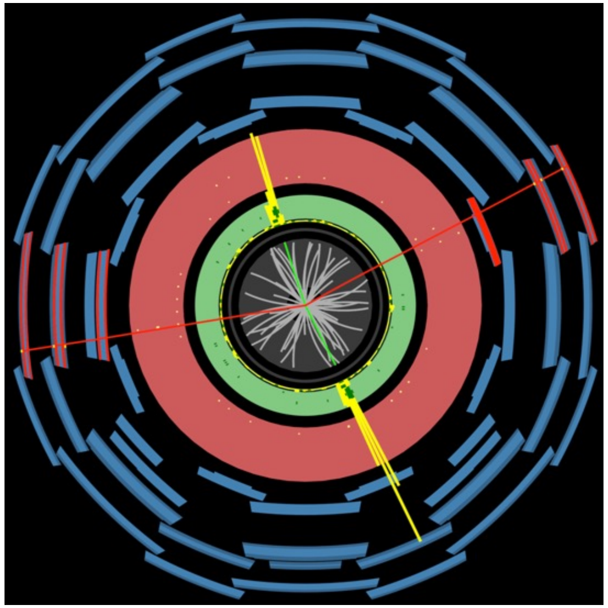
Higgs and Electroweak physics (II)

Les futurs collisionners et leur physique



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Higgs & EW physics part 2: Outline

Study of the gauge sector

★ **Z parameter measurements @ e^+e^- colliders ($\sqrt{s} \sim 91$ GeV)**

* M_Z , Γ_Z, σ^0_{had} , A^0_{FB}
* Energy calibration and luminosity measurements

★ **EW parameters measurements @ pp and $e^+ e^-$ colliders**

* $\sin^2 \vartheta_{eff}$
* $M_{W,} \Gamma_W$

★ **Diboson processes**

* Triple gauge couplings
* Vector boson scattering

The gauge sector of the Standard Model

Strength tensor of EW gauge bosons and of gluons

$D^{\mu}\,\gamma_{\mu} \equiv \not{D}^{\mu}$

$$\mathcal{L}_{gauge} = -\frac{1}{4}F^{a}_{\mu\nu}F^{a\,\mu\nu} + i\bar{\psi}\,\not{D}\psi$$

The gauge sector

$$D^{\mu} = \partial^{\mu} - igW_i^{\mu}\frac{\sigma^i}{2} - ig'\frac{Y\ (\psi)}{2}B^{\mu}$$

W_i, B = 4 vector fields

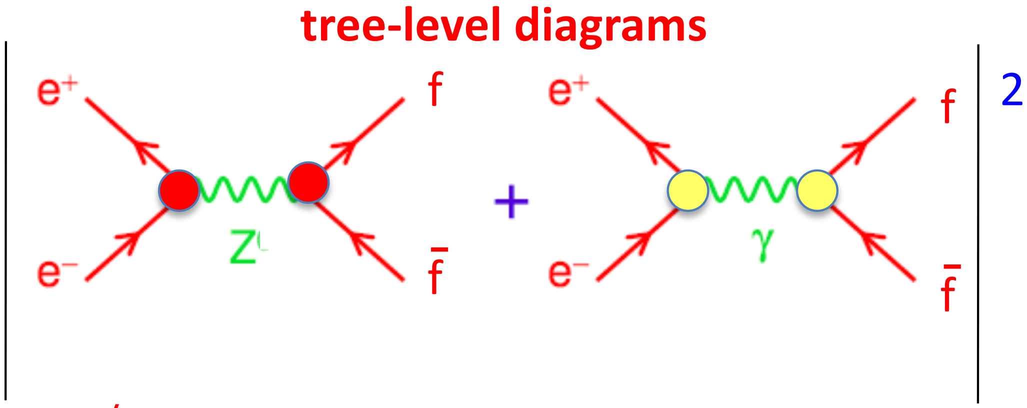
- Kinetic energy of gauge bosons (gluons and EW bosons)
- Give rise to boson self-couplings for **gluons** and **WEAK bosons**

- Kinetic energy of fermions and interactions between the fermions represented by spinor fields ψ and the gauge bosons
- Interactions from the invariance of the L under local gauge transformations of the fermion fields

In this lecture we treat the study of the interactions mediated by Z/γ, $W^{\pm}$

✓ **Motivation: we want to test the validity limits of SM**

Z parameter measurements @ e^+e^- colliders ($\sqrt{s} \sim 91$ GeV)



$$\bullet = -i \frac{g}{\cos\vartheta_W} \gamma^\mu \left(\frac{g_v^f - g_a^f \gamma_5}{2} \right)$$

g_V, $g_{A,}$ = Z couplings to fermions

$$g_v^f = T_f^3 - 2Q^f \sin^2\vartheta_W$$

$$g_a^f = T_f^3$$

T^3_f and Q^f : EW fermion quantum numbers

@ $\sqrt{s} = M_Z$:

$$\sigma^0_{\rm had} \equiv \frac{12\pi}{m_Z^2} \frac{\Gamma_{ee}\Gamma_{\rm had}}{\Gamma_Z^2}$$

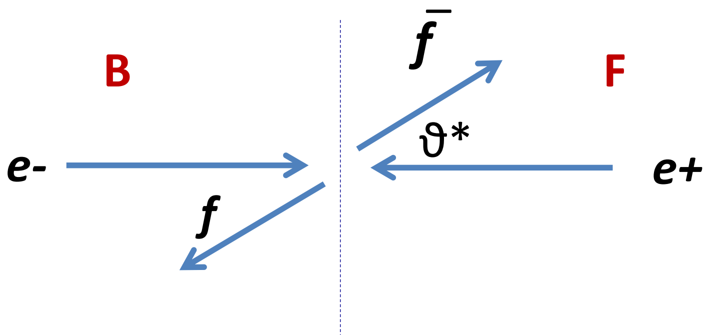
$$\Gamma_{Z\to ff} = N_c \frac{g_Z^2 M_Z}{48\pi} (g_V^2 + g_A^2)$$

$$g_V = (c_L - c_R)/2$$

$$g_A = (c_L + c_R)/2$$

$$R^0_\ell \equiv \Gamma_{\rm had}/\Gamma_{\ell\ell}$$

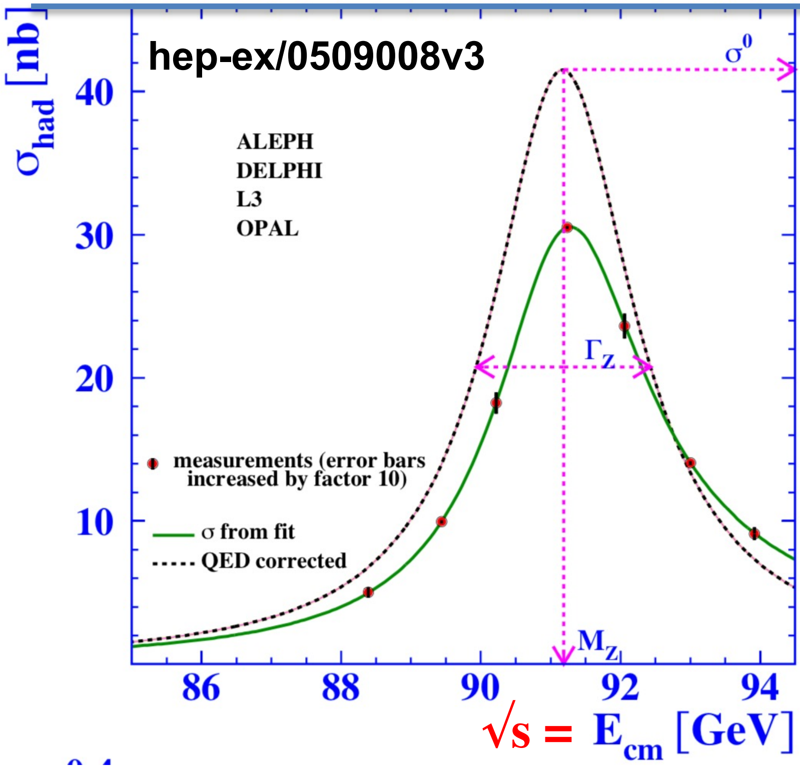
$$A_{FB} \equiv \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{4} A_e A_f$$



$$A_{e,f} = \frac{g_V * g_A}{(g_V^2 + g_A^2)}$$

- M_Z , Γ_Z, σ^0_{had} , A^0_{FB}

e^+e^- colliders @ $\sqrt{s} \sim 91$ GeV: $\sqrt{s}$ scan → M_Z, σ^0_{had}



* **M_Z is used as input to EW calculations**
  currently $\Delta M_Z \sim$ **2 MeV** (LEP)
* **@ future e^+e^- colliders very high statistics**:
  → Achieve precision well beyond LEP:
* Statistical uncertainty: **4 keV @** FCC-ee
* Dominant systematic:
  - o Absolute **beam energy** calibration (FCC-ee)
    resonant depolarisation: $\Delta\sqrt{s} \sim \Delta M_Z \sim$ **100 keV**
  - o Absolute momentum scale (LCF)
    $\Delta p \sim \Delta\, M_Z \sim$ **200 keV** with J/ψ mass ($K_S \to \pi\pi$)

* **σ^0_{had} peak cross-section**
* Sensitive to Zee coupling and total width Γ_Z, provides $N\nu$
* Limited by **luminosity** determination,
  $\delta L/L$ (Bhabha) ~ 10^{-4} (FCC-ee, LEP3, LCF)
  $e^+e^- \to \gamma\gamma \sim 2(4)\times10^{-5}$ (FCC-ee, LEP3)

$$\Gamma_Z = \sum_q \Gamma_{qq} + 3\,\Gamma_{ll} + N_\nu\, \Gamma_{\nu\nu}$$

$$\sigma^0_{had} \equiv \frac{12\pi}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{had}}{\Gamma_Z^2}$$

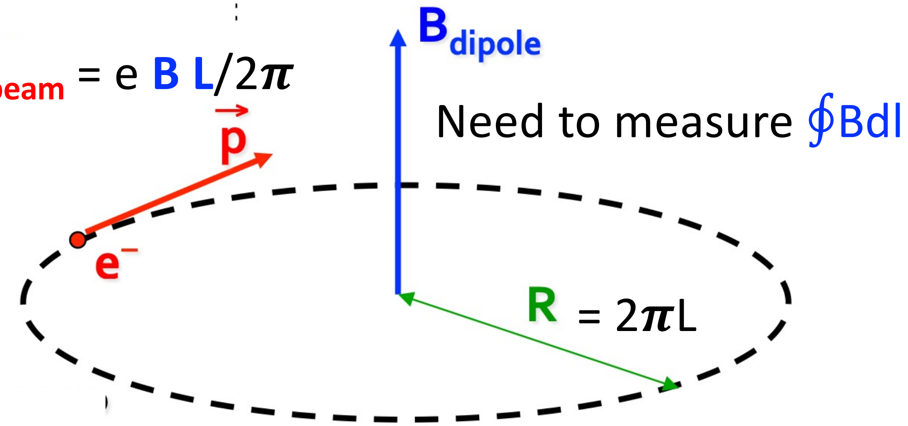
$$N_\nu \left(\frac{\Gamma_{\nu\nu}}{\Gamma_{\ell\ell}}\right)_{SM} = \left(\frac{12\pi}{m_Z^2}\frac{R^0_\ell}{\sigma^0_{had}}\right)^{\frac{1}{2}} - R^0_\ell - 3 - \delta_\tau$$

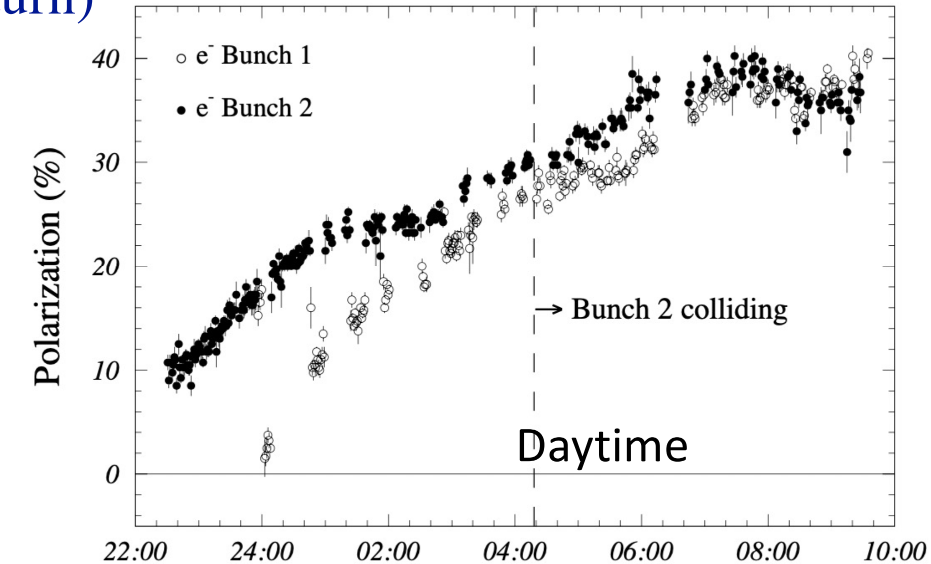
Absolute beam energy calibration @ e^+e^- colliders @ $\sqrt{s} \sim 91$ GeV)

P. Janot

- $\sqrt{s}$ calibration from spin tune (ν_s) measurements via **resonant depolarisation** (spin tune = number of precessions per turn)

$p \sim E_{beam} = e\,B\,L/2\pi$

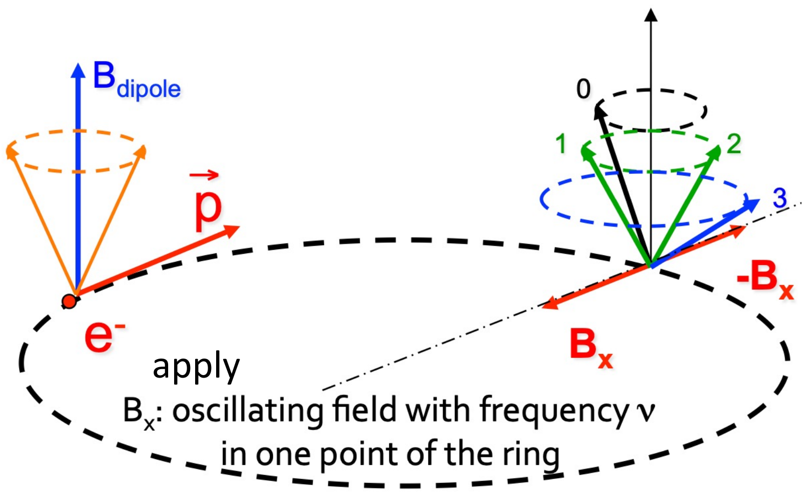


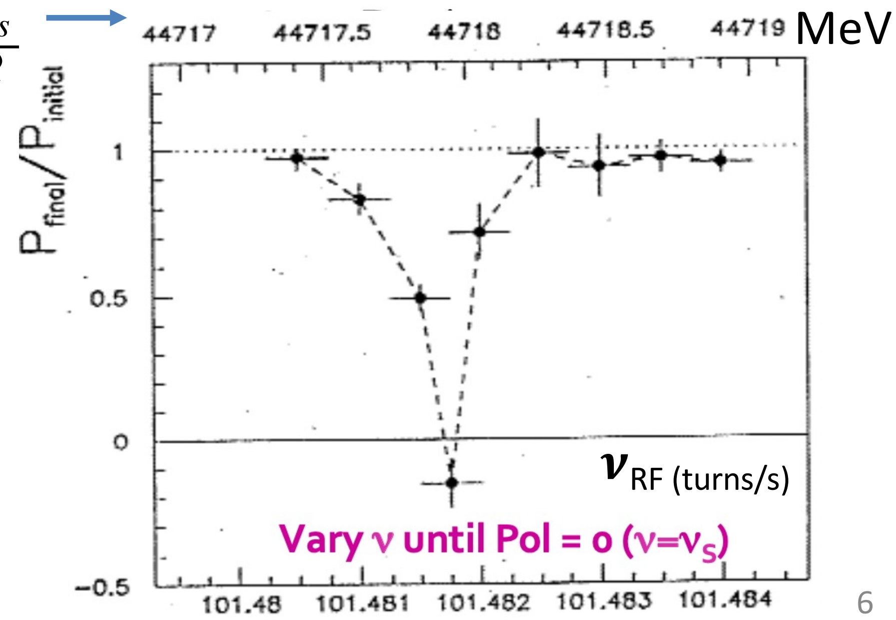


Precession frequency ν_s proportional to B

To mesure $\nu_s \rightarrow$ apply RF e.m. field

$$\frac{E_{beam}}{m_e} = \frac{2}{g_e - 2}\nu_s$$



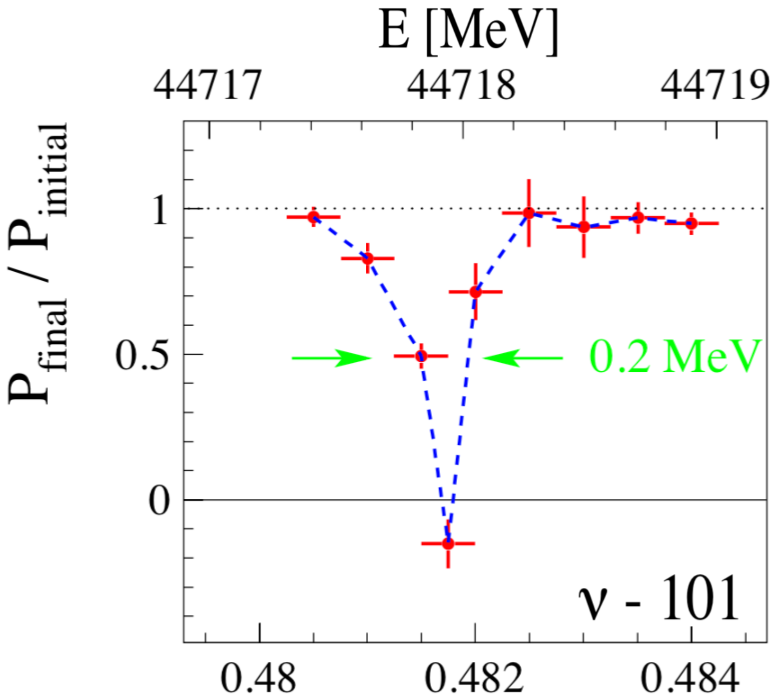


Absolute beam energy calibration @ e^+e^- colliders

- Common uncertainty across experiments
- √s calibration from spin tune (ν_s) measurements via **resonant depolarisation**

$$\frac{E}{m_e} = \frac{2\ \nu_s}{g_e - 2}$$

- Control of √s uncertainties essential for precision on $\mathbf{M_Z}$, Γ_Z , A_{FB}



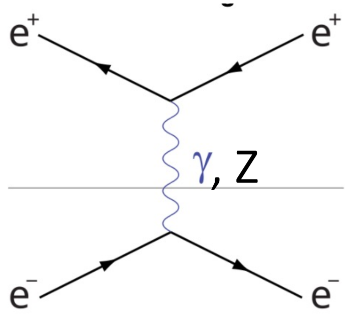
hep-ex/0509008v3

Origin of correction (approx. errors)	Error on m_Z [MeV]	Γ_Z [MeV]
Energy measurement by resonant depolarisation	0.4	0.5
Mean fill energy, from uncalibrated fills	0.5	0.8
Dipole field changes	1.7	0.6
Tidal deformations	0.0	0.1
e^+ energy difference	0.2	0.1
Bending field from horizontal correctors	0.2	0.1
IP dependent RF corrections	0.4	0.2
Dispersion at IPs	0.2	0.1

- Impact on EWPO uncertainty also from beam energy spread: δE
- @ FCC : δE increases wrt LEP and may fluctuate (beamstrahlung)
  Measured with $e^+e^- \rightarrow \mu^+\mu^-$ (5') (arXiv:1812.01004)

Luminosity measurement L @ e^+e^- colliders

- Luminosity **L** from **small-angle** Bhabha-scattering



$$L = \frac{dN}{d(\cos\theta)} \Big/ \frac{d\sigma}{d(\cos\theta)}$$

measure (counting) **theory**

$$\sigma = \frac{16\pi\alpha^2}{s}\left(\frac{1}{\theta^2_{\min}} - \frac{1}{\theta^2_{\max}}\right)$$

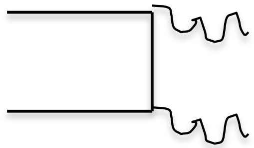
- **L** uncertainty important for σ^0_{had}
  (@LEP after combination contributes to ~ half its total error)

- Main experimental error on **L** :
  Definition of geometrical acceptance (use of special methods, or W mask)

- Theory error is the biggest single contribution (≈ 0.5‰ @ LEP)

- Total error @LEP : **ΔL/L ~ 10^{-3}** (ADL)
  (reanalysis 1908.01704 beam-beam effect: 10^{-3} bias)

- **@ FCC-ee** (1812.01004) (use also ee->γγ):
  ΔL/L: absolute ~ **10^{-4}** (→ reduction of factor 8 on ΔN_ν)
  ΔL/L: **√s** point-to-point **5×10^{-5}** (relevant for Γ_Z)



Z total width : Γ_Z @ e^+e^- colliders ($\sqrt{s} \sim 91$ GeV)

* **Z total width, Γ_Z** , sensitive to fermion couplings and to BSM

In SM

$\Gamma_Z = \sum_f \Gamma_{Z\to ff}$

At tree level:

$$\Gamma_{Z\to ff} = N_c \frac{g_Z^2 M_Z}{48\pi} (g_V^2 + g_A^2)$$

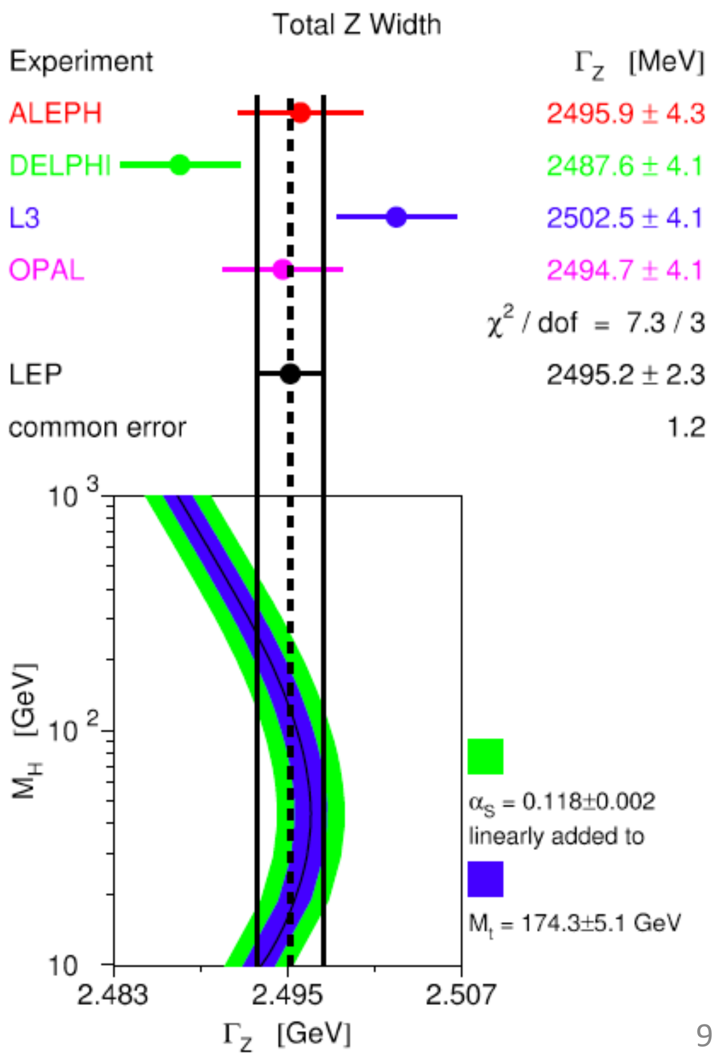
* Dependence on α_s, M_t, M_H through radiative corrections

* Currently **$\Delta\Gamma_Z \sim 2$ MeV**

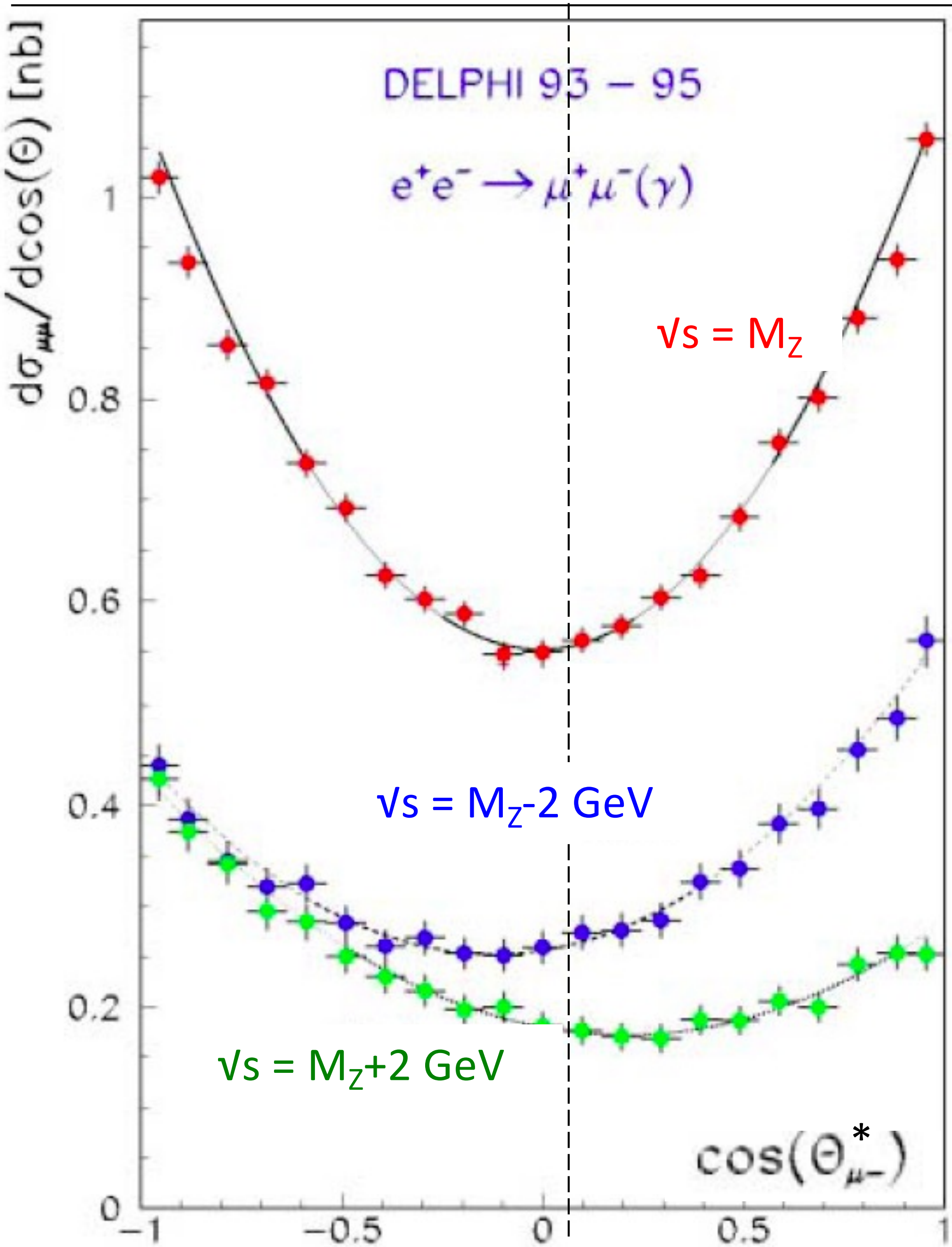
* Dominant systematic:

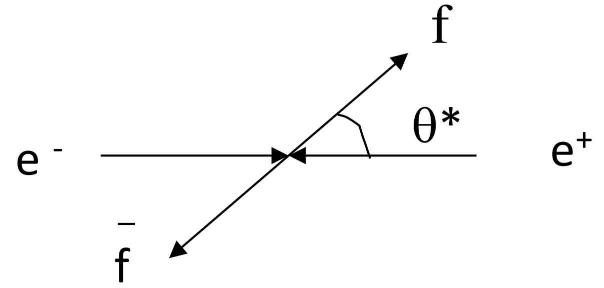
$\Delta\sqrt{s}$: point-to-point and absolute energy calibration can be measured in-situ with $\mu\mu$ events

$\Delta\Gamma_Z \sim 12$ keV @ FCC-ee



Z Forward-Backward (FB) Asymmetry (here in μ channel)





√s = M$_Z$

$$\frac{d\sigma}{d\cos\theta^*} \propto (g_v^{e\,2} + g_a^{e\,2})(g_v^{\mu\,2} + g_a^{\mu\,2})(1+\cos^2\theta^*) + 8\, g_v^e g_a^e g_v^\mu g_a^\mu \cos\theta^*$$

✷ Origin : parity violation in neutral weak interactions

$$\frac{d\sigma}{d\cos\theta^*} \propto (1+\cos^2\theta^* + \tfrac{8}{3} A_{FB}^{0,\mu} \cos\theta^*)$$

~ 2%

A_{FB}^0= Asymmetry @ peak

Asymmetries in Z final states

--> dependence on $\sin^2\vartheta_W$

Asymmetries @ √s = 91 GeV

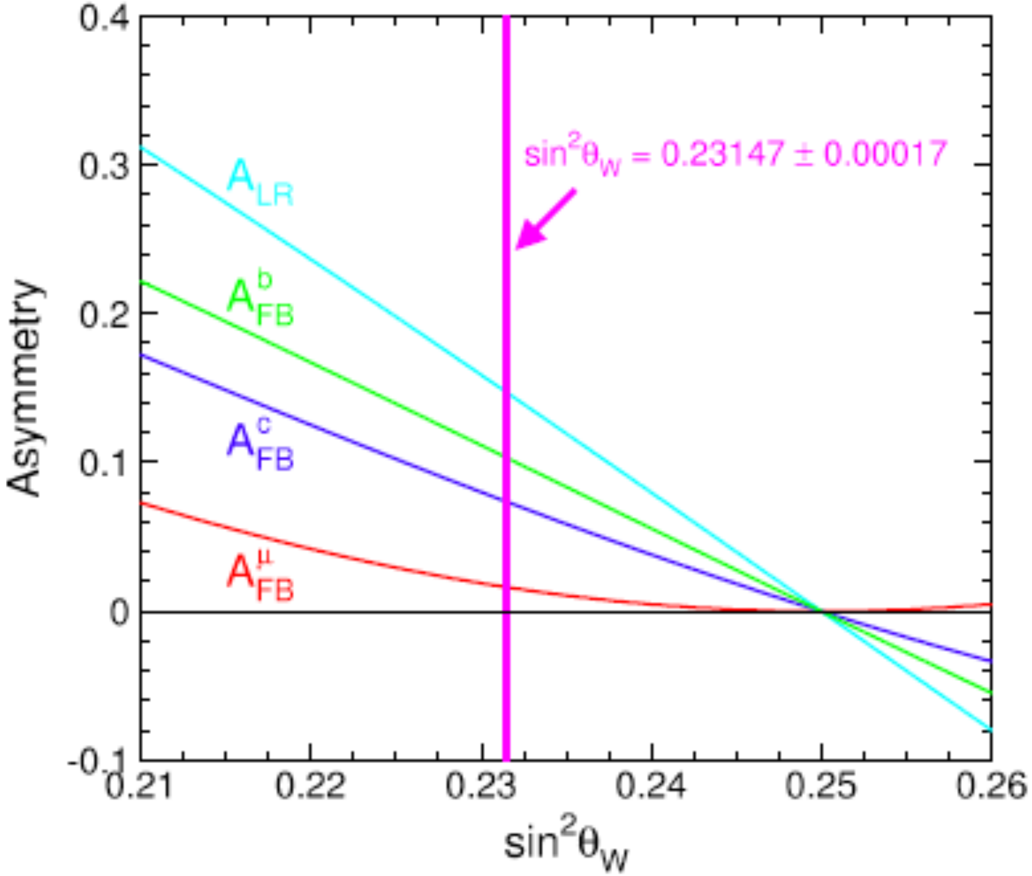
forward-backward

$$A_{FB} \equiv \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{4} A_e A_f$$

Left-right Beam polarization

$$A_{LR} \equiv \frac{\sigma(e_L) - \sigma(e_R)}{\sigma(e_L) + \sigma(e_R)} = A_e$$

$$\mathcal{A}_f = 2\frac{g_{Vf}/g_{Af}}{1 + (g_{Vf}/g_{Af})^2} = \frac{g_{Lf}^2 - g_{Rf}^2}{g_{Lf}^2 + g_{Rf}^2}$$



Asymmetries can be converted in a measurement of $\sin^2 \vartheta_W$

A_{LR} gives the largest asymmetry and greatest sensitivity (high slope)

Polarisation easier @ linear collider to work with polarised the beams

EW parameter: $\sin^2 \vartheta_{eff}^{lep}$ @ pp colliders ($\sqrt{s} \sim 91$ GeV)

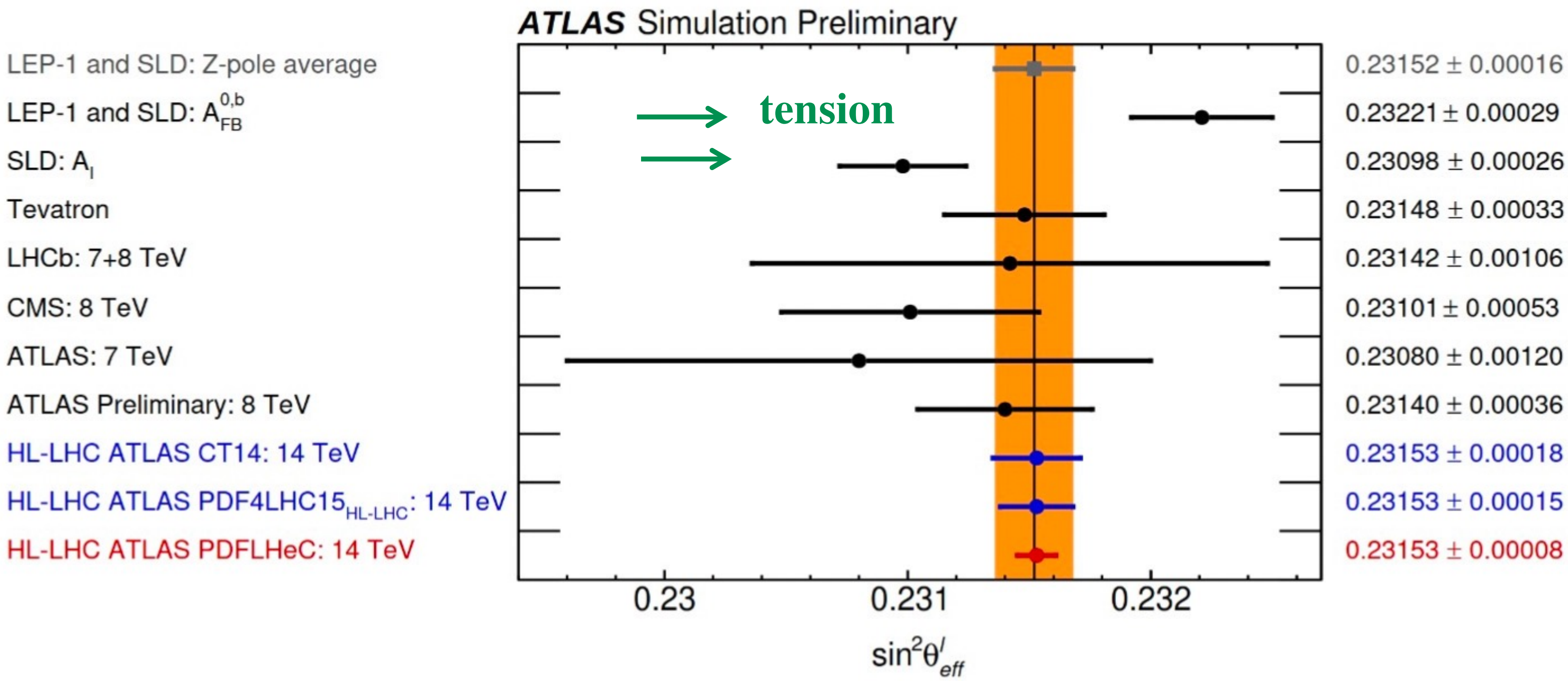
- **Tension between the most sensitive results**

$$\sin^2_{\rm eff}\theta_W = \left(1 - \frac{m_W^2}{m_Z^2}\right)\kappa$$

e.w. corrections

@ $p\overset{(-)}{p}$ colliders :

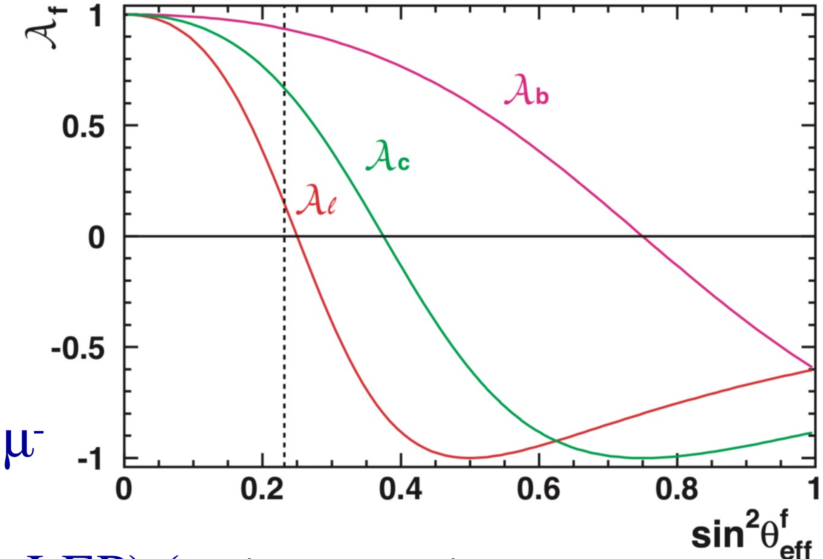
* **Forward Backward Asymmetry** (**A_{FB}**) in $q\bar{q} \rightarrow Z (\rightarrow ll)$
* Angular decomposition of the cross-section $q\bar{q} \rightarrow Z/\gamma* \rightarrow ll$
* Parton Distribution Function (PDF) source of main systematics
* Prospects for reaching LEP+SLD uncertainty **at the end of HL-LHC**



Extraction of $\sin^2\vartheta_{eff}^{\ell}$ @ e^+e^- circular colliders ($\sqrt{s}\sim 91$ GeV)

* **e^+e^- colliders** unique power for $\sin^2\vartheta_{eff}$ determination @ M_Z

$$A_{FB}^{0,f} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f \qquad \mathcal{A}_f = 2\frac{g_{Vf}/g_{Af}}{1+(g_{Vf}/g_{Af})^2}$$



@ LEP A_F asymmetries used to extract $\sin^2\vartheta_{eff}$

$$\sin^2\theta_{eff}^{f} = 0.23153 \pm 0.00016$$

* **@FCC** → extraction of $\sin^2\vartheta_{eff}^{\ell}$ from $e^+e^- \to \mu^+\mu^-$
assuming lepton universality
Uncertainty ~ 5 *10^{-6} (factor ~ 30 smaller wrt LEP) (main uncertainty point-to-point energy error)

* Using **τ polarisation** measurement avoids assumption on lepton universality

$$\mathcal{P}_\tau \equiv \frac{d(\sigma_r-\sigma_l)}{d\cos\theta}\Big/\frac{d(\sigma_r+\sigma_l)}{d\cos\theta} = -\frac{\mathcal{A}_f(1+\cos^2\theta)+2\mathcal{A}_e\cos\theta}{(1+\cos^2\theta)+2\mathcal{A}_f\mathcal{A}_e\cos\theta}$$

(ν_τ flies in the same (opposite) direction as τ for L(R) in the τ center-of-mass)

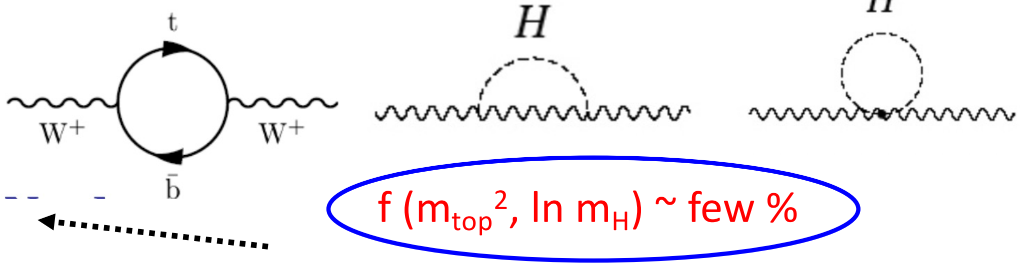
@ LEP several τ decay modes were used. Main uncertainties: from τ BR and hadronic τ decay modelling

→ @FCC use $\tau \to \rho\nu$ Uncertainty on $\sin^2\vartheta_{eff} \sim 6.6*10^{-6}$

M_W measurement : probe BSM via electroweak precision tests

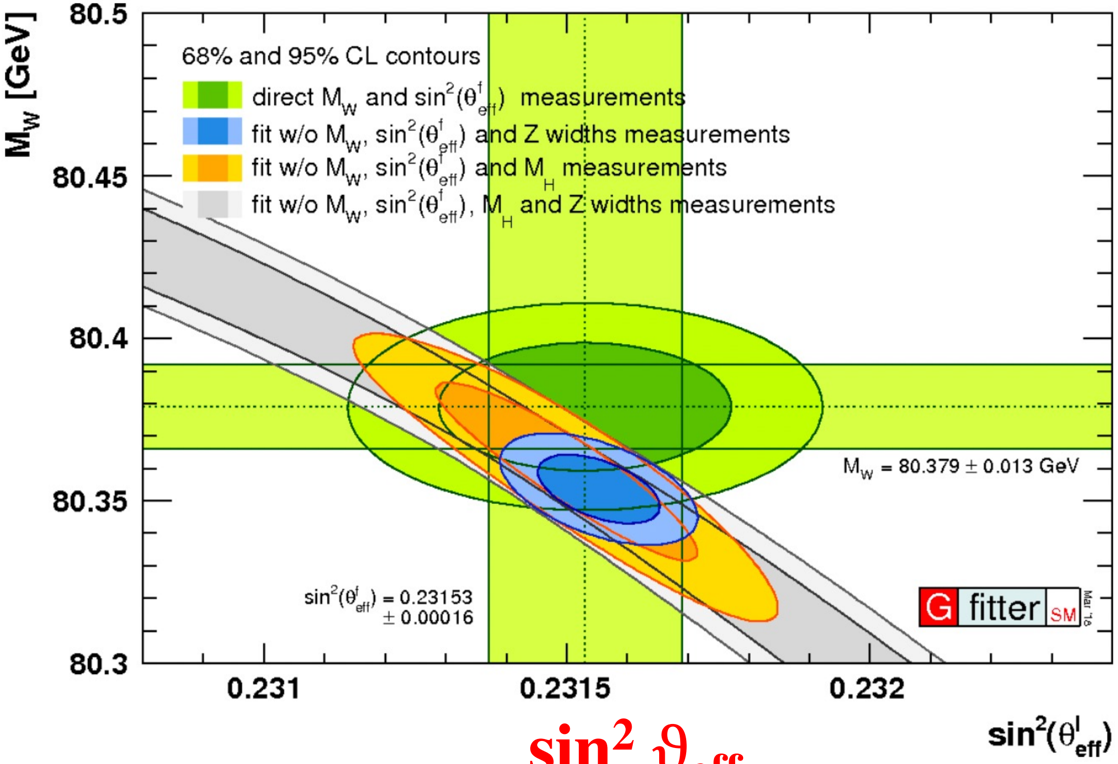
* Comparing indirect to direct M_W measurement tests SM internal consistency
→ BSM probe

$$M_W = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F}}\frac{1}{\sin\theta_W\sqrt{1-\Delta r}}$$



f (m_{top}^2, ln m_H) ~ few %

M_W



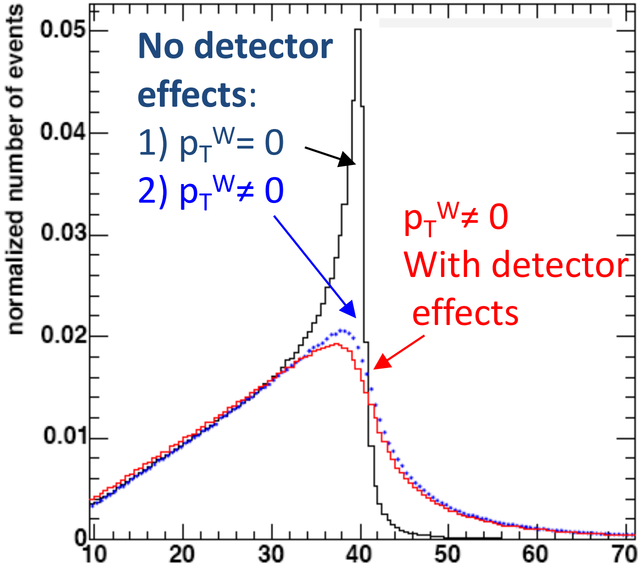
$\sin^2 \vartheta_{eff}$

* Current results consistent with the SM relations

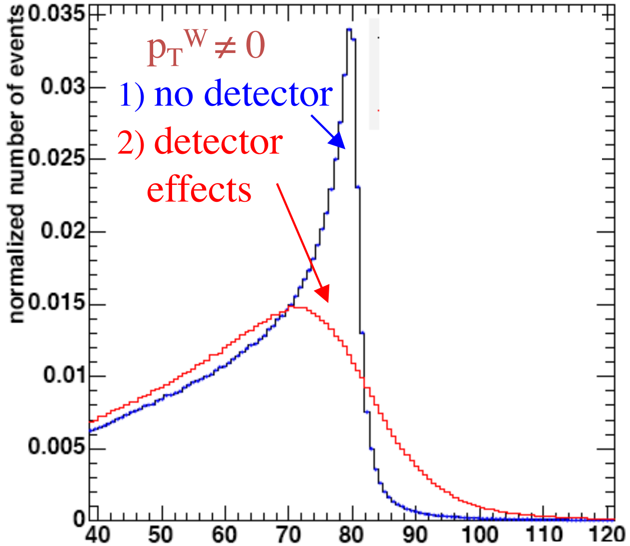
M_W measurement @ pp colliders

* Use W leptonic decays with **μ** or **e** $pp \to W \to \ell\nu$

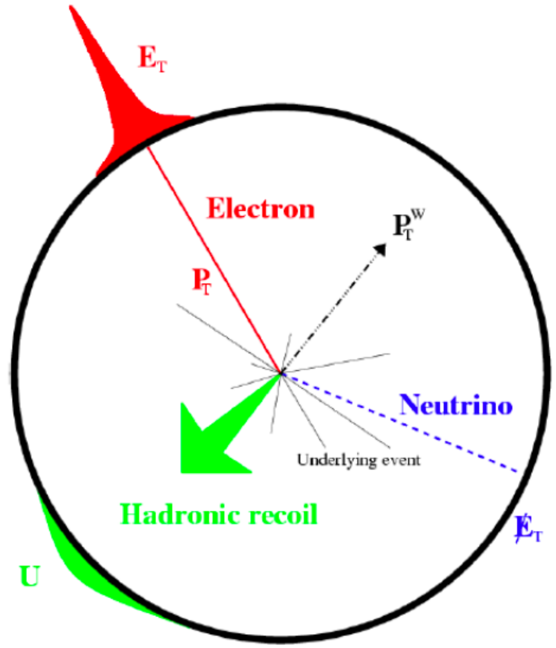
* Two main (**complementary**) variables sensitive to M_W



p_T^{lep}(GeV)



M_T^W (GeV) $= \sqrt{2 p_T^{\ell} p_T^{\nu} (1 - \cos\Delta\phi(\ell,\nu))}$



* **p_T^{lep}** more dependent on physics modelling

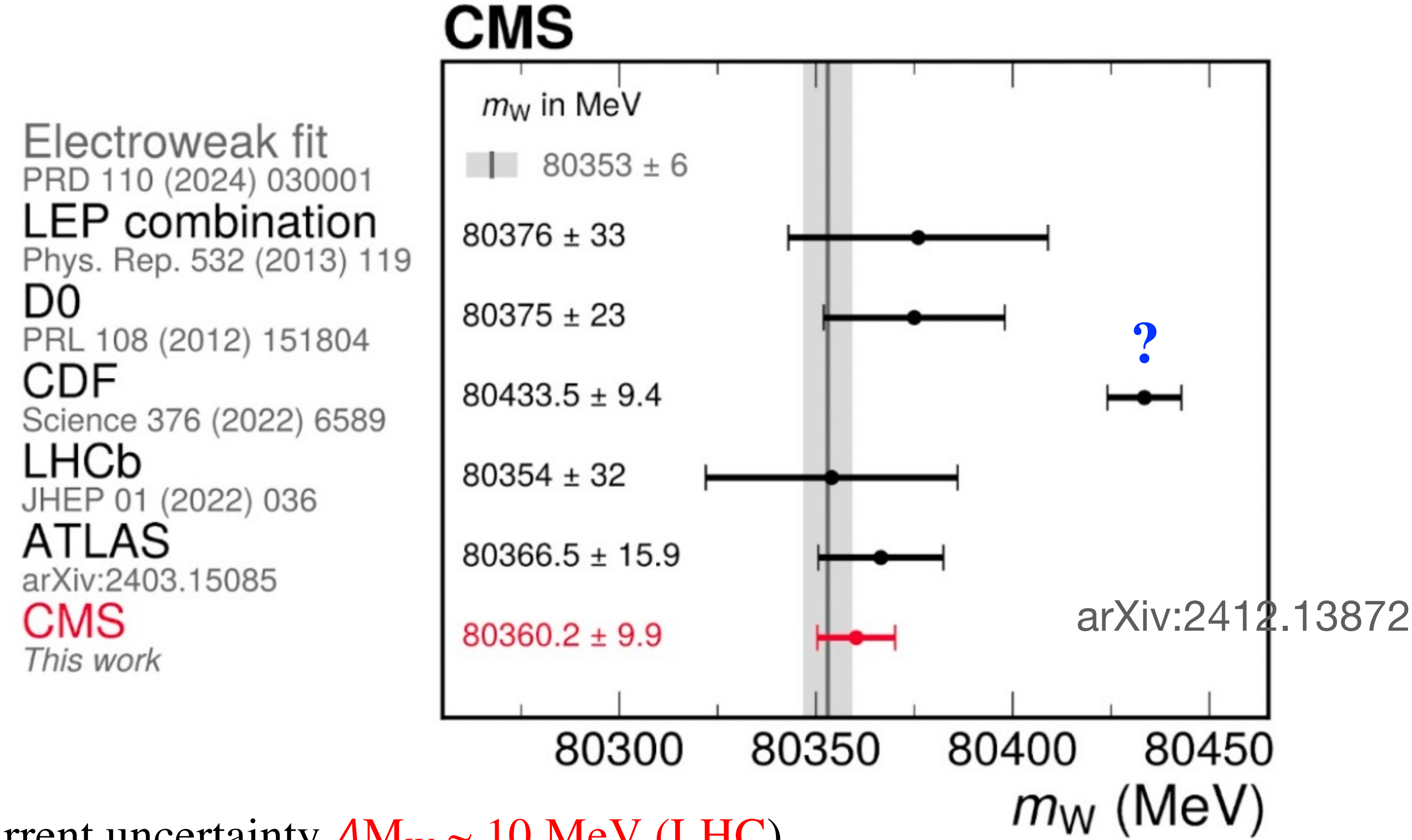
* **M_T^W** degrades at high pile-up, but less dependent on modelling

Challenges:

Ultra-precise detector calibration ~ 10^{-4}

Accurate theory predictions

M_W measurements



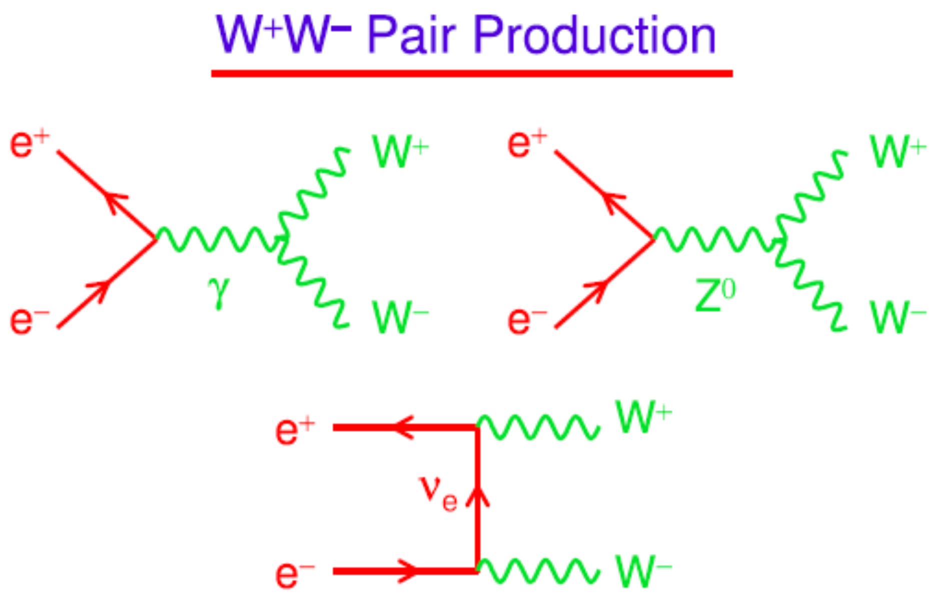
Current uncertainty $\Delta M_W \sim 10$ MeV (LHC)

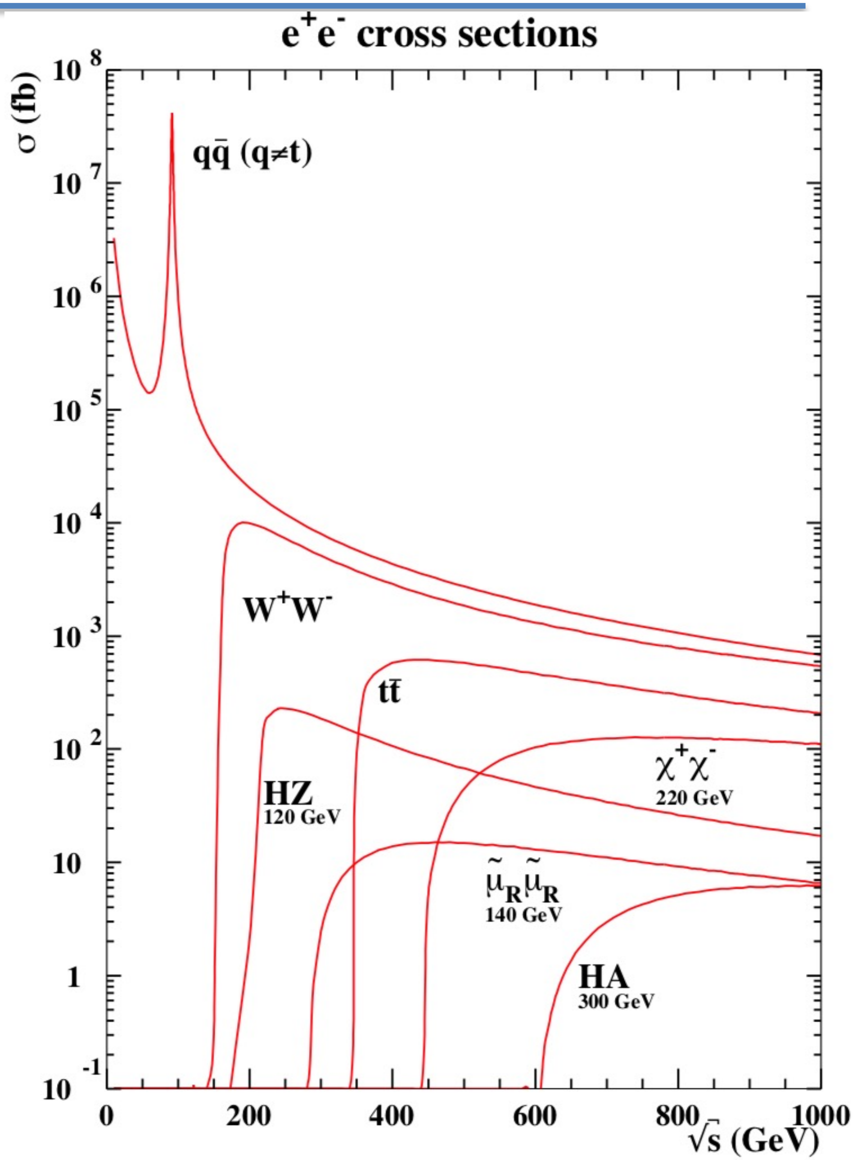
- @ p$\overset{(-)}{p}$ colliders: PDF main source of systematics (followed by QCD modelling)

$\Delta M_W^{HL\text{-}LHC} \sim 5 \div 10$ MeV **($\Delta M_W^{PDF} \sim 2$ MeV with LHeC)**

Measurements of M_W @ e^+e^- colliders

* **e^+e^- colliders** have a unique power to measure directly $\mathbf{M_W}$





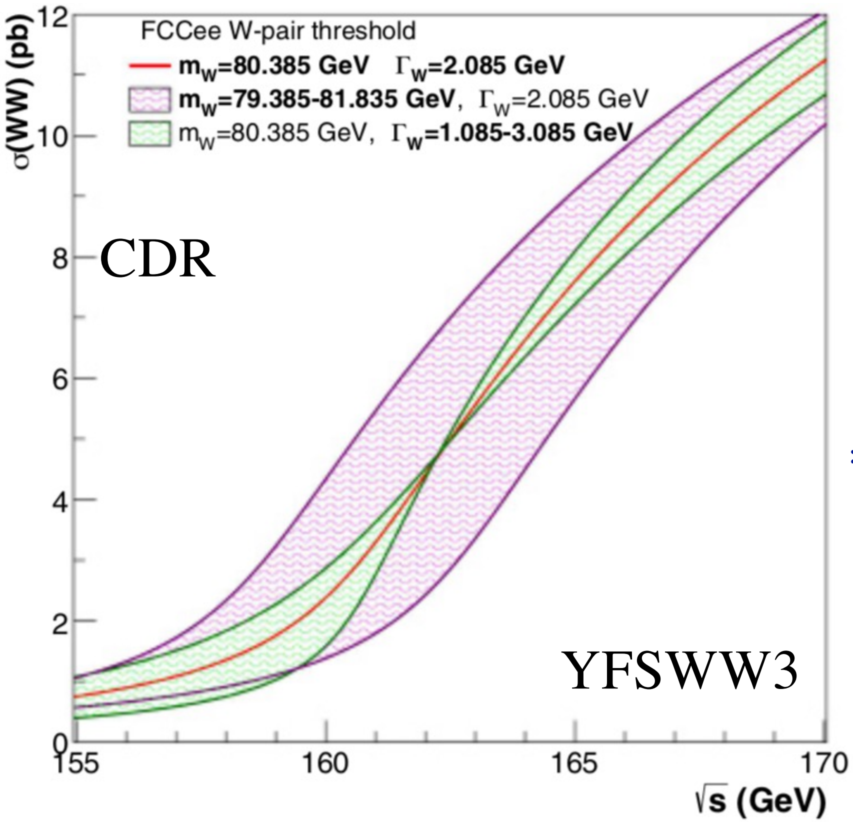
Two approaches:

1. Measurements at WW threshold

2. Direct reconstruction of the W mass (+ **kinematic fit**)

Measurements of M_W @ WW threshold(@ e^+e^- colliders)

* Scan : cross-section vs. beam energy
* Best sensitivity @ $\sqrt{s} \sim 162.3$ GeV where dependence on $\Gamma_W \sim$ vanishes



* With 2 or more energy points measure mass M_W and width Γ_W simultaneously

  $\Delta M_W^{stat} \sim 400$ keV (FCC-ee)

  $\Delta\Gamma_W^{stat} \sim 1$ MeV (FCC-ee)

* Dominant systematics

  absolute beam energy calibration

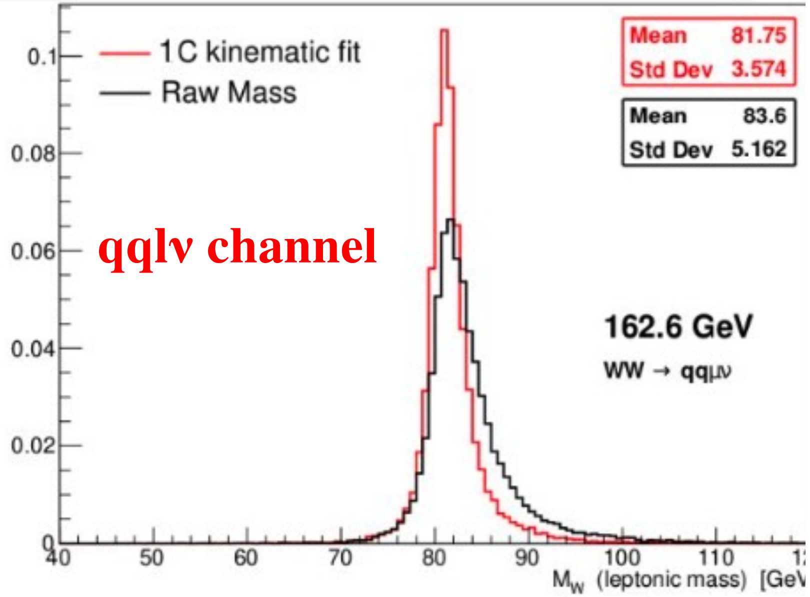
* Assuming 300 keV on $\sqrt{s}$ with resonant depolarisation

  $\Delta M_W^{syst} \sim 150$ keV (FCC-ee)

→ With 12 ab^{-1} : $\Delta M^{tot}_W \sim 0.5$ **MeV** within reach

Direct Measurements of M_W (@ e^+e^- colliders)

@ $\sqrt{s}$ ~160 GeV (WW threshold) & $\sqrt{s}$ ~ 240 GeV



* **M_W** through direct reconstruction of decay products **with kinematic fit**(as in LEP2)

* Best sensitivity from the **WW → qqlν channel**

★ Avoid issues with **color reconnection**

★ Allows to fully resolve the neutrino kinematics in the **kinematics fit** (4-3 = 1 constraint)

★ Use also the constraint that W masses are equal (2C fit)

★ Dominant systematics :

Absolute energy and beam energy scale calibration

Hadronization

Observable	present value	±	present uncertainty	FCC-ee Stat.	FCC-ee Syst.	Comment and leading uncertainty
m_Z (keV)	91 187 600	±	2000	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2 495 500	±	2300	**4**	12	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}$ ($\times 10^6$)	231,480	±	160	**1.2**	1.2	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)$ ($\times 10^3$)	128 952	±	14	**3.9** **0.8**	small tbc	From $A_{FB}^{\mu\mu}$ off peak From $A_{FB}^{\mu\mu}$ on peak QED&EW uncert. dominate
R_ℓ^Z ($\times 10^3$)	20 767	±	25	**0.05**	0.05	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_S(m_Z^2)$ ($\times 10^4$)	1 196	±	30	**0.1**	1	Combined R_ℓ^Z, Γ_{tot}^Z, σ_{had}^0 fit
σ_{had}^0 ($\times 10^3$) (nb)	41 480.2	±	32.5	**0.03**	0.8	Peak hadronic cross section Luminosity measurement
N_ν($\times 10^3$)	2 996.3	±	7.4	**0.09**	0.12	Z peak cross sections Luminosity measurement
R_b ($\times 10^6$)	216 290	±	660	**0.25**	0.3	Ratio of $b\bar{b}$ to hadrons
$A_{FB}^{b,0}$ ($\times 10^4$)	992	±	16	**0.04**	0.04	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1 498	±	49	**0.07**	0.2	τ polarisation asymmetry τ decay physics
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.005	ISR, τ mass
τ mass (MeV)	1 776.93	±	0.09	**0.002**	0.02	estimator bias, ISR, FSR
τ leptonic ($\mu\nu_\mu\nu_\tau$) BR (%)	17.38	±	0.04	**0.00007**	0.003	PID, π^0 efficiency
m_W (MeV)	80 360.2	±	9.9	**0.18**	0.16	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2 085	±	42	**0.27**	0.2	From WW threshold scan Beam energy calibration
$\alpha_S(m_W^2)$ ($\times 10^4$)	1 010	±	270	**2**	2	Combined R_ℓ^W, Γ_{tot}^W fit
N_ν ($\times 10^3$)	2 920	±	50	**0.5**	small	Ratio of invis. to leptonic in radiative Z returns

Many measurements (top measurement not included)

Systematic projections should be intended as targets for detectors/th. calculations

Study of multiboson processes. Why ?

Because it allows us to study this piece of the e.w. SM lagrangian(*) :

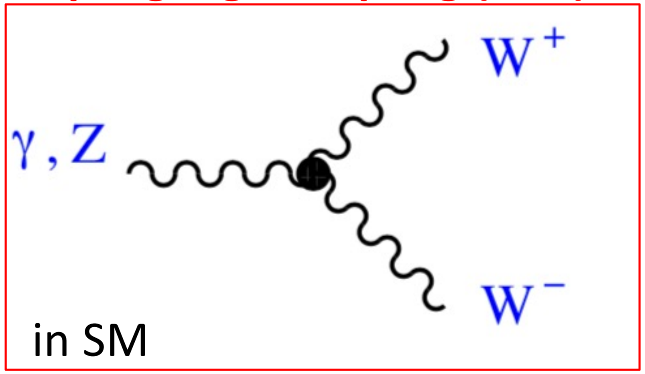
$$\mathcal{L}_{\rm Kin} = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W^i_{\mu\nu} W_i^{\mu\nu}$$

i =1,2,3

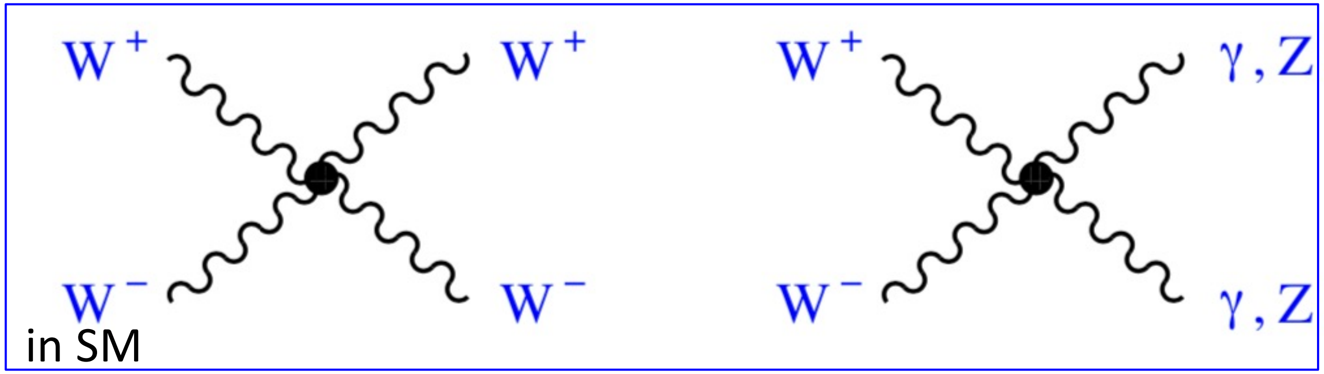
$$B_{\mu\nu} \equiv \partial_\mu B_\nu - \partial_\nu B_\mu$$

$$W^i_{\mu\nu} = \partial_\mu W^i_\nu - \partial_\nu W^i_\mu - g\,\epsilon^{ijk}\, W^j_\mu W^k_\nu$$

Triple gauge coupling (TGC)



Quartic GC



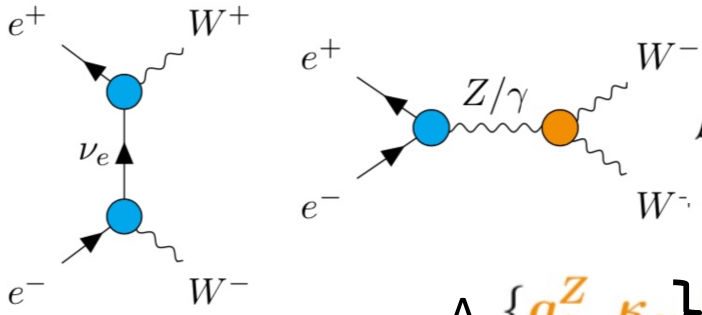
* Test of **the non-abelian structure** of the EW interactions

* Constraint on BSM

* **Probing the EWSB through the scattering of EW gauge bosons**

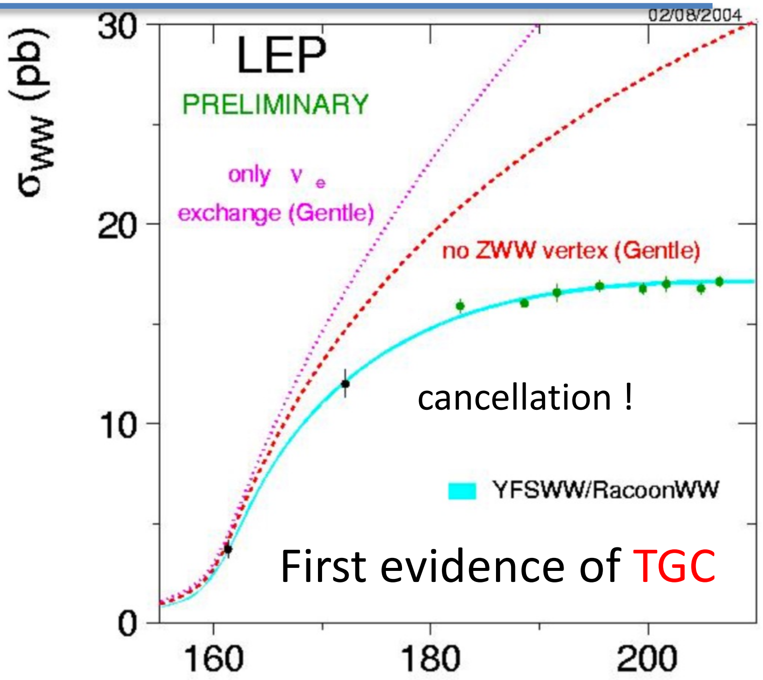
Goldone equivalence theorem:
At E >> M_V the amplitude for scattering of a **longitudinally polarised massive gauge boson** becomes equal to the amplitude for scattering of the **Goldstone bosons** (~ $-m_H^2/v^2$)

WW: anomalous Triple Gauge Couplings



$$\mathcal{L}_{\text{dim-6}} = \sum_i \frac{f_i^{(\text{dim-6})}}{\Lambda^2} \mathcal{O}_i^{(\text{dim-6})}$$

$$\Delta \{g_1^Z, \kappa_\gamma\} \lambda_\gamma \sim \{c_i \cdot m^2_{W/Z}\}$$

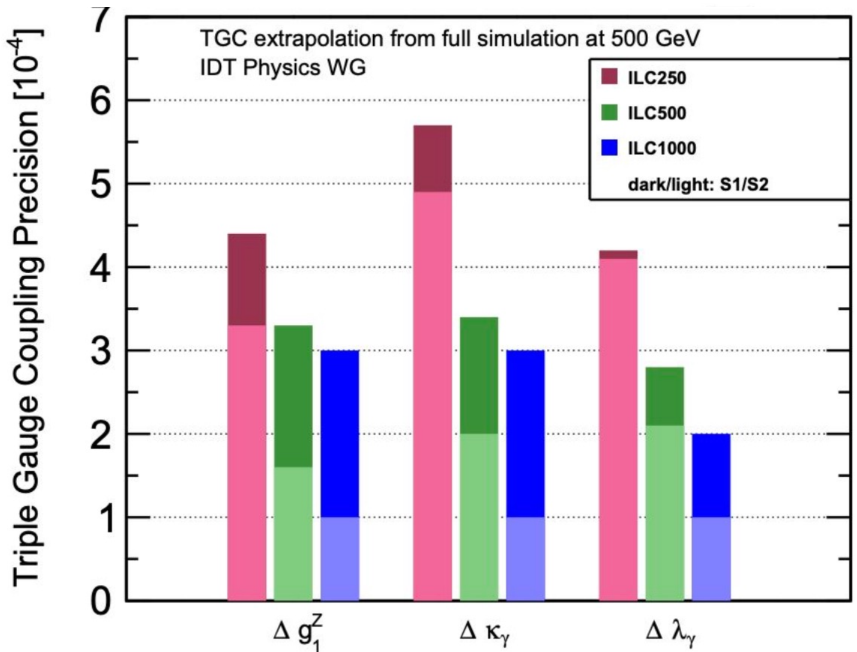


Very active field @ LHC

* High statistic and energy very important (energy growth of relevant operators)

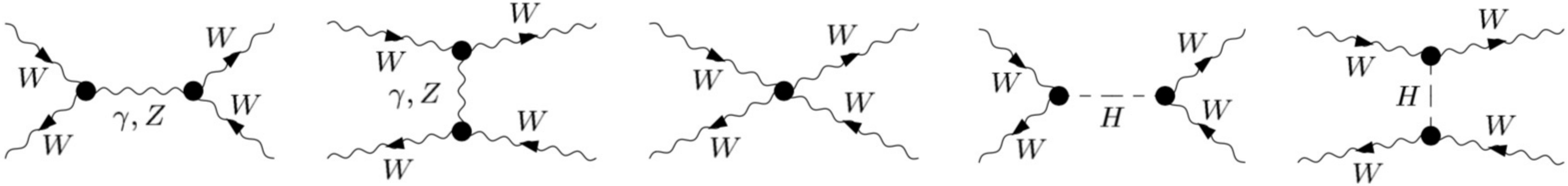
→ pp collider favoured but the precision allowed by kinematic fits helps when angular variables are exploited

* LCF has powerful constraints thanks to initial state polarisation

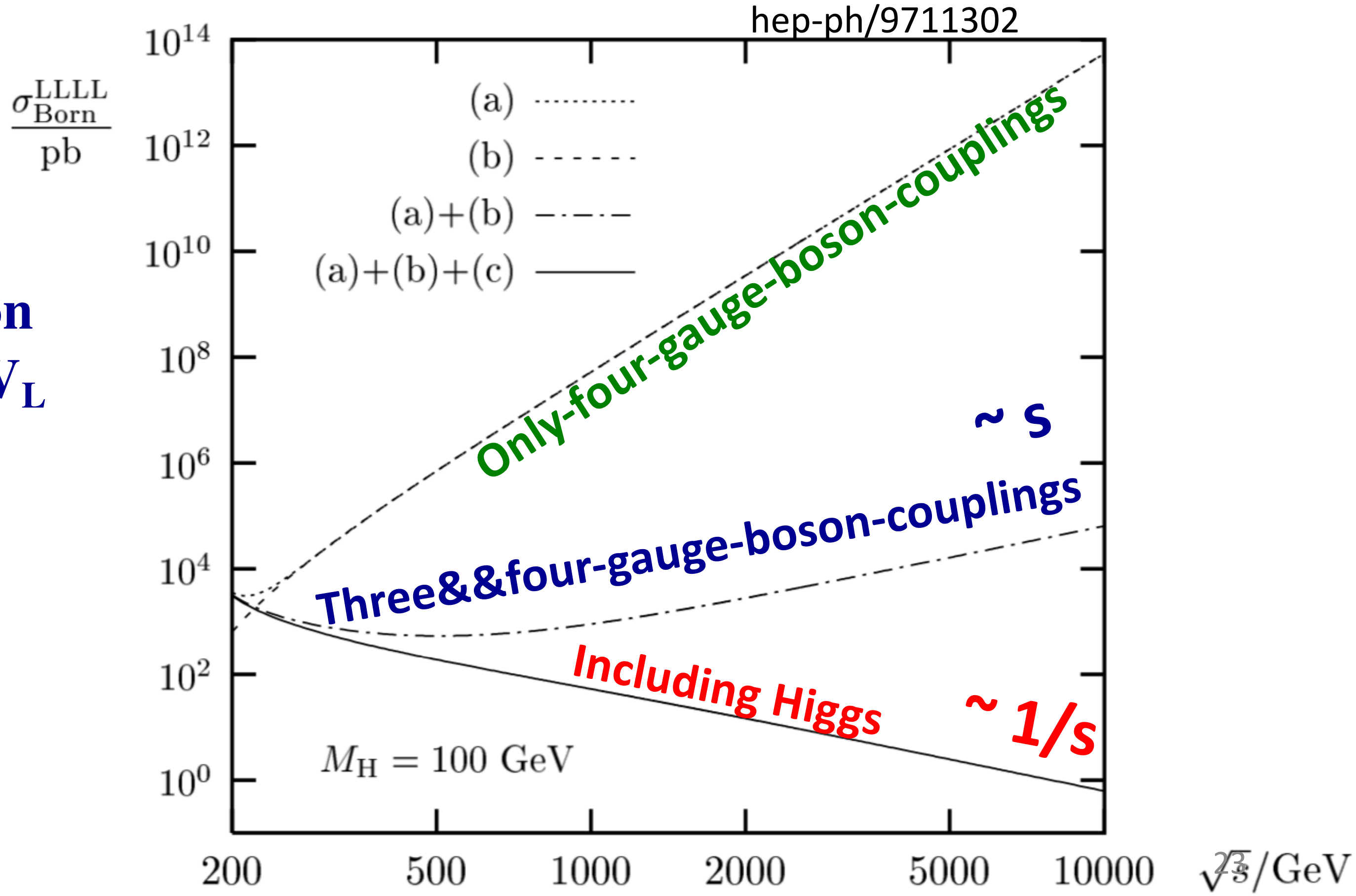


Scattering of EW gauge bosons

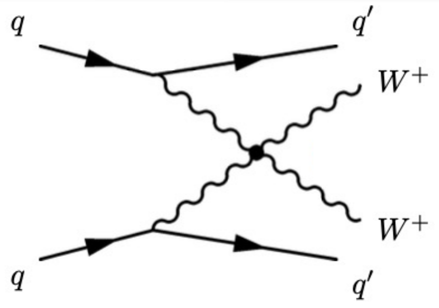
(Effective W approximation) WW → WW



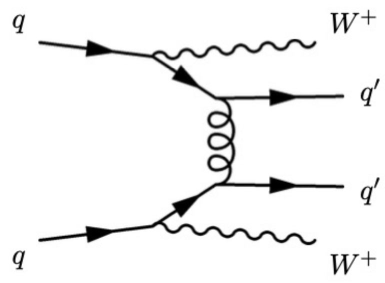
The unitarity cancellation ensure that $V_L V_L \rightarrow V_L V_L$ 'cross-section' decrease as 1/s at high energies



Scattering of EW gauge bosons



EW production



Strong production

★ Look for VV jj

★ Challenges:
* pp→VV jj low cross section
* The LL component is ~ 10%
* High bkg from strong production

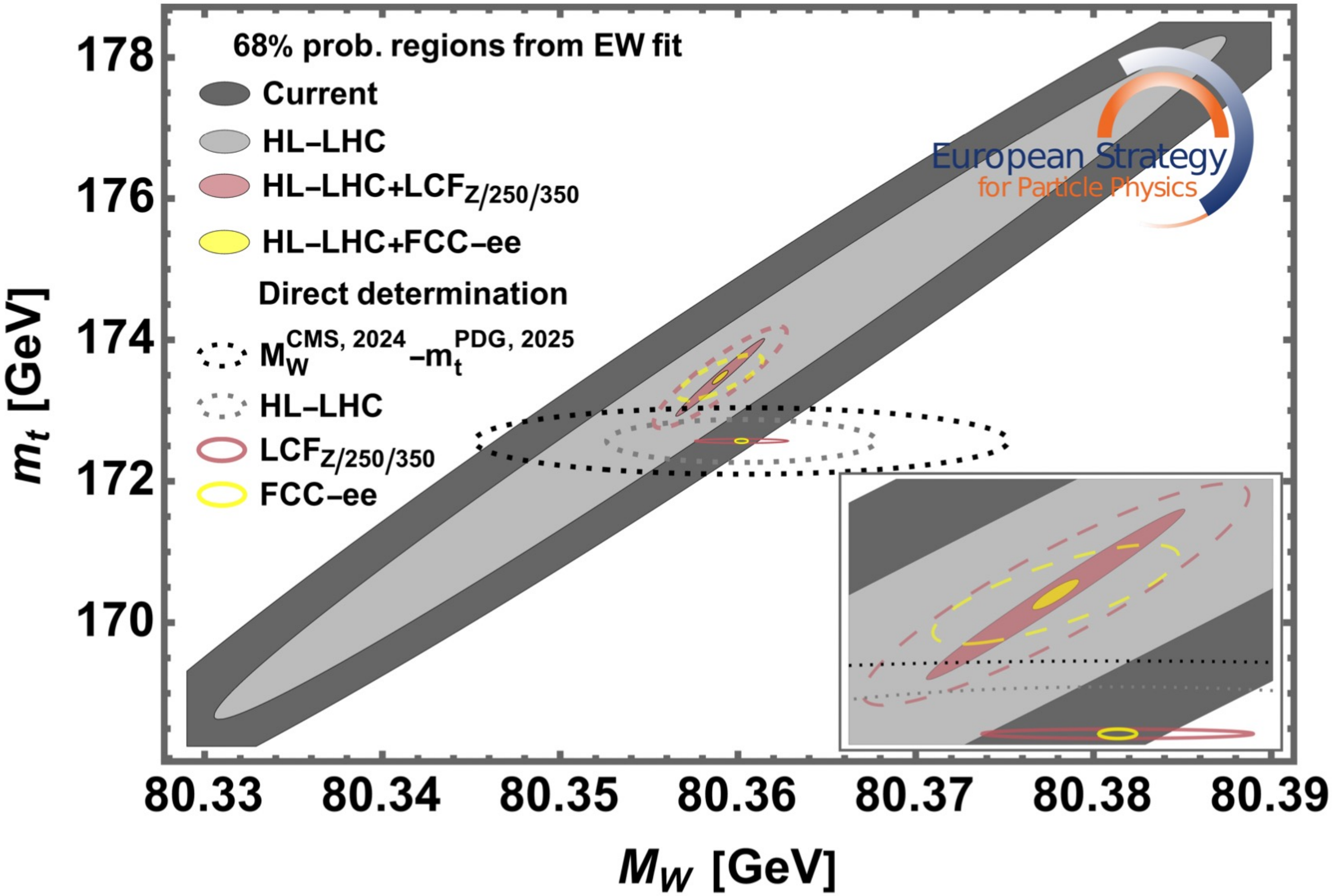
@ pp colliders **same sign WW scattering** is the golden channel greatly reduces background from strong production and removes s-channel Higgs process

★ @LHC (Run 2, ATLAS) **first 3. 3 σ** evidence for at least one **longitudinally** polarised W boson in $W^{\pm}W^{\pm}$ scattering

★ @HL-LHC expect to observe with > 5σ and measure $W_L W_L$ jj [**arXiv:2504.00672**]

★ $V_L V_L$ can be probed @
FCC-hh
muon collider (up to 10 TeV)
linear colliders (ILC, CLIC, ...) (up to 500-3 TeV)

ESPPU 2025 Briefing Book



Dashed ellipses indicate "conservative scenario" for theoretical uncertainties (likely realised improvements)

Conclusion

Accelerators offer a unique opportunity : high intensity and energy with known and tunable initial conditions

Many aspects of cosmology and astroparticle rely on particle physics

The LHC the most versatile science machine ever built:
SM: EW, Higgs, QCD, flavour, BSM searches, quark-gluon plasma

A lot of data in the near future : Runs 3–5 are 95% of the full (HL-) LHC dataset
→ for the next 25 years the LHC will be THE machine to explore the TeV scale

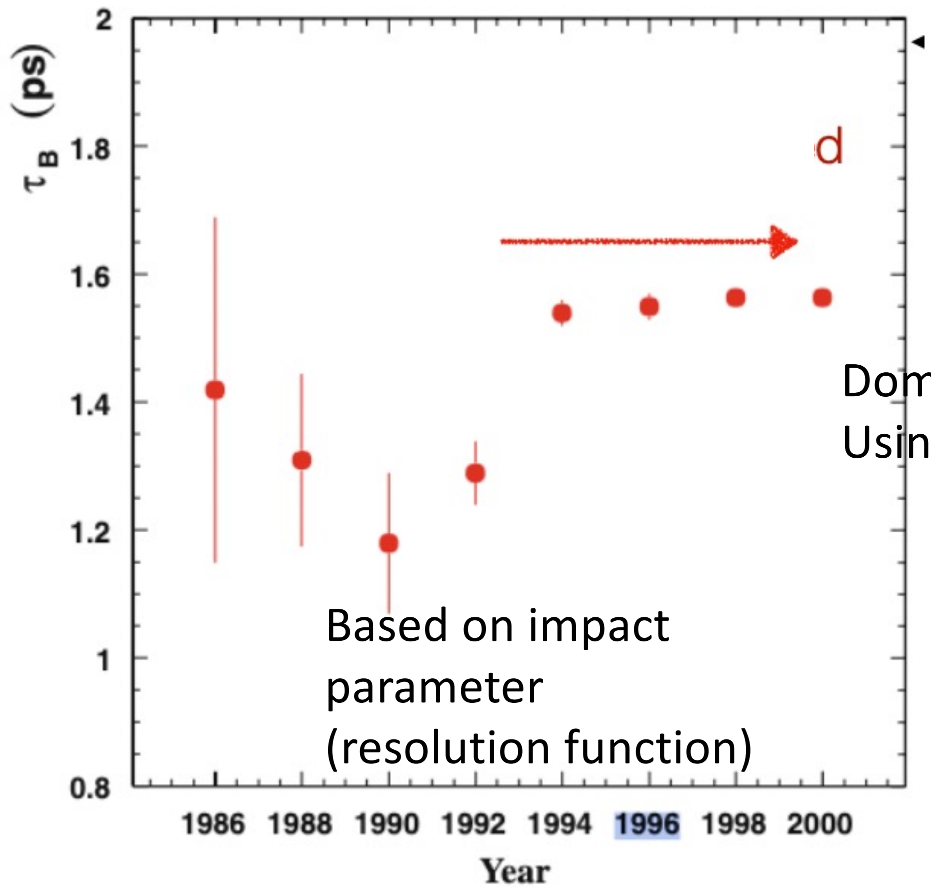
In the longer term an accelerator (whatever it is) capable to do the most precise Z, H, WW, top physics is the best option

The FCC integrated programme has (overall) an impressive reach for exploring fundamental interactions at energy scales of tens of TeV and beyond.

The (physics) program of the LHC is filled with exciting opportunities for Early Carrer Scientist

It is very valuable when doing precise measurements to use very different methods

AVERAGE B HADRON LIFETIME



Dominated by measurement
Using decay lenght

Based on impact
parameter
(resolution function)

Kinematical fit

Final state has known energy and momentum: $(\sqrt{s}, 0, 0, 0)$

Total energy and momentum are conserved :

$E_1 + E_2 + E_3 + E_4 - \sqrt{s} = 0$

$p_1^{x,y,z} + p_2^{x,y,z} + p_3^{x,y,z} + p_4^{x,y,z} = 0$

In semileptonic final state 1C fit (neutrino kinematics unknown)

In fully hadronic final state 4C fit

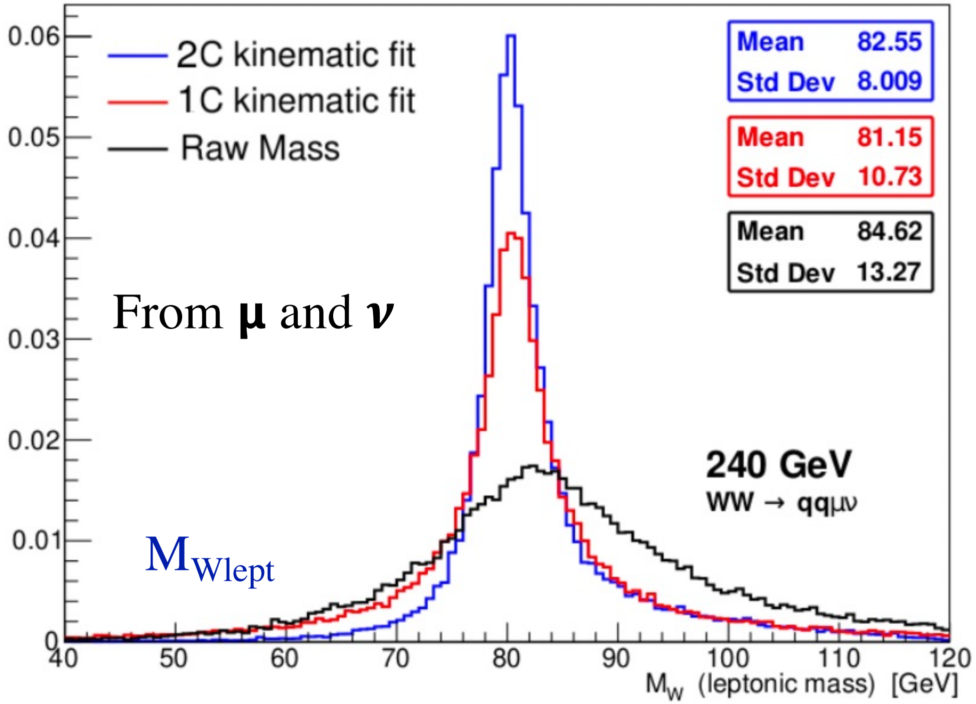
Additional constraints from the W masses ($M_{Wlept} = M_{Wquark}$)

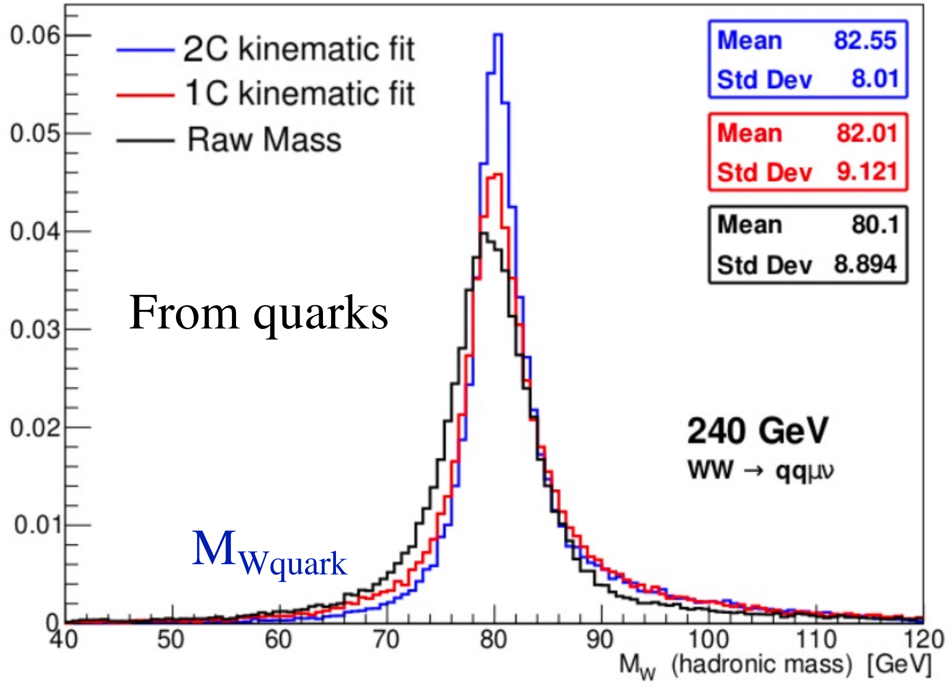
$e^+e^- \rightarrow W\,(q\,q)\,W\,(qq)$

$e^+e^- \rightarrow W(l\,nu)\,W(qq)$

$e^+e^- \rightarrow f_1+f_2+f_3+f_4$

Thesis Beguin





Kinematical fit

Final state has known energy and momentum: $(\sqrt{s}, 0, 0, 0)$

Total energy and momentum are conserved :

$e^+e^- \rightarrow W(q\,q)\,W(qq)$

$E_1 + E_2 + E_3 + E_4 - \sqrt{s} = 0$

$p_1^{x,y,z} + p_2^{x,y,z} + p_3^{x,y,z} + p_4^{x,y,z} = 0$

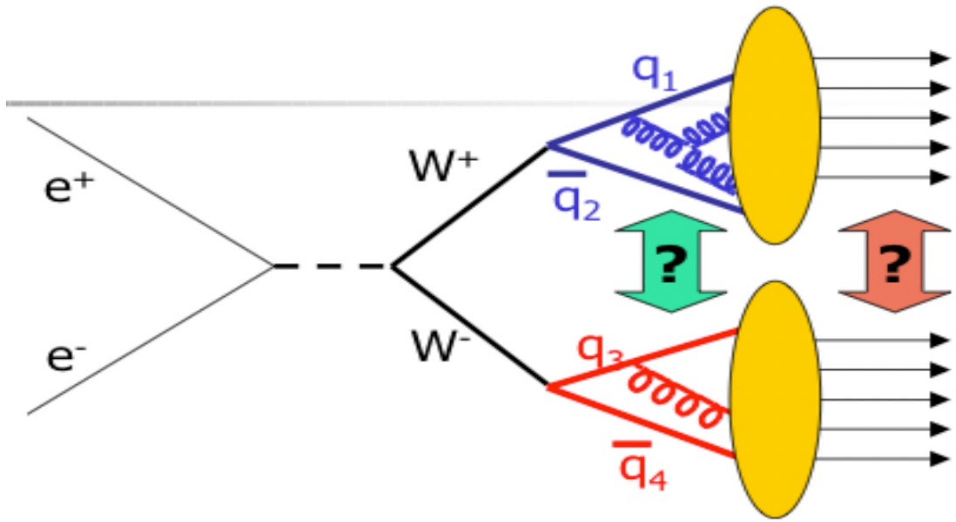
$$\begin{bmatrix} 1 & 1 & 1 & 1 \\ \beta_1^x & \beta_2^x & \beta_3^x & \beta_4^x \\ \beta_1^y & \beta_2^y & \beta_3^y & \beta_4^y \\ \beta_1^z & \beta_2^z & \beta_3^z & \beta_4^z \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \\ E_4 \end{bmatrix} = \begin{bmatrix} \sqrt{s} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Jet directions ($\beta_i = pi/E_i$) are very well measured →

Jet energies determined analytically by inverting the matrix

Additional constraints from the W masses

Color reconnection



EW bosonic operators

Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$Q_{\varphi W}$	$\varphi^\dagger \varphi\, W^I_{\mu\nu} W^{I\mu\nu}$
$Q_{\varphi \widetilde{W}}$	$\varphi^\dagger \varphi\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$
$Q_{\varphi B}$	$\varphi^\dagger \varphi\, B_{\mu\nu} B^{\mu\nu}$
$Q_{\varphi \widetilde{B}}$	$\varphi^\dagger \varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{\varphi \widetilde{W} B}$	$\varphi^\dagger \tau^I \varphi\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$

From effective lagrangian to SMEFT

$$\delta g_1^Z = \frac{v^2}{\Lambda^2}\frac{1}{c_W^2 - s_W^2}\left(\frac{s_W}{c_W}C_{HWB} + \frac{1}{4}C_{HD} + \delta v\right),$$

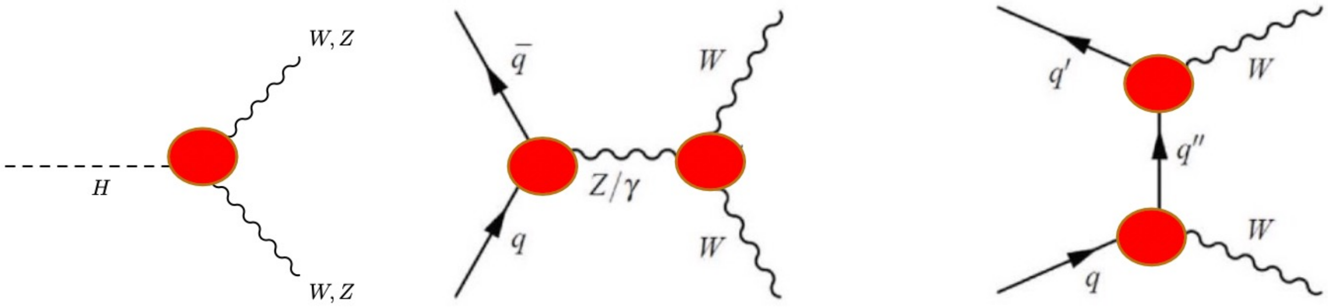
$$\delta \kappa^Z = \frac{v^2}{\Lambda^2}\frac{1}{c_W^2 - s_W^2}\left(2 s_W c_W C_{HWB} + \frac{1}{4}C_{HD} + \delta v\right)$$

$$\delta \kappa^\gamma = -\frac{v^2}{\Lambda^2}\frac{c_W}{s_W}C_{HWB},$$

$$\lambda^\gamma = \frac{v}{\Lambda^2} 3 M_W C_{3W},$$

$$\lambda^Z = \frac{v}{\Lambda^2} 3 M_W C_{3W},$$

Operators contributing to VVV vertices and Higgs-VV vertices

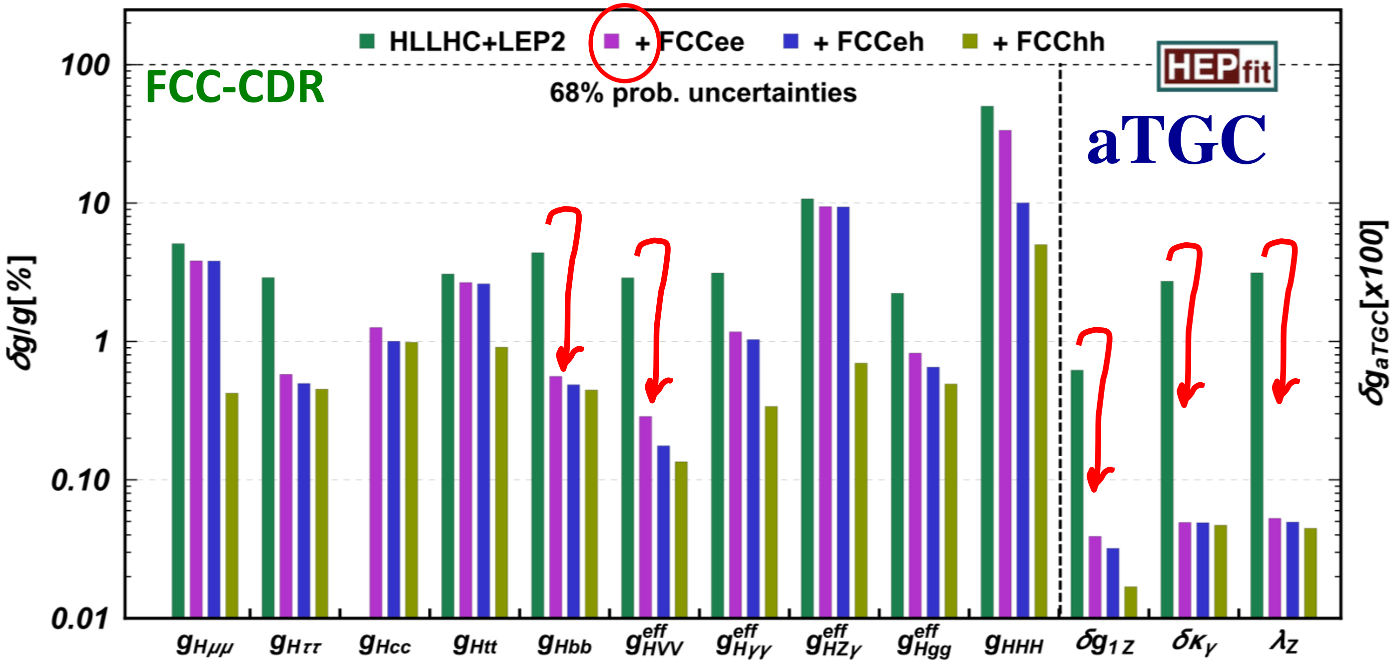


Changing (Z/γ)WW, vertices spoils high energy cancellations between contributions

Leads to concept of global fits

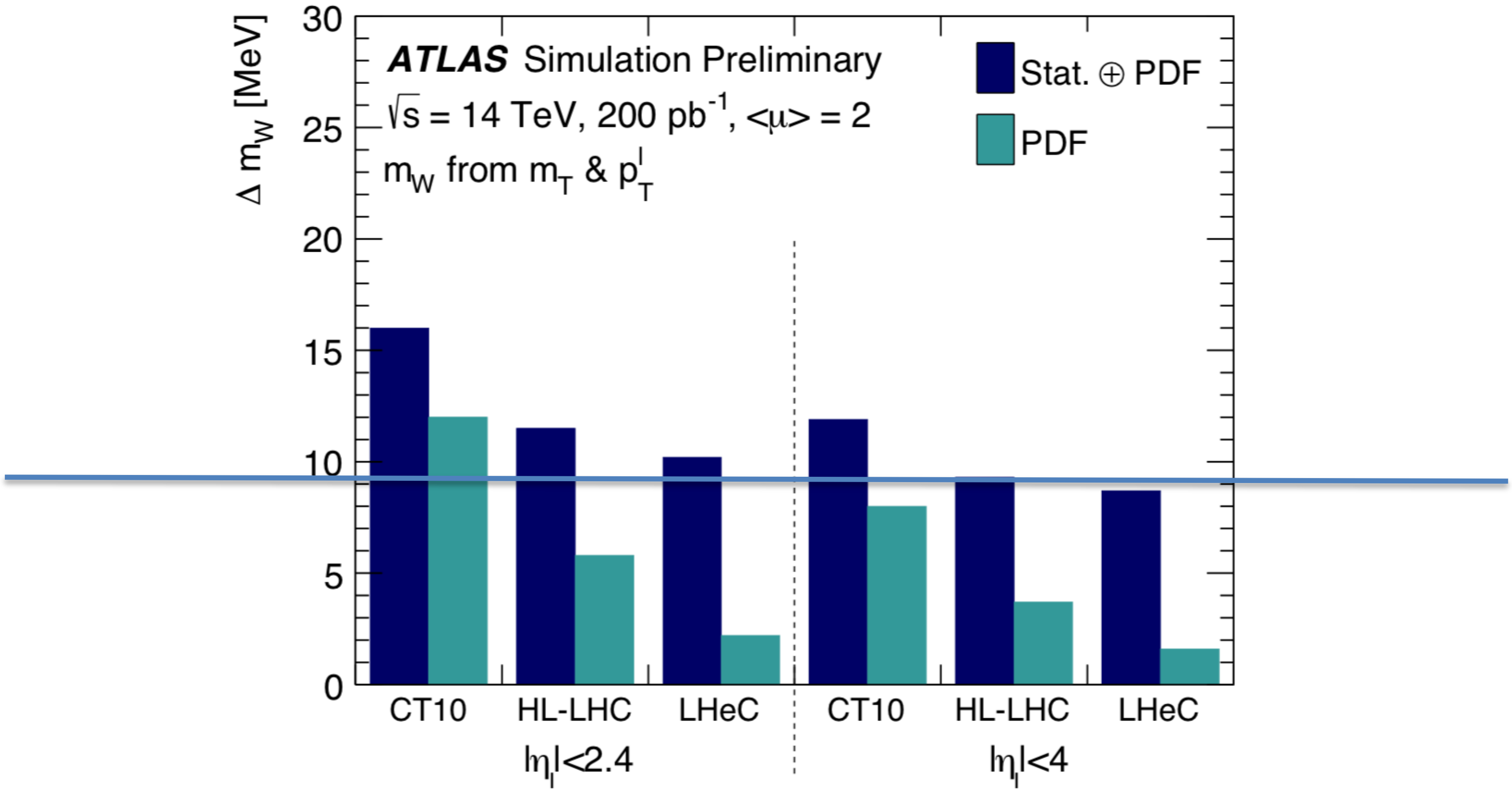
- Motivation: test of the SM consistency → improve mass reach in indirect search (equiv. to factor 5-10 in mass)

EFT fits of EW+WW+Higgs observables

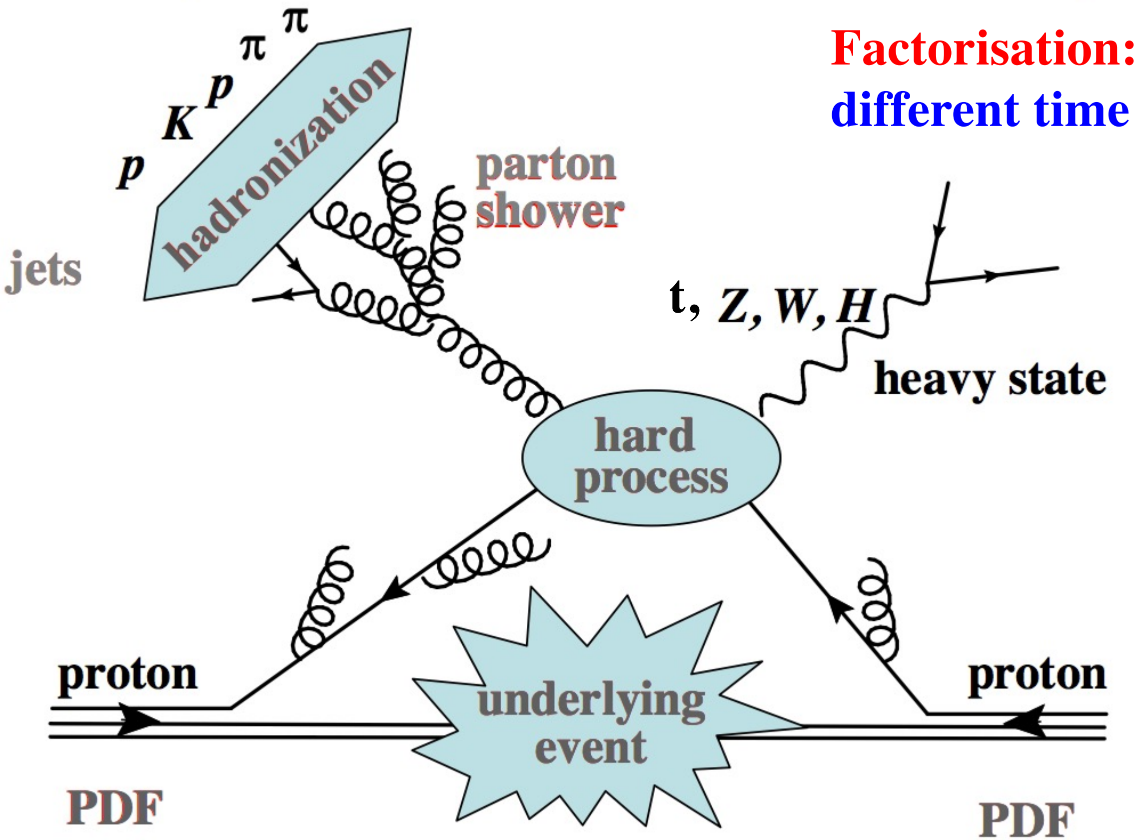


- A Z-pole program important for the robust extraction of the Higgs couplings

Expected sensitivity on mW ~ 10 MeV (with 200 pb-1 of low-μ data)



At Hadron Colliders: a Complex Picture



Factorisation: phenomena at different time scales factorize

PDF = Parton
Density
Functions
(describing the momentum distribution of partons in proton)

→ separation between phenomena @ high- and small-Q scale
The former are computed exactly, the latter are approximated or modeled

The factorisation scale μ_F arbitrarily separates hard from soft scales

Many aspects of QCD can/must be understood !

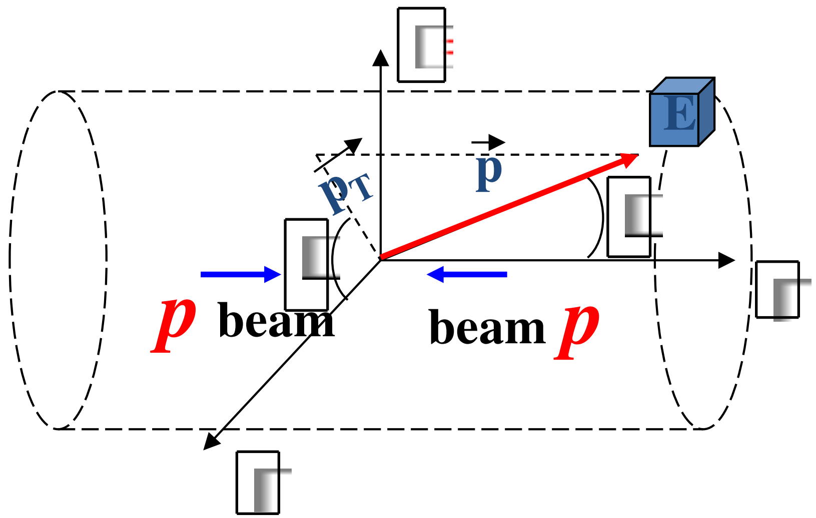
Variables used in the analysis of *p - p* collisions

Boost of parton-parton center of mass along beam line unknown

→ **use transverse quantities (in the plane ⊥ to the beam):**

- **Transverse momentum/energy :** $p_T = p \sin\theta$ $E_T = E \sin\theta$
- **Missing Transverse Energy :** $\vec{p}_T^{\,mis} = -\Sigma_{vis}\, \vec{p}_T$ $E_T^{\,mis} = |\vec{p}_T^{\,mis}|$

- **rapidity** $$Y = \frac{1}{2} \ln \frac{E+p_z}{E-p_z}$$



Angles :

- **pseudorapidity** $$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$
- **azimuthal angle** Φ

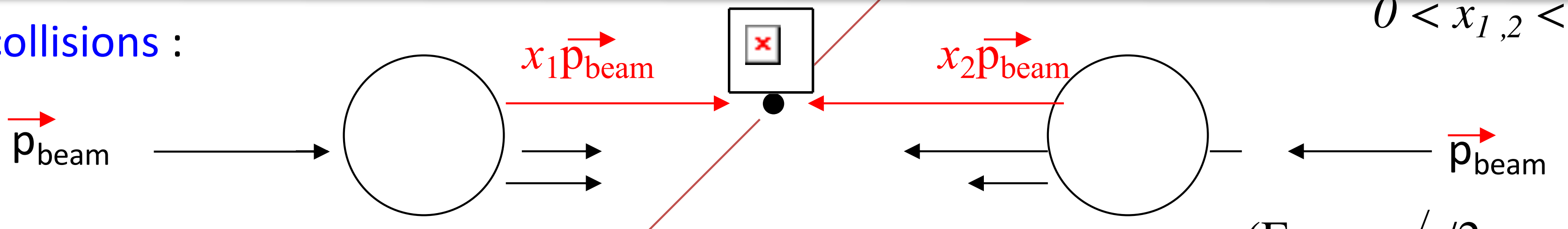
Important:

- $\Sigma^{in}\, \vec{p}_T = \Sigma_{vis}\, \vec{p}_T \approx 0$ → **Allows to evaluate the $\vec{p}_T$ of particles not detected (ν)**
- **p_T and ΔY are invariants for Lorentz transformations along the z axis**
- **m « E** → $Y \approx \eta$ **(η doesn't require particle identification)**
- **m « E** → $p_T \approx E_T$

Kinematics of *p* - *p* collisions

$0 < x_{1,2} < 1$

p- *p* collisions :



$(E_{beam} = \sqrt{s}/2 \approx p_{beam})$

- **4-mom of the initial partons** : $[\ (x_1+x_2)E_{beam}, 0, 0, (x_1-x_2)\ p_{beam}]$
- **Effective collision energy** = $\sqrt{\hat{s}} = Q = \sqrt{x_1 x_2 s}$
- $x_{1,2} = \frac{Q}{\sqrt{s}}\ e^{\pm y_{cm}}$

y_{cm} = *rapidity of the c.o.m. of the parton system*