Expectations for Standard Model Physics at the LHC

M. Dittmar (ETH–Zürich/CMS)

- SM at the start of the LHC?
- SM Physics at the LHC: a definition?
- Testing precision calculations at the LHC?
- Drell–Yan processes
- Massive Diboson production
- Top physics
- QCD measurements
- Outlook

Standard Model 2003(7)

We all know (don't we?):

SM is (not) correct description of nature!

... at least it seems to work!

- **up to** $Q^2 (= m^2) \approx (200 GeV)^2$
- **describes Z and W decays/couplings**
- $$\begin{aligned} \Delta M_Z/M_Z &= 2.3 \times 10^{-5} \\ \Delta M_W/M_W &= 4.8 \times 10^{-4} \\ \Delta G_F/G_F &= 8.6 \times 10^{-6} \\ \Delta sin^2\Theta_W/sin^2\Theta_W &= 6.5 \times 10^{-4} \end{aligned}$$
- **Neutrino masses? that's another story!**

so, why to continue SM studies at the LHC?

Well....

overall data consistency ($M_{top} \approx$ 175 GeV)

χ^2/dof= 30.5/15 (probability $\approx 1\%$)

(NUTEV $sin^2\Theta_W$ included)

$\longrightarrow$ data consistent with no new physics up to very large Λ

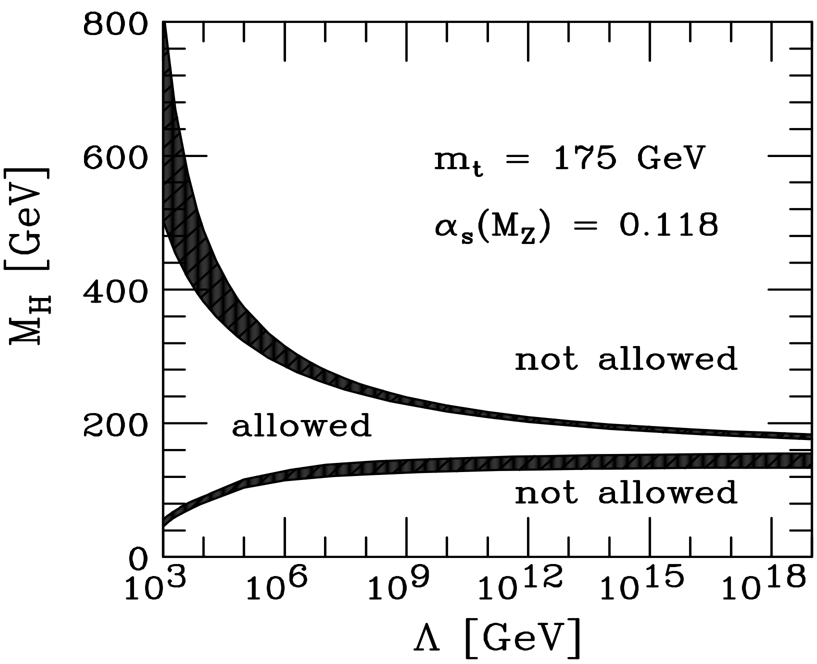


Figure 1: T. Hambye and K. Riesselmann, PRD 55,7255 (1997)

within SM: $\mathrm{M_{Higgs}} \approx 165 \pm 20$ GeV

SM Physics at the LHC: Looking for a definition?

What it is not:

- Searching for new particles (including the SM Higgs?)
- Searching for SM forbidden signatures

A working definition of SM Physics

1. Measure (calculable) event rates (cross sections)
   (relative, differential or absolute)
2. compare the measurements with theoretical predictions
3. establish agreement (SM) or disagreement (beyond SM)
4. demonstrate "working" experiment with well known processes
5. challenge theoretical calculations at high Q^2
   (at least experimental numbers should be more accurate!)

calculate, predict and measure interactions and decays of known particles!

SM measurements also needed to distinguish the NEW from the KNOWN!

Cross section measurements

$$\sigma_{\mathrm{pp}\rightarrow\mathrm{X}} = \frac{\mathrm{N}_{\mathrm{event}} - \mathrm{N}_{\mathrm{background}}}{\mathrm{L}_{\mathrm{pp}} \times \varepsilon}$$

we are not really interested in the precise number!

want to know at high Q^2:

$\sigma_{\mathrm{q,g}\rightarrow\mathrm{X}}$ **(Experiment) =** $\sigma_{\mathrm{q,g}\rightarrow\mathrm{X}}$ **(Theory)**
???

or better (?) establish differences!

measure/calculate with best adequate precision!

Some SM studies at the LHC?

No/perhaps

- SM Higgs (discover first!)
- beauty (charm, τ) physics? (low Q^2!)

Yes, but...

- M_W and $sin^2\Theta_W$

  very difficult to improve!
- M_{top} and top couplings

  depends very much on TEVATRON results!
- high mass Drell–Yan lepton pairs

  ($q\bar{q} \rightarrow (\gamma, Z)^* \rightarrow \ell\ell$ and $q\bar{q} \rightarrow W^* \rightarrow \ell\nu$)
- boson pair physics (WW, WZ, ZZ, Wγ etc)
- Precision cross sections measurements: theory and experiment (testing QCD predictions?)

The Parton–Parton Luminosity Method:

$pp \longrightarrow W^{\pm}, Z^{0}$ production as a precise parton luminosity monitor!

original proposal: M. D., F. Pauss and D. Zürcher; Phys. Rev. D56 (1997) 7284.

$$N_{pp\to Z} = L_{pp} \times PDF(x_1, x_2, Q^2) \times \sigma_{q,\bar{q}\to Z}$$

$$N'_{pp\to WW} = L_{pp} \times PDF(x'_1, x'_2, Q'^2) \times \sigma_{q,\bar{q}\to WW}$$

$$N'_{pp\to WW} = N_{pp\to Z} \times \frac{\sigma_{q\bar{q}\to WW}}{\sigma_{q\bar{q}\to Z}} \times \frac{PDF(x'_1,x'_2,Q'^2)}{PDF(x_1,x_2,Q^2)}$$

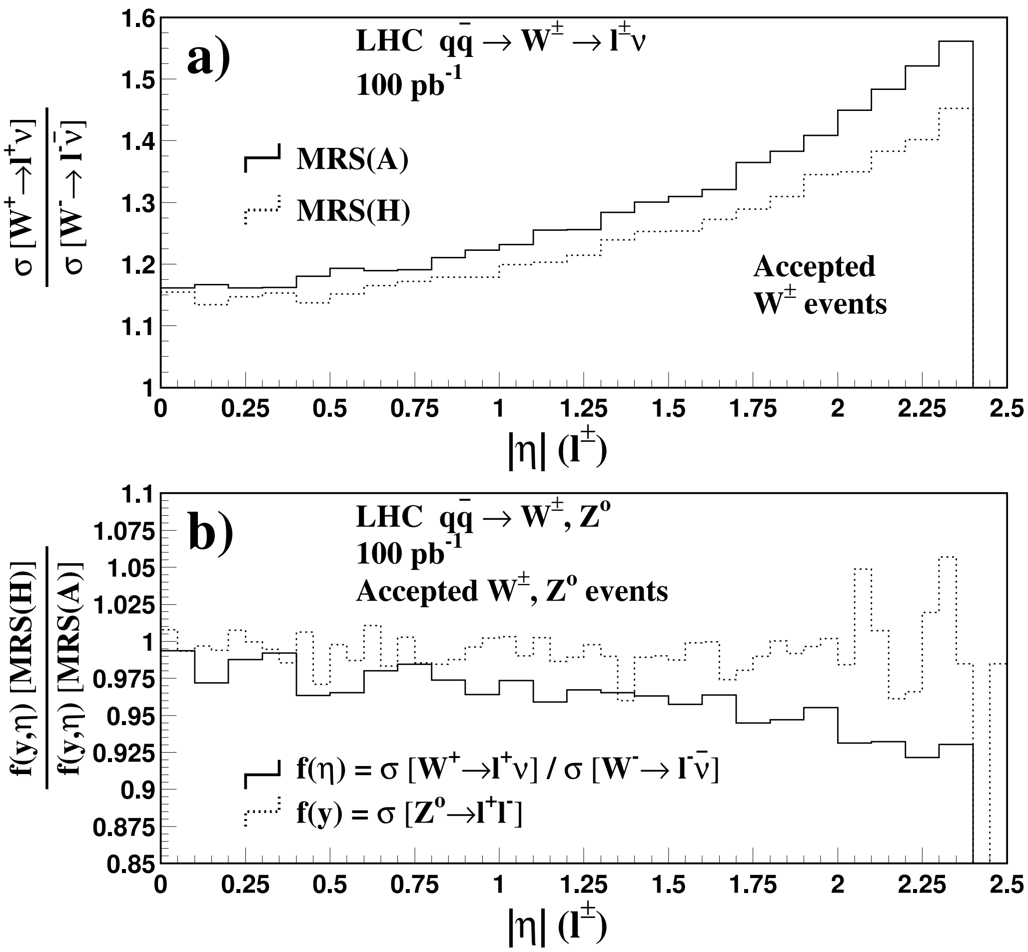
$\longrightarrow$ theoretical calculations do not require proton–proton luminosity!

parton–parton luminosity uncertainties:

- $\Delta \mathrm{L_{pp}} = 0!$
- $\Delta \mathrm{BR}(\mathrm{W} \rightarrow \ell\nu) \leq 1\%$
  $\Delta \mathrm{BR}(\mathrm{Z} \rightarrow \ell\ell) \leq 0.3\%$
- **negligible statistical errors**
  Δ (efficiency, backgrounds) $\approx 1\%$
  difficult but perhaps possible
  with the huge statistics of $W^{\pm}$, Z^{0} events?
- **higher order QCD corrections, α_s,**
  factorization, scale dependence etc..
  "some" theoretical uncertainties must
  cancel with ratios!
- **precise PDF's from W^{+}, W^{-} Z^{0} rapidity**
  distributions ("used" since many years!)

even small differences are observable!

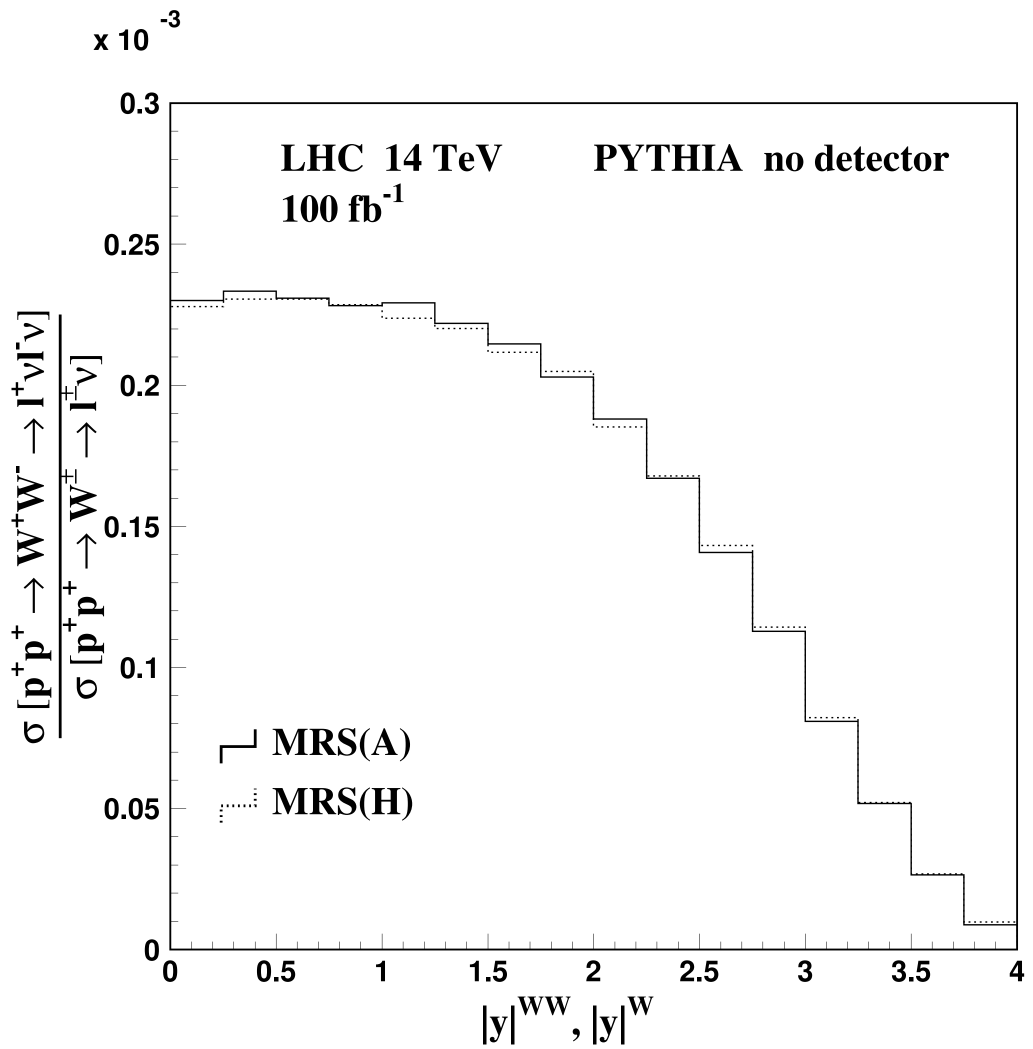
MRS(A) versus MRS(H):



precise ratio prediction ($\leq 1\%$) for
$\sigma(q\bar{q} \to W^+W)/\sigma(q\bar{q} \to W^{\pm})$

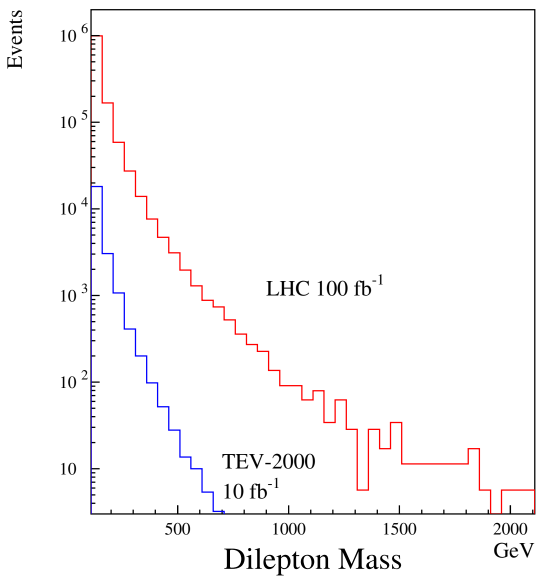
within the PYTHIA (LO) frame!

needs to be studied for higher order calculations!



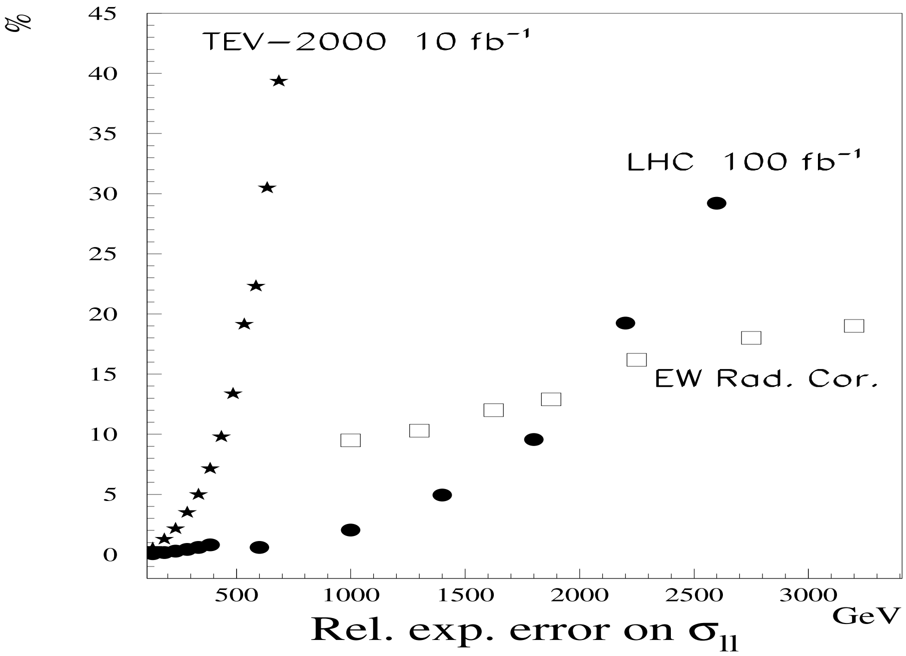
An obvious application:
Drell–Yan cross sections

for details: CERN 2000-004, pages 121–153, proceedings of the 1999 SM LHC workshop



D. Bourilkov, 1999 SM LHC workshop

Figure 2:

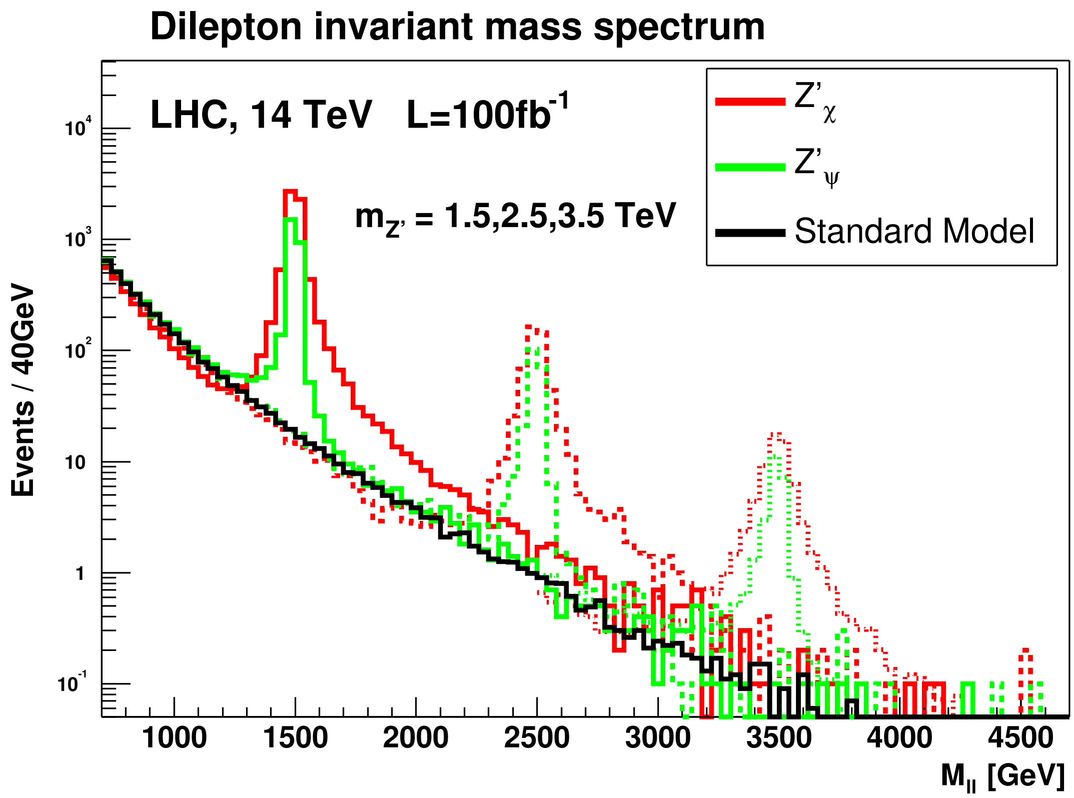


measure high mass Drell–Yan lepton pairs relative to Z production

$$\sigma(q\bar{q} \to \gamma^* \;\; Z^* \;\; Z' \to \ell^+\ell^-)$$

updating Z' studies at the LHC, M.D., A. Djouadi and Anne–Sylvie Nicollerat

hep–ph/0307020



not exactly SM but

one gets Z' almost for free!

$W \longrightarrow \ell\nu$ EW corrections!

for details: CERN 2000-004 pages 126–128, proceedings of the 1999 SM LHC workshop

the Devil is in the "little" details!

PYTHIA (approximations) $\neq$ precision SM calculations

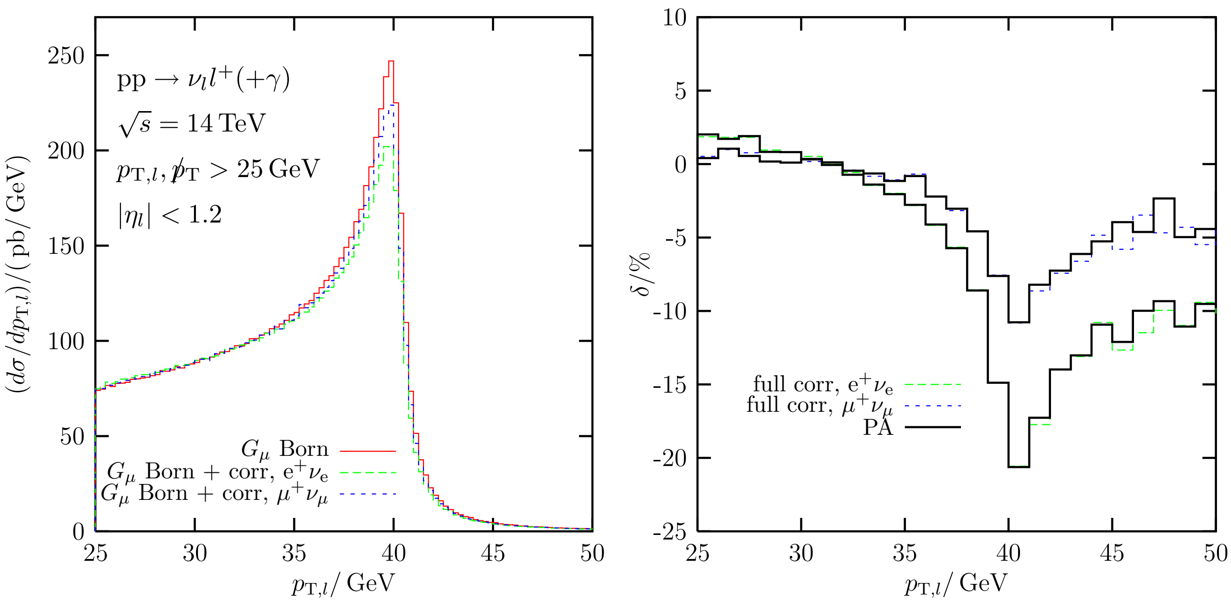


Fig. 6: Transverse-momentum distribution $(d\sigma/dp_{\mathrm{T},l})$ and relative corrections δ (results based on [60]).

Figure 3:

off shell $W^* \longrightarrow \ell\nu$ within SM not too interesting

however a W' comes (almost) for free!

WW, WZ, ZZ and Wγ studies

for details: CERN 2000-004, pages 156–193, proceedings of the 1999 SM LHC workshop

important background for searches!

isolated high p_t leptons from W and Z decays

"visible" channels:

$q\bar{q} \longrightarrow WW \longrightarrow \ell\nu\ell\nu$ ($\ell = e, \mu$) $\sigma(LO)\times$ BR = 3.7 pb

$q\bar{q} \longrightarrow WZ \longrightarrow \ell\nu\ell\ell$ ($\ell = e, \mu$)
$\sigma(LO)\times$ BR = 0.434 pb

$q\bar{q} \longrightarrow ZZ \longrightarrow \ell\ell\ell\ell$ ($\ell = e, \mu$)
$\sigma(LO)\times$ BR = 0.053 pb

known NLO K–factors: σ (NLO)/σ(LO)

reaction $pp \longrightarrow X$	K	K (Jet veto)	K (P_t(jet) 150–400 GeV)
$pp \longrightarrow W^+W^- \longrightarrow \ell\nu\ell\nu$	1.5	1.3	67(!)
$pp \longrightarrow W^\pm Z \longrightarrow \ell\nu\ell\ell$	1.9	1.4	30(!)
$pp \longrightarrow ZZ \longrightarrow \ell\ell\ell\ell$	1.4	1.4	6(!)

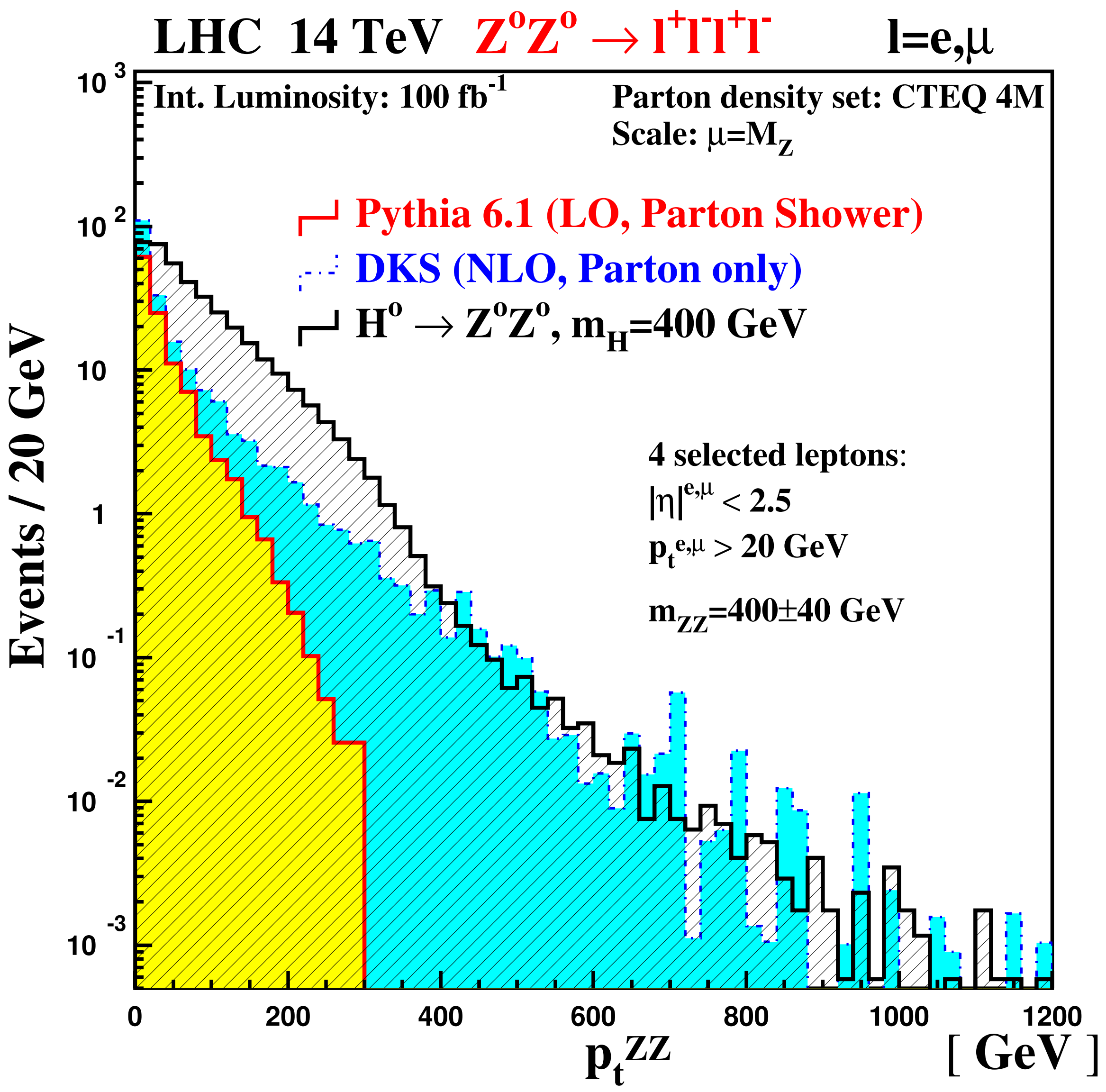
Table 1: inclusive K factors and with cuts!

systematic theoretical uncertainties????, a proposal:
0.5 (?) $\times$ K factor ($=\Delta\sigma$ from LO (NLO) to NLO (NNLO))!

WW, WZ and ZZ from PYTHIA versus NLO?

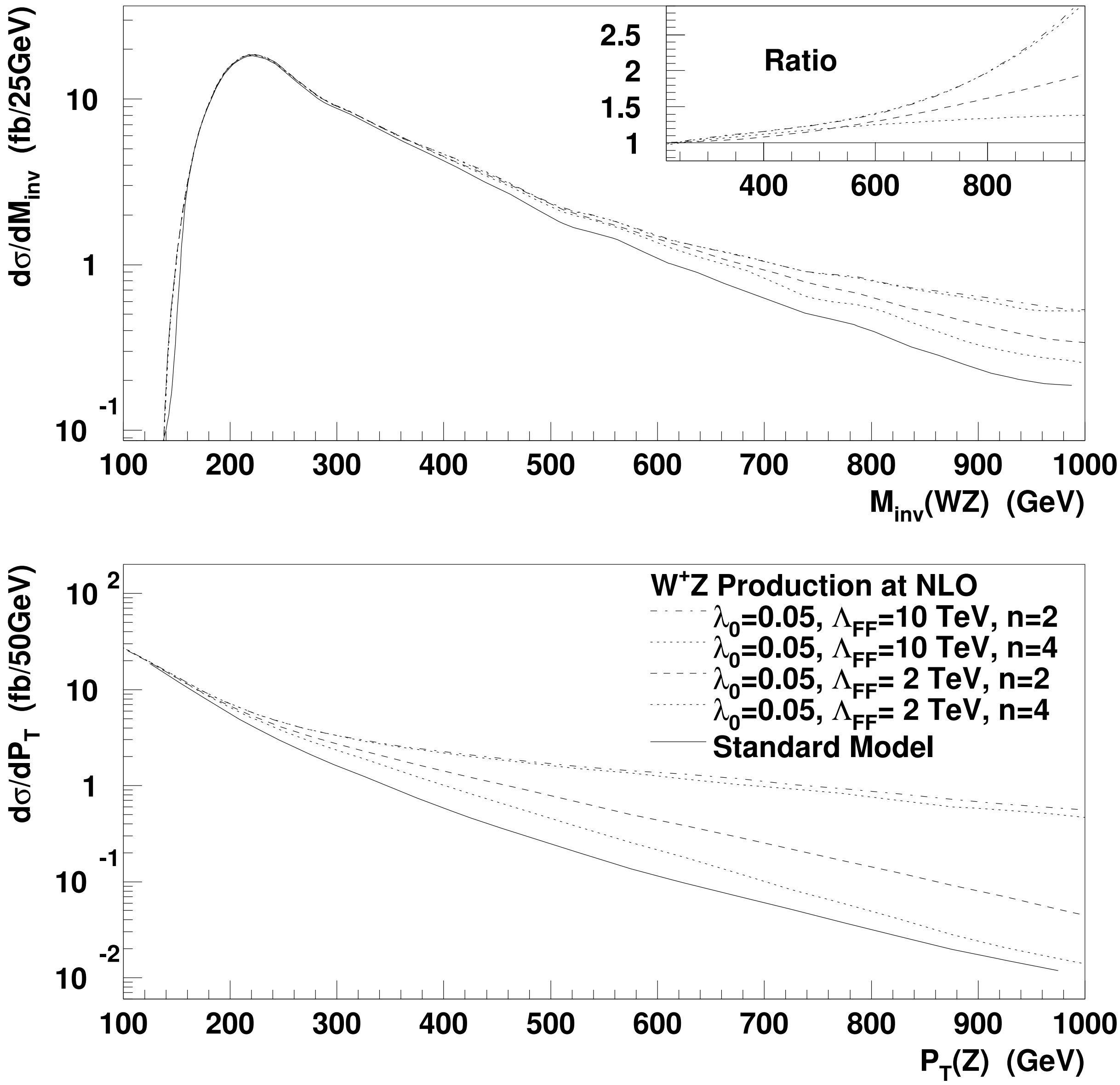
important implications for many studies!
not only the Higgs!

for details: CERN 2000-004, pages 162–164, proceedings of the 1999 SM LHC workshop



Anomalous WW, WZ, ZZ and Wγ studies (“fast” detector simulation plus PYTHIA)

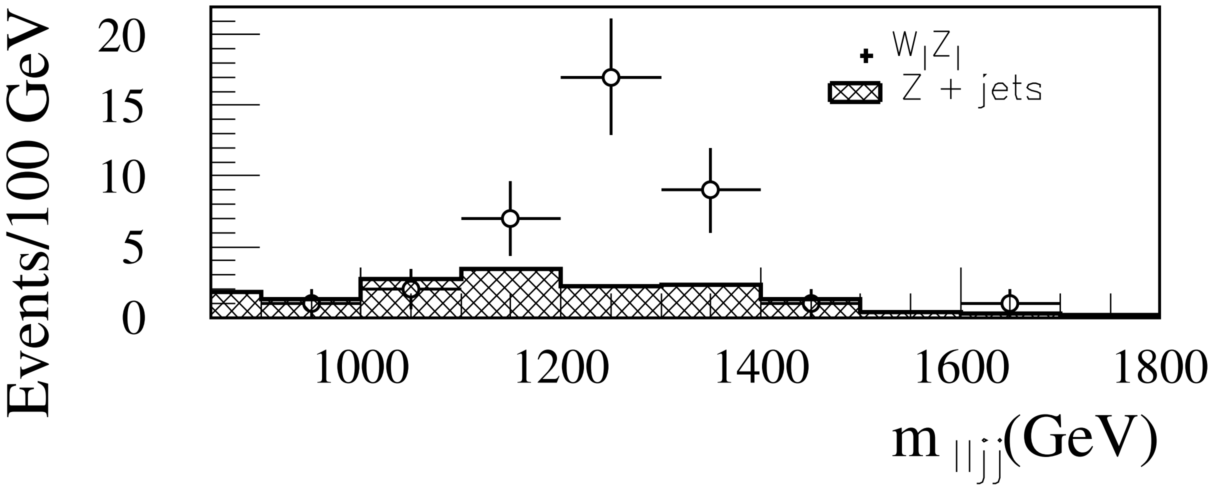
for details: CERN 2000-004, page 178, proceedings of the 1999 SM LHC workshop

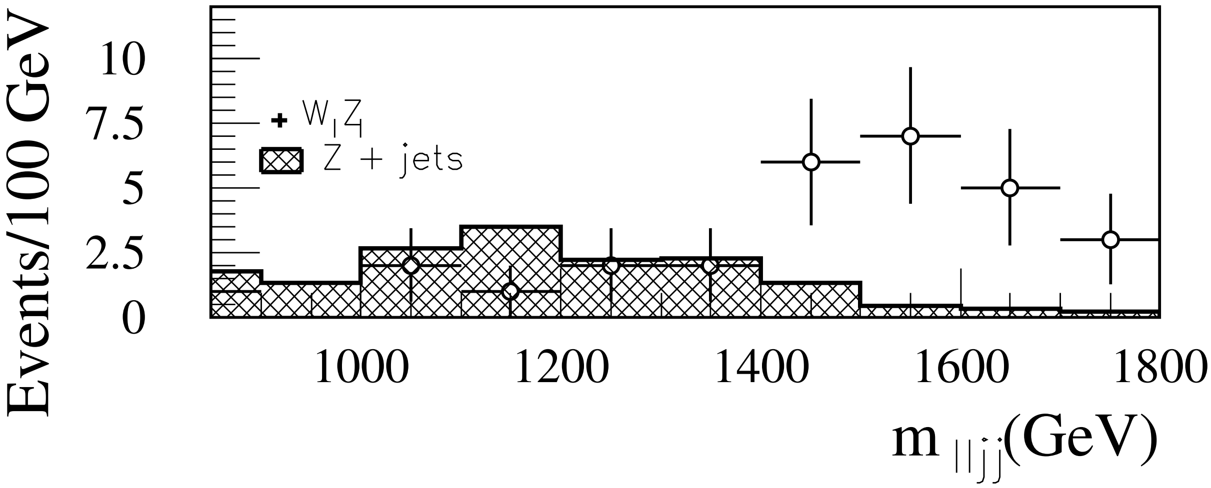


WW, WZ, ZZ scattering at high masses

for details: CERN 2000-004, pages 193–223, proceedings of the 1999 SM LHC workshop

few events but potentially rewarding!





top mass studies

for details: CERN 2000-004, pages 440–456, proceedings of the 1999 SM LHC workshop

many methods, statistical errors "easily" $\Delta m_t \leq 500$ MeV

systematics due modelling: $\Delta m_t = 1 - 2$ GeV

perhaps smaller for partially reconstructed B–decays

LHC workshop 1999 proceedings, page 448

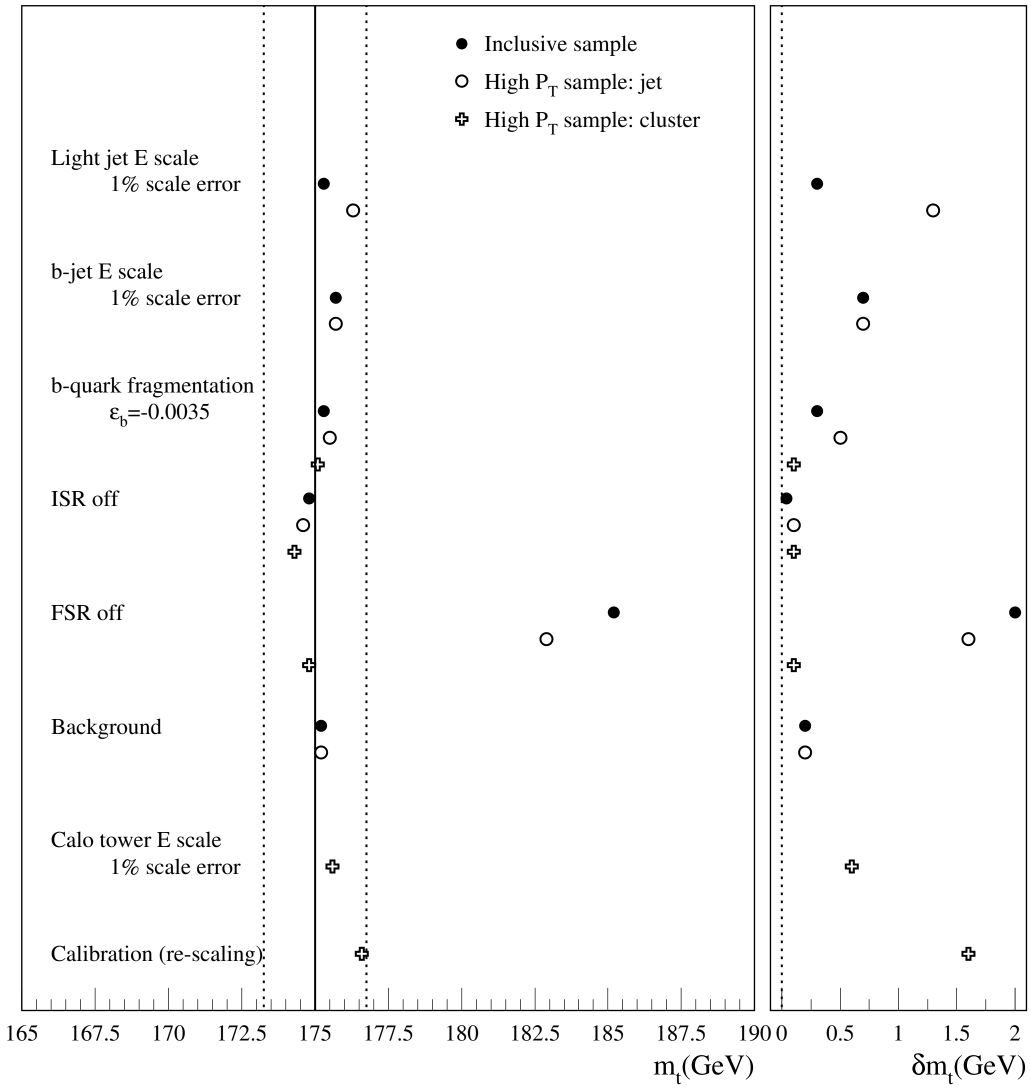


Figure 4:

Single top production $bW \longrightarrow t$
(99 CERN–LHC workshop)

large accepted cross section for 10 fb^{-1}
after cuts (t–channel production):
about 16000 (signal) above 7000 (background)

systematics limited?
$\Delta m_{top} \approx$ **2 GeV** $\quad \longrightarrow \Delta\sigma(top) = 2\%$

measuring top decays (within SM)
(99 CERN–LHC workshop)

$$\mathrm{BR}(t \longrightarrow bW) = 1$$
$$\mathrm{BR}(t \longrightarrow dW) = 10^{-4}$$

Expected 5σ sensitivity for FCNC top decays:

$$\mathrm{BR}(t \longrightarrow Zq) = 2 \times 10^{-4}$$
$$\mathrm{BR}(t \longrightarrow \gamma q) = 1 \times 10^{-4}$$

testing QCD?

$\Delta\alpha_s/\alpha_s(M_Z) \approx 2 - 3\%$

running $\alpha_s(Q^2)$ consistent with QCD!

but

- CDF deviation(?) for high E_T jets
- $\frac{\sqrt{s}=630GeV}{\sqrt{s}=1800GeV}$ cross section ratios

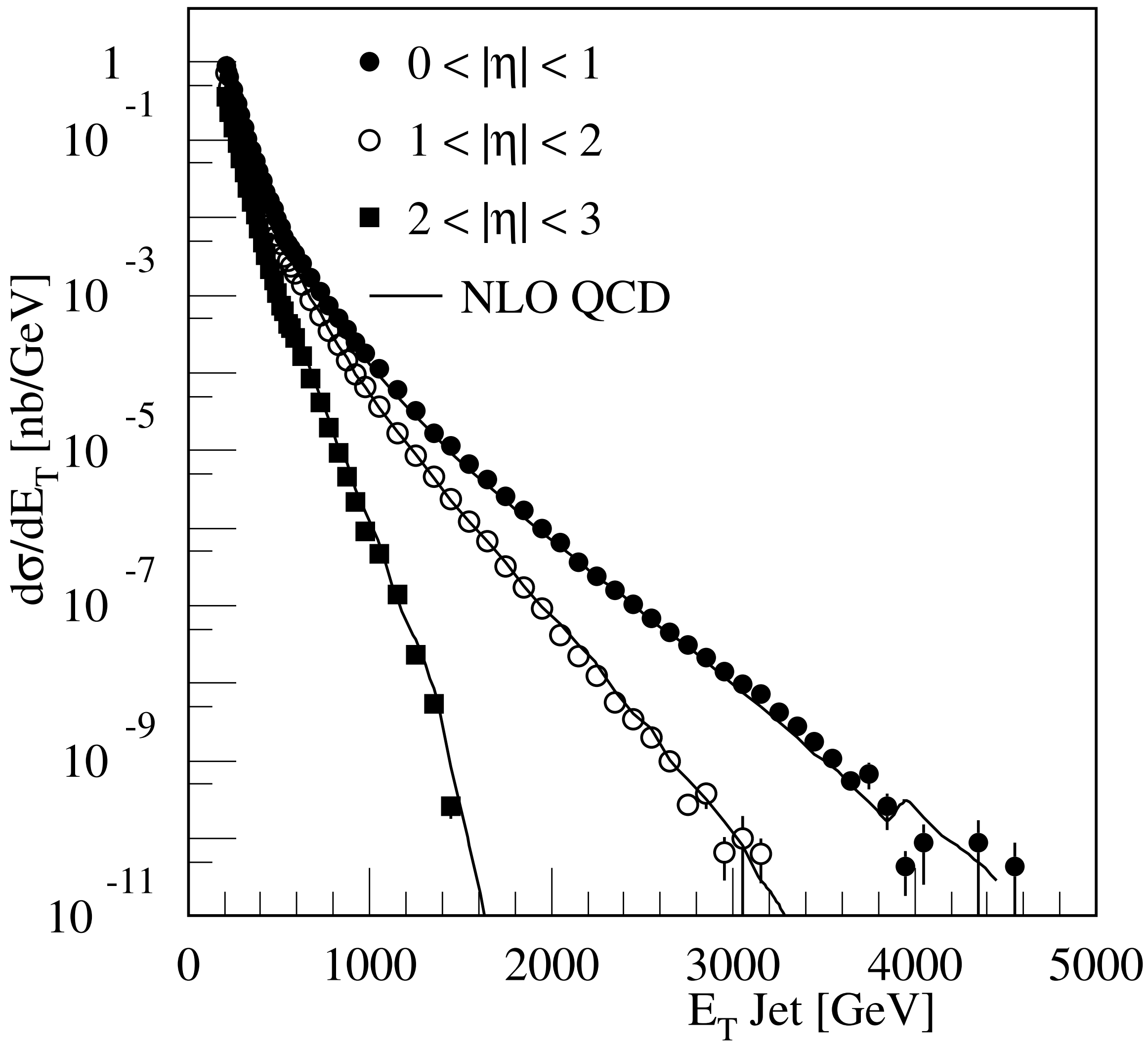
not "always" in agreement with expectations

LHC ($\sqrt{s} = 14$ TeV and perhaps lower?)

CMS/ATLAS should see deviations immediately!

high p_t jets

large rate QCD consistency test in the few TeV range!

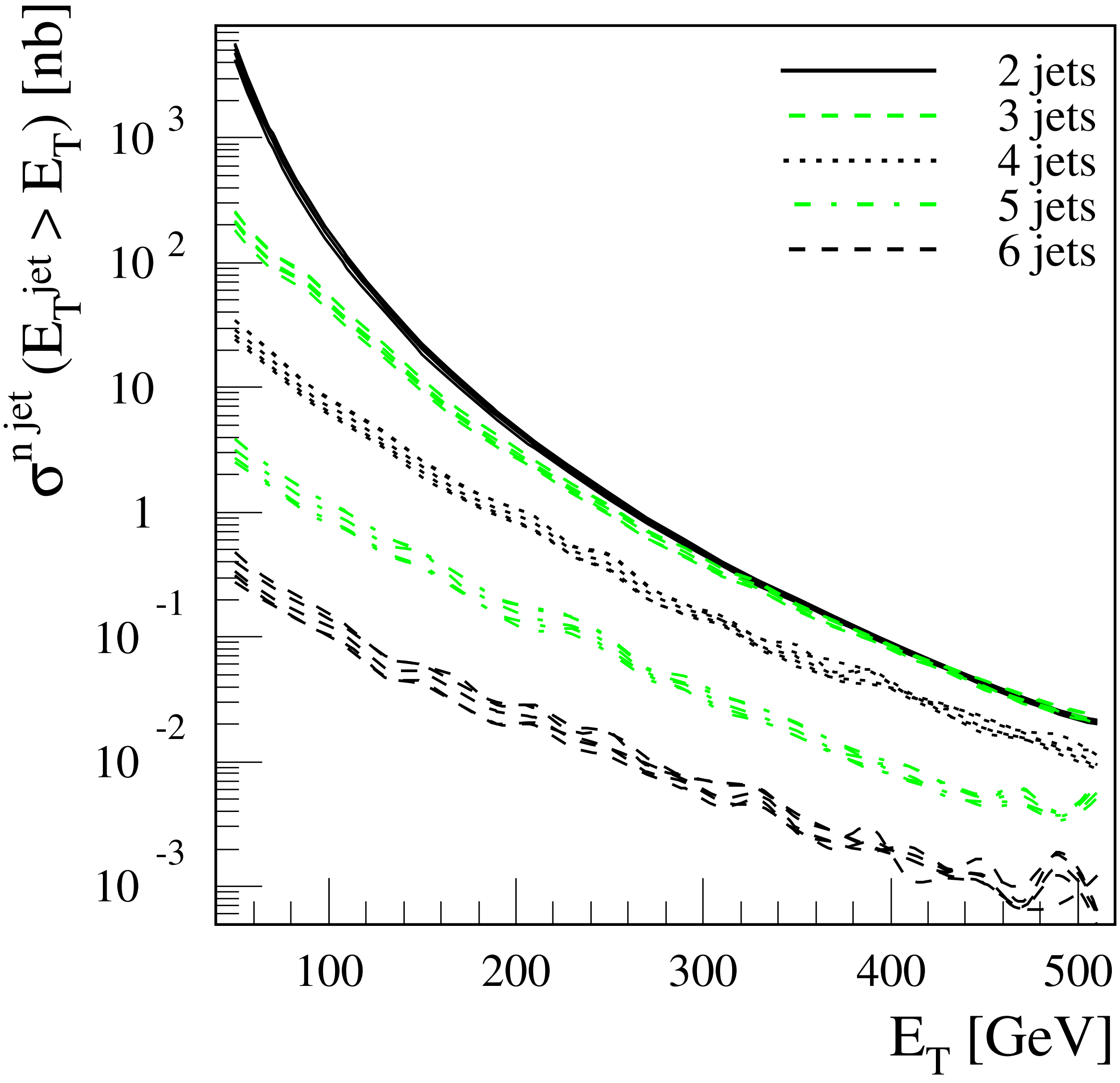


from ATLAS Physics TDR (1999) Figure 15-24

multi jet production at the LHC?

todays studies/calculations stop at 6 jets(?)

what are cross sections for 10(20) jet events?



from ATLAS Physics TDR (1999) Figure 15-30

Summary and Outlook

after $\approx$ 15 years of extensive LHC simulations:

- **LHC physics potential "known in LO PYTHIA" for most processes!**
  (We all know that ATLAS and CMS will be great for discoveries and for finding "small" deviations from SM predictions!)
- **achievable statistical precisions for "known" processes can be found in the literature.**
- **for the coming years:**
  need to study experimental and systematic limitations
  - **detector related systematics**
  - **have to remember: PYTHIA $\neq$ SM predictions**
  - **include theoretical errors, a proposal: 0.5 (?) $\times$ K factor ($=$ $\Delta\sigma$ from LO (NLO) to NLO (NNLO))!**

Parton Luminosities: remaining Work/Problems

- **Experimentalists and theorists have to compare "apples with apples"!**

- **Repeat Studies with NLO and perhaps NNLO Monte Carlo programs**

- **Define a realistic iterative LHC strategy to constrain PDF's (including γ–jet final states)**
- **detailed experimental efficiency studies with leptonic W and Z decays with large (unbiased) samples:**

- **develope a realistic parton luminosity counting scheme.**