# Studi di Fisica
# a
# SLHC

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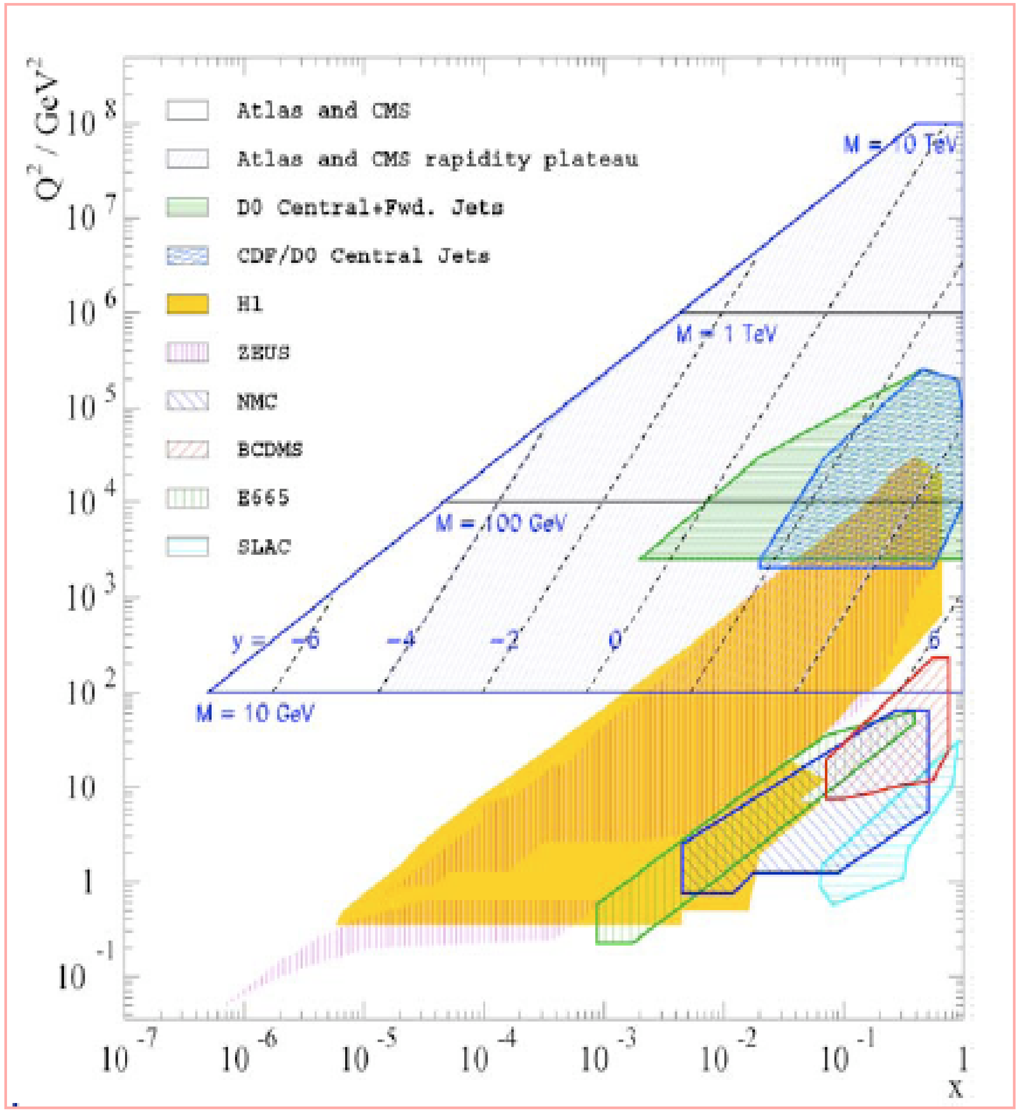
Incontro ATLAS/CMS per Upgrade a SLHC    Sestri Levante 13 Novembre 2008

# LHC kinematic reach




LHC opens up a new kinematic range

100-200 GeV physics is large x physics at Tevatron but small x physics at LHC

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

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

# LHC: the near future (5-10 years)

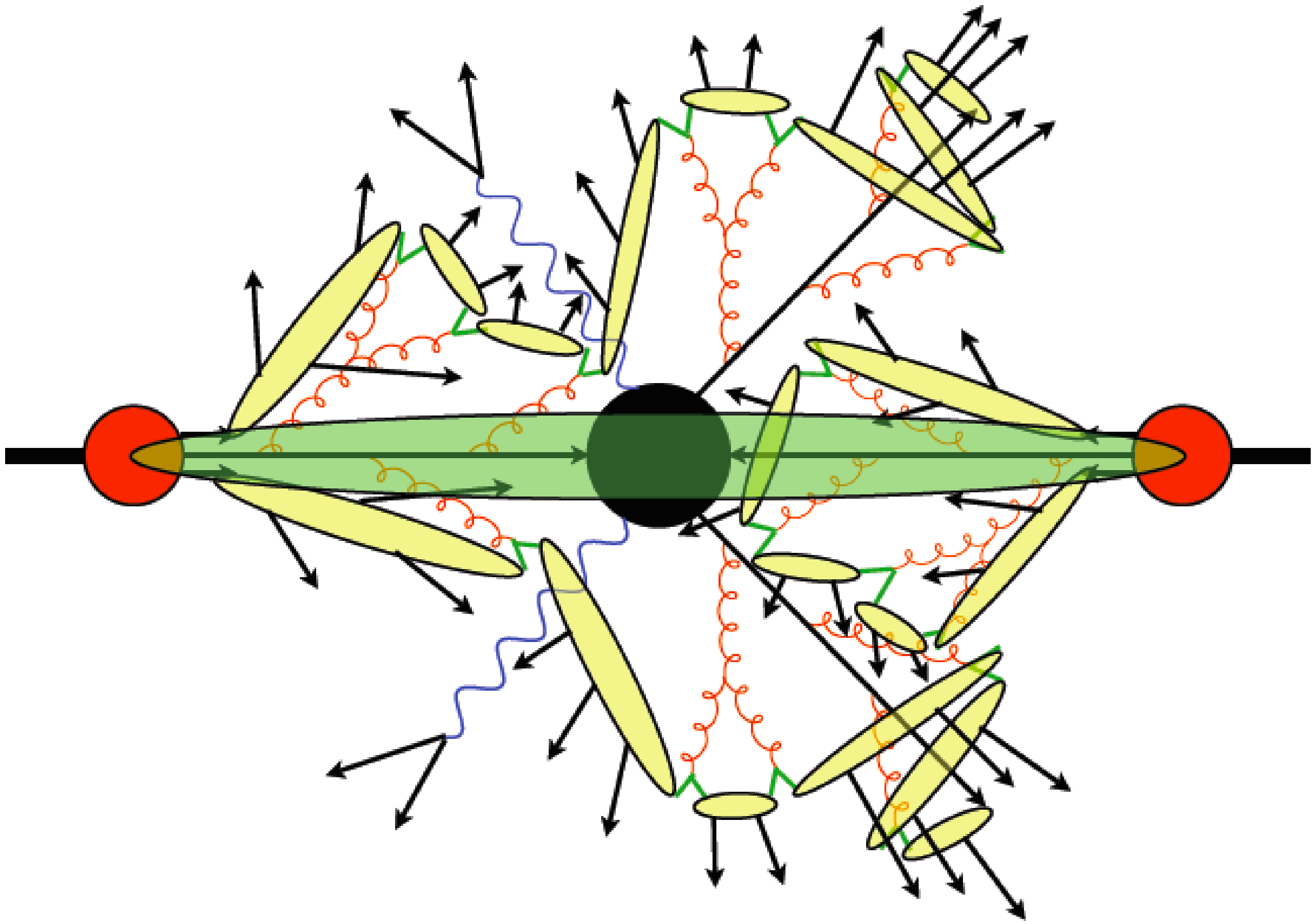
- calibrate the detectors, and re-discover the SM
  i.e. measure known cross sections: jets, $W, Z, t\bar{t}$

- understand the EWSB/find New-Physics signals
  (ranging from Z' → 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' → leptons)
precise QCD predictions play a crucial role

# LHC Event Simulation



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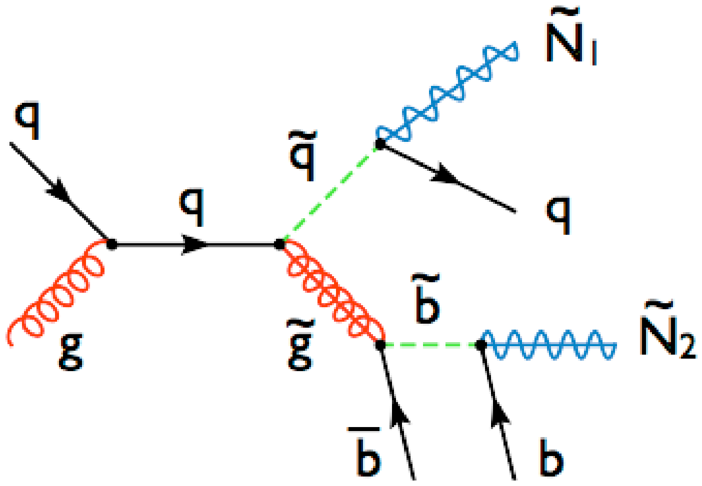
Parton showering and hadronisation are modelled through shower Monte Carlos (HERWIG o PYTHIA)

# Many-particle final states

At the SLHC, large number of high-multiplicity events

SM and NP processes accompanied by multi-jet events, which are typical signatures of known or new heavy particles, and possibly decay chains

SUSY:

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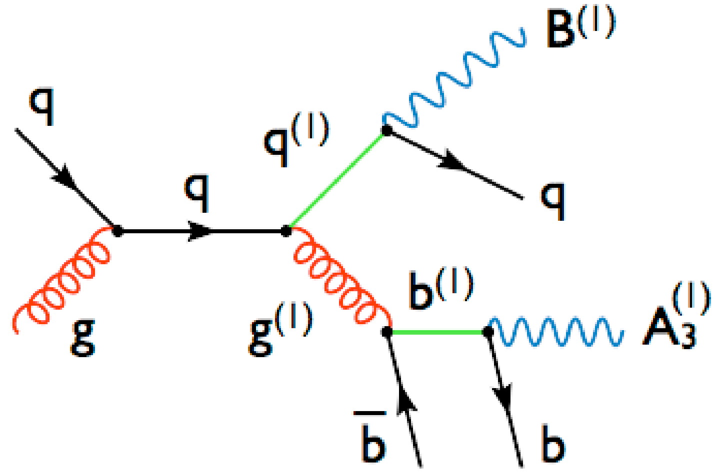
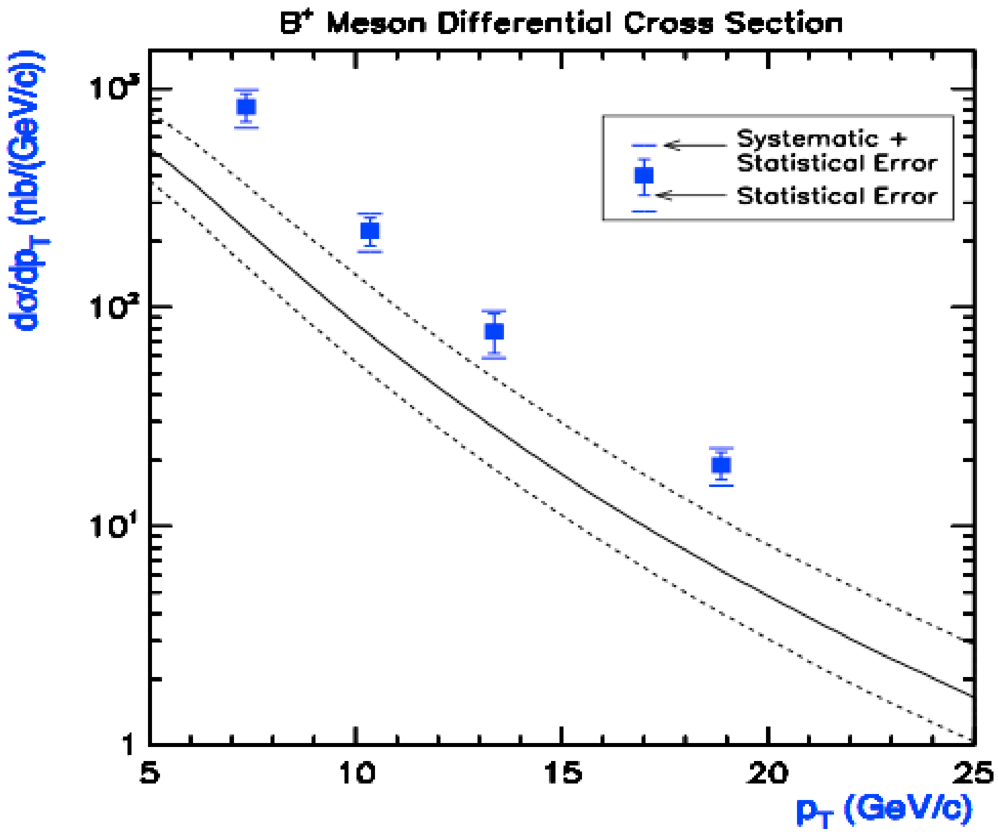
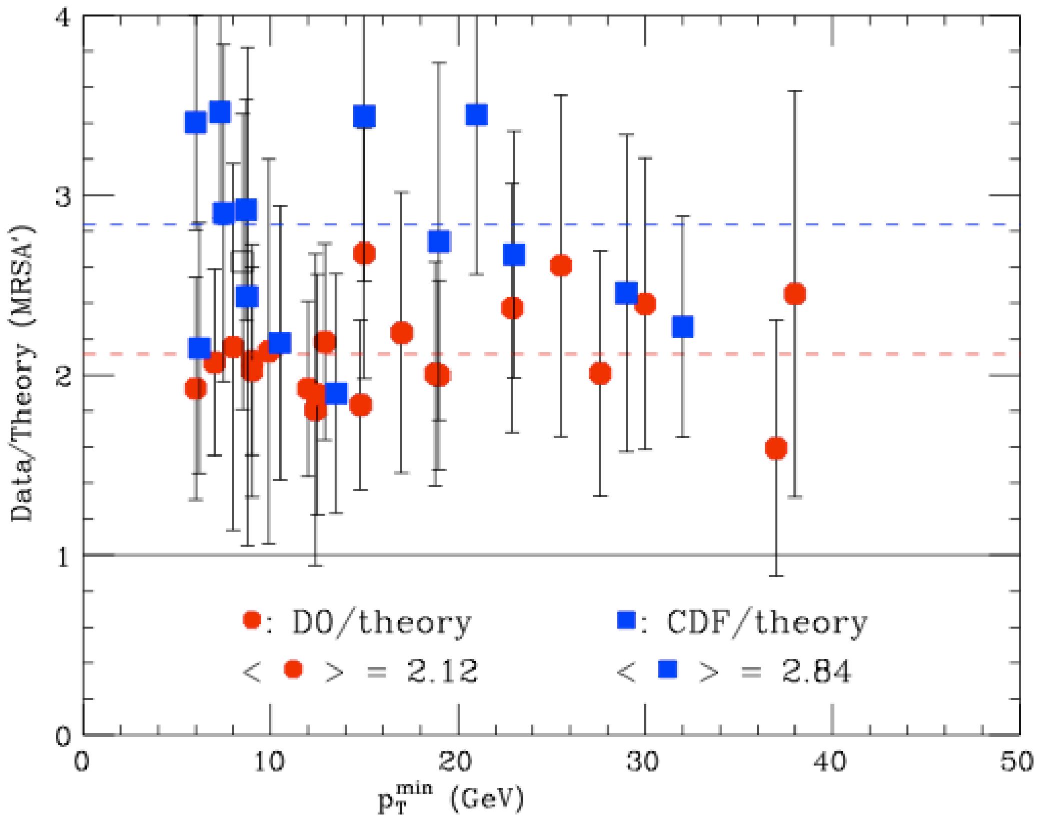



crucial to describe precisely high-multiplicity final states

Experience hints that a detailed knowledge of QCD is often necessary to understand collider events, and not to mis-interpret known physics as new physics

## B production: the 90's

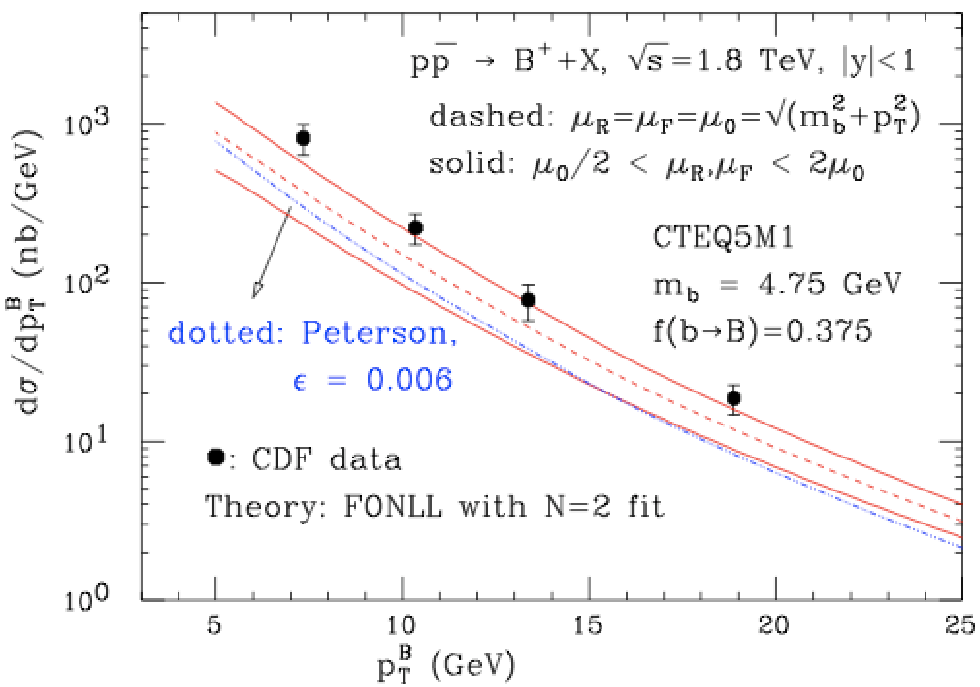


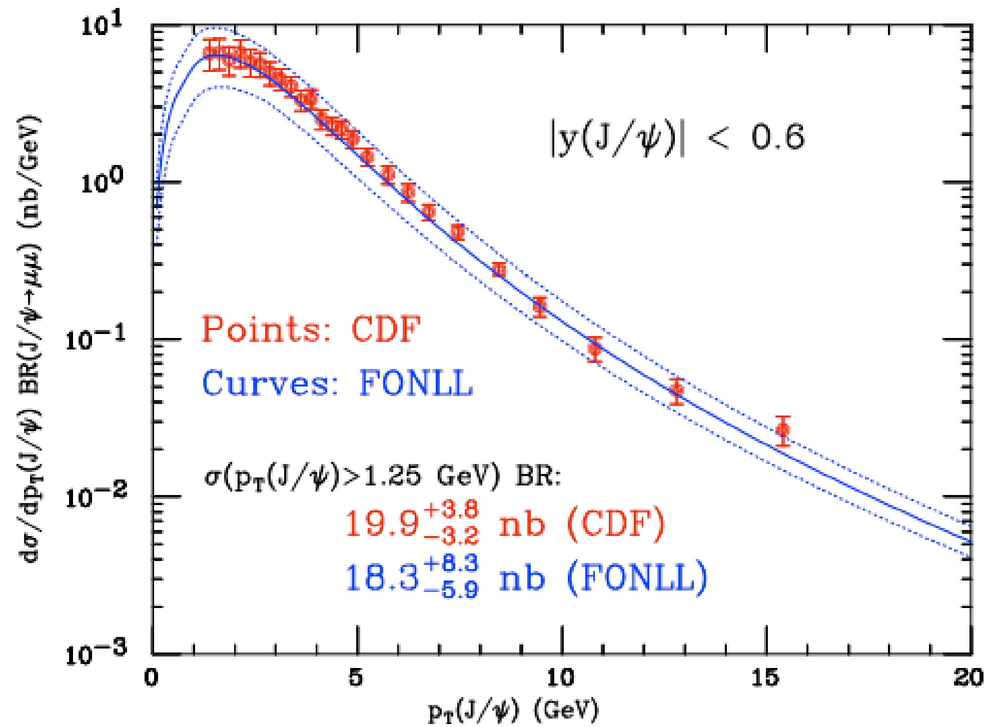




discrepancy between Tevatron data and NLO prediction

# 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

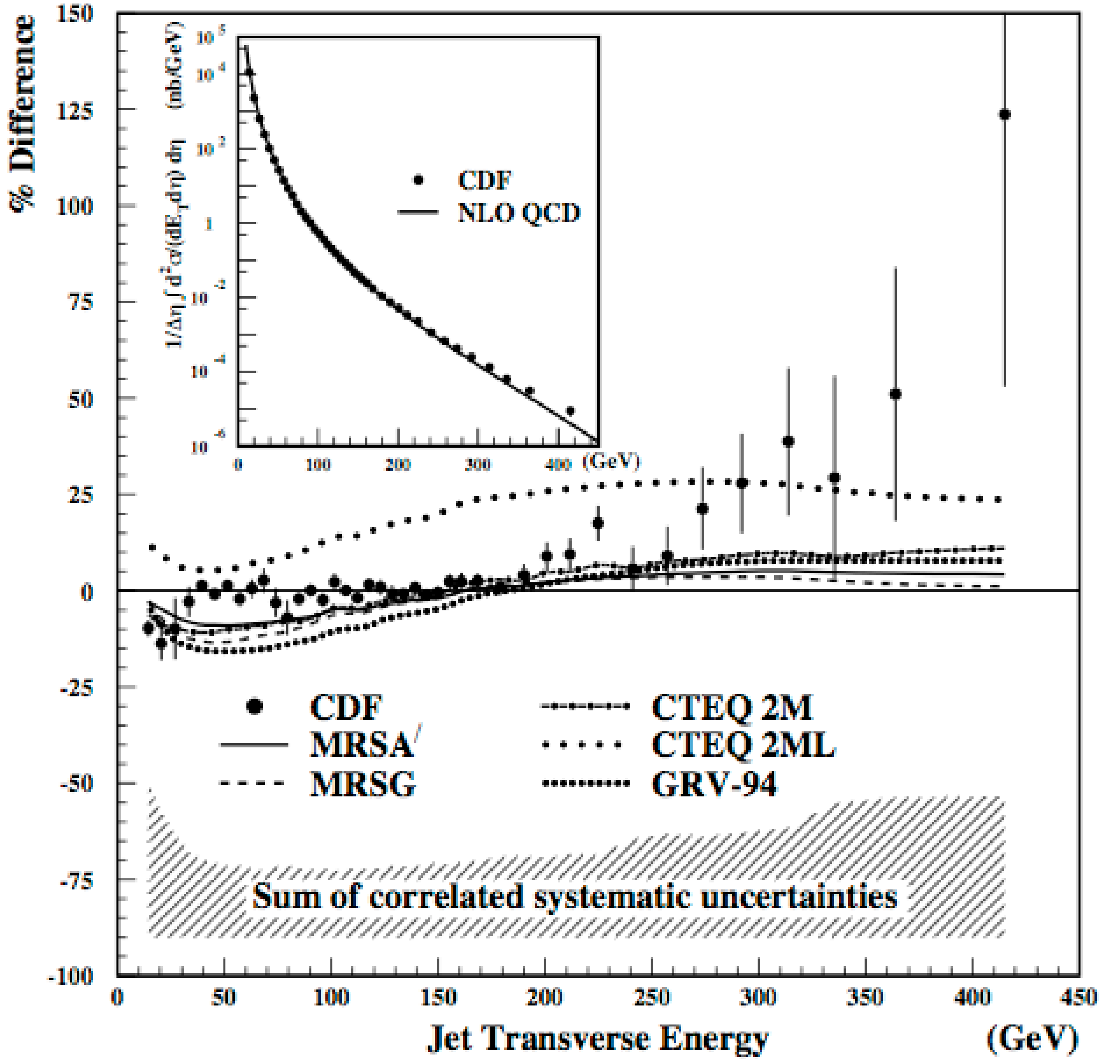
CDF hep-ex/0412071

better understanding of hadronisation

use of updated fragmentation functions (Cacciari & Nason)

→ good agreement with data → no New Physics

# High $p_T$ Jets at the Tevatron




Excess of data over theory reported by CDF (PRL77(1996)438) for $p_T > 250$ GeV in the inclusive 1-jet rate. Highest momentum transfer probed so far, most sensitive to NP

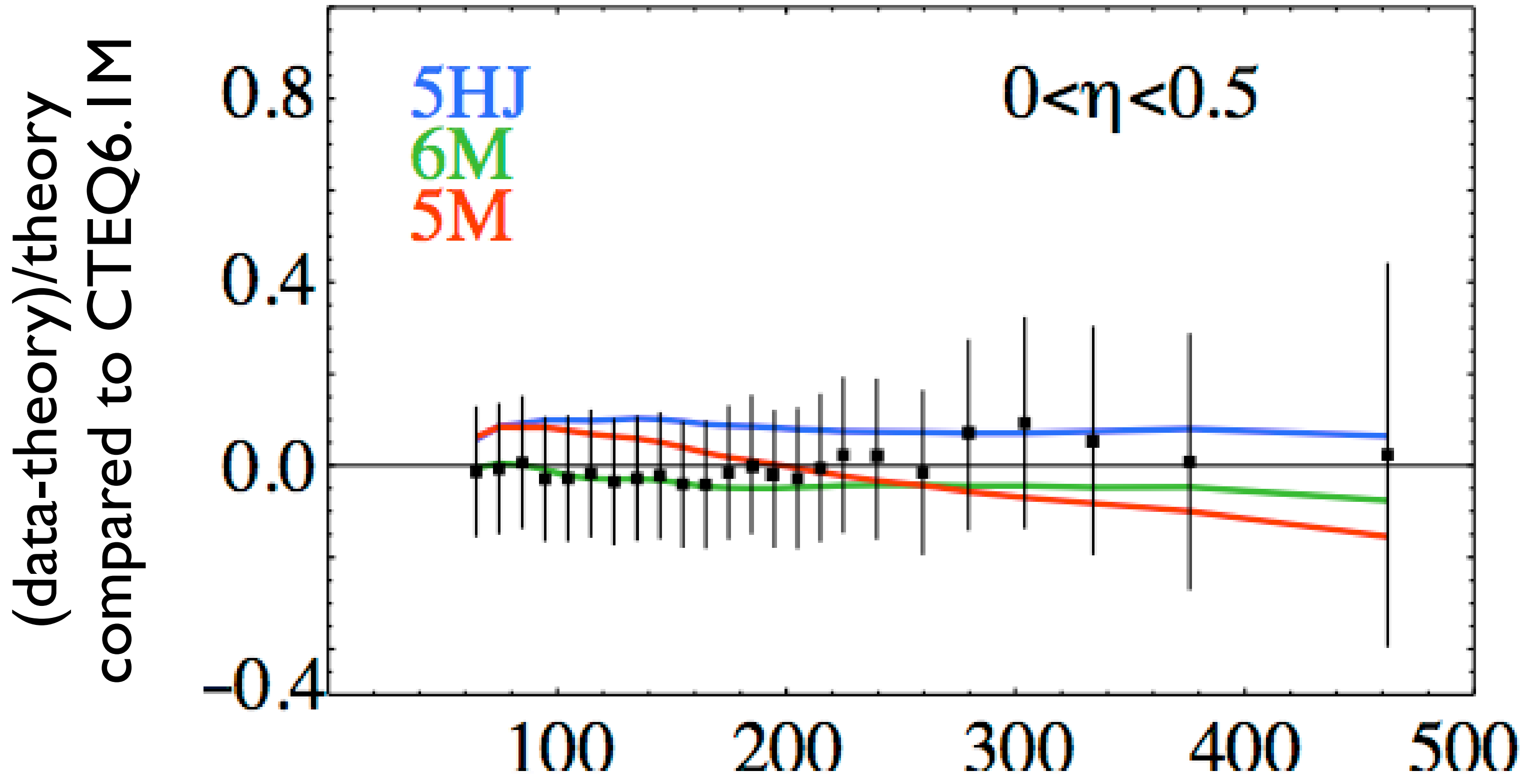
Many speculations about NP

Mundane solution: better PDF's

# Better PDF's

At high *x*'s, the gluon distribution is not constrained; with dedicated PDF's, which include the CDF inclusive 1-jet data, in case of compositeness, one should still find an excess in the central-rapidity region. Using D0 data, CTEQ showed there is no excess

Stump et al. (CTEQ) hep-ph/0303013




D0 inclusive jet cross section vs. $E_T$

For better PDF's: need larger data samples & more accurate theory

# Solid SLHC phenomenology needs

- accurate perturbative results
  - NLO (multi-leg), NNLO
  - jet studies
- improved Monte Carlo generators
  - multi-jet, tree-level matrix elements
  - interface with full NLO corrections (MC@NLO, POWHEG)
- soft, semi-hard physics
  - hadronisation in MC's
  - underlying and pile-up events (from 25 at LHC to ~300 at SLHC)
- precise inputs
  - PDF's and fragmentation functions
  - $\alpha_s$

# Tremendous progress in QCD over last 5 years

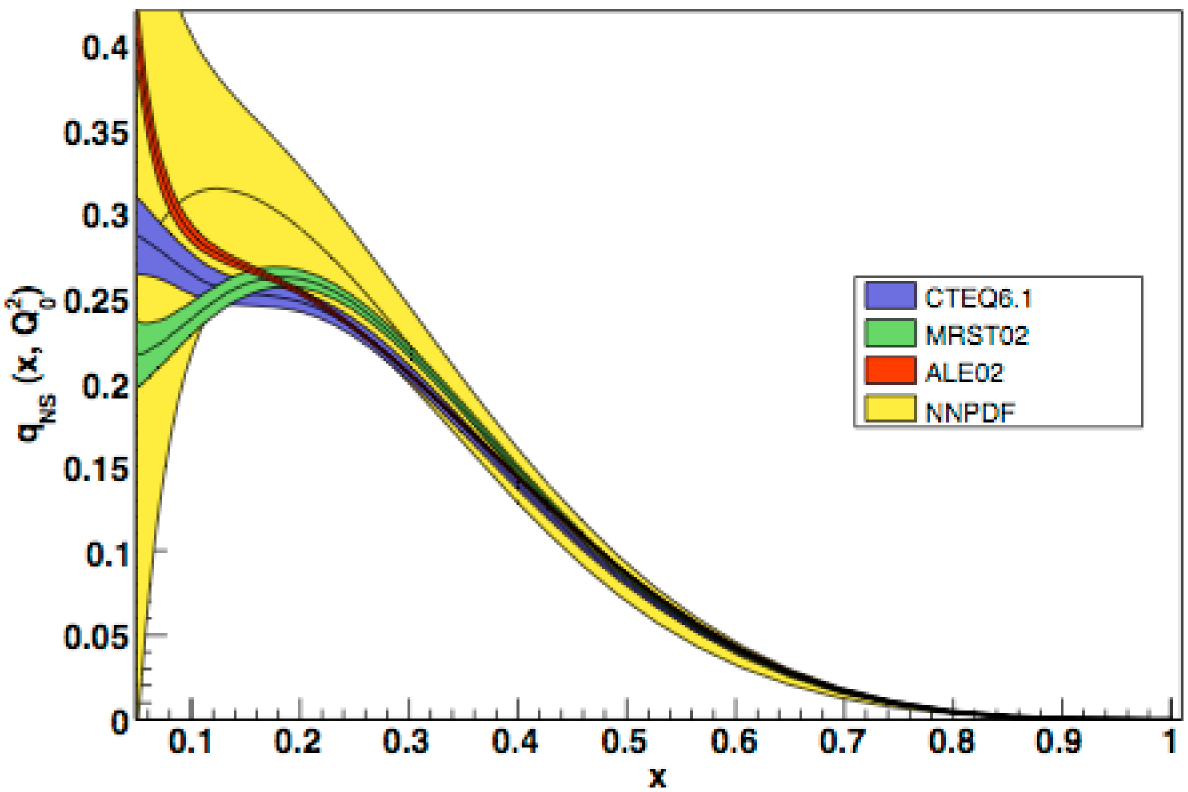
Matrix-element Monte Carlo generators up to 8-9 final-state particles

NLO matrix elements for W + 3 jets

Ellis, Giele, Kunszt, Melnikov, Zanderighi 08

NNLO determination of $\alpha_s$ from event shapes

PDF's with errors



# Physics issues at the SLHC

- Vector boson sector
  - triple and quartic gauge couplings
  - testing quintuple gauge coupling
  - vector boson scattering
  - new vector bosons
- Higgs sector
  - (self-)couplings
  - rare decays
  - dynamical symmetry breaking
- Top physics
  - rare decays by FCNC
- Compositeness

} will deal with this

- SUSY
- Extra dimensions

} won't deal with this

# Anomalous triple gauge couplings

after U(1)EM, C and P conservation, get an effective Lagrangian

$$\begin{aligned}\Delta\mathcal{L}_{GB} &= -ie\Big[\Delta g_1^Z(\overleftrightarrow{\partial} W^*_{\mu\nu}W^\mu Z^\nu - \overleftrightarrow{\partial} W_{\mu\nu}W^{*\mu}Z^\nu) \\ &\quad +\Delta\kappa^Z W^{*\mu}W^\nu\overleftrightarrow{\partial} Z_{\mu\nu} \\ &\quad +\frac{\lambda^Z}{m_W^2}\overleftrightarrow{\partial} W^*_{\rho\mu}\overleftrightarrow{\partial} W^\mu_\nu\overleftrightarrow{\partial} Z^{\nu\rho}\Big] \\ &\quad -ie\cot\theta_W\Big[\Delta\kappa^\gamma W^{*\mu}W^\nu\overleftrightarrow{\partial}\gamma_{\mu\nu} \\ &\quad +\frac{\lambda^\gamma}{m_W^2}\overleftrightarrow{\partial} W^*_{\rho\mu}\overleftrightarrow{\partial} W^\mu_\nu\overleftrightarrow{\partial}\gamma^{\nu\rho}\Big]\end{aligned}$$

in (tree-level) SM

$$\Delta g_1^Z = \Delta\kappa^Z = \lambda^Z = \Delta\kappa^\gamma = \lambda^\gamma = 0$$

At SLHC $W\gamma \to l\nu\gamma$ probes $\Delta\kappa^\gamma, \lambda^\gamma$

$WZ \to l\nu ll$ probes $g_1^Z, \Delta\kappa^Z, \lambda^Z$

$\Delta\mathcal{L}_{GB}$ spoils the high-energy behaviour of the amplitudes, which violate unitarity

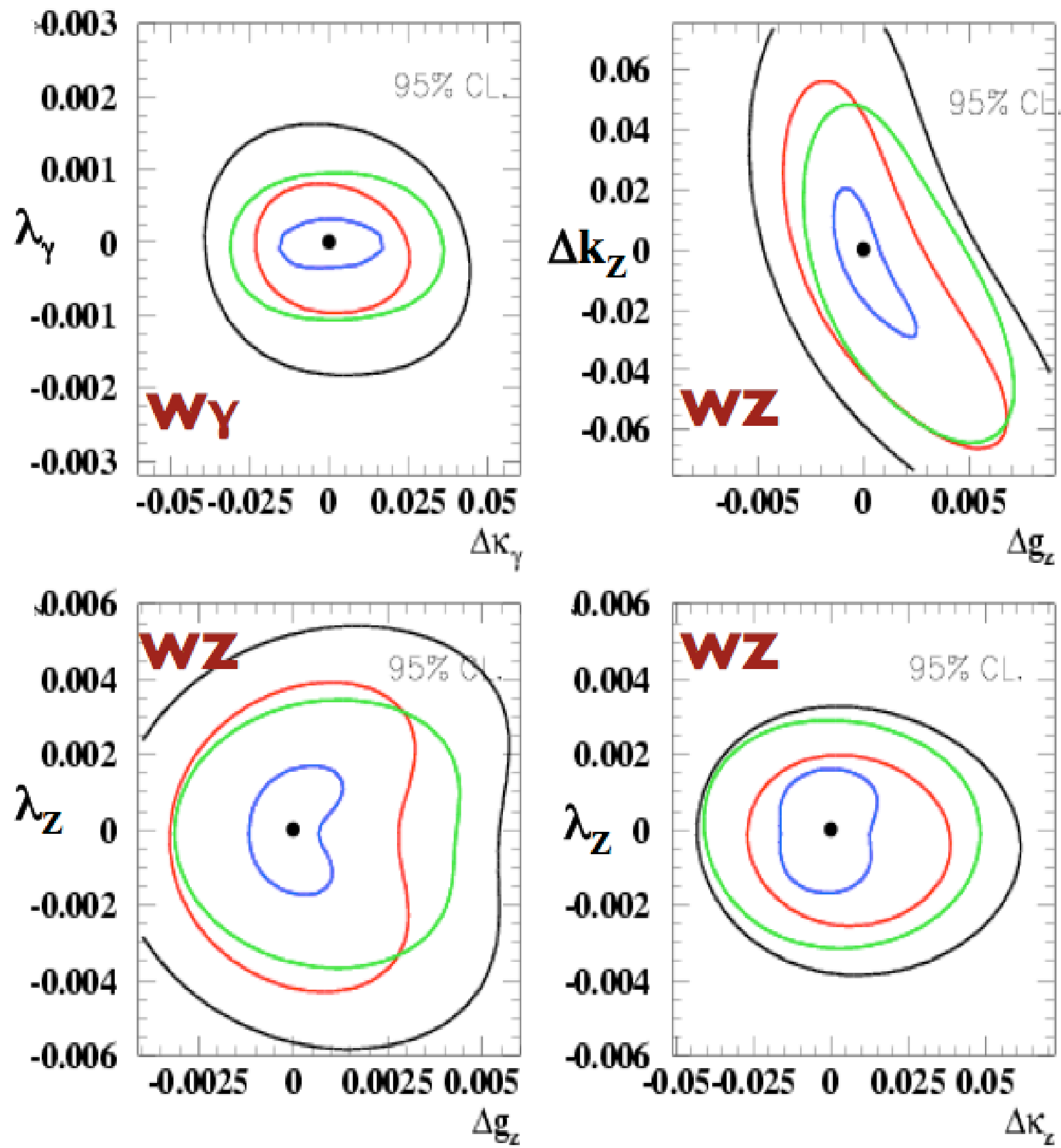
cut it off by hand through $c \to \dfrac{c}{1+s/\Lambda}$

95% CL constraints ($\Lambda$ = 10 TeV)
One parameter varies, others fixed at SM values
SM accuracy is at $10^{-3}$ level
⟶ required experimental accuracy

| Coupling | 14 TeV 100 fb$^{-1}$ | 14 TeV 1000 fb$^{-1}$ |
|---|---|---|
| $\lambda_\gamma$ | 0.0014 | 0.0006 |
| $\lambda_Z$ | 0.0028 | 0.0018 |
| $\Delta\kappa_\gamma$ | 0.034 | 0.020 |
| $\Delta\kappa_Z$ | 0.040 | 0.034 |
| $g_1^Z$ | 0.0038 | 0.0024 |

95% CL constraints ($\Lambda$ = 10 TeV)
2-parameter fits

14 TeV, 100 fb$^{-1}$, 1000 fb$^{-1}$
28 TeV, 100 fb$^{-1}$, 1000 fb$^{-1}$



# Anomalous quartic gauge couplings

global $SU(2)_L \otimes SU(2)_R$ broken to $SU(2)$

effective chiral Lagrangian in terms of $\Sigma(x) = \exp\left(i\frac{\phi^a(x)\tau^a}{v}\right)$

$\phi^a(x)$ pseudo-Goldstone boson $\tau^a$ Pauli matrix

$$
\begin{aligned}
\mathcal{L}_4 &= \alpha_4 \left[\mathrm{Tr}(V^\mu V^\nu)\right]^2 \\
\mathcal{L}_5 &= \alpha_5 \left[\mathrm{Tr}(V_\mu V^\mu)\right]^2 \\
\mathcal{L}_6 &= \alpha_6 \ \mathrm{Tr}(V_\mu V_\nu)\ \mathrm{Tr}(TV^\mu)\ \mathrm{Tr}(TV^\nu) \\
\mathcal{L}_7 &= \alpha_7 \ \mathrm{Tr}(V_\mu V^\mu)\left[\mathrm{Tr}(TV^\nu)\right]^2 \\
\mathcal{L}_{10} &= \frac{\alpha_{10}}{2}\left[\mathrm{Tr}(TV^\mu)\ \mathrm{Tr}(TV^\nu)\right]^2
\end{aligned}
$$

$$
\begin{aligned}
V_\mu &= (D_\mu \Sigma)\Sigma^\dagger \\
T &= \Sigma\tau^3\Sigma^\dagger
\end{aligned}
$$

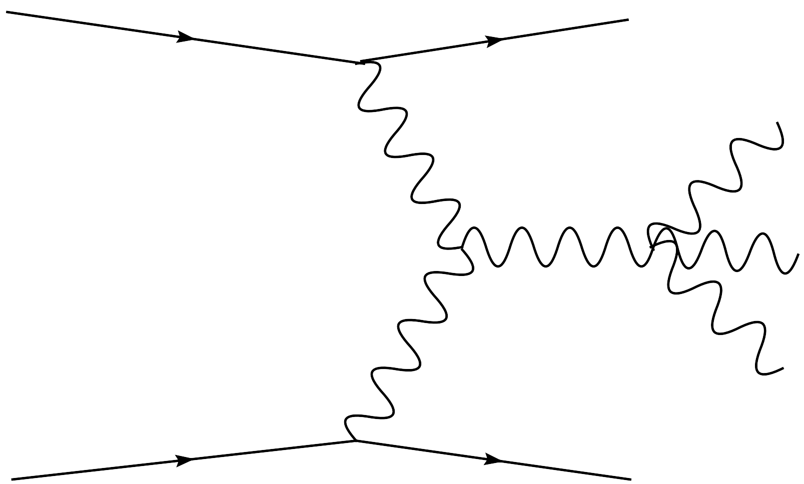
$D_\mu = SU(2)_L \otimes U(1)_Y$ covariant derivative

couplings probed by $pp \to qqVV \to VVjj$, $pp \to V^* \to VVV$ with $V = W^\pm, Z$

| Coupling | Indirect Limits (1$\sigma$) ($\times 10^{-3}$) | LHC, 100 fb$^{-1}$ (1$\sigma$) ($\times 10^{-3}$) | LHC, 6000 fb$^{-1}$ (1$\sigma$) ($\times 10^{-3}$) | LHC, 6000 fb$^{-1}$ 95% C.L. ($\times 10^{-3}$) |
|---|---|---|---|---|
| $\alpha_4$ | $-120. \le \alpha_4 \le 11.$ | $-1.1 \le \alpha_4 \le 11.$ | $-0.67 \le \alpha_4 \le 0.74$ | $-0.92 \le \alpha_4 \le 1.1$ |
| $\alpha_5$ | $-300. \le \alpha_5 \le 28.$ | $-2.2 \le \alpha_5 \le 7.7$ | $-1.2 \le \alpha_5 \le 1.2$ | $-1.7 \le \alpha_5 \le 1.7$ |
| $\alpha_6$ | $-20. \le \alpha_6 \le 1.8$ | $-9.6 \le \alpha_6 \le 9.1$ | $-3.5 \le \alpha_6 \le 3.2$ | $-4.3 \le \alpha_6 \le 3.9$ |
| $\alpha_7$ | $-19. \le \alpha_7 \le 1.8$ | $-10. \le \alpha_7 \le 7.4$ | $-4.4 \le \alpha_7 \le 2.2$ | $-5.4 \le \alpha_7 \le 2.8$ |
| $\alpha_{10}$ | $-21. \le \alpha_{10} \le 1.9$ | $-24. \le \alpha_{10} \le 24.$ | $-4.1 \le \alpha_{10} \le 4.1$ | $-4.8 \le \alpha_{10} \le 4.8$ |

# Quintuple gauge couplings

can be tested in triple boson production from vector-boson fusion



$ZW^{\pm} \to W^+W^-W^{\pm} \to 3l$

870 leptonic events for $m_H$ = 120 GeV and 6000 fb$^{-1}$

# ElectroWeak Symmetry Breaking

- a SM Higgs with $115 < m_H < 200$ GeV should be found with 10-15 $fb^{-1}$

- If a SM Higgs is found with 200 GeV $< m_H <$ 1 TeV (not much luminosity needed there), then need more luminosity to find the New Physics that explains the EW precision fits

- *If* $m_H >$ 1 TeV, then we face a scenario with a composite Higgs, vector-boson resonances ⟶ New Physics

anything beyond measuring a Higgs resonance, like studying the Higgs properties, couplings and quantum numbers might require SLHC luminosities

# Higgs couplings

The properties of the Higgs-like resonance are its

- couplings: gauge, Yukawa, self-couplings
- quantum numbers: charge, colour, spin, CP

## Dührssen et al.'s analysis for gauge and Yukawa couplings

hep-ph/0406323

- use narrow-width approx for Γ (fine for $m_H < 200$ GeV)
- production rate with $H$ decaying to final state $xx$ is

$$\sigma(H) \times \mathrm{BR}(H \to xx) = \frac{\sigma(H)^{\mathrm{SM}}}{\Gamma_p^{\mathrm{SM}}} \frac{\Gamma_p \Gamma_x}{\Gamma}$$

branching ratio for the decay is $\mathrm{BR}(H \to xx) = \frac{\Gamma_x}{\Gamma}$

observed rate determines $\frac{\Gamma_p \Gamma_x}{\Gamma}$

- VBF and gluon-fusion rates yield measurements of combinations of partial widths

$$\frac{\Gamma_W \Gamma_\gamma}{\Gamma} \quad \text{from} \quad qq \to qqH,\ H \to \gamma\gamma$$

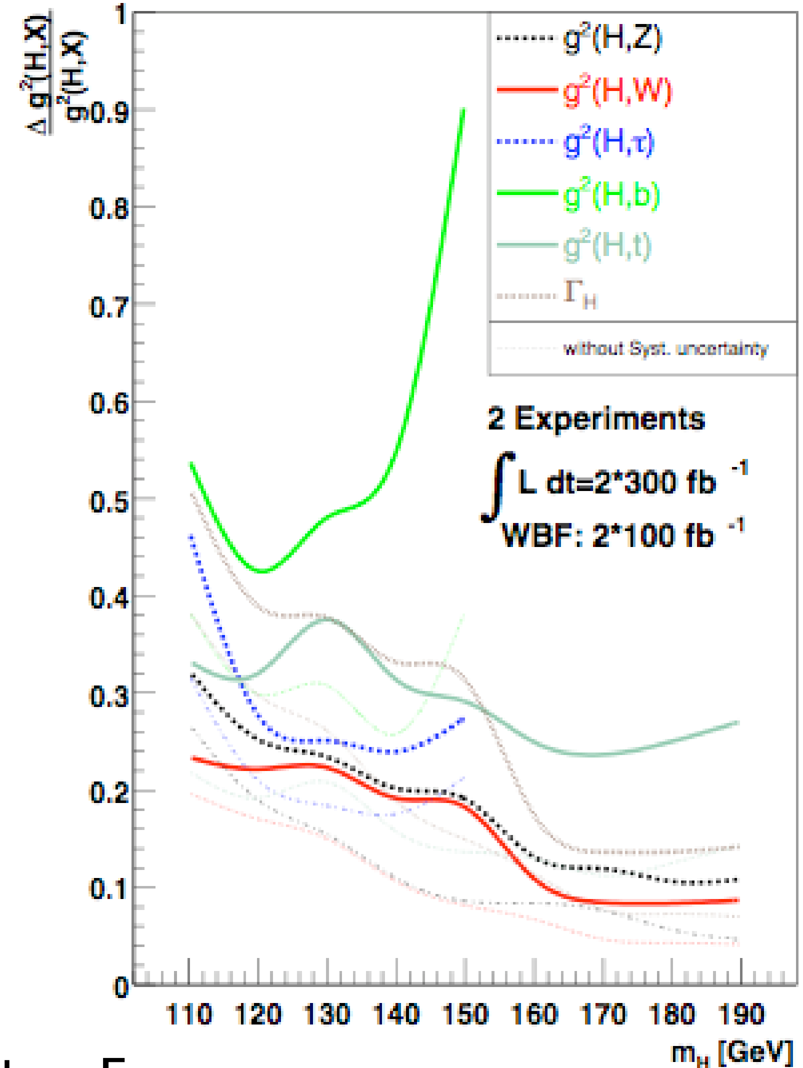
$$\frac{\Gamma_W \Gamma_\tau}{\Gamma} \quad \text{from} \quad qq \to qqH,\ H \to \tau\tau$$

$$\frac{\Gamma_W^2}{\Gamma} \quad \text{from} \quad qq \to qqH,\ H \to WW^*$$

$$\frac{\Gamma_g \Gamma_\gamma}{\Gamma} \quad \text{from} \quad gg \to H \to \gamma\gamma$$

$$\frac{\Gamma_g \Gamma_Z}{\Gamma} \quad \text{from} \quad gg \to H \to ZZ^*$$

$$\frac{\Gamma_g \Gamma_W}{\Gamma} \quad \text{from} \quad gg \to H \to WW^*$$




- Note that Γ can be estimated:

direct observation of Higgs yields lower bound on Γ

then assume $\Gamma_V \leq \Gamma_V^{\rm SM}$ $\quad V = W, Z$

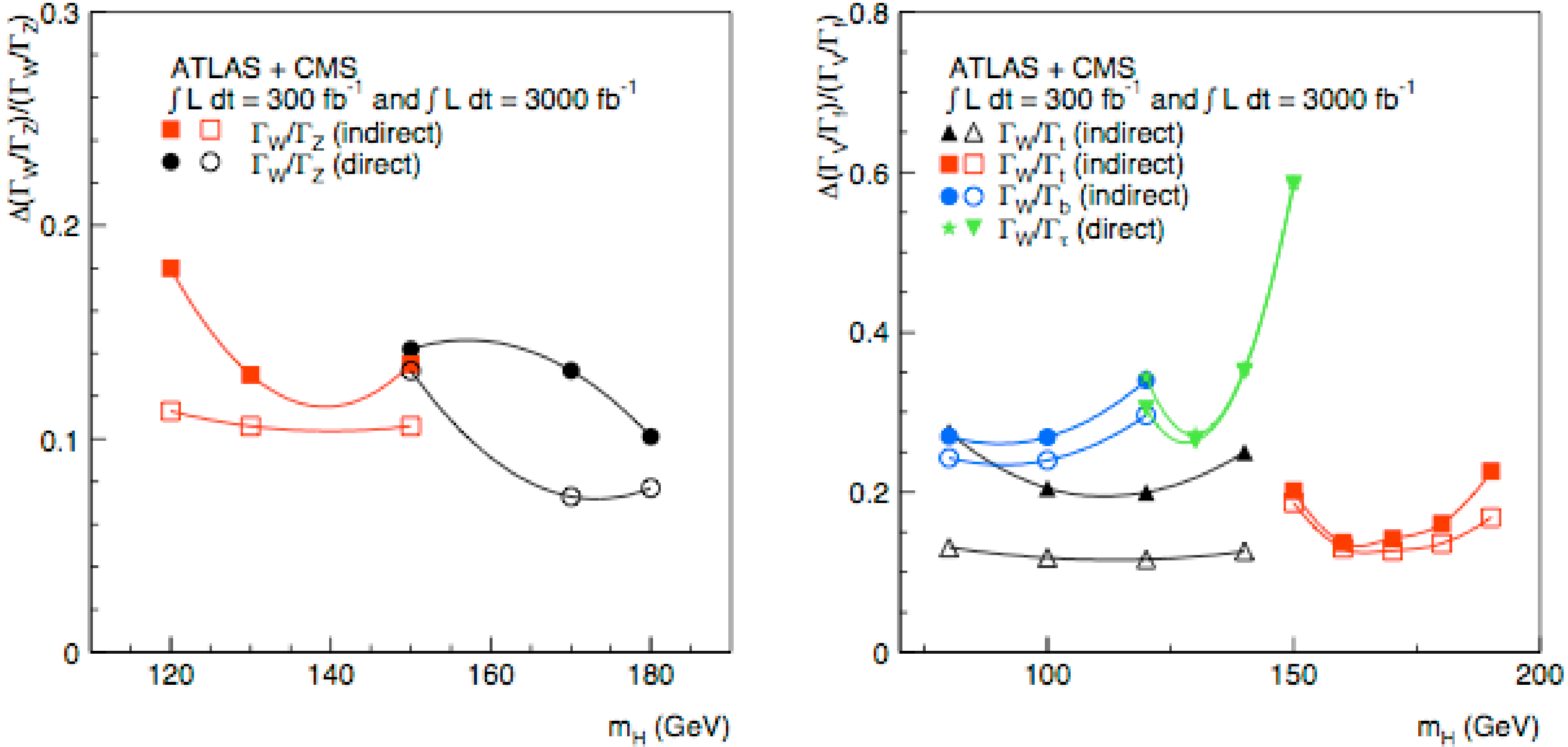
(true in any model with arbitrary # of Higgs doublets ⇒ true in MSSM)

combine $\Gamma_V \leq \Gamma_V^{\rm SM}$ with measure of $\Gamma_V^2/\Gamma$ from $H \to VV$

obtain upper bound on Γ

# Model-independent analysis based on the ratio of rates

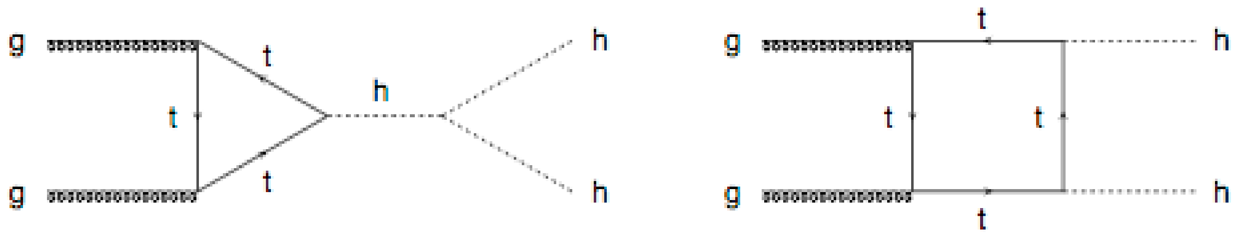
Zeppenfeld et al. 2000



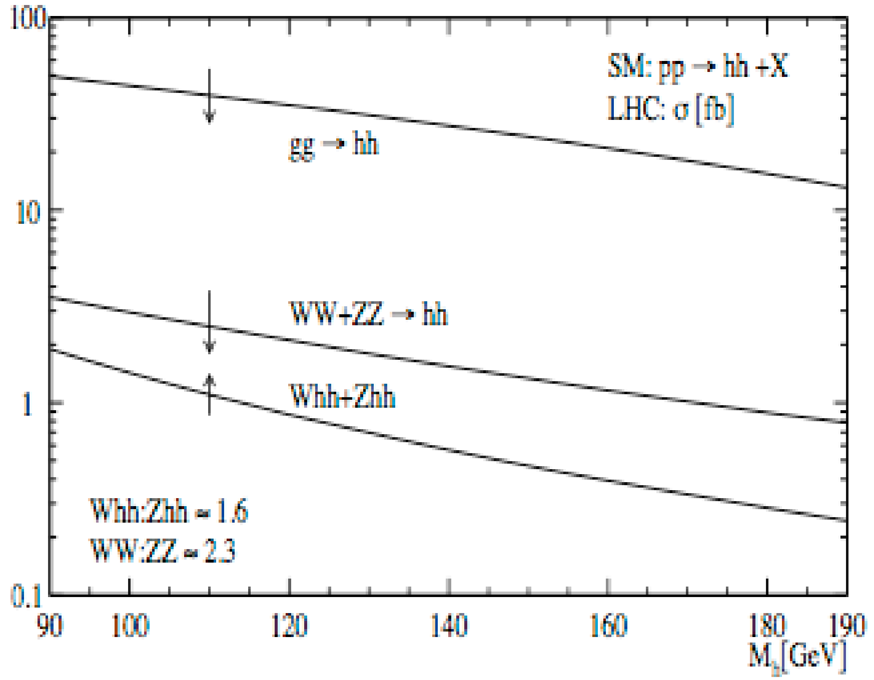

the improvement of SLHC over LHC is never better than a factor 2

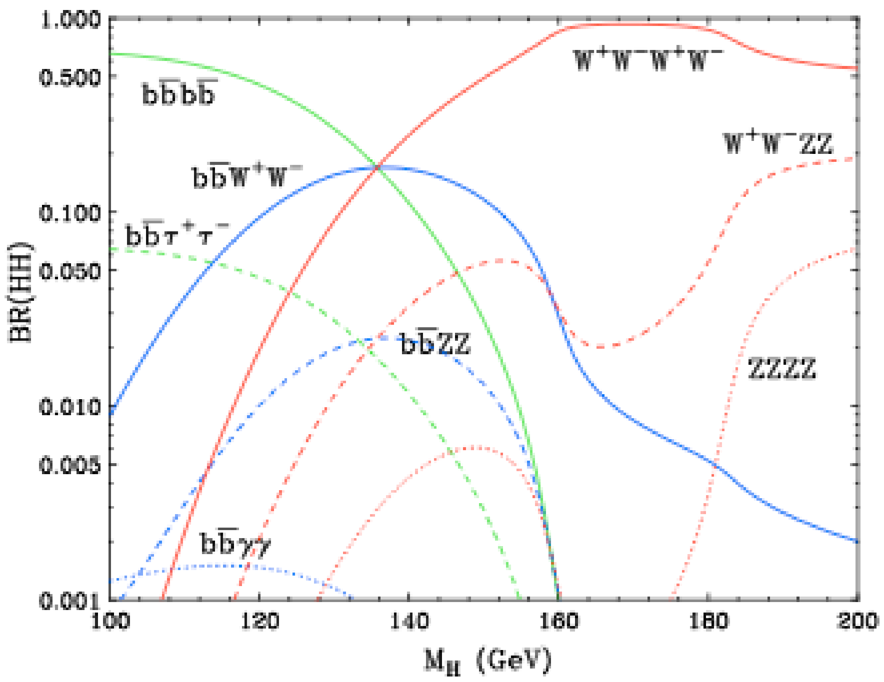
# Higgs self-couplings

Measurement of *HHH* coupling possible through *HH* production
dominant production mode is gluon fusion




large cancellation between the 2 diagrams makes the rate rather small
in addition, huge QCD backgrounds

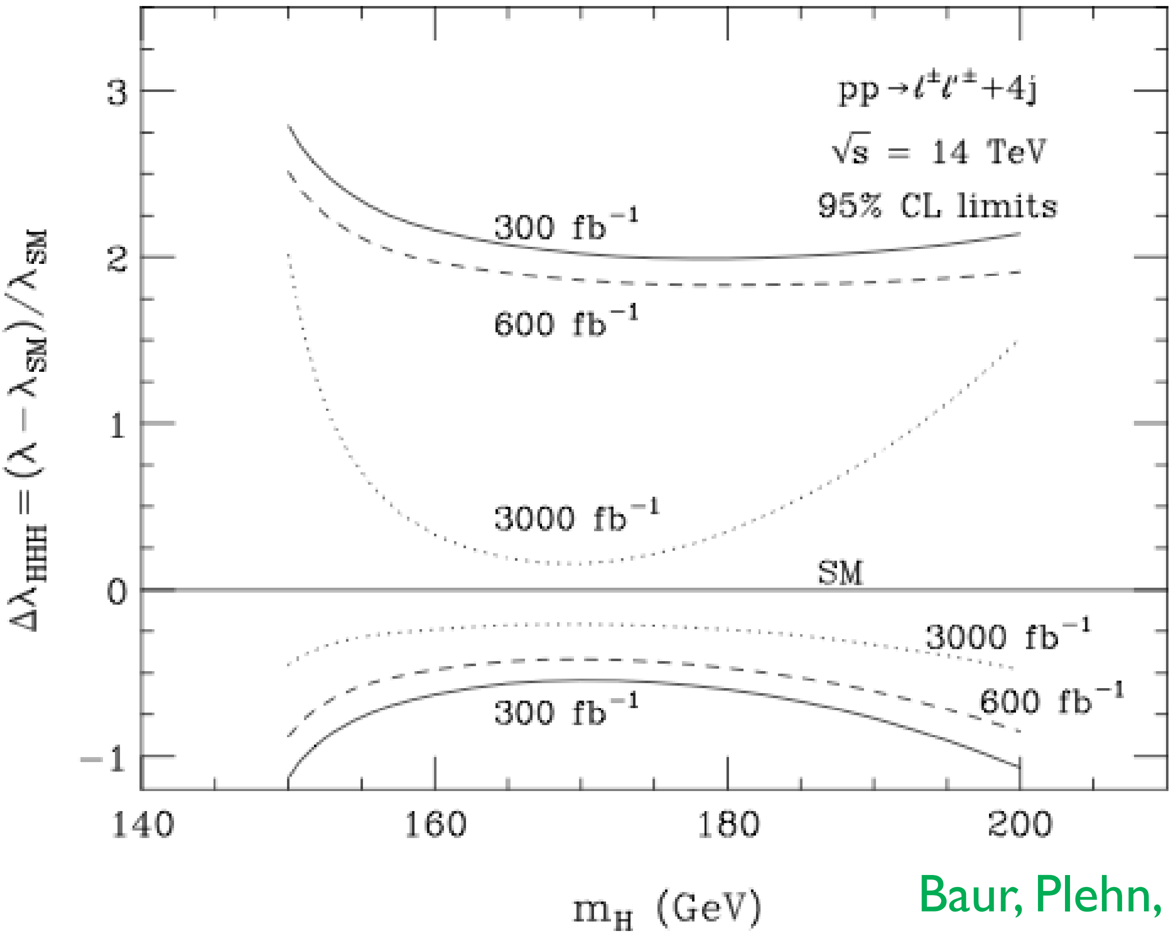


best chance to measure $\lambda_{HHH}$ is

$$gg \to HH \to W^+W^-W^+W^- \to \begin{cases} l^\pm l^\pm + 4j \\ l^+l^-l^\pm + 2j \end{cases}$$

main systematic uncertainties are
- limited knowledge of top Yukawa coupling, which drives production rate
- BR to $W^+ W^-$, which drives decay fraction
must be known very precisely for a measurement to be useful




$\Delta\lambda_{HHH}$ = -1 ⟶ no self-coupling

for $m_H$ > 150 GeV,
LHC can exclude $\lambda$ =0 at 95% CL

SLHC could measure
$\Delta\lambda_{HHH}$ to 20-30%

Baur, Plehn, Rainwater '03

# Rare Higgs decays

$H \to Z\gamma \to ll\gamma$

At LHC, with 600 fb$^{-1}$ $S/\sqrt{B} = 3.5\sigma$
At SLHC, with 6000 fb$^{-1}$ $S/\sqrt{B} = 11\sigma$

$H \to \mu^+\mu^-$

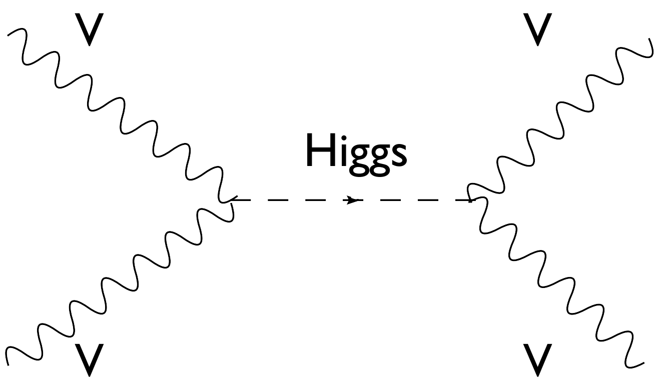
| $m_H$ (GeV) | $S/\sqrt{B}$ | $\frac{\delta\sigma\times\text{BR}(H\to\mu\mu)}{\sigma\times\text{BR}}$ |
|---|---|---|
| 120 GeV | 7.9 | 0.13 |
| 130 GeV | 7.1 | 0.14 |
| 140 GeV | 5.1 | 0.20 |
| 150 GeV | 2.8 | 0.36 |

# Composite Higgs

- For $E >> m_W$, the longitudinally polarised vector bosons are the Goldstone bosons of the EWSB.
  Thus, $V_L V_L \to V_L V_L$ probes the EWSB
- $\mathcal{L}_{SB}$ must produce observable effects at $\sqrt{s_{VV}} = \Lambda_{SB} \le 1.7$ TeV
- the scale $\Lambda_{SB}$ and the coupling strength $\lambda_{SB}$ are correlated;
  thus, if the Higgs is heavy it is also strongly interacting, and the strong vector-boson scattering can be analysed through chiral Lagrangians
- Example: σ-model effective Lagrangian $\mathcal{L} = \frac{c_H}{2f^2}\partial_\mu(H^\dagger H)\partial^\mu(H^\dagger H) + \cdots$

  σ-model scale $f$ is like the pion decay constant in low-energy QCD

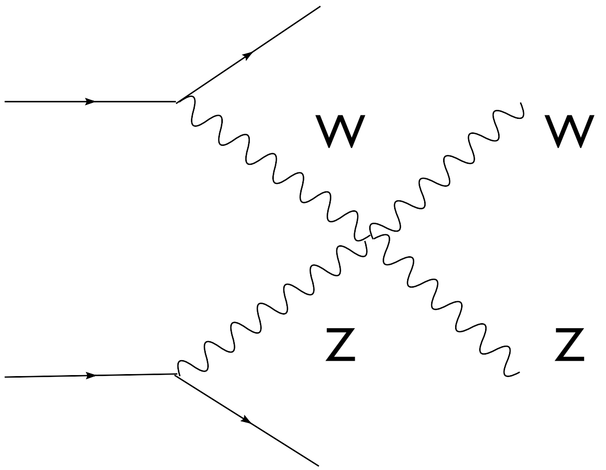
Giudice, Grojean, Pomarol, Rattazzi '07

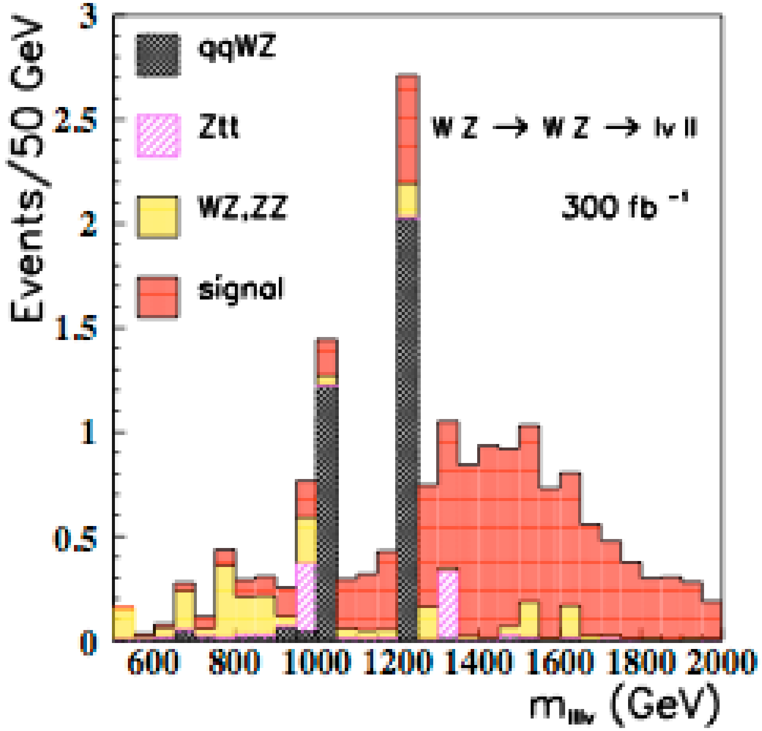


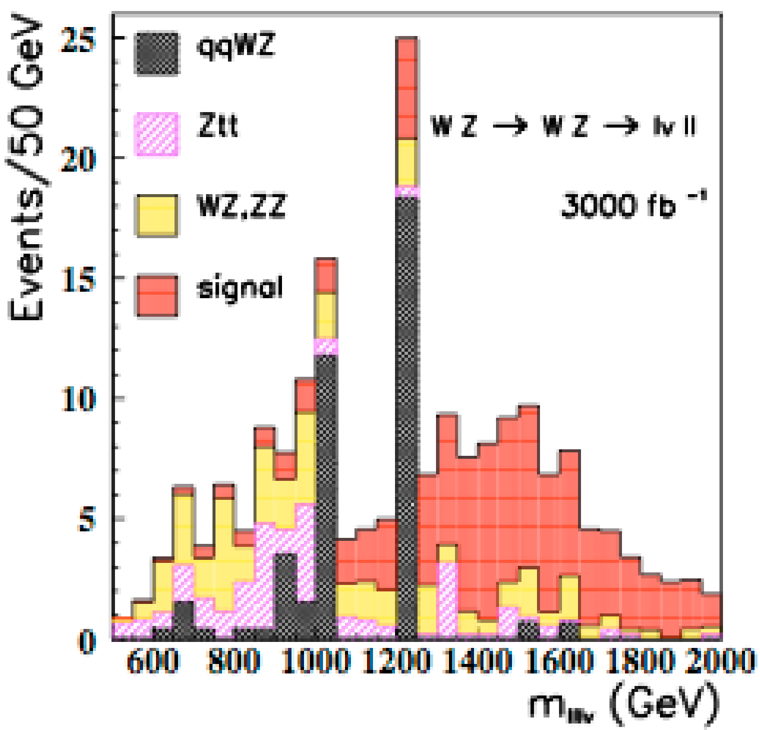

$$= \left(1 - c_H \frac{v^2}{f^2}\right) g^2 \frac{E^2}{m_W^2}$$

# Strong vector-boson scattering

$W_L Z_L \to 3l$



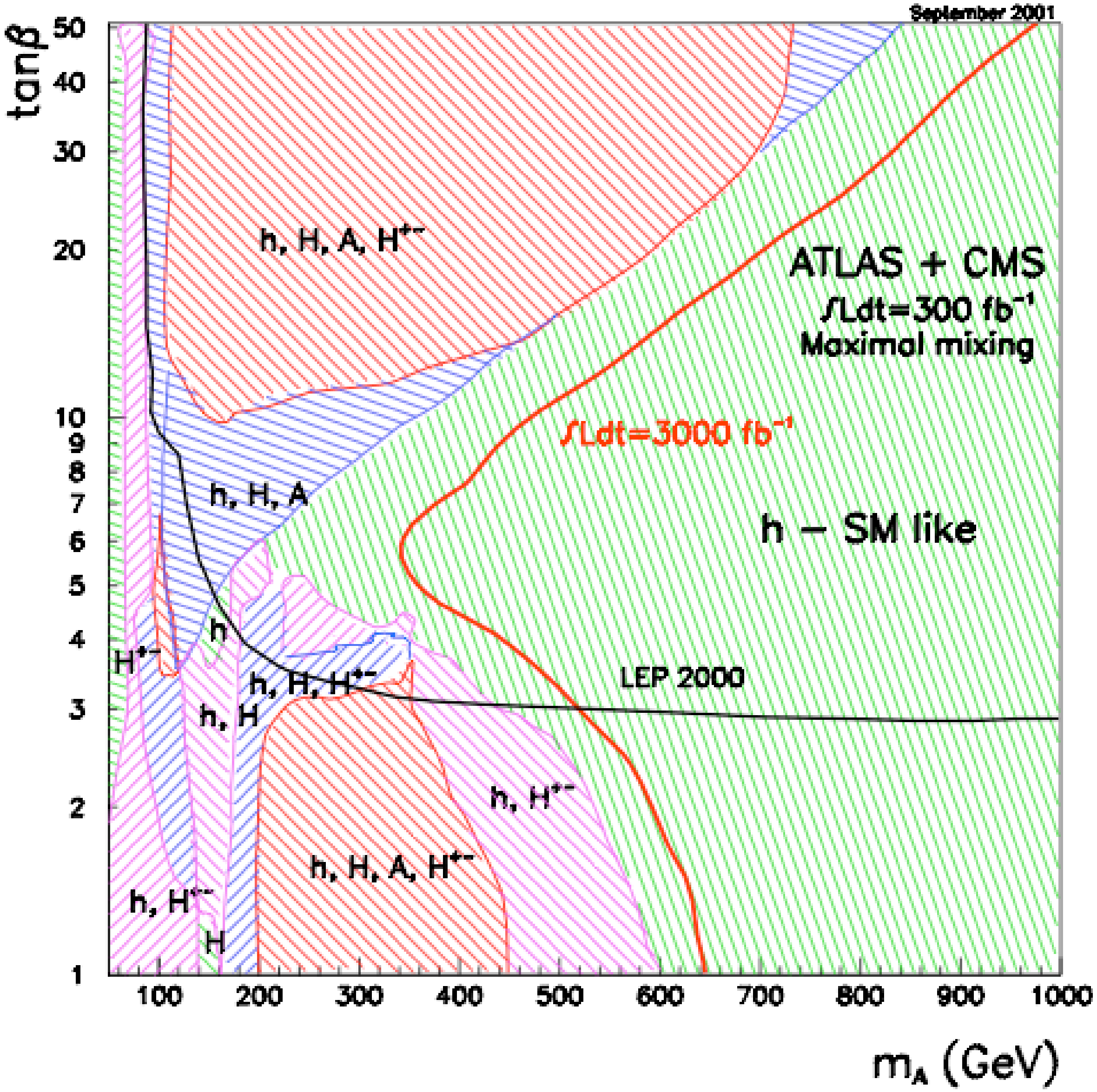




S= 6, B = 2

$S/\sqrt{B} = 10$

# Heavy Higgs in MSSM

SLHC improves LHC reach by 50-200 GeV



# Top physics

- FCNC-induced branching fractions are $\mathcal{O}(10^{-5} - 10^{-6})$ not large enough to be found at the LHC

*b*-tagging performance is crucial

- $t \to q\ \gamma$

| *b*-tagging | ideal | real. | $\mu$-tag |
|---|---|---|---|
| 600 $fb^{-1}$ | 0.48 | 0.88 | 3.76 |
| 6000 $fb^{-1}$ | 0.14 | 0.26 | 0.97 |

at same *b*-tagging, SLHC better than LHC by factor 3
Best BR = $0.14 \cdot 10^{-5}$

- $t \to q\ g$

| *b*-tagging | ideal | real. | $\mu$-tag |
|---|---|---|---|
| 600 $fb^{-1}$ | 22.3 | 60.8 | 210. |
| 6000 $fb^{-1}$ | 7.04 | 19.2 | 66.2 |

at same *b*-tagging, SLHC better than LHC by factor 3
Best BR = $7.04 \cdot 10^{-5}$

- $t \to q\ Z$

| *b*-tagging | ideal | real. | $\mu$-tag |
|---|---|---|---|
| 600 $fb^{-1}$ | 0.46 | 1.1 | 83.3 |
| 6000 $fb^{-1}$ | 0.05 | 0.11 | 8.3 |

at same *b*-tagging, SLHC better than LHC by factor 10
Best BR = $0.05 \cdot 10^{-5}$

# Conclusions

- Given our total ignorance about NP, physics case is straightforward, but not overwhelming. The overall picture should improve dramatically after the first couple years of LHC results

- R&D, rather than physics, should be the present priority. After the first couple years of LHC results (2011-12), the SLHC outlook could be re-assessed in a less speculative way, in particular for the very many NP models

- By 2012, we should also have much better QCD precision tools, to analyse signals and BG's

- we always assumed that the SLHC detector performance is not worse than the LHC detector performance

# Parton shower MonteCarlo generators

- HERWIG B. Webber et al. 1992

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

- PYTHIA T. Sjostrand 1994

## 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

# 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
  - SHERPA F. Krauss et al. 2003