New Physics at Hadron Colliders

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Outline

- Introduction
- Supersymmetry
- Higgs Physics
- Extra Dimensions
- Unparticle Physics
- Extra Vector Boson
- Model independent FCNC Couplings of Top Quark
- Summary

1.Introduction

- **The “Successful” Standard Model**

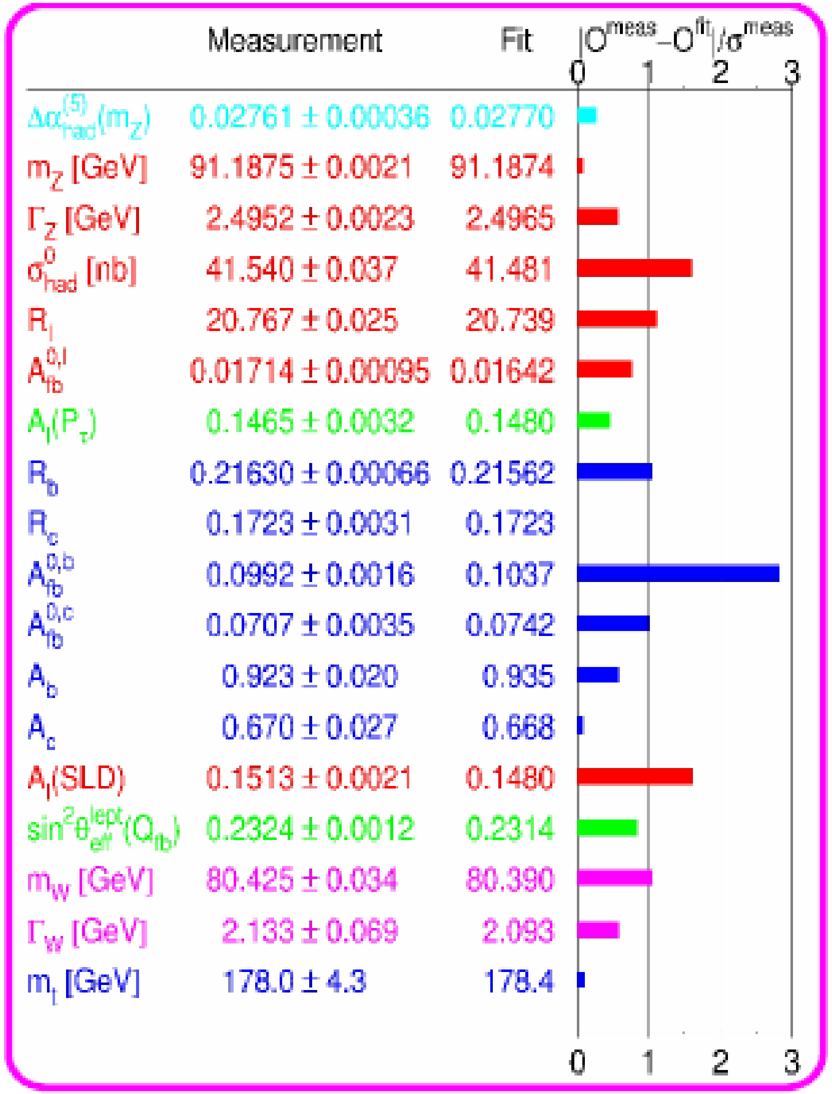
Comparing measurements and theoretical prediction of electroweak precision observables

1. The electroweak sector of SM is tested at the one-loop ,even two-loop level. (at the level of 1% and less).

2.The consistency of SM is checked by comparing direct measurements with indirect determinations of input parameters, e.g. m_t and M_W .

3. Global SM fit to all electroweak data from LEPEWWG

$\Rightarrow$



● Problems in the Standard Model

- **Electroweak symmetry breaking mechanics ?**
- **Hierarchy problem.**
- **Too many free parameters**
- **Flavor / Family problems and fermion masses problem**
- **Neutrinos mass and oscillations**
- **Dark matter**
- **…**

All these call for a more fundamental theory, and SM is just its low energy approximation $\Longrightarrow$ **New physics beyond SM**

● LHC is about to run!

- **The LHC, with its center-of-mass energy of 14 TeV and its high luminosity , offers the best prospects for discovering new physics beyond the SM.**
- **Mass searching at LHC can reach about 3 TeV.**
- **Most of new physics models predicts phenomena at TeV scale.**

• Luminosity of LHC

The rate of produced events for a given physics process is given by:

$$\boxed{N = L \quad \sigma}$$

L = Luminosity
σ = cross section

dimensions: $s^{-1} = cm^{-2}\, s^{-1} \cdot cm^{2}$

Luminosity depends on the machine:
important parameters: number of protons stored, beam focus at interaction region,….

In order to achieve acceptable production rates for the interesting physics processes, the luminosity must be high !

$L = 2 \cdot 10^{32}\ cm^{-2}\, s^{-1}$ design value for Tevatron Run II
$L = 10^{33}\ cm^{-2}\, s^{-1}$ planned for the initial phase of the LHC (1-2 years)
$L = 10^{34}\ cm^{-2}\, s^{-1}$ LHC design luminosity, very large !!
(1000 x larger than LEP-2, 50 x Tevatron Run II design)

One experimental year has ~ 10^7 s →

Integrated luminosity at the LHC: $10\ fb^{-1}$ per year, in the initial phase
$100\ fb^{-1}$ per year, later, design

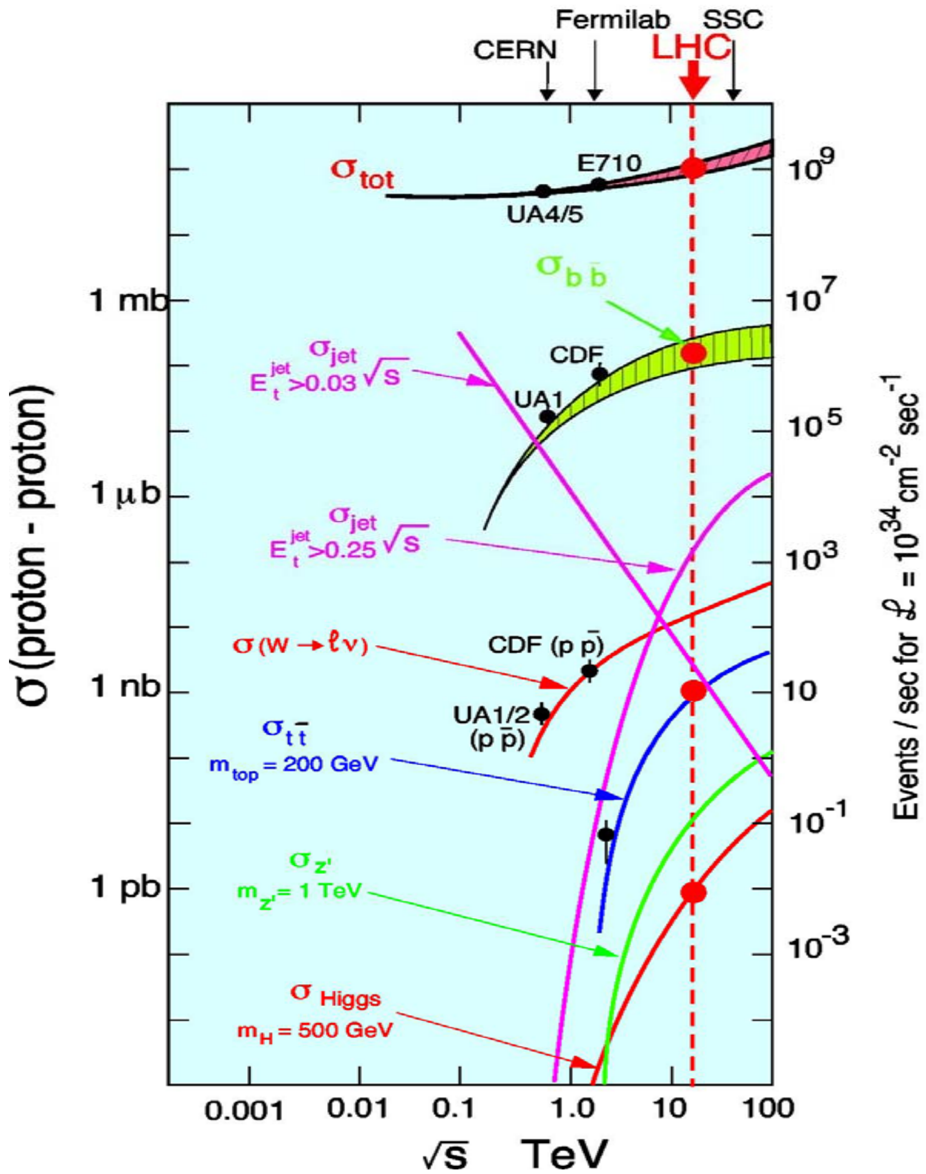
● Theoretical Calculation

- **Hadronic cross section:**

$$\sigma(S) = \sum_{a,b} \int dx_a dx_b f_{a/A}(x_a, \mu_f) f_{b/B}(x_b, \mu_f)\, \hat{\sigma}_{ab}(\hat{s} = x_a x_b S, \alpha_s),$$

- **Large scale uncertainties at LO:**
  - **Factorization scale in parton densities f(x,μ_F^2)**
  - **Renormalization scale in $\alpha_s(\mu_R^2)$**
- **Reduction of the dependence at NLO:**
  - **Virtual loop contributions**
  - **Real emission contributions**
- **Calculation at NNLO, ...**
- **Resummation to all orders**

• Cross Sections and Production Rates



Rates for L = 10^{34} cm^{-2} s^{-1}: (LHC)

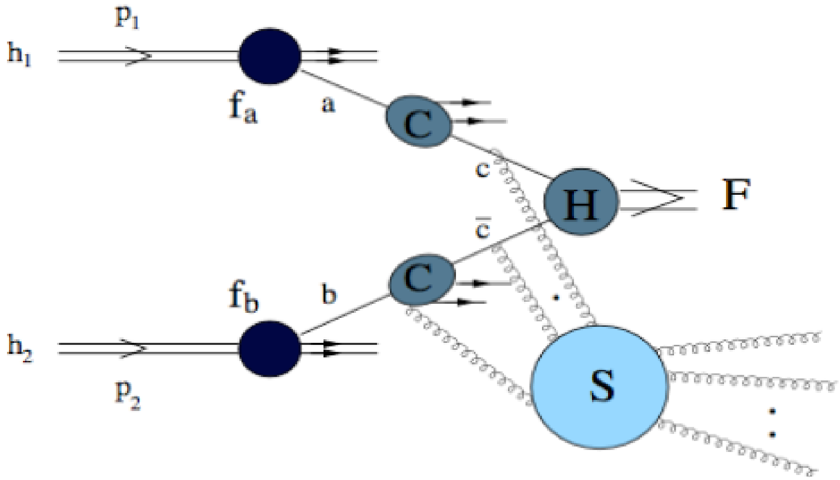
• Inelastic proton-proton reactions:	10^9 / s
• bb pairs • tt pairs	5 10^6 / s 8 / s
• W → e ν • Z → e e	150 / s 15 / s
• Higgs (150 GeV) • Gluino, Squarks (1 TeV)	0.2 / s 0.03 / s

LHC is a factory for:
top-quarks, b-quarks, W, Z, ……. Higgs, ……

The only problem: you have to detect them !

• QCD Effects in Searching for New Physics

Hadronic cross sections in perturbative QCD



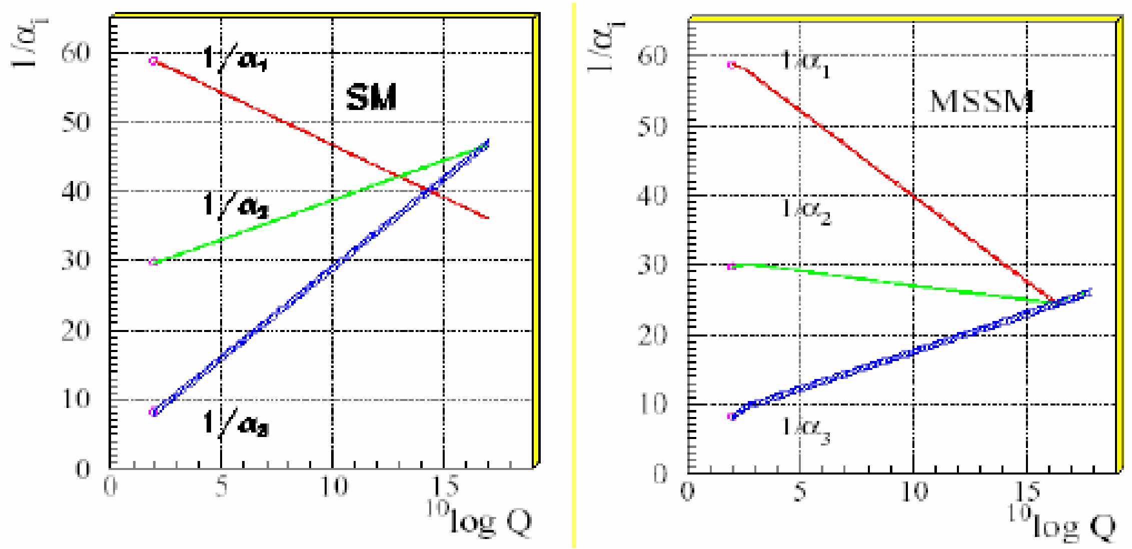
- **h_1, h_2 = initial state hadrons (with momenta p_1,p_2)**
- **f_a, f_b = parton distribution functions**
- **C = coefficient functions (partonic *splitting*)**
- **H = perturbatively computed partonic event**
- **F = final state particle(s)**
- **S = resummation of soft radiation from incoming partons**

- **At hadron colliders, we confront the complications of QCD: remnant of collision hadrons, parton showers, hadronization, etc..**
- **Especially, large QCD background becomes burden to search for new physics at the LHC.**

QCD effects at the LHC is very important!

2. Supersymmetry

- **Motivation for SUSY:**
  - **Solve hierarchy problem**
  - **Gauge coupling unification**
  - **Provide candidate for dark matter if R-parity conserves**
  - **SUSY is almost an essential ingredient in string theory**



• Minimal Supersymmetric Standard Model (MSSM)

Standard Model		Supersymmetrize	
$Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\Longleftrightarrow$	$\begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}$	squarks
$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\Longleftrightarrow$	$\begin{pmatrix} \tilde{\nu}_L \\ \tilde{l}_L \end{pmatrix}$	sleptons
$u^c,\ d^c,\ e^c$	$\Longleftrightarrow$	$\tilde{u}^c,\ \tilde{d}^c,\ \tilde{e}^c$	
$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$	$\Longleftrightarrow$	$\begin{pmatrix} \tilde{H}_u^+ \\ \tilde{H}_u^0 \end{pmatrix}$	higgsinos
$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$	$\Longleftrightarrow$	$\begin{pmatrix} \tilde{H}_d^0 \\ \tilde{H}_d^- \end{pmatrix}$	
g	$\Longleftrightarrow$	$\tilde{g}$	gluino
$W^\pm,\ W^0$	$\Longleftrightarrow$	$\tilde{W}^\pm,\ \tilde{W}^0$	winos
B	$\Longleftrightarrow$	$\tilde{B}$	bino

- **Higgs sector: CP-even h^0, H^0; CP-odd A^0; Charged Higgs boson $H^\pm$.**
- **The left-handed sfermions and right-handed sfermions mix to form mass eigenstates, especially the stop, sbottom and stau.**
- **Neutral higgsinos, wino, and bino mix to form mass eigenstates:** $\tilde{\chi}_1^0,\ \tilde{\chi}_2^0,\ \tilde{\chi}_3^0,\ \tilde{\chi}_4^0$
- **Charged higgsinos and winos mix to form mass eigenstates:** $\tilde{\chi}_1^\pm,\ \tilde{\chi}_2^\pm$

$$\mathcal{L}_{Gauge} = \sum_{SU(3),SU(2),U(1)} \frac{1}{4}\left(\int d^2\theta\ TrW^\alpha W_\alpha + \int d^2\bar{\theta}\ Tr\bar{W}^{\dot{\alpha}}\bar{W}_{\dot{\alpha}}\right) + \sum_{Matter} \int d^2\theta d^2\bar{\theta}\ \Phi_i^\dagger e^{g_3\hat{V}_3 + g_2\hat{V}_2 + g_1\hat{V}_1}\Phi_i,$$

$$\mathcal{L}_{SUSY} = \mathcal{L}_{Gauge} + \mathcal{L}_{Yukawa}$$

$$\mathcal{L}_{Yukawa} = \int d^2\theta\ (W_R + W_{NR}) + h.c.$$

$$W_R = \epsilon_{ij}(y^U_{ab}Q^j_a U^c_b H^i_2 + y^D_{ab}Q^j_a D^c_b H^i_1 + y^L_{ab}L^j_a E^c_b H^i_1 + \mu H^i_1 H^j_2),$$

$$W_{NR} = \epsilon_{ij}(\lambda^L_{abd}L^i_a L^j_b E^c_d + \lambda^{L\prime}_{abd}L^i_a Q^j_b D^c_d + \mu'_a L^i_a H^j_2) + \lambda^B_{abd}U^c_a D^c_b D^c_d.$$

R-parity

- **R-parity conservation:**

$R=(-1)^{3(B-L)+2S}$

R=+1 for SM particles

R=-1 for SUSY particles

The SUSY particles must be created in pairs at the colliders. The lightest SUSY particle (LSP) is stable and is candidate for dark matter.

- **R-parity violation**

In principle the superpotential can contain other interactions:

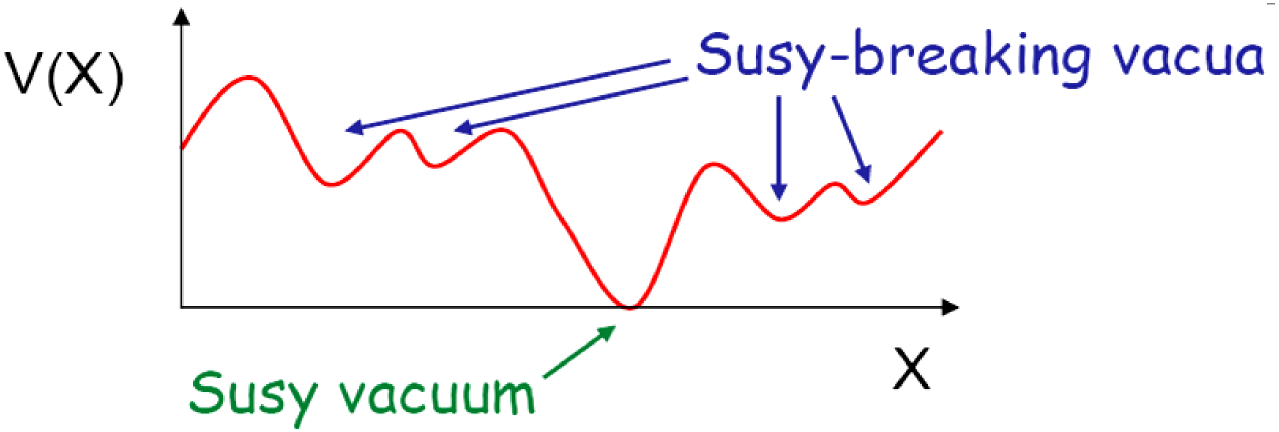
$$W_{NR} = \epsilon_{ij}(\lambda^{L}_{abd} L^i_a L^j_b E^c_d + \lambda^{L\prime}_{abd} L^i_a Q^j_b D^c_d + \mu'_a L^i_a H^j_2) + \lambda^{B}_{abd} U^c_a D^c_b D^c_d.$$

These terms violate either lepton or baryon number. Since both violations are not observed in Nature , these terms must be suppressed or excluded.

● SUSY Breaking

- **Spontaneously SUSY Breaking**

SUSY is spontaneously broken if $Q_\alpha \left|0\right\rangle \neq 0$ **which equals to** $E = \left\langle 0\right| H \left|0\right\rangle > 0$



The scalar potential for N=1 SUSY is

$$V = \sum_i \left|\frac{\partial W}{\partial \phi_i}\right|^2 + \frac{1}{2}\sum_a g_a{}^2 \left(\sum_{i,j} \phi_i^* T^a{}_{ij} \phi_j\right)^2 = F_i^* F_i + \frac{1}{2} D^a D^a$$

To generate a SUSY breaking scale, we have two choices

1. put a parameter with mass dimension in superpotential by hand

2. generate a scale via some quantum effects

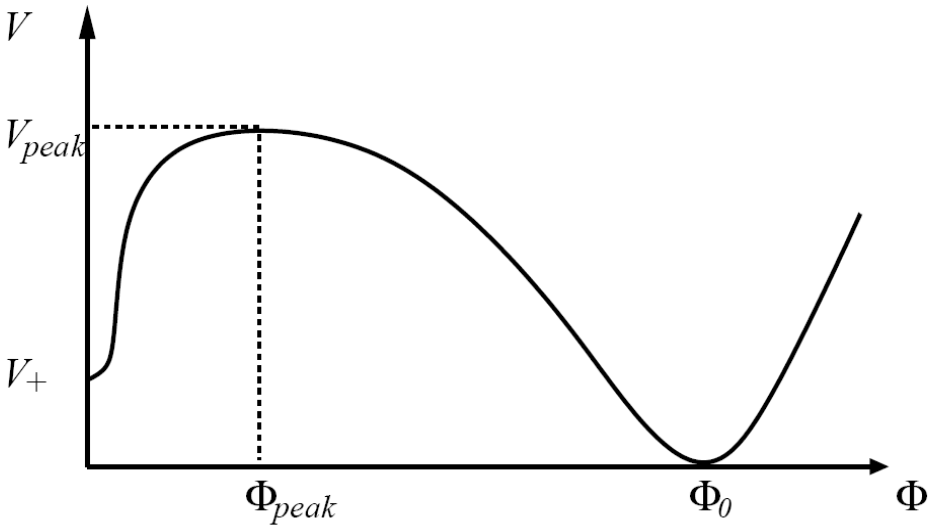
The first choice leads to a hierarchy problem. The second needs to introduce Dynamical Supersymmetry Breaking.

- **Dynamical SUSY Breaking**

- **SUSY QCD (a SU(N_c) SUSY gauge theory with N_f flavor vector like chiral superfields) is the most important DSB theory. In this theory, for N_c -1>N_f, a scale is generated via the gaugino condensation** $\left\langle \lambda^a \lambda^a \right\rangle = \Lambda^3$

- **Recently, a new model (ISS model) are proposed. In this model, N_c<N_f, so there is a real SUSY vacuum (stable vacuum). But there are also some non-zero minimum of the scalar potential (meta-stable vacuum). They assume that we are living in a long-lived meta-stable vacuum.**

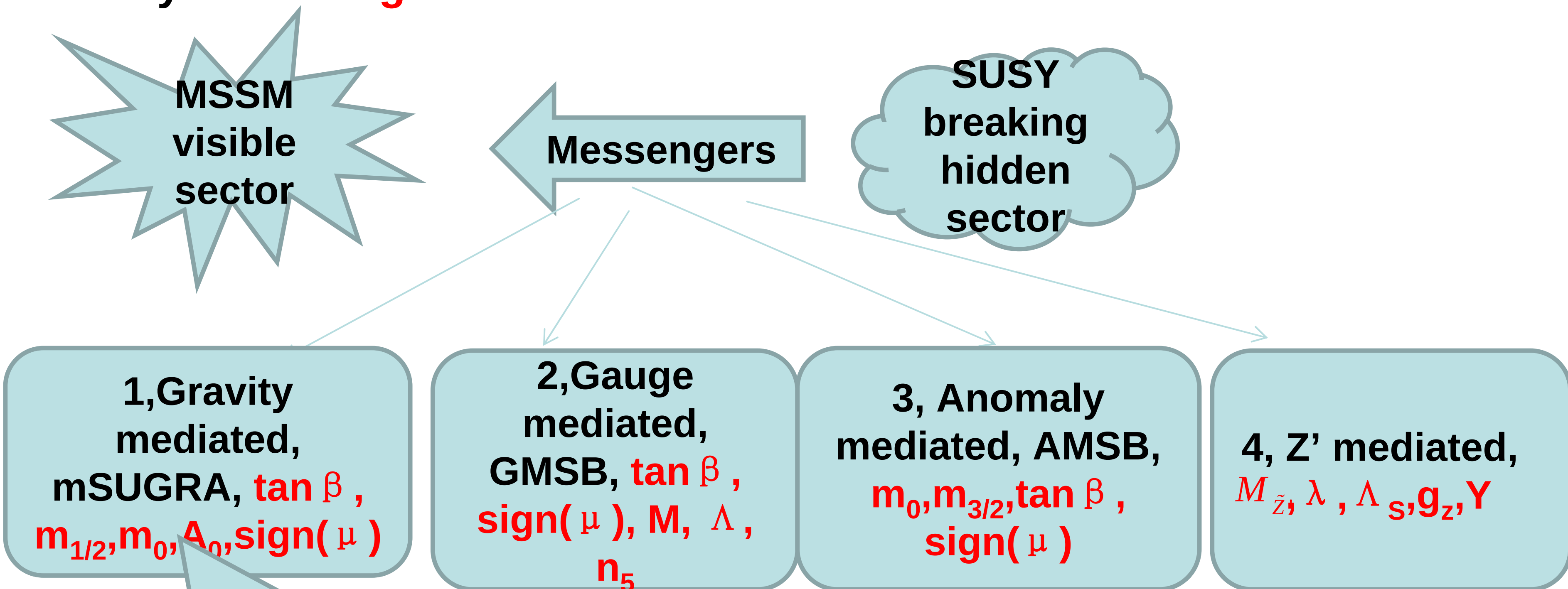
- **The phenomenological implication of this model to visible sector (such as MSSM) may be interesting.**

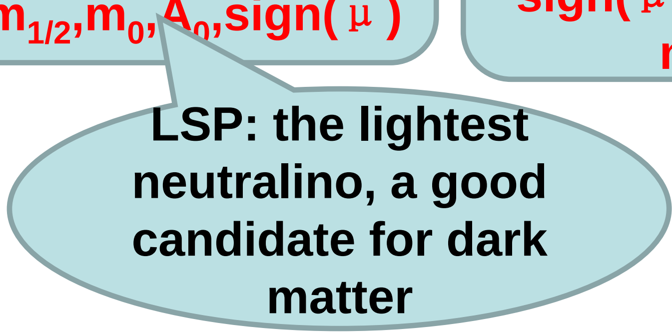


I. Affleck, M. Dine and N. Seiberg, Nucl. Phys. B241(1984) 493-534

K. Intriligator, N. Seiberg and D. Shih, JHEP04(2006) 021

- **Spontaneous SUSY breaking via the fields in MSSM has been forbidden by experiments. So it is suggested that SUSY is broken by some mechanism in a "Hidden sector" and the information of SUSY breaking is mediated to the "Visible sector" by "Messenger".**





1,A. H. Chamseddine *et al*. , PRL49, 970
2,Michael Dine *et al*. , PRD53:2658-2669
3,Lisa Randall *et al*. , Nucl.Phys.B557:79-118
4,P. Langacker, G. Paz, L.-T. Wang and I. Yavin, PRL100, 041802

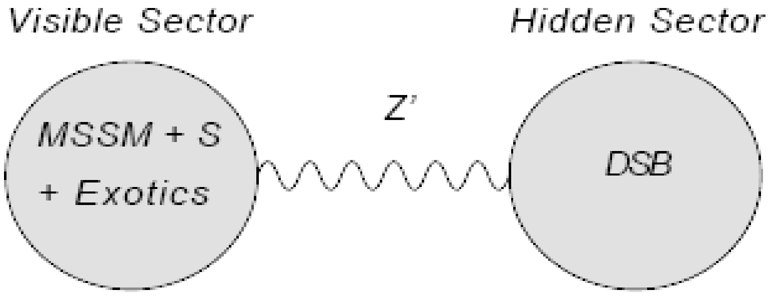
• Z'-mediated SUSY Breaking

- Recently, a new mediated **SUSY** breaking mechanism has been proposed by **Langacker** *et al.*

- In this model, **SUSY** breaking is mediated from the hidden sector to the visible sector by exotic **U(1)'** gauge interactions.

- The visible sector of this model contains the particles in **MSSM**, a **SM** gauge singlet **S**, which couples to Higgs like the singlet in **NMSSM**, and some exotic matter multiplets X_i with Yukawa couplings to **S**, which are included to cancel the anomalies associated with the new **U(1)'** gauge interaction.

$$W = W_{\mathrm{MSSM}} + \lambda S H_u H_d + \sum_{i \in \{\mathrm{exotics}\}} y_i S X_i X_i^c$$



P. Langacker, G. Paz, L.-T. Wang and I. Yavin, PRL100, 041802(2008)

- **Z'-mediated SUSY Breaking**

- **The gaugino masses are generated at two loop**

$$M_a \sim M_{\tilde{Z}'}/(16\pi^2)^2$$

LEP direct searches suggest gaugino (wino, zino and photino) masses >100GeV.

- **The sfermions receive soft mass terms at one loop**

$$m_{\tilde{f}_i}{}^2 \sim M_{\tilde{Z}'}{}^2/16\pi^2$$

therefore, the sfermions are expected heavy, typically about 100TeV.

- **In this model, the μ parameter comes from the U(1)' symmetry spontaneously broken which may be triggered by radiative corrections to S. An explicit $\mu H_u H_d$ term is forbidden by U(1)' gauge symmetry.**

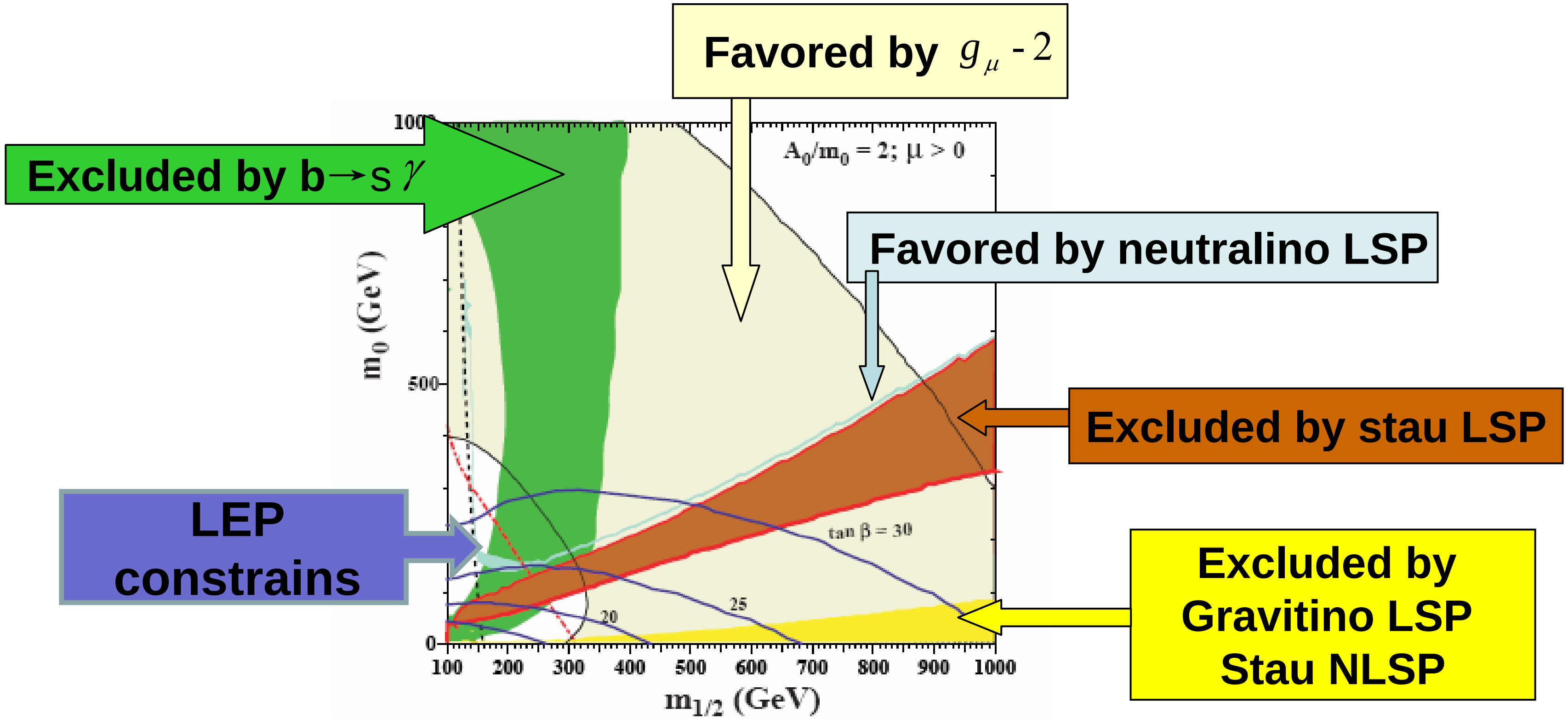
- **The spectrum contains heavy sfermions, Higgsinos, exotics, and Z'~10-100TeV, light gauginos~100-1000GeV, a light Higgs boson~140GeV, and a light singlino.**

• Constraints on SUSY parameters

Direct constraints due to the absence of SUSY particles at LEP and Tevatron. Indirect constraints include

- **Rare processes branching ratios b → s γ**
- **Cold dark matter relic density**
- **Anomalous magnetic moment of muon**
- **…**

An example in mSUGRA:



● Constraints on SUSY parameters (mSUGRA)

• **Main constrains:**

1. Gauge coupling constant unification: M_{SUSY}~1TeV

2. M_Z from EWSB

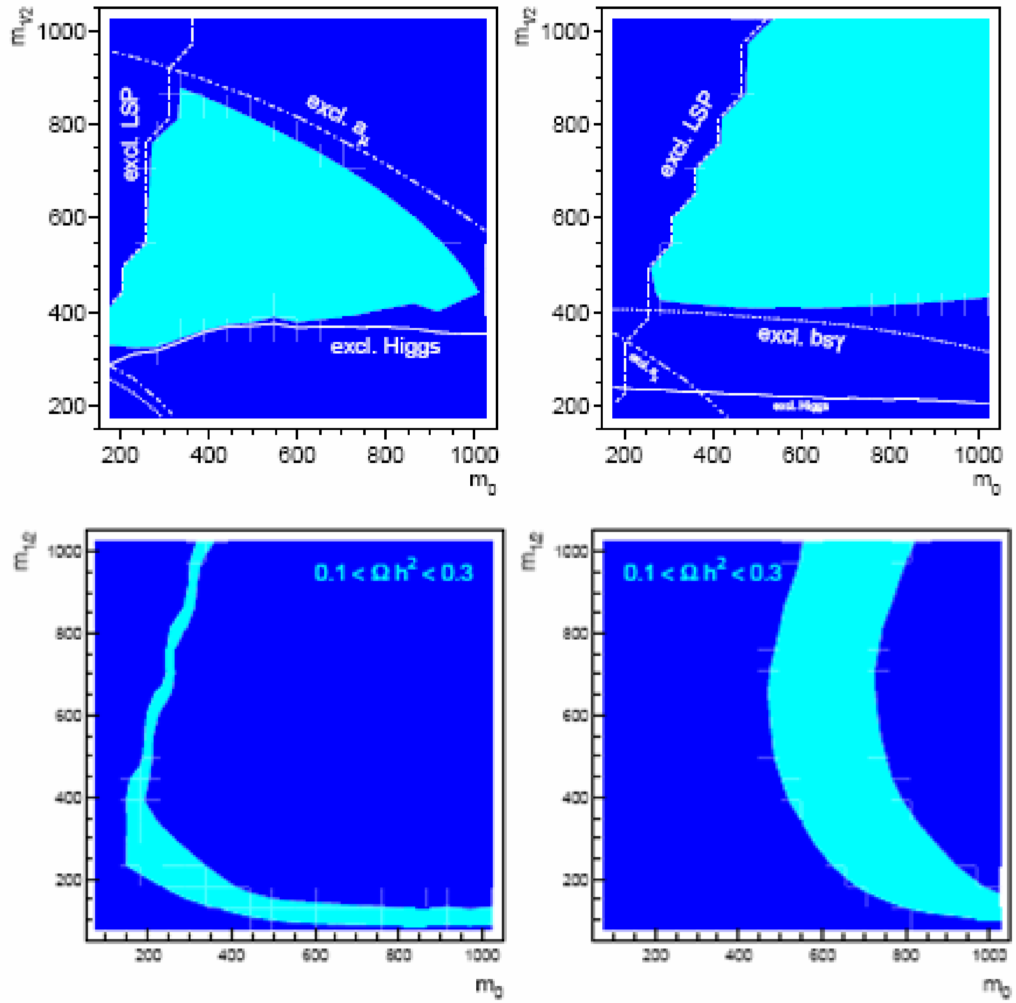
3. Yukawa coupling constant unification

4. Precision measurement of decay rates: BR(b→s γ)….

5. Anomalous magnetic moment of muon: requires positive sign of μ

6. Experimental lower limits on SUSY masses

7. Dark matter constraint



Left: tan β =35, Right: tan β =50

A.V. Gladyshev and D.I. Kazakov, Phys.Atom.Nucl.70:1553-1567,2007.

• Search for SUSY at the LHC

• SUSY signals

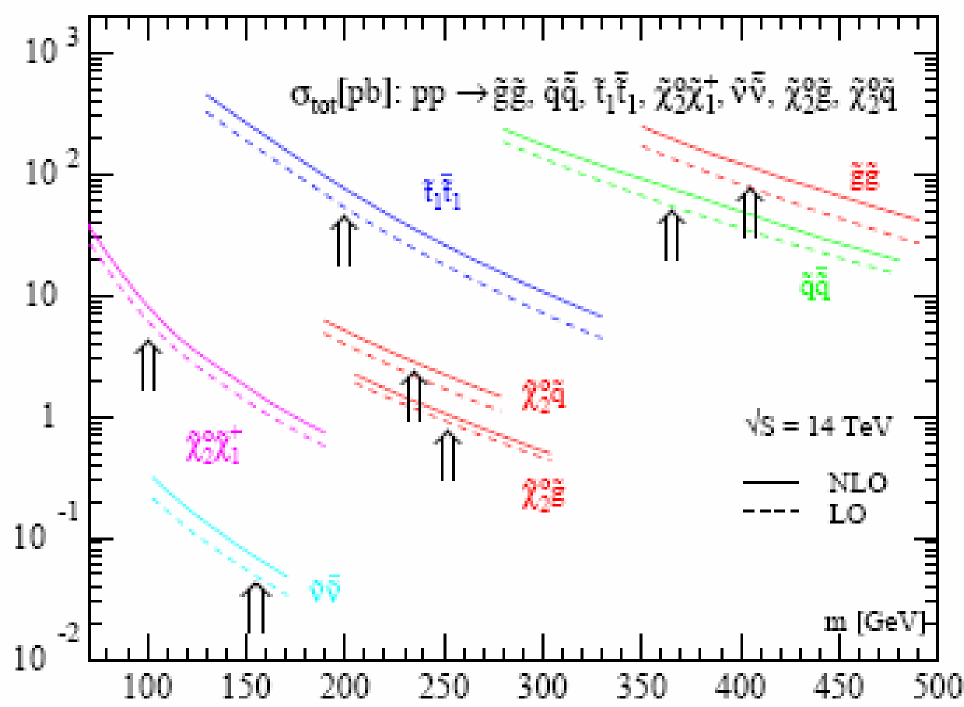
jets and $\not E_T$: $pp \to \tilde q\tilde q^*, \tilde g\tilde g, \tilde q\tilde g$

tops and large $\not E_T$: $pp \to \tilde t_1 \tilde t_1^*$

like sign dileptons: $pp \to \tilde g\tilde g$

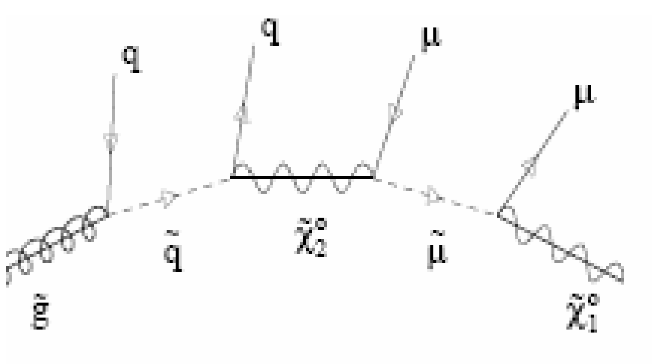
dilepton + jet + $\not E_T$: $pp \to \tilde t_1 \tilde\chi^\pm$

tri-leptons : $\tilde\chi_2^0\tilde\chi_1^- \cdots$



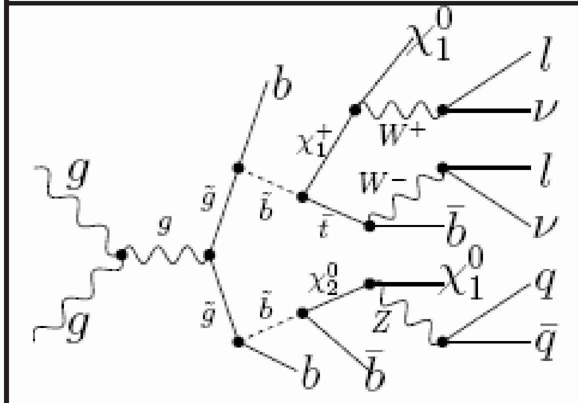
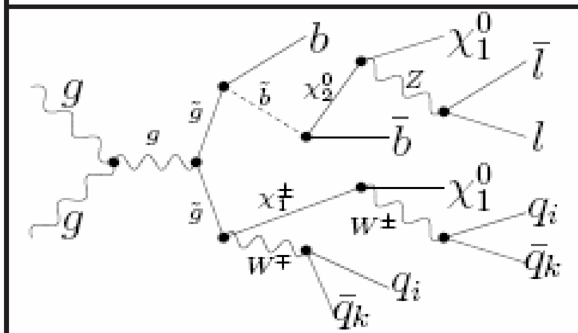
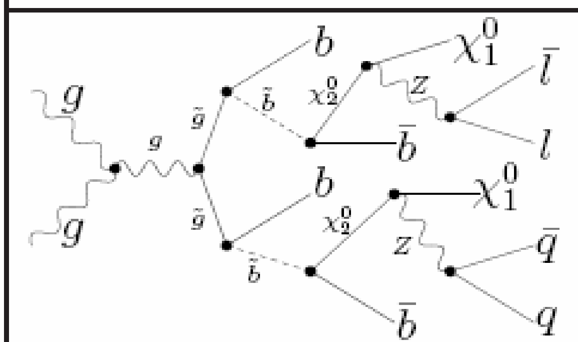
• Spectra from cascade decays

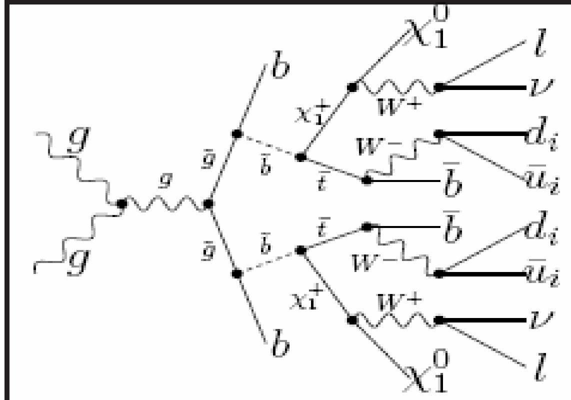
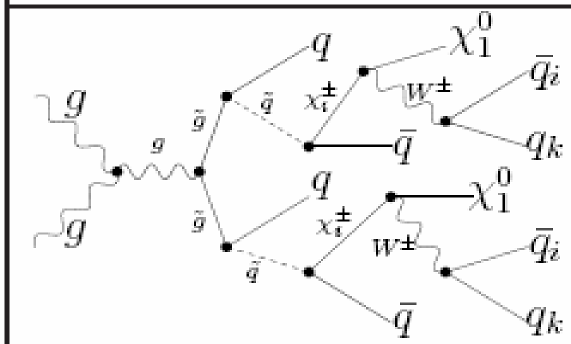
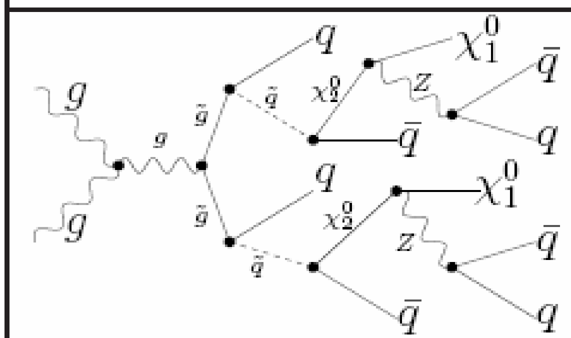
$$\tilde g \to \tilde q\bar q \to \tilde\chi_2^0 q\bar q \to \mu^+\mu^- q\bar q\tilde\chi_1^0 \quad \cdots$$



Creation	The main decay modes	Signature
• $\tilde g\tilde g, \tilde q\tilde q, \tilde g\tilde q$	$\left.\begin{array}{l}\tilde g \to q\bar q\tilde\chi_1^0 \\ \quad q\bar q'\tilde\chi_1^\pm \\ \quad g\tilde\chi_1^0\end{array}\right\} m_{\tilde q} > m_{\tilde g}$ $\left.\begin{array}{l}\tilde q \to q\tilde\chi_i^0 \\ \tilde q \to q'\tilde\chi_i^\pm\end{array}\right\} m_{\tilde g} > m_{\tilde q}$	$\not E_T +$ multijets (+leptons)
• $\tilde\chi_1^\pm\tilde\chi_2^0$	$\tilde\chi_1^\pm \to \tilde\chi_1^0\ell^\pm\nu,\ \tilde\chi_2^0 \to \tilde\chi_1^0\ell\ell$ $\tilde\chi_1^\pm \to \tilde\chi_1^0 q\bar q', \tilde\chi_2^0 \to \tilde\chi_1^0\ell\ell,$	trilepton $+ \not E_T$ dileptons + jet $+ \not E_T$
• $\tilde\chi_1^+\tilde\chi_1^-$	$\tilde\chi_1^+ \to \ell\tilde\chi_1^0\ell^\pm\nu$	dilepton $+ \not E_T$
• $\tilde\chi_i^0\tilde\chi_i^0$	$\tilde\chi_i^0 \to \tilde\chi_1^0 X, \tilde\chi_i^0 \to \tilde\chi_1^0 X'$	dilepton+jet $+ \not E_T$
• $\tilde t_1\tilde t_1$	$\tilde t_1 \to c\tilde\chi_1^0$ $\tilde t_1 \to b\tilde\chi_1^\pm, \tilde\chi_1^\pm \to \tilde\chi_1^0 q\bar q'$ $\tilde t_1 \to b\tilde\chi_1^\pm, \tilde\chi_1^\pm \to \tilde\chi_1^0\ell^\pm\nu,$	2 noncollinear jets $+ \not E_T$ single lepton $+ \not E_T + b's$ dilepton $+ \not E_T + b's$
• $\tilde l\tilde l, \tilde l\tilde\nu, \tilde\nu\tilde\nu$	$\tilde\ell^\pm \to \ell^\pm\tilde\chi_i^0, \tilde\ell^\pm \to \nu_\ell\tilde\chi_i^\pm$ $\tilde\nu \to \nu\tilde\chi_1^0$	dilepton $+ \not E_T$ single lepton $+ \not E_T$

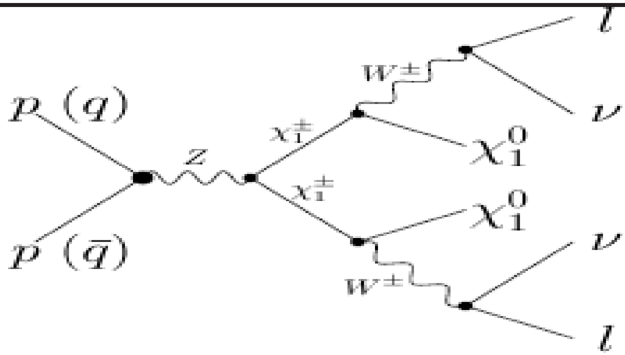
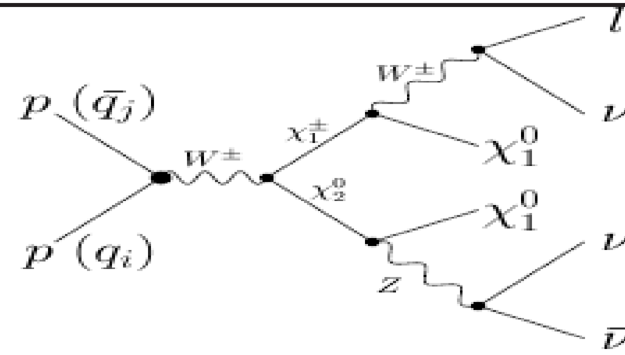
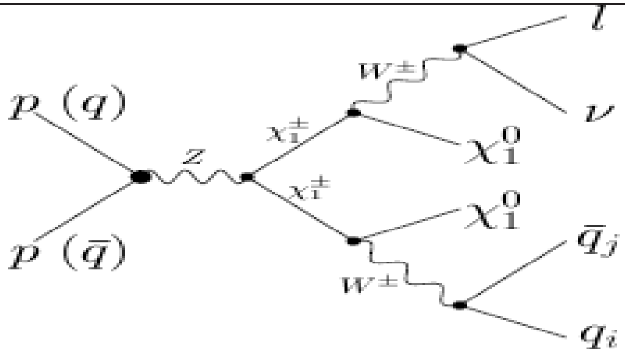
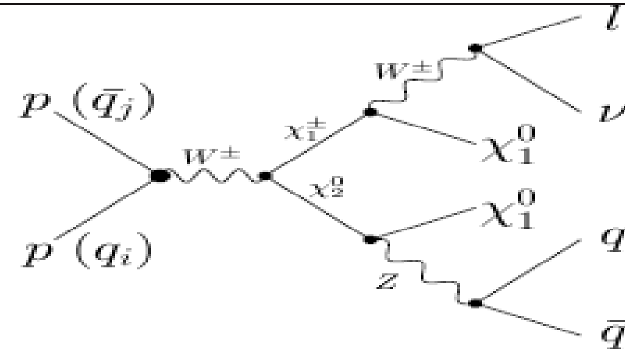
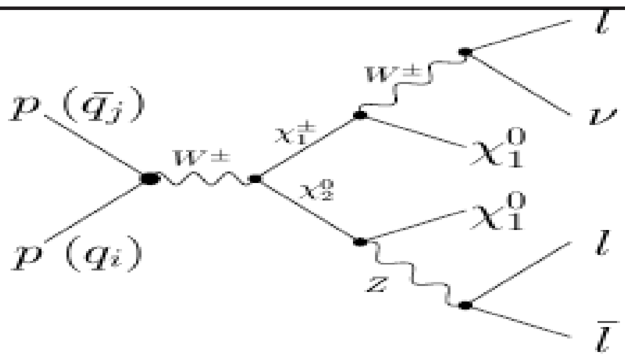
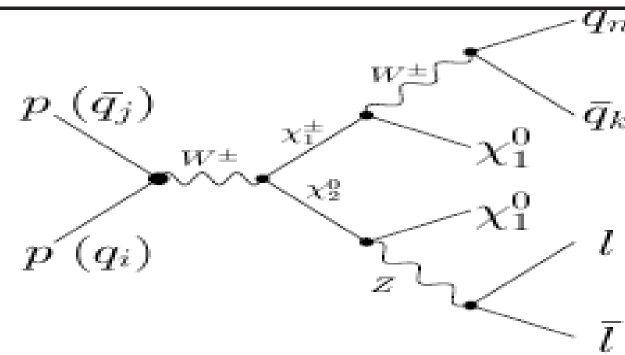
Table 3: Creation of the pair of gluino with further cascade decay

Process	final states
	2ℓ 2ν $6j$ $\not{E}_T$
	2ℓ $6j$ $\not{E}_T$
	2ℓ $6j$ $\not{E}_T$

Process	final states
	2ℓ 2ν $8j$ $\not{E}_T$
	$8j$ $\not{E}_T$
	$8j$ $\not{E}_T$

(hep-ph/0606288)

Table 4: Creation of the lightest chargino and the second neutralino with further cascade decay.

Process	final states	Process	final states
	2ℓ 2ν $\not{E}_T$		ℓ 3ν $\not{E}_T$
	ℓ ν $2j$ $\not{E}_T$		ℓ ν $2j$ $\not{E}_T$
	3ℓ ν $\not{E}_T$		2ℓ $2j$ $\not{E}_T$

(hep-ph/0606288)

• QCD NLO and Resummation effects

• NLO QCD predictions for productions $pp \rightarrow \tilde{t}_i \tilde{\chi}_k^{\pm} + X$

- **The total cross sections can reach 1 pb in the favorable parameter space , and in other cases they generally vary from 10fb to several hundred fb.**
- **The QCD NLO corrections enhance the LO results significantly, which are in general a few ten percent, and vastly reduce the dependence of the total cross sections on the renormalization/factorization scale.**

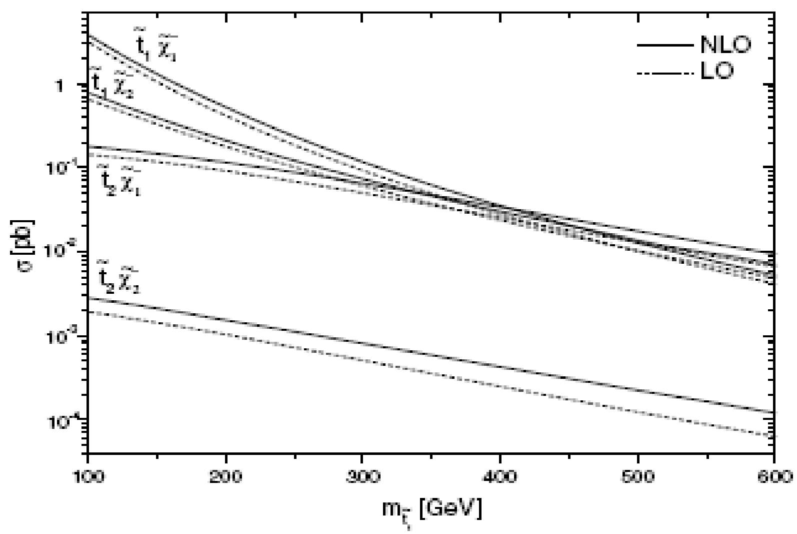


Fig. 7. Dependence of the total cross sections on $m_{\tilde{t}_1}$ for the $\tilde{t}_i\tilde{\chi}_k^-$ productions at the LHC, assuming $\mu = -200$ GeV, $M_2 = 300$ GeV and $\tan\beta = 30$

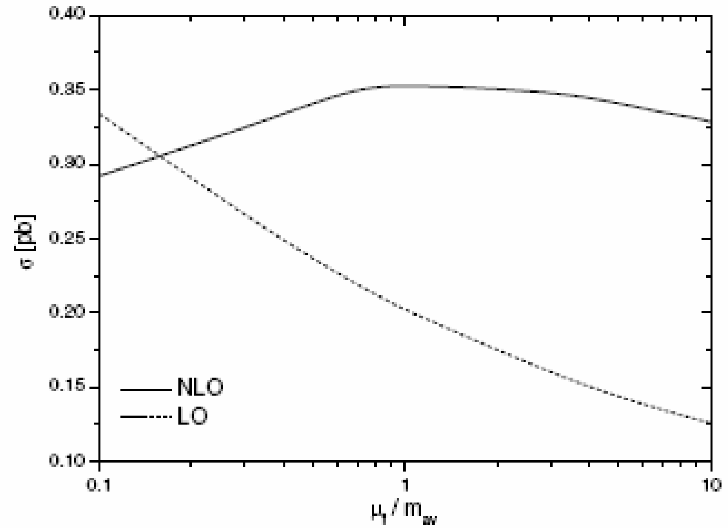
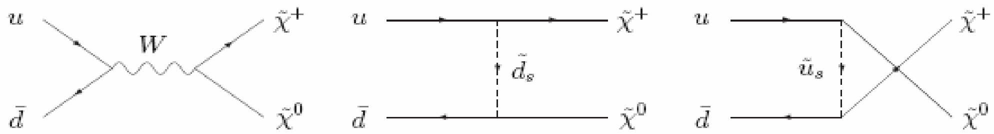


Fig. 10. Dependence of the total cross sections for the $\tilde{t}_1\tilde{\chi}_1^-$ production at the LHC on the renormalization/factorization scale, assuming $\mu = -200$ GeV, $M_2 = 300$ GeV, $\tan\beta = 30$, $m_{\tilde{t}_1} = 250$ GeV, $\mu_r = \mu_f$ and $m_{av} = (m_{\tilde{t}_1} + m_{\tilde{\chi}_1^-})/2$

Li-Gang Jin, Chong-Sheng Li, Jian Jun Liu, Eur.Phys.J.C30:77,2003

• Threshold resummation effects in the associated production of chargino and neutralino at hadron colliders.



- **NLO (SUSY) QCD corrections**

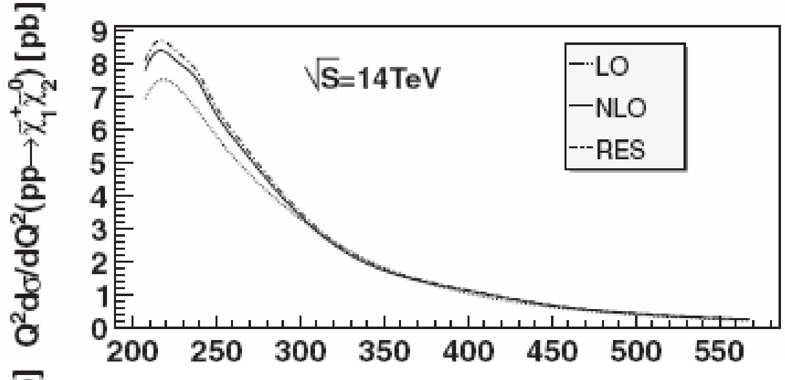
W. Beenakker, et. al., PRL83 (1999) 3780

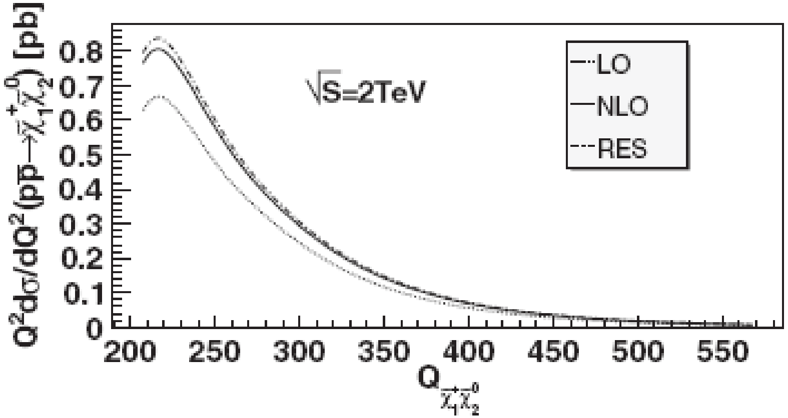
S. Hao, et. al., PRD73 (2006) 055002

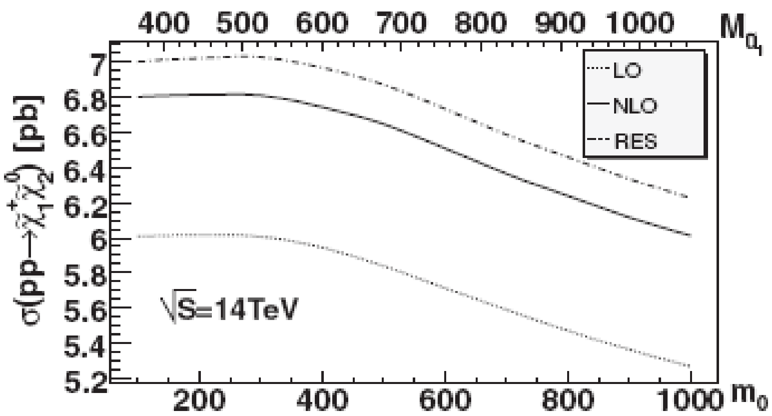
Chong Sheng Li, Zhao Li, Robert J. Oakes, Li Lin Yang, PRD77 (2008) 034010

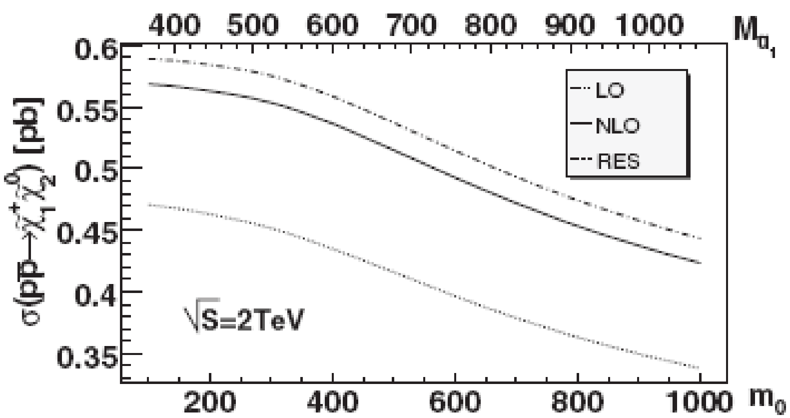
- **Threshold Resummation**

Chong Sheng Li, Zhao Li, Robert J. Oakes, Li Lin Yang, PRD77 (2008) 034010





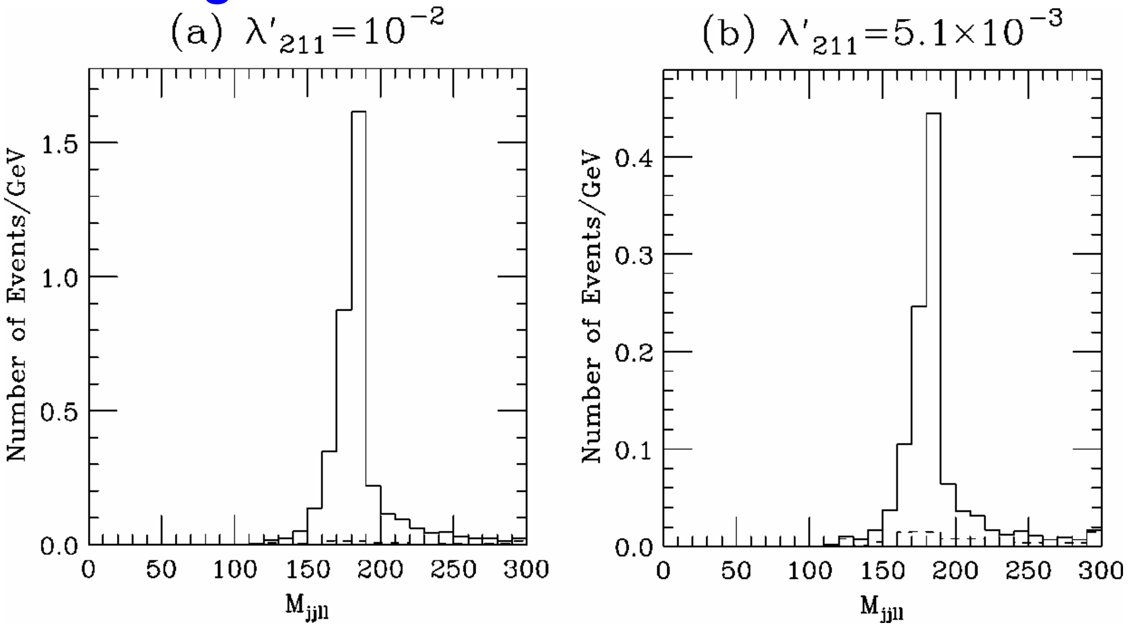




• **Single- slepton production in R-parity violating SUSY**

Resonant production of a single slepton can lead to interesting phenomenology at hadron colliders.

- **A charged slepton can decay into a neutralino and a charged lepton, and neutralino can subsequently decay into a charged lepton and two jets via λ'couplings.**
- **Because of the Majorana nature of neutralino, the two leptons can have either opposite or same charges. The case of two leptons of the same charges is more interesting due to the absence of large SM background.**



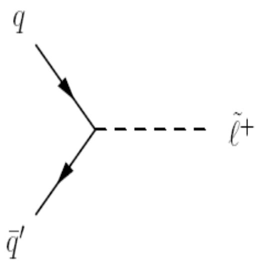
• **After suitable cuts the R-parity violation signals can be clearly distinguished from the suppressed SM and SUSY backgrounds.**

H. K. Dreiner, P. Richardson, and M. H. Seymour, PRD 63, 055008 (2001).

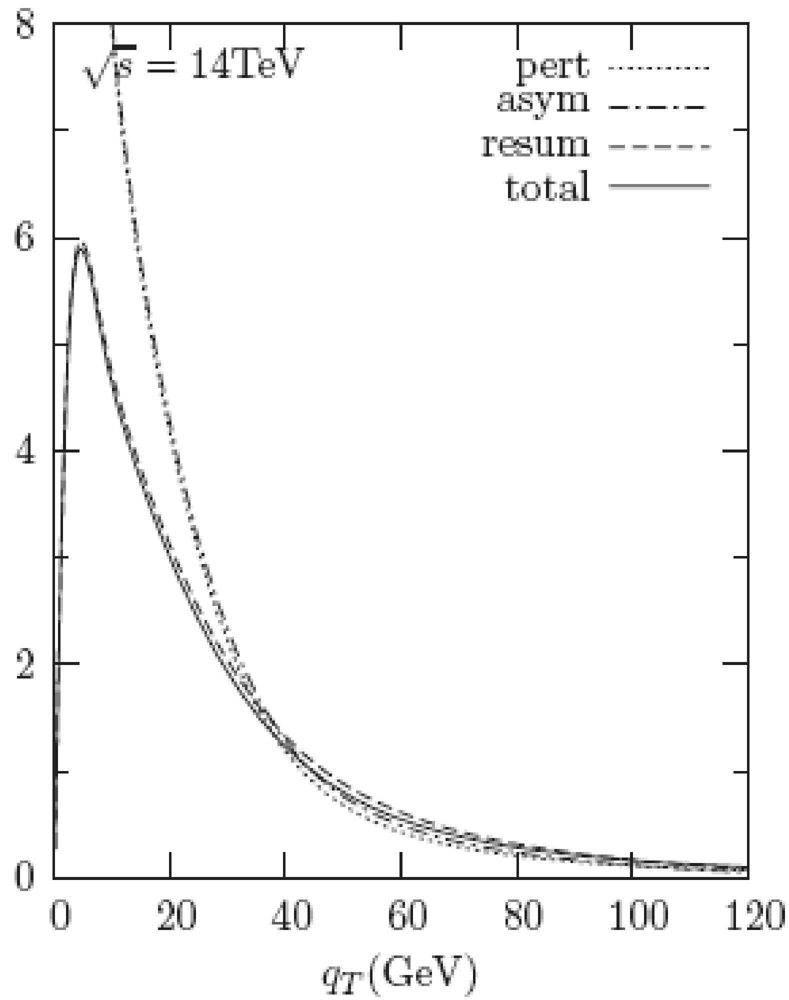
• q_T-Resummation in Single-Slepton Production at the LHC

- **R-parity violating L:**

$$W_{\not R_p} = \mu_i L_i H_2 + \frac{1}{2}\lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \frac{1}{2}\lambda''_{ijk} U_i^c D_j^c D_k^c,$$



- **NLO QCD corrections:**
  - D. Choudhury et al, Nucl. Phys. B660 (2003)
  - Li Lin Yang , Chong Sheng Li, Jian Jun Liu, Qiang Li, PRD 72 (2005) 074026
- **NLO SUSY-QCD corrections:**
  - Dreiner et al., ph/0611195
  - QCD parts agree
- **q_T-Resummation:**
  - Li Lin Yang , Chong Sheng Li, Jian Jun Liu, Qiang Li, PRD 72 (2005) 074026



• Others' calculations of QCD effects

• NLO QCD corrections to SUSY particle decays

• squark

$\tilde{q} \to q\tilde{g}$ 30% ~ 50%

W. Beenakker *et al*. PLB378 (1996) 159; ZPC75 (1997) 349

$\to \tilde{q}h^0/H^0/A^0, \tilde{q}'H^\pm$ - 40% ~ 20%

A. Arhrib *et al*. PRD57 (1998) 5860; A. Bartl *et al*. PRD59 (1999) 115007

$\to q\tilde{\chi}^0, q'\tilde{\chi}^\pm$ - 20% ~ 10%

S. Kraml *et al*. PLB386 (1996) 175; A. Djouadi *et al*. PRD55 (1997) 6975

$\to \tilde{q}Z^0, \tilde{q}'W^\pm$ -10% ~ -5%

A. Bartl *et al*. PLB419 (1998) 243

•gluino

$\tilde{g} \to q\bar{\tilde{q}} / \bar{q}\tilde{q}$ -10% ~ 10%

W. Beenakker *et al*. PLB378 (1996) 159; ZPC75 (1997) 349

● **Hadron colliders (including the NLO QCD corrections)**

- **squarks,gluinos**

$$p\bar{p}\,/\,pp \to \tilde{q}\bar{\tilde{q}}, \tilde{q}\tilde{q}, \tilde{g}\tilde{g}, \tilde{q}\tilde{g}$$

W.Beenakker *et al*. PRL 74 (1995) 2905;ZPC 69 (1995) 163;NPB 492 (1997) 51

- **top-squark pairs**

$$p\bar{p}\,/\,pp \to \tilde{t}\bar{\tilde{t}}$$

W.Beenakker *et al*. NPB 515 (1998) 3

- **gaugino pairs, slepton pairs**

$$p\bar{p}\,/\,pp \to \tilde{l}\bar{\tilde{l}}\,/\,\tilde{\chi}\tilde{\chi}$$

H. Baer *et al*. PRD 57 (1998) 5871;W.Beenakker *et al*. PRL 83 (1999) 3780

- **gluino and gaugino**

$$p\bar{p}\,/\,pp \to \tilde{g}\,\tilde{\chi}$$

E.L. Berger *et al*. PLB 459 (1999) 165; PRD 62 (2000) 095014;

PRD 67 (2003) 099901 (E)

- **R-parity violating processes**

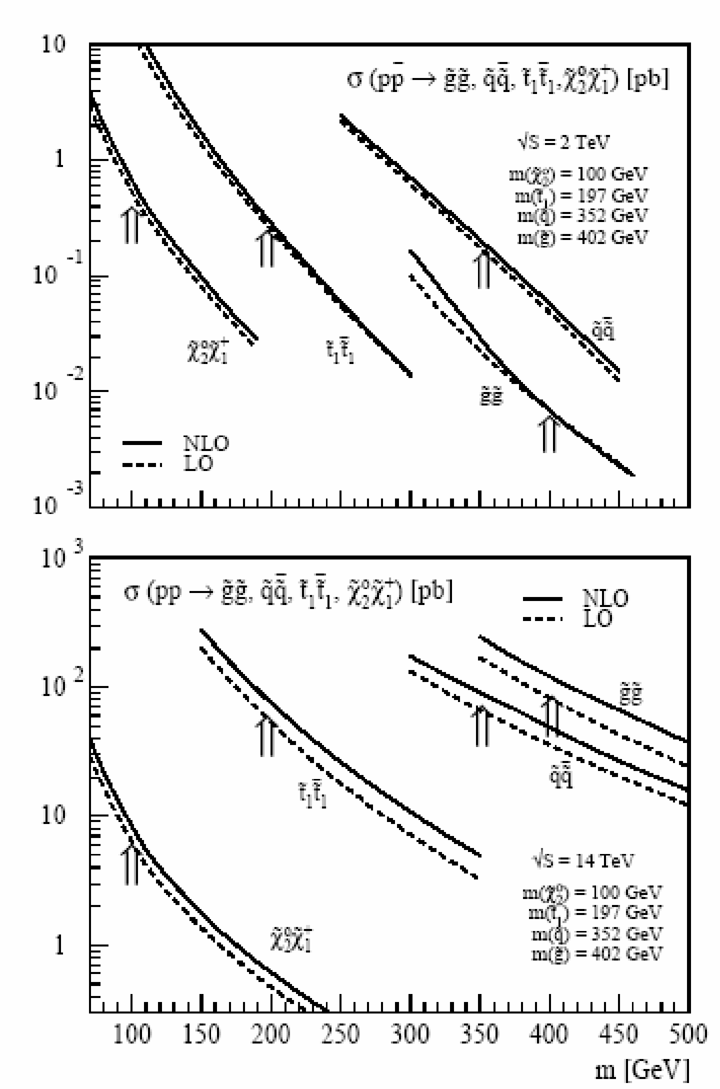
$$p\overline{p}\,/\,pp \rightarrow \tilde{t} \text{ through } \tilde{t}_1 \rightarrow b\tilde{\chi}_1^{+} \rightarrow b\overline{l}\,\nu\chi_1^{0}$$

T. Plehn, PLB 488 (2000) 359

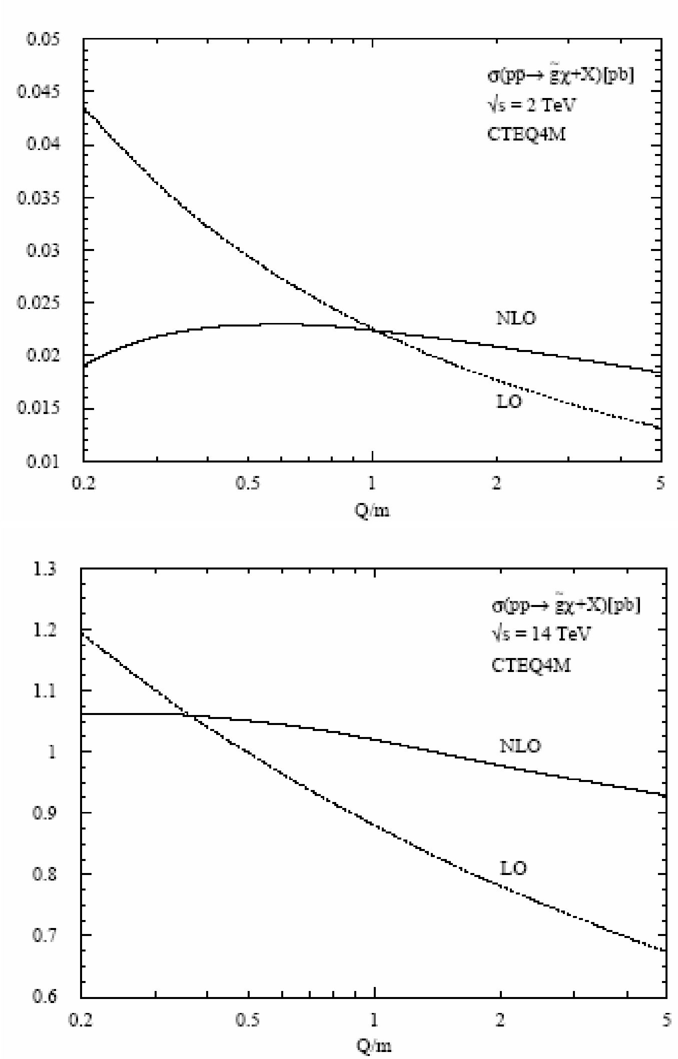
$$p\overline{p}\,/\,pp \rightarrow \tilde{t}l$$

A. Alves *et al*. PLB 558 (2003) 165

Some typical results



M. Krämer, **hep-ph/9809259**



M. Spira, **hep-ph/0211145**

• The NMSSM and its phenomenology

• Introduction of the NMSSM

• Motivation: μ problem in the MSSM

• Originally, the NMSSM is proposed for eliminating the so-called μ problem that plagues the MSSM.

• In the superpotential of MSSM, there is a term, $W_{MSSM} = \mu H_1 H_2$, whose coefficient μ has the dimensions of mass.

• This μ is the only dimensional parameter that enters in superpotential of MSSM, and has to be the order of electroweak scale for the phenomenological reason.

• However, the 'natural' mass scale would be the order of the GUT or Planck scale, so the μ term revives the hierarchy problem.

• Motivation: NMSSM 's solution to μ problem

• The μ problem is evaded in the NMSSM by introducing a Higgs singlet N. The superpotential of the NMSSM is as follow:

$$W = QY_u H_u U + QY_d H_d D + LY_e H_d E + \lambda H_d H_u N - \frac{1}{3} k N^3$$

• The μ term in the superpotential can be dynamically generated through $\mu = \lambda x$, where λ is a dimensionless coupling and x is the vacuum expectation value(VEV) of the singlet N.

Drees, et al , Int. J. Mod. Phys. A4, 3635(1989). J. Ellis, et al , PRD39, 844.
F. Franke, et al , Int. J. Mod. Phys A12, 479 (1997).

- **The Higgs spectrum in NMSSM**

There are seven Higgs bosons in NMSSM:

- **Two charged Higgs bosons H^+, H^-**
- **Three neutral scalar Higgs bosons $H^0_{1,2}$, h^0**
- **Two neutral pseudoscalar Higgs bosons $A^0_{1,2}$**

- **The Higgs potential of NMSSM**

$$V_{Higgs} = V_{soft} + V_F + V_D,$$

where

$$\begin{aligned} V_{soft} &= m_{H_d}^2|H_d|^2 + m_{H_u}^2|H_u|^2 - (\lambda A_\lambda H_d H_u N - \frac{1}{3}kA_k N^2 + \mathrm{H.c.}), \\ V_F &= |\lambda|^2(|H_d|^2 + |H_u|^2)|N|^2 + |\lambda H_d H_u - kN^2|^2, \\ V_D &= \frac{g^2 + g'^2}{8}(|H_d|^2 - |H_u|^2) + \frac{g^2}{2}|H_u^\dagger H_d|^2. \end{aligned}$$

V_{Higgs} has a global U(1) symmetry in the limit of coefficients of the trilinear terms vanaish $A_k,\ A_\lambda \to 0.$

- **The mass of A_1**

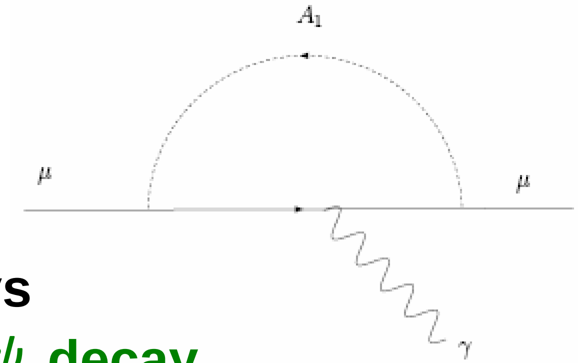
If the global U(1) symmetry is slightly broken, a light pseudoscalar naturally appears. In the limit of large-tan β , the mass of the lighter pseudoscalar Higgs boson can be expressed as:

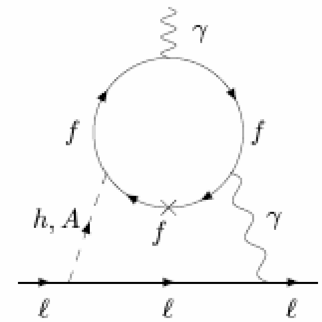
$$m_{A_1^0}^2 = 3kxA_\lambda + \mathcal{O}\left(\frac{1}{\tan\beta}\right)$$

- **Phenomenology of a light pseudoscalar boson**

1. **Contributions to g-2**

   Light pseudoscalar boson contributes largely at 1-loop and 2-loop levels



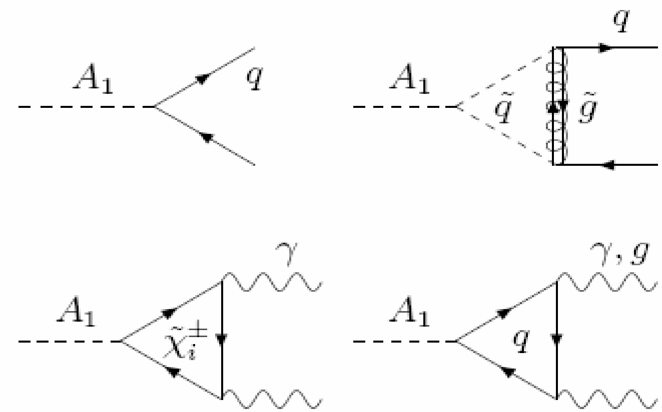


2. **Production via B meson decays**

   $b \rightarrow s\ A_1$, also in upsilon and J/ψ decay

3. **Decay of a light A_1**

   A_1 decays through mixing with the MSSM-like A_2 into qq, ll, gg; to chargino or neutralino pairs if kinematically allowed; via chargino loop to 2 photons.

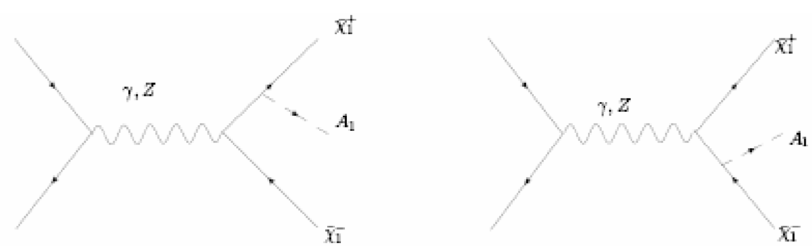


4. **Production: $h \rightarrow A_1 A_1$**

   $h \rightarrow A_1 A_1 \rightarrow 4\gamma$, 4τ

5. **Associated production of A_1 with a pair of charginos**

   an interesting final state is 2 charged leptons+2 photons+missing energy



6. HyperCP experiment at Fermilab

- **Charged current contributions**

- Three events for the decay mode $\Sigma^+ \rightarrow p\mu^+\mu^-$ with a dimuon invariant mass $m_{\mu+\mu-}$ = 214.3MeV has been observed by the HyperCP collaboration at Fermilab.
- Based on the three events, the branching ratio is

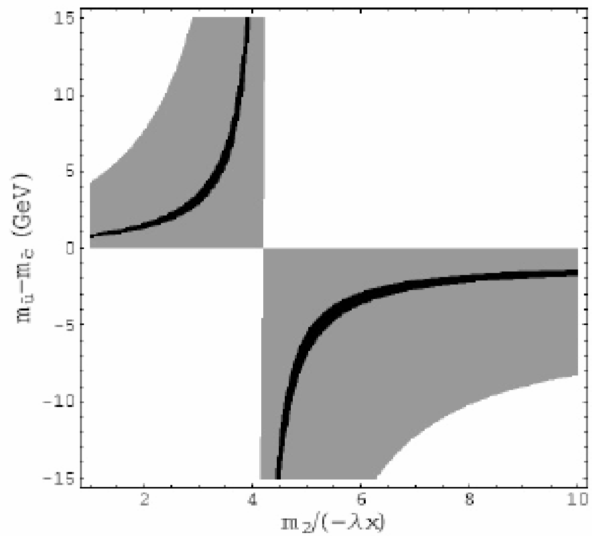
$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = [8.6^{+6.6}_{-5.4}(stat) \pm 5.5(syst)] \times 10^{-8}.$$

- There is not a 214.3MeV particle in SM.
- The narrow range of dimuon masses may indicate that the decay is mediated by an neutral unknown particle X

- **A_1 in the NMSSM can be particle X**

It was pointed out by He et al that the A_1 in the NMSSM can be used to explain the HyperCP events via SUSY charged current.

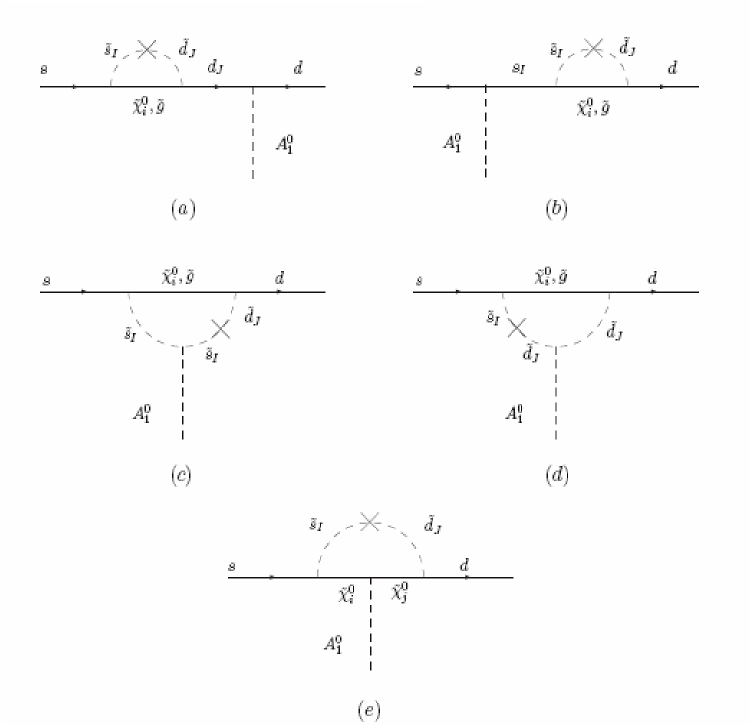
Xiao-Gang He, et al , Phys. Rev. Lett 98

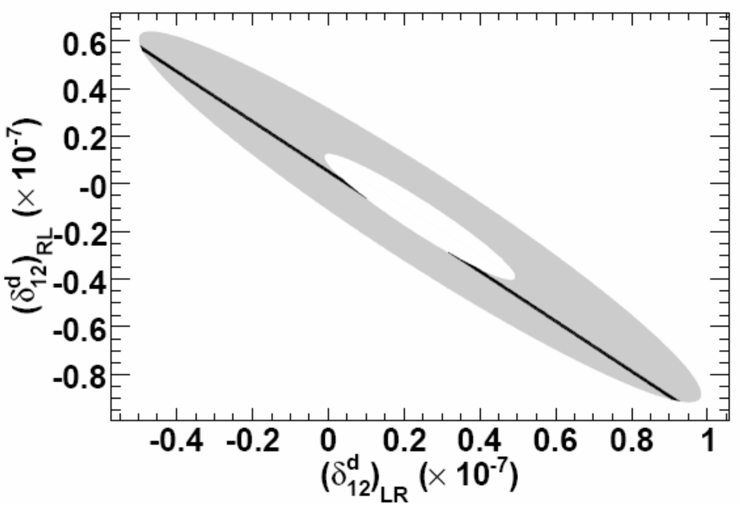


● **SUSY-FCNC mediated contributions**

- **We show that the SUSY-FCNC effects also can be used to explain the HyperCP events.**
- **The effective Lagrangian describing the interactions of s->dA1 can be written as:**

$$\mathcal{L}_{Asd} = C_L \bar{d}\frac{1-\gamma_5}{2} s A_1^0 + C_R \bar{d}\frac{1+\gamma_5}{2} s A_1^0 + H.c.$$





Possible regions in parameter spaces

Gao Xiangdong, Chong Sheng Li, Zhao Li, Hao Zhang, hep-ph/0712.0257, to be published in EPJC

• MSSM with explicit CP violation

• Complex parameters

In the general MSSM, many parameters can be complex, thus inducing explicit CP violation in the model:

$$M_i = |M_i|\, e^{i\phi_i}, \quad \mu = |\mu|\, e^{i\phi_\mu}, \quad A_f = |A_f|\, e^{i\phi_f}$$

The physical phases are Arg(M_im) and Arg(A_fm). They

- **affect sparticle masses and couplings through mixings**
- **induce CP mixing of (h, H, A) through radiative corrections**
- **influence various observables for Higgs, e.g. cross sections and BRs**
- **etc...**

• Higgs Mixing

Loop corrections can induce non-diagonal components in Higgs mass matrix. To obtain mass eigenstates, diagonalization is needed:

$$\mathcal{O}\mathcal{M}_H^2\mathcal{O}^\dagger = (m_{h_1}^2, m_{h_2}^2, m_{h_3}^2).$$

The new mass eigenstates are generally different from the CP eigenstates (h^0, H^0, A^0).

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \mathcal{O} \begin{pmatrix} -\sin\alpha & \cos\alpha & 0 \\ \cos\alpha & \sin\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} h^0 \\ H^0 \\ A^0 \end{pmatrix}$$

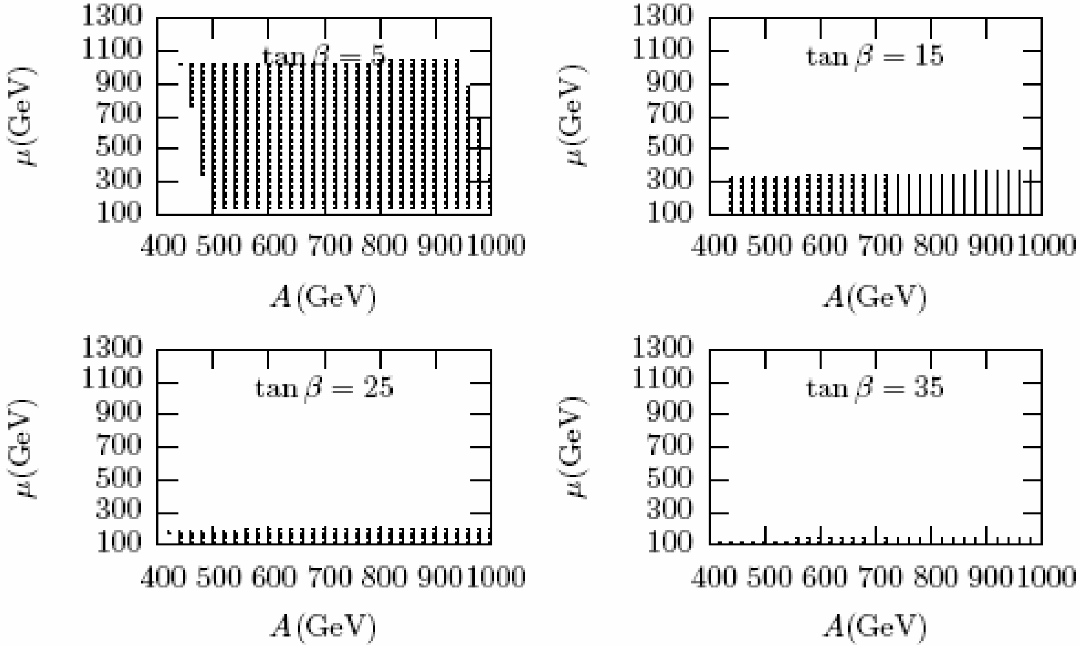
- **Constraints from EDMs**

  - **$|d_{Tl}| < 9 \times 10^{-25}$ e cm (Regan et al. PRL88, 071805)**
  - **$|d_{Hg}| < 2 \times 10^{-28}$ e cm (Romalis et al. PRL86, 2505)**
  - **$|d_n| < 6 \times 10^{-26}$ e cm (Harris et al. PRL82, 904)**

When interpreted as a quantity induced purely by the electron EDM d_e, the measurement of d_{Tl} can be translated into a tight bound

  - **$|d_e| < 1.6 \times 10^{-27}$ e cm**

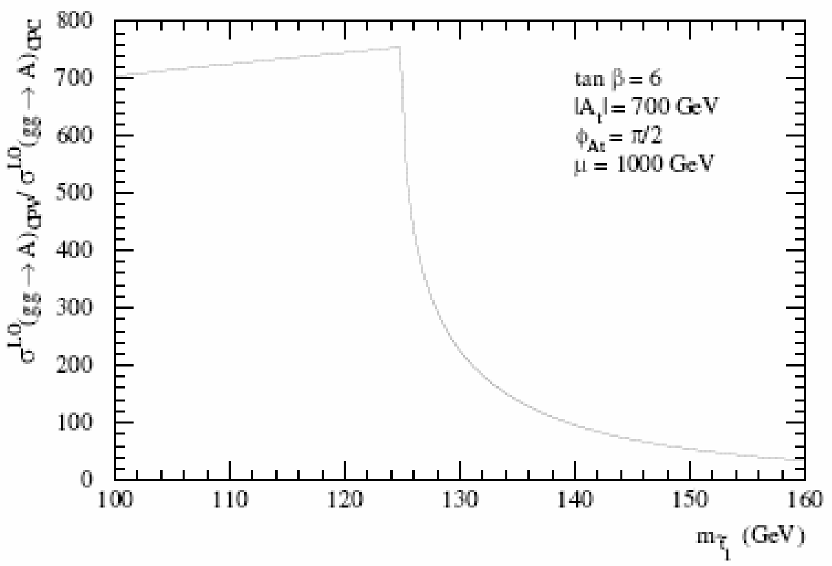
In MSSM with explicit CPV, the parameters are constrained by EDMs, e.g.



Zhao Li, Chong Sheng Li, Qiang Li, PRD73, 077701

• **Enhancement in the Higgs productions**

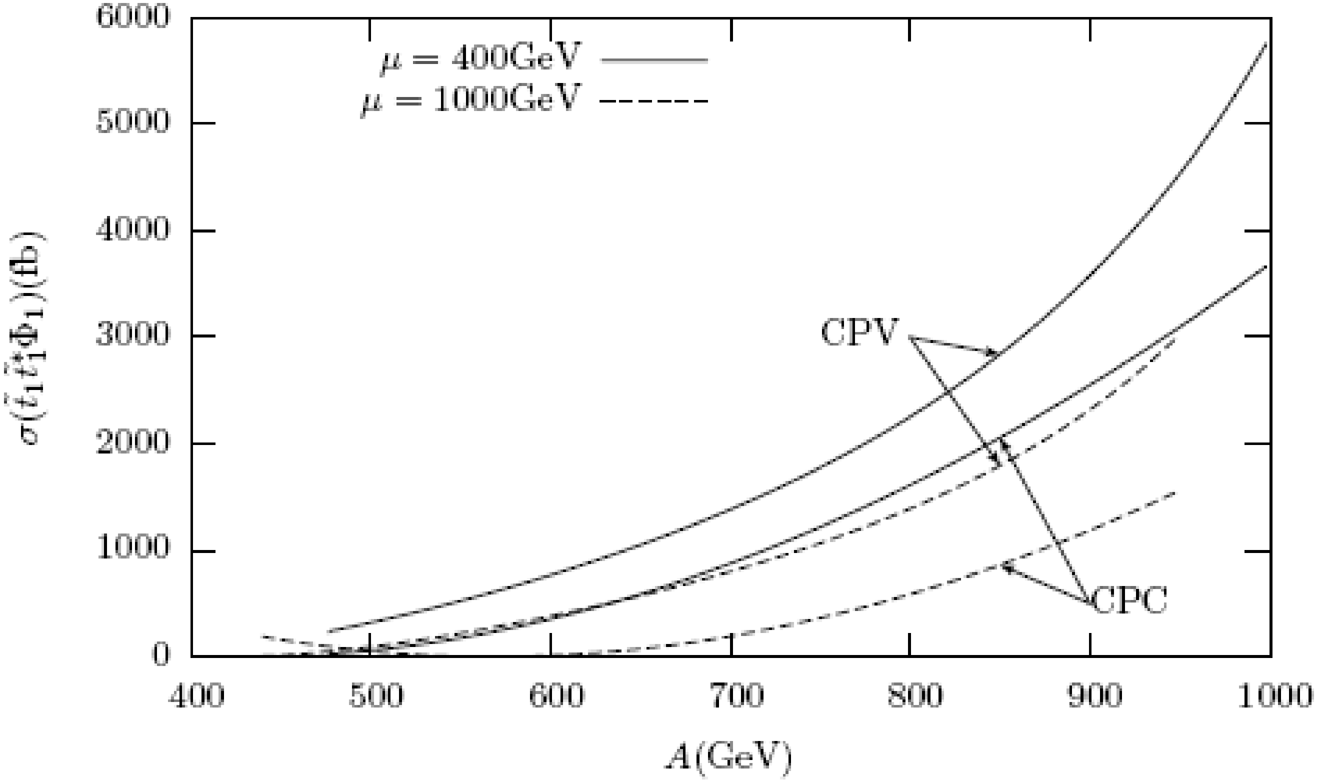
Large enhancement was discovered in gg-> "A^0" with large CPV angle. Here "A^0" is the mass eigenstate with largest A^0 component.



Q-H. Cao , C.-P.Yuan, et.al. Phys.Lett.B632, 688

However, in their calculations they did not consider the constraints on parameters from the experiments of EDMs.

Further, the enhancement was also discovered in the associated production of neutral Higgs Boson with squark pair in the MSSM with explicit CPV at LHC $pp \to \Phi \widetilde{q}_i \widetilde{q}'_j$.



$\sigma(h^0\tilde{t}_1\tilde{t}_1^*) < 10^{-3} fb, \quad \sigma(h_1\tilde{t}_1\tilde{t}_1^*) \approx 270 fb,$ **for A = 568 GeV and μ = 1000 GeV.**

Zhao Li, Chong Sheng Li, Qiang Li, PRD73, 077701

3. Higgs in SM and MSSM

- **Introduction**

- **The last missing ingredient of SM**
- **Key role for EWSB, also appear in many new physics model.**
- **Searching for Higgs is a major goal of LHC.**

- **Experimental Constraints**
- **light Higgs preferred by:**

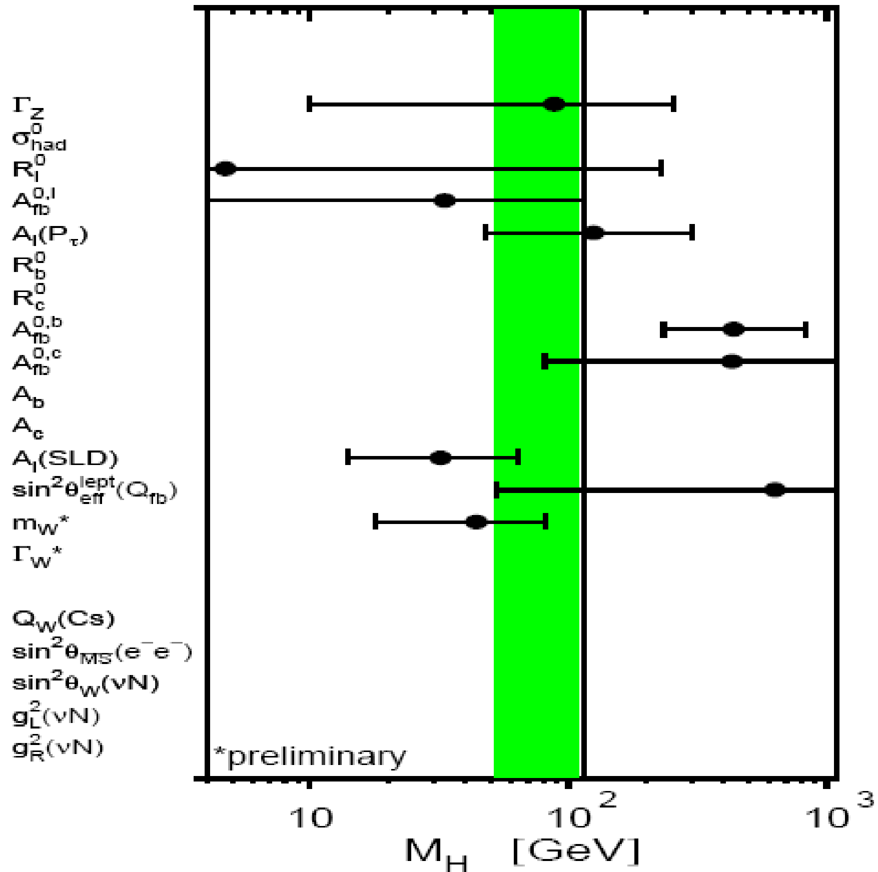
  M_W , A_l^{LR} (SLD)
- **heavier Higgs preferred by:**

  A_b^{FB} (LEP)

⇒ keeps SM alive

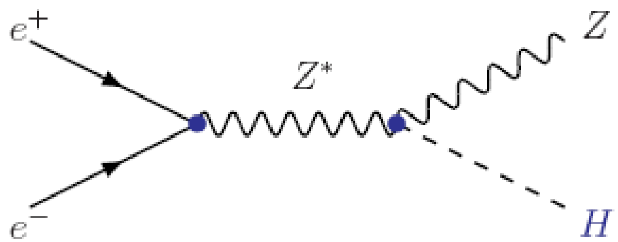
⇒ light Higgs boson preferred

$$M_H = 85^{+39}_{-28}\,\mathrm{GeV}$$



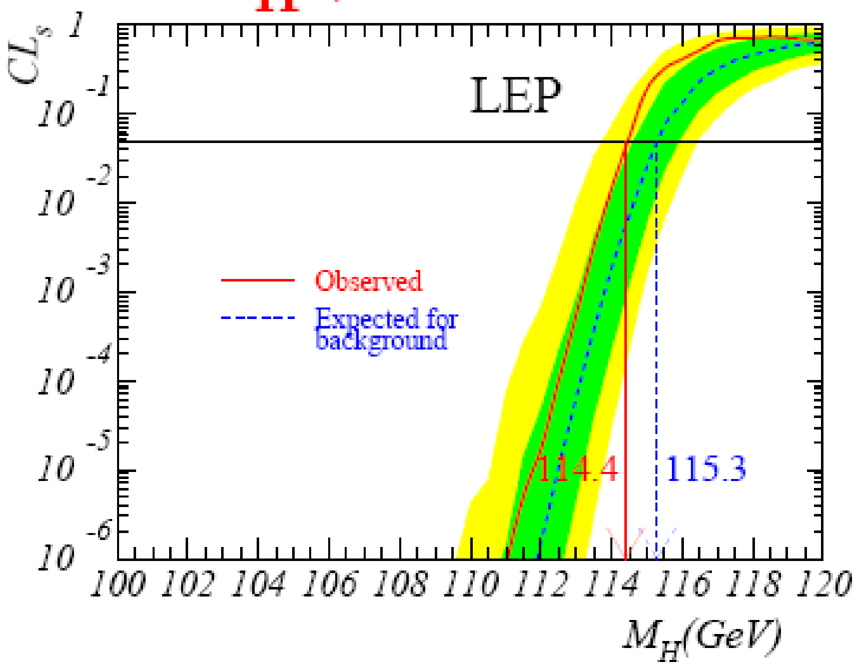
- **Direct Searches at LEP:**

H looked for in $e^+e^- \to ZH$



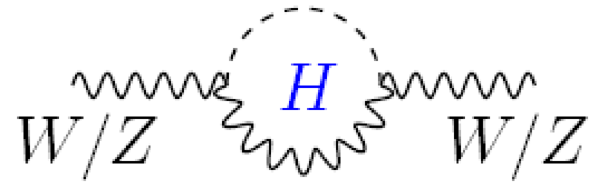
We have a limit at 95% CL:

$$M_H > 114.4 \text{ GeV}$$

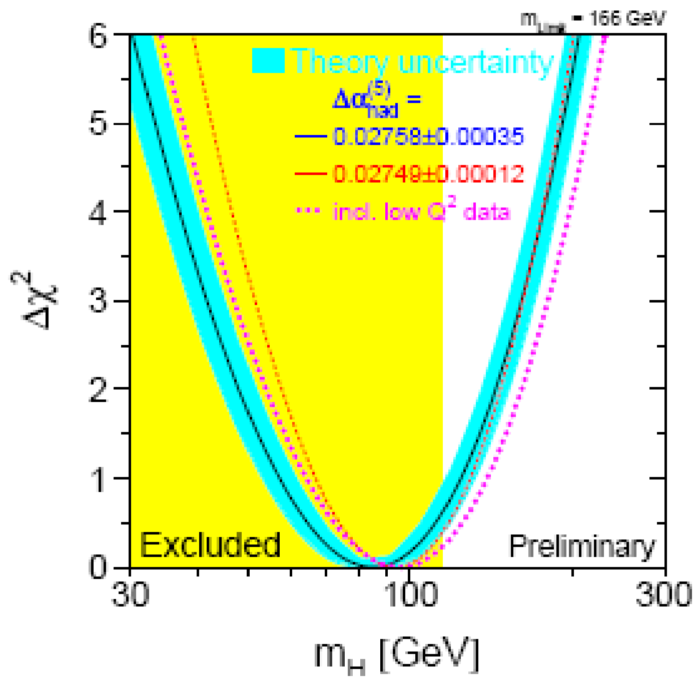


- **Indirect Higgs Searches:**

H contributes to RC to W/Z masses



Fit the EW precision measure-ments:



$$M_H \lesssim 166 \text{ GeV at 95\% CL}$$

• **Higgs in MSSM**

- **Need two Higgs doublets to give up- and down-type fermion masses and cancel anomalies**

  physical states: h^0, H^0 (neutral and CP-even)
  A^0 (neutral and CP-odd)
  $H^{\pm}$ (charged)

  input parameters: $M_A{}^2$, $\tan\beta$

- **At lowest order:** $M_{H^{\pm}}{}^2 = M_A{}^2 + M_W{}^2$

$$M_{h,H}{}^2 = \frac{1}{2}[M_A{}^2 + M_Z{}^2 \mp \sqrt{(M_A{}^2 + M_Z{}^2)^2 - 4M_Z{}^2 M_A{}^2 \cos^2 2\beta} \quad \rightarrow \quad M_h \le M_Z$$

- **Large radiative corrections:**

  Yukawa couplings: $\frac{e\, m_t}{2M_W s_W}, \; \frac{e\, m_t^2}{M_W s_W}, \; \ldots$

  Dominant one-loop corrections:

$$\Delta M_h^2 \sim G_\mu m_t^4 \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$$

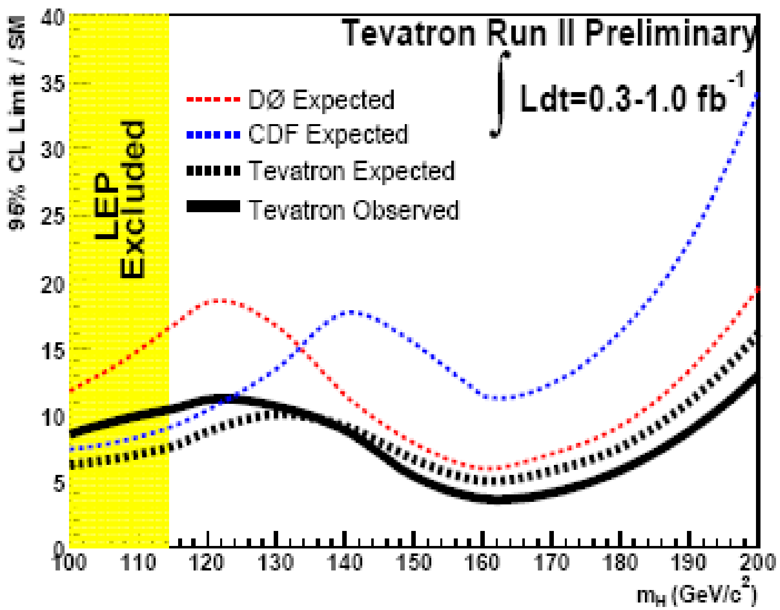
  Present status of M_h in the MSSM:
  complete one-loop and almost complete two-loop result available

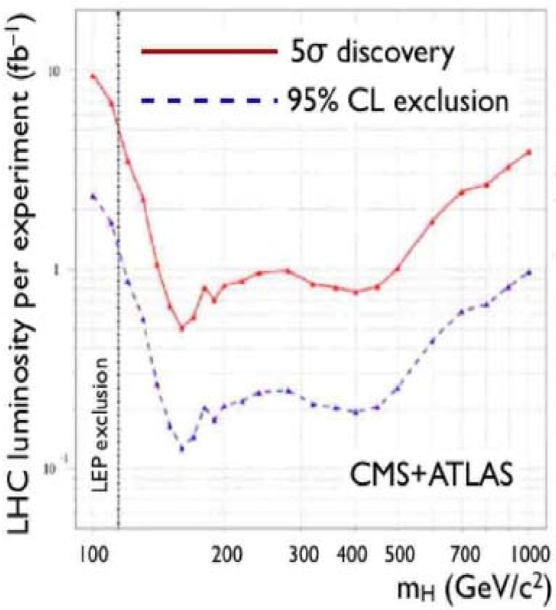
MSSM: $M_h \lesssim 140$ GeV

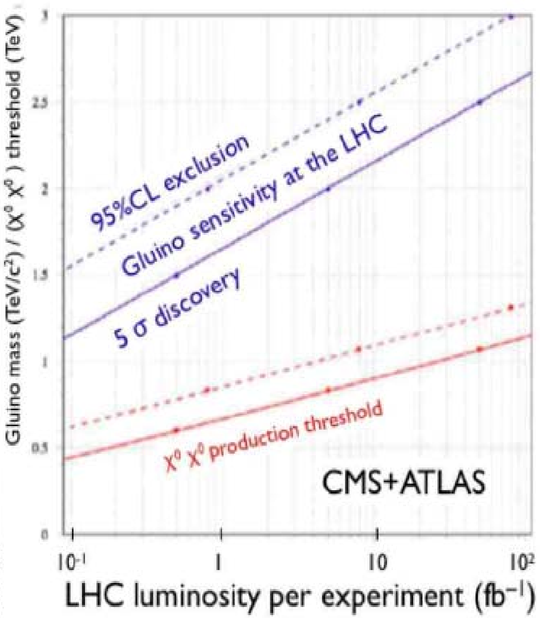
• Summary of Recent Experimental Analysis

J. Ellis, hep-ph/0710.4959

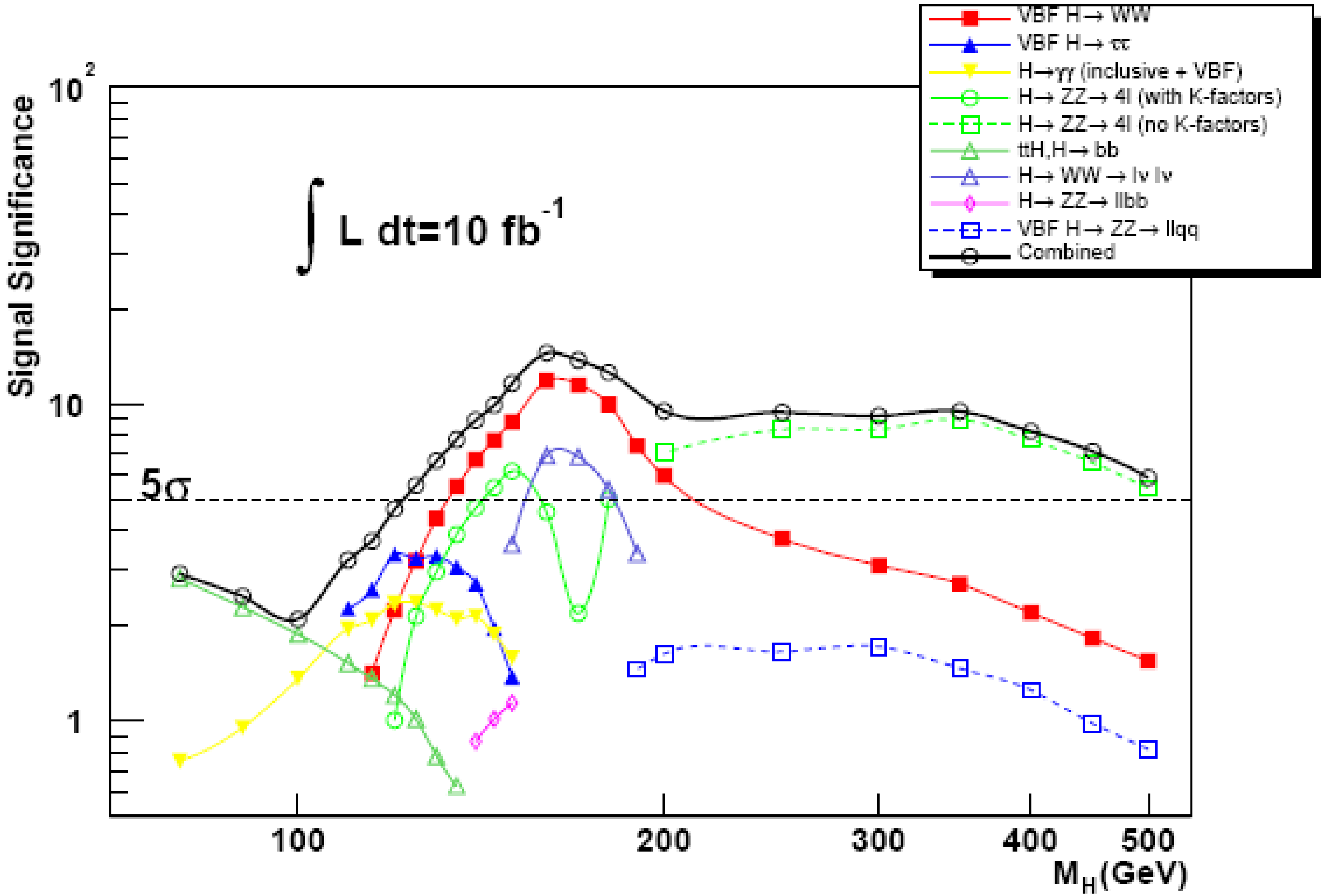
- **The search for the Higgs boson at the LHC will require combining $\gamma\gamma$, four-lepton, $\tau\tau$, bb, WW and ZZ signatures.**
  - **200pb^{-1} should suffice to exclude a SM Higgs between 140 and 500 GeV**
  - **1 fb^{-1} should enable a SM Higgs boson to be discovered with 5-σ significance over a similar mass range.**
  - **5 fb^{-1} should enable a discovery to discover whatever its mass**
  - **It is possible to measure SM Higgs couplings to $\tau\tau$, bb, WW and ZZ with accuracy ~ 20%(if M_H ~ 120 GeV).**
  - **There are also prospects for measuring the Higgs spin via its decays into ZZ.**



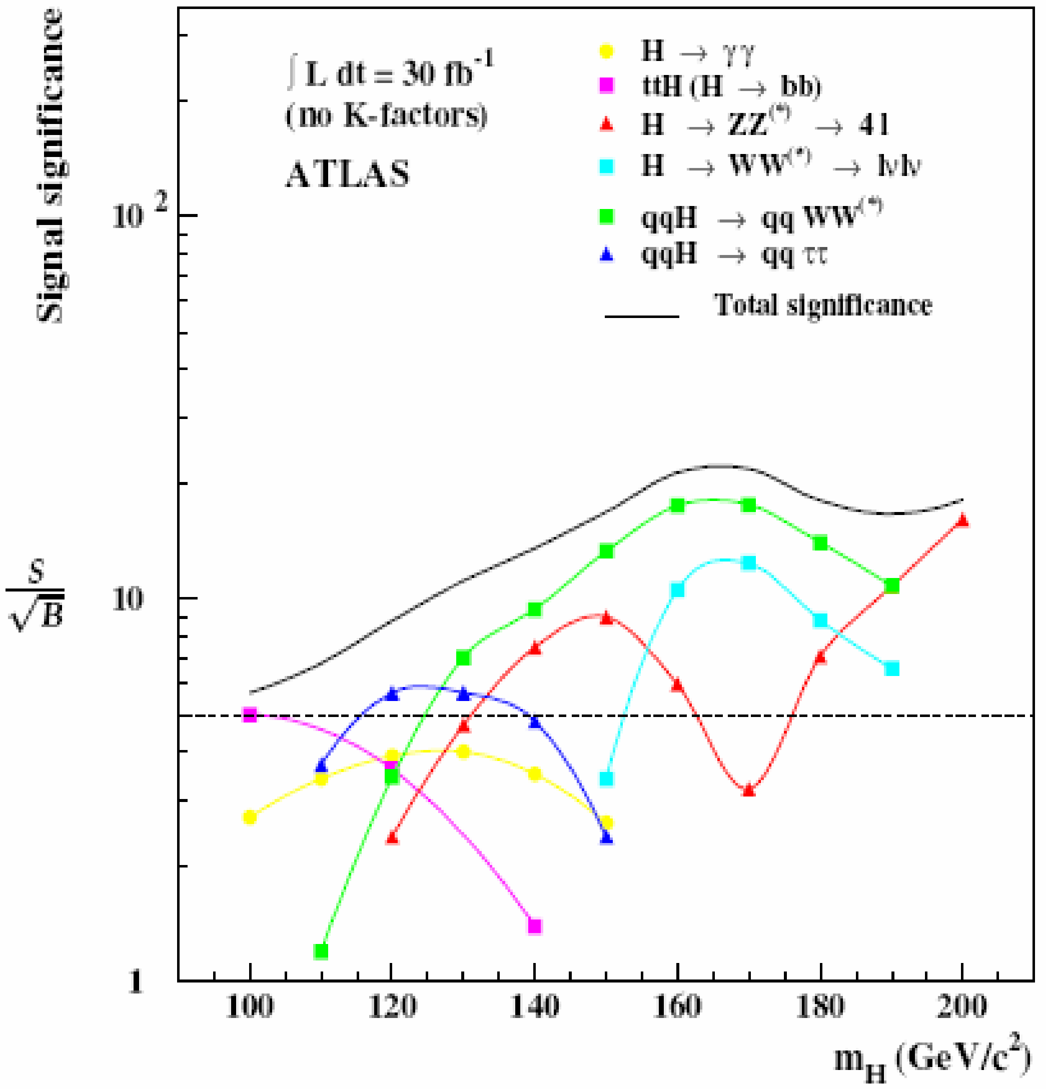




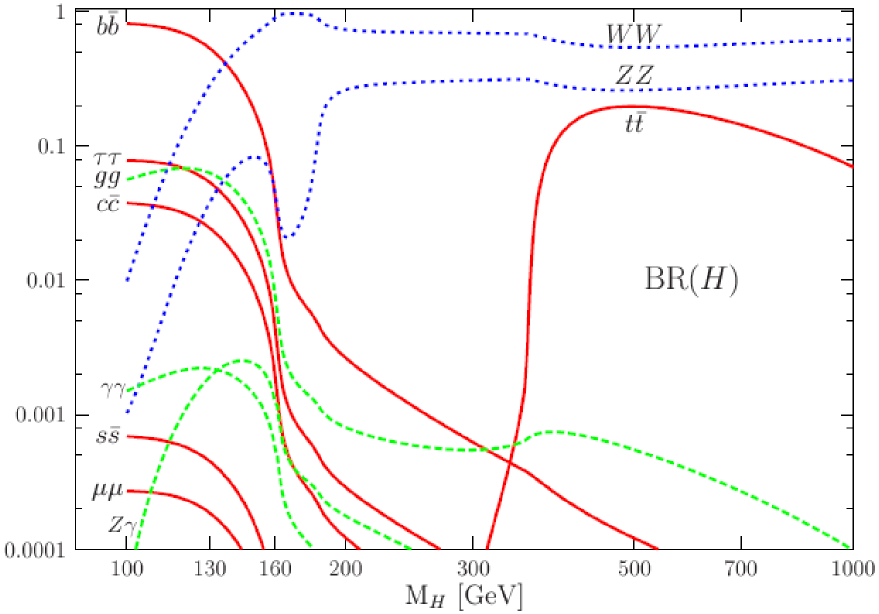
• **SM Higgs search at the LHC: ⇒ full parameter space accessible (ATLAS '05)**



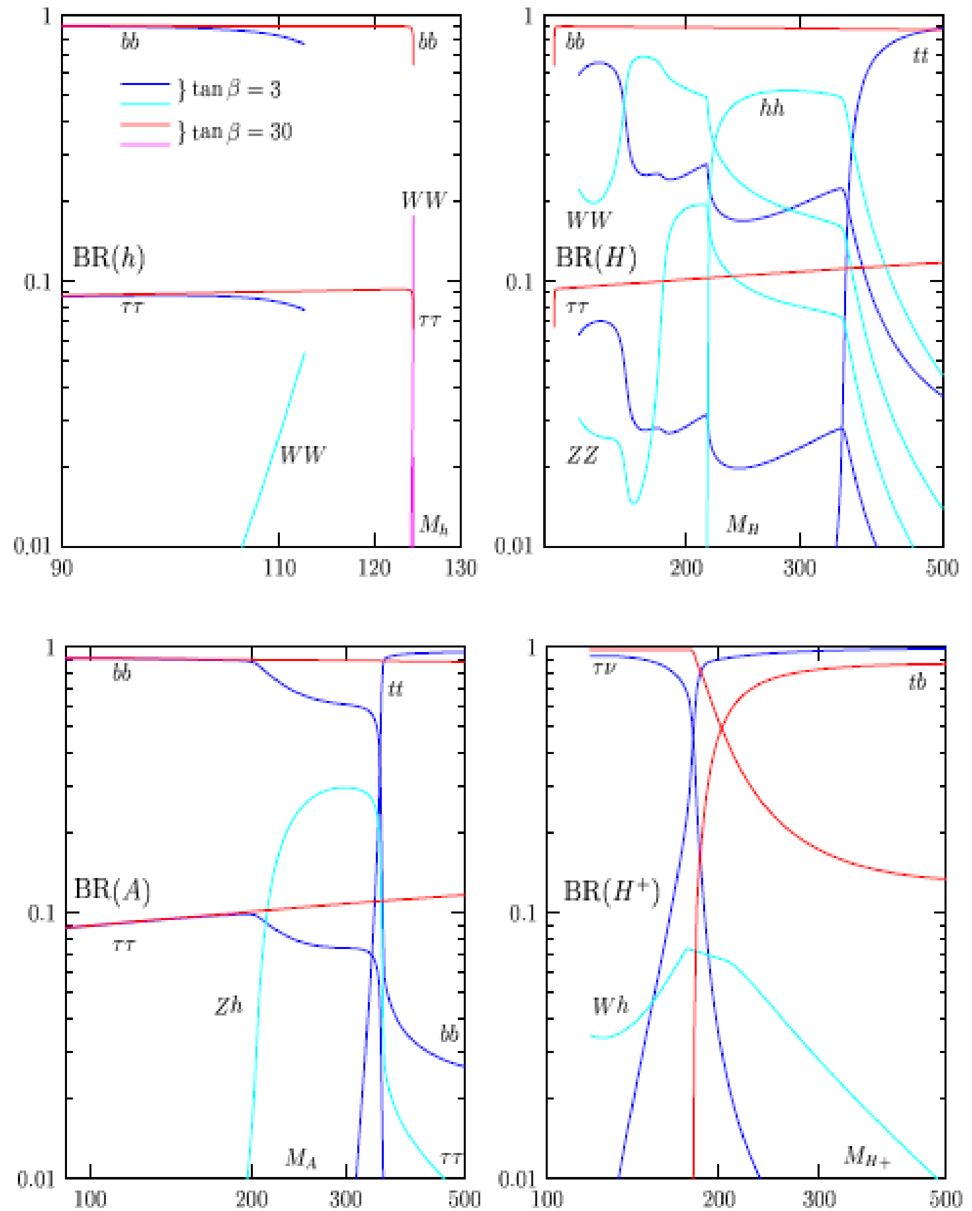
Higgs discovery potential



- **Higgs decays in SM:**



- **Higgs decays in MSSM:**



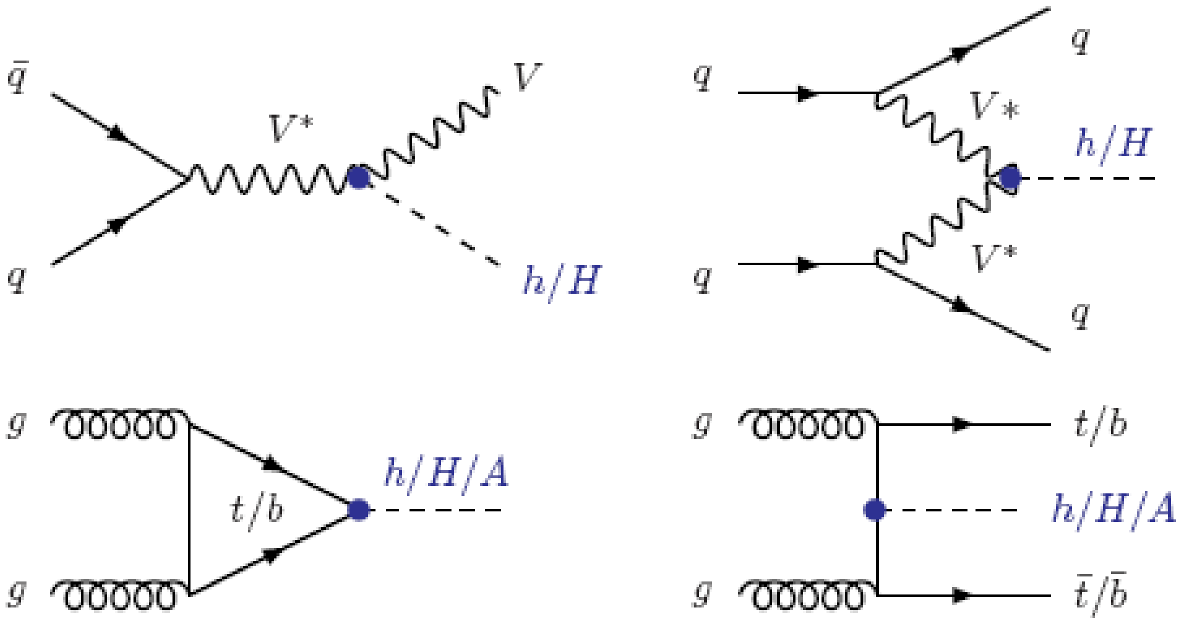
- **Measurements for a SM Higgs (or SM-like MSSM Higgs) at the LHC:**
  - **Measurement of σ × BR (narrow width approximation):**

$$\Rightarrow \sigma(H) \times \mathrm{BR}(H \to xx) = \sigma(H)^{\mathrm{SM}} \cdot \frac{\Gamma_{\mathrm{prod}}}{\Gamma_{\mathrm{prod}}^{\mathrm{SM}}} \times \frac{\Gamma_{\mathrm{partial}}}{\Gamma_{\mathrm{tot}}}$$

Djouadi, hep-ph/0503172, hep-ph/0503173

• Higgs Production at LHC

- **Neutral Higgs production (SM and MSSM)**
- **Gluon-gluon fusion:** $gg \to H$
- **Associated production with W/Z:** $q\bar{q} \to V + H$
- **Vector boson fusion:** $qq \to V^*V^* \to qq + H$
- **Associated production with heavy quarks:** $gg, q\bar{q} \to Q\bar{Q} + H$



- **Inclusive cross section for gg→H**

The history of QCD corrections to this process is long.14 years ago

- **NLO QCD corrections to gg→H are found to be large**

  A.Djouadi, M.Spira, P.M.Zerwas Phys.Lett.B264 (1991) 440

  S.Dawson Nucl.Phys.B359 (1991) 283

  D.Graudenz, M.Spira, P.M.Zerwas, Phys.Rev.Lett, 70 (1993) 1372

  M.Spira, A.Djouadi, D.Graudenz, P.M.Zerwas, Phys.Lett.B318 (1993) 347

  M.Spira, A.Djouadi, D.Graudenz, P.M.Zerwas, Nucl.Phys.B453 (1995) 17

- **NNLO QCD corrections to gg→H (effective Lagrangian method)**

  - **Two-loop corrections to H-g-g vertex**

    R.V.Harlander, Phys.Lett.B492 (2000) 74

  - **Soft-plus-virtual gluon corrections**

    S.Catani, D.de.Florian, M.Grazzini, JHEP 0105 (2001) 025

    R.V.Harlander,W.B.Kilgore,Phys.Rev.D64 (2001) 013015

  - **Two-to-three body processes**

    R.V.Harlander, W.B.Kilgore, Phys.Rev.Lett.88 (2002) 201801

    C.Anastasiou, K.Melnikov, Nucl.Phys.B646 (2002) 220

    V.Ravindran, J.Smith, W.L.Van Neerven, Nucl.Phys.B665 (2003) 325

    V.Ravindran, J.Smith, W.L.van Neerven, Pramana 62 (2004) 683

  - **NNLL**

    Catani et al., Laenen et al., vogelsang et al.

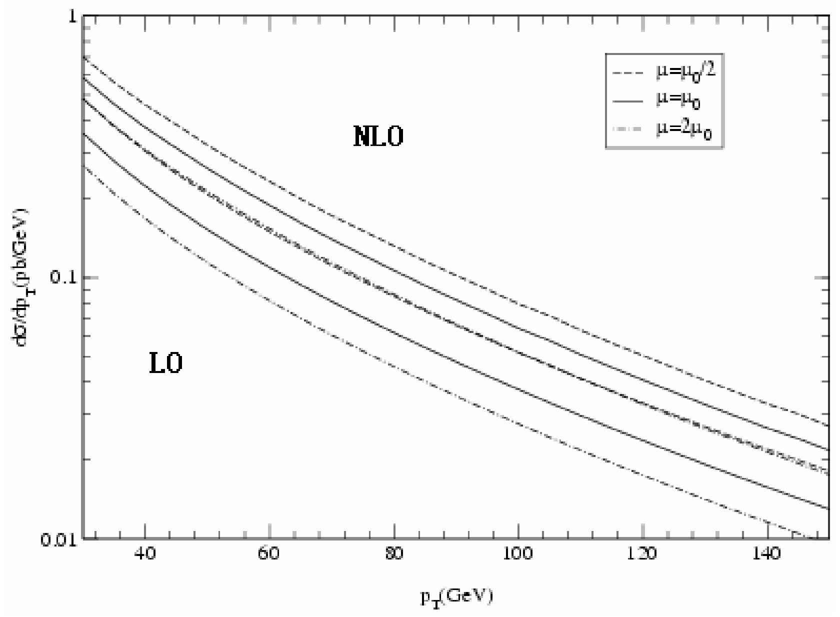
• **NLO QCD corrections to gg→H+1jet+X (in effective Lagrangian method)**

D.de.Florian, M.Grazzini, Z.Kunszt, Phys.Rev.Lett.82 (1999)5209

S.Catani, D.de Florian, M.Grazzini,JHEP 0201 (2002) 015

V.Ravindran, J.Smith, W.L.Van Neerven, Nucl.Phys.B634 (2002) 247

Christopher J.Glosser, Carl R.Schmidt, JHEP 0212 (2002) 016



• **NLO QCD correction to gg→diphoton (background to gg→H→diphoton)**

Z.Bern, L.J.Dixon, C.Schmidt Phys.Rev.D66 (2002) 074018

• **Associated production of Higgs with top pairs(NLO)**

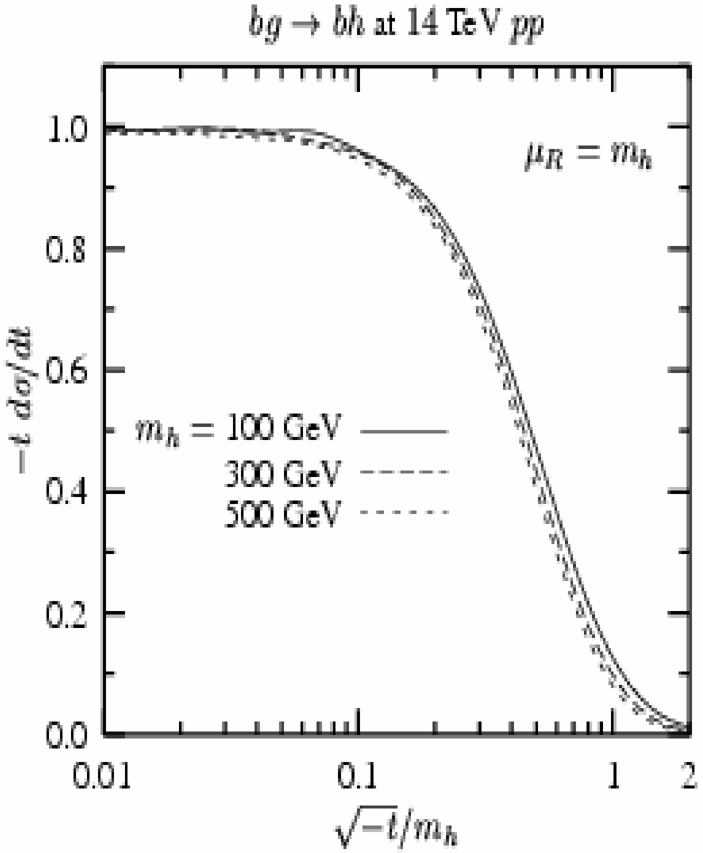
W.Beenakker, S.Dittmaier, M.Kramer, B.Plumper, M.Spira, P.M.Zerwas Nucl.Phys.B653 (2003) 151; Phys.Rev.Lett.87 (2001) 201805

S. Dawson, C. Jackson, L.H. Orr, L. Reina, D. Wackeroth Phys.Rev.D68 (2003) 034022

- $b\bar{b} \to h$ **The relevant Yukawa coupling can be large in SUSY models**

bg→bh at LHC

C.S. Huang & S.H. Zhu, PRD60:075012,1999
F. Maltoni, Z. Sullivan, S. Willenbrock, Phys.Rev. D67 (2003) 093005
S.Dawson etc., Phys.Rev.Lett. 94 (2005) 031802



In collinear limit

dσ/dt ~1/t

From the figure, the collinear limit is about $\sqrt{-t} \leq m_h/4$

After integration $\Rightarrow \ln(m_h/4m_b)$

The factorization should be about $m_h/4$

• **Exclusive Higgs Boson Production with bottom quarks pairs at Hadron Colliders (SM and SUSY Higgs boson)(NLO)**

S.Dawson, C.Jackson, L.H.orr, L.Reina, D.Wackeroth Phys.Rev. D69 (2004) 074027

• **QCD Corrections to Jet Correlations in Weak Boson Fusion**

T.Figy,D.Zeppenfeld, Phys.Lett. B591 (2004) 297, Phys.Rev. D68 (2003) 073005;
T.Figy, C.Oleari, D.Zeppenfeld, Phys.Rev. D68 (2003) 073005

• **NNLO QCD corrections to pp→(pseudo) scalar Higgs boson**

R.V.Harlander, W.B.Kilgore, JHEP 0210 (2002) 017
V.Ravindran,J.Smith,W.L.Van Neerven, Nucl.Phys.B665 (2003) 325
C.Anastasiou, K.Melnikov, Phys.Rev.D67 (2003) 037501
B.Field,J.Smith,M.E.Teieda-Yeomans,W.L.Van.Neerven
Phys.Lett. B551 (2003) 137

• **Effects of SUSY-QCD in hadronic Higgs production at NNLO**

R.V.Harlander, M.Steinhauser Phys.Rev. D68 (2003) 111701

• **NLO QCD corrections to Higgs+1 high P_T bottom quark production**

Stefan Dittmaier, Michael Krämer, Michael Spira, Phys.Rev. D70 (2004) 074010J. Campbell, R.K. Ellis, F. Maltoni, S. Willenbrock, Phys.Rev. D67 (2003) 095002J. Campbell, S. Dawson, S. Dittmaier, C. Jackson, M. Kramer, F. Maltoni, L. Reina, M. Spira, D. Wackeroth, S. Willenbrock, hep-ph/0405302

• **SUSY-QCD corrections to gb→bh**

Junjie Cao, Guangping Gao, Robert J. Oakes, Jin Min Yang, Phys.Rev. D68 (2003) 075012

• **NLO QCD corrections to Higgs+2 high P_T bottom quark production**

Stefan Dittmaier, Michael Krämer, Michael Spira, Phys.Rev. D70 (2004) 074010

S. Dawson, C.B. Jackson, L. Reina, D. Wackeroth, Phys.Rev. D69 (2004) 074027

• **NLO QCD corrections to gb→tH$^-$**

Shou-Hua Zhu Phys.Rev. D67 (2003) 075006,hep-ph/0112109

T.Plehn Phys.Rev. D67 (2003) 014018, hep-ph/0206121

E Berger, T Han, J Jiang, T Plehn, hep-ph/0312286

• **SUSY QCD corrections to gb->tH$^-$**

G. Gao ,G. Lu Z. Xiong, J.M.Yang Phys.Rev. D66 (2002) 015007

• **NLO QCD corrections to bb→WH**

Wolfgang Hollik, Shou-hua Zhu, Phys.Rev. D65 (2002) 075015

• **NLO QCD corrections to** $b\bar{b} \rightarrow H^+H^-$

Hou Hong-Sheng, Ma Wen-Gan, Zhang Ren-You, Jiang Yi, Han Liang, Xing Li-Rong, Phys.Rev. D71 (2005) 075014

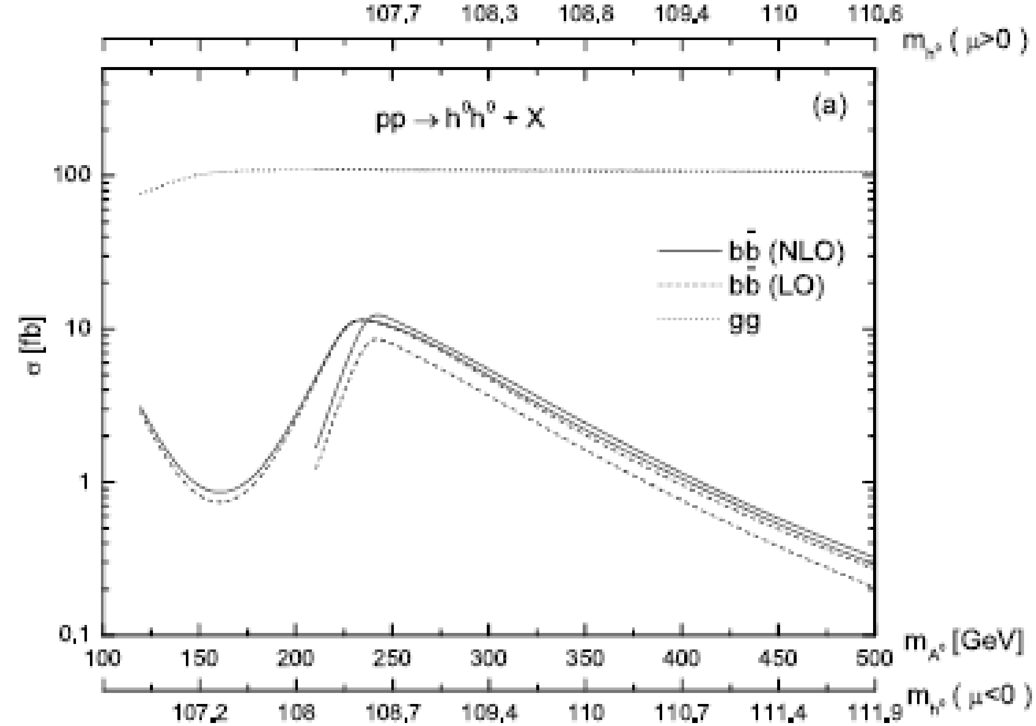
- **NLO QCD predictions for Pair Production of neutral Higgs bosons**

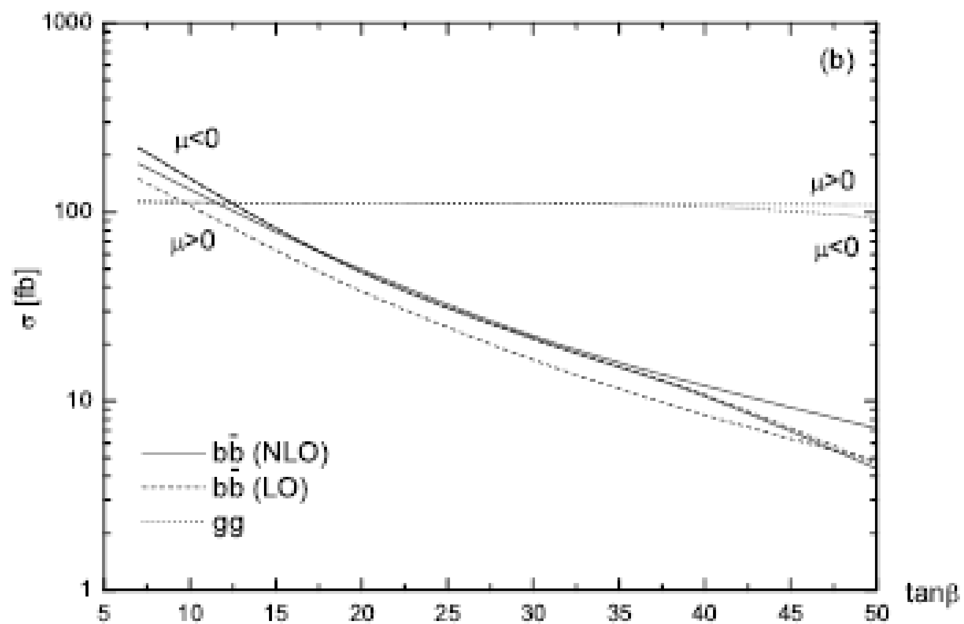
$$b\bar{b} \rightarrow H_i H_j (H_i = h, H, A)$$

QCD NLO: L.G. Jin, C. S. Li, Q. Li, J.J. Liu, and R. J. Oakes PRD71(2005) 095004

- **The $b\bar{b}$ -annihilation contributions can exceed ones of gg fusion and $q\bar{q}$ annihilation for h^0H^0, A^0h^0 and A^0H^0 productions when $\tan\beta$ is large.**

- **The QCD NLO corrections Can reach a few ten of percent .**

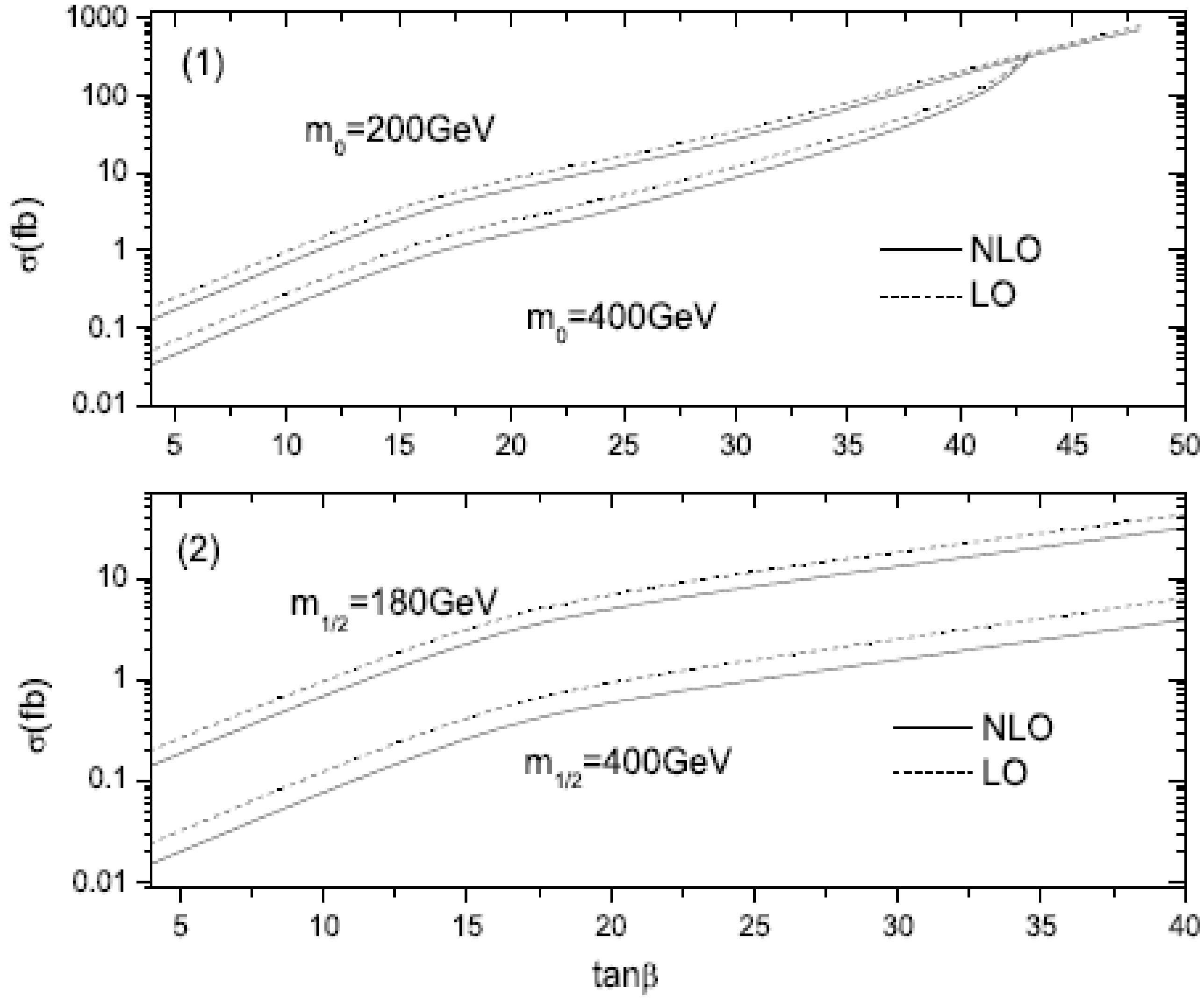




- **A^0 Z^0 associated prodution:**

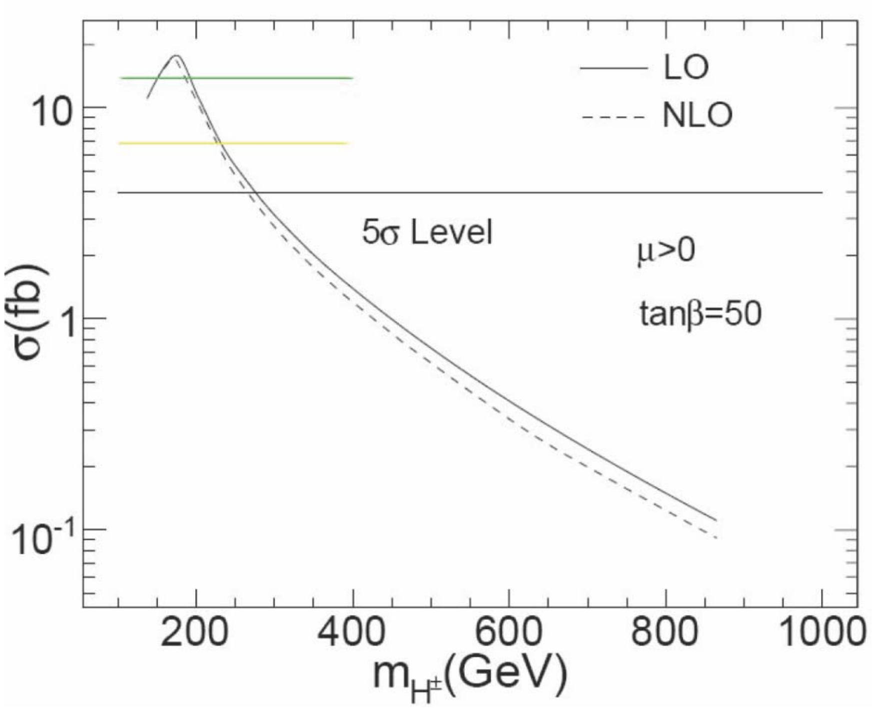
  QCD NLO predictions: Qiang Li, Chong Sheng Li, Jian Jun Liu, Li Gang Jin, C.-P. Yuan, PRD72(2005)034032

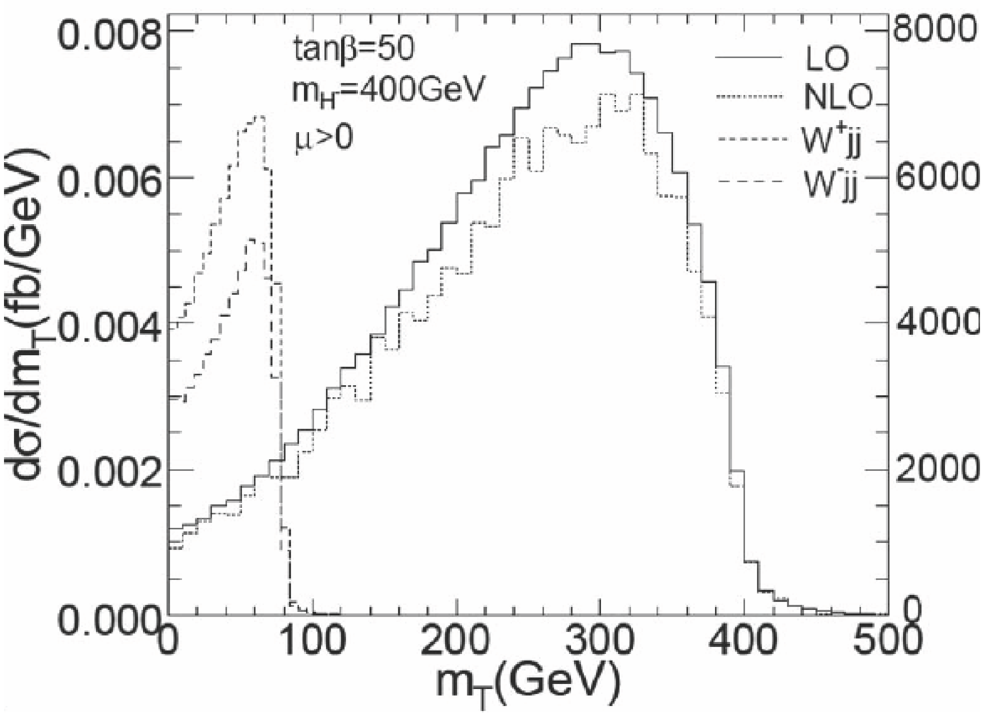
$$b\bar{b} \to AZ$$



- **Associated production of Charged Higgs and W± (simulation with NLO)**

$$b\bar{b} \rightarrow H^{\pm} + W^{\mp}$$





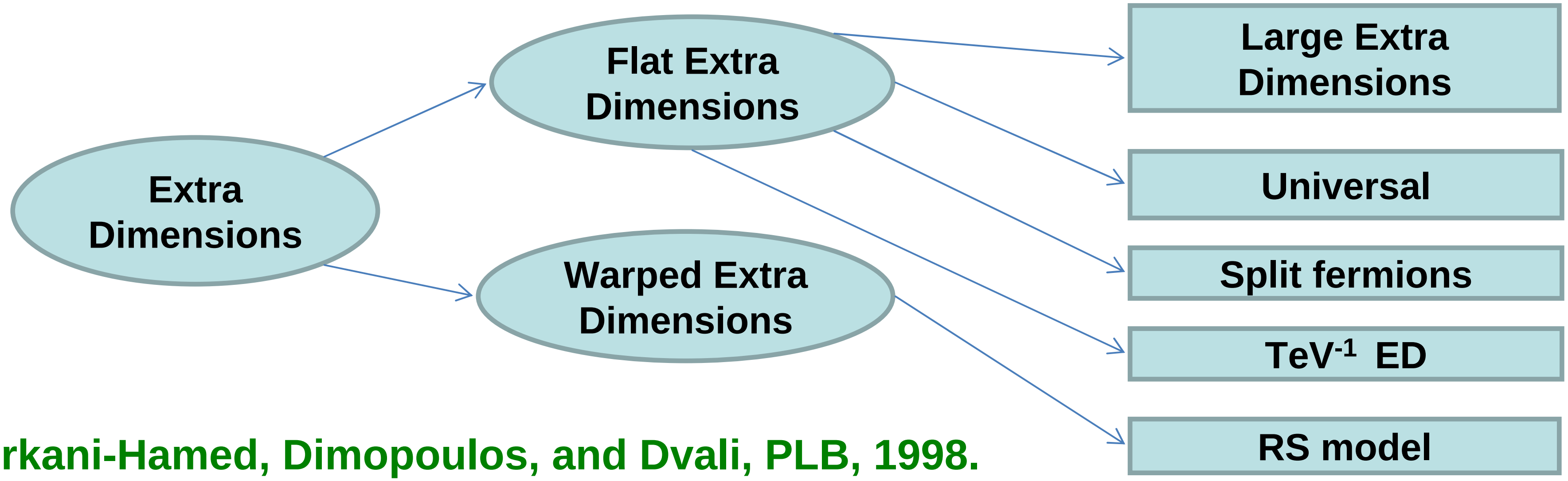
Jun Gao, Chong Sheng Li, Zhao Li, PRD77(2008)014032

4. Extra Dimensions

• Introduction of extra dimensions

According to the topology/geometry of the space – time manifold, the models can be classified into two classes:

- "Flat" (factorizable) ED
  - Large ED(Arkani-hamed, Dvali & Dimopoulos)
  - TeV-1 ED(variant of LED)
  - Universal ED(Appelquist, Cheng&Dobrescu)
- "Warped" (non-factorizable) ED(Randall and Sundrum



Arkani-Hamed, Dimopoulos, and Dvali, PLB, 1998.

Randall and Sundrum, PRL, 1999

● The ADD model

- The spacetime is flat, and the n-extra dimensions are compact to n-torus, the metric is:

$$ds^2 = (\eta_{\mu\nu} + h_{\mu\nu})dx^\mu dx^\nu - r^2 d\Omega_{(n)}^2$$

- The observed Planck scale M_{Pl} can be derived from the fundamental Planck scale M_D:

$$M_{Pl}^2 \sim M_D^{n+2} R^n$$

- The size of the EDs are not small, but can be as large as 0.2mm.

- If R is as large as mm, the fundamental Planck scale M_D is as low as TeV which means that the hierarchy problem disappears.

- The SM particles are confined in our 3+1 branes, while only the graviton can propagate in the Eds.

- The graviton plays central role in probing the large extra dimension model(LED).

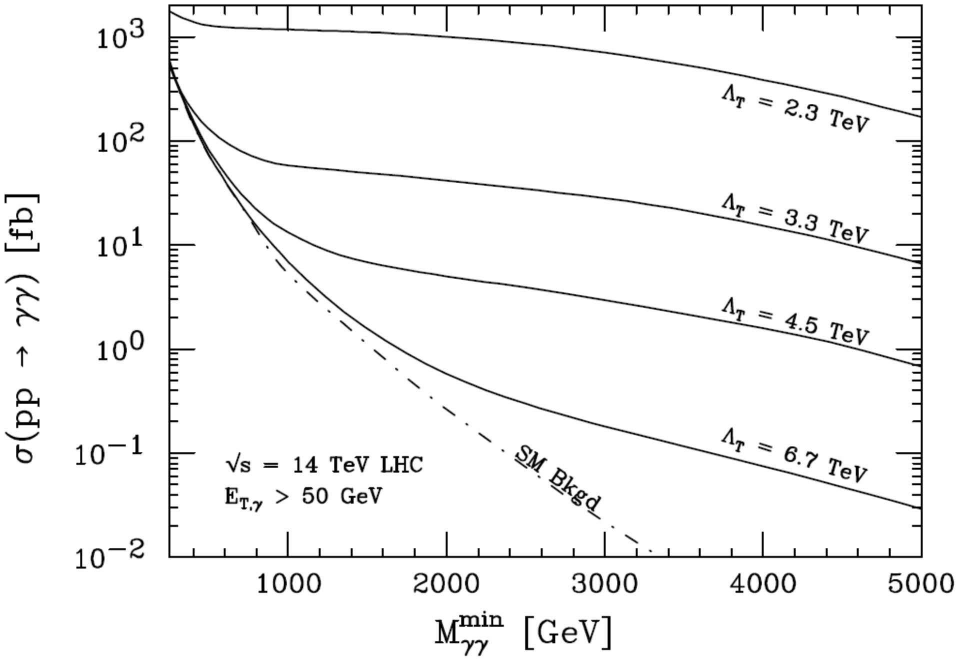
N. Arkani-Hamed, et. al., PLB429, 263(1998), PRD59, 086004(1999)
I. Antoniadis, et. al., PLB436, 257(1998)

● Phenomenology at LHC

- **The virtual graviton exchange**

- **Summing over all KK modes will lead to enhancement of cross-sections. The sum is UV divergent and sensitive to the UV cut.**

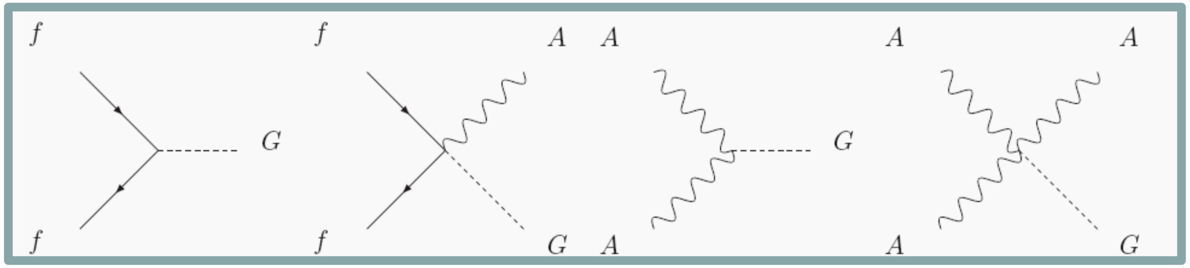
$$q\bar{q}, gg \rightarrow G^{(n)} \rightarrow l^+ l^-, \gamma\gamma, ZZ, f\bar{f}, hh$$



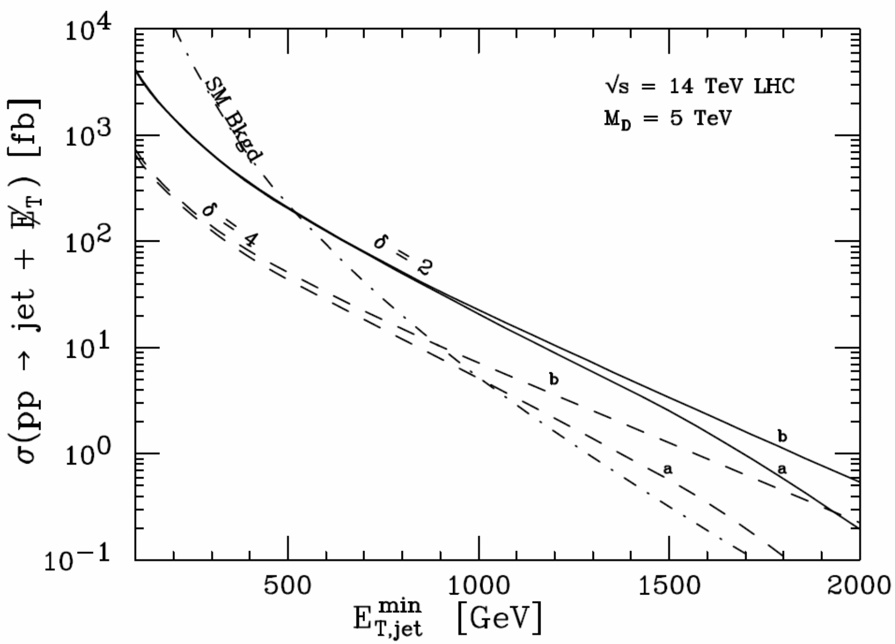
The total cross-section for pp → γ γ integrated for $\sqrt{\hat{s}} > M^{min}_{\gamma\gamma}$ with the requirement that $E_{T,\gamma}$ > 50GeV and $|\eta_\gamma| <$ 2.5 for each photon.

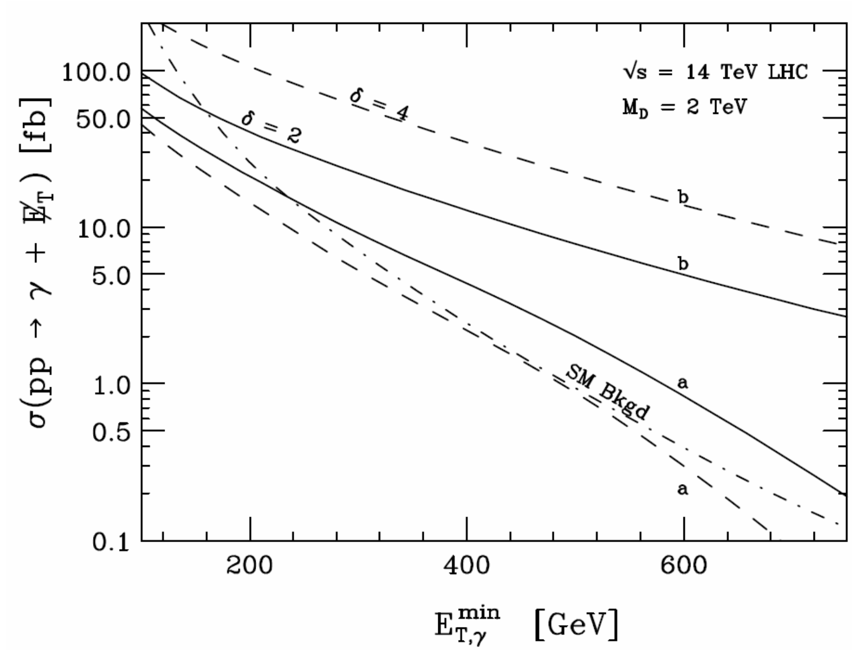
G. F. Giudice et al., NPB 544(1999)3-38; L Vacavant and I Hinchliffe, J. Phys. G; Nucl. Part. Phys. 27 (2001) 1839–1850
C. –P. Yuan et al., PRL 83 (1999) 2112-2115;

- **Graviton emission as missing energy**



$$p\bar{p} \;\rightarrow\; \gamma G, jG$$
$$\;\rightarrow\; ZG$$
$$\;\rightarrow\; WG$$





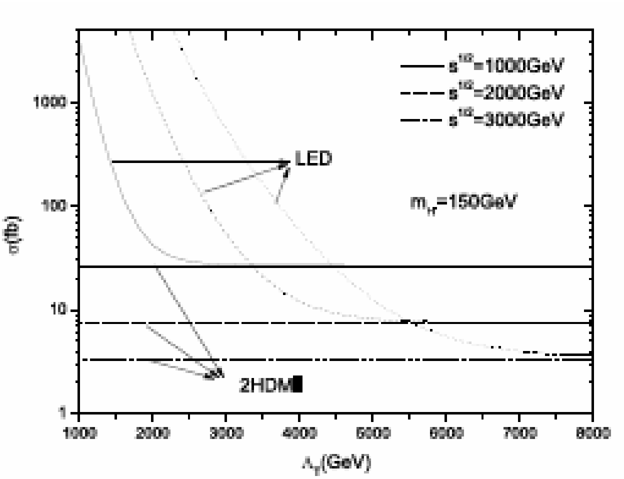
The total jet + nothing cross-section at the LHC integrated for all $E_{T,jet}$ > $E^{min}_{T,jet}$ with the requirement that $|\eta_{jet}| < 3.0$.

The total γ +nothing cross-section at the LHC integrated for all $E_{T,\gamma}$ > $E^{min}_{T,\gamma}$ with the requirement that $|\eta_{\gamma}| < 2.5$.

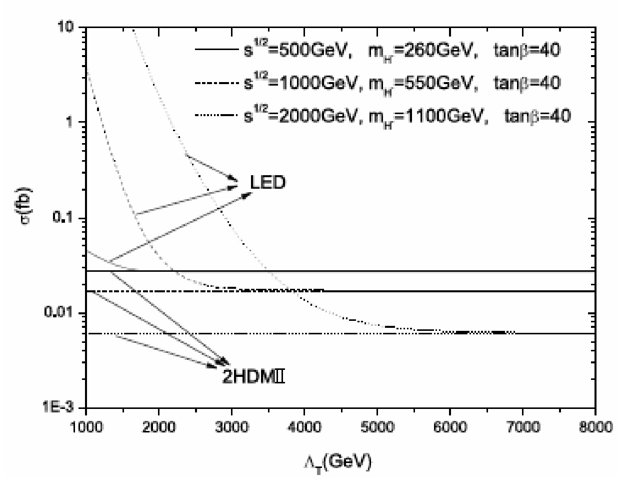
● Charged Higgs production at linear colliders in LED

• $e^+e^- \to H^+H^-$ and $e^+e^- \to H^-tb$ at future linear colliders (LC) in 2HDM with large extra dimensions (LED) via virtual KK gravitons exchange.

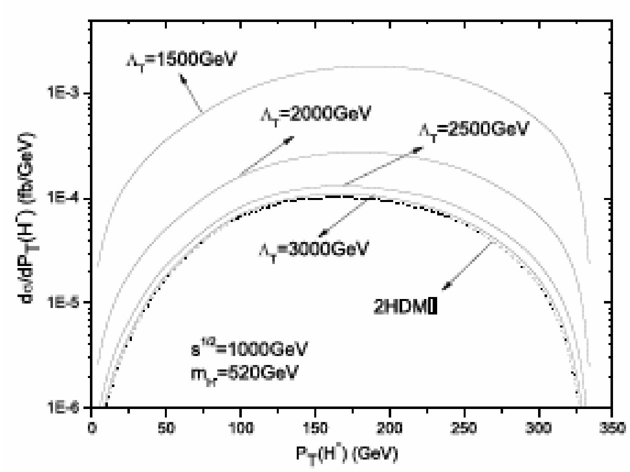
•The KK graviton effects can significantly modify these total cross sections and also their differential cross sections compared to their respective 2HDM values and, therefore, can be used to probe the effective scale up to several TeV.



Dependence of cross section in 2HDM II and LED for process $e^+e^- \to H^+H^-$



Dependence of the cross section in 2HDM II and LED for process $e^+e^- \to H^-tb$



The differential cross section d/dP_T (H–) in 2HDM II and LED for the process $e^+e^- \to H^-tb$

Qiang Li, Chong Sheng Li, Robert J. Oakes, and Li Lin Yang, Phys. Rev. D72 (2005) 076007.

• ZZ production in Extra Dimensions

LED

1. Production at LEP (K. Agashe and N. G. Deshpande Phys. Lett. B 456 (1999))
2. Production at Tevatron (Csaba Balazs, C.P. Yuan *et al*. Phys. Rev. Lett. 83 (1999) 2121)
3. Production at LHC (Martin Kobe *et al*. Phys. Rev. D 76:125001, 2007)

RS

1. Radion resonance (Prasanta Kumar Das, Phys. Rev. D 72, 055009 (2005))
2. Warped graviton production and decay(K. Agashe *et al*. Phys. Rev. D 76, 036006 (2007))
3. Both are considered(Seong Chan Park and H. S. Song. Phys. Rev. D 65, 015008(2002))

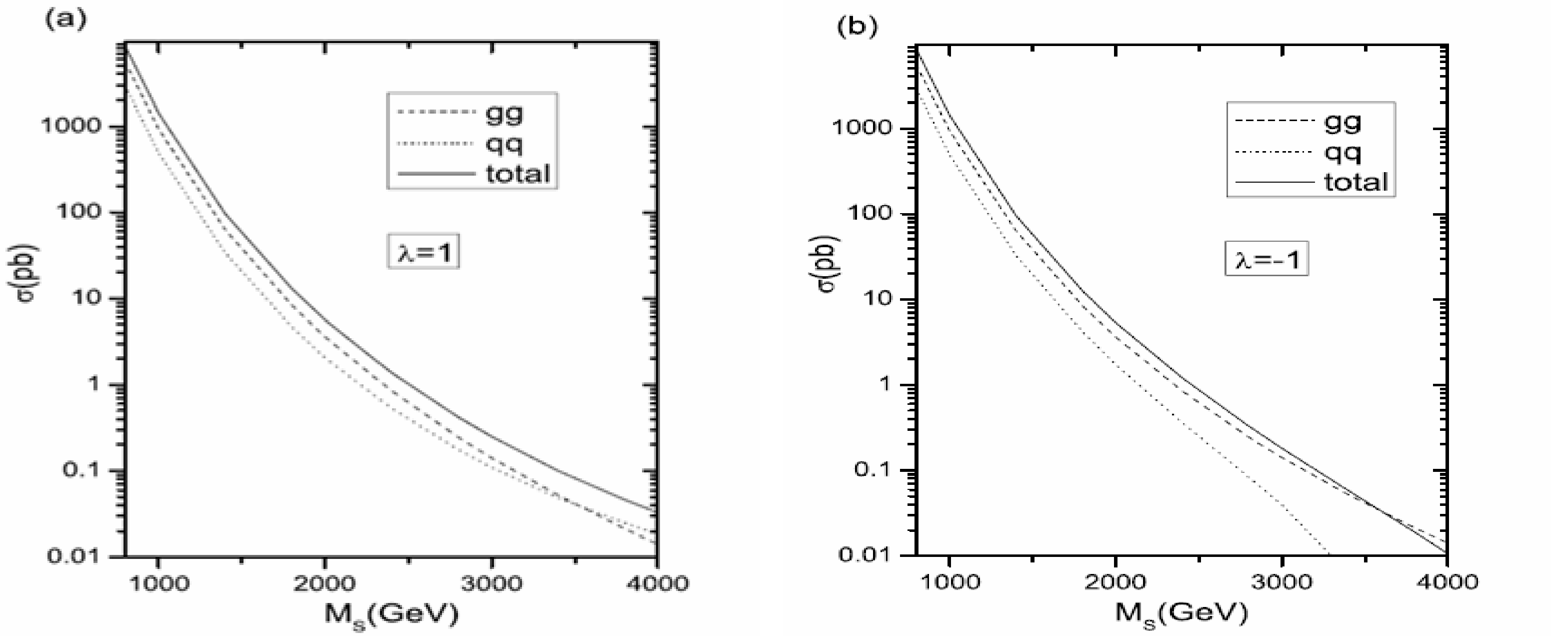
- The cross section of ZZ production through virtual graviton KK modes in the LED model at LHC (both gluon fusion and quark annihilation are considered) are calculated.
- There are two relevant parameters, M_s denoting the fundamental scale, $\lambda = \pm 1$ describing the interface between SM and LED.
- The contributions to the total cross section from LED can be divided into two parts:

Interface term
$\sim \lambda / M_s^4$

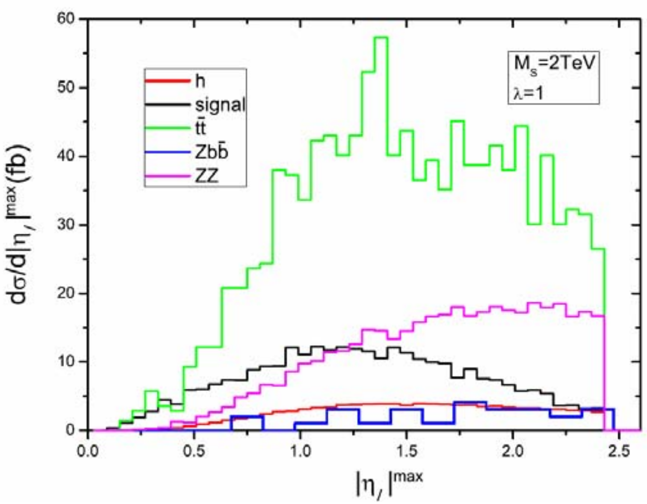
Other terms
$\sim 1/M_s^8$

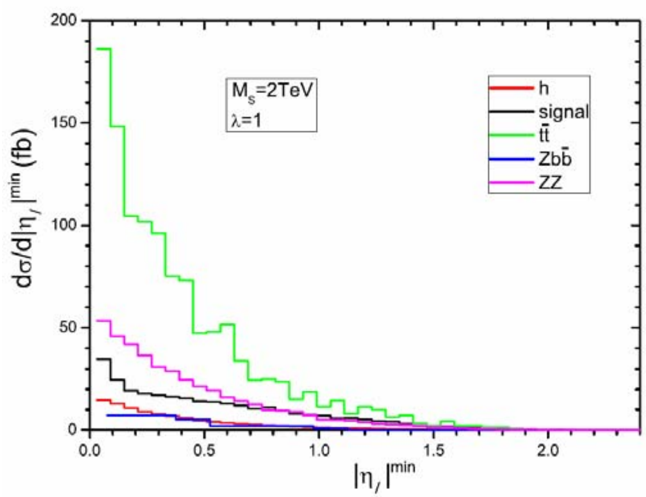
● ZZ production in LED

•The total cross section :



•Several distributions (basic cuts):





For the signal channel ZZ→4leptons (e, μ),

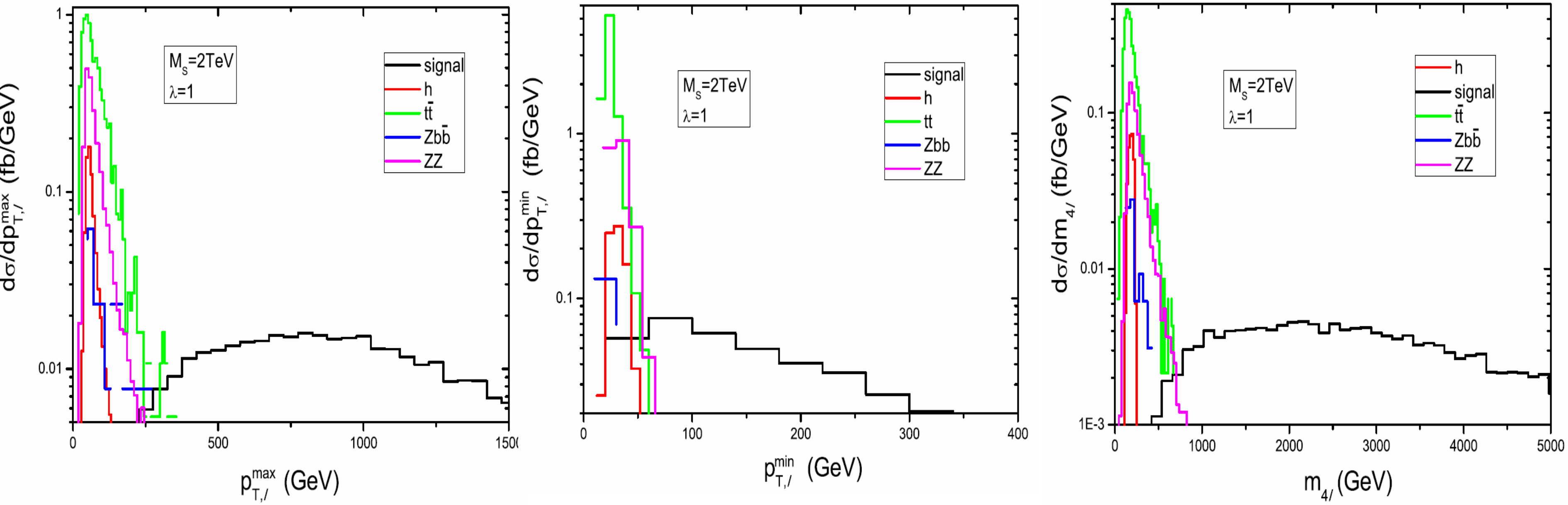
•basic cuts:

$p_t(l^{\pm}) > 15$ GeV,

$|\eta(l^{\pm})| < 2.4$,

$\Delta R_{ll} > 0.1$

•These basic cuts consider the cover range of detectors.



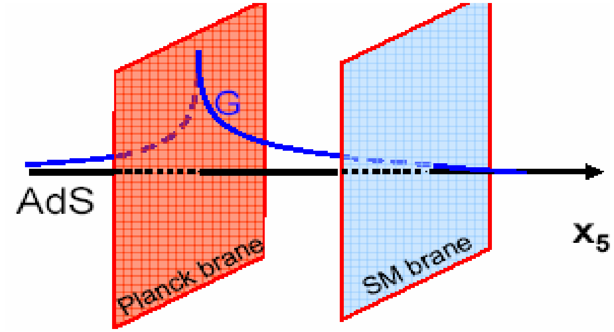
- **We need some additional cuts to suppress the backgrounds：m_{4l} > 1000 GeV. Then we get the following results for M_S=2 TeV, λ =+1:**

	Signal	backgrounds				
		$t\bar{t}$	$Z\bar{Z}$	$Zb\bar{b}$	h	total
Basic(fb)	17.5	70.0	25.0	9.6	6.0	110.6
Additional(fb)	15.9	<0.01	0.12	<0.01	<0.01	0.12

● The Randall-Sundrum Scenario

- **Warped extra dimensions**

Its metric tensor can be written as:



$$ds^2 = e^{-2k|y|} dx^\mu dx^\nu \eta_{\mu\nu} - dy^2$$

The extra dimension (5th-dim) y is “warped”.

● RS vs. LED

- **Same: Only the graviton propagate in the bulk.**
- **Different:**

1. Warped (RS) vs. flat (LED)

2. The unevenly spaced KK spectrum for the graviton (RS) vs. the evenly spaced KK spectrum (LED).

3. Each resonance has an 1/TeV order couplings (RS) vs. the sum of all the KK gravitons gives an 1/TeV couplings (LED).

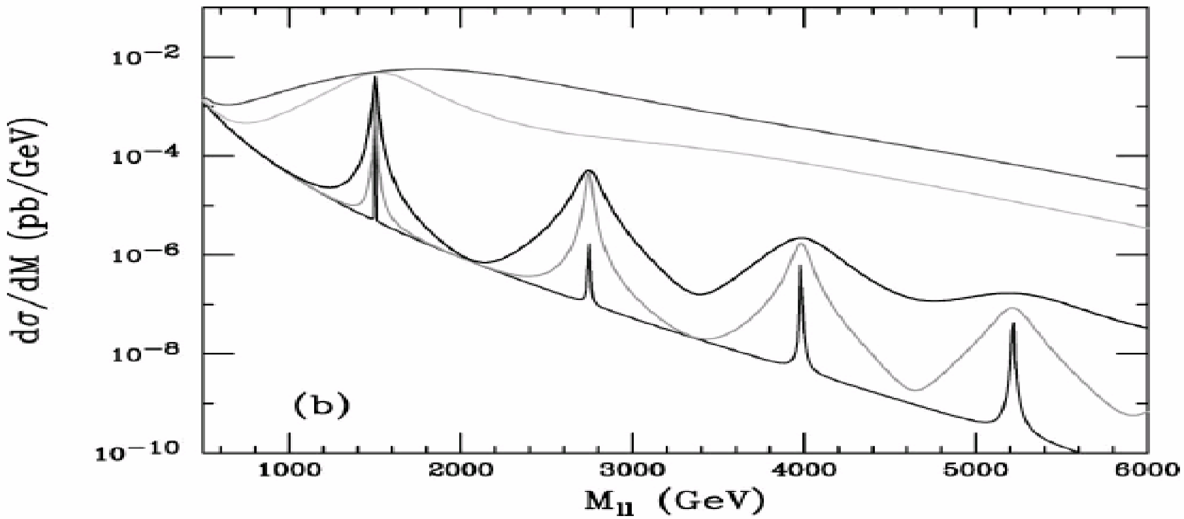
L.Randall and R.Sundrum, Phys. Rev. Lett. 83, 3370 (1999).

● Phenomenology of RS at LHC

- The individual KK graviton are heavy and strong coupled to the SM particles, and its effects can be detected at the LHC.

- The data analysis on the Drell-Yan and dijet process, as well as EW precise test strongly constrain the parameter space of RS model.

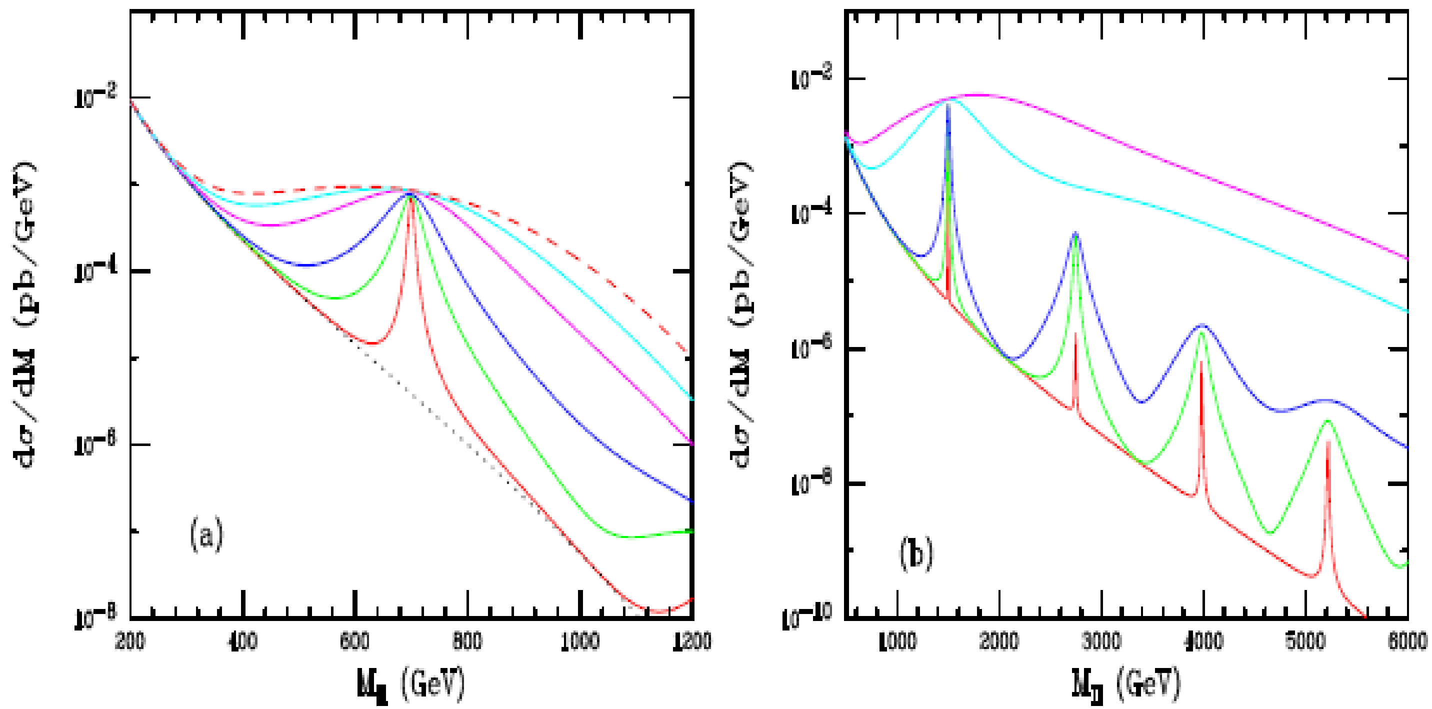
- Its phenomenology at the LHC has been extensively studied in literatures (e.g. Rizzo. et al). It is shown that the diphoton channel can be used to detect the graviton up to 2~3TeV.



The invariant mass distribution for the Drell-Yan Process at the LHC

Rizzo. et al., PRD 63, 075004 (2001)

Drell-Yan Production



Davoudiasl, Hewett, and Rizzo

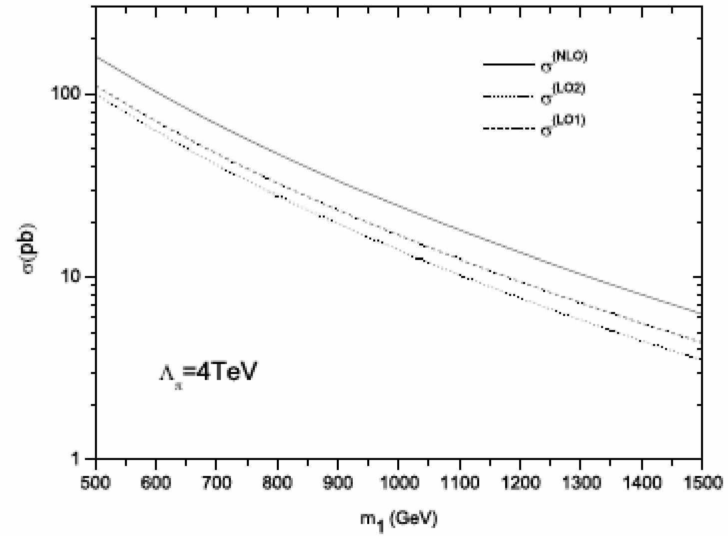
● Soft Gluon Resummation Effects in Single Graviton Production at LHC

- In the RS model, the lightest massive graviton can have a mass of several hundred GeV, and maybe produced copiously at LHC.

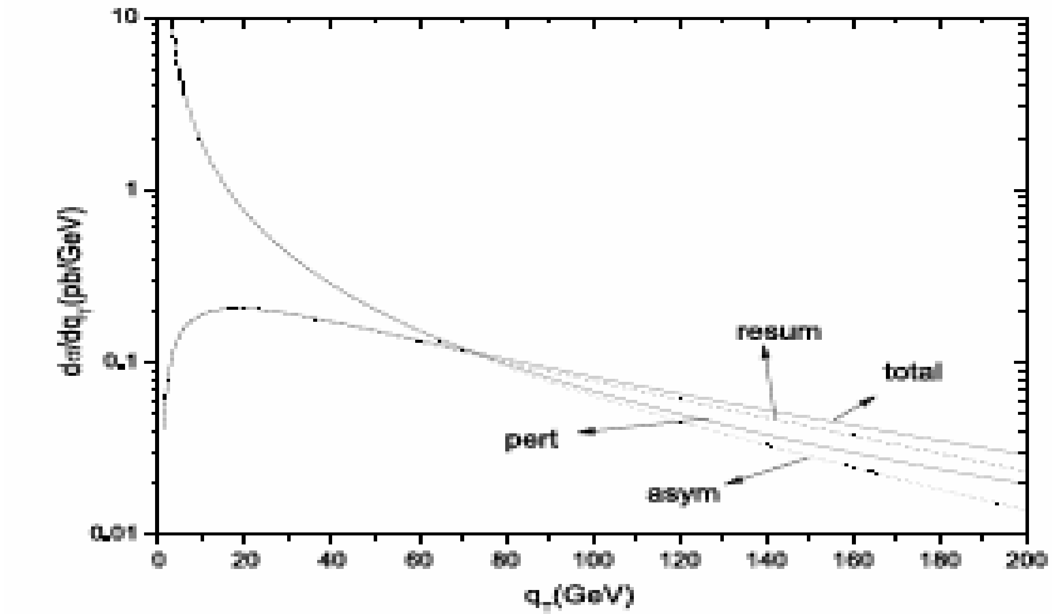
- More importantly, it has much larger couplings to the SM particles than the ones in the ADD model, thus it may decay into observable particles and hence be detected.

- The transverse momentum distribution of the massive graviton at NLO in QCD is also been studied, and all order soft gluon resummation eﬀects on the distribution to are considered to give reasonable predictions .

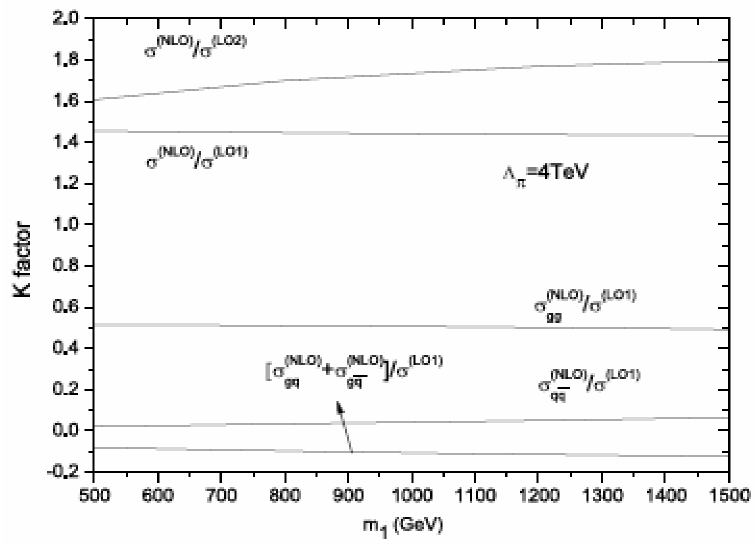
Qiang Li, Chong Sheng Li, Li Lin Yang, PRD74 (2006) 056002



Dependence of the total cross sections for the first KK graviton excitation mode direct production at the LHC on m_1.



The transverse momentum distribution of the first KK graviton excitation mode from pp→G process at theLHC



Dependence of the K -factor on m_1.

5. Unparticle Physics

● Introduction of unparticle

- **Last year, Georgi suggested a new candidate of TeV new physics which is called unparticle.**

- **Georgi's assumed the high energy theory contains fields of SM and a theory (BZ) with a nontrivial IR fixed point. They interact through the exchange of heavy particles. At TeV scale, the BZ will reach the IR fixed point. Thus, we have a scale invariant theory (unparticle sector) and SM sector. They interact through a unrenormalizable coupling.**

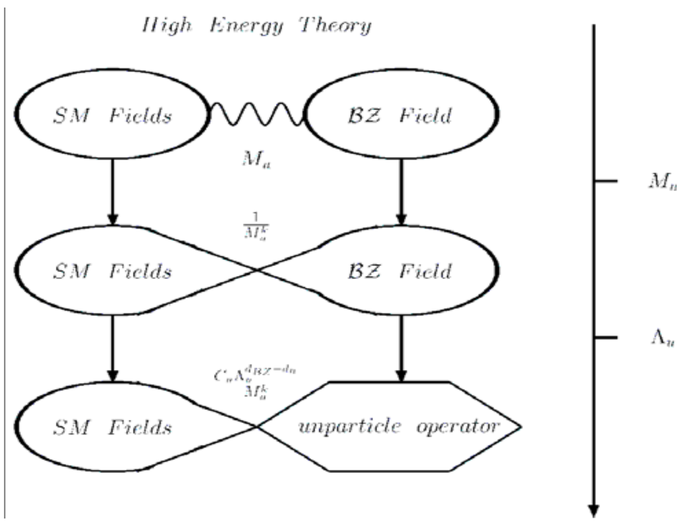
- **Georgi showed the phase space formula and the propagator of unparticle**

$$\left|\langle 0|O_U(0)|P\rangle\right|^2 \rho(P^2) = A_{d_U}\theta(P^0)\theta(P^2)(P^2)^{d_U-2} \qquad i\frac{A_{d_U}}{2\pi\sin(d_U\pi)}\left(-P^2-i\varepsilon\right)^{d_U-2}$$

- **After Georgi, the unparticle physics is investigated by many group. The interaction**

$$\frac{C_U \Lambda_U{}^{d_{BZ}-d_U}}{M_U{}^k} O_{sm} O_U$$

between the unparticle and SM has much uncertainty. The phenomenology of unparticle physics is very rich.



Phys. Rev. Lett, 98,221601(2007), Phys. Lett. B 650, 275 (2007)

- Follow Georgi, many papers are published from Chinese community soon.

- K. Cheung et al first investigated the signals of an unparticle at the colliders.
  PRL99, 051803 (2007),
  PRD76, 055003 (2007)

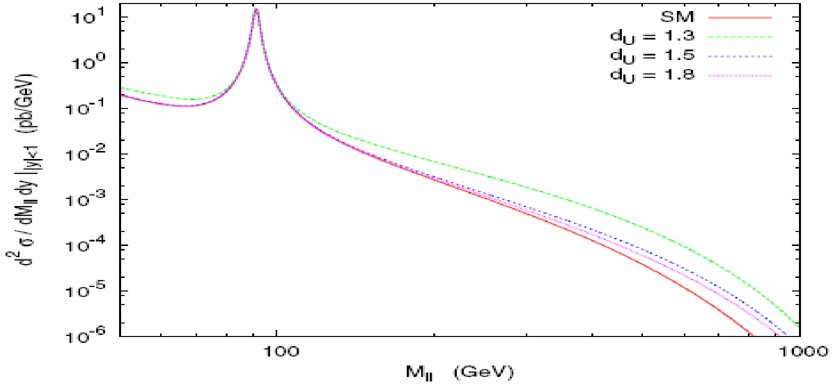
- Recently, the process of Higgs decays into a photon plus an unparticle has been investigated.
  K. Chueng, C. S. Li and T.C. Yuan, arXiv:0711.3361[hep-ph]

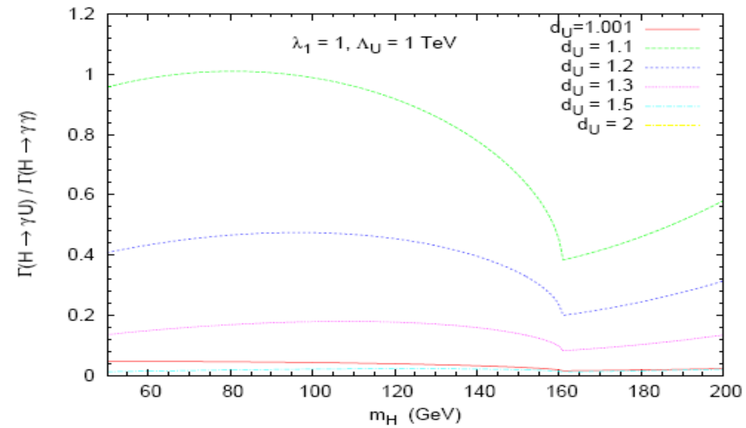
• SUSY and Unparticle

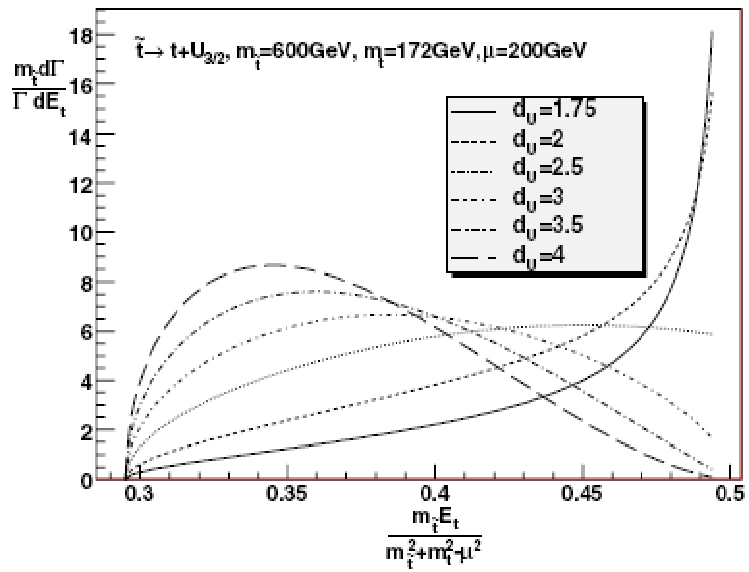
- We showed a natural form of the interaction between the unparticle and SUSY and discussed its phenomenology.

$$C_U \frac{\Lambda_U{}^{d_{BZ}-d_U}}{M_U{}^k} \bar{S}_\mu U^\mu{}_{3/2}$$

H. Zhang, C. S. Li and Z. Li, PRD76, 116003 (2007)

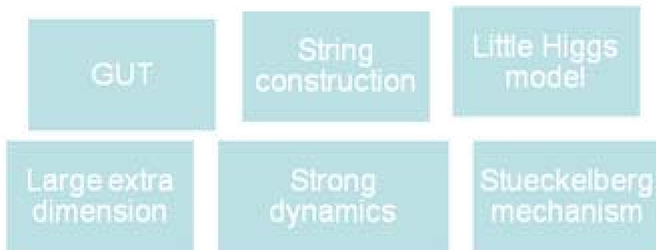


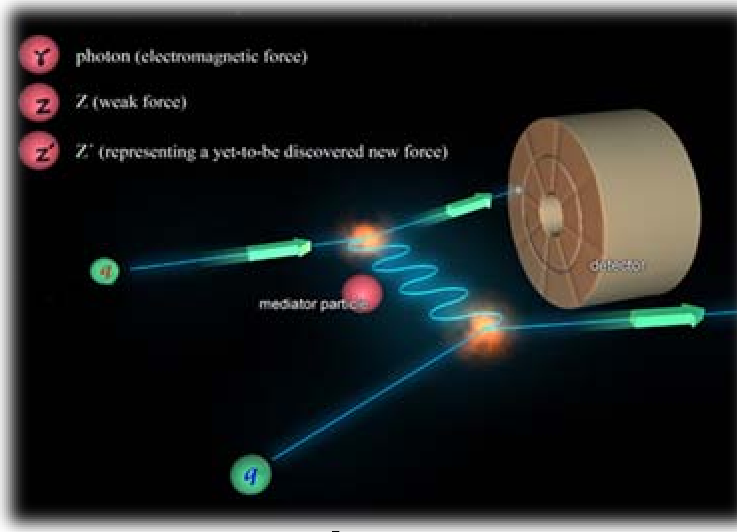




6. Extra Z Boson

- **Z': Why Theorists favour it?**
  - **U(1)' factors are extremely common in BSM :**





  - **The most economical extension of SM gauge group!**

- **Has nature ordered it?**

- **Many physicists believe that all the fundamental interactions should be unified at some Grand Unified Theory (GUT) energy scale. The physics at that scale was governed by a GUT gauge group.**
- **The GUT gauge group G must be broken to retain the SM gauge symmetry**
- $SU(3)\times SU(2)\times U(1)_Y$ **at low energy.**
- **Examples:**

$$E_6 \to SO(10)\times U(1)_\psi$$

$$SO(10) \to SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X$$
$$\to SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

● Basic Issues about Z' Physics

- **The most economical extension of SM:** $SU(3)_c \times SU(2)_L \times U(1)_Y \times U'(1)$
- **The neutral current can be generically written as**

$$-\mathscr{L}_{\rm NC} = eA_\beta J_\gamma^\beta + g_1 Z_\beta J_Z^\beta + g_2 Z'_\beta J_{Z'}^\beta$$

It contains the currents

$$J_\gamma^\beta = \sum_f \bar{f}\gamma^\beta v_f(0) f, \quad J_Z^\beta = \sum_f \bar{f}\gamma^\beta[v_f - \gamma_5 a_f] f, \quad J_{Z'}^\beta = \sum_f \bar{f}\gamma^\beta[v'_f - \gamma_5 a'_f] f$$

Where f is the SM fermions.

- **In general, there will be mass mixing between Z and Z'**

$$\mathscr{L}_M = \frac{1}{2}(Z, Z')M_{ZZ'}^2\begin{pmatrix} Z \\ Z' \end{pmatrix}, \quad M_{ZZ'}^2 = \begin{pmatrix} M_Z^2 & \delta M^2 \\ \delta M^2 & M_{Z'}^2 \end{pmatrix}$$

- **We can diagonalize the mass matrix by a rotation:**

$$\begin{pmatrix} Z_1 \\ Z_2 \end{pmatrix} = \begin{pmatrix} c_M & s_M \\ -s_M & c_M \end{pmatrix}\begin{pmatrix} Z \\ Z' \end{pmatrix}$$

- **The mass of the mass eigenstates are**

$$M_{1,2}^2 = \tfrac{1}{2}[M_Z^2 + M_{Z'}^2 \pm \sqrt{(M_Z^2 - M_{Z'}^2)^2 + 4(\delta M^2)^2}]$$

- **LEP 1 and SLC performed precision measurements of the mass eigenstate** Z_1 **.**

• Singlet extensions of the MSSM

- **In MSSM, there is an unnatural μ term:**

$$W = \mu H_u H_d$$

- **Problem: no symmetry to protect μ from radiative correction— Hierarchy !**
- **In the U(1)' extension of MSSM, the U(1)' symmetry naturally forbid an elementary μ term, but allows a trilinear superpotential coupling**

$$W = \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d$$

- **Where S is a complex standard model singlet field which couple to U(1)' gauge boson.**

- **The extended models can have interesting consequences in collider phenomenology:**
- **Because of the mixing between singlet S and doublet $H_{U,D}$, The lightest Higgs can be lighter than the LEP limit of m_h> 114 GeV, due to reduced Higgs coupling to SM fields.**
- **Z' decays may be a significant source for the production of sparticles.**

V. Barger et. al., New J. Phys. 9:333(2007)

• Spin measurement and FB asymmetry of Z'

- **After the discovery of a resonance in the dilepton channels, the next step would be to establish its spin-1 nature. This can be done by the angular distribution in the resonance rest frame, which for spin-1 is**

$$\frac{d\sigma^f_{Z'}}{d\cos\theta^*} \propto \frac{3}{8}(1+\cos^2\theta^*) + A^f_{FB}\cos\theta^*$$

- **Forward-Backward asymmetry to distinguish models**

  The FB asymmetry of the vector boson contain the informations of the charge assignments: useful in identifying gauge boson!

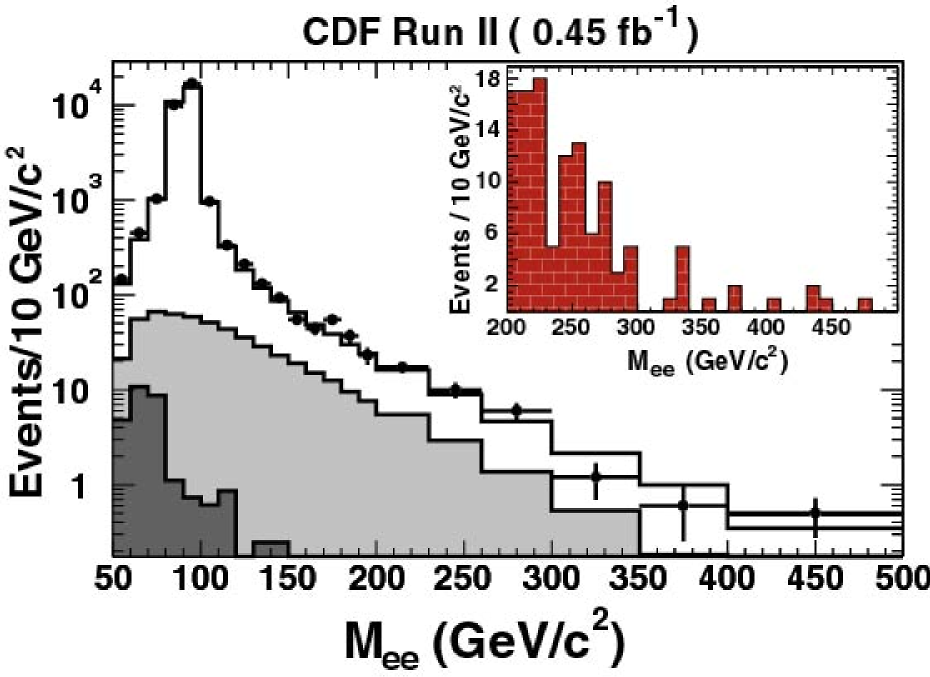
  Forward-backward asymmetry is defined as:

$$A^{i,f}_{FB} \equiv \frac{N_F - N_B}{N_F + N_B} = \frac{3}{4}\mathcal{A}_i\mathcal{A}_f, \qquad \mathcal{A}_f = \frac{(g^f_L)^2 - (g^f_R)^2}{(g^f_L)^2 + (g^f_R)^2}.$$

- **The leptonic forward-backward asymmetry is sensitive to a combination of quark and lepton chiral couplings and is a powerful discriminator between models.**

• Experimental constraints of Z'

The most recent Fermilab result on dielectron search of Z' (from the [Fermilab Today of Mar. 9, 2006]())



• The possible discovery channel of Z':

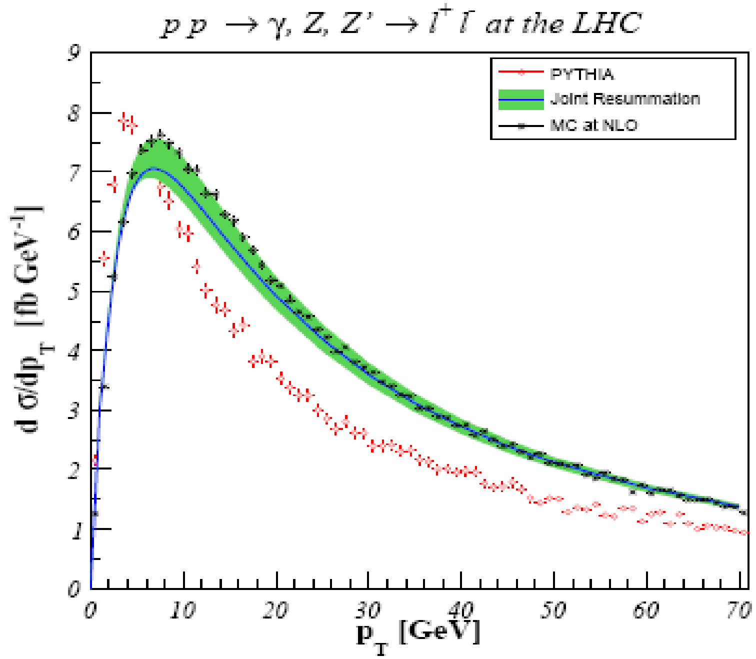
the dilepton channel provides very clean signals for discovery without much background. If we observe a spin-1 resonance peak ($\gg M_z$) in difermion channels, it may be Z'.

$M_{Z'}$ Lower Mass limits (GeV/c^2)

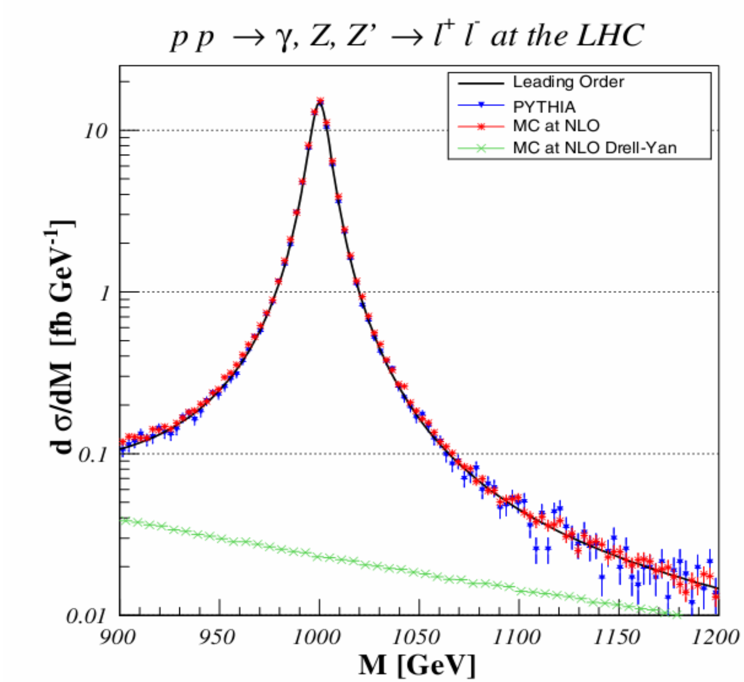
Model	ee	μμ	ll (Run I)
Z'_{SM}	770	740	825 (690)
Z'_ψ	645	585	675
Z'_χ	630	605	690
Z'_η	675	640	720
Z'_I	570	540	615

• Theoretical predictions improvement for Z' production

• **Recently, theoretical predictions for the production of extra neutral gauge bosons at hadron colliders have improved by implementing the Z' bosons in the MC@NLO generator and computing their differential and total cross sections in joint p_T and threshold resummation.**



•**This analysis lead to more precise determinations or limits of the Z' boson masses and couplings at hadron colliders.**



Qiang Li , M. Klasen et al. ,
Nucl.Phys.B797:322-339,2008

7. Model independent FCNC Couplings of Top quark

- Single top quark production as a probe of New Physics
- D0 recently reported[1] evidence for the production of single top quarks at significance of 3.4 standard deviations:
- Using a 0.9fb^{-1} dataset, D0 collaboration applies a multivariate analysis to separate signal from background and measure

$$\sigma(p\overline{p} \to tb + X, tqb + X) = 4.9 \pm 1.4\, pb$$

- Using the cross section measurement to directly determine the Cabibbo-Kobayashi-Maskawa matrix element that describes the Wtb coupling, they find

$0.68 < |V_{tb}| \leq 1$ at 95% C.L. within the standard model

[1] D0 collaboration, Phys. Rev. Lett 98, 181802(2007)

- This discovery created many new fields, especially, for searching new physics beyond SM.
- New physics can influence single-top quark production by inducing non-SM interactions via loop effects[2-4], or by providing new sources of single-top quark events.

[2] C.S. Li, R.J. Oakes, and J.M. Yang, Phys. Rev. D55, 1672(1997);

[3] C.S.Li R.J. Oakes, and J.M. Yang, Phys. Rev. D55,5780 (1997);

[4] C.S.Li R.J. Oakes, J.M. Yang, and H.Y. Zhou, Phys. Rev. D57,2009 (1998);

- Two kinds of methods to study new physics effects in FCNC processes:

1. Direct calculation in a specific new physics model.

   We studied top quark FCNC decay and production processes in the MSSM. Under the constraints from current experiments, the BRs of $t \to CV(V = g, \gamma, Z)$ can reach 10^{-4}, 10^{-6} and 10^{-6}, respectively. This indicates that the LHC may observe $t \to c\, g$ and $t \to c\, \gamma$ decays.

   ([5] C. S. Li, R. J. Oakes, J. M. Yang, Phys. Rev. D 49, 293,1994;
   [6] J. J. Liu, C. S. Li, L. L. Yang and L. G. Jin, Phys. Lett. B 599, 92,2004;
   [7] J. J. Liu, C. S. Li, L. L. Yang and L. G. Jin, Nucl. Phys. B705, 3,2005)

2. Model-independent effective Lagrangian method, where new physics contributions present in some anomalous couplings.

- Since we do not know which type of new physics will be responsible for a future deviation from the SM predictions, it is necessary to study the top quark FCNC production at the LHC in a model-independent way.

- It should be noted that very recent data from D0 collaboration has set upper limits on the top quark FCNC couplings[8].

[8] D0 Collaboration, Phys. Rev. Lett. 99,191802(2007)

The upper limits on the anomalous coupling parameters at 95% C.L. are:

$$\kappa^c{}_g / \Lambda < 0.15 \mathrm{TeV}^{-1}$$

$$\kappa^u{}_g / \Lambda < 0.037 \mathrm{TeV}^{-1}$$

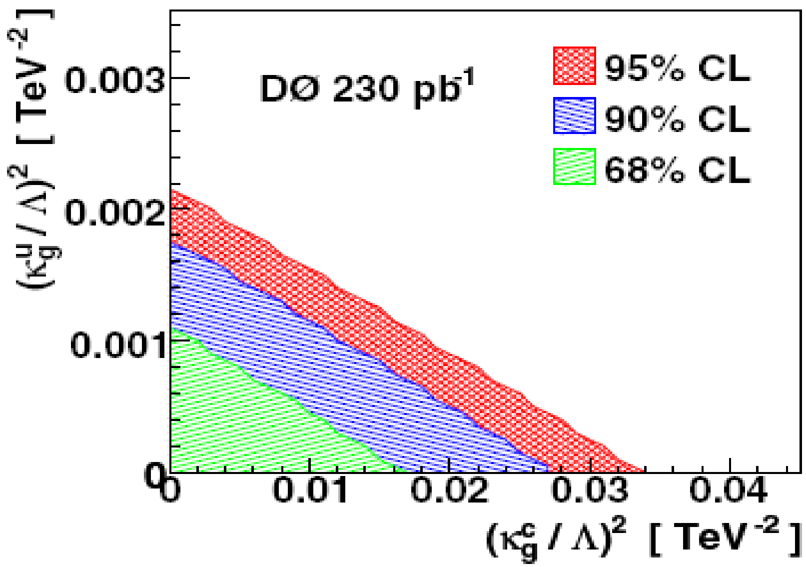


FIG. 3 (color online). Exclusion contours at various levels of confidence using 230 pb^{-1} of D0 data in both the electron and muon channels.

- **Single top quark production via anomalous couplings**

- Any new physics effect involved in top quark FCNC processes can be incorporated into an effective Lagrangian in a model independent way:

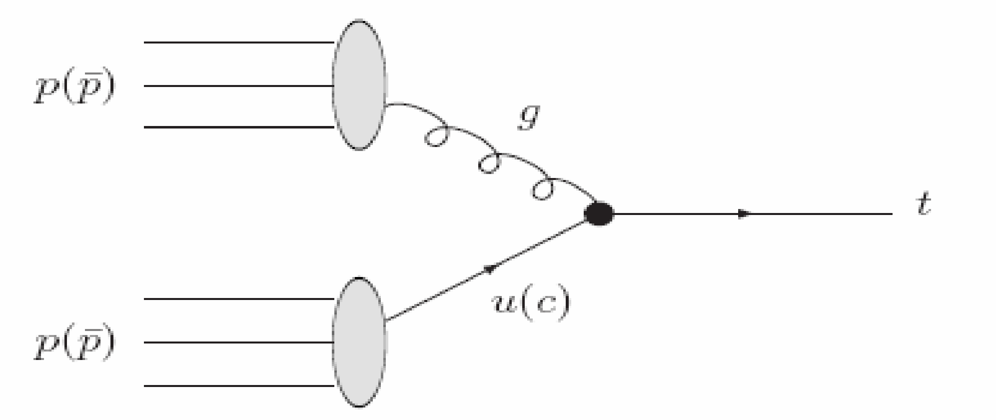
$$\mathcal{L}^{\rm eff} = -\frac{g}{2\cos\theta_W}\sum_{q=u,c}\bar{t}\gamma^\mu(v^Z_{tq} - a^Z_{tq}\gamma_5)qZ_\mu - \frac{g}{2\cos\theta_W}\sum_{q=u,c}\frac{\kappa^Z_{tq}}{\Lambda}\bar{t}\sigma^{\mu\nu}(f^Z_{tq} + ih^Z_{tq}\gamma_5)qZ_{\mu\nu}$$
$$-e\sum_{q=u,c}\frac{\kappa^\gamma_{tq}}{\Lambda}\bar{t}\sigma^{\mu\nu}(f^\gamma_{tq} + ih^\gamma_{tq}\gamma_5)qA_{\mu\nu} - g_s\sum_{q=u,c}\frac{\kappa^g_{tq}}{\Lambda}\bar{t}\sigma^{\mu\nu}T^a(f^g_{tq} + ih^g_{tq}\gamma_5)qG^a_{\mu\nu} + \text{h.c.}\,(1)$$

where Λ is the new physics scale, κ is normalized to be real and positive and f, h to be complex numbers satisfying for each term $|f|^2 + |h|^2 = 1$.

- The top quark FCNC processes induced by various anomalous couplings have been studied in detail[5,6,7]. In general, top quark decay processes provide the best place to discover top FCNC interactions involving anomalous $t-q-\gamma$ and $t-q-Z$ couplings. However, for $t-q-g$ anomalous couplings, the direct top quark production processes are the most sensitive ones[9,10,11,12].

[5]. C.S.Li, R.J. Oakes, J.M.Yang, Phys.RevD49, 293(1994);
[6]. J.J.Liu, C.S.Li, L.L. Yang, and L.G. Jin Phys. Lett. B599,92(2004)
[7]. J.J.Liu, C.S.Li, L.L. Yang, and L.G. Jin Nucl. Phys. B705,3(2005)
[9] J.A. Aguilar-Saavedra, Acta Phys. Polon. B 35, 2695 (2004).
[10] T. Han, M. Hosch, K. Whisnant, B.-L. Young, and X. Zhang, Phys. Rev. D 58, 073008 (1998); M. Hosch, K. Whisnant, and B.-L. Young, Phys. Rev. D 56, 5725 (1997).
[11] J.J. Liu, C.S.LI and L.L. Yang, Phys.Rev. D72,074018 (2005);
[12] L.L.Yang, C.S.Li, Y.Gao, and J.J. Liu, Phys.Rev.D73, 074017(2006)

- **Direct top quark production**



- This is the most sensitive process to t-g-c anomalous couplins.

- The analysis based on the leading order cross sections suggests that the anomalous couplings can be detected down to 0.019/ TeV for q=u and 0.016/TeV for q=c at the Tevatron Run2, respectively.
  (M. Hosch et al., PRD56,5725(1997),T. Han et al., PRD58, 073008(1998))

- Studies with a fast detector simulation for ATLAS indicate a similar reach at the LHC (O.Cakir et al., J. Phys.G31,N1(2005))

- **Direct top quark production**

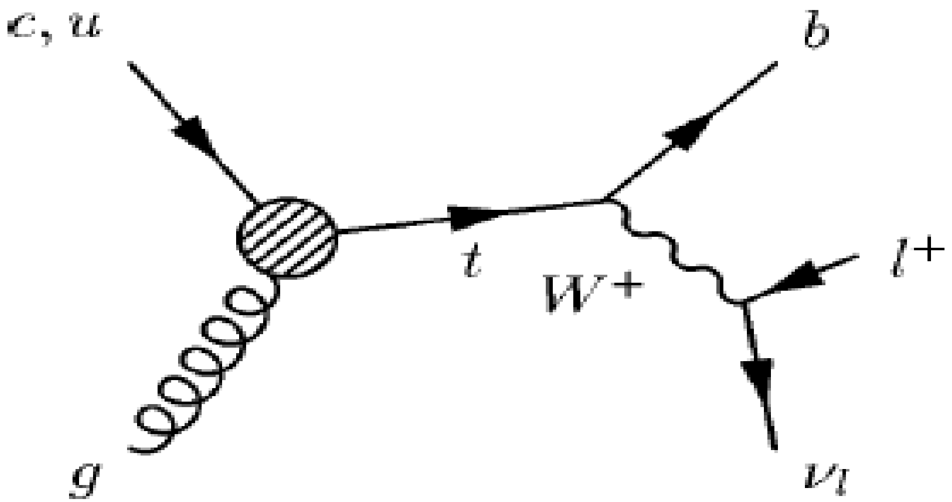


FIG. 1. Feynmann diagram for direct top quark production and subsequent decay into $b\,l\,\nu_l$.

The major source of background to this is the W+jet production. The additional background due to single top production, when the associated jets are not observed, should not exceed 20% of the total background and was therefore ignored (M. Beneke et al., top quark physics, published in the Report of the 1999 CERN Workshop on SM physics at the LHC, hep-ph/0003033)

• Numerical results of leading order[10]

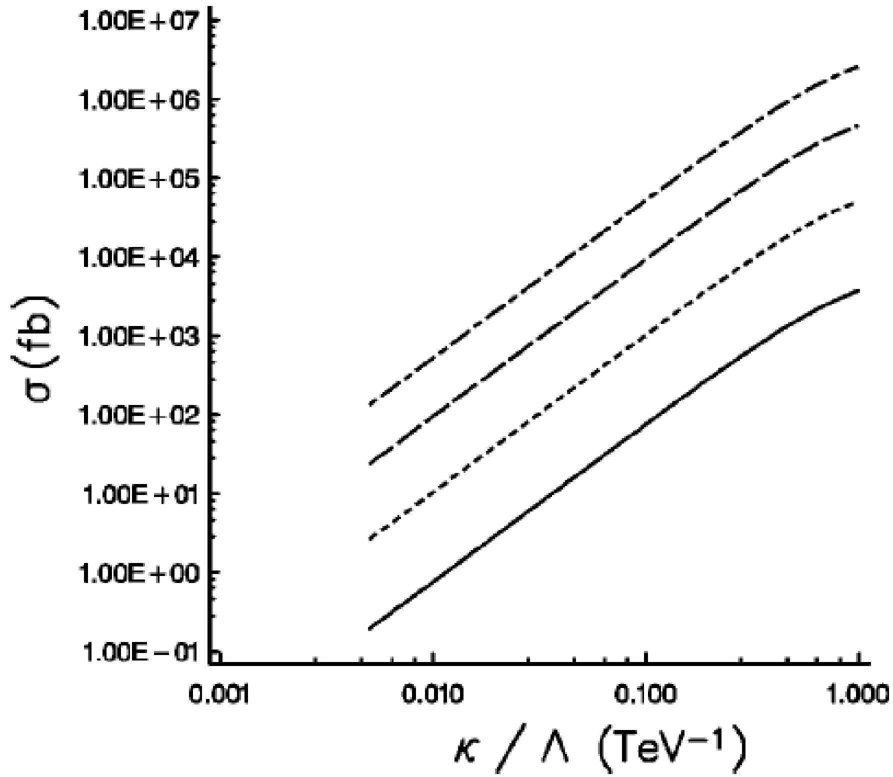


FIG. 1. Cross sections for single top-quark production $pp(\overline{p}) \to tj$ versus κ_f/Λ at the Tevatron and LHC. The solid and short dashed lines are for the $\overline{t}cg$ and $\overline{t}ug$ coupling at the Tevatron, respectively. The long dashed and dash-dotted lines are at the LHC.

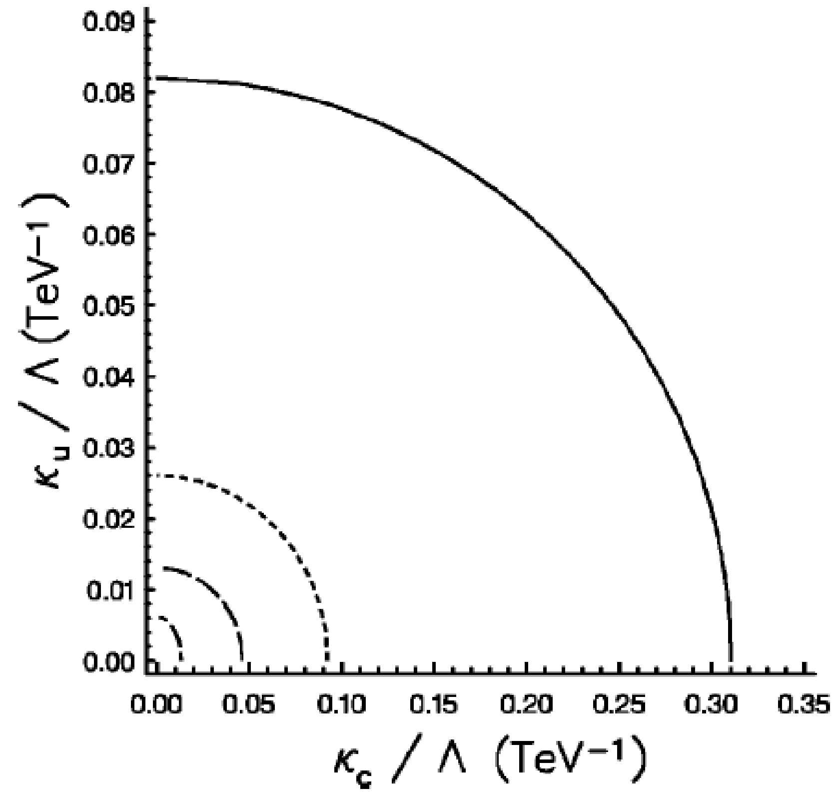


FIG. 6. Discovery limits for κ_c/Λ versus κ_u/Λ for each of the collider options considered. The solid, short dashed, and long dashed lines are at Runs 1, 2, and 3 at the Tevatron respectively. The dash-dotted line is at the LHC.

• NLO QCD corrections

J.J. Liu, C.S.LI and L.L. Yang, Phys.Rev. D72,074018 (2005):

Numerical results

subprocess	LHC (LO)	LHC (NLO)	Tevatron Run 2 (LO)	Tevatron Run 2 (NLO)
$gu \to t$	11069.8	16817.8	259.0	412.6
$gc \to t$	1817.1	2536.6	17.6	28.3

TABLE I: The LO and NLO cross sections of direct top quark production via anomalous FCNC couplings at the LHC and Tevatron Run 2 (fb). Here $\frac{\kappa^g_{tq}}{\Lambda} = 0.01\ \mathrm{TeV}^{-1}$ and $\mu_F = \mu_r = m_t$.

- The NLO QCD corrections results increase the experimental sensitivity to the anomalous couplings. Our results show that the NLO QCD corrections enhance the LO total cross sections at the Tevatron Run 2 about 60% for both κ^g_{tc} and κ^g_{tu} couplings, and enhance the LO total cross sections at the LHC about 40% for κ^g_{tc} couplings and 50% for κ^g_{tu} couplings, respectively.

• Threshold resummation effects

L.L.Yang, C.S.Li, Y. Gao, and J.J. Liu, PRD,73, 074017(2006)

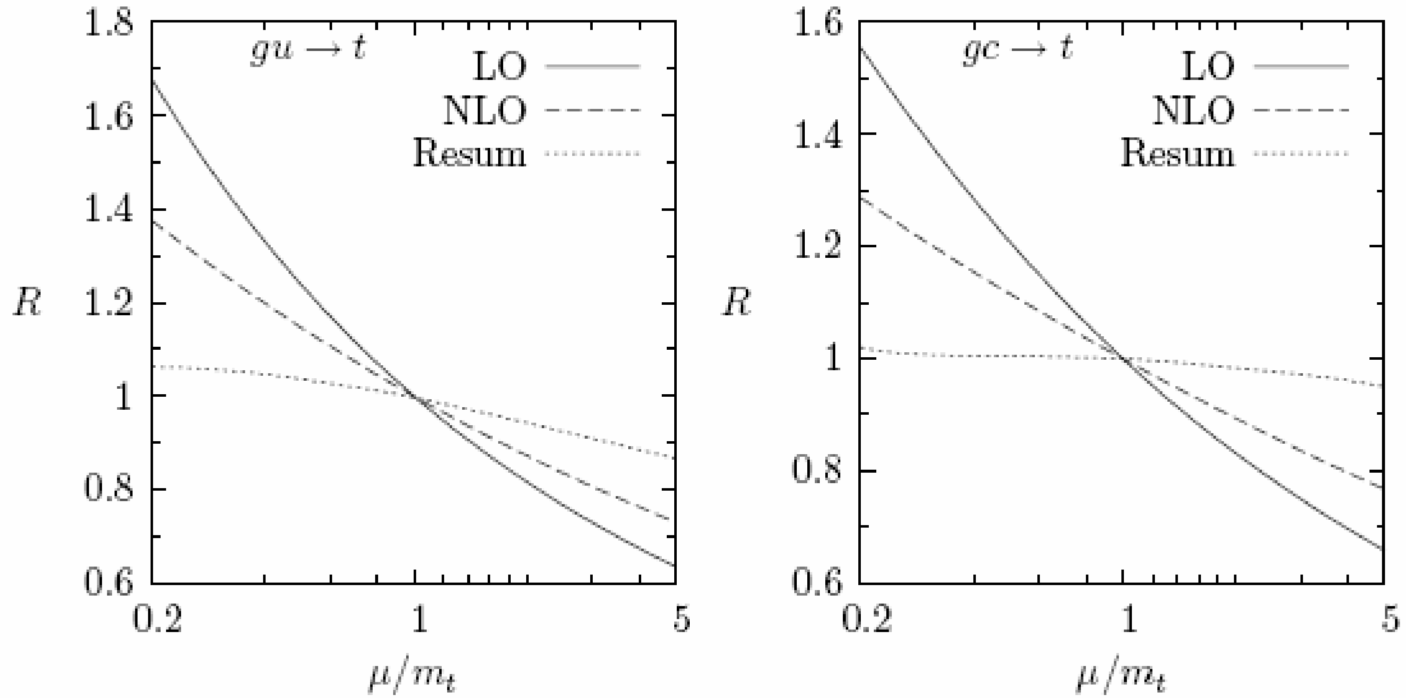
Numerical results

subprocess	PDF	LHC $\left(\frac{\kappa/\Lambda}{0.01\mathrm{TeV}^{-1}}\right)^2$ pb			Tevatron $\left(\frac{\kappa/\Lambda}{0.01\mathrm{TeV}^{-1}}\right)^2$ fb		
		LO	NLO	Resum	LO	NLO	Resum
$gu \to t$	CTEQ	12.9	17.0	23.7	268	425	547
	MRST	12.2	16.3	19.5	262	426	520
$gc \to t$	CTEQ	1.71	2.53	3.71	13.1	28.1	38.2
	MRST	1.68	2.38	2.92	17.0	30.3	38.6

Here $\mu_r = \mu_f = m_t$.

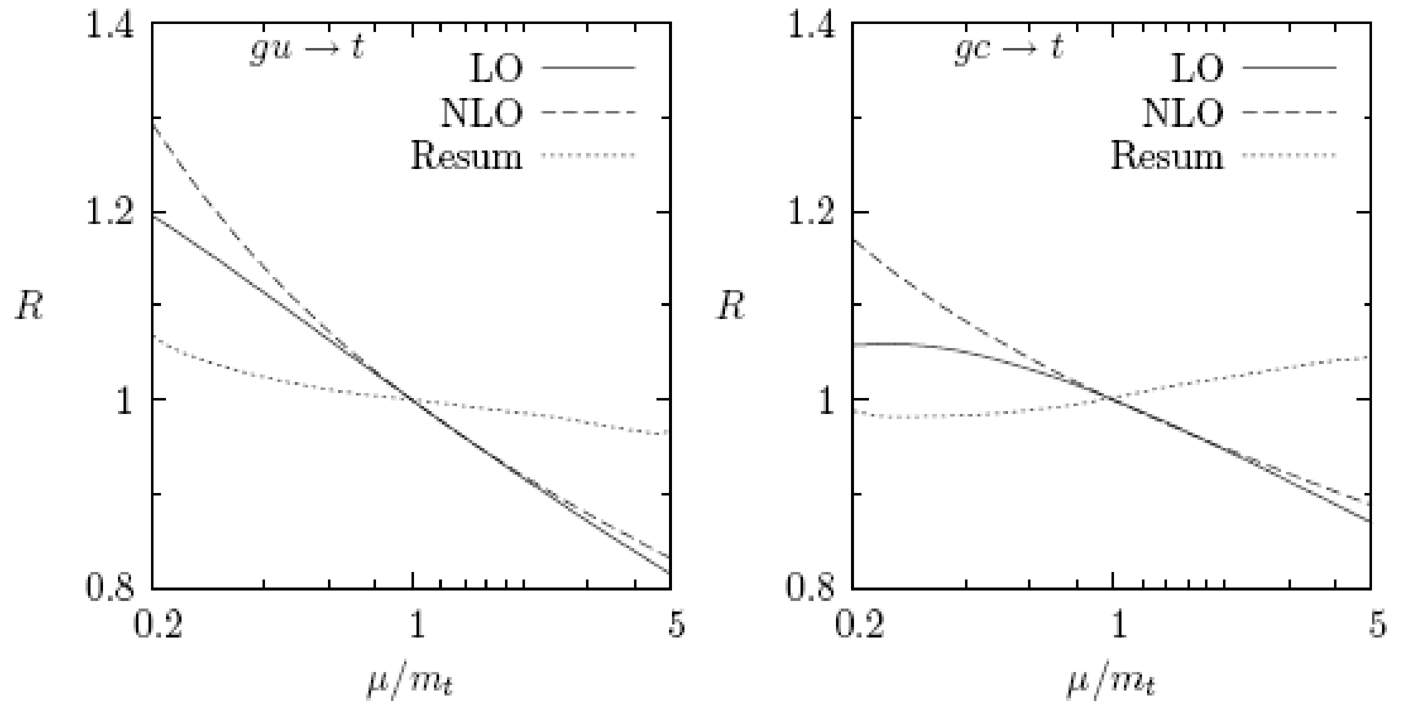
- The resummation effects further increase the NLO cross sections.
- The discrepancies between the different PDF sets are still large. These have to be improved by the fitting groups.

Scale dependence: Tevatron Run II



- NLO QCD corrections reduce the scale dependence of the cross sections.
- Threshold resummation effects further reduce such dependence, and make the theoretical predictions more reliable.

Scale dependence: LHC



- NLO corrections can not reduce the scale dependence of the cross sections. In the region $\mu < m_t$, the behavior of NLO results are even worse than that of the LO ones.
- Threshold resummation effects significantly reduce the scale dependence and improve the precision of the predictions.

8.Summary

- Higgs will surely be discovered by LHC, if Higgs exists.

- Various new physics models (Supersymmetry, Extra Dimension, etc.) all have definite signals at LHC, and LHC has the ability to discover them.

- High order QCD effects play an indispensable role in searching for new physics at LHC.

- It is necessary to include the QCD NLO (even resummation) effect in the simulation of the signals and background of new physics at the LHC.

- Distinguishing different extensions of the SM and making precise measurement of the new physics parameters with high accuracy may depend on future ILC.

Thanks!