PHYSICS PERSPECTIVES ON W, Z AND QCD

Fabio Cossutti – INFN Trieste

On behalf of the Standard Model working group

Workshop LTS1 2014 – La Biodola, 23/05/2014

Many presentations in the parallel session relevant for this topics

Thursday, 22 May 2014

15:00 - 15:15	Introduzione *15'* Speakers: Stefano Forte (MI), Aleandro Nisati (ROMA1), Giampiero Passarino (Universita' di Torino), Roberto Tenchini (PI)
15:15 - 15:45	Fisica Higgs a LHC *30'* Speakers: Paolo Giacomelli (BO), Dr. Biagio Di Micco (ROMA3), Stefano Rosati (ROMA1)
15:45 - 16:15	VV scattering e VBF *30'* Speakers: Pietro Govoni (MIB), Chiara Mariotti (TO), Chiara Maria Roda (PI)
16:15 - 16:45	Prospettive fisica W, Z, QCD *30'* Speakers: Alberto Mengarelli (BO), Fabio Cossutti (TS), Giancarlo Panizzo (UD)
16:45 - 17:15	Prospettive fisica del top *30'* Speakers: Patrizia Azzi (PD), Marina Cobal (UD)
17:15 - 17:35	coffee break
17:35 - 17:55	Fisica a ILC/CLIC *20'* Speaker: Barbara Mele (ROMA1)
17:55 - 18:15	Fisica a FCC (ee+pp) *20'* Speaker: Roberto Tenchini (PI)
18:15 - 18:30	Fisica a gamma-gamma colliders: Sapphire *15'* Speaker: Marco Zanetti (CERN)
18:30 - 18:45	Fisica a LHeC (ep colliders) *15'* Speaker: Monica D'Onofrio
18:45 - 19:00	Fisica a e+e- bassa energia *15'* Speaker: Graziano Venanzoni (LNF)
19:00 - 19:30	Discussione fisica a progetti futuri *30'*

W, Z, QCD: what is really hot for the future?

- Standard Model studies in ≥ 2014 mean indirect search of new physics
  - i.e. no precision for precision' sake, if new physics is hard to be accessed directly, this can be an early discovery tool
  - Otherwise important to characterize which new physics we might have seen

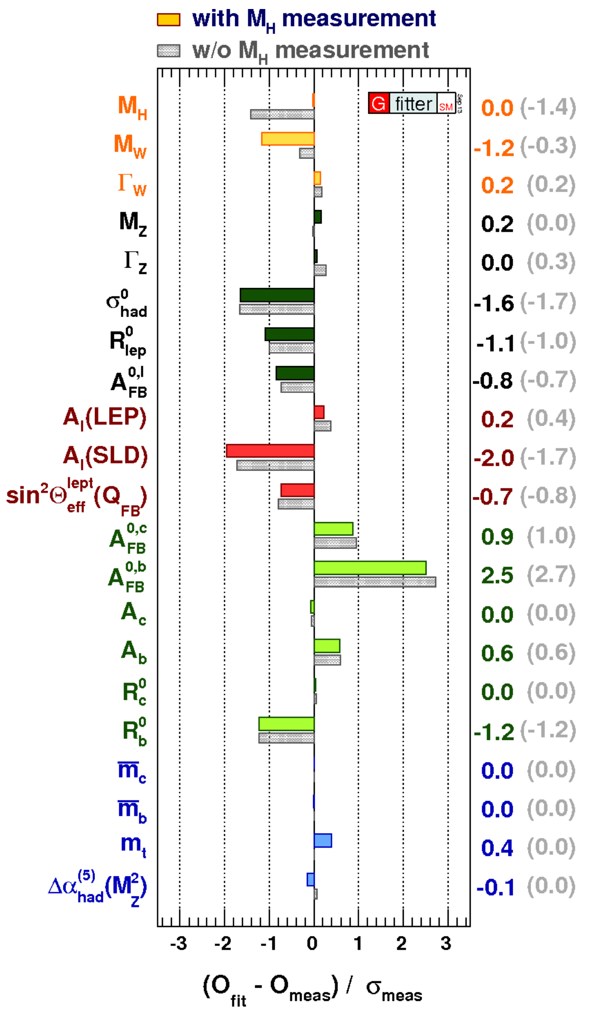
- Electroweak precision measurements
  - M_W , $\sin^2(\theta_{eff})$, …
  - α_{EM} and α_S important inputs for global electroweak fits

- Study of the multi-boson couplings
  - Fundamental test of the SM gauge sector: TGCs, QGCs
  - Direct connection with precision Higgs physics: VV scattering

- QCD: fundamental ingredients for the program above
  - Besides interesting in its own
  - No precision physics at hadron colliders without precise knowledge of PDFs and radiative corrections

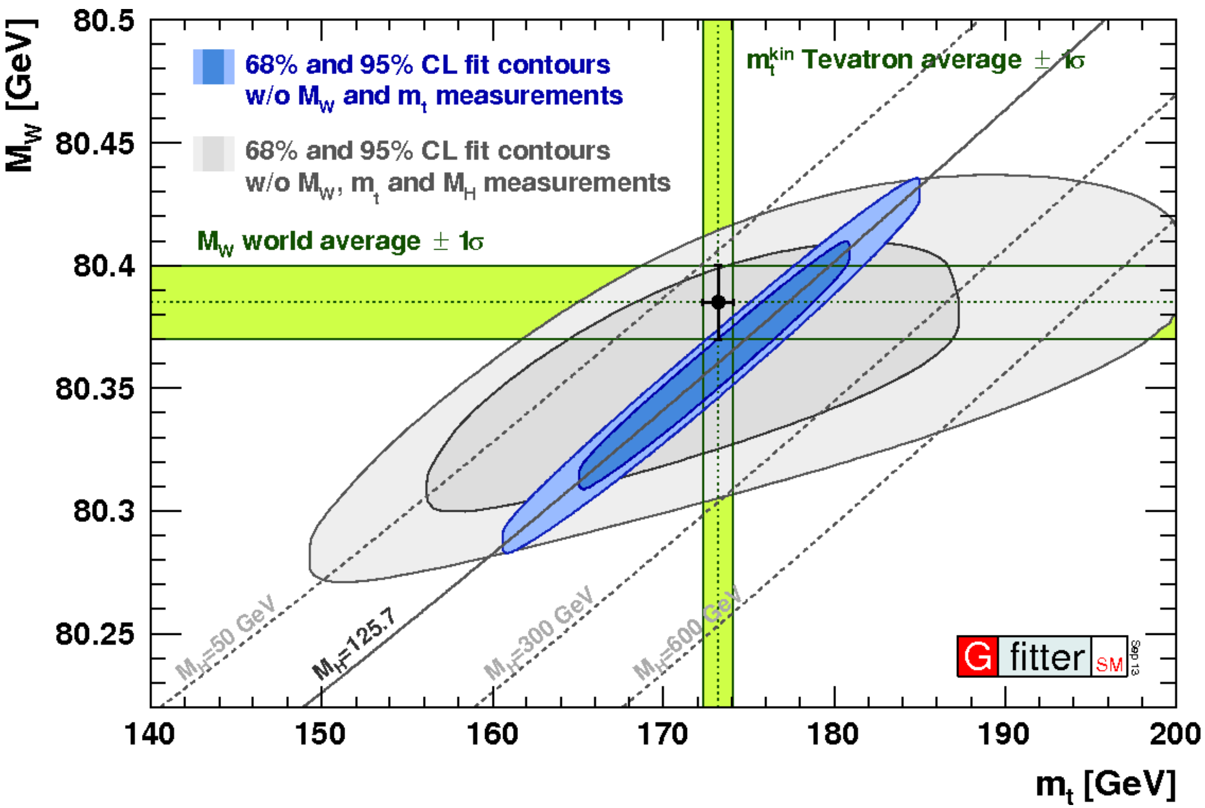
ELECTROWEAK PRECISION MEASUREMENTS

Precision observables and global fits after (a/the) Higgs boson discovery



Plot inspired by Eberhardt et al. [arXiv:1209.1101]

If the LHC Higgs boson is the SM one, global EW fit over-constrained: new level of precision accessible
Eur. Phys. J. C72, 2205 (2012)



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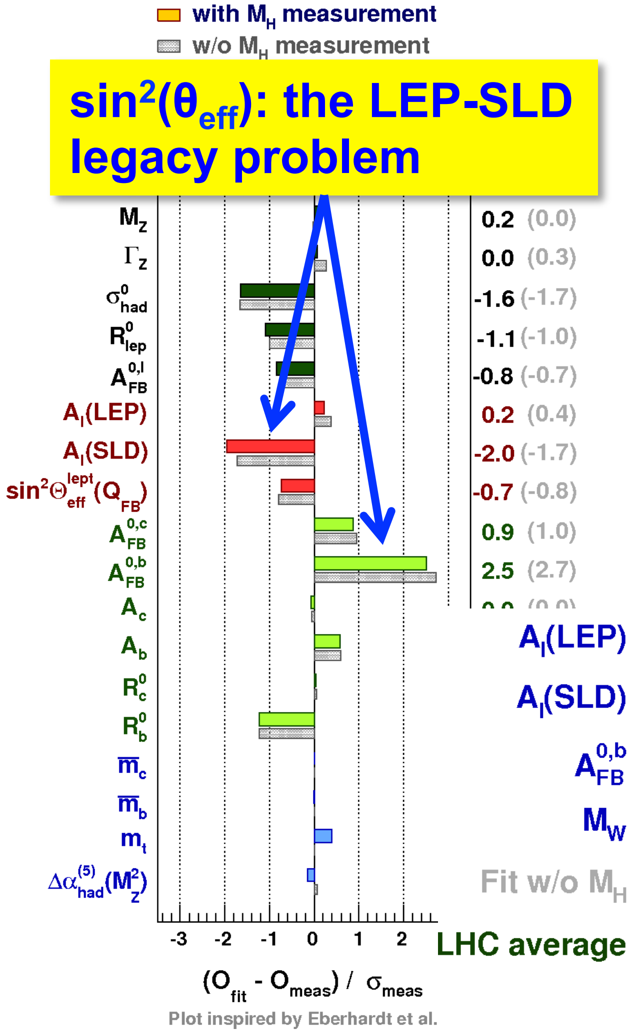

$\sin^2(\theta_{eff})$: the LEP-SLD legacy problem

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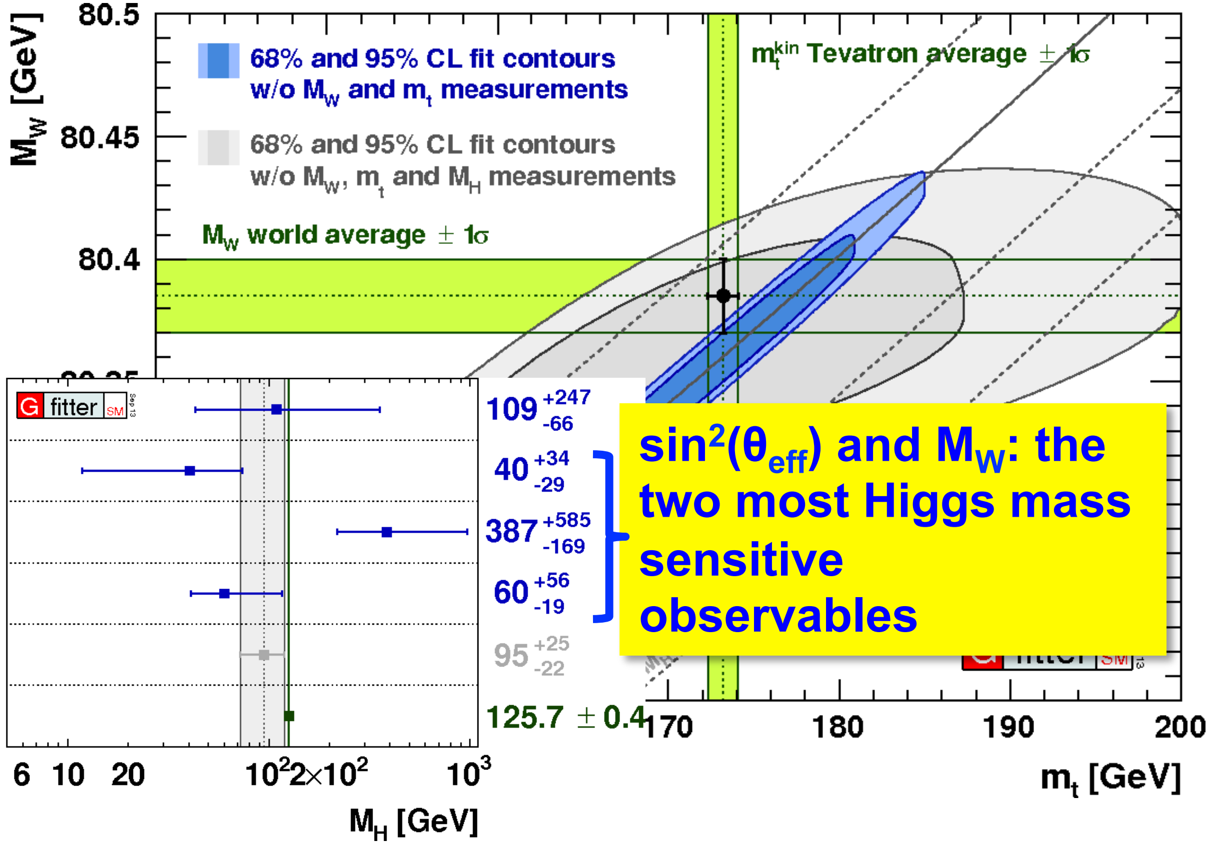
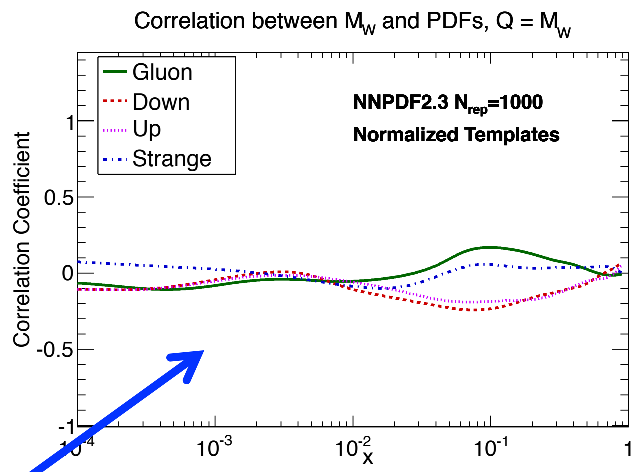


$\sin^2(\theta_{eff})$ and M_W: the two most Higgs mass sensitive observables

Medium term: W mass at hadronic colliders

- World average: 80.385 ± 0.015 GeV
- GFITTER: 80.359 ± 0.011 GeV
  - δtheo 7→4 MeV with m_t and $\Delta\alpha_{had}$ reduced by a factor ~ 2
- Final ΔM_W Tevatron expectation: ~ 9 MeV
  - Factor 2 from better detector understanding, data driven
  - Factor 2 from **better PDFs**
- How can we go beyond at LHC/HL-LHC?
  - The key issue is PDF
  - Assuming detector understanding scale with statistics

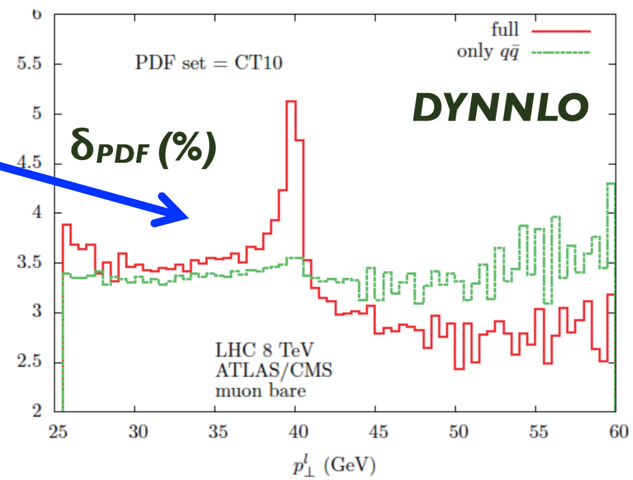


ΔM_W [MeV]	LHC		
$\sqrt{s}$ [TeV]	8	14	14
$\mathcal{L}[\mathrm{fb}^{-1}]$	20	300	3000
PDF	10	5	3
QED rad.	4	3	2
$p_T(W)$ model	2	1	1
other systematics	10	5	3
W statistics	1	0.2	0
Total	15	8	5

Transverse mass: all PDFs matter

Lepton p_T: gluon PDF particularly important

Snowmass 2013 projection: ~5 MeV achievable at LHC



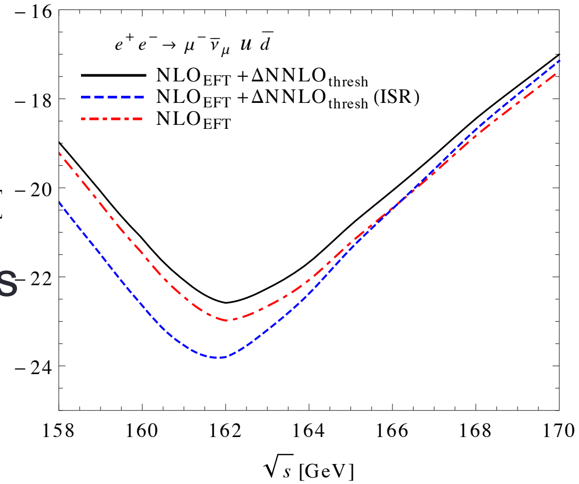
Long term: W mass at lepton colliders

- The winning method: σ_{WW} scan at production threshold

ΔM_W [MeV]	LEP2	ILC	ILC	e^+e^-	TLEP
$\sqrt{s}$ [GeV]	161	161	161	161	161
$\mathcal{L}$ [fb^{-1}]	0.040	100	480	600	3000×4
$P(e^-)$ [%]	0	90	90	0	0
$P(e^+)$ [%]	0	60	60	0	0
systematics	70			?	< 0.5
statistics	200			2.3?	0.5
experimental total	210	3.9	1.9	>2.3	< 0.7
beam energy	13	0.8-2.0	0.8-2.0	0.8-2.0	0.1
radiative corrections	-	1.0	1.0	1.0	1.0
total	210	4.1-4.5	2.3-2.9	>2.6-3.2	< 1.2

- Polarized beams
- ILC statistics allows good beam energy measurement in situ
- TLEP: resonant depolarization
  - δE_{beam} ~ 0.1 MeV ?

NNLO radiative correction matter
Worst at higher energies

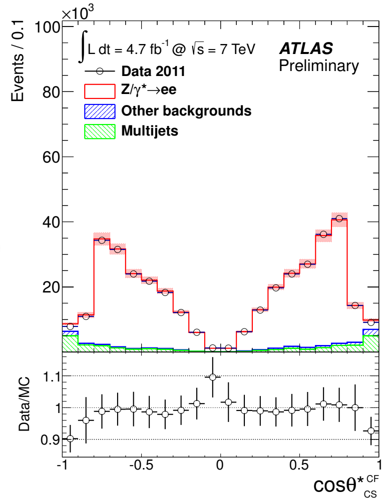


Possible alternatives interesting but less competitive:

- Kinematic reconstruction à la LEP2 > 3 MeV
  - Just semi-leptonic, use statistics to avoid FSI issues
- Hadronic mass in WW + single W: almost comparable
  - Single W abundant at higher √s
  - Different systematics, interesting cross check

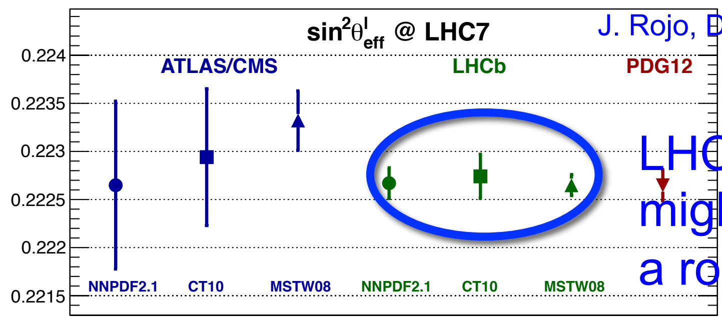
Medium term: $\sin^2(\theta_{eff})$ at hadronic colliders

- How to challenge LEP1/SLD precision before ILC/TLEP?
  - $\delta_{LEP1/SLD}$ =1.6×10^{-4} vs δ_{theo} ~ 7×10^{-5} (➔3×10^{-5} with m_t and $\Delta\alpha_{had}$ reduced by a factor ~ 2)
- Key problem: the quark direction definition introduces a dilution and PDF dependence
  - Tevatron : use the incoming proton direction
  - LHC : use the ll boost z component, more PDF dependent (from sea)
- δ_{CDF} (×10^{-4}) : 9 ➔4 ; δ_{ATLAS} : 11×10^{-4}
  - CDF event weighting method: compensate acceptance, drop detector systematics
  - ATLAS use of forward electrons: much smaller dilution, compensating statistics



$\Delta\sin^2\theta^l_{\rm eff}$ [10^{-5}]	ATLAS	CMS	LHC/per experiment		
$\sqrt{s}$ [TeV]	7	7	8	14	14
$\mathcal{L}$[fb^{-1}]	4.8	1.1	20	300	3000
PDF	70	130	35	25	10
higher order corr.	20	110	20	15	10
other systematics	70	181	60 (35)	20	15
statistical	40	200	20	5	2
Total	108	319	75 (57)	36	21

LHC 7 TeV - HORACE LO (PRELIMINARY)

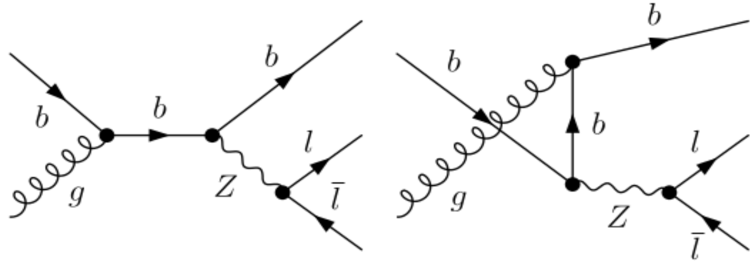


LHCb might play a role?

With expected improvements on PDFs, forward lepton tagging and smart analyses hadronic machines could approach LEP1/SLD precision

Medium term: $A^{b,0}_{FB}$ via $A^{b,\,LHC}_{FB}$

- Highest discrepancy in SM Global Fits
  - δLEP1 = 16×10-4 vs δtheo ~ 4×10-4
  - pull value 2.5 σ = 40 ‰



s-channel u-channel

- No experiment measured it after LEP ! Define:

$$A^{b,\mathrm{LHC}}_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

  - experimentally: adapt A_{FB} to LHC, where F/B defined event by event i
    Z rest frame by the lepton angle wrt b_{jet} axis
  - dilution due to b_{jet} charge measurement

$\delta A^{b,LHC}_{FB}$ [‰]	LHC	combined
$\sqrt{s}$ [TeV]	14	14
$\mathcal{L}$ [fb^{-1}]	400	3000
PDF	5	2
other systematics	20	15
statistical	$\lesssim 95$	$\lesssim 40$
Total	$\lesssim 97$	$\lesssim 43$

- Simplified feasibility studies set an upper bound on both statisti
  and systematic uncertainties

- Open field of research both from experimental and theoretical points of view (only LO prediction @ LHC): reduced uncertainties from PDFs and scale variations

http://dx.doi.org/10.1016/j.physletb.2014.01.010

Long term: $\sin^2(\theta_{eff})$ at lepton colliders

- All LEP1/SLD studies repeated at ILC-GigaZ and TLEP
- But the 10^{-5} barrier can be attacked with A_{LR}
- Key tool: longitudinal beam polarization
  - Electrons only (à la SLC): absolute polarization measurement limit
    - Possible $\delta P/P \sim 0.25\%$ ←→ $\delta\sin^2(\theta_{eff}) \sim 5\times10^{-5}$
  - Both e^+ / e^- : use the Blondel scheme

$$A_{\rm LR} = \sqrt{\frac{(\sigma_{++}+\sigma_{-+}-\sigma_{+-}-\sigma_{--})(-\sigma_{++}+\sigma_{-+}-\sigma_{+-}+\sigma_{--})}{(\sigma_{++}+\sigma_{-+}+\sigma_{+-}+\sigma_{--})(-\sigma_{++}+\sigma_{-+}+\sigma_{+-}-\sigma_{--})}},$$

- Still a relative polarization measurement is needed
- $\delta A_{LR} \sim 2.5 \times 10^{-5}$

- Beam energy/beamstrahlung knowledge also matters
  - A_{LR} slope due to γ-Z interference ~ 2×10^{-2} / GeV
  - $\delta A_{LR} \sim 10^{-4}$

$\Delta\sin^2\theta^l_{\rm eff}$ $[10^{-5}]$	ILC/GigaZ	TLEP(Z)
$\sqrt{s}$ [GeV]	91	91
$\mathcal{L}[\mathrm{fb}^{-1}]$	30	3000×4
systematics	1.1	0.2
statistical	0.5	0.1
higher order corr.	?	?
beam energy	0.5	0.05
total	1.3	0.3

- $\delta\sin^2(\theta_{eff}) \sim 10^{-5}$ claimed to be achievable at GigaZ
  - for $P^- \sim 80\%$, P^+ 30%
- TLEP: better precision on E_{beam} with resonant depolarization
  - but spin rotators needed for polarization combinations
  - $\delta\sin^2(\theta_{eff}) > 10^{-5}$

TeraZ @ TLEP: LEP1 reloaded?

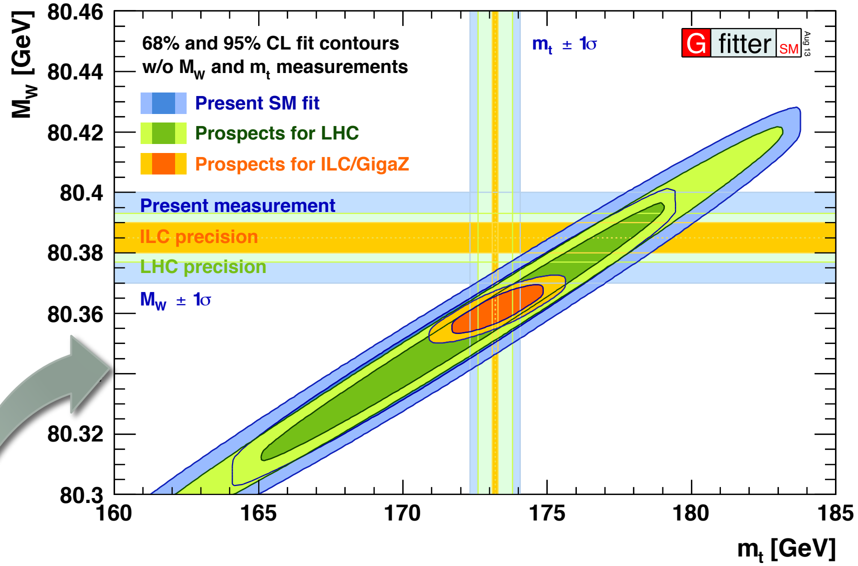
JHEP 1401 164 (2014)

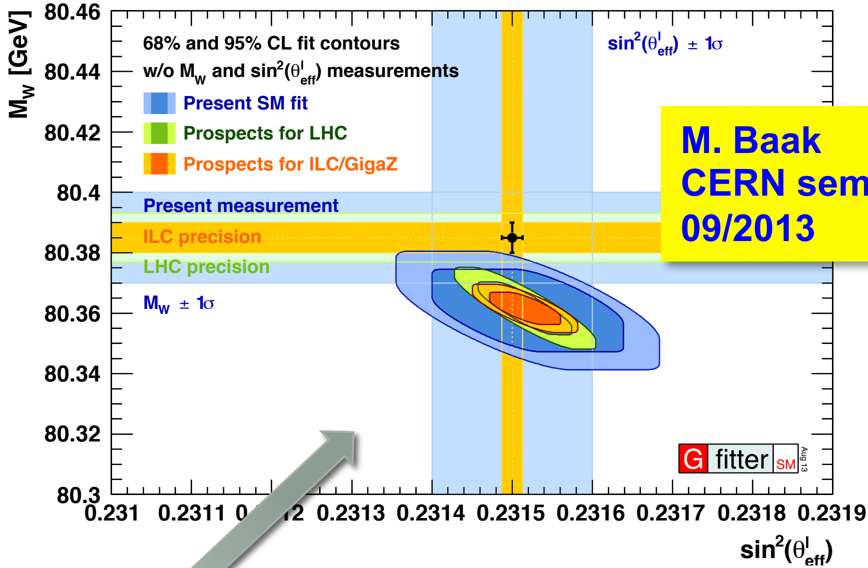
Quantity	Physics	Present precision	Measured from	Statistical uncertainty	Systematic uncertainty	Key	Challenge
m_Z (keV)	Input	91187500 ± 2100	Z Line shape scan	5 (6)	< 100	E_{beam} calibration	QED corrections
Γ_Z (keV)	$\Delta\rho$ (not $\Delta\alpha_{\mathrm{had}}$)	2495200 ± 2300	Z Line shape scan	8 (10)	< 100	E_{beam} calibration	QED corrections
R_ℓ	α_s, δ_b	20.767 ± 0.025	Z Peak	0.00010 (12)	< 0.001	Statistics	QED corrections
N_ν	PMNS Unitarity, …	2.984 ± 0.008	Z Peak	0.00008 (10)	< 0.004		Bhabha scat.
N_ν	…and sterile ν's	2.92 ± 0.05	$Z\gamma$, 161 GeV	0.0010 (12)	< 0.001	Statistics	
R_b	δ_b	0.21629 ± 0.00066	Z Peak	0.000003 (4)	< 0.000060	Statistics, small IP	Hemisphere correlations
A_{LR}	$\Delta\rho$, ϵ_3, $\Delta\alpha_{\mathrm{had}}$	0.1514 ± 0.0022	Z peak, polarized	0.000015 (18)	< 0.000015	4 bunch scheme, 2exp	Design experiment
m_W (MeV)	$\Delta\rho$, ϵ_3, ϵ_2, $\Delta\alpha_{\mathrm{had}}$	80385 ± 15	WW threshold scan	0.3 (0.4)	< 0.5	E_{beam}, Statistics	QED corrections
m_{top} (MeV)	Input	173200 ± 900	$t\bar{t}$ threshold scan	10 (12)	< 10	Statistics	Theory interpretation

- 1 year at Z peak 40% polarization + 1 year Z scan (50% at peak)

- The availability of resonant depolarization might allow to repeat the Z line shape study with a precision better by a factor ~ 10 at least
  - Linear colliders haven't this tool
- A large Z ➔ bb sample combined with an adequate detector would allow a similar improvement to study R_b

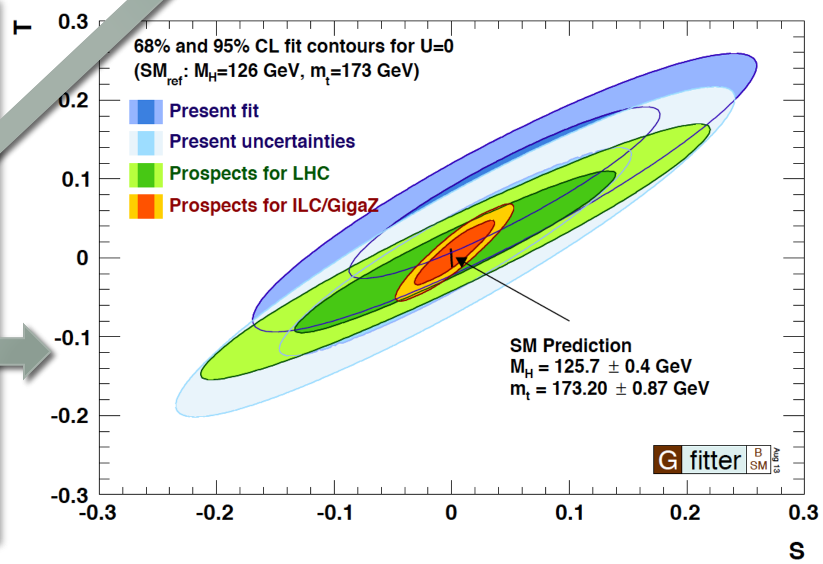
Possible achievements in global fits





M. Baak
CERN seminar
09/2013

- Program of improvements in EWPO can now shown internal SM inconsistency
  - Higgs and top essential ingredients as well
  - New physics in loops might become evident
- Can be translated in EW oblique observables limits
  - Fully model dependent?



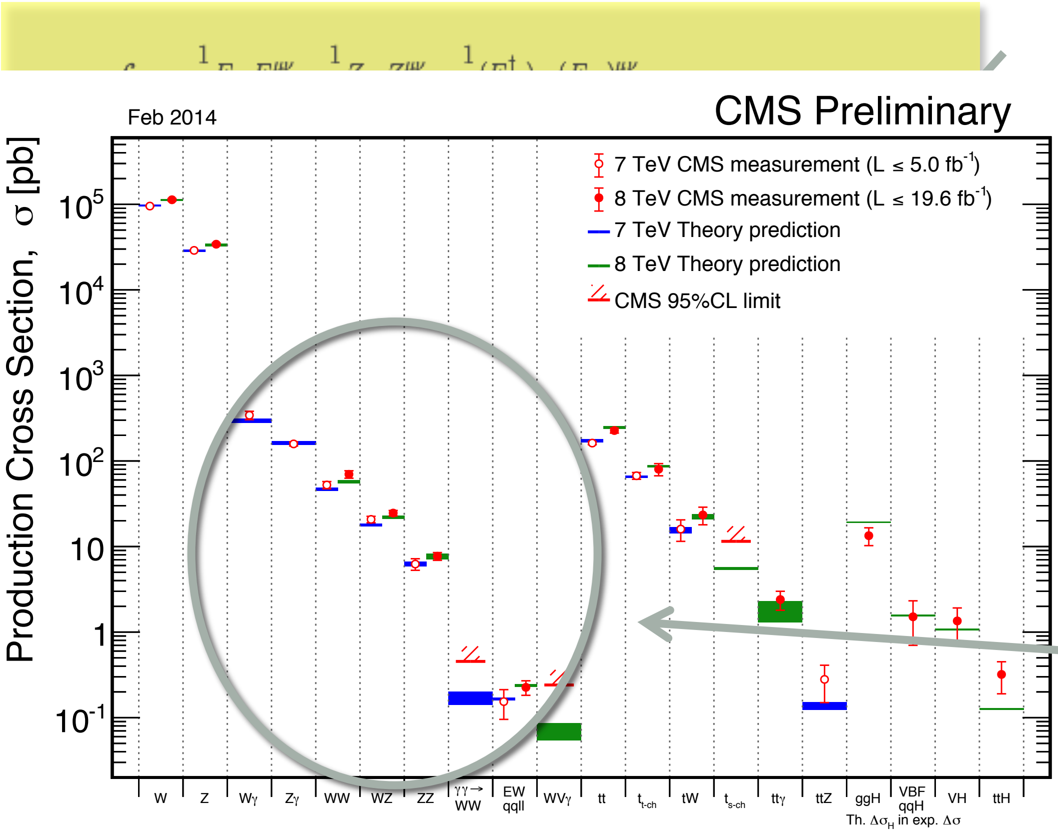
MULTI BOSONS MEASUREMENTS

Multi-boson final states: couplings, Higgs and new physics

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} - \frac{1}{2}(F_W^\dagger)_{\mu\nu}(F_W)^{\mu\nu} \\
& + \frac{1}{2}\partial_\mu H \partial^\mu H + \frac{1}{2}M_Z^2 Z_\mu Z^\mu + M_W^2 (W_-)_\mu (W_+)^\mu - \frac{1}{2}m_H^2 H^2 \\
& + \bar{e}(i\partial\!\!\!/ - m_e)e + i\bar{\nu}\partial\!\!\!/\nu \\
& + ig(\partial_\mu W_{+\nu} - \partial_\nu W_{+\mu})W_-^\nu(\cos\theta_W Z^\mu + \sin\theta_W A^\mu) \\
& + ig(\partial_\mu W_{-\nu} - \partial_\nu W_{-\mu})W_+^\mu(\cos\theta_W Z^\nu + \sin\theta_W A^\nu) \\
& + ig(W_-^\mu W_+^\nu - W_+^\mu W_-^\nu)\partial_\mu(\cos\theta_W Z_\nu + \sin\theta_W A_\nu) \\
& - g^2 W_{+\mu}W_-^\mu(\cos\theta_W Z_\nu + \sin\theta_W A_\nu)(\cos\theta_W Z^\nu + \sin\theta_W A^\nu) \\
& + g^2 W_+^\nu W_-^\mu(\cos\theta_W Z_\mu + \sin\theta_W A_\mu)(\cos\theta_W Z_\nu + \sin\theta_W A_\nu) \\
& + \frac{g^2}{2}W_{-\nu}W_{+\mu}(W_-^\nu W_+^\mu - W_-^\mu W_+^\nu) + e\bar{e}\gamma_\mu e A^\mu \\
& - \frac{g}{2\cos\theta_W}\left[\frac{1}{2}\bar{\nu}\gamma_\mu(1-\gamma^5)\nu + \bar{e}\gamma_\mu(g_V - g_A\gamma^5)e\right]Z^\mu \\
& - \frac{g}{2\sqrt{s}}\left[\bar{\nu}\gamma_\mu(1-\gamma^5)eW_+^\mu + \bar{e}\gamma_\mu(1-\gamma^5)\nu W_-^\mu\right] \\
& + \frac{g^2}{4}\left(2vH + H^2\right)W_{-\mu}W_+^\mu + \frac{(g^2+g'^2)}{8}\left(2vH + H^2\right)Z_\mu Z^\mu \\
& - \frac{\lambda}{4}\left(4vH^3 + H^4\right) - \frac{m_e}{v}\bar{e}eH
\end{aligned}
$$

- Gauge boson couplings: basic characteristics of a non-abelian theory
  - In SM triple and quartic GC
- Deviation from SM, i.e. anomalous couplings: new physics evidence
  - Similar study to EW global fit
- Vector boson scattering: need the Higgs to be unitarized as energy increase
  - Fundamental test of the SM
  - Bridge between Higgs and W/Z physics

Multi-boson final states: couplings, Higgs and new physics



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- Di- and tri-bosons: cross sections quite smaller than for single boson production
  - High luminosity is fundamental for precision studies
- VBS sensitivity to new physics grows with energy
  - Hadronic machines have a plus here
  - Forward region becomes fundamental

Anomalous couplings in the Effective Field Theory approach

- Effective Field Theory: extend the SM Lagrangian with dimension 6, 8 operators
  - Describe effective interactions mediated by particles with mass at a scale Λ

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \underbrace{\sum_{i=WWW,W,B,\Phi W,\Phi B} \frac{c_i}{\Lambda^2}\mathcal{O}_i}_{\text{dimension 6}} + \underbrace{\sum_{j=0,1} \frac{f_{S,j}}{\Lambda^4}\mathcal{O}_{S,j} + \sum_{j=0,\dots,9} \frac{f_{T,j}}{\Lambda^4}\mathcal{O}_{T,j} + \sum_{j=0,\dots,7} \frac{f_{M,j}}{\Lambda^4}\mathcal{O}_{M,j}}_{\text{dimension 8}}$$

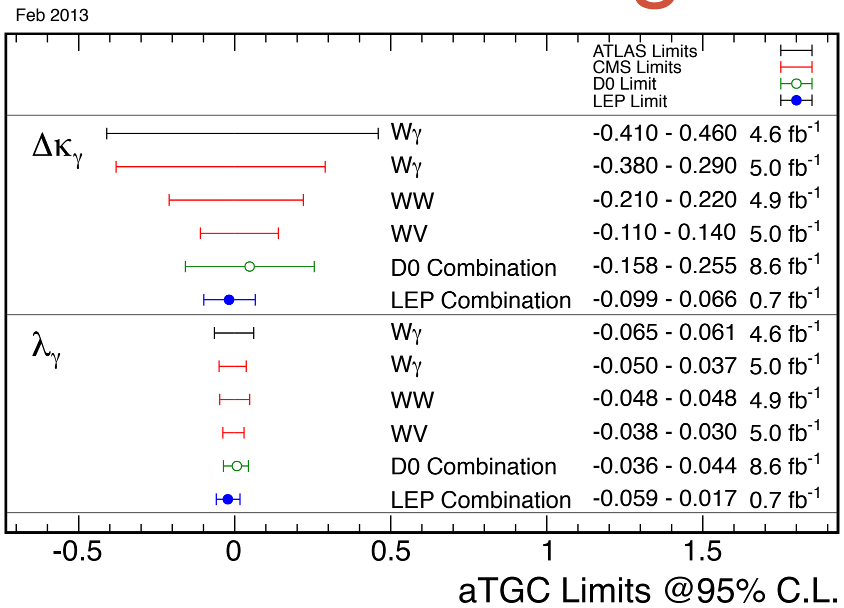
  - If Λ >> experimentally accessible scale, i.e. O(1-2 TeV), the SM is a low (compared to Λ) effective theory
  - Various representations of operators among different calculations, but relationships available for instance in arXiv.1310.6708
  - Both TGC and QGC in dimension 6 operators, dimension 8 add genuine QGC
  - Relationships also with the Lagrangian parameterizations used at LEP:

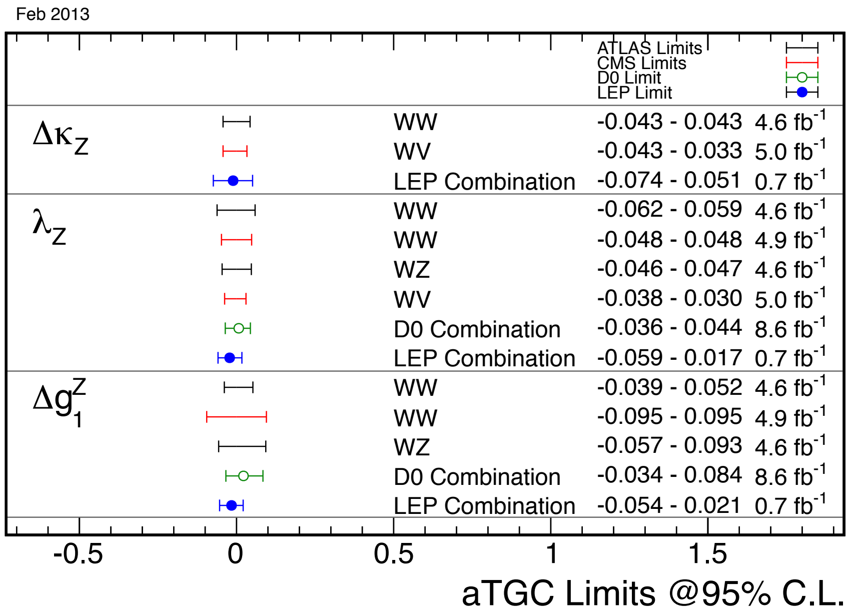
$$\begin{aligned}\mathcal{L} =& ig_{WWV}\Big(g_1^V(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2}W^{\nu+}_\mu W^{-\rho}_\nu V^\mu_\rho \\ &+ig_4^V W^+_\mu W^-_\nu(\partial^\mu V^\nu + \partial^\nu V^\mu) - ig_5^V\epsilon^{\mu\nu\rho\sigma}(W^+_\mu\partial_\rho W^-_\nu - \partial_\rho W^+_\mu W^-_\nu)V_\sigma \\ &+\tilde{\kappa}_V W^+_\mu W^-_\nu\tilde{V}^{\mu\nu} + \frac{\tilde{\lambda}_V}{m_W^2}W^{\nu+}_\mu W^{-\rho}_\nu\tilde{V}^\mu_\rho\Big)\,,\end{aligned}$$

$$\mathcal{L}_0 = -\frac{e^2}{16\pi\Lambda^2}a_0 F_{\mu\nu}F^{\mu\nu}\vec{W}^\alpha\vec{W}_\alpha$$
$$\mathcal{L}_c = -\frac{e^2}{16\pi\Lambda^2}a_c F_{\mu\alpha}F^{\mu\beta}\vec{W}^\alpha\vec{W}_\beta$$

C,P conservation + electromagnetic gauge invariance
Reduce to a minimal independent set Δg_1^Z, $\Delta\kappa_\gamma$, λ_γ

4-fermions: charged Triple Gauge Couplings



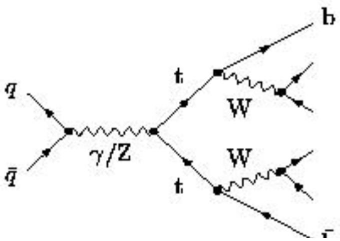


- LHC already competitive on λ , Δκ
- κ-type couplings: mostly sensitive to differential distributions
  - Cleaner environment in lepton colliders helps, ILC clearly winning
- λ-type couplings: strong √s dependence
  - Sensitivity in high p_T tail of diboson system, benefit from large statistics
  - HL-LHC not much worse than ILC800
  - HE-LHC could further improve

Obs.	Now	LHC 0.3/ab	HL-LHC 3/ab	ILC800
Δg_1^Z	$[-5,2]\times10^{-2}$	3×10^{-3}	2×10^{-3}	1.8×10^{-4}
κ_γ	$[-10,7]\times10^{-2}$	3×10^{-2}	1×10^{-2}	1.9×10^{-4}
λ_γ	$[-6,2]\times10^{-2}$	9×10^{-4}	4×10^{-4}	2.6×10^{-4}

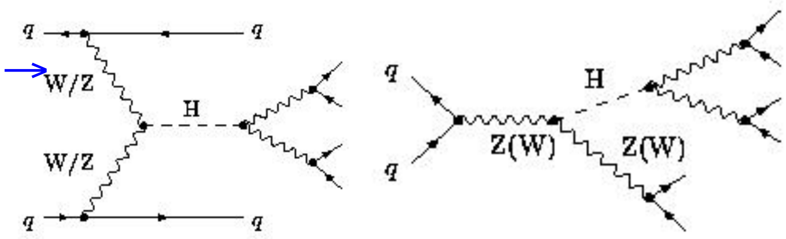
arXiv.1405.3841

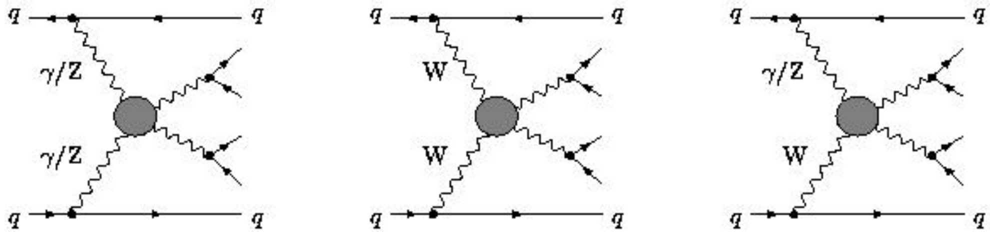
6-fermions: QGC and VBS



← top-top (EW)

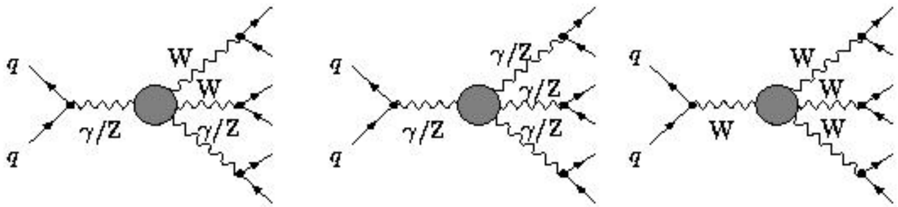
Higgs →

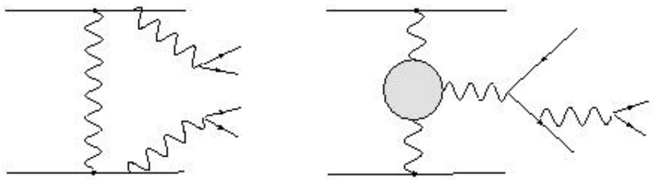




← VV-fusion

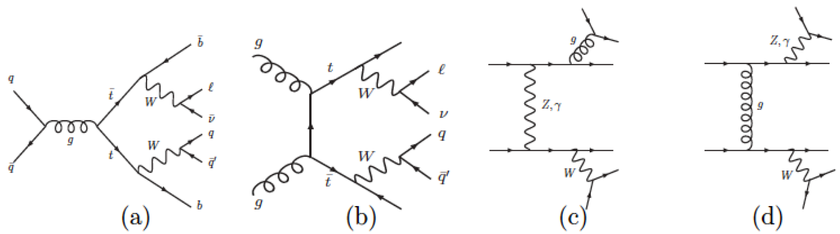
TGC & QGC →





← VV and non resonant

And $\alpha^2_s\,\alpha^4_{EW}$ →



6-fermions: QGC and VBS

- **Quartic Gauge Couplings: from both di- (e.g. WW,WZ,ZZ) and tri-boson production (e.g. Zγγ)**

← top-top (EW)

- **Vector Boson Fusion/Scattering: characteristic emission of very forward jets, large jj mass, large rapidity gap (colourless objects in the central region)**
- **In SM unitarity of VBS cross section with increasing √s guaranteed by the Higgs boson**
  - **Fundamental test of SM, one of the flagship measurements for HL-LHC**
  - **Natural bridge between Higgs and W/Z studies**

← VV and non resonant

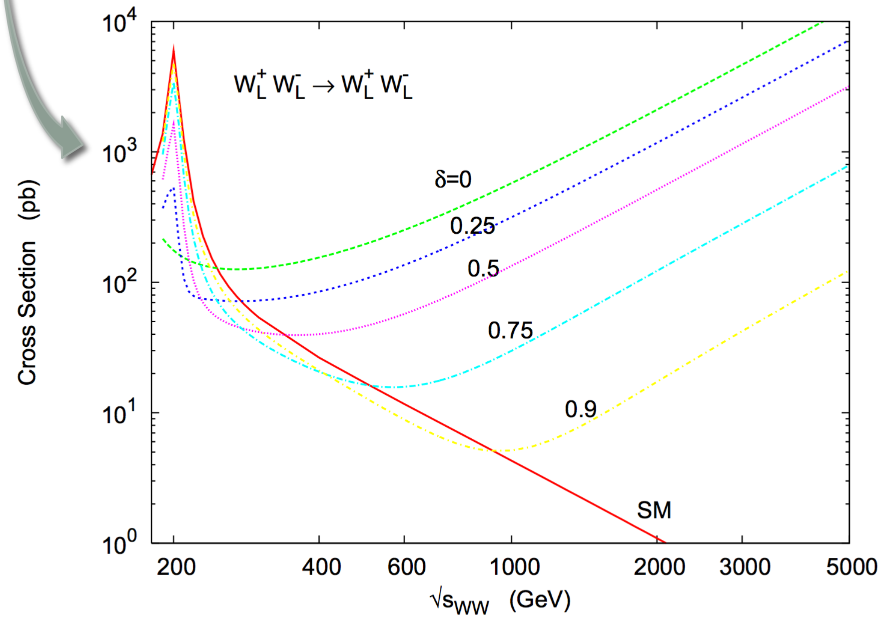
- **With typical experimental cuts EWK VV cross sections O(~ 10 fb)**

And $\alpha_s^2\,\alpha_{EW}^4$ →

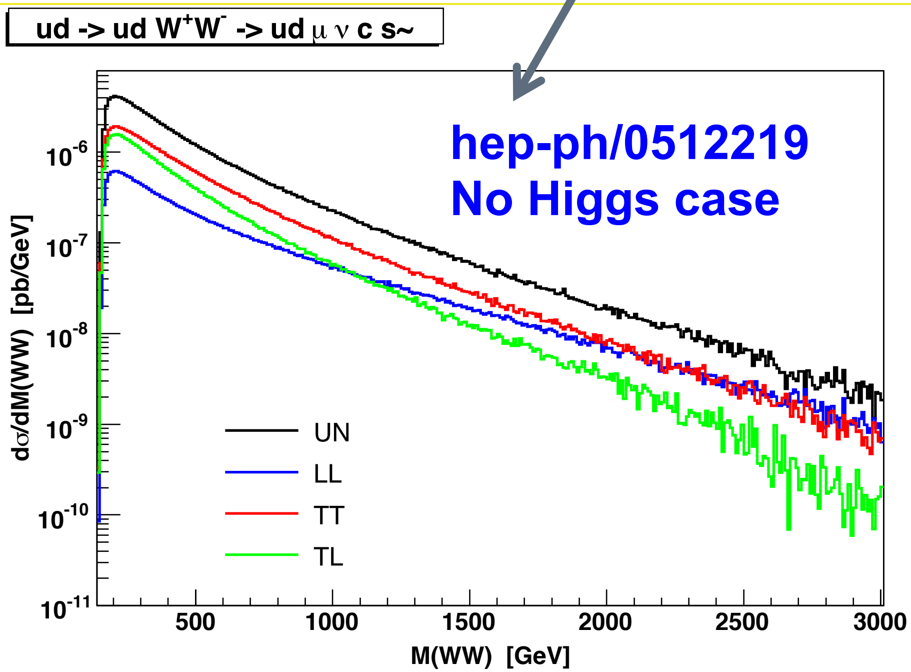
6-fermions: QGC and VBS

The study of m(VV) in $V_L V_L \rightarrow V_L V_L$ can probe whether the Higgs alone can describe the process of whether there is evidence for some new physics at higher scale, reducing the effective hVV coupling compared the SM by $\sqrt{\delta}$

In practice there is also the transverse polarization to take into account, and the PDFs suppress the growth, so a precise measurement of the production rate at high mass is needed



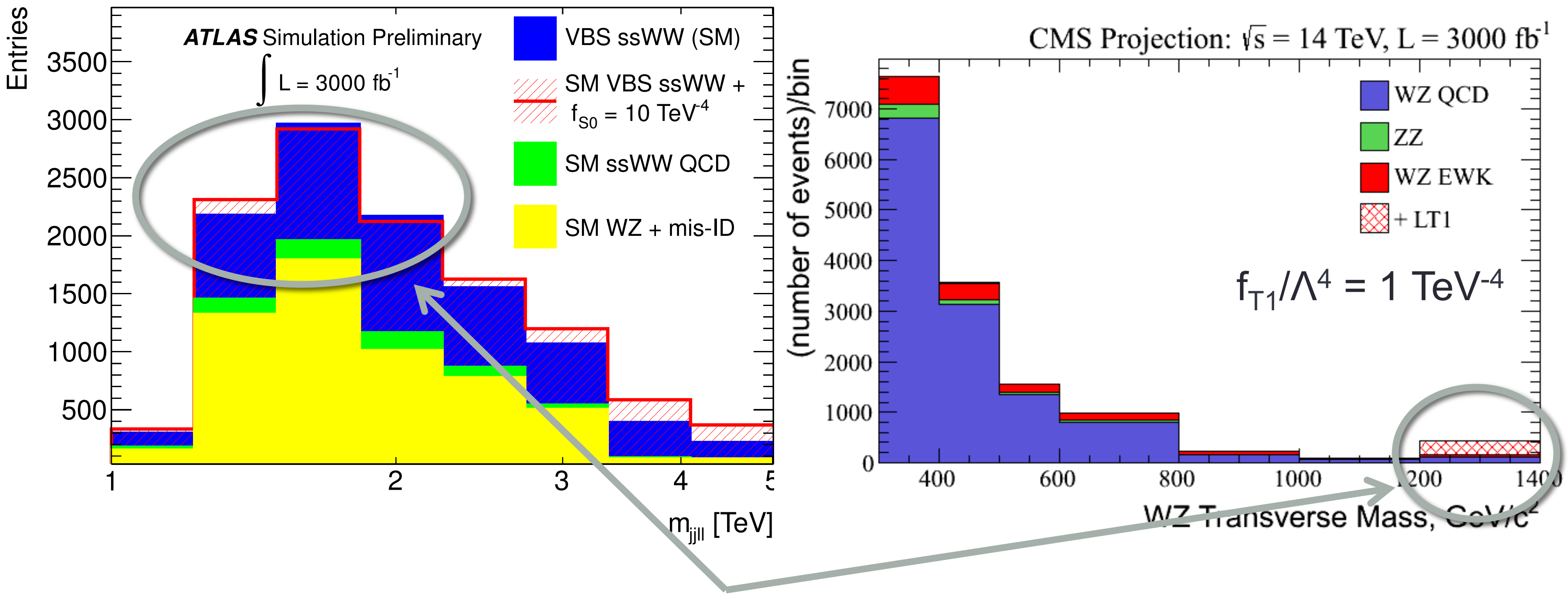
Cheung, Chiang, Yuan



hep-ph/0512219
No Higgs case

6-fermions: QGC and VBS

ATL-PHYS-PUB-2013-006 **CMS-FTR-13-006-PAS**



Examples of possible new physics signal expectations

HL-LHC projections for Snowmass 2013

Limits on QGC

ATLAS projections for Snowmass 2013
Clear sensitivity gain with luminosity increase

Parameter	dimension	channel	Λ_{UV} [TeV]	300 fb^{-1} 5σ	300 fb^{-1} 95% CL	3000 fb^{-1} 5σ	3000 fb^{-1} 95% CL
$c_{\Phi W}/\Lambda^2$	6	ZZ	1.9	34 TeV^{-2}	20 TeV^{-2}	16 TeV^{-2}	9.3 TeV^{-2}
$f_{S,0}/\Lambda^4$	8	$W^{\pm}W^{\pm}$	2.0	10 TeV^{-4}	6.8 TeV^{-4}	4.5 TeV^{-4}	0.8 TeV^{-4}
$f_{T,1}/\Lambda^4$	8	WZ	3.7	1.3 TeV^{-4}	0.7 TeV^{-4}	0.6 TeV^{-4}	0.3 TeV^{-4}
$f_{T,8}/\Lambda^4$	8	$Z\gamma\gamma$	12	0.9 TeV^{-4}	0.5 TeV^{-4}	0.4 TeV^{-4}	0.2 TeV^{-4}
$f_{T,9}/\Lambda^4$	8	$Z\gamma\gamma$	13	2.0 TeV^{-4}	0.9 TeV^{-4}	0.7 TeV^{-4}	0.3 TeV^{-4}

Kinematic selection satisfying unitarity

Lepton colliders not competitive on dimention-8 operators, LHC better by 1-2 orders of magnitude

- Limits in scale are model dependent
- From $f_{S,0}$ (WWWW) for simple models of bosonic resonances :

Type of resonance	LHC 300 fb^{-1} 5σ	LHC 300 fb^{-1} 95% CL	LHC 3000 fb^{-1} 5σ	LHC 3000 fb^{-1} 95% CL
scalar ϕ	1.8 TeV	2.0 TeV	2.2 TeV	3.3 TeV
vector ρ	2.3 TeV	2.6 TeV	2.9 TeV	4.4 TeV
tensor f	3.2 TeV	3.5 TeV	3.9 TeV	6.0 TeV

Snowmass 2013, arXiv.1307.6708

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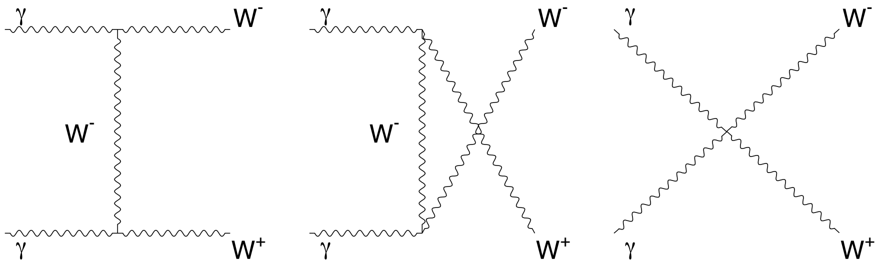
Lepton colliders not competitive on dimention-8 operators, LHC better by 1-2 orders of magnitude

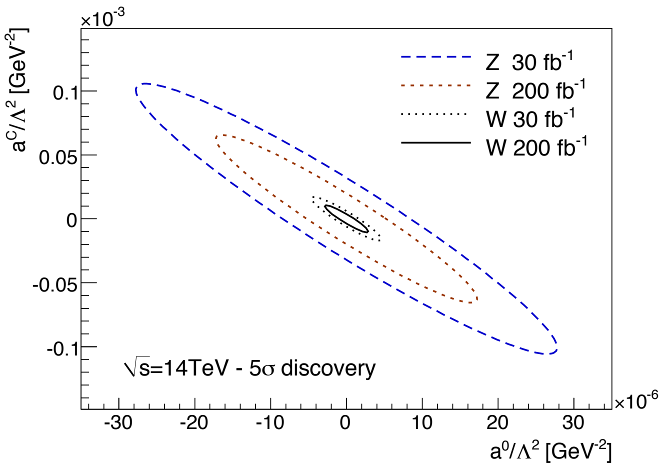
Parameter	$\sqrt{s}$	14 TeV	14 TeV	33 TeV	100 TeV
	Lum.	300 fb^{-1}	3000 fb^{-1}		
$f_{M,0}/\Lambda^4$ [TeV^{-4}]	5σ	7300 (830)	3600 (310)	1900 (190)	750 (120)
	95% CL	4200 (360)	1200 (160)	660 (120)	71 (59)
$f_{M,1}/\Lambda^4$ [TeV^{-4}]	5σ	7600 (1600)	3600 (680)	2100 (340)	1000 (220)
	95% CL	4500 (800)	1200 (290)	770 (160)	240 (126)
$f_{M,2}/\Lambda^4$ [TeV^{-4}]	5σ	3300 (130)	510 (48)	310 (26)	120 (16)
	95% CL	670 (56)	160 (21)	110 (13)	25 (10)
$f_{M,3}/\Lambda^4$ [TeV^{-4}]	5σ	2400 (250)	720 (120)	320 (66)	180 (34)
	95% CL	820 (133)	210 (52)	130 (23)	38 (15)

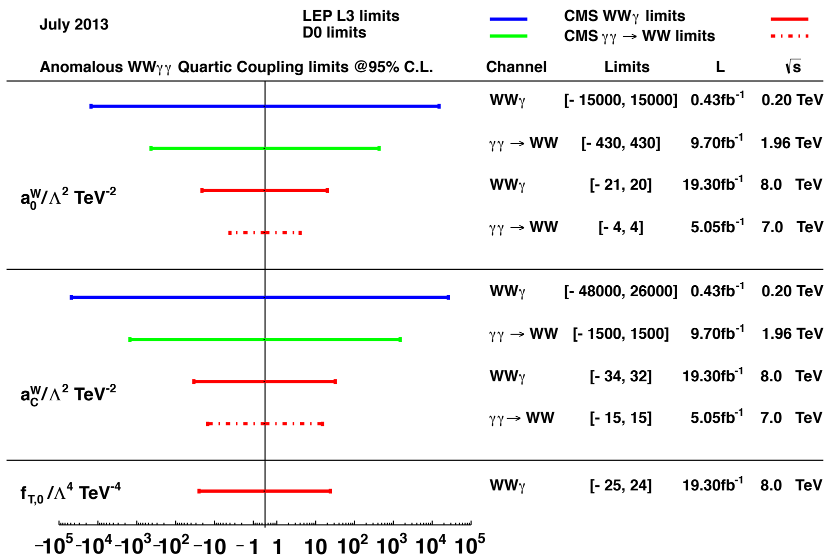
Sensitivity increase from 14 to 33 TeV
~ 1.2 - 2 for dim-6 (WZ,ZZ)
~ 12 for dim-8 (Zγγ)
Tribosons look very sensitive to √s

Photon-photon scattering and QGC

- Very forward proton taggers for ATLAS and CMS at ~200 m from the i.p. allow the study of Central Exclusive Production of boson pairs
  - Key additional tool for QGC studies







Orders of magnitude beyond LEP before ILC

PRD 81 074003 (2010)

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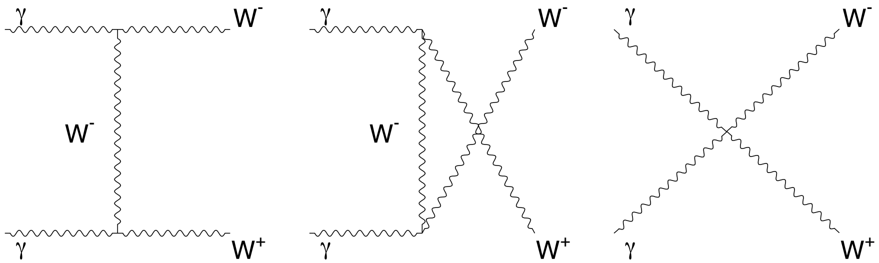
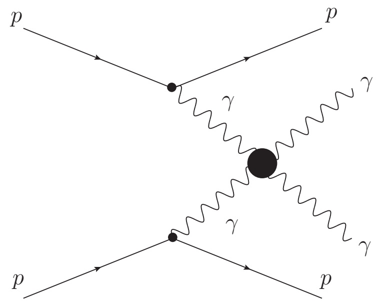
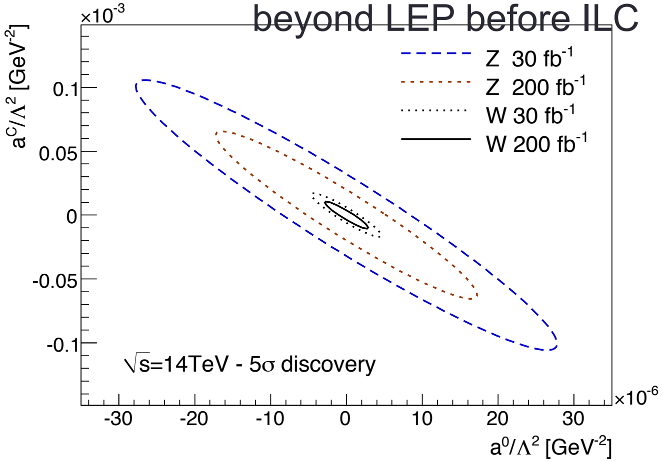


Strongly suppressed in SM



Orders of magnitude beyond LEP before ILC



PRD 81 074003 (2010)

$$\mathcal{L}_{4\gamma} = \zeta_1^\gamma F_{\mu\nu}F^{\mu\nu}F_{\rho\sigma}F^{\rho\sigma} + \zeta_2^\gamma F_{\mu\nu}F^{\nu\rho}F_{\rho\lambda}F^{\lambda\mu}$$

Luminosity	300 fb^{-1}	300 fb^{-1}	300 fb^{-1}	6000 fb^{-1}
pile-up (μ)	50	50	50	200
coupling (GeV^{-4})	$\geq$ 1 conv. γ 5 σ	$\geq$ 1 conv. γ 95% CL	all γ 95% CL	all γ 95% CL
ζ_1 f.f.	$1 \cdot 10^{-13}$	$7 \cdot 10^{-14}$	$4 \cdot 10^{-14}$	$2 \cdot 10^{-14}$
ζ_1 no f.f.	$3 \cdot 10^{-14}$	$2 \cdot 10^{-14}$	$1 \cdot 10^{-14}$	$6 \cdot 10^{-15}$
ζ_2 f.f.	$3 \cdot 10^{-13}$	$1.5 \cdot 10^{-13}$	$8 \cdot 10^{-14}$	$4 \cdot 10^{-14}$
ζ_2 no f.f.	$7 \cdot 10^{-14}$	$2 \cdot 10^{-14}$	$2 \cdot 10^{-14}$	$1 \cdot 10^{-14}$

arXiv.1312.5153

QCD MEASUREMENTS

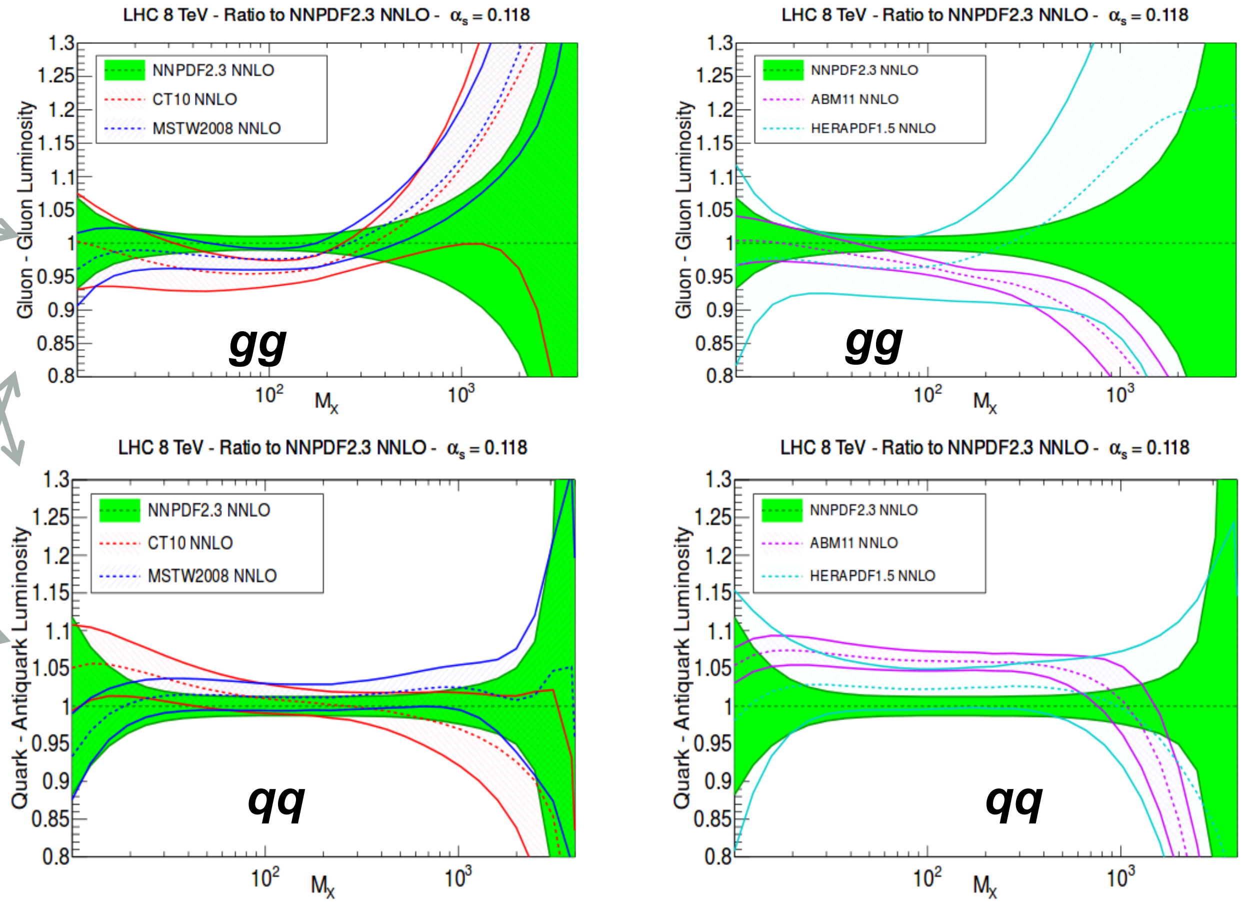
PDF: state of the art

- PDFs are the limiting factor in many predictions for hadronic colliders
  - $\sigma(gg \rightarrow H)$ has a ~ 8% uncertainty due to PDFs
  - m_W, $\sin^2(\theta_{eff})$,…
- LHC data starts to be used on top of HERA/Tevatron
  - NNPDF 2.3 (also add QED)

JHEP 1304, 125 (2013)

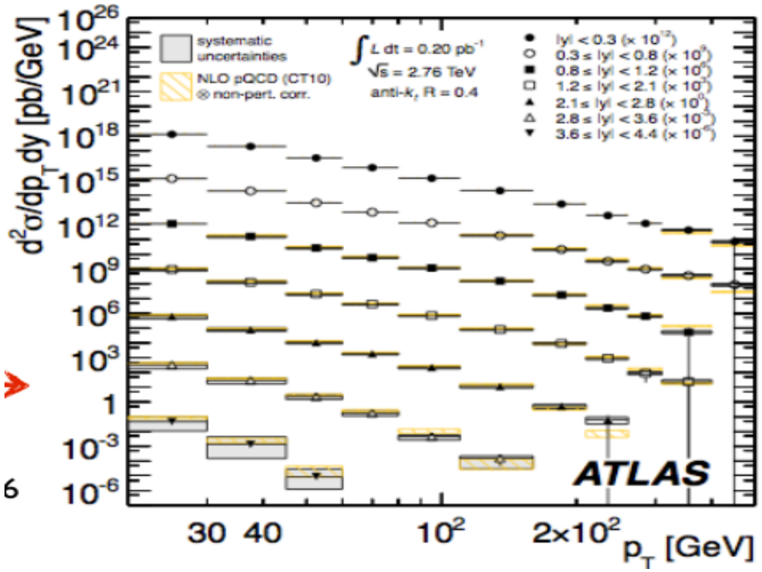
For ***gg*** luminosity not so good agreement in the region of the EW scale between GLOBAL PDF SET

- For ***qq*** luminosity quite good agreement in the region of the EW scale between GLOBAL PDF SET
- Uncertainty blow up for large-mass final states

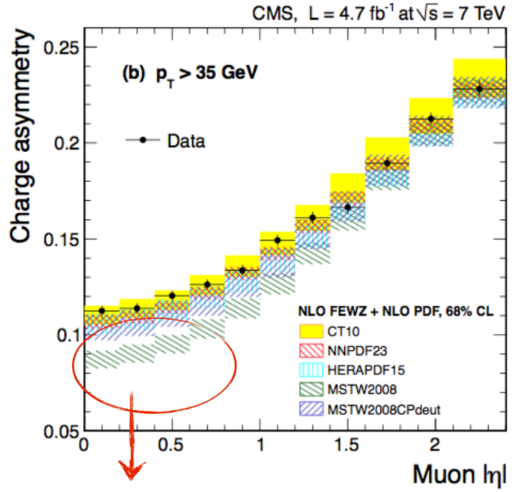


PDF: new inputs from LHC

- several new measurements available

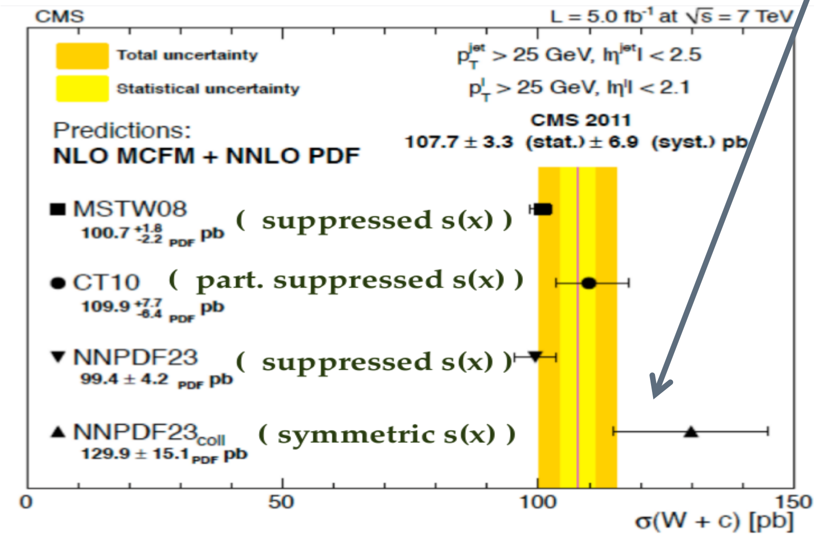


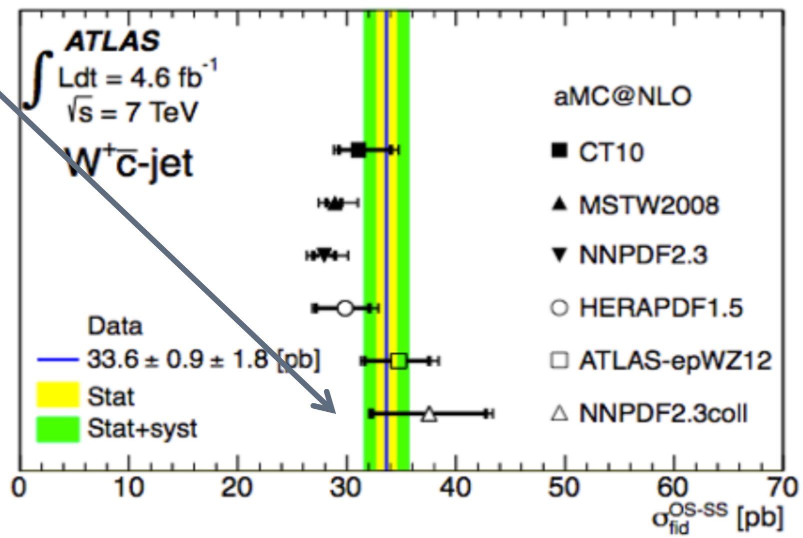
Jets cross section:
p_T < 800 GeV sensitive to gluon
p_T > 800 GeV sensitive to quark



W+c: sensitive to strange quark sea beyond DIS analyses
Different conclusions on s symmetry?

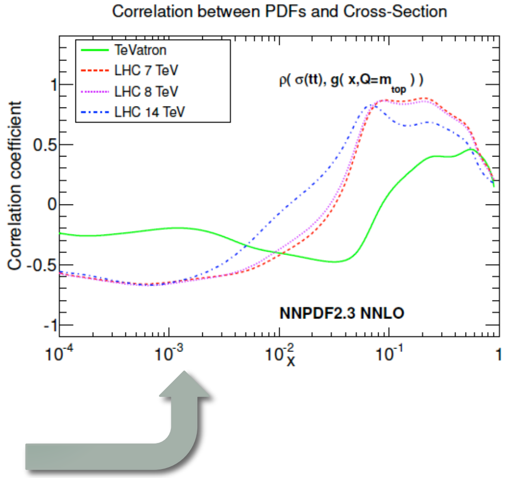
W charge asymmetry shows discrepancies with old PDFs
Sensitivity to valence quarks in $10^{-3} < x < 10^{-1}$ range





PDF: long(er) term wish list

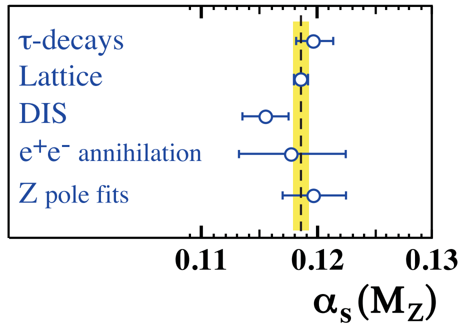
- LHC is enlarging the range of processes which can be studied (see PDF4LHC workshops)
  - Gluon PDFs at small x still dominated by HERA, but useful contributions can come on a wide range
    - Isolated photons, photons+jets: medium x gluons (QCD Compton scattering)
    - Vector bosons + jets (high p_T): small to medium x gluons (qg dominating at p_T > 100 GeV)
    - Low mass Drell-Yan: small x gluons (if resummed calculations available; LHCb particularly sensitive in its acceptance)
    - tt production (known at NNLO): large x gluons (important for high mass BSM)



  - Quark PDFs
    - Ratios of Ws and Z at high p_T : quark-antiquark separation (with small uncertainties)
    - High mass Drell-Yan: large x quarks (again high mass BSM would benefit)

The strong coupling constant

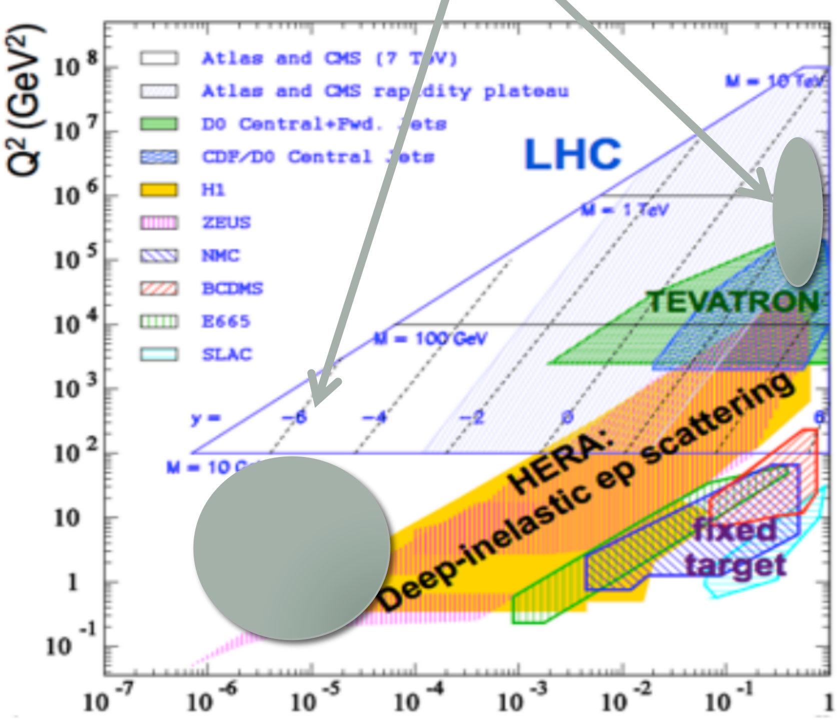
- Basic input of global EW fits and many predictions
  - E.g. H ➔ bb width
  - State of the art: $\alpha_S(M_Z) = 0.1185 \pm 0.0006$ (PDG 2013)
    - Driven by lattice precision
    - If $\delta_{lattice} \sim 0.0004$ can experimental determinations follow?

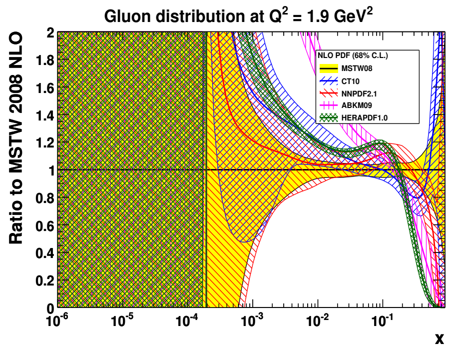


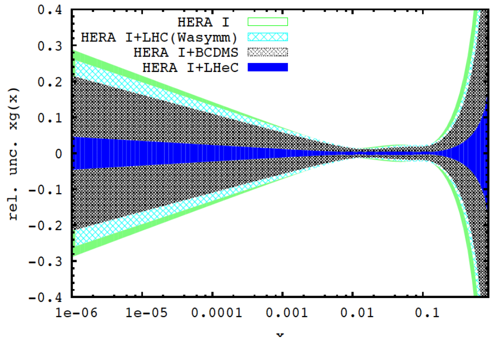
- Hadronic machines: NNLO σ(tt) is a powerful tool
  - CMS: $0.1178^{+0.0033}_{-0.0032}$
  - Further improvements expected by LHC with NNLO predictions, but hard to go below 1%
    - Still useful measurements at high Q^2, complementary to the bulk of determinations
- The most promising approach: $R_l=\Gamma(Z\rightarrow \text{hadrons})/\Gamma(Z\rightarrow ll)$ at GigaZ@ILC (0.0004) / TeraZ@TLEP (0.0001)
  - With the Higgs mass known the parametric uncertainty on α_S from R_l dominated by the experimental measurement
  - At TLEP also W branching ratios competitive
  - Other approaches at ~1%

PDF and α_S measurement potential from LHeC

- e(60 GeV) colliding on LHC protons
  - Very low x (10^{-6}) and high x – Q^2 (> 0.3, ~ 10^5) accessible, hot regions where gluon PDF is unconstrained by HERA







- Large improvements expected in both the low and high x range
- Complementary measurements would allow to disentangle all quark contributions
- α_S from NC – CC measurements at 0.2%
  - Theoretical NNNLO predictions uncertainty ~ 0.5%

J. Phys. G 39 075001 (2012)

Final remarks and hints for discussion

- The utility of the W/Z precision measurements depends on the scenario
  - If new physics directly discovered, they are a tool to characterize it
  - Otherwise they are a tool to probe regions kinematically inaccessible
  - m_W and $\sin^2(\theta_{eff})$ have different sensitivities to oblique corrections
- Boson couplings are sensitive to physics at high scales
  - Increasing both precision and energy allows to push sensitivity to new physics at higher scales
  - VV scattering study is a must, especially after the Higgs discovery
- The leptonic machines are preferable for the former, while hadronic machines look winning on QGC/VBS
- Hadronic machines require lots of ancillary QCD work to give the best results, both theoretical and experimental
  - PDFs first of all

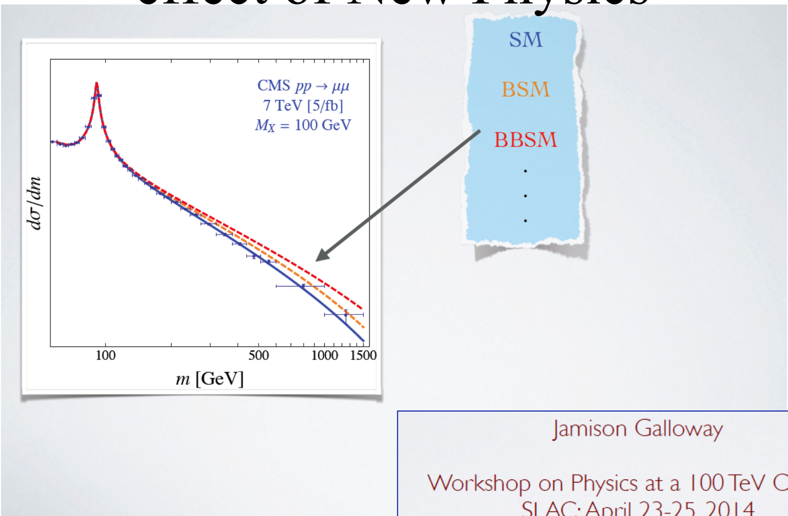
BACKUP

QCD higher order corrections

- State of the art: multi-body NLO predictions merged and matched with PS
- NNLO calculations are essential to reduce theoretical uncertainties
  - also in PDF analysis
- Up to last year, only small number of processes relevant for PDFs available at NNLO
- Recent important progress was made on some key processes
  - NNLO inclusive jet production in the gluon-gluon channel has been completed (arxiv: 1310.3993), jet data essential in PDF fits for gluons and large-x quarks
- In order to match the desired precision:
  - NNLO QCD 2 ➔ 2(3) often needed
    - σ(Higgs/W/Z) even NNNLO
  - At high energies EW and QCD corrections comparable, NLO EW needed: how to combine?
    - high p_T regions make predictions sensitive to EW already at 14 TeV
  - High jet multiplicities requires both NLO accuracies and higher order resummation
    - Geneva approach
  - NNLO + PS?

FCC-hh possibilities

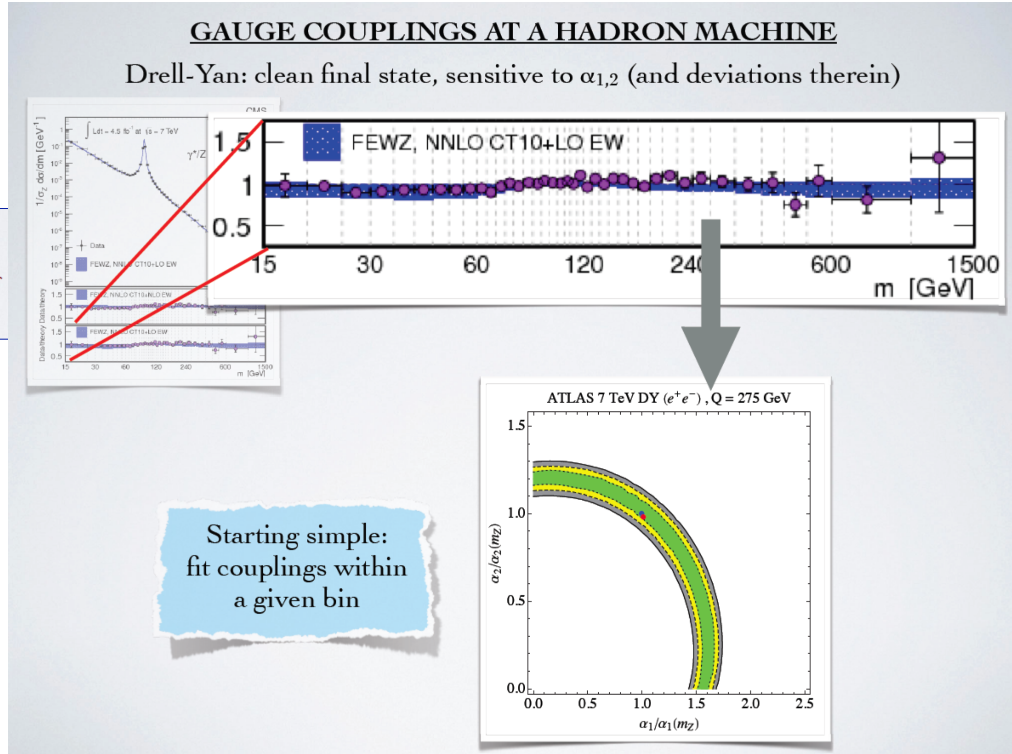
Coupling evolution in Drell Yan:
effect of New Physics



Jamison Galloway

Workshop on Physics at a 100 TeV Collider
SLAC: April 23-25, 2014

see R. Tenchini's talk

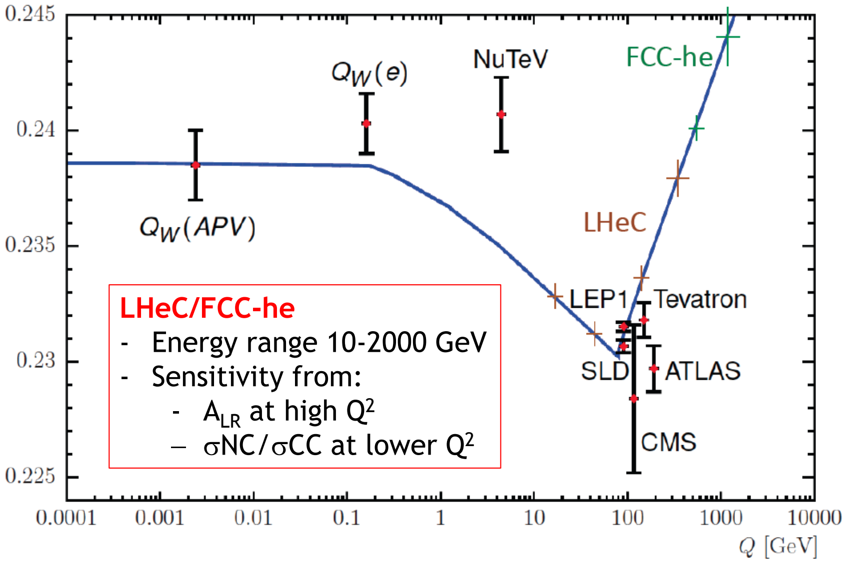


High energy regime allows to push studies in the far tails of distributions

$\sin^2(\theta_{eff})$ @ LHeC

Scale dependence of $\sin^2\theta_W$

- Preliminary sketch



See M. d'Onofio's talk

Electroweak Physics in ep (II)

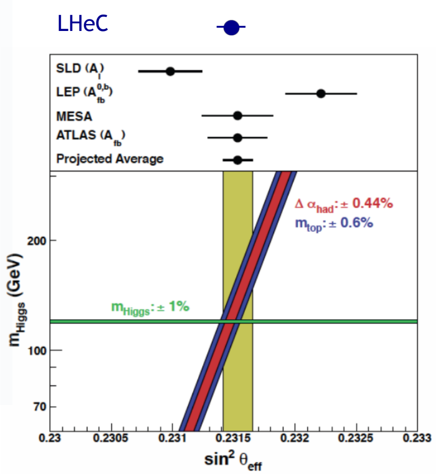
Polarisation Asymmetry A⁻(Q)

NC-to-CC Ratio R- for P=±0.8

Measure weak mixing angle redundantly with very high precision of about 0.0001 as a function of the scale.

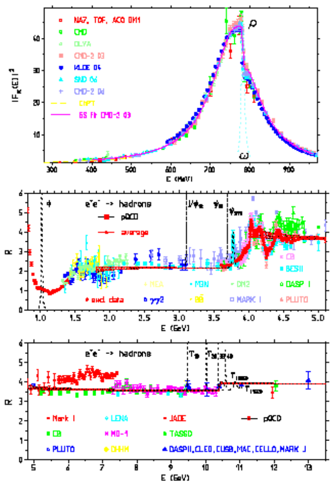
1% δM_{top} is about δ = 0.0001

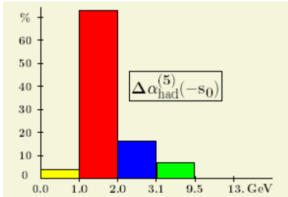
PDF uncertainty comes in at second order and ep provides very precise PDFs



$\alpha_{em}(M_Z)$ from e^+e^- for global fits

Hadronic contribution to $\alpha_{em}(M_Z)$ (Adler function)





$\delta^2\Delta\alpha^{(5)}_{had}(-s_0)$

Energy range	$\Delta\alpha^{(5)}_{had}$ [%](error) $\times 10^4$	rel. err.	abs. err.
ρ,ω $(E < 2M_K)$	32.45 [50.9](0.18)	0.6 %	7.2 %
$2M_K < E < 2$ GeV	13.90 [21.8](0.56)	4.1 %	68.7 %
2 GeV $< E < M_{J/\psi}$	6.06 [9.5](0.25)	4.2 %	13.8 %
$M_{J/\psi} < E < M_\Upsilon$	10.04 [15.7](0.22)	2.2 %	10.2 %
$M_\Upsilon < E < E_{cut}$	0.44 [0.7](0.02)	5.1 %	0.1 %
$E_{cut} < E$ pQCD	0.90 [1.4](0.00)	0.0 %	0.0 %
$E < E_{cut}$ data	62.89 [98.6](0.68)	1.1 %	100.0 %
total	63.79 [100.0](0.68)	1.1 %	100.0 %

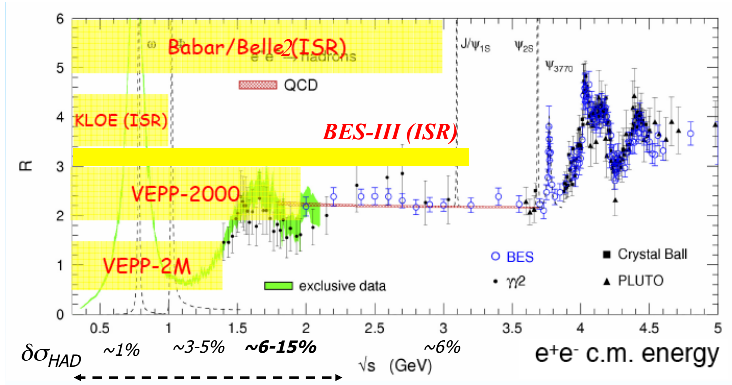
$$\Delta\alpha^{(5)}_{had}(M_Z^2) = 0.027498 \pm 0.000135$$

Courtesy of F. Jegerlehner

See G. Venanzoni's talk

Basic input for theoretical predictions both for EW global fit and muon g-2

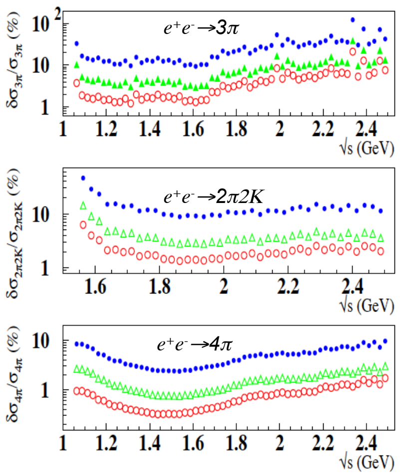
e^+e^- data into hadrons: current and future activities



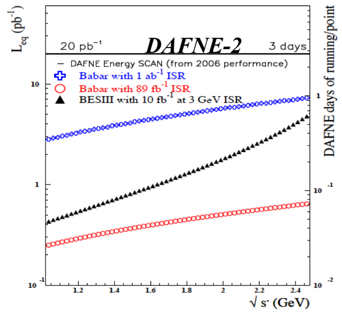
Possible Upgrade in energy of DAFNE

Impact of DAFNE-2 on exclusive channels in the range [1-2.5] GeV with a scan (Statistics only)

D. Babsuci et al, arXiv:1007.521



- *Published BaBar results: 89 fb^{-1} (ISR)*
- ▲ *"BaBar" × 10 (890 fb^{-1})*
- o *DAFNE-2 energy scan: 20 pb^{-1}/point @ L= 10^{32} cm^{-2} s^{-1}, 25 MeV bin ⇒ 1 year data-taking*



DAFNE-2 is ***statistically*** equivalent to 5÷10 ab^{-1} (Super)B-factory