Low Energy Precision Measurements:
neutral current measurements, g-2...

Shufang Su • U. of Arizona

Snowmass on Mississippi (2013)

Based on Review articles
Erler and Ramsey-Musolf (2005)
Ramsey-Musolf and SS (2006)
Kumar, Mantry, Marciano and Souder (2013)
Erler and SS (2013)

(A theorist's overview of)

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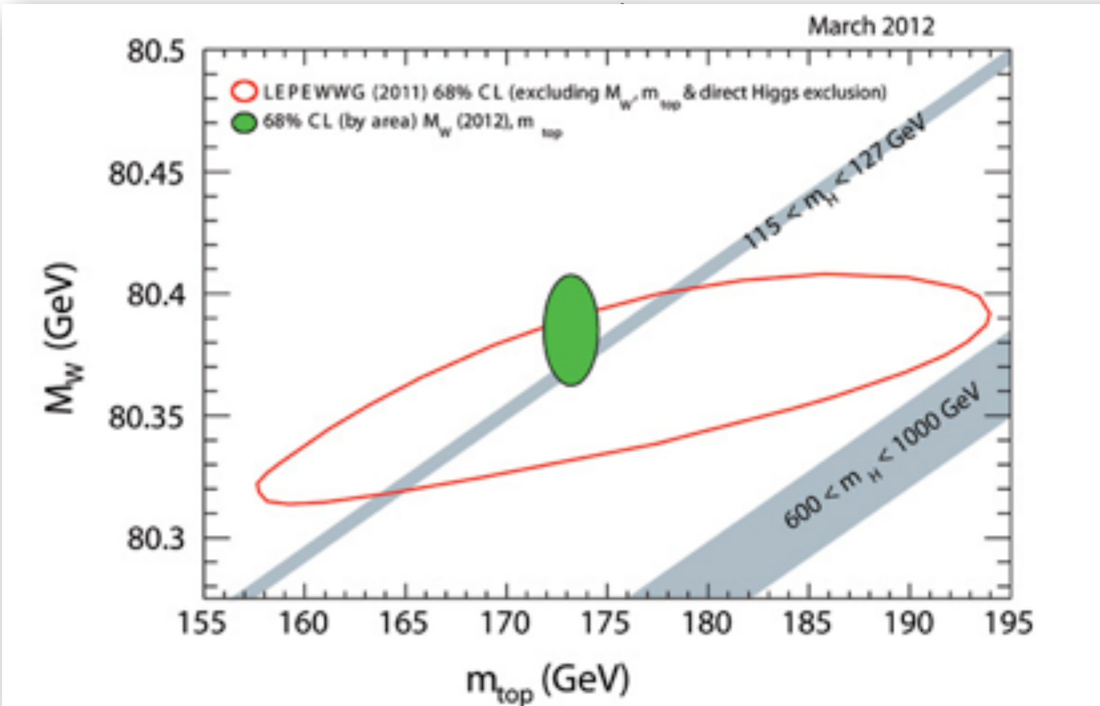
S. Su

Precision measurements vs. direct detection



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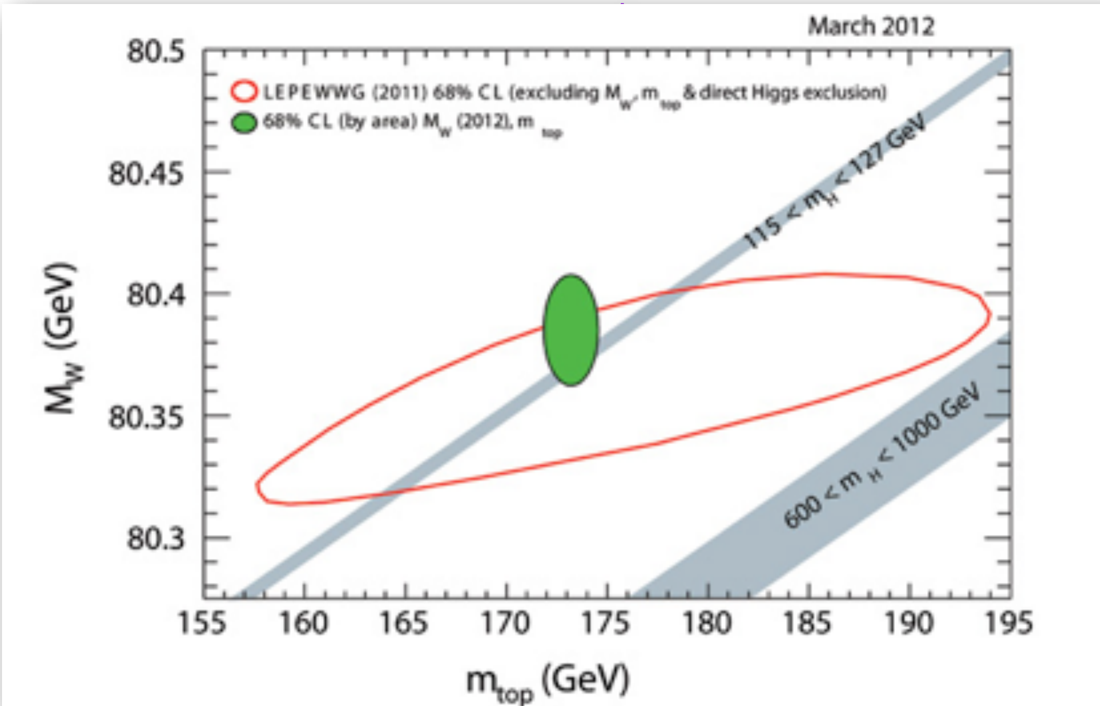
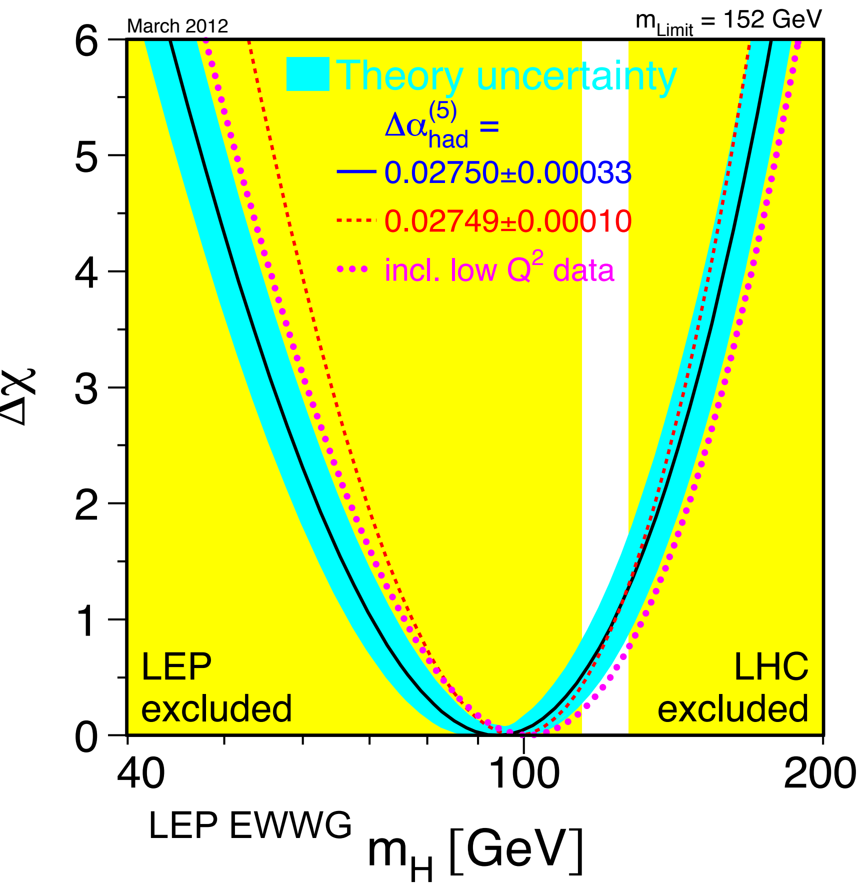


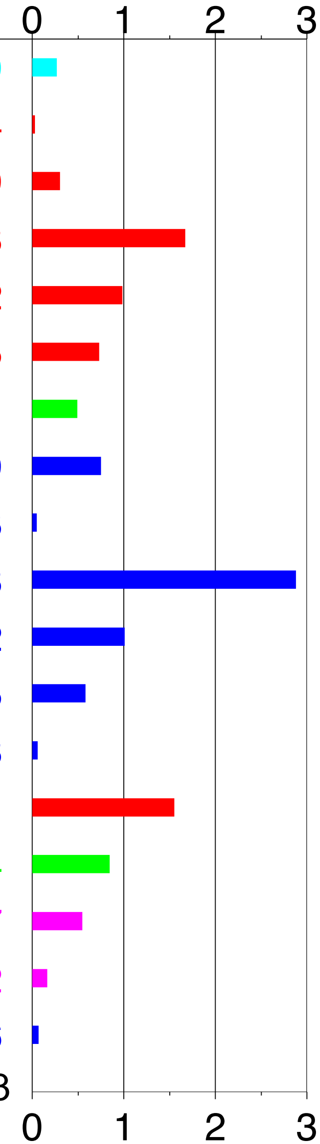
Direct vs. indirect detection

- provide complementary information
- success of SM
- consistency check of any new physics scenario

Z-pole precision measurements



	Measurement	Fit	$\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02750 ± 0.00033	0.02759	
m_Z [GeV]	91.1875 ± 0.0021	91.1874	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959	
σ^0_{had} [nb]	41.540 ± 0.037	41.478	
R_l	20.767 ± 0.025	20.742	
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481	
R_b	0.21629 ± 0.00066	0.21579	
R_c	0.1721 ± 0.0030	0.1723	
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038	
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1481	
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.385 ± 0.015	80.377	
Γ_W [GeV]	2.085 ± 0.042	2.092	
m_t [GeV]	173.20 ± 0.90	173.26	



March 2012

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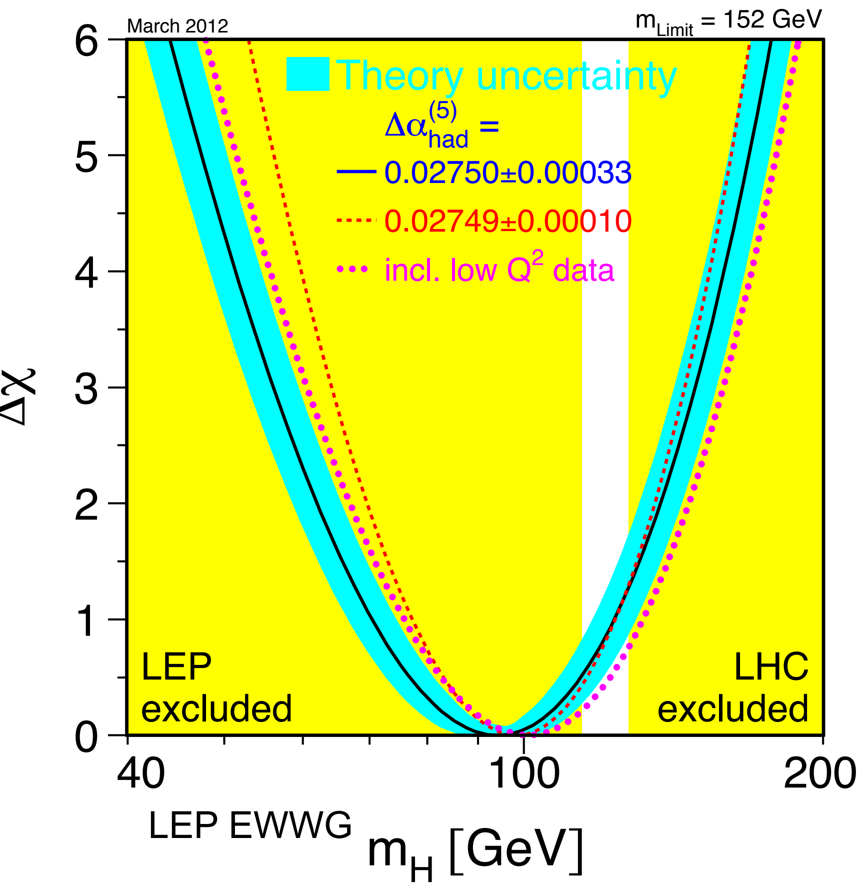
Z-pole precision measurements



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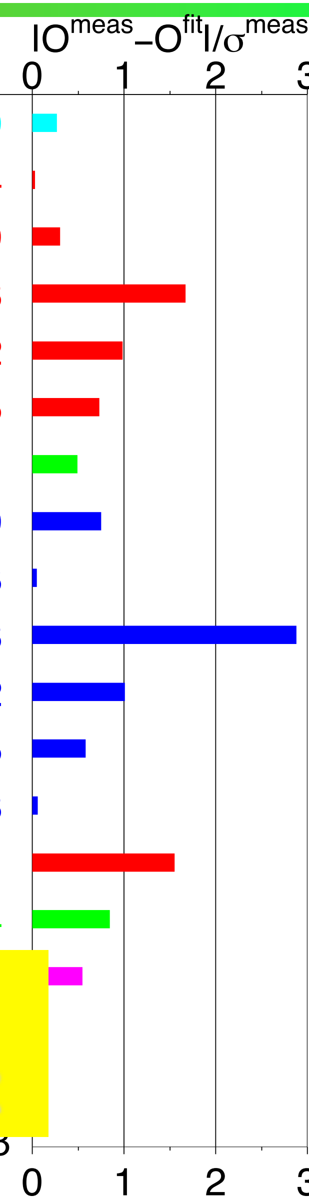


March 2012

- ◉ **Confirmation of SM @ quantum level**
- ◉ **Sensitive to new physics interact with W and Z**

Low energy precision measurements

- address questions difficult to study at high energy (LHC)

  weak interactions (parity violation)

- probe new physics off the Z-resonance

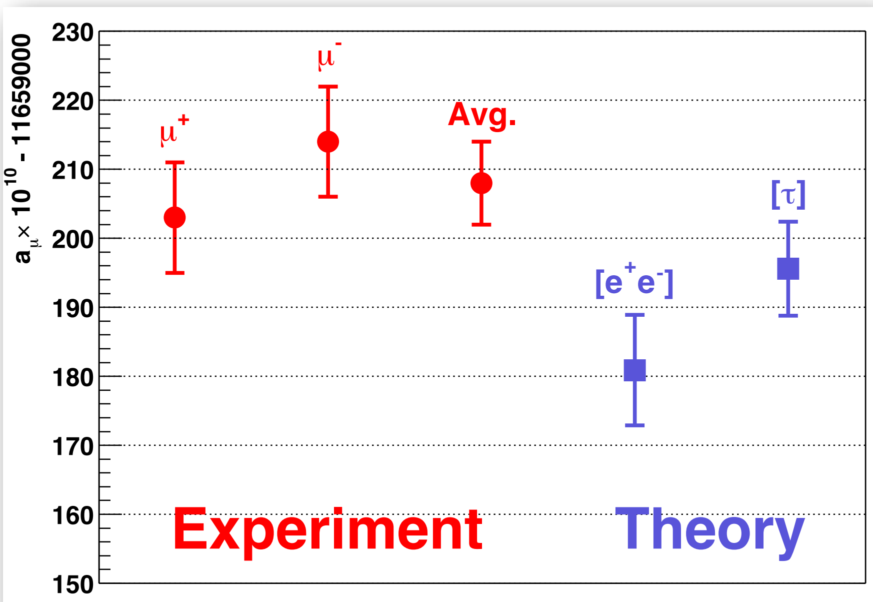
  - sensitive to new physics not mix with Z (and W)

- high precision low energy experiment available

muon g-2

size of loop effects from new physics: $(\alpha/\pi)(M/M_{new})^2$

muon g-2: $M=m_\mu$, $M_{new}=m_W \Rightarrow \delta^{new} \sim 2\times10^{-9}$, $\delta^{exp} < 10^{-9}$



BNL E821 exp

$$\mu = (1+a)\frac{Qe\hbar}{2m} \quad \text{with} \quad a = \frac{g-2}{2}.$$

$$a_\mu(\text{Expt}) = 116\,592\,089(54)(33)\times10^{-11}$$

$$a_\mu(\text{SM}) = 116\,591\,802(42)(26)(02)\times10^{-11}$$

$$\Delta a_\mu = 287(80)\times10^{-11}$$

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SM issues w.r.t. g-2: Ruth Van de Water

muon g-2: new physics

- sensitive to new physics related/unrelated to EWSB
- flavor-, CP-conserving, chirality flipping, loop induced
  - high energy colliders: chirality conserving
  - other LE precision observables: CP-, flavor- violating
- sensitive to lepton couplings

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$$a_\mu(\mathrm{N.P.}) = \mathcal{O}(1) \times \left(\frac{m_\mu}{\Lambda}\right)^2 \times \left(\frac{\delta m_\mu(\mathrm{N.P.})}{m_\mu}\right)$$

Czarnecki and Marciano (2001)

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Czarnecki and Marciano (2001)

- $C(\mathrm{N.P.}) \equiv \delta m_\mu(\mathrm{N.P.})/m_\mu \simeq 1$

$$a_\mu(\Lambda) \simeq \frac{m_\mu^2}{\Lambda^2} \simeq 1100 \times 10^{-11} \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2$$

- $C(\mathrm{N.P.}) = \mathcal{O}(\alpha/4\pi)$ a_μ small
- intermediate C(N.P.), a_μ could explain exp deviation

$$C(\mathrm{SUSY}) = \mathcal{O}(\tan\beta \times \alpha/4\pi)$$

Low energy precision measurements

- high precision low energy experiment available

size of loop effects from new physics: $(\alpha/\pi)(M/M_{new})^2$

- β-decay, π-decay: $M=m_W$, $\delta^{new} \sim 10^{-3}$, $\delta^{exp} \sim 10^{-3}$
- parity-violating electron scattering: $M=m_W$, $\delta^{new} \sim 10^{-3}$

$$\mathcal{L}_{PV} = -\frac{G_\mu}{2\sqrt{2}} Q_W^f \bar{e}\gamma^\mu\gamma_5 e \bar{f}\gamma_\mu f$$

$Q_W^{e,p} \sim 1\text{-}4 \sin^2\theta_W \sim 0.1$

✓ $1/Q_W^{e,p} \approx 10$ more sensitive to new physics

✓ need $\delta^{exp} \sim 10^{-2}$ ``easier'' experiment

- discriminatory power with an array of measurements

Neutral Current experiments

$\sin^2\theta_W$

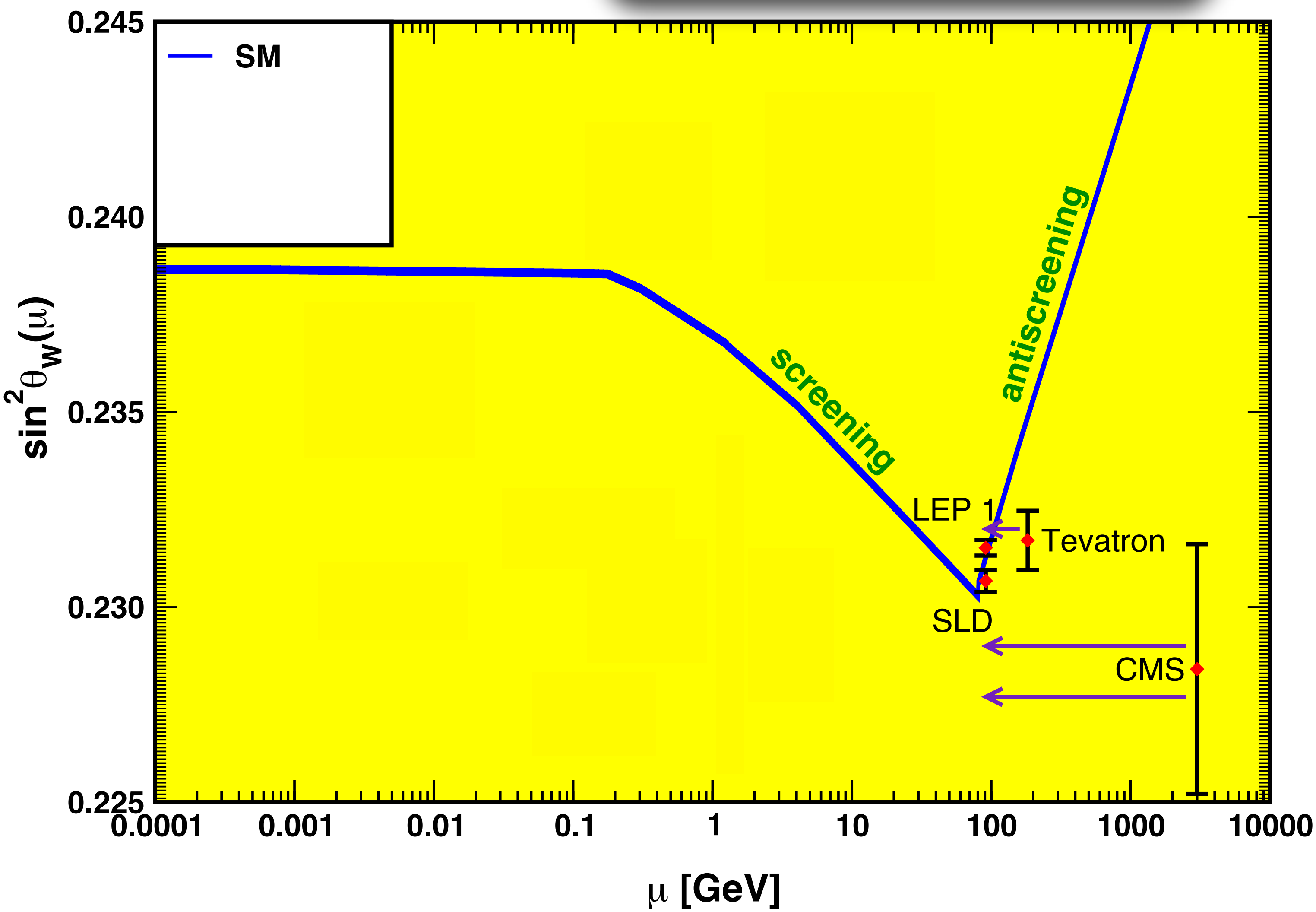
- APV (Cs,...)
- PVES (E158, Qweak,...)
- neutrino scattering (NuTeV...)
- eDIS

Test of $\sin^2\theta_W$ running

Weak mixing angle $\sin\theta_W$

$$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2} = \frac{g'^2}{g^2 + g'^2}$$

$e = g \sin\theta_W$
$= g' \cos\theta_W$



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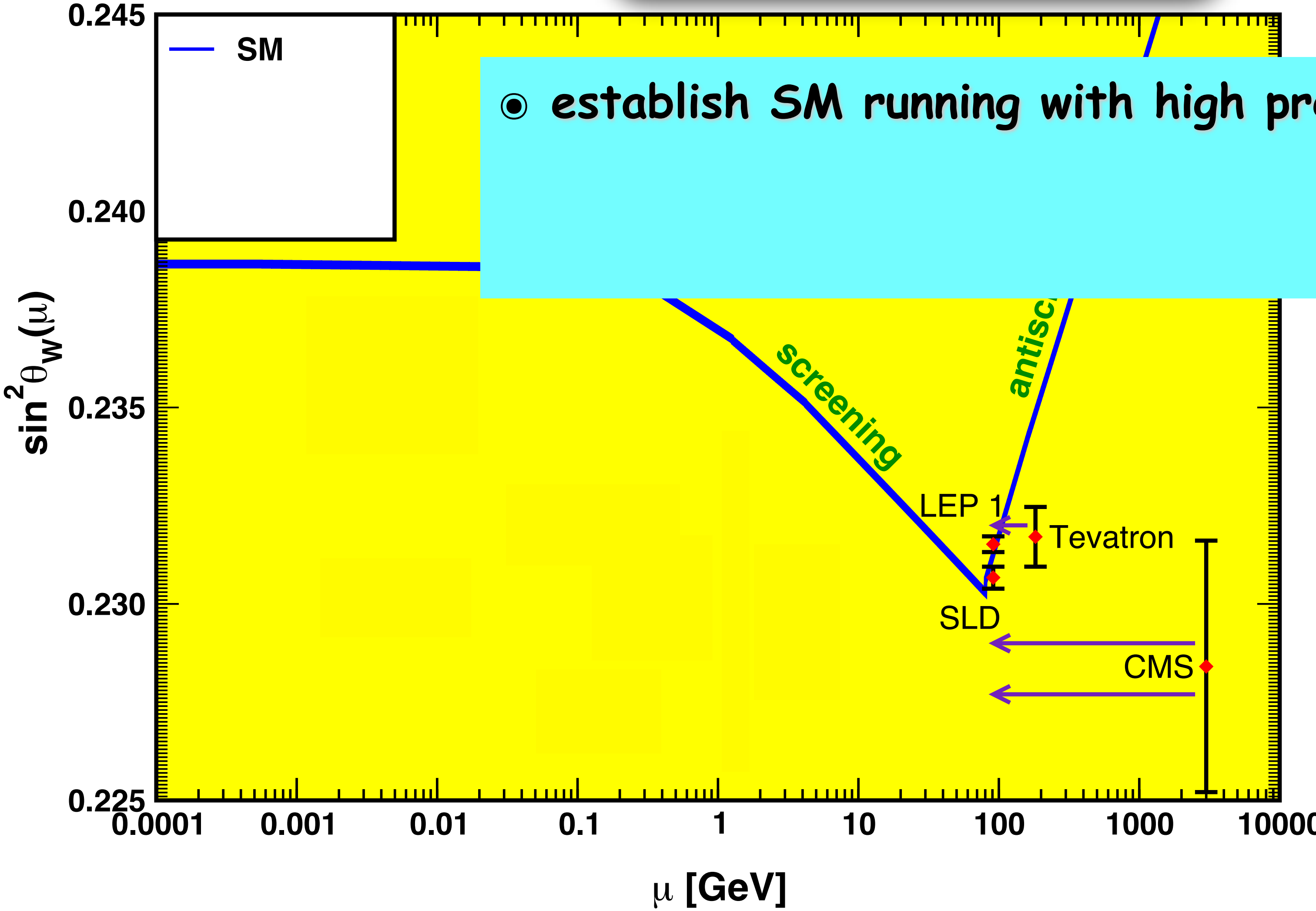

- establish SM running with high precision

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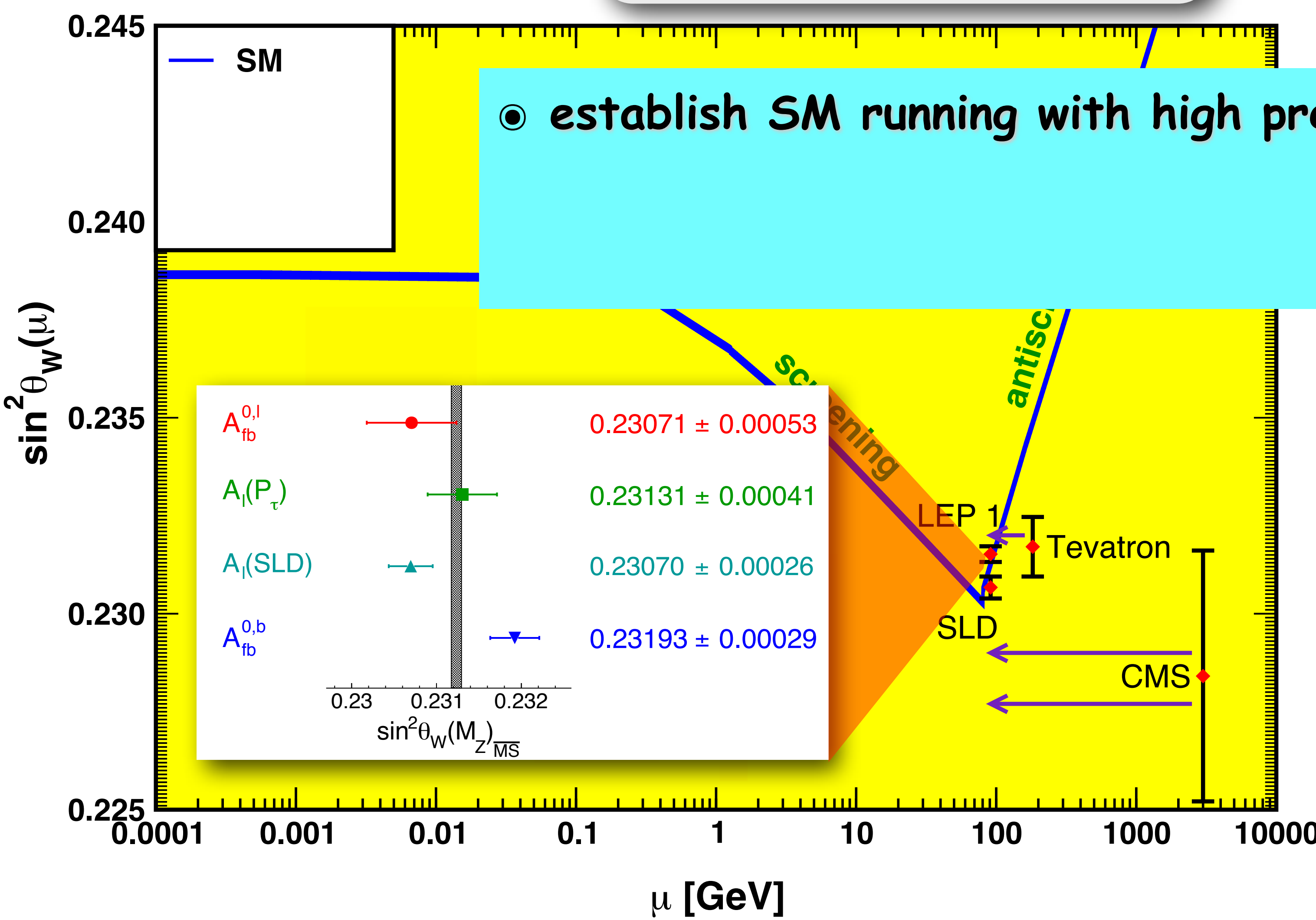

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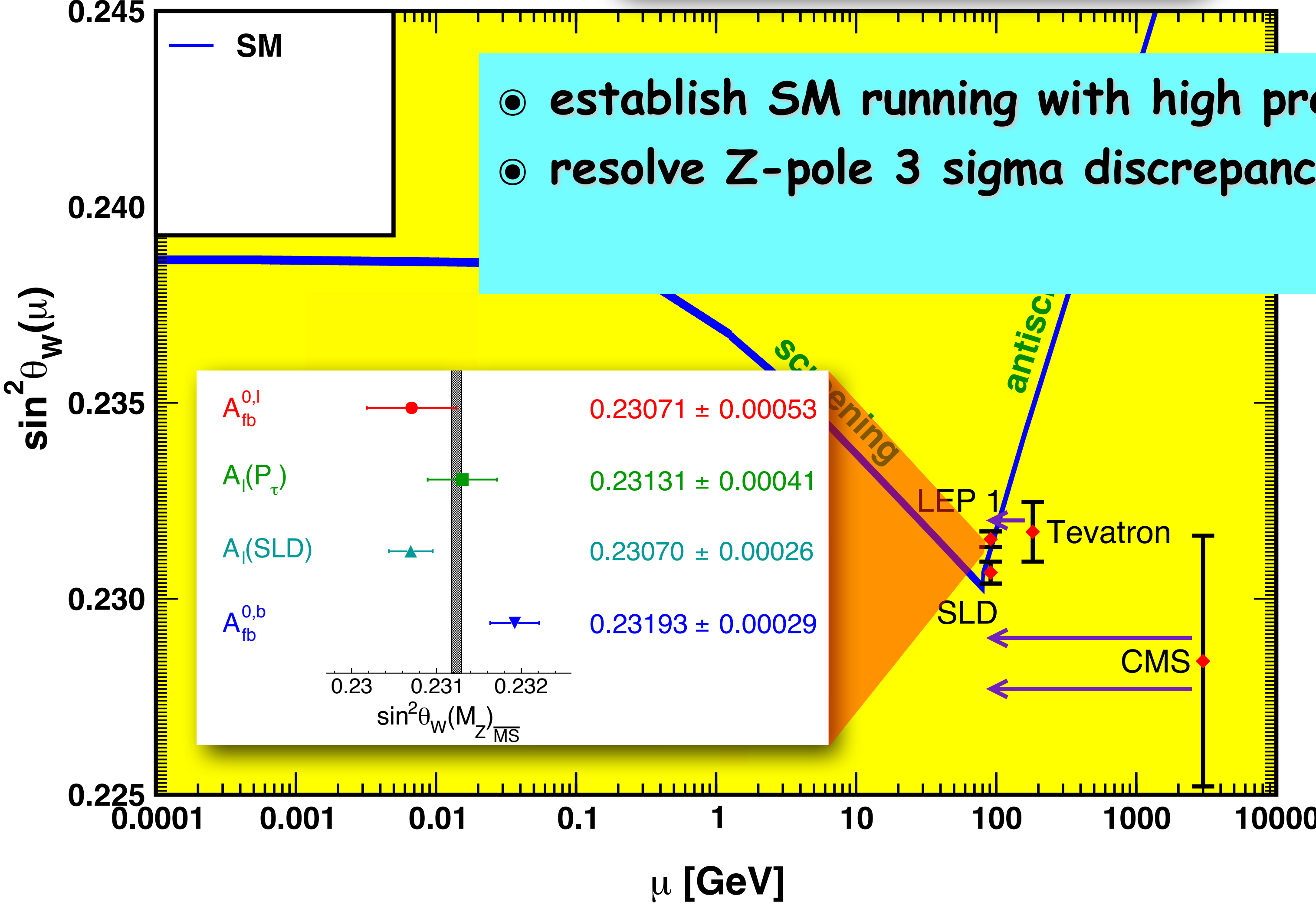
- establish SM running with high precision
- resolve Z-pole 3 sigma discrepancy



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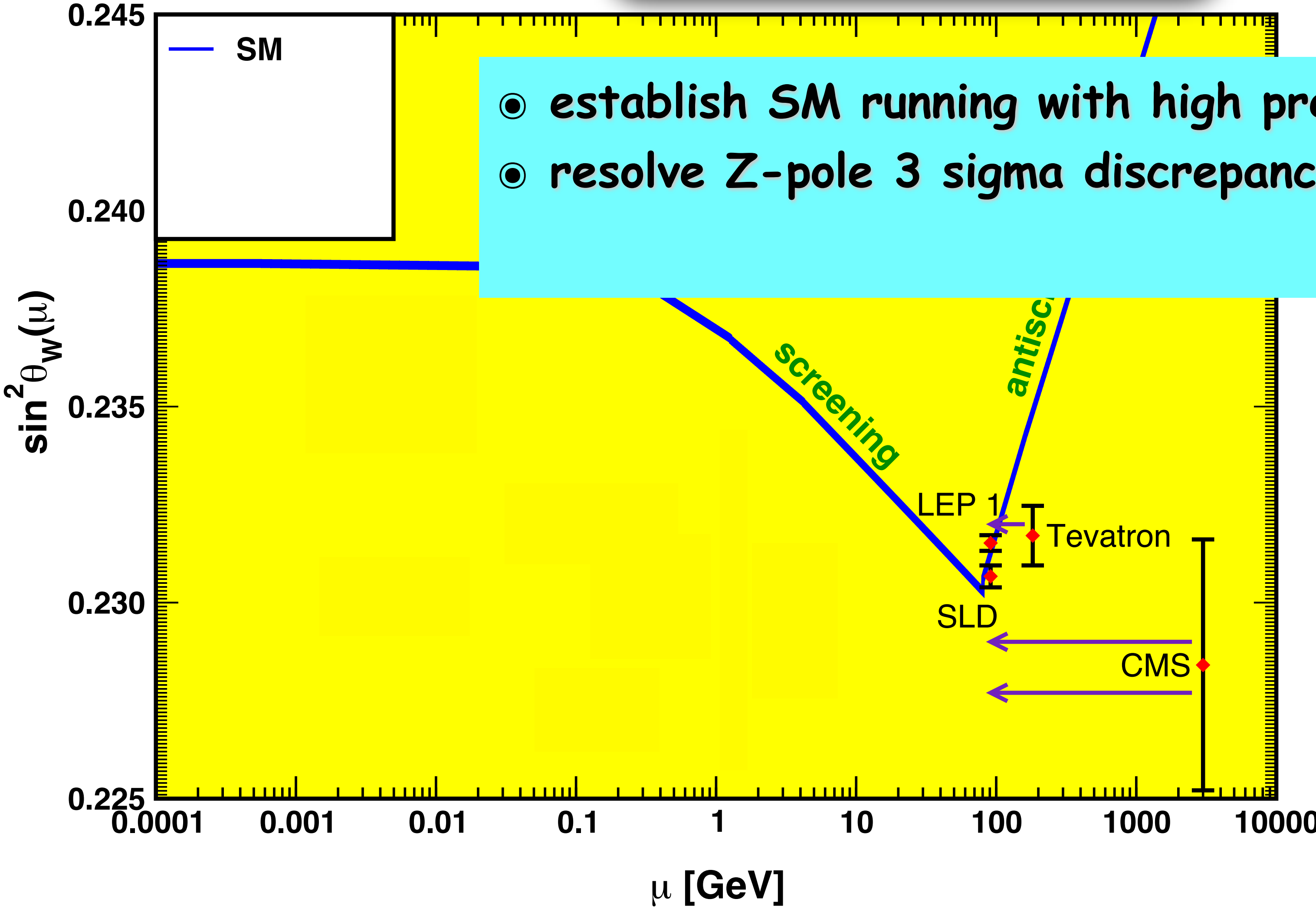

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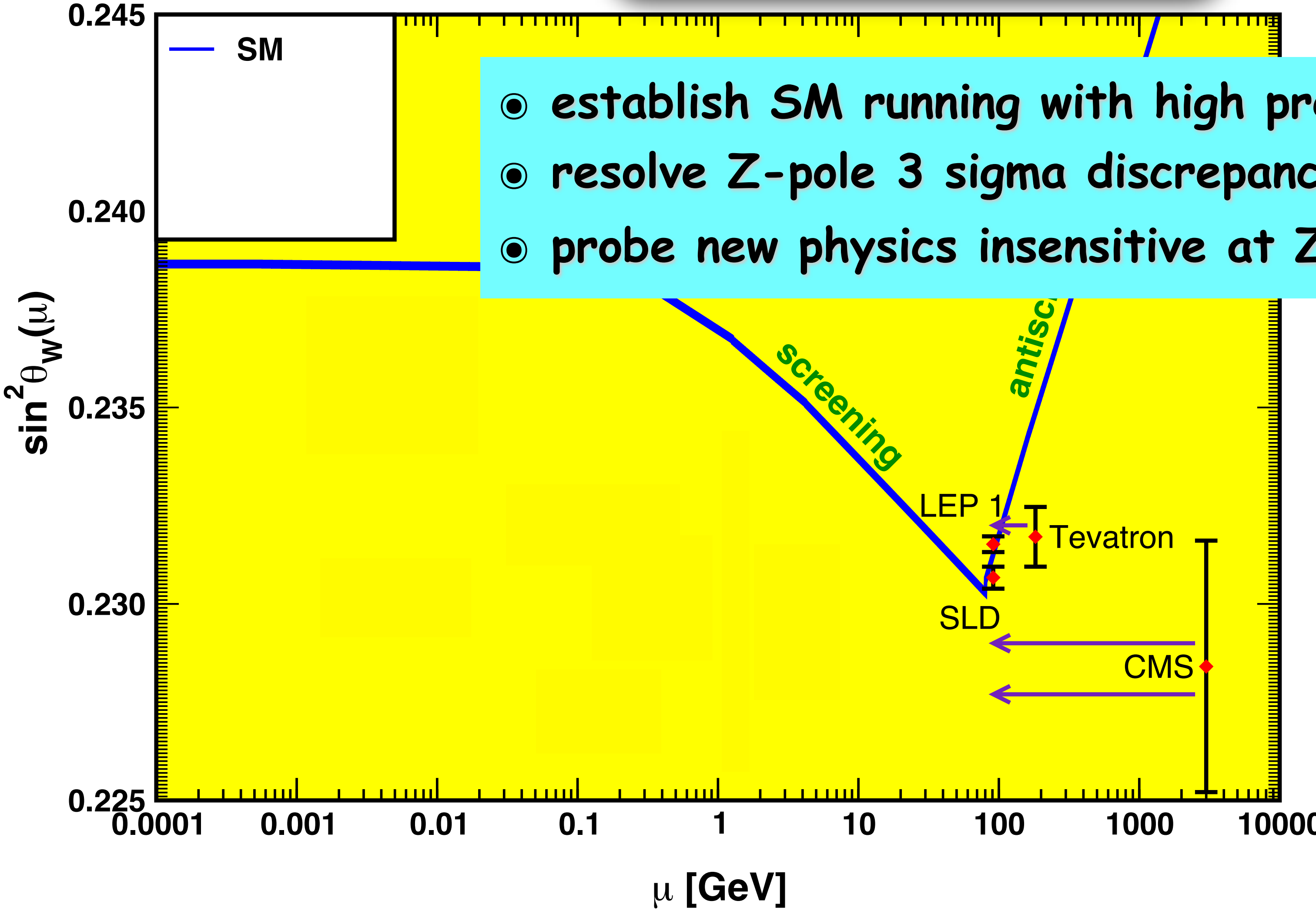

- establish SM running with high precision
- resolve Z-pole 3 sigma discrepancy
- probe new physics insensitive at Z-pole

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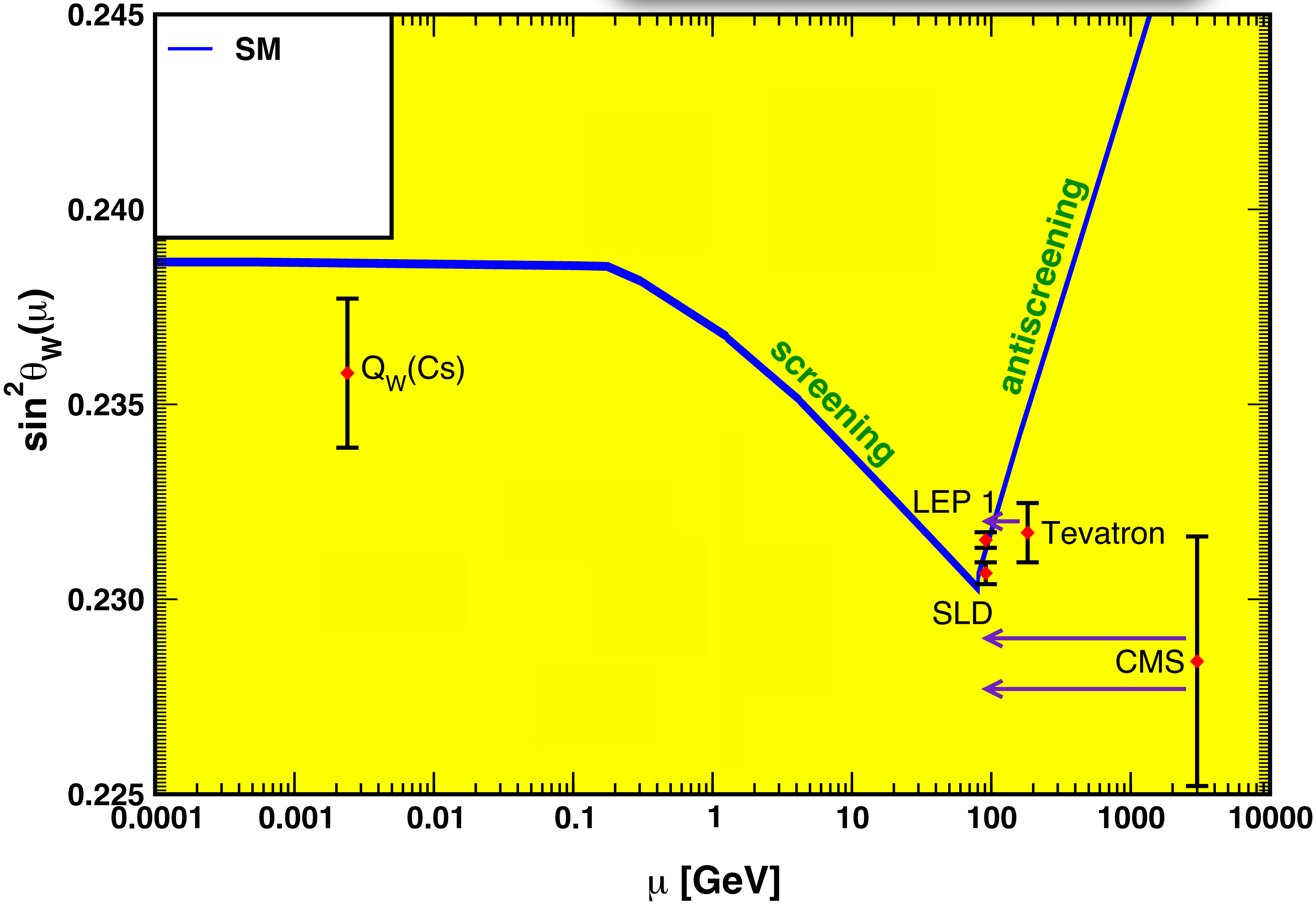

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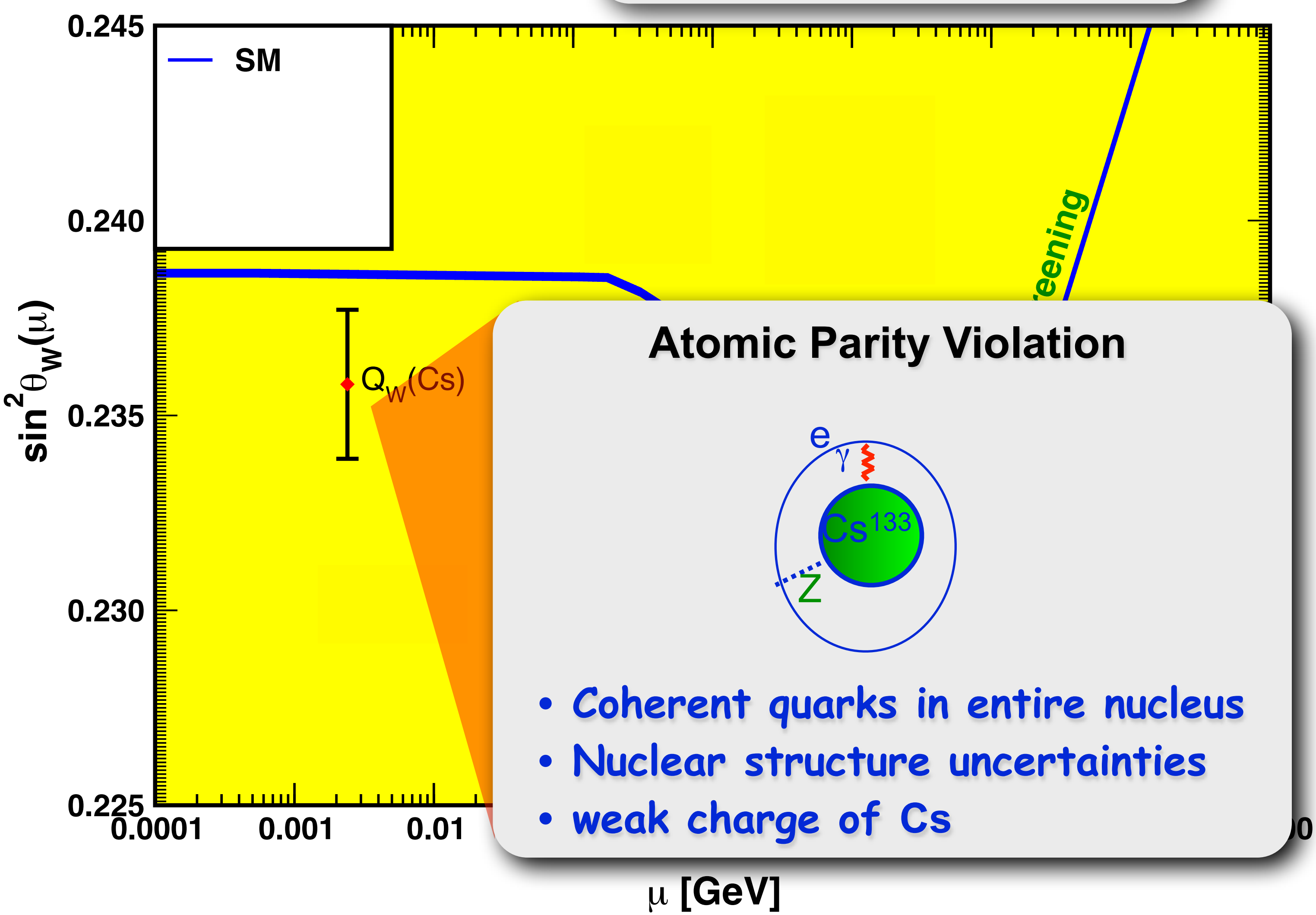

Atomic Parity Violation

- Coherent quarks in entire nucleus
- Nuclear structure uncertainties
- weak charge of Cs

Atomic parity violation

Two approaches

- rotation of polarization plane of linearly polarized light
- apply external E field $\Rightarrow$ parity forbidden atomic transition

Boulder group: cesium APV 0.35% exp uncertainty wood et. Al. (1997)

$$n'P_{1/2} \to nS_{1/2} \sim \frac{G_F}{2\sqrt{2}} C_{SP}(Z) Q_W(Z,N) + \ldots$$

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$$Q_W(Z,N) = (2Z+N) Q_W^u + (Z+2N) Q_W^d$$

$$\approx Z(1-4\sin^2\theta_W) - N \approx -N$$

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finite nuclear size
nucleon substructure
nuclear spin-dependent term
$\delta \sim \pm 0.15\%$
Pollock and Wieman (2001)
Musolf (1994)
Erler, Kurylov and Ramsey-Musolf (2003)

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atomic structure

1% Blundell et. al. (1990, 1992)

Dzuba et. Al. (1989)

$\Rightarrow$ reduced error 0.6% (exp + theory)

via transit dipole amplitude measurement

Bennett and Wieman (1999)

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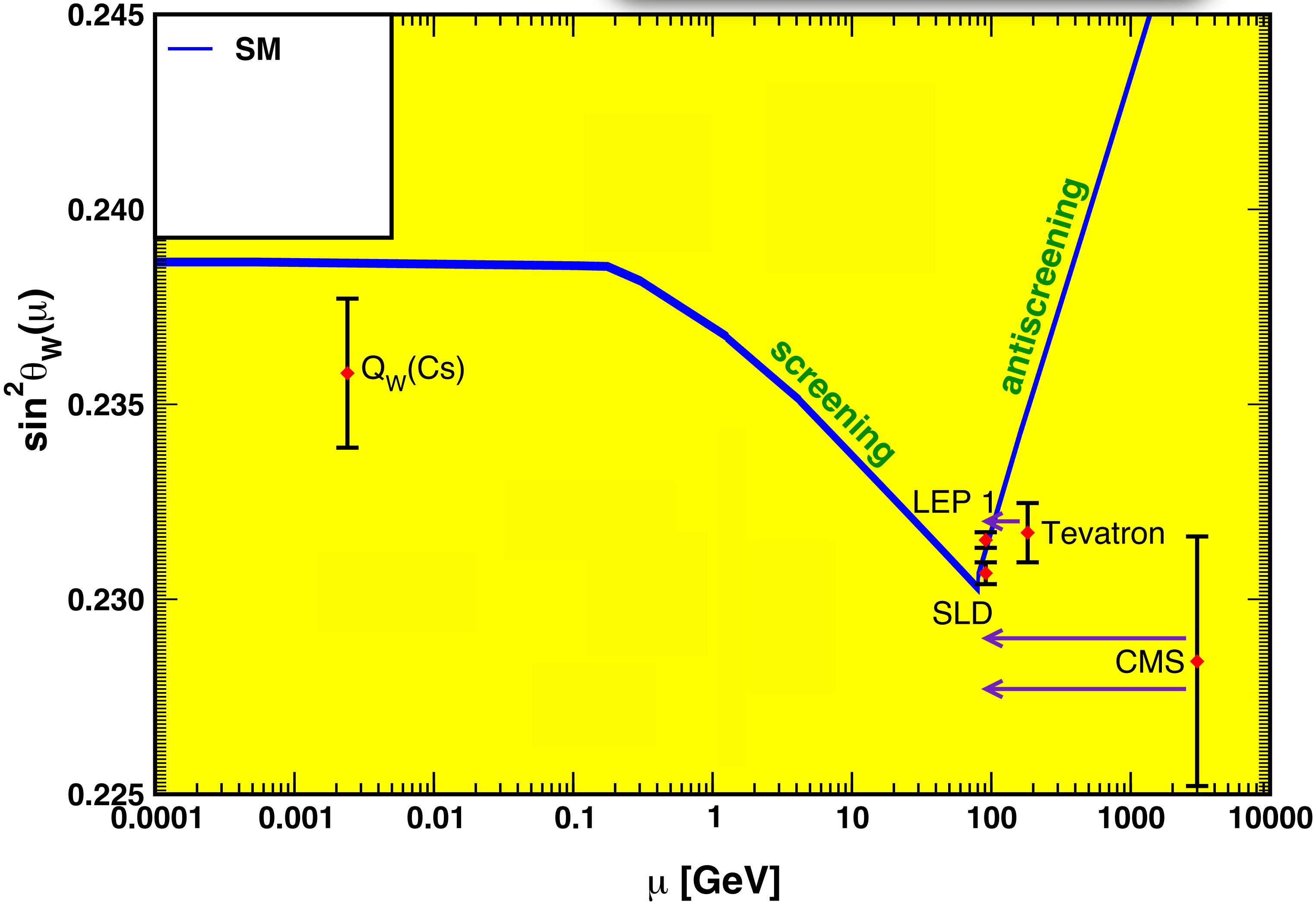
Q_W^{Cs} (exp) = -72.62 ± 0.43 Q_W^{Cs}(SM)=-73.23 (2) 1.5 σ deviation

Test of $\sin^2\theta_W$ running

Weak mixing angle $\sin\theta_W$

$$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2} = \frac{g'^2}{g^2 + g'^2}$$



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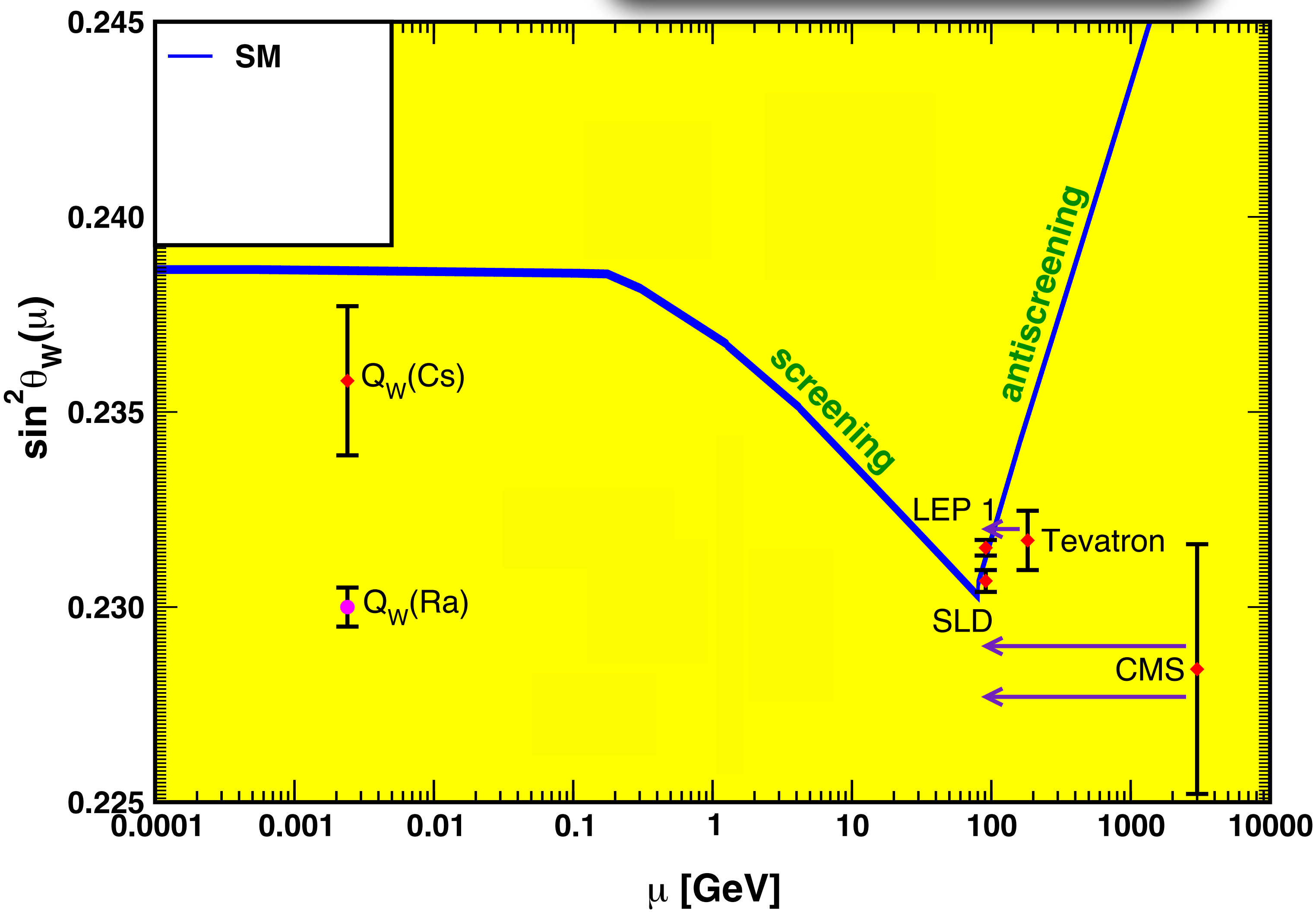

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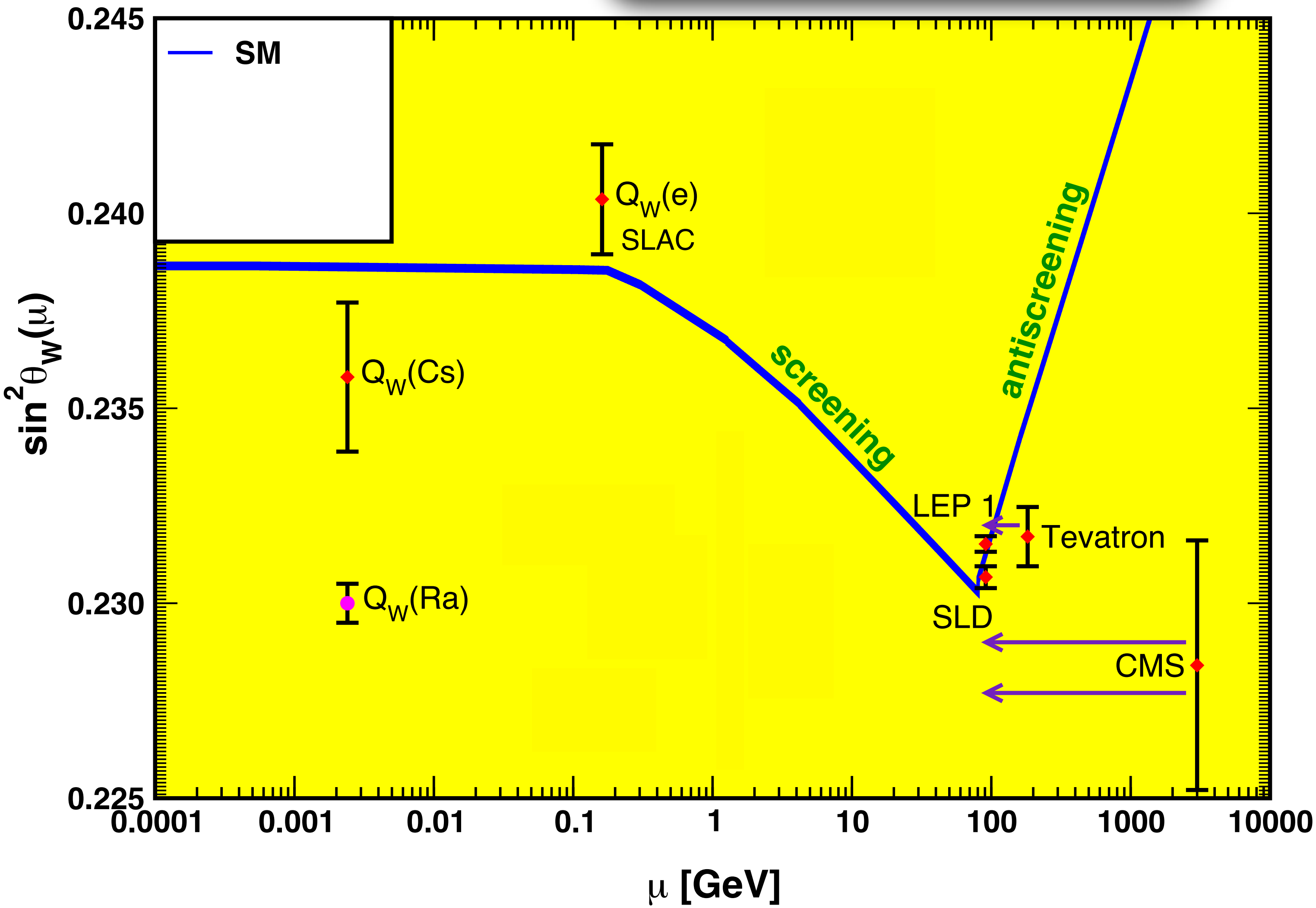

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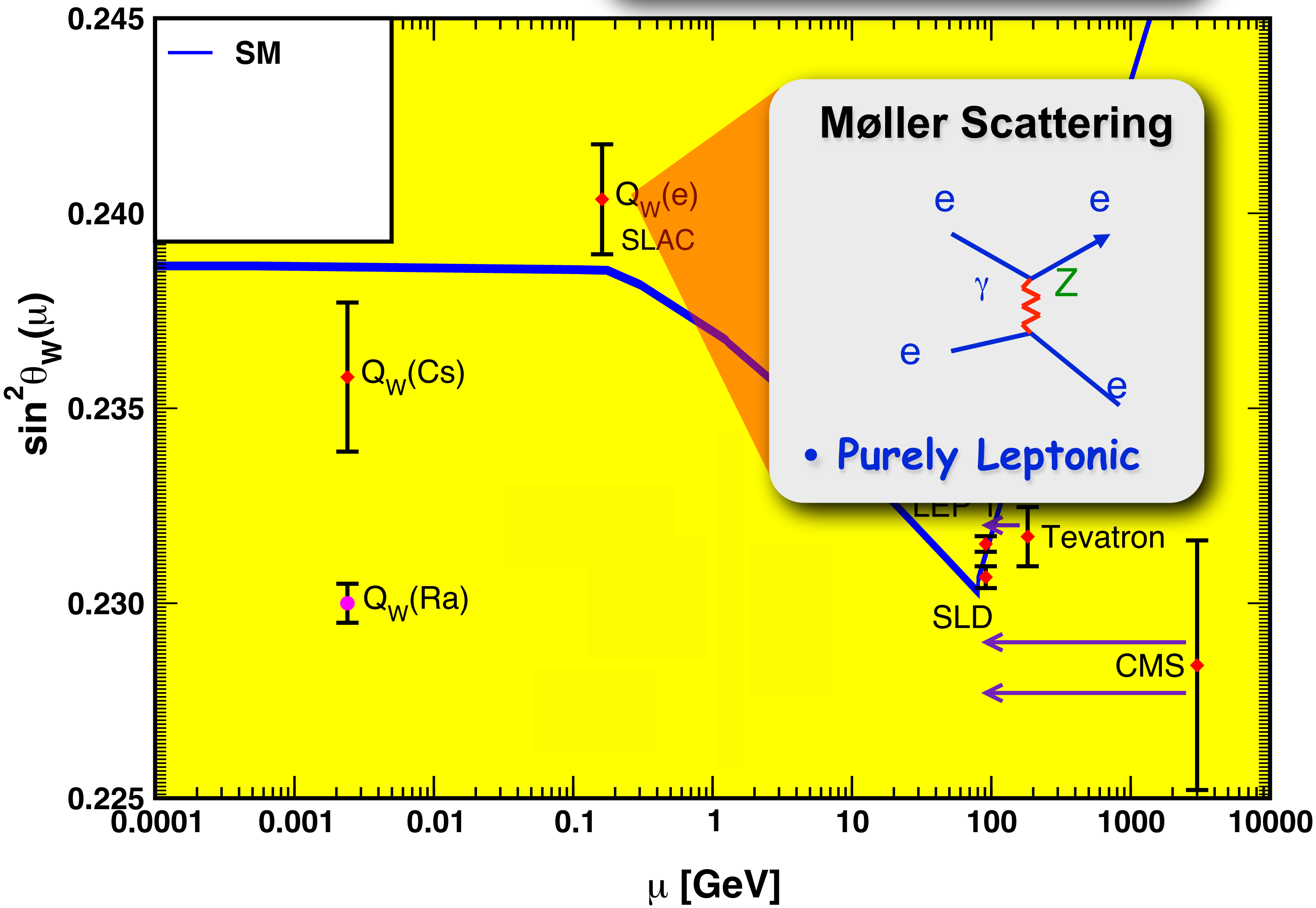
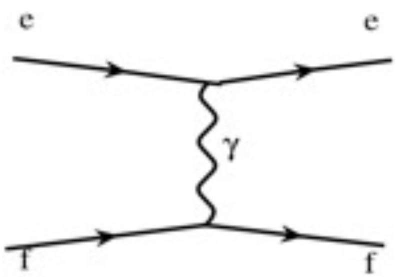
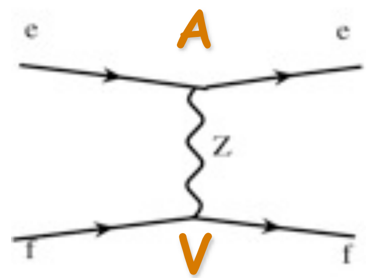


Moller

- polarized e beam scattering off unpolarized electron in liquid hydrogen target at low Q^2





$$\mathcal{L}_{PC} = \frac{e^2}{q^2} Q_e Q_f \bar{e}\gamma^\mu e \bar{f}\gamma_\mu f$$

$$\mathcal{L}_{PV} = \frac{G_\mu}{\sqrt{2}} g_A^e Q_W^f \bar{e}\gamma^\mu\gamma_5 e \bar{f}\gamma_\mu f$$

<u>weak charge</u>

$Q_W^f = 2g_V^f = 2\, I_3^f - 4Q_f s^2$

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \propto Q_W^f$$

	Q_W^e (SLAC)
Q_W^e tree	$-(1-4s^2)$
Q_W^e loop	-0.0449
q^2	0.026 GeV^2
A_{LR}	-0.131 ppm
exp precision	13%
$\delta \sin^2\theta_W$	0.0013

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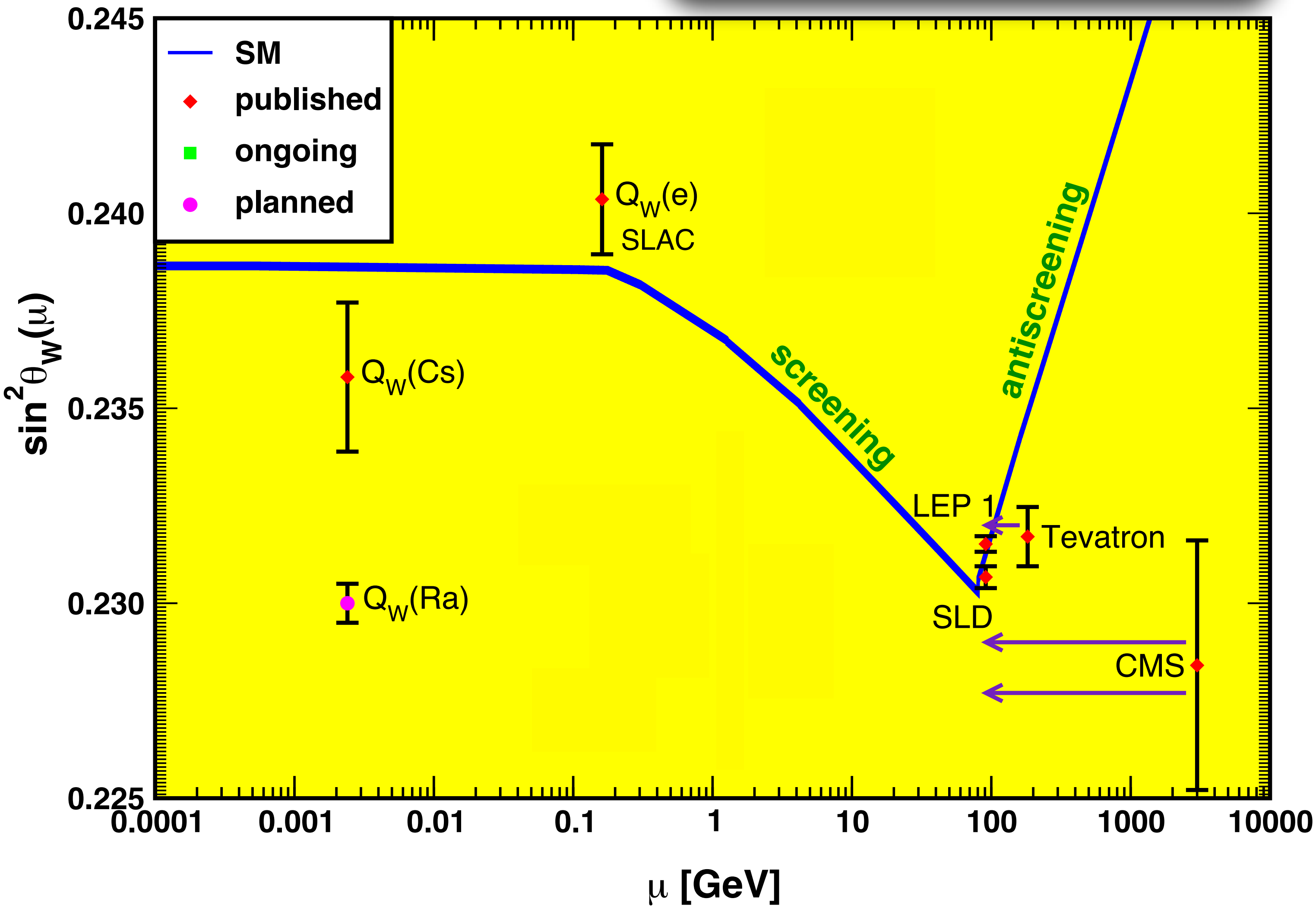

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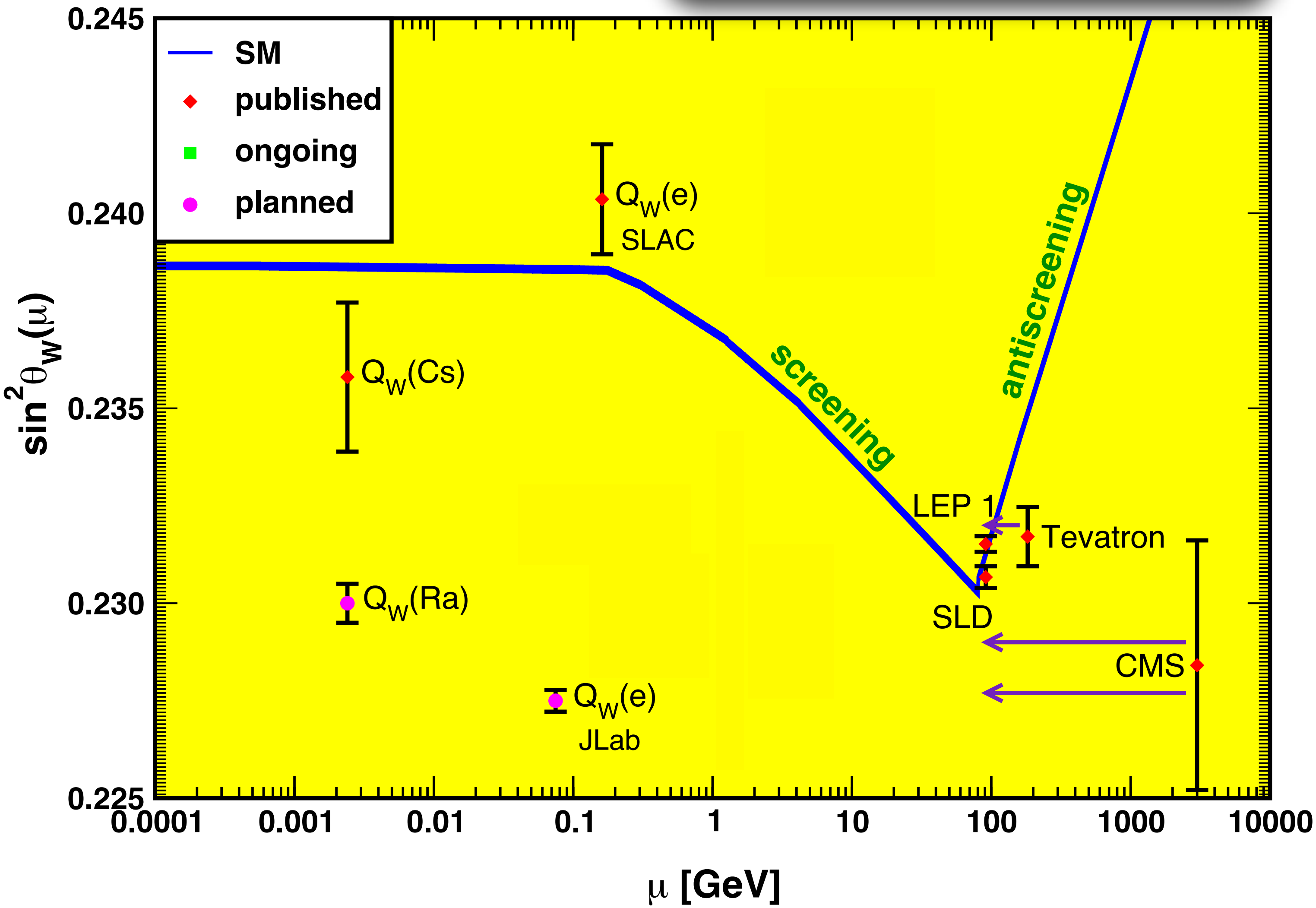

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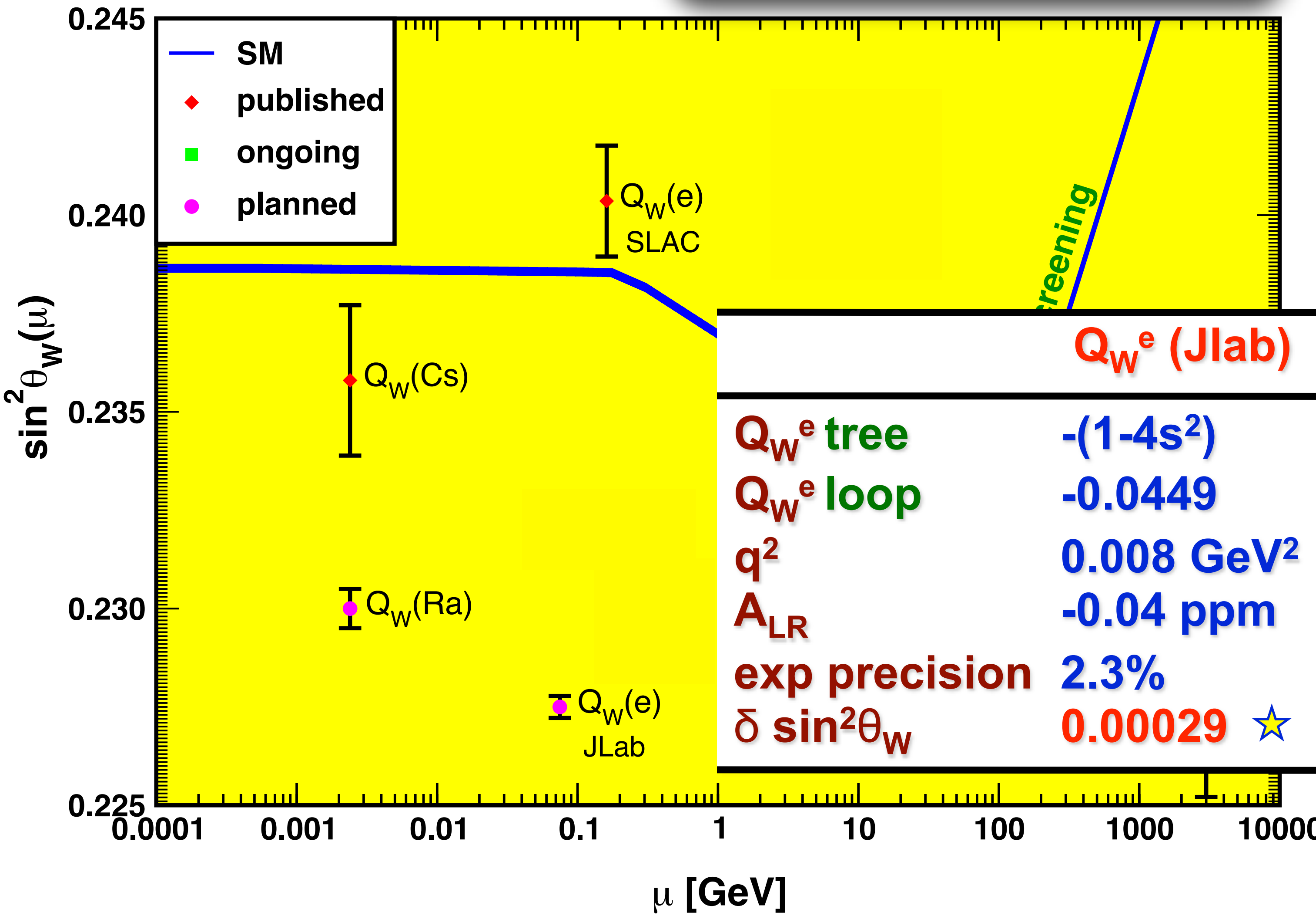

Q_W^e (Jlab)	
Q_W^e tree	$-(1-4s^2)$
Q_W^e loop	-0.0449
q^2	0.008 GeV^2
A_{LR}	-0.04 ppm
exp precision	2.3%
$\delta \sin^2\theta_W$	0.00029 ☆

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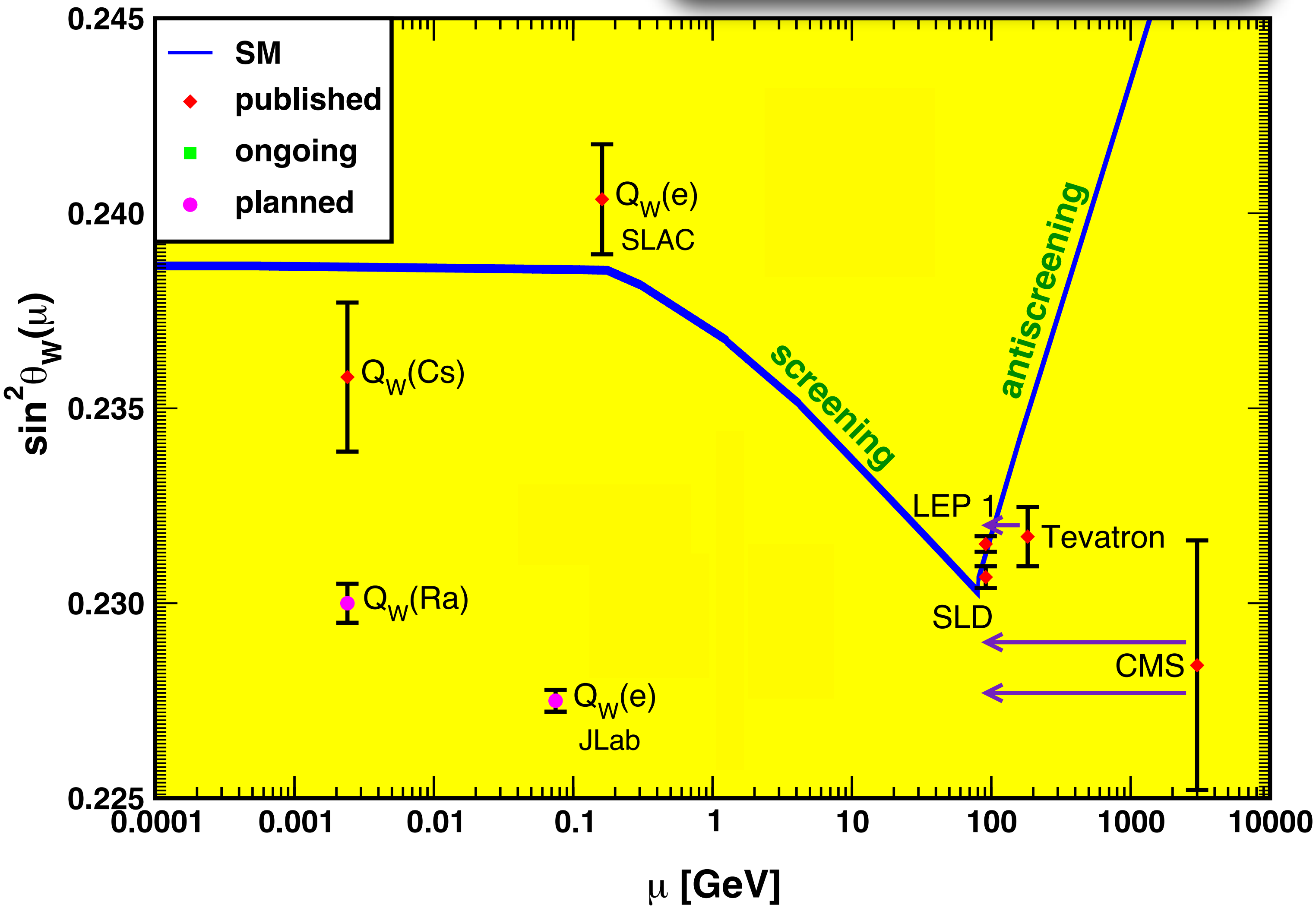

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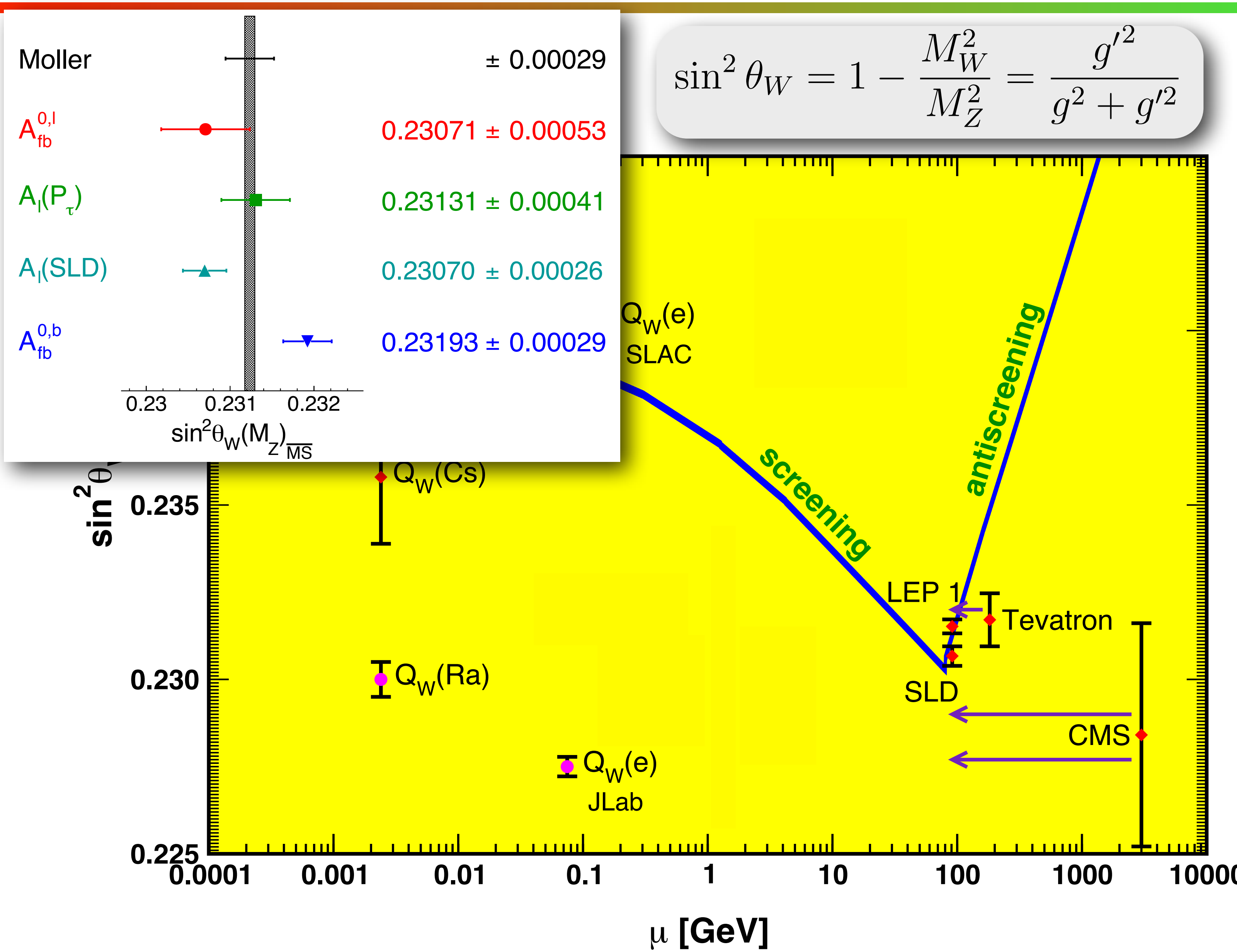

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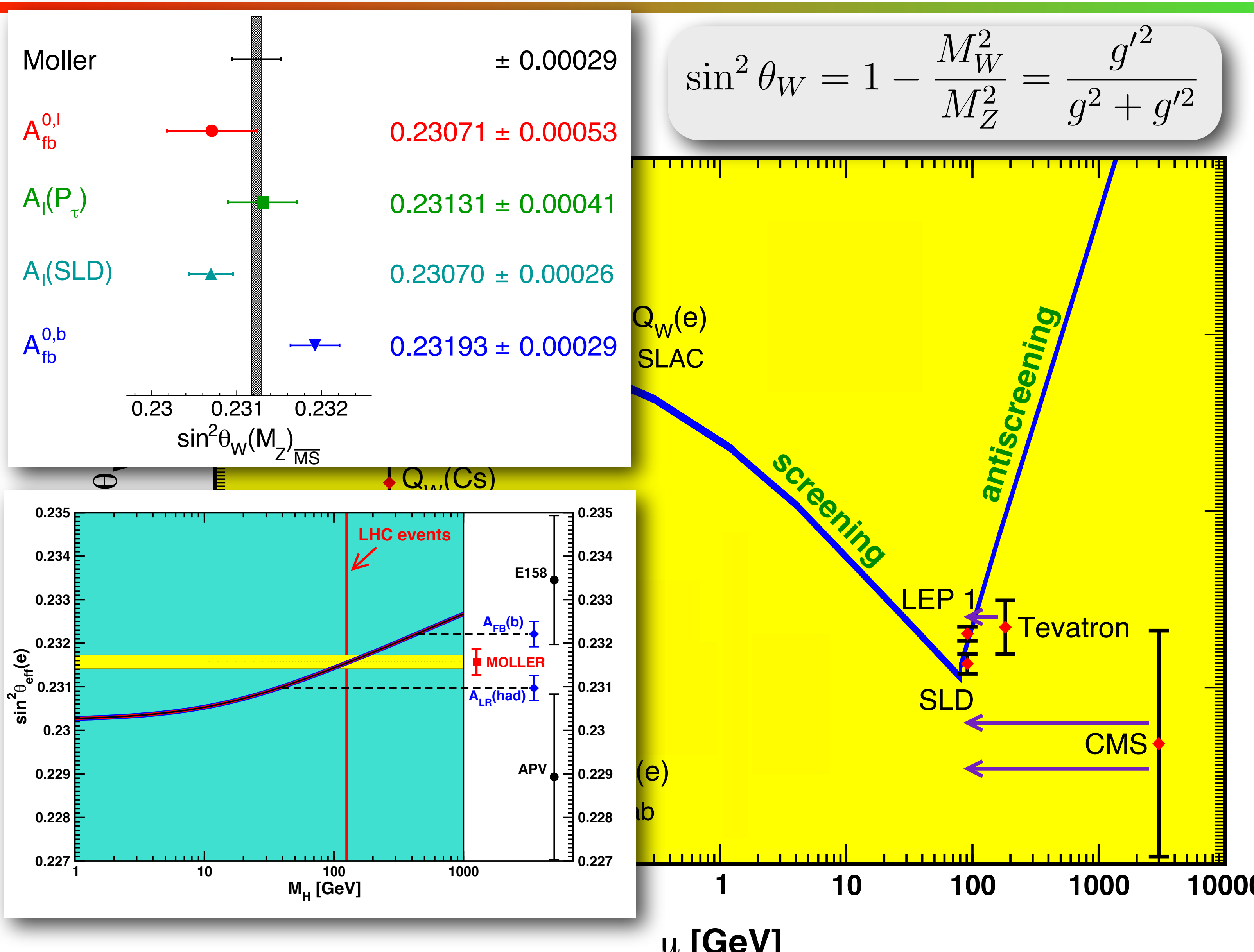

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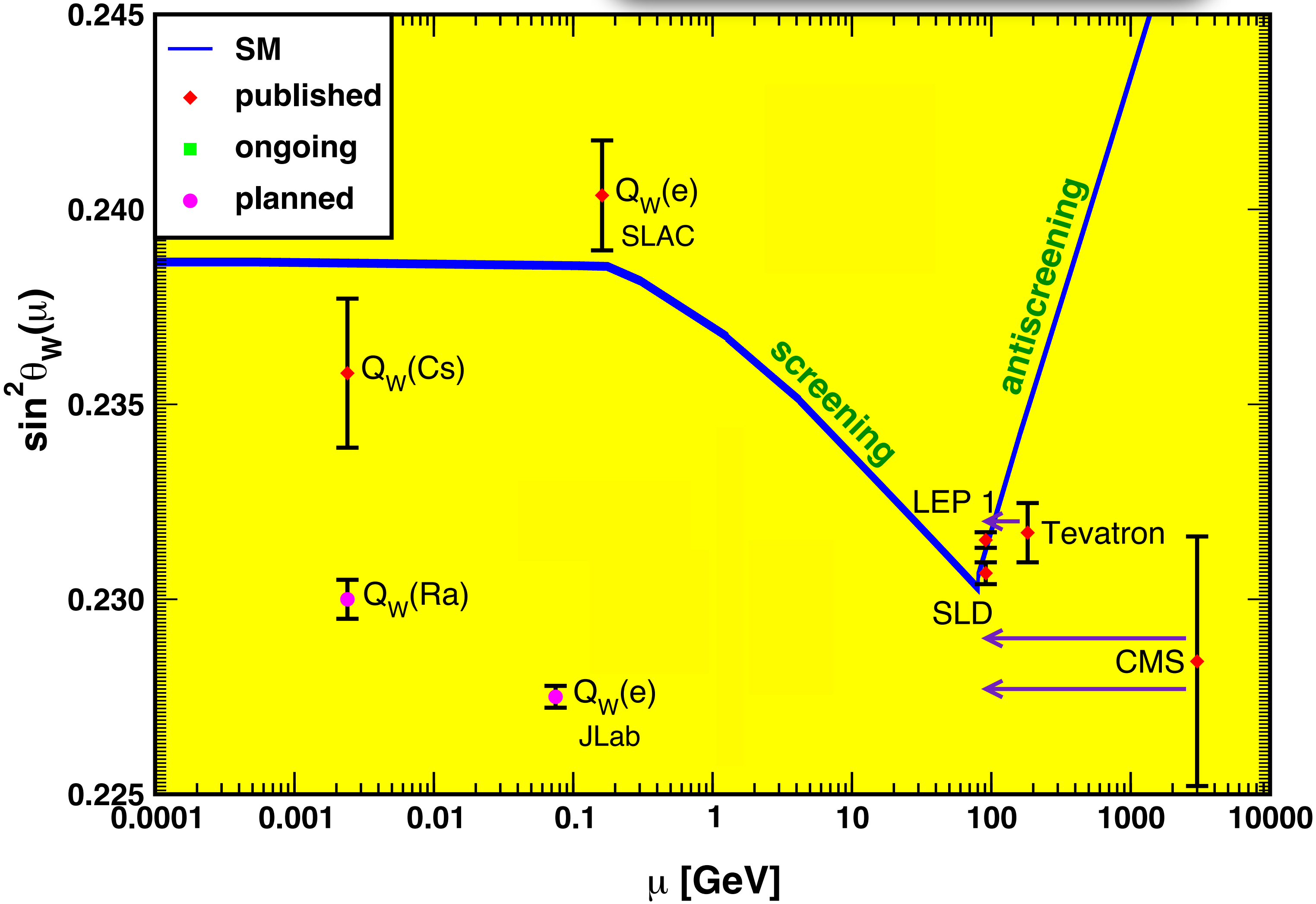

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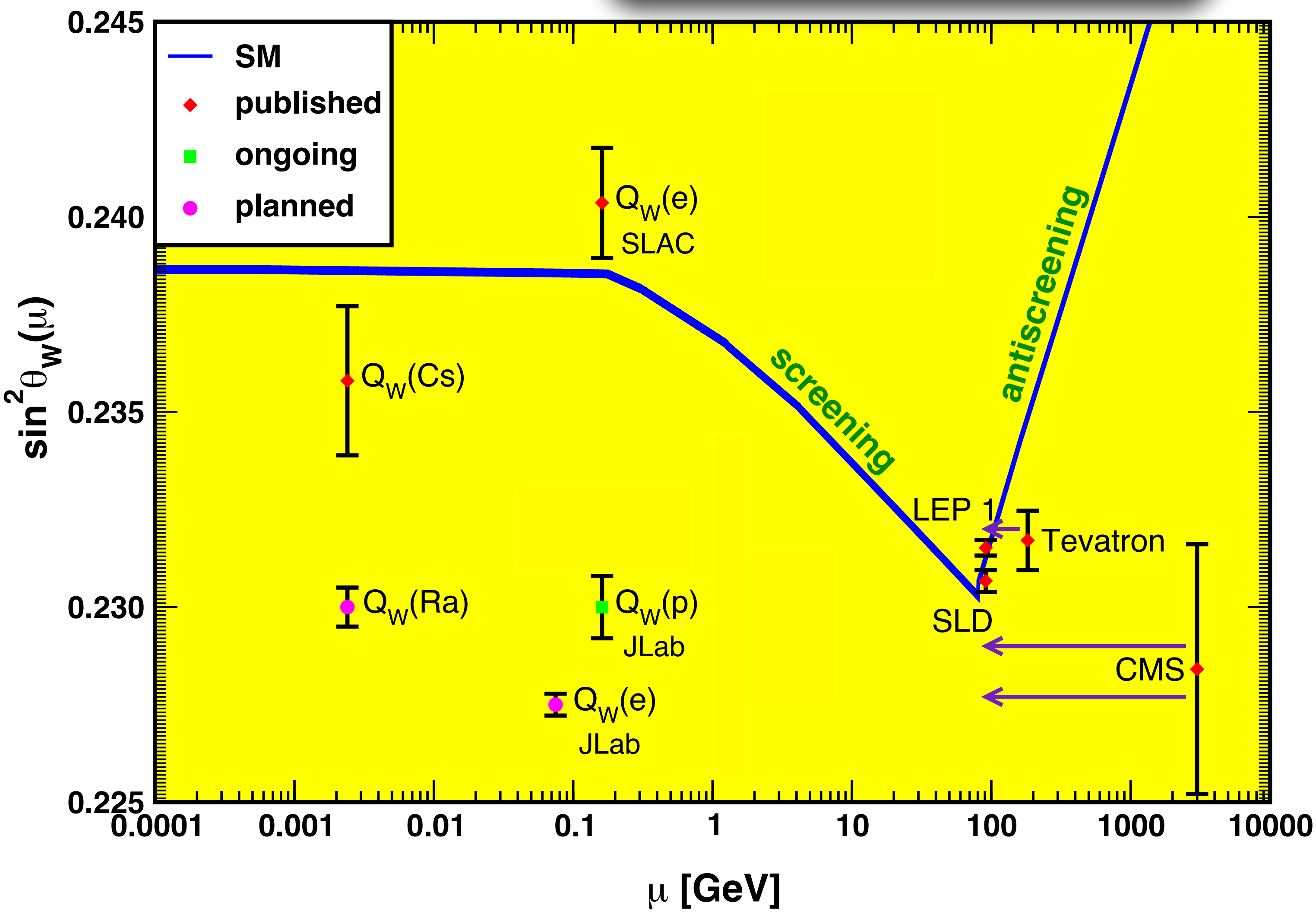

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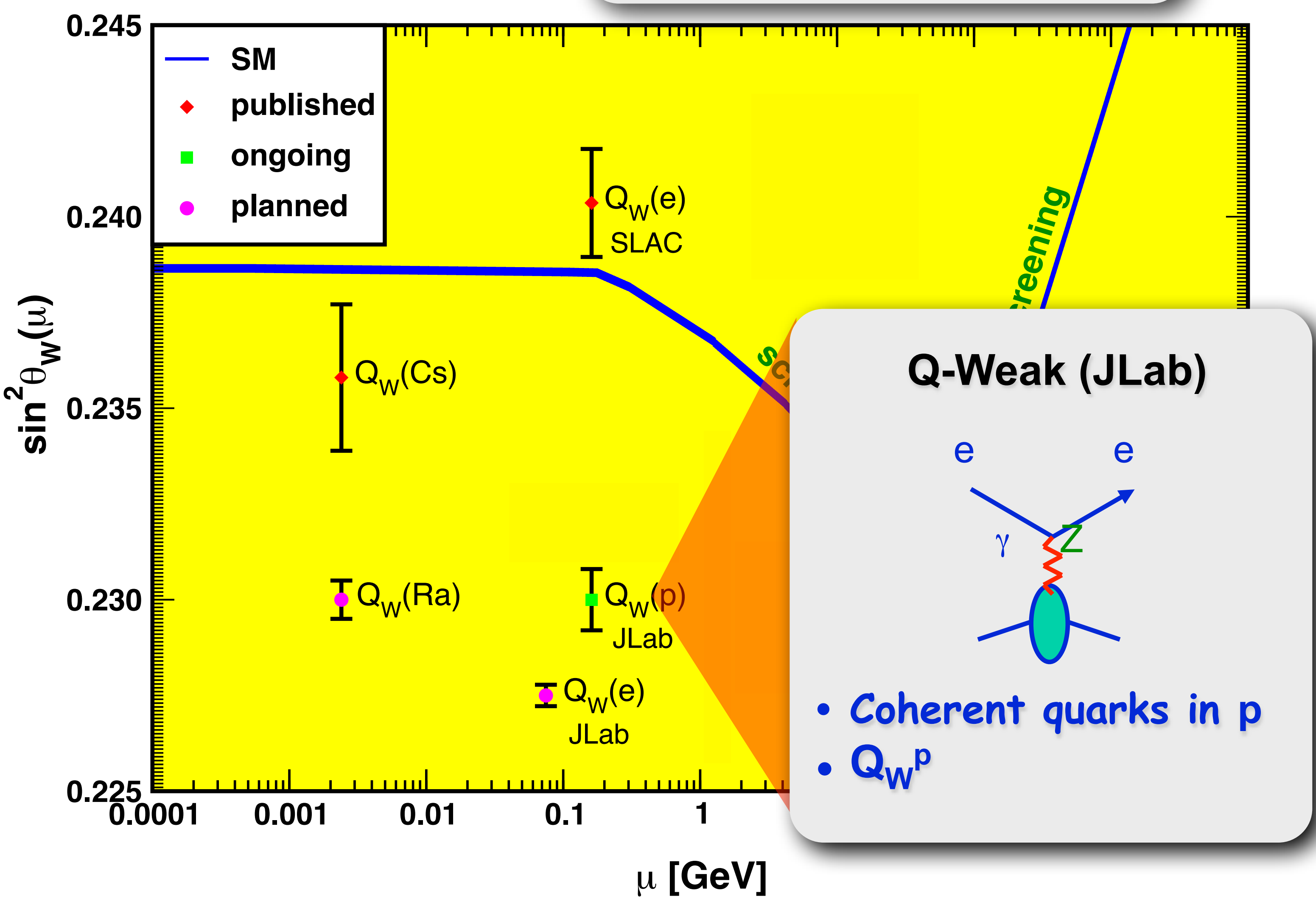


- Coherent quarks in p
- Q_W^p

QWEAK

- polarized e beam scattering off proton, elastic scattering

	Q_W^p (Qweak)	Q_W^e (SLAC)
$Q_W^{e,p}$ tree	$1-4s^2$	$-(1-4s^2)$
$Q_W^{e,p}$ loop	0.0721	-0.0449
q^2	0.03 GeV^2	0.026 GeV^2
A_{LR}	-0.27 ppm	-0.131 ppm
exp precision	4%	13%
$\delta \sin^2\theta_W$	0.0007	0.0013

Extract Q_W^p

use kinematics to simplify: at forward angle θ

$$A_{LR} = \frac{G_\mu}{4\sqrt{2}\pi\alpha} q^2 \left[Q_W^p + F(\theta, q^2) \right]$$

Musolf et. al., (1994)

?

$$F \sim \frac{q^2}{4m_p^2}(1+\mu_p)\mu_n + \text{stange quarks } \mathcal{O}(q^2) + \mathcal{O}(q^4)$$

- measure $F(\theta,q^2)$ over finite range in q^2, extrapolate F to small q^2
  existing PVES: SAMPLE, HAPPEX, G0, A4
- minimize effect of F by making q^2 small
- $q^2 \sim 0.03$ GeV^2, still enough statistics

$$\Rightarrow \delta Q^p_W / Q^p_W \mid_{\text{hadronic effects}} \approx 2\,\%$$

QCD correction to ep scattering

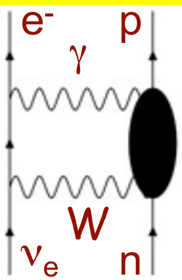
Box diagram contribution to Q_W^P

Erler, Kurylov and Ramsey-Musolf (2003)

$$\mathrm{box}_{\gamma Z} = \frac{5\alpha}{2\pi}(1-4s^2)\left[\ln\left(\frac{m_Z^2}{\Lambda^2}\right) + C_{\gamma Z}(\Lambda)\right]$$

suppression non-calculable

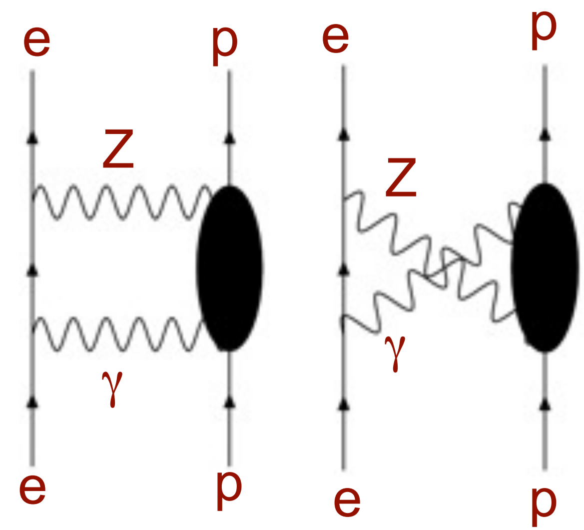
Similar to nuclear β-decay



$$= \frac{G_F}{\sqrt{2}}\frac{\alpha}{2\pi}\left[\ln\left(\frac{m_W^2}{\Lambda^2}\right) + C_{\gamma W}(\Lambda)\right]$$

$|C_{\gamma W}| < 2$ (CKM unitarity)

$|C_{\gamma Z}| < 2$



6%

$\Lambda_{QCD} < k_{loop} < O(m_Z)$

non-perturbative

0.65% (2% for energy dependent contribution)

Total theoretical uncertainty ~ 2%

QCD correction to ep scattering

Erler, Kurylov and Ramsey-Musolf (2003)

Box diagram contribution to Q_W^P

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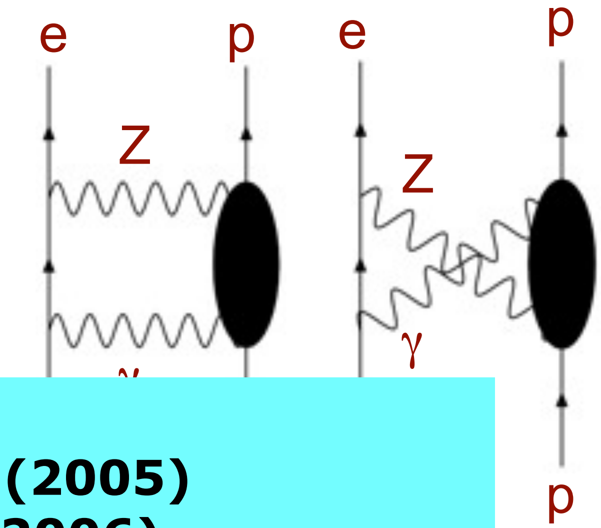
suppression   non-calculable

Similar to nuclear β-decay



Review Articles:
Erler and Ramsey-Musolf (2005)
Ramsey-Musolf and SS (2006)
Kumar, Mantry, Marciano and Souder (2013)
Erler and SS (2013)

$|C_{\gamma W}| < 2$ (CKM unitarity)

$|C_{\gamma Z}| < 2$ → 0.65% (2% for energy dependent contribution)

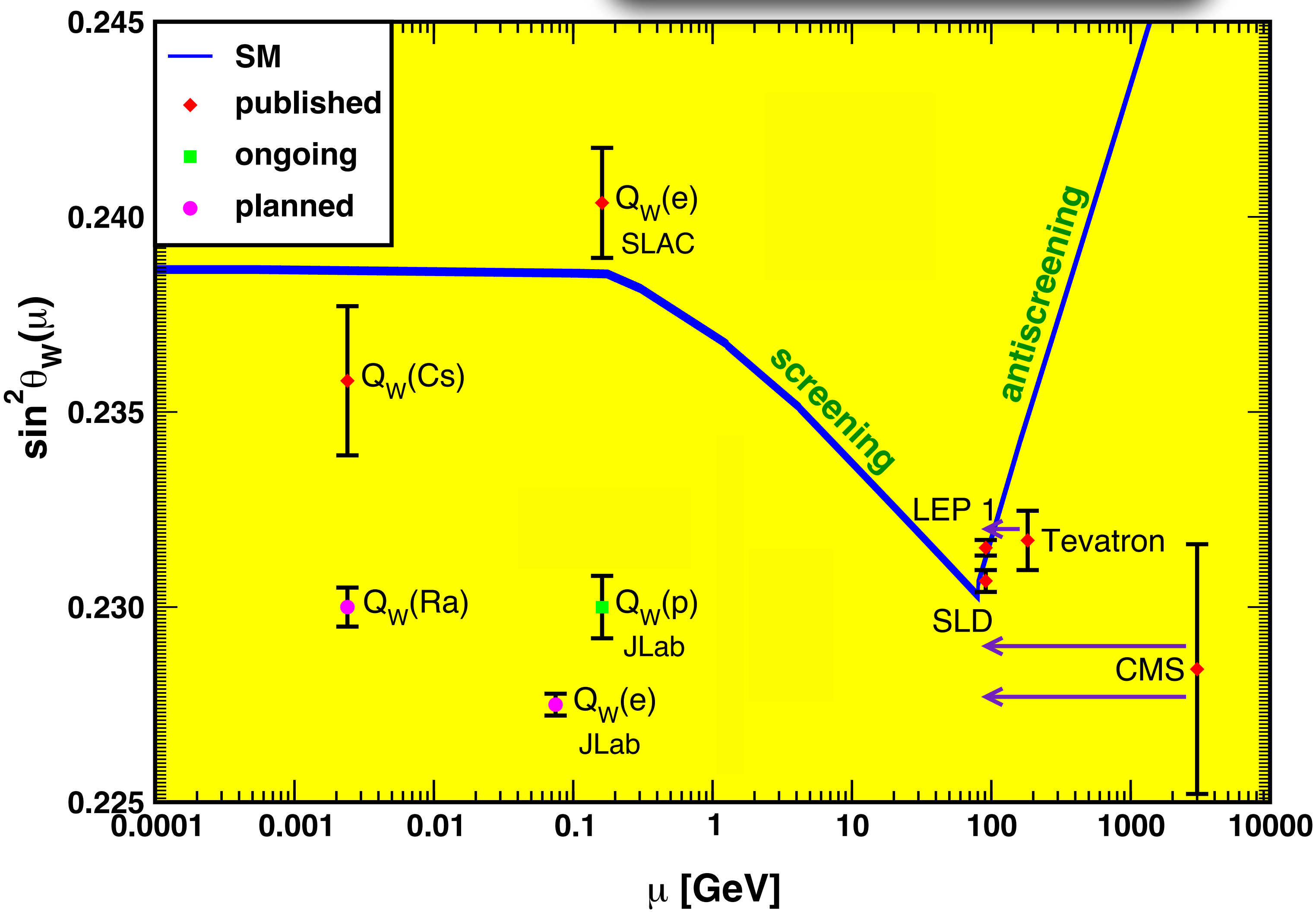
non-perturbative

Total theoretical uncertainty ~ 2%

Test of $\sin^2\theta_W$ running

Weak mixing angle $\sin\theta_W$

$$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2} = \frac{g'^2}{g^2 + g'^2}$$



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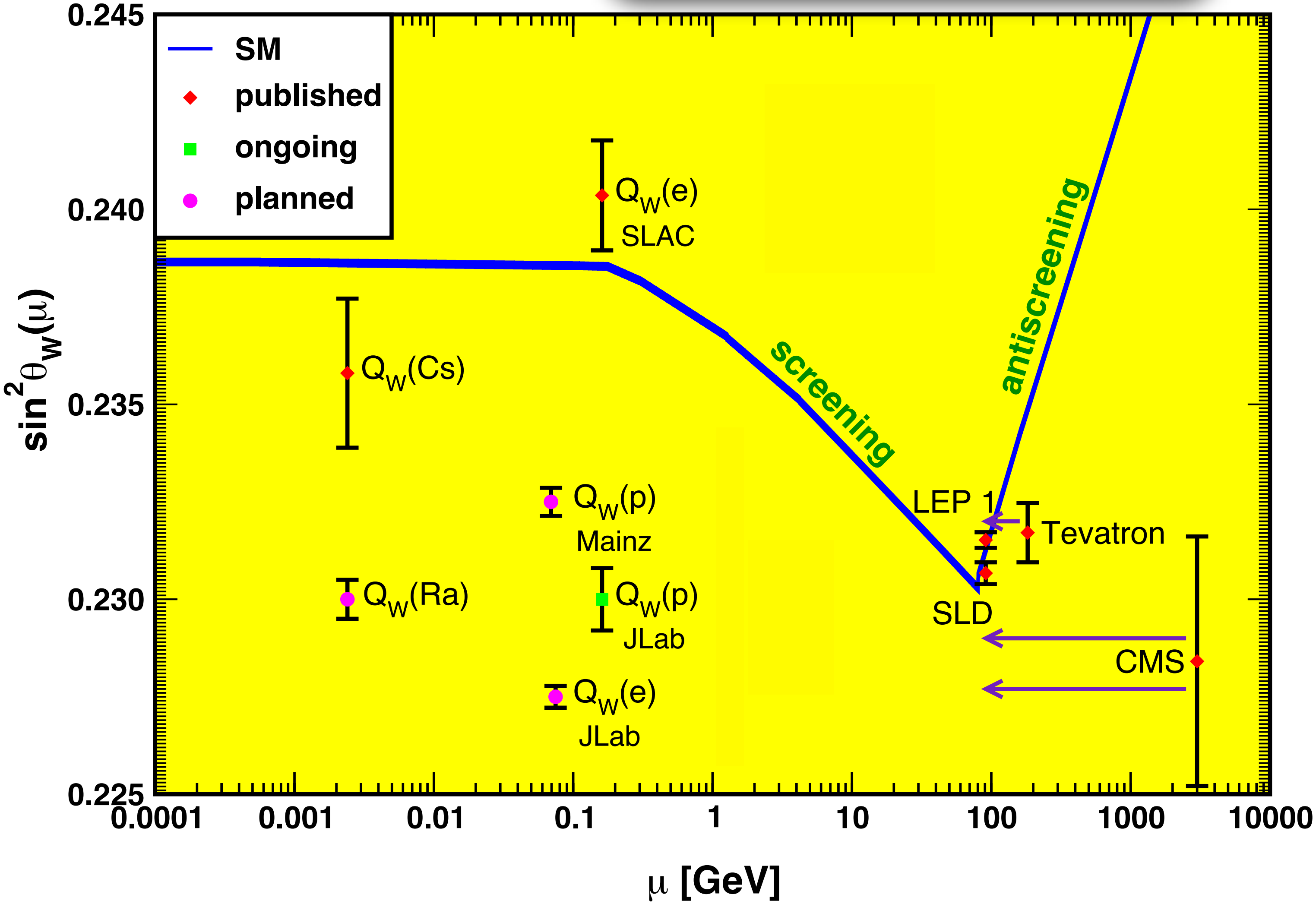

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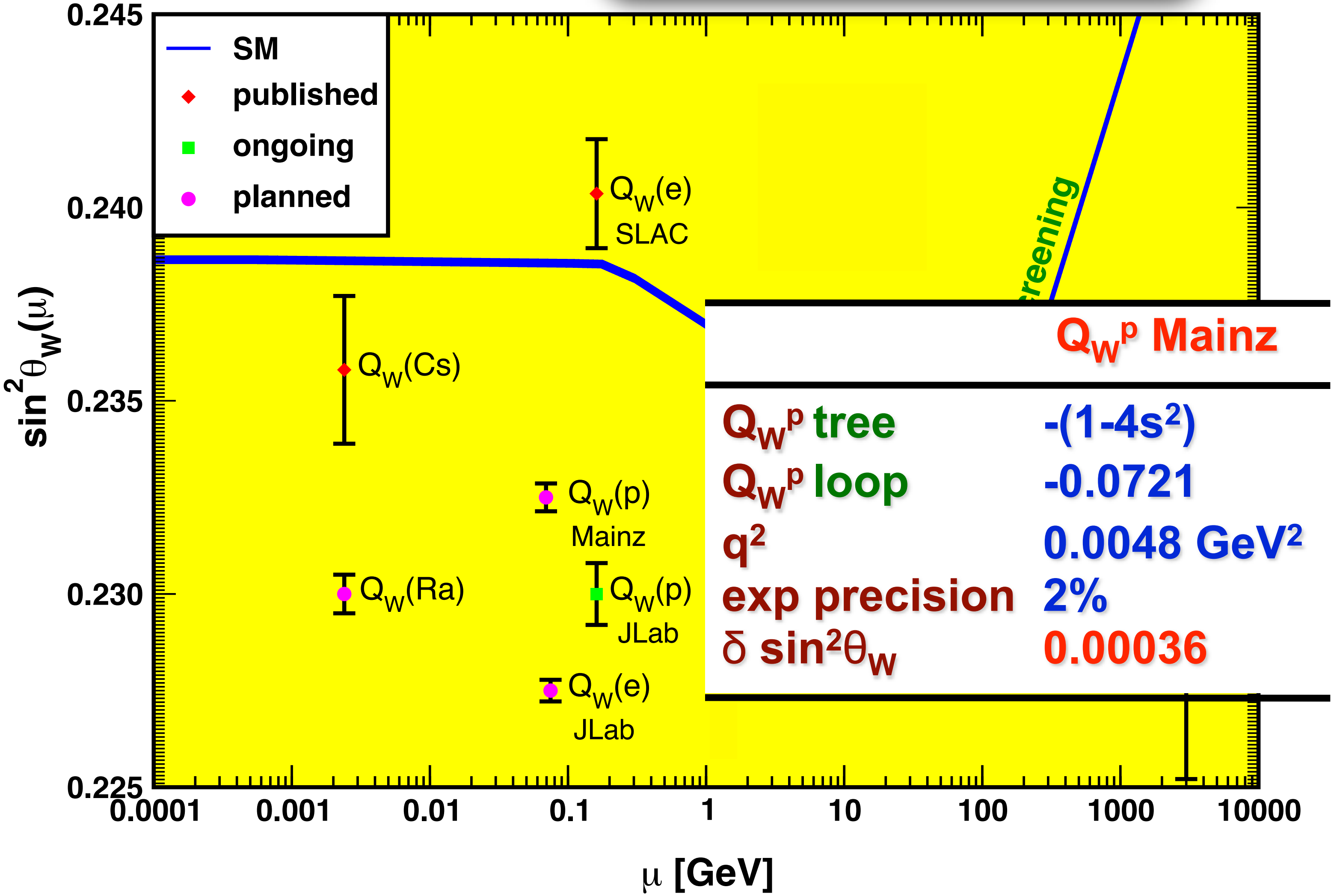

Q_W^p Mainz	
Q_W^p tree	$-(1-4s^2)$
Q_W^p loop	-0.0721
q^2	$0.0048\ \mathrm{GeV}^2$
exp precision	2%
$\delta \sin^2\theta_W$	0.00036

Test of $\sin^2\theta_W$ running

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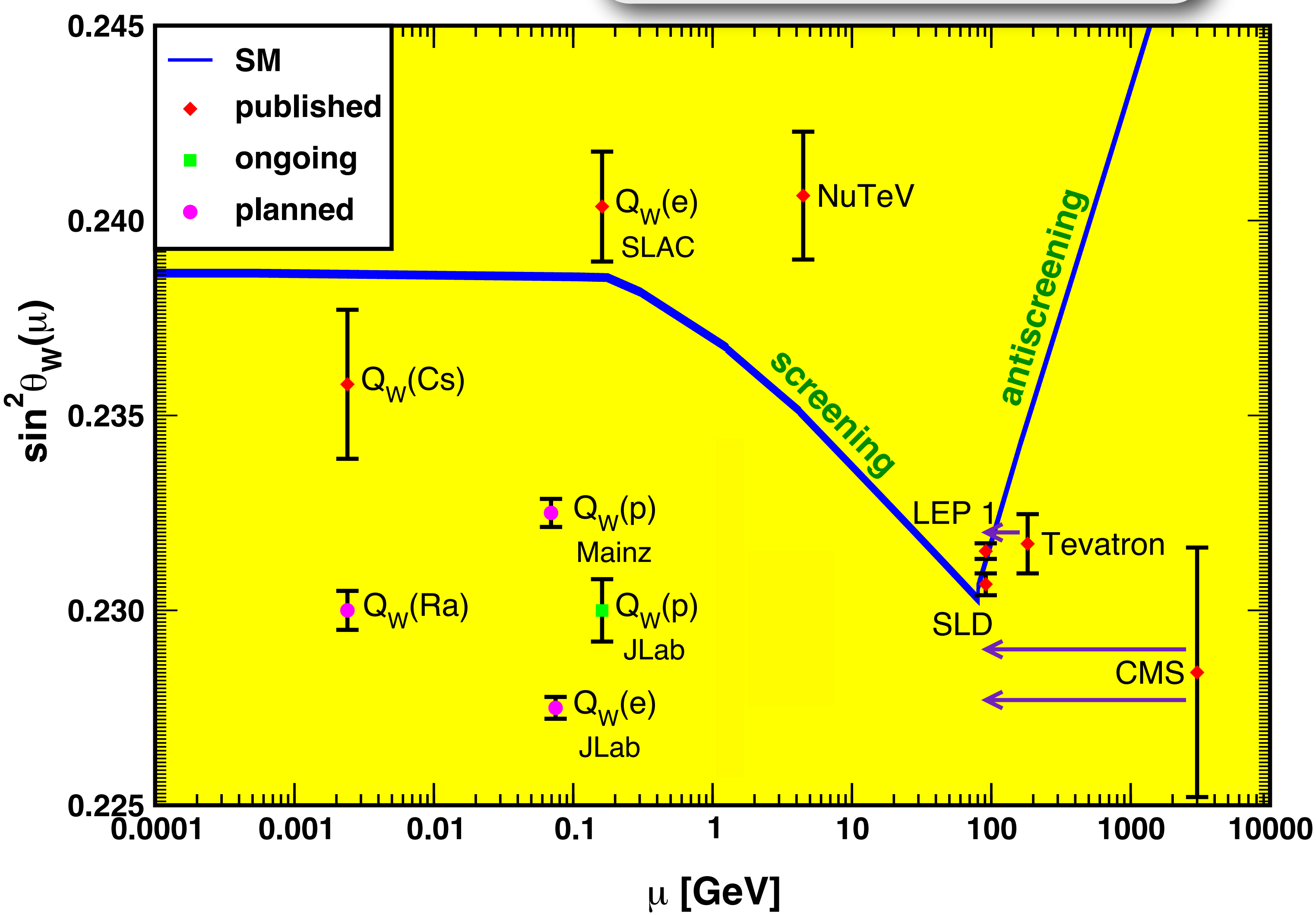

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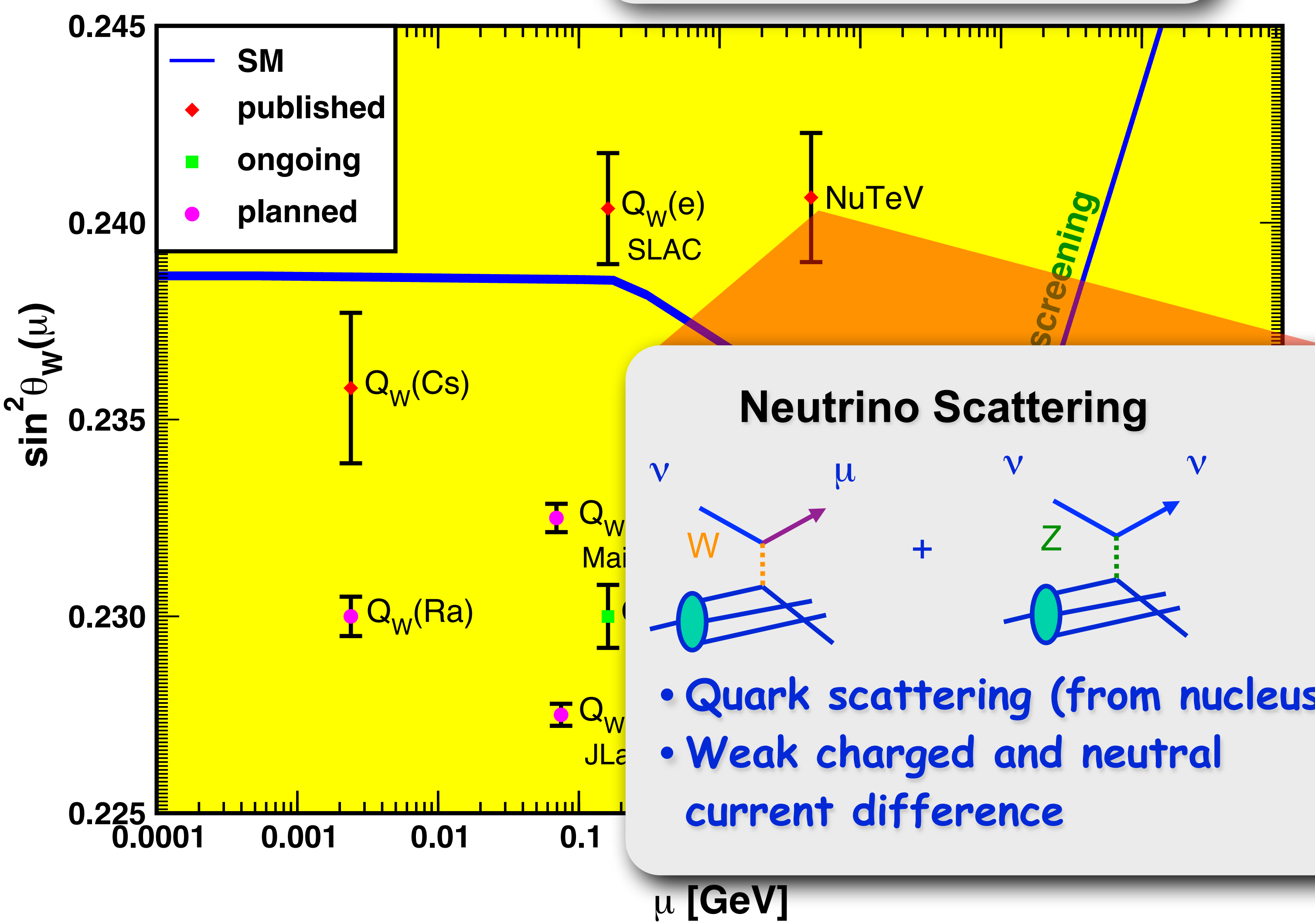
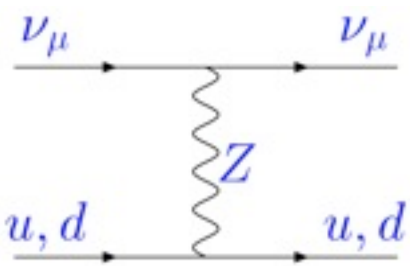


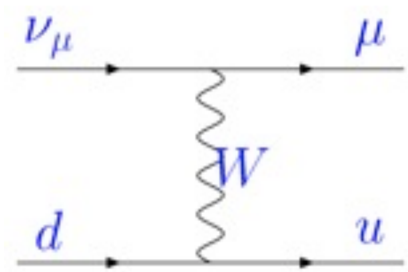
- Quark scattering (from nucleus)
- Weak charged and neutral current difference

Neutrino-nucleus DIS: NuTeV

NC



CC



$$\mathcal{L} = -\frac{G_\mu}{\sqrt{2}} \bar{\nu}\gamma^\mu(1-\gamma^5)\nu \times \left(\epsilon_L^f \bar{f}\gamma_\mu(1-\gamma^5)f + \epsilon_R^f \bar{f}\gamma_\mu(1+\gamma^5)f\right)$$

$g_{L,R}^2 = (\varepsilon^u_{L,R})^2 + (\varepsilon^d_{L,R})^2$

$$R_\nu = \frac{\sigma^{NC}_{\nu N}}{\sigma^{CC}_{\nu N}} = \frac{\sigma(\nu_\mu N \to \nu_\mu X)}{\sigma(\nu_\mu N \to \mu^- X)} = g_L^2 + r g_R^2 \qquad R_{\bar{\nu}} = \frac{\sigma^{NC}_{\bar{\nu} N}}{\sigma^{CC}_{\bar{\nu} N}} = \frac{\sigma(\bar{\nu}_\mu N \to \bar{\nu}_\mu X)}{\sigma(\bar{\nu}_\mu N \to \mu^+ X)} = g_L^2 + \bar{r} g_R^2$$

$$r \sim \frac{1}{\bar{r}} \sim \frac{\sigma^{CC}_{\bar{\nu} N}}{\sigma^{CC}_{\nu N}} \sim \frac{1}{2}$$

$\delta R^{\nu} = -0.0033 \pm 0.0015$ $\quad \delta R^{\bar{\nu}} = -0.0019 \pm 0.0026$

- **exp fit ($\rho=1$): $\sin^2\theta_W^{\text{on-shell}} = 0.2277 \pm 0.0016$**
- **SM fit to Z-pole: $\sin^2\theta_W^{\text{on-shell}} = 0.2227 \pm 0.00037$ (3 σ away)**

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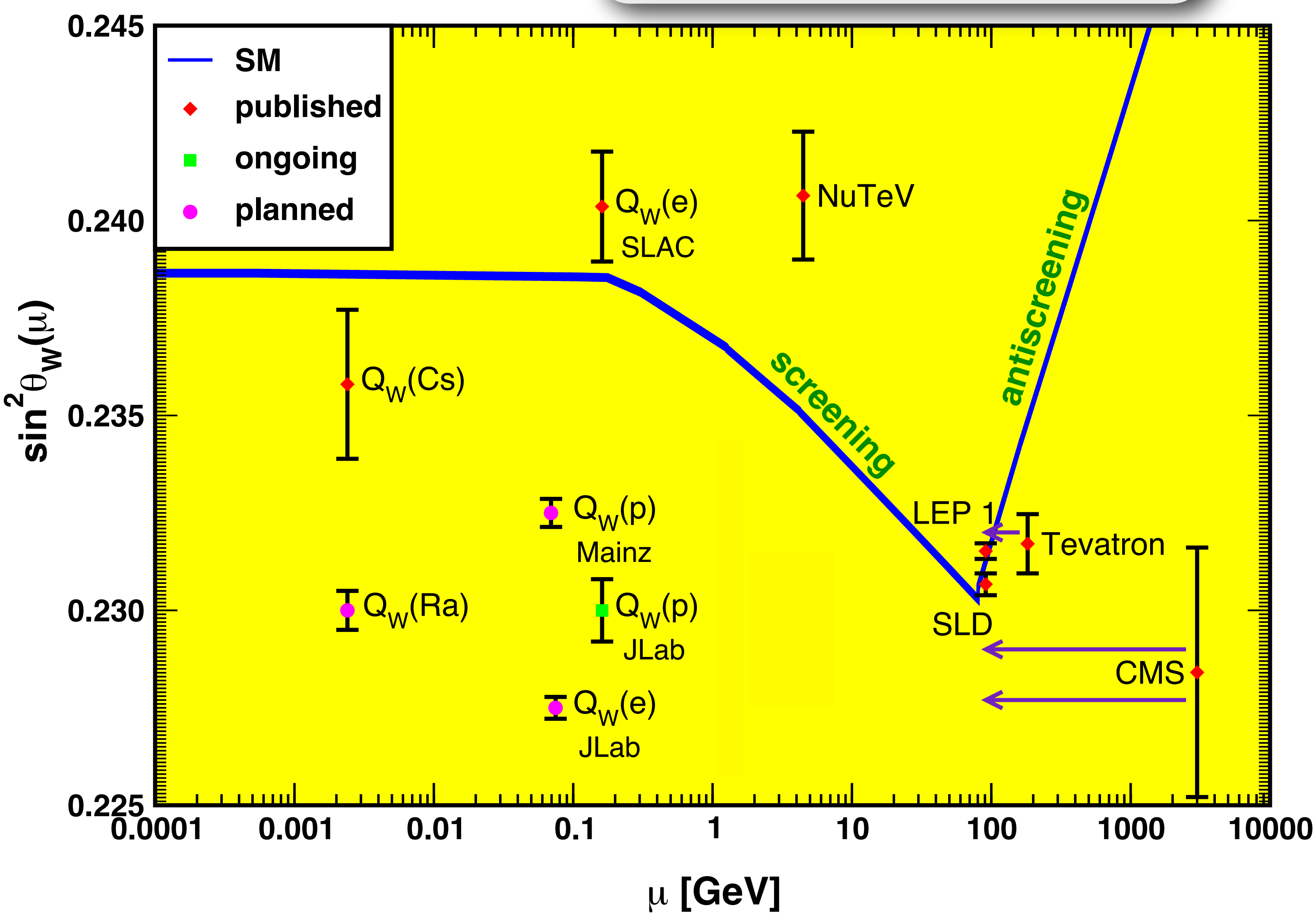

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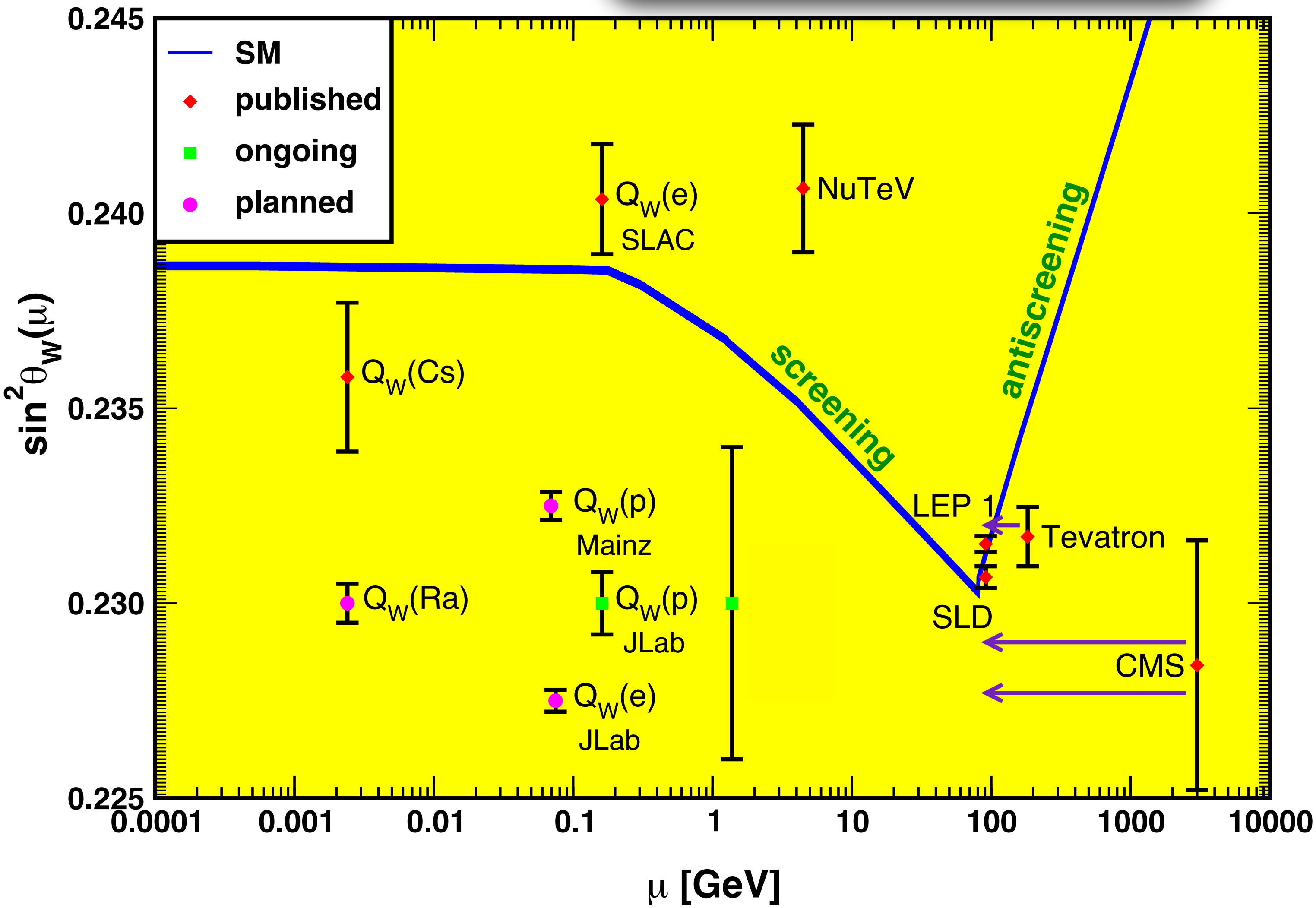

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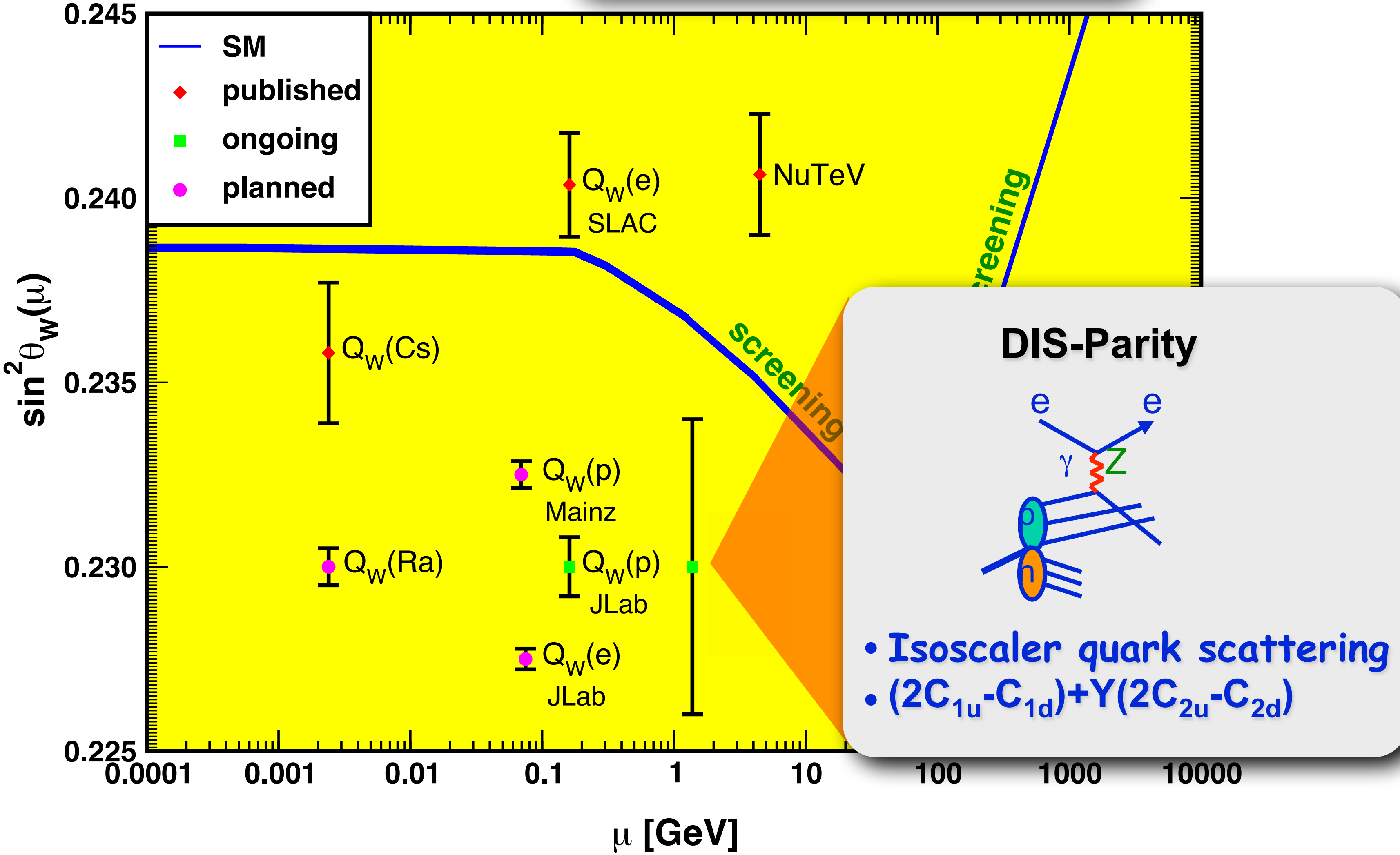
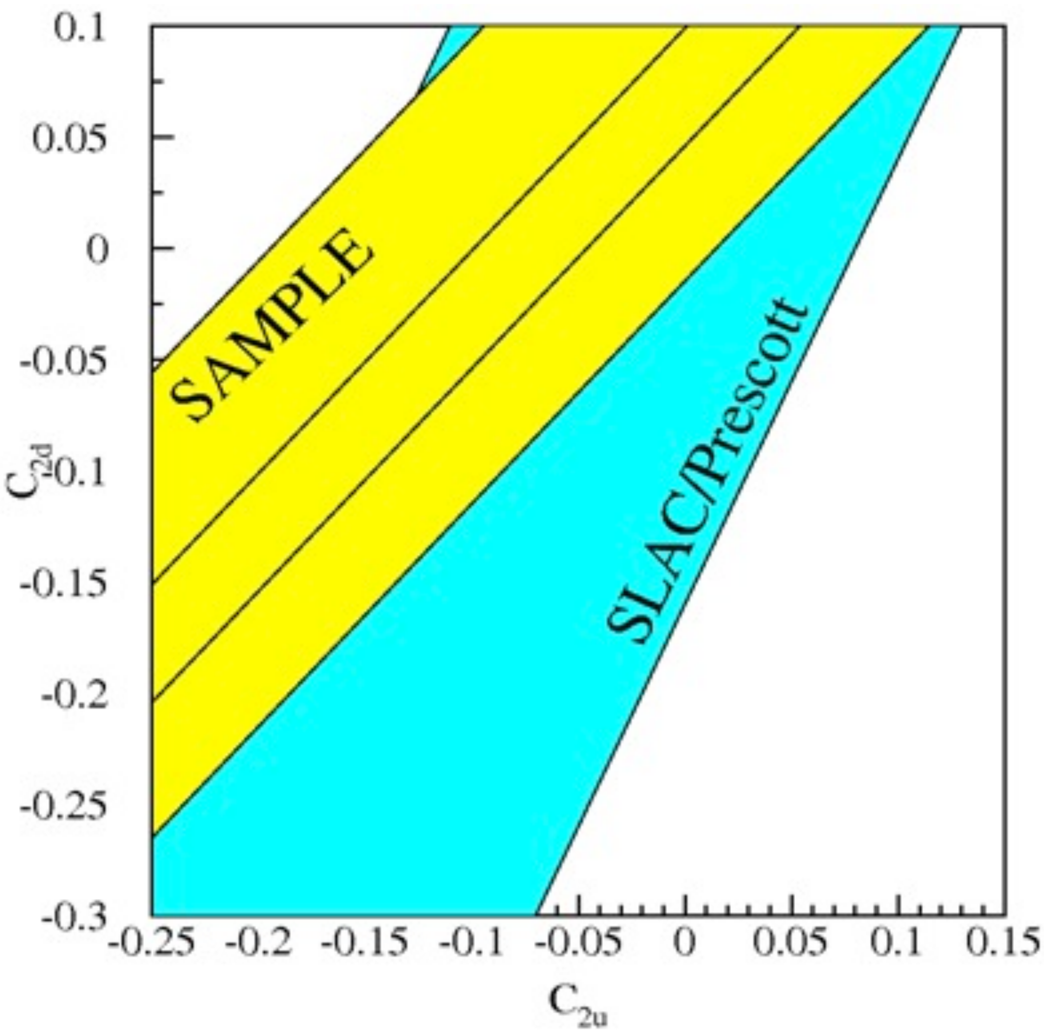


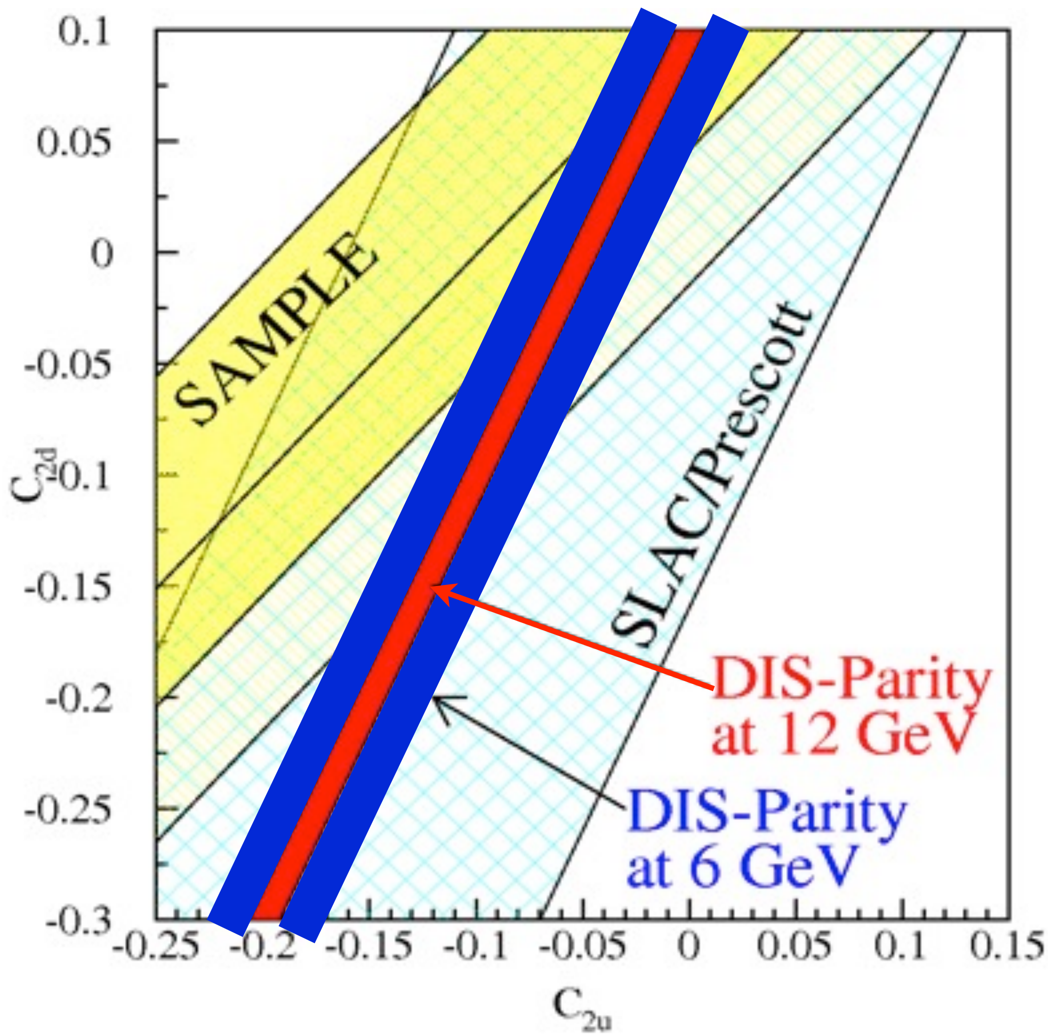
- Isoscaler quark scattering
- $(2C_{1u}-C_{1d})+Y(2C_{2u}-C_{2d})$

Ranges of C_{1u}, C_{1d}, C_{2u}, C_{2d}



Courtesy of P. Reimer

Ranges of C_{1u}, C_{1d}, C_{2u}, C_{2d}



Courtesy of P. Reimer

Precision of $\sin^2\theta_W$ determination

Measurement	$\Delta\sin^2\theta_W/\sin^2\theta_W$	$\Delta\sin^2\theta_W$
Z-pole	0.07%	0.00017
0.5% $Q_w(Cs)$	0.6%	0.0013
NuTeV	0.7%	0.0016
13.1% $Q_w(e)^{SLAC}$	0.5%	0.0013
4% $Q_W(p)$	0.3%	0.00072
2.3% $Q_w(e)^{Jlab}$	0.1%	☆ 0.00029 (on par with Z pole)
2% $Q_W(p)$ Mainz	0.15%	0.00036
2.5% (0.5%) eDIS	1.4% (0.28%)	0.003 (0.0006)

Sensitivity to new physics scale

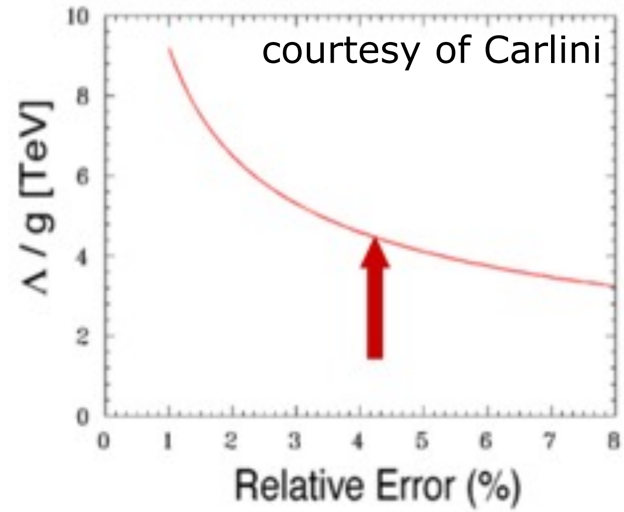
$$L_{eq}^{\mathrm{PV}} = L_{\mathrm{SM}}^{\mathrm{PV}} + L_{\mathrm{new}}^{\mathrm{PV}} = -\frac{G_\mu}{2\sqrt{2}} \bar{e}\gamma_\mu\gamma_5 e \sum_q Q_W^q \bar{q}\gamma^\mu q + \frac{g^2}{4\Lambda^2} \bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q \bar{q}\gamma^\mu q$$

Ramsey-Musolf(1999)

Λ: **new physics scale** **O(1)**

Take δQ_W^p=4%

$$\boxed{\frac{\Lambda}{g} \sim \frac{1}{\sqrt{\sqrt{2} G_F |\delta Q_W^p|}} \sim 4.6\,\mathrm{TeV}}$$



- **probe new physics scale comparable to LHC**
- **confirmation of LHC discovery (couplings, charges)**

Misc. model sensitivities (non-SUSY)

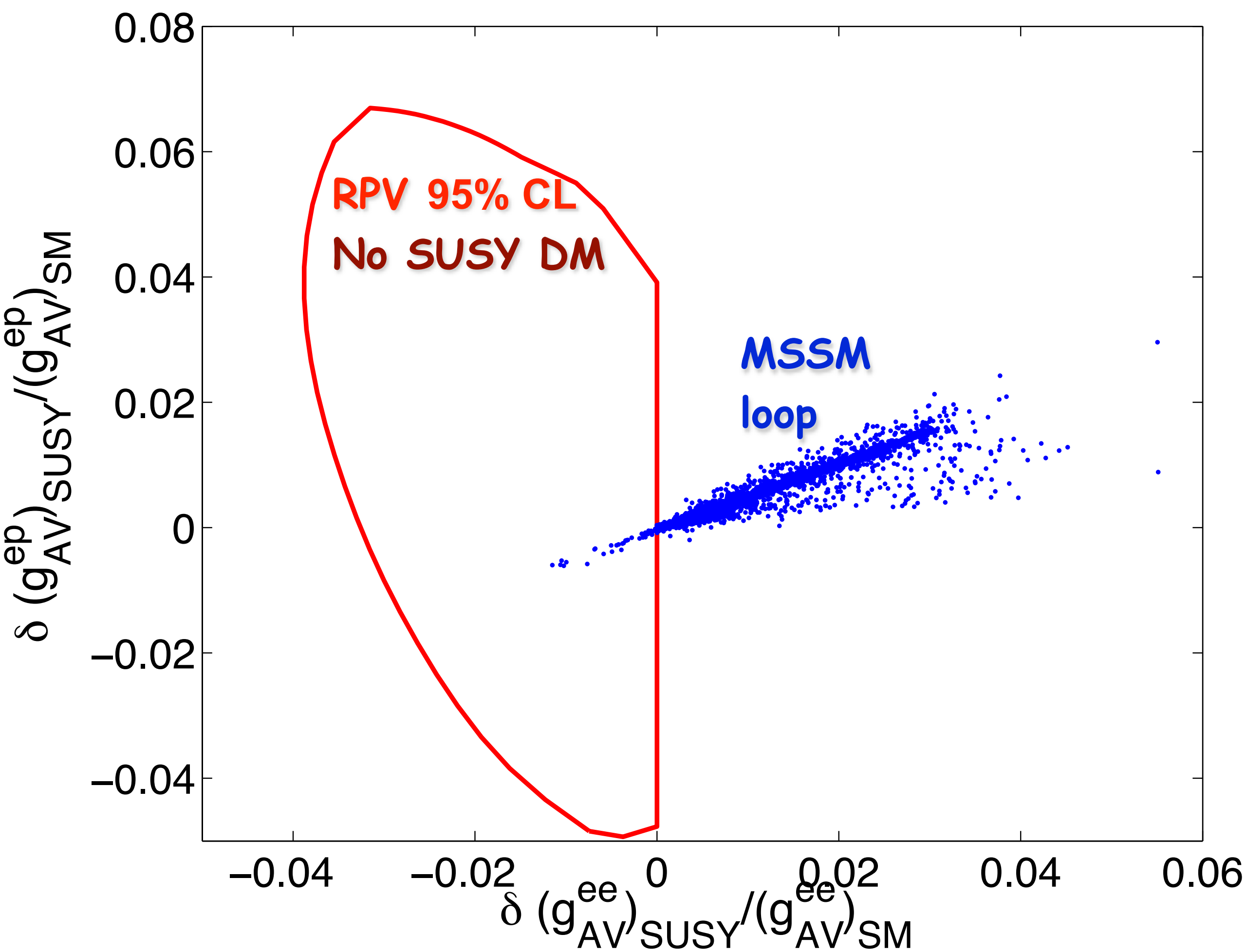
Courtesy of D. Mack

Experiment	Z' $M(Z_X)$ (TeV)	$M(Z_{LR})$ (TeV)	Leptoquarks M_{LQ}(up) (TeV)	M_{LQ}(down) (TeV)	Compositeness (LL) e-q (TeV)	e-e (TeV)
EW fit	0.78	0.86	1.5	1.5	11-26	8-10
0.5% Q_w(Cs)	1.2	★1.3	★ 4.0	3.8	★ 28	---
13.1% Q_w(e)	.66	.34	---	---	---	13
4% Q_w(p)	.95	.45	3.1	★4.3	★ 28	----
2.5% Q_w(e)	★ 1.5	.77	---	---	---	★29

scaled from R-Musolf, PRC 60 (1999), 015501

SUSY contributions

Kurylov, Ramsey-Musolf, Su (2003)



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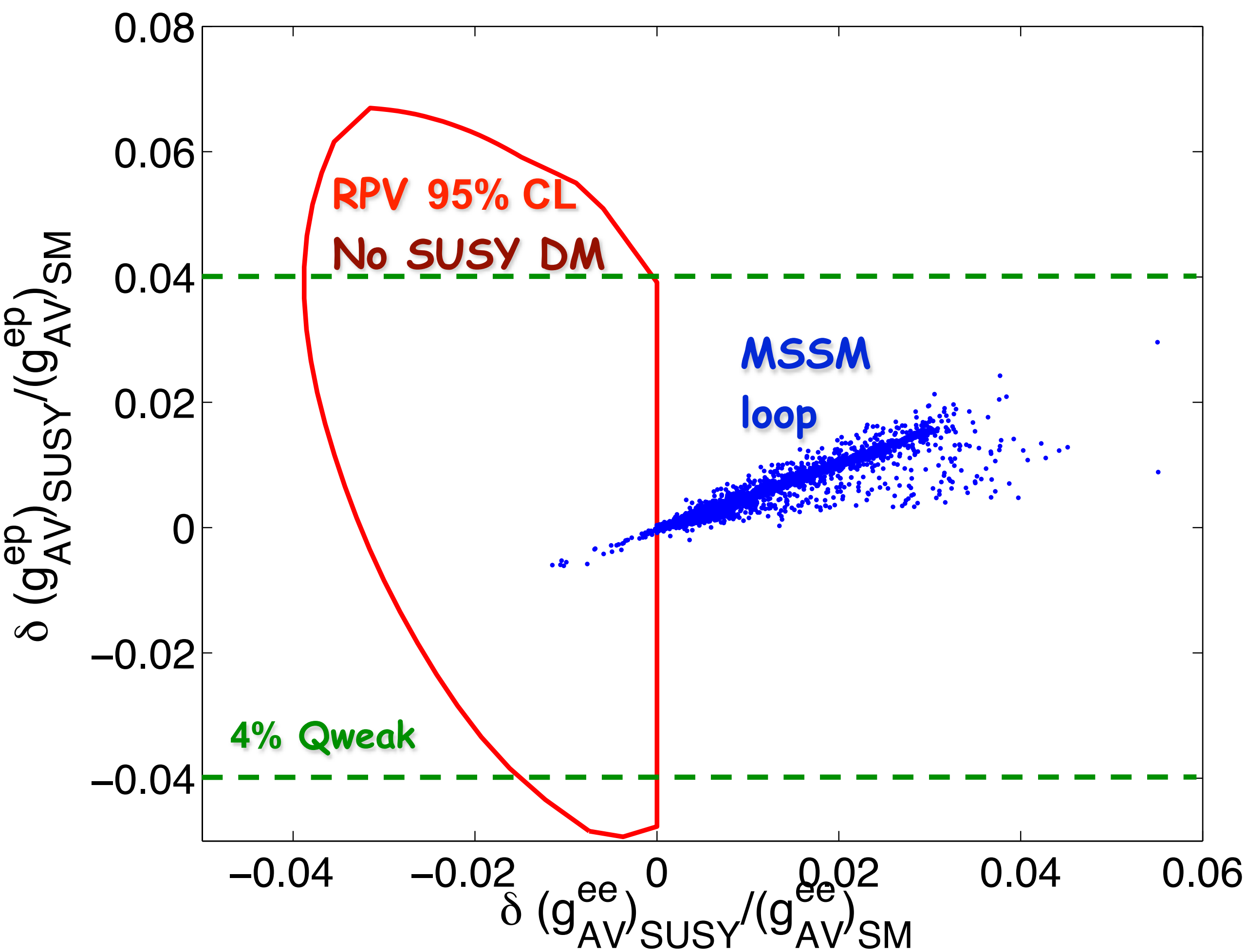

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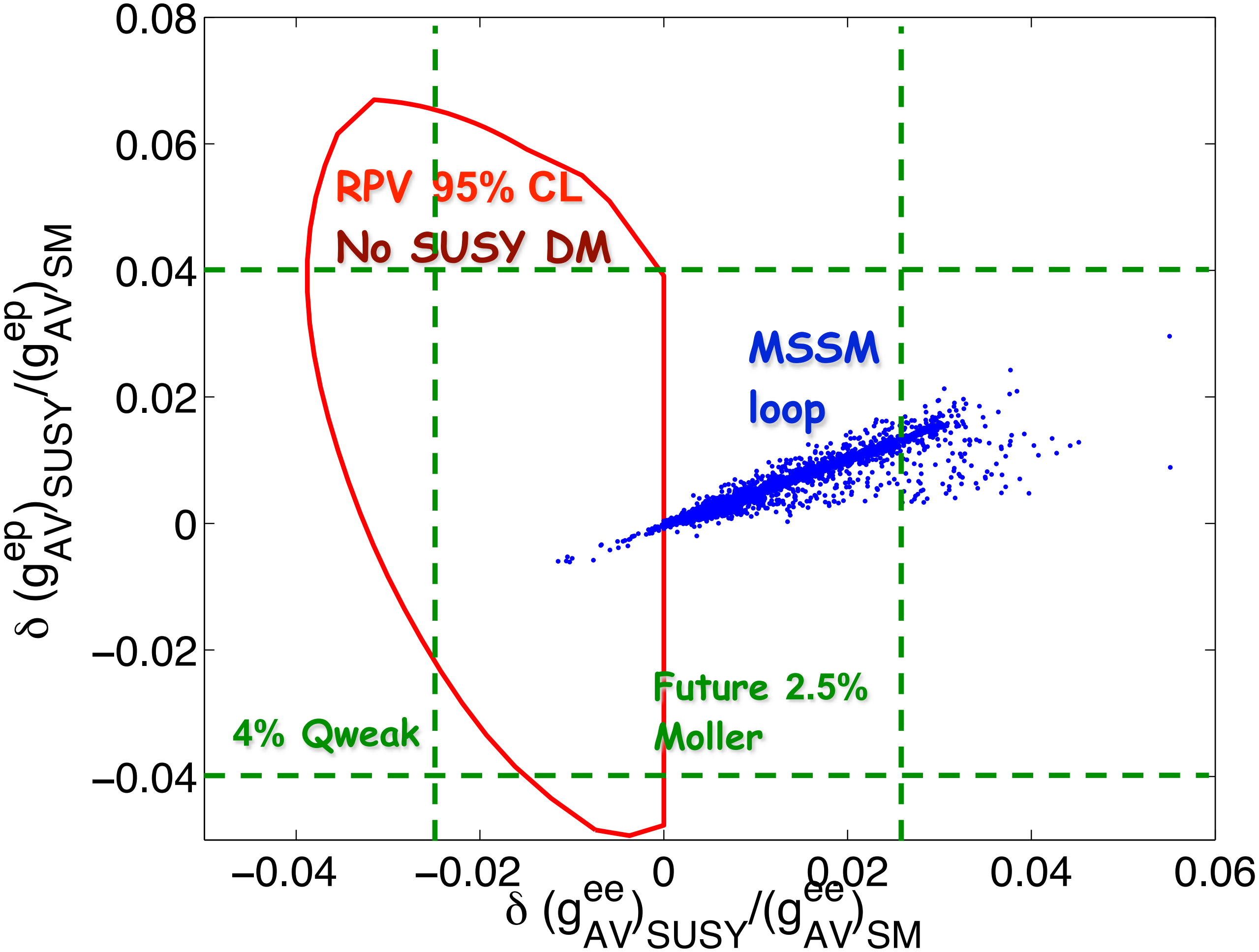
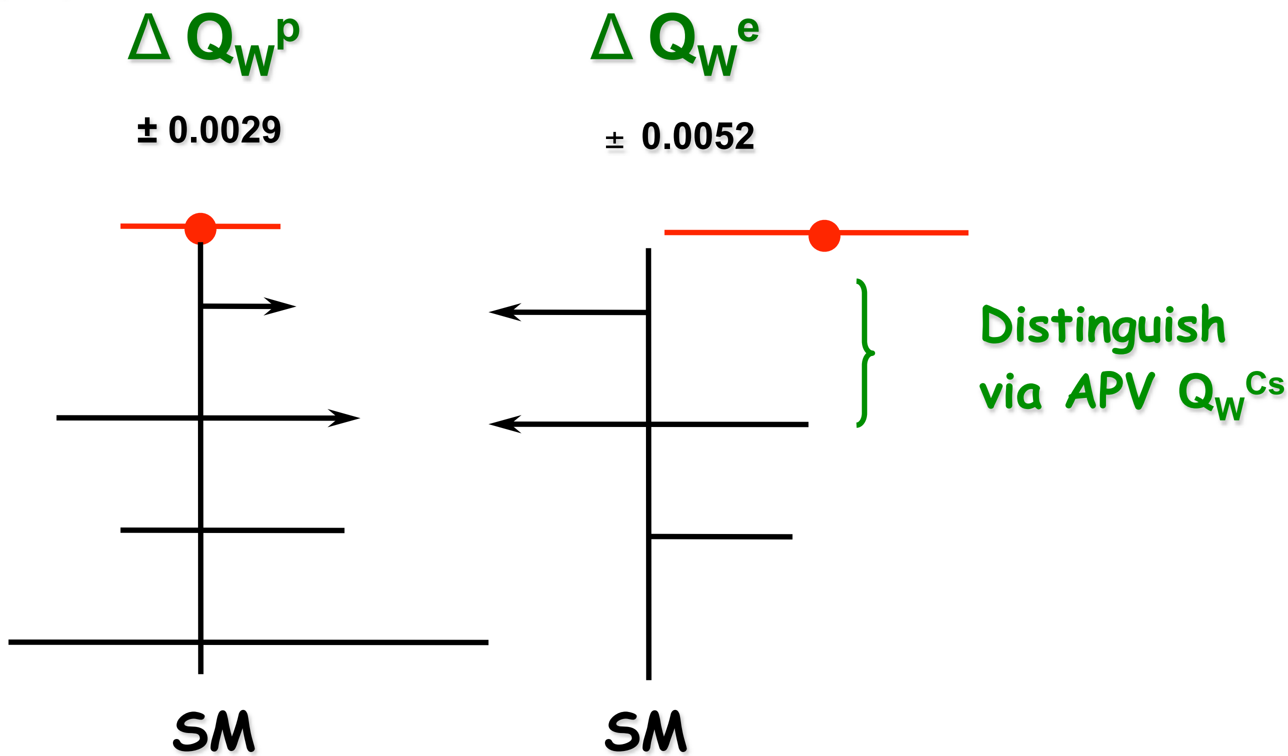


Correlation between Q_W^p, Q_W^e

<u>Distinguish new physics</u>   Erler, Kurylov and Ramsey-Musolf (2003)

- exp
- MSSM
- extra Z'
- RPV SUSY
- leptonquark



S. Su

Correlation between Q_W^p, Q_W^e

Distinguish new physics Erler, Kurylov and Ramsey-Musolf (2003)

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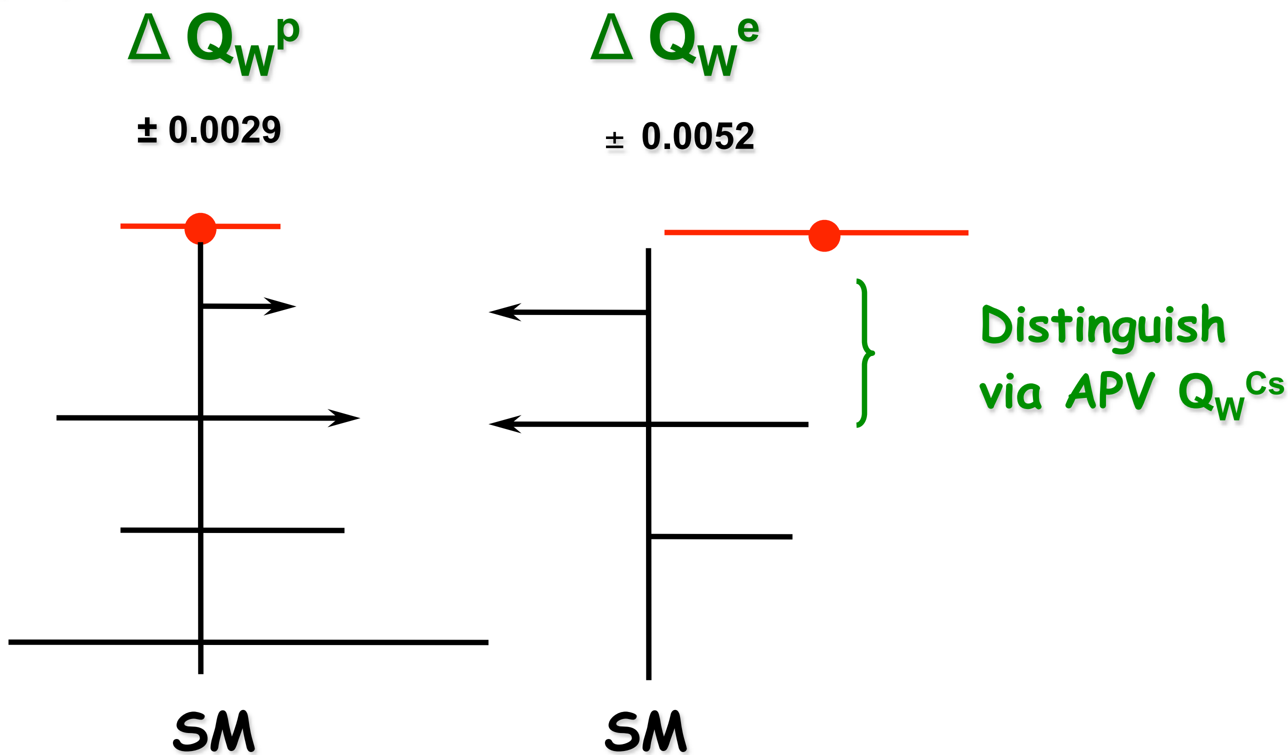

Combinations of NC exps could be used to distinguish various new physics

Conclusion

- Precision measurements played an important role in developing and testing SM
- They will be a crucial tool in probing new physics beyond the SM
- Low energy precision measurement can probe new physics not mix with Z (comparing with Z-pole precision observables)

  precision frontier
- Complementary to what we may learn from LHC
- Opportunities and challenges (0.1%) for both experimentalists and theorists