Too much beauty all around

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- **It there a common explanation?**
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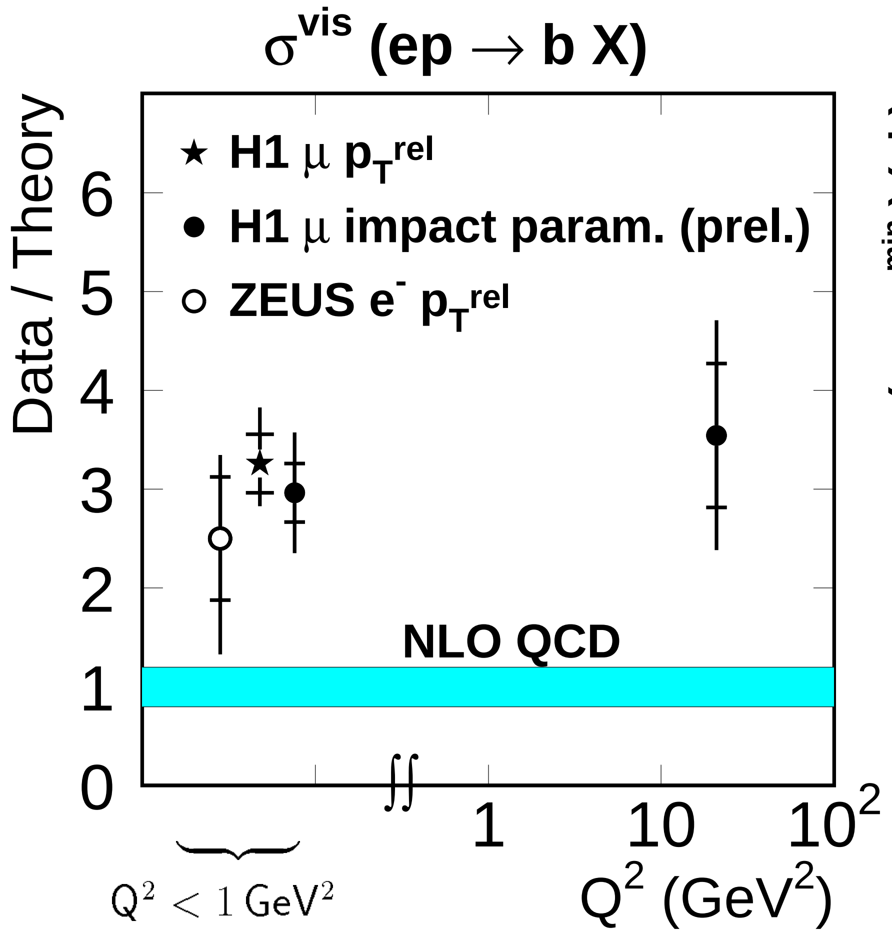
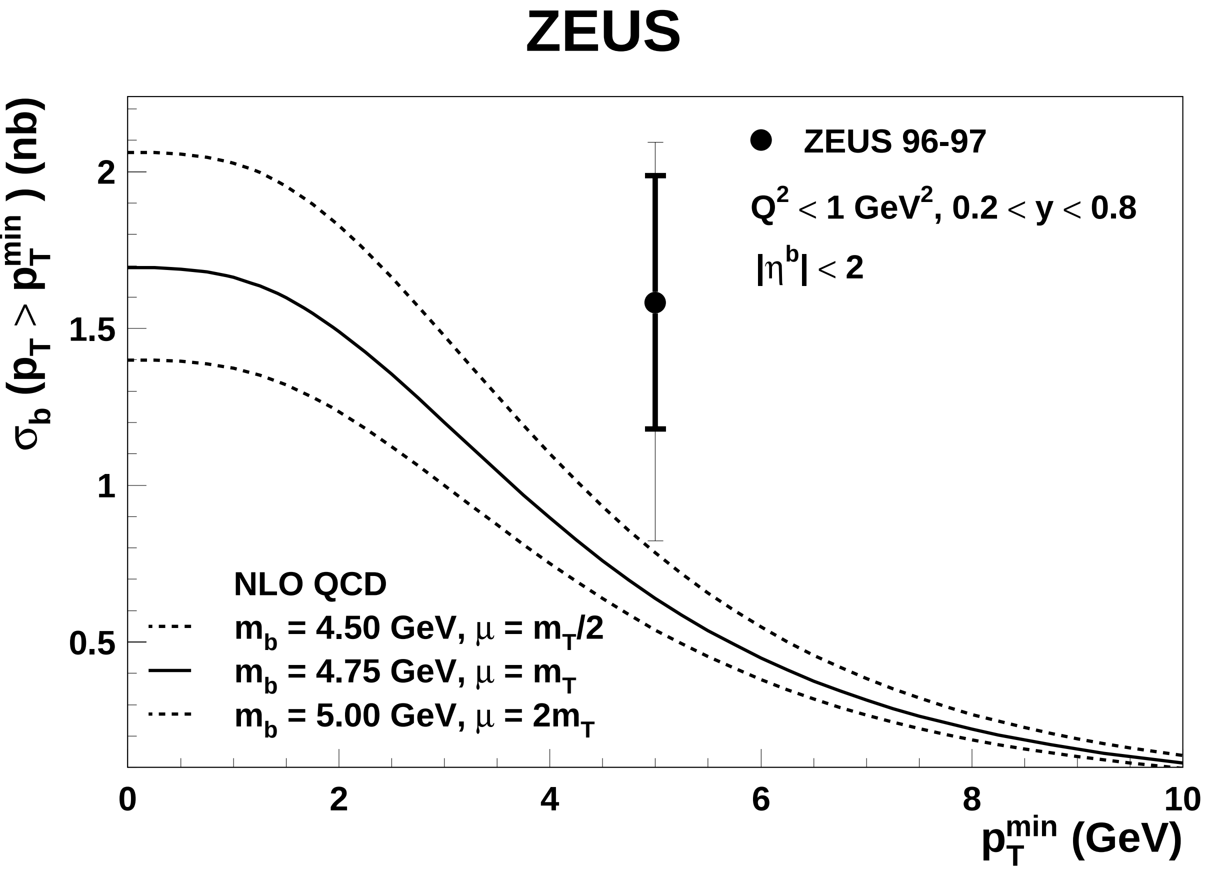
- **Numerical results**
- **Conclusions**

Details in **JHEP03(2003)042** and **hep-ph/0111469**

$\bar{b}b$ production in ep collisions



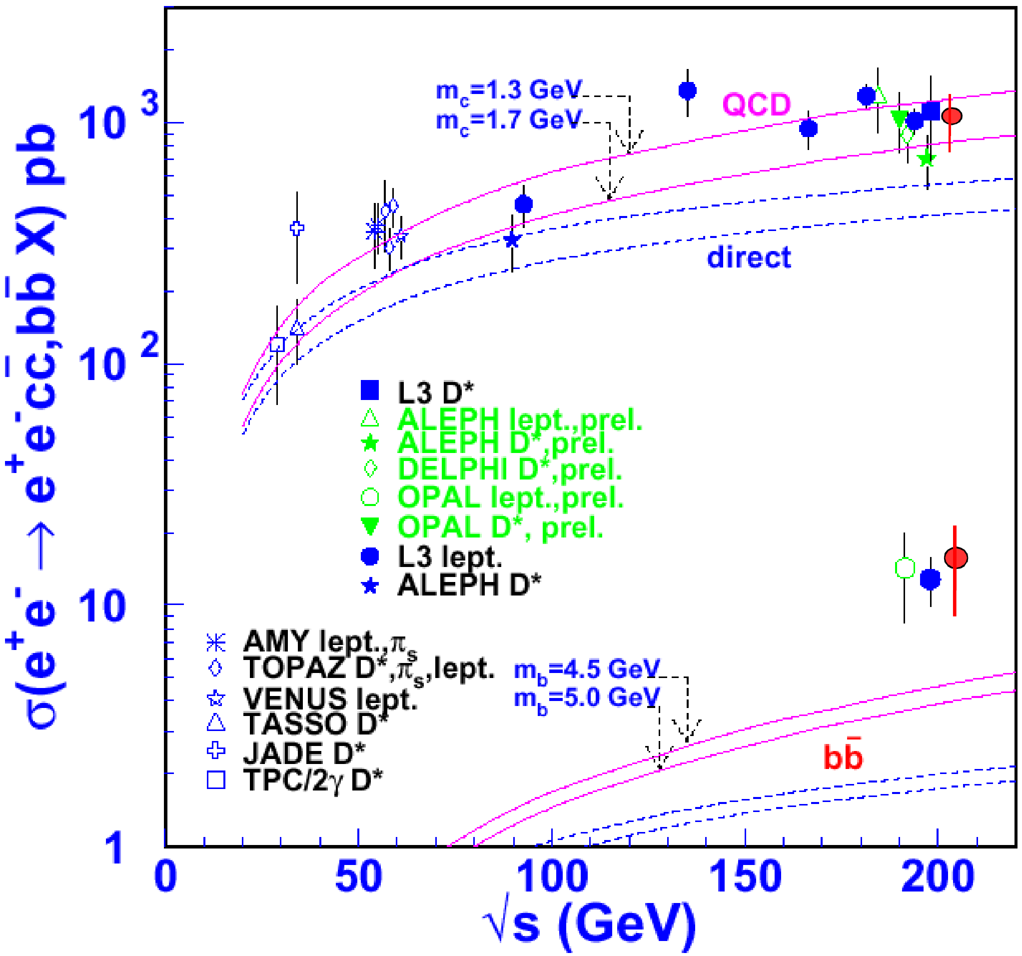


Clear **excess over PQCD** at $Q^2 = 0$ but data **not quite consistent** at high Q^2

$\bar{b}b$ production in $\gamma\gamma$ collisions

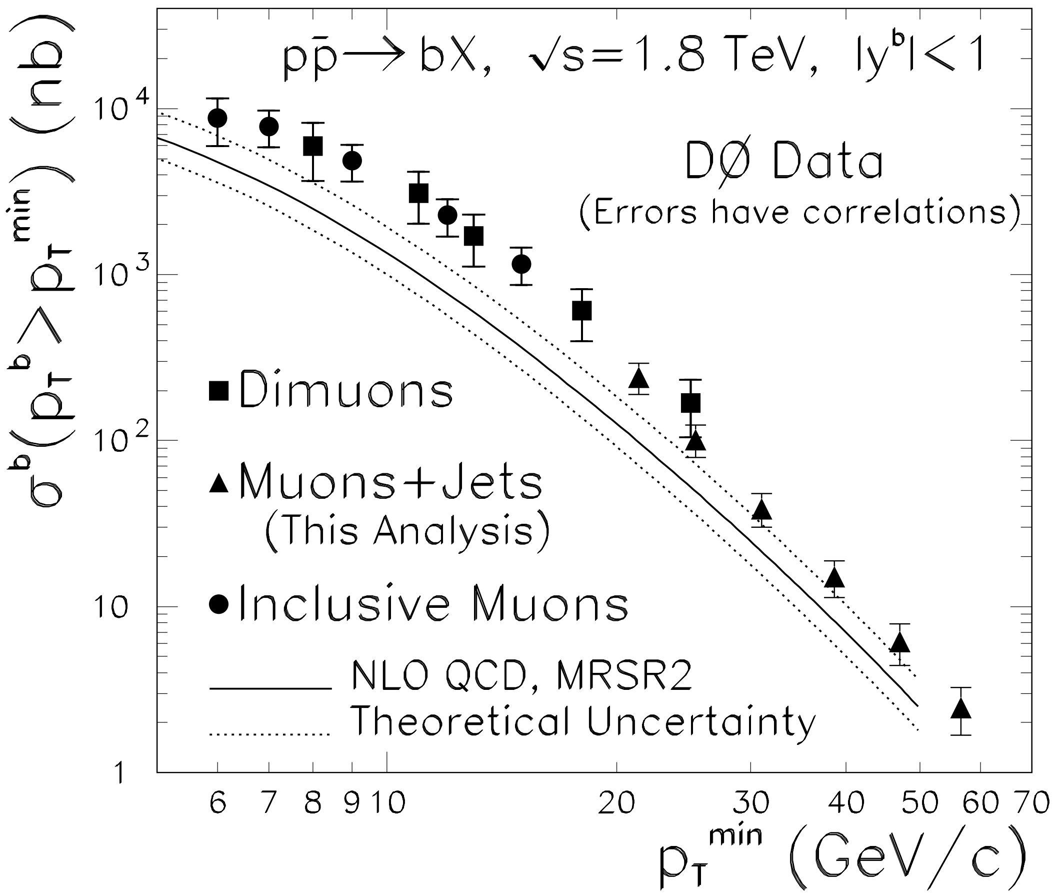
Comparison with L3 and OPAL

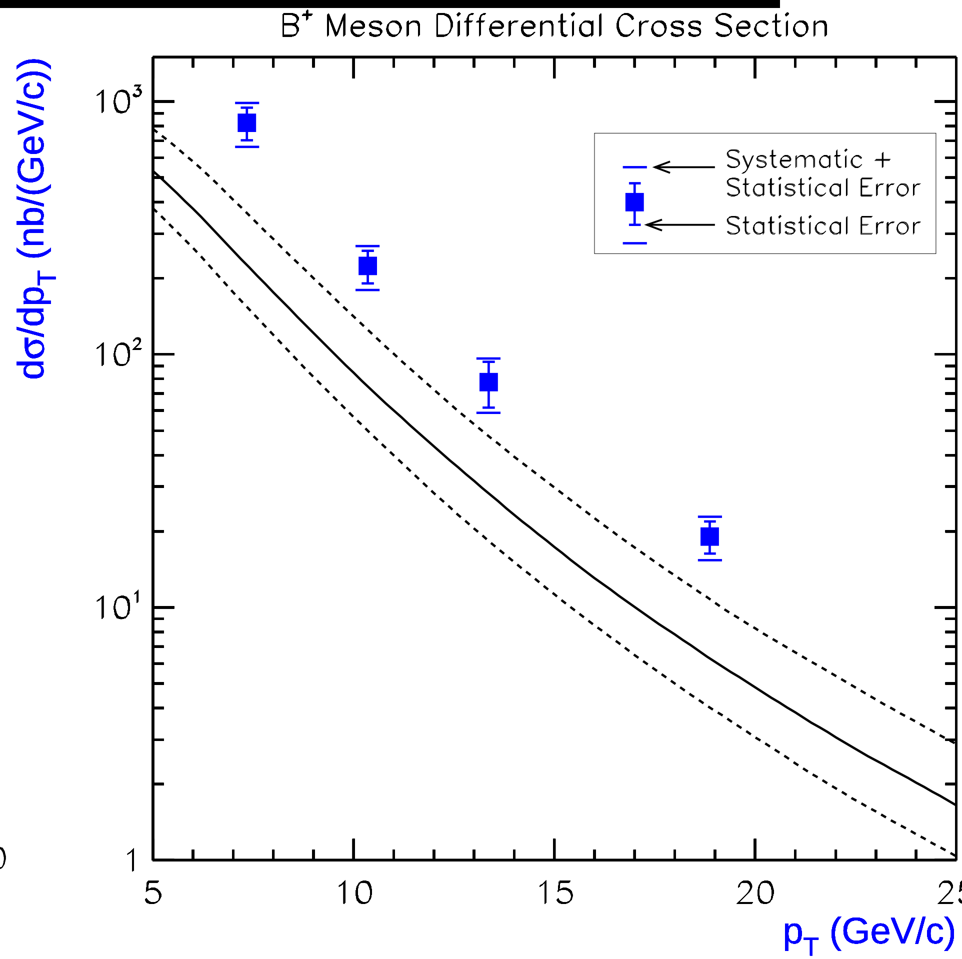
DELPHI



- New **DELPHI** data suggest **striking agreement** between the three LEP experiments
- and **dramatic disagreement** of their data with PQCD
- despite the fact that this process is expected to be the **cleanest test** of PQCD
- my view: current calculations **not truly NLO QCD**
- but **no relation to low x** physics

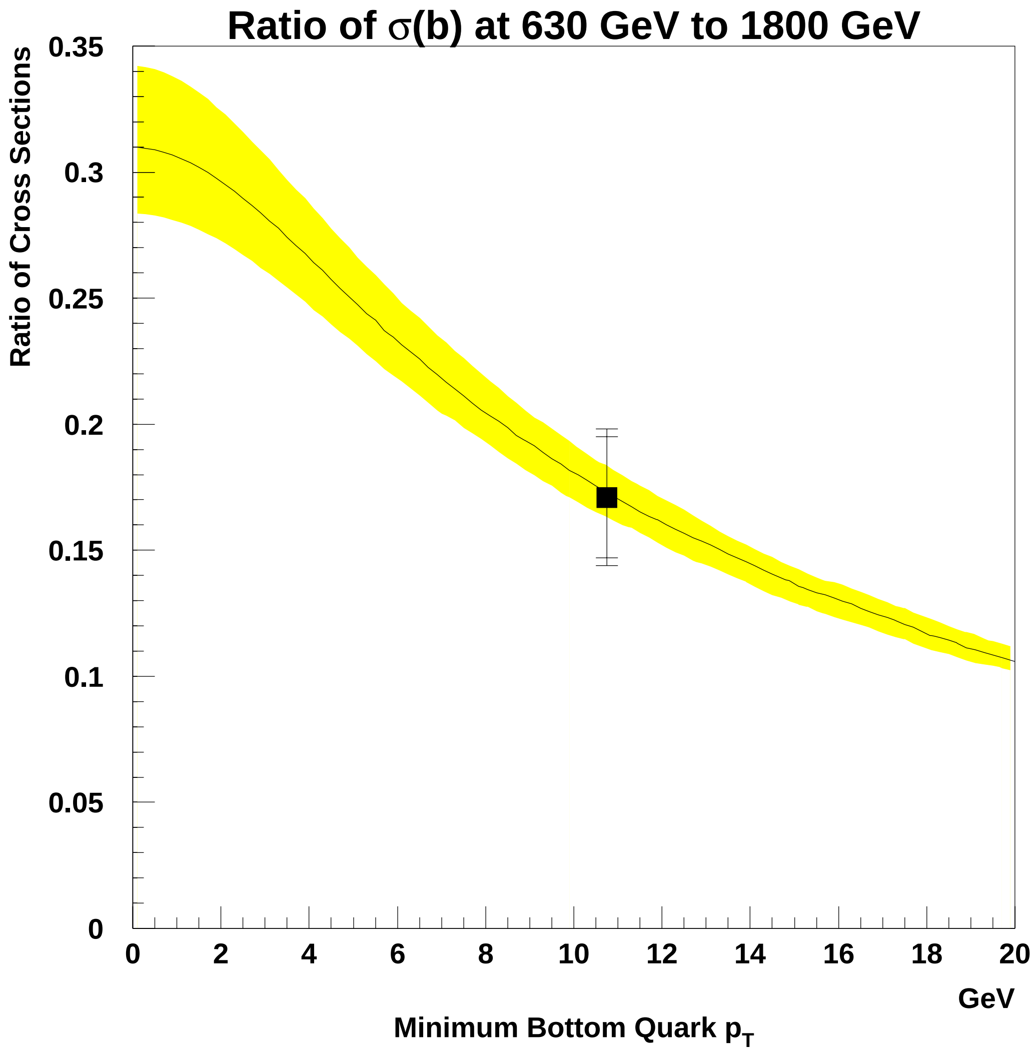
$\bar{b}b$ production in $\bar{p}p$ collisions at the TEVATRON

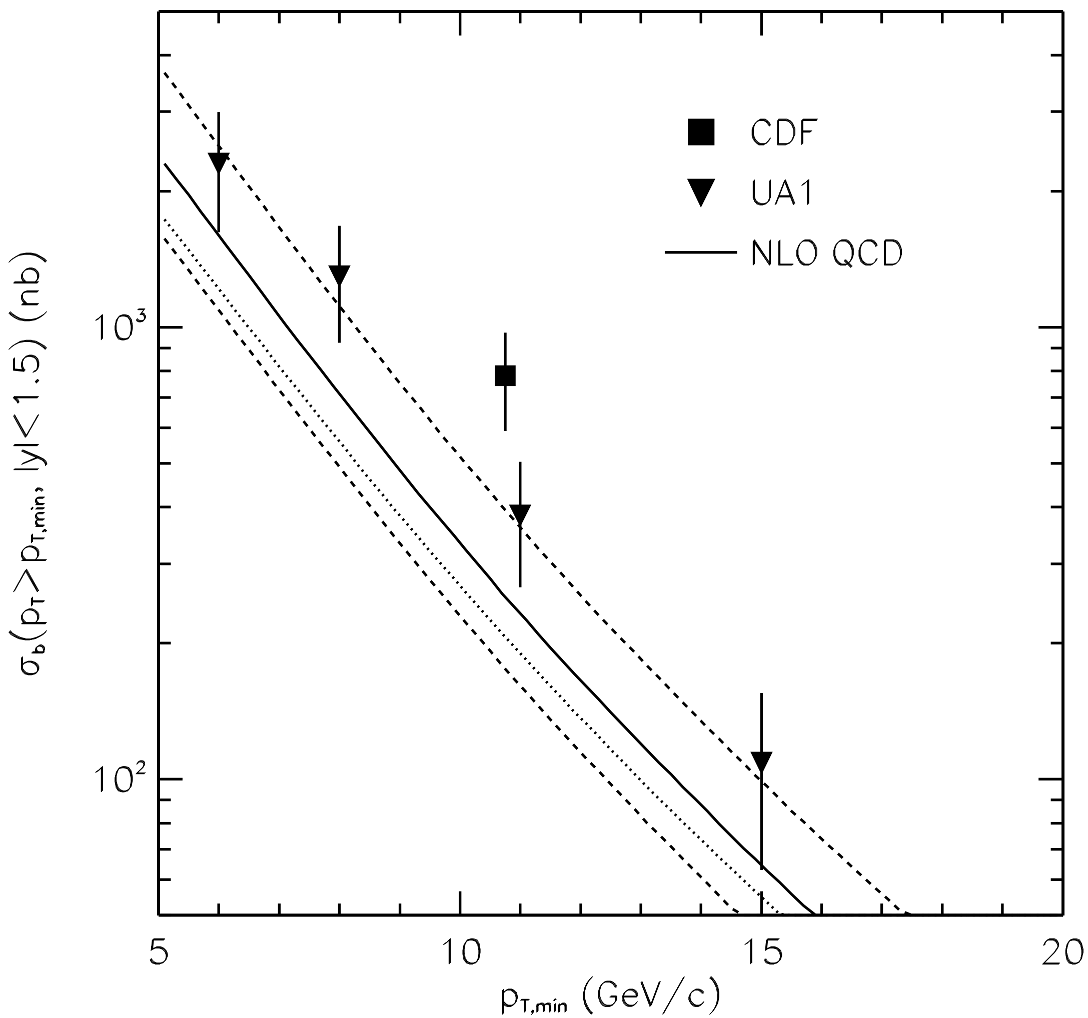




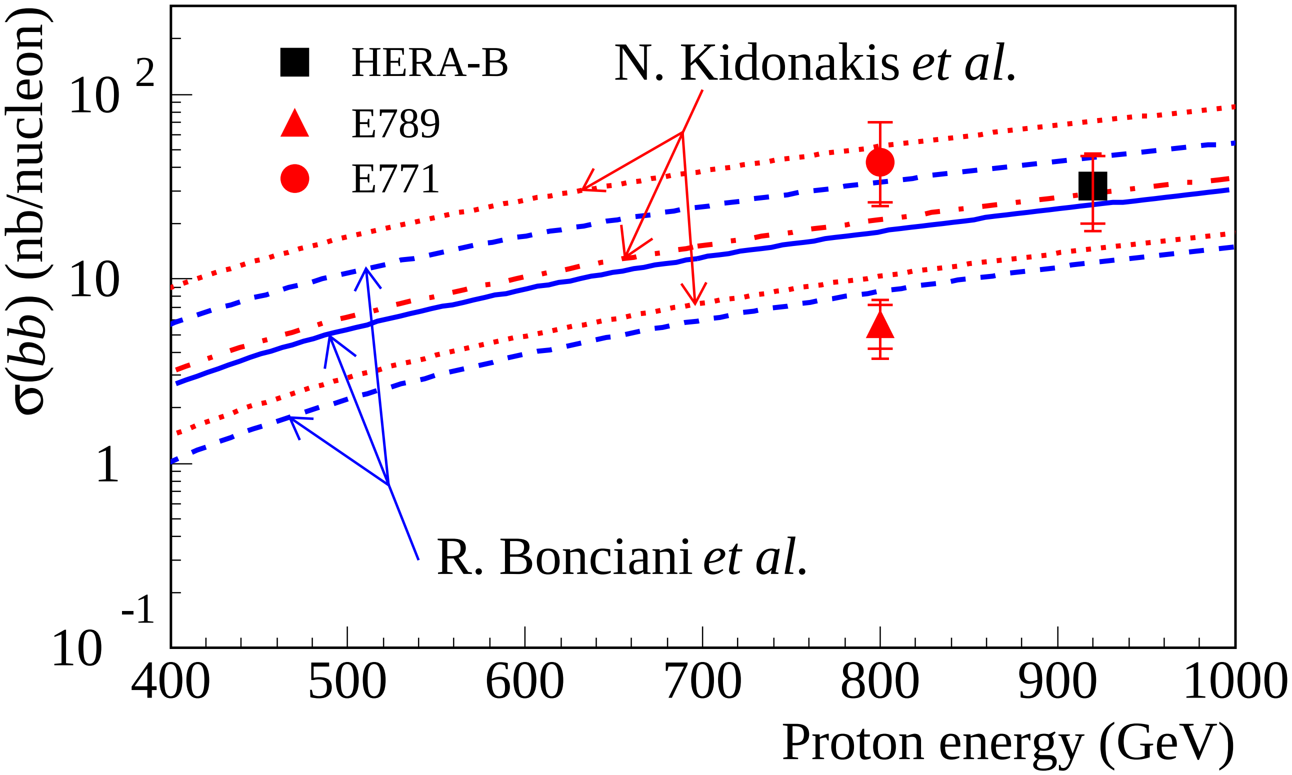
- Clear **excess of both data over PQCD**
- that comes from the **transition region to low x** as $\langle x \rangle \simeq 0.01$.

(In)consistency of $\bar{p}p$ results at TEVATRON and SPSC?





No problems at low energy?

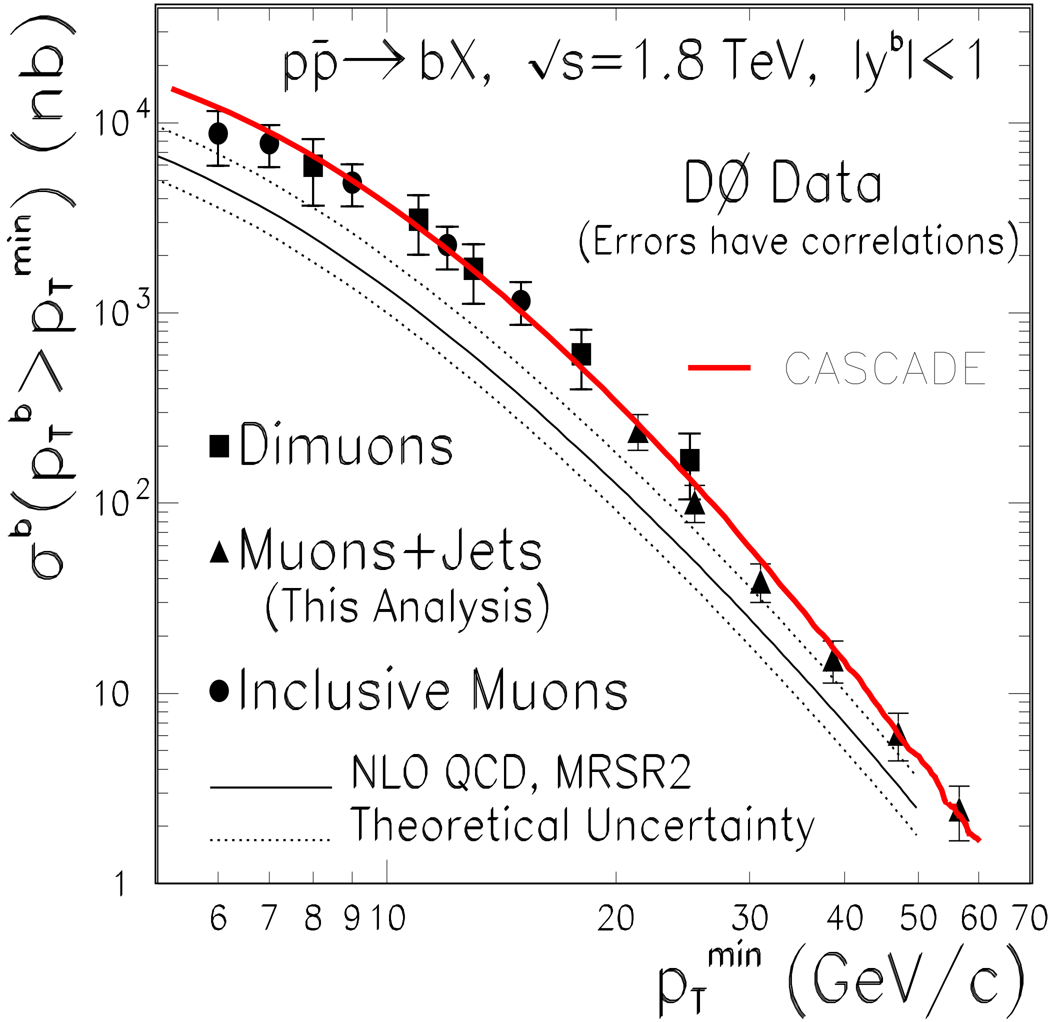


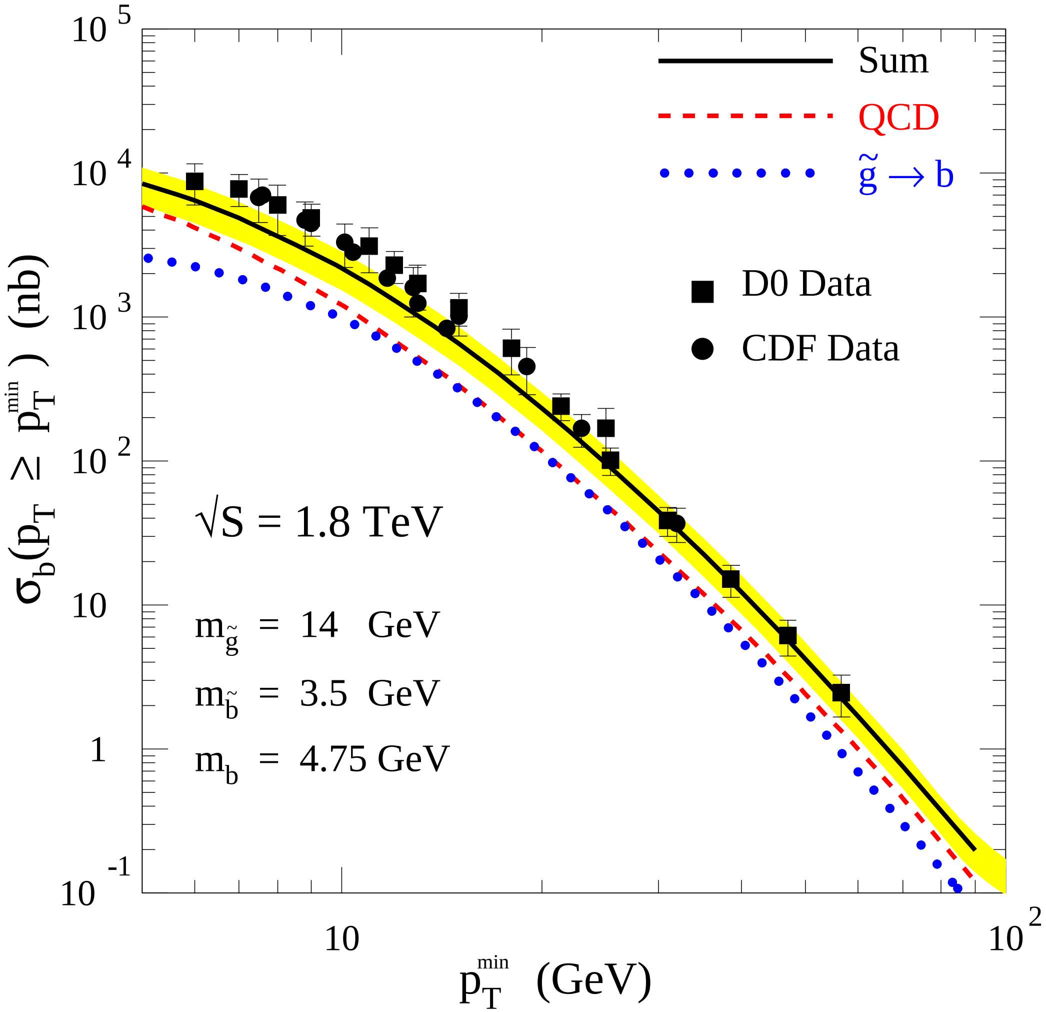
Message:

- **Good agreement** with PQCD at low energies!
- but large **experimental errors**
- and **theoretical uncertainties** to draw strong conclusions and
- and **not low x** physics.

New physics?

low x (BFKL/CCFM) or Supersymmetry?





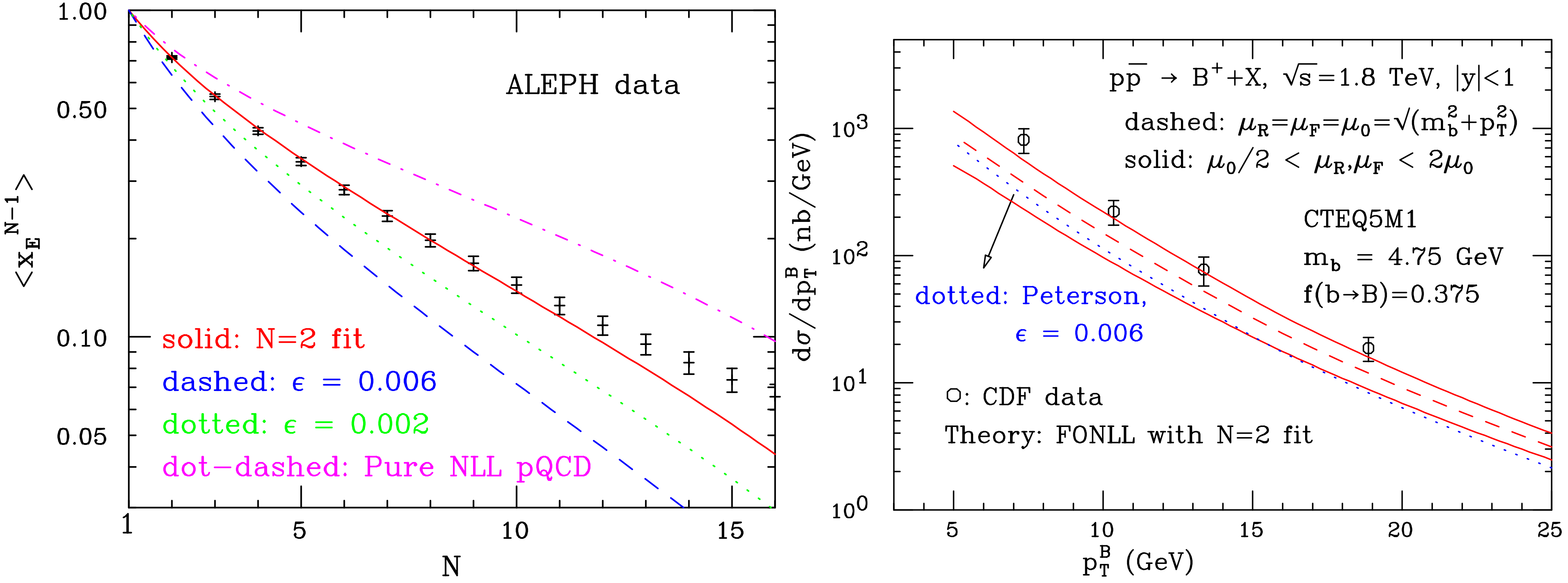
Or subtleties of conventional calculations?

There are several aspects of QCD calculations that must be taken properly into account in the comparison to data as they may significantly enhance the conventional results:

- correctly extracted **b-quark fragmentation functions**
- **threshold** effects
- **small** x effects
- resummation of large logs of the type $\ln(p_T/m_b)$
- choice of **renormalization** and **factorization** scales

Effect of proper parameterization of $D_b^D(z)$ (Cacciari, Nason)

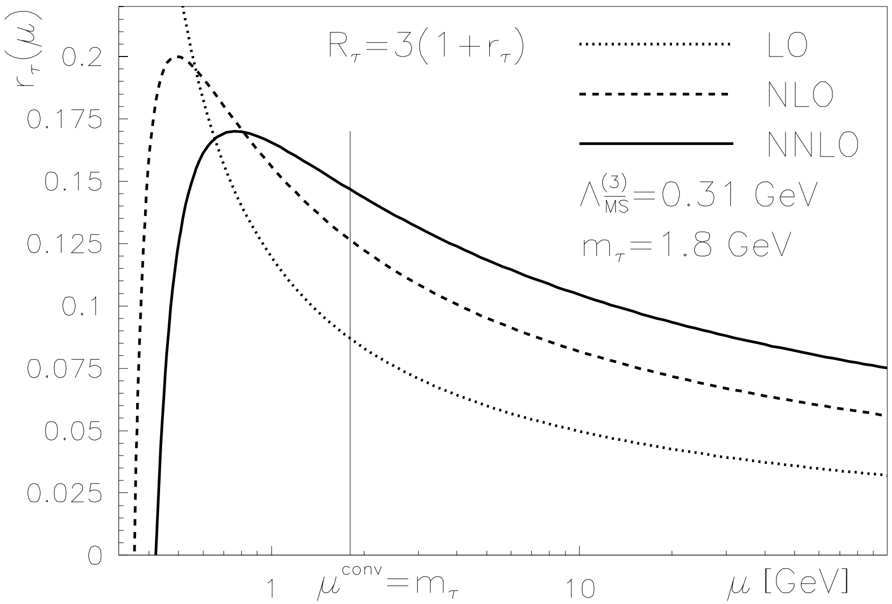
$$if\ \frac{d\hat{\sigma}}{d\hat{p}_T} = A\hat{p}_T^{-n} \Rightarrow \frac{d\sigma}{dp_T} = \frac{A}{p_T^n}D(n), \quad D(N) \equiv \int dz D_b^B(z)$$



Among them those damned scales

General form of perturbative expansion involving $a(s) \equiv \alpha_s(\mu)/\pi$ in a **given RS**:

$$r(Q) = a_s^k(\mu, \mathrm{RS})\left(r_0(Q) + r_1(Q/\mu, \mathrm{RS})a_s(\mu, \mathrm{RS}) + r_2(Q/\mu, \mathrm{RS})a_s^2(\mu, \mathrm{RS})\cdots\right)$$



$$\frac{\beta_0}{4\pi}\ln\left(\frac{\mu^2}{\Lambda_{\mathrm{RS}}^2}\right) = \frac{1}{\alpha_s(\mu)} + c\ln\frac{c\alpha_s(\mu)}{1+c\alpha_s(\mu)},$$

Example:

$$R_\tau \equiv \frac{\Gamma(\tau^- \to \nu_\tau + \mathrm{hadrons})}{\Gamma(\tau^- \to \nu_\tau\mu^-\overline{\nu}_\mu)} = 3\,(1+r_\tau)$$

$$r_1(Q/\mu, \mathrm{RS}) = kb\ln\frac{\mu}{\Lambda_{\mathrm{RS}}} - \rho(Q),$$

$$\rho(Q) \equiv kb\ln(Q/\Lambda_{\mathrm{RS}}) - r_1(1, \mathrm{RS})$$

is a renormalization scale and scheme **invariant**.

which RS scale to choose? Only two points truly exceptional: maximum which defines the Principle of Minimal Sensitivity and intersection LO=NLO=NNLO defining the Effective Charges approach

A common origin of the discrepancies? Not quite.

$\overline{p}p$: **complete NLO**

- $\langle x_1 x_2 \rangle \doteq 6.5\ 10^{-2}$ for $\sqrt{S} = 50$ GeV
- $\langle x_1 x_2 \rangle \doteq 8\ 10^{-4}$ for $\sqrt{S} = 600$ GeV
- $\langle x_1 x_2 \rangle \doteq 1.3\ 10^{-4}$ for $\sqrt{S} = 1.8$ TeV $\Rightarrow$ **low x?**
- $\langle x_1 x_2 \rangle \doteq 6.5\ 10^{-6}$ for $\sqrt{S} = 14$ TeV $\Rightarrow$ **low x!**

γp: **incomplete NLO,** $\langle x \rangle \doteq 0.03$ at **HERA**

$\gamma\gamma$: **incomplete NLO,** $\langle x_1 x_2 \rangle \gtrsim 0.01$ at **LEP**

In all cases the **renormalization** and **factorization** scales **play different role** and should therefore be kept as **independent parameters** of the QCD calculations.

General form of $\sigma_{tot}(Q\overline{Q})$

$$\sigma_{tot}(\overline{p}p \to \overline{Q}Q, S) = \iint \mathrm{dxdy} \sum_{ij} D_i^{\overline{p}}(x, M) D_j^{p}(y, M) \sigma_{ij}(s = xyS, M)$$

$$\sigma_{ij}(s, M) = \alpha_s^2(\mu)\sigma_{ij}^{(2)}(s) + \alpha_s^3(\mu)\sigma_{ij}^{(3)}(s, M, \mu) + \cdots,$$

at the NLO

$$\sigma_{tot}^{\mathrm{NLO}}(M, \mu) = \alpha_s^2(\mu) \left\{ \iint \mathrm{d}x\mathrm{d}y \sum_{i=1}^{2n_f} q_i(x, M) q_i(y, M) \left[\sigma_{q\overline{q}}^{(2)}(xy) + \alpha_s(\mu)\sigma_{q\overline{q}}^{(3)}(xy, M, \mu)\right] + \right.$$

$$2 \iint \mathrm{d}x\mathrm{d}y \Sigma(x, M) G(y, M) \alpha_s(\mu) \sigma_{qG}^{(3)}(xy, M) +$$

$$\left. \iint \mathrm{d}x\mathrm{d}y G(x, M) G(y, M) \left[\sigma_{GG}^{(2)}(xy) + \alpha_s(\mu)\sigma_{GG}^{(3)}(xy, M, \mu)\right] \right\}$$

Crucial point: keep the **factorization** and **renormalization** scales **independent!**
Similar expression for **differential cross sections** as well.

Factorization scale dependence of the NLO approximation:

$$\frac{\mathrm{d}\sigma_{tot}^{\mathrm{NLO}}(M,\mu)}{\mathrm{d}\ln M^2} = \iint \mathrm{d}x\mathrm{d}y G(x,M)G(y,M)W_{GG}(xy,M,\mu)+ \tag{1}$$

$$\iint \mathrm{d}x\mathrm{d}y\left[\sum_{i=1}^{2n_f} q_i(x,M)q_i(y,M)W_{qq}(xy,M,\mu)+\Sigma(x,M)G(y,M)W_{qG}(xy,M,\mu)\right].$$

Denoting $\dot{f}\equiv \mathrm{df}/\mathrm{d}\ln \mathrm{M}^2$, the functions W_{ij} are given as

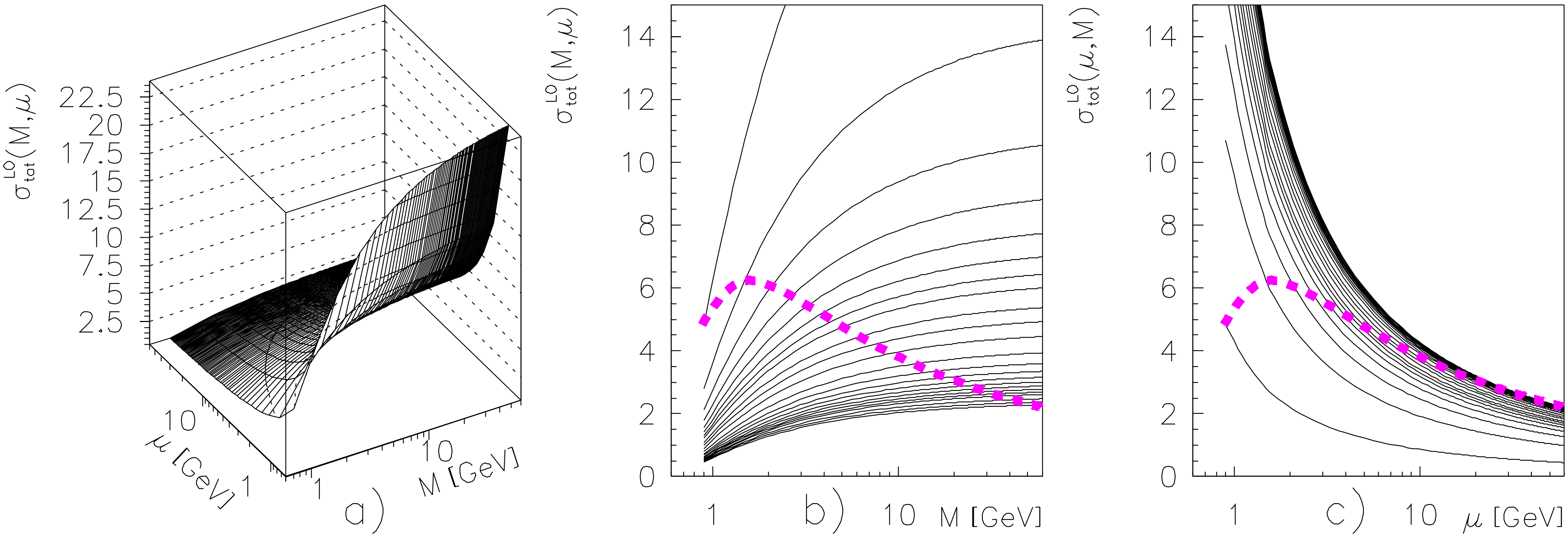
$$W_{GG}(x,M,\mu) = \frac{\alpha_s^3(\mu)}{\pi}\left\{2\pi\dot{\sigma}_{GG}^{(3)}(x)+\int \mathrm{d}z P_{GG}^{(0)}(z)\sigma_{GG}^{(2)}(xz)\right\}+\cdots \tag{2}$$

$$W_{q\overline{q}}(x,M,\mu) = \frac{\alpha_s^3(\mu)}{\pi}\left\{2\pi\dot{\sigma}_{q\overline{q}}^{(3)}(x)+2\int \mathrm{d}z P_{qq}^{(0)}(z)\sigma_{q\overline{q}}^{(2)}(xz)\right\}+\cdots \tag{3}$$

$$W_{qG}(x,M,\mu) = \frac{\alpha_s^3(\mu)}{\pi}\left\{2\pi\dot{\sigma}_{qG}^{(3)}(x)+\int \mathrm{d}z\left[P_{qG}^{(0)}(z)\sigma_{q\overline{q}}^{(2)}(xz)+P_{Gq}^{(0)}(z)\sigma_{GG}^{(2)}(xz)\right]\right\}+\cdot \tag{4}$$

Theoretical consistency requires that the expressions standing in the above expressions by α_s^3 **vanish which, indeed, they do**.

What is wrong with the conventional assumption $M = \mu$?

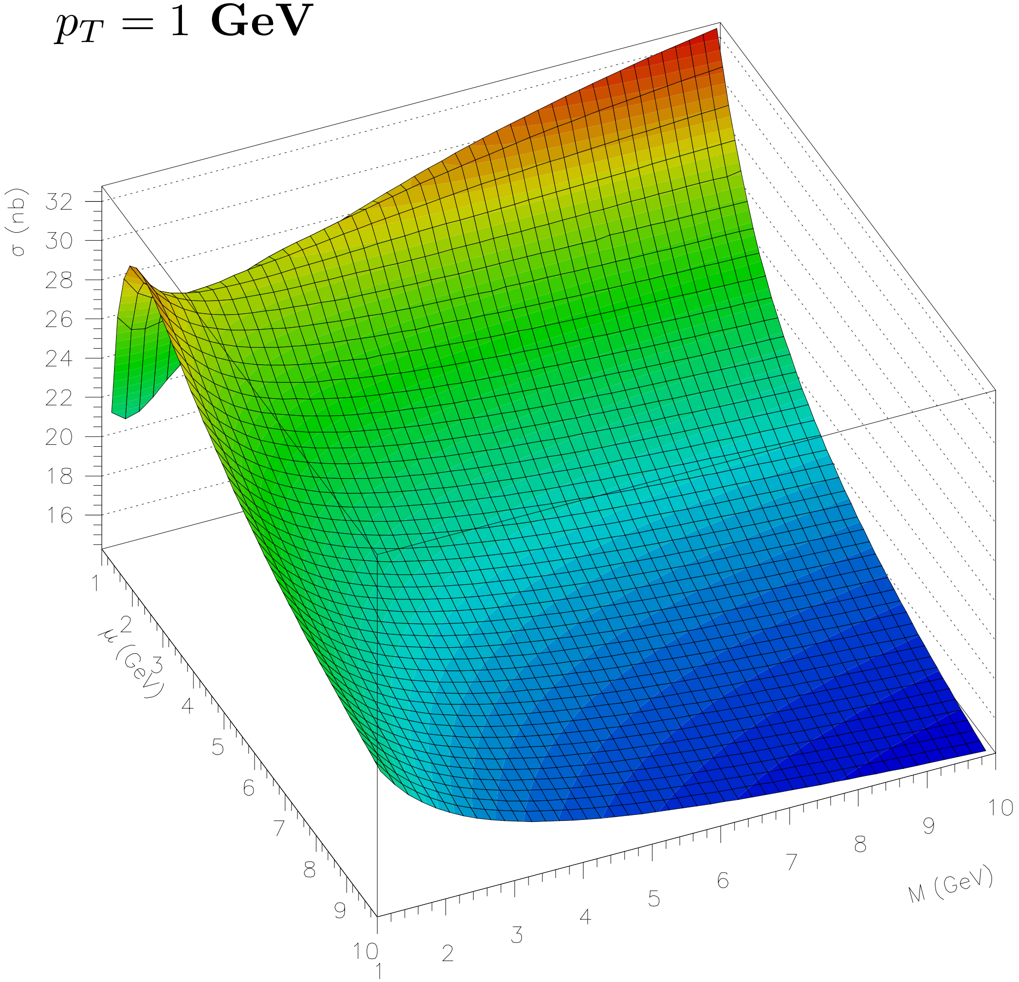


Fakes the stability where there is none
Leads away from genuine stability region

Numerical results at the NLO

$\bar{b}b$, $\sqrt{S} = 1800$ **GeV**

$p_T = 1$ **GeV**



$$r^{(N)} \equiv \sum_{j=k}^{N} r_{j-k} a_s^j$$

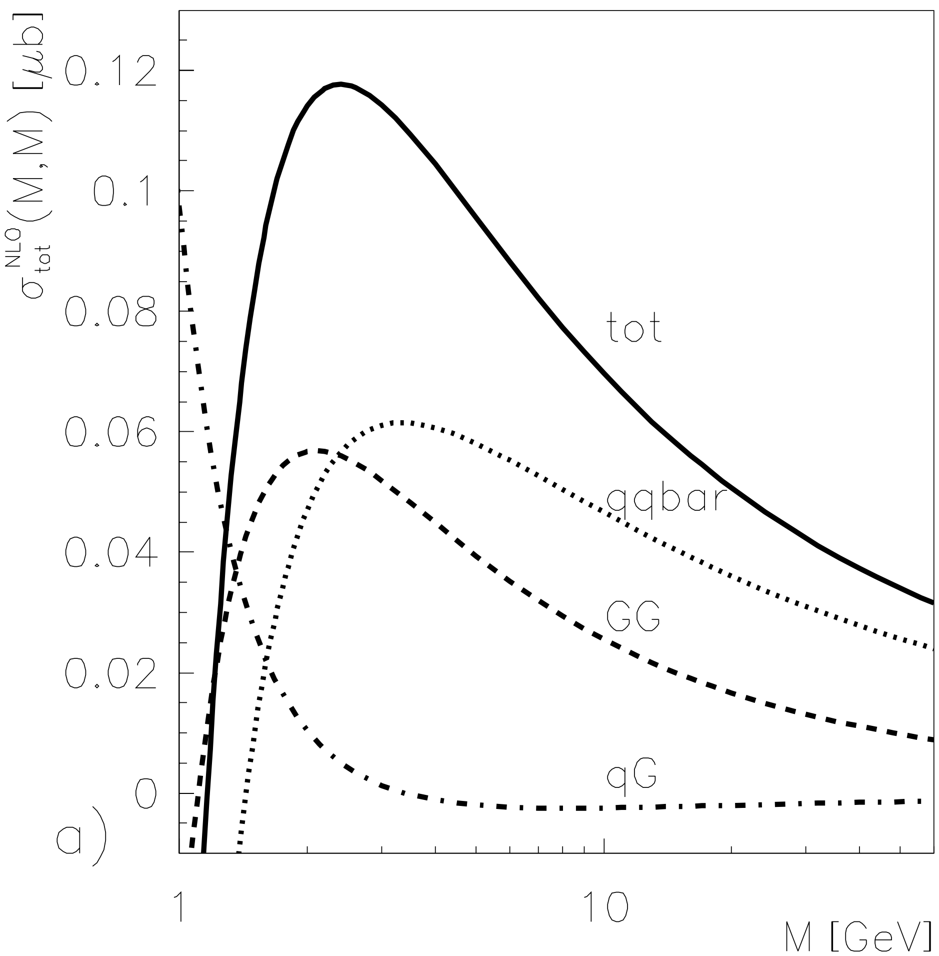
$$\Downarrow$$

$$\frac{\mathrm{d}r^{(N)}}{\mathrm{d}\ln M} = \frac{\mathrm{d}r^{(N)}}{\mathrm{d}\ln \mu} = O(a_s^{N+1})$$

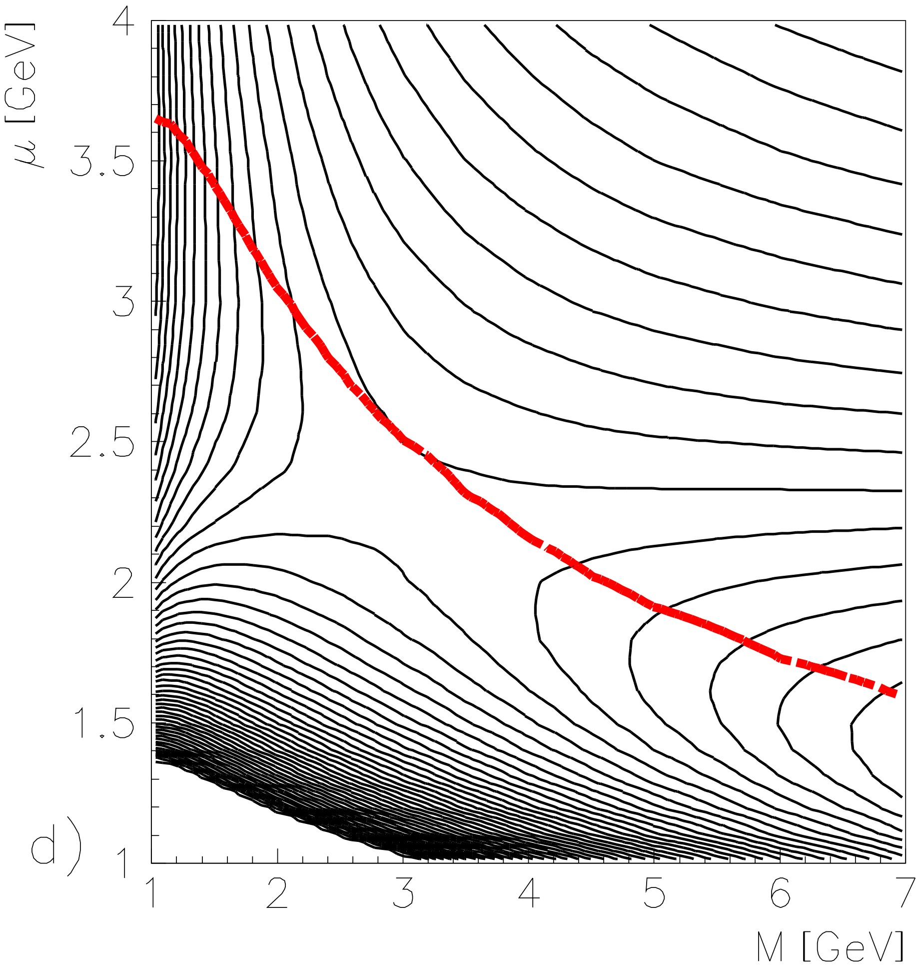
$$\Downarrow$$

Saddle point defines the most stable prediction

$\sigma_{tot}^{\rm NLO}(M,\mu)$ at $\sqrt{S}=62$ GeV

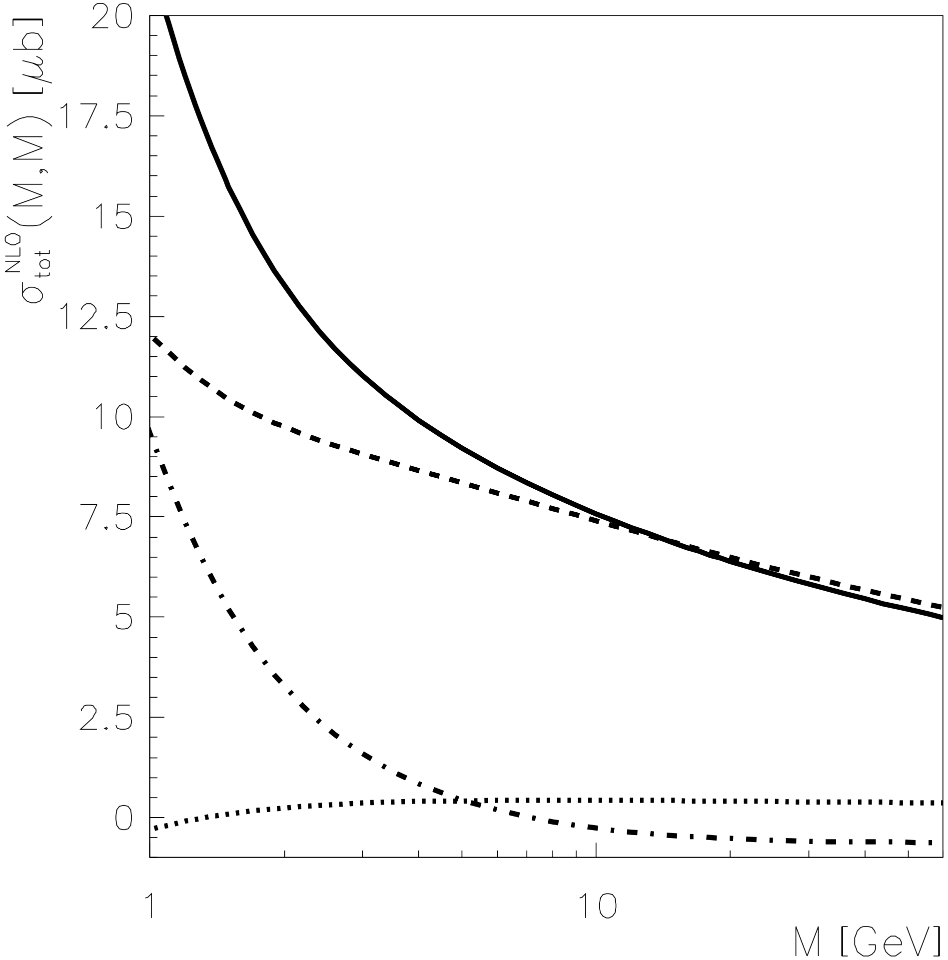


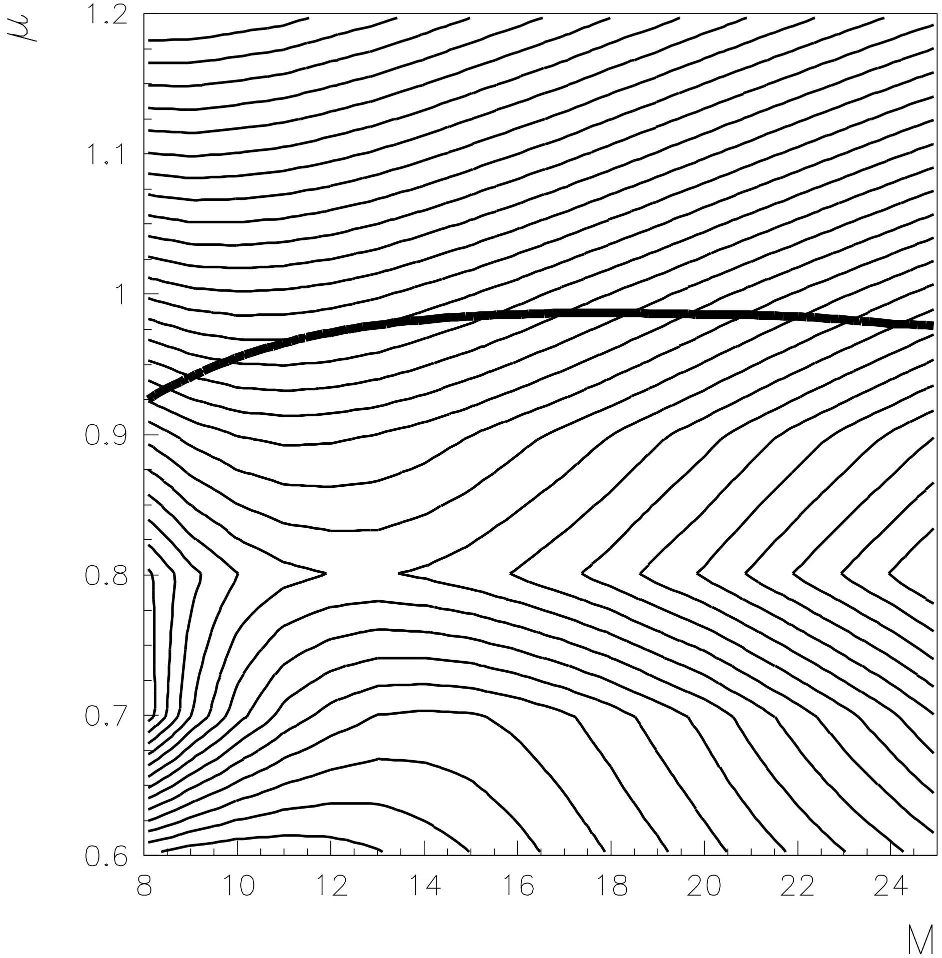
Quark dominated processes



Saddle close to the diagonal $M=\mu$

$\sigma^{\rm NLO}_{tot}(M,\mu)$ at $\sqrt{S}=630$ GeV

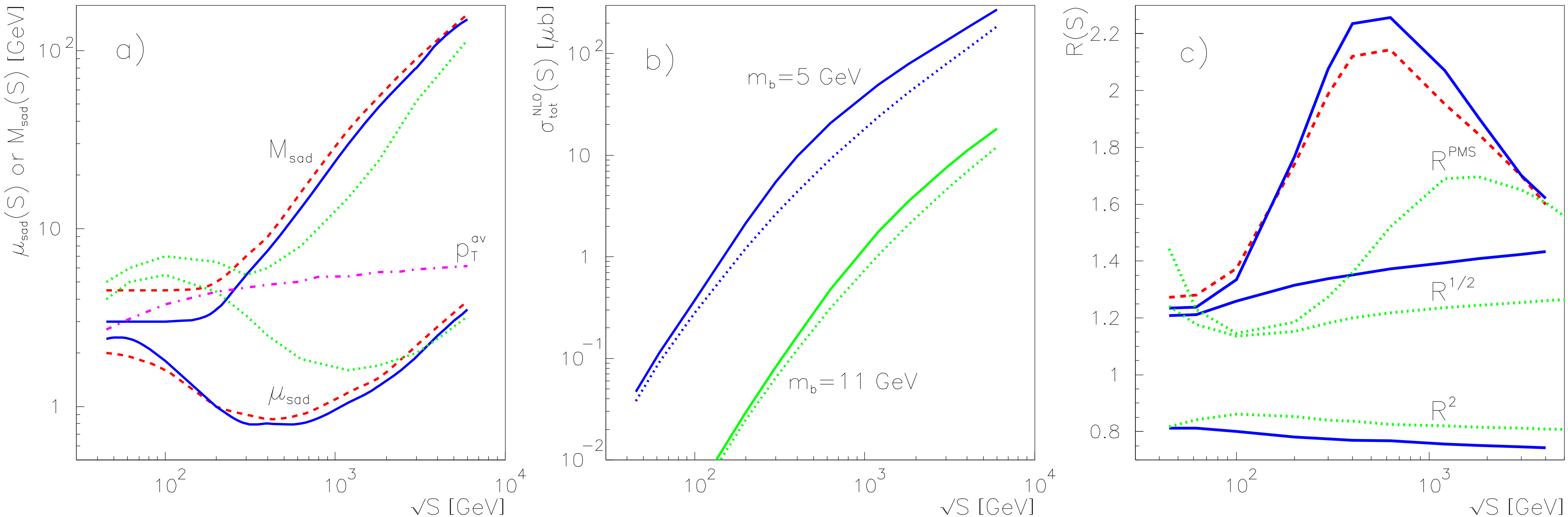




Gluon dominated processes

Saddle far from the diagonal $M=\mu$

Energy dependence of $\sigma_{tot}^{\rm NLO}(M,\mu)$



Non-diagonal energy dependence of the saddle

Different energy dependence of $\sigma_{tot}^{\rm NLO}(saddle)$

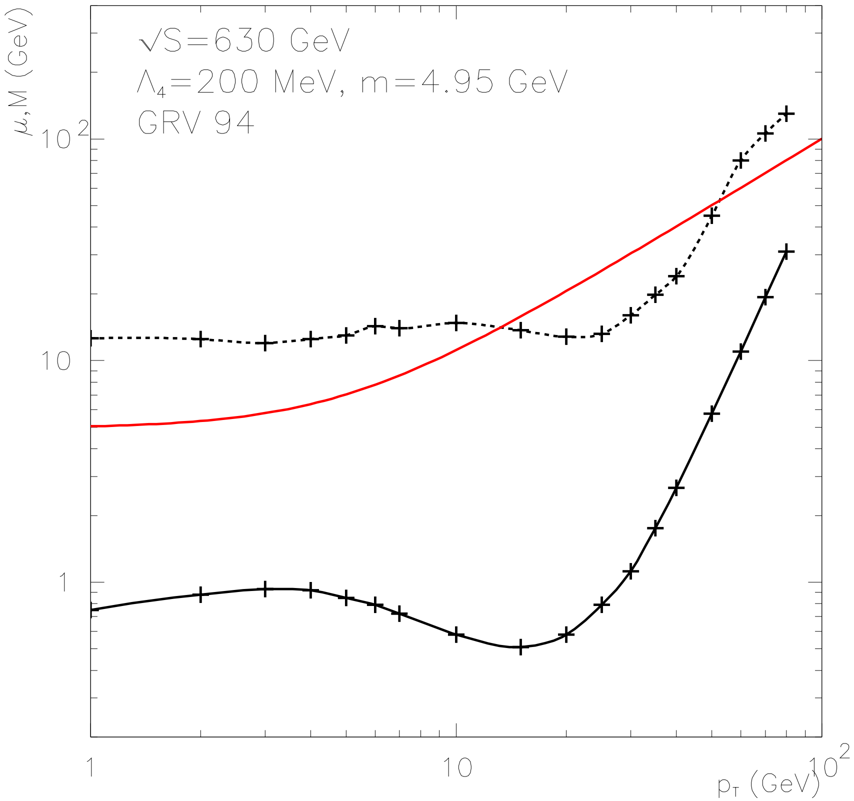
particularly **in the TEVATRON** energy range

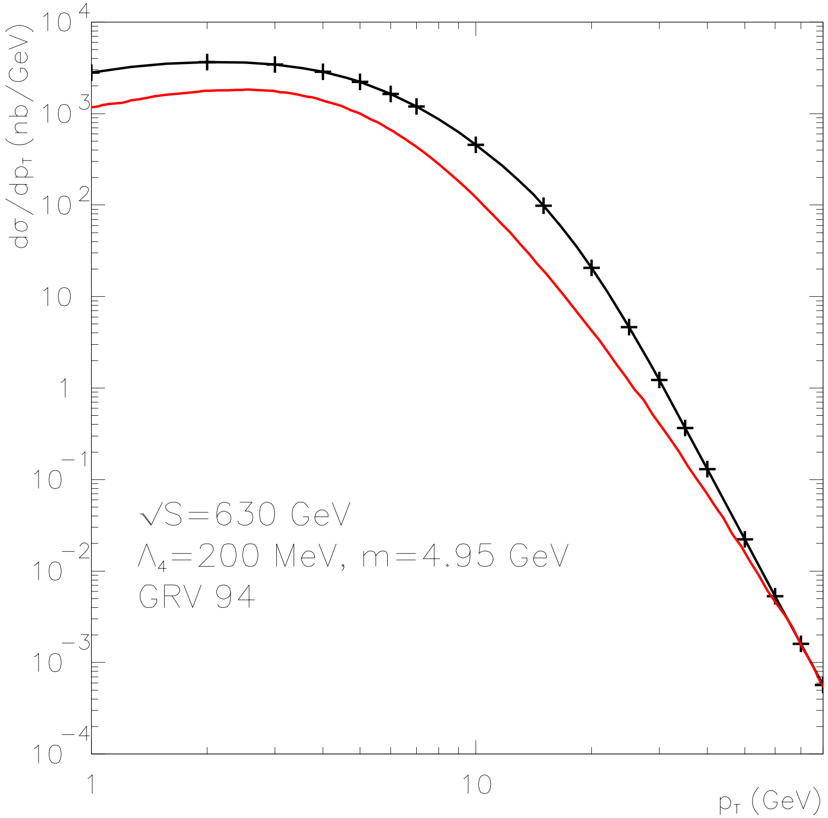
The effect **decreases with increasing** m_b

$$R^{\rm PMS}(S) \equiv \frac{\sigma_{tot}^{\rm NLO}(M_{sad},\mu_{sad})}{\sigma_{tot}^{\rm NLO}(m_b,m_b,\overline{\rm MS})}$$

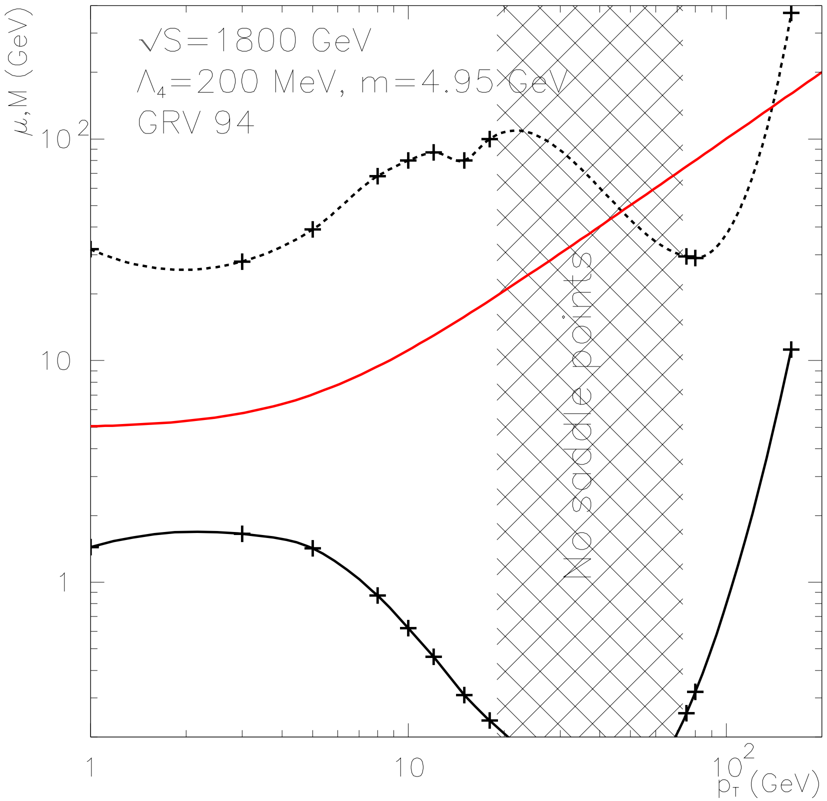
$$R^{\kappa}(S) \equiv \frac{\sigma_{tot}^{\rm NLO}(\kappa m_b,\kappa m_b,\overline{\rm MS})}{\sigma_{tot}^{\rm NLO}(m_b,m_b,\overline{\rm MS})}$$

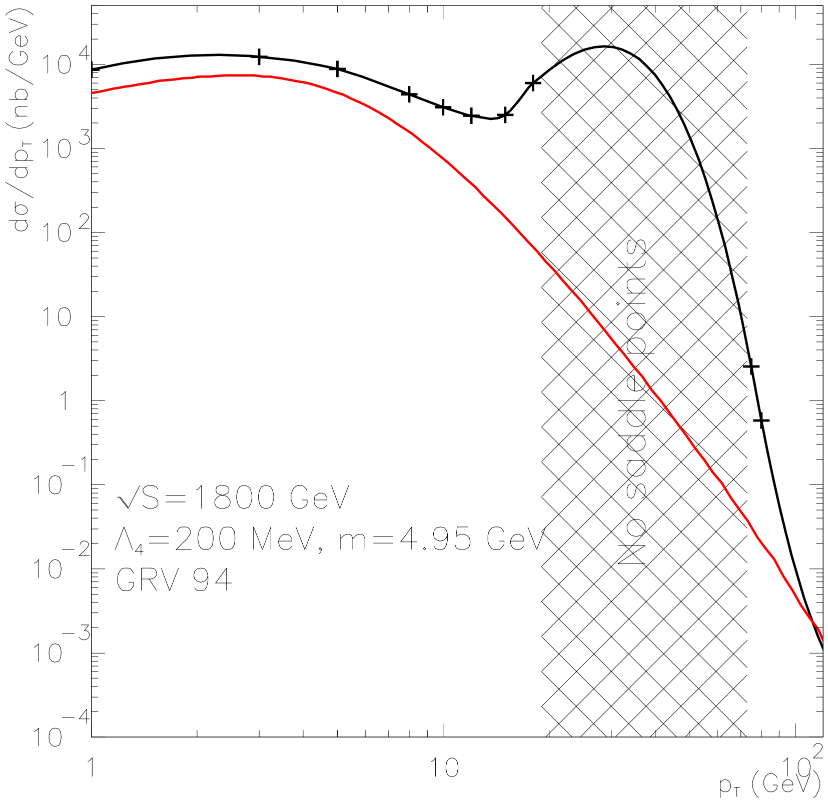
p_T dependence at $\sqrt{S} = 630$ GeV



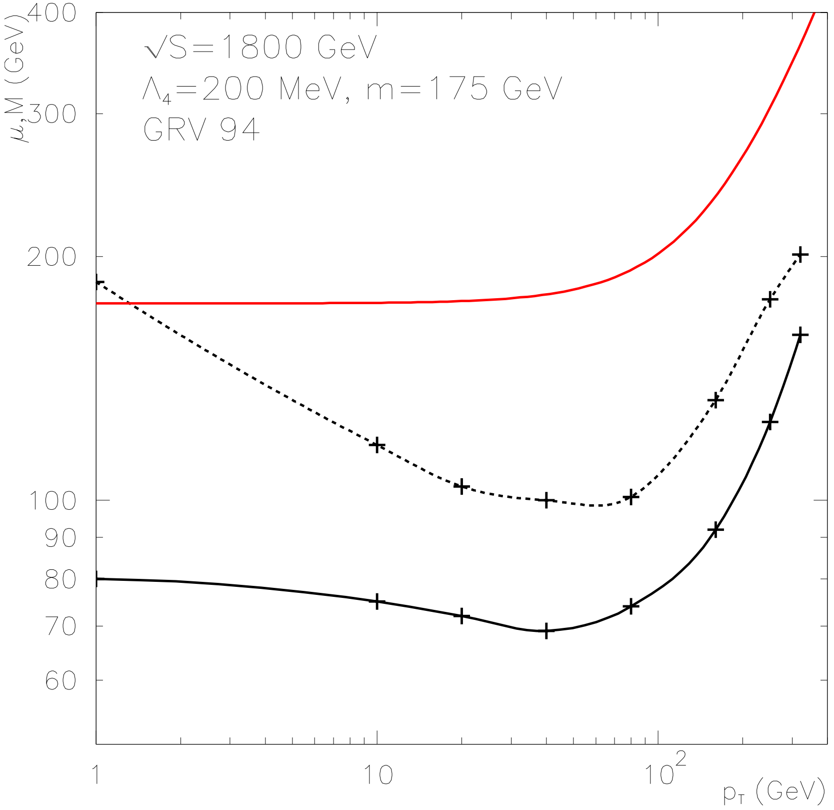


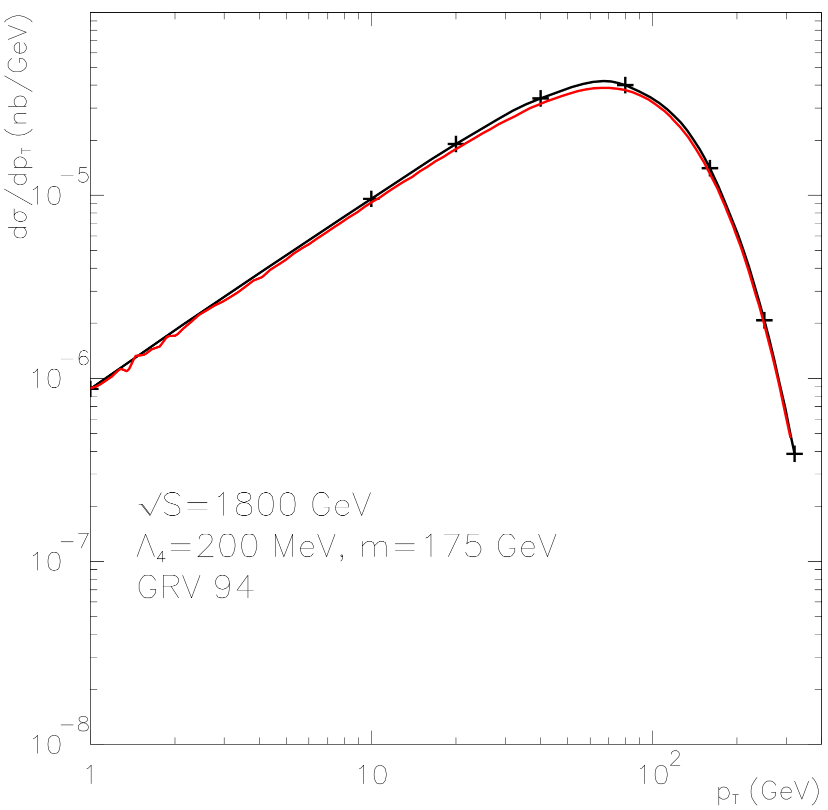
p_T dependence at $\sqrt{S} = 1800$ GeV



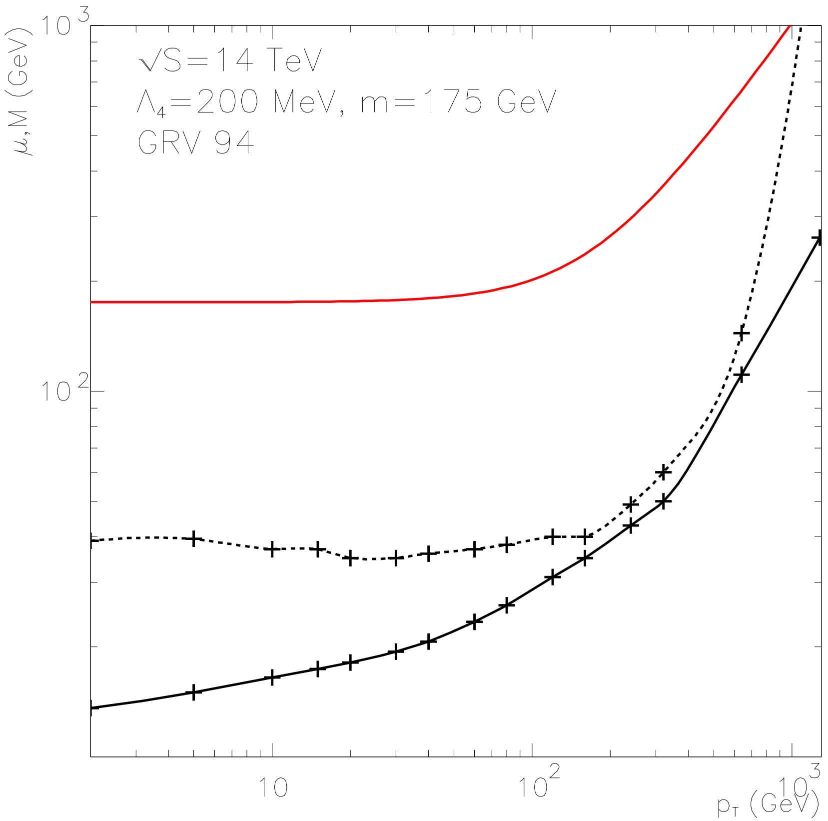


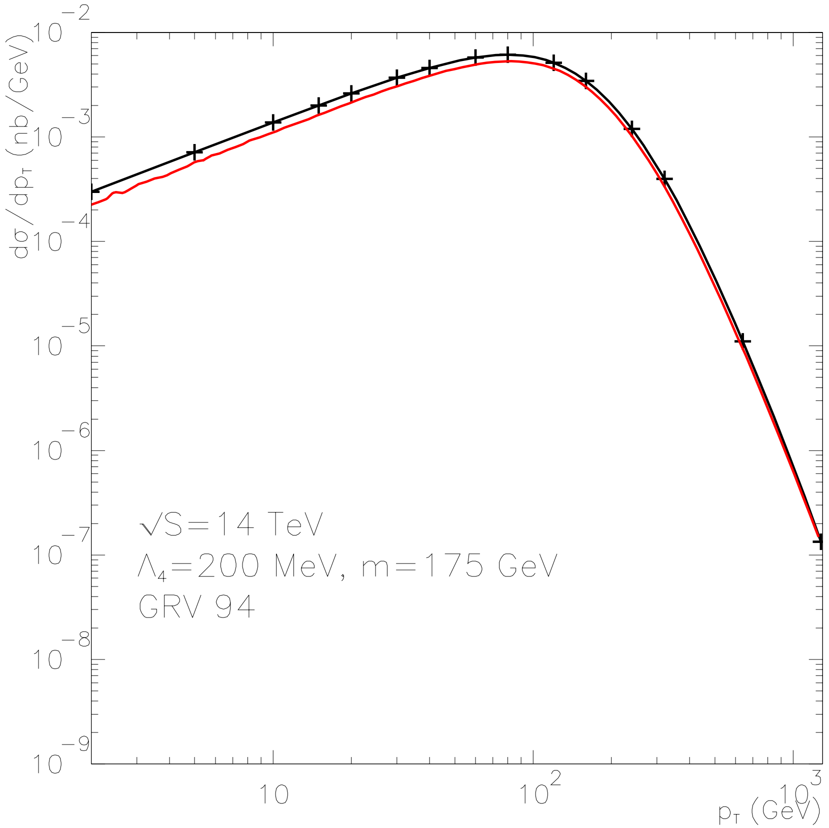
Top is safe at the TEVATRON





as well as LHC





Conclusions

- The proper choice of scales is **crucial** for application of PQCD
- Renormalization and factorization scales **should not be identified**
- PMS optimized results that are
  - **significantly above** the conventional ones in the TEVATRON energy range
  - but **close to them** at SPSC and LHC energies
- Predictions for the **top quark are safe**
- Not **the sole explanation** of the discrepancy
- Analyses of γp and $\gamma\gamma$ **will follow**