Hadron collider phenomenology

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INFN LNF

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hadron collider phenomenology
is a very broad topic

I had to make drastic choices

I focused on some aspects of high Q^2 physics
at CDF, D0, ATLAS, CMS

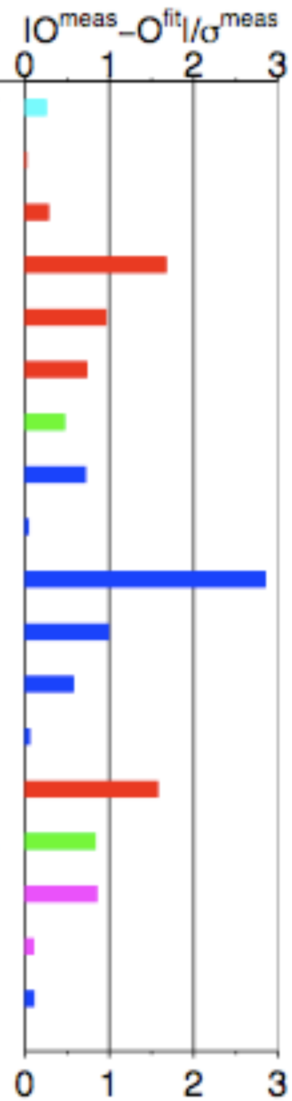
$\color{red}{S}$tandard $\color{red}{M}$odel

Past & Present:
the LEP/SLD/Tevatron legacy

The Standard Model has been a spectacular success, weathering out all challenges

The comparison with the electroweak precision measurements has not changed much in the last years

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.743
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01643
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21581
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.377
Γ_W [GeV]	2.097 ± 0.048	2.092
m_t [GeV]	172.6 ± 1.4	172.8



March 2008

Top quark production

Moriond 10

- CDF cross section is

  $\sigma = 7.50 \pm 0.48$ pb

  relative uncertainty is

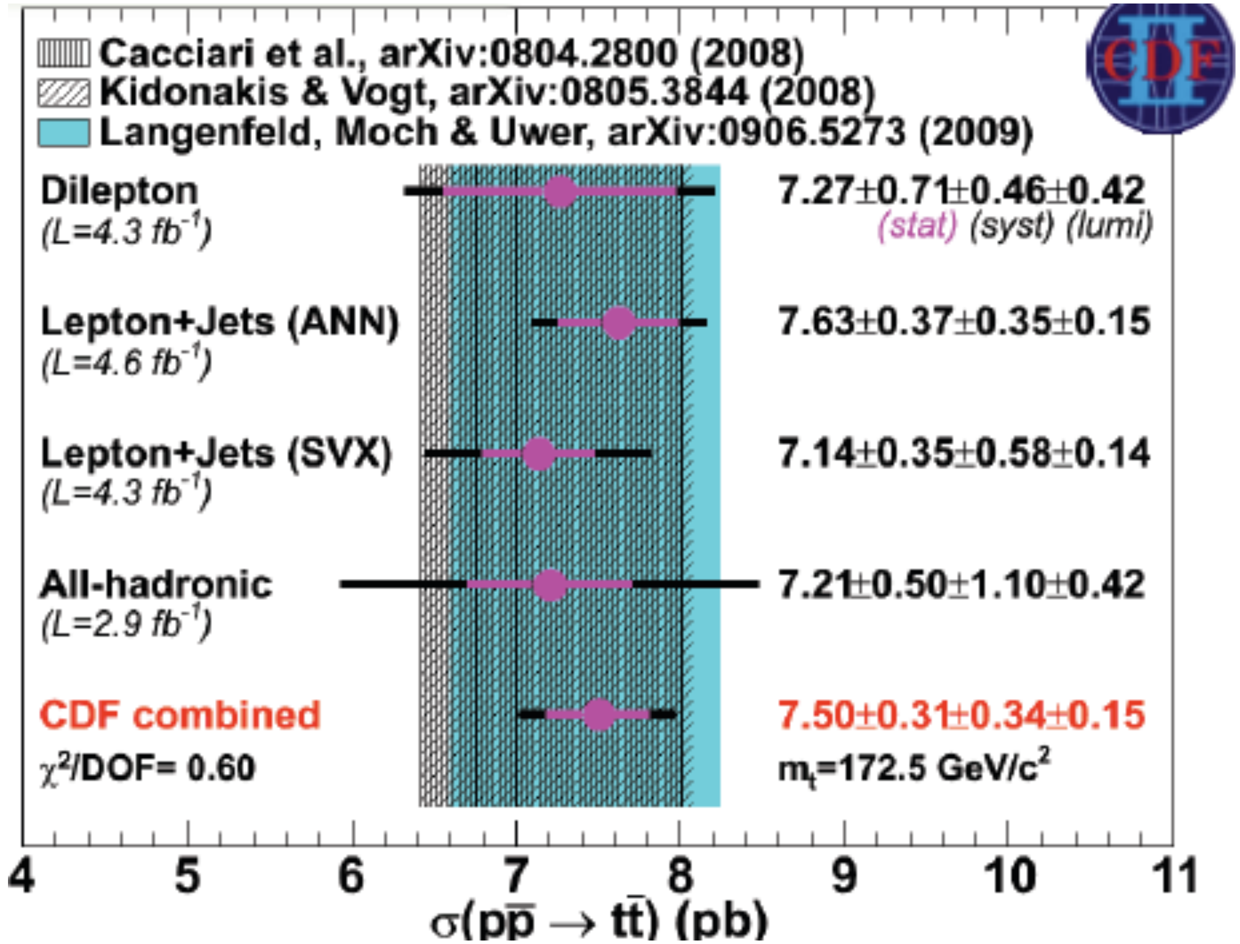
  $\Delta\sigma/\sigma = 6.4\%$

- D0 cross section is

  $\sigma = 8.18^{+0.98}_{-0.87}$ pb

  but with a smaller sample (~ $1 pb^{-1}$)

- CDF & D0 cross sections not combined yet; likely this winter



Top quark Mass

ICHEP 10

Tevatron

Run I: 178.0 ± 4.3 GeV

Run I + II: 173.3 ± 1.1 GeV

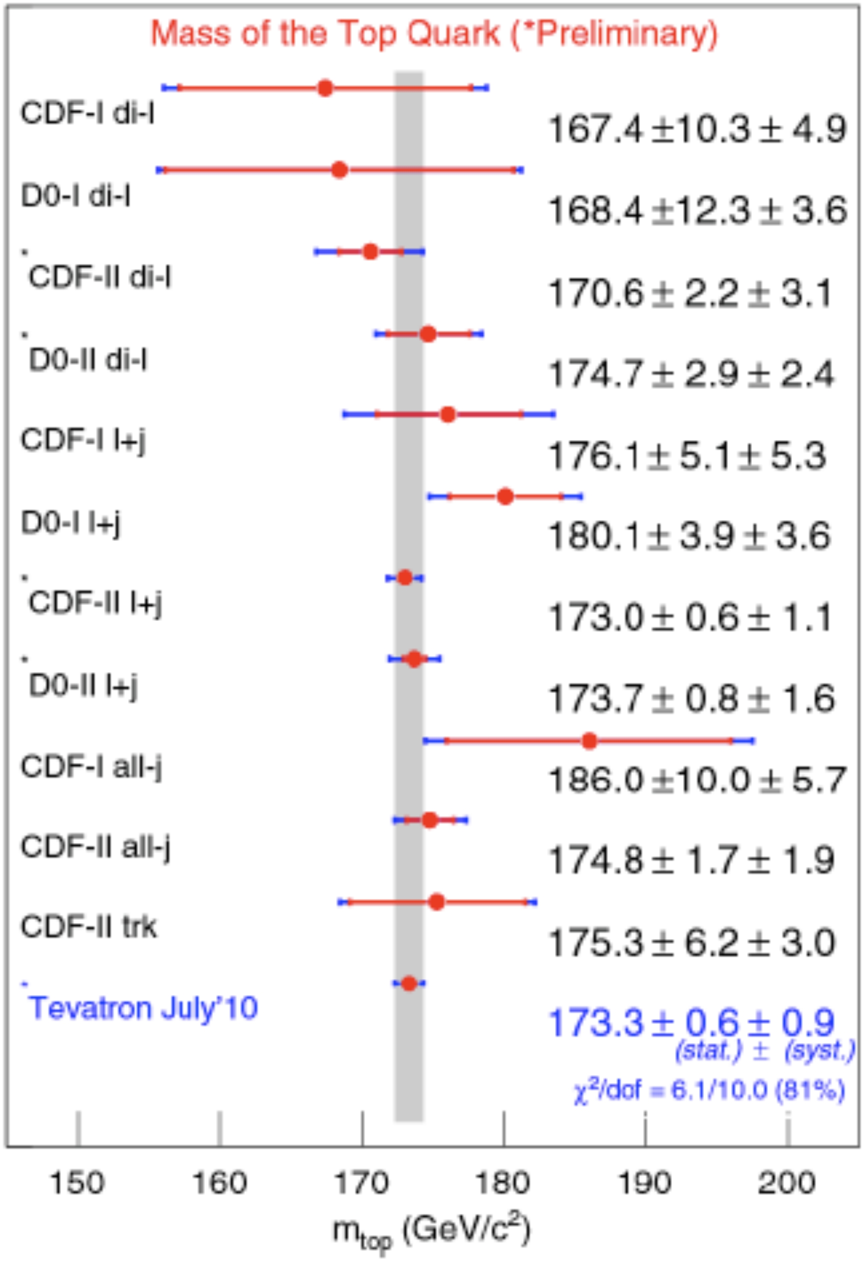
$\Delta m/m = 0.6$ %

Theory

$\Delta m/m = 0.2\ \Delta\sigma/\sigma$

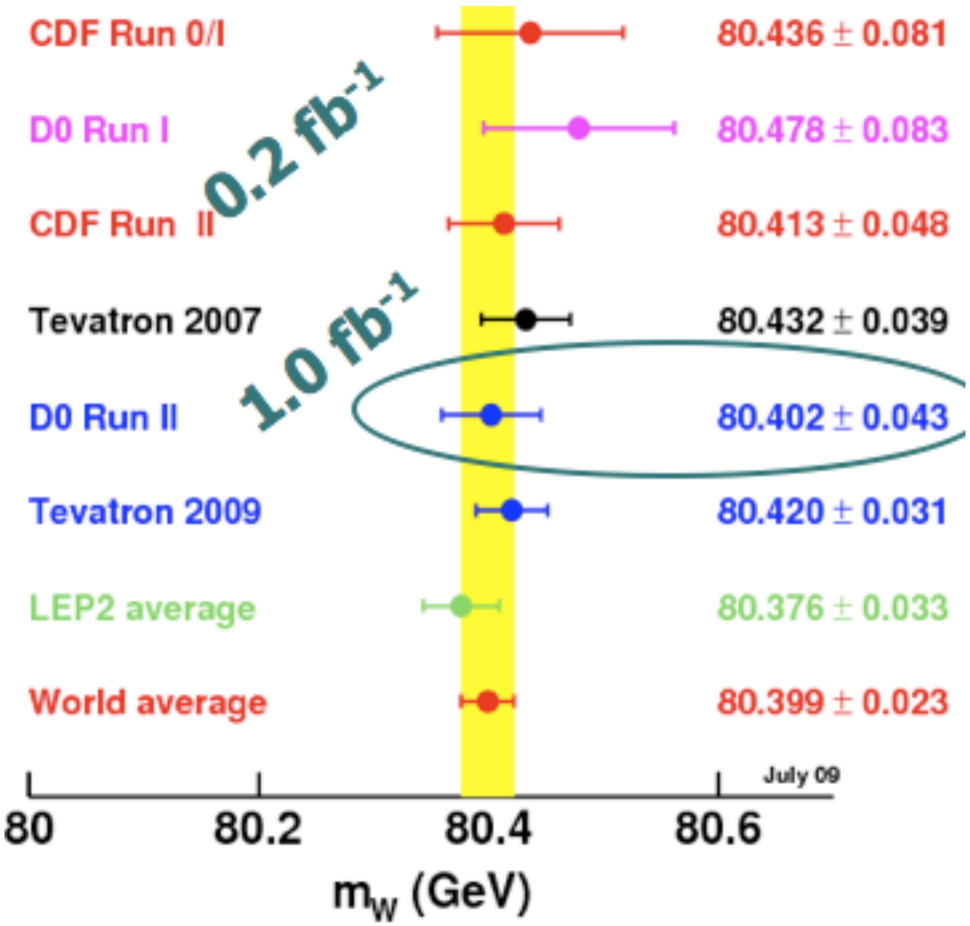
$\Delta\sigma/\sigma = 6\%$ → $\Delta m = 2$ GeV

the EXP error is $\Delta m = 1$ GeV
so the TH σ should be known at 3% level



W boson Mass

Moriond 10



D0's is world best measurement

$\Delta m_W/m_W = 0.03\%$

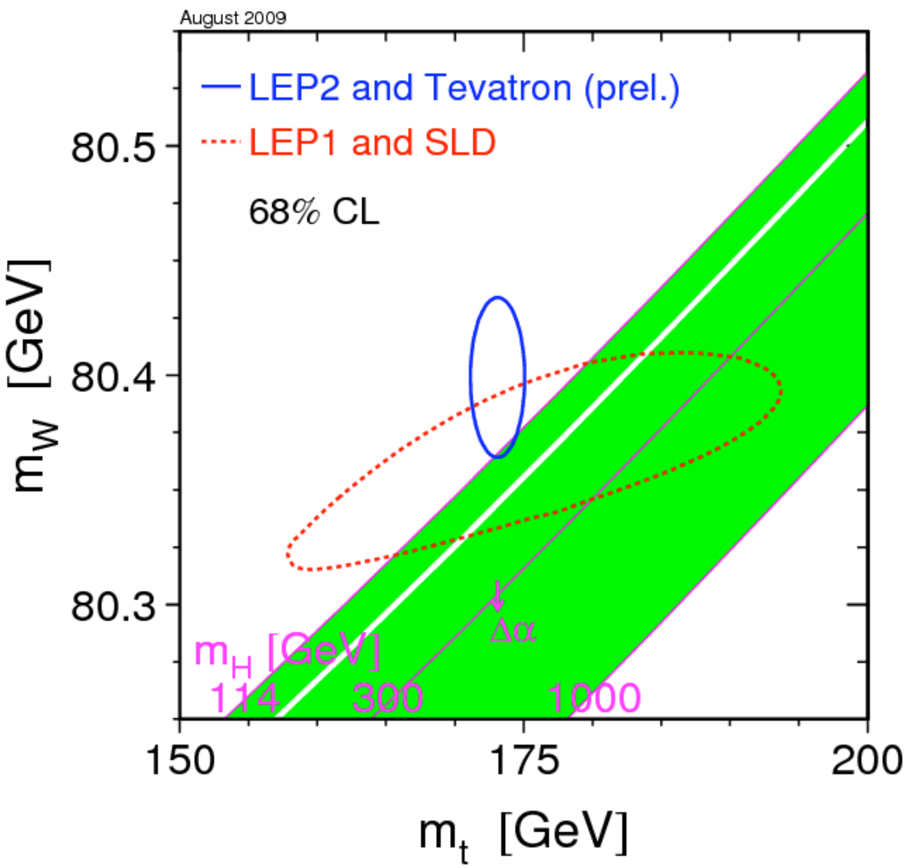
not changed much over last years

- Tevatron average more precise than LEP's
- D0 measurement based on 500k *W*'s
- ATLAS, CMS will collect each as many *W*'s after ~ 200 pb^{-1}

Effects on global EW fits

ElectroWeak fits point to a light Higgs boson

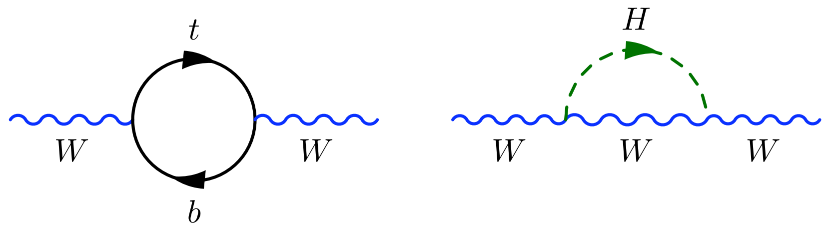
Moriond 10



tree level $m_W = m_Z \cos\theta_W$

one loop

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right) = \frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$



$$\Delta r_t = -\frac{3\alpha}{16\pi}\frac{\cos^2\theta_W}{\sin^4\theta_W}\frac{m_t^2}{m_W^2}$$

$$\Delta r_H = \frac{11\alpha}{48\pi\sin^2\theta_W}\ln\frac{m_H^2}{m_W^2}$$

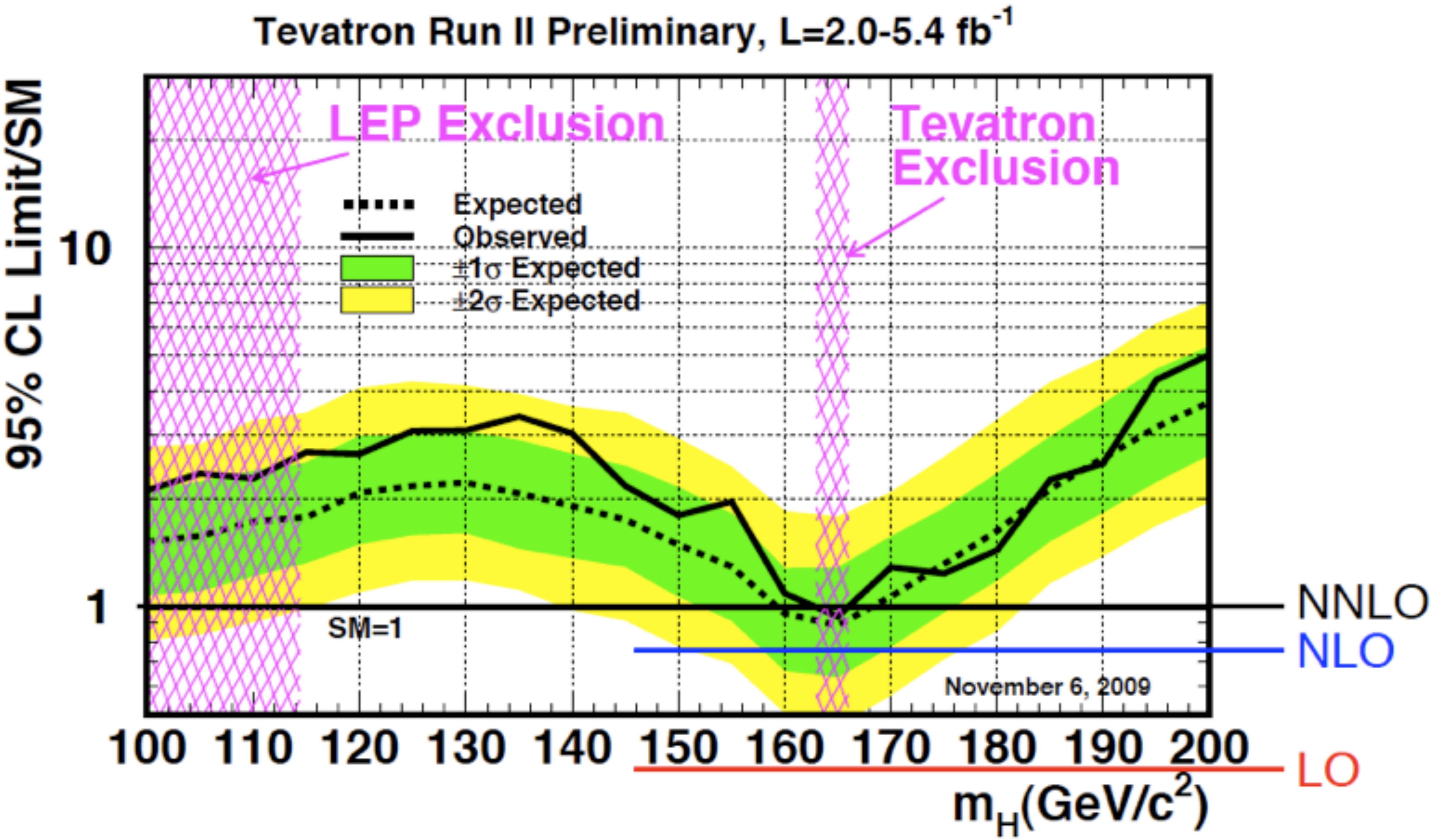
so $\delta m_W \propto m_t^2$

$\delta m_W \propto \ln m_H$

- reducing the top mass error

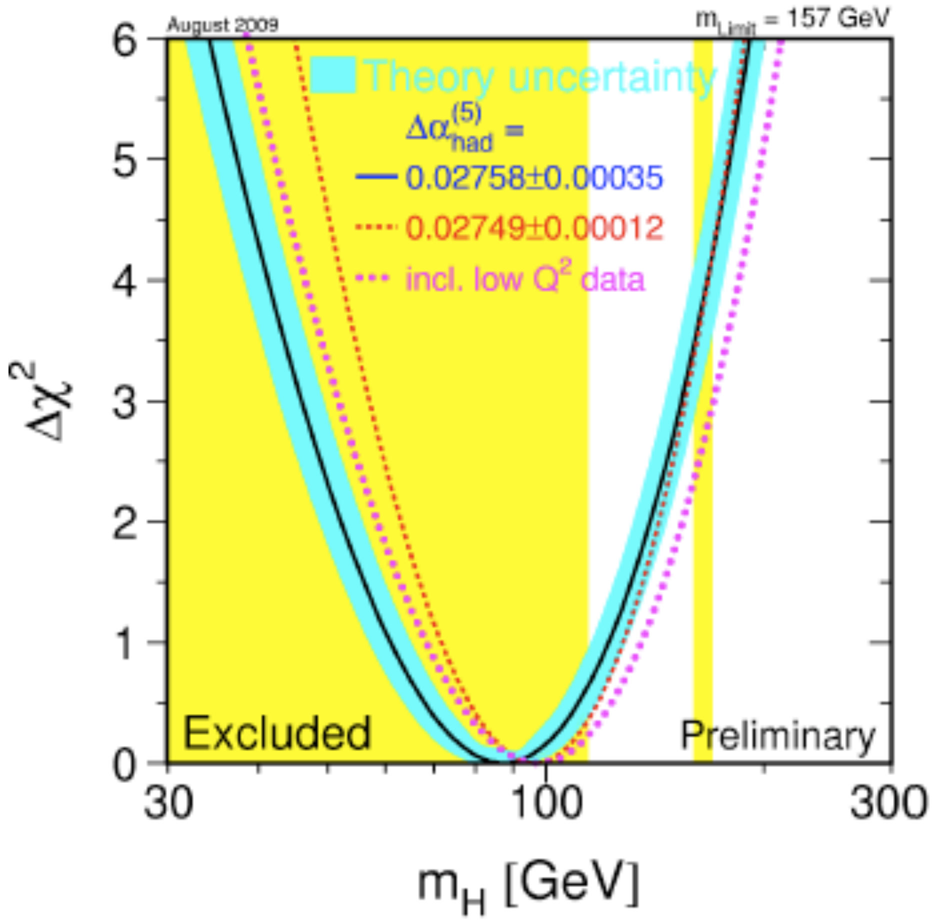
  δm_t = 1 GeV ⇒ $\delta m_W(m_t)$ = 6 MeV

Higgs search at Tevatron



Higgs boson Mass

Moriond 10



m_H > 114.4 GeV
from direct search at LEP

$m_H = 87^{+36}_{-27}$ GeV
from EW fits

At 95% CL
m_H < 160 GeV from EW fits
m_H < 190 GeV combined with direct search at LEP

- use m_t to estimate m_H from EW corrections
- as m_t changes, large shifts in m_H

the Standard Model is in excellent shape, but ...

ElectroWeak Symmetry Breaking	not tested
neutrino masses and mixings	not included
dark matter	?
baryogenesis	?

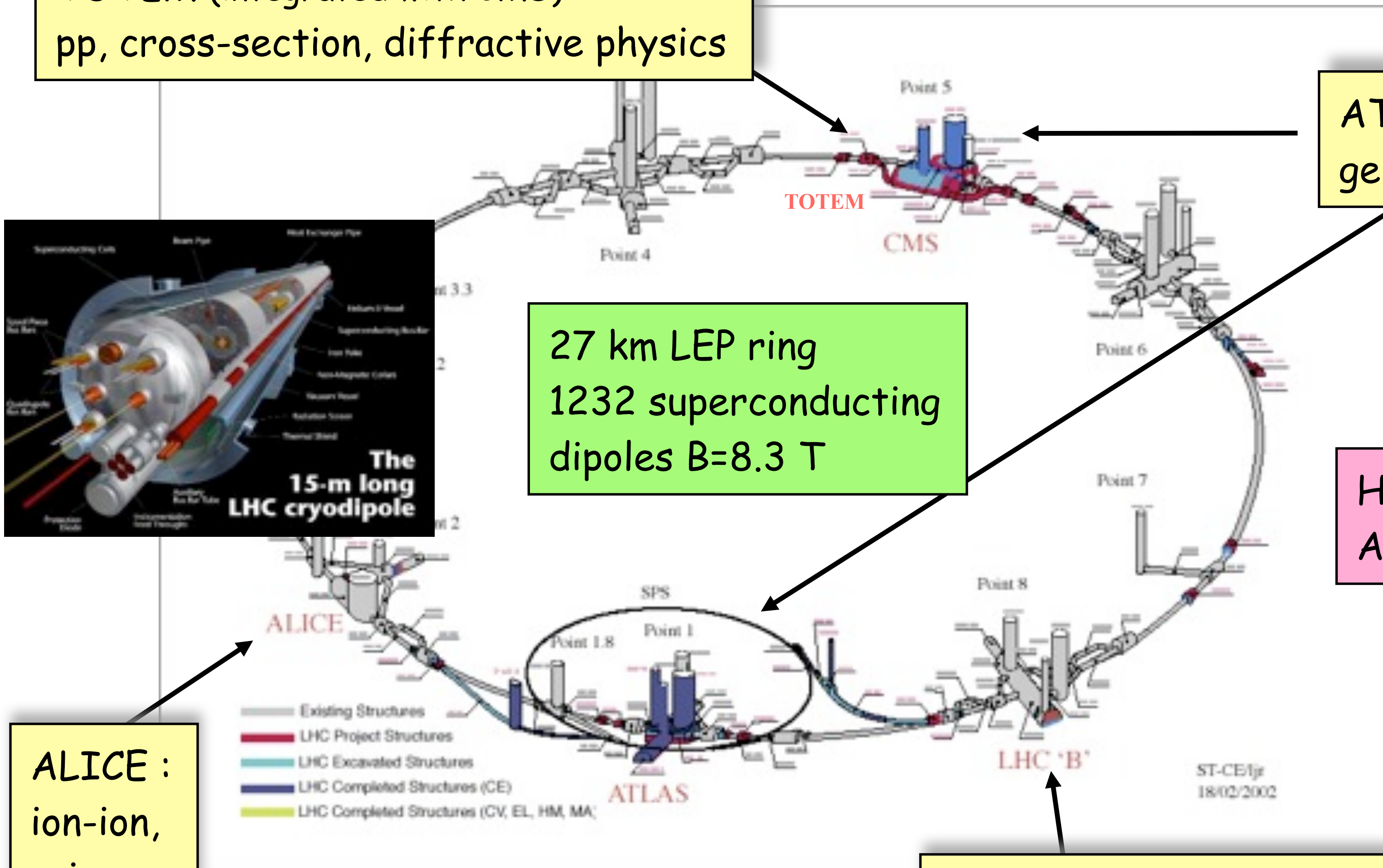
- foremost task of the LHC is to understand the EWSB: find the Higgs boson or whatever else is the cause of it

LHC

- pp $\sqrt{s}$ = 14 TeV $L_{design} = 10^{34}\ cm^{-2}\ s^{-1}$ (after 2013)
  $\sqrt{s}$ = 7 TeV $L_{initial} \leq 10^{33}\ cm^{-2}\ s^{-1}$ (2010-2011)
- Heavy ions (e.g. Pb-Pb at $\sqrt{s}$ ~ 1000 TeV)

TOTEM (integrated with CMS):
pp, cross-section, diffractive physics

ATLAS and CMS :
general purpose



27 km LEP ring
1232 superconducting
dipoles B=8.3 T

Here:
ATLAS and CMS

ALICE :
ion-ion,
p-ion

LHCb :
pp, B-physics, CP-violation

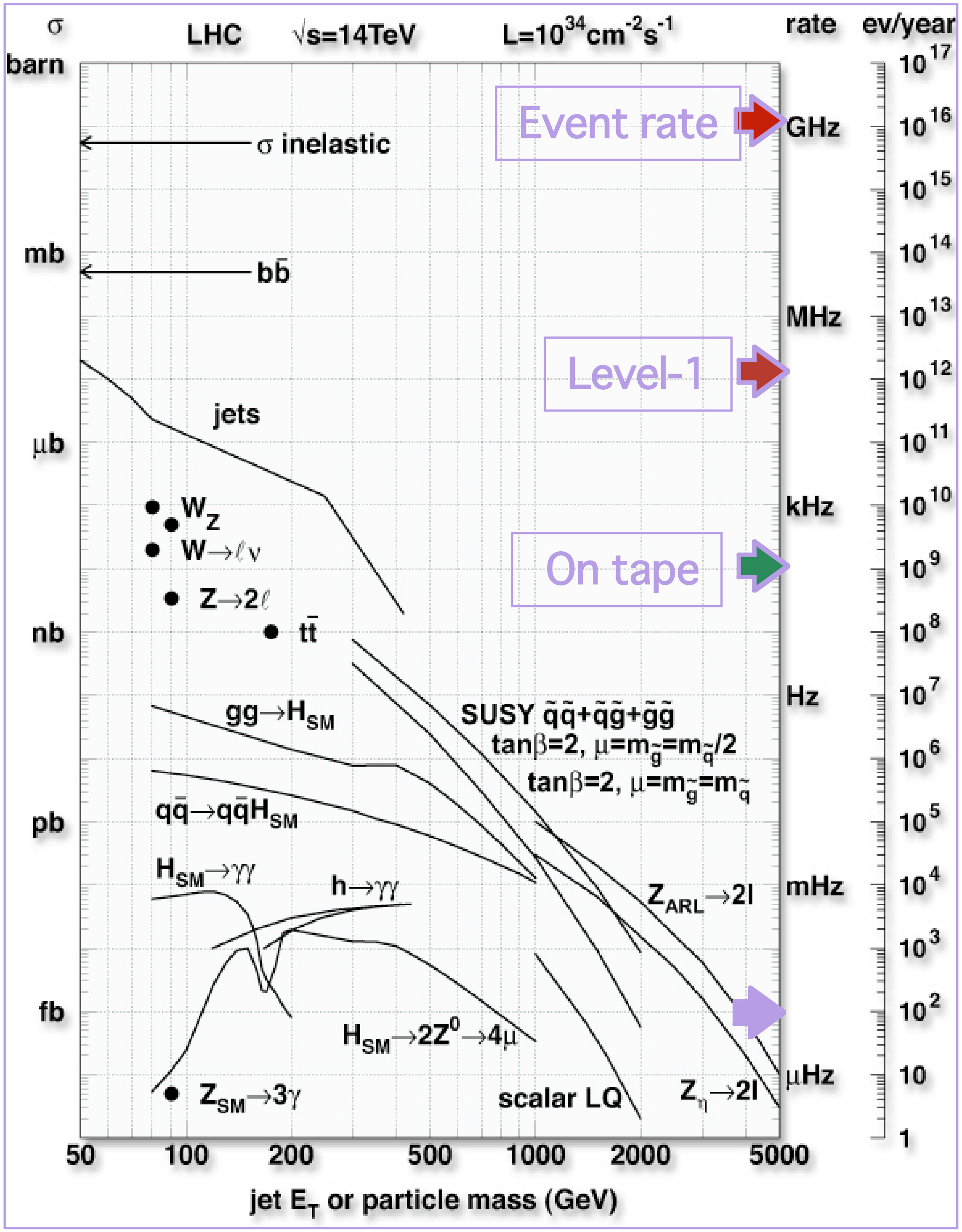
LHC at present (end of August 2010)

average luminosity 7.08×10^{30} cm^{-2} s^{-1}

peak luminosity 1.07×10^{31} cm^{-2} s^{-1}
to be increased by a factor 10 (100) by end of 2010 (2011)

integrated luminosity   3.7 pb^{-1}
(but 1.7 pb^{-1} collected in the last week of running)

LHC at design energy and luminosity



the LHC will be a SM factory with (perhaps) lots of New Physics signals

design luminosity

$L = 10^{34}\ cm^{-2}\ s^{-1} = 10^{-5}\ fb^{-1}\ s^{-1}$

integrated luminosity (per year)

$L \approx 100\ fb^{-1}\ yr^{-1}$

With 1 fb^{-1} at 14 TeV we shall get

final state	events	overall # of events
jets (p_T > 100 GeV)	10^9	
jets (p_T > 1 TeV)	10^4	
$W \to e\nu, \mu\nu$	$2 \cdot 10^7$	10^7 (Tevatron)
$Z \to \ell\ell$	$2 \cdot 10^6$	10^6 (LEP)
$b\bar{b}$	$5 \cdot 10^{11}$	10^9 (BaBar, Belle)
$t\bar{t}$	$8.5 \cdot 10^5$	10^4 (Tevatron)

even at 1 fb^{-1} luminosity, LHC beats all the other accelerators

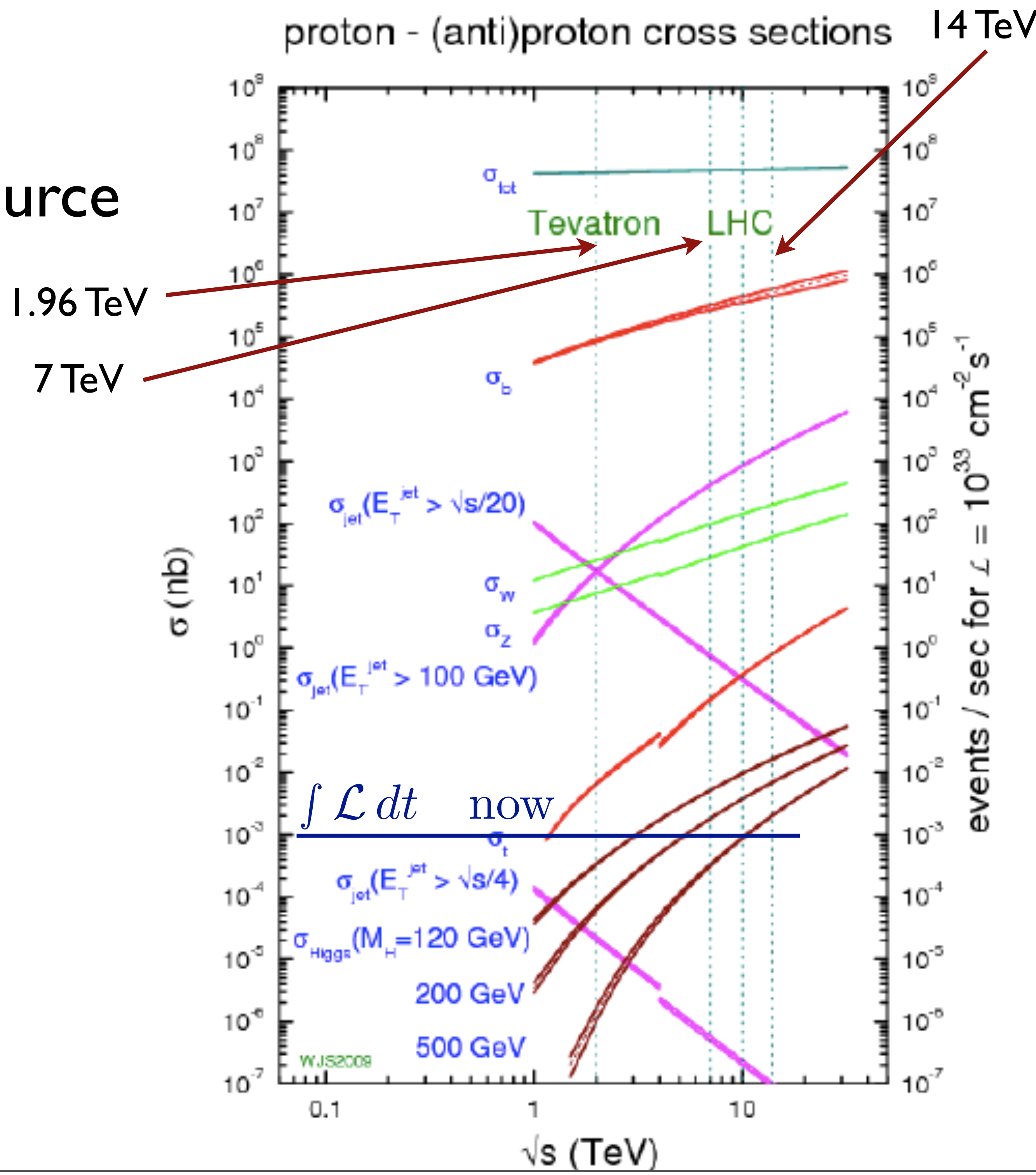
at 7 TeV, figures are slightly reduced:

W x-sect goes from 20 nb at 14 Tev to 10 nb at 7 TeV

tt x-sect goes from 850 pb at 14 TeV to 450 pb at 7 TeV

Tevatron - LHC reach as a function of the energy

Even at 7 TeV,
LHC is a copious source of SM processes,
in particular lots of
W, *Z*, top, jets



LHC: present & future

- calibrate the detectors, and re-discover the SM
  i.e. measure known cross sections: jets, *W*, *Z*, *tt*

- understand the EWSB/find New-Physics signals
  (ranging from Z' to leptons, to gluinos in SUSY
  decay chains, to finding the Higgs boson)

- constrain and model the New-Physics theories

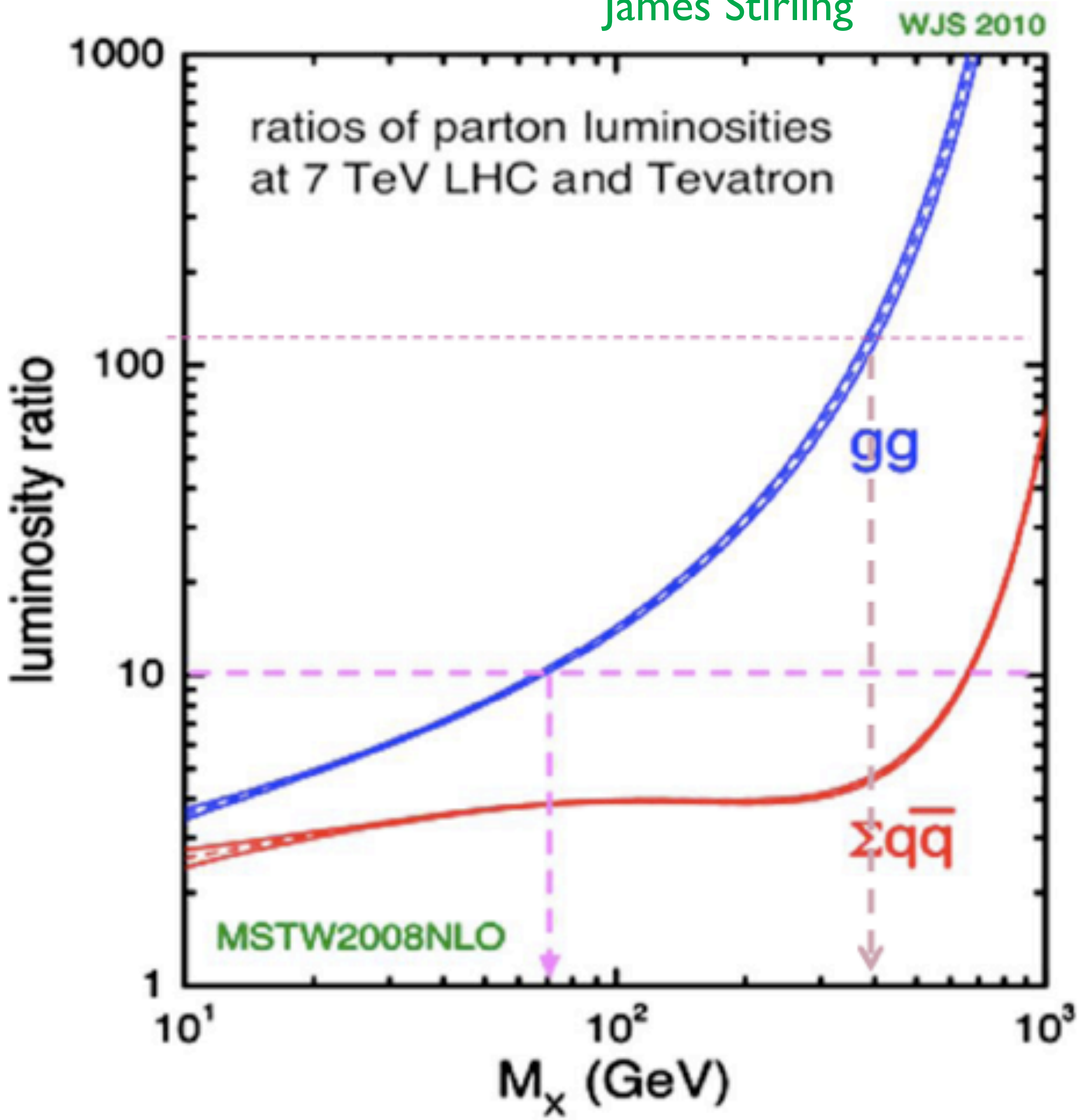
in all the steps above (except probably Z' to leptons)
precise QCD predictions play a crucial role

SM Higgs at the LHC at 7 TeV

How do the production rates change when going from Tevatron to the LHC at 7 TeV ?

Higgs: mainly gg fusion
→ gain a factor ~ 15

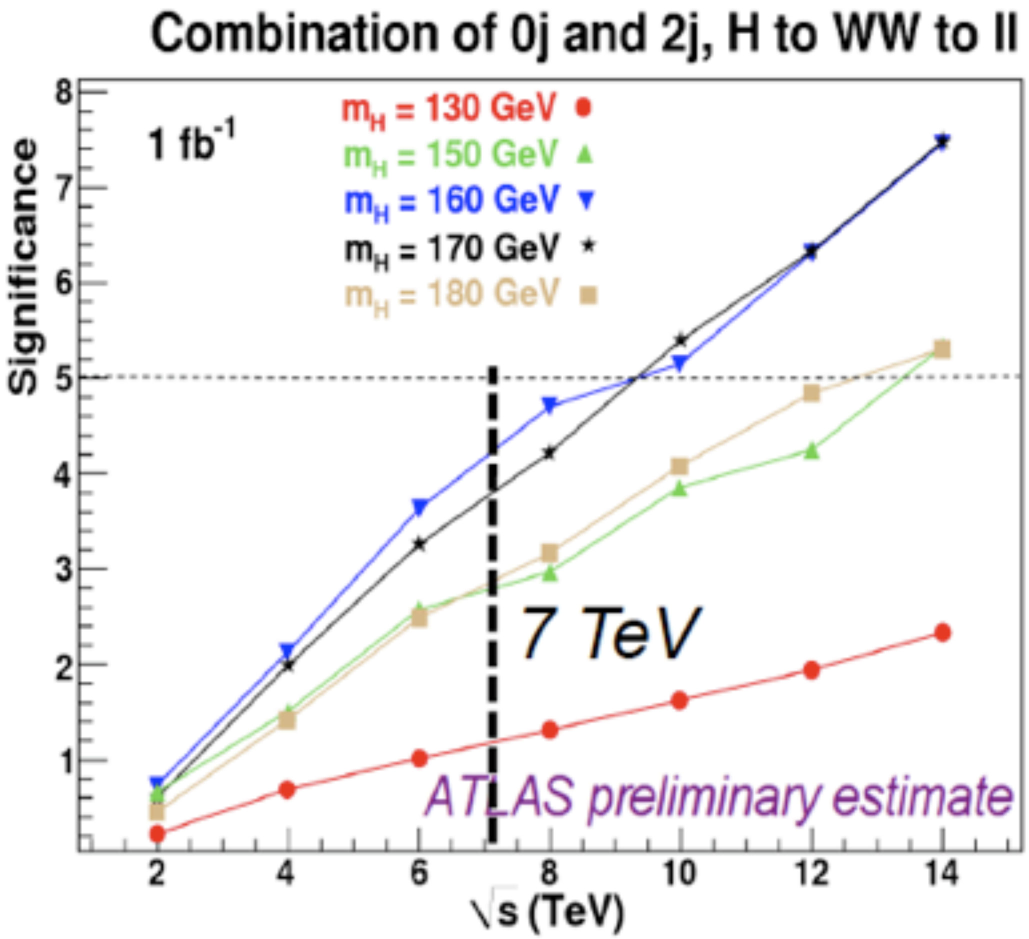
James Stirling



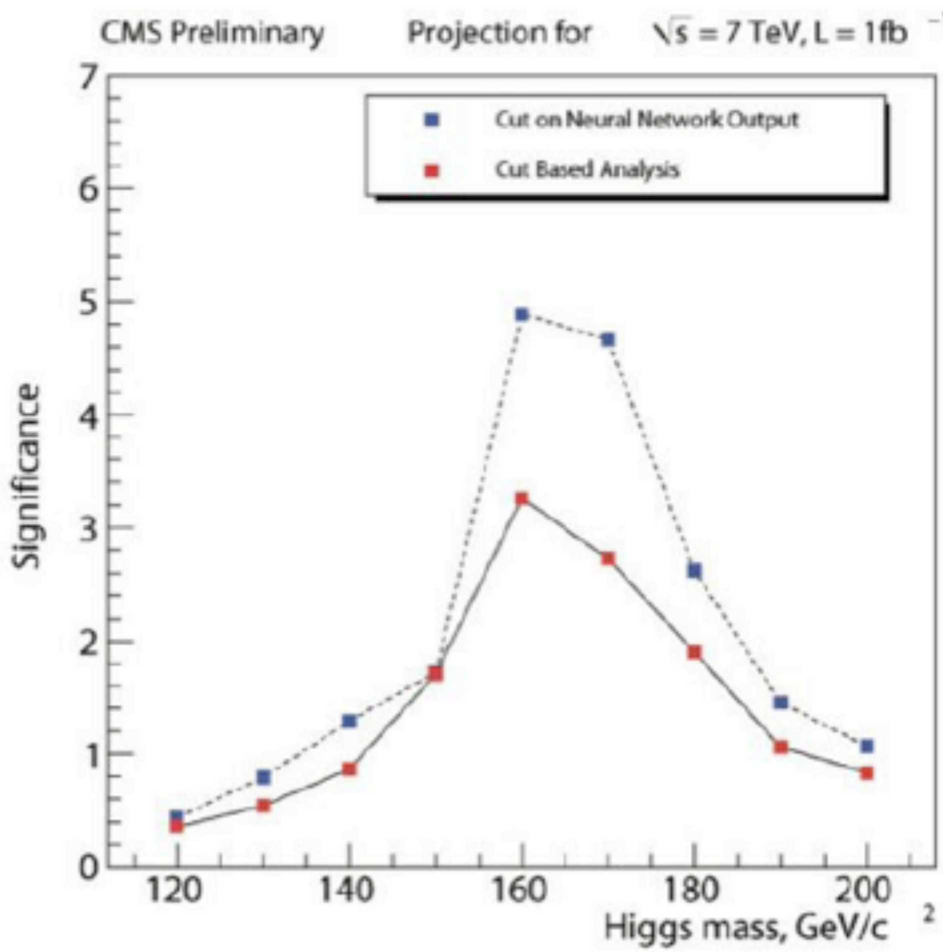
SM Higgs at the LHC at 7 TeV

LHCC meeting of 5/05/10

$1 fb^{-1}$ ATLAS H→WW→ll



CMS H→WW→ll



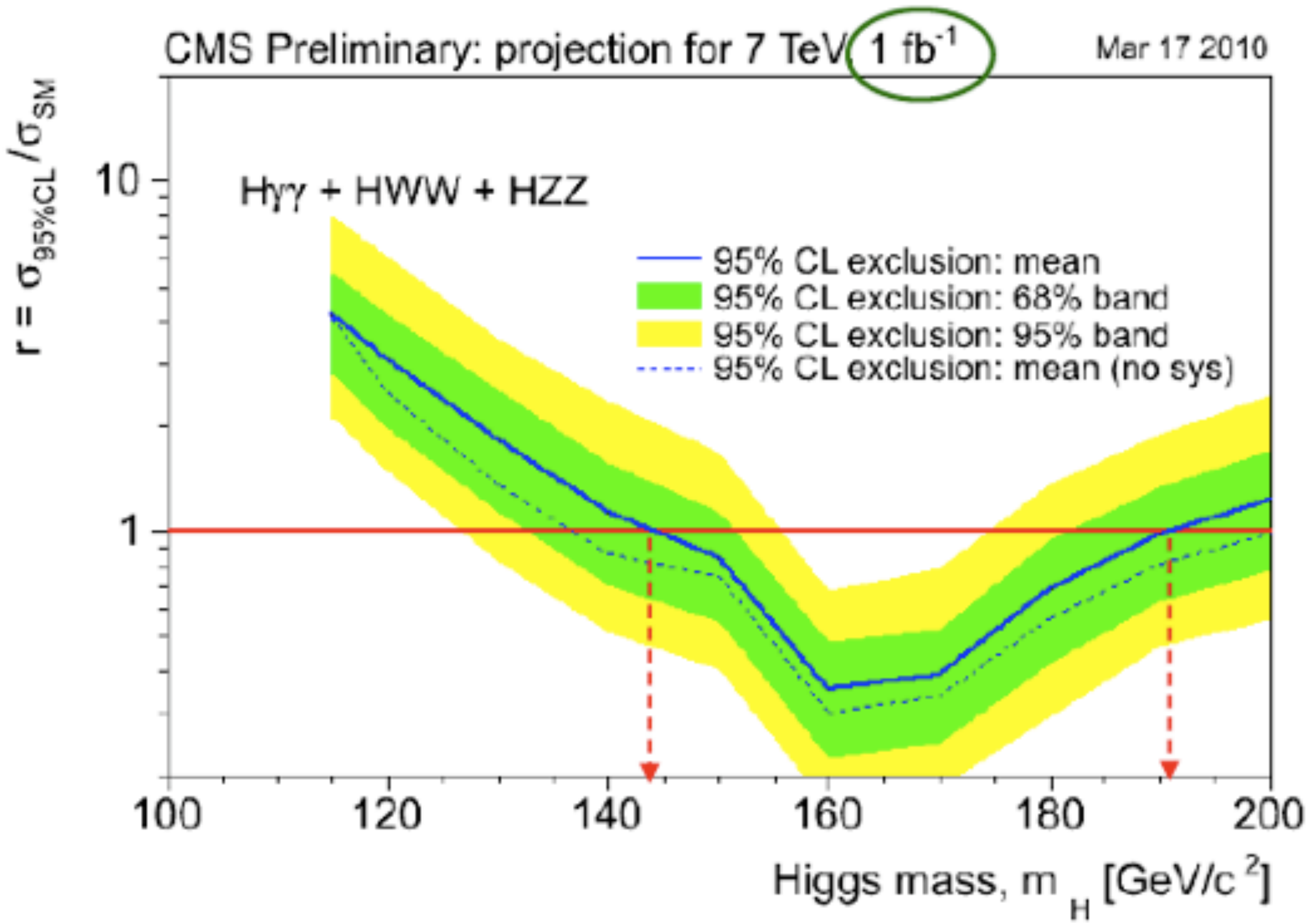
- depending on the analysis technique, discovery at 3 to 5 σ at m_H ~ 160 GeV

SM Higgs at the LHC at 7 TeV

1fb^{-1}

LHCC meeting of 5/05/10

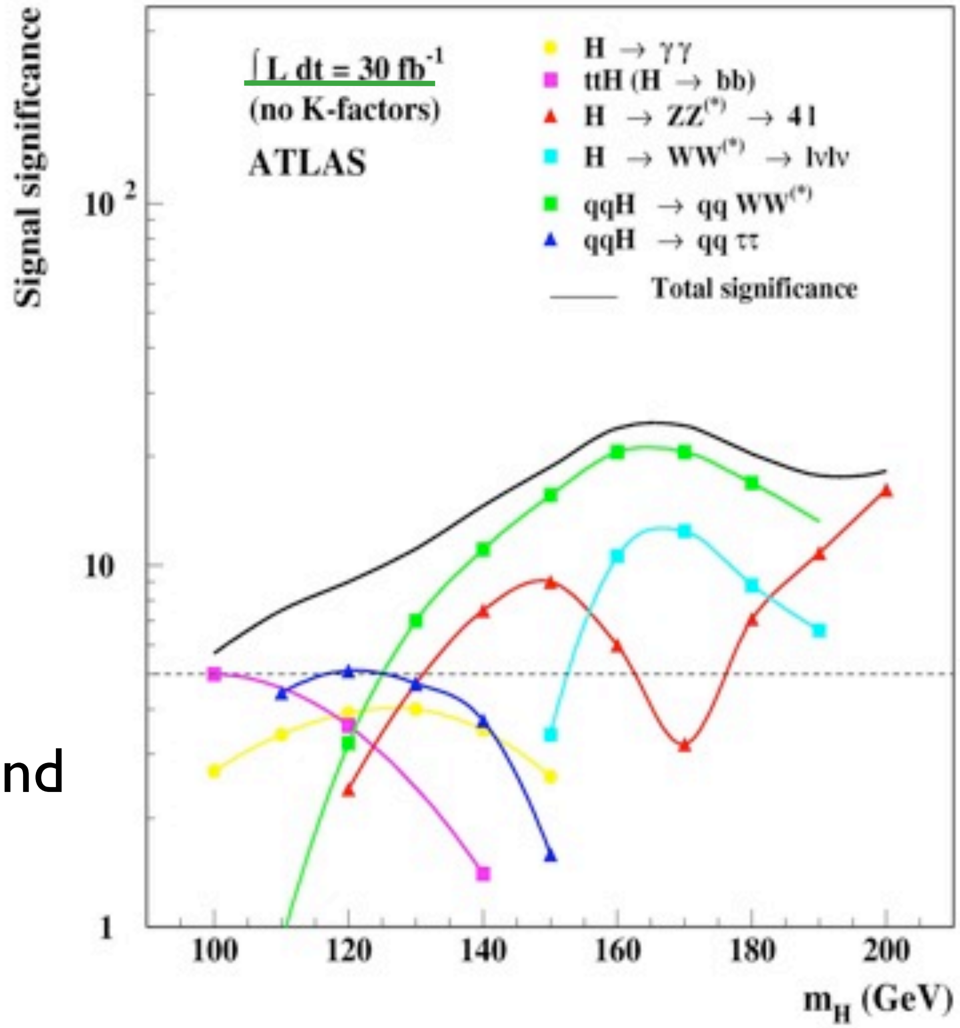
Exclusion: One experiment only



- exclusion range ~ 145 - 190 GeV

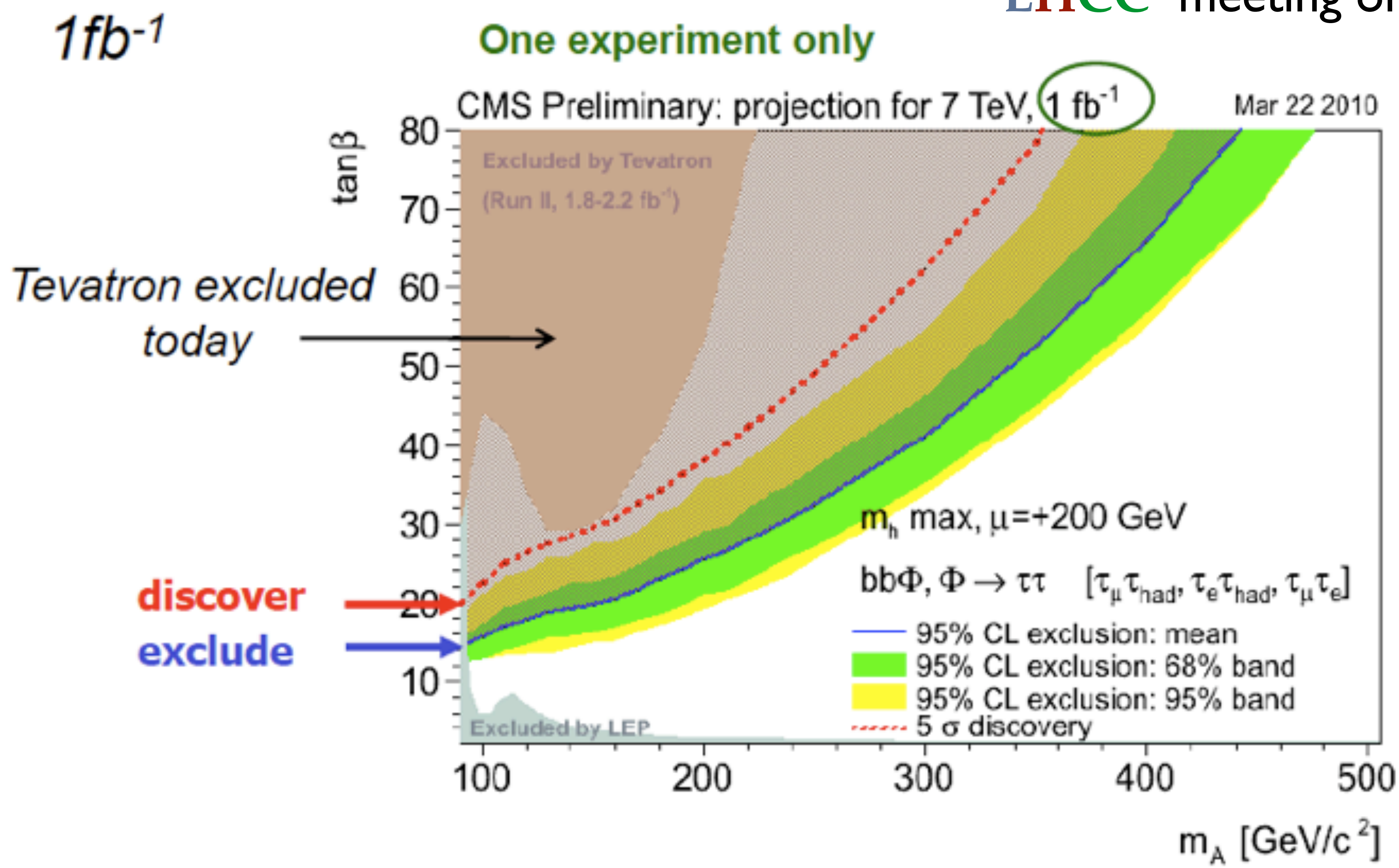
SM Higgs at the LHC at 14 TeV

- ... of course production rates are much bigger at 14 TeV with an adequate luminosity
- however, when energy and luminosity are fixed, the issue is to estimate accurately the significance
- *i.e.* to compute accurately signal and background production rates
- background = *W*, *Z*, top + *n* jets
- an accurate estimate of the background is the hardest thing to do
- more on that later



MSSM neutral Higgs at the LHC at 7 TeV

LHCC meeting of 5/05/10

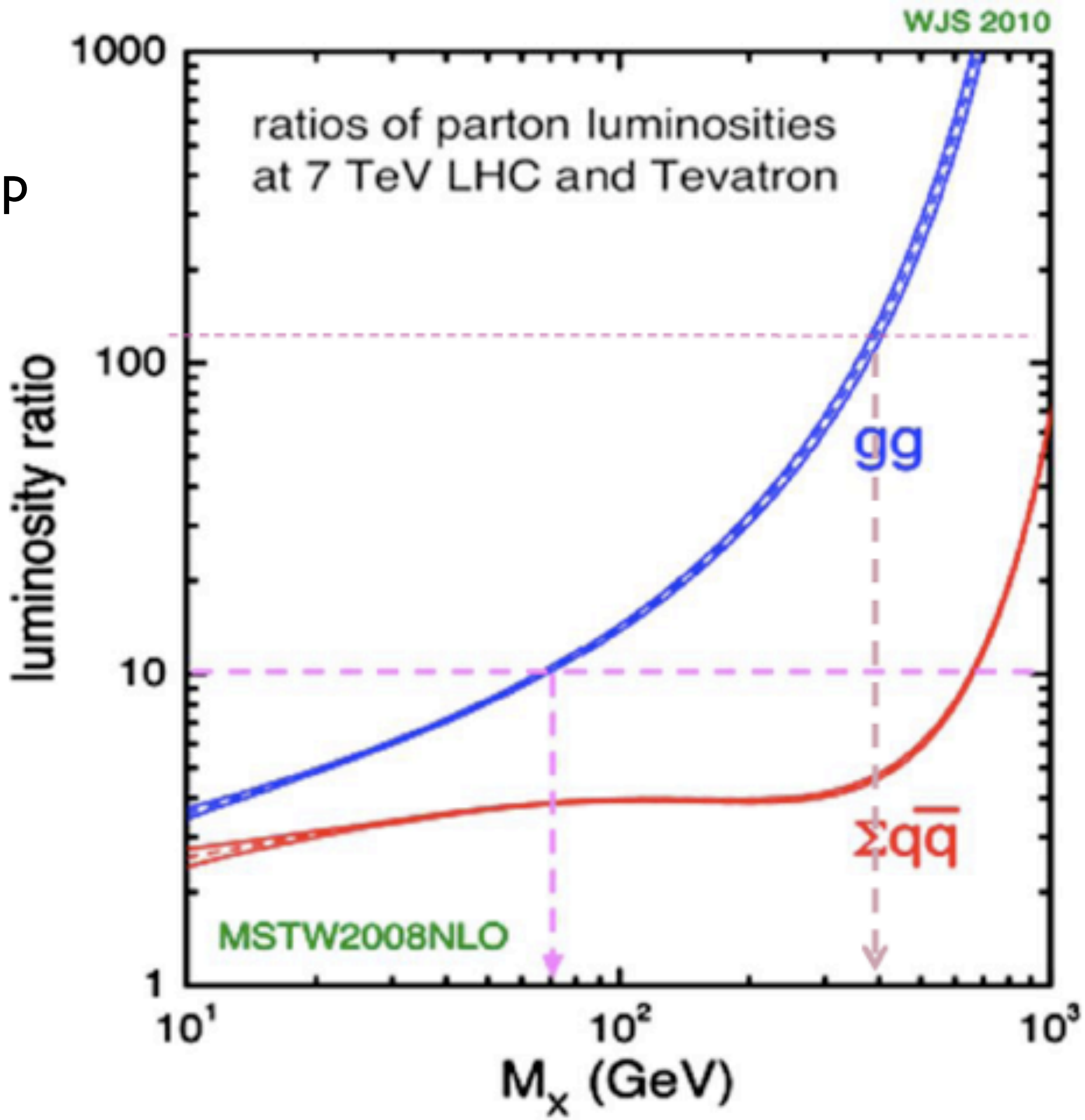


- discovery (exclusion) down to tan $\beta \sim 20$ (15) at low m_A
- with 1 fb^{-1} at 7 TeV, LHC overtakes Tevatron at 10 fb^{-1} on all Higgs searches

New Physics at the LHC at 7 TeV

squarks at m ~ 350 GeV
assume production like for top
85% qq + 15% gg
0.85 x 10 + 0.15 x 1000
→ gain a factor ~ 150 - 200

Z' at m ~ 1 TeV
qq production
→ gain a factor ~ 50



New Physics at the LHC at 7 TeV

- don't have time to cover the many New Physics production channels (please see the minutes of the LHCC meeting of 5/05/10)
  it suffices to say that with 1 fb^{-1} at 7 TeV:

- for SUSY, LHC will be able to discover squarks with 500 GeV < *m* < 1 TeV,

- for dilepton resonances (*Z'*), sensitivity (discovery/exclusion) up to 1.5 TeV, (with 100 pb^{-1} up to 1 TeV)

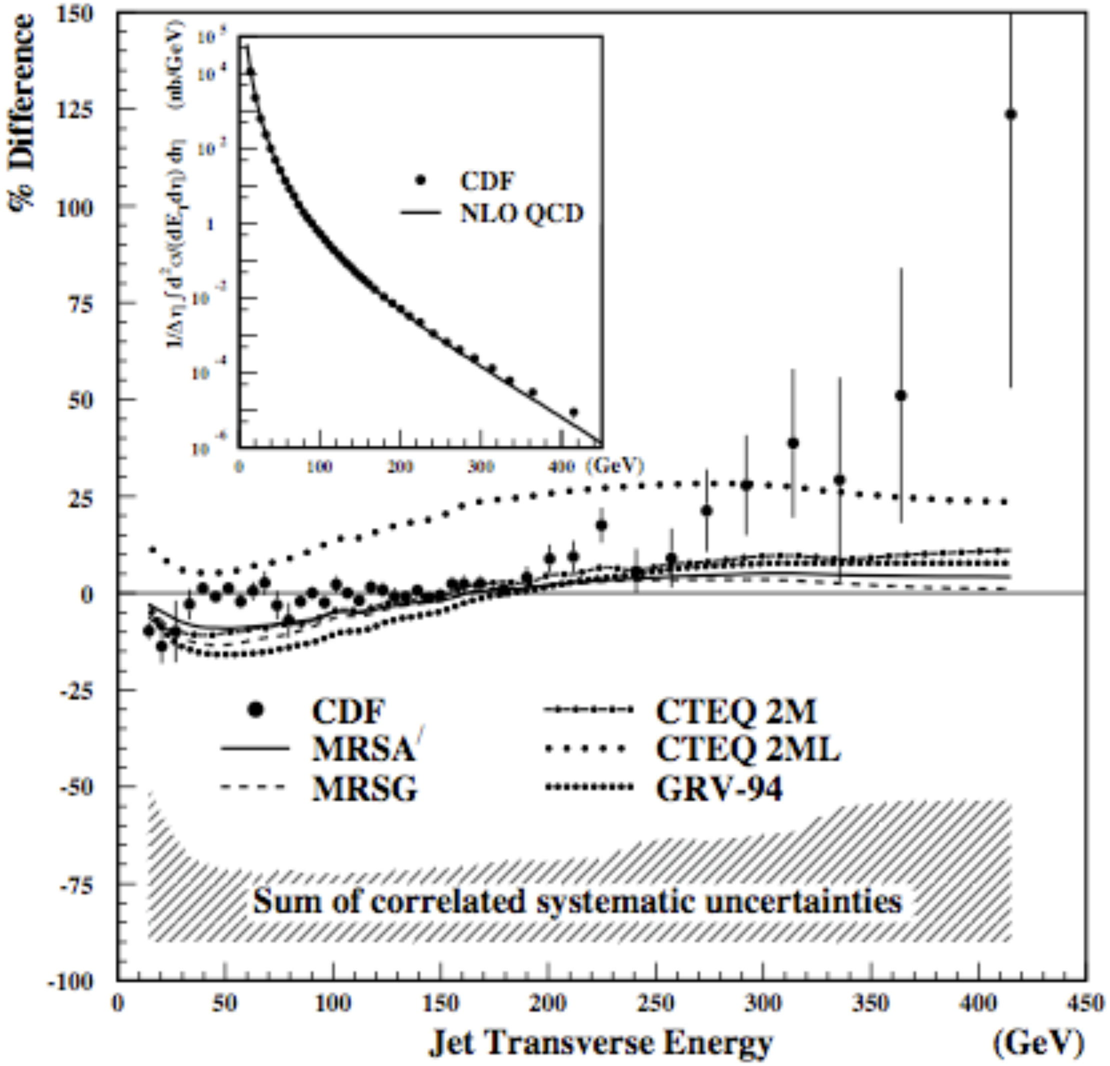
- and a long list of exotica (compositeness, Randall-Sundrum gravitons, excited leptons, 4th generation quarks, large extra dimension monojets and photon pairs ...) can be probed with 0.1 - 1 fb^{-1}

New Physics caveat: tales from the past - 1

Jets at high transverse energy

inclusive 1-jet spectrum

CDF Collab. PRL 77 (1996) 438



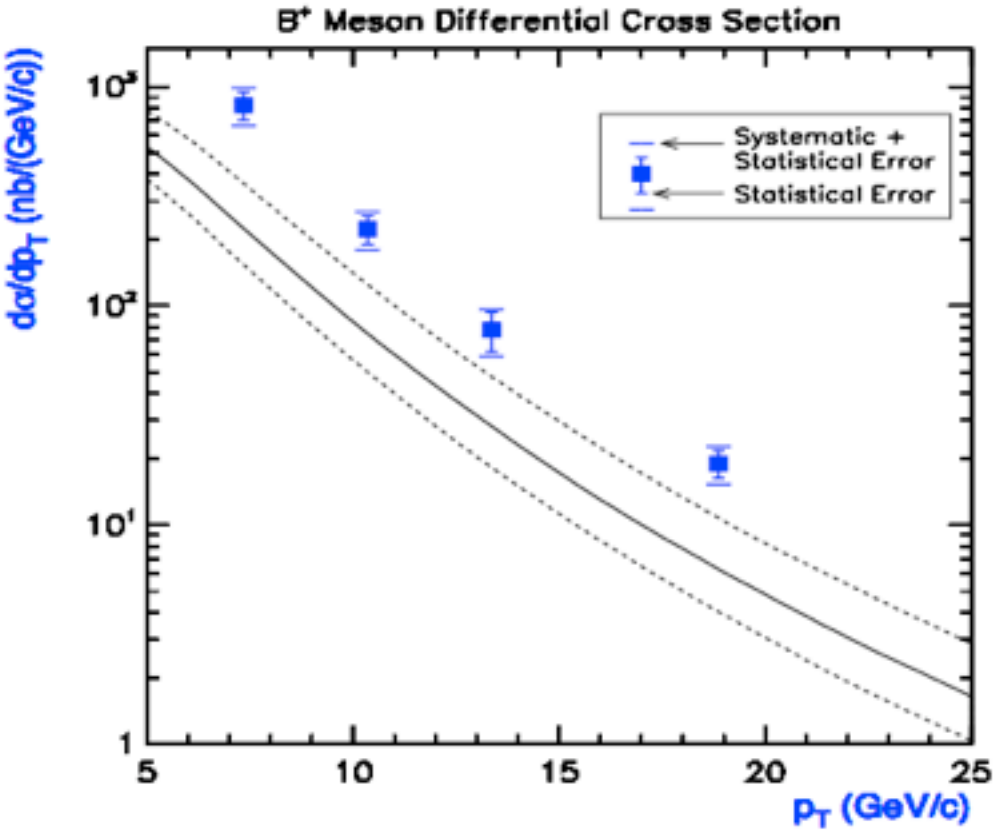
excess of data over theory

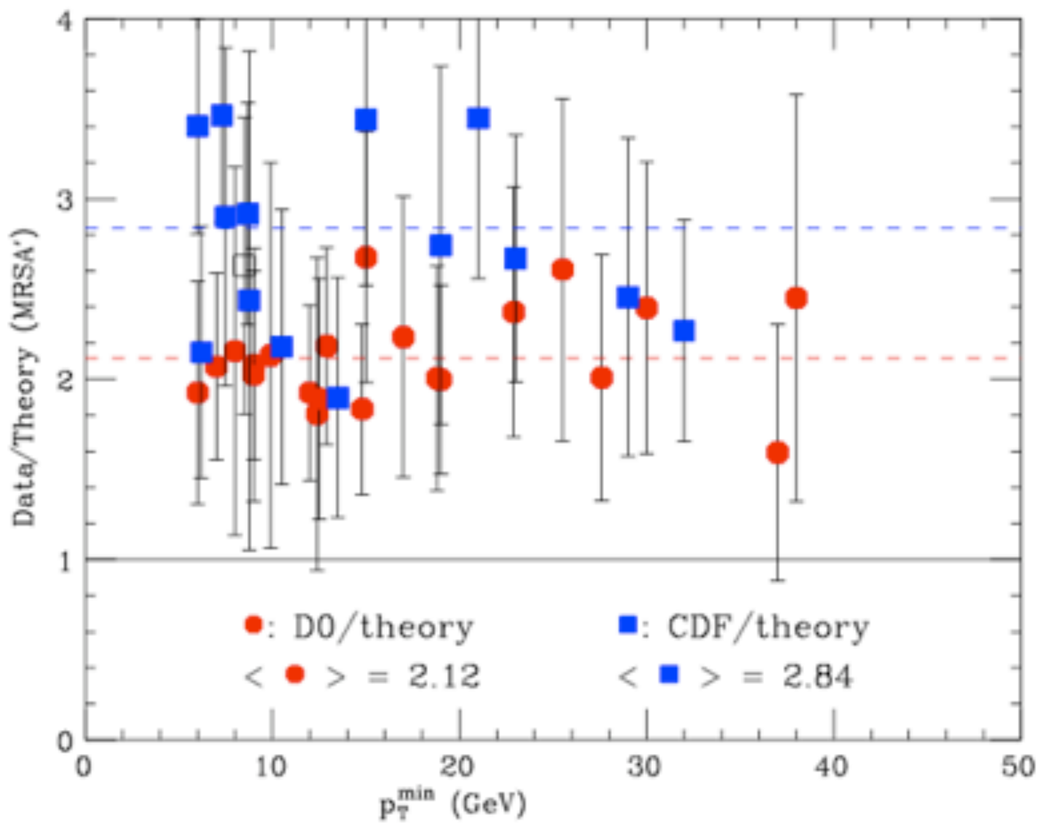
Could it be contact interactions ?
⇒ New Physics ?

more prosaic explanation:
gluon density at high *x*
was largely unknown;
use Tevatron 2-jet data
to measure it:
no more excess

New Physics caveat: tales from the past - II

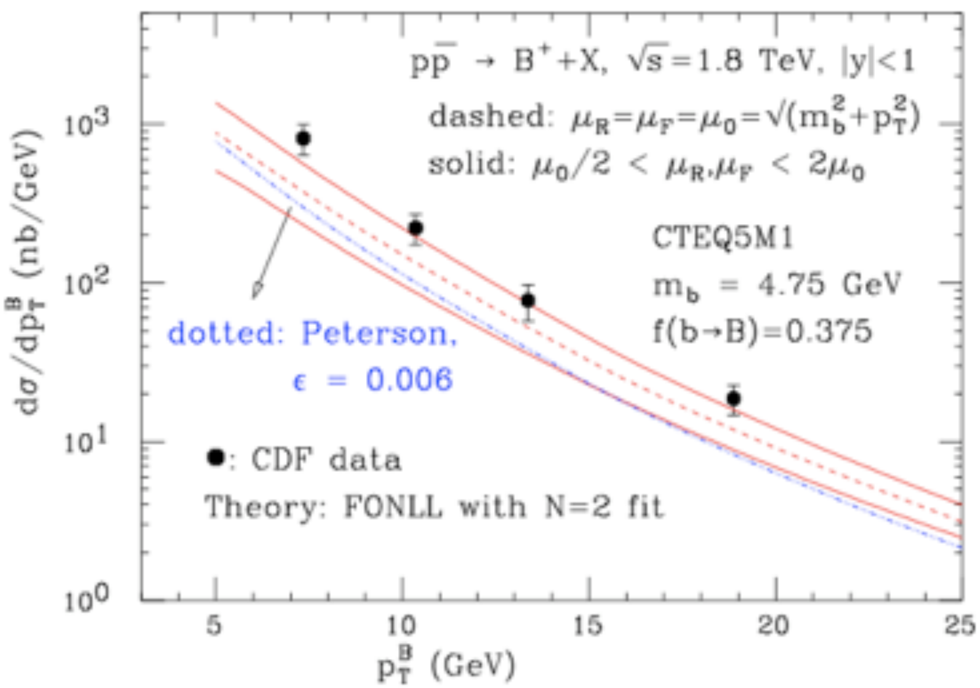
B production in the 90's



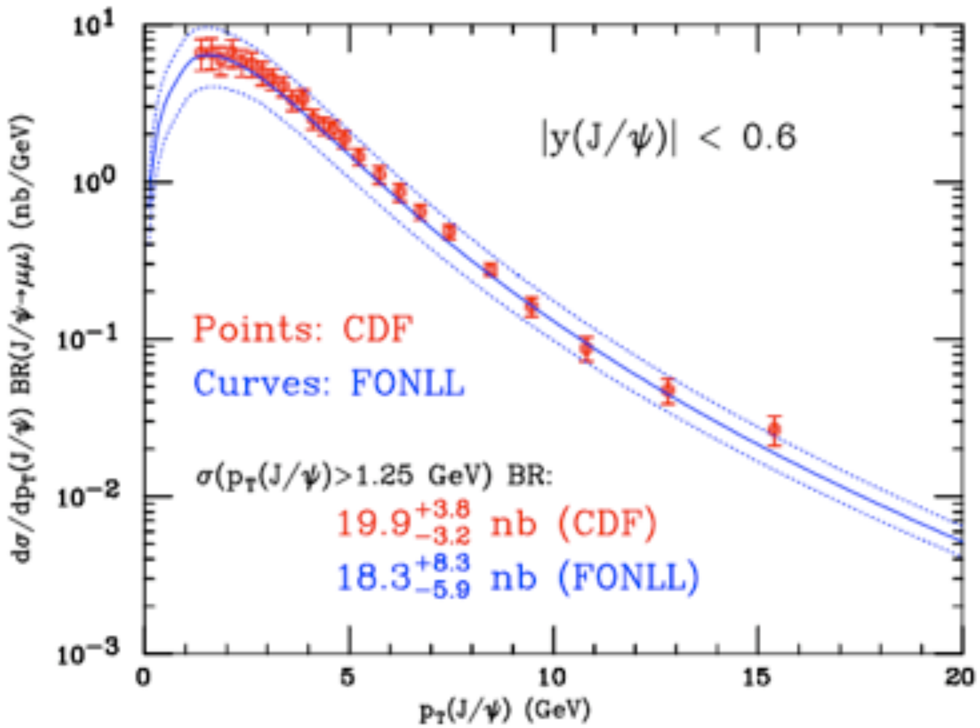


discrepancy between Tevatron data and NLO prediction

B cross section in $p\bar{p}$ collisions at 1.96 TeV



$d\sigma(p\bar{p} \to H_b X, H_b \to J/\psi\ X)/dp_T(J/\psi)$



FONLL = NLO + NLL

total x-sect is $19.4 \pm 0.3(stat)^{+2.1}_{-1.9}(syst)$ nb

Cacciari, Frixione, Mangano, Nason, Ridolfi 2003

CDF hep-ex/0412071

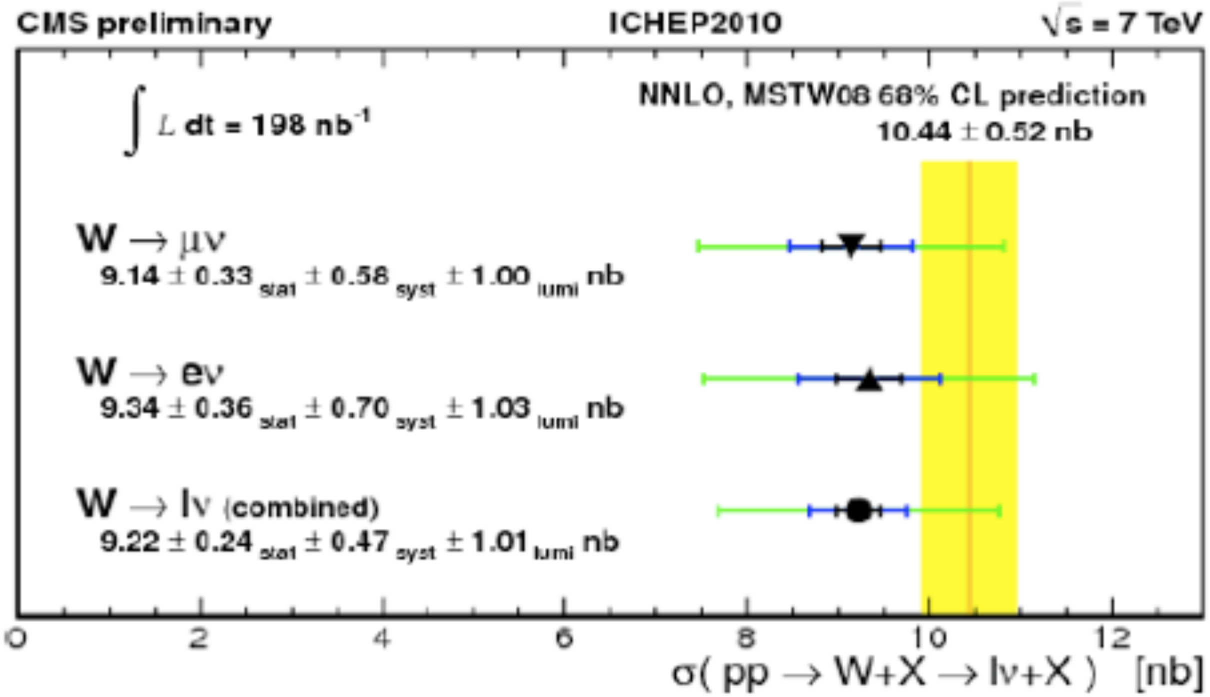
use of updated fragmentation functions by Cacciari & Nason and resummation

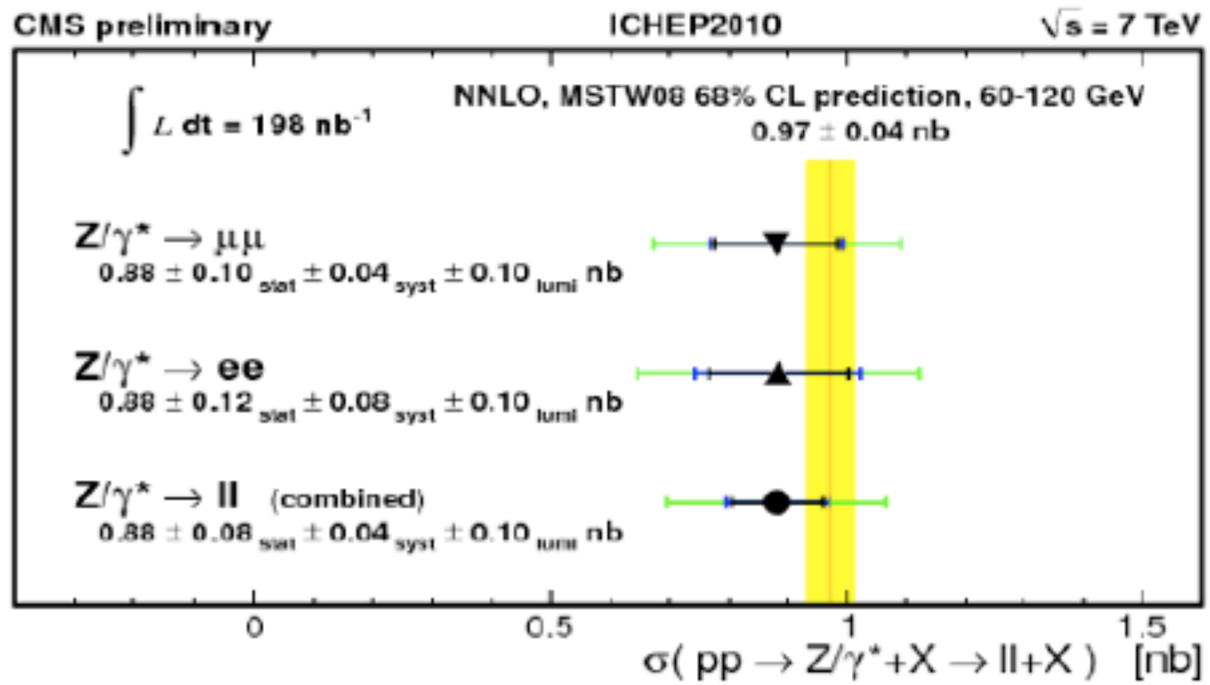
good agreement with data → no New Physics

W, Z at the LHC at 7 TeV

with a few pb^{-1}
ATLAS, CMS have collected
a few thousand *W*'s so far

here is the cross section
with 0.2 pb^{-1} presented
at ICHEP 2010





W charge asymmetry at Tevatron

from the parton model

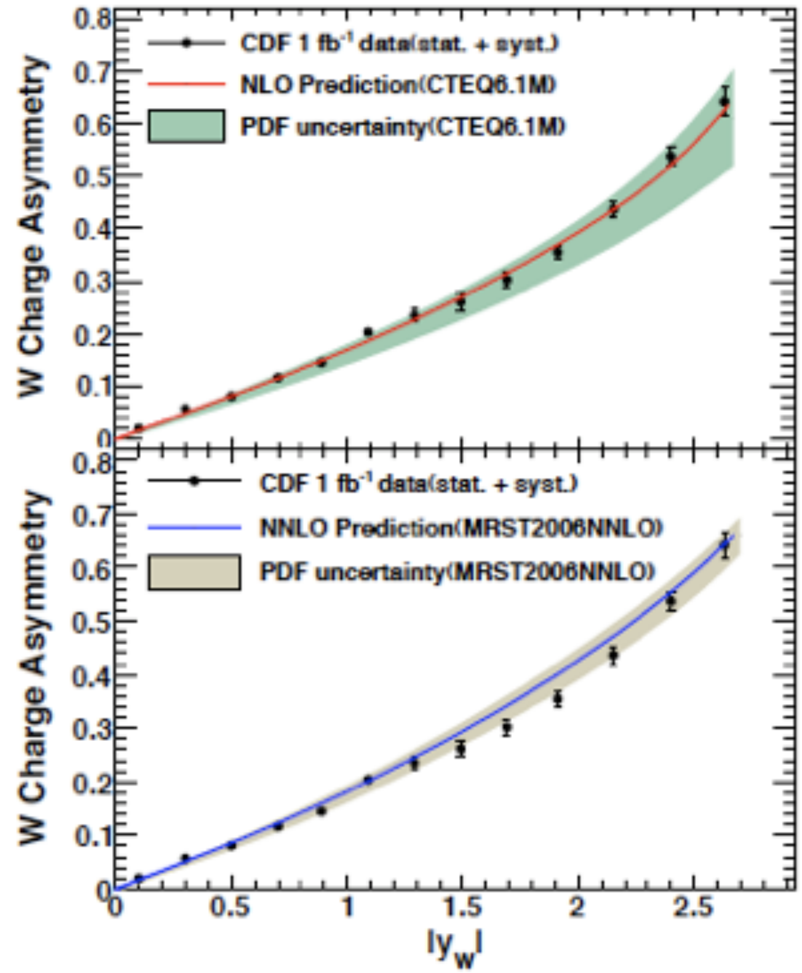
$\sigma(W^+) \propto u(x_1)\bar{d}(x_2)$ $\qquad$ $\sigma(W^-) \propto d(x_1)\bar{u}(x_2)$

because the *ubar* distribution in the antiproton is the same as the *u* distribution in the proton, at Tevatron $\sigma(W^+) = \sigma(W^-)$
however the *u*'s carry more proton momentum than the *d*'s, so the quantity

$$A(y_W) = \frac{\frac{d\sigma(W^+)}{dy_W} - \frac{d\sigma(W^-)}{dy_W}}{\frac{d\sigma(W^+)}{dy_W} + \frac{d\sigma(W^-)}{dy_W}}$$

called charge asymmetry, is non zero

it has been measured by CDF & D0



W^+/W^- at the LHC

At LHC there is no W charge asymmetry: it's $pp \rightarrow$ an even function of y_W

however, u distribution is larger than d

$\rightarrow \quad \sigma(W^+) > \sigma(W^-)$

the ratio

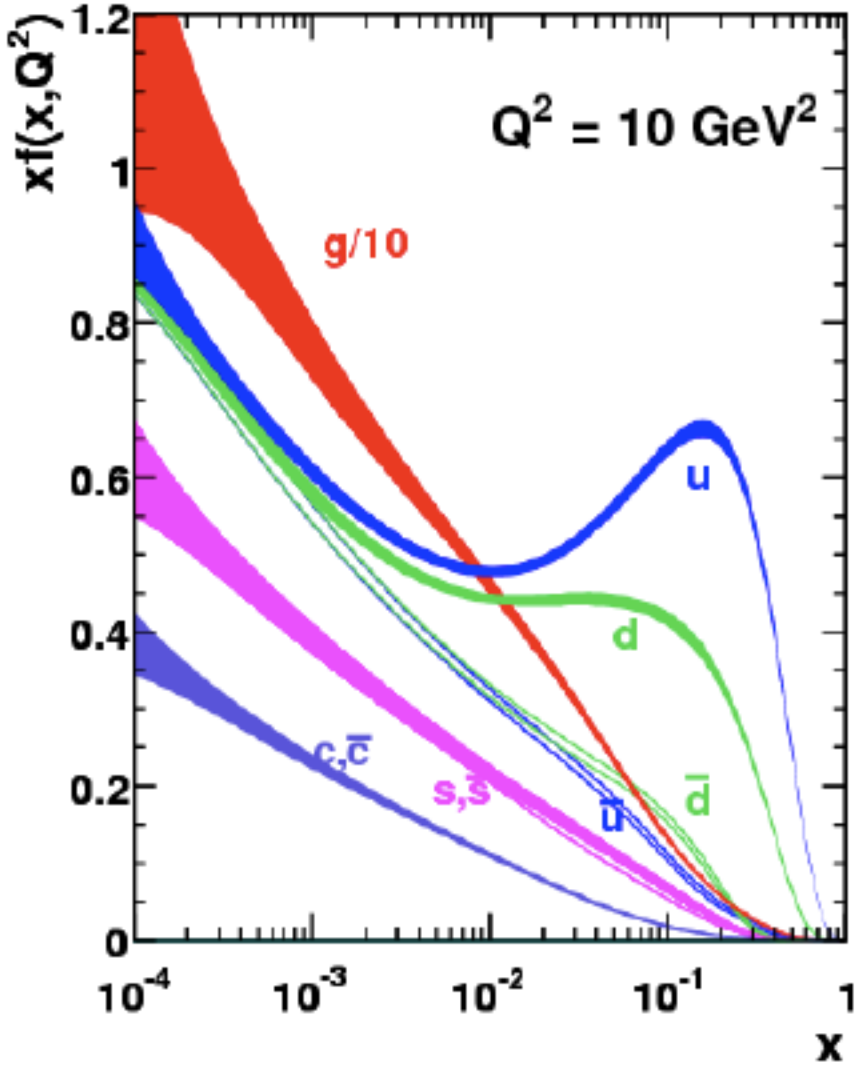
$$R^{\pm} = \frac{\sigma(W^+ \to \ell^+ \bar{\nu})}{\sigma(W^- \to \ell^- \nu)} = \frac{u(x_1)\bar{d}(x_2)}{d(x_1)\bar{u}(x_2)}$$

is larger than 1

Kom Stirling 2010

	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 14$ TeV
MSTW 2008 LO	1.463 ± 0.014	1.365 ± 0.011
MSTW 2008 NLO	1.422 ± 0.012	1.325 ± 0.010
MSTW 2008 NNLO	1.429 ± 0.013	1.328 ± 0.011

MSTW2008NLO



R grows with x, so it decreases with $\sqrt{s}$

R has

- small EXP systematics
- (N)NLO QCD corrections of $\leq 2\%$
- PDF uncertainty ~ 1-2%, driven by valence $u(x)/d(x)$ at not-so-small x

W^+/W^- at the LHC

At LHC there is no W charge asymmetry: it's pp → an even function of y_W

however, u distribution is larger than d

→ $\sigma(W^+) > \sigma(W^-)$

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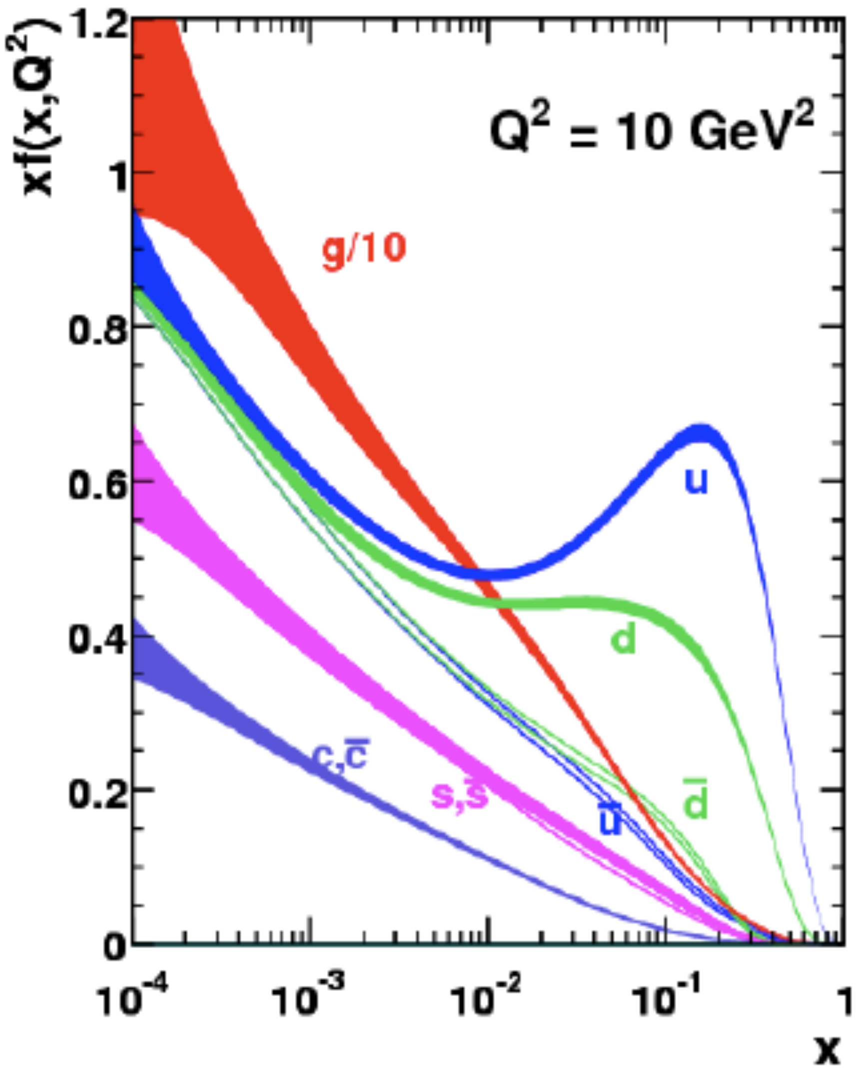
R grows with x, so it decreases with $\sqrt{s}$

MSTW2008NLO



R has

- small EXP systematics
- (N)NLO QCD corrections of ≤ 2%
- PDF uncertainty ~ 1-2%, driven by valence $u(x)/d(x)$ at not-so-small x

W^+/W^- + *n* jets at the LHC

assuming that we know the *u/d* ratio precisely,

fixing $\sigma_{\rm SM} = \sigma_{\rm SM}(W^+ + {\rm jets}) + \sigma_{\rm SM}(W^- + {\rm jets})$

includes *tt* and *H* production, which are *W* symmetric

assuming $\sigma_{\rm NP}(W^+ + {\rm jets}) = \sigma_{\rm NP}(W^- + {\rm jets})$

the ratio

$$R^{\pm}(n) = \frac{\sigma(W^+ \to n \text{ jets})}{\sigma(W^- \to n \text{ jets})}$$

probes New Physics in *W* + jets

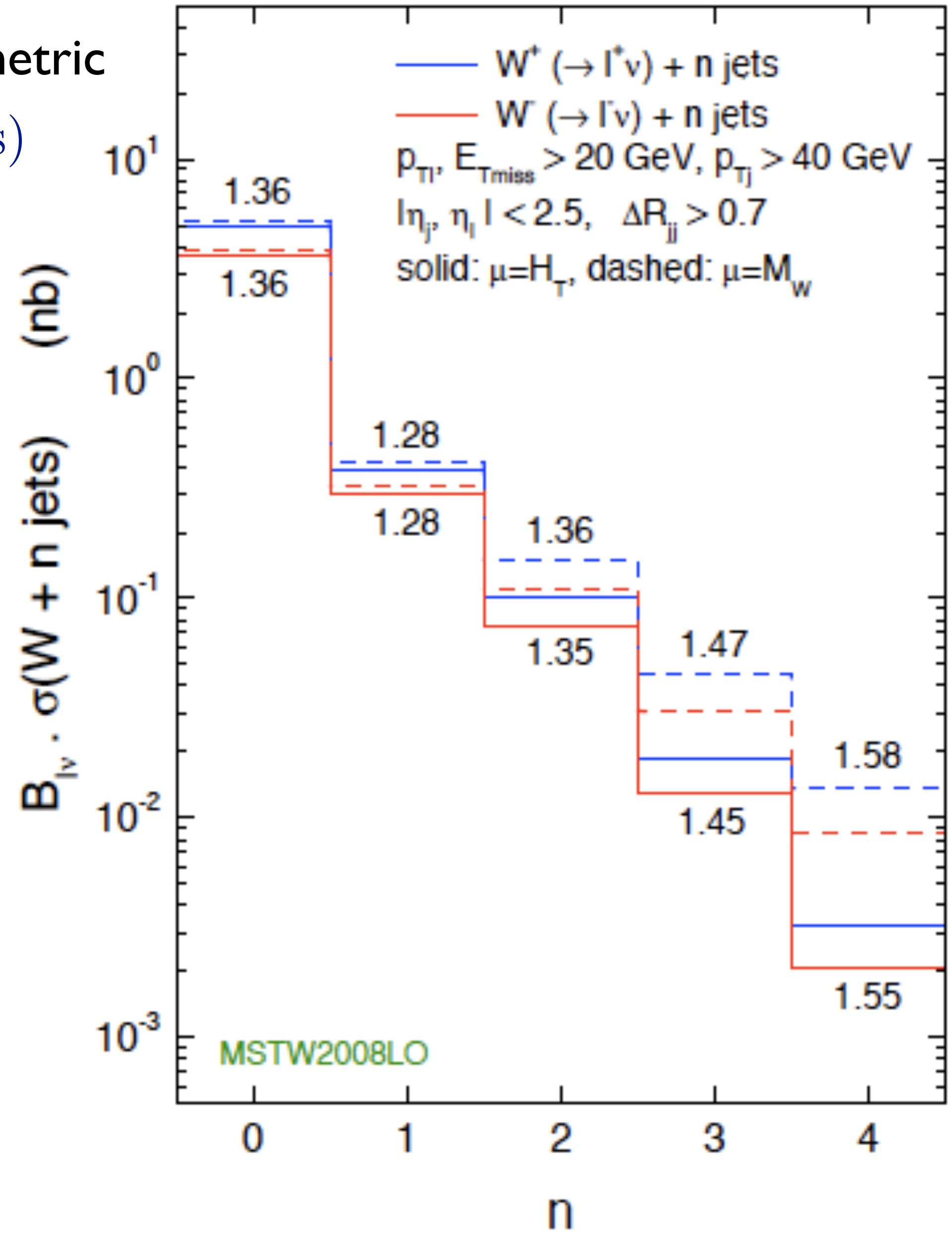
$$f_{\rm NP} = \frac{\sigma_{\rm NP}}{\sigma_{\rm SM}} = \frac{2(R^{\pm}_{\rm SM} - R^{\pm}_{\rm exp})}{(R^{\pm}_{\rm SM}+1)(R^{\pm}_{\rm exp}+1)}$$

$R^{\pm}_{\rm exp}$ measured ratio

R grows with *x*, which grows with *n*

however, note that *R* first decreases from n=0 to 1 then increases for *n* > 1 ...

Kom Stirling 2010

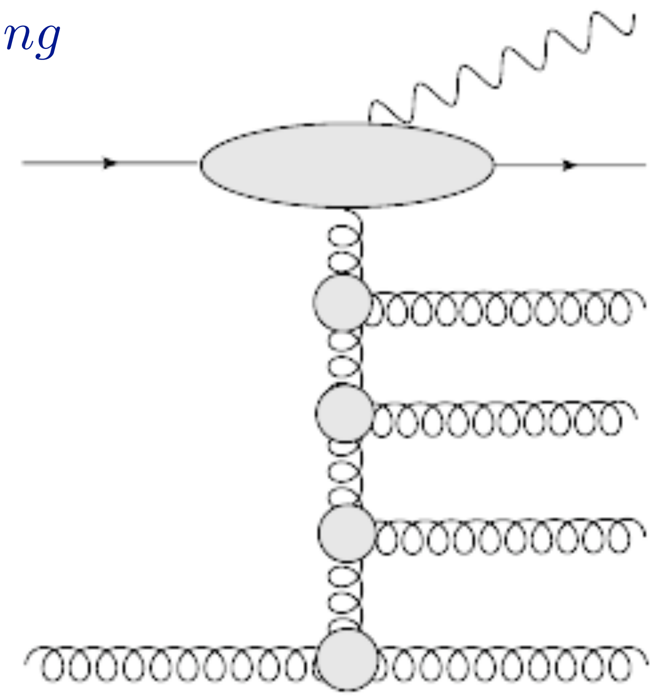


W^+/W^- + n jets at the LHC

possible dynamic explanation: dominance of BFKL-like configuration for $n > 1$

- in any scattering process with $s >> t$, gluon exchange dominates
- for $s >> t$, BFKL resums the (next-to-)leading logarithmic contributions, $\ln(s/t)$, to the radiative corrections to gluon exchange in the t channel
- in W + jets, gluon exchange occurs with at least 2 jets
- the dominant subprocess is $q + g \to q + W^{\pm} + ng$
- the leading-order subprocess breakdown is

n	QQ	Qg	gg
0	100	0	0
1	18	82	0
2	21	73	6
3	23	70	7
4	25	67	8



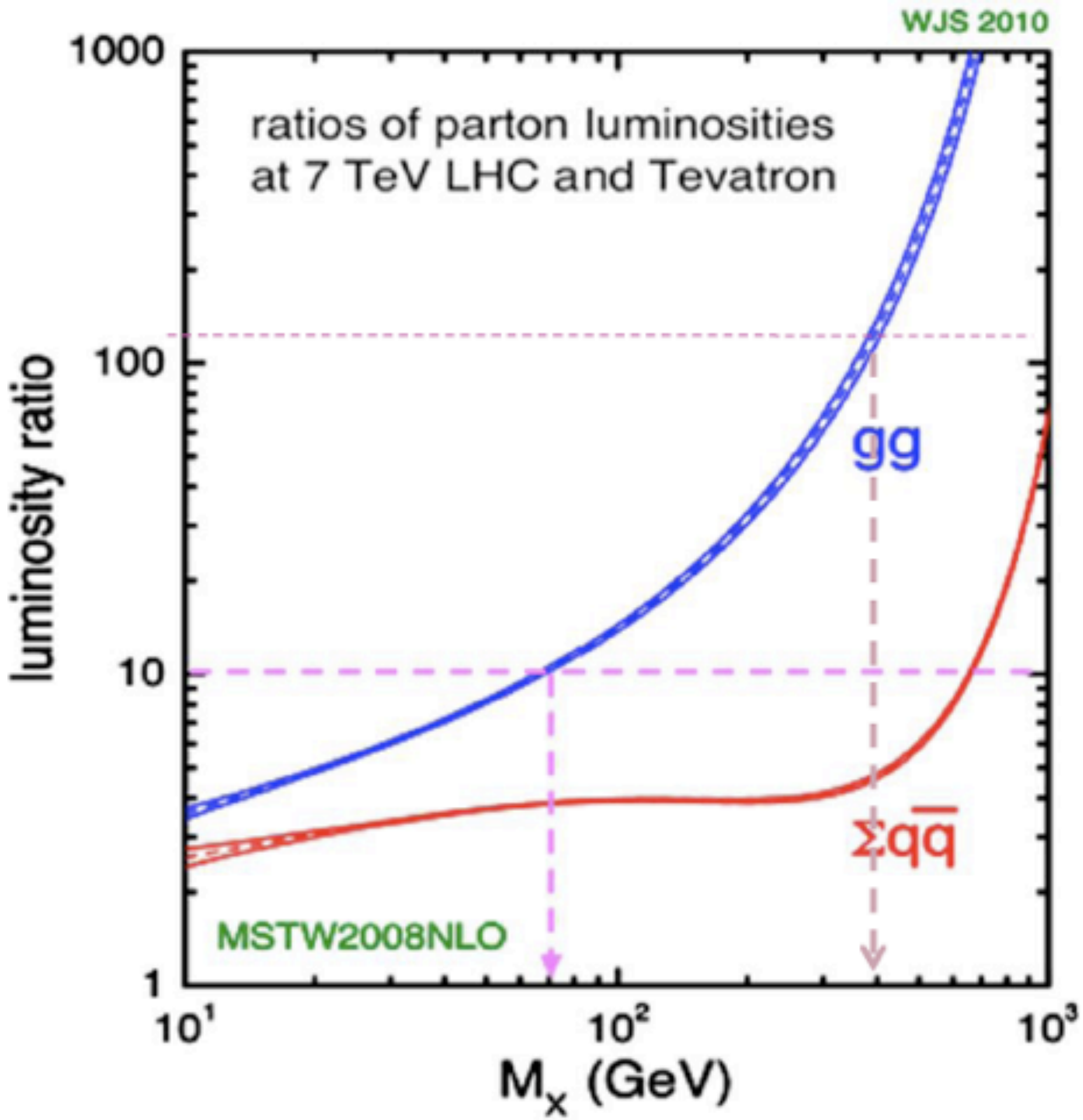
- the issue can be further analysed using NLO production, known up to W + 4 jets

Berger *et al.* (BlackHat) 2010

Andersen VDD Maltoni Stirling 2001

Top at the LHC at 7 TeV

top at m ~ 170 GeV
85% *qq* + *15%* *gg*
0.85 x 5 + 0.15 x 100
→ gain a factor ~ 20



Top at the LHC at 7 TeV

- With ~ 100 pb^{-1}, LHC sample comparable to Tevatron's
- With ~ a few hundred pb^{-1}, physics programme will look familiar
  - top cross section
  - top mass
  - single top
  - rare decays
- If LHC reaches 1 fb^{-1} by end 2011,
  and Tevatron increases yield by a factor 10,
  samples will still be comparable

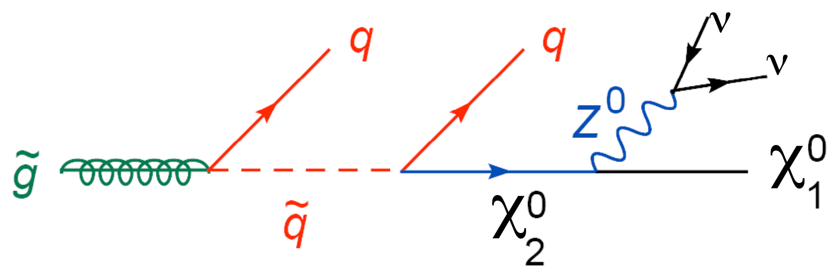
Radiative corrections at the LHC

En passant, we have mentioned higher order corrections in

- Higgs exclusion limit
- background to Higgs production
- jets at high transverse energy
- *b*, *t* production

- SM production of W, Z, *t* + jets is background to Higgs, New Physics processes

SUSY decay chain



signal: missing energy + 4 jets

background: Z (→νν) + 4 jets

NLO cross sections: experimenter's wishlist

2005 Les Houches

QCD, EW & Higgs working group hep-ph/0604210

Table 42: The LHC "priority" wishlist for which a NLO computation seems now feasible.

process ($V \in \{Z, W, \gamma\}$)	relevant for
1. $pp \to V\,V$ jet	$t\bar{t}H$, new physics
2. $pp \to t\bar{t}\,b\bar{b}$	$t\bar{t}H$
3. $pp \to t\bar{t} + 2$ jets	$t\bar{t}H$
4. $pp \to V\,V\,b\bar{b}$	VBF$\to H \to VV$, $t\bar{t}H$, new physics
5. $pp \to V\,V + 2$ jets	VBF$\to H \to VV$
6. $pp \to V + 3$ jets	various new physics signatures
7. $pp \to V\,V\,V$	SUSY trilepton

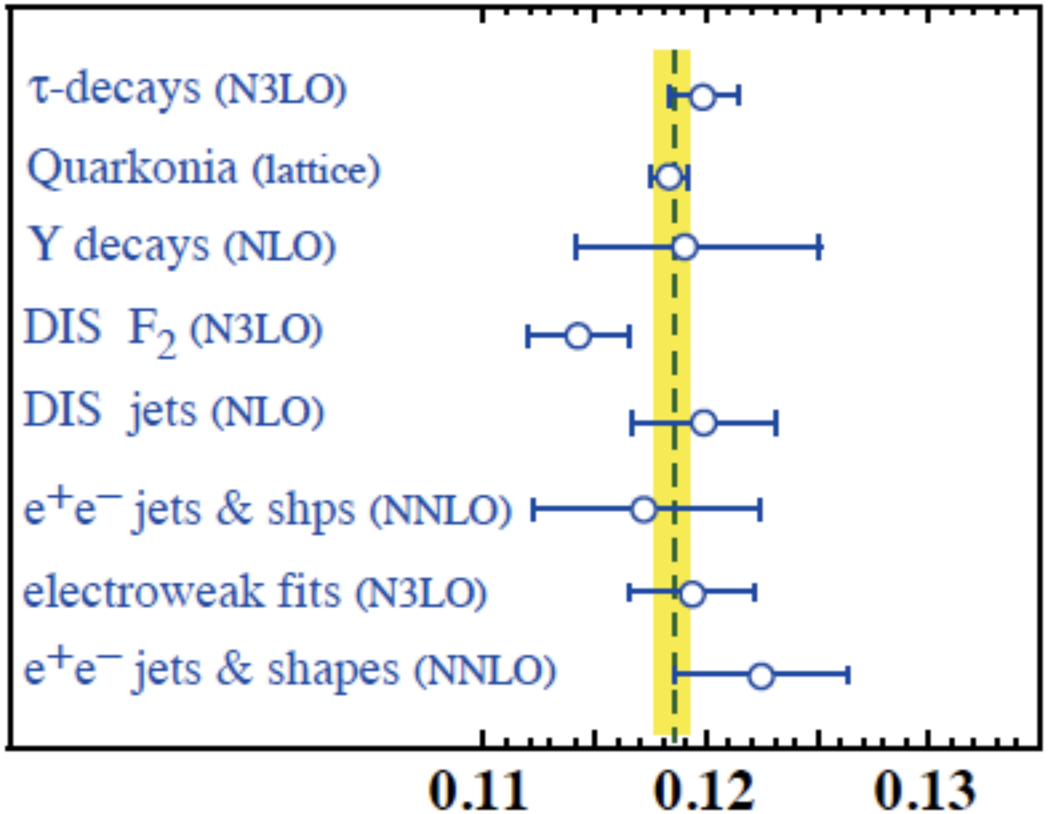
QCD at high Q^2

- Parton model
- Perturbative QCD
  - factorisation
  - universality of IR behaviour
  - cancellation of IR singularities
  - IR safe observables: inclusive rates
    - jets
    - event shapes

World average of $\alpha_S(M_Z)$

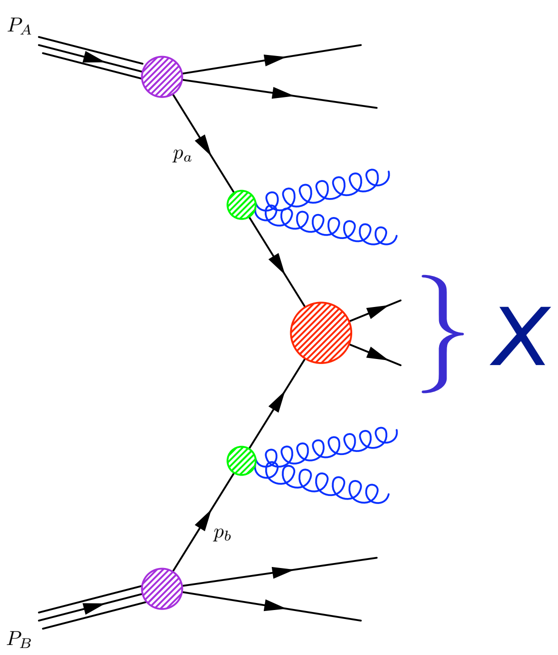
$$\alpha_s(M_Z) = 0.1184 \pm 0.0007 \qquad \frac{\Delta\alpha_s}{\alpha_s} = 0.6\%$$

S. Bethke arXiv:0908.1135



- vertical line and shaded band mark the world average
- first time that shapes are included at NNLO

Factorisation



is the separation between
the short- and the long-range interactions

$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2 \, f_{a/A}(x_1, \mu_F^2) \, f_{b/B}(x_2, \mu_F^2)$$

$$\times \; \hat{\sigma}_{ab \to X} \left(x_1, x_2, \{p_i^\mu\}; \alpha_S(\mu_R^2), \alpha(\mu_F^2), \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2} \right)$$

$$X = W, Z, H, Q\bar{Q}, \text{high-}E_T\text{jets}, \ldots$$

$\hat{\sigma}$ is known as a fixed-order expansion in α_S

$$\hat{\sigma}(\alpha_S, \mu_R, \mu_F) = (\alpha_S(\mu_R))^n \left[\hat{\sigma}^{(0)} + \left(\frac{\alpha_S}{2\pi} \right) \hat{\sigma}^{(1)}(\mu_R, \mu_F) + \left(\frac{\alpha_S}{2\pi} \right)^2 \hat{\sigma}^{(2)}(\mu_R, \mu_F) + \ldots \right]$$

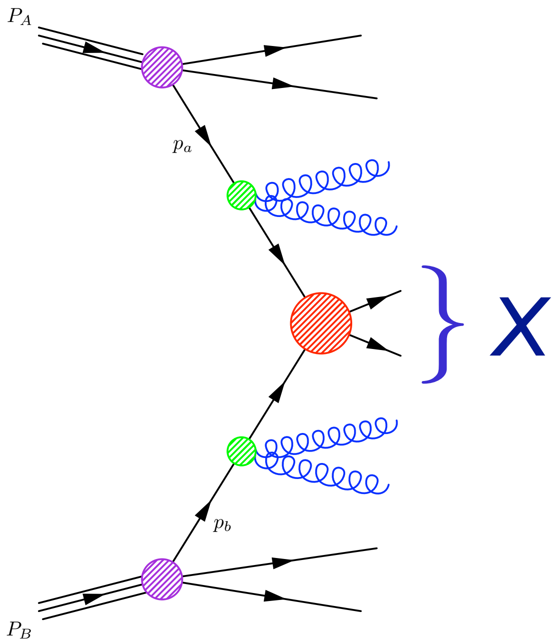
$\hat{\sigma}^{(0)}$ = LO $\quad$ $\hat{\sigma}^{(1)}$= NLO $\quad$ $\hat{\sigma}^{(2)}$ = NNLO

LO: maximal dependence on scales. Poor convergenge of expansion in α_S
NLO: (usually) good estimate of x-sect
NNLO: good estimate of uncertainty

Factorisation

extracted from data
evolved through DGLAP

is the separation between
the short- and the long-range interactions



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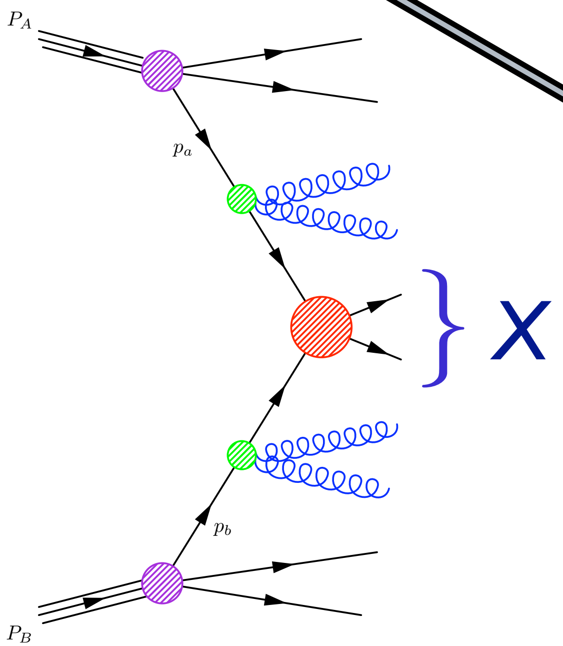
evolved through DGLAP

computed in pQCD

is the separation between
the short- and the long-range interactions



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Factorisation-breaking contributions

- underlying event
- power corrections
  - MC's and theory modelling of power corrections laid out and tested at LEP where they provide an accurate determination of α_S models still need be tested in hadron collisions (see e.g. Tevatron studies at different $\sqrt{s}$) ⇨
- diffractive events ⇨
- double-parton scattering

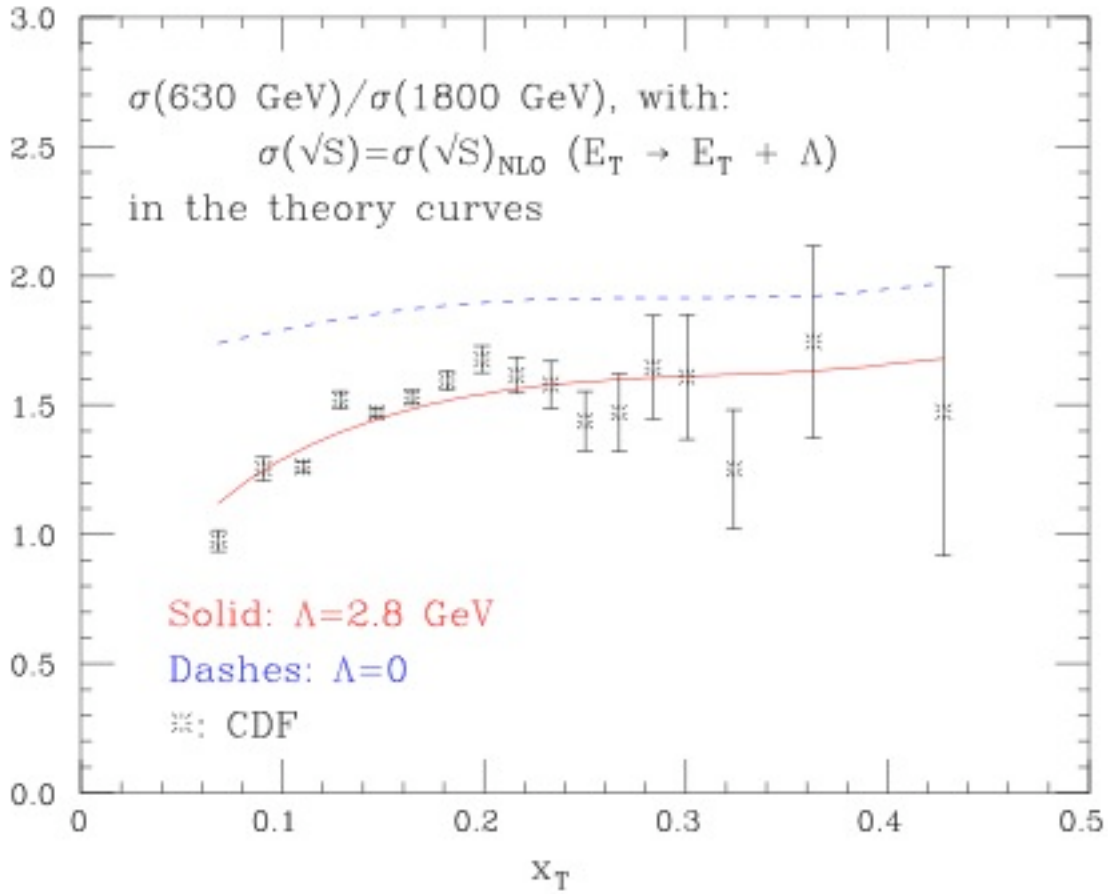
  observed by Tevatron CDF in the inclusive sample

  $p\bar{p} \to \gamma + 3 \text{ jets}$

  potentially important at LHC $\sigma_D \propto \sigma_S^2$
- breakdown in dijet production at N^3LO ? Collins Qiu 2007

Power corrections at Tevatron

Ratio of inclusive jet cross sections at 630 and 1800 GeV



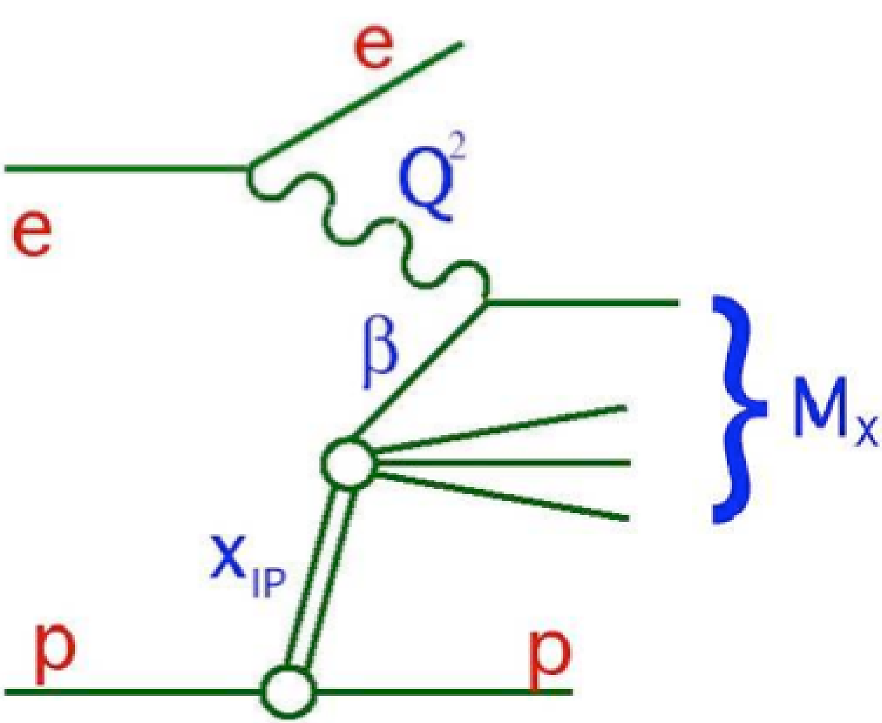
M.L. Mangano
KITP collider conf 2004

Bjorken-scaling variable

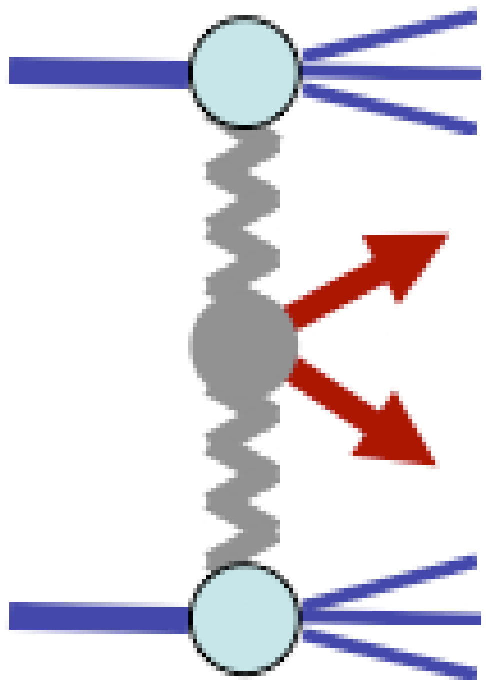
$$x_T = \frac{2E_T}{\sqrt{s}}$$

- In the ratio the dependence on the pdf's cancels
- dashes: theory prediction with no power corrections
- solid: best fit to data with free power-correction parameter Λ in the theory

Factorisation in diffraction ??



diffraction in DIS



double pomeron exchange in $p\bar{p}$

- no proof of factorisation in diffractive events
- data do not seem to support it

PDF evolution

- factorisation scale μ_F is arbitrary
  - cross section cannot depend on μ_F

$$\mu_F \frac{d\sigma}{d\mu_F} = 0$$

implies DGLAP equations

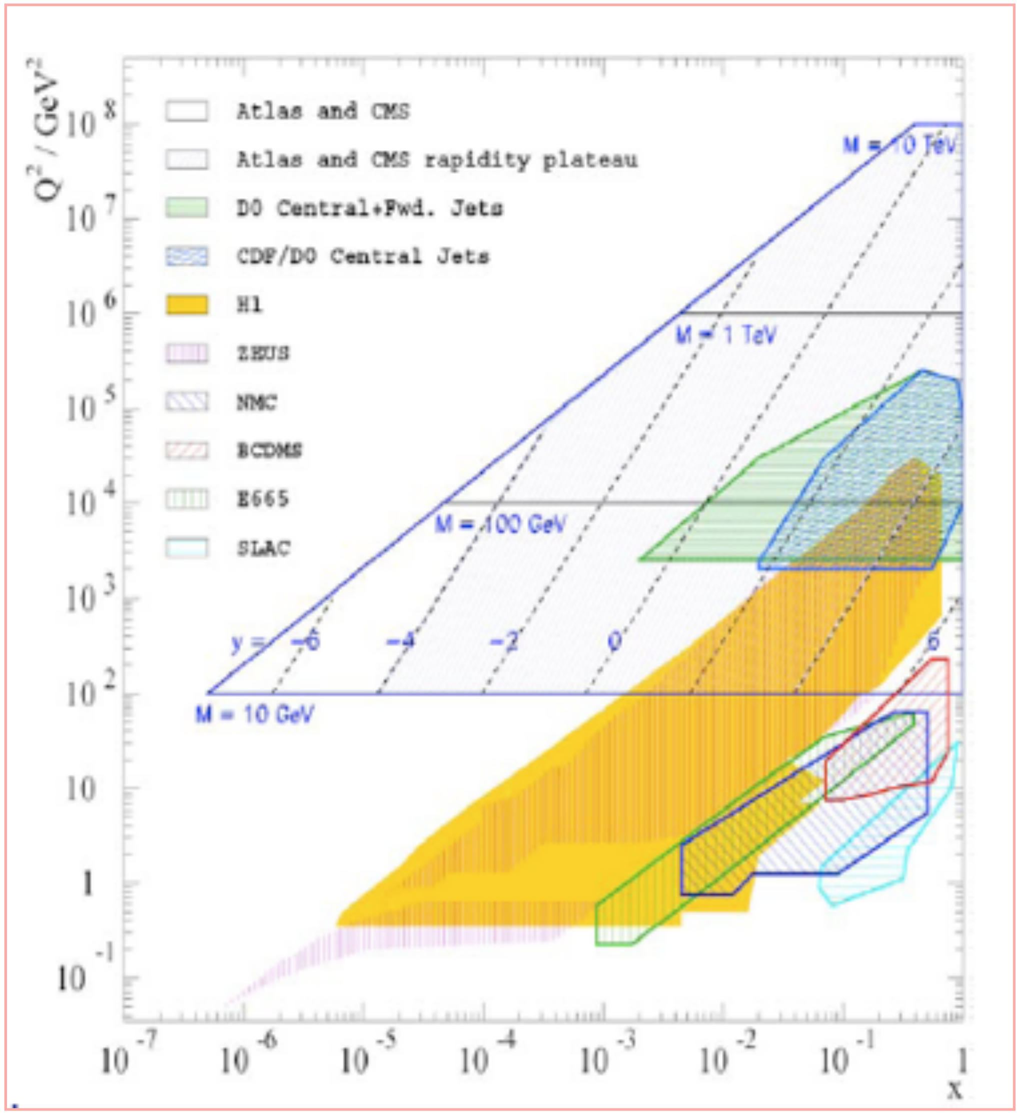
V. Gribov L. Lipatov; Y. Dokshitzer
G. Altarelli G. Parisi

$$\mu_F \frac{df_a(x,\mu_F^2)}{d\mu_F} = P_{ab}(x,\alpha_S(\mu_F^2)) \otimes f_b(x,\mu_F^2) + \mathcal{O}(\frac{1}{Q^2})$$

$$\mu_F \frac{d\hat{\sigma}_{ab}(Q^2/\mu_F^2,\alpha_S(\mu_F^2))}{d\mu_F} = -P_{ac}(x,\alpha_S(\mu_F^2)) \otimes \hat{\sigma}_{cb}(Q^2/\mu_F^2,\alpha_S(\mu_F^2)) + \mathcal{O}(\frac{1}{Q^2})$$

  - $P_{ab}(x,\alpha_S(\mu_F^2))$ is calculable in pQCD

LHC kinematic reach



LHC opens up a new kinematic range

x range covered by HERA but Q^2 range must be provided by DGLAP evolution

100-200 GeV physics is large *x* physics (valence quarks) at Tevatron, but smaller *x* physics (gluons & sea quarks) at the LHC

rapidity distributions span widest *x* range

Feynman x's for the production of a particle of mass M $$x_{1,2} = \frac{M}{14\,\text{TeV}} e^{\pm y}$$

Parton cross section

3 complementary approaches to $\hat{\sigma}$

	matrix-elem MC's	fixed-order x-sect	shower MC's
final-state description	hard-parton jets. Describes geometry, correlations, ...	limited access to final-state structure	full information available at the hadron level
higher-order effects: loop corrections	hard to implement: must introduce negative probabilities	straightforward to implement (when available)	included as vertex corrections (Sudakov FF's)
higher-order effects: hard emissions	included, up to high orders (multijets)	straightforward to implement (when available)	approximate, incomplete phase space at large angles
resummation of large logs	?	feasible (when available)	unitarity implementation (i.e. correct shapes but not total rates)

M.L. Mangano KITP collider conf 2004

Parton shower MonteCarlo generators

- **HERWIG** B. Webber *et al.* 1992

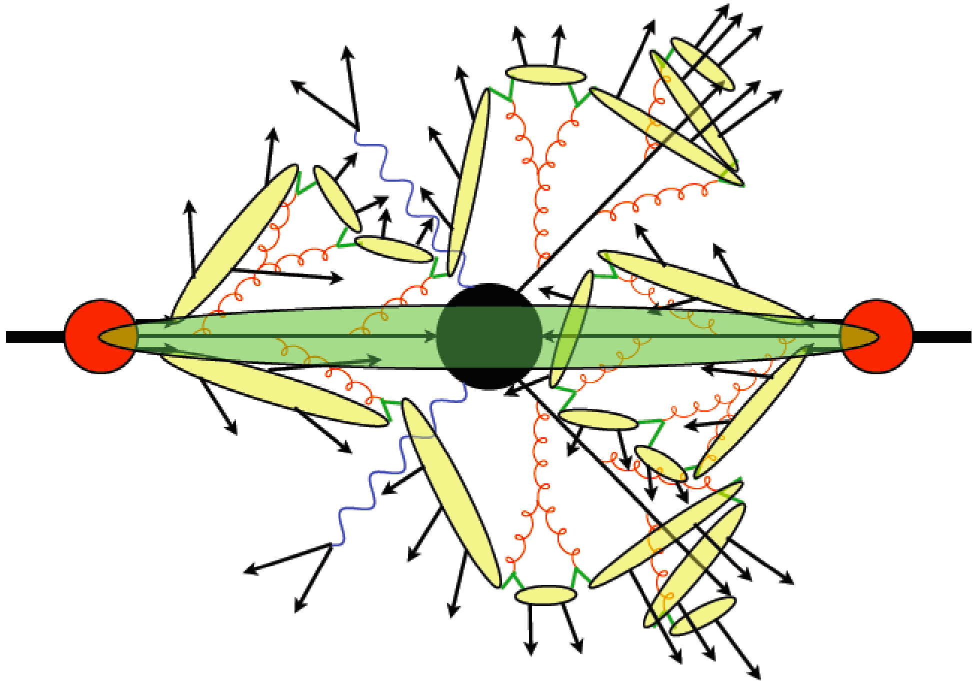
  re-written as a C++ code (HERWIG++)

- **PYTHIA** T. Sjostrand 1994 (also re-written as a C++ code)

- **SHERPA** F. Krauss *et al.* 2003

model parton showering and hadronisation

LHC Event Simulation



Matrix-element MonteCarlo generators

- ↑ several automated codes to yield large number of (up to 8-9) final-state partons
- ↑ can be straightforwardly interfaced to parton-shower MC's
- ↑ ideal to scout new territory
- ↓ large dependence on ren/fact scales example: Higgs (via gluon fusion) + 2 jets is $\alpha_s^4(Q^2)$

⇒ unreliable for precision calculations

Matrix-element MonteCarlo generators

- multi-parton LO generation: processes with many jets (or V/H bosons)
  - ALPGEN M.L.Mangano M. Moretti F. Piccinini R. Pittau A. Polosa 2002
  - MADGRAPH/MADEVENT W.F. Long F. Maltoni T. Stelzer 1994/2003
  - COMPHEP A. Pukhov et al. 1999
  - GRACE/GR@PPA T. Ishikawa *et al.* K. Sato *et al.* 1992/2001
  - HELAC C. Papadopoulos *et al.* 2000
- processes with 6 final-state fermions
  - PHASE E. Accomando A. Ballestrero E. Maina 2004
- merged with parton showers
  - all of the above, merged with HERWIG or PYTHIA

MonteCarlo interfaces

- CKKW S. Catani F. Krauss R. Kuhn B. Webber 2001

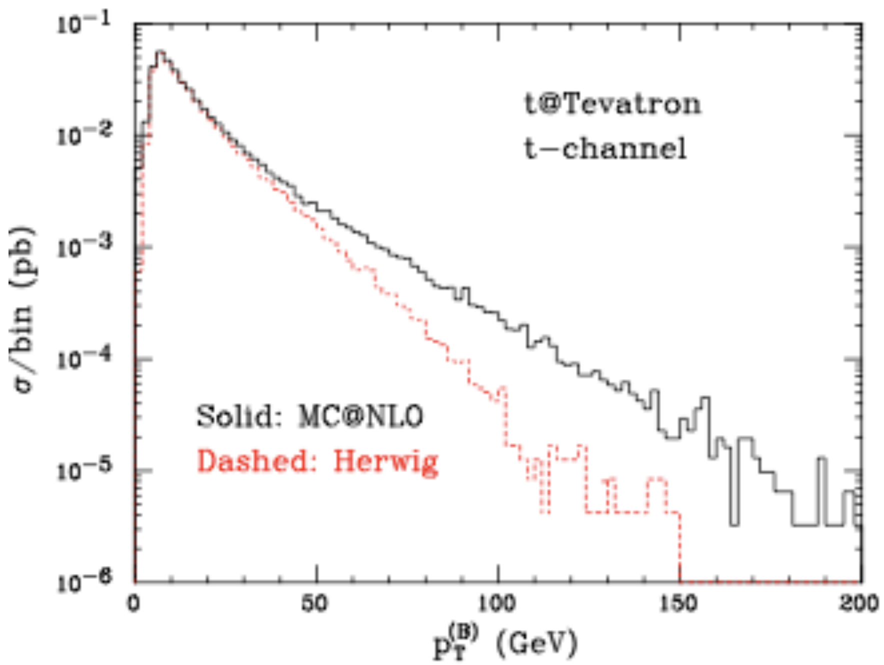
  MLM L. Lonnblad 2002 M.L. Mangano 2005

  procedures to interface parton subprocesses with a different number of final states to parton-shower MC's

- MC@NLO S. Frixione B. Webber 2002

  POWHEG P. Nason 2004

  procedures to interface NLO computations to parton-shower MC's



Single top in MC@NLO

Frixione Laenen Motylinski Webber 2005

at low p_T, parton shower models collinear radiation

at high p_T, NLO models hard radiation

Matrix-element MonteCarlo generator at NLO

- desirable to have a multi-parton NLO generator
  interfaced to a parton shower:
  a sort of MadGraph cum MC@NLO

- a step in this direction: automation of subtraction of IR divergences

  Frederix Frixione Maltoni Stelzer 2009

  MadGraph provides real amplitude
  user inputs virtual amplitude
  procedure provides subtraction counterterms

Accuracy of pQCD calculations

- LO 2 → 2 process + shower & hadronisation (HERWIG, PYTHIA, SHERPA)
- LO 2 → n process + shower (ALPGEN, MADGRAPH/MADEVENT)
- NLO parton level
- NLO + shower (MC@NLO, POWHEG)
- NNLO parton level

- bottom line: use best available accuracy (ideally NLO + shower)

High (EXP) demand for cross sections of $X + n$ jets
$X = W, Z$, Higgs, heavy quark(s), ...
Big TH community effort

To compute the NLO cross section of $X + n$ jets, we need:
1) tree-level amplitude for $X + (n+3)$ partons
2) one-loop amplitude for $X + (n+2)$ partons
3) a method to cancel the IR divergences
and so to compute the cross section

3: until the mid 90's, we did not have systematic methods
to cancel the IR divergences
2: until 2007-8, we did not have systematic methods
to compute the one-loop amplitudes

NLO cross sections (2010)

2005 Les Houches list almost completed

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 Berger 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

$pp \to V + 4$ jets new physics C. Berger *et al* (BlackHat) 2010

- in the past, long time span to add one more jet to a x-section
- in the last few years, huge progress
- $2 \to 2$ and $2 \to 3$ processes:
  almost all computed and included into NLO packages
- $2 \to 4$ processes: a few computed

  $pp \to t\,\bar{t}\,b\,\bar{b}$ Bredenstein Denner Dittmaier Pozzorini; Bevilacqua Czakon Papadopoulos Pittau Worek 2009

  $pp \to Q\bar{Q} + 2\,\text{jets}$ Bevilacqua Czakon Papadopoulos Worek 2010

  $pp \to H + 3\ \text{jets}$ (VBF) Figy Hankele Zeppenfeld 2007

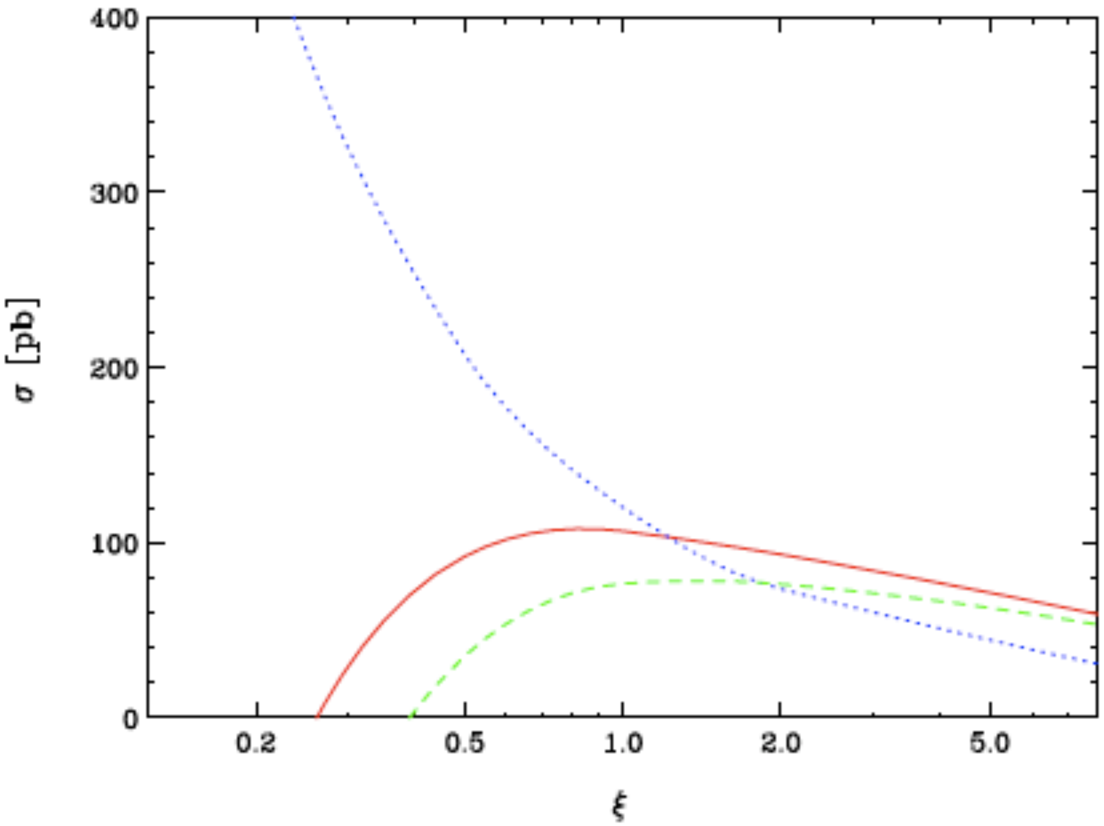
  $pp \to V + 3\ \text{jets}$ Berger *et al.* (BlackHat); K. Ellis Melnikov Zanderighi 2009
- $2 \to 5$ processes: just one

  $pp \to V + 4\ \text{jets}$ Berger *et al.* (BlackHat) 2010

$pp \rightarrow t\,\bar{t} + 2\,\mathrm{jets}$ at NLO

Scale dependence of total x-sect

Bevilacqua Czakon Papadopoulos Worek 2010



$\mu_R = \mu_F = \xi\,\mu_0$ with $\mu_0 = m_t$

dots: LO
solid: NLO
dash: NLO with jet veto of 50 GeV

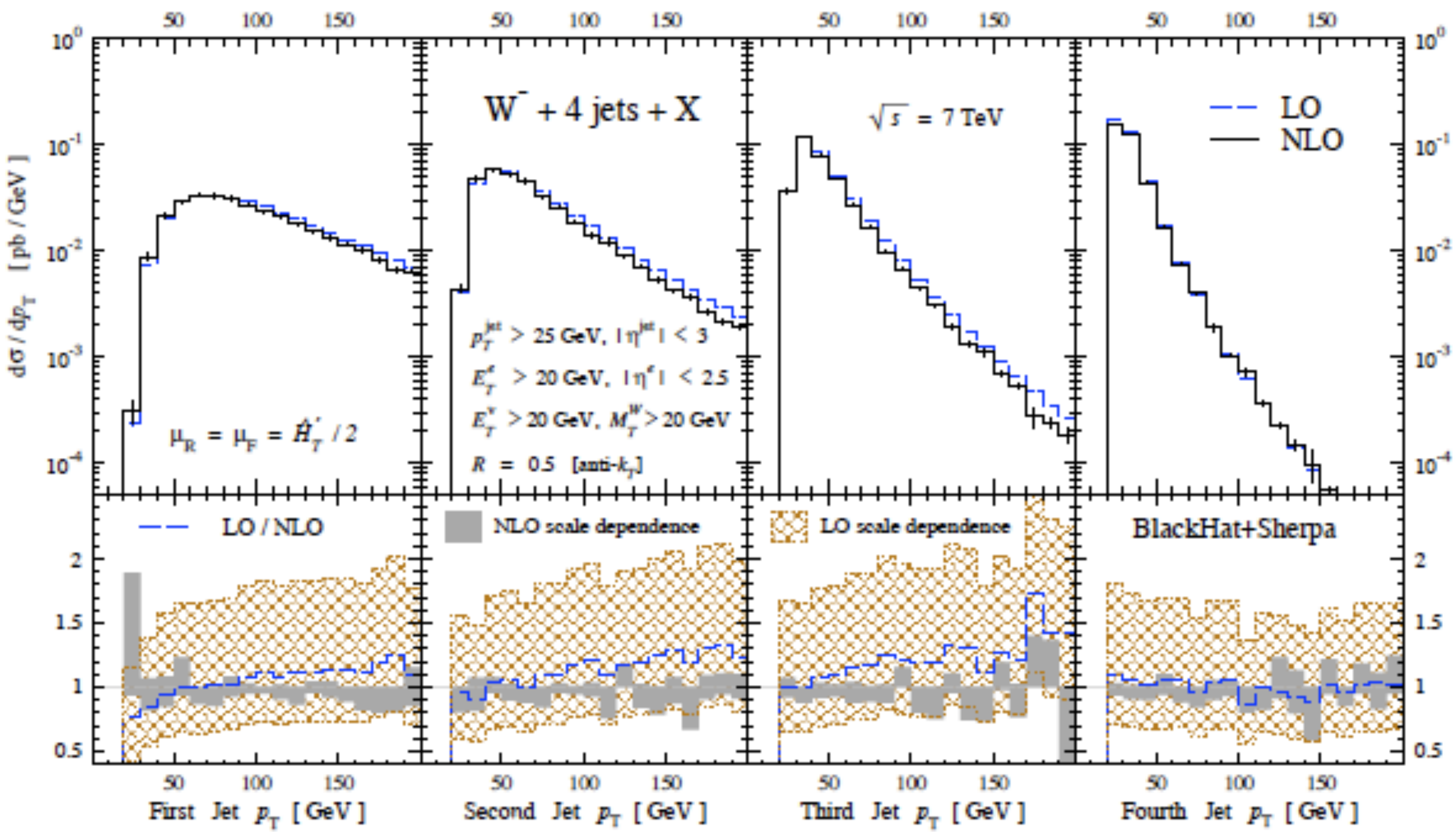
- reducible background to $pp \rightarrow H\,t\,\bar{t}$
- NLO/LO ≡ *K* factor = 0.89
- Reduced theoretical error: 40-70% at LO; 12-13% at NLO

W + 4 jets at NLO

A C++ code based on generalised unitarity, and on-shell recursion for the rational parts

BlackHat: Berger et al. 2010

computes
- real $W + 7$ parton amplitudes
- one-loop $W + 6$ parton amplitudes (leading colour)



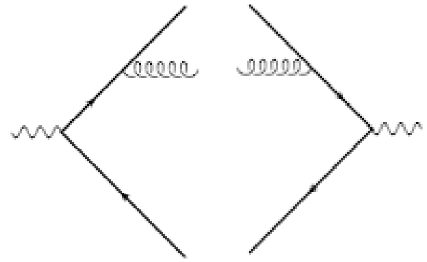
Conclusions

- an exciting period of LHC phenomenology is about to begin
- signals and backgrounds for Higgs and New Physics are evaluated with better and better accuracy, thanks to
- a lot of progress in pQCD in the last few years in
  - Monte Carlo generators
  - NLO computations with many jets

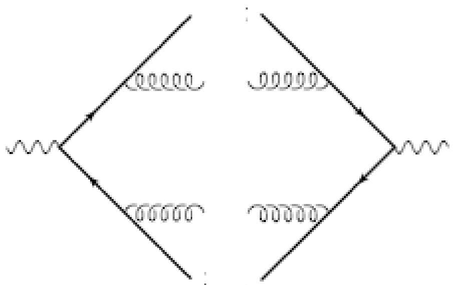
NLO assembly kit

example $e^+e^- \rightarrow 3$ jets

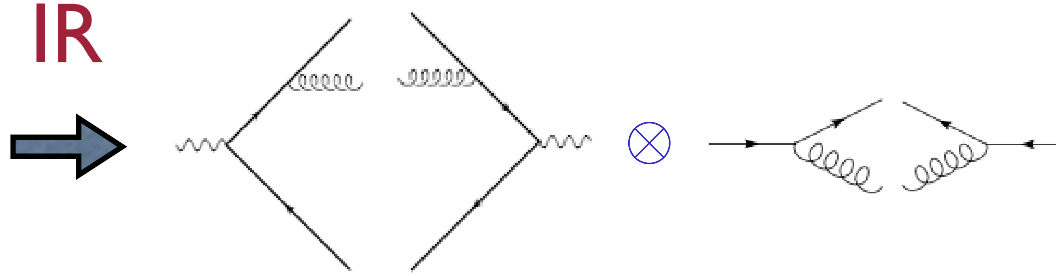
leading order $|\mathcal{M}_n^{tree}|^2$



NLO real



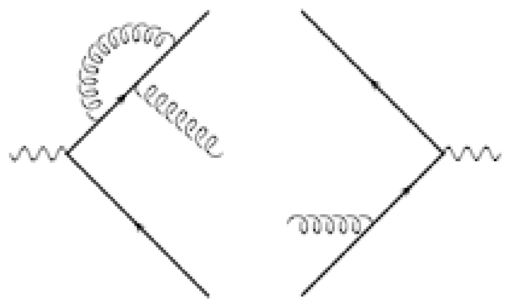
IR



$$|\mathcal{M}_{n+1}^{\text{tree}}|^2 \rightarrow |\mathcal{M}_n^{\text{tree}}|^2 \times \int dPS |P_{\text{split}}|^2$$

$$= -\left(\frac{A}{\epsilon^2} + \frac{B}{\epsilon}\right)$$

NLO virtual



$d = 4 - 2\epsilon$

$$\int d^d l \; 2(\mathcal{M}_n^{loop})^* \mathcal{M}_n^{tree} = \left(\frac{A}{\epsilon^2} + \frac{B}{\epsilon}\right) |\mathcal{M}_n^{tree}|^2 + fin.$$

NLO production rates

Process-independent procedure devised in the 90's

- slicing — Giele Glover Kosower 1992-3
- subtraction — Frixione Kunszt Signer 1995; Nagy Trocsanyi 1996
  - dipole — Catani Seymour 1996
  - antenna — Kosower 1997; Campbell Cullen Glover 1998

$$\sigma = \sigma^{\text{LO}} + \sigma^{\text{NLO}} = \int_m d\sigma_m^B \; J_m + \sigma^{\text{NLO}}$$

$$\sigma^{\text{NLO}} = \int_{m+1} d\sigma_{m+1}^{\text{R}} J_{m+1} + \int_m d\sigma_m^{\text{V}} J_m$$

the 2 terms on the rhs are divergent in d=4

use universal IR structure to subtract divergences

$$\sigma^{\text{NLO}} = \int_{m+1} \left[d\sigma_{m+1}^{\text{R}} J_{m+1} - d\sigma_{m+1}^{\text{R,A}} J_m \right] + \int_m \left[d\sigma_m^{\text{V}} + \int_1 d\sigma_{m+1}^{\text{R,A}} \right] J_m$$

the 2 terms on the rhs are finite in d=4

Observables must be IR safe

observable function J_m

J_m vanishes when one parton becomes soft or collinear to another one

$$J_m(p_1, ..., p_m) \to 0\,, \quad \text{if} \quad p_i \cdot p_j \to 0$$

⇨ $d\sigma_m^{\rm B}$ is integrable over 1-parton IR phase space

J_{m+1} vanishes when two partons become simultaneously soft and/or collinear

$$J_{m+1}(p_1, ..., p_{m+1}) \to 0\,, \quad \text{if} \quad p_i \cdot p_j \text{ and } p_k \cdot p_l \to 0 \quad (i \neq k)$$

R and V are integrable over 2-parton IR phase space

observables are IR safe

$$J_{n+1}(p_1, .., p_j = \lambda q, .., p_{n+1}) \to J_n(p_1, ..., p_{n+1}) \quad \text{if} \quad \lambda \to 0$$
$$J_{n+1}(p_1, .., p_i, .., p_j, .., p_{n+1}) \to J_n(p_1, .., p, .., p_{n+1}) \quad \text{if} \quad p_i \to zp\,,\ p_j \to (1-z)p$$

for all $n \geq m$