QCD for the LHC

J. C. Bose Memorial Lecture

Keith Ellis
Fermilab

April 2011

Large Hadron Collider

12/16/1994

-Project approval

2008

– Accelerator complete

– Ring cold and under vacuum

• 9/10/2008

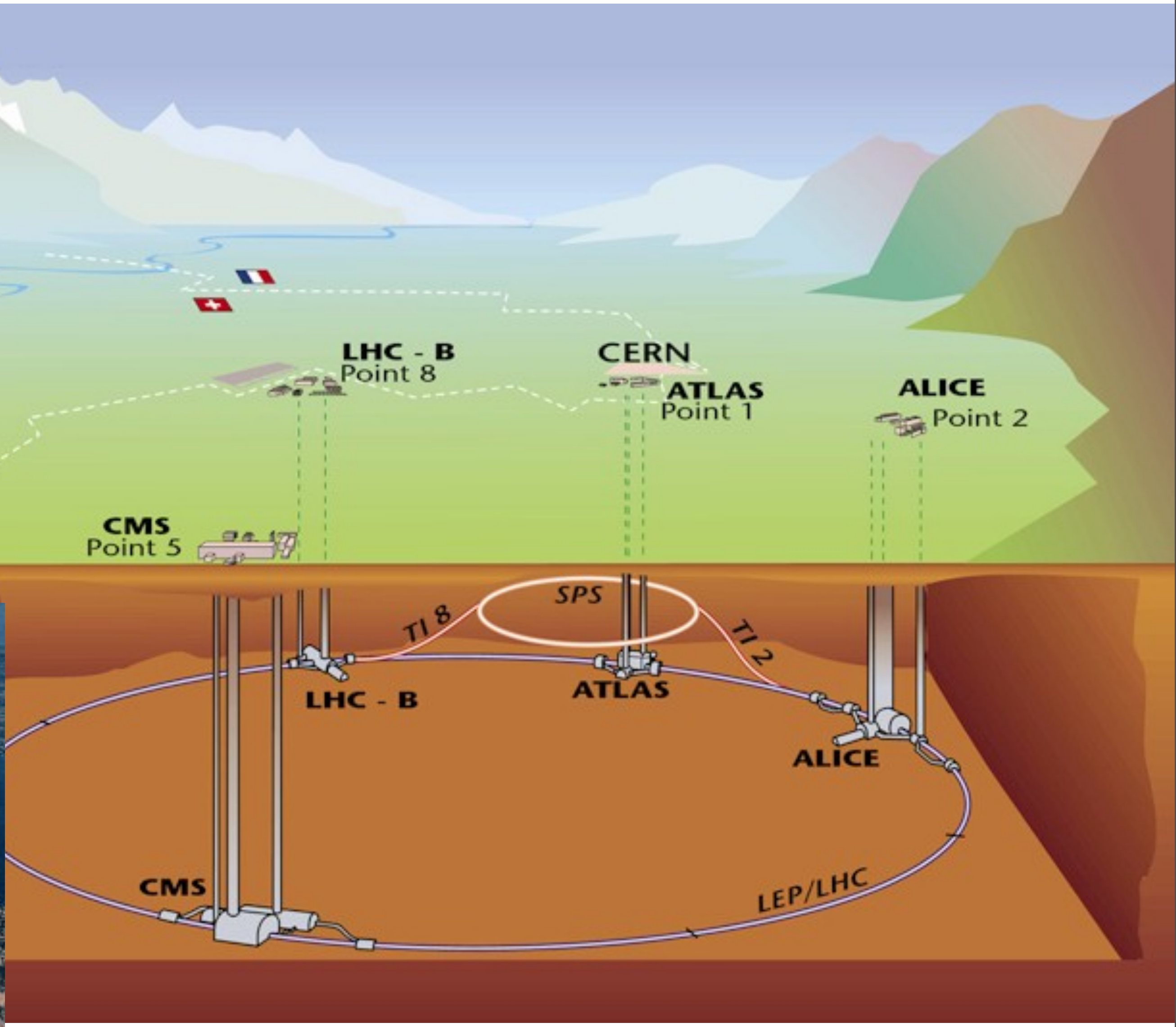
– First beams around

• 9/19/2008

– Machine damaged in incident

• 2008 – 2009

– 12 months of major repairs and consolidation



9/20/2009

– First beams around again

• 9/29/2009

– Both beams accelerated to 1.18 TeV simultaneously

•10/8/2009

– First collisions at 2.36 TeV cm!

•2010/2011

– ~50+26pb^{-1} accumulated luminosity at $\sqrt{s}$=7 TeV

LHC in numbers

	Tevatron (2011)	LHC 2011(2012)	LHC (2014<t<2030)
Beams	p-$\bar{p}$	p-p and Pb-Pb	p-p and Pb-Pb
Circumference [km]	6	26	26
c.o.m. Energy [TeV]	1.96	7(8)	~14
Luminosity [$cm^{-2}\ s^{-1}$]	1.00E+32	2.00E+32	5.00E+34
Projected Accumulated Luminosity [fb^{-1}]	10	1(5)	3000
Bunch spacing [ns]	392	75/50	25
Collisions/crossing	6	1-10	20
Number of collaborators (General purpose detectors)	~300	~3000	??

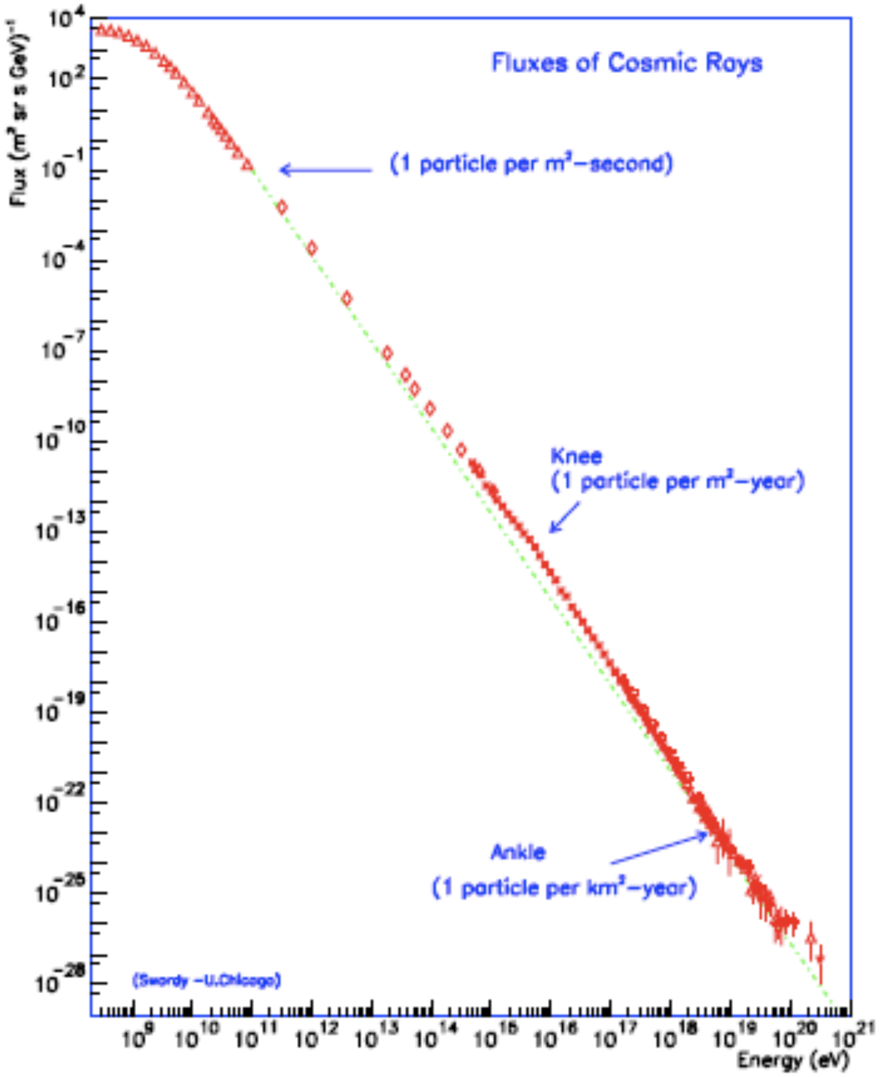
LHC collisions .. not new

$$E_{1,2} = 7\ \mathrm{TeV} \rightarrow s = (E_1 + E_2)^2 \sim 2 \times 10^8\ \mathrm{GeV}^2$$

The equivalent fixed target energy E_{FT} is

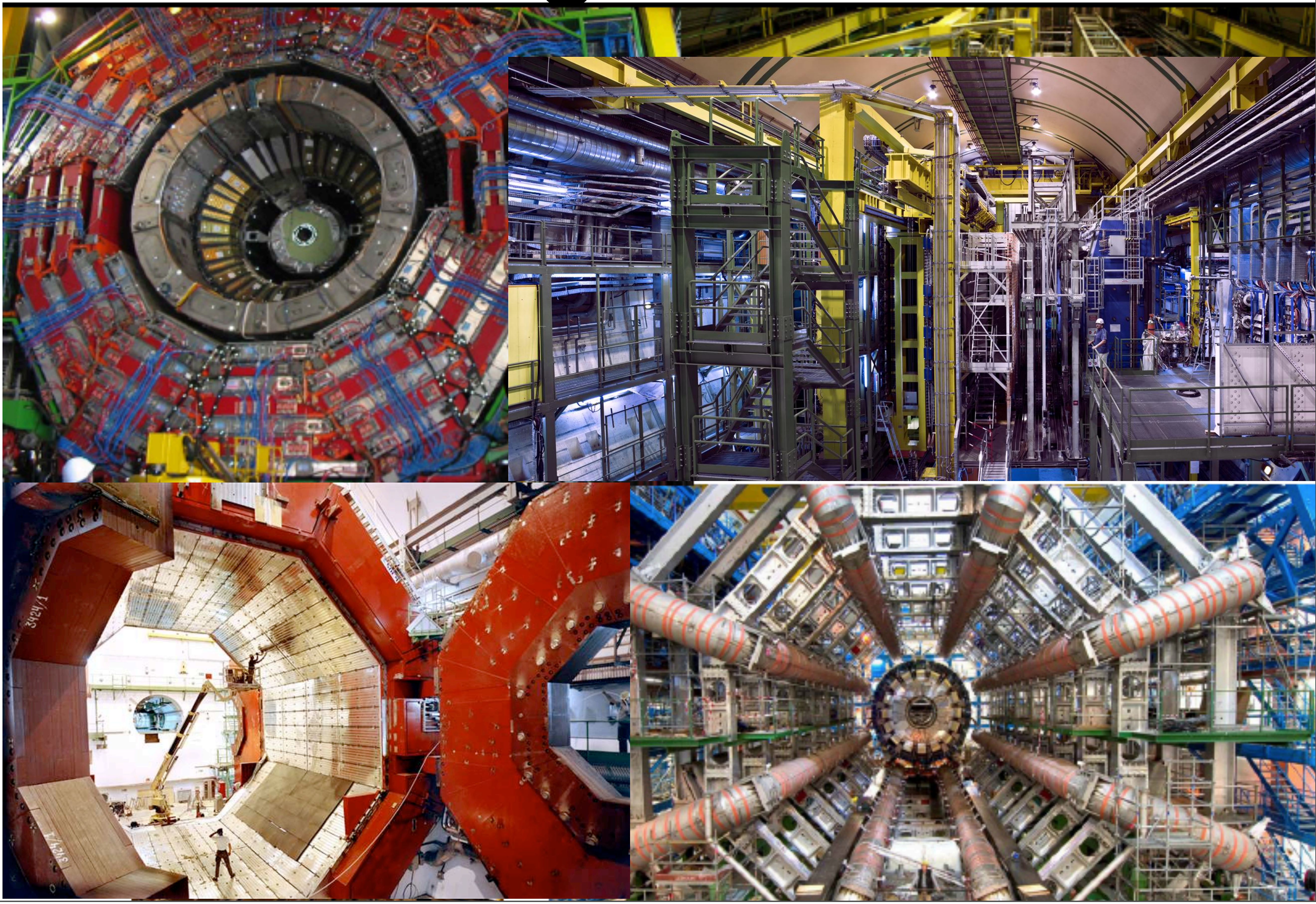
$$s = 2m_P E_{FT} \rightarrow E_{FT} = 10^8\ \mathrm{GeV} \equiv 10^{17}\ \mathrm{eV}$$

Energies above 10^{17} have been observed in cosmic rays.



What is new is the observation of these events in a controlled way by 4 sophisticated detectors.

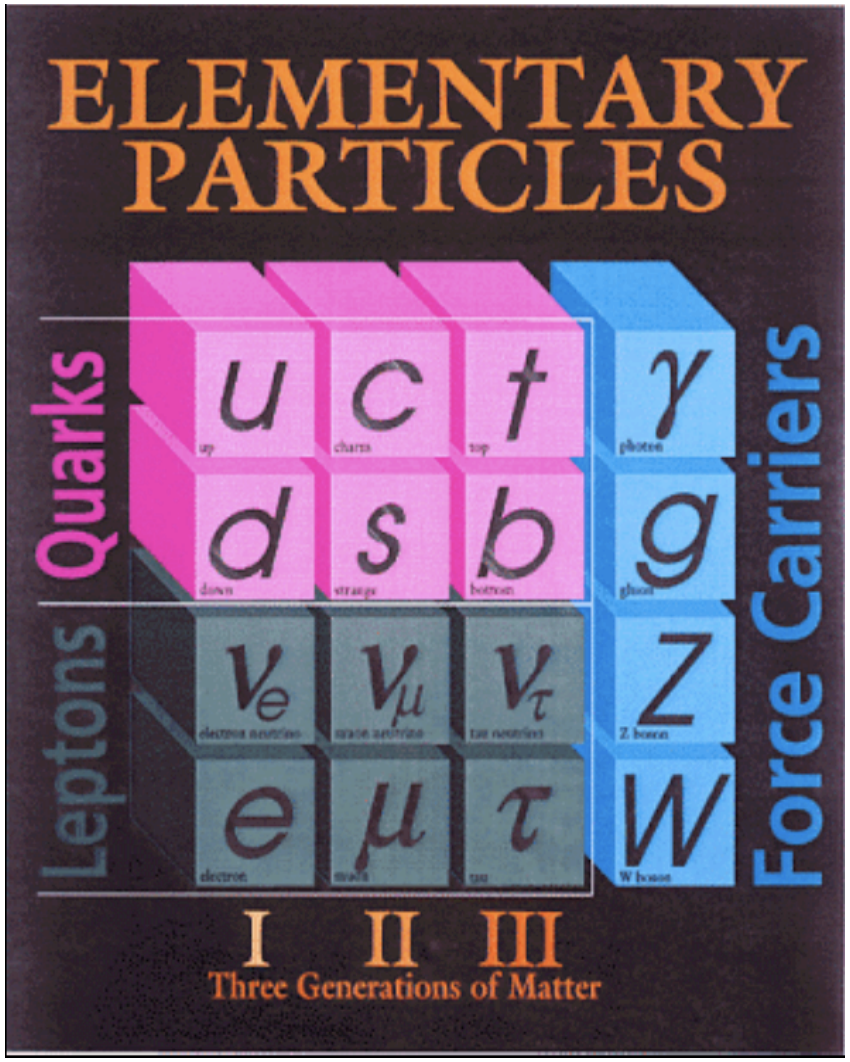
Four large detectors



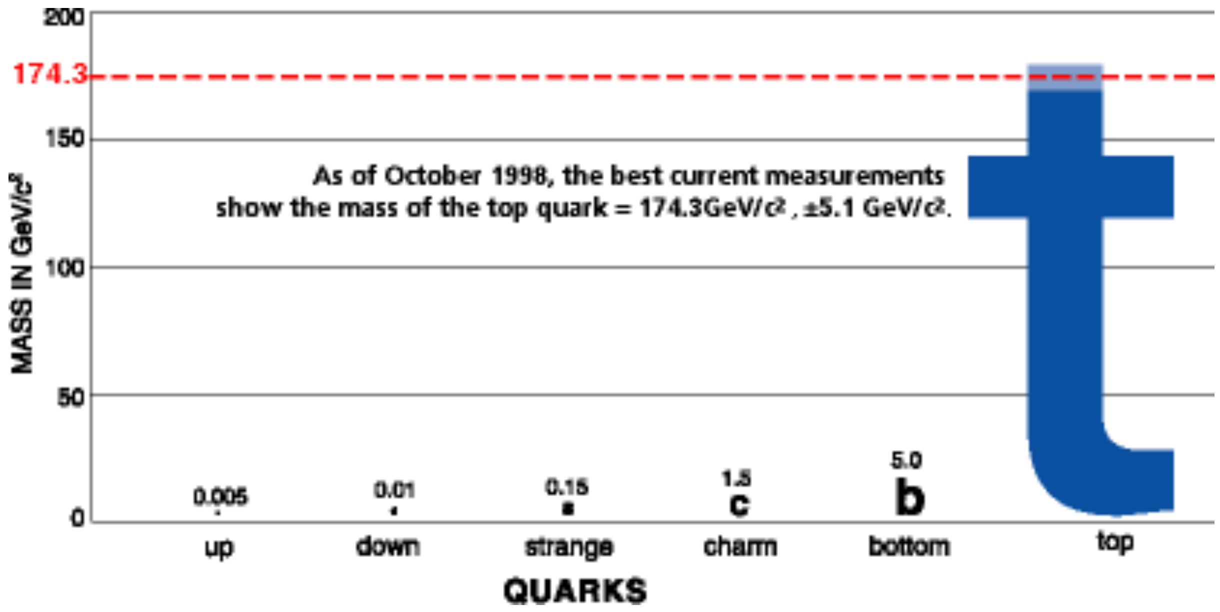
The detectors compared

- CMS is 12,000 tons (2 x ATLAS)
- ATLAS has 8 times the volume of CMS.
- ALICE is bigger than CMS and heavier than ATLAS, specialized for heavy ion physics.
- LHCb has the best instrumented coverage of the forward region, specialized for b-physics.

Bestiary of elementary particles



Masses of the six quarks



As of October 1998, the best current measurements show the mass of the top quark = 174.3GeV/c², ±5.1 GeV/c².

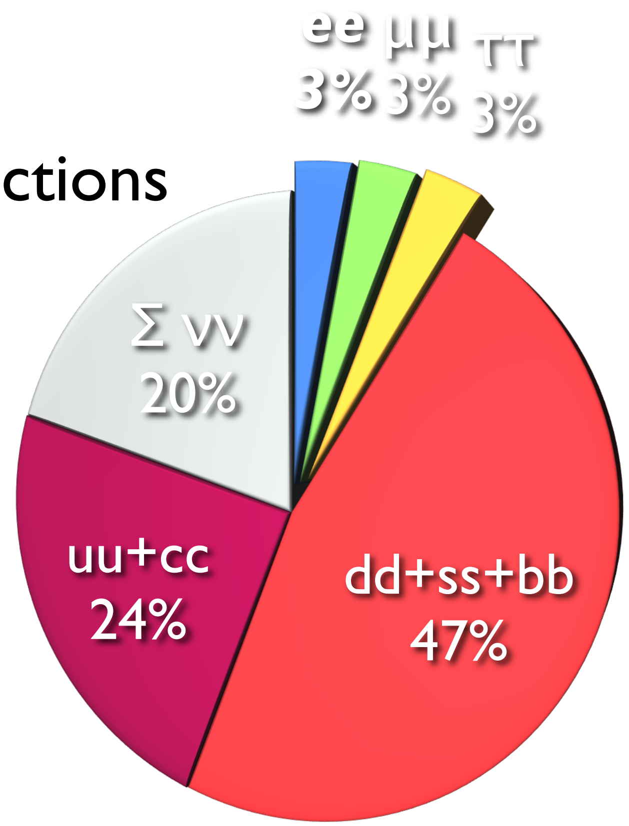
Mass of the Z-boson=91.1876±0.0021 GeV
Mass of the W-boson 80.413±0.048 GeV
Mass of the photon =0
(Mass of the proton 0.938 GeV)

Primary problem of particle physics - mechanism of EW symmetry breaking.

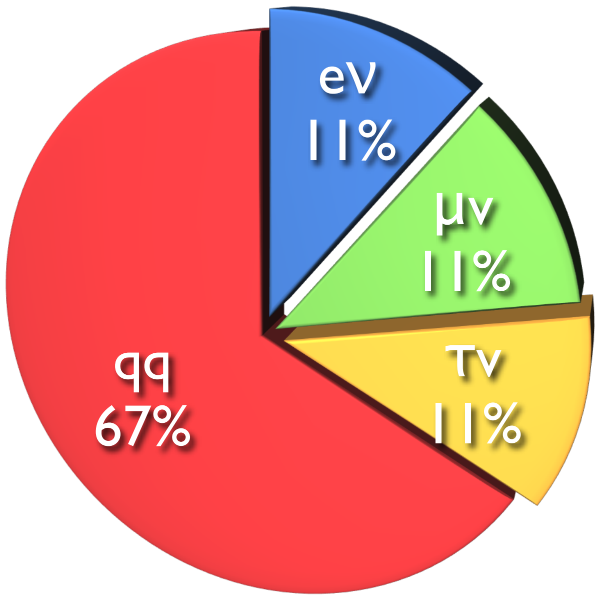
Decays of the Z and W

- W and Z decay by weak interaction.
- Z decays 20% of the time to neutrinos - the invisible width.
- Z has a 3.4% branching ratio into each type of charged lepton.
- W has an 11% branching ratio into each flavour of lepton neutrino.
- The remaining decays are to quarks.

Z branching fractions



W branching fractions



A triumph of 20th century physics: Standard model

$SU(3) \otimes SU(2)_L \otimes U(1)$

QCD QEW

Three couplings $g_S, g_W, g_{W'}$

Three families of quarks
Each quark comes in three colours

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

Eight colours of self-coupled gluons ***A***

$$F^A_{\alpha\beta} = \left[\partial_\alpha \mathcal{A}^A_\beta - \partial_\beta \mathcal{A}^A_\alpha - g f^{ABC} \mathcal{A}^B_\alpha \mathcal{A}^C_\beta\right]$$

The QCD Lagrangian has a familiar form, similar to QED, but the self coupling of the gluons, leads to a different behaviour of the coupling.

$$\mathcal{L} = -\frac{1}{4} F^A_{\alpha\beta} F^{\alpha\beta}_A + \sum_{\text{flavours}} \bar{q}_a (i\not{D} - m)_{ab} q_b$$

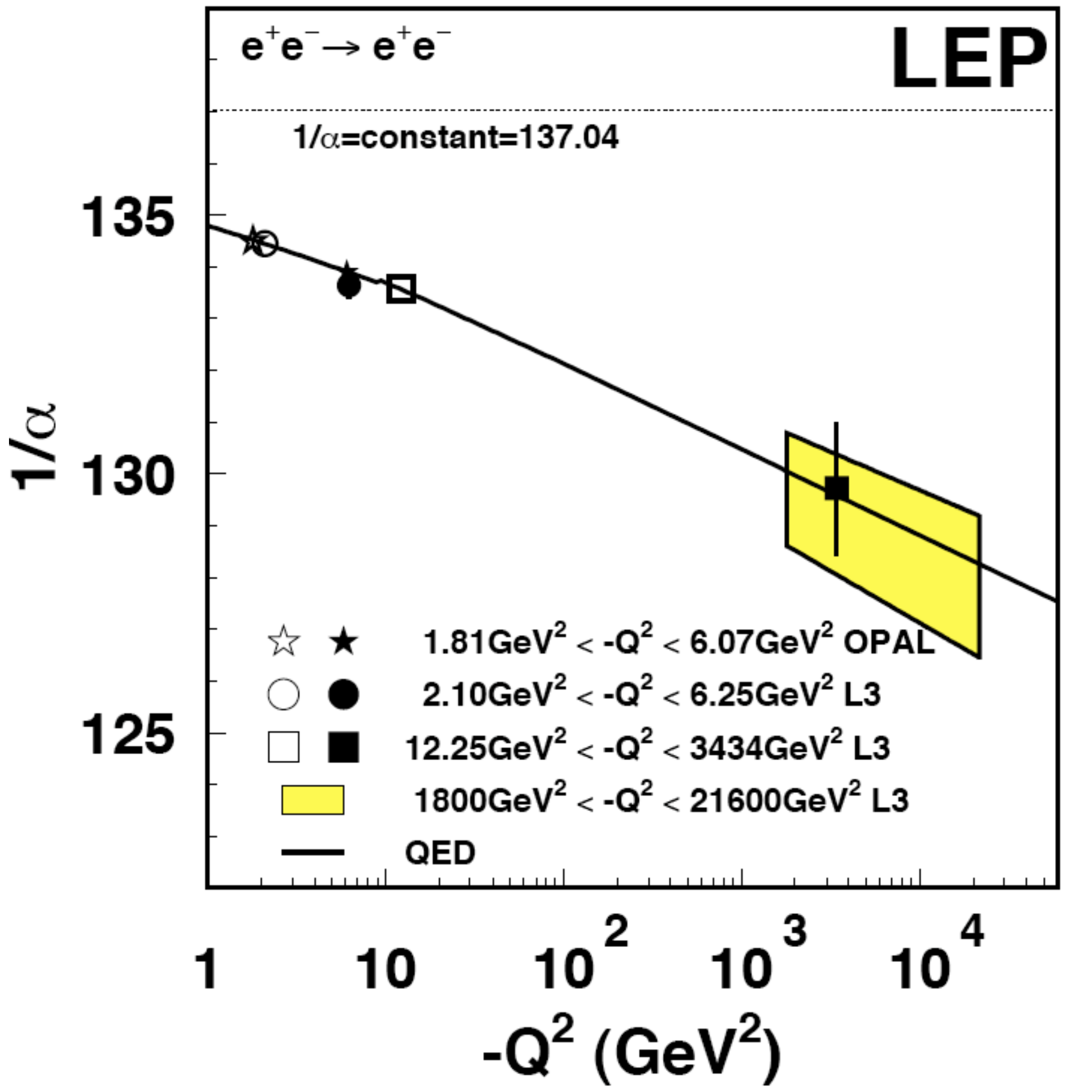
Charge screening in QED

The expected behaviour of the electromagnetic coupling is confirmed by experiments on Bhabha scattering at LEP.

$$\alpha = \frac{e^2}{4\pi}$$

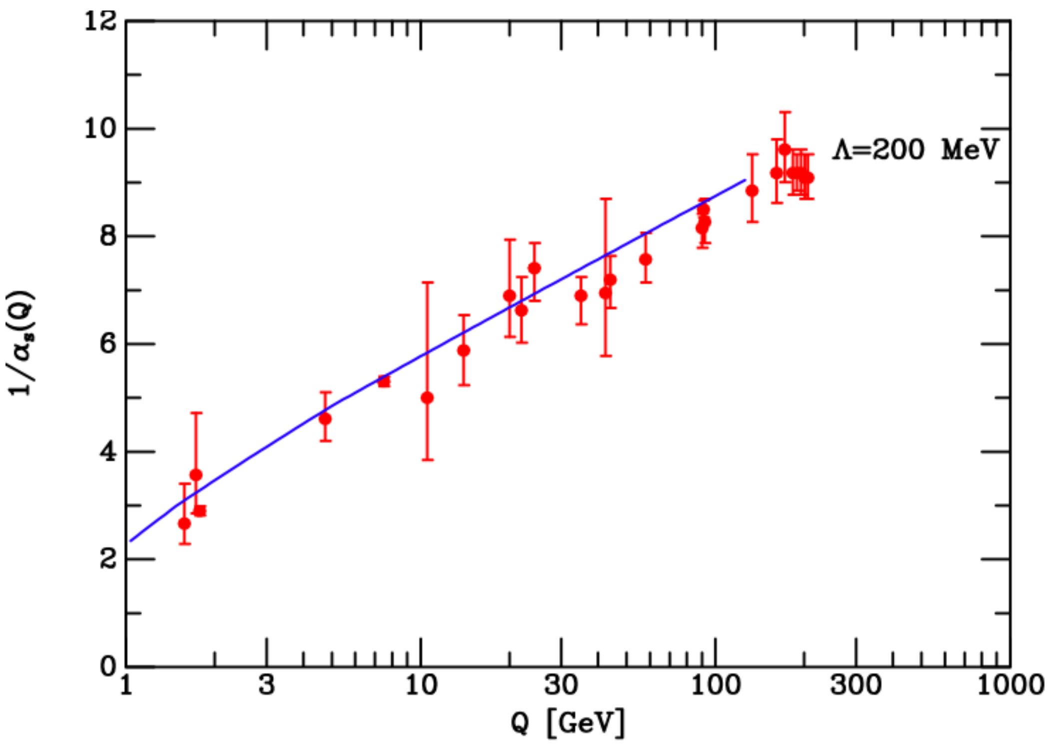
$$\frac{1}{\alpha(Q)} = \frac{1}{\alpha_0} - \frac{2Q_f^2}{3\pi}\ln\left(\frac{Q}{m_f}\right)$$

Mele,hep-ex/0610037



Charge anti-screening in QCD

QCD has the property of
anti-screening because of
the self-interaction of the gluons



Quark anti-quark pairs screen as in QED,
but gluons lead to anti-screening.

$$\alpha_s = \frac{g_s^2}{4\pi}$$

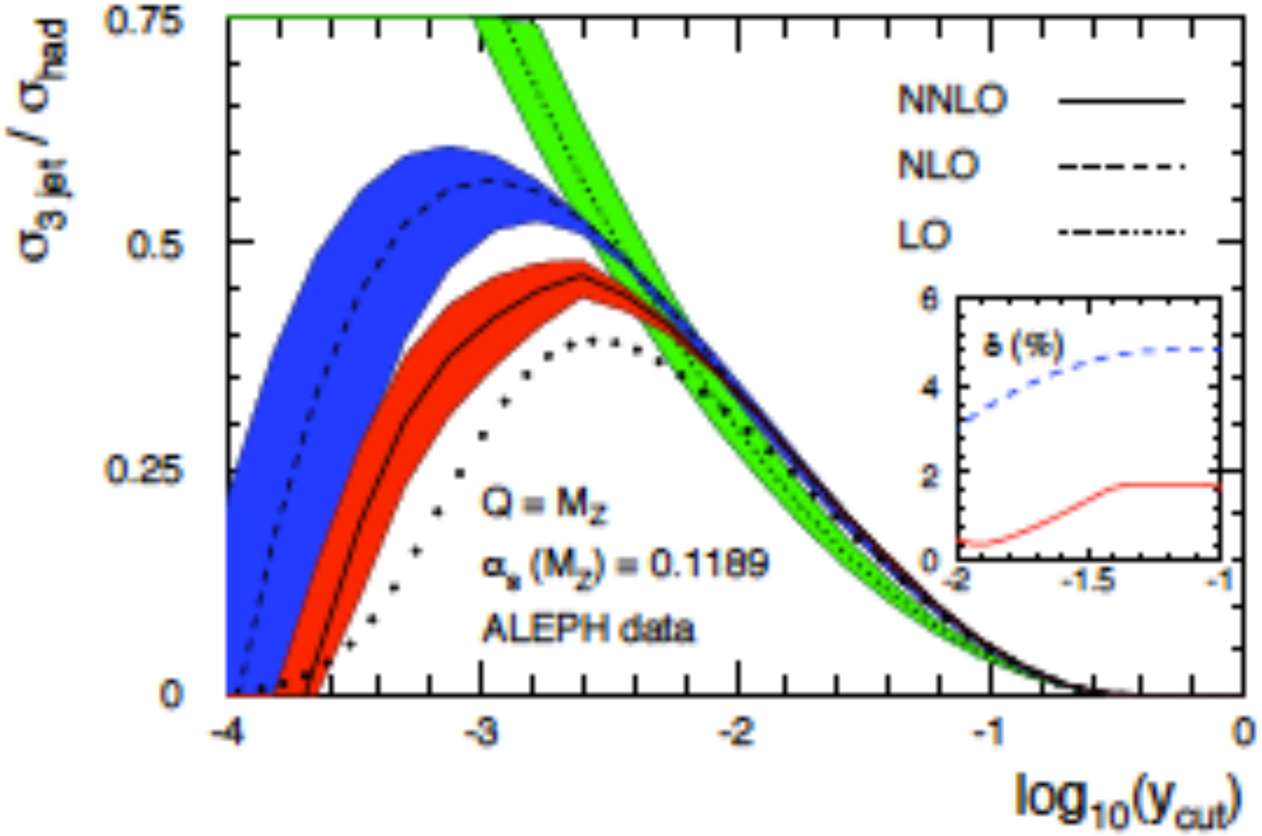
$$\frac{1}{\alpha_S(Q)} = \frac{(33 - 2n_f)}{6\pi} \ln\frac{Q}{\Lambda} + \ldots$$

This is the phenomenon of asymptotic freedom.
Since the coupling is small at high energy we may use the
methods of perturbation theory.

Measurement of α_s at high energy

e.g. from three-jet rate

Dissertori et al, 0910.4283

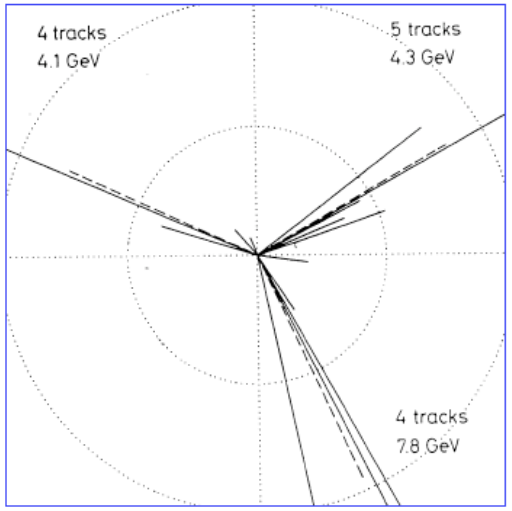


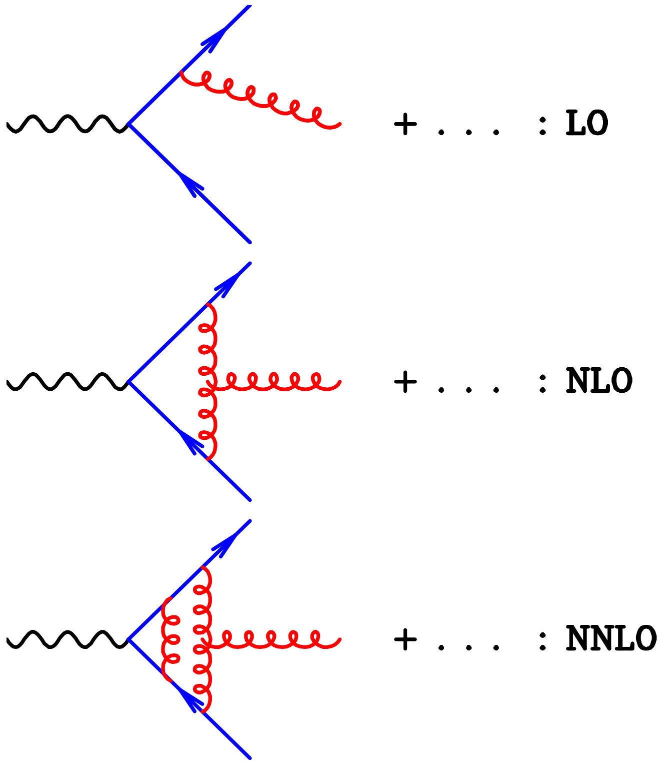
requires a jet definition

fit at y_{cut} =0.02

α_s = 0.1175±0.0020(exp)±0.0015(th)

An early three jet event from Tasso (1979)





Results for αs

The strong coupling at the scale M_Z is known to about 1%.

2009 World average

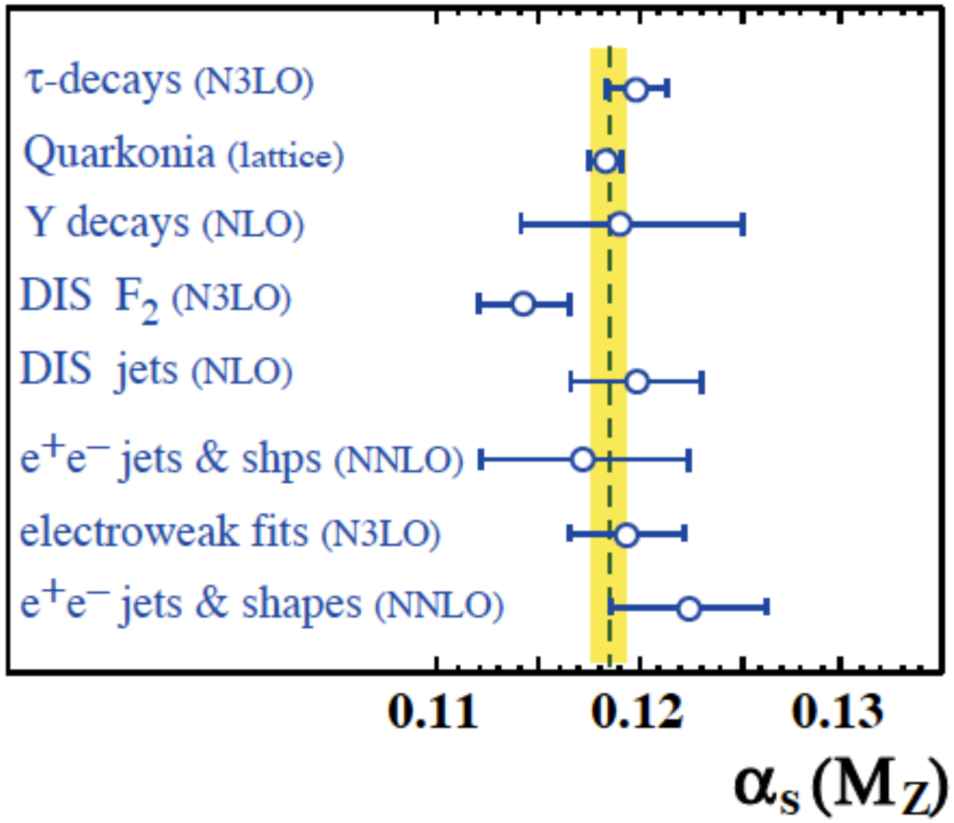
$\alpha_s(M_z) = 0.1184 \pm 0.0007$

Currently the most precise value of α_S comes from interpreting low energy measurements using lattice QCD.

The most precise high energy value is from jets and event shapes in e^+e^- annihilation.

The error on α_S will not be the dominant error in making predictions for LHC.

Bethke, arXiv:0908.1135



$\alpha_s(Mz)$ is smallish, but 16 times bigger than $\alpha_{QED}(Mz)$

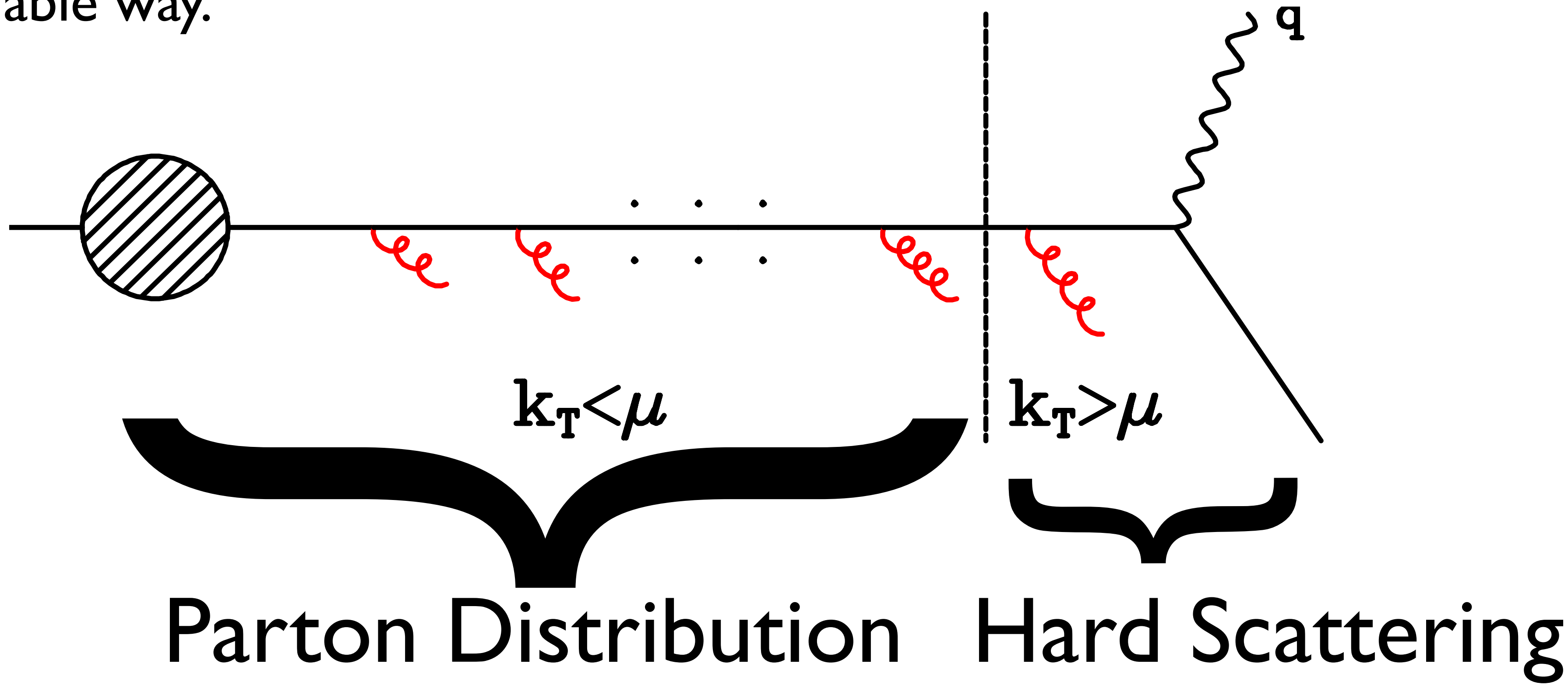
⇨ radiative corrections will be even more important than they are for QED

The standard model and the proton

- We wish to use the standard model to describe the physical world composed of protons, pions, and kaons etc. Quarks and gluons are not observed as asymptotic states.
- The binding of quarks and gluons into protons is a non-perturbative problem, most systematically described by lattice gauge theory.
- Surprisingly, a large class of processes at high energy can be described by perturbative methods, akin to those used with such success in QED.
- a) IR safe quantities such as jet cross sections, which are insensitive to soft and collinear radiation (such as e^+e^- 3-jet cross section)
- b) Quantities in which we can separate the high and low energy parts (factorizable quantities).

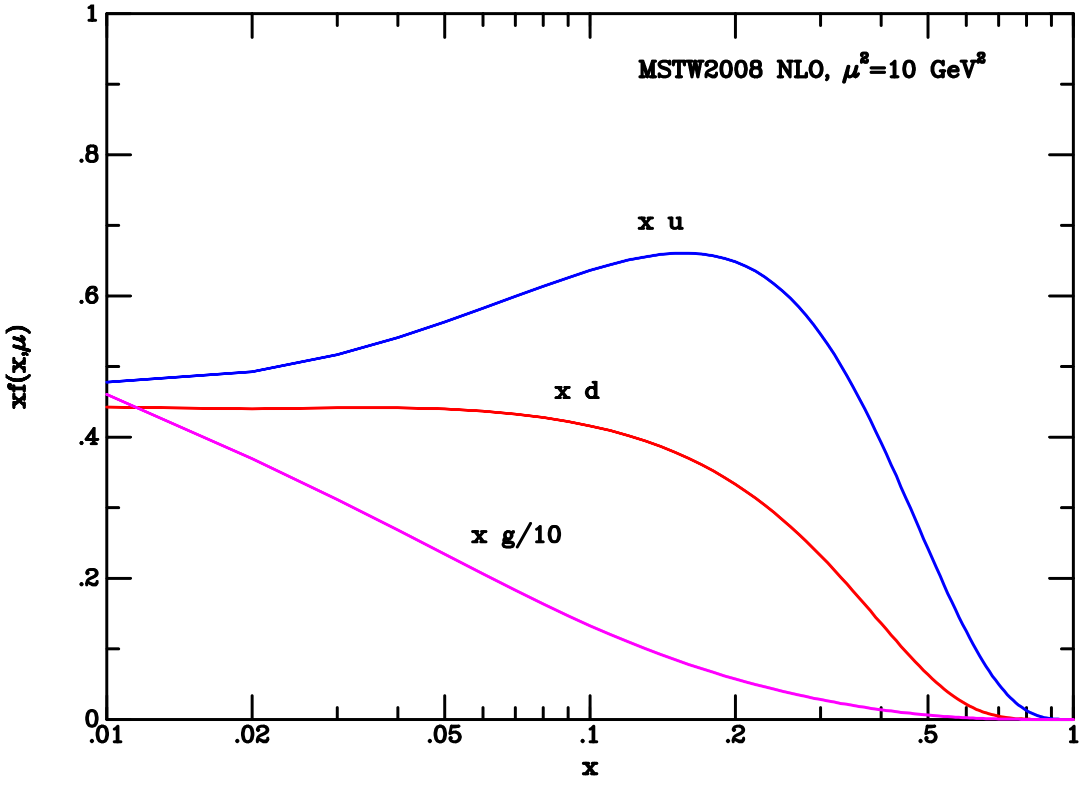
Factorization

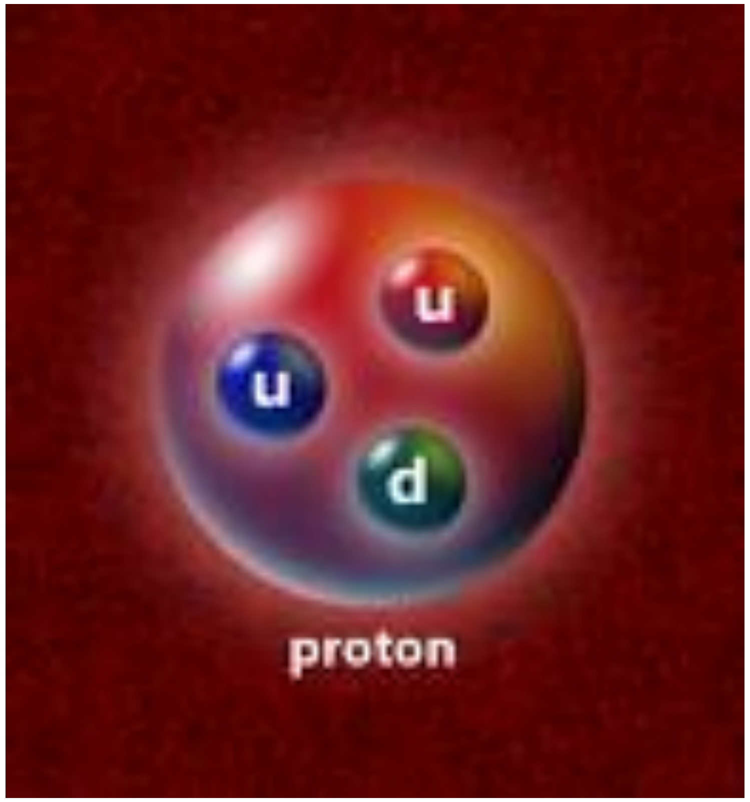
- Approach to deal with quantities which are IR sensitive.
- General idea is to factorize process independent low energy pieces into a lumped parameter which can be measured in one process and applied in another
- We have to introduce a factorization scale μ to separate the low energy and high energy parts.
- The lumped parameter (the parton distribution function) depends on μ in a calculable way.



Proton structure

The lumped parameter is the parton distribution function. x is the fraction of the longitudinal momentum of the proton carried by a quark.

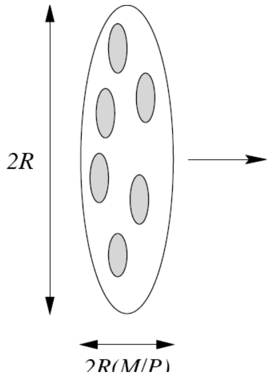




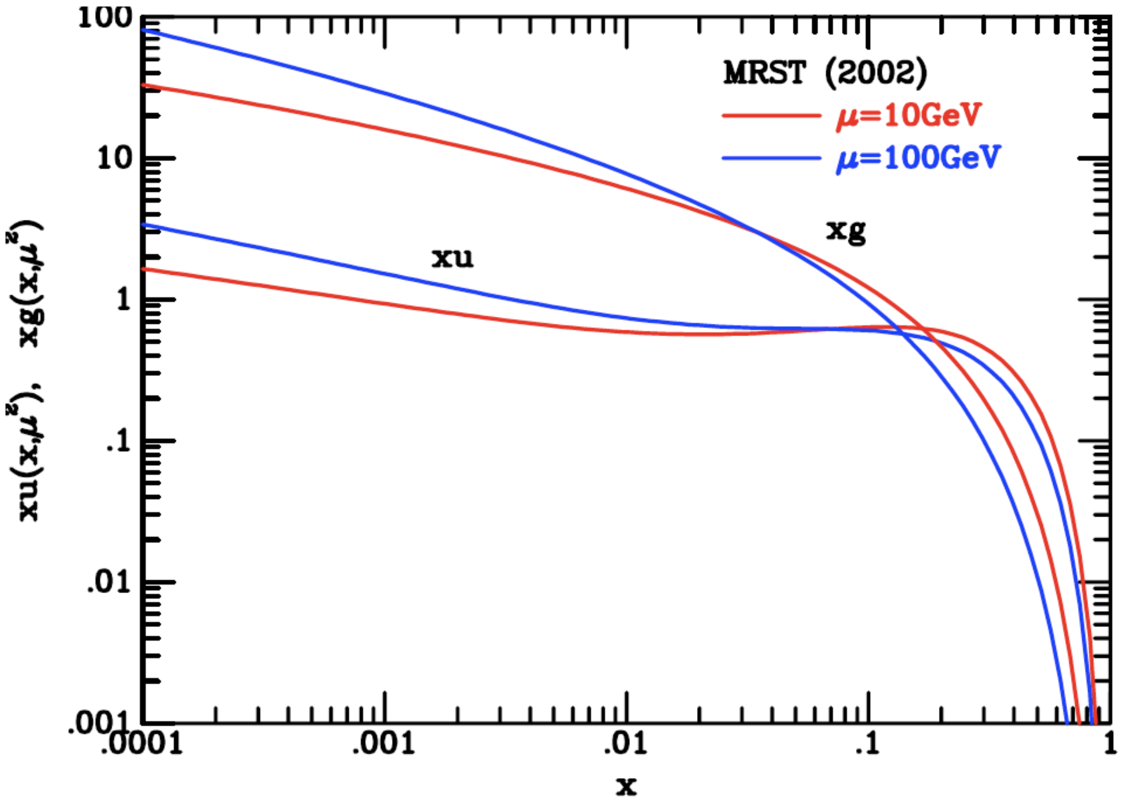
If we consider the proton to be made up of 3 quarks which carry half the momentum of the proton, the average momentum fraction per quark is <x>=1/6. Therefore (on average):-
The Tevatron gives us q-qbar collisions at the mass scale ~330 GeV and the LHC@14TeV will give us q-q collisions at the mass scale ~2.3 TeV.

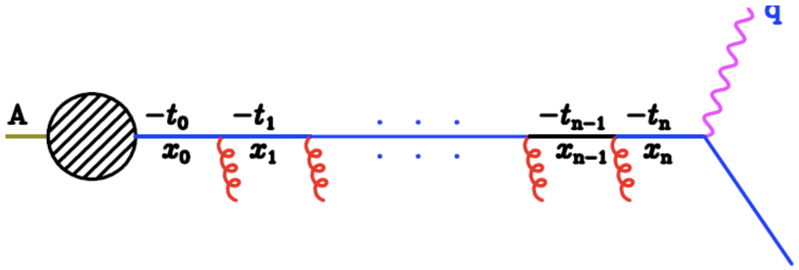
The evolution of partons within the proton

At low resolution (small) a high energy proton can be viewed as a dilute system of partons.



As we observe the proton with higher resolution (increasing μ) the number of partons grows, in a calculable way.

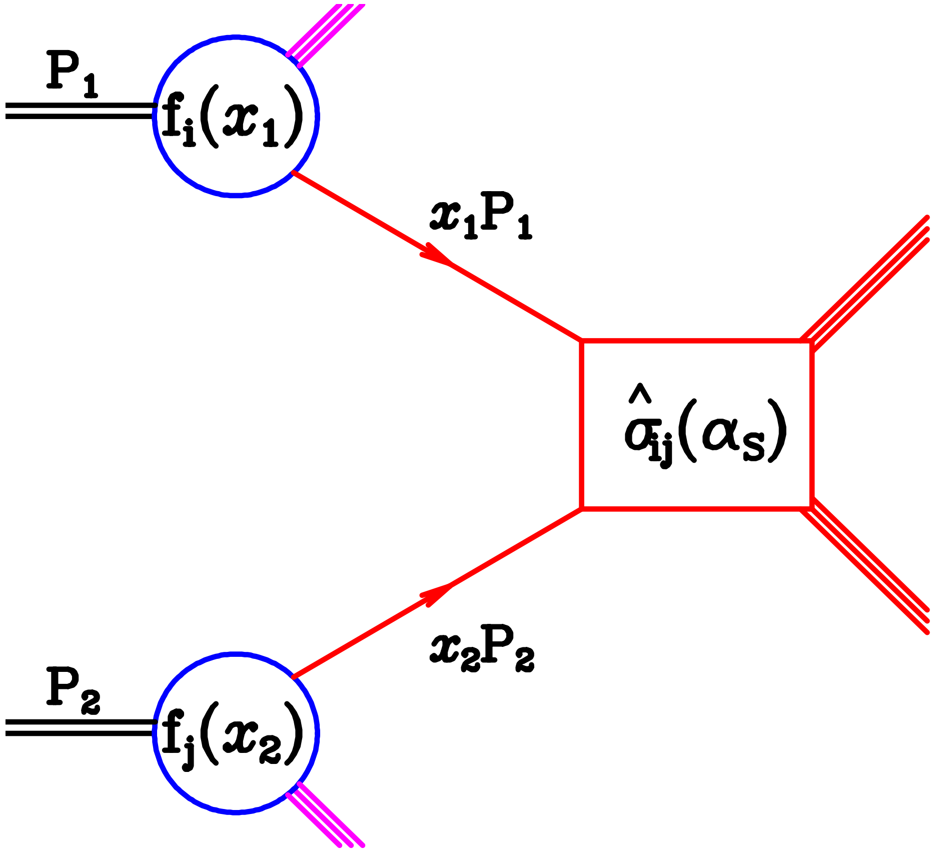




Parton shower

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 μF and μ R



$$\sigma(P_1,P_2)=\sum_{i,j}\int dx_1dx_2\; f_i(x_1,\mu_F)f_j(x_2,\mu_F)\;\hat{\sigma}_{ij}(p_1,p_2,\alpha_S(\mu_R),Q^2,\mu_R,\mu_F).$$

Physical cross section

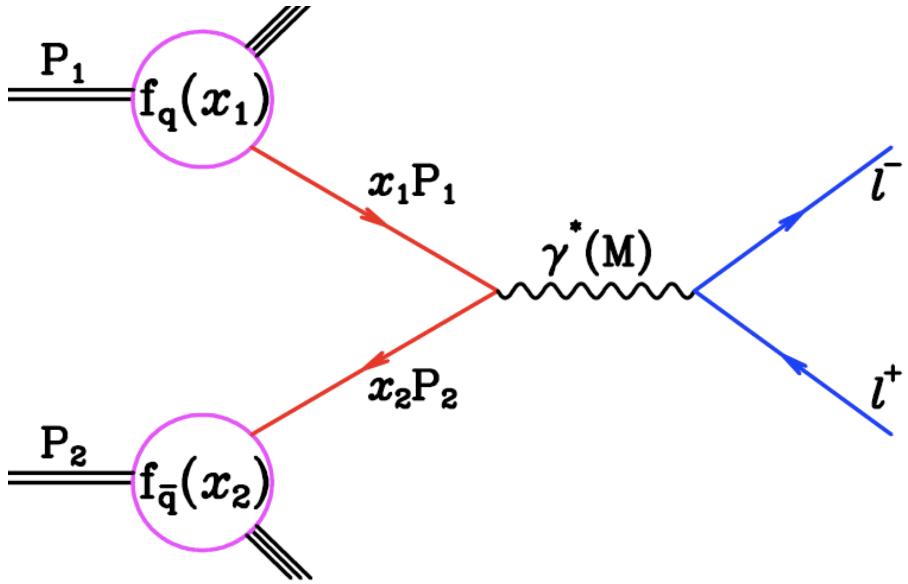
Parton distributions

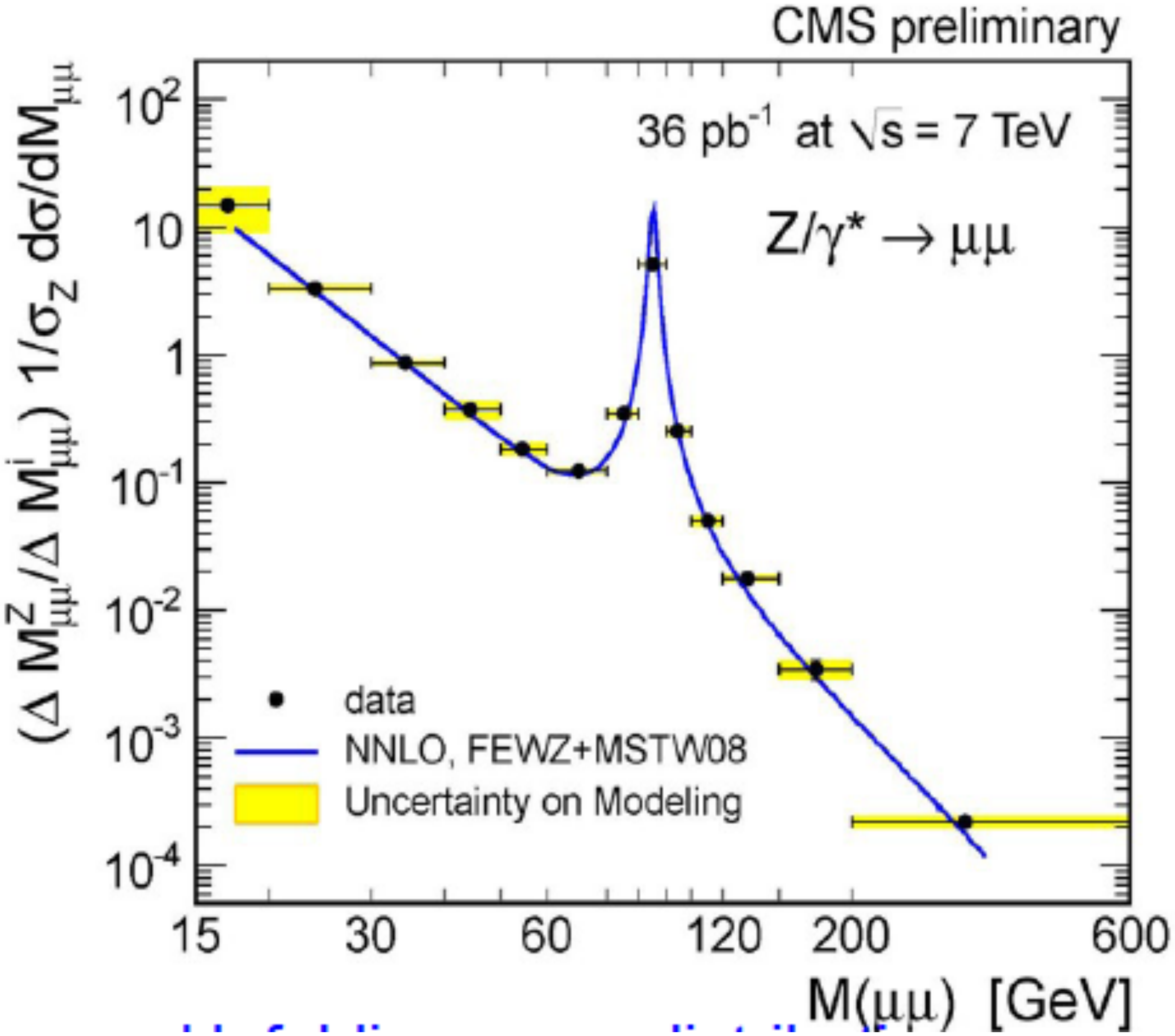
Strong Coupling

short-distance cross section σ in LO,NLO,...

Lepton pair production

This is the simplest process we can consider with two incoming hadrons.





$$(x_1P_1+x_2P_2)^2 \approx x_1x_2\, S=M^2$$

$$z=M^2/s$$

Drell-Yan type processes (γ*,W,Z)

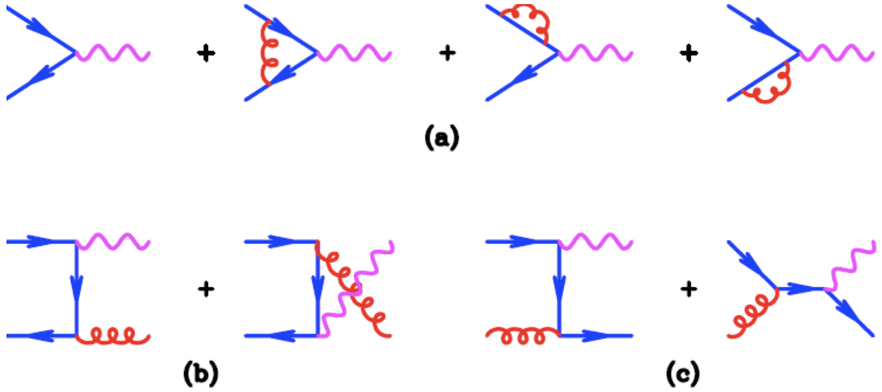
QCD provides a systematic way of improving the calculations of cross sections

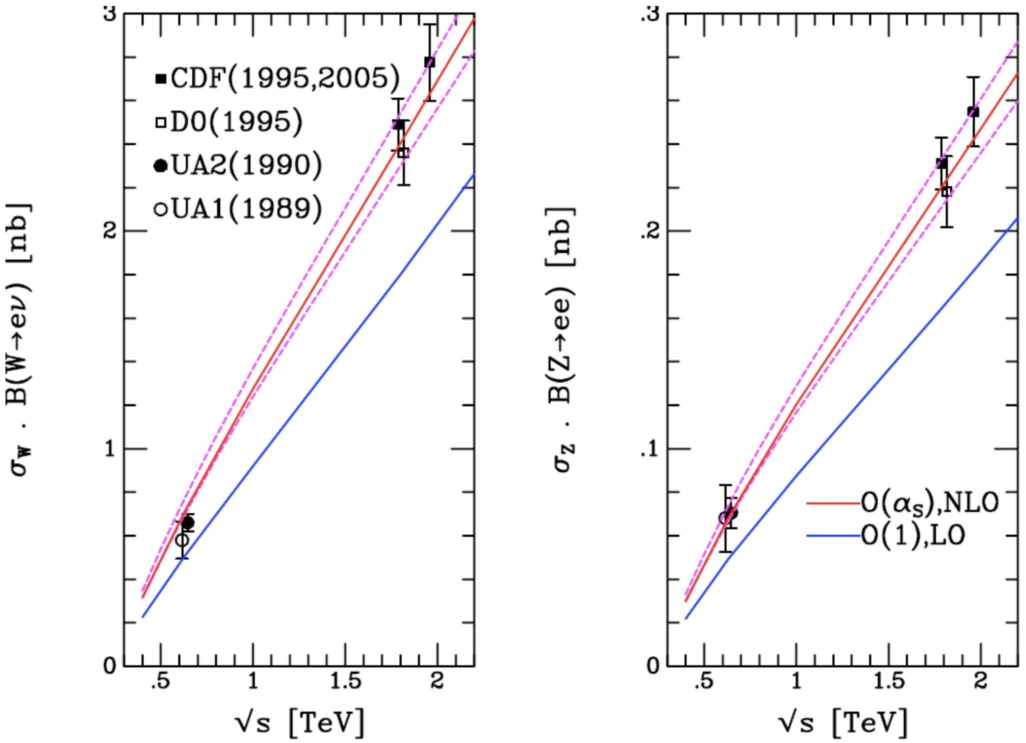
$$\hat{\sigma}(z) = \delta(1-z) + \frac{\alpha_s}{2\pi} f_1(z) + \left(\frac{\alpha_s}{2\pi}\right)^2 f_2(z) + \ldots$$

by expanding in the small coupling α_S. Corrections are large at $O(\alpha_S)$ but needed to needed to achieve agreement with data.

(α_S^2 corrections also known and lead to a further modest increase.)

Diagrams for NLO prediction



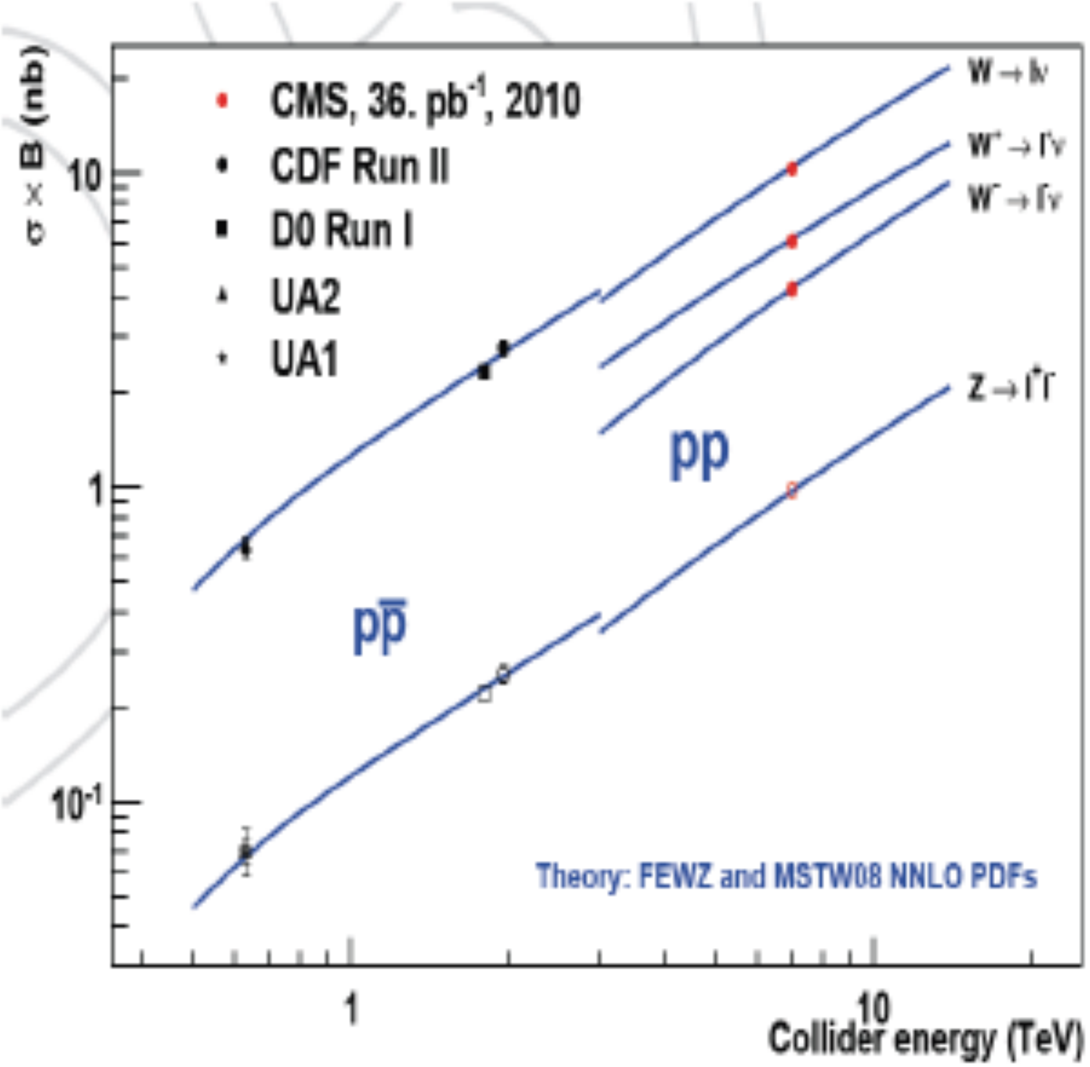


Moral: at least NLO corrections are needed.

W production

New

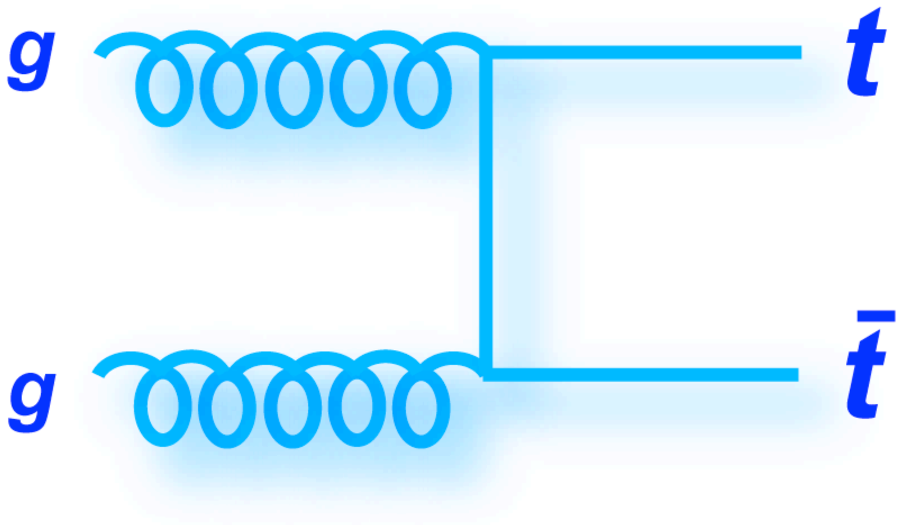
Results from $\sqrt{s}$=0.63 - 7 TeV

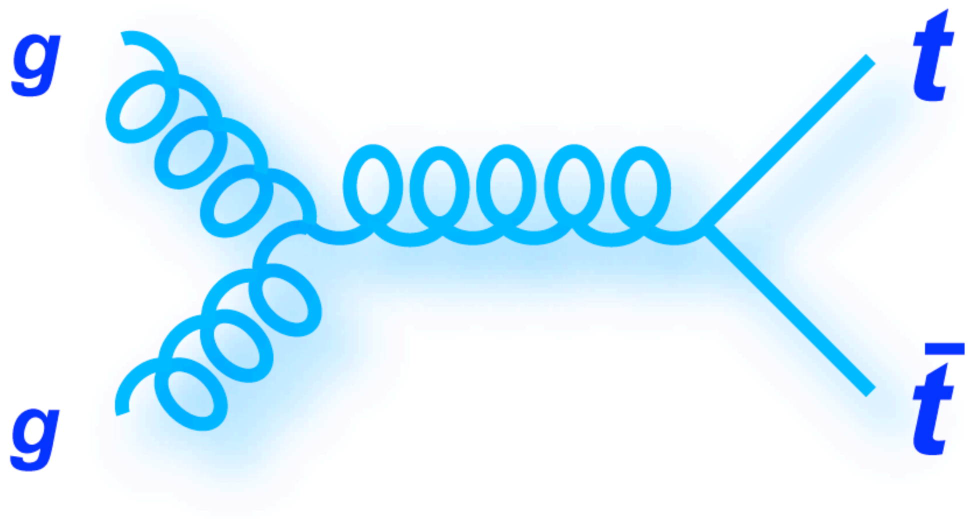


Stability of the perturbation series at $\sqrt{s}$=7 TeV

MSTW2008 (FEWZ)	LO	NLO	NNLO	Predominant Parton Process
$\sigma(W^+)\ .B(W^+ \to \nu e^+)$ [nb]	5.06	6.20	6.28	$u\bar{d}+\bar{d}u$
$\sigma(W^-)\ .B(W^- \to \nu e^-)$ [nb]	3.45	4.30	4.38	$d\bar{u}+\bar{u}d$

Top quark production

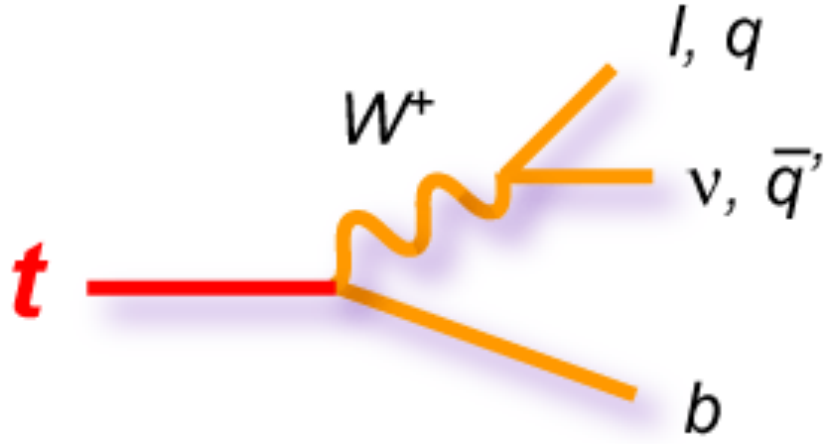




- At the LHC the top quark is produced mainly by gluon-gluon fusion (80% at 7TeV).
- The top quark has a mass of ~172 GeV, about the same as an atom of tungsten. QCD should work well for such a high mass scale.

Decay of the top quark

The top quark decays by a semi-weak process



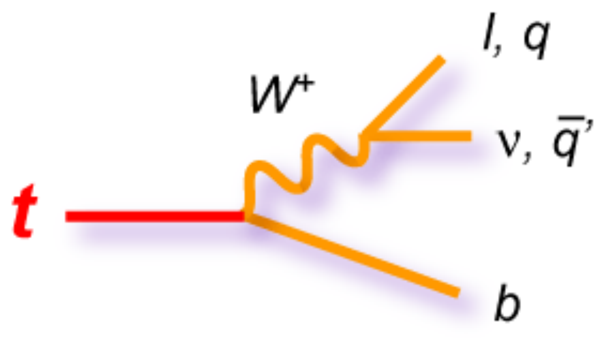
$$\Gamma(t \to bW^+) = \frac{G_F m_t^3}{8\pi\sqrt{2}} |V_{tb}|^2 \left(1 - \frac{M_W^2}{m_t^2}\right)^2 \left(1 + \frac{2M_W^2}{m_t^2}\right)$$

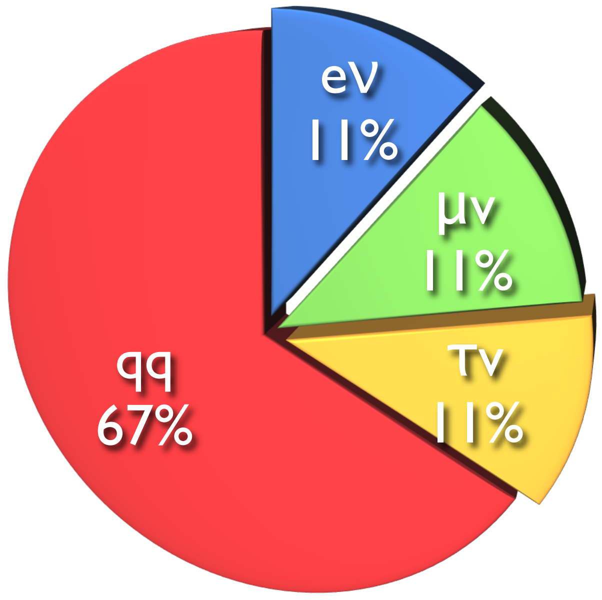
With three generations of quarks we can constrain the Cabibbo-like angle Vtb=0.9991±0.0003, so that for m_t=172 GeV and M_W=80.41 GeV

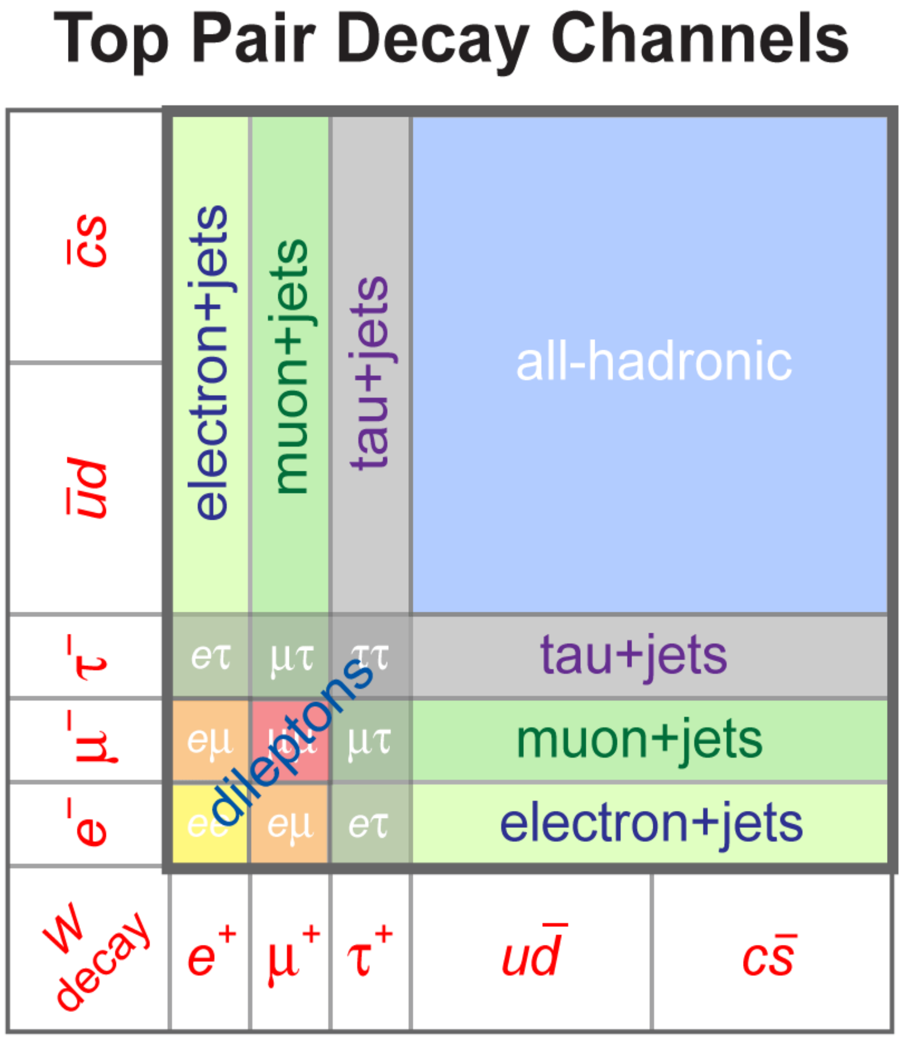
$$\Gamma(t \to bW^+) = 1.46 \text{ GeV} \Longrightarrow \tau_t = 0.45 \times 10^{-24} s$$

The time scale of top decay is shorter than a typical hadronic scale. The top quark decays before it has time to form hadrons.

Top pair decay





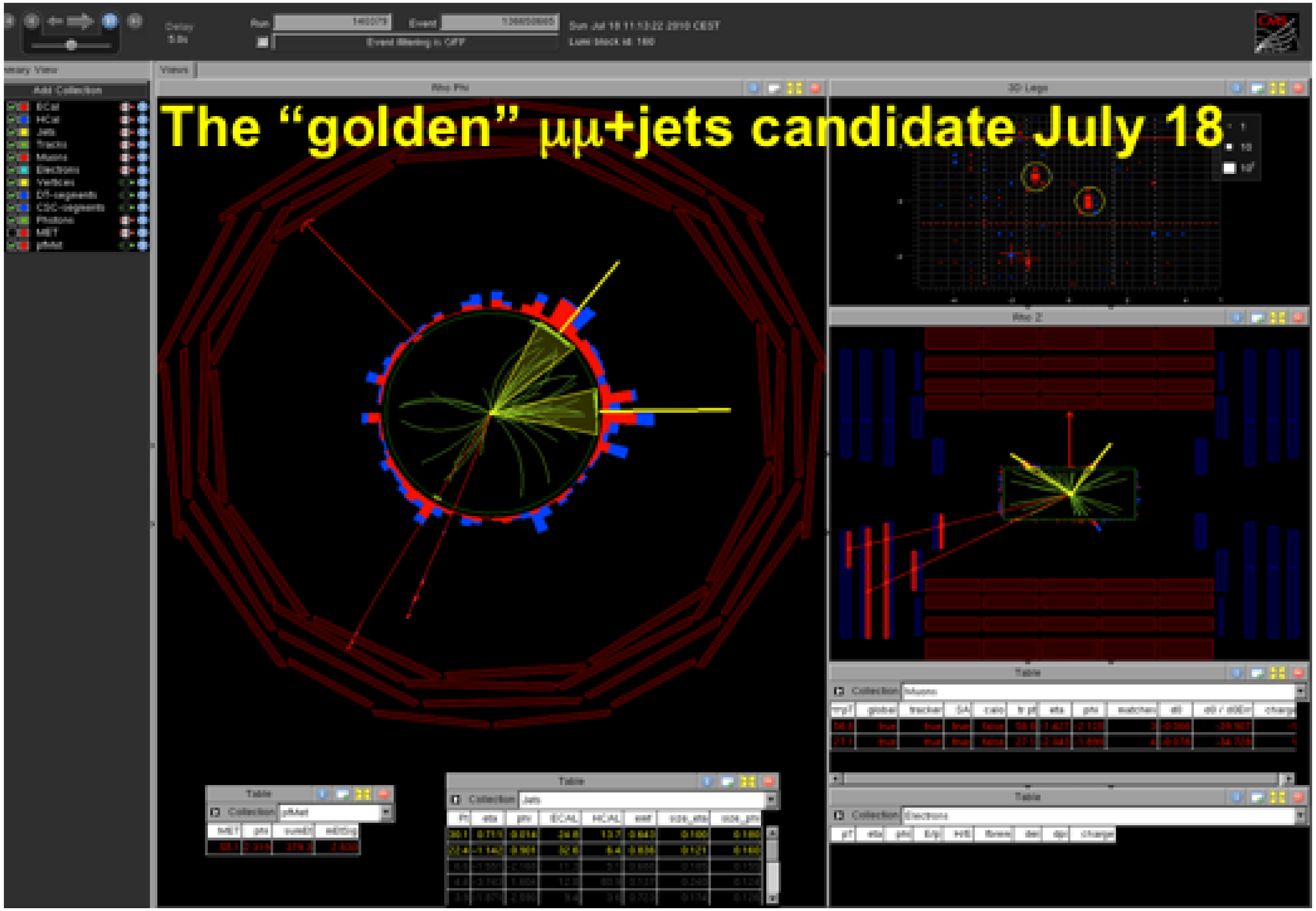

Top Pair Decay Channels

Top quark branching fractions are fixed by the decay modes of the W.

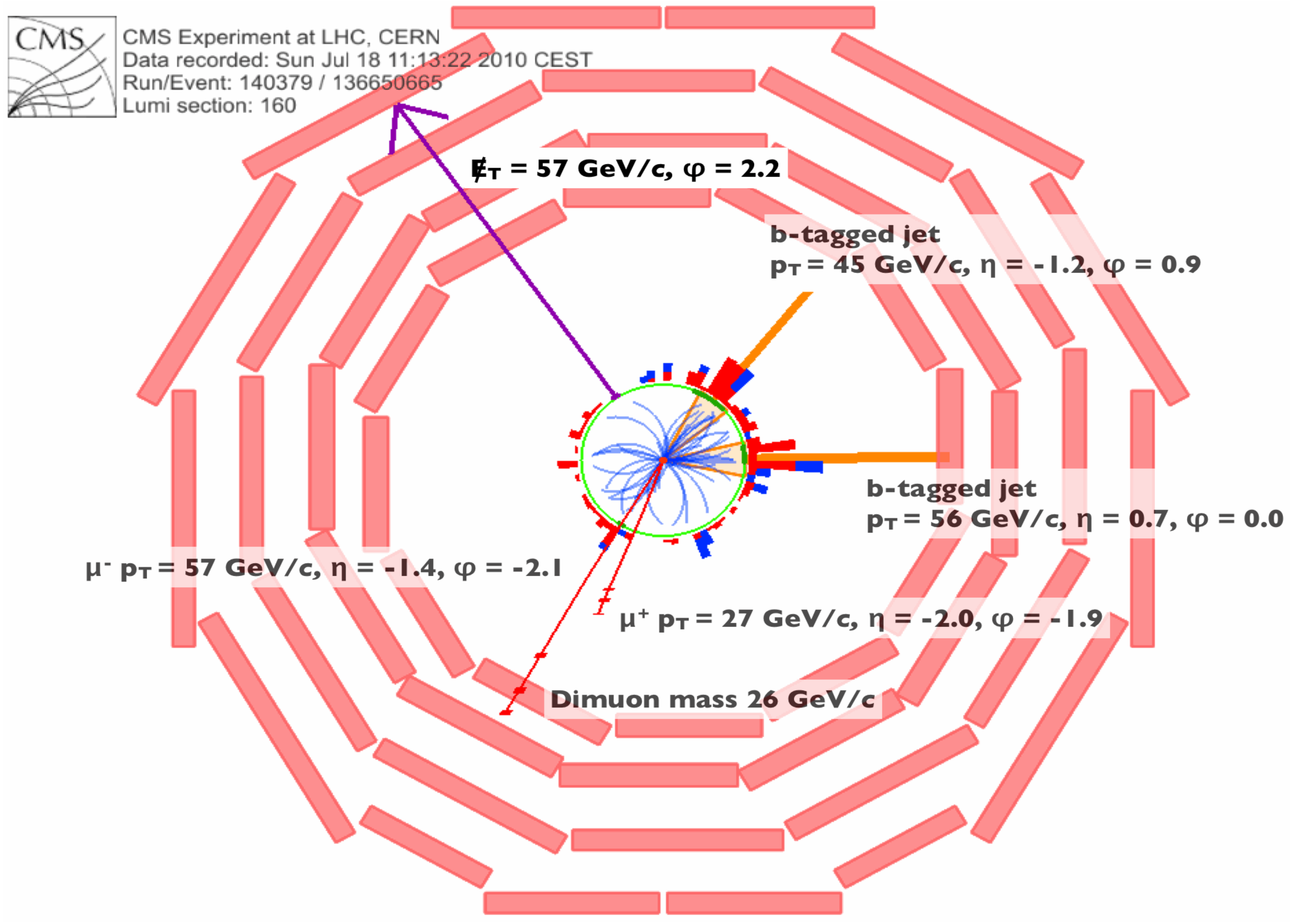
At the LHC (and Tevatron) the $t\bar{t}$ process is most easily observed in the lepton+jets, or dilepton channel.

Early top quark event at LHC (July 2010)

CMS@ICHEP: $\mu^+\mu^-$ + 2b-tagged jets + missing energy



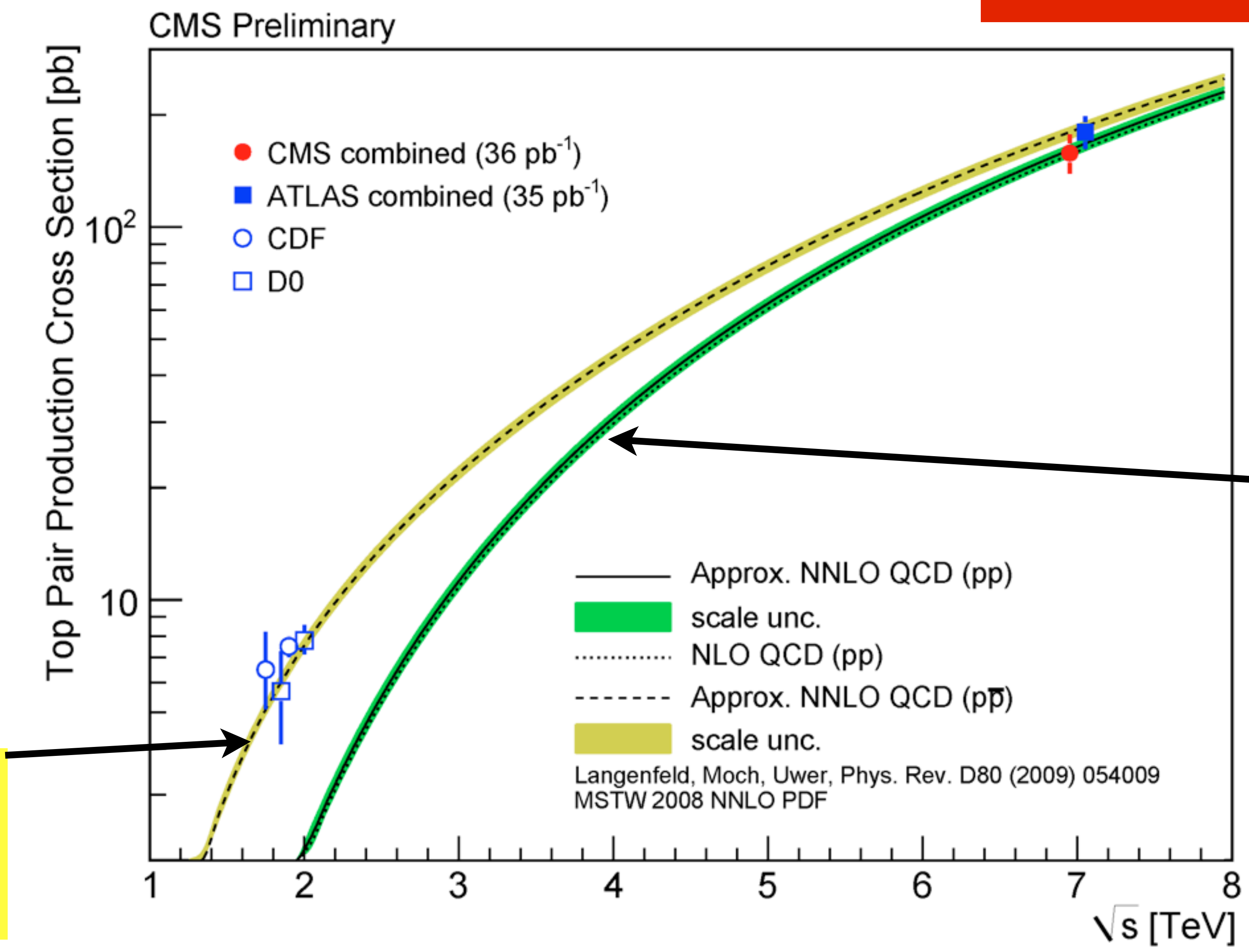
Alternative view of this event



Reconstructed mass is in the range 160–220 GeV/c^2 (consistent with m_{top})

Top quark cross section measurements at LHC

Theory curves similar to NLO prediction



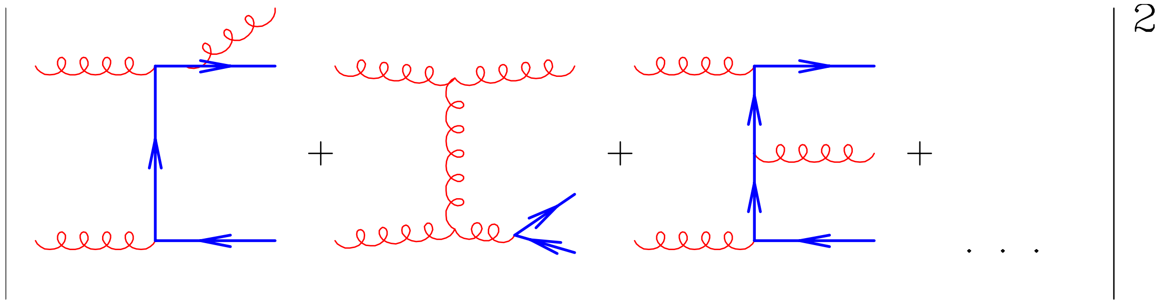
proton proton

proton anti-proton

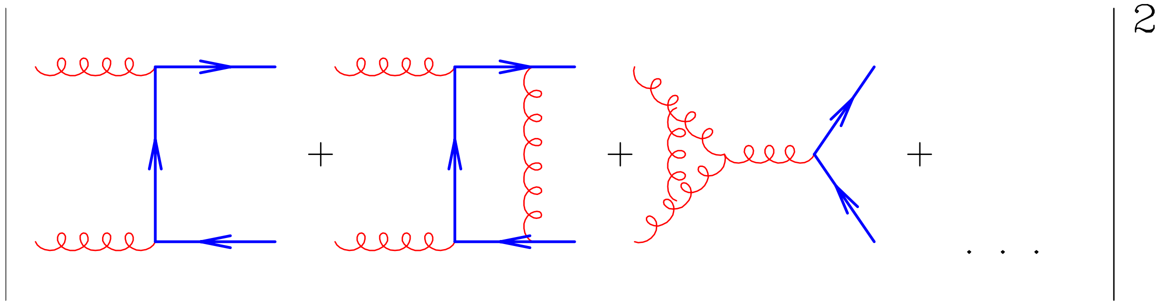
Ingredients of a NLO calculation

Example $gg \to t\bar{t}$

- Born process (LO).
- Interference of one-loop with LO
- Real radiation
- Theoretical issues are efficient calculation of phase space and calculation of loop diagrams.

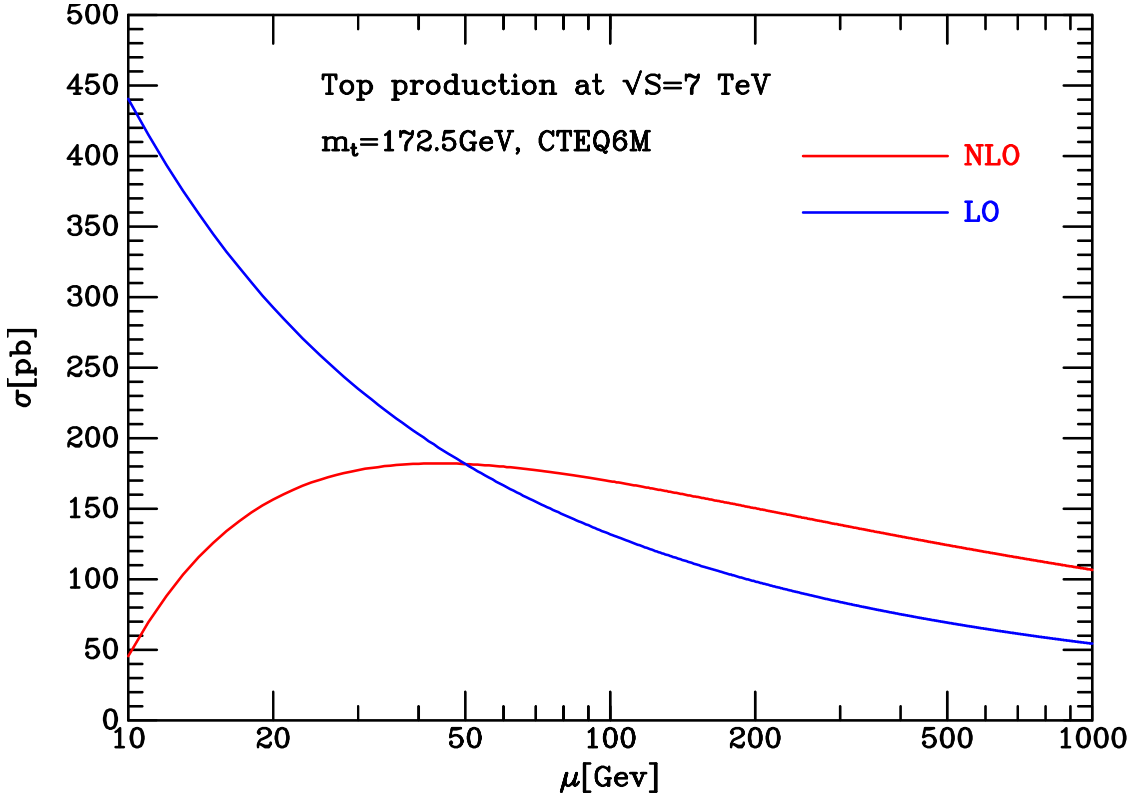


Real emission diagrams



Virtual emission diagrams

10% predictions from perturbative QCD?



At high energy the short distance cross sections are calculable in the

$$= c_0\alpha_S^n + c_1\alpha_S^{n+1} + c_2\alpha_S^{n+2} \quad \ldots$$

LO NLO NNLO

Although α_S is of order 0.1, leading order is not sufficient for 10% corrections.
This problem becomes more acute for large n, ie, as the number of jets increases.

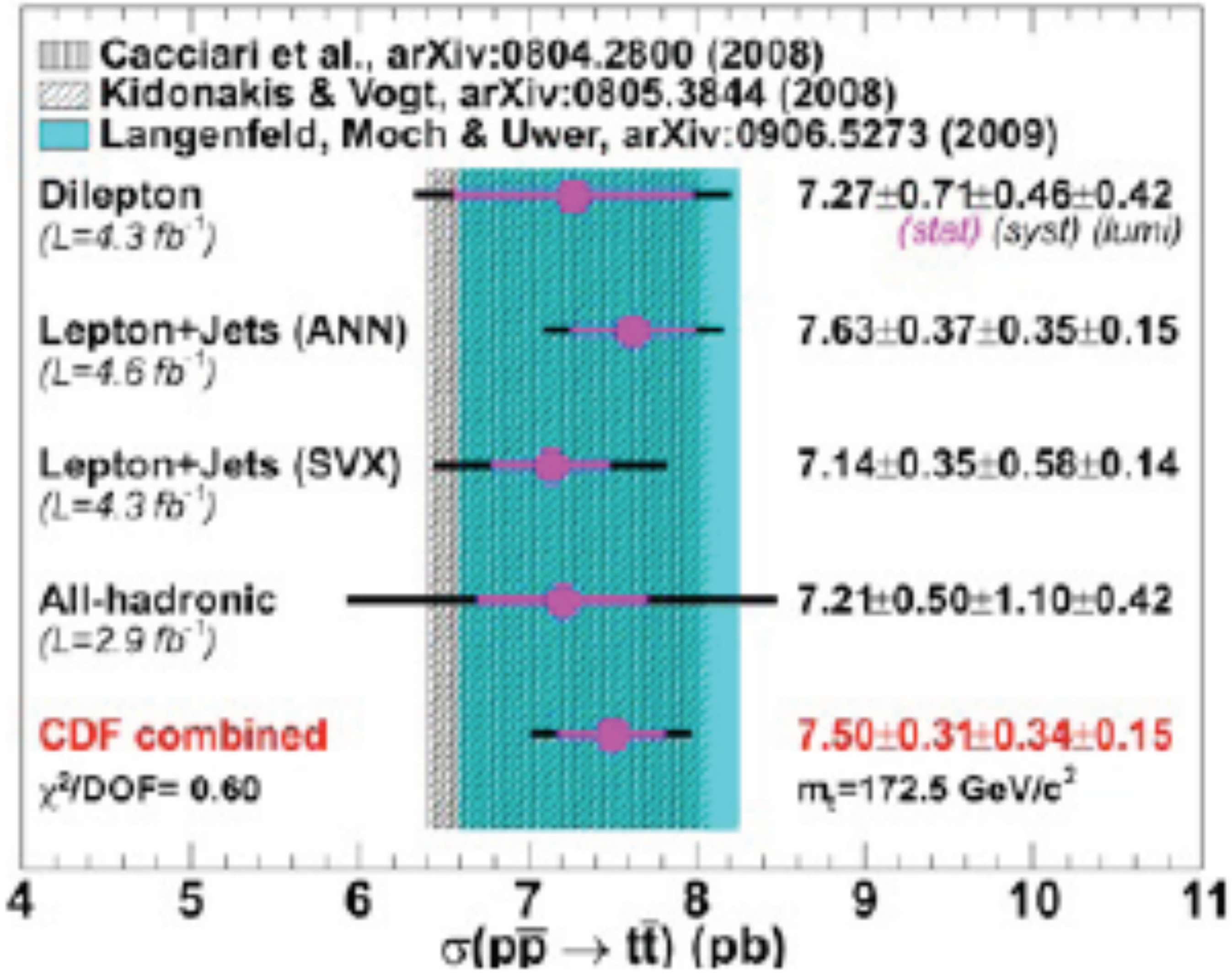
μ is the renorm/factorization scale-an unphysical parameter

$$\mu\frac{d\sigma}{d\mu} = 0 \qquad \sigma_{tt}^{NLO} = c_2\alpha_S^2 + c_3\alpha_S^3 \text{ therefore } \mu\frac{d\sigma_{tt}^{NLO}}{d\mu} = O(\alpha_S^4)$$

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

At the Tevatron

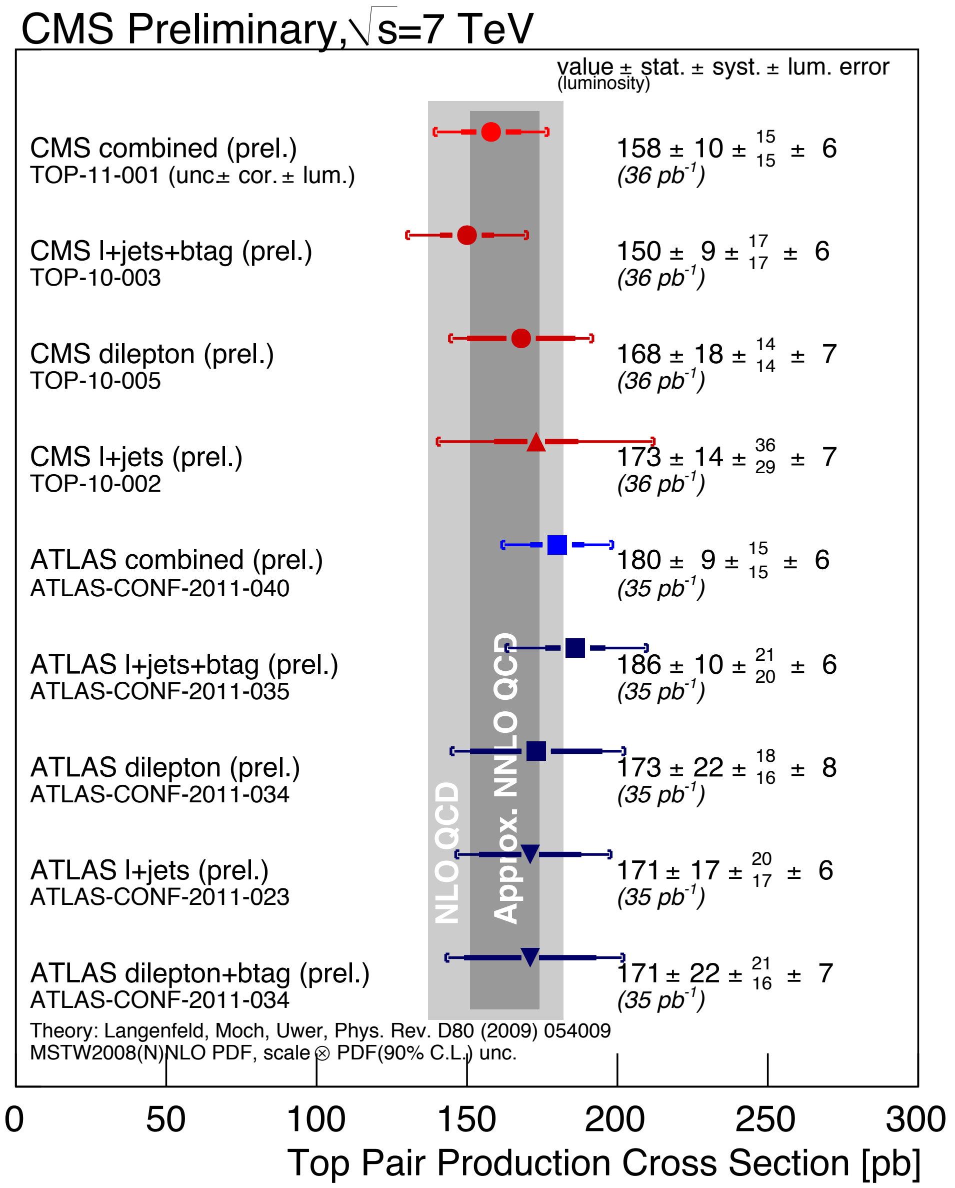
Precision of the NLO theory is challenged by experiment.



Studies ongoing to extend theory prediction to NNLO ...

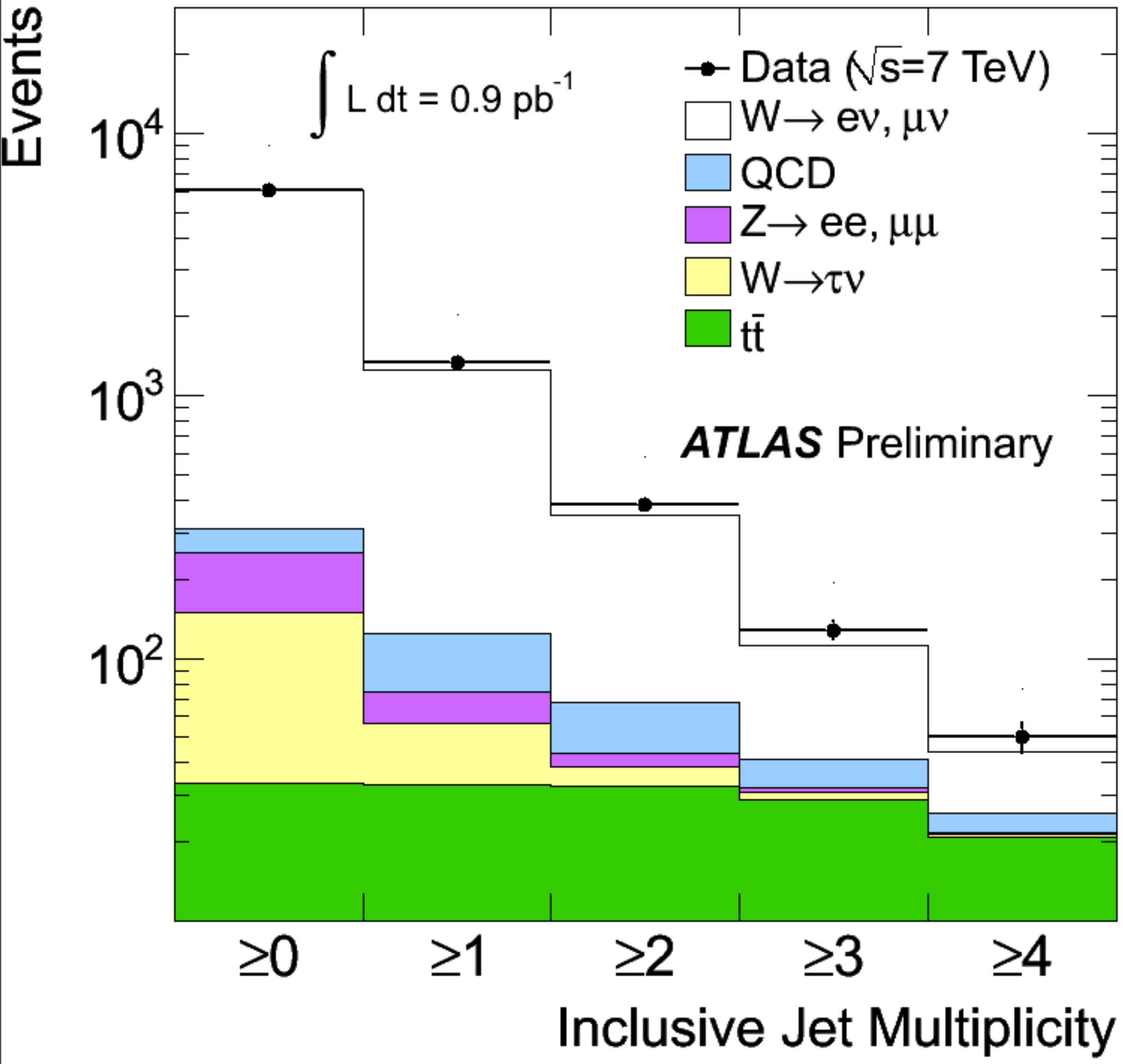
Comparison of top production cross section with theory at $\sqrt{s}$=7 TeV

Data is already so precise with only 35pb^{-1} that theory calculated in NLO has an estimated error larger than experimental error.
(NNLO calculations under way).



CMS-PAS-TOP-11-001

W+jets data at 7 TeV



So W + 4 jet events are here and we need to have (at least) NLO theoretical predictions for them.

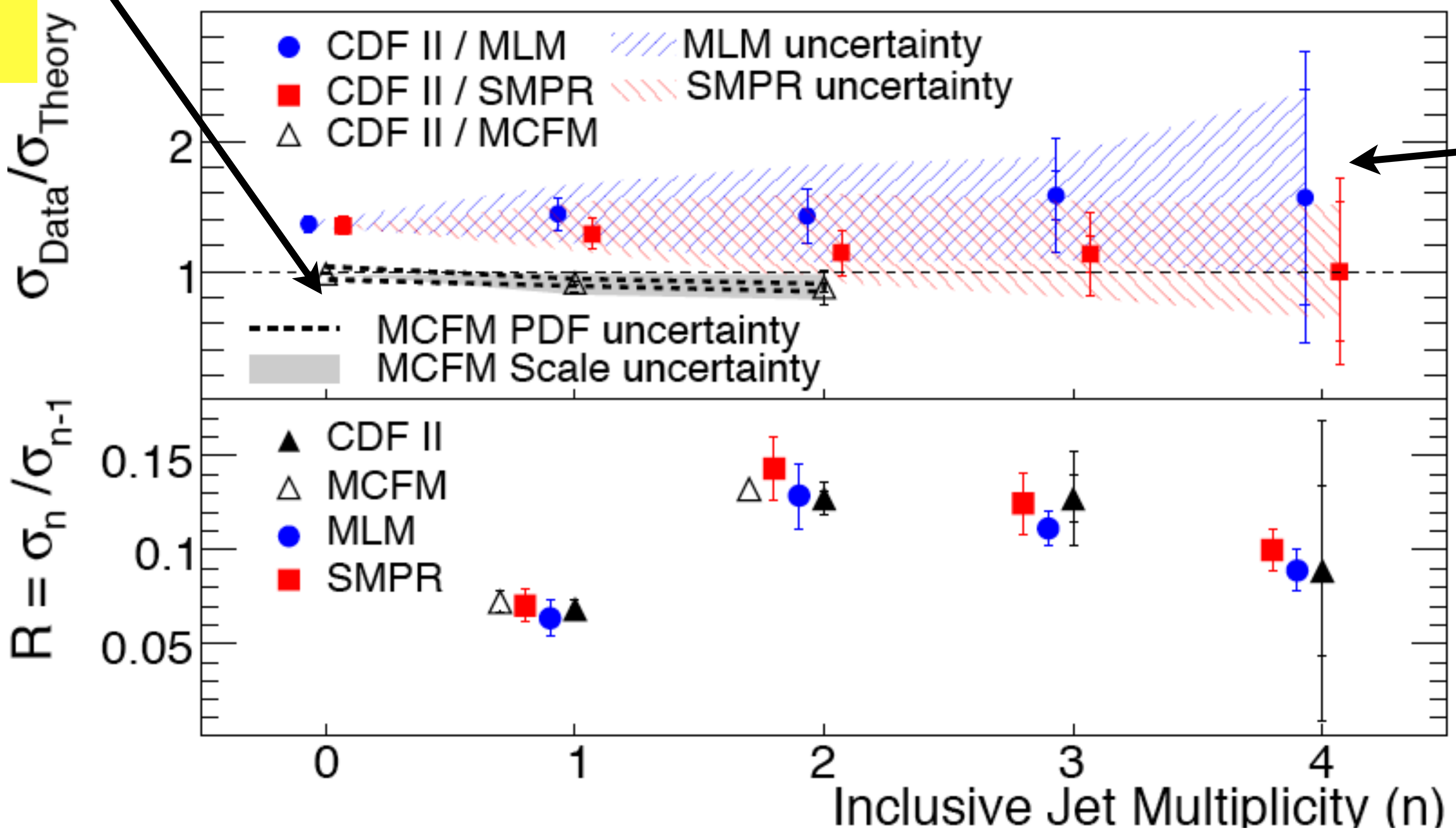
No published measurements to compare with yet at LHC, but at the Tevatron....

W + n-jet rates from CDF

Aaltonen et al., arXiv: 0711.4044

NLO results

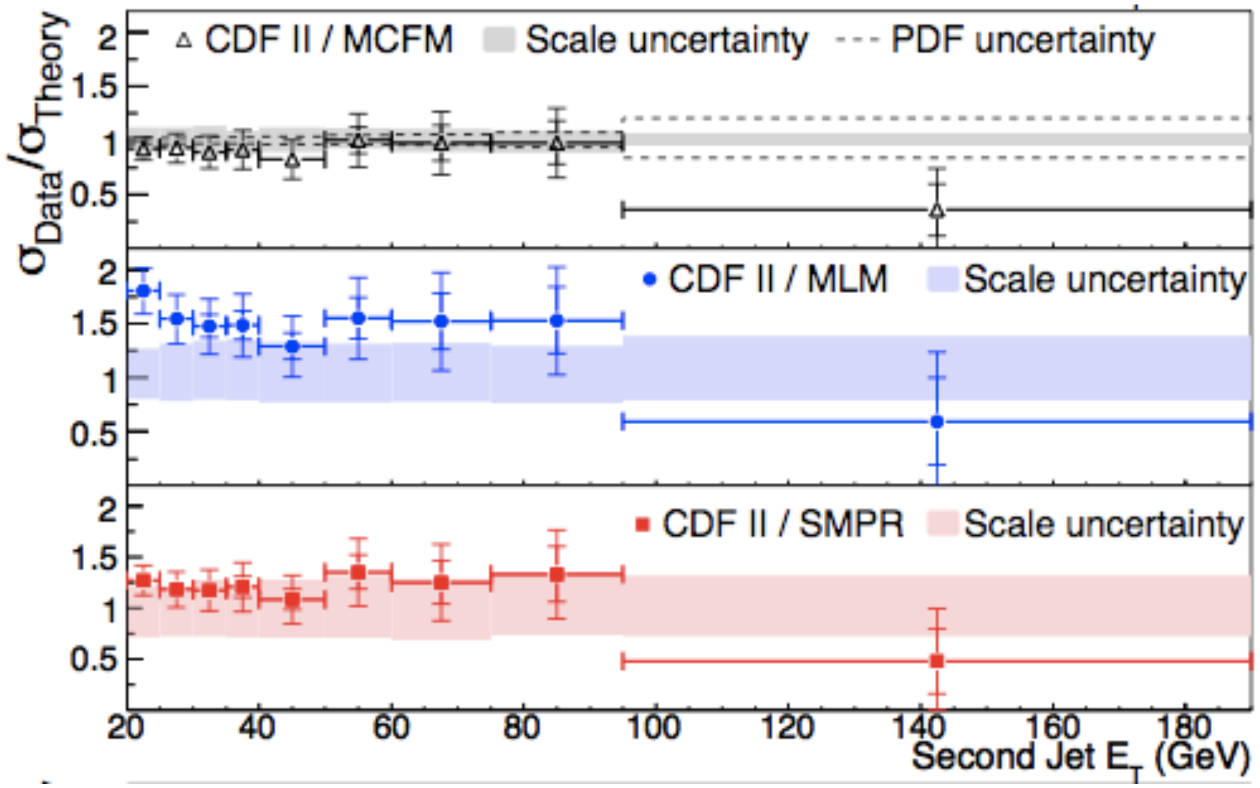
Tree graphs



Both uncertainty on rates and deviation of Data/Theory from 1 are smaller in MCFM (NLO) than in other calculations. The ratio R agrees well for all theory calculations, but only available from MCFM for n<3 in 2007. Note the increasing uncertainty with the number of jets in tree graph calculations.

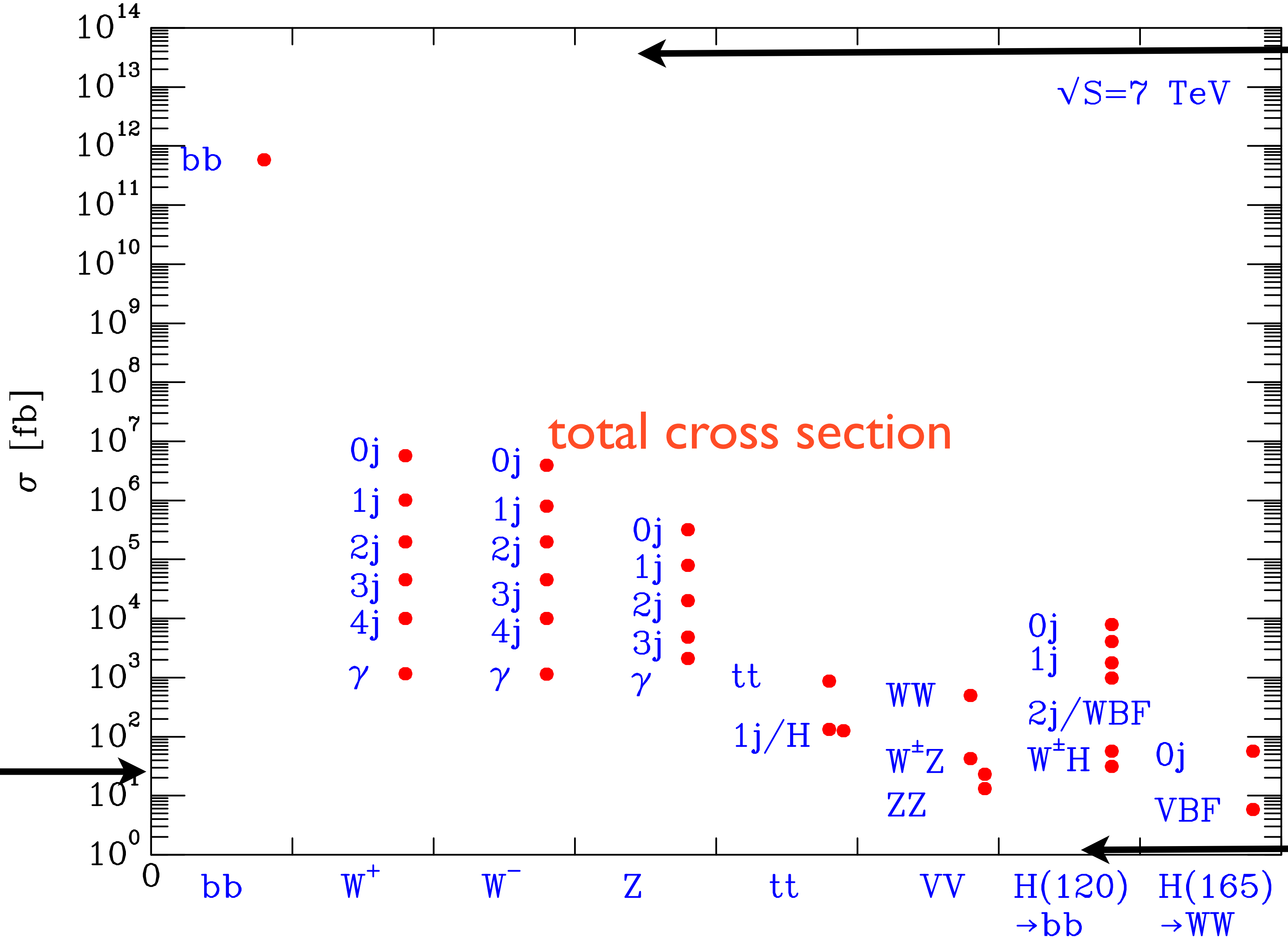
W+n jet results at the Tevatron

W+0,1 and 2 jet rates from NLO (MCFM) have been compared successfully (including shapes in E$_T$) with data at the Tevatron.



Success of W+1,2 jets predictions and the fact that LO uncertainties become larger as the number of jets increases -- strong motivation to calculate vector boson + 3,4.... jets

SM Ladder at 7 TeV



total cross section

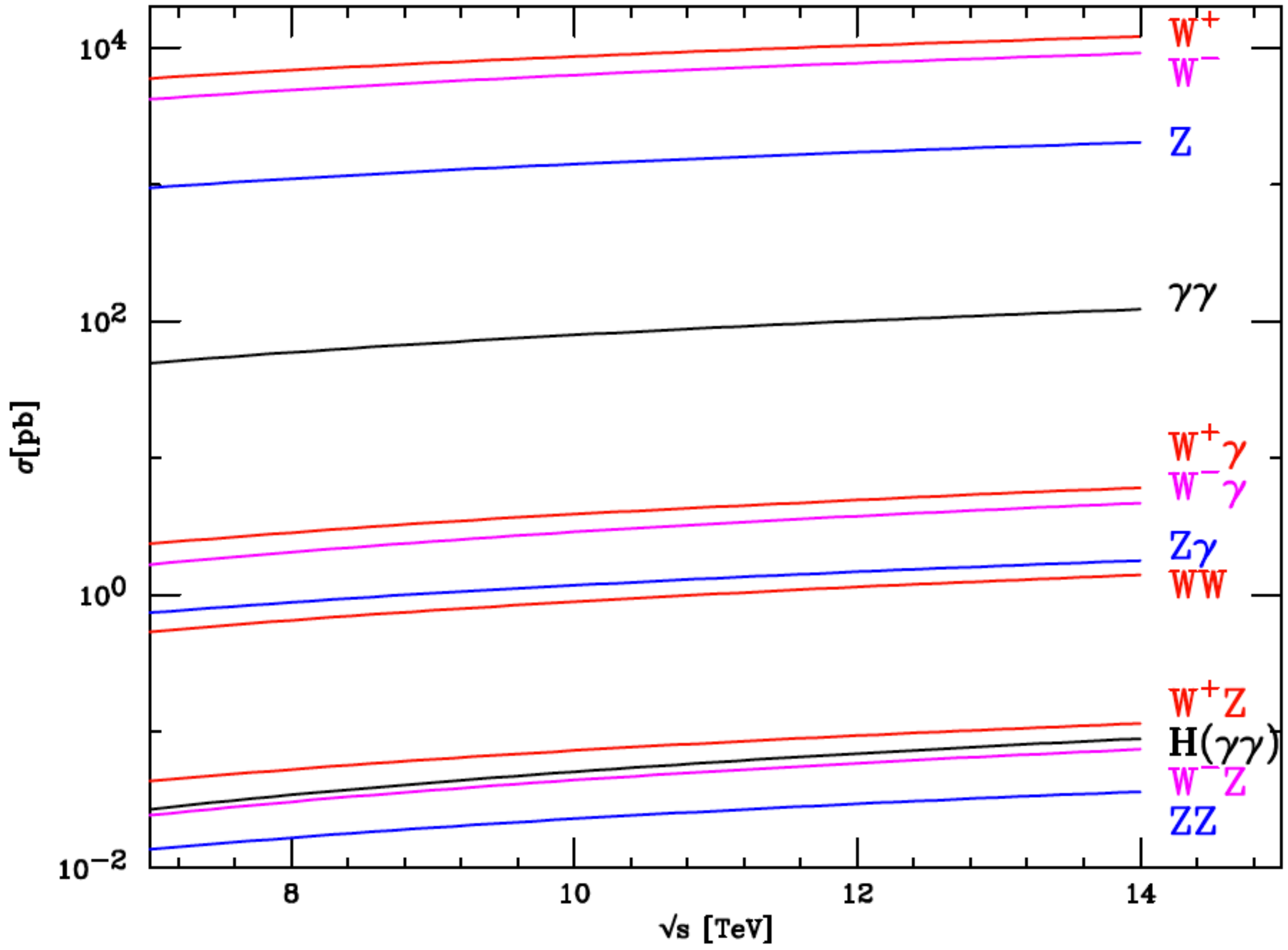
total cross section

LHC is here ~0.028fb^{-1}

goal for Nov 2011

Includes decay of W/Z to one species of charged lepton and semi-leptonic decay of top (t → b l ν) (where applicable) and jets, Et> 25 GeV.

Ladder of EW processes at the LHC 7 TeV



Cross sections including decay of vector bosons to one species of charged lepton (where appropriate)

10 events at end of 2011

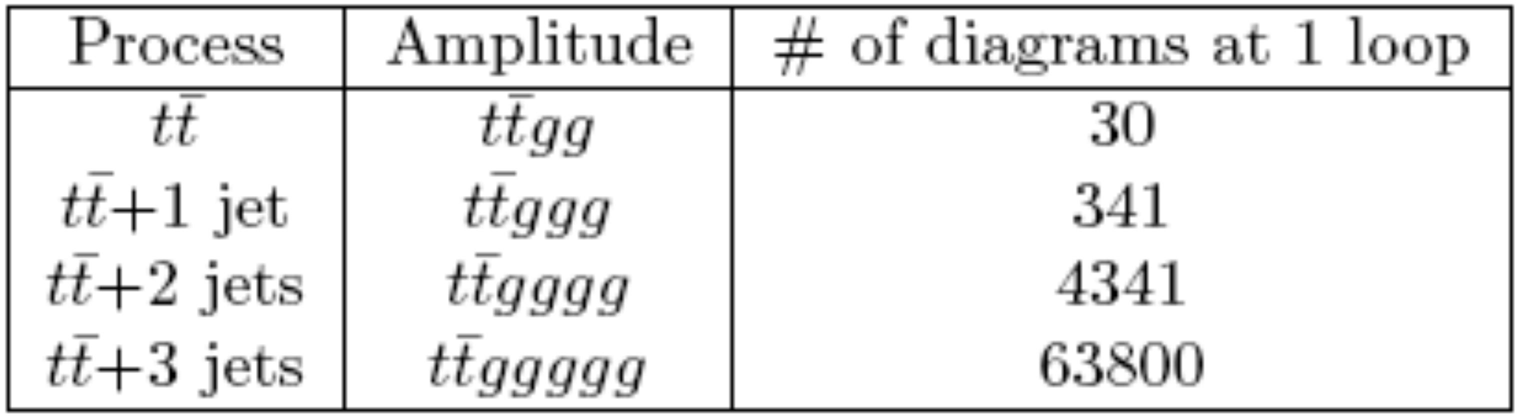
All of these processes will be examined in 2011.

Industrial approach to NLO

- Preceding examples show us that NLO calculations can really improve the quality of the predictions.
- This will be important as we rediscover the SM at the LHC and also for the estimation of backgrounds to BSM physics.
- Backgrounds are best estimated from data, but in many circumstances it is helpful to have corroborating theoretical estimates.
- Hence an industrial style approach to NLO QCD is needed.
- Automatic generation of NLO corrections is the wave of the future.

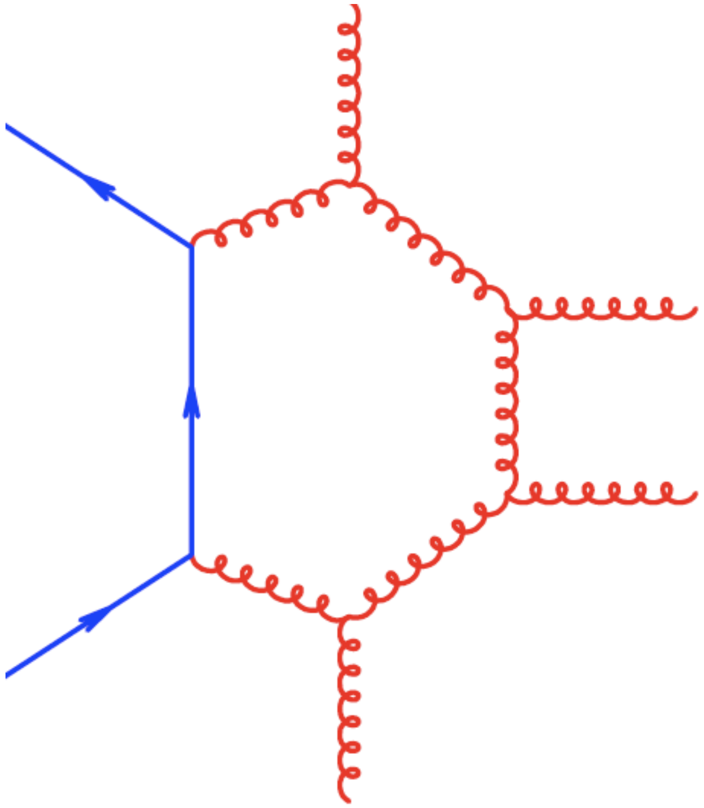
Calculation of one-loop amplitudes

Feynman diagrams can be the answer for a moderate number of external legs, but will not be the answer as the number of legs increases. There are too many diagrams with cancellations between them.

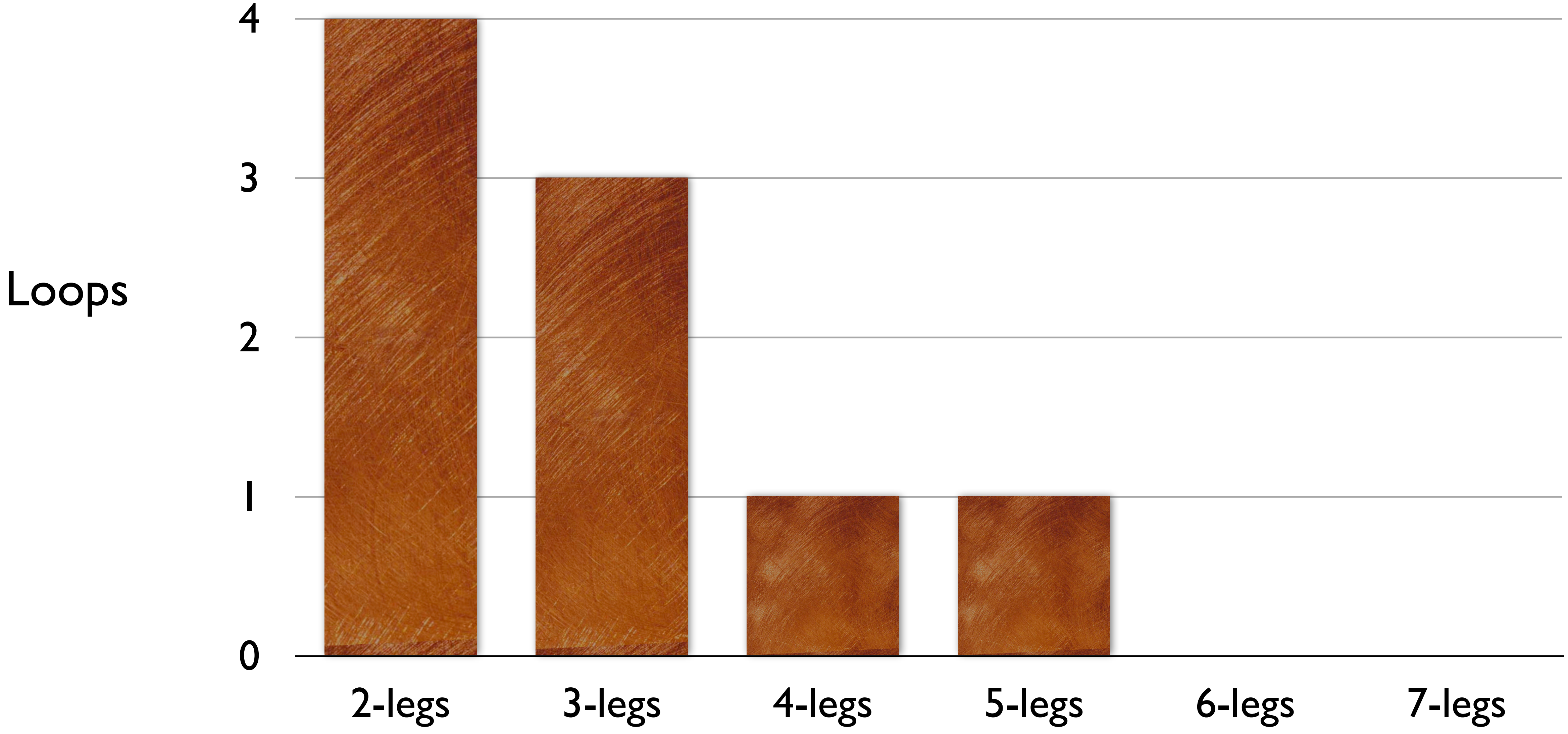


Process	Amplitude	# of diagrams at 1 loop
$t\bar{t}$	$t\bar{t}gg$	30
$t\bar{t}$+1 jet	$t\bar{t}ggg$	341
$t\bar{t}$+2 jets	$t\bar{t}gggg$	4341
$t\bar{t}$+3 jets	$t\bar{t}ggggg$	63800

One of the 4,341 Feynman diagrams



Loops and legs (circa 2007)



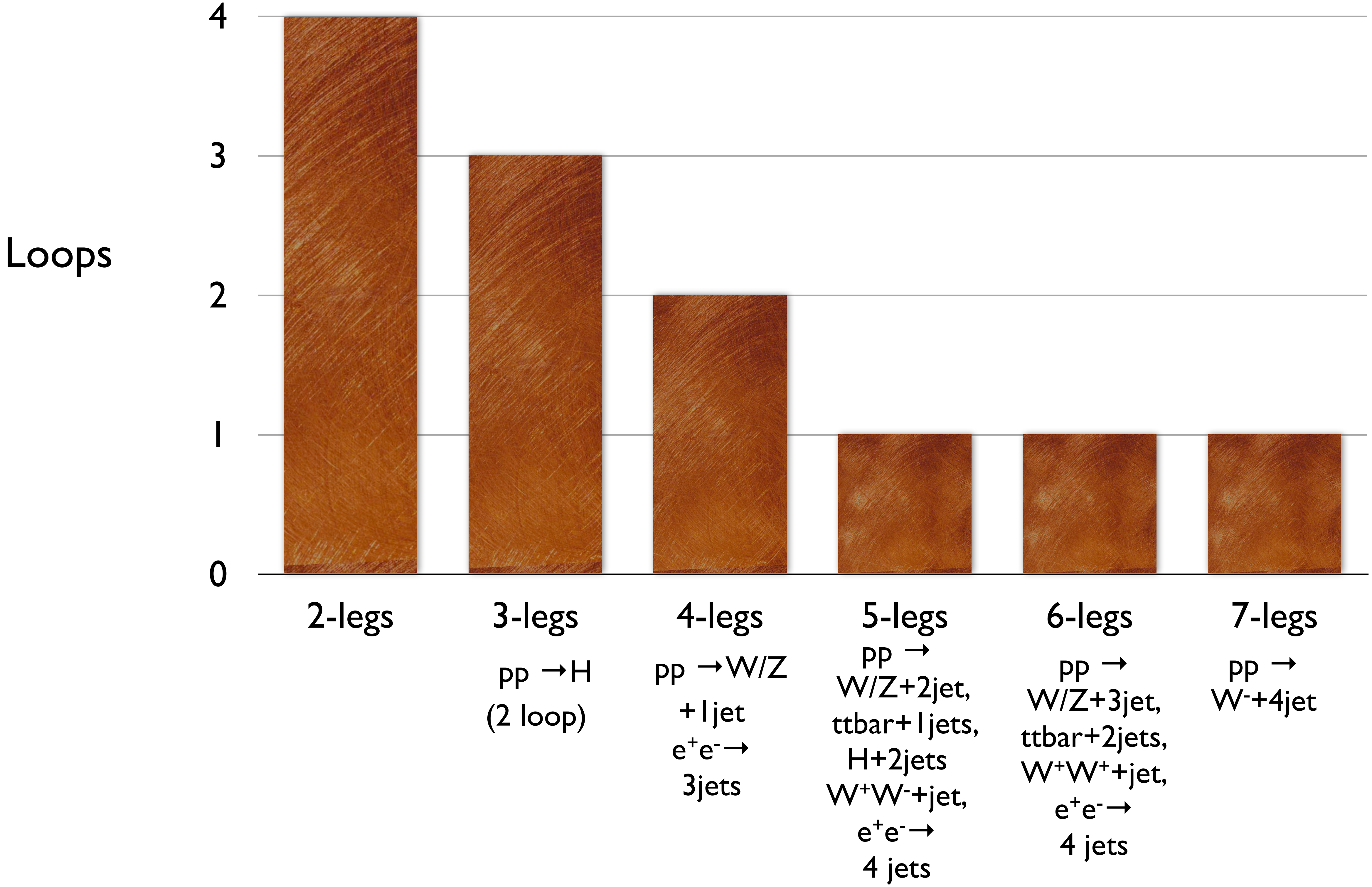
QCD beta function

anomalous dimensions, form factors

pp → W/Z+1jet, $e^+e^- \to$ 3jets

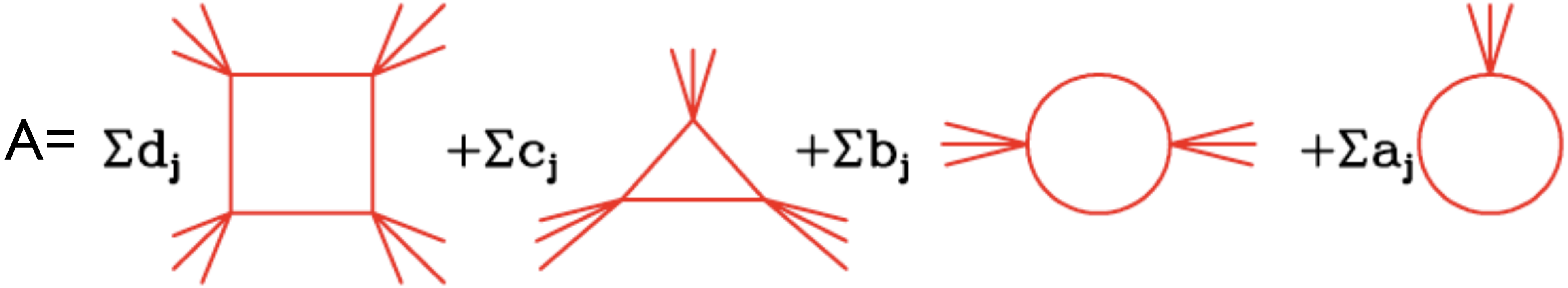
pp → W/Z+2jet, $e^+e^- \to$ 3jets

Loops and legs - 2011



Ingredients in a one-loop calculation

- For NLO calculations, any one-loop amplitude (no matter how many legs) can be written as a sum of sums of scalar boxes, triangles, bubbles and tadpoles (+ so-called rational piece).



- The determination of the coefficients, d_j, c_j, b_j, a_j can be determined by semi-numerical methods, especially D-dimensional unitarity.

- The scalar integrals are all known analytically, see e.g. QCDLoop.fnal.gov, (RKE,Zanderighi)

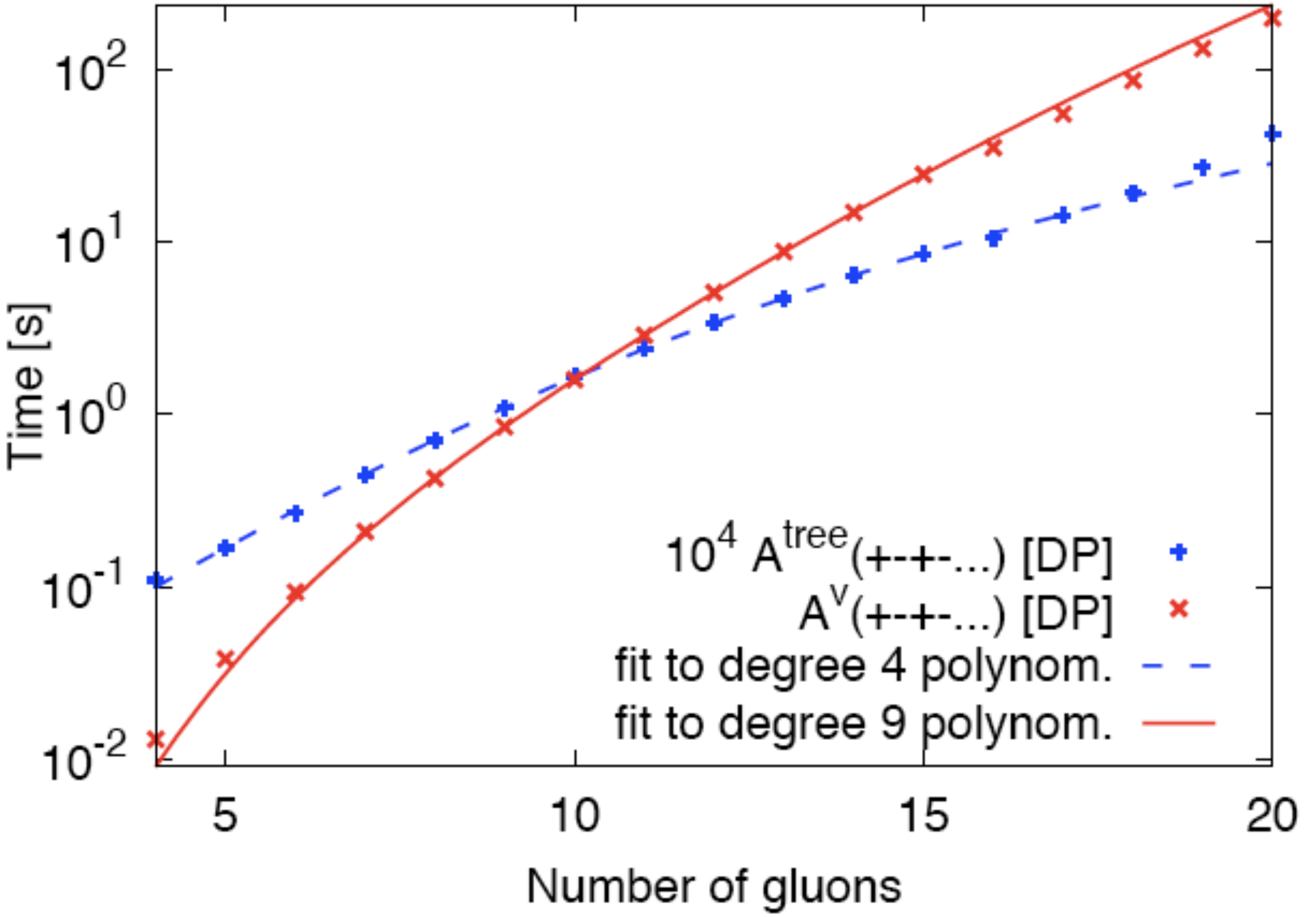
$$I_4^D(p_1^2,p_2^2,p_3^2,p_4^2;s_{12},s_{23};m_1^2,m_2^2,m_3^2,m_4^2) = \frac{\mu^{4-D}}{i\pi^{\frac{D}{2}} r_\Gamma}$$

$$\times \int d^D l \, \frac{1}{(l^2-m_1^2+i\varepsilon)((l+q_1)^2-m_2^2+i\varepsilon)((l+q_2)^2-m_3^2+i\varepsilon)((l+q_3)^2-m_4^2+i\varepsilon)},$$

One loop calculation of pure gluon amplitudes

Time to calculate one-loop amplitude scales as N^9 as expected. For small numbers of legs N=4,5,6 the times are of the order of 10’s of milliseconds

4g:Ellis-Sexton(1985)
5g:Bern-Dixon-Kosower(1993)
6g:Ellis-Giele-Zanderighi(2006)

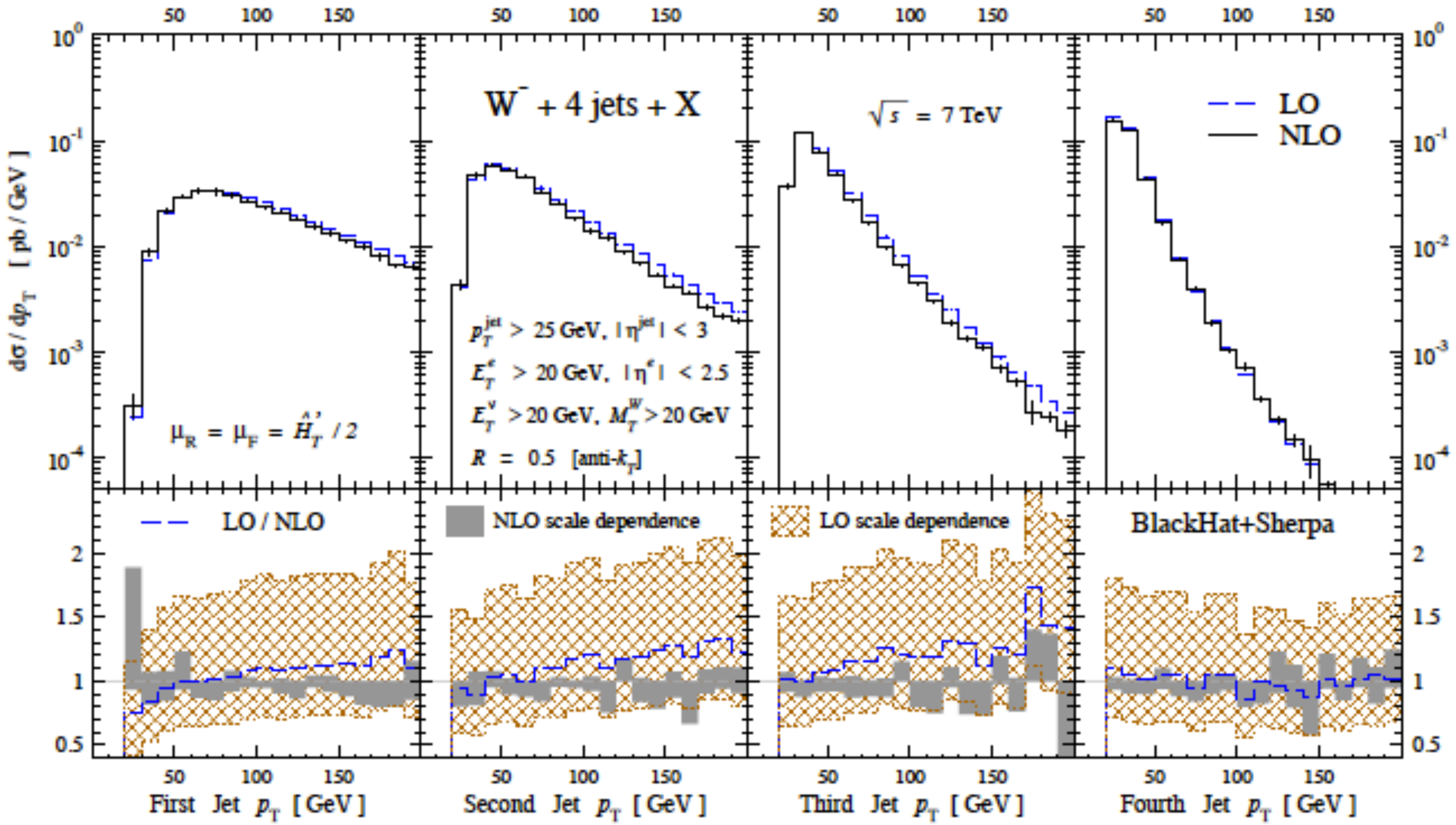


Giele, Zanderighi arXiv:0805.2152

D-dimensional unitarity is a disruptive technology!

W^-+4jets at NLO at 7 TeV

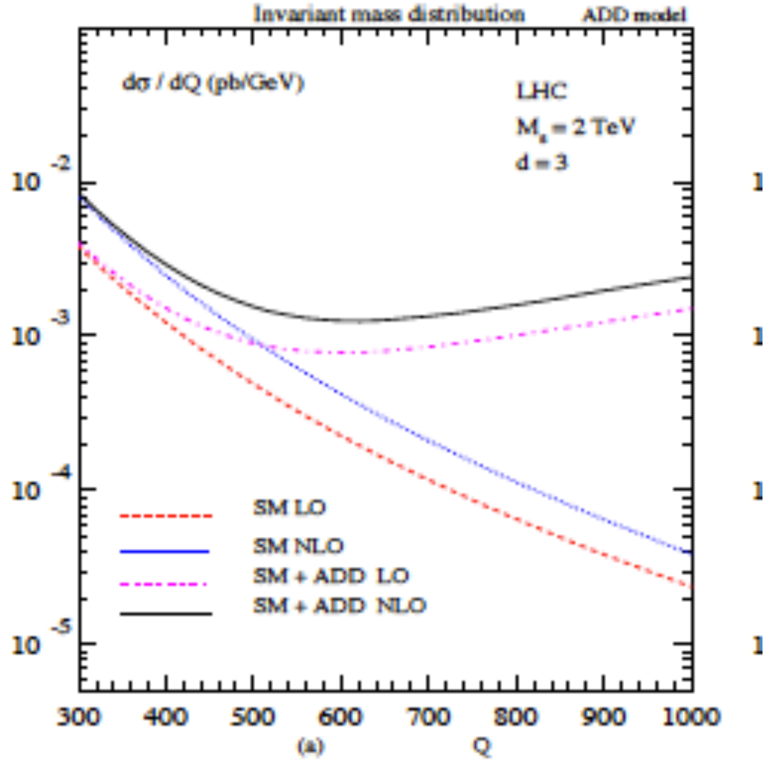
Blackhat-Sherpa, arXiv:1009.2338v2 (Feb 2011)



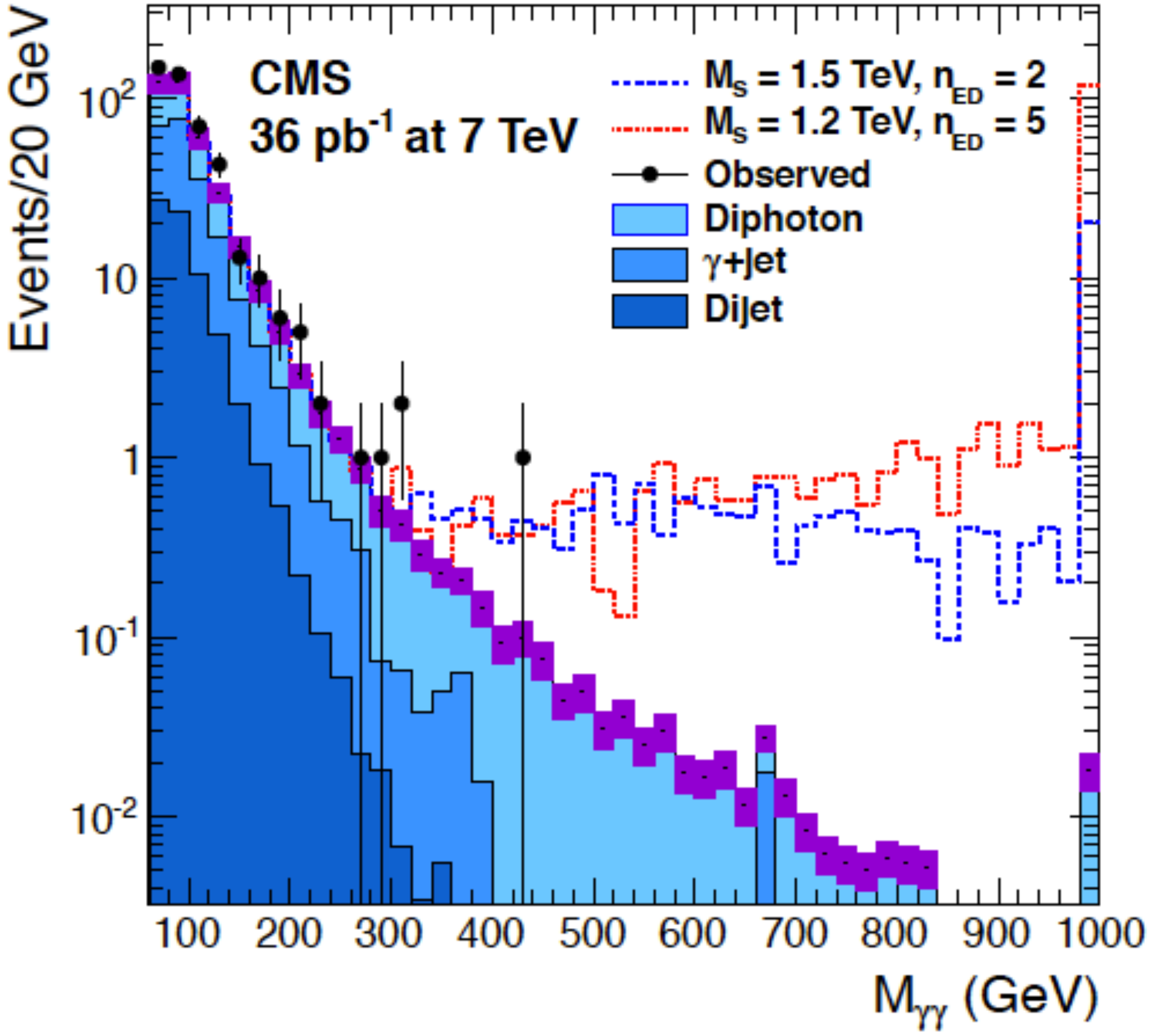
Currently in leading colour approximation for virtual amplitudes

NLO corrections for new physics processes

For example in a ADD model in which gravity extends into extra dimensions.



Kumar, Mathews, Ravindran & Tripathi hep-ph/0902.4894

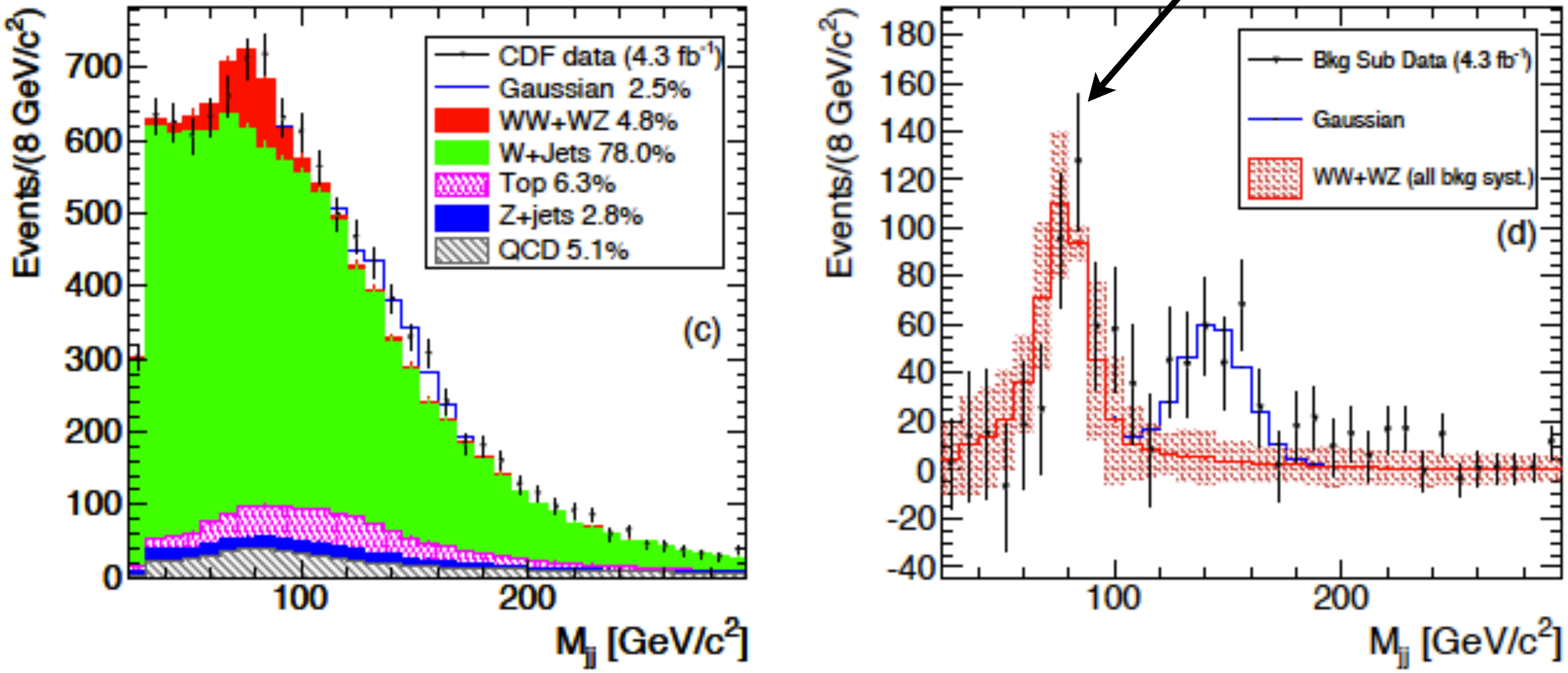


Limit on model would be degraded if NLO corrections were not included

Backgrounds to new physics processes

CDF:New April 4th, 2011

W+V(→jj)



"Invariant mass distribution of jet pairs produced in association with a W boson in ppbar collisions at √s=1.96 TeV", arXiv:1104.0699

Cross section WX times branching ratio X(→two jets) is estimated to be 4pb

Background

- Significance of the signal clearly depends on validity of estimation of background, especially W+2 jet background.
- Current significance of signal is 3.2 σ if LO order estimates are used and increases to 3.4 σ if NLO estimate is used.

NLO Wishlist

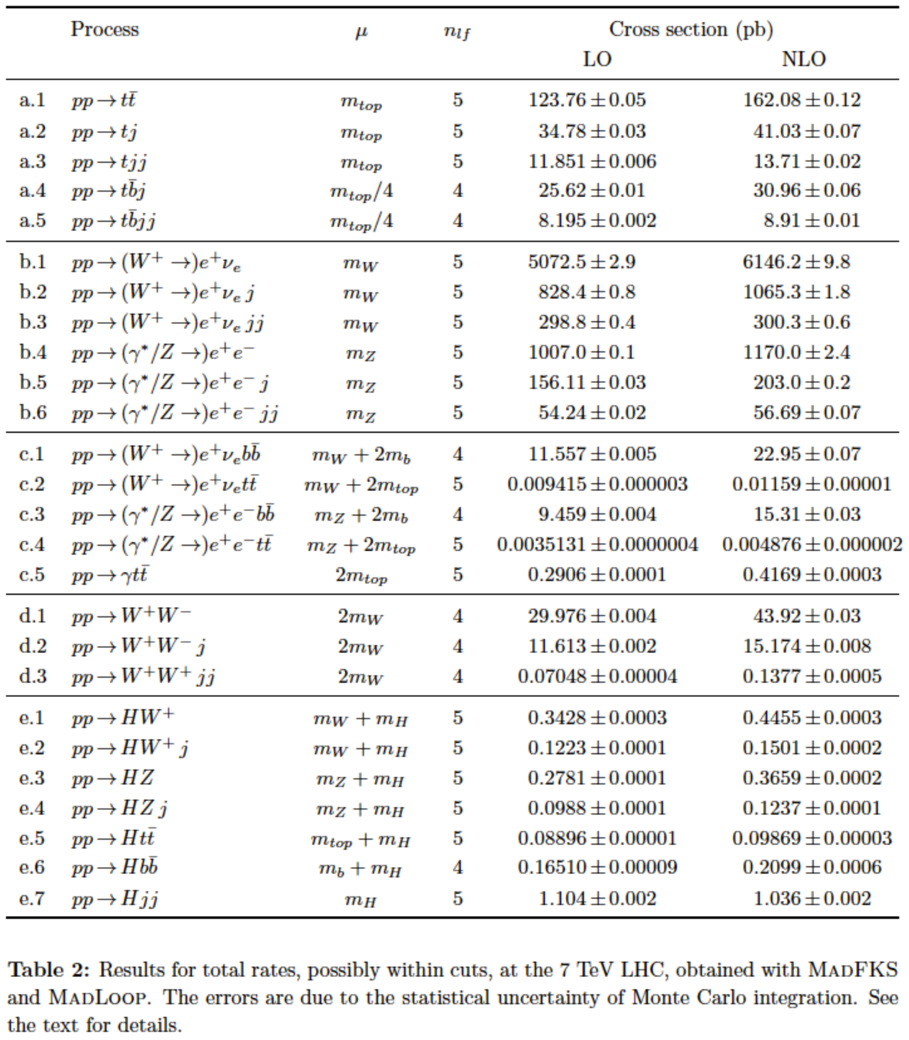
2010

	process wanted at NLO	background to
✓	1. $pp \to VV +$ jet	$t\bar{t}H$, new physics Dittmaier, Kallweit, Uwer; Campbell, Ellis, Zanderighi
✓	2. $pp \to H + 2$ jets	H in VBF Campbell, Ellis, Zanderighi; Ciccolini, Denner Dittmaier
✓	3. $pp \to t\bar{t}b\bar{b}$	$t\bar{t}H$ Bredenstein, Denner Dittmaier, Pozzorini; Bevilacqua, Czakon, Papadopoulos, Pittau, Worek
✓	4. $pp \to t\bar{t} + 2$ jets	$t\bar{t}H$ Bevilacqua, Czakon, Papadopoulos, Worek
✗	5. $pp \to VVb\bar{b}$	VBF $\to H \to VV$, $t\bar{t}H$, new physics
✓	6. $pp \to VV + 2$ jets	VBF $\to H \to VV$ VBF: Bozzi, Jäger, Oleari, Zeppenfeld
✓	7. $pp \to V + 3$ jets	new physics CFB, Bern, Dixon, Febres Cordero, Forde, Gleisberg, Ita, Kosower, Maitre; Ellis, Melnikov, Zanderighi
✓	8. $pp \to VVV$	SUSY trilepton Lazopoulos, Melnikov, Petriello; Hankele, Zeppenfeld; Binoth, Ossola, Papadopoulos, Pittau
✓	9. $pp \to b\bar{b}b\bar{b}$	Higgs, new physics GOLEM

Table from Carola Berger

Madloop - Automatic generation of NLO corrections

- For many years there has been an automatic generator of LO matrix elements, (Madgraph) and events (Madevent)
- A similar development for NLO has just appeared, (Rikkert Frederix et al), (Madloop).
- Open issues are the computation time for this Feynman graph-based method and its scaling with the number of legs.



	Process	μ	n_{lf}	Cross section (pb) LO	Cross section (pb) NLO
a.1	$pp\to t\bar{t}$	m_{top}	5	123.76 ± 0.05	162.08 ± 0.12
a.2	$pp\to tj$	m_{top}	5	34.78 ± 0.03	41.03 ± 0.07
a.3	$pp\to tjj$	m_{top}	5	11.851 ± 0.006	13.71 ± 0.02
a.4	$pp\to t\bar{b}j$	$m_{top}/4$	4	25.62 ± 0.01	30.96 ± 0.06
a.5	$pp\to t\bar{b}jj$	$m_{top}/4$	4	8.195 ± 0.002	8.91 ± 0.01
b.1	$pp\to(W^+\to)e^+\nu_e$	m_W	5	5072.5 ± 2.9	6146.2 ± 9.8
b.2	$pp\to(W^+\to)e^+\nu_e\, j$	m_W	5	828.4 ± 0.8	1065.3 ± 1.8
b.3	$pp\to(W^+\to)e^+\nu_e\, jj$	m_W	5	298.8 ± 0.4	300.3 ± 0.6
b.4	$pp\to(\gamma^*/Z\to)e^+e^-$	m_Z	5	1007.0 ± 0.1	1170.0 ± 2.4
b.5	$pp\to(\gamma^*/Z\to)e^+e^-\, j$	m_Z	5	156.11 ± 0.03	203.0 ± 0.2
b.6	$pp\to(\gamma^*/Z\to)e^+e^-\, jj$	m_Z	5	54.24 ± 0.02	56.69 ± 0.07
c.1	$pp\to(W^+\to)e^+\nu_e b\bar{b}$	m_W+2m_b	4	11.557 ± 0.005	22.95 ± 0.07
c.2	$pp\to(W^+\to)e^+\nu_e t\bar{t}$	m_W+2m_{top}	5	0.009415 ± 0.000003	0.01159 ± 0.00001
c.3	$pp\to(\gamma^*/Z\to)e^+e^-b\bar{b}$	m_Z+2m_b	4	9.459 ± 0.004	15.31 ± 0.03
c.4	$pp\to(\gamma^*/Z\to)e^+e^-t\bar{t}$	m_Z+2m_{top}	5	0.0035131 ± 0.0000004	0.004876 ± 0.000002
c.5	$pp\to\gamma t\bar{t}$	$2m_{top}$	5	0.2906 ± 0.0001	0.4169 ± 0.0003
d.1	$pp\to W^+W^-$	$2m_W$	4	29.976 ± 0.004	43.92 ± 0.03
d.2	$pp\to W^+W^-\, j$	$2m_W$	4	11.613 ± 0.002	15.174 ± 0.008
d.3	$pp\to W^+W^+\, jj$	$2m_W$	4	0.07048 ± 0.00004	0.1377 ± 0.0005
e.1	$pp\to HW^+$	m_W+m_H	5	0.3428 ± 0.0003	0.4455 ± 0.0003
e.2	$pp\to HW^+\, j$	m_W+m_H	5	0.1223 ± 0.0001	0.1501 ± 0.0002
e.3	$pp\to HZ$	m_Z+m_H	5	0.2781 ± 0.0001	0.3659 ± 0.0002
e.4	$pp\to HZ\, j$	m_Z+m_H	5	0.0988 ± 0.0001	0.1237 ± 0.0001
e.5	$pp\to Ht\bar{t}$	$m_{top}+m_H$	5	0.08896 ± 0.00001	0.09869 ± 0.00003
e.6	$pp\to Hb\bar{b}$	m_b+m_H	4	0.16510 ± 0.00009	0.2099 ± 0.0006
e.7	$pp\to Hjj$	m_H	5	1.104 ± 0.002	1.036 ± 0.002

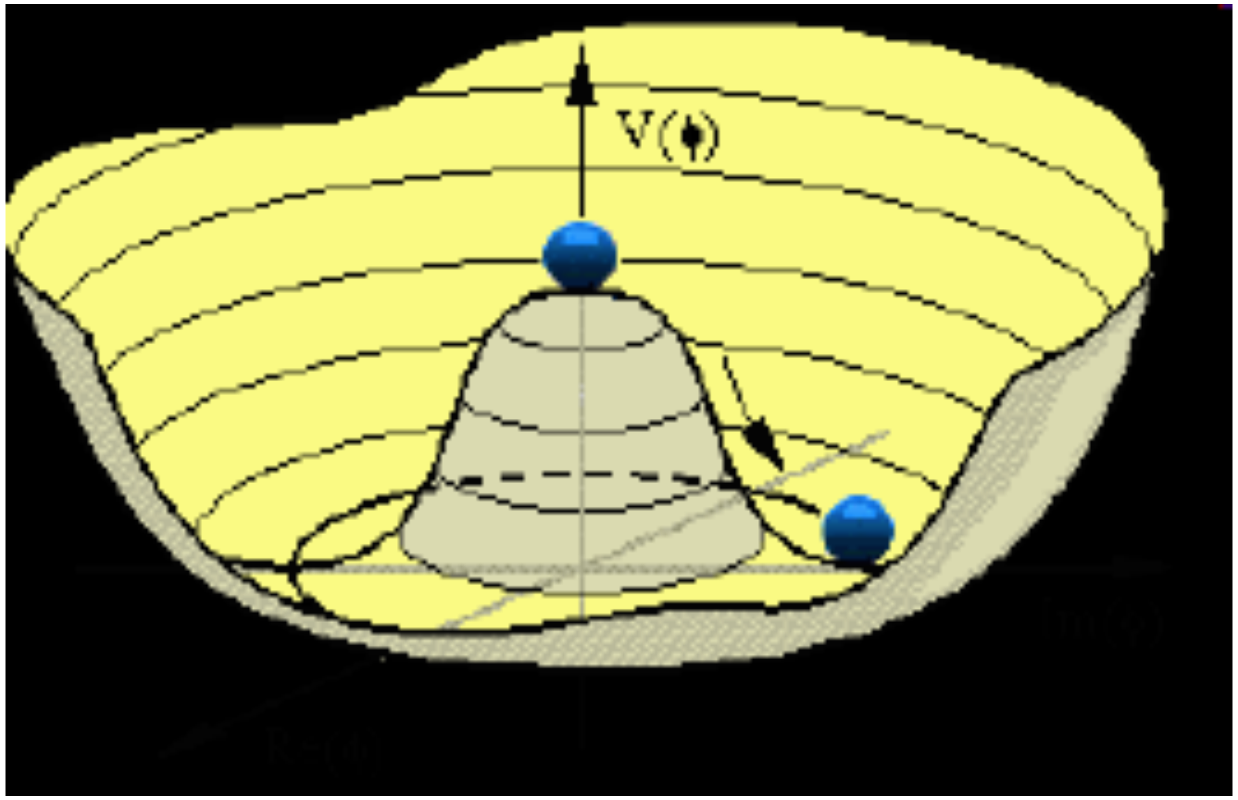
Table 2: Results for total rates, possibly within cuts, at the 7 TeV LHC, obtained with MadFKS and MadLoop. The errors are due to the statistical uncertainty of Monte Carlo integration. See the text for details.

Hirschi et al , arXiv:1103.0621

NLO results available for any arbitrary process, with acceptable computing times for small enough N

The Higgs mechanism

- We require a gauge invariant way to give mass to the W and Z, but not to the photon.
- A solution is the Higgs mechanism.
- The mechanism relies on Broken symmetry.

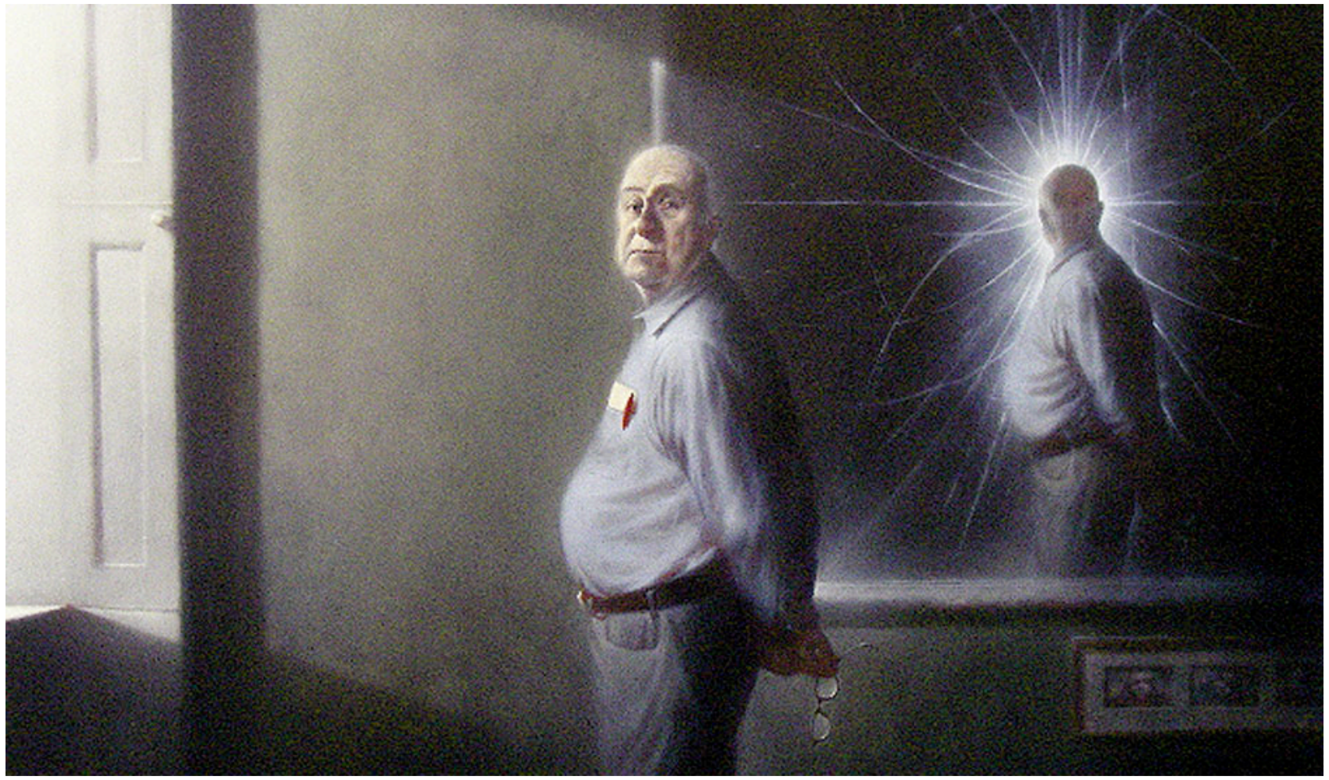


Choice of the minimum breaks the symmetry

The Higgs boson

- Add a complex doublet of scalar fields (4 degrees of freedom)
- Couple the doublet to massless gauge fields
- 3 degrees of freedom are absorbed to give longitudinal degrees of freedom to the W^+,W^-,Z^0, (thus evading the Goldstone theorem).
- The remaining degree of freedom is the physical Higgs boson, a necessary consequence of the Higgs mechanism.

Peter Higgs: portrait by Ken Currie



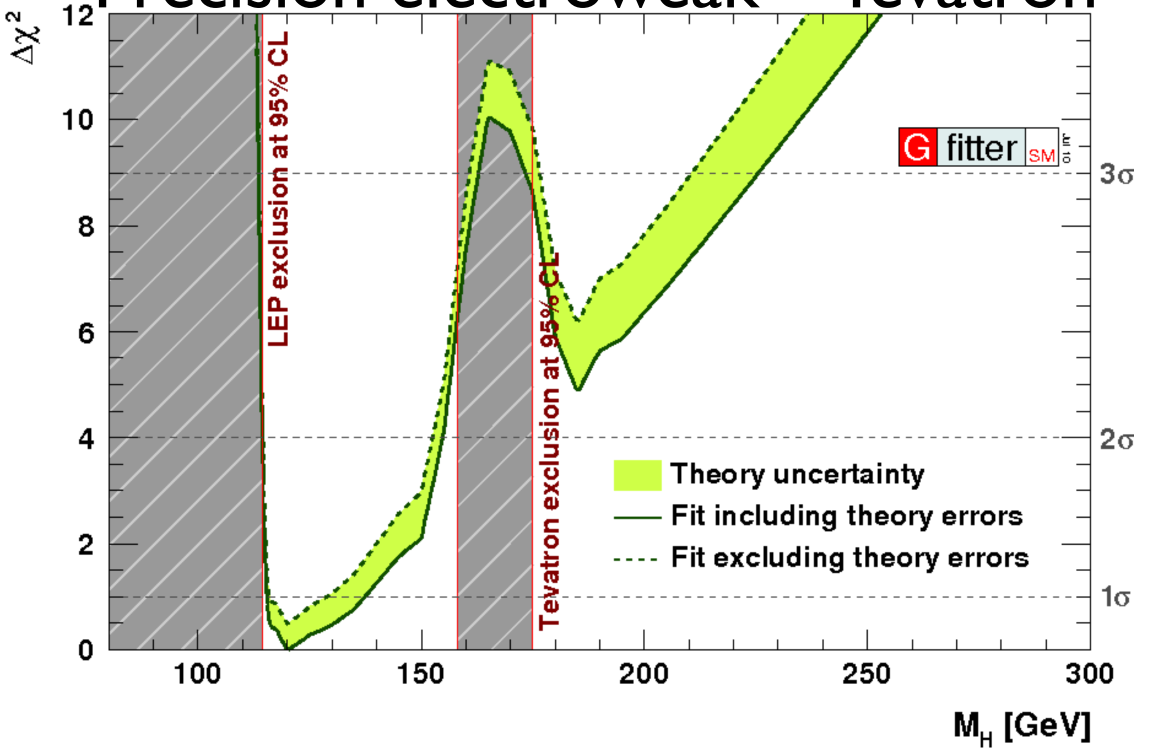
`The next day Stanley Deser had arranged for me to talk at Harvard, where an equally skeptical audience awaited. Sidney Coleman told me (in 1989) that they "had been looking forward to tearing apart this idiot who thought he could get around the Goldstone theorem." '

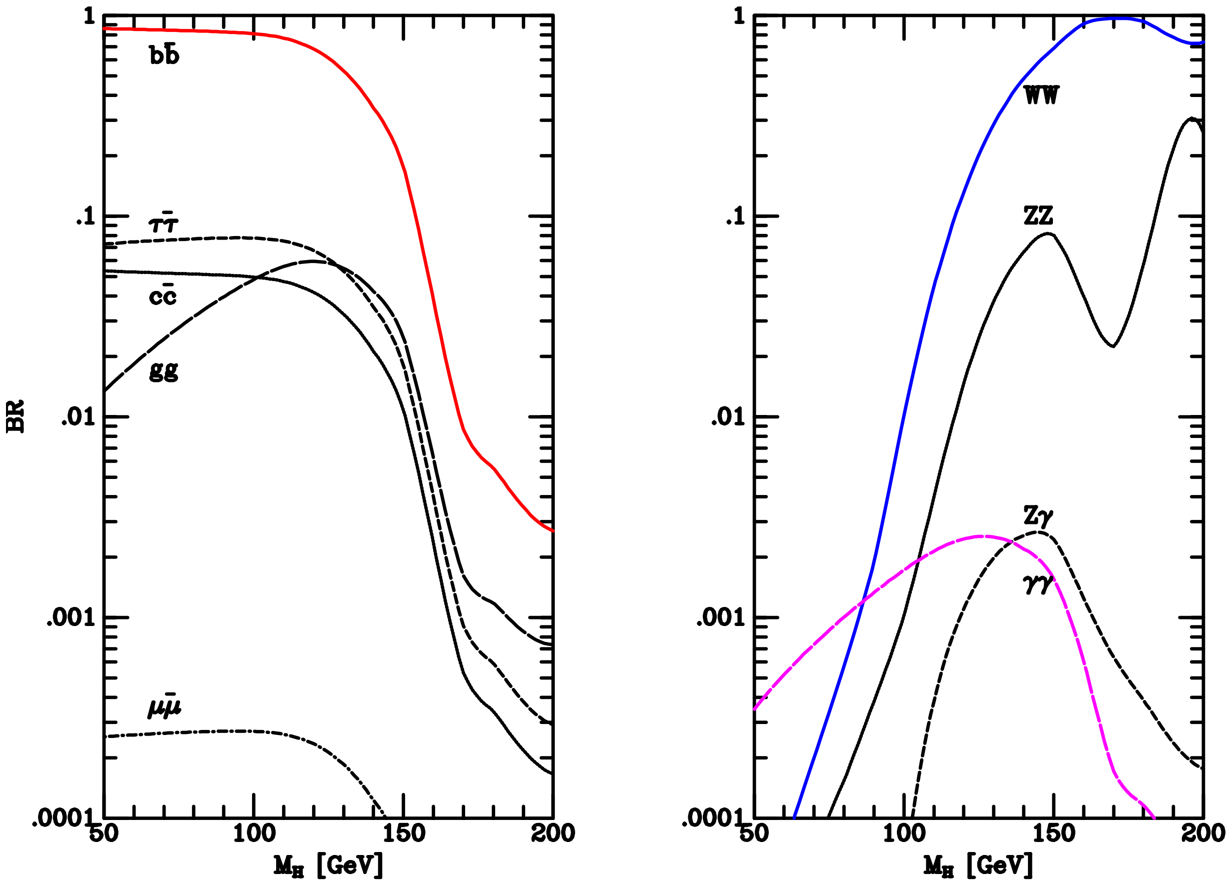
Peter Higgs in 'My life as a boson: The story of "The Higgs"'

Expectations for the Higgs

$M_H = 121^{+17}_{-6}$ GeV

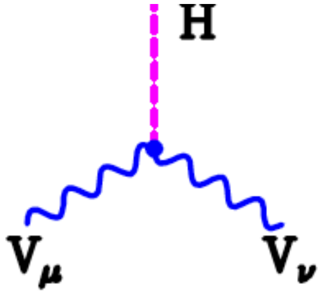
Precision electroweak + Tevatron





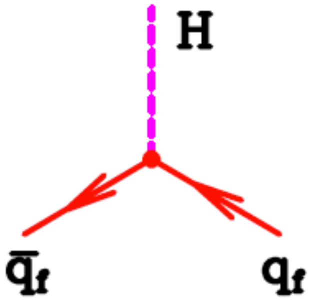
In the low mass region the Higgs decays primarily into bb

Higgs boson interactions



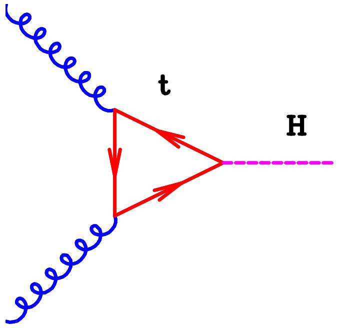
$$+ig_{VH}M_W g_{\mu\nu}$$

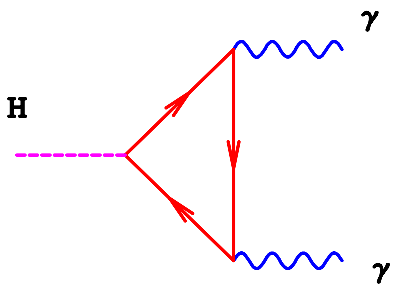
$$(g_{WH}=g_W,\ g_{ZH}=g_W/\cos^2\theta_W)$$



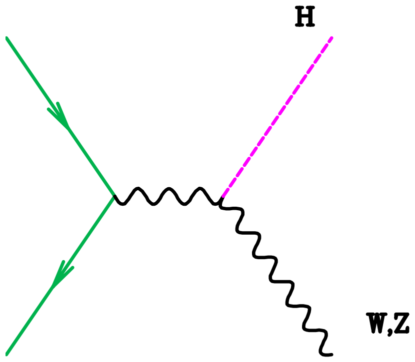
$$\frac{-ig_W m_f}{2M_W}$$

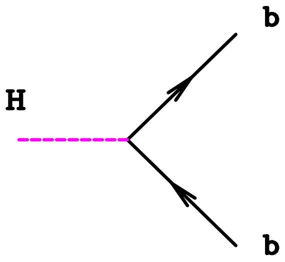
The Higgs boson couples proportional to mass





Favoured mode for detection of a light Higgs at LHC proceeds (both in production and decay) through loops





Favoured mode for the detection of a light Higgs at Tevatron proceeds (both in production and decay) through tree diagrams.

Higgs limits at the Tevatron

The Tevatron Higgs limits depend on an accurate estimate of the cross section, including its perturbative stability.

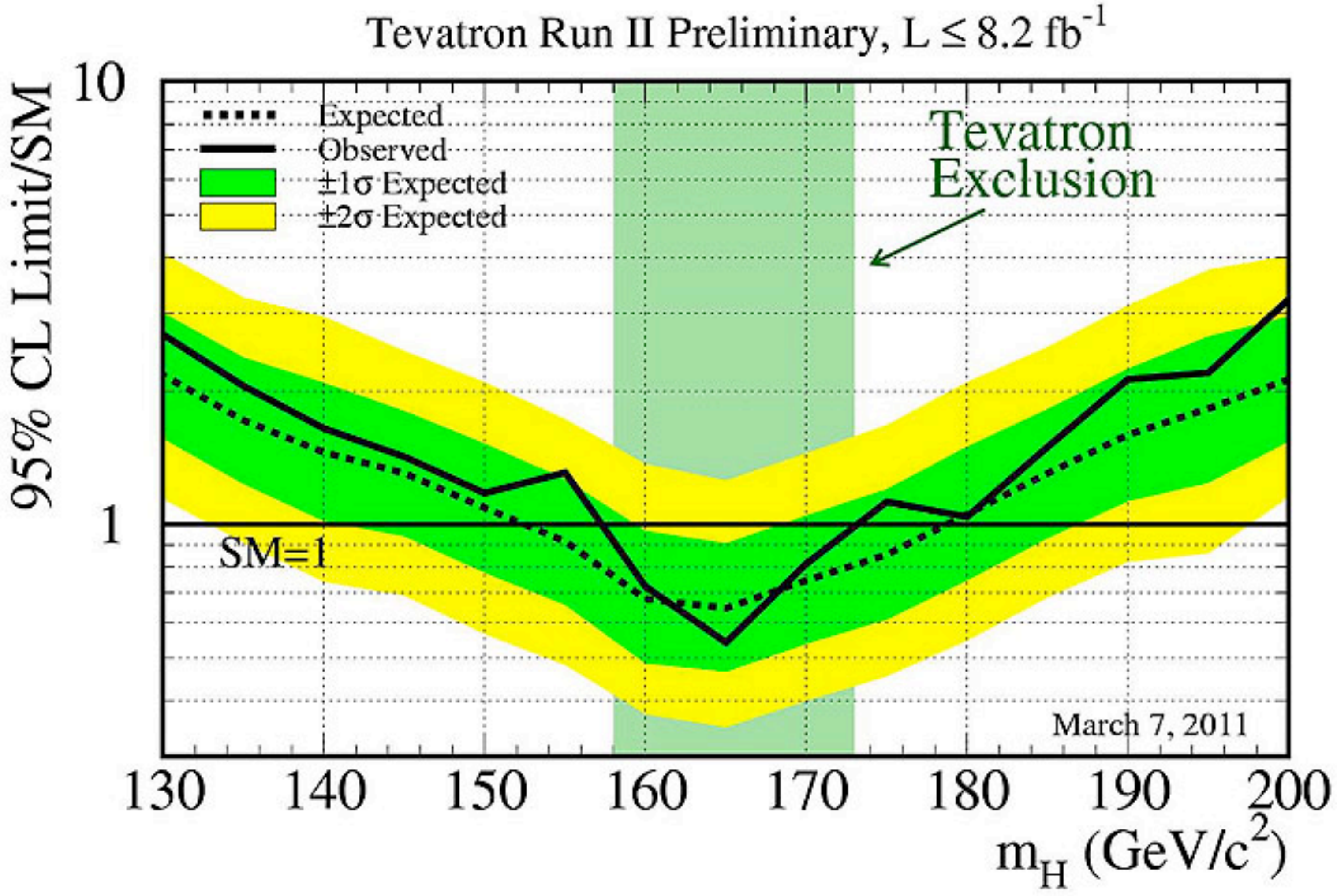
Anastasiou et al, arXiv:0905.3529

$\sigma(pp \to H \to W^+W^-)$ [fb]	LO	NLO	NNLO	K^{NLO}	K^{NNLO}
total($\mu = m_H$)	1.398±0.001	3.366±0.003	4.630±0.010	2.412	3.312
with selection cuts ($\mu = m_H$)	0.525±0.001	1.129±0.003	1.383±0.004	2.150	2.594

Selection cuts, especially veto on jet activity, increase the perturbative stability.

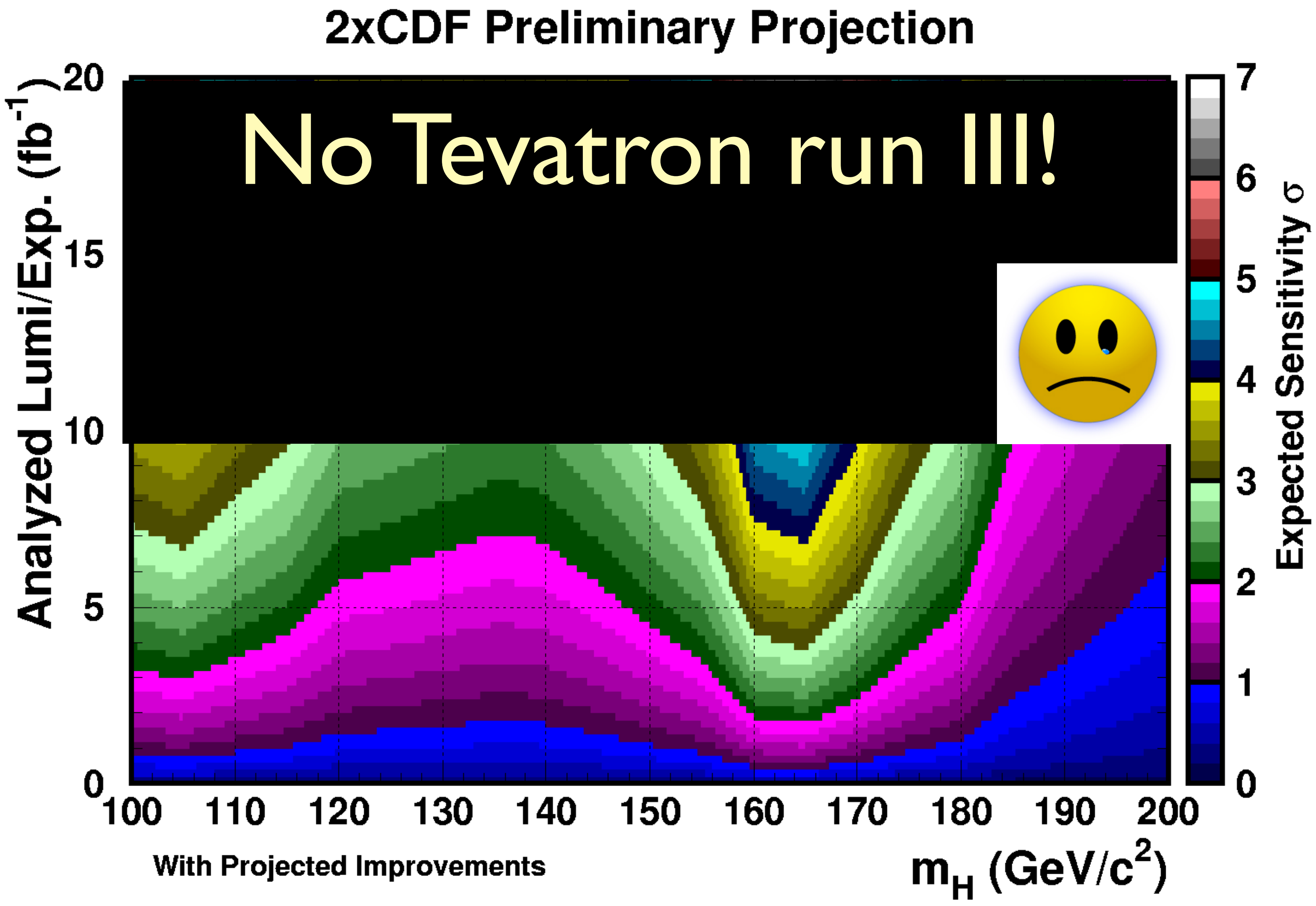
Moral: NNLO corrections are sometimes important;
we need exclusive information so that we can apply selection cuts.

Tevatron High Mass exclusion



Tevatron operating at $\sqrt{s}$=1.96 TeV excludes Higgs between 158 < M_H < 173 GeV at 95%cl

Higgs search projections at the Tevatron



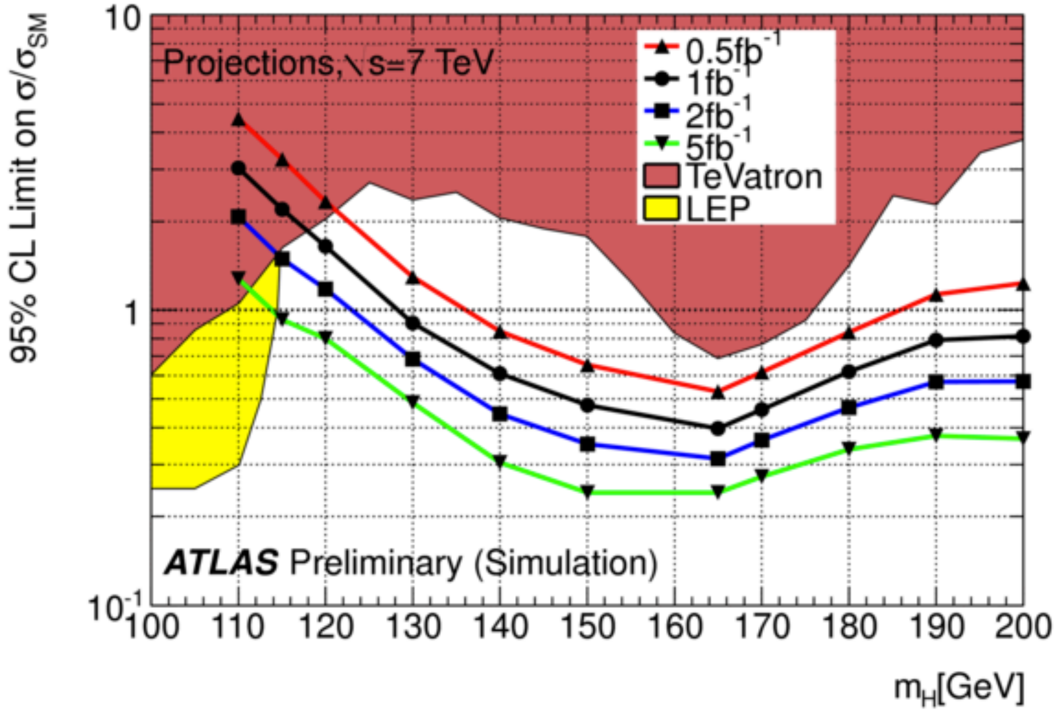
No Tevatron run III!

Tevatron luminosity
10 fb^{-1}per
experiment by end of
2011

By the end of 2011,
2.4 σ across the mass range 114 <m_H <180 GeV
3σ at m_H =114 GeV

Projected LHC Higgs sensitivity at 7 TeV

State of the art cross sections:NNLO for gg→ H, NLO for VBF,VH ; Background processes at NLO (MCFM)



ATLAS + CMS ≈ 2 x CMS	95% CL exclusion	3σ sensitivity	5σ sensitivity
1 fb^{-1}	120 - 530	135 - 475	152 - 175
2 fb^{-1}	114 - 585	120 - 545	140 - 200
5 fb^{-1}	114 - 600	114 - 600	128 - 482
10 fb^{-1}	114 - 600	114 - 600	117 - 535

The Higgs boson, if it exists between masses of 114-600 GeV will be discovered or ruled out in the next two years! (with a slightly worrying exception for 5 σ for the low mass region).

Radiative Corrections

- Precision tests of the standard model.
- Estimation of backgrounds:
  shapes for extrapolation and to subtract irreducible backgrounds, (ie cases where background and signature are not distinguishable).
- Before discovery of new physics -- to set accurate limits
- After discovery of new physics -- to determine the parameters of the model

Conclusions

- Significant advances in the calculation of one-loop multi-leg processes in the last three years. (We are almost in a position where the majority of the processes to be explored at LHC@7TeV with one fb^{-1} are calculated).
- Dream of automatic NLO calculation is becoming a reality.
- And there are already calculations needed at NNLO.....

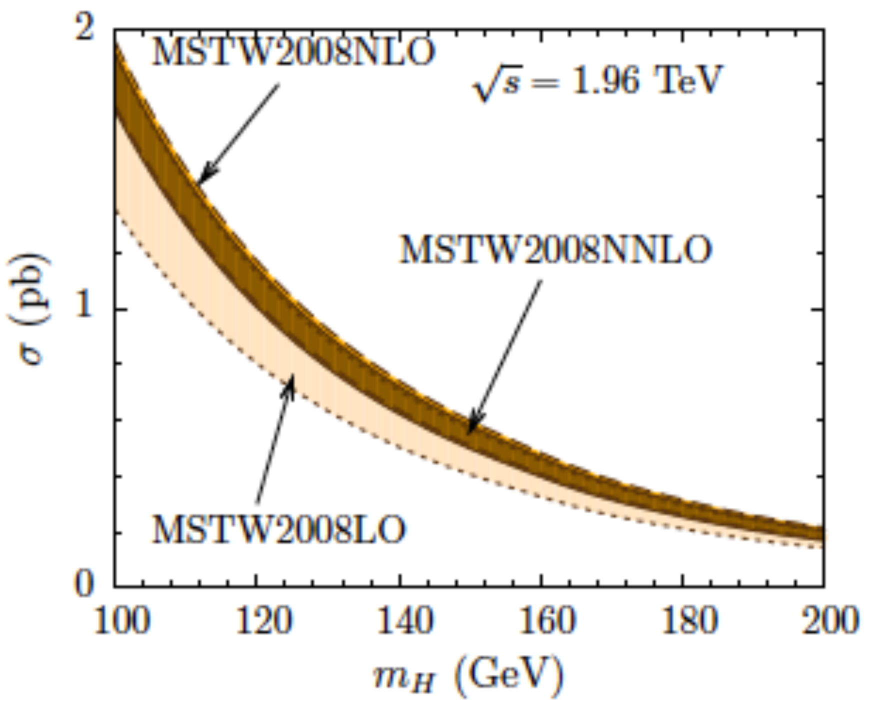
Backup

Higgs boson at 1.96TeV

Two contrasting views on the uncertainty
on the gluon-gluon fusion Higgs cross section

Ahrens et al, (ABNY) 0808.3008.0809.4283,1008.3162 $\sigma_{\rm ABNY}(M_H = 165) = 385^{+6}_{-2}{}^{+30}_{-32}$ fb

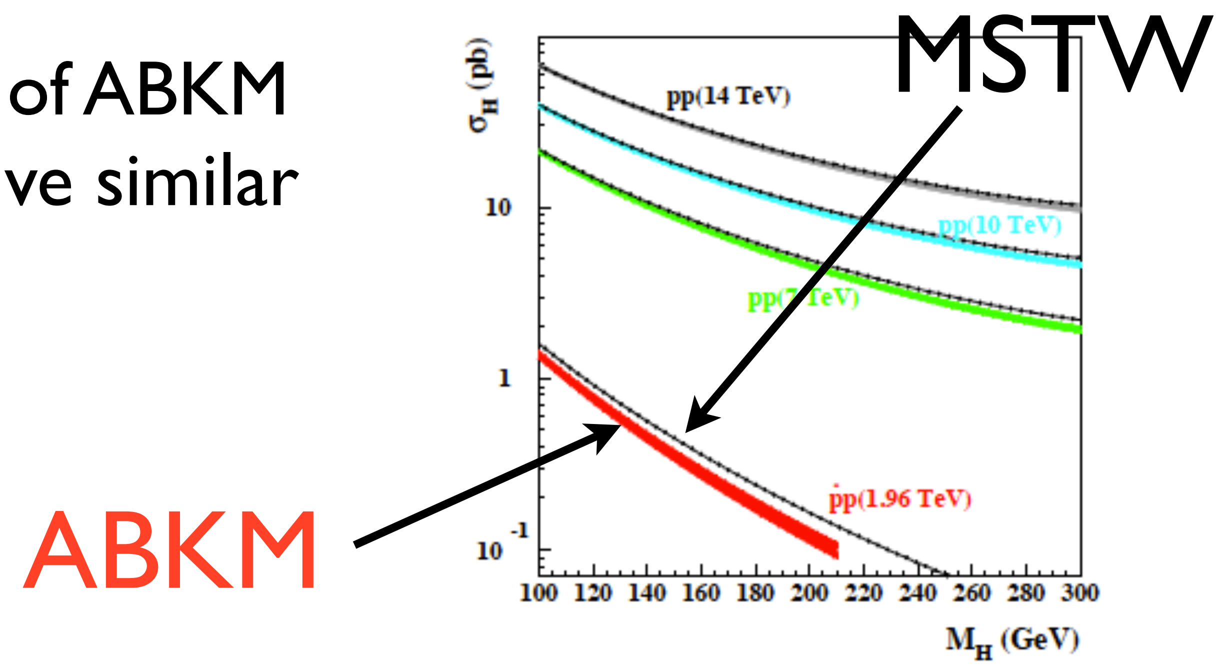
Baglio and Djouadi, (BD)1003.4266,1009.1363 $\sigma_{\rm BD}(M_H = 165) = 377^{+154}_{-135}$ fb



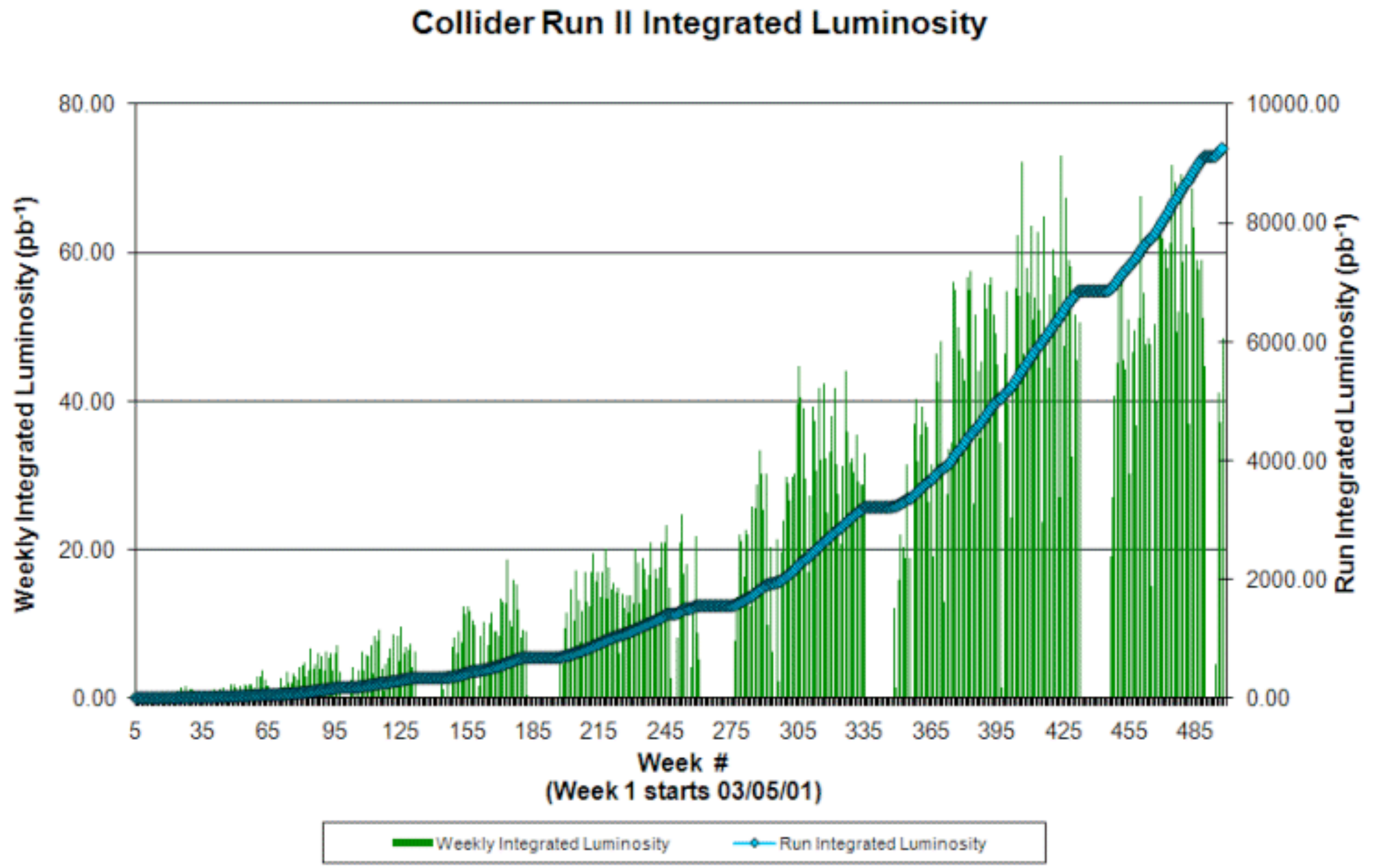
Source of uncertainty	ABNY	BD
Scale variation	3%(N^{3}LL)	+15%/-20%(NNLO)
PDF	5-10%	25% (including α_s)
α_s	6% (not strong correlation with PDF)	strongly correlated (included with PDF)

Major source of discrepancy is inclusion of ABKM parton distribution, MSTW and CTEQ give similar results.

Long(?) term solution : find the Higgs!



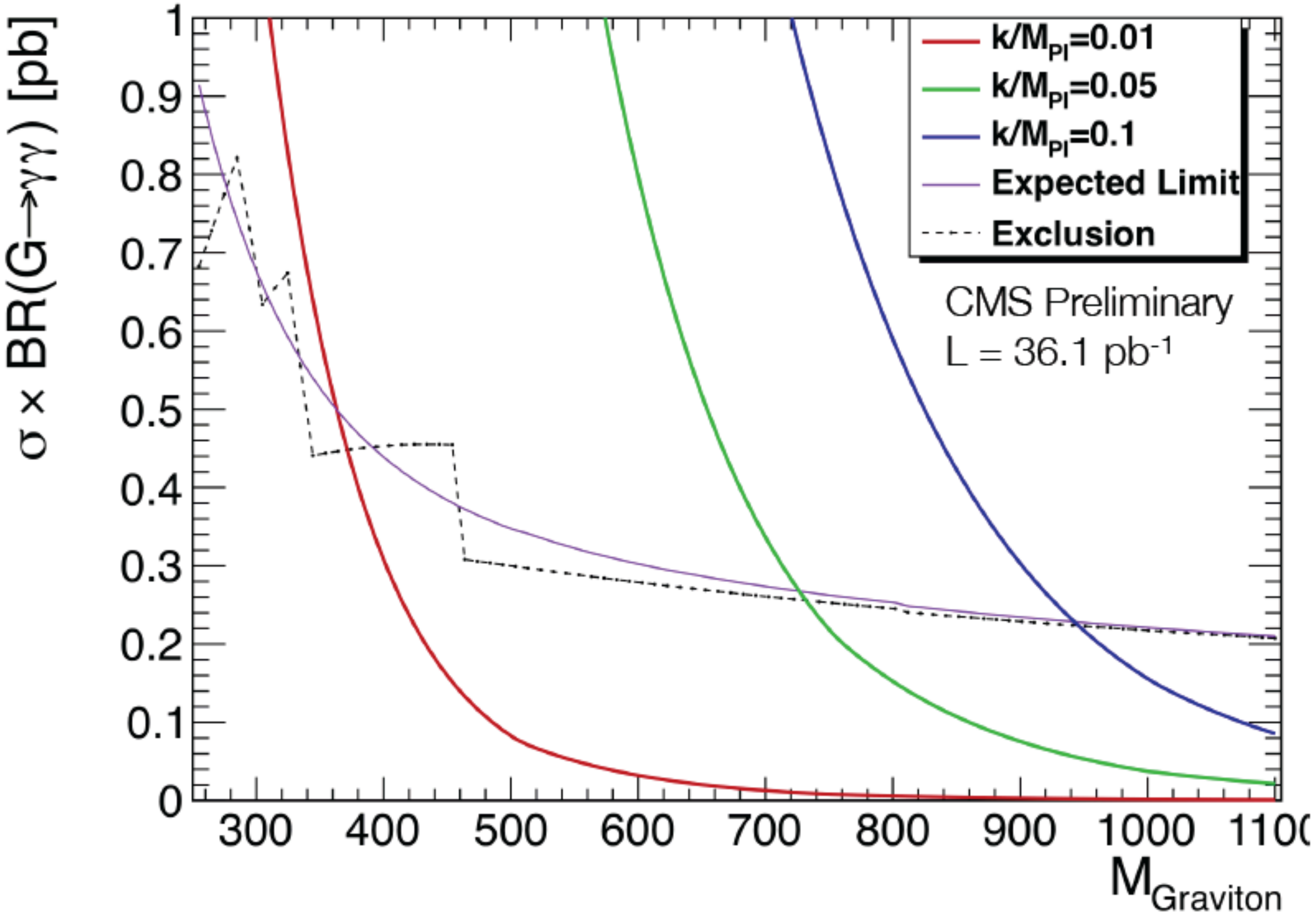
Tevatron Luminosity



Average weekly luminosity exceeds 50pb^{-1}!

Data taking efficiency CDF (~85%) and D0 (~92%)

RS Graviton → γ γ cross section limits



0.45 pb

0.26 pb

0.22 pb

allowed
region

Unitarity for one-loop diagrams

Important steps include:-

- First modern use of the idea Bern, Dixon,Kosower
- Cuts w.r.t. to loop momenta give (box) coefficients directly, complex momenta Britto, Cachazo, Feng
- OPP tensor reduction scheme, Ossola, Pittau, Papadopoulos
- Integrating the OPP procedure with unitarity Ellis, Giele, Kunszt
- D-dimensional unitarity Giele, Kunszt, Melnikov

Ossola,Papadopoulos,Pittau:hep-ph/0609007

Semi-numerical unitarity in a nutshell

Imagine an integrand expressible in terms of bubbles (two denominators) and tadpoles(one denominator).

$$\mathcal{A}(l) = \frac{b}{d_1(l)d_2(l)} + \frac{a_1}{d_1(l)} + \frac{a_2}{d_2(l)}$$

$$d_1(l) = l^2 - m^2, \quad d_2(l) = (l+q)^2 - m^2$$

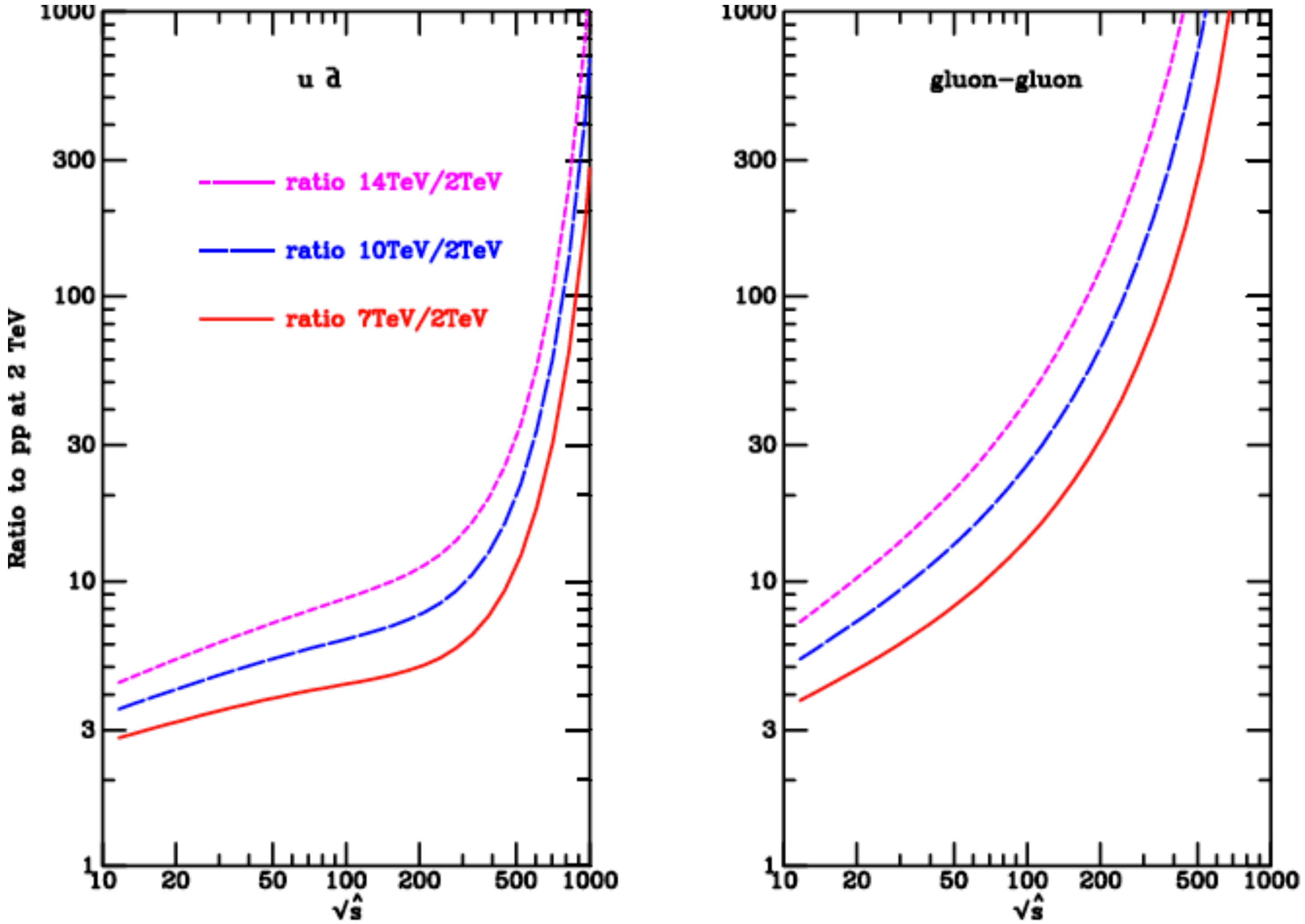
l-independent coefficients b,a₁,a₂ can be extracted numerically

$$\begin{aligned} b &= \left\{ d_1(l)d_2(l)\Big[\mathcal{A}(l)\Big] \right\}\Big|_{l=l_{12}} \\ a_1 &= \left\{ d_1(l)\left[\mathcal{A}(l) - \frac{b}{d_1(l)d_2(l)}\right] \right\}\Big|_{l=l_1} \\ a_2 &= \left\{ d_2(l)\left[\mathcal{A}(l) - \frac{b}{d_1(l)d_2(l)}\right] \right\}\Big|_{l=l_2} \end{aligned}$$

Fine print: Need complete understanding of parametric form of integrand (including terms which vanish upon integration and extension to d-dimensions)

Parton luminosities
Tevatron vs LHC

Not all of the beam energy is available for interaction.
The available energy is determined by the parton distribution functions which can be combined into parton luminosities



- For qqbar initiated physics at a mass scale below 200 GeV, the Tevatron with 10fb^{-1} is superior to the LHC at $\sqrt{s}$=7 TeV with 1fb^{-1}.