Collider Physics

in The LHC Era And Beyond

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Basics of Collider physics

Physics at an e^+e^- Collider

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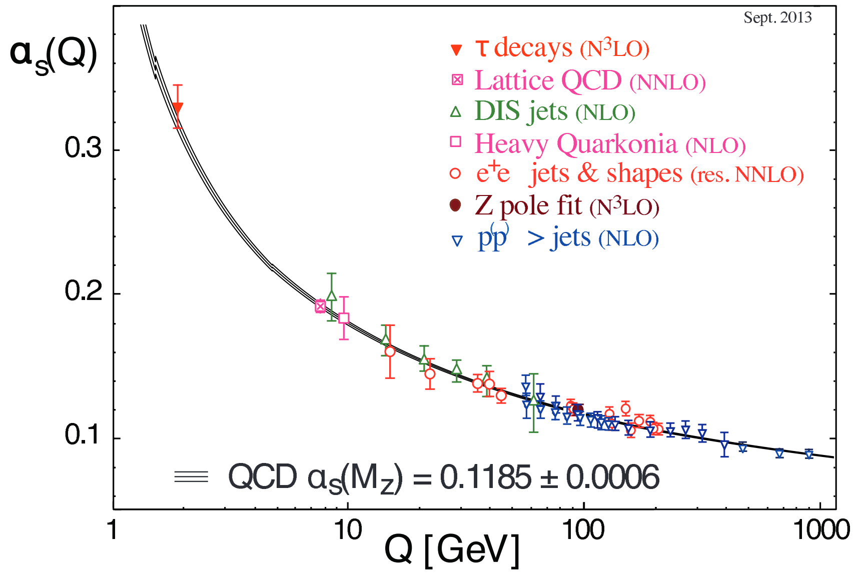
II-A. Perturbative QCD at a Glance

(A). Running of the strong coupling:

$$\alpha_s(Q^2) = \frac{\alpha_s(Q_0^2)}{1 + \frac{(33-2n_f)\alpha_s(Q_0^2)}{12\pi} \ln \frac{Q^2}{Q_0^2}} \quad (33 - 2n_f > 0), \quad \{\alpha_{em}(Q^2) = \frac{\alpha_{em}(Q_0^2)}{1 - \frac{\alpha_{em}(Q_0^2)}{3\pi} \ln \frac{Q^2}{Q_0^2}}\}$$



Significant implications (D. Gross, D. Politzer, F. Wilczek, Nobel Prize 2004):

† Confinement at low energies (hadrons: the observable world);

† Asymptotic freedom at high energies (quarks, gluons and perturbation techniques);

† Possibility of Grand Unification; Description of the early universe.

(B). Parton Distribution Functions (PDF)

• Factorization theorem: (Collins, Soper, Sterman, 1985)

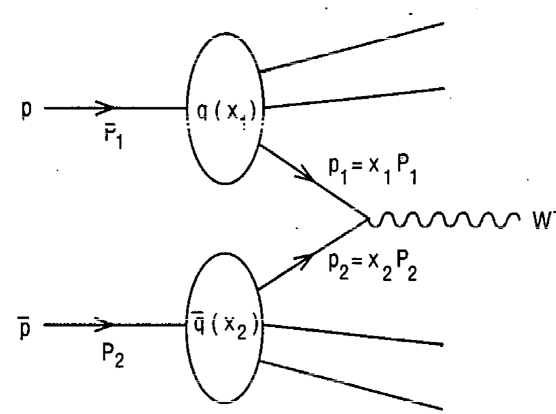
In high energy collisions involving a hadron, the total cross sections can be factorized into two factors:

(1). hard subprocess of parton scattering with a large scale $\mu^2 \gg \Lambda^2_{QCD}$;

(2). "parton distribution functions" (hadronic structure with $Q^2 < \mu^2$.)

Observable cross sections at hadron level:

$$\sigma_{pp}(S) = \int dx_1 dx_2 P_1(x_1, Q^2) P_2(x_2, Q^2)\ \hat{\sigma}_{parton}(s).$$



† $\hat{\sigma}_{parton}(s)$ is theoretically calculated by perturbation theory (in the SM or models beyond the SM).

Ultra violet (UV) divergence (beyond leading order) is renormalized;
Infra-red (IR) divergence is cancelled by soft gluon emissions;
Co-linear divergence (massless) is factorized into PDF
– The essence of "factorization theorem".

† $P(x, Q^2)$ is the "Parton Distribution Functions" (PDF): The probability of finding a parton P with a momentum fraction x inside a proton.

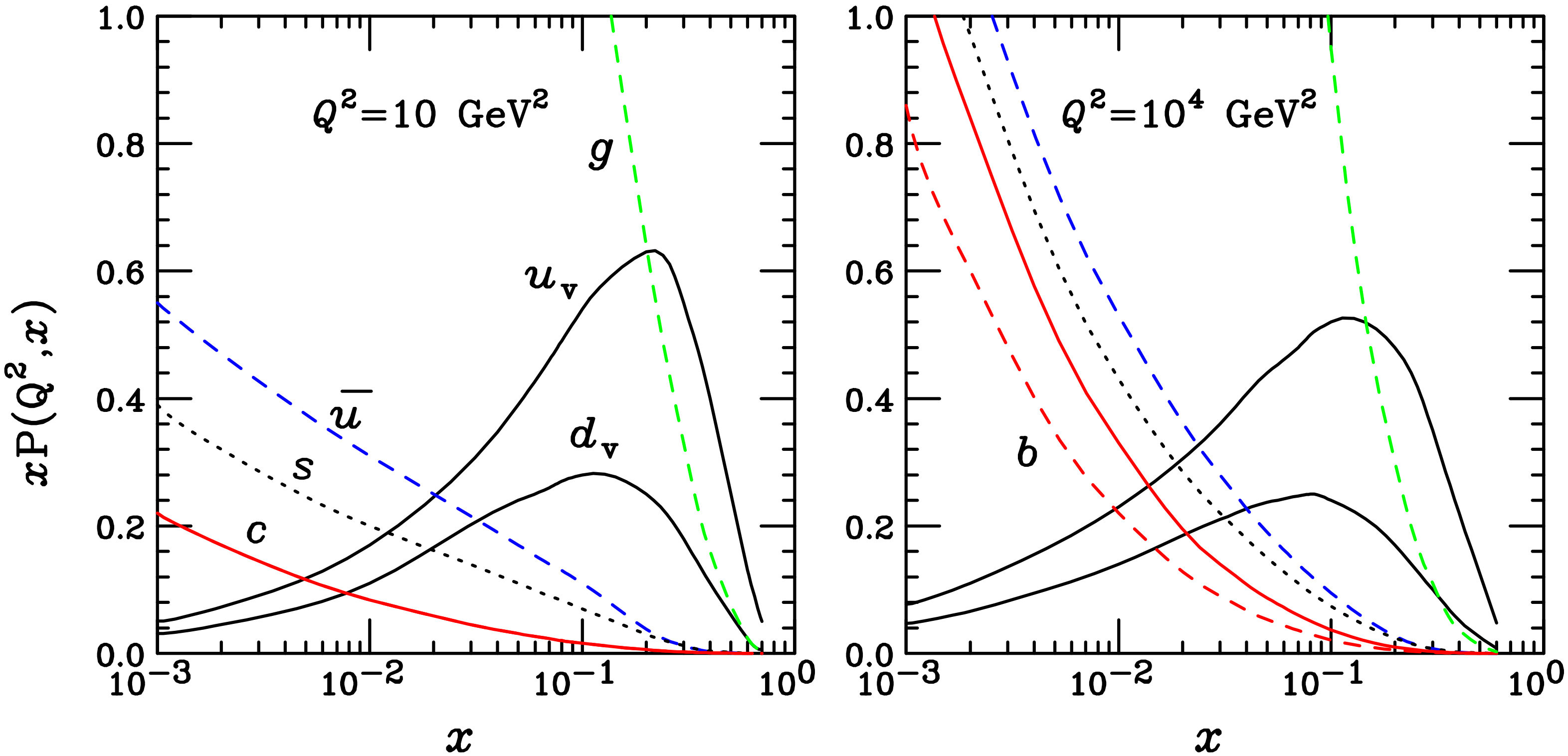
$P(x, Q^2)$ cannot be calculated from first principles, only extracted by fitting data, assuming a boundary condition at $Q_0^2 \sim (2 \text{ GeV})^2$.

The PDF's should match the parton-level cross section $\hat{\sigma}_{parton}(s)$ at a given order in α_s.

† Q^2 is the "factorization scale", below which it is collinear physics. It is NOT uniquely determined, leading to intrinsic uncertainty in QCD perturbation predictions. But its uncertainty is reduced with higher order calculations.

Several dedicated groups are developing PDF's:
CTEQ (Michigan State U.); MRSxxx (Durham U.) ... ...

Typical quark/gluon parton distribution functions:



(CTEQ-5)

Better understanding of the SM cross section, in particular in QCD are crucial for observing new physics as deviations from the SM.

(C). Jets and fragmentation functions

Upon production of a colored parton (quark/gluon):

† At the scale $\Lambda_{QCD} \sim 10^{-24}$s or 1 fm, the parton "hadronizes (fragments)" into massive, color-neutral, hadrons $\pi,\ n,\ p,\ K\ \ldots$

The "fragmentation function" is like the reverse of the PDF:

$$\frac{d\sigma(pp \to hX)}{dE_h} = \sum_q \int \frac{d\sigma(pp \to qX)}{dE_q} \frac{dE_q}{E_q} f_q^h(z, Q^2)$$

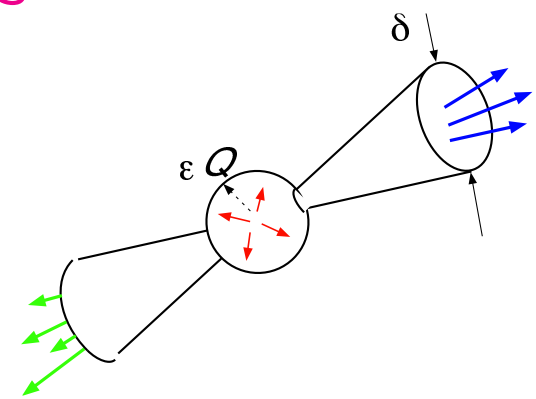
where $z = E_h/E_q$.

Non-perturbative and cann't be calculated from first principles.

† For most of the purposes in high energy collisions, we do not need to keep track of the individual hadrons, and thus the "inclusive processes".

Jets

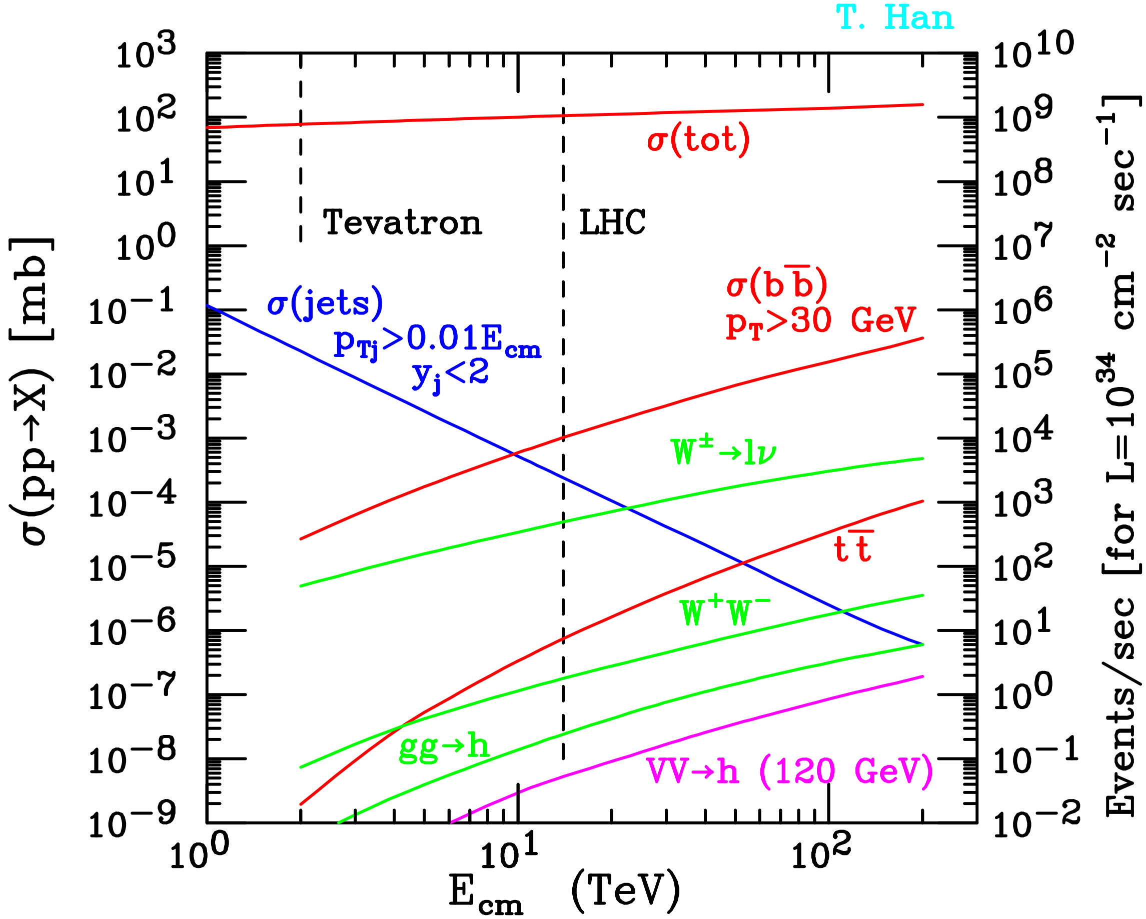
When $E_q \gg m_q$, then $\delta \approx \frac{2}{\gamma} = \frac{2m_q}{E_q}$.
It becomes a "jet", kinematically:



Need realistic algorithms to define the observable jets.

II-B. Hadron Collider Physics

LHC Event rates for various SM processes:



$10^{34}/\mathrm{cm}^2/\mathrm{s} \Rightarrow 100\ \mathrm{fb}^{-1}/\mathrm{yr}.$

Annual yield # of events $= \sigma \times L_{int}$:

10B $W^{\pm}$; 100M $t\bar{t}$; 10M $W^{+}W^{-}$; 1M H^{0}...

Discovery of the Higgs boson opened a new chapter of HEP!

Theoretical challenges:

Unprecedented energy frontier

(a) Total hadronic cross section: Non-perturbative.
The order of magnitude estimate:

$$\sigma_{pp} = \pi r_{eff}^2 \approx \pi / m_\pi^2 \sim 120 \text{ mb}.$$

Energy-dependence?

$$\sigma(pp) \begin{cases} \approx 21.7 \; (\frac{s}{\text{GeV}^2})^{0.0808} \;\; \text{mb}, & \text{Empirical relation} \\ < \frac{\pi}{m_\pi^2} \; \ln^2 \frac{s}{s_0}, & \text{Froissart bound.} \end{cases}$$

(b) Perturbative hadronic cross section:

$$\sigma_{pp}(S) = \int dx_1 dx_2 P_1(x_1, Q^2) P_2(x_2, Q^2) \; \hat{\sigma}_{parton}(s).$$

- Accurate (higher orders) partonic cross sections $\hat{\sigma}_{parton}(s)$.
- Parton distribution functions to the extreme (density):

$$Q^2 \sim (a \;\, few \;\, TeV)^2, \quad x \sim 10^{-3} - 10^{-6}.$$

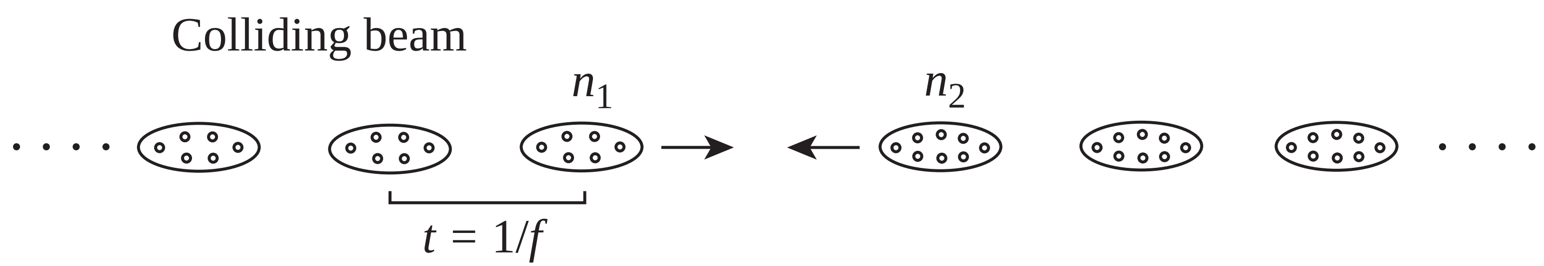
Experimental challenges:

- The large rate turns to a hostile environment:

  $\approx$ 1 billion event/sec: impossible read-off !

  $\approx$ 1 interesting event per $1,000,000$: selection (triggering).

  $\approx$ 25 overlapping events/bunch crossing:



$\Rightarrow$ Severe backgrounds!

Triggering thresholds (hardware/software):

	ATLAS	
Objects	η	p_T (GeV)
μ inclusive	2.4	6 (20)
e/photon inclusive	2.5	17 (26)
Two e's or two photons	2.5	12 (15)
1-jet inclusive	3.2	180 (290)
3 jets	3.2	75 (130)
4 jets	3.2	55 (90)
τ/hadrons	2.5	43 (65)
$\not\!\!E_T$	4.9	100
Jets+$\not\!\!E_T$	3.2, 4.9	50,50 (100,100)

$(\eta = 2.5 \Rightarrow 10^\circ; \qquad \eta = 5 \Rightarrow 0.8^\circ.)$

With optimal triggering and kinematical selections:

$p_T \geq 30 - 100$ GeV, $\quad |\eta| \leq 3 - 5; \quad \not\!\!E_T \geq 100$ GeV.

(B). Special kinematics for hadron colliders

Hadron momenta: $P_A = (E_A, 0, 0, p_A), \quad P_B = (E_A, 0, 0, -p_A),$
The parton momenta: $p_1 = x_1 P_A, \quad p_2 = x_2 P_B.$

Then the parton c.m. frame moves randomly, even by event:

$$\beta_{cm} = \frac{x_1 - x_2}{x_1 + x_2}, \quad \text{or :}$$
$$y_{cm} = \frac{1}{2}\ln\frac{1+\beta_{cm}}{1-\beta_{cm}} = \frac{1}{2}\ln\frac{x_1}{x_2}, \quad (-\infty < y_{cm} < \infty).$$

The four-momentum vector transforms as

$$\begin{pmatrix} E' \\ p'_z \end{pmatrix} = \begin{pmatrix} \gamma & -\gamma\ \beta_{cm} \\ -\gamma\ \beta_{cm} & \gamma \end{pmatrix} \begin{pmatrix} E \\ p_z \end{pmatrix}$$
$$= \begin{pmatrix} \cosh y_{cm} & -\sinh y_{cm} \\ -\sinh y_{cm} & \cosh y_{cm} \end{pmatrix} \begin{pmatrix} E \\ p_z \end{pmatrix}.$$

This is often called the "boost".

One wishes to design final-state kinematics invariant under the boost:
For a four-momentum $p \equiv p^\mu = (E, \vec{p})$,

$$\begin{aligned} E_T &= \sqrt{p_T^2 + m^2}, \quad y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}, \\ p^\mu &= (E_T \cosh y,\ p_T \sin\phi,\ p_T \cos\phi,\ E_T \sinh y), \\ \frac{d^3\vec{p}}{E} &= p_T dp_T d\phi\ dy = E_T dE_T d\phi\ dy. \end{aligned}$$

Due to random boost between Lab-frame/c.m. frame event-by-event,

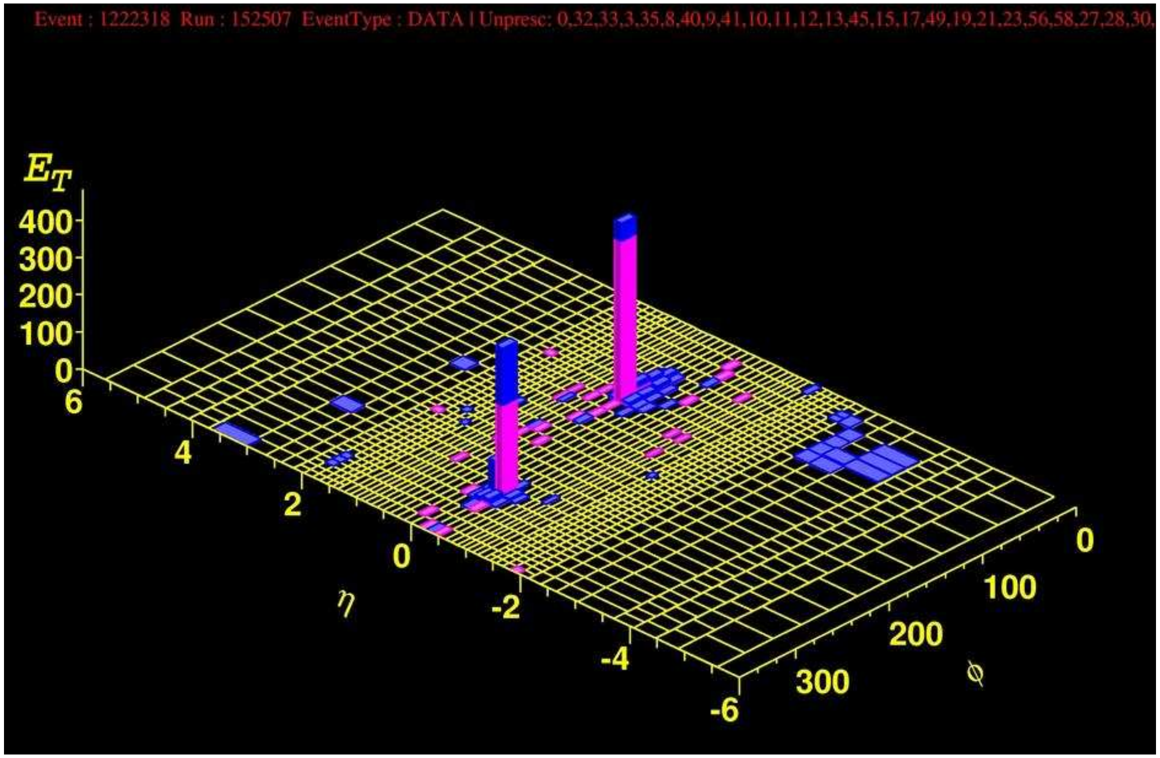
$$y' = \frac{1}{2}\ln\frac{E'+p'_z}{E'-p'_z} = \frac{1}{2}\ln\frac{(1-\beta_{cm})(E+p_z)}{(1+\beta_{cm})(E-p_z)} = y - y_{cm}.$$

In the massless limit, rapidity $\to$ pseudo-rapidity:

$$y \to \eta = \frac{1}{2}\ln\frac{1+\cos\theta}{1-\cos\theta} = \ln\cot\frac{\theta}{2}.$$

`Exercise 4.1:  Verify all the above equations.`

The “Lego” plot:



A CDF di-jet event on a lego plot in the $\eta - \phi$ plane.

$\phi, \Delta y = y_2 - y_1$ is boost-invariant.

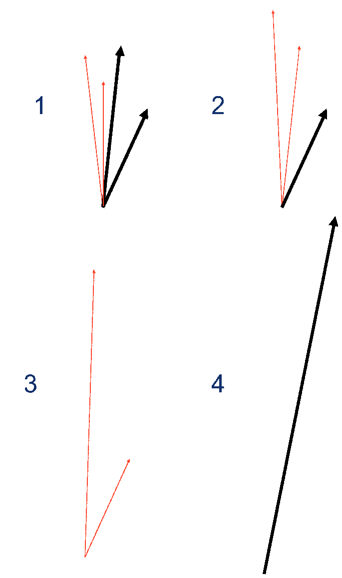
Thus the “separation” between two particles in an event

$$\Delta R = \sqrt{\Delta\phi^2 + \Delta y^2}$$ is boost-invariant,

and lead to the “cone definition” of a jet.

The Jets! Alternative algorithms: Successive combination

- Given a cluster of proto-jets, $i = 1, 2, ..., n,$ pick an initial pair $i, j.$



- Calculate their "beam distance" $d_i =$
and angular separation $\Delta R^2 = \Delta\phi^2 +$

- With respect to an angular resolutio
define a "pair distance"

$$d_{ij} = min(d_i, d$$

- If $d_{ij} < d_i, d_j,$ then combine $p_i + p_j$ in

- If d_i $(d_j) < d_{ij},$ then leave the proto-jet i (j) alone as a "finished jet".

Repeat this procedure until every proto-jet becomes a finished jet.

† Cambridge-Aachen algorithm: $d_i = 1.$ (the cone algorithm)

† k_T-algorithm: $d_i = p_{Ti}^2.$ (d_{ij} is the relative p_T^2 between i and j)

† Anti-k_T-algorithm: $d_i = p_{Ti}^{-2}.$ (higher pT proto-jet serves as the seed)

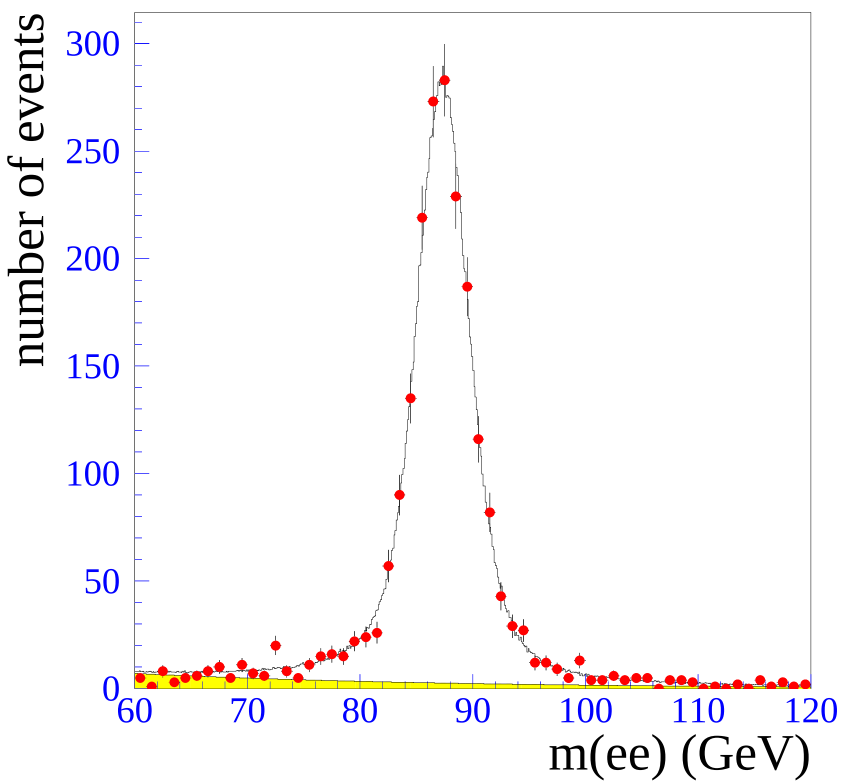
(C). Kinematical features:

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

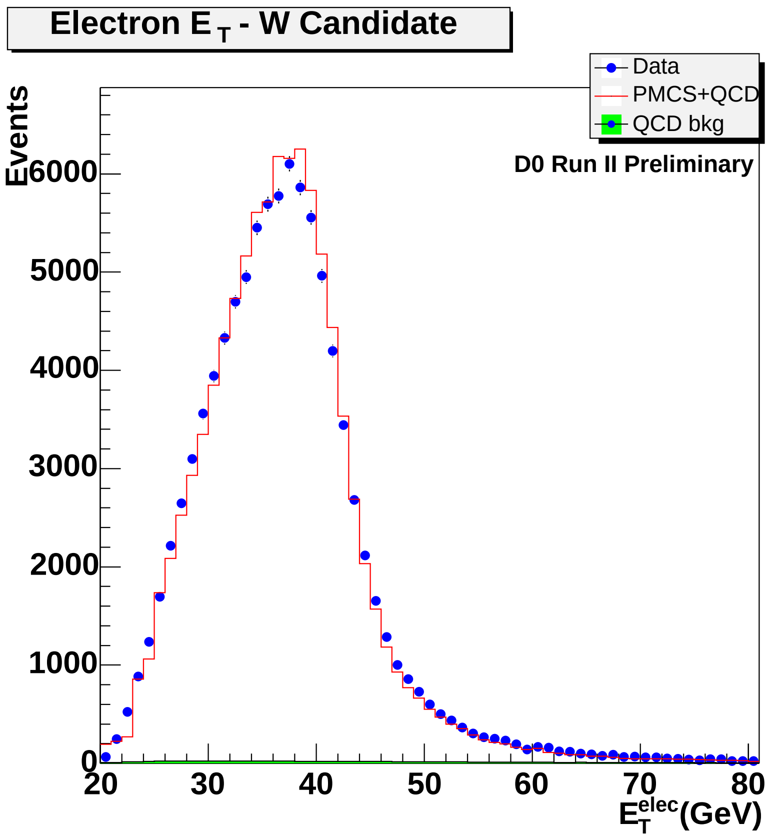
- invariant mass of two-body $R \to ab$: $m_{ab}^2 = (p_a + p_b)^2 = M_R^2$.

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

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



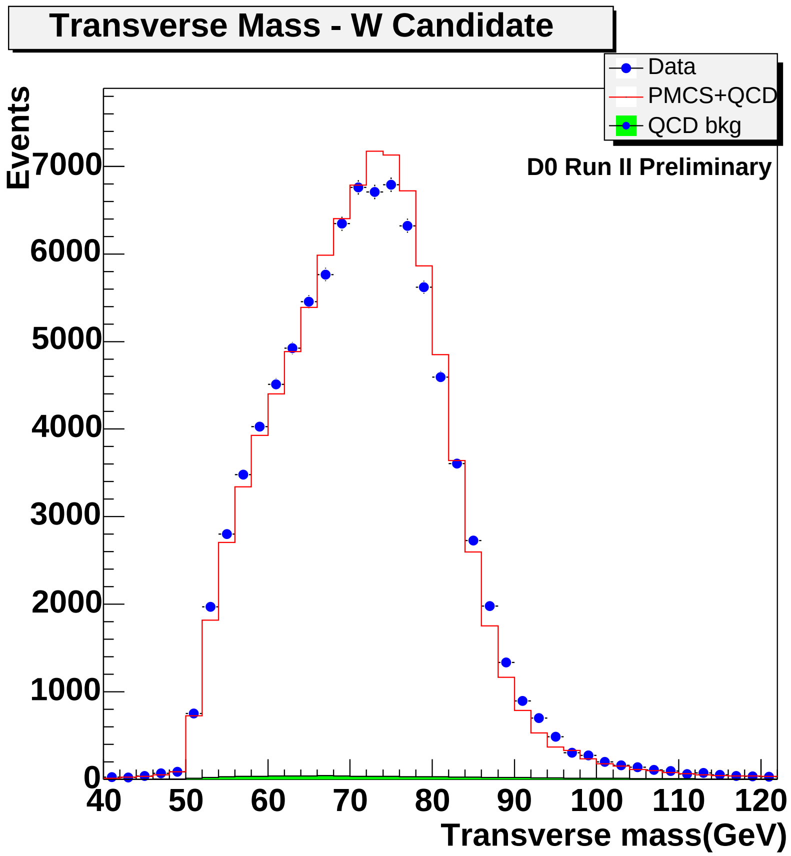
$Z \to e^+e^-$

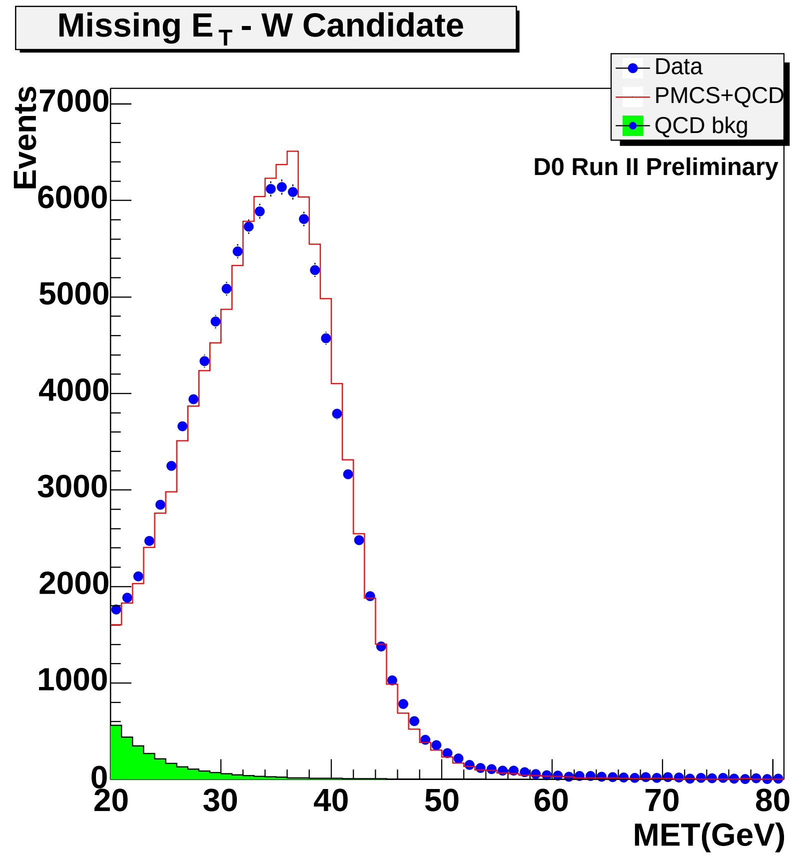


$W \to e\nu$

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

$$m_{e\nu\ T}^2 = (E_{eT} + E_{\nu T})^2 - (\vec{p}_{eT} + \vec{p}_{\nu T})^2$$
$$= 2E_{eT}E_T^{miss}(1 - \cos\phi) \leq m_{e\nu}^2.$$





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:

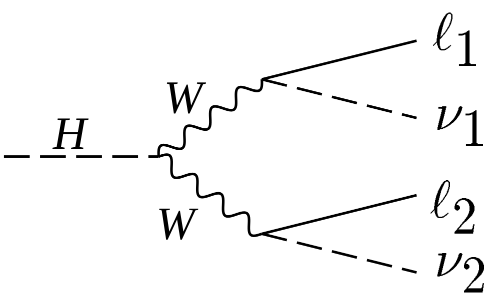
$$p'_{eT} \sim p_{eT}\ [1 + \delta P_V/M_V],$$
$$m'^2_{e\nu\ T} \sim m^2_{e\nu\ T}\ [1 - (\delta P_V/M_V)^2],$$
$$m'^2_{ee} = m^2_{ee}.$$

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

cluster transverse mass (I):

$$m^2_{WW\ T} = (E_{W_1T} + E_{W_2T})^2 - (\vec{p}_{jjT} + \vec{p}_{eT} + \vec{p}_T^{\,miss})^2$$
$$= (\sqrt{p^2_{jjT} + M^2_W} + \sqrt{p^2_{e\nu T} + M^2_W})^2 - (\vec{p}_{jjT} + \vec{p}_{eT} + \vec{p}_T^{\,miss})^2 \le M^2_H.$$

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



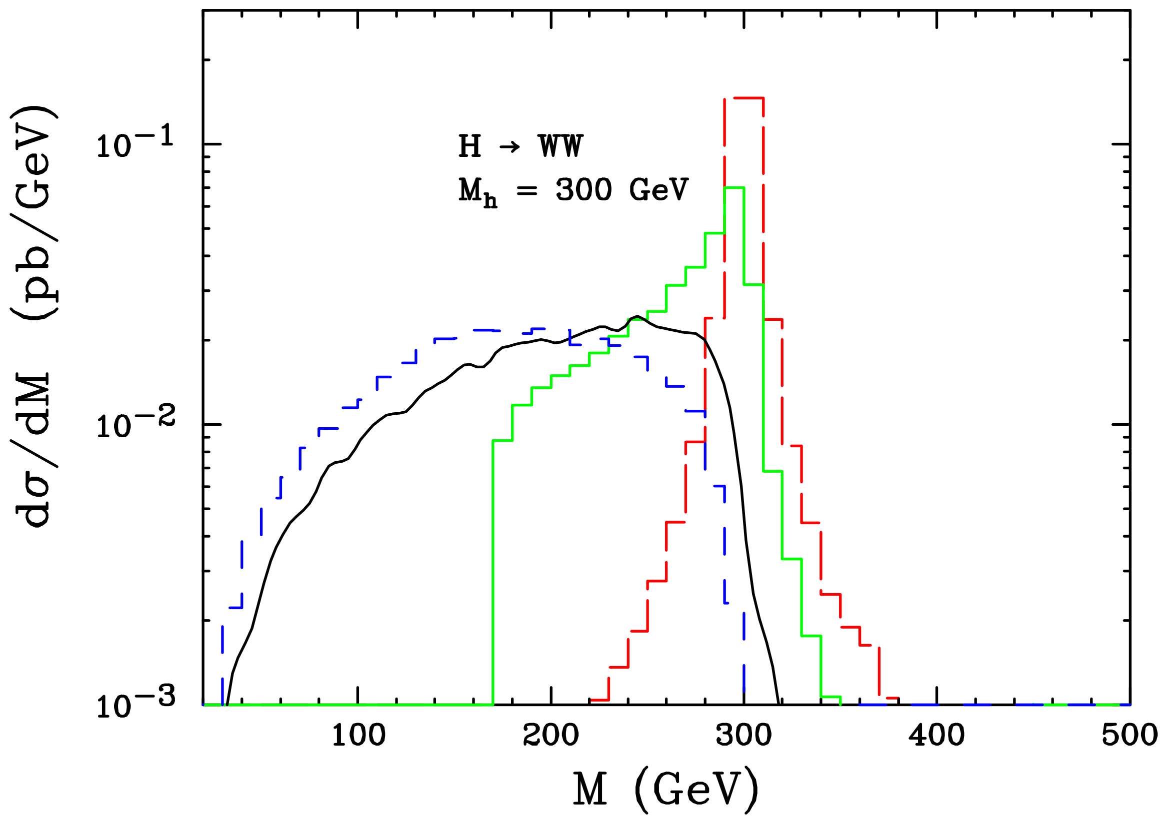
- $H^0 \to W^+W^- \to e^+\nu_e\ e^-\bar{\nu}_e$:

"effecive" transverse mass:

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

cluster transverse mass (II):

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



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): - - - - - - - -

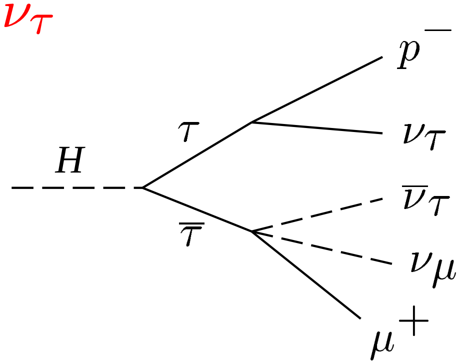
$M_{WW,\,C}$ cluster trans. mass (two missing particles): ————————

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 $\nu's$?



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

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

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

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

$$T \to W b \to \ell\nu, \; b.$$

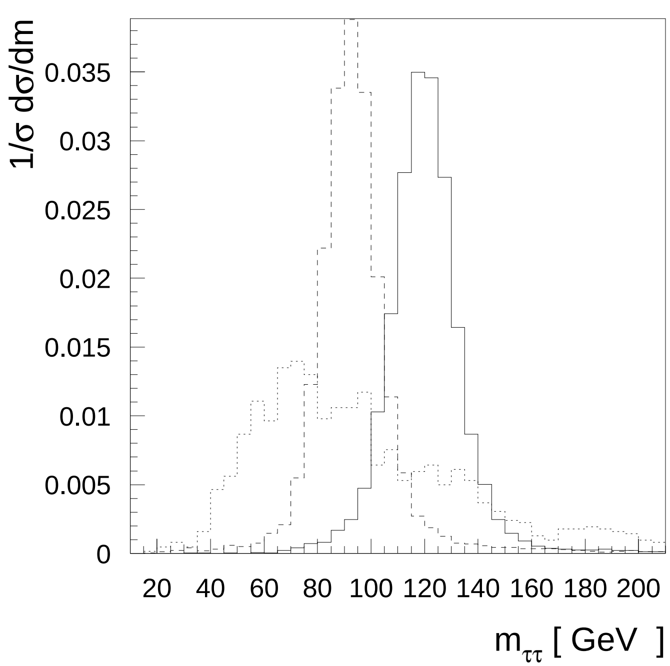
Experimental measurements: p_{ρ^-}, p_{μ^+}, $\not{p}_T$:

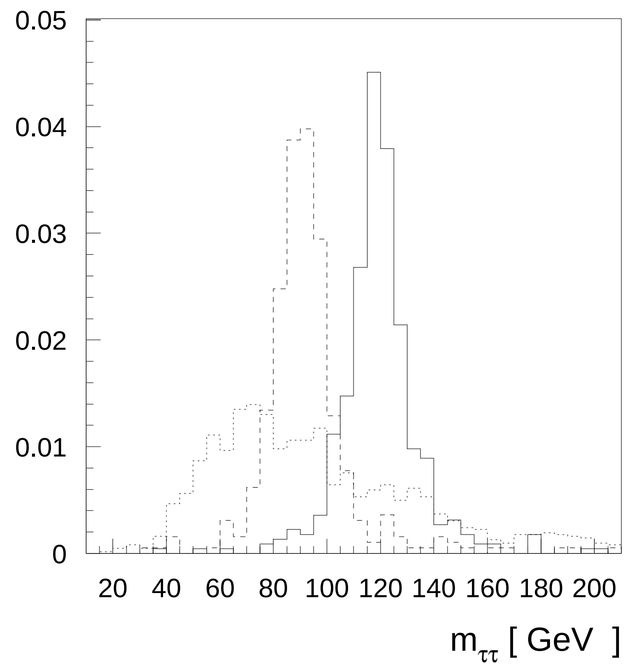
$$c_+(p_{\mu^+})_x + c_-(p_{\rho^-})_x = (\not{p}_T)_x,$$
$$c_+(p_{\mu^+})_y + c_-(p_{\rho^-})_y = (\not{p}_T)_y.$$

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.





(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: $E_\mu^0 = \frac{M_{\tilde{\mu}_R}^2 - m_\chi^2}{2M_{\tilde{\mu}_R}}$.

In the Lab-frame:

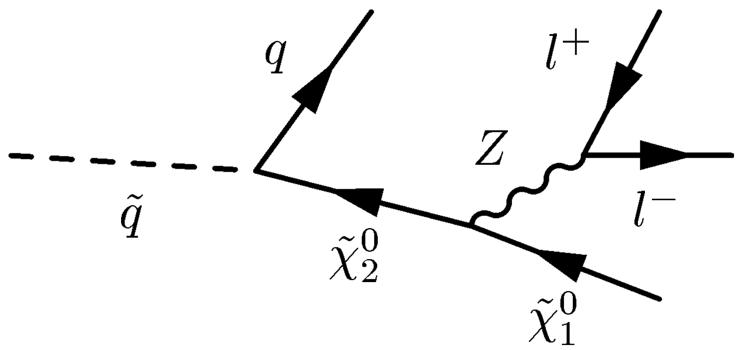
$$(1-\beta)\gamma E_\mu^0 \le E_\mu^{lab} \le (1+\beta)\gamma E_\mu^0$$
$$\text{with} \quad \beta = \left(1 - 4M_{\tilde{\mu}_R}^2/s\right)^{1/2}, \quad \gamma = (1-\beta)^{-1/2}.$$

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 ...

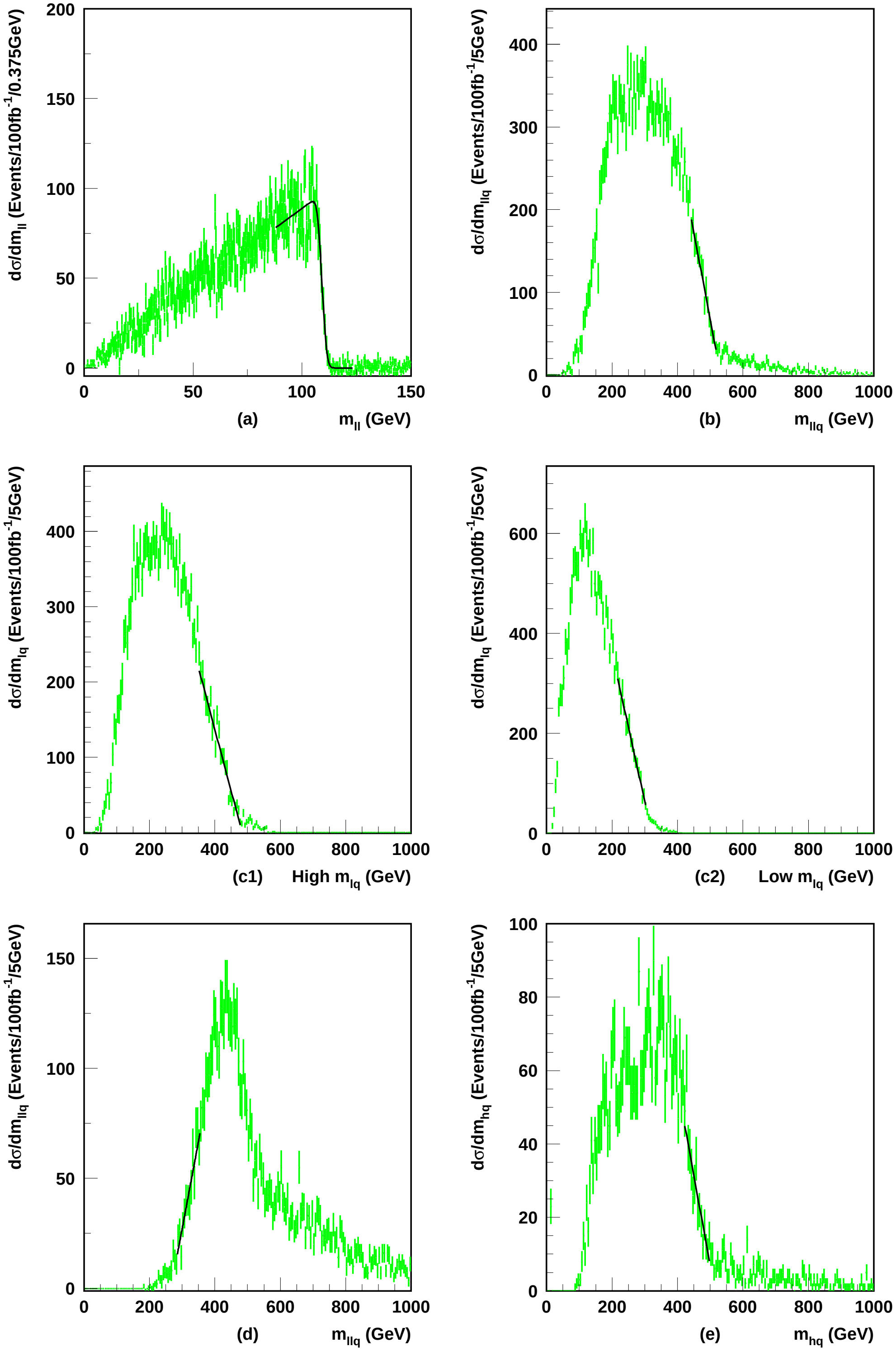
Consider a squark cascade decay:



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

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

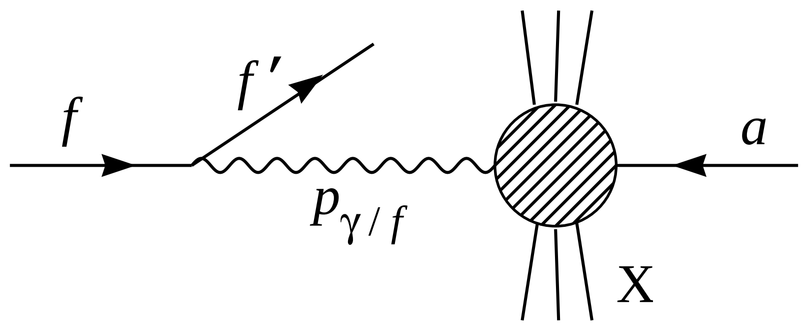
`Exercise 5.4:  Verify these relations.`


dσ/dm_ll (Events/100fb^-1/0.375GeV)
m_ll (GeV)
(a)
dσ/dm_llq (Events/100fb^-1/5GeV)
m_llq (GeV)
(b)
dσ/dm_lq (Events/100fb^-1/5GeV)
(c1)
High m_lq (GeV)
dσ/dm_lq (Events/100fb^-1/5GeV)
(c2)
Low m_lq (GeV)
dσ/dm_llq (Events/100fb^-1/5GeV)
(d)
m_llq (GeV)
dσ/dm_hq (Events/100fb^-1/5GeV)
(e)
m_hq (GeV)

(c). t-channel singularity: splitting.

- Gauge boson radiation off a fermion:

The familiar Weizsäcker-Williams approximation



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

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

† 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:

$$P^T_{V/f}(x,p_T^2) = \frac{g_V^2+g_A^2}{8\pi^2}\,\frac{1+(1-x)^2}{x}\,\frac{p_T^2}{(p_T^2+(1-x)M_V^2)^2},$$
$$P^L_{V/f}(x,p_T^2) = \frac{g_V^2+g_A^2}{4\pi^2}\,\frac{1-x}{x}\,\frac{(1-x)M_V^2}{(p_T^2+(1-x)M_V^2)^2}.$$

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

At low-p_{jT},

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

At high-p_{jT},

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

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

(D). 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:

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

Perfectly fine for Z/Z'-type:

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

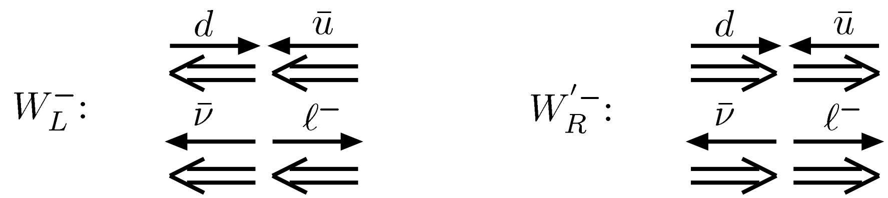
In pp collisions, however, what is the direction of $\vec{p}_{quark}$?

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

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

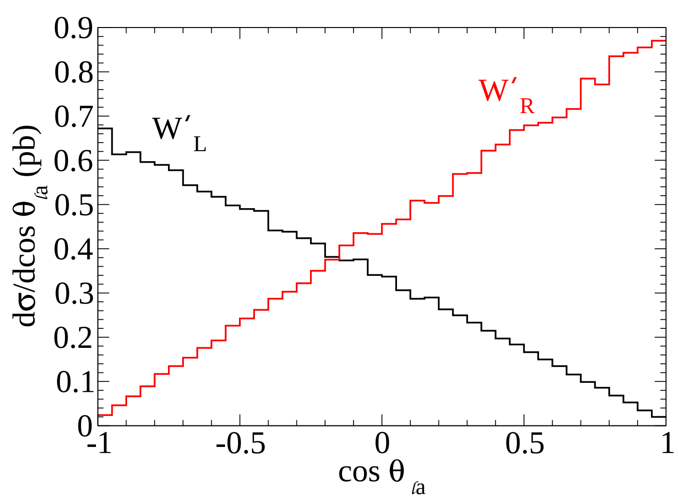
In $p\bar{p}$ collisions, $\vec{p}_{proton}$ is the direction of $\vec{p}_{quark}$,
AND ℓ^{+} (ℓ^{-}) along the direction with $\bar{q}$ (q) $\Rightarrow$ OK at the Tevatron,

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)

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



(E). CP asymmetries A_{CP}:

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

Definition: A_{CP} vanishes if CP-violation interactions do not exist (for the relevant particles involved).

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

Two ways:

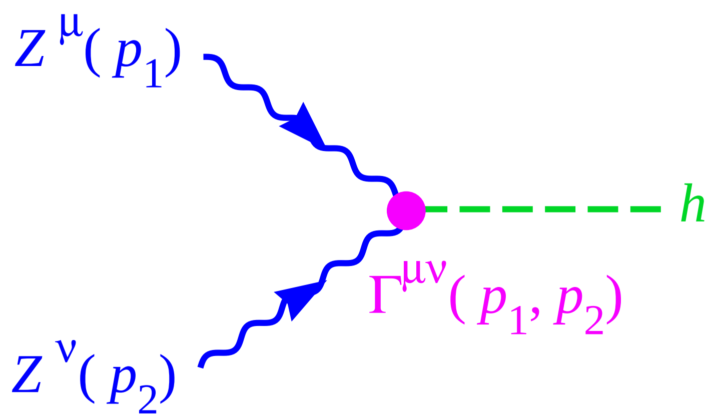
a). Compare the rates between a process and its CP-conjugate process:

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

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

$$\mathcal{M} \sim M_1 + M_2 \sin\theta,$$
$$A_{CP} = \sigma^F - \sigma^B = \int_0^1 \frac{d\sigma}{d\cos\theta} d\cos\theta - \int_{-1}^0 \frac{d\sigma}{d\cos\theta} d\cos\theta$$

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:

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

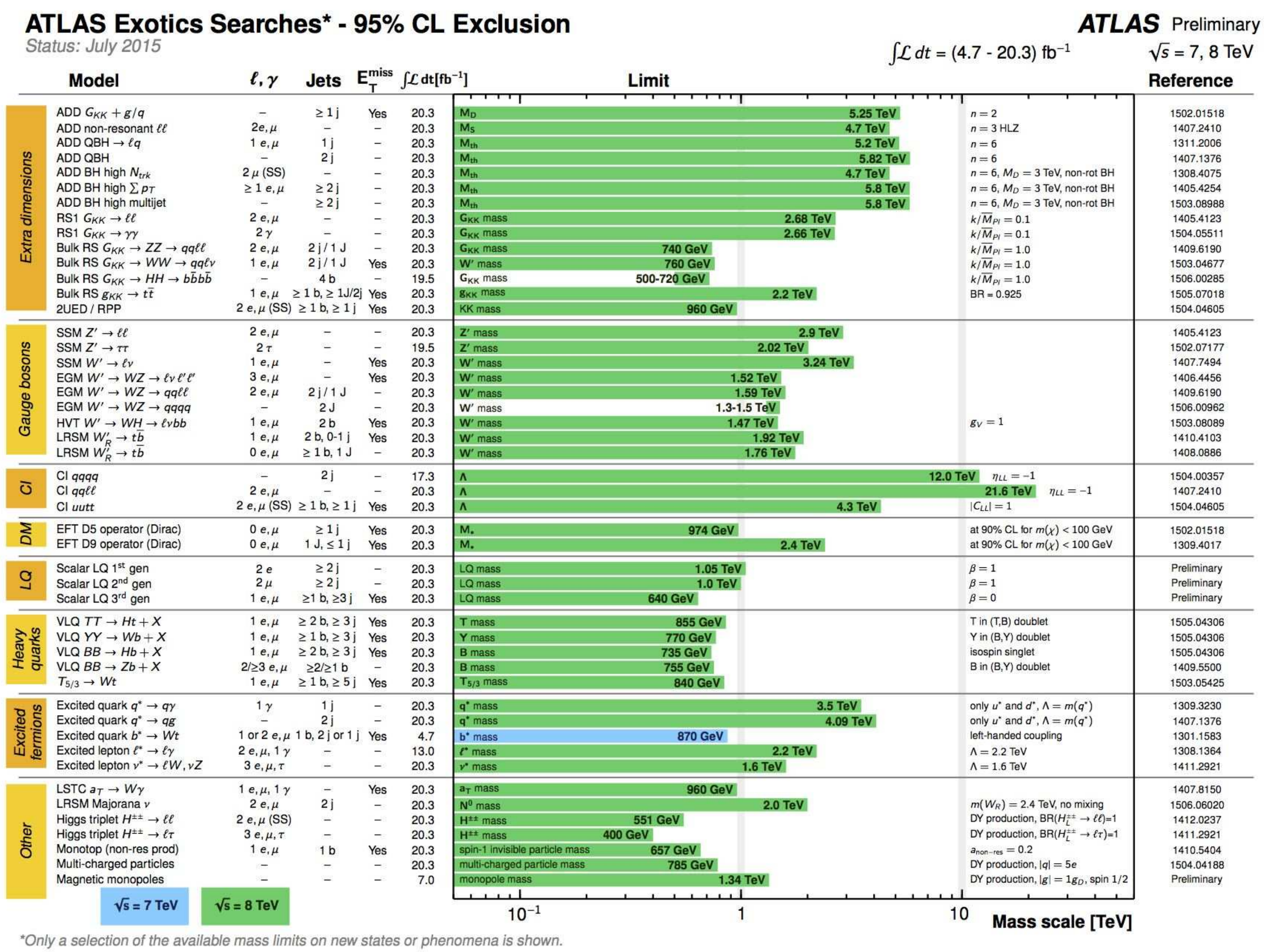
E.g. 2: $H \to t(p_t)\bar{t}(p_{\bar{t}}) \to e^+(q_1)\nu_1 b_1,\ e^-(q_2)\nu_2 b_2.$

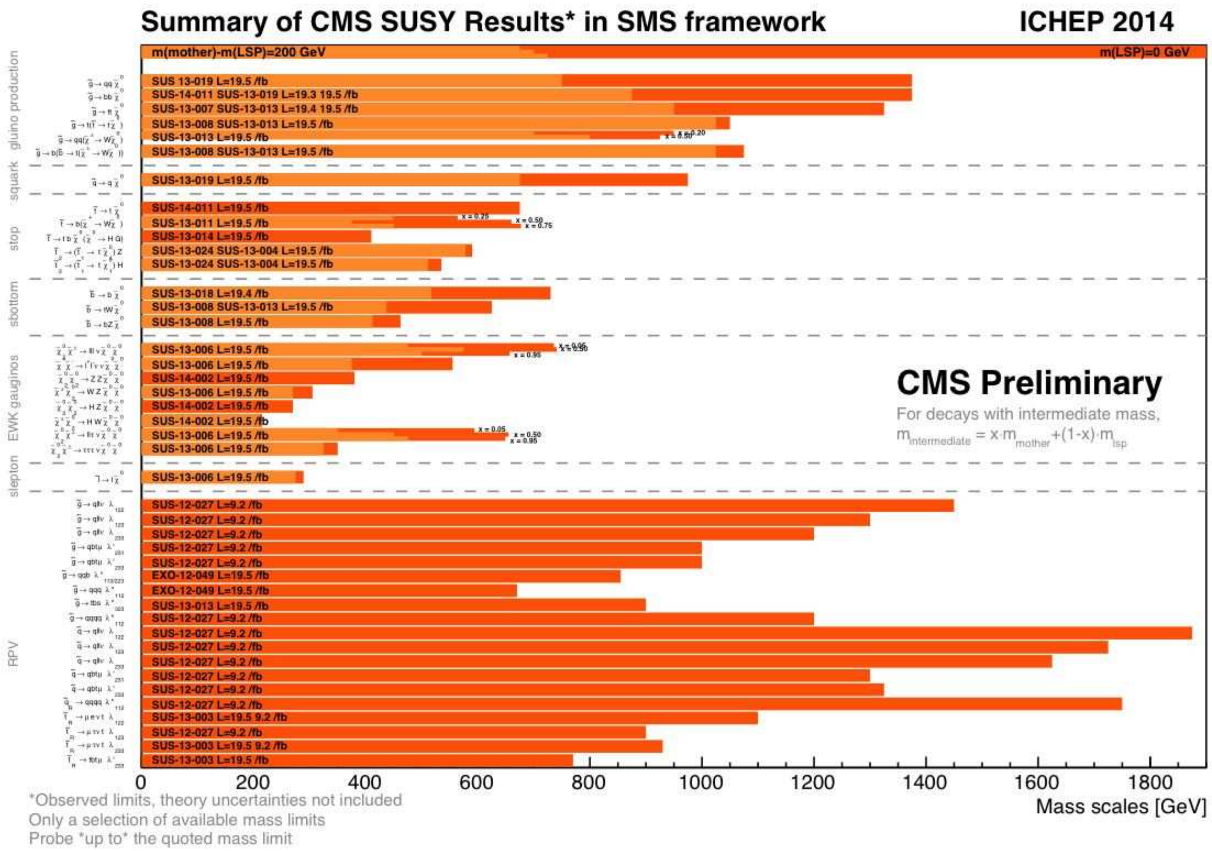
$$-\frac{m_t}{v}\bar{t}(a + b\gamma^5)t\ H$$
$$O_{CP} \sim (\vec{p}_t - \vec{p}_{\bar{t}}) \cdot (\vec{p}_{e^+} \times \vec{p}_{e^-}).$$

thus define an asymmetry angle.

II-C. Physics Perspectives at a 100-TeV Hadron Collider (3–30 ab^{-1})

Current LHC Searches:



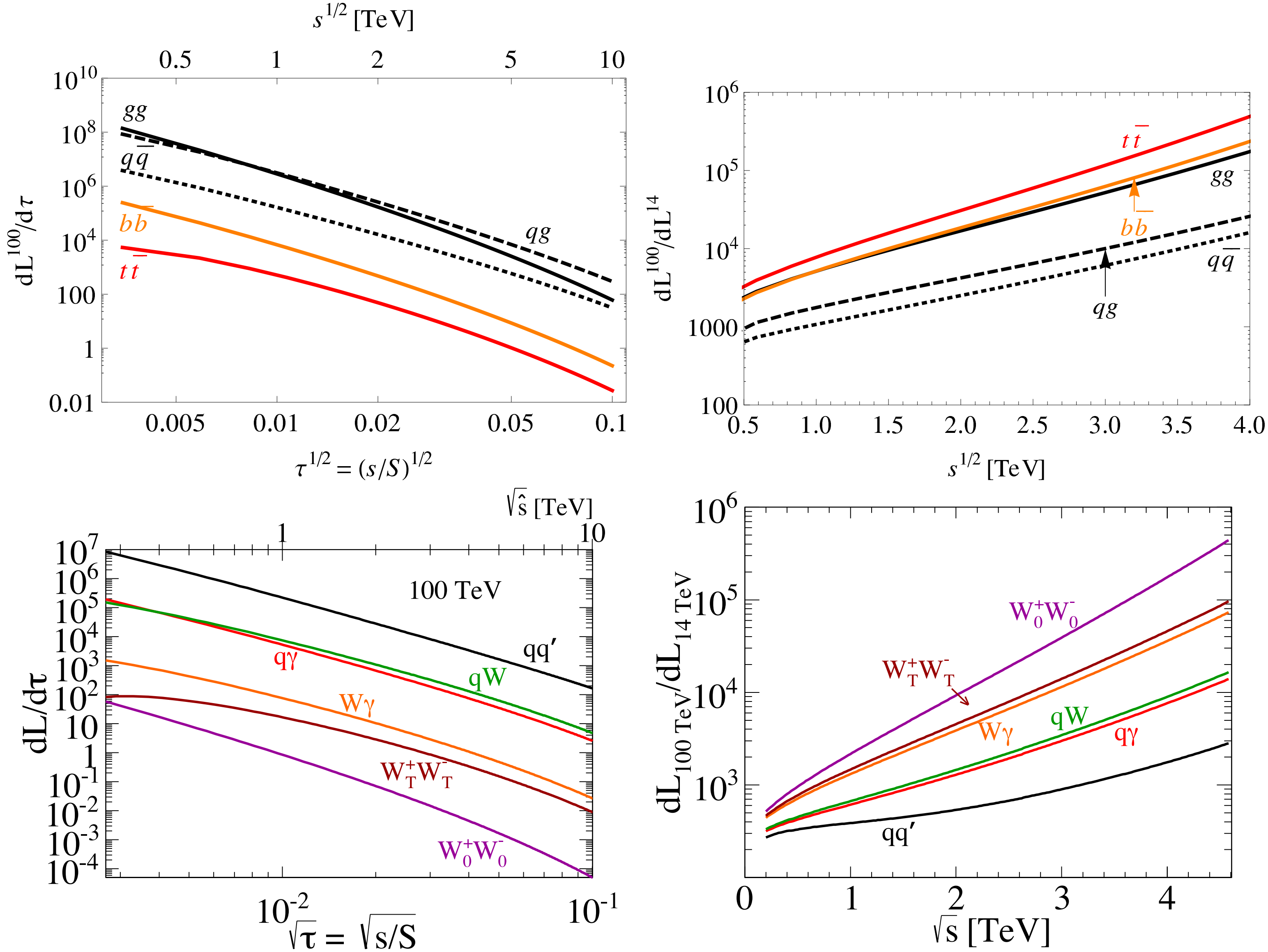


No Sign for New Physics (yet)!

LHC searches will continue, its legacy will be carried on...

(A). SM Bread and Butter at 100 TeV:

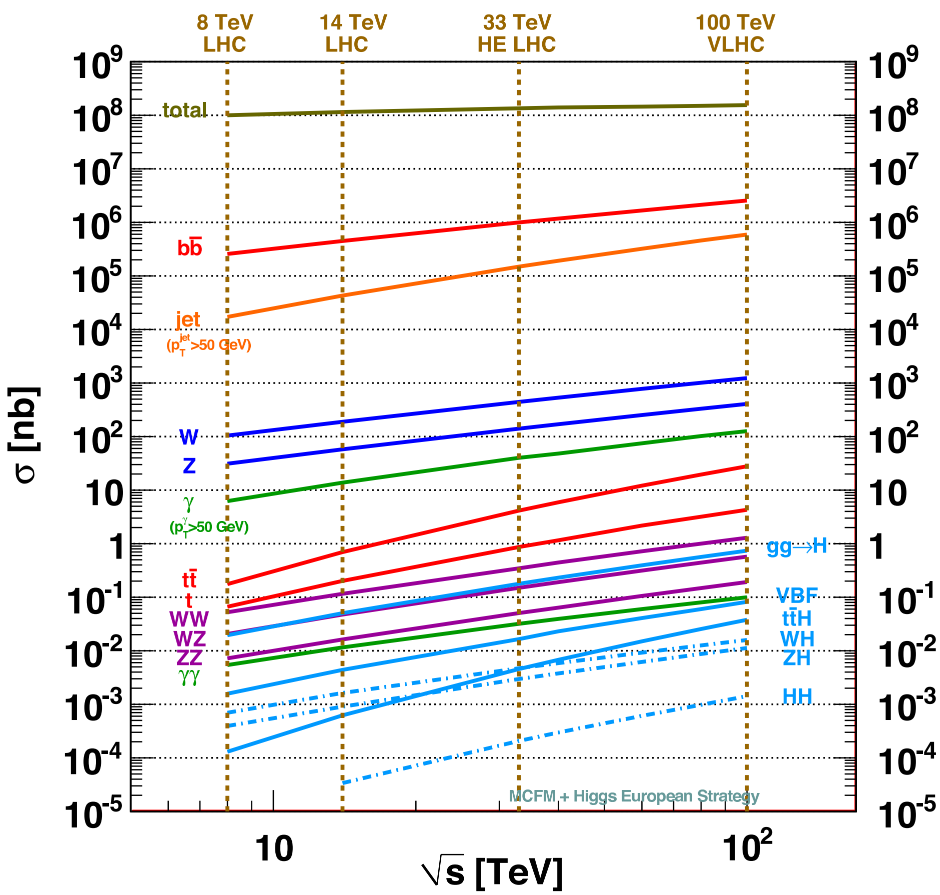
Partonic luminosities substantially increased: *

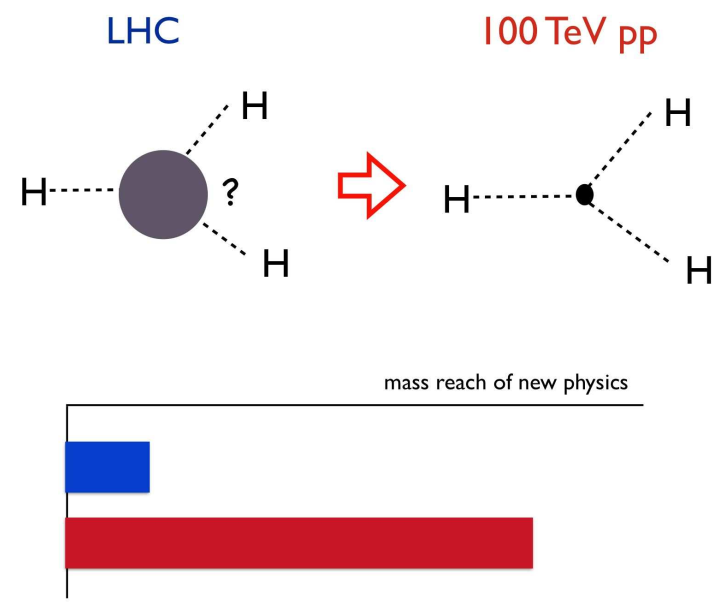


*(Arkani-Hamed, T.Han, M.Mangano, L.-T.Wang, to appear.)

SM Rates Enhanced Big: 10 – 50

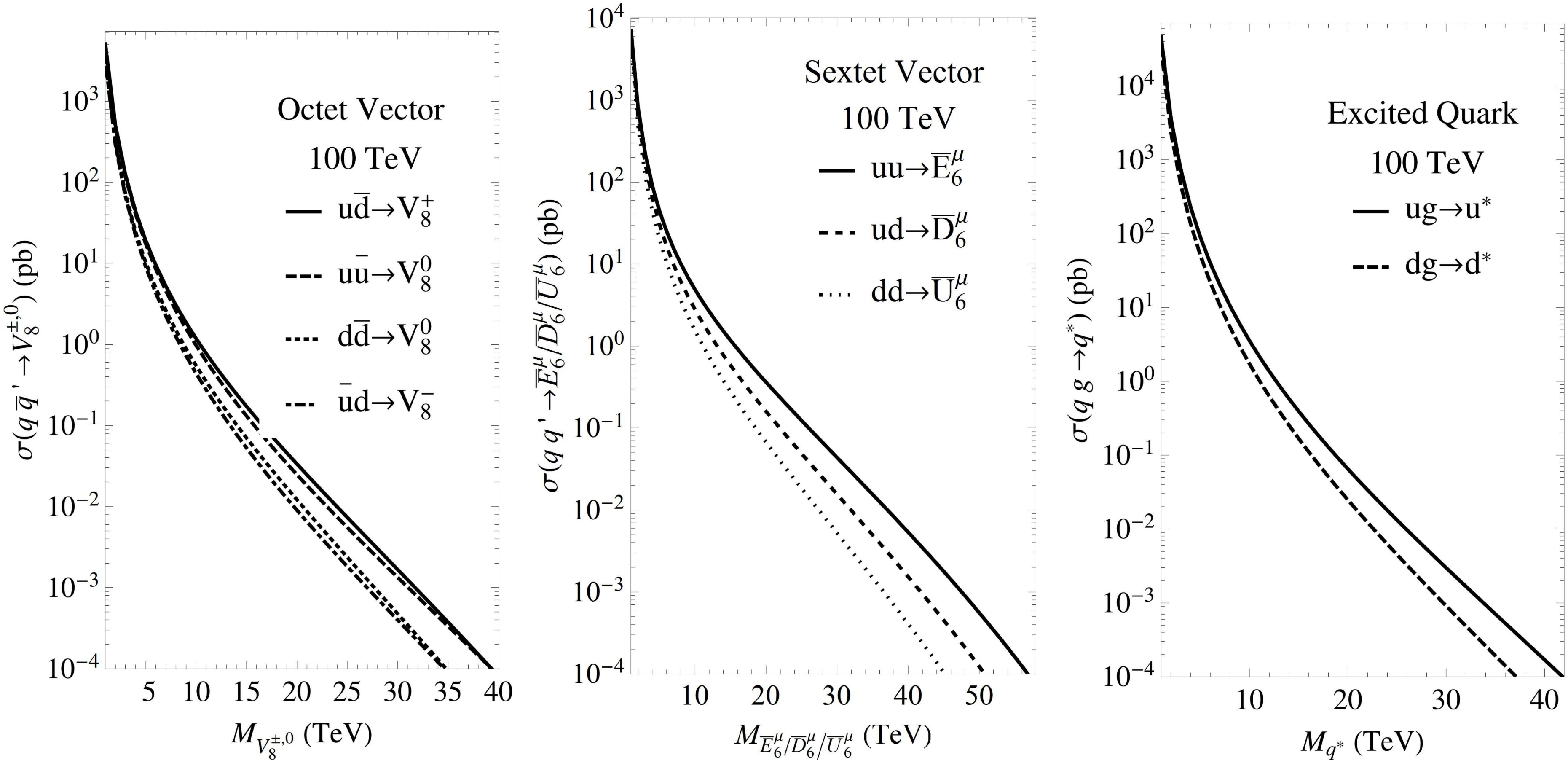
SM precision and New Physics far-reaching (×5):





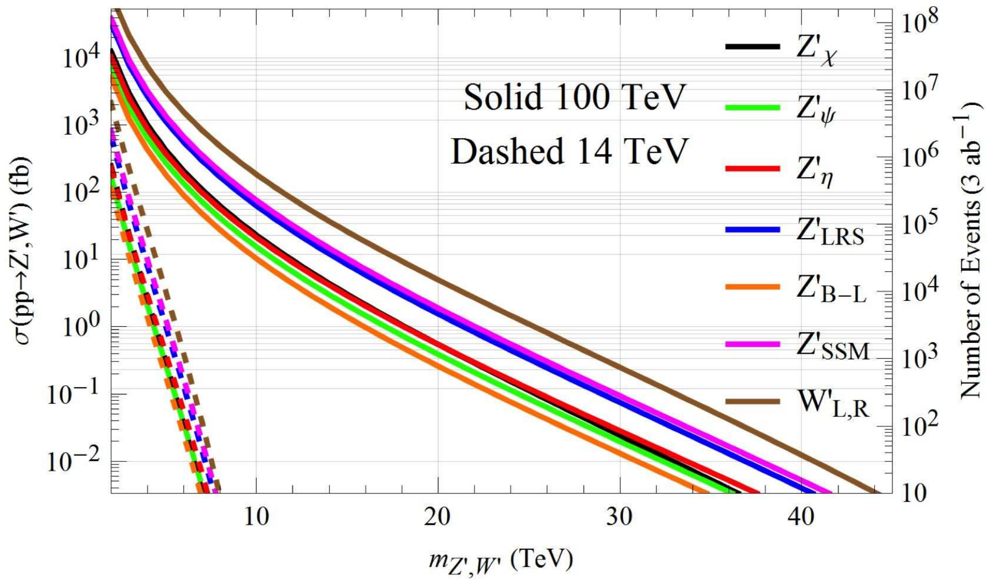
(B). Heavy Colored Resonances:

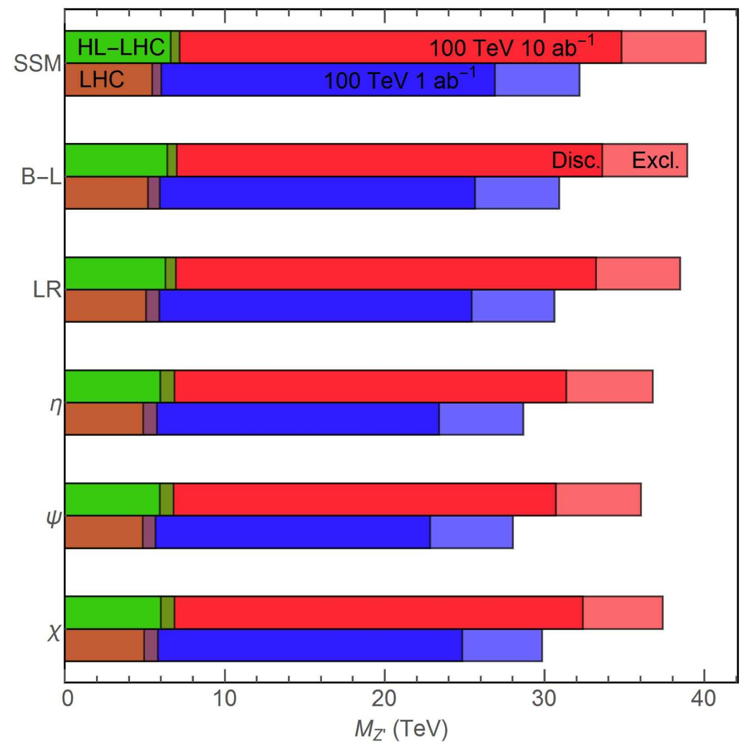
Colored resonance production largest rate, simplest topology:
Mass reach extended to 20 – 50 TeV!



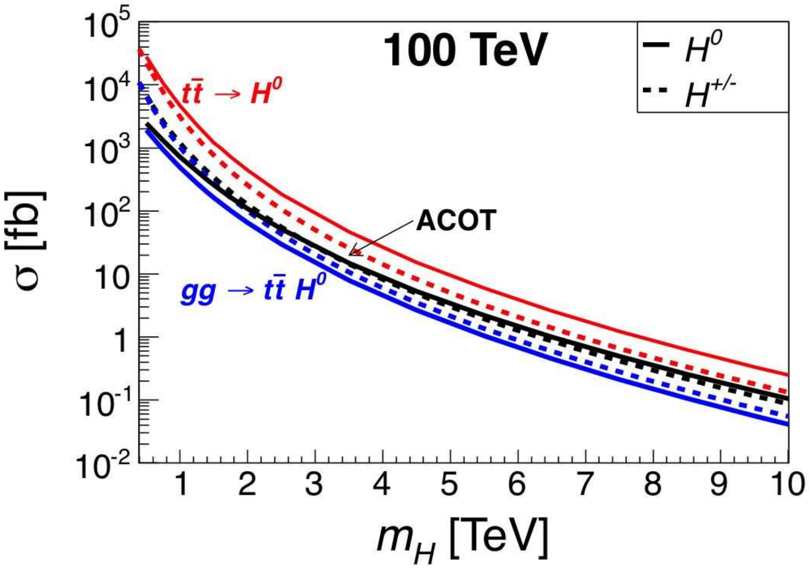
(C). W', Z':

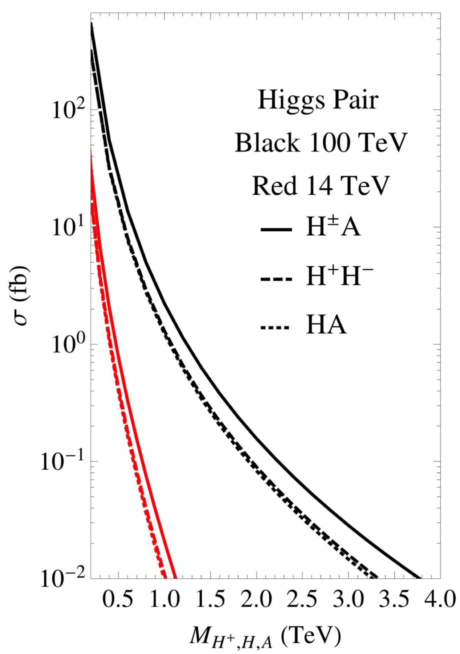
Lepton pair signal the best:
Mass reach increased by 5, to $\sim$ 30 TeV!

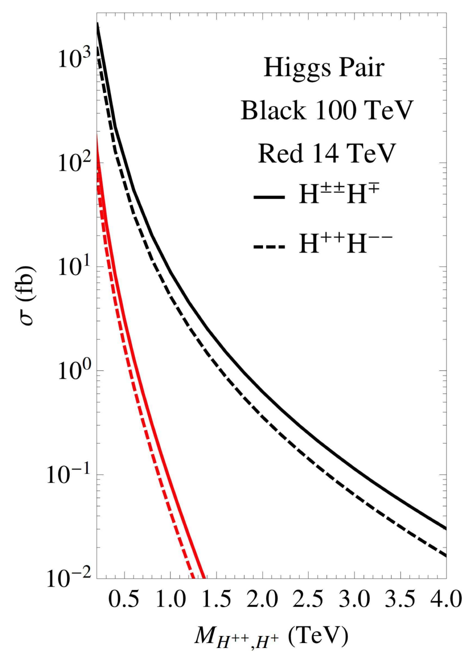




(D). Heavy Higgses:



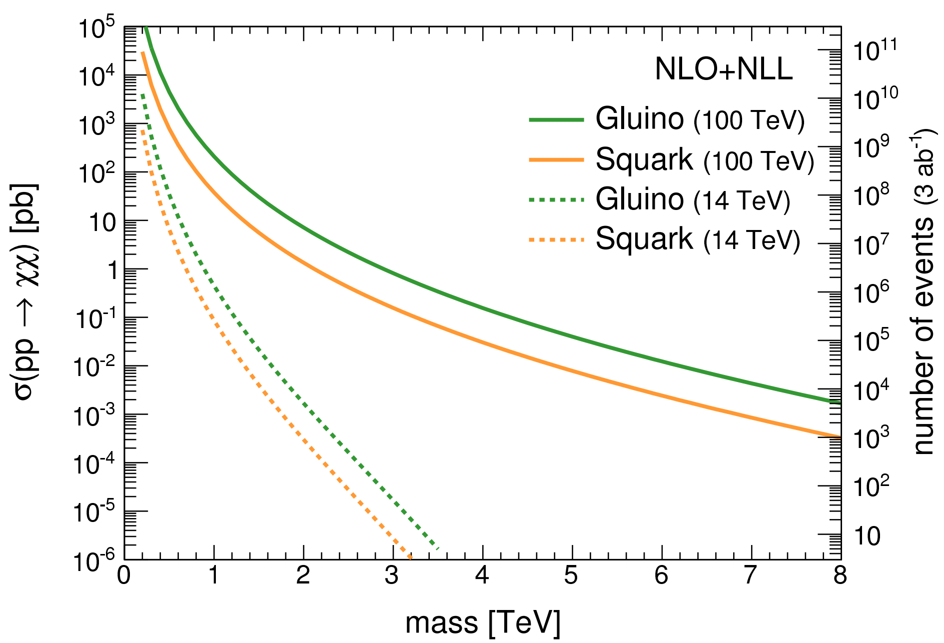


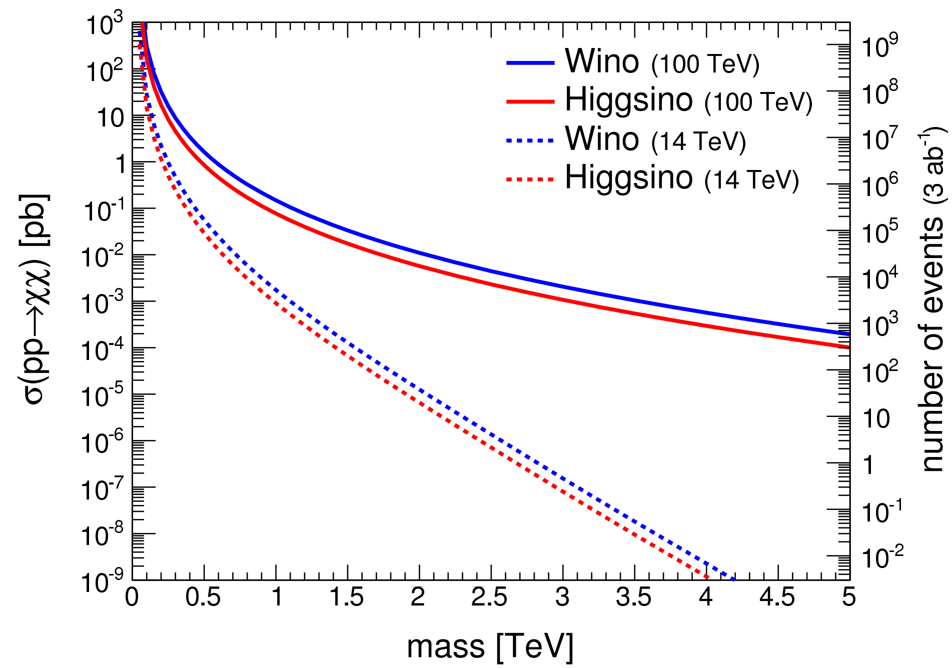


(E). S-particle Factory:

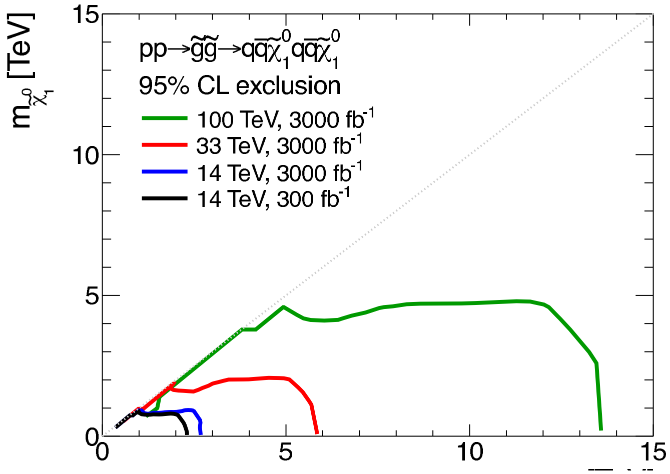
QCD production: $q\bar{q},\ gq,\ gg \to \tilde{q}\bar{\tilde{q}},\ \tilde{q}\tilde{g},\ \tilde{g}\tilde{g}.$

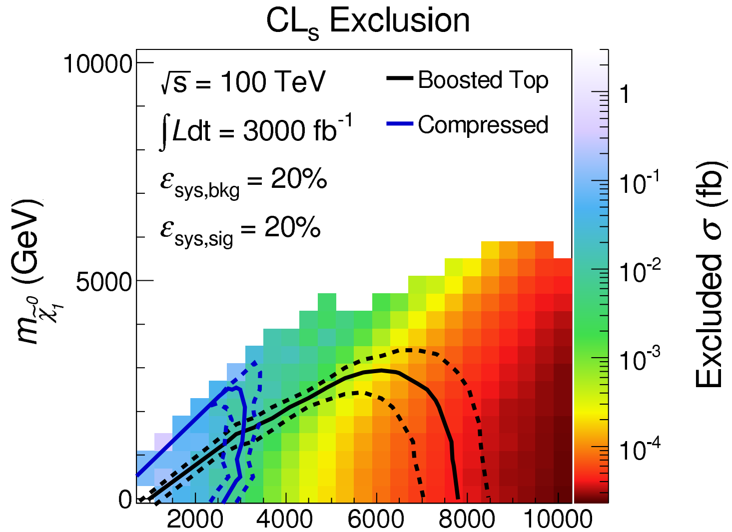
E.W. production: $q\bar{q} \to \tilde{\chi}_1^+\tilde{\chi}_1^-,\ \tilde{\chi}_1^\pm\tilde{\chi}_1^0,\ \tilde{\chi}_1^\pm\tilde{\chi}_2^0.$

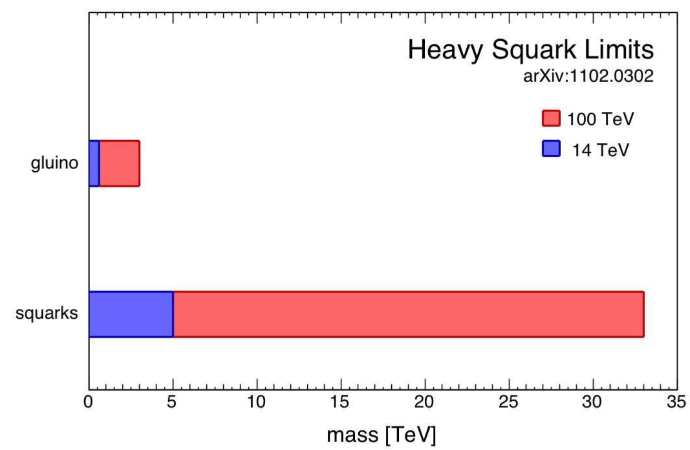




Mass reach easily extended by 5 – 8:

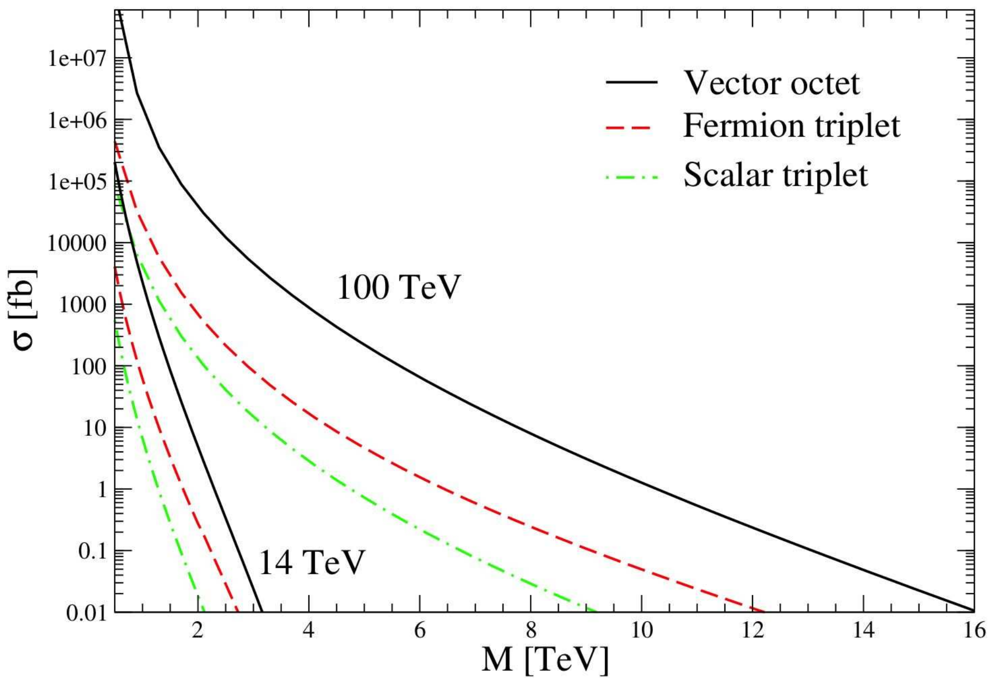


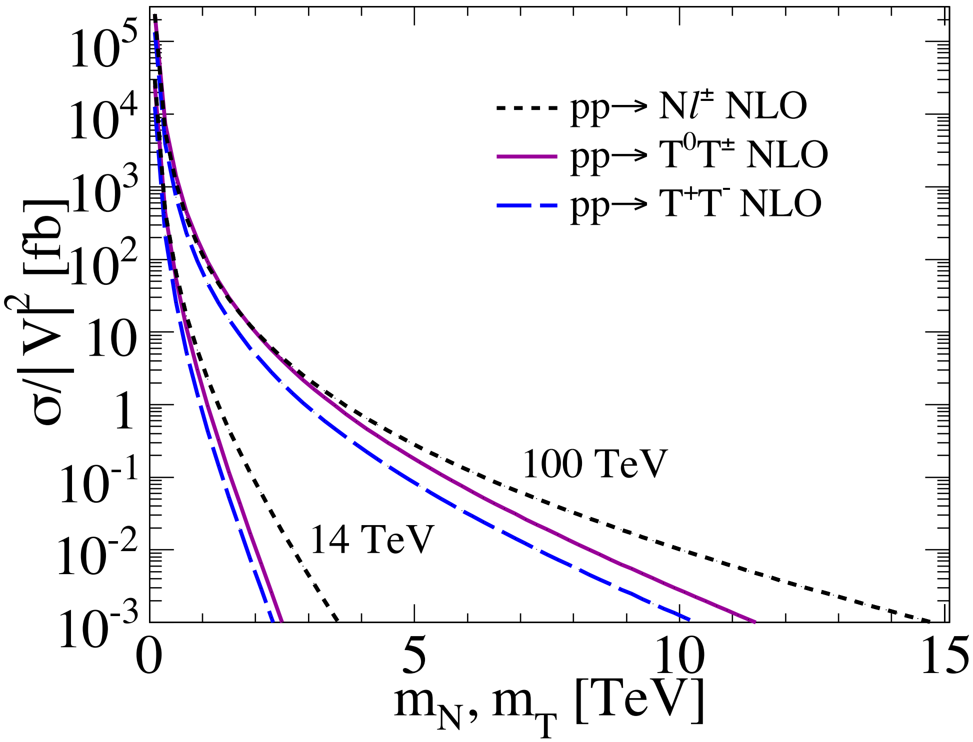




(F). New Heavy Fermions

Vector like quarks and leptons:



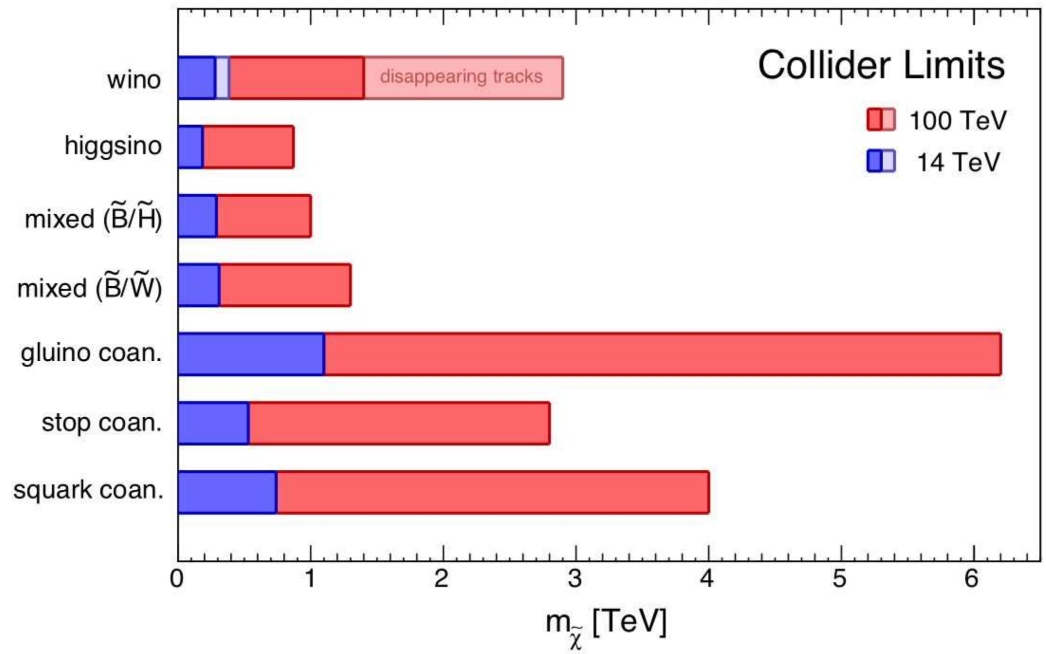


Mass reach:

$M_Q \sim 15-20$ TeV; $M_L \sim 10-15$ TeV.

(G). Dark Matter Connection:

Substantial coverage in DM searches:
Another factor of 5 in mass reach!



Concluding Remarks:

- LHC is real life: Will dominate for the next 10–15 years; and deliver rich physics!

- An e^+e^- Higgs factory is a MUST! (ILC/FCC$_{ee}$/CEPC...)

- The FCC$_{hh}$/SPPC/VLHC is the future of HEP.

We are a lucky generation to witness the discovery!

Please join the excitement and contribute!