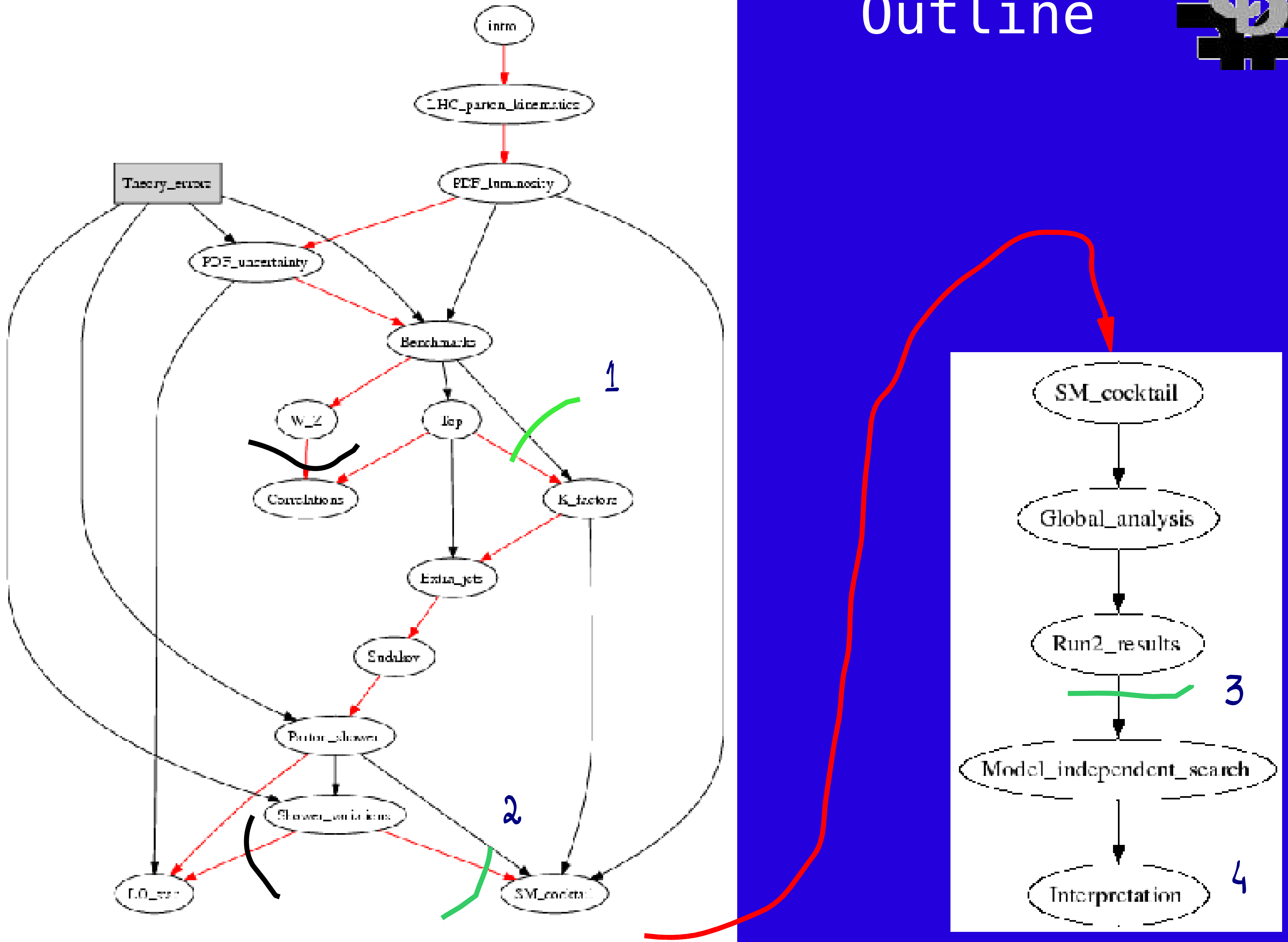
Outline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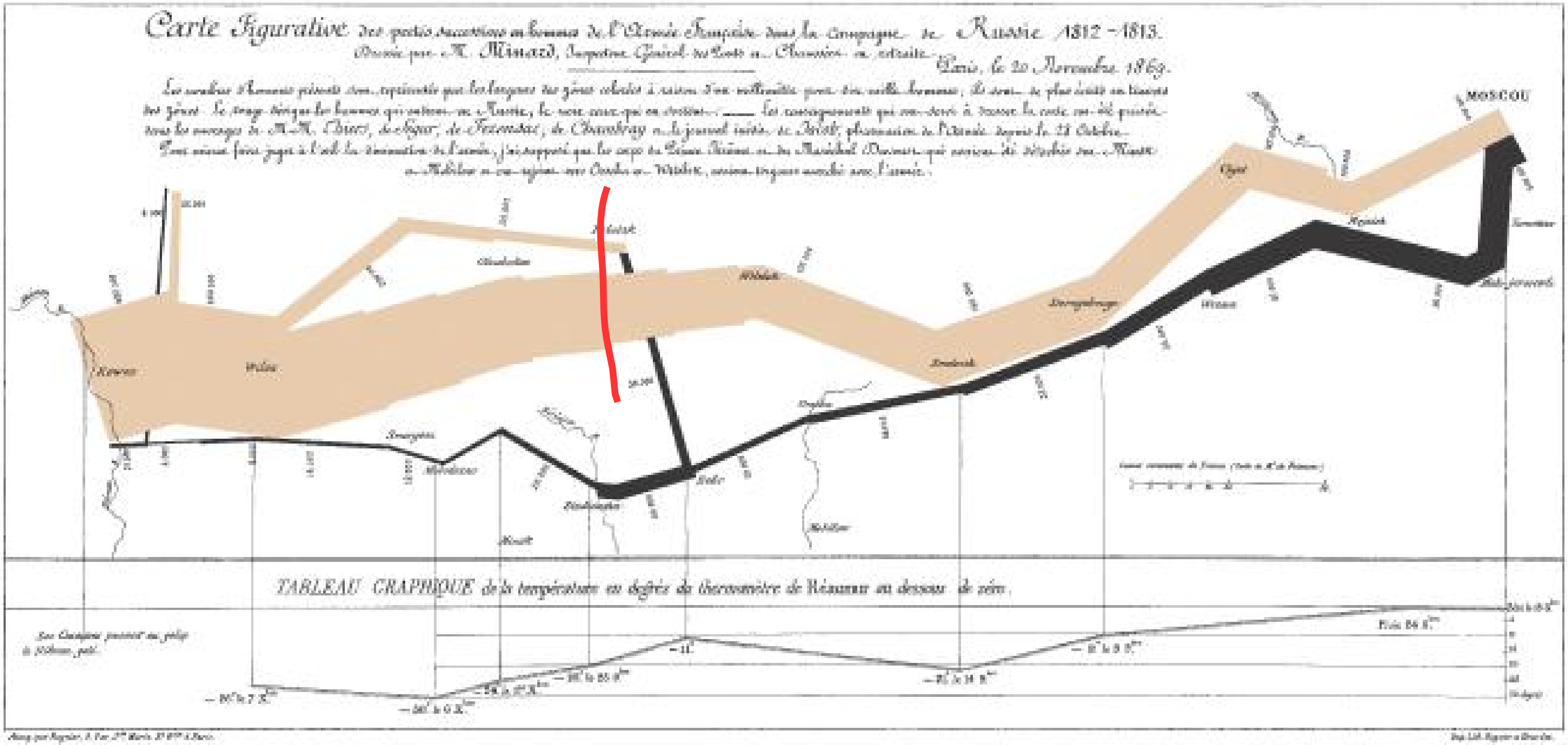


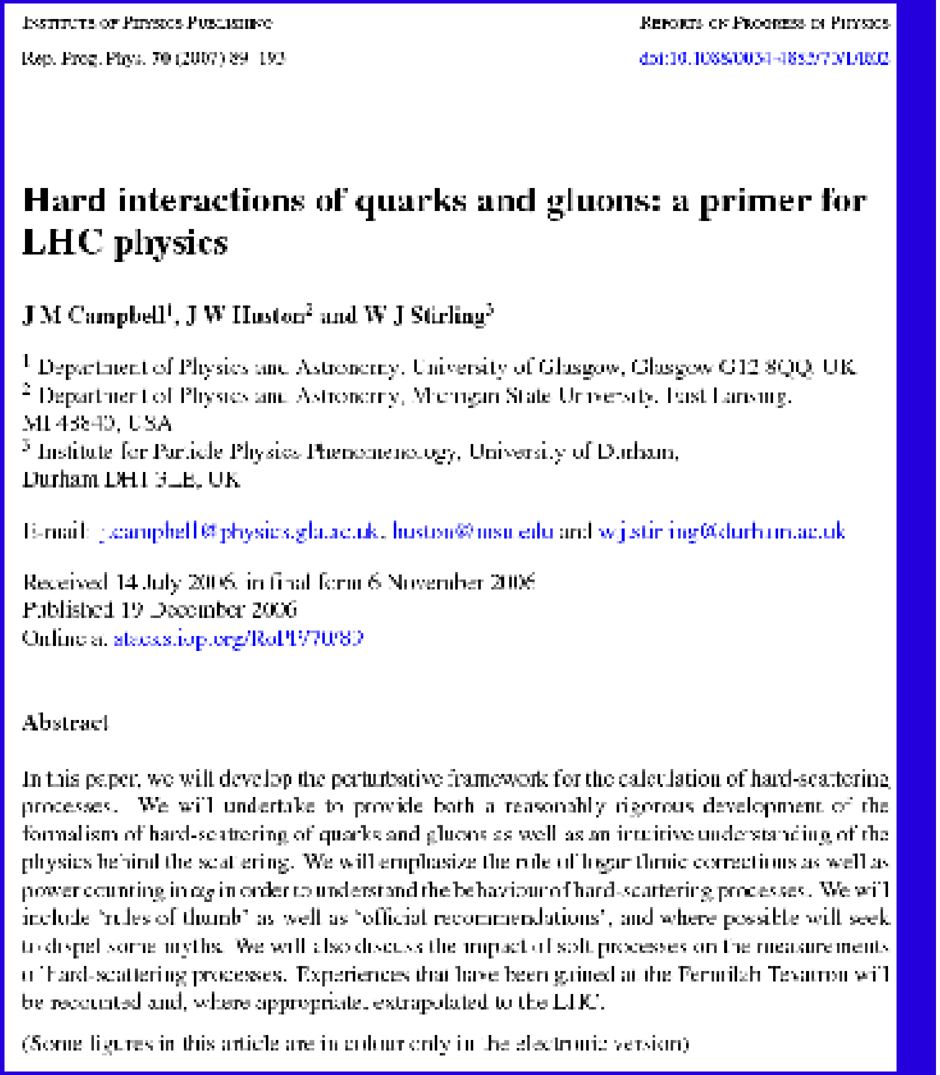
Napoleon's March to Moscow The War of 1812

Charles Joseph Minard

This classic of Charles Joseph Minard (1781-1870), the French engineer, shows the terrible fate of Napoleon's army in Russia. Described by E. J. Marey as seeming to defy the pen of the historian by its brutal eloquence, this combination of data map and time-series, drawn in 1869, portrays the devastating losses suffered in Napoleon's Russian campaign of 1812. Beginning at the left on the Polish-Russian border near the Niemen River, the thick band shows the size of the army (422,000 men) as it invaded Russia in June 1812. The width of the band indicates the size of the army at each place on the map. In September, the army reached Moscow, which was by then sacked and deserted, with 100,000 men. The path of Napoleon's retreat from Moscow is depicted by the darker, lower band, which is linked to a temperature scale and dates at the bottom of the chart. It was a bitterly cold winter, and many froze on the march out of Russia. As the graphic shows, the crossing of the Berezina River was a disaster, and the army finally struggled back into Poland with only 10,000 men remaining. Also shown are the movements of auxiliary troops, as they sought to protect the rear and the flank of the advancing army. Minard's graphic tells a rich, coherent story with its multivariate data, far more enlightening than just a single number bouncing along over time. Six variables are plotted: the size of the army, its location on a two-dimensional surface, direction of the army's movement, and temperature on various dates during the retreat from Moscow. It may well be the best statistical graphic ever drawn.

Edward R. Tufte, *The Visual Display of Quantitative Information*   Graphics Press, Box 430, Cheshire, Connecticut 06410

References



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Hard interactions of quarks and gluons: a primer for LHC physics

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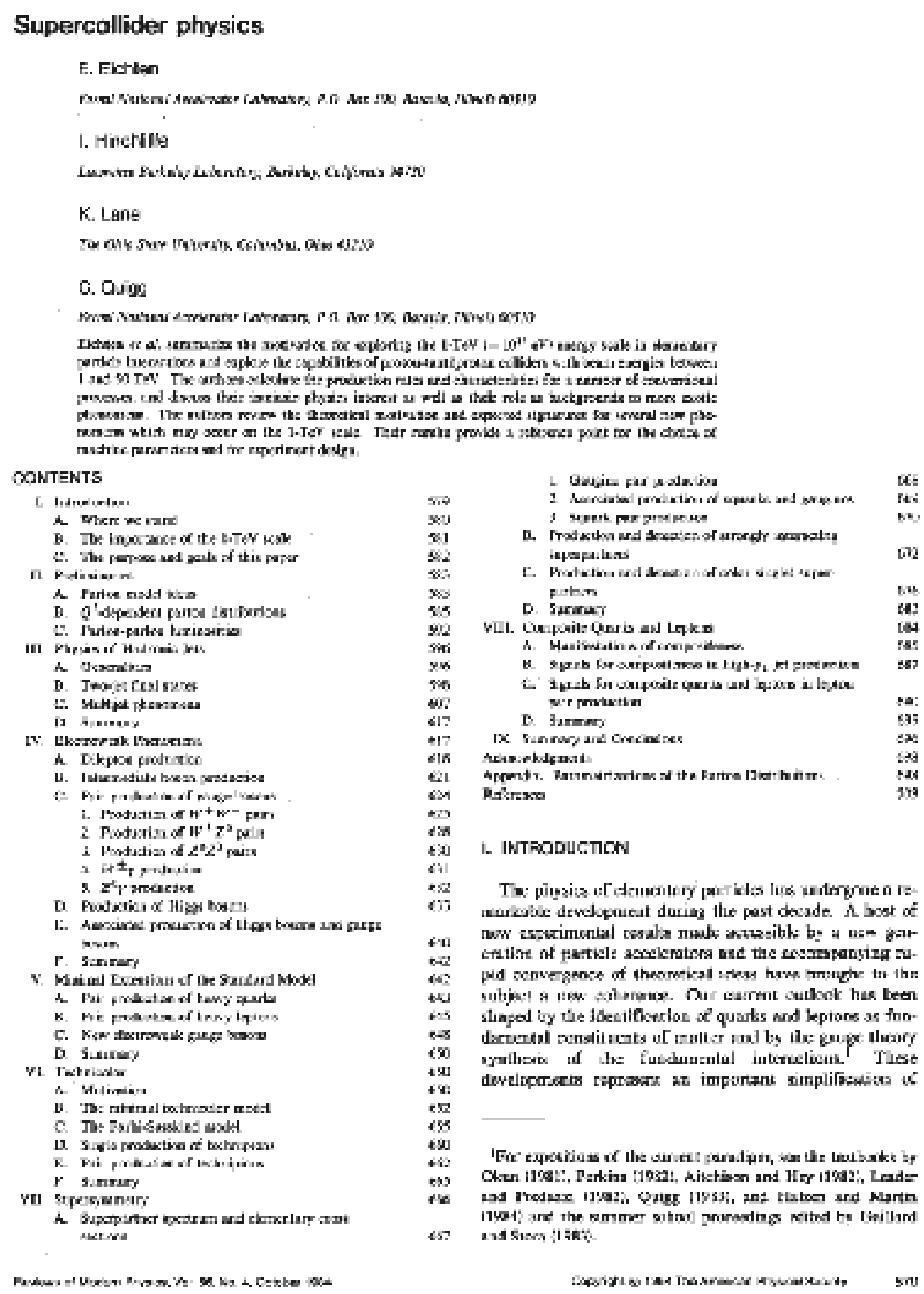
Abstract

In this paper, we will develop the perturbative framework for the calculation of hard-scattering processes. We will undertake to provide both a reasonably rigorous development of the formalism of hard-scattering of quarks and gluons as well as an intuitive understanding of the physics behind the scattering. We will emphasize the role of logarithmic corrections as well as power counting in α_S in order to understand the behaviour of hard-scattering processes. We will include 'rules of thumb' as well as 'official recommendations', and where possible will seek to dispel some myths. We will also discuss the impact of soft processes on the measurements of hard-scattering processes. Experiences that have been gained at the Fermilab Tevatron will be recounted and, where appropriate, extrapolated to the LHC.

(Some figures in this article are in colour only in the electronic version)



Supercollider physics

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C. Quigg
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Eichten *et al.* summarize the motivation for exploring the 1-TeV (=10^{12} eV) energy scale in elementary particle interactions and explore the capabilities of proton-(anti)proton colliders with beam energies between 1 and 50 TeV. The authors calculate the production rates and characteristics for a number of conventional processes, and discuss their intrinsic physics interest as well as their role as backgrounds to more exotic phenomena. The authors review the theoretical motivation and expected signatures for several new phenomena which may occur on the 1-TeV scale. Their results provide a reference point for the choice of machine parameters and for experiment design.

CONTENTS

I. INTRODUCTION

The physics of elementary particles has undergone a remarkable development during the past decade. A host of new experimental results made accessible by a new generation of particle accelerators and the accompanying rapid convergence of theoretical ideas have brought to the subject a new coherence. Our current outlook has been shaped by the identification of quarks and leptons as fundamental constituents of matter and by the gauge theory synthesis of the fundamental interactions.[1] These developments represent an important simplification of

---

[1] For expositions of the current paradigm, see the textbooks by Okun (1981), Perkins (1982), Aitchison and Hey (1982), Leader and Predazzi (1982), Quigg (1983), and Halzen and Martin (1984) and the summer school proceedings edited by Gaillard and Stora (1983).

Reviews of Modern Physics, Vol. 56, No. 4, October 1984

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W/Z Overview

- W/Z → luminosity
  - Otherwise 15-20% → 5-10% uncertainty
- Processes like W/Z have smaller PDF error in ratio
- gg → X has increased d-PDF when calibrated on Z
- Can we use Top production as an additional normalization tool?

Cross Section Correlations

$$N(t\,\bar{t}) = (lumi)\,x\,(efficiency)\,x\,((pdf)_{ij}\,x\,\sigma(ij\to t\,\bar{t}))$$

$$N(W) = (lumi)\,x\,(efficiency)\,x\,((pdf)_{ij}\,x\,\sigma(ij\to W))$$

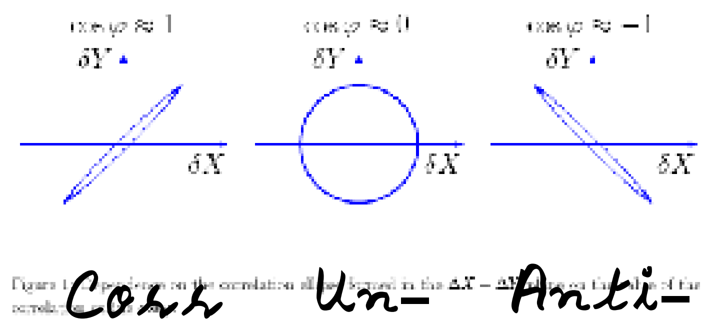
$$R = \frac{N(t\,\bar{t})}{N(W)} \text{ has no (lumi) uncertainty}$$

$$\frac{\sigma_R^2}{R^2} = \frac{\delta^2(t)}{t^2} + \frac{\delta^2(W)}{W^2} - 2\frac{V_{tW}}{tW}$$

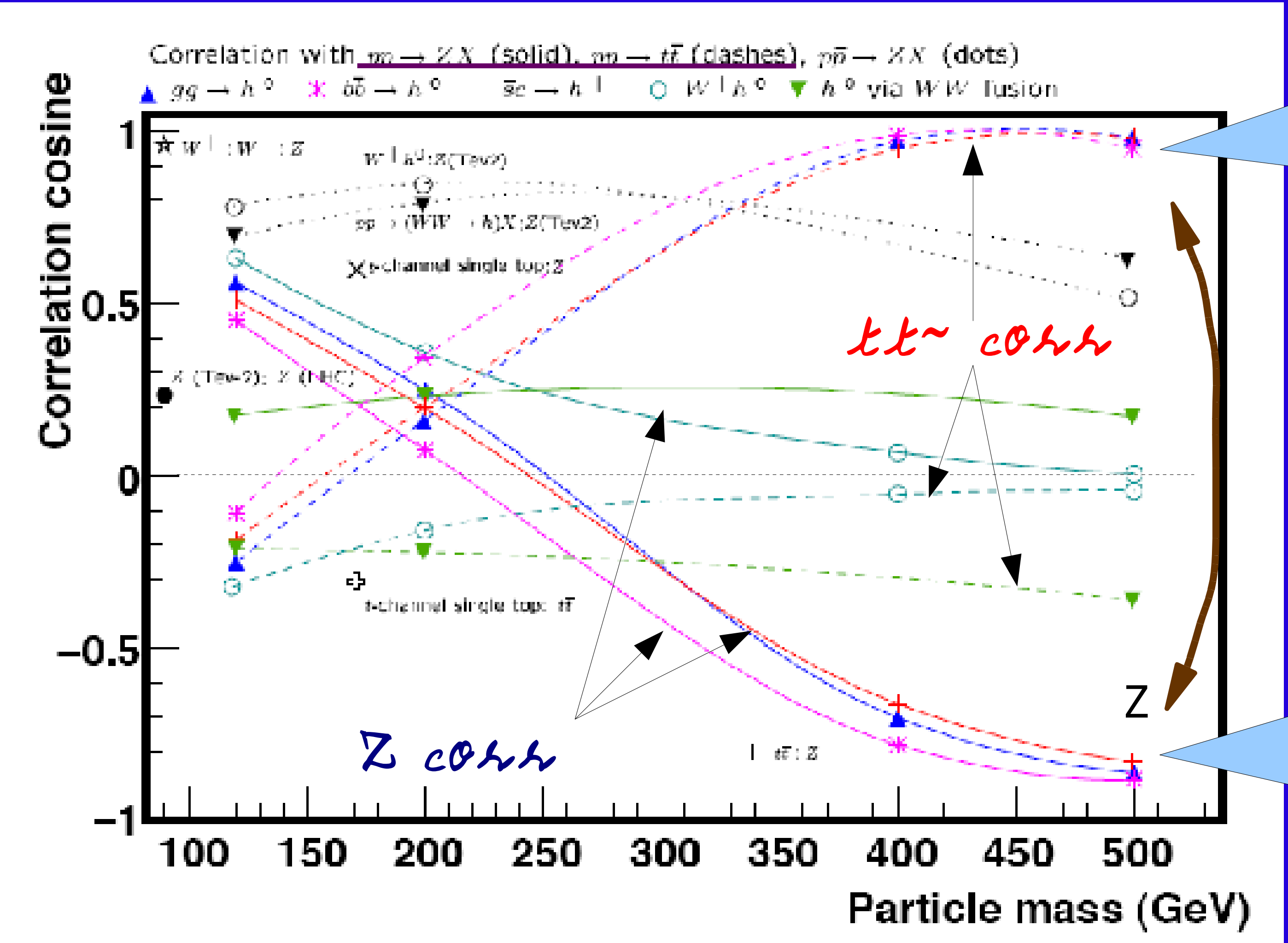
Correlation Matrix

Method 2: N(Wbb+jets) = MC(Wbb+jets)/MC(W+jets)
x N(W+jets)

Correlation (cosine) with Z,tt~



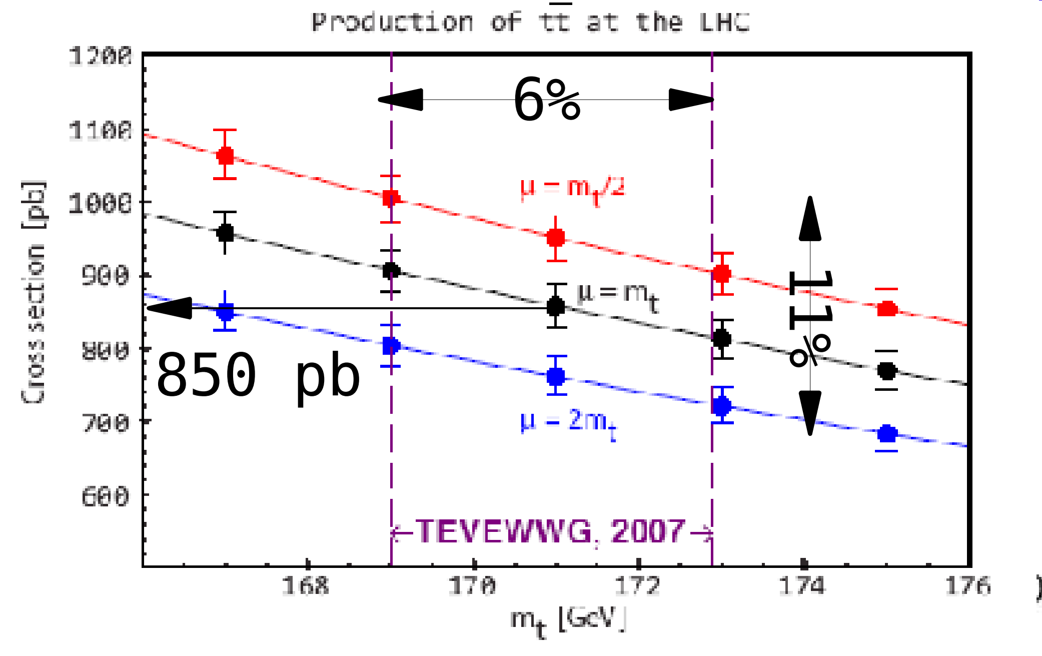
gg->H(500 GeV)
has 4% d-PDF

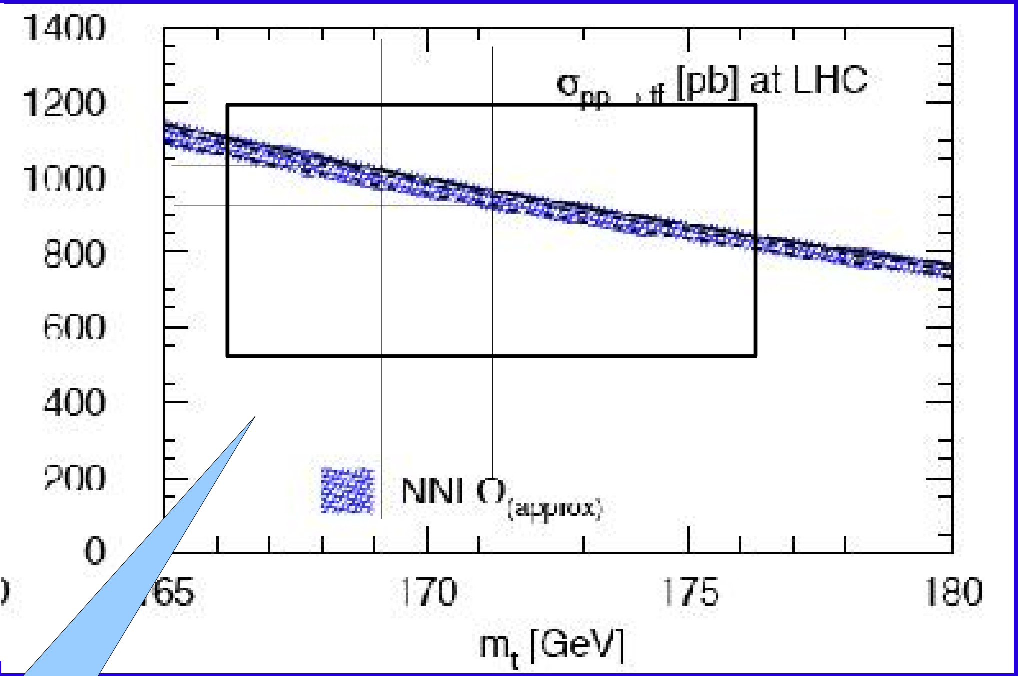


gg->H(500 GeV)
has 1.5% d-PDF
if using tt~

gg->H(500 GeV)
has 7% d-PDF
if using Z

Theoretical uncertainty on tt~





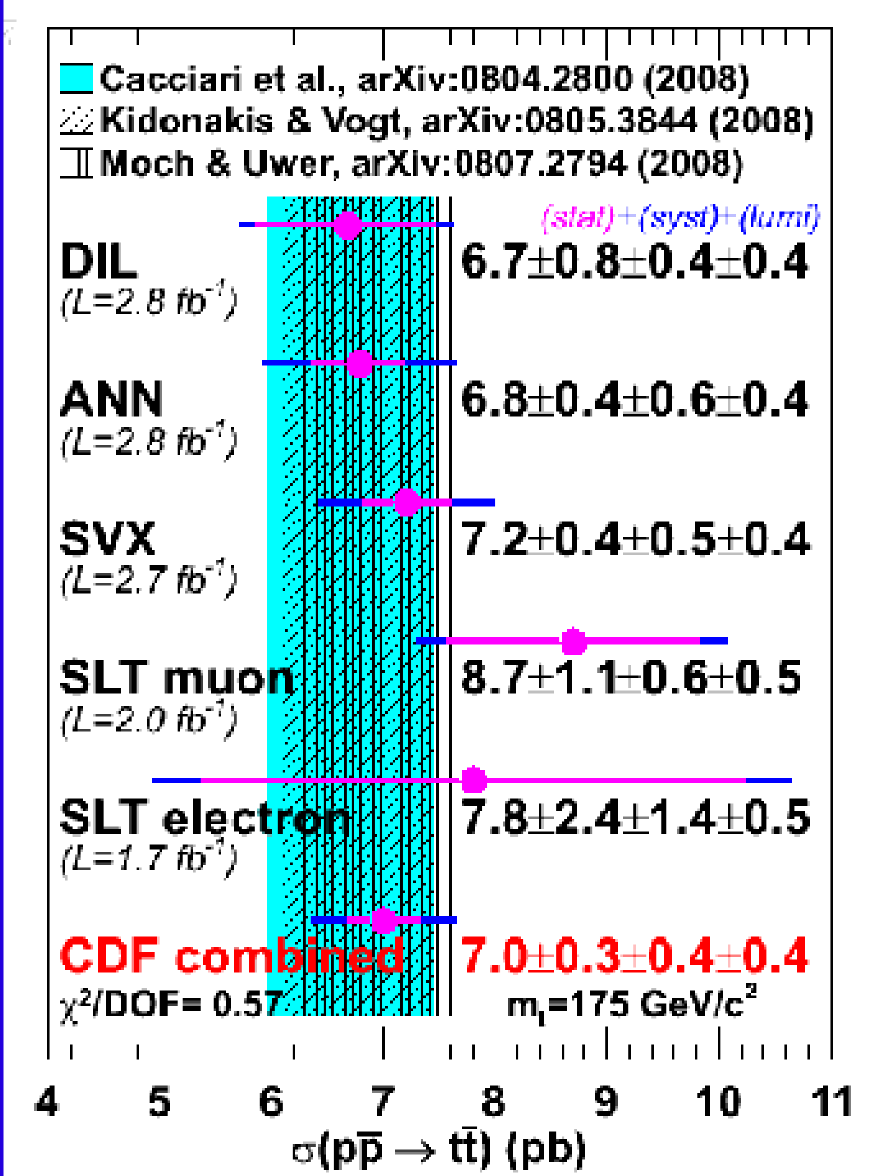
Run2
CDF/D0
goal

Full NNLO
tt~ in progress

- threshold resummation reduces scale dependence to ~3% (Moch and Uwer)
- 6%?? → worse than Z
  - d-PDF is smaller

What about experimental uncertainties?

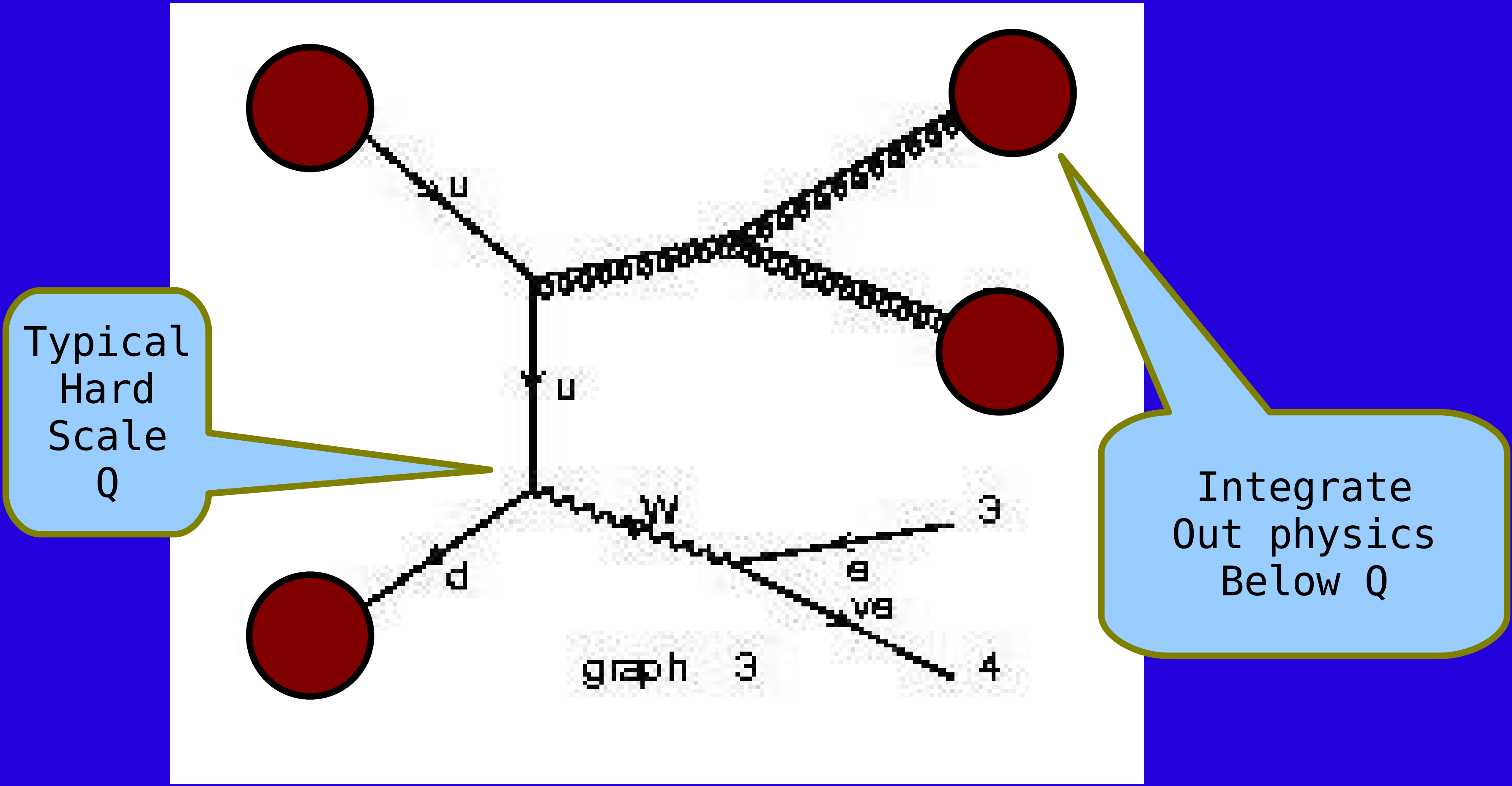
- 10-15% in year 1
  - unfortunately, which is where we would most like to have a precise value
- Ultimately, ~5%?
  - dominated by b-tagging uncertainty
  - systematic errors in common with other complex final states, which may cancel in a ratio?
- Tevatron now does 8% (non-lumi)



More on NLO

- Importance of NLO:
  - PDF fitting and uncertainty
    - Sensible output
  - Precision cross section estimates
    - Significantly reduces scale dependence
    - … and stabilizes shapes
- Limitations
  - Inclusive enough observables
  - Hard

Leading order



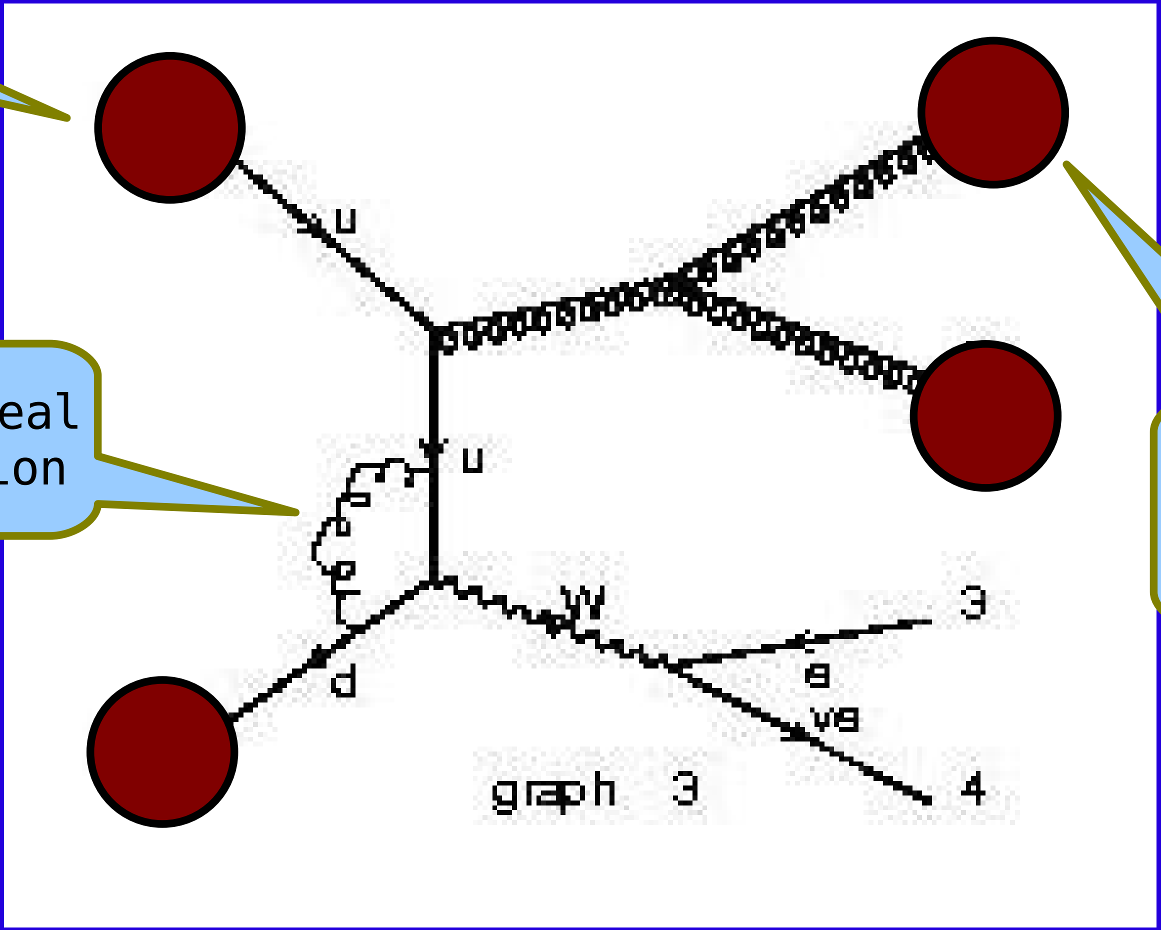
Typical
Hard
Scale
Q

Integrate
Out physics
Below Q

$$\alpha_s^2 + O(\alpha_s^3), \alpha_s \sim .12$$

Next-to-Leading Order

PDF
Defined
At NLO



Plus real
emission

Don't look at
Jets with
E<<Q

Defined
At NLO

$$\alpha_s(\infty + O(1) - \infty + O(1)')$$

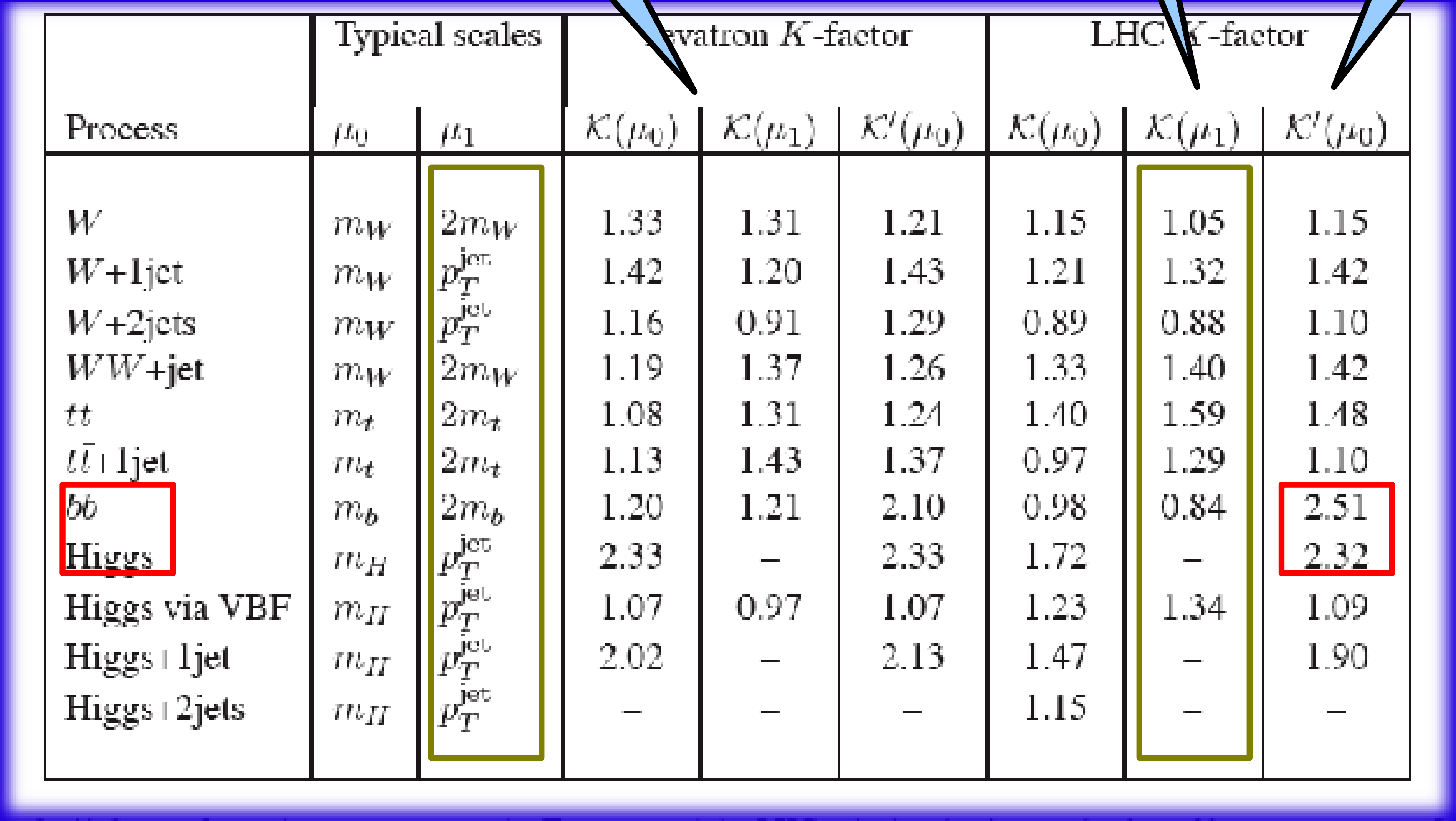
K-factors: how important is NLO?

Ignores shape changes

K=NLO/LO

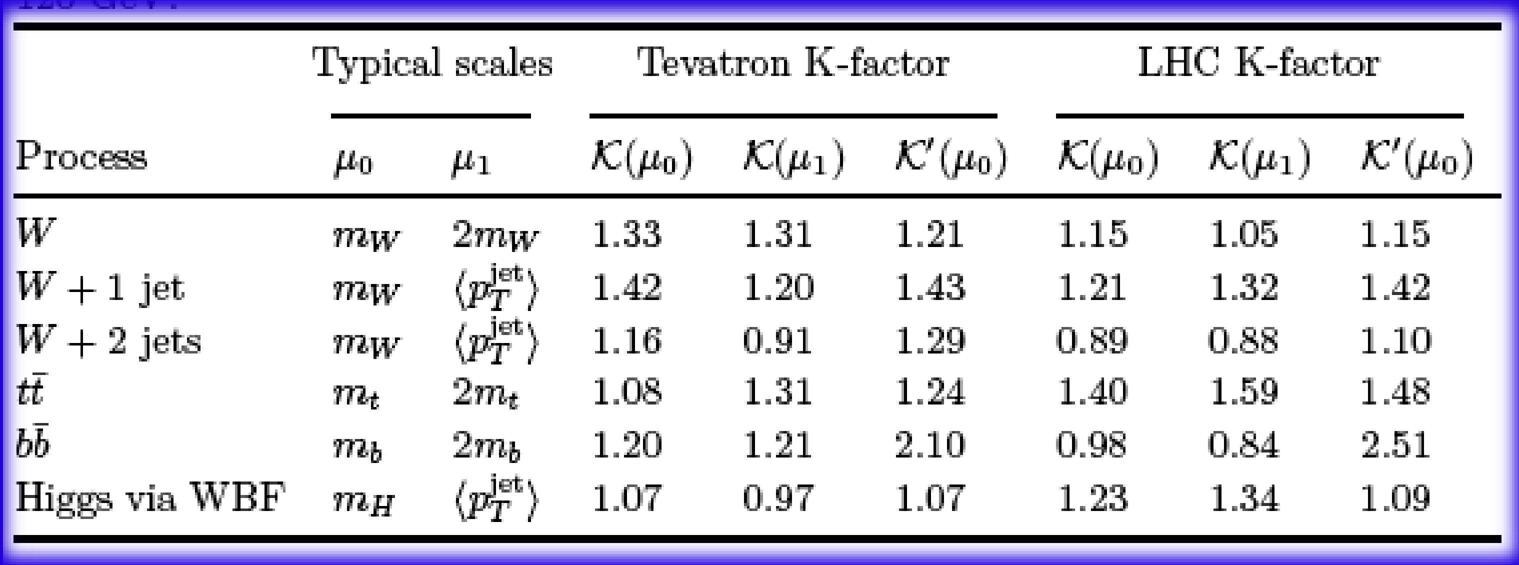
6M/6L1

6M/6M



Process	Typical scales		evatron K-factor			LHC K-factor		
	μ_0	μ_1	$K(\mu_0)$	$K(\mu_1)$	$K'(\mu_0)$	$K(\mu_0)$	$K(\mu_1)$	$K'(\mu_0)$
W	m_W	$2m_W$	1.33	1.31	1.21	1.15	1.05	1.15
W+1jet	m_W	p_T^{jet}	1.42	1.20	1.43	1.21	1.32	1.42
W+2jets	m_W	p_T^{jet}	1.16	0.91	1.29	0.89	0.88	1.10
WW+jet	m_W	$2m_W$	1.19	1.37	1.26	1.33	1.40	1.42
tt	m_t	$2m_t$	1.08	1.31	1.24	1.40	1.59	1.48
$t\bar{t}$+1jet	m_t	$2m_t$	1.13	1.43	1.37	0.97	1.29	1.10
bb	m_b	$2m_b$	1.20	1.21	2.10	0.98	0.84	2.51
Higgs	m_H	p_T^{jet}	2.33	–	2.33	1.72	–	2.32
Higgs via VBF	m_H	p_T^{jet}	1.07	0.97	1.07	1.23	1.34	1.09
Higgs+1jet	m_H	p_T^{jet}	2.02	–	2.13	1.47	–	1.90
Higgs+2jets	m_H	p_T^{jet}	–	–	–	1.15	–	–

K-factor lore



	Typical scales		Tevatron K-factor			LHC K-factor		
Process	μ_0	μ_1	$\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$	$\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$
W	m_W	$2m_W$	1.33	1.31	1.21	1.15	1.05	1.15
$W + 1$ jet	m_W	$\langle p_T^{\rm jet} \rangle$	1.42	1.20	1.43	1.21	1.32	1.42
$W + 2$ jets	m_W	$\langle p_T^{\rm jet} \rangle$	1.16	0.91	1.29	0.89	0.88	1.10
$t\bar{t}$	m_t	$2m_t$	1.08	1.31	1.24	1.40	1.59	1.48
$b\bar{b}$	m_b	$2m_b$	1.20	1.21	2.10	0.98	0.84	2.51
Higgs via WBF	m_H	$\langle p_T^{\rm jet} \rangle$	1.07	0.97	1.07	1.23	1.34	1.09

NLO corrections increase when more color is annihilated:

K(gg->H) ~ K(gg->γγ)
K(gg->X) > K(qq~->X)

NLO corrections decrease as more final-state legs are added:

K(gg->H + 2 jets)
< *K*(gg->H + 1 jet)
< *K*(gg->H)

Exception: new g channel

Simple rule:
Casimirs(initial)-
Casimir(final)

K(W/H+3j) ~ 1 ?

Shape dependence of a K-factor

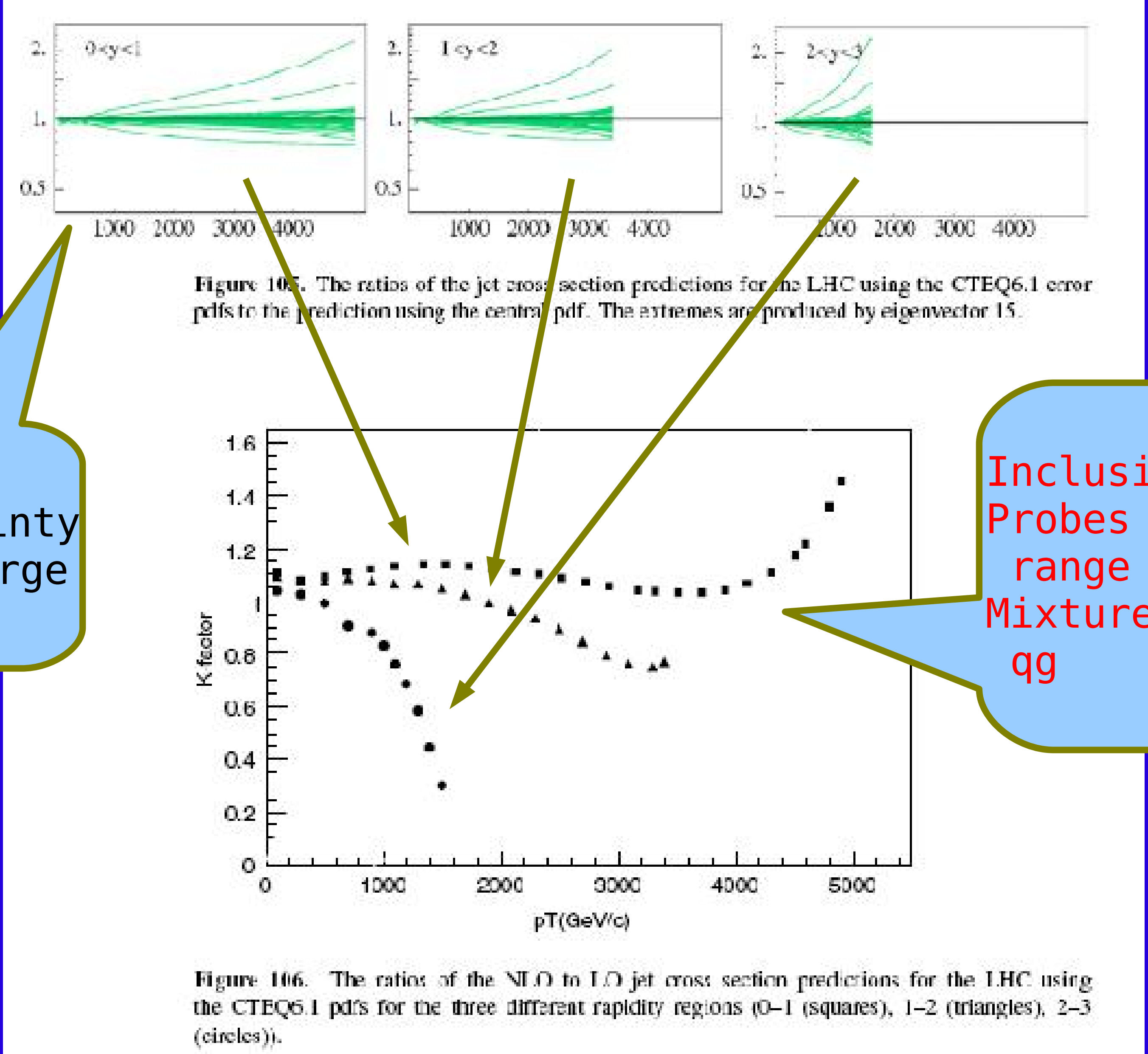


Figure 105. The ratios of the jet cross section predictions for the LHC using the CTEQ6.1 error pdfs to the prediction using the central pdf. The extremes are produced by eigenvector 15.

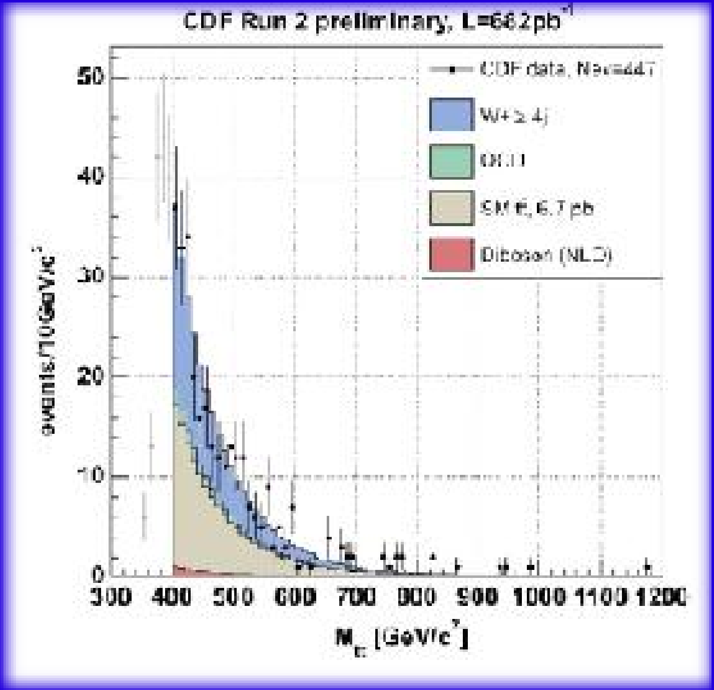
Figure 106. The ratios of the NLO to LO jet cross section predictions for the LHC using the CTEQ6.1 pdfs for the three different rapidity regions (0–1 (squares), 1–2 (triangles), 2–3 (circles)).

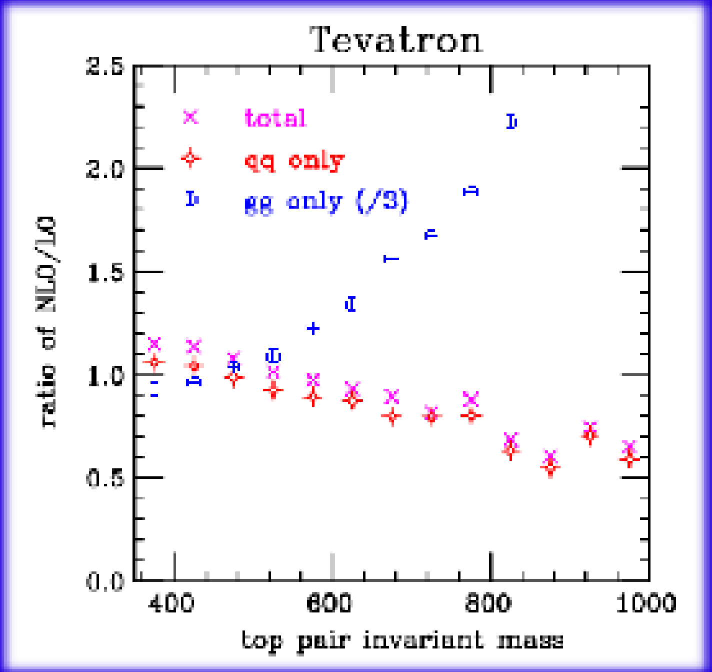
PDF uncertainty
Range is large

Inclusive jet:
Probes a wide
range of x, Q
Mixture of qq,gg,
qg

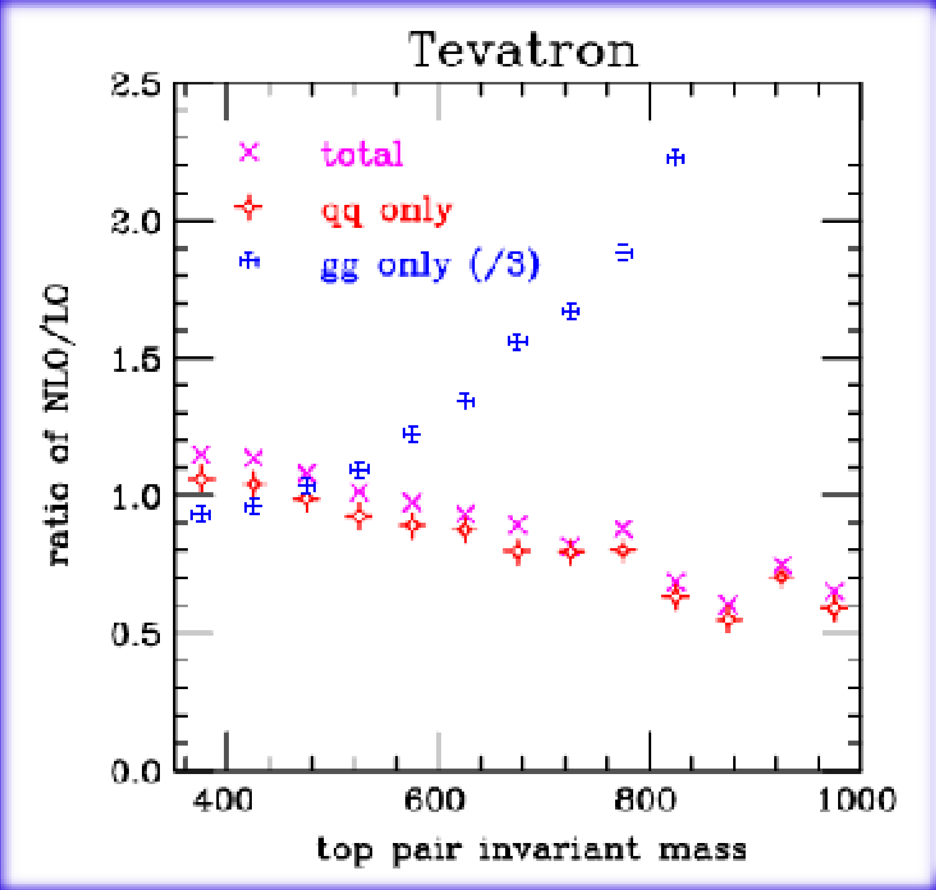
Top Production @TeV2

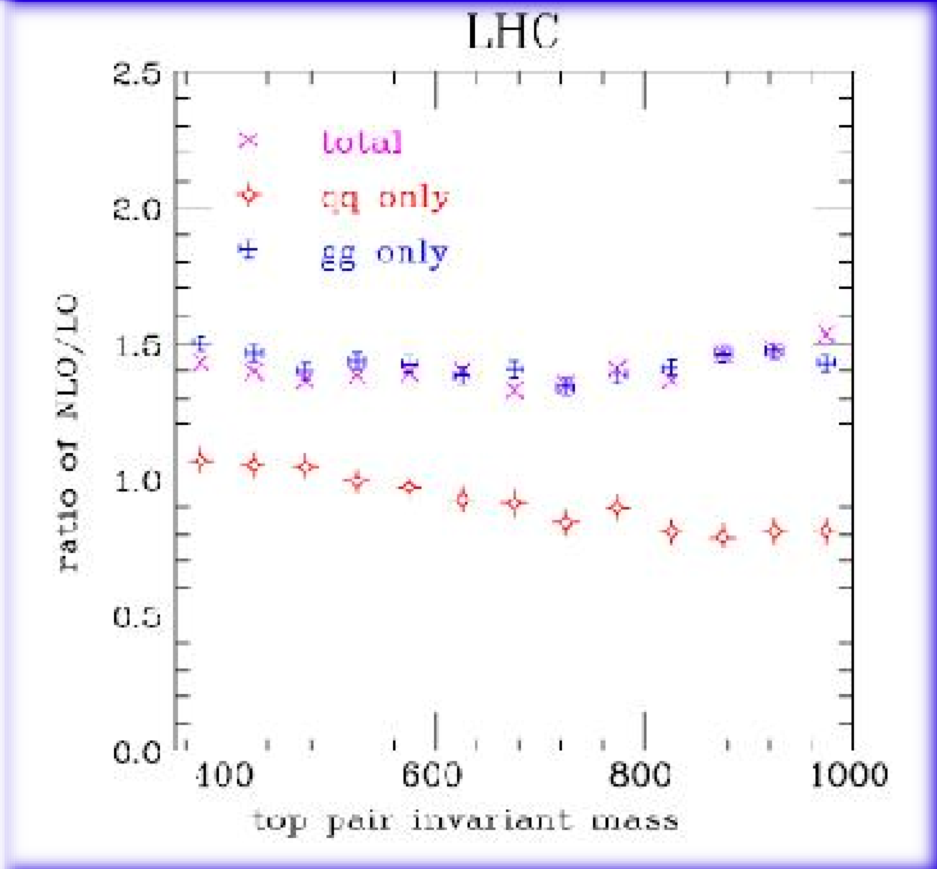
- Suppose you measure the high m_{tT} region looking for new physics
- Your measurement agrees well with Pythia
- Have you missed something?
- Yes, because NLO prediction at high mass is about .7 LO
  - partially pdf’s
  - partially matrix elements



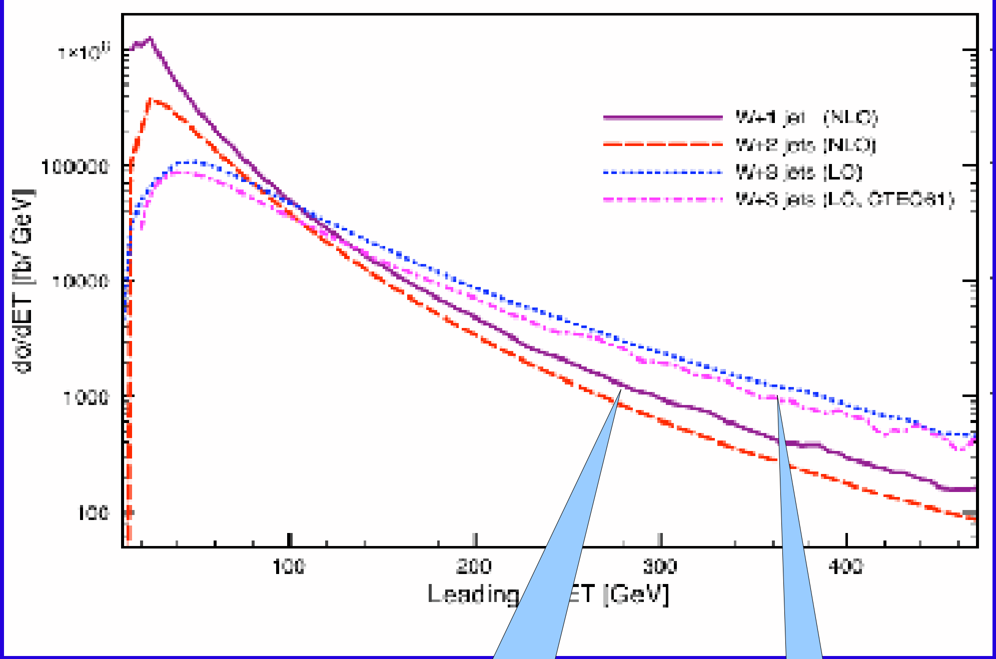


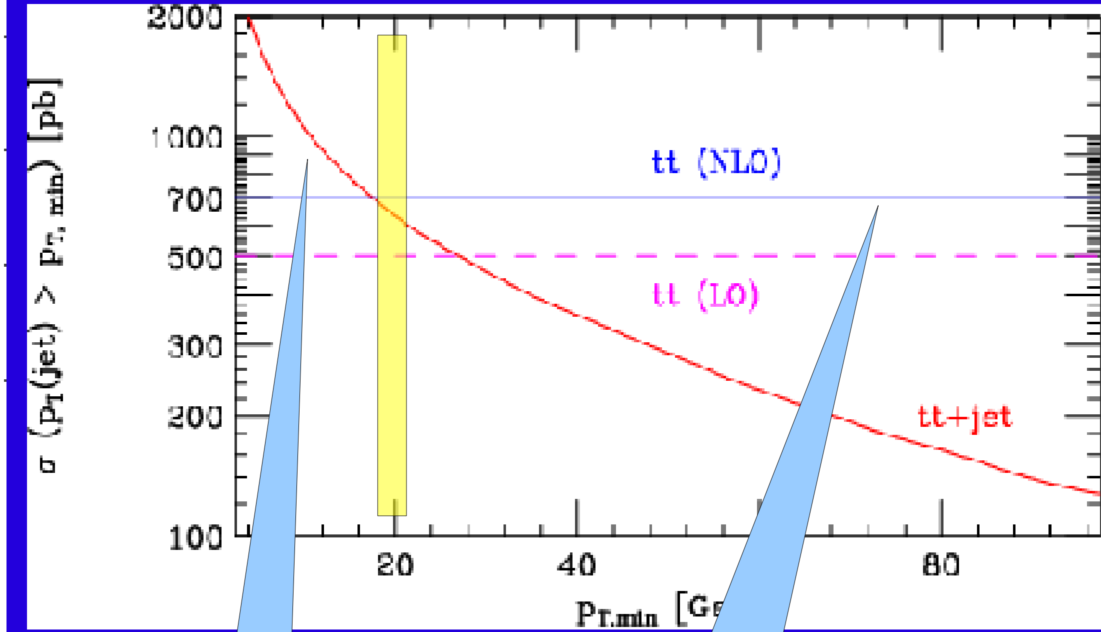
@TeV2 vs @LHC?


Tevatron
× total
qq only
gg only (/3)
ratio of NLO/LO
top pair invariant mass
0.0
0.5
1.0
1.5
2.0
2.5
400
600
800
1000


LHC
× total
qq only
gg only
ratio of NLO/LO
top pair invariant mass
0.0
0.5
1.0
1.5
2.0
2.5
400
600
800
1000

The LHC: a very *jetty* place





W+2j NLO

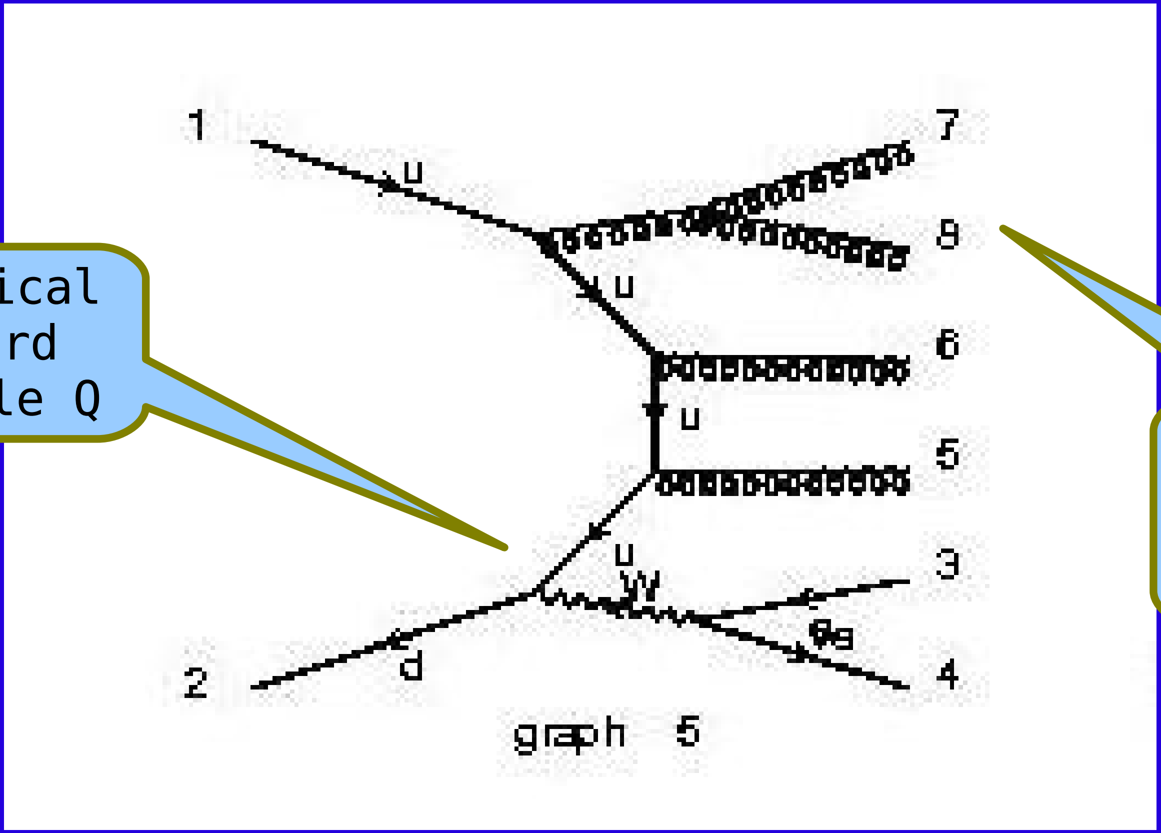
W+3j LO

tt~+j LO

Top total
inclusive NLO

Has perturbation theory gone wrong?

Perturbation Theory 101:
Feynman diagram approach

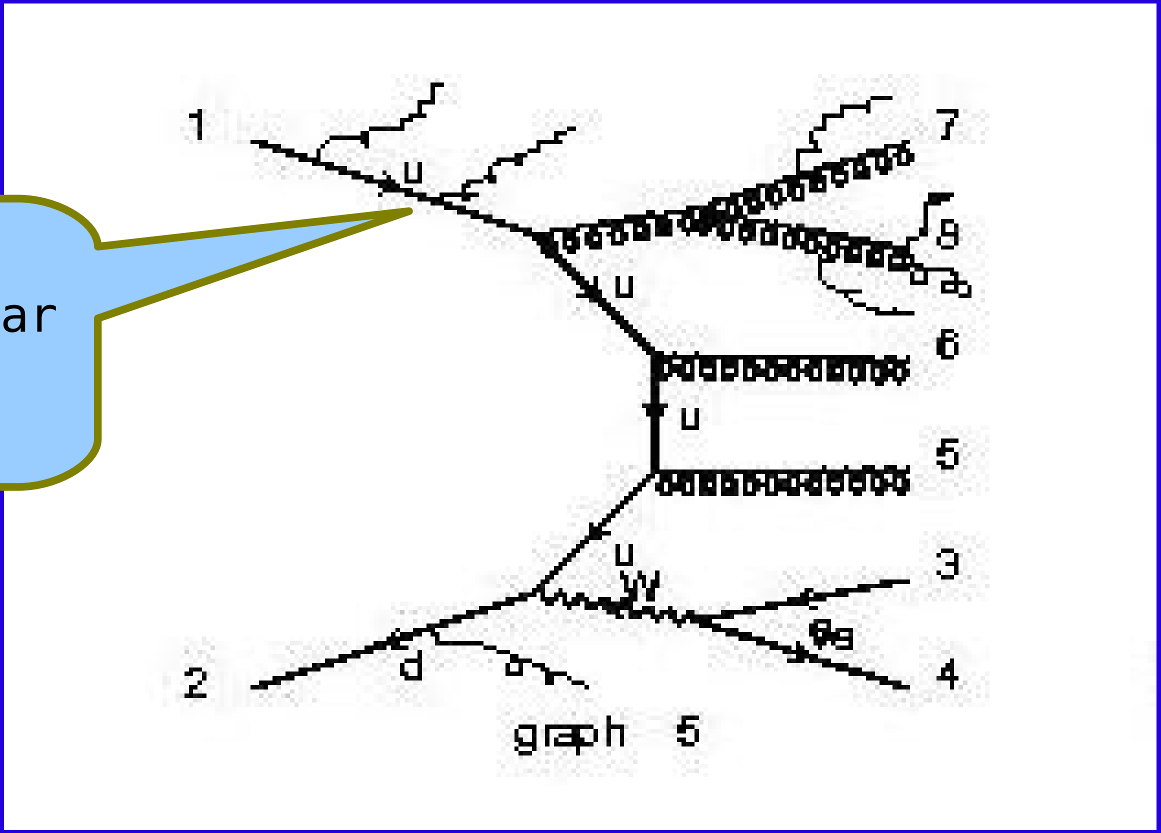


Typical
Hard
Scale Q

Typical
pT/Q > O(.1)

$$\alpha_s^4 + O(\alpha_s^5), \alpha_s \sim .12$$

+ additional soft/collinear gluons



Soft/collinear
if pT << Q

$$\alpha_s \sim \frac{1}{\ln\left(\frac{p_T}{Q}\right)}$$

$$\alpha_s \ln\left(\frac{p_T}{Q}\right)\left(\ln\left(\frac{p_T}{Q}\right)+1\right)+O\left(\alpha_s{}^N \ln^{2N,\,2N-1}\right)$$

Perturbation Theory 102: Sudakov form factors

$$\Delta(t) = \exp[-\int_{t_0}^{t}\int \frac{dt'}{t'}\frac{dz}{z}\frac{\alpha_S(z,t')}{2\pi}P(z)\frac{f(x/z,t')}{f(x,t')}]$$

- Basis for resummation and parton showering
- Sums effects of soft and collinear gluon emission, but not large energy, wide angle gluon emission
- Initial state and final state logs summed separately
  - FSR has no PDF reweighting
  - FSR modeling tested extensively at LEP
- Gives the probability **not** to radiate a gluon greater than some energy

Sudakov form factors

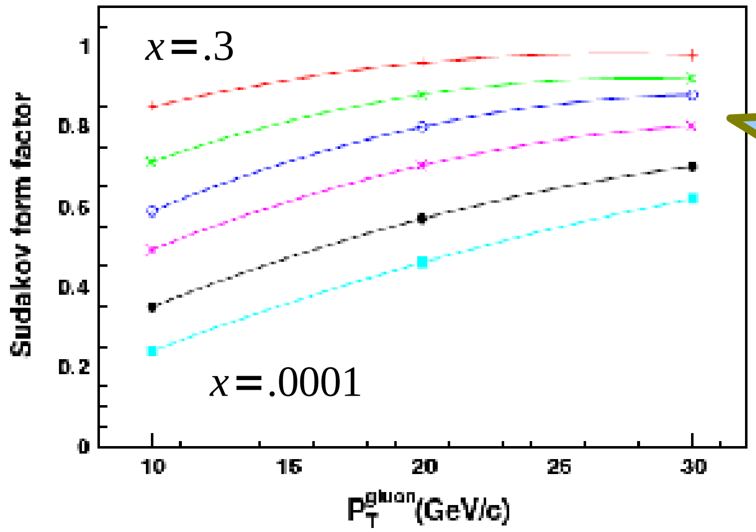


Figure 21. The Sudakov form factors for initial-state gluons at a hard scale of 100 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3, 0.1, 0.03, 0.01, 0.001 and 0.0001.

Q_hard = 100 GeV
ISR gluon

Q_hard = 500 GeV
ISR gluon

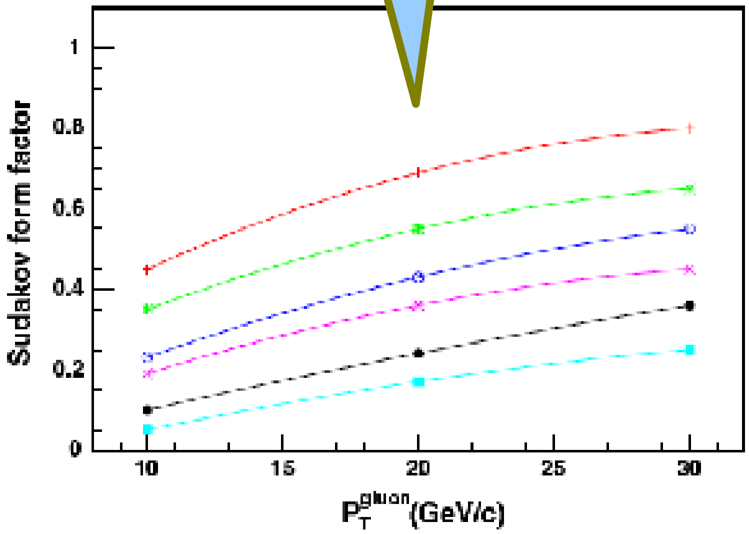
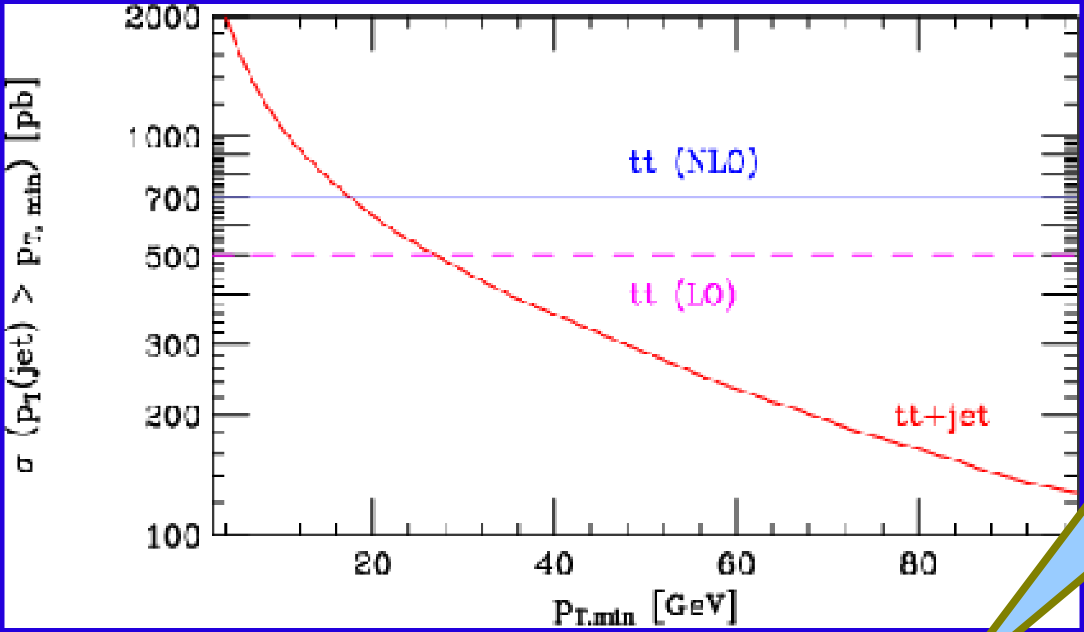
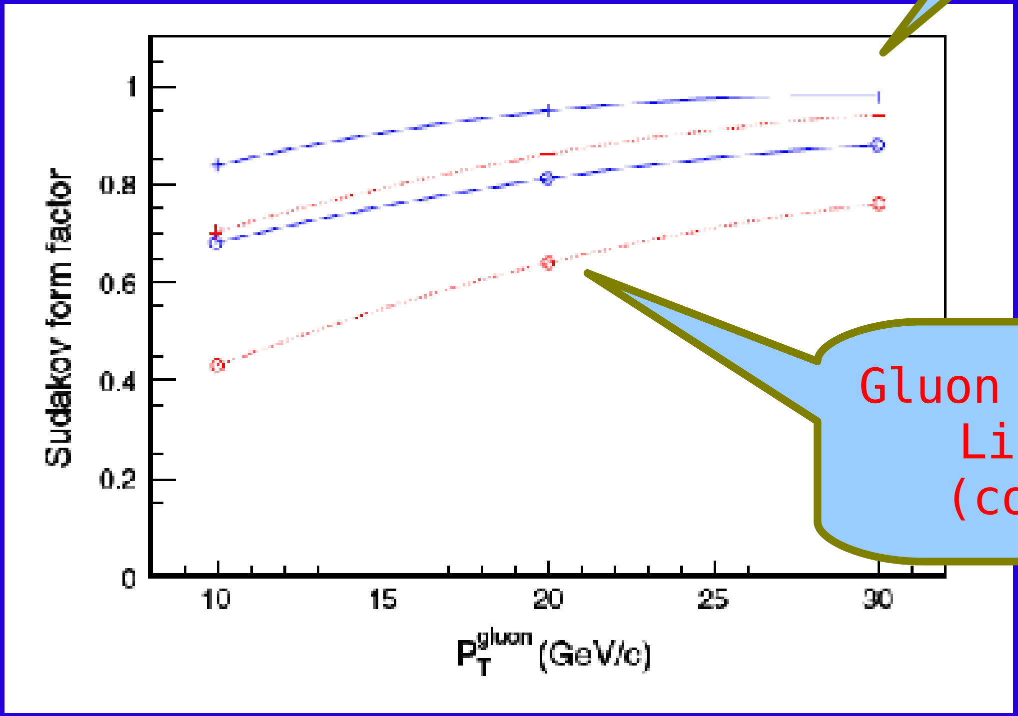


Figure 22. The Sudakov form factors for initial-state gluons at a hard scale of 500 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3, 0.1, 0.03, 0.01, 0.001 and 0.0001.

Prob incoming gluon
to t-tbar does
NOT radiate

Sudakov form factors for Top





Quark @TeV2 radiates
Less (color=4/3)

Gluon @LHC radiates
Like q+qbar
(color=3~8/3)

LHC Radiation Lessons

- LHC will be a jetty place
- Tt+1j > Tt does not violate Pert Theory
  - Indicates multiple gluon emission
    - Described by parton showers
  - Resummation softens pT spectra
- Jet cuts @LHC will have to be harder

Typical Pythia run card

```
pythiaUESettings = cms.vstring(
'MSTJ(11)=3 ! Choice of the fragmentation function',
'MSTJ(22)=2 ! Decay those unstable particles',
'PARJ(71)=10 . ! for which ctau 10 mm',
'MSTP(2)=1 ! which order running alphaS',
'MSTP(33)=0 ! no K factors in hard cross sections',
'MSTP(51)=10042 ! structure function chosen (external PDF CTEQ6L1)',
'MSTP(52)=2 ! work with LHAPDF',
'MSTP(81)=1 ! multiple parton interactions 1 is Pythia default',
'MSTP(82)=4 ! Defines the multi-parton model',
'MSTU(21)=1 ! Check on possible errors during program execution',
'PARP(82)=1.8387 ! pt cutoff for multiparton interactions',
'PARP(89)=1960. ! sqrts for which PARP82 is set',
'PARP(83)=0.5 ! Multiple interactions: matter distrbn parameter',
'PARP(84)=0.4 ! Multiple interactions: matter distribn parameter',
'PARP(90)=0.16 ! Multiple interactions: rescaling power',
'PARP(67)=2.5 ! amount of initial-state radiation',
'PARP(85)=1.0 ! gluon prod. mechanism in MI',
'PARP(86)=1.0 ! gluon prod. mechanism in MI',
'PARP(62)=1.25 ! ',
'PARP(64)=0.2 ! ',
'MSTP(91)=1 !',
'PARP(91)=2.1 ! kt distribution','PARP(93)=15.0 ! ')
```

Why so many #!&% parameters?

Theory uncertainties: (educated) guesses about

- Higher orders of perturbation theory (fixed order and resummed) than have been implemented
- Incomplete application of known physics due to approximations
- Simplified models of complex semi-hard or non-perturbative physics
- Unsimulated phenomenon

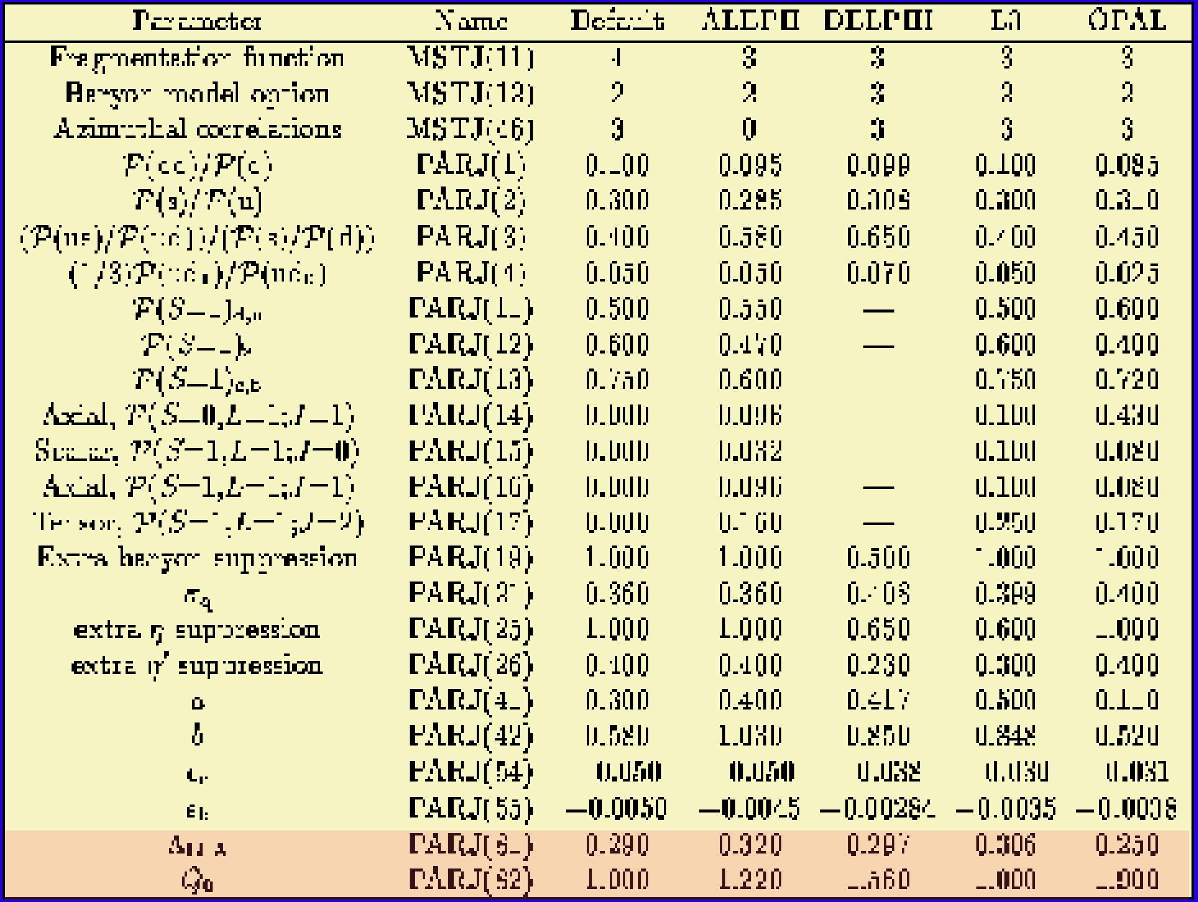
Error estimates needed for:

- Measurements (signals)
  - Inclusive jet cross section
  - W, Top mass
- Limit setting
  - Higgs mass
- Data-driven background estimates

What is done in practice?
Top Mass Systematics (CDF/D0)

- Radiation (ISR/FSR)
  - Variation of Lambda_QCDs
- PDF
  - Shift in hard kinematics (y_W)
- Generator
  - Different implementations, logs
- UE
  - Ave. of several models
- Jet Energy Corrections
  - Variation of parton->hadron map

Correlation of Parameters



Parameter	Name	Default	ALEPH	DELPHI	L3	OPAL
Fragmentation function	MSTJ(11)	4	3	3	3	3
Baryon model option	MSTJ(12)	2	2	3	2	2
Azimuthal correlations	MSTJ(46)	3	0	3	3	3
$P(qq)/P(q)$	PARJ(1)	0.100	0.095	0.099	0.100	0.085
$P(s)/P(u)$	PARJ(2)	0.300	0.285	0.309	0.300	0.310
$(P(us)/P(ud))/(P(s)/P(d))$	PARJ(3)	0.400	0.580	0.650	0.400	0.450
$(1/3)P(ud_1)/P(ud_0)$	PARJ(4)	0.050	0.050	0.070	0.050	0.025
$P(S=1)_{d,u}$	PARJ(11)	0.500	0.550	—	0.500	0.600
$P(S=1)_s$	PARJ(12)	0.600	0.470	—	0.600	0.400
$P(S=1)_{c,b}$	PARJ(13)	0.750	0.600		0.750	0.720
Axial, $P(S=0,L=1;J=1)$	PARJ(14)	0.000	0.096		0.100	0.430
Scalar, $P(S=1,L=1;J=0)$	PARJ(15)	0.000	0.032		0.100	0.080
Axial, $P(S=1,L=1;J=1)$	PARJ(16)	0.000	0.096	—	0.100	0.080
Tensor, $P(S=1,L=1;J=2)$	PARJ(17)	0.000	0.160	—	0.250	0.170
Extra baryon suppression	PARJ(19)	1.000	1.000	0.500	1.000	1.000
σ_q	PARJ(21)	0.360	0.360	0.408	0.399	0.400
extra η suppression	PARJ(25)	1.000	1.000	0.650	0.600	1.000
extra η' suppression	PARJ(26)	0.400	0.400	0.230	0.300	0.400
a	PARJ(41)	0.300	0.400	0.417	0.500	0.110
b	PARJ(42)	0.580	1.030	0.850	0.848	0.520
ϵ_c	PARJ(54)	0.050	0.050	0.032	0.030	0.031
ϵ_b	PARJ(55)	−0.0050	−0.0045	−0.00284	−0.0035	−0.0038
Λ_{LLA}	PARJ(81)	0.290	0.320	0.297	0.306	0.250
Q_0	PARJ(82)	1.000	1.220	1.560	1.000	1.900

Effects on other parameters ignored in Lambda_QCD +/- (or other) variation

No unique separation between radiation, hadronization, UE either in data or MC

Tune A == event tune != UE tune

Event Generators use PDFs for:

- Setting kinematics at high Q
- Backwards evolution ISR
  - Transverse evolution: $P_{T\,,\,boson}$
- Underlying Event (semi-hard QCD,low x)
  - Important for modeling: triggering, track occupancy, jet energy, isolation, etc.

Monte Carlo PDFs

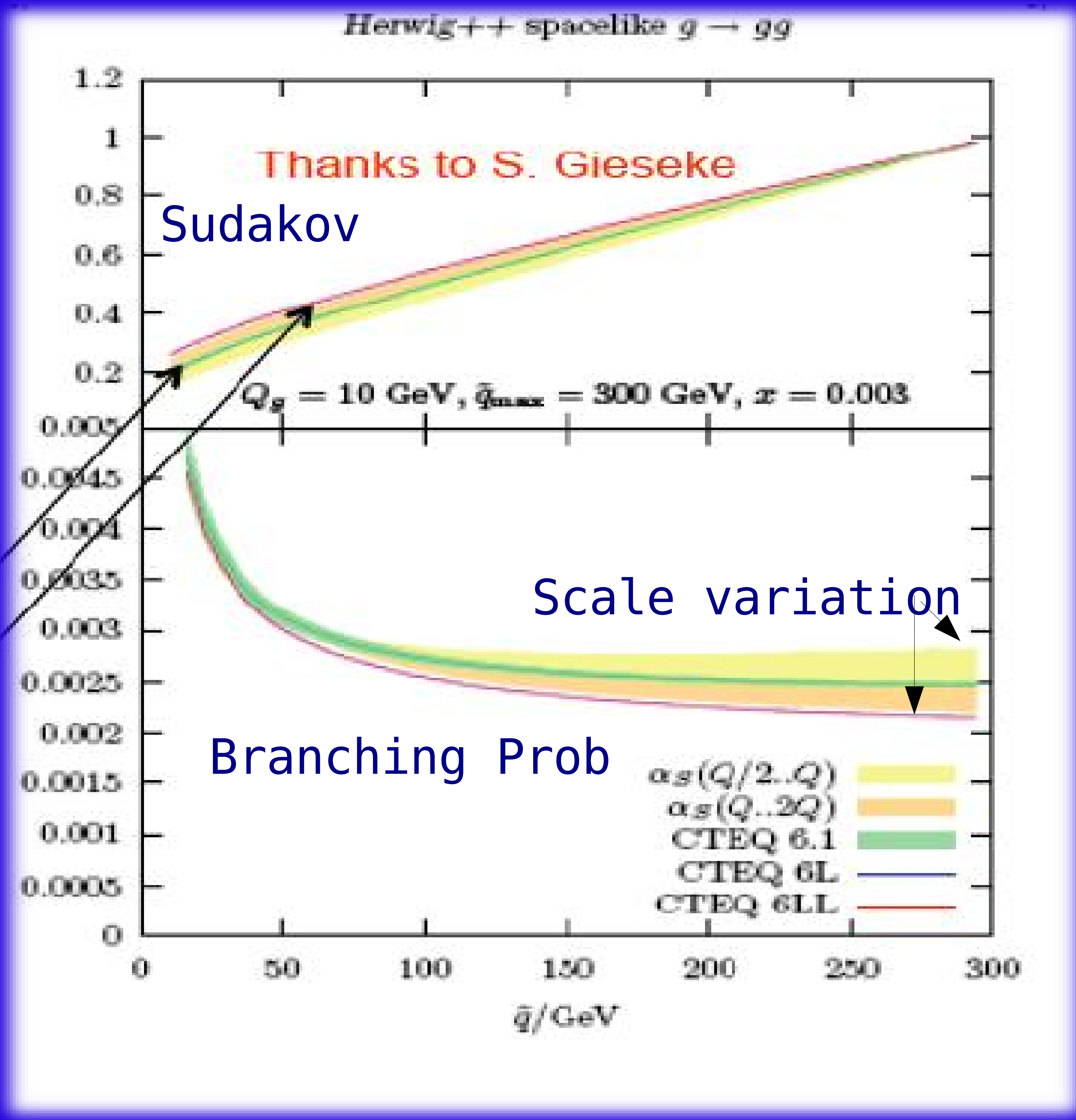
- Which PDFs for parton shower Monte Carlos?
  - standard to use LO PDFs, most commonly CTEQ5L/CTEQ6L, in Pythia, Herwig, Sherpa, ALPGEN/Madgraph+…
- Concerns:
  - LO PDFs can create LHC cross sections/acceptances that differ in both shape and normalization from NLO
    - due to influence of HERA data
    - and lack of ln(1/x) and ln(1-x) terms in LO PDFs and evolution
  - … outside NLO error bands

Effect on Sudakov

Not shown:
UE variation

NLO PDF band
very narrow

Sudakov
LO PDF



PDF error treatment in MC

- NLO error PDFs are used in combination with the central LO PDF
    - an error in PDF re-weighting due to non-matching of Sudakov form factors

$$f_{LO}(x,Q)\times\frac{f_{NLO,error}(x,Q)}{f_{NLO,central}(x,Q)}$$

Times a ratio of LO PDFs from ISR for each emission

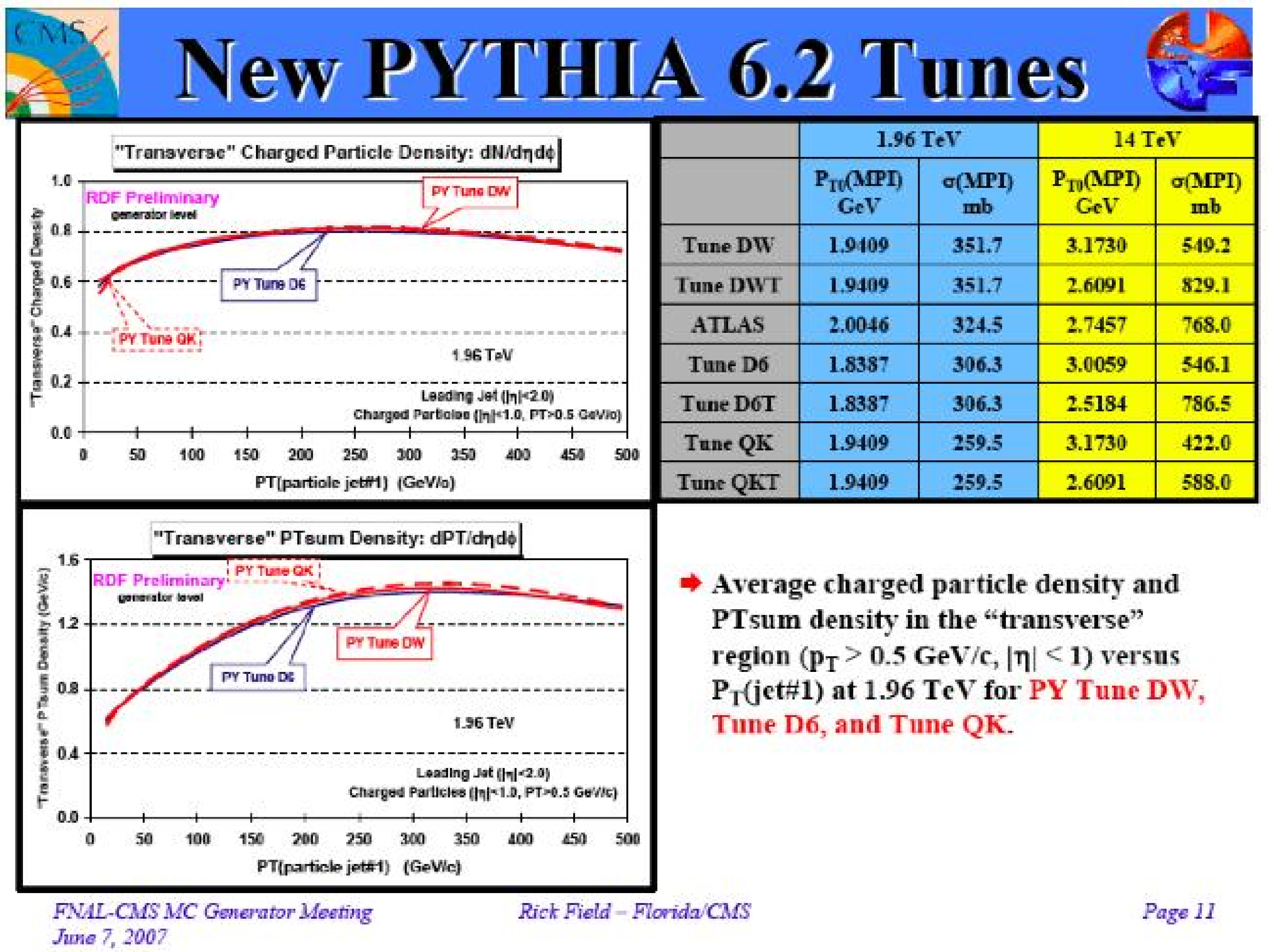
From ME in Alpgen, Pythia, etc

PDF error estimate

Modified LO pdf's (LO*)

- …but
    - the low x behavior of LO PDFs are used in models of the underlying event (UE) at the Tevatron and its extrapolation to the LHC
    - Also used for calculating low x cross sections at the LHC
- → motivation for modified LO PDFs

Tunes with CTEQ6L



New PYTHIA 6.2 Tunes

	1.96 TeV		14 TeV	
	P_{T0}(MPI) GeV	σ(MPI) mb	P_{T0}(MPI) GeV	σ(MPI) mb
Tune DW	1.9409	351.7	3.1730	549.2
Tune DWT	1.9409	351.7	2.6091	829.1
ATLAS	2.0046	324.5	2.7457	768.0
Tune D6	1.8387	306.3	3.0059	546.1
Tune D6T	1.8387	306.3	2.5184	786.5
Tune QK	1.9409	259.5	3.1730	422.0
Tune QKT	1.9409	259.5	2.6091	588.0

- Average charged particle density and PTsum density in the "transverse" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus P_T(jet#1) at 1.96 TeV for **PY Tune DW, Tune D6, and Tune QK.**

FNAL-CMS MC Generator Meeting
June 7, 2007

Rick Field – Florida/CMS

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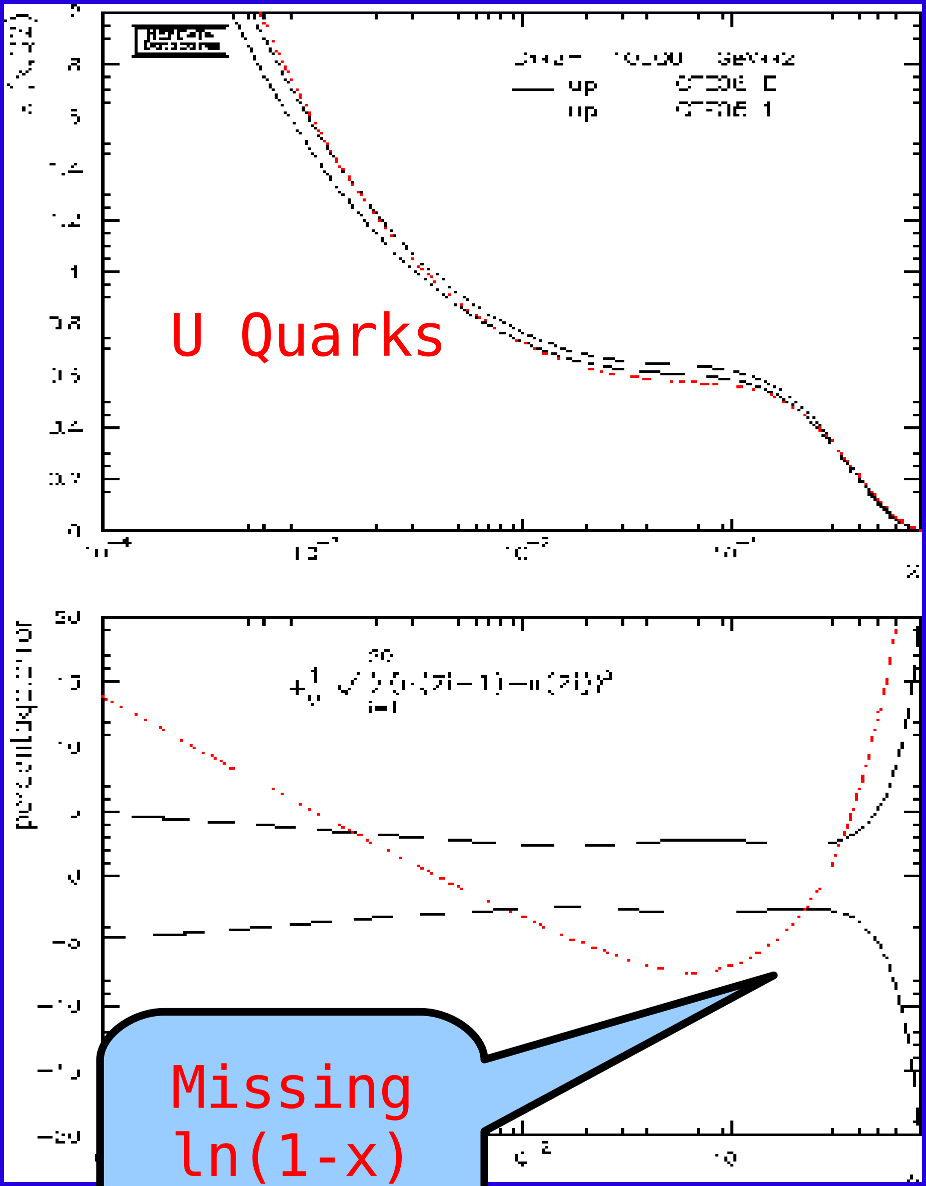
Reasonable behavior

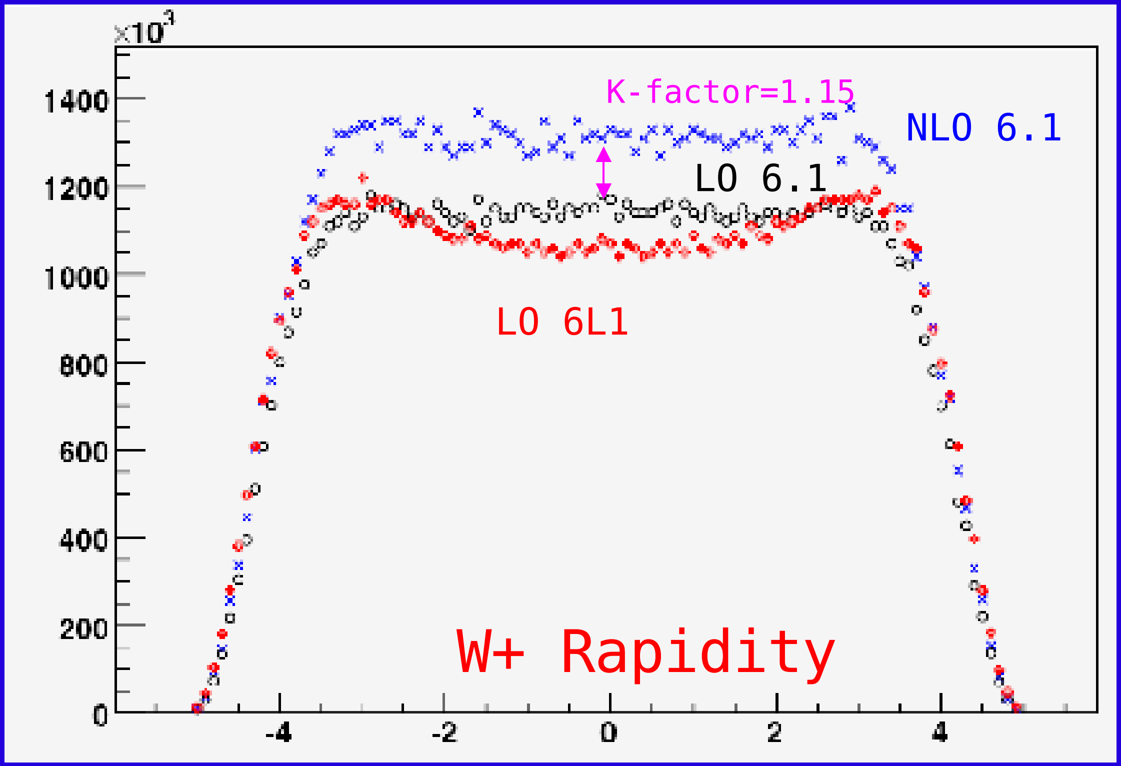
- LO* PDFs should behave as LO as x->0; as close to NLO as possible as x->1
- LO* PDFs should be universal and produce reasonable results out of the box
- It should be possible to produce error PDFs:
  - similar Sudakov form factors
  - similar UE
  - so PDF re-weighting makes sense
- LO* PDFs should describe UE @TeV with a tune similar to CTEQ6L (for convenience) and extrapolate to a *reasonable* UE at the LHC

Where are the differences between LO and NLO partons?



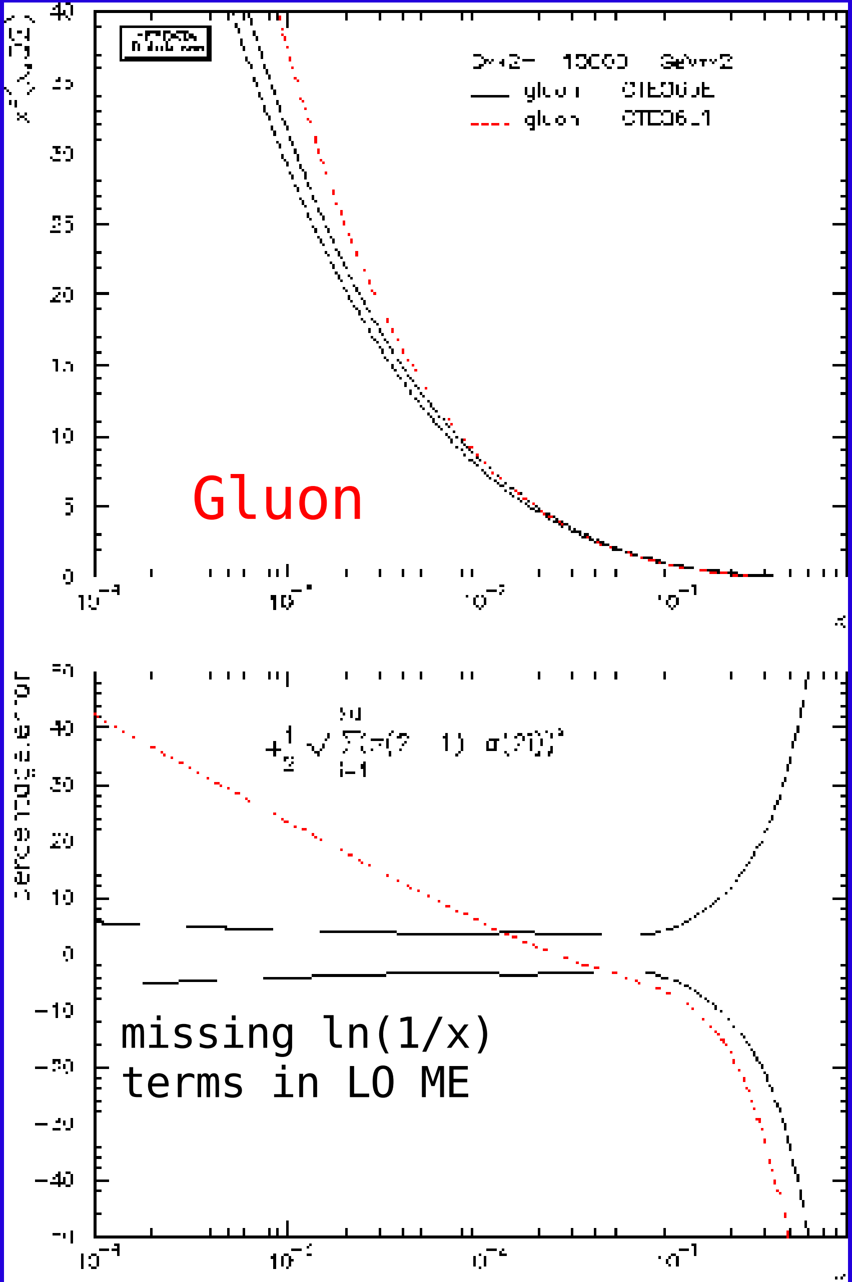
Missing ln(1-x) at LO

W^+ rapidity distribution at LHC



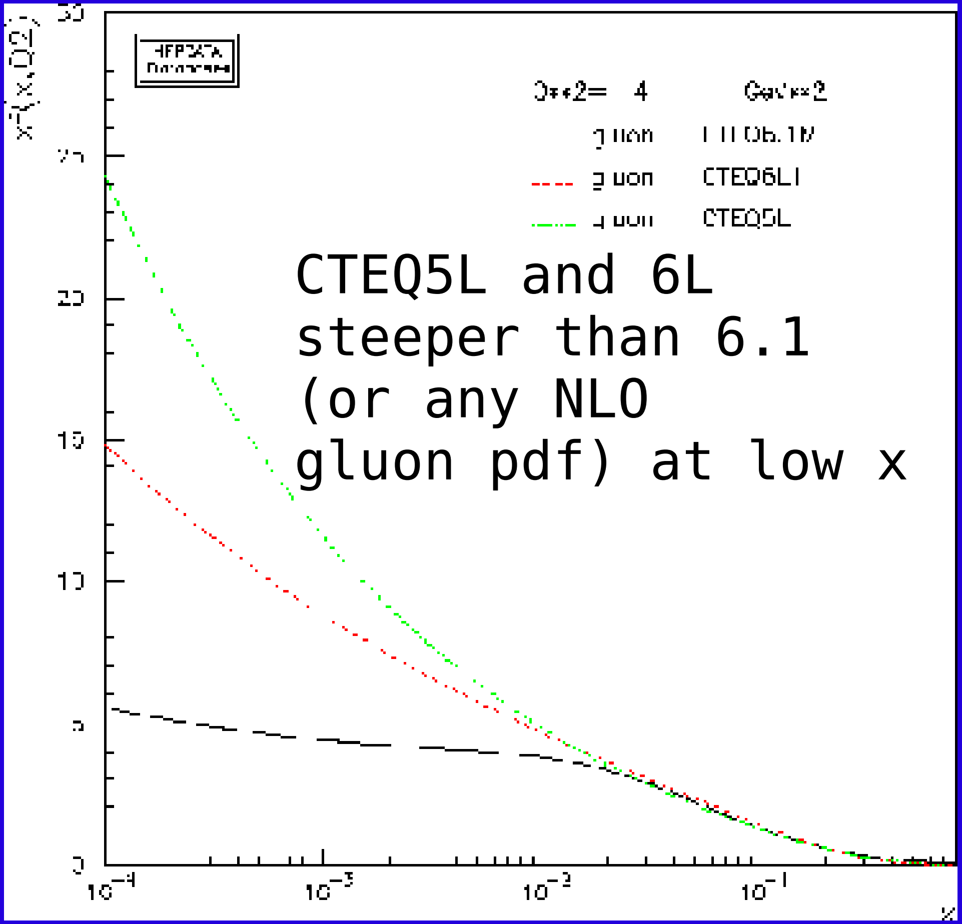
LO 6L1 == (LO ME) (LO PDF)
LO 6.1 == (LO ME) (NLO PDF)
NLO 6.1 == (NLO ME) (NLO PDF)

Where are the differences:gluons?



Gluon

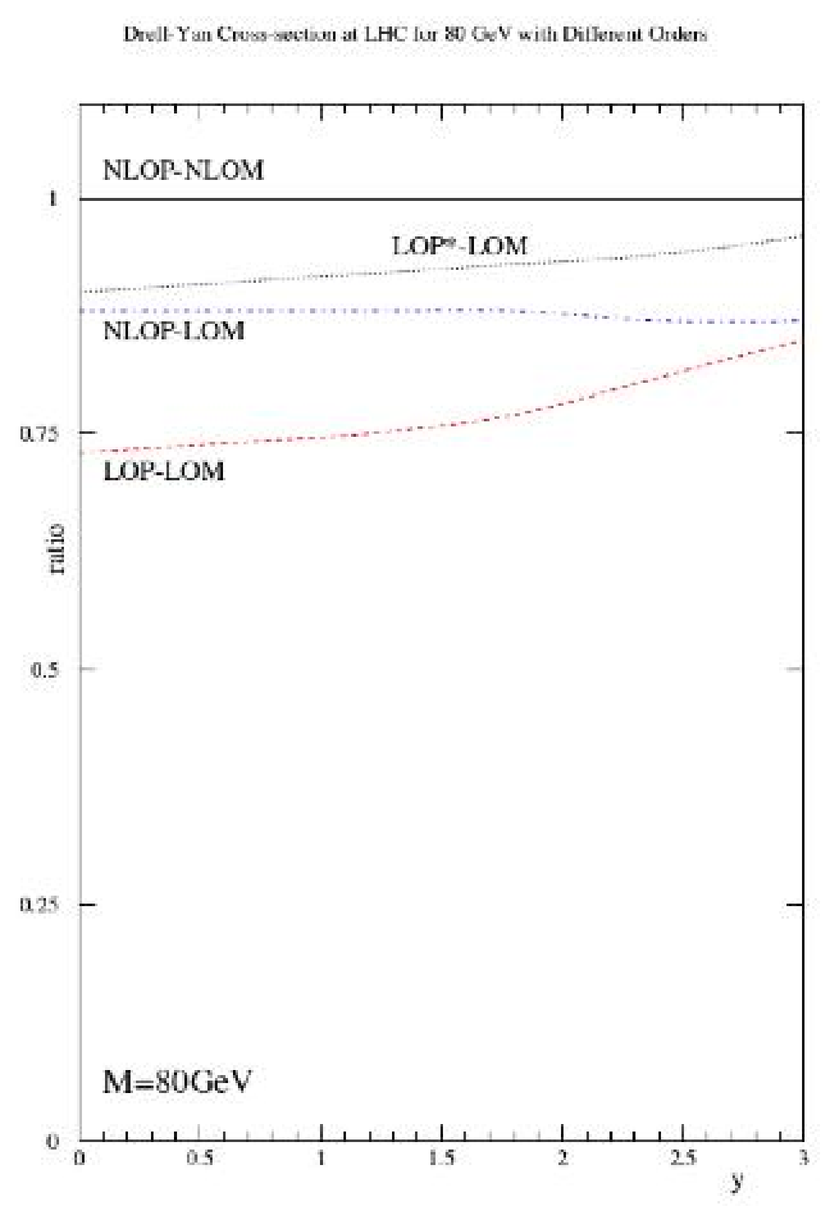
missing ln(1/x)
terms in LO ME



CTEQ5L and 6L
steeper than 6.1
(or any NLO
gluon pdf) at low x

MRSTLO*

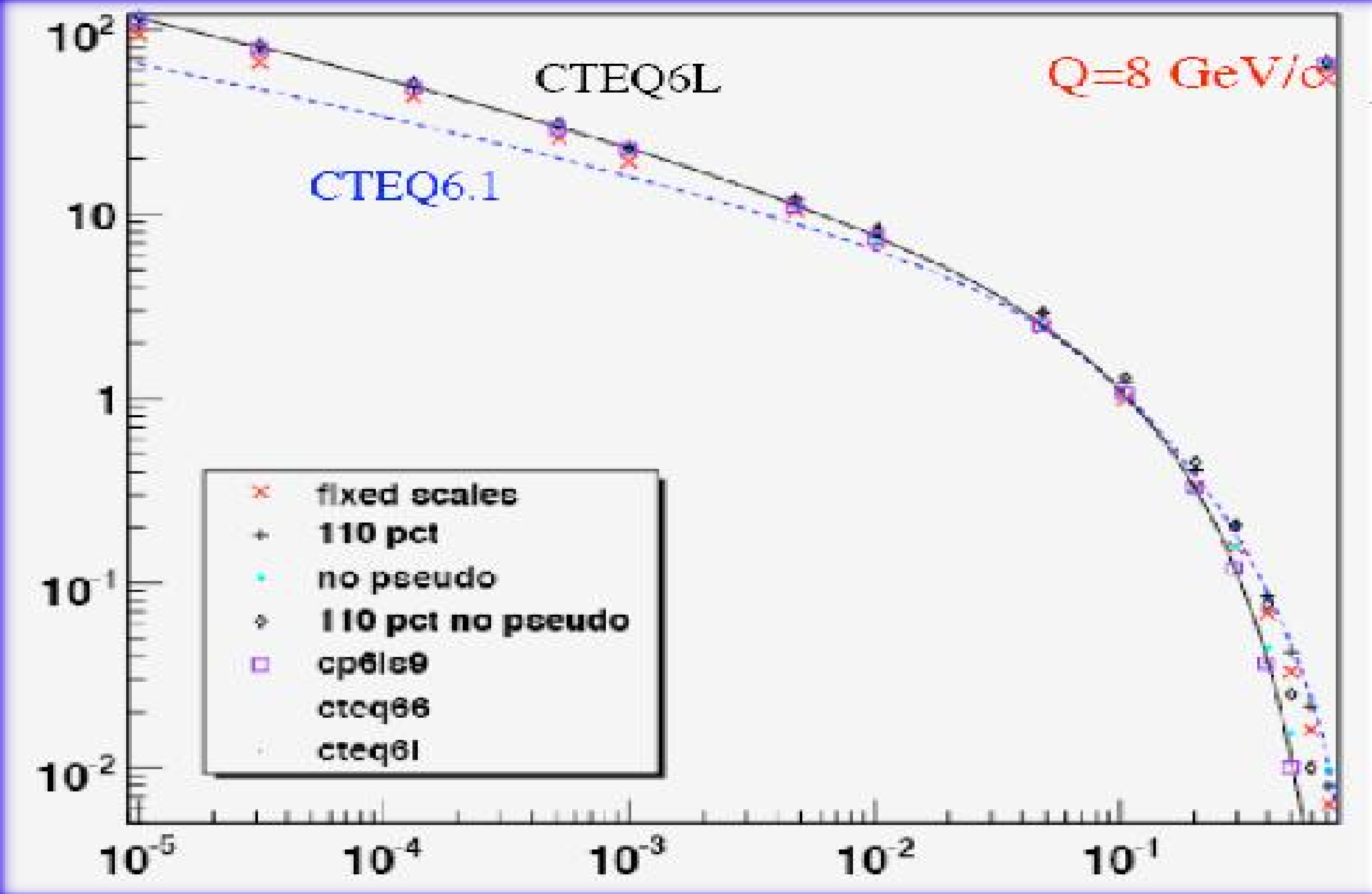
- The MRST group has a modified LO pdf that tries to incorporate many of these points
- They relax the momentum sum rule (114%) and achieve a better agreement (than MRST LO pdf’s) with some important LHC benchmark cross sections
- Available in LHAPDF



CTEQ variations

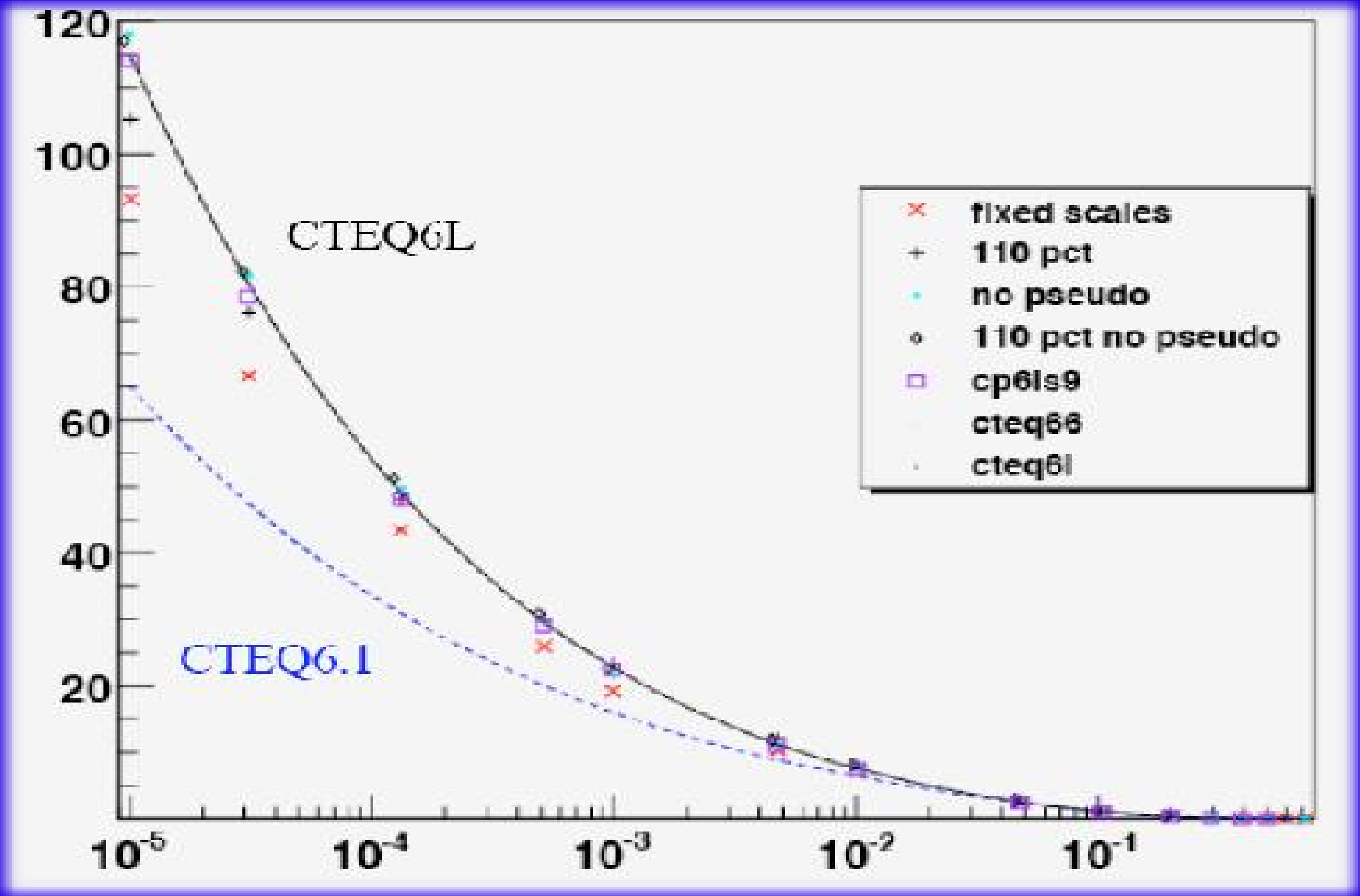
- INCLUDE IN LO* FIT (WEIGHTED) **PSEUDO-DATA** FOR CHARACTERISTIC LHC PROCESSES PRODUCED USING CTEQ6.6 NLO PDF’S WITH NLO MATRIX ELEMENTS (USING MCFM)
- Use of 2-loop or 1-loop α_s
  - Herwig preference for 2-loop
  - Pythia preference for 1-loop
- Fixed momentum sum rule, or not
  - re-arrange momentum within proton and/or add extra momentum
  - extra momentum appreciated by some of pseudo-data sets but not others and may lose some useful correlations
- Fix pseudo-data normalizations to K-factors expected from higher order corrections, or let float
- Scale variation within reasonable range for fine-tuning of agreement with pseudo-data
  - vector boson scale varies from 0.5 m_B to 2.0 m_B

Results: gluon distribution



- Candidate pdf titled *fixed scales* tries to fit pseudo-data
- Larger than CTEQ6L at high x, but smaller at low x
- With *110%* momentum in proton, gluon is larger at high x
- Including the pseudo-data in the fit increases the high x gluon even more

Focus on small-x



Desired Perturbative Variations for Shower Uncertainty

- Radiation functions
- Evolution variables
- Phase space mapping
- Internal scales
- ...

Skands/Giele/Kosower VINCIA is the closest match to this

VINCIA

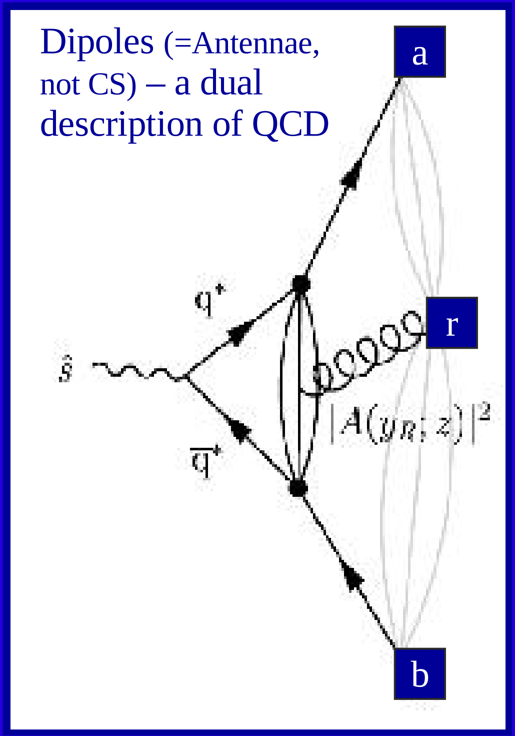
VIRTUAL NUMERICAL COLLIDER WITH INTERLEAVED ANTENNAE

Gustafson, PLB175(1986)453; Lönnblad (ARIADNE), CPC71(1992)15
Azimov, Dokshitzer, Khoze, Troyan, PLB165B(1985)147
Kosower PRD57(1998)5410; Campbell,Cullen,Glover EPJC9(1999)24

- Based on Dipole-Antennae
  - Shower off color-connected pairs of partons
  - Plug-in to PYTHIA 8 (C++)
- So far:

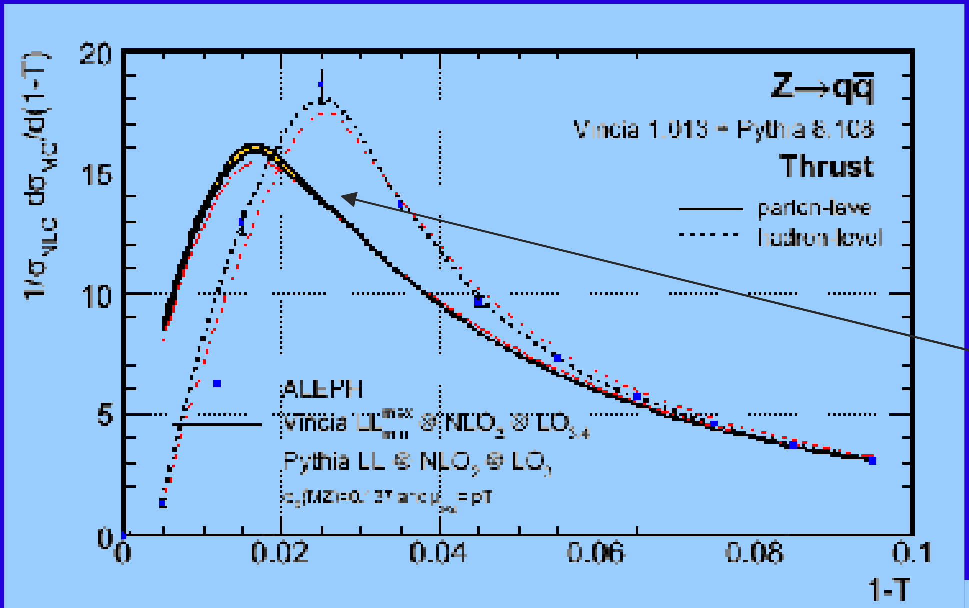
Giele, Kosower, PS : hep-ph/0707.3652 + Les Houches 2007

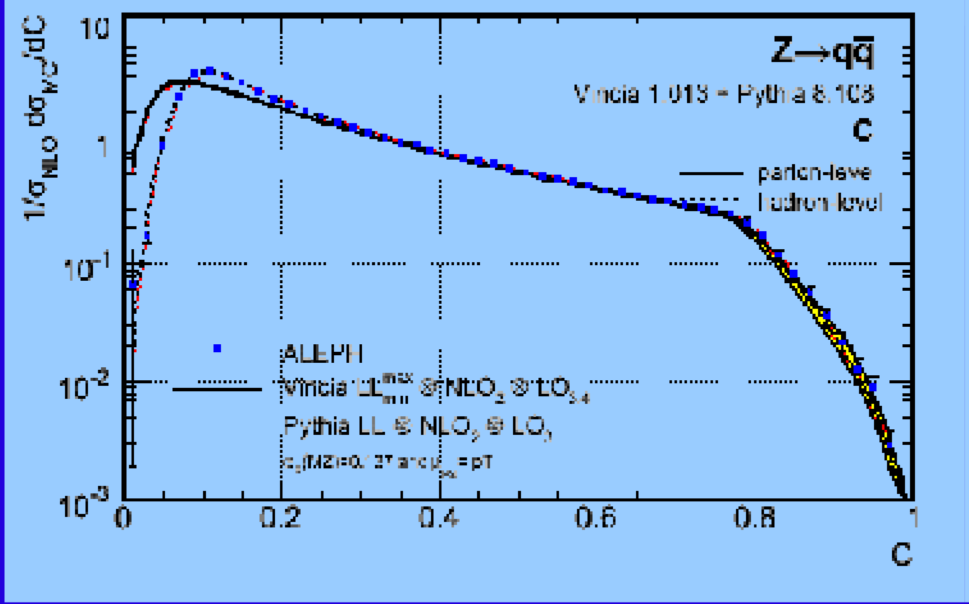
  - 3 different shower evolution variables:
    - pT-ordering (= ARIADNE ~ PYTHIA 8)
    - Dipole-mass-ordering (~ but not = PYTHIA 6, SHERPA)
    - Thrust-ordering (3-parton Thrust)
  - For each: an infinite family of antenna functions
  - Shower cutoff contour: independent of evolution variable
  - Several different choices for α_s (evolution scale, p_T, mother antenna mass, 2-loop, …)
  - Phase space mappings: 2 different choices implemented
    - Antenna-like (ARIADNE angle) or Parton-shower-like: Emitter + longitudinal Recoiler

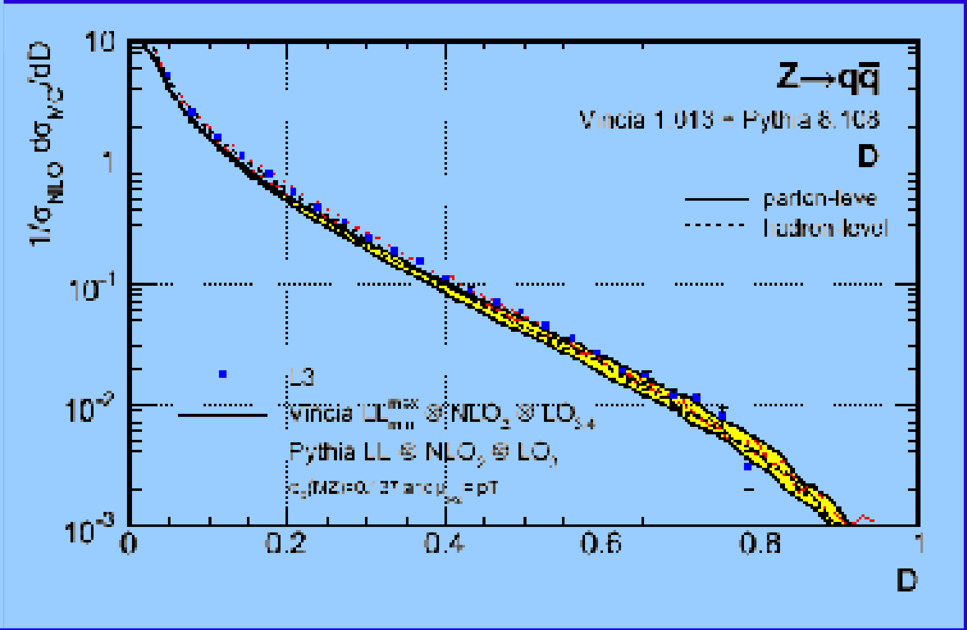


Dipoles (=Antennae, not CS) – a dual description of QCD

VINCIA in Action







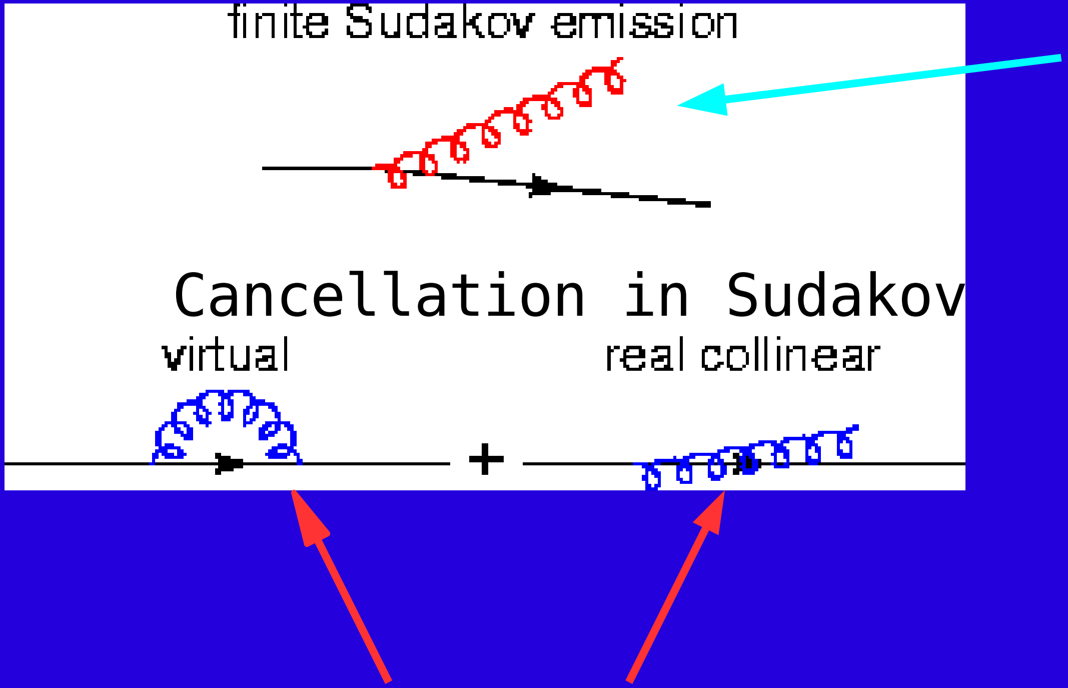
- Can vary
  - evolution variable, kinematics maps, radiation functions, renormalization choice, matching strategy (here just showing radiation functions)
- After 2nd order matching

➔ Non-pert part can be precisely constrained.

(will need 2nd order logs as well for full variation)

Giele, Kosower, PS : PRD78(2008)014026 + Les Houches 'NLM' 2007

NLO and Parton Showers



Piece of a parton shower prediction

Inside a NLO calculation

Methods for including PS corrections to NLO predictions must remove the overlap

Highly non-trivial: can depend on subtraction method, shower, etc.

In some cases, already covered by ME corrections in showers

MC@NLO, POWHEG, NL^3(e+e-) (Vincia)