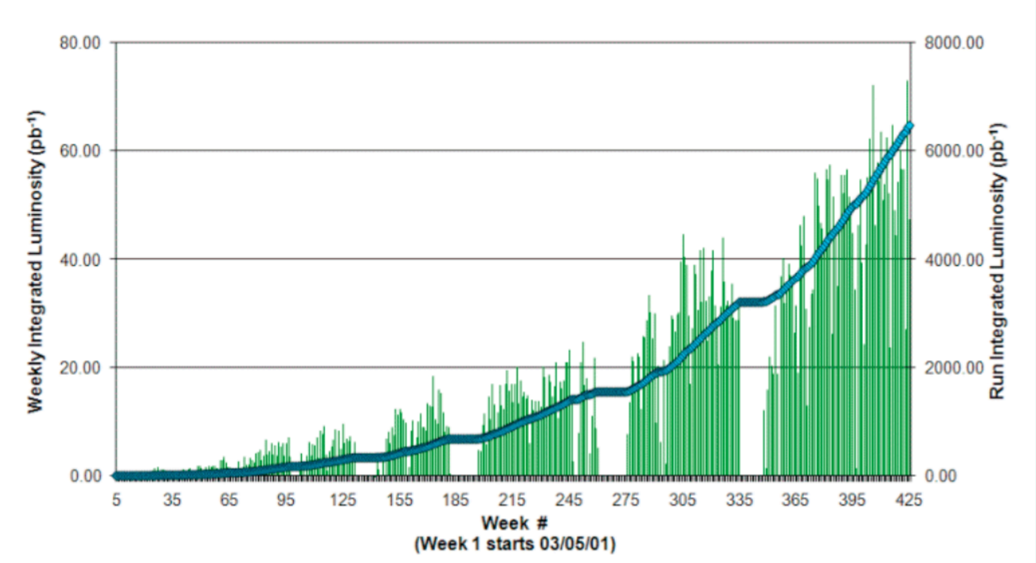
Last Talk

Keith Ellis
Fermilab

Tevatron Luminosity

Accumulations of more than 70 pb^{-1} per week!

If we were to run for 50 weeks with 50 pb^{-1} per week, an extra 2.5 fb^{-1} would be achieved in fiscal 2010.



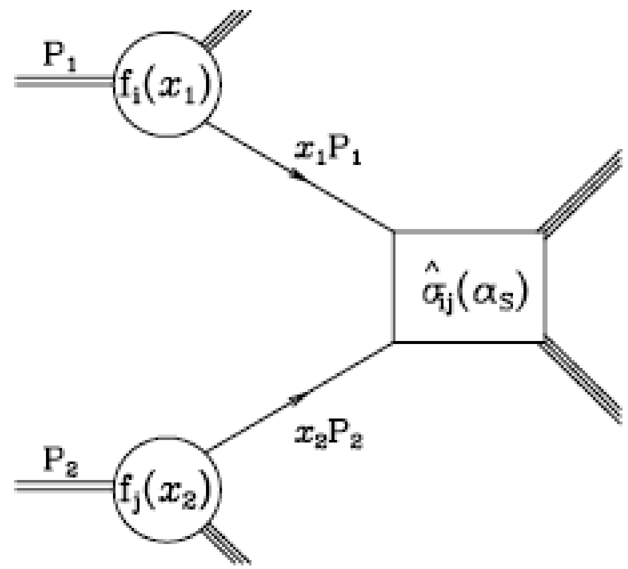
The error in the luminosity measurement sets the scale for High Precision QCD, unless we want to use the process as a standard candle.
Tevatron Luminosity error ~ 5%
LHC luminosity error, initially 10% -> 3%.

Tevatron

- RunII has data samples of delivered luminosity in excess of 6 fb^{-1}. About 80% of this is useful for analysis.
- Tevatron will shut down on June 15 for delayed maintenance (and to allow Nova construction).
- Budget guidance from the DOE calls for run to restart in September and run through Fiscal 2010 (October 2009-September 2010).
- Proposal to run in Fiscal 2011 has been presented to the DOE and was "well received".

QCD improved parton model

Hard QCD cross section is represented as the convolution of a short distance cross-section and non-perturbative parton distribution functions.
Physical cross section is formally independent of μ_{F} and μ_{R}



Physical cross section

Parton distribution function

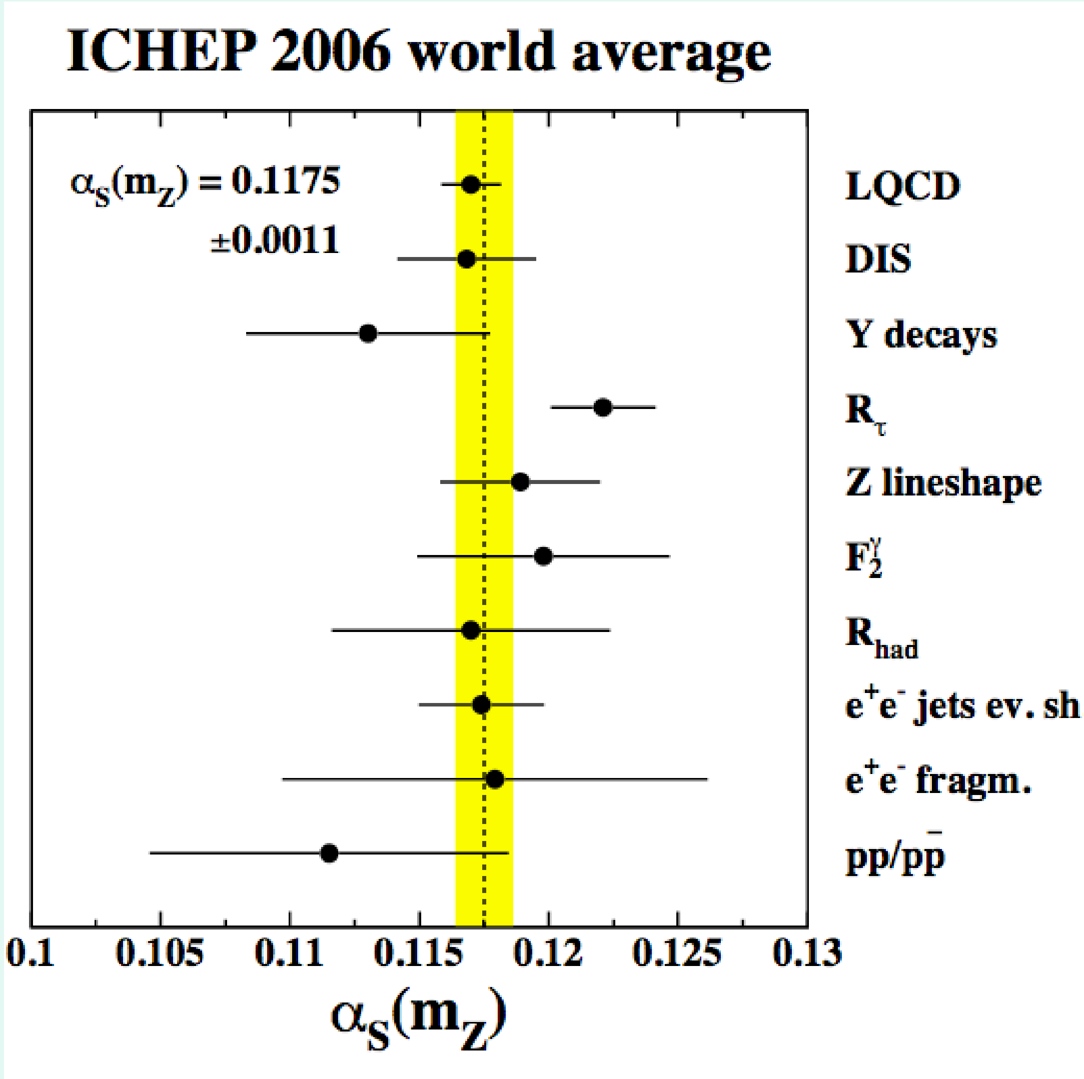
Renormalization scale μ_R

$$\sigma(P_1, P_2) = \sum_{i,j} \int dx_1 dx_2\, f_i(x_1, \mu_F) f_j(x_2, \mu_F)\, \hat{\sigma}_{ij}(p_1, p_2, \alpha_S(\mu_R), Q^2, \mu_R, \mu_F).$$

Factorization scale μ_F

Short distance cross section, calculated as a perturbation series in α_S

S Kluth, hep-ex/0609020



2006 World average $\alpha_s(M_z) = 0.1175 \pm 0.0011$

De Florian, Sturm, Ozeren

Update on Higgs cross sections

- Update to MSTW 2008 NNLO distributions (pdf uncertainties)

- Use effective Lagrangian for top quark contribution and normalize to Born result

- Core of the cross-section: top quark contribution computed to NNLL+NNLO accuracy

- Bottom contribution and top-bottom interference exact at NLO↑ $\sigma^{QCD} = \sigma_{top}^{NNLL+NNLO} + \sigma_{bottom}^{NLO}$ Anastasiou, Boughezal, Petriello (2008)

- Include EW effects assuming complete factorization

$$\sigma^{best} = (1 + \delta_{EW})\, \sigma^{QCD}$$

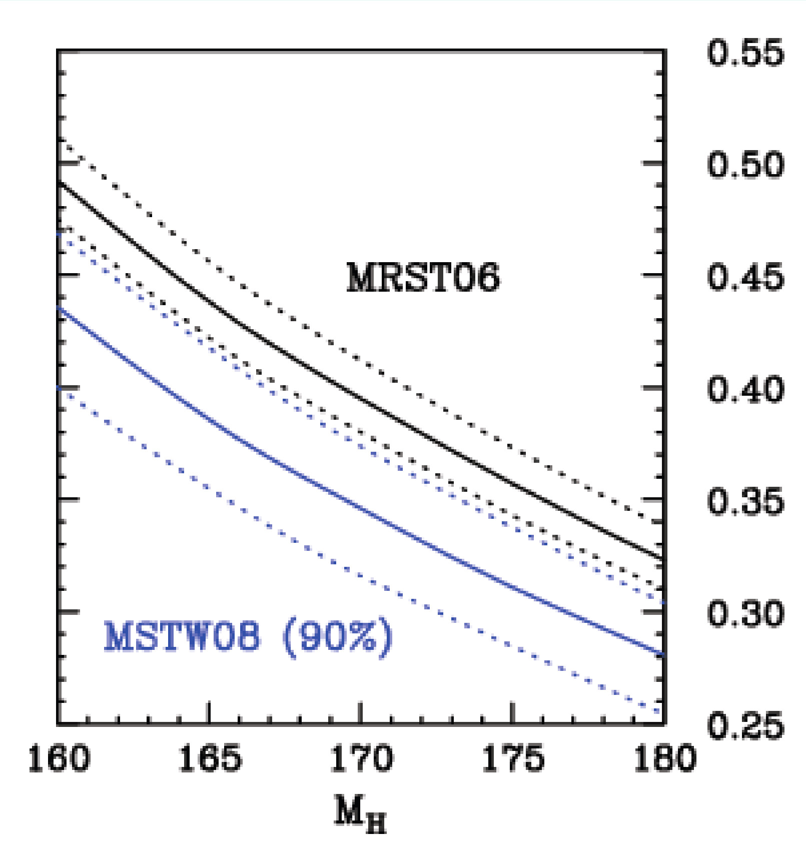
Actis, Passarino, Sturm, Uccirati (2008)

Higgs cross section uncertainties

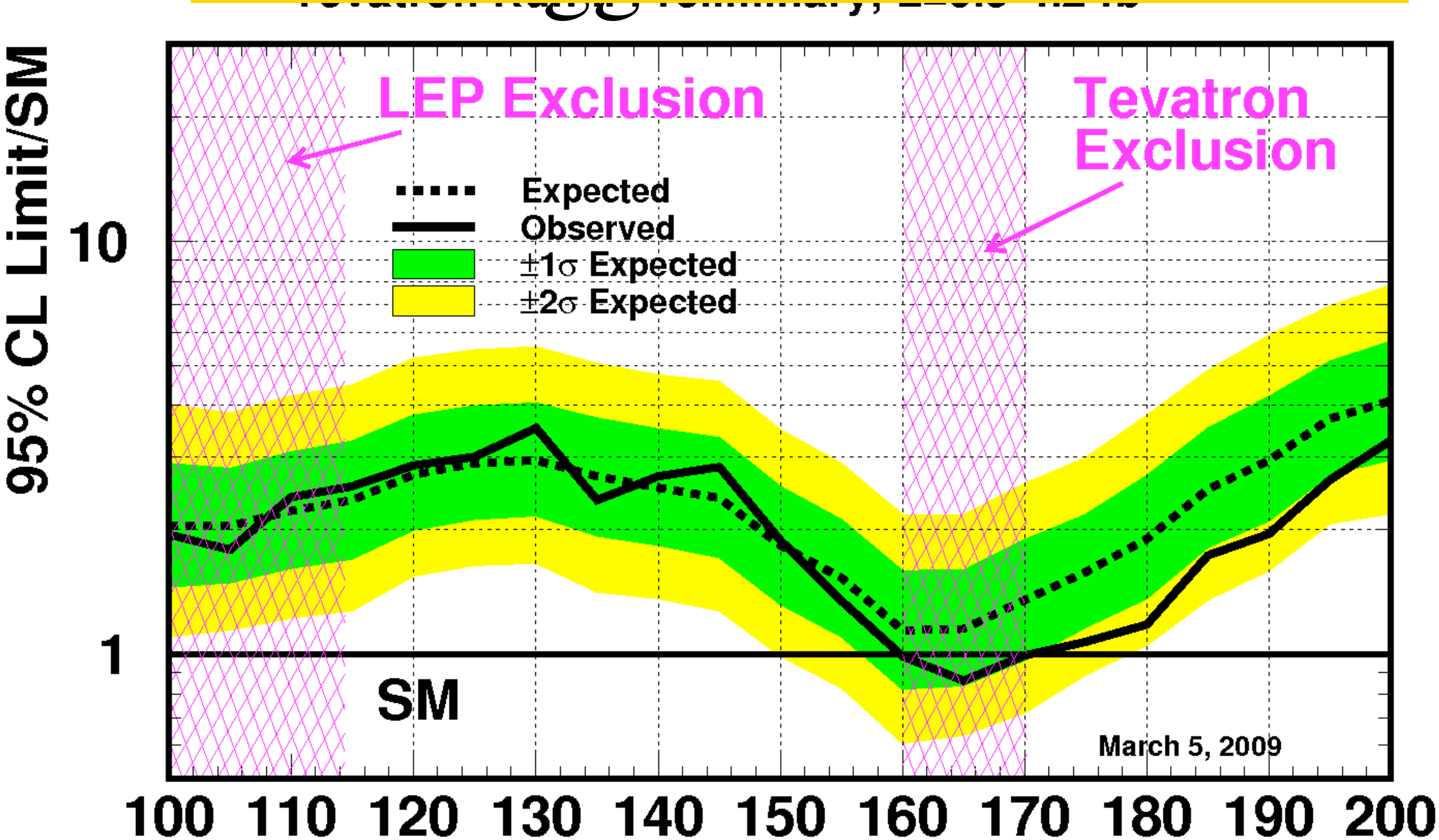
At Tevatron for m_H=170GeV, best prediction is (De Florian),

$$\sigma = 0.349^{+0.032}_{-0.027}(\text{scale})^{+0.028}_{-0.029}(\text{PDF})\ \text{pb}$$

But historical record on PDF uncertainty would suggest a larger error.



Exp. 1.1 @ 160/165, 1.4 @ 170 GeV



Exp. 2.4 @115

Obs. 0.99 @ 160/170, 0.86 @ 165 GeV

Low mass Higgs

Current limit on low mass Higgs is based on ~2.7fb^{-1}

By the end of Fiscal 2010, one may expect an additional 2.5fb^{-1} delivered, for a total of 9 fb^{-1} delivered, of which 7.5 fb^{-1} could be useful.

Almost a factor of 3 in useable luminosity!

Schulze, Moch, Mitov, Kidonakis, Falgari

Top cross section and resummation

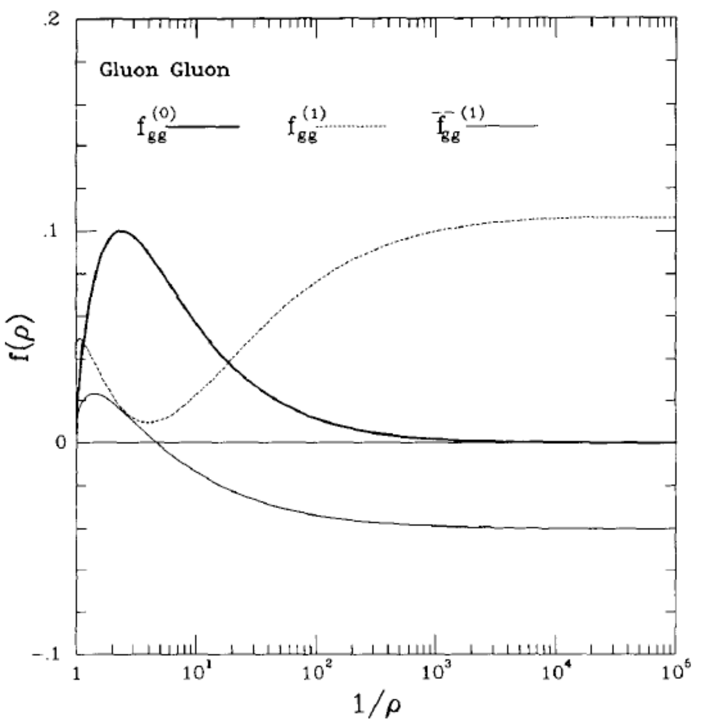
A number of contributions on top production, primarily on the issue of resummation.

Top total cross section at NLO

Short distance cross section given by

$$\hat{\sigma}_{ij}(s, m^2, \mu^2) = \frac{\alpha_S^2(\mu^2)}{m^2} f_{ij}\left(\rho, \frac{\mu^2}{m^2}\right)$$

$$\rho = \frac{4m^2}{s}, \quad \beta = \sqrt{1-\rho}$$



$$f_{ij}(\rho, \mu^2/m^2) = f_{ij}^{(0)}(\rho) + g^2(\mu^2)\left[f_{ij}^{(1)}(\rho) + \bar{f}_{ij}^{(1)}(\rho)\ln(\mu^2/m^2)\right]$$

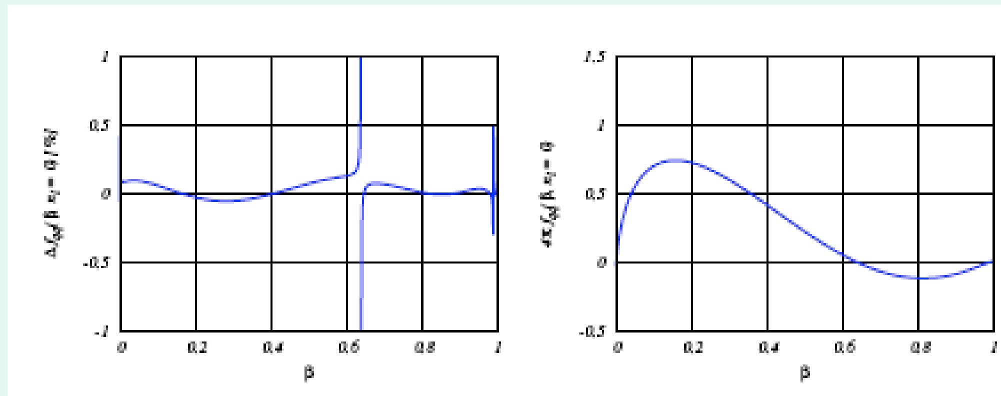
NDE 1988: $f_{ij}^{(0)}$ and $\bar{f}_{ij}^{(1)}$ calculated analytically,
$f_{ij}^{(1)}$ provided as a numerical fit with accuracy better than 1%

Czakon-Mitov arXiv:0811.4119

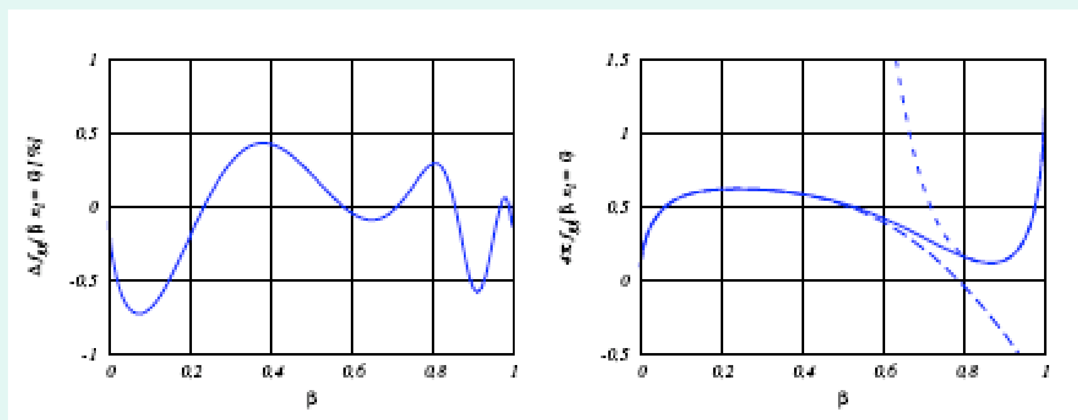
Total cross section for top: Analytic results (2008)

- Czakon and Mitov have analytic results for the total cross section.
- Results agree with NDE fit within stated tolerance (1%).

Comparison with NDE fit for q-qbar



Comparison with NDE fit for g-g



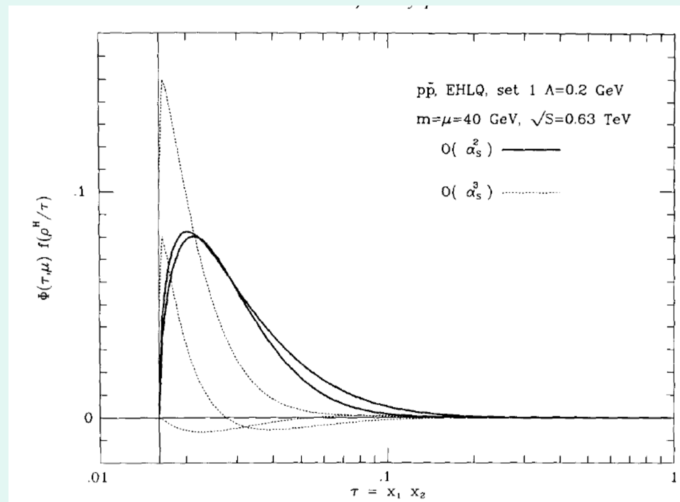
Resummation and contribution of threshold region

$$\Phi_{ij}(\tau,\mu)=\tau\int_0^1 \mathrm{d}x_1\int_0^1 \mathrm{d}x_2\, F_i^{\mathrm{A}}(x_1,\mu)F_j^{\mathrm{B}}(x_2,\mu)\delta(x_1x_2-\tau)$$

$$\sigma(S,m^2)=\frac{\alpha_S^2(\mu^2)}{m^2}\sum_{i,j}\int_{\rho^{\mathrm{H}}}^1\frac{\mathrm{d}\tau}{\tau}\Phi_{ij}(\tau,\mu)f_{ij}\left(\frac{\rho^{\mathrm{H}}}{\tau},\frac{\mu^2}{m^2}\right)$$

Although it looks like a large correction from threshold, only a small contribution comes from the region in which ln(β) is large.

$\beta < 0.1$, $\tau < \rho^{H}/0.99$



Go ahead and perform resummation, but error may not be credible.

MCFM
A NLO parton level generator

- pp → W/Z
- pp → W+Z, WW, ZZ
- pp → W/Z + 1 jet
- pp → W/Z +2 jets
- pp → t W
- pp → tX (s&t channel)
- pp → tt
- pp → W/Z+H
- pp (gg) → H
- pp→(gg) → H + 1 jet
- pp→(gg) → H + 2 jets
- pp(VV) → H +2 jets
- pp → W/Z +b , W+c
- pp → W/Z +bb

Processes calculated at NLO, but no automatic procedure for including new processes.

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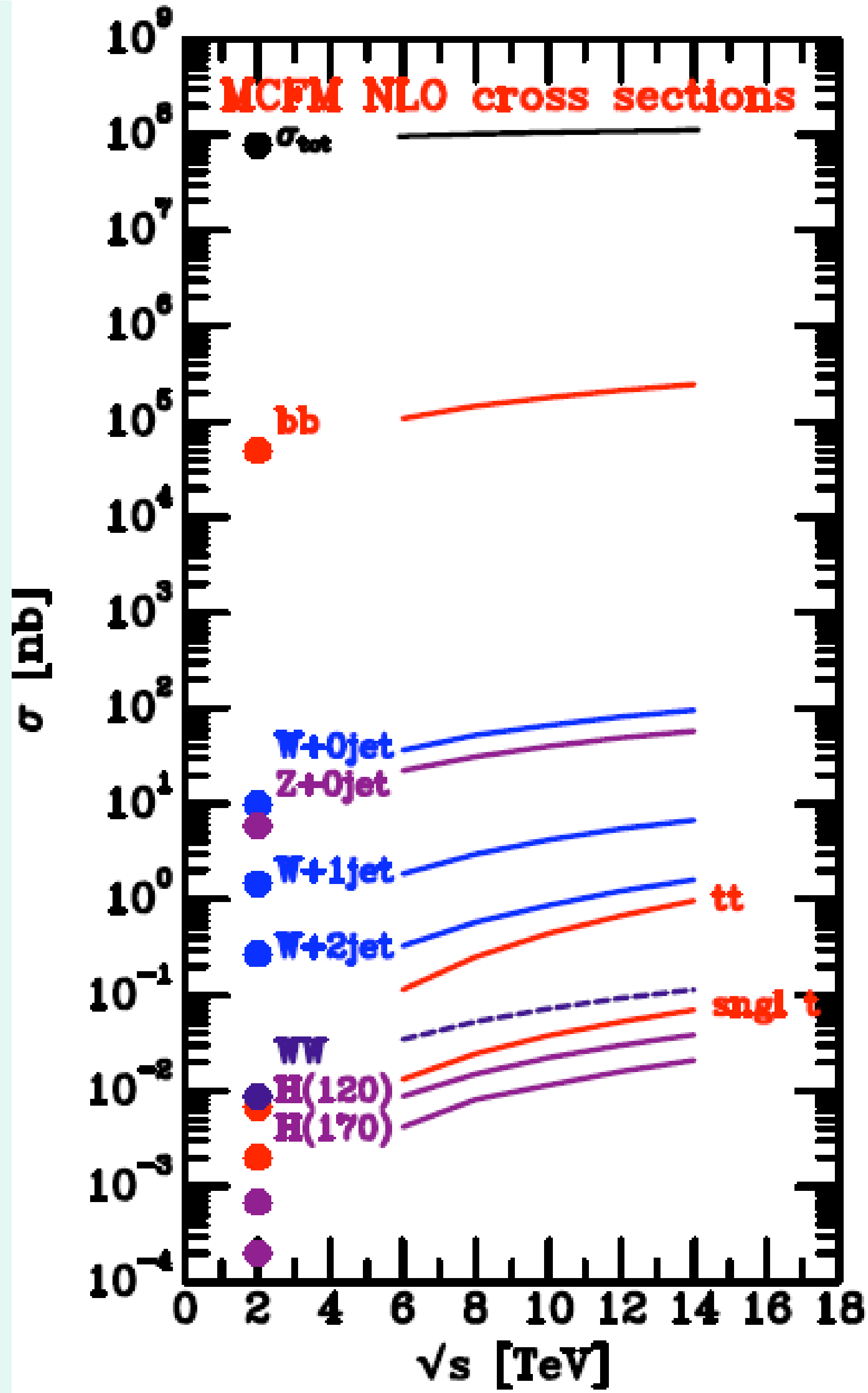
Code available at http://mcfm.fnal.gov

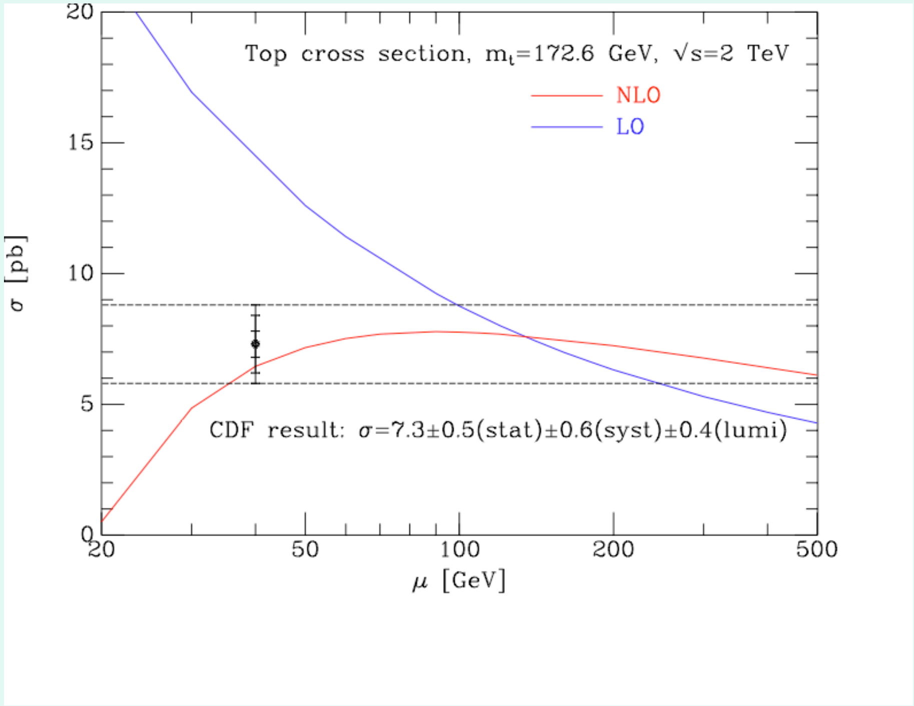
Current version 5.4 (March 11 2009)

The big picture

- LHC will be a great machine because of the increase of both energy and luminosity wrt to the Tevatron
- Dramatic growth with energy of gluon-induced processes (eg tt)



Why NLO?



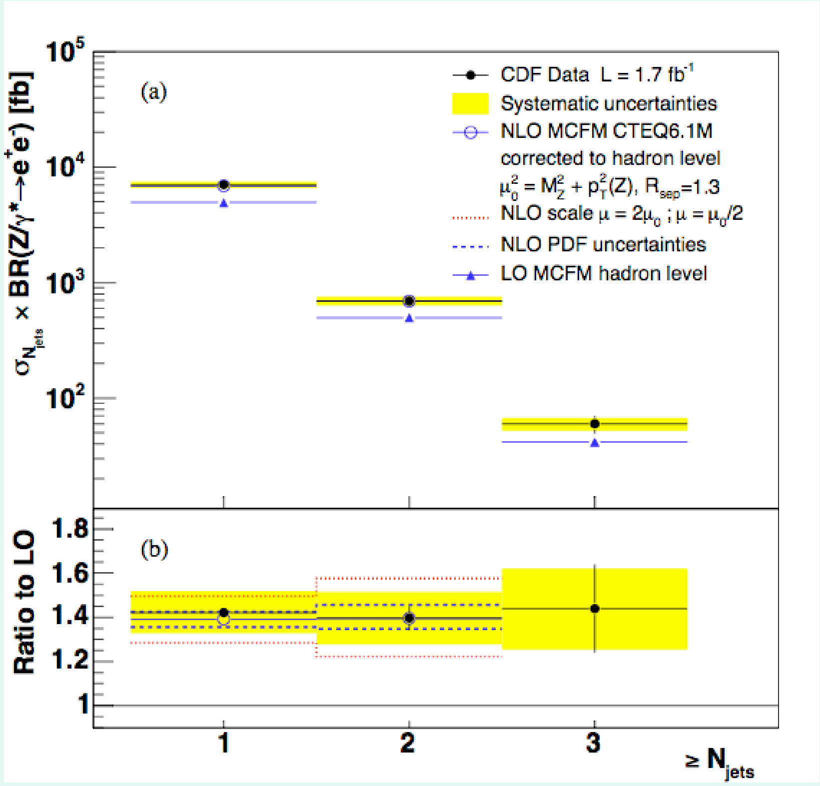
In order to get ~10% accuracy we need to include NLO.

- Less sensitivity to unphysical input scales, (eg. renormalization and factorization scales)
- NLO first approximation in QCD which gives an idea of suitable choice for μ.
- NLO has more physics, parton merging to give structure in jets, initial state radiation, more species of incoming partons enter at NLO.
- A necessary prerequisite for more sophisticated techniques which match NLO with parton showering.

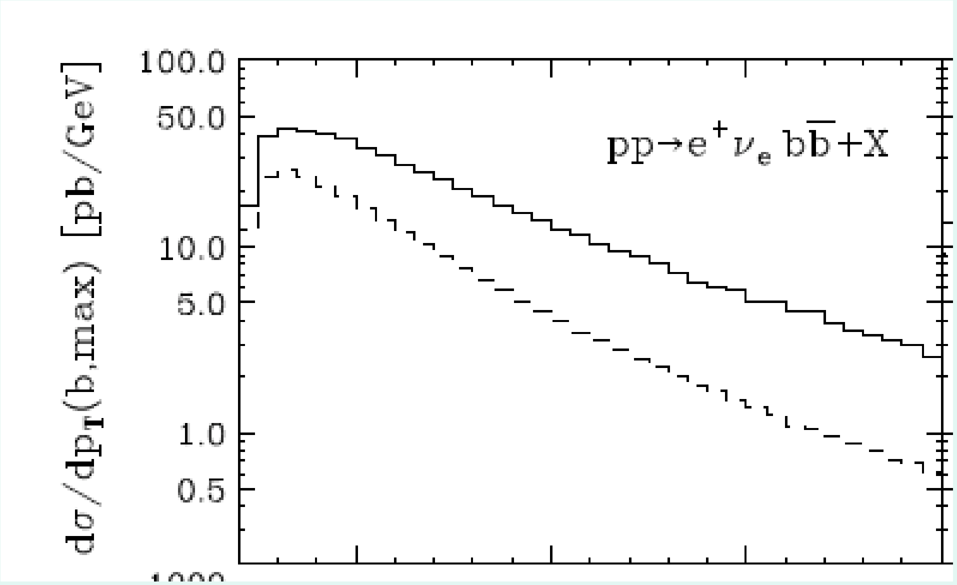
Isn't it just an overall K-factor?

Sometimes…..

but not always



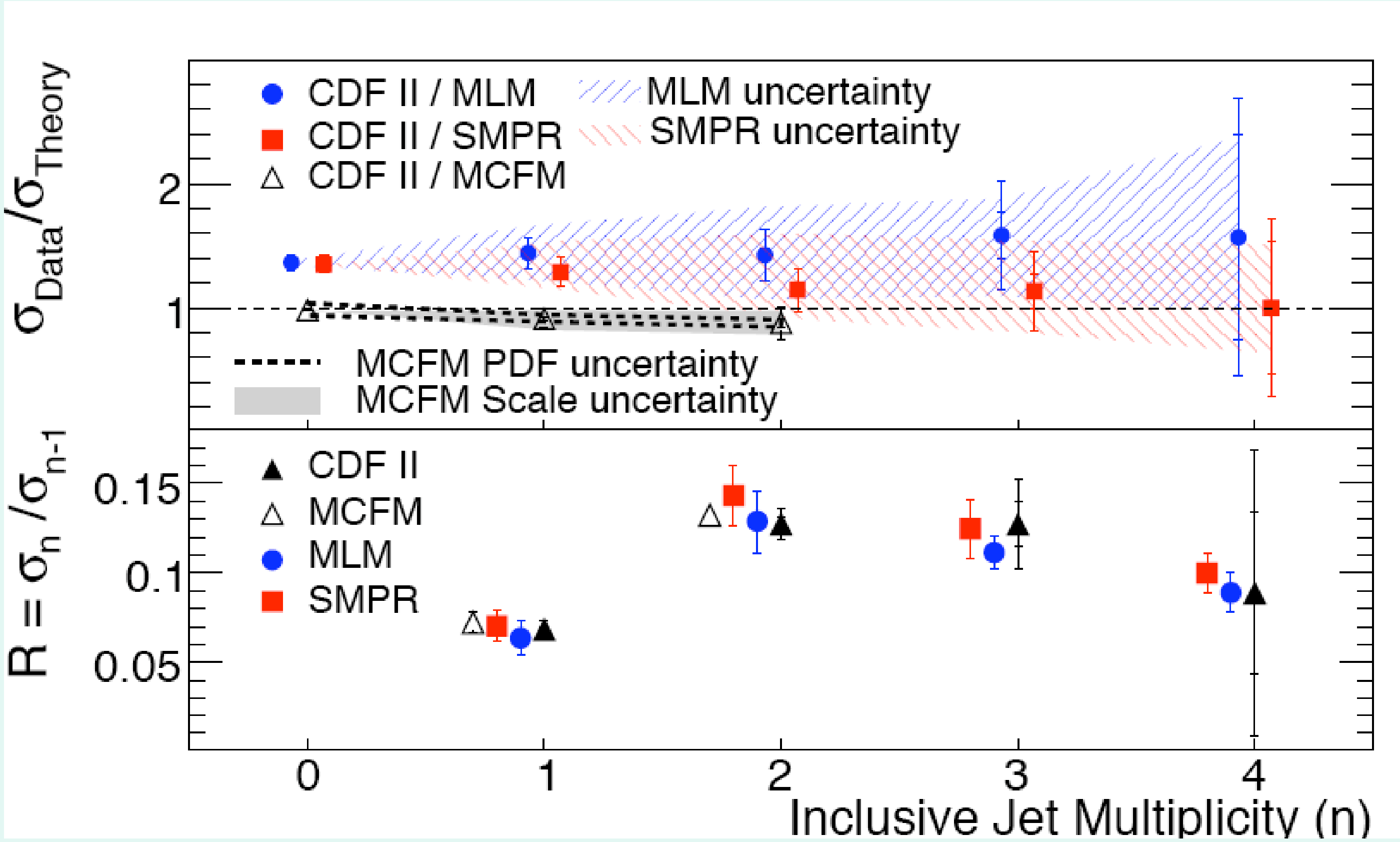
Z+jet production at the Tevatron



NLO-solid, LO-dashed

Wbb production at the LHC

W+n jet rates from CDF



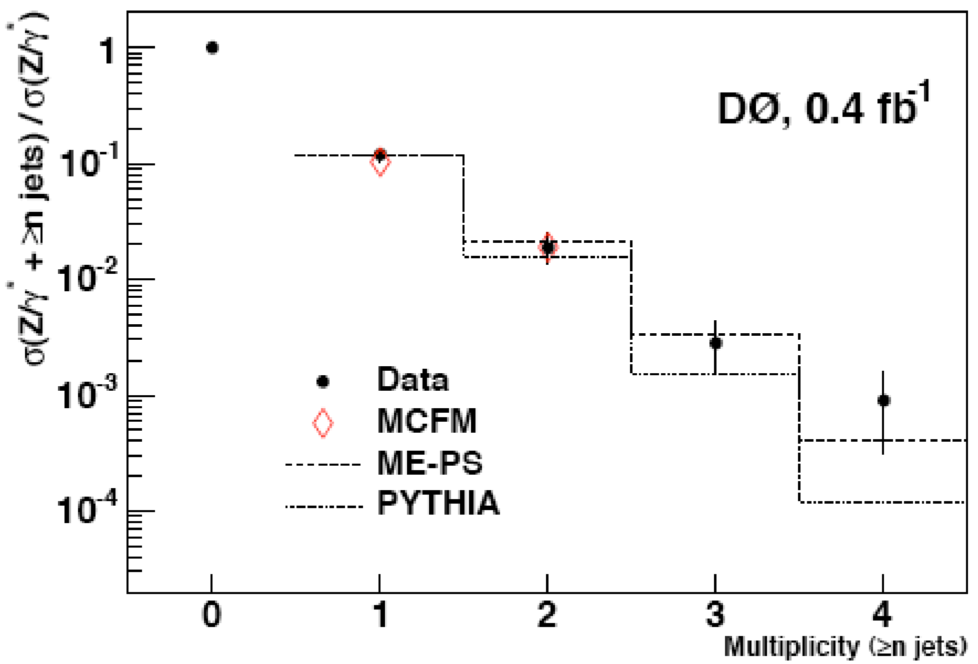
Both uncertainty on rates and deviation of Data/Theory from 1 are smaller than other calculations. The ratio R agrees well for all theory calculations, but only available with from MCFM with small error for n≤2.

MCFM RKE, Campbell

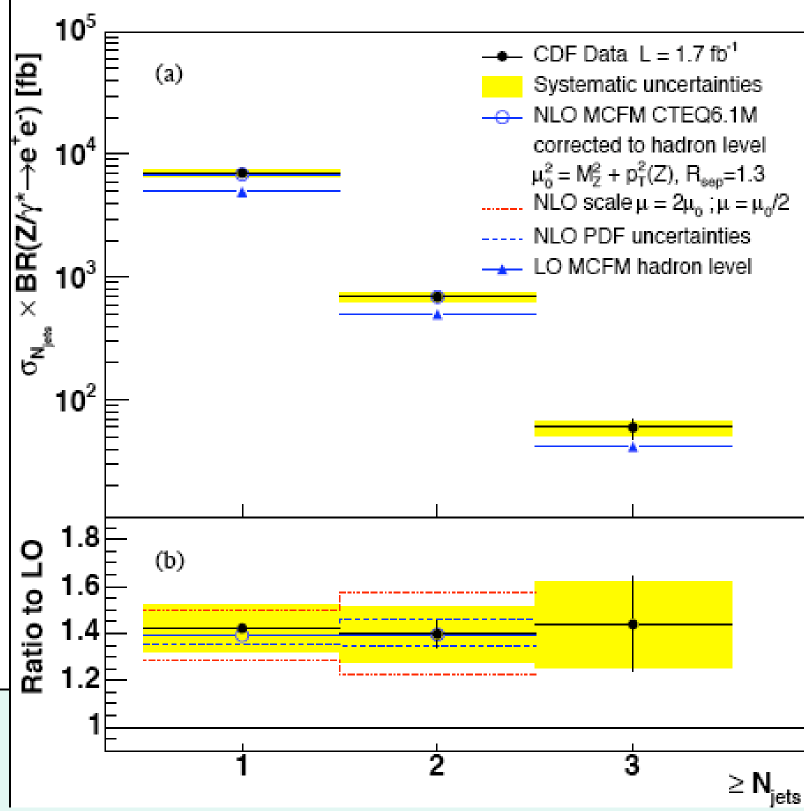
Z + jets

NLO QCD (which for Z + jets currently only available for n ≤ 2) does a good job of describing the inclusive cross sections.

D0 arXiv:hep/ex 0608052v3

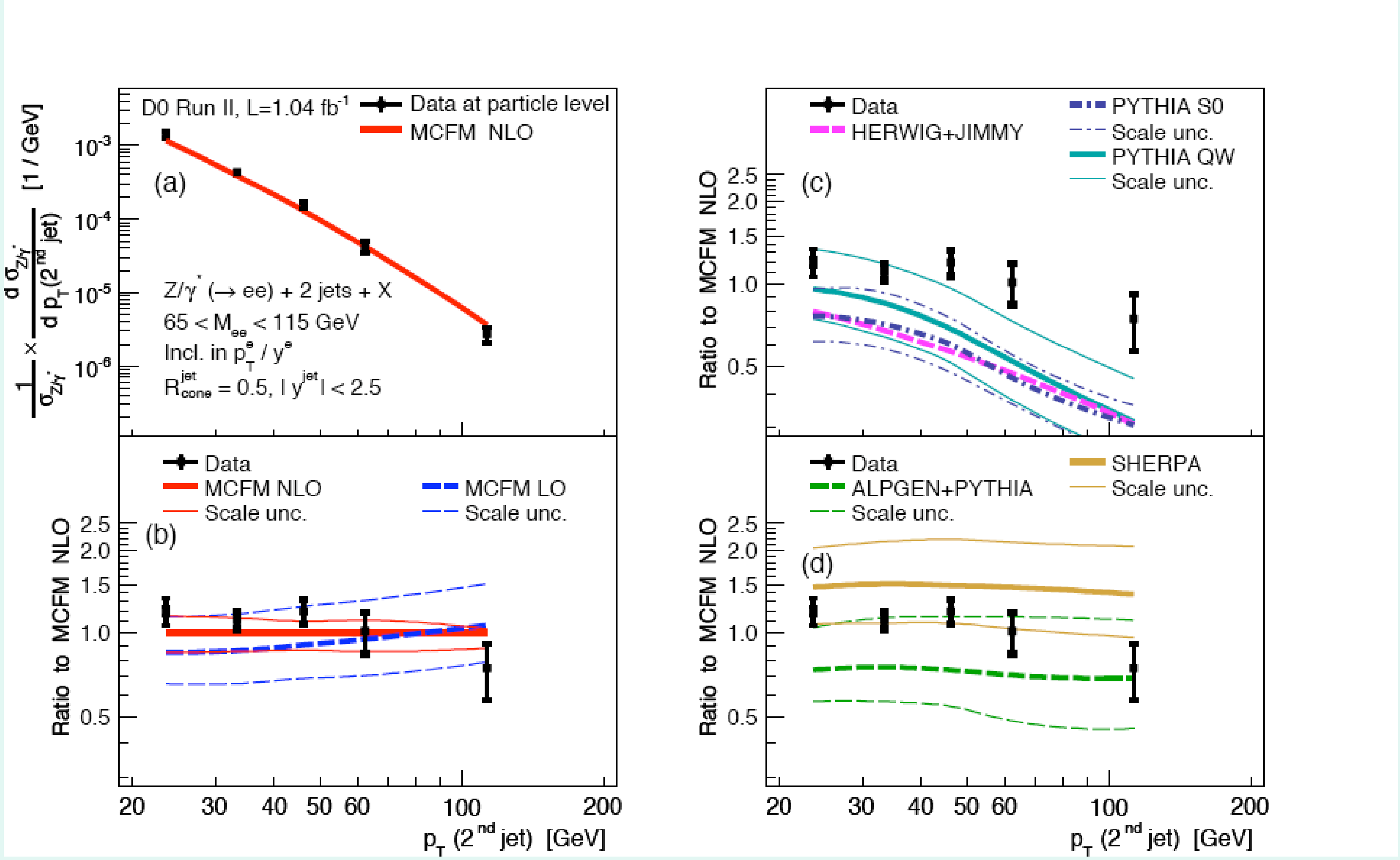


CDF arXiv:0711.3717v1



D0 arXiv:0903.1748

New Z + jets results from D0

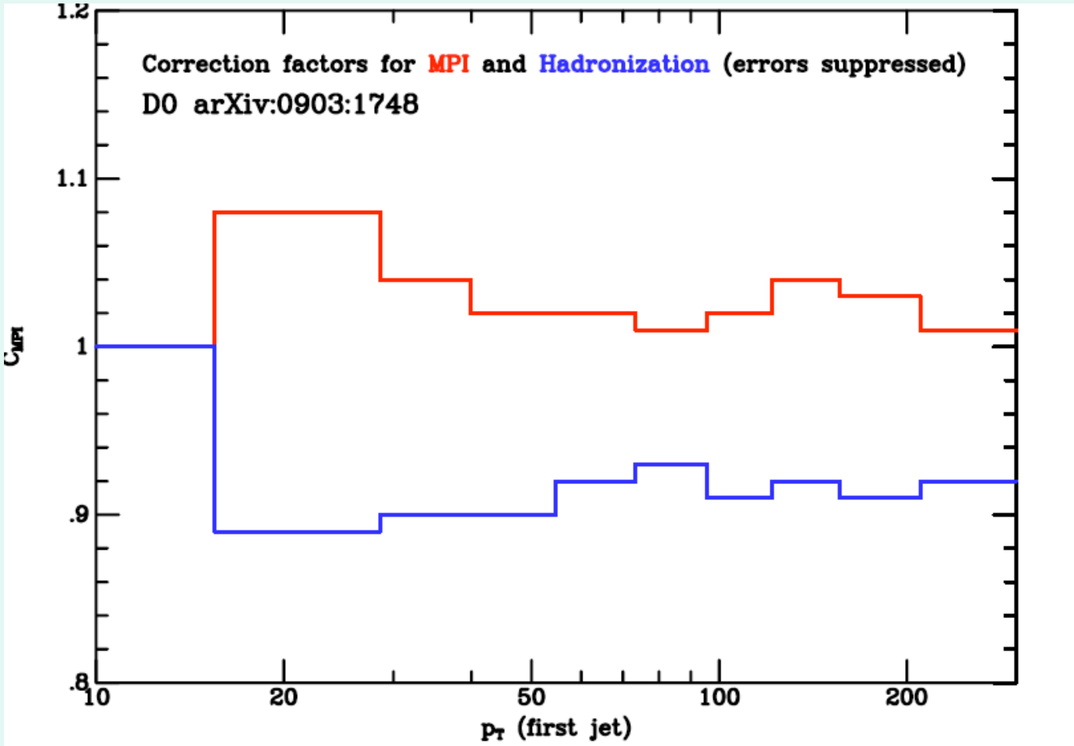


- MCFM, LO and NLO agrees with data;
- shower-based generators show significant differences with data;
- matrix element + parton shower models agree in shape, but with larger normalization uncertainties.

Comparison of parton level results with real data

Correction factors are required for multiple parton interactions and for hadronization.

The general pattern at the Tevatron is that these corrections are small, O(10%), opposite in sign and decreasing functions of P_T



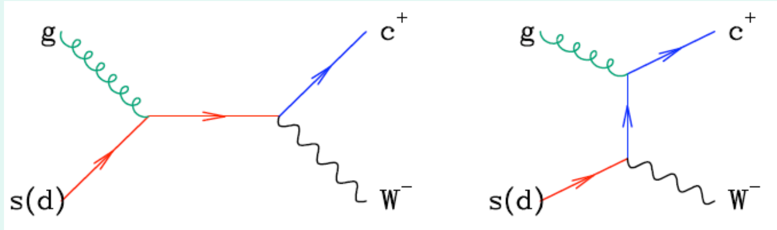
Vector boson + jets containing heavy flavors

- The data is much more limited
- The stakes are higher (single top, WH, ZH, …)
- The theory predictions can depend on poorly known heavy flavor distributions in the proton.
- The theory predictions can be performed with either a fixed or variable flavor schemes.

D0:PLB666(2008)23,CDF:PRL100(2008)091803

W + charm

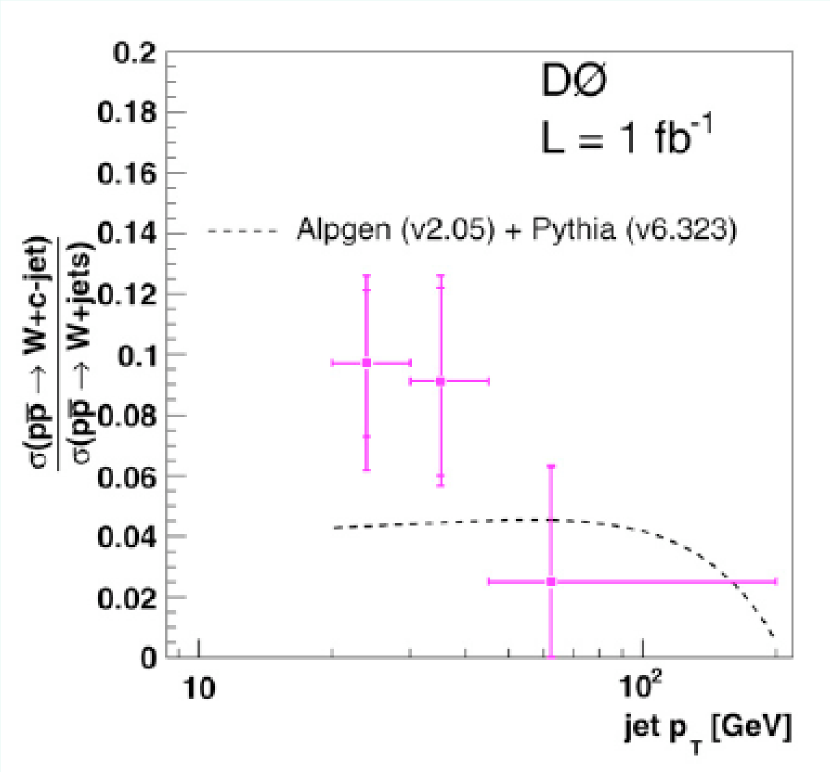
- W+charm samples are isolated by exploiting the opposite charge of the W and charm.
- Measurements from CDF and D0



$$\frac{\sigma[W+c\text{−jet}]}{\sigma[W+\text{jets}]} = 0.074 \pm 0.019(\text{stat})^{+0.012}_{-0.014}(\text{syst})$$

$$\frac{\sigma[W+c\text{−jet}]}{\sigma[W+\text{jets}]} = 0.044 \ (\text{Alpgen})$$

$$\frac{\sigma[W+c\text{−jet}]}{\sigma[W+\text{jets}]} = 0.045 \ (\text{MCFM})$$



- Agreement within the large errors, (theory errors ~ 10%)
- It will be important to have the more precise kinematic distributions.

CDF arXiv:0812.4458

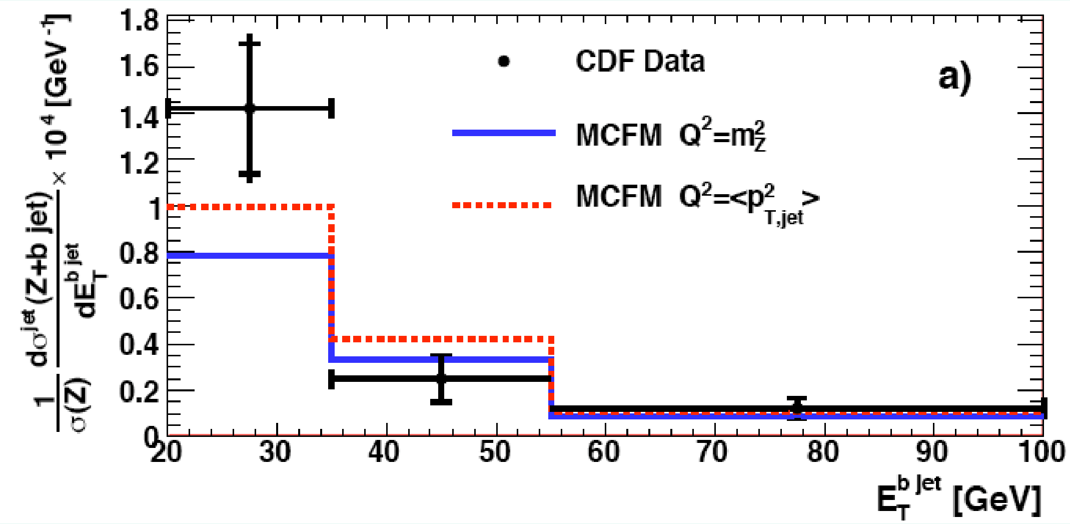
Z + bottom

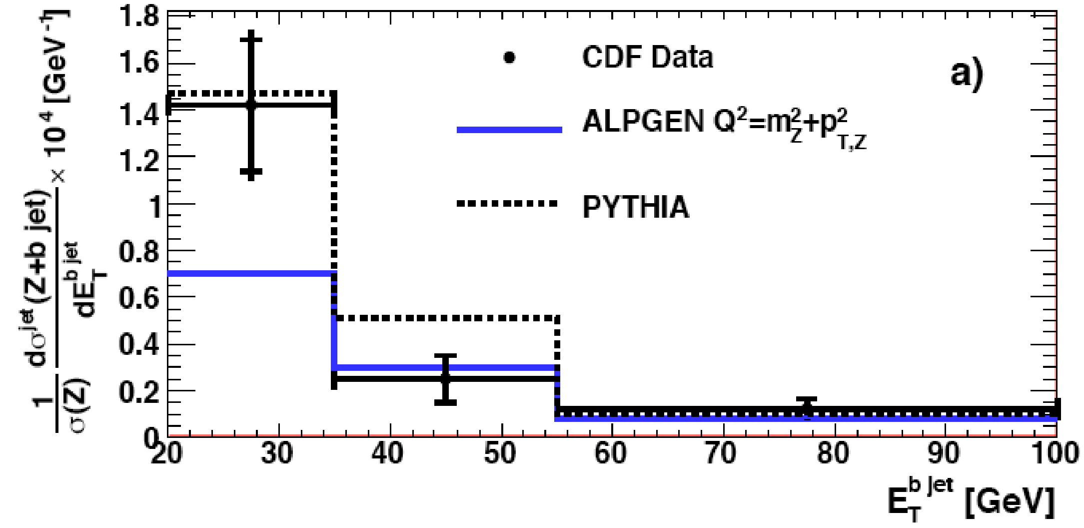
- Data still quite limited
- Low scale preferred to try and explain data
- All of the models seem to have difficulty to describe the shape of the data.
- CDF result is:-

$E_T > 20$ GeV, $|\eta| < 1.5$

$\sigma(Z + b\text{jet})/\sigma(Z) =$

$(3.32 \pm 0.53(\text{stat}) \pm 0.42(\text{syst})) \times 10^{-3}$



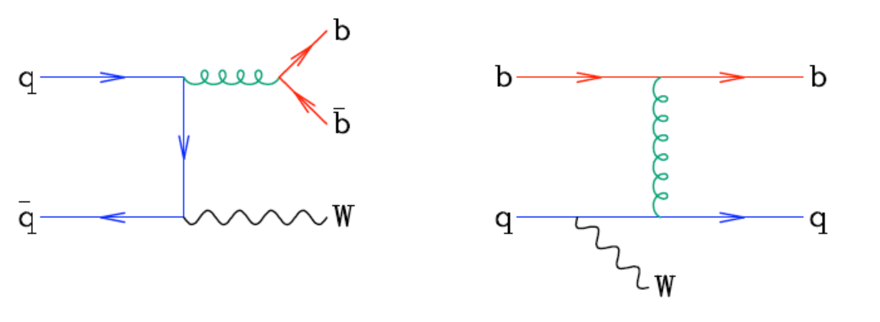


W + bottom

- W + 1 or 2 jets, either or both of which may be b-tagged.
- Important for single top, WH, etc …
- CDF measurements, b's identified by secondary vertex tag, (1 or 2 E_T>20GeV,|η|<2 jets (CDF Note 9321)

$$\sigma_{b-\mathrm{jets}}(W + b\mathrm{-jets}) \times \mathrm{BR}(W \to \ell\nu) = 2.74 \pm 0.27(\mathrm{stat}) \pm 0.42(\mathrm{syst})\mathrm{pb}$$
$$\sigma_{b-\mathrm{jets}}(W + b\mathrm{-jets}) \times \mathrm{BR}(W \to \ell\nu)\mathrm{Alpgen} = 0.78\mathrm{pb}$$

- Ongoing work to combine two sources of W+b events at NLO, (Cordero)



One-loop QCD and Parton showers

About 30% of the talks at this conference were about parton one-loop QCD corrections to hard processes.
The final aim should be to produce results useful for the experimenters.

Marketplace of NLO+shower (MC@NLO and POWHEG) is now large enough that we can begin to compare products.

Why NLO+Shower

- NLO results are cumbersome to use; they yield differential cross sections that are not positive definite (that in fact have canceling positive and negative infinities).
- Experimental results can be compared to NLO results only after unfolding detector effects. With NLO+Showers one can feed the output through detector simulation, and compare to raw data.
- Experimentalists have always asked for it (and sometimes tried hard to do it themselves).
- It can be done: it should be done!

30 years of one-loop QCD

We were stumbling about trying to figure out how to regularize the divergent pieces.

Regulating the singularities dimensionally we found that there were large NLO corrections to the DY process.

LARGE PERTURBATIVE CORRECTIONS TO THE DRELL-YAN PROCESS IN QCD *

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Received 17 April 1979

Clarified earlier work by AEM and Kubar-Andre & Paige calculated using less efficient regulators.

K-factor

First introduced by Altarelli at the Geneva EPS conference in 1979

LEPTON PAIR PRODUCTION IN HADRONIC COLLISIONS

G. Altarelli

In view of this large non leading terms it is interesting to inquire whether the experiments allow to draw some conclusion on the measured scale of the cross section in comparison with the prediction of the naive Drell--Yan formula. It is remarkable that actually there are consistent indications in the data for a cross section larger than expected. We consider first the new data on πN collisions. Let us introduce a scale factor defined as

$$\left(\frac{d\sigma}{dQ^2}\right)_{EXP} = K \left(\frac{d\sigma}{dQ^2}\right)_{NAIVE\ D.Y.} \qquad (20)$$

Much higher degree of social organization now. We now have wishlists!

Wishlist 07

Process ($V \in \{Z, W, \gamma\}$)	Comments
Calculations completed since Les Houches 2005	
1. $pp \to VV$ jet	WW jet completed by Dittmaier/Kallweit/Uwer [3]; Campbell/Ellis/Zanderighi [4] and Binoth/Karg/Kauer/Sanguinetti (in progress)
2. $pp \to$ Higgs+2jets	NLO QCD to the gg channel completed by Campbell/Ellis/Zanderighi [5]; NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier [6, 7]
3. $pp \to VVV$	ZZZ completed by Lazopoulos/Melnikov/Petriello [8] and WWZ by Hankele/Zeppenfeld [9]
Calculations remaining from Les Houches 2005	
4. $pp \to t\bar{t}\, b\bar{b}$	relevant for $t\bar{t}H$
5. $pp \to t\bar{t}$+2jets	relevant for $t\bar{t}H$
6. $pp \to VV\, b\bar{b}$,	relevant for VBF $\to H \to VV$, $t\bar{t}H$
7. $pp \to VV$+2jets	relevant for VBF $\to H \to VV$ VBF contributions calculated by (Bozzi/)Jäger/Oleari/Zeppenfeld [10–12]
8. $pp \to V$+3jets	various new physics signatures
NLO calculations added to list in 2007	
9. $pp \to b\bar{b}b\bar{b}$	Higgs and new physics signatures
Calculations beyond NLO added in 2007	
10. $gg \to W^*W^*$ $\mathcal{O}(\alpha^2\alpha_s^3)$	backgrounds to Higgs
11. NNLO $pp \to t\bar{t}$	normalization of a benchmark process
12. NNLO to VBF and Z/γ+jet	Higgs couplings and SM benchmark
Calculations including electroweak effects	
13. NNLO QCD+NLO EW for W/Z	precision calculation of a SM benchmark

Progress

Partial list

Process	Authors	Status	Code Released
$pp \to WW$+jet	Dittmaier et al	0710.1577	
	Campbell et al	0710.1832	
$pp \to ZZ$+jet	Karg	Virtual only	
$pp \to$Higgs +2 jets	Campbell et al,	hep-ph/0608194	
$pp \to$Higgs +2 jets(VBF)	Ciccolini et al	0710.4749	
$pp \to VVV$			
ZZZ	Lazopoulos et al	hep-ph/0703273	
	Binoth et al	0804.0350	
WWZ	Hankele et al	0712.3544	✓
	Binoth et al	0804.0350	
WZZ	Campanario et al	0809.0790	✓
	Binoth et al	0804.0350	
WWW	Campanario et al	0809.0790	✓
	Binoth et al	0804.0350	
$pp \to t\bar{t}bb$	Bredenstein et al	0905.0110	
$pp \to tt + 2jets$			
$pp \to VVbb$			
$pp \to VV + 2jets$			
$pp \to V + 3jets$			
$pp \to W + 3jets$	Ellis et al	0901.4101 (leading color)	
	Berger et al	0902.2760	
$pp \to bbbb$			
$u\bar{u} \to b\bar{b}b\bar{b}$	Reuter	(Virtual only)	

Very few cases where the code has been released so that it can be used by experimenters.

RKE Slide, 2008

What is the bottle-neck?

- Consider for example W+n jets.
  (W+4 jets is a background to top production).
- W+n (LO) and W+(n+1)-parton amplitudes known since 1989 Berends et al.
- Subtraction method understood 1980.
  Ellis, Ross & Terrano, Catani & Seymour
- NLO parton evolution known since 1980.

  Curci, Furmanski & Petronzio
- Bottleneck is the calculation of one loop amplitudes. In fact only the one-loop amplitudes for W+1 jet and W+2 jets are known.
  Bern et al (1997); Campbell, Glover & Miller (1997).

We are way past the bottle-neck.
We are now deep into the bottle!

PV-based approaches

Inverse Gram determinant problem is a self-inflicted wound.

One assumes that external vectors are linearly independent for form-factor expansion - so you inevitably run in to problems when they are not. However the original integrals have no such problem.

I refer you to the beautiful paper of Denner &Dittmaier (2005) for a discussion of ‘bail-out’ prcedures all the dangerous regions.

OPP

G. O., C. G. Papadopoulos and R. Pittau
Nucl. Phys. B **763**, 147 (2007)

Some of the advantages:

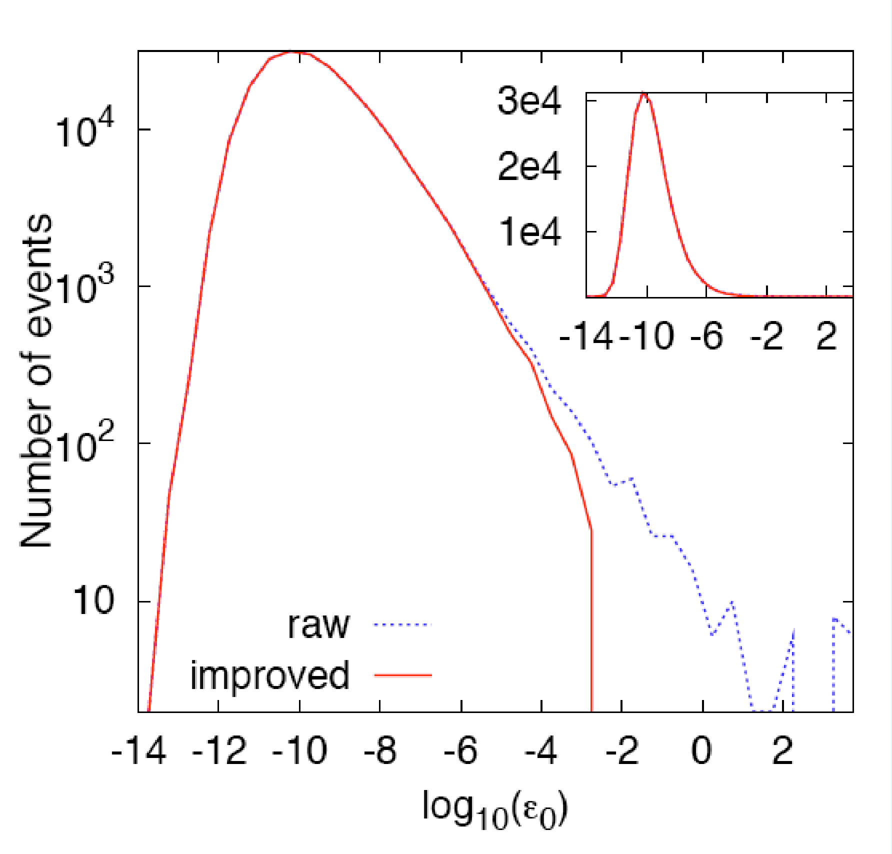
- Universal - applicable to any process
- Simple - based on basic algebraic properties
- Automatizable - easy to implement in a computer code

In some measure all unitarity-based use this idea to some degree.

A proper summary talk would analyze all the variants, times etc in an attempt to draw some conclusions.

Numerical problems in Unitarity-based approaches

Use of multiple precision
to solve numerical problems,
Is ‘quick and dirty’ but is
perhaps to be deprecated.



W+3 jets

Results from Blackhat/Sherpa Berger, Bern, Dixon, Febres-Cordero, Forde, Gleisberg, Ita, Kosower and Maitre

number of jets	CDF	LC NLO	NLO
1	53.5 ± 5.6	$58.3^{+4.6}_{-4.6}$	$57.8^{+4.4}_{-4.0}$
2	6.8 ± 1.1	$7.81^{+0.54}_{-0.91}$	$7.62^{+0.62}_{-0.86}$
3	0.84 ± 0.24	$0.908^{+0.044}_{-0.142}$	$0.882(5)^{+0.057}_{-0.138}$

Preliminary

It is interesting that for theoretical central value $\sigma_3/\sigma_2 < \sigma_2/\sigma_1$

	CDF	LC NLO	NLO
σ_2/σ_1	0.127	0.133	0.131
σ_3/σ_2	0.123	0.116	0.116

Errors not quoted!

Note that experimenters are intensely interested: Theorists should quote.

“Support basic science for a big bang down the road”

From the Wisconsin State Journal, May 8, 2009, Bill Andrews

“… Consider the Large Hadron Collider, a machine in Europe capable of recreating conditions from the theoretical birth of the universe, the Big bang. This machine will either prove current models of physics correct by detecting a hitherto elusive and necessary particle or it will deem them incorrect by failing to detect it.
This particle, the Higgs boson, is no less fascinating a concept than life on Mars…”

Thanks to the organizers!

Ulrich Baur, *SUNY Buffalo*
Sally Dawson, *BNL*
Frank Petriello, *UW-Madison*
Doreen Wackeroth, *SUNY Buffalo*

Baha Balantekin, Chair of the Dept of Physics
Aimee Lefkow and Theresa Sherron.