Top Quark Physics

Helmholtz - DIAS International Summer School 2019

Markus Schulze

Humboldt-University Berlin

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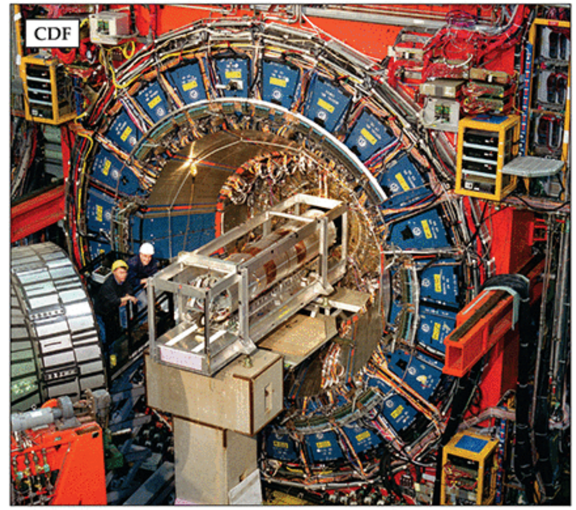
1.a: Top Quark Discovery

Physics Today ,
Volume 68, Issue 4
10.1063/PT.3.2749



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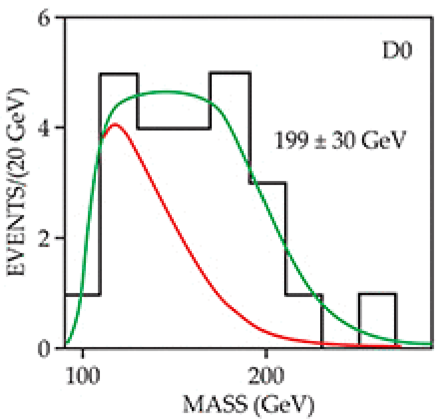

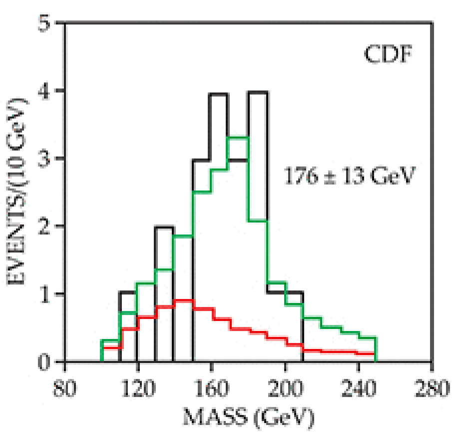

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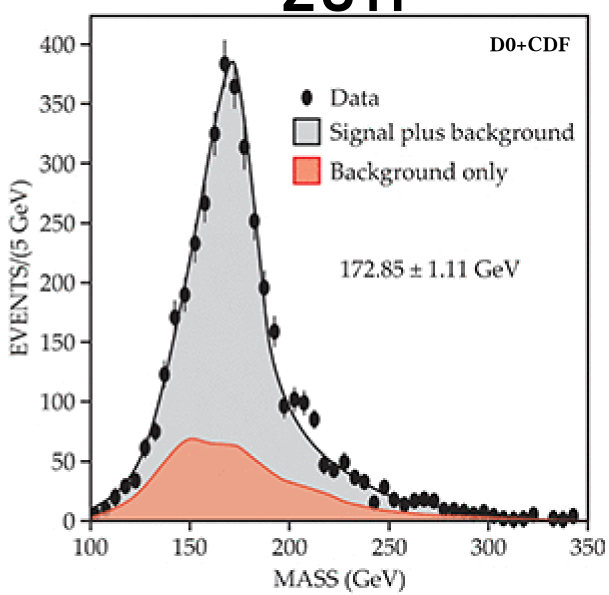

1.a: Top Quark Discovery

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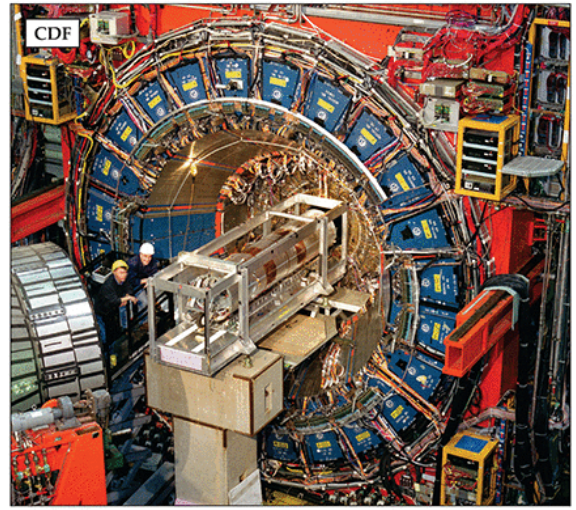

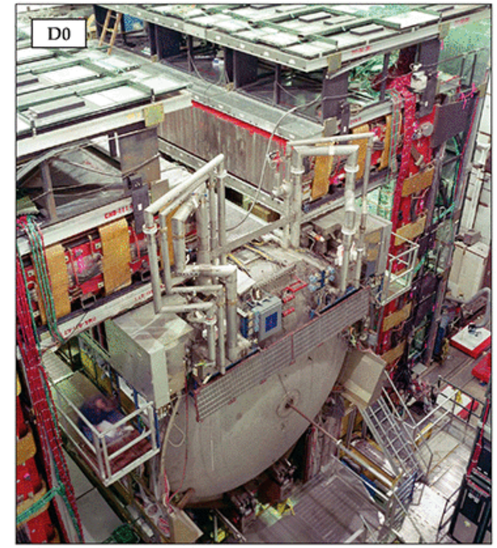

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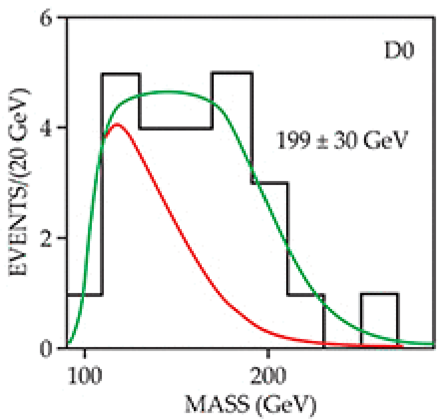

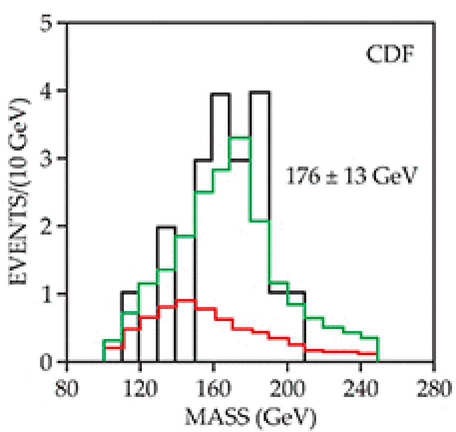

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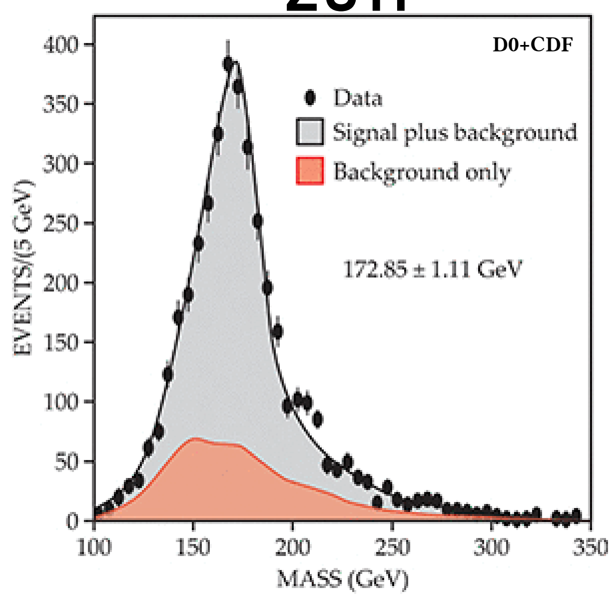
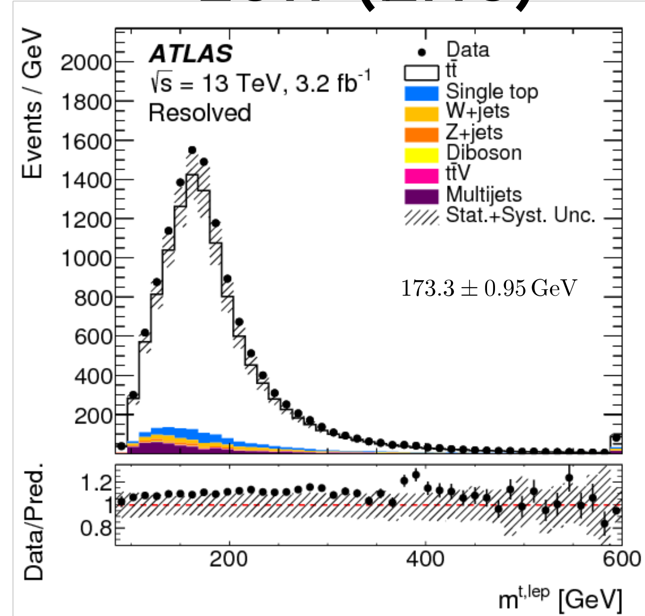
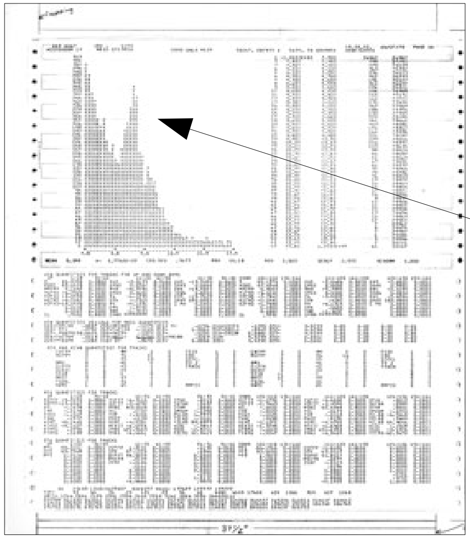


2017 (LHC)



1.b: Pre-Discovery

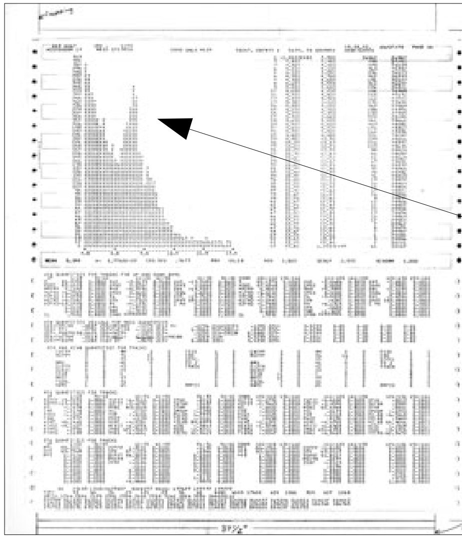


1977: Discovery of the bottom quark

E288 Experiment at Fermilab

$\Upsilon = (b\bar{b})$ at 9.5 GeV

1.b: Pre-Discovery



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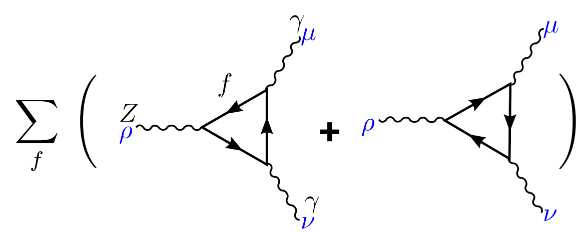
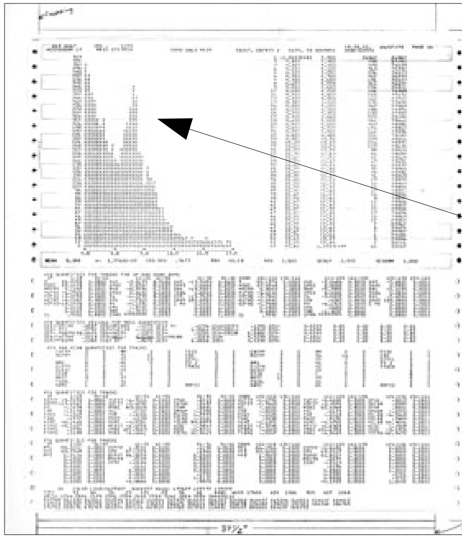


1.b: Pre-Discovery



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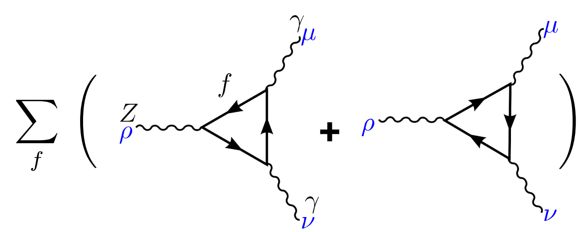


$$\sum_{f=t,b,\nu_\tau,\tau} g_{\text{ax}}^f Q_f^2 = \left(+\frac{1}{2}\right)\left(+\frac{2}{3}\right)^2 + \left(-\frac{1}{2}\right)\left(-\frac{1}{3}\right)^2 + \left(+\frac{1}{2}\right)(0)^2 + \left(-\frac{1}{2}\right)(-1)^2 = 0$$

1.b: Pre-Discovery Mass Estimates

1) Perturbativity: $\mathcal{L}_{\rm SM} \supset y_t\,(\bar{t}_{\rm L} t_{\rm R} + {\rm h.c.}) \left(\frac{v+H}{\sqrt{2}}\right)$ with $y_t = \frac{m_t}{v}$

Assume $\frac{y_t^2}{4\pi} < 1$ (i.e. perturbative) $\rightarrow$ $m_t < \sqrt{4\pi} v \approx 872\,{\rm GeV}$

2) Unitarity: Unitarity bound for elastic $t\bar{t} \rightarrow t\bar{t}$ scattering yields $|{\rm Re}(a_0)| \leq \frac{1}{2}$

with $a_0(t\bar{t} \rightarrow t\bar{t}) = -\frac{3}{8}\frac{\alpha}{s_w^2}\frac{m_t^2}{M_W^2}$ $\rightarrow$ $m_t \leq 500\,{\rm GeV}$

3) Electroweak Precision Data:

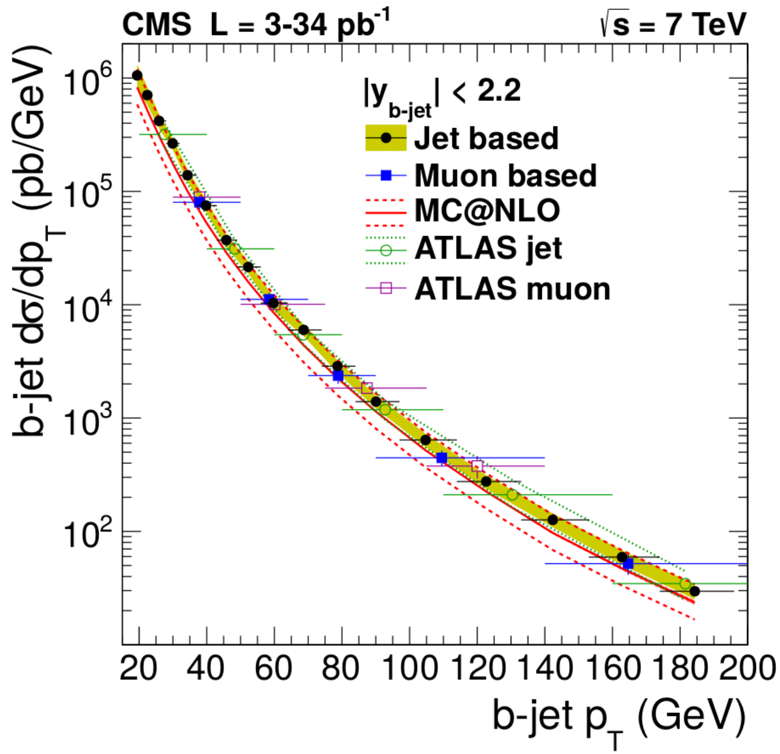
No discovery at LEP $\rightarrow$ $m_t \gtrsim 100\,{\rm GeV}$

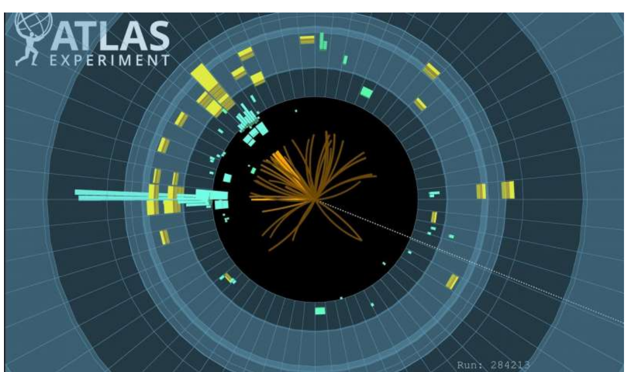
Measurement of *Z* and *W* boson properties: $\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = \begin{cases} 1 & \text{at LO} \\ \neq 1 & \text{beyond LO} \end{cases}$

$$\rho - 1 = \frac{\Sigma_{\rm T}^{ZZ}(0)}{M_Z^2} - \frac{\Sigma_{\rm T}^{WW}(0)}{M_W^2} \approx \alpha\left(\#\frac{m_t^2}{M_W^2} + \#\log\frac{M_H^2}{M_W^2} + \ldots\right) \rightarrow m_t = 177 \pm 27\,{\rm GeV}$$

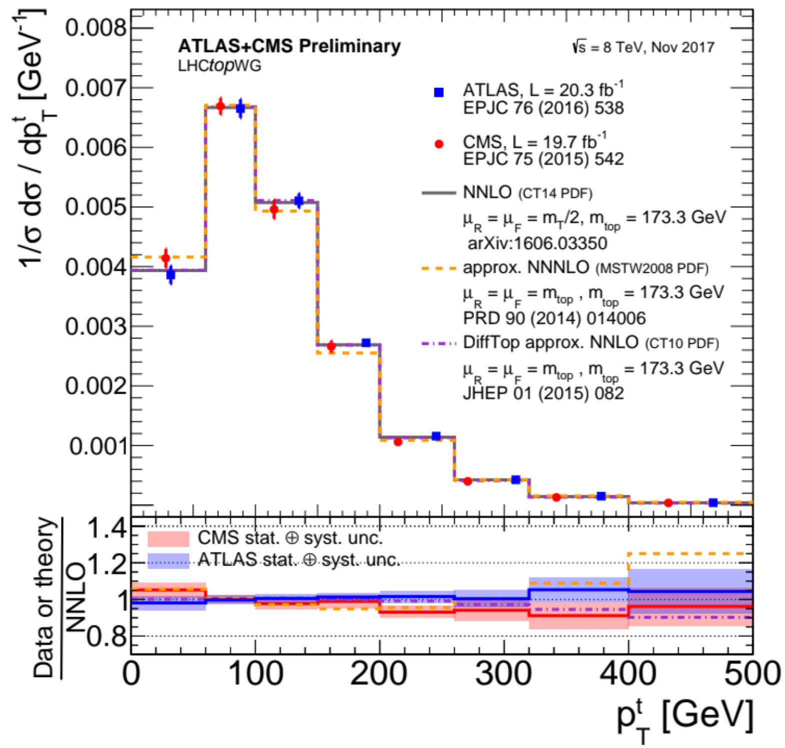
1.c: Top Quark Pair Production at Hadron Colliders

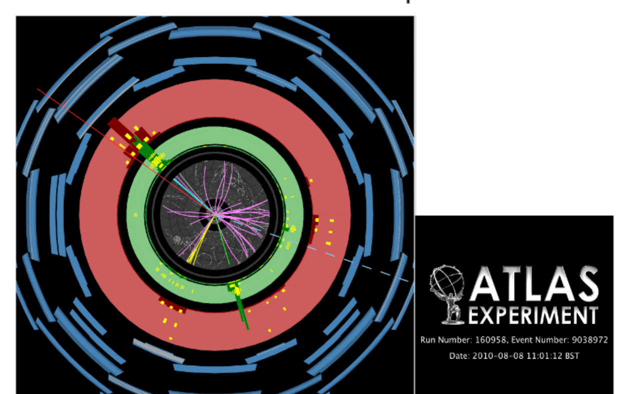
Bottom quark pairs





Top quark pairs





1.c: Top Quark Pair Production at Hadron Colliders

```
In[1]:= M2qq[beta_, z_] = (2 Pi)^2 * as^2 * 8 / 9 (2 - beta^2 + beta^2 z^2);
        Flux = 1 / (2 * s);
        dPS = beta / (16 Pi);
        dsigmaqq[beta_, z_] = Flux * dPS * M2qq[beta, z];
        sigmaqq[beta_] = Integrate[dsigmaqq[beta, z], {z, -1, 1}] //. s → 4 m^2 / (1 - beta^2) // FullSimplify
```

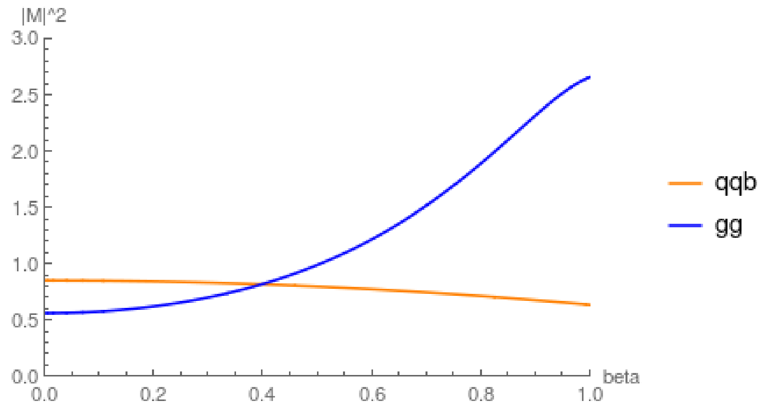
Out[5]= $\frac{as^2\,beta\,(3 - 4\,beta^2 + beta^4)\,\pi}{27\,m^2}$

```
In[6]:= M2gg[beta_, z_] = (2 Pi)^2 *as^2 * (9 - 2 + 9 z^2 beta^2) / ((1 - z^2 beta^2)^2 * 3 * 2) (1 - z^4 beta^4 + 2 beta^2 (1 - z^2) (1 - beta^2));
        dsigmagg[beta_, z_] = Flux * dPS * M2gg[beta, z];
        sigmagg[beta_] = Integrate[dsigmagg[beta, z], {z, -1, 1}, Assumptions → {beta < 1, beta > 0}] //. s → 4 m^2 / (1 - beta^2) // FullSimplify
```

Out[8]= $\frac{as^2\,(-1 + beta^2)\,\pi\,\left(59\,beta - 31\,beta^3 + (33 - 18\,beta^2 + beta^4)\,\mathrm{Log}\left[-1 + \frac{2}{1+beta}\right]\right)}{96\,m^2}$

```
as = 0.11; m = 173.0;
Plot[{M2qq[beta, 0.7], M2gg[beta, 0.7]}, {beta, 0, 1},
 PlotRange → {{0, 1}, {0, 3}}, PlotStyle → {Orange, Blue},
 PlotLegends → Placed[LineLegend[{"qqb", "gg"}], Right],
 AxesLabel → {"beta", "|M|^2"}]
```

Out[12]=



1.c: Top Quark Pair Production at Hadron Colliders

In[1]:=
```
M2qq[beta_, z_] = (2 Pi)^2 * as^2 * 8 / 9 (2 - beta^2 + beta^2 z^2);
Flux = 1 / (2 * s);
dPS = beta / (16 Pi);
dsigmaqq[beta_, z_] = Flux * dPS * M2qq[beta, z];
sigmaqq[beta_] = Integrate[dsigmaqq[beta, z], {z, -1, 1}] //. s → 4 m^2 / (1 - beta^2) // FullSimplify
```

Out[5]= $\frac{\text{as}^2\,\text{beta}\,\left(3-4\,\text{beta}^2+\text{beta}^4\right)\pi}{27\,\text{m}^2}$

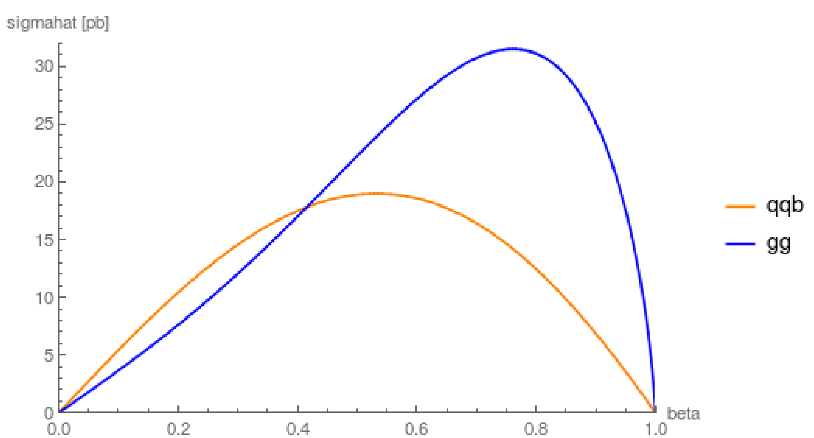
In[6]:=
```
M2gg[beta_, z_] = (2 Pi)^2 * as^2 * (9 - 2 + 9 z^2 beta^2) / ((1 - z^2 beta^2)^2 * 3 * 2) (1 - z^4 beta^4 + 2 beta^2 (1 - z^2) (1 - beta^2));
dsigmagg[beta_, z_] = Flux * dPS * M2gg[beta, z];
sigmagg[beta_] = Integrate[dsigmagg[beta, z], {z, -1, 1}, Assumptions → {beta < 1, beta > 0}] //. s → 4 m^2 / (1 - beta^2) // FullSimplify
```

Out[8]= $\frac{\text{as}^2\left(-1+\text{beta}^2\right)\pi\left(59\,\text{beta}-31\,\text{beta}^3+\left(33-18\,\text{beta}^2+\text{beta}^4\right)\text{Log}\left[-1+\frac{2}{1+\text{beta}}\right]\right)}{96\,\text{m}^2}$

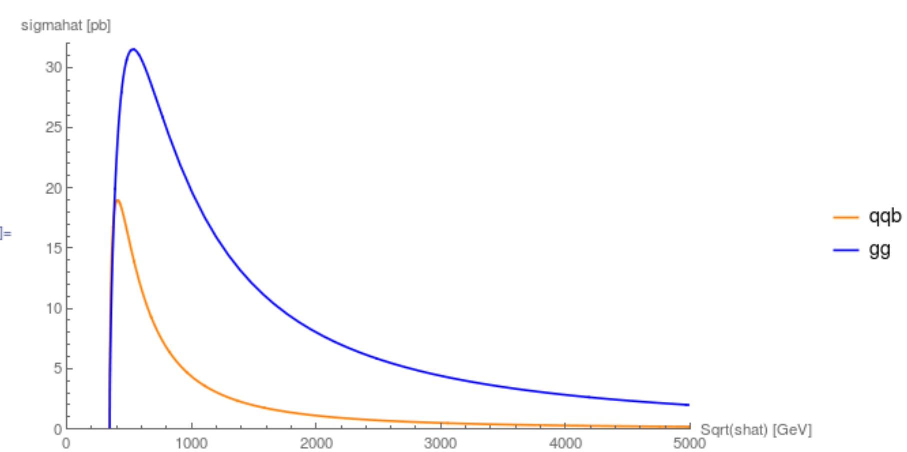
In[41]:=
```
pbGeVm2 = 0.389379 * 10^9;
Plot[{pbGeVm2 * sigmaqq[beta], pbGeVm2 * sigmagg[beta]}, {beta, 0, 1},
 PlotRange → {{0, 1}, {0, 32}}, PlotStyle → {Orange, Blue},
 PlotLegends → Placed[LineLegend[{"qqb", "gg"}], Right], AxesLabel → {"beta", "sigmahat [pb]"}]

beta = Sqrt[1 - 4 m^2 / sqrtshat^2];
Plot[{pbGeVm2 * sigmaqq[beta], pbGeVm2 * sigmagg[beta]} , {sqrtshat, 2 * 173, 5000},
 PlotRange → {{0, 5000}, {0, 32}}, PlotStyle → {Orange, Blue},
 PlotLegends → Placed[LineLegend[{"qqb", "gg"}], Right], AxesLabel → {"Sqrt(shat) [GeV]", "sigmahat [pb]"}]
```

Out[42]=



Out[40]=



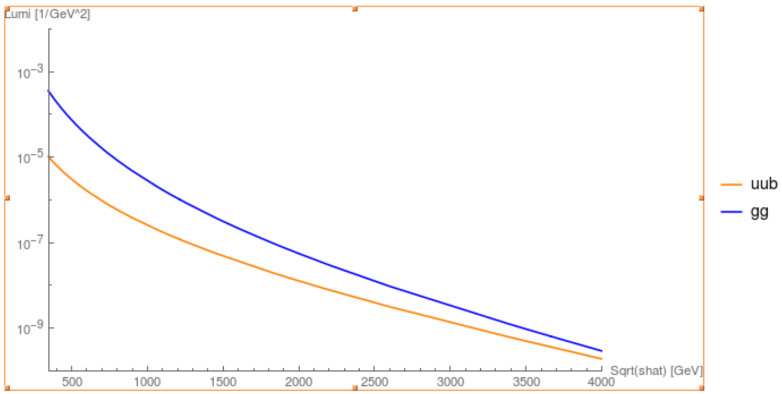
1.c: Top Quark Pair Production at Hadron Colliders

```
In[15]:= SetDirectory["/users/pep/mschulze/lib/nCTEQ_mma/"];
subDir = "./PDS"; (* PDS files are in subDir *)
filelist = FileNames["*.pds", subDir];
<< "pdfParsePDS.m";
pdf[x__] := pdfCTEQfunction[x];
pdfResetCTEQ;
pdfBatchCTEQparse[subDir];
proton = 3; glu = 0; up = 1; dn = 1; Aup = -1; Adn = -2;
xmin = pdfXmin[proton];
q0 = 173.0;

In[24]:= Lumigg[spart_, shadr_] := 1 / shadr * NIntegrate[1 / sig * pdf[sig / shadr, q0, glu, proton] * pdf[spart / sig, q0, glu, proton] , {sig, spart, shadr}, AccuracyGoal → 3, PrecisionGoal → 3, Method -> "LocalAdaptive"];
Lumiuub[spart_, shadr_] := 1 / shadr * NIntegrate[1 / sig * pdf[sig / shadr, q0, up, proton] * pdf[spart / sig, q0, Aup, proton] , {sig, spart, shadr}, AccuracyGoal → 3, PrecisionGoal → 3, Method -> "LocalAdaptive"];

In[26]:= LogPlot[{Lumiuub[En ^ 2, 13000 ^ 2], Lumigg[En ^ 2, 13000 ^ 2]}, {En, 2 * 173, 14000}, PlotPoints → 10, PlotStyle → {Orange, Blue}, PlotLegends → Placed[LineLegend[{"uub", "gg"}], Right],
 AxesLabel → {"Sqrt(shat) [GeV]", "Lumi [1/GeV^2]"}, PlotRange → {{2 * 173, 4000}, {10 ^ -10, 0.01}}]
```

Out[26]=




```
pb * pbGeVm2 * NIntegrate[ Hold[ 2 sqrtshat * sigmaqq[ beta] * Lumiuub[sqrtshat ^ 2, 13000 ^ 2] ], {sqrtshat, 2 * 173, 13000}, AccuracyGoal → 5, PrecisionGoal → 5, Method -> "GlobalAdaptive"]
Out[35]= 20.6754
In[36]:= pb * GeVm2 * NIntegrate[ Hold[2 sqrtshat * sigmagg[ beta] * Lumigg[sqrtshat ^ 2, 13000 ^ 2] ], {sqrtshat, 2 * 173, 13000}, AccuracyGoal → 5, PrecisionGoal → 5, Method -> "GlobalAdaptive"]
Out[36]= 9[illegible]1.432 p
```

$$\sigma_{PP}^{t\bar{t},\mathrm{LO}}(13\,\mathrm{TeV}) = 537\,\mathrm{pb} \qquad (gg : q\bar{q}) = (86\% : 14\%)$$ [MCFM]

$$\sigma_{PP}^{t\bar{t},\mathrm{data}}(13\,\mathrm{TeV}) = 818 \pm 43\,\mathrm{pb} \qquad \to 123\,\mathrm{Mio.}\ t\bar{t}\ \mathrm{pairs}$$ [ATLAS] (3.2 fb^{-1})

1.d: Going beyond Leading Order

Fixed order perturbation theory:

$$\hat{\sigma}^{t\bar{t}} = \alpha_s^2 \left(\hat{\sigma}^{\mathrm{LO}}_{\mathrm{QCD}} + \alpha_s \hat{\sigma}^{\delta\mathrm{NLO}}_{\mathrm{QCD}} \qquad\qquad\qquad\qquad \right)$$

1.d: Going beyond Leading Order

Fixed order perturbation theory:

$$\hat{\sigma}^{t\bar{t}} = \alpha_s^2 \left(\hat{\sigma}^{\text{LO}}_{\text{QCD}} + \alpha_s \hat{\sigma}^{\delta\text{NLO}}_{\text{QCD}} + \alpha \; \hat{\sigma}^{\delta\text{NLO}}_{\text{QCD-EW}} \qquad\qquad\qquad\qquad \right)$$

1.d: Going beyond Leading Order

Fixed order perturbation theory:

$$\hat{\sigma}^{t\bar{t}} = \alpha_s^2 \left(\hat{\sigma}^{\rm LO}_{\rm QCD} + \alpha_s \hat{\sigma}^{\delta\rm NLO}_{\rm QCD} + \alpha \, \hat{\sigma}^{\delta\rm NLO}_{\rm QCD\text{-}EW} + \alpha_s^2 \hat{\sigma}^{\delta\rm NNLO}_{\rm QCD} + \ldots\right)$$

1.d: Going beyond Leading Order

Fixed order perturbation theory:

$$\hat{\sigma}^{t\bar{t}} = \alpha_s^2 \left(\hat{\sigma}_{\text{QCD}}^{\text{LO}} + \alpha_s \hat{\sigma}_{\text{QCD}}^{\delta\text{NLO}} + \alpha \; \hat{\sigma}_{\text{QCD-EW}}^{\delta\text{NLO}} + \alpha_s^2 \hat{\sigma}_{\text{QCD}}^{\delta\text{NNLO}} + \ldots\right) + \alpha^2 \; \hat{\sigma}_{\text{EW}}^{\text{LO}}$$

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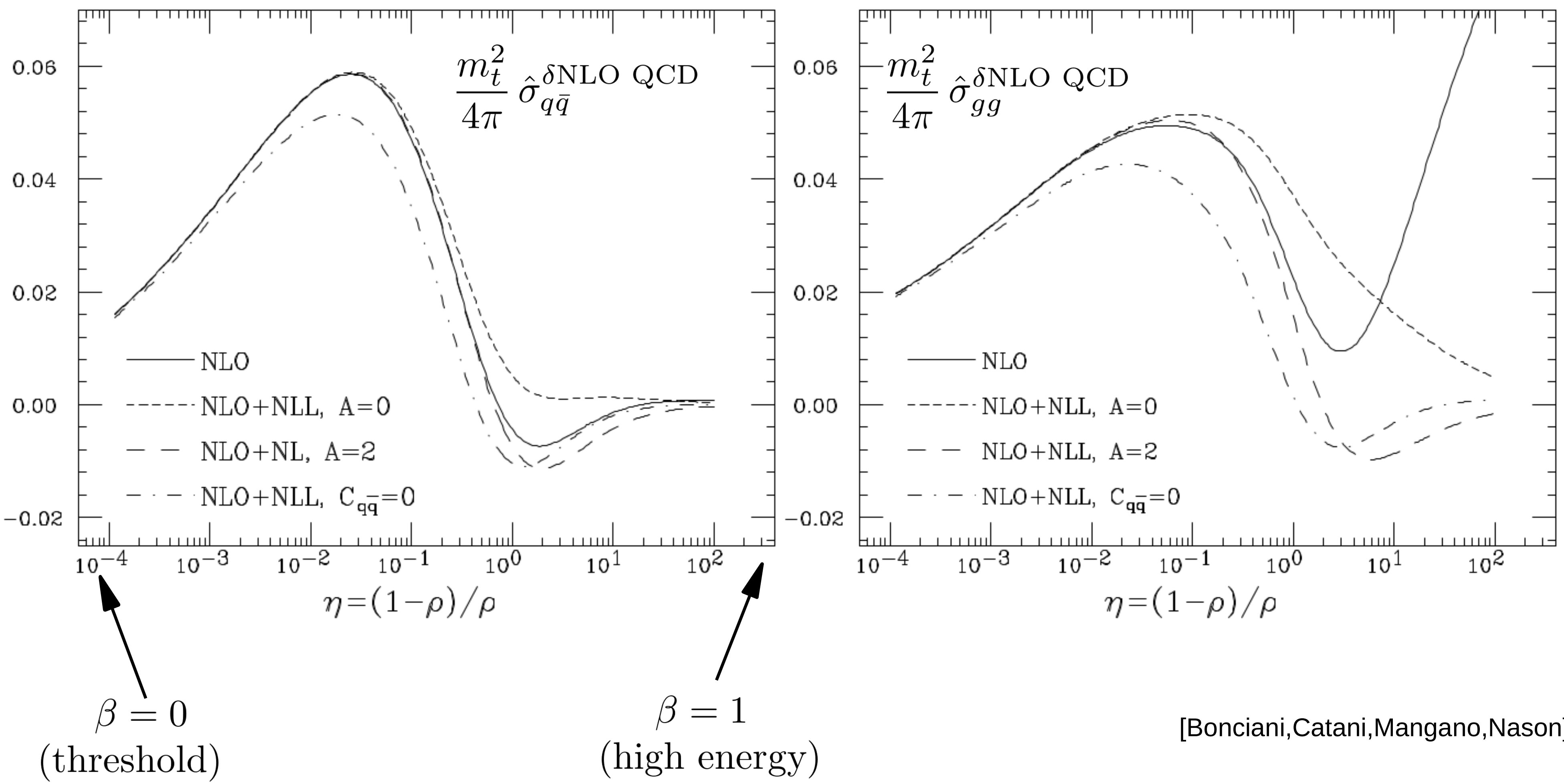
Fixed order perturbation theory:

$$\sigma^{t\bar{t}} = \alpha_s^2 \left(\sigma_{\text{QCD}}^{\text{LO}} + \alpha_s \sigma_{\text{QCD}}^{\delta\text{NLO}} + \alpha\, \sigma_{\text{QCD-EW}}^{\delta\text{NLO}} + \alpha_s^2 \sigma_{\text{QCD}}^{\delta\text{NNLO}} + \ldots\right) + \alpha^2\, \sigma_{\text{EW}}^{\text{LO}}$$

O(10%) O(1%) O(1%) O(0.005%)

For precision at the few percent level, NNLO QCD and EW NLO corrections are required.

1.d: Going beyond Leading Order



[Bonciani,Catani,Mangano,Nason]

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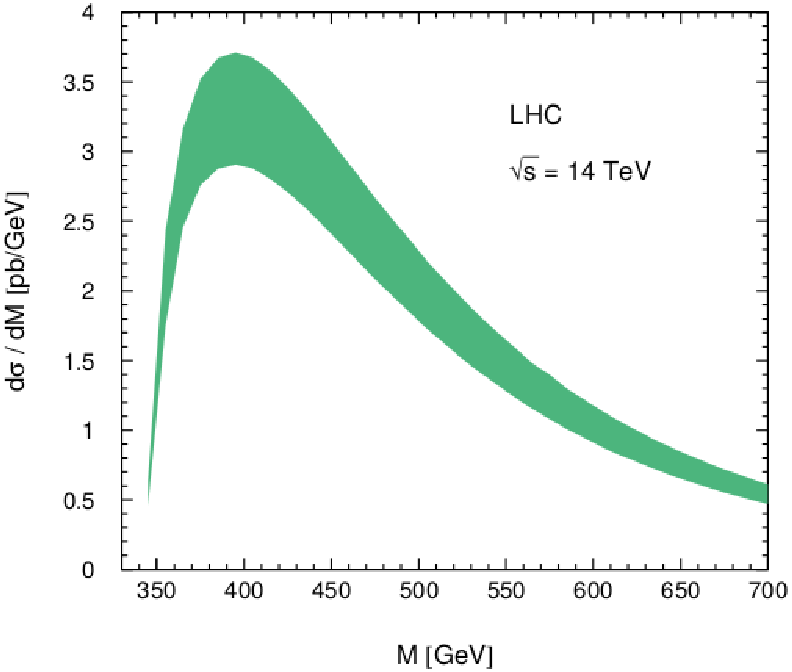

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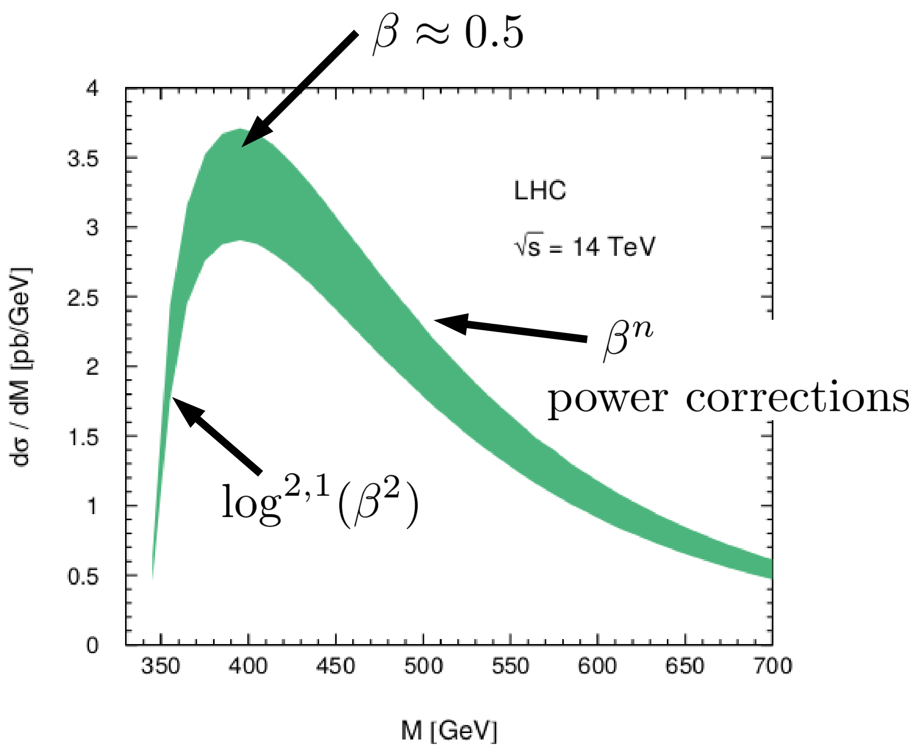

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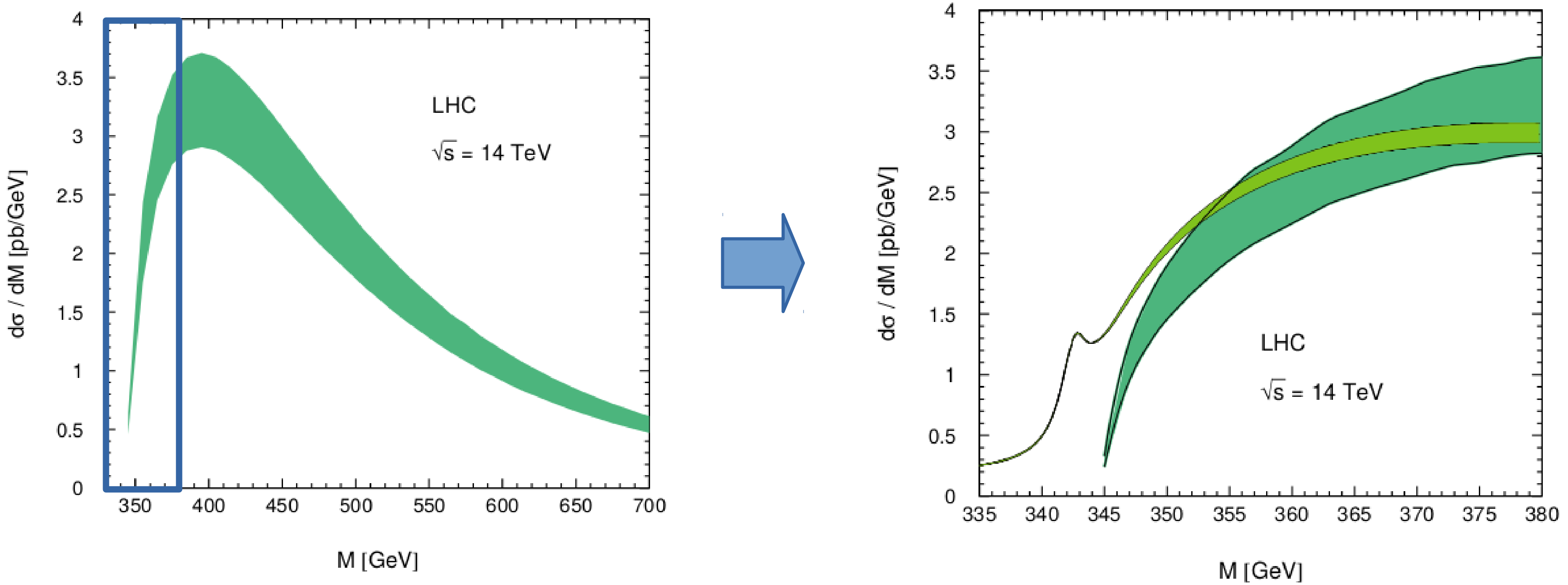

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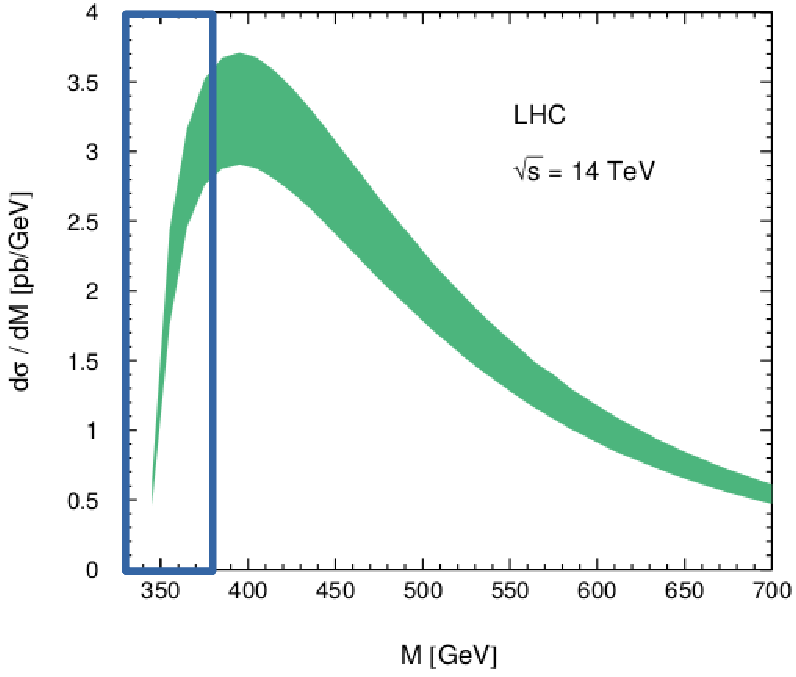

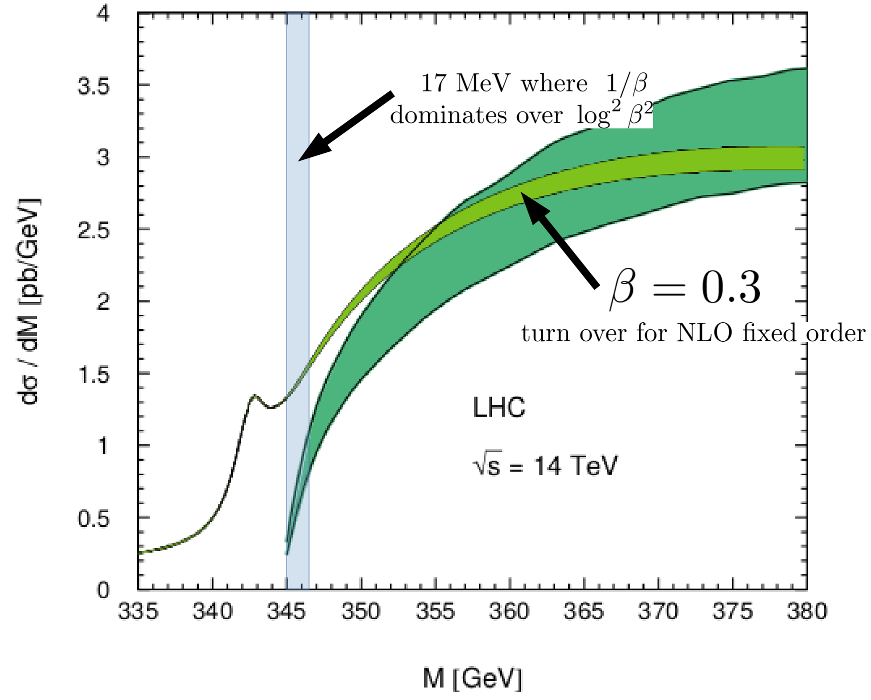

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