Vector boson + heavy quark(s): a case study for HF PDF's

Fabio Maltoni

Center for Particle Physics and Phenomenology

Université Catholique de Louvain

work in collaboration with

John Campbell, Keith Ellis, Scott Willenbrock

work in progress with

John Campbell, Francesco Tramontano, Michelangelo Mangano

John Campbell, Fernando Cordero, Keith Ellis, Laura Reina, Doreen Wackeroth, Scott Willenbrock

Outline

- Introduction
- V + Q : current status
- A case study: Wc
  - MLM's anatomy
  - First comparison $2\rightarrow1$ & $2\rightarrow2$ at NLO
- Outlook

Motivations

#3 : Background to BSM discoveries:
(H,A)bb, gluinos/squarks,...

#2 : Background to key
SM measurements/Higgs discovery:
tt, (tb,tW), (HZ, HW)...

#1 : SM measurements:
b-pdf, b-tagging/JES studies at the LHC,
MC's validation...

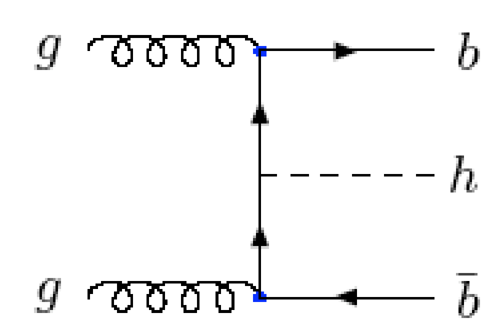
Some examples of b-initiated processes

Process	Interest	Accuracy
qb→tq (t-channel)	SM, top EW couplings and polarization, Vtb. Anomalous couplings.	NLO
gb→tW		NLO
qb→Wbj	SM, bkg to single top	NLO
qb→Zbj		NLO
gb→gamma+b	SM, SUSY bkg, b-pdf	NLO
gb→Z+b		NLO
qq+qb→W+b		NLO
bb→ h,A	SUSY discovery/ measurements at large tan(beta)	NNLO
gb→(h,A)+b		NLO
gb→H^+ + t	SUSY discovery, couplings	NLO

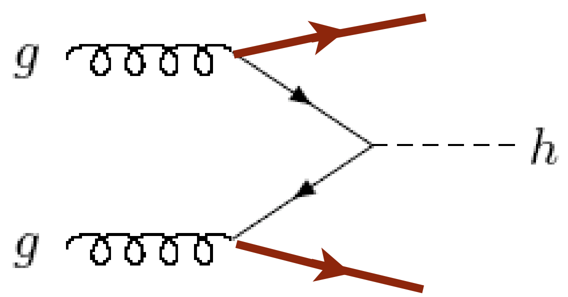
Example: Higgs production with bottom quarks

Two ways of performing the calculation:

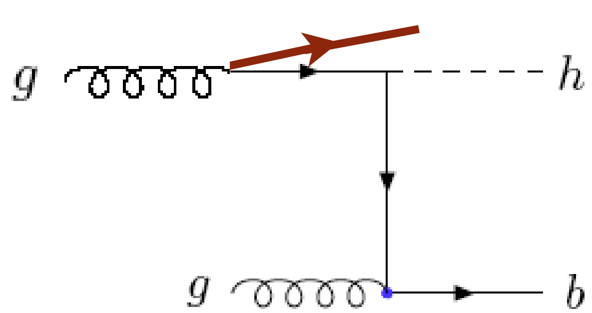
1."Naive" approach (FF)
There are no b in the proton, only gluons (or light quarks). The b mass acts as an infrared cutoff and there are no divergences. This is the Fixed Flavor Scheme. This is the born diagram independently of the final state signature (# b jets in the final state).



2."Improved" approach (VF)
First consider the signature (e.g. total cross section or 1,2 b jets in the final state).
Look for the dominant configuration in phase space (log(mh/mb) enhanced), in this case one or both b's at low pt/large rapidities).
Promote these configurations to Born amplitudes and reorganize the perturbative series.



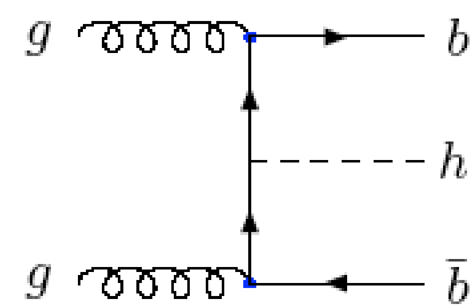
FULLY INCLUSIVE



1 b at high p_T

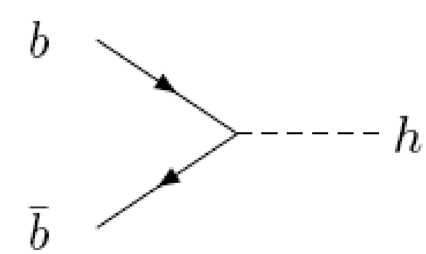
FF vs VF : Comments

The two approaches are EXACTLY equivalent at all orders in PT.
Differences arise at fixed order and predictions can be affected.



FF approach

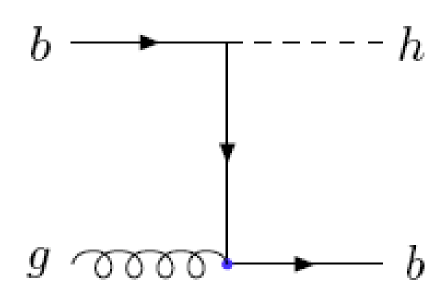
1. It does not resum (possibly) large logs (⇒norm. uncertainties)
2. Going NLO might be difficult.
3. Mass effects are there at any order in PT.
4. "Not so easy" MC implementation with ME/PS merging and no resummation (IS or FS).



VF approach

1. It resums initial state large logs, leading to more stable predictions
2. Going NLO (and NNLO) "easy".
3. Mass effects are normally corrections and enter at higher orders.
4. No brainer implementation in MC, but rely on mass effects given by the PS (which are presently not very accurate).

FULLY INCLUSIVE



1 b at high p_T

Z+Qjets: available calculations

- pp→ZQQ @ NLO, in the FF , but with m_Q=0, [Campbell & Ellis,1999]
  ⇒ Suitable to describe Z+2jets events with 2 b-tags.
- pp→ZQ @ NLO in the VF [Campbell, Ellis, FM, Willenbrock;2003]
  ⇒ Suitable to describe Z+1jet events with 1 b-tag.
- pp→Z(QQ) @ NNLO in the VF, [FM, McElmurry, Willenbrock;2005]
  ⇒ Suitable to inclusive Z with a soft b-tag.
- pp→ZQj @ NLO in the 5FS, [Campbell,Ellis, FM, Willenbrock;2006]
  ⇒ Suitable to inclusive Z +2jets events with a 1 b-tag.
- pp→ZQQ @ NLO in the 4FS, $m_Q \neq 0$ [Cordero, Reina, Wackeroth;2008]
  ⇒ Suitable to inclusive Z +2jets events with a 2 b-tags and more...

W + b-jets: available calculations

- pp→Wbb @ NLO, in the 4FS, but with m_Q=0, [Campbell & Ellis, 1999]
  ⇒ Suitable to describe W+2jets events with 2 b-tags.

- pp→Wbj @ NLO in the 5FS, [Campbell, Ellis, FM, Willenbrock; 2007]
  ⇒ Suitable to inclusive W +2jets events with a 1 b-tag.

- pp→Wbb @ NLO in the 4FS, $m_Q \neq 0$ [Cordero, Reina, Wackeroth; 2007]
  ⇒ Suitable to inclusive W +2jets events with a 2 b-tags and more...

- pp→Wb @ NLO in the 5FS, $m_Q \neq 0$ [Campbell, Cordero, Ellis, FM, Reina, Wackeroth,, Willenbrock, in progress]
  ⇒ Suitable to inclusive W +1 jet events with a 1 b-tag.

W + c-jets: available calculations

- pp→Wcc @ NLO, in the 4FS, but with m_c=0, [Campbell & Ellis,1999]
  ⇒ Suitable to describe W+2jets events with 2 c-tags.

- pp→Wcc @ NLO in the 4FS, $m_Q \neq 0$ [Cordero, Reina, Wackeroth;2007]
  ⇒ Suitable to inclusive W +2jets events with a 2 c-tags and more...

- pp→W(c) @ NLO, in the 3FS, [Berger, Halzemn,Kim,Willenbrock,1989]
  ⇒ Suitable to describe W with a soft charm tag.

- pp→Wc @ NLO, in the 4FS, $m_c \neq 0$, [Laenen et al., 1996; Campbell, Ellis, Tramontano, 2005]
  ⇒ Suitable to describe W+ c-jet events with 1 charm tag

- pp→Wcj @ NLO, in the 4FS, m_c=0, MISSING

ZQ at the Tevatron

Cross sections (pb)	Tevatron				
	ZQ	$Z(Q\bar{Q})$	ZQj	$ZQ\bar{Q}$	ZQ inclusive
$gb \to Zb$	(8.23) 10.4	0.169	2.19	0.631	$13.4 \pm 0.9 \pm 0.8 \pm 0.8$
$q\bar{q} \to Zb\bar{b}$	3.32	1.92		1.59	6.83
$gc \to Zc$	(11.3) 16.5	0.130	3.22	0.49	$20.3\ ^{+1.8}_{-1.5} \pm 0.1^{+1.3}_{-1.2}$
$q\bar{q} \to Zc\bar{c}$	5.66	6.45		1.70	13.8
	Zj		Zjj		Zj inclusive
$q\bar{q} \to Zg, gq \to Zq$	(876) 870		137		$1010\ ^{+44}_{-40}\ ^{+9}_{-2}\ ^{+7}_{-12}$

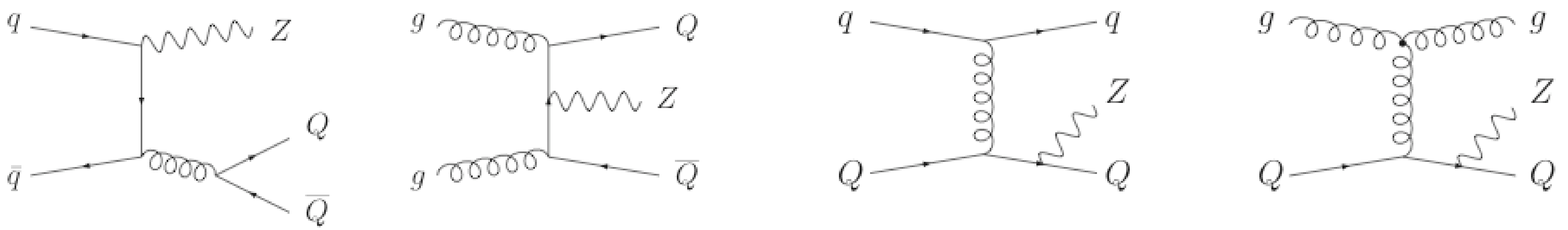
* pt>15 GeV and |η|<2.0 (jets in the taggable region).

* number in parenthesis are at LO

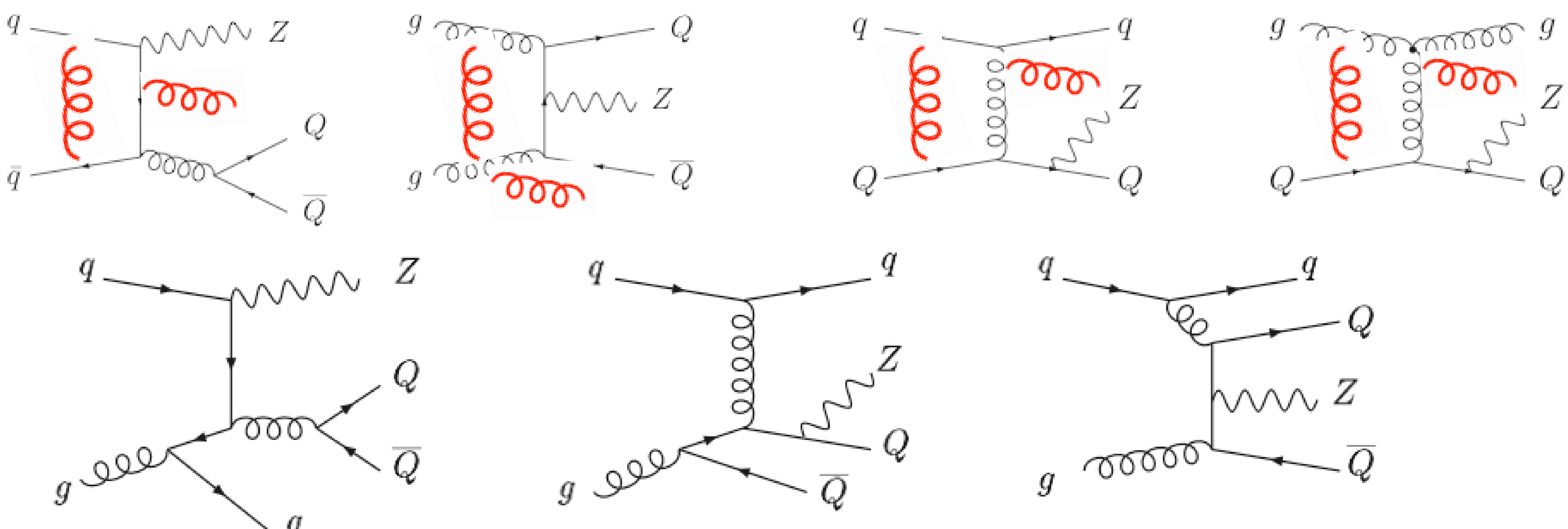
* gb channel dominates over qq "usual" channel.

ZQQ and ZQj

Leading order:



Next-to-leading order :



ZQj and ZQQ at the Tevatron

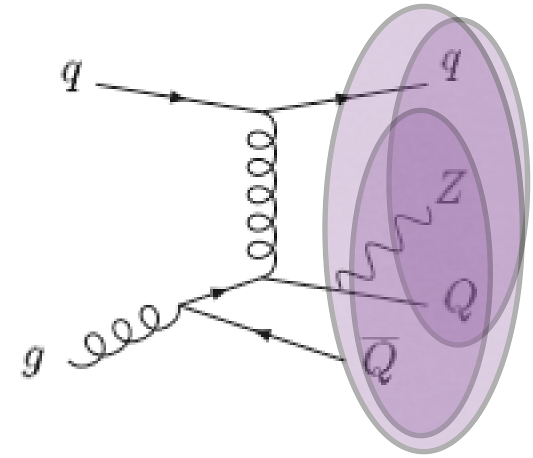
Tevatron	σ (pb)				
	ZQj	$ZQ\bar{Q}$	$Z(Q\bar{Q})j$	$ZQ\bar{Q}j$	$ZQjj$
bottom	(2.18) 4.37	(2.47) 3.07	0.634	0.672	0.326
charm	(3.20) 7.35	(2.34) 2.75	2.00	0.621	0.495
	Zjj			$Zjjj$	
Z+jets	(163) 182			22.9	

* pt>15 GeV and |η|<2.0 (taggable region)

* number in parenthesis are at LO

* Use well-defined physical signatures to avoid double counting and/ or miss contributions

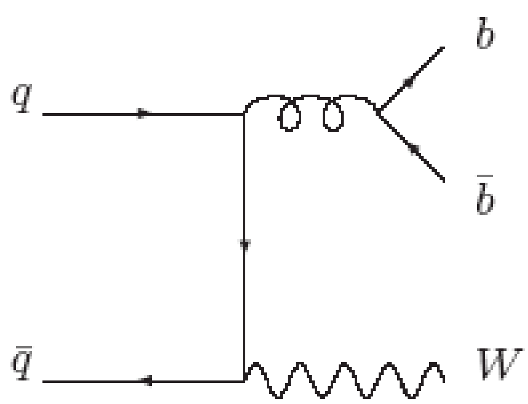
* ZQj similar to ZQQ ⇒ change in the way we picture Zjj events with one b tag!

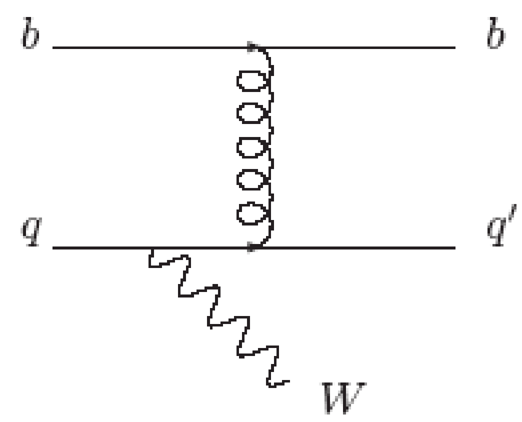


Fraction (%) of heavy quarks in Z + jets

Collider	quark	Inclusive NNLO	1 Q-jet NLO	2 Q-jets NLO	1 jet + 1 Q-jet NLO
Tevatron	bottom	0.71	2.0	1.9	3.2
	charm	2.2	3.4	1.5	5.2
LHC	bottom	3.6	6.9	2.4	9.2
	charm	8.0	9.3	1.8	14.0

Wbj and Wbb at the Tevatron





	Cross sections (pb)				
Collider	Wbj	$Wb\bar{b}$	$W(b\bar{b})j$	$Wbjj$	$Wb\bar{b}j$
TeV $W^+(=W^-)$	(1.06) 2.54	(2.48) 3.14	0.89	0.18	0.65
LHC W^+	(51.7) 96.2	(9.5) 14.3	27.0	13.8	11.6
LHC W^-	(35.6) 66.4	(6.6) 9.6	19.0	9.3	7.6
	Wjj			$Wjjj$	
TeV $W^+(=W^-)$	(261) 290			39	
LHC W^+	(4990) 4170			1280	
LHC W^-	(3650) 3030			890	

* pt>15 GeV and |η|<2.0 (taggable region)

* number in parenthesis are at LO

* Use well-defined physical signatures to avoid double counting and/or miss contributions

* Wbj similar to Wbb ⇒

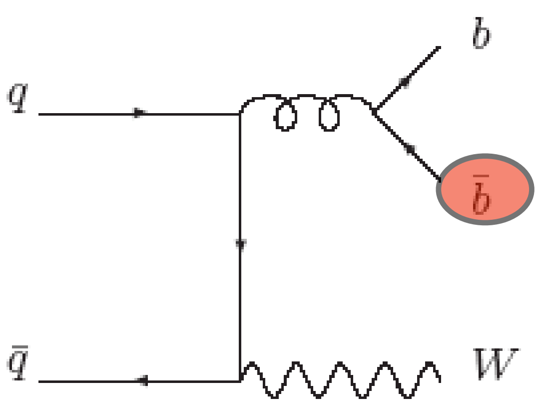
change in the way we picture Wjj events with one b tag!

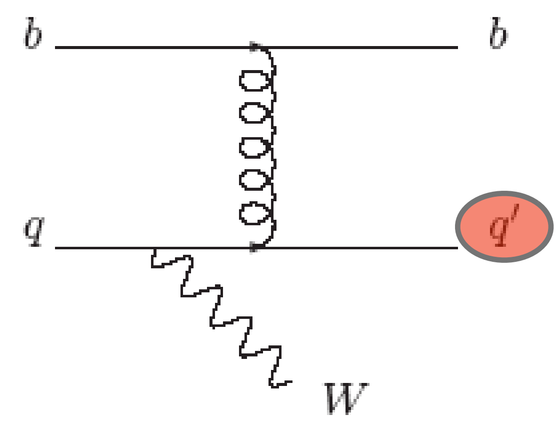
*gq>bb~Wq' mb>0

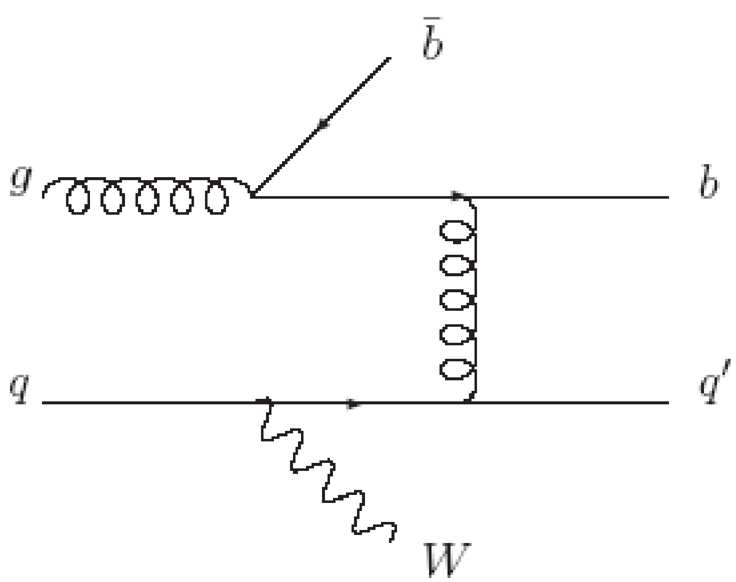
*at the LHC Wbj dominates

What about Wb?

[Campbell,Cordero, Ellis, FM, Reina,Wackeroth,Willenbrock, in progress]







N.B. The above diagram has two different interpretations in FF and VF. In FF it is a new finite as^3 contribution to inclusive Wb. In VF is the NLO contribution to Wb with both b's at high pt (ie the above diagram minus the counterterm: gq>bbqW- bq>bqW).

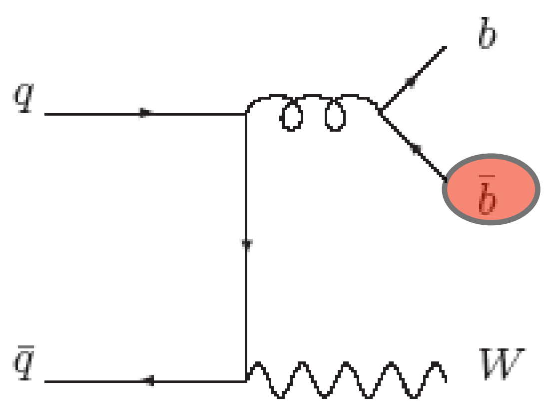
* Both LO diagrams are finite: one of the (massive b) is lost in the first and the light quark in the second ⇒

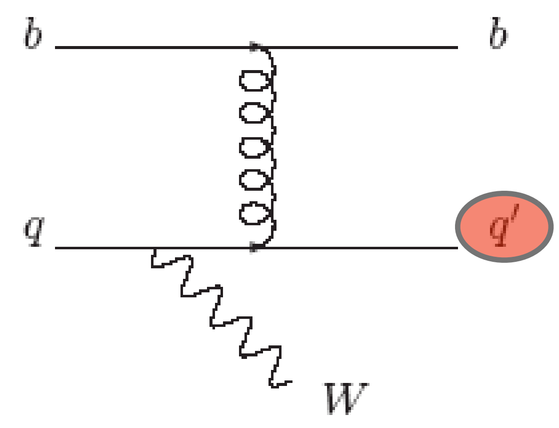
NLO corrections to W+b+X can be calculated!

* Strategy: divide et impera. Merge the two independent calculations for Wbb and Wbj.

* At NLO only one process in common, which needs to be calculated (once!) with mb>0.

Wb @ NLO : results





	Inclusive cross sections (pb)	
Collider	$Wb+X$	$W(b\bar{b})+X$
TeV $W^+(=W^-)$	(7.56+1.81=9.37) 11.77+2.40=14.17	(2.66) 4.17+0.38=4.55
LHC W^+	(39.4+106.0=145.4) 53.6+136.1=189.7	(17.6) 25.1+35.9=61.0
LHC W^-	(28.0+67.0=95.0) 39.2+88.2=127.4	(12.9) 18.9+23.6=42.5
	$Wj+X$	
TeV $W^+(=W^-)$	(1410) 2030	
LHC W^+	(14240) 20000	
LHC W^-	(11040) 15220	Preliminary

* Cuts:

Tevatron: $p_{Tj} > 15$ GeV $\quad |\eta_j| < 2$
LHC: $p_{Tj} > 25$ GeV $\quad |\eta_j| < 2.5$
$|\Delta R_{b\bar{b}}| > 0.7 \quad |\Delta R_{bj}| > 0.7$

* K-factor around 2

* qq gives the dominant contribution at TeV, qb dominant at the LHC.

* (bb) not negligible

Fraction (%) of b quarks in W + jets

Collider	1 b-jet NLO	1 jet + 1 b-jet NLO	2 b-jets NLO
Tevatron	1.0	1.1	1.1
LHC	1.6	2.0	0.46

FF vs VF : a closer look

The two approaches are EXACTLY equivalent at all orders in PT.
Differences arise at fixed order and predictions can be affected.

Are these differences important? Where do they arise: total rates, distributions? If two results differ which one is right?

FF approach
1. It does not resum (possibly) large logs.
2. Going NLO might be difficult.
3. Mass effects are there at any order in PT.
4. "Not so easy" MC implementation with ME/PS merging and no resummation (IS or FS).

Are the logs really large and dominating?

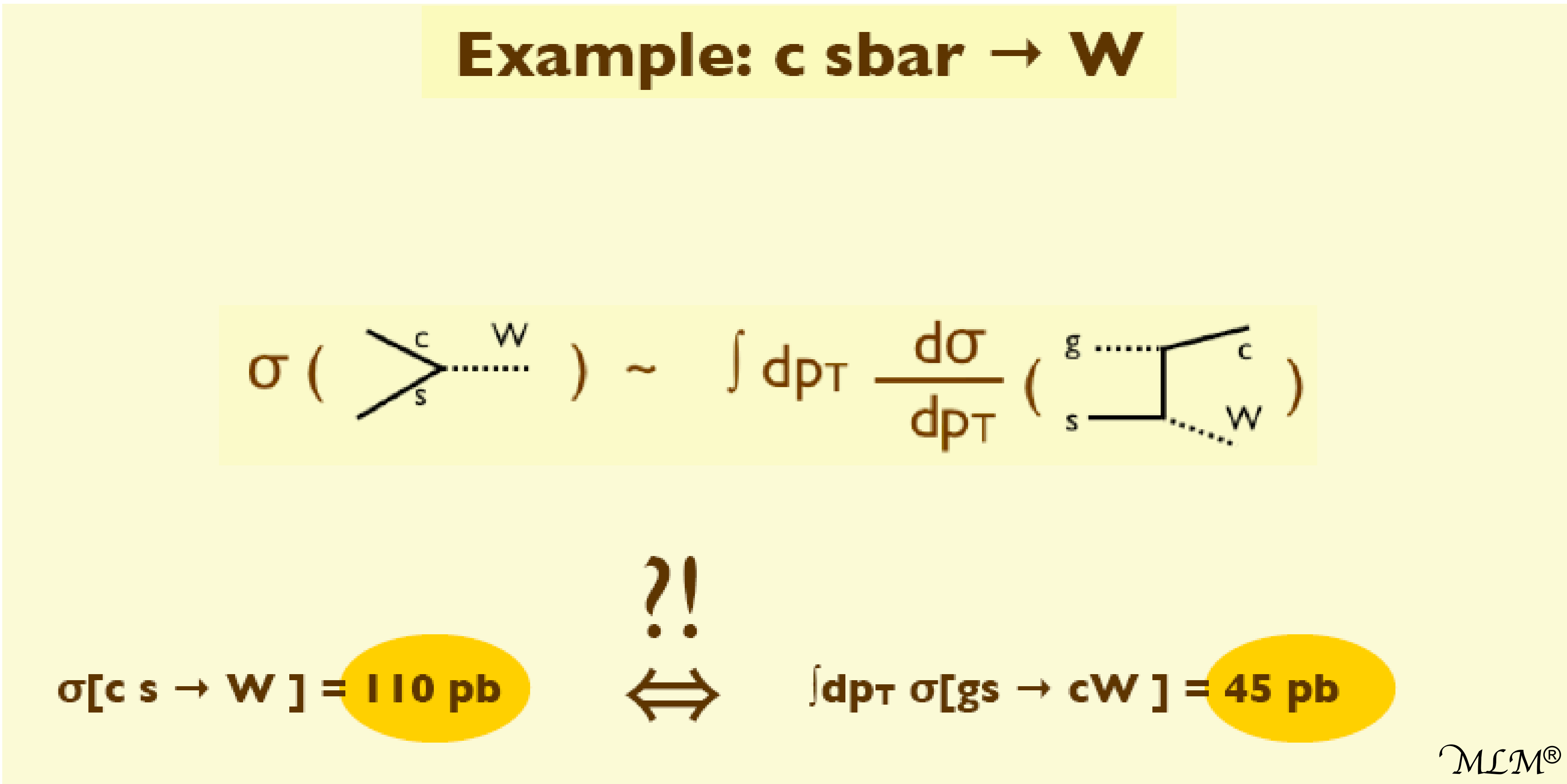
If I have only a LO calculation, which scheme should I use in the MC?

VF approach
1. It resums initial state large logs, leading to more stable predictions.
2. Going NLO (and NNLO) "easy".
3. Mass effects are normally corrections and enter at higher orders.
4. No brainer implementation in MC, but rely on mass effects given by the PS.

Can I use K-factor from a VF even if I am using a LO MC with VF?

How do I account for mass effects in a LO calculation? Is the PS accurate enough?

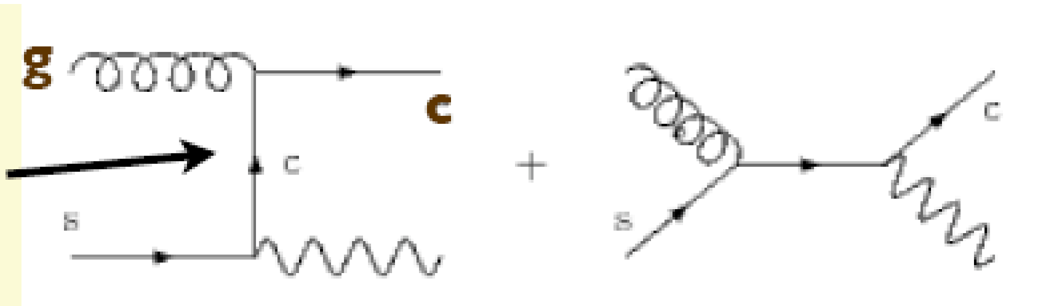
cs→W vs sg→Wc



The simplest of all possible processes. First analyzed in [Berger, Halzemn,Kim,Willenbrock,1989]. Differences arise at fixed order and predictions can be affected.

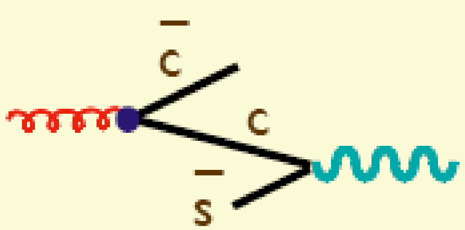
MLM's anatomy of Wc

$q^2 = 2\, c\cdot g$



$$\sigma(gs \to cW) = \int \frac{dx_1}{x_1}\frac{dx_2}{x_2}\,\frac{f_s(x_1,\mu_F)\, f_g(x_2,\mu_F)}{16\pi S}\,\frac{dq^2}{\hat{s}}\,\overline{\sum}|M^2_{gs}|$$

In the collinear limit: $$\overline{\sum}|M^2_{gs}| \to \frac{2}{xq^2}\,\frac{\alpha_s(\mu_R)}{2\pi} P_{Qg}(x,q^2)\,\overline{\sum}|M^2_{cs}|$$



where: $$P_{Qg}(x,q^2) = \frac{1}{2}\left[x^2 + (1-x)^2 + \frac{2m_c^2}{q^2}\right]$$

and: $$\sigma(cs \to W(c)) = \int \frac{dx_1}{x_1} f_s(x_1,\mu_F)\, \tilde{f}_c(x_2, q^2_{max})\,\frac{\pi}{m_W^2 S}\overline{\sum}|M^2_{cs}|$$

where: $$\frac{d\tilde{f}_c(y,q^2)}{d\log q^2} = \frac{\alpha_s(q^2)}{2\pi}\int_y^{x_{max}} \frac{dx}{x} P_{Qg}(x,q^2)\, f_g(y/x,q^2)$$

MLM®

MLM's anatomy of Wc

Massive collinear approx

$$\int \frac{dx_1}{x_1} f_s(x_1,\mu_F)\,\tilde{f}_c(x_2,q^2_{max})\,\frac{\pi}{m_W^2 S}\overline{\sum}|M^2_{cs}|$$

$$\tilde{f}_c(y,\mu) = \int_{q^2_{min}}^{\mu^2} \frac{dq^2}{q^2}\frac{\alpha_s(q^2)}{2\pi}\int_y^{x_{max}}\frac{dx}{x}\,P_{Qg}\,f_g(\mu_F)$$

$$P_{Qg}(x,q^2) = \frac{1}{2}\left[x^2+(1-x)^2+\frac{2m_c^2}{q^2}\right]$$

$$q^2_{max} = \sqrt{\hat{s}}(c^0+|\vec{c}|)$$

$$q^2_{min} = \sqrt{\hat{s}}(c^0-|\vec{c}|) = \hat{s}\,\frac{m_c^2}{q^2_{max}} \xrightarrow{\text{@ threshold}} m_c m_W$$

$$\frac{(m_W+m_c)^2}{S} < x_1 < 1$$

Massless PDF

$$\int \frac{dx_1}{x_1} f_s(x_1,\mu_F)\,f_c(x_2,\mu_F)\,\frac{\pi}{m_W^2 S}\overline{\sum}|M^2_{cs}|$$

$$f_c(y,\mu) = \int_{m_Q^2}^{\mu^2}\frac{dq^2}{q^2}\frac{\alpha_s(q^2)}{2\pi}\int_y^1\frac{dx}{x}\,[P_{Qg}\,f_g(q^2)+P_{QQ}\,f_c(q^2)]$$

$$P_{Qg}(x) = \frac{1}{2}[x^2+(1-x)^2]$$

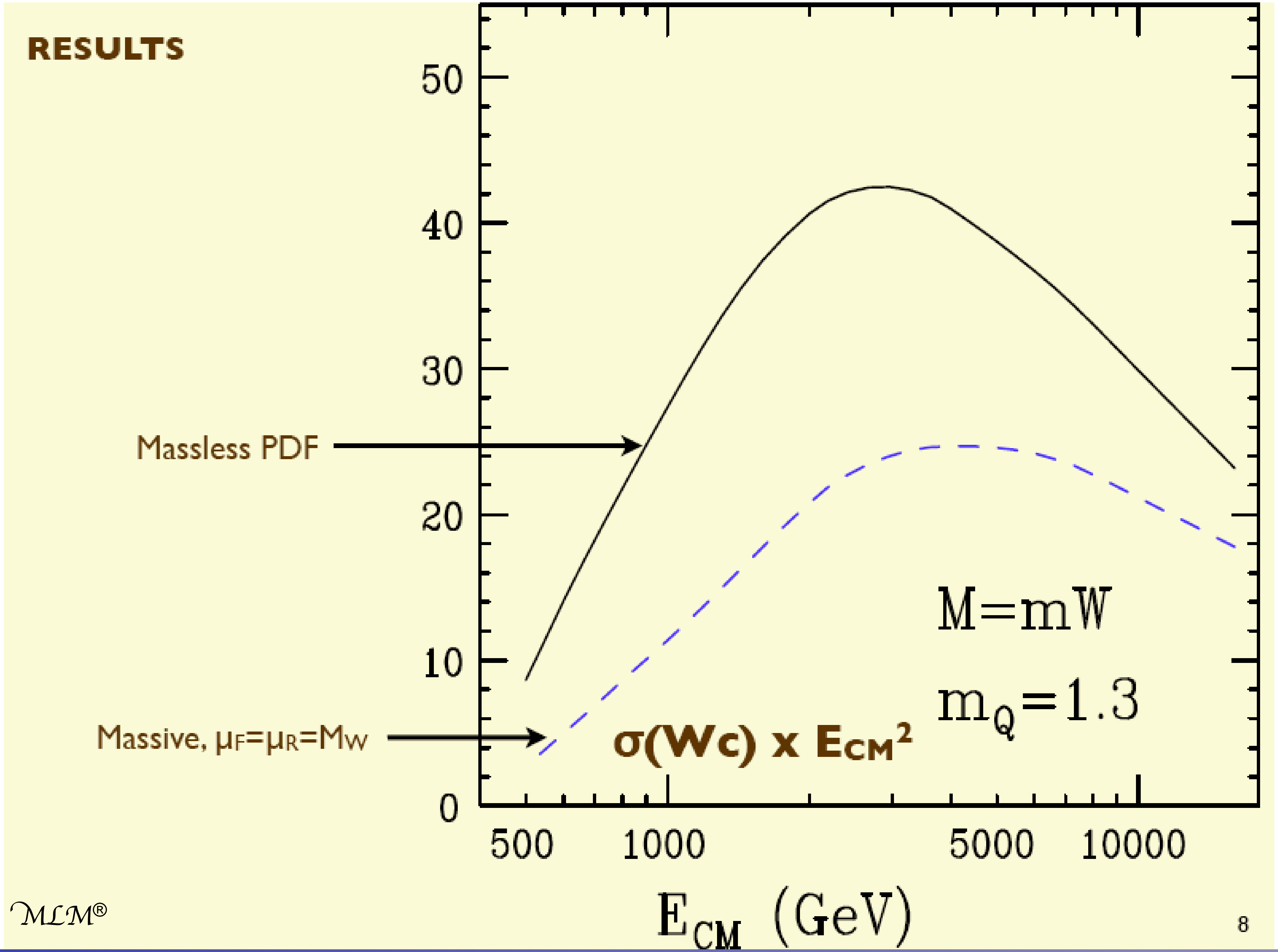
$$q^2_{max} = \mu_F^2$$

$$q^2_{min} = m_c^2$$

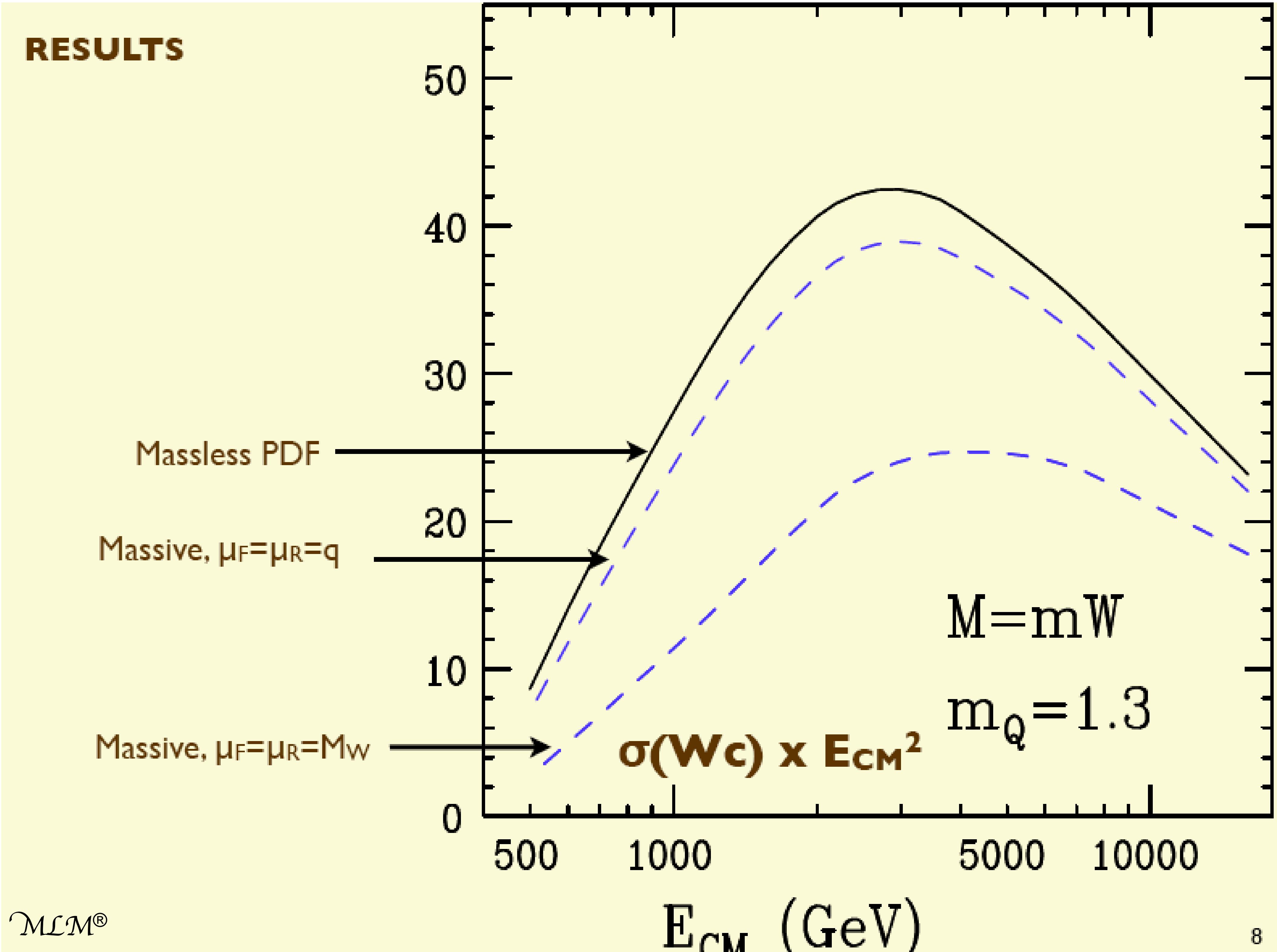
$$\frac{m_W^2}{S} < x_1 < 1$$

$\mathcal{MLM}$® 7

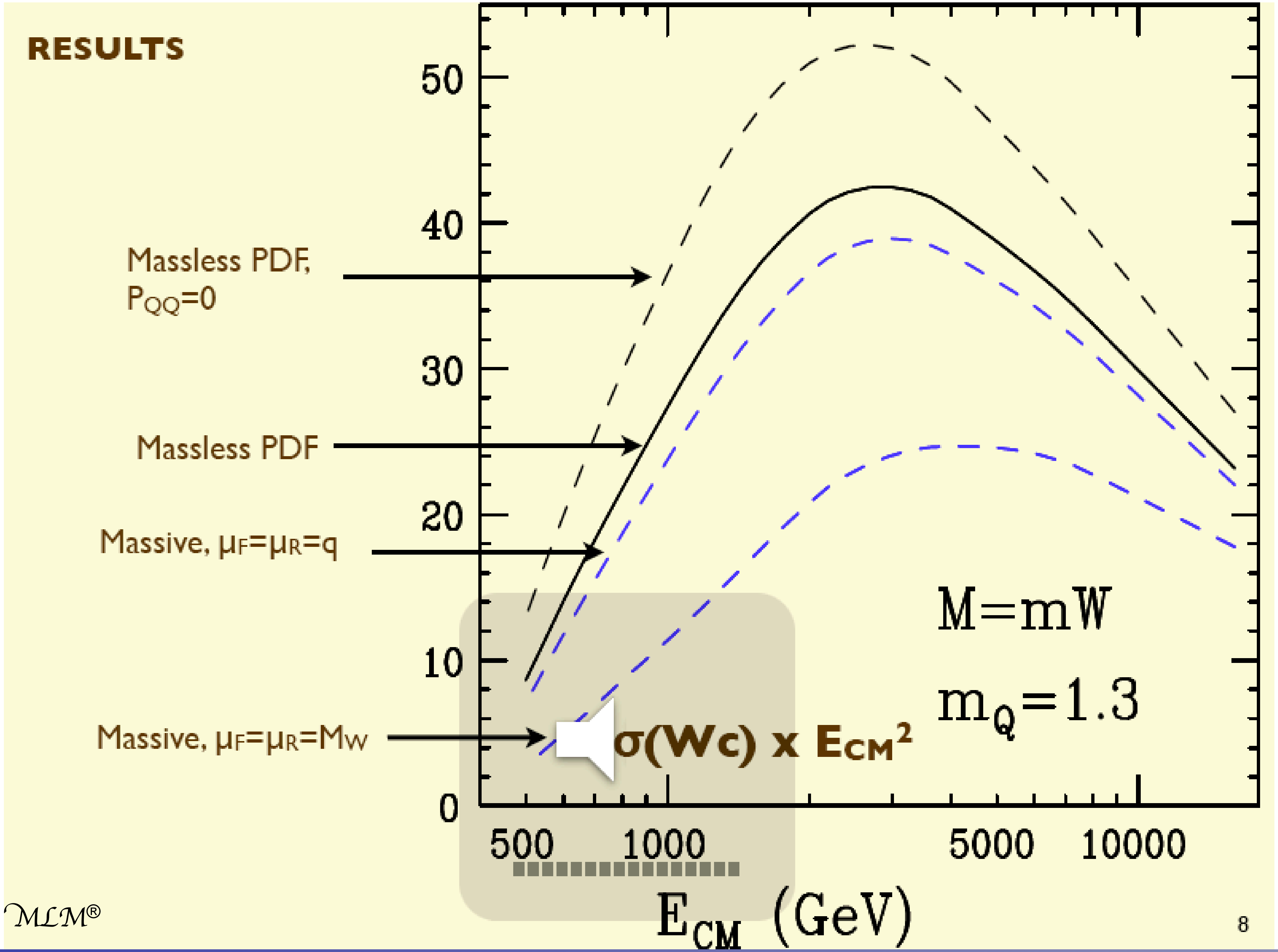
MLM's anatomy of Wc



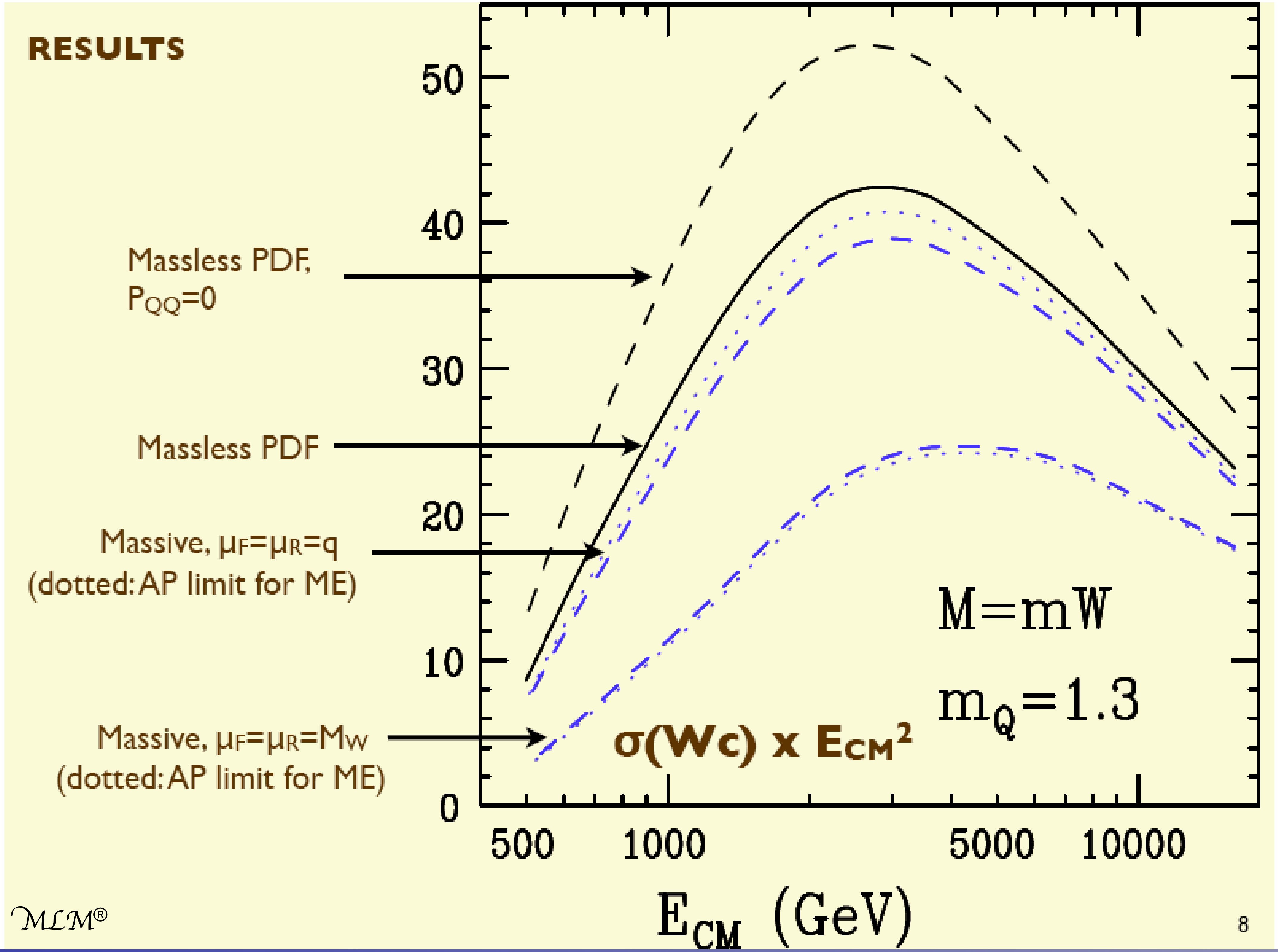
MLM's anatomy of Wc



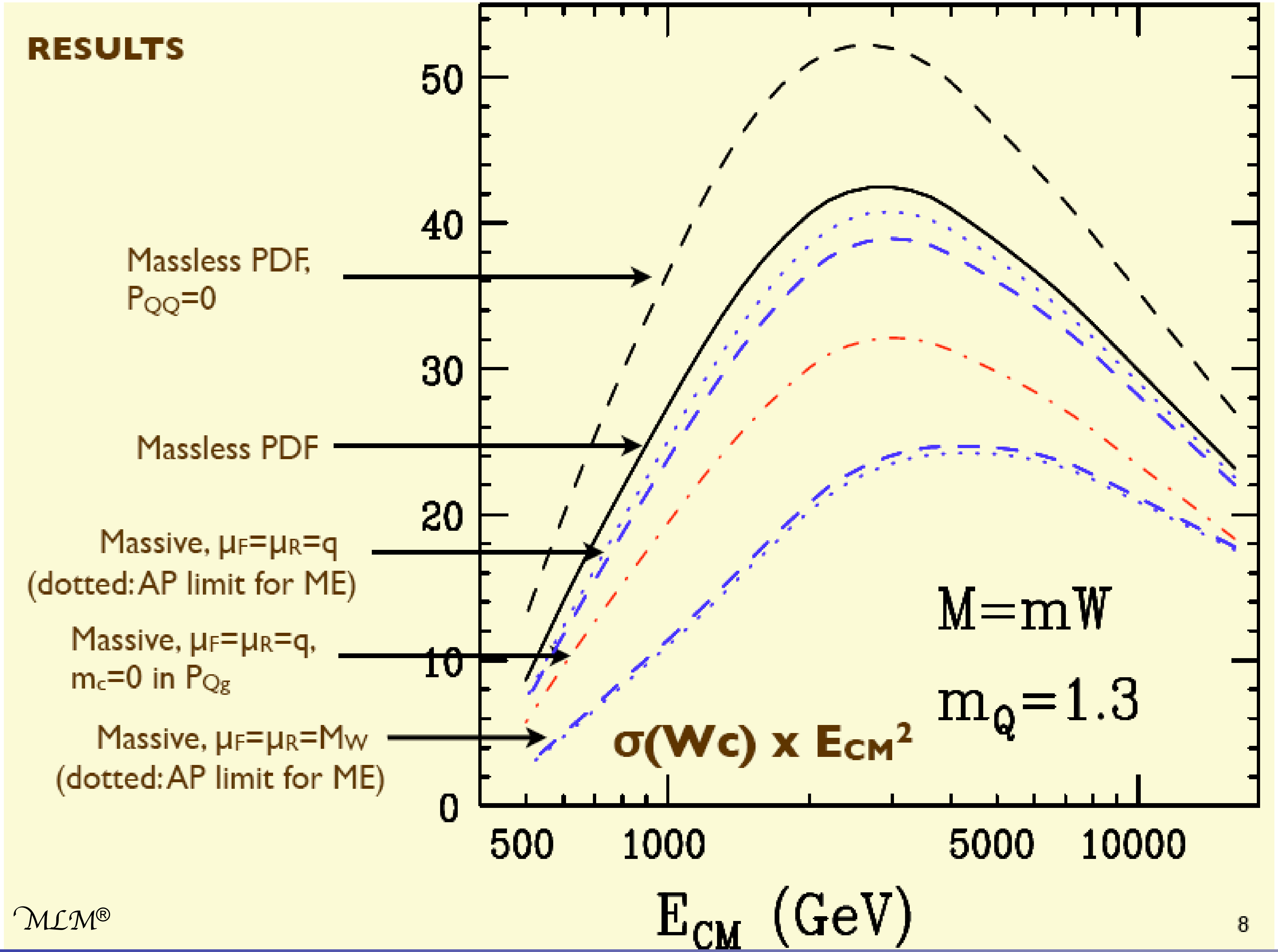
MLM's anatomy of Wc



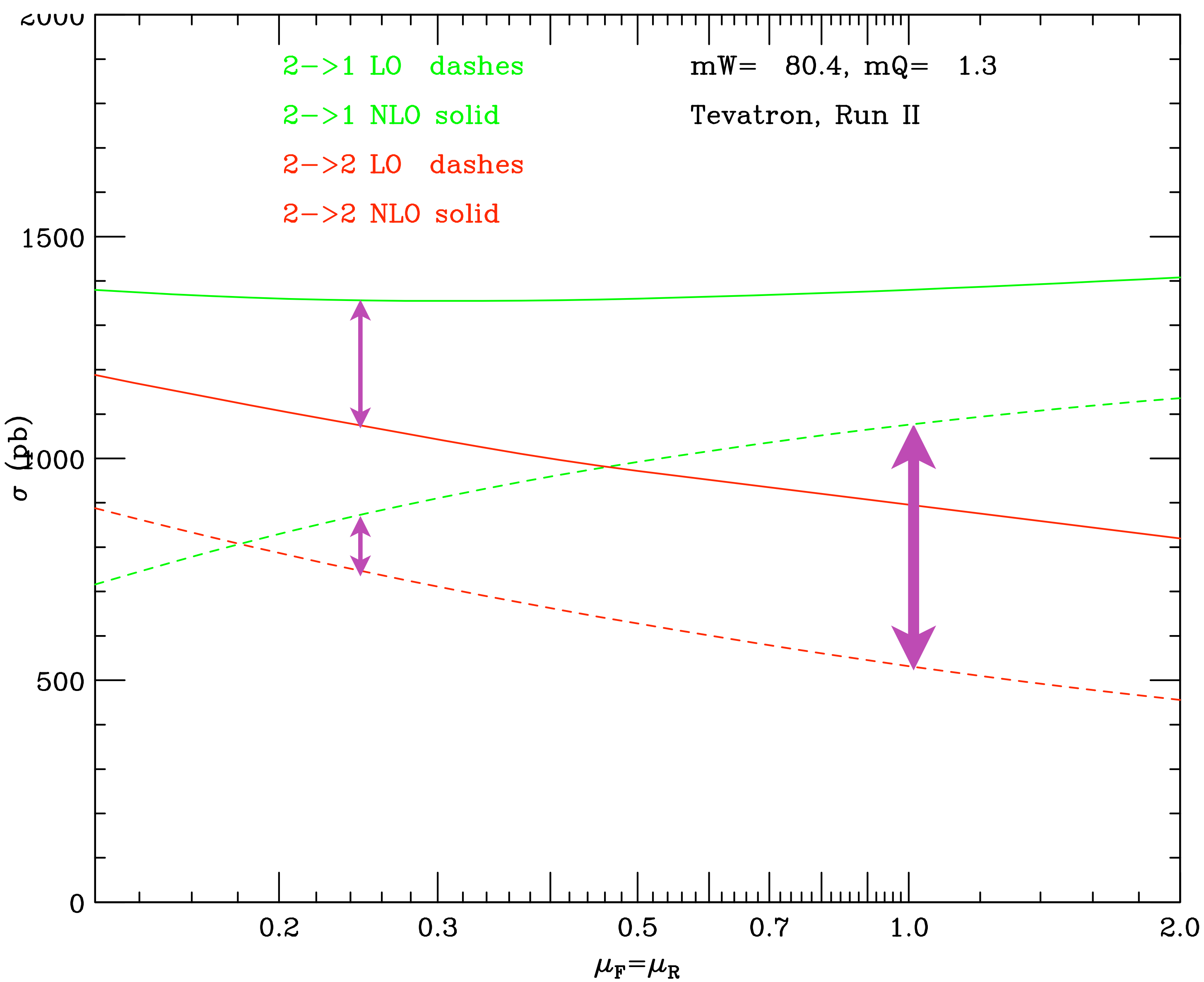
MLM's anatomy of Wc



MLM's anatomy of Wc



Wc: 2→1 vs 2→2



* Factor of 2 difference at LO for scales of the order m_W.

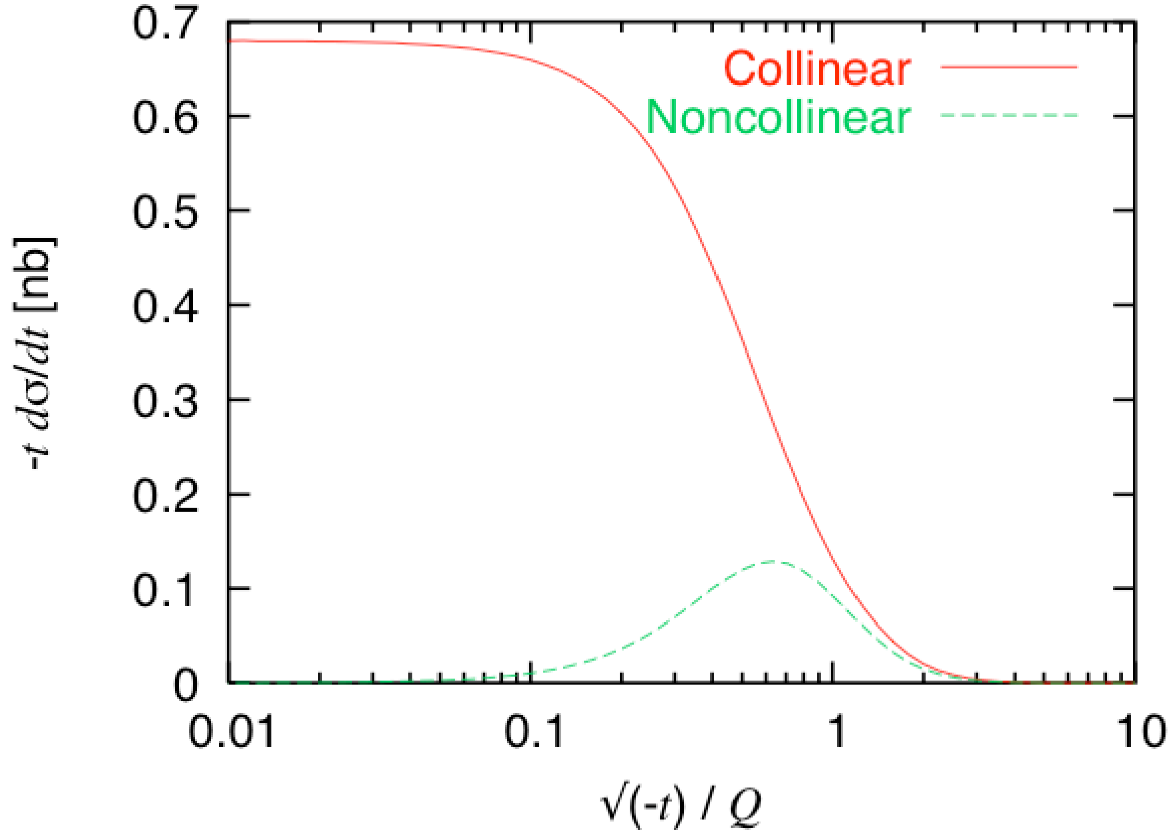
* Much smaller differences at smaller scales

* At NLO, at small scales, differences are of the order 20%.

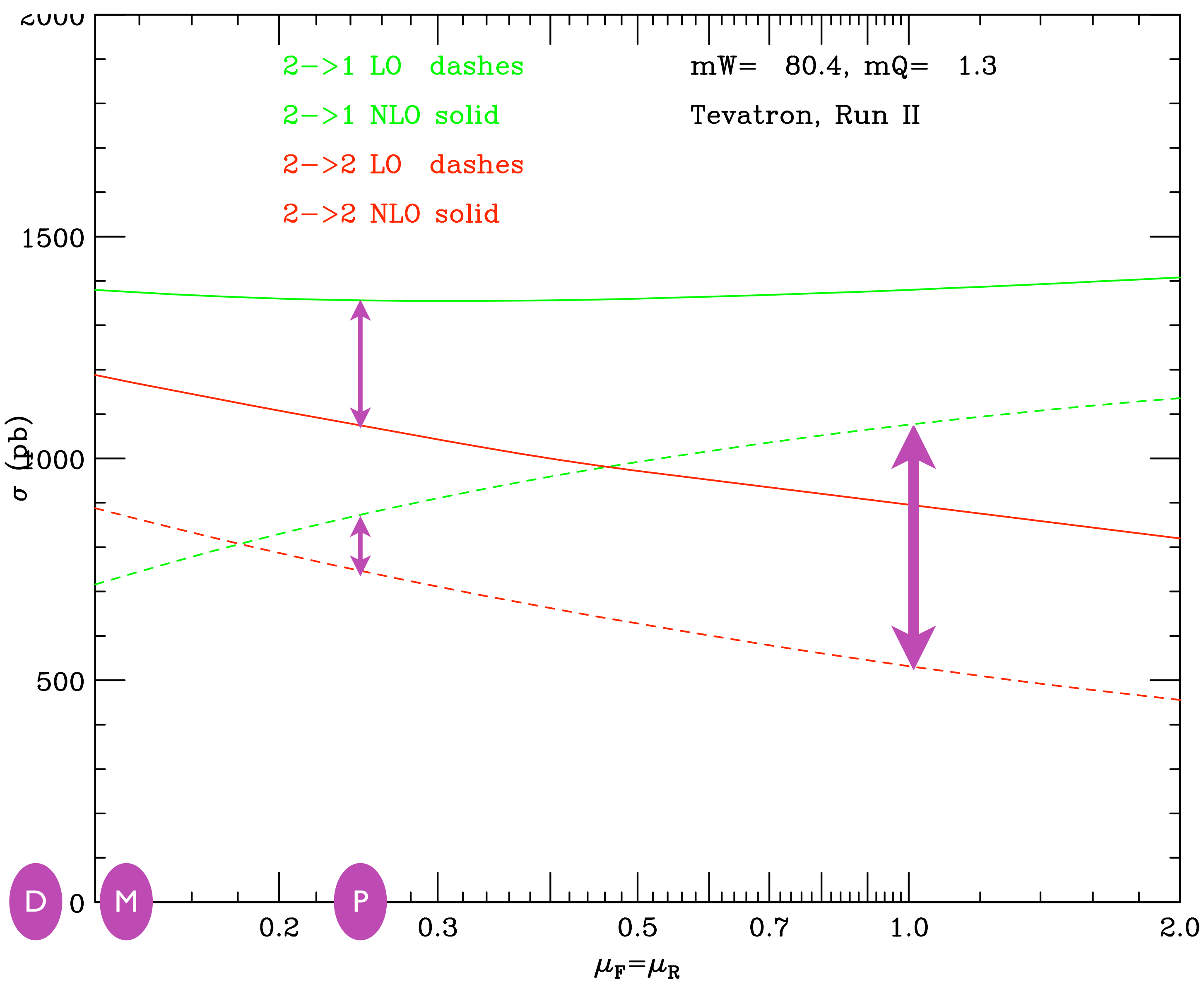
* 2→1 very stable while 2→2 sizable scale dependence.

Why should I choose a small scale?

- MLM's argument on the available phase space in the 2→2 process M
- Dynamical scale. D
- The "collinear plateaux" argument [FM, MCElmurry Putnam, Willenbrock, hep-ph/0703156], which typically gives ~$m_W/4$ P



Wc: 2→1 vs 2→2



* Factor of 2 difference at LO for scales of the order m_W.

* Much smaller differences at smaller scales

* At NLO, at small scales, differences are of the order 20%.

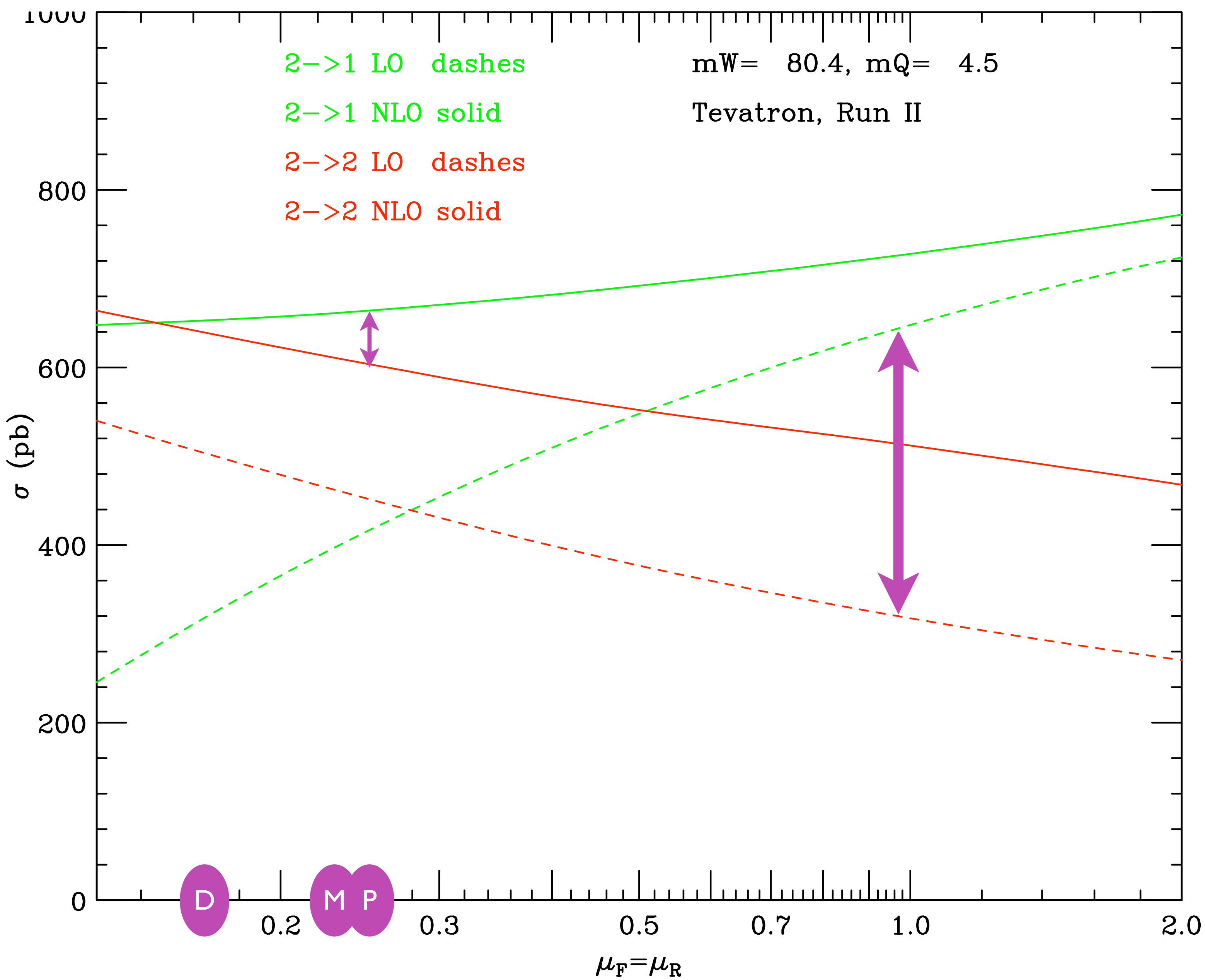
* 2→1 very stable while 2→2 sizable scale dependence.

D =dynamical scale=m_T

M = $\sqrt{m_Q * m_W}$

P = $m_W/4$

Wc: 2→1 vs 2→2



* Factor of 2.5 at LO for scales of the order m_W.

* Much smaller differences at smaller scales

* At NLO, at small scales, differences are less than 10%

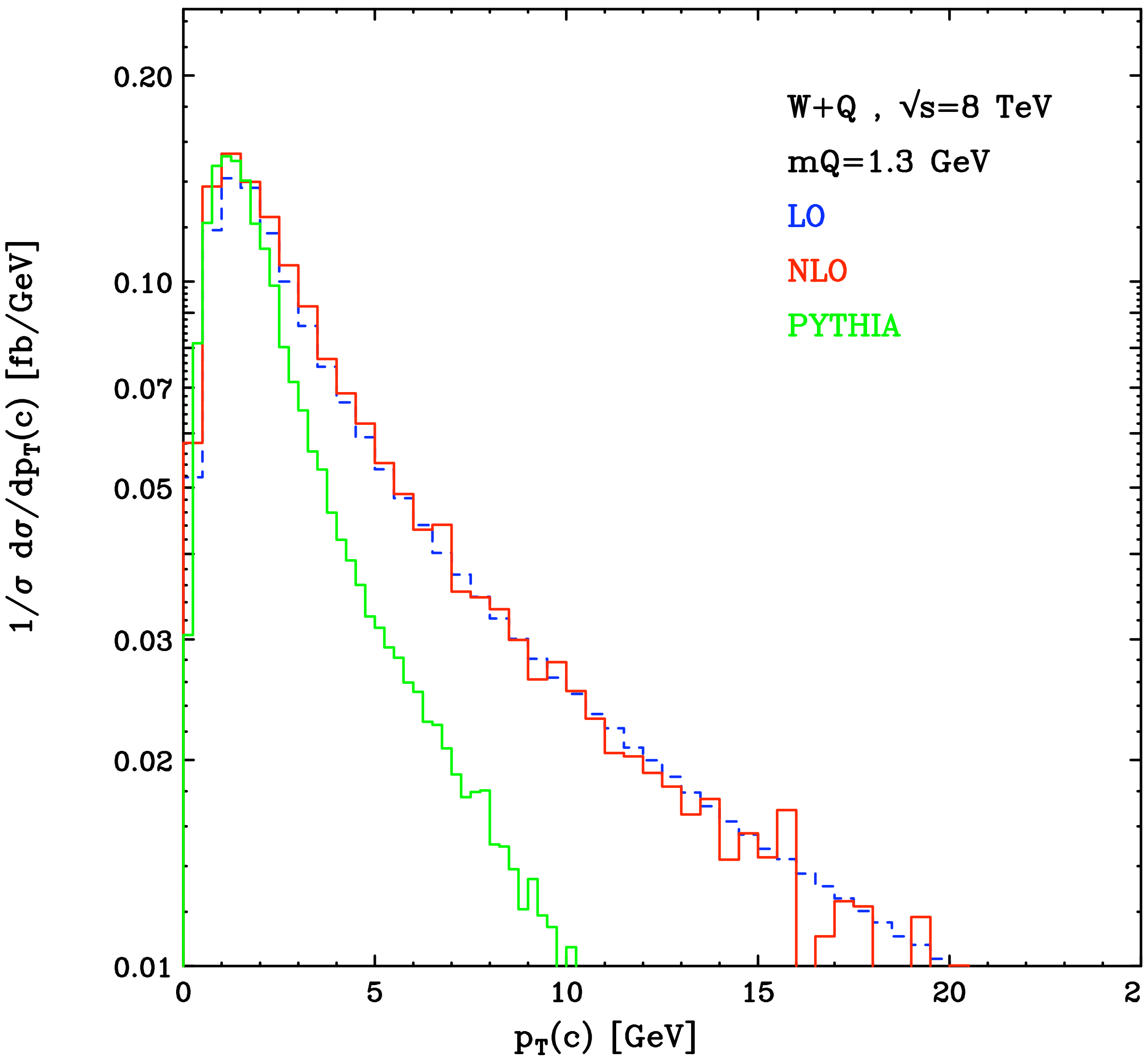
* Similar results for higher m_W masses

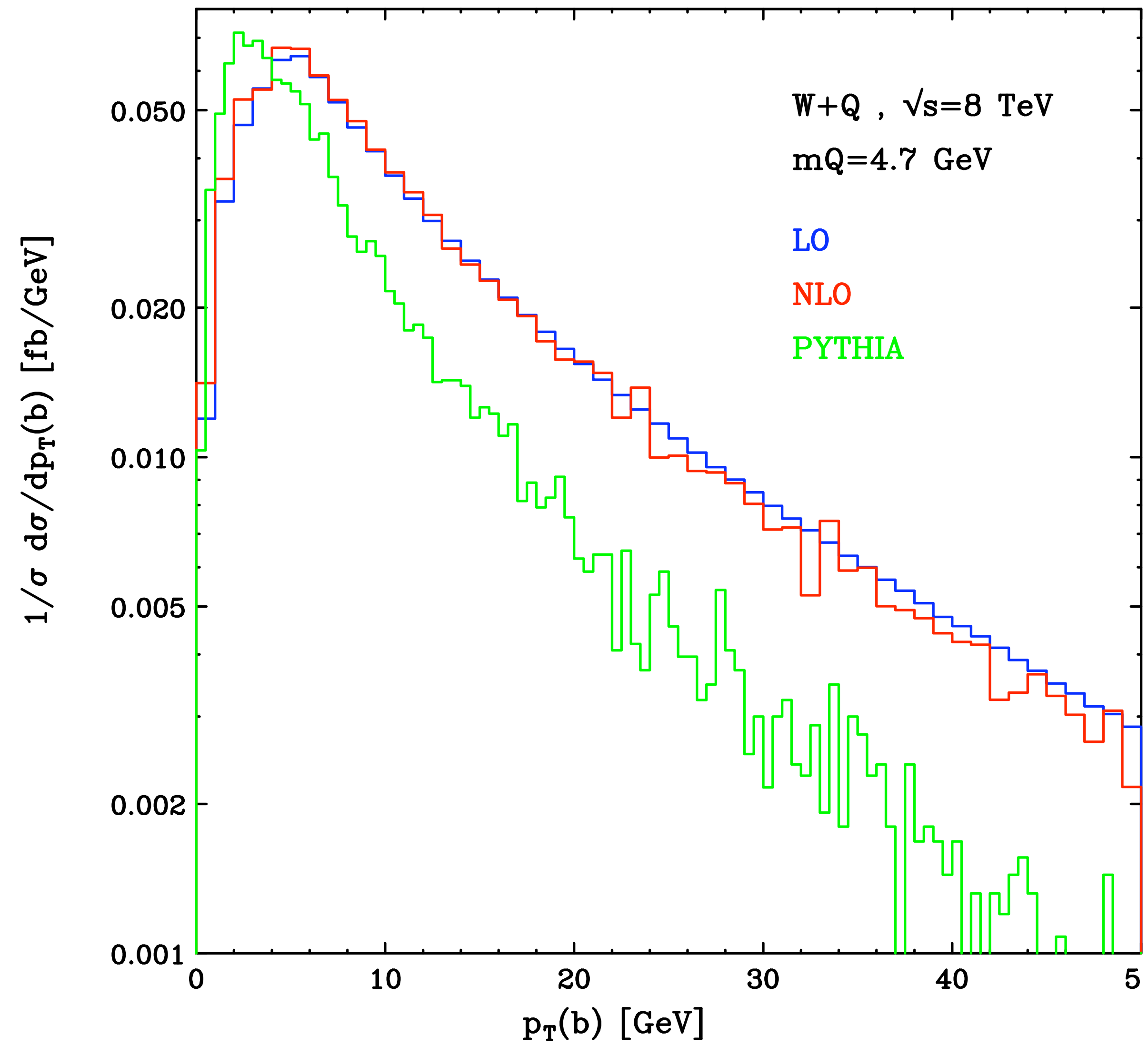
D =dynamical scale=m_T

M = $\sqrt{m_Q * m_W}$

P = $m_W/4$

p_T distributions

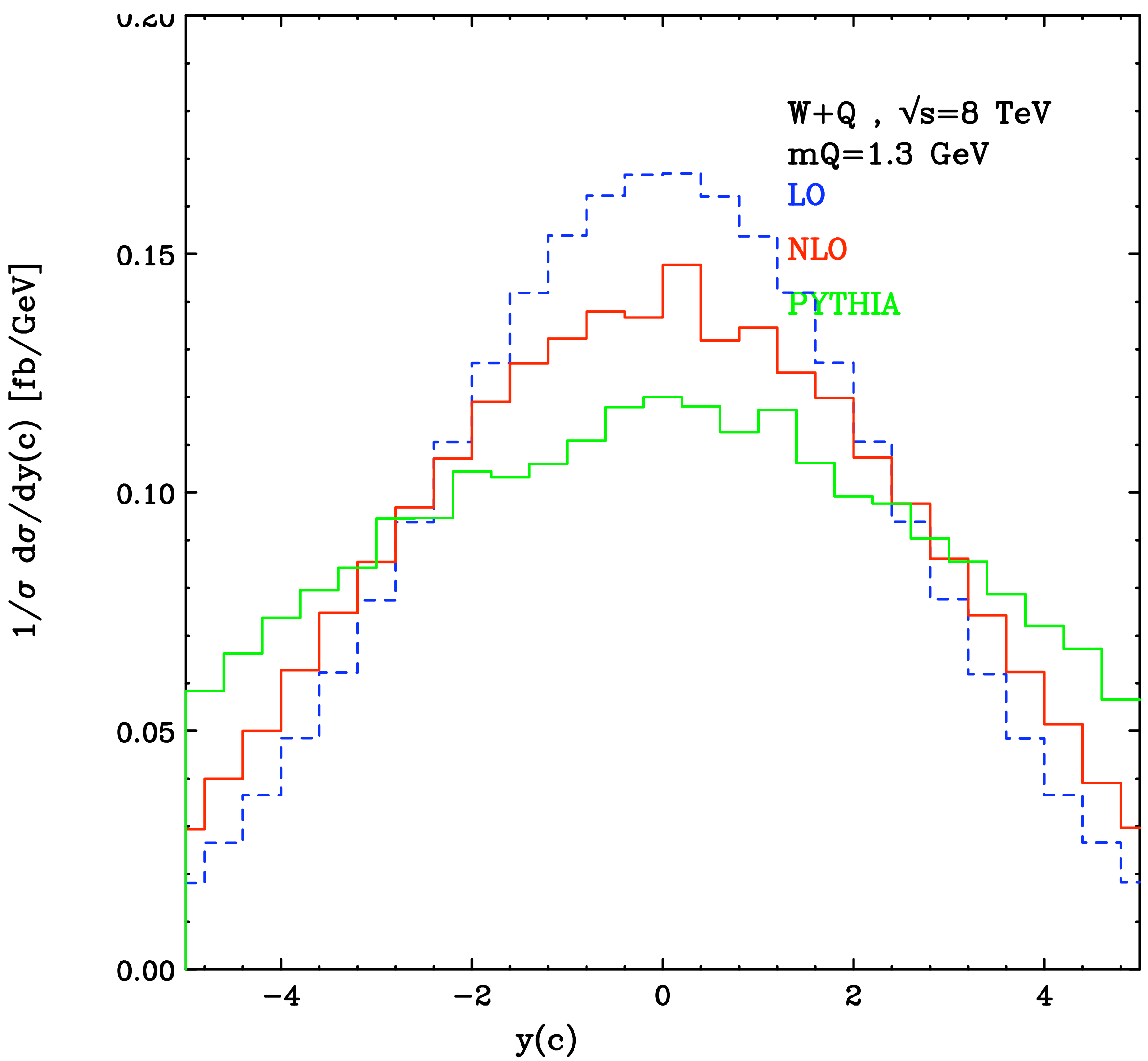


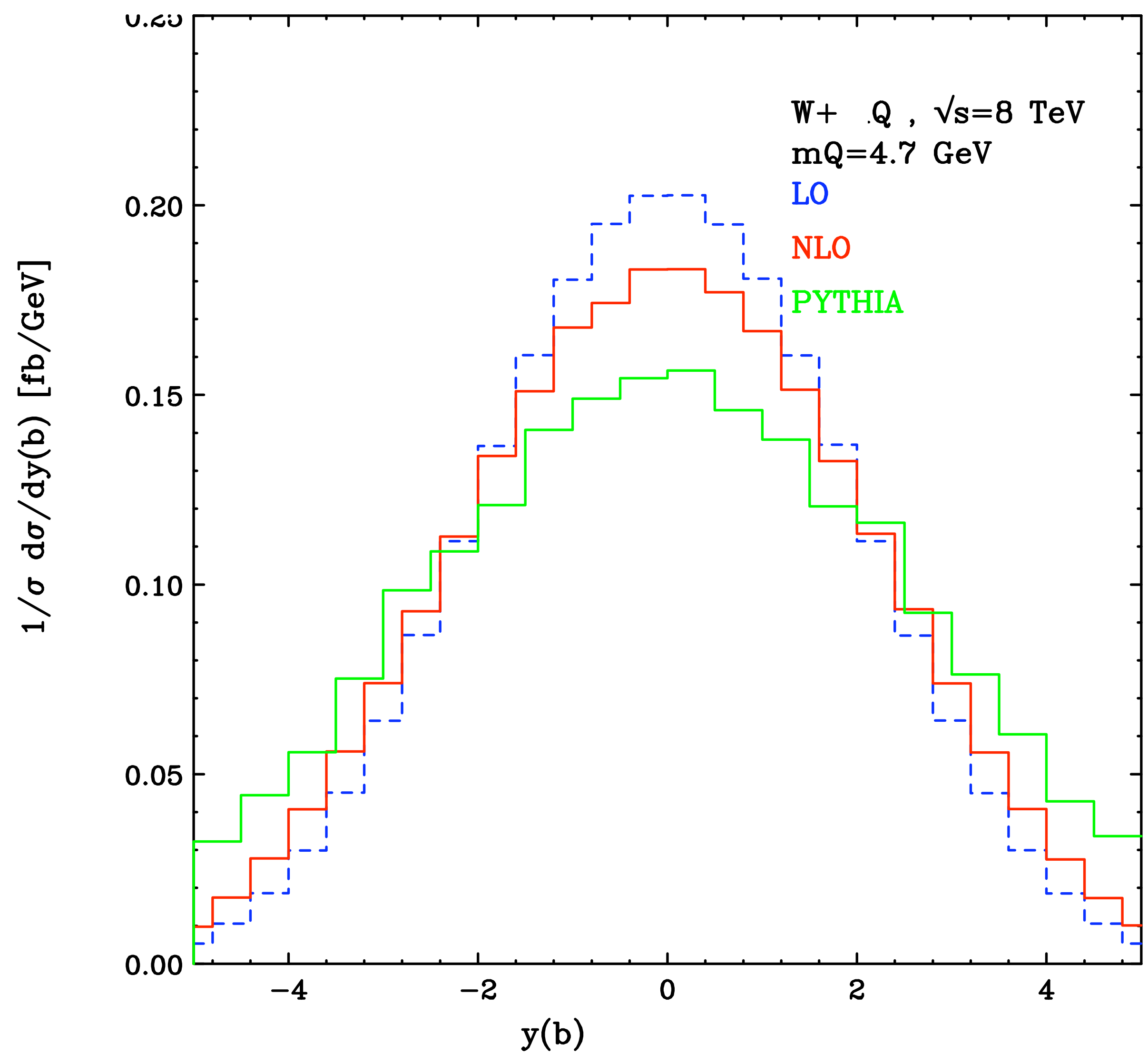


* No significant difference between LO and NLO ⇒ where's the effect of large logs?

* MC approach is inadeguate at "large" p_T (no surprise). At small p_T does a good job for charm mass, not very good for bottom. HERWIG also does not do a good job with b's (No dependence at all on the mass in HERWIG++). What about SHERPA or ARIADNE?

Rapidity distributions





* Broadening of the distributions at NLO
* MC approach might be ok....

Summary & Open questions

- Significant number of key calculations for V+HQ both in the FF an VF schemes.
- The FF and VF approaches have advantages (and disavantages) and are complementary:

Property	VF	FF
Resums large IS logs	☺	☹
Easy (=feasible) calculation	☺	☹
Accuracy of total rates	☺	☺
Mass effects	☺	☺
MC naive implementation	☹	☺

- Good agreement between NLO results once "physical" scale choices are made.

Summary & Open Questions

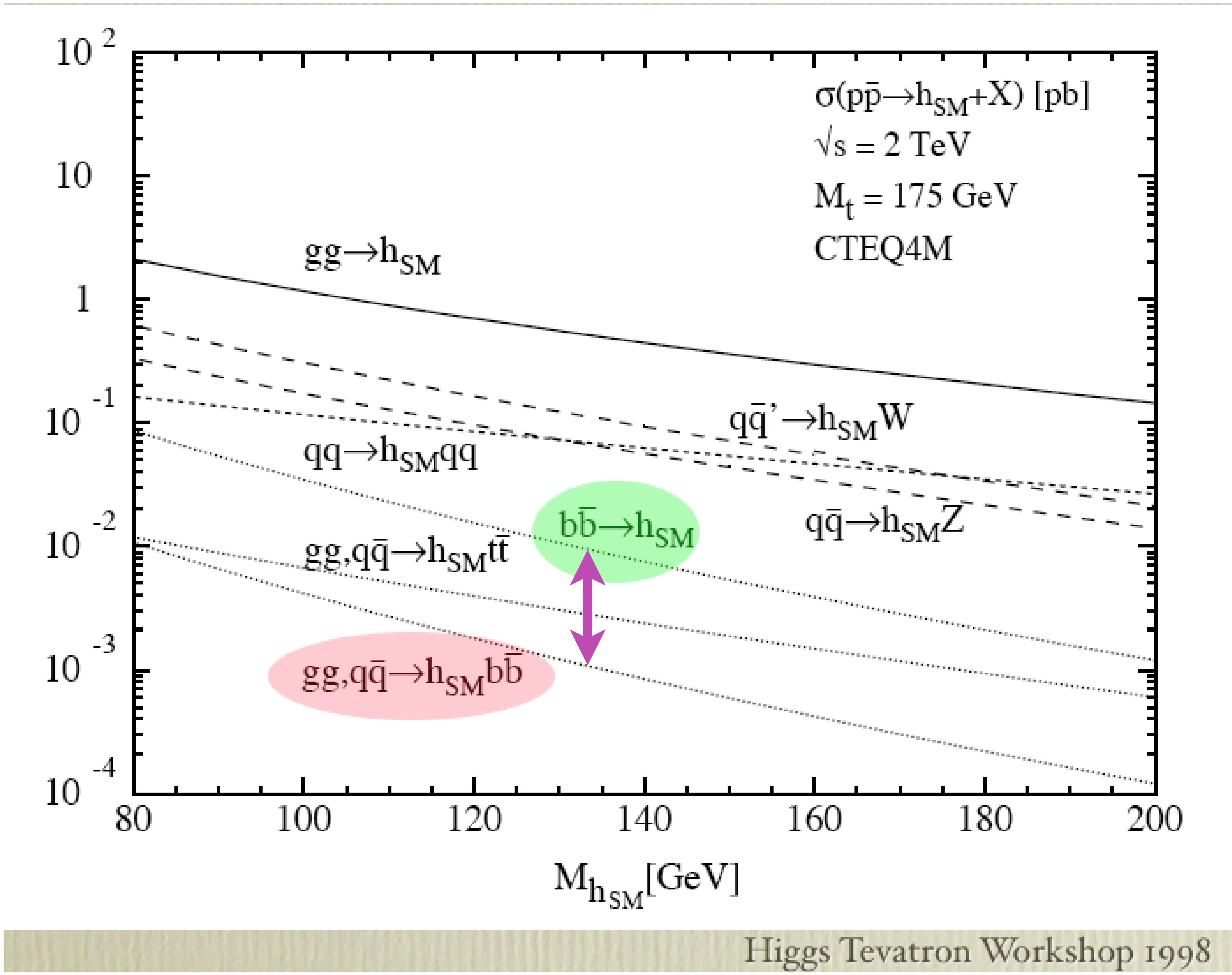
However,...

- The reason(s) and the extent of such an agreeement is not clear yet (cfr MLM's anatomy). Are these logs really large or not?
- What is the best way to simulate these events? Are the current parton-shower approaches reliable? It does not seem so......
- Probably an improved PS with massive splitting kernels for ISR + ME merging could give an accurate description.

Everything we need (NLO results in FF and VF, new PS, new ME/PS merging) to get this working well is there......

A few more slides
(as if there were not enough already)

Theoretical status in the 1998



Factor of 10 !!

Les Houches 2003

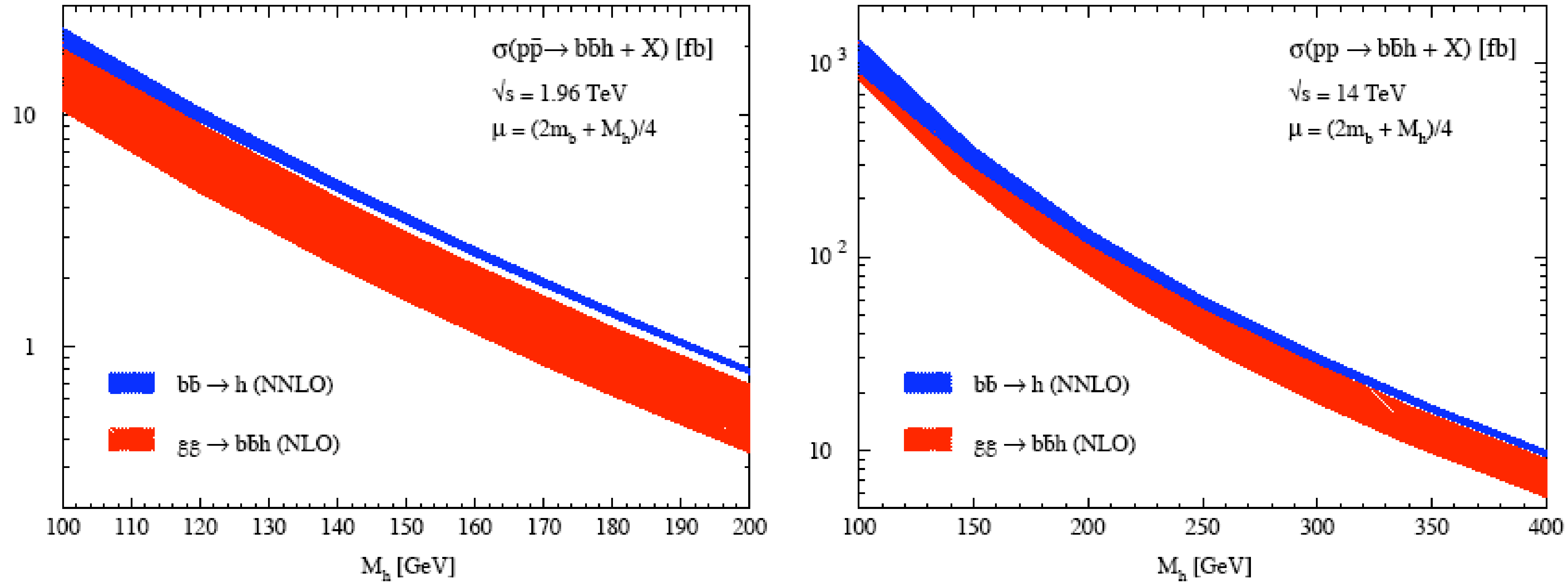
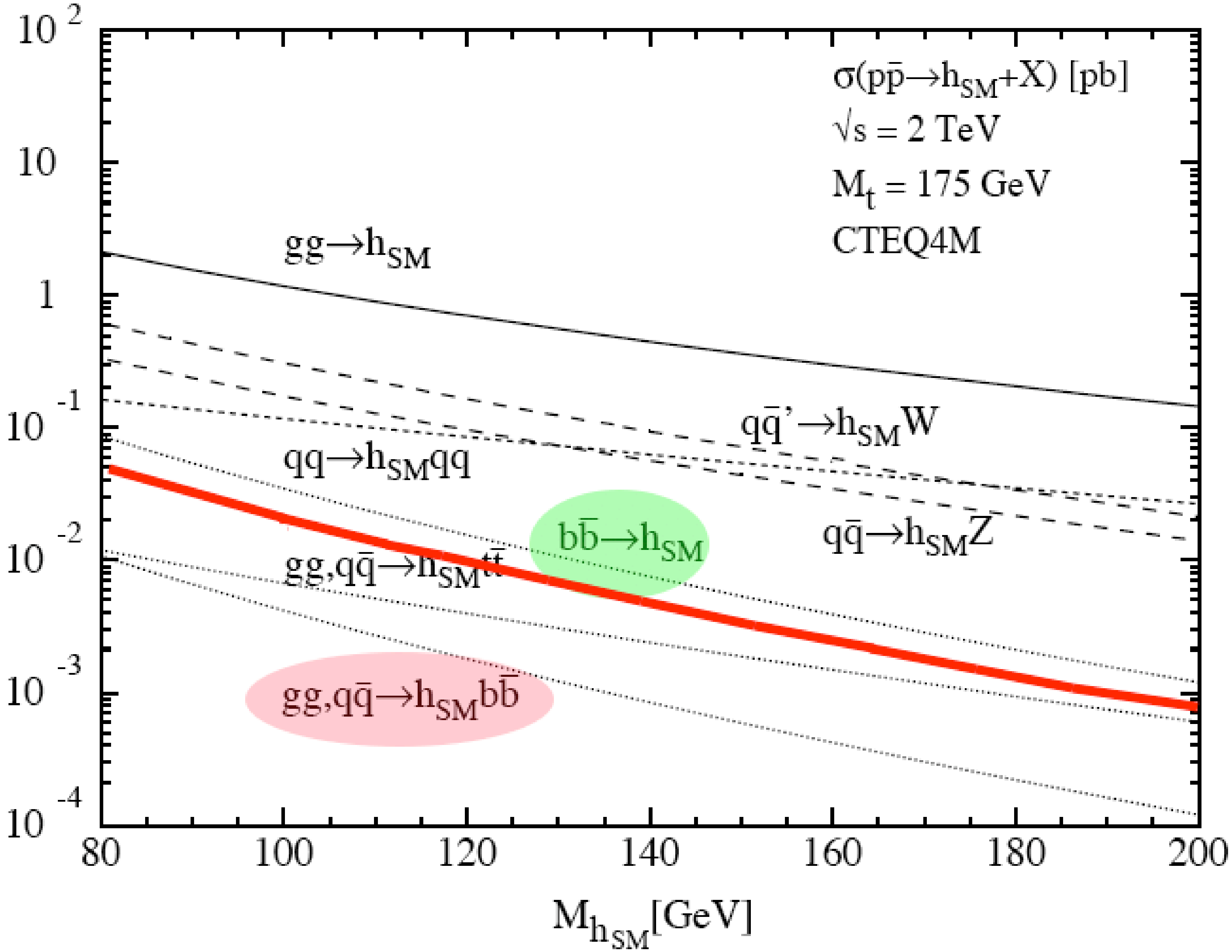


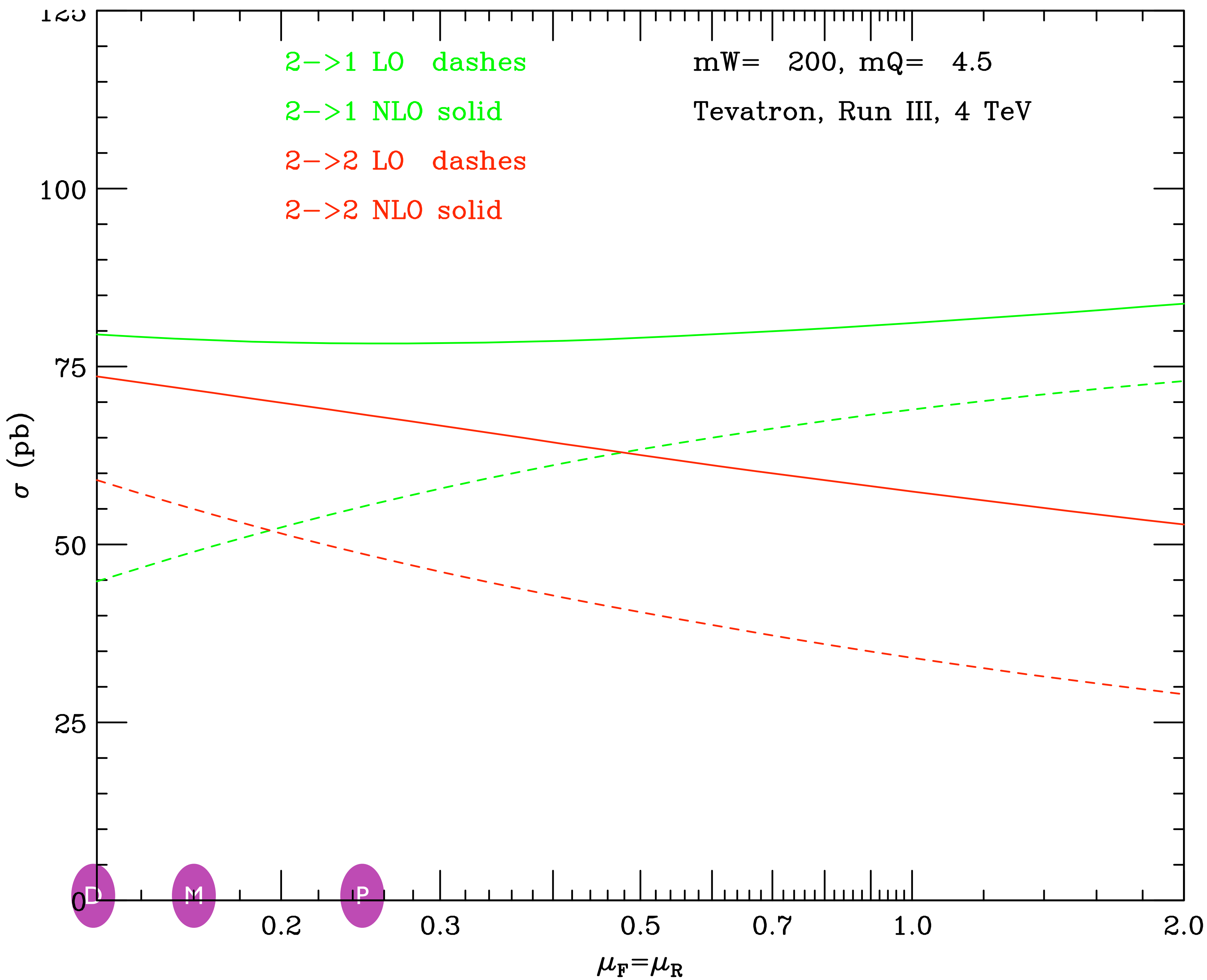
Fig. 8: Total cross sections for $p\bar{p}(pp) \to b\bar{b}h + X$ at the Tevatron and the LHC as a function of the Higgs mass M_h with no b jet identified in the final state. The error bands correspond to varying the scale from $\mu_R = \mu_F = (2m_b + M_h)/8$ to $\mu_R = \mu_F = (2m_b + M_h)/2$. The NNLO curves are from Ref. [10].

[Campbell et al, Les Houches 2003]

Theoretical status in 2004



Wc: 2→1 vs 2→2



* Higher W mass.

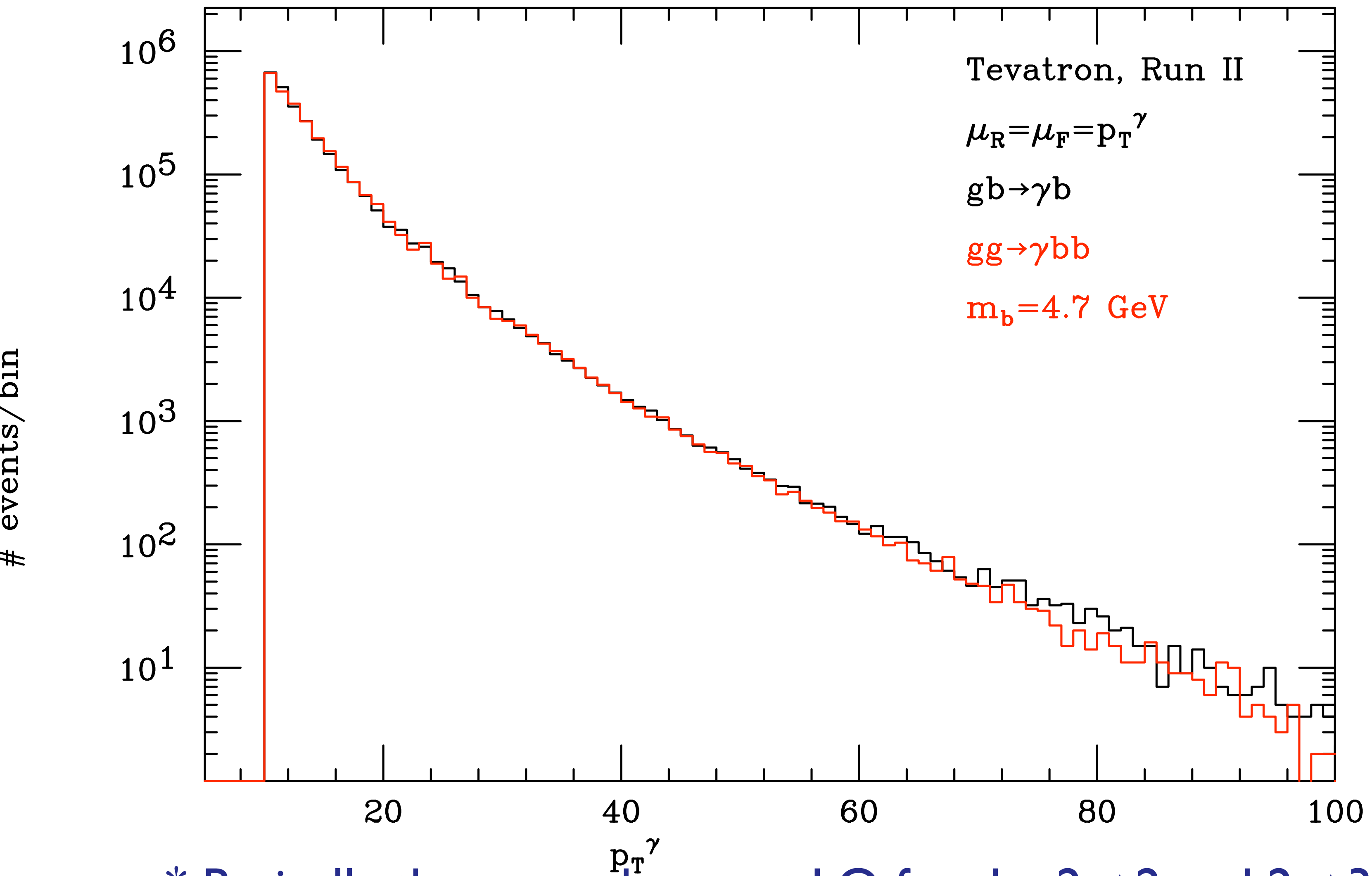
D =dynamical scale=m_T

M = $\sqrt{m_Q * m_W}$

P = $m_W/4$

Example: photon+Q

Different from Z+Q since here the scale of the process is the pt of the gamma.



bottom. mb=4.7 GeV

pta>	gg>bba	gb>ba	R(gg/gb)
10	931	1534	0.61
30	15.01	24.62	0.61
100	0.0189	0.0373	0.51
200	0.0000776	0.000176	0.44

charm, mc=1.4 GeV

pta>	gg>cca	gc>ca	R(gg/gc)
10	10501	14378	0.73
20	664	1061	0.63
40	24.47	47.3	0.52
80	0.484	1.10	0.44
160	0.00339	0.00877	0.38

* Basically the same shapes at LO for the 2→2 and 2→3 processes. A possible sign of a resummation effect for charm but not for bottom.
* Rates differ by almost a factor of two at muf=mur=pt (is significant?)
* Would be interesting to see what happens at NLO....