Celebration for retirement of Kirk McDonald
Princeton University, 17 June 2019

Memories and remarks about three moments of my professional career:

- Experiment E615 at Fermilab
  (the experiment of my Ph.D. thesis, Kirk was my advisor)
- Space charge in ionization detectors
- Muon pairs rare decays in B physics today

Sandro Palestini

Part 1: Before E615: the results of E444 on the photon polarization

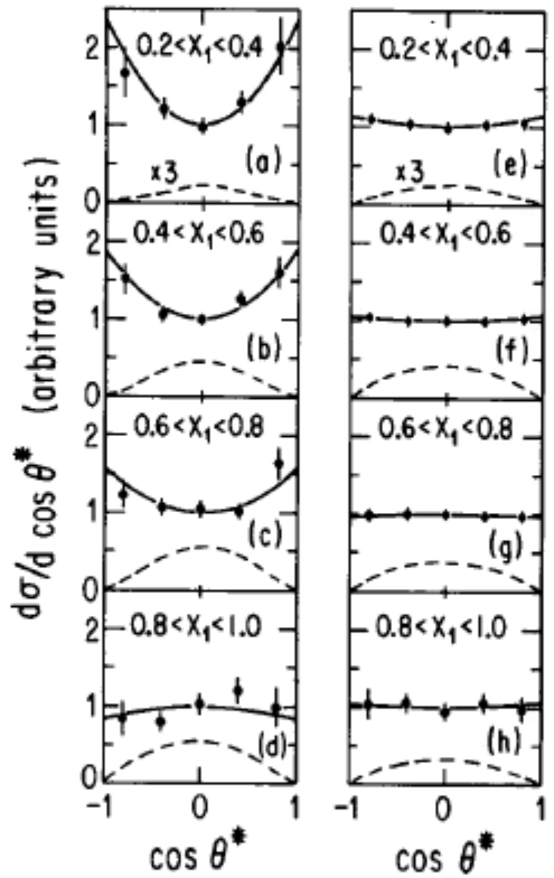


FIG. 1. $d\sigma/d\cos\theta^*$ in the t-channel helicity frame for various x_1 intervals. (a)–(d) Results for the mass continuum with $M > 4$ GeV; (e)–(h) results for the J/ψ resonance in the same x_1 intervals. Data are integrated over

Angular distribution of muon pairs from E444 (1979)
PRL 43, 1219 (1979)

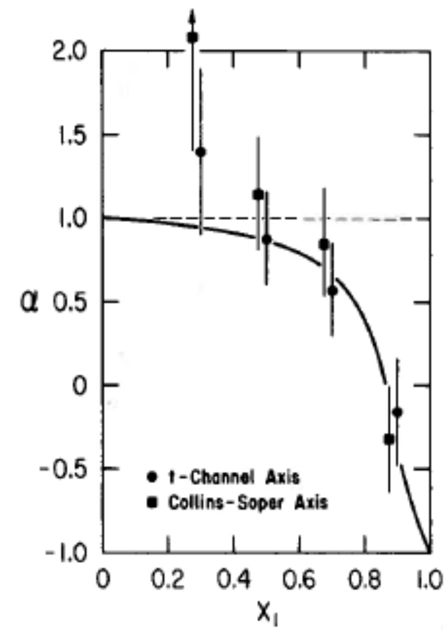
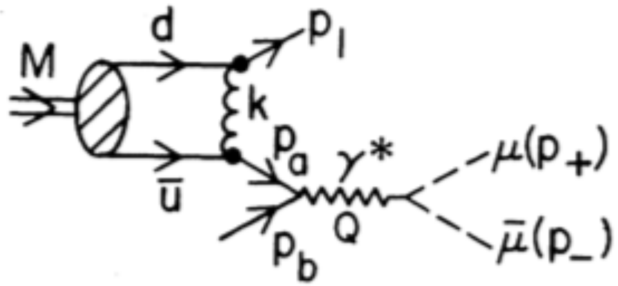


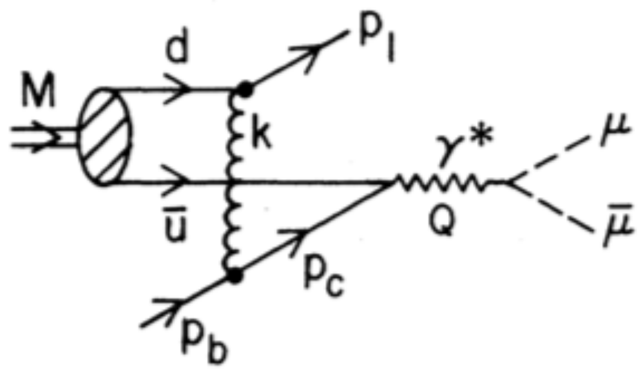
FIG. 2. The dependence of α on x_1 for data with $M > 4$ GeV. The dashed line is the expected result for the naive Drell-Yan model. The solid curve is the QCD prediction of Berger and Brodsky (Ref. 8).

Higher-twist effects prediction at large x_F



Berger and Brodsky, PRL42, 940 (1979):

- longitudinal photon polarization as x_π (or x_F) -> 1
- higher-twist term



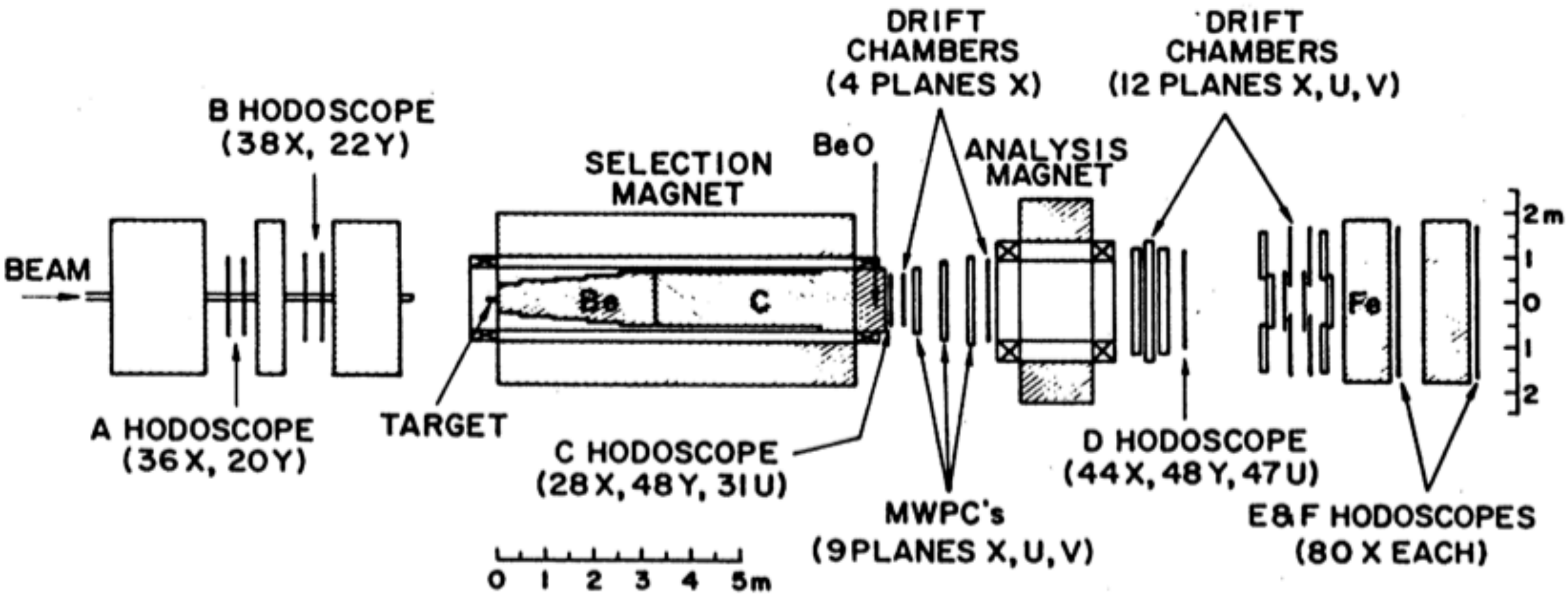
$$d\sigma \propto (1-x)^2(1+\cos^2\theta) + \frac{4}{9}(\langle k_T^2\rangle/Q^2)\sin^2\theta$$

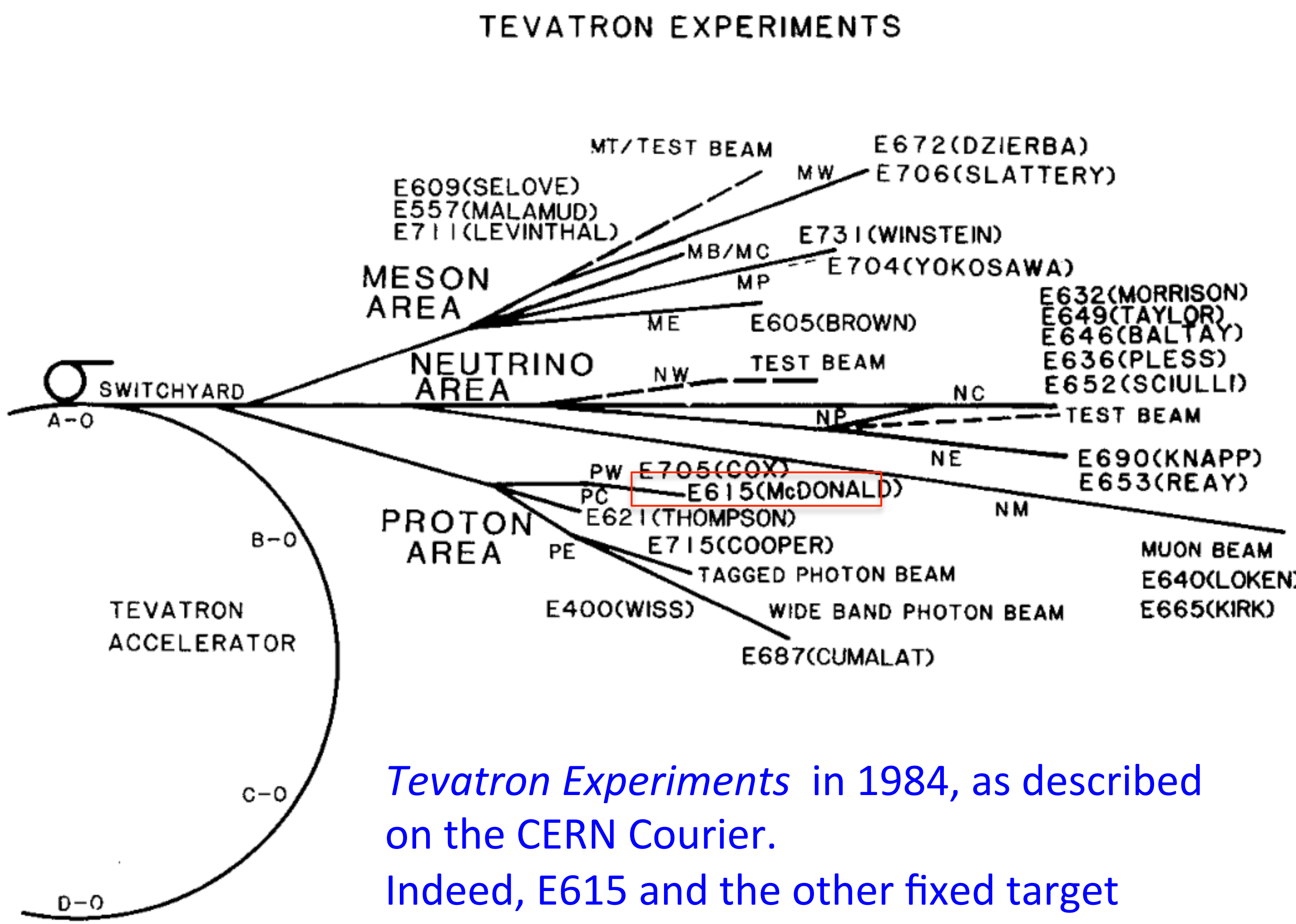
E444 supported the prediction for the longitudinal photon polarization.

The observation of transverse polarization, together the comparison of the dimuon production for different interacting hadrons, had contributed to the success of the Drell-Yan model (annihilation of *free* quark and antiquark, with helicity conservation and transverse polarization of the virtual photon).
The higher-twist effect is a step beyond the simplest picture.

Experiment Fermilab E615

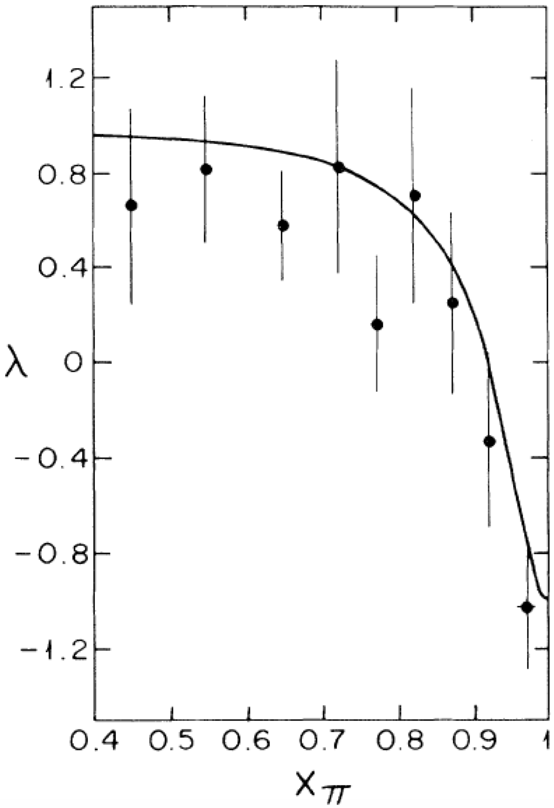
E615 :   U of Chicago, Iowa SU, Princeton
π-N interactions, high intensity, high x_F coverage.
Proton West area of Fermilab
Data collected in 1982 and 1983-1984, with 80 and 250 GeV pion beams.

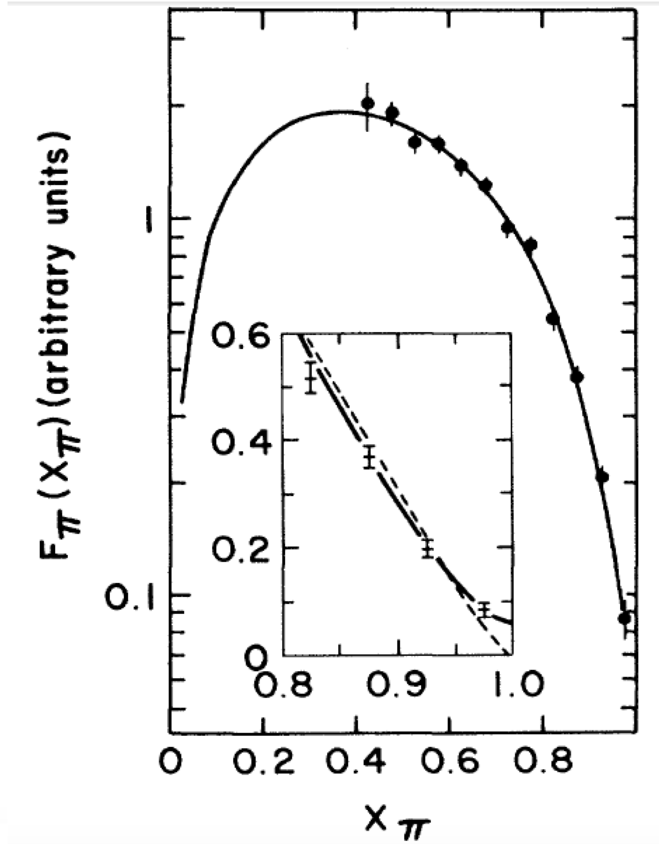


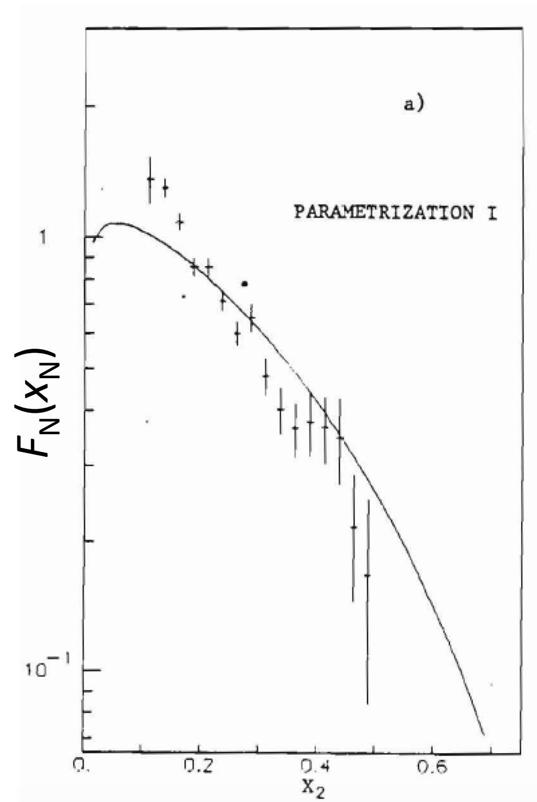


Tevatron Experiments in 1984, as described on the CERN Courier.
Indeed, E615 and the other fixed target experiments were the first user of the 1 TeV accelerator.

CERN Courier, May 1984







The nucleon structure function does not look like the one observed in DIS

Results with 80 GeV pion beam (M > 4 GeV) :

$$F_\pi(x_\pi) \propto x_\pi^\alpha \left[(1-x_\pi)^\beta + \gamma\right]$$

Fit	α	β	γ	χ^2/d.o.f.
a	0.05 ± 0.54	1.12 ± 0.18	0, fixed	138/126
b	0.92 ± 0.38	1.59 ± 0.18	0.0060 ± 0.0016	130/125
c	0.4, fixed	1.37 ± 0.07	0.0072 ± 0.0021	132/126
d	1.58 ± 0.35	1.72 ± 0.16	0.0049 ± 0.0012	192/140

PRL 55, 2649 (1985)

Pion Structure as Observed in the Reaction $\pi^- N \rightarrow \mu^+ \mu^- X$ at 80 GeV/c

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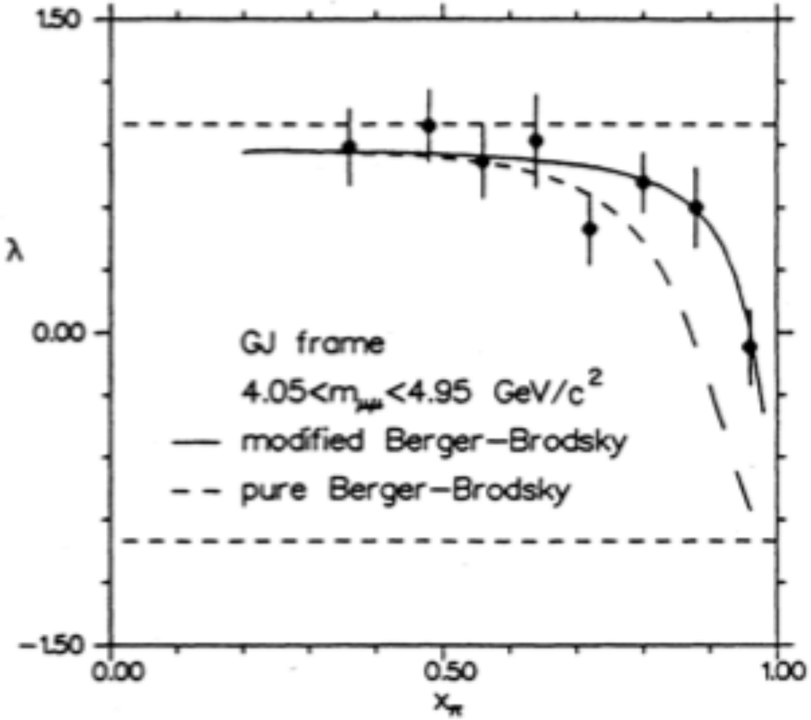
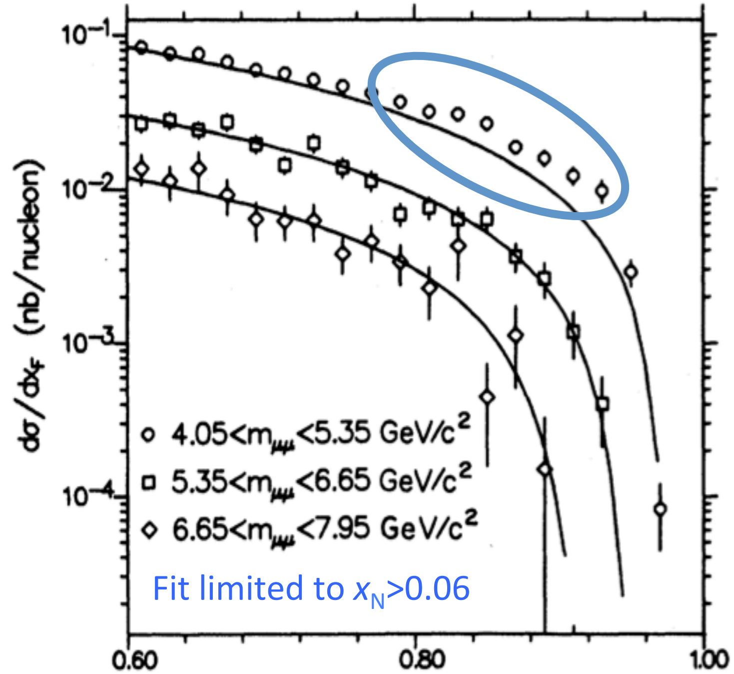
(Received 19 September 1985)

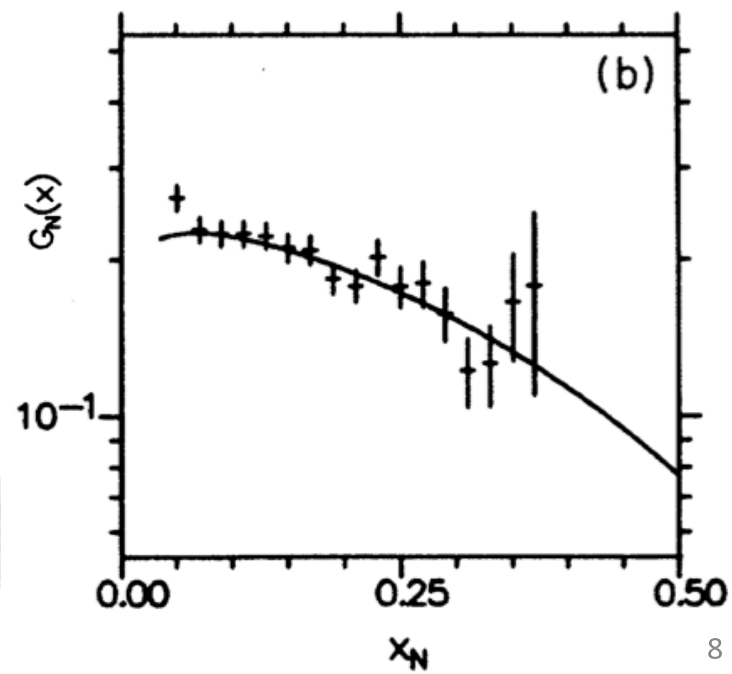
Some comments here about the collaboration and the people:

- *Everybody was generously committed, available and friendly*
- *Dining-out, or spending the free time together was part of the collaboration life - this covers Princeton as well as Chicago and Iowa people*
- *Kirk in particular was excellent in caring also about the life beyond physics and the experiment for me and Cristina (movies, dinners in special restaurants, jazz music in South Chicago, etc.). Cristina is presenting more memories about that.*





The larger sample of data collected at **250 GeV** (M > 4.05 GeV) confirmed the higher-twist terms, but the effect appeared more clearly limited to the **lowest range in dimuon mass, or nucleon x_N.**
PR D 39, 92 (1989)



$\alpha = 0.59 \pm 0.03$

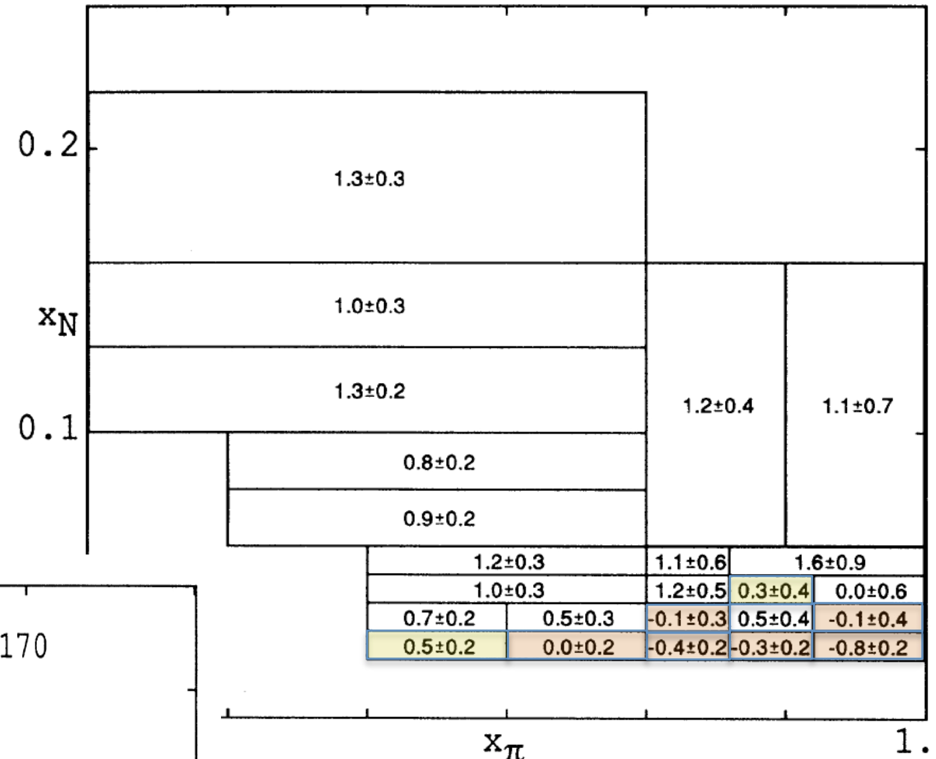
$\beta = 1.25 \pm 0.03$

$\gamma = 1.31 \pm 0.11$

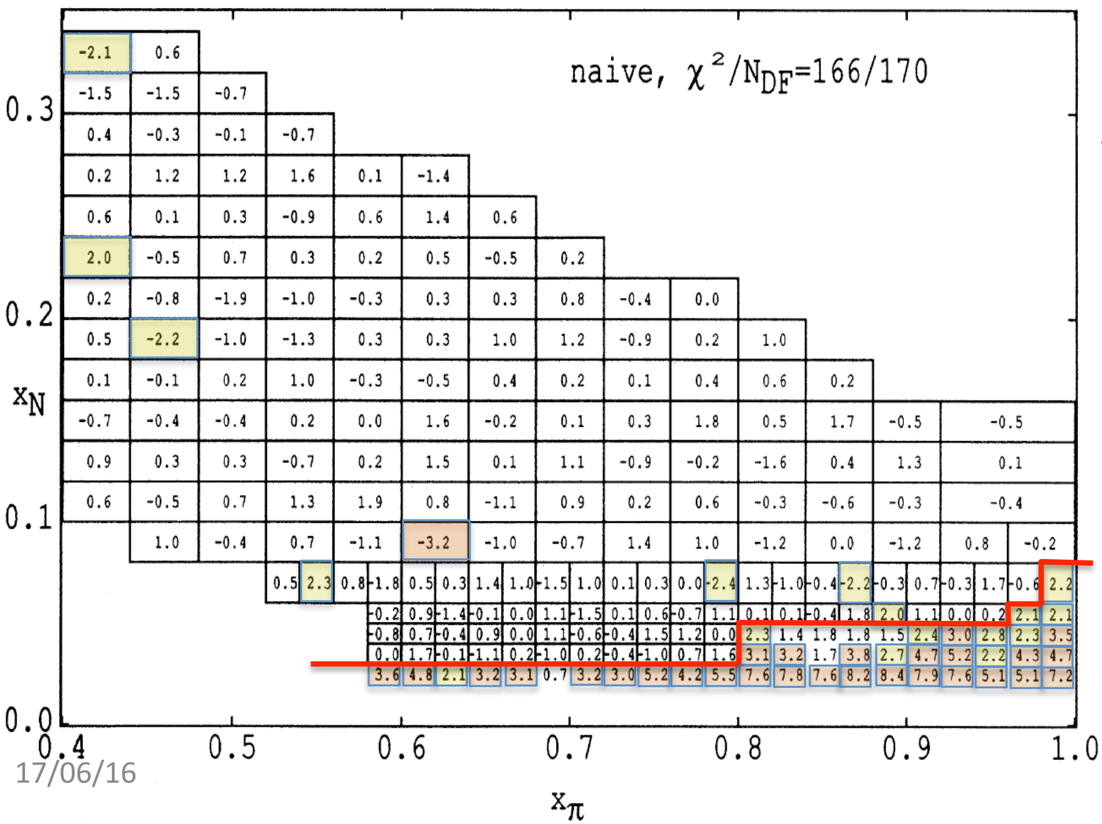
$$F^{v}_{\pi}(x_{\pi}) = A^{v}_{\pi}\left[x^{\alpha}_{\pi}(1-x_{\pi})^{\beta} + \gamma\frac{2x^{2}_{\pi}}{9m^{2}_{\mu\mu}}\right]$$

Finally, the situation was further clarified with an analysis extending to ***M* > 3.0 GeV**, with the subtraction of the J/psi, psi(2S) contributions. Higher twist effects:

- $1/M^4$ term in F_π
- longitudinal component in the photon polarization for $x_\pi > 0.6 - 0.7$, $x_N < 0.5$
- Underlying F_π in agreement with DIS



Fit to the λ parameter in the muon angular distribution.



Residuals between data and simplified fit to $d^2\sigma/dx_N dx_\pi$, performed in the region excluding lowest x_N and high x_π bins.

PRD 44, 1909 (1991)

VOLUME 56, NUMBER 10 PHYSICAL REVIEW LETTERS 10 MARCH 1986

Upper Limits on the Decay $D^0 \to \mu^+\mu^-$ and on D^0-$\bar{D}^0$ Mixing

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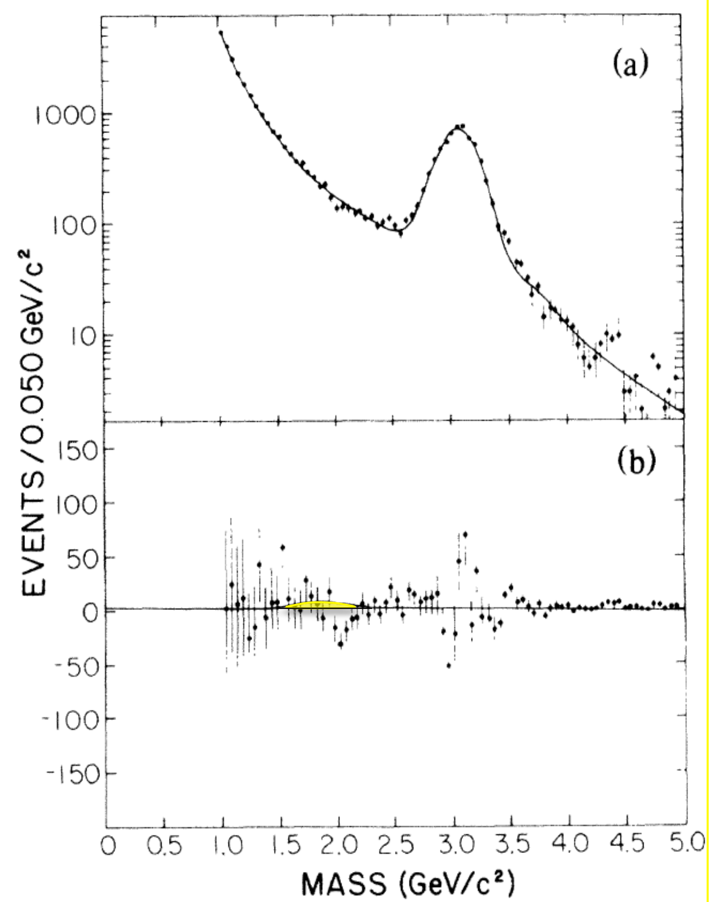
(Received 20 November 1985)



$\Gamma(\mu^+\mu^-)/\Gamma_{total}$ **Γ_{237}/Γ**

A test for the $\Delta C = 1$ weak neutral current. Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<6.2 × 10^{-9}	90	AAIJ	13AI	LHCB	pp at 7 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.6–8.1 × 10^{-7}	90	[1] LEES	12Q	BABR	$e^+e^- \approx$ 10.58 GeV
<2.1 × 10^{-7}	90	AALTONEN	10X	CDF	$p\bar{p}$, $\sqrt{s}$ = 1.96 TeV
<1.4 × 10^{-7}	90	PETRIC	10	BELL	$e^+e^- \approx \Upsilon(4S)$
<2.0 × 10^{-6}	90	ABT	04	HERB	pA, 920 GeV
<1.3 × 10^{-6}	90	AUBERT,B	04Y	BABR	$e^+e^- \approx \Upsilon(4S)$
<2.5 × 10^{-6}	90	ACOSTA	03F	CDF	See AALTONEN 10X
<1.56 × 10^{-5}	90	PRIPSTEIN	00	E789	p nucleus, 800 GeV
<5.2 × 10^{-6}	90	AITALA	99G	E791	$\pi^- N$ 500 GeV
<4.1 × 10^{-6}	90	ADAMOVICH	97	BEAT	π^- Cu, W 350 GeV
<4.2 × 10^{-6}	90	ALEXOPOU...	96	E771	p Si, 800 GeV
<3.4 × 10^{-5}	90	FREYBERGER	96	CLE2	$e^+e^- \approx \Upsilon(4S)$
<7.6 × 10^{-6}	90	ADAMOVICH	95	BEAT	See ADAMOVICH 97
<4.4 × 10^{-5}	90	KODAMA	95	E653	π^- emulsion 600 GeV
<3.1 × 10^{-5}	90	[2] MISHRA	94	E789	-4.1 ± 4.8 events
<7.0 × 10^{-5}	90	ALBRECHT	88G	ARG	e^+e^- 10 GeV
<1.1 × 10^{-5}	90	LOUIS	86	SPEC	π^- W 225 GeV
<3.4 × 10^{-4}	90	AUBERT	85	EMC	Deep inelast. $\mu^- N$

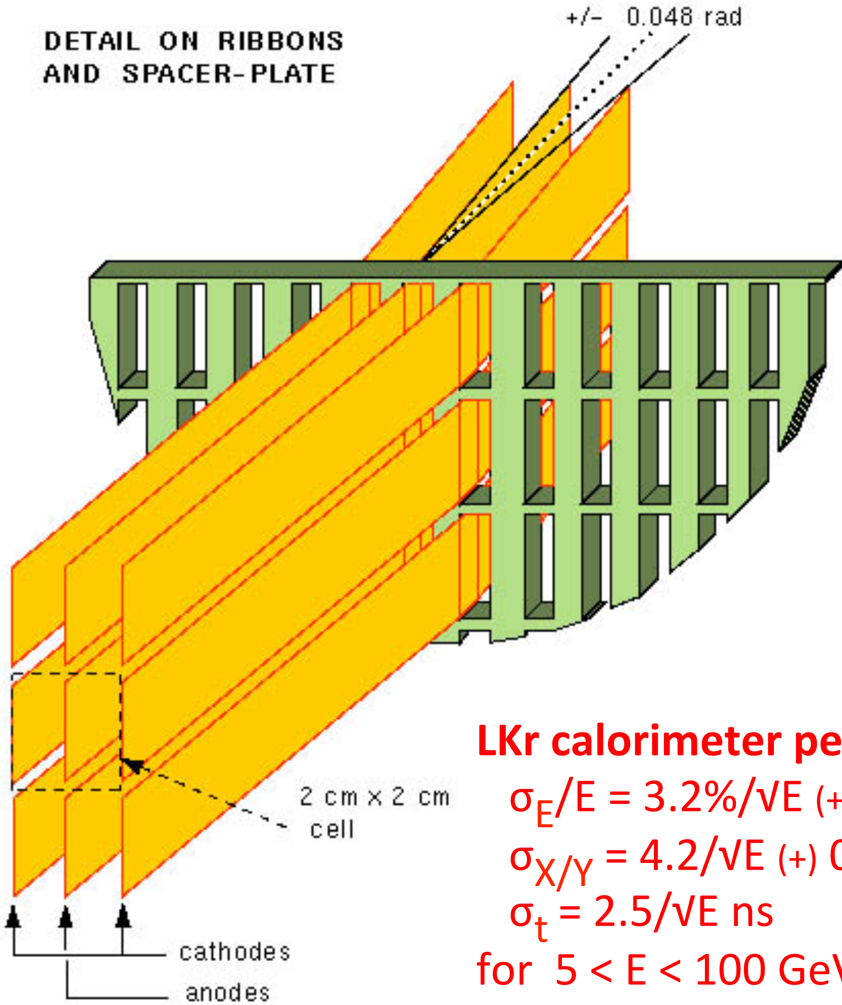
The limit on mixing was $R_M < 5.6\times10^{-3}$ at 90% CL, with today's best $< 0.61\times10^{-3}$ (BELLE 2008) for semileptonic decays and time-integrated analyses.

Part -2 : Space charge in ionization detectors

After completing my studies in Princeton, my main activities dealt with

- Charmonium studies (formed in antiproton-proton collision at Fermilab)
- Proposal and R&D for colliders detectors for B physics (shared interest with Kirk …)
- Study of direct CP violation in K_L decays (CERN NA48).
    - Here our interest converged on the subject discussed here: the effects of build-up of space charge due to positive ions.

The liquid krypton EM calorimeter of NA48



Quasi homogeneous detector, 10 m^3, longitudinal *ribbon* electrodes (13,000 channels), moderate *accordion* geometry.

Dear to me because I coordinated the design, procurement and assembly of the electrode structure (and I studied the effects of space-charge)

LKr calorimeter performance:

$\sigma_E/E = 3.2\%/\sqrt{E} \oplus 9\%/E \oplus 0.42\%$

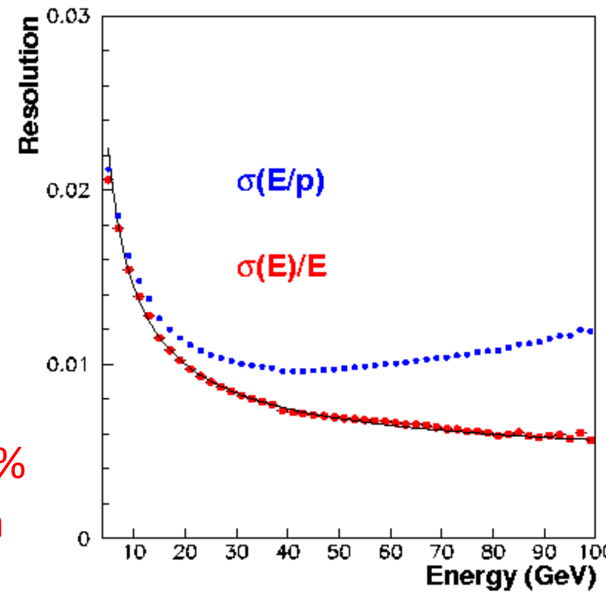
$\sigma_{X/Y} = 4.2/\sqrt{E} \oplus 0.6$ mm

$\sigma_t = 2.5/\sqrt{E}$ ns

for $5 < E < 100$ GeV

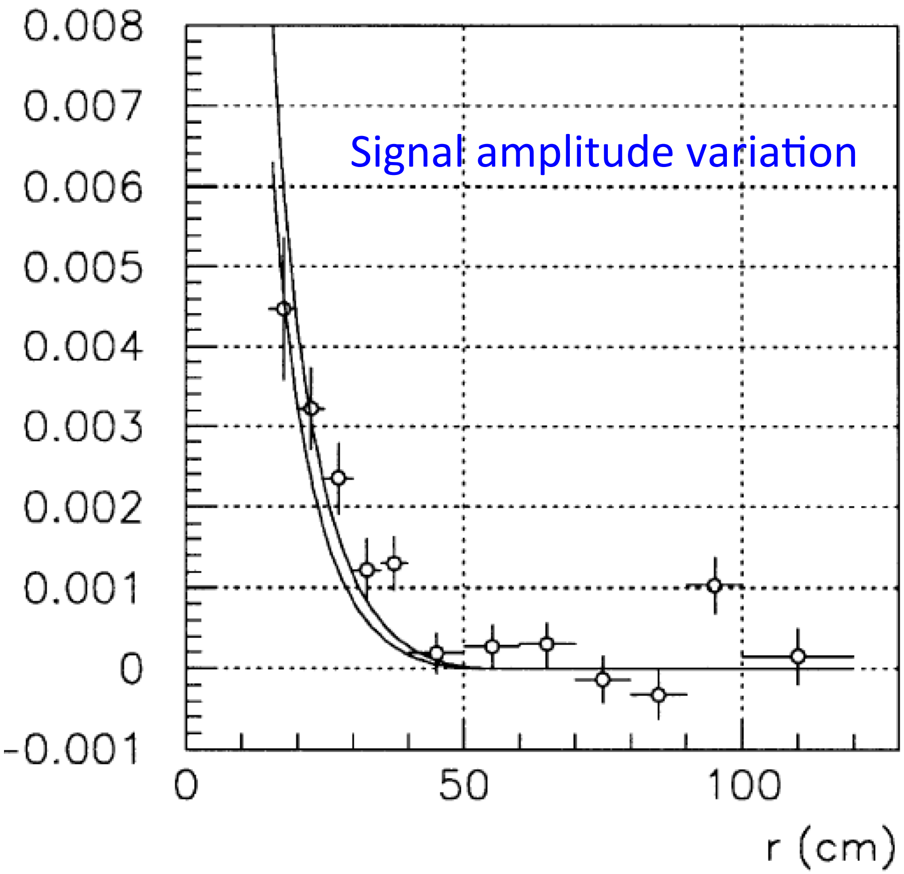
Long-term energy scale stability: 0.01 %

Transverse dim. accuracy < 100 µm/m



- Energy flow into the calorimeter:
  - up to 1.3×10^3 GeV/cm^2 (or 130 pC/cm^{3}s of effective charge density injection, for positive ions)
- Data collected in 1997 with 1.5 kV of bias over the 1 cm cell
  - the maximum drift time for ions was about 1.5 s

- In this regime the effects of space charge were visible, and they were time-dependent:
  a) In between beam-extractions (12 s), the space charge goes to zero (or near zero)
  b) In the first ≅1.5 second of extraction the space charge builds up
     - The profile of the electric field changes, the average detector signal is reduced.
  c) During the remaining few seconds of the beam extraction the the situation is stable.



NA48 applied a *time-dependent* and *radius-dependent* correction to the data collected in 1997 (from which its first measurement of ε'/ε was obtained),

(The bias voltage was doubled in the following years, and the space charge effects became negligible).

The detector still works with the same excellent performance after 20 years.

Fractional drop in detector response to EM showers, obtained comparing t < 0.1 s to t > 1.6, for different radial position. The curves are from calculation without fitted parameters, and correspond to different values of the ion mobility).
The data points from a small sample of collected data.
NIM A 421 , 75 (1999)

Kirk's interest in space charge is related to large liquid-Argon drift detectors for neutrino physics. For drift distance above a few meters, the ionization due to cosmic rays alone may affect the response of the detector.

From http://physics.princeton.edu/~mcdonald/examples ;

Space Charge in Ionization Detectors

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Kirk T. McDonald

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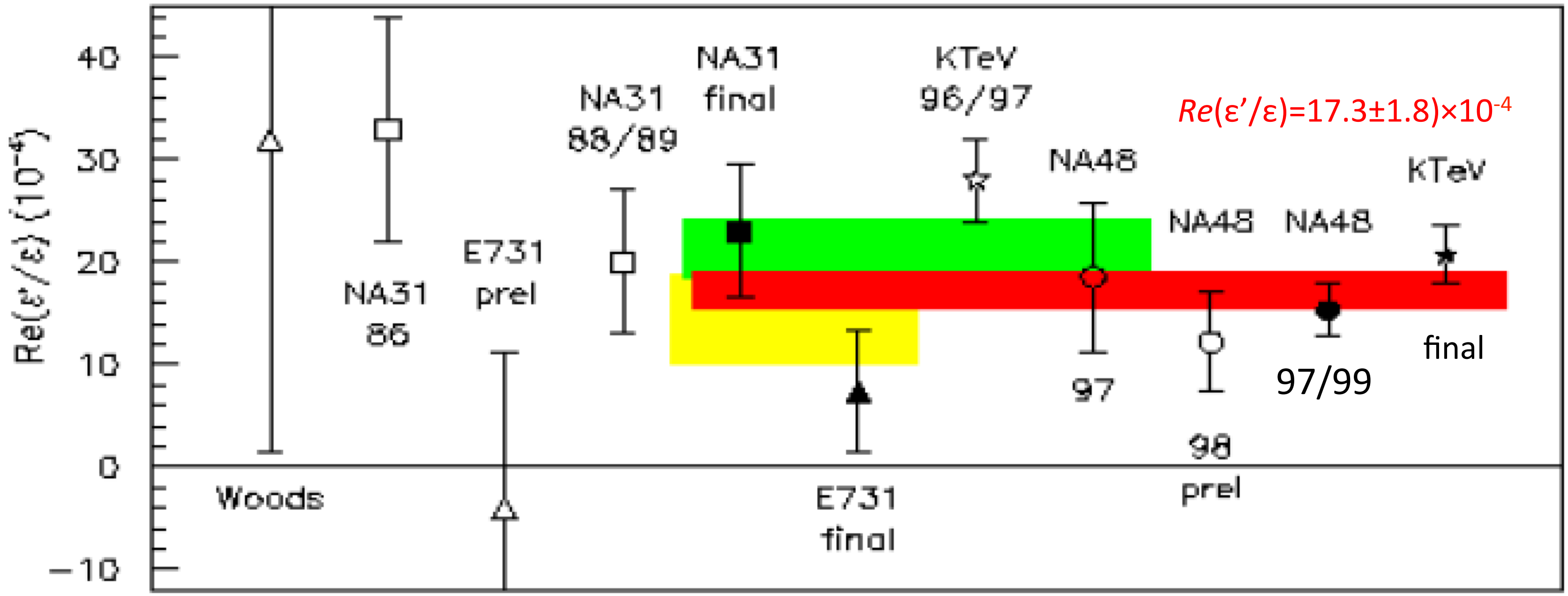
(March 25, 2007; updated June 1, 2016)

I am very interested in knowing the development of this subject in the context of the the DUNE detector (Kirk's current interest)

Direct CP violation in K^0 decays



Results on direct CP violation in K0 decays:

$$A(K_L \to \pi^+ \pi^-) \,/\, A(K_S \to \pi^+ \pi^-) = \eta_{+-} = \varepsilon + \varepsilon'$$
$$A(K_L \to \pi^0 \pi^0) \,/\, A(K_S \to \pi^0 \pi^0) = \eta_{00} = \varepsilon - 2\,\varepsilon'$$

ε' is proportional to the ratio of amplitudes and phase difference of the isospin 2 and isospin 0 amplitudes for $K^0 \to \pi\pi$, and experimentally is obtained from the double ratio:

$$R = \frac{BR(K_L \to \pi^0\pi^0)\; BR(K_S \to \pi^+\pi^-)}{BR(K_S \to \pi^0\pi^0)\; BR(K_L \to \pi^+\pi^-)} = 1 - 6\,Re(\varepsilon'/\varepsilon)$$

Experiment and theory

- Including data collected in 2011, the final result of NA48 is *Re(ε′/ε)* = (14.7 ± 2.2) × 10^{-4}. The PDG average is (16.5 ± 2.3) × 10^{-4}.
- On the theory side, there has been recently some advance in lattice based computations:
  - Nicolas Garron, Moriond EW 2016 (or also arXiv: 1512.02440):

$$Re(\varepsilon'/\varepsilon) = Re\left\{ \frac{i\omega \exp(i\delta_2 - \delta_0)}{\sqrt{2}\varepsilon} \left[\frac{\mathrm{Im}(A_2)}{\mathrm{Re}A_2} - \frac{\mathrm{Im}A_0}{\mathrm{Re}A_0} \right] \right\}$$

Combining our new value of $\mathrm{Im}A_0$ and δ_0 with

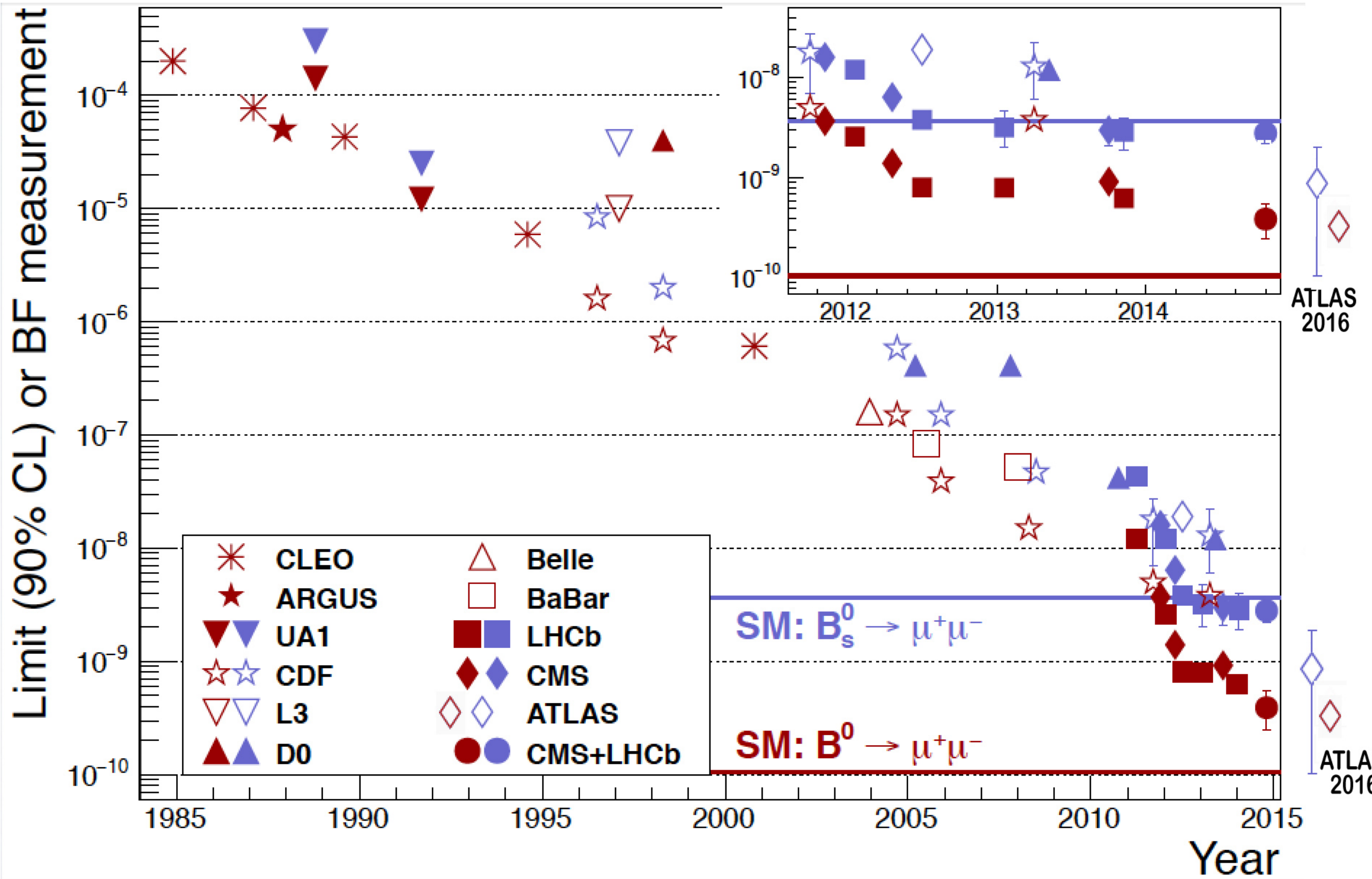
- our continuum value for $\mathrm{Im}A_2$
- the experimental value for ReA_0, ReA_2 and their ratio ω

we find

$$Re(\varepsilon'/\varepsilon) = 1.38(5.15)(4.43) \times 10^{-4}$$

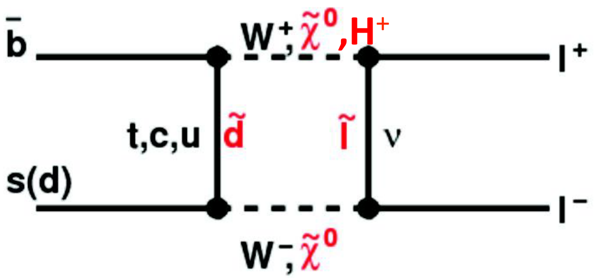
  - Recent discussion also by Andrzej Buras (A.J.B. and-M. Gérard, arXiv 1603.0568), who has different views on how the computation on lattice should be used.
- Altogether, still difficult to compute, and still disagreement between predictions and observation.

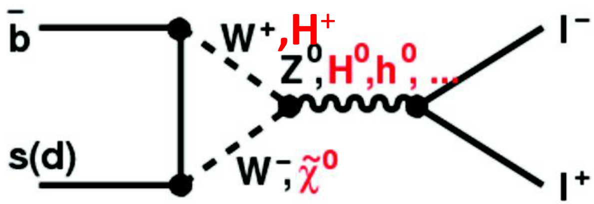
Part 3 : Rare B^0, B^0_s decays into muon pairs



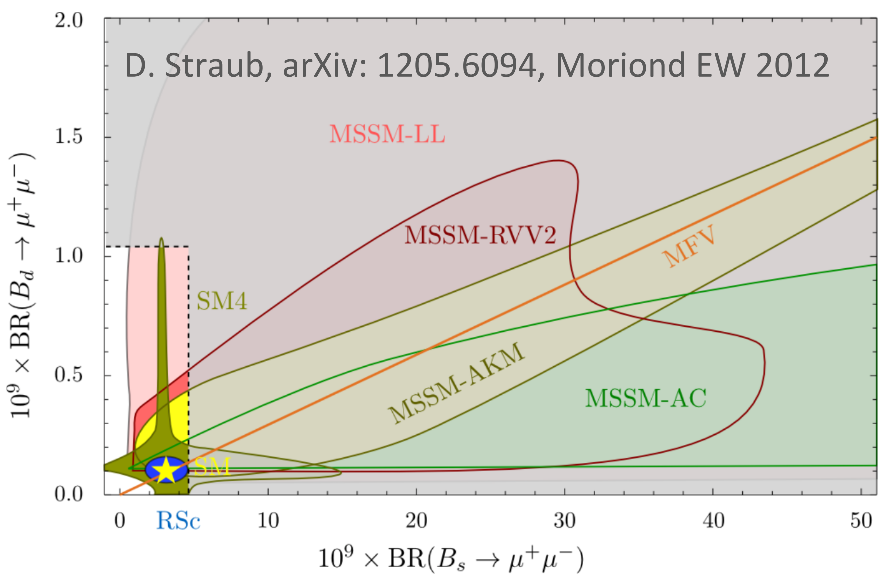
A history as long as the one of *D^0* decays into muon pairs.

My last analysis effort. Jim Pilcher has chaired the reviewing panel.





- FCNC process
- further affected by helicity suppression
- predicted accurately in the SM:
  - $BR(B^0_s)=(3.65\pm0.23)\times10^{-9}$,
  - $BR(B^0)=(1.06\pm0.09)\times10^{-10}$ [C. Bobeth et al., PRL 112 (2104) 101801]
- Hence, sensitive to physics BSM

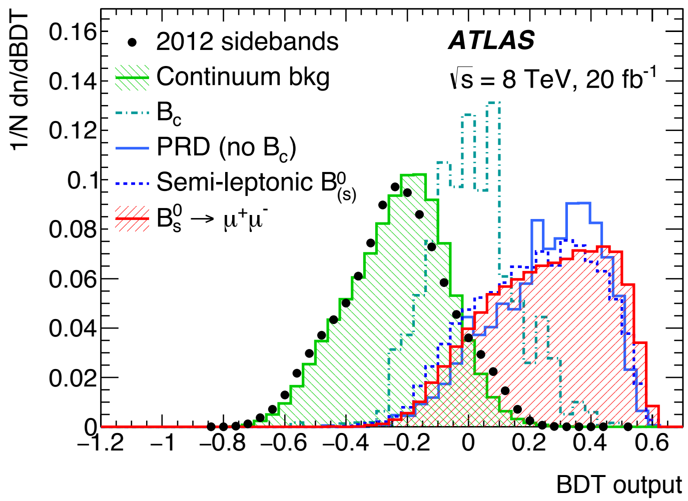


CMS and LHCb combined result:

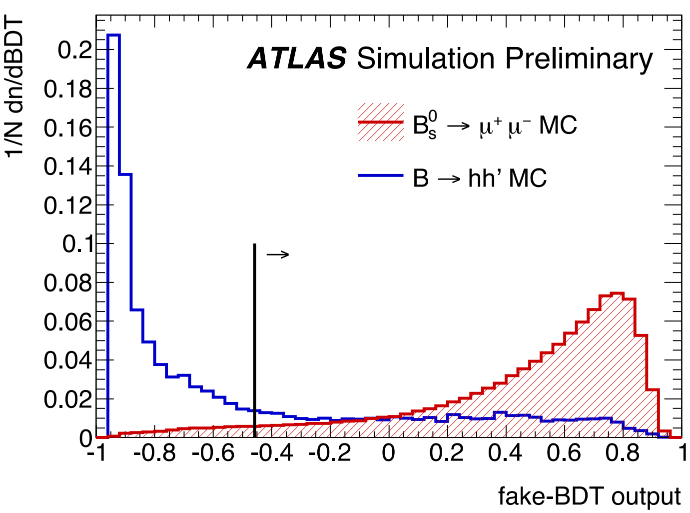
- $BR(B^0_s) = (2.8+0.7-0.6)\times10^{-9}$
- $BR(B^0) = (3.9+1.6-1.4)\times10^{-10}$

[Nature 522 (2015) 68-72]

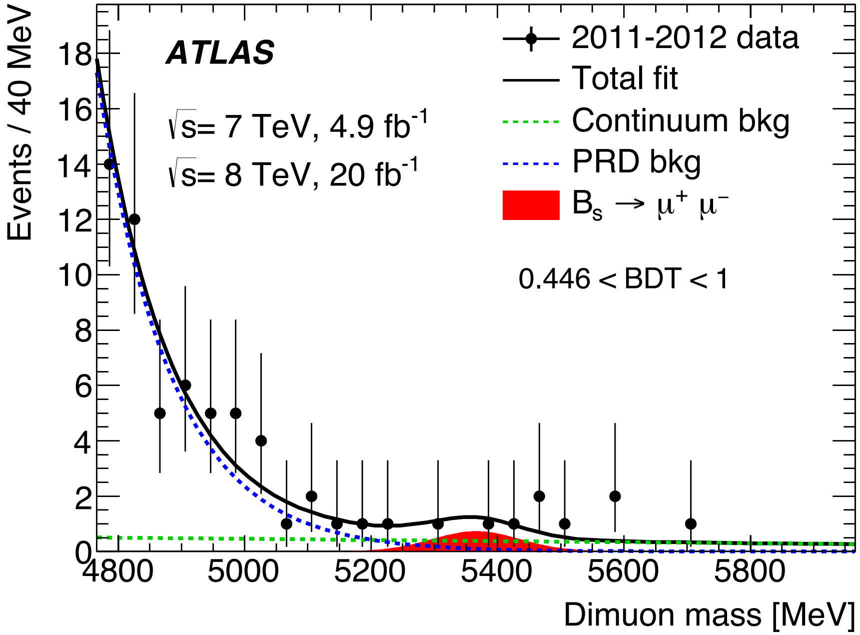
ATLAS has to overcome disadvantages in mass resolution, and in trigger coverage, compensated with a larger effort in the reduction of background.

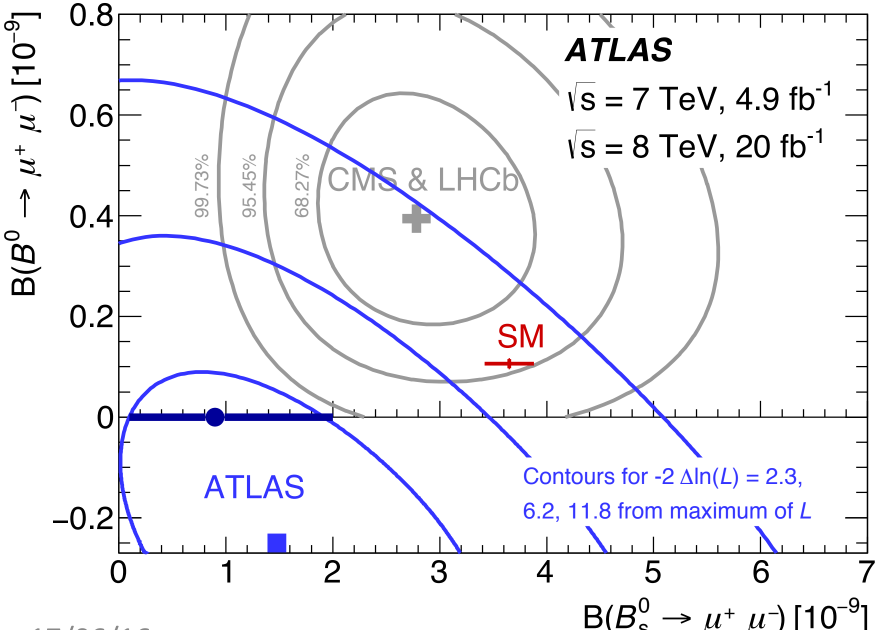


- Continuum background (p pbar -> b bbar X -> μ-μ+X)
  - Reduced with multivarariate analysis
  - BDT trained with simulation (1.4 G events, the largest MC production made by ATLAS for a single analysis). Signal/background ratio improved by ≈1000.



- Hadrons misidentified as muons
  - Affect partially reconstructed background   (*e.g.,* B^0_s *-> K+ μ- ν* with *K+ -> μ+ υ)*
  - and resonant background   (*e.g.,* B^0_s *-> K+ K-* with double misindetification)
  - BDT trained on MC (validated on data): only 0.1%, 0.05% of *K*, π are mistaken as muons)





After unblinding, we have found fewer B^0_s events than expected:

BR(B^0_s->μ+μ-) = $(0.9\ ^{+1.1}_{-0.8}) \times 10^{-9}$,

or $< 3.0 \times 10^{-9}$ at 95% CL

Our sensitivity for B^0 is small
(the limited mass resolution σ≈70 MeV cannot be overcome there),
but the result is interesting because CMS & LHCb claim an excess over the SM prediction.

For the combined measurement, the compatibility with the SM prediction is at the level of 5%

Conclusion

- *Warm thanks to Stew for the organization of this event*
- *Congratulations to Kirk for his career, and thanks for all what I received from him*
- *Thanks to the audience for the attention.*