Intro to collider physics

Lian-Tao Wang
University of Chicago

XV Mexican School on Particles and Fields
Puebla, Mexico. September, 2012

New physics searches at the LHC

Two possible scenarios for new physics searches at the LHC

- A new layer of TeV new physics, excesses in many different channels.
  - Good discovery potential.
  - Complicated signal, challenging to interpret.
- New physics is difficult to discover.
  - In particular, hadronic final states.

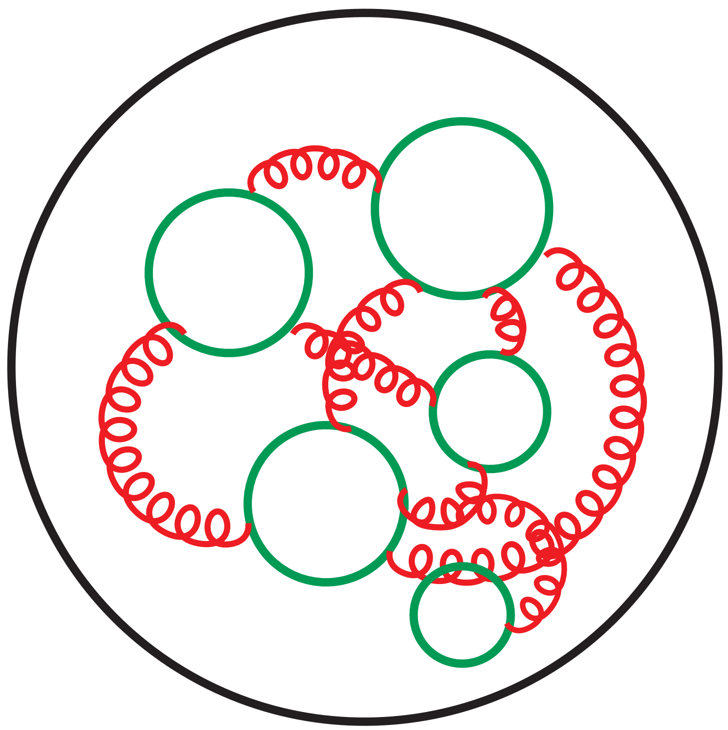
Before we start

- This is a huge subject.
  - Focus more on intuitive understanding, generic feature, less on specifics.
  - Only a (small) subset.
- Focus on methodology, rather than specific models.

Hopefully, this serves as the starting point of your further study.

Many good references, such as
Tao Han, TASI lecture, hep-ph/0508097

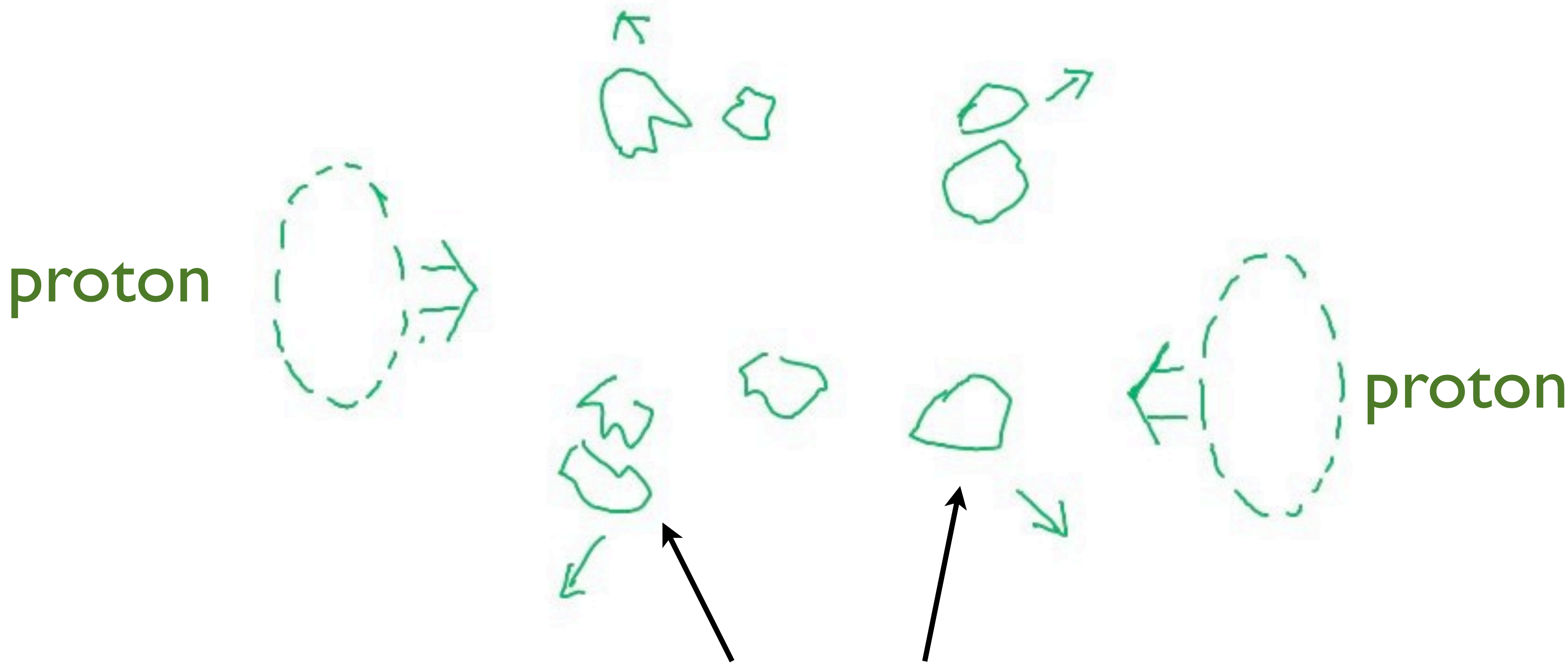
proton



Partons:
gluon
valence: u, d
“sea”: qbar, s sbar, c, cbar, b, bbar

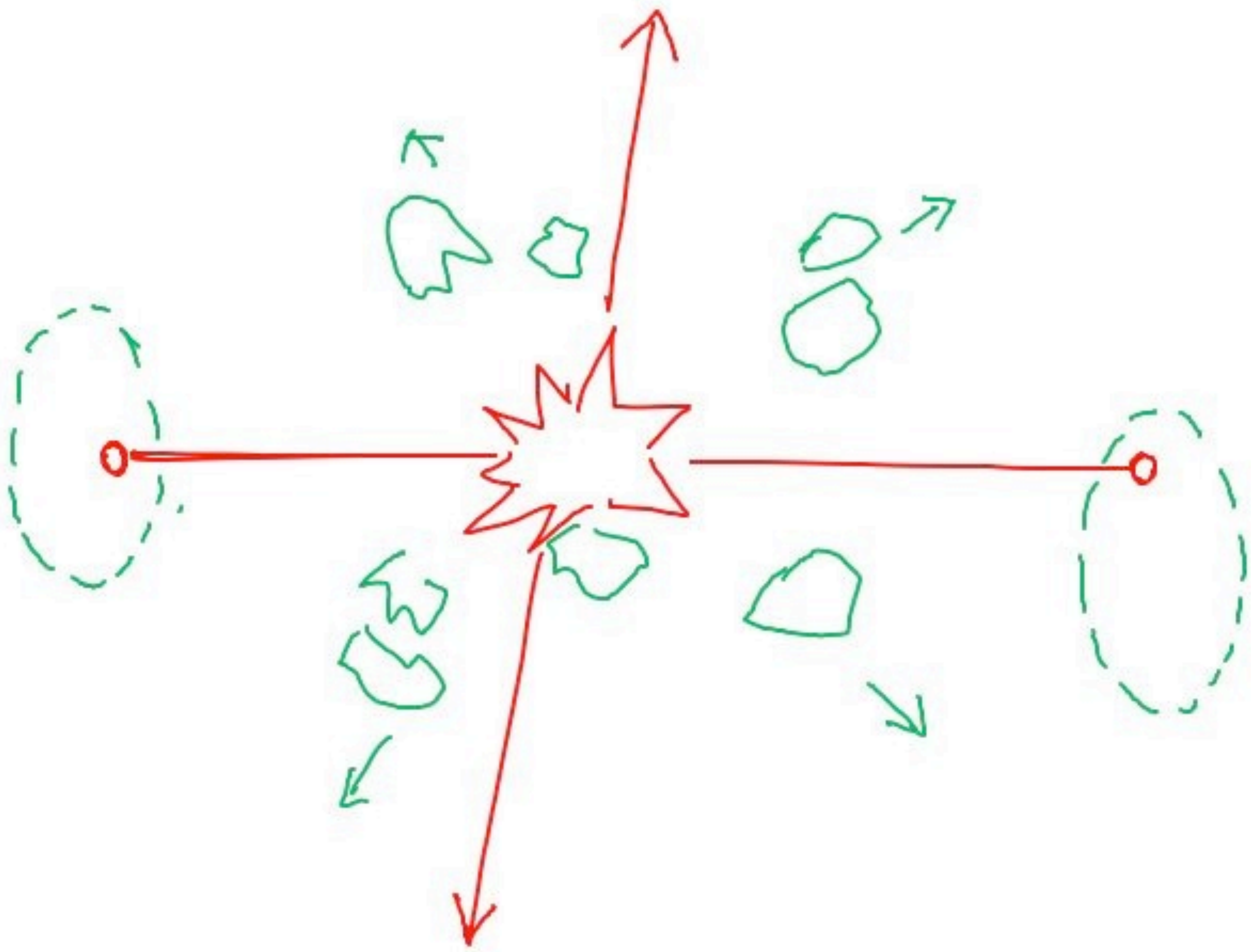
binding energy ~ GeV

Most of the time

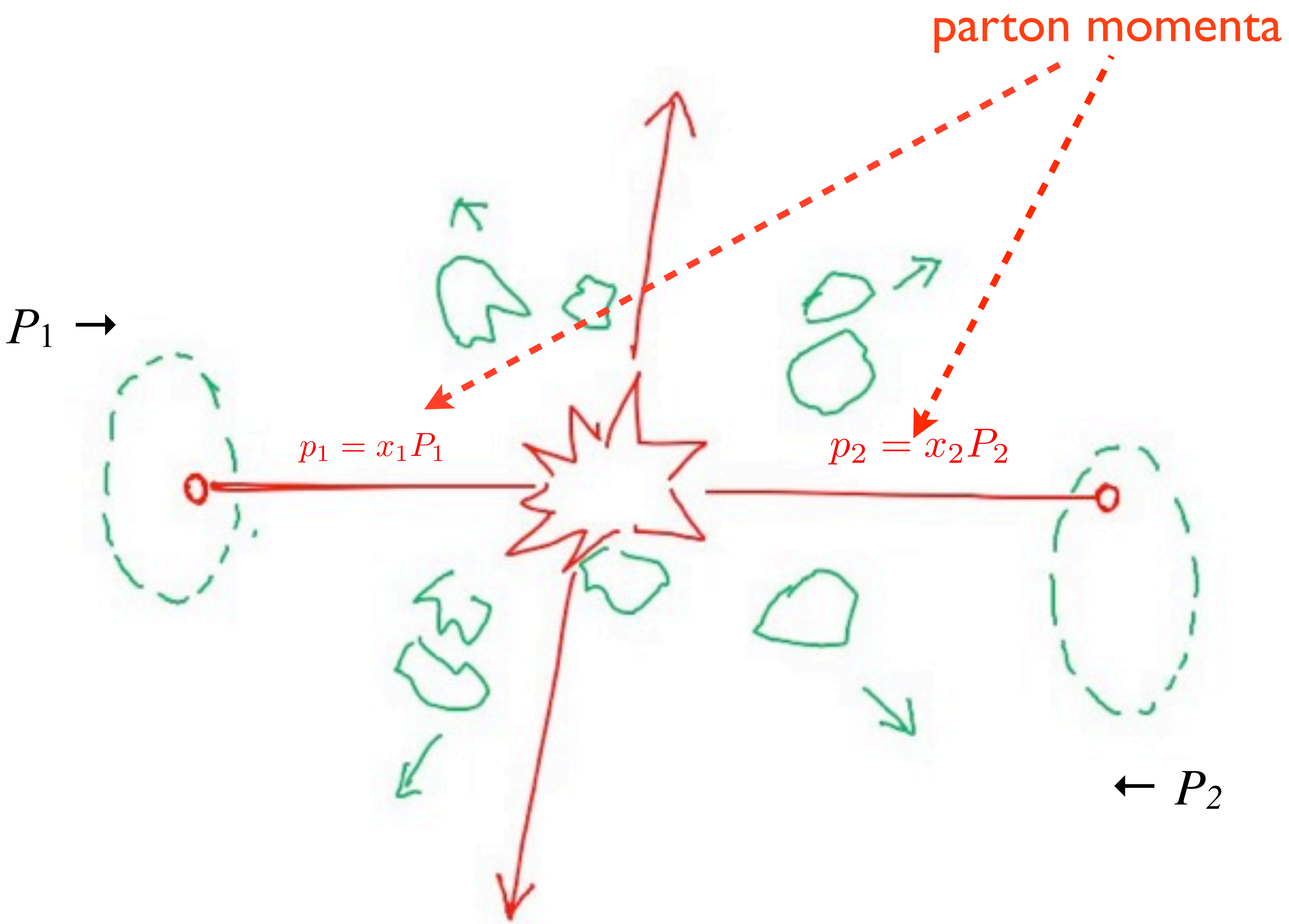


low energy fragments: E $\sim$ GeV

High energy collision rare



Kinematics



$$P_1 = (E_1, 0, 0, E_1), \;\; P_2 = (E_2, 0, 0, -E_2) \qquad \sqrt{S} = E_{\rm cm}^{\rm collider} = E_1 + E_2$$

$$\sqrt{\hat{s}} = \sqrt{(p_1 + p_2)^2} = E_{\rm cm}^{\rm parton} = \sqrt{x_1 x_2 S}$$

Rapidity

Define rapidity

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$$

$$p^\mu = (E_T \cosh y, p_T \sin\phi, p_T \cos\phi, E_T \sinh y), \qquad E_T = \sqrt{p_T^2 + m^2}$$

Under boost along z-direction

$$y' = \frac{1}{2} \ln \frac{E' + p'_z}{E' - p'_z} = \frac{1}{2} \ln \frac{(1-\beta_0)(E+p_z)}{(1+\beta_0)(E-p_z)} = y - y_0$$

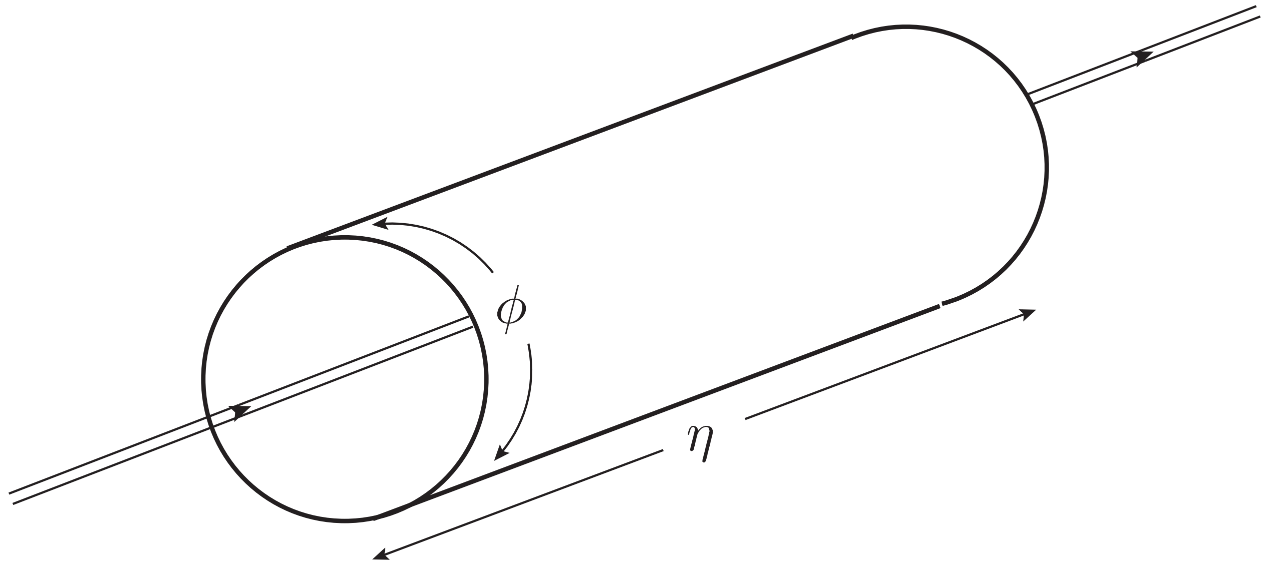
$$\rightarrow \frac{d}{dy} = \frac{d}{dy'}$$

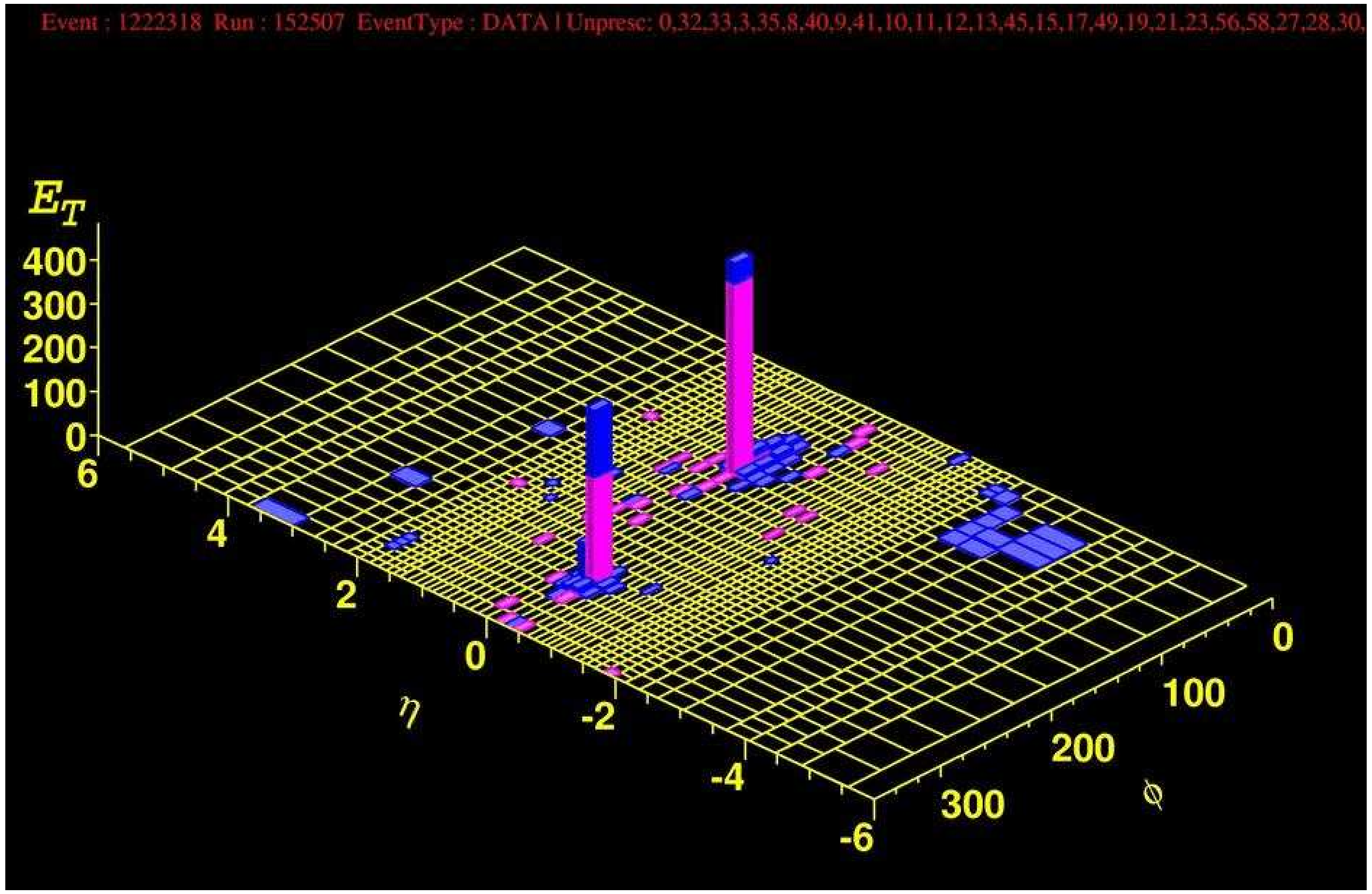
In the massless limit : pseudo-rapidity

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

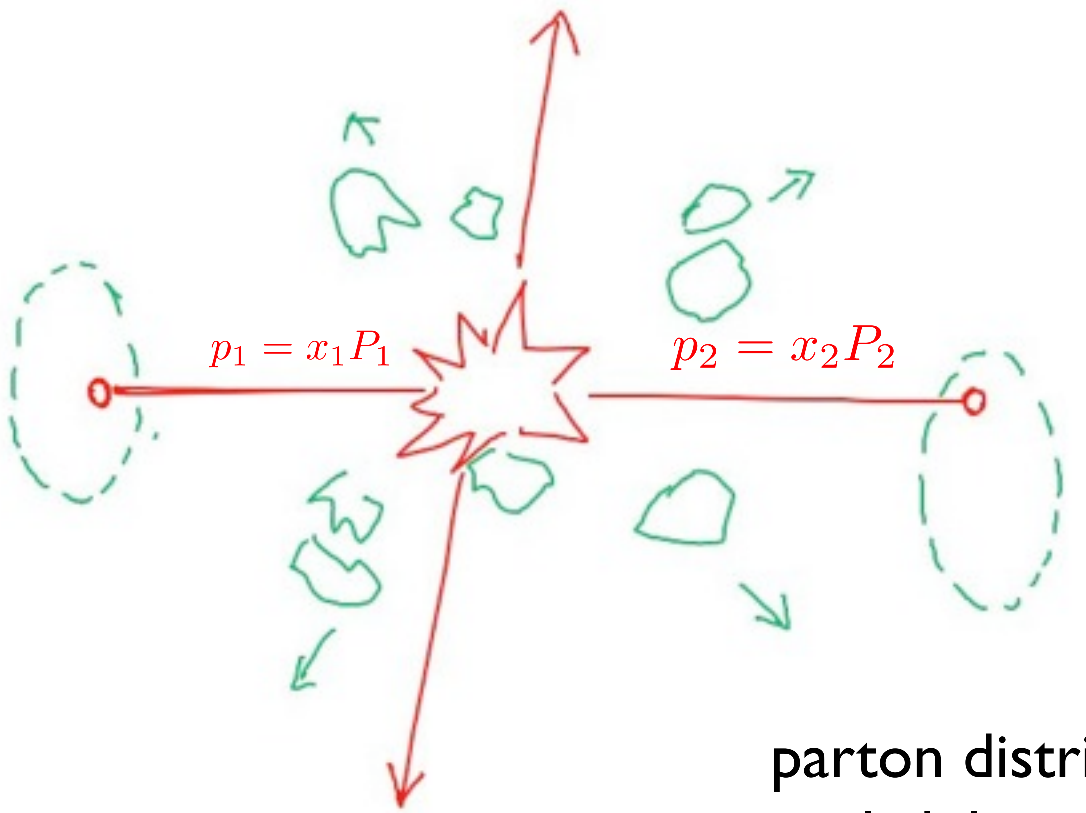
Coordinate System

$$\eta = -\ln\left[\cot\left(\frac{\theta}{2}\right)\right]$$





Parton Distribution Function (PDF)



Partons can be gluon,
or different flavors of quarks,
labelled by a, b...

parton distribution function $f_a(x)$:
probability of finding parton a with momentum fraction x

- $f_a(x)$ can not be computed.
- However, we can measure them using certain processes.
- They are universal! Can be used everywhere!

Prediction for hadron collisions

$$a + b \to \ldots$$

$$\sigma = \sum_{a,b} \int dx_1 dx_2 f_a(x_1) f_b(x_2) \hat{\sigma}$$

PDF, long distance
Universal

"Hard scattering"
Short distance
Partonic cross section
Calculable

Factorization!

Intuitively, make sense:
short distance physics should not "know" about long distance physics.

In practice, very difficult to prove.

However, it is used anyway (otherwise we cannot calculate anything).
And, it works very well.

A useful representation

$$P_1 = (E,0,0,E), \quad P_2 = (E,0,0,-E) \qquad p_1 = x_1 P_1, \quad p_2 = x_2 P_2$$

Define Parton center of mass rapidity: Y $e^Y = \sqrt{\frac{x_1}{x_2}}$

We can verify $\cosh Y = \frac{(x_1 + x_2)E}{\sqrt{\hat{s}}}$ ⇒ boost of parton c.o.m frame

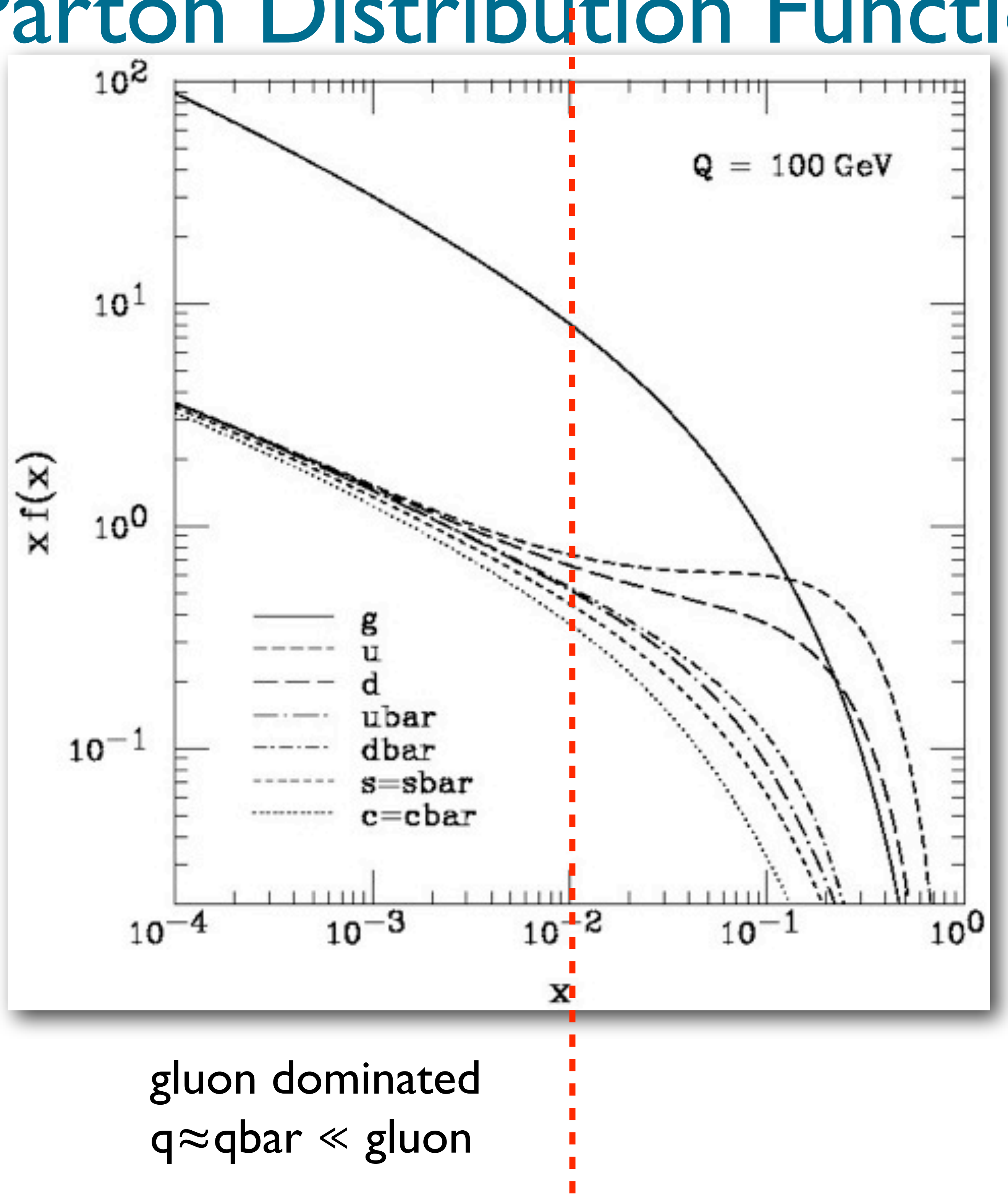
Starting with $$\frac{d^2\sigma(a,b \to \cdots)}{dx_1 dx_2} = \sum_{a,b} f_a(x_1) f_b(x_2) \hat{\sigma}(a,b \to \cdots)$$

Using Jacobian: $$\frac{\partial|\hat{s}, \quad Y|}{\partial|x_1, x_2|} = \frac{\hat{s}}{x_1 x_2}$$

We obtain:

$$\frac{d^2\sigma(a,b \to \cdots)}{d\hat{s}\ dY} = \frac{1}{\hat{s}} \sum_{a,b} \underline{x_1 f_a(x_1)}\ \underline{x_2 f_b(x_2)}\ \hat{\sigma}(a,b \to \cdots)$$

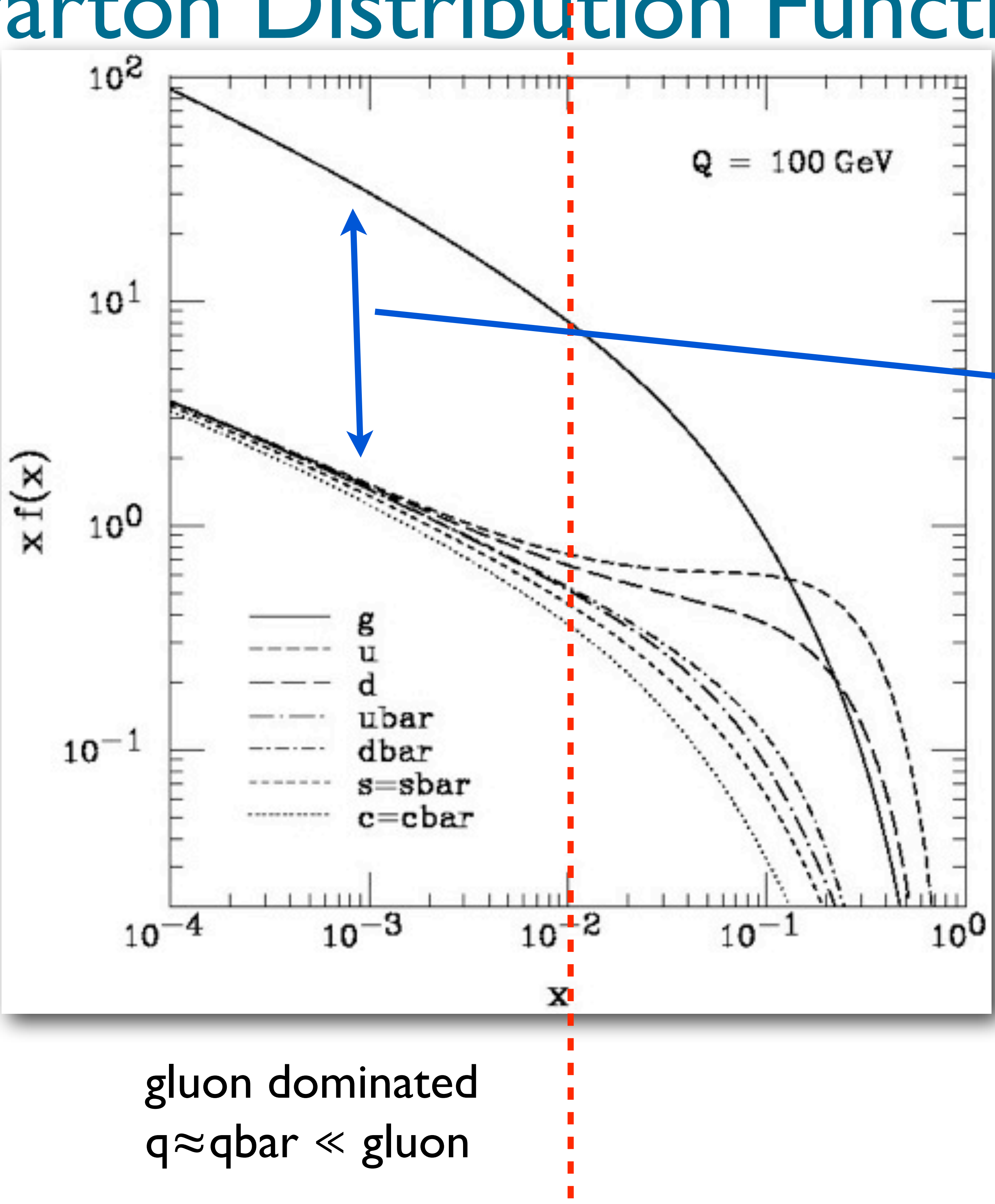
Parton Distribution Function



$$x = \frac{p_{\text{parton}}}{P_{\text{proton}}}$$

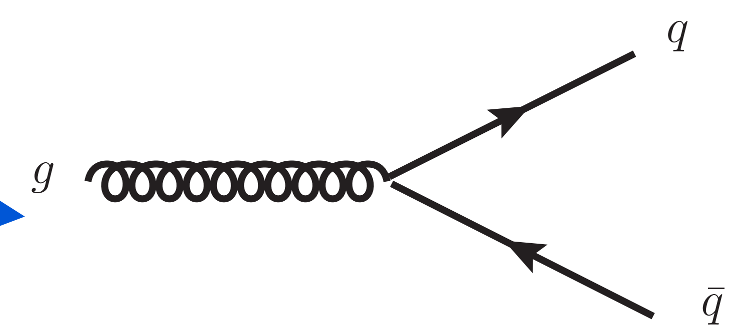
gluon dominated
q≈qbar ≪ gluon

Parton Distribution Function



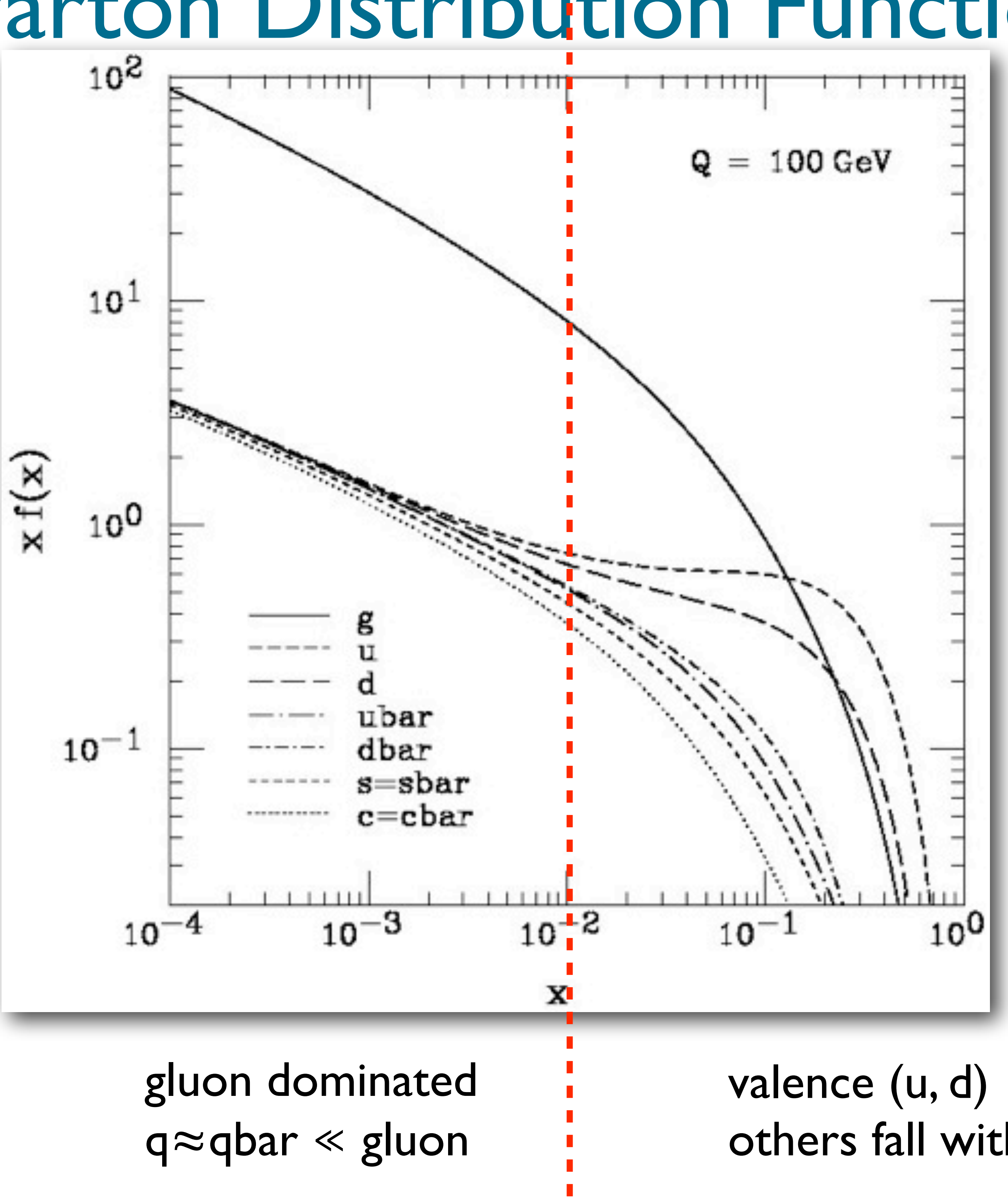
gluon dominated
q≈qbar ≪ gluon

$$x = \frac{p_{\text{parton}}}{P_{\text{proton}}}$$



gluon splitting
main "source" for quark PDF

Parton Distribution Function



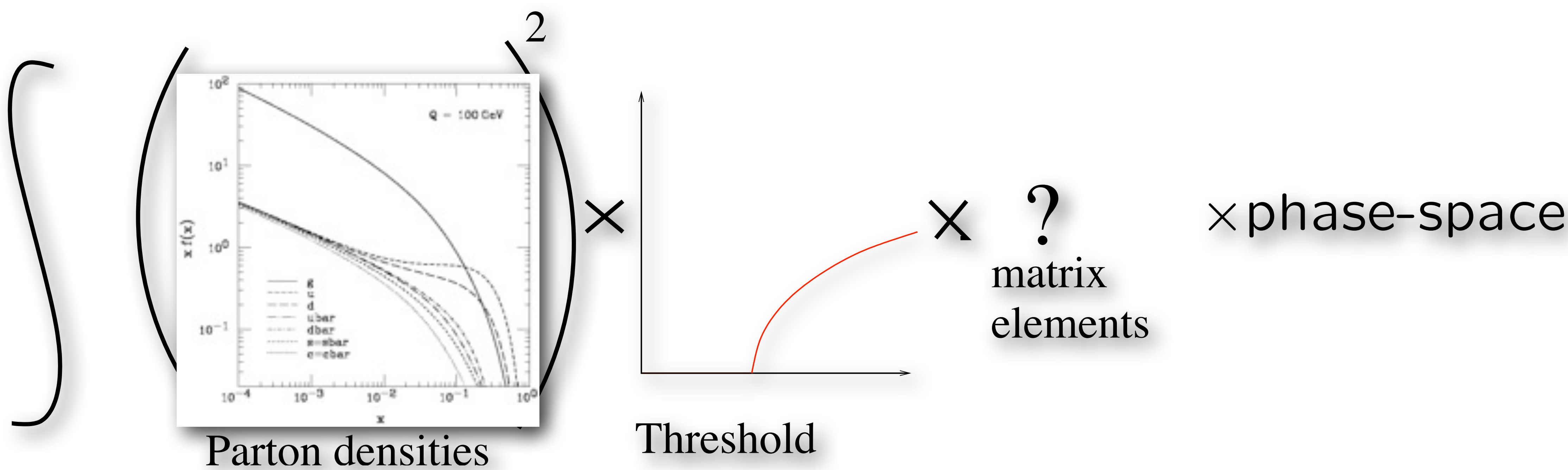
$$x = \frac{p_{\rm parton}}{P_{\rm proton}}$$

gluon dominated
q≈qbar ≪ gluon

valence (u, d) ↑
others fall with gluon

Production.

- Schematics of production at hadron colliders.
  - Dominated by parton densities and thresholds (mass and cut).



$$a + b \to \ldots$$

$$\frac{d^2\sigma(a,b\to\cdots)}{d\hat{s}\ dY} = \frac{1}{\hat{s}}\sum_{a,b} x_1 f_a(x_1)\ x_2 f_b(x_2)\ \hat{\sigma}(a,b\to\cdots)$$

Partonic cross section

Another parameterization, parton luminosity

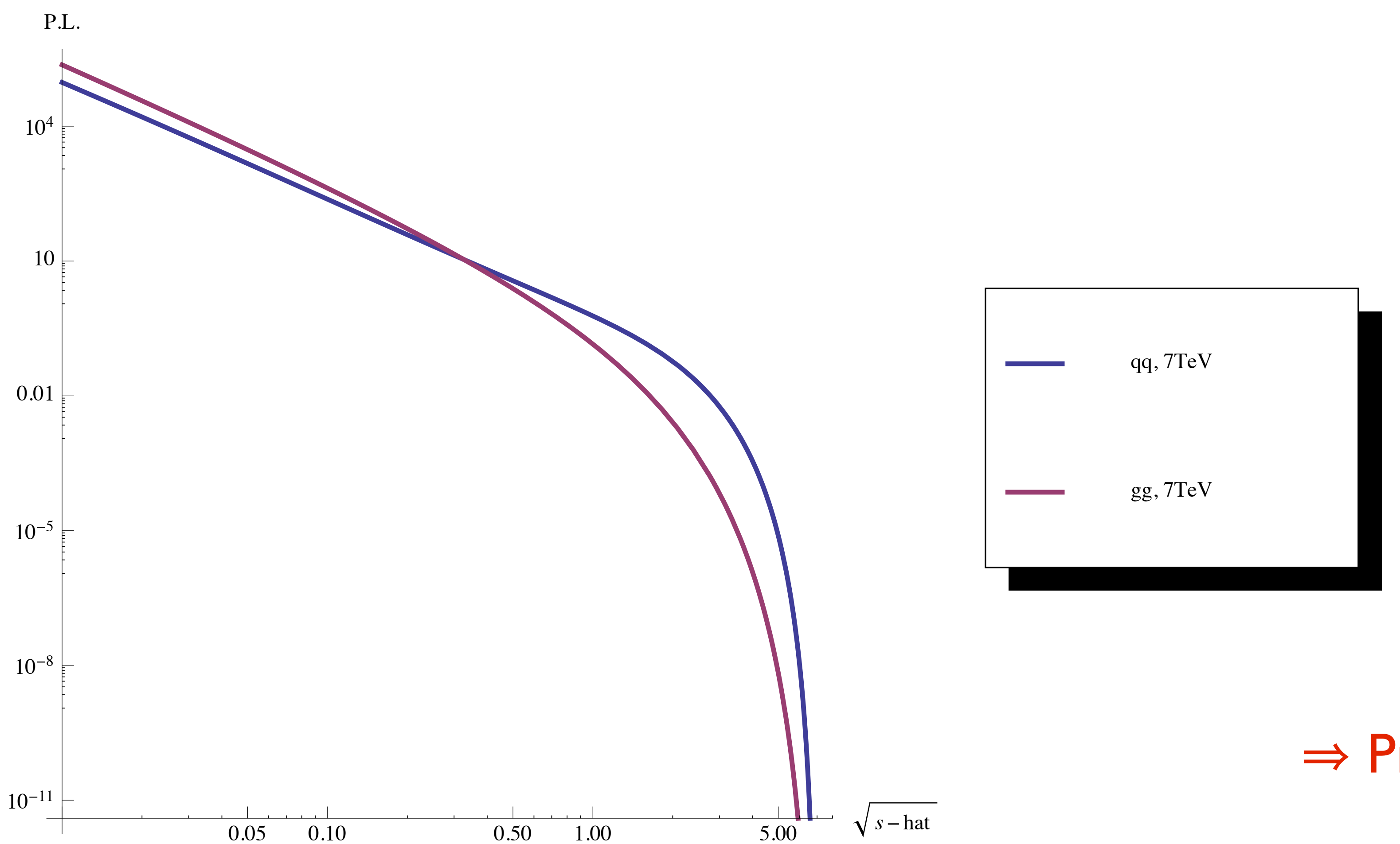
- The cross section can be written as

$$\sigma = \sum_{a,b} \int d\tau \boxed{\frac{dL_{ab}}{d\tau}} \hat{\sigma}$$

parton luminosity

$$\tau = \frac{\hat{s}}{S} = x_1 x_2$$

$$L_{ab}(\tau) = \frac{1}{1+\delta_{ab}} \int_\tau^1 \frac{dx}{x} \left[f_a(x) f_b\left(\frac{\tau}{x}\right) + f_a\left(\frac{\tau}{x}\right) f_b(x) \right]$$



TeV, log scale

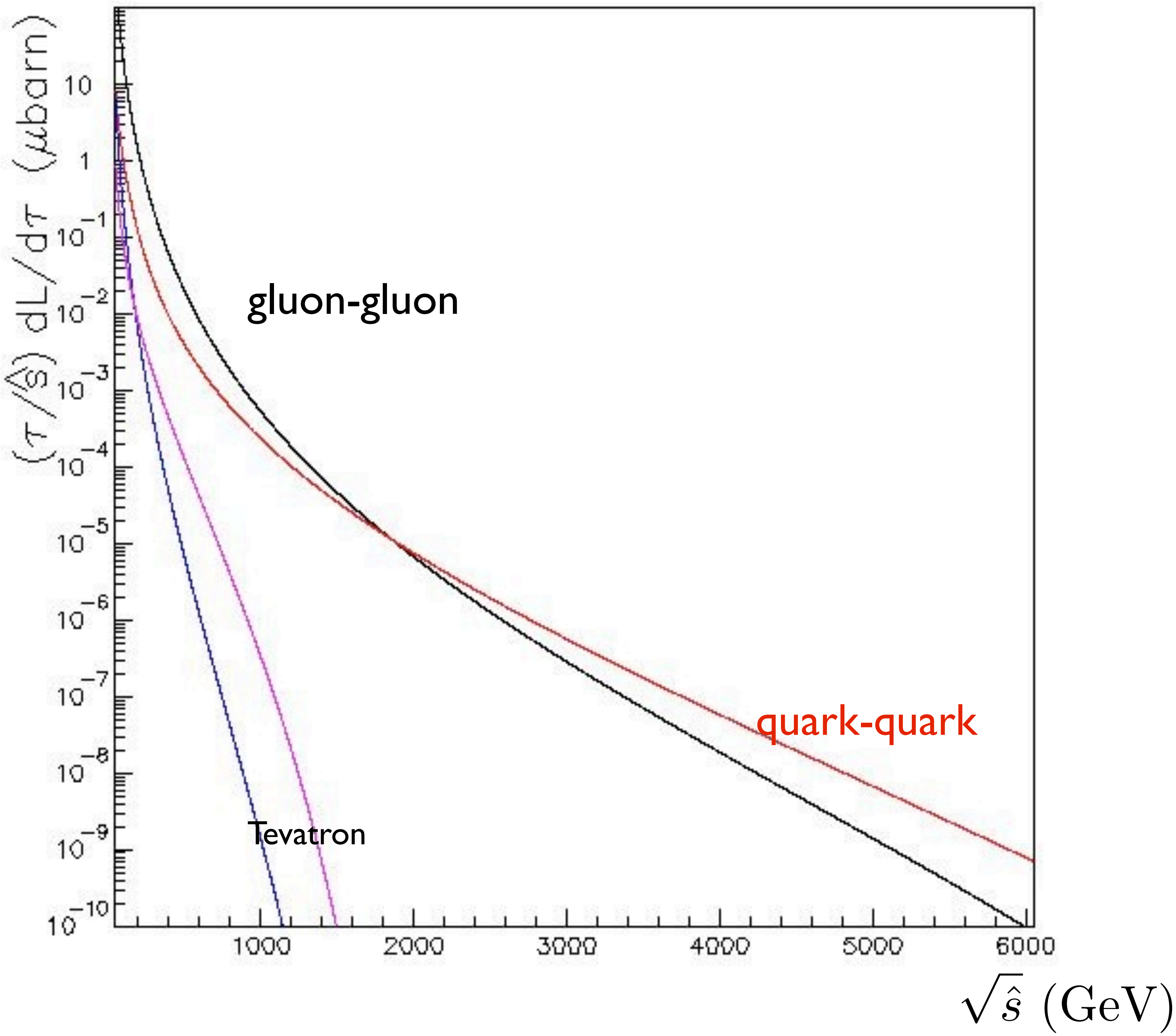
Very sharp falling

$$\propto \frac{1}{\tau^{3-3.5}}$$

Falls by a factor of 10 for every 600 GeV

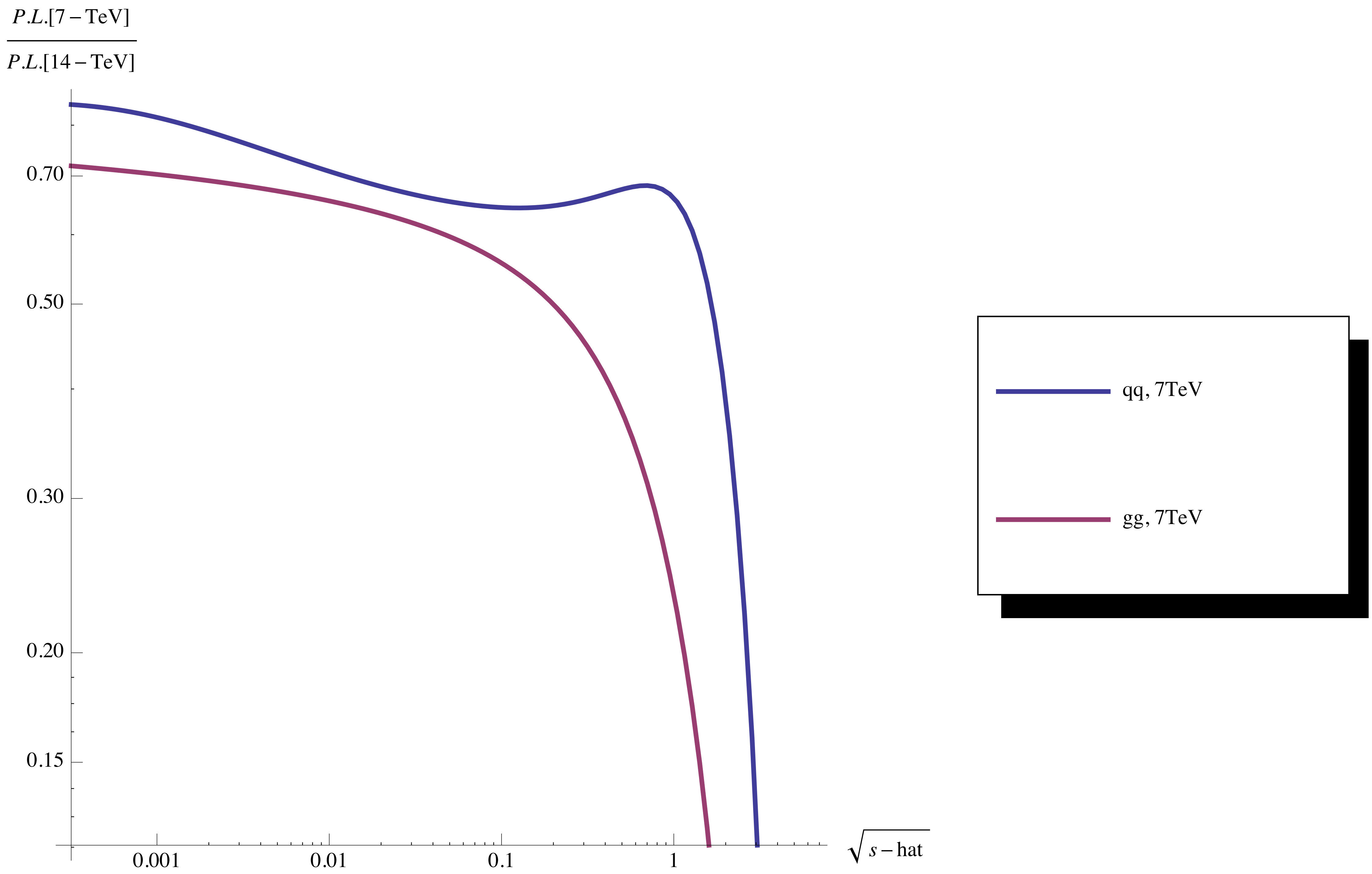
$\Rightarrow$ Production dominantly on threshold

14 TeV



gluon-gluon
quark-quark
Tevatron
$(\tau/\hat{s})\ dL/d\tau\ (\mu barn)$
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
1000
2000
3000
4000
5000
6000
$\sqrt{\hat{s}}$ (GeV)

7 TeV vs 14 TeV



$\sqrt{\hat{s}}$ (TeV)

For 7 TeV, PL shuts off at around TeV,
For 14 TeV, around 2 TeV.

Reach scales roughly with E_{cm} (same x).

Why is it hard to discover TeV-scale new physics at the LHC

- p p collider, "prefers" to produce lighter states.
- Production rates scale roughly as $\sigma_{pp\to M} \sim \frac{1}{M^6}$
- TeV new physics $M_{\rm NP} \sim 5 - 10 \times M_{\rm SM(W,Z,t,...)}$
  - $\sigma_{\rm SM} \geq 10^6 \times \sigma_{\rm NP}$
- Dominated by QCD: A messy environment.
- Need:
  - Precise knowledge of the SM processes.
  - Anticipation of potential new physics states and their properties.

Phase space

- General phase space factor:

$$d\Pi_n = \Pi_f \left(\int \frac{d^3 p_f}{(2\pi)^3} \frac{1}{2E_f} \right) (2\pi)^4 \delta^{(4)}(p_a + p_b - \sum p_f)$$

- One additional final state particle

$$\sim \text{an additional factor of } \frac{1}{16\pi^2}$$

- For example

... variables $\subset \{0, 1\}$

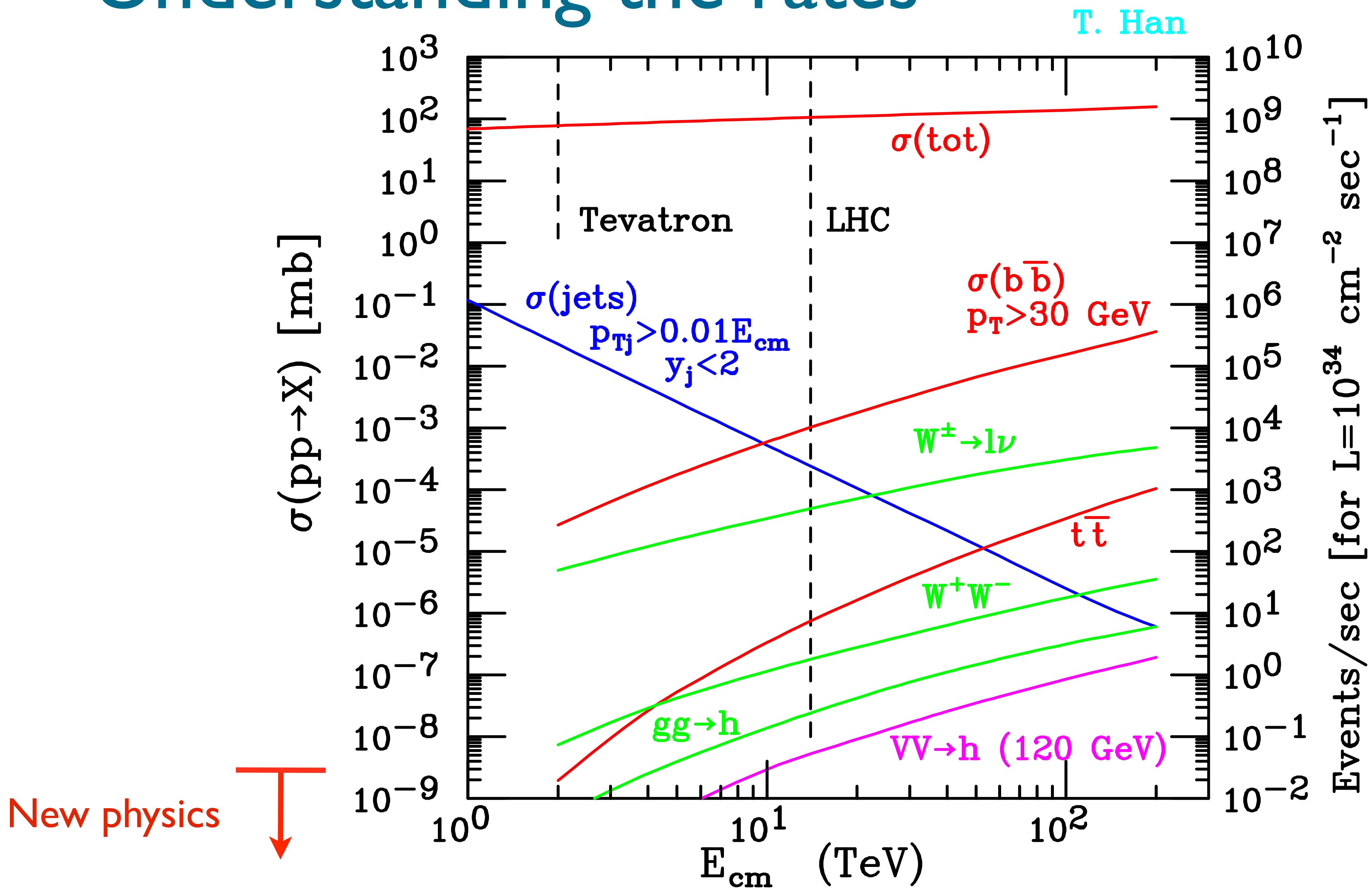
$$d\Pi_2 = \frac{1}{4\pi} \frac{1}{2} \lambda^{1/2}(1, m_1^2/\hat{s}, m_2^2/\hat{s}) d...$$

$$d\Pi_3 = \frac{1}{(4\pi)^3} \lambda^{1/2}(1, m_1^2/m_{23}^2, m_2^2/m_{23}^2) 2|\vec{p}_1| dE_1 d...$$

Rate also depends on

- Coupling constants
  - More final state particles, higher power of coupling constants.
  - QCD process dominates over weak processes.
- Singularities (enhancements) of matrix elements
  - Resonances.
  - Collinear and soft regime...

Understanding the rates

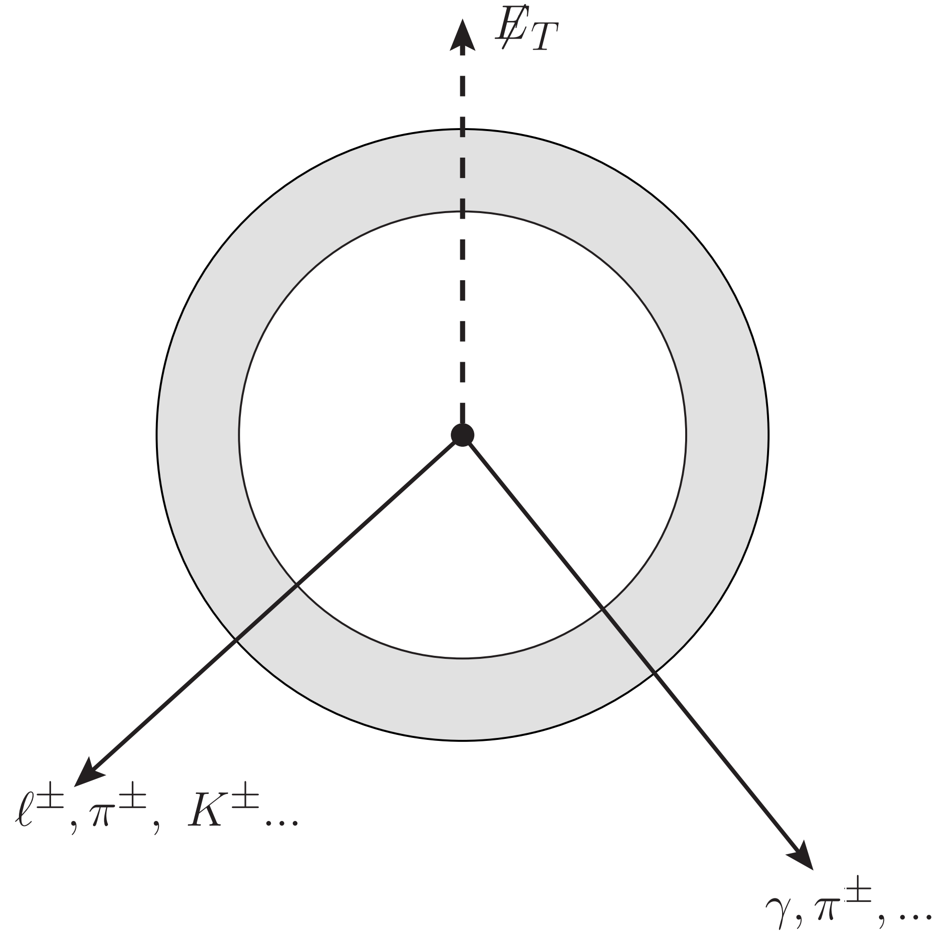


Example: considering ttbar vs $W^+ W^-$,
The relevant factors are:
top is twice as heavy as W (2 times higher threshold)
α_s^2 vs α_w^2
ttbar is gg dominated, WW is qqbar.

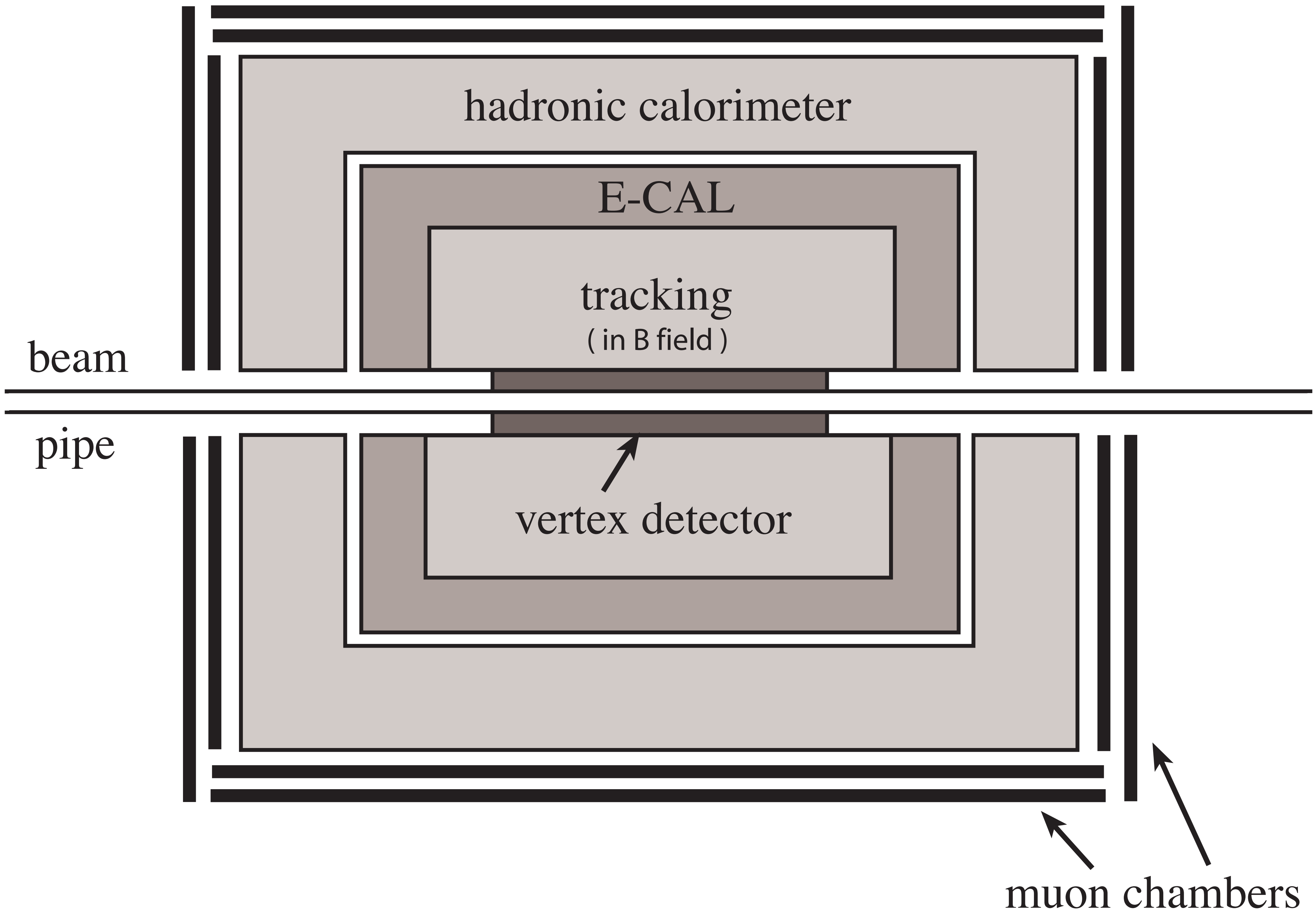
Being produced does not mean we can see them!

Final state Objects

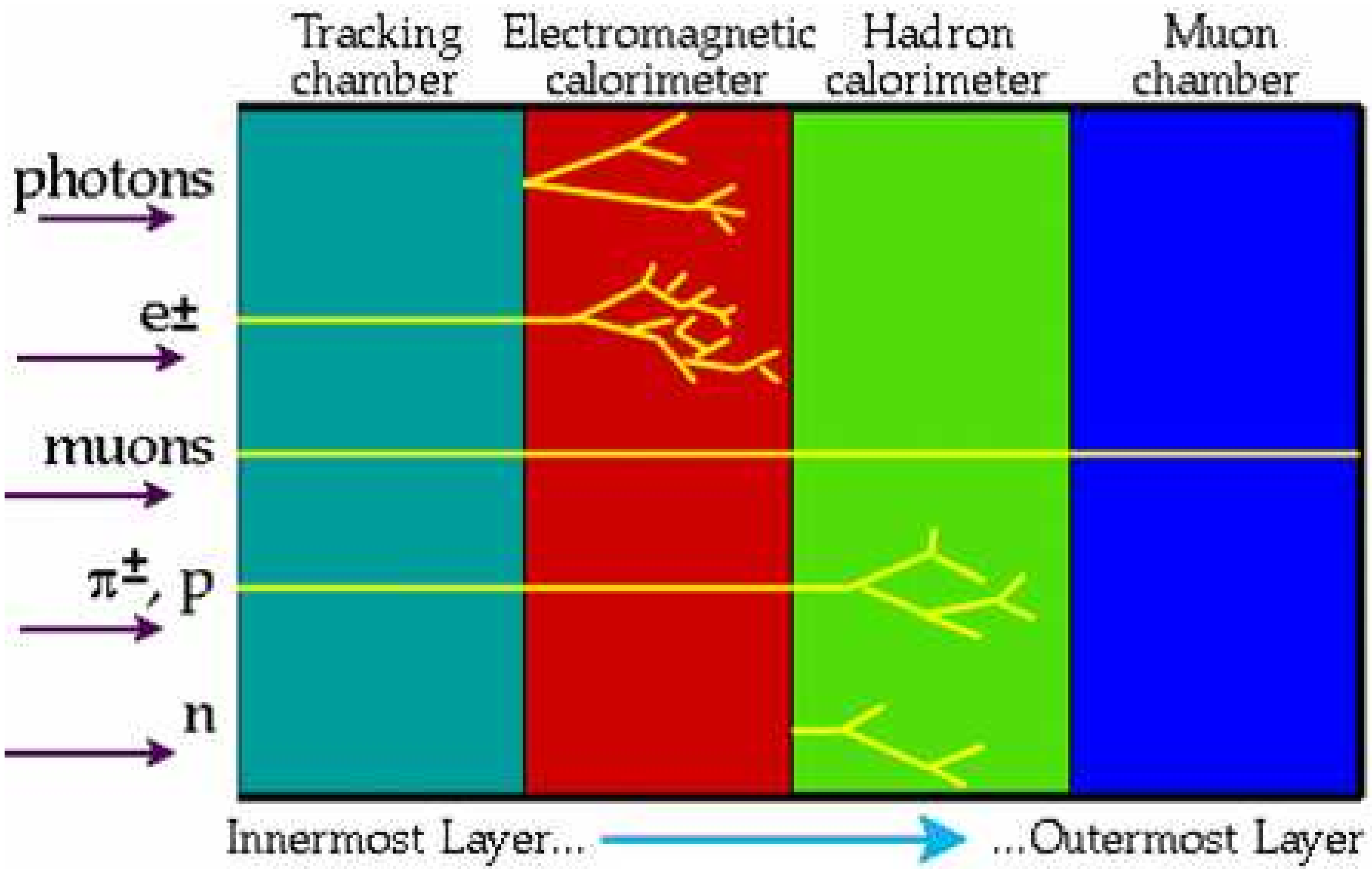
- Colored particles: cluster of hardonic energy, jet
- Leptons: electron, muon
- Photon
- Heavy flavor: bottom (charm)
- Missing energy (MET)



Modern detector (cartoon)



Identifying particles



From SM processes

- QCD: quark, gluon $\longrightarrow$ jets
- QCD heavy flavor: b, c.
- Z: $Z \rightarrow (q\bar{q},\ \ell^+\ell^-,\ \nu\bar{\nu}) \rightarrow \text{jets, lepton pair, } \not{E}_T$
- W: $W^\pm \rightarrow (q\bar{q}',\ \ell^\pm\nu) \rightarrow \text{jets, lepton+} \not{E}_T$
- Top: $t \rightarrow b + (W \rightarrow q\bar{q}' \text{ or } \bar{\ell}\nu)$
- Tau lepton: narrow jet(s), lepton.

SM Rates at 7 TeV:

- QCD di-jet: $p_T^j > 100 \text{ GeV}, \ 300 \text{ nb}$
- Heavy flavor: $b\bar{b}, \ p_T^b > 100 \text{ GeV}, 1 \text{ nb}$
- W+... : $W^\pm \to \ell\nu, \ 14 \text{ nb}$

$$W^\pm(\to \ell\nu) + 1 \text{ jet}, \ p_T^j > 100 \text{ GeV}, \ 70 \text{ pb}$$

one lepton + jets + MET

$$W^\pm(\to \ell\nu) + 2 \text{ jet}, \ p_T^j > 100 \text{ GeV}, \ 2 \text{ pb}$$

$$W^\pm(\to \ell\nu) + 1 \text{ jet}, \ p_T^j > 200 \text{ GeV}, \ 5 \text{ pb}$$

- Z + ... : $Z(\to \ell^+\ell^-), \ 1.4 \text{ nb}$

di-lepton + jets

$$Z(\to \ell^+\ell^-) + 1 \text{ jet}, \ p_T^j > 100 \text{ GeV} \ , 10 \text{ pb}$$

New Physics: ~ pb

SM rates at 7 TeV

- di-boson: W^+W^- : 30 pb di-lepton + MET, ~ 1.2 pb

  $W^+W^- +$ 1 jet, $p_T^j > 100$ GeV, 2 pb

  di-lepton+jet+MET ~ 0.1 pb

  W^+Z : 7 pb, W^-Z : 3.7 pb

  tri-lepton + MET ~ 0.1 pb

- top pair: 160 pb! Always has 6 objects.

  $t\bar{t} \to bbW^+W^- \to bbjj\ell\nu, \; bb\ell\nu\ell\nu, bbjjjj$

  - (MET+lepton+Jet 40%, Heavy flavor...)
  - Looks like new physics, pair production of a massive particle followed by a decay cascade.

Two possible ways of discovery:

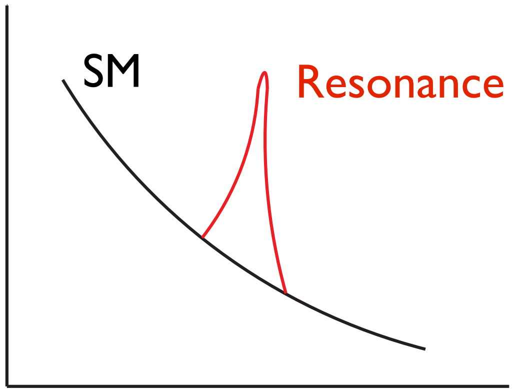
final state	rate estimate
begin with ≥ 2 hard jets	10^5 Hz
in addition	
hard jet	10^2 Hz
or $\not{E}_T \gtrsim 10^2$ GeV	$\sim 10^2$ Hz
or 1 lepton	10^2 Hz
or 2 lepton	1 Hz
or $2\ell = e^{\pm} + \mu^{\pm}$	10^{-4} Hz

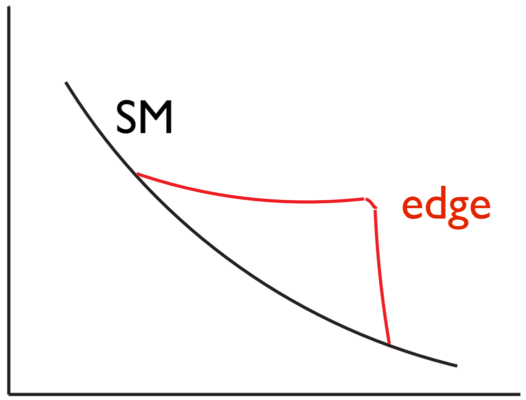
- Rate: final states with more energetic (hard) objects, for example:

  $(\geq 3 \text{ jets}) + \not{E}_T$

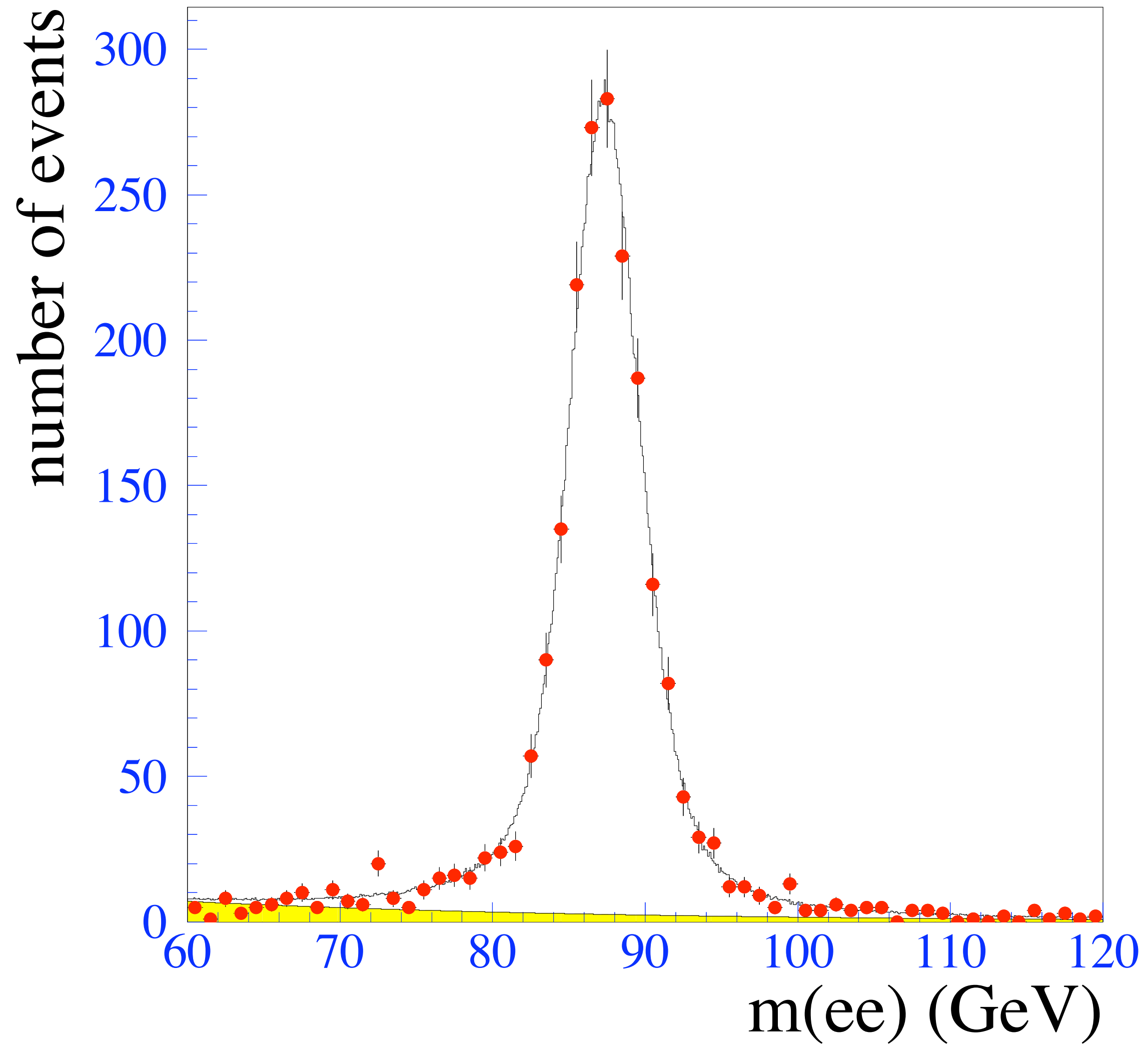
  $(\geq 2 \text{ jets}) + (\geq 1\ell) + \not{E}_T$

- Special kinematical features, resonances, edges, ...





Resonance



$$pp \to Z^0 \to e^+e^-$$

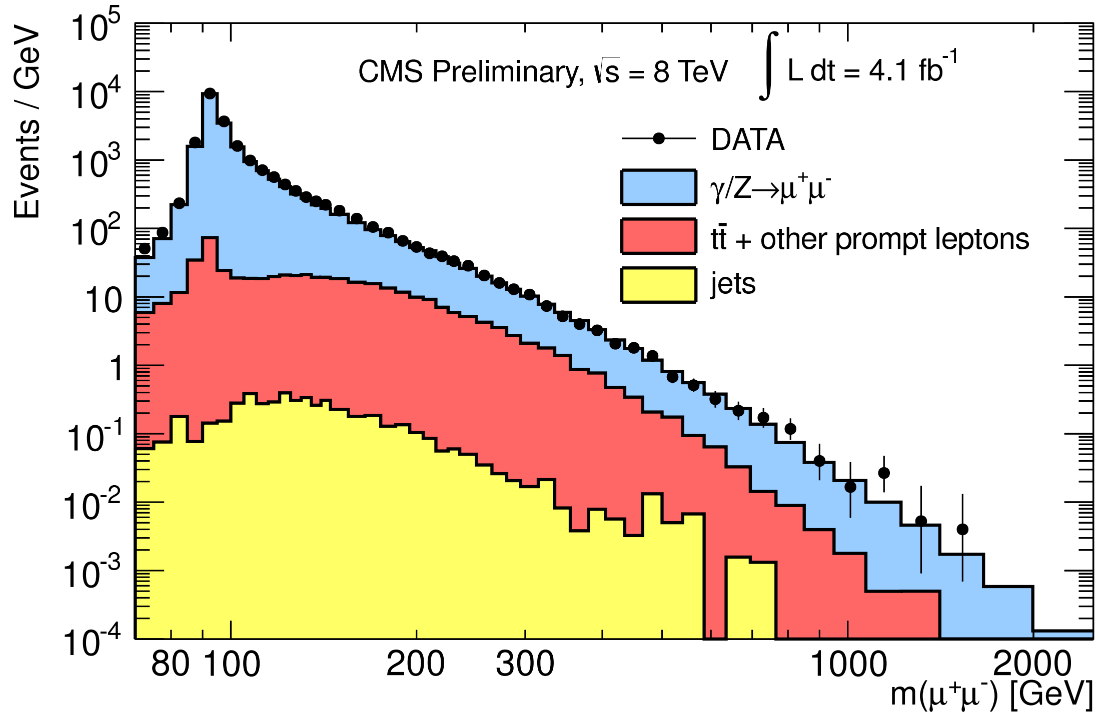
$$\hat{s} = m_{ee}^2 = (p_{e_1} + p_{e_2})^2$$

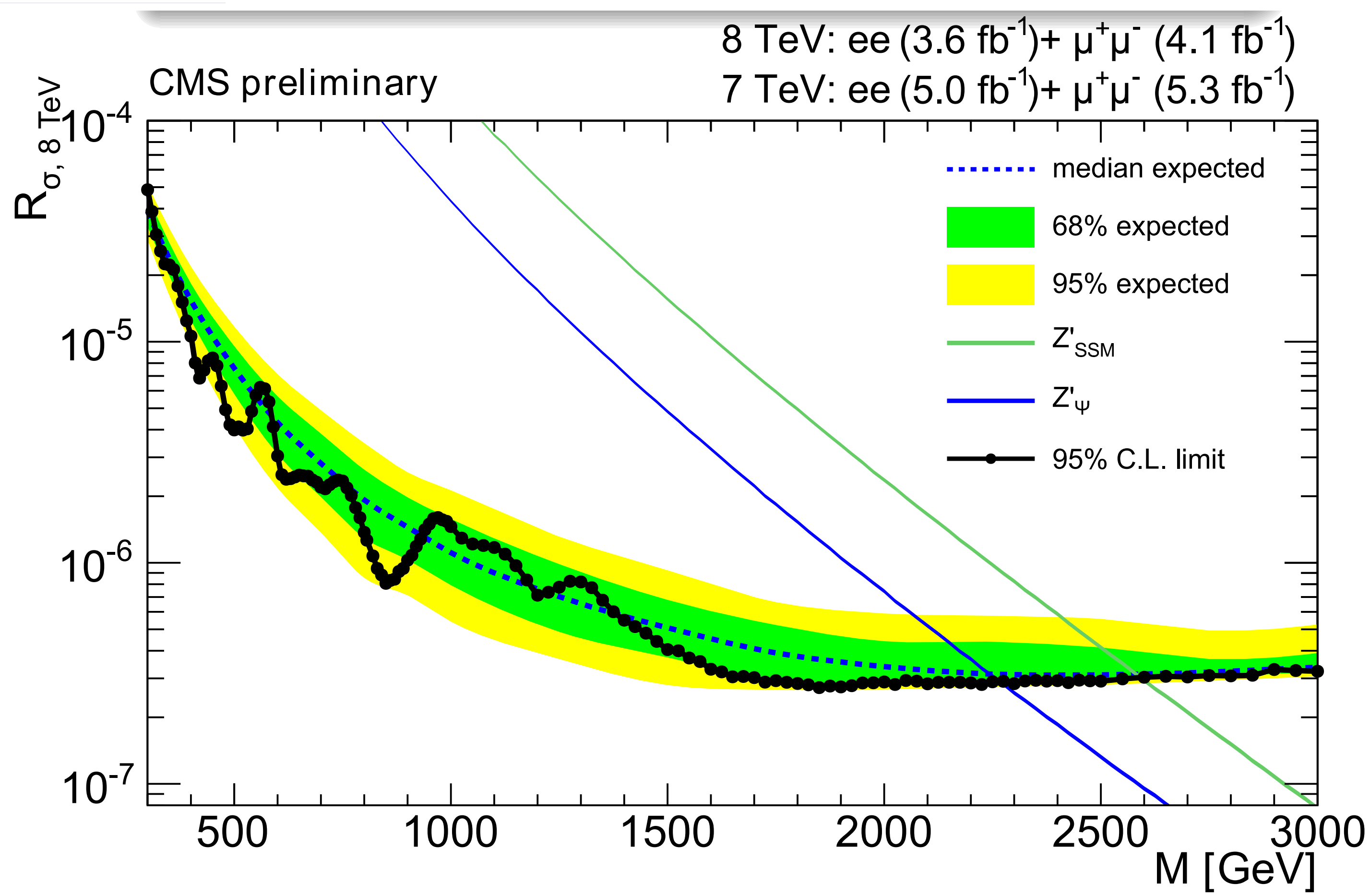
Invariant mass (Lorentz inv.)

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

From matrix element: Breit-Wigner

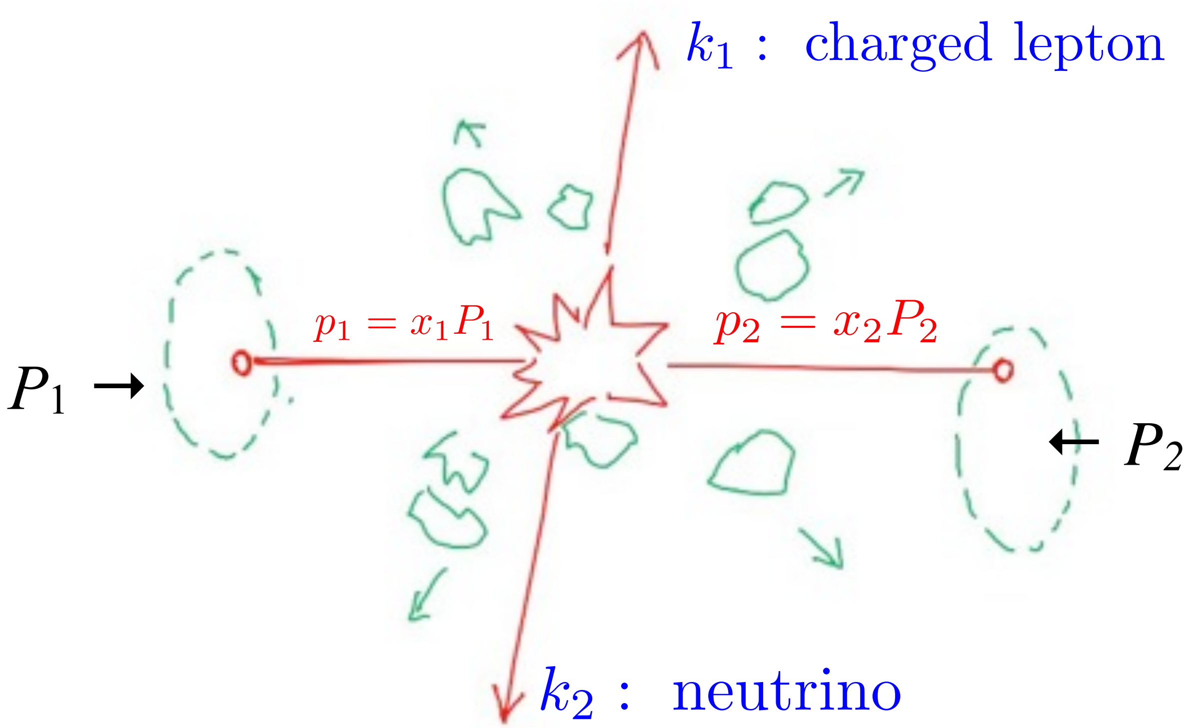
New resonance, Z', search





Almost a resonance:

- What if we don't observe all the final state particles. For example, consider $pp \to W \to \ell\nu$
- Cannot form an interesting Lorentz invariant variable.
  - At least can look for something invariant under boost along z-direction, e.g., transverse component of k_l



$$k_{1T}^2 = \frac{1}{4}\hat{s}\sin^2\hat{\theta}$$

$\hat{\theta}$ in parton c.o.m frame

$$\frac{d}{dk_{1T}^2} = \frac{d}{d\cos\hat{\theta}}\frac{d\cos\hat{\theta}}{dk_{1T}^2}$$

$$\frac{d\cos\hat{\theta}}{dk_{1T}^2} = -\frac{2}{\hat{s}}\left[1 - \frac{4k_{1T}^2}{\hat{s}}\right]^{-1/2}$$

recall $\hat{s} = m_W^2$ $\quad$ k_{1T} distribution singular at $\frac{m_W}{2}$!

Jacobian peak

Transverse mass.

Define

$$m_T^2 = (E_{1T} + E_{2T})^2 - (\vec{k}_{1T} + \vec{k}_{2T})^2 < m_{12}^2, \quad E_{iT}^2 = \vec{k}_{iT}^2 + m_i^2$$

Without additional radiation

$$|k_{1T}| = |k_{2T}| = E_{1T} = E_{2T} = \frac{m_T}{2}$$

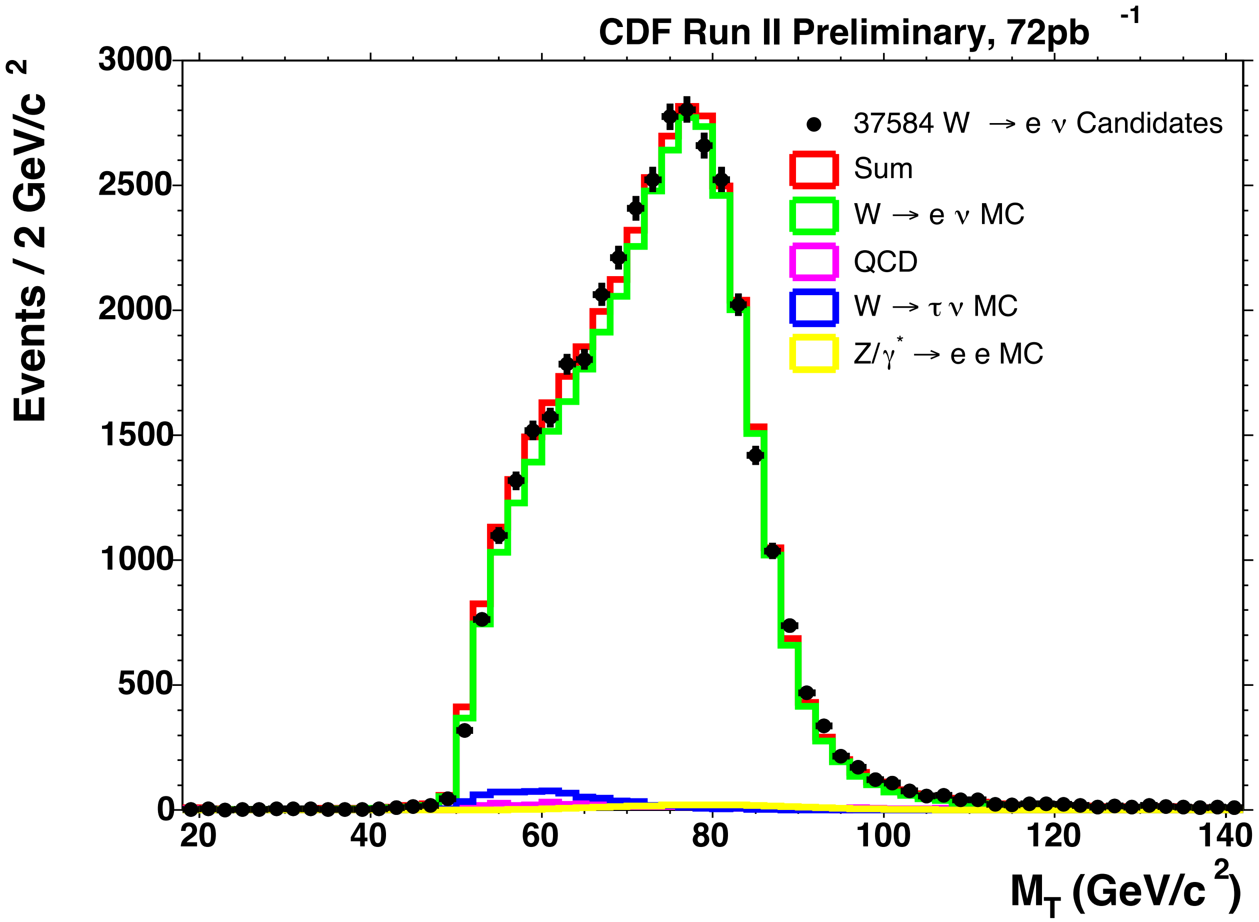
We have

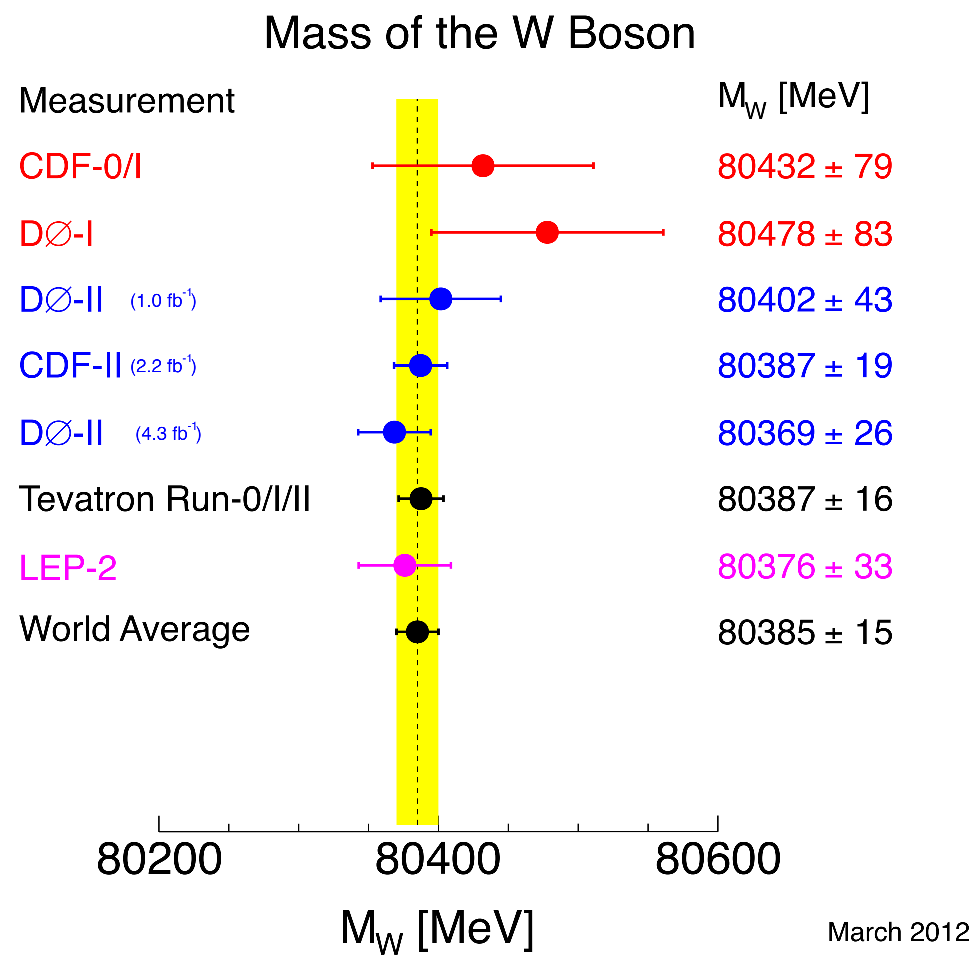
$$\frac{d^2\hat{\sigma}}{dm_{12}^2 dm_T^2} \propto \frac{\Gamma_W m_W}{(m_{12}^2 - m_W^2)^2 + \Gamma_W^2 m_W^2} \frac{1}{m_W^2} \frac{1}{\sqrt{m_W^2 - m_T^2}}$$

Due to the missing neutrino, m_{12} is not observable, must integrate over it.
However, transverse mass distribution has a singularity at m_W!

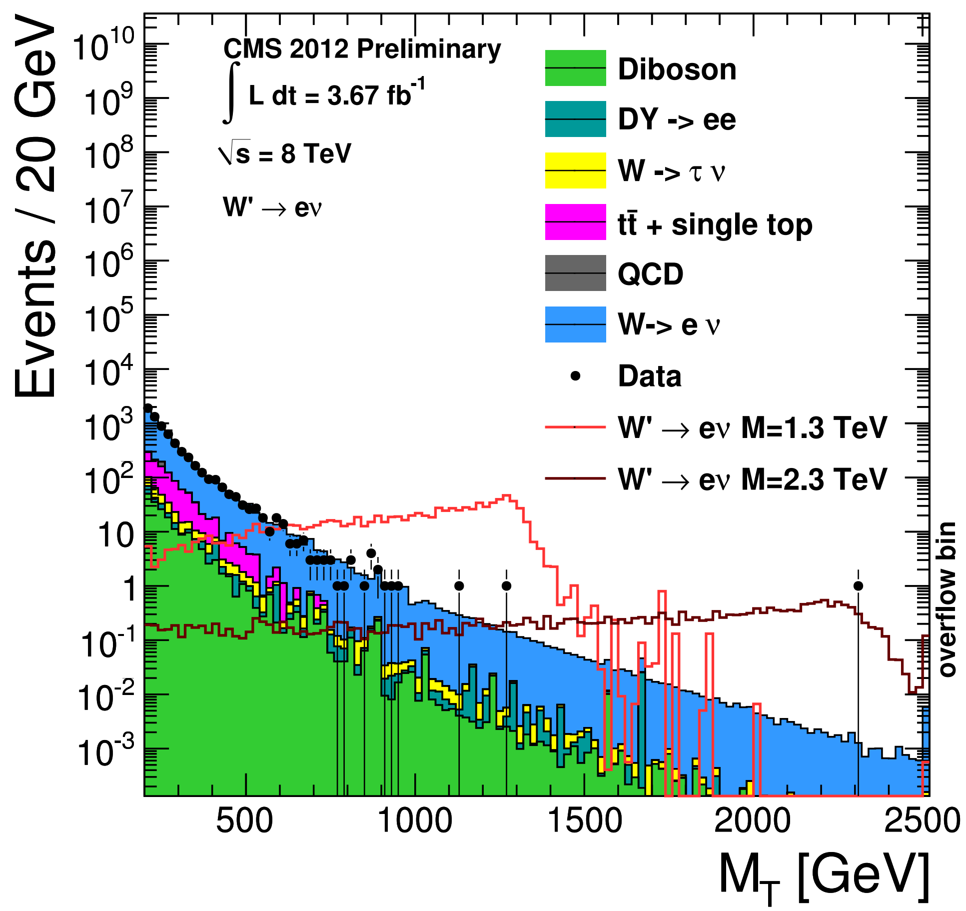
In reality, there is always some additional radiation, and W will have some transverse momentum. This, together with the W width, tends to smear out and correct the shape of the distribution a little bit.

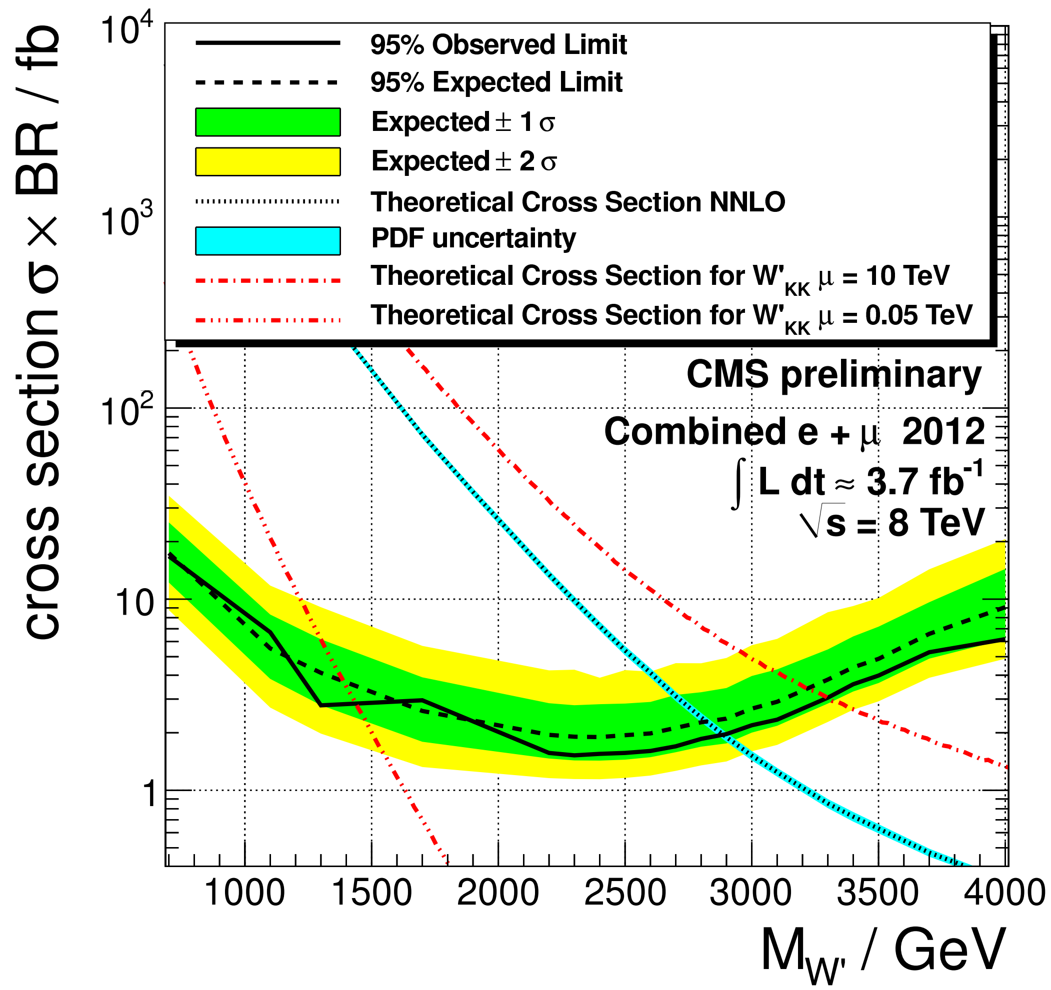
Measuring the W mass





W' search


CMS 2012 Preliminary
∫ L dt = 3.67 fb-1
√s = 8 TeV
W' → eν
Diboson
DY -> ee
W -> τ ν
tt̄ + single top
QCD
W-> e ν
Data
W' → eν M=1.3 TeV
W' → eν M=2.3 TeV
overflow bin
Events / 20 GeV
M_T [GeV]


95% Observed Limit
95% Expected Limit
Expected ± 1 σ
Expected ± 2 σ
Theoretical Cross Section NNLO
PDF uncertainty
Theoretical Cross Section for W'KK μ = 10 TeV
Theoretical Cross Section for W'KK μ = 0.05 TeV
CMS preliminary
Combined e + μ 2012
∫ L dt ≈ 3.7 fb-1
√s = 8 TeV
cross section σ × BR / fb
M_W' / GeV

Complicated New physics signals

Partners:
New physics states with similar interactions to those of the Standard Model particles, such as the superpartners in Supersymmetry.

TeV Supersymmetry (SUSY)

- Supersymmetry. $|\text{boson}\rangle \Leftrightarrow |\text{fermion}\rangle$
- An extension of spacetime symmetry.
- New states: “Partners”

SM	spin	(super)partner	spin
gluon, g	1	gluino: $\tilde{g}$	1/2
$W^{\pm}, Z$	1	gaugino: $\tilde{W}^{\pm}, \tilde{Z}$	1/2
quark: q	1/2	squark: $\tilde{q}$	0
...		...	

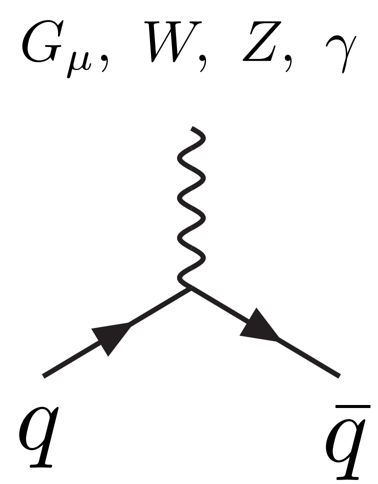
- Couplings relate to SM interactions via supersymmetry.
  - ~ same strength.
- Mass of superpartners ~ TeV.

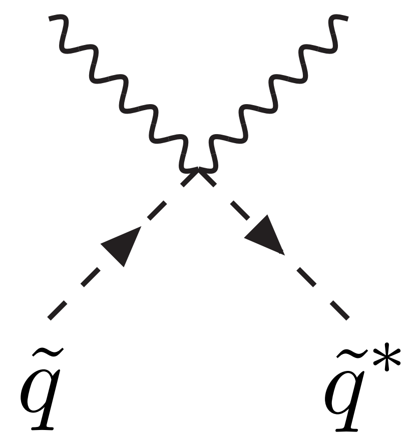
Review: S. Martin “A Supersemmtry Primer”, hep-ph/9709356

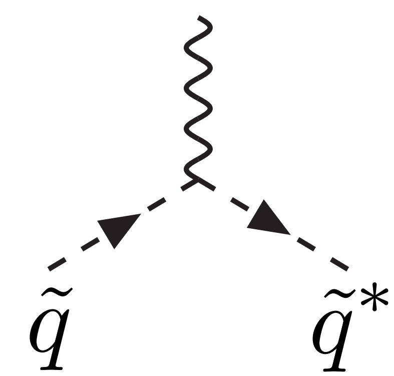
Interactions.

More details: for example, S. Martin "Supersymmmetry Primer"

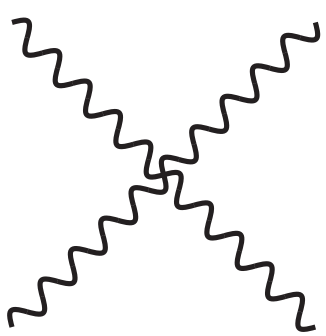
- Superpartners have the same gauge quantum numbers as their SM counter parts.
  - Similar gauge interactions.

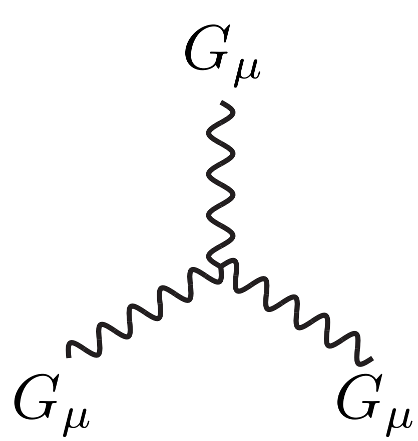


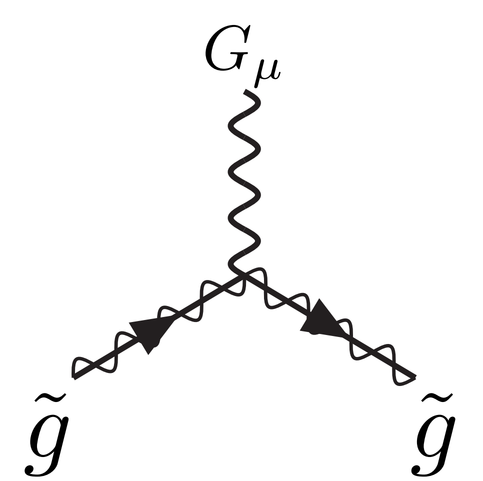




non-Abelian



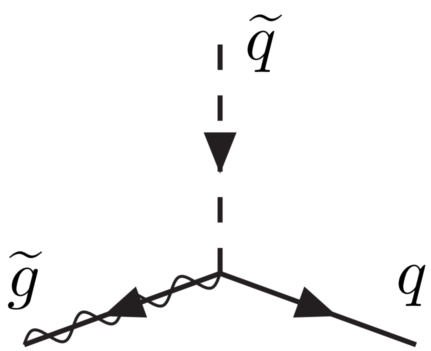




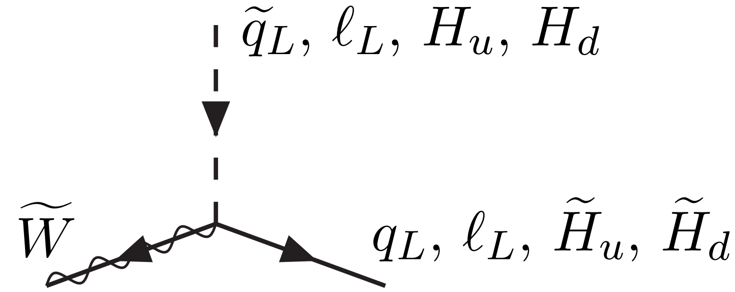
Interactions.

- SUSY$\Rightarrow$ additional couplings
  - strength fixed by corresponding gauge couplings.

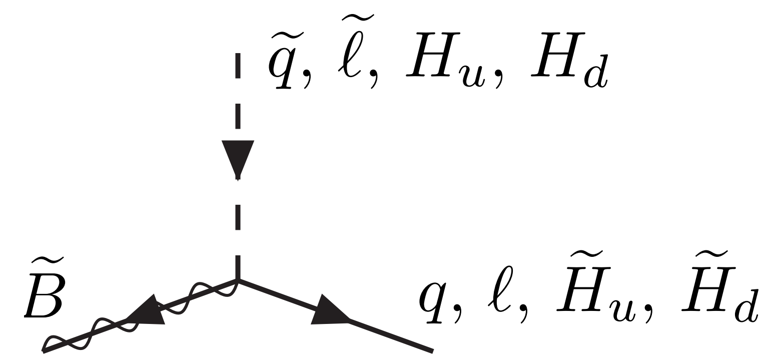
SU(3)$_{color}$



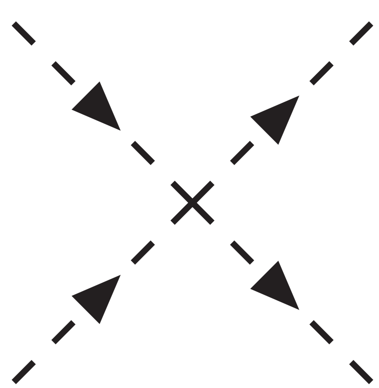
SU(2)$_L$



U(1)$_Y$

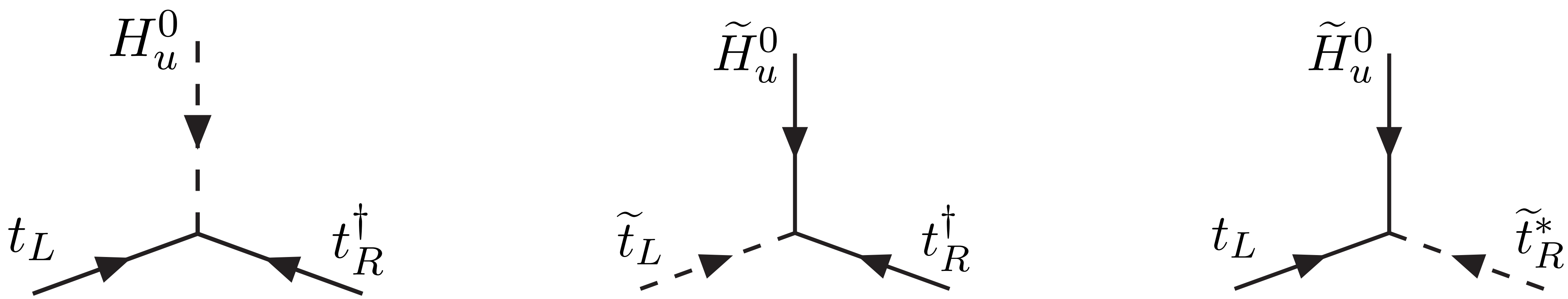


D-term: $\propto$ **g^2**

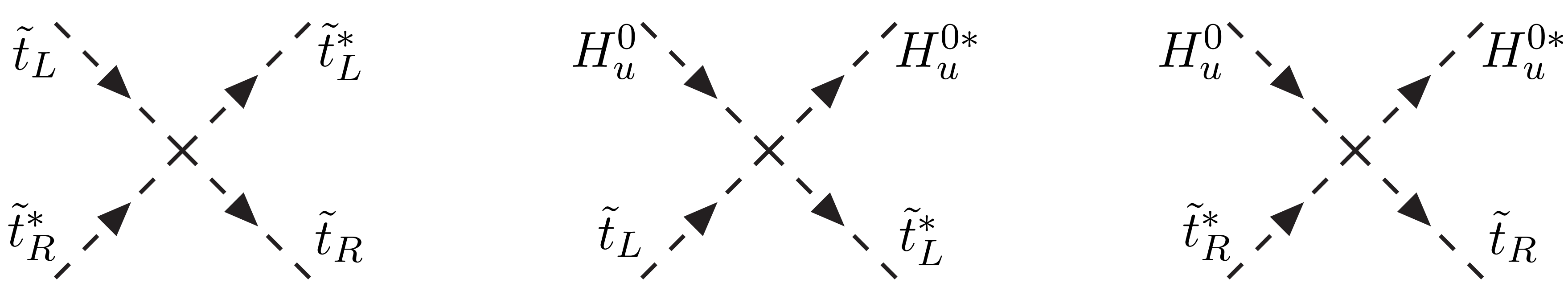


Interactions.

- SM fermions (such as the top quark) receive masses by coupling to the Higgs boson.
  - Yukawa couplings ⇒ SUSY counter parts.

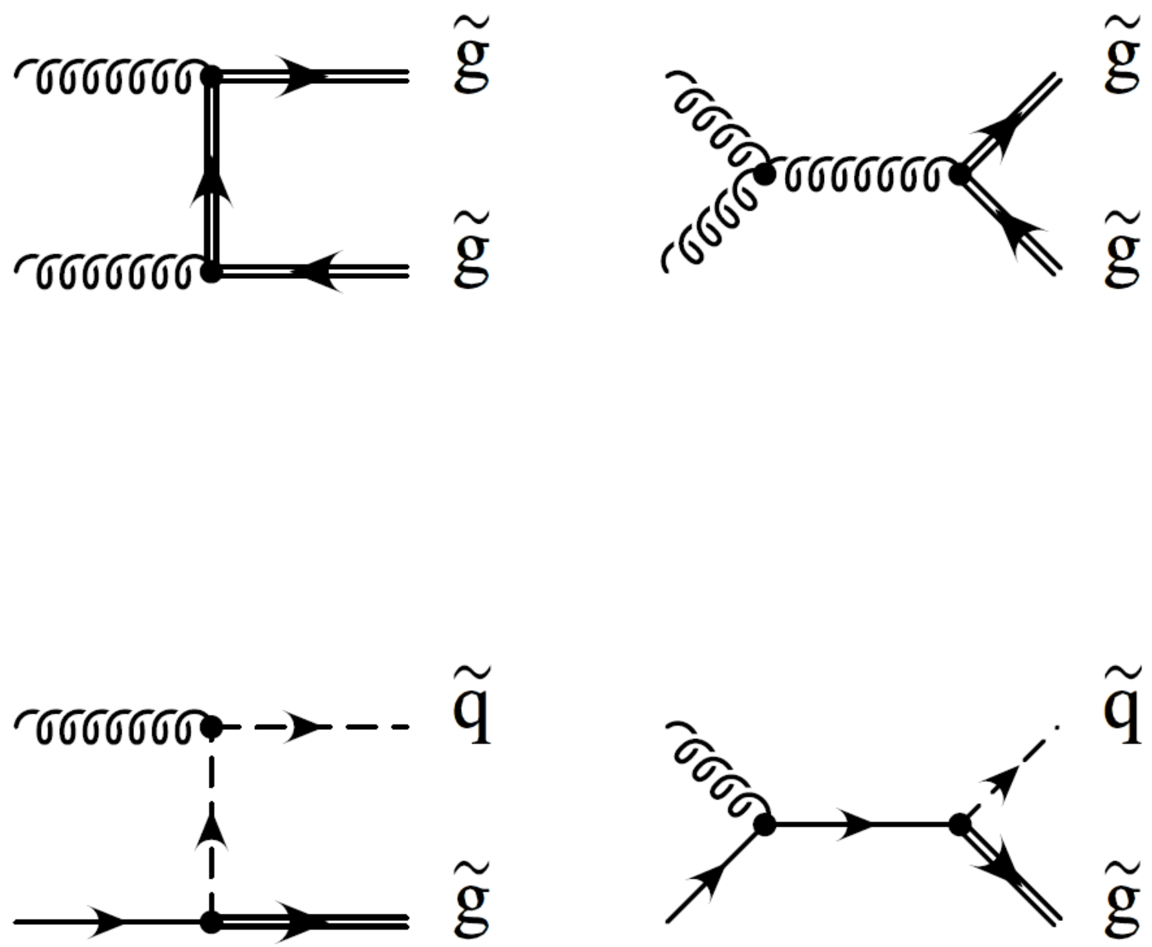


F-terms:



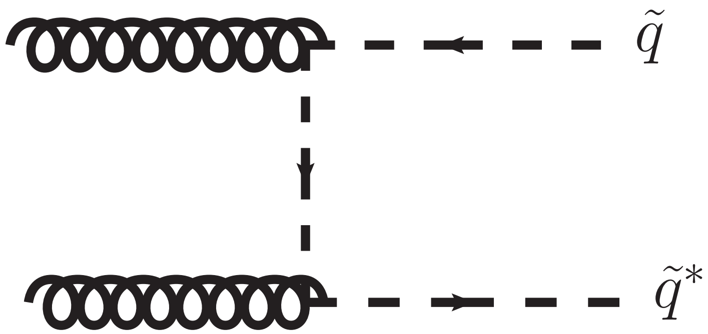
Examples of production: colored

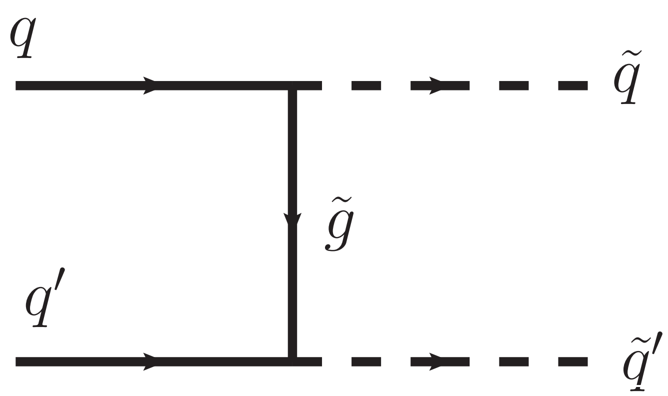
- Squark and gluino production.



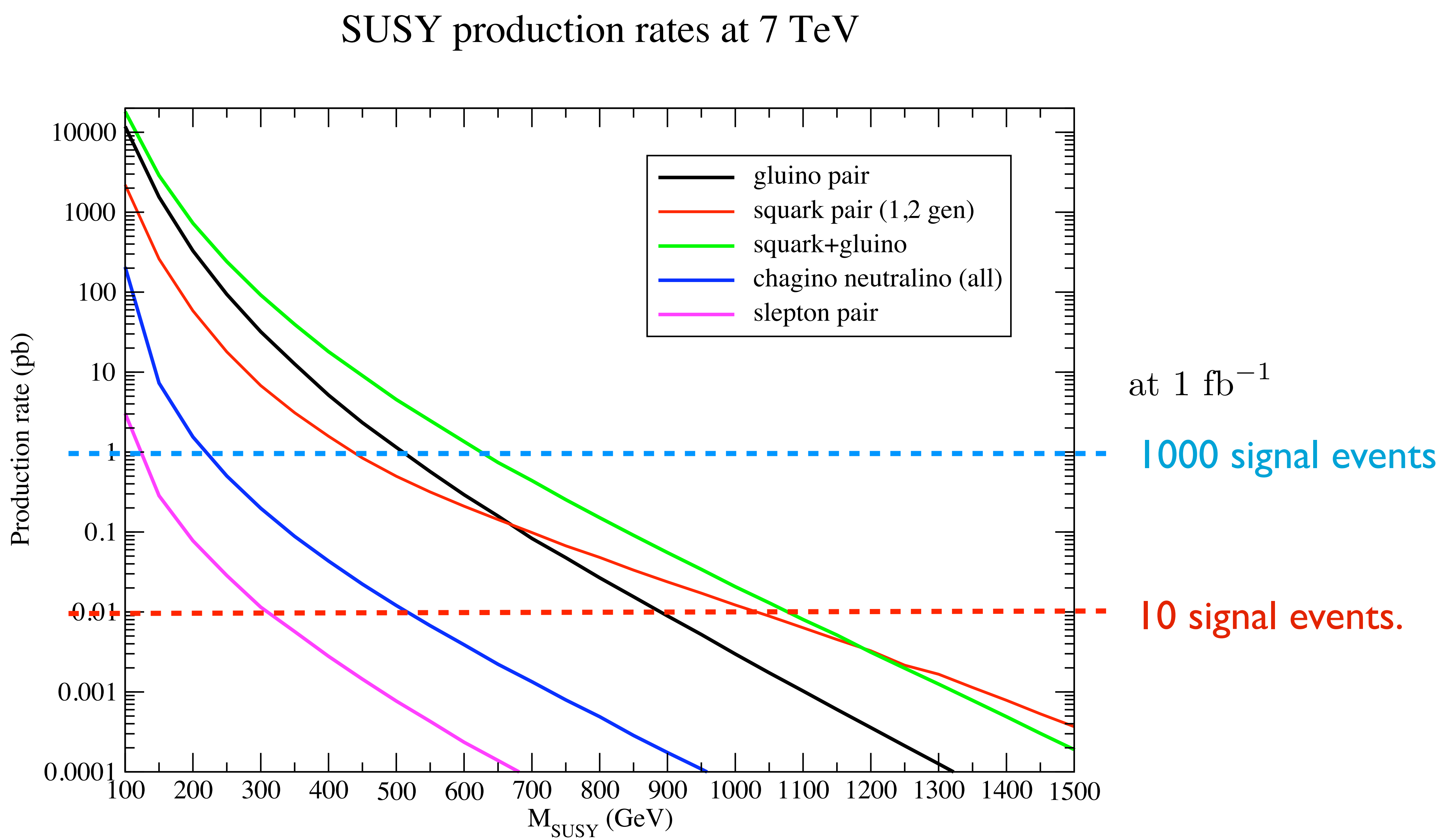
Examples of production

- Squark pair





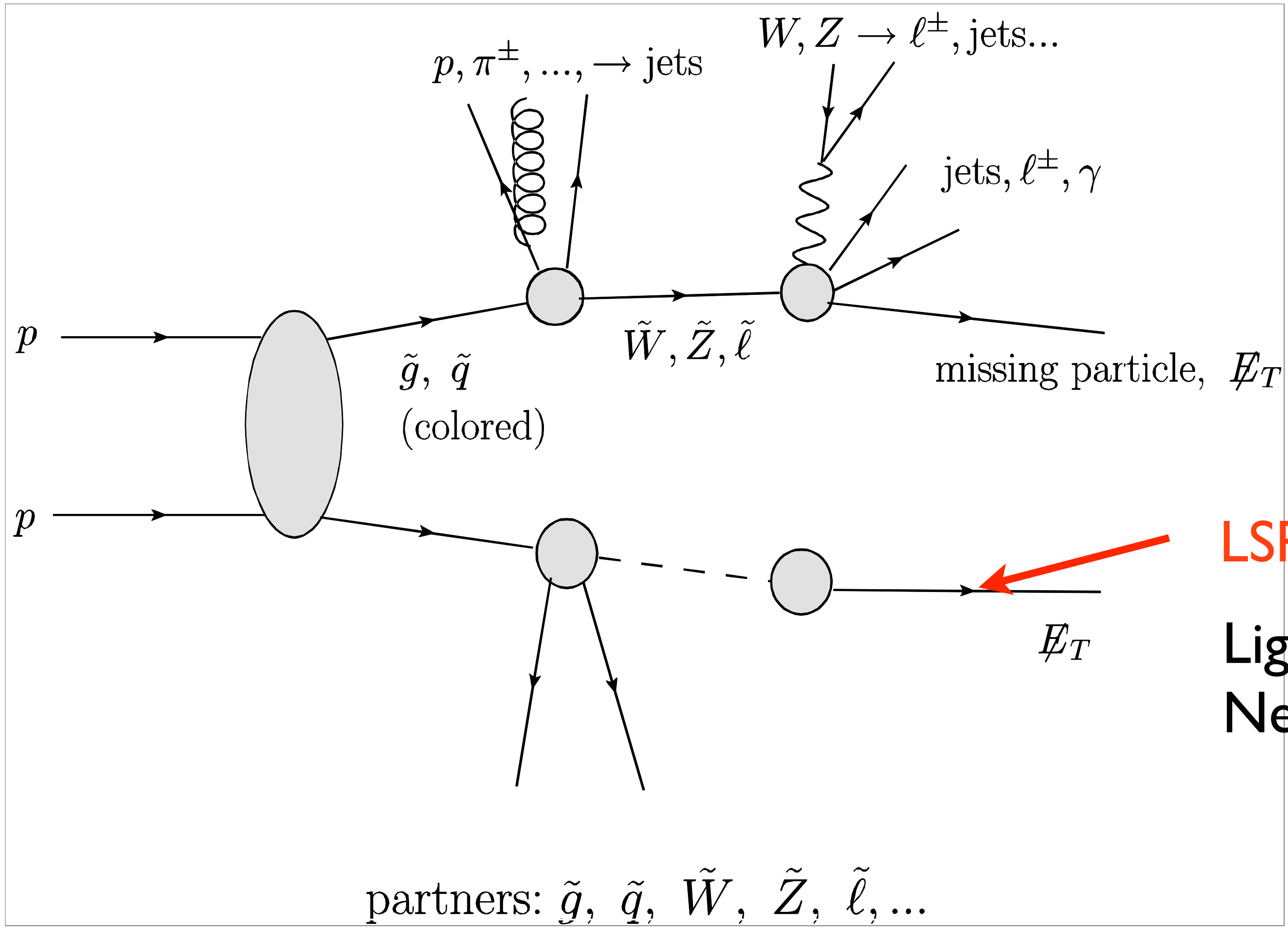
Production.



Dominated by the production of colored states.

Similar pattern for other scenarios. Overall rates scaled by spin factors.

SUSY at colliders

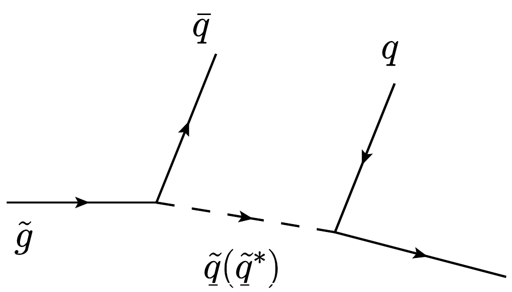


Lightest superpartner (LSP)
Neutral and stable.

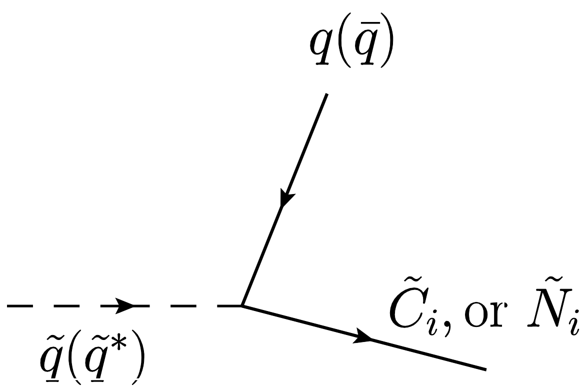
- long decay chain.
- jets, leptons, missing E_T ....
- Nice signal, good discovery potential.

Decay of squark and gluino

- Gluino always decays into squark (on or off-shell).
  - Glunino -> squark + Jets

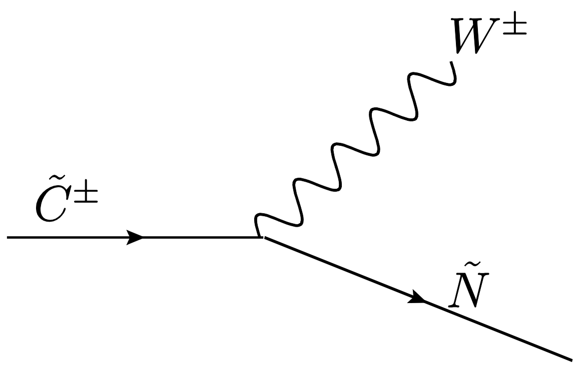


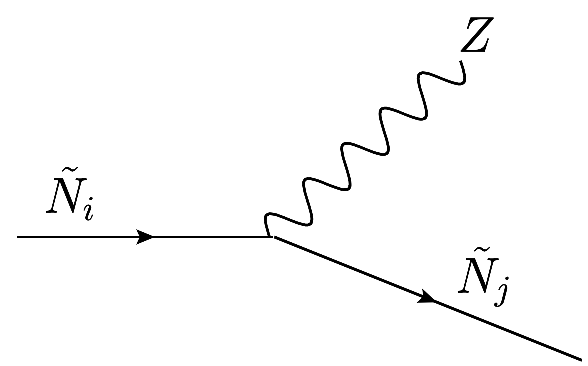
- Squark decay.
  - Jet +
    - To gluino, then go through off-shell squark.
    - To chargino or neutralino.



Next steps

- To W or Z (maybe Higgs.)





- Lepton (suppressed by W/Z-> lepton BR.)
  - 1 or 2 leptons.
- Jets (softer, constrained by W and Z mass).

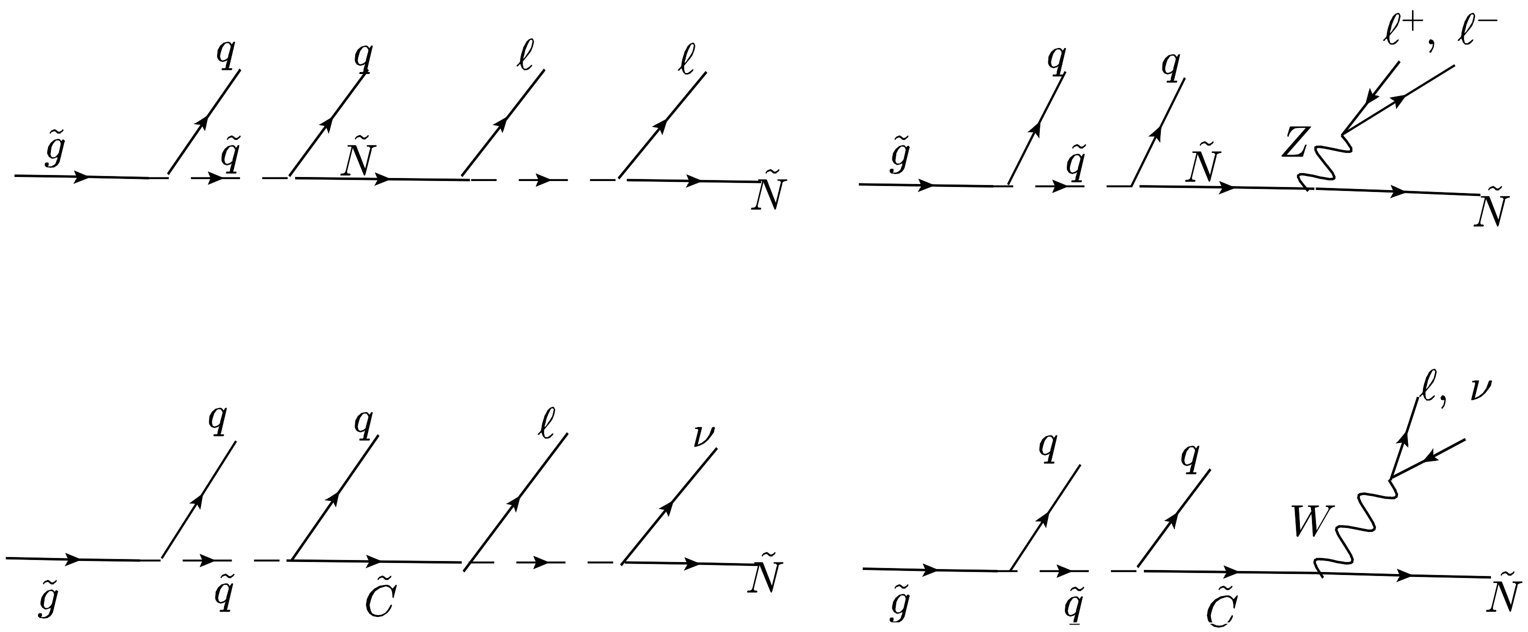
Simple rules.

- Typically, there are many channels through which a superpartner can decay.
- 2 body mode (almost) always dominate over 3-body mode.
    - A factor 1/100 suppression from phase space.
- Charge channel often bigger than the neutral channels.
- Higgsino prefers 3rd generation.
- Wino prefers left-handed.
- Typically, only one or two modes dominates.
    - Signature easier to understand.

Exercise:
Choose a SUSY spectrum, such as one of the so called SNOWMASS Points and Slopes (SPS) benchmarks, http://arxiv.org/abs/hep-ph/0202233
Use a spectrum and coupling calculator such as SUSPECT, SoftSUSY, or just PYTHIA...
Understand the output.

Long decay chains

- Putting the pieces together.
- Many channels, many final states.



2-lepton chain

1-lepton chain

$$
\begin{aligned}
\tilde{g} &\rightarrow q_1[\tilde{q}] \rightarrow q_1 q_2 \tilde{N}_0 \\
\tilde{g} &\rightarrow q_1[\tilde{q}] \rightarrow q_1 q_2[\tilde{N}_i] \rightarrow q_1 q_2[Z]\tilde{N}_0 \rightarrow q_1 q_2 q_3 q_4 \tilde{N}_0 \\
\tilde{g} &\rightarrow q_1[\tilde{q}] \rightarrow q_1 q_2[\tilde{C}_i] \rightarrow q_1 q_2[W]\tilde{N}_0 \rightarrow q_1 q_2 q_3 q_4 \tilde{N}_0 \\
\tilde{g} &\rightarrow q_1[\tilde{q}] \rightarrow q_1 q_2[\tilde{N}_i] \rightarrow q_1 q_2[Z]\tilde{N}_0 \rightarrow q_1 q_2 \ell^+ \ell^- \tilde{N}_0 \\
\tilde{g} &\rightarrow q_1[\tilde{q}] \rightarrow q_1 q_2[\tilde{N}_i] \rightarrow q_1 q_2 q_3 q_4 (\ell^+ \ell^-)\tilde{N}_0
\end{aligned}
$$

Exercise: draw diagrams for tri-lepton, same sign di-lepton

Typical variables I: counts.

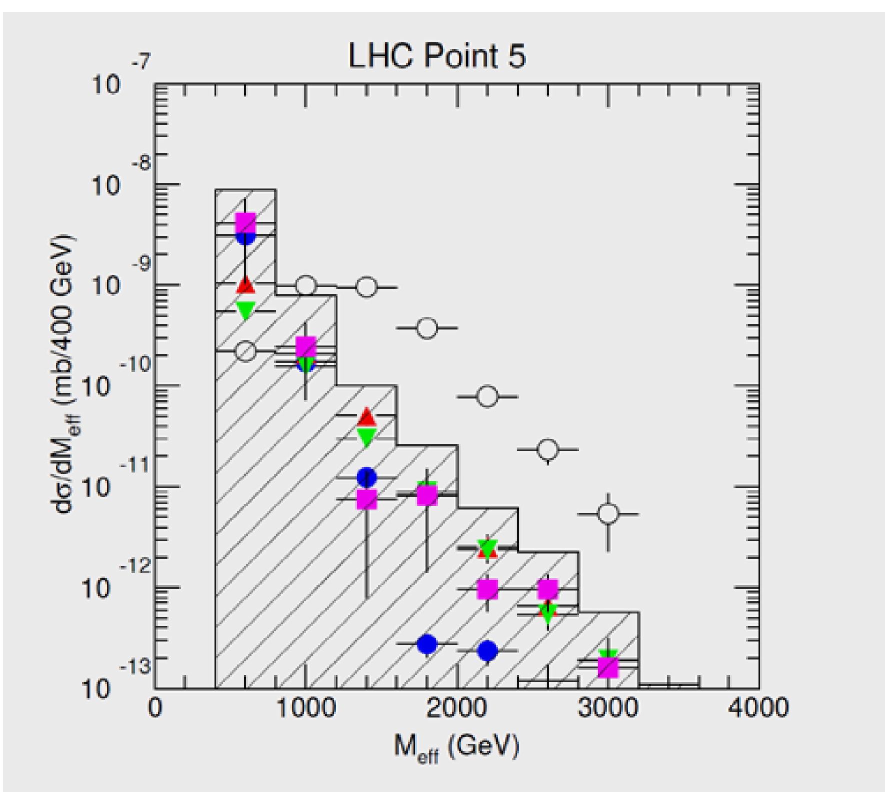
- Inclusive counts. Useful for signal >> backrgound.

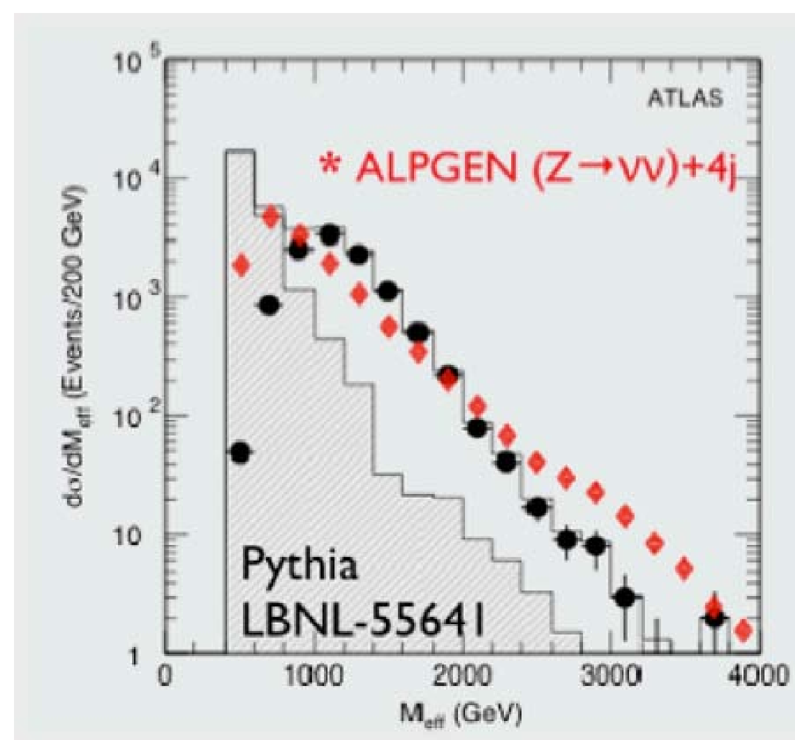
$n_j \times$ jet	b-jet non-b-jet
$+$	
$n_\ell \times$ lepton	ℓ all flavor and charge combo: e.g. $2\ell \rightarrow 21$ comb.
$+$	
$n_\gamma \times \gamma$	

Kinematical features: transverse variables.

- Multiple hard objects.
- No resonance.
- Transverse variables made of several energetic objects. M_{eff} H_{T}

$$M_{eff} = \not{E}_T + p_{T,1} + p_{T,2} + p_{T,3} + p_{T,4}$$

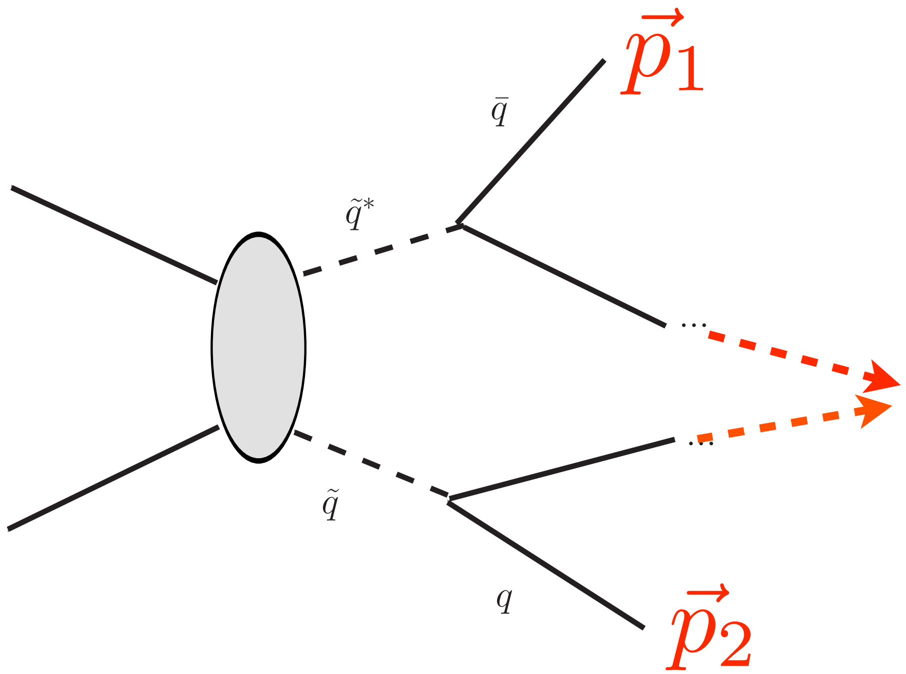




Be careful.

Gianotti and Mangano, 2005

Another example: α_T



Define: $\alpha_T = \dfrac{p_{2T}}{m_T}$ $\quad m_T = \sqrt{(p_{1T} + p_{2T})^2 - (\vec{p}_{1T} + \vec{p}_{2T})^2}$

Define p_T fractions $\quad x_i = \dfrac{p_{iT}}{\sum_{i=1,3} p_{iT}}, \quad x_i \leq 1 \text{ and } \sum_{i=1,3} x_i = 2$

We obtain $\quad \alpha_T = \dfrac{1}{2} \dfrac{x_2}{\sqrt{1 - x_3}}$

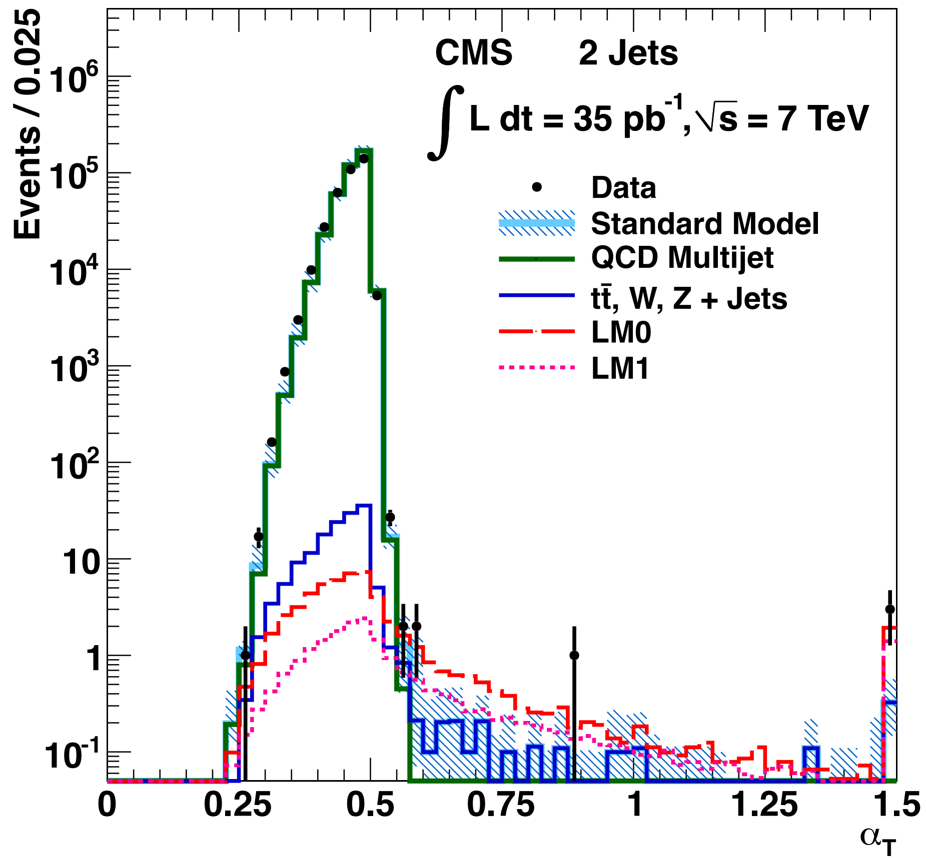
α_T can be either <1/2 (more often), or > 1/2

For a nice review, see Michael Peskin, "Razor and Scissors"

Another example: α_T

- In comparison, consider QCD di-jet, with one of the jet (say p_{2T}) energy miss measured.

$$\vec{p}_{2T} = -\lambda \vec{p}_{1T}, \quad \lambda \leq 1 \qquad \alpha_T^{\mathrm{di-jet}} = \frac{1}{2}\sqrt{\lambda} \leq \frac{1}{2}$$



Many additional transverse variables: M_{T2} , Razor, ...

Kinematical variables: invariant masses

- Most useful: di-lepton edges and endpoints. (Mentioned earlier in neutralino decay).
  - Clean.
- Invariant mass distribution also carry spin information. Probably needs high statistics.

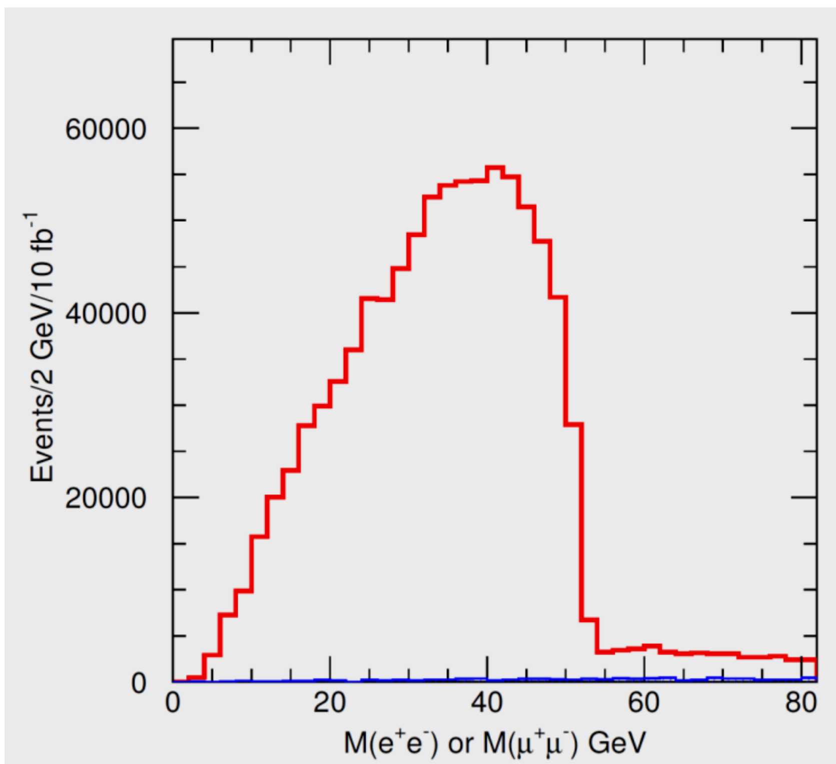
For a review: See LW and I. Yavin, 2008

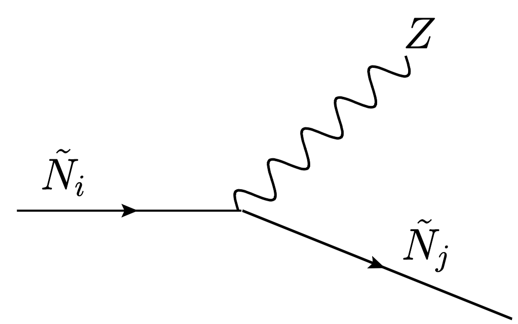
- More complicated invariant masses in longer decay chains possibly useful, but feature is less sharp. May need high statistics as well.

For example, see Miller and Osland. A set of papers.

Special case: off-shell Z

- 3-body. End-point in di-lepton invariant mass.
  - Same flavor di-lepton.
  - Combinatorials can be suppressed with flavor subtraction.



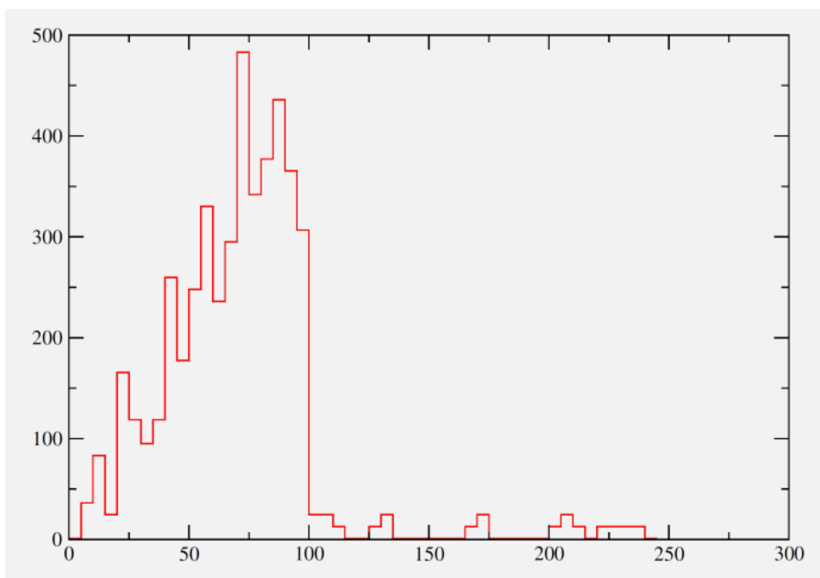


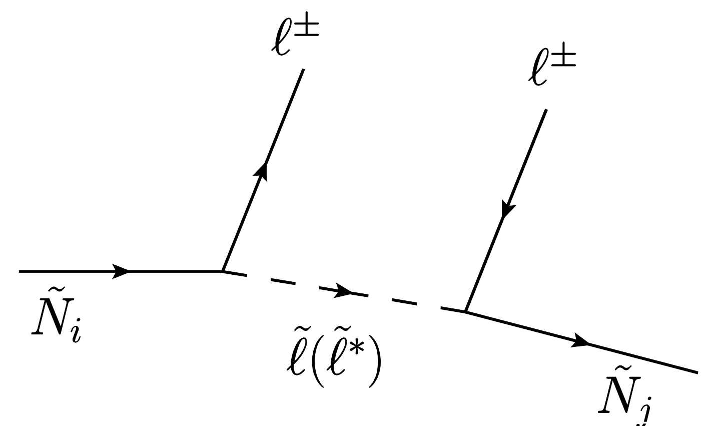
$$M_{\tilde{N}_2} - M_{\tilde{N}_1} < m_Z \longrightarrow \tilde{N}_2 \rightarrow \tilde{N}_1 + \ell^+ + \ell^- \text{ Only 3-body}$$

$$m_{\ell\ell} = \sqrt{(p_{\ell+}^2 + p_{\ell-}^2)} \longrightarrow \text{end-point at } M_{\tilde{N}_2} - M_{\tilde{N}_1}$$

More leptons if we are lucky

- A lot of leptons. No branching ratio suppression.
- On shell slepton, very distinctive feature.
  - Edge in di-lepton invariant mass.





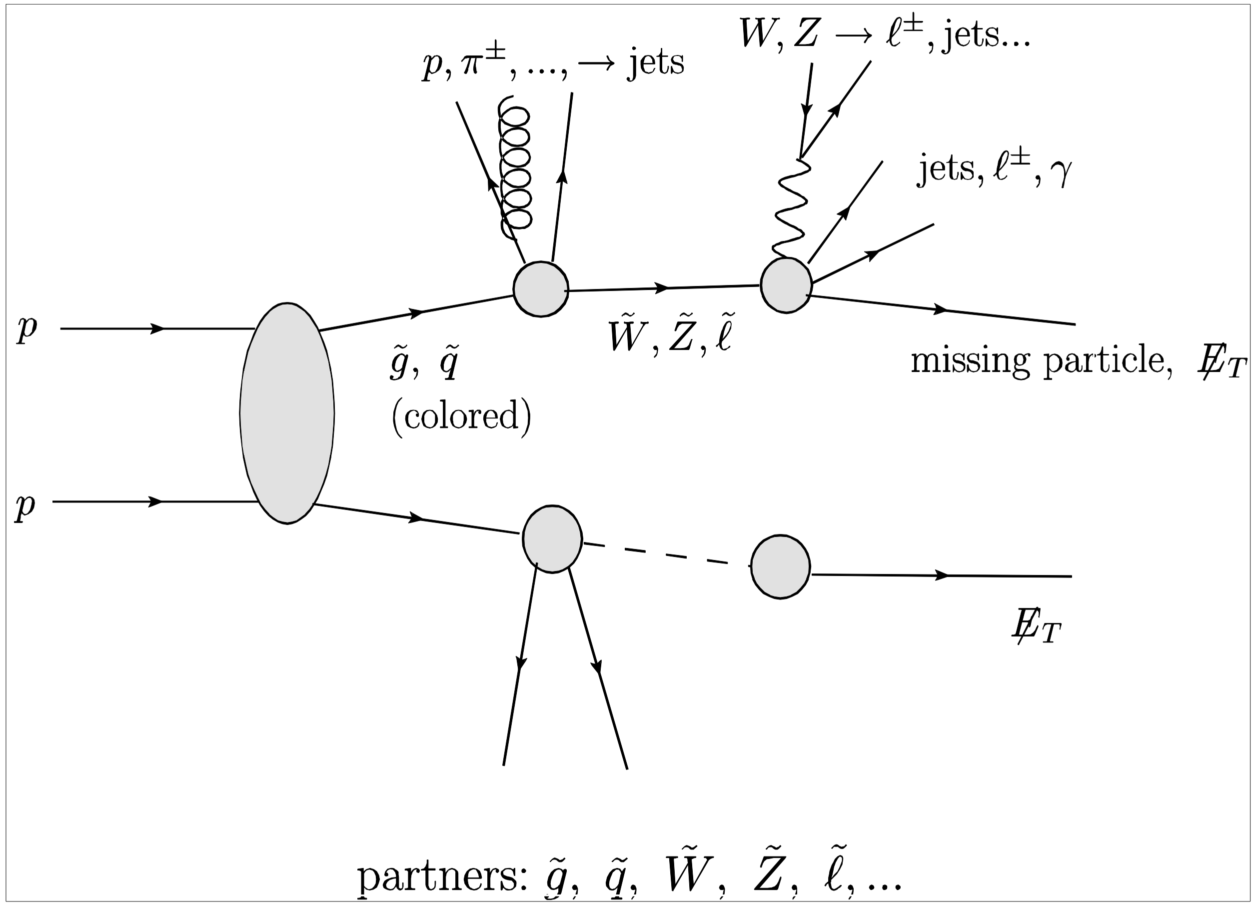
$$m_{\tilde{\ell}} < M_{\tilde{N}_2} \longrightarrow \tilde{N}_2 \to \tilde{N}_1 + [\tilde{\ell}] \to \tilde{N}_1 + \ell^+ + \ell^-$$

$$M_{\ell\ell}^{\mathrm{max}} = M_{\tilde{N}_2} \sqrt{1 - \frac{m_{\tilde{\ell}}^2}{M_{\tilde{N}_2}^2}} \sqrt{1 - \frac{M_{\tilde{N}_1}^2}{m_{\tilde{\ell}}^2}}$$

- More complicated edges useful, but need high statistics.

See several papers by: Miller, Osland.

Topology: model independent approach



partners:
Same gauge interactions as the SM particles
Similar signatures.

$\tilde{g},\ \tilde{q},\ \tilde{W}, \tilde{Z},\ \tilde{\ell}...$
$g^{\rm KK},\ q^{\rm KK},\ W^{\rm KK}, Z^{\rm KK},\ \ell^{\rm KK}...$

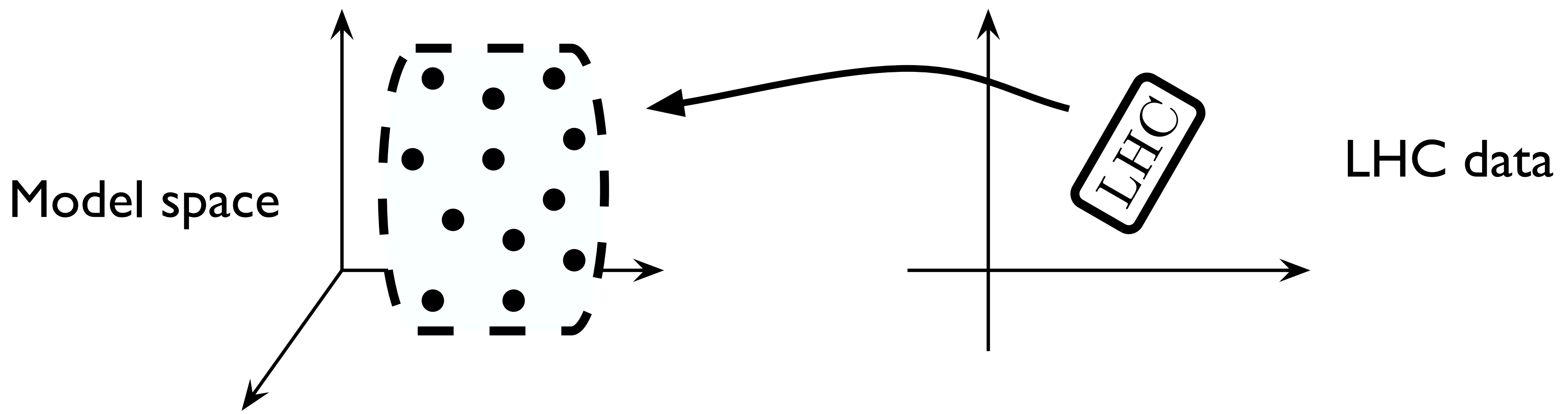
http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=94910

http://www.lhcnewphysics.org/web/Overview.html

Signals can be challenging to understand.

- After the discovery, we can derive some basic properties, such as whether the new particles are colored or not, whether they decay to leptons, and so on.

- Many possible interpretations.



Degeneracies! Quantum number, mass, spin...

For example: in supersymmetry, bino vs wino, squark vs gluino...

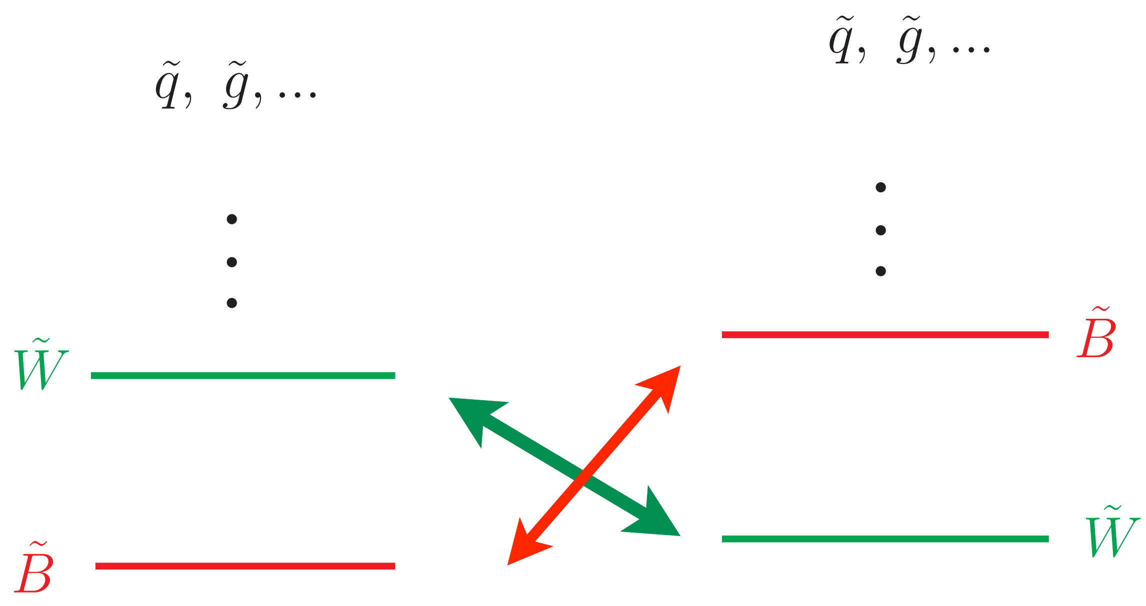
Arkani-Hamed, Kane, Thaler, and Wang, JHEP 0608:070,2006.

Hard work, but we will be able to figure it out.

Possible degeneracies in:

- The identity of new physics particles. For example:

Two different SUSY spectra.



Identity swap, hard to distinguish

Arkani-Hamed, Kane, Thaler, and Wang, JHEP 0608:070,2006

- Spin.
  - SUSY: 1/2 spin difference from the SM particle.
  - Extra-dimension: same spin.

For a review: Wang and Yavin, Int. J. Mod. Phys. A 23, 4647 (2008)

A promising, and complicated, scenario.

$> \text{TeV}$ — $\tilde{u},\ \tilde{d},\ \ldots$; $\tilde{t},\ \tilde{b}$

$\sim 100\text{s GeV}$ — $\tilde{g}$; $\tilde{N}$

The Dominant channel

$$p\,p \to \tilde{g}\tilde{g} \to t\bar{t}t\bar{t}(\text{or } t\bar{t}b\bar{b},\ t\bar{t}t\bar{b}\ \ldots)$$

$$\tilde{g} \to t\bar{t}(b\bar{b}) + \tilde{N},\ \text{or}\ \ t\bar{b} + \tilde{C}^- \quad t \to b\ell^+\nu$$

- Multiple b, multiple lepton final state.
  - Good early discovery potential.
  - Challenging to interpret: top reconstruction difficult.

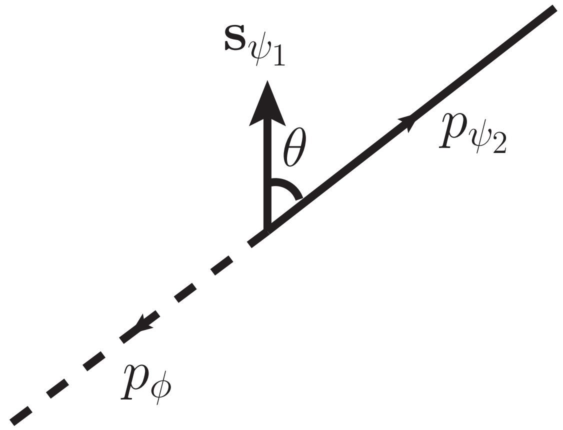
A new method of fitting branching ratio to various final states

Acharya, Grajek, Kane, Kuflik, Suruliz, Wang, arXiv:0901.3367

An example of a challenging measurement: spin

or distinguishing SUSY with others.

Spin of new resonances

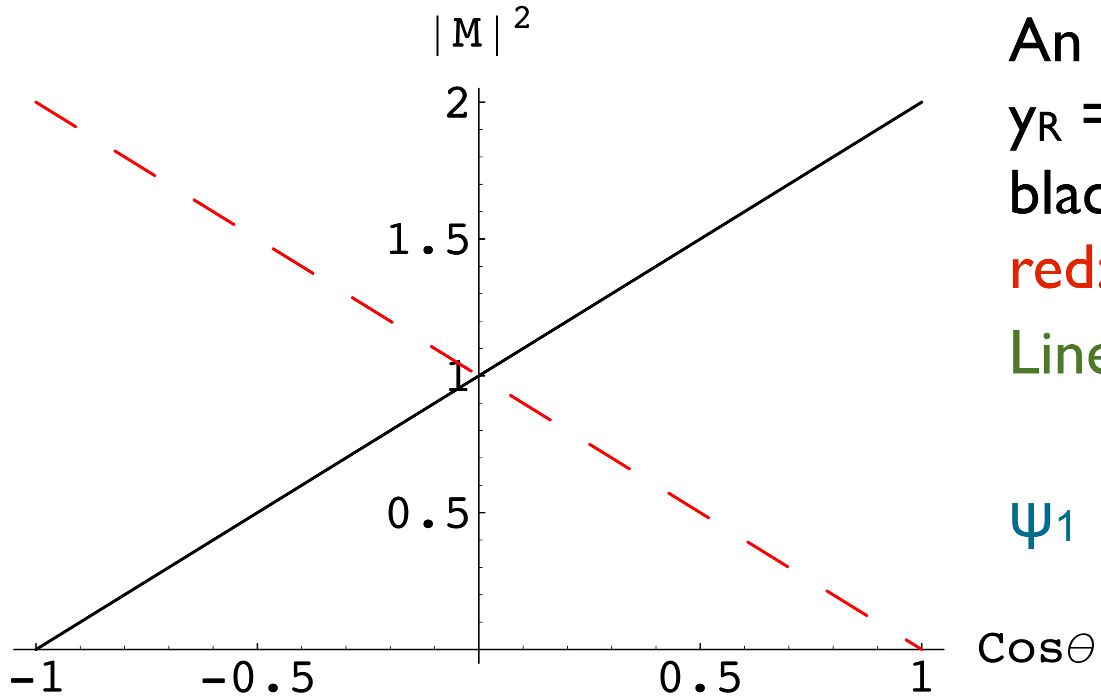


$$\psi_1 \to \psi_2 + \phi$$

$$y_L \phi \bar{\psi}_2 P_L \psi_1 + y_R \phi \bar{\psi}_2 P_R \psi_1$$

- Eample spin of fermion.
  - In the rest frame of the fermion.
  - Define angle θ of the decay product w.r.t. the polarization axis of ψ_1 .
  - Coupling could be chiral if $y_L \neq y_R$

Fermion spin

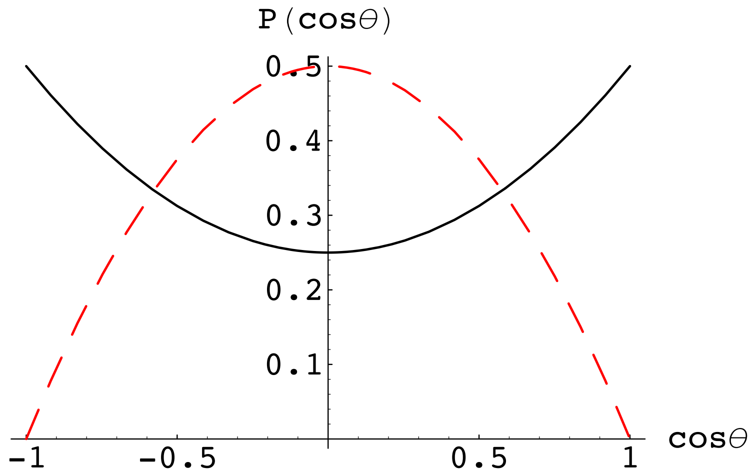


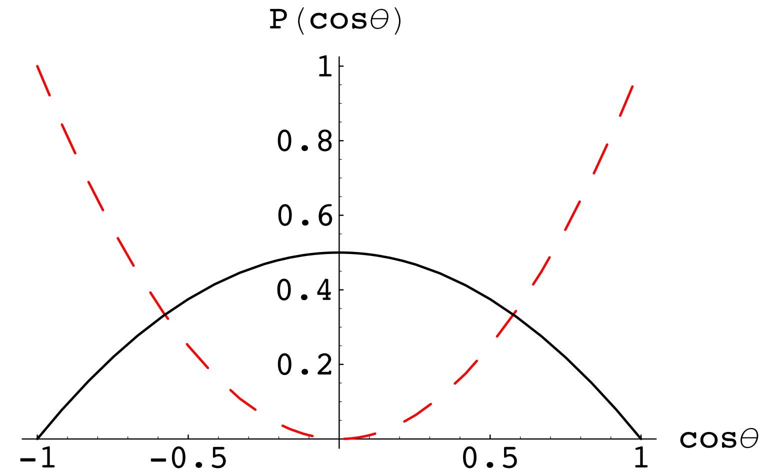
An Example
$y_R = 0$
black: ψ_1 right-handed,
red: ψ_1 left-handed
Linear in $\cos\theta$

ψ_1 not polized, no correlation, no spin information

- Go to the rest frame.
- Coupling chiral.
- ψ_1 polarized.

Spin-1





$A'_{\text{transverse}} \to \psi_1 + \psi_2$

$A'_{\text{longitudinal}} \to \psi_1 + \psi_2$

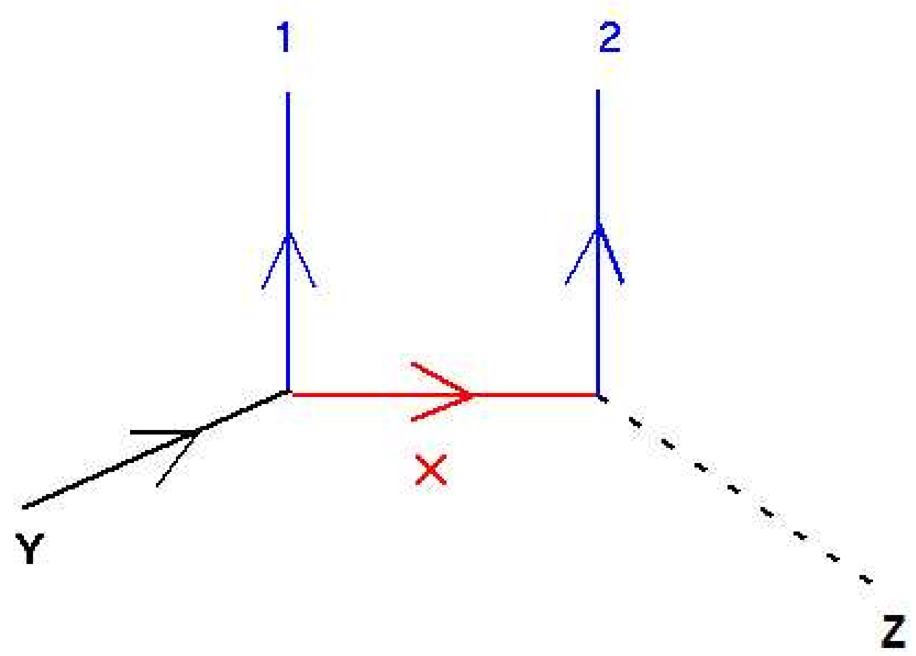
$A'_{\text{transverse}} \to \phi_1 + \phi_2$

$A'_{\text{longitudinal}} \to \phi_1 + \phi_2$

$$|\mathcal{M}|^2 \propto \cos\theta^2$$

In general: $|\mathcal{M}|^2 \propto \cdots + \cos\theta^{2J_{\text{mother}}}$

Example of spin measurement



1 and 2 are observable particles, q, ℓ, $W^{\pm}$....

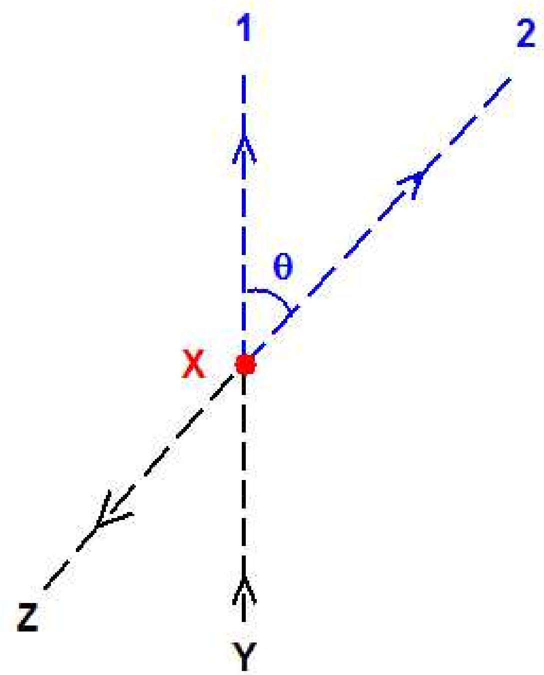
We are interested in the spin of **X** (on-shell).

We choose to use

$$t_{12} = (p_1 + p_2)^2.$$

In general, can not reconstruct the rest frame of X

Consider the rest frame of X



$$t_{12} \propto (1 - \cos\theta)^2$$

Direction of Y and 1 can be chosen to define the polarization of X

For X with spin $\mathrm{J_X}$

$$\frac{d\Gamma}{dt_{12}} = a\ t_{12}^{2J_X} + b\ t_{12}^{2J_X - 1} + \cdots$$

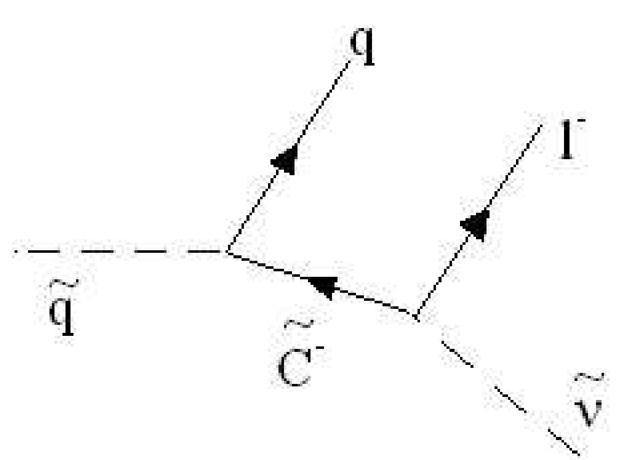
In principle, fitting the degree of this polynomial tells the the spin of X.

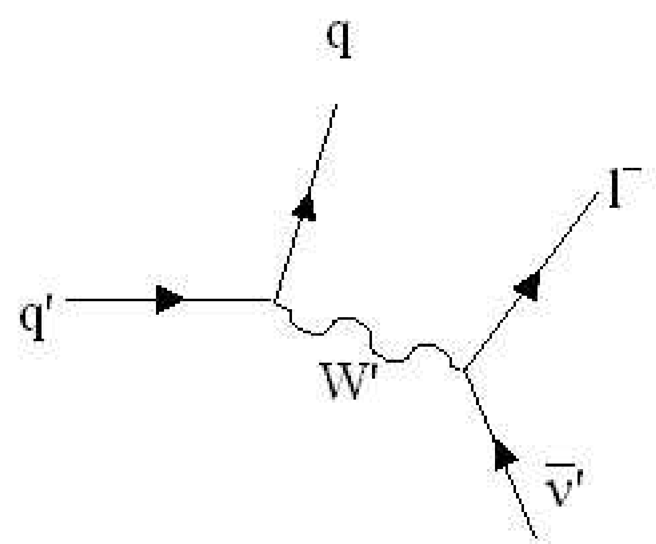
In practice, whether the coefficient a, b, ... are non-zero depends on the chirality of the coupling between X and 1, 2, Z, Y, and the mass differences between them.

Interpreting the results correctly depending on our understanding the spectrum and couplings.

Example: SUSY vs spin-1 partner

Decay through charged partners $\tilde{\chi}^{\pm}$, $W'^{\pm}$...





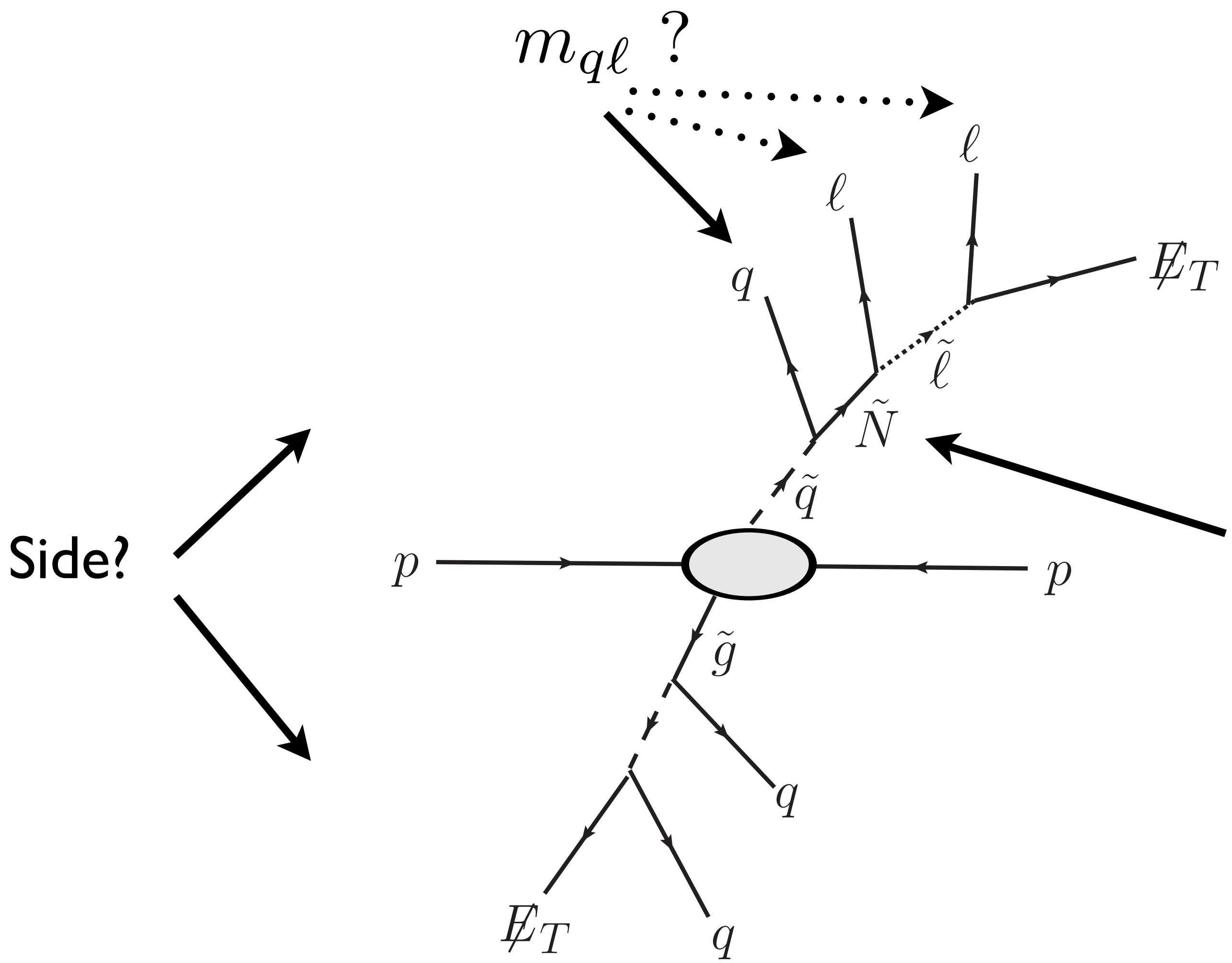
$\propto t_{q\ell} + ...$
$\tilde{q} - q - \tilde{C}$ chiral
q boosted
$\tilde{C} - \tilde{\nu} - \ell$ chiral

$\propto t_{q\ell}^2 + ...$
$m_{q'} \quad >> \quad m_{W'}$
W' boosted

Usually there are more leptons in the decay chain.

Near/far lepton has to be separated.

Spin measurements. Supersymmetry?



Example: spin of $\tilde{N}$

Clean exclusive sample

Boost (kinematics) vs matrix element (spin)

$\rightarrow$ Consider $m_{q\ell}$

Combinatorics

- No universally applicable method. Different strategies will be used in different scenarios.

A review: LTW and Yavin, arXiv:0802.2726

- More information of the signal, masses and underlying processes, is crucial.