Studies on accuracy of the contributions from pair production in Babayaga generator - a status report

Michal Gunia

Working Group 'Radio Monte CarLow', Frascati

28 March 2011

Table of contents

Aim of the work

- calculation of the virtual (determined by the package bha_nnlo_hf) and real corrections (Monte Carlo generators EKHARA, BHAGHEN–1PH+... and HELAC–PHEGAS) at NNLO for Bhabha scattering
- discussion of the numerical results for energies and with realistic cuts used at the Φ factory Dafne, at the B factories PEP-II and at KEK and at the charm/τ factory BEPC II, Beijing
- comparison complete calculations with approximate ones realized in the MC generator BabaYaga

Collaboration: C. Carloni Calame, H. Czyż, J. Gluza, G. Montagna, O. Nicrosini, F. Piccinini, T. Riemann, M. Worek

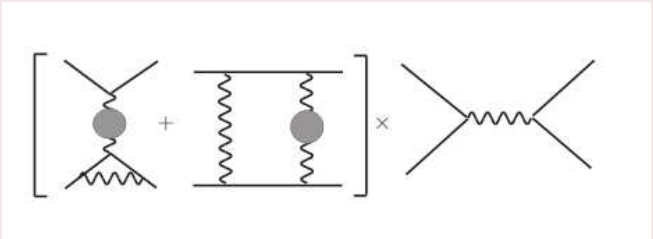
The massive NNLO corrections

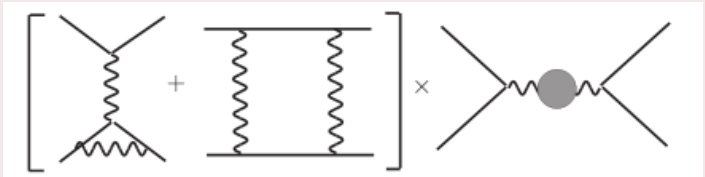
The complete NNLO $N_f = 1, 2$ corrections to Bhabha scattering consist of three parts:

$$\begin{aligned} \frac{d\sigma^{\mathrm{NNLO}}_{N_f}}{d\Omega} &= \frac{d\sigma^{\mathrm{NNLO}\ 1}_{virt}}{d\Omega} + \frac{d\sigma^{\mathrm{NLO}\ 2}_{\gamma}}{d\Omega} + \frac{d\sigma^{\mathrm{LO}\ 3}_{real}}{d\Omega} \\ &= \frac{d\sigma_{e^+e^-}}{d\Omega} + \frac{d\sigma_{\mu^+\mu^-}}{d\Omega} + \frac{d\sigma_{\tau^+\tau^-}}{d\Omega} + \frac{d\sigma_{had}}{d\Omega}. \end{aligned} \tag{1}$$

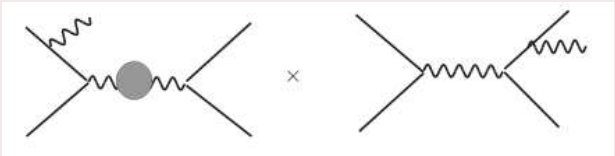
1 - bha_nnlo_hf
2 - BHAGHEN–1PH+...,bha_nnlo_hf
3 - HELAC–PHEGAS,EKHARA

- the $\sigma^{\mathrm{NNLO}}_{virt}$ consists of virtual two-loop corrections $\sigma^{\mathrm{NNLO}}_{2L}$ and loop-by-loop corrections $\sigma^{\mathrm{NNLO}}_{1L1L}$





- contributions with real photon emission $\sigma^{\mathrm{NLO}}_{\gamma} = \sigma^{\mathrm{NLO}}_{\gamma,soft}(\omega) + \sigma^{\mathrm{NLO}}_{\gamma,hard}(\omega)$



- contributions with real pair or hadron emission $\sigma^{\mathrm{LO}}_{real} = \sigma^{\mathrm{LO}}_{e^+e^-(e^+e^-)} + \sigma^{\mathrm{LO}}_{e^+e^-(f^+f^-)} + \sigma^{\mathrm{LO}}_{e^+e^-(hadrons)}$

First results:

,,Quest for precision in hadronic cross sections at low energy: Monte Carlo tools vs. experimental data", EPJC(2010)66

Cuts dependence study for different experiments

1.Φ factories KLOE/DAΦNE (Frascati)

(a) $\sqrt{s} = 1.02$ GeV
(b) $E_{min} = 0.4$ GeV
(c) For $\theta\pm$ two selections have to be checked
i. tighter selection $55^\circ < \theta\pm < 125^\circ$
ii. wider selection $20^\circ < \theta\pm < 160^\circ$
(d) ζ_{max}=4,5,6,7,8,...,14°, with reference value ζ_{max}=9°

2. B-factories BABAR/PEP-II (SLAC) & BELLE/KEKB (KEK)

(a) $\sqrt{s} = 10.56$ GeV
(b) $|\vec{p}_+|/E_{beam} > 0.75$ and $|\vec{p}_-|/E_{beam} > 0.50$
or $|\vec{p}_-|/E_{beam} > 0.75$ and $|\vec{p}_+|/E_{beam} > 0.50$
(c) For $|cos(\theta\pm)|$ the following selections have to be checked
i. $|cos(\theta\pm)| < 0.65$ and $|cos(\theta+)| < 0.60$ or $|cos(\theta-)| < 0.60$
ii. $|cos(\theta\pm)| < 0.70$ and $|cos(\theta+)| < 0.65$ or $|cos(\theta-)| < 0.65$
iii. $|cos(\theta\pm)| < 0.60$ and $|cos(\theta+)| < 0.55$ or $|cos(\theta-)| < 0.55$
(d) ζ^{3d}_{max}= 20,22,24,...,40°, with reference value ζ^{3d}_{max}=30°

Cuts dependence study for different experiments

3. BES-III experiment at BEPCII (Beijing)

(a) $\sqrt{s} = 3.686$ GeV, 3.65 GeV and 3.097 GeV
(b) $|\cos\theta| < 0.8$, where θ is the polar angle of the electron or positron in the lab system, this corresponds to the barrel region of BES-III detector. Since in BEPC, e^+ and e^- beams are colliding with equal energy but at a 22mrad crossing angle, the lab system is slightly different from the CoM system.
(c) $E_{e^+} > 1.0\ \mathrm{GeV}$ and $E_{e^-} > 1.0\ \mathrm{GeV}$, where E is the energy deposited in the electromagnetic calorimeter (EMC).
(d) E/p for one track greater than 0.5 and the other track greater than 0.8, here E is the energy deposited in the electromagnetic calorimeter (EMC), and p is the track momentum measured in the Main Drift Chamber.
To see how the NNLO corrections depend on the event selection we obtained results also for $|\cos\theta| < 0.7,\ 0.75,\ 0.85$ and 0.9

4. *B*-factory Belle (KEK)- the reference event selection

Belle runs at an asymmetric e^+e^- collider, but all criteria are expressed in the CoM fram (a) $\sqrt{s}$ =10.58 GeV
(b) For $\theta\pm$ two selections have to be checked
i. $50.5^\circ < \theta_\pm < (180 - 50.5)^\circ$
ii. $45.5^\circ < \theta_\pm < (180 - 45.5)^\circ$
iii. $55.5^\circ < \theta_\pm < (180 - 55.5)^\circ$
(c) Two charged tracks have momentum $>$ 2.645 GeV
(d) The track with maximum deposited energy in EMC greater than 2 GeV,
(e) The sum of the deposited energies of all tracks in EMC is greater than 4 GeV (both charged and neutral particle can deposite energy in EMC and it is not checked if the particle is charged or neutral)
(f) Acollinearity angle (2D) ζ_{max}=5,6,7,8,...,15°, with reference value ζ_{max}=10°
(g) Transverse momentum of any observed charged particle greater than 0.1 GeV

Where:

$$\zeta = |\theta_+ + \theta_- - 180| \tag{2}$$

$$\zeta^{3d} = |\arccos s(\vec{p}_+\vec{p}_-/|\vec{p}_+|/|\vec{p}_-|)180/\pi - 180| \tag{3}$$

KLOE:

BORN = 542.663(6) nb

σ_{BY} **= 455.71(5) nb** - all σ_{BY} without vacuum polarisation

$\sqrt{s} = 1.02$ GeV

$E_{min} = 0.4$ GeV

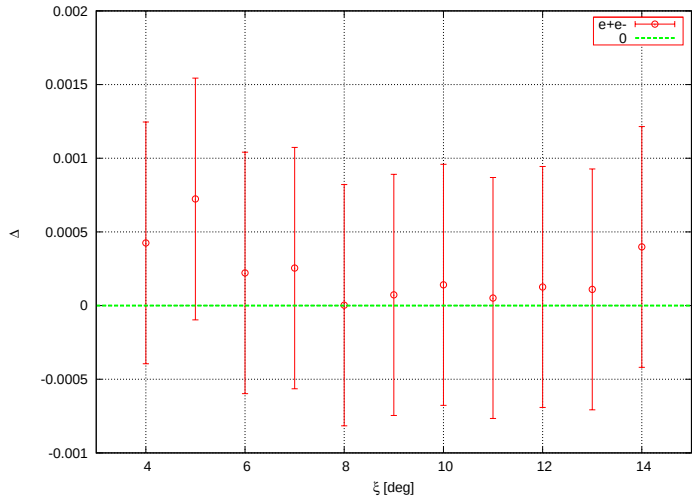
$55^\circ < \theta\pm < 125^\circ$

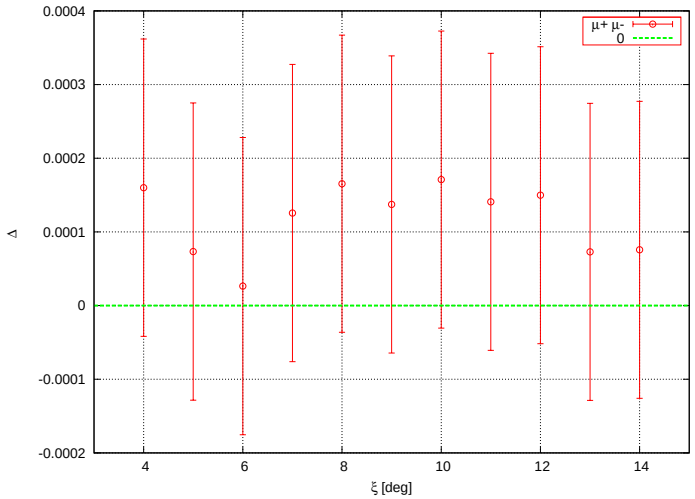
ζ_{max}=9°

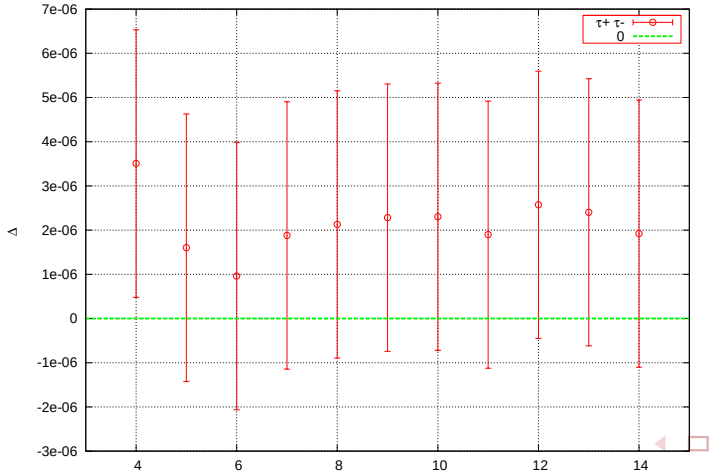
particles	σ_h [nb]	σ_{v+s} [nb]	σ_{pairs} [nb]	sum [nb]
NNLO				
electron	9.5021(2)	-11.5666	0.2712(15)	-1.7933(3)
muon	1.49406(3)	-1.7356(2)	0.246(7)*10^{-7}	-0.2415(2)
tau	0.0201637(4)	-0.023412(2)	0	-0.003248(2)
sum all: σ^{NNLO}				**-2.0381(4)**
BabaYaga NNLO				
electron	9.5020(8)	-11.0722(1)	-	-1.5702(8)
muon	1.4941(1)	-1.74421(6)	-	-0.2501(1)
tau	0.020164(2)	-0.0237027(6)	-	-0.003539(2)
sum all: σ_{BY}^{NNLO}				**-1.8239(8)**
$\sigma^{NNLO} - \sigma_{BY}^{NNLO}$				-0.2143(9)
relative difference: $\lvert\sigma^{NNLO} - \sigma_{BY}^{NNLO}\rvert/\sigma_{BY}$				**0.471(4)‰**

Attention: $\sigma_{BY}^{20<\theta\pm<160,\zeta_{max}=9}$ = 6114.9(6) nb

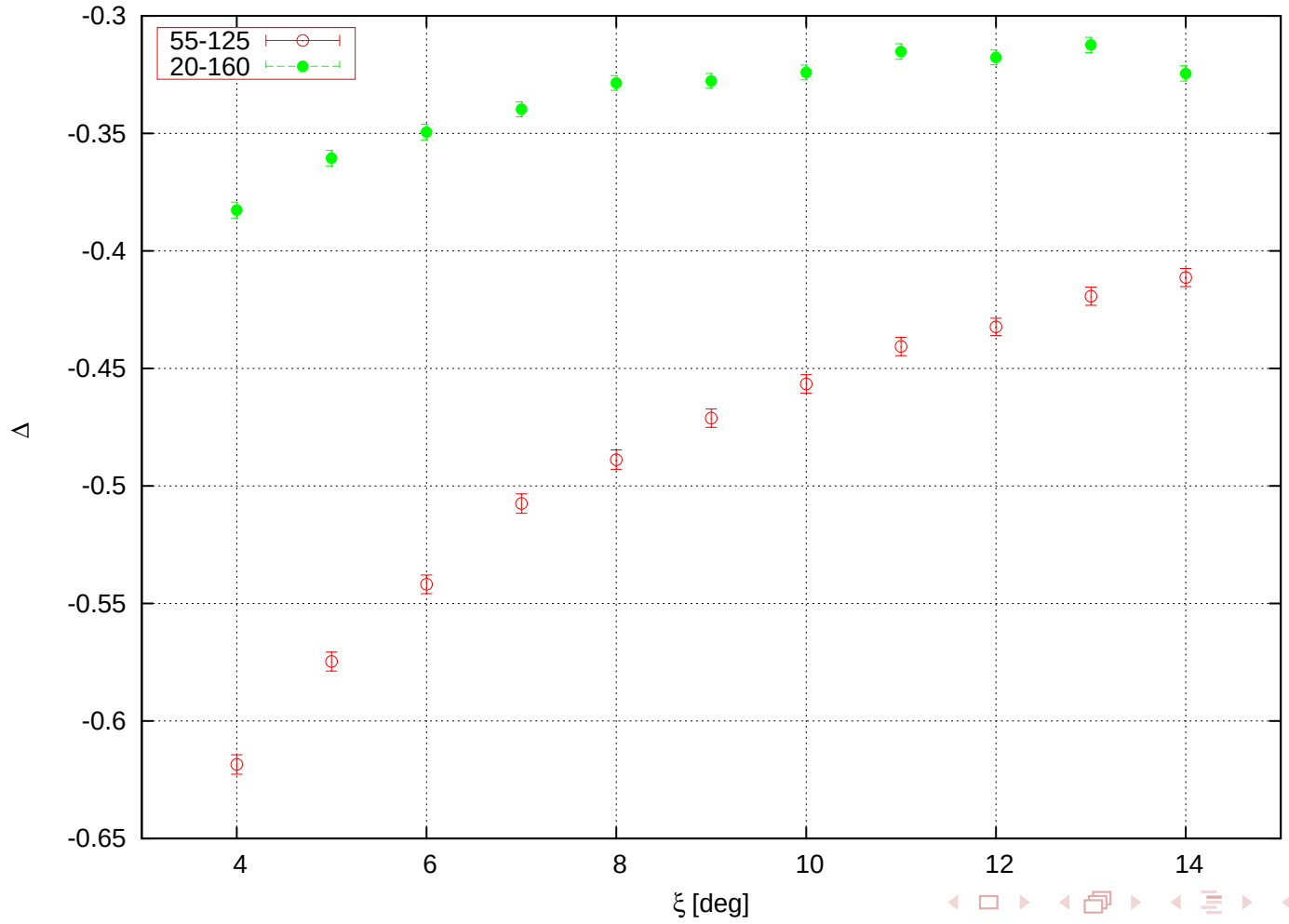
$\Delta = \frac{|\sigma_h - \sigma_{hBY}|}{\sigma_h}$ - comparision between hard parts







$\Delta = \frac{\sigma^{NNLO} - \sigma^{NNLO}_{BY}}{\sigma_{BY}} 10^3$ - relative difference ‰



BaBar:

BORN = 5.481(1) nb

σ_{BY} **= 5.195(2) nb**

(a) $\sqrt{s} = 10.56$ GeV

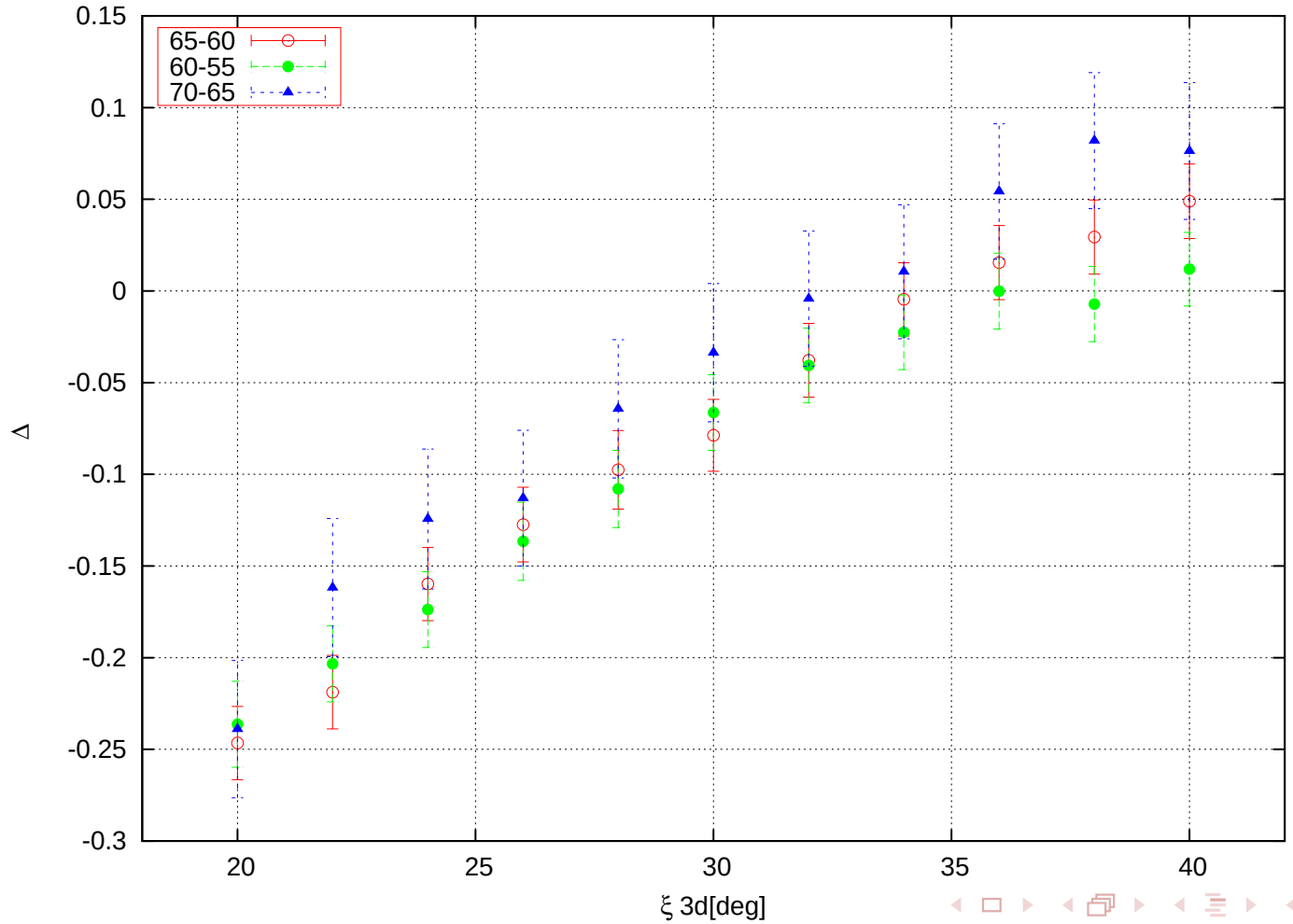
(b) $|\vec{p}_+|/E_{beam} > 0.75$ and $|\vec{p}_-|/E_{beam} > 0.50$
or $|\vec{p}_-|/E_{beam} > 0.75$ and $|\vec{p}_+|/E_{beam} > 0.50$

(c) $|cos(\theta\pm)| < 0.65$ and $|cos(\theta+)| < 0.60$ or $|cos(\theta-)| < 0.60$

(d) $\zeta^{3d}_{max} = 30^\circ$

articles	σ_h $[nb]$	σ_{v+s} $[nb]$	σ_{pairs} $[nb]$	sum $[nb]$
NNLO				
electron	0.202439(6)	-0.223667	0.01355(8)	-0.00768(8)
muon	0.0757889(2)	-0.079231(2)	0.000451(2)	-0.002991(3)
tau	0.0138398(4)	-0.0144654(2)	0.120(3)*10^{-8}	-0.0006257(5)
sum all: σ^{NNLO}				**-0.01130(8)**
BabaYaga NNLO				
electron	0.20244(2)	-0.20971(5)	-	-0.00727(5)
muon	0.07580(1)	-0.07872(2)	-	-0.00292(2)
tau	0.013847(4)	-0.014541(4)	-	-0.000694(6)
sum all: σ^{NNLO}_{BY}				**-0.01088(5)**
$\sigma^{NNLO} - \sigma^{NNLO}_{BY}$				-0.00042(9)
relative difference: $\|\sigma^{NNLO} - \sigma^{NNLO}_{BY}\|/\sigma_{BY}$				**0.08(2)‰**

$\Delta = \frac{\sigma^{NNLO} - \sigma^{NNLO}_{BY}}{\sigma_{BY}} 10^3$ - relative difference ‰



BES

Born $= 173.98(2)$ nb

$\sigma_{BY} = \mathbf{158.23(2)}$

(a) $\sqrt{s} = 3.097$ GeV

(b) $|\cos\theta| < 0.8$

articles	σ_h [nb]	σ_{v+s} [nb]	σ_{pairs} [nb]	sum [nb]
NNLO				
electron	4.16202(12)	-4.71708	0.19977(116)	-0.3553(12)
muon	1.01652(3)	-1.09665(1)	0.001337(5)	-0.078793(3)
tau	0.049672(2)	-0.0540(1)	0	-0.0044(1)
sum all: σ^{NNLO}				**-0.439(1)**
BabaYaga NNLO				
electron	4.1620(10)	-4.48183(21)	-	-0.3198(10)
muon	1.0165(3)	-1.0961(1)	-	-0.0796(3)
tau	0.04966(2)	-0.05421(1)	-	-0.00455(2)
sum all: σ_{BY}^{NNLO}				**-0.404(1)**
$\sigma^{NNLO} - \sigma_{BY}^{NNLO}$				-0.035(1)
relative difference: $\lvert\sigma^{NNLO} - \sigma_{BY}^{NNLO}\rvert/\sigma_{BY}$				**0.23(8)‰**

BES

BORN $=$ 129.0958(4) nb

σ_{BY} **$=$ 116.41(2) nb**

(a) $\sqrt{s} = 3.65$ GeV

(b) $|\cos\theta| < 0.8$

articles	σ_h [nb]	σ_{v+s} [nb]	σ_{pairs} [nb]	sum [nb]
NNLO				
electron	3.19544(9)	-3.55544	0.188856(997)	-0.171(1)
muon	0.83245(2)	-0.88149(1)	0.002003(6)	-0.04704(1)
tau	0.058674(2)	-0.0633(1)	0	-0.0046(1)
sum all: σ^{NNLO}				**-0.223(1)**
BabaYaga NNLO				
electron	3.1960(3)	-3.3730(2)	-	-0.1770(4)
muon	0.83252(7)	-0.88041(9)	-	-0.0479(1)
tau	0.058679(7)	-0.06323(2)	-	-0.00455(2)
sum all: σ_{BY}^{NNLO}				**-0.2295(4)**
$\sigma^{NNLO} - \sigma_{BY}^{NNLO}$				0.006(1)
relative difference: $\|\sigma^{NNLO} - \sigma_{BY}^{NNLO}\|/\sigma_{BY}$				**0.057(9)‰**

BES

BORN $= 123.32(1)$ nb

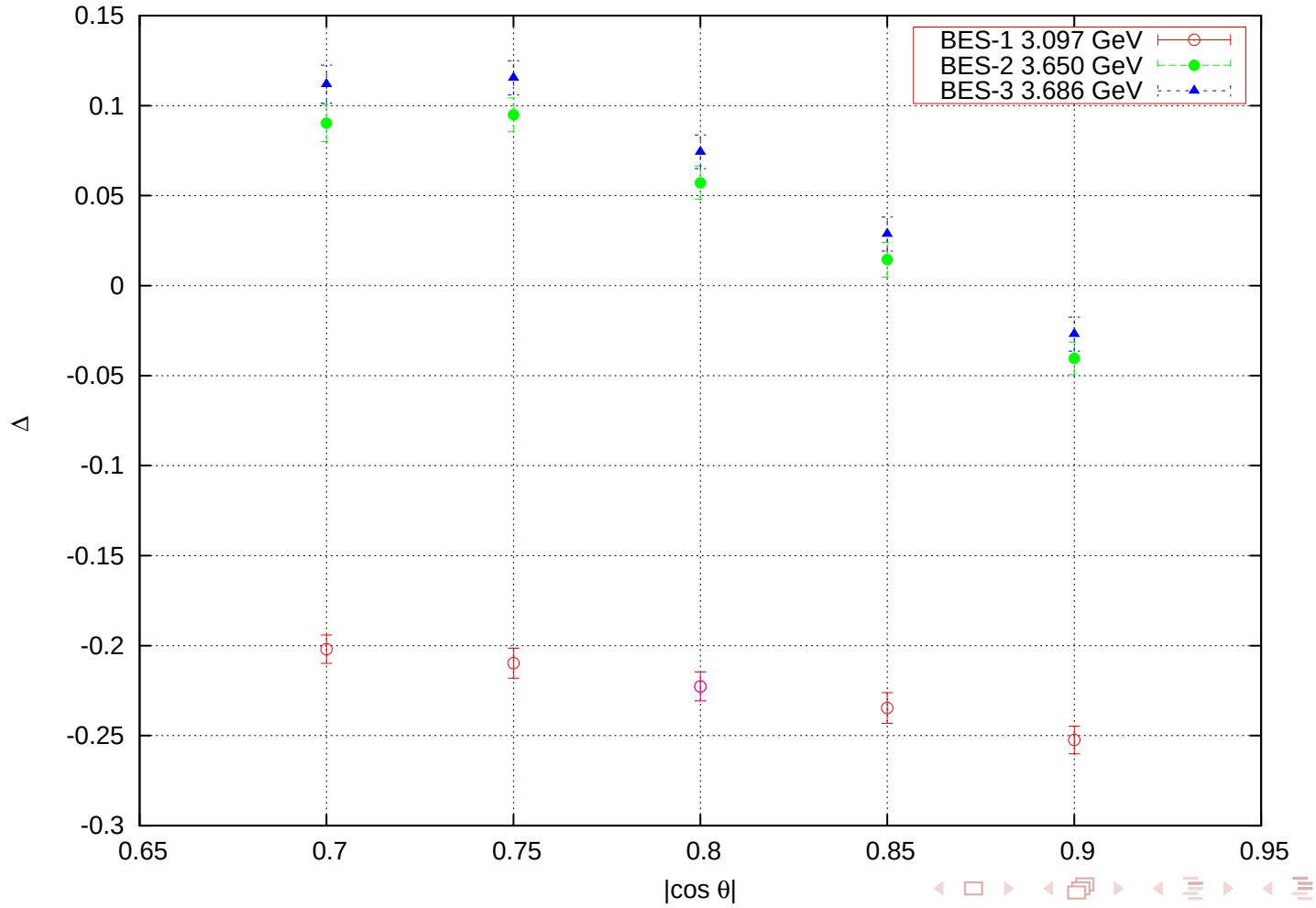
$\sigma_{BY} = \mathbf{114.27(2)\ nb}$

(a) $\sqrt{s} = 3.686$ GeV

(b) $|\cos\theta| < 0.8$

articles	σ_h $[nb]$	σ_{v+s} $[nb]$	σ_{pairs} $[nb]$	sum $[nb]$
NNLO				
electron	3.14439(9)	-3.49579	0.187401(985)	-0.1640(9)
muon	0.82215(2)	-0.86988(1)	0.00203527(637)	-0.04570(7)
tau	0.057923(2)	-0.0622(1)	-	-0.0043(1)
sum all: σ^{NNLO}				**-0.2140(9)**
BabaYaga NNLO				
electron	3.1447(3)	-3.3163(2)	-	-0.1716(4)
muon	0.82221(7)	-0.8688(1)	-	-0.04659(12)
tau	0.057928(7)	-0.06219(2)	-	-0.00426(2)
sum all: σ_{BY}^{NNLO}				**-0.2225(4)**
$\sigma^{NNLO} - \sigma_{BY}^{NNLO}$				0.0085(1)
relative difference: $\lvert\sigma^{NNLO} - \sigma_{BY}^{NNLO}\rvert/\sigma_{BY}$				**0.074(9)‰**

$\Delta = \frac{\sigma^{NNLO} - \sigma^{NNLO}_{BY}}{\sigma_{BY}} 10^3$ - relative difference ‰



BELLE:

BORN = 6.73555(4) nb

σ_{BY} **= 5.501(5) nb**

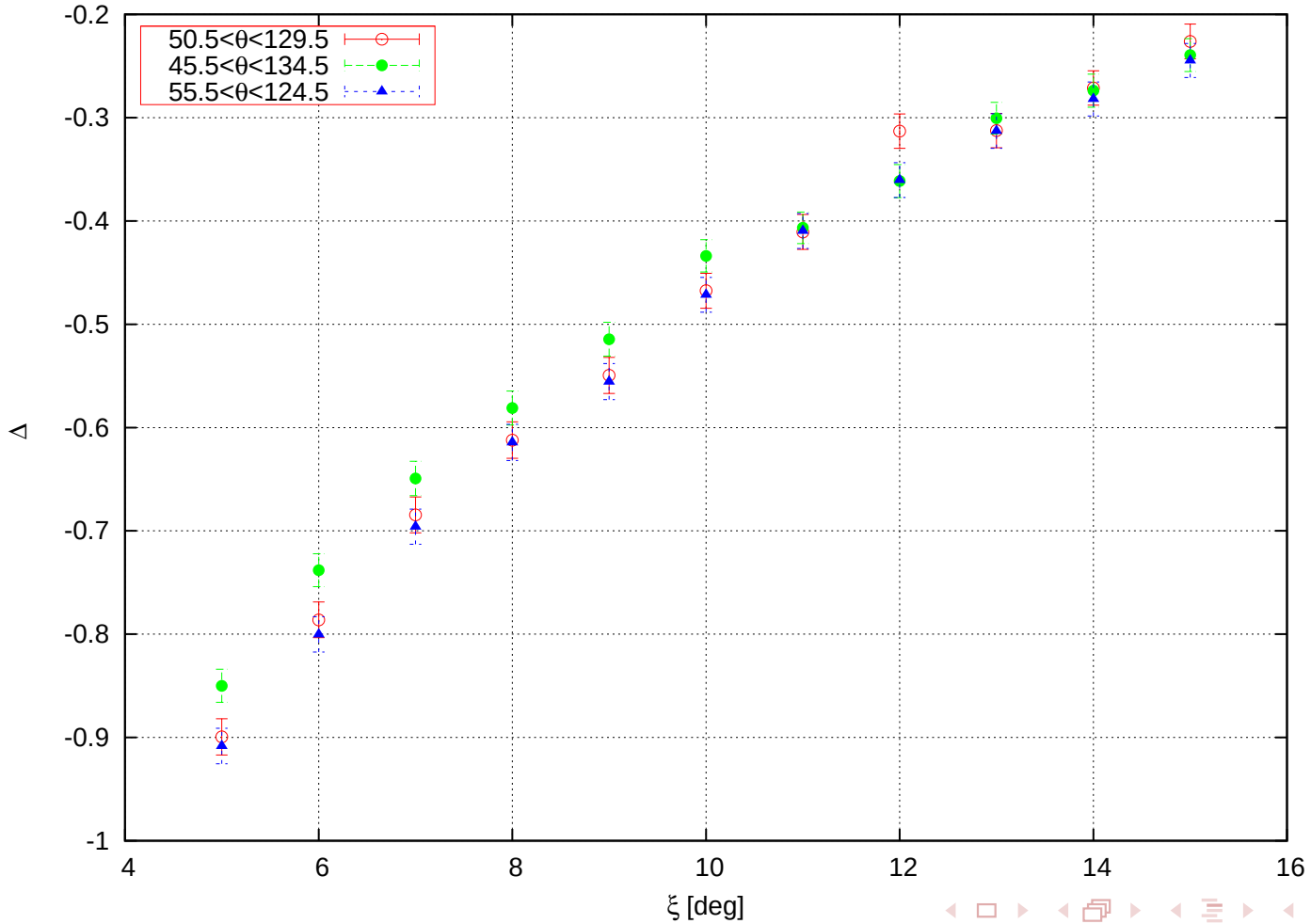
(a) $\sqrt{s}$ =10.58 GeV

(b) $50.5^\circ < \theta_\pm < (180 - 50.5)^\circ$

(c) ζ_{max}=10°

articles	σ_h [nb]	σ_{v+s} [nb]	σ_{pairs} [nb]	sum [nb]
NNLO				
electron	0.21572(7)	-0.25596	0.01310(5)	-0.02714(9)
muon	0.080377(8)	-0.09009(1)	0.000759(1)	-0.00895(2)
tau	0.014428(4)	-0.01602(1)	0.0000321(1)	-0.00156(1)
sum all: σ^{NNLO}				**-0.03765(9)**
BabaYaga NNLO				
electron	0.21563(2)	-0.23994(2)	-	-0.02431(3)
muon	0.080376(6)	-0.08948(2)	-	-0.009104(2)
tau	0.014423(1)	-0.016091(7)	-	-0.001668(7)
sum all: σ^{NNLO}_{BY}				**-0.03508(3)**
$\sigma^{NNLO} - \sigma^{NNLO}_{BY}$				-0.00257
relative difference: $\lvert\sigma^{NNLO} - \sigma^{NNLO}_{BY}\rvert/\sigma_{BY}$				**0.47(2)‰**

$\Delta = \frac{\sigma^{NNLO} - \sigma^{NNLO}_{BY}}{\sigma_{BY}} 10^3$ - relative difference ‰



"Monte Carlo luminosity tools:status and perspectives", Guido Montagna, 8th Meeting of the RMCLow Working Group Liverpool, 18 19 September, 2010

Status of the MC theoretical accuracy

Main conclusion of the Luminosity Section of the WG Report

Putting the various sources of uncertainties (for large–angle Bhabha) all together...

Source of error (%)	$\Phi-$factories	$\sqrt{s}$ = 3.5 GeV	$B-$factories
$\lvert\delta^{\rm err}_{\rm VP}\rvert$ [Jegerlehner]	0.00	0.01	0.03
$\lvert\delta^{\rm err}_{\rm VP}\rvert$ [HMNT]	0.02	0.01	0.02
$\lvert\delta^{\rm err}_{{\rm SV},\alpha^2}\rvert$	0.02	0.02	0.02
$\lvert\delta^{\rm err}_{{\rm HH},\alpha^2}\rvert$	0.00	0.00	0.00
$\lvert\delta^{\rm err}_{{\rm SV,H},\alpha^2}\rvert$ [in progress]	0.05	0.05	0.05
$\lvert\delta^{\rm err}_{\rm pairs}\rvert$ [in progress]	$\sim$0.05	$\sim$0.1[1]	$\sim$0.02[2]
$\lvert\delta^{\rm err}_{\rm total}\rvert$ linearly	0.12÷0.14	0.18	0.11÷0.12
$\lvert\delta^{\rm err}_{\rm total}\rvert$ in quadrature	0.07÷0.08	0.11	0.06÷0.07

- For the experiments on top of and closely around the J/ψ resonance, the accuracy slightly deteriorates, because of the differences between the predictions of independent $\Delta\alpha^{(5)}_{\rm had}(q^2)$ routines [see next slide]
- ★ The present error estimate appears to be rather robust and sufficient for high–precision luminosity measurements. It is comparable with that achieved about ten years ago for small–angle Bhabha luminosity monitoring at LEP/SLC

[1] Very preliminary, work in progress using realistic BES-III and CLEO-c luminosity cuts

[2] Preliminary and assuming BaBar cuts. Work in progress for BELLE event selection

KLOE:

$|\delta^{err}_{pairs}|$ ~0.5 ‰

$|\frac{\sigma^{NNLO}-\sigma^{NNLO}_{BY}}{\sigma_{BY}}|_{reference} = 0.471(4)$ ‰, $|\frac{\sigma^{NNLO}-\sigma^{NNLO}_{BY}}{\sigma_{BY}}|_{max} = 0.619(4)$ ‰

B - factories:

$|\delta^{err}_{pairs}|$ ~0.2 ‰

BaBar: $|\frac{\sigma^{NNLO}-\sigma^{NNLO}_{BY}}{\sigma_{BY}}|_{reference} = 0.08(2)$ ‰, $|\frac{\sigma^{NNLO}-\sigma^{NNLO}_{BY}}{\sigma_{BY}}|_{max} = 0.1(2)$ ‰

Belle: $|\frac{\sigma^{NNLO}-\sigma^{NNLO}_{BY}}{\sigma_{BY}}|_{reference} = 0.47(2)$ ‰, $|\frac{\sigma^{NNLO}-\sigma^{NNLO}_{BY}}{\sigma_{BY}}|_{max} = 0.91(2)$ ‰

BES vs. $\sqrt{s} = 3.5 GeV$:

$|\delta^{err}_{pairs,\sqrt{s}=3.5}|$ ~1 ‰

BES:

$\sqrt{s} = 3.097 GeV$: $|\frac{\sigma^{NNLO}-\sigma^{NNLO}_{BY}}{\sigma_{BY}}|_{reference} = 0.23(8)$‰, $|\frac{\sigma^{NNLO}-\sigma^{NNLO}_{BY}}{\sigma_{BY}}|_{max} = 0.25(7)$ ‰

$\sqrt{s} = 3.650 GeV$: $|\frac{\sigma^{NNLO}-\sigma^{NNLO}_{BY}}{\sigma_{BY}}|_{reference} = 0.057(9)$‰, $|\frac{\sigma^{NNLO}-\sigma^{NNLO}_{BY}}{\sigma_{BY}}|_{max} = 0.095(9)$ ‰

$\sqrt{s} = 3.686 GeV$: $|\frac{\sigma^{NNLO}-\sigma^{NNLO}_{BY}}{\sigma_{BY}}|_{reference} = 0.074(9)$‰, $|\frac{\sigma^{NNLO}-\sigma^{NNLO}_{BY}}{\sigma_{BY}}|_{max} = 0.11(1)$ ‰

Hadrons - in progress

particles	σ_h	σ_{v+s}	σ_{pairs}	sum
KLOE, 55° $< \theta\pm <$ 125 °, ζ_{max}=9°				
NNLO				
pions	1.17402(8)	-1.35988(2)	0	-0.18586(8)
hadrons	1.5248(5)	in progress	-	in progress
BabaYaga NNLO				
hadrons	1.5247(5)	-1.126(2)	-	0.399(2)

particles	σ_h	σ_{v+s}	σ_{pairs}	sum
BaBar, $\lvert cos(\theta\pm)\rvert < 0.65$ **and** $\lvert cos(\theta+)\rvert < 0.60$ **or** $\lvert cos(\theta-)\rvert < 0.60$, ζ^{3d}_{max}**= 30°**				
NNLO				
pions	0.051037(2)	-0.053328(3)	0.000030(3)	-0.002261(5)
hadrons	0.17995(2)	in progress	-	in progress
BabaYaga NNLO				
hadrons	0.17984(2)	-0.18760(4)	-	-0.00776(4)

All results in nb

Issues to be discussed here

Comparison of results with vacuum polarization obtained using :VPHLMNT (T.Teubner et all.) and hadr5n09 (F. Jegerlehner) (all results from BabaYaga) - all results in nb

KLOE: $55^\circ < \theta\pm < 125\ ^\circ$, ζ_{max}=4°
σ_{BY} **=436.85(5)**

vacpol	σ_h	σ_{v+s}	sum:
VPHLMNT(2009)	1.4346(5)	-1.126(2)	0.309(2)
hadr5n09	1.6264(6)	-1.405(2)	0.221(2)
relative difference: $\left\lvert \frac{\sigma^{NNLO}_{VPHLMNT} - \sigma^{NNLO}_{hadr5n09}}{\sigma_{BY}} \right\rvert$			0.201(6)‰

BES: $\sqrt{s} = 3.650$ GeV, $|\cos\theta| < 0.8$
σ_{BY} **= 116.41(2) nb**

vacpol	σ_h	σ_{v+s}	sum:
VPHLMNT2.0(2010)	1.6613(3)	-1.7860(2)	-0.1247(4)
hadr5n09	1.6471(7)	-1.7686(2)	-0.1215(7)
relative difference: $\left\lvert \frac{\sigma^{NNLO}_{VPHLMNT} - \sigma^{NNLO}_{hadr5n09}}{\sigma_{BY}} \right\rvert$			0.0275‰

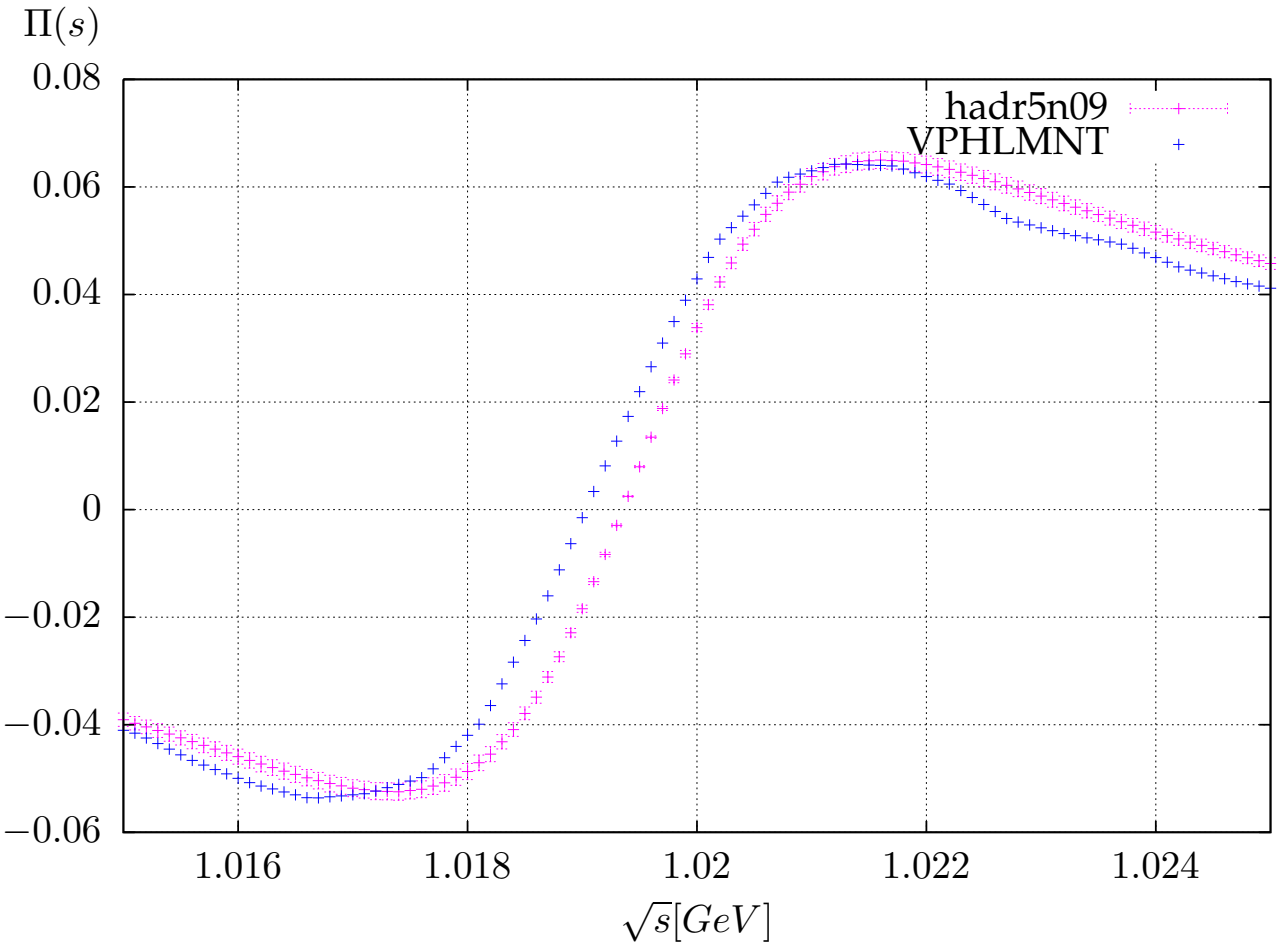
Issues to be discussed here

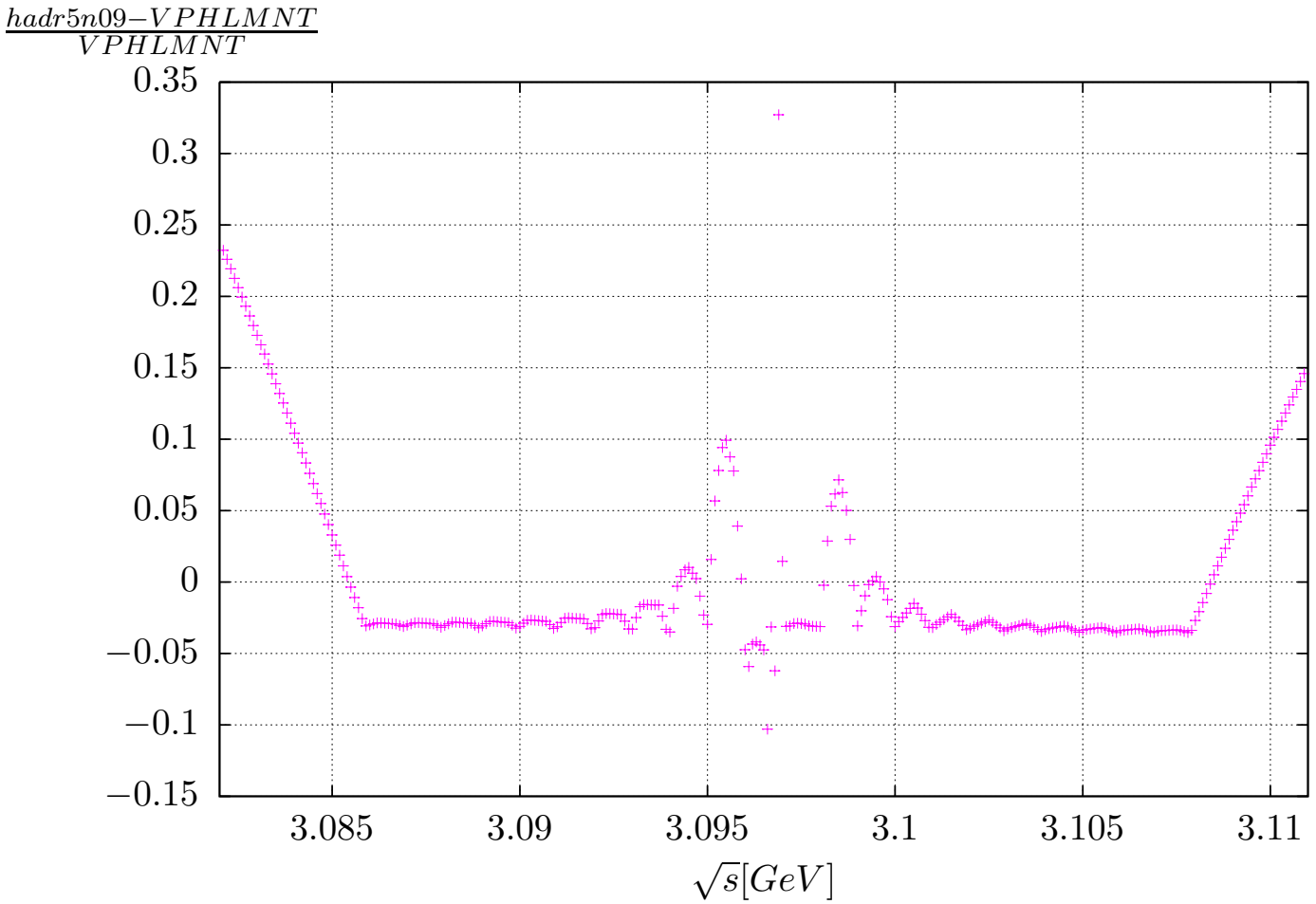
BES: $\sqrt{s} = 3.686$ GeV, $|\cos\theta| < 0.8$
σ_{BY} **= 114.27(2) nb**

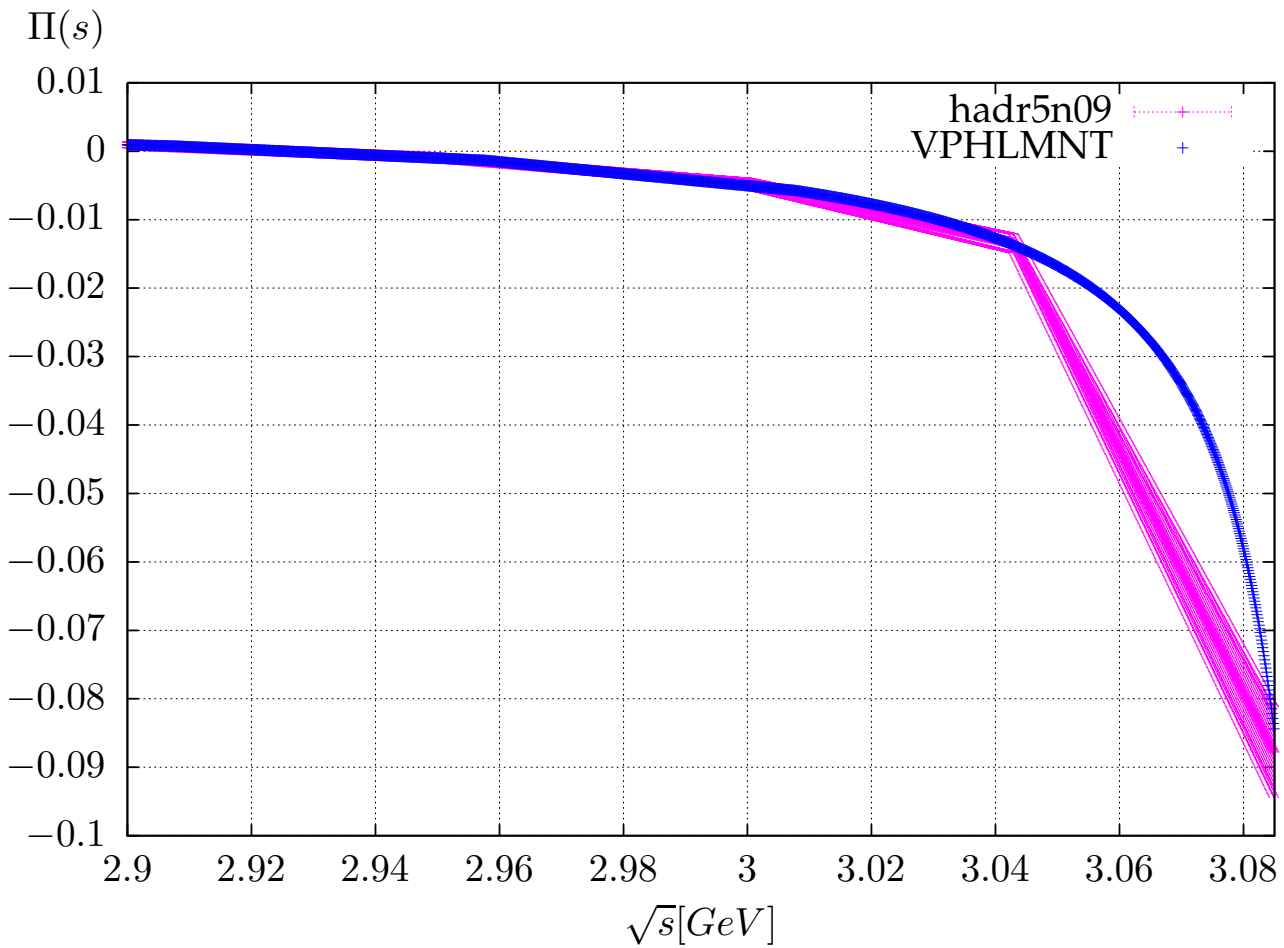
vacpol	σ_h	σ_{v+s}	sum:
VPHLMNT2.0(2010)	10.006(4)	-16.80(1)	-6.79(1)
hadr5n09	9.60(1)	-16.28(2)	-6.68(3)
relative difference: $\left\|\frac{\sigma^{NNLO}_{VPHLMNT} - \sigma^{NNLO}_{hadr5n09}}{\sigma_{BY}}\right\|$			0.96‰

BES: $\sqrt{s} = 3.097$ GeV, $|\cos\theta| < 0.9$
σ_{BY} **= 378.48(5) nb**

vacpol	σ_h	σ_{v+s}	sum:
VPHLMNT2.0(2010)	-116.50(6)	287.7(3)	171.2(3)
hadr5n09	-119.1(2)	291.9(3)	172.8(4)
relative difference: $\left\|\frac{\sigma^{NNLO}_{VPHLMNT} - \sigma^{NNLO}_{hadr5n09}}{\sigma_{BY}}\right\|$			4.227‰


$\Pi(s)$
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
1.016
1.018
1.02
1.022
1.024
$\sqrt{s}[GeV]$
hadr5n09
VPHLMNT


$\frac{hadr5n09-VPHLMNT}{VPHLMNT}$
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
−0.05
−0.1
−0.15
3.085
3.09
3.095
3.1
3.105
3.11
$\sqrt{s}[GeV]$


$\Pi(s)$
0.01
0
−0.01
−0.02
−0.03
−0.04
−0.05
−0.06
−0.07
−0.08
−0.09
−0.1
2.9
2.92
2.94
2.96
2.98
3
3.02
3.04
3.06
3.08
$\sqrt{s}[GeV]$
hadr5n09
VPHLMNT