References and further reading

Basics of SM theory, and LEP

- F. Mandl, G. Shaw, *Quantum Field Theory*, ch. 19, ISBN 978-0-471-49683-0
- T.P. Cheng, L.F. Li, *Gauge theory of Elementary Particle Physics*, DOI 10.1088/0031-9112/36/5/028

Collider Physics lectures

- Previously at GGI: M. Peskin, J. Thaler, M. Strassler
- T. Han, *Collider Physics: basic knowledge and techniques*, hep-ph/0508097

Experimental LEP Physics

(1) *Precision Electroweak Measurements on the Z Resonance*, hep-ex/0509008

(2) See e.g., *Standard model measurements in ee collisions at E >190 GeV* https://cds.cern.ch/record/925725/files/cer-002593638.pdf

Accelerator Physics

- *Accelerator Physics of Colliders*, ch. 31 of *The Review of Particle Physics* https://pdg.lbl.gov/

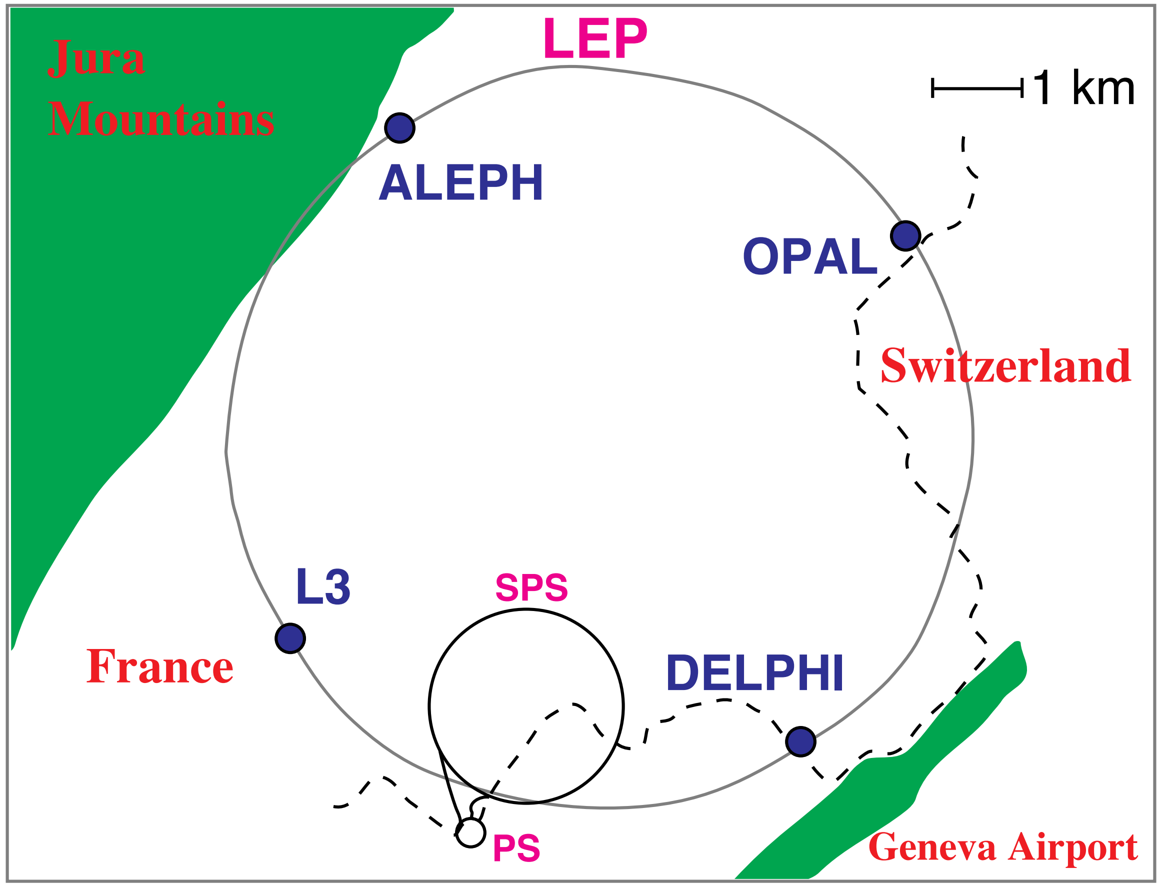
References and further reading

PDFs, and DGLAP

- M. Peskin, D. V. Schroeder, *Quantum Field Theory*, ch. 17.5

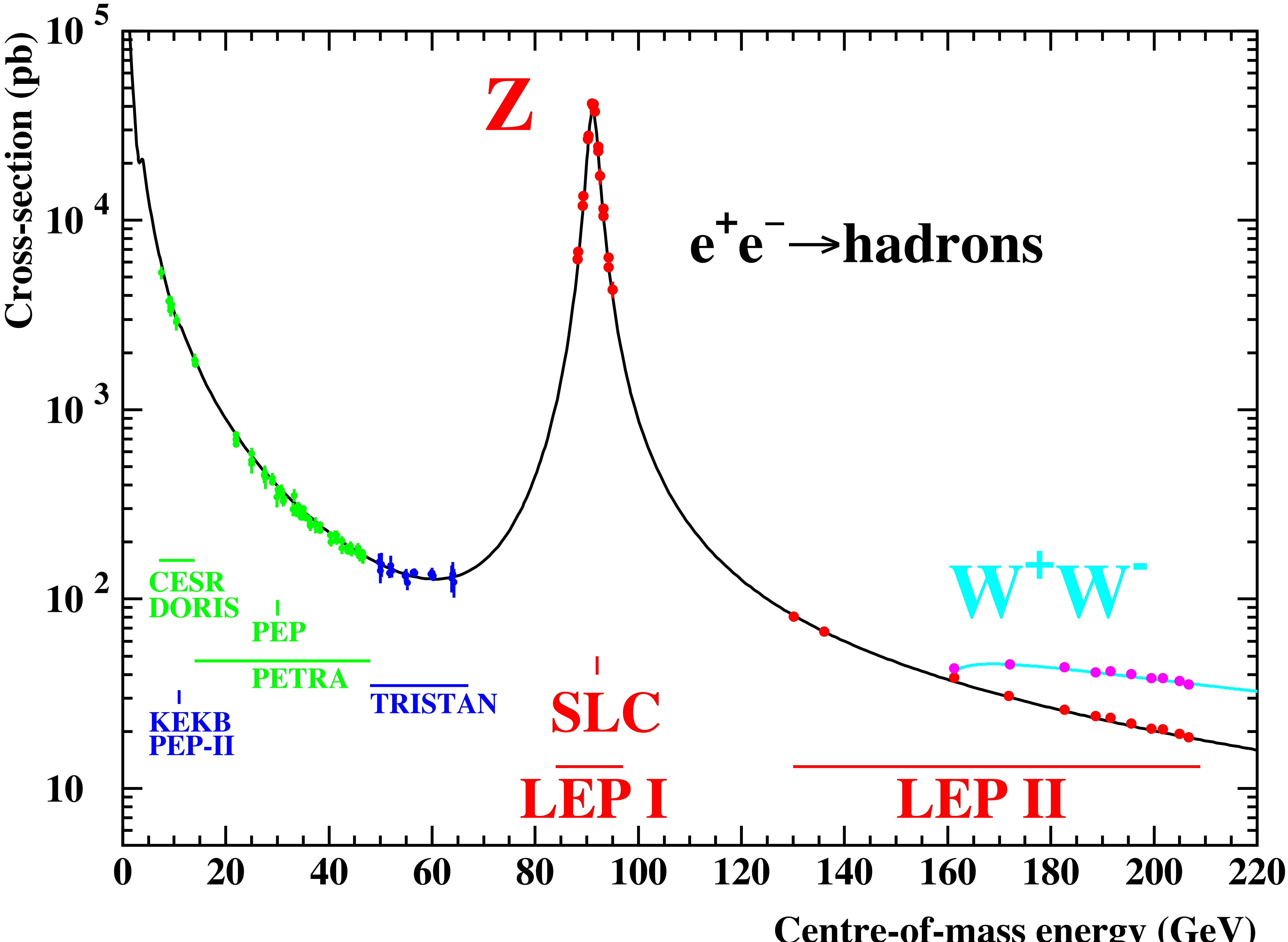
Goldstone Equivalence

- 1309.6055, 1911.12366, and references therein



Year	Centre-of-mass energy range [GeV]	Integrated luminosity [pb^{-1}]
1989	88.2 – 94.2	1.7
1990	88.2 – 94.2	8.6
1991	88.5 – 93.7	18.9
1992	91.3	28.6
1993	89.4, 91.2, 93.0	40.0
1994	91.2	64.5
1995	89.4, 91.3, 93.0	39.8

Year	$\int \mathcal{L}dt$ (pb^{-1})	E_b ($\mathrm{GeV/c^2}$)	k_b	I_{tot} (mA)	$\mathcal{L}$ $10^{30}\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
1989	1.74	45.6	4	2.6	4.3
1990	8.6	45.6	4	3.6	7
1991	18.9	45.6	4	3.7	10
1992	28.6	45.6	4/8	5.0	11.5
1993	40.0	45.6	8	5.5	19
1994	64.5	45.6	8	5.5	23.1
1995	46.1	45.6	8/12	8.4	34.1
1996	24.7	80.5 - 86	4	4.2	35.6
1997	73.4	90 - 92	4	5.2	47.0
1998	199.7	94.5	4	6.1	100
1999	253	98 - 101	4	6.2	100
2000	233.4	102 - 104	4	5.2	60


Cross-section (pb)
10^5
10^4
10^3
10^2
10
Z
$e^+e^- \rightarrow$ hadrons
CESR
DORIS
PEP
PETRA
KEKB
PEP-II
TRISTAN
SLC
LEP I
LEP II
W^+W^-
0
20
40
60
80
100
120
140
160
180
200
220
Centre-of-mass energy (GeV)

Number of Events/**1000**										
	$Z \to q\bar{q}$					$Z \to \ell^+\ell^-$				
Year	A	D	L	O	LEP	A	D	L	O	LEP
1990/91	433	357	416	454	1660	53	36	39	58	186
1992	633	697	678	733	2741	77	70	59	88	294
1993	630	682	646	649	2607	78	75	64	79	296
1994	1640	1310	1359	1601	5910	202	137	127	191	657
1995	735	659	526	659	2579	90	66	54	81	291
Total	4071	3705	3625	4096	15497	500	384	343	497	1724

Cross-sections at $\sqrt{s} = 192$ GeV					
Channel		$\int \mathcal{L}dt$ (pb^{-1})	**Events**	σ (pb)	σ^{SM} (pb)
$q\bar{q}X$		28.2	2924	$111.9 \pm 2.2 \pm 2.3$	110.9
$q\bar{q}$	$s'/s > 0.01$	28.2	2505	$95.3 \pm 2.1 \pm 2.4$	95.0
	$s'/s > 0.7225$		639	$22.8 \pm 1.0 \pm 0.5$	21.2
e^+e^-	$\lvert\cos\theta\rvert < 0.9$, $\theta_{acol} < 170°$	28.2	2940	$105.0 \pm 2.0 \pm 1.4$	108.5
	$\lvert\cos\theta_{e^-}\rvert < 0.7$, $\theta_{acol} < 10°$		544	$19.2 \pm 0.8 \pm 0.2$	19.7
	$\lvert\cos\theta\rvert < 0.96$, $\theta_{acol} < 10°$		8633	$301.4 \pm 3.4 \pm 2.6$	302.2
$\mu^+\mu^-$	$s'/s > 0.01$	29.2	177	$7.49 \pm 0.56 \pm 0.28$	7.49
	$s'/s > 0.7225$		80	$2.89 \pm 0.33 \pm 0.20$	3.10
$\tau^+\tau^-$	$s'/s > 0.01$	29.2	113	$8.41 \pm 0.79 \pm 0.38$	7.48
	$s'/s > 0.7225$		63	$3.29 \pm 0.42 \pm 0.11$	3.10

		Correlations								
		m_Z	Γ_Z	σ^0_{had}	R^0_e	R^0_μ	R^0_τ	$A^{0,e}_{FB}$	$A^{0,\mu}_{FB}$	$A^{0,\tau}_{FB}$
$\chi^2/\mathrm{dof} = 169/176$		ALEPH								
m_Z [GeV]	91.1891 ± 0.0031	1.000								
Γ_Z [GeV]	2.4959 ± 0.0043	0.038	1.000							
σ^0_{had} [nb]	41.558 ± 0.057	−0.091	−0.383	1.000						
R^0_e	20.690 ± 0.075	0.102	0.004	0.134	1.000					
R^0_μ	20.801 ± 0.056	−0.003	0.012	0.167	0.083	1.000				
R^0_τ	20.708 ± 0.062	−0.003	0.004	0.152	0.067	0.093	1.000			
$A^{0,e}_{FB}$	0.0184 ± 0.0034	−0.047	0.000	−0.003	−0.388	0.000	0.000	1.000		
$A^{0,\mu}_{FB}$	0.0172 ± 0.0024	0.072	0.002	0.002	0.019	0.013	0.000	−0.008	1.000	
$A^{0,\tau}_{FB}$	0.0170 ± 0.0028	0.061	0.002	0.002	0.017	0.000	0.011	−0.007	0.016	1.000

SM theory implications

- ‰ - level test of gauge vertex for the Z-boson to fermions
- EW loop corrections (and QCD) at work. Indirect sensitivity to mt, mH!
- Physics of QCD jets
- Best measurement of mZ, sinW SM input parameters …
- ….

			Correlations							
		m_Z	Γ_Z	σ^0_{had}	R^0_e	R^0_μ	R^0_τ	$A^{0,e}_{FB}$	$A^{0,\mu}_{FB}$	$A^{0,\tau}_{FB}$
$\chi^2/\mathrm{dof} = 169/176$						ALEPH				
m_Z [GeV]	91.1891 ± 0.0031	1.000								
Γ_Z [GeV]	2.4959 ± 0.0043	0.038	1.000							
σ^0_{had} [nb]	41.558 ± 0.057	−0.091	−0.383	1.000						
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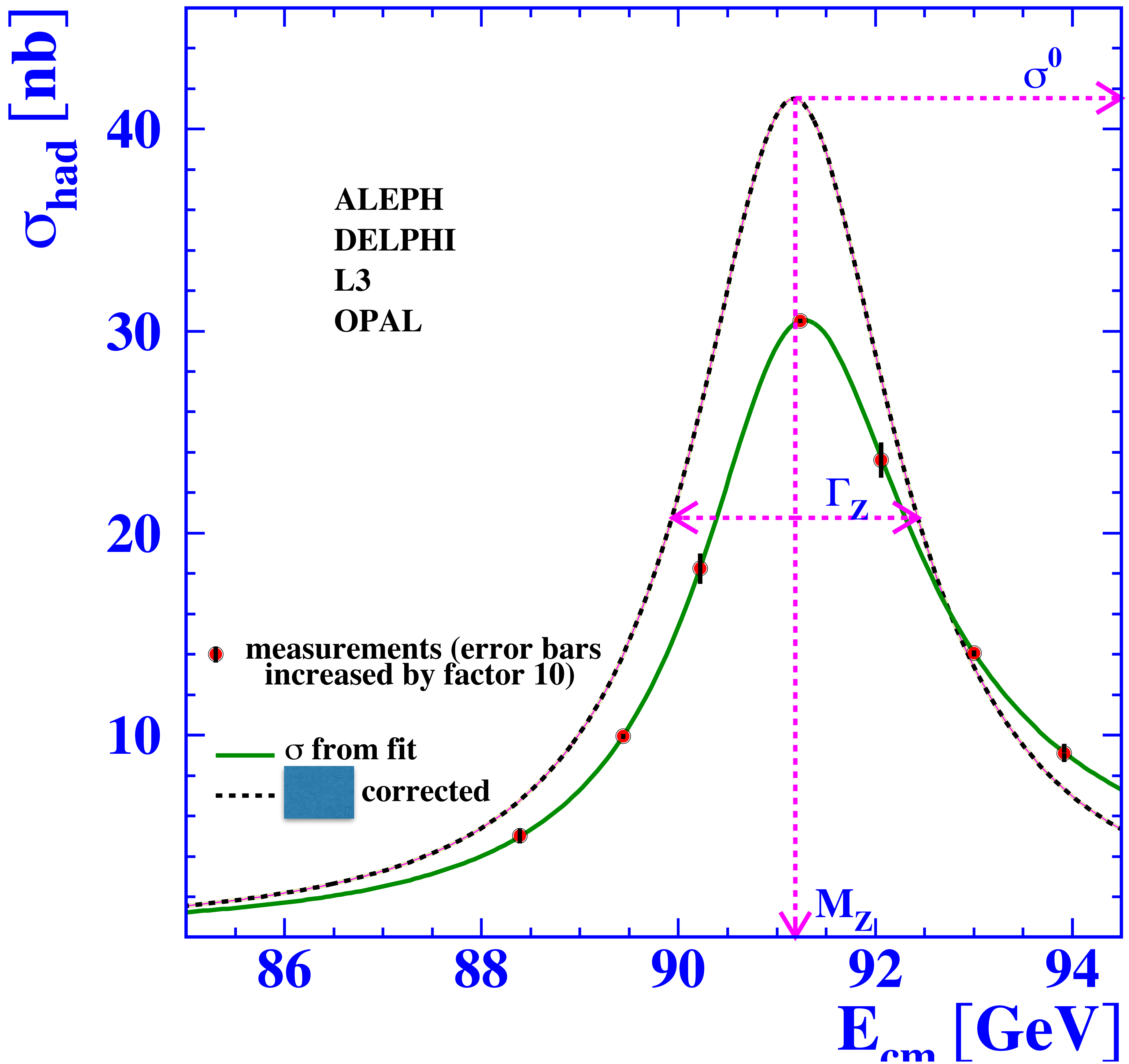
R^0_μ	20.801 ± 0.056	−0.003	0.012	0.167	0.083	1.000				
R^0_τ	20.708 ± 0.062	−0.003	0.004	0.152	0.067	0.093	1.000			
$A^{0,e}_{FB}$	0.0184 ± 0.0034	−0.047	0.000	−0.003	−0.388	0.000	0.000	1.000		
$A^{0,\mu}_{FB}$	0.0172 ± 0.0024	0.072	0.002	0.002	0.019	0.013	0.000	−0.008	1.000	
$A^{0,\tau}_{FB}$	0.0170 ± 0.0028	0.061	0.002	0.002	0.017	0.000	0.011	−0.007	0.016	1.000

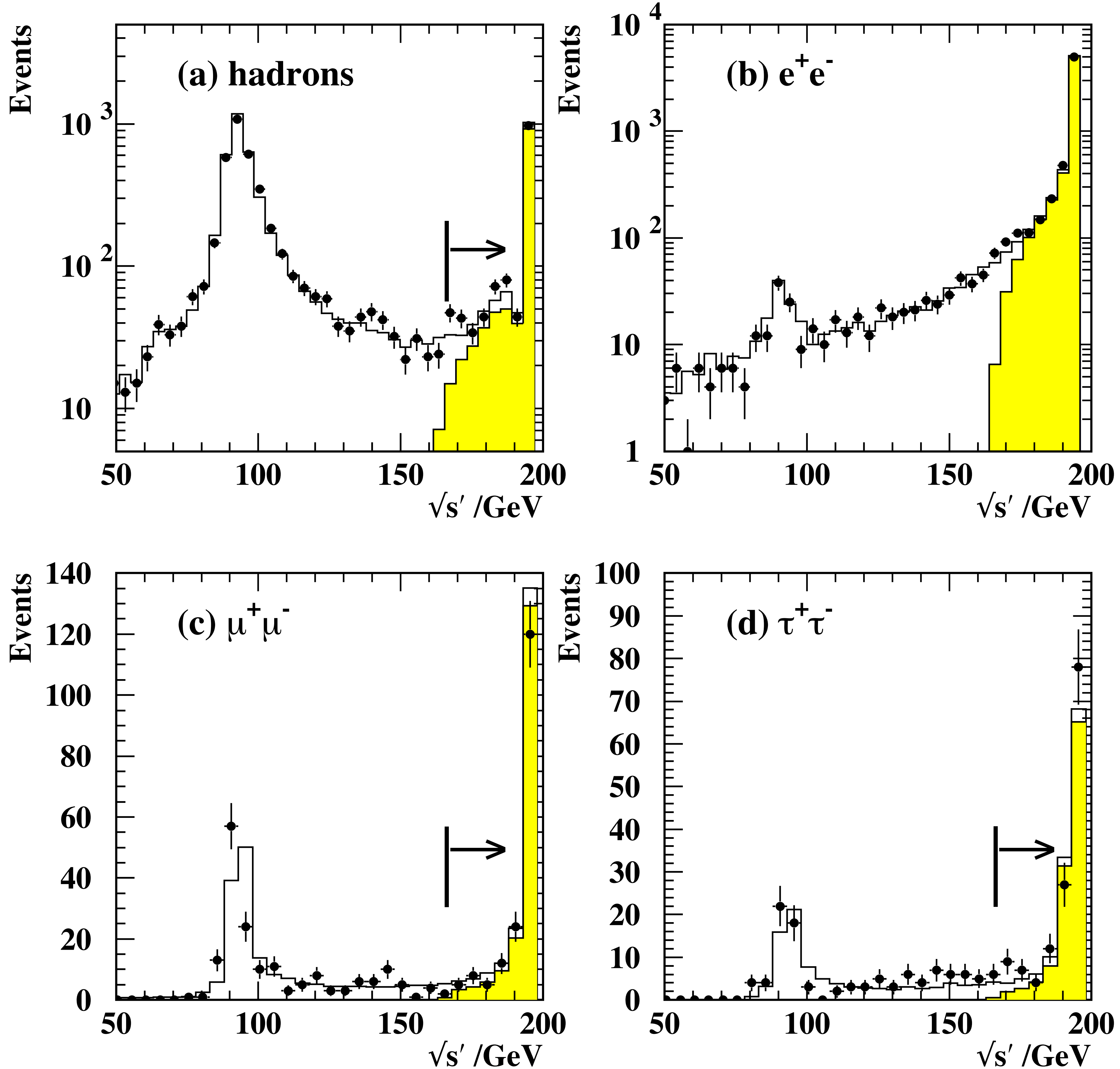
BSM theory implications

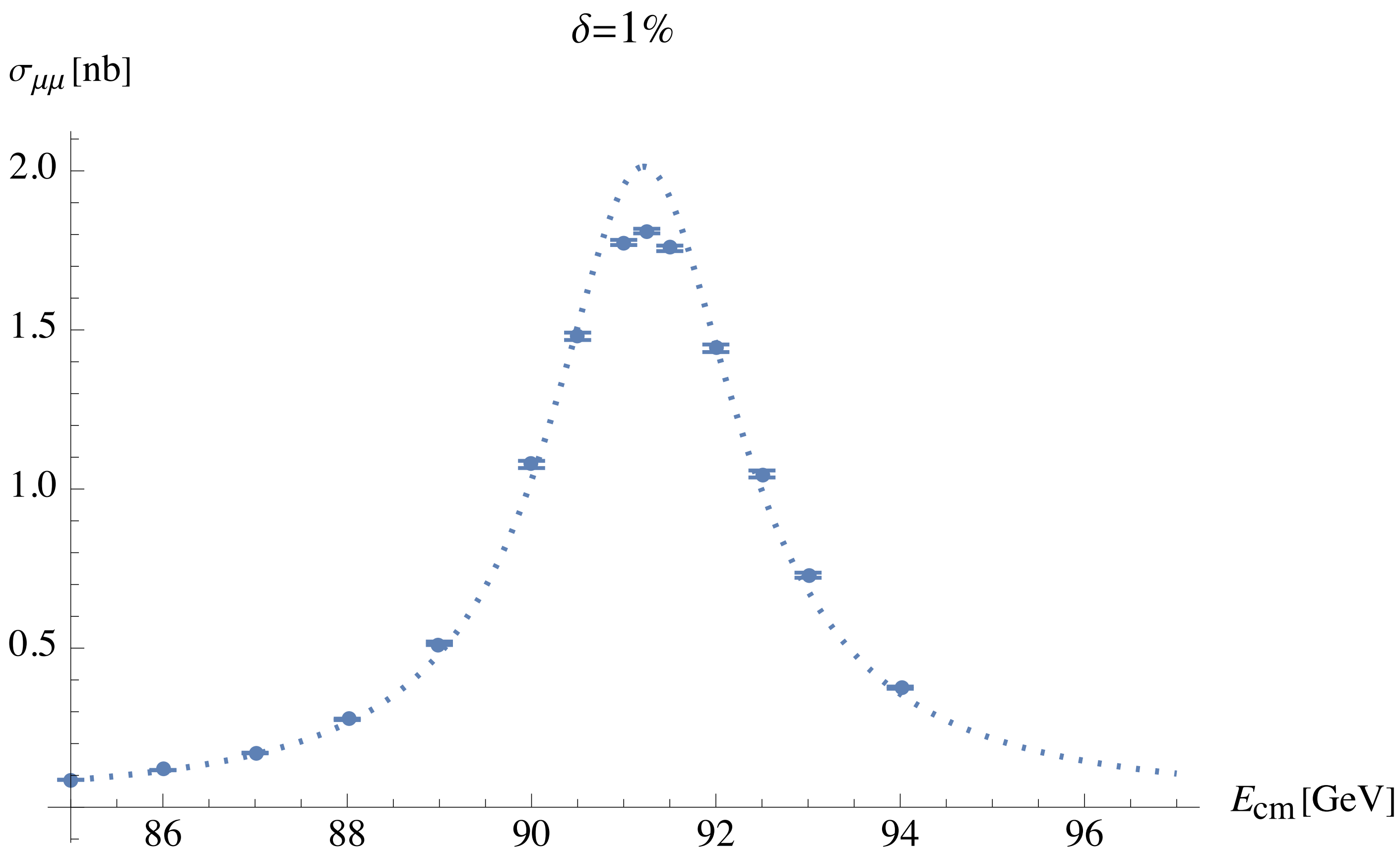
- "Number of neutrinos" (bound on Z to invisible)
- Excluding new virtual light particles. EWPT (EW precision test)
- Excluding "very natural" SUSY (especially, LEP-II)
- ….

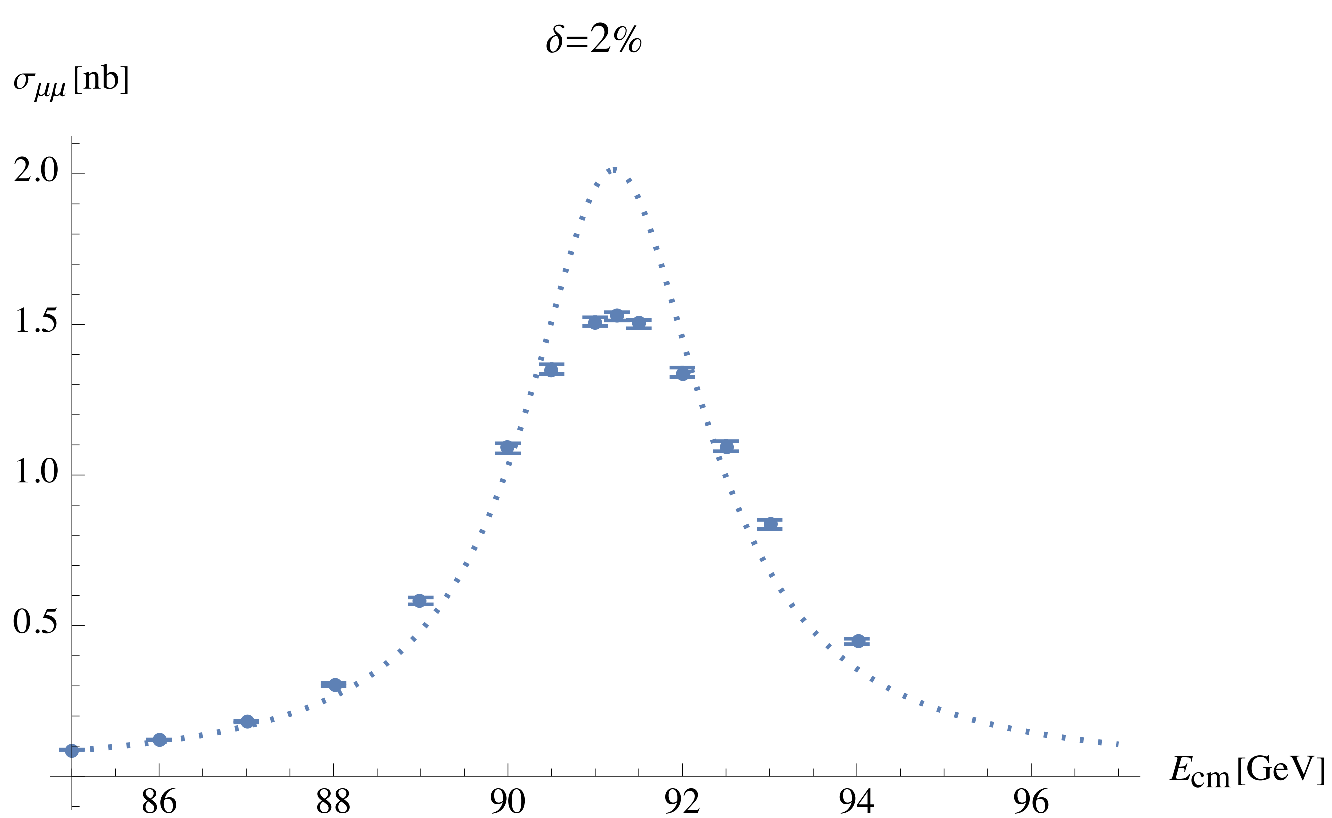


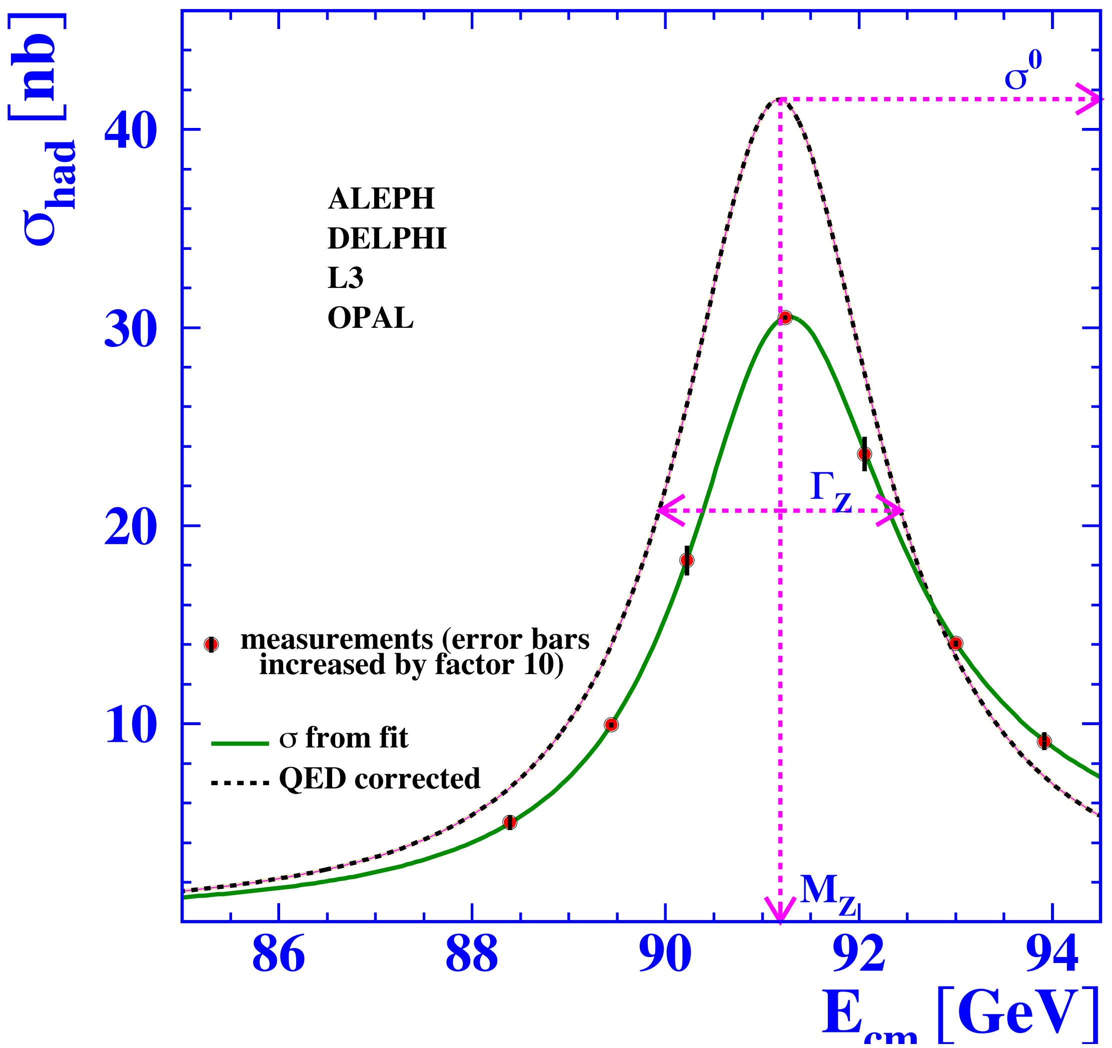
σ_{had} [nb]
40
30
20
10
86
88
90
92
94
E_{cm} [GeV]
σ^0
Γ_Z
M_Z
ALEPH
DELPHI
L3
OPAL
measurements (error bars increased by factor 10)
σ from fit
corrected

OPAL 196 GeV preliminary

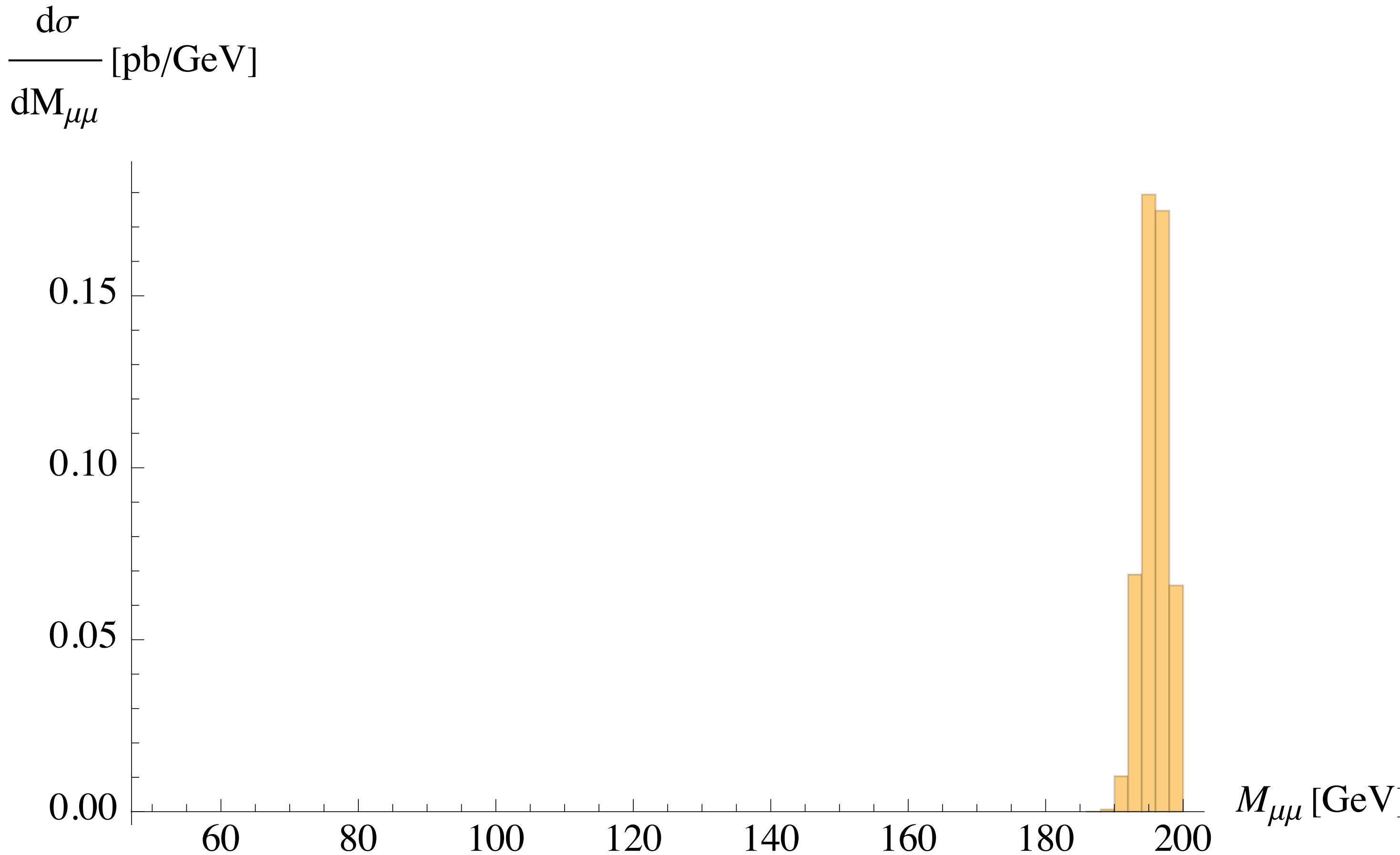


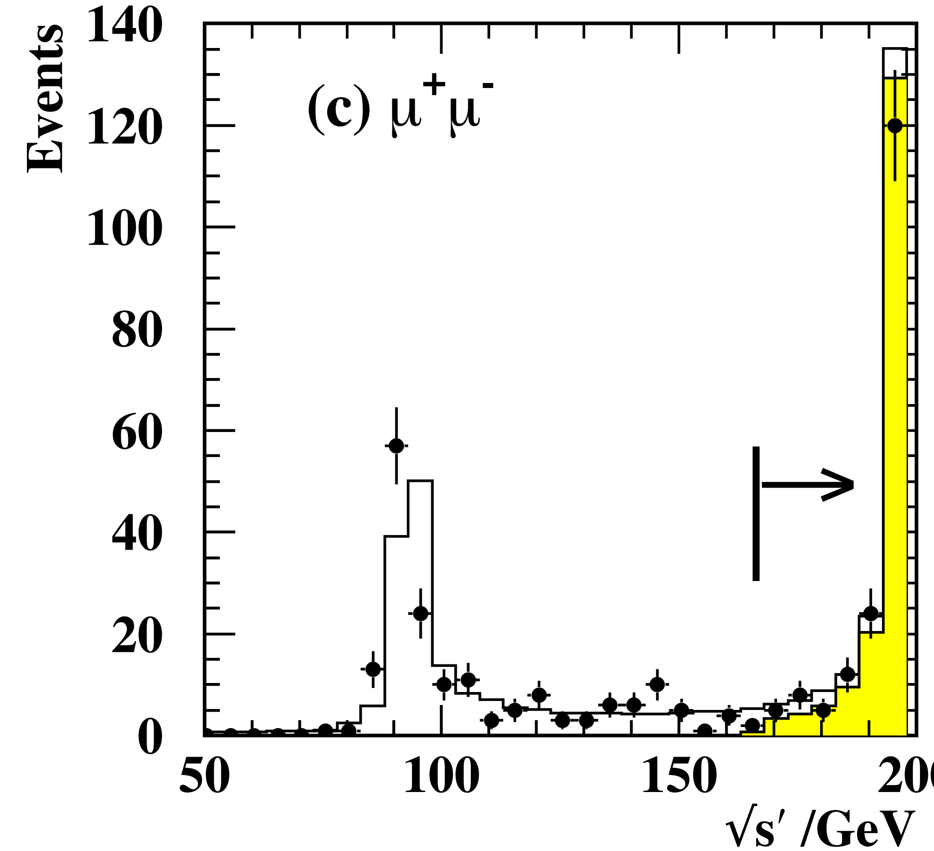

δ=1%
σ_μμ [nb]
2.0
1.5
1.0
0.5
86
88
90
92
94
96
E_cm [GeV]


δ=2%
σ_μμ [nb]
2.0
1.5
1.0
0.5
86
88
90
92
94
96
E_cm [GeV]

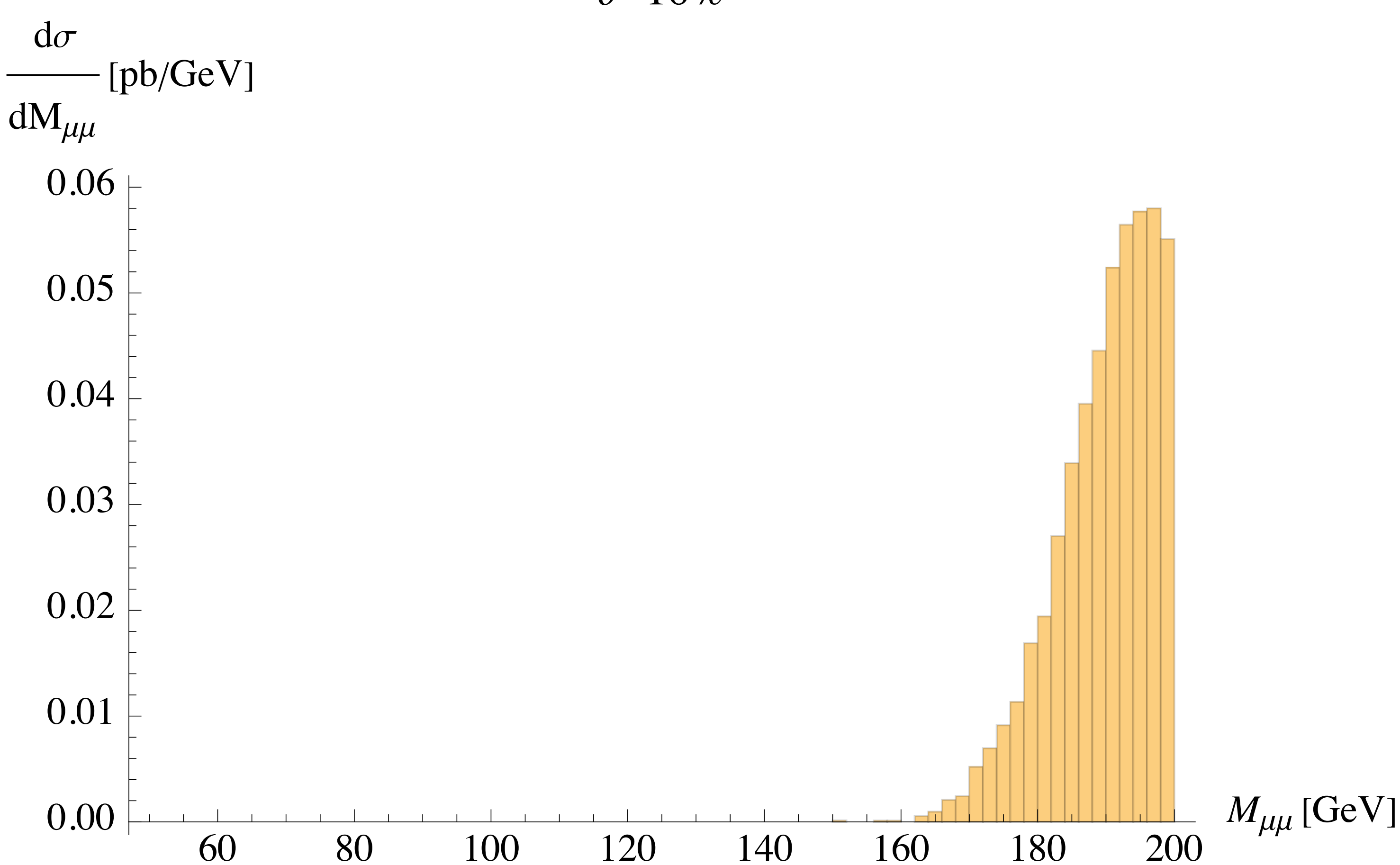

σ_had [nb]
σ^0
40
30
20
10
ALEPH
DELPHI
L3
OPAL
Γ_Z
measurements (error bars increased by factor 10)
σ from fit
QED corrected
M_Z
86
88
90
92
94
E_cm [GeV]

δ=2%





δ=10%



High-Energy Collider Parameters: e^+e^- Colliders (II)

Table 32.2: Updated in March 2020 with numbers received from representatives of the colliders (contact E. Pianori, LBNL). The ta shows the parameter values achieved. Quantities are, where appropriate, r.m.s.; unless noted otherwise, energies refer to beam ener, H and V indicate horizontal and vertical directions; s.c. stands for superconducting. ILC and CLIC parameters are documented the Accelerator physics of colliders review.

	CESR (Cornell)	CESR-C (Cornell)	LEP (CERN)	SLC (SLAC)
Physics start date	1979	2002	1989	1989
Physics end date	2002	2008	2000	1998
Maximum beam energy (GeV)	6	6	100 - 104.6	50
Delivered integrated luminosity per experiment (fb^{-1})	41.5	2.0	0.221 at Z peak 0.501 at 65 – 100 GeV 0.275 at >100 GeV	0.022
Luminosity (10^{30} cm^{-2}s^{-1})	1280 at 5.3 GeV	76 at 2.08 GeV	24 at Z peak 100 at > 90 GeV	2.5
Time between collisions (μs)	0.014 to 0.22	0.014 to 0.22	22	8300
Full crossing angle (μ rad)	±2000	±3300	0	0
Energy spread (units 10^{-3})	0.6 at 5.3 GeV	0.82 at 2.08 GeV	0.7→1.5	1.2
Bunch length (cm)	1.8	1.2	1.0	0.1
Beam radius (μm)	H:460 V:4	H:340 V:6.5	H:200→300 V:2.5→8	H:1.5 V:0.5
Free space at interaction point (m)	±2.2 (±0.6 to REC quads)	±2.2 (±0.3 to PM quads)	±3.5	±2.8
Luminosity lifetime (hr)	2–3	2–3	20 at Z peak 10 at > 90 GeV	—
Turn-around time (min)	5 (topping up)	1.5 (topping up)	50	120 Hz (pulsed)
Injection energy (GeV)	1.8–6	1.5–6	22	45.64
Transverse emittance (10^{-9} m)	210 1	120 3.5	H:20–45 V:0.25→1	H:0.5 V:0.05
β^*, amplitude function at interaction point (m)	1.0 0.018	0.94 0.012	1.5 0.05	0.0025 0.0015
Beam-beam tune shift per crossing (10^{-4}) or disruption	250 620	e^-: 420 (H), 280 (V) e^+: 410 (H), 270 (V)	830	0.75 (H) 2.0 (V)
RF frequency (MHz)	500	500	352.2	2856
Particles per bunch (units 10^{10})	1.15	4.7	45 in collision 60 in single beam	4.0
Bunches per ring per species	9 trains of 5 bunches	8 trains of 3 bunches	4 trains of 1 or 2	1
Average beam current per species (mA)	340	72	4 at Z peak 4→6 at > 90 GeV	0.0008
Beam polarization (%)	—	—	55 at 45 GeV 5 at 61 GeV	e^-: 80
Circumference or length (km)	0.768	0.768	26.66	1.45 +1.47
Interaction regions	1	1	4	1
Magnetic length of dipole (m)	1.6–6.6	1.6–6.6	11.66/pair	2.5
Length of standard cell (m)	16	16	79	5.2
Phase advance per cell (deg)	45–90 (no standard cell)	45–90 (no standard cell)	102/90	108
Dipoles in ring	86	84	3280 + 24 inj. + 64 weak	460+440
Quadrupoles in ring	101 + 4 s.c.	101 + 4 s.c.	520 + 288 + 8 s.c.	—
Peak magnetic field (T)	0.3 / 0.8 at 8 GeV	0.3 / 0.8 at 8 GeV, 2.1 wigglers at 1.9 GeV	0.135	0.597

Initial State Radiation at LEP

Called "ISR" because diagrams with photon attached to incoming line play (naively) a bigger role.

Basic formula:

$$d\sigma = \int_0^1 dx_1 \int_0^1 dx_2 f_e^{(e)}(x_1; Q^2) f_{\bar{e}}^{(\bar{e})}(x_2; Q^2) d\hat{\sigma}[e^-(x_1)e^+(x_2) \to f\bar{f}]$$

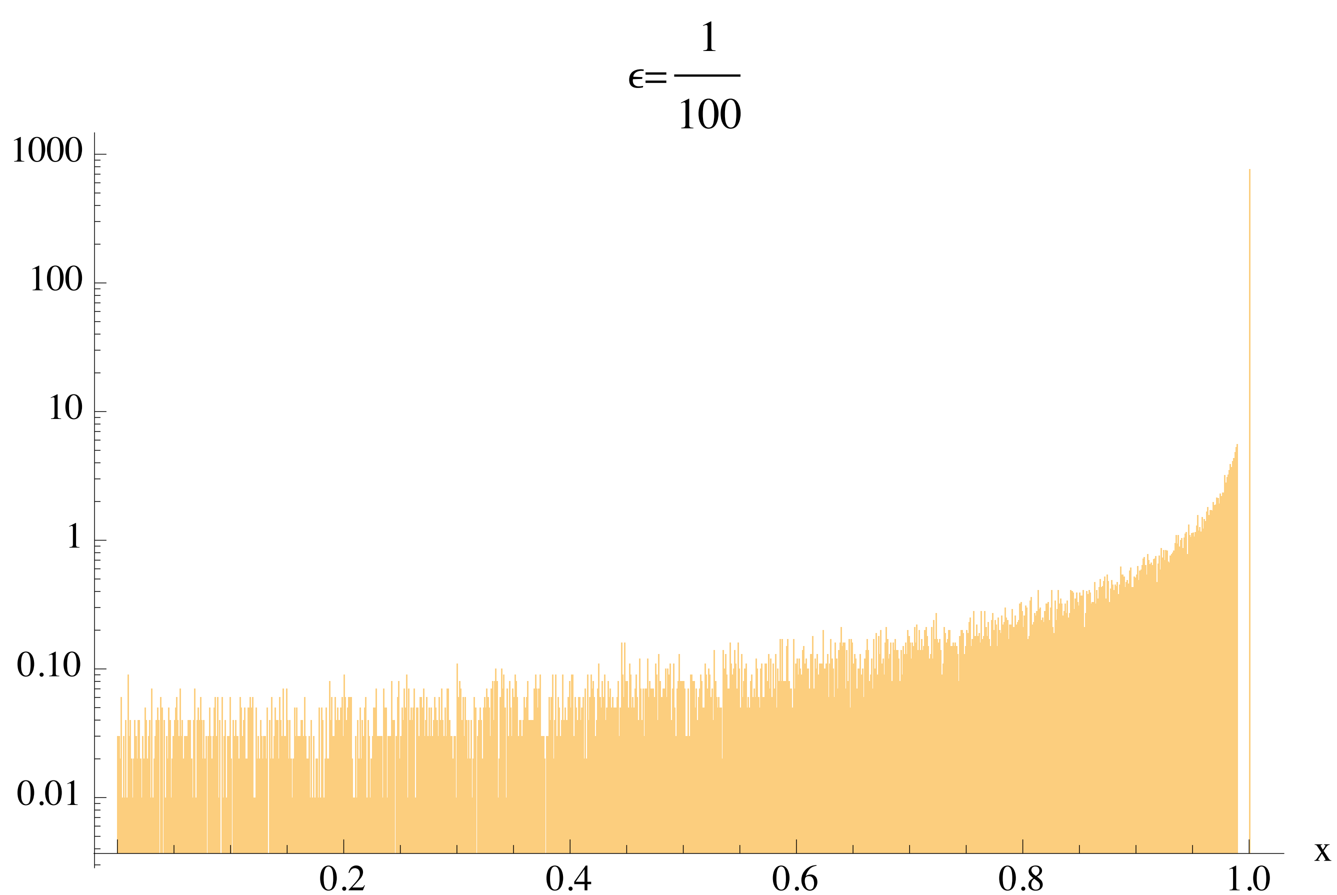
This is the PDF for the electron "parton" in the electron "particle"
It is the same one for the positron in the positron.

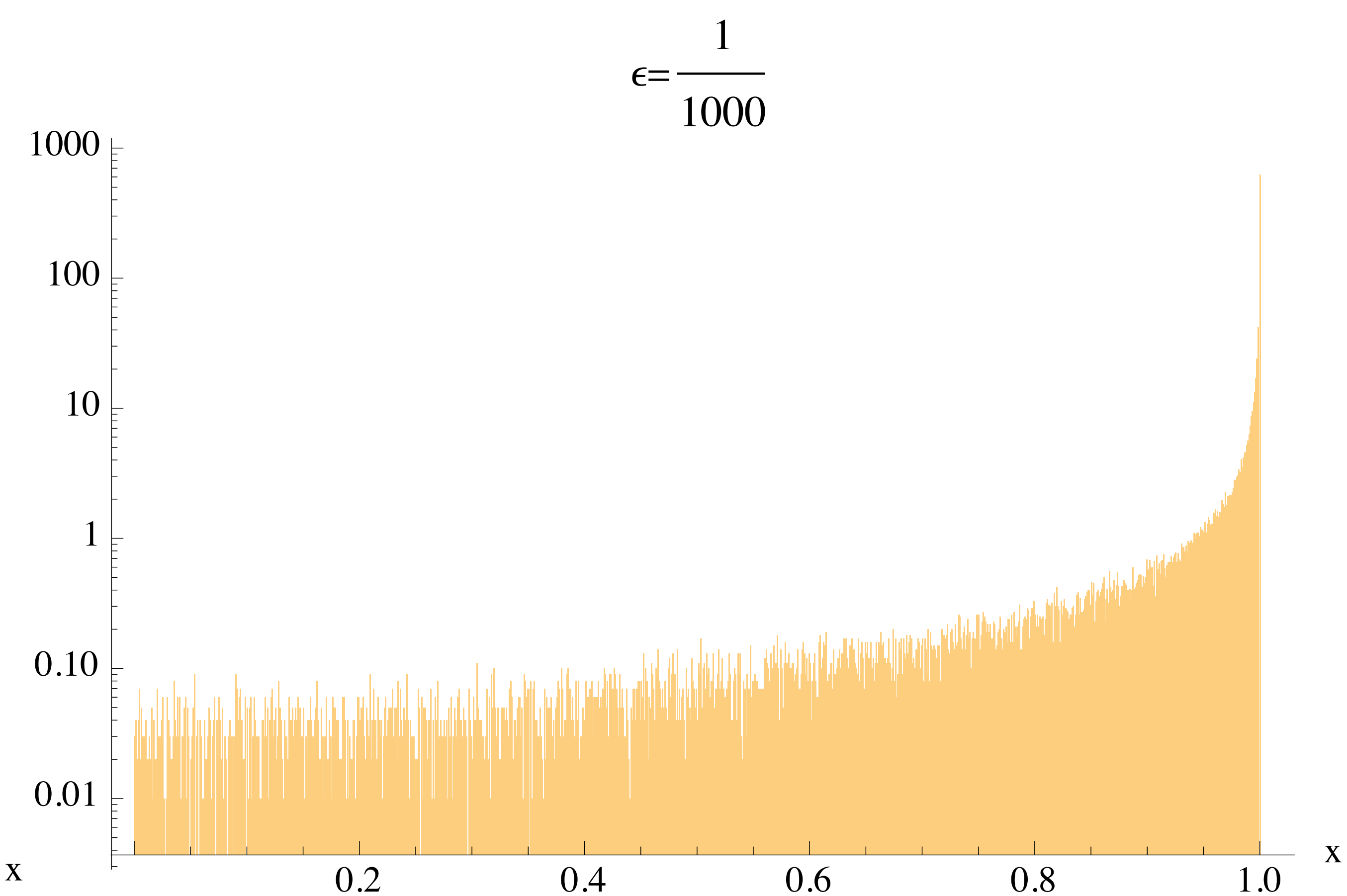
Initial State Radiation at LEP

The PDF is the sum of real and virtual:

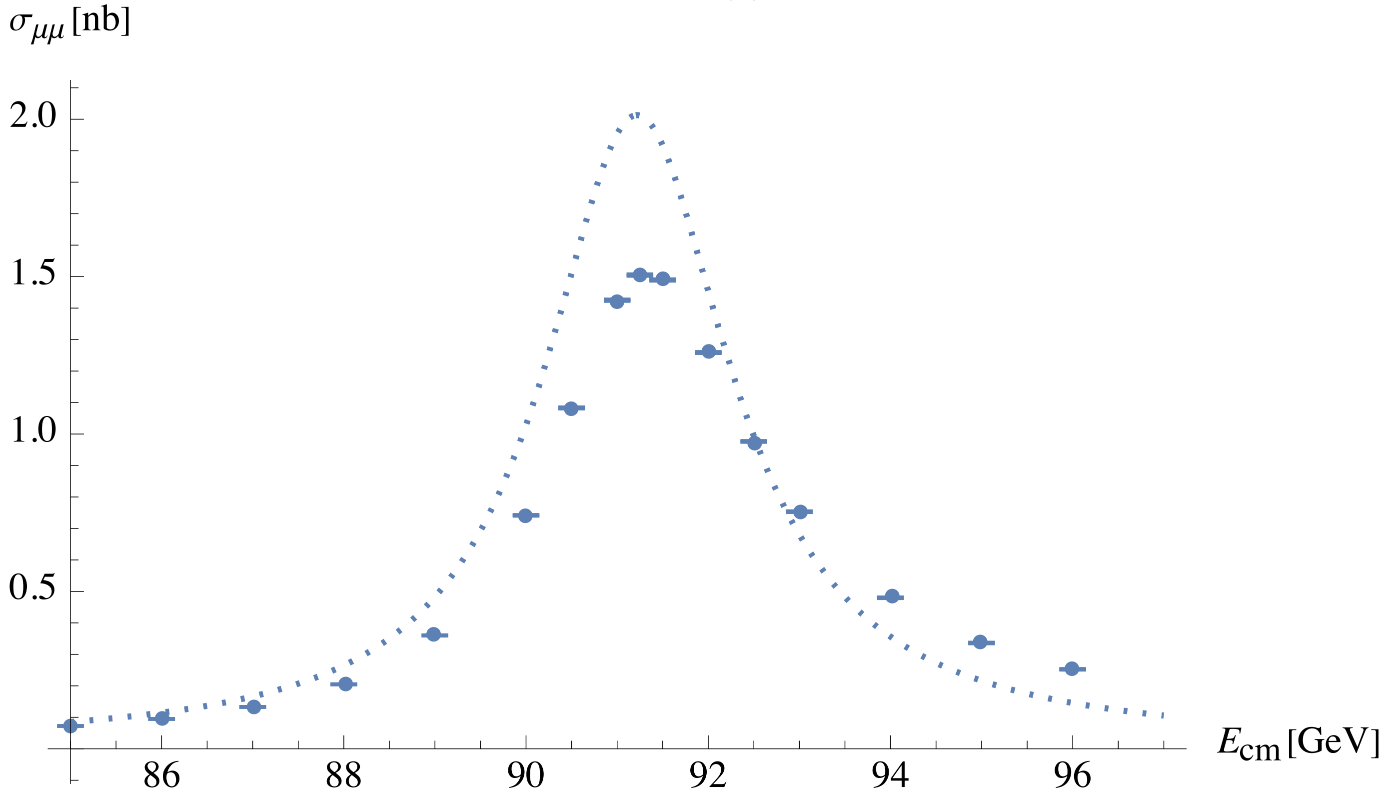
$$f(x;Q^2) = f_{\rm Re} + f_{\rm Vi} = \frac{\alpha}{2\pi}\log\frac{Q^2}{m_e^2}\frac{1+x^2}{1-x} + p_{\rm Vi}\delta(1-x)$$

We generate x samples using $f_{\rm Re}$ below $1-\epsilon$, and adding $x=1$ points until we reach unit total probability

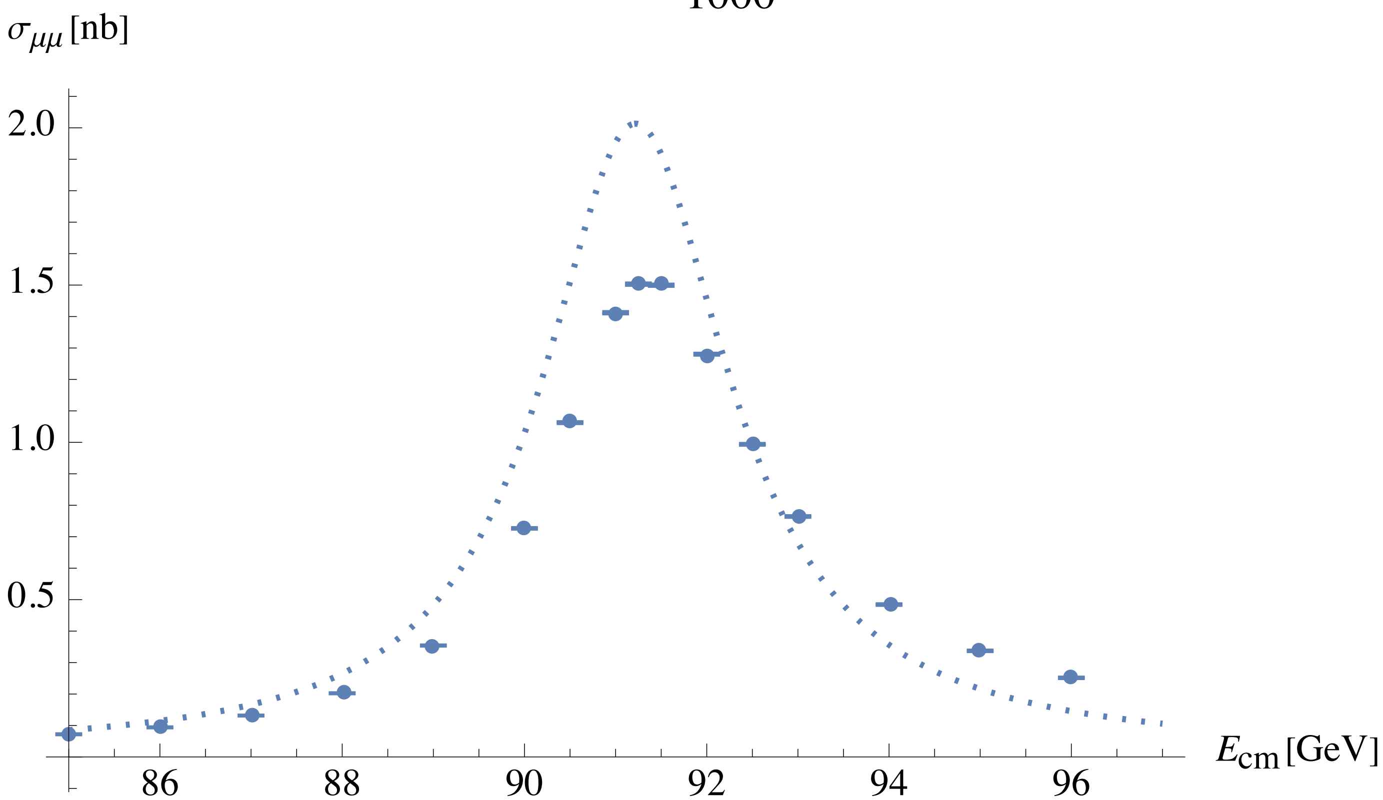


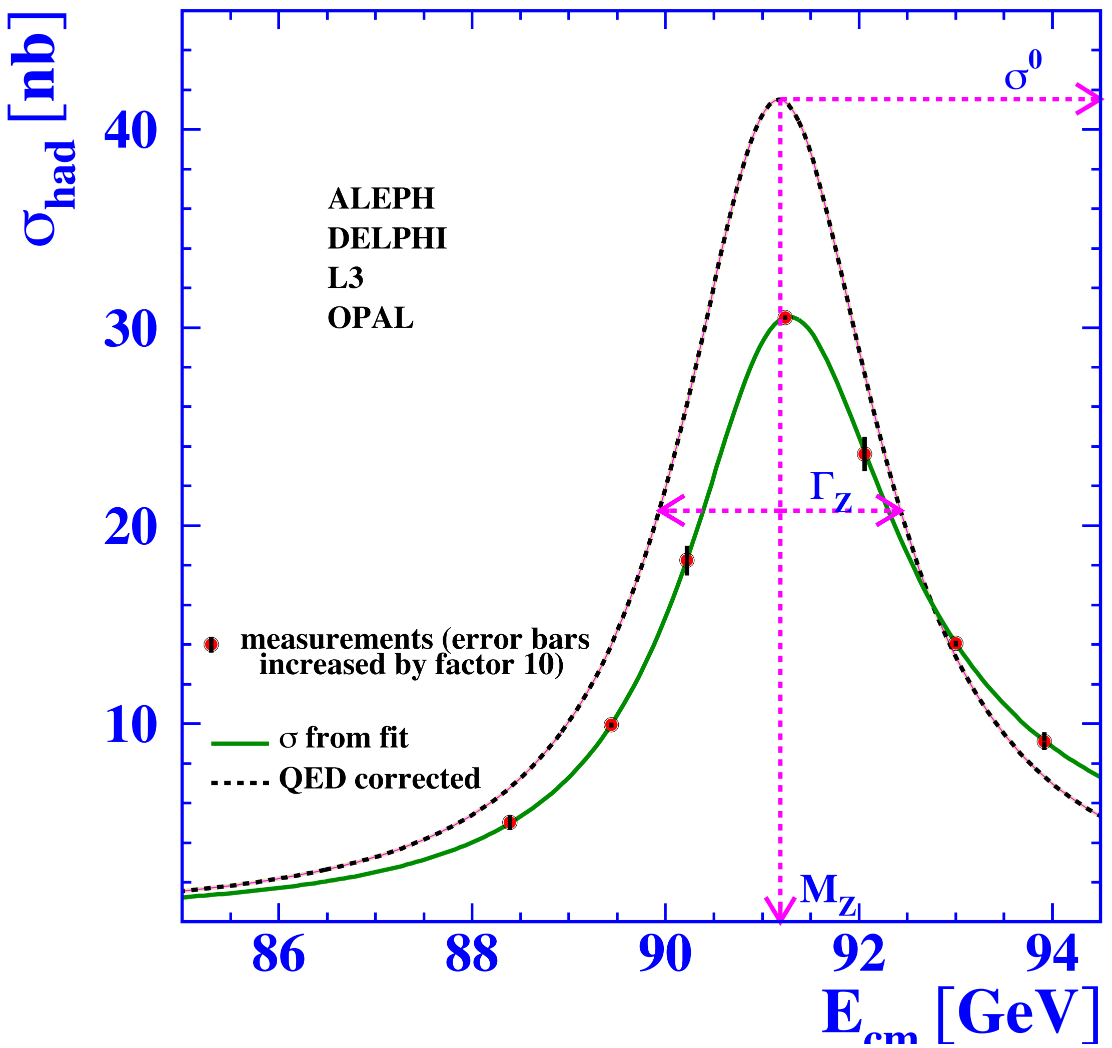


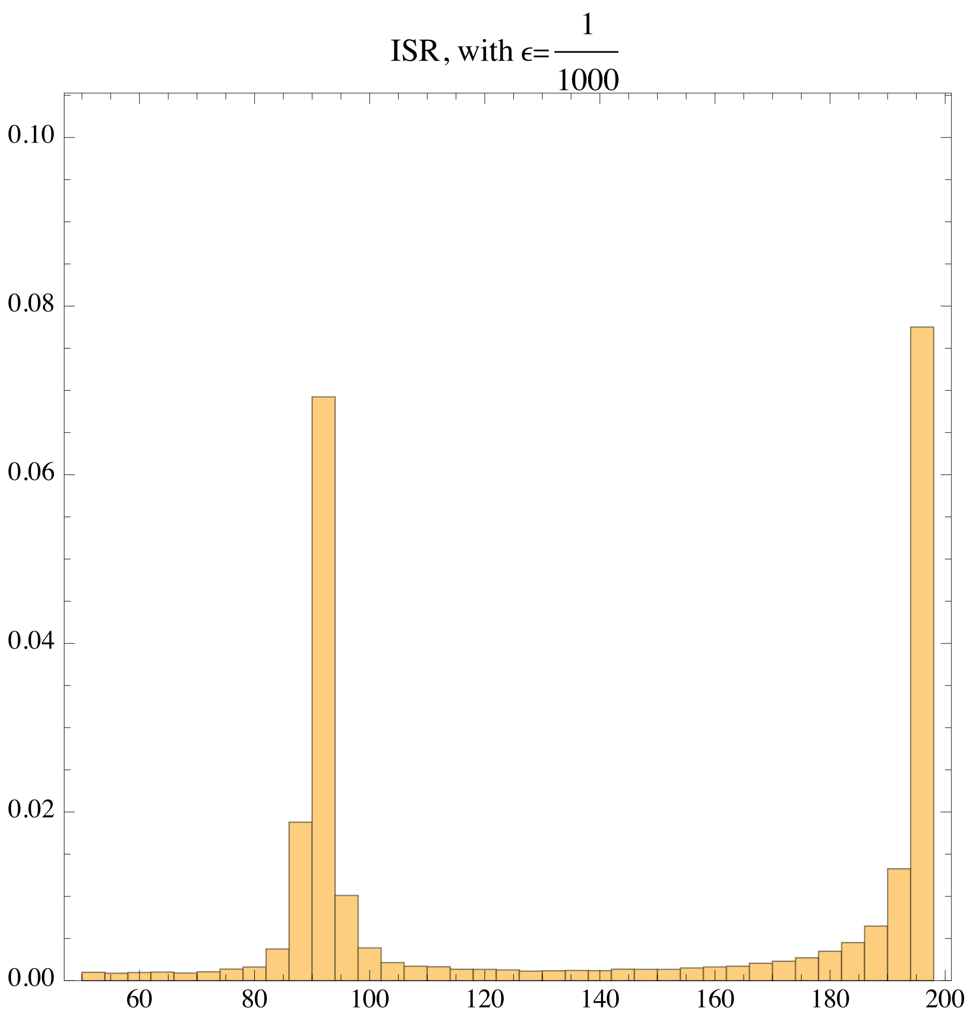
$\text{ISR, with } \epsilon = \frac{1}{100}$

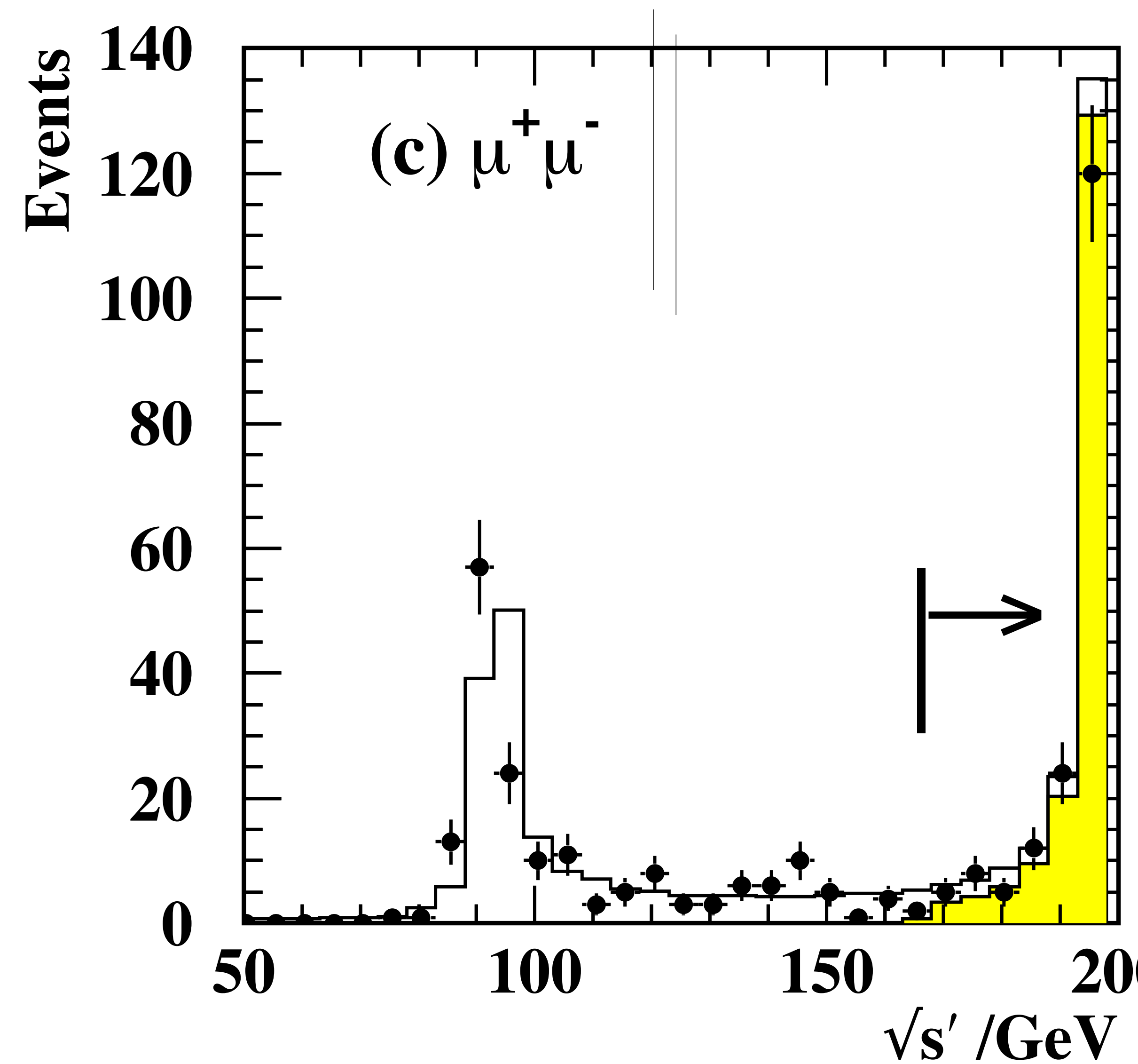


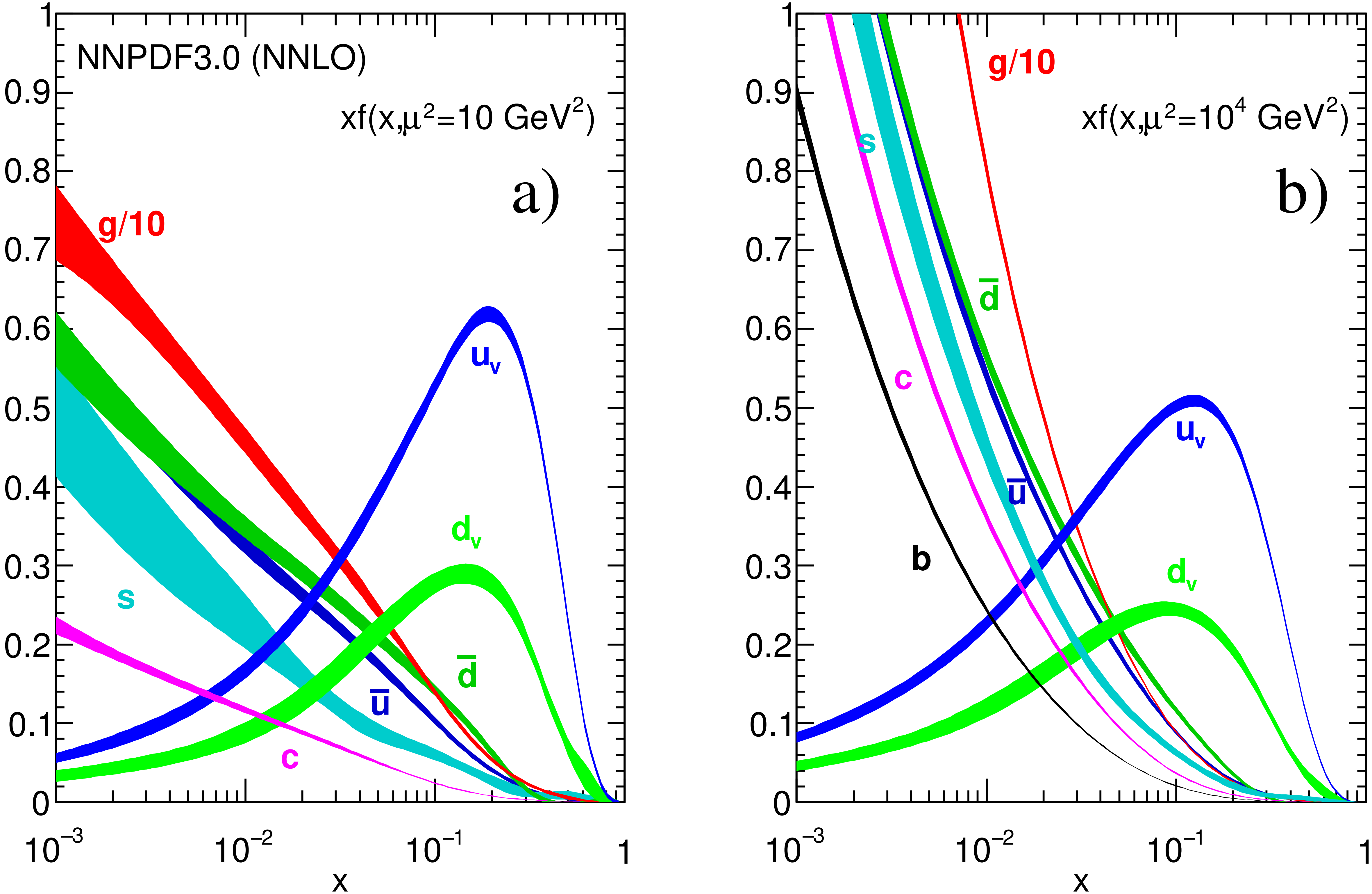
$\text{ISR, with } \epsilon = \frac{1}{1000}$






ISR, with $\epsilon = \frac{1}{1000}$
0.10
0.08
0.06
0.04
0.02
0.00
60
80
100
120
140
160
180
200


Events
140
120
100
80
60
40
20
0
(c) $\mu^+\mu^-$
50
100
150
200
$\sqrt{s'}$ /GeV



$$\sigma = \int_0^1 dx_1 dx_2 \sum_{p,p' \in \text{parton}} f_p(x_1; Q^2) f_{p'}(x_2; Q^2) \hat{\sigma}[p(x_1)p'(x_2) \to ?]$$

Standard Model Production Cross Section Measurements

Status: July 2021