Uli Baur and the
W Boson Mass Measurement at the Tevatron

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Uli's Interests in Precision Physics

- QCD and PDF-related measurements
  - P_T spectrum of Z bosons
  - Measurement of angular decay distribution coefficients in W and Z boson decays to leptons
  - Charge asymmetry in W boson production and decay
  - Z boson rapidity spectrum

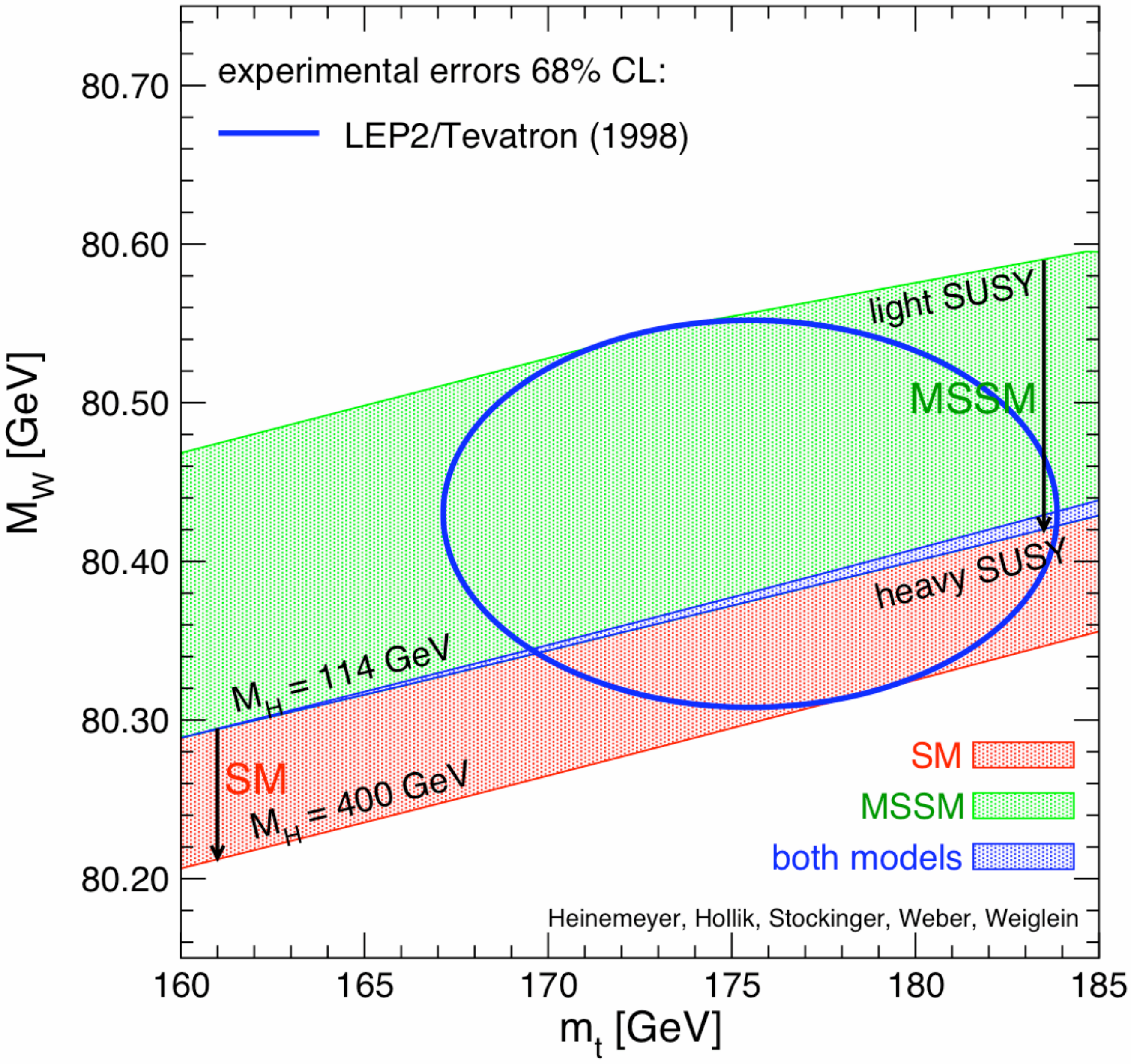
- Measurements related to electroweak sector
  - Top quark mass measurement
  - W boson mass measurement
  - W boson width measurement
  - Forward-backward asymmetry (A_{FB}) in Z boson decays
    - On-peak and high-mass

Uli's interest in the W boson mass

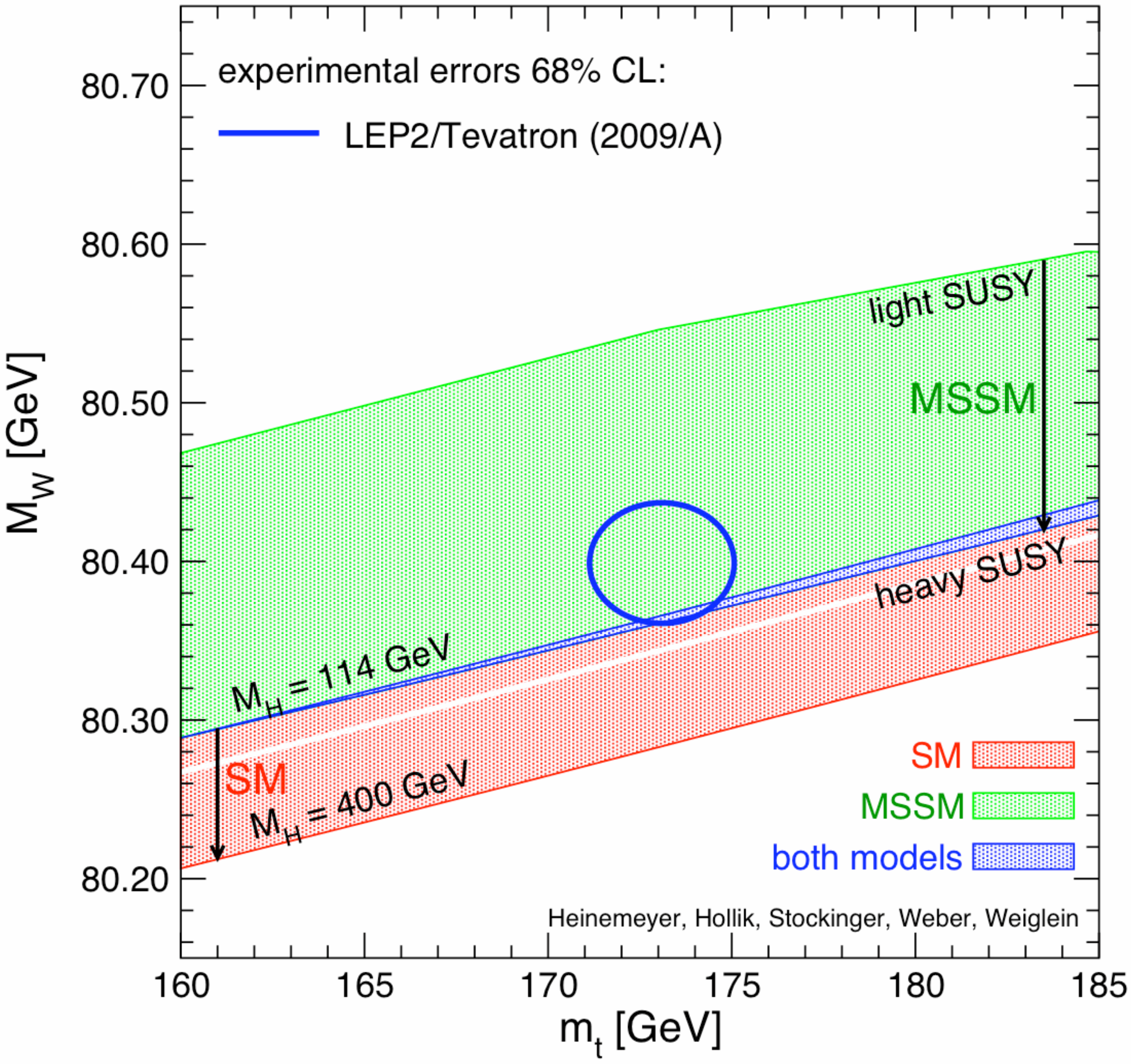
- Uli's took a deep and personal interest in the W boson mass measurement at the Tevatron
  - Recall long conversations about nitty-gritty details of the W mass analysis, starting 1995

- Uli as an experimentalist
  - He supervised Zarah Casilum, an experimental HEP student who worked on D0 via Stony Brook U.
  - Zarah and I worked together on the electronics upgrade of the D0 calorimeter for Tevatron Run II

Pre-Tevatron Run 2 M_W *vs* M_{top}



Current Tevatron & LEPII M_W *vs* M_{top}



W Boson Mass Fit Uncertainties (MeV) from CDF

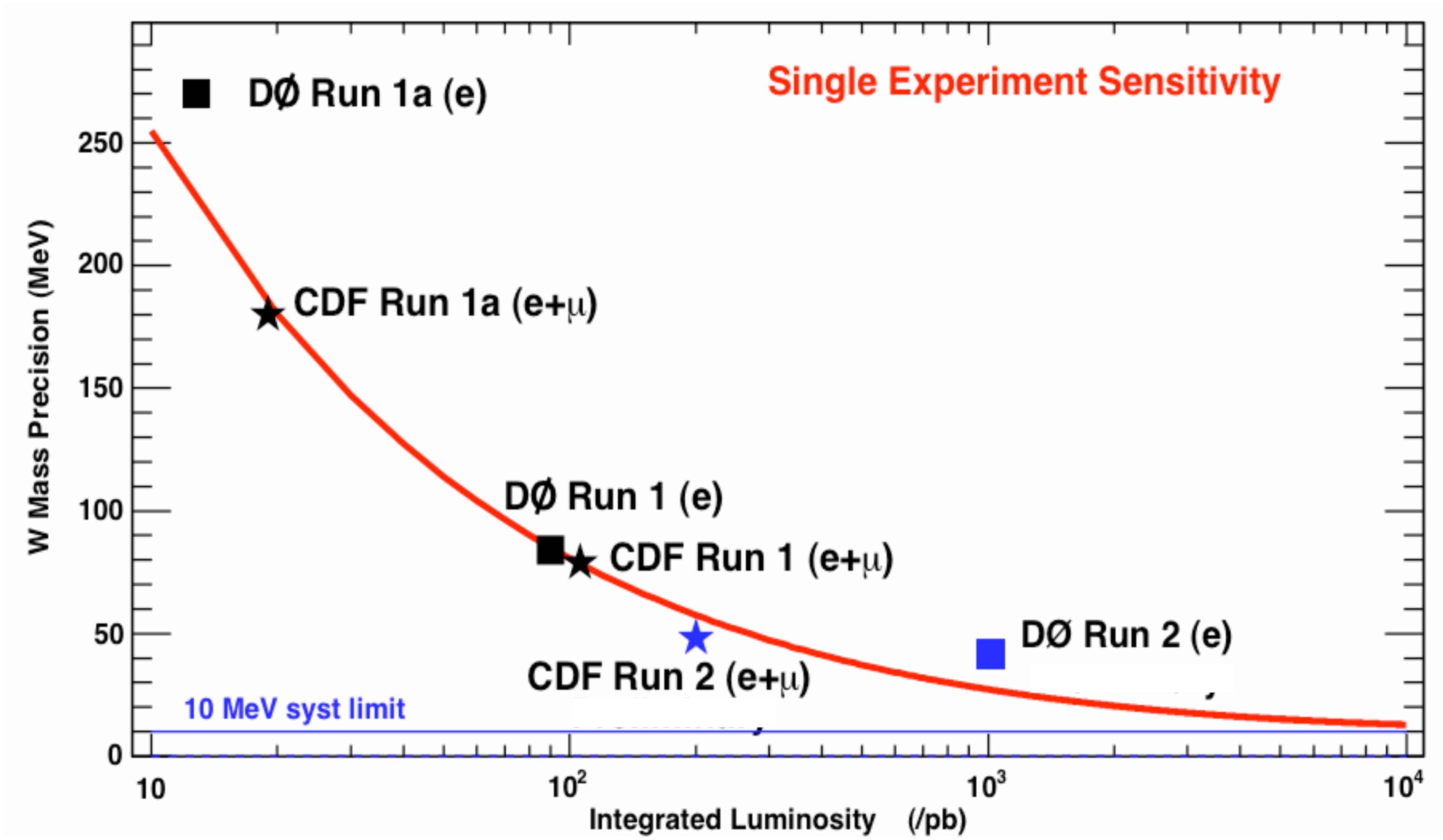
(CDF, PRL 99:151801, 2007; Phys. Rev. D 77:112001, 2008)

	electrons	*muons*	*common*
W statistics	48	54	0
Lepton energy scale	30	17	17
Lepton resolution	9	3	-3
Recoil energy scale	9	9	9
Recoil energy resolution	7	7	7
Selection bias	3	1	0
Lepton removal	8	5	5
Backgrounds	8	9	0
production dynamics	3	3	3
Parton dist. Functions	11	11	11
QED rad. Corrections	11	12	11
Total systematic	39	27	26
Total	62	60	

Uli helped with QED

Systematic uncertainties shown in green: statistics-limited by control data samples

Improvement of M_W Uncertainty with Sample Statistics



Next target: 15-20 MeV measurement of M_W from the Tevatron

W Mass Status

- The *W* boson mass is a very interesting parameter to measure with increasing precision
- CDF Run 2 W mass result with 200 pb^{-1} data:
  - $M_W = 80413 \pm 48$ MeV
- D0 Run 2 W mass result with 1 fb^{-1} data:
  - $M_W = 80401 \pm 43$ MeV
- Many systematics limited by statistics of control samples
  - CDF and D0 are both working on $\delta M_W < 25$ MeV measurements from ~ 2 fb^{-1} (CDF) and ~ 4 fb^{-1} (D0)
- Learning as we go: Tevatron → LHC may produce $\delta M_W \sim 5$-10 MeV

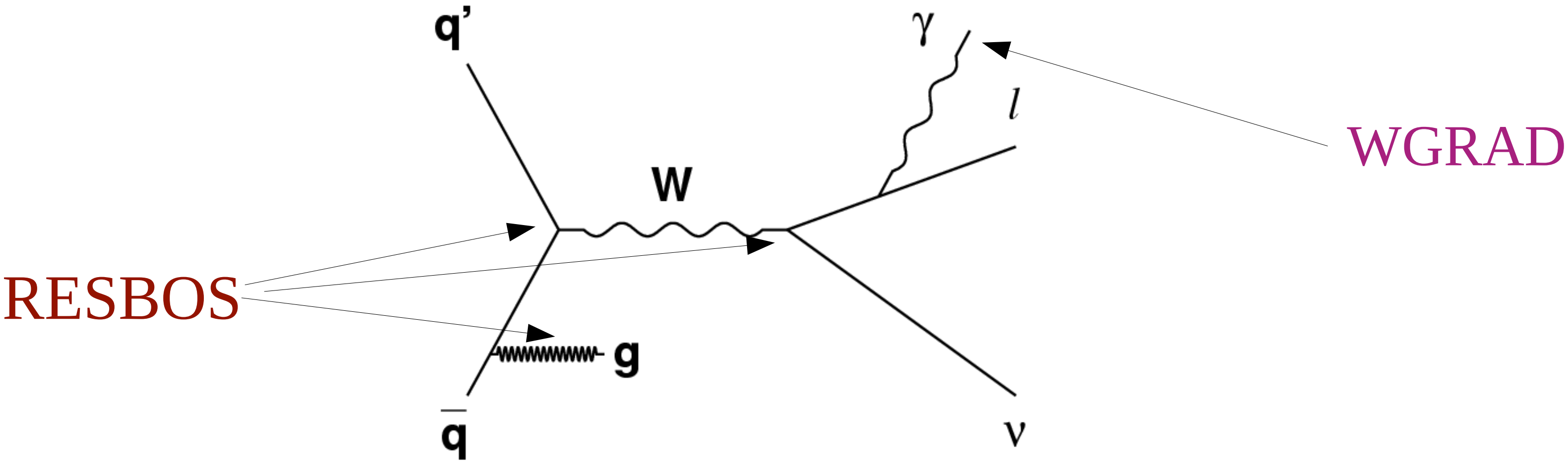
M_W Measurement at LHC

- Very high statistics samples of W and Z bosons
  - 10 fb^{-1} at 14 TeV: 40 million W boson and 4 million Z boson candidates per decay channel per experiment
- Statistical uncertainty on W mass fit ~ 2 MeV
- Calibrating lepton energy response using the Z → *ll* mass resonance, best-case scenario of statistical limit ~ 5 MeV precision on calibrations
- Calibration of the hadronic calorimeter based on transverse momentum balance in Z → *ll* events also ~ 2 MeV statistical limit
- Total uncertainty on M_W ~ 5 MeV if Z → *ll* data can measure all the W boson systematics

M_W Measurement at LHC

- Can the Z → *ll* data constrain all the relevant W boson systematics?
- We must add other constraints from other mass resonances and tracking detectors
- With every increase in statistics of the data samples, we climb a new learning curve on the systematic effects
  - Improved calculations of QED radiative corrections will be needed
  - Better understanding of parton distributions from global fitting groups (CTEQ, MSTW, NN PDFs, Giele *et al*,)
- large sample statistics at the LHC imply the potential is there for 5-10 MeV precision on M_W

Generator-level Signal Simulation

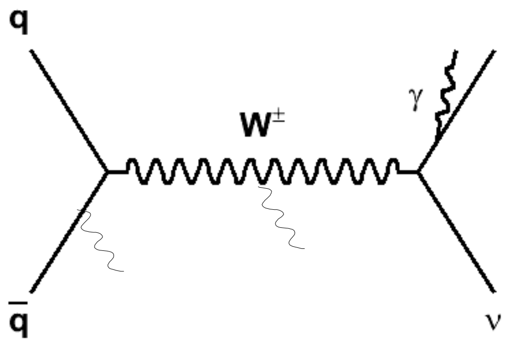


RESBOS

WGRAD

- Generator-level input for W & Z simulation provided by RESBOS (C. Balazs & C.-P. Yuan, PRD56, 5558 (1997) and references therein), which
  - Calculates triple-differential production cross section, and p_T-dependent double-differential decay angular distribution
  - calculates boson p_T spectrum reliably over the relevant p_T range: includes tunable parameters in the non-perturbative regime at low p_T
- Radiative photons generated according to energy *vs* angle lookup table from WGRAD (U. Baur, S. Keller & D. Wackeroth, PRD59, 013002 (1998))

QED Radiative Corrections



- We used Uli's complete NLO QED calculation (WGRAD) for single photon emission
  - We simulated final state radiation (FSR) photons
  - We estimated initial state radiation (ISR) and ISR-FSR interference to contribute ~ 5 MeV each, on top of ~200 MeV mass shift due to FSR.

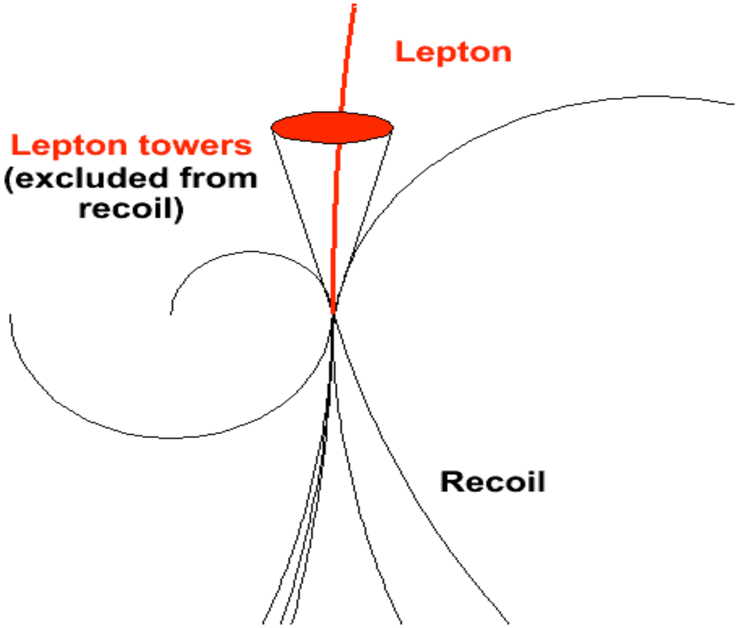
- Based on 2-photon calculation (Carloni Calame *et. al.*, PRD69, 037301 (2004)) prediction: we took 5% of the total QED mass shift (~200 MeV) as systematic uncertainty

$$\Delta M_W = 10 \text{ MeV}$$

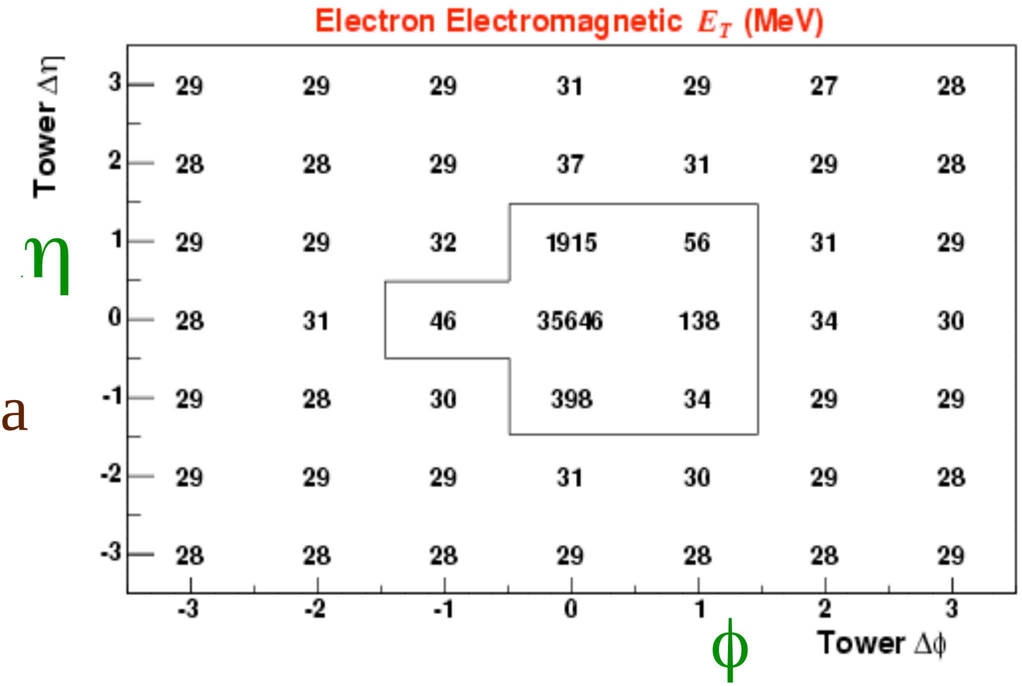
QED Radiative Corrections

- We remove the calorimeter towers containing lepton energy from the missing E_T calculation

- 2nd photon energy correction (10 ± 5) %
  - Energy and angular distribution of 2nd radiated photon needed



Electron channel W data



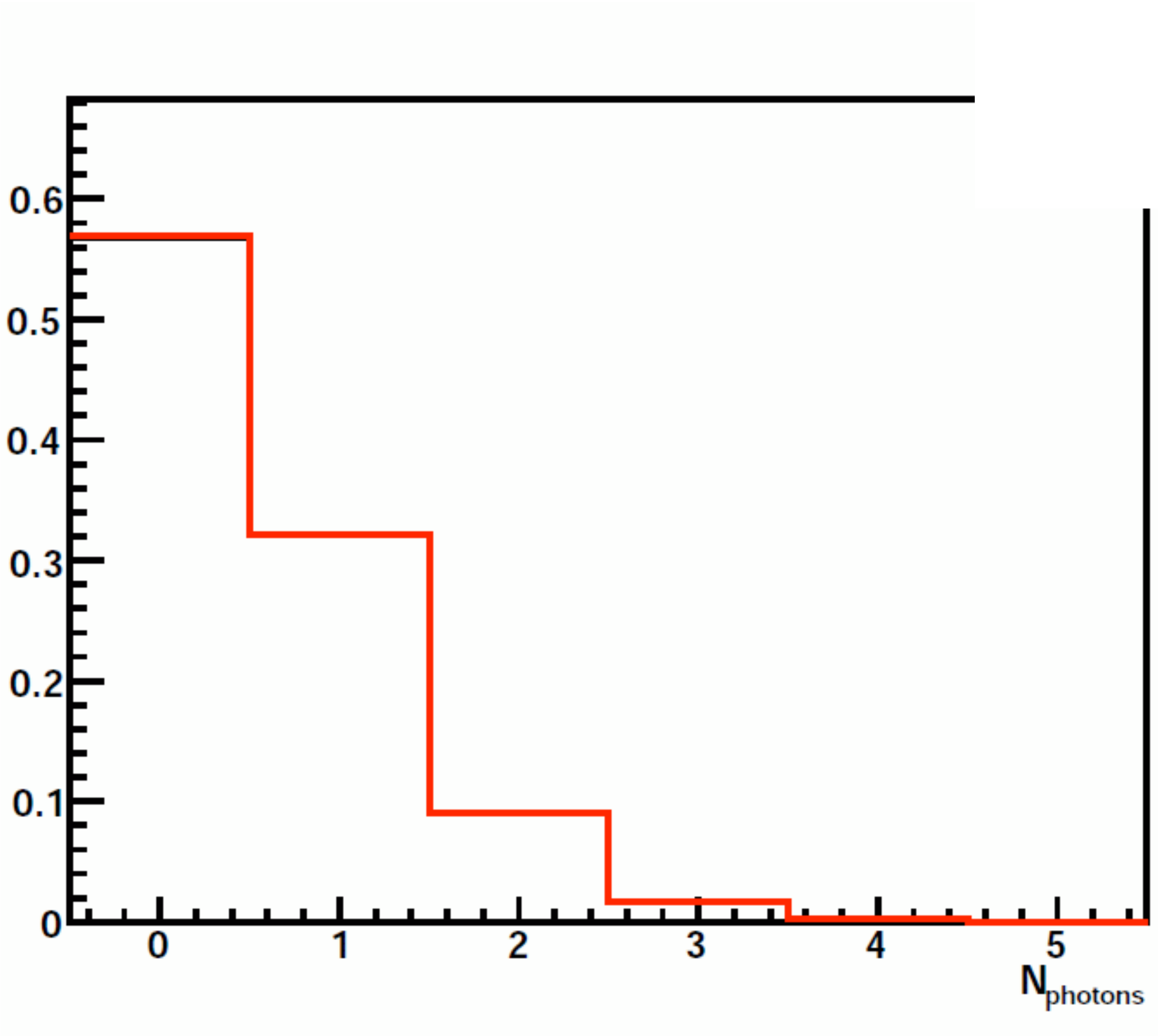
Electron Electromagnetic E_T (MeV)

Tower Δη \ Tower Δϕ	-3	-2	-1	0	1	2	3
3	29	29	29	31	29	27	28
2	28	28	29	37	31	29	28
1	29	29	32	1915	56	31	29
0	28	31	46	35646	138	34	30
-1	29	28	30	398	34	29	29
-2	29	29	29	31	30	29	28
-3	28	28	28	29	28	28	29

Multi-photon QED Generators

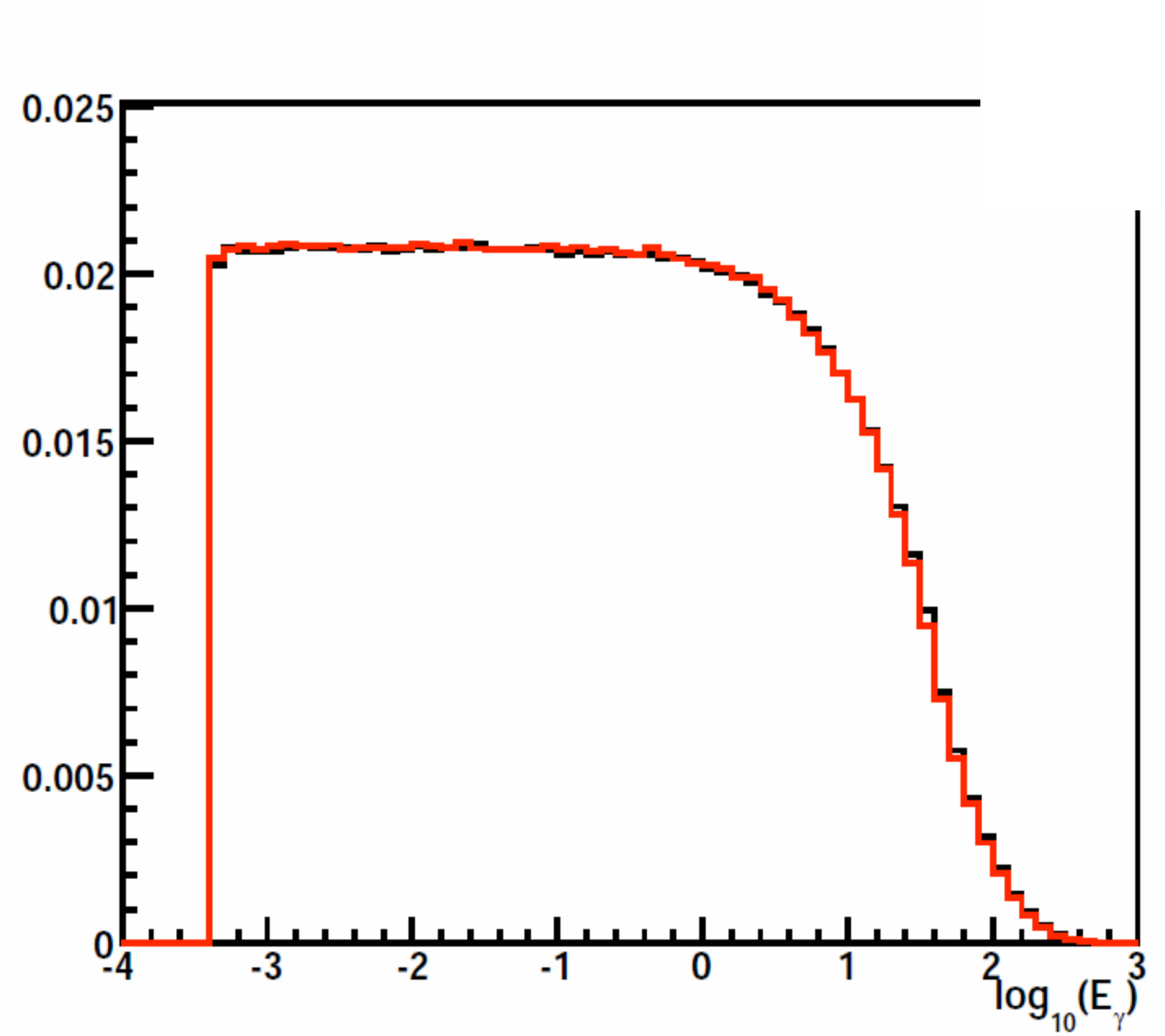
- New Strategy: benchmark multi-photon generators against each other and against WGRAD/ZGRAD programs at $O(\alpha)$
  - HORACE (Carloni Calame *et al*)
  - PHOTOS (Barberio & Was)
  - Both are leading-log photon showering algorithms
  - HORACE has exact $O(\alpha)$ mode to compare to WGRAD/ZGRAD
  - Show today: multi-photon spectra from HORACE and PHOTOS [studies by Ilija Bizjak (UCL), Bodhitha Jayatilaka (Duke), A. Kotwal (Duke)]
    - Number of FSR photons emitted per event
    - Energy of FSR photons
    - Angle between FSR photons and nearest lepton

HORACE-PHOTOS Comparison for W->eυ process



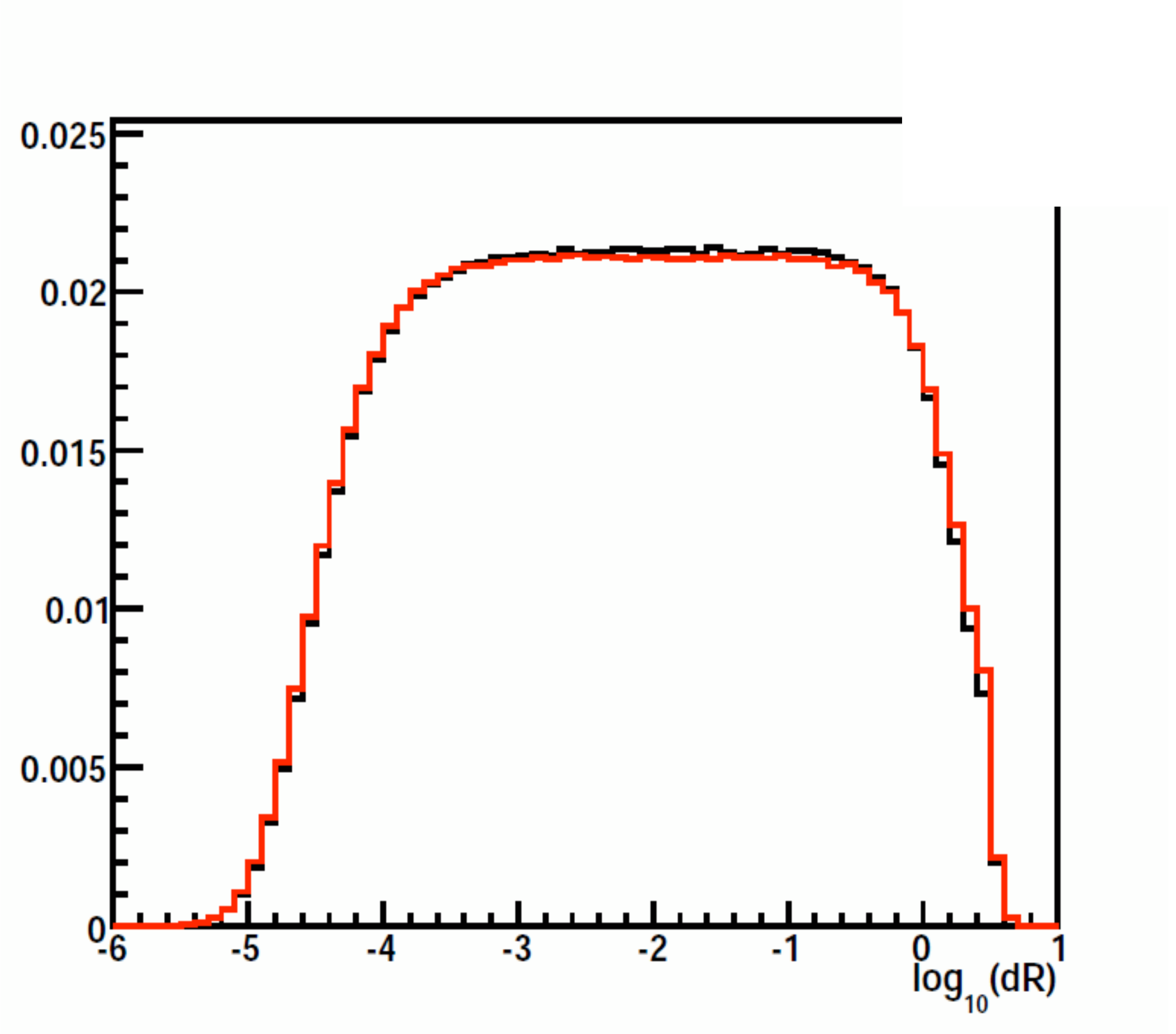
Number of FSR photons above 0.4 MeV

HORACE-PHOTOS Comparison for W->eυ process



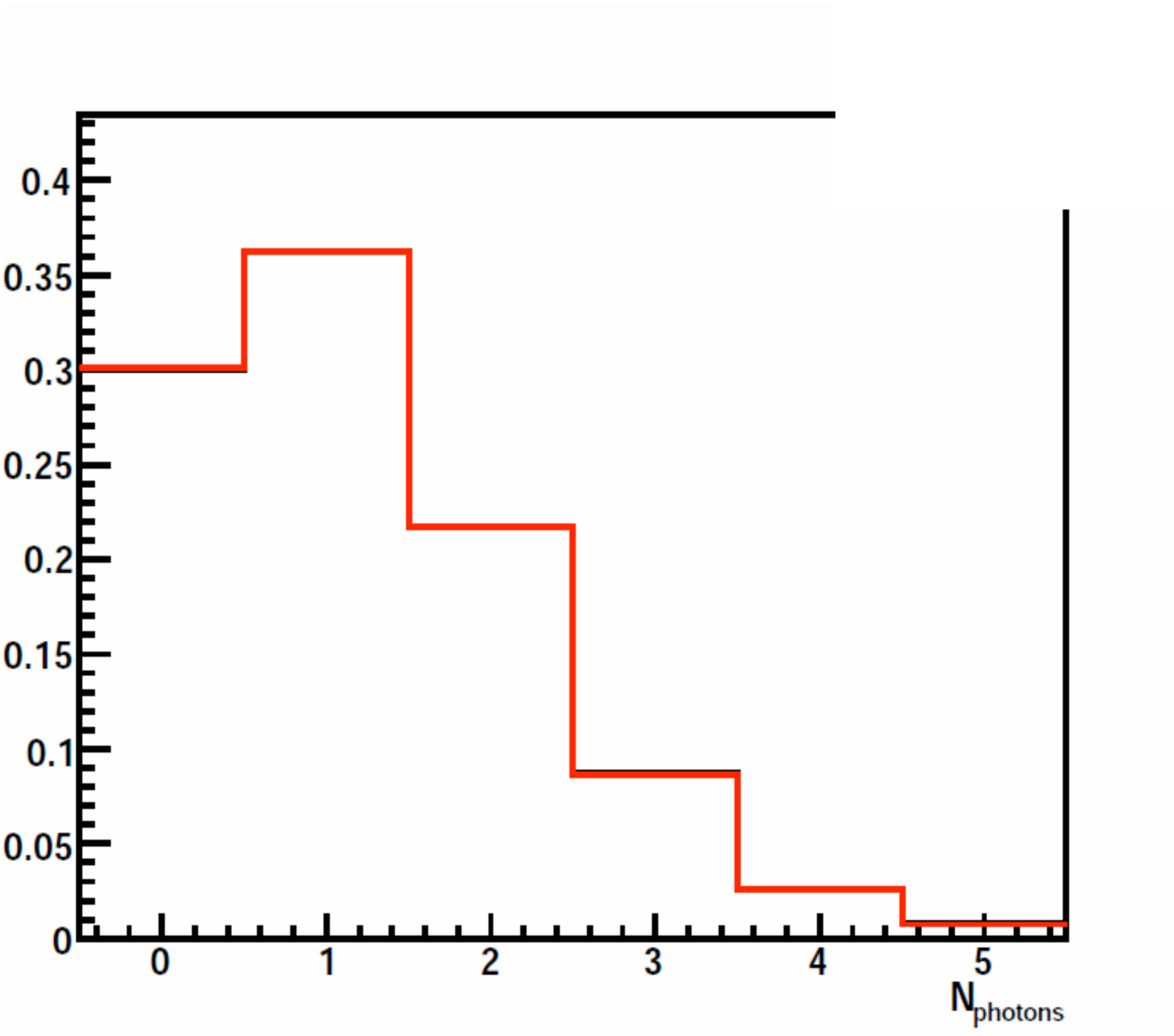
$\log_{10}$(energy/MeV) distribution for FSR photons above 0.4 MeV

HORACE-PHOTOS Comparison for W->eυ process



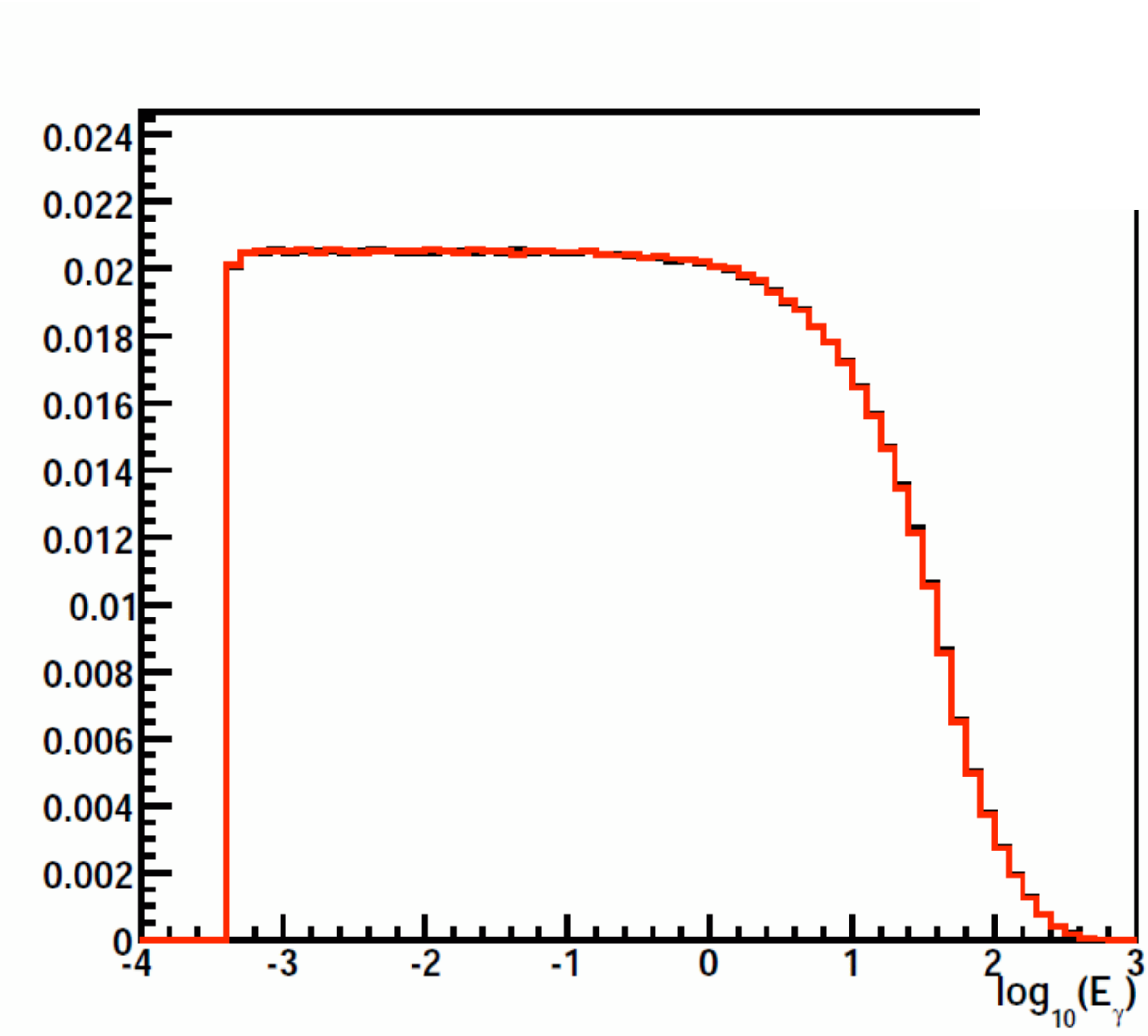
$\log_{10}$(photon-lepton angle) distribution for FSR photons above 0.4 MeV

HORACE-PHOTOS Comparison for Z->ee process



Number of FSR photons above 0.4 MeV

HORACE-PHOTOS Comparison for Z->ee process

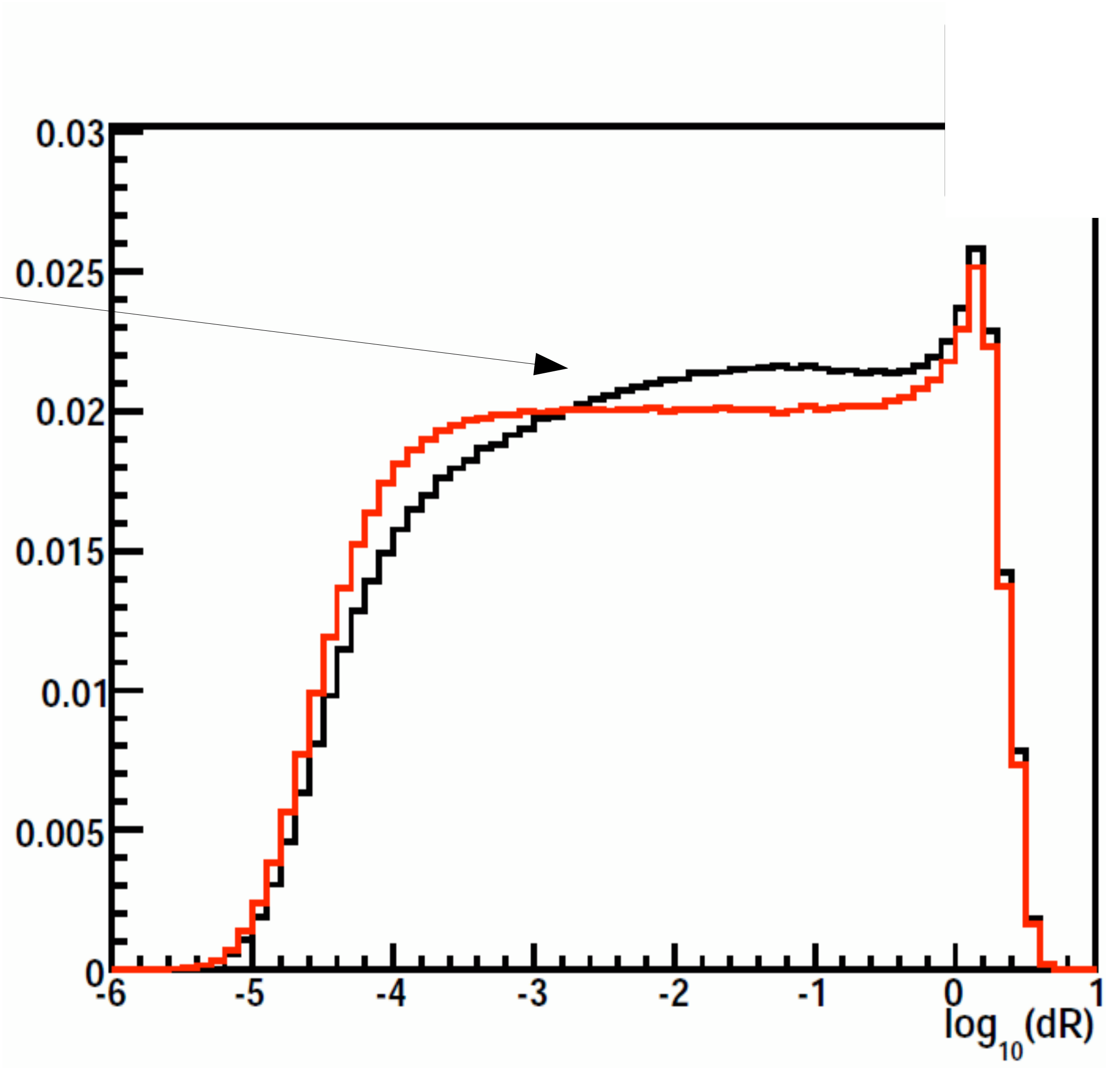


$\log_{10}$(energy/MeV) distribution for FSR photons

HORACE-PHOTOS Comparison for Z->ee process

Difference for small-angle FSR emission in electron channel

Muon channel shows no difference at large angles

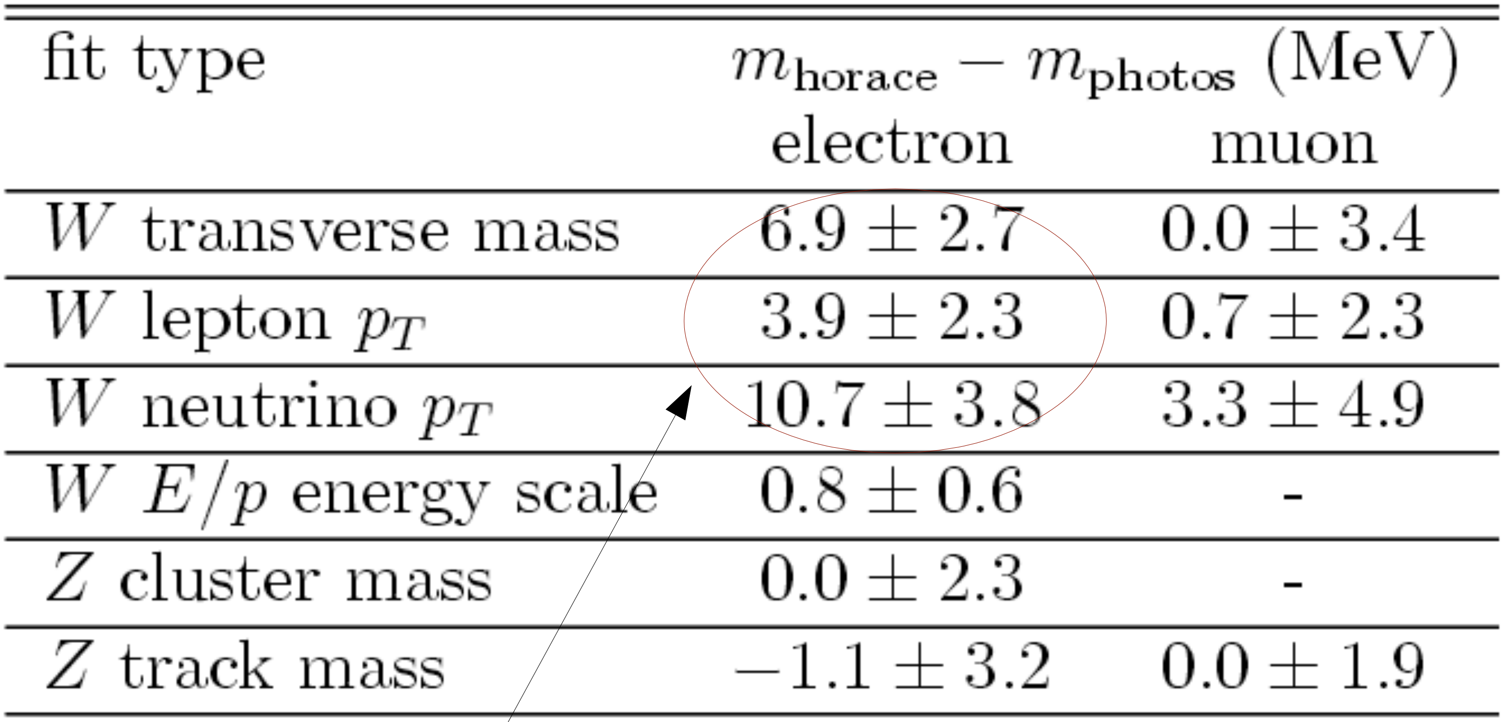


Pileup is artifact of choosing lepton closest to photon

$\log_{10}$(photon-lepton angle) distribution for FSR photons above 0.4 MeV

HORACE-PHOTOS Comparisons of boson mass fits

- We quantify the systematic differences between these generators by fitting simulated pseudo-data
- Differences in fitted masses shown below, with MC statistical error



fit type	$m_{\mathrm{horace}} - m_{\mathrm{photos}}$ (MeV)	
	electron	muon
W transverse mass	6.9 ± 2.7	0.0 ± 3.4
W lepton p_T	3.9 ± 2.3	0.7 ± 2.3
W neutrino p_T	10.7 ± 3.8	3.3 ± 4.9
W E/p energy scale	0.8 ± 0.6	-
Z cluster mass	0.0 ± 2.3	-
Z track mass	-1.1 ± 3.2	0.0 ± 1.9

To be investigated...

Inspiration from Uli

- Using exact $O(\alpha)$ calculation as benchmark, we should be able to pin down QED systematic on next W mass measurement to 5 MeV

- At our recent W mass measurement workshop at Fermilab last year, Uli and Doreen talked about performing an exact $O(\alpha^2)$ calculation of $W+2\gamma$ and $Z+2\gamma$

- These programs would provide the ultimate QED benchmark for W boson mass measurement at the 1-2 MeV level of precision

- We will keep improving the W mass precision and hope that these programs become necessary!