Collider Phenomenology
— From basic knowledge
to new physics searches

Tao Han
University of Wisconsin – Madison

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Outline:

Lecture I: Colliders and Detectors

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Lecture II: Basics Techniques and Tools

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(b). Perturbative QCD at Hadron Colliders
(c). Hadron Colliders Physics

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Lecture IV: From Kinematics to Dynamics

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Main reference: TASI 04 Lecture notes
hep-ph/0508097,
plus the other related lectures in this school.

IV. From Kinematics to Dynamics

(A). Characteristic observables:

Crucial for uncovering new dynamics.

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Selective experimental events

$\Longrightarrow$ Characteristic kinematical observables

(spatial, time, momentaum phase space)

$\Longrightarrow$ Dynamical parameters

(masses, couplings)

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(A). Characteristic observables: Crucial for uncovering new dynamics.

Selective experimental events
$\Longrightarrow$ Characteristic kinematical observables
(spatial, time, momentaum phase space)
$\Longrightarrow$ Dynamical parameters
(masses, couplings)

Energy momentum observables $\Longrightarrow$ mass parameters
Angular observables $\Longrightarrow$ nature of couplings;
Production rates, decay branchings/lifetimes $\Longrightarrow$ interaction strengths.

(B). Kinematical features:

(a). s-channel singularity: bump search we do best.

- invariant mass of two-body $R \to ab$: $m_{ab}^2 = (p_a + p_b)^2 = M_R^2$.

combined with the two-body Jacobian peak in transverse momentum:

$$\frac{d\hat{\sigma}}{dm_{ee}^2 \; dp_{eT}^2} \propto \frac{\Gamma_Z M_Z}{(m_{ee}^2 - M_Z^2)^2 + \Gamma_Z^2 M_Z^2} \; \frac{1}{m_{ee}^2 \sqrt{1 - 4p_{eT}^2/m_{ee}^2}}$$

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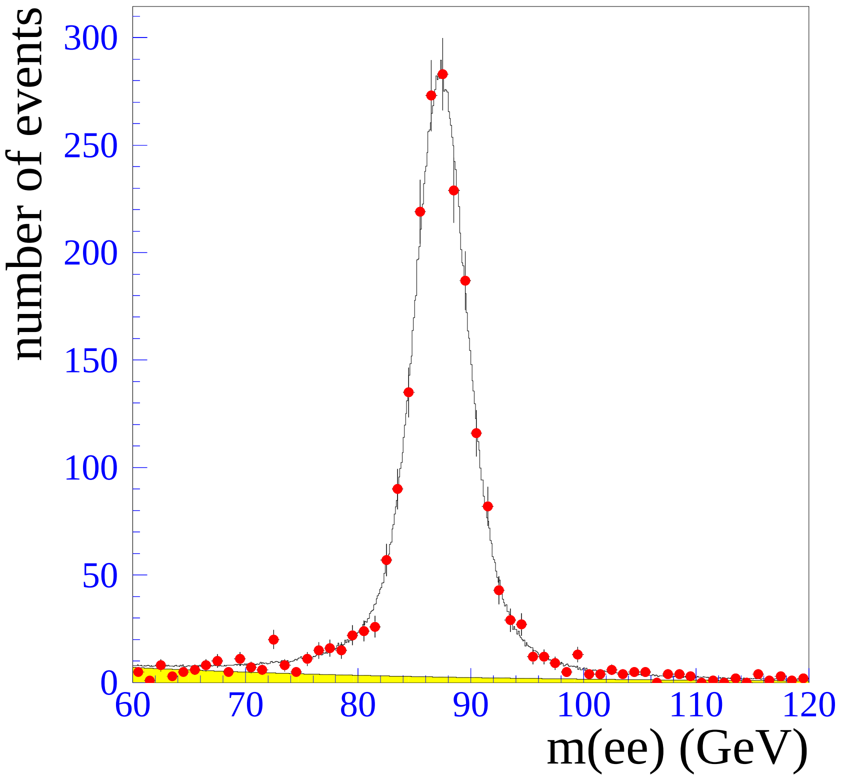
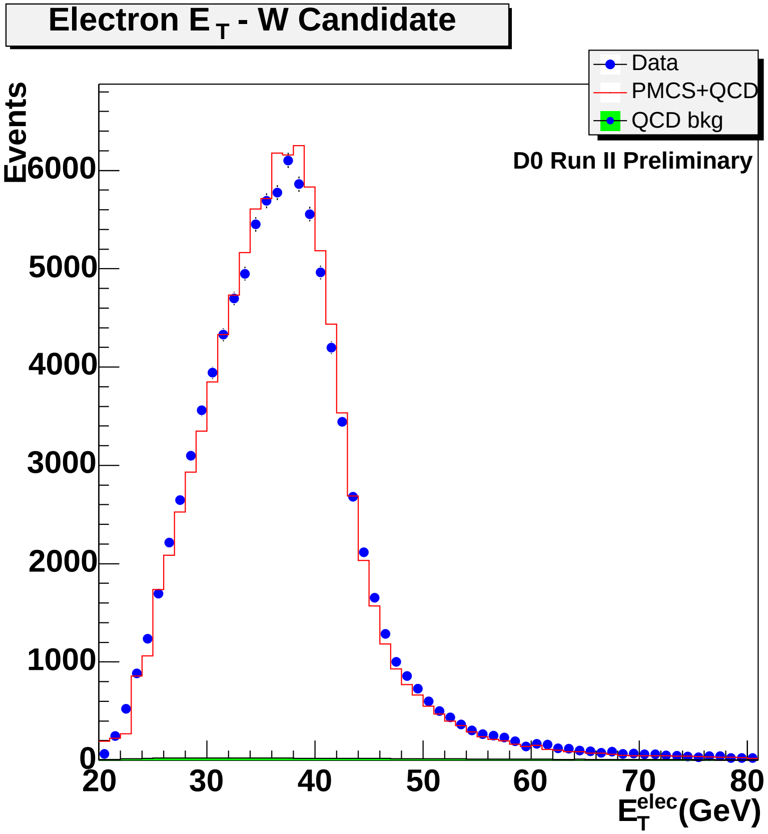


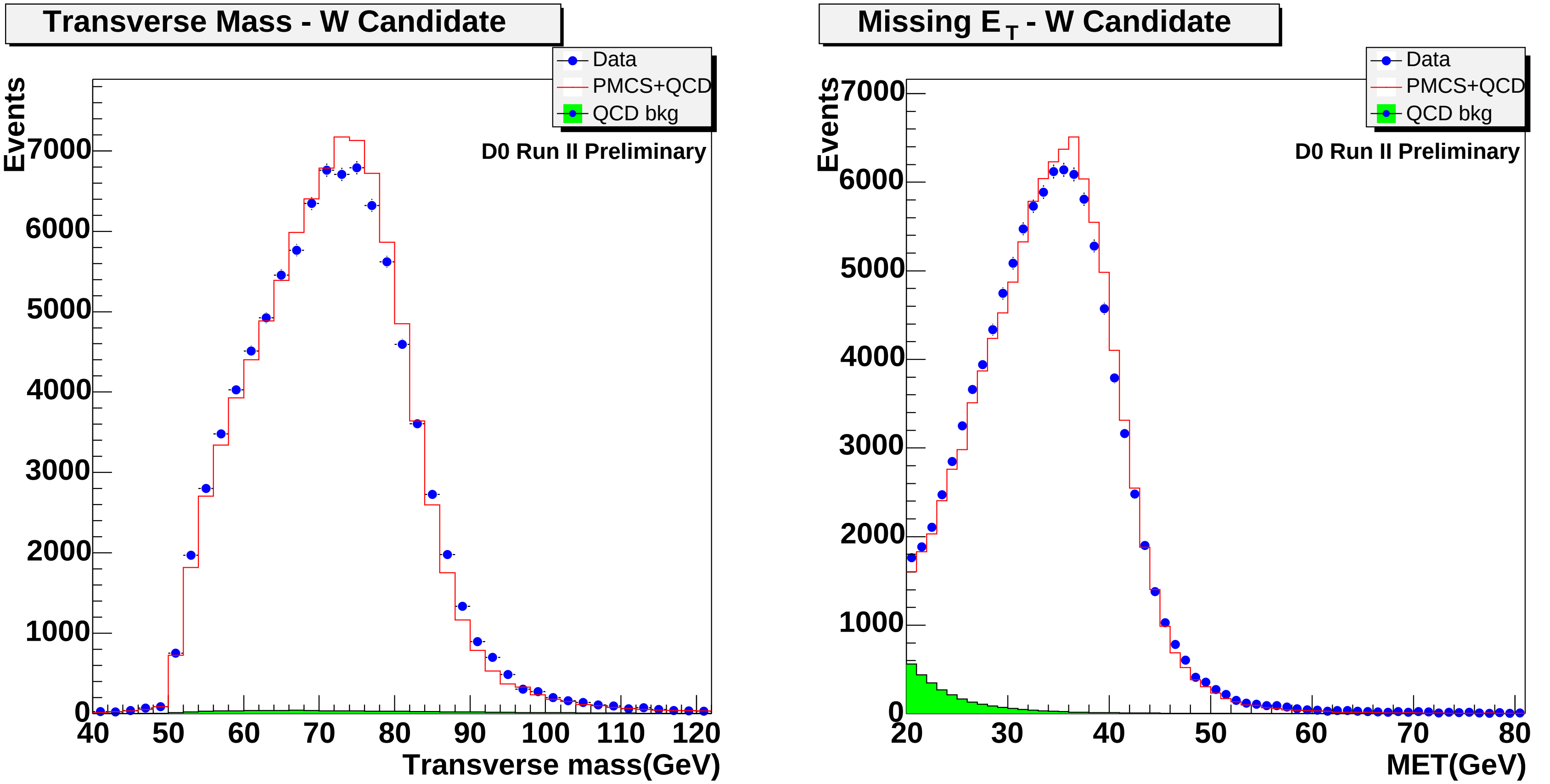
$Z \to e^+e^-$



$W \to e\nu$

- “transverse” mass of two-body $W^- \to e^- \bar{\nu}_e$:

$$\begin{aligned} m^2_{e\nu\ T} &= (E_{eT} + E_{\nu T})^2 - (\vec{p}_{eT} + \vec{p}_{\nu T})^2 \\ &= 2E_{eT}E_T^{miss}(1 - \cos\phi) \le m^2_{e\nu}. \end{aligned}$$



If $p_T(W) = 0$, then $m_{e\nu\ T} = 2E_{eT} = 2E_T^{miss}$.

Exercise 5.1: For a two-body final state kinematics, show that

$$\frac{d\hat{\sigma}}{dp_{eT}} = \frac{4p_{eT}}{s\sqrt{1-4p_{eT}^2/s}}\ \frac{d\hat{\sigma}}{d\cos\theta^*}.$$

where $p_{eT} = p_e \sin\theta^*$ is the transverse momentum and θ^* is the polar angle in the c.m. frame. Comment on the apparent singularity at $p_{eT}^2 = s/4$.

Exercise 5.2: Show that for an on-shell decay $W^- \to e^-\bar{\nu}_e$:

$$m_{e\nu\ T}^2 \equiv (E_{eT} + E_{\nu T})^2 - (\vec{p}_{eT} + \vec{p}_{\nu T})^2 \le m_{e\nu}^2.$$

Exercise 5.3: Show that if W/Z has some transverse motion, δP_V, then:

$$p'_{eT} \sim p_{eT}\ [1 + \delta P_V/M_V],$$
$$m'^2_{e\nu\ T} \sim m^2_{e\nu\ T}\ [1 - (\delta P_V/M_V)^2],$$
$$m'^2_{ee} = m^2_{ee}.$$

- $H^0 \to W^+W^- \to j_1 j_2\ e^- \bar{\nu}_e$:

cluster transverse mass (I):

$$\begin{aligned} m^2_{WW\ T} &= (E_{W_1 T} + E_{W_2 T})^2 - (\vec{p}_{jjT} + \vec{p}_{eT} + \vec{p}_T^{\,miss})^2 \\ &= (\sqrt{p^2_{jjT} + M^2_W} + \sqrt{p^2_{e\nu T} + M^2_W})^2 - (\vec{p}_{jjT} + \vec{p}_{eT} + \vec{p}_T^{\,miss})^2 \leq M^2_H. \end{aligned}$$

where $\vec{p}_T^{\,miss} \equiv \vec{\not{p}}_T = -\sum_{obs}\ \vec{p}_T^{\,obs}$.

- $H^0 \to W^+W^- \to j_1 j_2\ e^-\bar{\nu}_e$:

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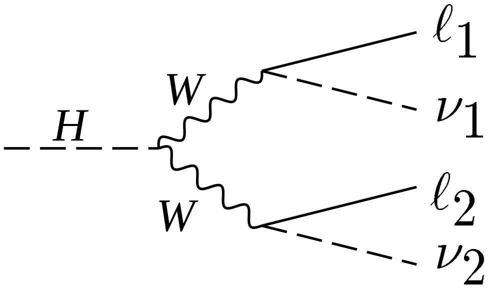

- $H^0 \to W^+W^- \to e^+\nu_e\ e^-\bar{\nu}_e$:

“effecive” transverse mass:

$$\begin{aligned} m^2_{eff\ T} &= (E_{e1T}+E_{e2T}+E_T^{miss})^2 - (\vec{p}_{e1T}+\vec{p}_{e2T}+\vec{p}_T^{\,miss})^2 \\ m_{eff\ T} &\approx E_{e1T}+E_{e2T}+E_T^{miss} \end{aligned}$$

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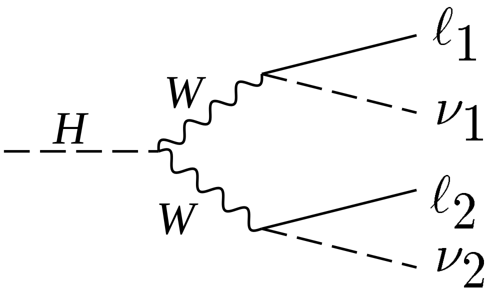

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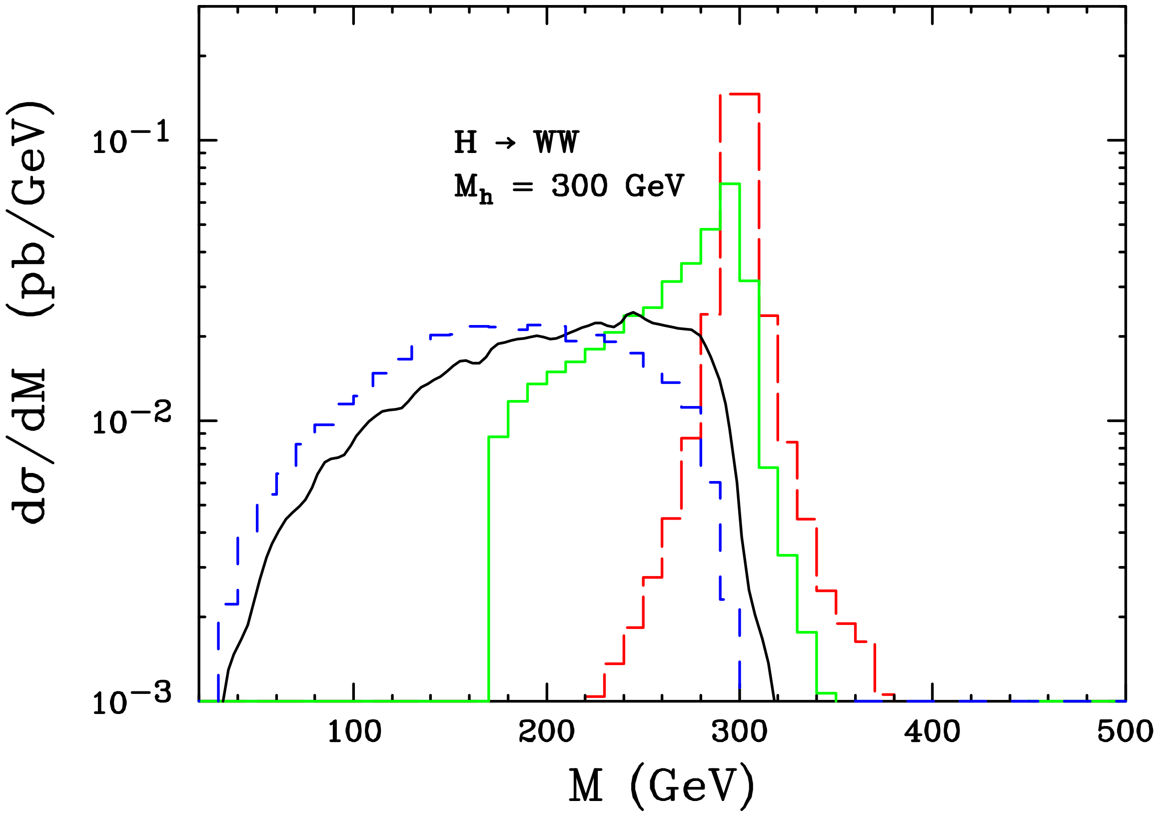
cluster transverse mass (II):

$$\begin{aligned} m^2_{WW\ C} &= \left(\sqrt{p^2_{T,\ell\ell}+M^2_{\ell\ell}}+\not{p}_T\right)^2 - (\vec{p}_{T,\ell\ell}+\vec{\not{p}}_T)^2 \\ m_{WW\ C} &\approx \sqrt{p^2_{T,\ell\ell}+M^2_{\ell\ell}}+\not{p}_T \end{aligned}$$

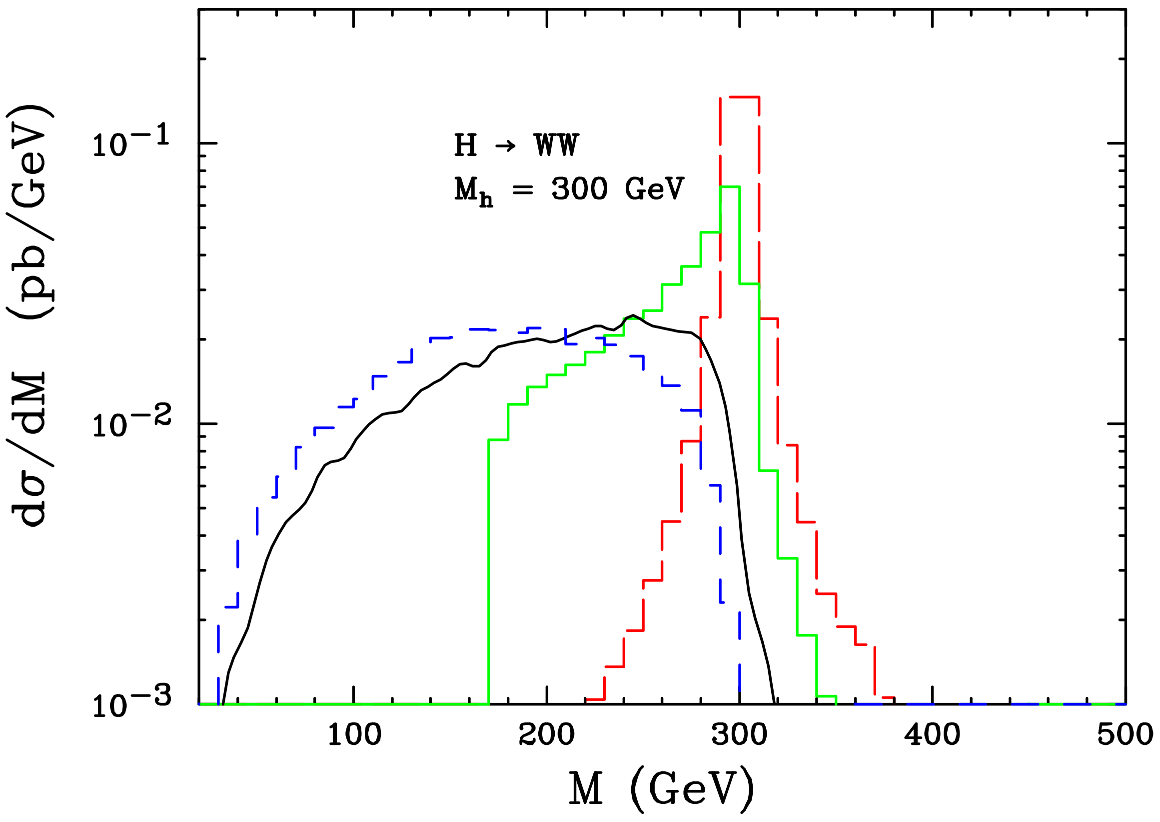


M_{WW} invariant mass (WW fully reconstructable): - - - - - - - - -

$M_{WW,\,T}$ transverse mass (one missing particle ν): ————————

$M_{eff,\,T}$ effetive trans. mass (two missing particles): - - - - - - - -

$M_{WW,\,C}$ cluster trans. mass (two missing particles): ————————



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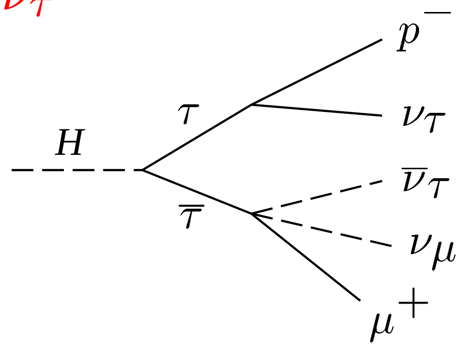
$M_{WW,\ C}$ cluster trans. mass (two missing particles): ————————

YOU design an optimal variable/observable for the search.

- cluster transverse mass (III):

$H^0 \to \tau^+\tau^- \to \mu^+\ \bar{\nu}_\tau\ \nu_\mu, \quad \rho^-\ \nu_\tau$

A lot more complicated with (many) more $\nu's$?



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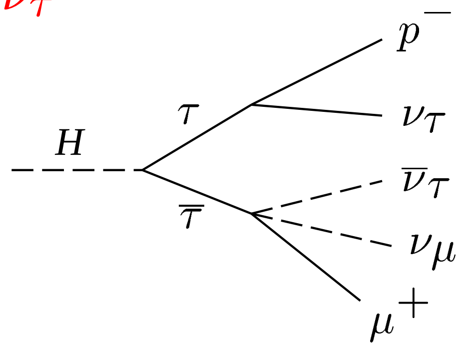

Not really!

$\tau^+\tau^-$ ultra-relativistic, the final states from a τ decay highly collimated:

$$\theta \approx \gamma_\tau^{-1} = m_\tau / E_\tau = 2m_\tau / m_H \approx 1.5^\circ \quad (m_H = 120 \text{ GeV}).$$

We can thus take

$$\begin{aligned} \vec{p}_{\tau^+} &= \vec{p}_{\mu^+} + \vec{p}_+^{\,\nu's}, \quad \vec{p}_+^{\,\nu's} \approx c_+ \vec{p}_{\mu^+}. \\ \vec{p}_{\tau^-} &= \vec{p}_{\rho^-} + \vec{p}_-^{\,\nu's}, \quad \vec{p}_-^{\,\nu's} \approx c_- \vec{p}_{\rho^-}. \end{aligned}$$

where $c_\pm$ are proportionality constants, to be determined.

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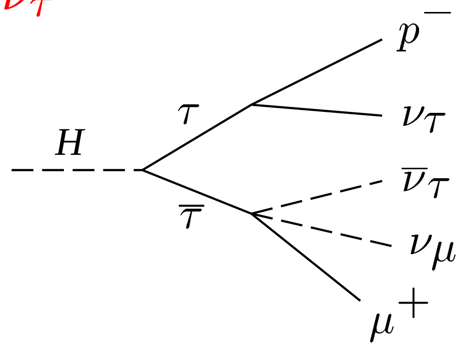

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where $c_\pm$ are proportionality constants, to be determined.

This is applicable to any decays of fast-moving particles, like

$$T \to Wb \to \ell\nu,\ b.$$

Experimental measurements: p_{ρ^-}, p_{μ^+}, $\not{p}_T$:

$$\begin{aligned} c_+(p_{\mu^+})_x + c_-(p_{\rho^-})_x &= (\not{p}_T)_x, \\ c_+(p_{\mu^+})_y + c_-(p_{\rho^-})_y &= (\not{p}_T)_y. \end{aligned}$$

Unique solutions for $c_\pm$ exist if

$$(p_{\mu^+})_x/(p_{\mu^+})_y \neq (p_{\rho^-})_x/(p_{\rho^-})_y.$$

Physically, the τ^+ and τ^- should form a finite angle, or the Higgs should have a non-zero transverse momentum.

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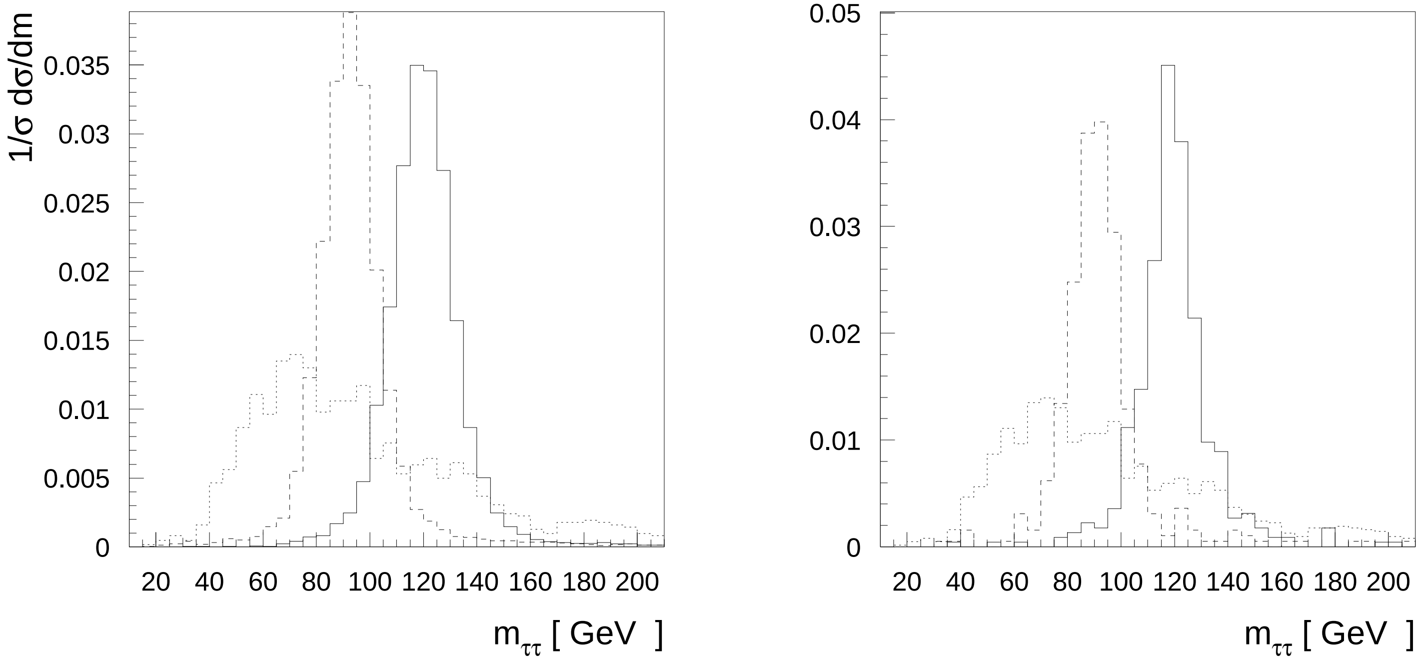

(b). Two-body versus three-body kinematics

- Energy end-point and mass edges:

utilizing the “two-body kinematics”

Consider a simple case:

$$e^+e^- \to \tilde{\mu}_R^+ \; \tilde{\mu}_R^-$$

$$\text{with two} - \text{body decays}: \quad \tilde{\mu}_R^+ \to \mu^+ \tilde{\chi}_0, \quad \tilde{\mu}_R^- \to \mu^- \tilde{\chi}_0.$$

In the $\tilde{\mu}_R^+$-rest frame: $E_\mu^0 = \frac{M^2_{\tilde{\mu}_R} - m^2_\chi}{2M_{\tilde{\mu}_R}}$.

In the Lab-frame:

$$(1-\beta)\gamma E_\mu^0 \le E_\mu^{lab} \le (1+\beta)\gamma E_\mu^0$$

$$\text{with} \quad \beta = \left(1 - 4M^2_{\tilde{\mu}_R}/s\right)^{1/2}, \quad \gamma = (1-\beta)^{-1/2}.$$

Energy end-point: $E_\mu^{lab} \Rightarrow M^2_{\tilde{\mu}_R} - m^2_\chi$.

Mass edge: $m^{max}_{\mu^+\mu^-} = \sqrt{s} - 2m_\chi$.

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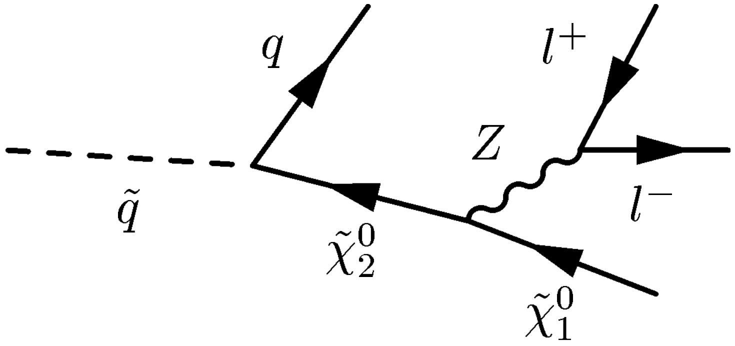
Energy end-point: $E_\mu^{lab} \Rightarrow M_{\tilde{\mu}_R}^2 - m_\chi^2$.

Mass edge: $m_{\mu^+\mu^-}^{max} = \sqrt{s} - 2m_\chi$.

Same idea can be applied to hadron colliders ...

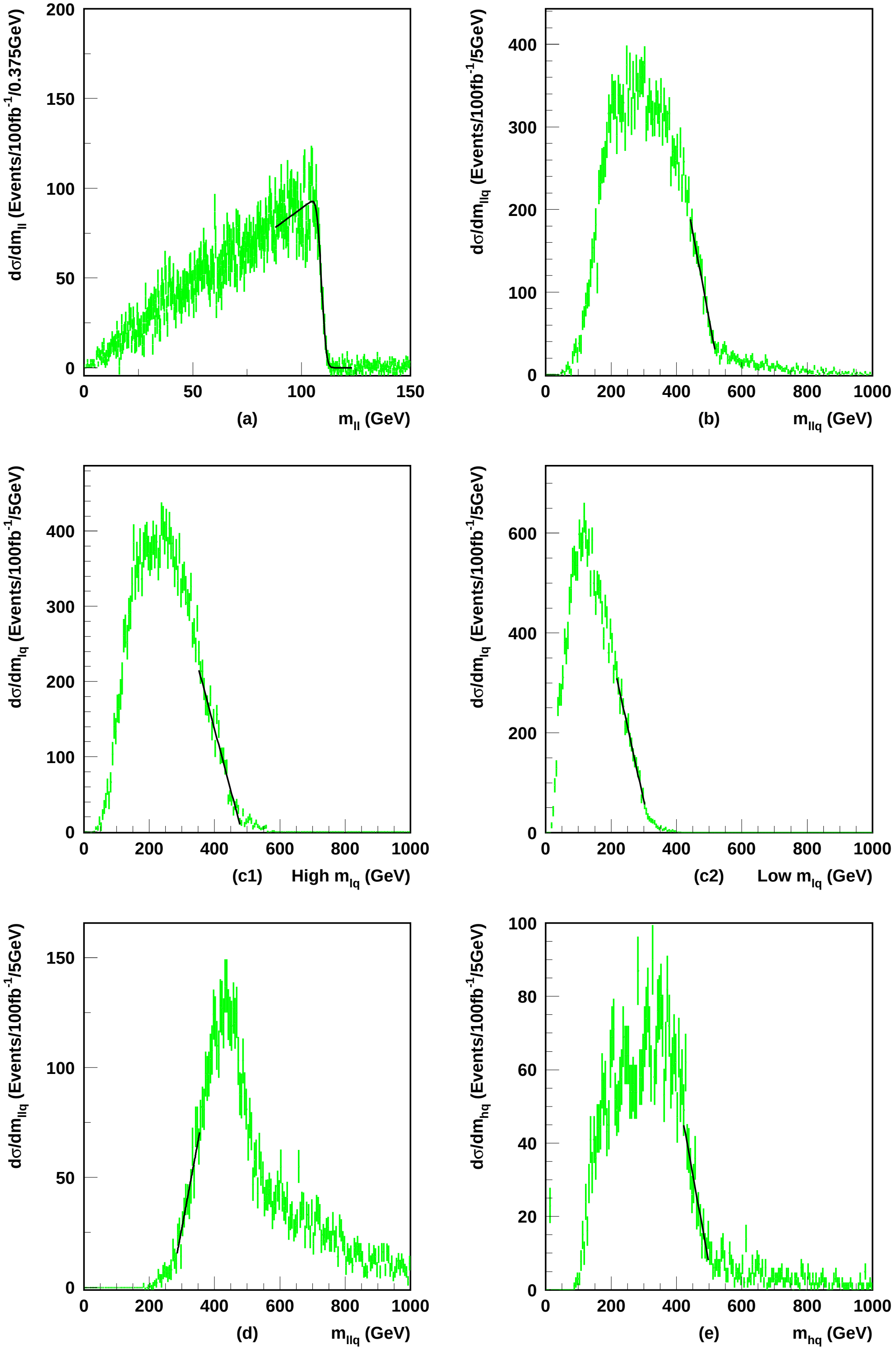
Consider a squark cascade decay:



1st edge : $M^{max}(\ell\ell) = M_{\chi_2^0} - M_{\chi_1^0}$;

2nd edge : $M^{max}(\ell\ell j) = M_{\tilde{q}} - M_{\chi_1^0}$.

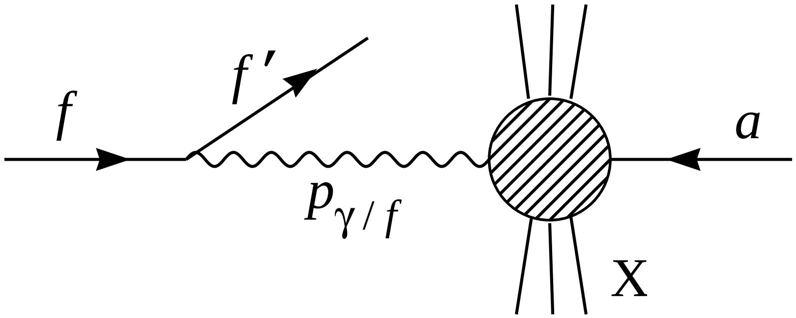
`Exercise 5.4: Verify these relations.`


dσ/dm_ll (Events/100fb^-1/0.375GeV)
200
150
100
50
0
0
50
100
150
(a)
m_ll (GeV)
dσ/dm_llq (Events/100fb^-1/5GeV)
400
300
200
100
0
0
200
400
600
800
1000
(b)
m_llq (GeV)
dσ/dm_lq (Events/100fb^-1/5GeV)
400
300
200
100
0
0
200
400
600
800
1000
(c1)
High m_lq (GeV)
dσ/dm_lq (Events/100fb^-1/5GeV)
600
400
200
0
0
200
400
600
800
1000
(c2)
Low m_lq (GeV)
dσ/dm_llq (Events/100fb^-1/5GeV)
150
100
50
0
0
200
400
600
800
1000
(d)
m_llq (GeV)
dσ/dm_hq (Events/100fb^-1/5GeV)
100
80
60
40
20
0
0
200
400
600
800
1000
(e)
m_hq (GeV)

(c). t-channel singularity: splitting.

- Gauge boson radiation off a fermion:

The familiar Weizsäcker-Williams approximation



$$\sigma(fa \to f'X) \approx \int dx\ dp_T^2\ P_{\gamma/f}(x, p_T^2)\ \sigma(\gamma a \to X),$$

$$P_{\gamma/e}(x, p_T^2) = \frac{\alpha}{2\pi} \frac{1 + (1-x)^2}{x} \left(\frac{1}{p_T^2} \right) |_{m_e}^{E}.$$

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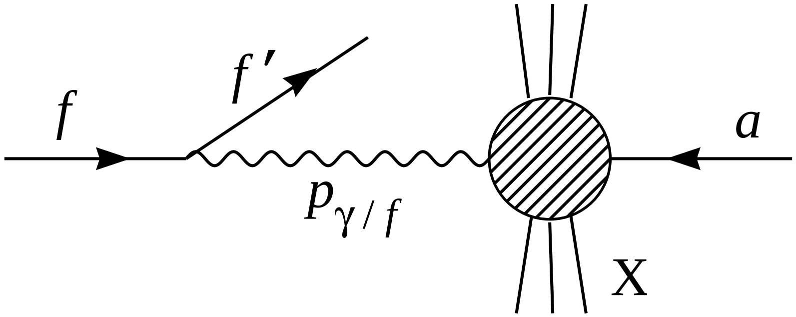

$$\sigma(fa \to f'X) \approx \int dx\ dp_T^2\ P_{\gamma/f}(x, p_T^2)\ \sigma(\gamma a \to X),$$
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† The kernel is the same as $q \to qg^*$ $\Rightarrow$ generic for parton splitting;

† The form $dp_T^2/p_T^2 \to \ln(E^2/m_e^2)$ reflects the collinear behavior.

- Generalize to massive gauge bosons:

$$P^{T}_{V/f}(x,p_T^2) = \frac{g_V^2+g_A^2}{8\pi^2}\,\frac{1+(1-x)^2}{x}\,\frac{p_T^2}{(p_T^2+(1-x)M_V^2)^2},$$

$$P^{L}_{V/f}(x,p_T^2) = \frac{g_V^2+g_A^2}{4\pi^2}\,\frac{1-x}{x}\,\frac{(1-x)M_V^2}{(p_T^2+(1-x)M_V^2)^2}.$$

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Special kinematics for massive gauge boson fusion processes:
For the accompanying jets,

At low-p_{jT},

$$\left.\begin{array}{l} p_{jT}^2 \approx (1-x)M_V^2 \\ E_j \sim (1-x)E_q \end{array}\right\} \textit{forward jet tagging}$$

At high-p_{jT},

$$\left.\begin{array}{l} \frac{d\sigma(V_T)}{dp_{jT}^2} \propto 1/p_{jT}^2 \\ \frac{d\sigma(V_L)}{dp_{jT}^2} \propto 1/p_{jT}^4 \end{array}\right\} \textit{central jet vetoing}$$

has become important tools for Higgs searches, single-top signal etc.

(C). Charge forward-backward asymmetry A_{FB}:

The coupling vertex of a vector boson V_μ to an arbitrary fermion pair f

$$i\sum_{\tau}^{L,R} g_\tau^f\ \gamma^\mu\ P_\tau \qquad \rightarrow \qquad \text{crucial to probe chiral structures.}$$

The parton-level forward-backward asymmetry is defined as

$$A_{FB}^{i,f} \equiv \frac{N_F - N_B}{N_F + N_B} = \frac{3}{4}\mathcal{A}_i\mathcal{A}_f,$$

$$\mathcal{A}_f = \frac{(g_L^f)^2 - (g_R^f)^2}{(g_L^f)^2 + (g_R^f)^2}.$$

where N_F (N_B) is the number of events in the forward (backward) direction defined in the parton c.m. frame relative to the initial-state fermion $\vec{p}_i$.

At hadronic level:

$$A_{FB}^{\mathsf{LHC}} = \frac{\int dx_1 \sum_q A_{FB}^{q,f} \Big(P_q(x_1)P_{\bar{q}}(x_2) - P_{\bar{q}}(x_1)P_q(x_2)\Big)\,\mathsf{sign}(x_1 - x_2)}{\int dx_1 \sum_q \Big(P_q(x_1)P_{\bar{q}}(x_2) + P_{\bar{q}}(x_1)P_q(x_2)\Big)}.$$

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Perfectly fine for Z/Z'-type:

In $p\bar{p}$ collisions, $\vec{p}_{proton}$ is the direction of $\vec{p}_{quark}$.

In pp collisions, however, what is the direction of $\vec{p}_{quark}$?

At hadronic level:

$$A_{FB}^{\mathrm{LHC}} = \frac{\int dx_1 \sum_q A_{FB}^{q,f} \Big(P_q(x_1)P_{\bar{q}}(x_2) - P_{\bar{q}}(x_1)P_q(x_2)\Big)\, \mathrm{sign}(x_1 - x_2)}{\int dx_1 \sum_q \Big(P_q(x_1)P_{\bar{q}}(x_2) + P_{\bar{q}}(x_1)P_q(x_2)\Big)}.$$

Perfectly fine for Z/Z'-type:

In $p\bar{p}$ collisions, $\vec{p}_{proton}$ is the direction of $\vec{p}_{quark}$.

In pp collisions, however, what is the direction of $\vec{p}_{quark}$?

It is the boost-direction of $\ell^+\ell^-$.

How about $W^{\pm}/W'^{\pm}(\ell^{\pm}\nu)$-type?

In $p\bar{p}$ collisions, $\vec{p}_{proton}$ is the direction of $\vec{p}_{quark}$,
AND ℓ^{+} (ℓ^{-}) along the direction with $\bar{q}$ (q) ⇒ OK at the Tevatron,

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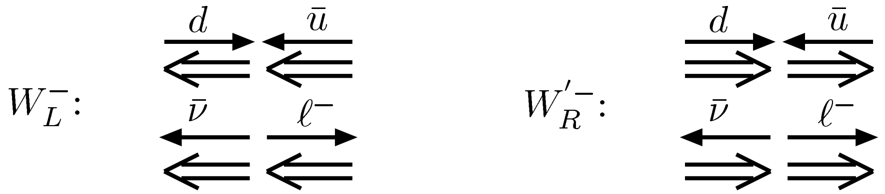
But: (1). cann't get the boost-direction of $\ell^{\pm}\nu$ system;
(2). Looking at $\ell^{\pm}$ alone, no insight for W_L or W_R!



(a) (b)

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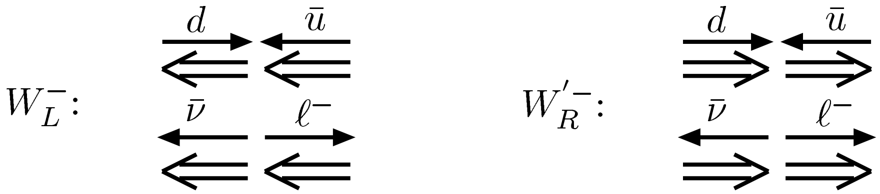
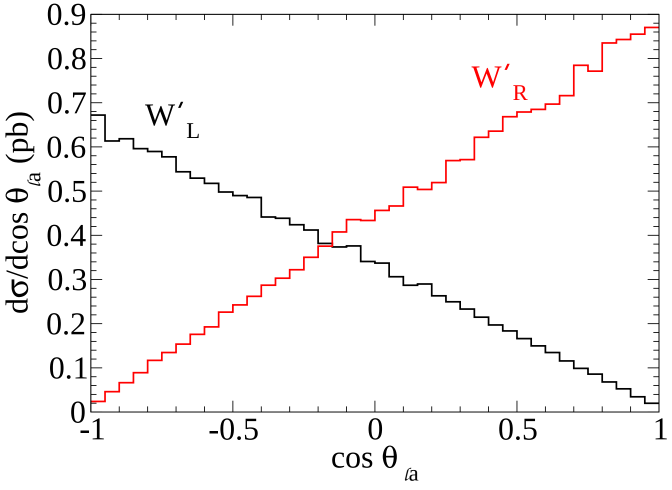


(a) (b)

In $p\bar{p}$ collisions: (1). a reconstructable system; (2). with spin correlation:
Only tops: $W' \to t\bar{b} \to \ell^{\pm}\nu\ \bar{b}$:



(D). CP asymmetries A_{CP}:

To non-ambiguously identify CP-violation effects, one must rely on CP-odd variables.

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This is meant to be in contrast to an observable:
that'd be *modified* by the presence of CP-violation,
but is *not zero* when CP-violation is absent.

e.g. $M_{(\chi^{\pm}\ \chi^{0})}$, $\sigma(H^{0},\ A^{0}), \ldots$

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Two ways:
a). Compare the rates between a process and its CP-conjugate process:

$$\frac{R(i\to f)-R(\bar{i}\to \bar{f})}{R(i\to f)+R(\bar{i}\to \bar{f})}, \quad \text{e.g.} \quad \frac{\Gamma(t\to W^{+}q)-\Gamma(\bar{t}\to W^{-}\bar{q})}{\Gamma(t\to W^{+}q)+\Gamma(\bar{t}\to W^{-}\bar{q})}.$$

b). Construct a CP-odd kinematical variable for an initially CP-eigenstate:

$$\mathcal{M} \sim M_1 + M_2 \sin\theta,$$

$$A_{CP} = \sigma^F - \sigma^B = \int_0^1 \frac{d\sigma}{d\cos\theta} d\cos\theta - \int_{-1}^0 \frac{d\sigma}{d\cos\theta} d\cos\theta$$

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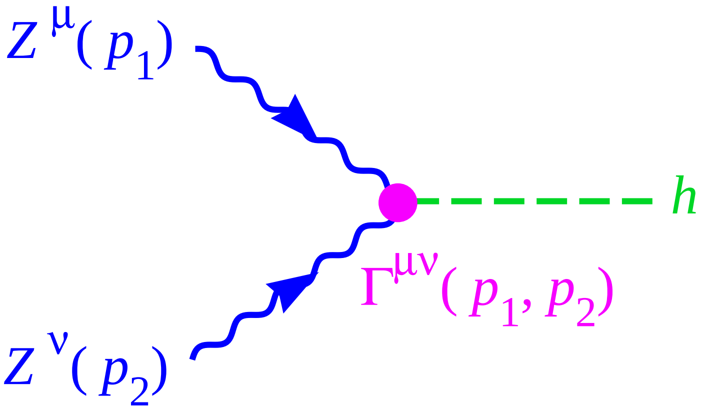
E.g. 1: $H \to Z(p_1)Z^*(p_2) \to e^+(q_1)e^-(q_2),\ \mu^+\mu^-$



$$\Gamma^{\mu\nu}(p_1,p_2) = i\frac{2}{v}\ h[a\ M_Z^2 g^{\mu\nu} + b\ (p_1^\mu p_2^\nu - p_1 \cdot p_2 g^{\mu\nu}) + \tilde{b}\ \epsilon^{\mu\nu\rho\sigma} p_{1\rho} p_{2\sigma}]$$

$a = 1,\ b = \tilde{b} = 0$ for SM.

In general, $a,\ b,\ \tilde{b}$ complex form factors,

describing new physics at a higher scale.

For $H \to Z(p_1)Z^*(p_2) \to e^+(q_1)e^-(q_2),\ \mu^+\mu^-$, define:

$$O_{CP} \sim (\vec{p}_1 - \vec{p}_2) \cdot (\vec{q}_1 \times \vec{q}_2),$$

$$\text{or}\quad \cos\theta = \frac{(\vec{p}_1 - \vec{p}_2) \cdot (\vec{q}_1 \times \vec{q}_2)}{|\vec{p}_1 - \vec{p}_2||\vec{q}_1 \times \vec{q}_2)|}.$$

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E.g. 2: $H \to t(p_t)\bar{t}(p_{\bar{t}}) \to e^+(q_1)\nu_1 b_1,\ e^-(q_2)\nu_2 b_2.$

$$-\frac{m_t}{v}\bar{t}(a + b\gamma^5)t\ H$$
$$O_{CP} \sim (\vec{p}_t - \vec{p}_{\bar{t}}) \cdot (\vec{p}_{e^+} \times \vec{p}_{e^-}).$$

thus define an asymmetry angle.

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Yet more to come:

Tevatron: EW, top sector, Higgs (?), new particle searches...

LHC: Higgs studies, comprehensive new particle searches...

LC: more on top sector, precision Higgs and new light particles...

High energy cosmic rays: AUGER, ICECUBE ... ...

Tevatron is reaching a record-high luminosity:

$2 \times 10^{32}/\mathrm{cm}^2/\mathrm{s} \;\Rightarrow 2\;\; \mathrm{fb}^{-1}/\mathrm{yr}/\mathrm{detector}.$

current plan for one more year (till 2011),

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In (almost) ANY TeV scale new physics scenario,

the LHC will significantly contribute!

Contents:

(A). Higgs Searches at the Tevatron and the LHC

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(A). Higgs Searches at the Tevatron and the LHC

(B). Weak Scale Supersymmetry

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(A). Higgs Searches at the Tevatron and the LHC

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(C). New gauge bosons and heavy fermions

(D). LHC–Dark Matter connection

(E). Deep into extra-dimensions

Contents:

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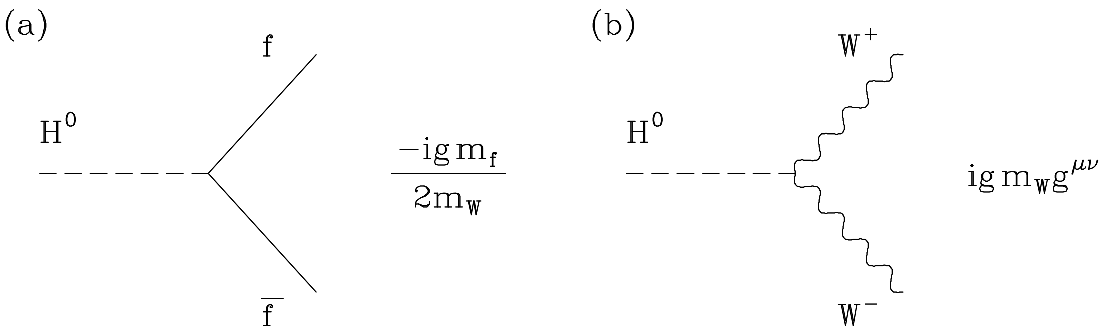
Realize the Tevatron potential!

Go LHC!

Major breakthrough ahead of us!

(A). Higgs Searches at the Tevatron and the LHC:

The crucial features: Couplings proportional to masses.



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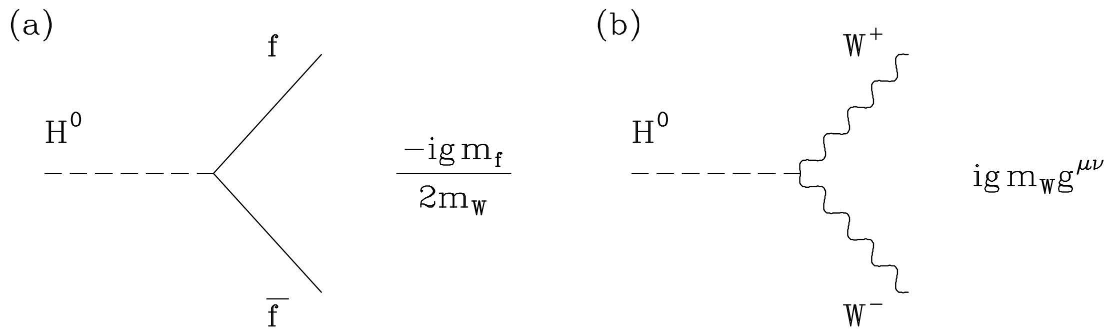
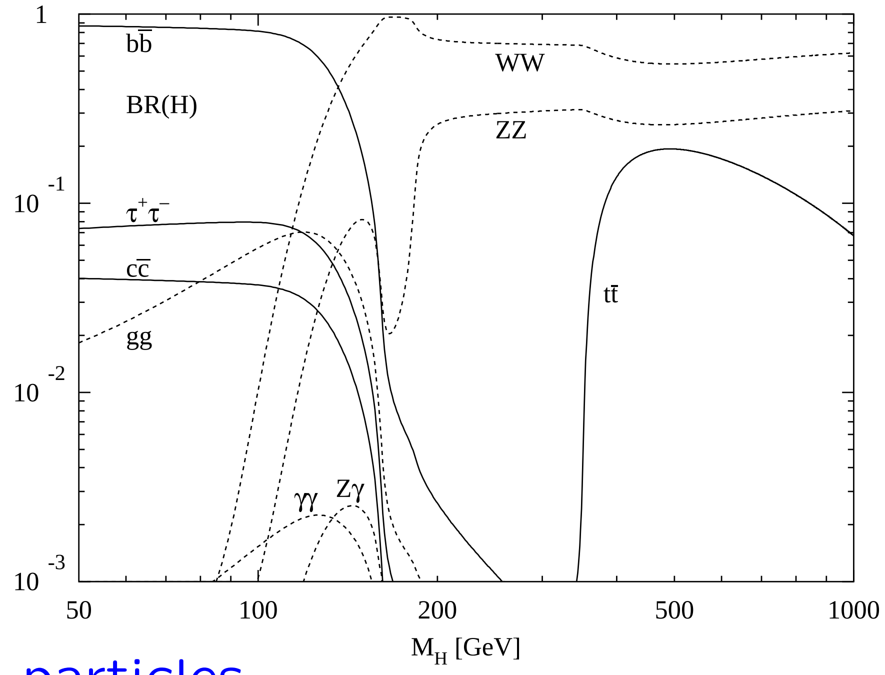
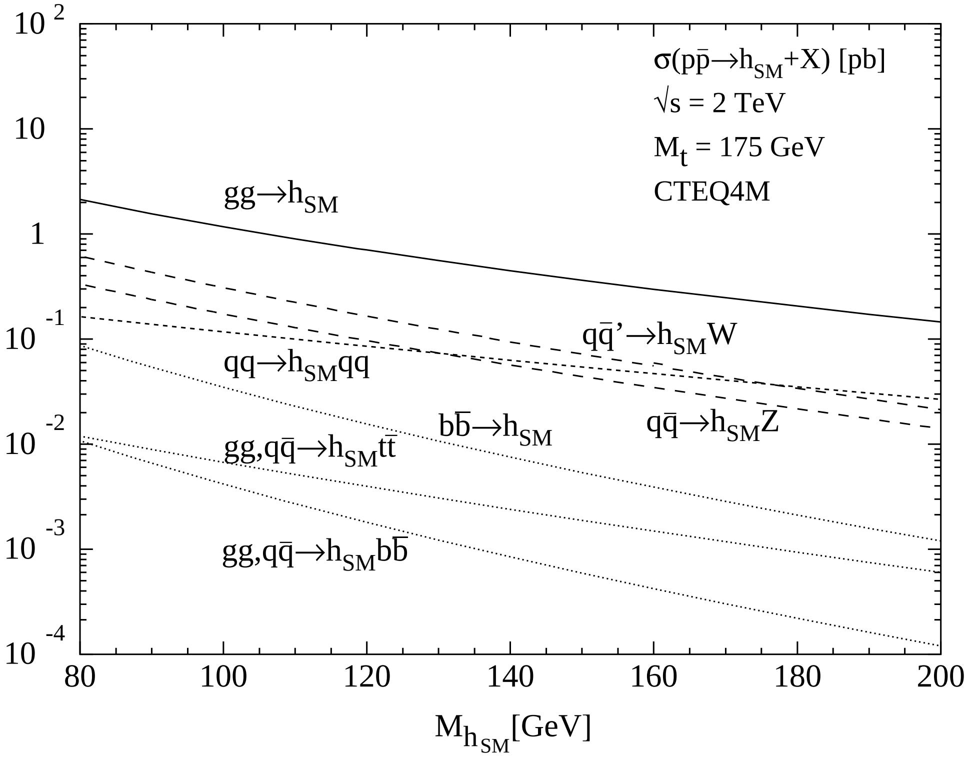


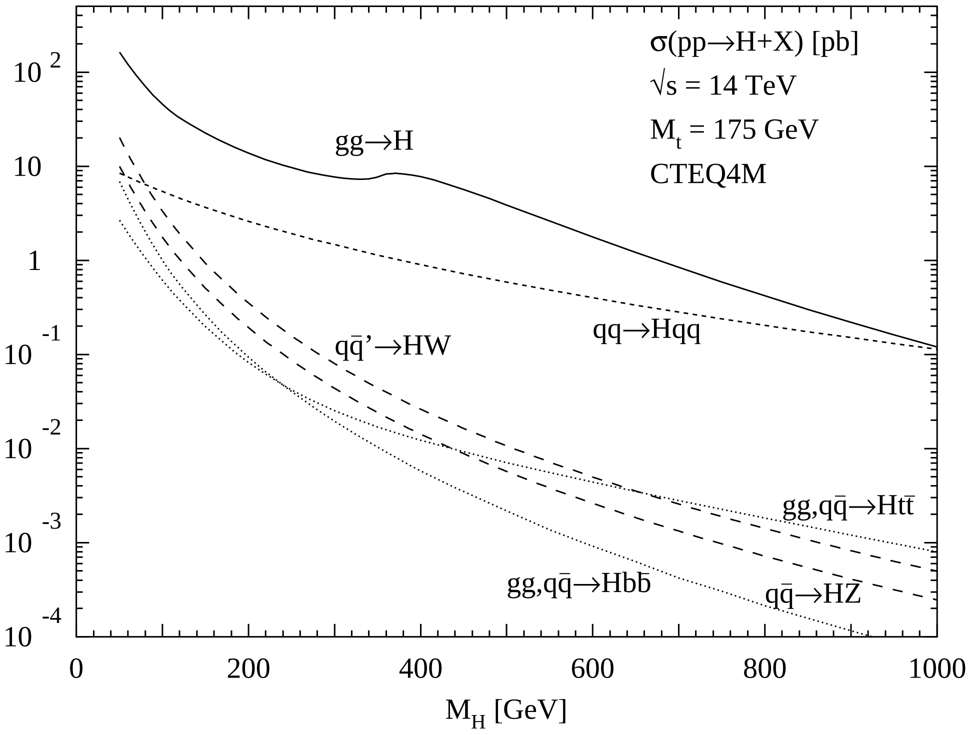
SM Higgs boson decay branching fractions:



preferably to heavier particles.

SM Higgs boson production rates:





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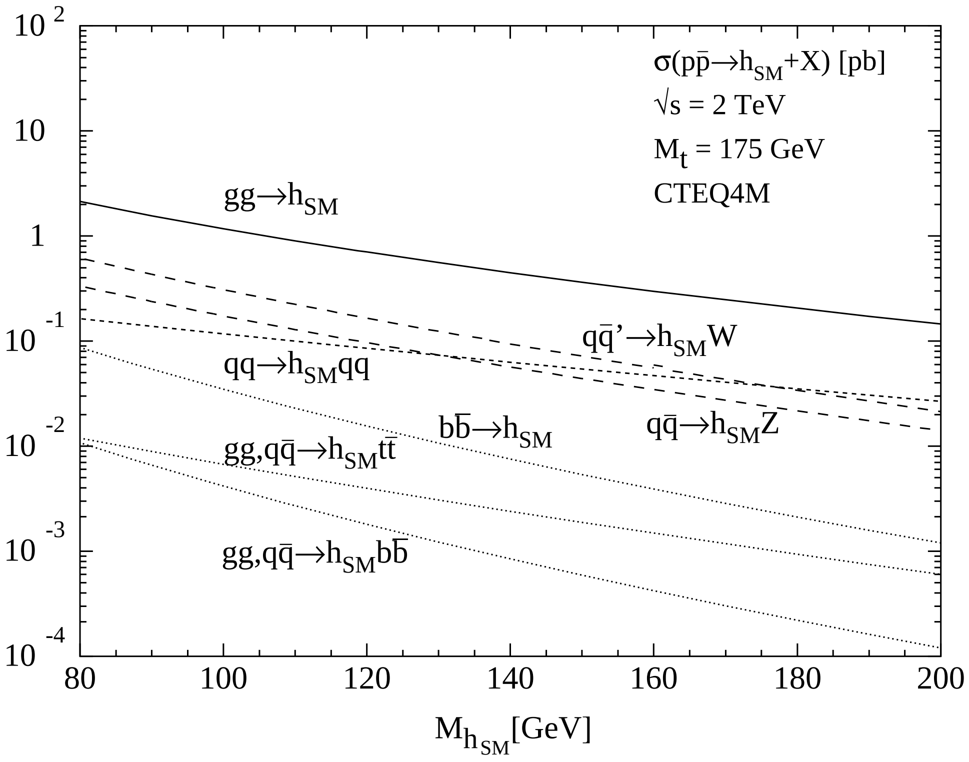
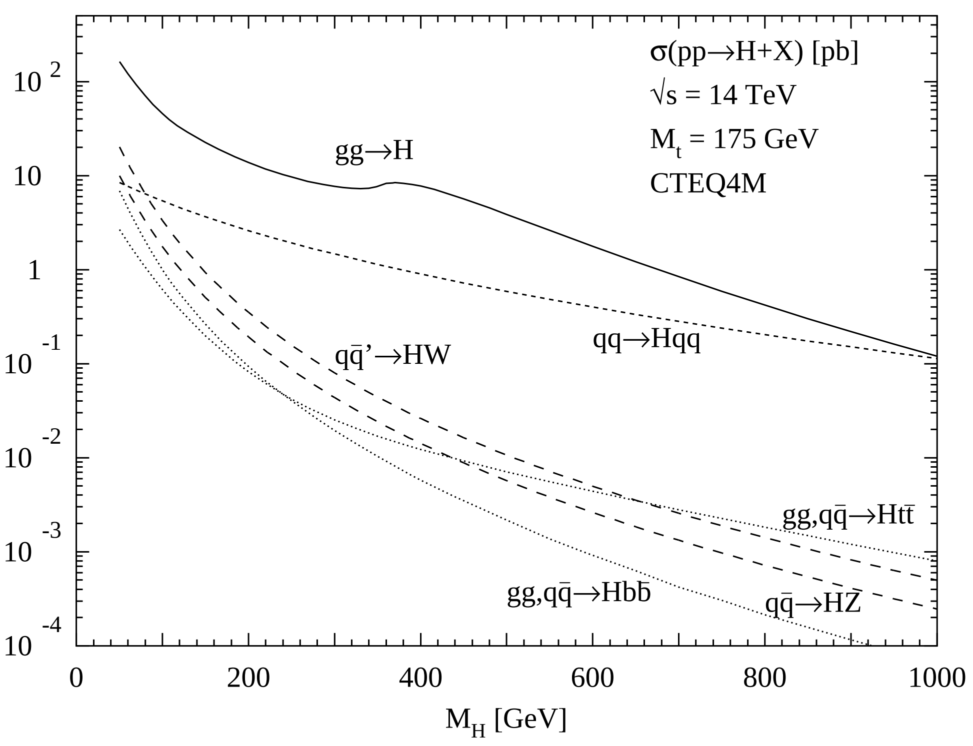


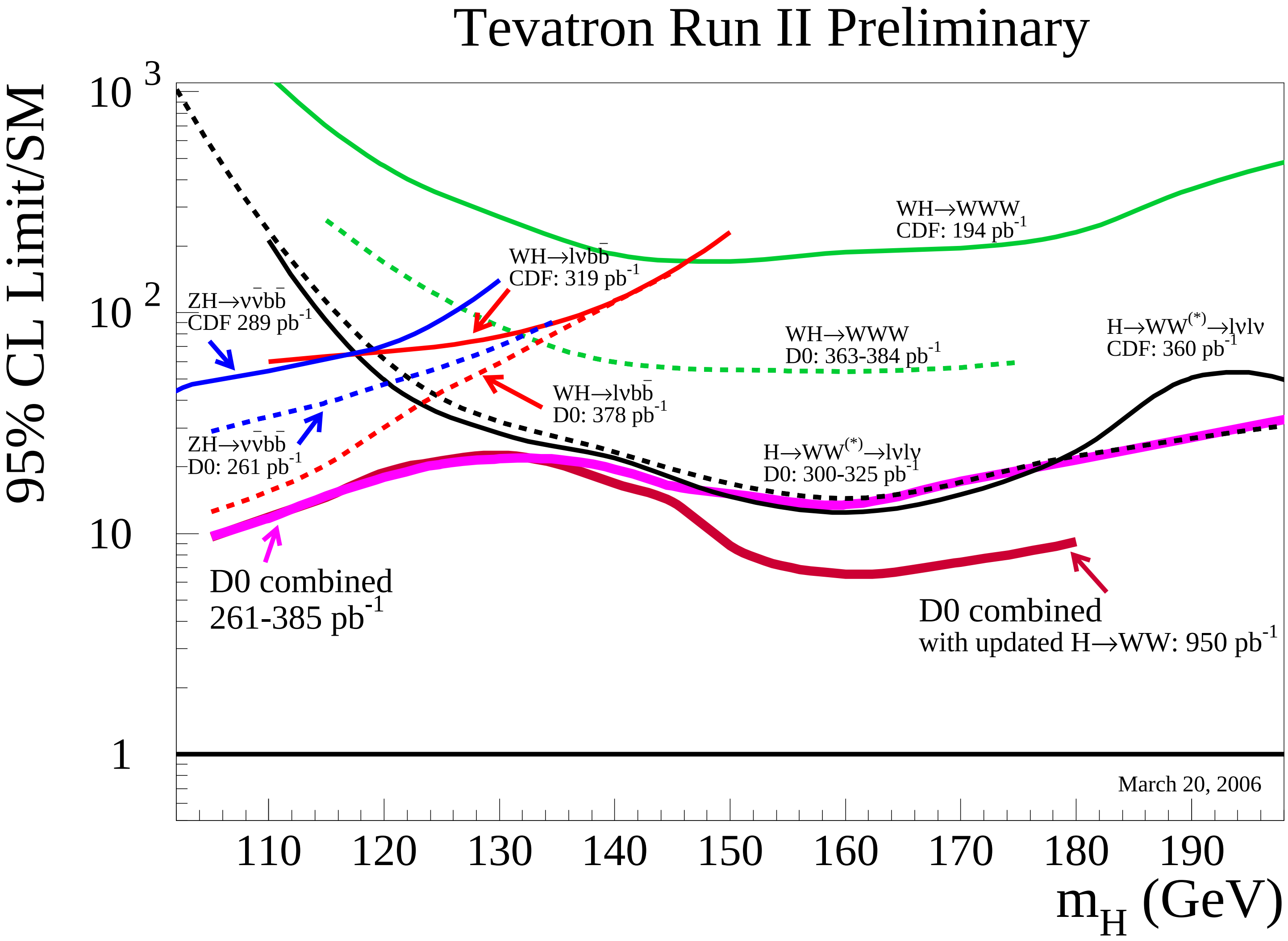


- At the Tevatron: hundreds of Higgs bosons may have been produced, for $m_h \lesssim 200$ GeV with 1 fb^{-1}.
- At the LHC: hundreds of thousand may be produced, for $m_h \lesssim 700$ GeV with 100 fb^{-1}.

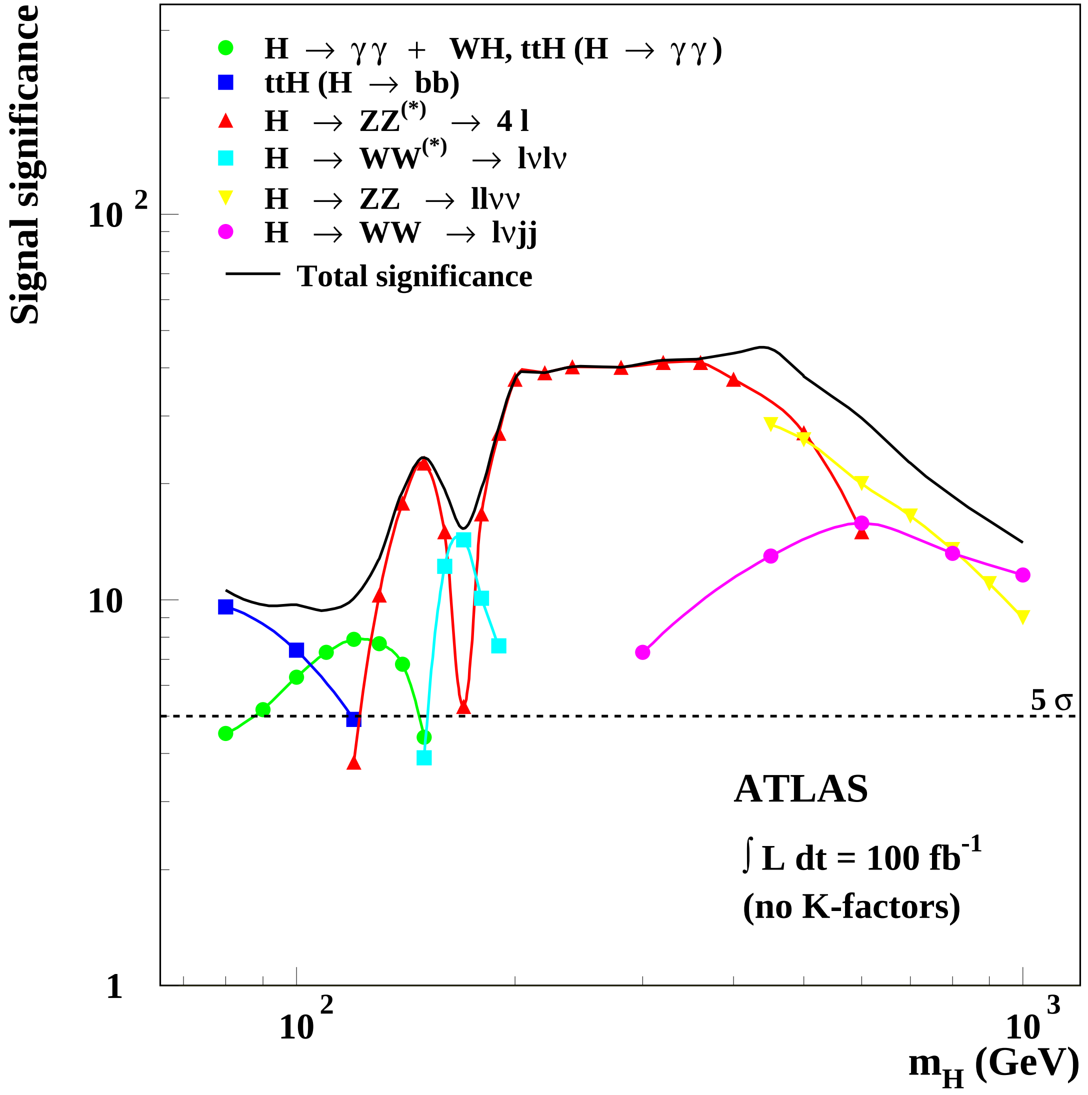
- Higgs first shot at the Tevatron:

$$q\bar{q}' \to Wh,\ Zh, \quad h \to b\bar{b}$$

$$gg \to h, \quad h \to WW^*,\ ZZ^*,\ \tau^+\tau^-$$



- SM Higgs fully covered at the LHC:

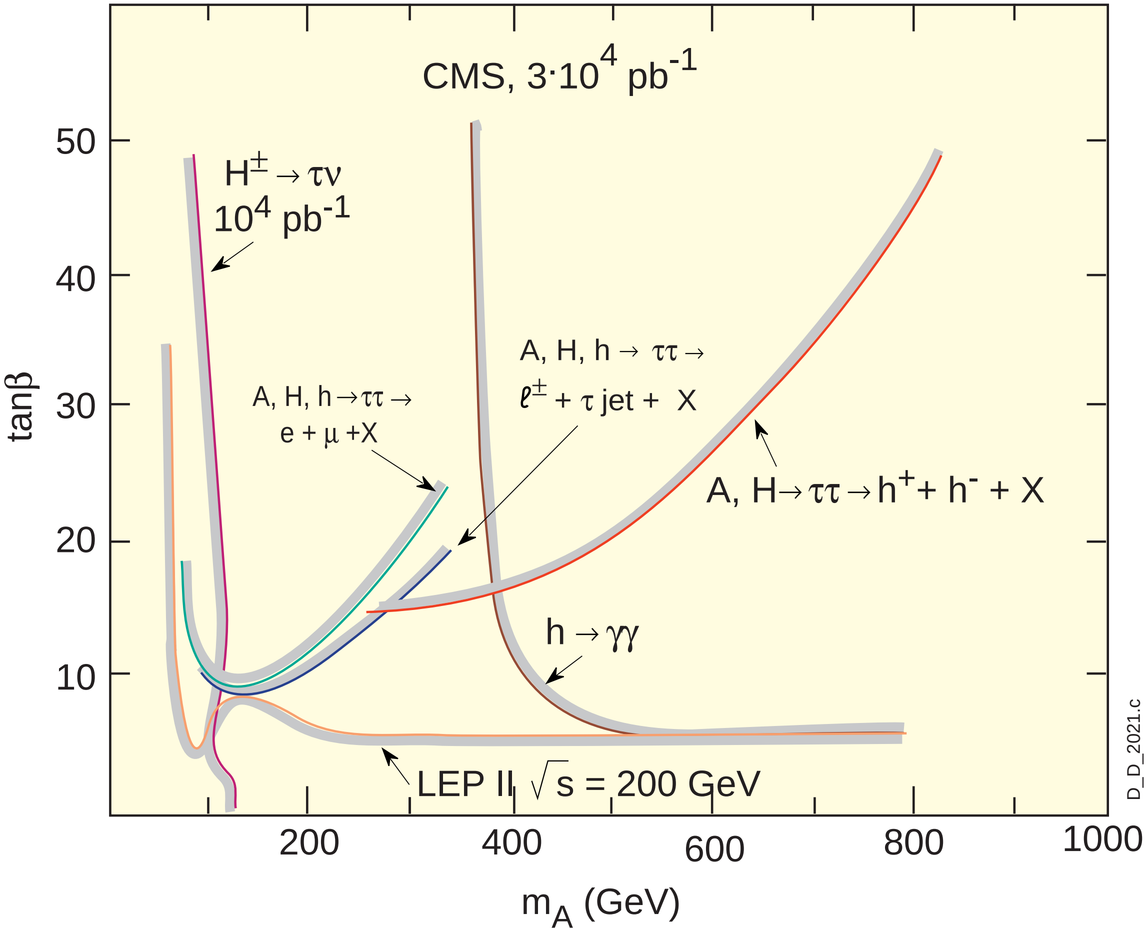


ATLAS report: combining multiple channels, 10σ observation achievable.

Significance contours for SUSY Higgses

Regions of the MSSM parameter space (m_A, tgβ)
explorable through various SUSY Higgs channels

- 5 σ significance contours
- two-loop / RGE-improved radiative corrections
- m_{top} = 175 GeV, m_{SUSY} = 1 TeV, no stop mixing ;

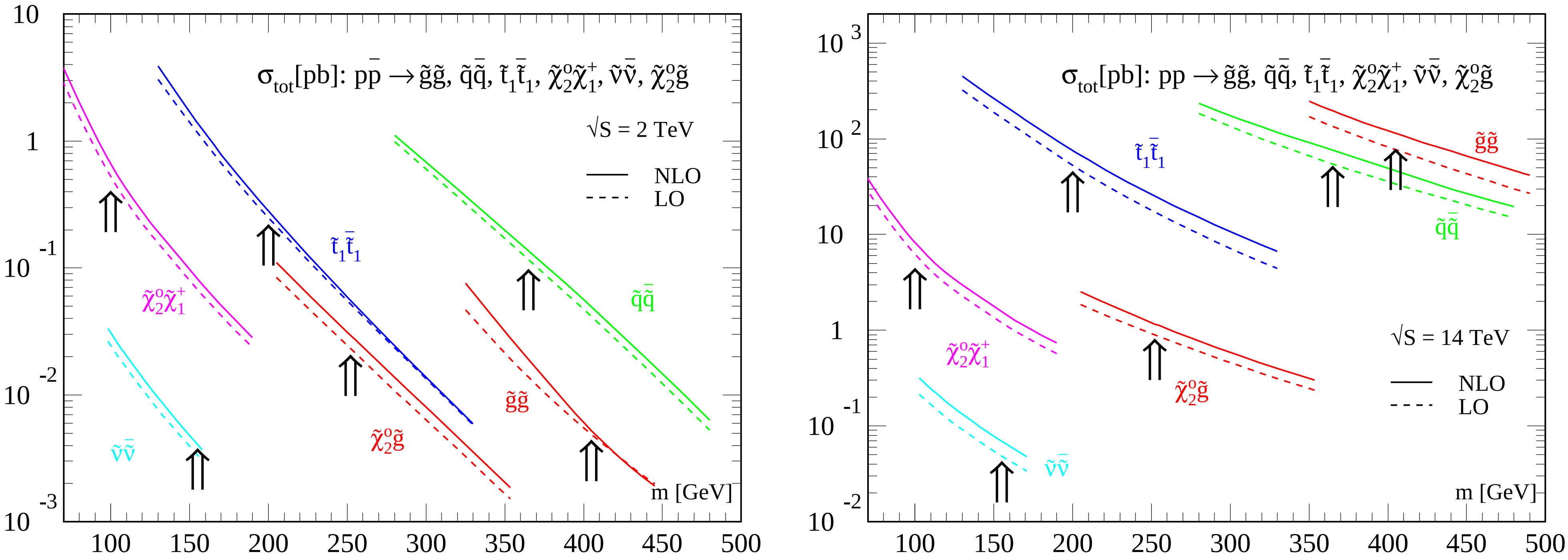


(B). Weak Scale Supersymmetry

Hadron colliders can be a S-particle factory:

QCD production: $q\bar{q},\ gq,\ gg \to \tilde{q}\bar{\tilde{q}},\ \tilde{q}\tilde{g},\ \tilde{g}\tilde{g}.$

E.W. production: $q\bar{q} \to \tilde{\chi}_1^+\tilde{\chi}_1^-,\ \tilde{\chi}_1^\pm\tilde{\chi}_1^0,\ \tilde{\chi}_1^\pm\tilde{\chi}_2^0.$



Typically,

$$\sigma(Tevatron) \approx \mathcal{O}(0.1 - 1\ \text{pb});\quad \sigma(LHC) \approx \mathcal{O}(10 - 100\ \text{pb}).$$

New ball-game for signal searches:

The lightest SUSY particle (LSP $\tilde{\chi}_1^0$) is stable (R-parity), and nearly non-interacting (in detectors),

$\Rightarrow$ large missing energy is the characteristics;
difficult to reconstruct a mass peak for the sparticle.

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Details depend on the model...

- mSUGRA scenario: SUSY breaking near M_{GUT}.

Supergravity as messenger to transmit SUSY breaking effects.

$$m_0,\ m_{1/2},\ A,\ \tan\beta, \text{ and } sign(\mu)$$

Sparticle decays:

$$\begin{array}{ll} \tilde{\chi}_1^+ \to \tilde{\chi}_1^0 \ell^+ \nu, & \tilde{\chi}_1^0 q \bar{q}' \\ \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-, & \tilde{\chi}_1^0 q \bar{q} \end{array}$$

$$\begin{array}{lll} \tilde{g} \to \tilde{\chi}_2^0 q \bar{q}, & \tilde{g} \to \tilde{\chi}_1^+ \bar{q} q, & \tilde{g} \to \tilde{q} \bar{q}, \\ \tilde{t}_1 \to \tilde{\chi}_1^0 t, & \tilde{t}_1 \to \tilde{\chi}_2^0 t, & \tilde{t}_1 \to \tilde{\chi}_1^+ b. \end{array}$$

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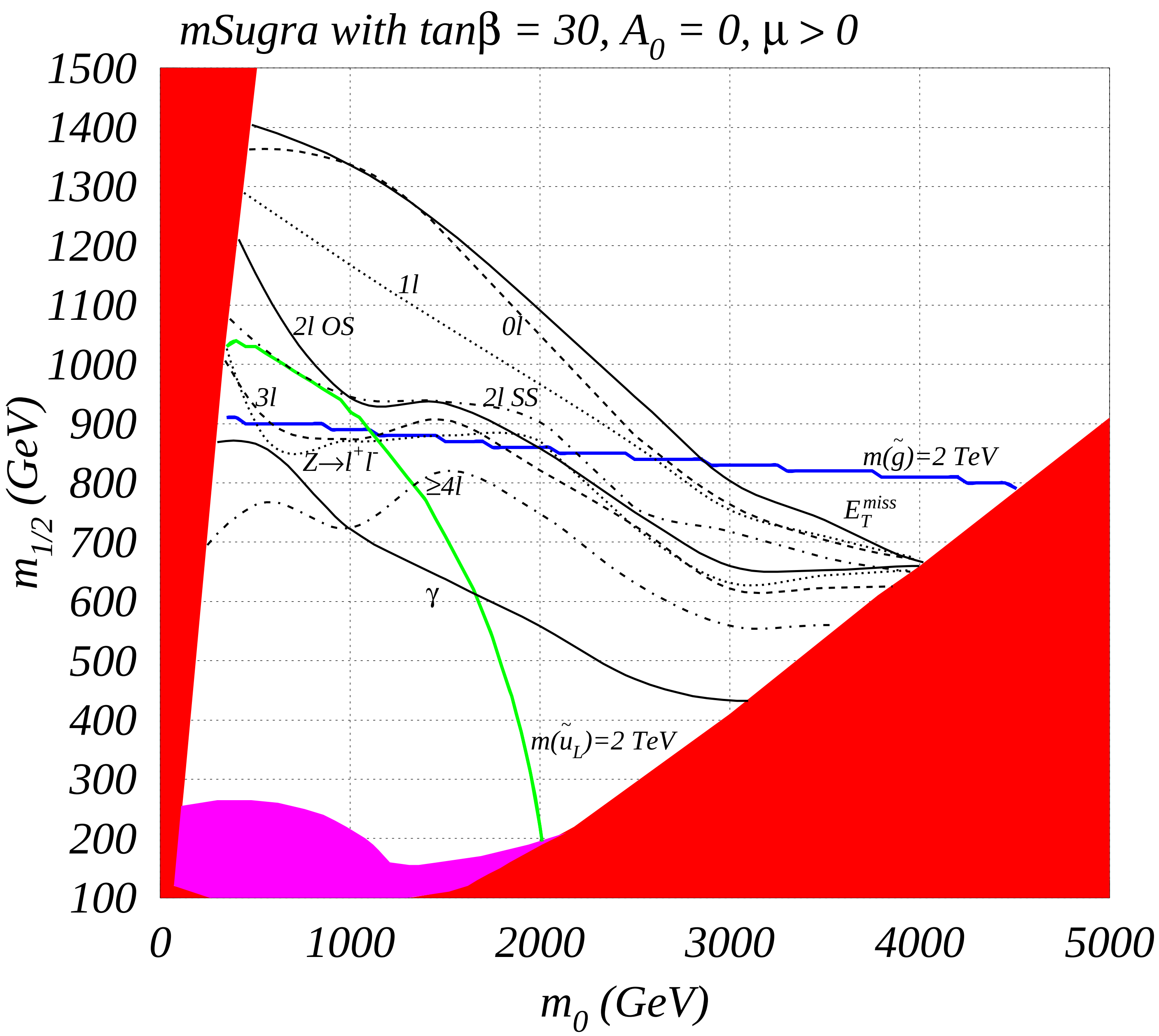
$$\tilde{g} \to \tilde{\chi}_2^0 q \bar{q}, \quad \tilde{g} \to \tilde{\chi}_1^+ \bar{q} q, \quad \tilde{g} \to \tilde{q} \bar{q},$$
$$\tilde{t}_1 \to \tilde{\chi}_1^0 t, \quad \tilde{t}_1 \to \tilde{\chi}_2^0 t, \quad \tilde{t}_1 \to \tilde{\chi}_1^+ b.$$

Generically, $\tilde{\chi}_1^0$ leads to missing energy signal:

"missing $\not{E}_T$ plus jets": $\not{E}_T$+jets

"dilepton plus missing $\not{E}_T$" $\ell\ell + \not{E}_T \quad (\pm\pm \ or \ +-)$

"trilepton plus missing $\not{E}_T$" $\ell\ell\ell + \not{E}_T$



LHC: $m_0 > 4000$ GeV, $m_{1/2} > 1400$ GeV, $\tan\beta \gtrsim 45$.

(C). New gauge bosons and heavy fermions

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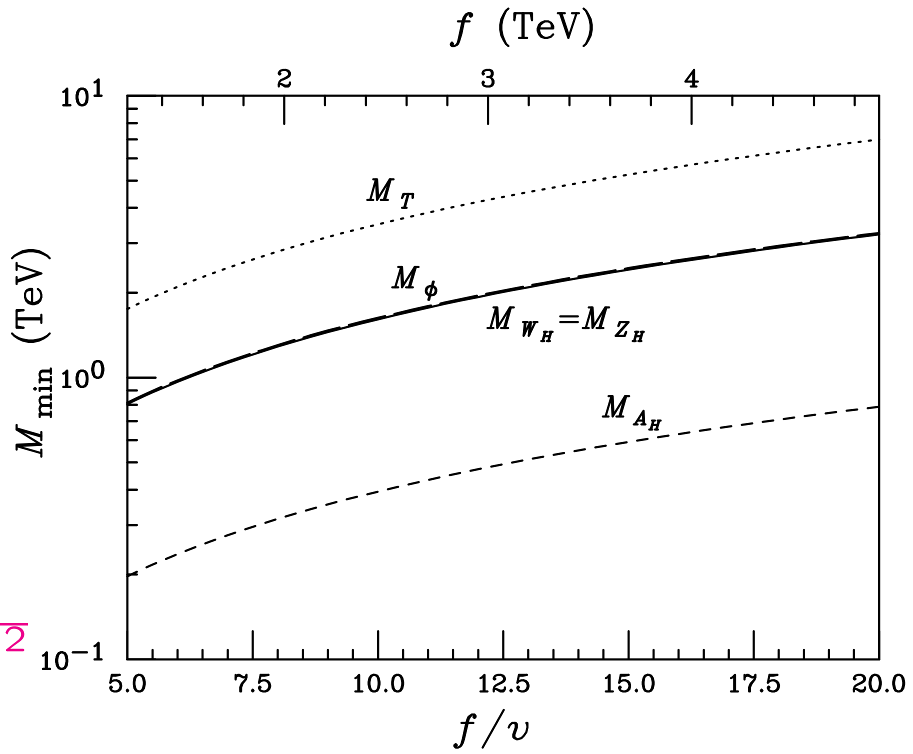
Little Higgs models as an example

In the Littlest Higgs model:*

Heavy particles	Mass
A_H	$m_z^2 s_{\rm W}^2\ \frac{f^2}{5s'^2c'^2v^2}$
Z_H	$m_{\rm W}^2\ \frac{f^2}{s^2c^2v^2}$
W_H	$m_{\rm W}^2\ \frac{f^2}{s^2c^2v^2}$
$\phi^{0,\ \pm,\ \pm\pm}$	$\frac{2m_H^2 f^2}{v^2}\ \frac{1}{1-(4v'f/v^2)^2}$
T	$\sqrt{\lambda_1^2+\lambda_2^2}\ f$



(where $m_{\rm W} = gv/2.$)

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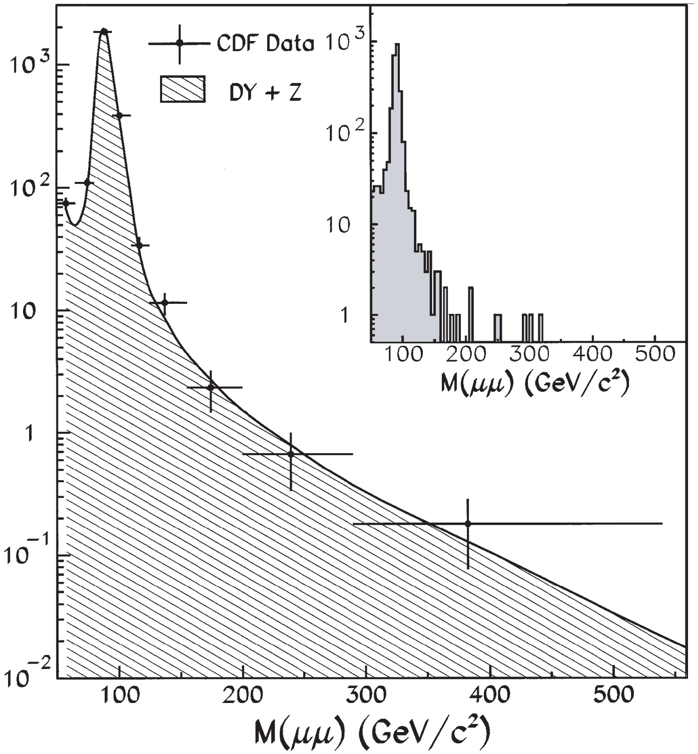
*Arkani-Hamed, Cohen, Katz, Nelson, `hep-ph/0206021`.

• New gauge bosons in DY process:

Recall CDF searches for a $Z' \rightarrow \mu^+\mu^-$: [PRL 79, (1997)]



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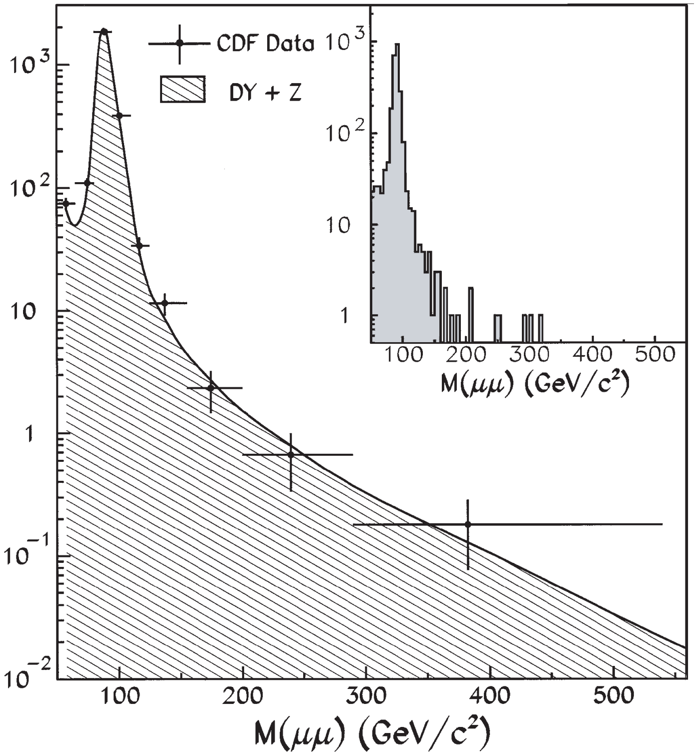

including:

$$
\begin{aligned}
&p\bar{p} \to Z,\gamma \to \mu^+\mu^- X,\\
&p\bar{p} \to W^+W^- \to \mu^+\nu_\mu\mu^-\bar{\nu}_\mu X,\\
&p\bar{p} \to b\bar{b} \to \mu^+\mu^- + hadrons + X,\\
&p\bar{p} \to t\bar{t} \to W^+b\ W^-\bar{b} \to \mu^+\nu_\mu\mu^-\bar{\nu}_\mu b\bar{b}\ X.
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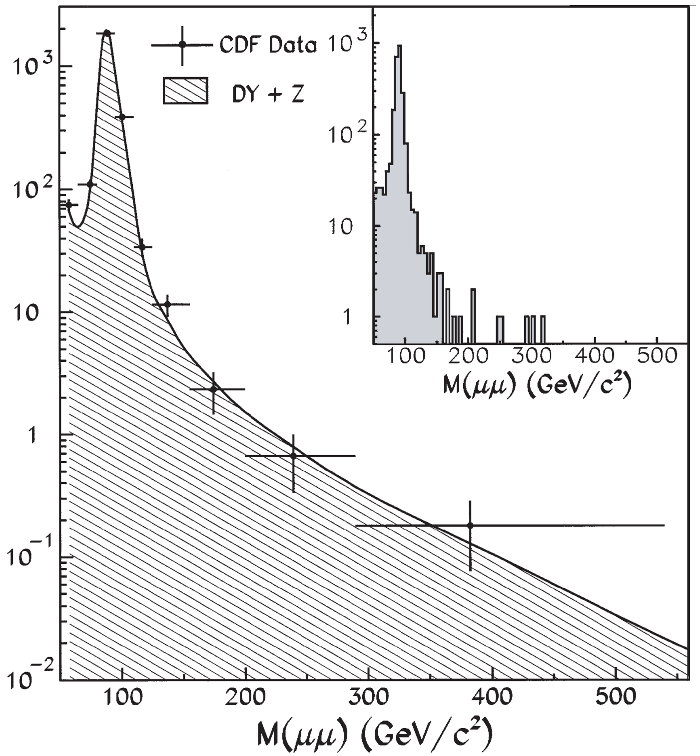

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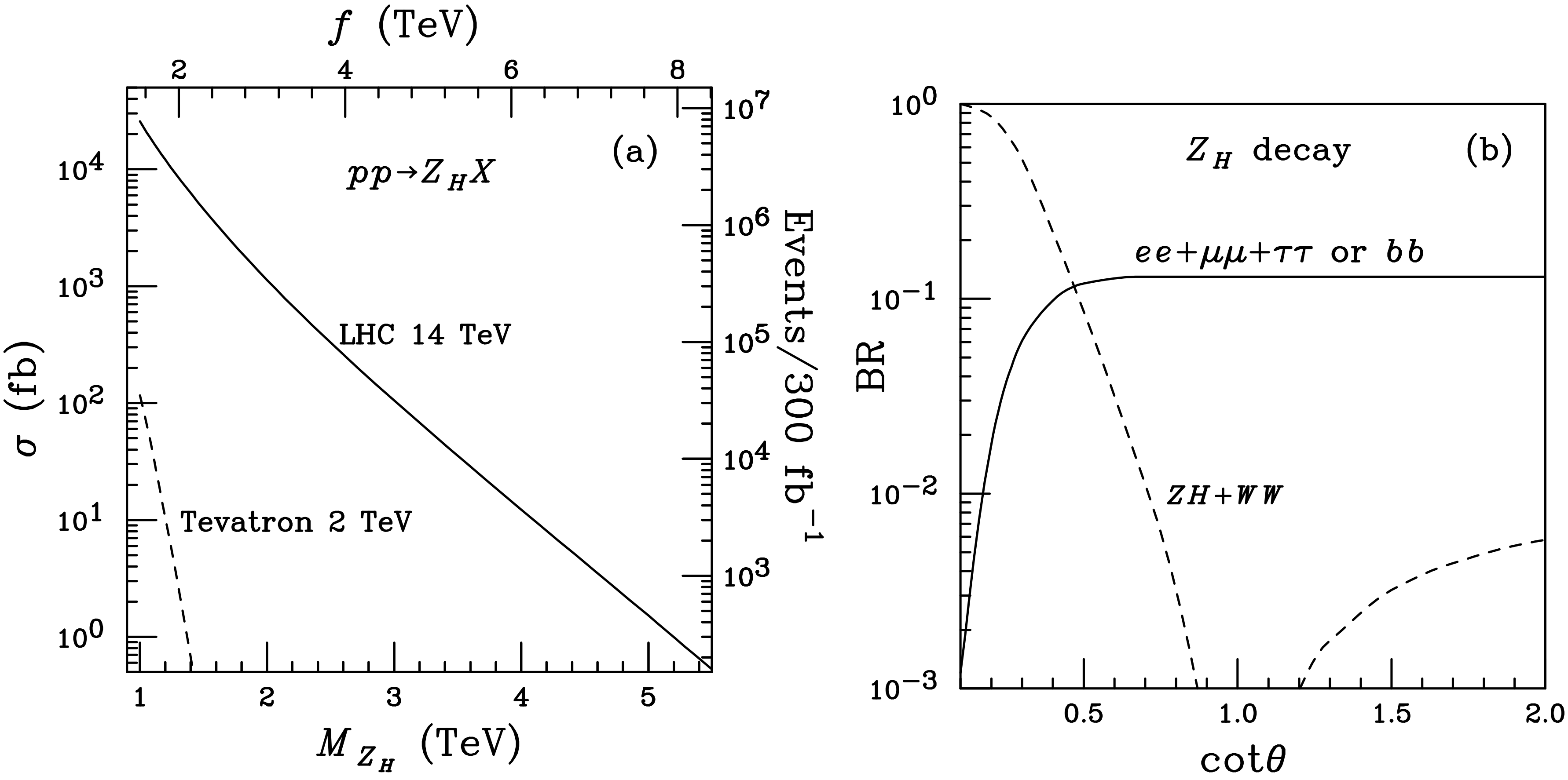
$\sigma <$ 40 fb $\Rightarrow$ $\mathrm{M}_{Z'} >$ 600 GeV.

- Z_H/W_H rebust new state
- DY production rate large



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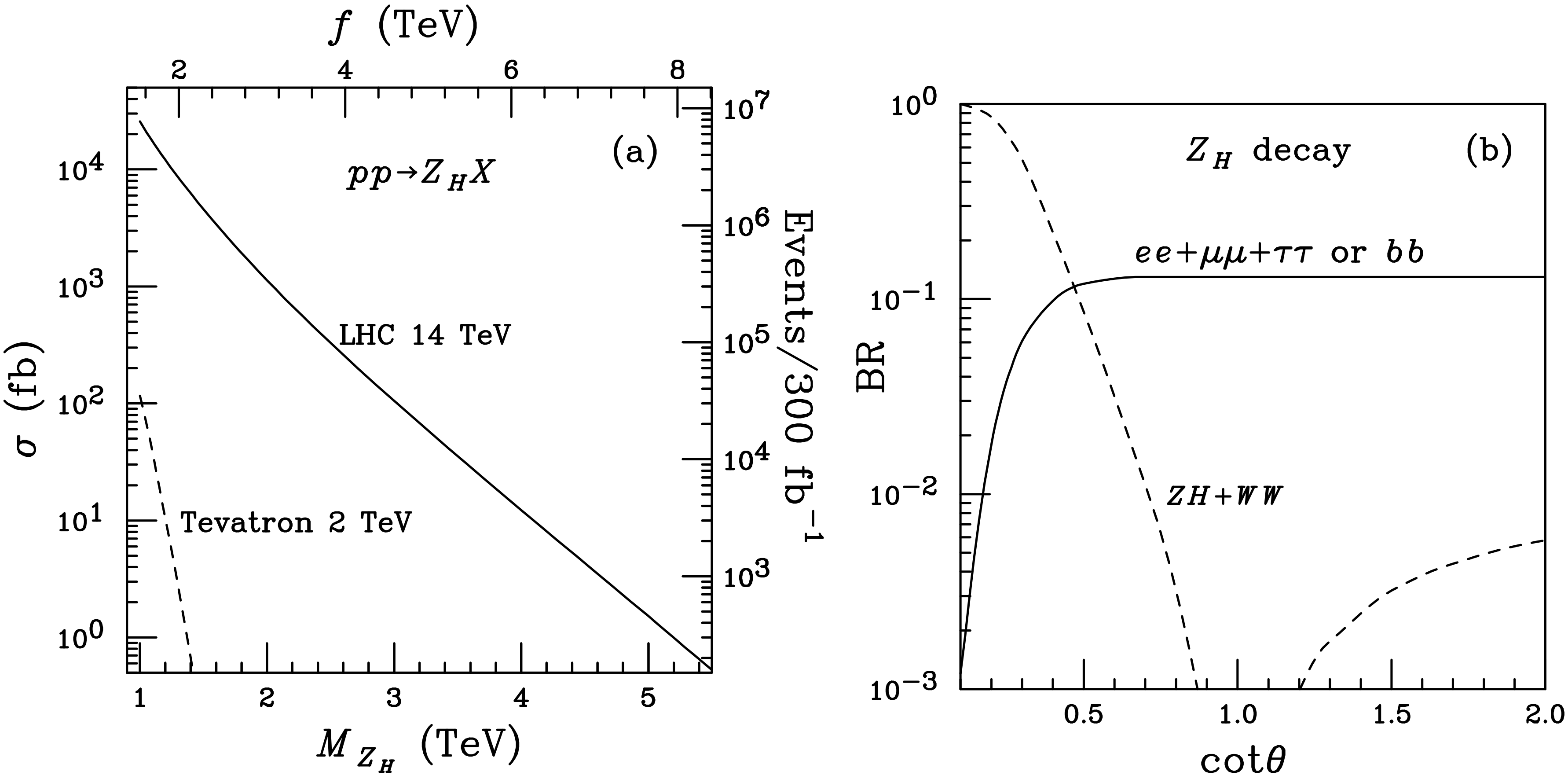
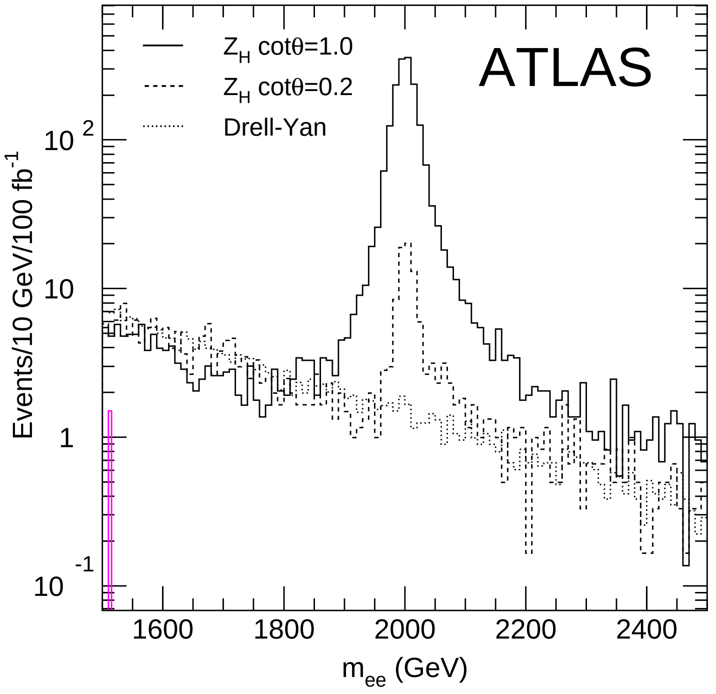
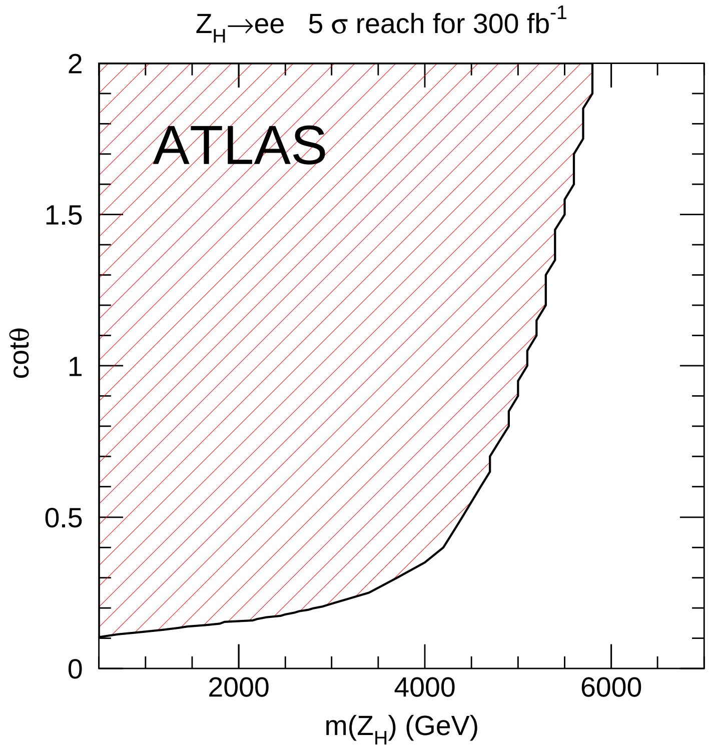


Tevatron: not quite accessible (except for A_H);

LHC: $M_{Z_H} \sim 5$ TeV or $f \sim 8$ TeV.

ATLAS simulations for $Z \to \ell^+\ell^-$:





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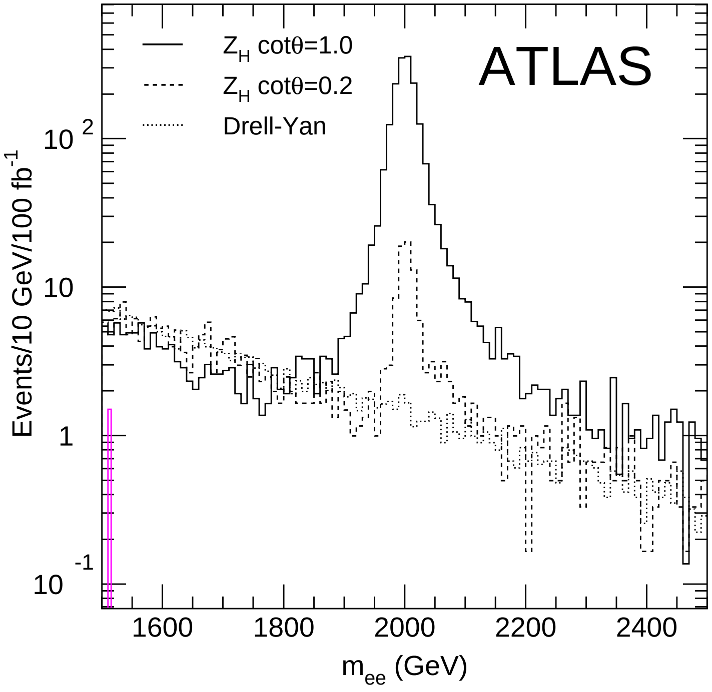

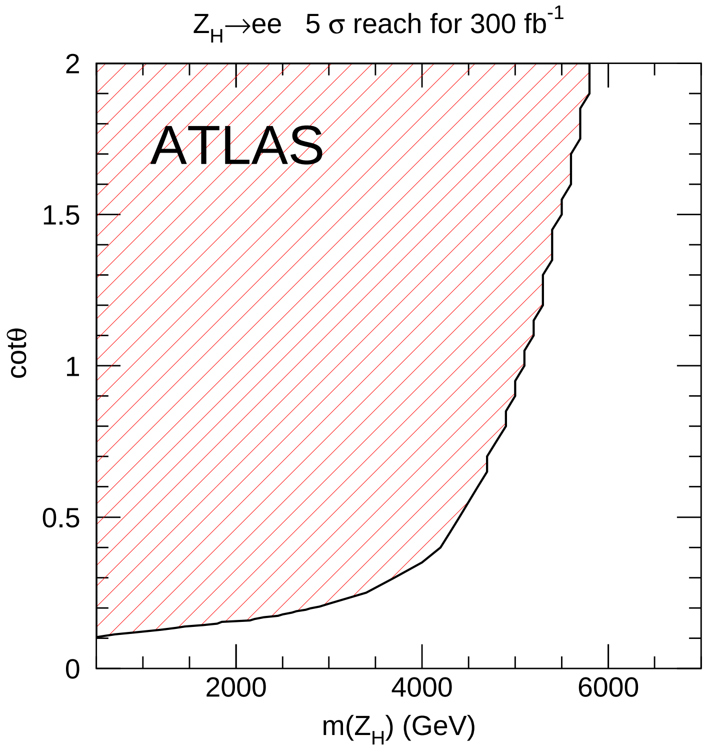

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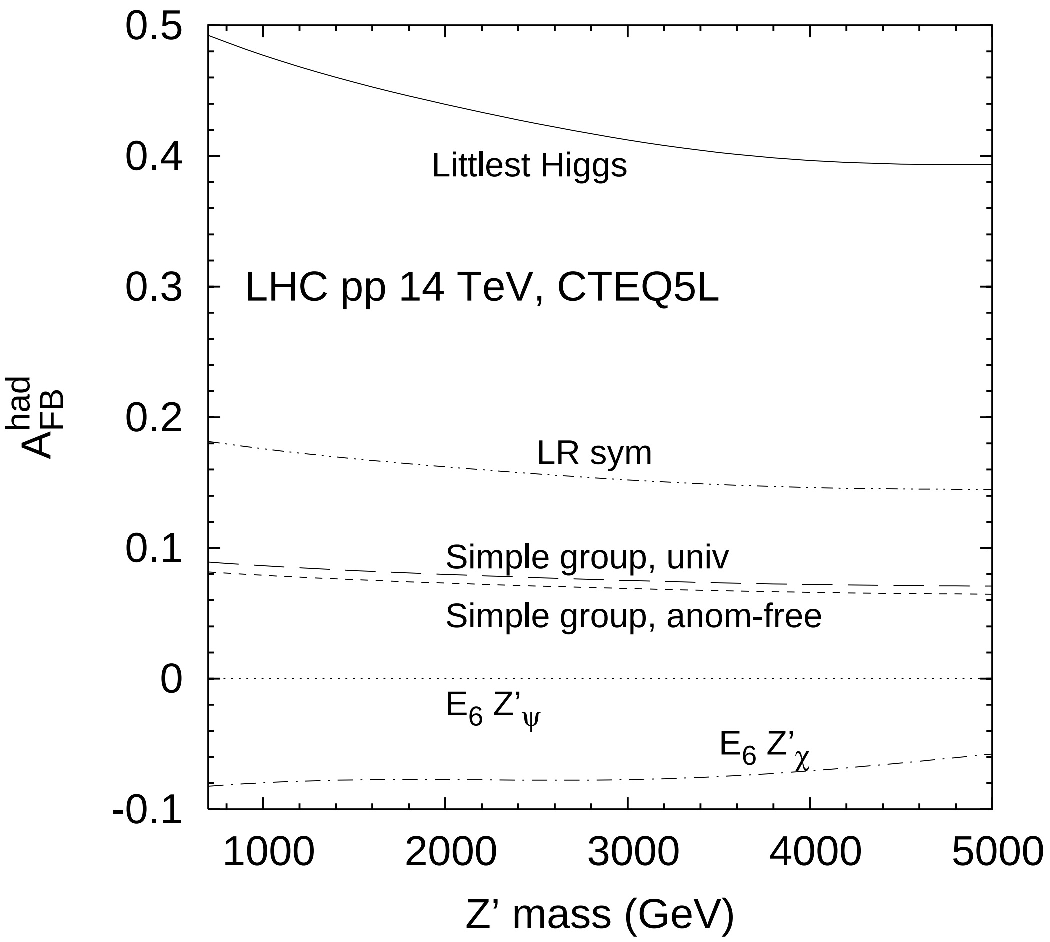
Cross-sectiions measure $\cot\theta$: $N(\ell^+\ell^-)$ versus $N(Zh)$.

Mass peak M_{Z_H} determines f.

Significant differences for FB asymmetry among Z's:

$$A_{FB}^{i,f} = \frac{3}{4} A_i A_f, \qquad A_i = \frac{g_L^2 - g_R^2}{g_L^2 + g_R^2}.$$

$$A_{FB}^{\text{had}} = \frac{\int dx_1 \sum_{q=u,d} A_{FB}^{qe} \left(F_q(x_1) F_{\bar{q}}(x_2) - F_{\bar{q}}(x_1) F_q(x_2)\right) \text{sign}(x_1 - x_2)}{\int dx_1 \sum_{q=u,d,s,c} \left(F_q(x_1) F_{\bar{q}}(x_2) + F_{\bar{q}}(x_1) F_q(x_2)\right)},$$



- Heavy quark signals:

Recall the top-quark searches at hadron colliders
The leading production channels:

$$q\bar{q} \to t\bar{t}, \quad \text{Tevatron 90\%; LHC 10\%}$$

$$gg \to t\bar{t}, \quad \text{Tevatron 10\%; LHC 90\%}$$

$$\text{with } t\bar{t} \to W^{+}b\ W^{-}\bar{b} \to ...$$

Top-quark discovered (1993): $m_t \approx 178$ GeV.

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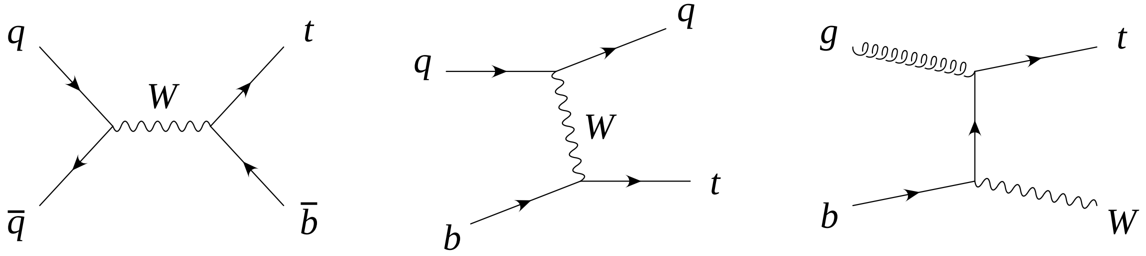

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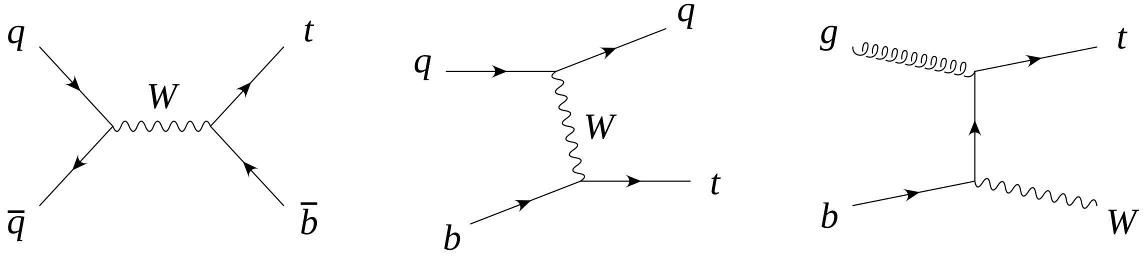

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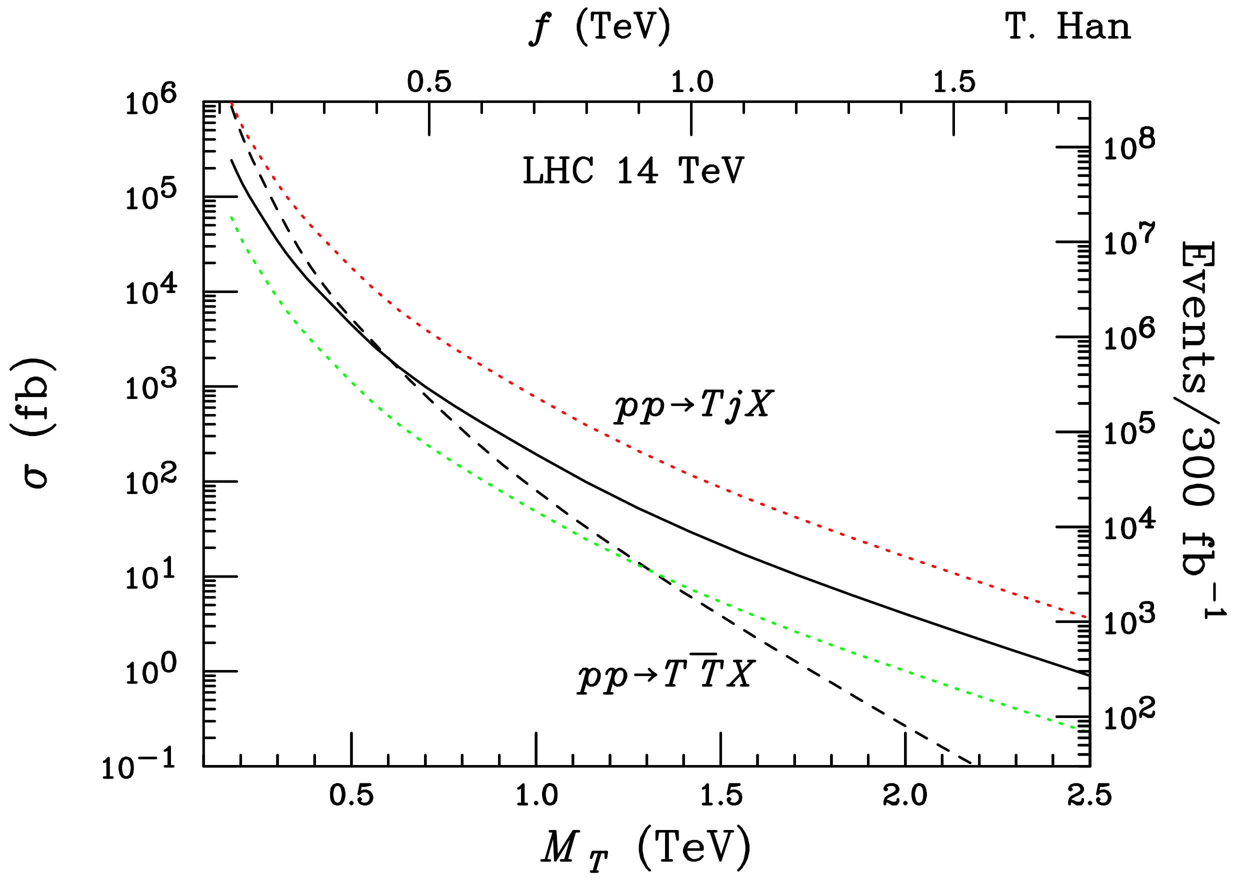
Recently observed at the Tevatron: measure V_{tb} and test tbW_L coupling.

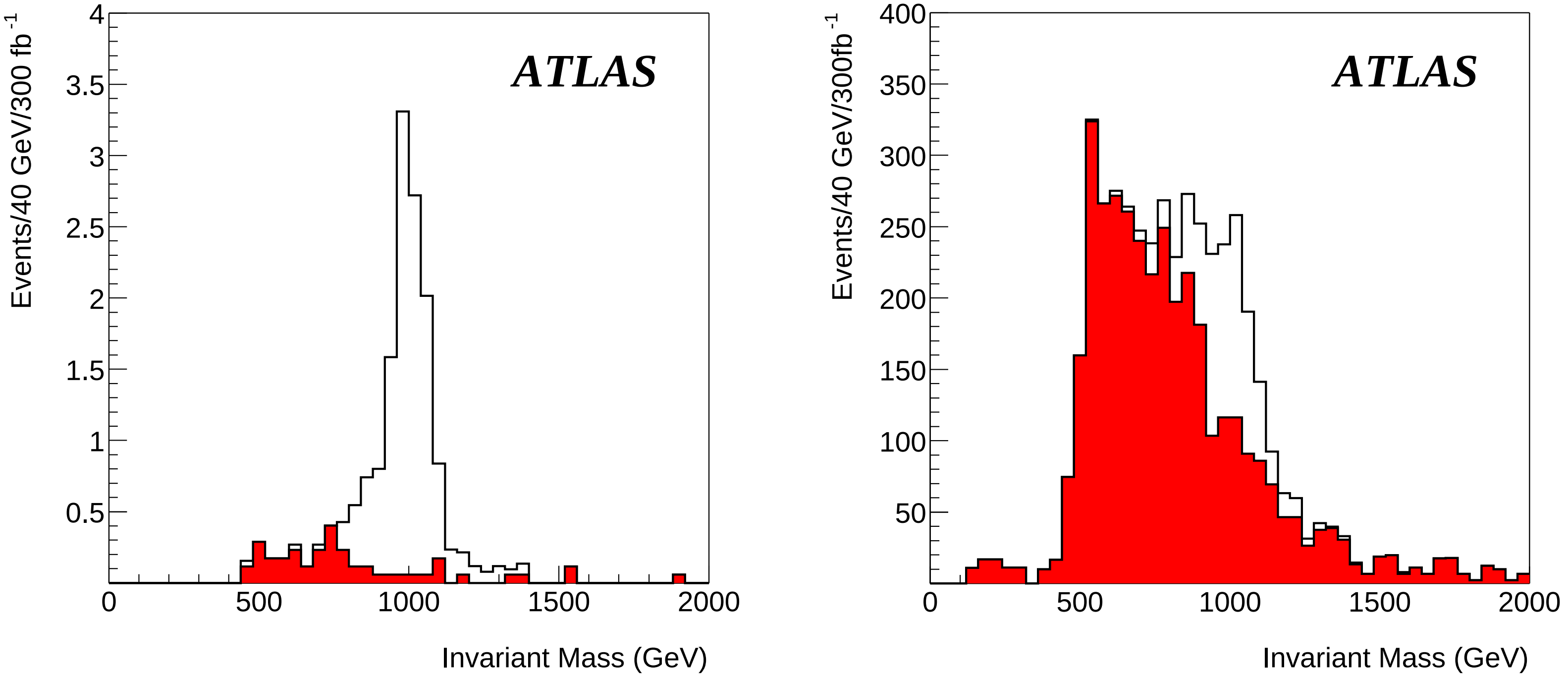
The heavy T signal at the LHC



$gg \to T\bar{T}$ phase-space suppression;

$qb \to q'T$ via t-channel $W_L b \to T$.

ATLAS simulations for $T \to tZ,\ bW$:



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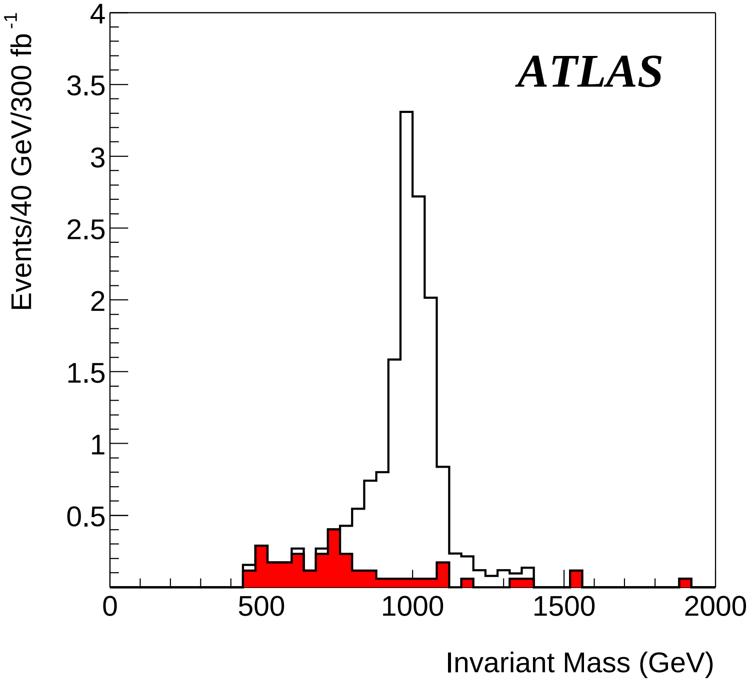

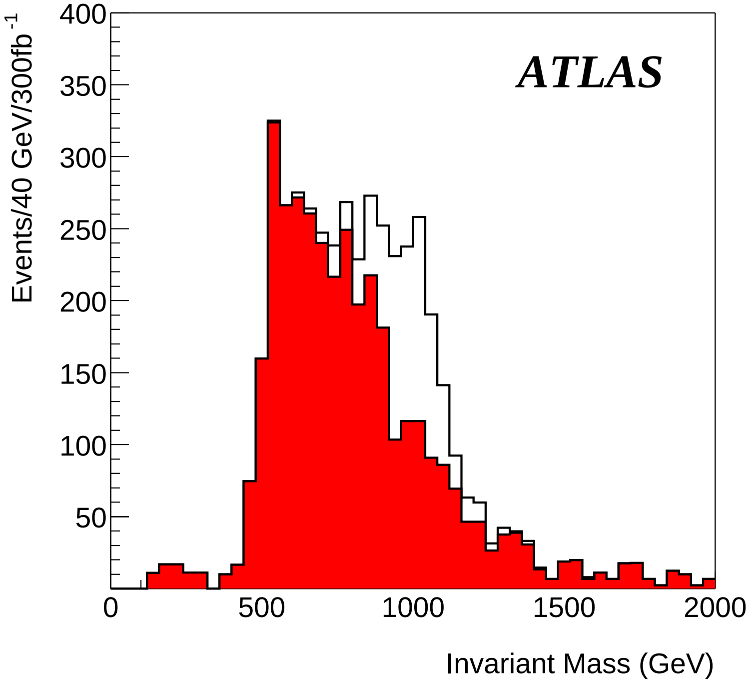

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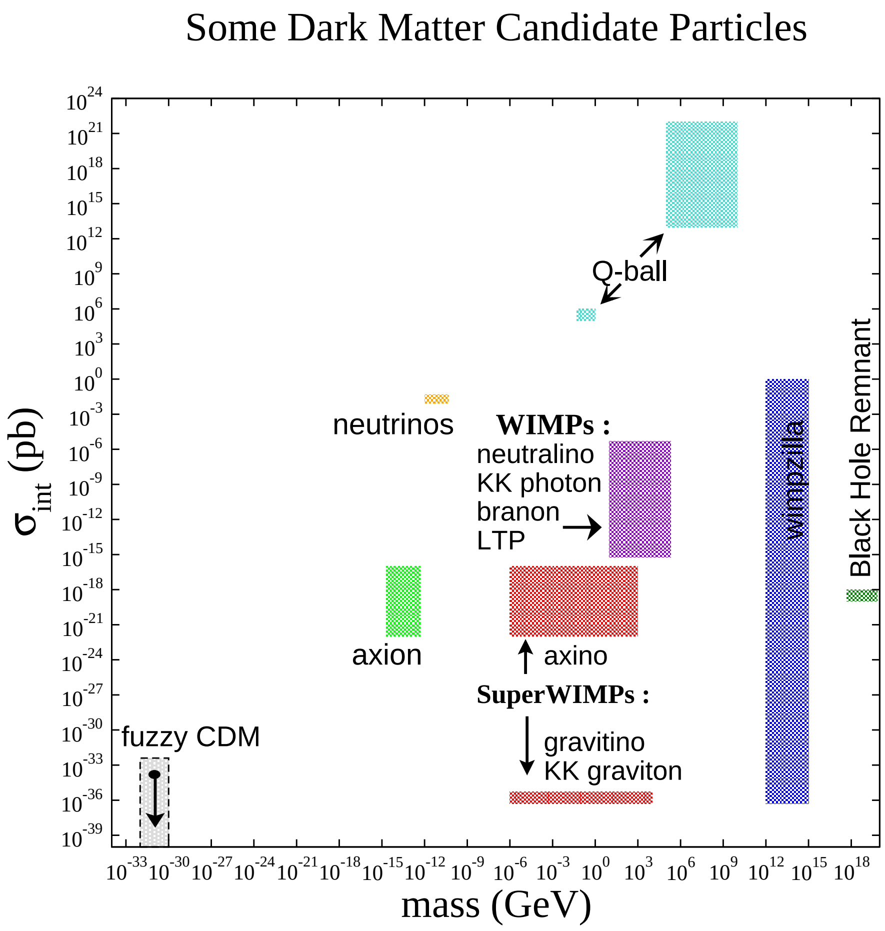
Cross-sectiions measure coupling x_λ.

Mass peak M_T determines $f:\ \ v/f = m_t/M_T(x_\lambda + x_\lambda^{-1})$

$\Longrightarrow$ check consistency with f from M_{Z_H}.

(D). LHC–Dark Matter connection:

The most likely DM candidates seem
to be of particle-physics origin, but beyond the SM. †


Some Dark Matter Candidate Particles

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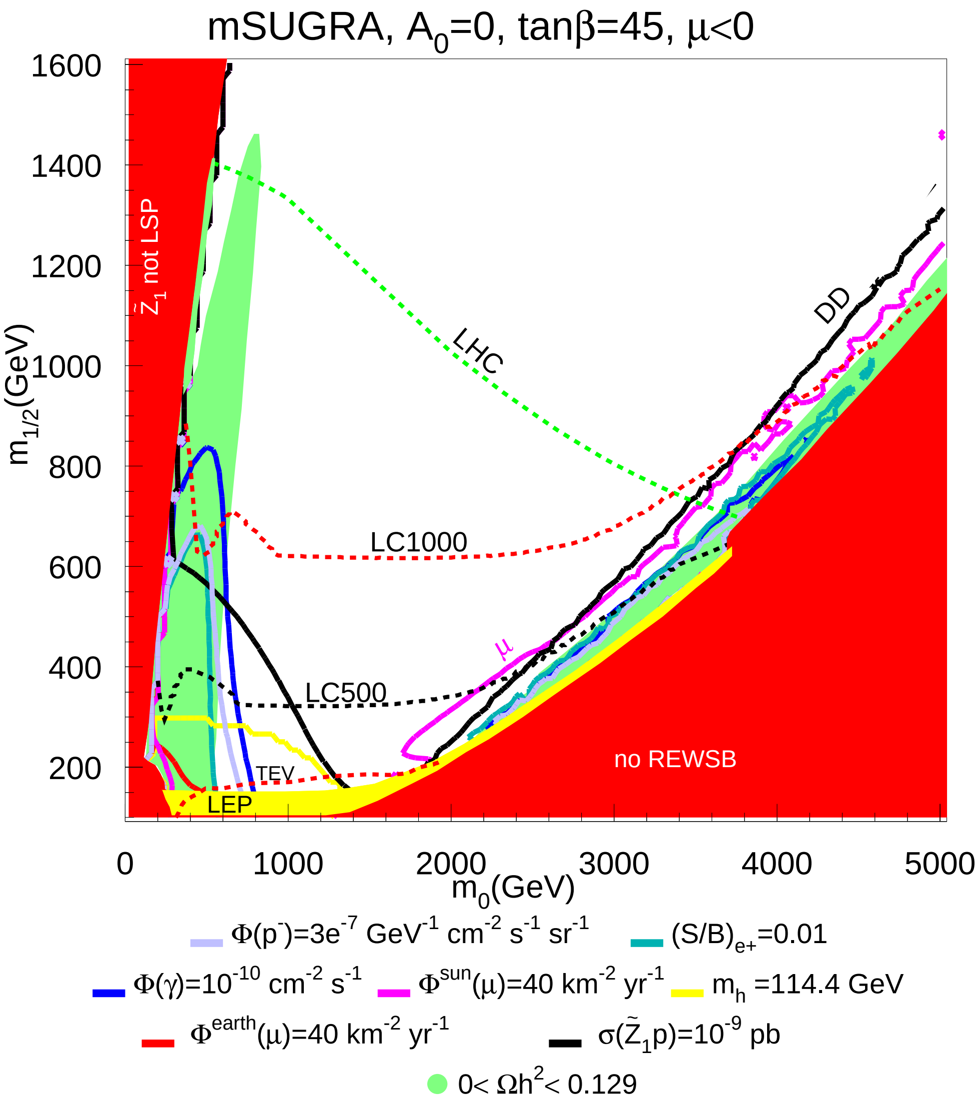
† For recent review, H.Baer and X.Tata (2008).

LHC-ILC Connection: SUSY WIMP example
Neutralino LSP as the best candidate in mSUGRA



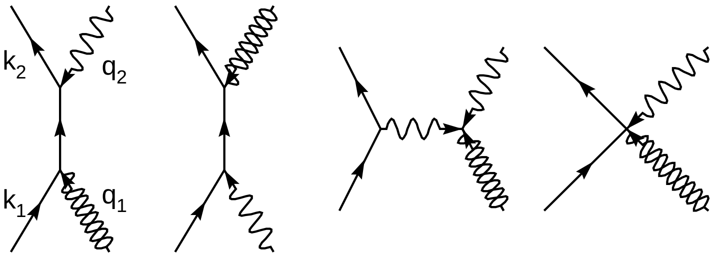
(E). Deep into extra-dimensions at the LHC:

- Collider Searches for Extra Dimensions:

A. Collider Signals I (ADD)

Real KK Emission: Missing Energy Signature

a. $e^+e^- \to \gamma + KK$ (γ+missing energy)



n – dim : at LEP2
$n = 4$ $M_S > 730$ (GeV)
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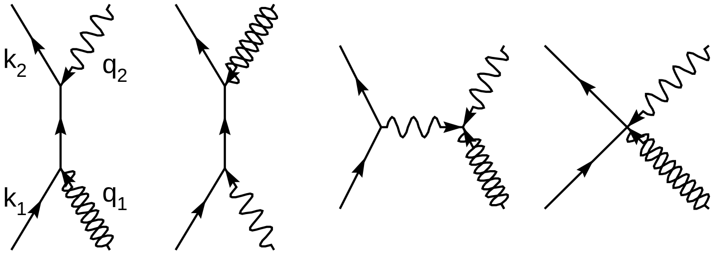

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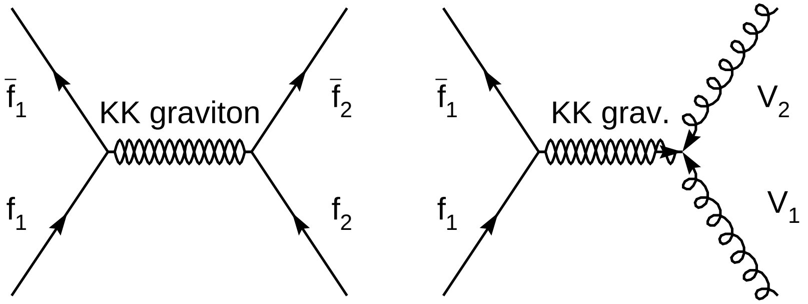
b. $p\bar{p} \to jet + KK$ (mono-jet+missing energy)

n – dim :	at Tevatron	at LHC
$n = 4$	$M_S > 900$ (GeV)	3400
$n = 6$	$M_S > 810$ (GeV)	3300

B. Collider Signals II (ADD)

Virtual KK Graviton Effects

On four-particle contact interactions:



Sum over virtual KK exchanges:

$$
\begin{aligned}
i\mathcal{M} \;&\sim\; \overline{f}\mathcal{O}_i f\;\overline{f}\mathcal{O}_j f \int_0^\infty \frac{dm^2_{\vec{n}}\;\kappa^2\rho(m_{\vec{n}})}{s - m^2_{\vec{n}} + i\epsilon} \\
&\sim\; \frac{s^2}{M_S^4}\,\overline{f}\mathcal{O}_i f\;\overline{f}\mathcal{O}_j f.
\end{aligned}
$$

Again, effective coupling $\kappa^2 \sim \frac{1}{M^2_{pl}} \to \frac{1}{M^2_S}$!

C. KK Resonant States at Colliders: (RS)

If the SM fields (photons, electrons, $Z, W, H^0 \ldots$) also propagate in extra dimensions, then they have KK excitations.

Direct search bounds:

$$M^{*}_{\gamma,Z,W} \sim \frac{1}{R} > 4 \text{ TeV}.$$

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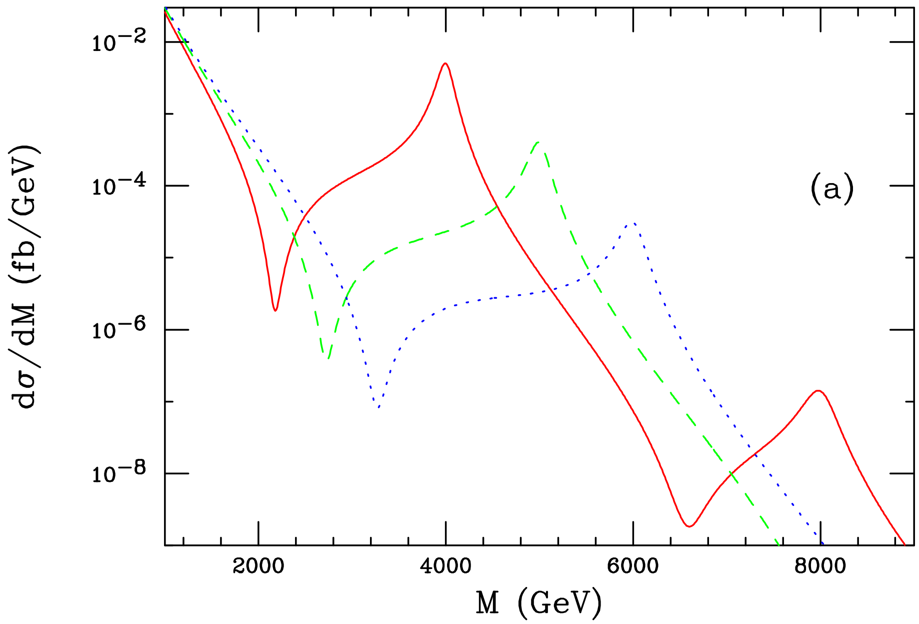
Resonant production at the LHC:



D. Stringy States at Colliders

Future colliders may reach the TeV string threshold thus directly produce the “stringy” resonant states.

Amplitude factor near the resonance

$$\mathcal{M}(s,t) \sim \frac{t}{s - nM_S^2}, \quad \text{its mass } M_n = \sqrt{n} M_S.$$

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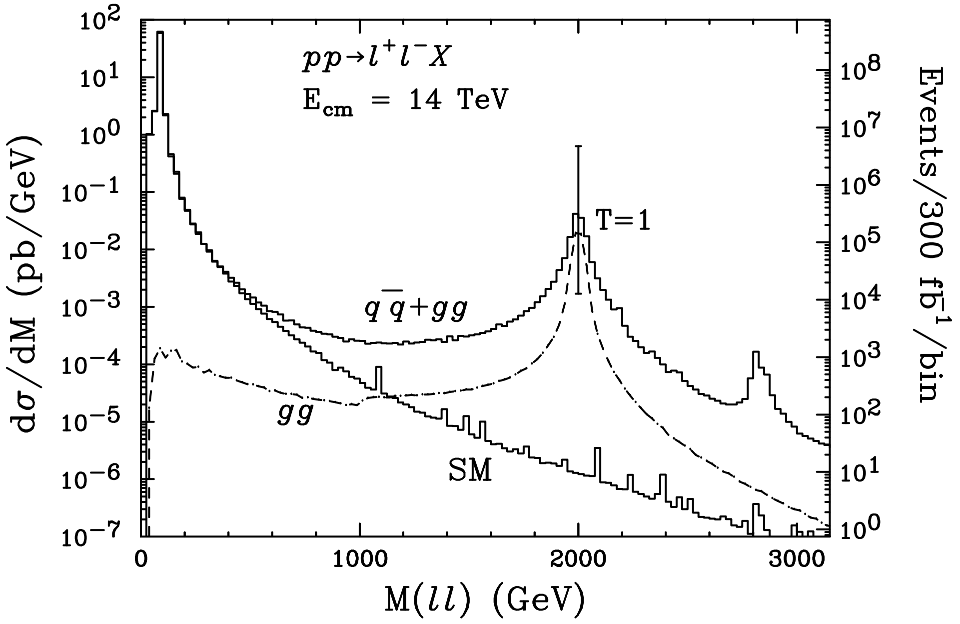
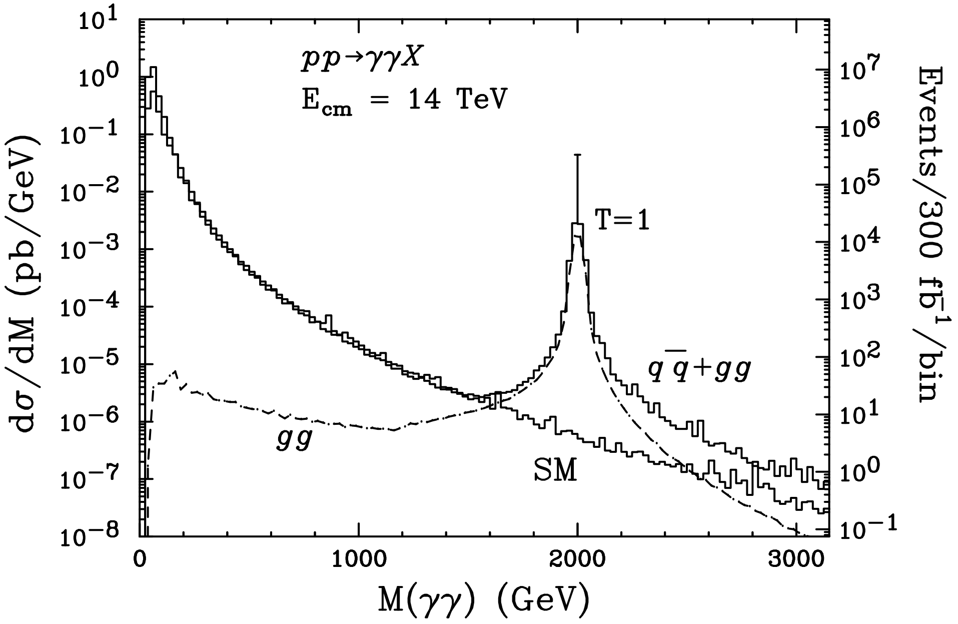
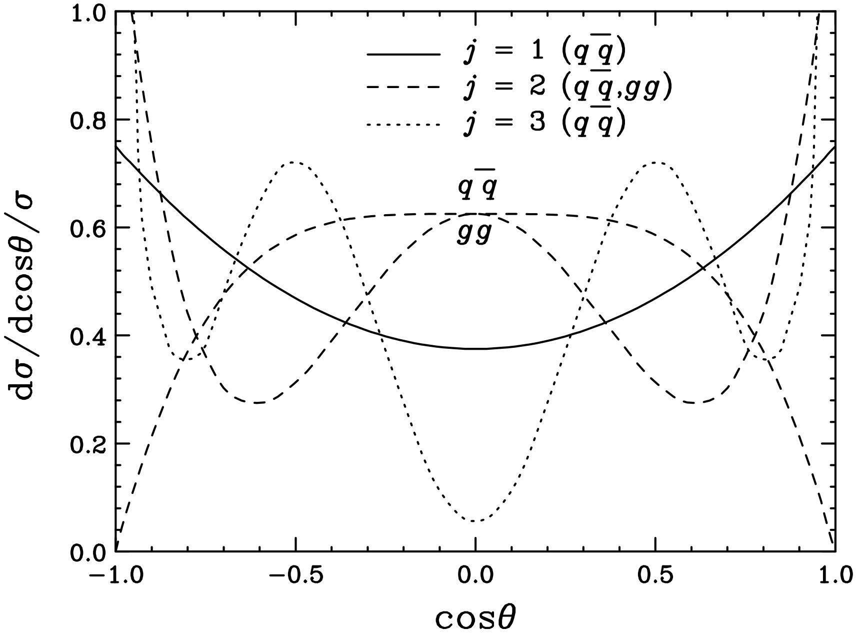


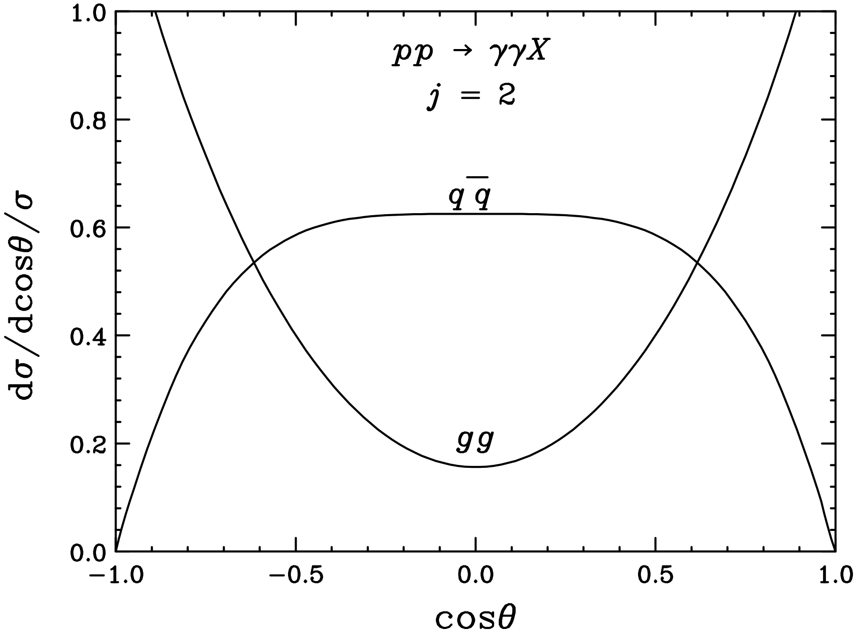


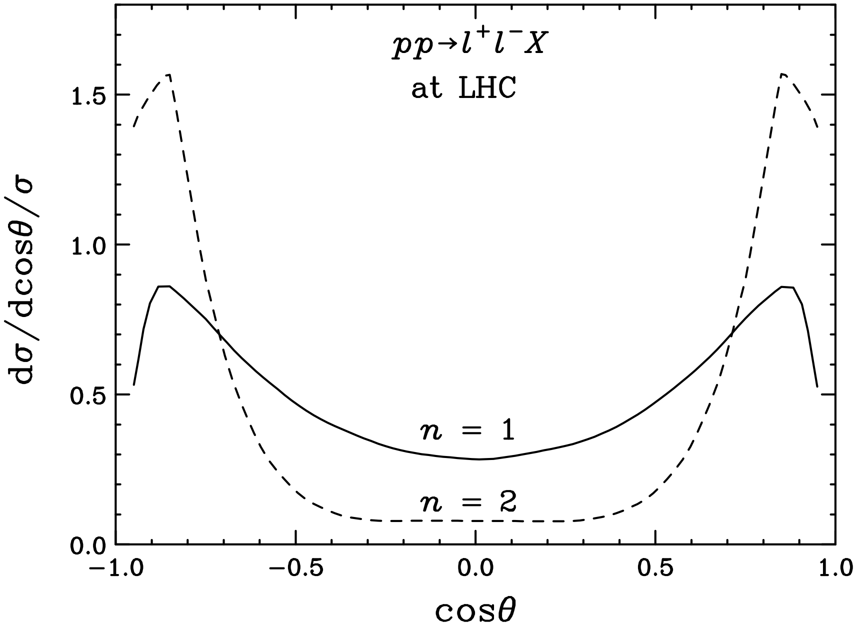
where T is an unkown gauge factor (Chan-Simon factor), typically $1-4$.
With 300 fb^{-1}, if no signal seen, we expect to reach bounds for

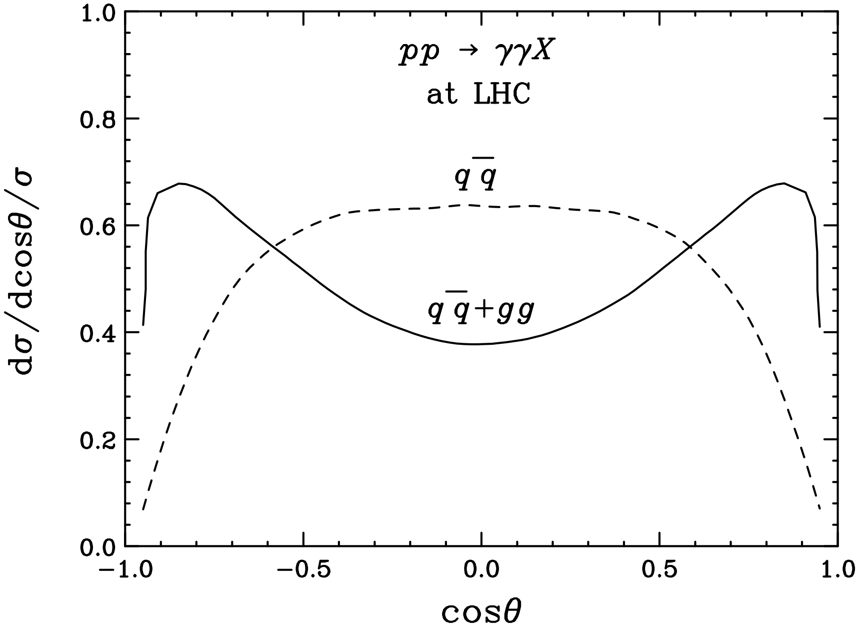
$$M_S > 8\ (10)\ \text{TeV for } T = 1-4.$$

Very rich structure of angular distributions:









E. Black Hole Production at Colliders

For a black hole of mass M_{BH}, its size is

$$r_{bh} \approx \frac{1}{M_D}\left(\frac{M_{BH}}{M_D}\right)^{\frac{1}{n+1}} \to \frac{M_{BH}}{M_{pl}^2} \text{ in 4d.}$$

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At higher energies and shorter distances (impact parameter)

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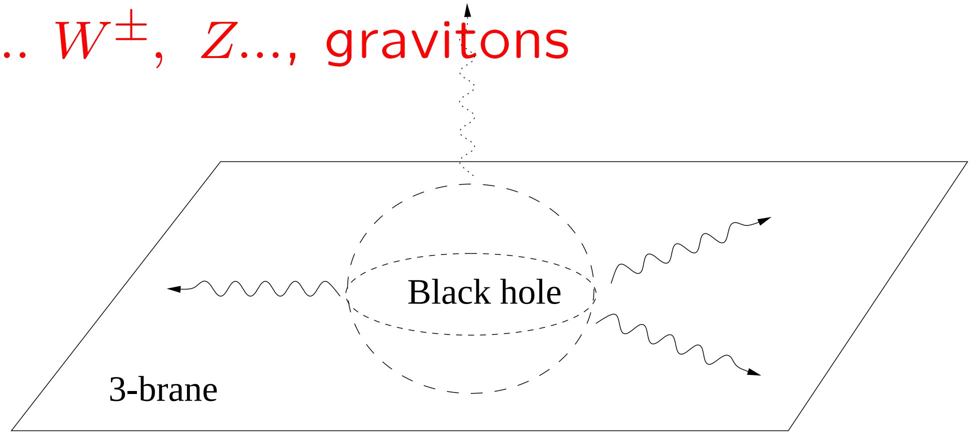
Black holes copiously produced at the LHC energies:

M_{BH}	$n = 4$	$n = 6$
5 TeV	1.6×10^5 fb	2.4×10^5 fb
7 TeV	6.1×10^3 fb	8.9×10^3 fb
10 TeV	6.9 fb	10 fb

Black holes “decay” via Hawking radiation:

$\gamma,\ \nu,\ e^{\pm},\ hadrons, \ldots\ W^{\pm},\ Z\ldots,$ gravitons



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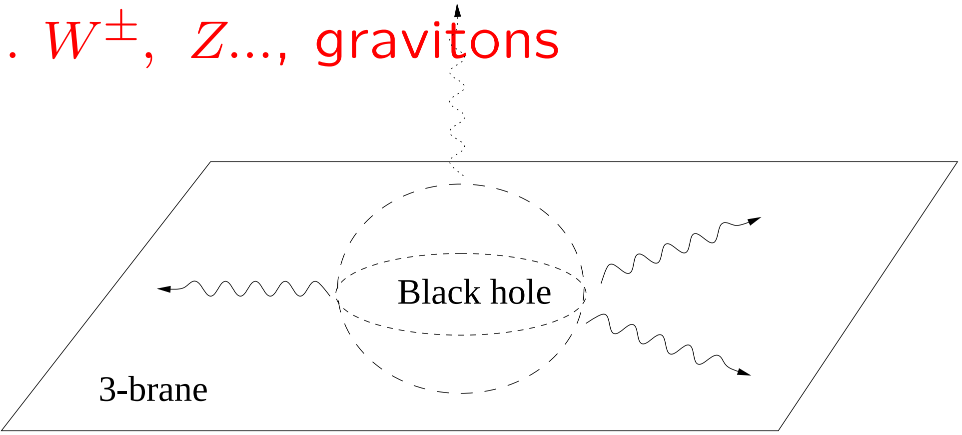

Spectacular events:

- very luminous in the detector!
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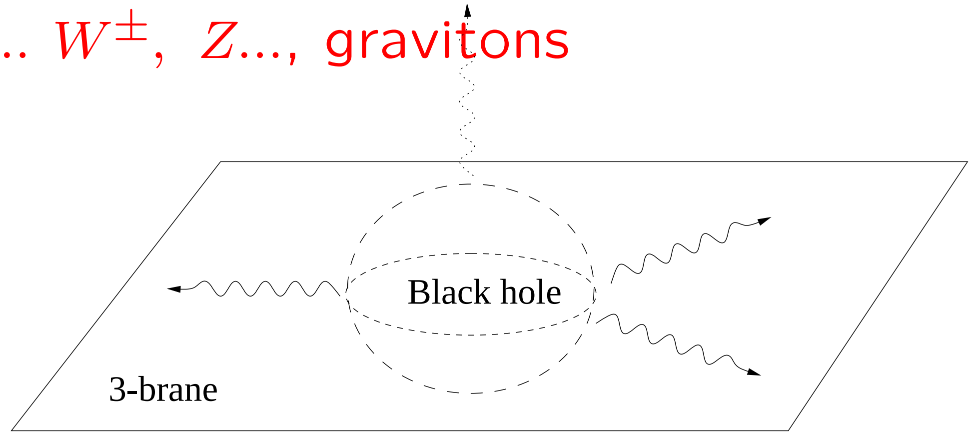

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- to the least, LHC is a "safe machine". [†]

[†] S.Giddings and M.Mangano, arXiv:0806.3381

(F). Final remarks:

(a.) Kinematics can help a lot!

Basic techniques/considerations seeking for new particles and interactions. are applicable to many new physics searches.

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Prominent examples include:

- Drell-Yan type of new particle production in s-channel:

$Z' \to \ell^+\ell^-,\ W^+W^-;\quad W' \to \ell\nu,\ W^\pm Z;$
$Z_H \to ZH;\quad W_H \to W^\pm H;$
$V^{0,\pm} \to t\bar{t},\ W^+W^-;\quad t\bar{b},\ W^\pm Z;$
heavy KK/stringy states $\to \ell^+\ell^-,\ \gamma\gamma, ...;$
single $\tilde{q},\ \tilde{\ell}$ via R parity violation.

- t-channel gauge boson fusion processes:

$W^+W^-,\ ZZ,\ W^\pm Z \to H,\ V^{0,\pm},$ light SUSY partners;
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However, at hadron collider environments, certain class of experimental signals may be way more complex than the simple examples above.

The following scenarios make the new physics identification difficult:

- A new heavy particle may undergo a complicated cascade decay, so that it is impossible to reconstruct its mass, charge etc.

For example, a typical gluino decay in SUSY theories

$$\tilde{g} \to \bar{q}\ \tilde{q} \to \bar{q}\ q'\tilde{\chi}^+ \to \bar{q}\ q'\ \tilde{\chi}^0 W^+ \to \bar{q}\ q'\ \tilde{\chi}^0\ e^+\nu.$$

- New particles involving electroweak interactions often yield weakly coupled particles in the final state, resulting in missing transverse momentum or energy, making it difficult for reconstructing the kinematics:

$$\nu's,\ \tilde{\chi}_1^0,\ \gamma_1,\ A^0,...$$

- Many new particles may be produced only in pair due to a conserved quantum number, such as the R-parity in SUSY, KK-parity in UED, and T-parity in LH, leading to a smaller production rate due to phase space suppression and more involved kinematics, lack of characteristics.

On the other hand, one may consider to take the advantage:

- Substantial missing transverse energy is an important hint
for new physics beyond the SM.

- High multiplicity of isolated high p_T particles,
such as multiple charged leptons and jets,
may indicate the production and decay of new heavy particles.

- Heavy flavor enrichment is another important feature for new physics:

$$H \to, b\bar{b}, \tau^+\tau^-;\ H^+ \to t\bar{b}, \tau^+\nu;\ \tilde{H} \to \tilde{\chi}H;\ \tilde{t} \to \tilde{\chi}^+ b, \tilde{\chi}^0 t;\ V_8, \eta_t \to t\bar{t}\ etc.$$

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Major discoveries highly anticipated at the LHC,

but get ready for the challenges !

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  new strong dynamics
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Realize the Tevatron potential!

Go LHC!

Major breakthrough ahead of us!