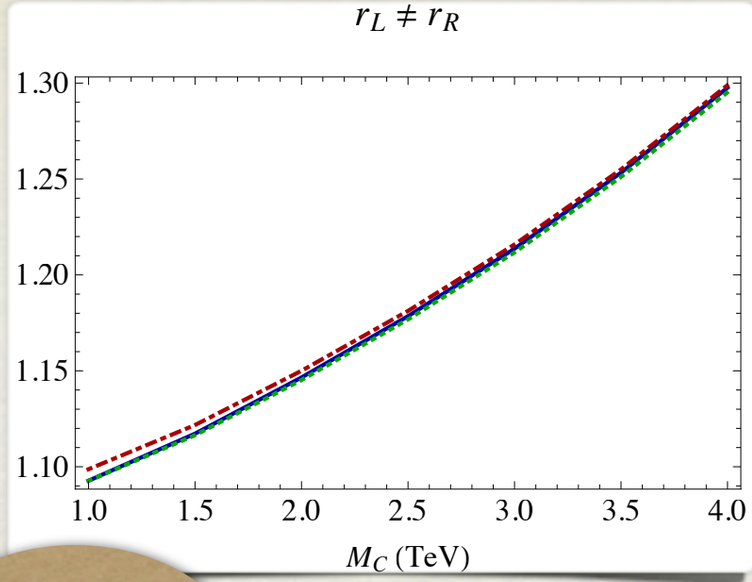

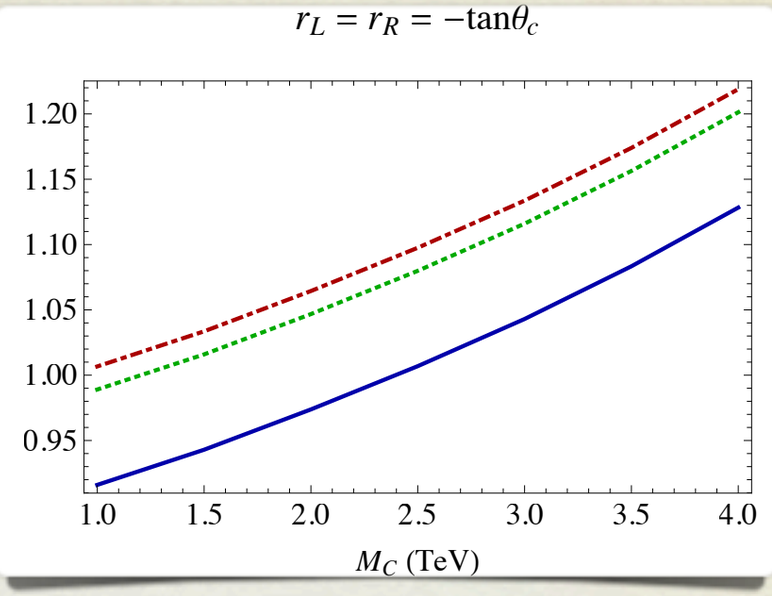

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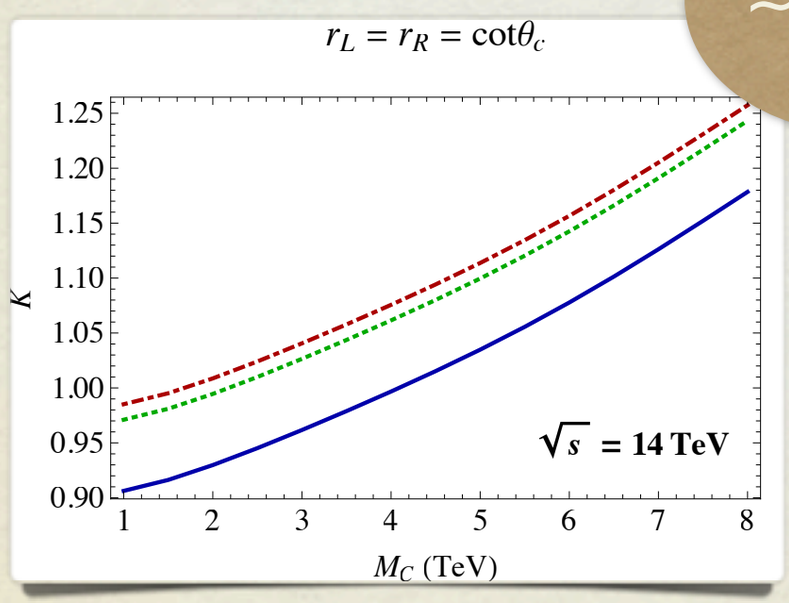

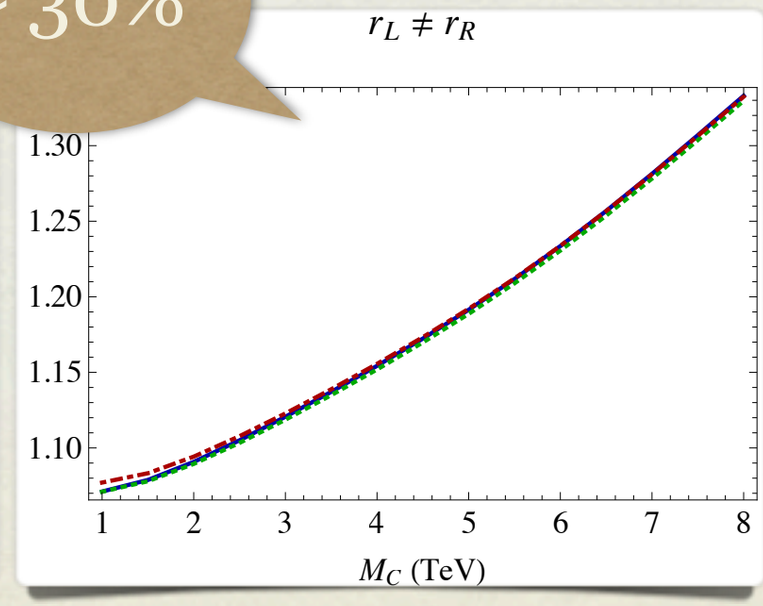

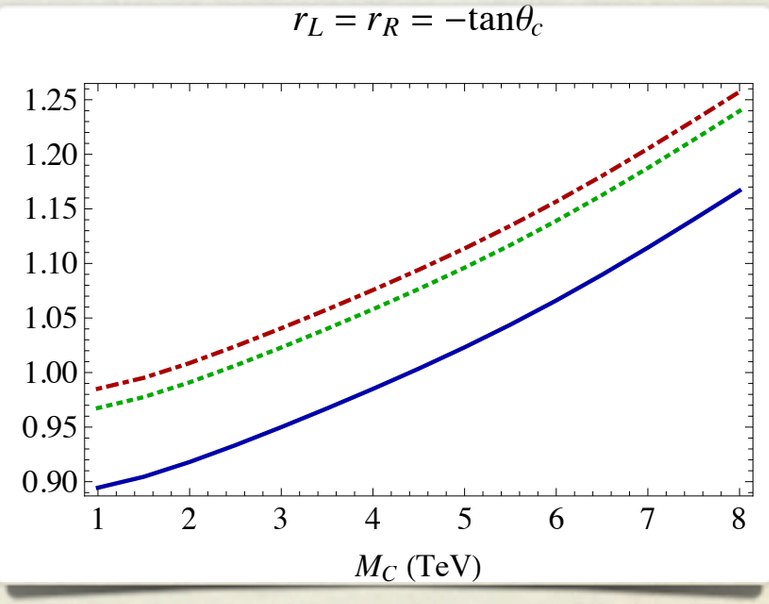

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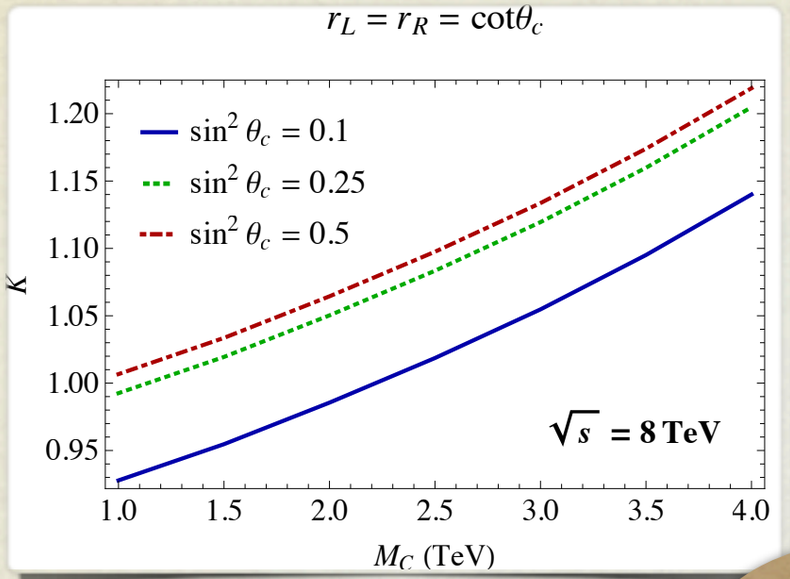

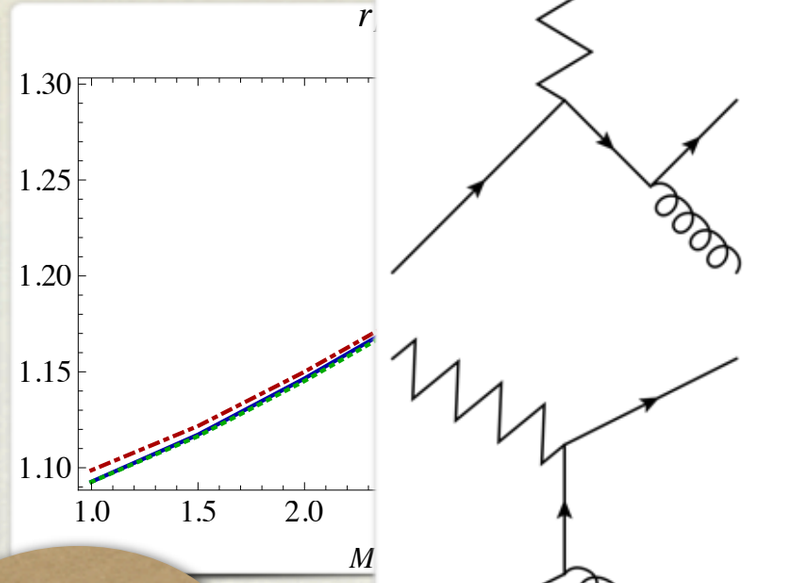

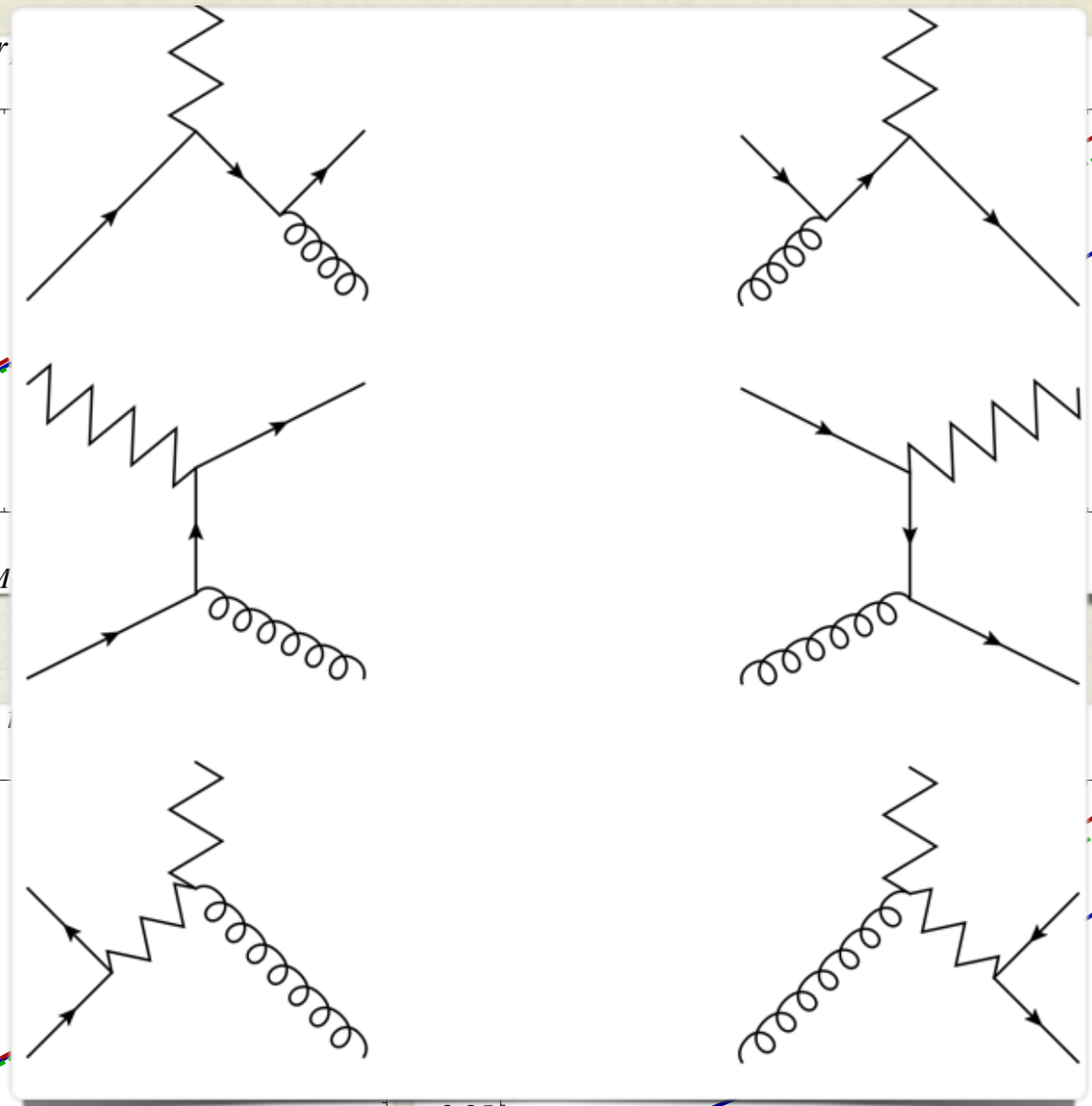

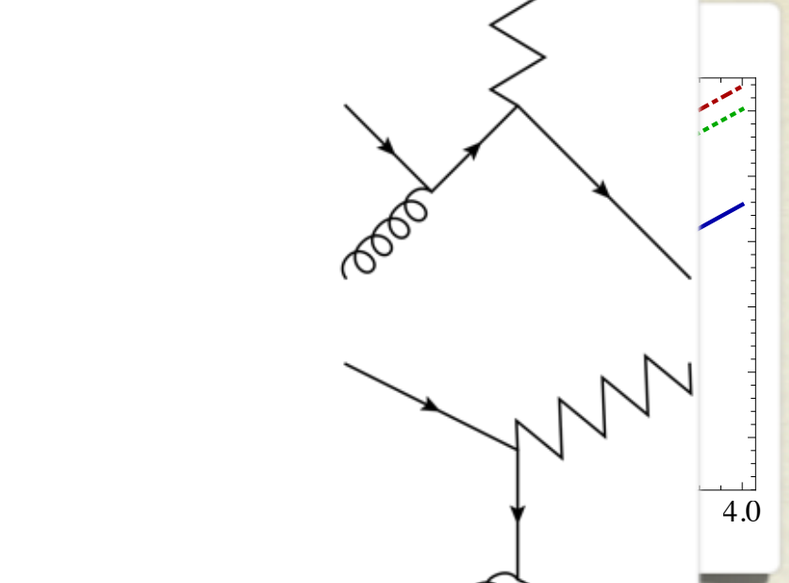

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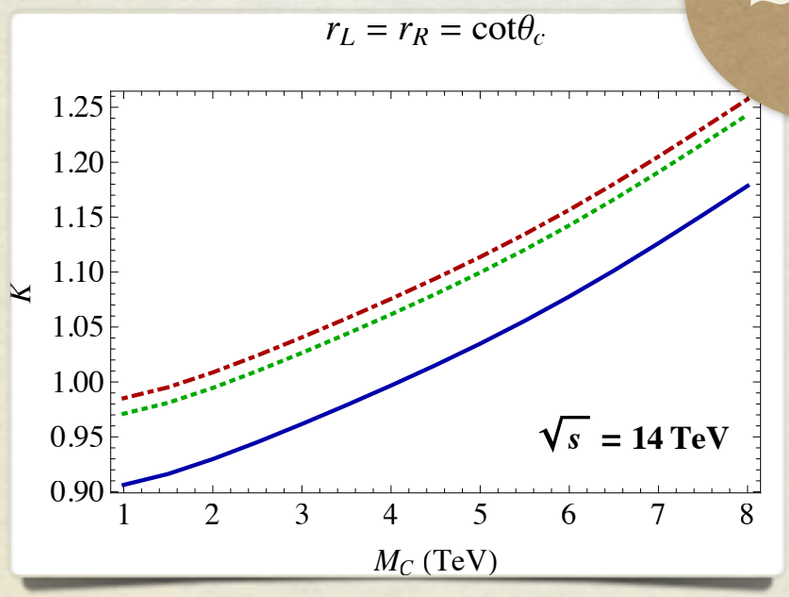
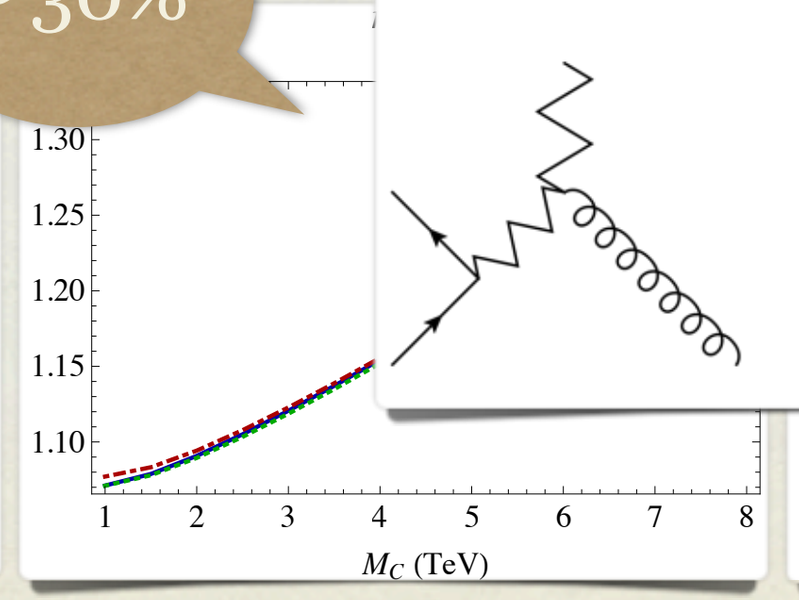
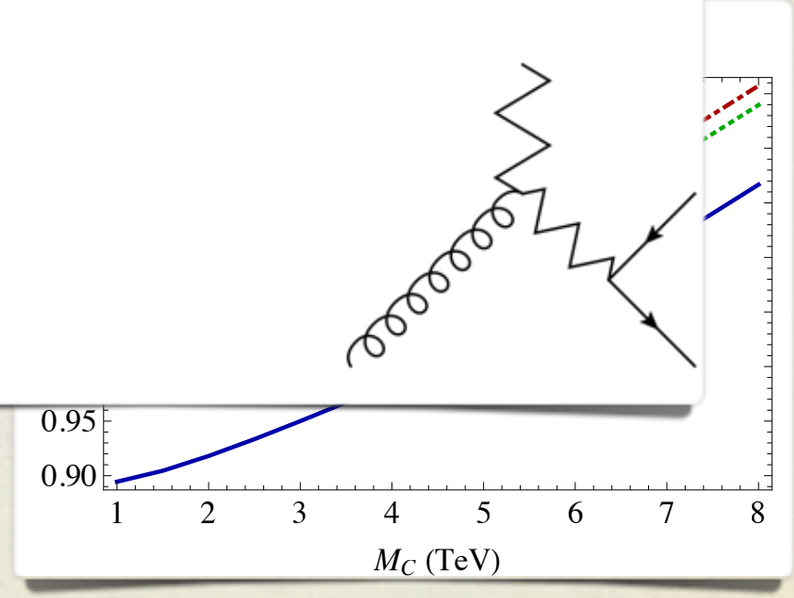
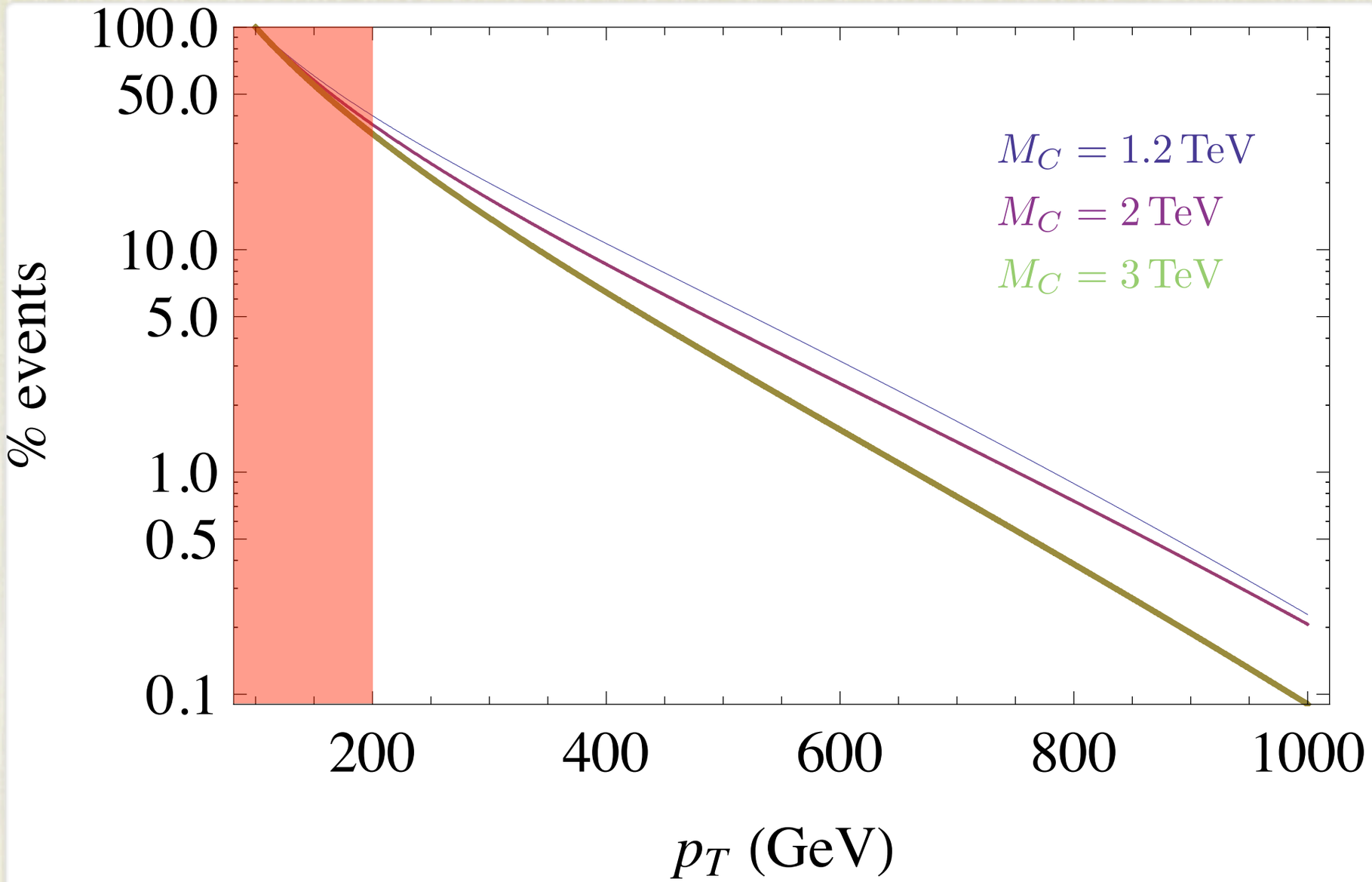




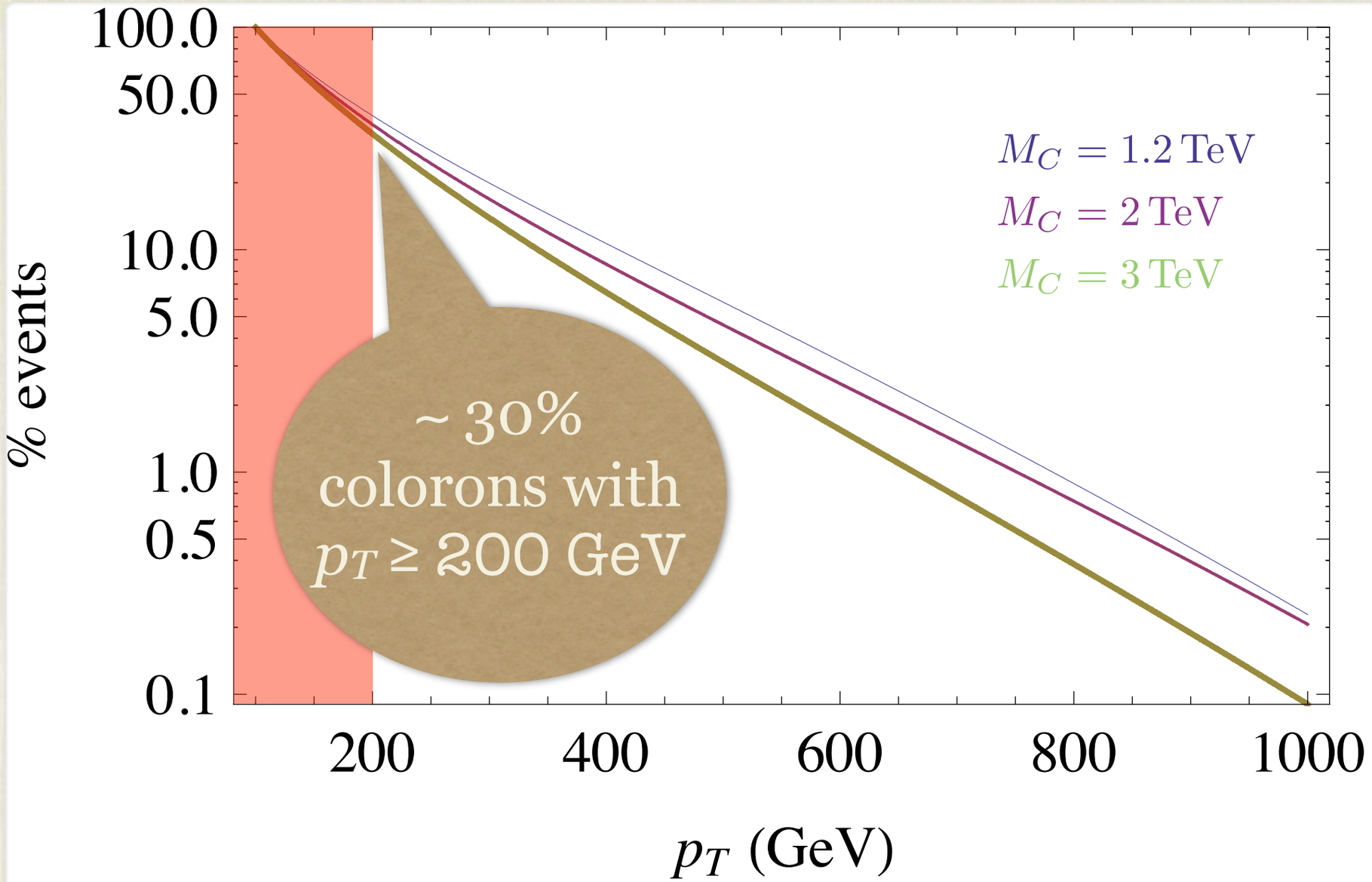




$$r_L = r_R = -\tan\theta_c$$

$$\sin^2\theta_c = 0.05$$

COLORON P_T-DISTRIBUTION



$$r_L = r_R = -\tan\theta_c$$

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COLORON P_T-DISTRIBUTION

COLORON PRODUCTION VIA GLUON-FUSION

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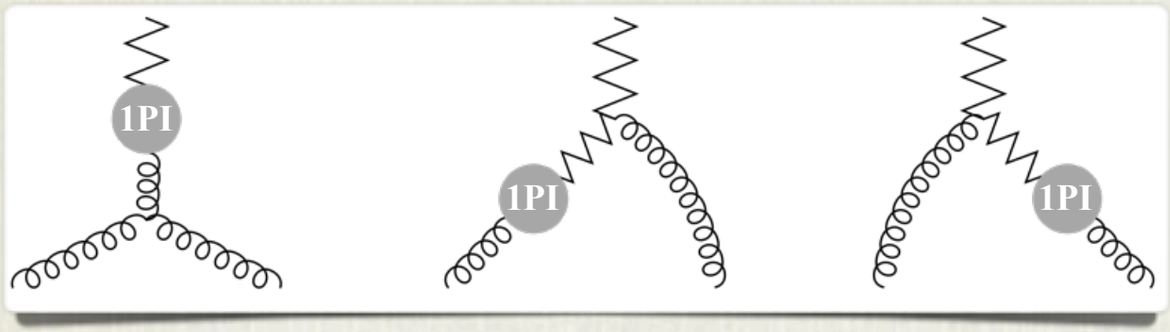
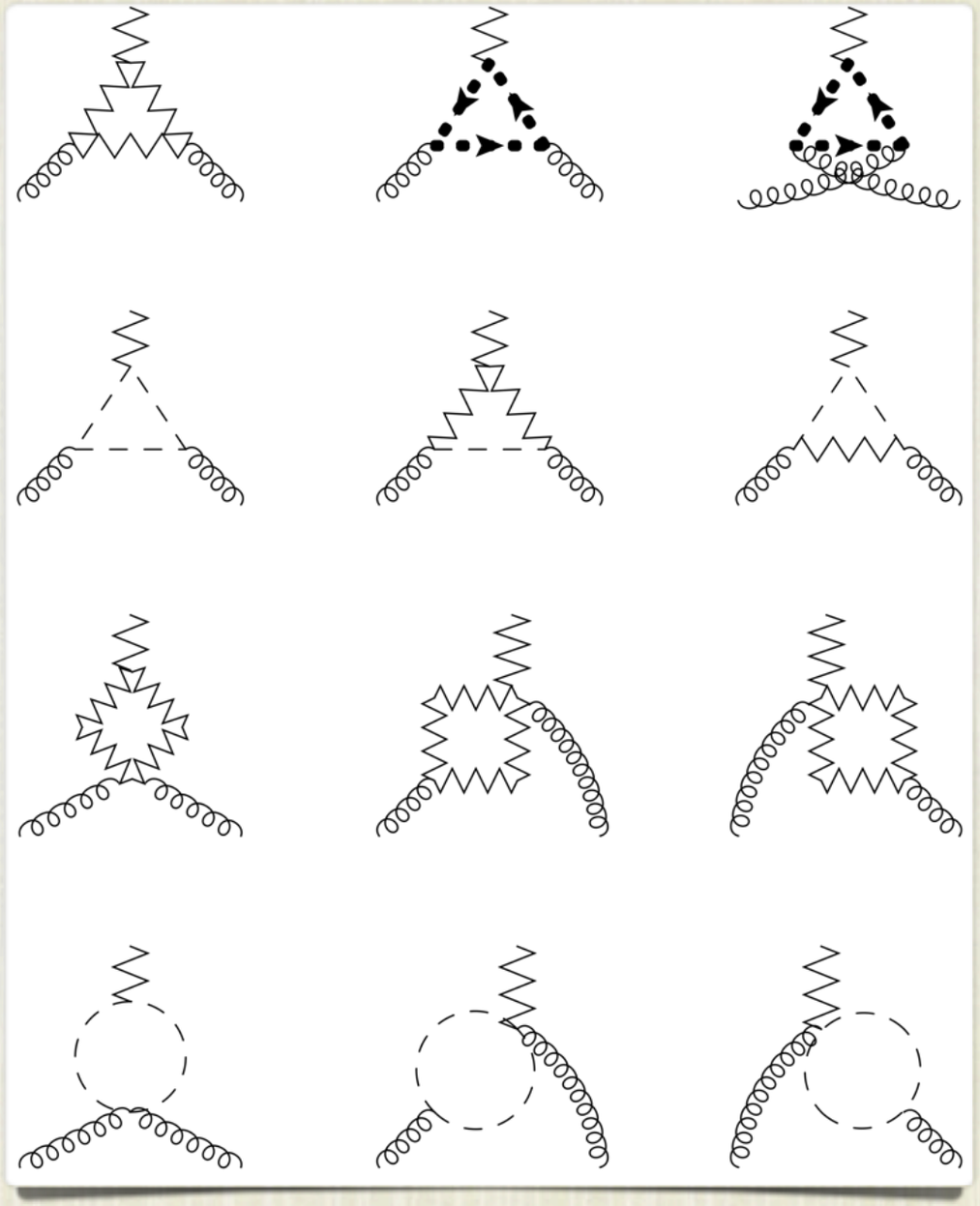
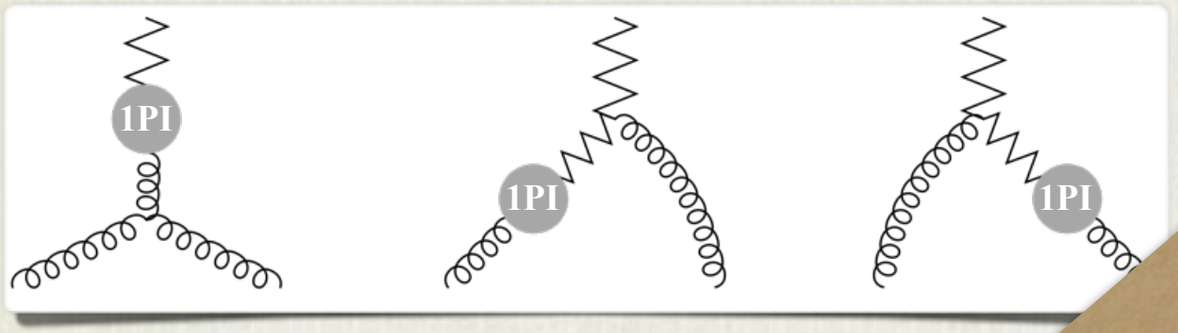
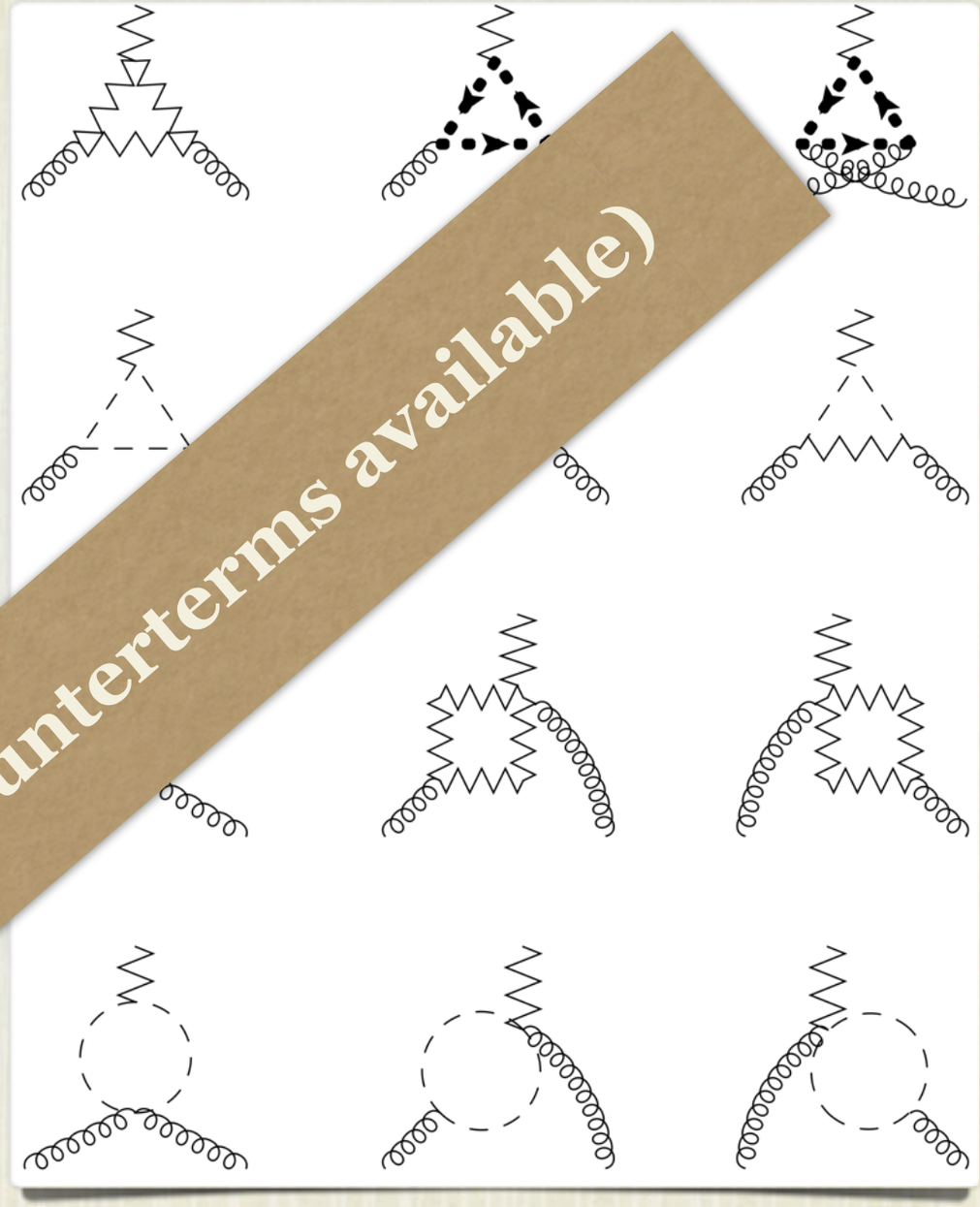
- BUT, at LHC there are many many more gluons!! ➙ Might compensate for the suppression?!





GLUON-FUSION: BOSONIC DIAGRAMS





UV- AND IR-FINITE!! (no counterterms available)

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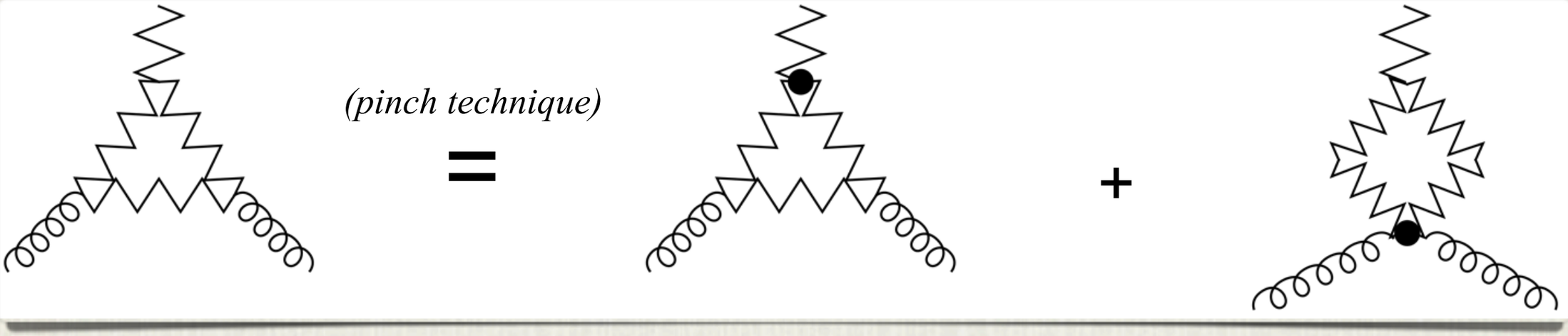
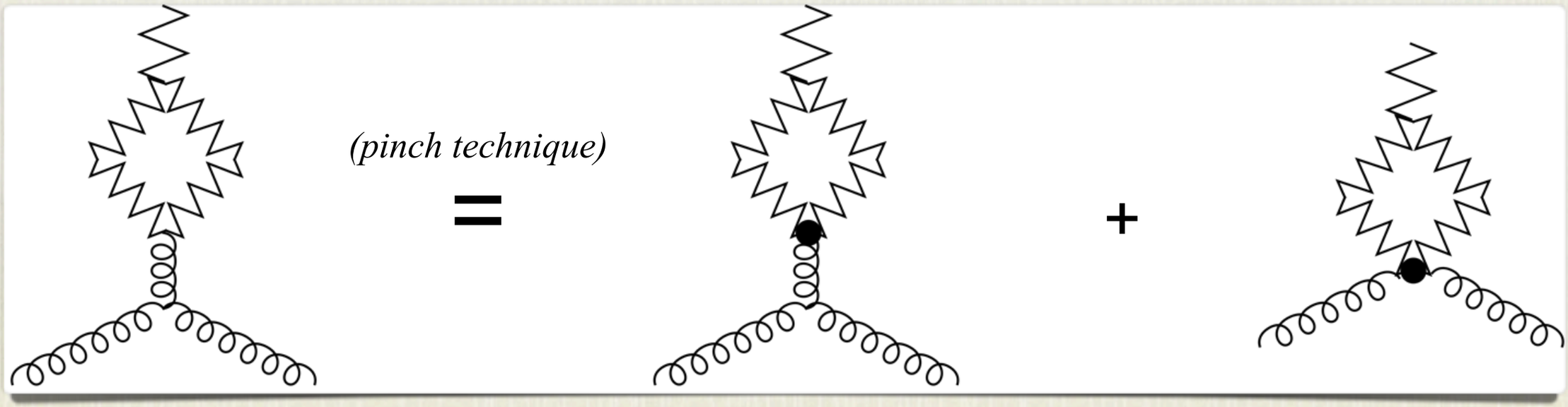
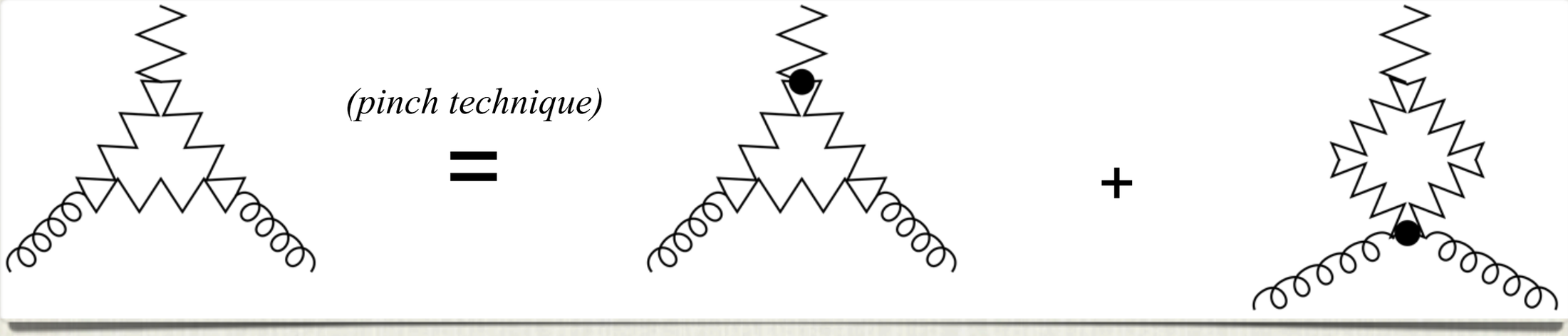
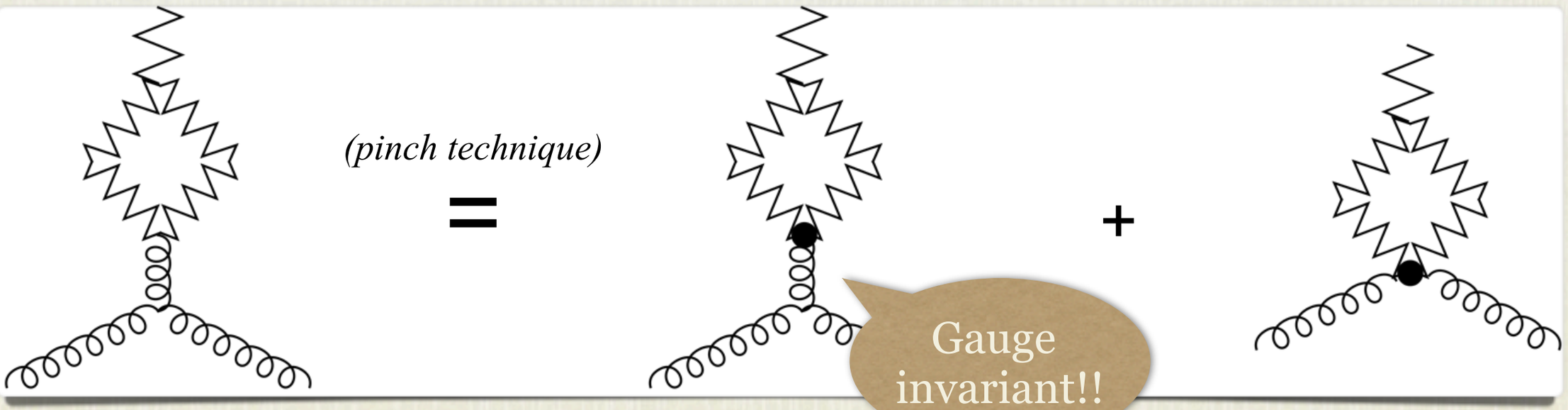




TO SHOW THIS, AGAIN USE PINCH TECHNIQUE





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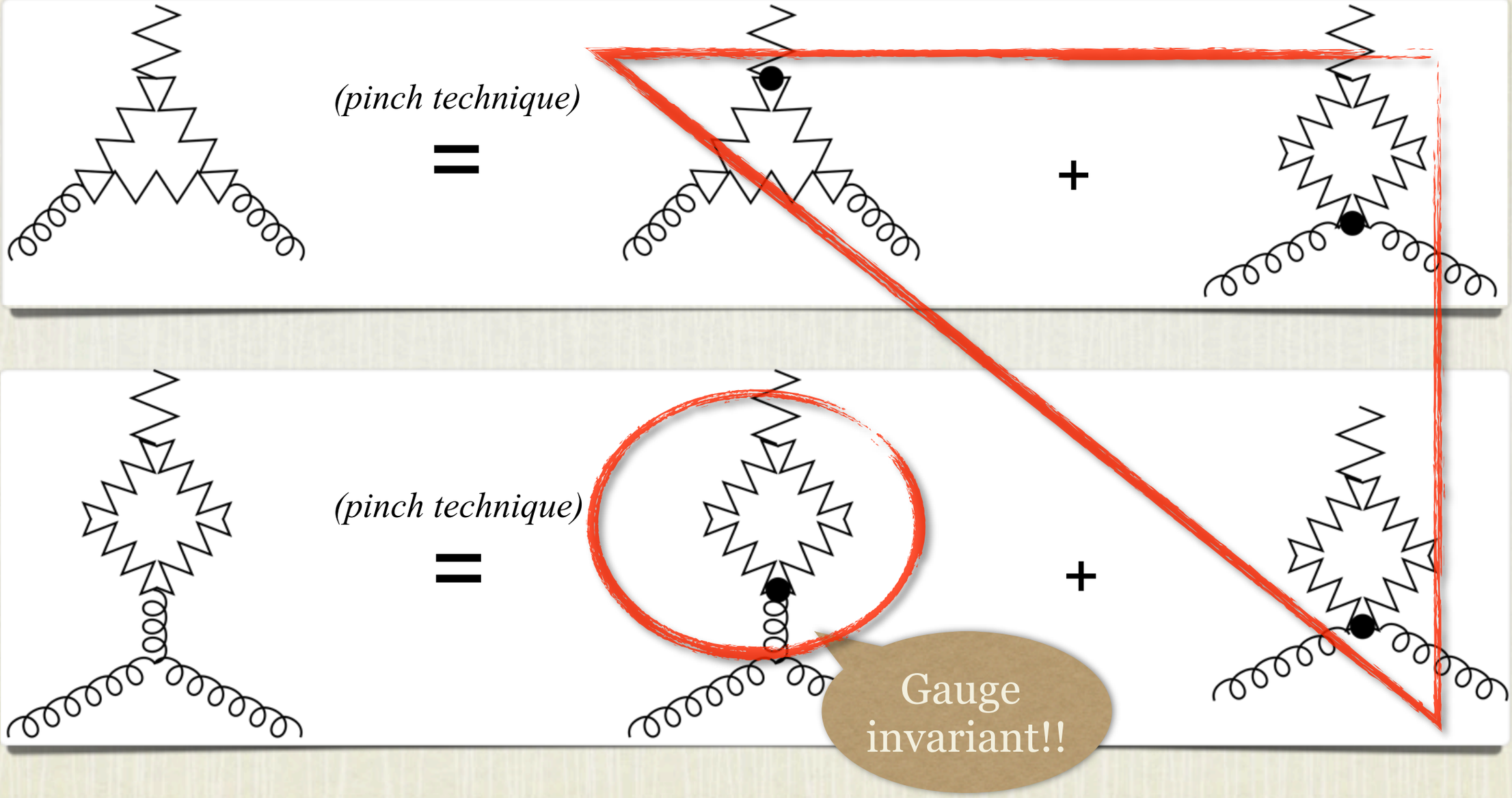

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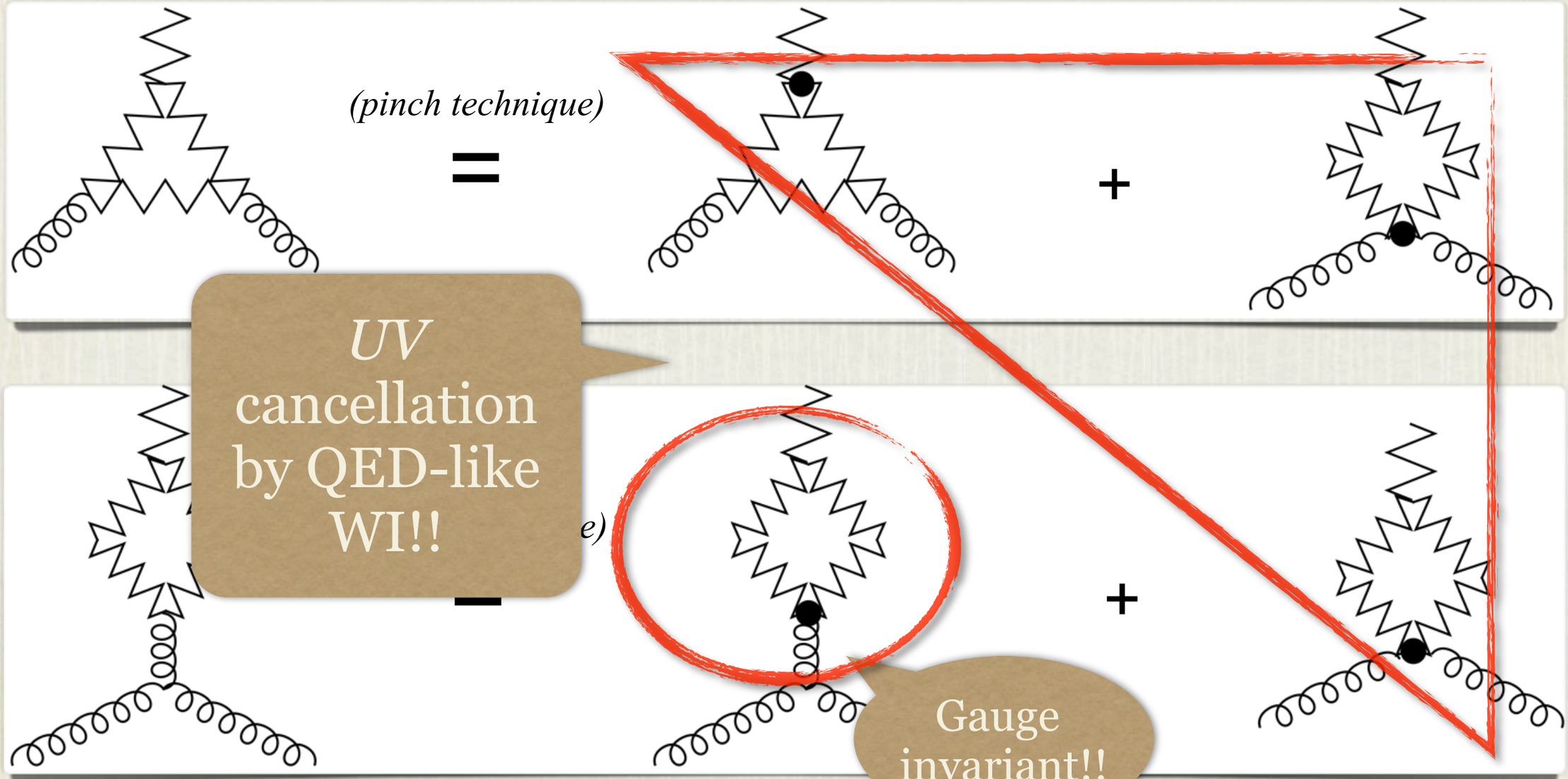

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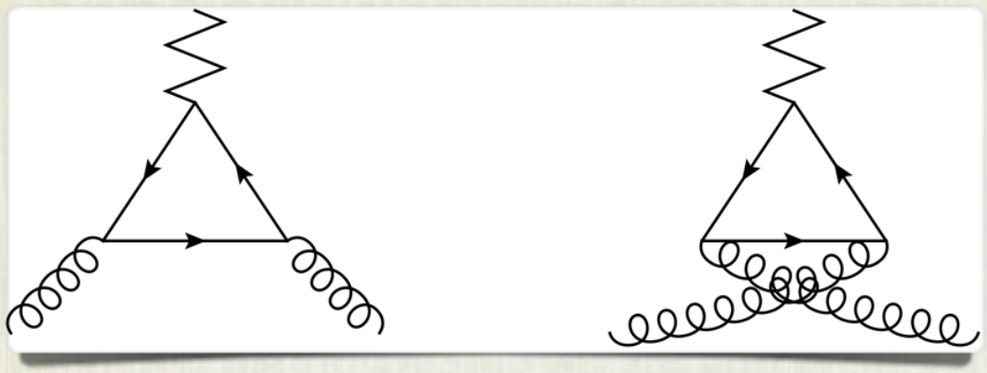
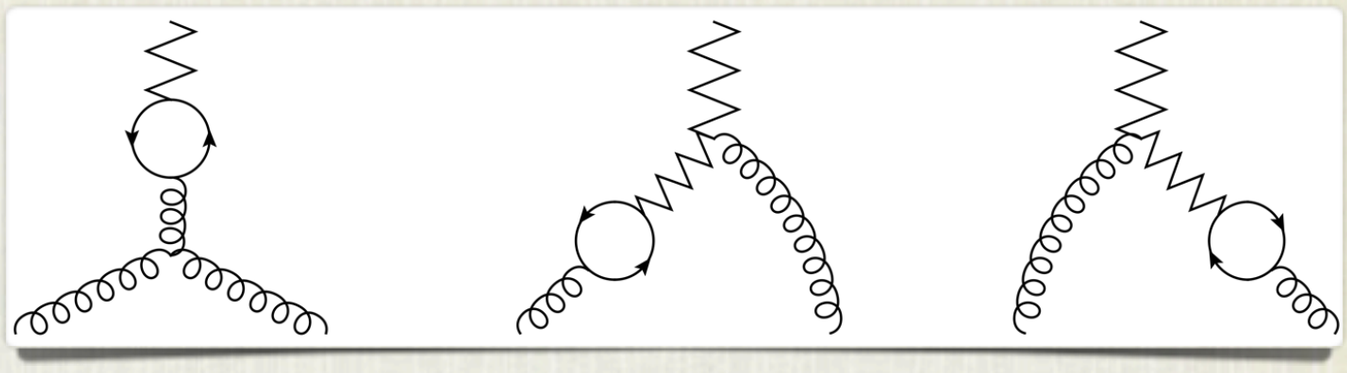
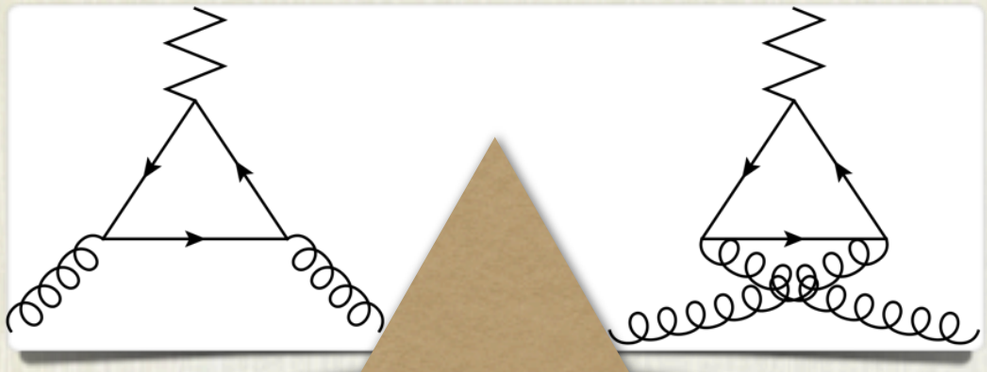


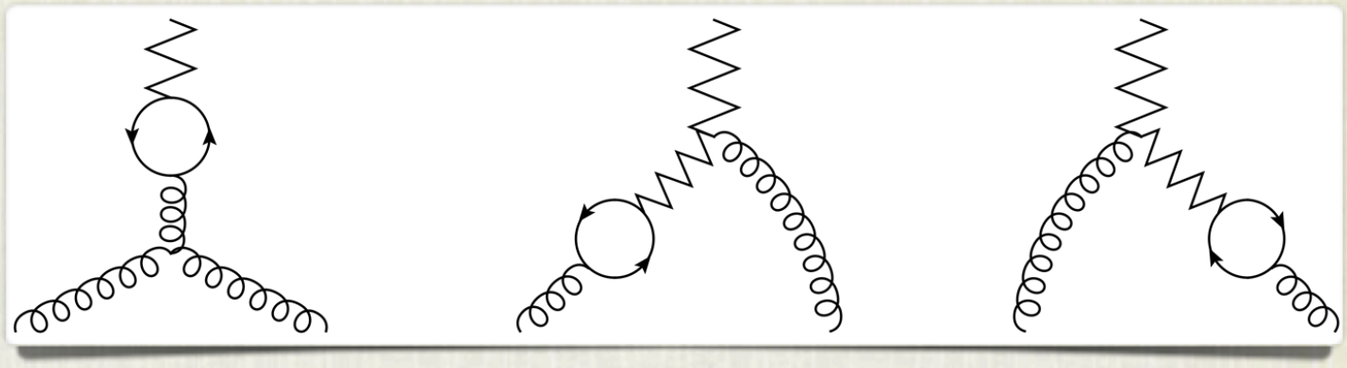


$$q\bar{q}C_{\mu}^{a} = i\gamma_{\mu}\left(g_{L}P_{L} + g_{R}P_{R}\right)t^{a}$$

GLUON-FUSION: FERMIONIC DIAGRAMS



ANOMALY!!



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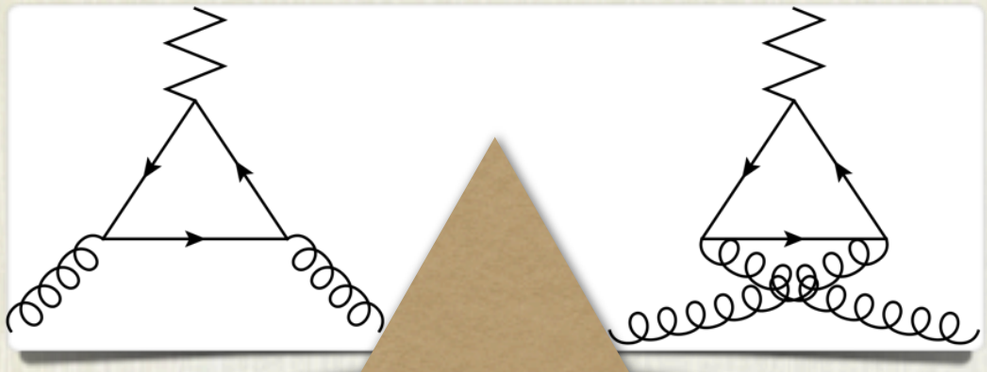

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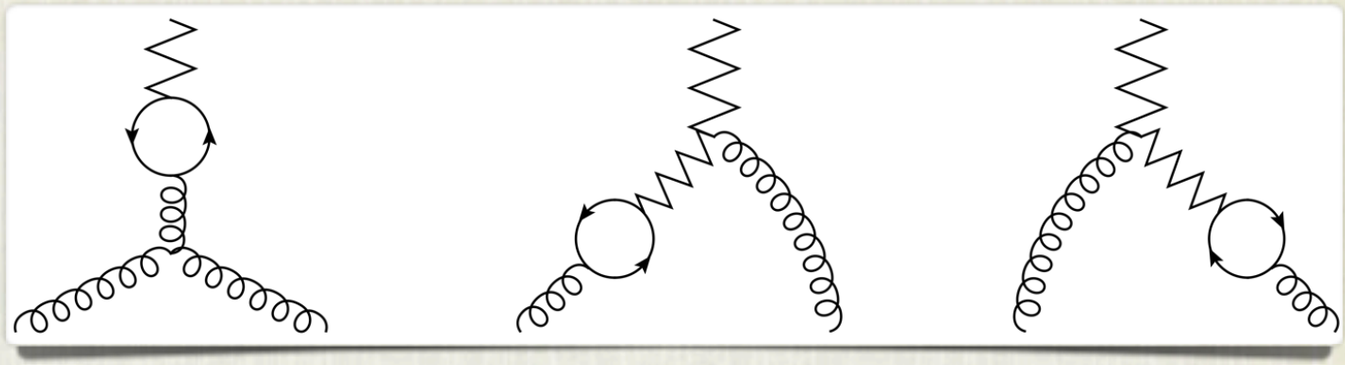

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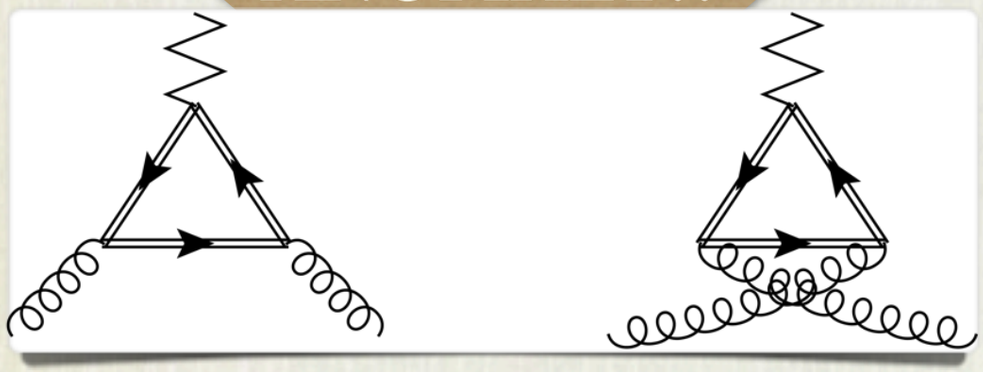

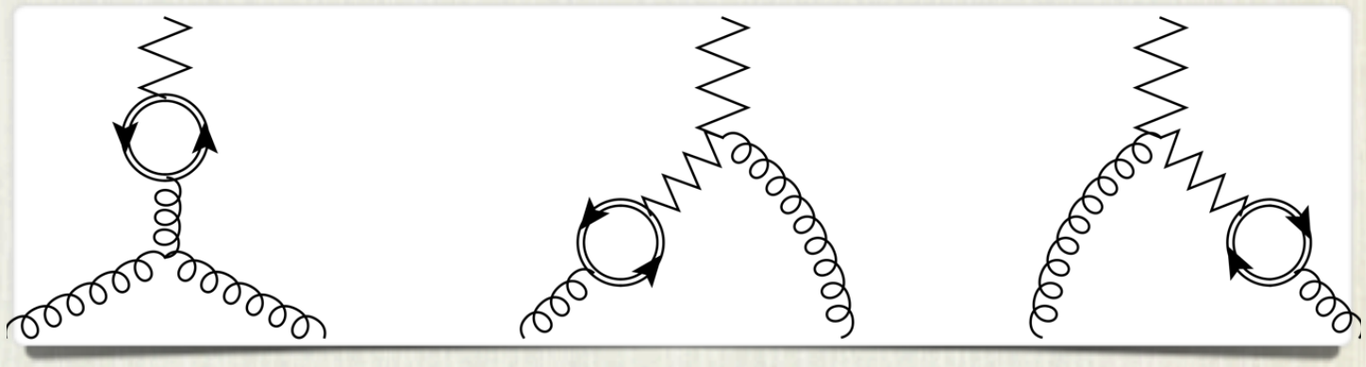

heavy spectator fermions: $Q\bar{Q}C_\mu^a = i\gamma_\mu \left(g_R P_L + g_L P_R\right) t^a$

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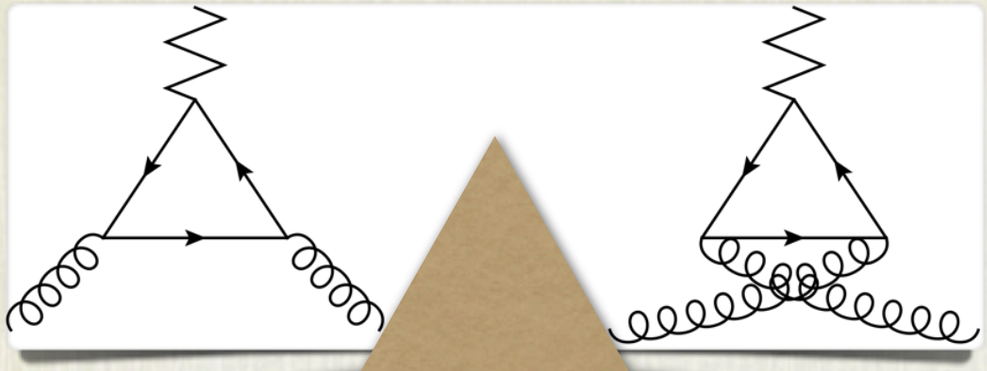

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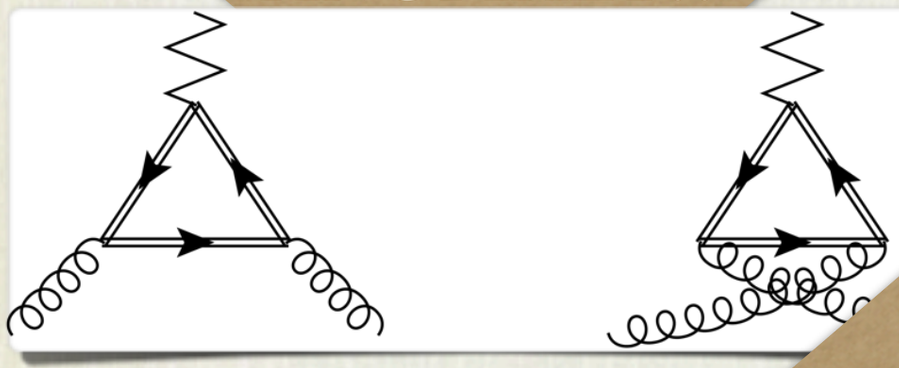

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GLU… …USION: FE… …ONIC DIAGRAMS

COLORON PRODUCTION VIA GLUON-FUSION, RECAP

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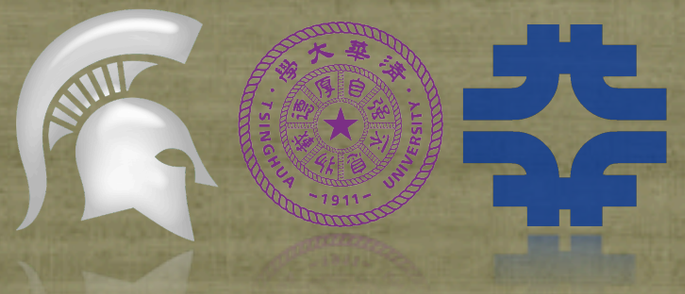
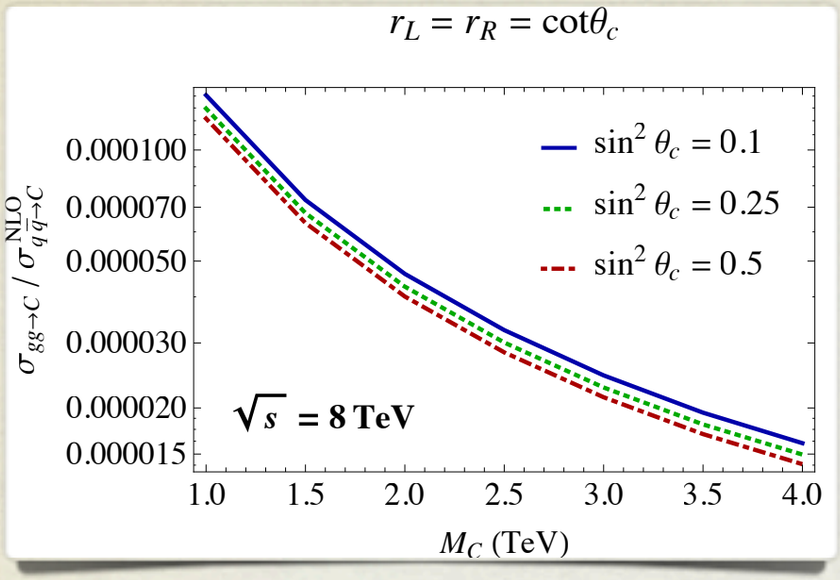
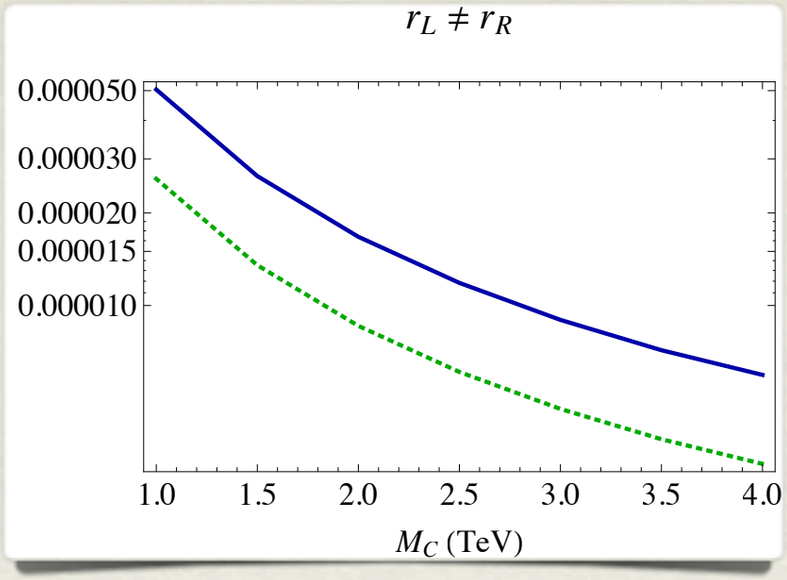
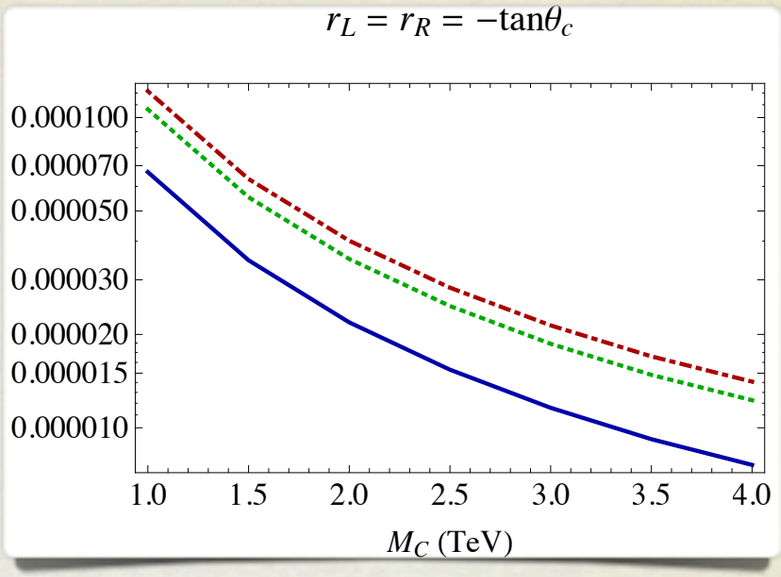
- Gluon-fusion to **axigluon** ($\theta_c = \pi/4$) vanishes identically to all orders in perturbation theory, due to parity symmetry exchanging $SU(3)_{1c}$ and $SU(3)_{2c}$, under which the gluon is even and the coloron is odd.

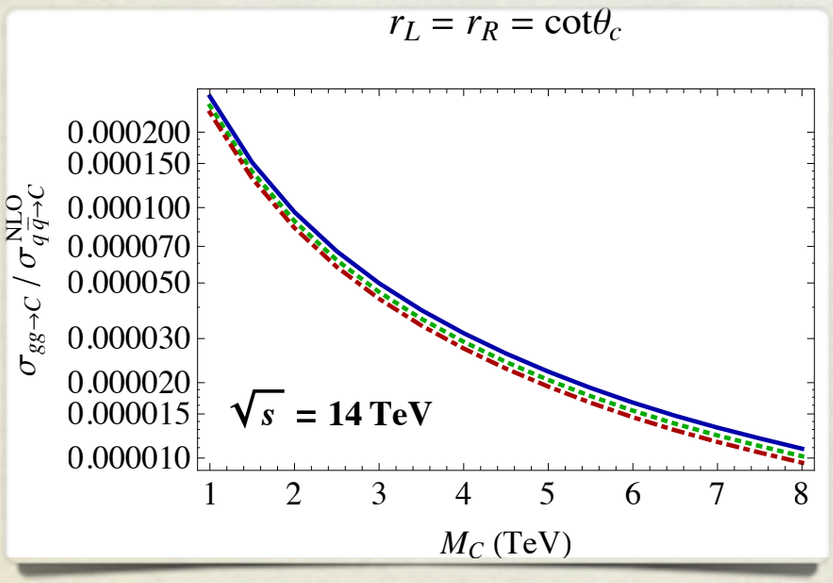
DOES GLUON-FUSION PROCESS MATTER?

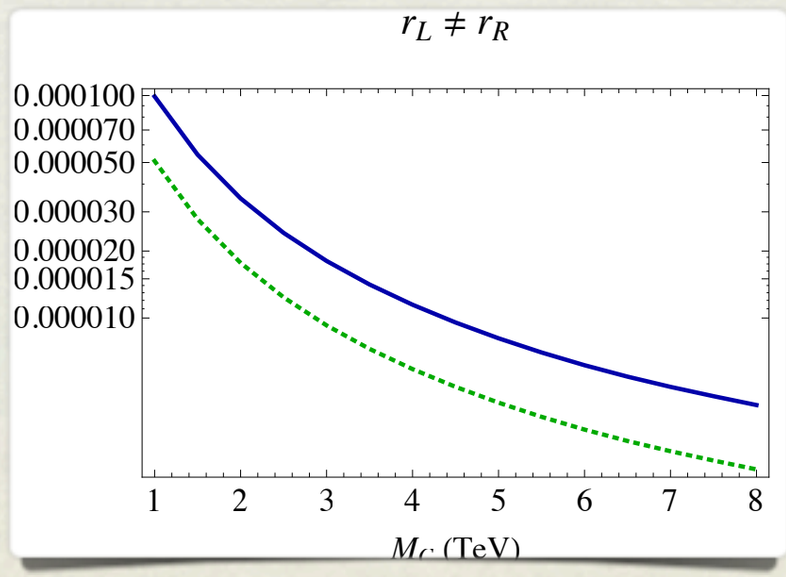


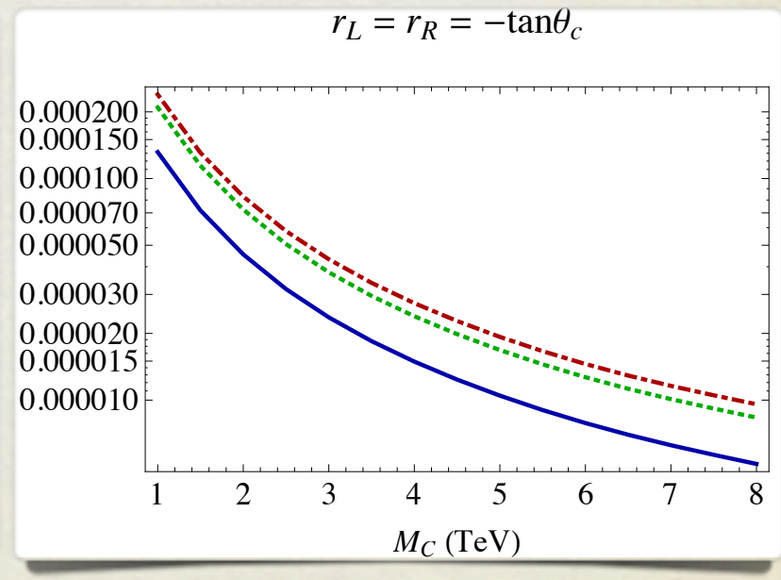












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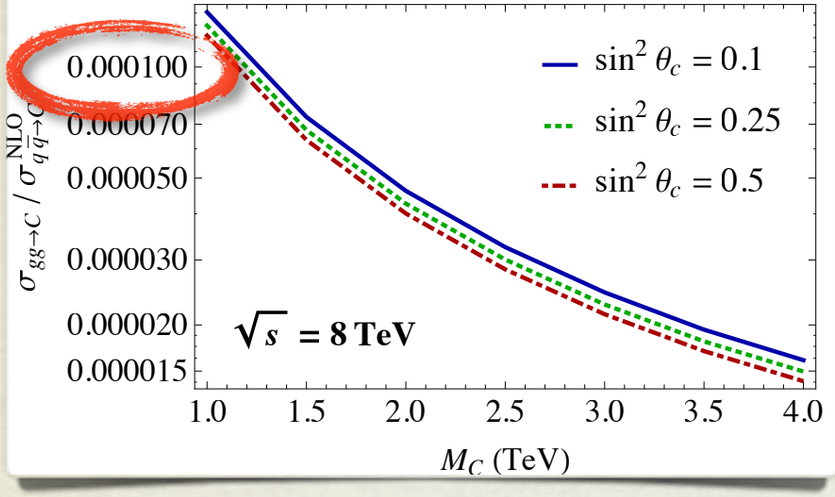

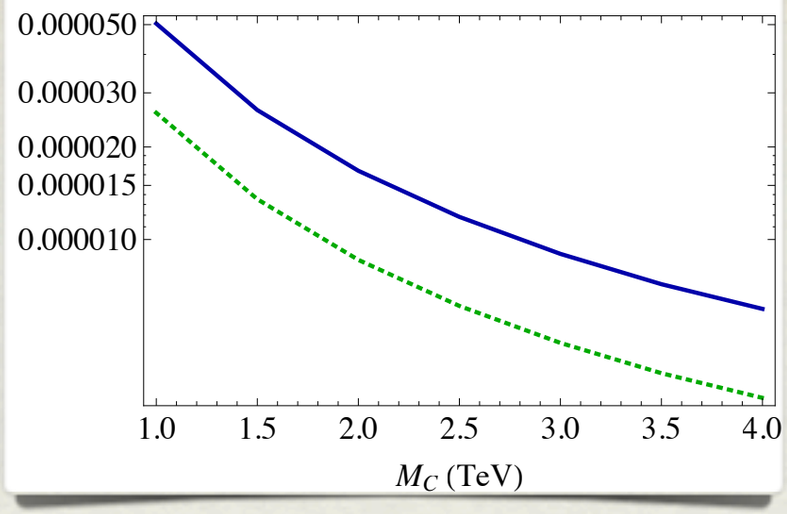

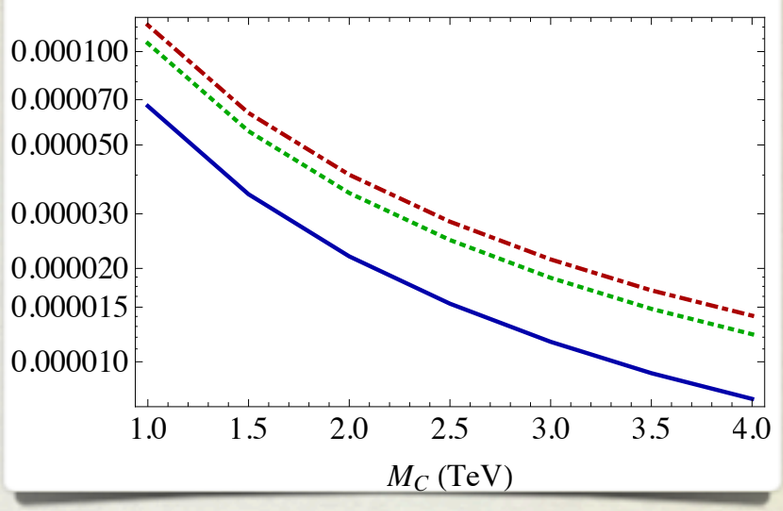

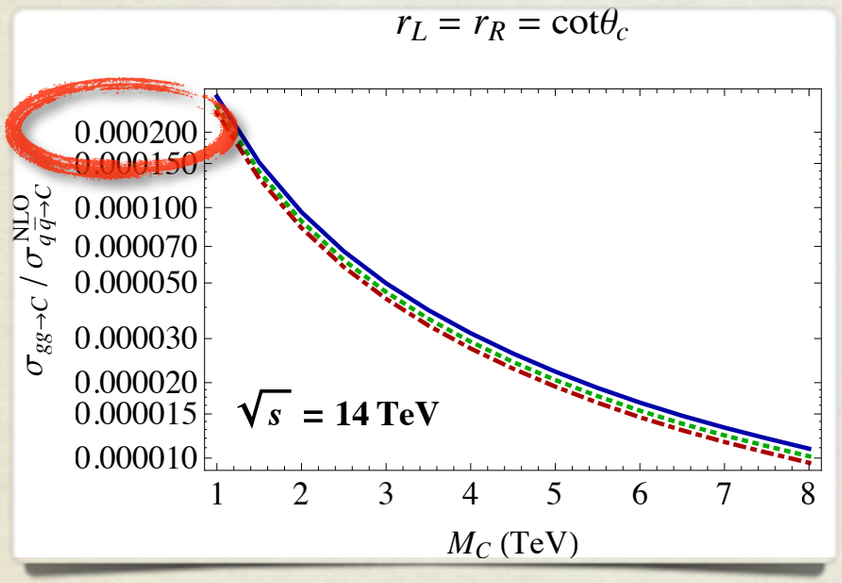

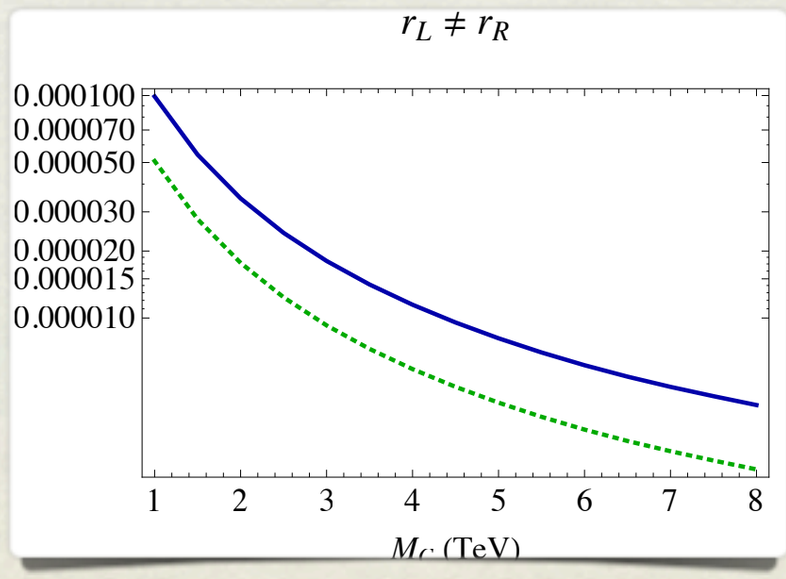

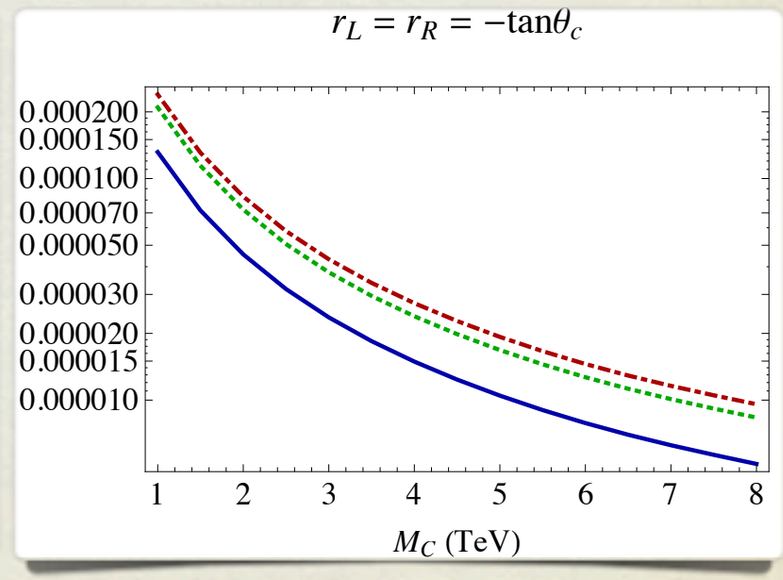

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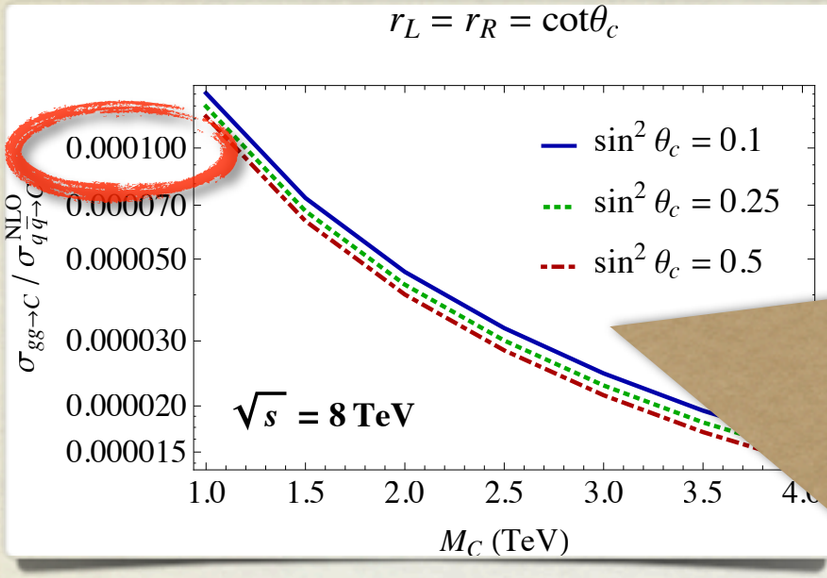

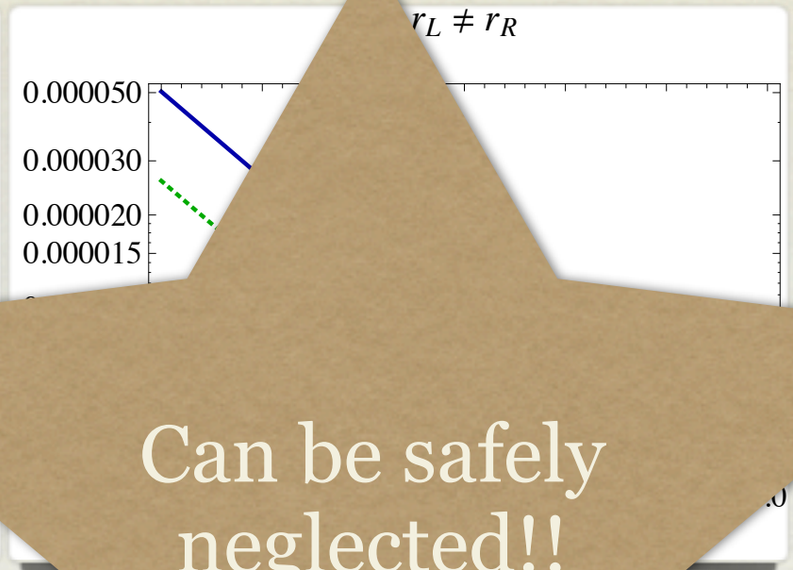

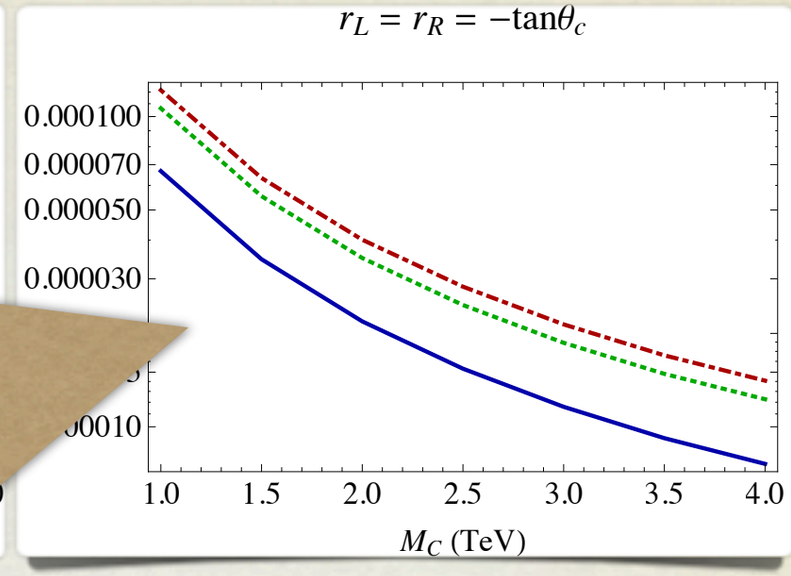

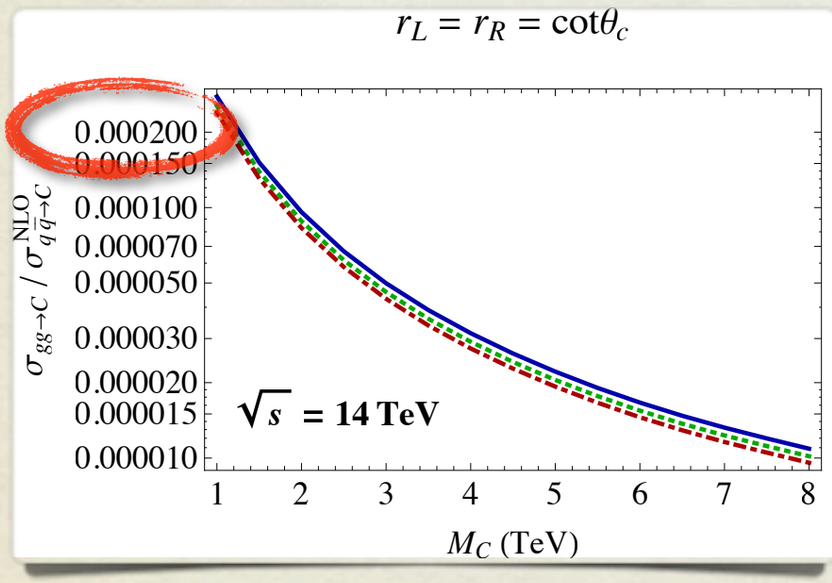

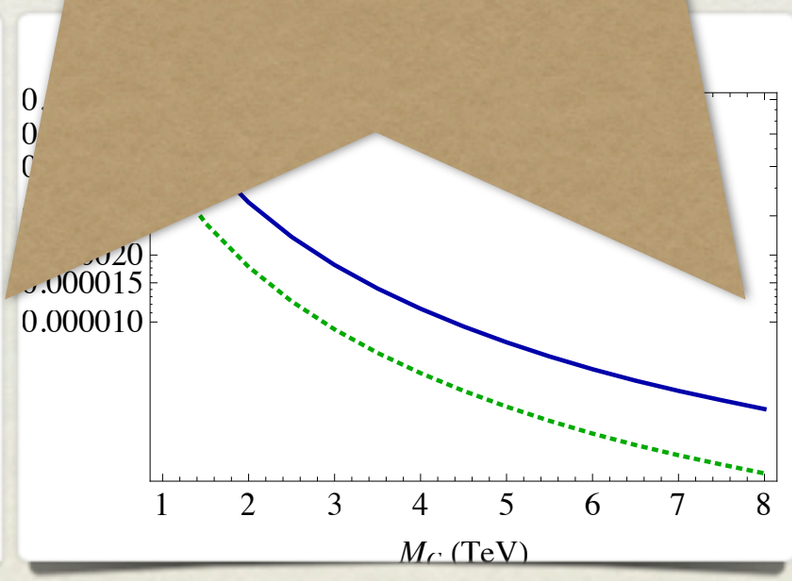

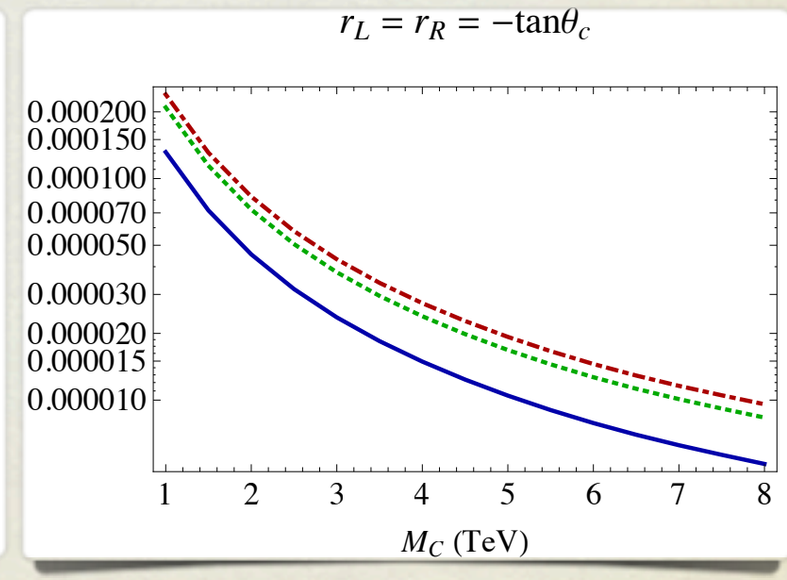

Can be safely neglected!!

CONCLUSION PART I

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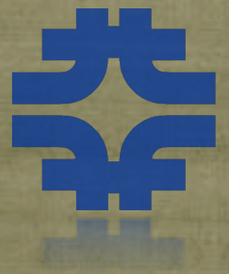

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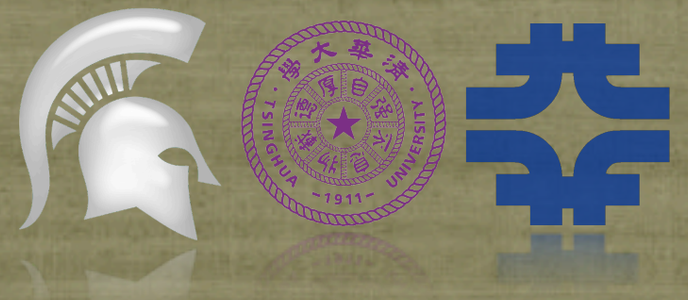

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USE IT!!

PART II

CONSTRAINTS ON THE SCALAR SECTOR OF THE RENORMALIZABLE COLORON MODEL

R.S. CHIVUKULA, A. F., J. REN, E.H. SIMMONS, [ARXIV:1307.1064 [HEP-PH]]

IN PART II..

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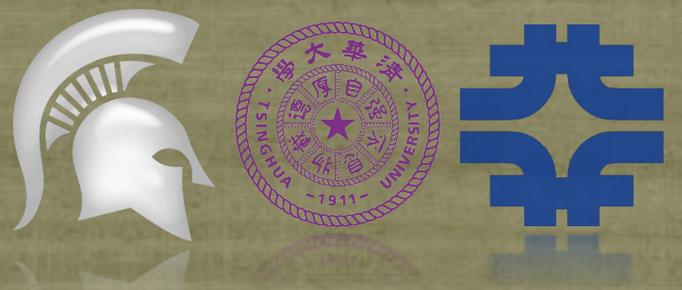

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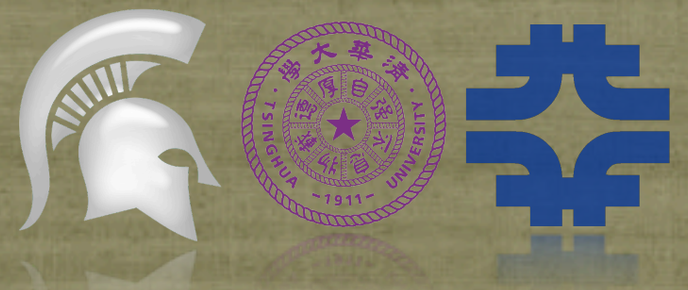

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- Investigate **experimental** bounds: Electroweak precision tests & the new 125 GeV scalar state results

IN PART II..

- **LHC has discovered a new 125 GeV (Higgs-like) scalar state!!** Of any relevance here?!

- ➙ Renormalizable Coloron Model *[Hill, Parke (1994); Bai, Dobrescu (2011)]*

- New (colored) scalar states, in addition to the new gauge bosons (colorons) and the new fermions (spectators)

- Investigate **theoretical** bounds: Stability & Unitarity

- Investigate **experimental** bounds: Electroweak precision tests & the new 125 GeV scalar state results

- ➙ Constrain the scalar sector!!

FORMALISM

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general scalar potential

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$\Phi \to u_1 \Phi\, u_2^\dagger$
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$$\begin{pmatrix}h_0\\ s_0\end{pmatrix}=R_\chi\begin{pmatrix}h\\ s\end{pmatrix}\qquad\qquad(\lambda_s'\equiv\lambda_s+\kappa_s)$$

$$R_\chi\equiv\begin{pmatrix}\cos\chi & \sin\chi\\ -\sin\chi & \cos\chi\end{pmatrix}\ ,\qquad\cot 2\chi\equiv\frac{1}{6\lambda_m}\left[\lambda_s'\left(1-\frac{r_\Delta}{2}\right)\frac{v_s}{v_h}-\lambda_h\frac{v_h}{v_s}\right]$$

MASS SPECTRUM

- CP-even scalars: $$m^2_{h,s} = \frac{1}{6}\left\{\lambda_h v_h^2 + \lambda'_s v_s^2\left(1-\frac{r_\Delta}{2}\right) \pm \left[\lambda_h v_h^2 - \lambda'_s v_s^2\left(1-\frac{r_\Delta}{2}\right)\right]\sec 2\chi\right\}$$
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- Coloron: $$M_C = \sqrt{\frac{2}{3}}\frac{g_s\, v_s}{\sin 2\theta_c}$$
- Spectator fermions: $$M_Q = \frac{y_Q}{\sqrt{6}}\, v_s$$

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$m_h = 125$ GeV
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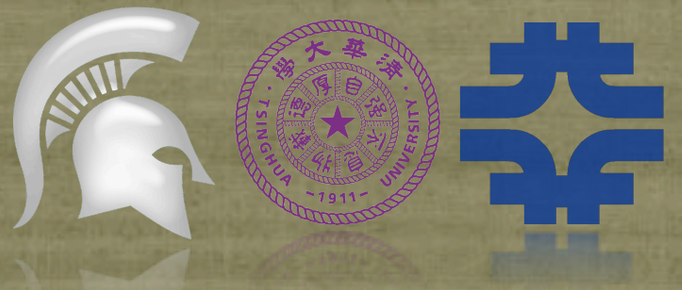

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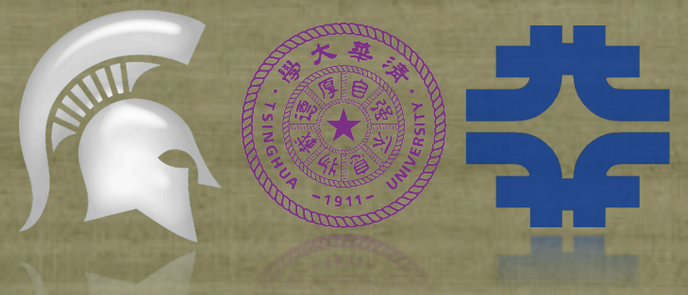
Model-dependence!! (# of flavors, electric charges, etc.)

MODEL'S FREE PARAMETERS



- The model's (formal) free parameters may be conveniently taken to be

$$\{\underbrace{v_s, m_s, \sin\chi}, m_{\mathcal{A}}, m_{G_H}, M_C, M_Q\}$$

Exclusion plots!!

- Constrain the 2D plane m_s - $\sin\chi$ for various benchmark values of the remaining parameters

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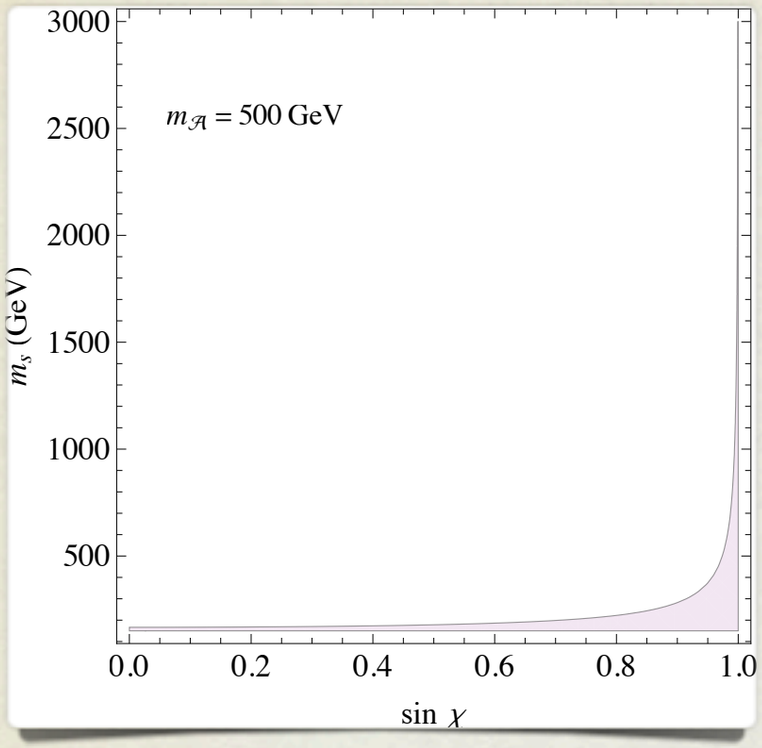
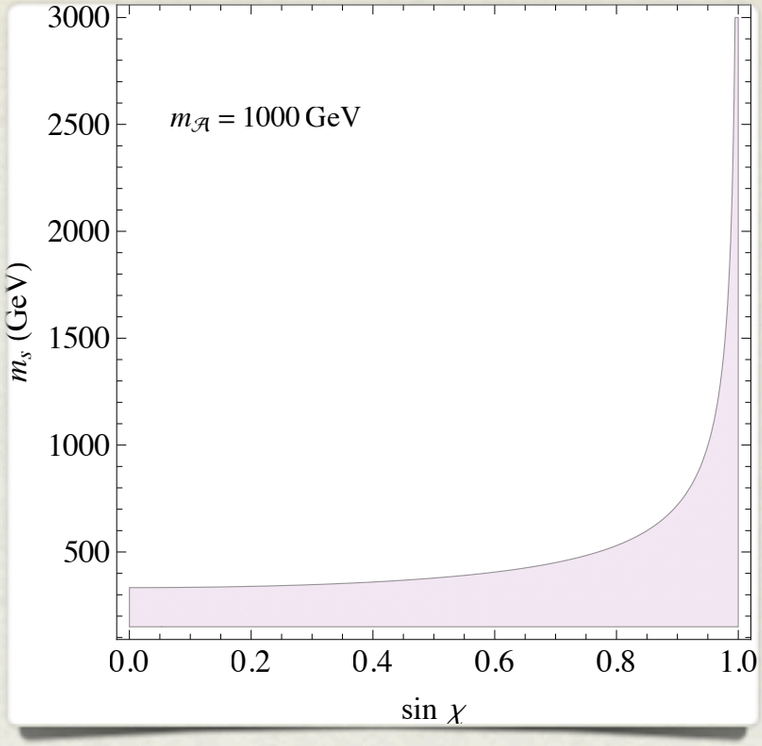
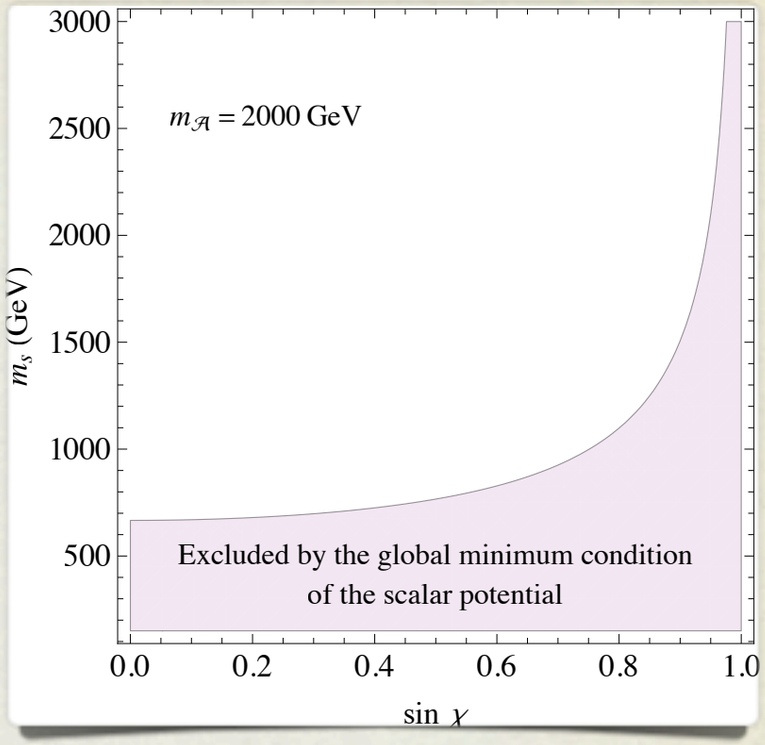
Translates into varying m_A in m_s - $\sin\chi$ plane

Automatically satisfied in m_s - $\sin\chi$ plane

THEORETICAL BOUNDS: STABILITY







$$\sin\chi \to 0 \qquad m_s \geq \frac{m_{\mathcal{A}}}{3}$$

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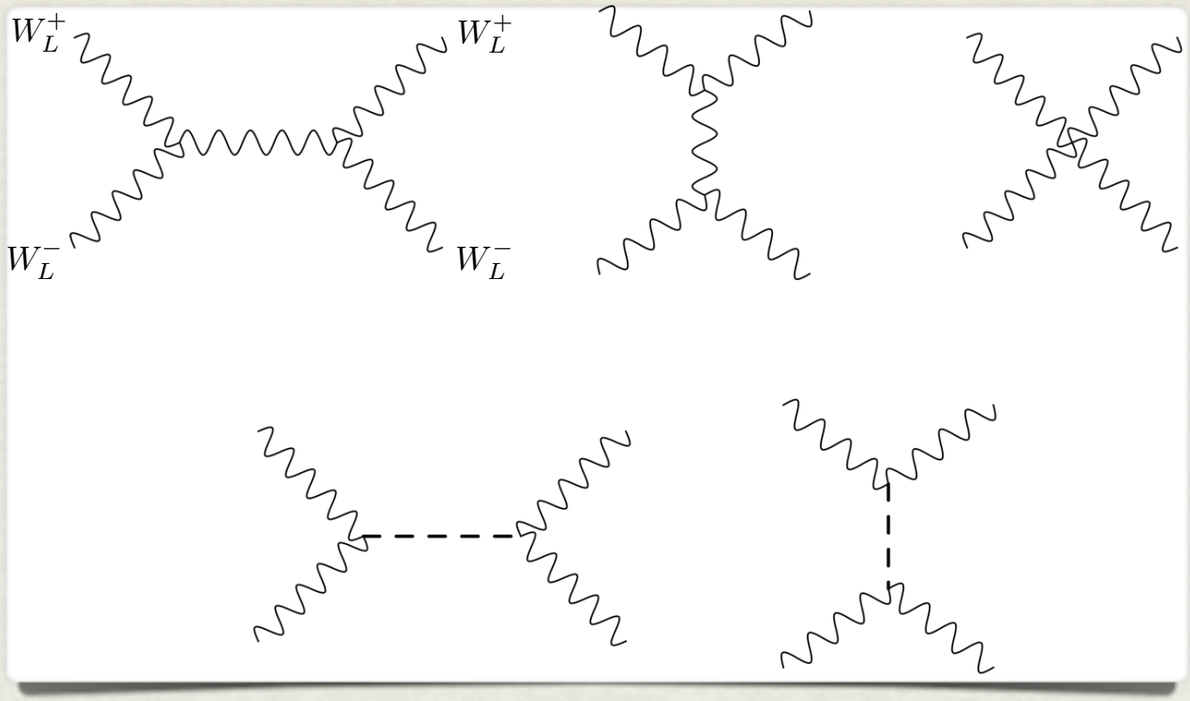

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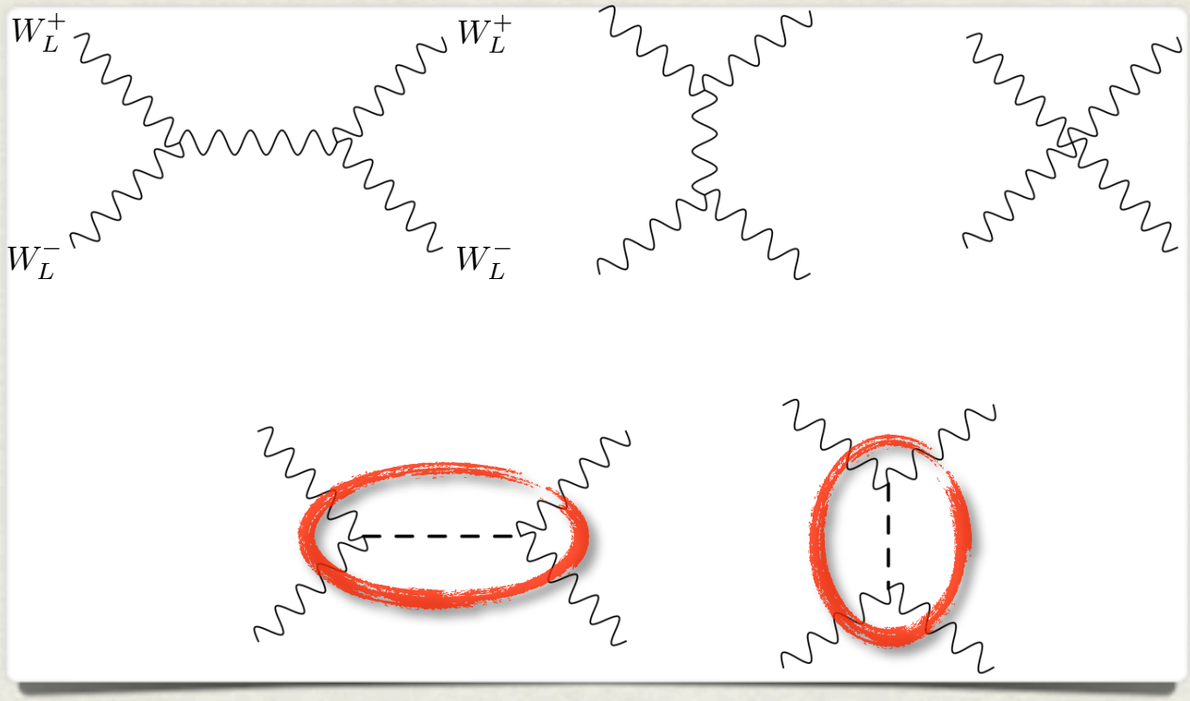

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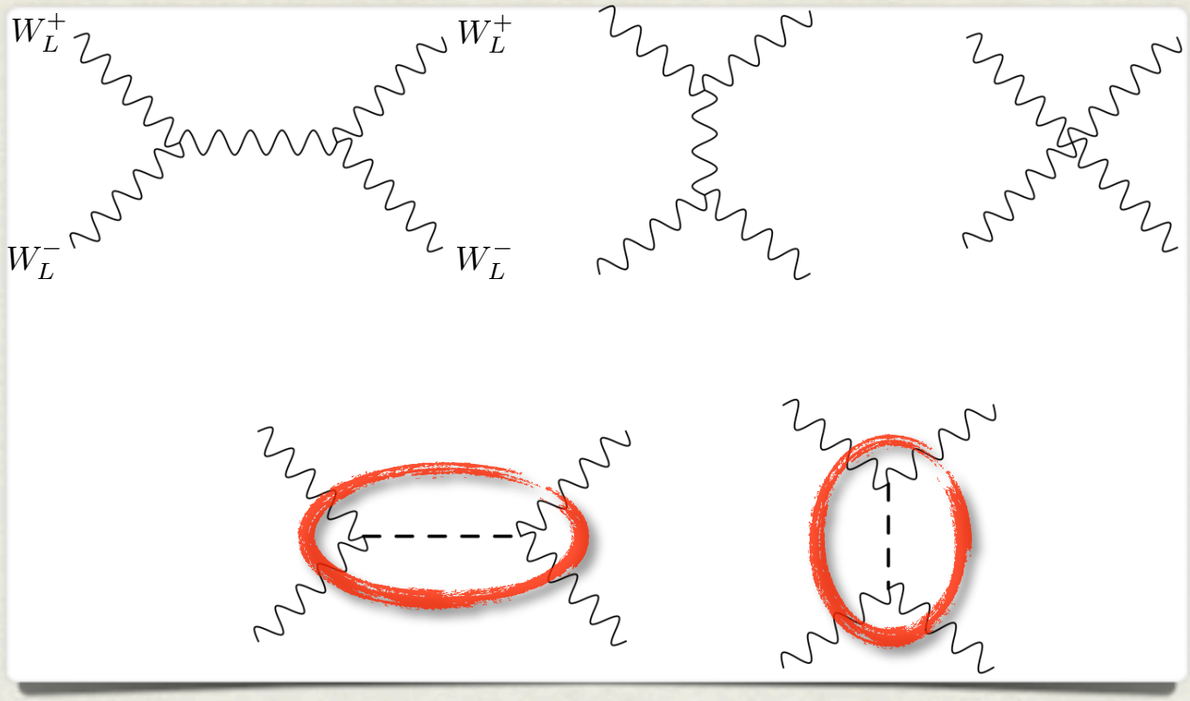

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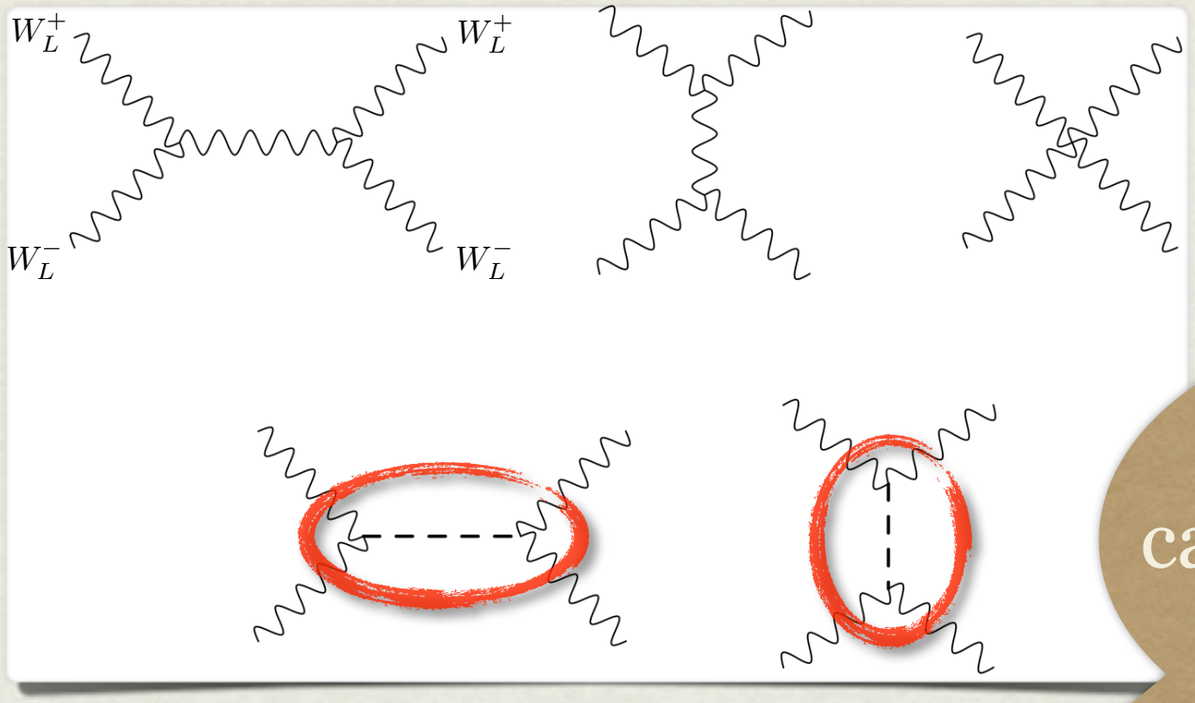

The same cancellation as in SM follows!!

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- Normalized bases $\left(\frac{1}{\sqrt{8}}G_G^aG_H^a \quad s_0\mathcal{A}\right)$ $\left(h_0s_0 \quad \pi^0s_0 \quad h_0\mathcal{A} \quad \pi^0\mathcal{A} \quad h_0\pi^0\right)$

$$\left(\pi^+\pi^- \quad \frac{1}{\sqrt{2}}h_0h_0 \quad \frac{1}{\sqrt{2}}\pi^0\pi^0 \quad \frac{1}{\sqrt{2}}s_0s_0 \quad \frac{1}{\sqrt{2}}\mathcal{A}\mathcal{A} \quad \frac{1}{4}G_G^aG_G^a \quad \frac{1}{4}G_H^aG_H^a\right)$$

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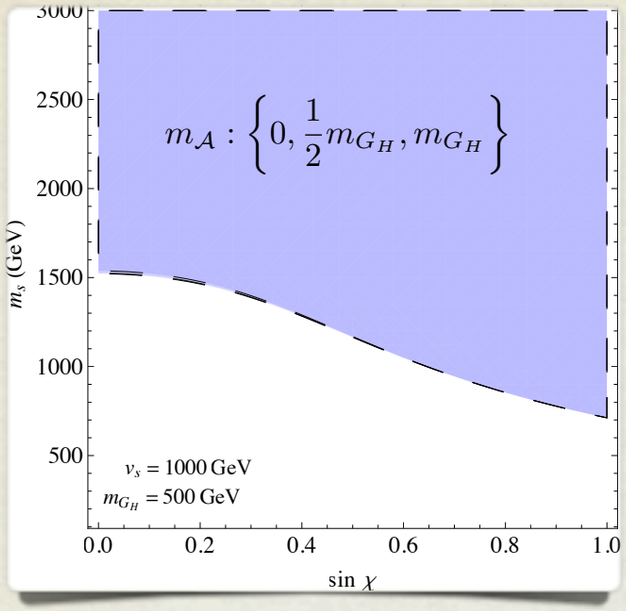
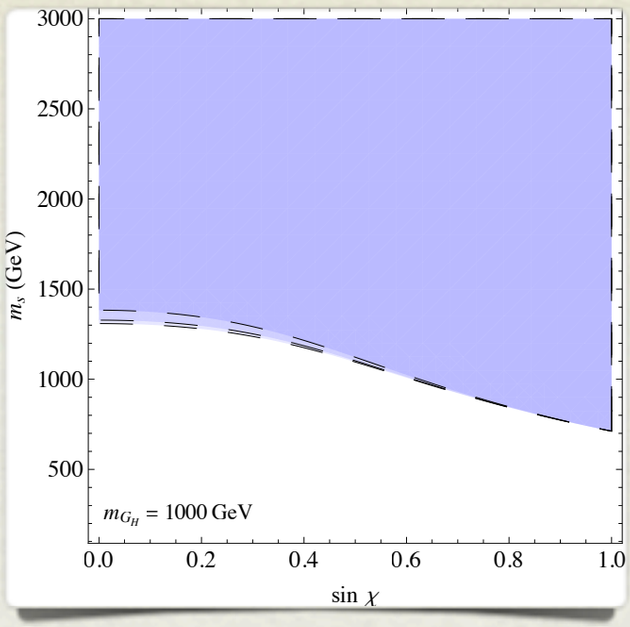
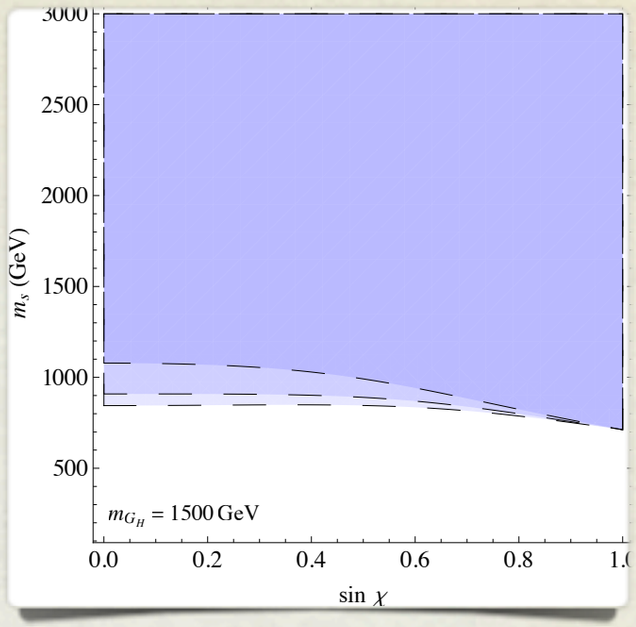
amplitude

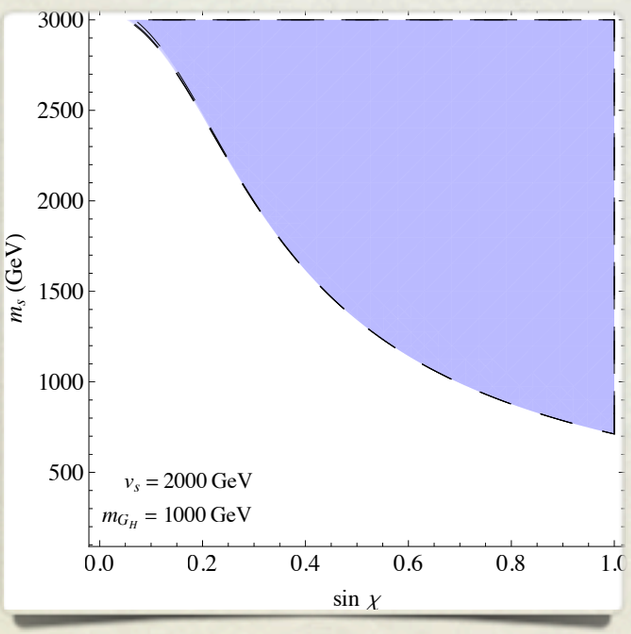
unitarity condition

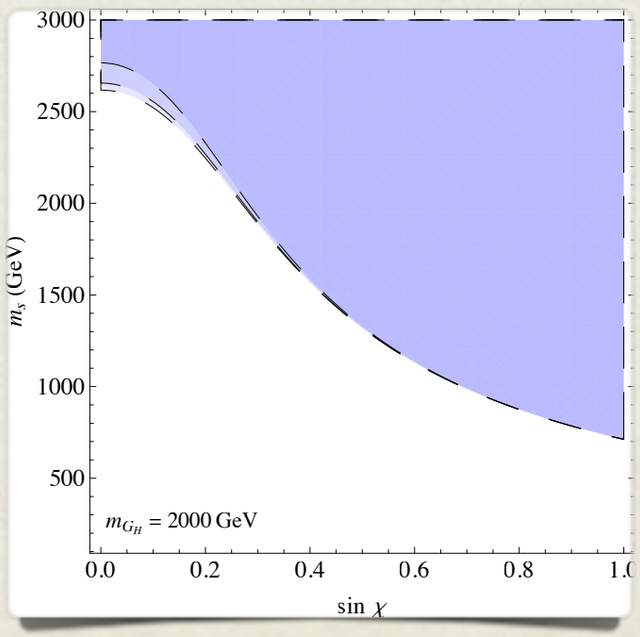
THEORETICAL BOUNDS: UNITARITY

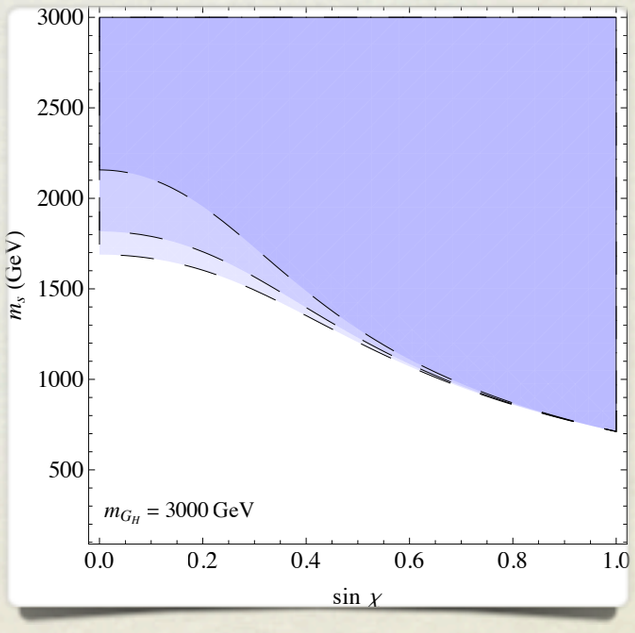






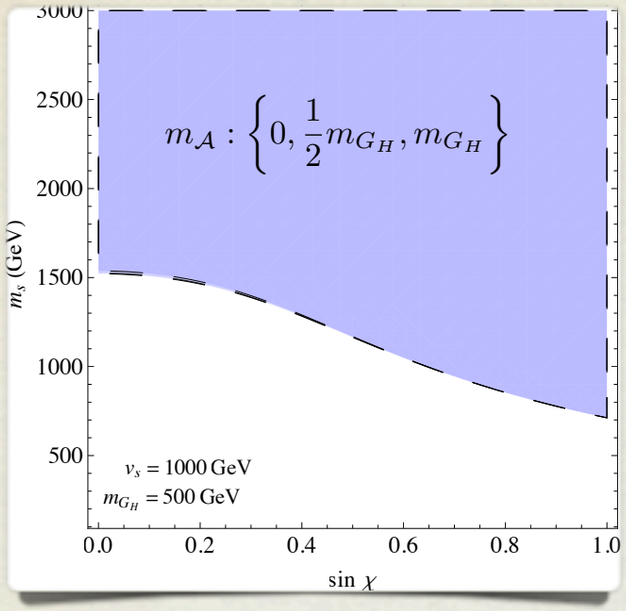


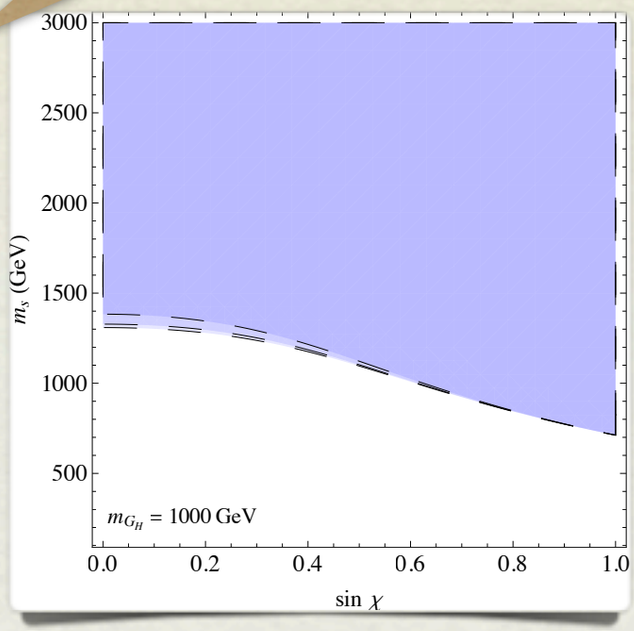


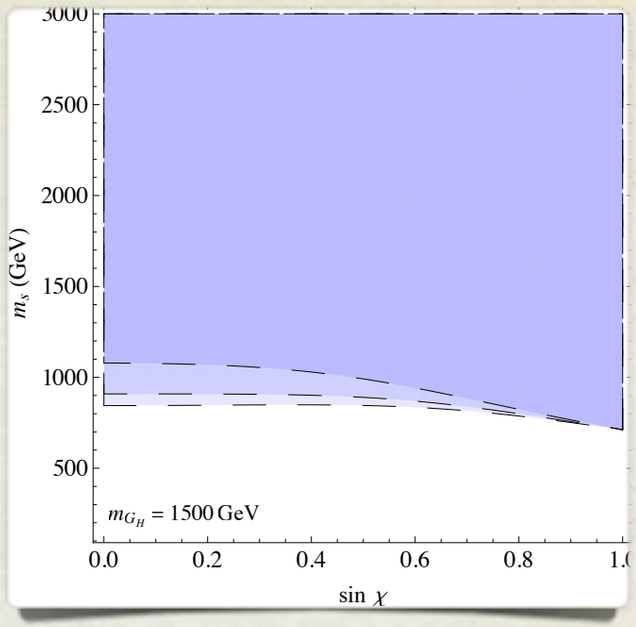


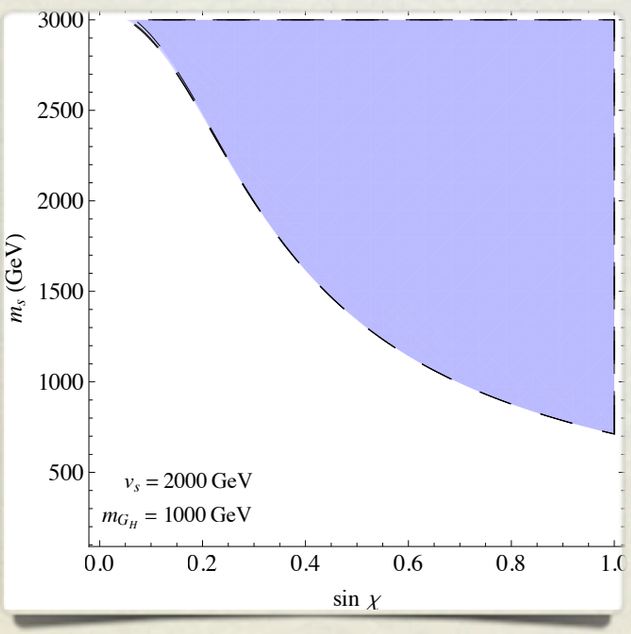
THEORETICAL BOUNDS: UNITARITY

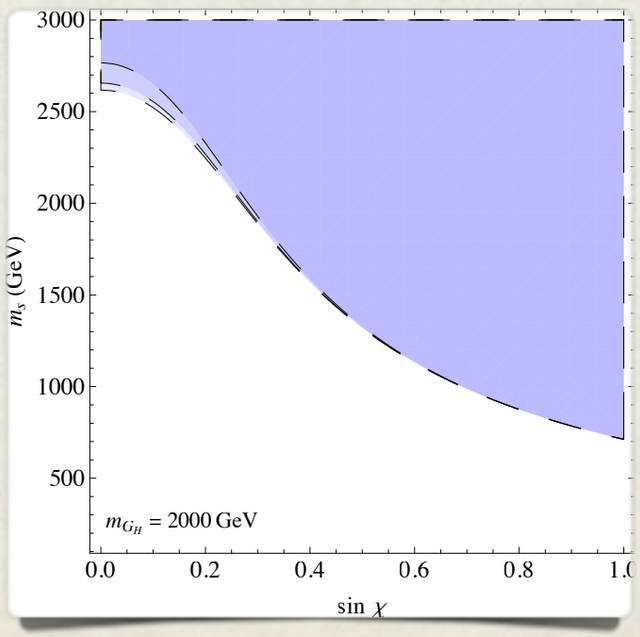
$m_s/v_s \leq 1.5$

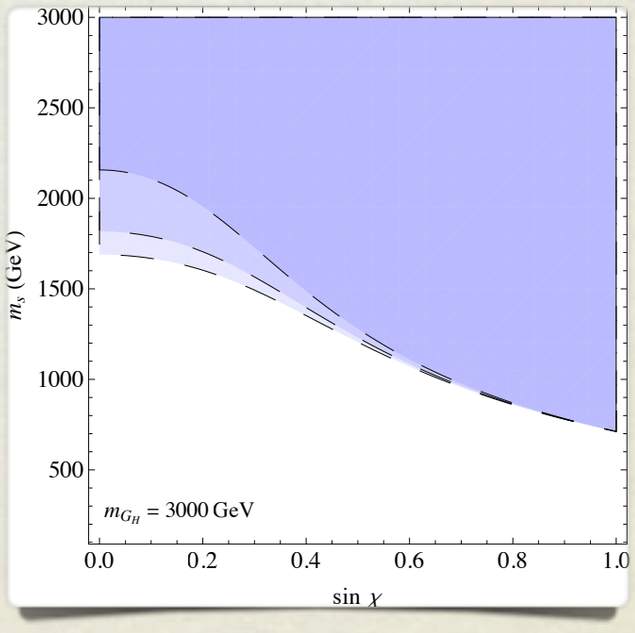












EXPERIMENTAL BOUNDS: EW PRECISION TESTS

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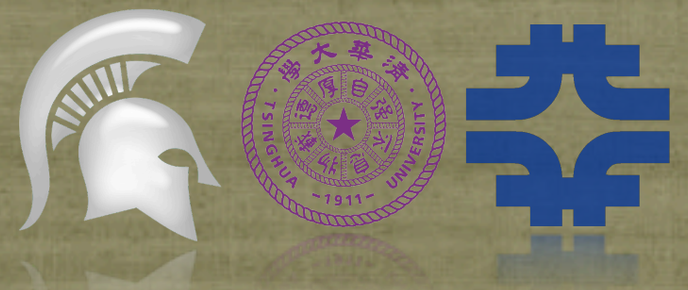

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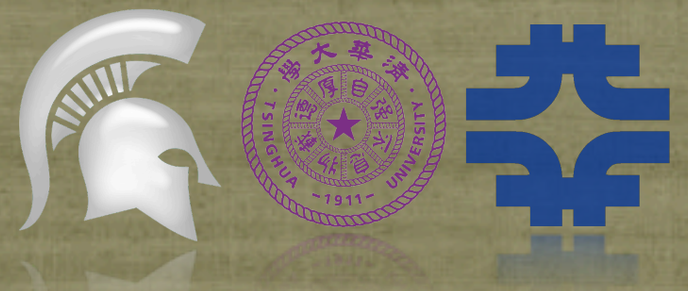

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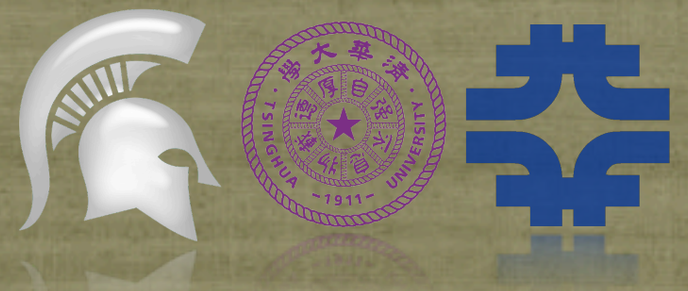

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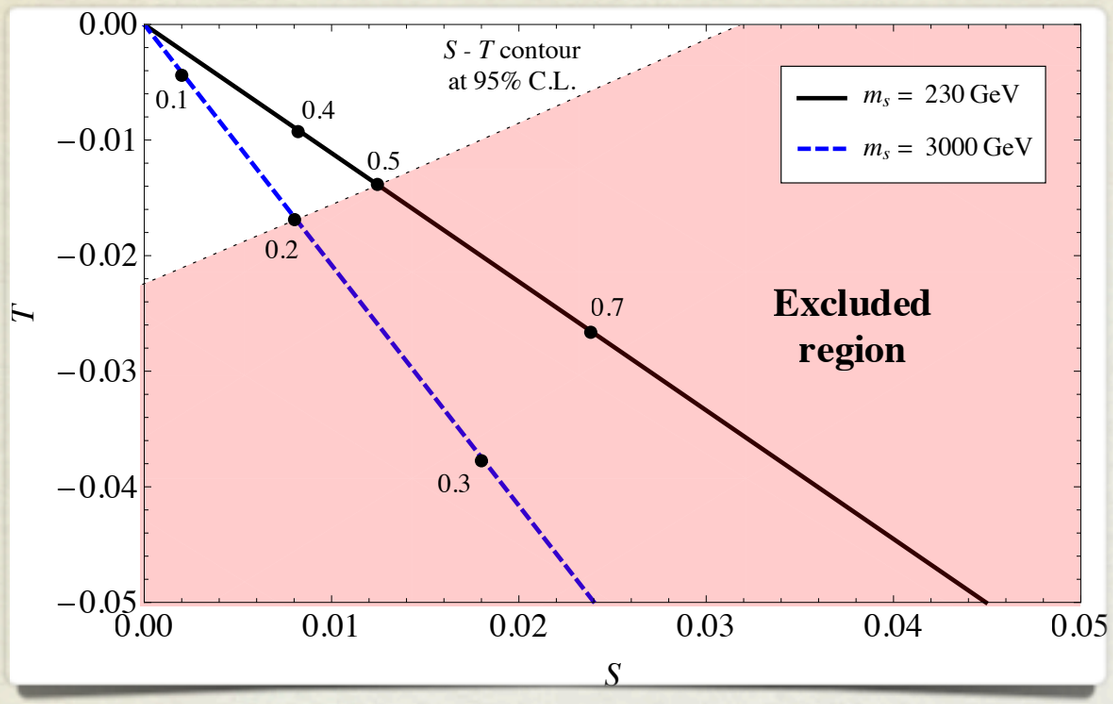
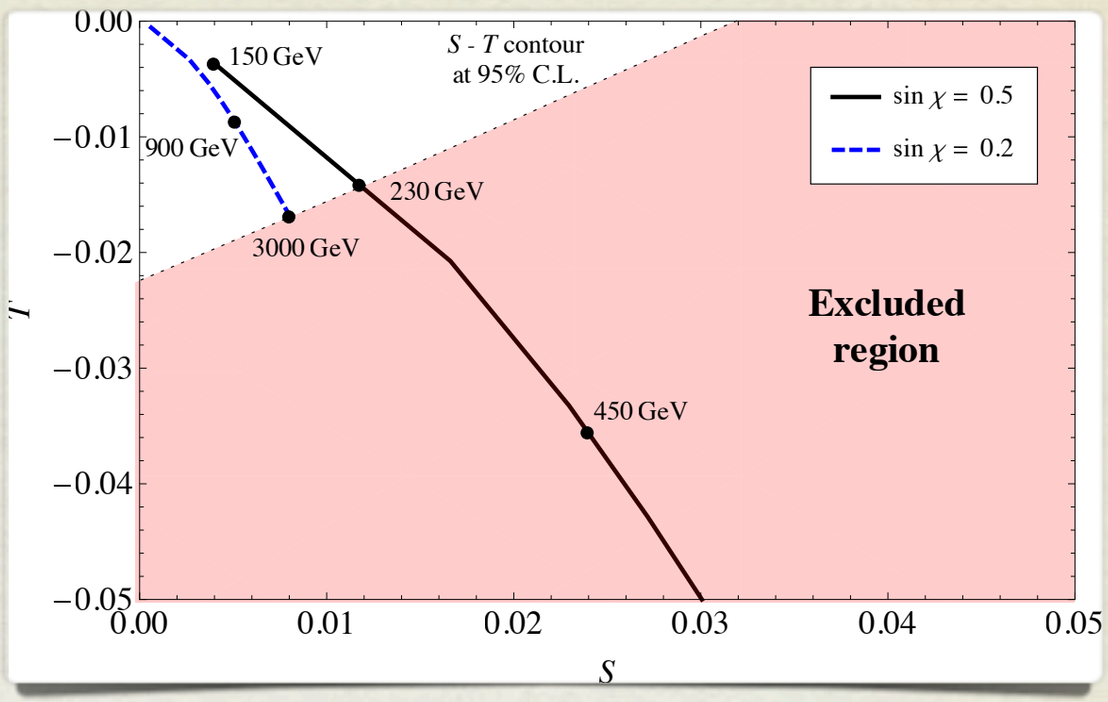
- Compare to the post-Higgs discovery bounds *[Baak et al. (2012)]*

$\boldsymbol{S = 0.03 \pm 0.10}$, $\boldsymbol{T = 0.05 \pm 0.12}$ (S-T correlation coeff. 0.89)

EXPERIMENTAL BOUNDS: EW PRECISION TESTS





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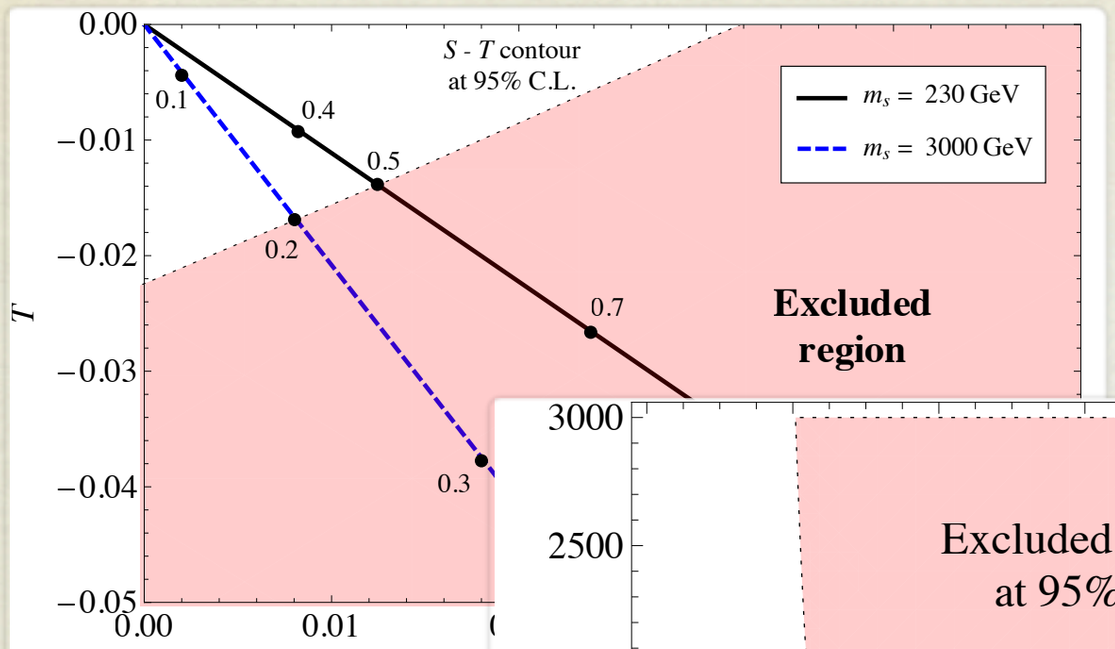

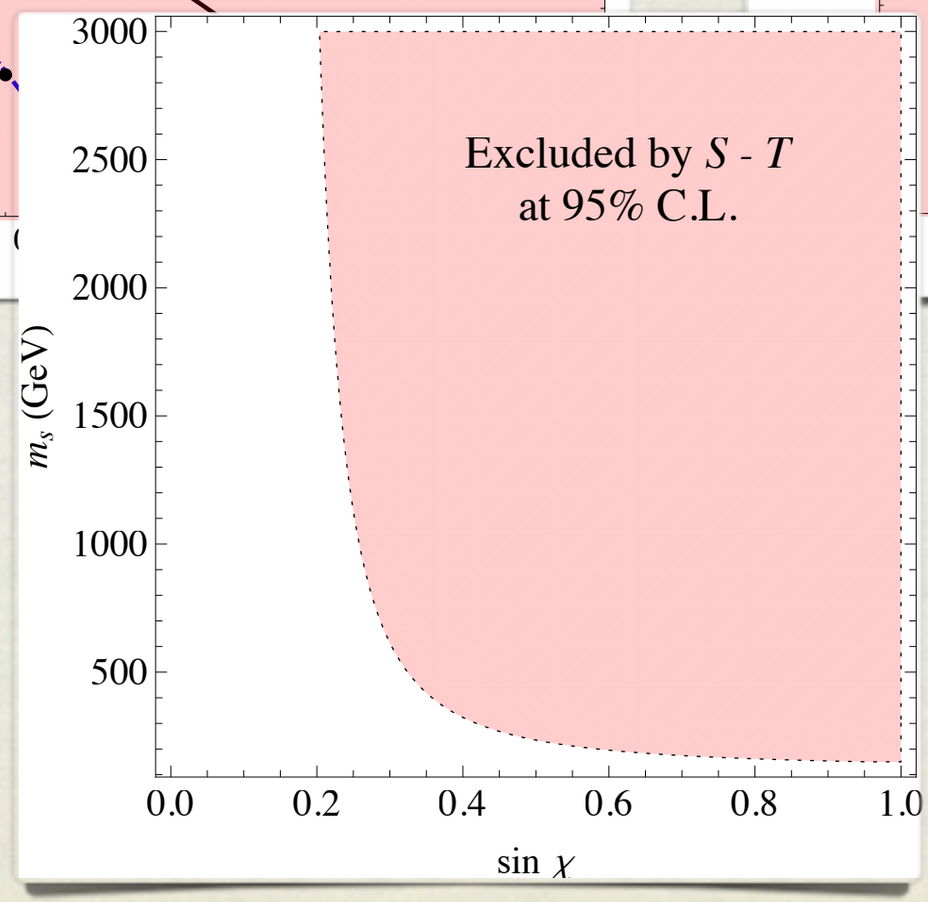

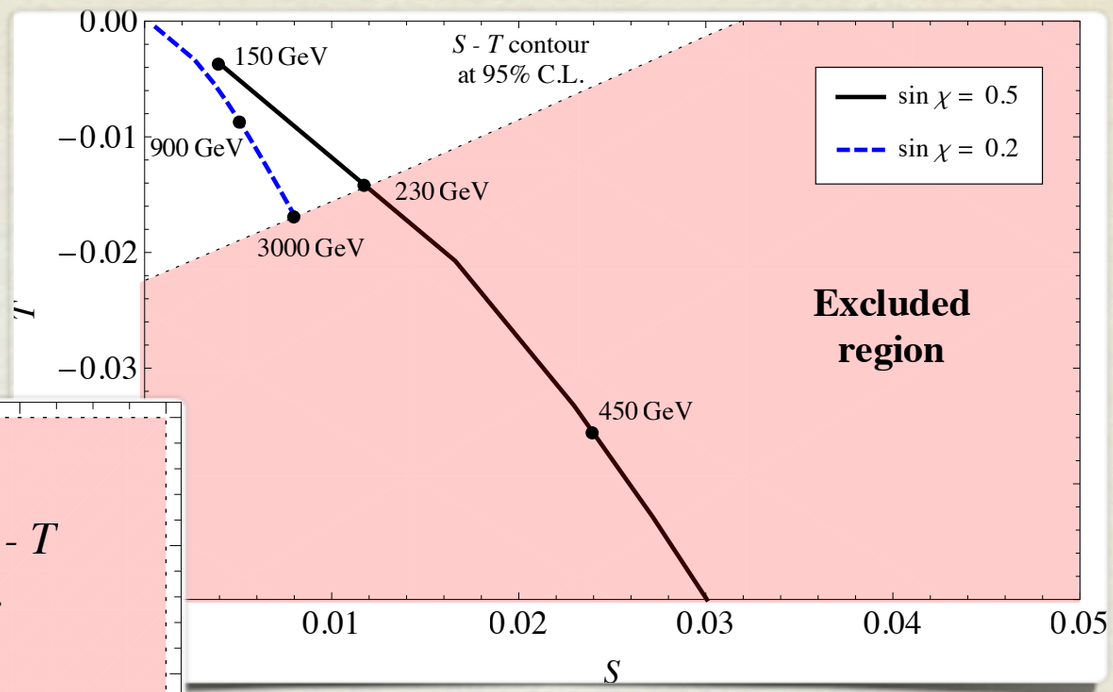

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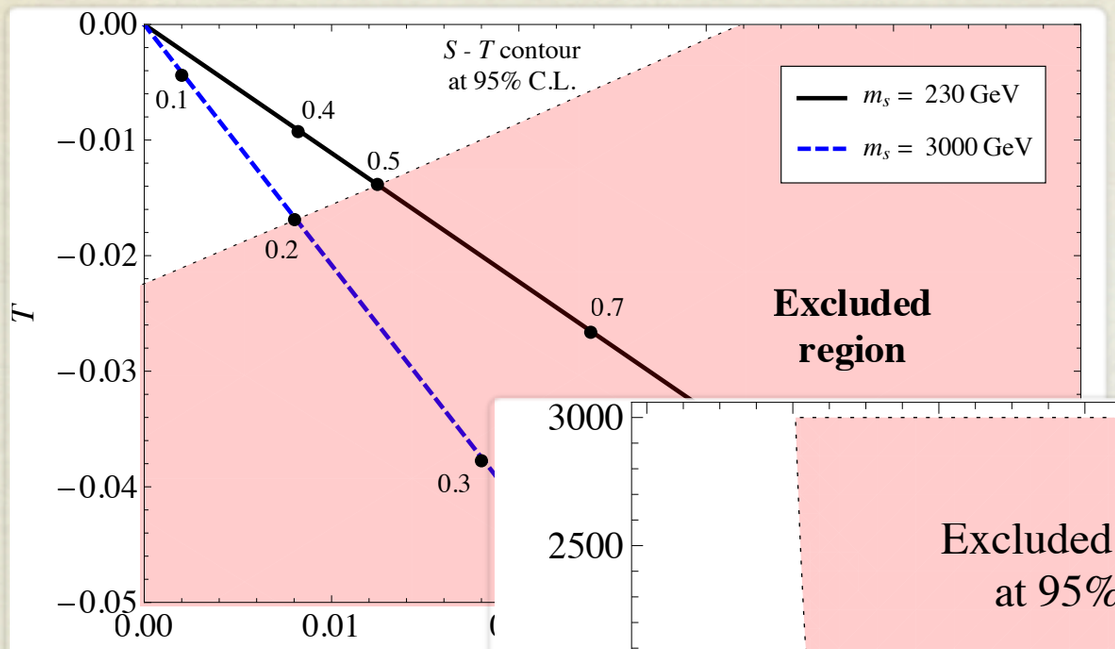

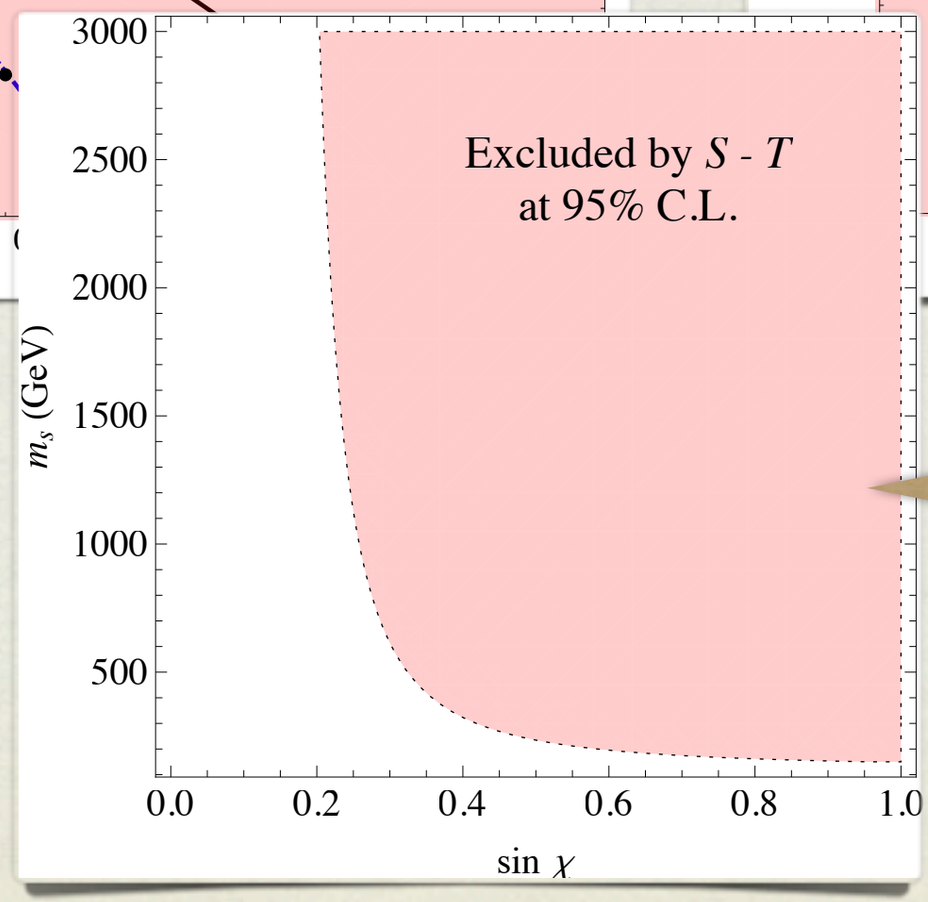

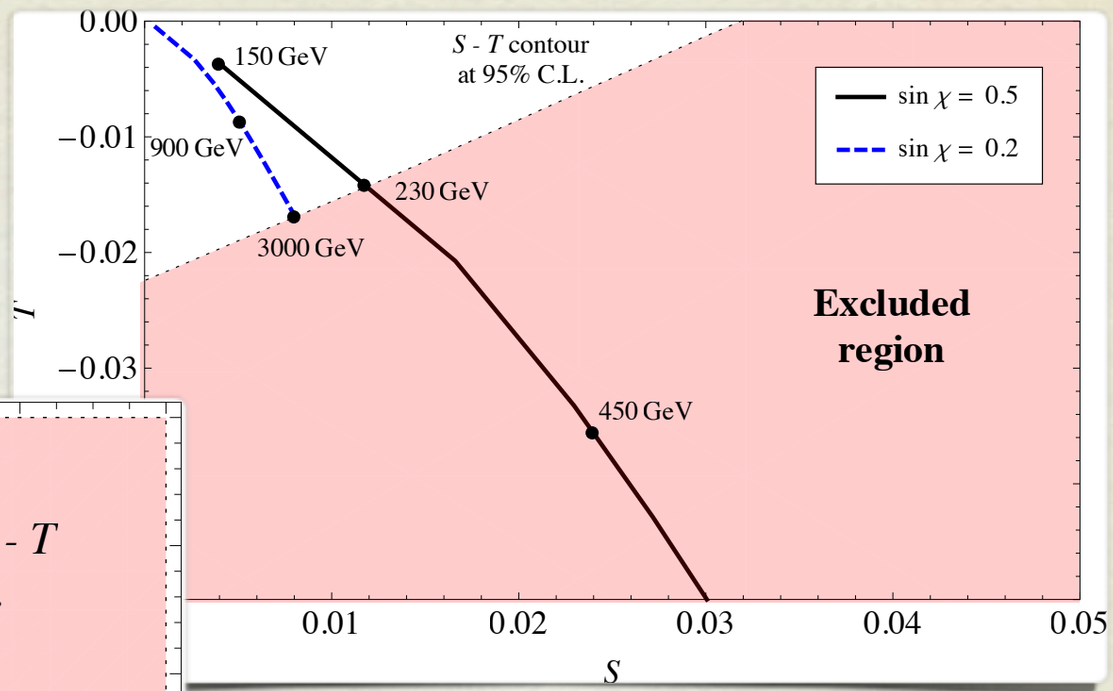

A large mixing is severely restricted!!

EXPERIMENTAL BOUNDS: NEW SCALAR BOSON RESULTS

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- Mass range $m_{GH} \in [50, 125]$ GeV is ruled out by Tevatron
  ➙ No $h \to G_H^a G_H^a$ decay!!

EXPERIMENTAL BOUNDS: NEW SCALAR BOSON RESULTS

$$\mathcal{L}_{\text{eff}} = c_V \frac{2m_W^2}{v_h} h W_\mu^+ W^{-\mu} + c_V \frac{m_Z^2}{v_h} h Z_\mu Z^\mu - c_b \frac{m_b}{v_h} h\bar{b}b - c_\tau \frac{m_\tau}{v_h} h\bar{\tau}\tau - c_c \frac{m_c}{v_h} h\bar{c}c$$
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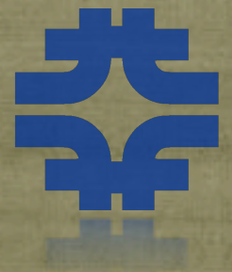

- Use an effective Lagrangian to fit the LHC data

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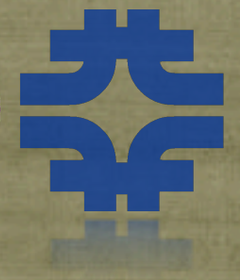

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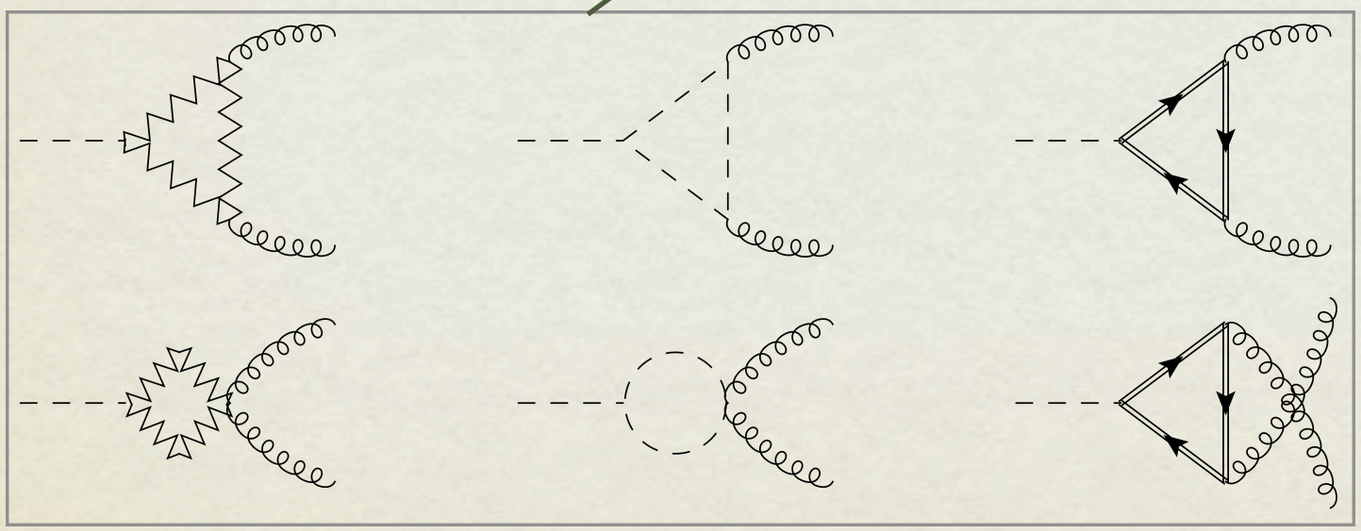

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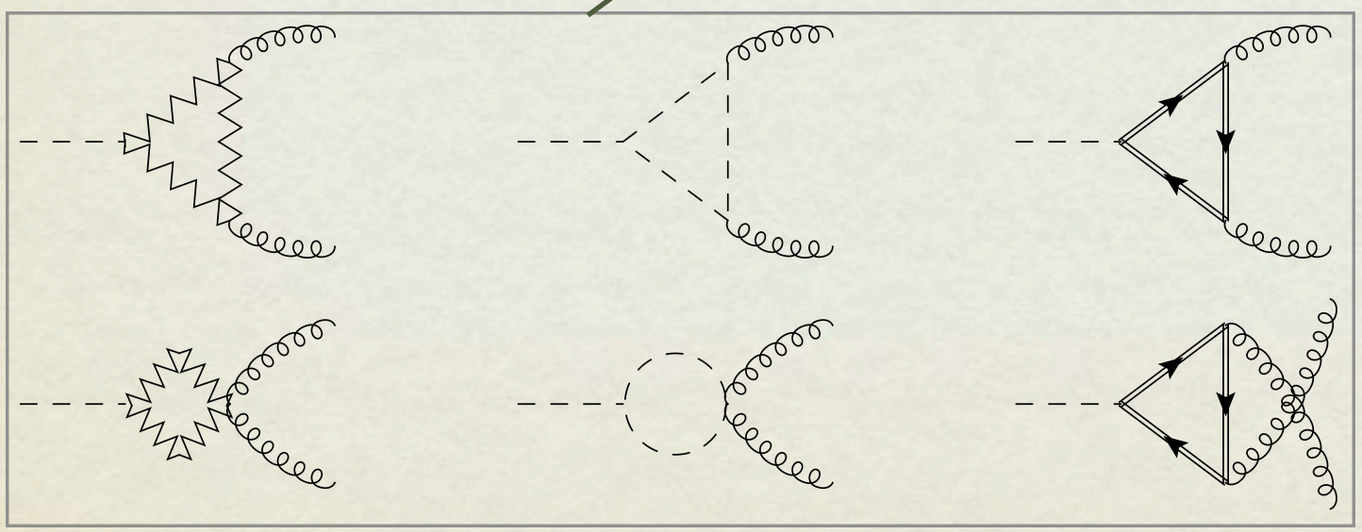

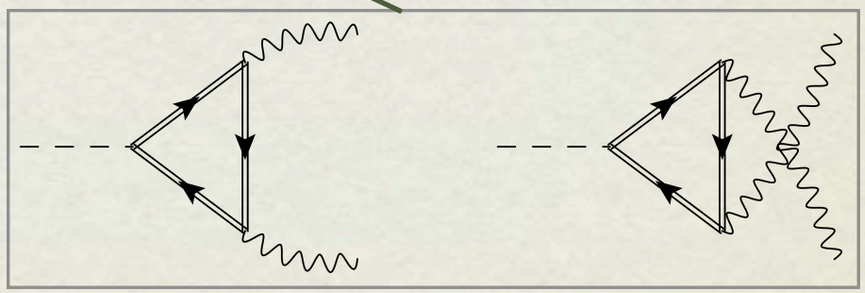

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spectator model-dependence!!

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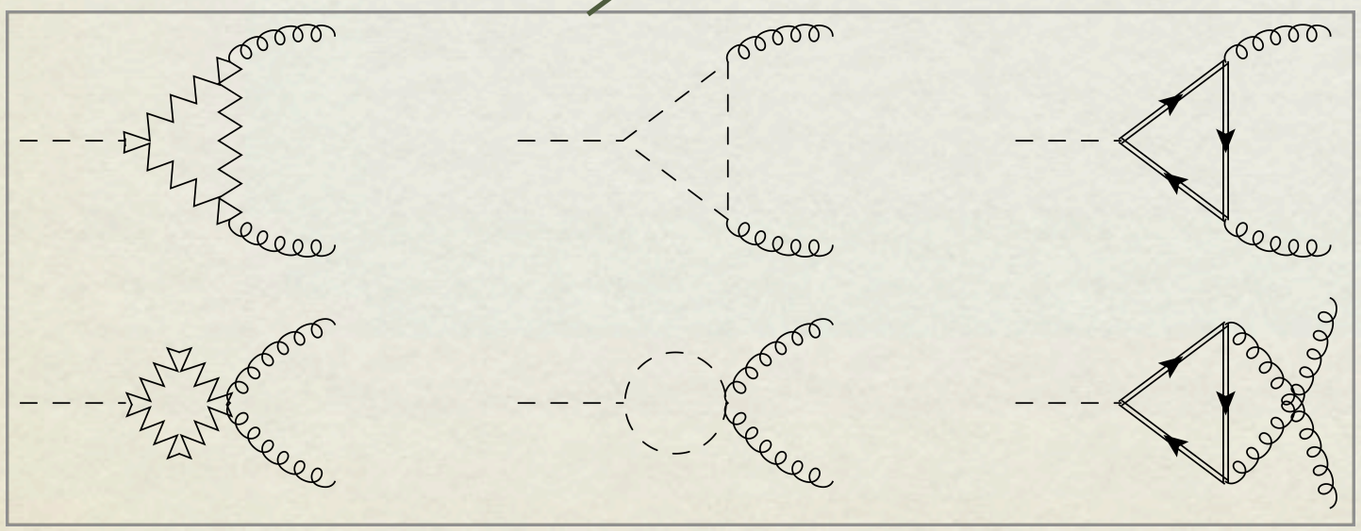
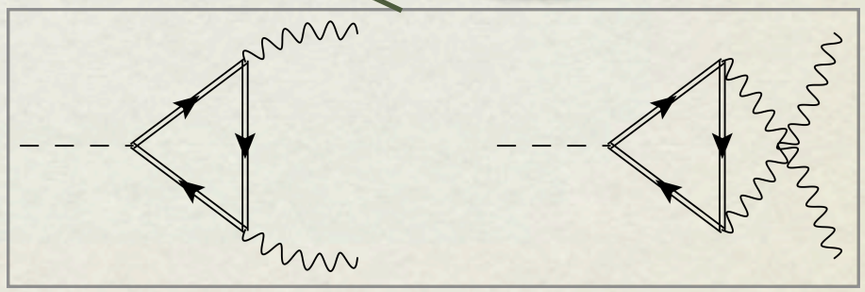
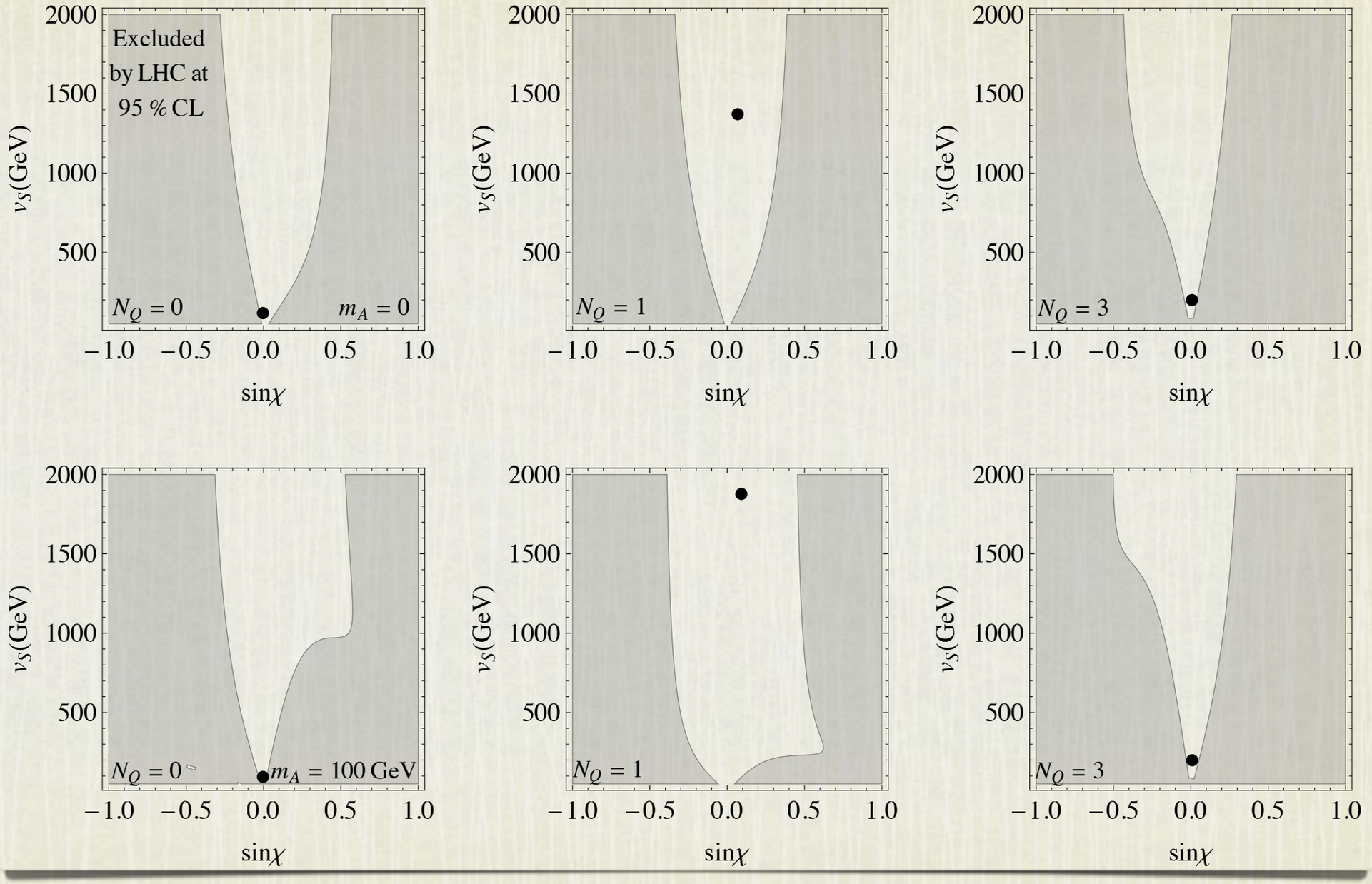


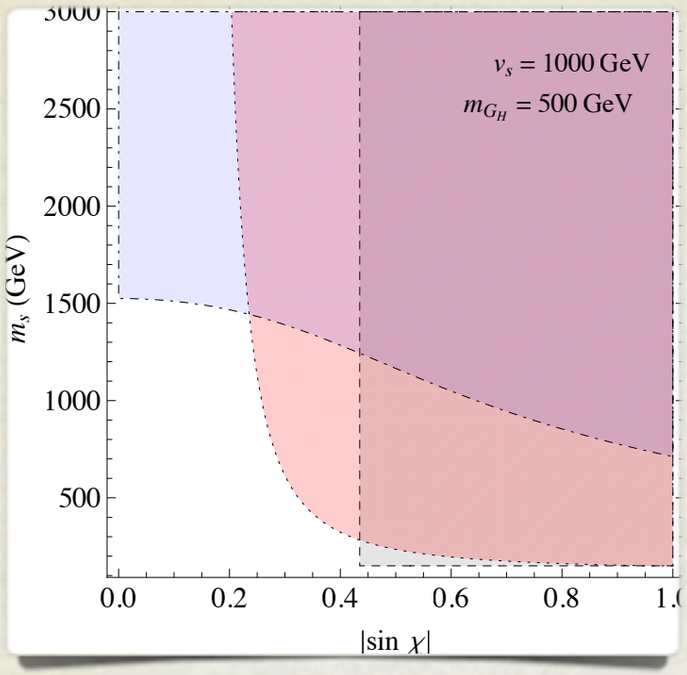


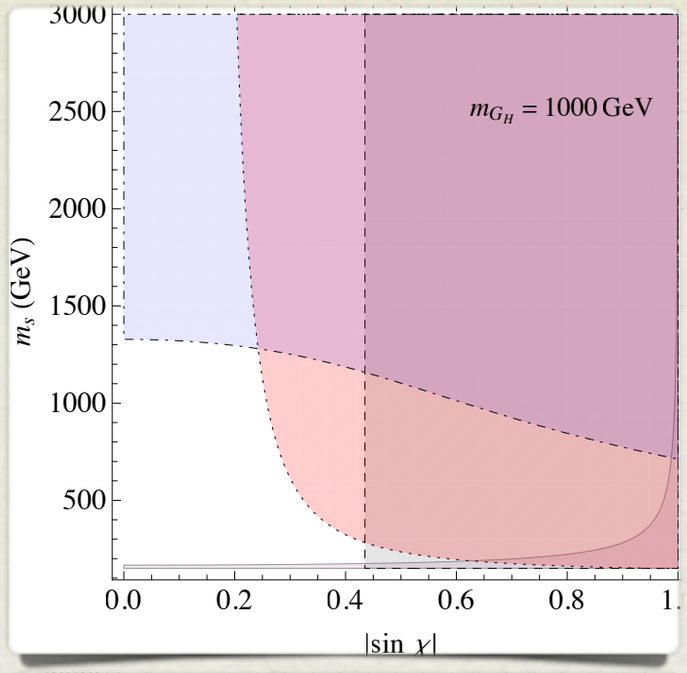
- No m_s-dependence
- m_{GH}, M_C, M_Q decouple for ≳ 125 GeV

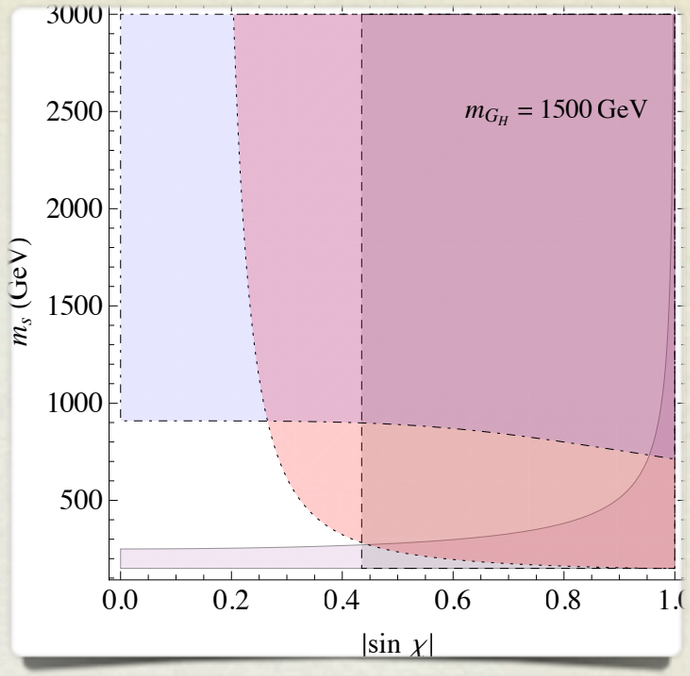


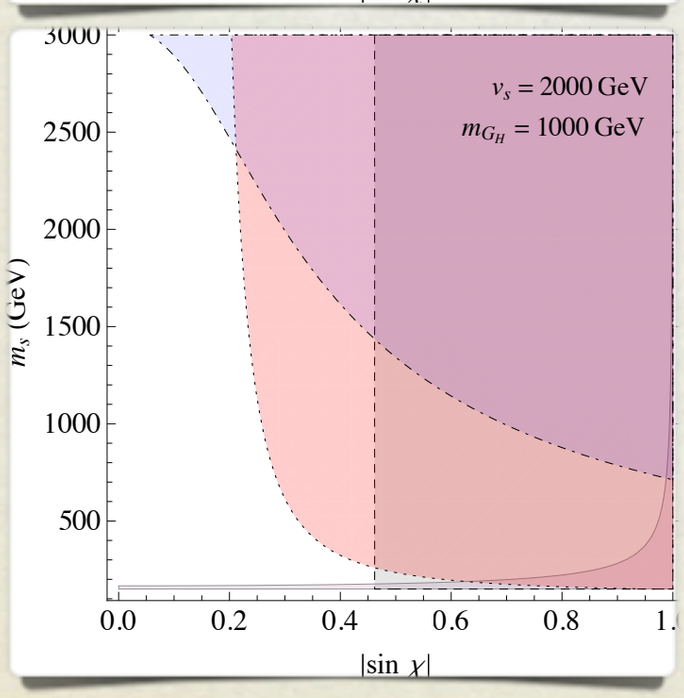
EXPERIMENTAL BOUNDS: NEW SCALAR BOSON RESULTS

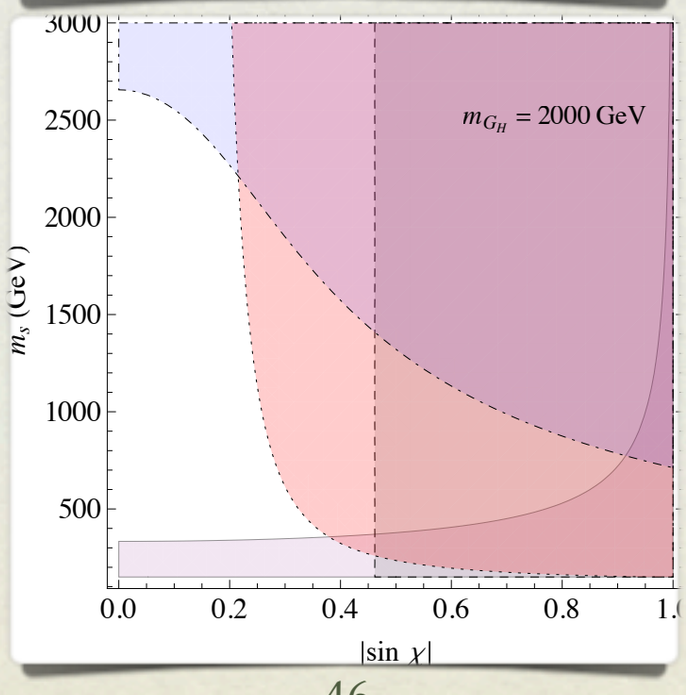
CONSTRAINTS ON THE SCALAR SECTOR

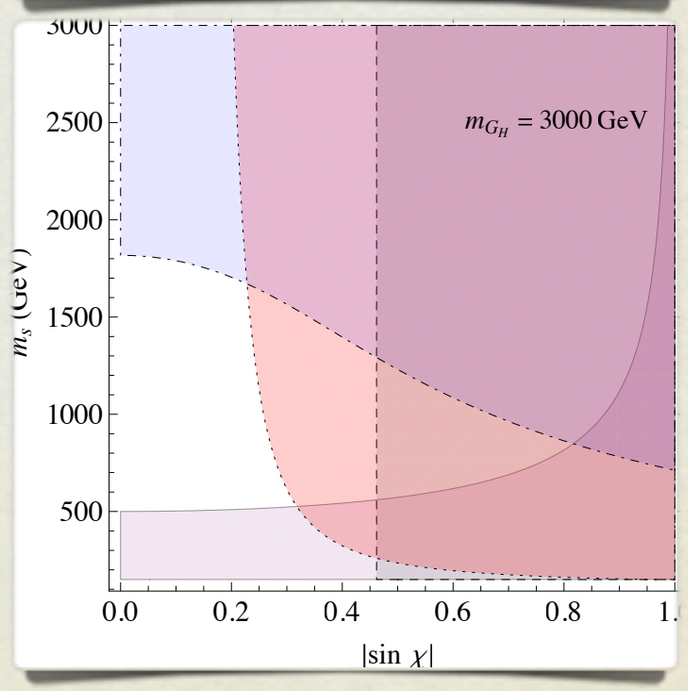






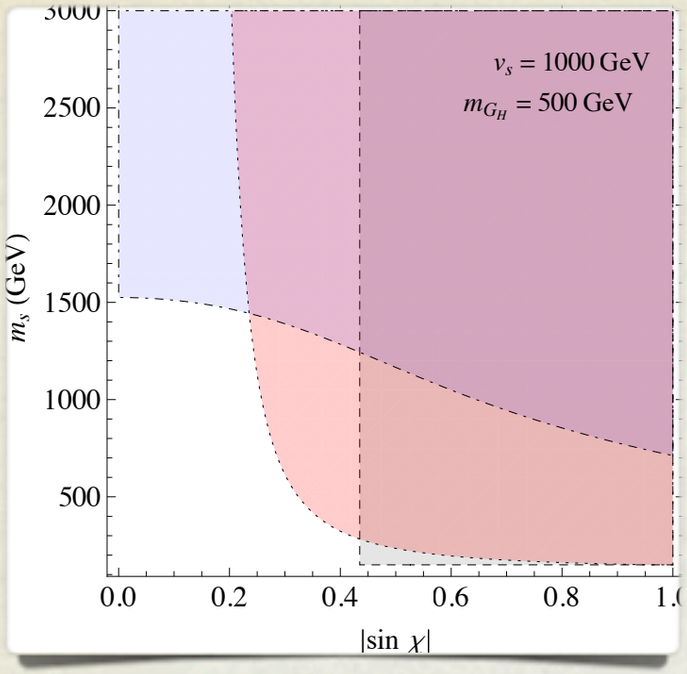


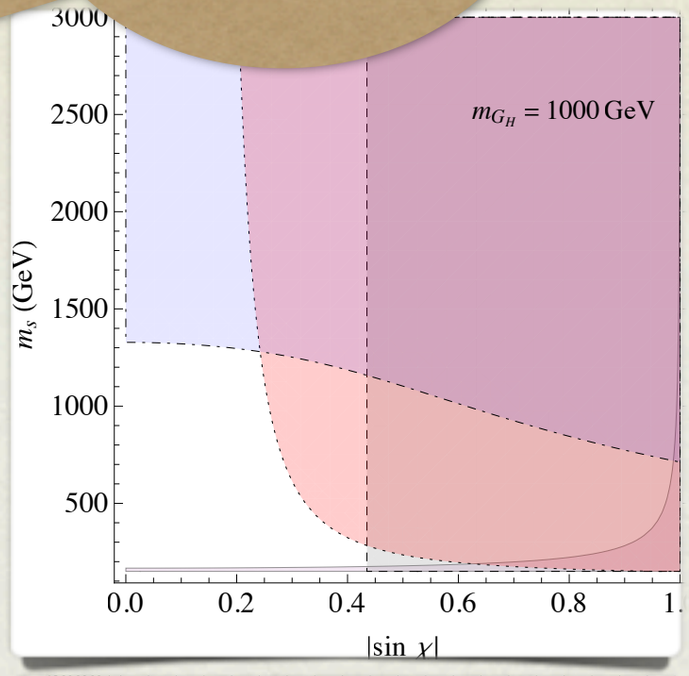


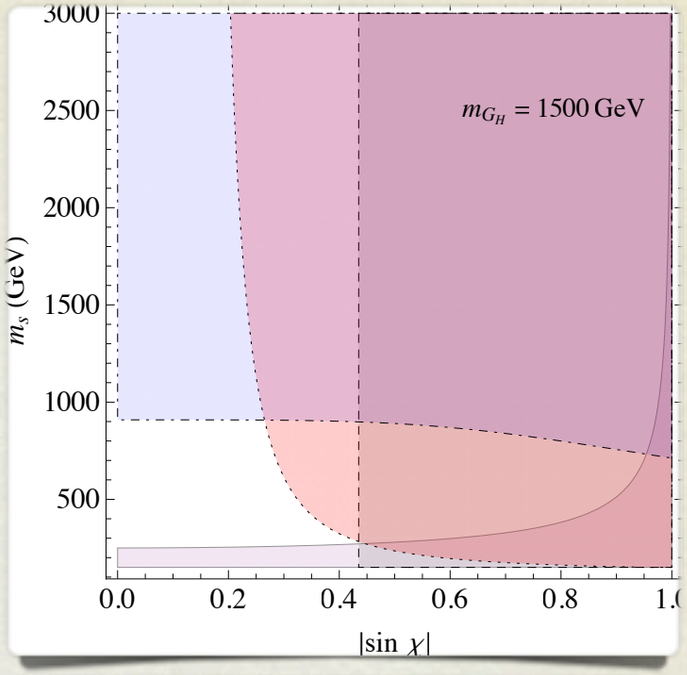


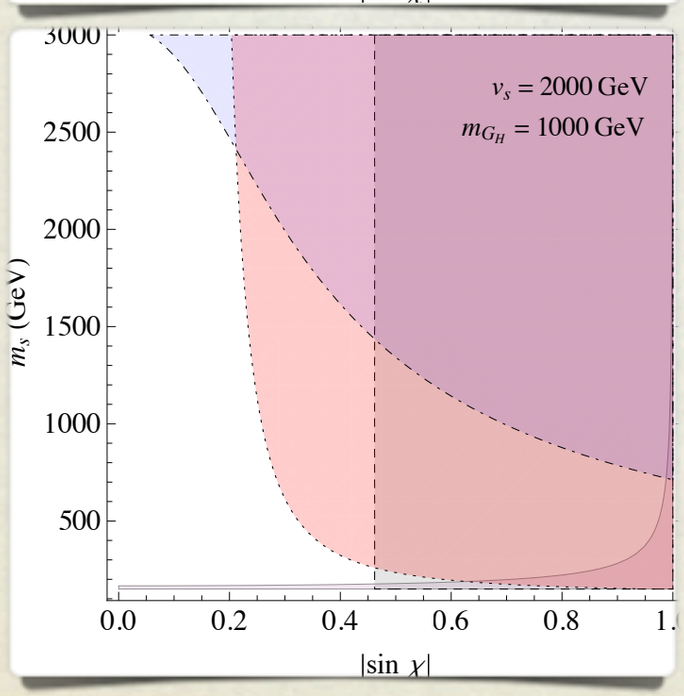
CONSTRAINTS ON THE SCALA TOR

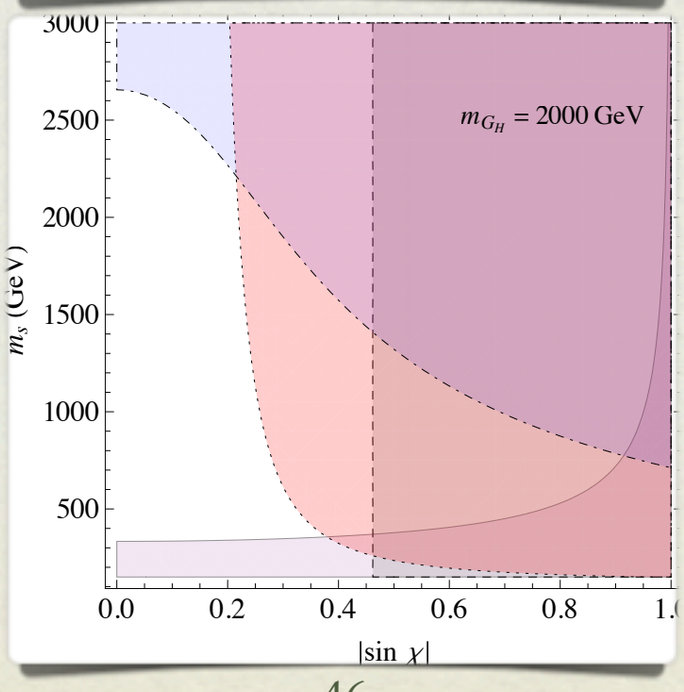
$m_A = 1/2\ m_{GH}$
(mild dependence)
&
Most conservative
collider bounds

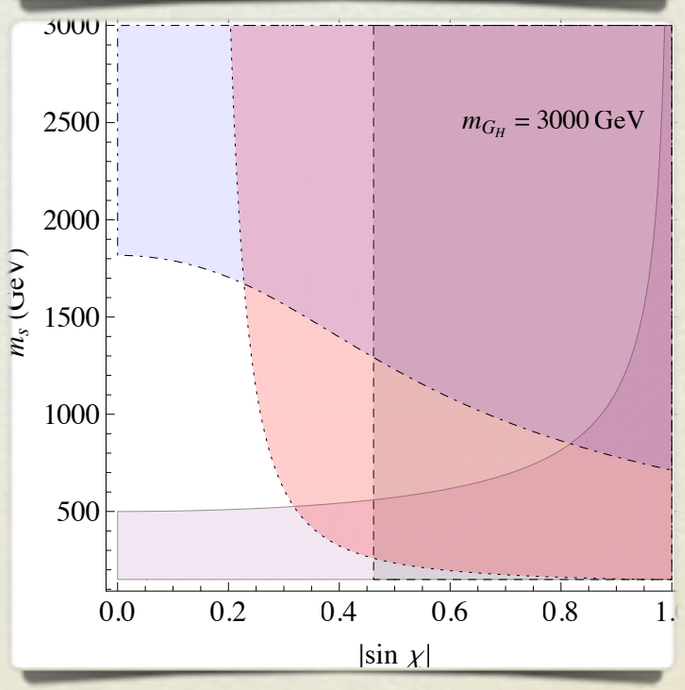












CONCLUSION PART II

CONCLUSION PART II

- Constraining the scalar sector of the renormalizable coloron model by formal and experimental analyses

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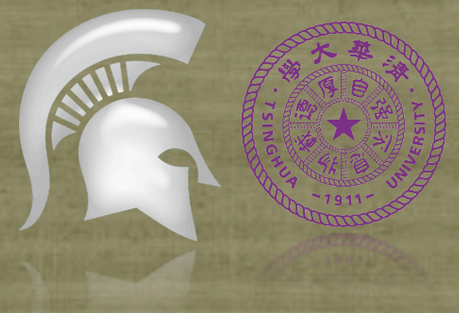

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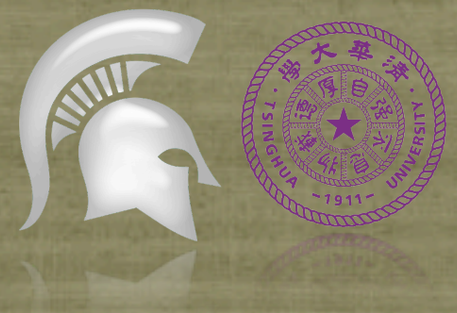

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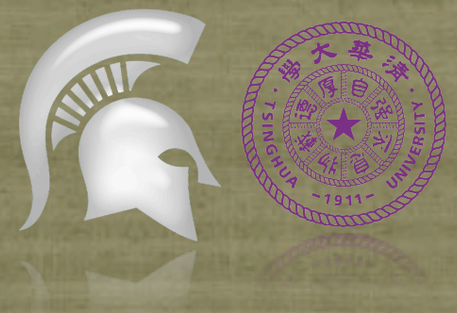

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MICHIGAN STATE
UNIVERSITY

THANK YOU..