Intro to collider physics

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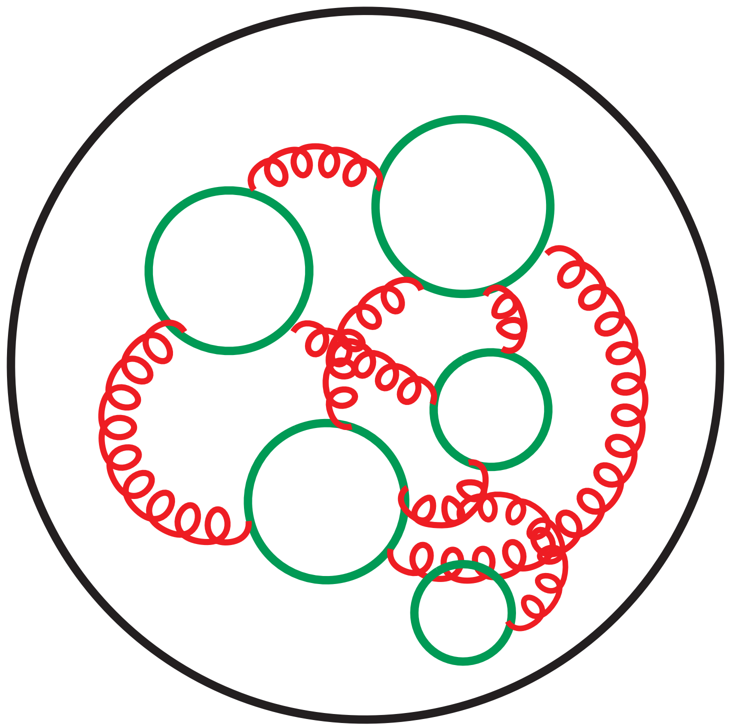
Before we start

- 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

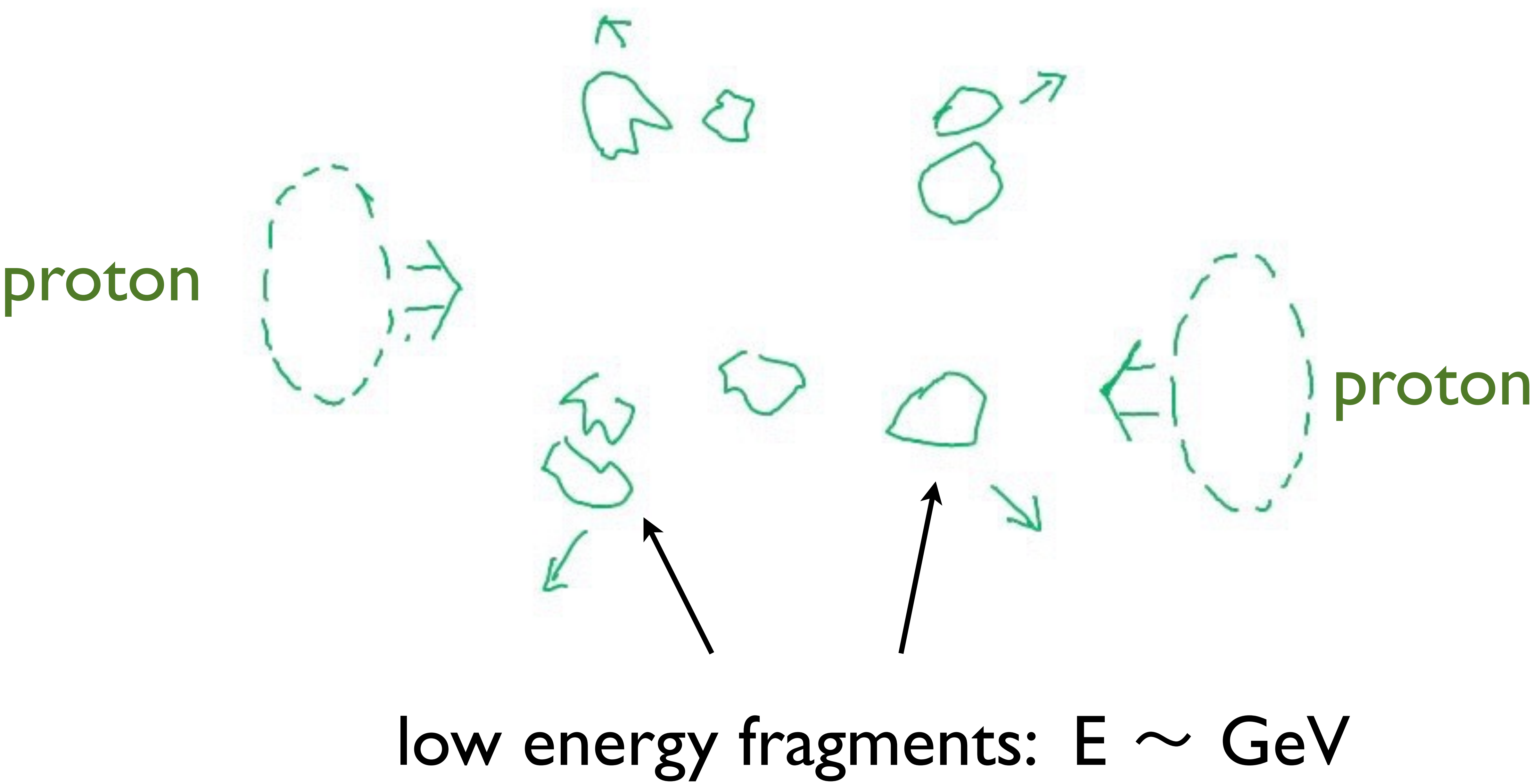
proton



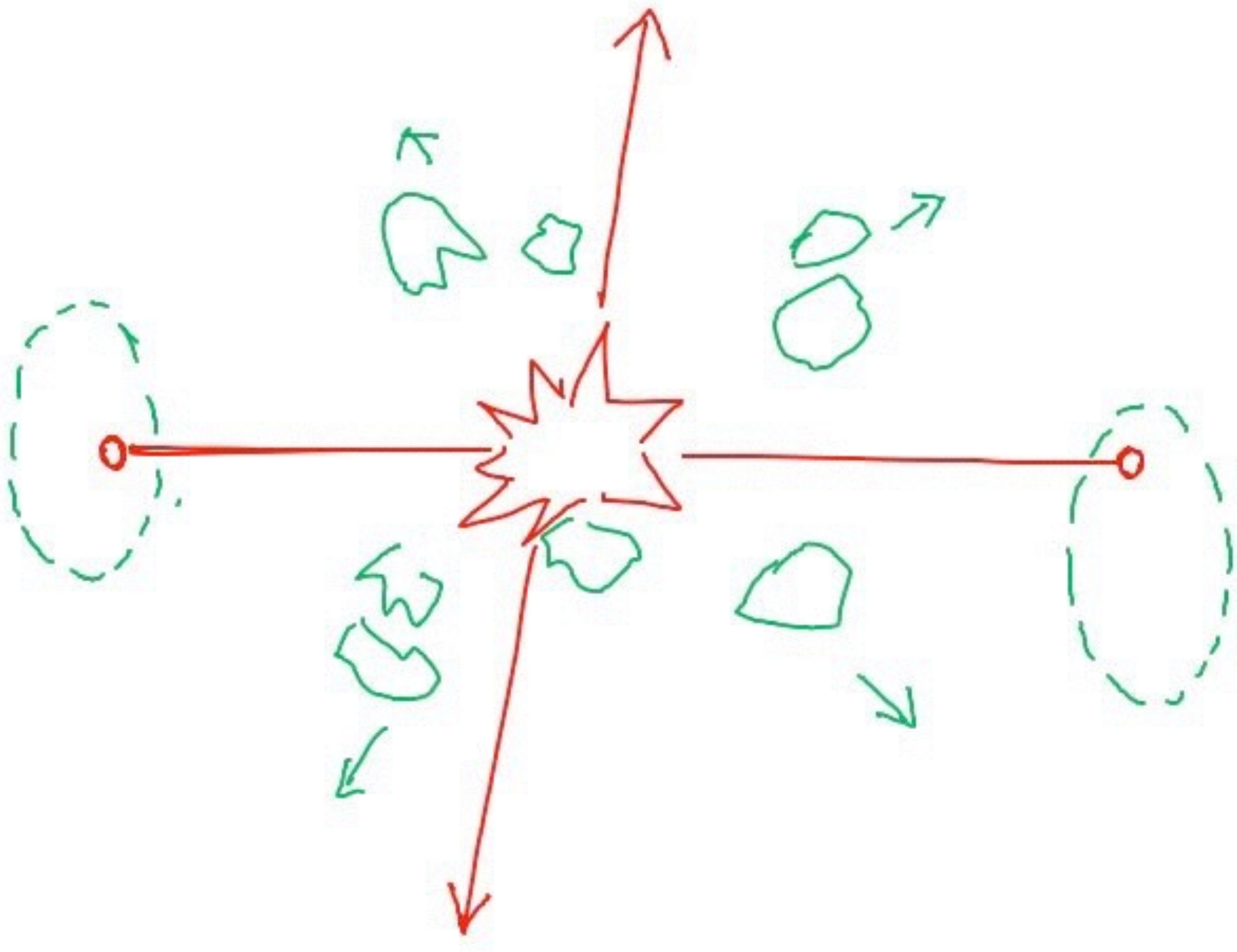
Partons:
gluon
valence: u, d
“sea”: qbar, s sbar, c, cbar, b, bbar

binding energy ~ GeV

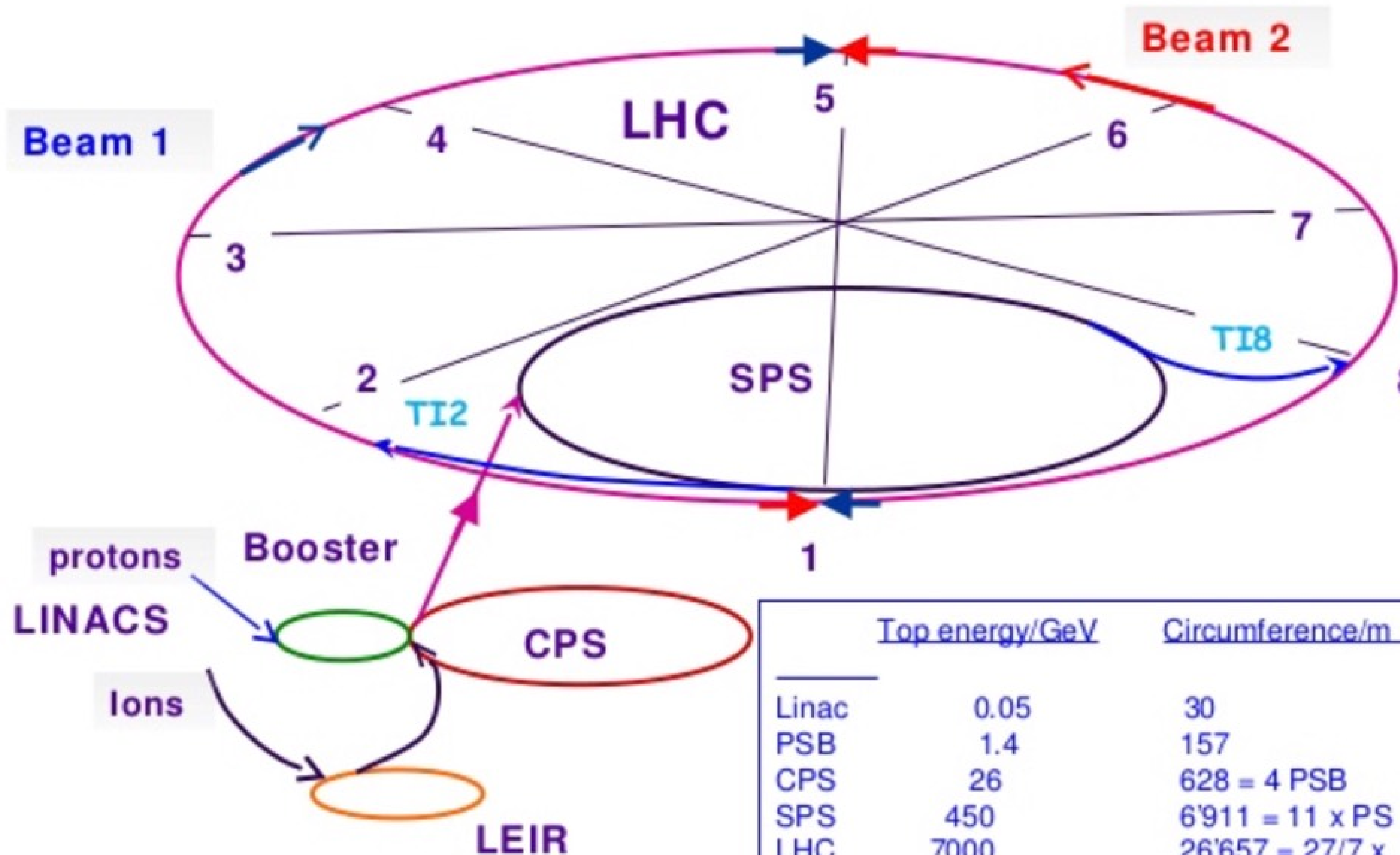
Most of the time



High energy collision rare



The Large Hadron Collider (LHC)



	Top energy/GeV	Circumference/m
Linac	0.05	30
PSB	1.4	157
CPS	26	628 = 4 PSB
SPS	450	6'911 = 11 x PS
LHC	7000	26'657 = 27/7 x SPS

Note the energy gain/machine of 10 to 20.
The gain is typical for the useful range of magnets.

Luminosity

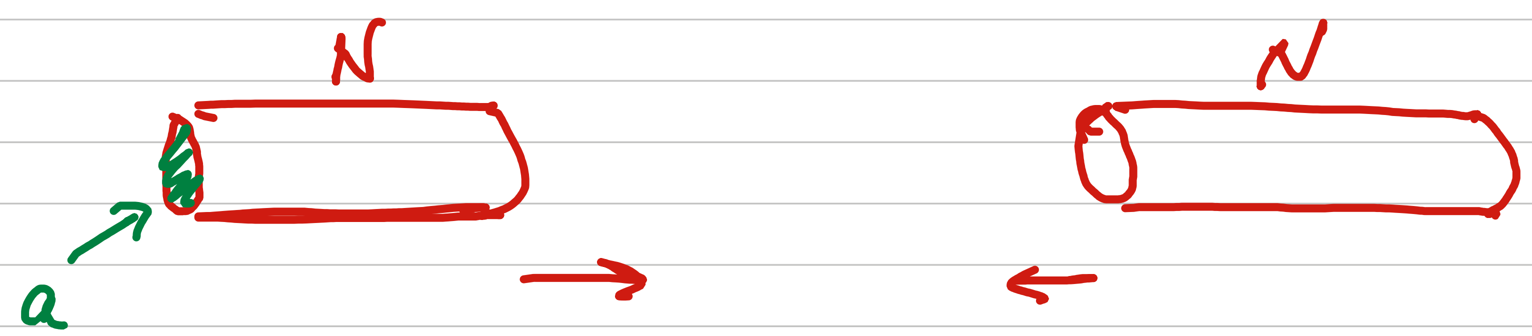
$$L \propto kN^2 f / a$$

f: revolution freq $\qquad f \sim 11.25$ kHz

N: # of protons in a bunch. $\qquad N \sim 10^{11}$

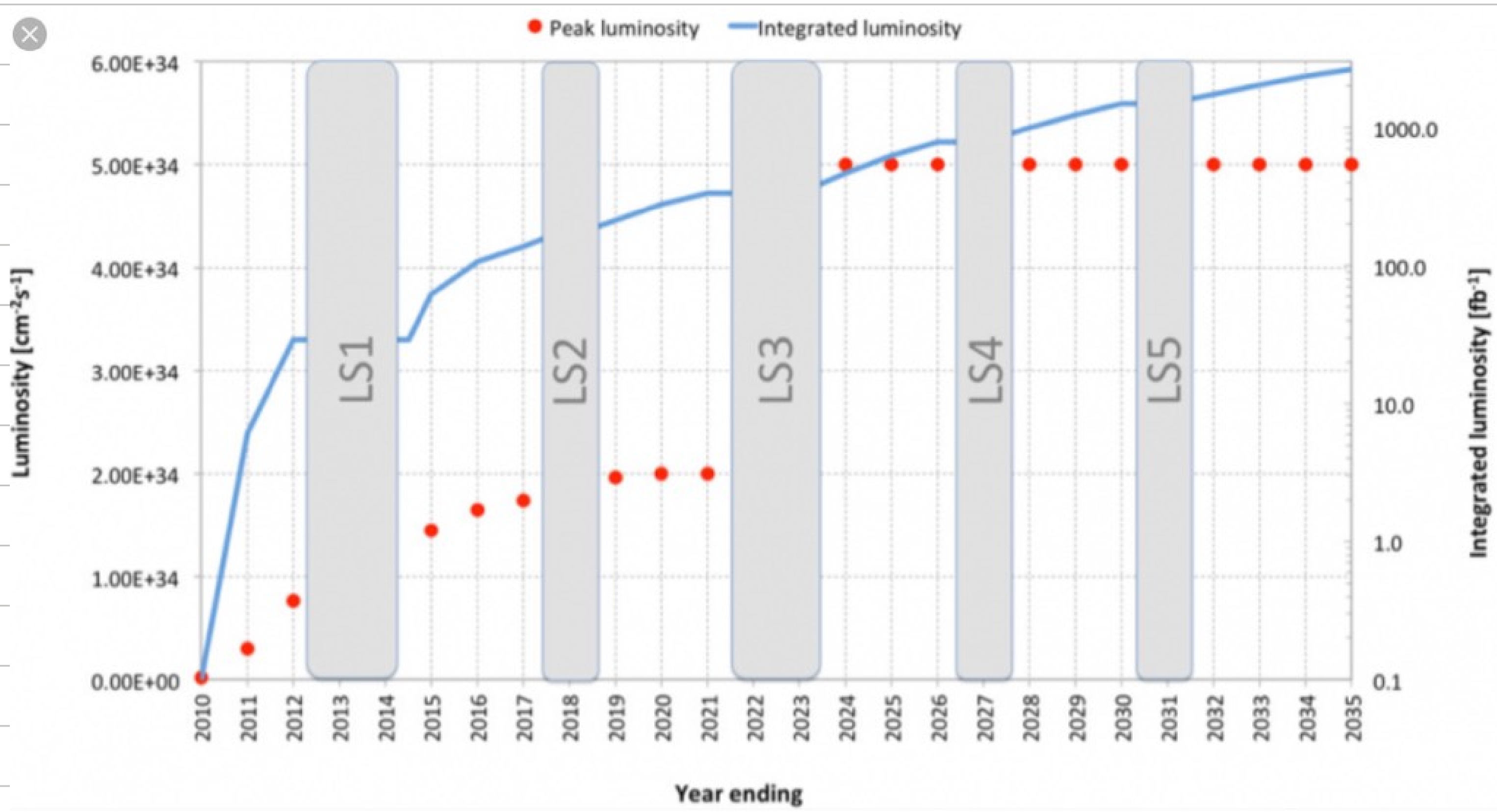
k: # of bunches $\qquad k = 2808$

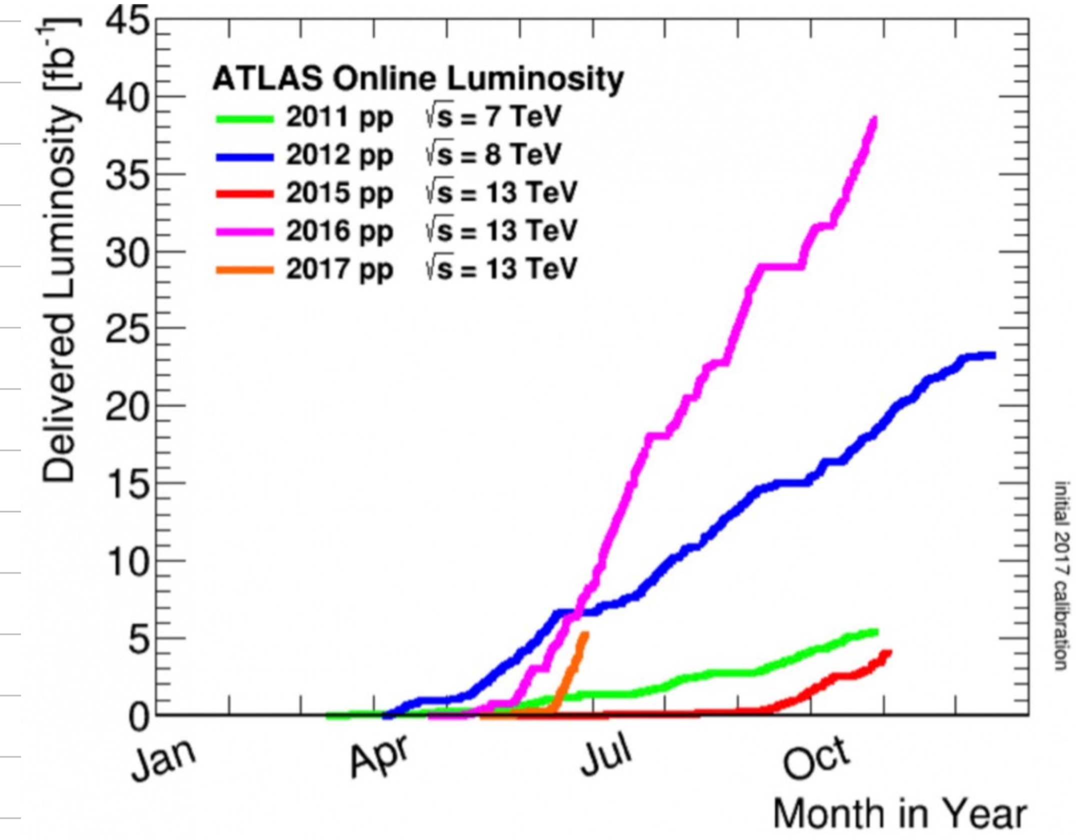
a: beam size (area) $\qquad A \sim \pi (16\,\mu m)^2$



events $= L \cdot \sigma$ $\qquad \sigma$: cross section.

LHC Luminosity

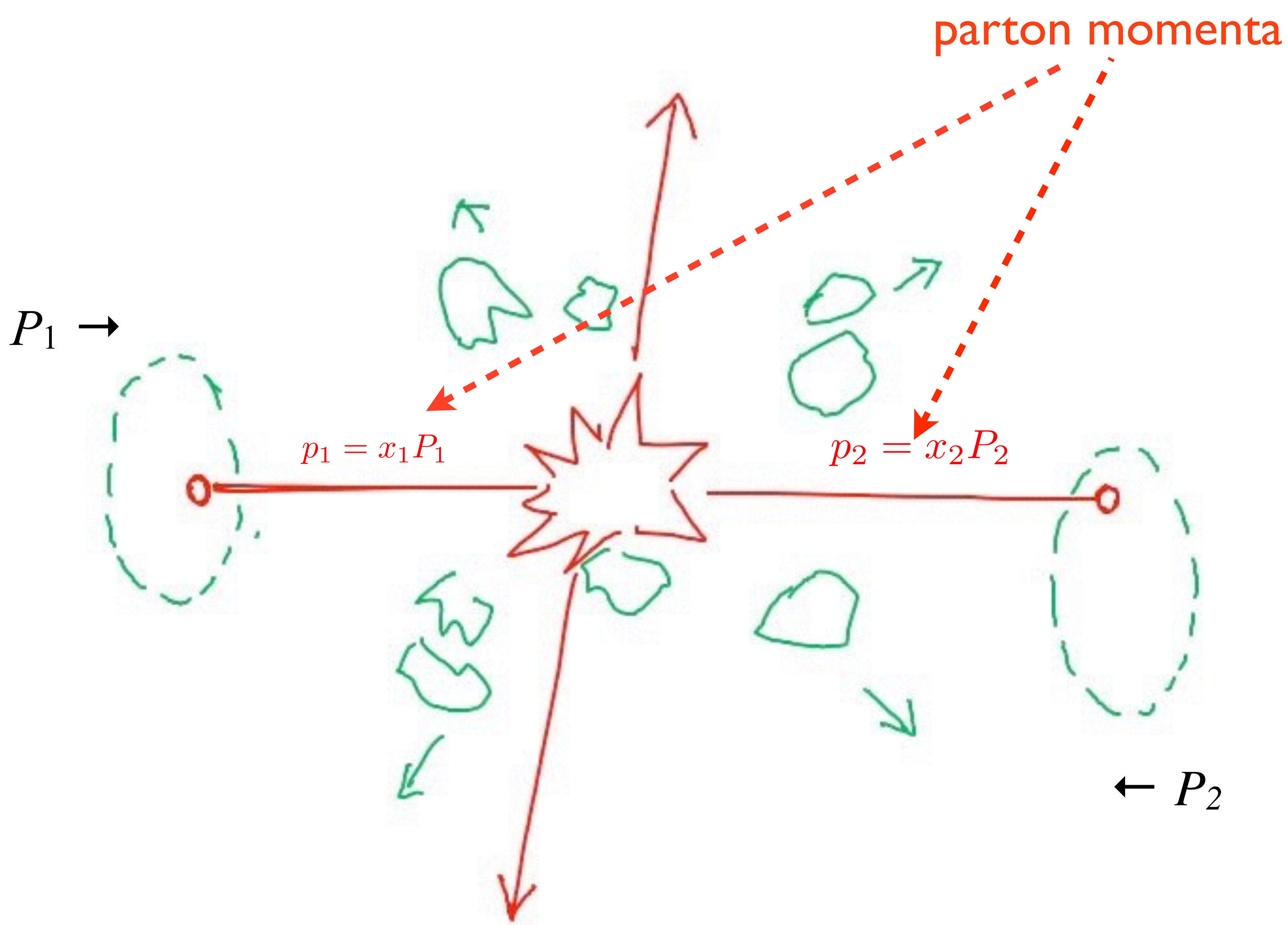




$$1\,\text{mb} \equiv 10^{-27}\,\text{cm}^2 = 2.56\,(\text{GeV})^{-2}$$

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

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

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

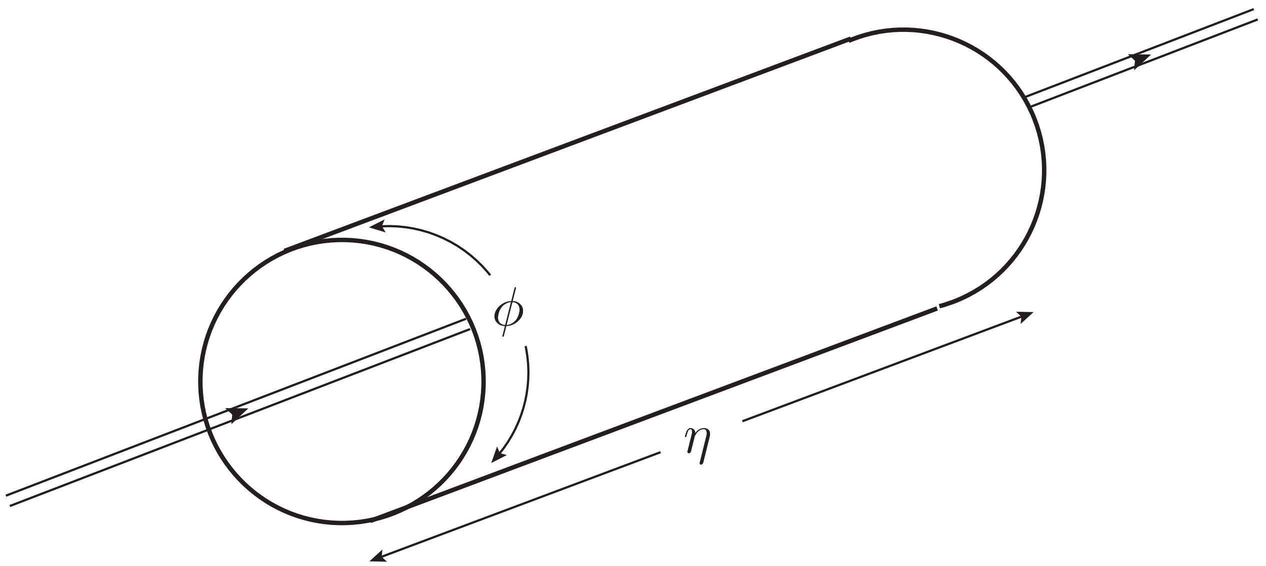
$$\to \frac{d}{dy} = \frac{d}{dy'}$$

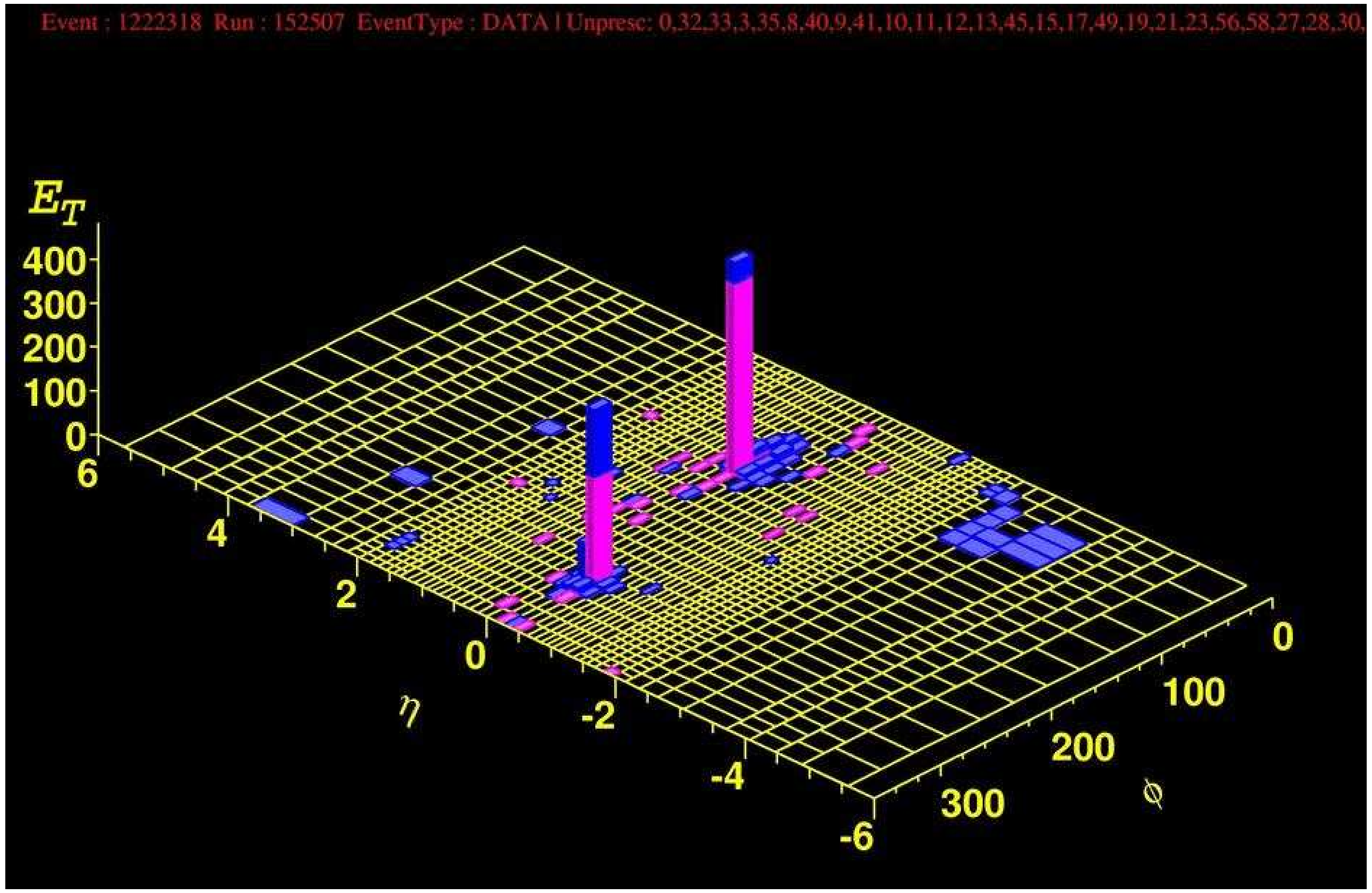
In the massless limit : pseudo-rapidity

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

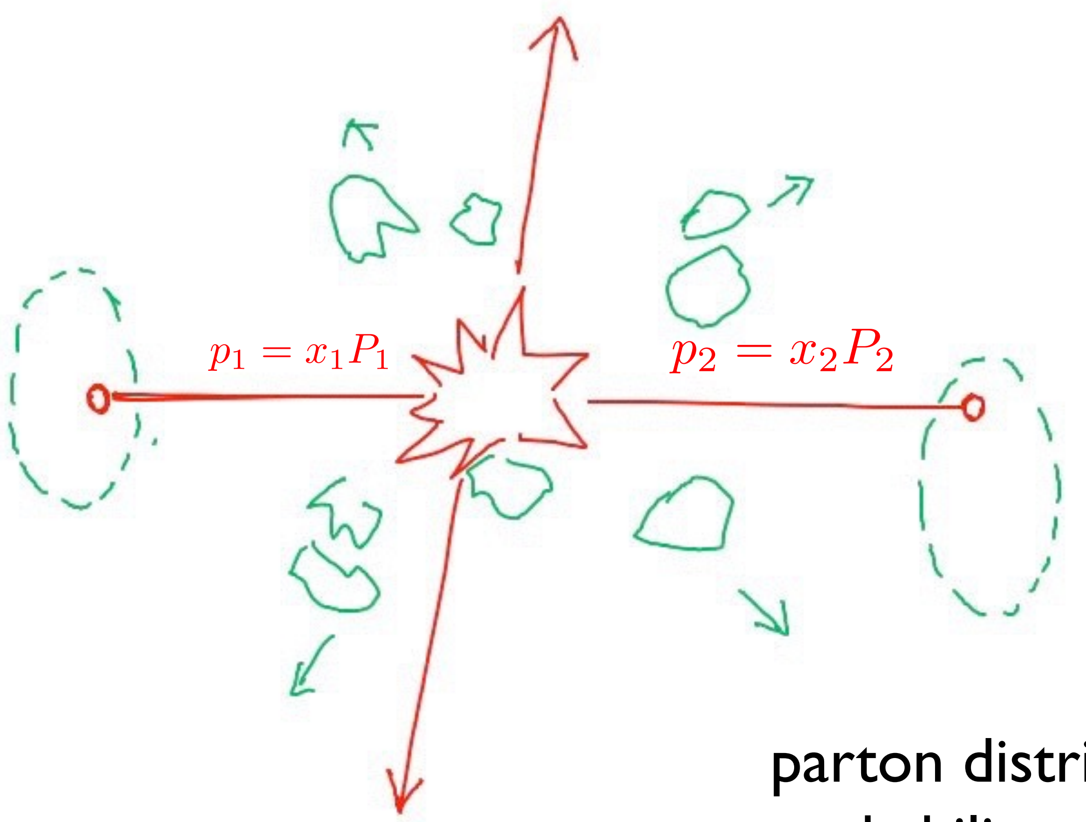
Coordinate System

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





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

$$a + b \rightarrow \ldots$$

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

$\hat{\sigma} \sim \frac{1}{M^2}$

M: scale of hard interaction.

PDF, long distance
Universal

"Hard scattering"
Short distance
Partonic cross section
Calculable

Factorization!

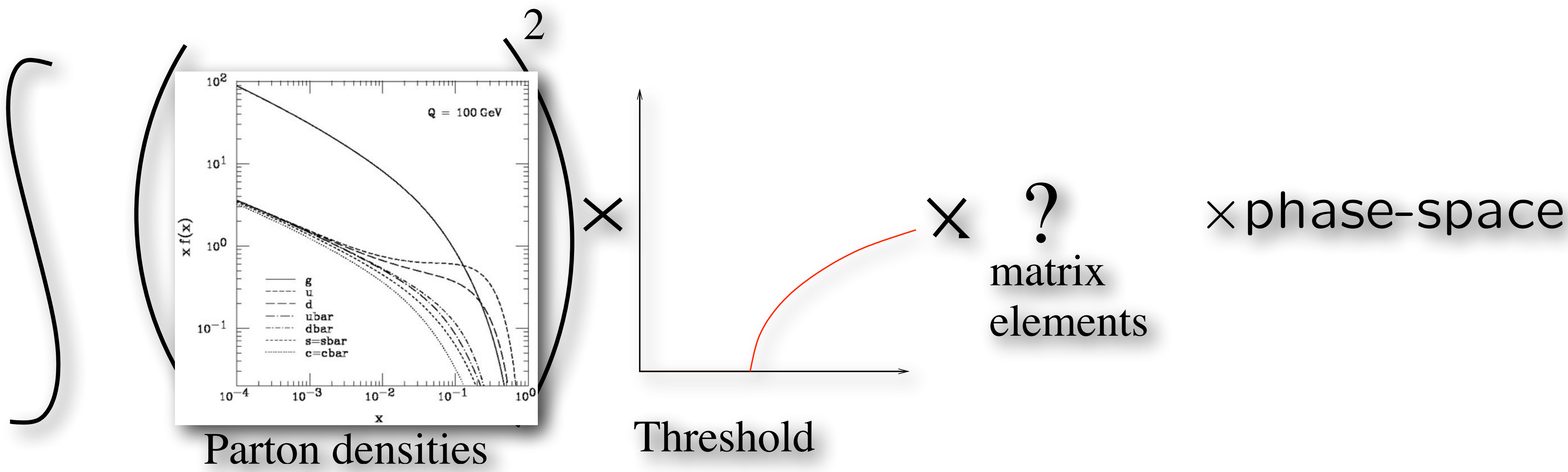
Intuitively, make sense:
short distance physics should not "know" about long distance physics.

In practice, very difficult to prove.

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

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

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

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

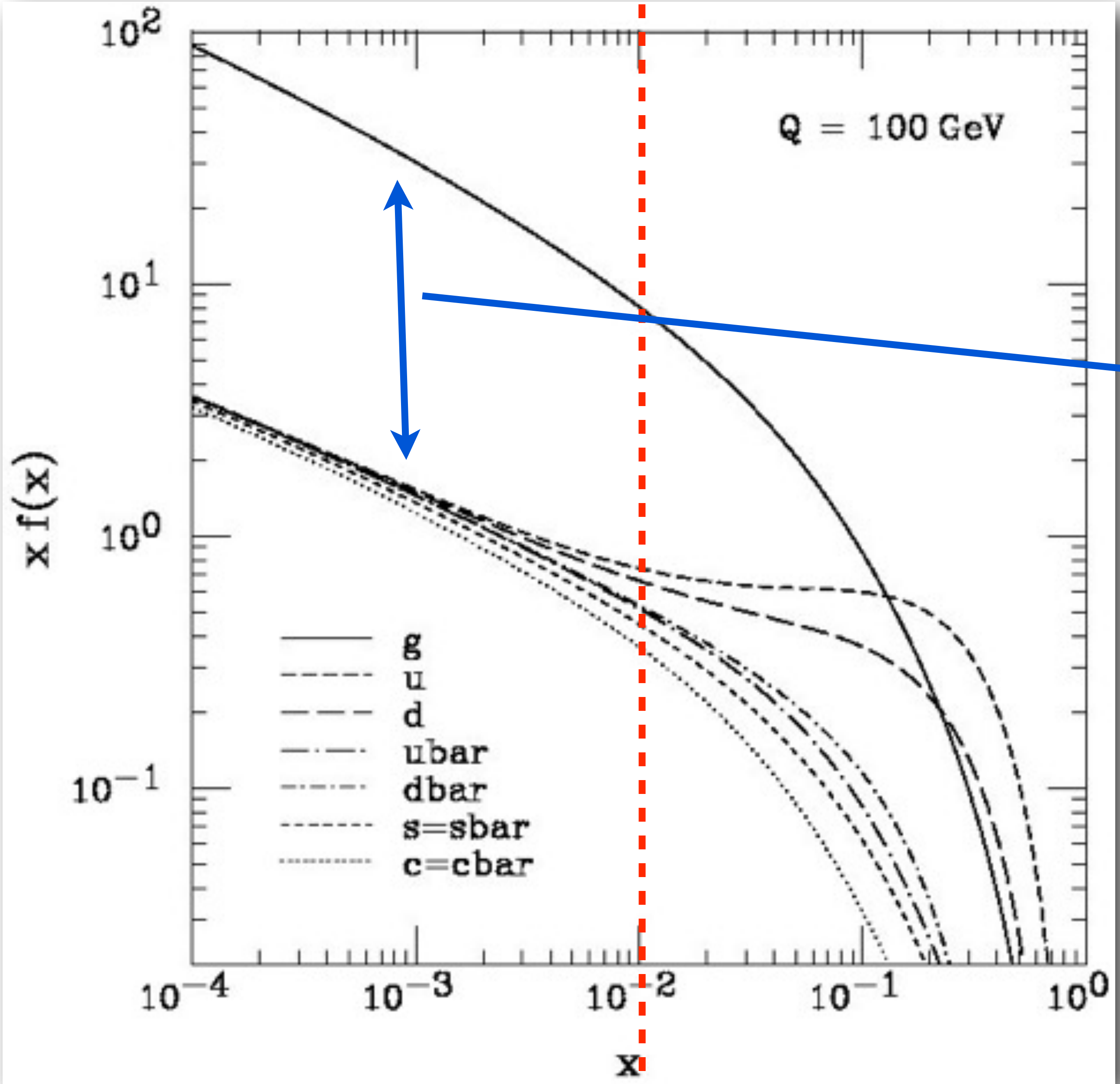
Starting with $\quad \frac{d^2\sigma(a, b \to \cdots)}{dx_1 dx_2} = \sum_{a,b} f_a(x_1) f_b(x_2) \hat{\sigma}(a, b \to \cdots)$

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

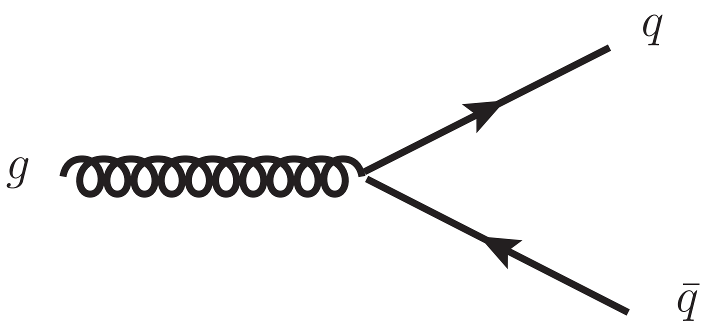
We obtain:

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

Parton Distribution Function



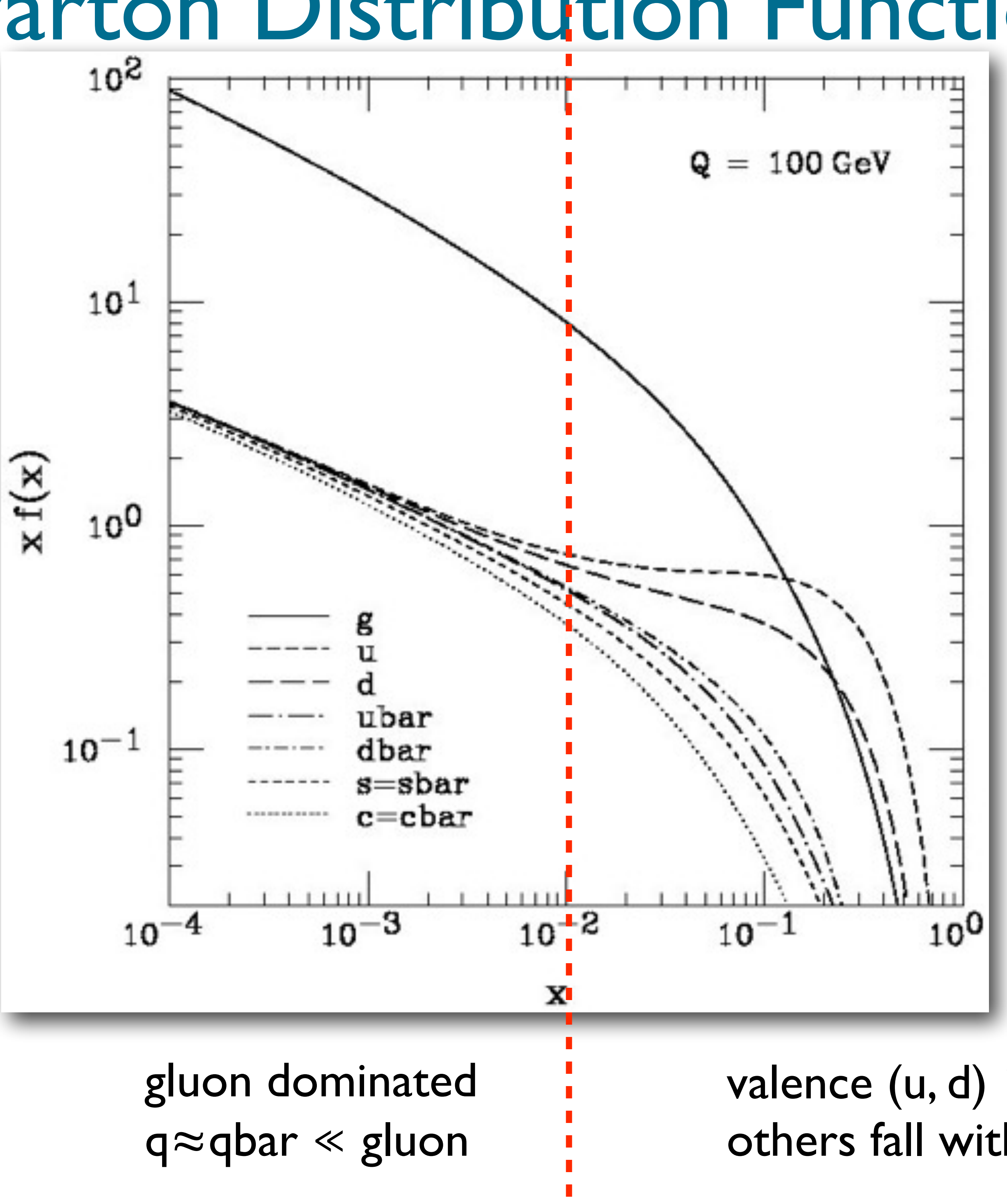
$$x = \frac{p_{\rm parton}}{P_{\rm proton}}$$



gluon splitting
main "source" for quark PDF

gluon dominated
q≈qbar ≪ gluon

Parton Distribution Function



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

gluon dominated
q≈qbar ≪ gluon

valence (u, d) ↑
others fall with gluon

Parton luminosity

$$\sigma = \int dx_1 \int dx_2 \; f_1(x_1)\, f_2(x_2)\; \hat{\sigma}$$

define $\tau = x_1 x_2$ $\quad x = x_1$ $\quad \frac{\hat{s}}{s} = \tau$

Jacobian for variable change

$$\frac{\partial(x_1, x_2)}{\partial(\tau, x)} = \frac{1}{x}$$

$$\sigma = \int d\tau \underbrace{\int_x^1 dx \, \frac{1}{x} f_1(x)\, f_2\!\left(\frac{\tau}{x}\right)}_{\text{parton luminosity } L(\tau)} \hat{\sigma}$$

Another parameterization, parton luminosity

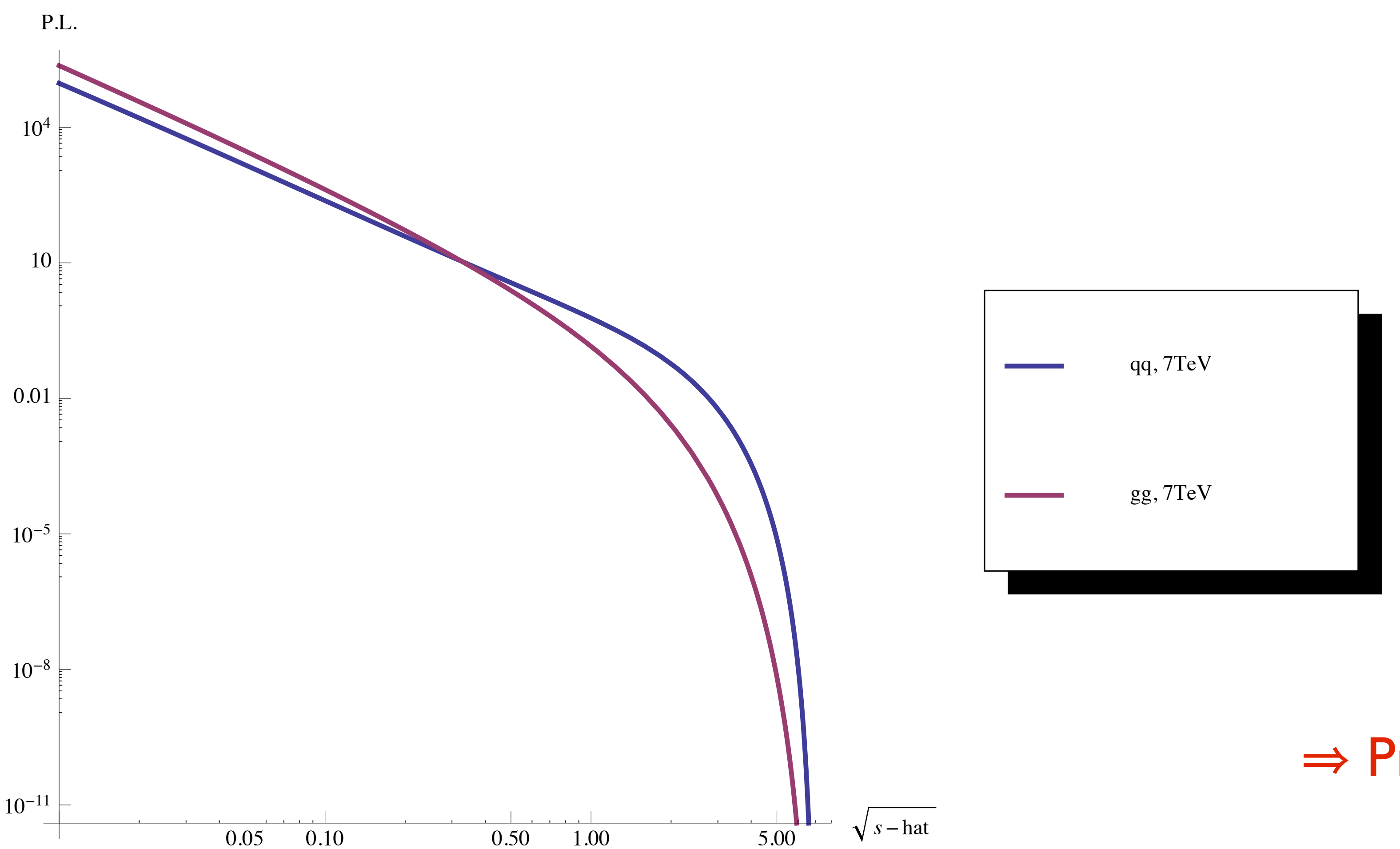
- The cross section can be written as

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

parton luminosity

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

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



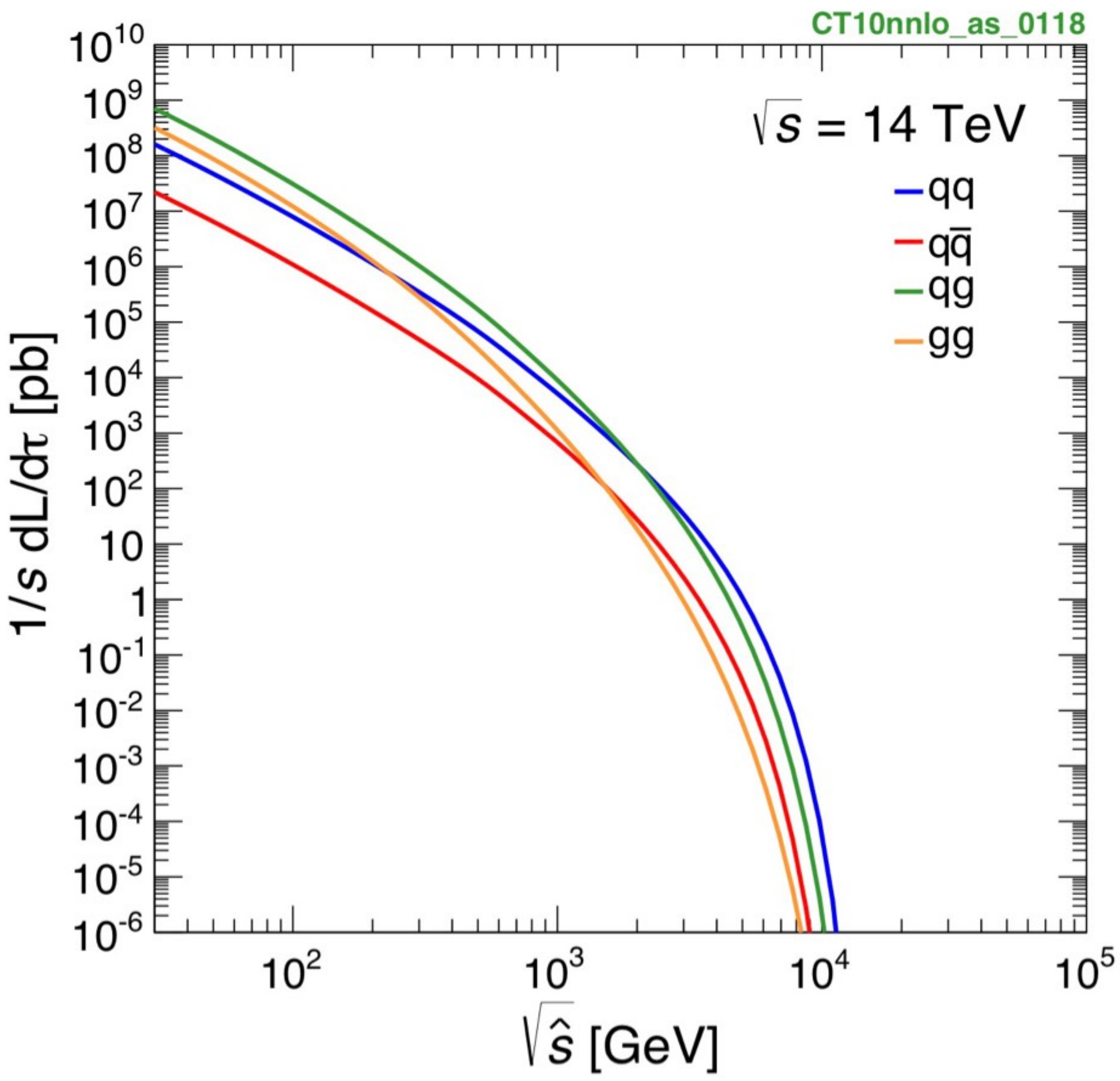
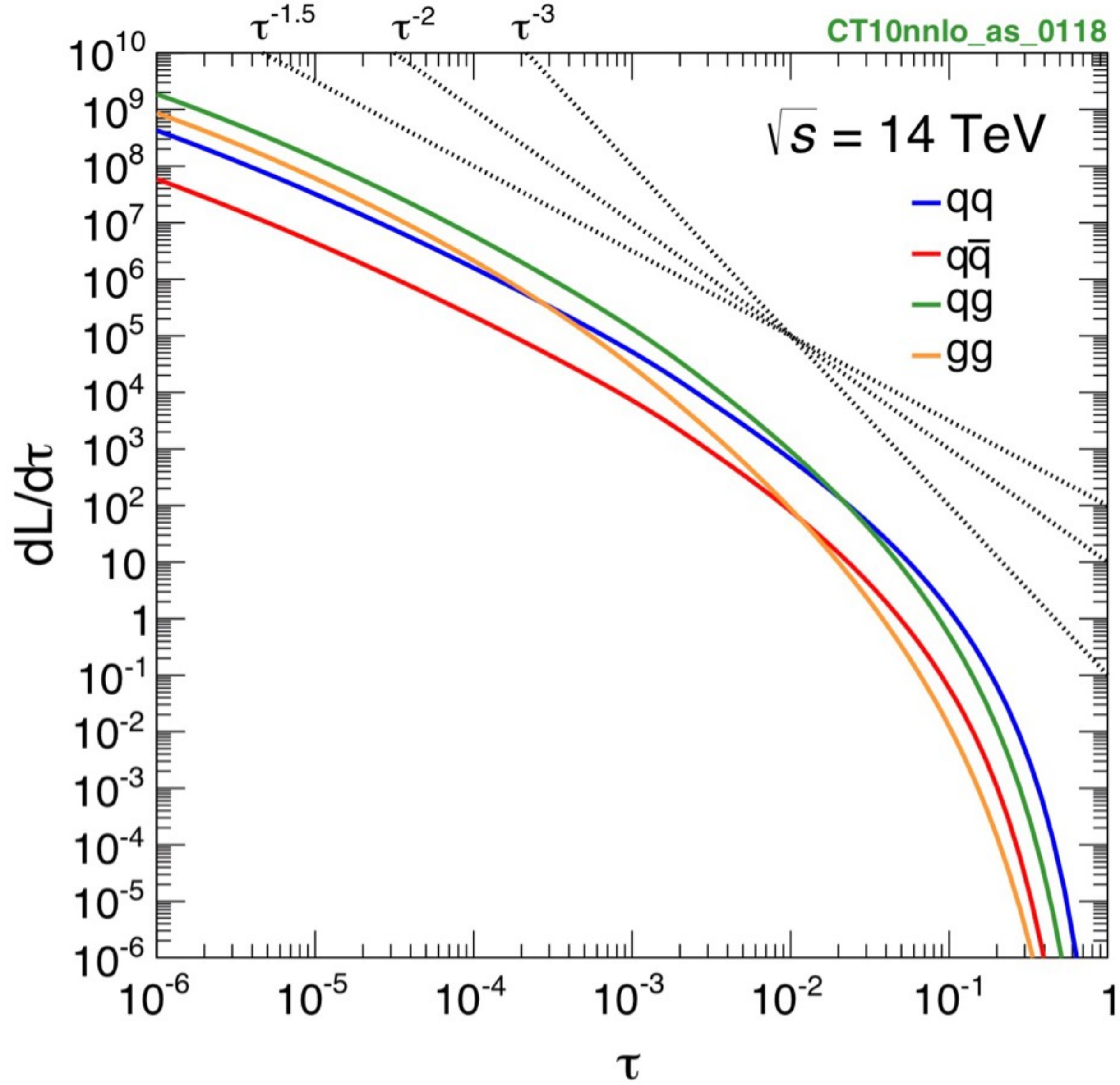
TeV, log scale

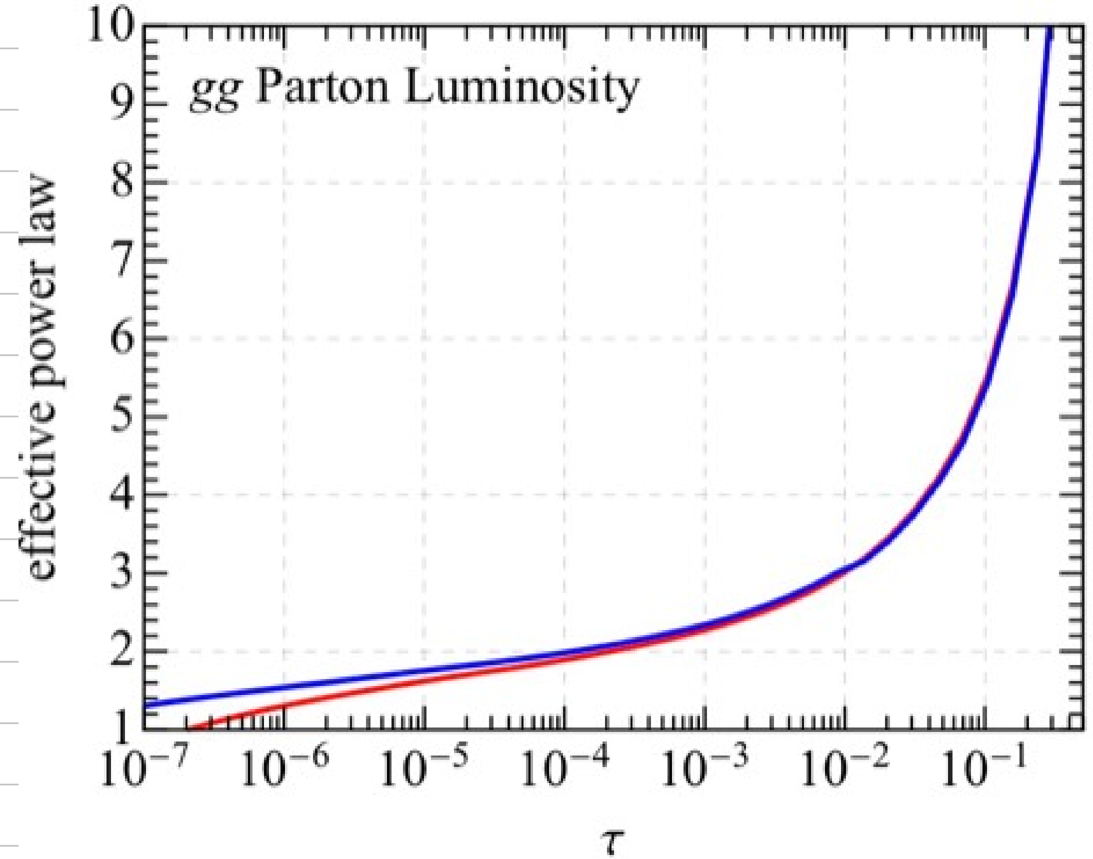
Very sharp falling

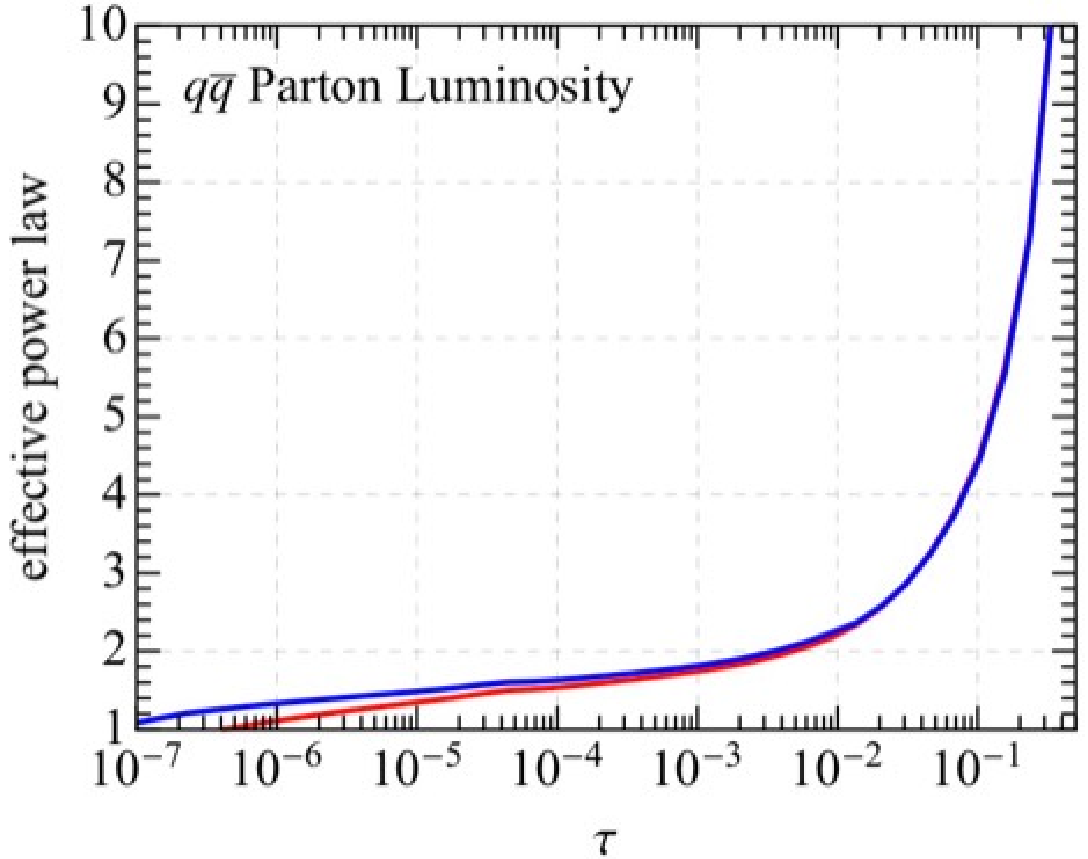
$$\propto \frac{1}{\tau^{3-3.5}}$$

Falls by a factor of 10 for every 600 GeV

⇒ Production dominantly on threshold


CT10nnlo_as_0118
$\sqrt{s}$ = 14 TeV
qq
$q\bar{q}$
qg
gg
1/s dL/dτ [pb]
$\sqrt{\hat{s}}$ [GeV]

CT10nnlo_as_0118
$\tau^{-1.5}$
τ^{-2}
τ^{-3}
$\sqrt{s}$ = 14 TeV
qq
$q\bar{q}$
qg
gg
dL/dτ
τ


gg Parton Luminosity
effective power law
τ
10
9
8
7
6
5
4
3
2
1
10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1}


$q\bar{q}$ Parton Luminosity
effective power law
τ
10
9
8
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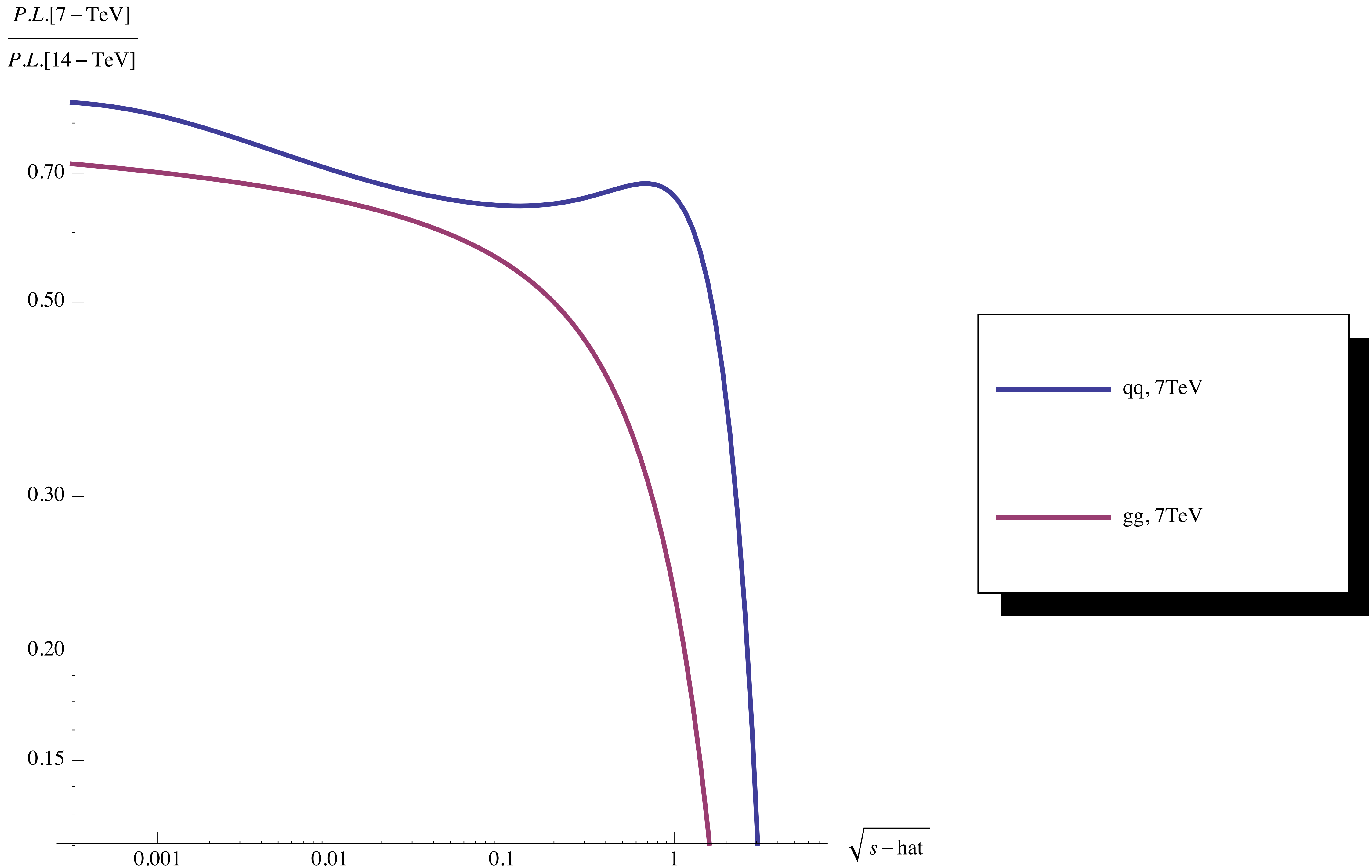
2
1
10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1}

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).

Rough estimates of discovery reach

$$\sigma \sim L_p \cdot \hat{\sigma} \sim \frac{1}{\tau^a}\hat{\sigma}$$

$$L_p : \text{ parton luminosity}, \ \hat{\sigma} : \text{ parton cross section}$$

Production of new physics particle of mass M

Fast falling parton luminosity ⇒

dominant contribution from
parton cross section near threshold

$$\hat{s} \sim M^2 \to \tau \sim \frac{M^2}{S}$$

$$\hat{\sigma} \sim \frac{1}{M^2}$$

Number of new physics particle produced:

$$N = \sigma \cdot \mathcal{L}$$
$$\mathcal{L} : \text{ luminosity}$$

Discovery reach

Consider 2 colliders.
Collider 1: $E_{cm} = E_1$, or $S_1 = E_1^2$. Collider 2: $E_{cm} = E_2$, or $S_2 = E_2^2$.

$E_2 > E_1$

Reach for new physics at these 2 colliders
Collider 1: M_1 . Collider 2: M_2.

Assume the reach is obtained from the same number of signal events

$$\frac{1}{\tau_1^a}\frac{1}{M_1^2}\mathcal{L}_1 = \frac{1}{\tau_2^a}\frac{1}{M_2^2}\mathcal{L}_2$$

used $\hat{\sigma} \sim \frac{1}{M^2}$

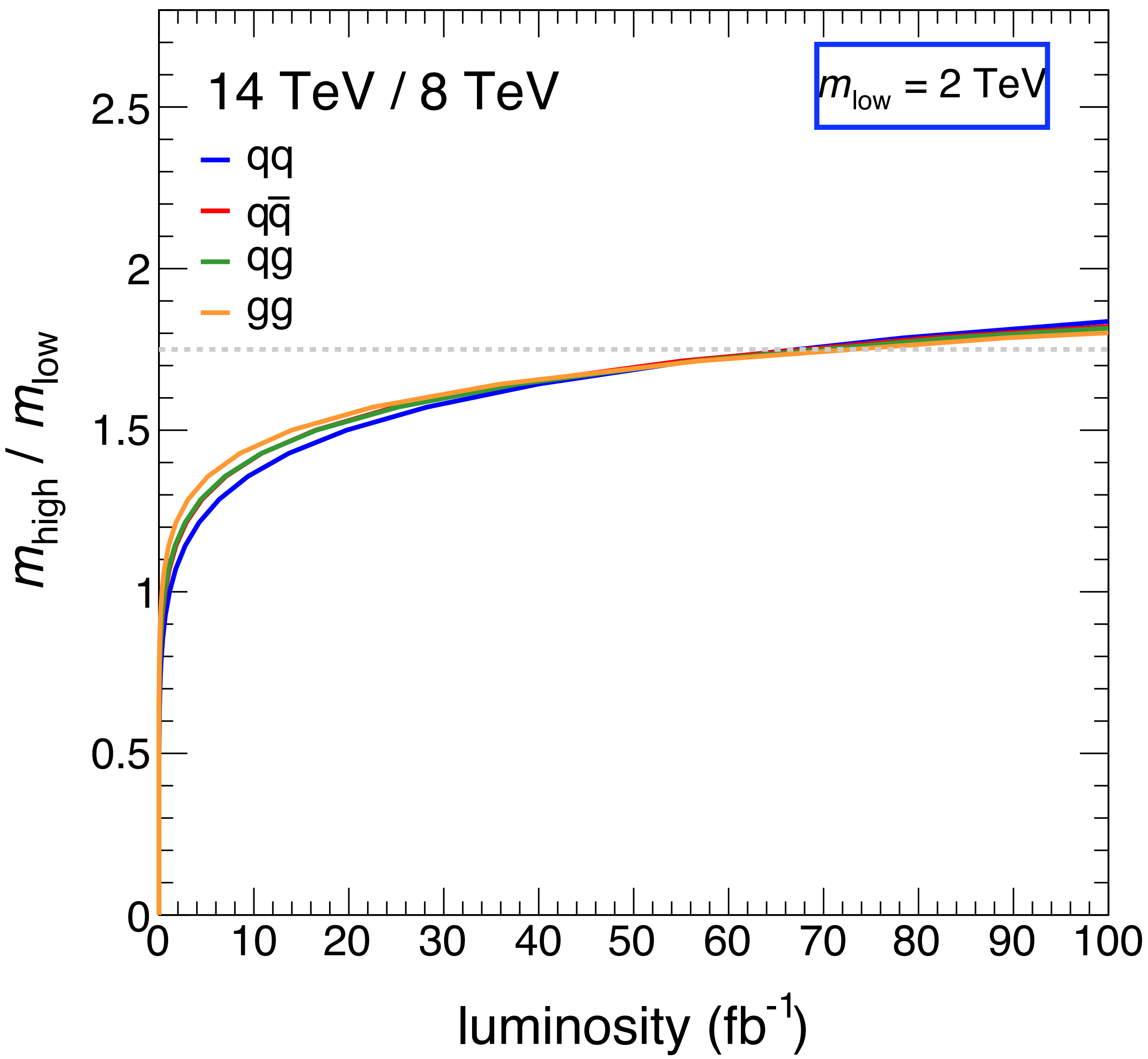
We have

$$\frac{M_2}{M_1} = \left(\frac{S_2}{S_1}\right)^{1/2}\left(\frac{S_1}{S_2}\frac{\mathcal{L}_2}{\mathcal{L}_1}\right)^{\frac{1}{2a+2}}$$

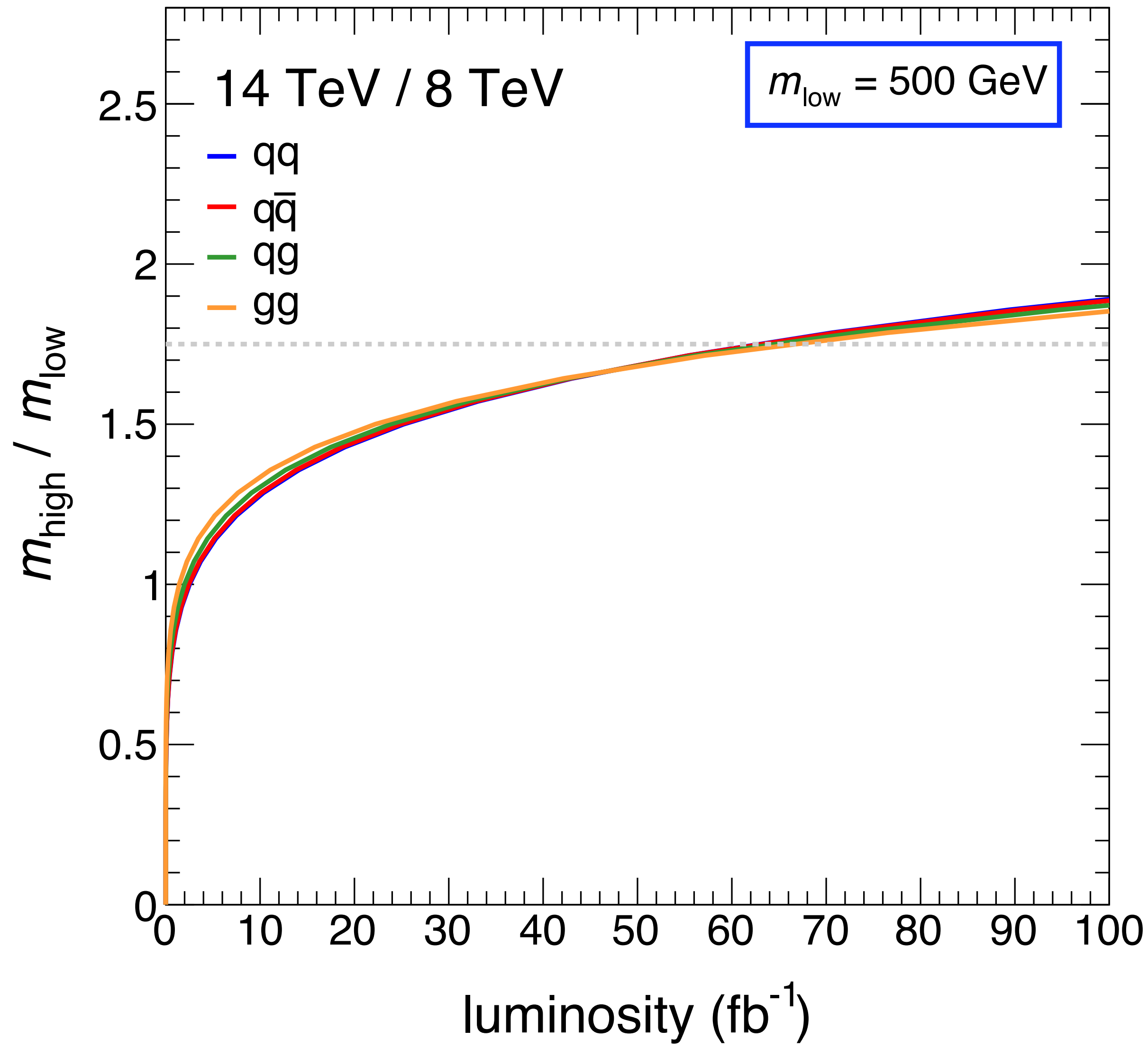
used $\hat{s} \sim M^2 \to \tau \sim \frac{M^2}{S}$

As data accumulates

Run 1 limit 2 TeV, e.g. pair of 1 TeV gluino.



500 GeV, e.g. pair of 250 GeV electroweak-ino



Rapid gain initial 10s fb^{-1}, slow improvements afterwards.

Reaching the "slow" phase after Moriond 2017

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

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

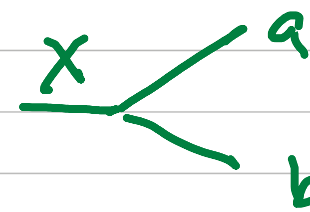
- For example

$$\ldots \text{ variables } \subset \{0, 1\}$$

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

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

2-body



$$X_\mu = a_\mu + b_\mu.$$

X may or may not be a particle.

$$d\Pi_2 = (2\pi)^4 \delta^{(4)}(X_\mu - a_\mu - b_\mu) \frac{d^3\vec{a}}{(2\pi)^3 2a_0} \frac{d^3\vec{b}}{(2\pi)^3 2b_0}$$

$$= \frac{1}{8\pi} \lambda^{1/2}\left(1, \frac{a^2}{X^2}, \frac{b^2}{X^2}\right) \frac{d\Omega}{4\pi} = \frac{1}{4\pi} \frac{|\vec{p}_a|}{X} \frac{d\Omega}{4\pi}$$

$$\lambda(x,y,z) = x^2 + y^2 + z^2 - 2xy - 2yz - 2xz$$

Assume: $a^2 = b^2 = m^2$ for simplicity

$$\lambda^{1/2} = \left(1 - \frac{4m^2}{X^2}\right)^{1/2}$$

Near threshold $\quad X^2 \doteq (2m + \delta)^2$

$$\lambda^{1/2} \simeq \left(\frac{\delta}{2m}\right)^{1/2} + \cdots$$

$$d\Pi_2 \propto \delta^{1/2}$$

3 body.

$$Y_\mu = p_{1\mu} + p_{2\mu} + p_{3\mu}$$

$$d\Pi_3 = (2\pi)^4 \delta^{(4)}(Y - p_1 - p_2 - p_3) \prod_{i=1}^{3} \frac{d^3\vec{p}_i}{(2\pi)^3\, 2p_{i0}}$$

Decompose $\quad Y = X + p_3 \qquad X = p_1 + p_2$

$$d\Pi_3 = \frac{1}{2\pi}\, d\Pi_2(Y \to X\, p_3)\, d\Pi_2(X \to p_1, p_2)\, dX^2$$

$$m_1 + m_2 \le \sqrt{X^2} \le \sqrt{Y^2} - m_3$$

Way above threshold, energy is the only dim-ful quantity

$$d\Pi_3 \sim \frac{1}{16\pi^2} E^2\, d\Pi_2$$ suppressed w.r.t. 2-body

Near threshold. $\quad Y^2 \sim (3m + \delta)^2$

$$d\Pi_2(Y \to X\, p_3) \sim d\Pi_2(x \to p_1\, p_2) \sim \delta^{1/2}$$

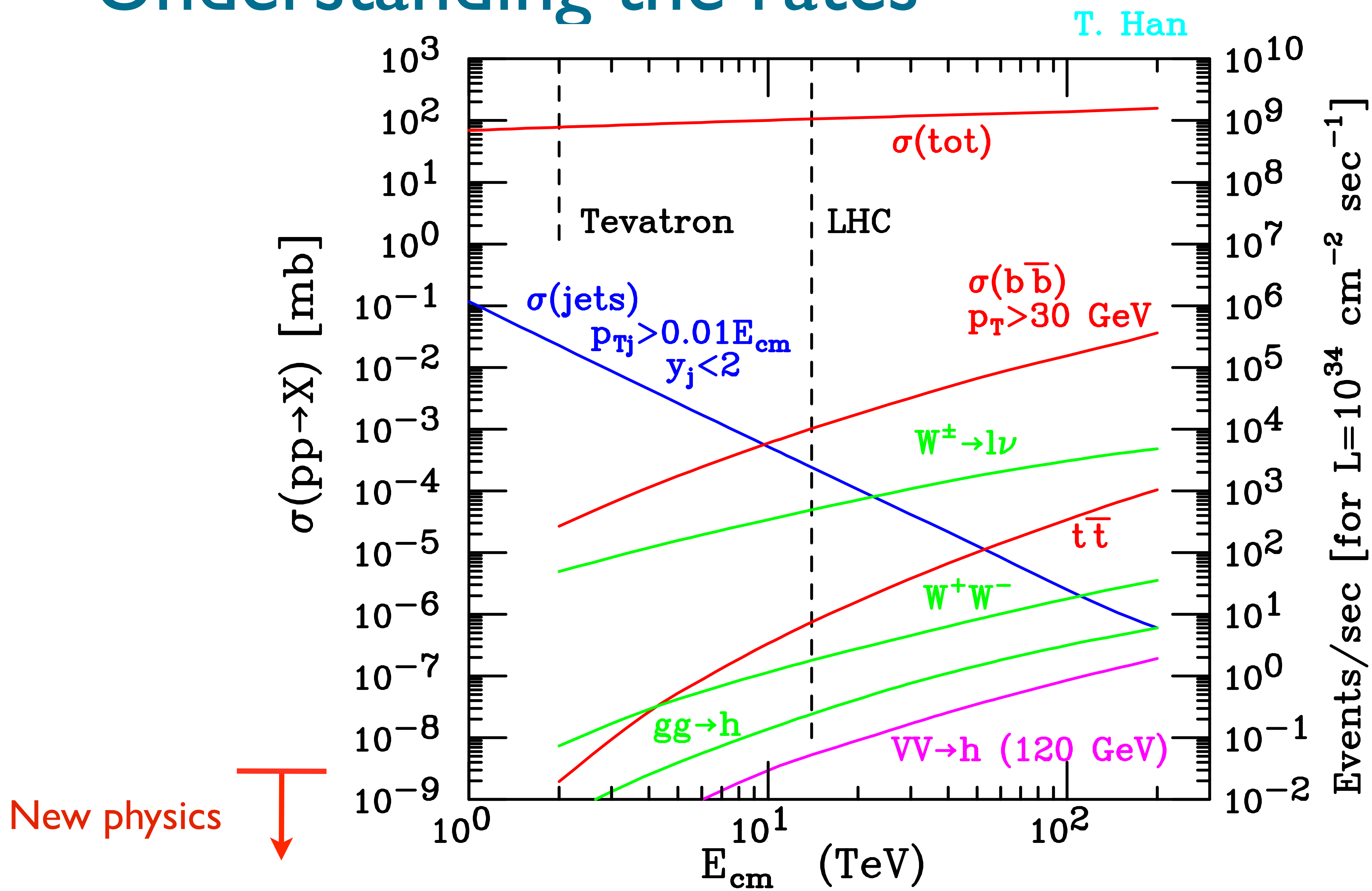
$$\int dX^2 \sim m\delta$$

$d\Pi_3 \propto \delta^2 \qquad$ open slower than 2-body

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 $W^+ W^-$,

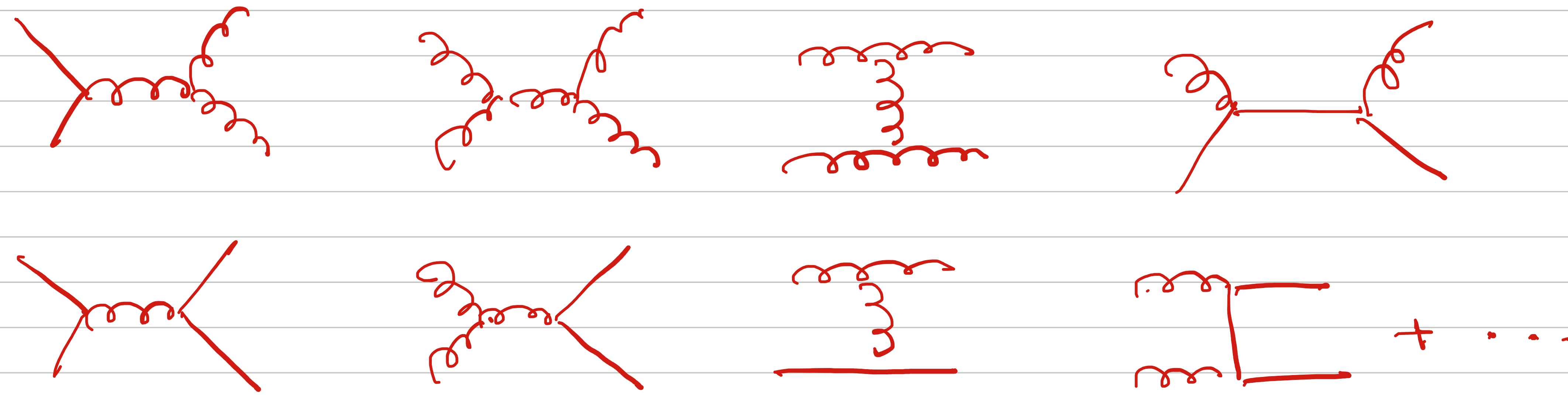
The relevant factors are:

top is twice as heavy as W (2 times higher threshold)

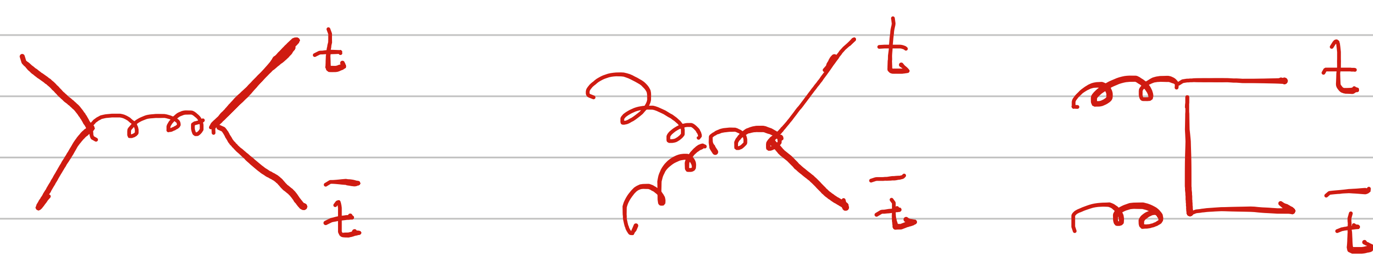
α_s^2 vs α_w^2

ttbar is gg dominated, WW is qqbar.

dijet

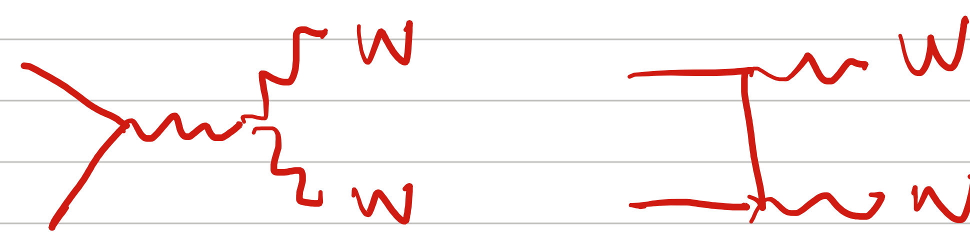


$t\bar{t}$

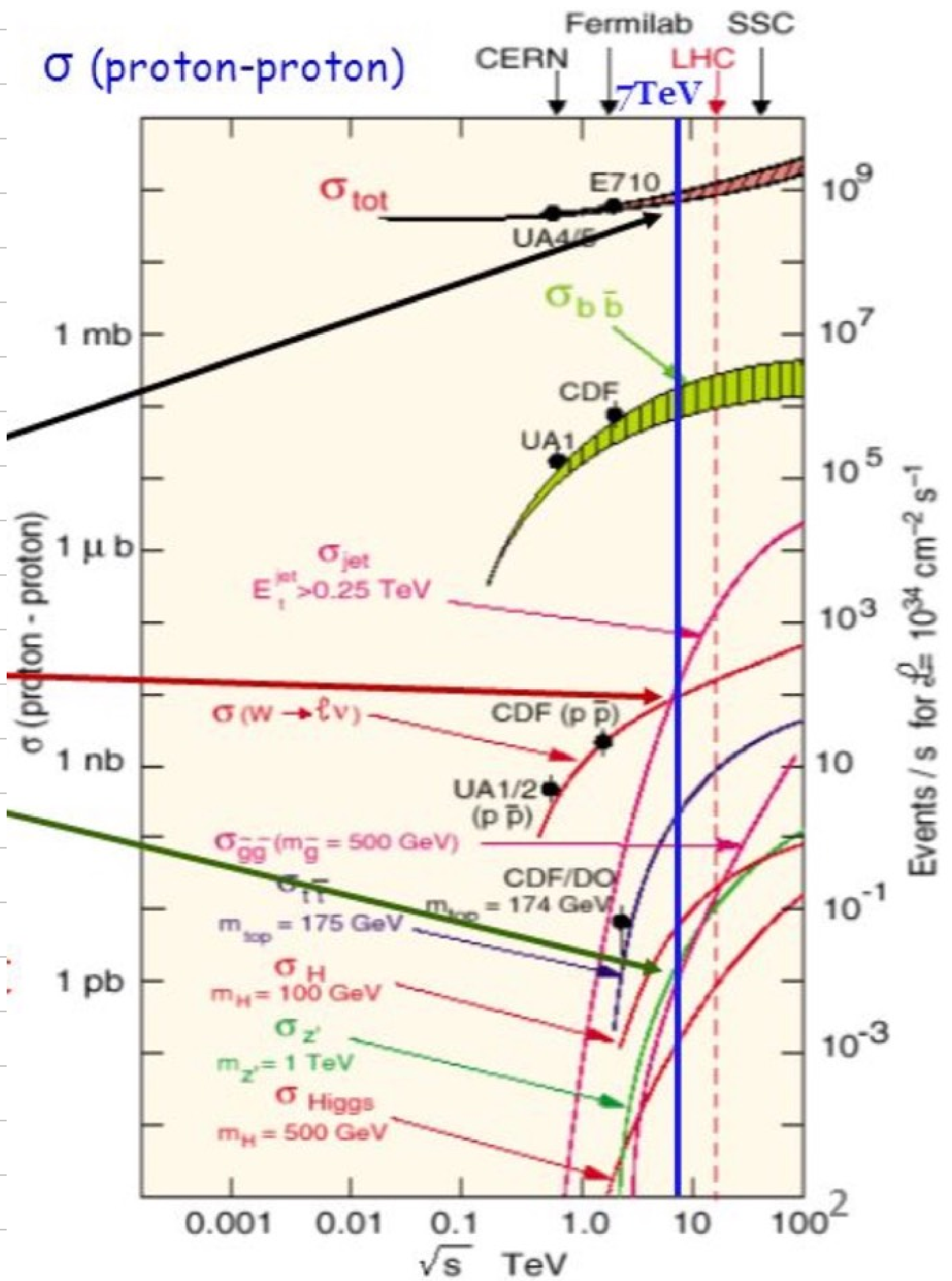


W

WW



h



$pp \to X$

X:

$W \to \ell\nu$	20 nb
(W inclusive	100 nb)
$Z \to \ell^+\ell^-$	2 nb
$t\bar{t}$	900 pb
h	20 pb
WW	100 pb
QCD di-jet $P_T > 250$ GeV	100 nb

Qualitative understanding of SM rates

	$t\bar{t}$	WW
PDF	gg ...	$q\bar{q}$
coupling	α_s^2	α_W^2
mass threshold	350	160

$gg(350) \lesssim q\bar{q}(160)$

$\alpha_s^2 \sim 10\, \alpha_W^2$

$\sigma_{t\bar{t}} \sim \sigma_{WW}$

	W	h
PDF	$q\bar{q}$	gg
couplin'	α_W	$\left(\frac{1}{16\pi^2}\right)^2 \alpha_s^2$
mass threshold	80	125

$q\bar{q}(80) \sim \frac{1}{5}\, gg(125)$

$\alpha_W \sim 3\times10^4 \left(\frac{1}{16\pi^2}\right)^2 \alpha_s^2$

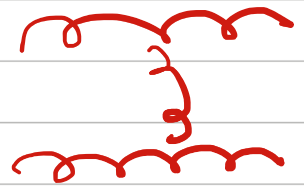
$\sigma_W \sim 5\times10^3\, \sigma_h$.

dijet vs $t\bar{t}$

$\sigma(\text{dijet}, p_T^j > 250) \sim 100\ \sigma_{t\bar{t}}$

- Many more diagrams for di-jet. $\mathcal{O}(10)$ enhancement

- Forward singularity in di-jet



etc.

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

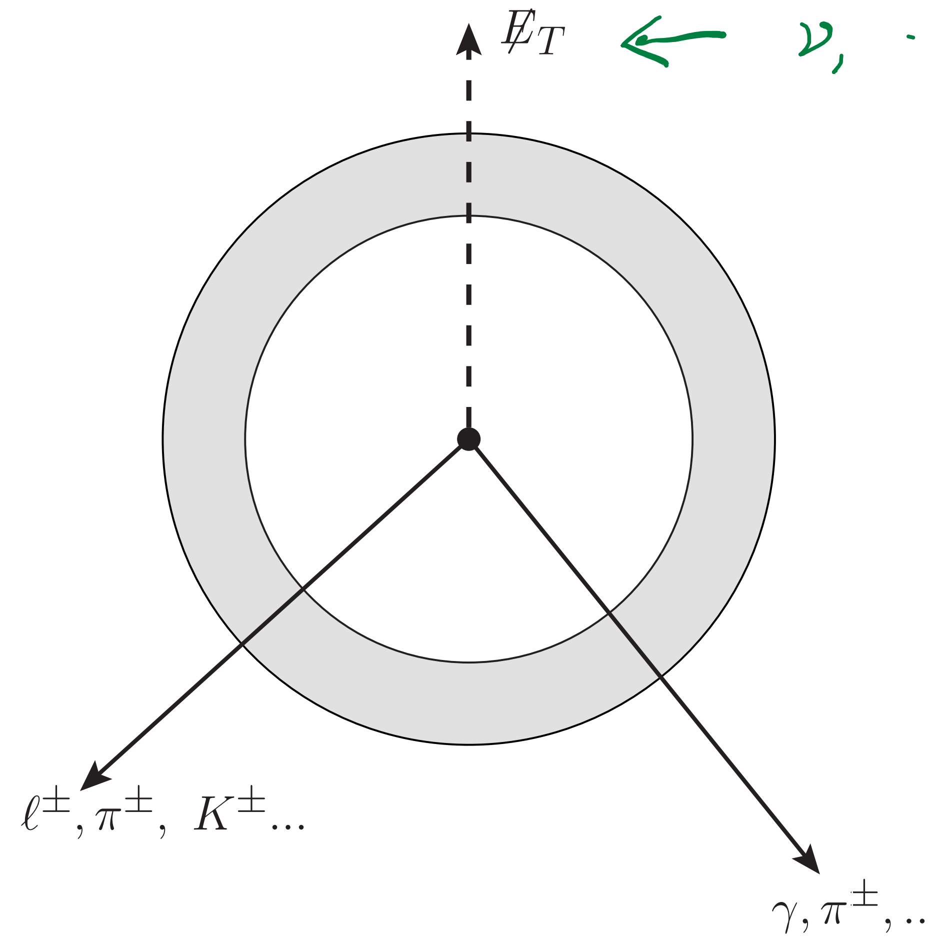
- p p collider, "prefers" to produce lighter states.
- Production rates scale roughly as $\sigma_{pp\to M} \sim \frac{1}{M^6}$
- TeV new physics $M_{\rm NP} \sim 5 - 10 \times M_{\rm SM(W,Z,t,...)}$
  - $\sigma_{\rm SM} \geq 10^6 \times \sigma_{\rm NP}$
- Dominated by QCD: A messy environment.
- Need: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

Being produced does not mean we can see them!

Final state Objects

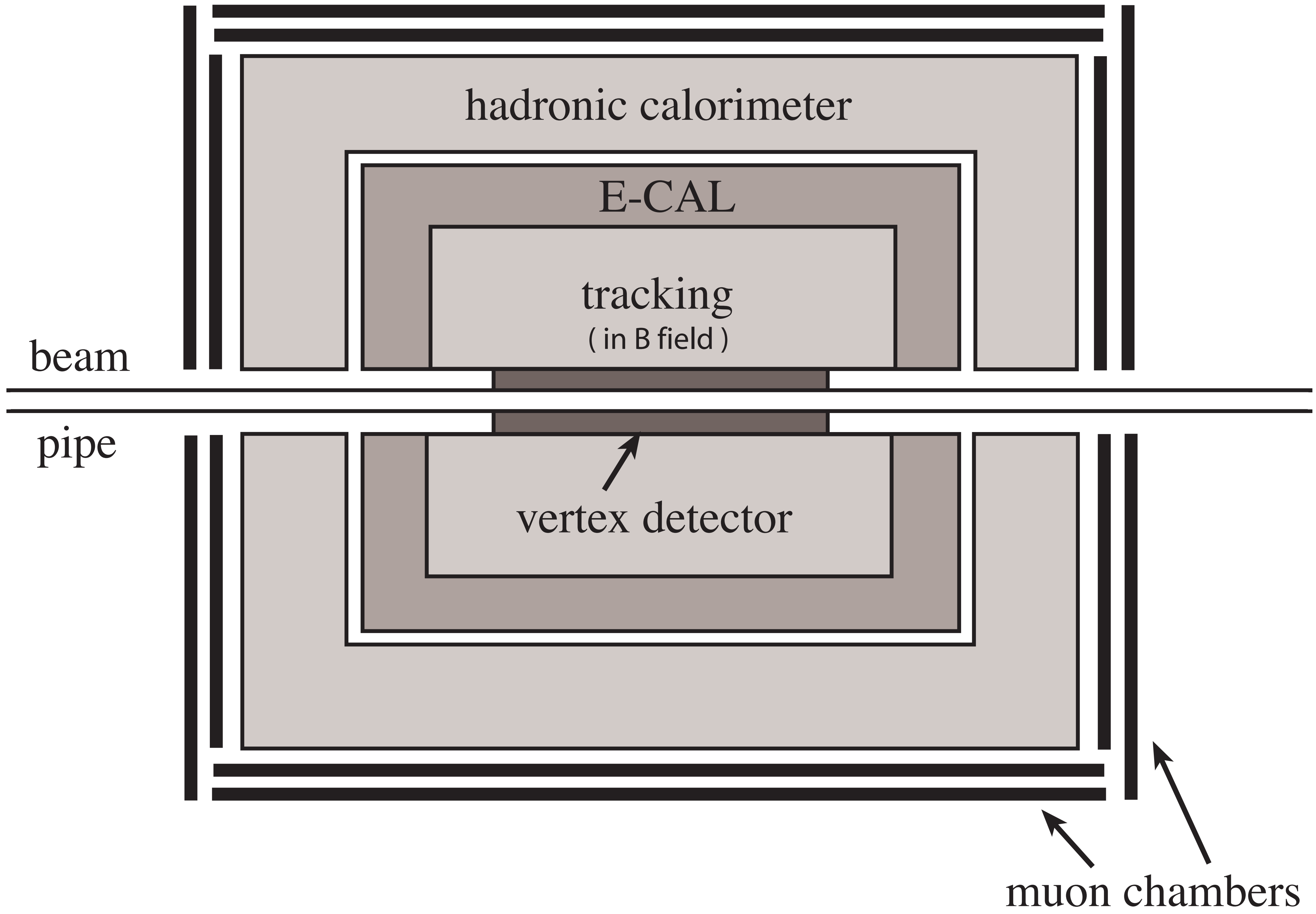
- Colored particles: cluster of hardonic energy, jet ← q, g ← τ
- Leptons: electron, muon
- Photon
- Heavy flavor: bottom (charm)

  $\tau_b \sim 10^{-12}$ s. $\tau_c \sim 10^{-13}$ s
- Missing energy (MET)

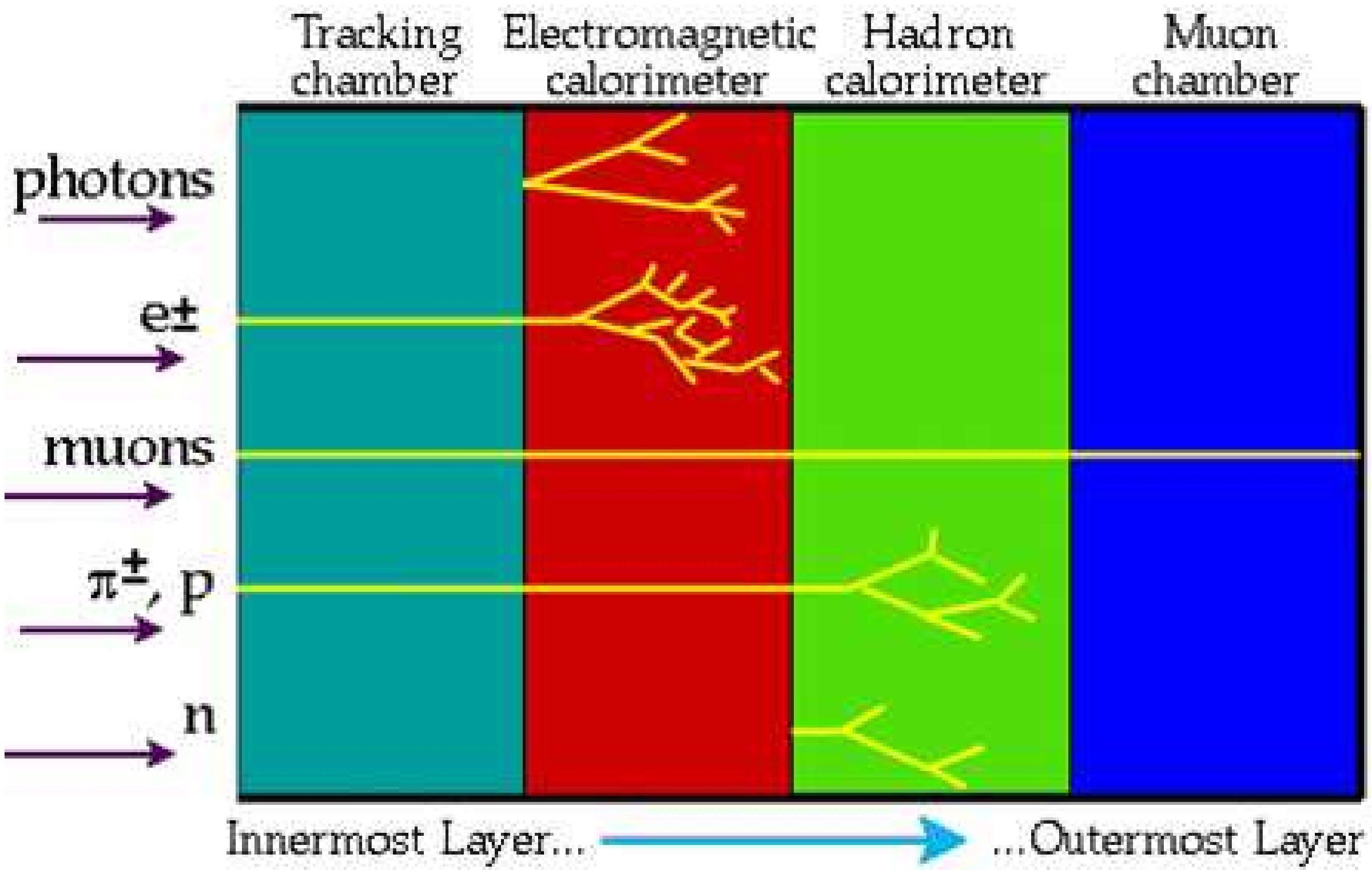


← ν, ...

Modern detector (cartoon)



Identifying particles



From SM processes

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

SM Rates at 7 TeV:

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

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

one lepton + jets + MET

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

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

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

di-lepton + jets

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

New Physics: ~ pb

SM rates at 7 TeV

- di-boson: $W^+W^- : 30 \text{ pb}$ di-lepton + MET, ~ 1.2 pb

  $W^+W^- + \ 1 \text{ jet}, \ p_T^j > 100 \text{ GeV}, \ 2 \text{ pb}$

  di-lepton+jet+MET ~ 0.1 pb

  $W^+Z : \ 7 \text{ pb}, \ W^-Z : \ 3.7 \text{ pb}$

  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.

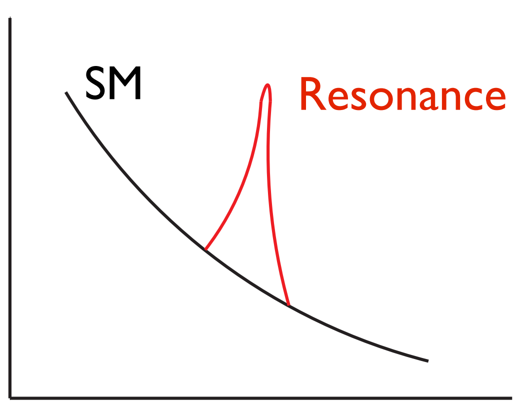
Two possible ways of discovery:

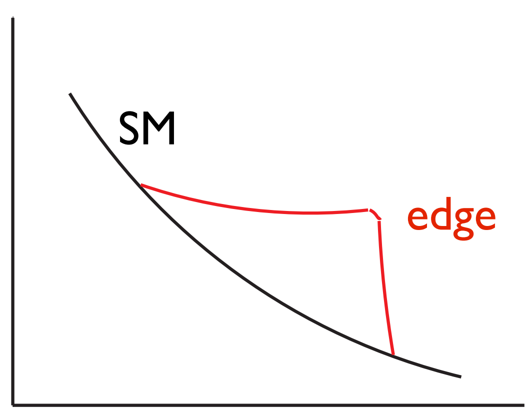
final state	rate estimate
begin with ≥ 2 hard jets	10^5 Hz
in addition	
hard jet	10^2 Hz
or $\not{E}_T \gtrsim 10^2$ GeV	$\sim 10^2$ Hz
or 1 lepton	10^2 Hz
or 2 lepton	1 Hz
or $2\ell = e^\pm + \mu^\pm$	10^{-4} Hz

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

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

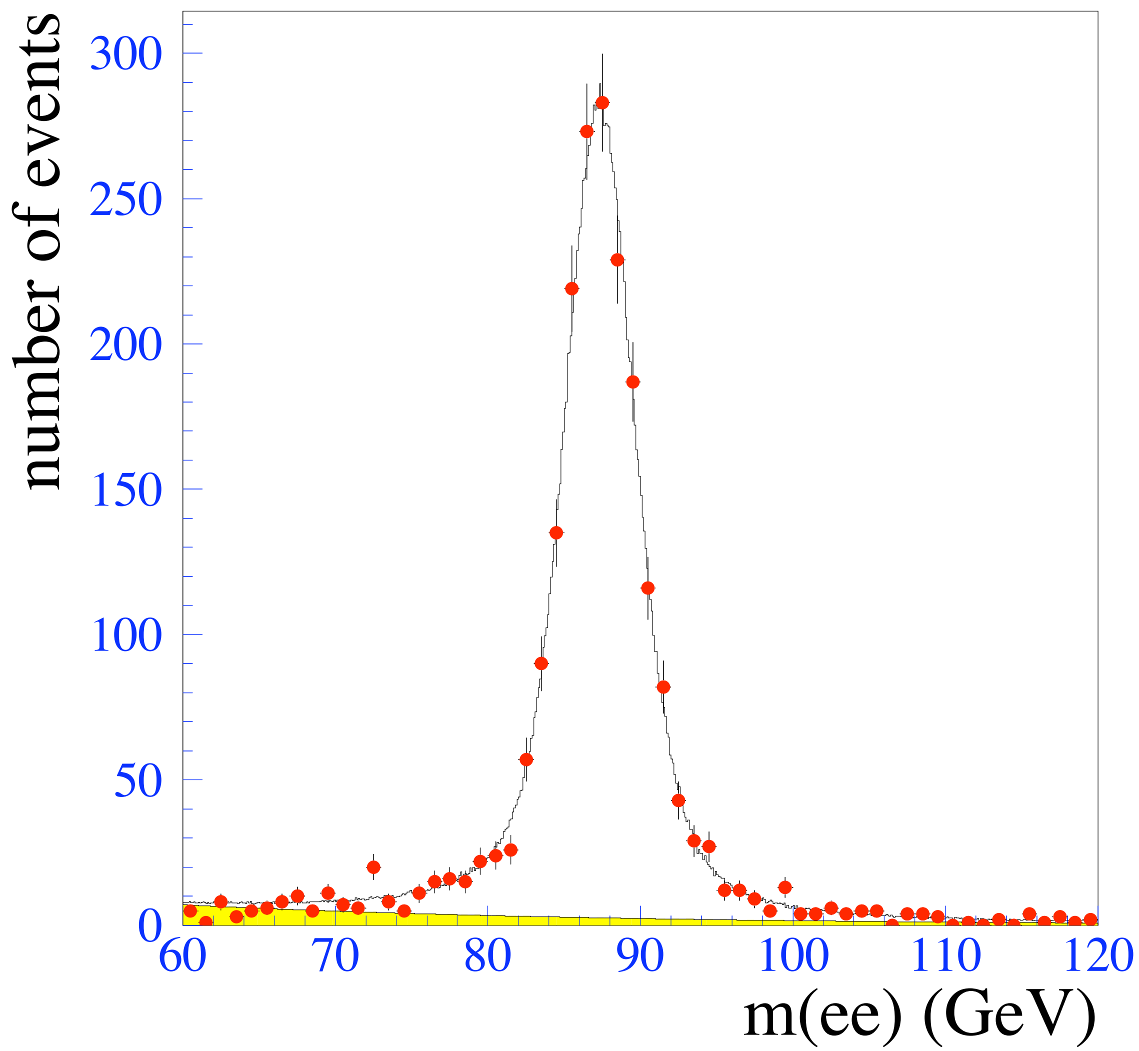
$(\geq 2 \text{ jets}) + (\geq 1\ell) + \not{E}_T$





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

Resonance



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

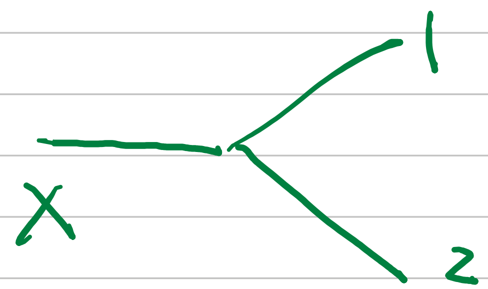
$$\hat{s} = m_{ee}^2 = (p_{e_1} + p_{e_2})^2$$

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

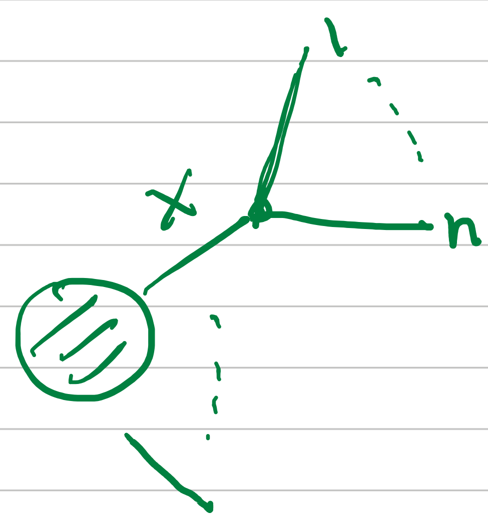
Narrow width approximation



$$|\mathcal{M}|^2 \propto \frac{1}{(s_X - m_X^2)^2 + \Gamma_X^2 m_X^2} \approx \frac{\pi}{m_X \Gamma_X} \delta(s_X - m_X^2) \text{ if } \Gamma_X \ll m_X$$

$$\left(\text{from } \lim_{\epsilon \to 0} \frac{\epsilon}{\epsilon^2 + x^2} = \pi \delta(x) \right)$$

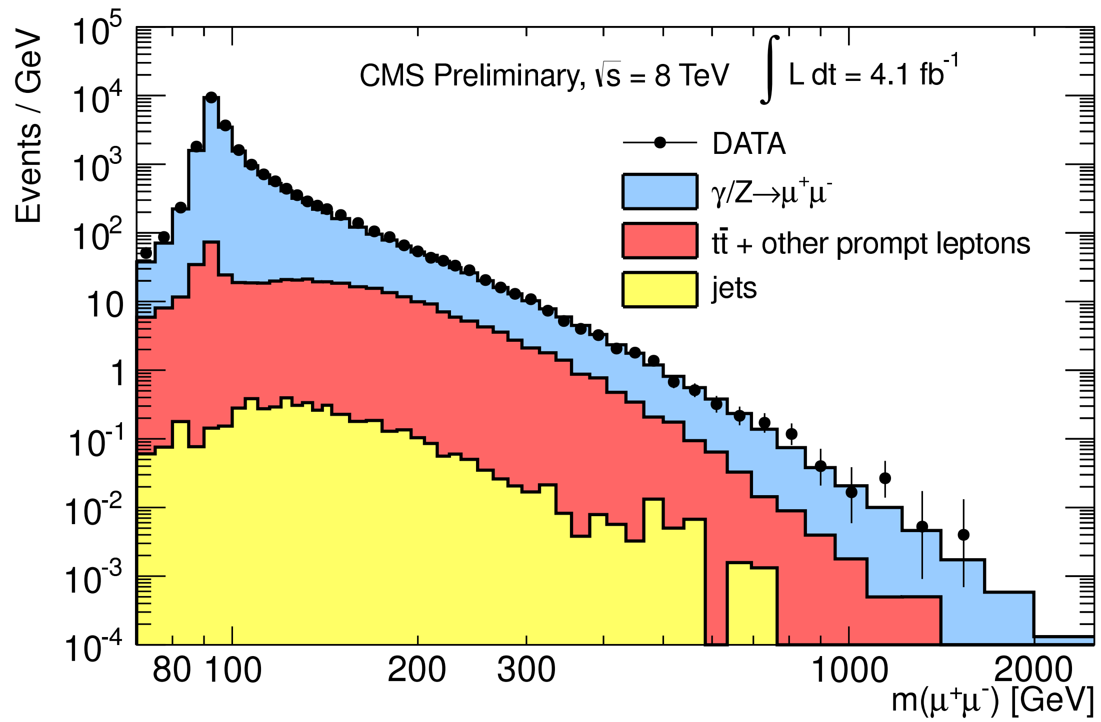
General final state

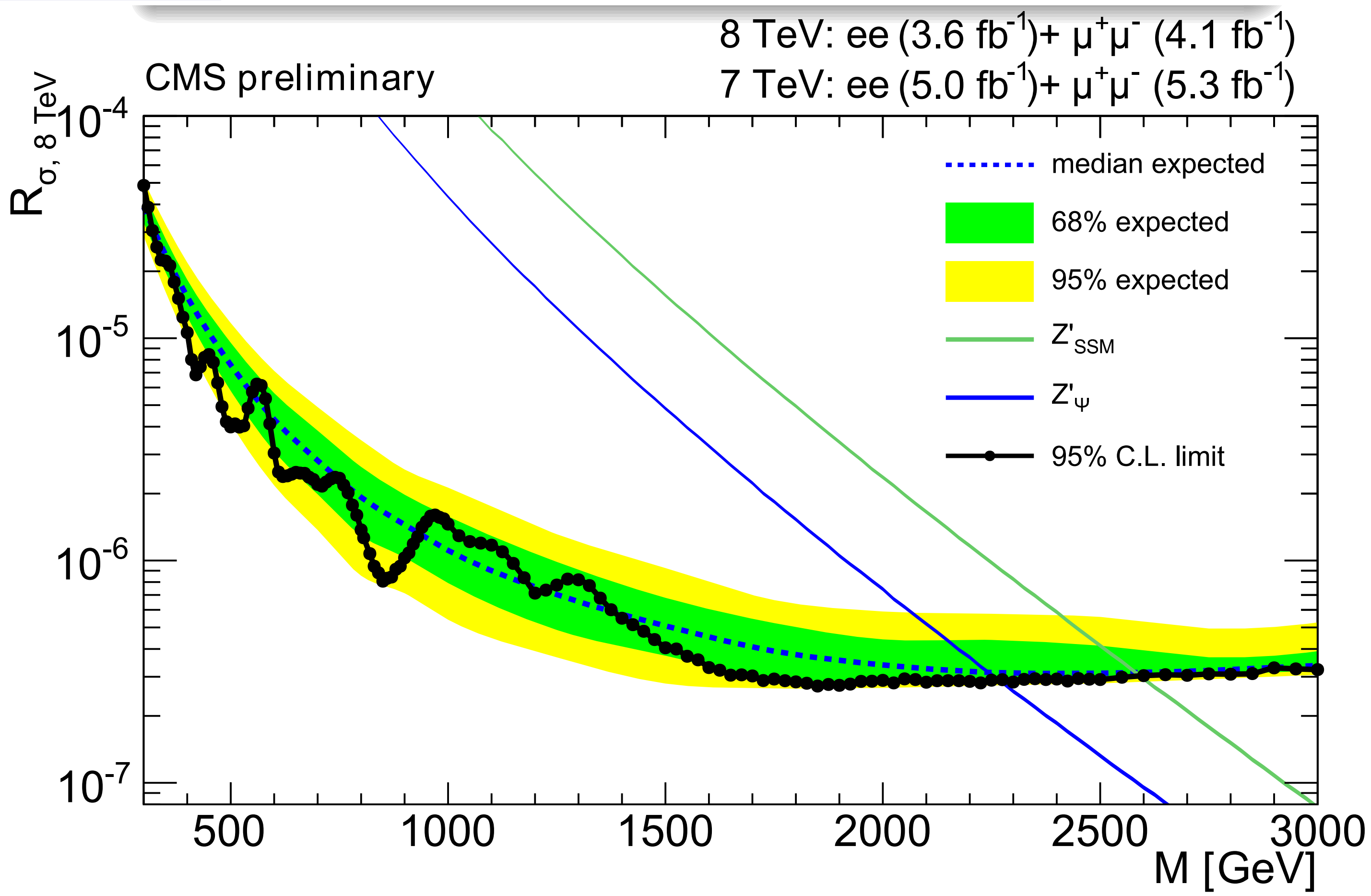


$$d\Pi \propto ds_X \frac{1}{(s_X - m_X)^2 + \Gamma_X^2 m_X^2} d\Pi(X \to 1, \cdots n)$$

$$\overset{\text{NWA}}{\Longrightarrow} \frac{\Gamma(X \to 1, 2 \cdots n)}{\Gamma_X} = B_r(X \to 1 \cdots n)$$

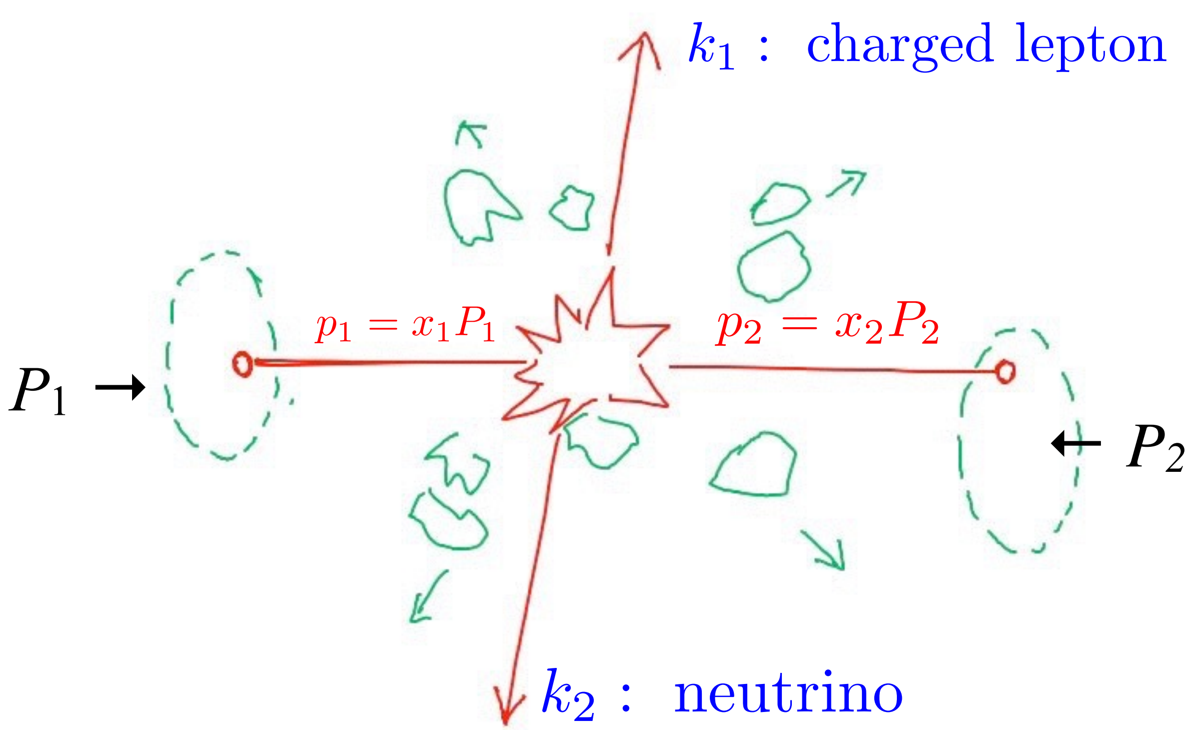
New resonance, Z', search





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



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

$\hat{\theta}$ 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

$$m_{12}^2 = (E_e + E_\nu)^2 - (\vec{k}_{1T} + \vec{k}_{2T})^2 - (k_{1z} + k_{2z})^2$$

Define

$$\vec{\not p}_T = \vec{k}_{2T} \qquad \not E_T = |\vec{k}_{2T}| \qquad E_{eT} \equiv |\vec{k}_{1T}| = |\vec{k}_{2T}| \equiv E_{\nu T}$$

Define transverse mass

$$m_T^2 = (E_{eT} + E_{\nu T})^2 - (\vec{k}_{1T} + \vec{k}_{2T})^2$$

End point

$m_{12}^2 > m_T^2$ end point at $m_T = m_{12} = m_W$

Proof for the end point.

$$E_e = \sqrt{E_{eT}^2 + k_{1z}^2}$$

$$E_\nu = \sqrt{E_{\nu T}^2 + k_{2z}^2}$$

$$m_{12}^2 = (E_e + E_\nu)^2 - (\vec{k}_{1T} + \vec{k}_{2T}) - (k_{1z} + k_{2z})^2$$

$$m_T^2 = (E_{eT} + E_{\nu T})^2 - (\vec{k}_{1T} + \vec{k}_{2T})^2$$

$$(E_e + E_\nu)^2 = E_{eT}^2 + E_{\nu T}^2 + k_{1z}^2 + k_{2z}^2 + 2\sqrt{E_{eT}^2 + k_{1z}^2}\sqrt{E_{\nu T}^2 + k_{2z}^2}$$

$$m_{12}^2 - m_T^2$$

$$= 2\sqrt{E_{eT}^2 + k_{1z}^2}\sqrt{E_{\nu T}^2 + k_{2z}^2} - 2k_{1z}k_{2z} - 2E_{eT}E_{\nu T} \geq 0$$

$$\nearrow$$

$$① = \left(\sqrt{}\sqrt{}\right)^2 = E_{eT}^2 E_{\nu T}^2 + k_{1z}^2 k_{2z}^2 + E_{eT}^2 k_{2z}^2 + E_{\nu T}^2 k_{1z}^2$$

$$② = (k_{1z}k_{2z} + E_{eT}E_{\nu T})^2 = E_{eT}^2 E_{\nu T}^2 + k_{1z}^2 k_{2z}^2 + 2k_{1z}k_{2z}E_{eT}E_{\nu T}$$

$$① - ② = E_{eT}^2 k_{2z}^2 + E_{\nu T}^2 k_{1z}^2 - 2k_{1z}k_{2z}E_{eT}E_{\nu T}$$

$$= (E_{eT}k_{2z} - E_{\nu T}k_{1z})^2 \geq 0$$

Jacobian peak in m_T

If W produced without transverse boost.

$$m_T = 2|k_{1T}| = 2|k_{2T}|$$

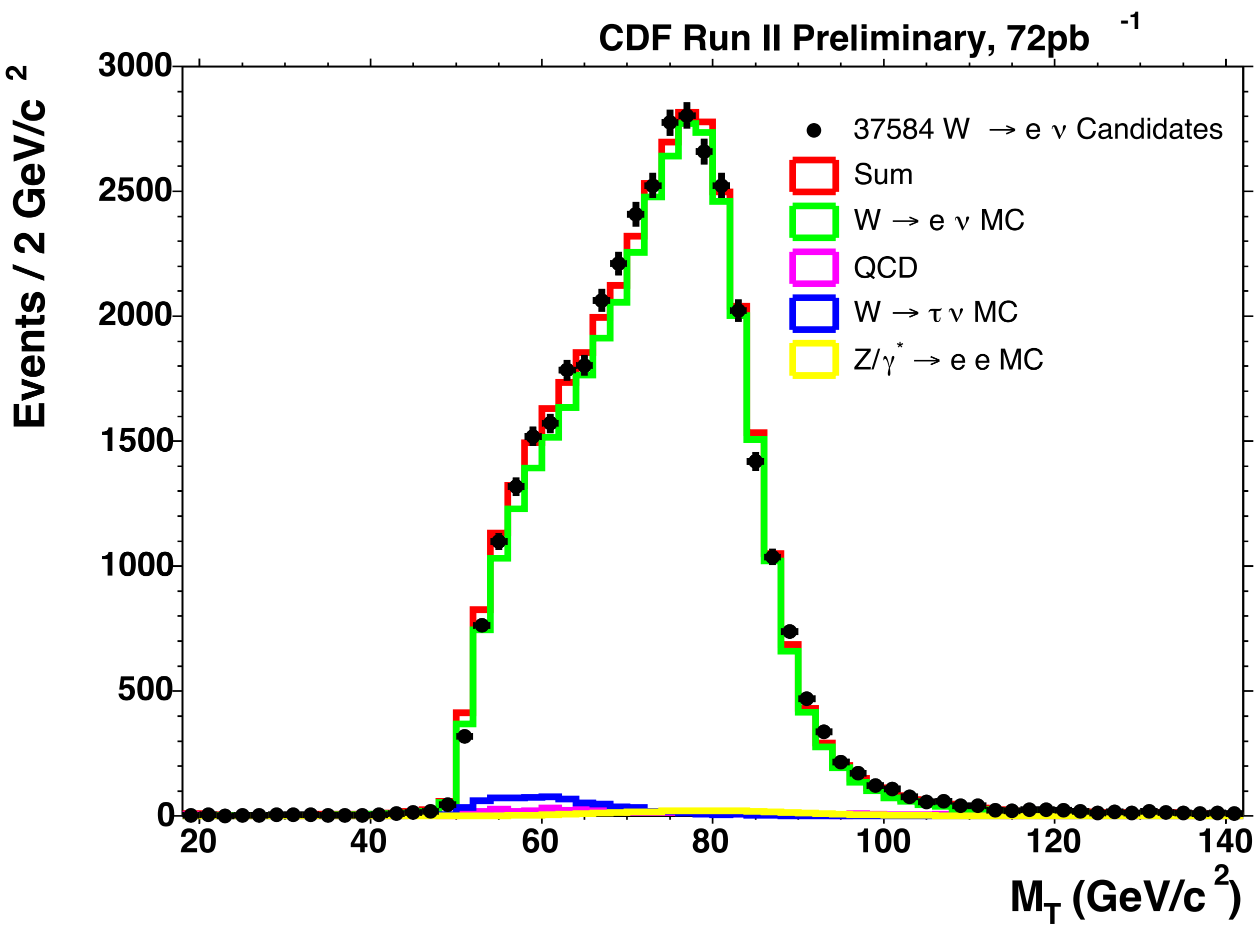
$$\frac{d}{dm_T^2} = \frac{1}{4}\frac{d}{dk_{1T}^2} \rightarrow \text{Jacobian peak at } m_T^2 = m_W^2$$

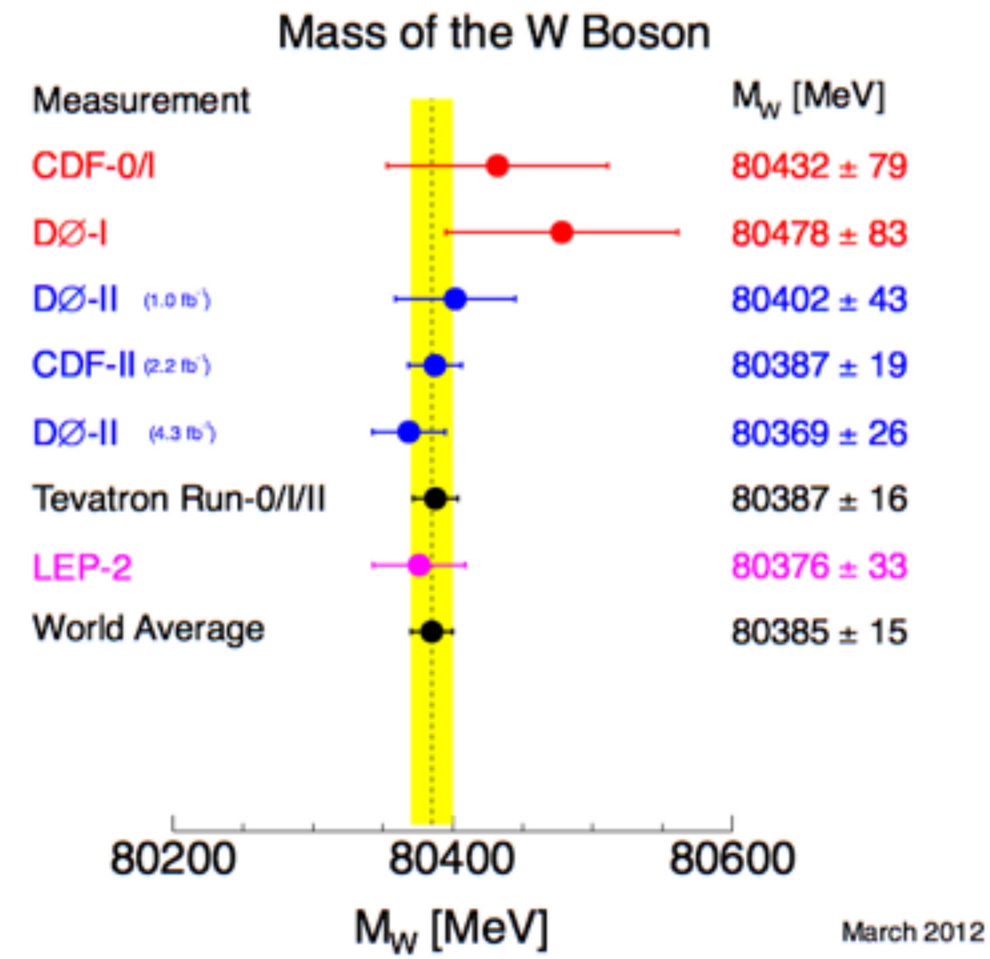
$$\frac{d\hat{\sigma}}{dm_T^2} \sim \frac{1}{4\pi}\frac{(G_F m_W)^2}{2}\frac{1}{(\hat{s}-m_W^2)^2+(\Gamma_W m_W)^2}\frac{2-m_T^2/\hat{s}}{(1-m_T^2/\hat{s})^{1/2}}$$

Position of Jacobian peak smeared by width, resolution

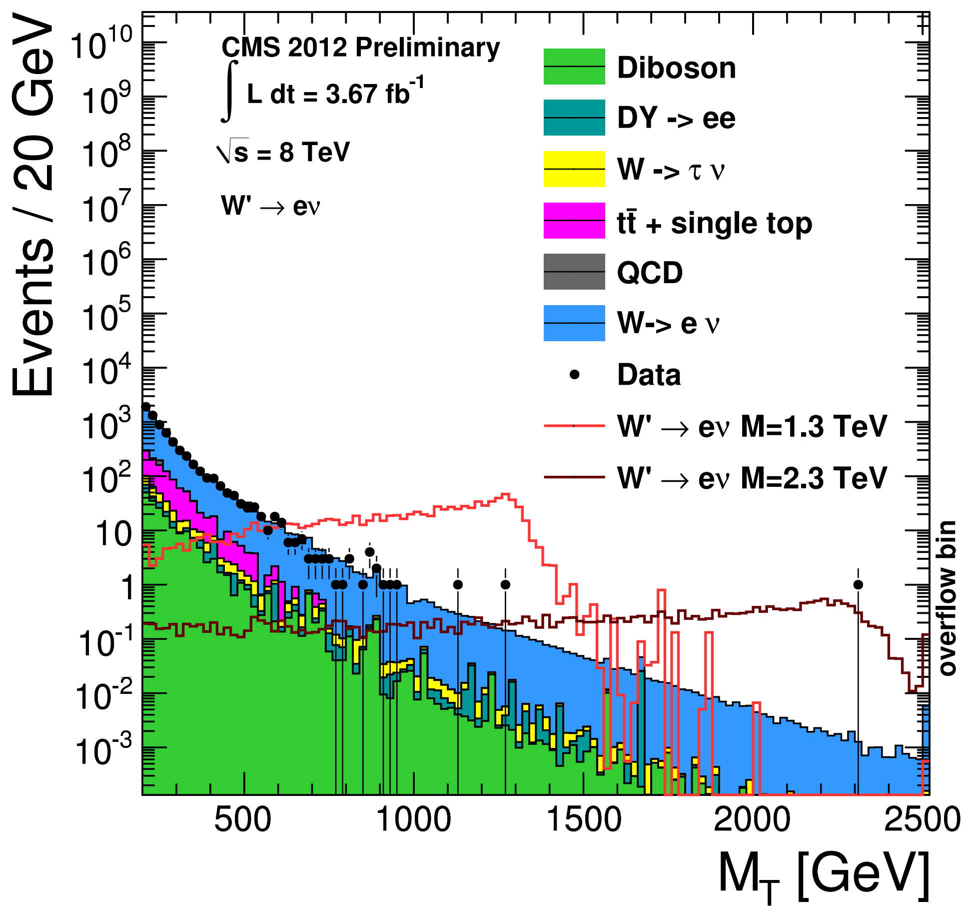
Shape of Jacobian peak changed by transverse boost.

Measuring the W mass

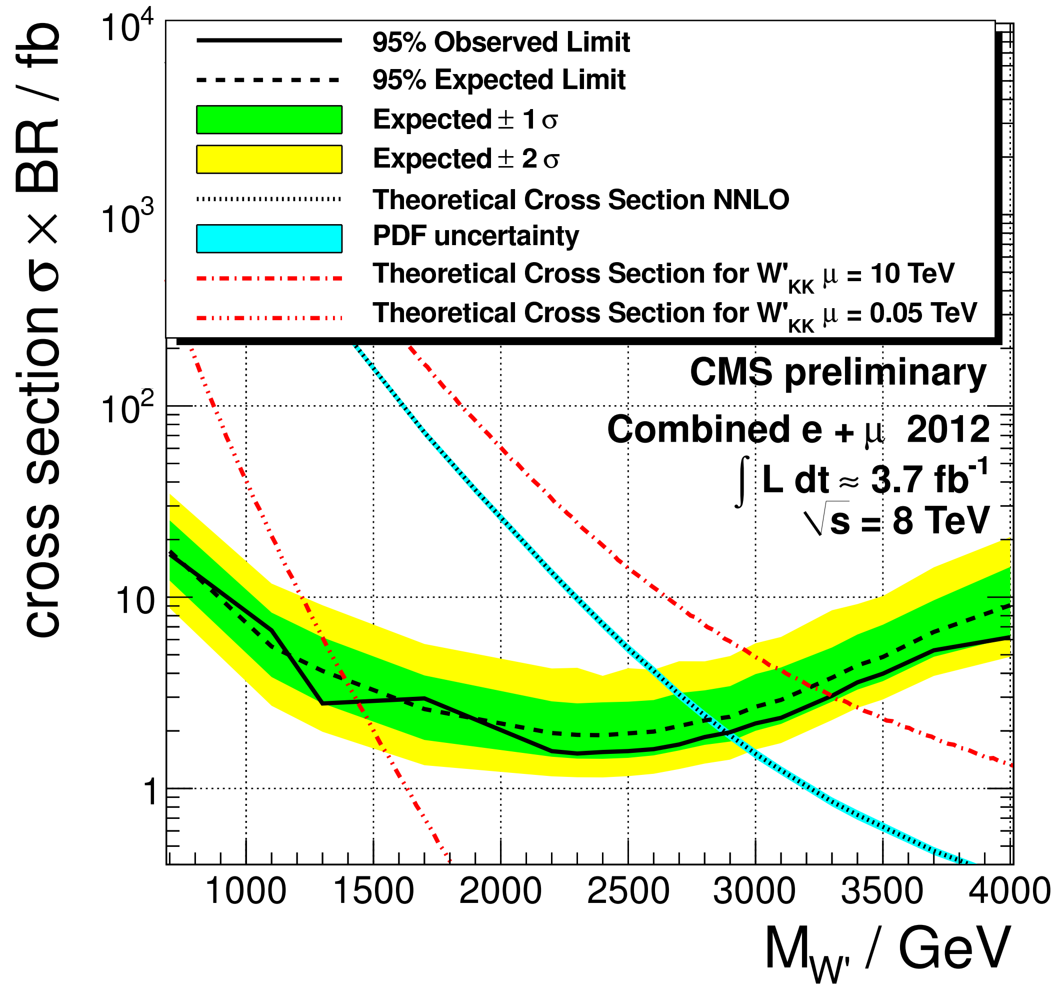




W’ search

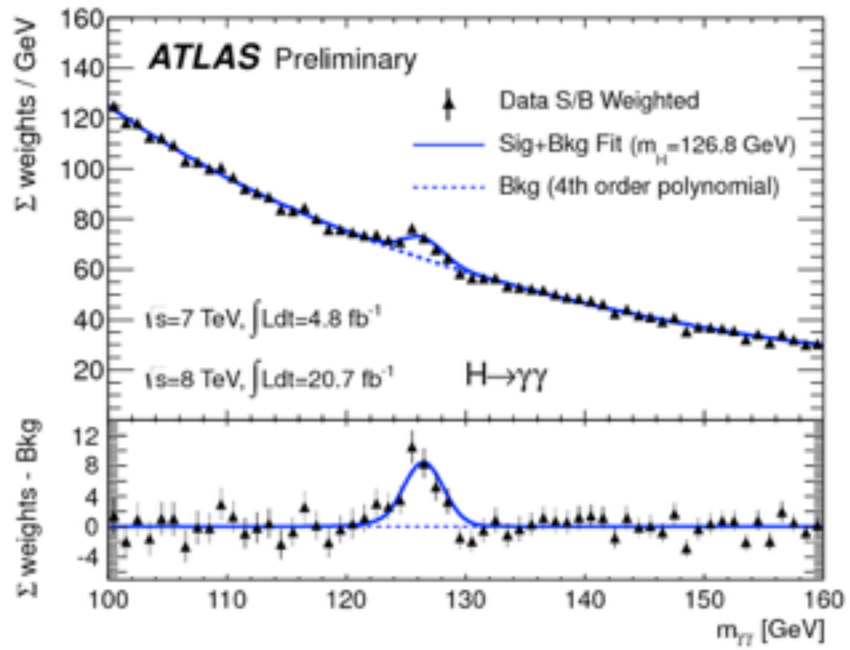


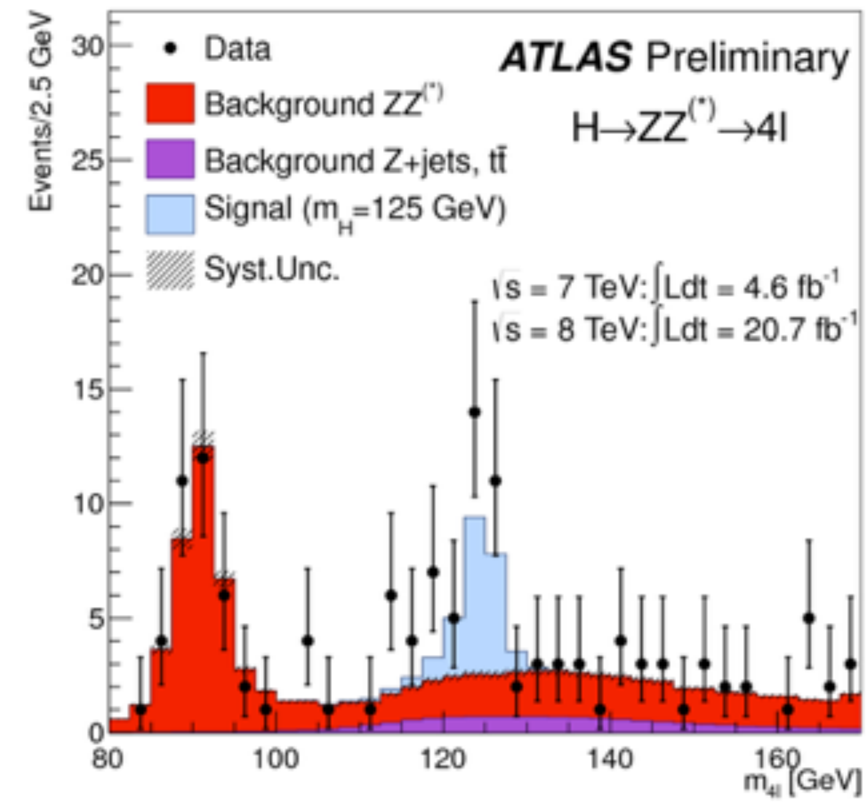
CMS 2012 Preliminary
$\int$ L dt = 3.67 fb^{-1}
$\sqrt{s}$ = 8 TeV
W' → eν
Diboson
DY -> ee
W -> τ ν
tt̄ + single top
QCD
W-> e ν
Data
W' → eν M=1.3 TeV
W' → eν M=2.3 TeV
overflow bin
Events / 20 GeV
M_T [GeV]

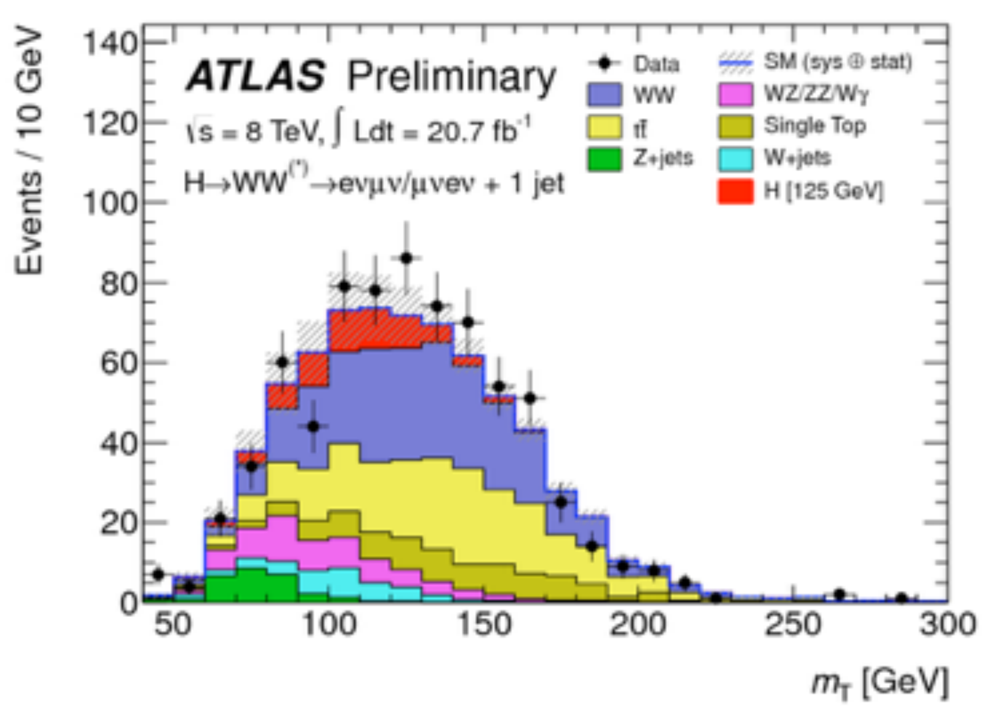


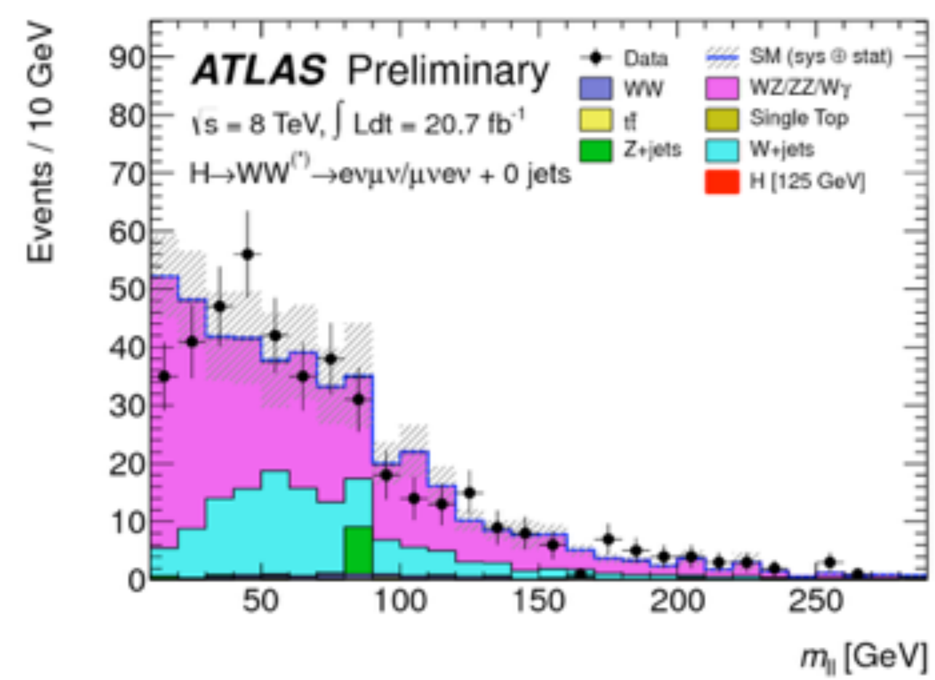
95% Observed Limit
95% Expected Limit
Expected ± 1 σ
Expected ± 2 σ
Theoretical Cross Section NNLO
PDF uncertainty
Theoretical Cross Section for W'_{KK} μ = 10 TeV
Theoretical Cross Section for W'_{KK} μ = 0.05 TeV
CMS preliminary
Combined e + μ 2012
$\int$ L dt ≈ 3.7 fb^{-1}
$\sqrt{s}$ = 8 TeV
cross section σ × BR / fb
$M_{W'}$ / GeV

Seeing Higgs









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”

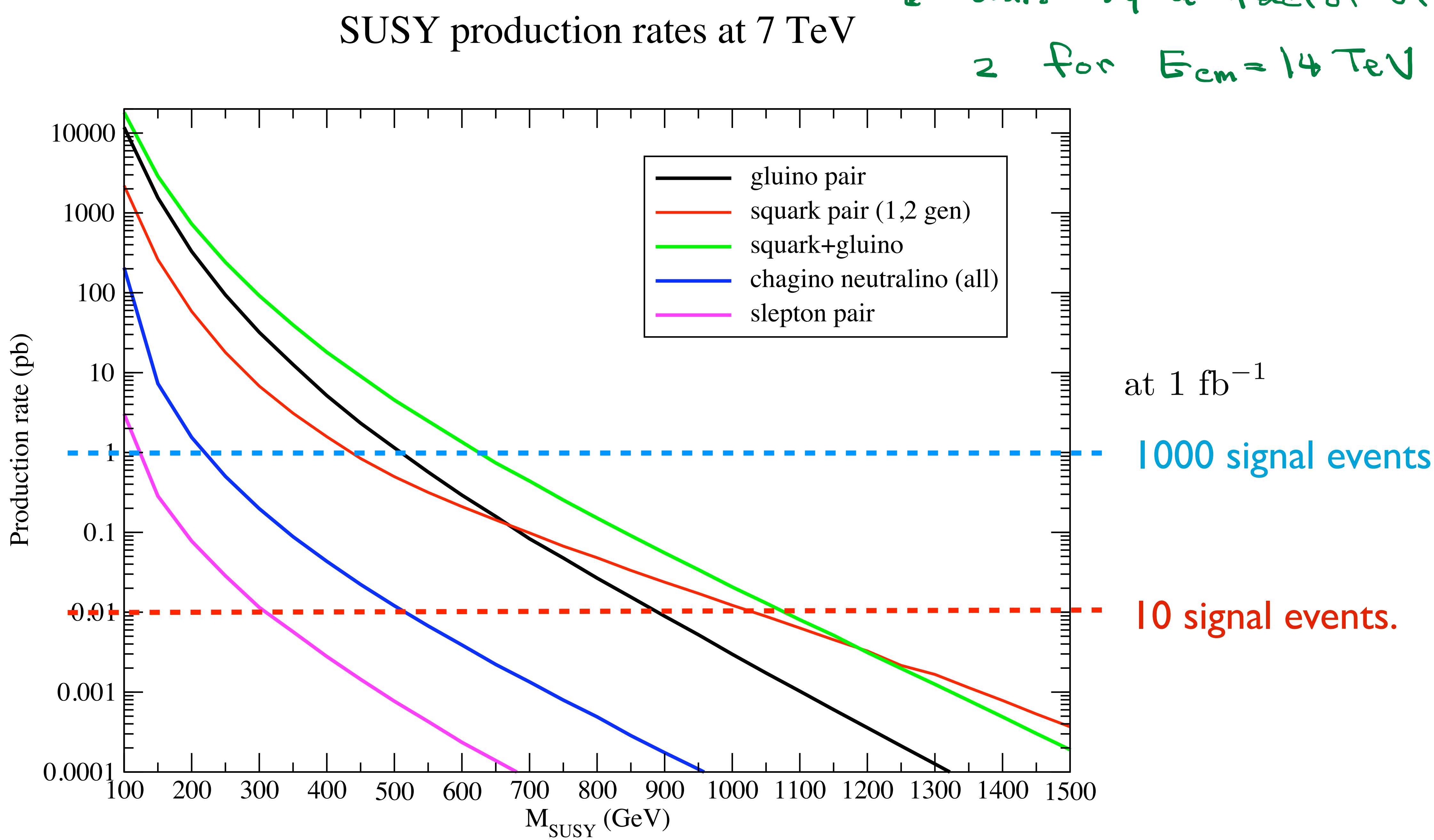
	spin		spin
gluon, g	1	gluino: $\tilde{g}$	1/2
$W^{\pm}, Z$	1	gaugino: $\tilde{W}^{\pm}, \tilde{Z}$	1/2
quark: q	1/2	squark: $\tilde{q}$	0
…		…	
SM		(super)partner	

- Couplings relate to SM interactions via supersymmetry.
    - ~ same strength.

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

Production.

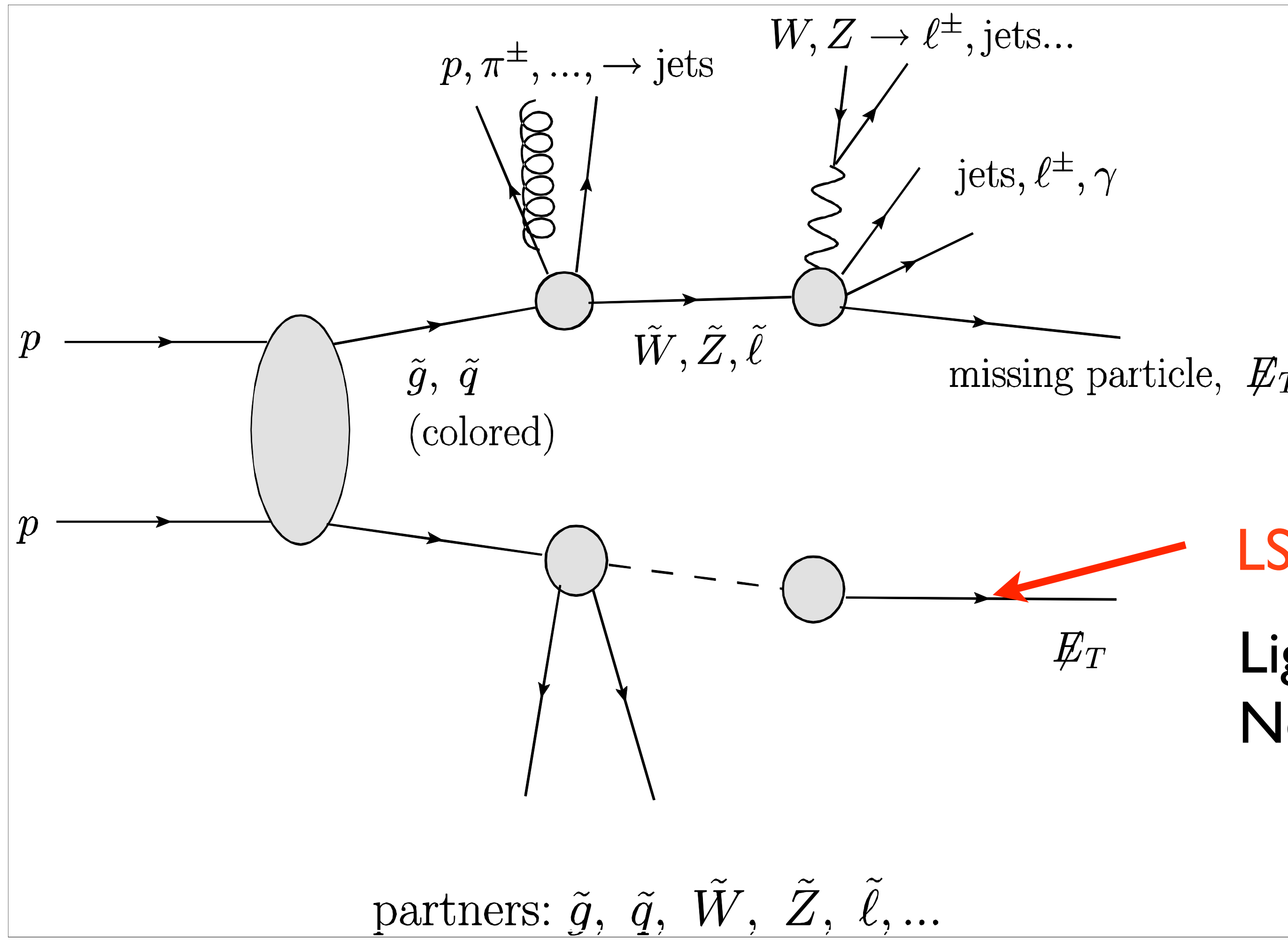
Scale the horizontal axis by a factor of 2 for E_{cm} = 14 TeV



Dominated by the production of colored states.

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

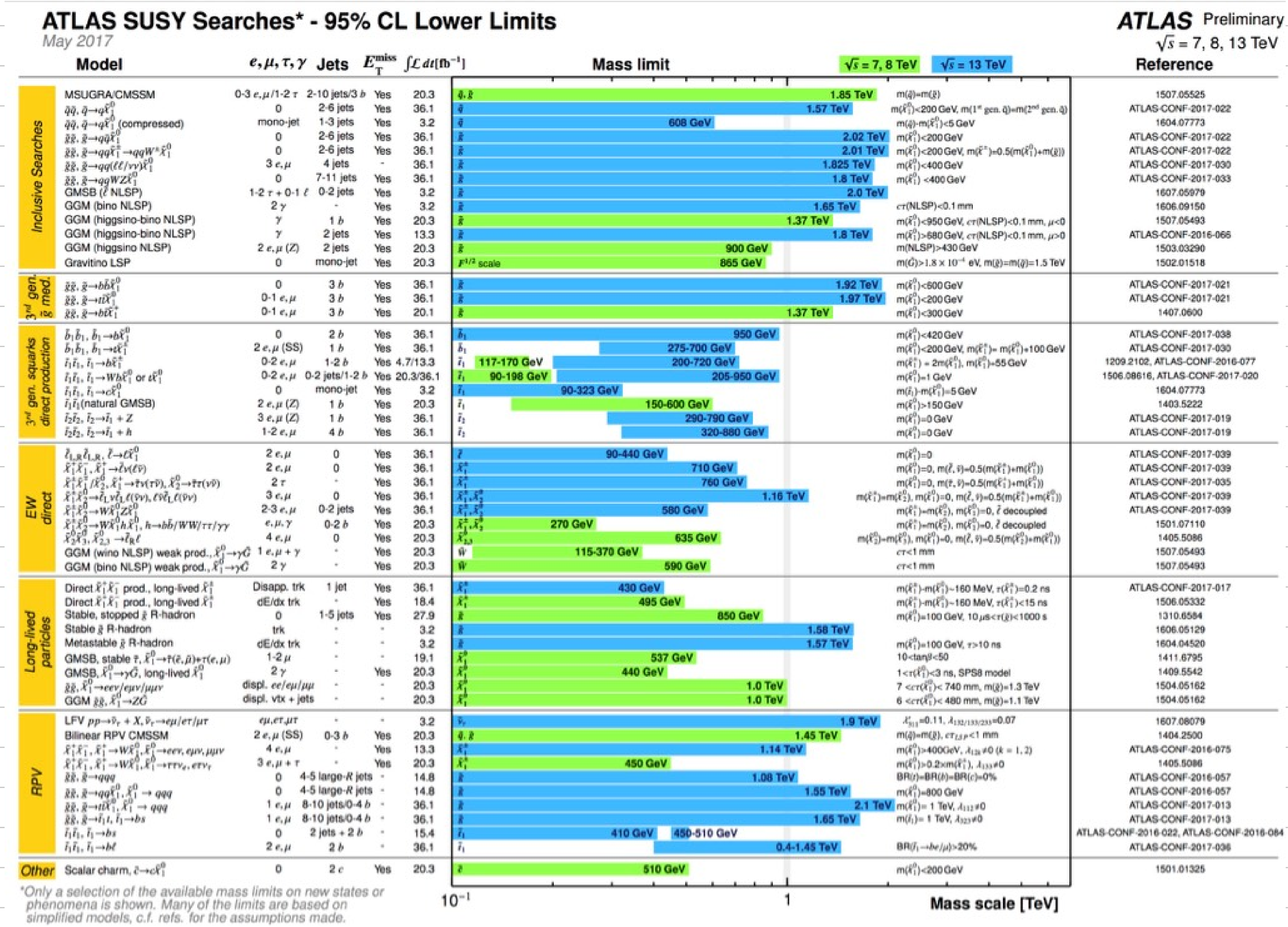
SUSY at colliders

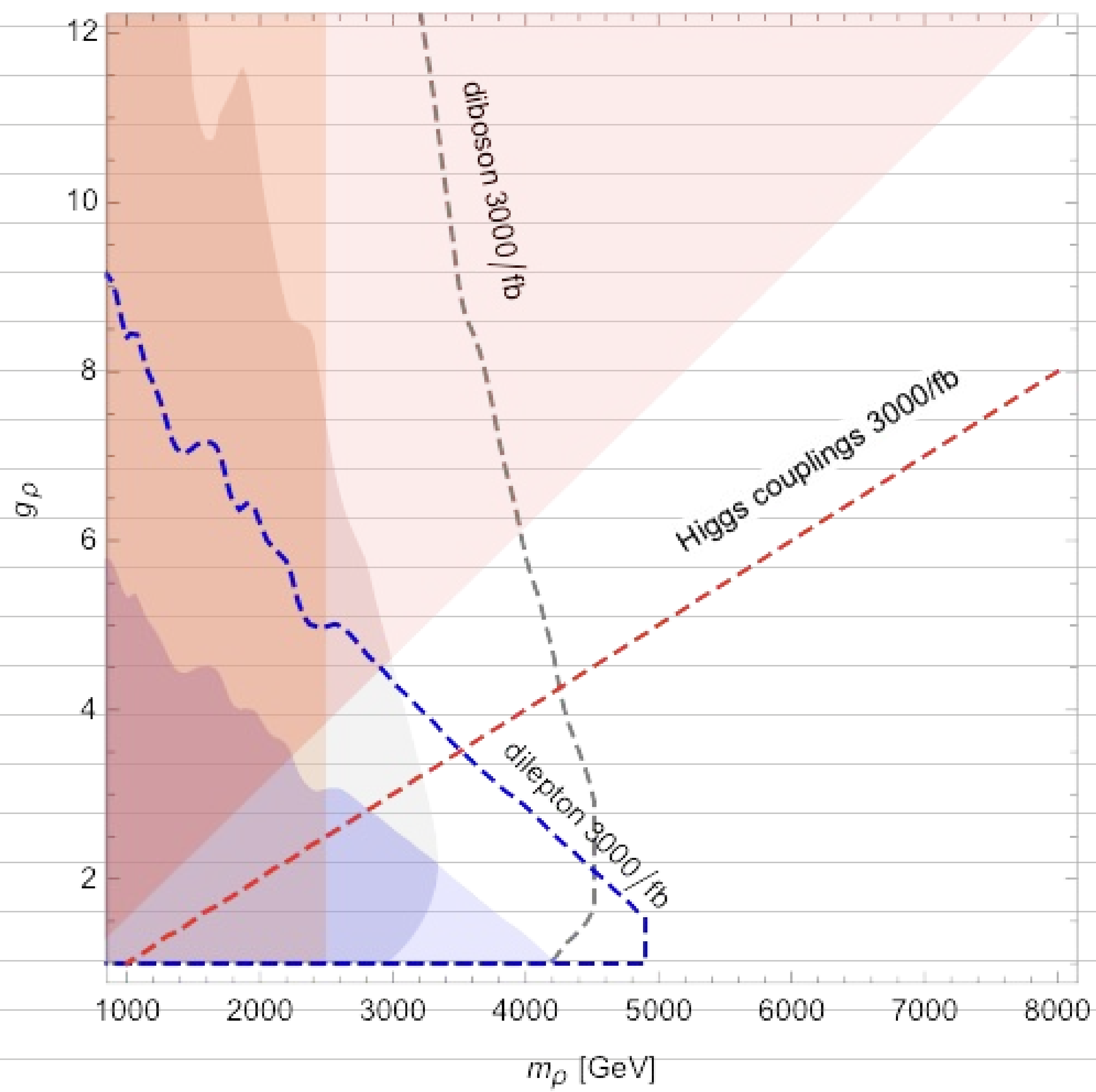


LSP, DM candidate

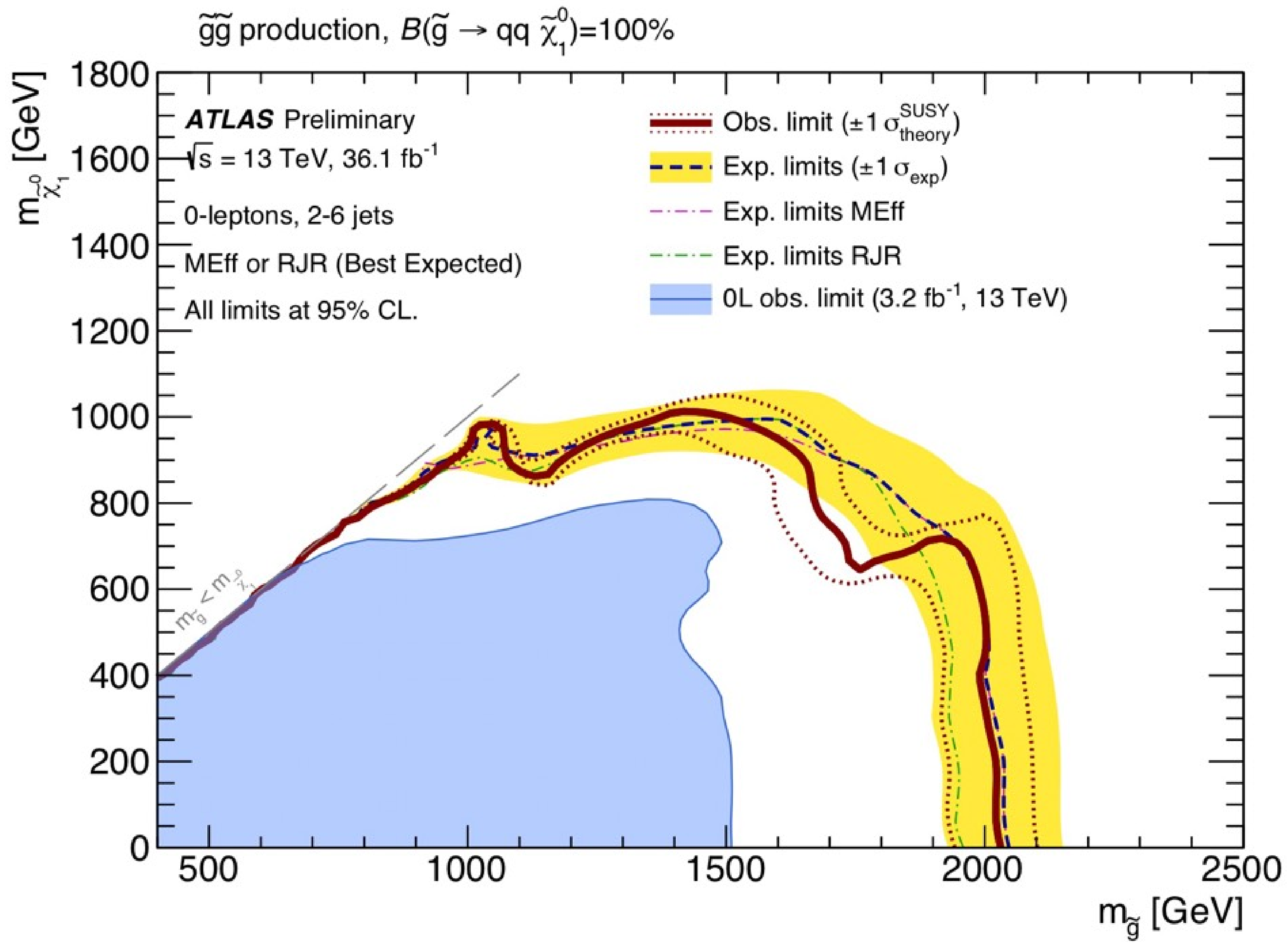
Lightest superpartner (LSP)
Neutral and stable.

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


ATLAS SUSY Searches* - 95% CL Lower Limits
May 2017
ATLAS Preliminary
√s = 7, 8, 13 TeV
Model
e, μ, τ, γ
Jets
E_T^miss
∫L dt[fb^-1]
Mass limit
√s = 7, 8 TeV
√s = 13 TeV
Reference
Inclusive Searches
3rd gen. g̃ med.
3rd gen. squarks direct production
EW direct
Long-lived particles
RPV
Other
1.85 TeV
1.57 TeV
608 GeV
2.02 TeV
2.01 TeV
1.825 TeV
1.8 TeV
2.0 TeV
1.65 TeV
1.37 TeV
1.8 TeV
900 GeV
865 GeV
1.92 TeV
1.97 TeV
1.37 TeV
950 GeV
275-700 GeV
117-170 GeV
200-720 GeV
90-198 GeV
205-950 GeV
90-323 GeV
150-600 GeV
290-790 GeV
320-880 GeV
90-440 GeV
710 GeV
760 GeV
1.16 TeV
580 GeV
270 GeV
635 GeV
115-370 GeV
590 GeV
430 GeV
495 GeV
850 GeV
1.58 TeV
1.57 TeV
537 GeV
440 GeV
1.0 TeV
1.0 TeV
1.9 TeV
1.45 TeV
1.14 TeV
450 GeV
1.08 TeV
1.55 TeV
2.1 TeV
1.65 TeV
410 GeV
450-510 GeV
0.4-1.45 TeV
510 GeV
10^-1
1
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.



12
10
8
6
4
2
g_ρ
1000
2000
3000
4000
5000
6000
7000
8000
m_ρ [GeV]
diboson 3000/fb
Higgs couplings 3000/fb
dilepton 3000/fb



$\tilde{g}\tilde{g}$ production, $B(\tilde{g} \rightarrow qq\, \tilde{\chi}_1^0)$=100%
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
0-leptons, 2-6 jets
MEff or RJR (Best Expected)
All limits at 95% CL.
Obs. limit ($\pm 1\, \sigma_{theory}^{SUSY}$)
Exp. limits ($\pm 1\, \sigma_{exp}$)
Exp. limits MEff
Exp. limits RJR
0L obs. limit (3.2 fb^{-1}, 13 TeV)
$m_{\tilde{g}} < m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{g}}$ [GeV]

Qualitative understanding of gluino reach.

$\sigma(m_{gluino} = 2\,\text{TeV}) \sim 1\,\text{fb}$

Main signal: jets + MET

SM background:

jets + $Z \to \nu\nu$ - QCD dijet ($p_T^j > 250$) 100 nb

- scaling PDF from 500 GeV → 4 TeV gives a factor of 10^{-3}
- Adding a Z $10^{-2} - 10^{-3}$
- Adding one or two more jets $10^{-2} - 10^{-3}$

→ fb-ish

jet + $W \to e\nu$ - similar. — $\sigma_W \sim O(10)\,\sigma_Z$

- But need to miss lepton. $\sim O(10^{-1})$

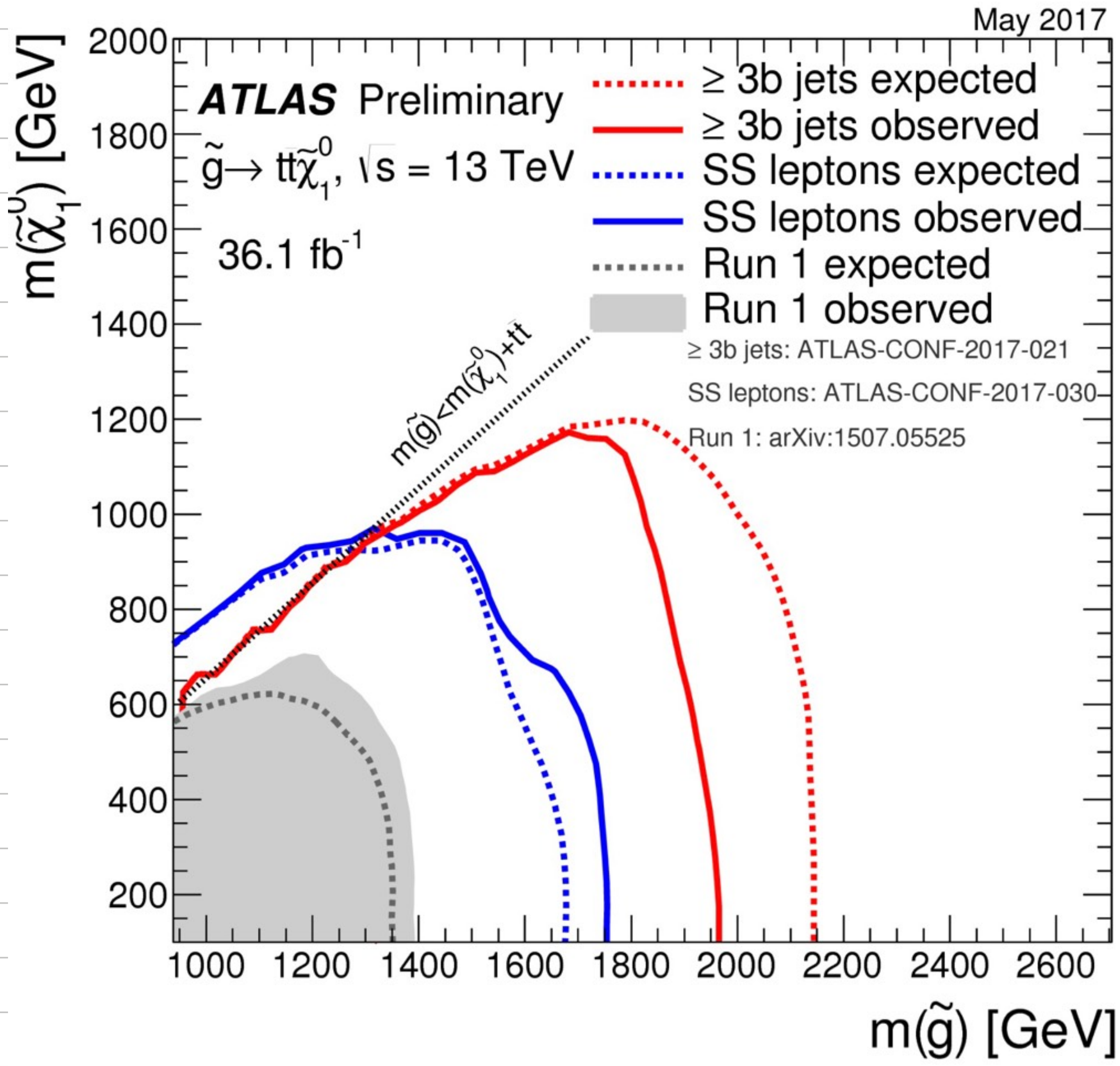
$t\bar{t}$ – PDF from $t\bar{t}$ threshold to 4 TeV gives a factor of $10^{-5} - 10^{-6}$

– MET from $W \to \ell \nu$, need to hide lepton.
~ another factor of 10 (also perhaps b-veto)

→ fb-ish.

- Which channel dominant depends on cuts.

- For $M_{gluino} > 2$ TeV, background falls slower
(e.g., jets + Z from $q\bar{q}$).
Also, signal drops very fast. "run out of rate"



Reach in muti-bjet channel.

$t\bar{t}$ + bjet background.

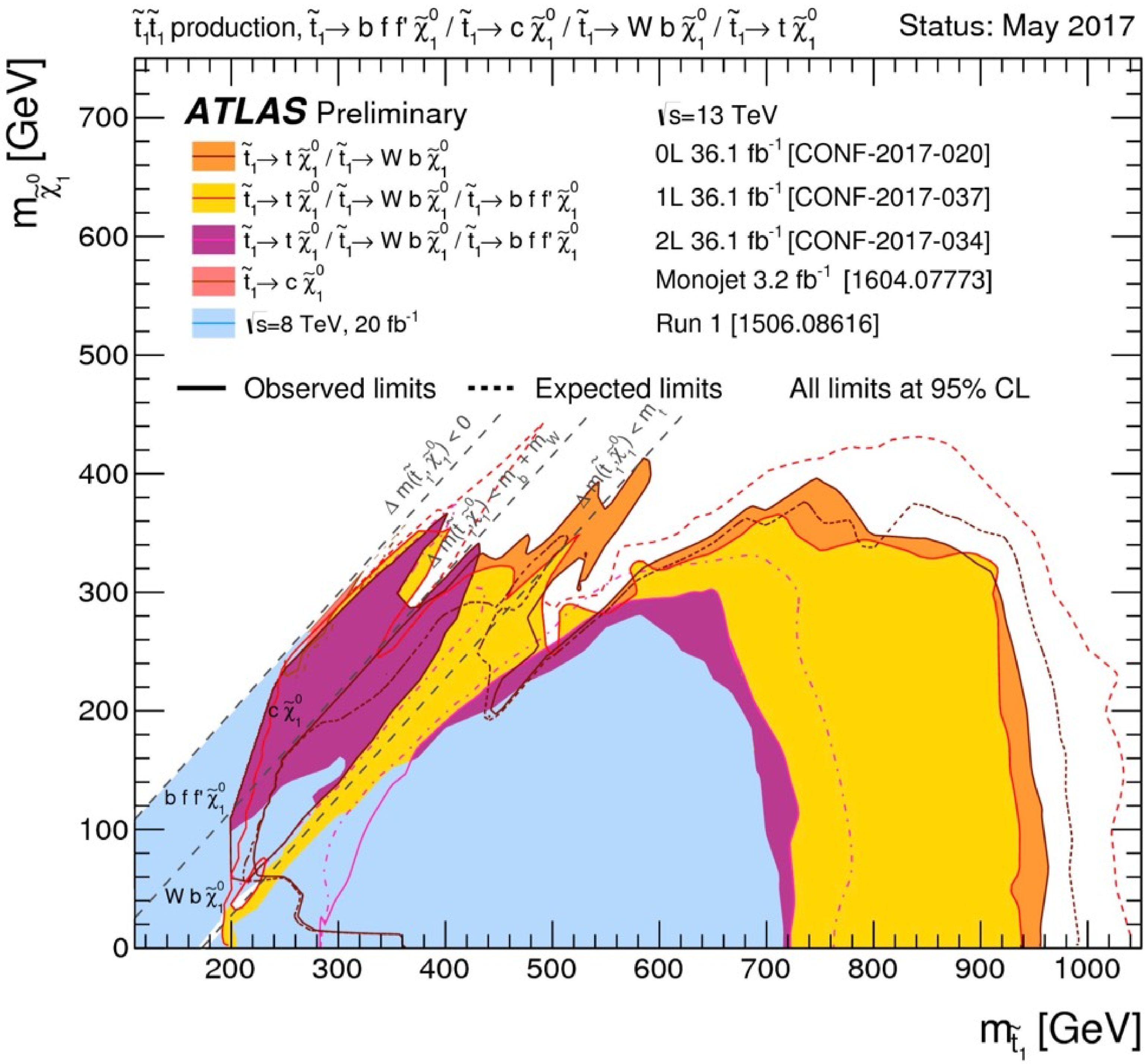
Similar argument as the gluino → jj + Met case.

SSDL channel.

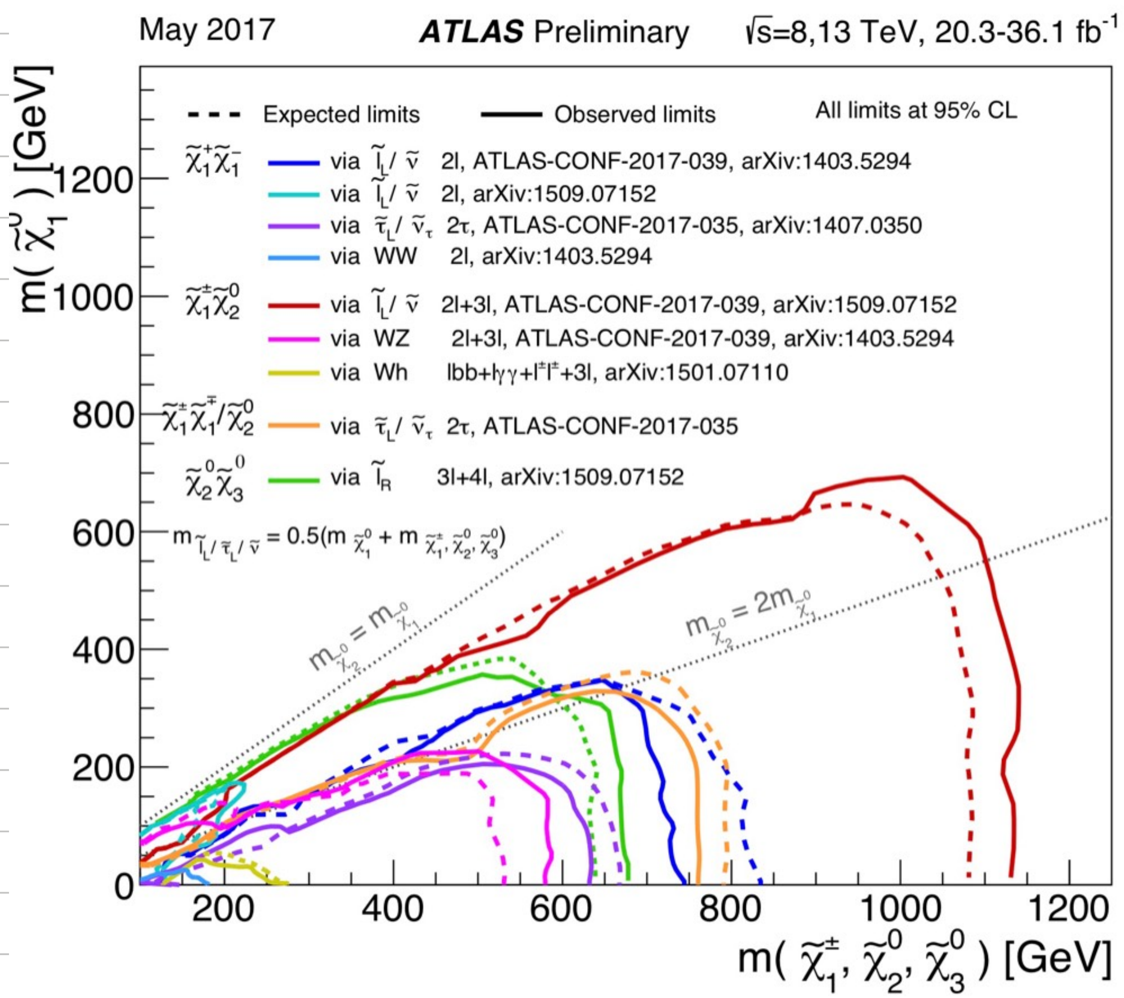
Rate smaller by about a factor of 10

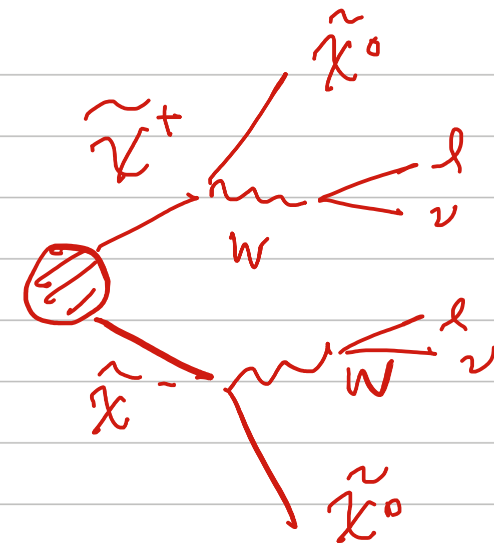
Reach weaker by 50%.

Caution: reach in SSDL more "fool-proof" multi-jet channel need very good modeling of background



t̃₁t̃₁ production, t̃₁→ b f f' χ̃⁰₁ / t̃₁→ c χ̃⁰₁ / t̃₁→ W b χ̃⁰₁ / t̃₁→ t χ̃⁰₁
Status: May 2017
ATLAS Preliminary
√s=13 TeV
t̃₁→ t χ̃⁰₁ / t̃₁→ W b χ̃⁰₁
0L 36.1 fb⁻¹ [CONF-2017-020]
t̃₁→ t χ̃⁰₁ / t̃₁→ W b χ̃⁰₁ / t̃₁→ b f f' χ̃⁰₁
1L 36.1 fb⁻¹ [CONF-2017-037]
t̃₁→ t χ̃⁰₁ / t̃₁→ W b χ̃⁰₁ / t̃₁→ b f f' χ̃⁰₁
2L 36.1 fb⁻¹ [CONF-2017-034]
t̃₁→ c χ̃⁰₁
Monojet 3.2 fb⁻¹ [1604.07773]
√s=8 TeV, 20 fb⁻¹
Run 1 [1506.08616]
Observed limits
Expected limits
All limits at 95% CL
c χ̃⁰₁
b f f' χ̃⁰₁
W b χ̃⁰₁
m_χ̃⁰₁ [GeV]
m_t̃₁ [GeV]





WW energy ~ 500 GeV

Production rate for 600 GeV chargino $\lesssim$ 1 pb

SM background

Rate for W^+W^- on threshold ~ 100 pb

Scaling w/ PDF → a factor of 10^{-2}

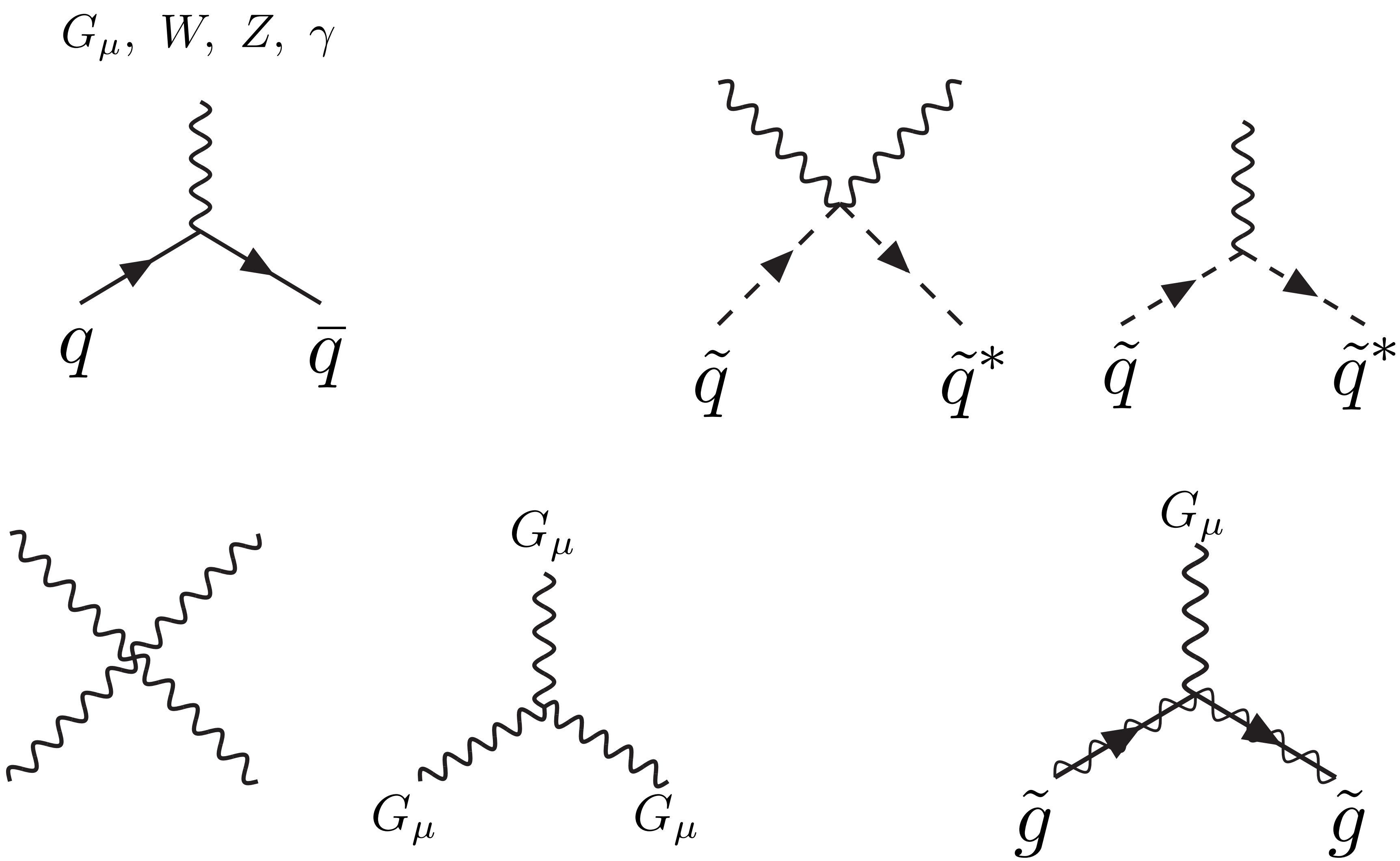
for WW energy about 500 GeV

Interactions.

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

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

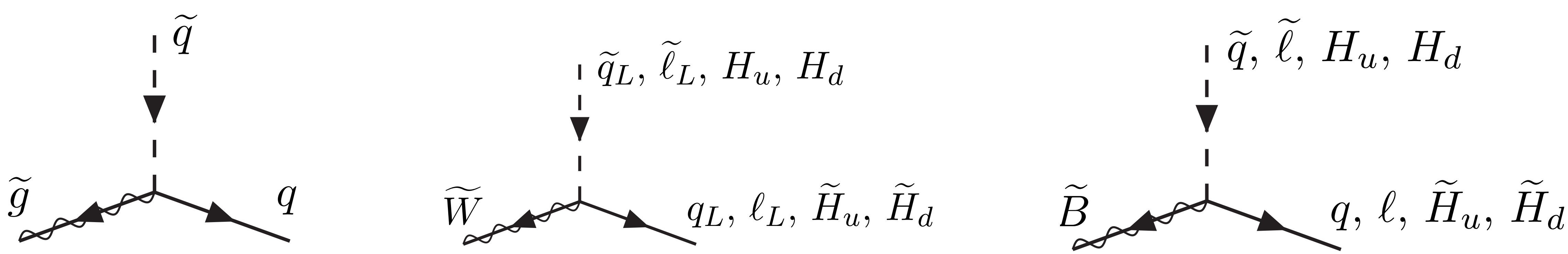
non-Abelian



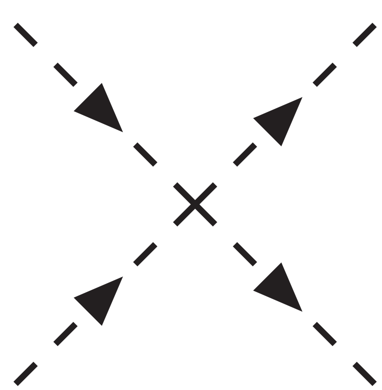
Interactions.

- SUSY⇒ additional couplings
  - strength fixed by corresponding gauge

$SU(3)_{color}$ $SU(2)_L$ $U(1)_Y$

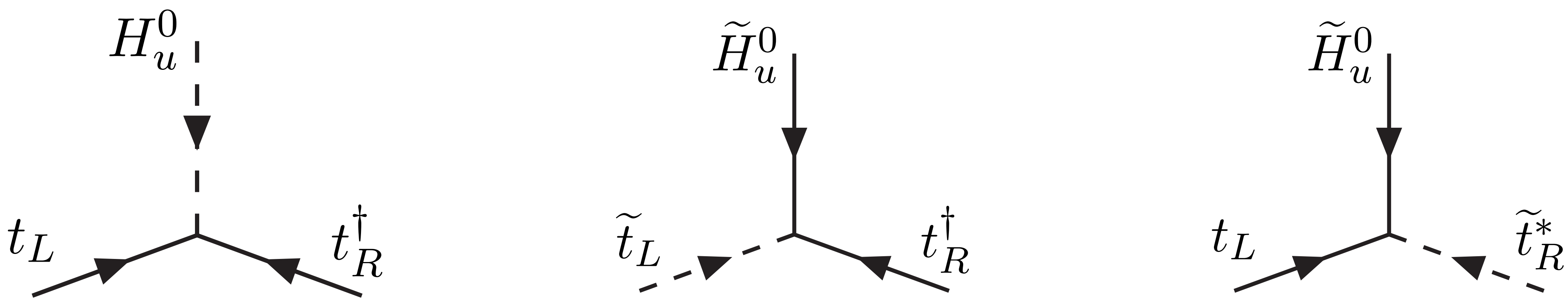


D-term: $\propto g^2$

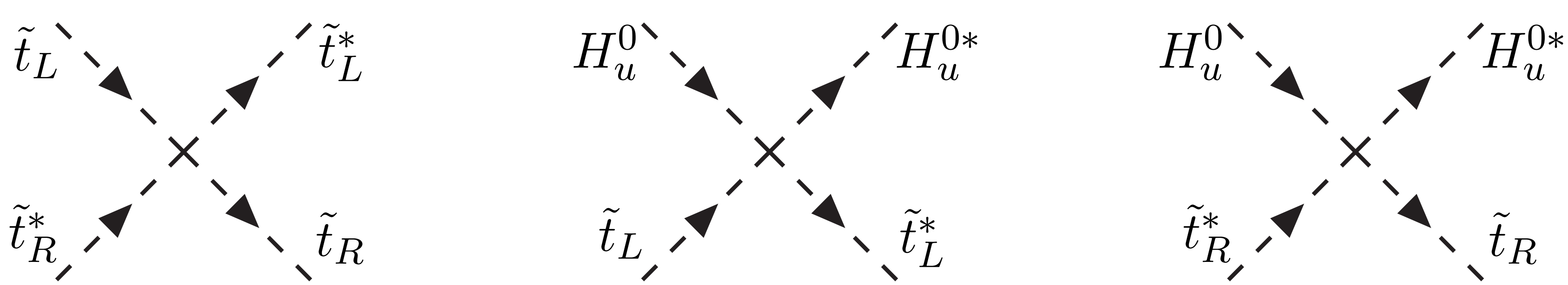


Interactions.

- SM fermions (such as the top quark) receive masses by coupling to the Higgs boson.

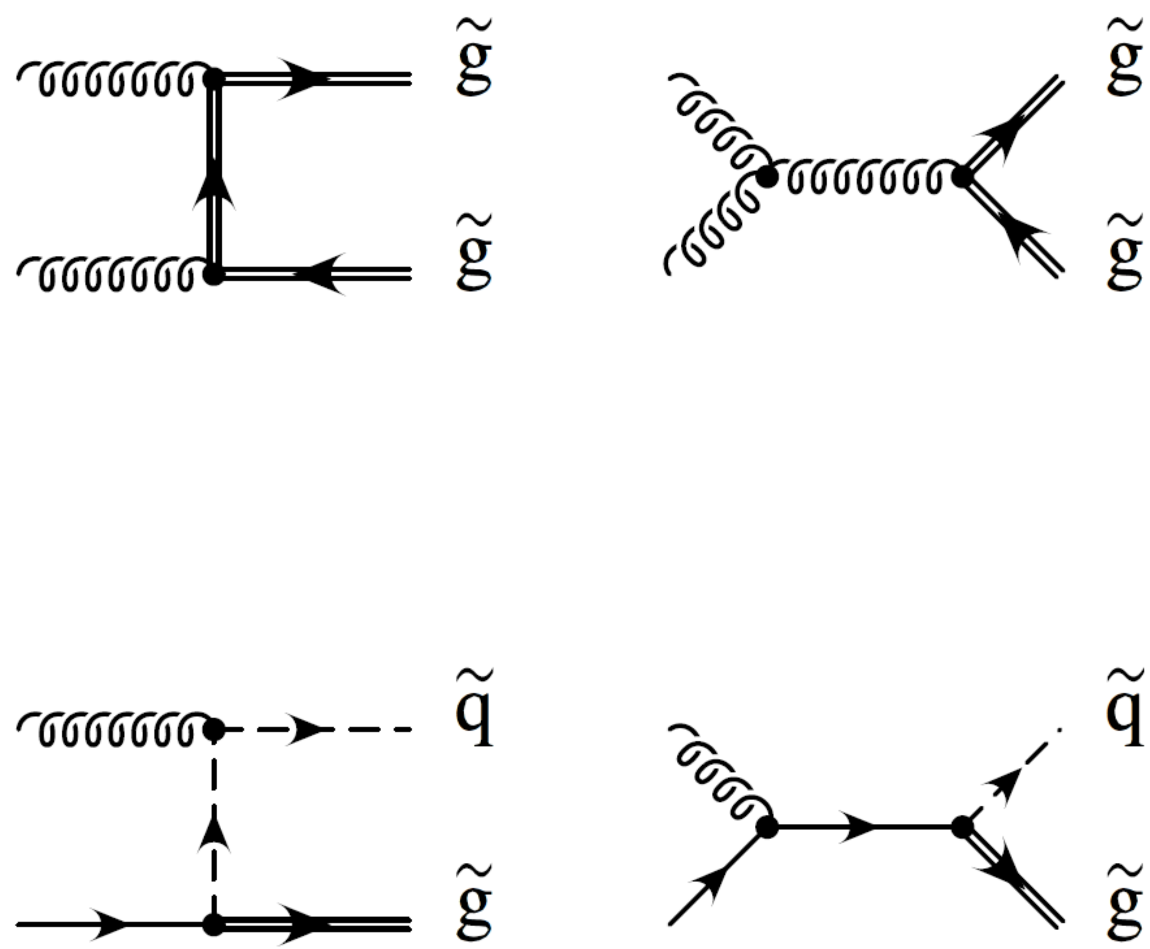


F-terms:



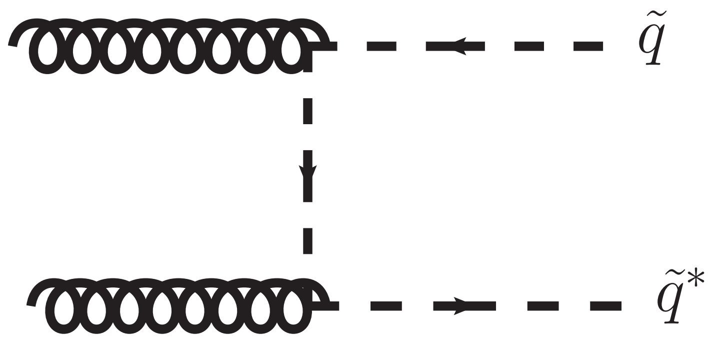
Examples of production: colored

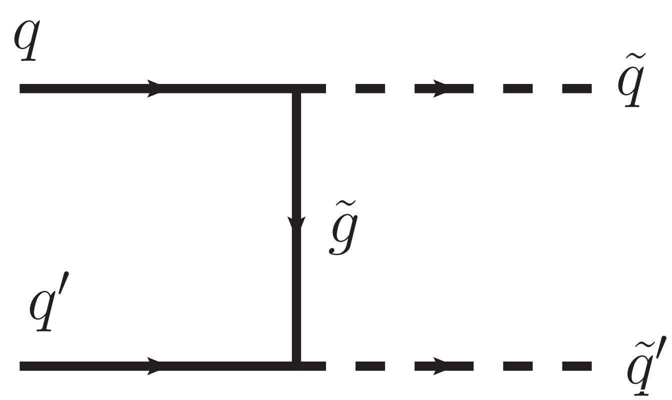
- Squark and gluino production.



Examples of production

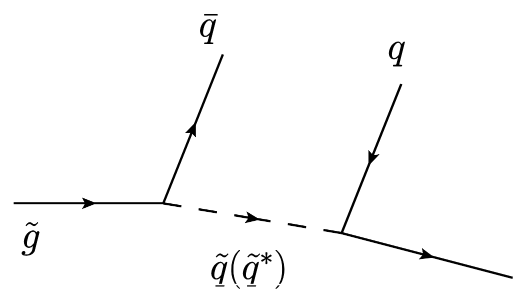
- Squark pair



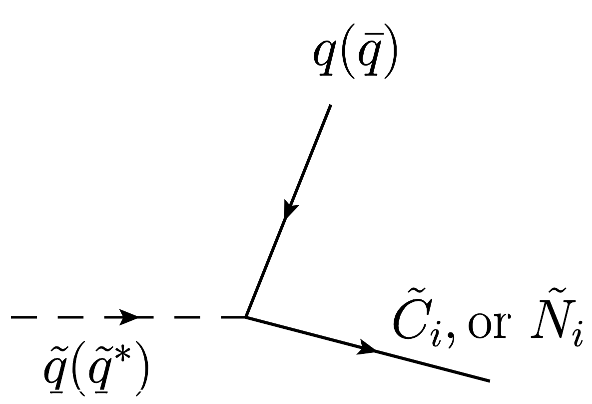


Decay of squark and gluino

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

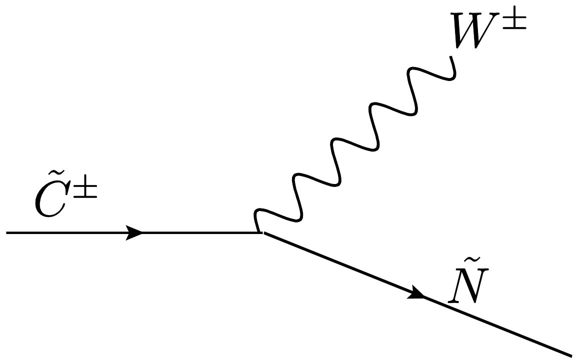


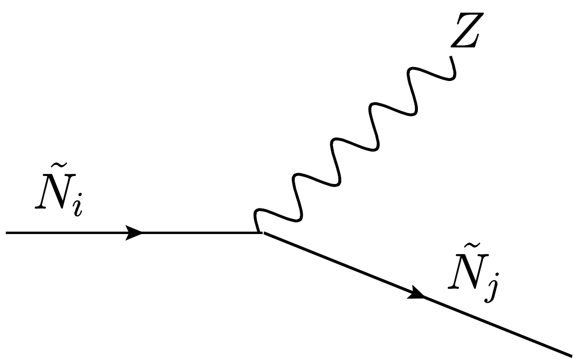
- Squark decay.
  - Jet +
    - To gluino, then go through off-shell squark.
    - To chargino or neutralino.



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).

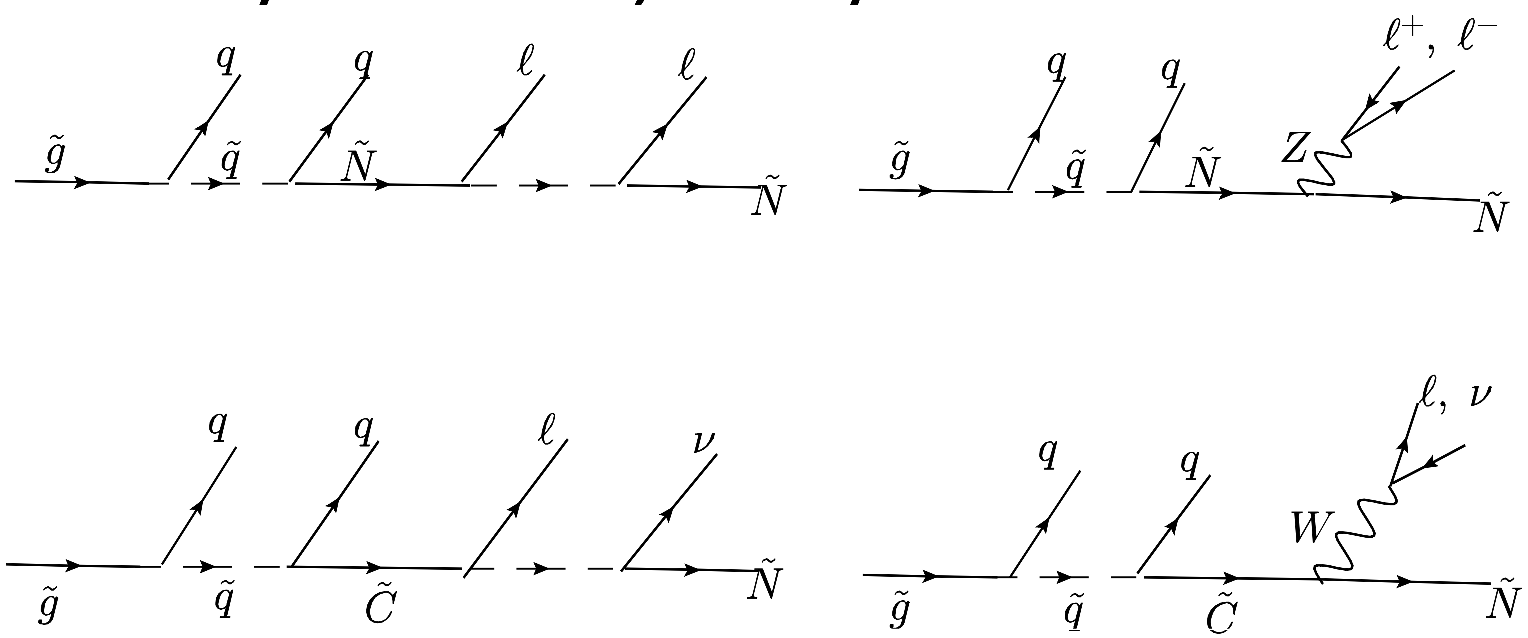
Simple rules.

- 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.

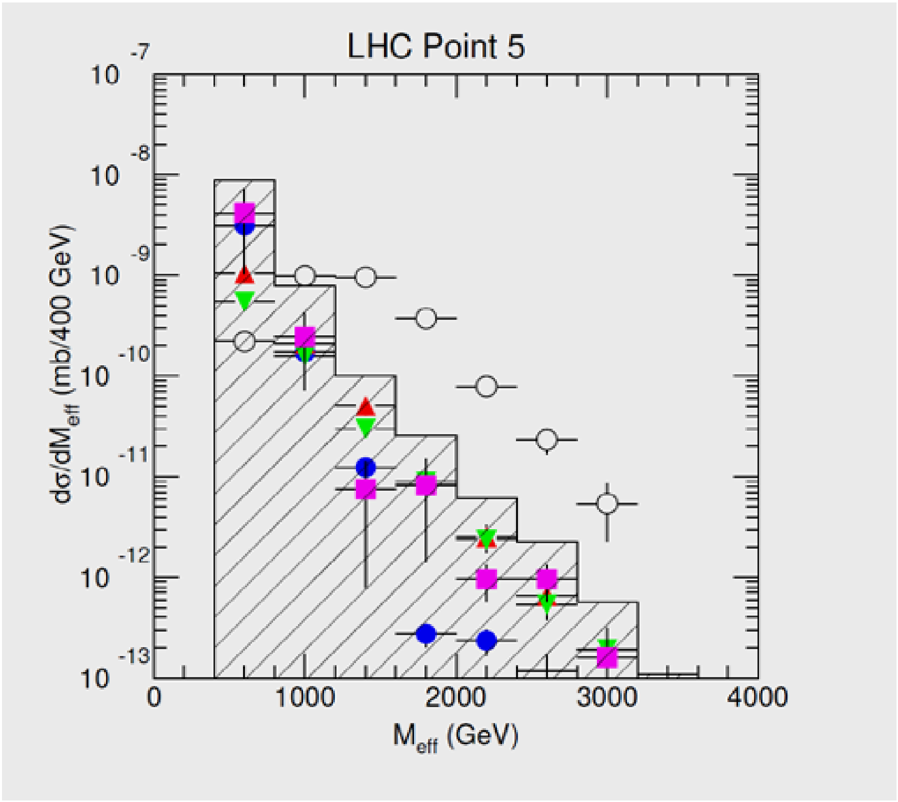
- Inclusive counts. Useful for signal >> backrgound.

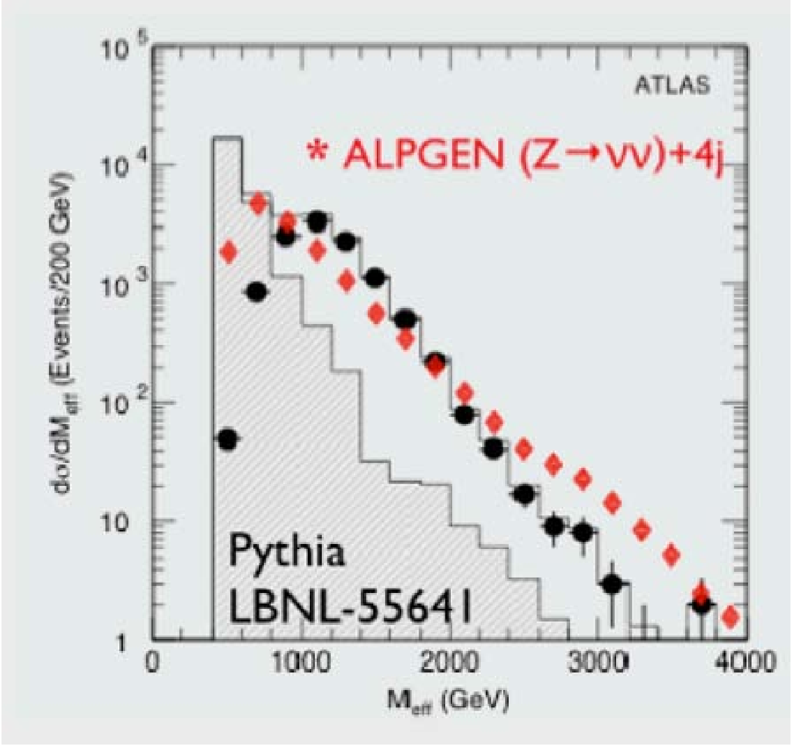
$n_j \times$ jet	b-jet non-b-jet
$+$	
$n_\ell \times$ lepton	ℓ all flavor and charge combo: e.g. $2\ell \rightarrow 21$ comb.
$+$	
$n_\gamma \times \gamma$	

Kinematical features: transverse variables.

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

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

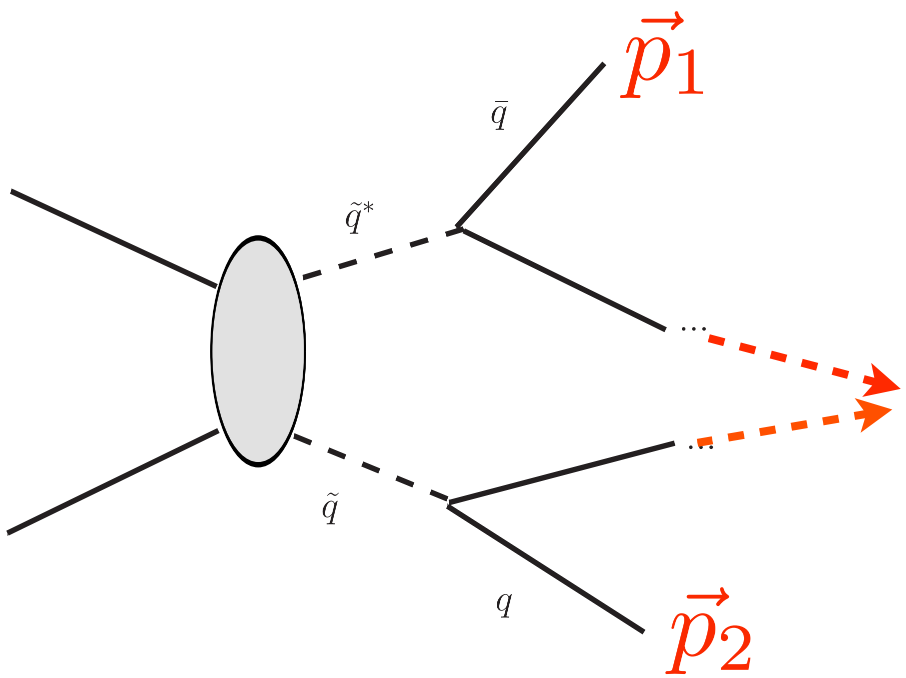




Be careful.

Gianotti and Mangano, 2005

Another example: α_T



momenta labelled so that $p_{1T} \geq p_{2T}$

missing particles, total momentum $\vec{p}_3$

$$\vec{p}_{1T} + \vec{p}_{2T} + \vec{p}_{3T} = 0$$

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

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

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

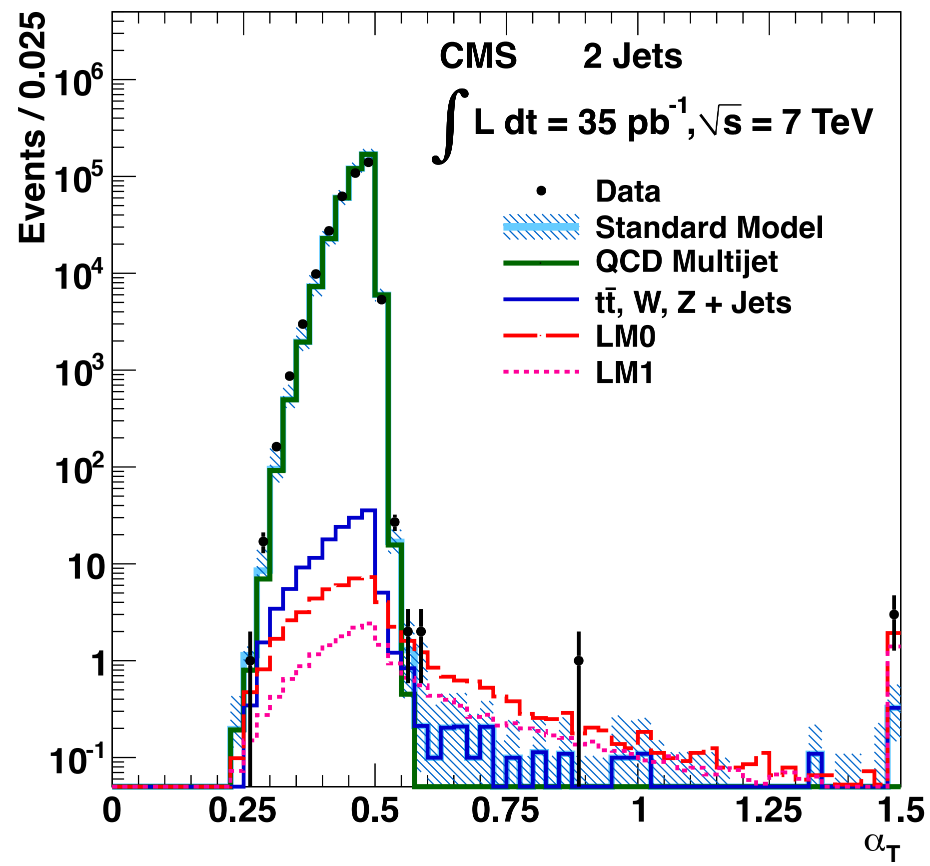
α_T can be either <1/2 (more often), or > 1/2

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.

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



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.

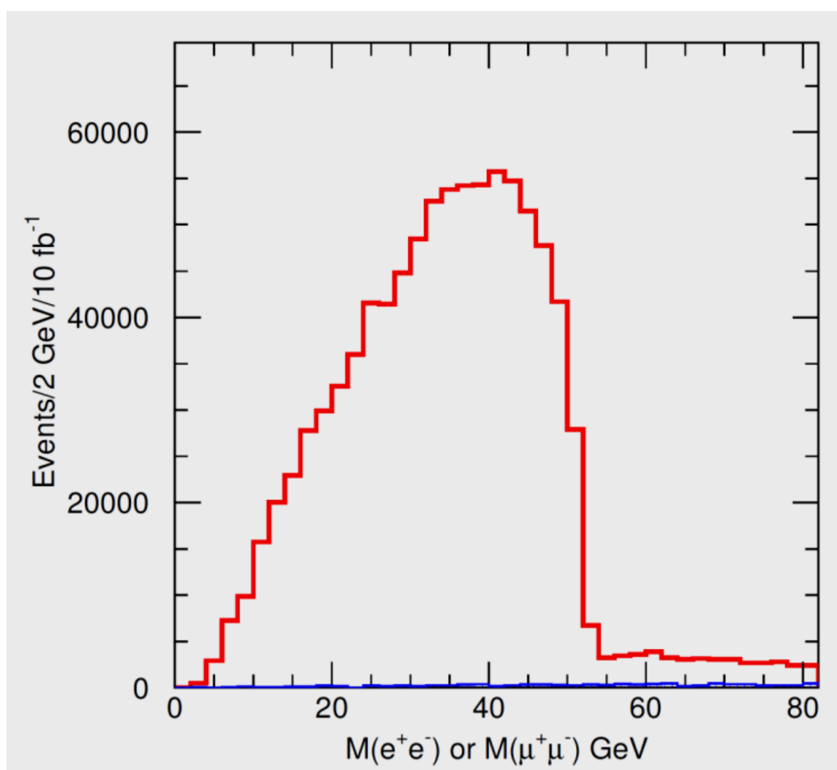
For a review: See LW and I. Yavin, 2008

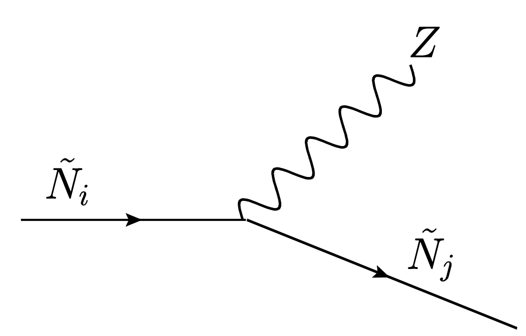
- More complicated invariant masses in longer decay chains possibly useful, but feature is less sharp. May need high statistics as well.

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.



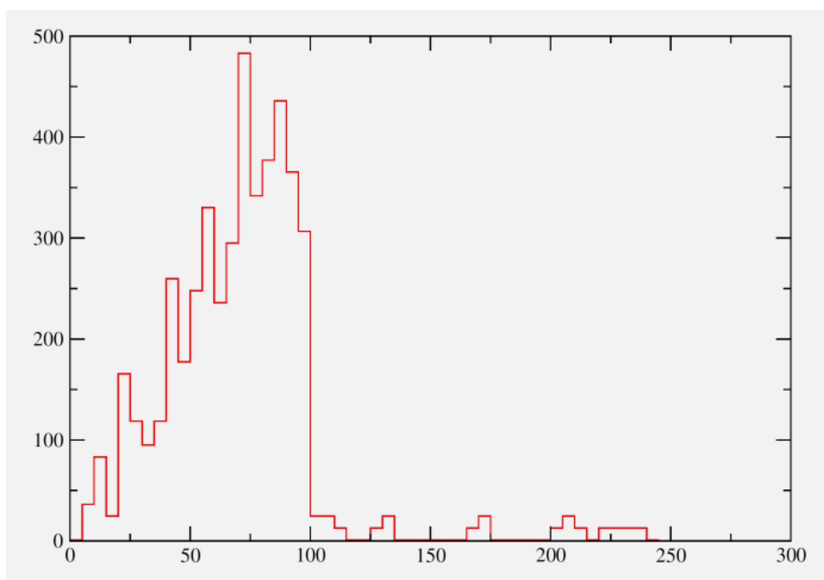


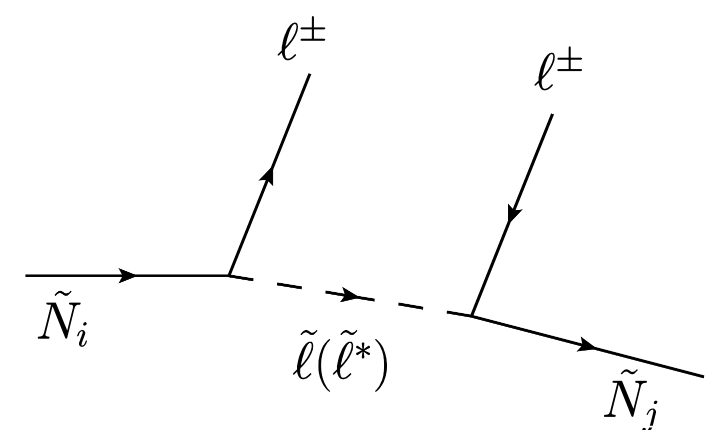
$M_{\tilde{N}_2} - M_{\tilde{N}_1} < m_Z \longrightarrow \tilde{N}_2 \to \tilde{N}_1 + \ell^+ + \ell^-$ Only 3-body

$m_{\ell\ell} = \sqrt{(p_{\ell+}^2 + p_{\ell-}^2)} \longrightarrow$ 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.





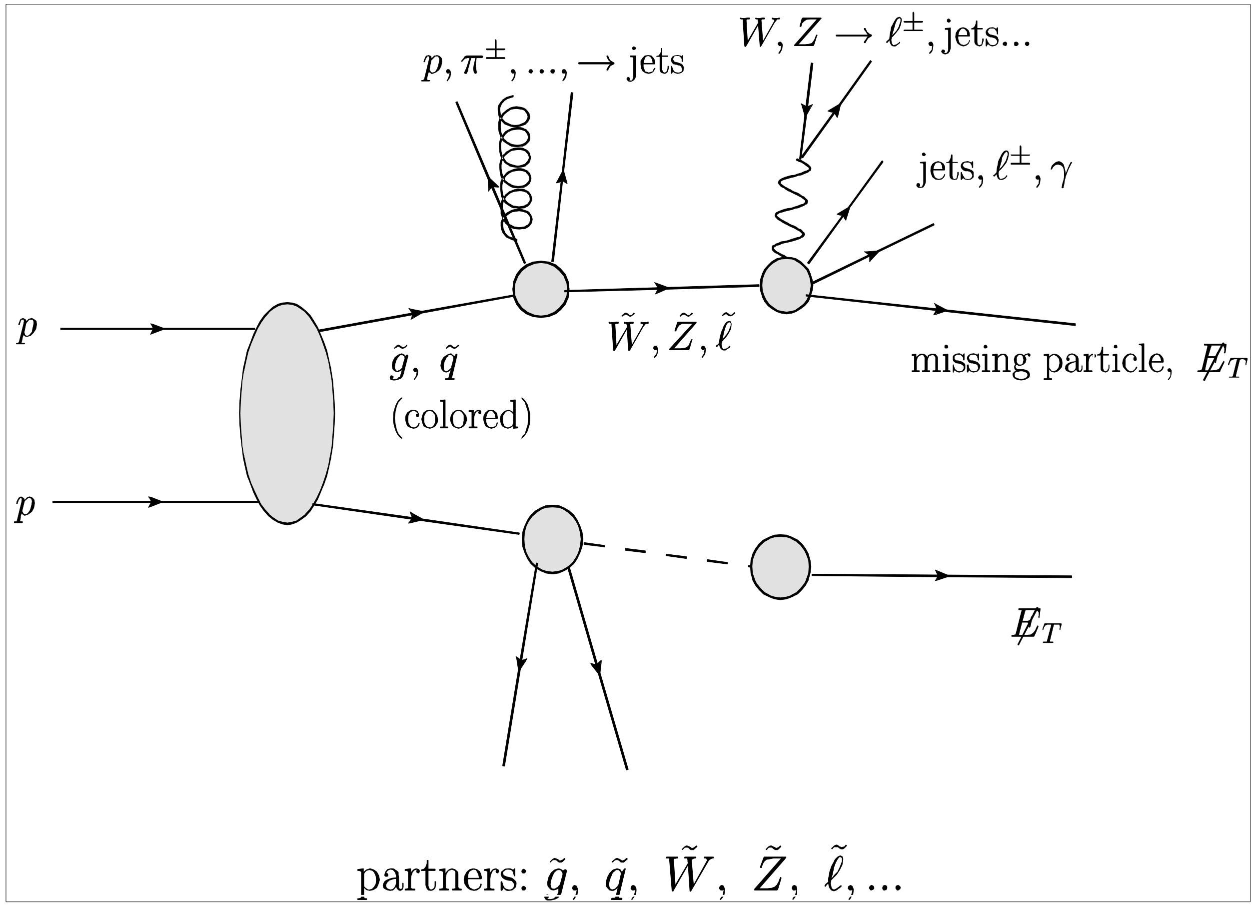
$$m_{\tilde{\ell}} < M_{\tilde{N}_2} \quad \longrightarrow \tilde{N}_2 \to \tilde{N}_1 + [\tilde{\ell}] \to \tilde{N}_1 + \ell^+ + \ell^-$$

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

- 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.

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

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

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

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

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

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

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

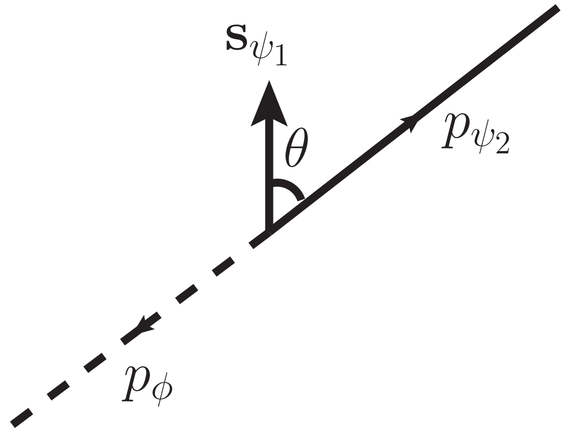
- Multiple b, multiple lepton final state.
  - Good early discovery potential.
  - Challenging to interpret: top reconstruction

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

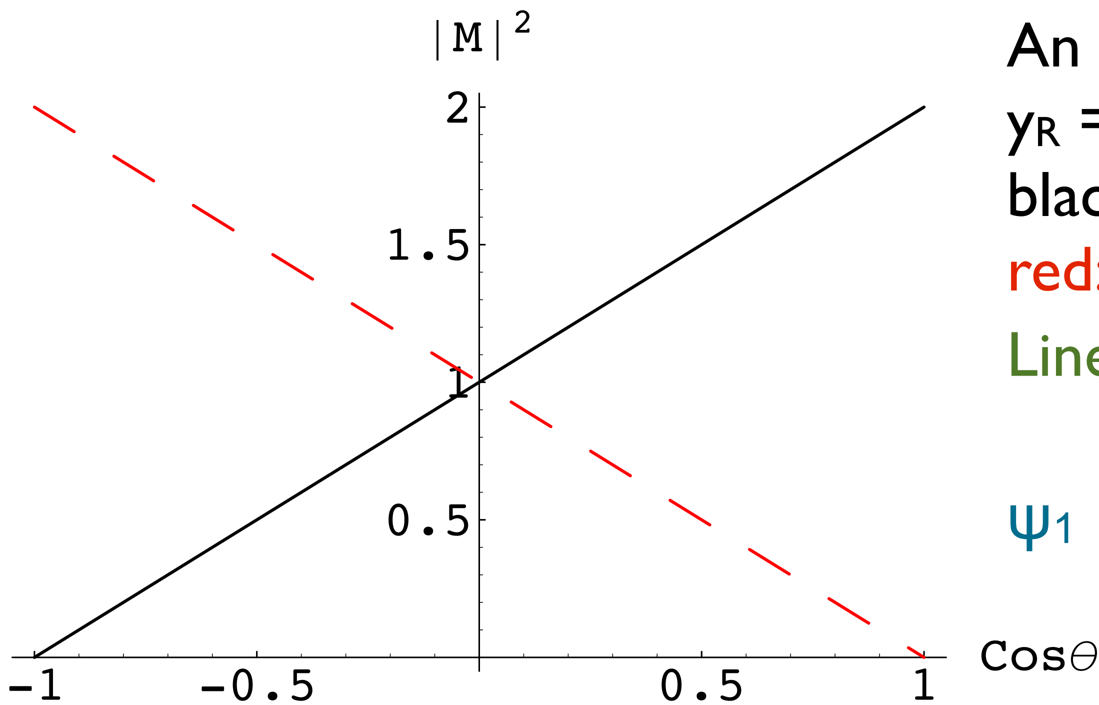


$$\psi_1 \to \psi_2 + \phi$$

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

- 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,

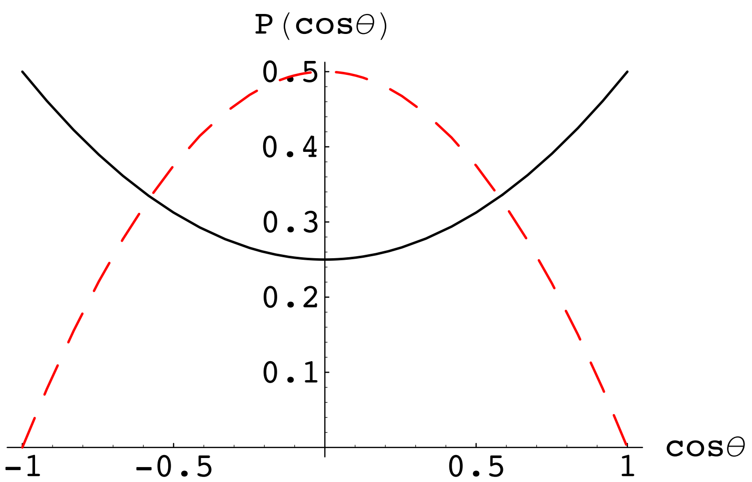
red: ψ_1 left-handed

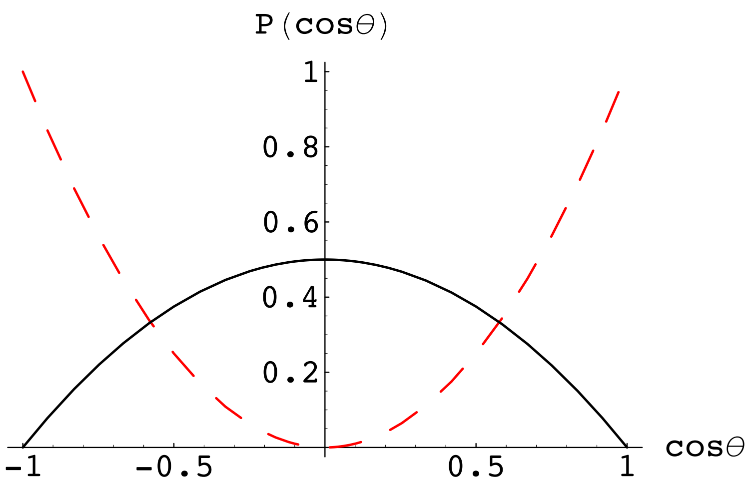
Linear in $\cos\theta$

ψ_1 not polized, no correlation, no spin information

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

Spin-1





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

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

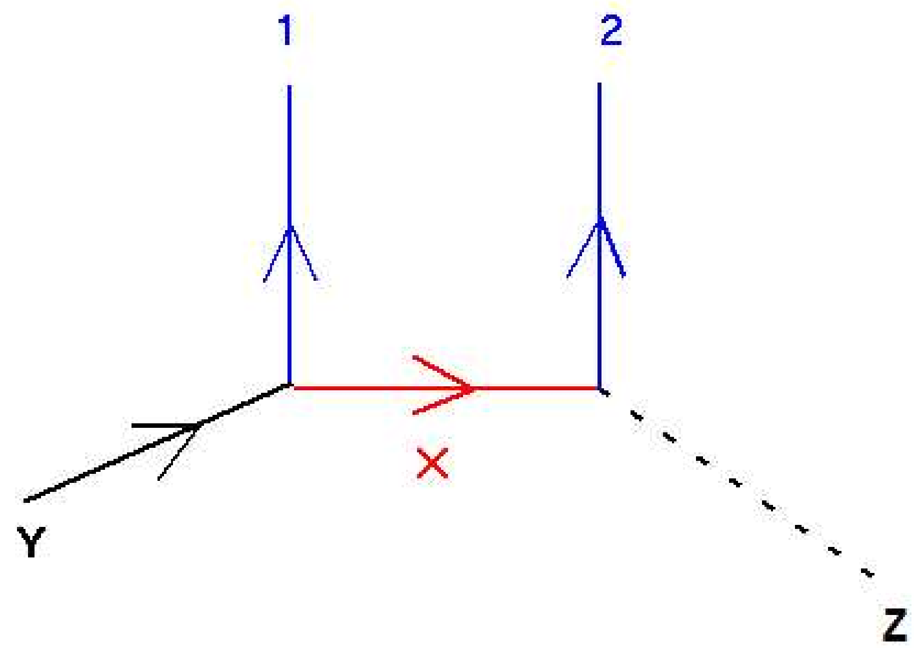
$$A'_{\text{transverse}} \to \phi_1 + \phi_2$$

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

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

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

Example of spin measurement



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

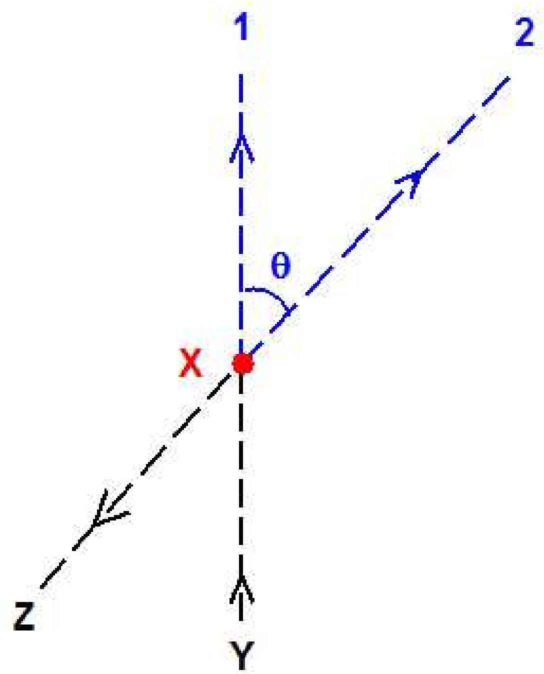
We are interested in the spin of **X** (on-shell).

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 $\mathrm{J_X}$

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

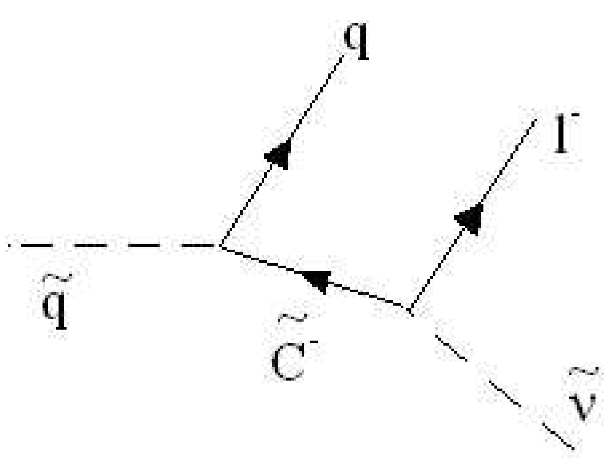
In principle, fitting the degree of this polynomial tells the the spin of X.

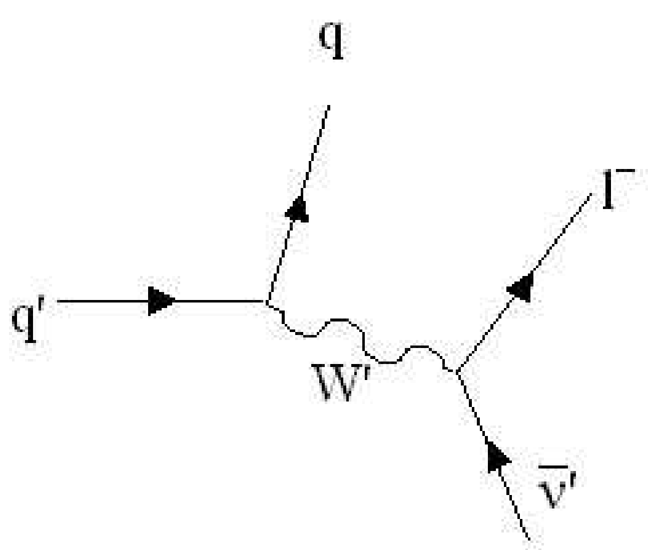
In practice, whether the coefficient a, b, ... are non-zero depends on the chirality of the coupling between X and 1, 2, Z, Y, and the mass differences between them.

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

Example: SUSY vs spin-1 partner

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





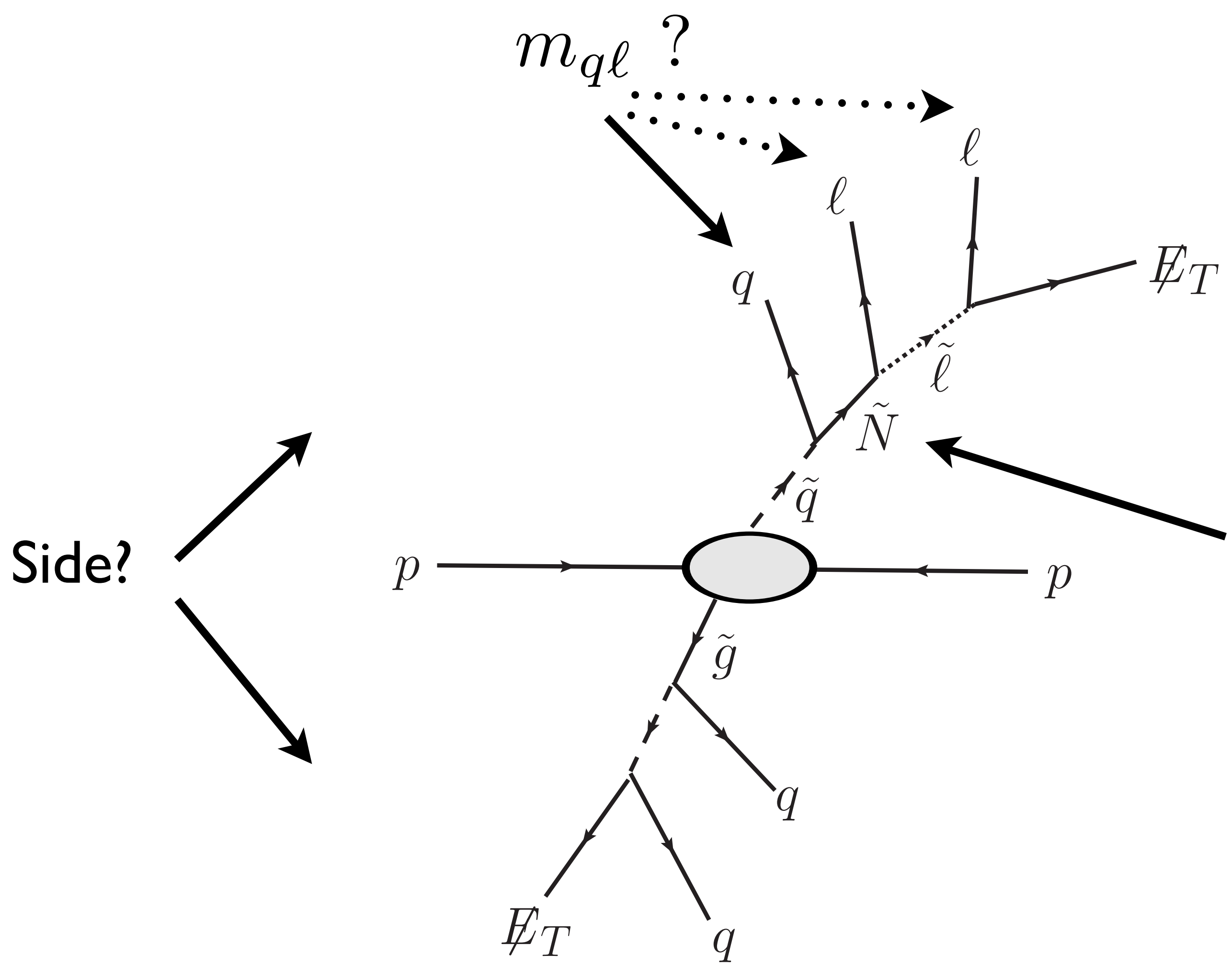
$\propto t_{q\ell} + ...$
$\tilde{q} - q - \tilde{C}$ chiral
q boosted
$\tilde{C} - \tilde{\nu} - \ell$ chiral

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

Lepton colliders

- Fixed c.o.m.
- Much cleaner environment.
- Energy not as high.