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A high-precision determination of the weak mixing angle $\sin^2(\theta_W)$ at MESA

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(Johannes Gutenberg University Mainz and Helmholtz Institute Mainz)

HISKP Institutskolloquium, Universität Bonn, May 8, 2014

Outline

MESA: energy recovering linear accelerator

Weak Mixing Angle

Experimental Method: A_{PV}

Experimental Setup

JG|U

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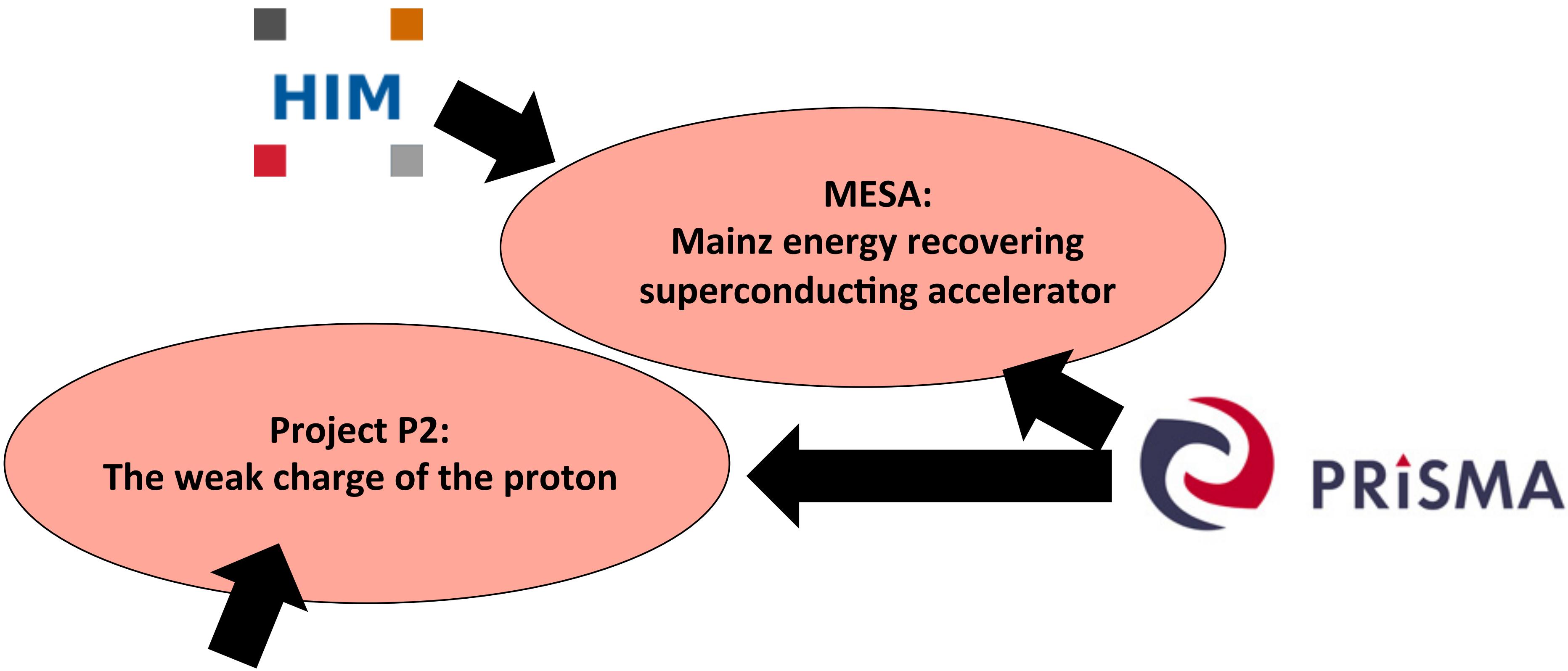

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Collaborative Research Center 1044 at Johannes Gutenberg-University Mainz:
The Low-Energy Frontier of the Standard Model
From Quarks and Gluons to Hadrons and Nuclei.

MESA-Accelerator

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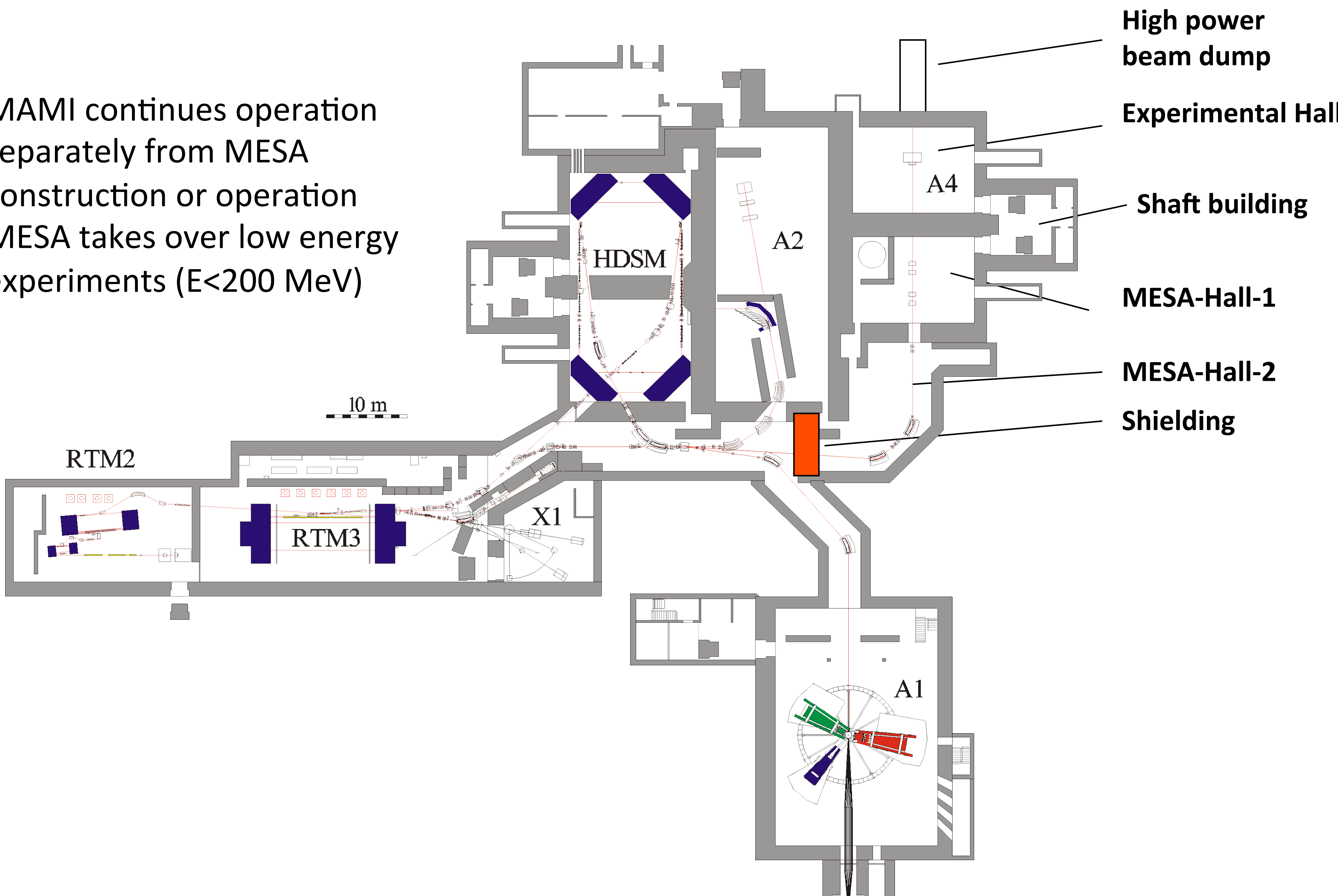
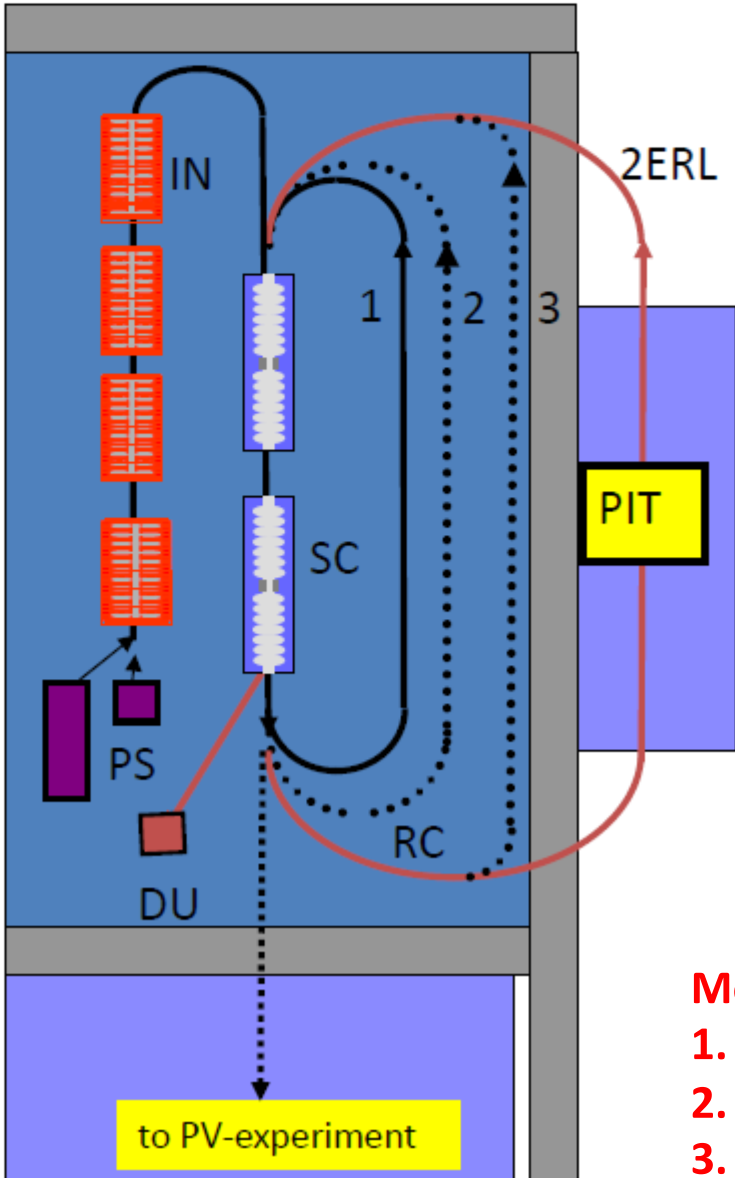
- MAMI continues operation separately from MESA construction or operation
- MESA takes over low energy experiments (E<200 MeV)





Mainz **e**nergy recovering **s**uperconducting **a**ccelerator

1.3 GHz c.w. beam
Normal conducting injector LINAC
Superconducting cavities in recirculation beamline

ERL mode (Energy recovering mode):
10 mA, 100 MeV unpolarized beam (pseudo internal gas hydrogen target L~10^{35} $cm^{-2}s^{-1}$)

EB mode (External beam):
300 µA, 150 MeV polarized beam (liquid Hydrogen target L~10^{39} $cm^{-2}s^{-1}$)

Motivation for MESA-Accelerator:

1. **New accelerator technique (ERL)**
2. **Search for Dark Photon (ERL)**
3. **Measurement of the weak charge of the Proton (EB)**

MESA: Beam parameter

Beam Energy ERL/EB [MeV]	105/155 (105/205)
Operation mode	1300 MHz, c.w.
Elektron-sources	1.) Polarised : NEA GaAsP/GaAs superlattice , 200keV (?) 2.) unpolarised KCsSb, 200keV
Bunch Charge EB/ERL [pC] 7.7pC=10mA@1300MHz	0.15/0.77 (0.15/7.7)
Norm. Emittance EB/ERL [μm]	0.1/<0.5 (0.1/<1)
Spin Polarisation (EB-mode only)	> 0.85
Recirculations	2 (3)
Beampower at Exp. ERL/EB [kW]	100/22.5 (1050/30)
R.f.-Power installed [kW]	140 (180)

MESA: Lattice concept

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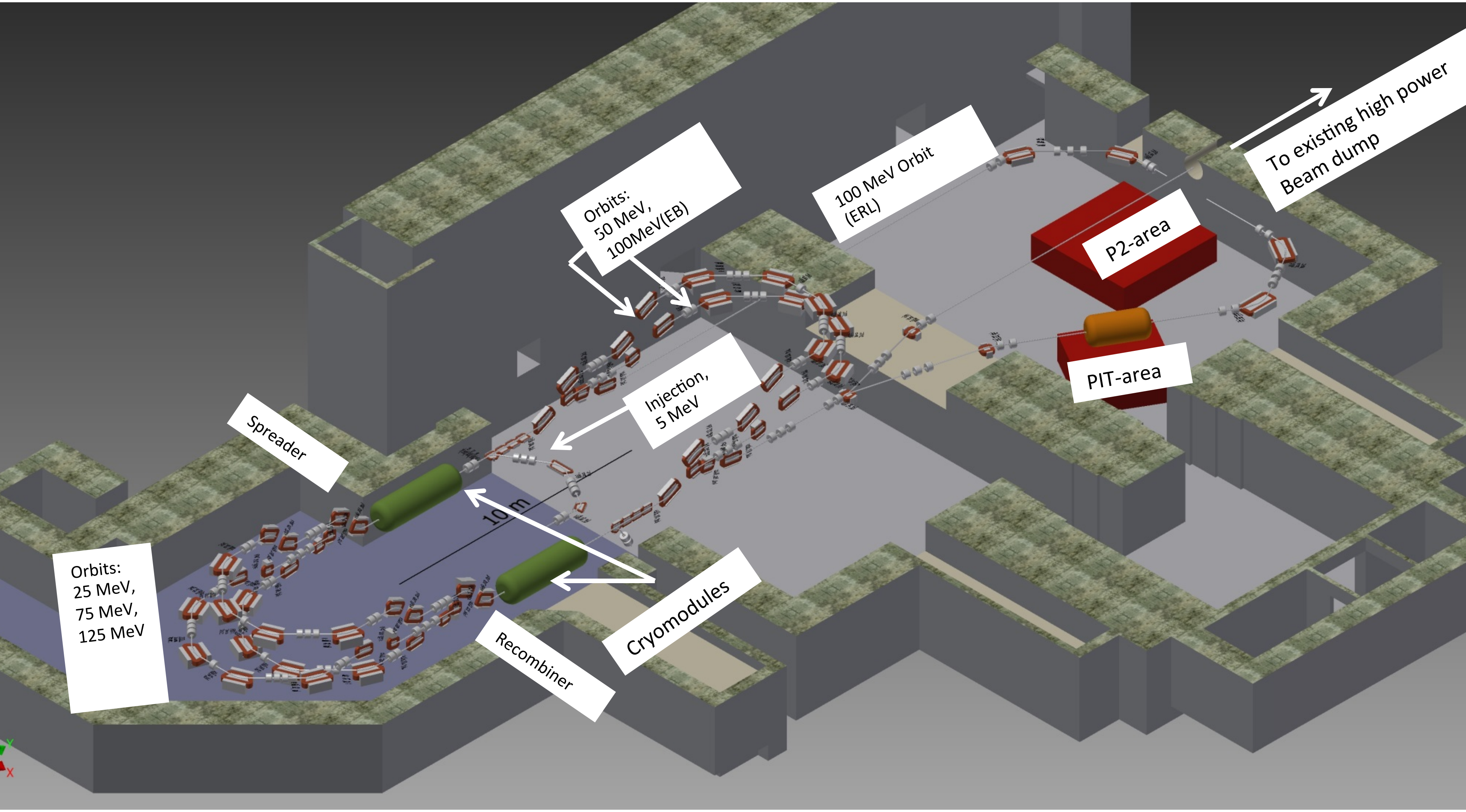
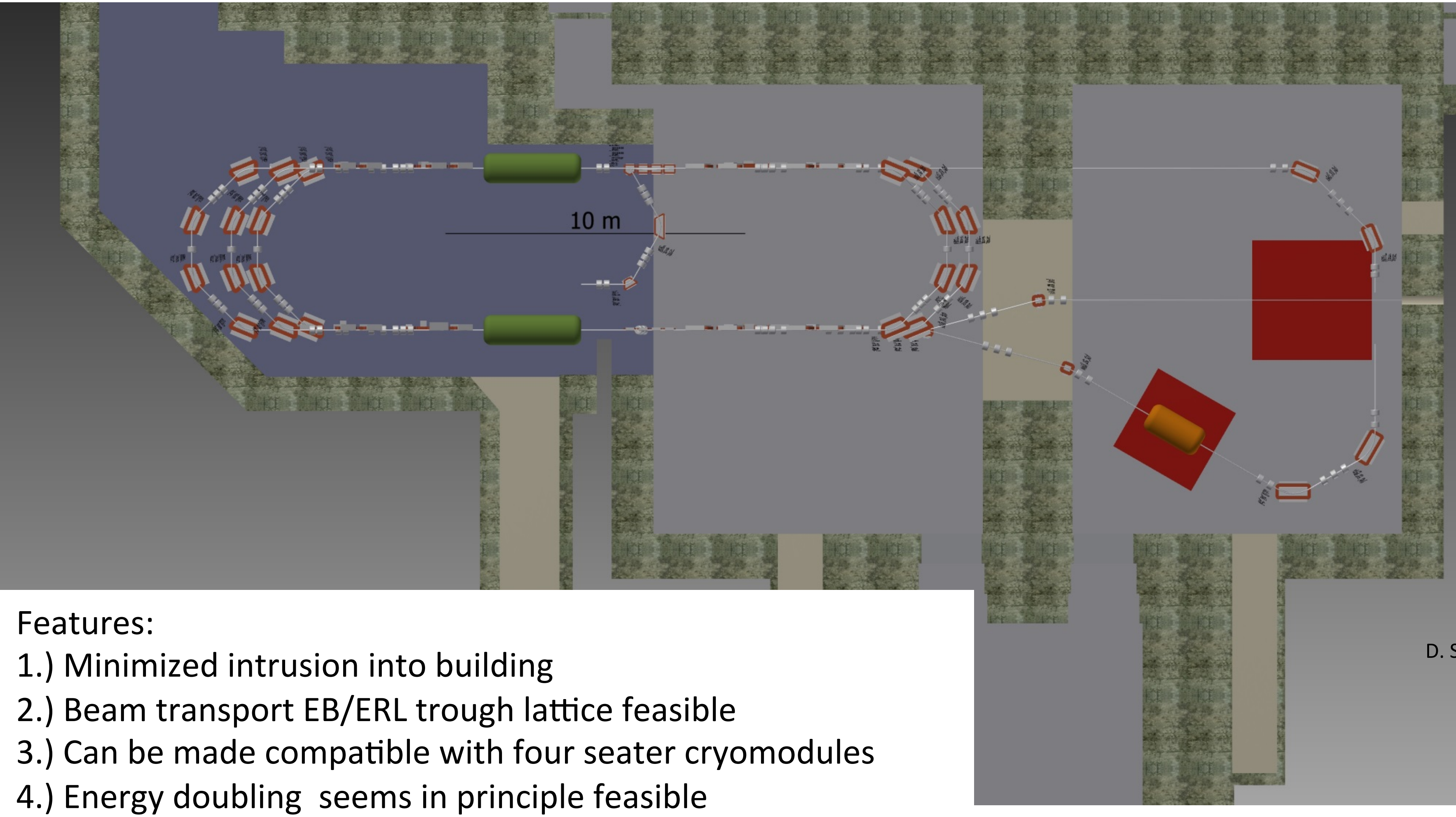


„Double axis“ acceleration, CEBAF inspired

D. Simon/K.H. Kaiser

MESA-Layout



Features:

1.) Minimized intrusion into building

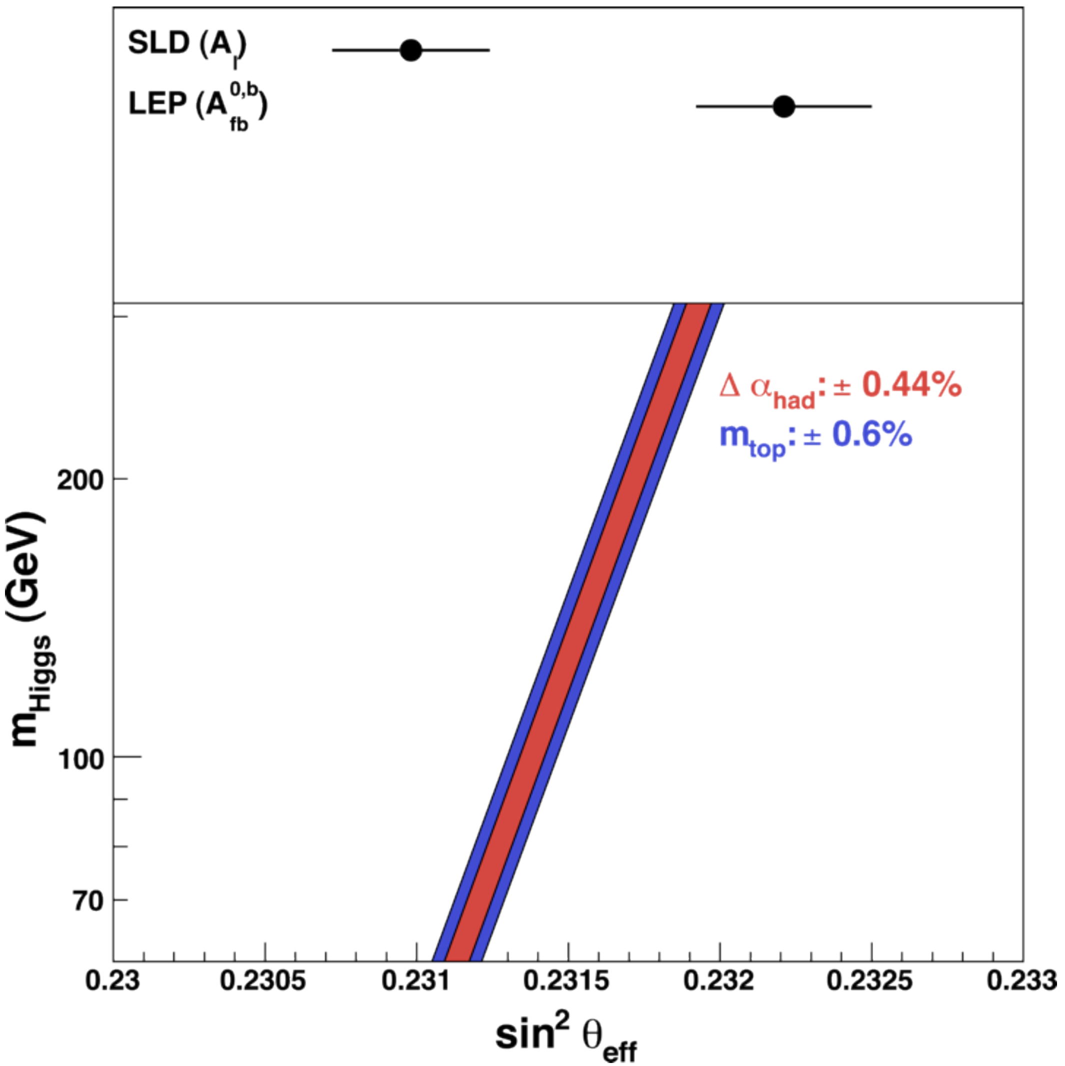
2.) Beam transport EB/ERL trough lattice feasible

3.) Can be made compatible with four seater cryomodules

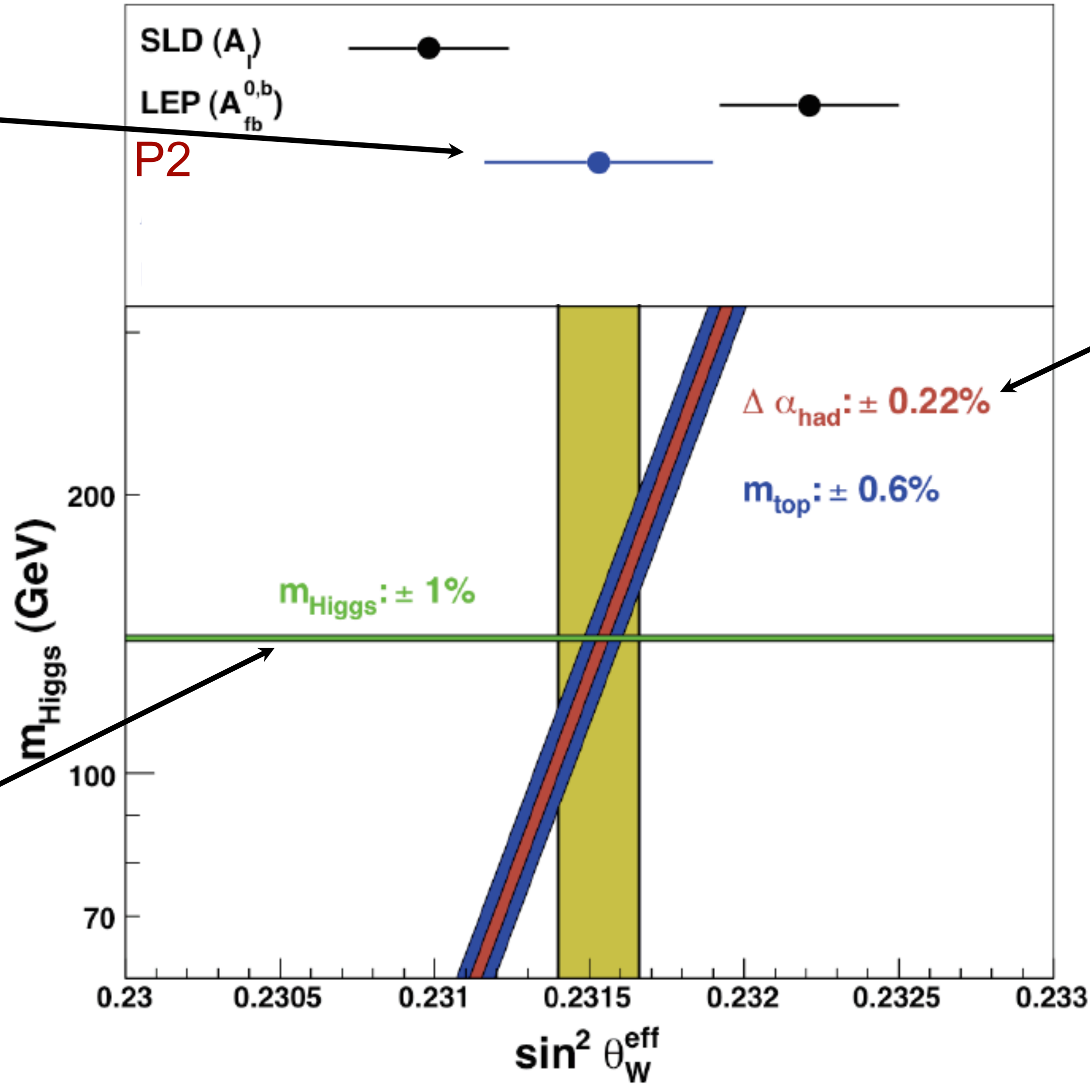
4.) Energy doubling seems in principle feasible
(200MeV ERL/300MeV EB)

D. S

„running“ $\sin^2\theta_{eff}$ or $\sin^2\theta_W(\mu)$


SLD (A_l)
LEP ($A_{fb}^{0,b}$)
$\Delta\alpha_{had}$: ± 0.44%
m_{top}: ± 0.6%
200
100
70
m_{Higgs} (GeV)
0.23
0.2305
0.231
0.2315
0.232
0.2325
0.233
$\sin^2\theta_{eff}$

Projection for project P2



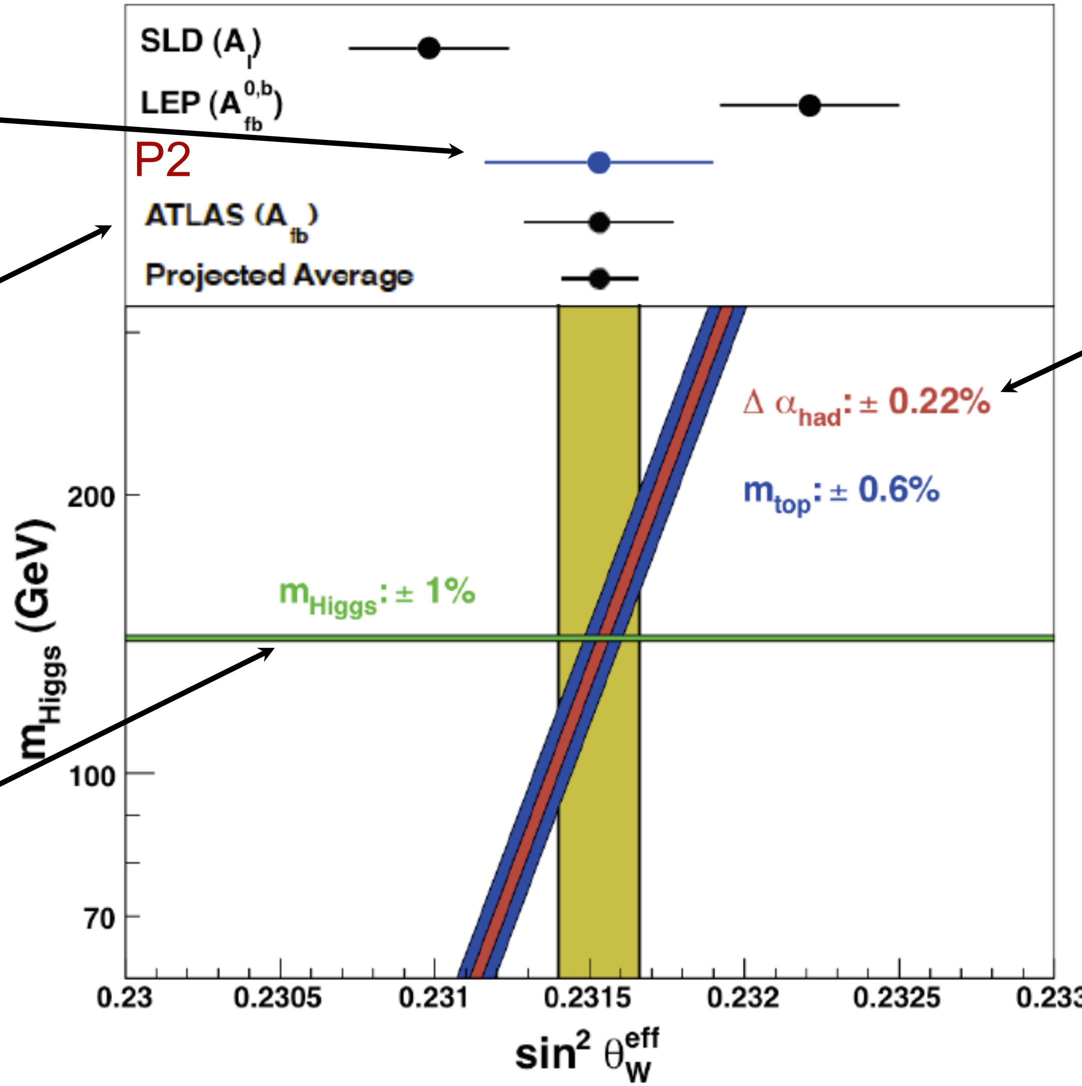
Projection for project P1

LHC

Projection for project P2

Projection

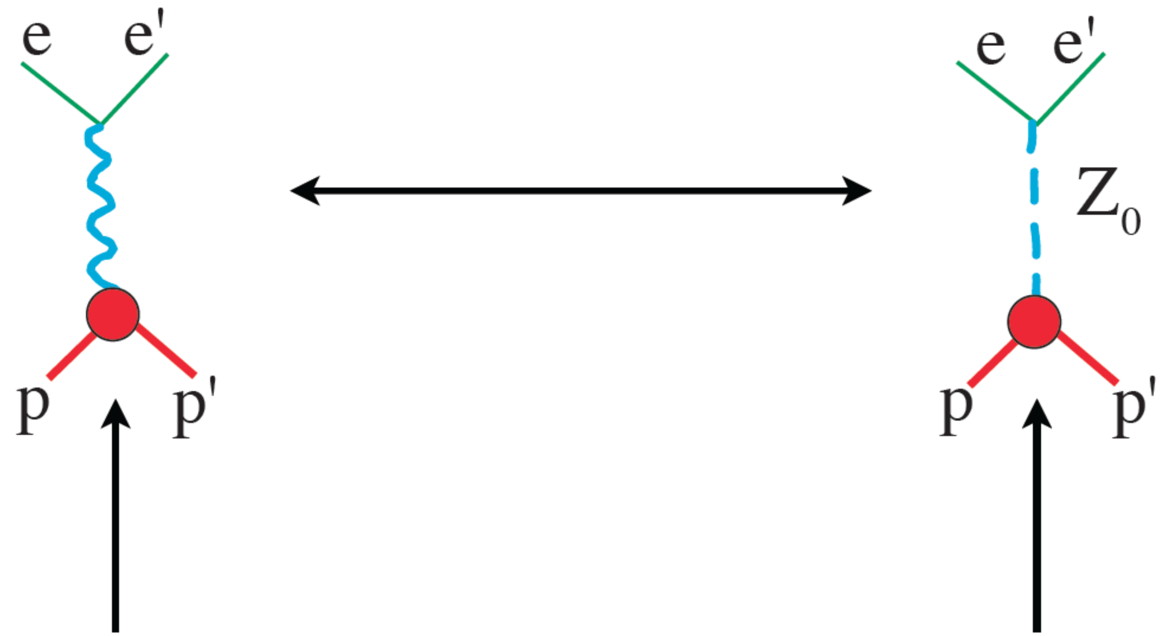
Expectation from LHC



Projection for project P1

The role of the weak mixing angle

The relative strength between the weak and electromagnetic interaction is determined by the weak mixing angle: $\sin^2(\theta_W)$

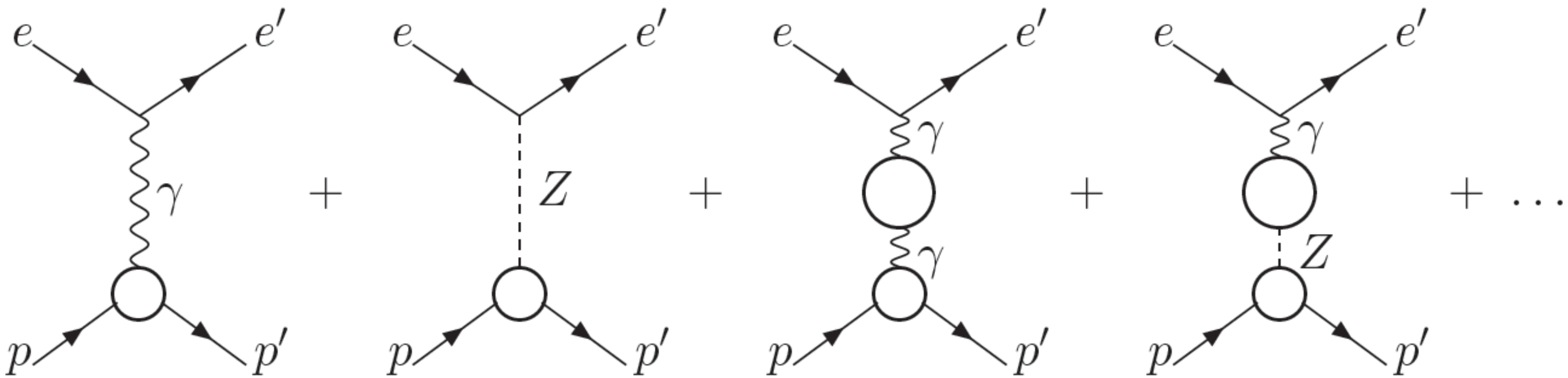


$Q_e(p) = +e$
electric charge of the proton

$Q_W(p) = 1 - 4 \sin^2 \theta_W$
weak charge of the proton

$\sin^2 \theta_W$: a central parameter of the standard model

Precision measurements and quantum corrections:

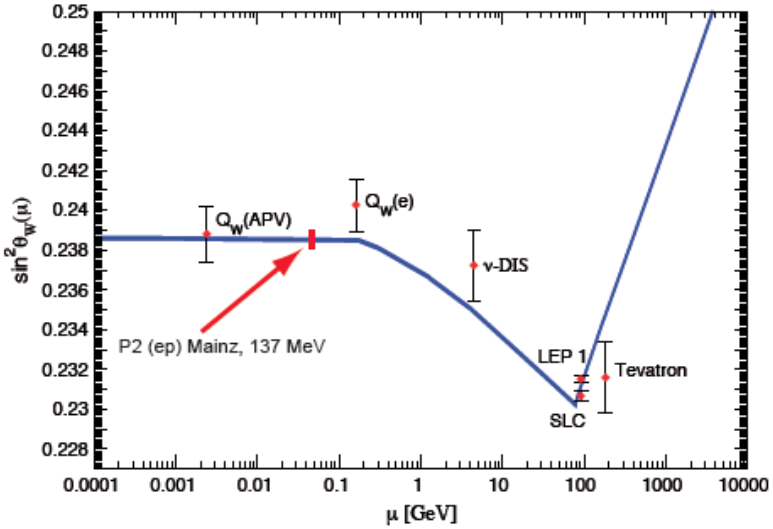


running α
(P1)

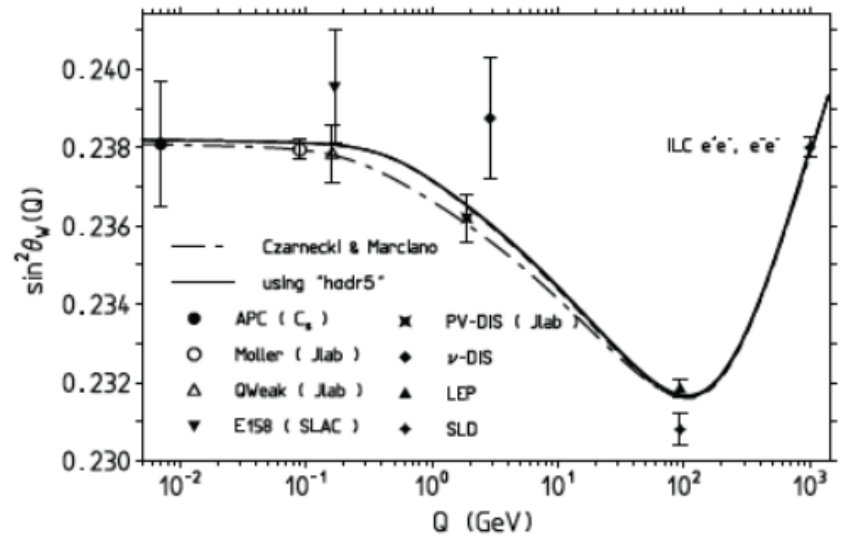
running $\sin^2 \theta_W(\mu)$
(P2)

Universal quantum corrections: can be absorbed into a scale dependent, „running" $\sin^2 \theta_{eff}$ or $\sin^2 \theta_W(\mu)$

Theory



Erler, Ramsey-Musolf

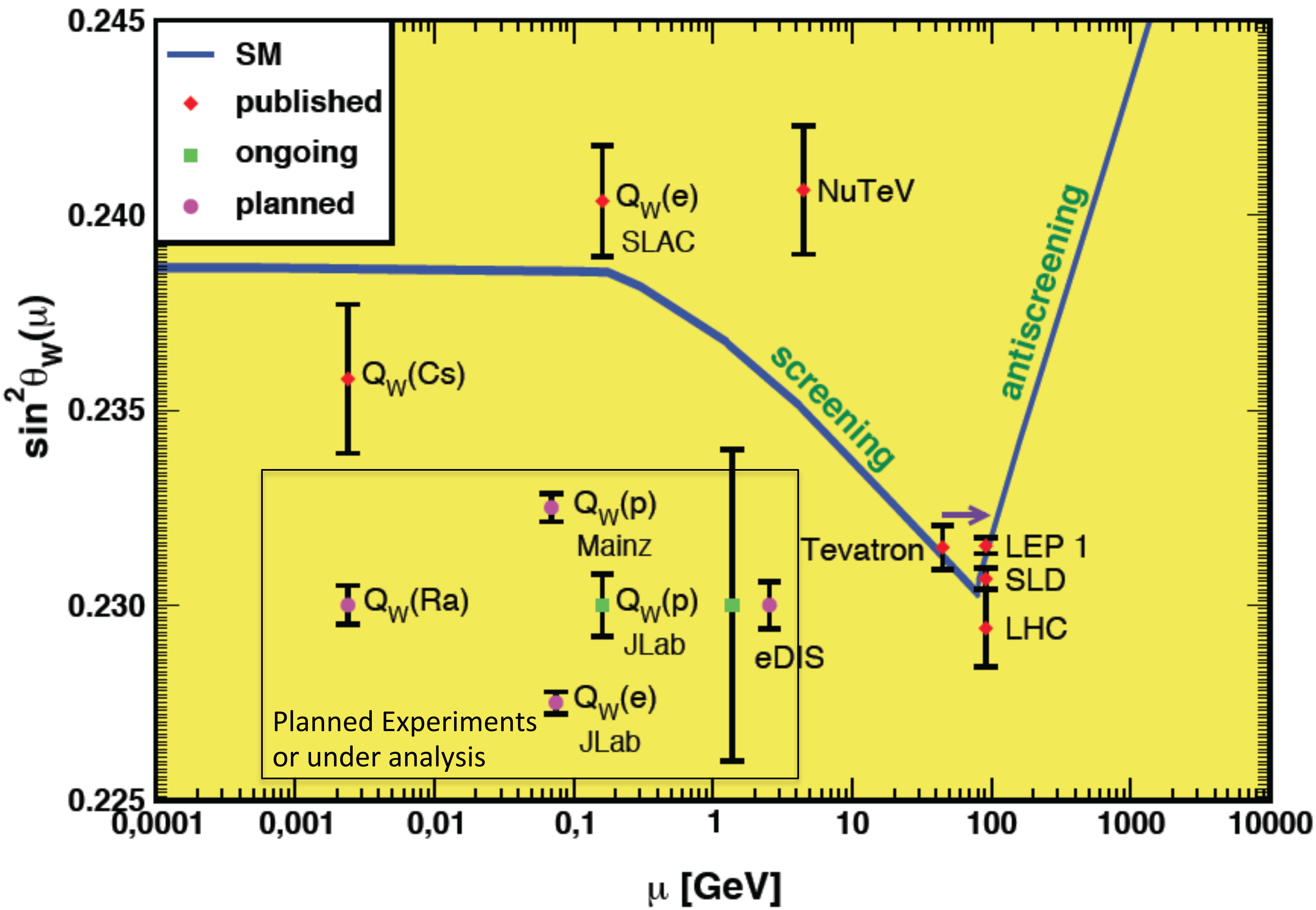


Jegerlehner

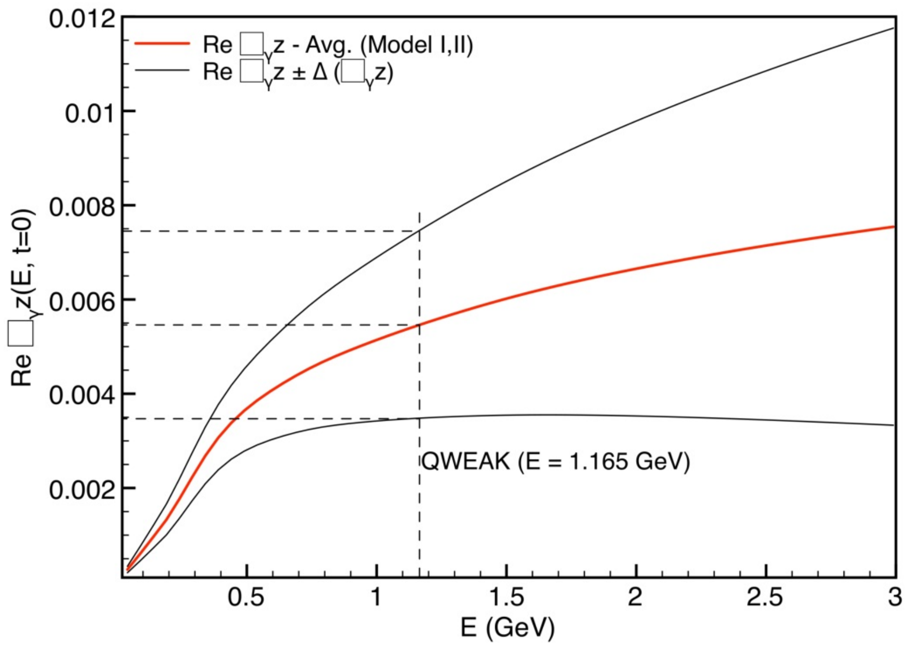
Different prescriptions for the definition of the scale dependence
➜ set up full 1-loop corrected expression for the observable A_{ep}

Theory uncertainties: parameter dependence and hadronic input

Jens Erler: PRISMA guest professor (since August 1)

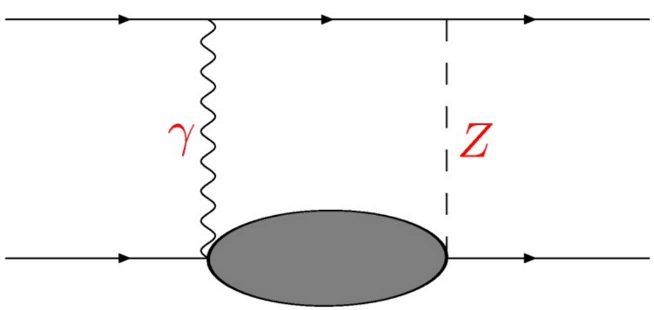

SM
published
ongoing
planned
0.245
0.240
0.235
0.230
0.225
sin²θ_W(μ)
0,0001
0,001
0,01
0,1
1
10
100
1000
10000
μ [GeV]
Q_W(e)
SLAC
NuTeV
Q_W(Cs)
screening
antiscreening
Q_W(p)
Mainz
Q_W(Ra)
Q_W(p)
JLab
eDIS
Q_W(e)
JLab
Tevatron
LEP 1
SLD
LHC
Planned Experiments
or under analysis

- γZ box graph contributions obtained by modelling hadronic effects:



[... olf 2011]

- Hadronic uncertainties suppressed at lower energies
- Planned experiment:
  P2 @ MESA



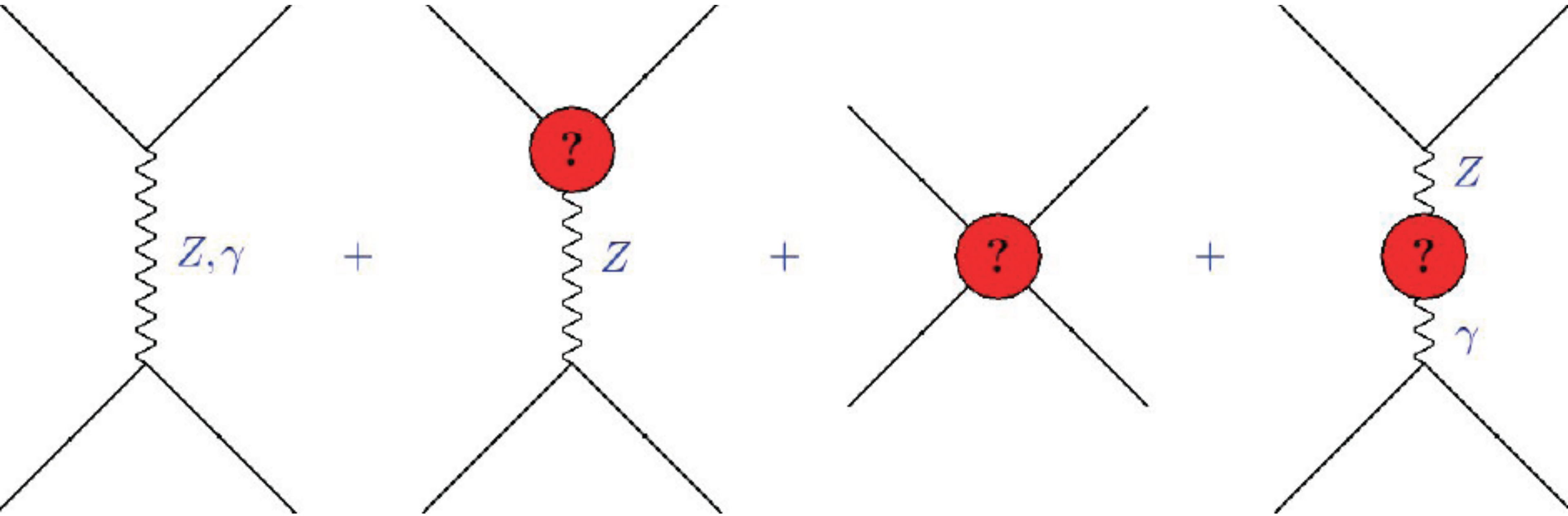
Dominant theoretical uncertainty:

γZ box graphs, $\Box_{\gamma Z}$

Sensitive to hadronic effects

Sensitivity to new physics beyond the Standard Model

Sensitivity to new physics beyond the Standard Model



Extra Z

Mixing with Dark photon or Dark Z

Contact interaction

New Fermions

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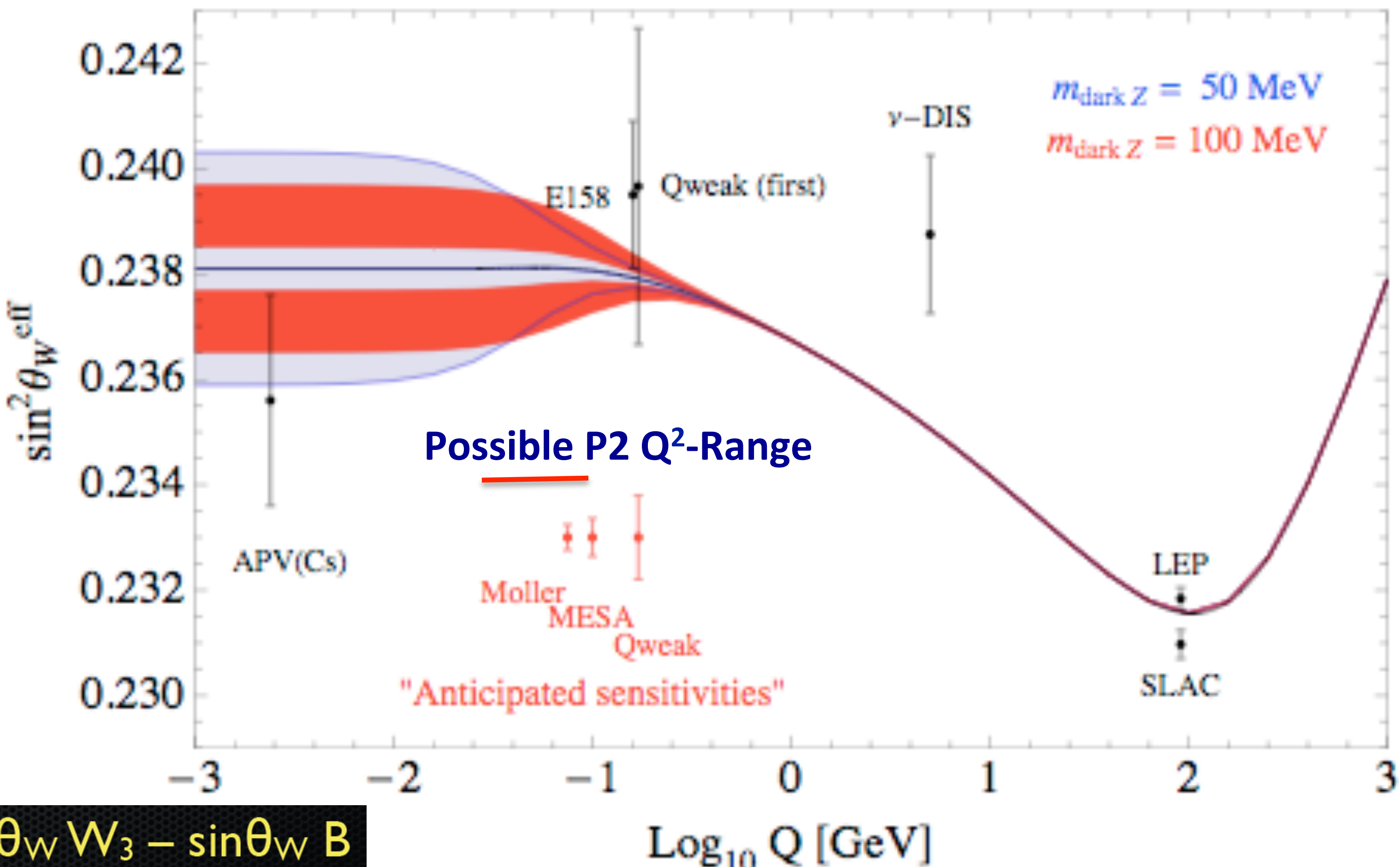
Running $\sin^2\theta_W$ and Dark Parity Violation

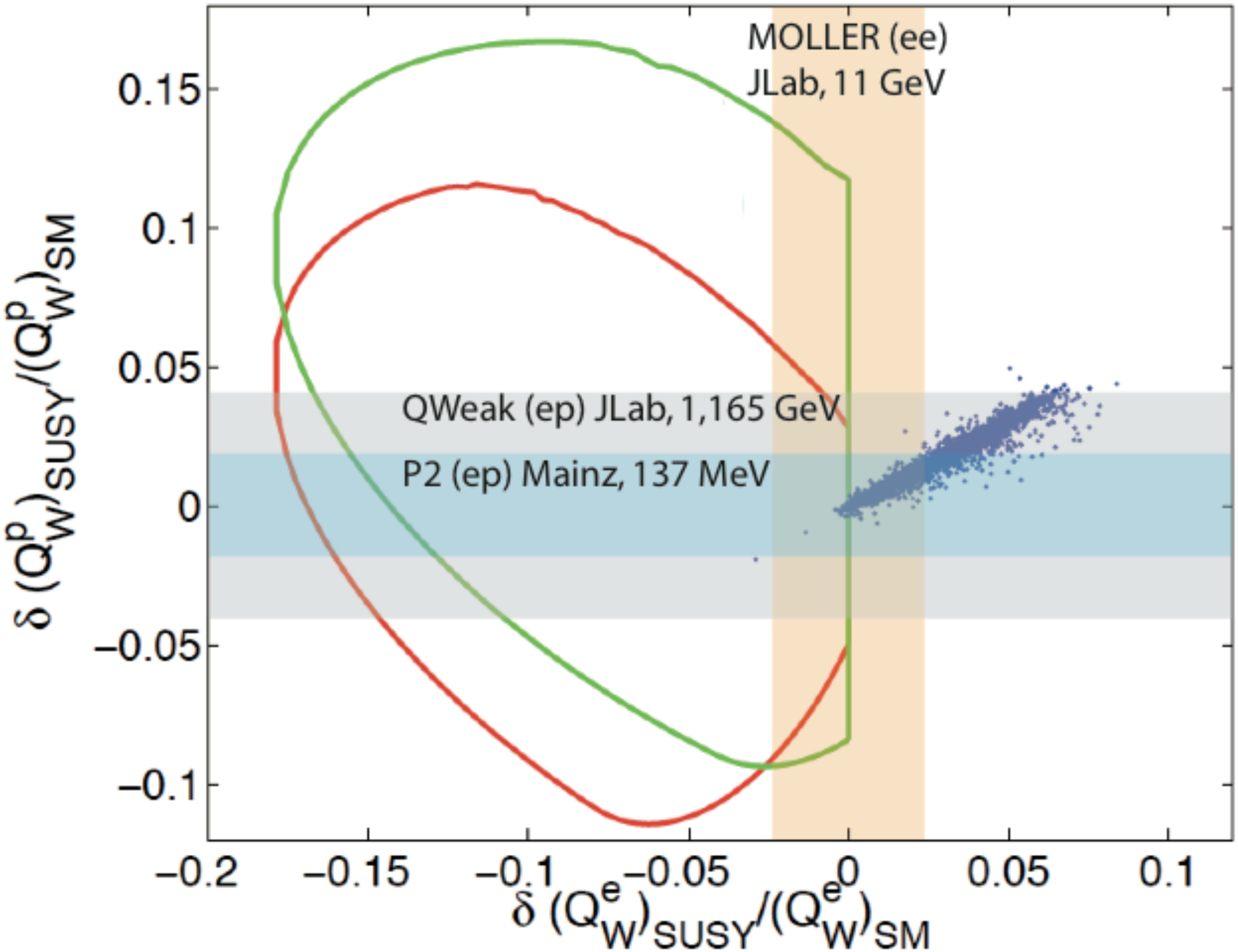


$Z = \cos\theta_W W_3 - \sin\theta_W B$

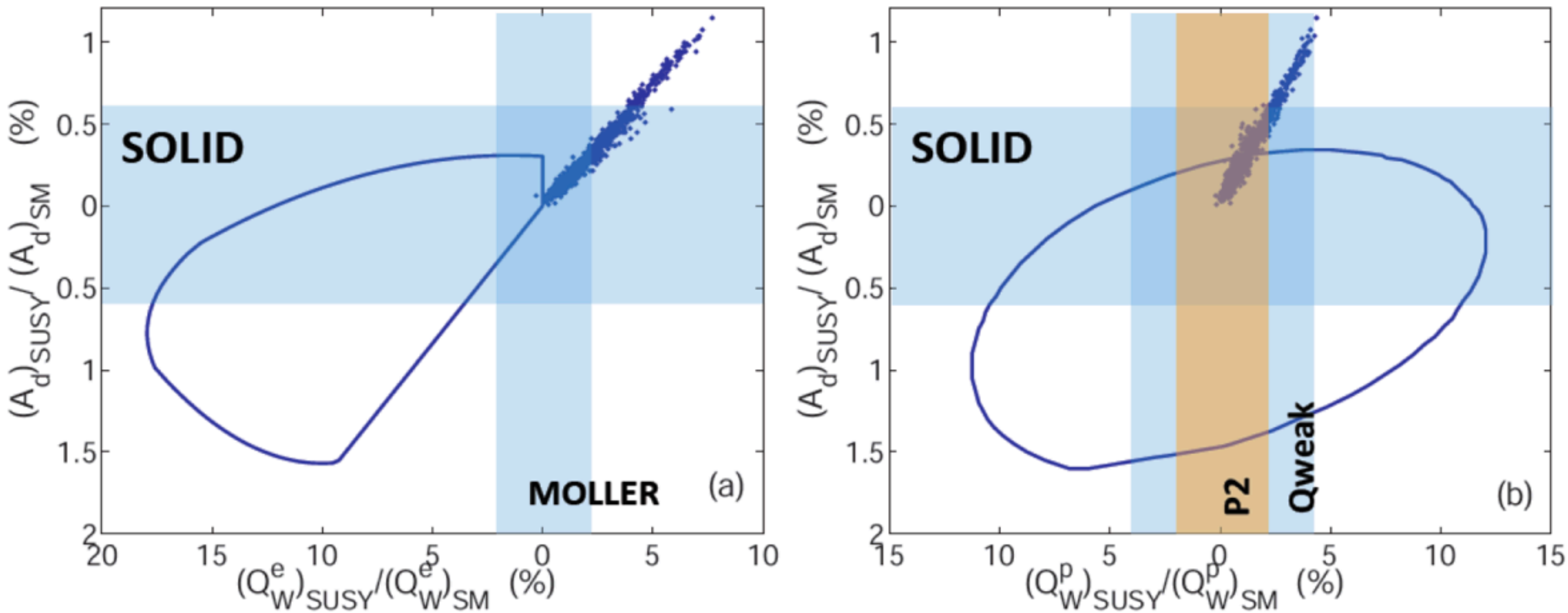
$A = \sin\theta_W W_3 + \cos\theta_W B$

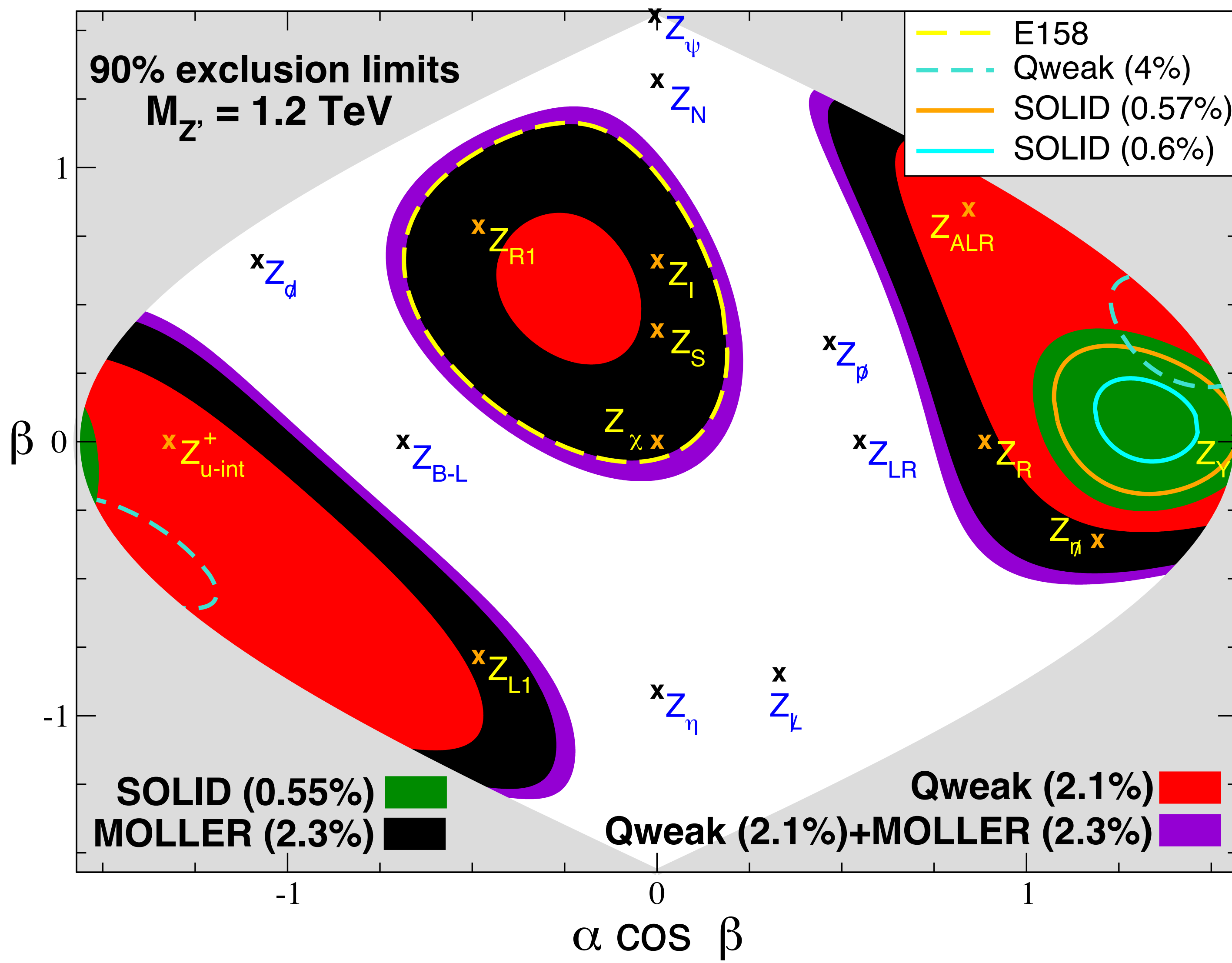
Bill Marciano

Example: supersymmetric Standard Model extensions

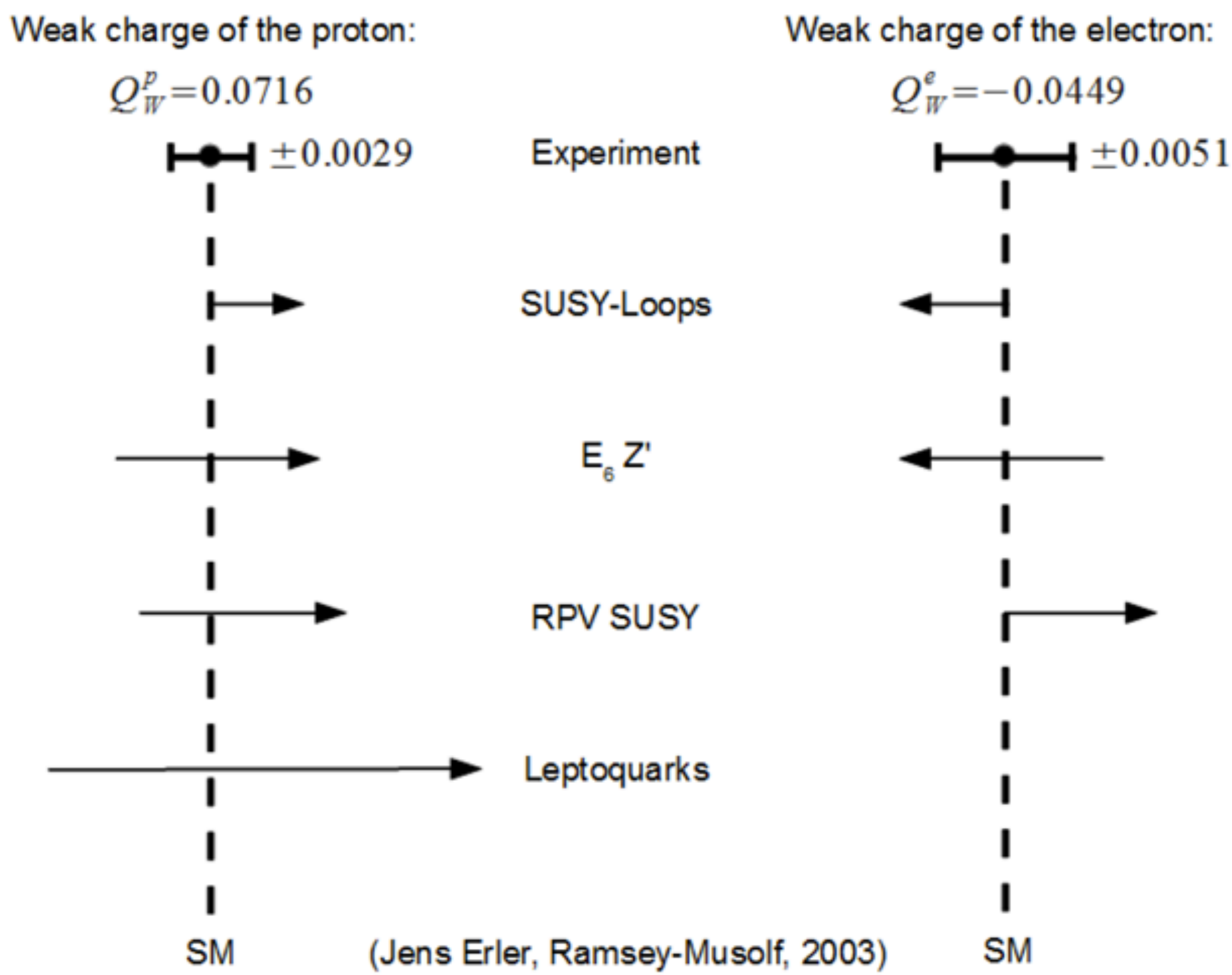


Ramsey-Musolf and Su, ***Phys. Rep. 456 (2008)***




90% exclusion limits
$M_{Z'}$ = 1.2 TeV
E158
Qweak (4%)
SOLID (0.57%)
SOLID (0.6%)
SOLID (0.55%)
MOLLER (2.3%)
Qweak (2.1%)
Qweak (2.1%)+MOLLER (2.3%)
Z_ψ
Z_N
Z_{R1}
Z_I
Z_S
Z_χ
Z_{ALR}
Z_R
Z_Y
Z_{LR}
Z_{B-L}
Z^+_{u-int}
Z_{L1}
Z_η
$Z_{\not d}$
$Z_{\not p}$
$Z_{\not \eta}$
$Z_{\not L}$
β
α cos β
1
0
-1

- Complementary access by weak charges of proton and electron



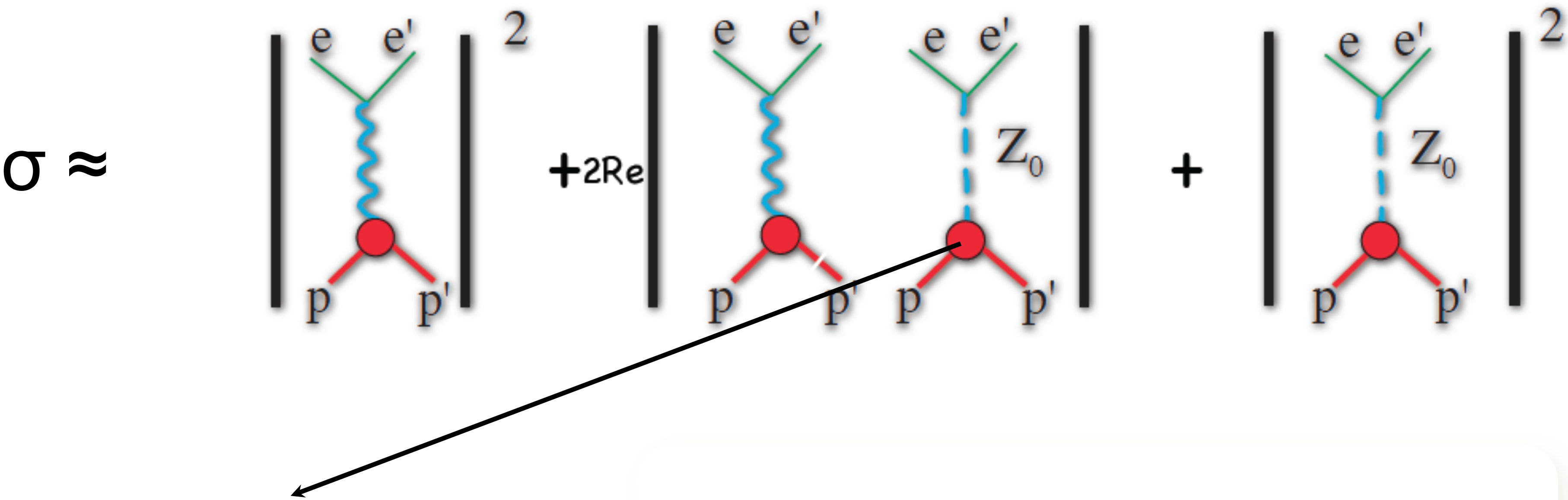
Physics sensitivity from contact interaction

	precision	$\Delta \sin^2\bar{\theta}_W(0)$	Λ_{new} (expected)
APV Cs	0.58 %	0.0019	32.3 TeV
E158	14 %	0.0013	17.0 TeV
Qweak I	19 %	0.0030	17.0 TeV
Qweak final	4.5 %	0.0008	33 TeV
PVDIS	4.5 %	0.0050	7.6 TeV
SoLID	0.6 %	0.00057	22 TeV
MOLLER	2.3 %	0.00026	39 TeV
P2	2.0 %	0.00036	49 TeV
PVES ^{12}C	0.3 %	0.0007	49 TeV

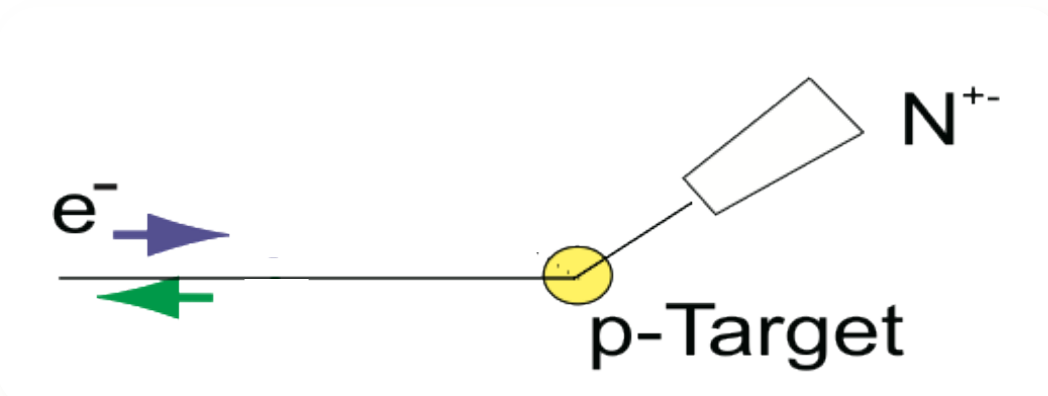
Jens Erler

Experimental Method

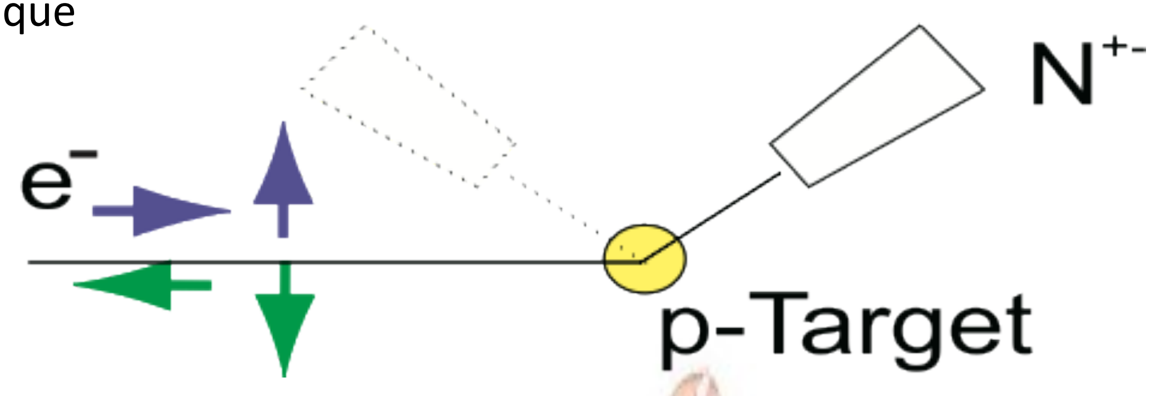
Parity Violating Asymmetry in elastic electron proton scattering



V-A coupling:
parity-violating
cross section asymmetry A_{LR}
longitudinally pol. electrons
unpolarised protons

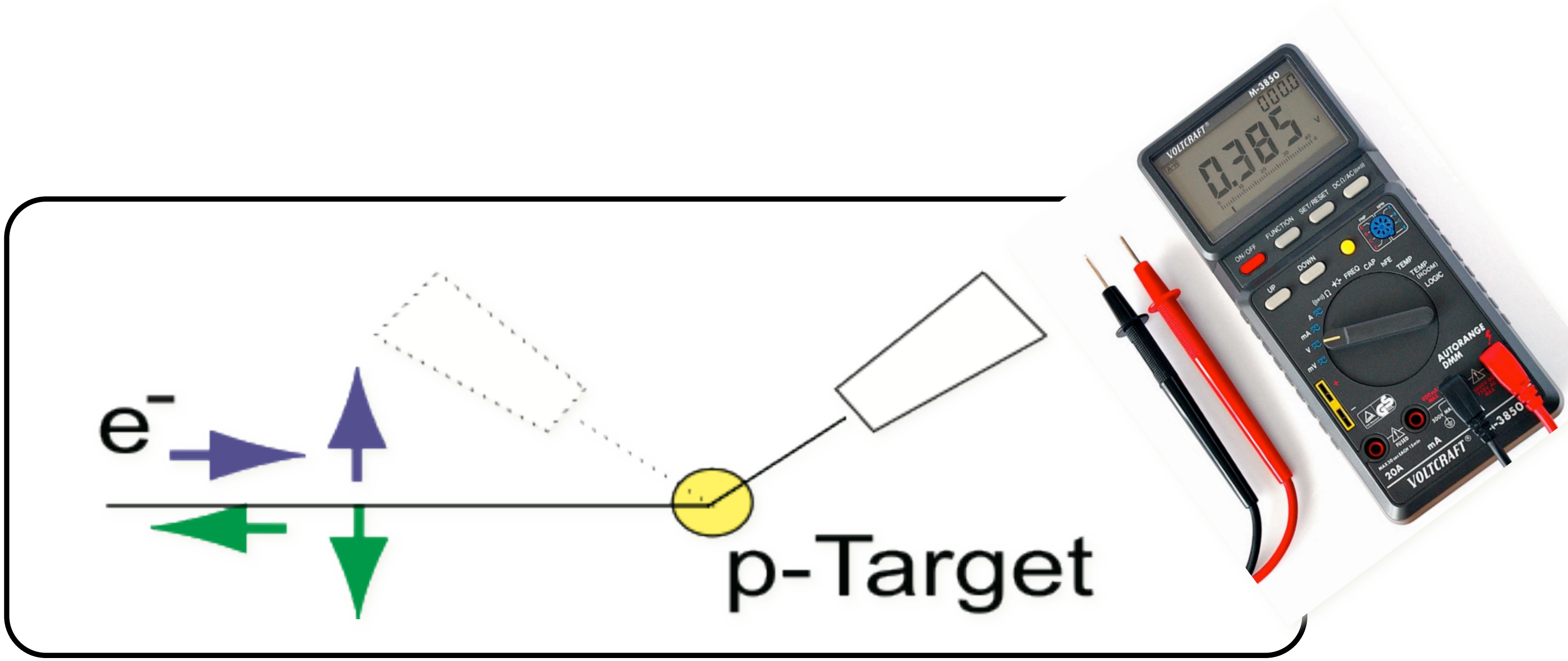


Counting Technique



Count scattered electrons:
- pile-up (double count losses)
- Background Asymmetry
- Very Fast Counting (MHz)
- Measure TOF or Energy

Analogue Technique



Measure Flux of Scattered electrons:
- no pile-up (double count losses)
- sensitive to small electr. fields.
- no separation of phys. process

Parity violating cross section asymmetry

weak charge

$$A_{LR} = \frac{\sigma(e\uparrow) - \sigma(e\downarrow)}{\sigma(e\uparrow) + \sigma(e\downarrow)} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left(Q_W - F(Q^2)\right)$$

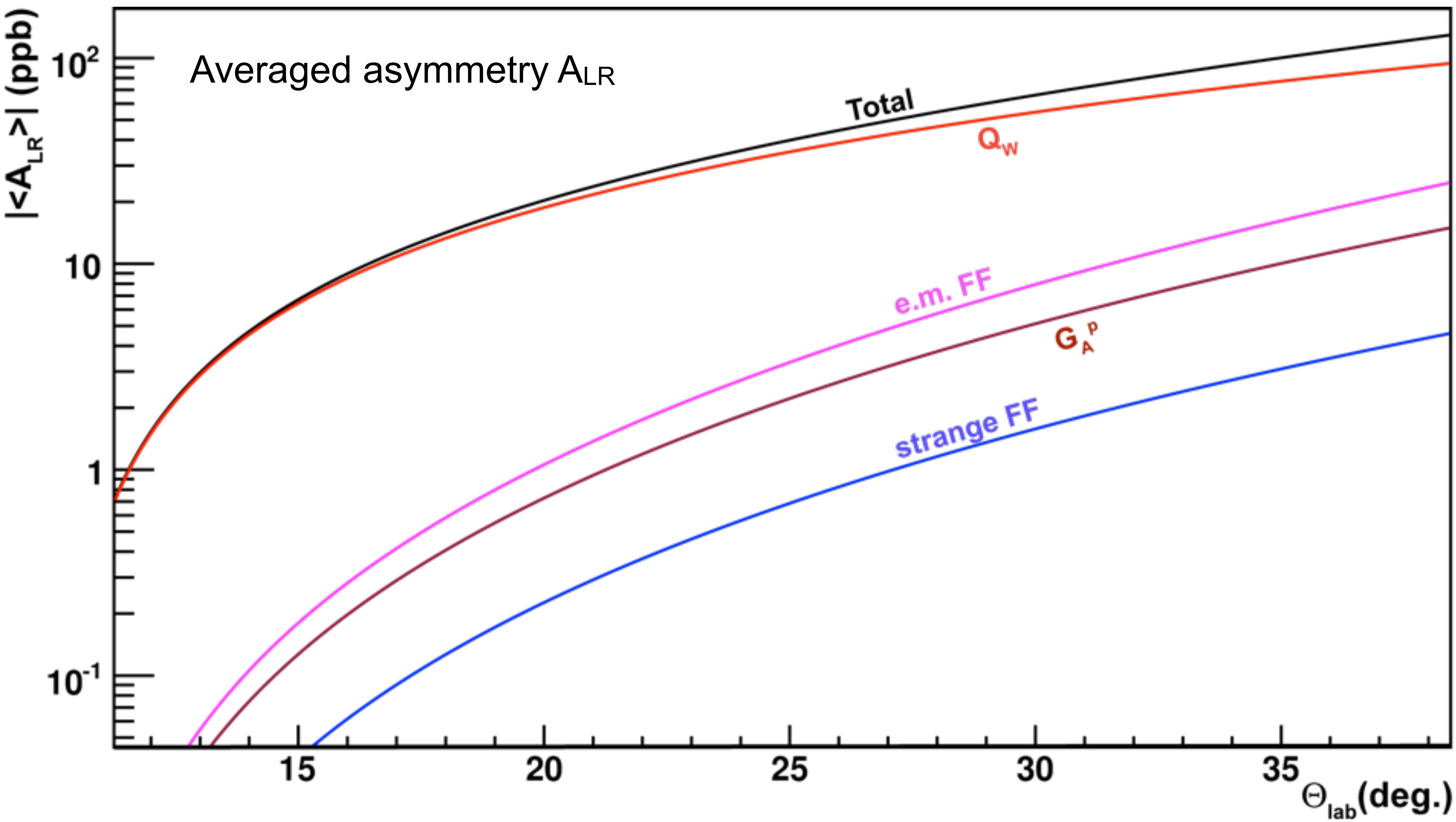
$$Q_W = 1 - 4\sin^2\theta_W(\mu)$$

hadron structure

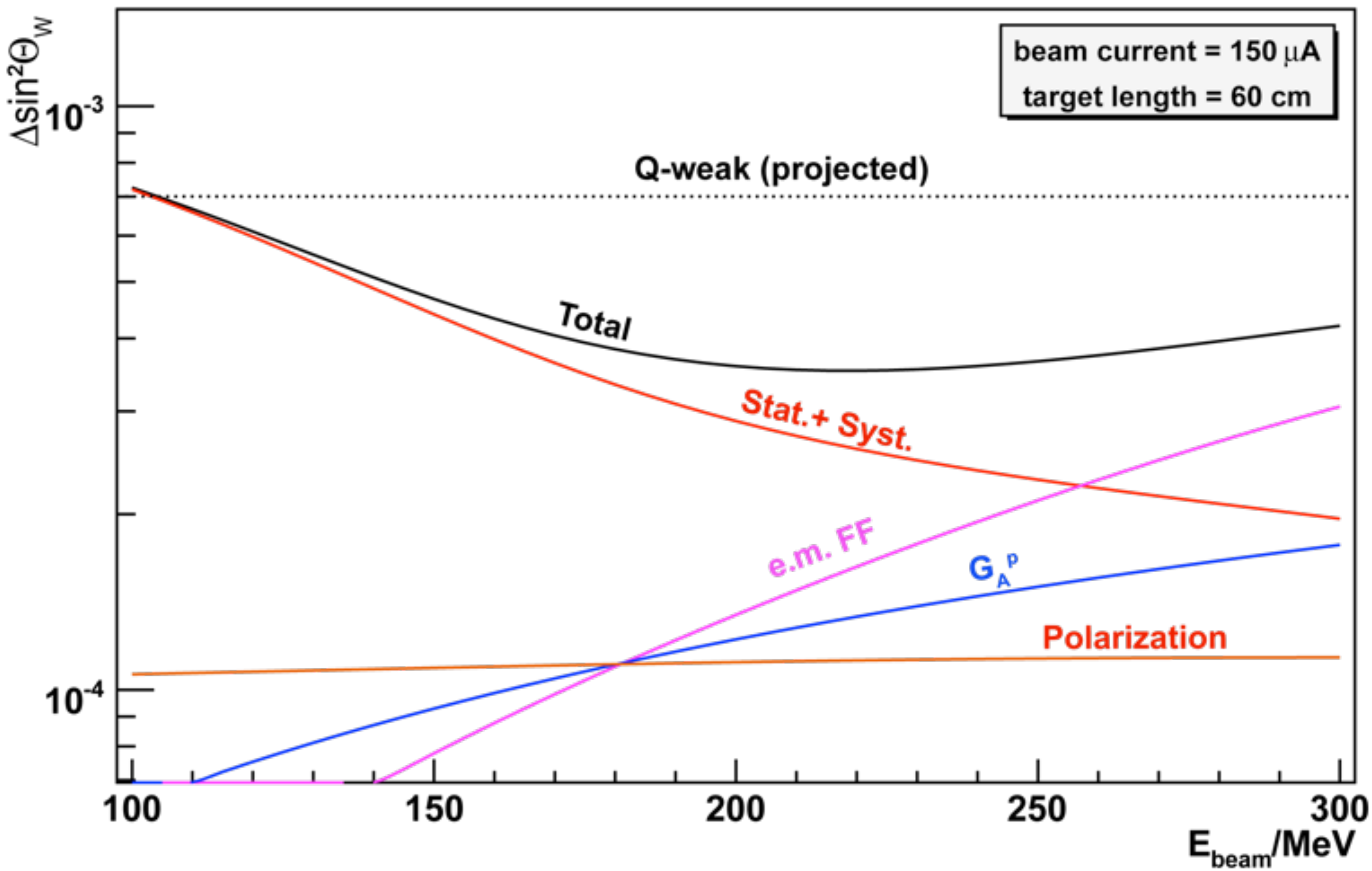
$$F(Q^2) = F_{EM}(Q^2) + F_{Axial}(Q^2) + F_{Strange}(Q^2)$$

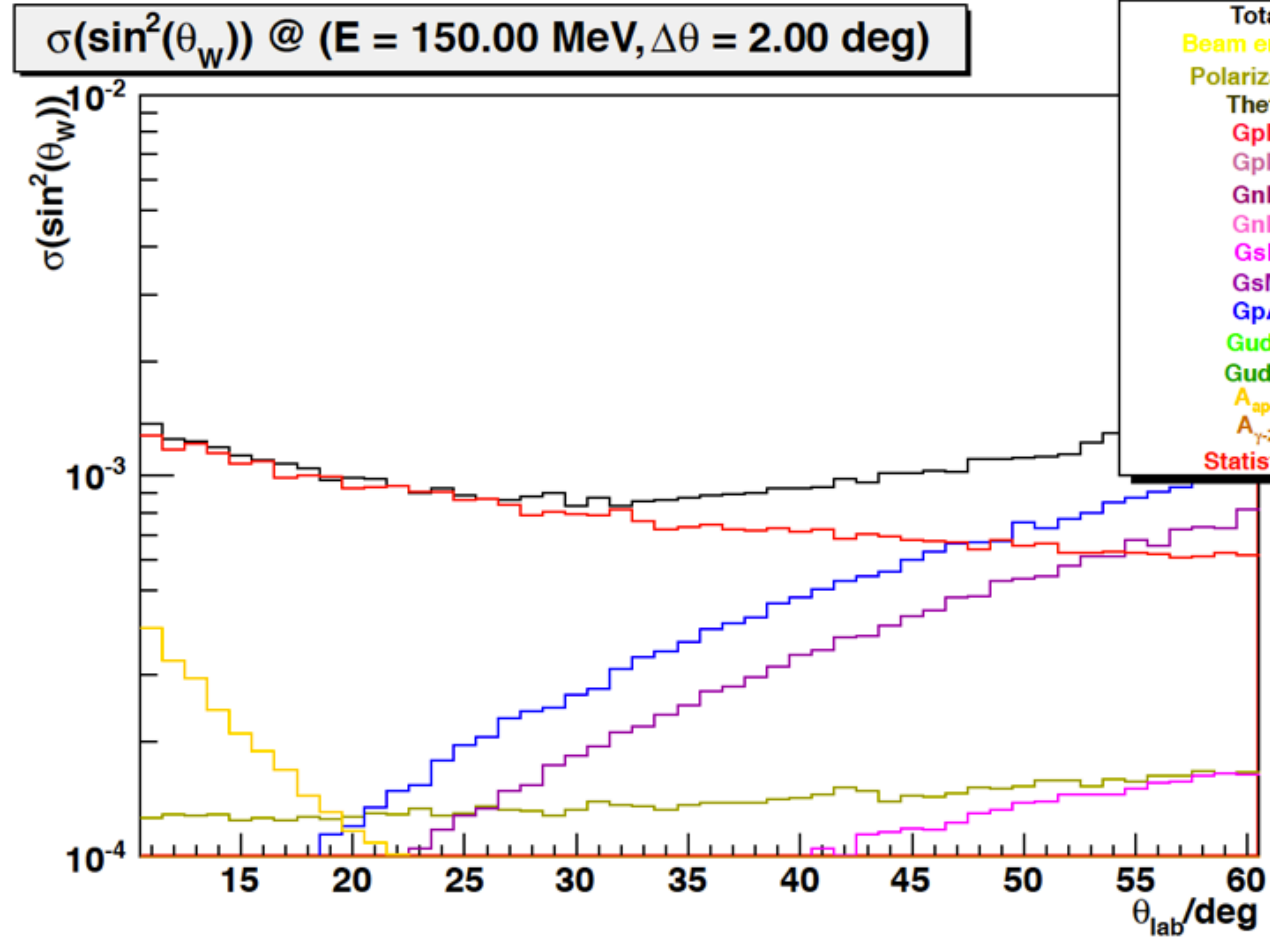
Important input from other projects (S1, S3)

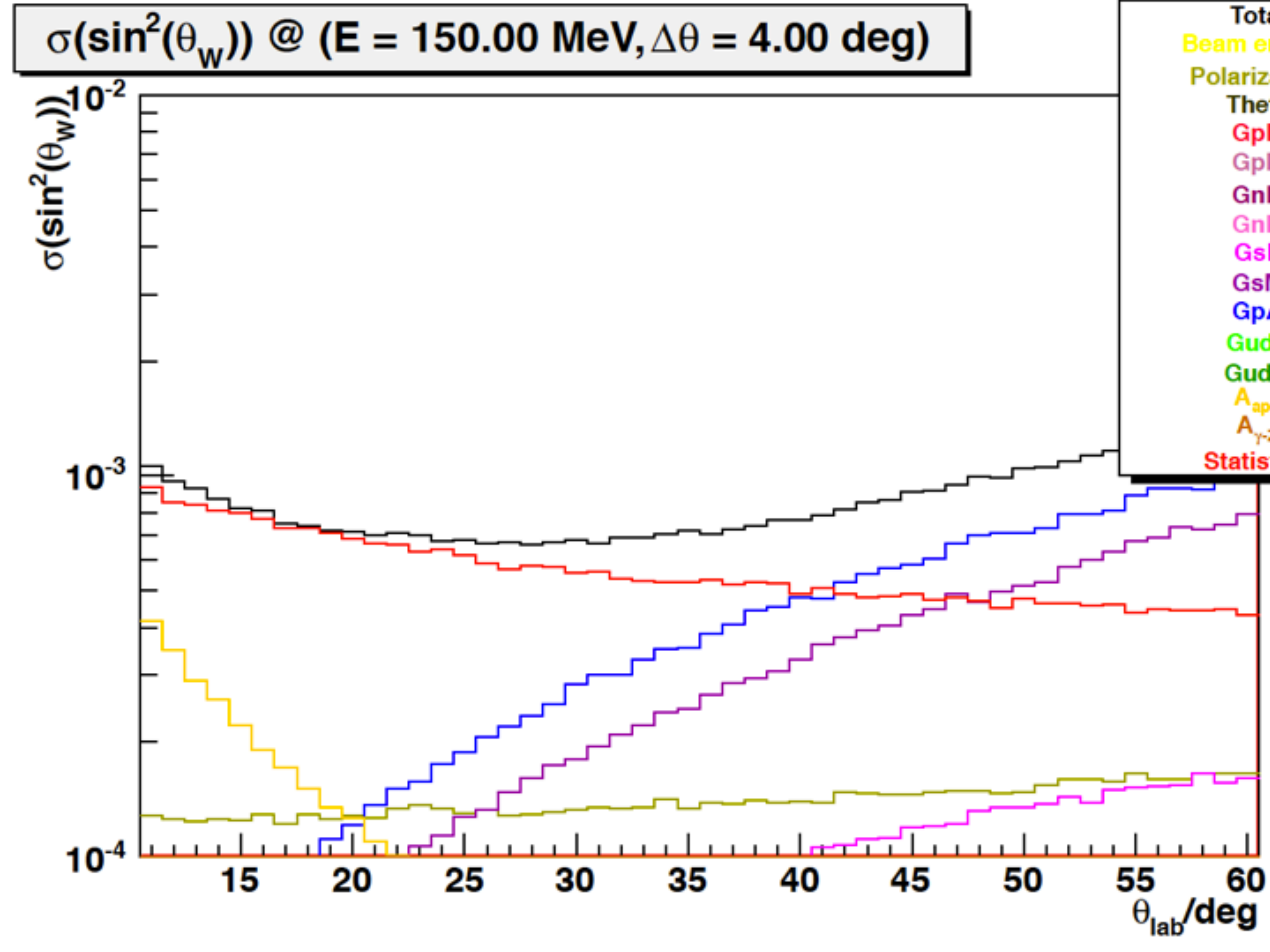
Parity violating cross section asymmetry



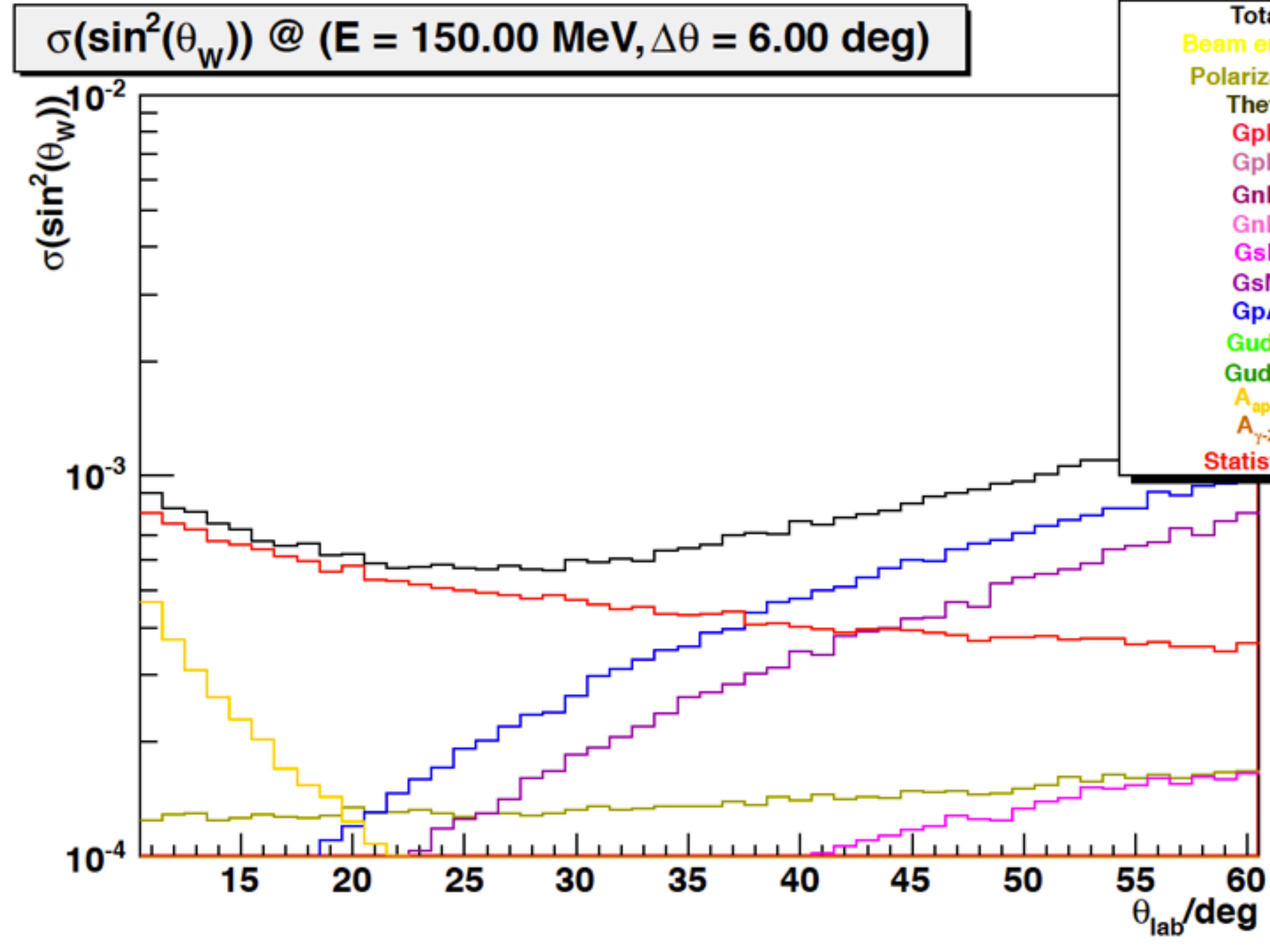
Precision in Determination of $\sin^2 \theta_W$

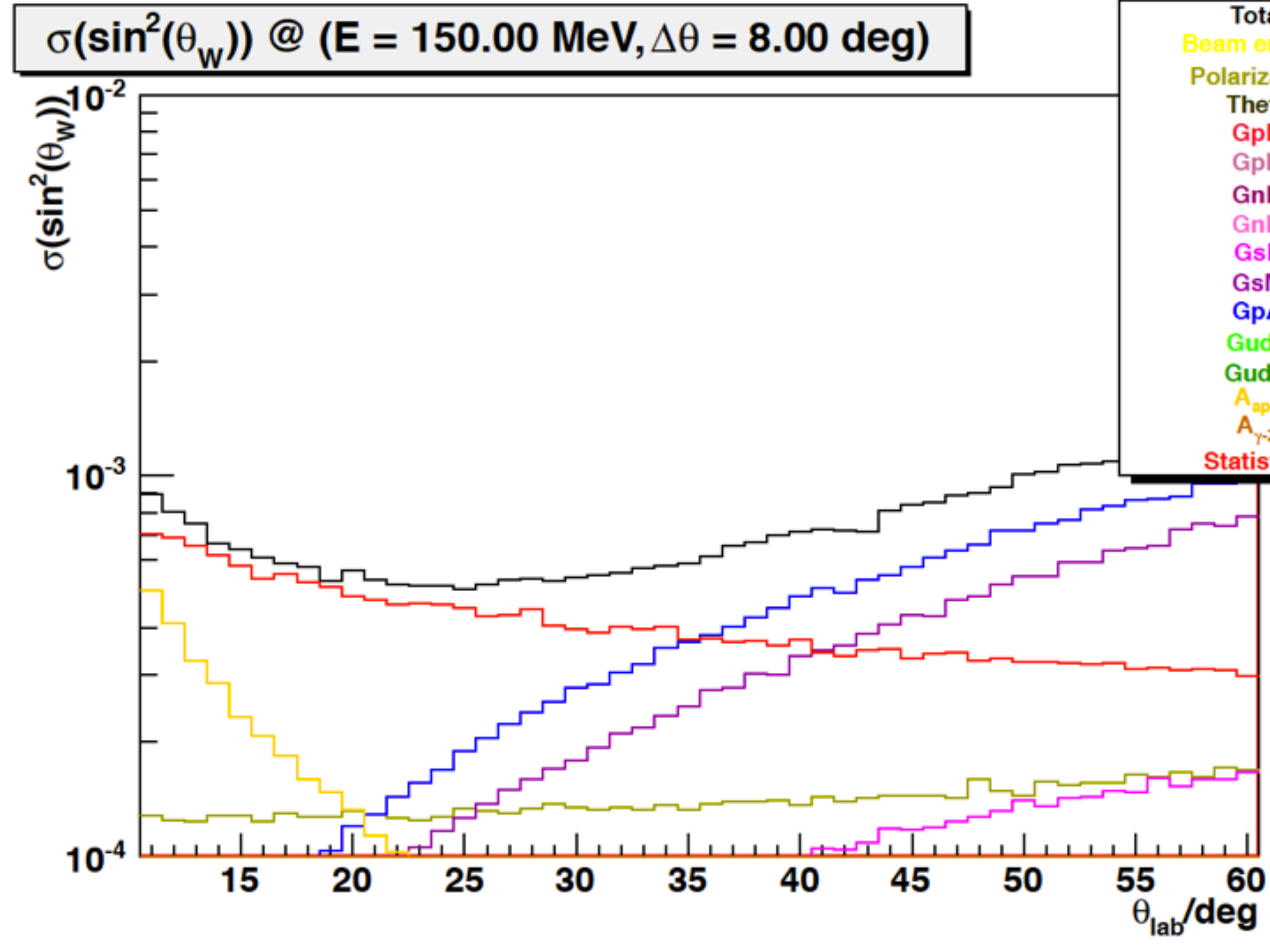



σ(sin²(θ_W)) @ (E = 150.00 MeV, Δθ = 2.00 deg)
σ(sin²(θ_W))
10⁻²
10⁻³
10⁻⁴
15
20
25
30
35
40
45
50
55
60
θ_lab/deg
Tota
Beam e
Polariz
Thet
Gpl
Gpl
Gnl
Gnl
Gsl
Gsl
Gp
Gud
Gud
Statis

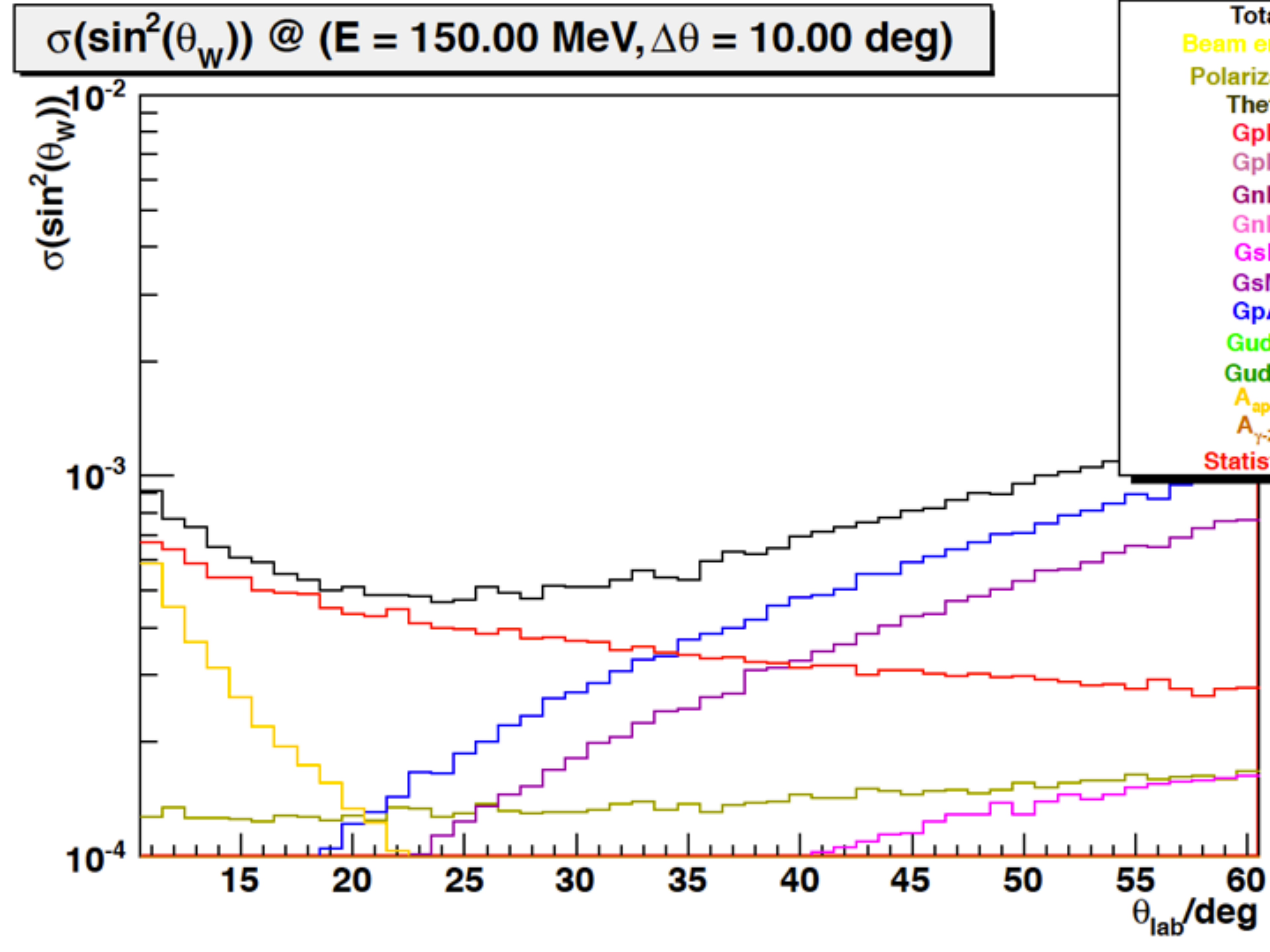


σ(sin²(θ_W)) @ (E = 150.00 MeV, Δθ = 4.00 deg)
σ(sin²(θ_W))
10⁻²
10⁻³
10⁻⁴
15
20
25
30
35
40
45
50
55
60
θ_lab/deg
Tota
Beam e
Polariz
The
Gp
Gp
Gn
Gn
Gs
Gs
Gp
Gud
Gud
A
A
Statis

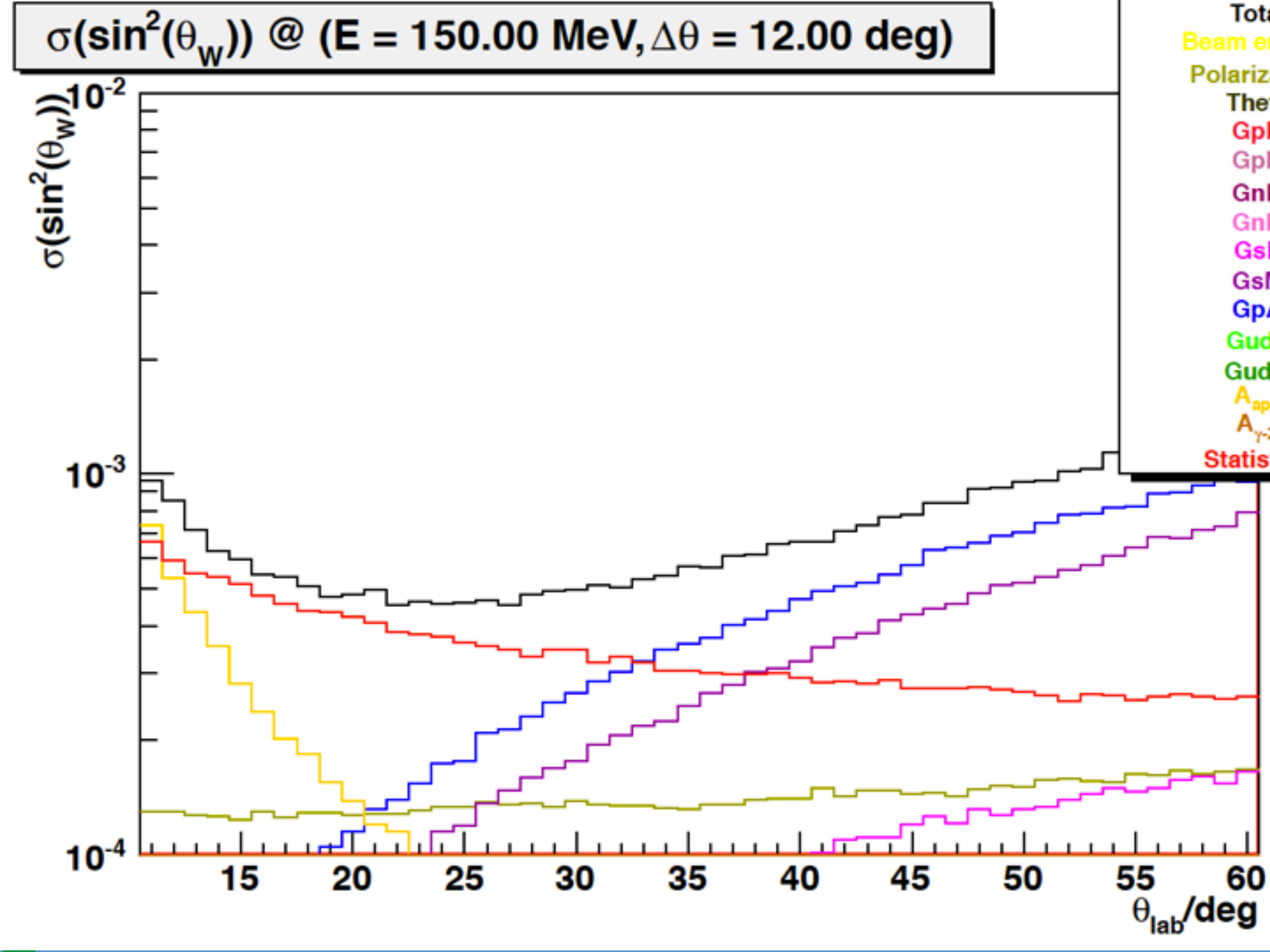

σ(sin²(θ_W)) @ (E = 150.00 MeV, Δθ = 6.00 deg)
σ(sin²(θ_W))
θ_lab/deg
10⁻²
10⁻³
10⁻⁴
15
20
25
30
35
40
45
50
55
60



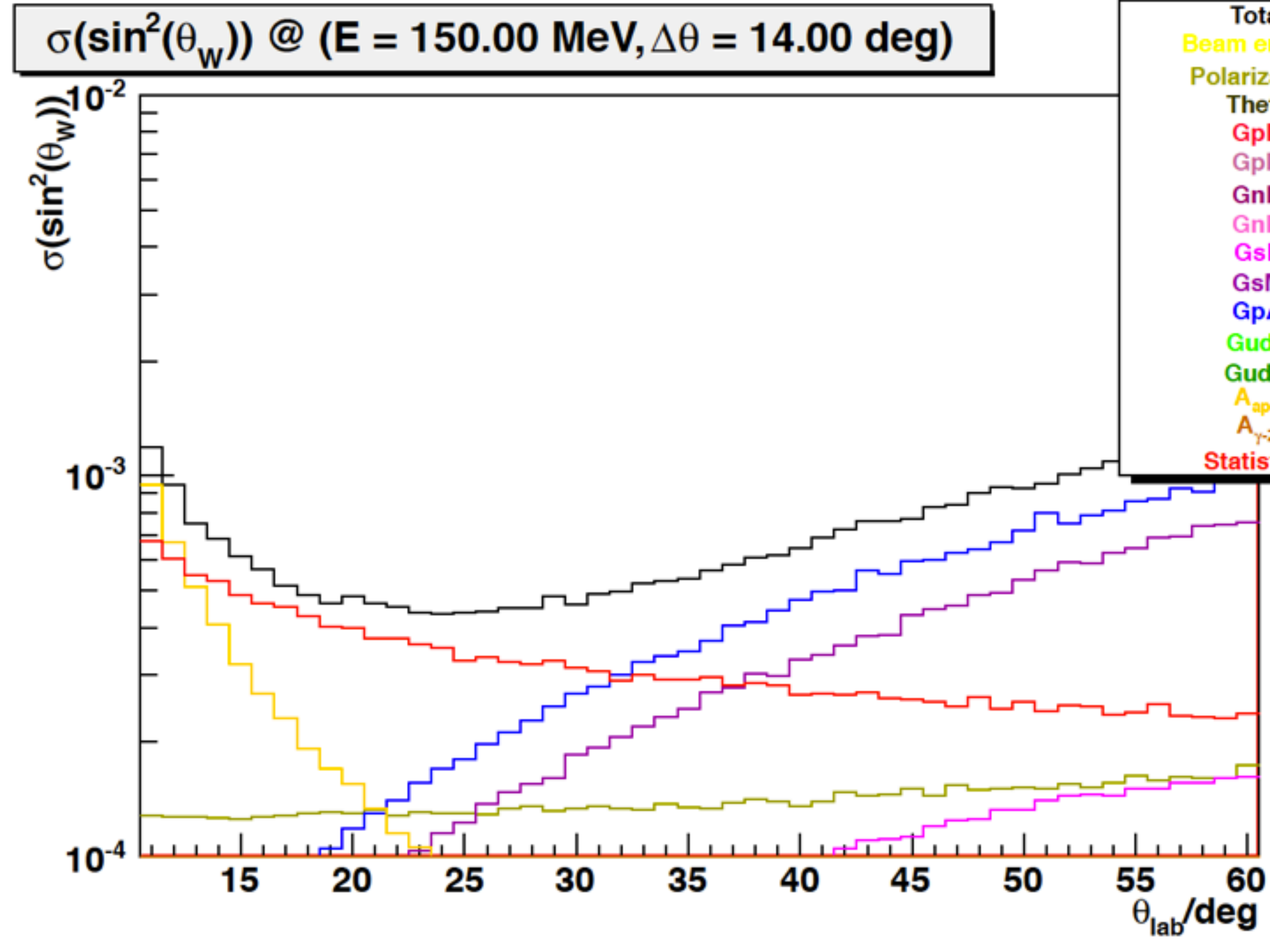
σ(sin²(θ_W)) @ (E = 150.00 MeV, Δθ = 8.00 deg)
σ(sin²(θ_W))
10⁻²
10⁻³
10⁻⁴
15
20
25
30
35
40
45
50
55
60
θ_lab/deg

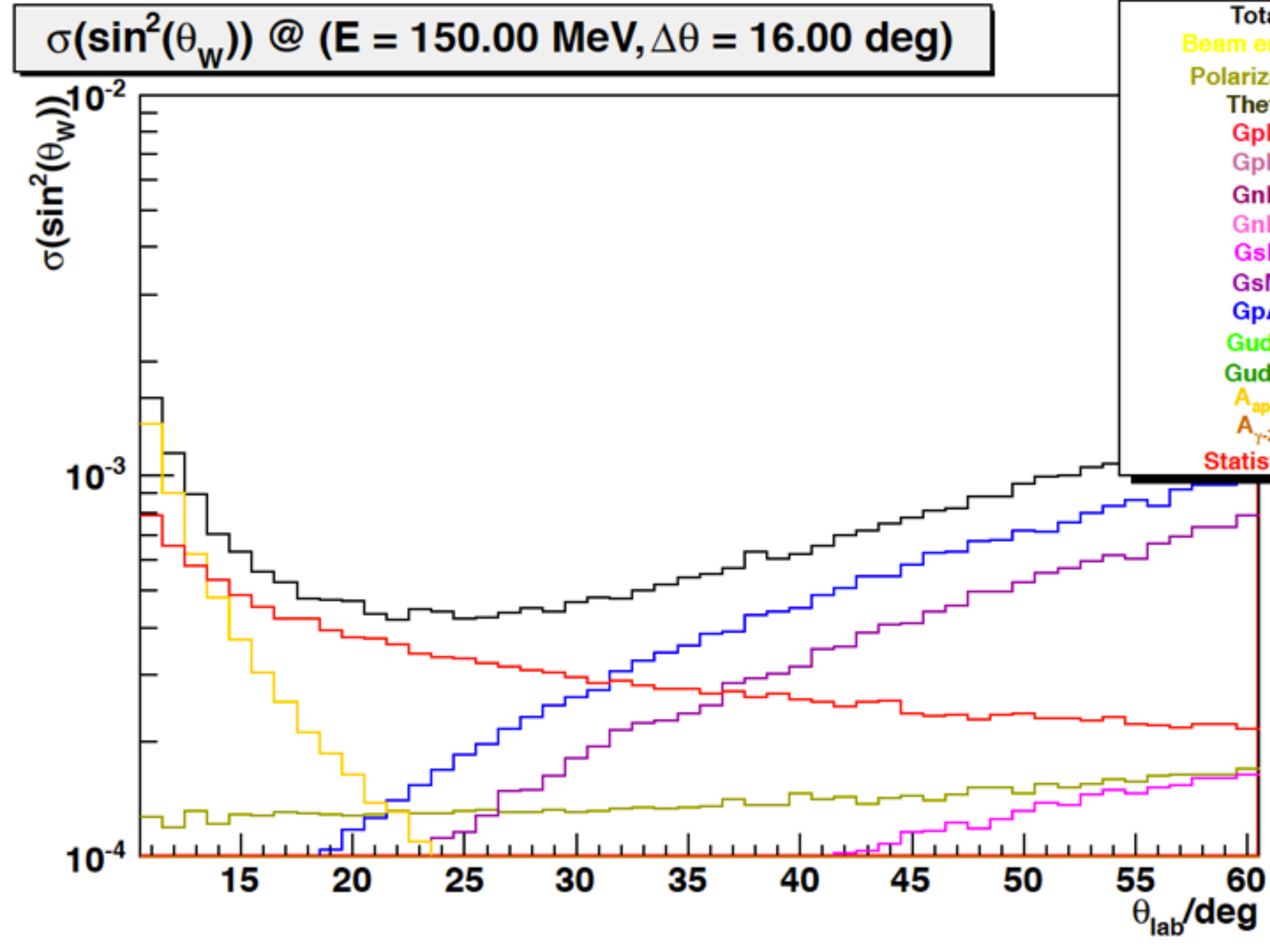


σ(sin²(θ_W)) @ (E = 150.00 MeV, Δθ = 10.00 deg)
σ(sin²(θ_W))
10⁻²
10⁻³
10⁻⁴
15
20
25
30
35
40
45
50
55
60
θ_lab/deg

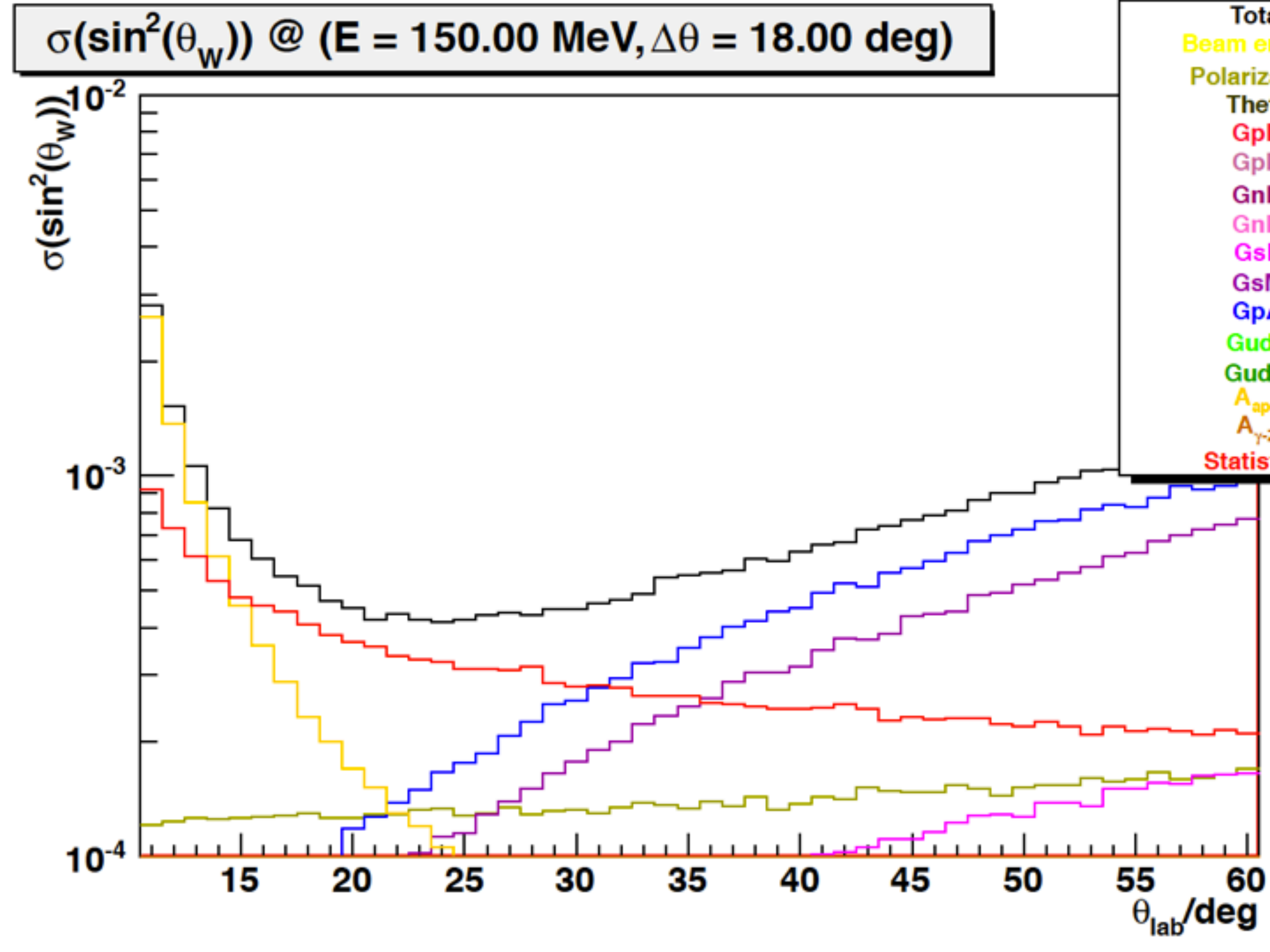


σ(sin²(θ_W)) @ (E = 150.00 MeV, Δθ = 12.00 deg)
σ(sin²(θ_W))
10⁻²
10⁻³
10⁻⁴
15
20
25
30
35
40
45
50
55
60
θ_lab/deg

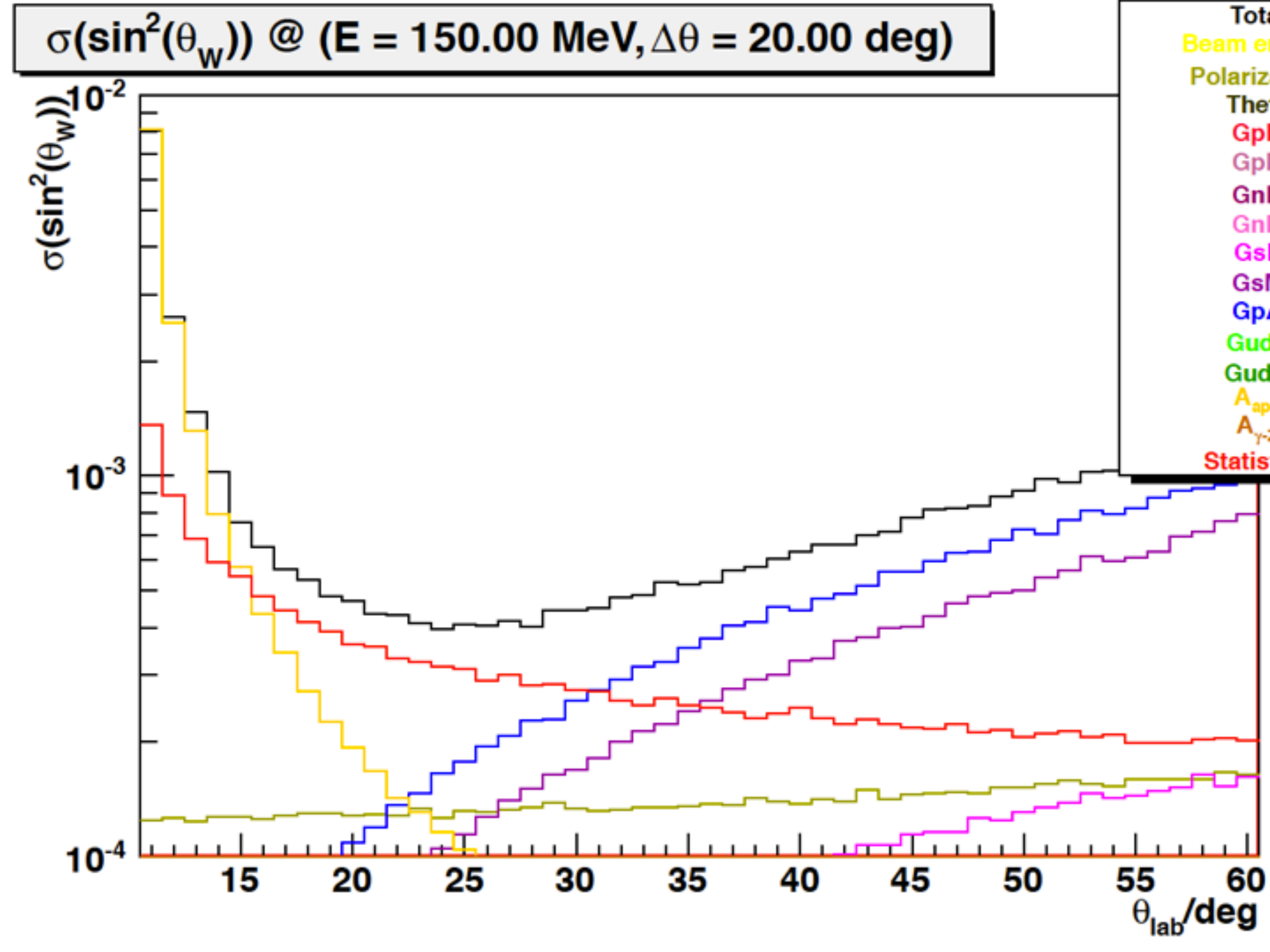

σ(sin²(θ_W)) @ (E = 150.00 MeV, Δθ = 14.00 deg)
σ(sin²(θ_W))
10^-2
10^-3
10^-4
15
20
25
30
35
40
45
50
55
60
θ_lab/deg
Beam e
Polariz
Statis



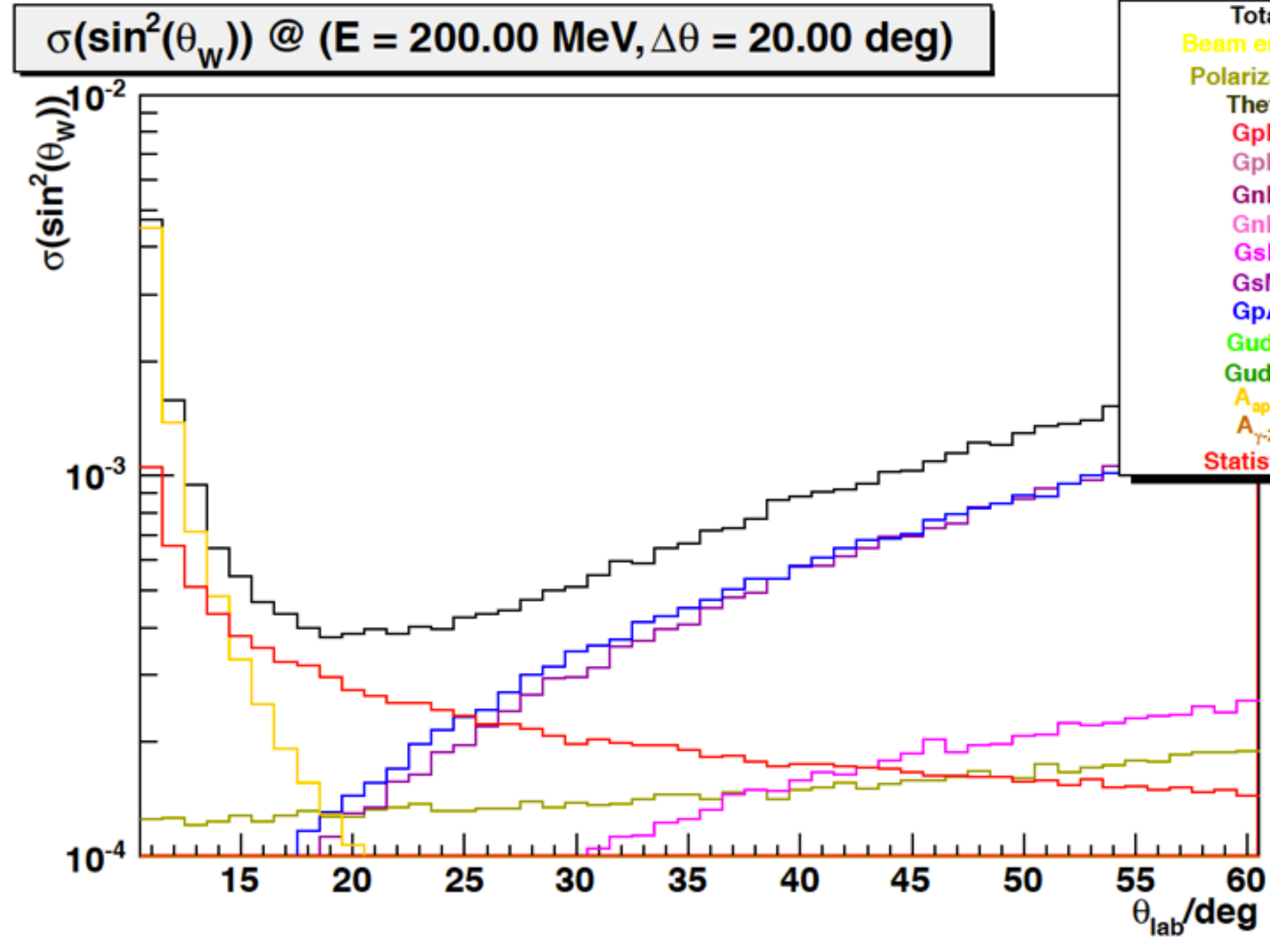
σ(sin²(θ_W)) @ (E = 150.00 MeV, Δθ = 16.00 deg)
σ(sin²(θ_W))
θ_lab/deg
10⁻²
10⁻³
10⁻⁴
15
20
25
30
35
40
45
50
55
60

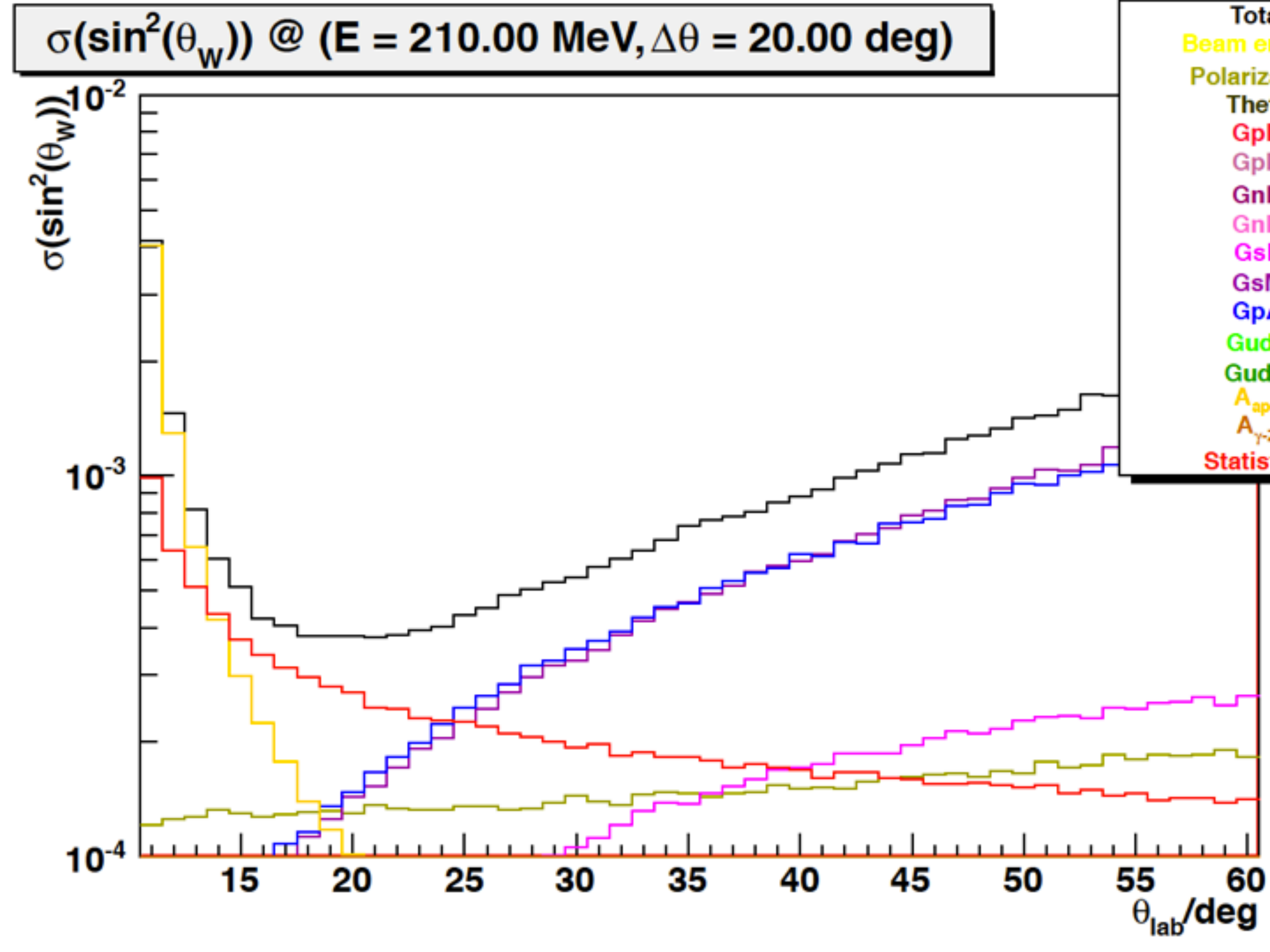


σ(sin²(θ_W)) @ (E = 150.00 MeV, Δθ = 18.00 deg)
σ(sin²(θ_W))
10^-2
10^-3
10^-4
15
20
25
30
35
40
45
50
55
60
θ_lab/deg

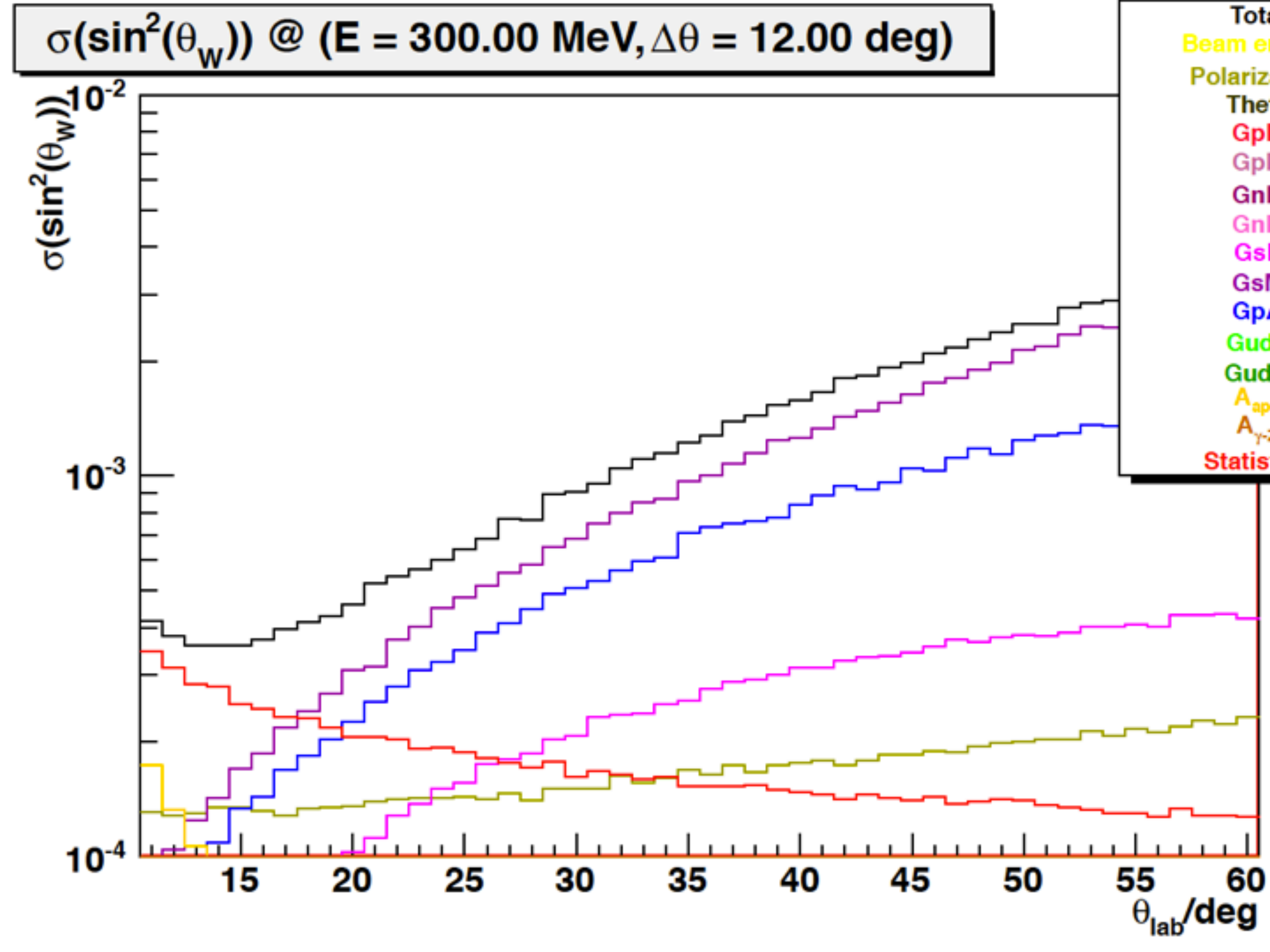


σ(sin²(θ_W)) @ (E = 150.00 MeV, Δθ = 20.00 deg)
σ(sin²(θ_W))
10⁻²
10⁻³
10⁻⁴
15
20
25
30
35
40
45
50
55
60
θ_lab/deg

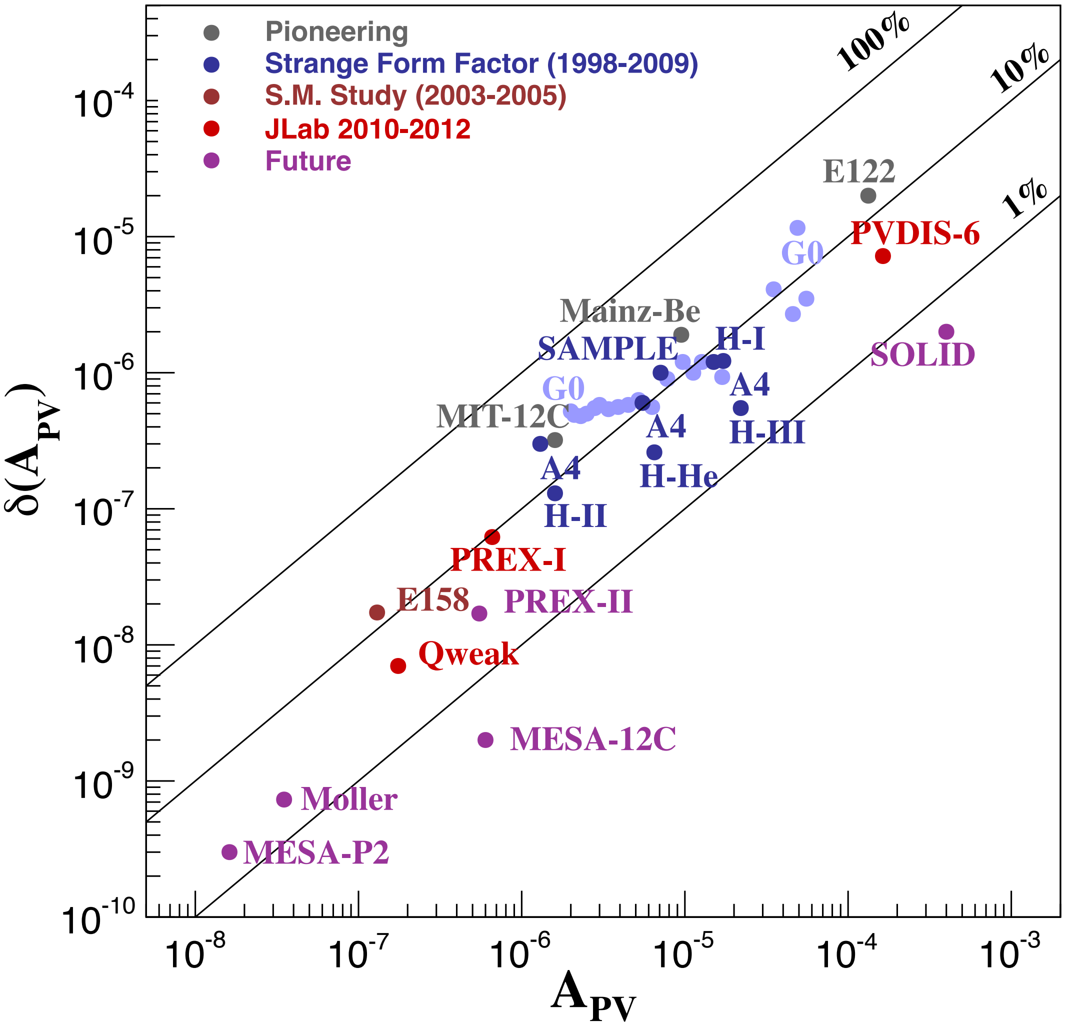

σ(sin²(θW)) @ (E = 200.00 MeV, Δθ = 20.00 deg)
σ(sin²(θW))
10⁻²
10⁻³
10⁻⁴
15
20
25
30
35
40
45
50
55
60
θlab/deg



σ(sin²(θ_W)) @ (E = 210.00 MeV, Δθ = 20.00 deg)
σ(sin²(θ_W))
10^-2
10^-3
10^-4
15
20
25
30
35
40
45
50
55
60
θ_lab/deg
Beam en
Polariz


σ(sin²(θ_W)) @ (E = 300.00 MeV, Δθ = 12.00 deg)
σ(sin²(θ_W))
10⁻²
10⁻³
10⁻⁴
15
20
25
30
35
40
45
50
55
60
θ_lab/deg
Tota
Beam e
Polariz
The
Gp
Gp
Gn
Gn
Gs
Gs
Gp
Gu
Gu
A
A
Statis

PVeS Experiment Summary



Physics Reach

Roger Carlini (co-chair)
Frank Maas (co-chair)
Richard Milner (co-chair)
+ many conveners

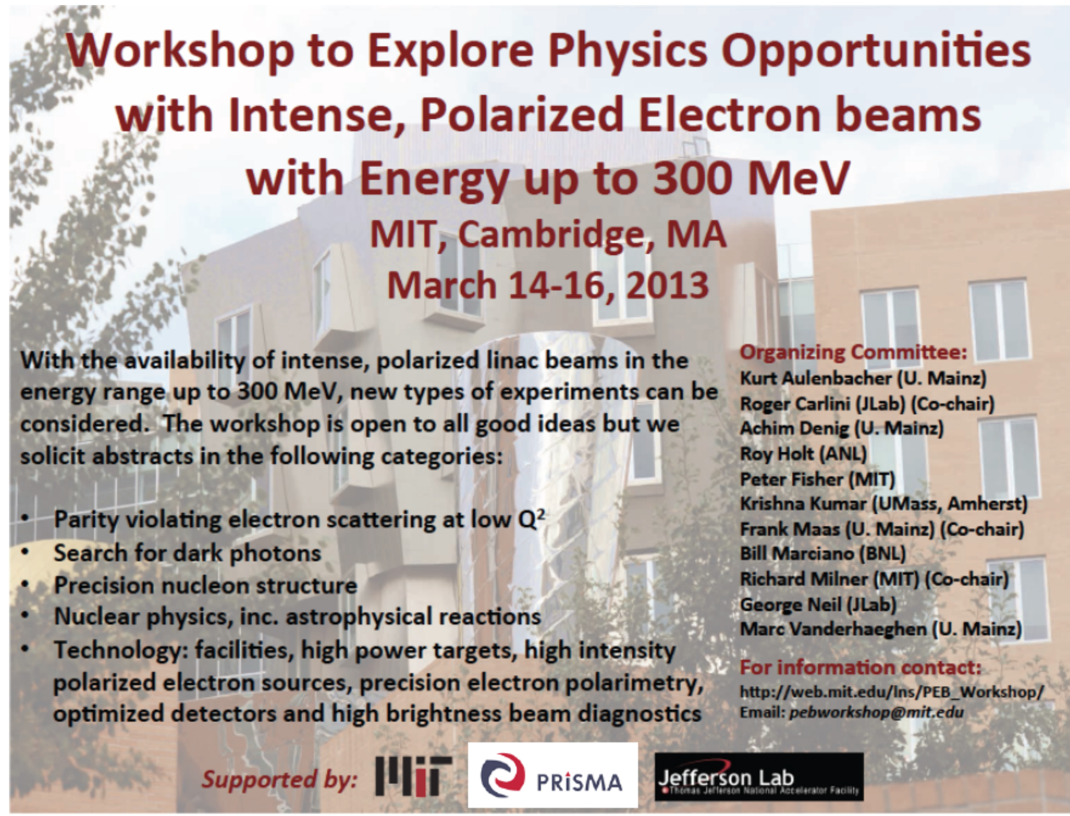
P2 and "beyond":

- Studied additional backward angle Measurement (G_A, G_M^s): S.Baunack

- Studied additional measurement on Carbon: K. Gerz

- Studied different beam energies: D. Becker

- Studied additional measurement in heavier nuclei (lead): C.Sfienti



P2 Parameters

E_{Beam}	200 MeV
Q^2/θ_e	0.0048 GeV^2/20°
Time/current/target	10000h/150μA/60cm
A_{phys}	-20.25 ppb
ΔA_{tot}	0.34 ppb (1.7 %)
ΔA_{stat}	0.25 ppb
ΔA_{sys}	0.19 ppb (0.9%)
Polarization	(85 ± 0.5) %
Rate	0.44 10^{12} Hz
$\Delta \sin^2 \theta_{W\ stat}$	2.8 10^{-4}
$\Delta \sin^2 \theta_{W\ tot}$	3.6 10^{-4} (0.15 %)

High rates: 440 GHz, polarization precision: 0.5 %

General Experiment Kinematics

Comparison: P2 with and without back angle measurement

Without back angle measurement

E/MeV	θ/deg	Δθ/deg	$\Delta\sin^2(\theta_w)/10^{-4}$	$\Delta\sin^2(\theta_w)/\sin^2(\theta_w)$
240	17	18	3.57	0.15 %
200	20	20	3.60	0.15 %
150	24	20	3.97	0.17 %
130	25	20	4.33	0.18 %

With back angle measurement

E/MeV	θ/deg	Δθ/deg	$\Delta\sin^2(\theta_w)/10^{-4}$	$\Delta\sin^2(\theta_w)/\sin^2(\theta_w)$
240	24	18	2.41	0.10 %
200	28	16	2.52	0.11 %
150	33	18	2.73	0.11 %
130	37	18	2.87	0.12 %

→

- $\Delta\sin^2(\theta_w)$ drops from $3.60\cdot10^{-4}$ to $2.52\cdot10^{-4}$ → possible reduction of Δt
- $\sin^2(\theta_w)$-measurement at larger scattering angles (more easy to measure)

Polarimetry (<0.5%)

The double scattering Mott polarimeter:

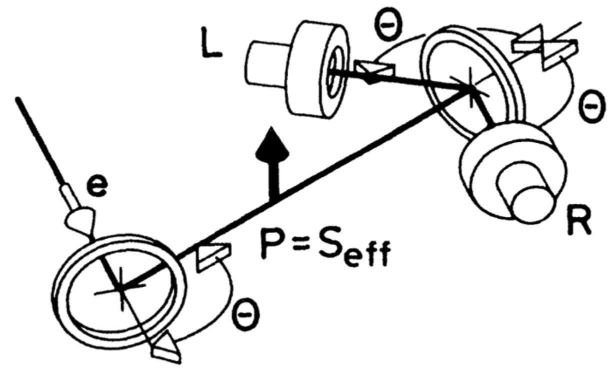
Mott Polarimeter:

- Measuring left/right asymetry to calculate spin polarisation
- Analysing power of target foils has to be extrapolated

Double Scattering Polarimeter (DSP):

- Analysing power of the targets can be calculated directly from measurements
- Allows for higher precision measurement of spin polarisation

- Invasive polarimetry at the electron source



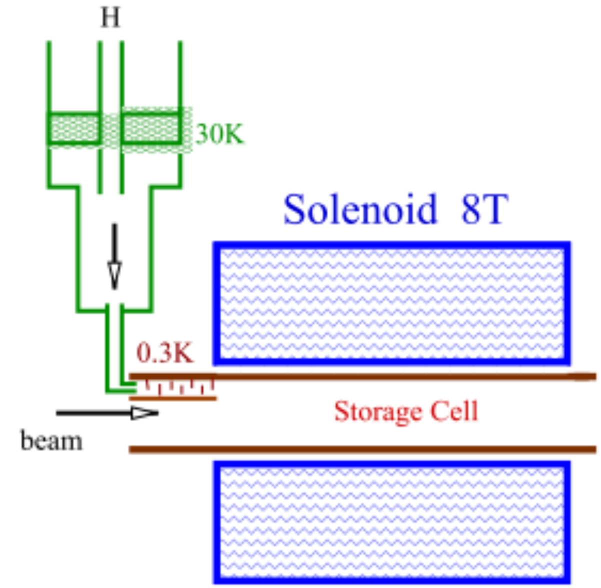
A. Gellrich and J. Kessler, Phys. Rev. A 43, 204 (1991)

Hydro Möller Polarimeter

The promise:(*)

- **Hydro-Möller: Atomic trap with completely electron-spin polarized Hydrogen**
- **Online capability, high accuracy (<0.5%)**
- **Statistical efficiency approaches 0.5% in 2 hours (Target: $3*10^{-16}$ cm^{-2})**
- **Acceptance similar to conventional Möller**

(*)E. Chudakov, V. Luppov: IEEE Trans. Nucl. Sc. 51, 1533 (2004)



Corroded $^3He/^4He$ dilution Refrigerator (achieved 27mW(*) At 0.35K)

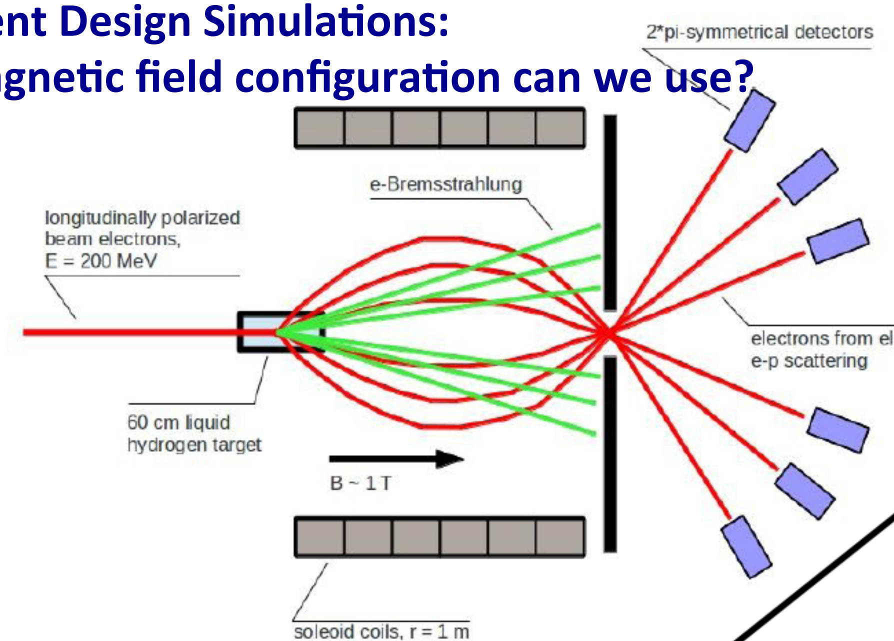
Solenoid (Beam) axis

Complete trap with 77mm diam.
Cold bore 7T Solenoid
$\Delta B/B < 10^{-5}$ ($1cm^3$ Volume)(**)

(*): T. Roser et. al. NIM A **301** 42-46 (1990)
(**): W. Kaufmann et. al. NIM A **335** 17-25 (1993)

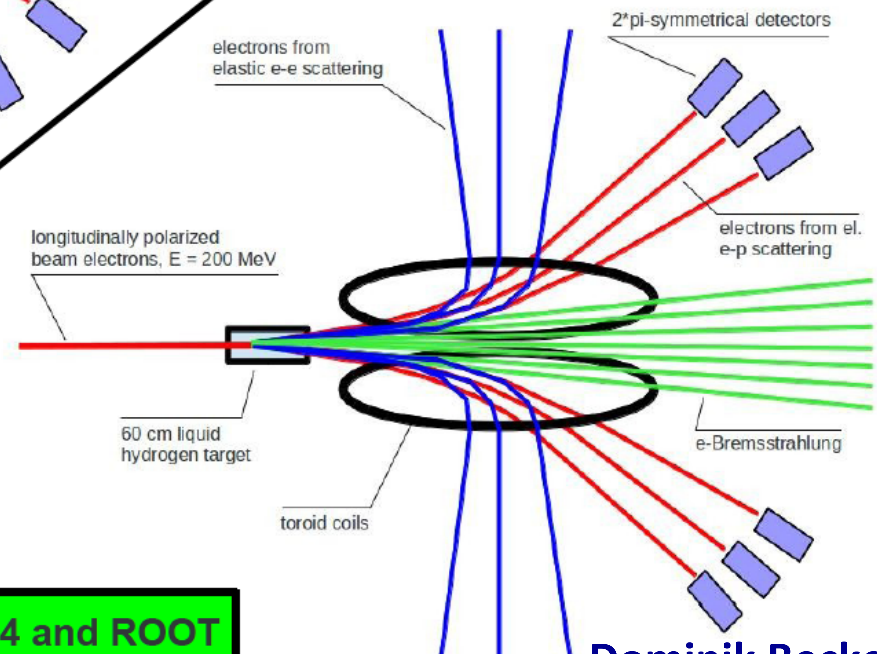
Detector Concept

Experiment Design Simulations:
What Magnetic field configuration can we use?



Solenoid:
- Full azimuthal coverage
- Compact setup
- Superconducting coils

P. Souder in "Parity violation in electron scattering"
Proceedings of a workshop at CalTeck
Ed: E. J. Beise and R. D. McKeown
World Scientific, 1990

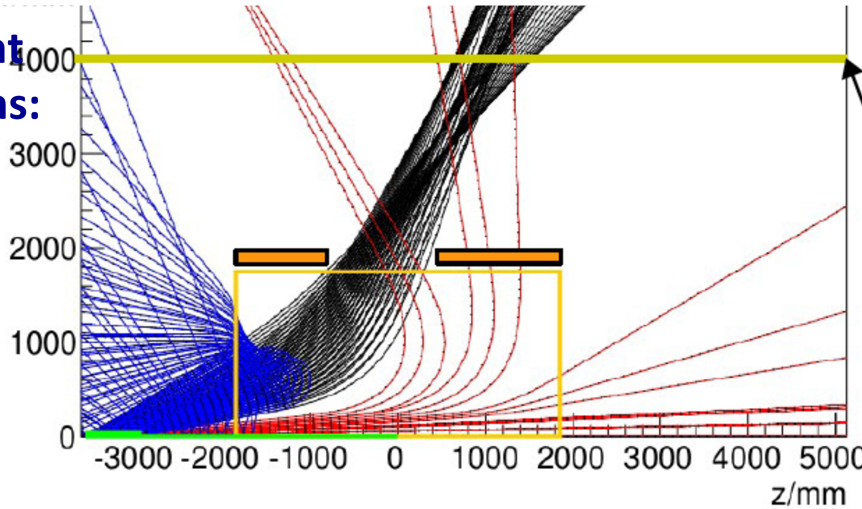


Toroid:
- Loss of ~50% solid angle
  → double measurement time
- Larger setup
- Copper coils

→ **Feasibility study with Geant4 and ROOT**

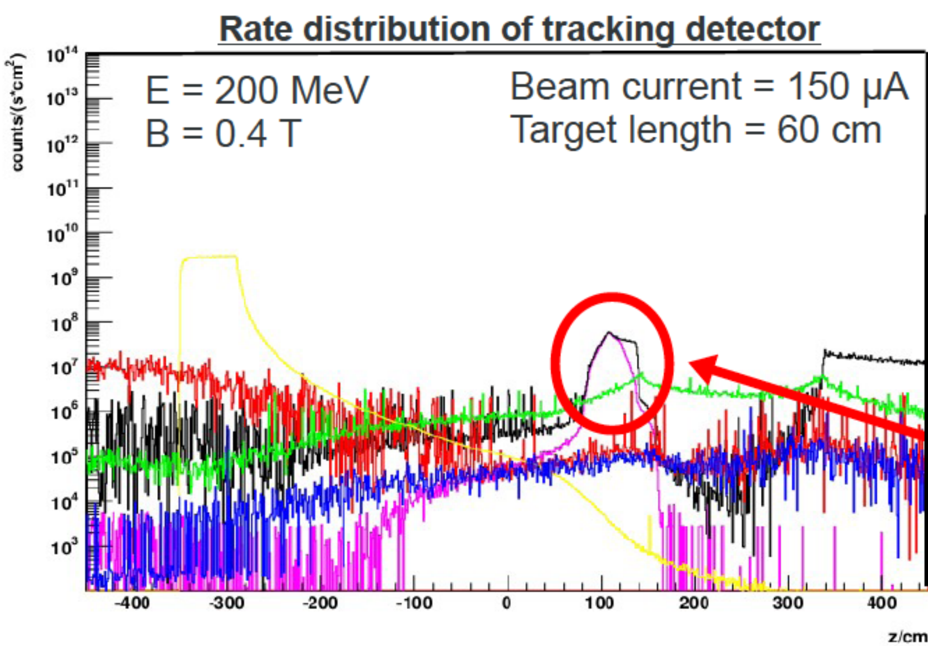
Dominik Becker

Experiment Simulations: Toroid possible!



- el. e-p scattering (black)
- Moeller scattering in [0°, 5°] (red)
- Moeller scattering in [10°, 30°] (blue)

Simple tracking detector:
- Consists of vacuum
- Analyses particles that fly through



- e-, el. e-p scattering, [10°, 30°] (magenta)
- e-, el. e-p scattering, [1°, 75°] (black)
- e-, background (red)
- e+ (blue)
- γ (green)
- p (yellow)

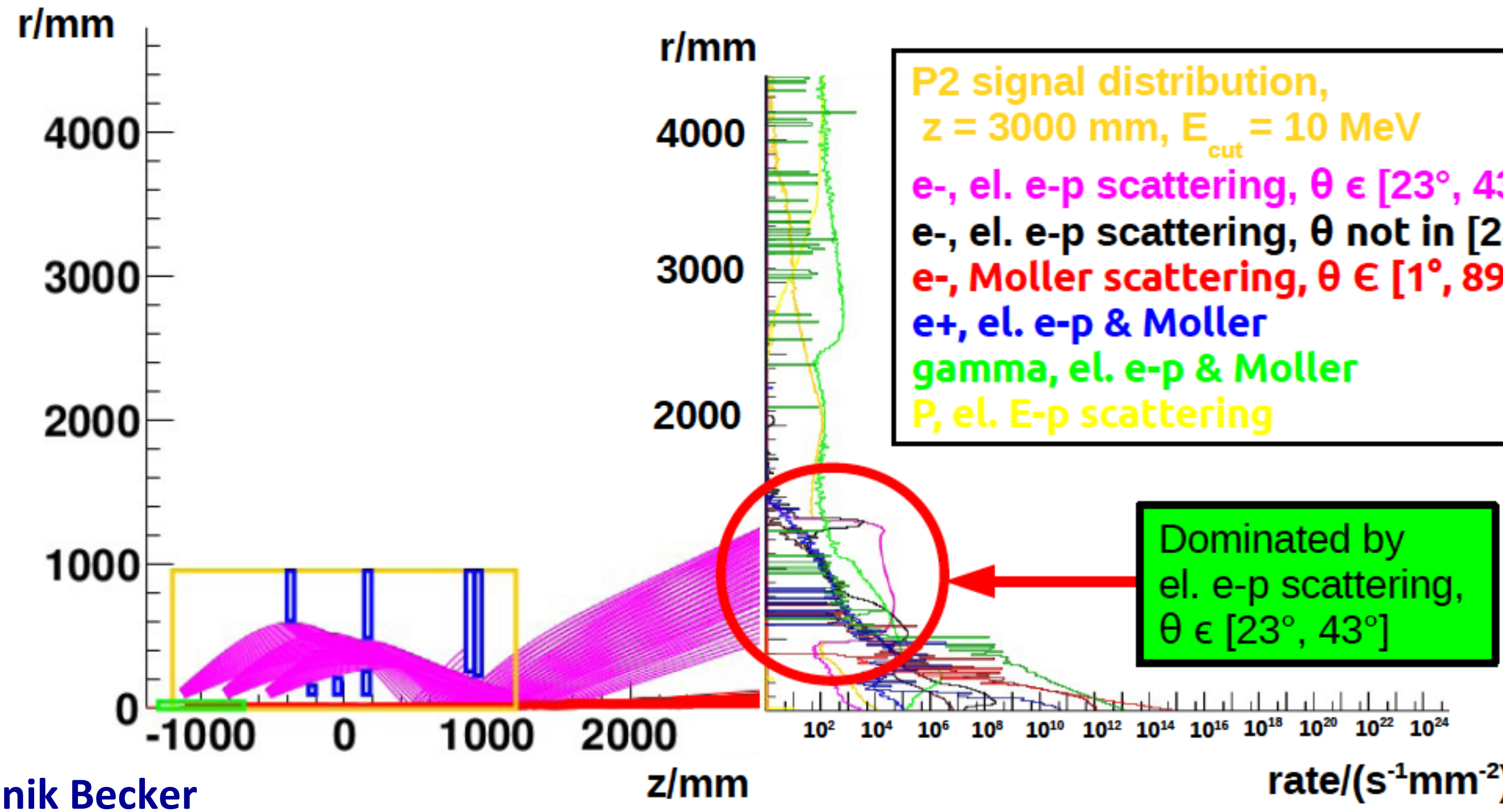
Dominated by el. e-p scattering $\theta \in [10°, 30°]$

Dominik Becker

Experiment Design Simulations: Solenoid possible!

E = 150 MeV
B = 1.08 T
el. e-p scattering, θ ∈ [23°, 43°]
Moller scattering, θ ∈ [1°, 89°]

Primary event generators of Monte Carlo simulation:
el. e-p scattering, θ ∈ [1°, 90°]
Moller scattering, θ ∈ [1°, 89°]



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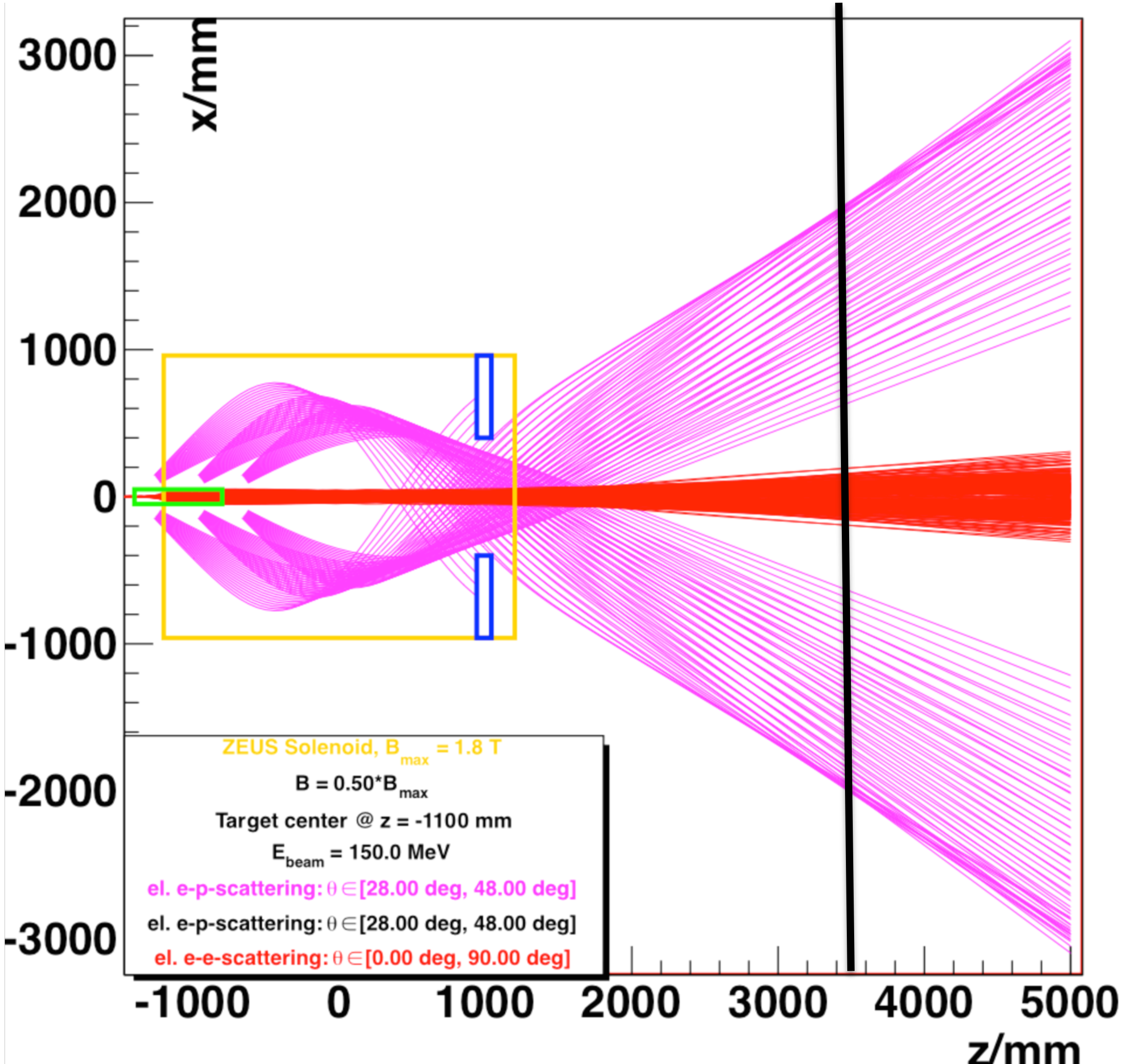

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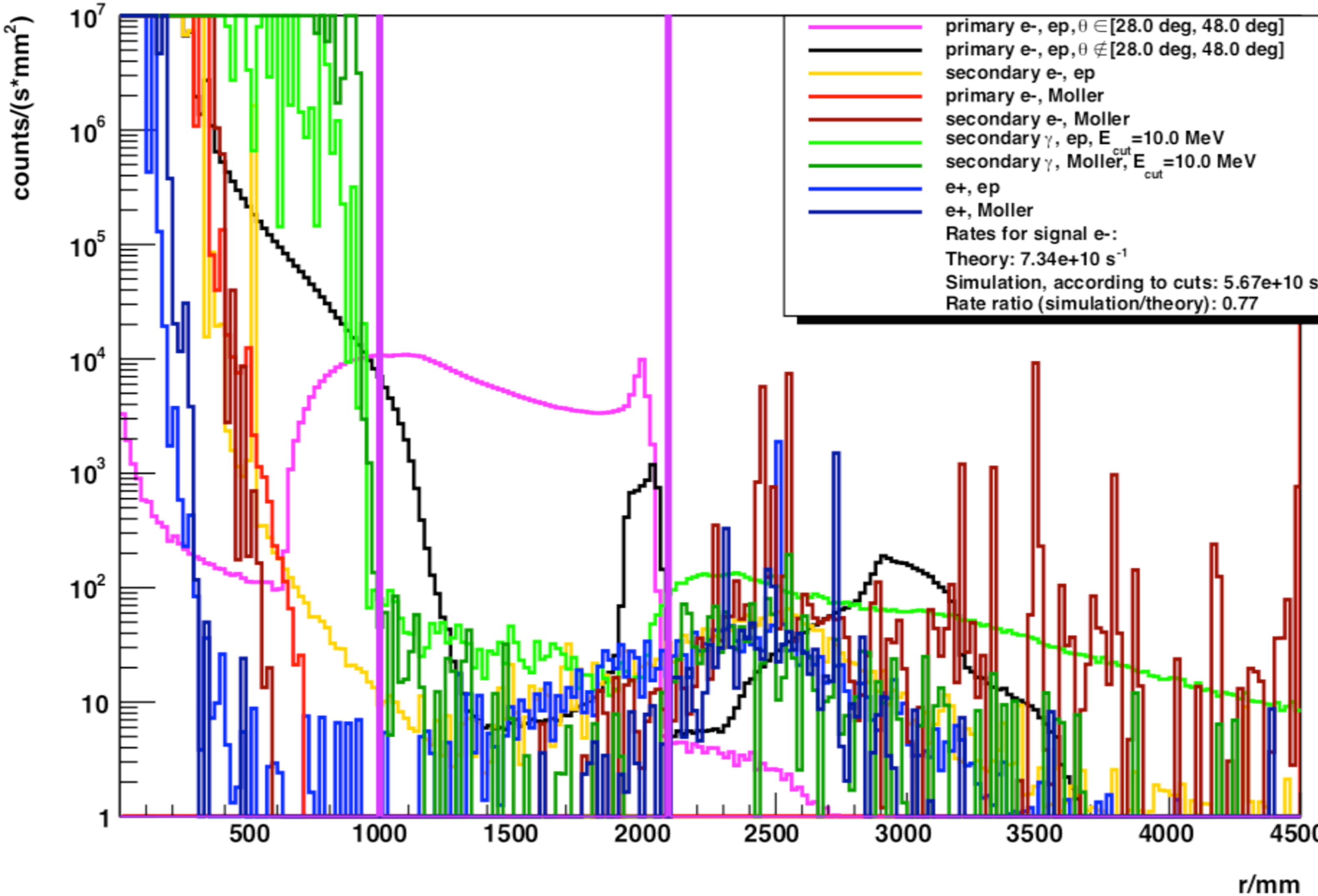
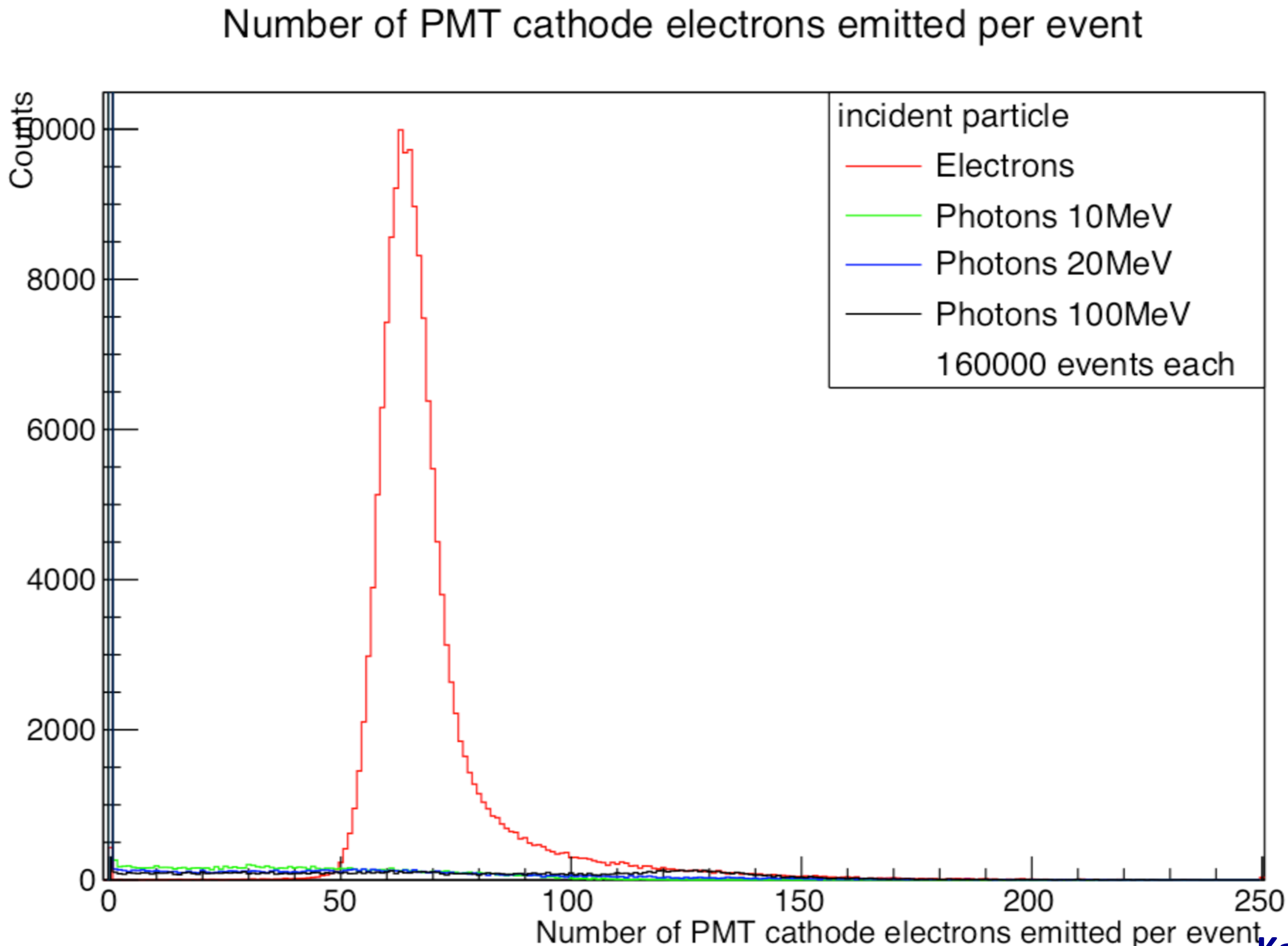
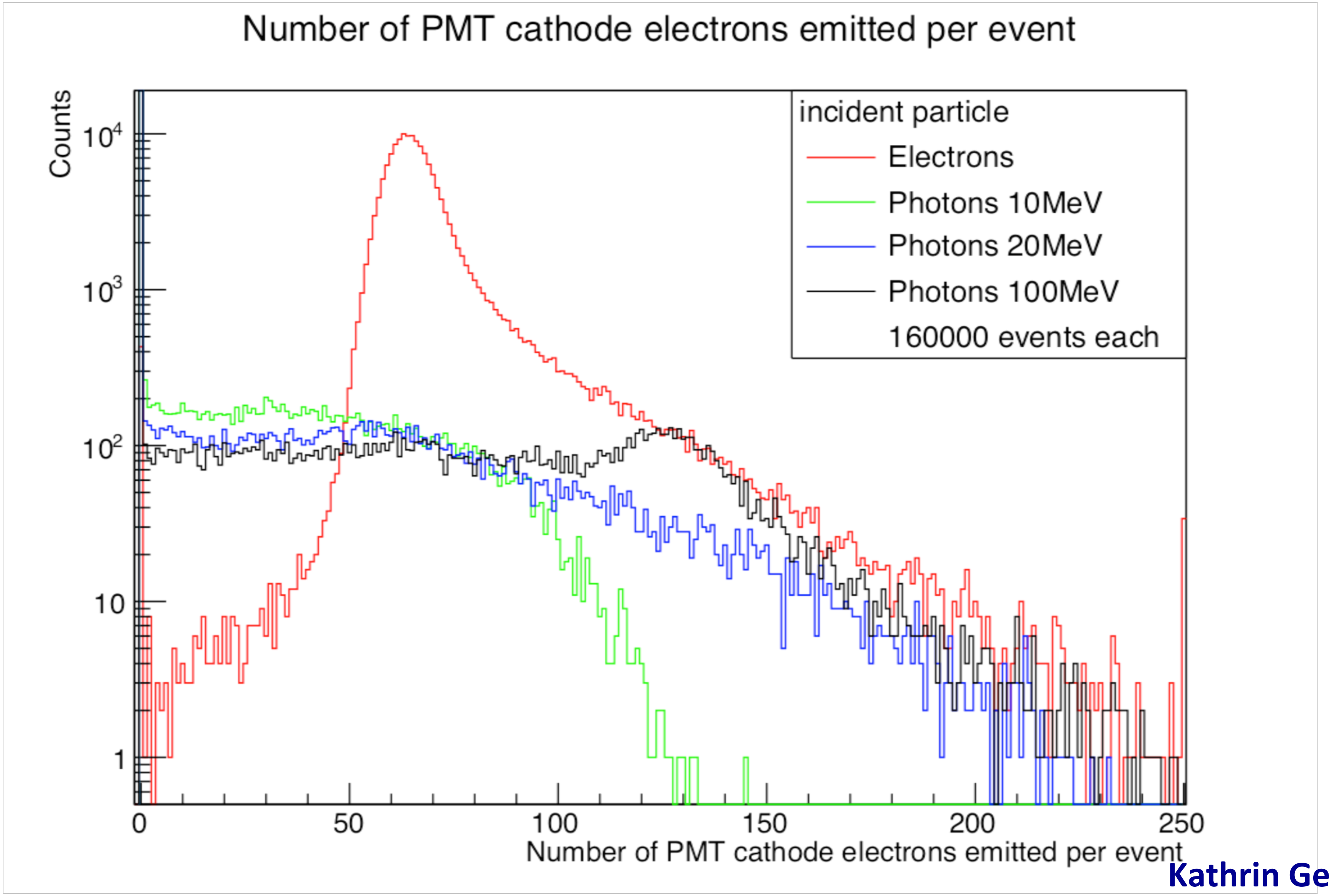
Rate distribution in tracking detector nb 1 @ z = 3500 mm



Dominik Becker

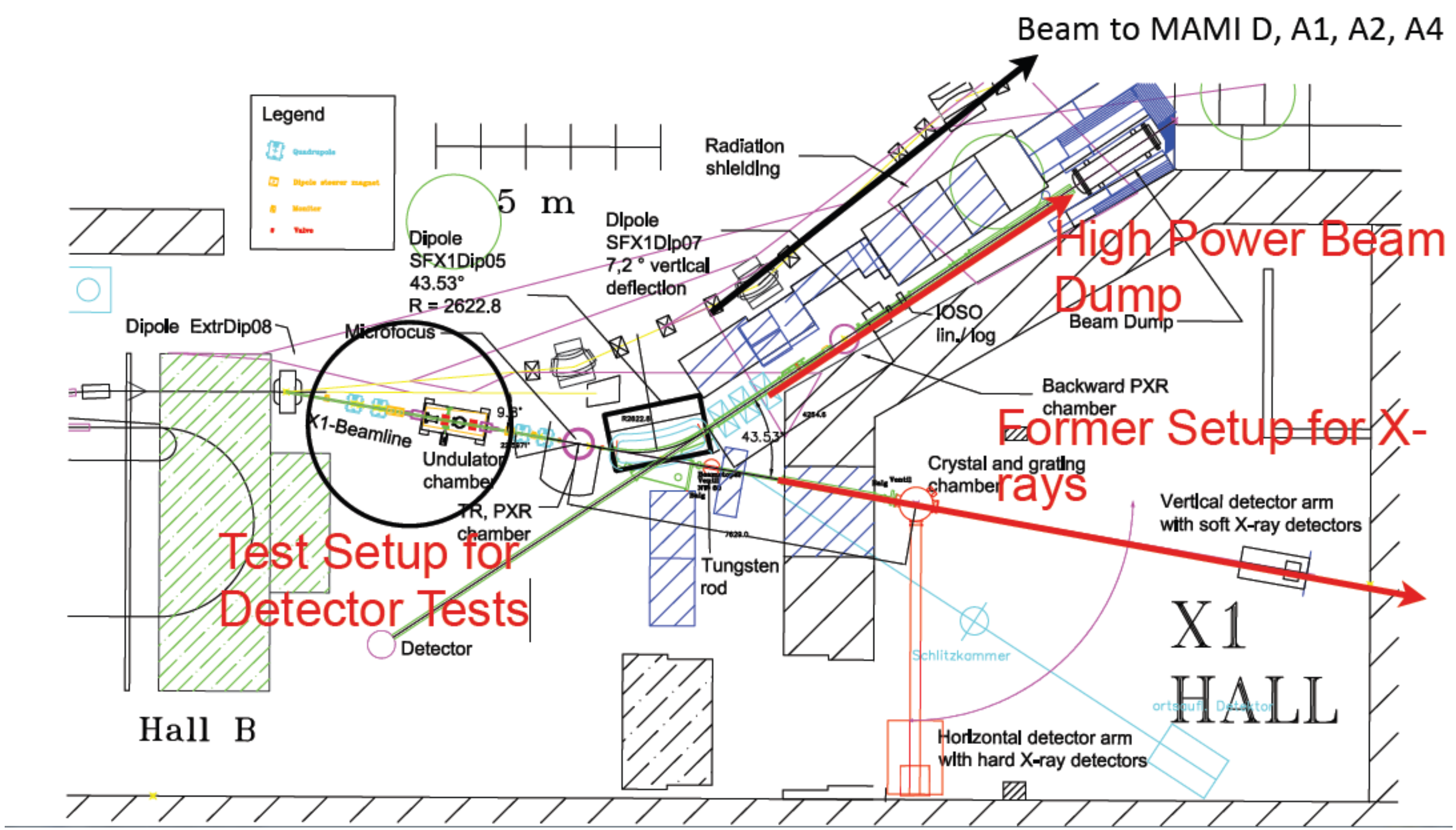


Kathrin Gerz

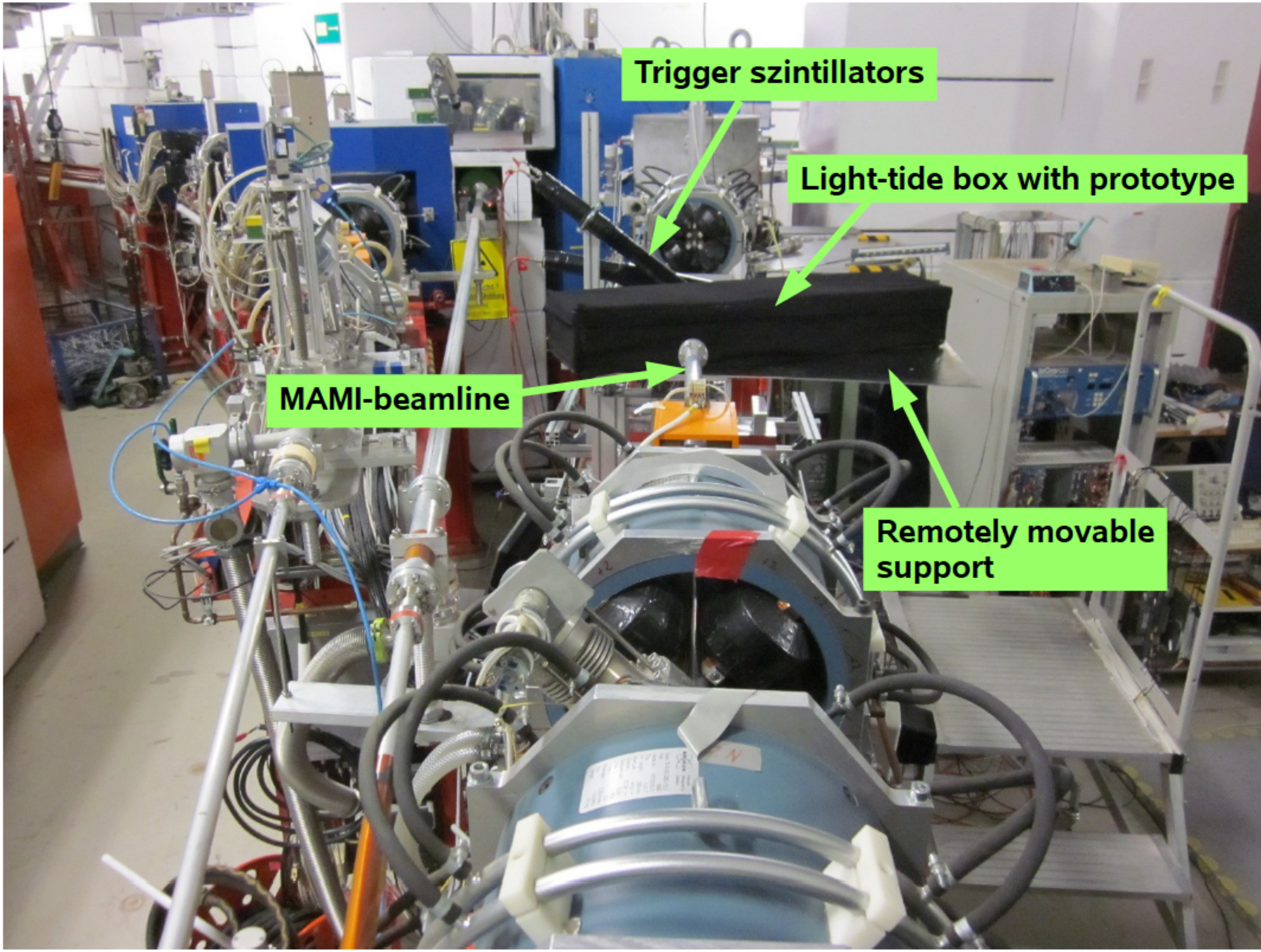


Kathrin Gerz

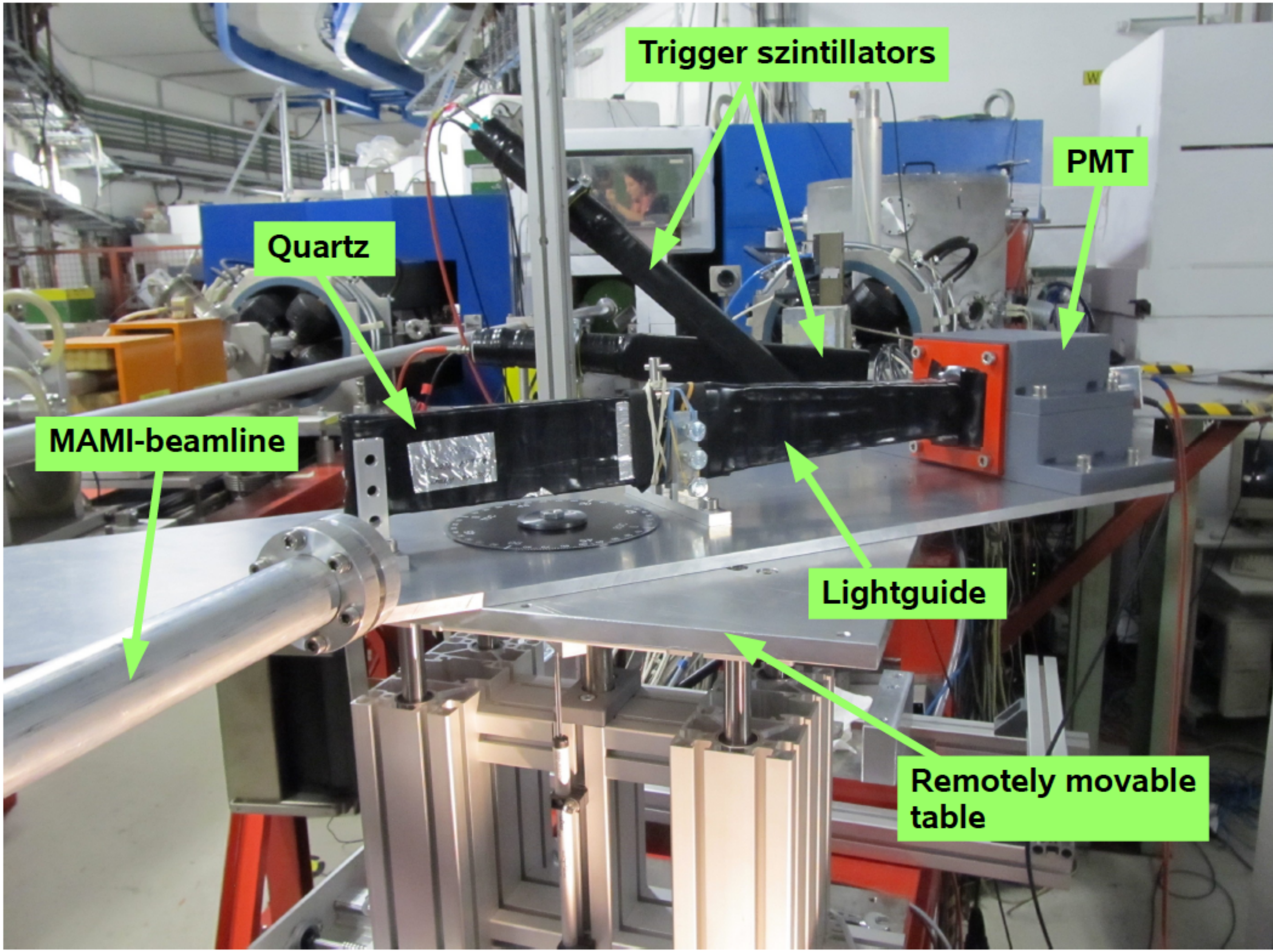
First detector prototype tests



P2 Experimental setup (first testbeam October 2013)



P2 Experimental setup (second testbeam January 2014)



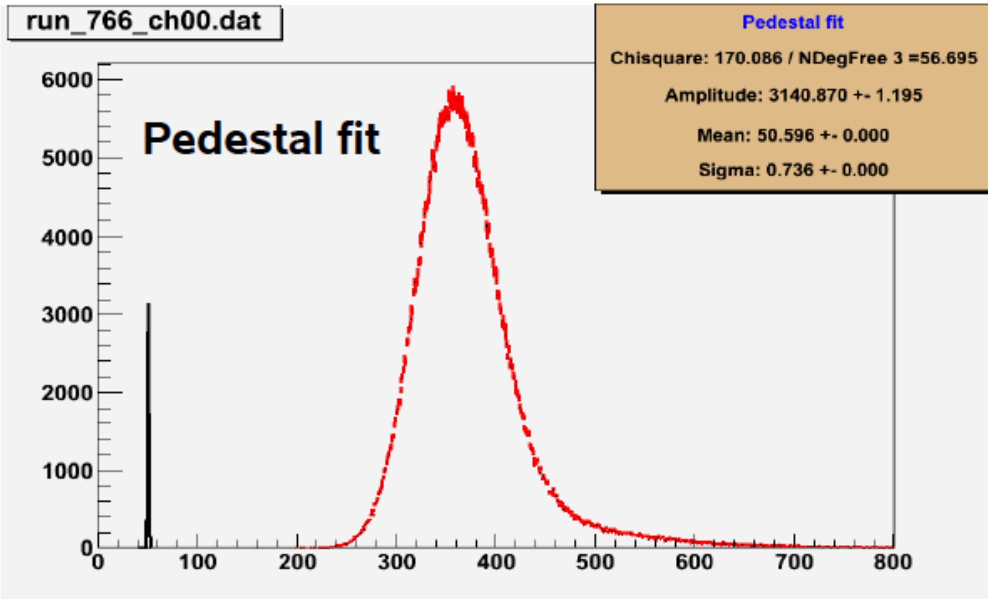
First detector prototype tests

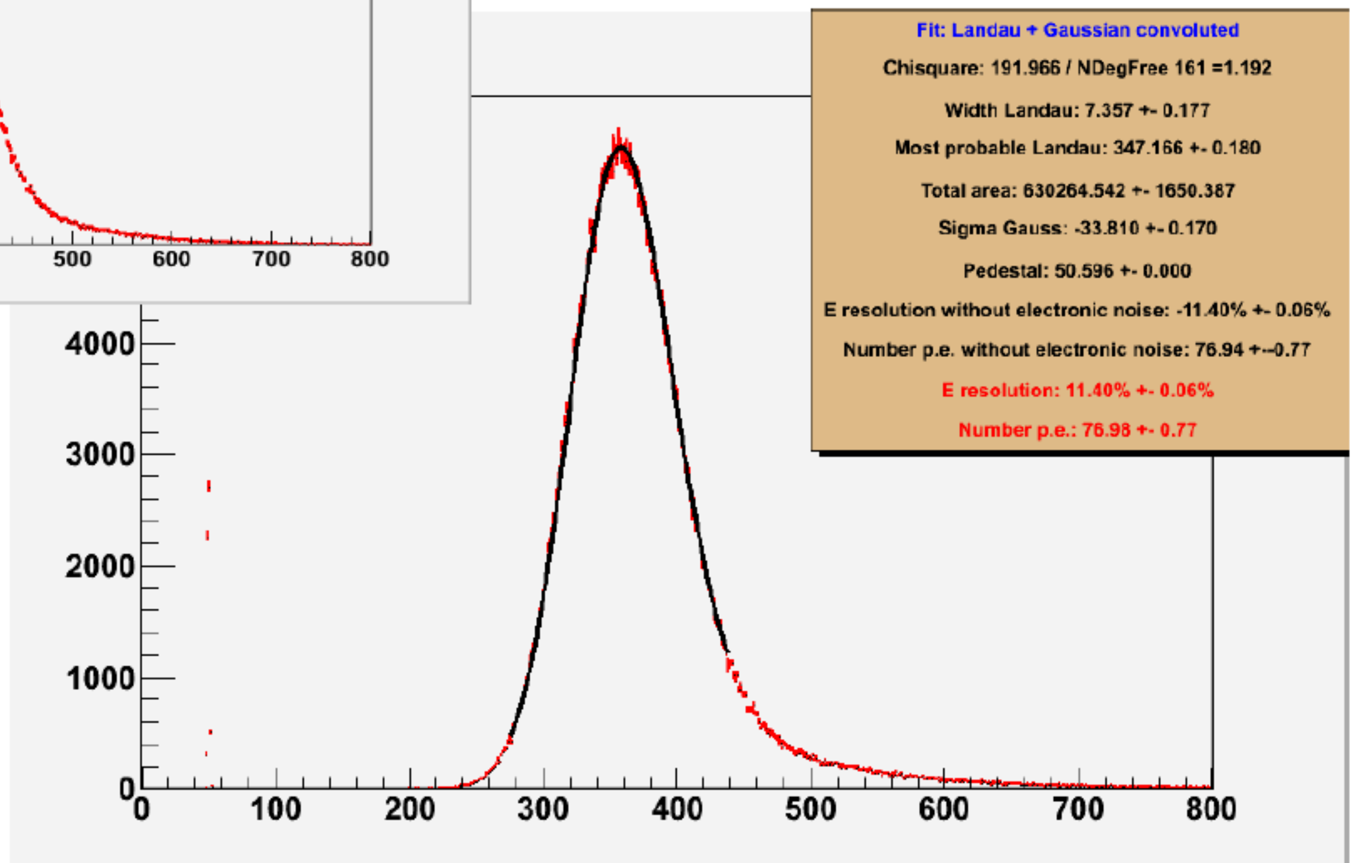
About 100 runs taken
Variation of

- Flame polished/unpolished
- Wrapping
- Light guide material
- Impact positions
- Orientation

Setup	Varying parameter
Spectrosil 2000 polished Wrapped with Alanod Light guide: Alanod	Different impact positions horizontal, vertical **In total 25 runs**
Spectrosil 2000 polished Wrapped with Millipore Light guide: Alanod	Different angles **In total 15 runs**
Spectrosil 2000 unpolished Light guide: Alanod	Unwrapped, Wrapped 45°, 90° **In total 6 runs**
Spectrosil 2000 polished Wrapped with Millipore Lightguide: Mylar	Different angles **In total 12 runs**
Spectrosil 2000 polished Wrapped with Alanod No Lightguide	Different impact positions **In total 19 runs**
Spectrosil 2000 polished Wrapped with Mylar No Lightguide	Different impact positions **In total 9 runs**
Spectrosil 2000 polished Wrapped with Millipore No lightguide	Different impact positions Different angles **In total 13 runs**

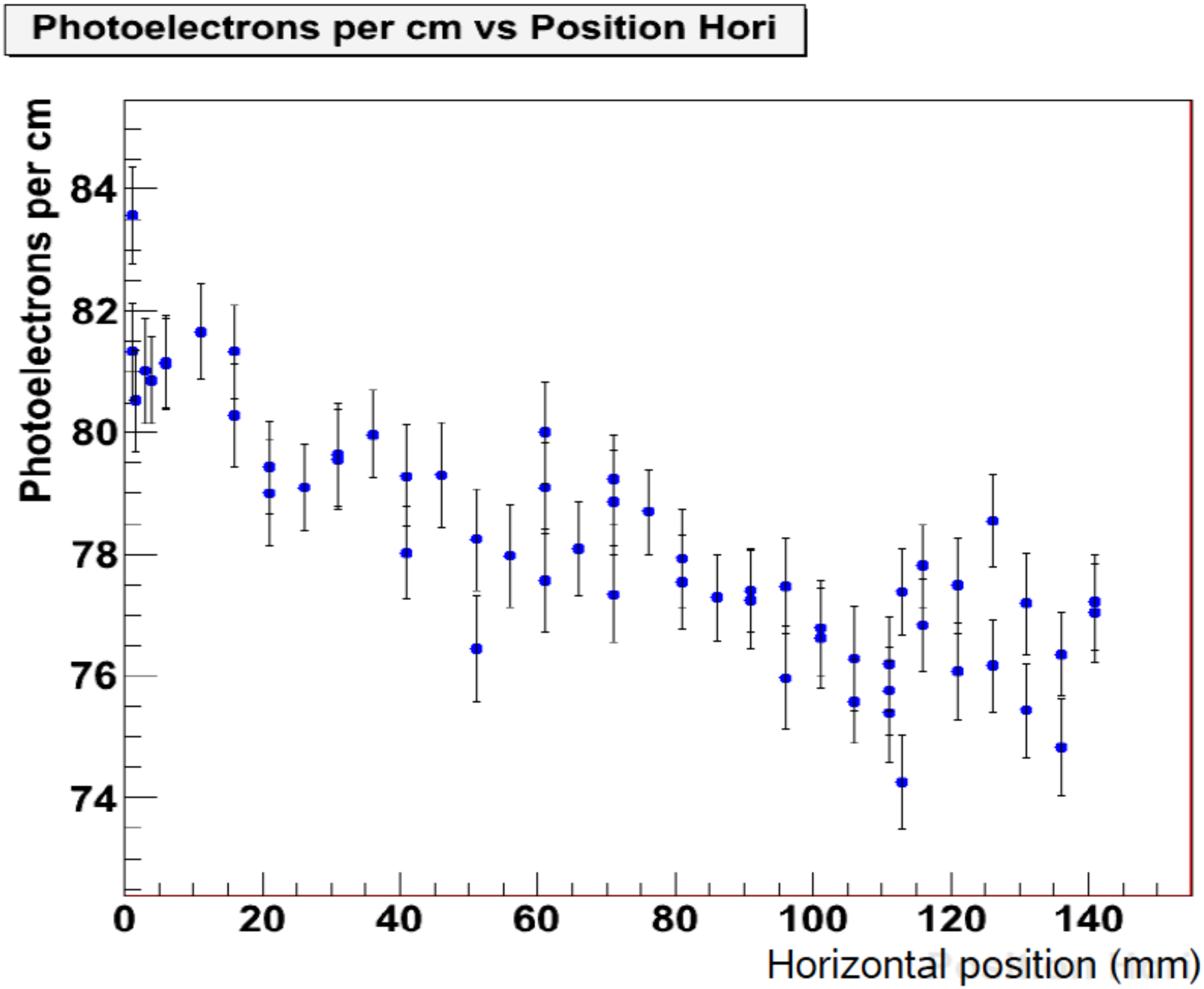
Single Electron Response: Quartz plus PMT





Fit function: Convolution of Gaussian and Landau

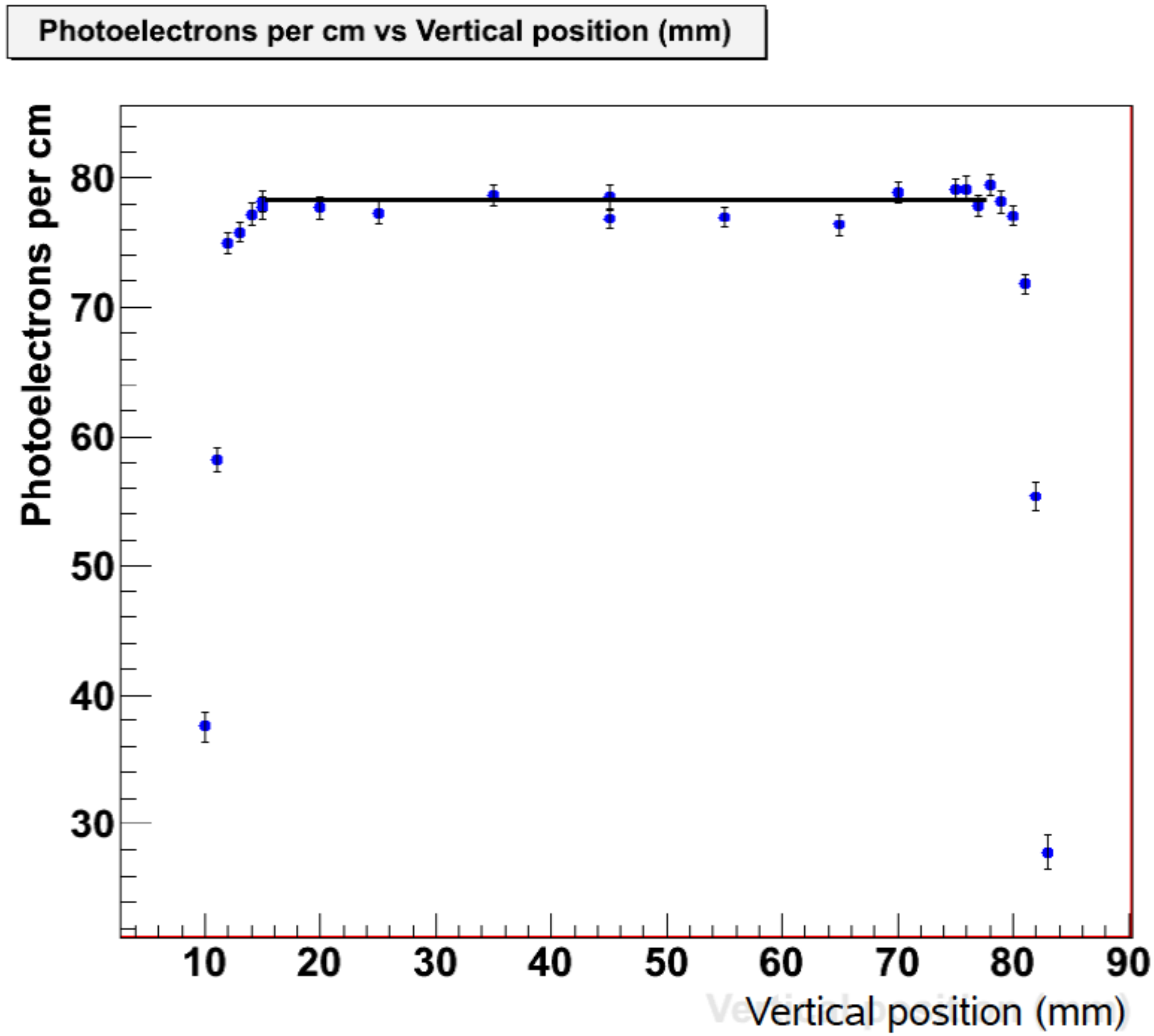
Horizontal position scan



Spectrosil 2000, 45° Cut
Mechanically polished
Wrapping: Alanod 4300
No Lightguide
PMT: ET9305QKMB 518

Angle: 90°

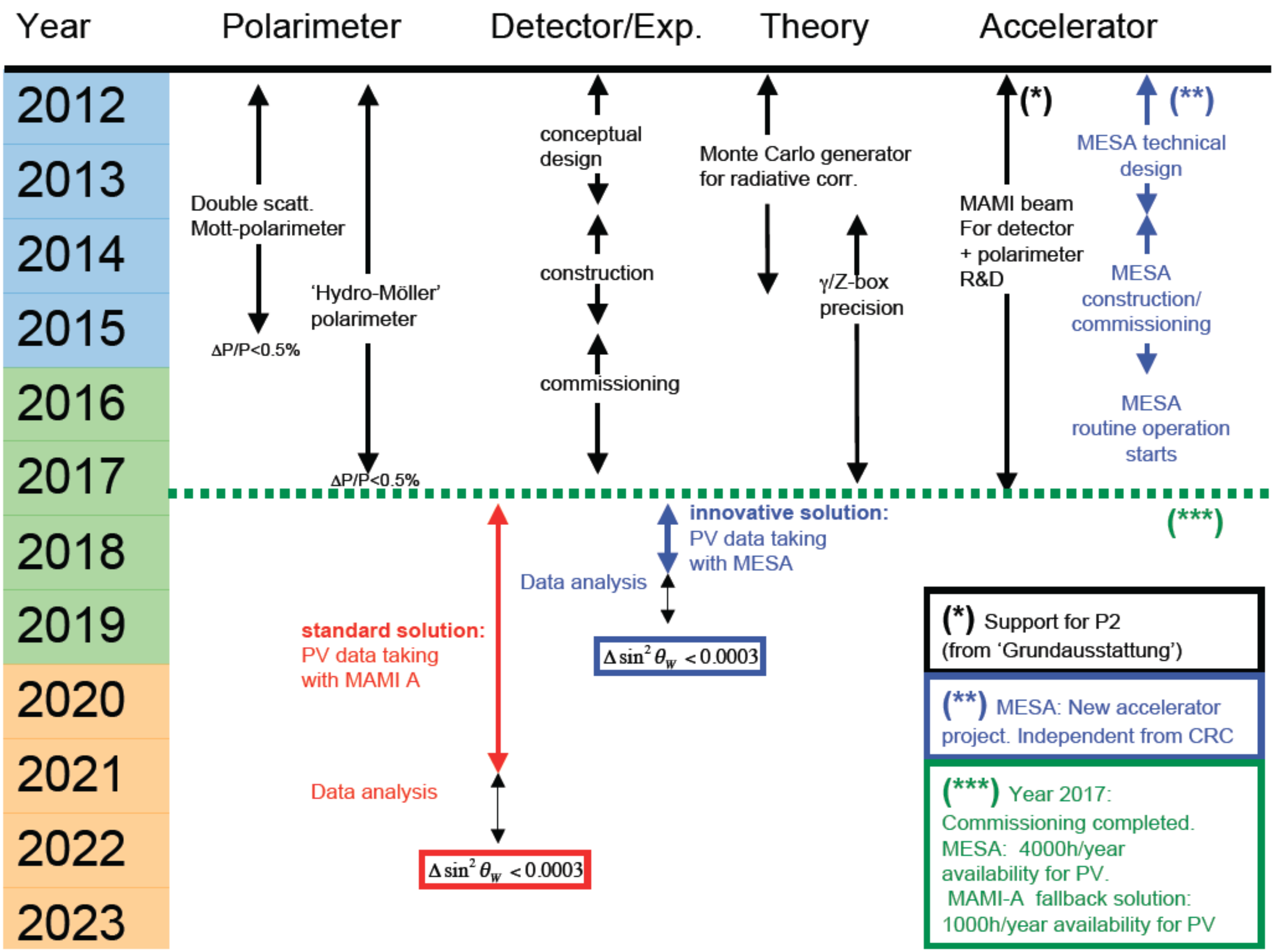
Vertical position scan



Spectrosil 2000, 45° Cut
Mechanically polished
Wrapping: Alanod 4300
No Lightguide
PMT: ET9305QKMB 518

Angle: 90°

Timeline P2


Year
Polarimeter
Detector/Exp.
Theory
Accelerator
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
Double scatt. Mott-polarimeter
ΔP/P<0.5%
'Hydro-Möller' polarimeter
ΔP/P<0.5%
conceptual design
construction
commissioning
Monte Carlo generator for radiative corr.
γ/Z-box precision
(*)
MAMI beam For detector + polarimeter R&D
(**)
MESA technical design
MESA construction/ commissioning
MESA routine operation starts
(***)
innovative solution:
PV data taking with MESA
Data analysis
$\Delta \sin^2\theta_W < 0.0003$
standard solution:
PV data taking with MAMI A
Data analysis
$\Delta \sin^2\theta_W < 0.0003$
(*) Support for P2 (from 'Grundausstattung')
(**) MESA: New accelerator project. Independent from CRC
(***) Year 2017: Commissioning completed. MESA: 4000h/year availability for PV. MAMI-A fallback solution: 1000h/year availability for PV

Conclusions:

$\sin^2(\text{theta}_W)$ important parameter of the standard model
measure through weak charge of the proton, A_{PV}=20ppb

Precise determination important for test of standard model on the two loop level, sensitivity to new physics

Theory: Work in Progress to calculate Two-Loop-contribution, Box-graphs, EM-radiative corrections, Hadronic Contributions, Running

Polarimetry/Beam diagnosis: Project defined, Solenoid usable, $^3He/^4He$-mixture cryostat to be renewed, Double Scattering Polarimeter has first data.

Experiment Design Simulations: Solenoid will work

First Beam Tests: Test of detetctor materials and PMTs: Already light output sufficient!

Ready to form international collaboration
(Almost) Ready to design the experiment