Cat among the Pigeons

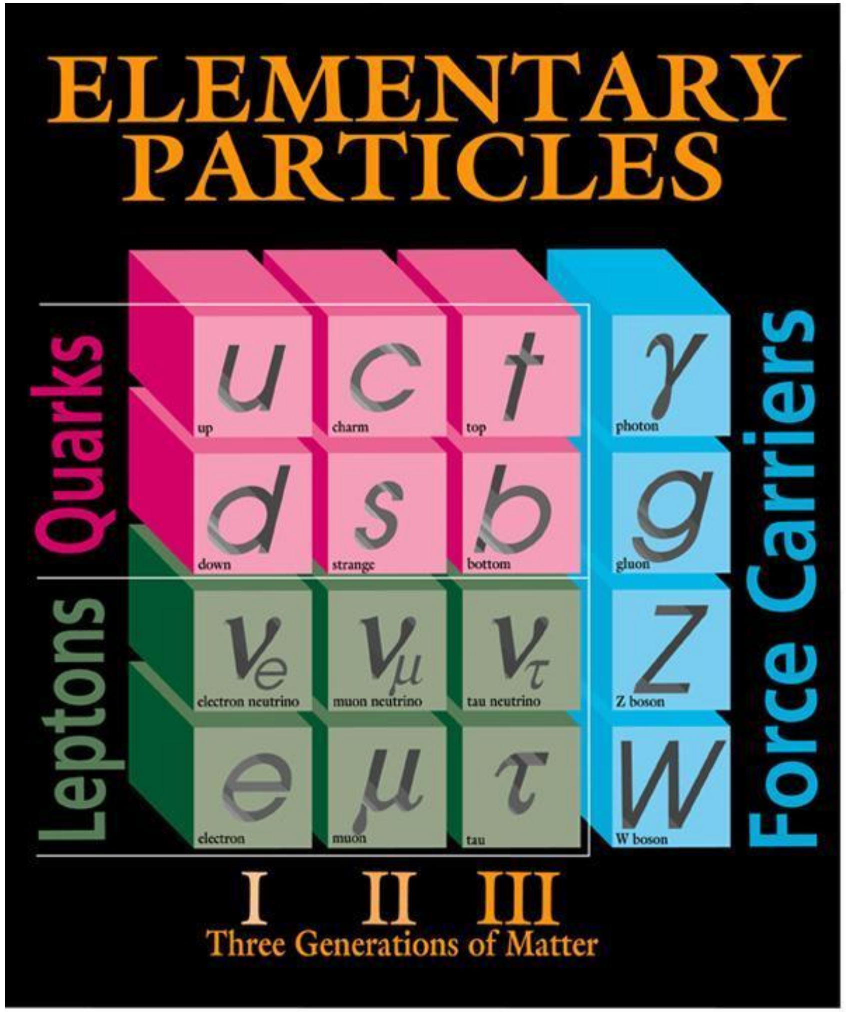
Cat among the pigeons – a new measurement of the W-mass

A Gurtu

TIFR, 1969 – 2011

PDG (Z, W) 1993 – present

But, to begin at the very beginning; what every school child knows today… the SM of Particle Physics…



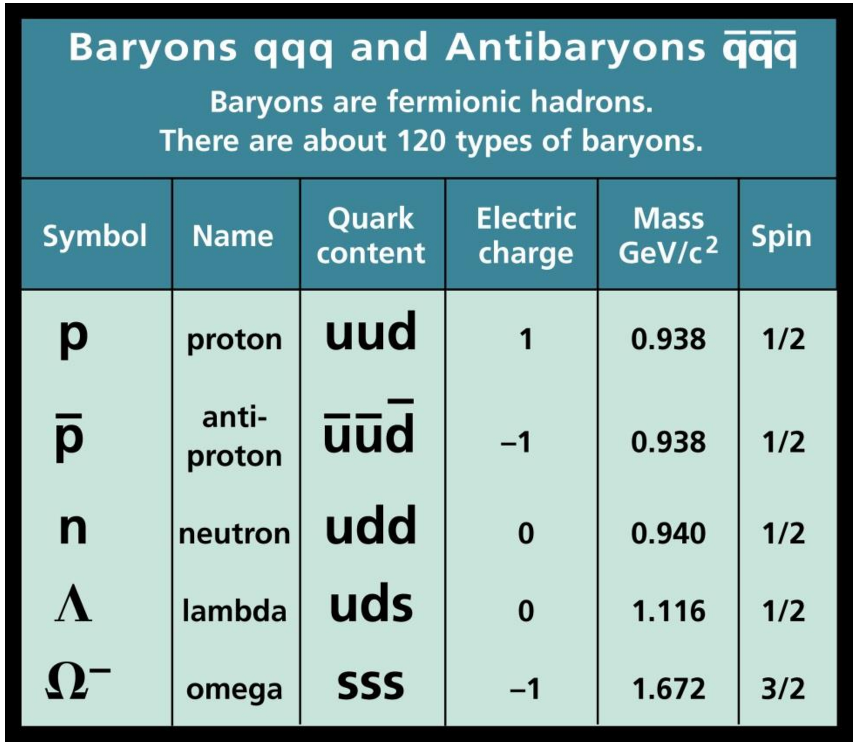
Fermilab 95-759

All objects around us need ONLY 1st generation

2nd, 3rd generations discovered in high energy particle interactions

+ Higgs

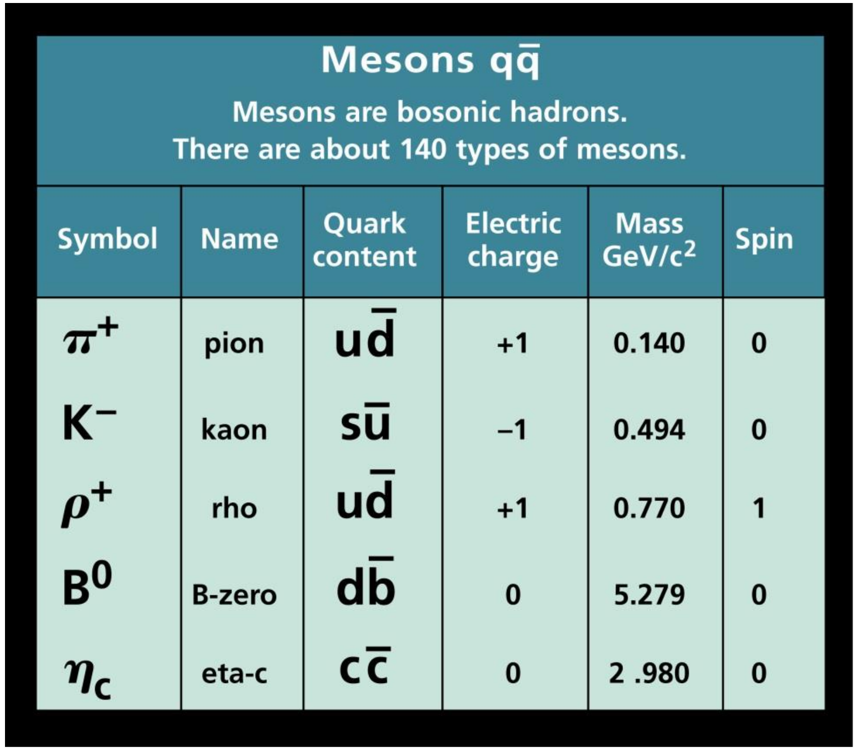
“Visible” hadrons
(quarks are never seen)



Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

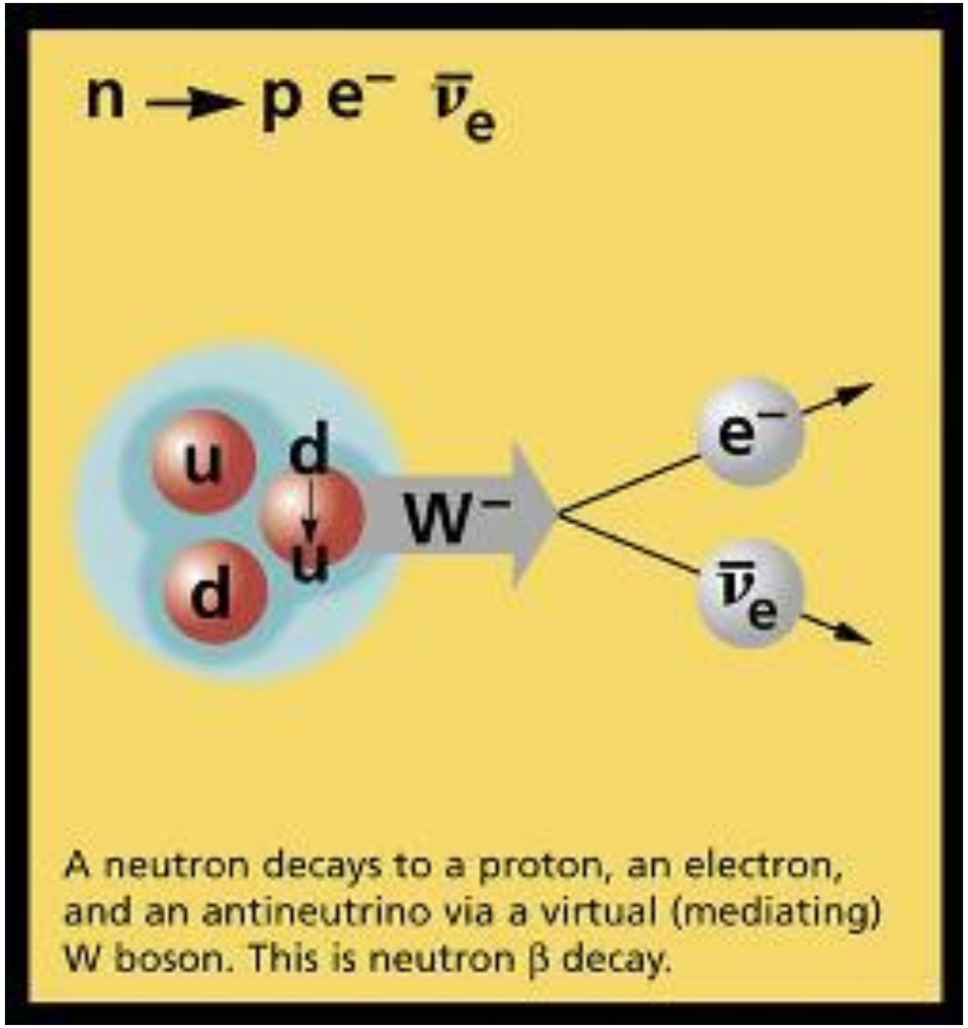


Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

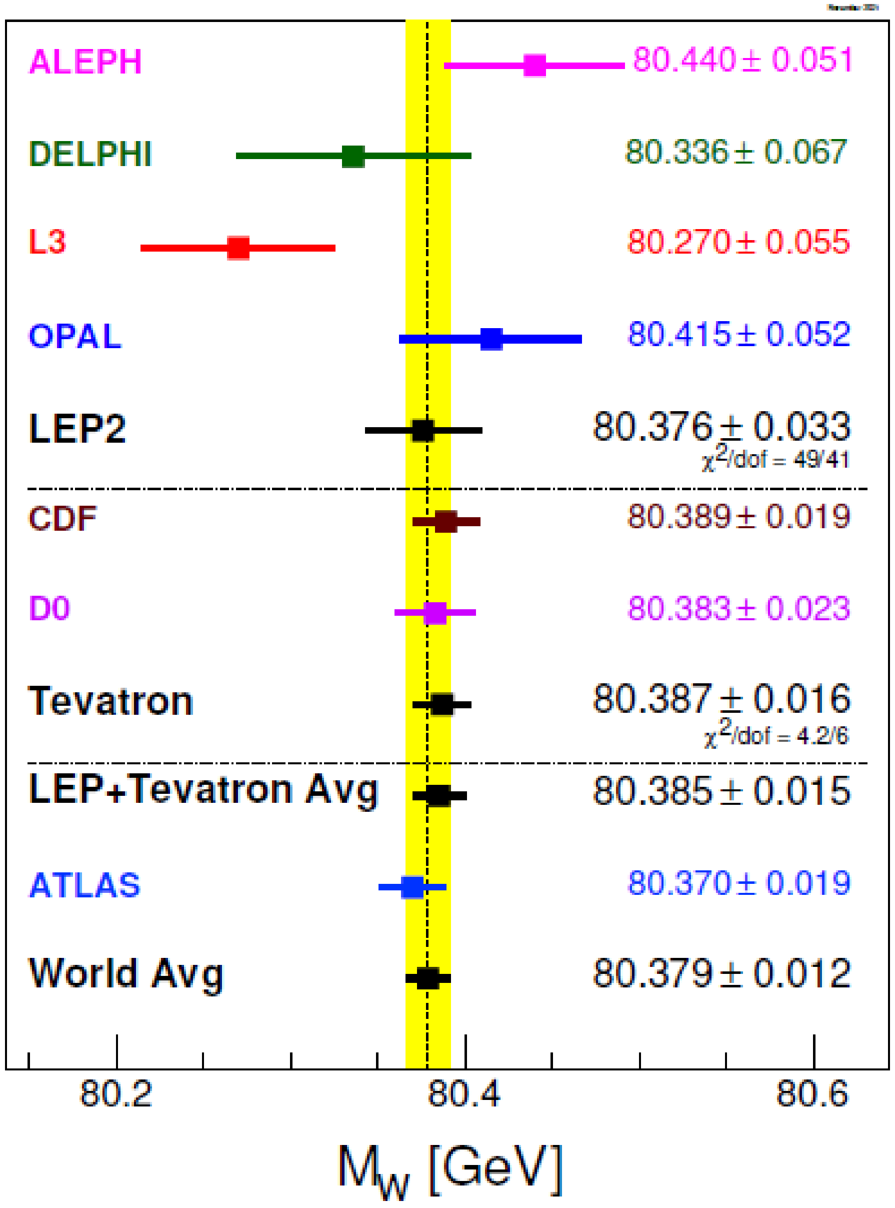
Simplest example of a W mediated decay



A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

W-mass
data till
2021

Pigeons
living
peacefully



SM fit
excluding W-
mass data →
80.356±0.006

within 2σ of
experimental
W-mass avg.

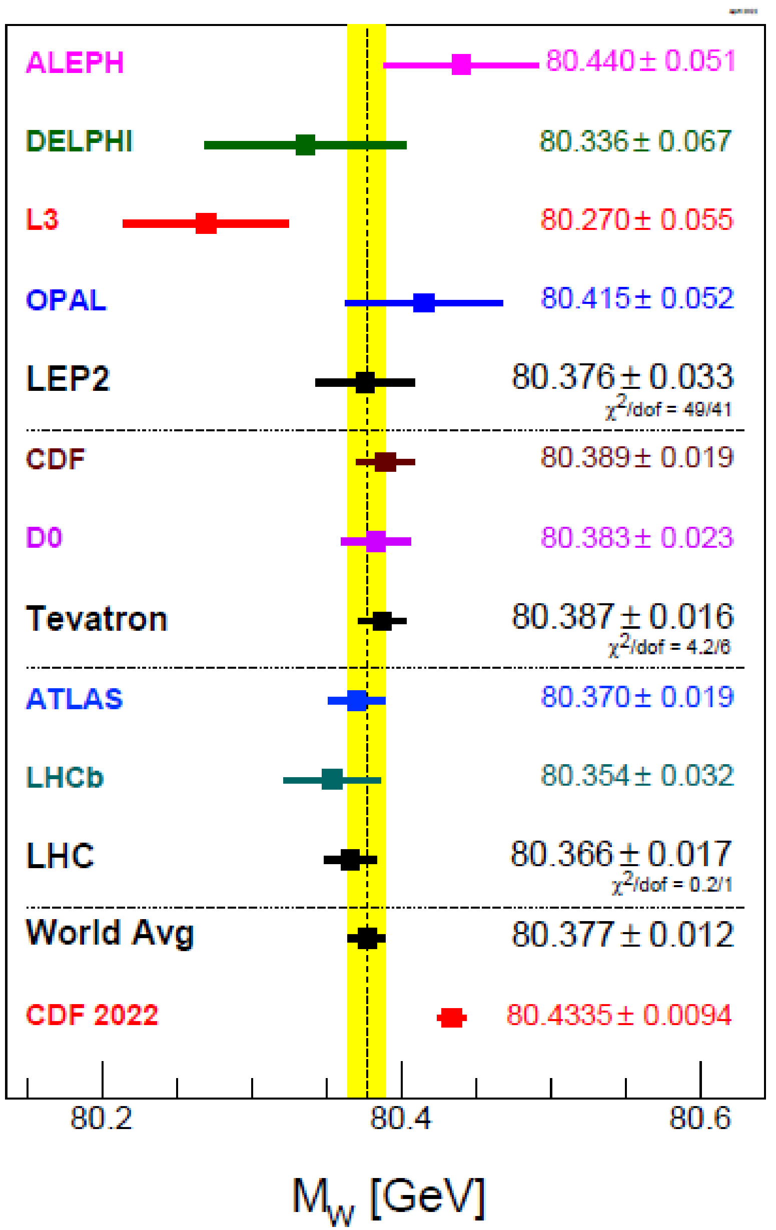
SM fit to all relevant data excluding W-mass yields 80.356±0.006

The entry of the CAT

April 2022 CDF paper with FULL data set (4M evts).

M_W = 80.4335 ± 0.0094
differs by around 7σ from the SM prediction, and by around 4σ from the earlier world average.

Note that a 5σ difference is sufficient to establish NEW PHYSICS



History: Discovery of the W and Z particles

- W, Z are the carriers of the weak force, W responsible for the “charged current” and Z for the “neutral current”. Z was a prediction of the Unified EW theory.
- 1973: Indirect discovery of the Z as a neutral current in the CERN experiment using the Gargamelle bubble chamber with a neutrino beam
- [Rumoured that Nobel was not given for this discovery as one of the guiding spirits behind the experiment, Paul Musset, had died and the Nobel can’t be given posthumously].

Volume 46B, number 1 PHYSICS LETTERS 3 September 1973

OBSERVATION OF NEUTRINO-LIKE INTERACTIONS WITHOUT MUON OR ELECTRON IN THE GARGAMELLE NEUTRINO EXPERIMENT

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Received 25 July 1973

Events induced by neutral particles and producing hadrons, but no muon or electron, have been observed in the CERN neutrino experiment. These events behave as expected if they arise from neutral current induced processes. The rates relative to the corresponding charged current processes are evaluated.

Hunt for the W and Z: S pbar p S at CERN

- Having indirect evidence of the Z in 1973, CERN designed and constructed an anti-proton proton collider (Super pbar p Synchrotron) with sufficient c.m. energy (540 GeV, later 630 GeV) to directly produce the W and Z particles
- UA1 and UA2 (U = Underground) Collaborations led by Carlo Rubbia and Pierre Darriulat
- The discovery detection signature was the decay $W^{\pm} \rightarrow e^{\pm}\nu$

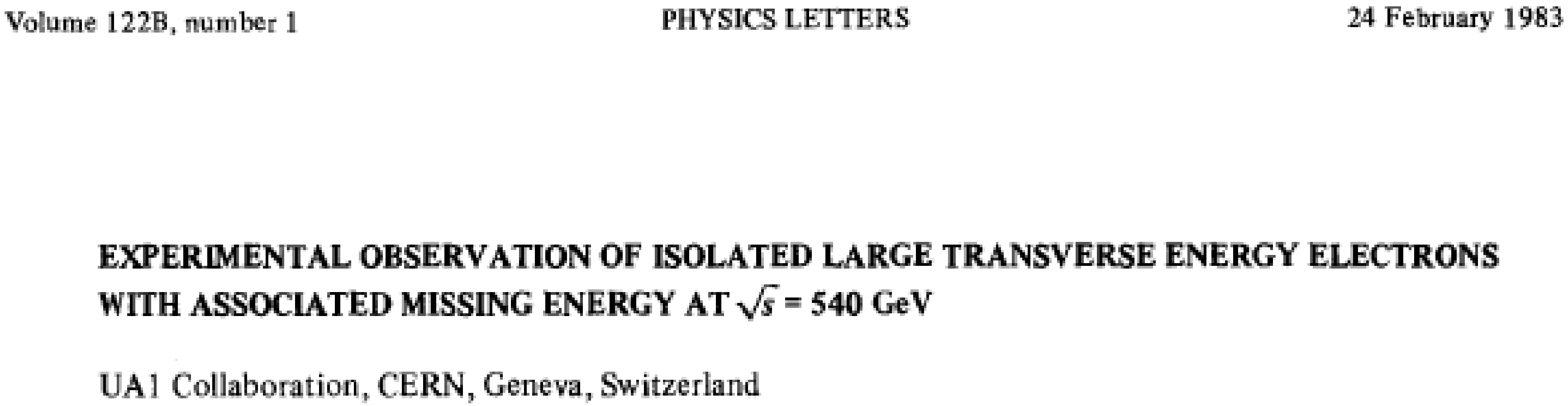
As M_W is ≈80 GeV, the $e^{\pm}$ is easily tagged by it's high transverse momentum, p_T or E_T.

W decay modes

- W → eν or μν or τν leptonic decays
- The leptonic decays provide a “clean” signature, a high transverse momentum lepton; favoured at hadron colliders

- W → u d-bar or c s-bar hadronic decays

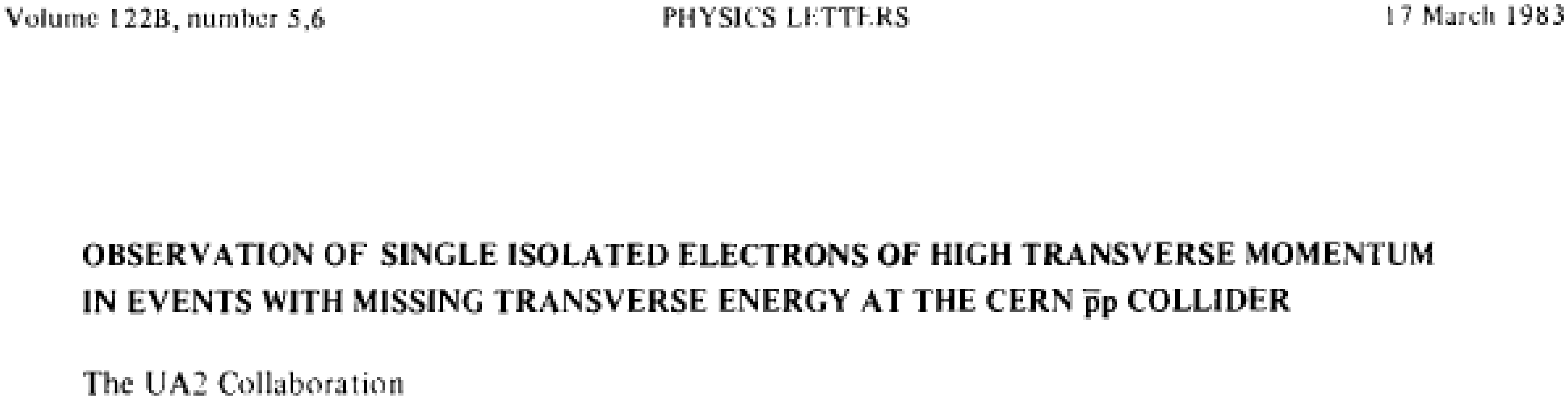
- Both used effectively at LEP II as beams were e^+e^- of precisely known energy so energy-momentum conservation can be used to reconstruct the W decays



Volume 122B, number 1 PHYSICS LETTERS 24 February 1983

EXPERIMENTAL OBSERVATION OF ISOLATED LARGE TRANSVERSE ENERGY ELECTRONS WITH ASSOCIATED MISSING ENERGY AT $\sqrt{s}$ = 540 GeV

UA1 Collaboration, CERN, Geneva, Switzerland



Volume 122B, number 5,6 PHYSICS LETTERS 17 March 1983

OBSERVATION OF SINGLE ISOLATED ELECTRONS OF HIGH TRANSVERSE MOMENTUM IN EVENTS WITH MISSING TRANSVERSE ENERGY AT THE CERN $\bar{p}p$ COLLIDER

The UA2 Collaboration

2 W candidate events from the UA1 paper

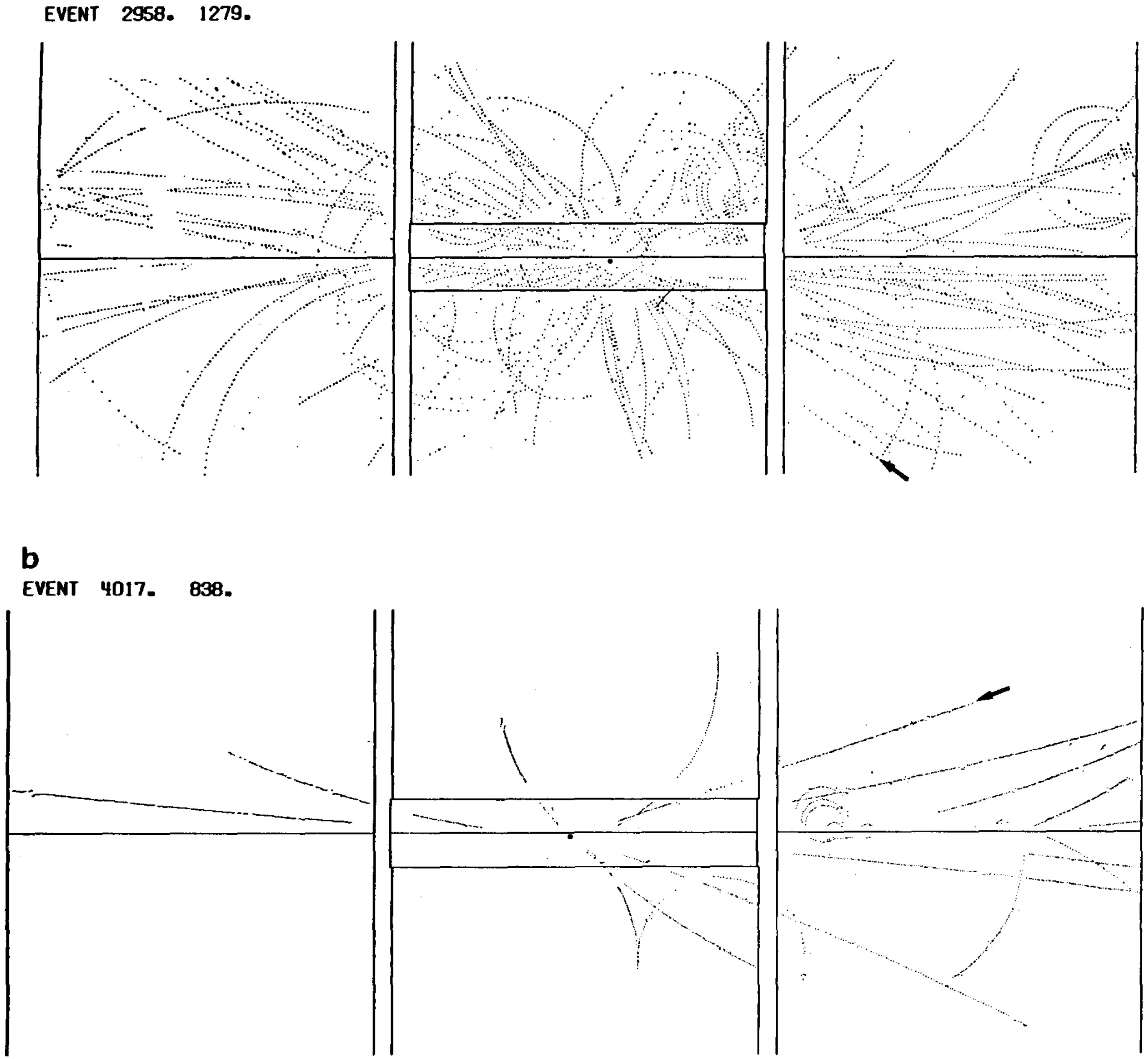


Fig. 6. The digitization from the central detector for the tracks in two of the events which have an identified, isolated, well-measured high-p_T electron: (a) high-multiplicity, 65 associated tracks; (b) low-multiplicity, 14 associated tracks.

And here are the first measurements of W-mass:

81.	± 5.	6	ARNISON	83	UA1	$E_{\rm cm}^{ee}$ = 546 GeV
80.	$^{+10.}_{-6.}$	4	BANNER	83B	UA2	Repl. by ALITTI 90B

Later the Z was also discovered by both UA1 and UA2

For precision studies of Z, W particles → LEP @ CERN
Indian Connection: TIFR in L3

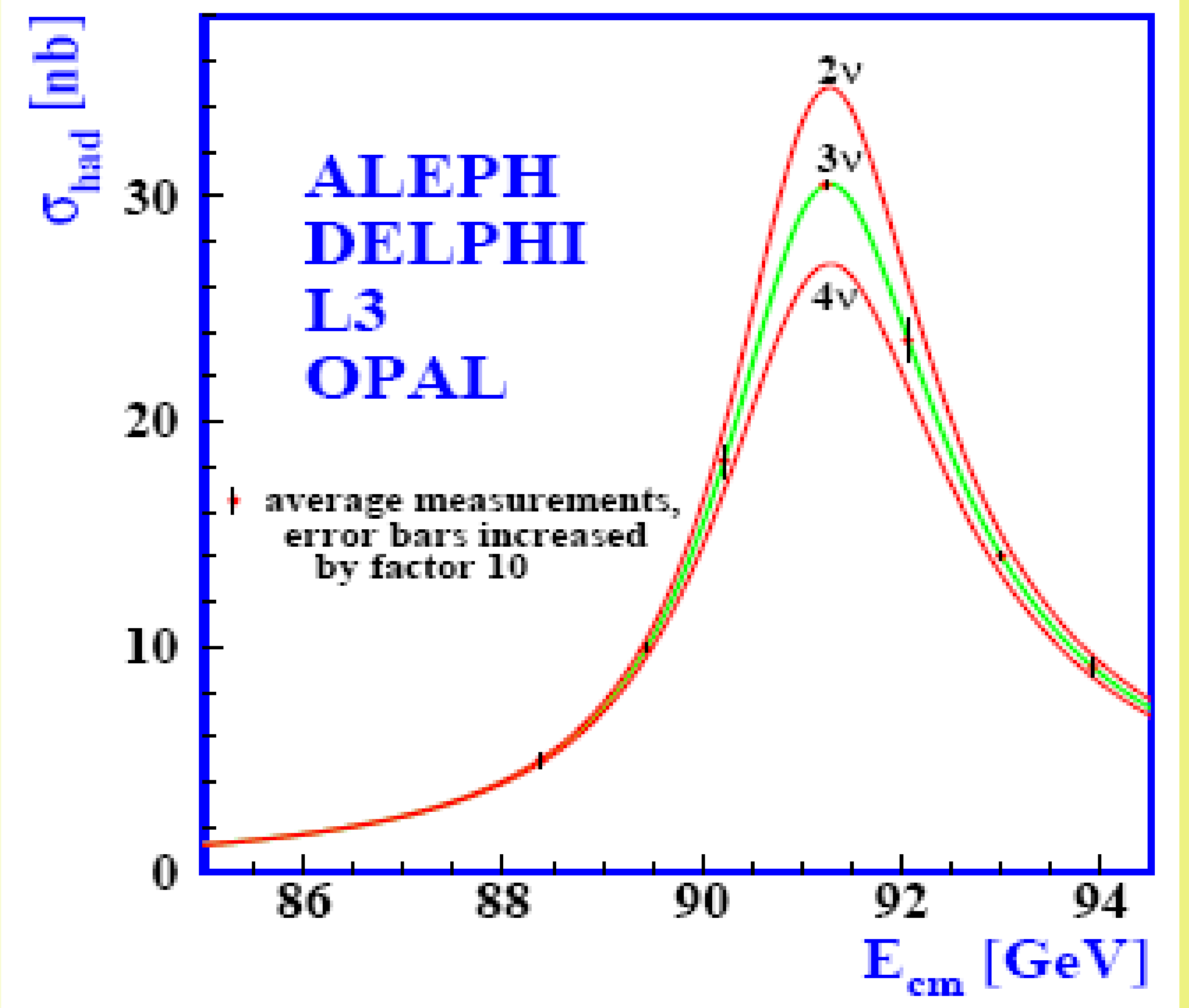
- **1983: TIFR-EHEP group joined the LEP-L3 collaboration.**
- **LEP I: 1989-96 e^+e^- collisions at C.M. energy 88 – 94 GeV for precision Z studies.**

  → fabricated brass tube proportional chambers for HCAL end-cap (with Aachen-I group)

  → Significant role in core software development

- **The group was responsible for L3 Z-lineshape fits and analysis over the entire LEP-100 period → precision determination of Z mass, widths, couplings, # of ν species…**

LEP: determination of light neutrino species (number of matter generations?)



TIFR in L3

- **Strong contributions in**
  - -- b-physics (neural net)
  - -- QCD (event shape, α_s determination)
  - -- higgs searches

- LEP II, 1996 → 2002; C.M. energy 130 – 209 GeV

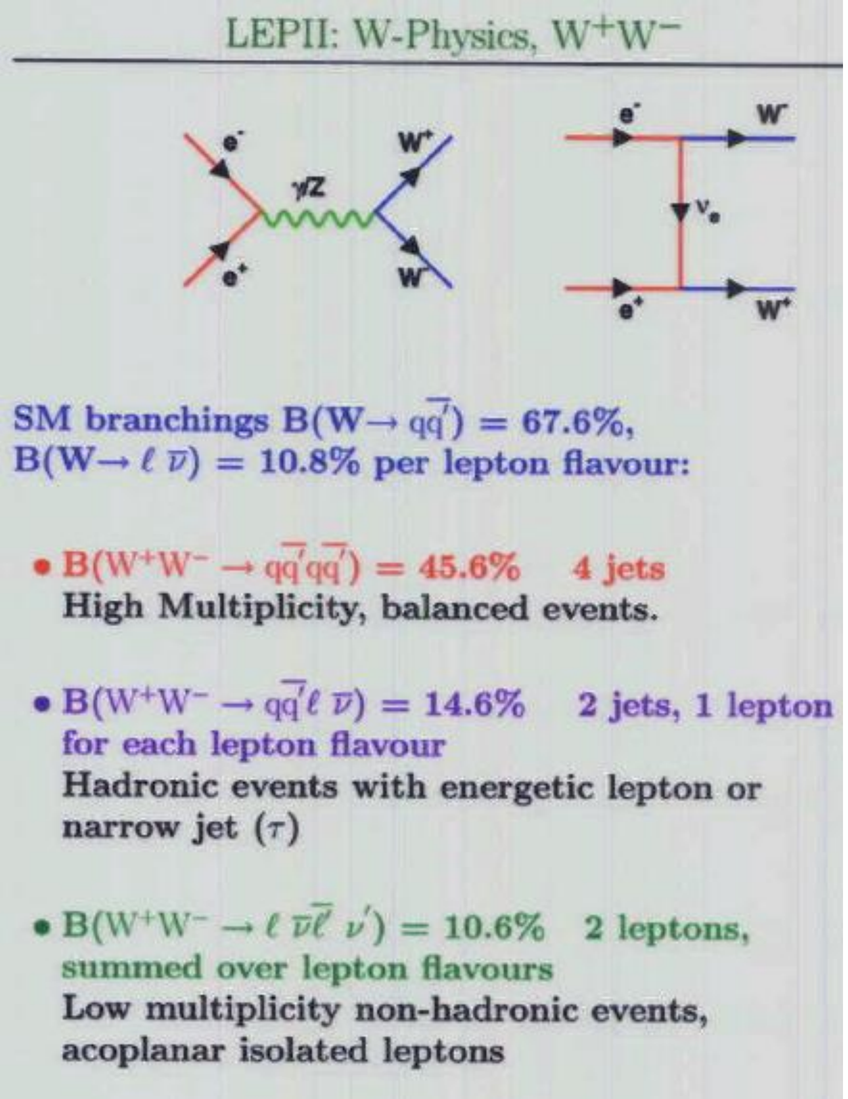
  TIFR EHEP studied channels WW →qqqq, qqeν

  W mass/width (threshold, reconstructed)

  (Ph.D.'s on W physics: T.Moulik, A.Rahman, N.Raja, +?)

  QCD, 4-jets, b-physics, SUSY/higgs searches.

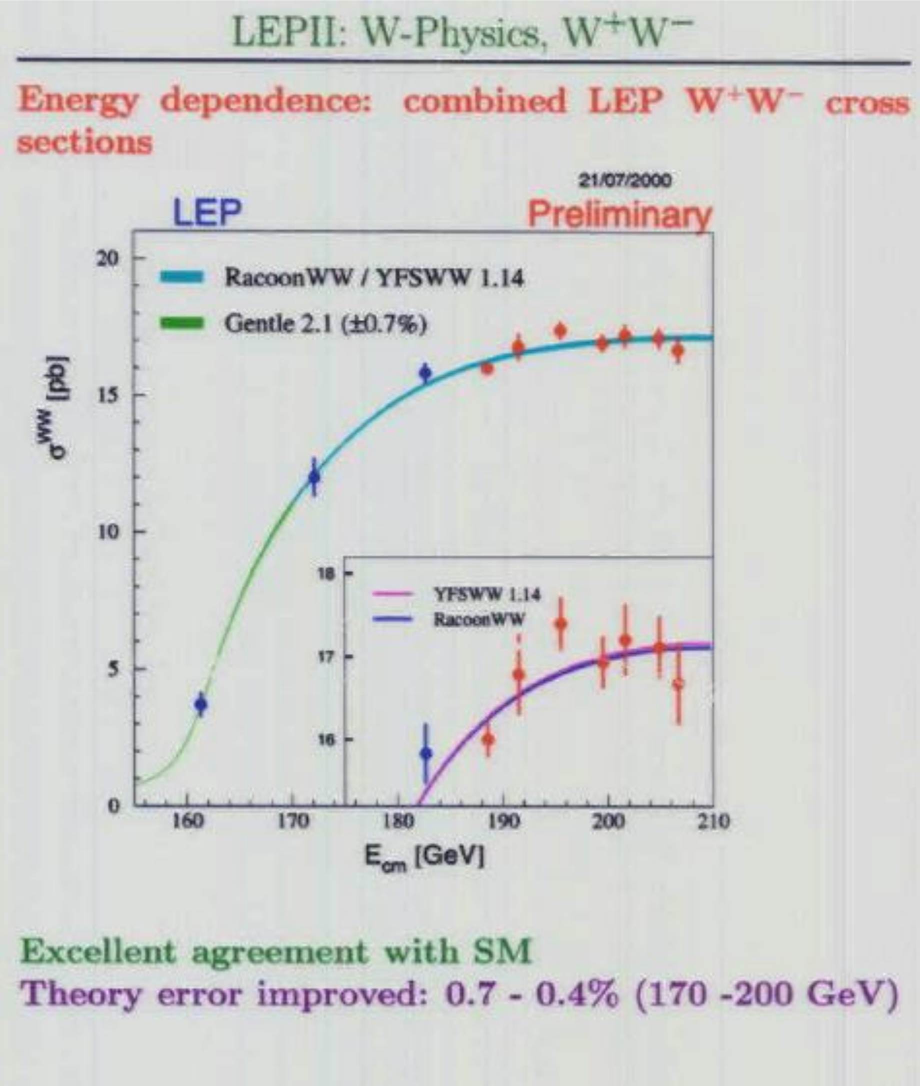
e^+e^- -> W^+W^- at LEP II



LEPII: W-Physics, W^+W^-

SM branchings $B(W\to q\bar{q}') = 67.6\%$,
$B(W\to \ell\,\bar{\nu}) = 10.8\%$ per lepton flavour:

- $B(W^+W^-\to q\bar{q}'q\bar{q}') = 45.6\%$ 4 jets
  High Multiplicity, balanced events.
- $B(W^+W^-\to q\bar{q}'\ell\,\bar{\nu}) = 14.6\%$ 2 jets, 1 lepton for each lepton flavour
  Hadronic events with energetic lepton or narrow jet (τ)
- $B(W^+W^-\to \ell\,\bar{\nu}\bar{\ell}'\,\nu') = 10.6\%$ 2 leptons, summed over lepton flavours
  Low multiplicity non-hadronic events, acoplanar isolated leptons

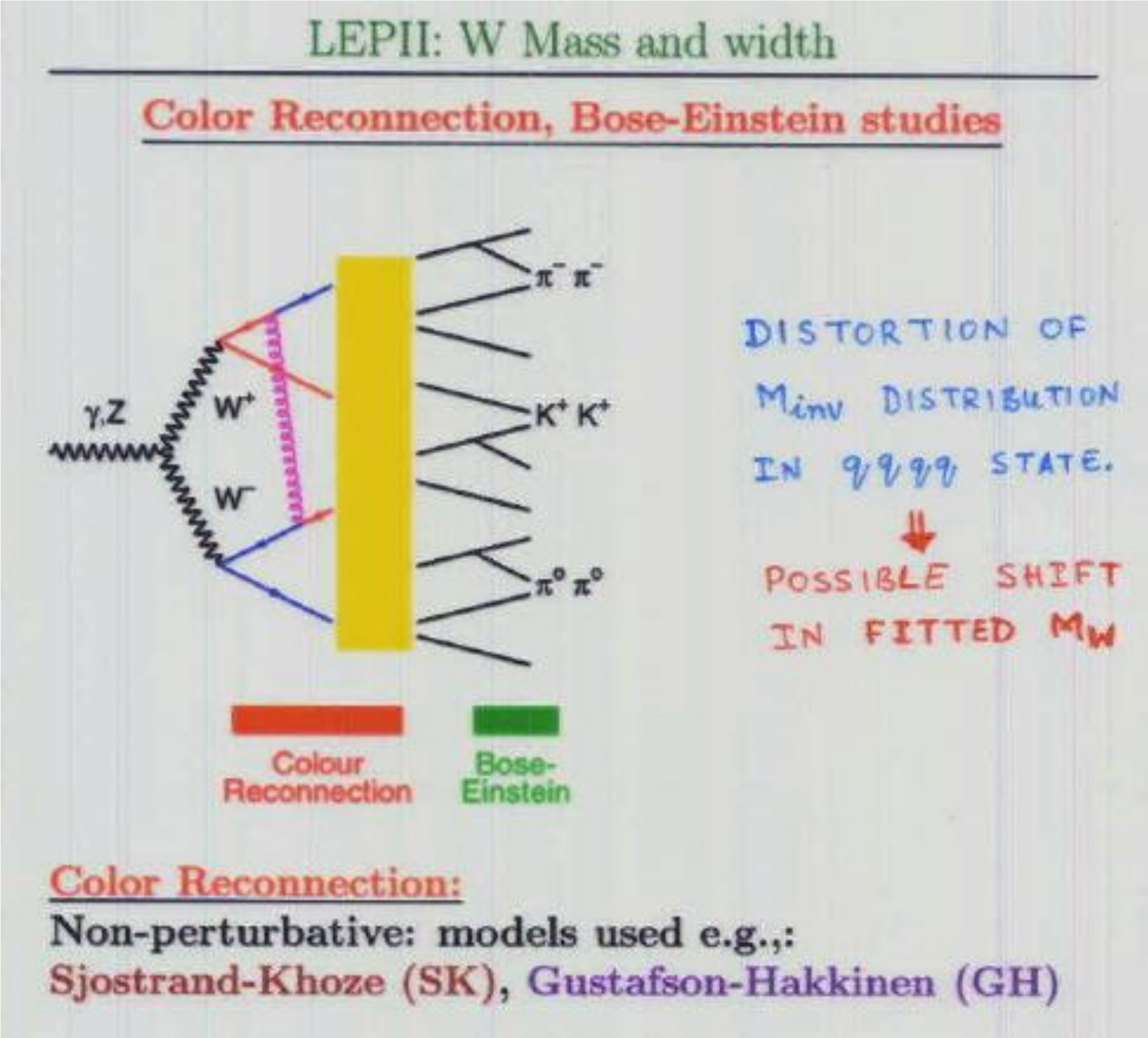


LEPII: W-Physics, W^+W^-

Energy dependence: combined LEP W^+W^- cross sections

Excellent agreement with SM
Theory error improved: 0.7 - 0.4% (170 -200 GeV)

Systematic error in LEP W-mass reconstruction.
Color Reconnection
&
Bose-Einstein effects



LEPII: W Mass and width

Color Reconnection, Bose-Einstein studies

DISTORTION OF M_{inv} DISTRIBUTION IN $qqqq$ STATE.

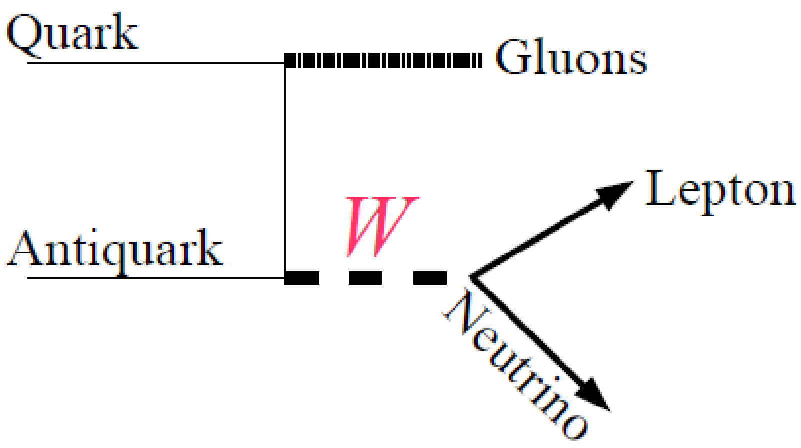
⇓

POSSIBLE SHIFT IN FITTED M_W

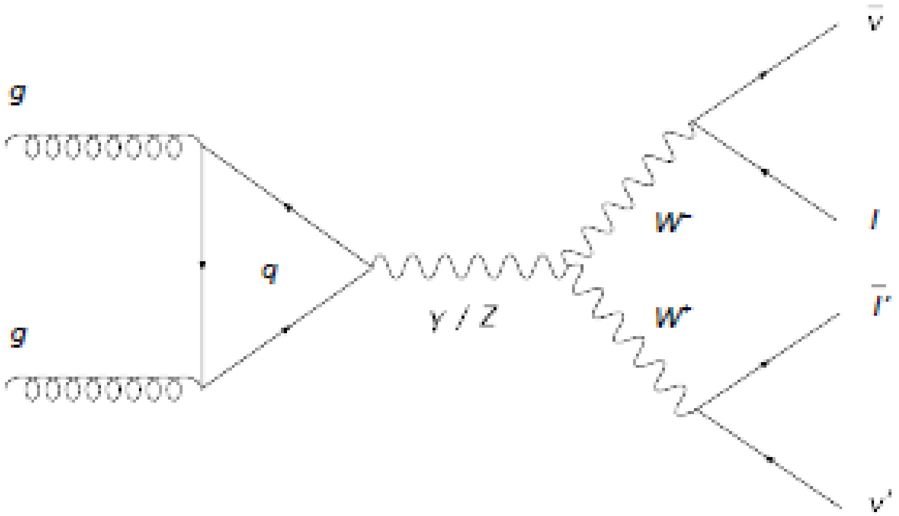
Color Reconnection:

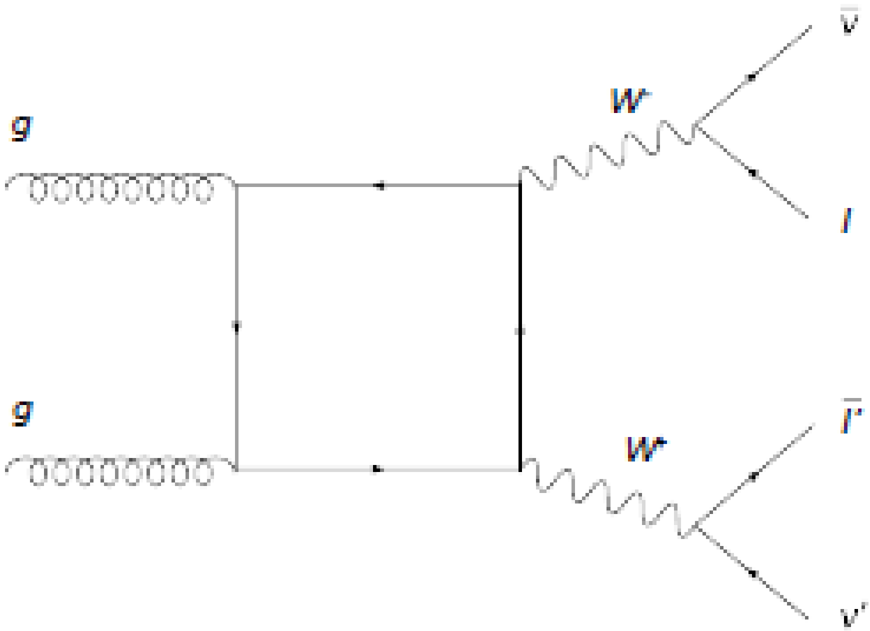
Non-perturbative: models used e.g.,:

Sjostrand-Khoze (SK), Gustafson-Hakkinen (GH)



At the Tevatron & LHC
Quark-anti quark and gluon- gluon interactions





electron-positron vs hadron collisions for W-mass

e^+e^- :

Precisely known E_{cm}. So, can use energy-momentum conservation to constrain the event-fit & reconstruct mass of W's. Even with one W decaying leptonically the decays can be reconstructed.

Hadronic collisions:

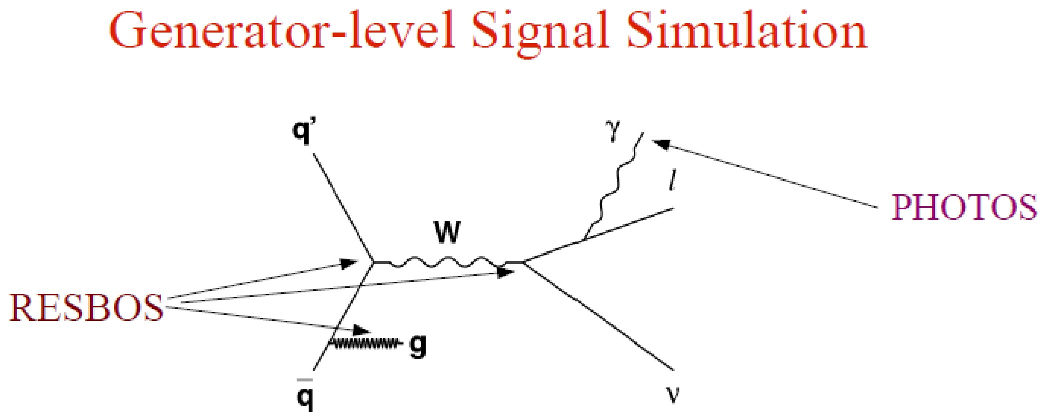
As **proton = partons (quarks/gluons)** and it's a parton-parton collision

- c.m. energy UNKNOWN, need to use PDFs etc…
- Can't balance energy or momentum; need to work ONLY with transverse momentum/energy
- One fits the **W m_T** and the **p_T** distributions of the **charged lepton & neutrino** with generated templates of varying W-mass to **determine M_W**

e^+e^- vs hadron colliders for W-mass

- Thus, many layers of complication enter the determination of W mass in hadronic interactions
- BUT, hadronic colliders have had ONE great advantage:

  statistics. LEP: all 4 experiments combined had ≈ 40,000 WW evts
- Each of D0 and CDF have millions of W events, the latest CDF paper is based upon 4 million W → e and μ.



CDF Collab *et al.*, ***Science 376***, 170-176 (2022) 8 April 2022

Left: W → μν

**Right:
W → eν**

m_T (W)

p_T (μ or e)

p_T (ν)

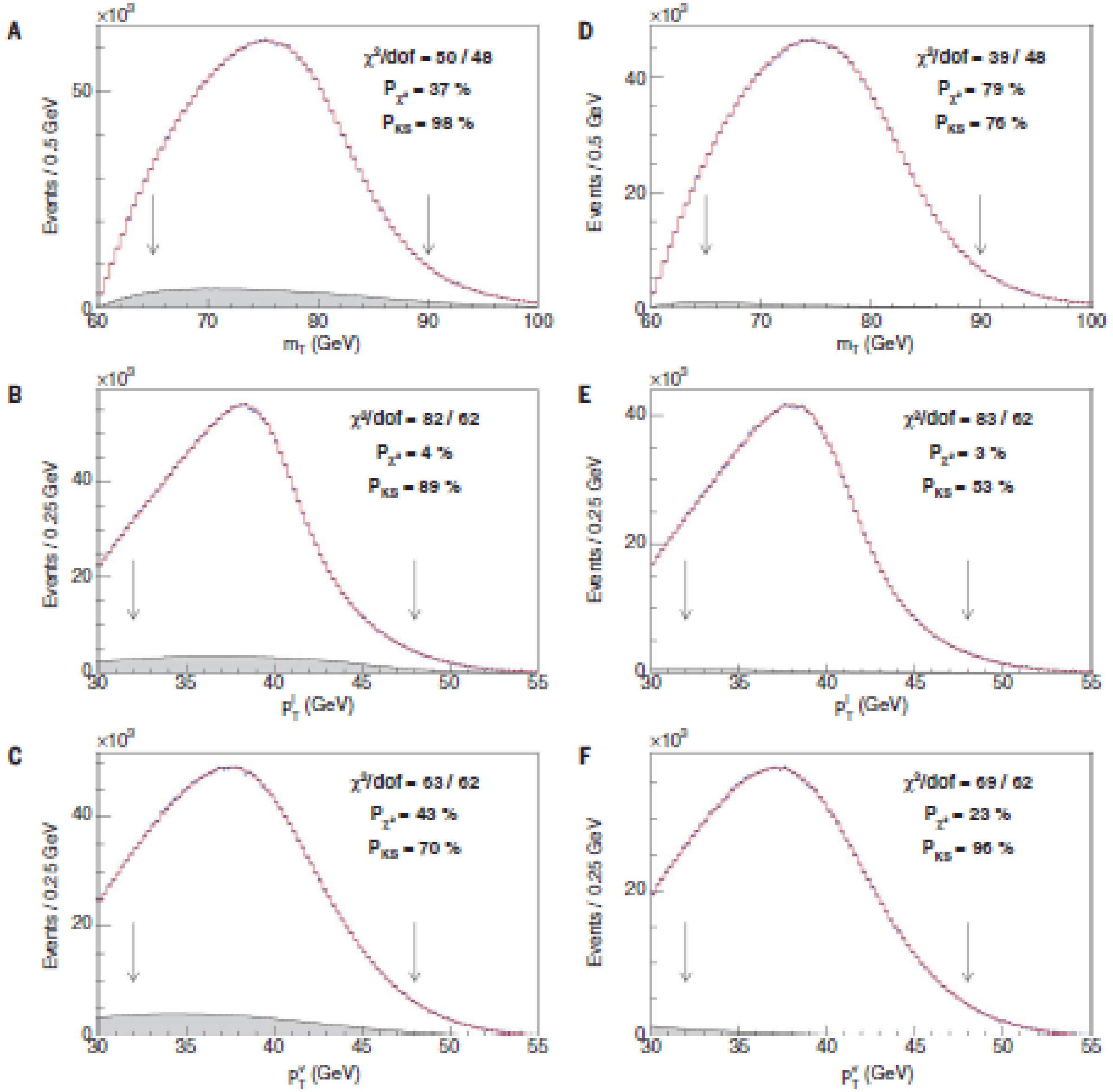


Fig. 4. Decay of the *W* boson. (**A** to **C**) Distributions for m_T (A), p_T^ℓ (B), and p_T^ν (C) for the muon channel. (**D** to **F**) Same as in (A) to (C) but for the electron channel. The data (points) and the best-fit simulation template (histogram) including backgrounds (shaded regions) are shown. The arrows indicate the fitting range.

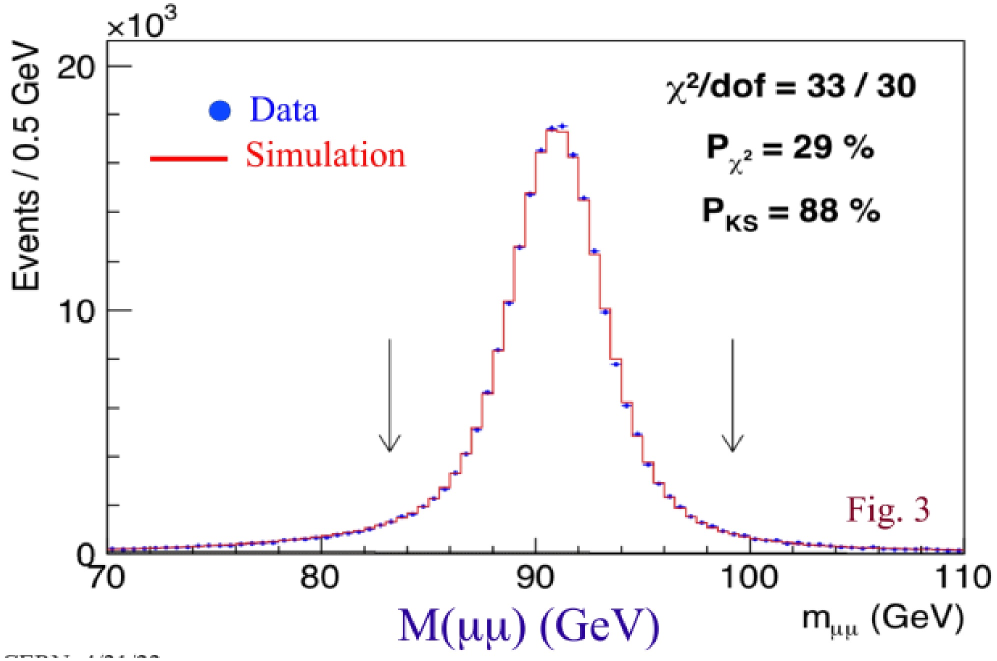
Combined electrons (3 fits): $M_W = 80424.6 \pm 13.2$ MeV, $P(\chi^2) = 19\%$

Combined muons (3 fits): $M_W = 80437.9 \pm 11.0$ MeV, $P(\chi^2) = 17\%$

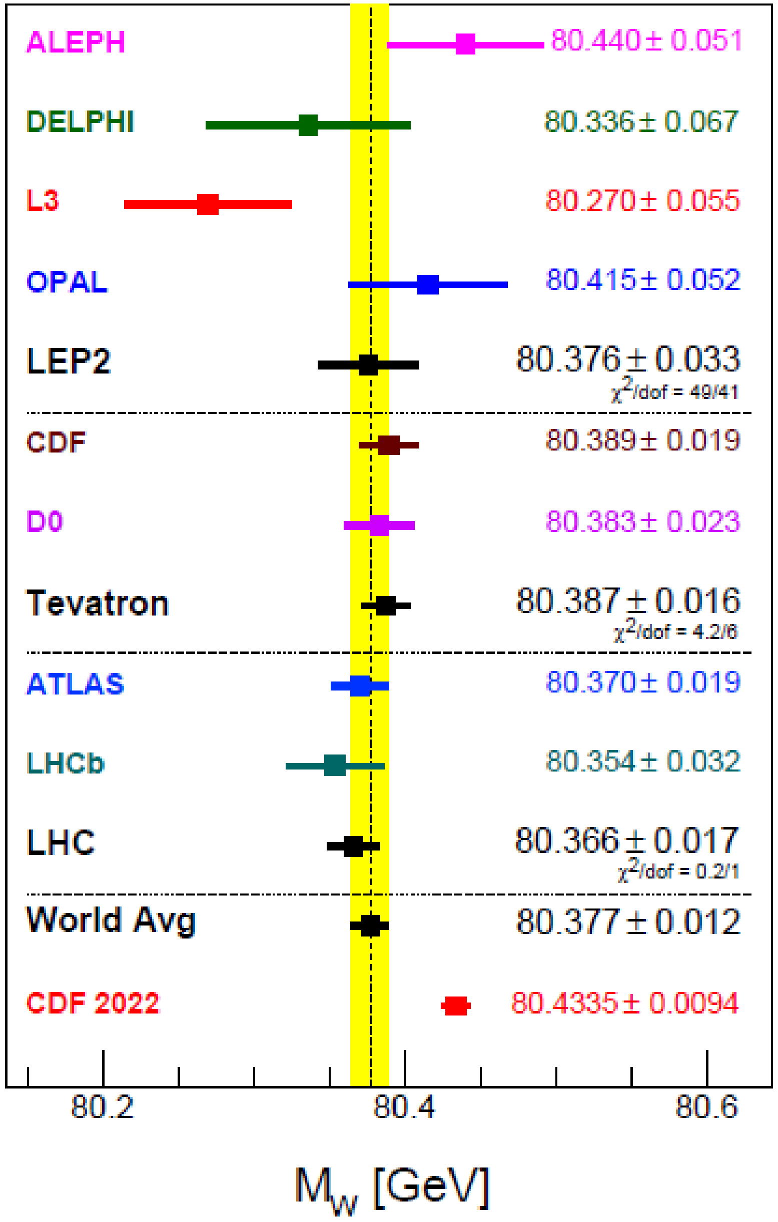
All combined (6 fits): $M_W = 80433.5 \pm 9.4$ MeV, $P(\chi^2) = 20\%$

Z→μμ Mass Cross-check & Combination

- Using the J/ψ and Υ momentum scale, performed "blinded" measurement of *Z* boson mass
  - *Z* mass consistent with PDG value (91188 MeV) (0.7σ statistical)
  - $M_Z = 91192.0 \pm 6.4_{stat} \pm 2.3_{momentum} \pm 3.1_{QED} \pm 1_{alignment}$ MeV



Whatever the complications due to energy calibration, resolutions, etc., the Z mass turns out consistent with the world average (LEP)



So, what is the current scenario? How to combine such discrepant data?

A “combination group” of physicists from CDF, D0, ATLAS, LHCb is trying to go over the various inputs that go into their W mass determinations and trying to figure out the issues.

Possible Consequences

- Suppose the new CDF value IS closer to the truth?
- It would imply new physics… already theorists are busy speculating which BSM models and which particles may be contributing to this “heavier than expected” W.
- BUT, then what consequences would THAT have for the other SM parameters? Could that be accommodated?
- Early stages yet, may take many months or longer to disentangle the issue. **IMPORTANT EXPECTATION: Mw from CMS! And improved Mw from ATLAS and LHCb…. Let’s see…**

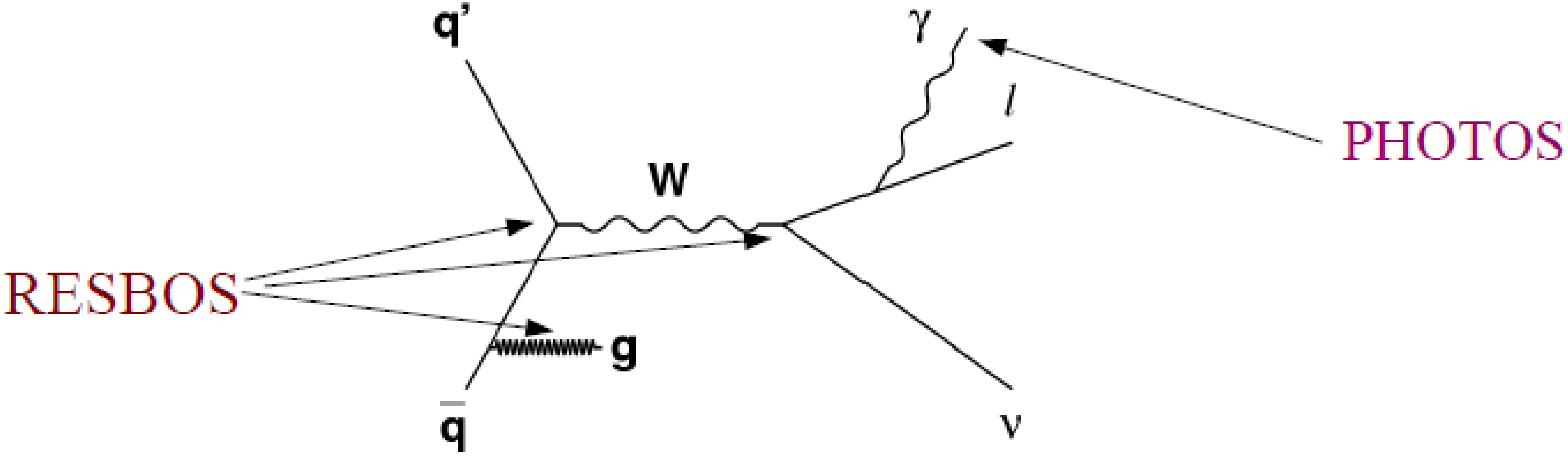
Will the CAT scatter the pigeons?
Or will the pigeons scare away the CAT?

Looking forward to the future!!

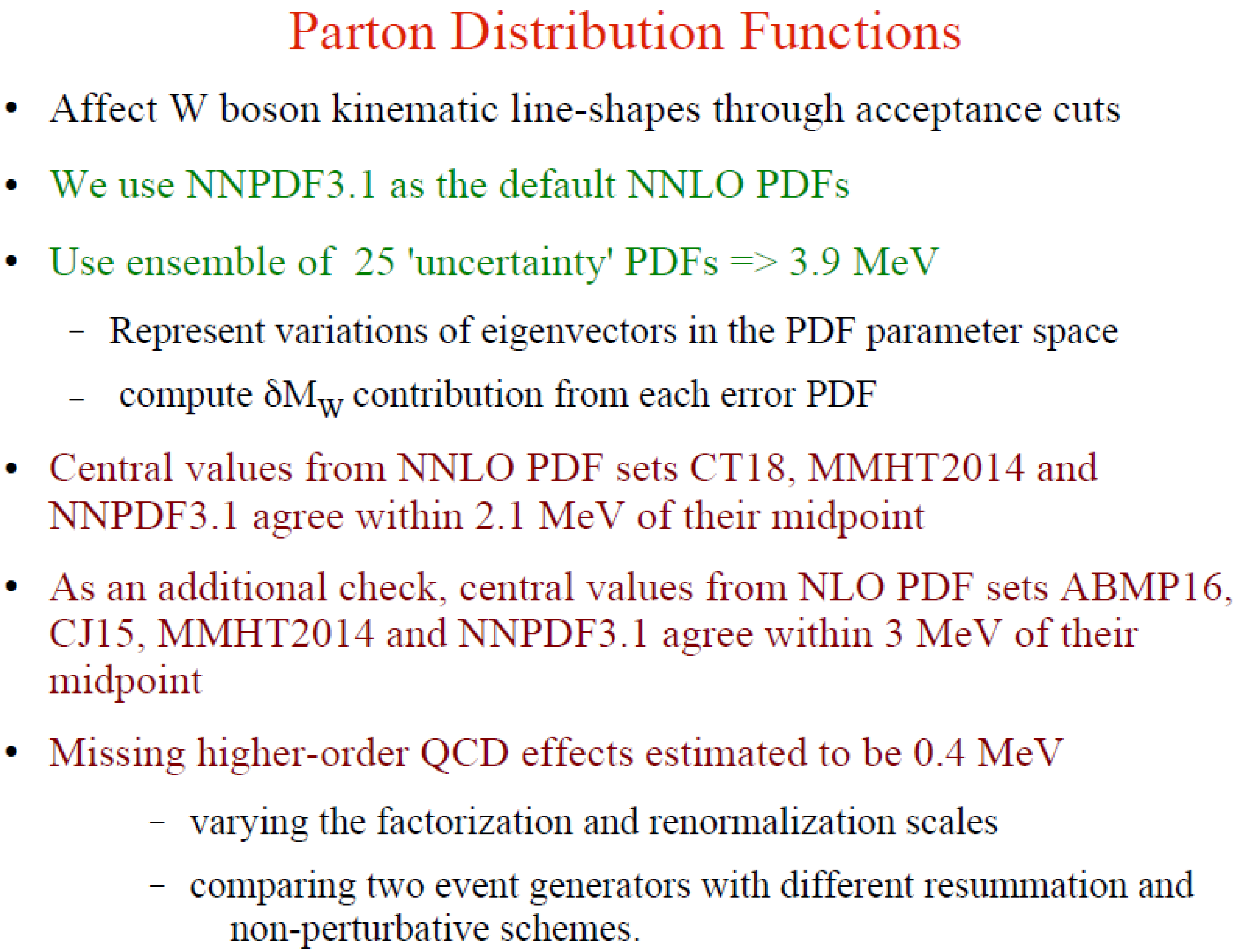
THANK YOU!

Backup – Resummation program RESBOS

Generator-level Signal Simulation



Backup



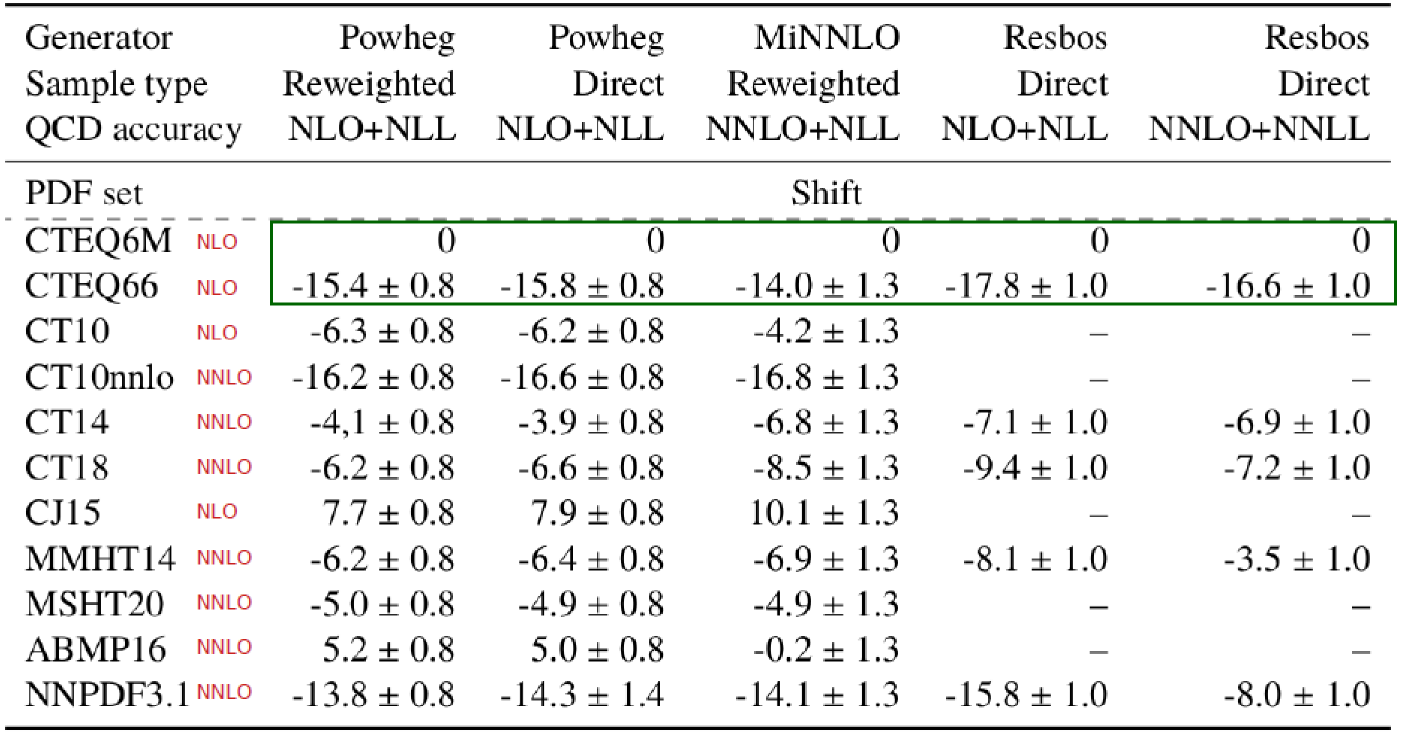
Parton Distribution Functions

- Affect W boson kinematic line-shapes through acceptance cuts
- We use NNPDF3.1 as the default NNLO PDFs
- Use ensemble of 25 'uncertainty' PDFs => 3.9 MeV
  - Represent variations of eigenvectors in the PDF parameter space
  - compute δM_W contribution from each error PDF
- Central values from NNLO PDF sets CT18, MMHT2014 and NNPDF3.1 agree within 2.1 MeV of their midpoint
- As an additional check, central values from NLO PDF sets ABMP16, CJ15, MMHT2014 and NNPDF3.1 agree within 3 MeV of their midpoint
- Missing higher-order QCD effects estimated to be 0.4 MeV
  - varying the factorization and renormalization scales
  - comparing two event generators with different resummation and non-perturbative schemes.

Backup

PDF extrapolations (including generator dependence)

- Example, for CDF (defines reference PDF):



Generator		Powheg	Powheg	MiNNLO	Resbos	Resbos
Sample type		Reweighted	Direct	Reweighted	Direct	Direct
QCD accuracy		NLO+NLL	NLO+NLL	NNLO+NLL	NLO+NLL	NNLO+NNLL
PDF set		Shift				
CTEQ6M	NLO	0	0	0	0	0
CTEQ66	NLO	-15.4 ± 0.8	-15.8 ± 0.8	-14.0 ± 1.3	-17.8 ± 1.0	-16.6 ± 1.0
CT10	NLO	-6.3 ± 0.8	-6.2 ± 0.8	-4.2 ± 1.3	–	–
CT10nnlo	NNLO	-16.2 ± 0.8	-16.6 ± 0.8	-16.8 ± 1.3	–	–
CT14	NNLO	-4,1 ± 0.8	-3.9 ± 0.8	-6.8 ± 1.3	-7.1 ± 1.0	-6.9 ± 1.0
CT18	NNLO	-6.2 ± 0.8	-6.6 ± 0.8	-8.5 ± 1.3	-9.4 ± 1.0	-7.2 ± 1.0
CJ15	NLO	7.7 ± 0.8	7.9 ± 0.8	10.1 ± 1.3	–	–
MMHT14	NNLO	-6.2 ± 0.8	-6.4 ± 0.8	-6.9 ± 1.3	-8.1 ± 1.0	-3.5 ± 1.0
MSHT20	NNLO	-5.0 ± 0.8	-4.9 ± 0.8	-4.9 ± 1.3	–	–
ABMP16	NNLO	5.2 ± 0.8	5.0 ± 0.8	-0.2 ± 1.3	–	–
NNPDF3.1	NNLO	-13.8 ± 0.8	-14.3 ± 1.4	-14.1 ± 1.3	-15.8 ± 1.0	-8.0 ± 1.0

→ Significant difference between CTEQ6M and CTEQ6.6 (not accounted for this far)