Collider Physics

— From basic knowledge to new physics searches

Tao Han [than(at)pitt.edu]

University of Pittsburgh/Tsinghua University

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Prelude: LHC Run-II is in mission!

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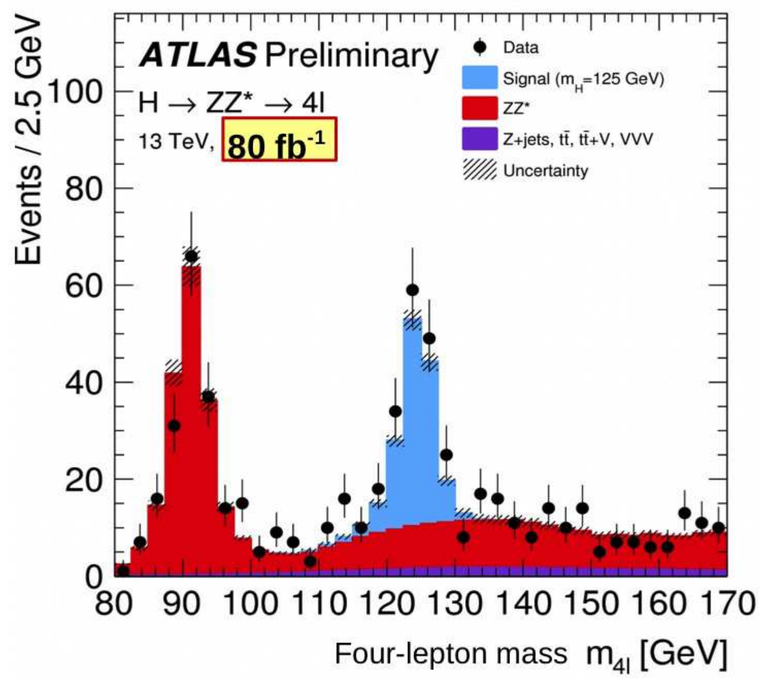
New era in science begun!

Already reaching $\approx 100\ \text{fb}^{-1}$/expt
Run-II: till the end of 2018.

L=80 fb^{-1} at 13 TeV



195 events for 115< m_{4l} < 130 GeV

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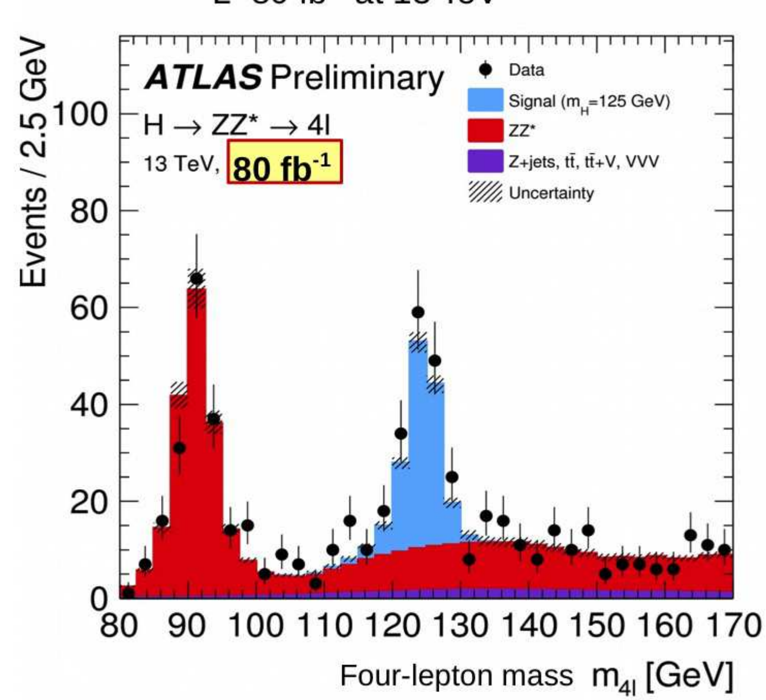

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High Energy Physics IS at an extremely interesting time!

The completion of the Standard Model: With the discovery of the Higgs boson, for the first time ever, we have a consistent relativistic quantum-mechanical theory, weakly coupled, unitary, renormalizable, vacuum (quasi?) stable, valid up to an exponentially high scale!

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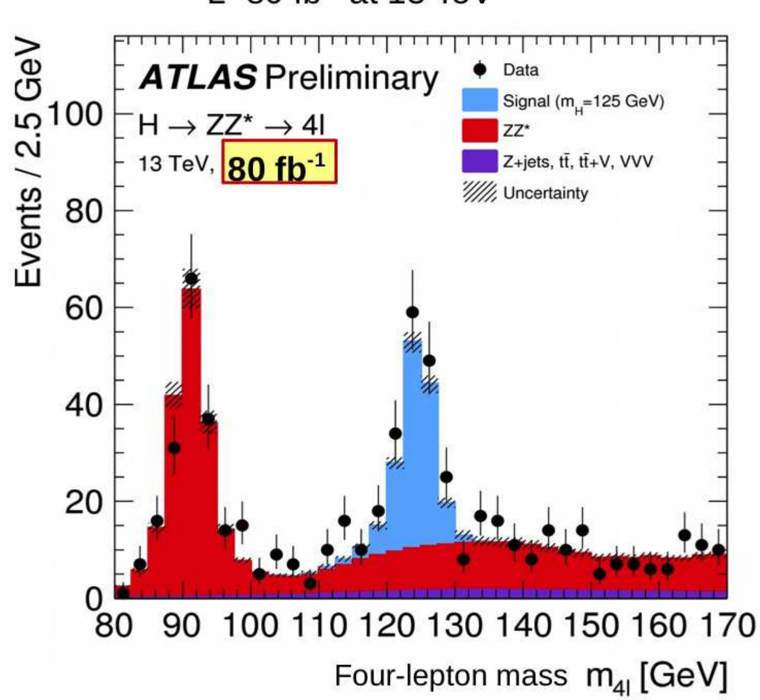

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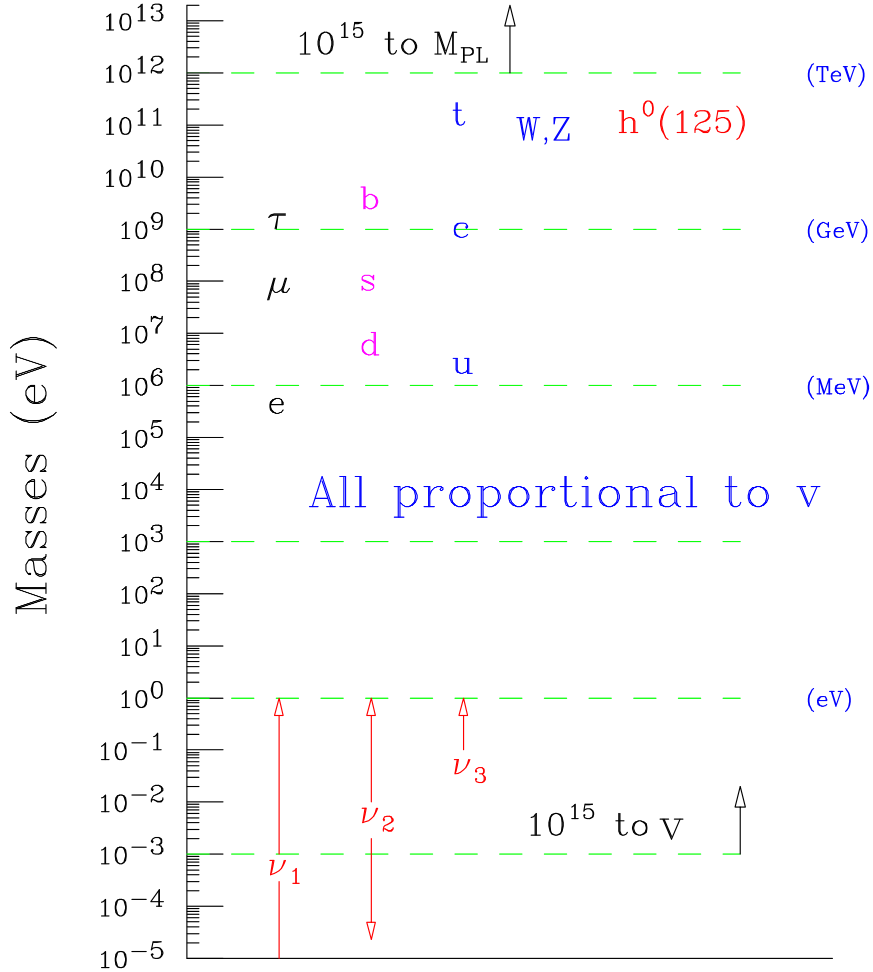
Question: Where IS the next scale?

$\mathcal{O}$(1 TeV)? M_{GUT}? M_{Planck}?

Large spread of masses for elementary particles:



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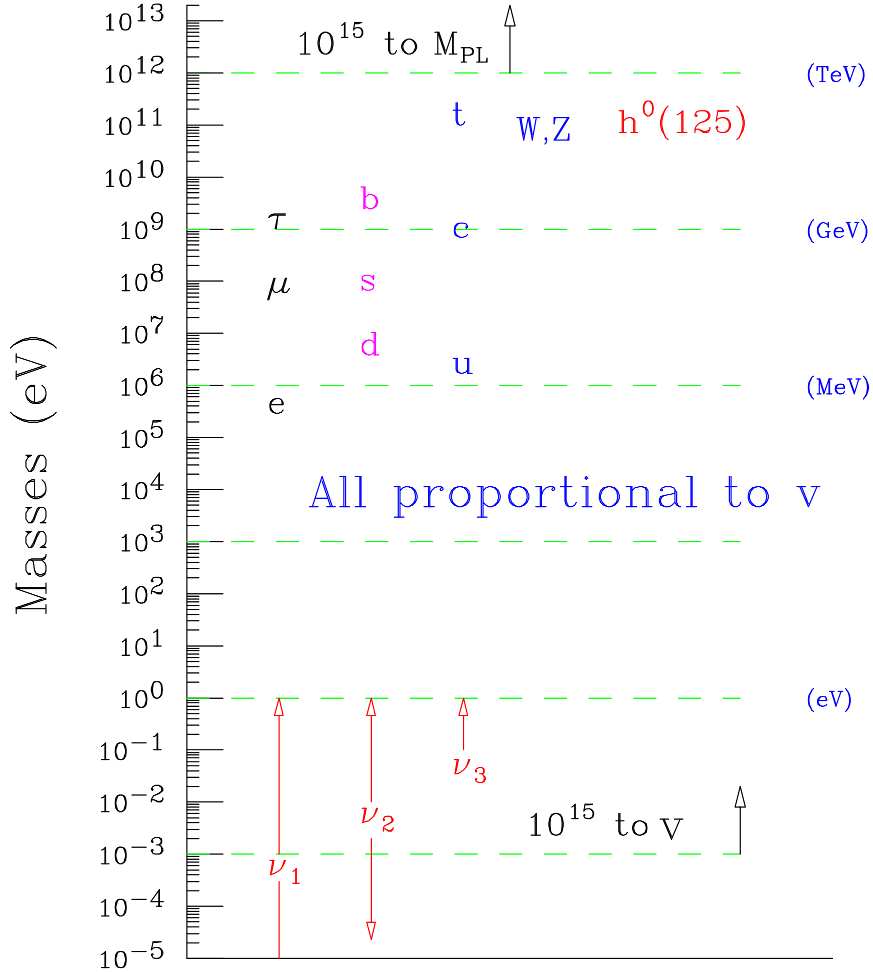

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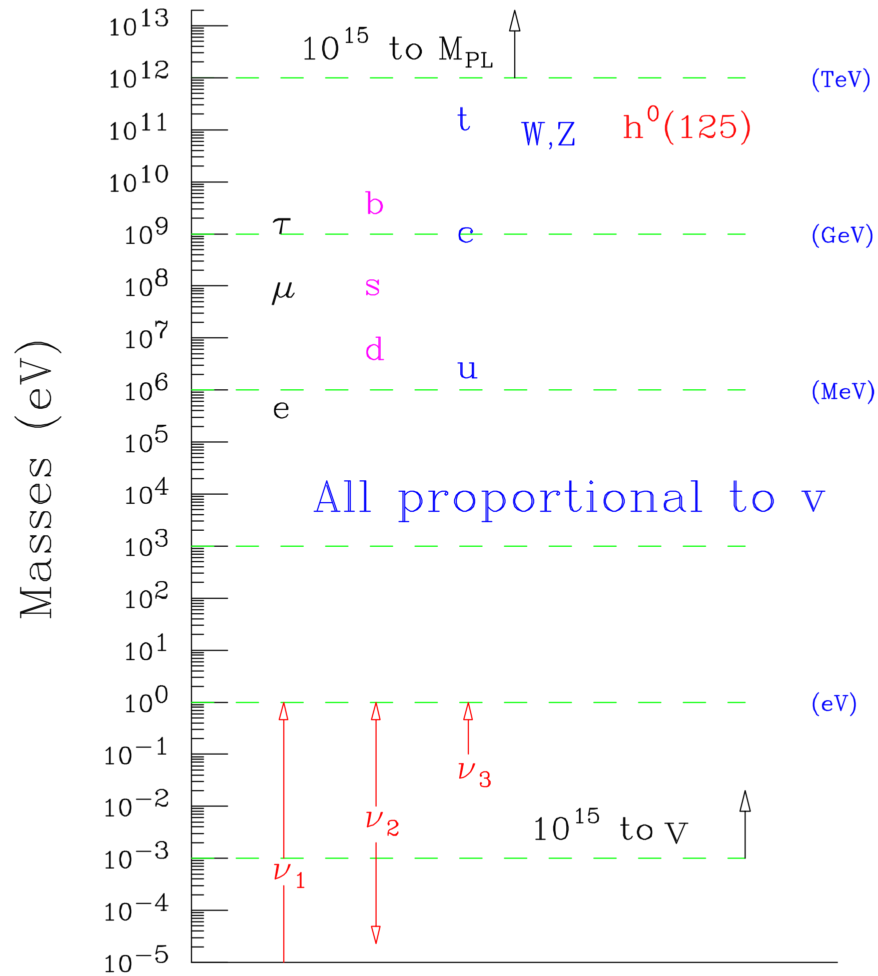

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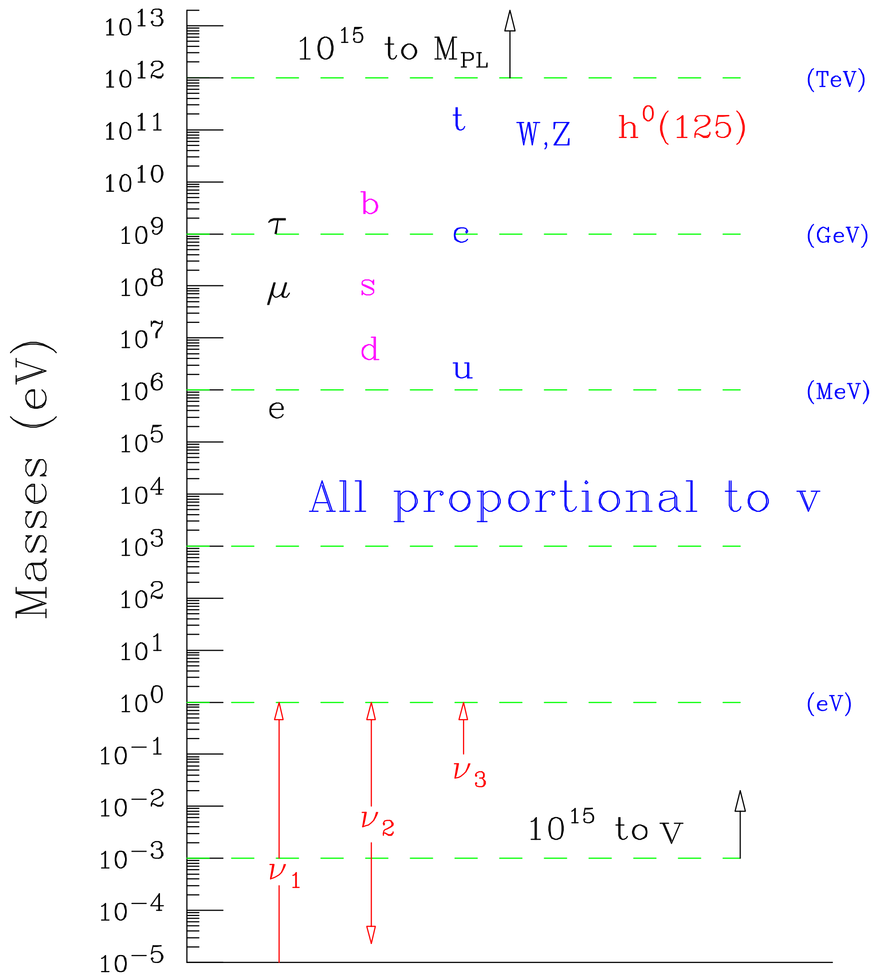

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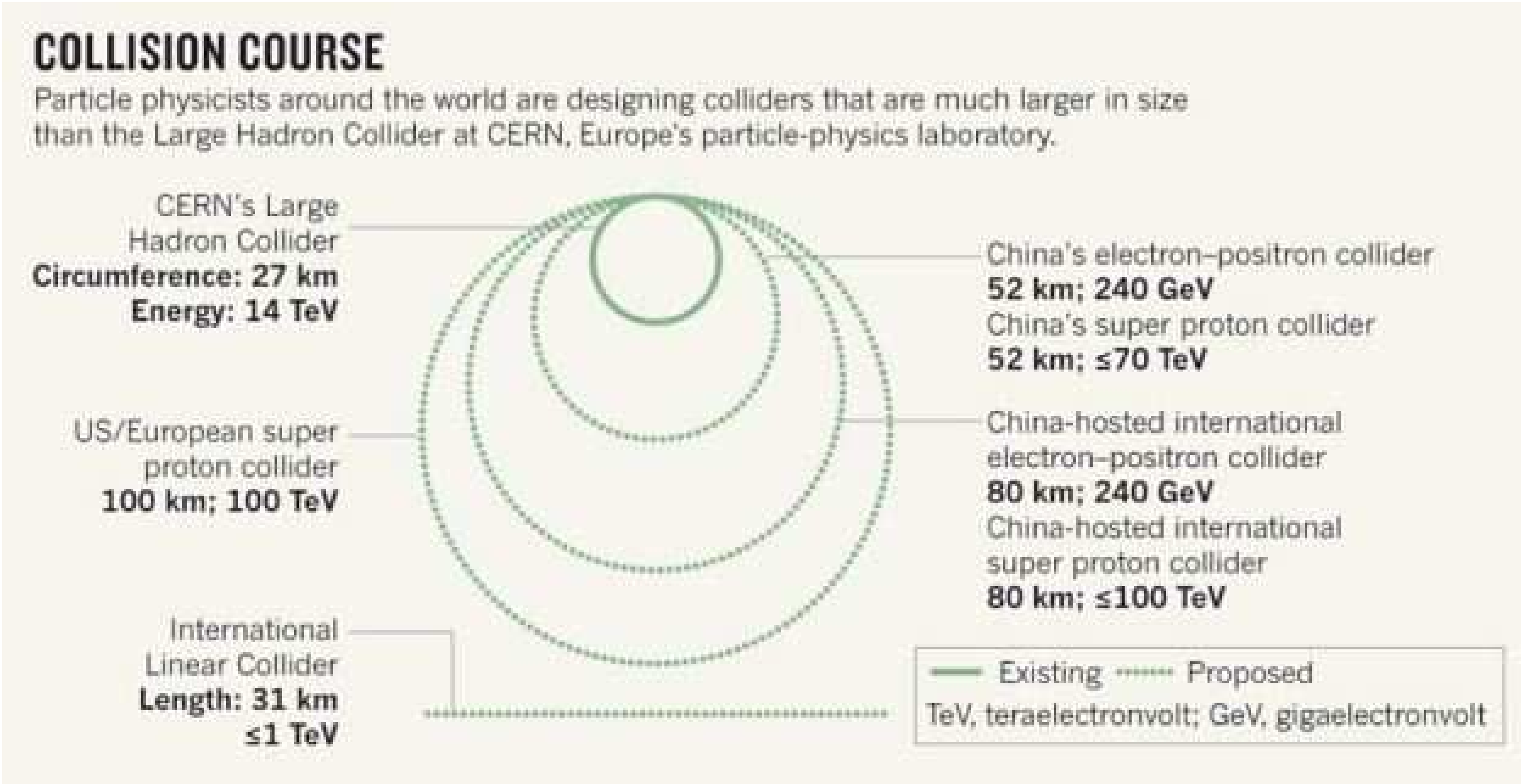
Consult with the other excellent lectures.

That motivates us to the new energy frontier! *



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- HE-LHC at 27 TeV, 15 ab^{-1} under consideration: start 2035–2040?

*Nature News (July, 2014)

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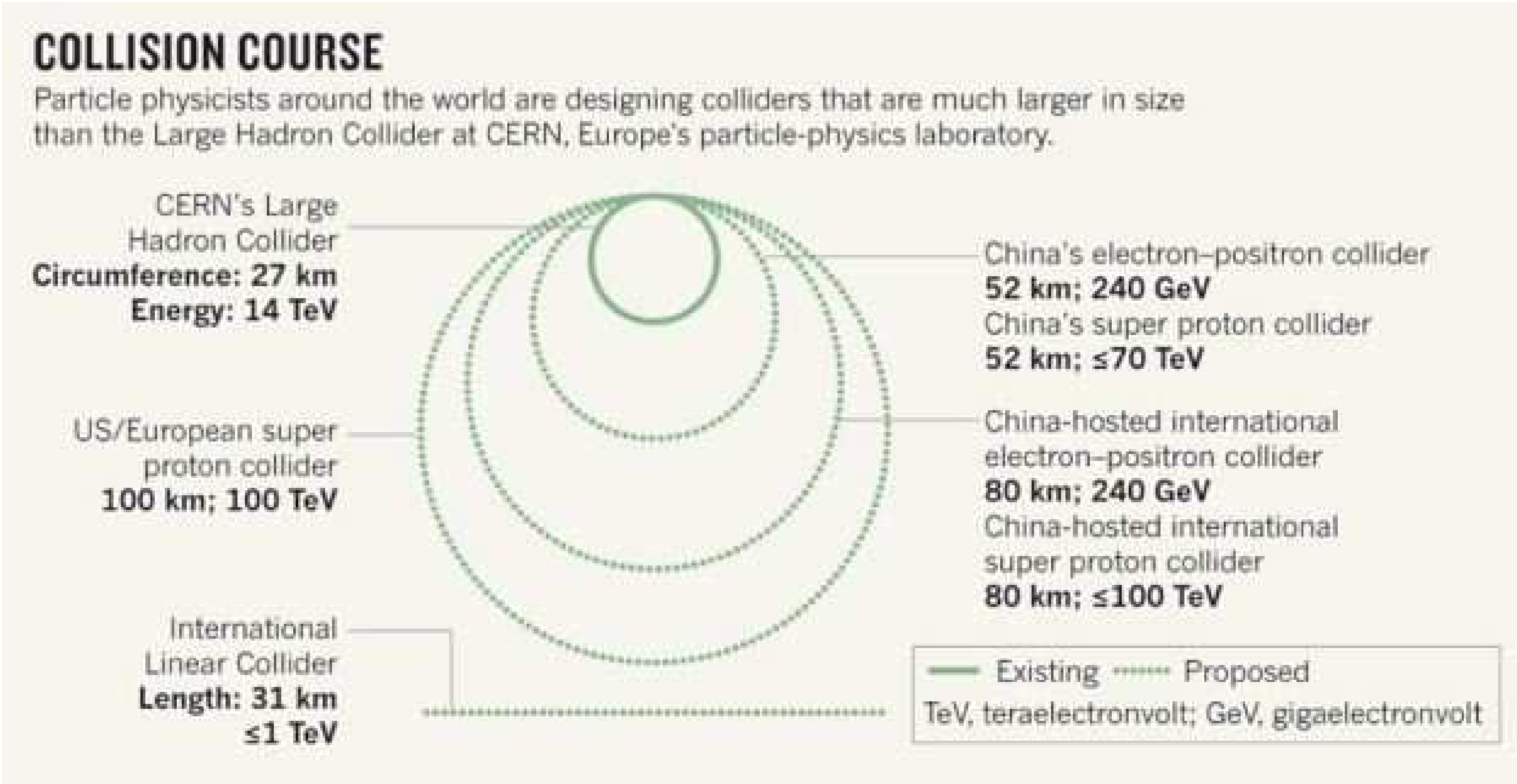

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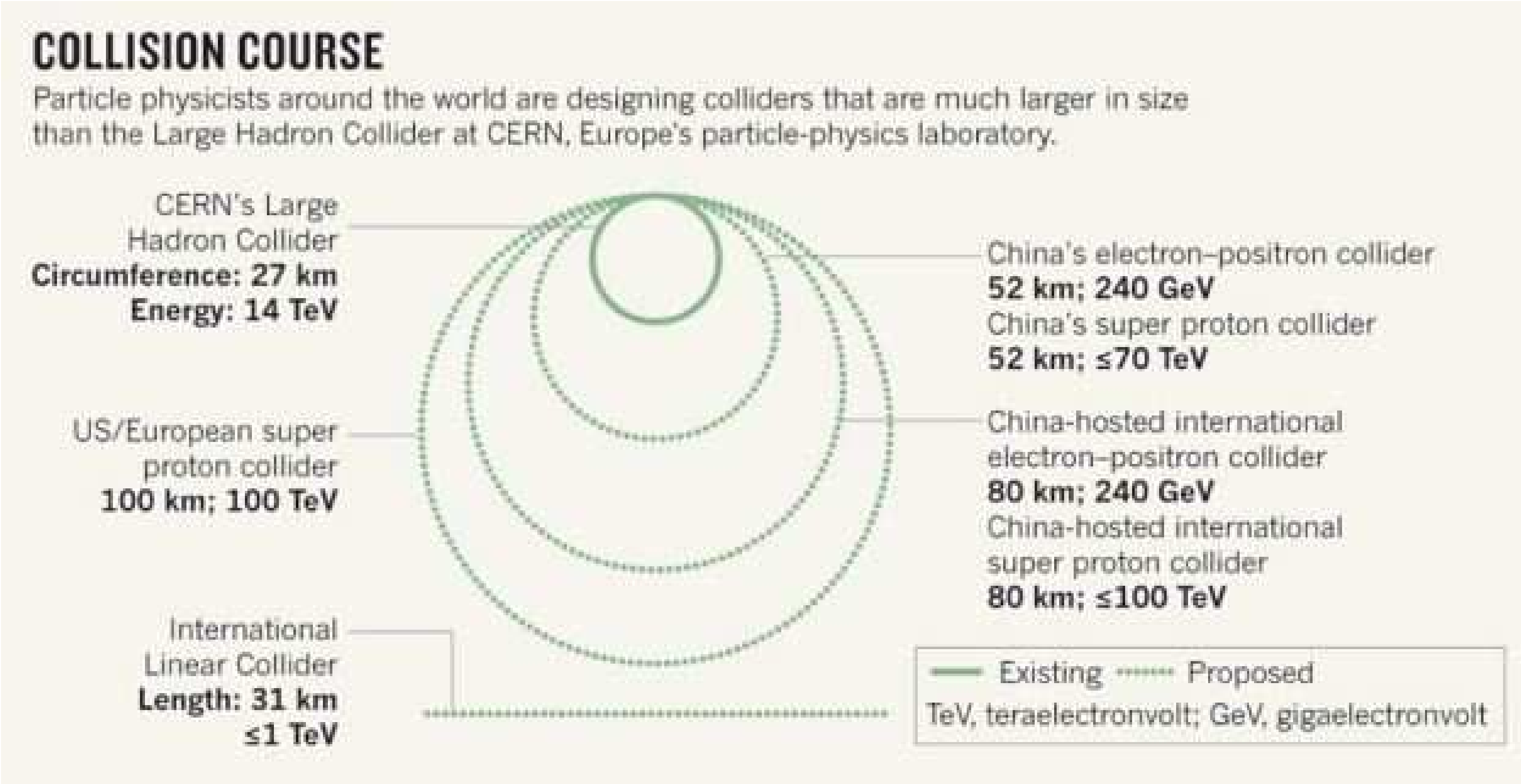

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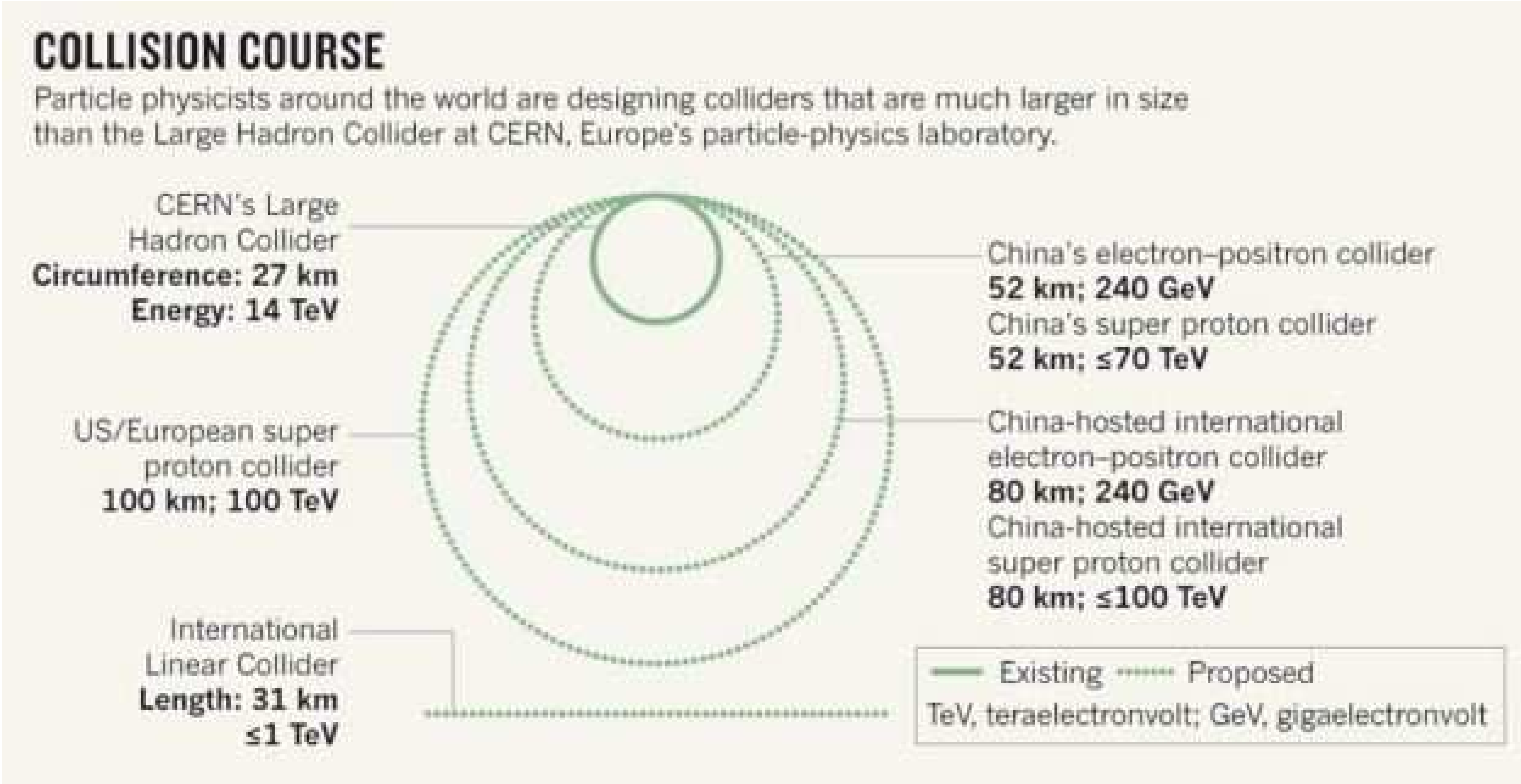

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- FCC_{hh}/SPPC/VLHC (100 TeV, 3 ab^{-1}) to the energy frontier: 2040?

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Rutherford's experiments were the first to study matter structure:

I-A. Colliders and Detectors

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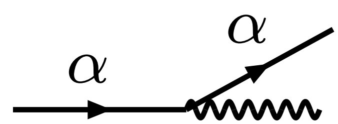

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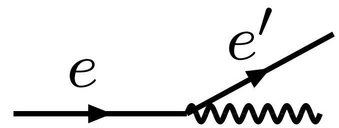

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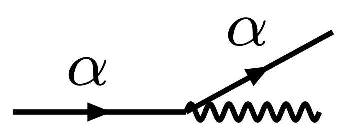
to study matter structure: 

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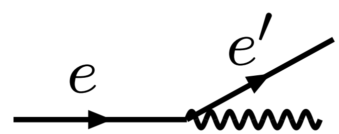
SLAC-MIT DIS experiments 

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$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E^2 \sin^4\theta/2}\left(\frac{F_1(x,Q^2)}{m_p}\sin^2\frac{\theta}{2} + \frac{F_2(x,Q^2)}{E-E'}\cos^2\frac{\theta}{2}\right)$$

QCD parton model $\Rightarrow 2xF_1(x,Q^2) = F_2(x,Q^2) = \sum_i x f_i(x) e_i^2.$

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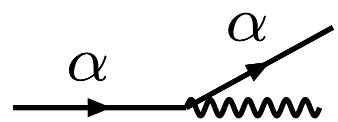

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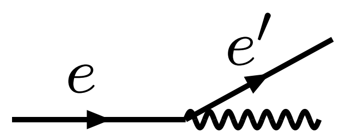

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Rutherford's legendary method continues to date!

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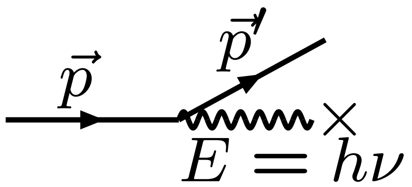
To study the deepest layers of matter,
we need the probes with highest energies.



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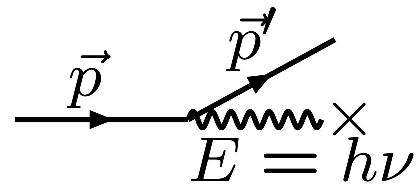

Two parameters of importance:

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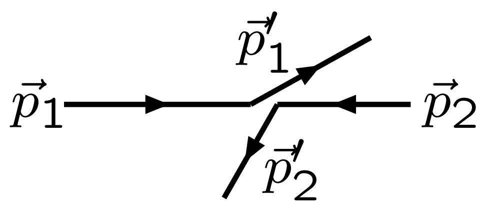

$$s \equiv (p_1 + p_2)^2 = \begin{cases} (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2, \\ m_1^2 + m_2^2 + 2(E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2). \end{cases}$$

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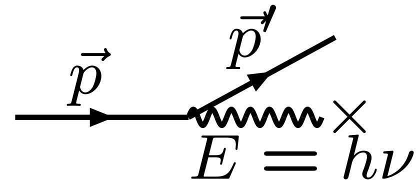

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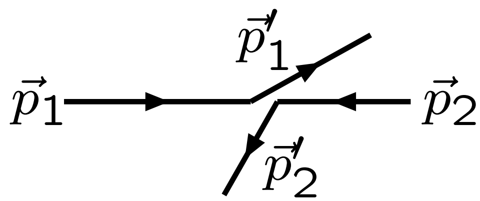

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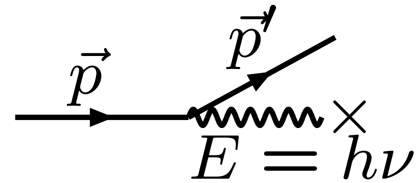

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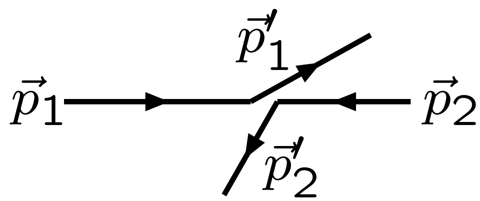

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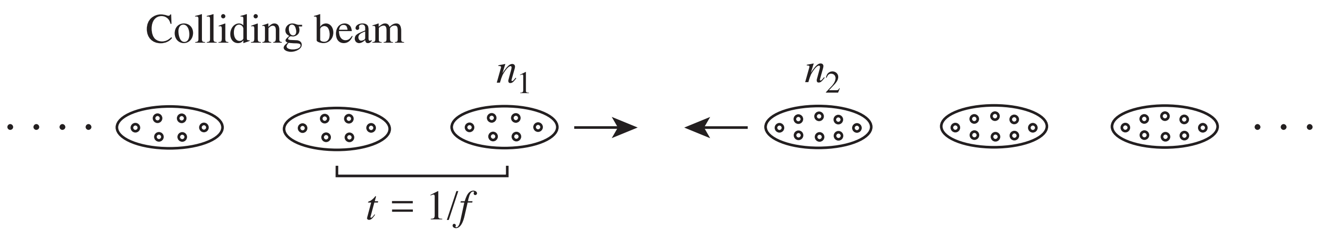

$$\mathcal{L} \propto f n_1 n_2 / a,$$

(a some beam transverse profile) in units of #particles/cm^2/s

$\Rightarrow$ 10^{33} cm^{-2}s $^{-1}$ = 1 nb^{-1} s^{-1} $\approx$ 10 fb^{-1}/year.

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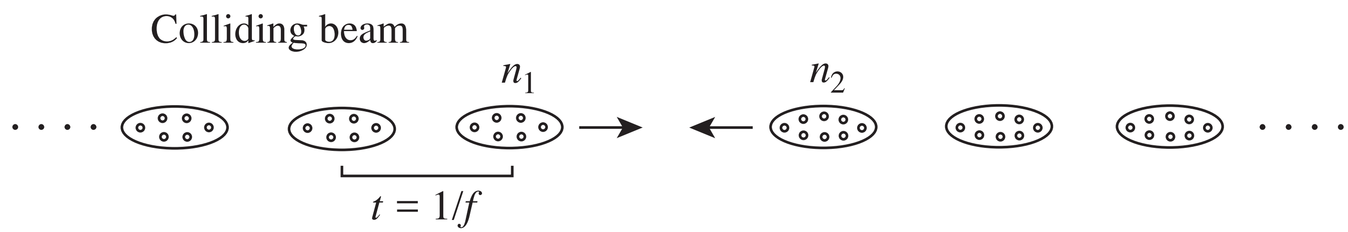

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Current and future high-energy colliders:

Hadron Colliders	$\sqrt{s}$ (TeV)	$\mathcal{L}$ (cm^{-2}s^{-1})	$\delta E/E$	f (MHz)	#/bunch (10^{10})	L (km)
LHC Run (I) II	(7,8) 13	(10^{32}) 10^{33}	0.01%	40	10.5	26.66
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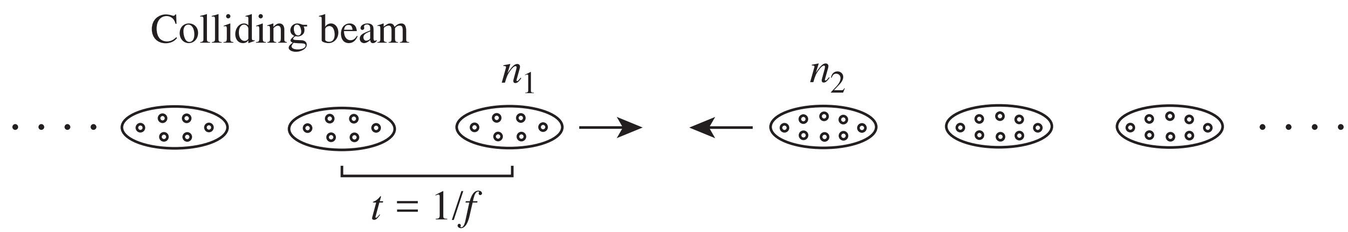

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e^+e^- Colliders	$\sqrt{s}$ (TeV)	$\mathcal{L}$ (cm^{-2}s^{-1})	$\delta E/E$	f (MHz)	polar.	L (km)
ILC	0.5–1	2.5×10^{34}	0.1%	3	80, 60%	14 – 33
CEPC	0.25–0.35	2×10^{34}	0.13%			50-100
CLIC	3–5	$\sim 10^{35}$	0.35%	1500	80, 60%	33 – 53

(B). e^+e^- Colliders

The collisions between e^- and e^+ have major advantages:

- The system of an electron and a positron has zero charge, zero lepton number etc.,

$\Longrightarrow$ it is suitable to create new particles after e^+e^- annihilation.

- With symmetric beams between the electrons and positrons, the laboratory frame is the same as the c.m. frame,

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- With well-understood beam properties,

$\Longrightarrow$ the scattering kinematics is well-constrained.

- Backgrounds low and well-undercontrol:

For $\sigma \approx 10$ pb $\Rightarrow 0.1$ Hz at 10^{34} cm^{-2}s^{-1}.

- Linear Collider: possible to achieve high degrees of beam polarizations,

$\Longrightarrow$ chiral couplings and other asymmetries can be effectively explored.

Disadvantages

- Large synchrotron radiation due to acceleration,

$$\Delta E \sim \frac{1}{R} \left(\frac{E}{m_e}\right)^4 .$$

  Thus, a multi-hundred GeV e^+e^- collider will have to be made a linear accelerator.

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CEPC/FCC$_{ee}$ Higgs Factory

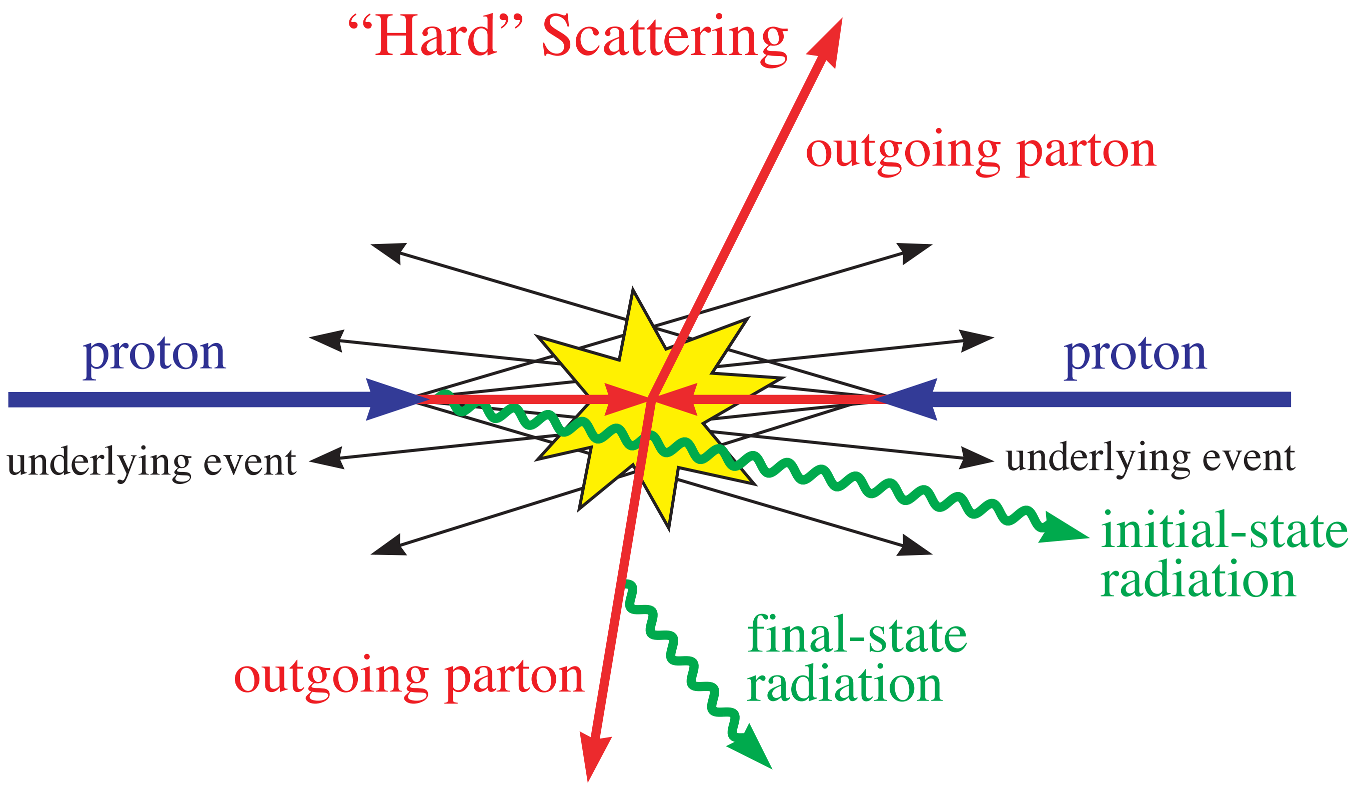
It has been discussed to build a circular e^+e^- collider

$$E_{cm} = 245 \text{ GeV}-350 \text{ GeV}$$

with multiple interaction points for very high luminosities.

(C). Hadron Colliders

LHC: the new high-energy frontier



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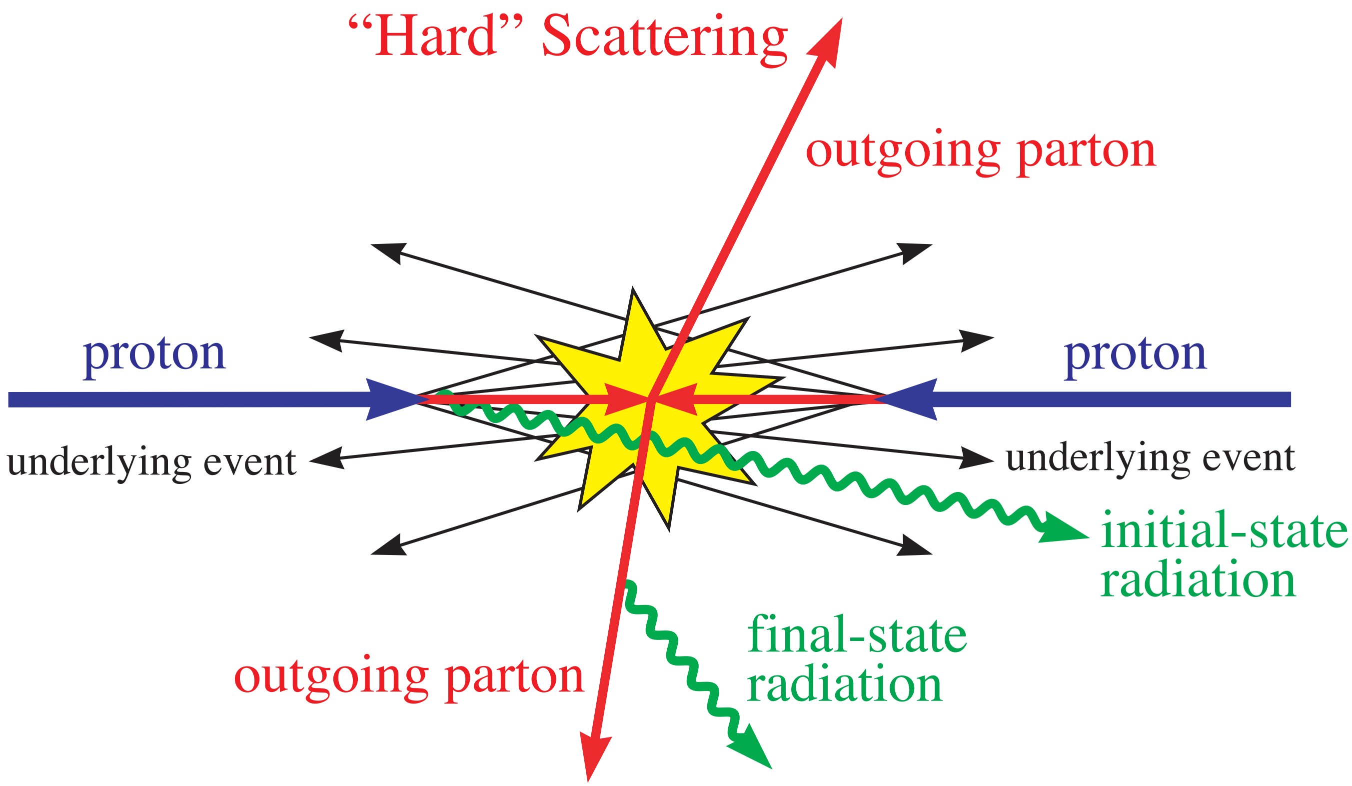

Advantages

• Higher c.m. energy, thus higher energy threshold:

$\sqrt{S} = 14$ TeV: $\quad M_{new}^2 \sim s = x_1 x_2 S \quad \Rightarrow \quad M_{new} \sim 0.3\sqrt{S} \sim 4$ TeV.

- Higher luminosity: 10^{34}/cm^2/s $\Rightarrow$ 100 fb^{-1}/yr.
  Annual yield: 1B $W^{\pm}$; 100M $t\bar{t}$; 10M $W^{+}W^{-}$; 1M H^{0}...

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- Multiple (strong, electroweak) channels:

  $q\bar{q}',\ gg,\ qg,\ b\bar{b} \to$ colored; $Q = 0, \pm 1$; $J = 0, 1, 2$ states;

  $WW,\ WZ,\ ZZ,\ \gamma\gamma \to I_W = 0, 1, 2$; $Q = 0, \pm 1, \pm 2$; $J = 0, 1, 2$ states.

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- Initial state unknown:

  colliding partons unknown on event-by-event basis;

  parton c.m. energy unknown: $E_{cm}^2 \equiv s = x_1 x_2 S$;

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- The large rate turns to a hostile environment:

  $\Rightarrow$ Severe backgrounds!

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- Multiple (strong, electroweak) channels:

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  WW, WZ, ZZ, $\gamma\gamma \to I_W = 0, 1, 2$; $Q = 0, \pm 1, \pm 2$; $J = 0, 1, 2$ states.

Disadvantages

- Initial state unknown:

  colliding partons unknown on event-by-event basis;

  parton c.m. energy unknown: $E_{cm}^2 \equiv s = x_1 x_2 S$;

  parton c.m. frame unknown.

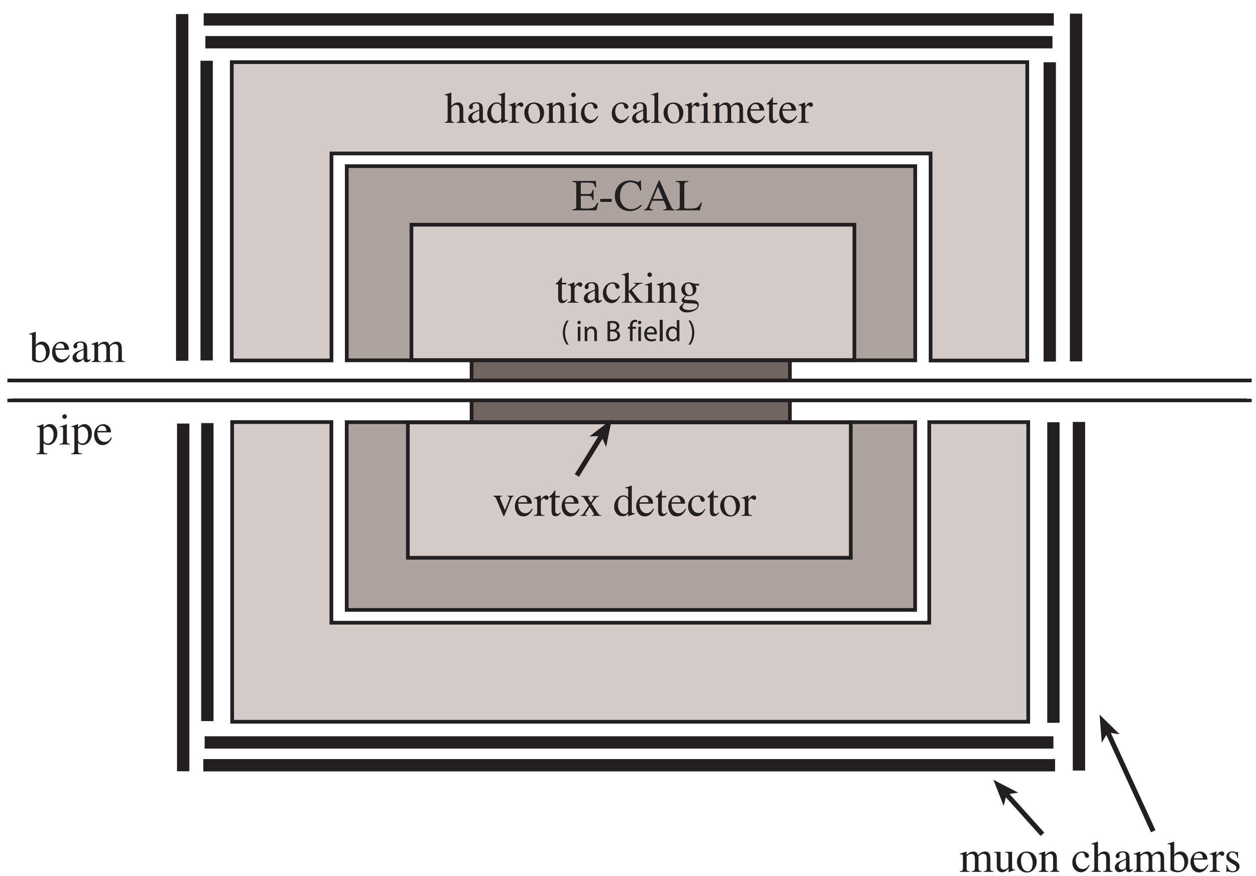
  $\Rightarrow$ largely rely on final state reconstruction.
- The large rate turns to a hostile environment:

  $\Rightarrow$ Severe backgrounds!

Our primary job !

(D). Particle Detection:

The detector complex:
Utilize the strong and electromagnetic interactions between detector materials and produced particles.



What we "see" as particles in the detector: (a few meters)

For a relativistic particle, the travel distance:

$$d = (\beta c\ \tau)\gamma \approx (300\ \mu m)(\frac{\tau}{10^{-12}\ s})\ \gamma$$

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$$p,\ \bar{p},\ e^{\pm},\ \gamma$$

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- a life-time $\tau \sim 10^{-12}$ s may display a secondary decay vertex, "vertex-tagged particles":

$$B^{0,\pm},\ D^{0,\pm},\ \tau^{\pm}...$$

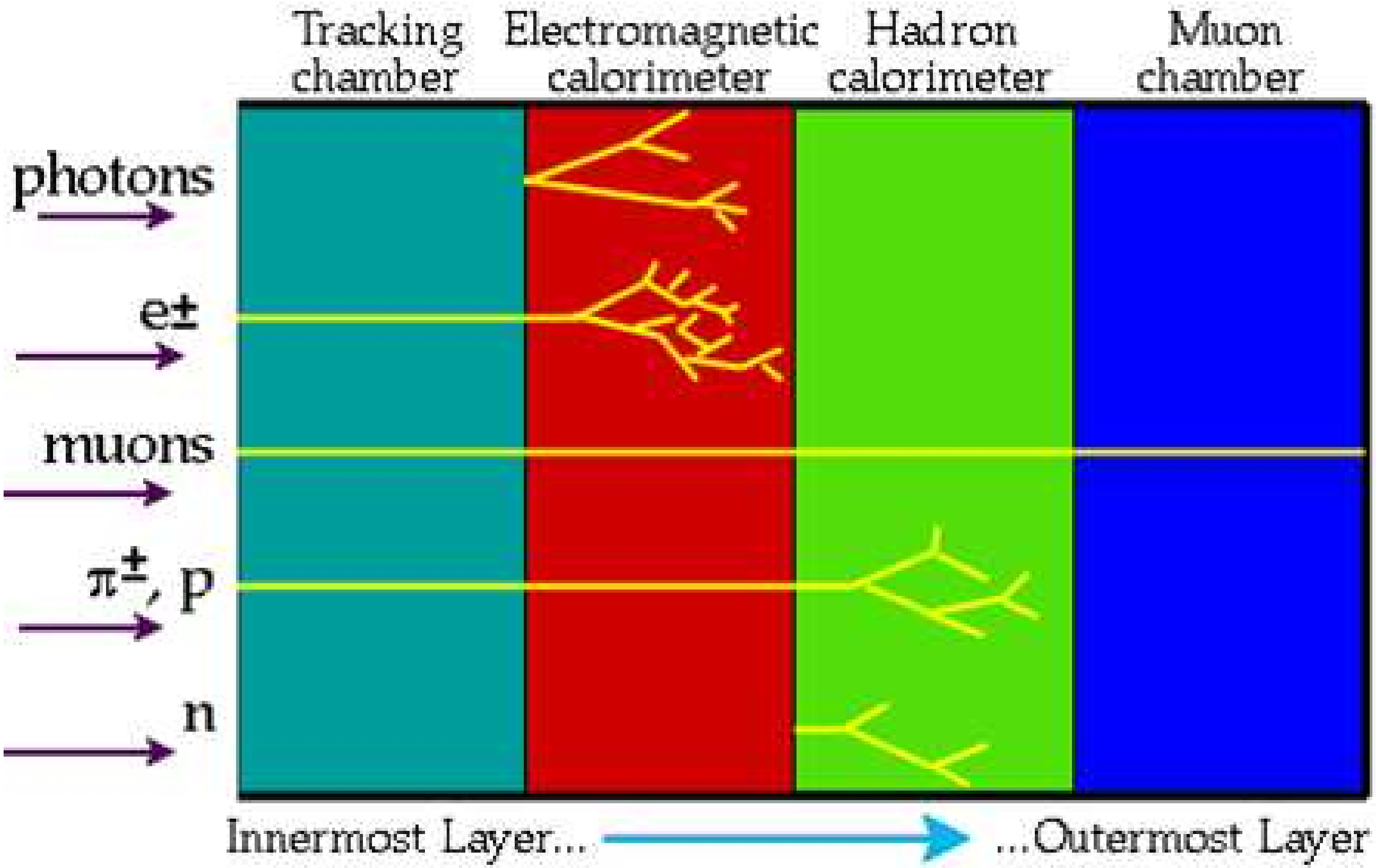
- short-lived not "directly seen", but "reconstructable":

$$\pi^0,\ \rho^{0,\pm}...\ ,\quad Z, W^{\pm}, t, H...$$

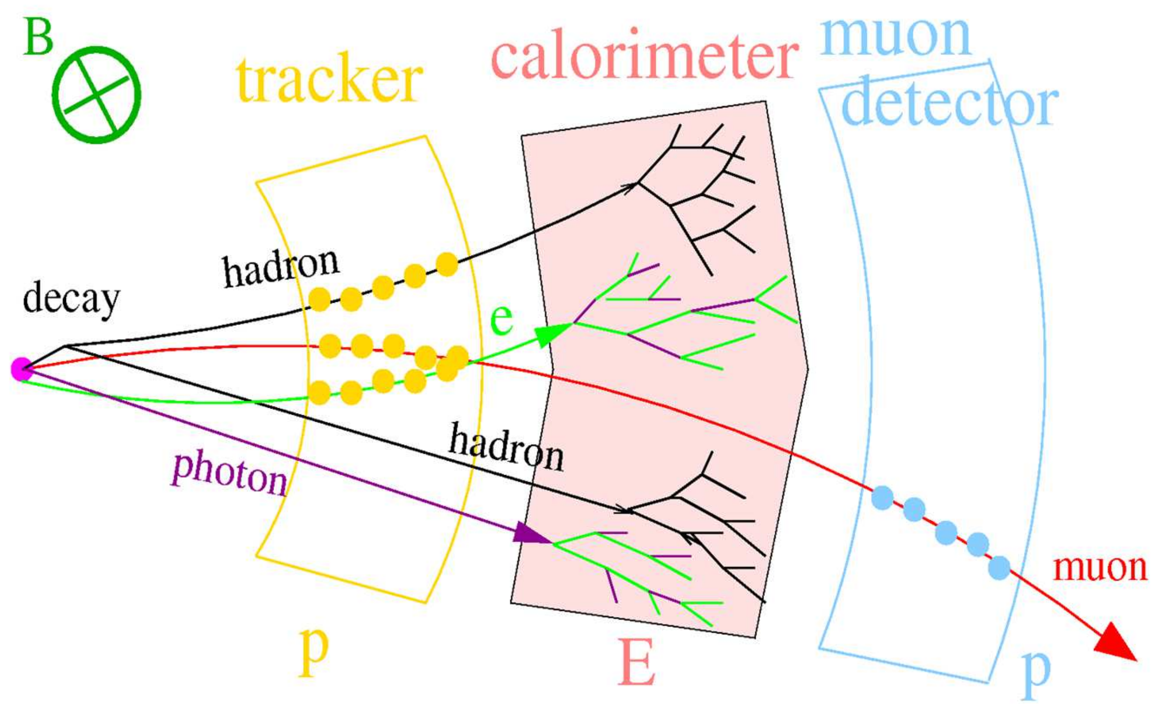
- missing particles are weakly-interacting and neutral:

$$\nu,\ \tilde{\chi}^0, G_{KK}...$$

† For stable and quasi-stable particles of a life-time $\tau \geq 10^{-10} - 10^{-12}$ s, they show up as



A closer look:



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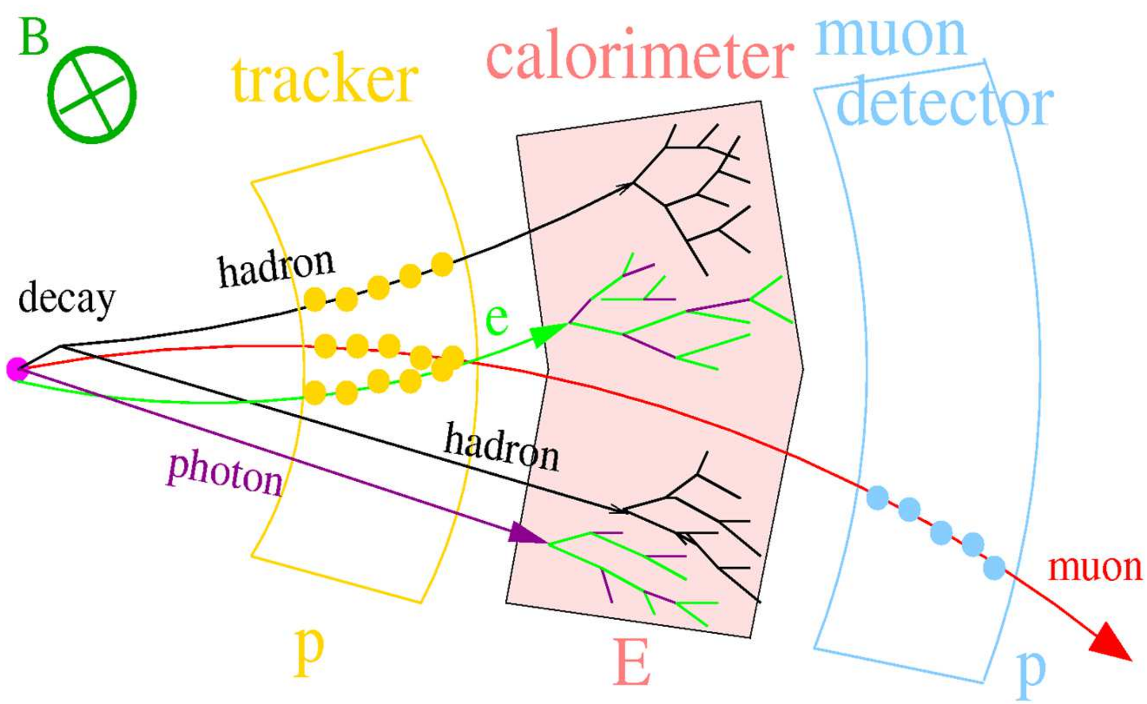
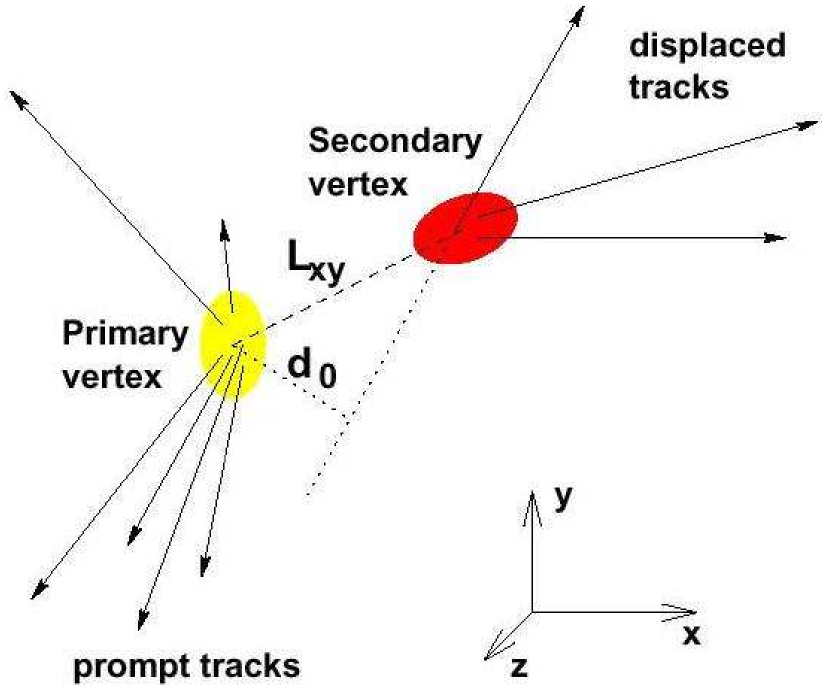


Theorists should know:

$$\text{For charged tracks}: \quad \Delta p/p \;\propto\; p,$$
$$\text{typical resolution}: \quad \sim\; p/(10^4\ \text{GeV}).$$
$$\text{For calorimetry}: \quad \Delta E/E \;\propto\; \frac{1}{\sqrt{E}},$$
$$\text{typical resolution}: \quad \sim\; (10\%_{ecal},\ 50\%_{hcal})/\sqrt{E/\text{GeV}}$$

† For vertex-tagged particles $\tau \approx 10^{-12}$ s,

heavy flavor tagging: the secondary vertex:



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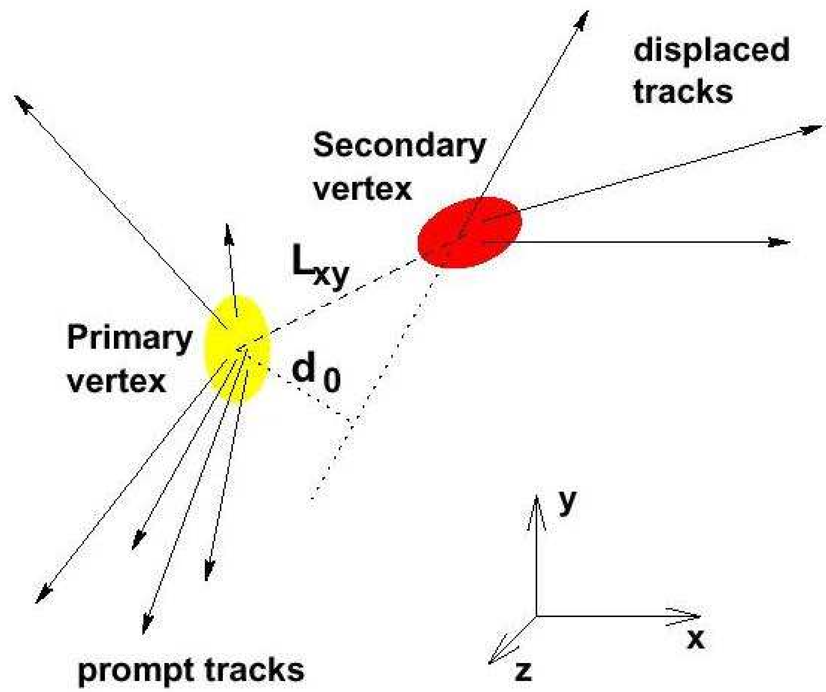

Typical resolution: $d_0 \sim 30 - 50\ \mu$m or so

$\Rightarrow$ Better have two (non-collinear) charged tracks for a secondary vertex;

Or use the "impact parameter" w.r.t. the primary vertex.

For theorists: just multiply a "tagging efficiency":

$$\epsilon_b \sim 70\%; \quad \epsilon_c \sim 40\%; \quad \epsilon_\tau \sim 40\%.$$

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$$0 = \sum_f^{obs.} \vec{p}_{f\ T} \; + \; \vec{p}_{miss\ T}.$$

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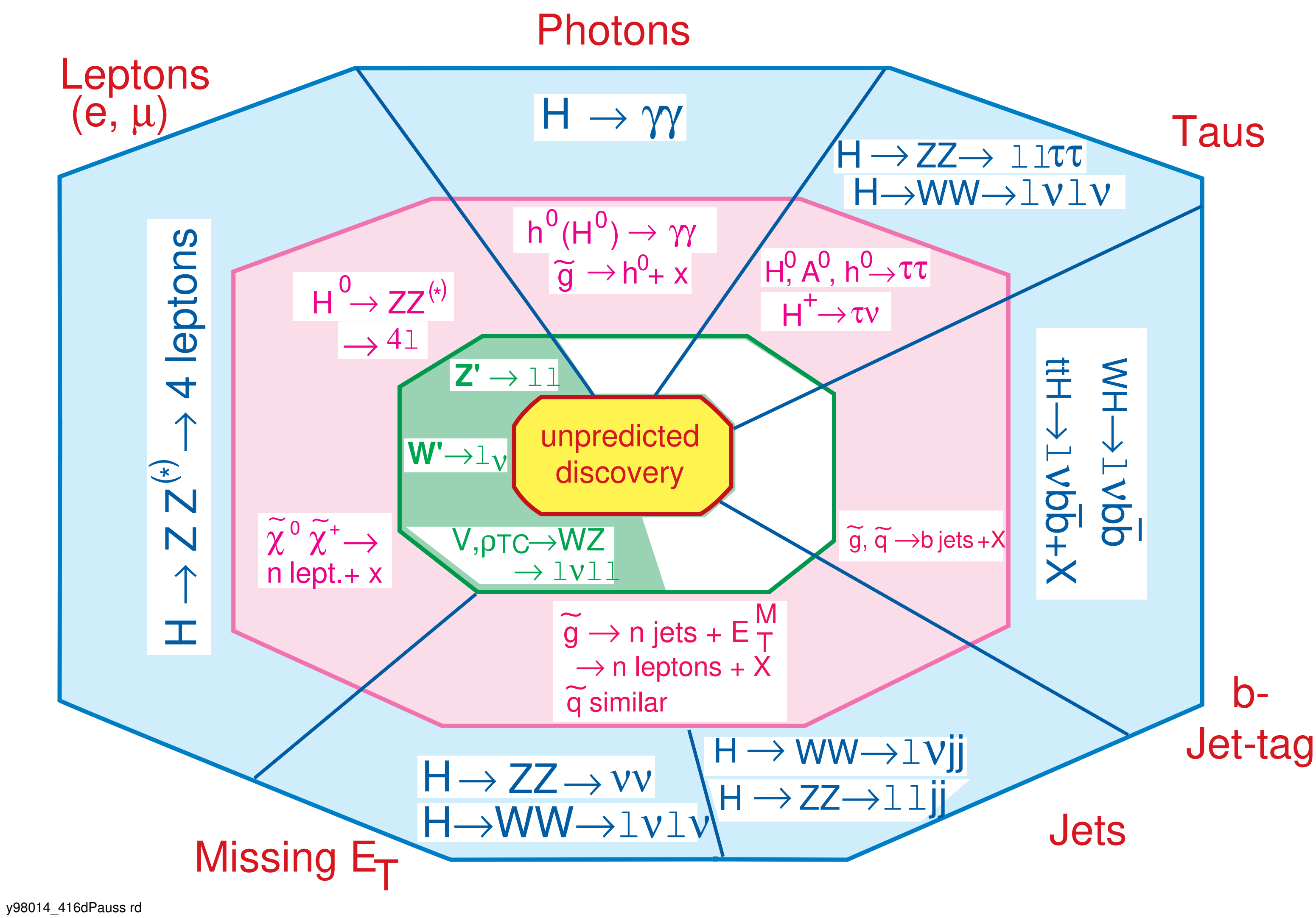
Note: "missing E_T" (MET) is *conceptually* ill-defined!
It is only sensible for massless particles: $\not{E}_T = \sqrt{\vec{p}^{\,2}_{miss\ T} + m^2}$.

What we “see” for the SM particles: no universality!

What we "see" for the SM particles: no universality! How to search for new particles?



I-B. Basic Techniques and Tools for Collider Physics

(A). Scattering cross section

For a $2 \to n$ scattering process:

$$\sigma(ab \to 1+2+...n) = \frac{1}{2s} \overline{\sum} |\mathcal{M}|^2 \, dPS_n,$$

$$dPS_n \equiv (2\pi)^4 \, \delta^4 \left(P - \sum_{i=1}^{n} p_i \right) \Pi_{i=1}^{n} \frac{1}{(2\pi)^3} \frac{d^3\vec{p}_i}{2E_i},$$

$$s = (p_a + p_b)^2 \equiv P^2 = \left(\sum_{i=1}^{n} p_i \right)^2,$$

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For a $1 \to n$ decay process, the partial width in the rest frame:

$$\Gamma(a \to 1 + 2 + ...n) = \frac{1}{2M_a} \overline{\sum}|\mathcal{M}|^2 \, dPS_n.$$

$$\tau = \Gamma_{tot}^{-1} = (\sum_f \Gamma_f)^{-1}.$$

(B). Phase space and kinematics *

One-particle Final State $a + b \to 1$:

$$\begin{aligned} dPS_1 &\equiv (2\pi)\ \frac{d^3\vec{p}_1}{2E_1}\delta^4(P - p_1) \\ &\doteq \pi|\vec{p}_1|d\Omega_1\delta^3(\vec{P} - \vec{p}_1) \\ &\doteq 2\pi\ \delta(s - m_1^2). \end{aligned}$$

where the first and second equal signs made use of the identities:

$$|\vec{p}|d|\vec{p}| = EdE, \quad \frac{d^3\vec{p}}{2E} = \int d^4p\ \delta(p^2 - m^2).$$

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The "dimensinless phase-space volume" is $s(dPS_1)=2\pi$.

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Two-particle Final State $a + b \to 1 + 2$:

$$
\begin{aligned}
dPS_2 &\equiv \frac{1}{(2\pi)^2}\ \delta^4\left(P - p_1 - p_2\right) \frac{d^3\vec{p}_1}{2E_1}\frac{d^3\vec{p}_2}{2E_2} \\
&\doteq \frac{1}{(4\pi)^2}\ \frac{|\vec{p}_1^{\,cm}|}{\sqrt{s}}\ d\Omega_1 = \frac{1}{(4\pi)^2}\ \frac{|\vec{p}_1^{\,cm}|}{\sqrt{s}}\ d\cos\theta_1 d\phi_1 \\
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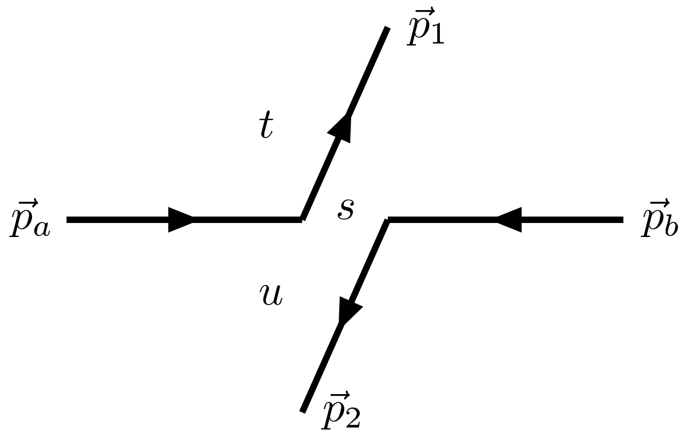
$$

The phase-space volume of the two-body is scaled down with respect to that of the one-particle by a factor

$$
\frac{dPS_2}{s\ dPS_1} \approx \frac{1}{(4\pi)^2}.
$$

just like a "loop factor".

Consider a $2 \to 2$ scattering process $p_a + p_b \to p_1 + p_2$,



the (Lorentz invariant) Mandelstam variables are defined as

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& s + t + u = m_a^2 + m_b^2 + m_1^2 + m_2^2.
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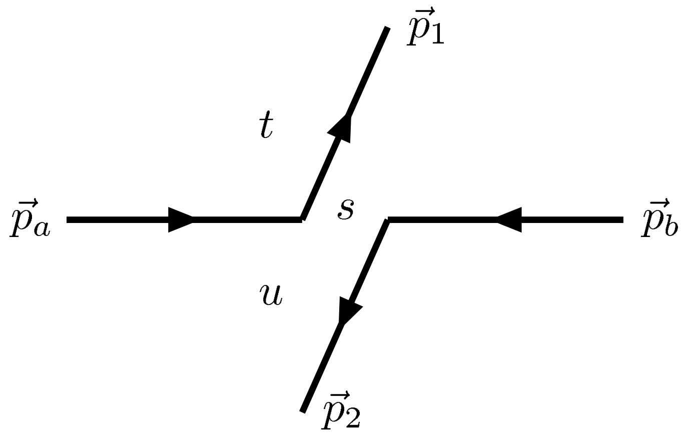

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The two-body phase space can be thus written as

$$dPS_2 = \frac{1}{(4\pi)^2} \, \frac{dt \;\, d\phi_1}{s \;\, \lambda^{1/2}\left(1, m_a^2/s, m_b^2/s\right)}.$$

Three-particle Final State $a + b \to 1 + 2 + 3$:

$$
\begin{aligned}
dPS_3 &\equiv \frac{1}{(2\pi)^5}\ \delta^4\left(P - p_1 - p_2 - p_3\right) \frac{d^3\vec{p}_1}{2E_1}\frac{d^3\vec{p}_2}{2E_2}\frac{d^3\vec{p}_3}{2E_3} \\
&\doteq \frac{|\vec{p}_1|^2\ d|\vec{p}_1|\ d\Omega_1}{(2\pi)^3\ 2E_1}\ \frac{1}{(4\pi)^2}\ \frac{|\vec{p}_2^{(23)}|}{m_{23}}\ d\Omega_2 \\
&= \frac{1}{(4\pi)^3}\ \lambda^{1/2}\left(1, \frac{m_2^2}{m_{23}^2}, \frac{m_3^2}{m_{23}^2}\right)\ 2|\vec{p}_1|\ dE_1\ dx_2 dx_3 dx_4 dx_5.
\end{aligned}
$$

$$
\begin{aligned}
d\cos\theta_{1,2} &= 2dx_{2,4}, \quad d\phi_{1,2} = 2\pi dx_{3,5}, \quad 0 \le x_{2,3,4,5} \le 1, \\
& |\vec{p}_1^{cm}|^2 = |\vec{p}_2^{cm} + \vec{p}_3^{cm}|^2 = (E_1^{cm})^2 - m_1^2, \\
& m_{23}^2 = s - 2\sqrt{s}E_1^{cm} + m_1^2, \quad |\vec{p}_2^{23}| = |\vec{p}_3^{23}| = \frac{\lambda^{1/2}(m_{23}^2, m_2^2, m_3^2)}{2m_{23}},
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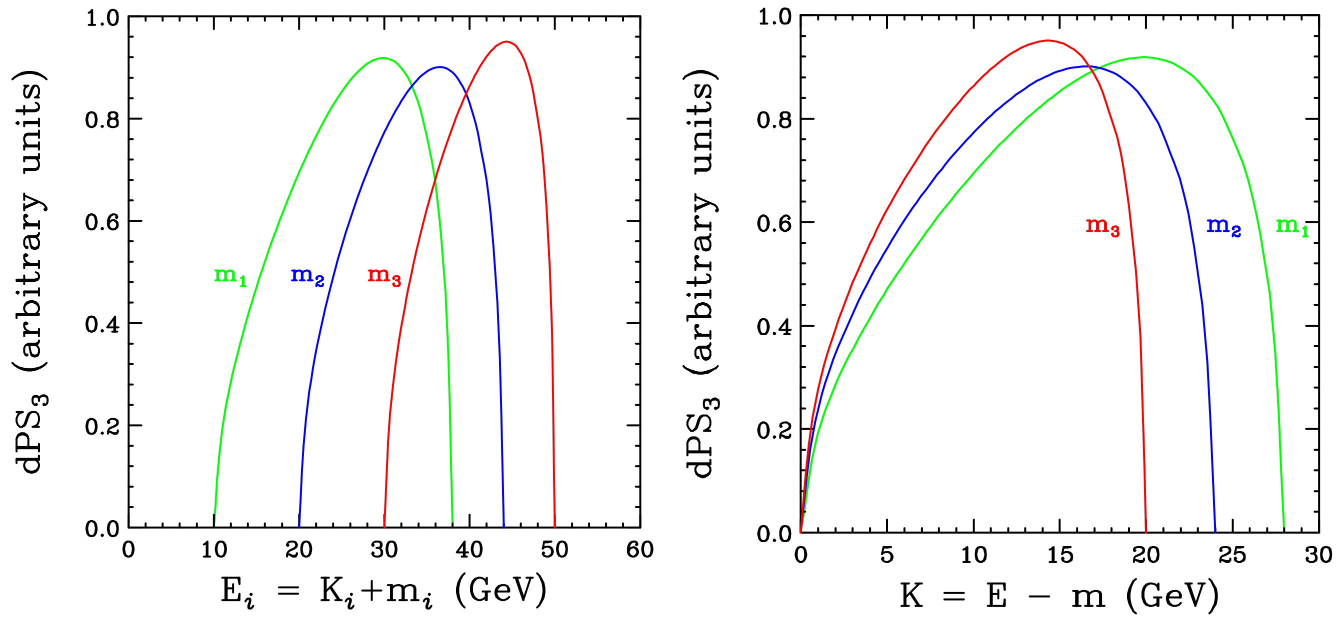
The particle energy spectrum is not monochromatic.
The maximum value (the end-point) for particle 1 in c.m. frame is

$$E_1^{max} = \frac{s+m_1^2-(m_2+m_3)^2}{2\sqrt{s}},\quad m_1\le E_1\le E_1^{max},$$

$$|\vec{p}_1^{max}| = \frac{\lambda^{1/2}(s,m_1^2,(m_2+m_3)^2)}{2\sqrt{s}},\quad 0\le p_1\le p_1^{max}.$$

With $m_i = 10,\ 20,\ 30,\ \sqrt{s} = 100$ GeV.



More intuitive to work out the end-point for the kinetic energy,
– recall the direct neutrino mass bound in β-decay:

$$K_1^{max} = E_1^{max} - m_1 = \frac{(\sqrt{s} - m_1 - m_2 - m_3)(\sqrt{s} - m_1 + m_2 + m_3)}{2\sqrt{s}}.$$

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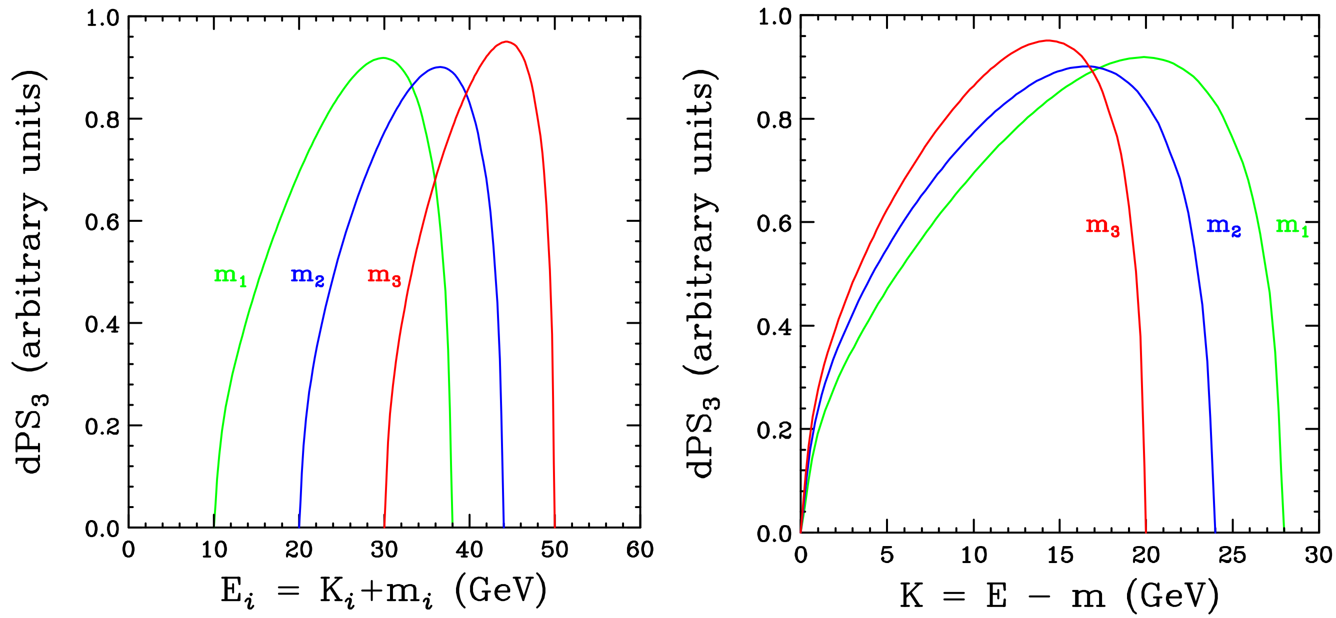

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For $n \to p^+ e^- \bar{\nu}_e$,

$$K_e^{max} \approx (m_n - m_p - m_e) - m_\nu.$$

In general, the 3-body phase space boundaries are non-trivial.
That leads to the "Dalitz Plots".

One practically useful formula is: A particle of mass M decays to 3 particles $M \to abc$.
Show that the phase space element can be expressed as

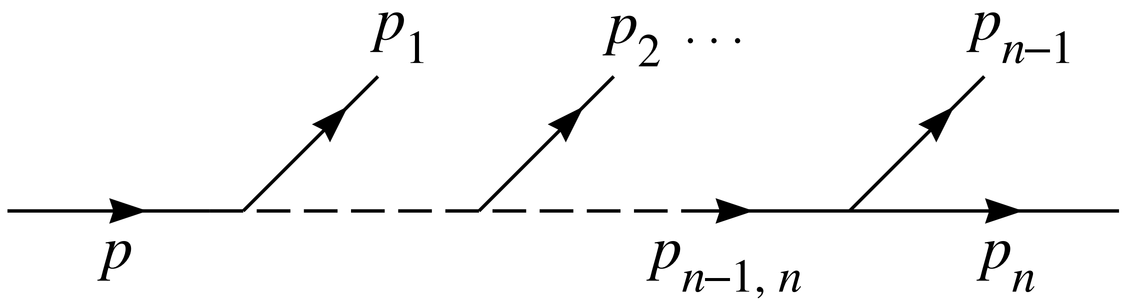
$$dPS_3 = \frac{1}{2^7 \pi^3}\ M^2 dx_a dx_b.$$

$$x_i = \frac{2E_i}{M},\ (i = a, b, c,\ \sum_i x_i = 2).$$

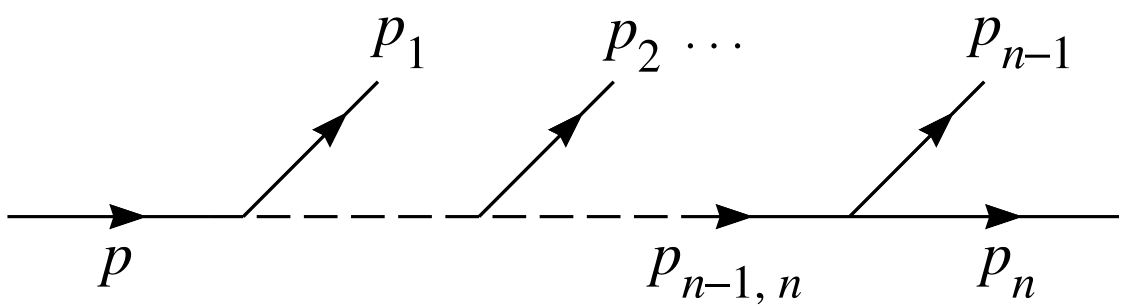
where the integration limits for $m_a = m_b = m_c = 0$ are

$$0 \le x_a \le 1, \quad 1 - x_a \le x_b \le 1.$$

Recursion relation $P \to 1 + 2 + 3 ... + n$:



Recursion relation $P \to 1 + 2 + 3 ... + n$:



$$dPS_n(P; p_1, ..., p_n) = dPS_{n-1}(P; p_1, ..., p_{n-1,n})$$
$$dPS_2(p_{n-1,n}; p_{n-1}, p_n)\frac{dm^2_{n-1,n}}{2\pi}.$$

For instance,

$$dPS_3 = dPS_2(i)\ \frac{dm^2_{prop}}{2\pi}\ dPS_2(f).$$

This is generically true, but particularly useful when the diagram has an s-channel particle propagation.

Breit-Wigner Resonance, the Narrow Width Approximation

An unstable particle of mass M and total width Γ_V, the propagator is

$$R(s) = \frac{1}{(s - M_V^2)^2 + \Gamma_V^2 M_V^2}.$$

the Narrow Width Approximation

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Consider a three-body decay of a top quark,
$t \to bW^* \to b\ e\nu$. Making use of the phase space recursion relation and the narrow width approximation for the intermediate W boson, show that the partial decay width of the top quark can be expressed as (ignore spin correlations)

$$\Gamma(t \to bW^* \to b\ e\nu) \approx \Gamma(t \to bW) \cdot BR(W \to e\nu).$$

"Proof": Consider an intermediate state V^*

$$a \to bV^* \to b\ p_1 p_2.$$

By the reduction formula, the resonant integral reads

$$\int_{(m_*^{min})^2=(m_1+m_2)^2}^{(m_*^{max})^2=(m_a-m_b)^2} dm_*^2.$$

Variable change

$$\tan\theta = \frac{m_*^2 - M_V^2}{\Gamma_V M_V},$$

resulting in a flat integrand over θ

$$\int_{(m_*^{min})^2}^{(m_*^{max})^2} \frac{dm_*^2}{(m_*^2 - M_V^2)^2 + \Gamma_V^2 M_V^2} = \int_{\theta^{min}}^{\theta^{max}} \frac{d\theta}{\Gamma_V M_V}.$$

In the limit

$$(m_1 + m_2) + \Gamma_V \ll M_V \ll m_a - m_b - \Gamma_V,$$

$$\theta^{min} = \tan^{-1}\frac{(m_1+m_2)^2 - M_V^2}{\Gamma_V M_V} \to -\pi,$$

$$\theta^{max} = \tan^{-1}\frac{(m_a-m_b)^2 - M_V^2}{\Gamma_V M_V} \to 0,$$

then the Narrow Width Approximation

$$\frac{1}{(m_*^2 - M_V^2)^2 + \Gamma_V^2 M_V^2} \approx \frac{\pi}{\Gamma_V M_V}\ \delta(m_*^2 - M_V^2).$$

(C). Matrix element: The dynamics

Properties of scattering amplitudes $T(s, t, u)$

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• Unitarity:
S-matrix unitarity leads to :

$$-i(T - T^{\dagger}) = TT^{\dagger}$$

Partial wave expansion for $a + b \to 1 + 2$:

$$\mathcal{M}(s,t) = 16\pi \sum_{J=M}^{\infty} (2J+1) a_J(s) d^J_{\mu\mu'}(\cos\theta)$$

$$a_J(s) = \frac{1}{32\pi} \int_{-1}^{1} \mathcal{M}(s,t)\ d^J_{\mu\mu'}(\cos\theta) d\cos\theta.$$

where $\mu = s_a - s_b,\ \mu' = s_1 - s_2,\ M = \max(|\mu|, |\mu'|)$.

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By Optical Theorem: $\sigma = \frac{1}{s}\mathrm{Im}\mathcal{M}(\theta = 0) = \frac{16\pi}{s} \sum_{J=M}^{\infty} (2J+1)|a_J(s)|^2$.

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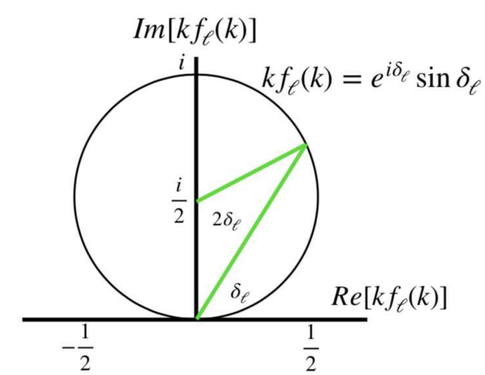
The partial wave amplitude have the properties:

(a). partial wave unitarity: $\mathrm{Im}(a_J) \geq |a_J|^2$, or $|\mathrm{Re}(a_J)| \leq 1/2$,



Argand diagram for partial wave unitarity

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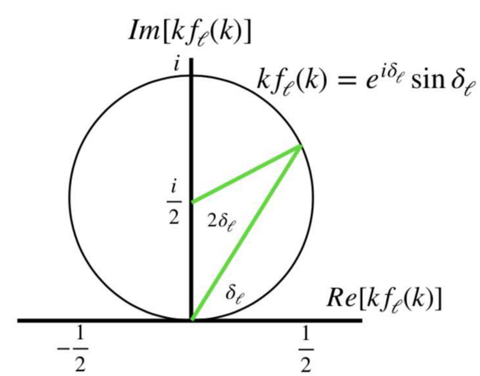
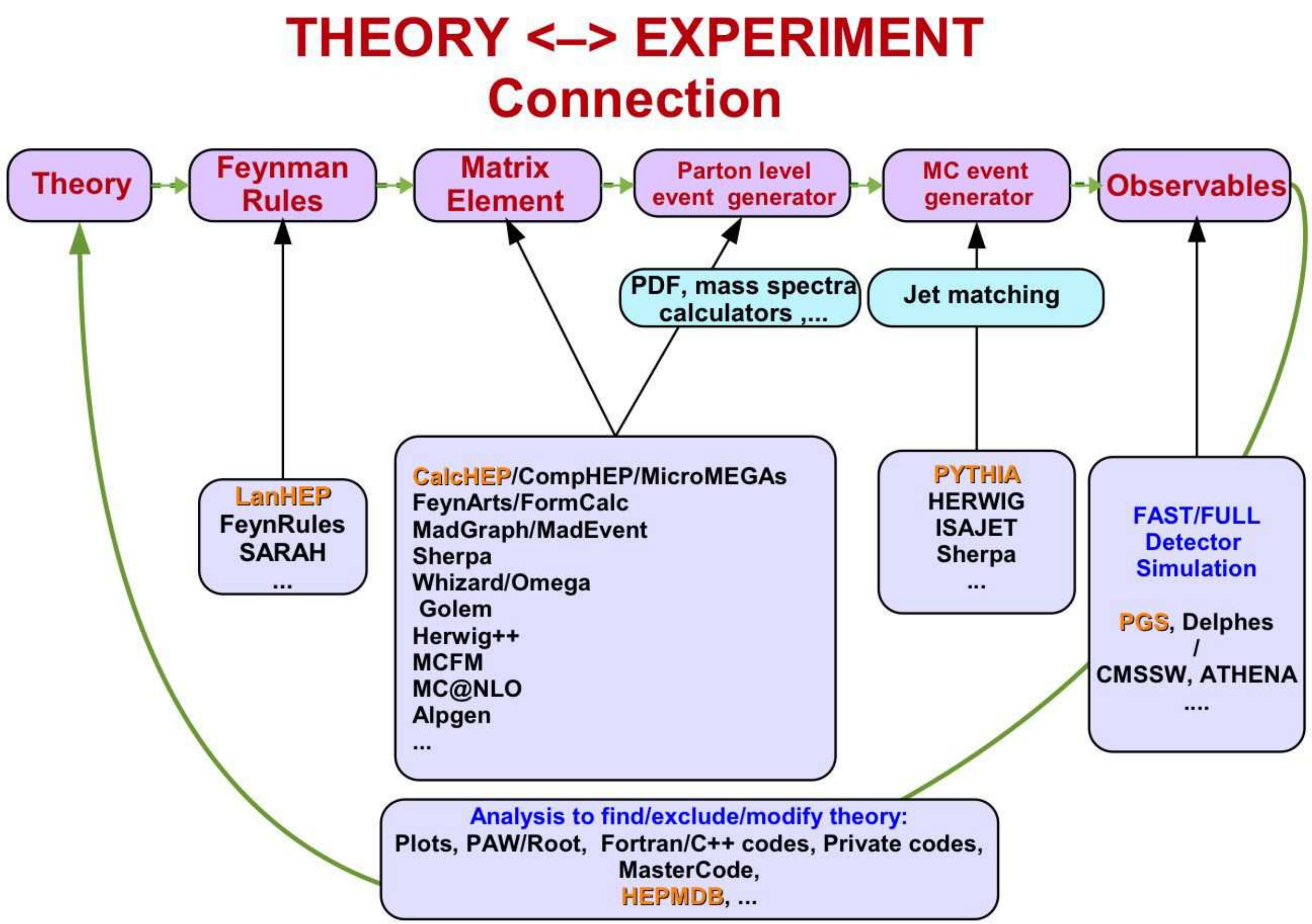


Argand diagram for partial wave unitarity (b). kinematical thresholds: $a_J(s) \propto \beta_i^{l_i}\ \beta_f^{l_f}\ (J = L + S)$.

(b). kinematical thresholds: $a_J(s) \propto \beta_i^{l_i}\ \beta_f^{l_f}\ (J = L + S)$.

$\Rightarrow$ well-known behavior: $\sigma \propto \beta_f^{2l_f+1}$.

(D). Calculational Tools



II. Physics at an e^+e^- Collider

(A.) Simple Formalism

Event rate of a reaction:

$$\begin{aligned} R(s) &= \sigma(s)\mathcal{L}, \quad \text{for constant } \mathcal{L} \\ &= \mathcal{L}\int d\tau \frac{dL(s,\tau)}{d\tau}\,\sigma(\hat{s}), \quad \tau = \frac{\hat{s}}{s}. \end{aligned}$$

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As for the differential production cross section of two-particle a, b,

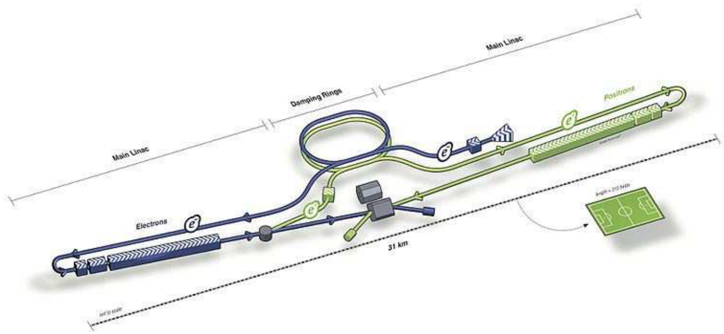
$$\frac{d\sigma(e^+e^- \to ab)}{d\cos\theta} = \frac{\beta}{32\pi s}\overline{\sum}|\mathcal{M}|^2$$

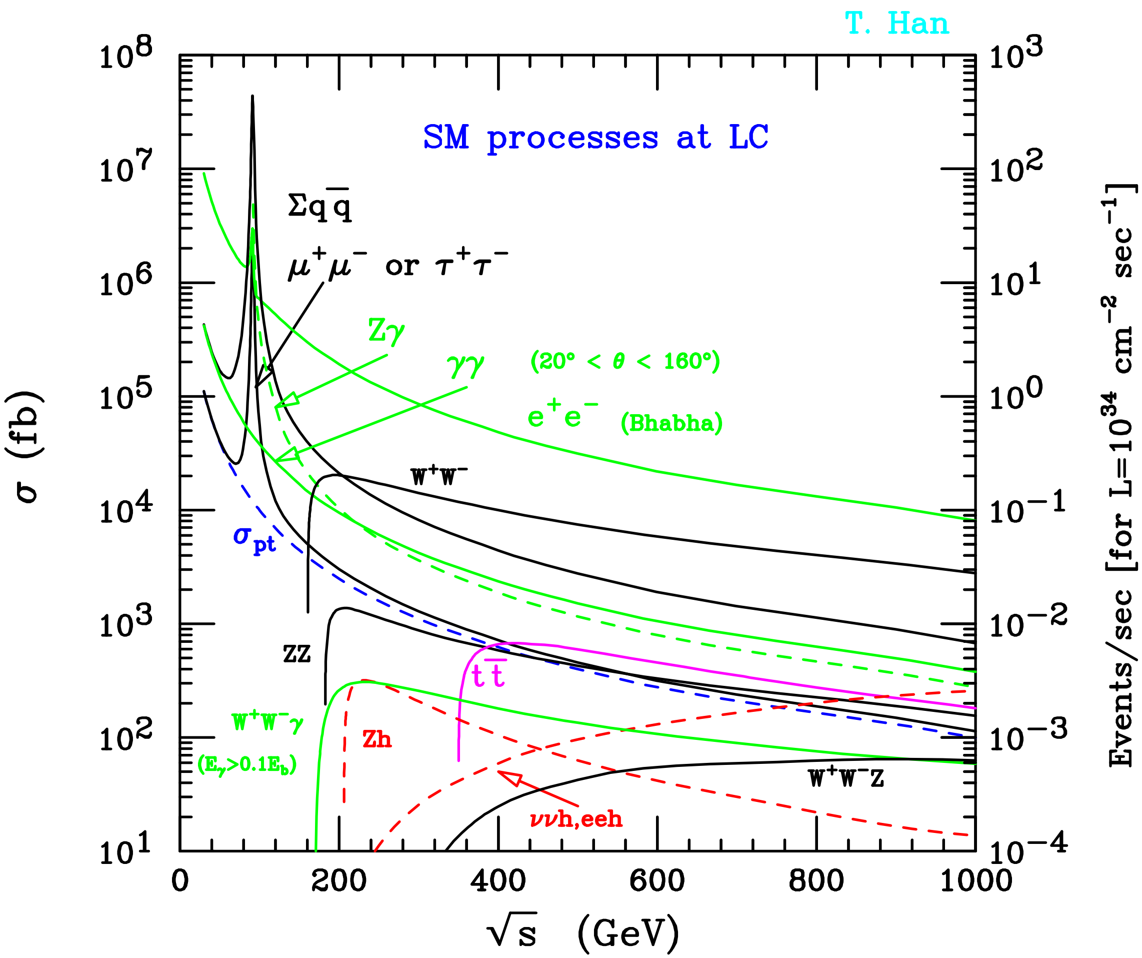
where

• $\beta = \lambda^{1/2}(1, m_a^2/s, m_b^2/s)$, is the speed factor for the out-going particles in the c.m. frame, and $p_{cm} = \beta\sqrt{s}/2$,

• $\overline{\sum|\mathcal{M}|^2}$ the squared matrix element, summed and averaged over quantum numbers (like color and spins etc.)

• unpolarized beams so that the azimuthal angle trivially integrated out, Total cross sections and event rates for SM processes:





(B). Resonant production: Breit-Wigner formula

$$\frac{1}{(s-M_V^2)^2+\Gamma_V^2 M_V^2}$$

If the energy spread $\delta\sqrt{s} \ll \Gamma_V$, the line-shape mapped out:

$$\sigma(e^+e^- \to V^* \to X) = \frac{4\pi(2j+1)\Gamma(V\to e^+e^-)\Gamma(V\to X)}{(s-M_V^2)^2+\Gamma_V^2 M_V^2}\ \frac{s}{M_V^2}.$$

(physical examples?)

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(physical examples?)

If $\delta\sqrt{s} \gg \Gamma_V$, the narrow-width approximation:

$$\frac{1}{(s-M_V^2)^2+\Gamma_V^2 M_V^2} \ \to \ \frac{\pi}{M_V\Gamma_V}\ \delta(s-M_V^2),$$

$$\sigma(e^+e^- \to V^* \to X) \ = \ \frac{2\pi^2(2j+1)\Gamma(V \to e^+e^-)BF(V \to X)}{M_V^2}\frac{dL(\hat{s}=M_V^2)}{d\sqrt{\hat{s}}}$$

(physical examples?)

Away from resonance

For an s-channel or a finite-angle scattering:

$$\sigma \sim \frac{1}{s}.$$

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For an s-channel or a finite-angle scattering:

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For forward (co-linear) scattering:

$$\sigma \sim \frac{1}{M_V^2} \ln^2 \frac{s}{M_V^2}.$$

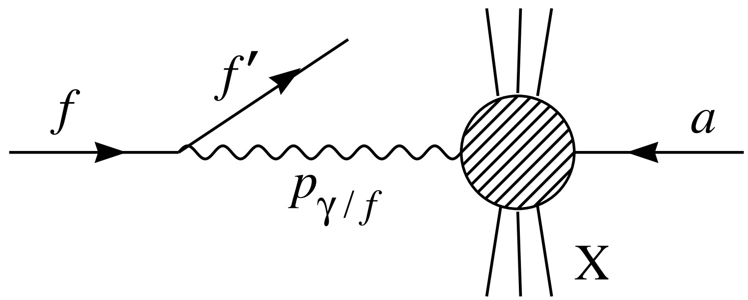
- The simplest reaction

$$\sigma(e^+e^- \to \gamma^* \to \mu^+\mu^-) \equiv \sigma_{pt} = \frac{4\pi\alpha^2}{3s}.$$

In fact, $\sigma_{pt} \approx 100\ \text{fb}/(\sqrt{s}/\text{TeV})^2$ has become standard units to measure the size of cross sections.

(C). Gauge boson radiation:

A qualitatively different process is initiated from gauge boson radiation, typically off fermions:



The simplest case is the photon radiation off an electron, like:

$$e^+e^- \to e^+,\ \gamma^* e^- \to e^+e^-.$$

The dominant features are due to the result of a t-channel singularity, induced by the collinear photon splitting:

$$\sigma(e^- a \to e^- X) \approx \int dx\ P_{\gamma/e}(x)\ \sigma(\gamma a \to X).$$

The so called the effective photon approximation.

For an electron of energy E, the probability of finding a collinear photon of energy xE is given by

$$P_{\gamma/e}(x) = \frac{\alpha}{2\pi} \frac{1 + (1-x)^2}{x} \ln \frac{E^2}{m_e^2},$$

known as the Weizsäcker-Williams spectrum.

```
Exercise 3.3:  Try to derive this splitting function.
```

We see that:

- m_e enters the log to regularize the collinear singularity;
- $1/x$ leads to the infrared behavior of the photon;
- This picture of the photon probability distribution is also valid for other photon spectrum:

Based on the back-scattering laser technique, it has been proposed to produce much harder photon spectrum, to construct a "photon collider"...

(massive) Gauge boson radiation:

A similar picture may be envisioned for the electroweak massive gauge bosons, $V = W^{\pm}, Z$.

Consider a fermion f of energy E, the probability of finding a (nearly) collinear gauge boson V of energy xE and transverse momentum p_T (with respect to $\vec{p}_f$) is approximated by

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

Although the collinear scattering would not be a good approximation until reaching very high energies $\sqrt{s} \gg M_V$, it is instructive to consider the qualitative features.

(D). Recoil mass technique:

One of the most important techniques, that distinguishes an e^+e^- collisions from hadronic collisions.

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$$e^+ + e^- \to V + X,$$

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Then:

$$p_{e^+} + p_{e^-} = p_V + p_X, \ (p_{e^+} + p_{e^-} - p_V)^2 = p_X^2,$$
$$M_X^2 = (p_{e^+} + p_{e^-} - p_V)^2 = s + M_V^2 - 2\sqrt{s}E_V.$$

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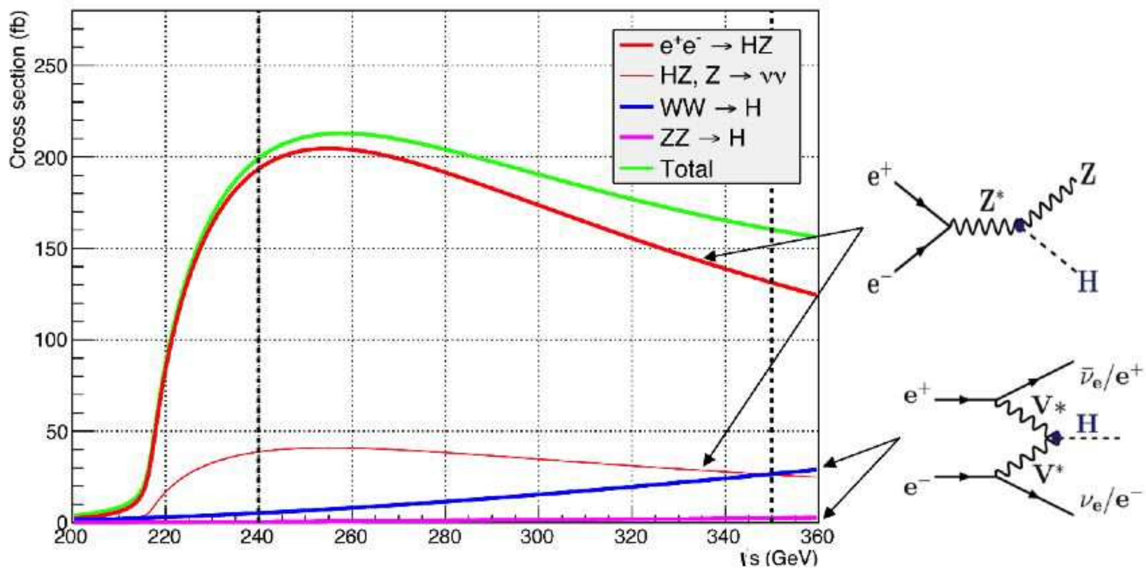
One thus obtain the "model-independent" inclusive measurements

a. mass of X by the recoil mass peak

b. coupling of X by simple event-count at the peak

(E). Physics at a Higgs Factory:



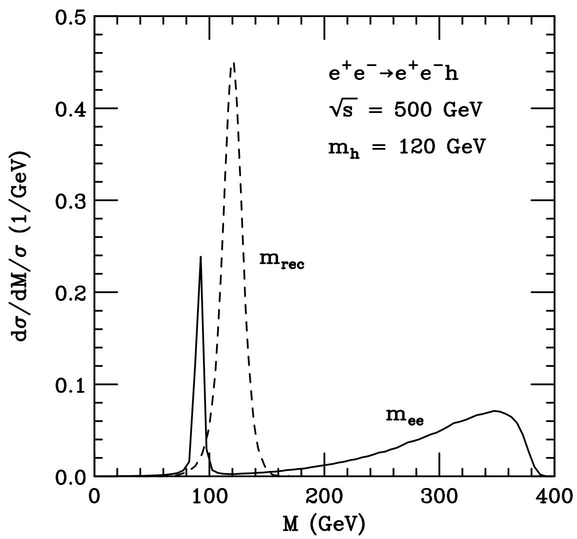
At peak cross section $\approx$ 200 fb with 5 ab^{-1} $\Rightarrow$ 1M h^0!

The key point for a Higgs factory:

Model-independent measurements on the ZZh coupling in a clean experimental environment.

Consider: $e^{+} + e^{-} \to f\bar{f} + h.$

$$M_h^2 = (p_{e^+} + p_{e^-} - p_f - p_{\bar{f}})^2 = s + M_V^2 - 2\sqrt{s}E_{f\bar{f}}.$$



Kinematical selection of "inclusive" signal events!

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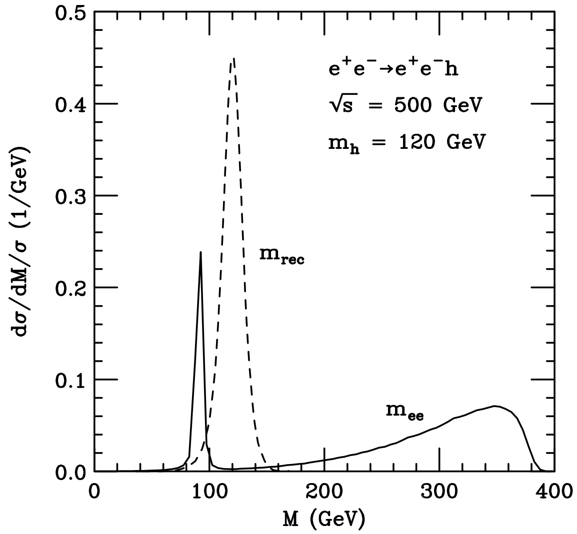
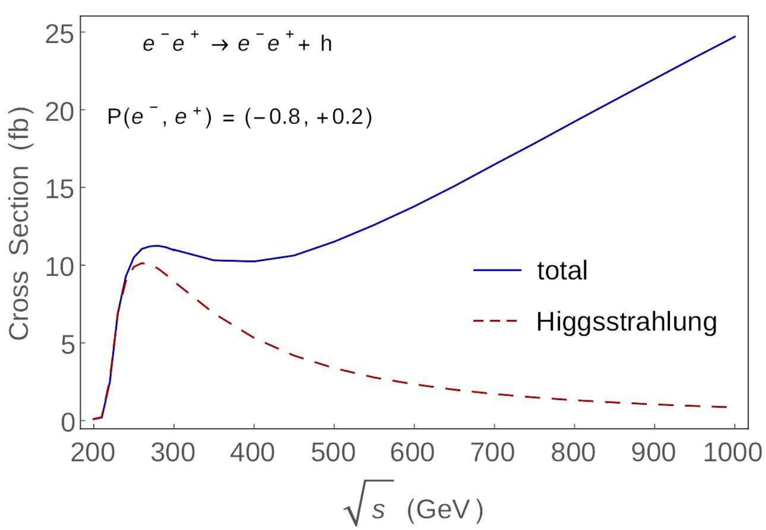
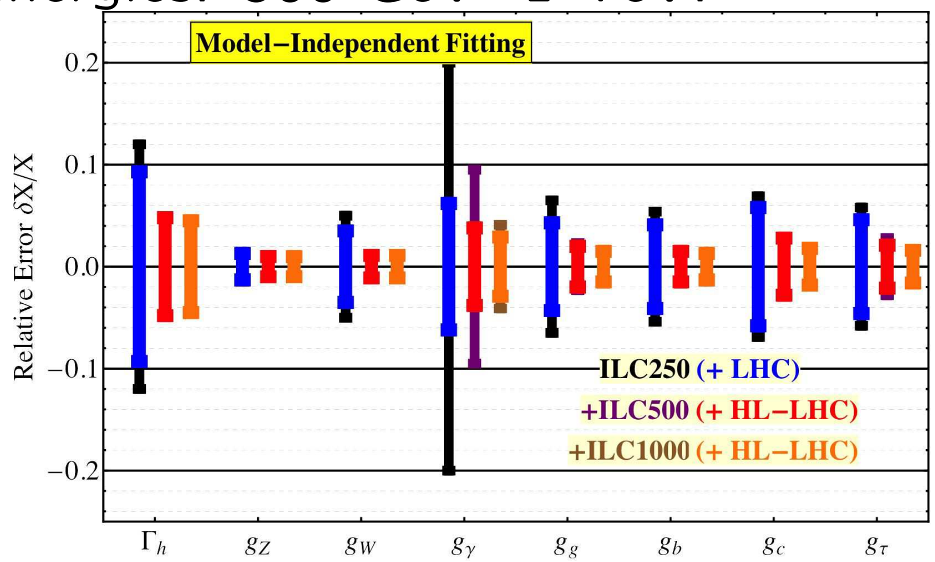


Kinematical selection of "inclusive" signal events!

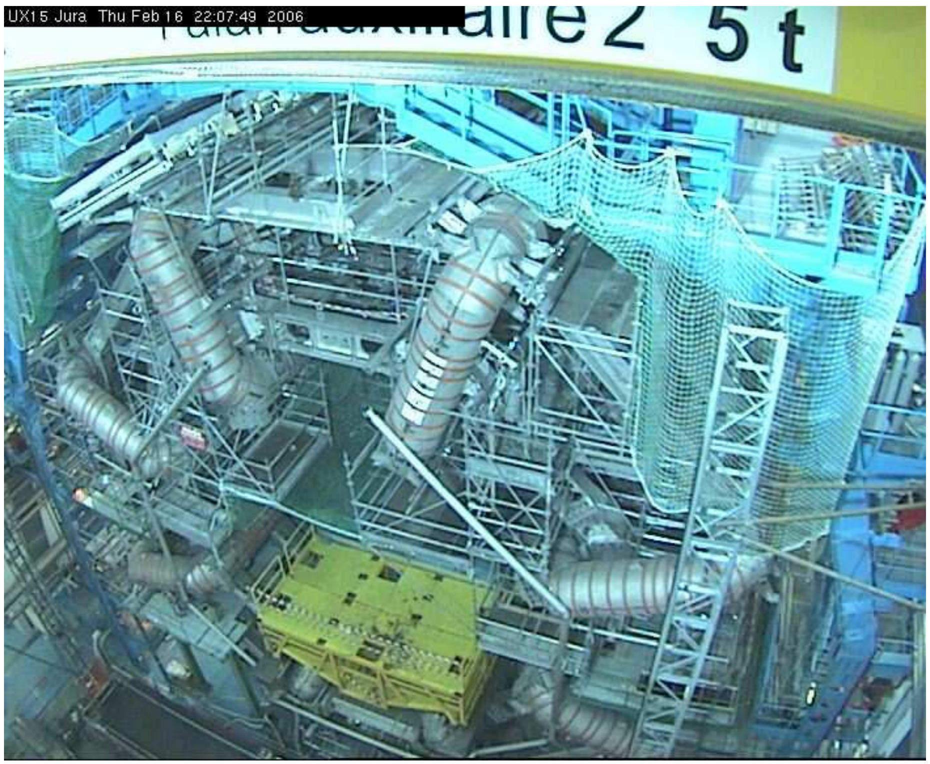
Marching to higher energies: 500 GeV–1 TeV:





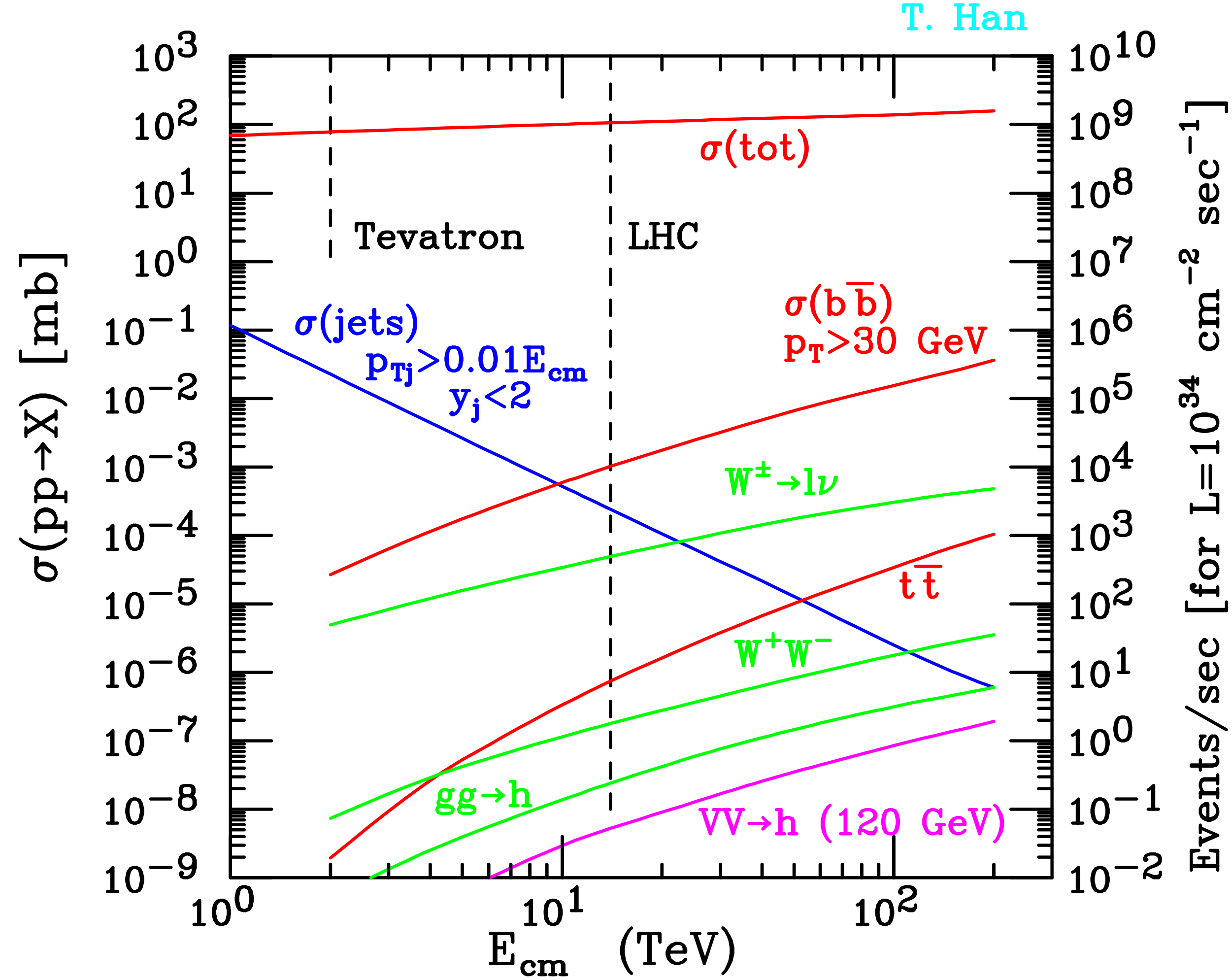
III. Hadron Collider Physics

(A). New HEP frontier: the LHC
The Higgs discovery and more excitements ahead ...



ATLAS (90m underground) CMS

LHC Event rates for various SM processes:



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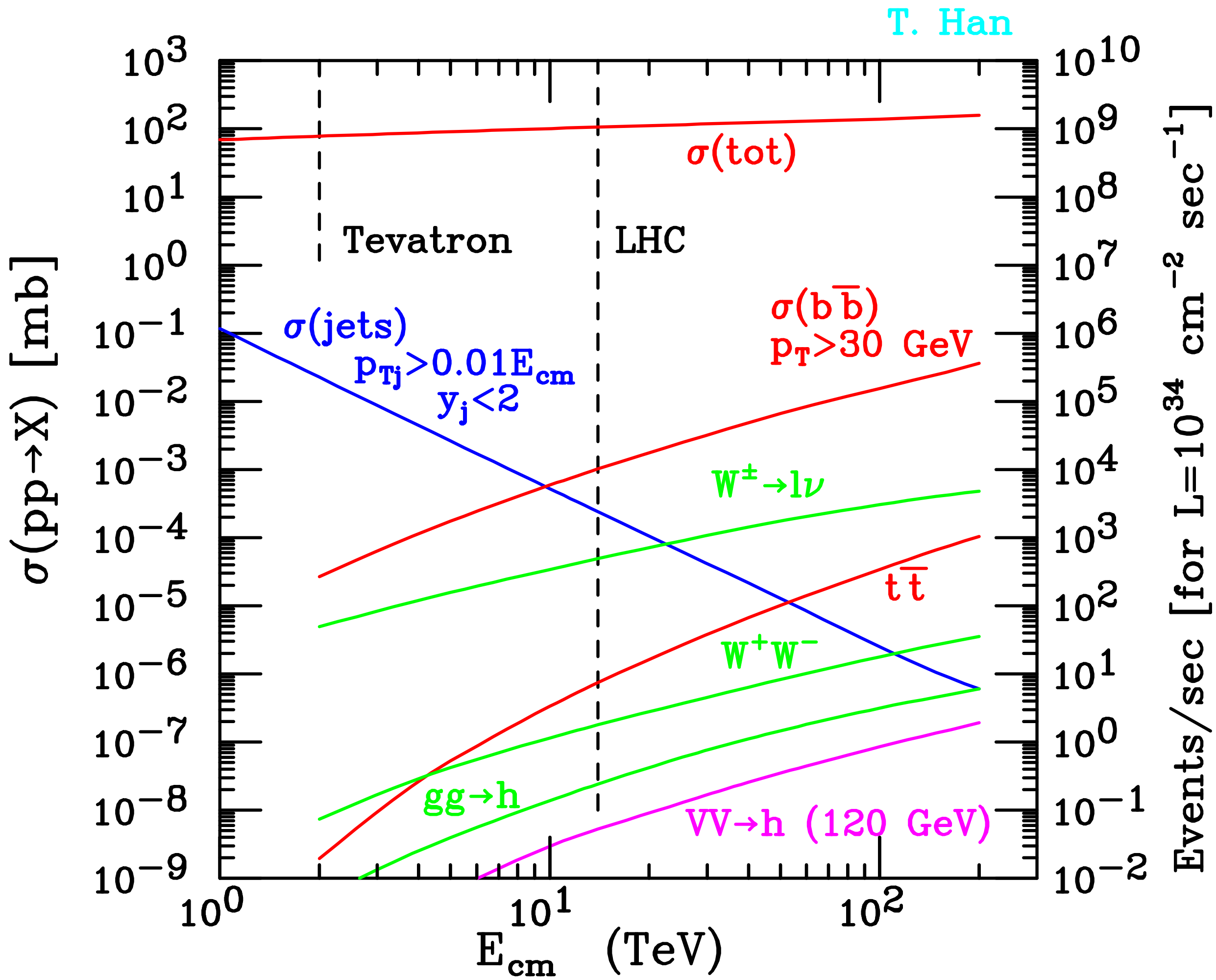

$10^{34}/\text{cm}^2/\text{s} \Rightarrow 100\ \text{fb}^{-1}/\text{yr}.$

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

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(a) Total hadronic cross section: Non-perturbative.

The order of magnitude estimate:

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

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

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(b) Perturbative hadronic cross section:

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

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- 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:
  - ≈ 1 billion event/sec: impossible read-off !
  - ≈ 1 interesting event per $1,000,000$: selection (triggering).

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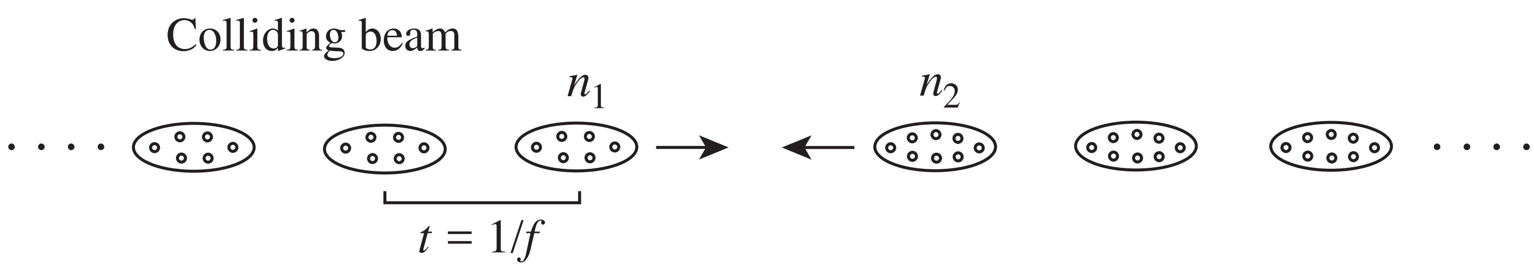
  - $\approx$ 1 billion event/sec: impossible read-off !
  - $\approx$ 1 interesting event per $1,000,000$: selection (triggering).
  - $\approx$ 25 overlapping events/bunch crossing:



$\Rightarrow$ Severe backgrounds!

Triggering thresholds:

	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)

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

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With optimal triggering and kinematical selections:

$p_T \geq 30 - 100$ GeV, $|\eta| \leq 3 - 5$; $\not{E}_T \geq 100$ 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:

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

(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 $p \equiv p^\mu = (E, \vec{p})$,

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

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

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

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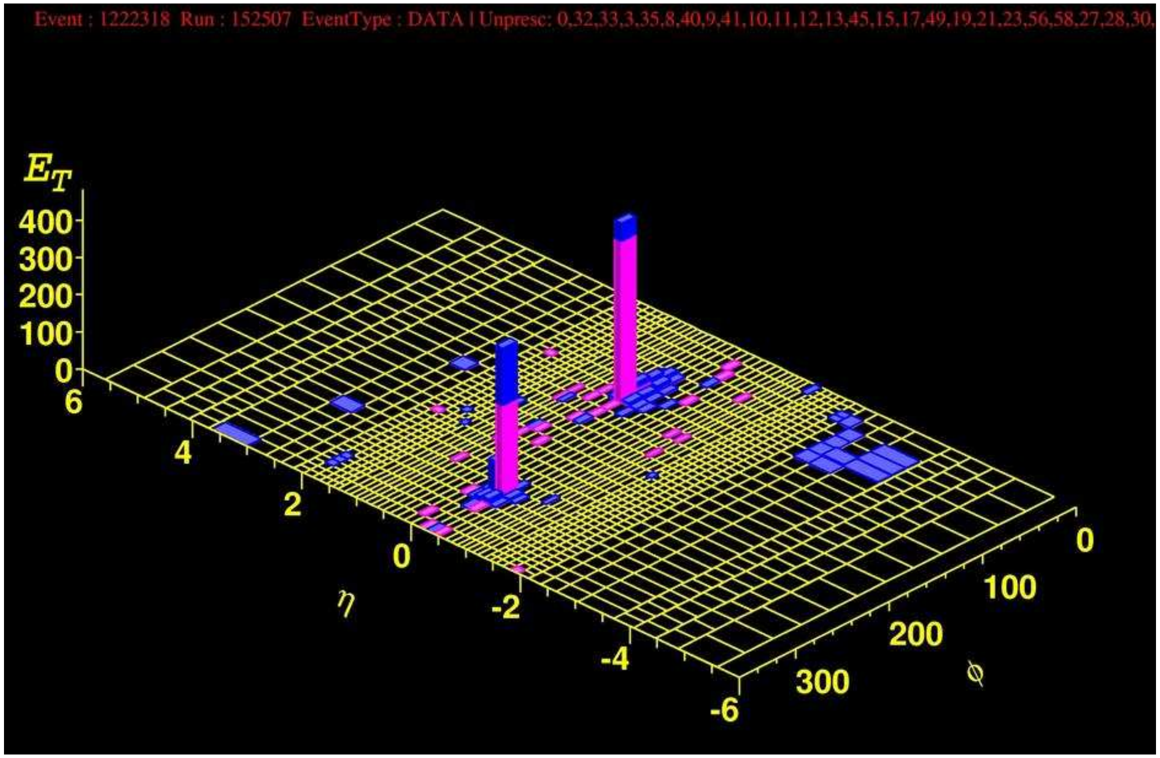
In the massless limit, rapidity $\to$ pseudo-rapidity:

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

The "Lego" plot:



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

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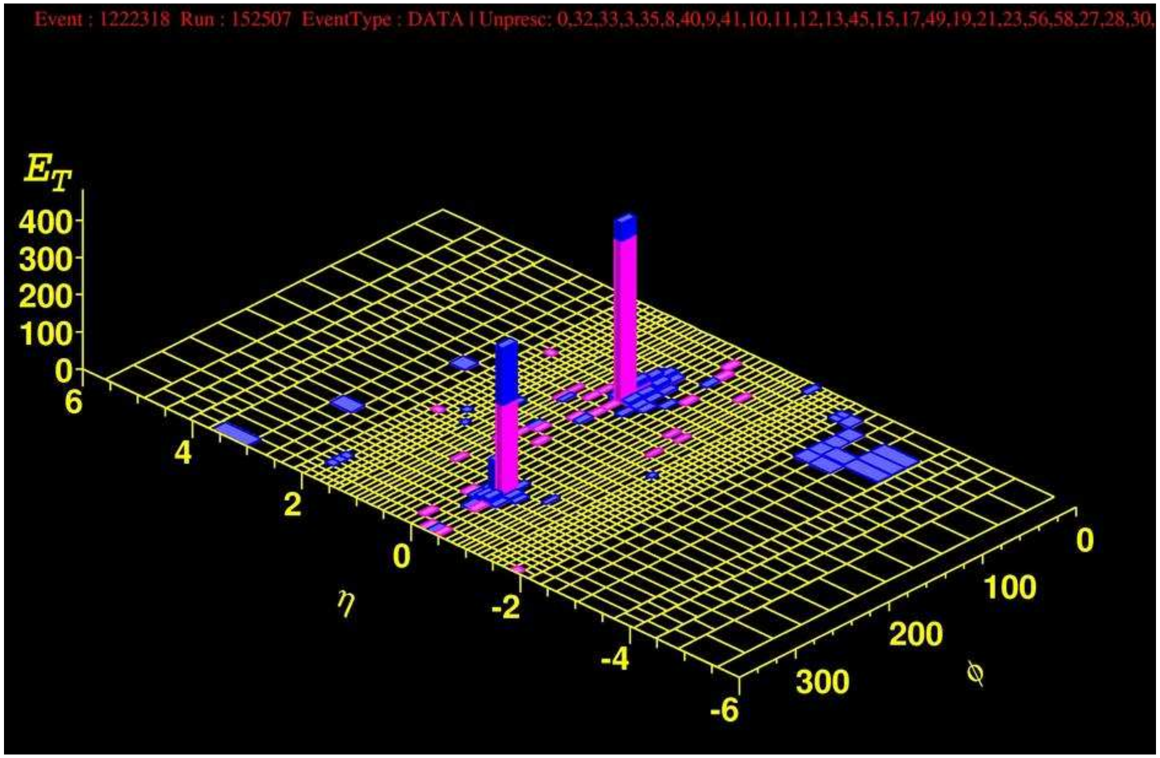

A CDF di-jet event on a lego plot in the $\eta - \phi$ plane.

$\phi, \Delta y = y_2 - y_1$ 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.

(C). Characteristic observables:

Crucial for uncovering new dynamics.

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Selective experimental events

$\Longrightarrow$ Characteristic kinematical observables

(spatial, time, momentaum phase space)

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(masses, couplings)

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(spatial, time, momentaum phase space)

$\Longrightarrow$ Dynamical parameters

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Energy momentum observables $\Longrightarrow$ mass parameters

Angular observables $\Longrightarrow$ nature of couplings;

Production rates, decay branchings/lifetimes $\Longrightarrow$ interaction strengths.

(D). 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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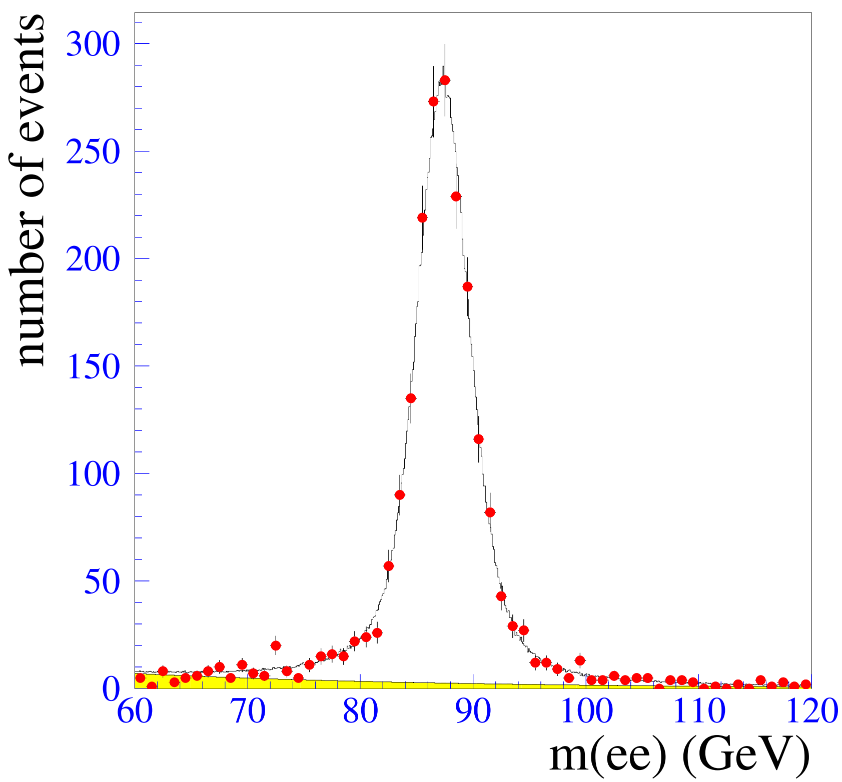
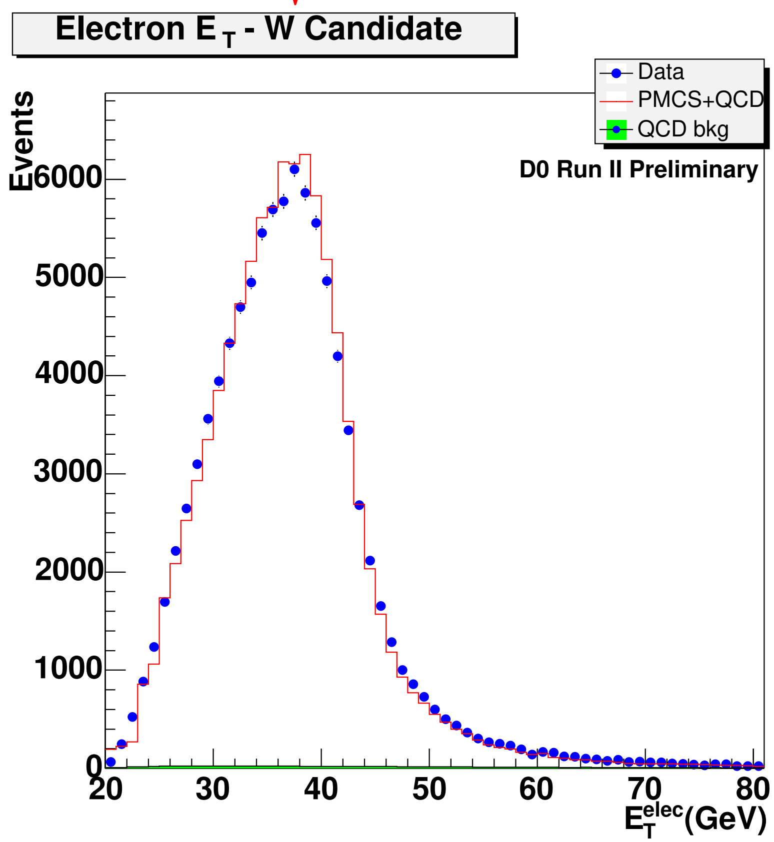


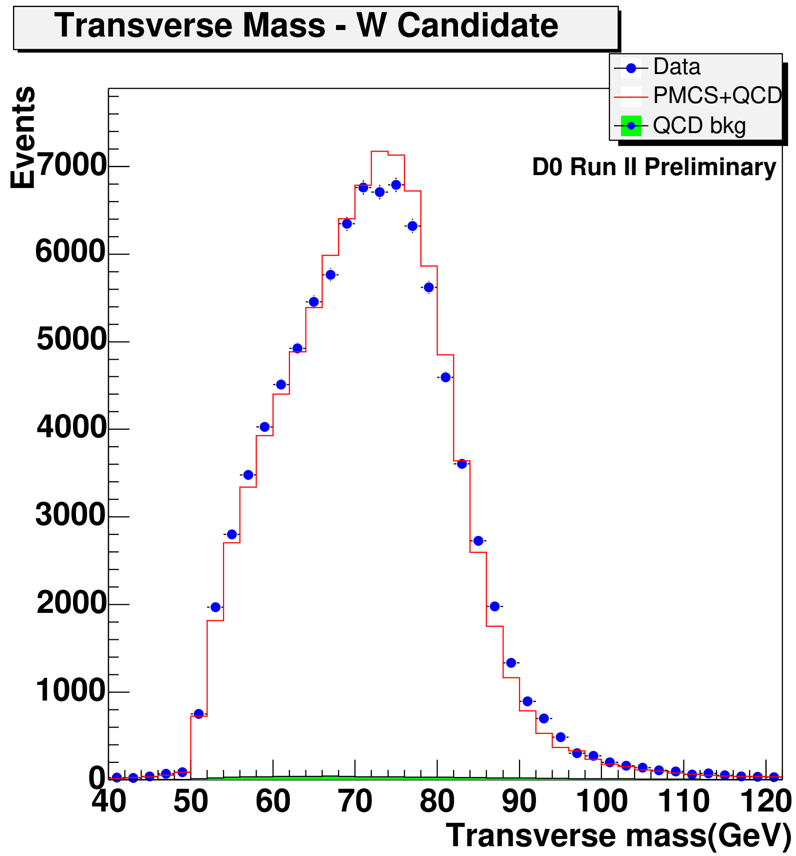
$Z \to e^+e^-$

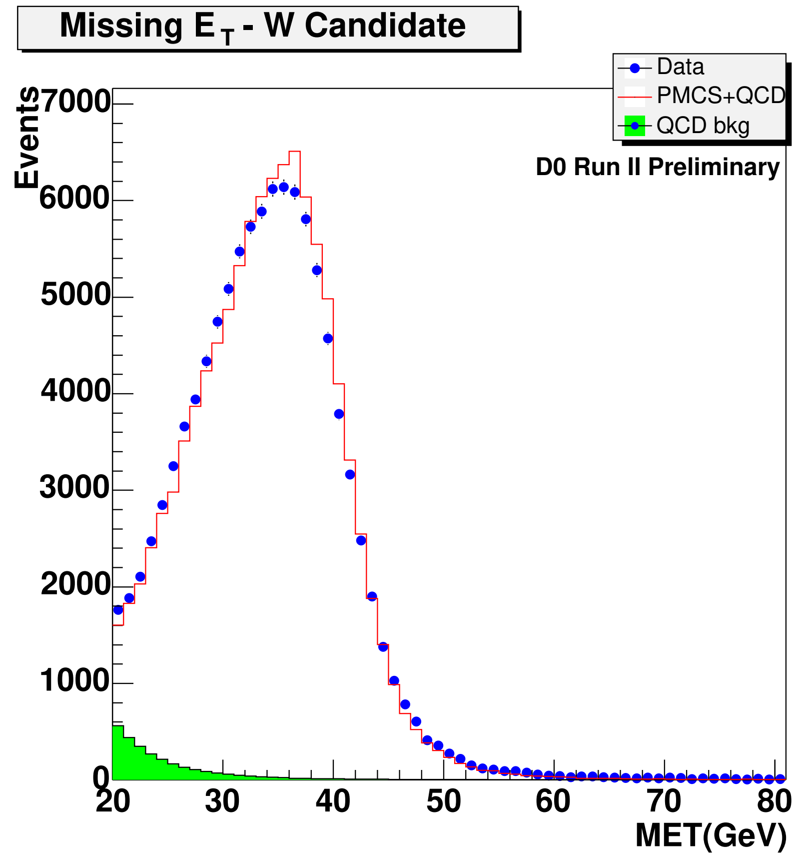


$W \to e\nu$

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

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





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

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

cluster transverse mass (I):

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

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

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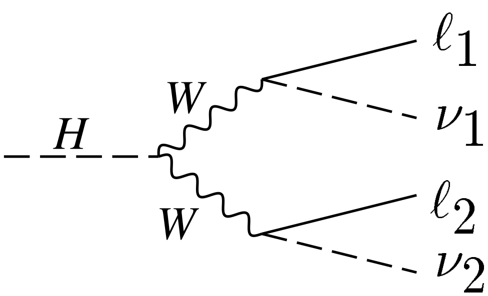

- $H^0 \to W^+W^- \to e^+\nu_e\ e^- \bar{\nu}_e$:

"effecive" transverse mass:

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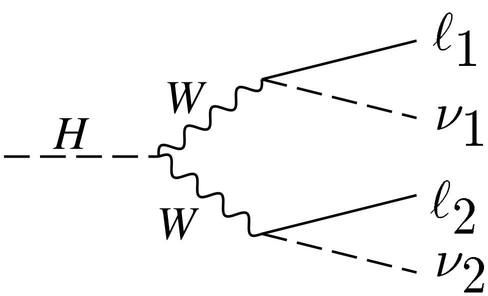

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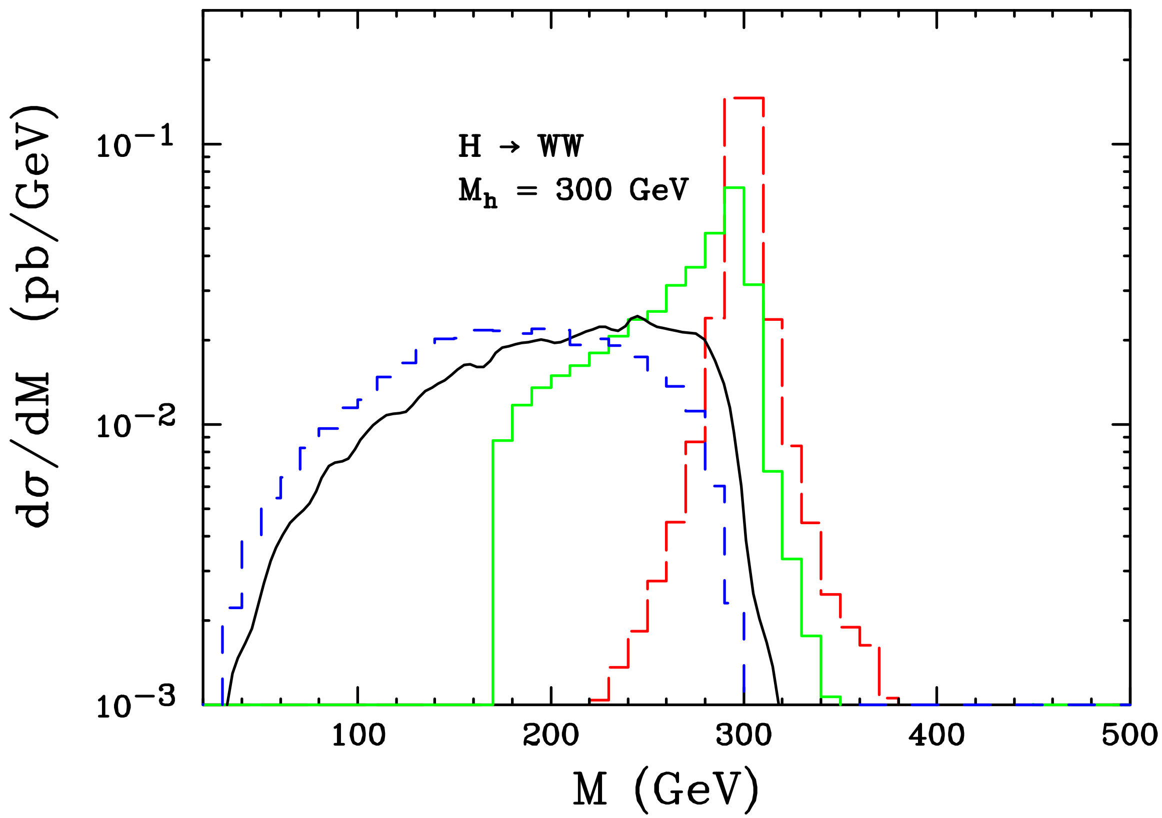
$$m_{eff\ T} \approx E_{e1T} + E_{e2T} + E_T^{miss}$$

cluster transverse mass (II):

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

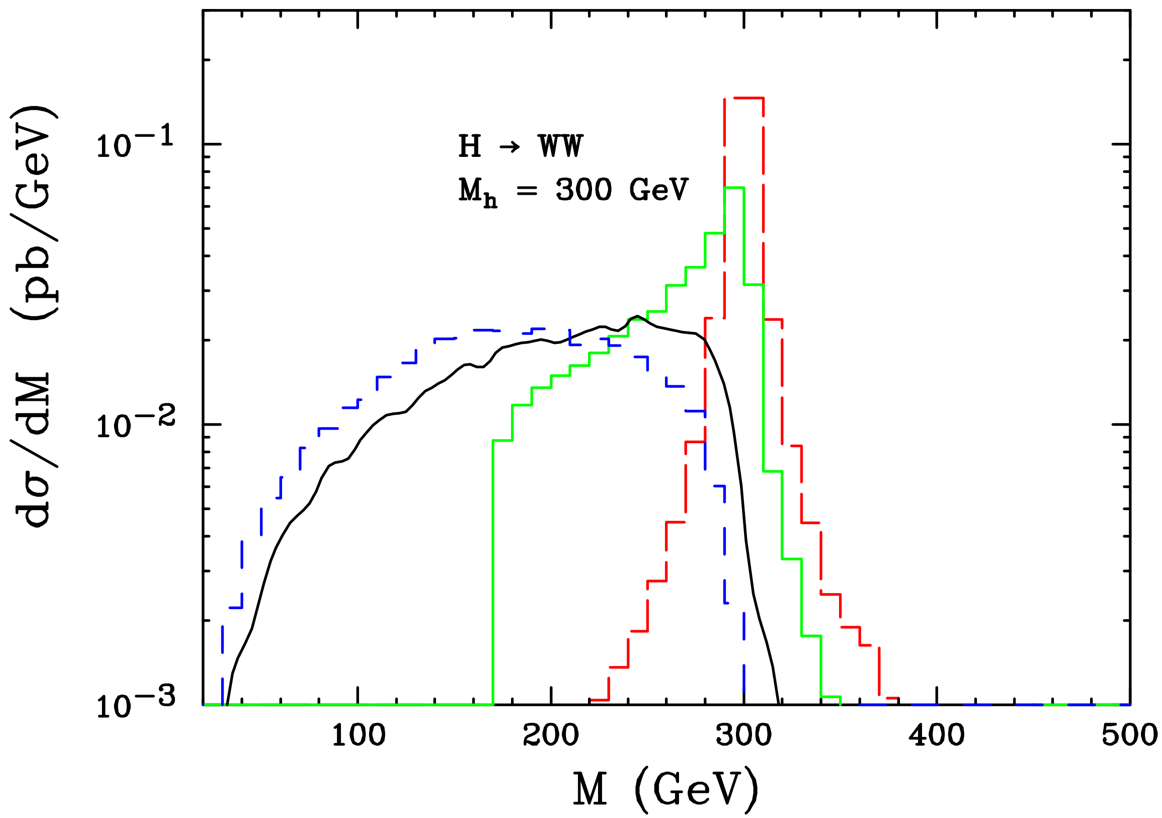


M_{WW} invariant mass (WW fully reconstructable): - - - - - - - - -

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

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

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



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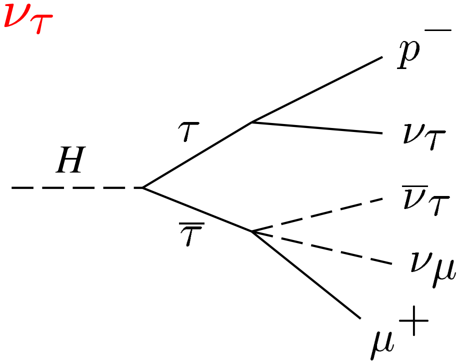
YOU design an optimal variable/observable for the search.

- 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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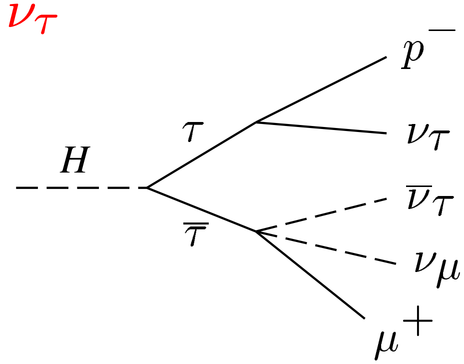

Not really!

$\tau^+\tau^-$ 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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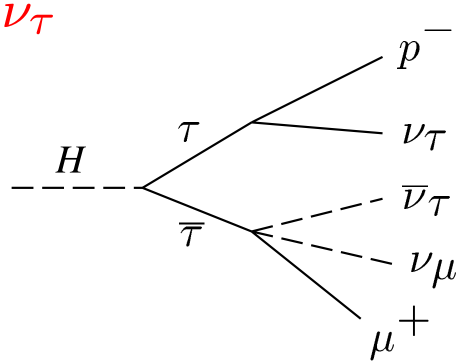

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where $c_\pm$ are proportionality constants, to be determined.

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

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

Experimental measurements: $p_{\rho^-},\ p_{\mu^+},\ \not{p}_T$:

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

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.

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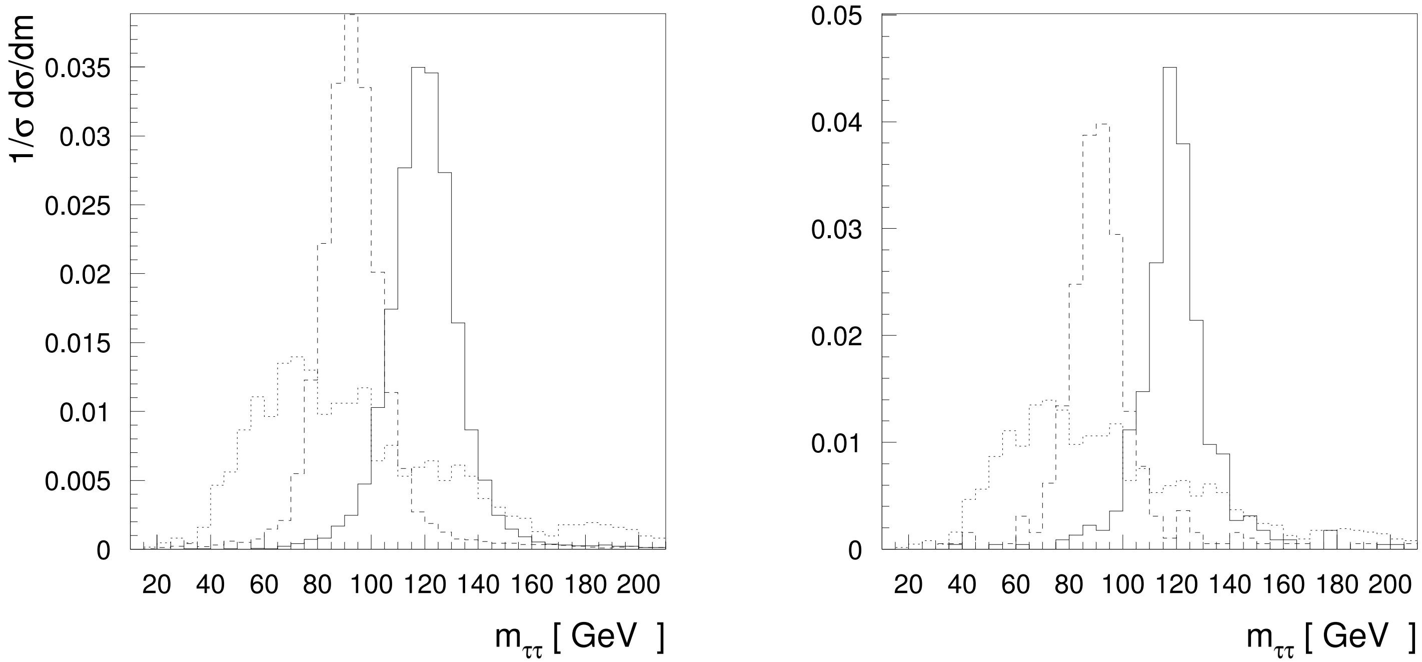

(b). Two-body versus three-body kinematics

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

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

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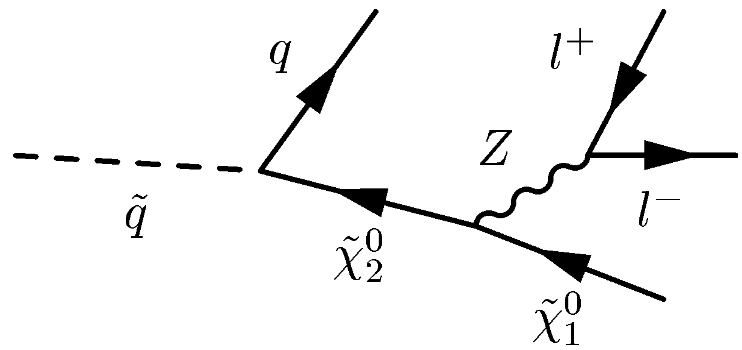
Mass edge: $m_{\mu^+\mu^-}^{max} = \sqrt{s} - 2m_\chi$.

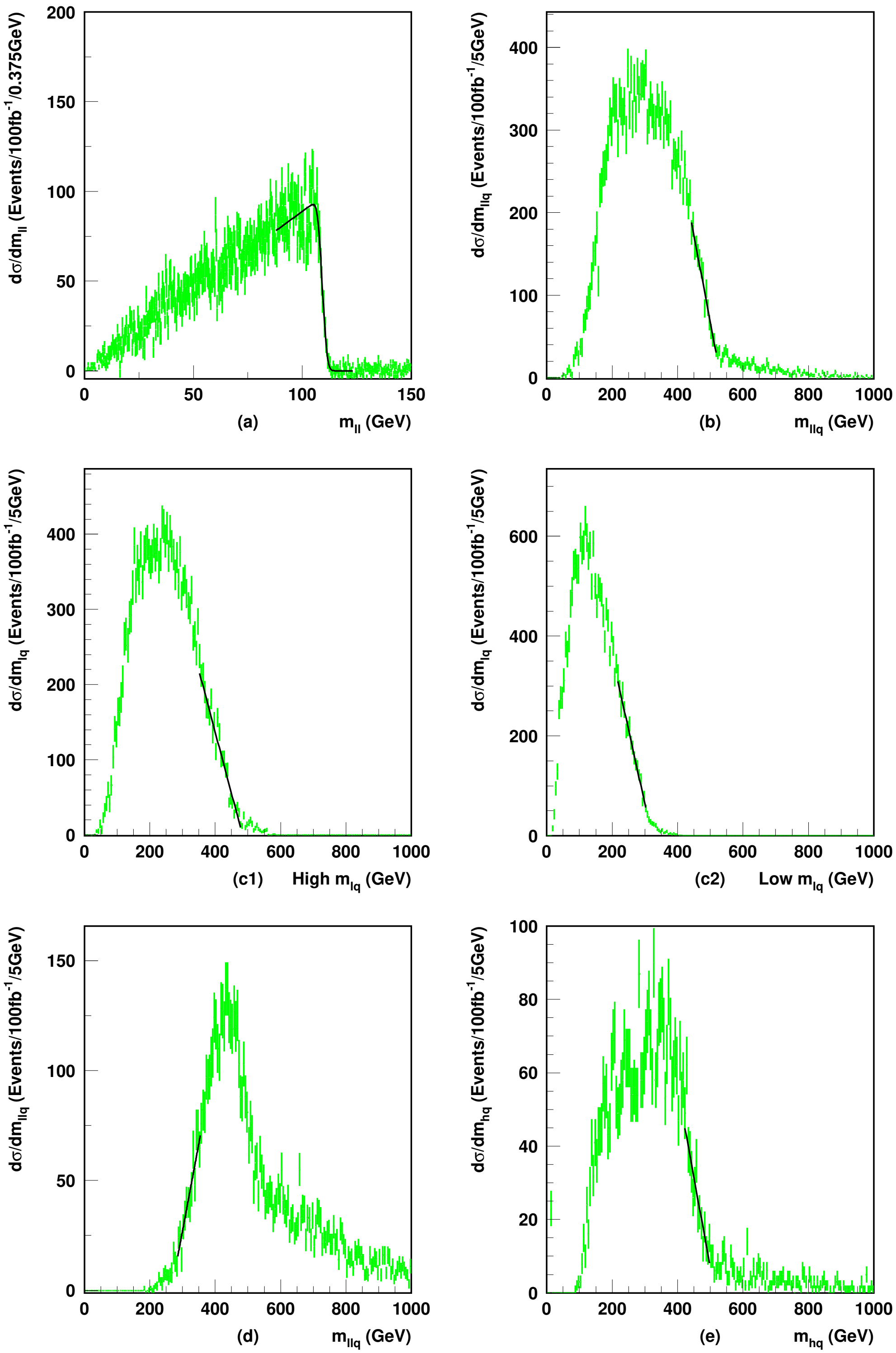
Same idea can be applied to hadron colliders ...

Consider a squark cascade decay:



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

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

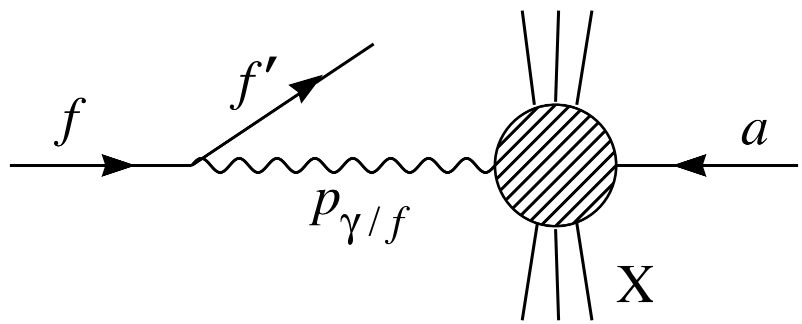


dσ/dm_ll (Events/100fb^-1/0.375GeV)
(a) m_ll (GeV)
dσ/dm_llq (Events/100fb^-1/5GeV)
(b) m_llq (GeV)
dσ/dm_lq (Events/100fb^-1/5GeV)
(c1) High m_lq (GeV)
dσ/dm_lq (Events/100fb^-1/5GeV)
(c2) Low m_lq (GeV)
dσ/dm_llq (Events/100fb^-1/5GeV)
(d) m_llq (GeV)
dσ/dm_hq (Events/100fb^-1/5GeV)
(e) m_hq (GeV)

(c). t-channel singularity: splitting.

- Gauge boson radiation off a fermion:

The familiar Weizsäcker-Williams approximation



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

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

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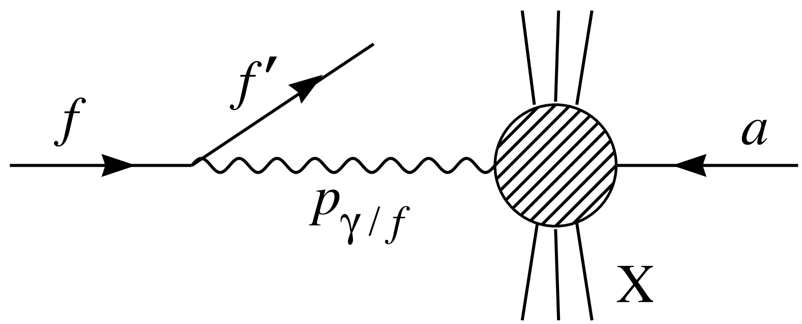

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† The kernel is the same as $q \to qg^*$ $\Rightarrow$ generic for parton splitting;

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

- Generalize to massive gauge bosons:

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

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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.

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

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

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

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

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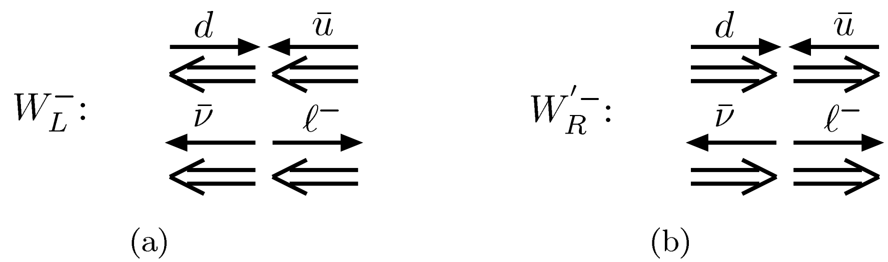

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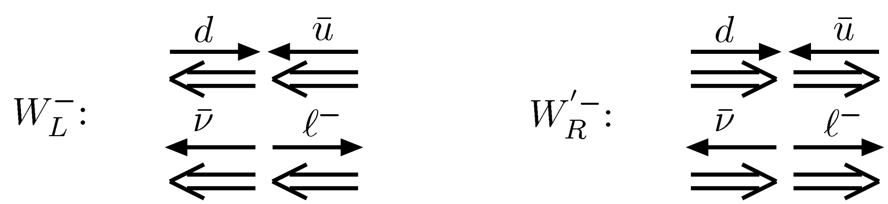
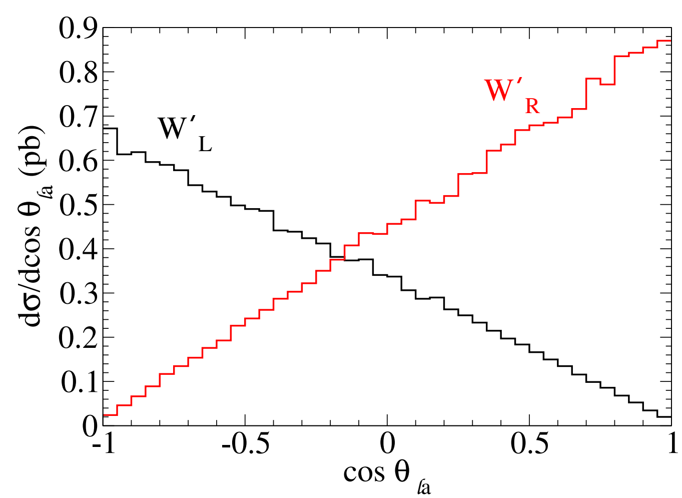


(a) (b)

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



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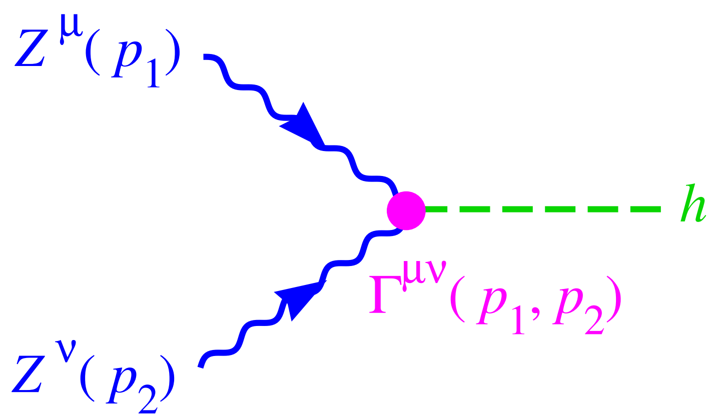
E.g. 1: $H \to Z(p_1)Z^*(p_2) \to e^+(q_1)e^-(q_2),\ \mu^+\mu^-$



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

$a = 1,\ b = \tilde{b} = 0$ 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:

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

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

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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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A general phenomenological Approach: (mine)

– From a theory to experimental predictions

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- Display the key structure of the theory:
  (new particle spectrum, interactions, basic parameters $\mathcal{L}$)
  - EWSB ⇒ m_H and $W_L W_L$ interactions.
  - full interaction Lagrangian

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