Precision Cross Sections at the LHC: Experimental and Theoretical Prospects

Michael Dittmar (ETH-Zürich)

- Introduction

  including a few remarks about LHC status

- Measurements at the LHC: the "old" view

- Using cross section ratios: towards a "new" view

  (M.D., F. Pauss and D. Zürcher, Phys.Rev.D56(1997) 7284-7290)

- Some examples: LHC precision reactions

- Short report from the 2003 Binn workshop

Introduction: some LHC goals

- discoveries (absolute measurements):
  LHC potential for H^0, Supersymmetry, Z′ etc.. well(?) known!
  but: how many of us care about exact value of M_H
  I prefer 168 GeV (165 GeV or 173 GeV also ok!)

- test (in)consistency of the Standard Model
  combination of $M_Z, M_W, \sin^2\Theta_W, M_{top}$

Cross Section Measurements

1. Measure event rates
   (absolute, relative and differential)

2. Compare results with theoretical predictions

3. Establish agreement (SM) or disagreement (beyond SM):
   measure/calculate with adequate precision!

4. Demonstrate "working" experiment with well known processes

5. Challenge theoretical calculations at high Q^2
   (at least experimental numbers should be more accurate!)

Experimental Event Counting

$$N_{\text{signal}} = N_{\text{observed}} - N_{\text{background}}$$

$$N_{\text{corrected}} = N_{\text{signal}} / \textbf{ efficiency}$$

Experiment = Theory Prediction?

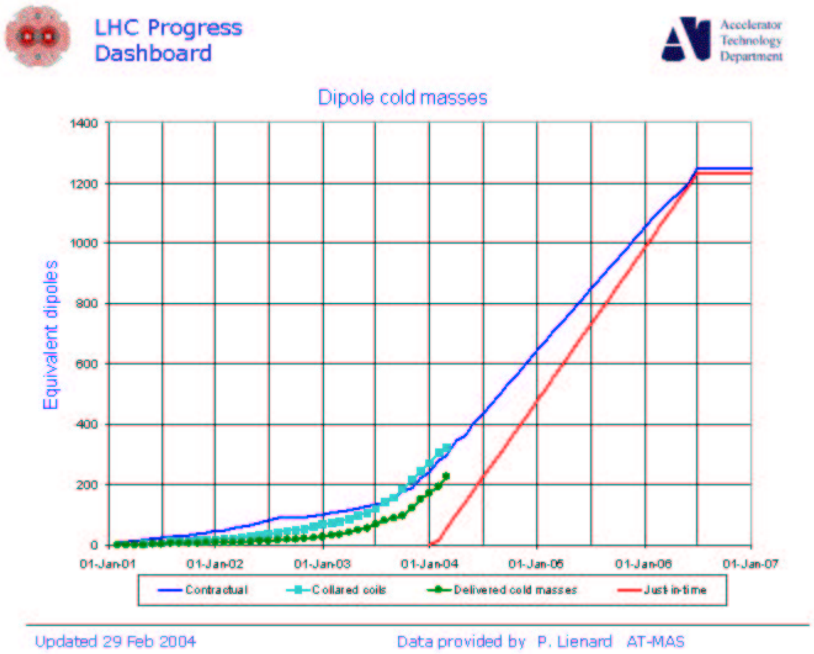
$$N_{\text{expected}} = \sigma_{\text{theory}} \times \textbf{ L (luminosity)}$$

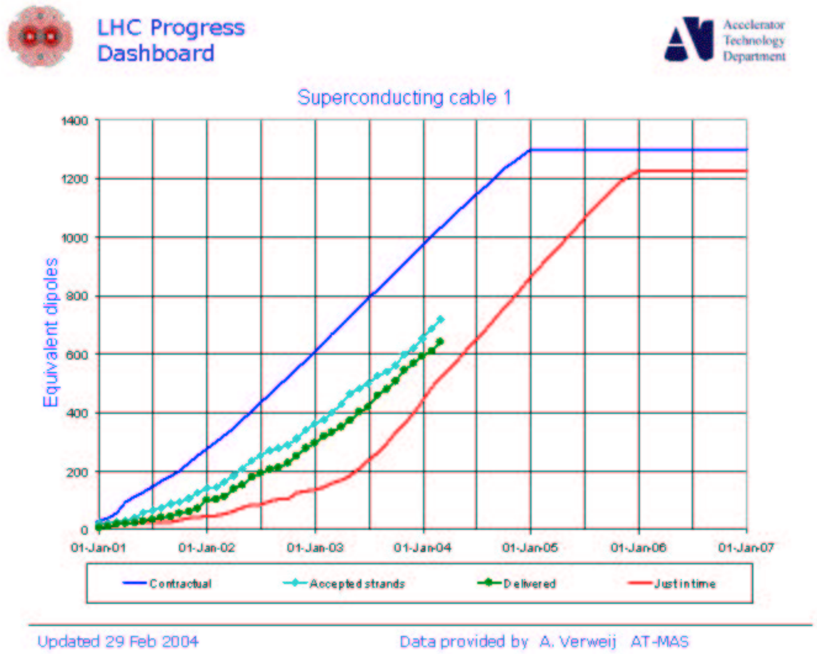
from protons to partons

$$N_{\text{expected}} = \sigma_{q,g \to X} \times \text{PDF}(x_1, x_2, Q^2) \times L_{pp}$$

remarks about the LHC status

Pilot LHC run.. for now:spring 2007





from the LHC dashboard

CMS and ATLAS: delays for some components but expect some "functioning" detectors by spring 2007

measuring hard processes: the old view

$$N_{event} = \sigma_{q,g \to X} \times (PDF(q,g)) \times L_{proton-proton}$$

systematic errors: "optimistic" goals (Aachen 1990)
experimental uncertainties:

Luminosity: $\Delta L_{proton-proton} \approx 5 - 10\%$

efficiency, backgrounds: $\Delta\sigma \approx 1 - 5\%$

PDF's (HERA, Tevatron etc..): $\Delta \approx 5\%$

theoretical uncertainties (cross section predictions):

$\Delta\sigma_{q,g \to X} \approx \Delta\sigma_{born}$ (small)

$\Delta\sigma(Q^2, \alpha_s, etc..) \approx 5 - 10\%$ (goal!?)

depressing mismatch of statistics (1%)
and systematics (5 – 10%)!

“the old view”

$pp \rightarrow W^{\pm}, Z^{0}$ production
as a proton-proton luminosity monitor?

SDC Technical design proposal (SSC)
(section 3.7.4 W and Z production:)

... The uncertainty coming from the choice of structure functions is significantly larger. This precludes the possibility of using Z production as a 10% luminosity monitor. ...

“the old view”

ATLAS Technical Proposal (1994)

(section 6.1, 6.2):
Absolute and relative luminosity measurement

... The main contributions to the uncertainty in cross-sections ($of\ \ W,\ \ and\ \ Z$) arise from higher order QCD corrections, structure functions, the choice of scale and the choice of the renormalization scheme. A quadratic sum of the contributions gives an overall error which at present is $\approx$ 10%. A more optimistic value for the precision on the timescale of the LHC is $\approx$ 5%, which may be regarded as a target for the measurement of the absolute luminosity...

... As discussed above, W and Z decays can be used to measure the integrated ($proton - proton$) luminosity with a precision of 5 %.

Towards a "new" view

want to calculate/measure with best precision
but perhaps one should be more modest

measure/calculate with "adequate" precision!

a practical LHC example:

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

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

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

$\to$ **Use W and Z production for normalization!**

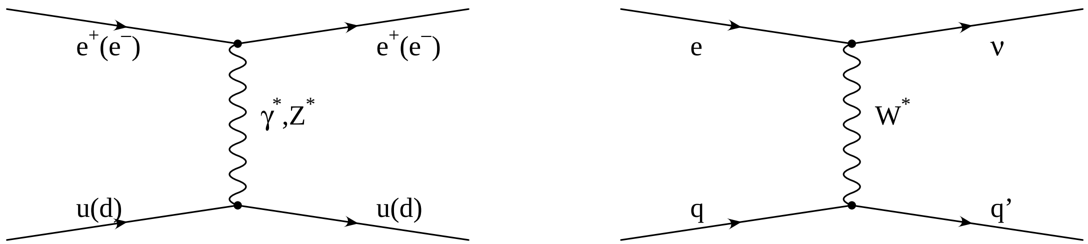
$\to$ **but W and Z events provide much more!**

Towards a new view:

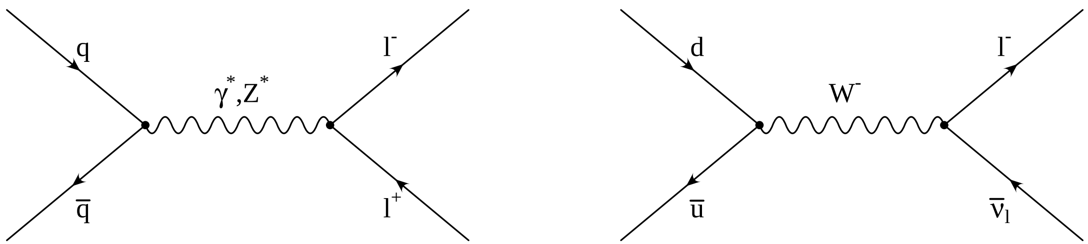
W and Z production at the LHC
a precise parton–parton luminosity counter

(M.D., F. Pauss and D. Zürcher, Phys.Rev.D56(1997) 7284-7290)

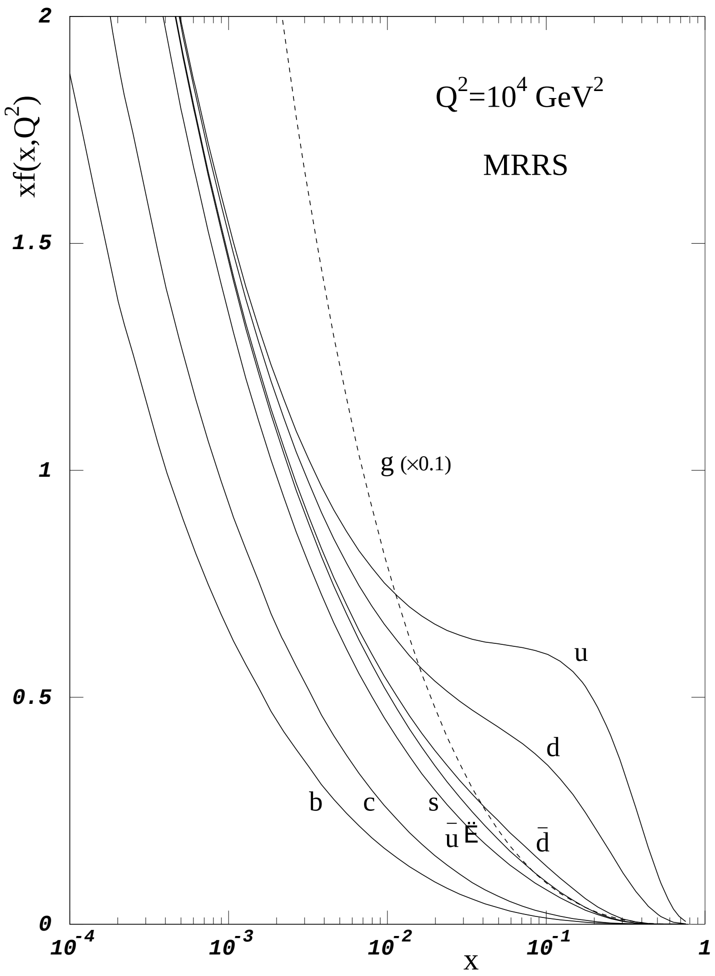
constraining PDF's at HERA

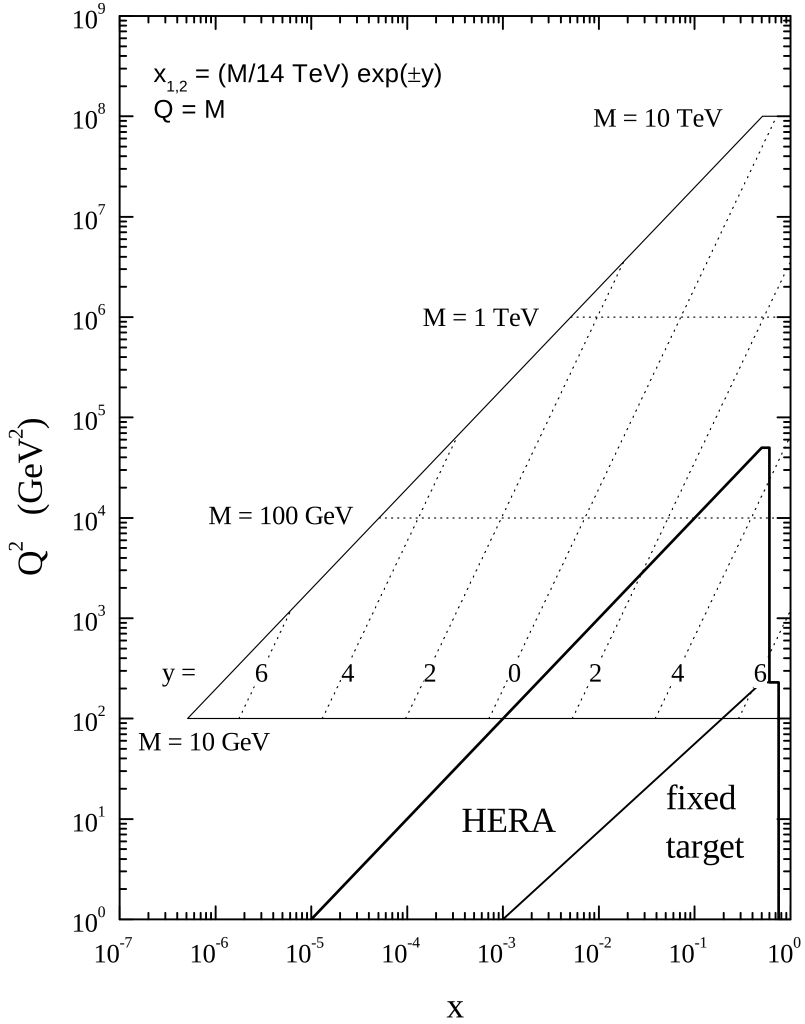


constraining PDF's at LHC



PDF's and Rapidity distributions





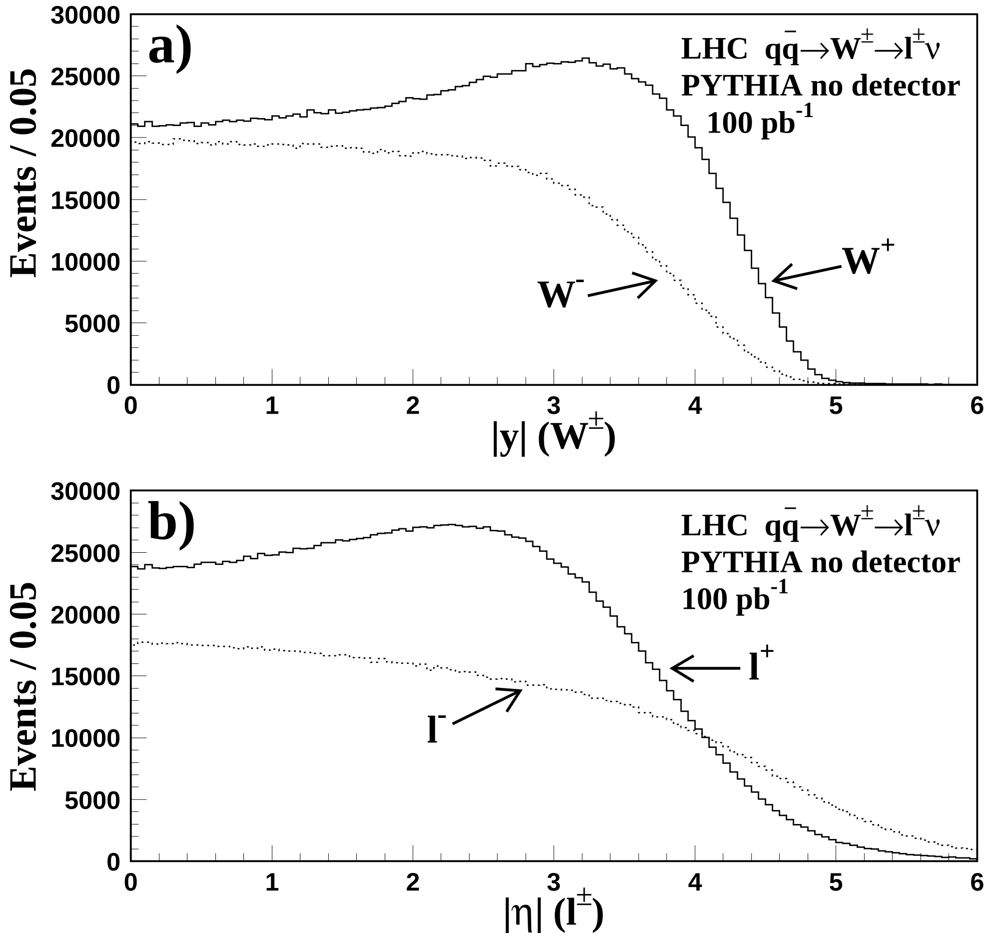
plots from J. Stirling

$M^2 = s\ x_1 \times x_2$ $\quad$ $Y = 1/2\ ln(x_1/x_2)$

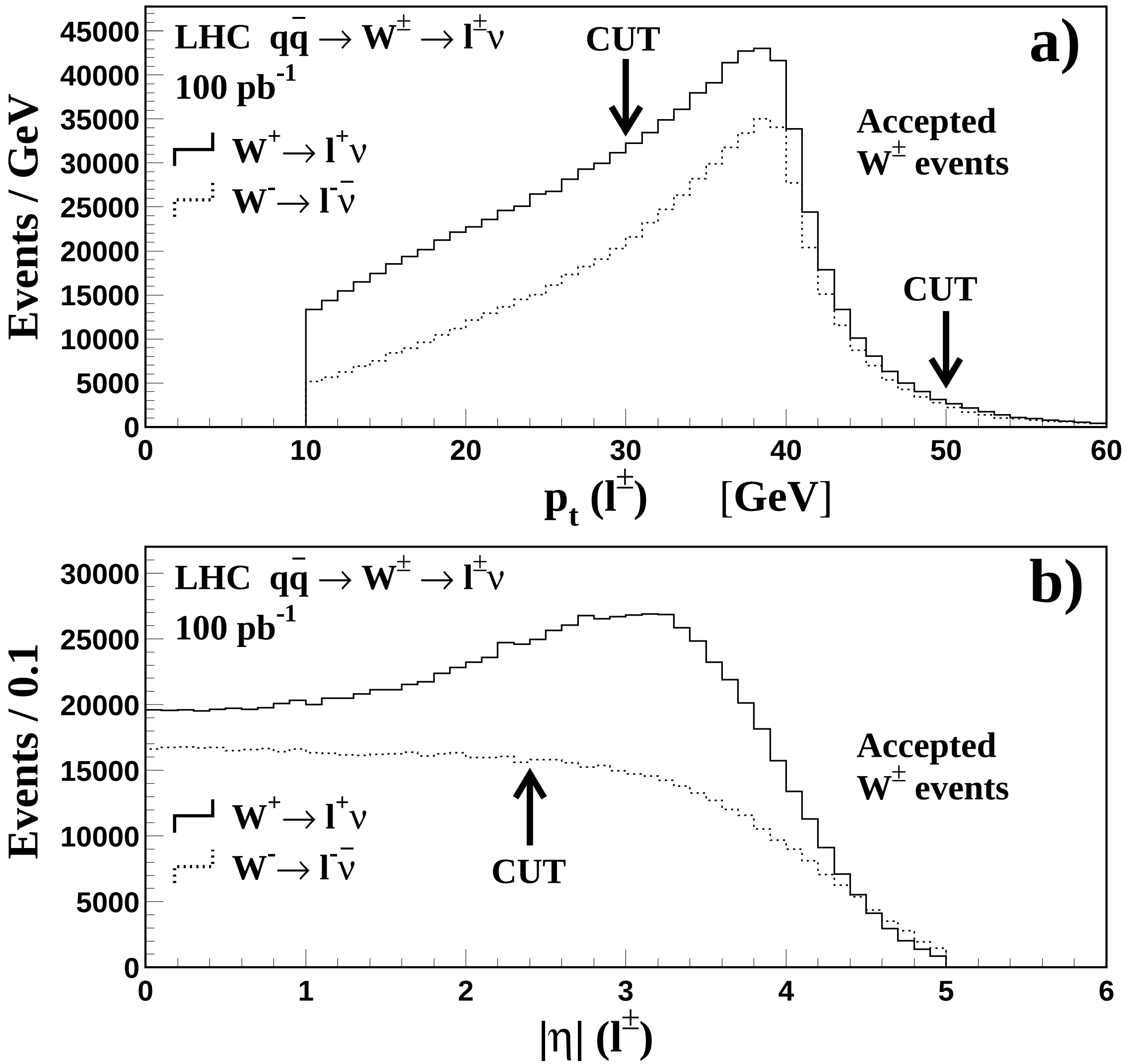
Using the W, Z rapidity distributions!

$Y \approx 0 \;\rightarrow x_1 \approx x_2 \approx 10^{-2}$: quarks/anti-quarks from sea

$Y \approx 2.5 \rightarrow x_1 \approx 0.1 (x_2 \approx 3 \times 10^{-4})$: valence quarks/sea anti-quarks

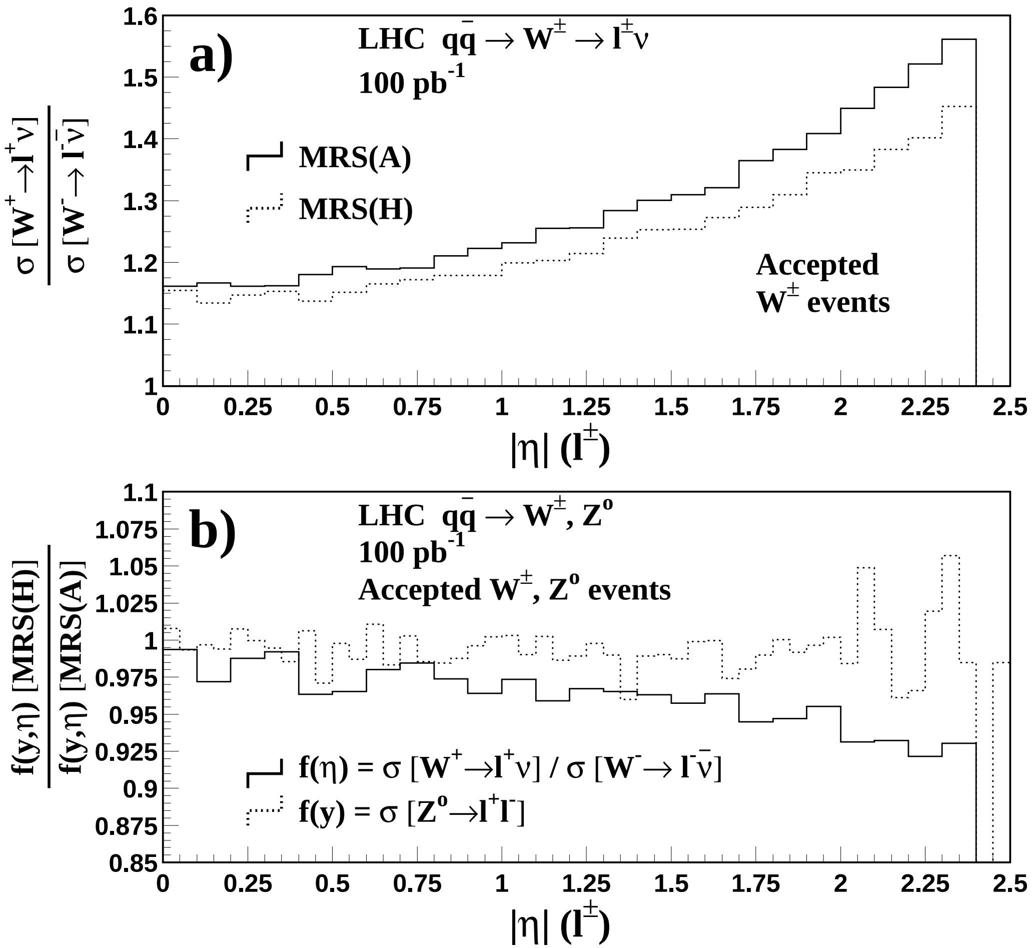


simple/standard W, Z (→ leptons) selection criteria



Measuring and calculating ratios!

small differences should become observable!
MRS(A) versus MRS(H) (1997):



parton–parton luminosity uncertainties:

- $\mathbf{\Delta L_{pp} = 0}$!

- ΔBR(W $\to \ell\nu$) $\leq$ 1% ΔBR(Z $\to \ell\ell$) $\leq$ 0.3%

- negligible statistical errors, Δ (efficiency, backgrounds) $\approx$ 1%?
  difficult but perhaps possible: huge statistics of $W^{\pm}, Z^0$ events!

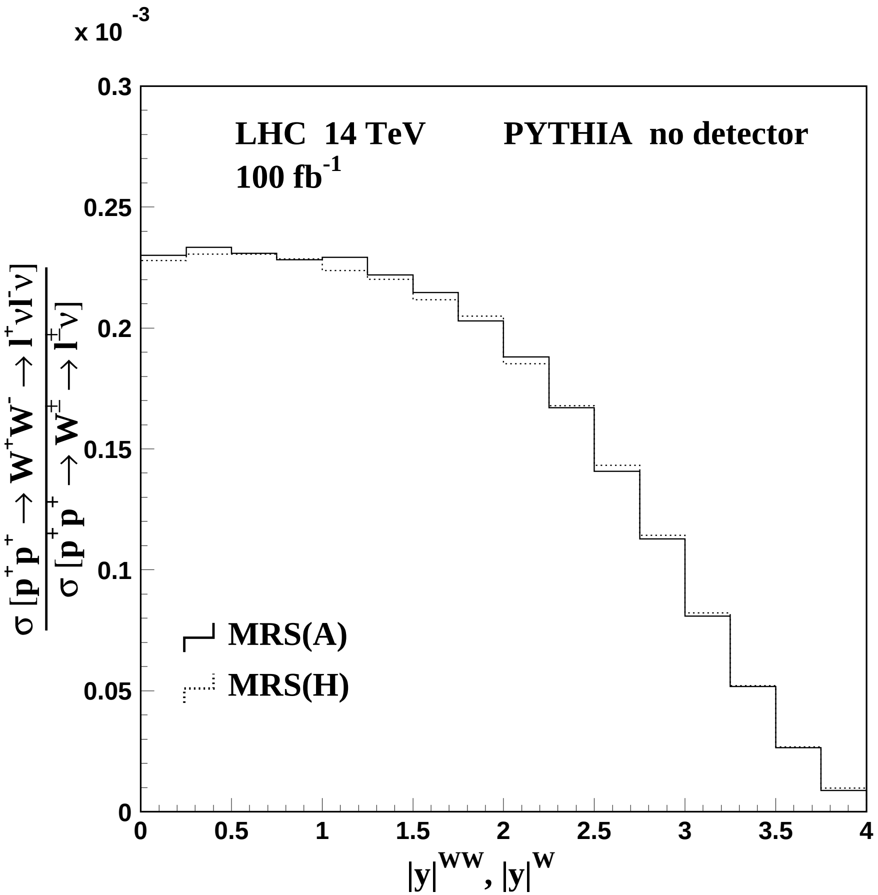
- higher order QCD corrections, α_s uncertainty,
  factorization, scale dependence etc..
  "some" theoretical uncertainties must cancel with ratios!

- precise PDF's from W^+, W^- and Z^0 rapidity distributions
  ("used" since many years!)

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!



constraining gluons and "heavy" quarks: measuring $qg \to \gamma, W, Z(H)$ jet(s)

simple/clean experimental event selection (PYTHIA study):

- Photon $p_t \geq 40$ GeV and $|\eta| \leq 1.45$

- Z^0: $|M_{\ell^+\ell^-} - M_Z| \leq 2$ GeV

- 1 Jet with $p_t \geq 30$ GeV, $|\eta| \leq 2.5$

- $\Delta\phi \geq 174\,\text{deg}$ (jet back to back with γ/Z^0)
  p_t of boson–jet system "known"!

serious analysis requires more detailed Monte Carlo (NLO?)!

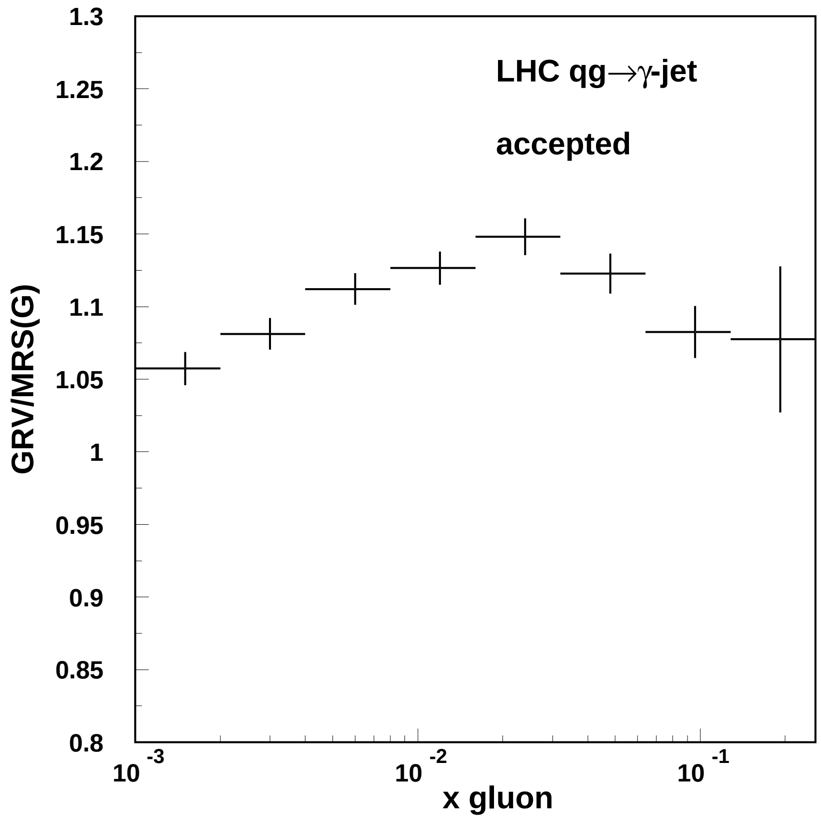
for details: CERN 2000-004, page 25–28, proceedings of the 1999 SM LHC workshop and

M. D., and K. Mazumdar; CMS Note 2001/002

accessible x_{gluon} with γ–Jet events

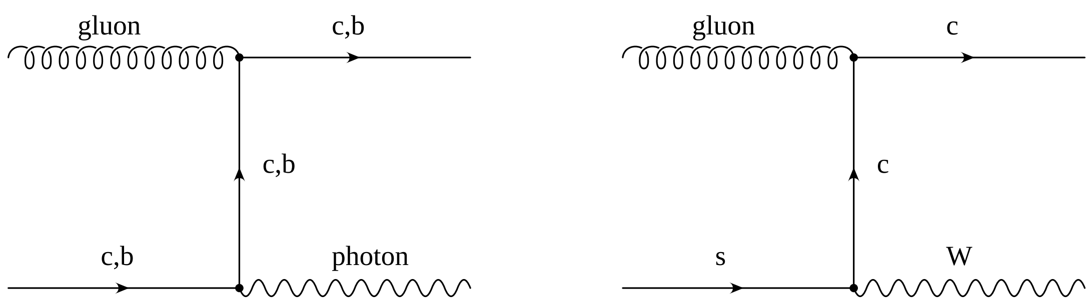
small statistical errors with only 1 fb^{-1} LHC data!

"easy" to see differences between MRS(G) and GRV–94(HO)



heavy quark (c, b and s) luminosities

Selection: photon–jet events with jet–flavor tagging



$cg \rightarrow \gamma c$: isolated high p_t photon plus c–jet

charm tagging with inclusive muons ($p_t > 5 - 10$ GeV)

$bg \rightarrow \gamma b$: isolated photon plus b–jet

standard b tagging (b lifetime)

$sg \rightarrow Wc$: isolated lepton plus c–jet

charm tagging with inclusive muons ($p_t > 5 - 10$ GeV)

measurement limited by knowledge of charm and beauty tagging efficiency $\pm 5 - 10\%$?

Experimental requirements for LHC precision reactions:

- counting statistics: $\Delta N/N = 1/\sqrt{N} \rightarrow 10^4$ events $\pm 1\%$
- backgrounds: (reduced/controlled by cuts)
- efficiency and geometrical acceptance (as high as possible!)

some optimization between:
$\sqrt{N}$, signal/background and efficiency
(use reaction ratios to reduce systematics!)

CMS/ATLAS potential (my guess)

"Isolated" electrons, photons: $\Delta E/E_{e,\gamma} =$ few % $/\sqrt{E}$ + 0.5 %
excellent angular resolution, "high" efficiency and
"small/negligible" backgrounds
for $p_t \geq 10$ GeV (?) and $|\eta| \leq 2.5$(?)

"Isolated" muons: $\Delta p_t/p_t \approx 2 - 5\%$
excellent angular resolution "high" efficiency and
"small/negligible" backgrounds
for $p_t \geq 10$ GeV (?) and $|\eta| \leq 2.5$(?)

"Isolated(??)" jets: $\Delta E_t/E_t \approx 100 - 200\%/\sqrt{E}$ + 5% (??)
good angular resolution and efficiency, but "difficult" systematics
(nonlinearity)
for $p_t \geq 30$ GeV (??) and $|\eta| \leq 4.5$(??)

Missing transverse momentum: depends on final state!
in general a mixture between lepton and jet accuracies

Leptonic (plus γ) final states

- resonance production of W and Z, the normalization process:
  ($q\bar{q} \to Z \to \ell\ell$ and $q\bar{q} \to W \to \ell\nu$)

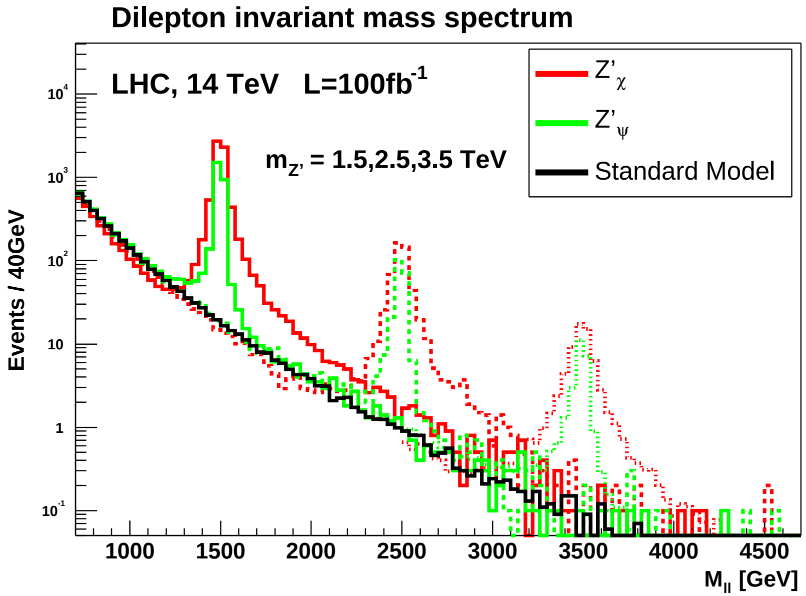
- high mass Drell–Yan lepton pairs
  $q\bar{q} \to (\gamma, Z)^* \to \ell\ell$ and
  $q\bar{q} \to W^* \to \ell\nu$

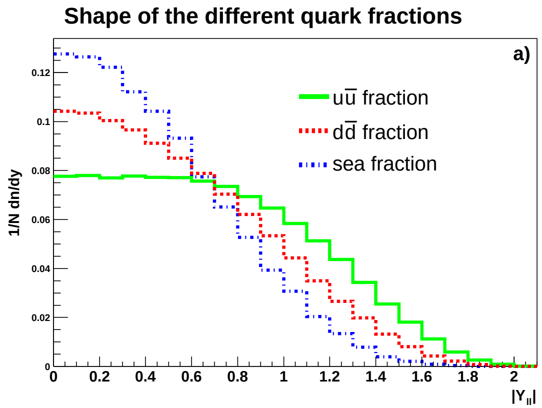
- boson pair physics (WW, WZ, ZZ, Wγ etc)
  $q\bar{q} \to WW(WZ, ZZ, W\gamma)$
  with $W, Z \to$ leptons
  ($ZZ \to \ell\ell\ell\ell$ has small cross section)

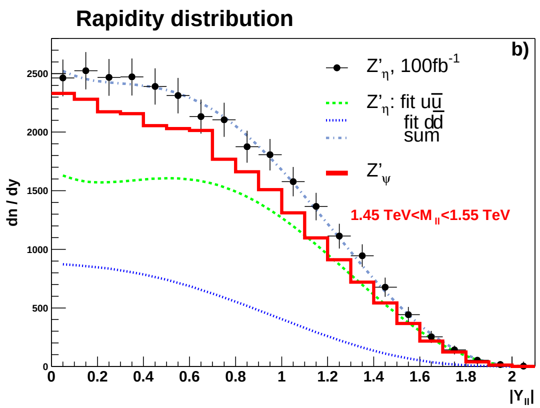
expect clean event samples, but diboson mass (Q^2)
sometimes not well measured($W \to \ell\nu$)
to be compensated with accurate Monte Carlo!

a good example: high mass Drell–Yan (Z') relative to Z production

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







M.D., A. Djouadi and Anne–Sylvie Nicollerat, Phys.Lett.B583(2004) 111-120(hep–ph/0307020).

WW, WZ, ZZ and Wγ studies

for more details: CERN 2000-004 (1999 SM LHC workshop), pages 156–193

important background for searches!

isolated high p_t leptons from W and Z decays

"visible" channels with leptonic W and Z decays ($\ell = e, \mu$) :

$q\bar{q} \to WW \to$: $\sigma(LO)\times$ **BR = 3.7 pb**

$q\bar{q} \to WZ \to$: $\sigma(LO)\times$ **BR = 0.434 pb**

$q\bar{q} \to ZZ \to$: $\sigma(LO)\times$ **BR = 0.053 pb**

known NLO K–factors: σ (NLO)/σ(LO)

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

$t\bar{t}$ production at the LHC (huge statistics)

Want to know/calculate: total $t\bar{t}$ cross section $t\bar{t}$ mass spectrum rapidity and p_t distribution of $t\bar{t}$ system

experimentally very difficult (an optimistic guess):

- at least one isolated high p_t lepton (Δefficiency: $\approx$ 1%)
- some missing p_t (Δmissing transverse energy: $\approx$ few %)
- some b–jet tagging (Δb tagging: $\approx$ 5%)
- complicated multi–jet final state!(Δ event cuts: $\approx$ few %)

expect: at best $\pm$ 5% systematic uncertainty??

cross section interpretations: some theoretical aspects

- need to compare apples with apples!
  need to define what should be calculated/measured!
  (example W counting versus narrow width approximation!)

- $\triangle$ QED corrections
  (with and without γ veto)

- α_s and (unknown) higher order corrections with and without jet cuts.. can we define a ΔK systematics?

- PDF uncertainties?

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

for details: CERN 2000-004 (1999 SM LHC workshop) pages 126–128

the devil will be in the "little" details!
PYTHIA (approximations) $\neq$ precision SM calculations

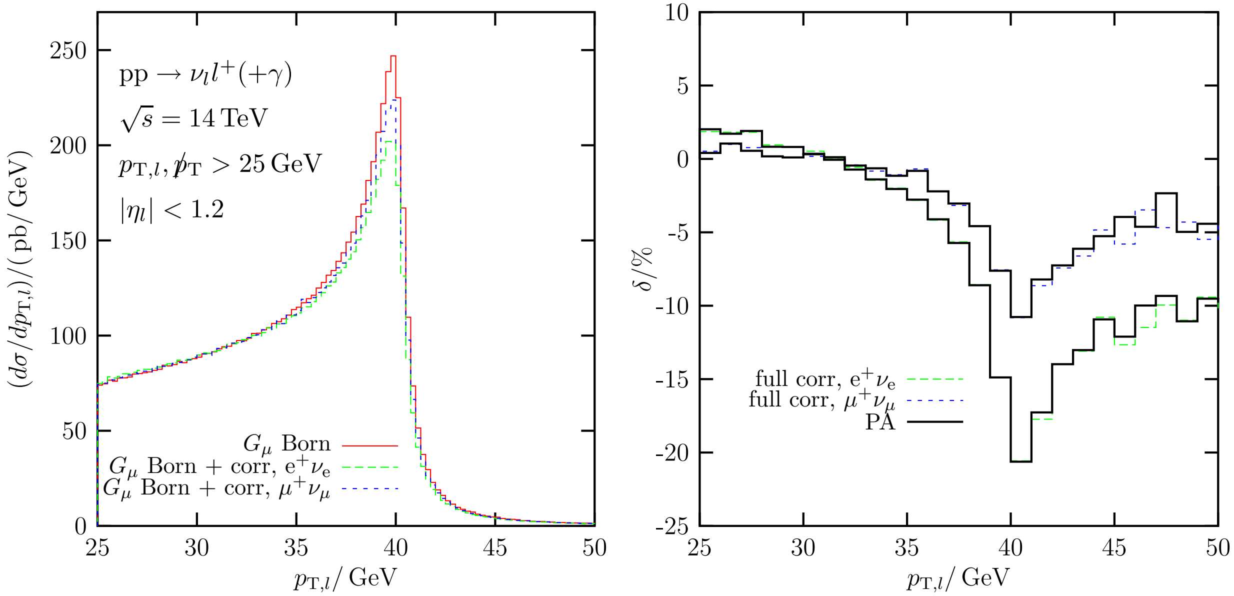


Fig. 6: Transverse-momentum distribution $(d\sigma/dp_{T,l})$ and relative corrections δ (results based on [60]).

from S. Dittmaier and M. Krämer

Higher Order QCD predictions

ELECTROWEAK GAUGE BOSON RAPIDITY DISTRIBUTIONS AT NNLO

C. Anastasiou, L. Dixon, K. Melnikov and F. Petriello Dec 2003, hep-ph/0312266

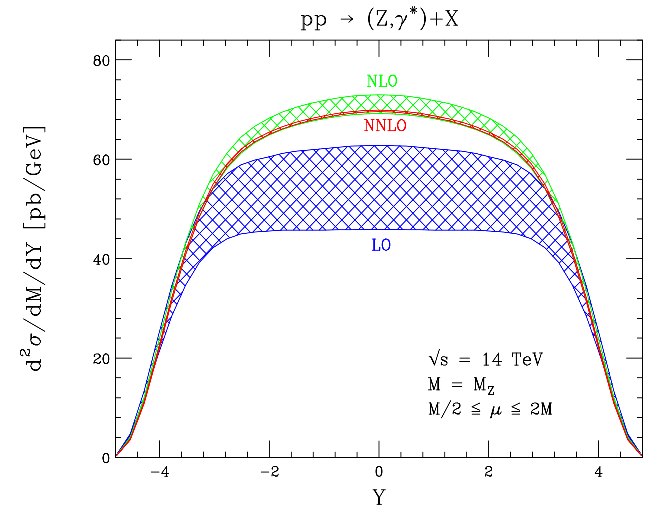


Figure 3: The CMS rapidity distribution of an on-shell Z boson at the LHC. The LO, NLO, and NNLO results have been included. The bands indicate the variation of the renormalization and factorization scales in the range $M_Z/2 \leq \mu \leq 2M_Z$.

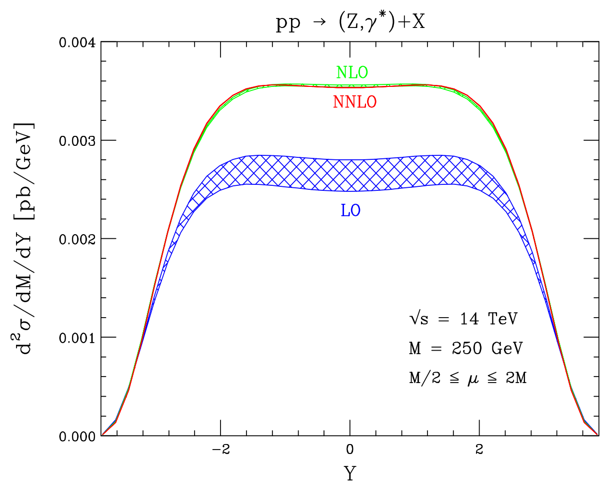


Figure 14: The rapidity distribution for (Z, γ^*) production at the LHC for an invariant mass M = 250 GeV. The LO, NLO, and NNLO results have been included. The bands indicate the residual scale dependences.

from the Binn Workshop (17.-19.10.2003)

23 Participants (22 talks) from Theory and Experiment!
$\rightarrow$ 2 days full of discussions!

http://wwweth.cern.ch/WorkShopBinn/home.html

ETH Institute for Particle Physics

ETH

Precise Cross Section Measurements at the LHC : Binn, 2003

Home

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Welcome to the home page for the

Workshop in Binn, Wallis, Switzerland, 2003:

Precision Cross Section Measurements at the LHC?

October 17th - 19th, 2003

organized by the Insitute for Particle Physics, ETH Zürich

Coordination and contact

Michael Dittmar ,

Günther Dissertori ,

Gabriele Kogler

On this Website you find information about the workshop programme, accomodation and how to reach Binn in Switzerland, and about the preparation of a write-up.

For Registration, simply send an email to one of the above listed persons. We will get in contact with you.

We expect to bring about 20-25 interested experimentalists and theorists together to discuss the physics the "Parton Luminosity Method" and potential precision cross section measurements at the LHC in detail. The workshop will be organized in 1.5-2 hour sessions on Friday and Saturday. Each session should allow for a small 20 min introduction talk and plenty of room for discussions and small (2 transparency) presentations. As a goal of the Workshop we expect to write a report about the potential accuracy for measurements of particular final states at the LHC and about the potential for accurate theoretical predictions and interpretations within or beyond the Standard Model. The document should also outline the remaining experimental and theoretical obstacles and the efforts which are required before the potential accurate measurements can be made at the LHC.
We would very much appreciate your comments and suggestions in order to organize an interesting and effective workshop in October 2003.

October 2003

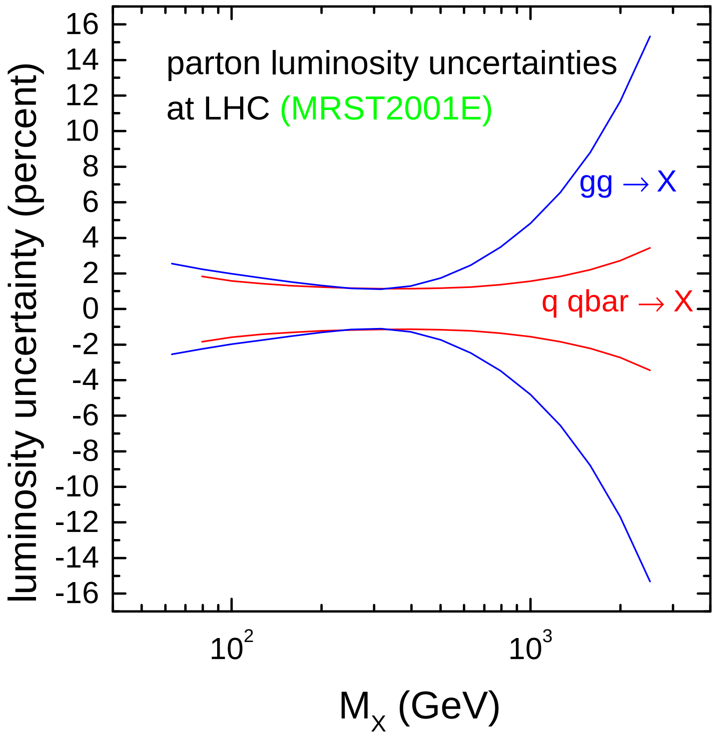
goals of the Binn Workshop

- understand experimental/theoretical limitations

- define promising reactions and reaction ratios!
  (where can todays knowledge be improved?)

- what should be measured/calculated
  and how accurate?

$q\bar{q}$, gg luminosity uncertainties at LHC as estimated by MRST2001E

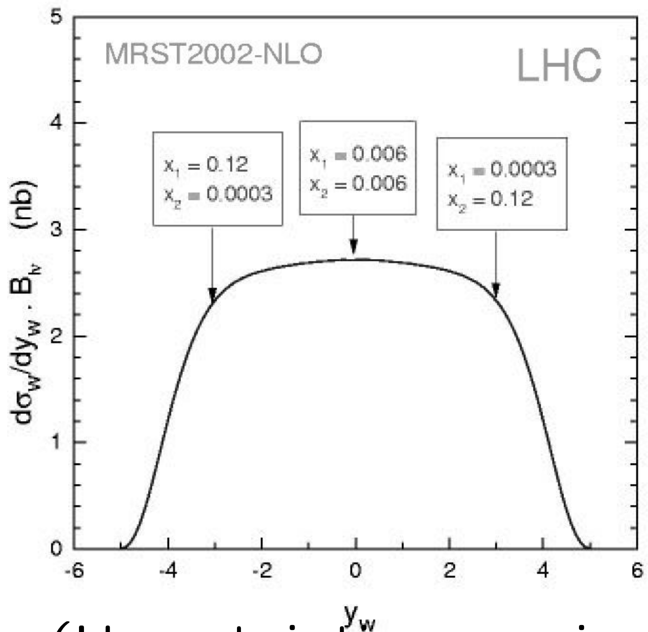


James Stirling (Uncertainties.. a view from a theorist)

- current best (MRST) estimate

$$\delta\sigma_{W,Z}^{\rm NNLO}(\text{total pdf}) = \pm 4\%$$

- *cf.* $\pm 2\%$ for 'expt. pdf' errors only
- but note that there is a much greater uncertainty in the NLO prediction, due to problems at small x in the global fit to DIS data (see talk by Thorne)
- this is because the large rapidity W and Z total cross sections sample very small x



2. cross section ratios

- $\sigma(W^+)/\sigma(W^-)$ is gold-plated

$$R_\pm = \frac{\sigma(W^+)}{\sigma(W^-)} \simeq \frac{u(x_1)\bar{d}(x_2)}{d(x_1)\bar{u}(x_2)} \simeq \frac{u(x_1)}{d(x_1)}$$

since sea is u, d symmetric at small x, and using MRST2001E

$$\delta\sigma_{W^\pm}(\text{expt. pdf}) = \pm 2\%, \qquad \delta R_\pm(\text{expt. pdf}) = \pm 1.4\%$$

Assuming all other uncertainties cancel, this is probably the most accurate SM cross section test at LHC

Note: attempt to pin down d/u ratio at large x using forward $W^\pm$ production appears hopeless

Example II: $(gg \to)$ Higgs cross section

- a light (SM or MSSM) Higgs dominantly produced via $gg \to H$ and the cross section has small pdf uncertainty because $g(x)$ at small x is well constrained by HERA DIS data

- current best (MRST) estimate, for $M_H = 120$ GeV:

$$\delta\sigma_H^{\rm NNLO}(\text{total pdf}) = \pm 3\%$$

... with less sensitivity to small x than $\sigma(W)$.

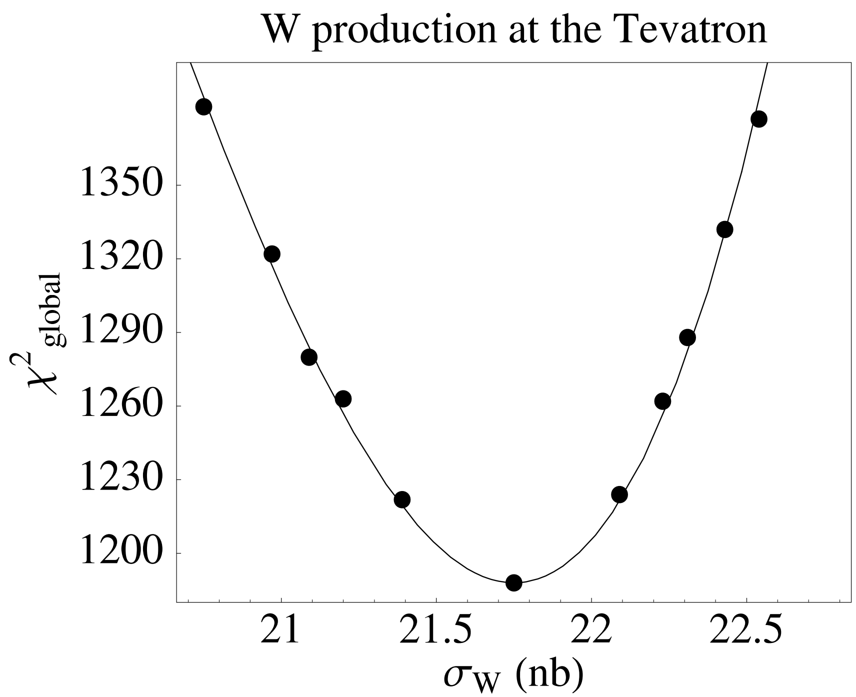
- this is *much* smaller than the uncertainty from higher-order corrections, for example (Catani et al, hep-ph/0306211):

$$\begin{aligned} \delta\sigma_H^{\rm NNLO}(\text{scale variation}) &= \pm 10\%, \\ \delta\sigma_H^{\rm NNLL}(\text{scale variation}) &= \pm 8\% \end{aligned}$$

Can also look at uncertainty on a given physical quantity using Lagrange Multiplier method, first suggested by CTEQ and concentrated on by MRST. Minimize

$$\Psi(\lambda, a) = \chi^2_{global}(a) + \lambda F(a).$$

Gives best fits for particular values of quantity $F(a)$ without relying on Gaussian approx for χ^2. Uncertainty then determined by deciding allowed range of $\Delta\chi^2$.



CTEQ obtain for $\alpha_S = 0.118$

$$\Delta\sigma_W(\text{LHC}) \approx \pm 4\% \quad \Delta\sigma_{\rm W}(\text{Tev}) \approx \pm 4$$

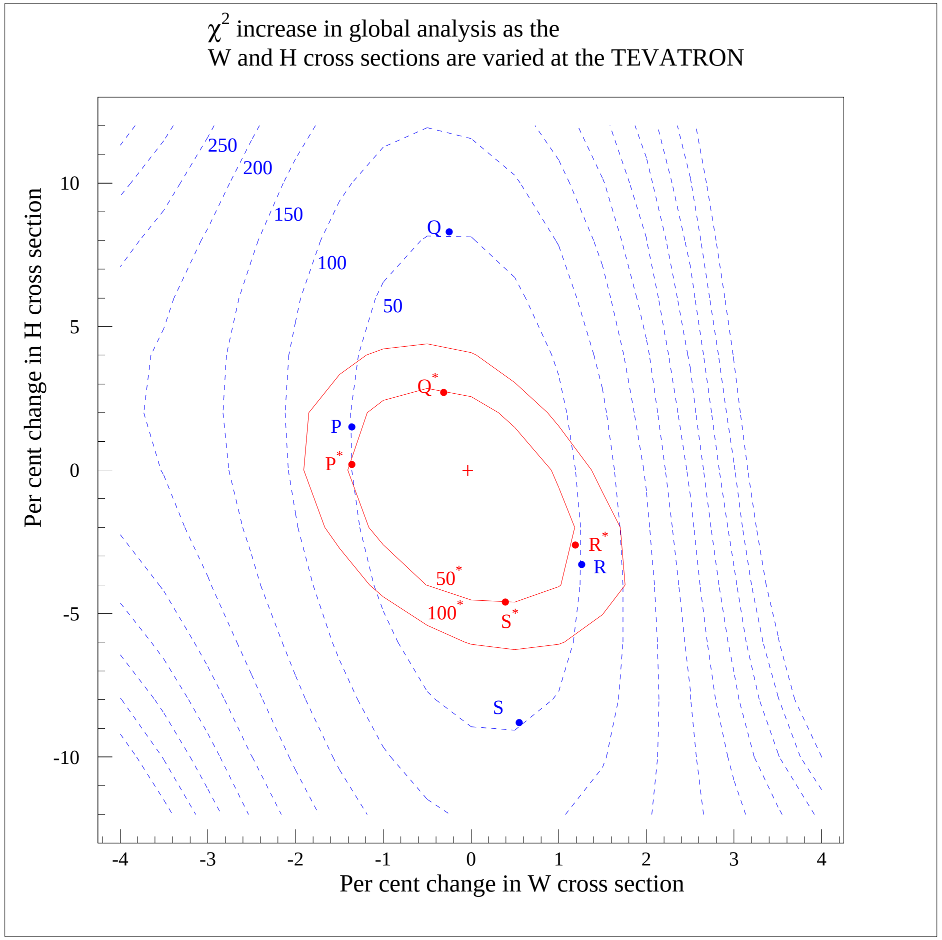
$$\Delta\sigma_H(\text{LHC}) \approx \pm 5\%.$$

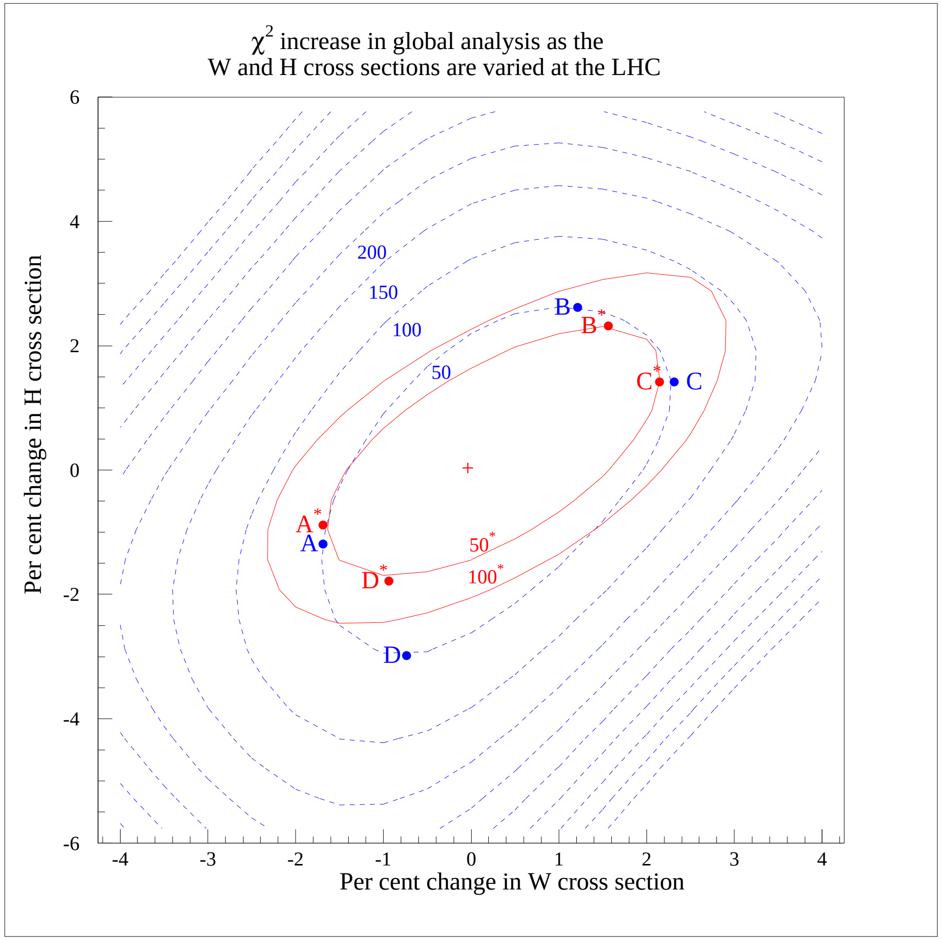
MRST use a wider range of data, and if $\Delta\chi^2 \sim 50$ find for $\alpha_S = 0.119$

$$\Delta\sigma_W(\text{Tev}) \approx \pm 1.2\% \quad \Delta\sigma_{\rm W}(\text{LHC}) \approx \pm 2\%$$

$$\Delta\sigma_H(\text{Tev}) \approx \pm 4\% \quad \Delta\sigma_{\rm H}(\text{LHC}) \approx \pm 2\%.$$

MRST also allow α_S to be free.

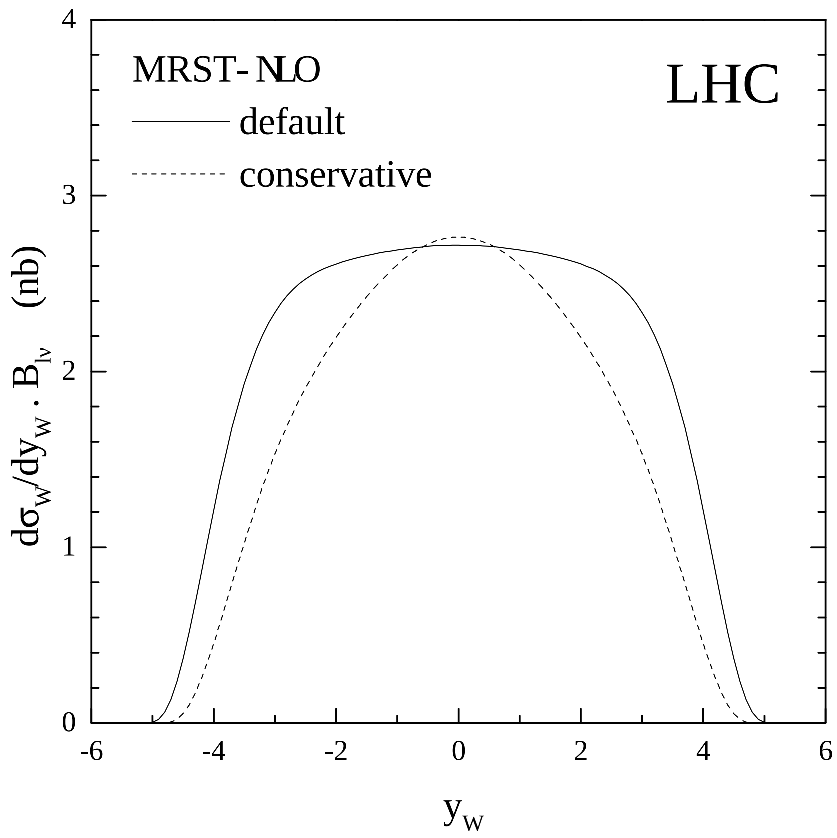




χ^2-plots for W and Higgs (120GeV) production at the Tevatron and LHC α_S free (blue) and fixed (red) at $\alpha_S = 0.119$.

Comparison of prediction for $(d\sigma_W/dy_W)$ for the standard MRST partons and the conservative set. The reduction in the total cross-section in the latter case is clearly due to the huge reduction at high y_W and represents the possible type of theoretical uncertainty in this region when working at NLO.

Note a slight increase in cross-section for $y_W = 0$ $(x = 0.006)$. Due to increased evolution of quarks here.



Parton Luminosities: remaining Work/Problems

- Experimentalists and theorists have to "learn" how to measure and calculate the same things!

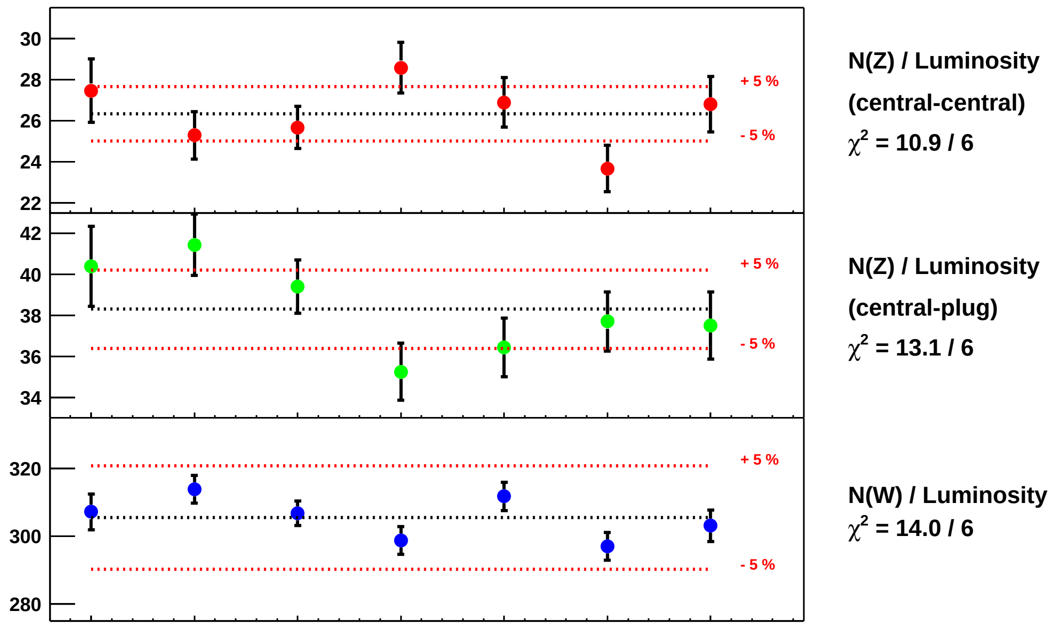
- Repeat Studies with NLO (perhaps NNLO) Monte Carlo programs

- Define a realistic iterative HERA–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 (effects of a jet veto?)

- Develop a realistic parton luminosity counting for CMS/ATLAS.

try to learn from W and Z counting at the Tevatron:



M.D. and A.S Nicollerat CDF note 6411 (2003)

Summary and Outlook

- New approach to the LHC Luminosity:
  replace $L_{proton-proton}$ with $L_{parton-parton}$

- lepton rapidity distributions from $q\bar{q} \rightarrow W^{+}, W^{-}, Z^{0}$ constrain $x_{q,\bar{q}}$ between 3×10^{-4} and $\approx 10^{-1}$

- precise predictions for other $q, \bar{q}$ processes!
  $$N'_{q\bar{q}\rightarrow WW} = N_{q\bar{q}\rightarrow Z} \times \frac{\sigma_{q\bar{q}\rightarrow WW}}{\sigma_{q\bar{q}\rightarrow Z}} \times \frac{\mathrm{PDF}(x'_1, x'_2, Q'^2)}{\mathrm{PDF}(x_1, x_2, Q^2)}$$

- Similar approach to constrain x_{gluon}:
  $qg \rightarrow \gamma q$ and $qg \rightarrow Z^0 q$

- experimental accuracy of the approach $\Delta L/L \leq 1\% (\ll 5\%)$ possible!

- Can theory match experimental errors?

LHC Physics

Solving cross-section challenges at the LHC

A small workshop held recently in Switzerland considered the challenges to be overcome before accurate cross-section measurements can be made at the LHC.

For three days in October the population of Binn, a beautiful village in the Oberwallis in Switzerland, increased by almost 20% when 23 experimental and theoretical particle physicists attended a workshop on cross-section measurements at the Large Hadron Collider (LHC).

The main purpose of this small workshop, organized by Günther Dissertori and Michael Dittmar of the CMS group at ETH Zürich, was to investigate how well the different types of physics reactions and reaction ratios expected at the LHC can be measured and calculated. About half the time at the workshop was devoted to thought-provoking review talks, while the rest remained free for questions, discussion and critical comments.

Binn

The workshop began with an introduction to general aspects and problems of cross-section measurements at the LHC. The participants were reminded that in addition to the experimental uncertainties from efficiency, backgrounds and the machine luminosity, there are potentially important theoretical uncertainties in the calculations, such as those arising from uncertainties in the parton distribution functions (PDFs) and from unknown higher-order corrections. It was also pointed out that normalizing various interesting high-Q^2 reactions to the well-understood and abundant production of W and Z

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The success of the meeting could also be judged by a comment from one participant during an additional "special session" on Sunday afternoon: "This was the first conference where I not only participated in all the sessions but even listened to all the talks." Falling asleep would in any case have been difficult during this last "session": a four-hour hike to the Mässersee and back!

Further reading
Details about the workshop and the different presentations can be found at http://wwweth.cern.ch/WorkShopBinn.

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