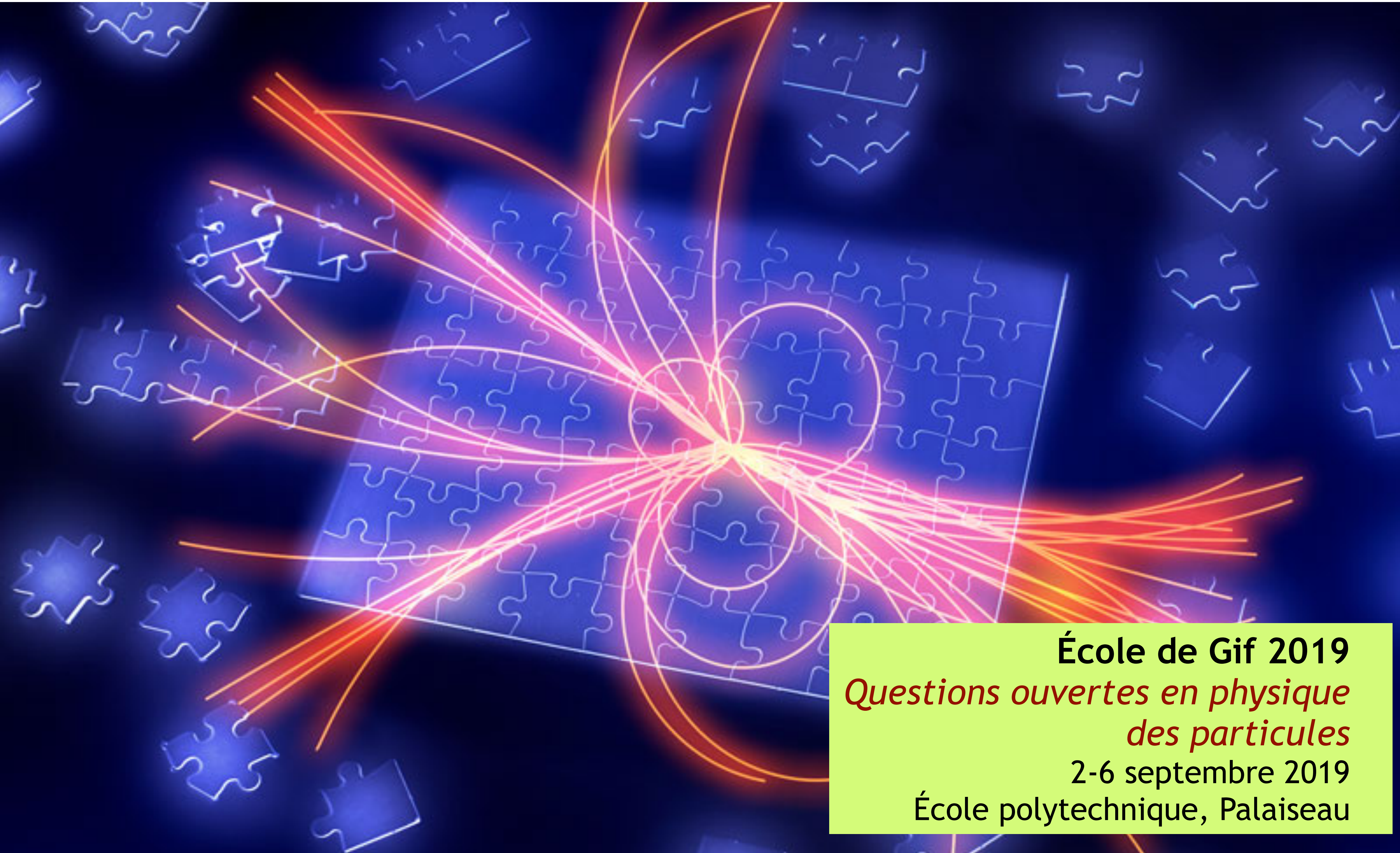
Les expériences du futur : potentiel de physique

Physique du modèle standard



École de Gif 2019

Questions ouvertes en physique des particules

2-6 septembre 2019

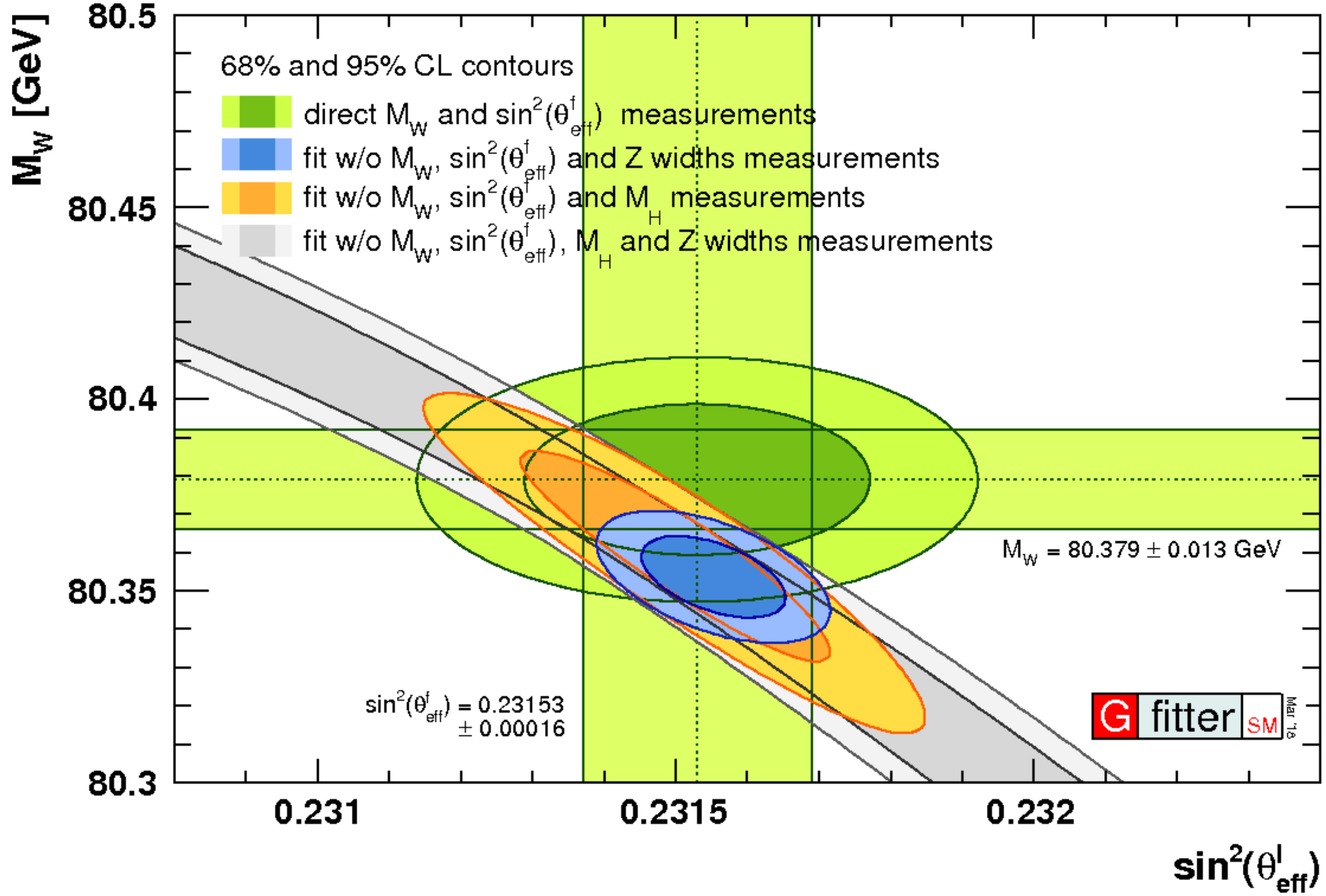
École polytechnique, Palaiseau

The Electroweak Fit

$$M_W{}^2 = (1 + \Delta\rho) M_Z{}^2 (1 - \sin^2\theta_{\text{eff}})$$

with $\Delta\rho = f(m_t{}^2, \ln M_H)$

(of order 1%)



Another projection of the electroweak fit, this time showing M_W versus $\sin 2\theta^{\ell}{}_{\text{eff}}$

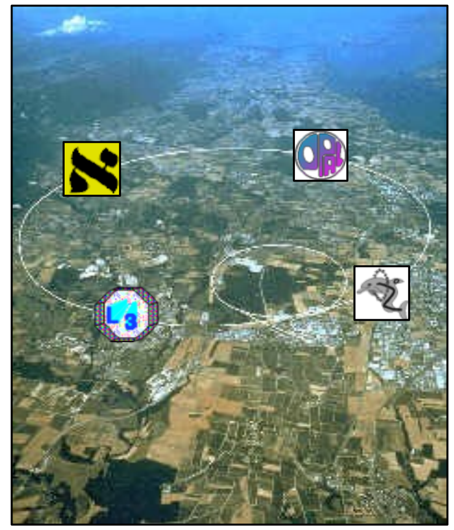
Electroweak Precision Observable (EWPO) measured at LEP/SLD

Physics at the Z-Pole

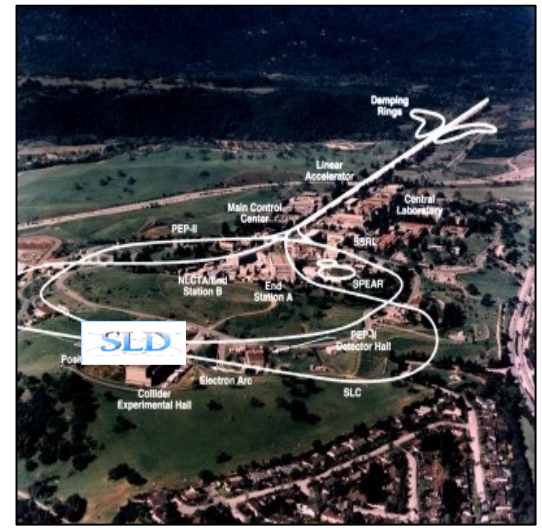
e^+e^- colliders $\sqrt{s}$ = 91 GeV

LEP-1 at CERN
- 1989-1992
- circular
- ALEPH, DELPHI, L3, OPAL
- 20 million Z's

27 km ∅



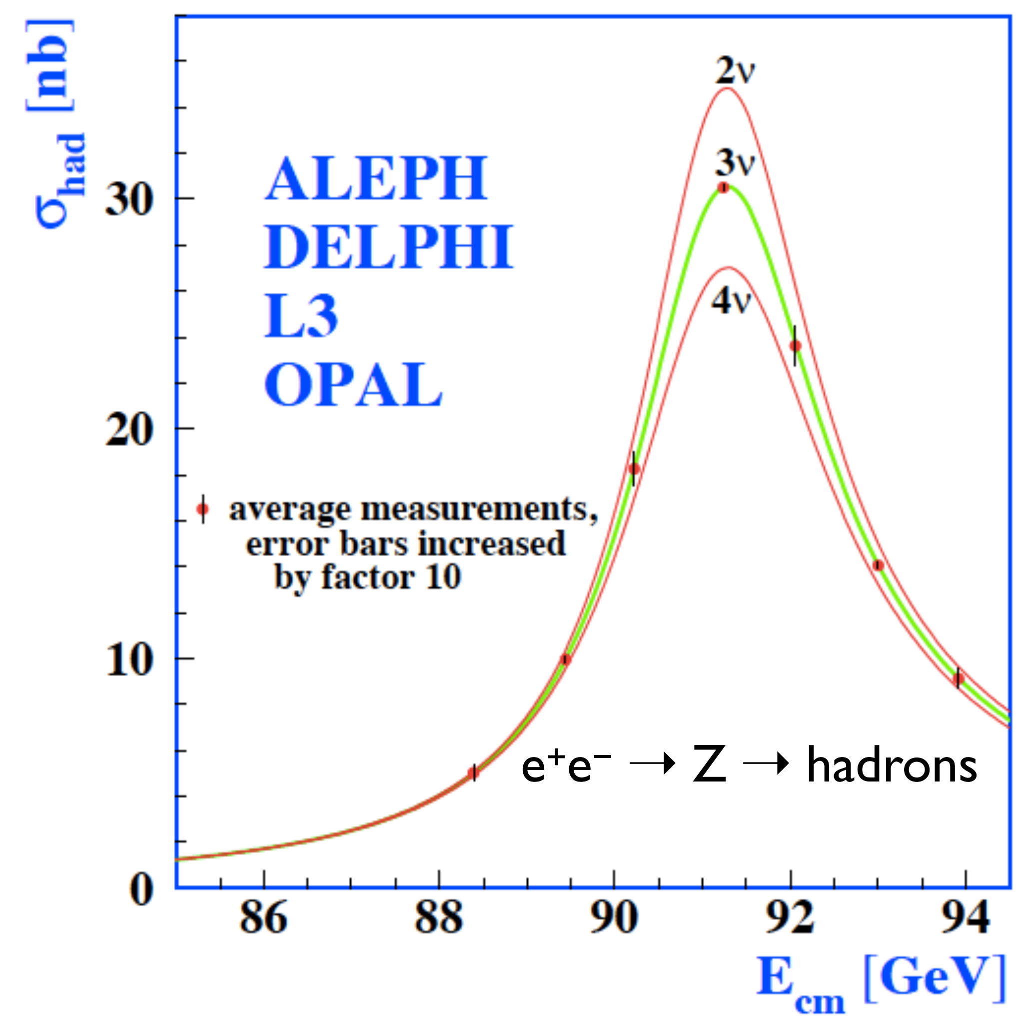
1.2 mile long



SLC at SLAC
- 1989-1998
- linear
- e^- beam polarisation
- SLD
- 550,000 Z's

A fantastic legacy!

M_Z =	**91187.5 ± 2.1 MeV**	*from Z line shape*
Γ_Z =	2495.2 ± 2.3 MeV	
$\sin^2\theta_{eff}$ =	**0.23153 ± 0.00016**	*from LR and FB asymmetries* (tension "leptons" vs "quarks")
α_s =	0.1190 ± 0.0025	*from multi-jets*
N_ν =	**2.9840 ± 0.0082**	*from peak cross -section and ratio of partial widths* (2σ deficit)



Only three species of *active*, *light* neutrinos

Maximum Violation of Parity

left-handed doublets | right-handed singlets

(3 families)

Leptons

$$L^{\ell}{}_{L} \equiv \frac{1}{2}(1-\gamma^5)\begin{pmatrix}\nu_\ell \\ \ell\end{pmatrix} \quad Y_L = -1$$

$$\ell_R \equiv \frac{1}{2}(1+\gamma^5)\,\ell \qquad Y_R = -2$$

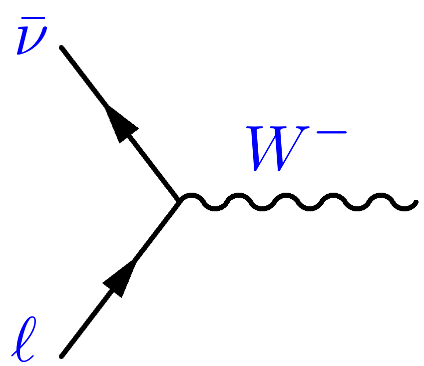
Quarks (x3)

$$Q^{j}{}_{L} \equiv \frac{1}{2}(1-\gamma^5)\begin{pmatrix}u_j \\ d'_j\end{pmatrix} \quad Y_L = 1/3$$

$$u_{jR} \equiv \frac{1}{2}(1+\gamma^5)\,u_j \qquad Y_R = 4/3$$

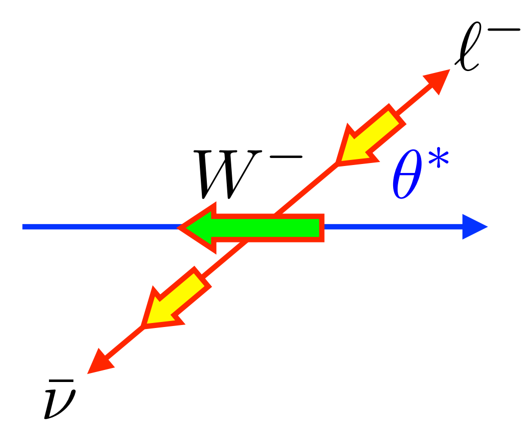
$$d'_{jR} \equiv \frac{1}{2}(1+\gamma^5)\,d'_j \qquad Y_R = -2/3$$

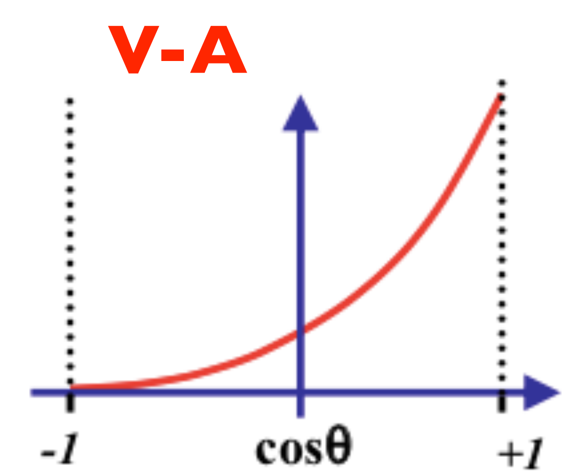
Electric charge $\quad Q = T^3 + \frac{1}{2}Y \quad$ Gell-Mann—Nishijima



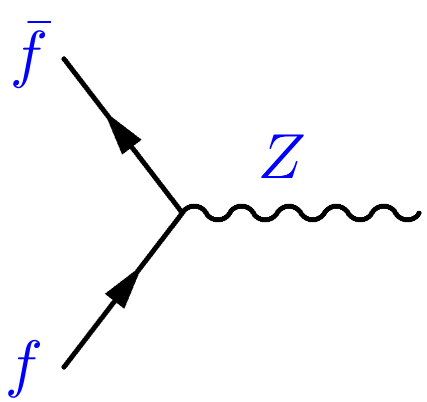
Charged weak currents

$$\frac{g}{2\sqrt{2}}\bar{\nu}_\ell\gamma^\mu(1-\gamma^5)\ell W^-_\mu$$





$(1+\cos\theta^*)^2$



Neutral weak currents

$$\frac{g}{2\cos\theta_W}\bar{f}\gamma^\mu\left(R_f(1+\gamma^5)+L_f(1-\gamma^5)\right)f Z_\mu$$

Weak Neutral Currents

axial current $a_f = (L_f - R_f)/2 = T_f^3$

vector current $v_f = (L_f + R_f)/2 = T_f^3 - 2Q_f \sin^2\theta_W$

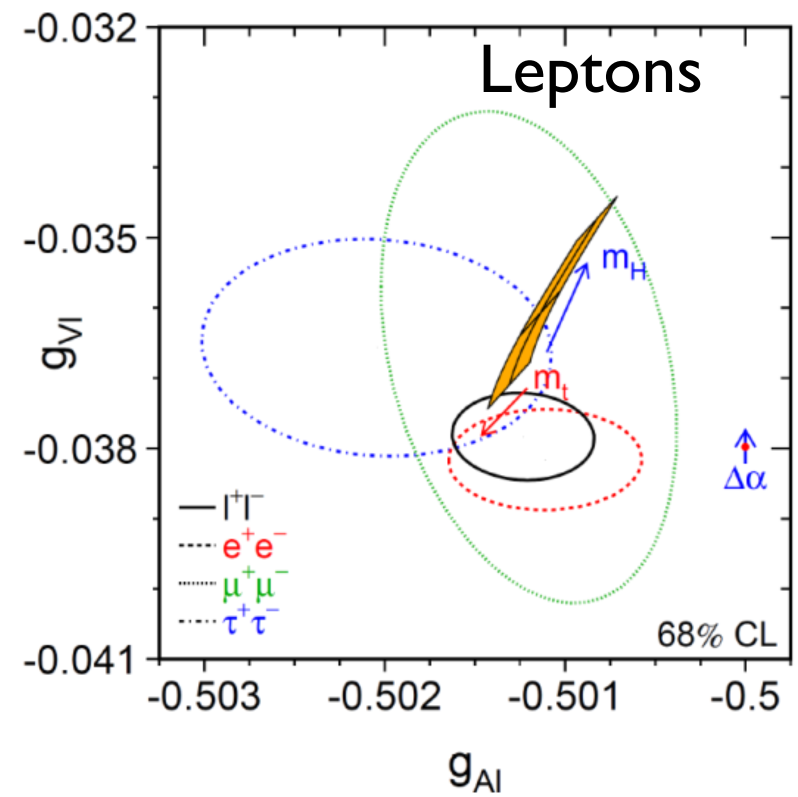
Vector and axial-vector couplings to the Z boson $\sin^2\theta_W = 0.2312$

Fermion	$v_f = T_f^3 - 2Q_f \sin^2\theta_W$	$a_f = T_f^3$	L_f	R_f	$v_f^2 + a_f^2$
$\nu_e,\ \nu_\mu,\ \nu_\tau$	$1/2$	$1/2$	$1/2$	0	$1/2$
$e,\ \mu,\ \tau$	$-\ 1/2 + 2\ \sin^2\theta_W \simeq -0.038$	$-1/2$	$\simeq -0.269$	$\simeq +0.231$	$\simeq 0.251$
$u,\ c,\ t$	$1/2 - 4/3\ \sin^2\theta_W \simeq +0.192$	$1/2$	$\simeq +0.346$	$\simeq -0.154$	$\simeq 0.287$
$d,\ s,\ b$	$-\ 1/2 + 2/3\ \sin^2\theta_W \simeq -0.346$	$-1/2$	$\simeq -0.423$	$\simeq +0.077$	$\simeq 0.370$

Effective couplings

$$g_{Vf} = \sqrt{\bar\rho}\,(T_f^3 - 2Q_f \sin^2\theta_W^{\mathrm{eff}})$$
$$g_{Af} = \sqrt{\bar\rho}\,T_f^3$$

$$\sin^2\theta_W^{\mathrm{eff}\,f} = \frac{1}{4|Q_f|}(1 - g_{Vf}/g_{Af})$$



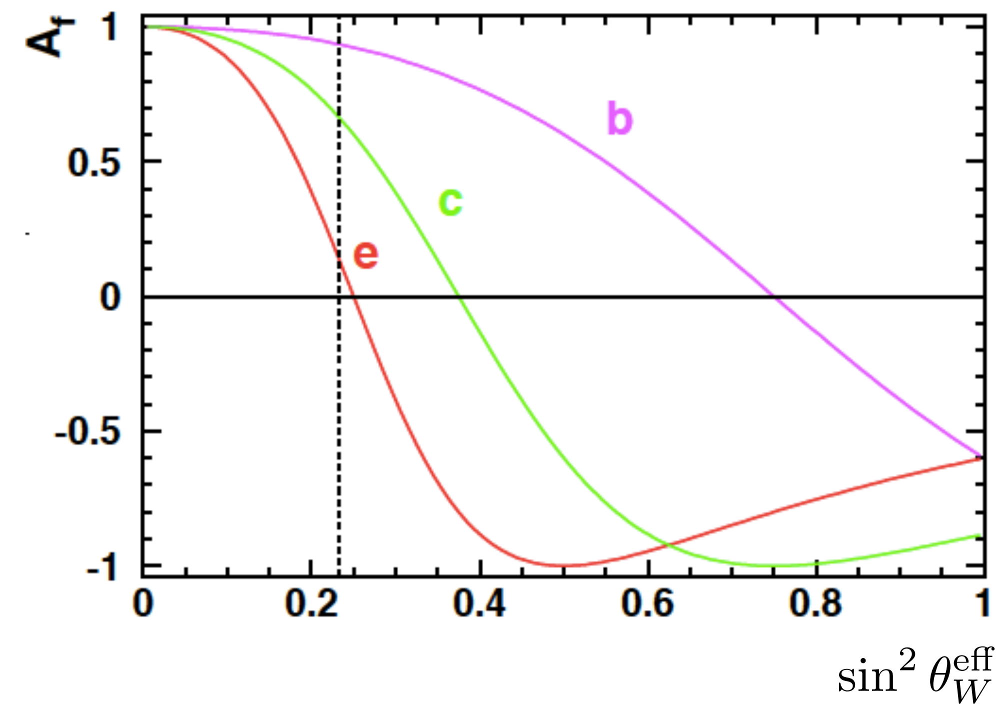
Left-Right Asymmetries

Asymmetry in left- and right-handed couplings

$$\mathcal{A}_f = \frac{L_f - R_f}{L_f + R_f} = 2\frac{g_{\mathrm{V}f}/g_{\mathrm{A}f}}{1 + (g_{\mathrm{V}f}/g_{\mathrm{A}f})^2}$$

Depends on vector to axial-vector ratios

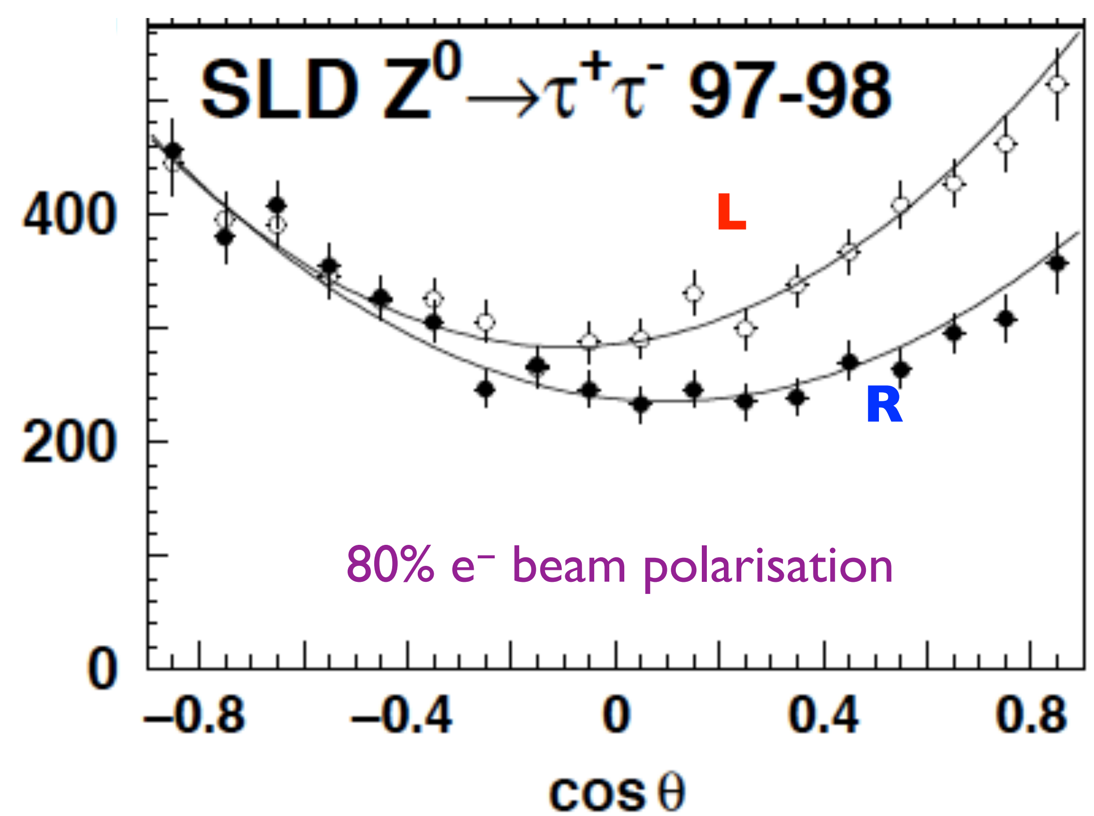
- small for leptons
- large for down-type quarks
- sensitive to $\sin^2\theta_W$



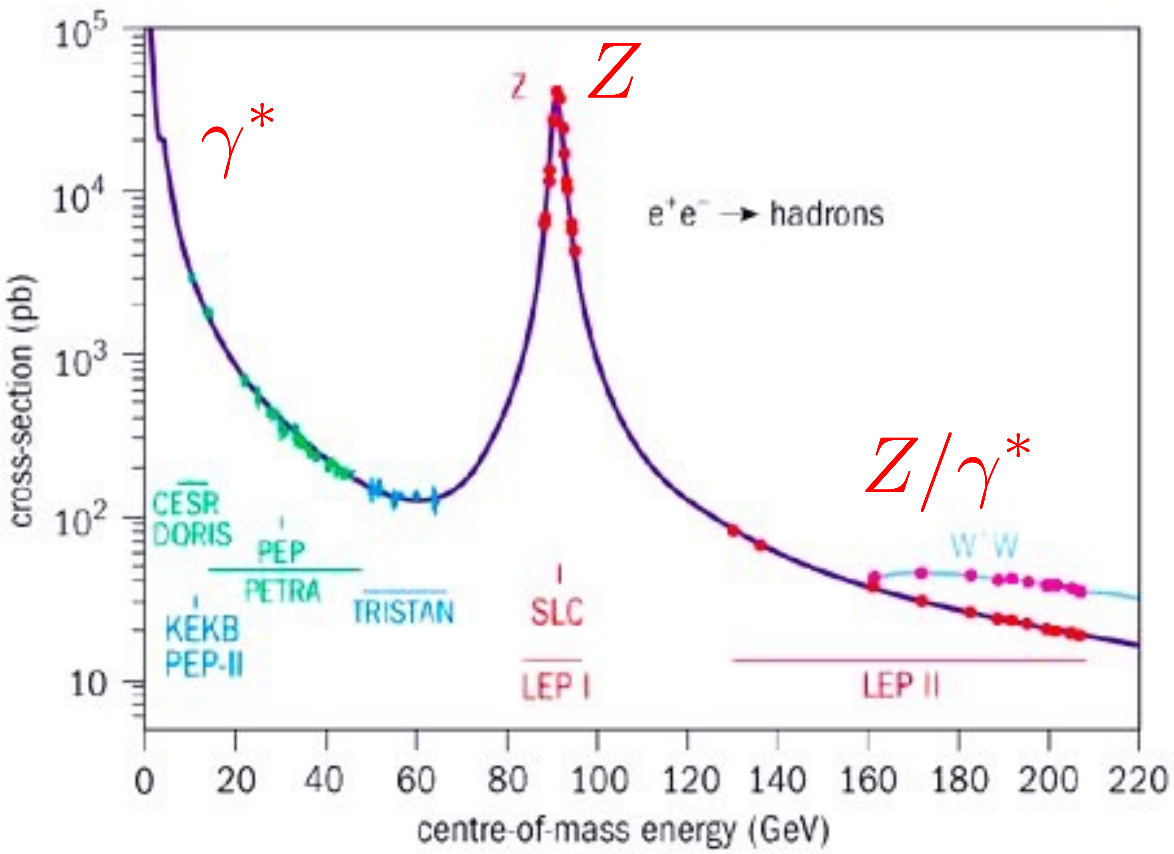
Left-right asymmetries can be measured at the Z pole with longitudinally polarised beams (i.e., at SLD)

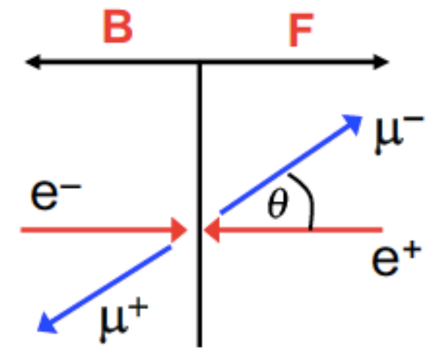
$$A_{\mathrm{LR}} = \frac{\sigma_{\mathrm{L}} - \sigma_{\mathrm{R}}}{\sigma_{\mathrm{L}} + \sigma_{\mathrm{R}}} \quad \Rightarrow \quad \mathcal{A}_{\mathrm{e}}$$

Polar distributions of Z decays to lepton pairs $\Rightarrow$ $\mathcal{A}_\mu, \mathcal{A}_\tau$



Forward-Backward Asymmetries



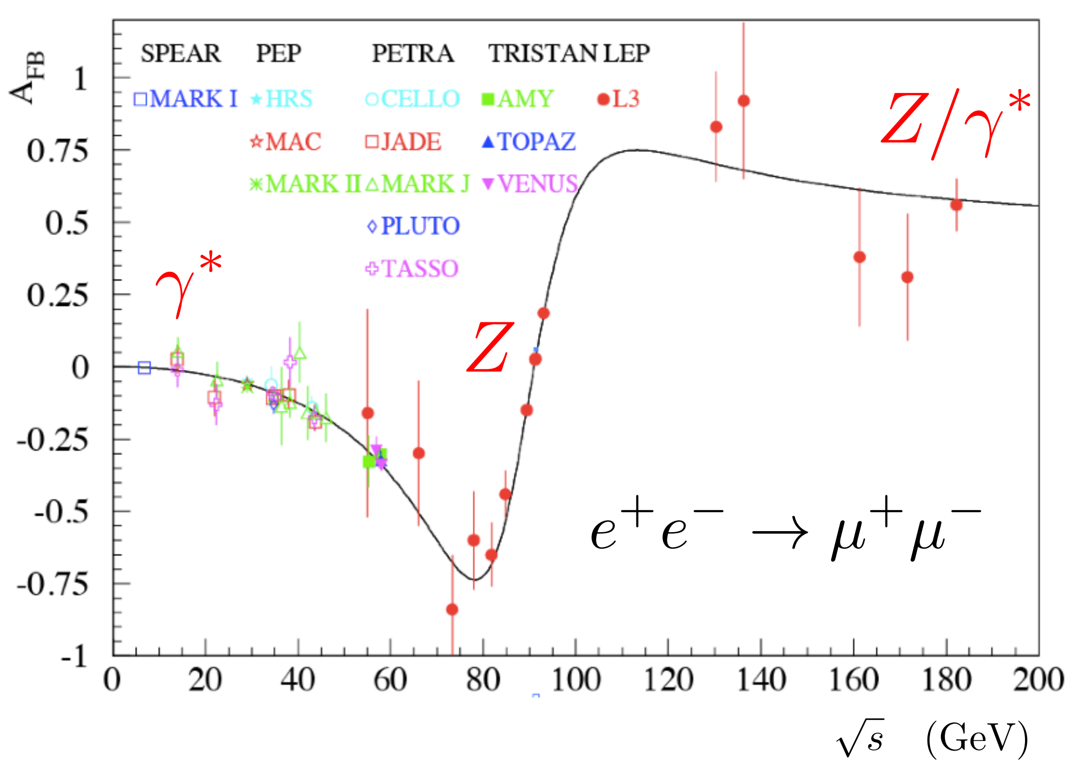


FB Asymmetry

$$A_{\mathrm{FB}} = \frac{\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}}}{\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}}}$$

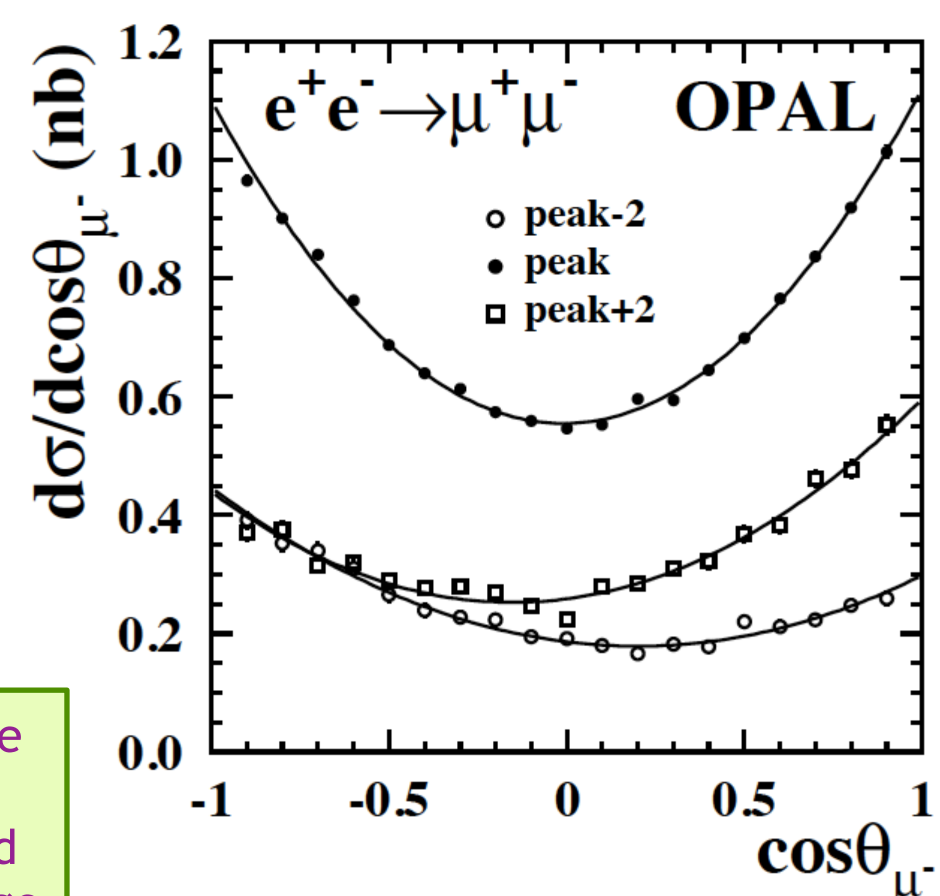
$$\frac{d\sigma}{d\cos\theta} \propto 1 + \cos^2\theta + \frac{3}{8} A_{\mathrm{FB}} \cos\theta$$

at the Z pole: $A_{\mathrm{FB}}^{0\,f} = \frac{3}{4}\mathcal{A}_e\,\mathcal{A}_f$



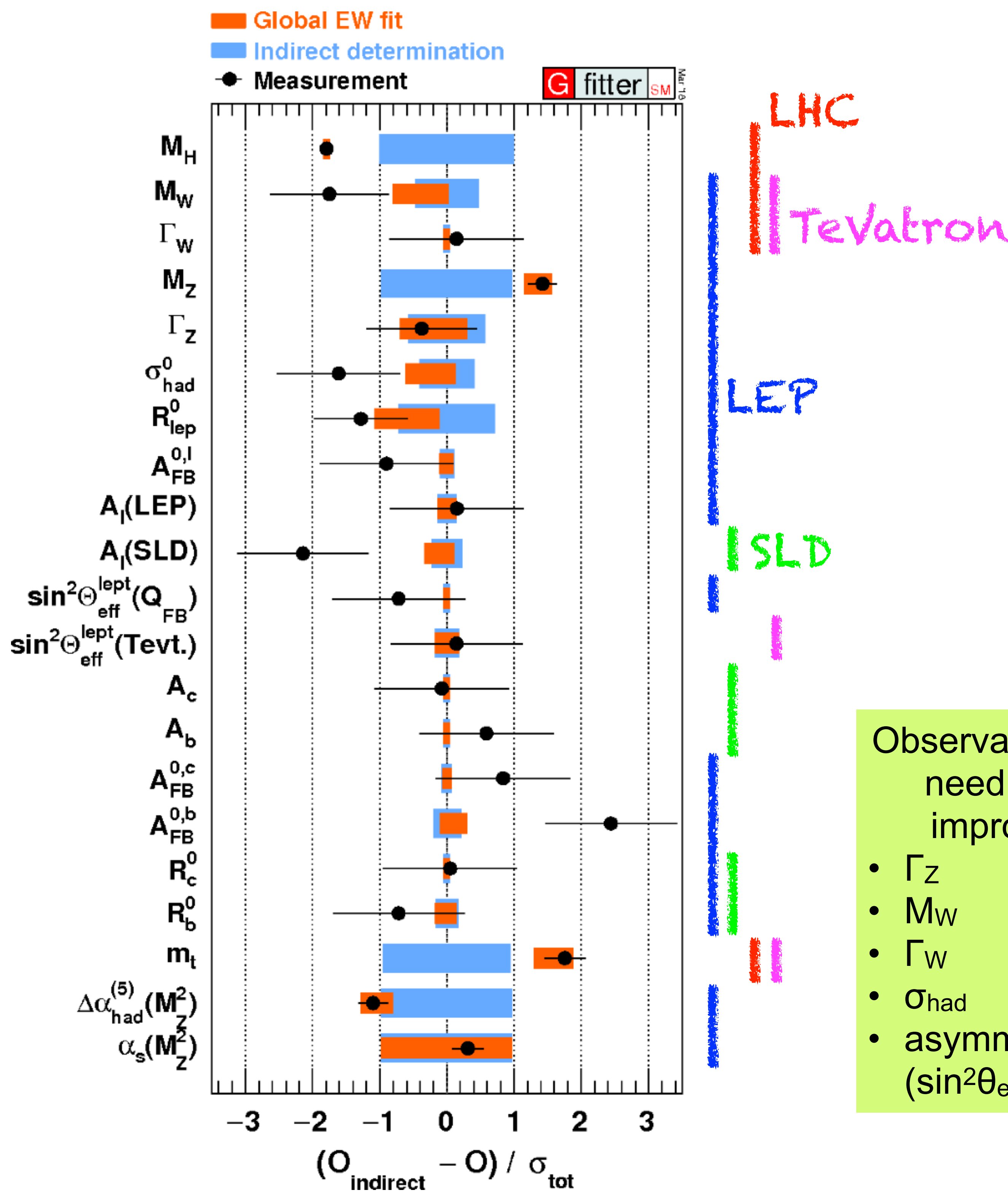
LEP (with unpolarised beams)

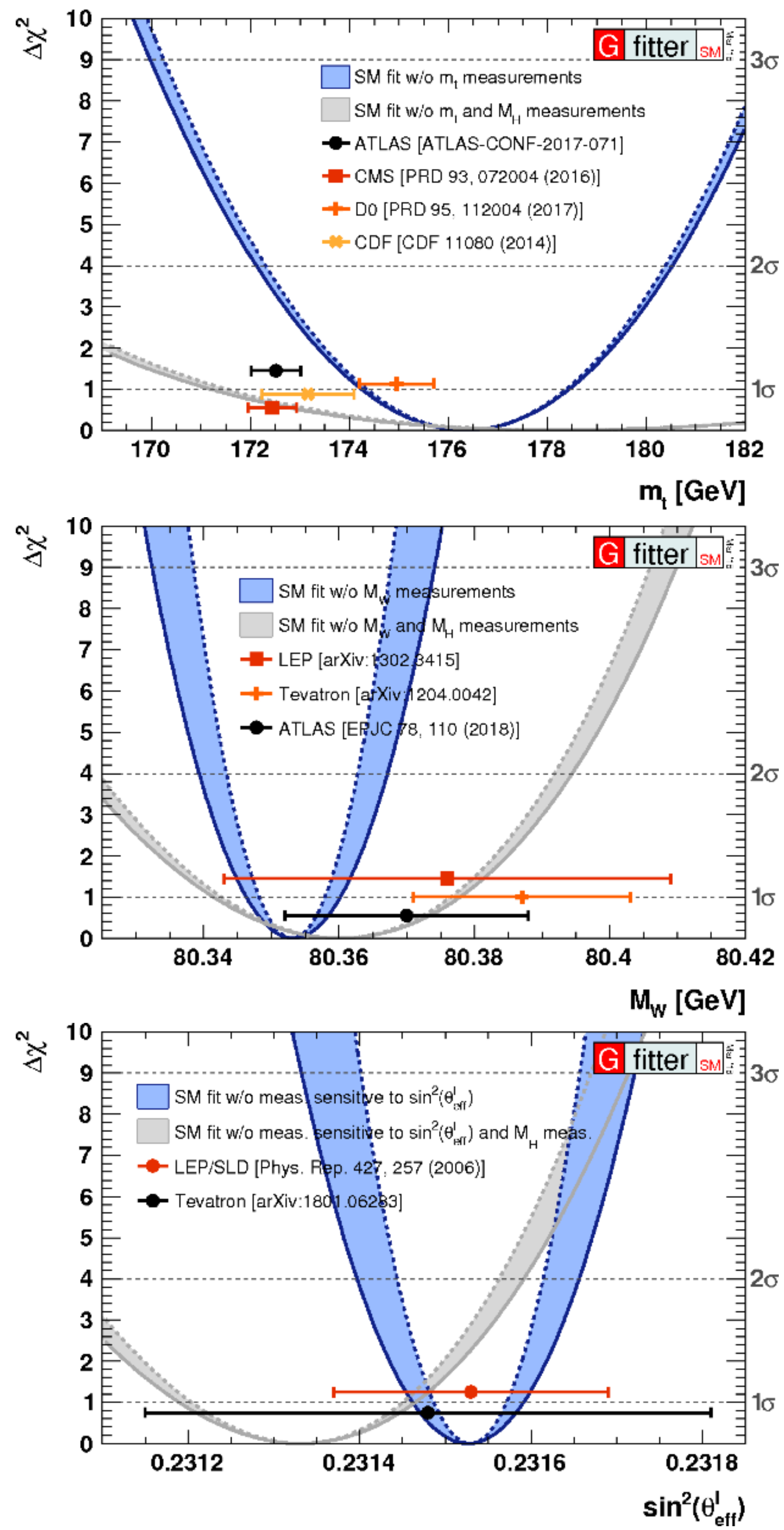
- measurements for leptons and heavy quarks



√s dependance due to interference between the Z and the photon exchange

The Electroweak Fit





Observables that need to be improved:

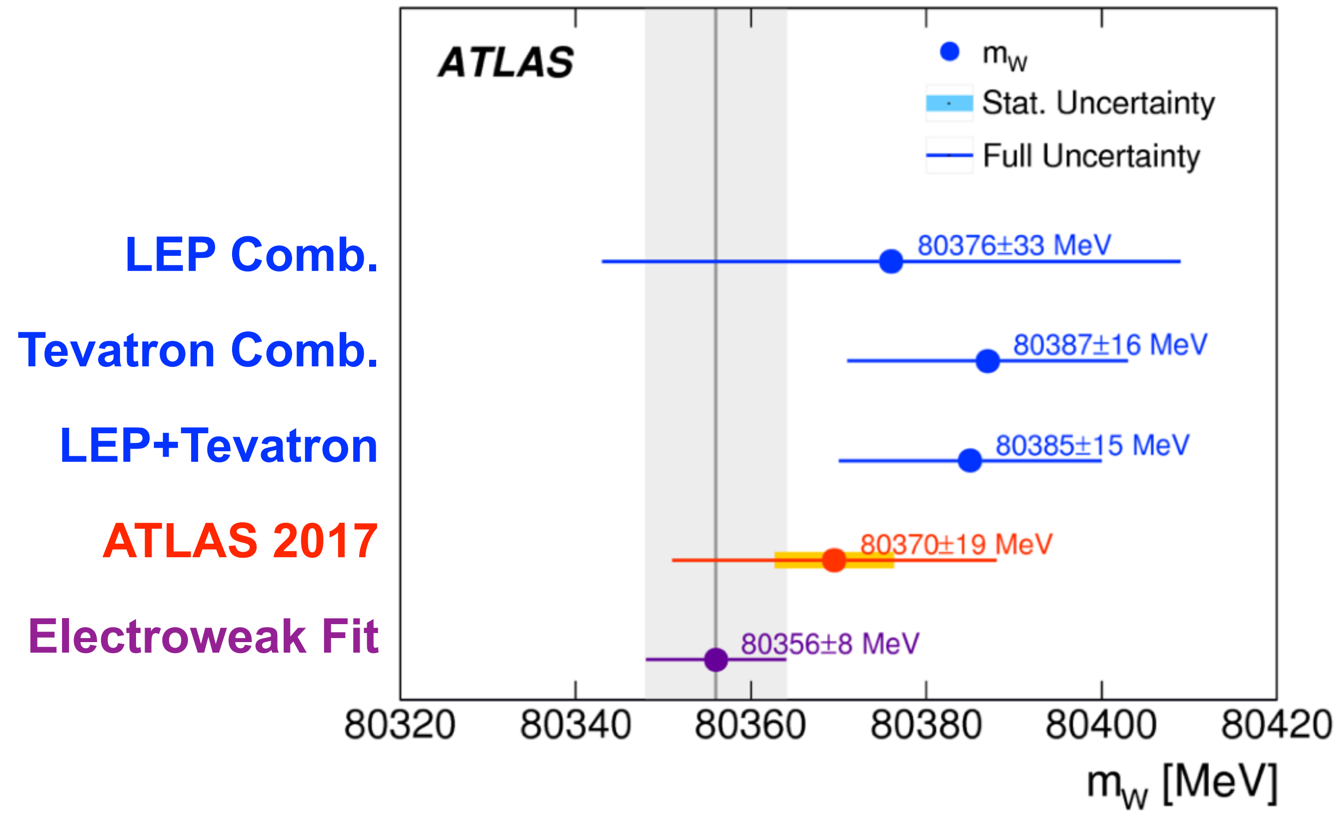
- Γ_Z
- M_W
- Γ_W
- σ_{had}
- asymmetries ($\sin^2\theta_{eff}$)

p-value Prob(χ^2_{min},15) = 0.23

M_W : Parametric Errors

Experimental

$$M_{\rm W} = 80.385 \pm 0.015 \text{ GeV}$$



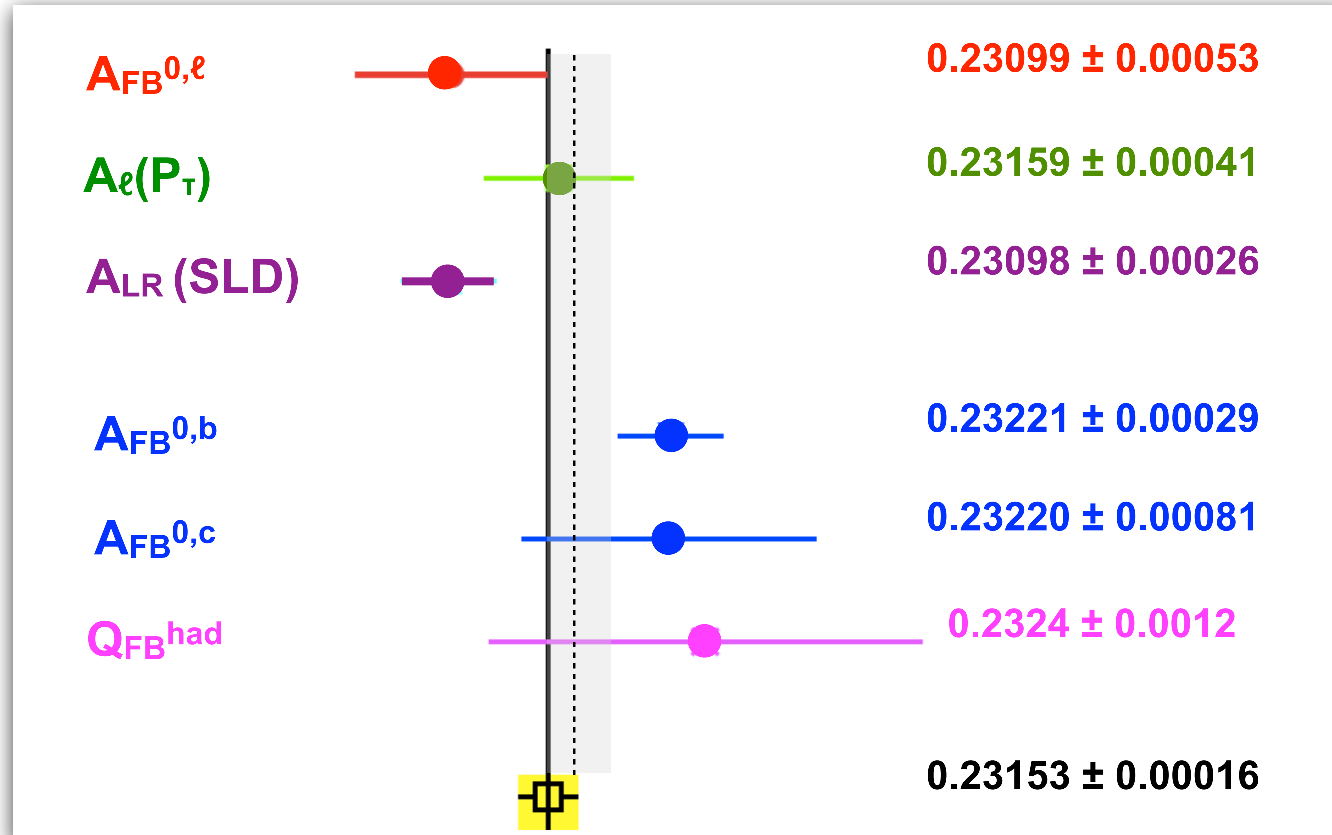
Electroweak Fit

$$\begin{aligned}
M_{\rm W} = \ & 80.3584 \text{ GeV} & \pm\ 8.0 \text{ MeV} \\
& \pm (\delta M_{\rm W})_{\rm th} & 4.0 \text{ MeV} \\
& \pm (\delta M_{\rm W})_{\rm top} & (\delta M_{\rm top}/0.76 \text{ GeV}) \times 5.5 \text{ MeV} \\
& \pm (\delta M_{\rm W})_{\rm H} & (\delta M_{\rm H}/0.24 \text{ GeV}) \times 0.1 \text{ MeV} \\
& \pm (\delta M_{\rm W})_{\rm Z} & (\delta M_{\rm Z}/2.1 \text{ MeV}) \times 2.5 \text{ MeV} \\
& \pm (\delta M_{\rm W})_{\alpha} & (\delta \alpha/10^{-4}) \times 1.8 \text{ MeV} \\
& \pm (\delta M_{\rm W})_{\alpha_{\rm s}} & (\delta \alpha_{\rm s}/3\times 10^{-3}) \times 2.0 \text{ MeV}
\end{aligned}$$

Main parametric errors:

- **top mass**
- **theory**
- Z boson mass
- α
- α_s
- Higgs mass

$\sin^2\theta_{\text{eff}}$: Parametric Errors



Experimental

$$\boxed{\sin^2\theta^{\ell}_{\text{eff}} = 0.23153 \pm 0.00016}$$

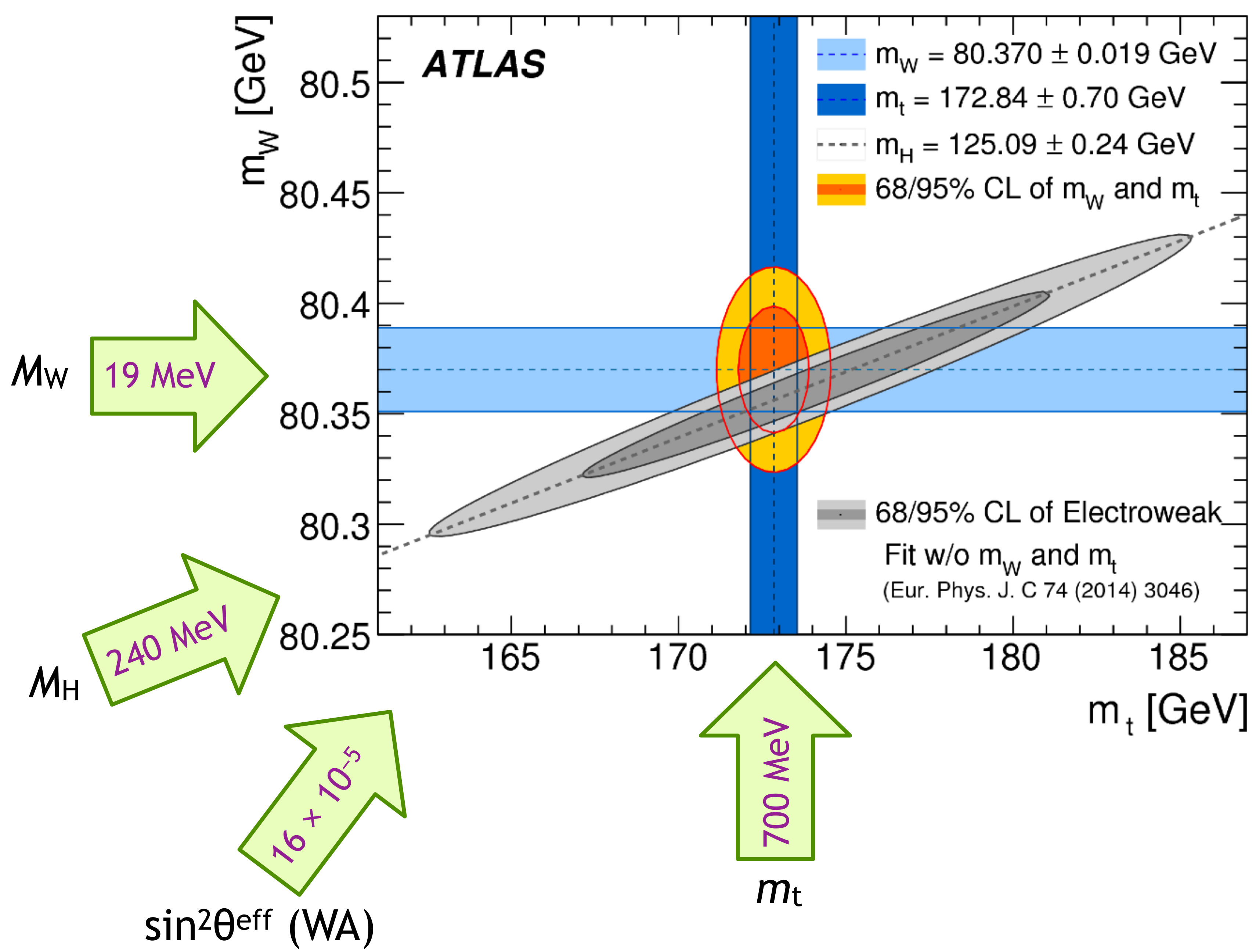
Electroweak Fit

$$
\begin{aligned}
\sin^2\theta^{\ell}_{\text{eff}} = \;& 0.231488 && \pm 7.0\times 10^{-5} \\
& \pm (\delta\sin^2\theta^{\text{eff}}_{\text{W}})_{\text{th}} && 4.7\times 10^{-5} \\
& \pm (\delta\sin^2\theta^{\text{eff}}_{\text{W}})_{\text{top}} && (\delta M_{\text{top}}/0.76\ \text{GeV}) \times 2.9\times 10^{-5} \\
& \pm (\delta\sin^2\theta^{\text{eff}}_{\text{W}})_{\text{H}} && (\delta M_{\text{H}}/0.24\ \text{GeV}) \times 0.1\times 10^{-5} \\
& \pm (\delta\sin^2\theta^{\text{eff}}_{\text{W}})_{\text{Z}} && (\delta M_{\text{Z}}/2.1\ \text{MeV}) \times 1.5\times 10^{-5} \\
& \pm (\delta\sin^2\theta^{\text{eff}}_{\text{W}})_{\alpha} && (\delta\alpha/10^{-4}) \times 3.5\times 10^{-5} \\
& \pm (\delta\sin^2\theta^{\text{eff}}_{\text{W}})_{\alpha_s} && (\delta\alpha_s/3\times 10^{-3}) \times 1.0\times 10^{-5}
\end{aligned}
$$

Main parametric errors:

- **theory**
- α
- **top mass**
- Z mass
- α_S
- Higgs mass

The Electroweak Fit at LHC



the most complete consistency test of the electroweak sector of the Standard Model

Main ingredients:
- effective weak mixing angle
- mass of the W boson
- width of the W boson
- mass of the top quark
- (mass of the Higgs boson)

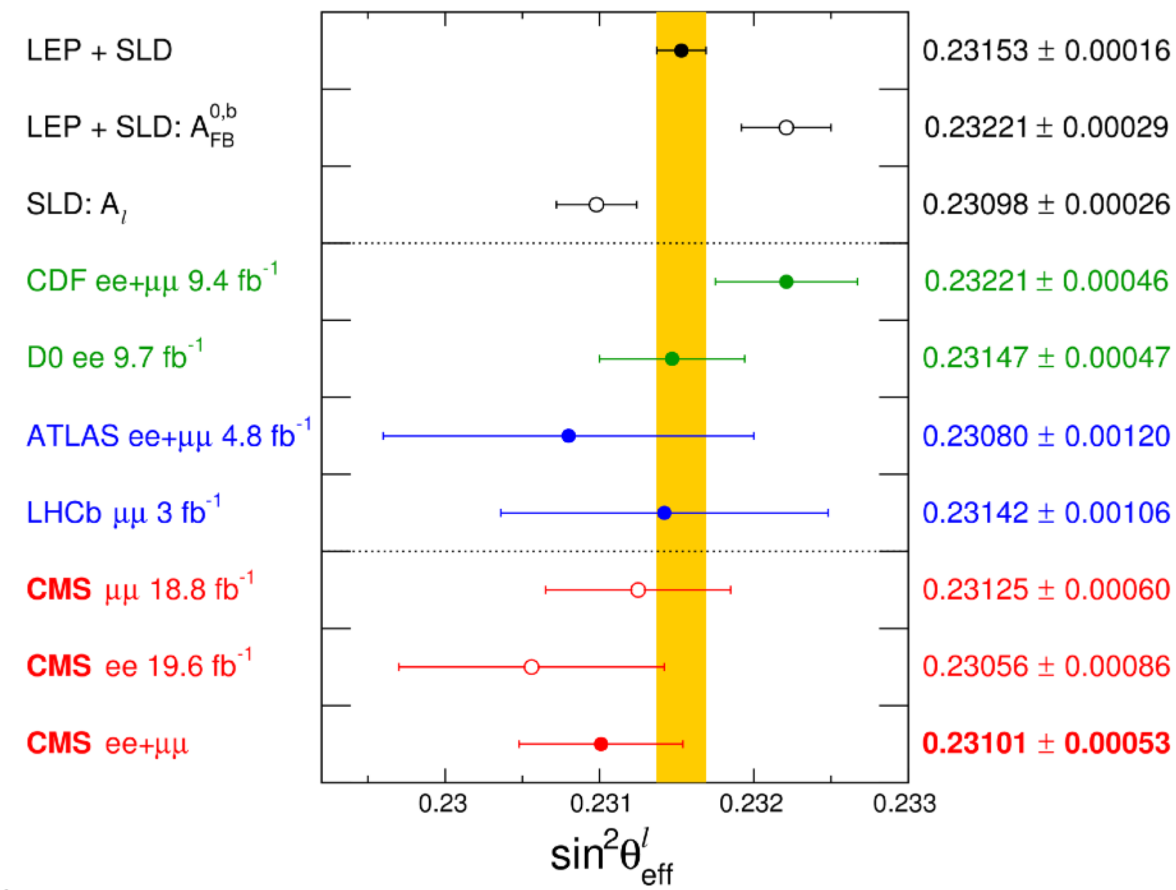
Effective Weak Mixing Angle at HL-LHC

CMS Run-1
2017

EPJC 78 (2018) 701

From A_{FB} ($\ell\ell$) in 6 rapidity bins

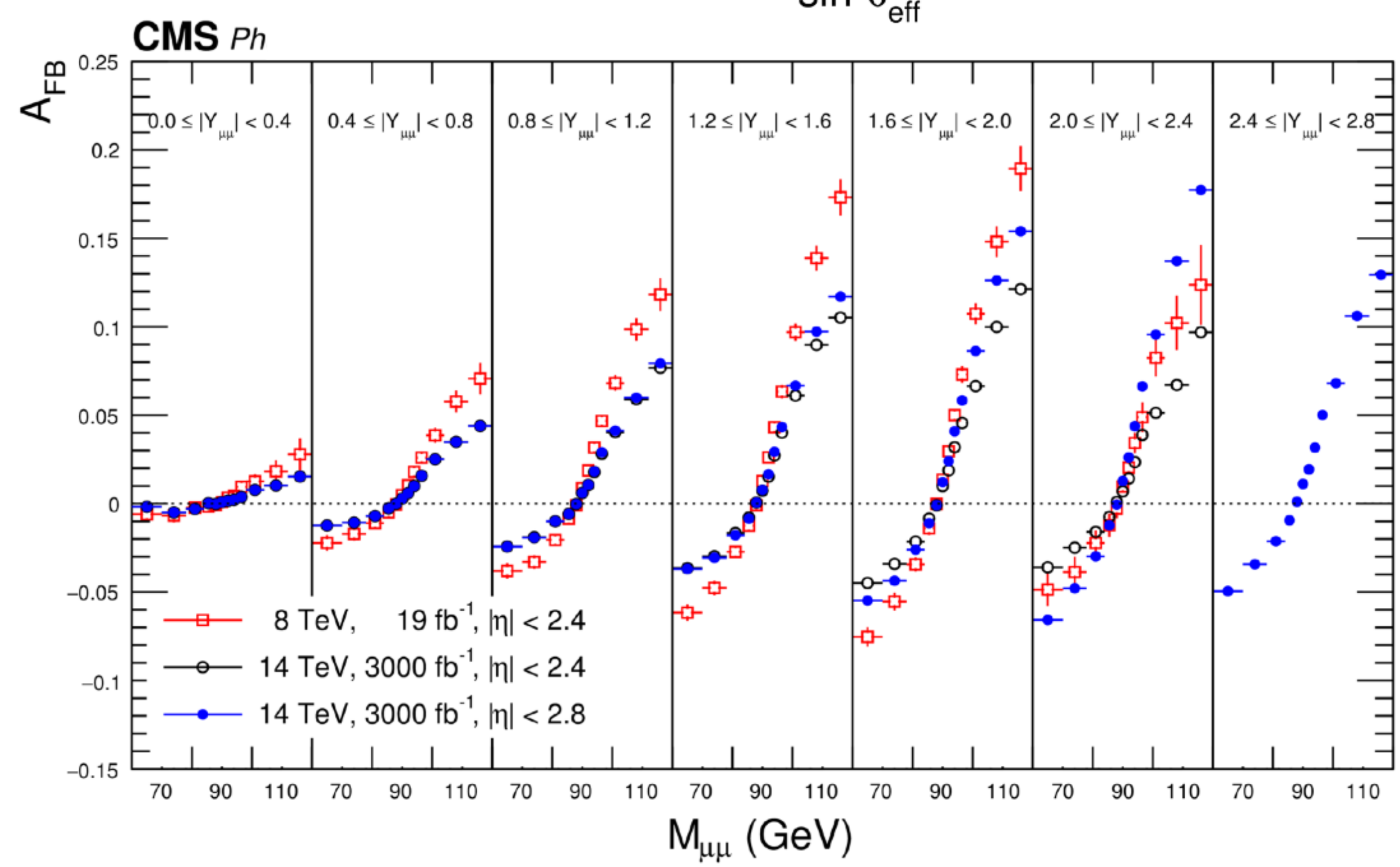
- data: Run-1 at 8 TeV
- best sensitivity in bin at larger rapidity ($2.0 < |Y_{\ell\ell}| < 2.4$)
- event reweighing method to cancel acceptance effects
- main uncertainty from PDF, but reduced by constraints from data
- combined uncertainty: ±0.00053



CMS HL-LHC
14 TeV

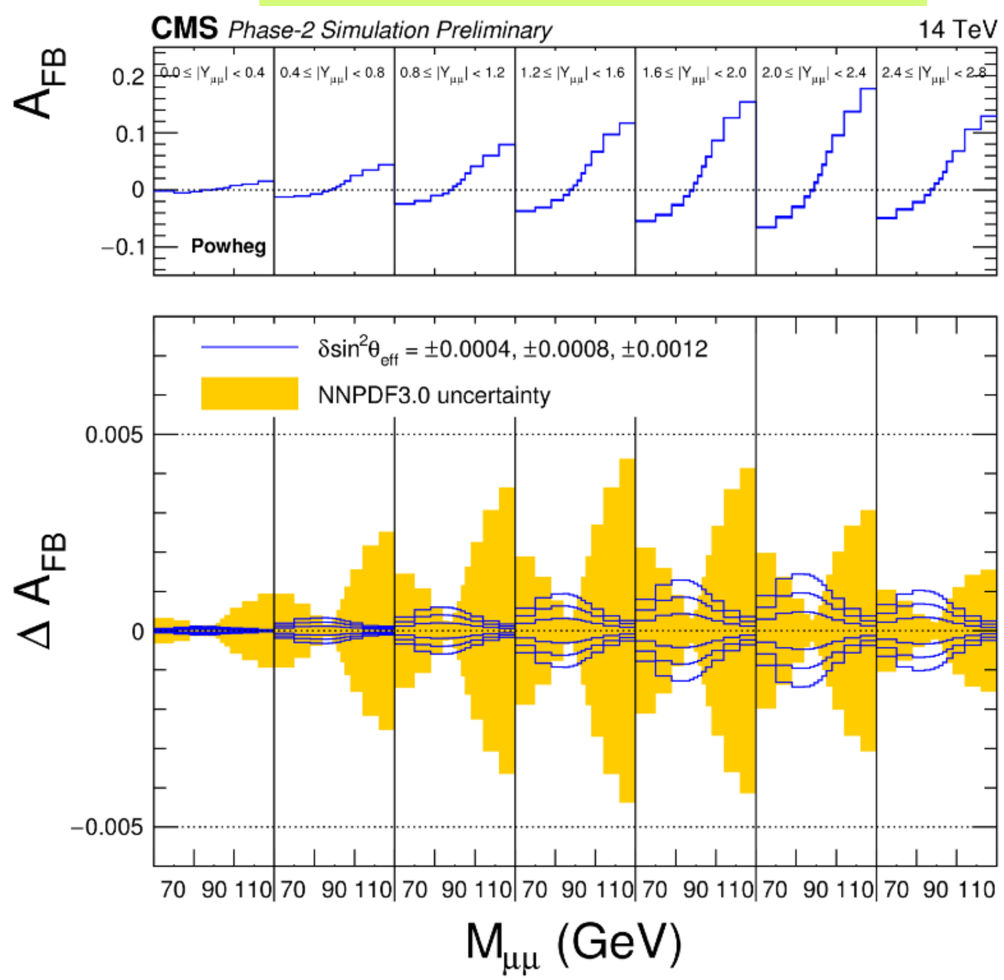
CMS-PAS-FTR-17-001

- 14 TeV ➠ smaller asymmetries at low rapidity due to wider rapidity plateau
- extension of tracker acceptance
  ➠ additional rapidity bin :
  $2.4 < |Y_{\ell\ell}| < 2.8$

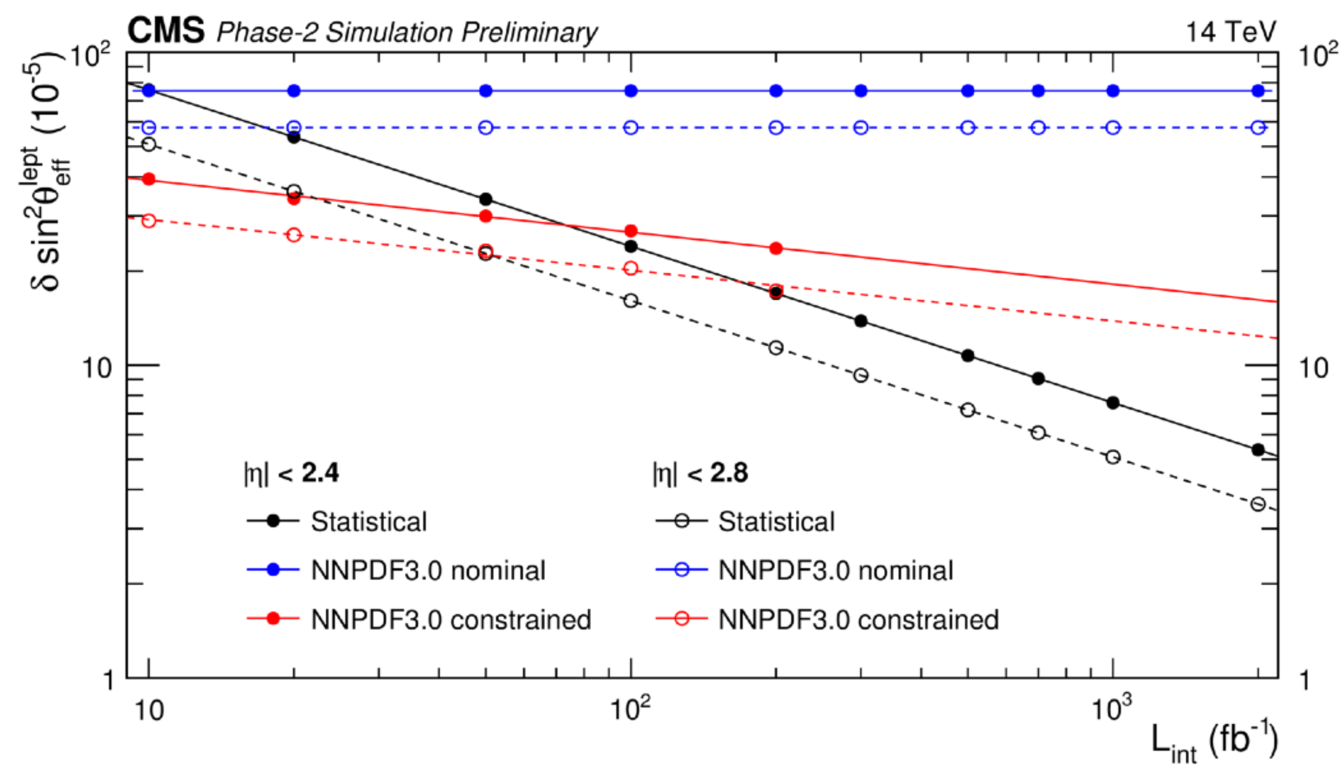


Effective Weak Mixing Angle at HL-LHC

PDF constraints from the data



CMS HL-LHC
14 TeV



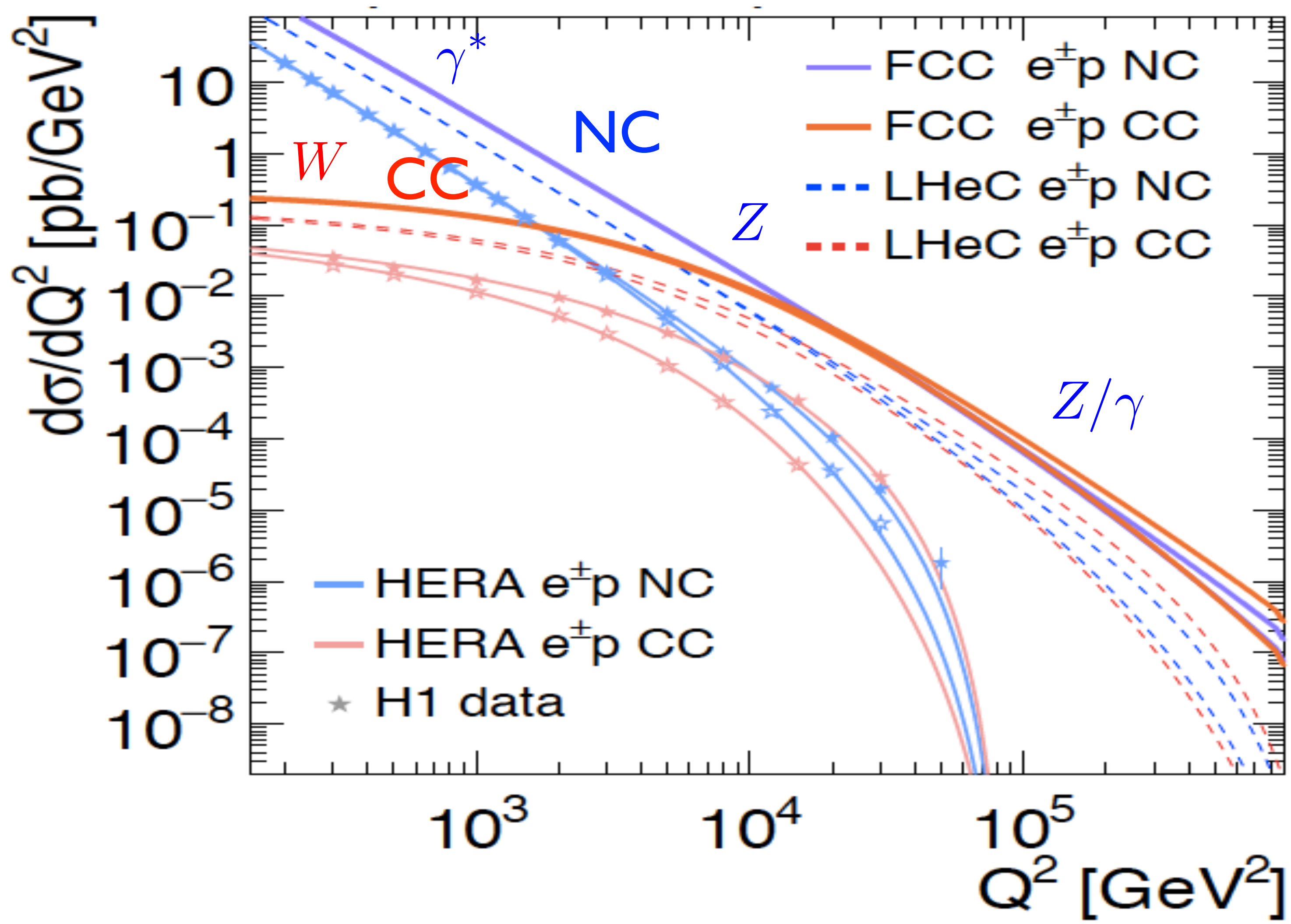
- extend di-lepton acceptance from |Y| < 2.4 to |Y| < 2.8
  ➠ improvement 30% statistical and 20% PDF uncertainty
- statistical uncertainty negligible beyond L = 300 fb^{-1}
- with 3000 fb^{-1} and constraining PDF from the data, envision reaching present LEP/SLD uncertainty (±0.00020)

CMS-PAS-FTR-17-001

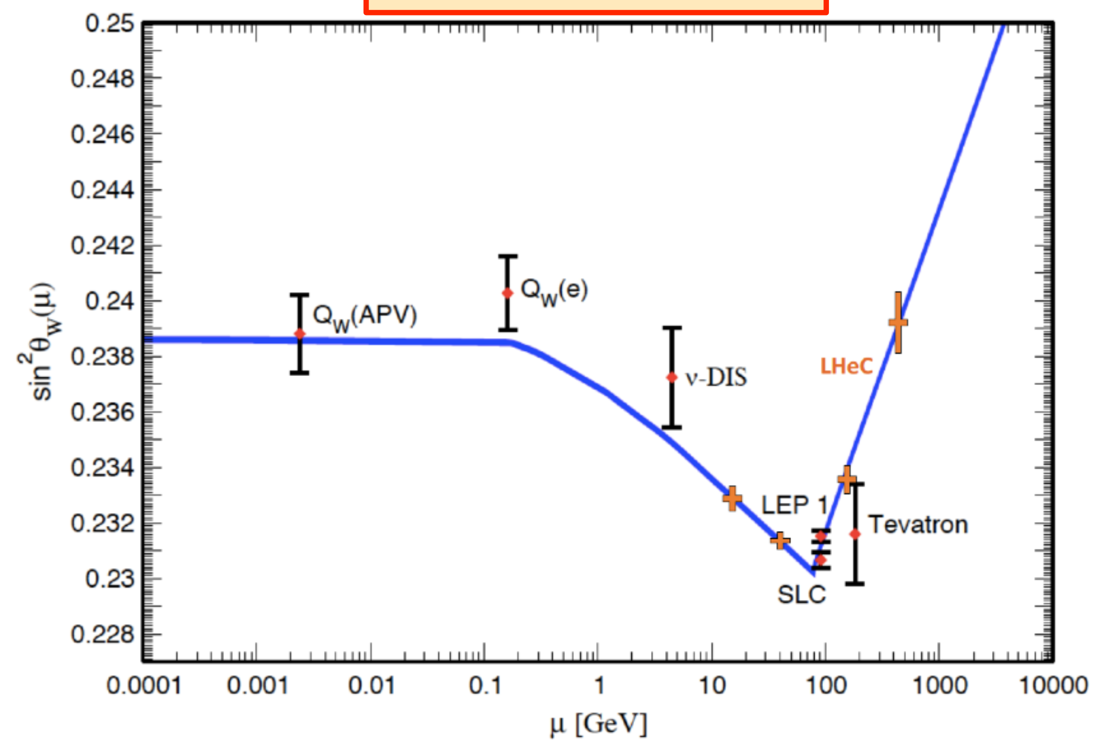
A ±0.00020 error in $\sin^2\theta_{eff}$ is equiv. to ±10 MeV error in M_W (indirect)

Vector and Axial Couplings at LHeC

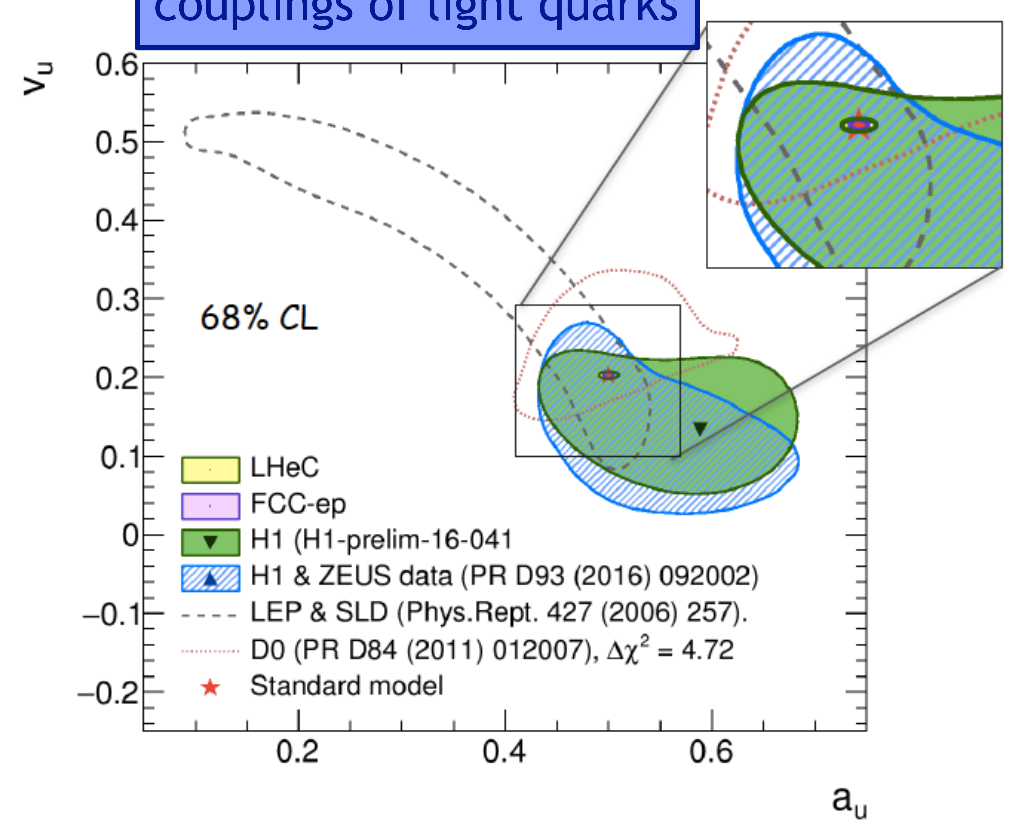
unpolarised e±p cross section



running of $\sin^2\theta_W(\mu)$



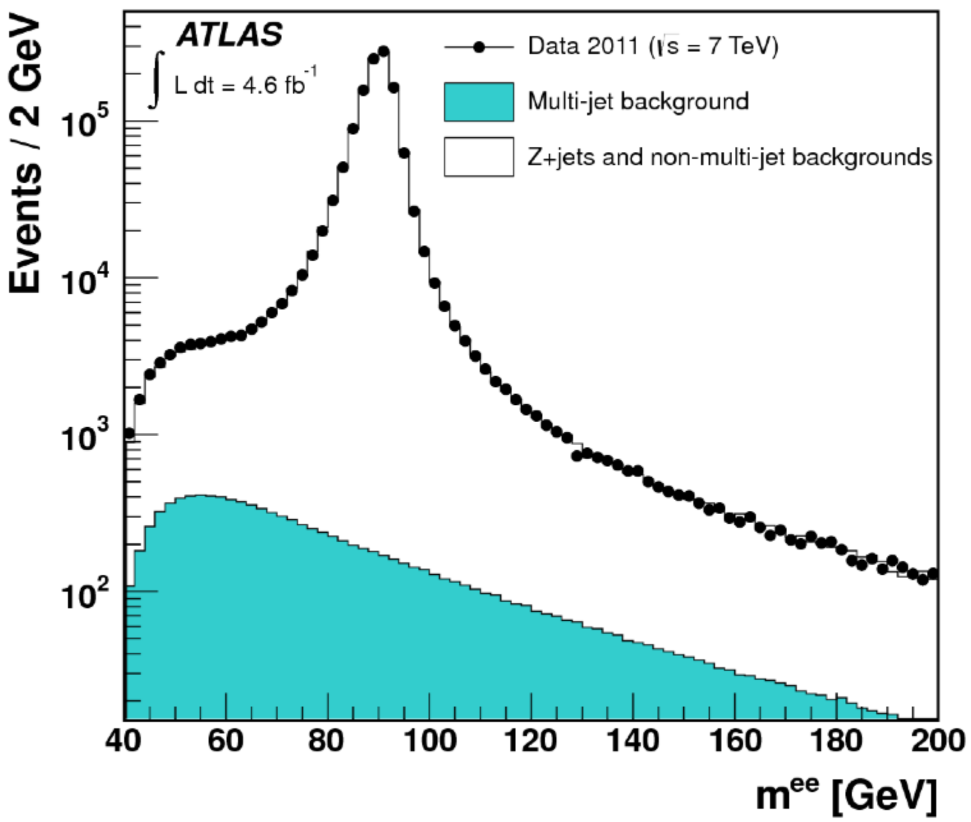
couplings of light quarks

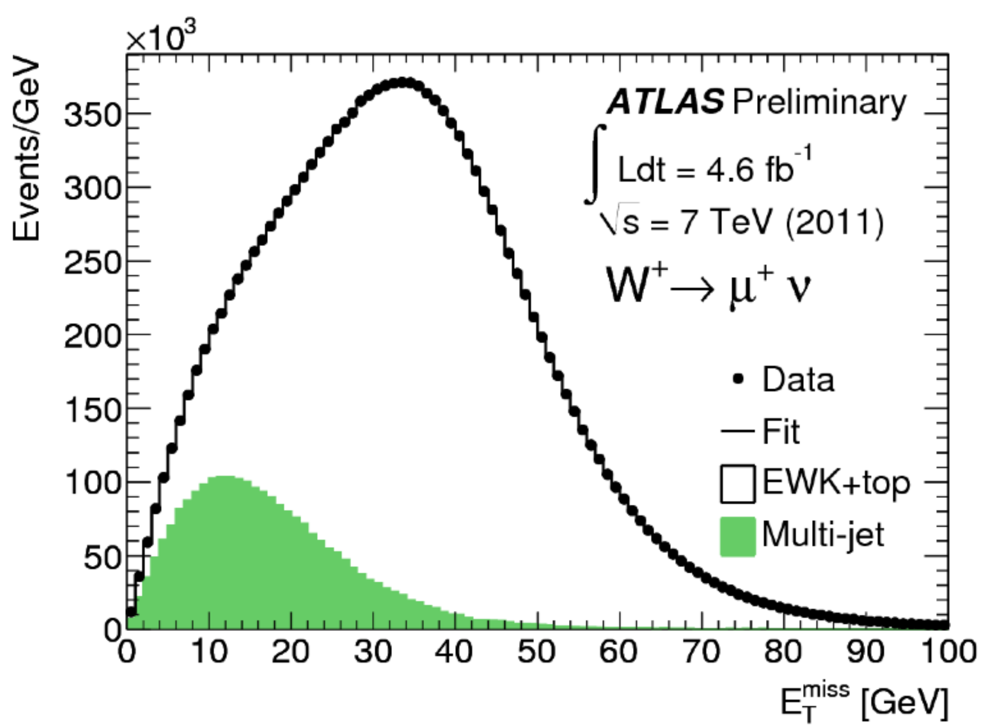


- NC cross sections at high Q^2 receive important Z boson and γ/Z interference contributions
- together with CC cross sections, they are sensitive to electroweak parameters
- also interesting Higgs and BSM physics

$$\alpha_W^{-1} = \alpha_{\rm QED}^{-1} \sin^2\theta_W \simeq 30$$

EWK Bosons at LHC





Z boson

- Dilepton invariant mass

$$M^2 = 2\, p_{\mathrm{T}}(\ell_1) p_{\mathrm{T}}(\ell_2)\, (\cosh \Delta\eta_{12} - \cos \Delta\phi_{12})$$

W boson

- Lepton transverse momentum
- Missing transverse energy

$$p_{\mathrm{T}}(\nu) = E_{\mathrm{T}}^{\mathrm{miss}}$$

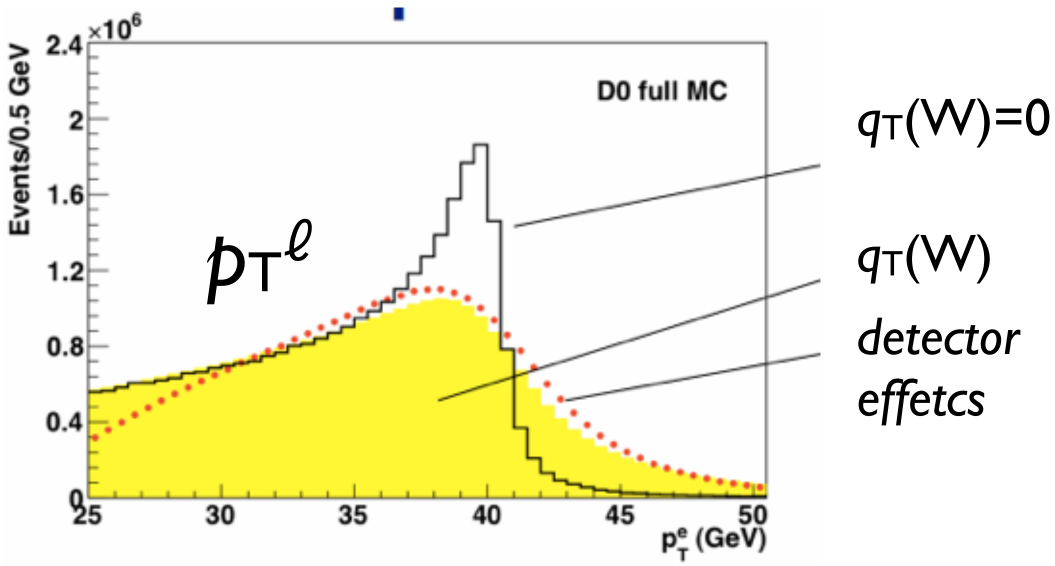
- Transverse mass

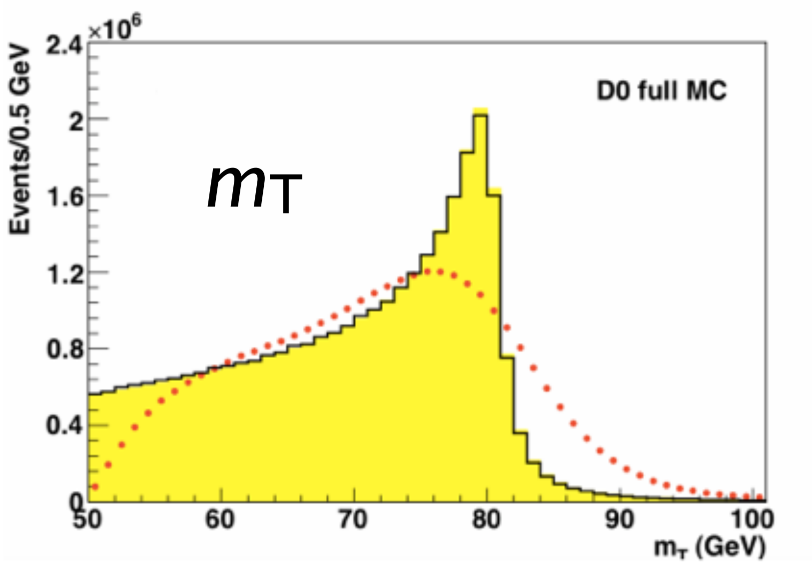
$$M_{\mathrm{T}}^2 = 2\, p_{\mathrm{T}}(\ell) p_{\mathrm{T}}(\nu)\, (1 - \cos \Delta\phi(\ell, \nu))$$

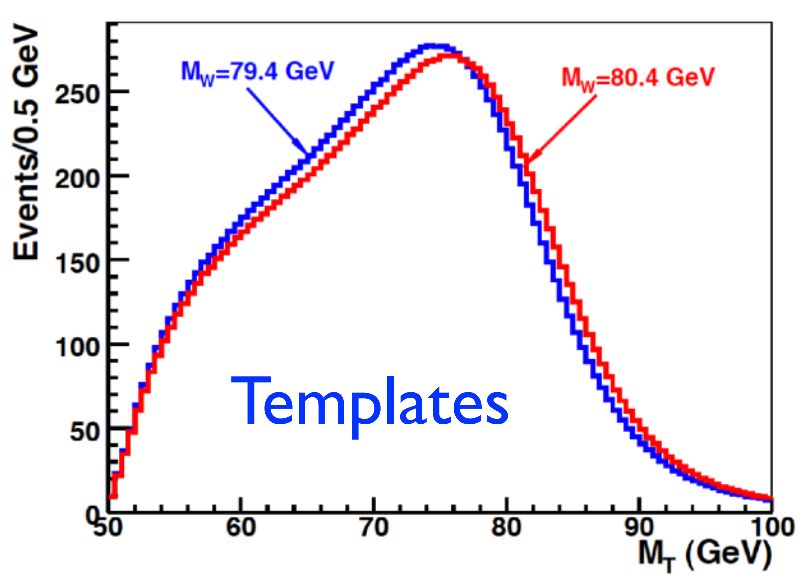
$$\Delta\phi(\ell, \nu)$$

angle between lepton and
missing momentum
in transverse plane

Principle of W Mass Measurement at LHC







The transverse mass is

- less sensitive to the $q_T(W)$ spectrum
- much more sensitive to the hadronic recoil

But, due to pile-up, lepton p_T is the most promising at the LHC

Experimental challenges

- control the lepton energy scale at < 0.1%
- pile up conditions

Theoretical challenges

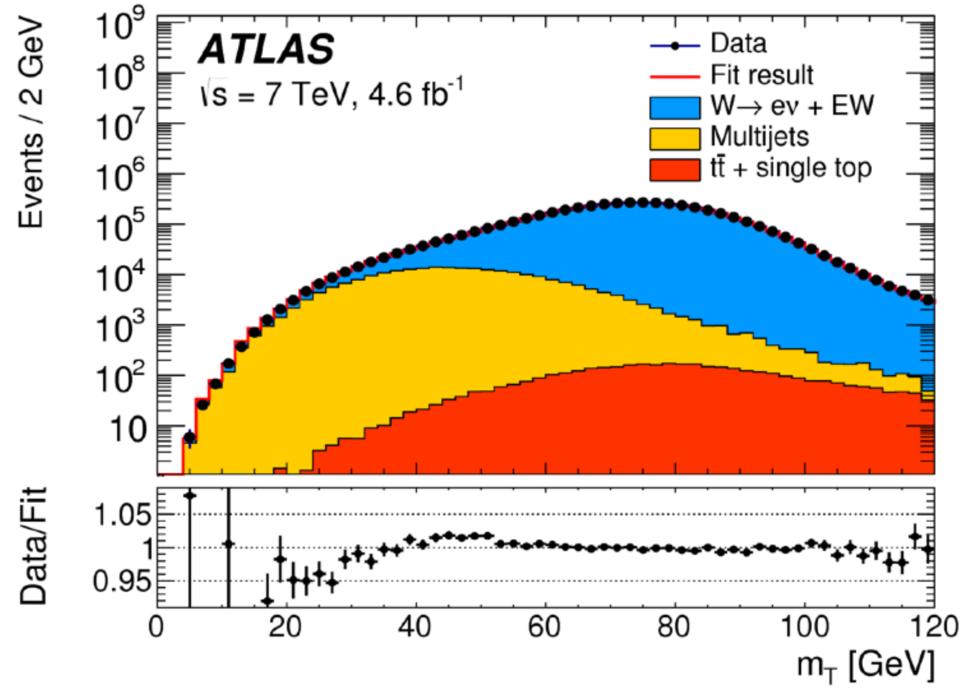
- modelling of the $q_T(W)$
- modelling of the templates obtained from simulation with corrections in q_T, y and A_i
- knowledge of the PDFs

W Mass Measurement at LHC

ATLAS: first measurement of the W mass

One of the most challenging measurements at the LHC

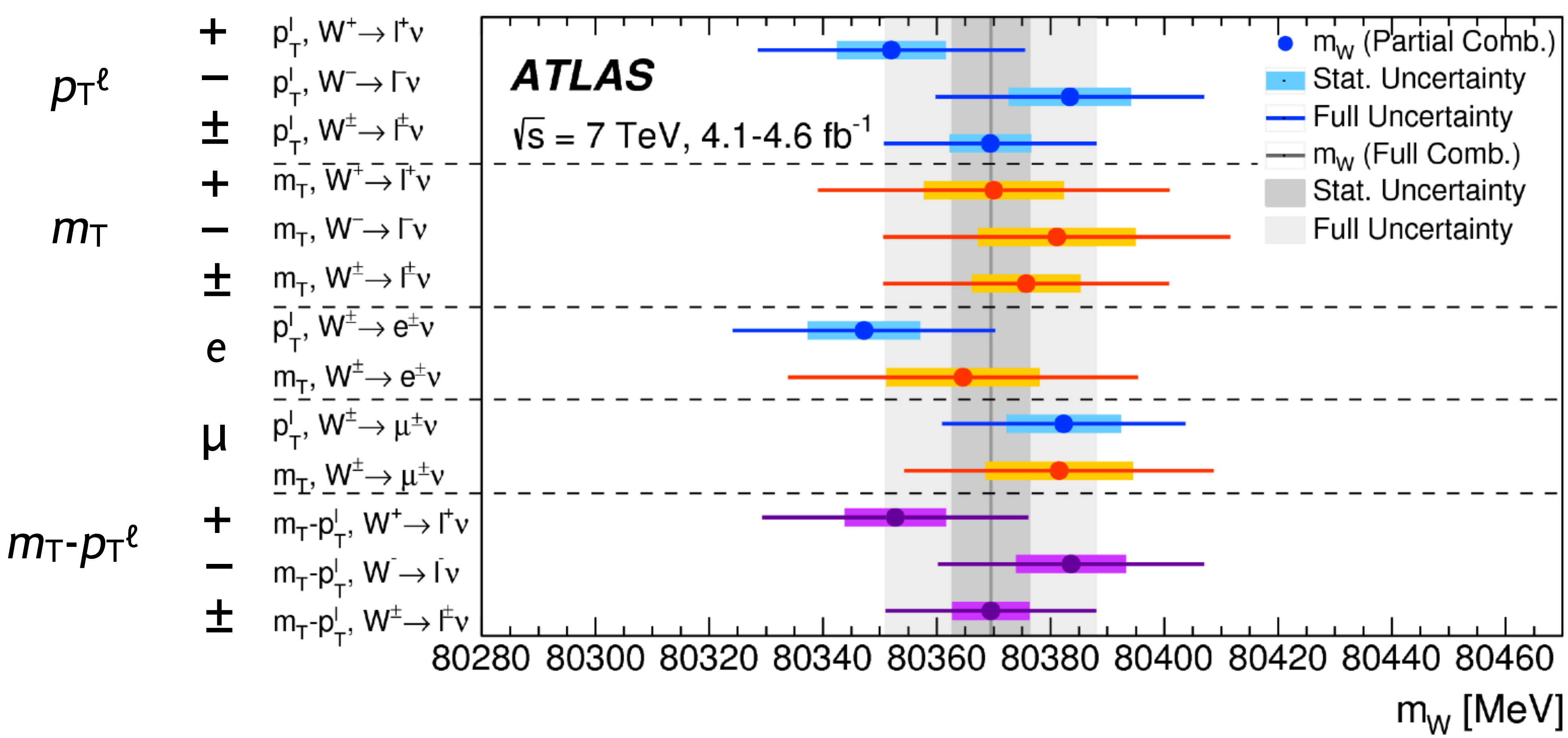
arXiv:1701.07240



Error budget

- total = 18.5 MeV
- stat. = 6.8 MeV
- PDF = 9.2 MeV
- QCD = 8.3 MeV

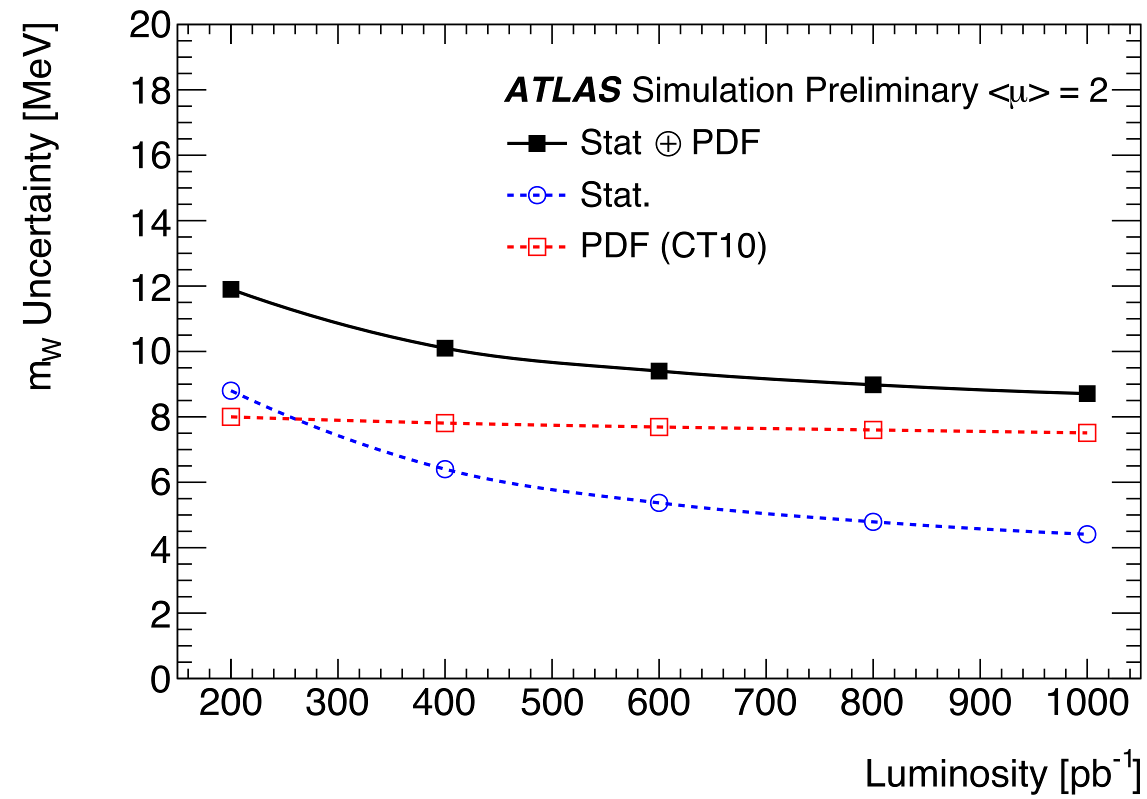
Crosschecks in many categories



W Mass Measurement at HL/EH-LHC

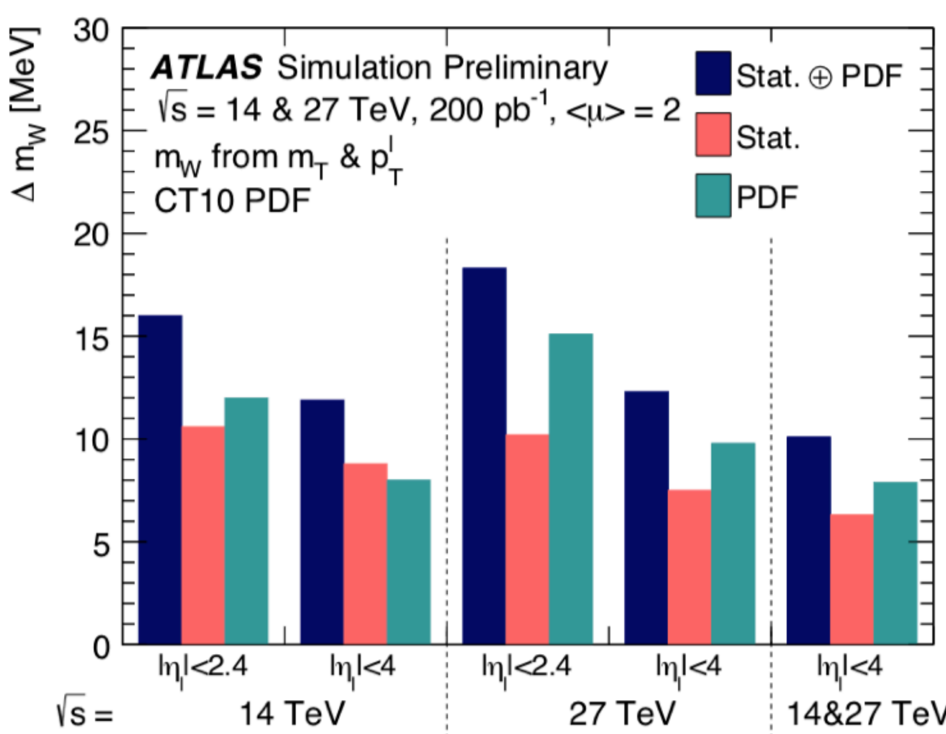
- Low-PU special runs to exploit missing transverse momentum
- Sizeable improvement from acceptance extended to |η| < 4 due to barrel/endcap anti-correlations

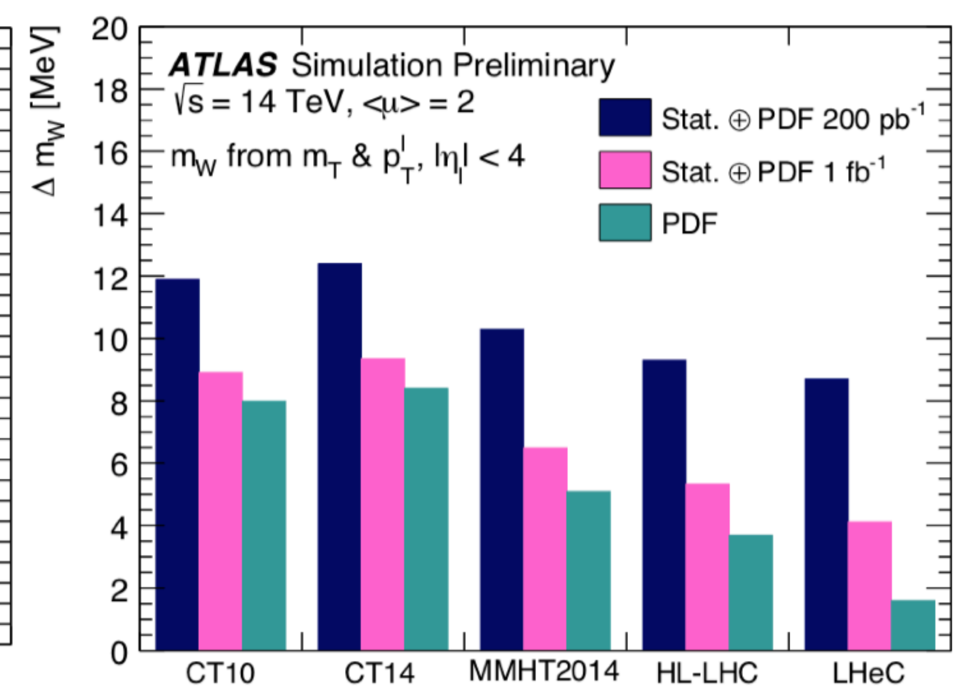
HL-LHC Low-PU special runs (<μ> = 2)			
$\mathscr{L}$	acceptance	# of events	δm_W (MeV)
200 pb^{-1}	|η| < 2.4	2×10^6	16
	|η| < 4		**12**
1 fb^{-1}	|η| < 4		9
	with ultimate PDFs		**5**



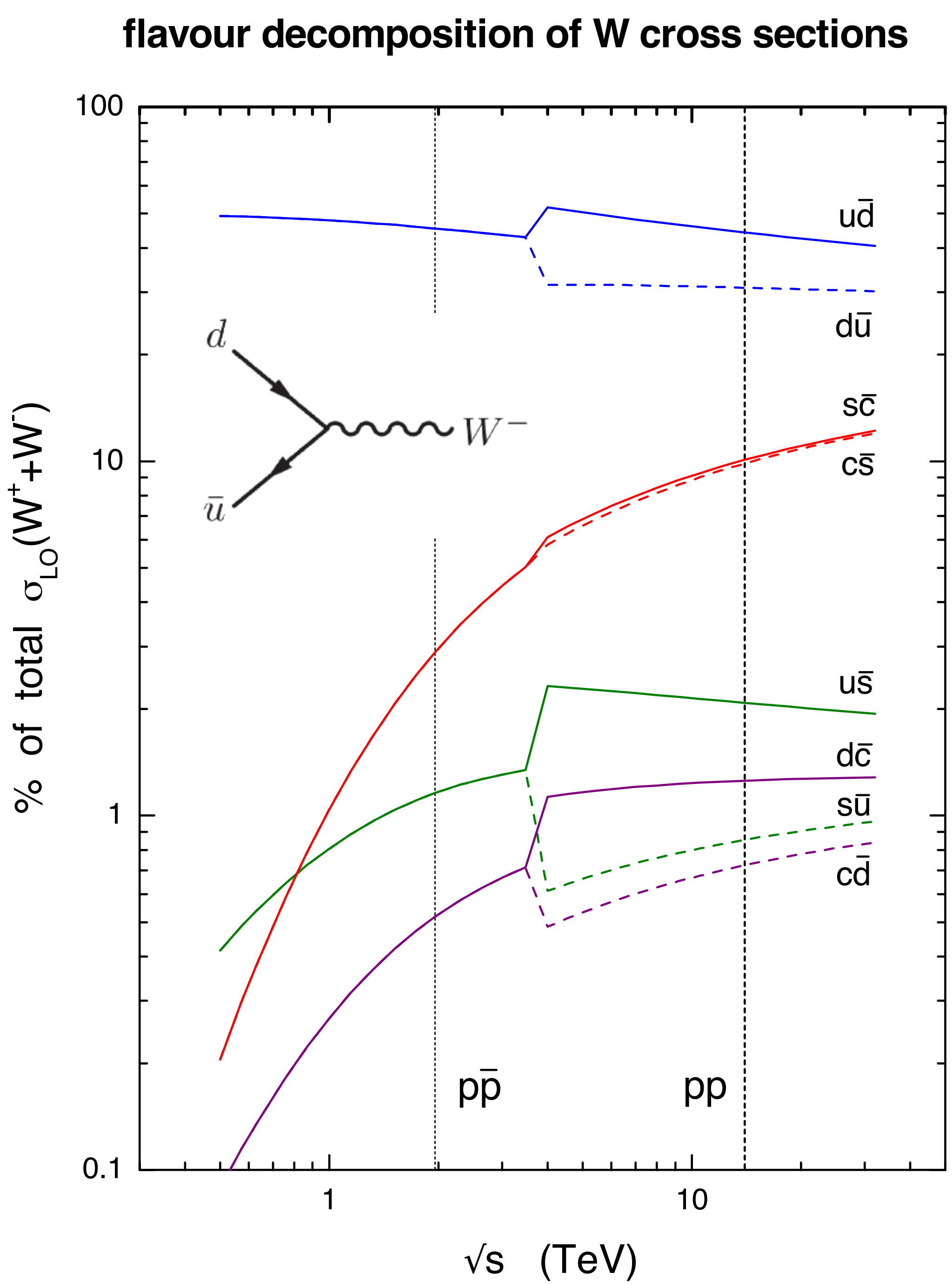
Above 200 fb−1 uncertainties are dominated by PDFs

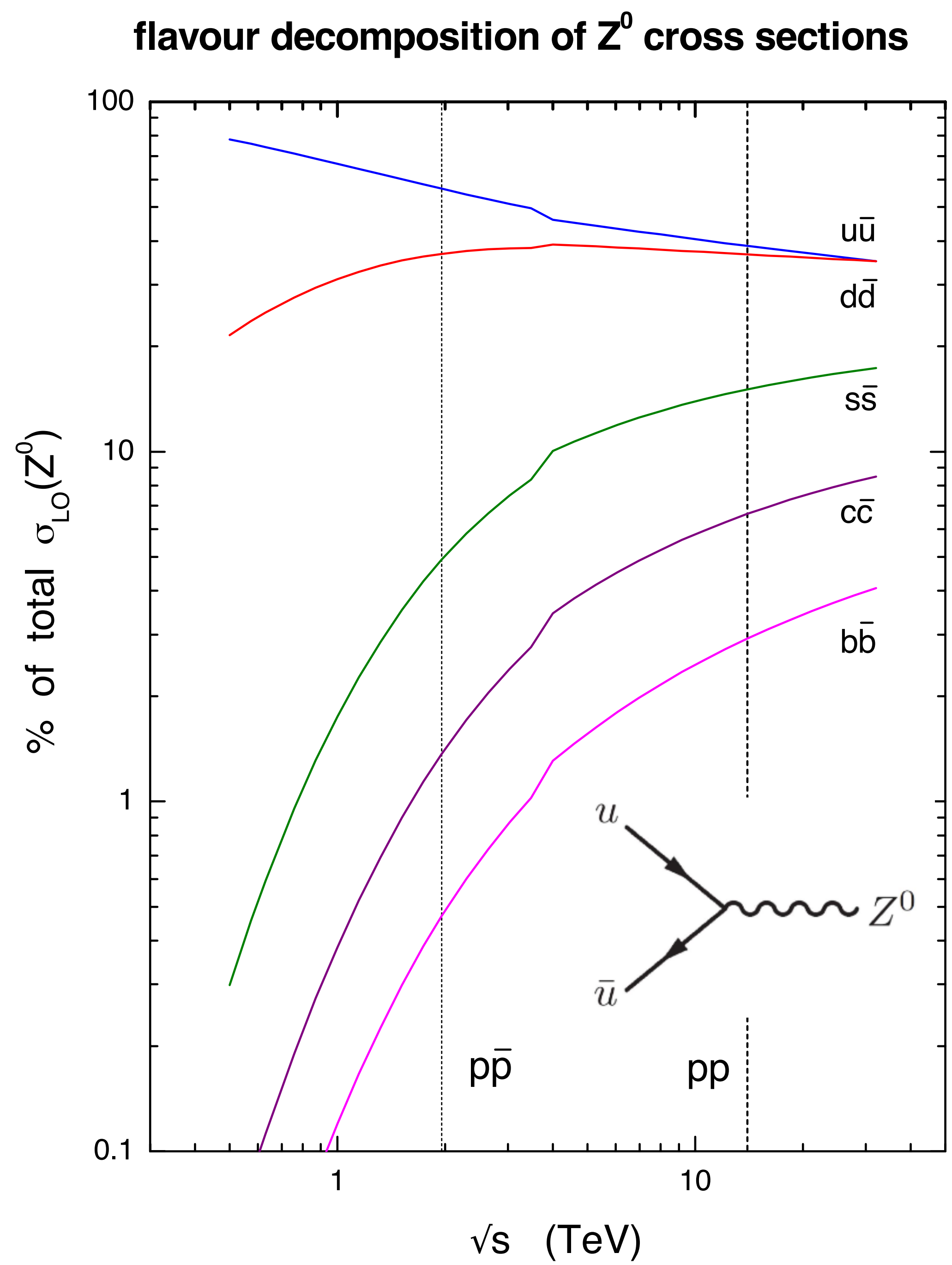
Improvements on the knowledge of PDFs (including for heavy flavours) are essential





DY and Heavy Flavour

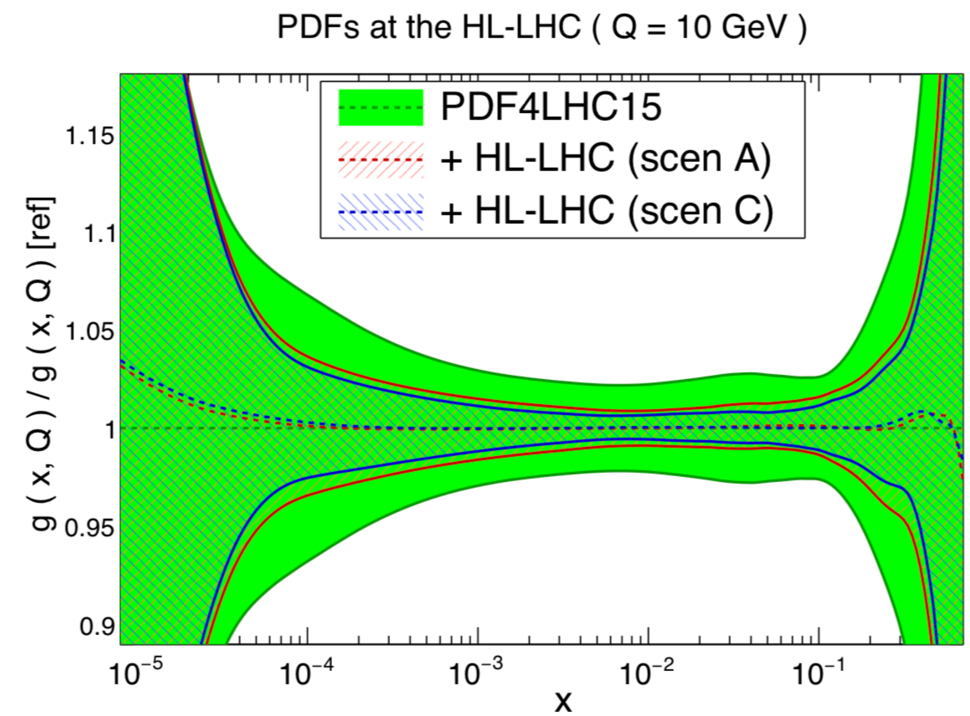


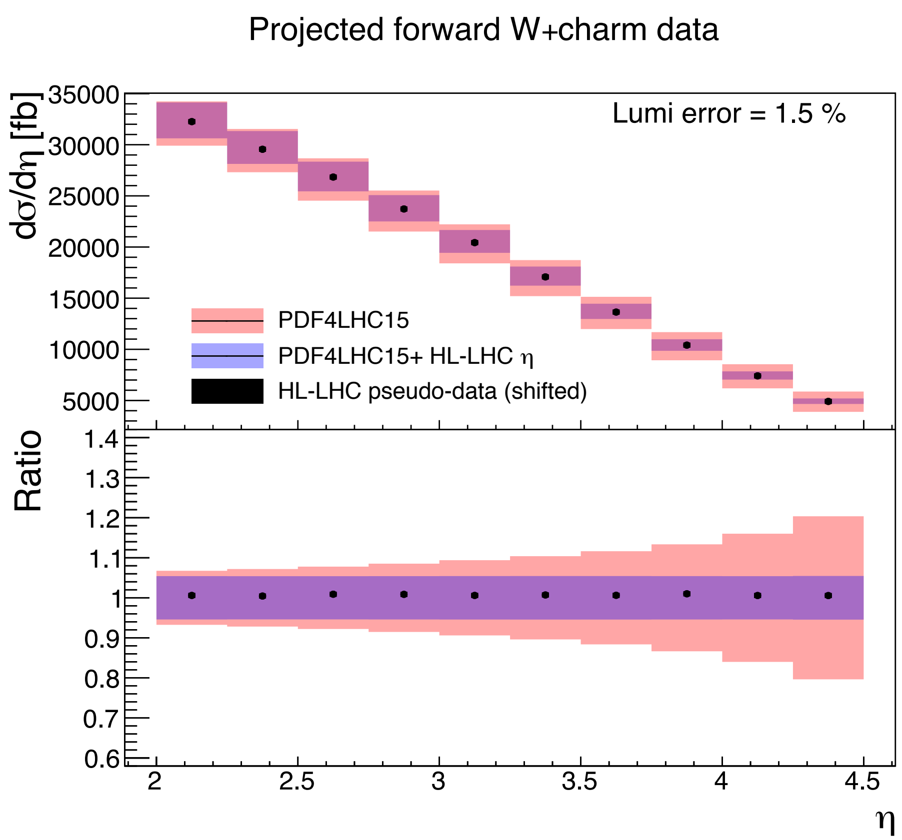


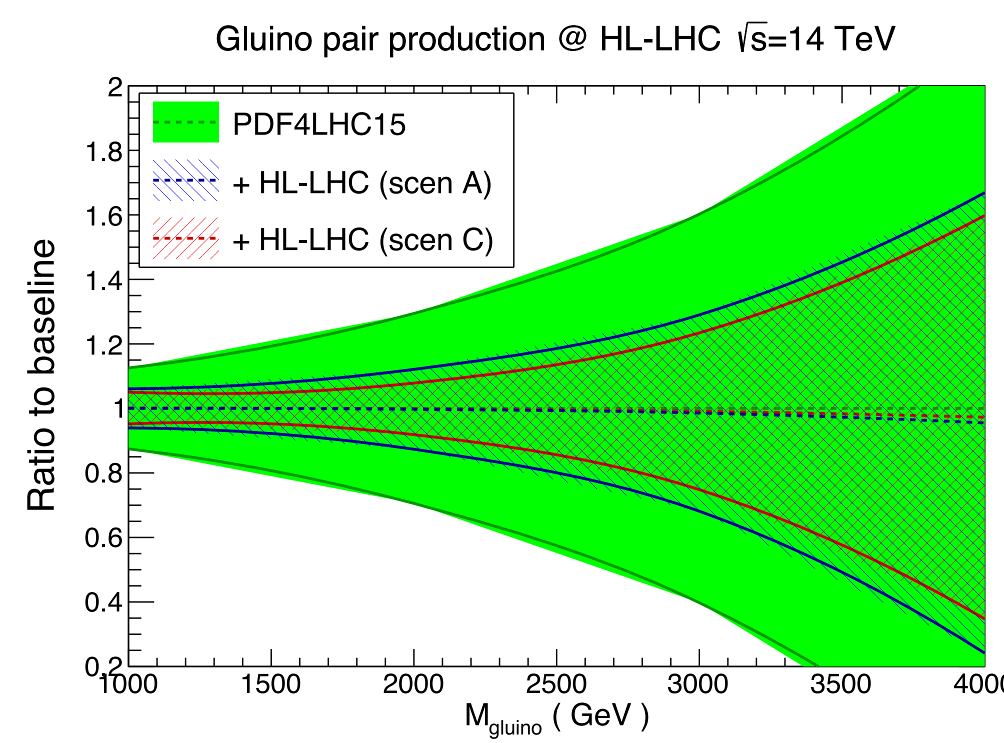
- the contribution of sea quarks is much more important at the LHC
- the use of the Z control sample for the W mass is not trivial at the LHC

Parton Density Functions

- PDFs contribute to systematic uncertainties in many flagship analyses at LHC (including Higgs coupling measurements)
- LHC participates to PDFs improvements for HL-LHC through $t\bar{t}$, DY, W+charm, inclusive jet and photon differential production cross-sections







arXiv:1810.03639

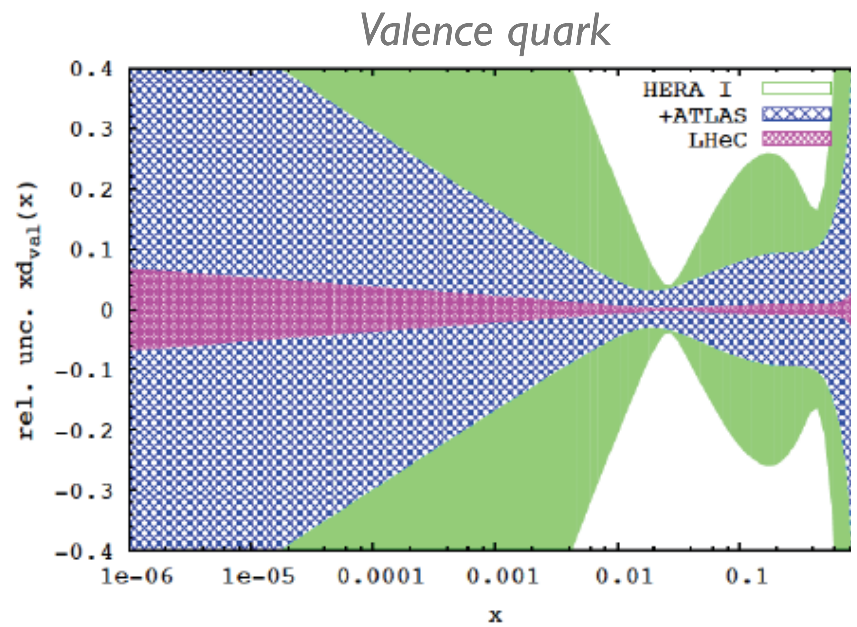
improvements by factor of 2-5 possible

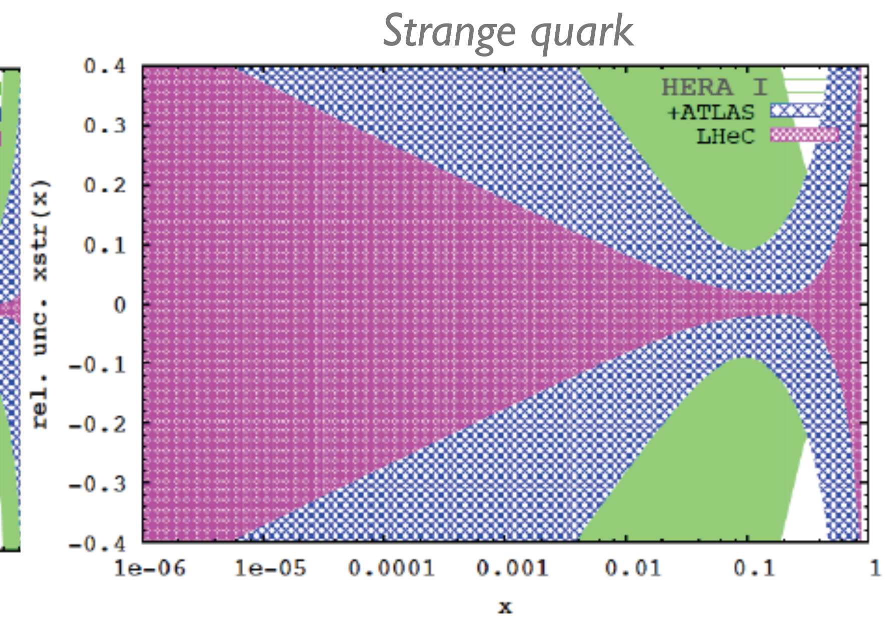
Improved Precision with LHeC

PDFs at LHeC

☛ CC and NC
- unprecedented precision in extended kinematic region

☛ CC DIS with charm tagging
- strange quark PDFs





Electroweak precision measurements at the LHC are limited by PDF uncertainties

M_W at ATLAS (2017)
- total = 18.5 MeV
- stat. = 6.8 MeV
- **PDF = 9.2 MeV**
- QCD = 8.3 MeV

$\sin^2\theta_{eff}$ at CMS (2018)
- total = 53×10^{-5}
- stat. = 36×10^{-5}
- **PDF = 31×10^{-5}**
- theory = 16×10^{-5}

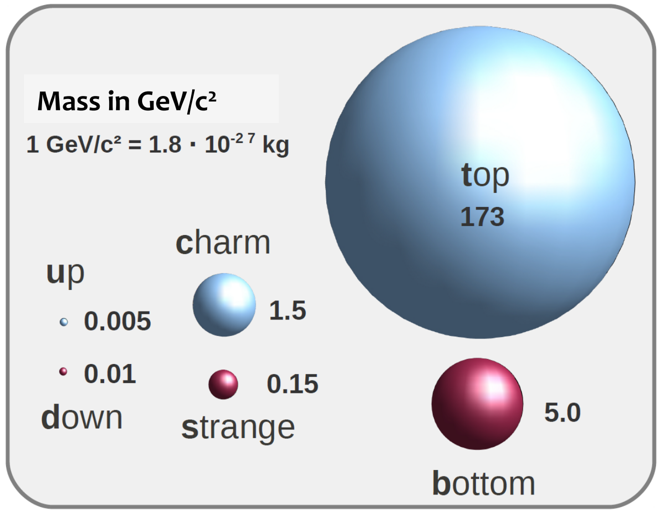
With full HL-LHC
- 5-9 MeV on M_W
- 15×10^{-5} on $\sin^2\theta_{eff}$

With full HL-LHC+LHeC
- <2 MeV on M_W
- 4×10^{-5} on $\sin^2\theta_{eff}$

LHeC greatly empowers LHC/HL-LHC results
- NP exclusion limits
- x-section measurements
- high precision QCD measurements
- per-mil α_s measurement

ATL-PHYS-PUB-2018-026

The Top Quark



40 times heavier than the b quark!

The top quark

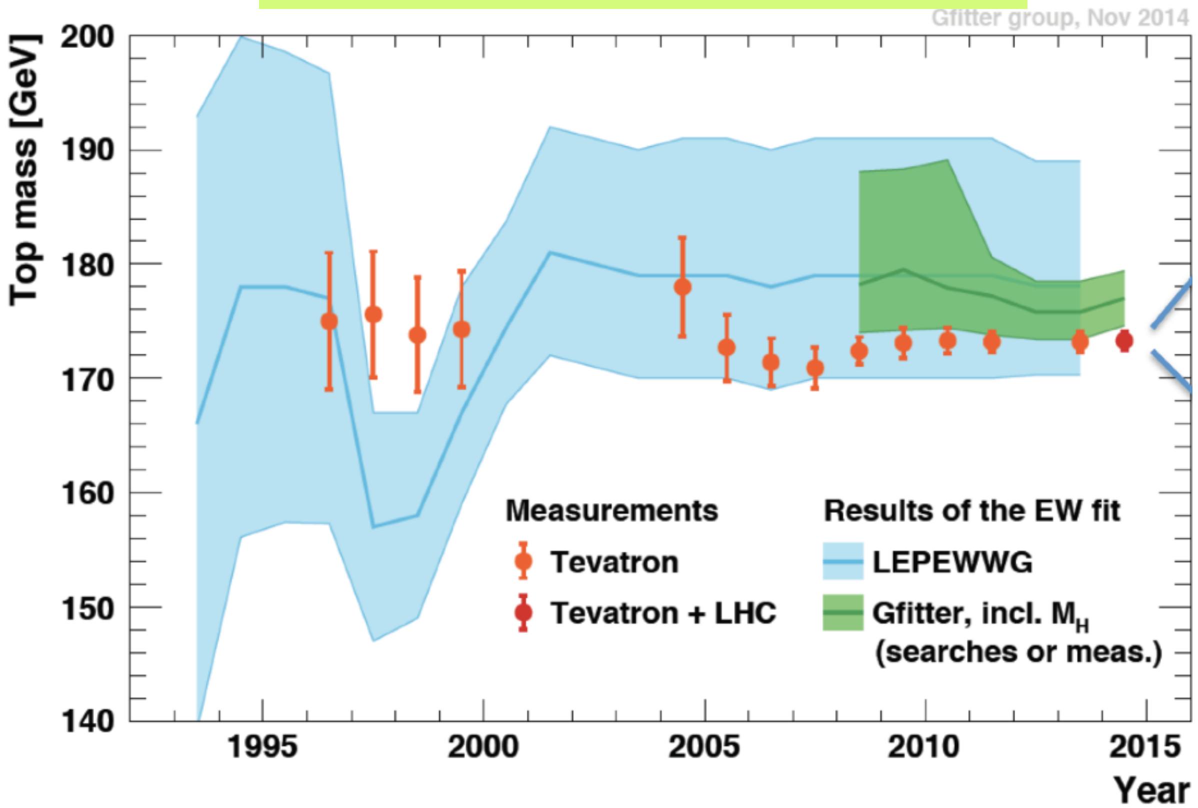
- is the $SU(2)_L$ partner of the bottom quark
- is the heaviest known fundamental particle

$$m_t = y_t v/\sqrt{2} \simeq 173 \text{ GeV}$$

- is the only fermion with "natural" coupling to the Higgs field

$$\Rightarrow \quad y_t \simeq 1$$

top quark first discovered "virtually"



- plays a special role in electroweak physics, flavour physics and Higgs physics
- decays almost exclusively to bW
- decays before it has time to hadronise

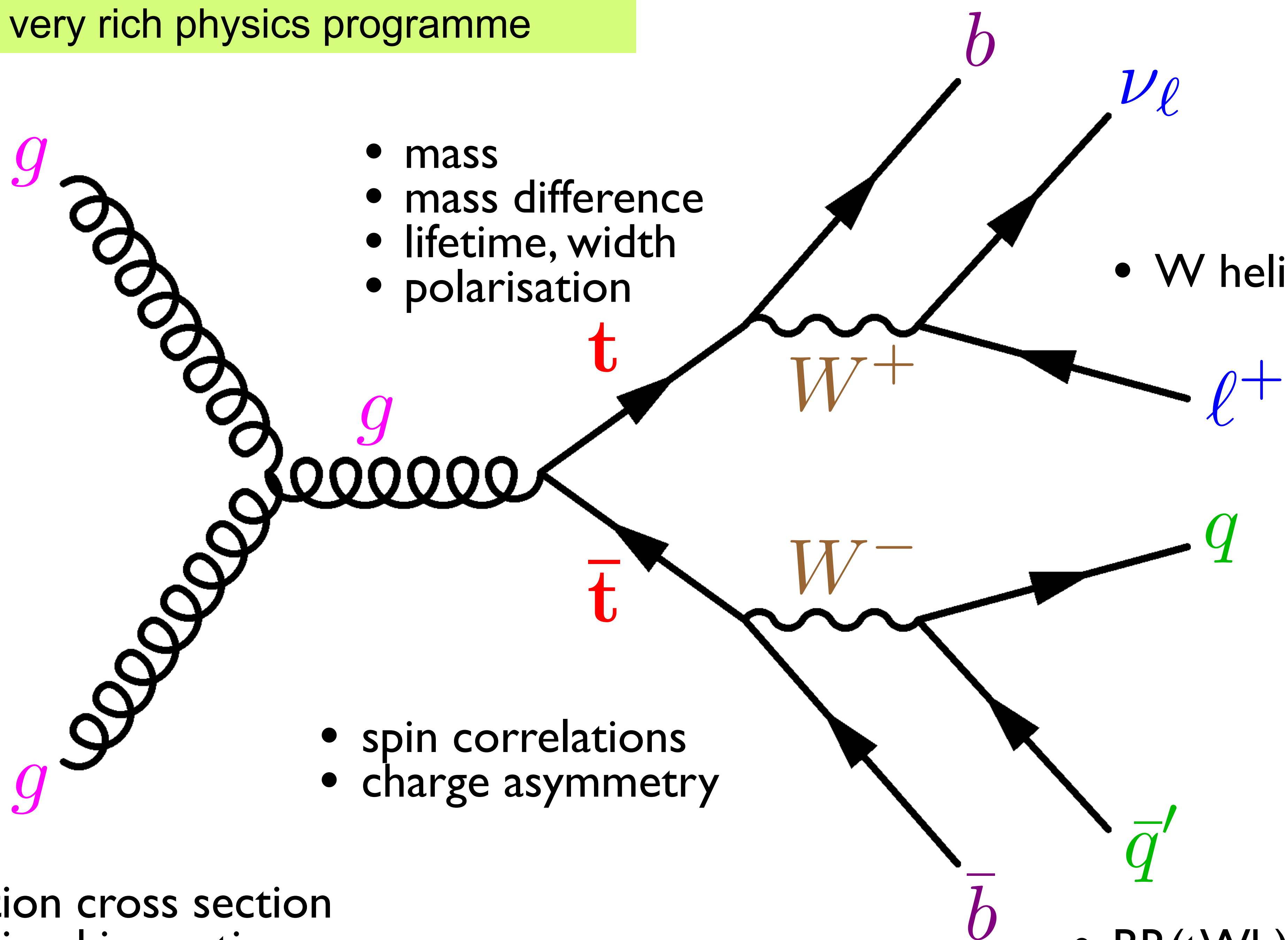
$$\Gamma(t \to bW^+) \approx \frac{\alpha}{16 s_W^2} |V_{tb}|^2 \frac{m_t^3}{m_W^2}$$

$\sim$1.5 GeV (> Λ_{QCD})

typical top decay time: 5×10^{-25} s
typical hadronisation time: 2×10^{-24} s

Top Pair Production

a very rich physics programme



- mass
- mass difference
- lifetime, width
- polarisation

- W helicity

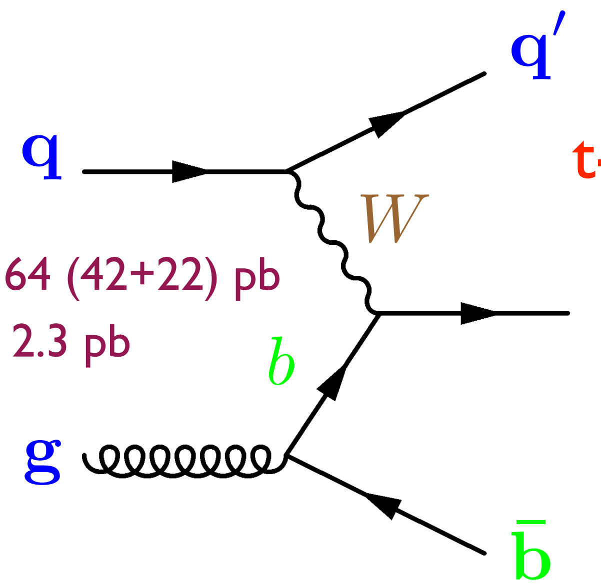
- spin correlations
- charge asymmetry

- production cross section
- production kinematics
- resonances, new particles

- BR(tWb)/BR(tWq)
- new decays

Single Top Production

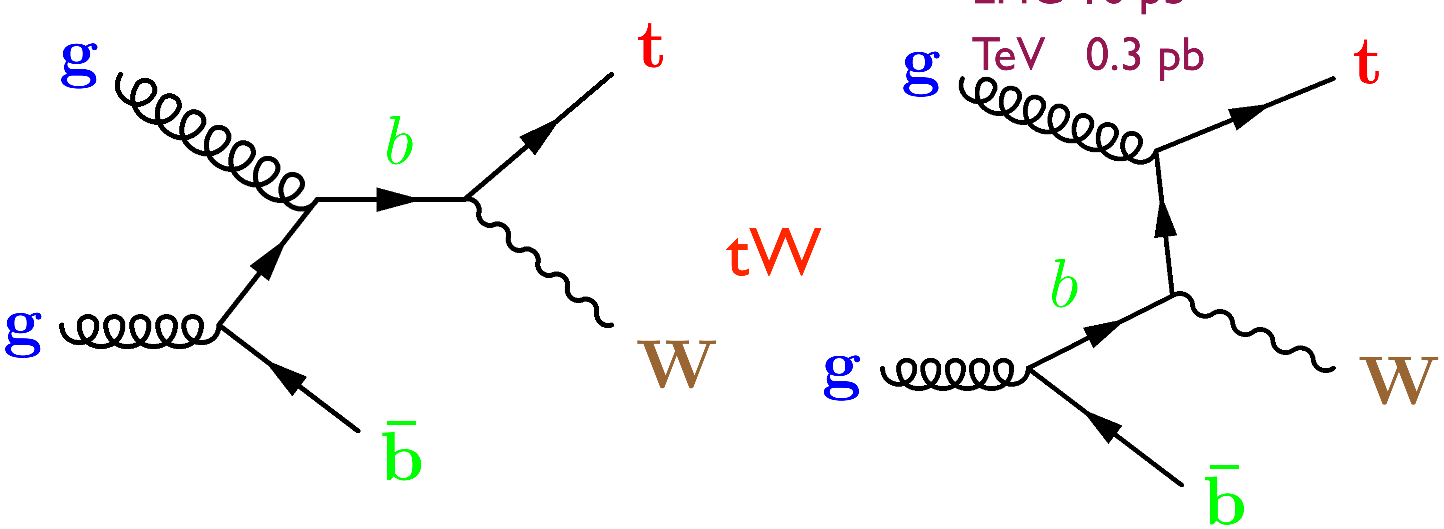
EW production of a top quark



t-channel

LHC 64 (42+22) pb
TeV 2.3 pb

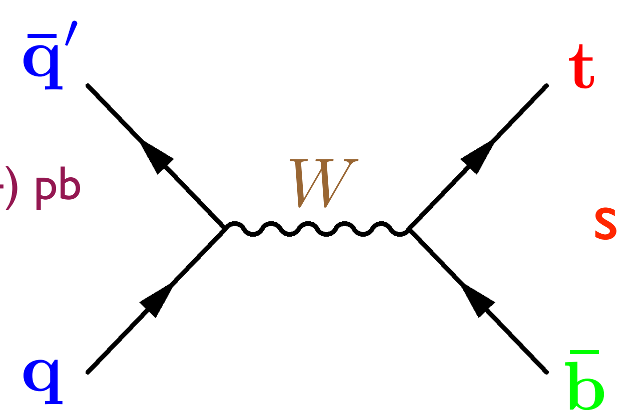
measured



tW

LHC 16 pb
TeV 0.3 pb

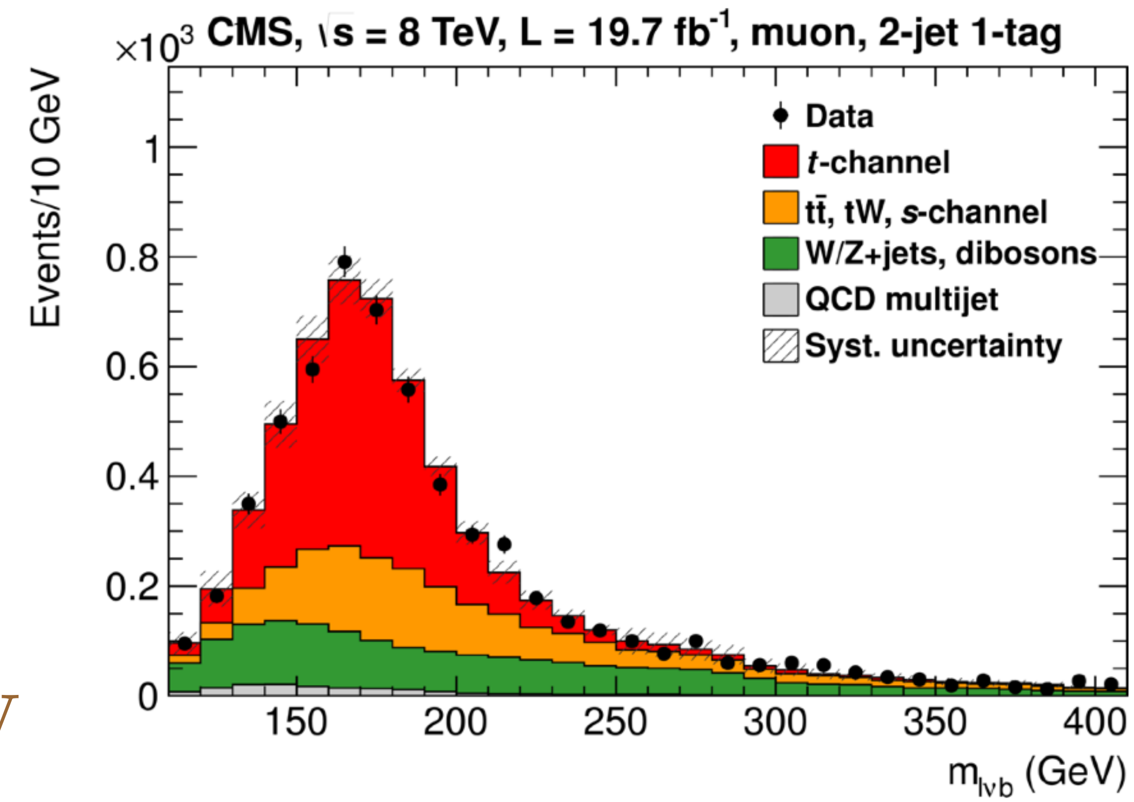
seen



s-channel

LHC 4.5 (3.2+1.4) pb
TeV 1.00 pb

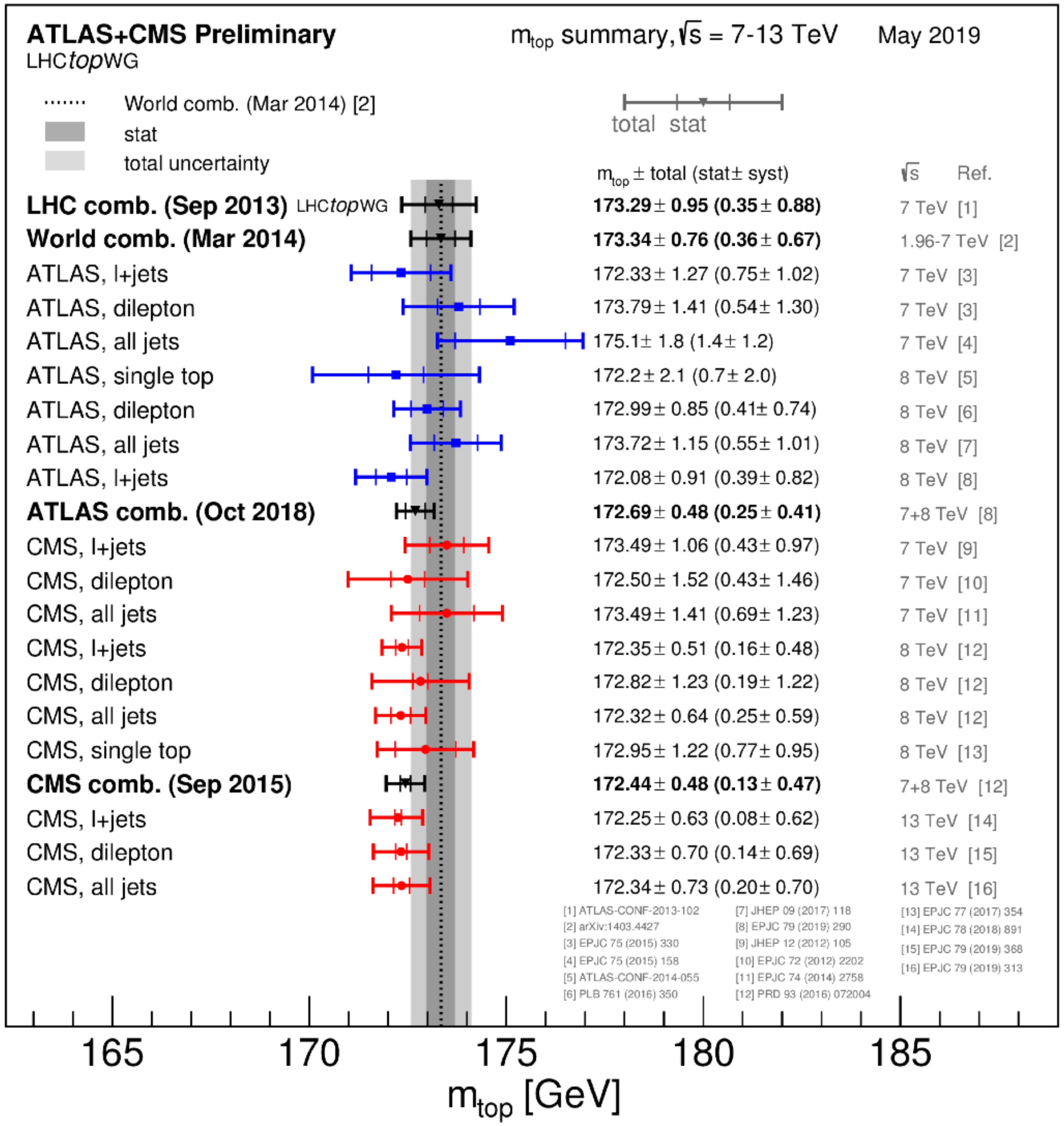
not seen yet

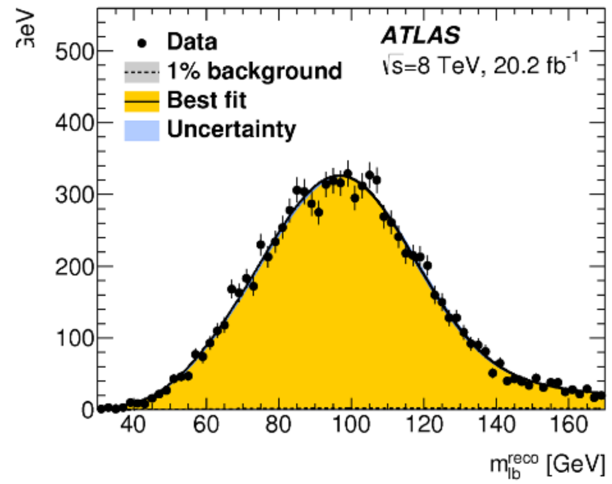


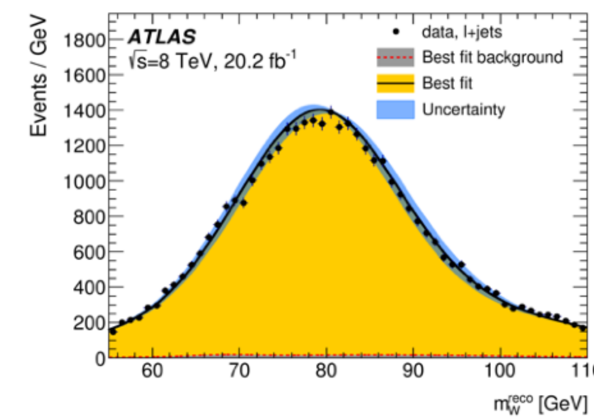
allows direct measurements of V_{tb}

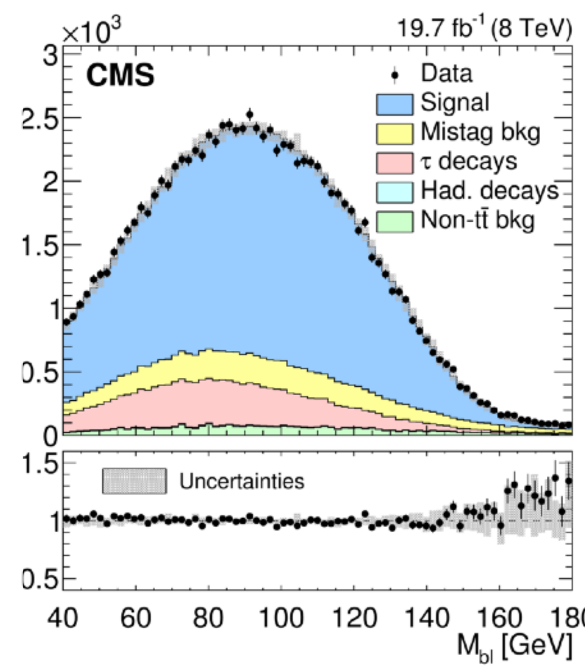
also, with high statistics. at HL-LHC, top mass measurement with different modelling systematics

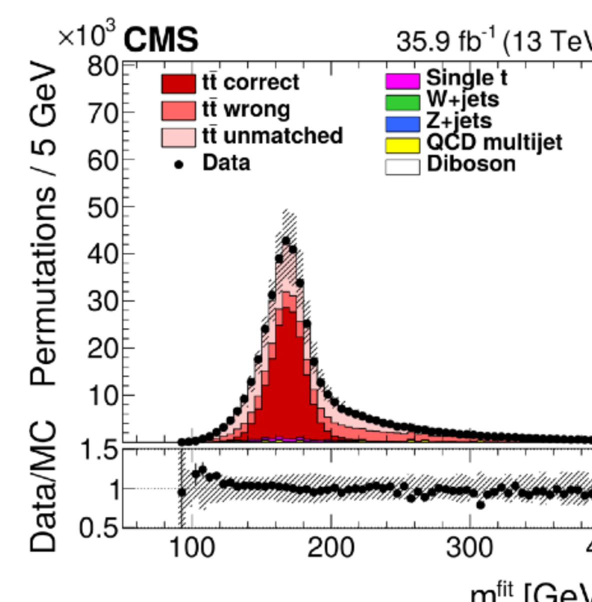
Top Mass Measurement at LHC









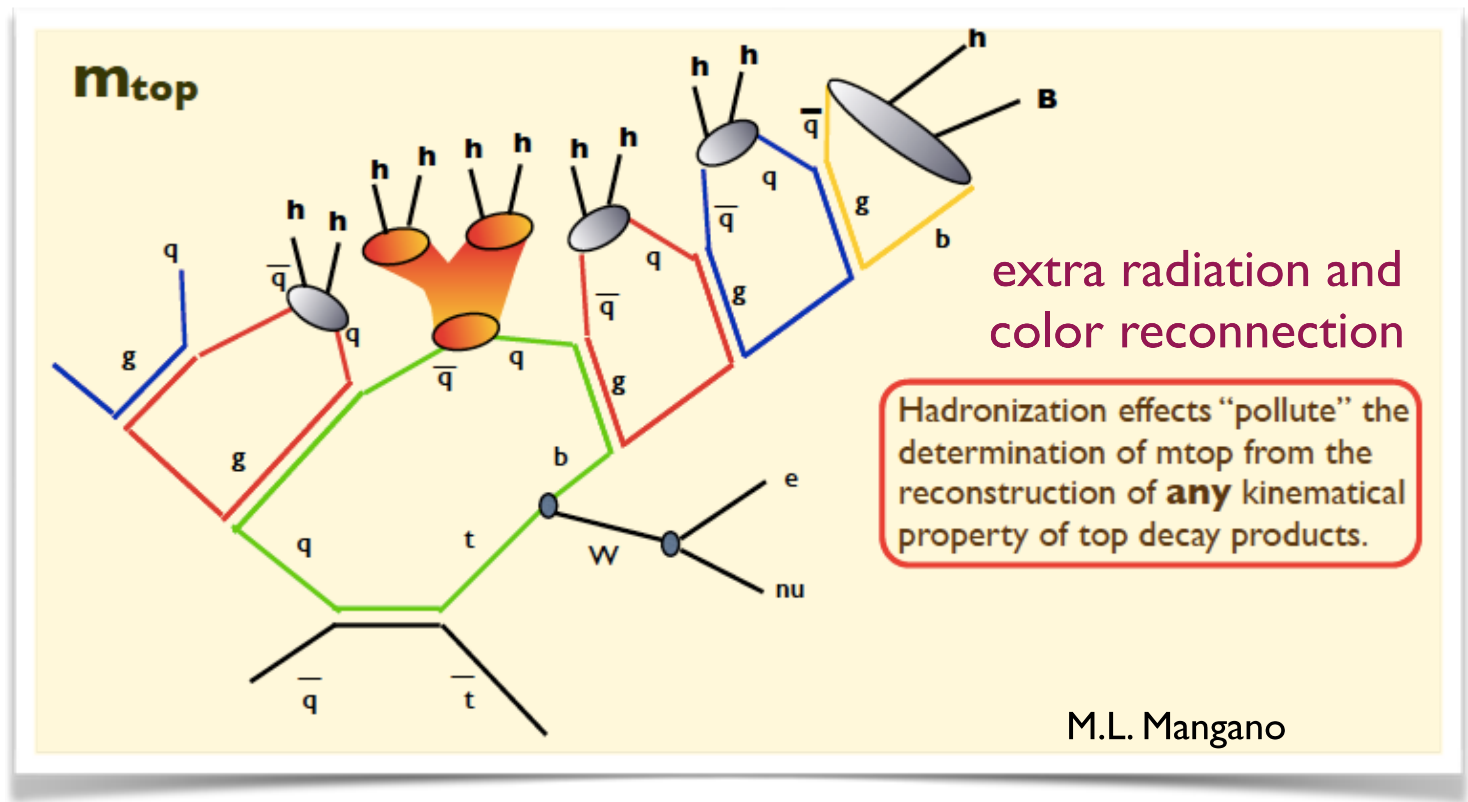


Which Top Mass for the Electroweak Fit?

The definition of the mass of the top quark is ill-defined

- the mass measured from bW decay products is assumed to be close from pole m_{pole}
- problem: m_{pole} for a coloured particle cannot be determined with accuracy better than Λ_{QCD} ($\approx$ 0.2 GeV)
- the top quark decays before hadronising but still the b quark has to hadronise

Which final state particles to assign to the original top quark?



- Importance of measuring the mass using alternate techniques
  - mass and end point of bℓ spectrum
  - decay length (boost) of B hadrons

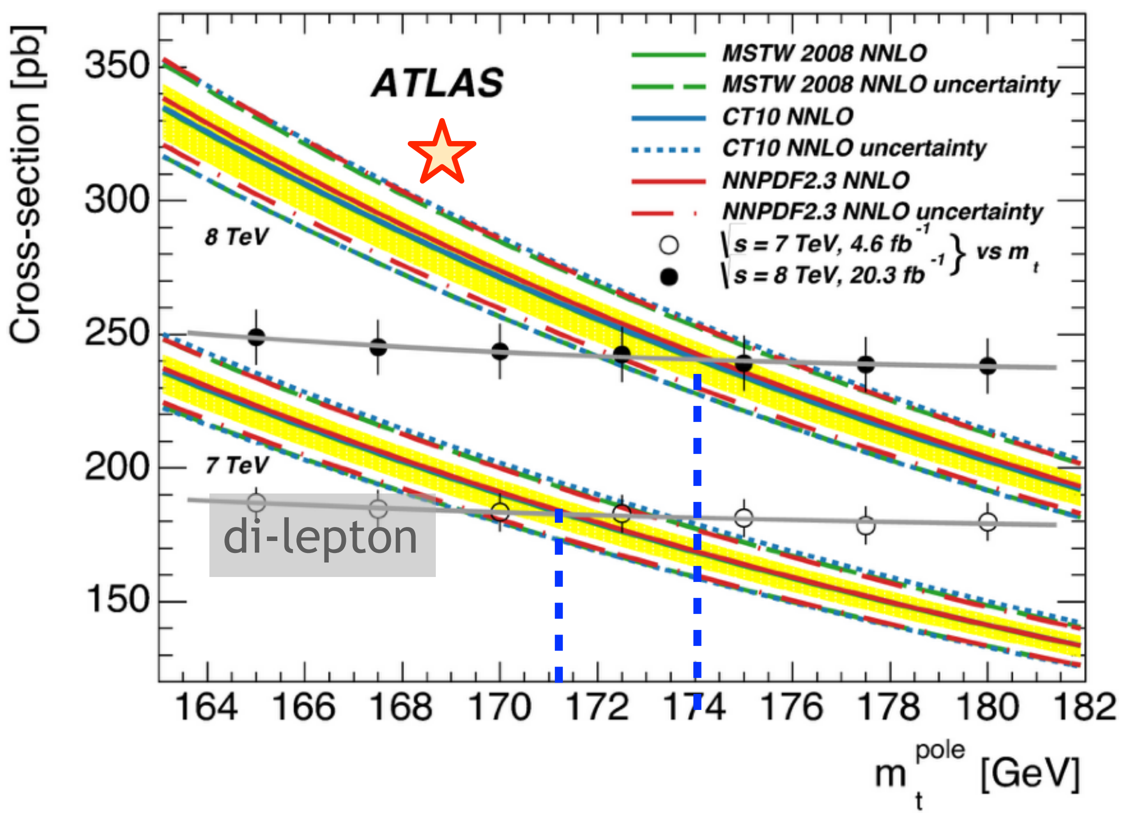
theoretically a good approach is to extract the mass from measurements of the cross section

Pole Mass Measurements

Initially, using

- an inclusive x-section measurement
- NLO calculations of $t\bar{t}$ x-section as a function of pole m_t
- fit together with $\alpha_s(m_t)$

±2.6 GeV



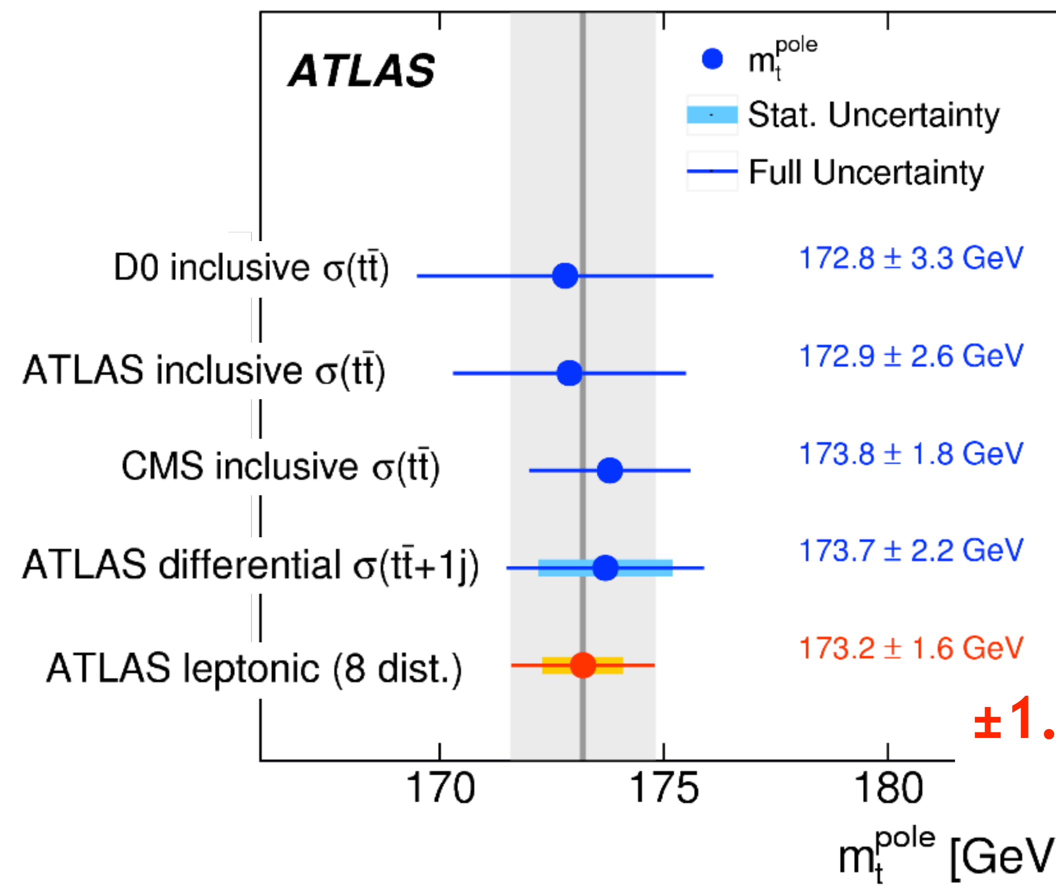
exp. 8TeV

theo. 8 TeV

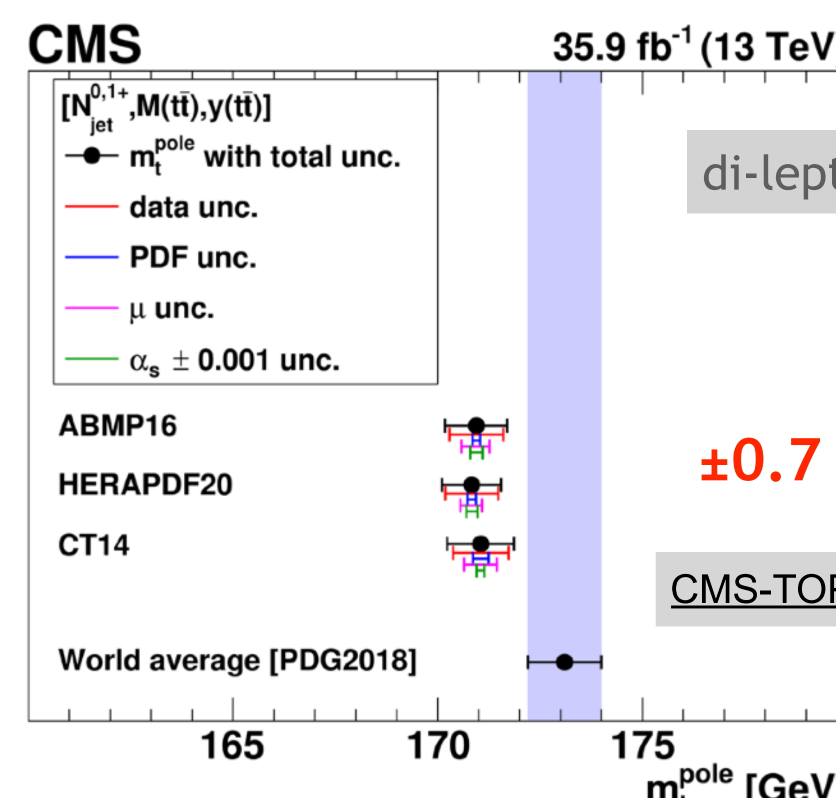
exp. 7TeV

theo. 7 TeV

EPJC 77 (2017) 804



±1.6 GeV



di-lepton

±0.7 GeV!

CMS-TOP-18-004

More recently, using

- normalised multi-differential cross-sections

Top Mass Measurements at HL-LHC

More statistics

☛ semi-exclusive channels

- mitigate JES
- better calibrations
- different systematics

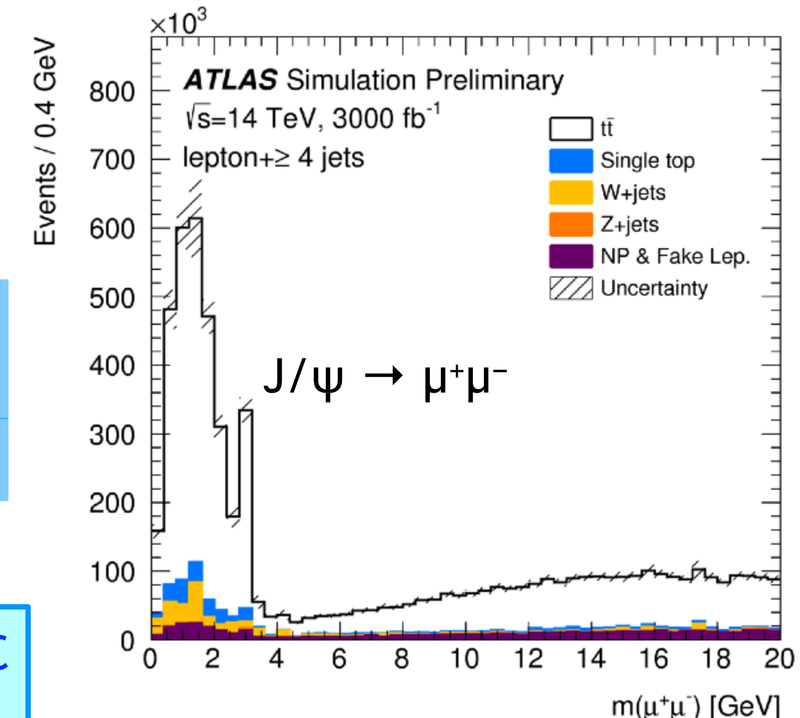
example

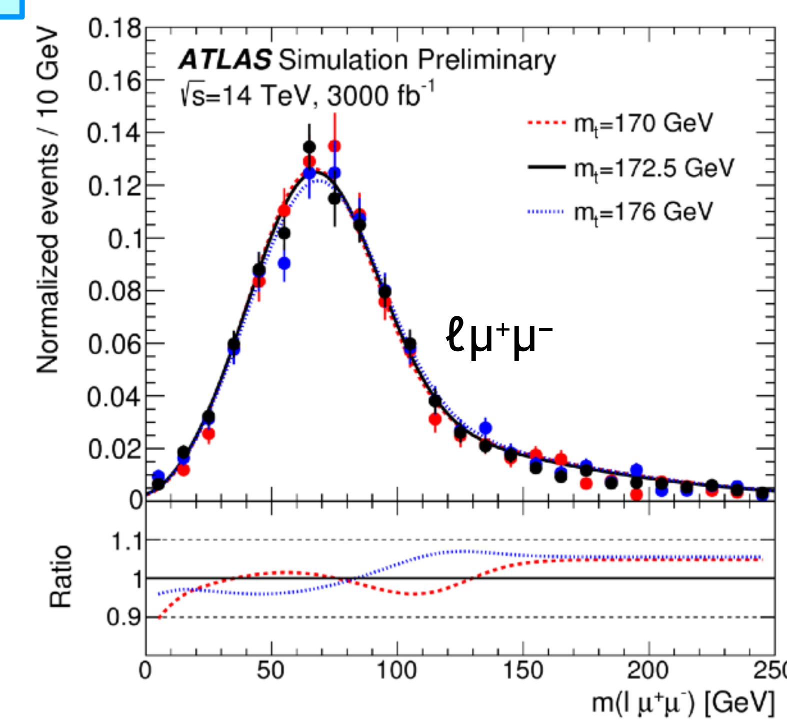
$t \to bW \to J/\psi\, X\ell\nu$

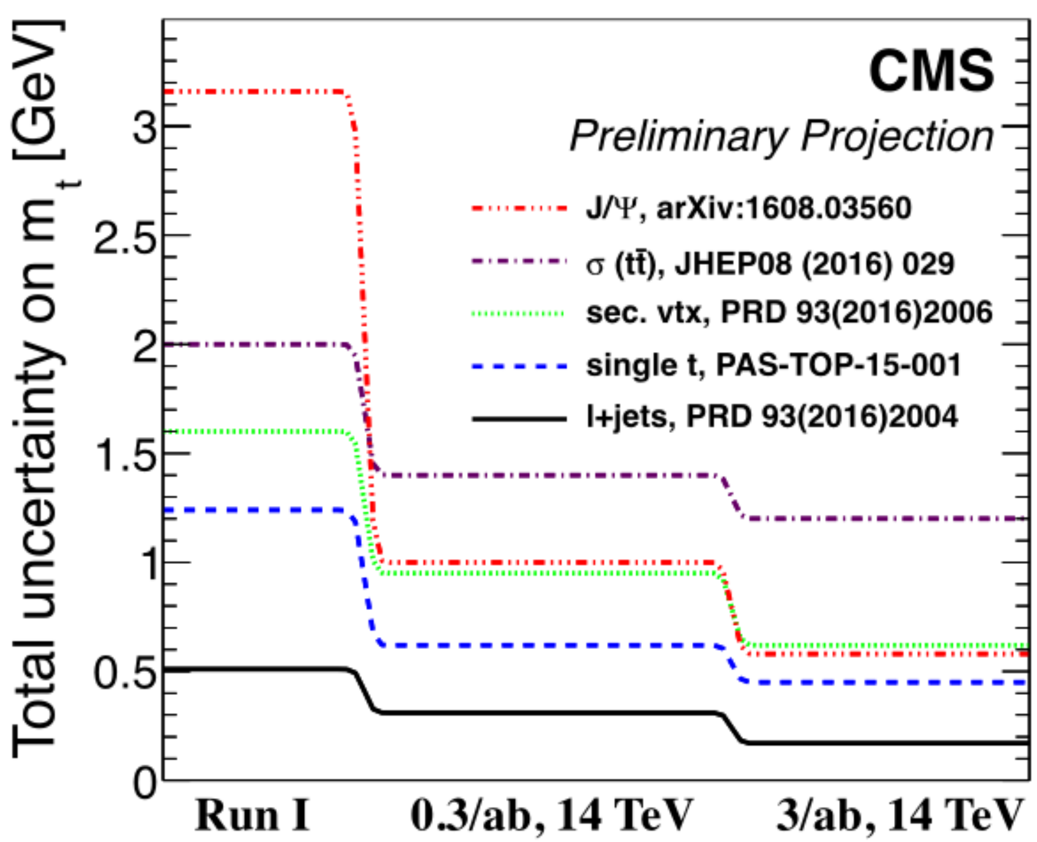
select $t\bar{t}$ events with 2 additional soft muons

BR = 0.04%

ATLAS HL-LHC
3000 fb^{-1}







m_{pole} from $\sigma(t\bar{t})$

secondary vertex

J/ψ

single top

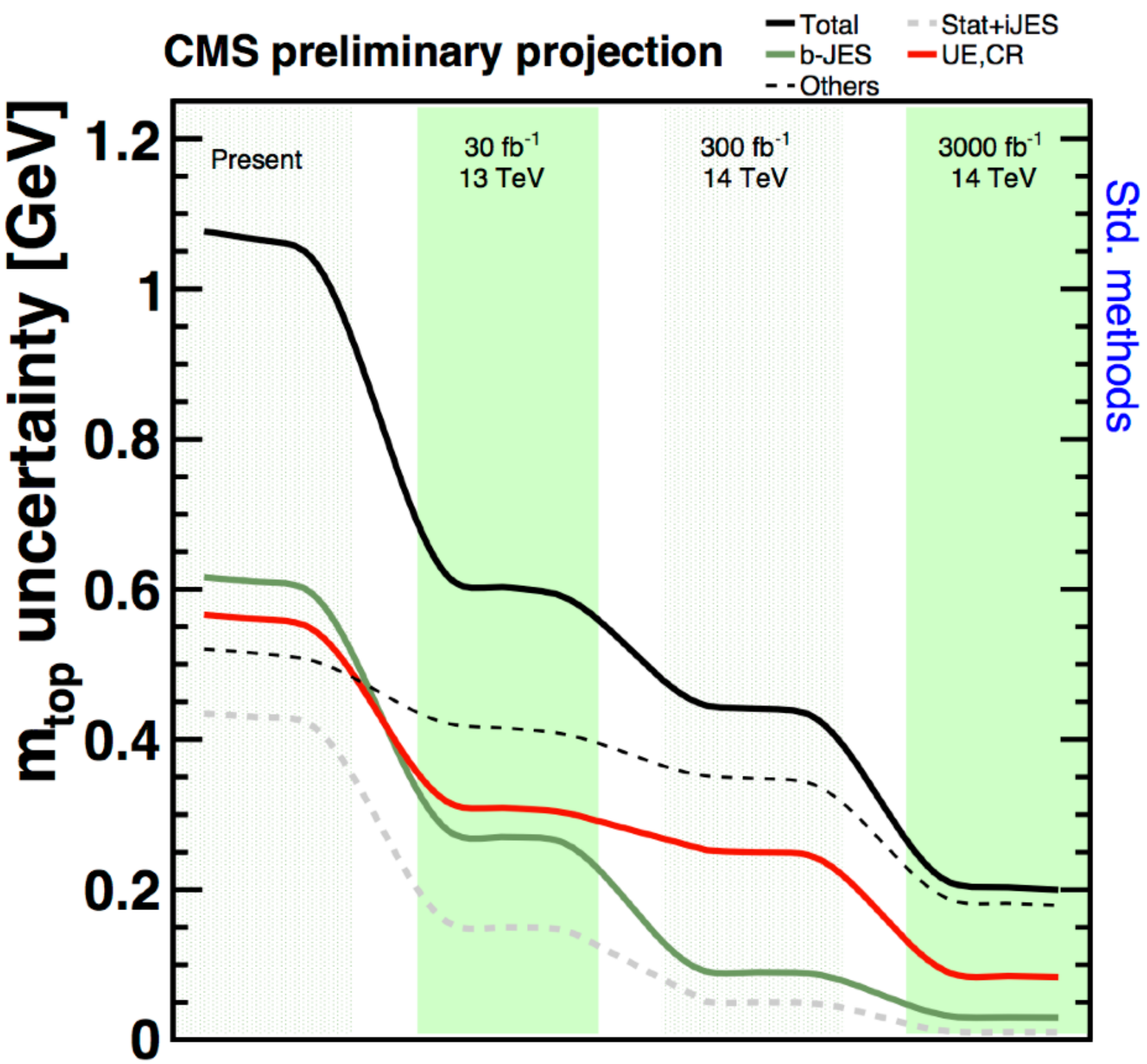
ℓ+jets

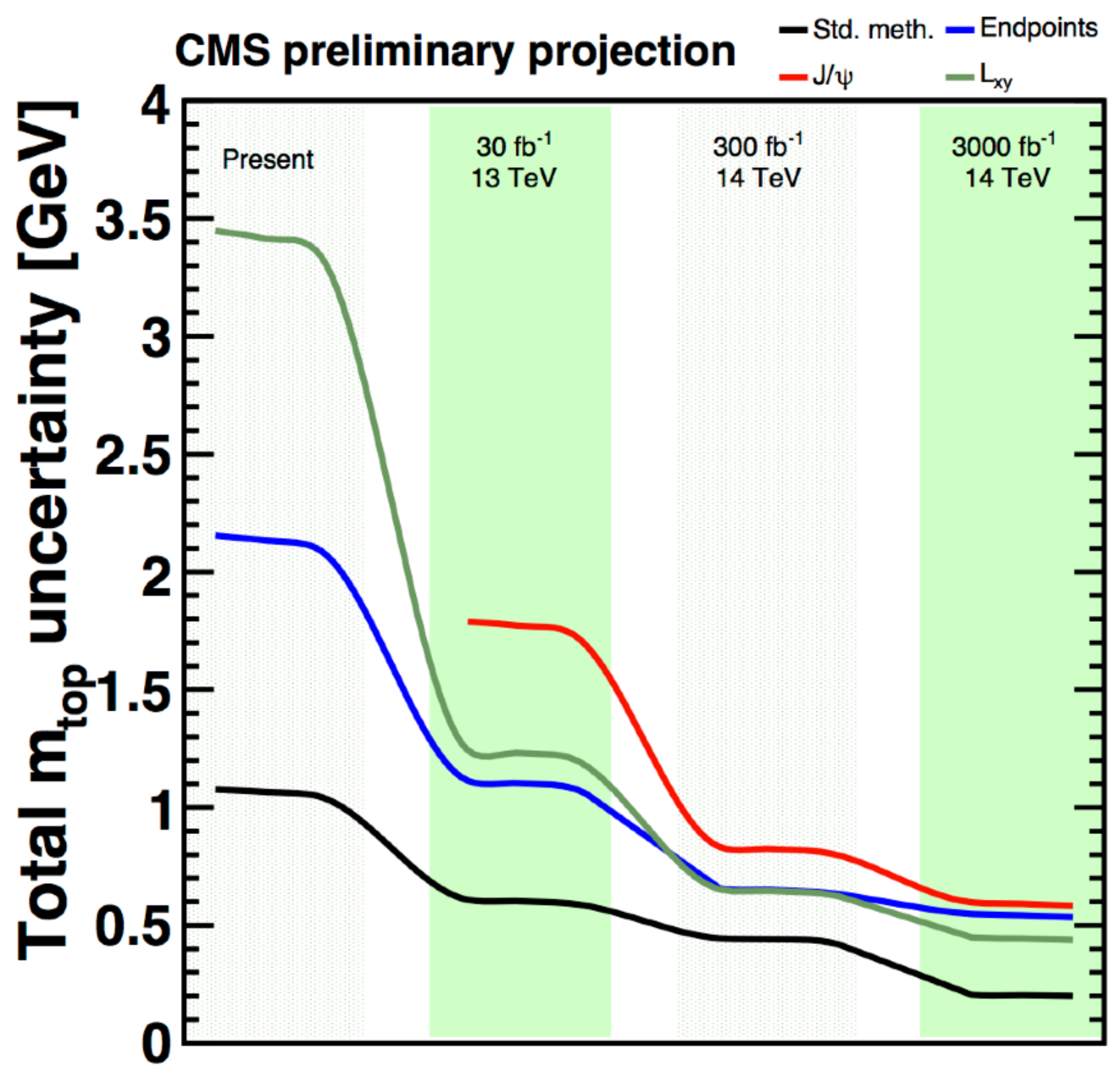
δm_{top} = ±500 MeV
(stat=±140, syst=±480)

CMS-PAS-FTR-16-006

ATL-PHYS-PUB-2018-042

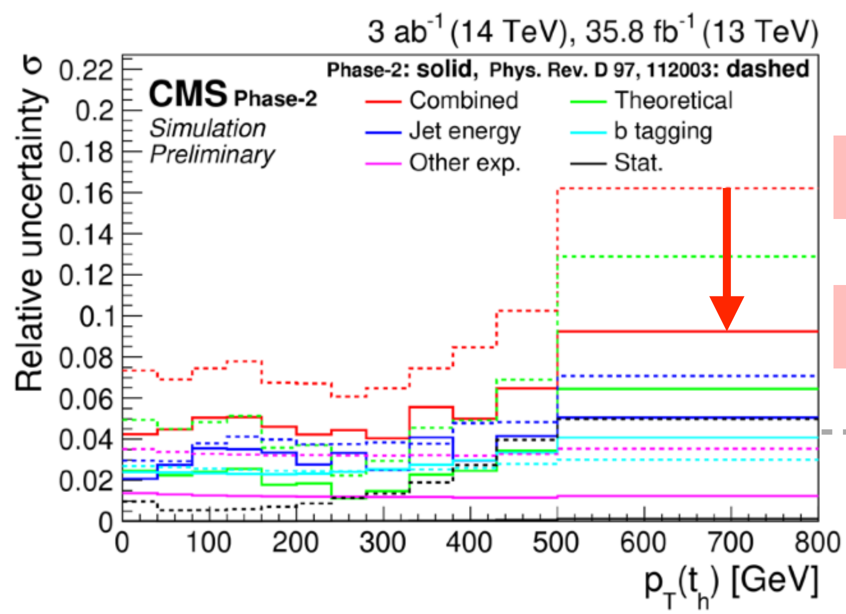
Top Mass Measurements Error Budget





Top Differential x-Sections at HL-LHC

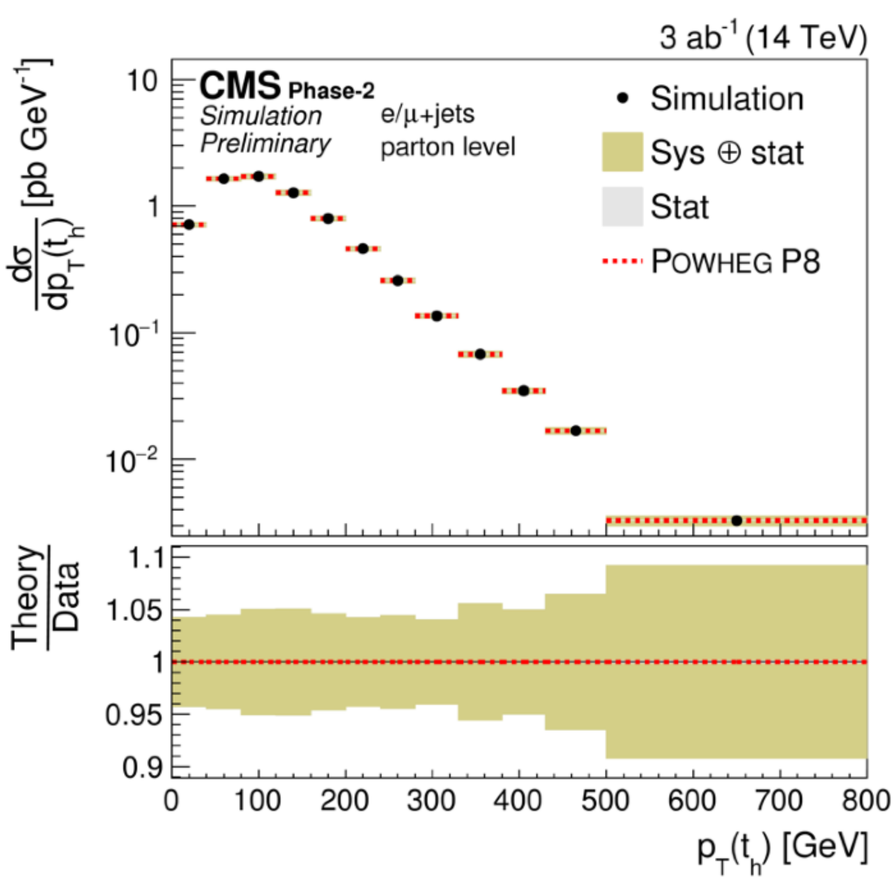
CMS-PAS-FTR-18-015



2016

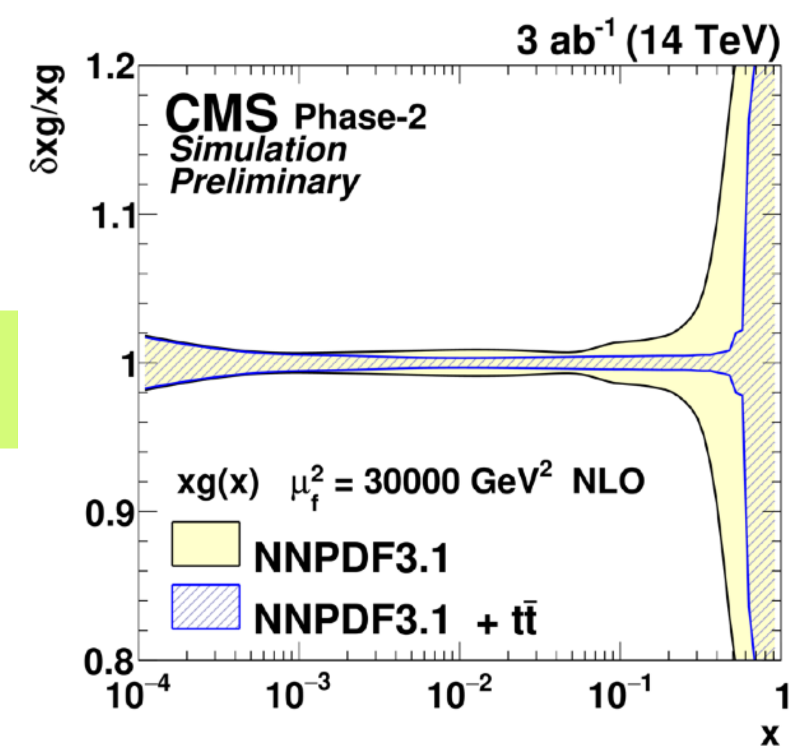
HL-LHC

O(5%) relative uncertainties



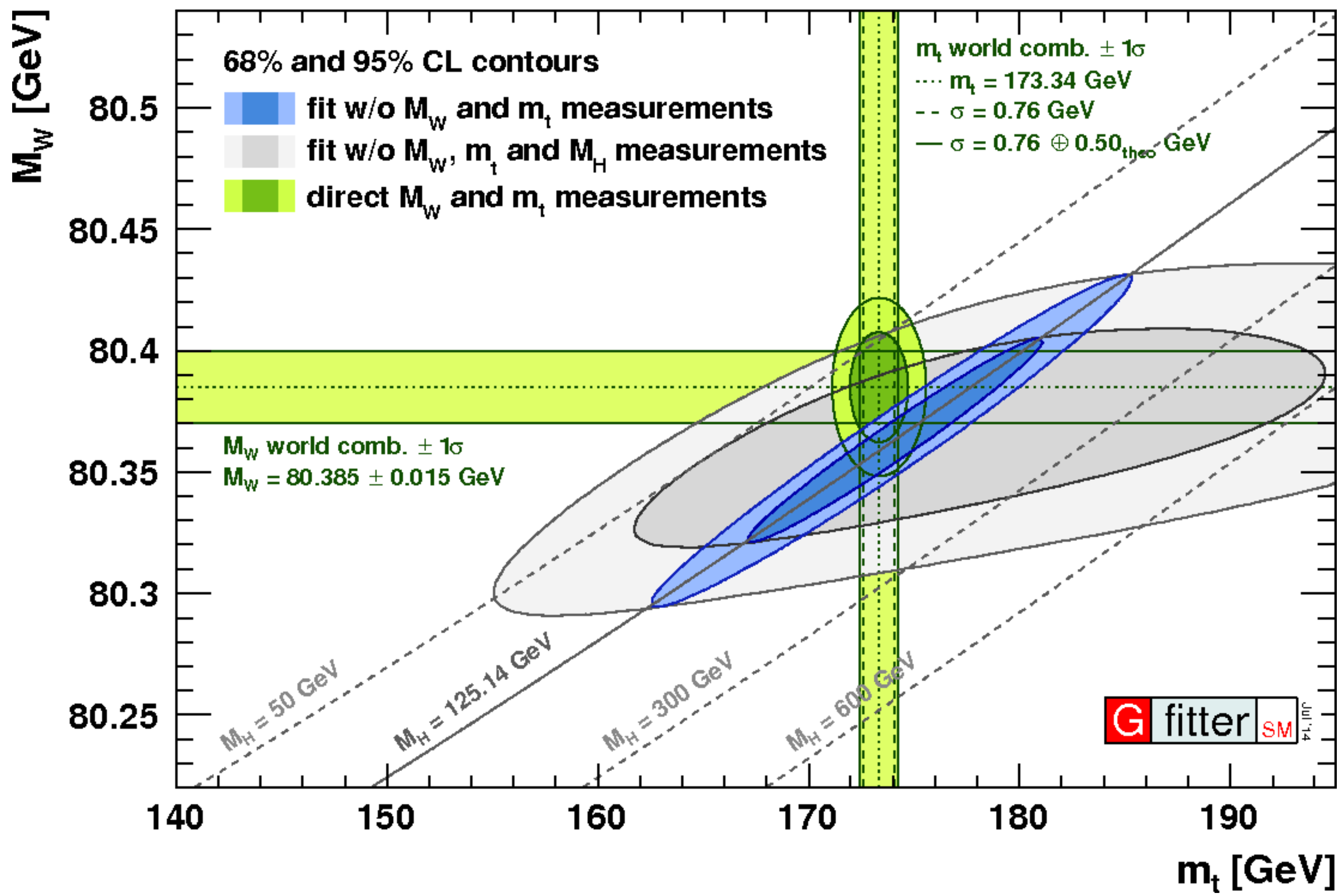
- real benefit from extended tracker coverage
- PU mitigation : unfolding purity similar to Run-II

significant impact on high-x gluon PDF



also, sensitivity on quark PDFs thanks to high rapidity analysis at LHCb with 300 fb^{-1} (HL-LHC)

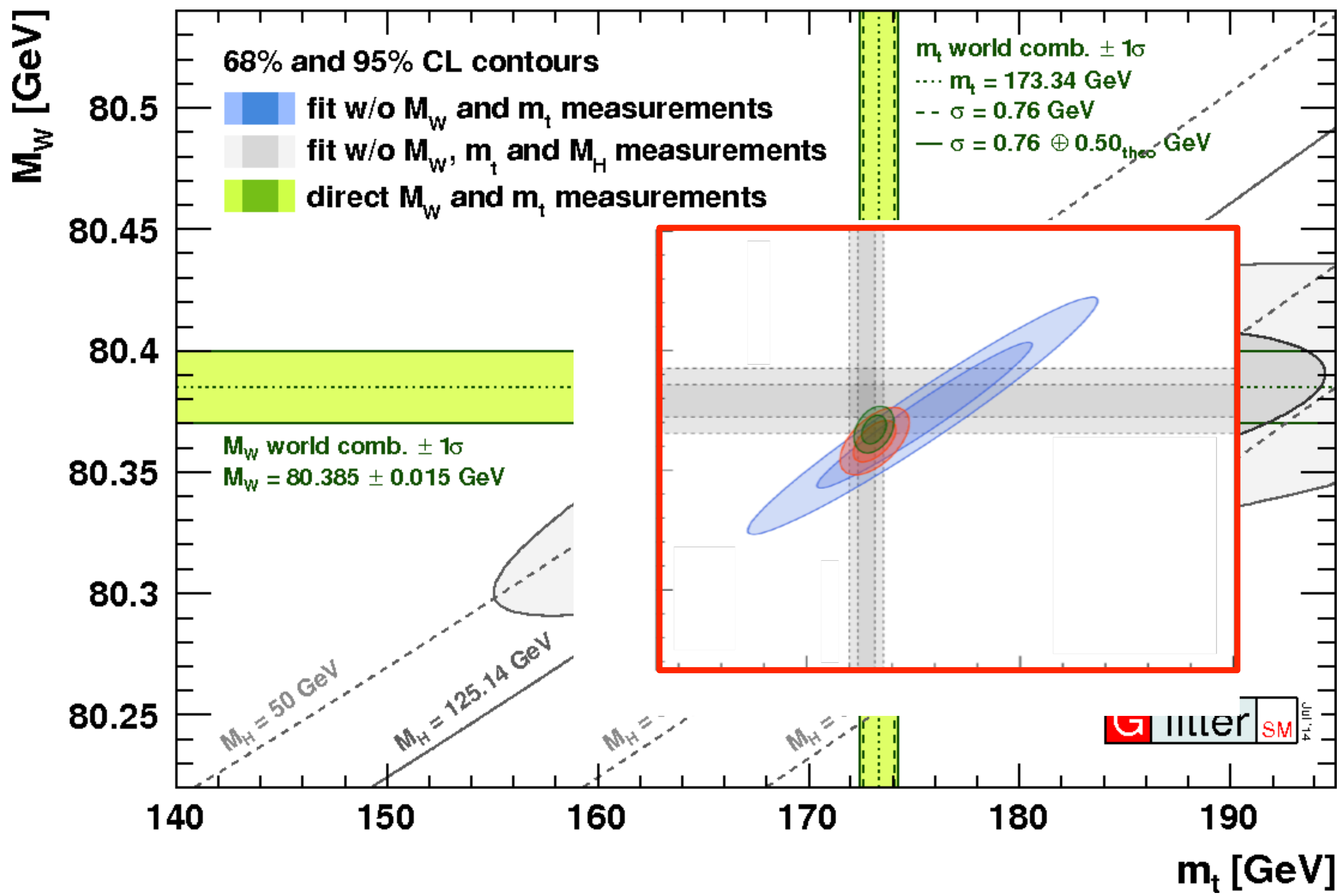
Electroweak Fit at HL-LHC



Uncertainties 2018

- $\sin^2\theta_{eff}$ (WA) 0.00016
- W mass (WA) 15 MeV
- W width (WA) 42 MeV
- top mass (WA) 760 MeV
- (Higgs mass (WA) 240 MeV)

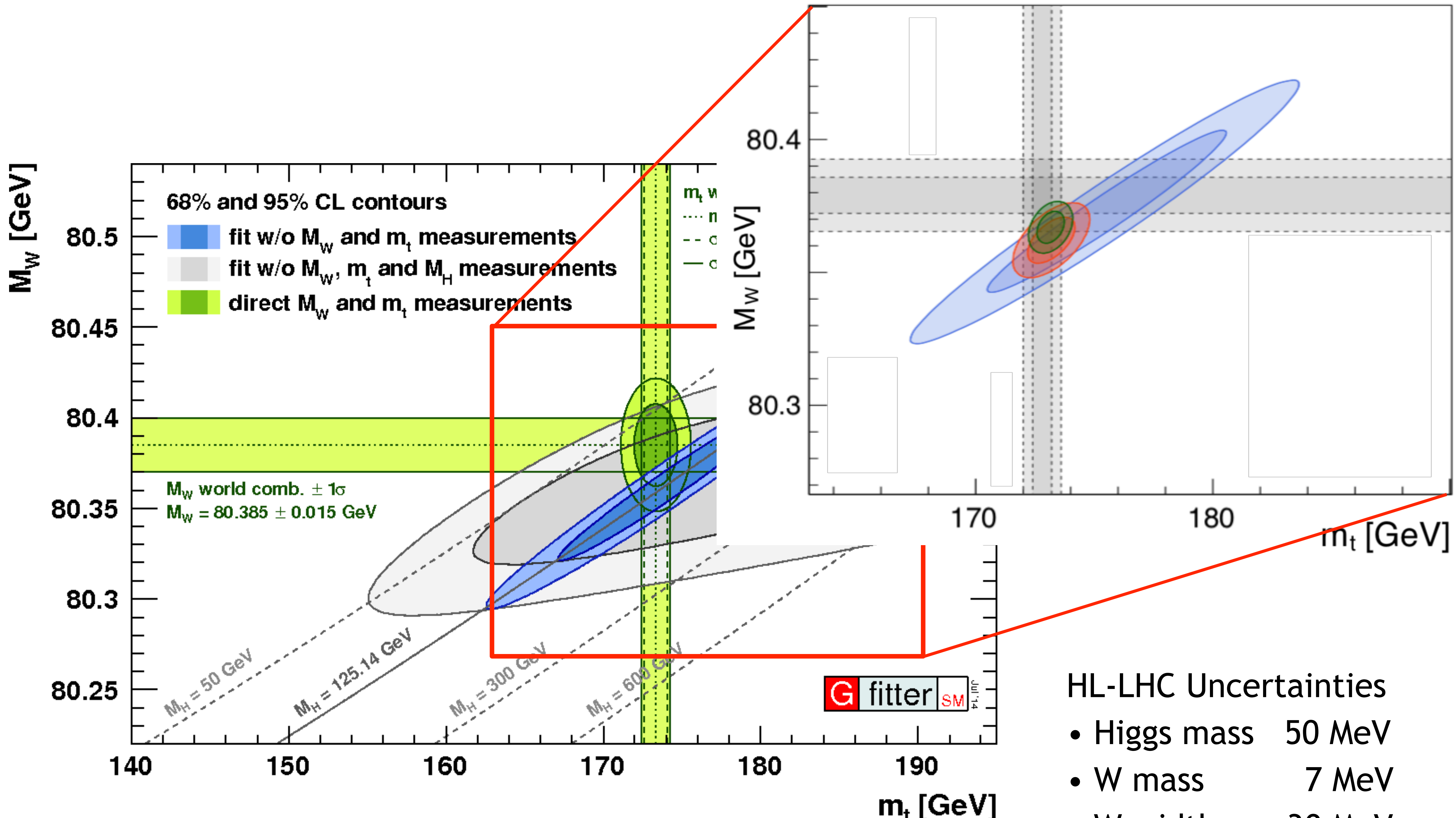
Electroweak Fit at HL-LHC



HL-LHC Uncertainties

- $\sin^2\theta_{eff}$ 0.00015
- W mass 7 MeV
- W width 30 MeV
- top mass 400 MeV
- (Higgs mass 50 MeV)

Electroweak Fit at HL-LHC



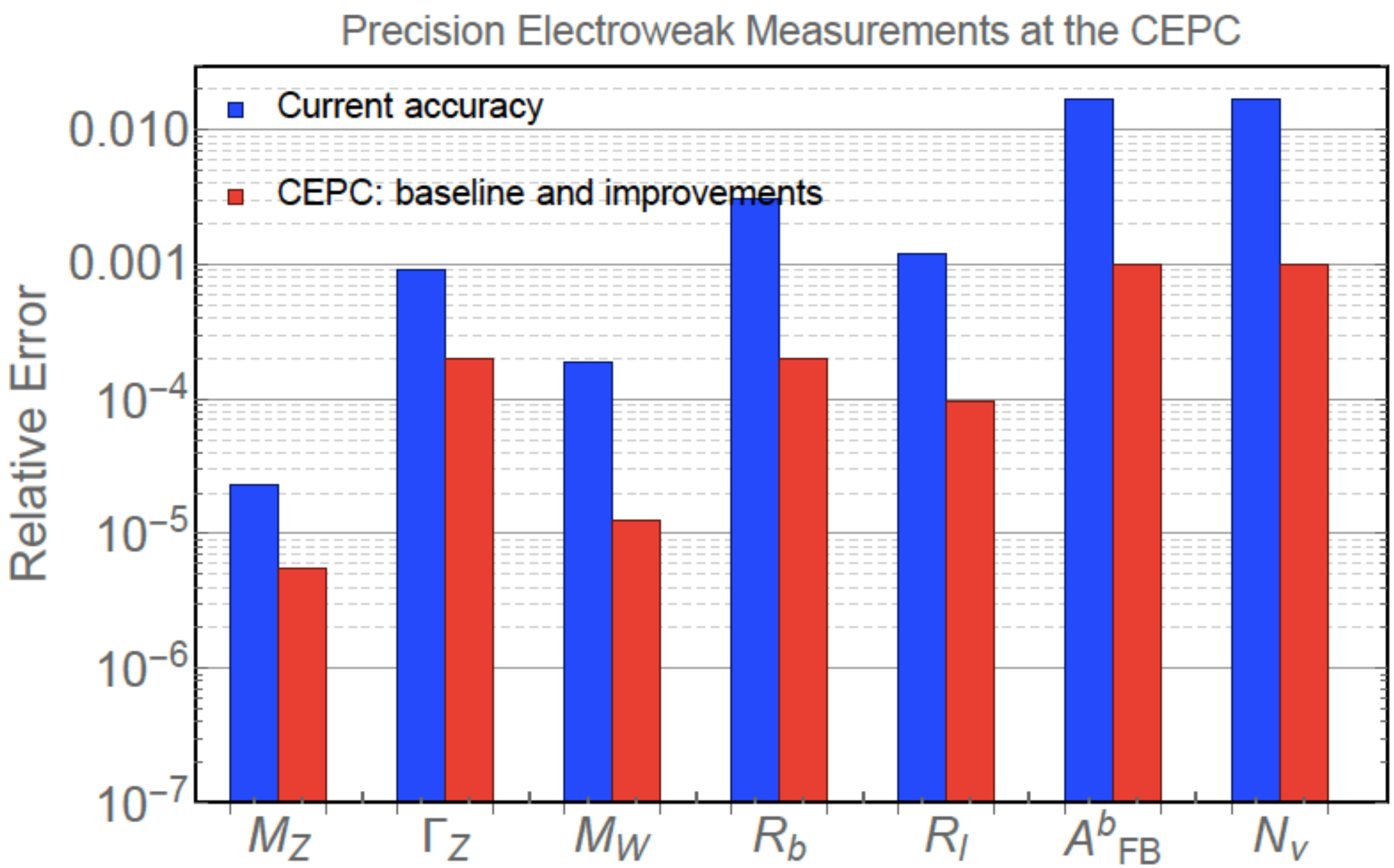
with present central values and HL-LHC uncertainties:
➠ 3σ tension between direct and indirect M_W and m_t

HL-LHC Uncertainties

• Higgs mass	50 MeV
• W mass	7 MeV
• W width	30 MeV
• top mass	400 MeV
• $\sin^2\theta_{eff}$	0.00015

Physics with 3×10^{11} Z Bosons

CEPC



Jump by
factor 5 to 20
in relative precision

EWPO at FCC-ee

TeraZ (5×10^{12} Z)	*OkuWW (10^8 WW)*
From data collected in a lineshape energy scan: • Z mass (key for jump in precision for ewk fits) • Z width (jump in sensitivity to ewk rad corr) • R_l = hadronic/leptonic width ($\alpha_s(m^2_Z)$, lepton couplings) • peak cross section (invisible width, N_ν) • $A_{FB}(\mu\mu)$ ($\sin^2\theta_{eff}$, $\alpha_{QED}(m_Z^2)$, lepton couplings) • Tau polarization ($\sin^2\theta_{eff}$, lepton couplings, $\alpha_{QED}(m_Z^2)$) • R_b, R_c, $A_{FB}(bb)$, $A_{FB}(cc)$ (quark couplings)	From data collected around and above the WW threshold: • W mass (key for jump in precision for ewk fits) • W width (first precise direct meas) • $R^W = \Gamma_{had}/\Gamma_{lept}$ ($\alpha_s(m^2_Z)$) • Γ_e, Γ_μ, Γ_τ (precise universality test) • Triple and Quartic Gauge couplings (jump in precision, especially for charged couplings)

Physics with 5×10^{12} Z Bosons

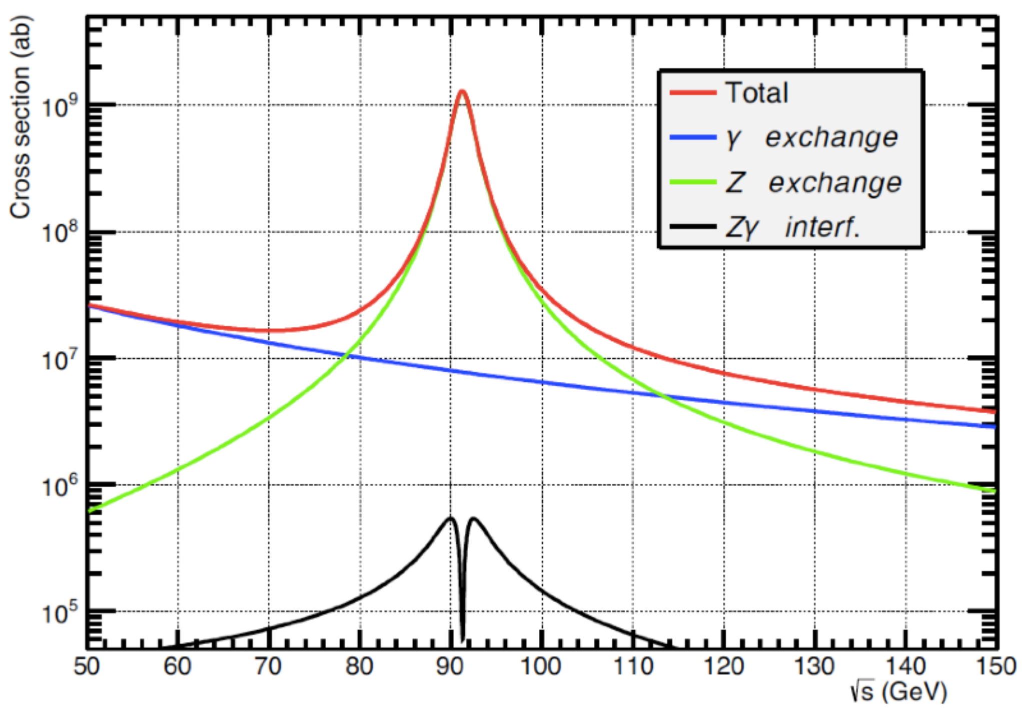
FCC-ee

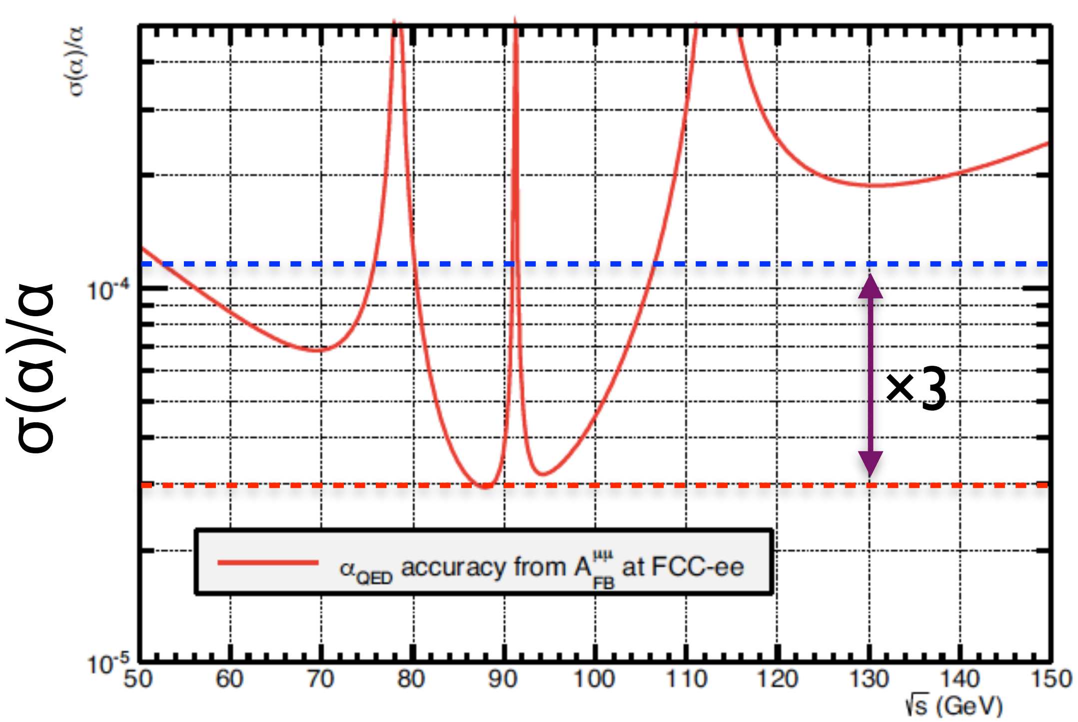
observable	present value	FCC-ee stat syst	from	main source of systematics
M_Z (MeV)	91187.5 ± **2.1**	**0.005** ± **0.1**	line shape	beam energy calibration
Γ_Z (MeV)	2495.2 ± **2.3**	**0.008** ± **0.1**		
$\sin^2\theta_{eff}$ ($\times10^5$)	23153 ± **16**	**0.3** ± **0.2-0.5**	$A_{FB}^{\mu,0}$	
$A_{FB}^{b,0}$ ($\times10^4$)	992 ± **16**	**0.002** ± **1-3**	b-quark asymmetry	b-jet charge
R_ℓ ($\times10^3$)	20767 ± **25**	**0.06** ± **0.2-1**	hadrons to leptons	lepton acceptance
α_s ($\times10^4$)	1990 ± **25**	**0.1** ± **0.4-1.6**	R_ℓ	
$1/\alpha$ ($\times10^3$)	128952 ± **14**	**4** ± **<1**	A_{FB}^{μ} off-peak	
σ_{had}^0 (pb)	41541 ± **37**	**0.1** ± **4**	peak cross-sections	luminosity measurement
N_ν ($\times10^4$)	29840 ± **82**	**0.05** ± **10**		

- ☛ continuous $\sqrt{s}$ calibration by RDP
  - $\Delta E/E \sim \mathcal{O}(10^{-6})$
  - 100 (500) keV at Z-pole (WW)
- ☛ energy spread (~60 MeV) at 1% from scattering angle of μ pairs
- ☛ W+Si luminometer
  - small angle Bhabha scattering
  - absolute (relative) : 10^{-4} (5×10^{-5})

From asymmetries and partial width measurements, improvement by 1 to 2 orders of magnitude on Z vector and axial-vector couplings to leptons (e, μ and τ) and quarks (b and c)

QED Coupling Constant $\alpha(M_Z^2)$





one year of running at any given $\sqrt{s}$

$1/\alpha(M_Z^2) = 128.952 \pm 0.014$ ($\rightarrow \delta\alpha/\alpha \approx 1.1\times10^{-4}$)

- uncertainty dominated by hadronic vacuum polarisation (from low energy data)
- currently *second* largest source of parametric error on $\sin^2\theta_{eff}$ (first=theory)
- can be measured from the slope of the FB μ asymmetry in the vicinity of the Z pole

$$A_{\mathrm{FB}}^{\mu}(s) \simeq A_{\mathrm{FB}}^{0\,\mu}\left[1+\frac{s-M_{\mathrm{Z}}^2}{2s}\,\frac{8\pi\sqrt{2}\,\alpha}{M_{\mathrm{Z}}^2 G_{\mathrm{F}}(1-4\sin^2\theta_{\mathrm{eff}})^2}\right]$$

FCC-ee $1/\alpha(M_Z^2)$ at the 4×10^{-5} level from 40 fb^{-1} at ±3 GeV of Z pole

- param. error < 1.2×10^{-5} on $\sin^2\theta_{eff}$
- param. error < 0.6 MeV on M_W

P. Janot, JHEP 02 (2016) 053

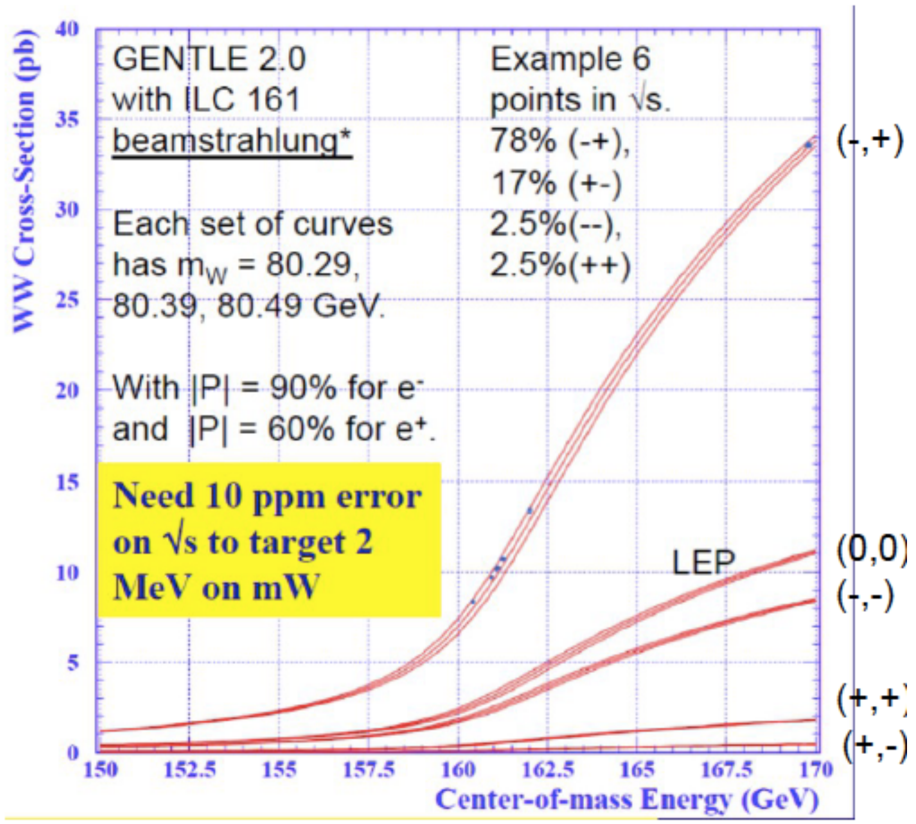
Note: computation of missing EW higher-order corrections is needed

W Mass at e^+e^- Colliders

ILC at threshold with polarisation

- use LR to enhance WW
- use RL to measure backgrounds
- use LL and RR to control polarisation
- 500 fb^{-1} ($\pm$80%,$\mp$30%) ➔ $\delta M_W \approx 2.1$ MeV (stat+syst)

A run at $\sqrt{s}$ = 160 GeV not in the current staged running scenario at the ILC



Above threshold

- 1000 times LEP-2 statistics
- much better detectors

FCC-ee at threshold, unpolarised

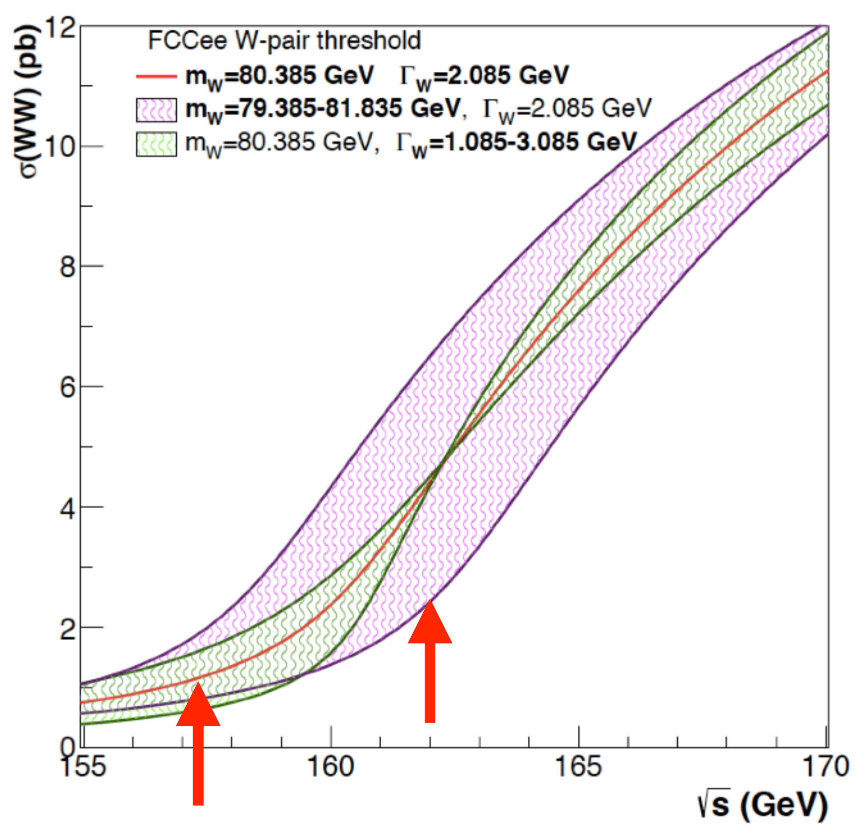
Center-of-mass energy (unc. 0.3 MeV)

- known by resonant depolarisation

Luminosity (unc. $<2\times10^{-4}$)

- from Bhabha events

Carefully chosen energy points



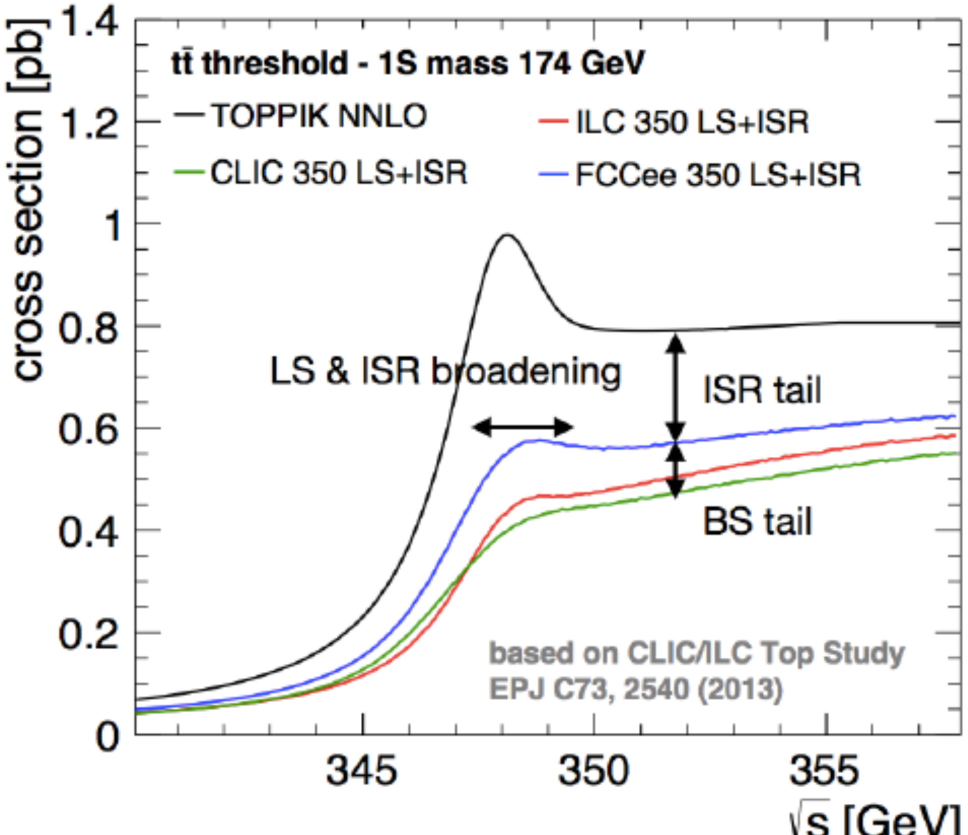
ΔM_W = 0.7 MeV

$\Delta\Gamma_W$ = 1.5 MeV

Top Mass at Pair Threshold

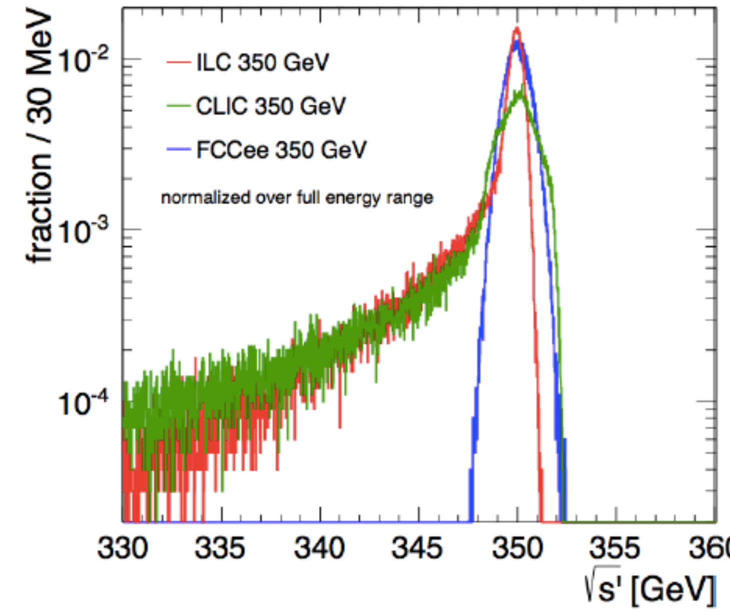
Which definition for the top quark mass?

- HL-LHC → *MC mass* with uncertainty <200 MeV
- can the *pole mass* be determined at better than $\mathcal{O}(\Lambda_{QCD})$?



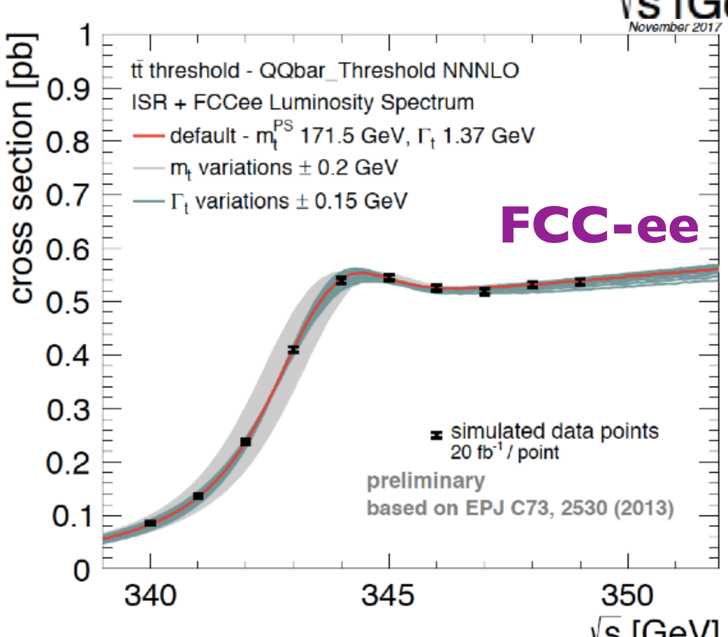
Threshold mass

- *safe* definition
- can be translated to *pole mass* with uncertainty <100 MeV



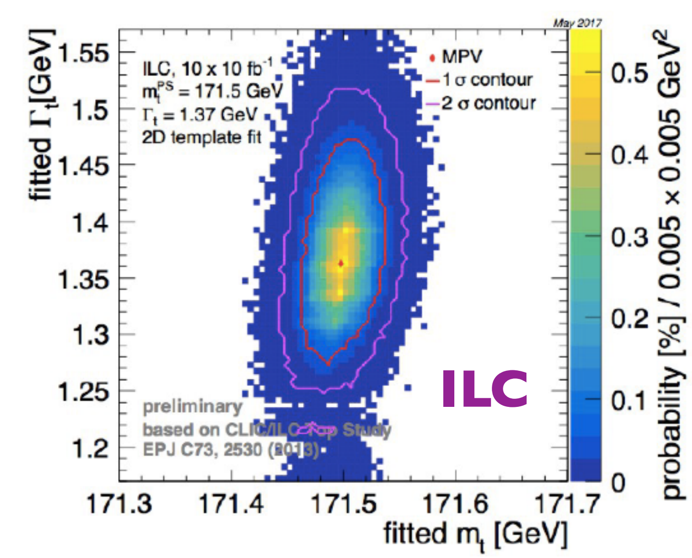
Different luminosity spectra at different machines

Cross section at threshold affected by properties of the top quark (mass, width, y_{top}) and QCD (α_s)



Energy scan

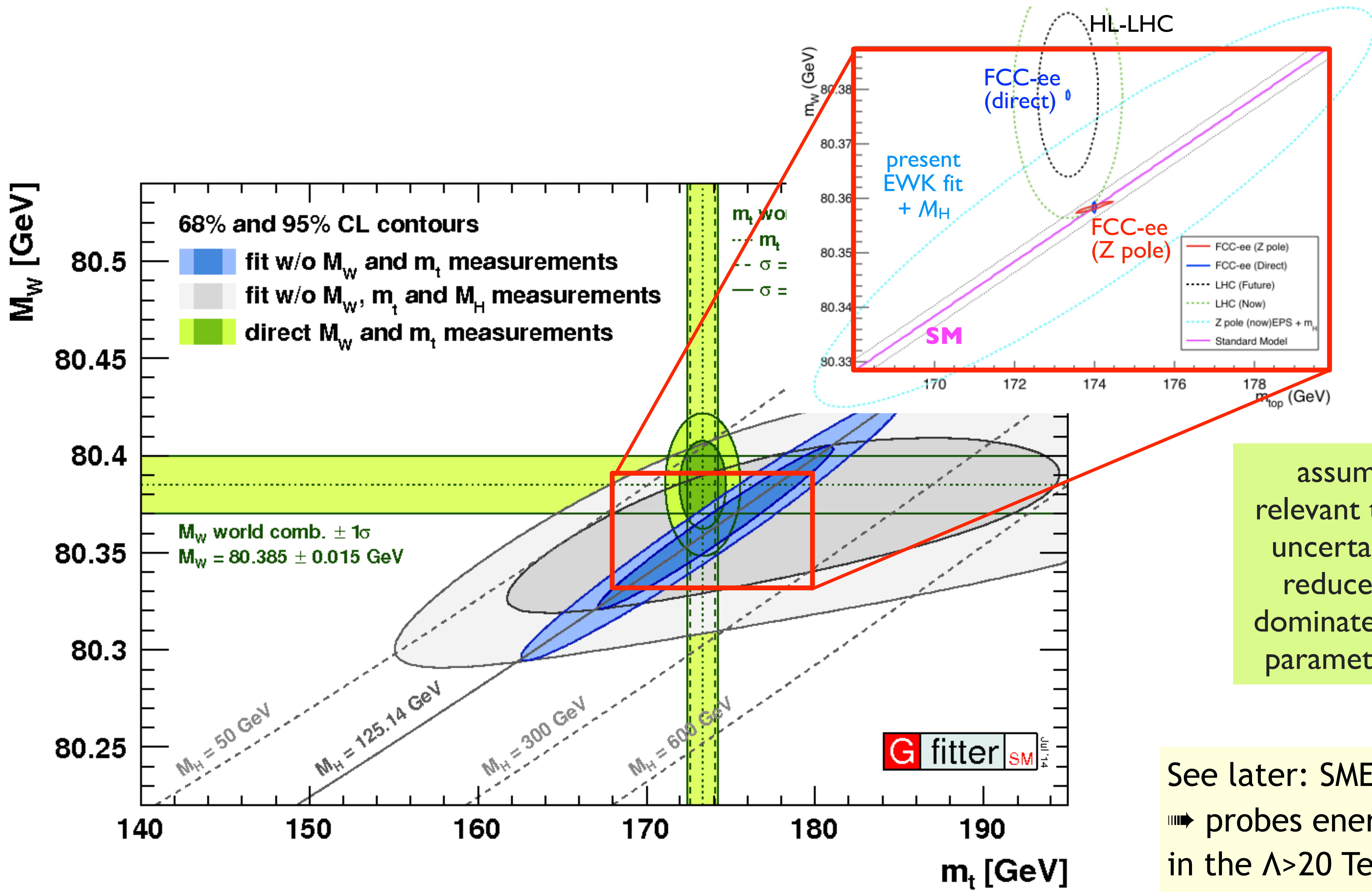
- optimal choice of points
- typically 20 fb⁻¹ per point
- stat: 15-20 MeV on M_{top}
- theory (NNNLO): 40 MeV



also:

- Γ_{top} at <100 MeV
- indirect y_{top} at 10%

Electroweak Fit after FCC-ee Z/WW/HZ/tt



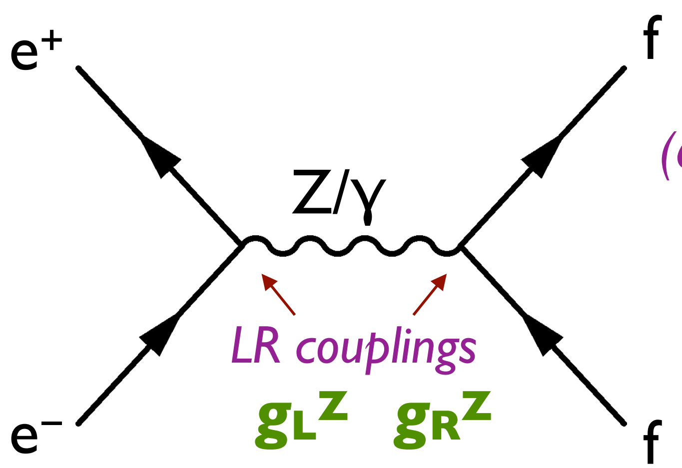
assumes that relevant theoretical uncertainties are reduced to not dominate the set of parametric errors

See later: SMEFT
➠ probes energy scales in the Λ>20 TeV range for certain NP operators

FCC-ee CDR (2018)

Fermion Pair Production

Electroweak fermion pair production



8 form factors
(6 CP-conserving)

F_{1V}^{γ} F_{1A}^{γ}

F_{1V}^{Z} F_{1A}^{Z}

$F_{2V}^{\gamma/Z}$ $F_{2A}^{\gamma/Z}$

At tree level in SM

$\sin^2\theta_W \sim 0.234$

	lepton	b quark	top quark
F_{1V}^{γ}	−1	−1/3	+2/3
F_{1V}^{Z}/F_{1A}^{Z}	$1-4\sin^2\theta_W$ +0.064	$1-(4/3)\sin^2\theta_W$ +0.688	$1-(8/3)\sin^2\theta_W$ +0.376
g_L^Z	−0.266	−0.422	+0.344
g_R^Z	+0.234	+0.078	−0.156

Of special interest:

F_{1A}^{γ} is 0 in SM as a result of QED gauge invariance

Tensor couplings
- 0 in SM
- sensitive to bound state effects
- $F_{2V}^{\gamma/Z}$ are related to anomalous magnetic dipole moment
- $F_{2A}^{\gamma/Z}$ are CP violating

Chiral structure of third generation of quarks

☛ top quark: mass close to the EWSB scale
- top Yukawa close to one

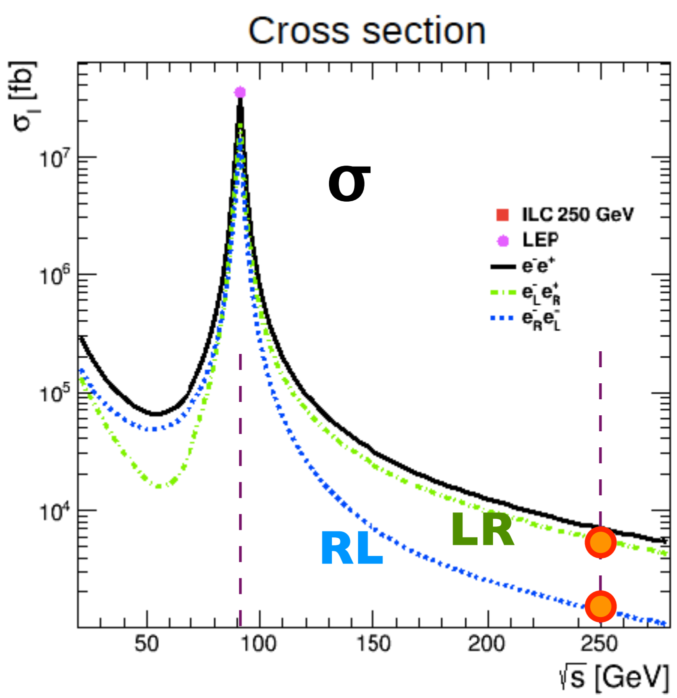
☛ could be (partially) composite?

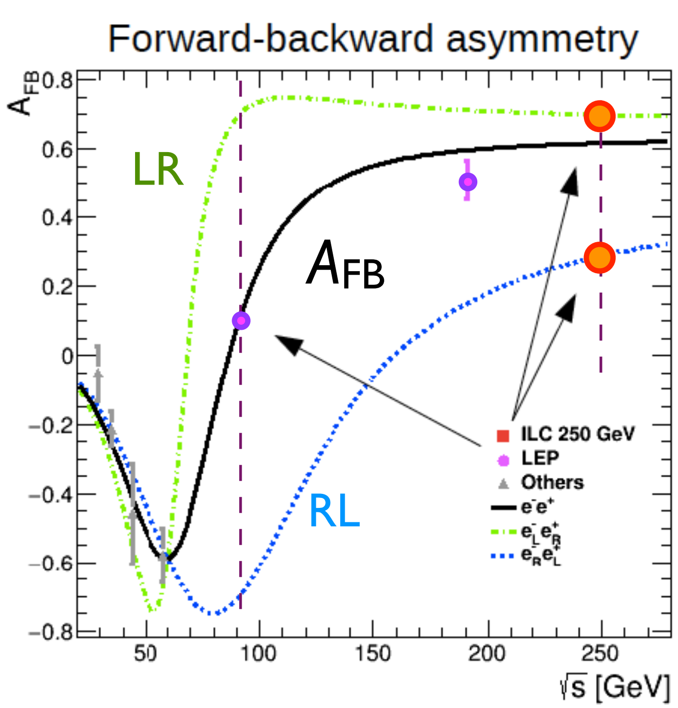
The top quark is a candidate to be a messenger in many new physics models, including composites and/or large extra dimensions

☛ b quark: weak isospin partner

b-Quark EWK Couplings

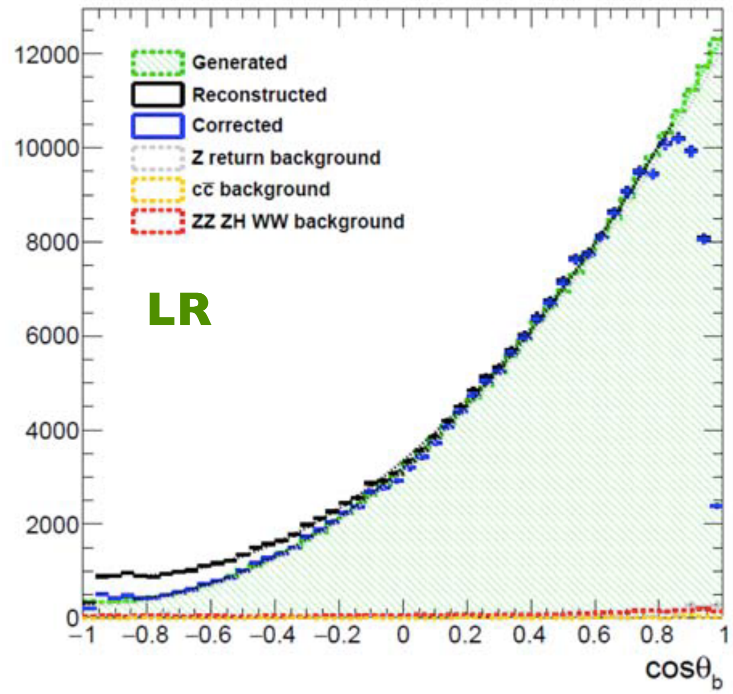
Observables sensitive to chiral structure: σ and A_{FB}

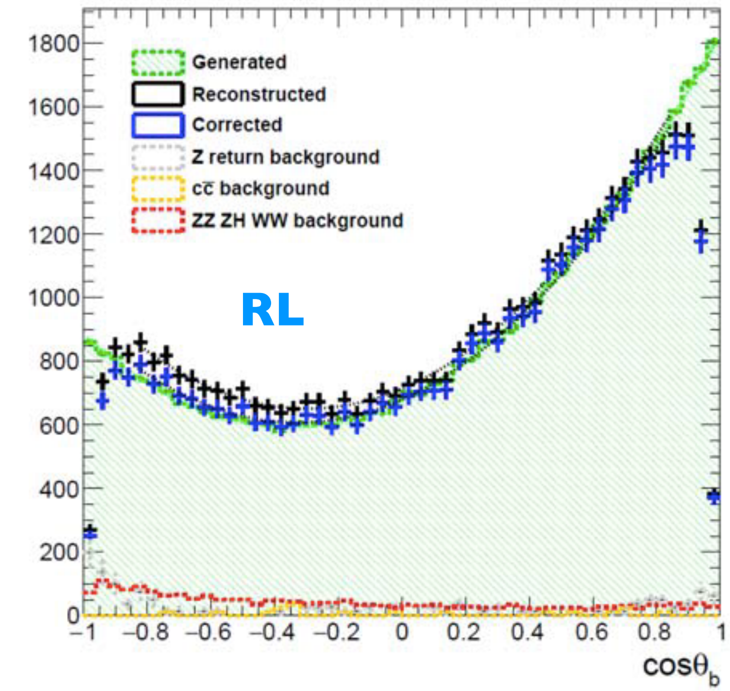




Differential cross sections as a function of $\cos\theta_b$

S $(1+\cos^2\theta_b)$ + **A** $\cos\theta_b$



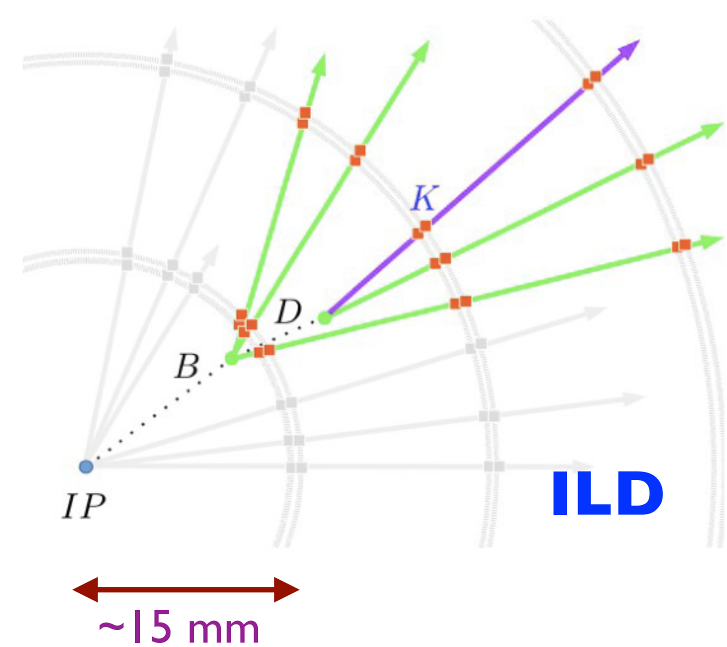


ILC-250
250 fb^{-1}
(ILD full sim)

blue: corrected for charge migrations (from data)

Excellent b- and c-tagging
- ☛ size of the beam spot
  - reduced tube radius
- ☛ particle identification (TPC)

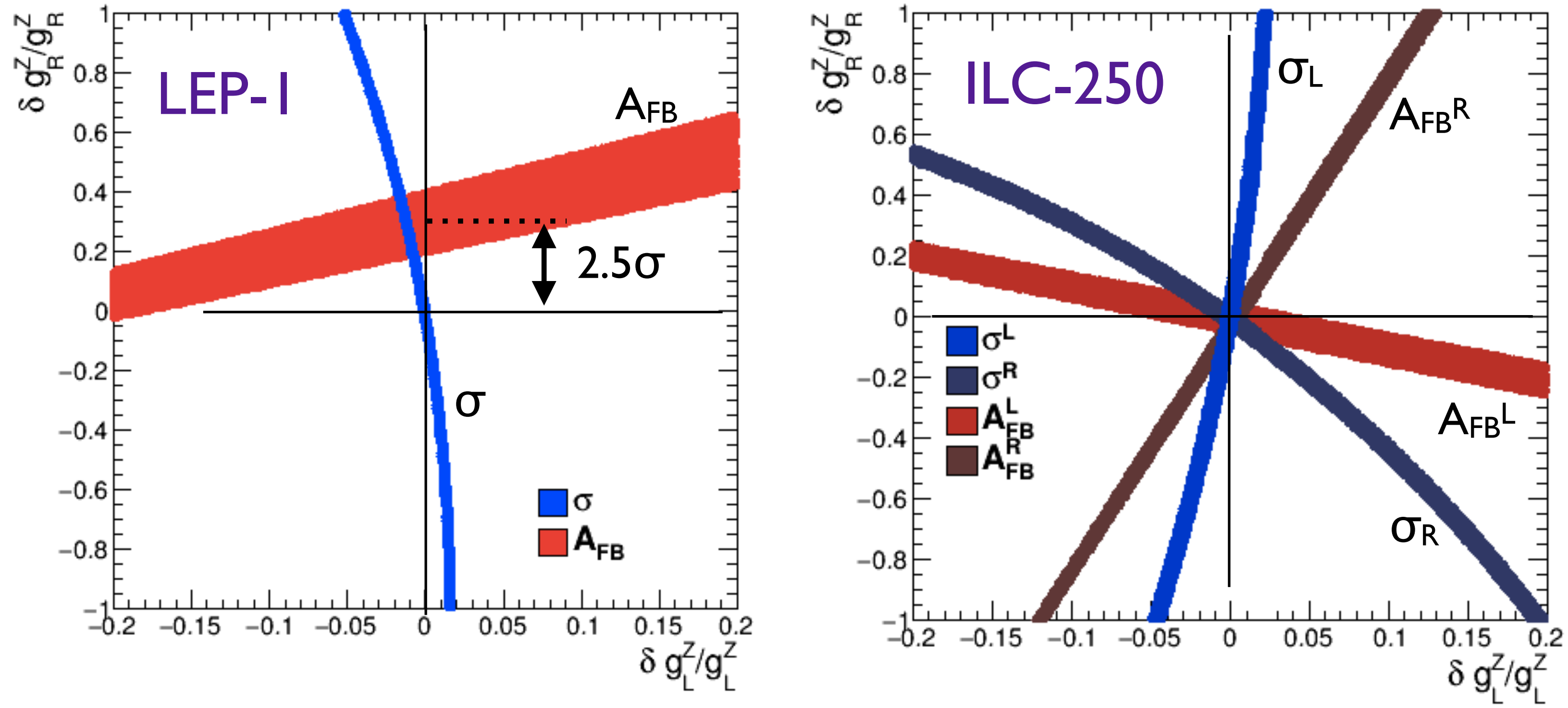
b-charge determination
- on event-by-event basis
- sum of charges at secondary and tertiary vertices



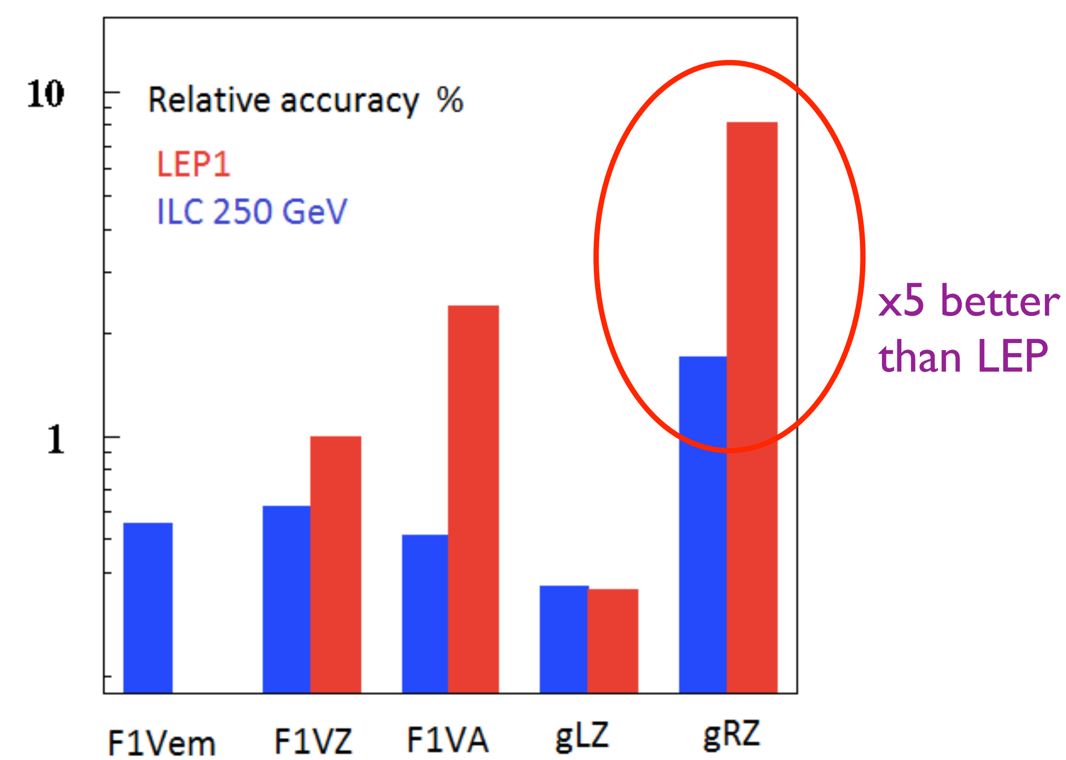
S. Bilokin at al, arxiv:1709.04289

Tackling the LEP Anomaly

Long-standing LEP anomaly
- a 2.5σ tension between A_{FB}^{ℓ} and A_{FB}^{b}
- corresponds to a deviation of 30% of the g_R^Z coupling
- hint of heavy quark compositeness?



ILC-250 with beam polarisation provides access to vector and axial couplings
- $\delta g_R^Z / g_R^Z$ ~ 2% (10% at LEP)
- discard or confirm the anomaly with >5σ confidence
- sign ambiguity in the anomaly can be resolved



also:
- ☛ constraints on tensor couplings
- ☛ sensitivity to BSM scenarios (e.g., Randall-Sundrum)

F. Richard, LCWS 2017

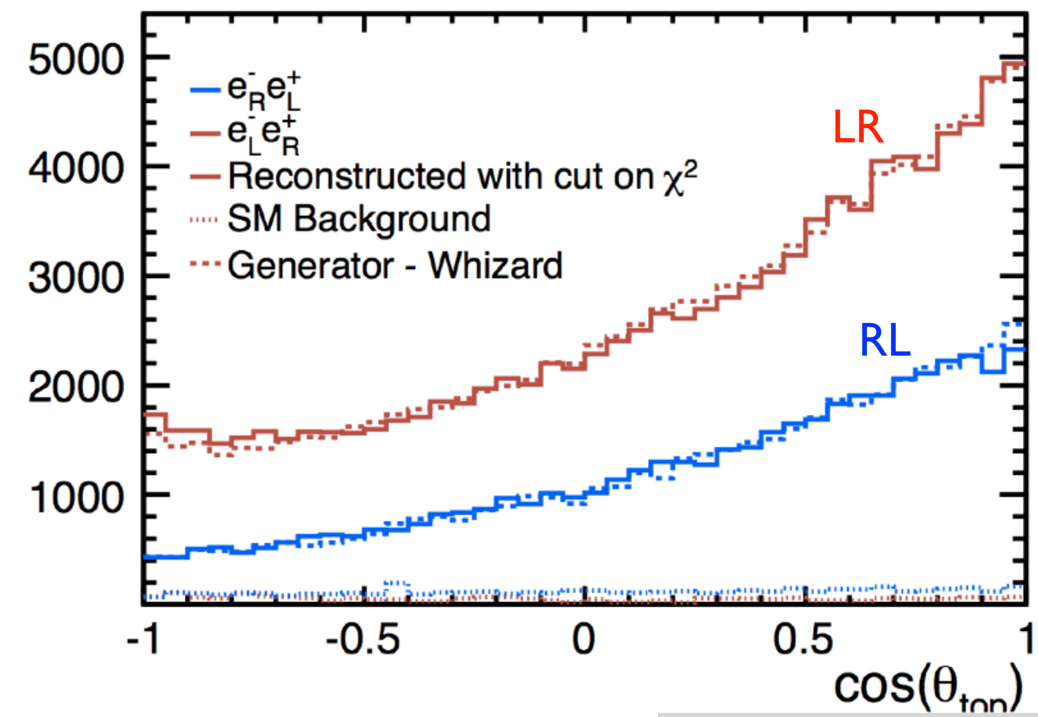
R. Pöschl, Tohoku 2018

Top-Quark EWK Couplings

Focus on most sensitive channel:
☛ semileptonic (44%)
  e+e− → tt → ℓνqqbb (ℓ = e, μ)

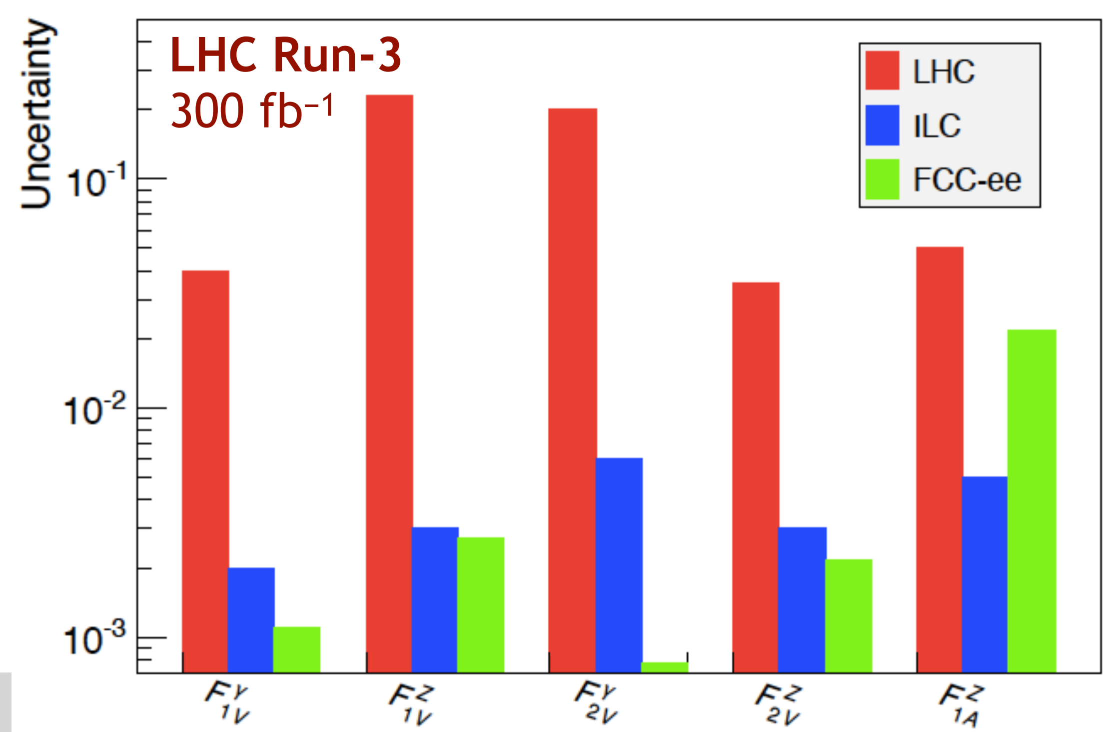
ILC 500 fb^{-1}@500 GeV
- precise reconstruction in both polarisations
- b-charge needed to solve ambiguities in LR
- 2% precision on A_{FB}
- improved precision with 2 ab^{-1}

ILC TDR



J. Rouene, PhD thesis

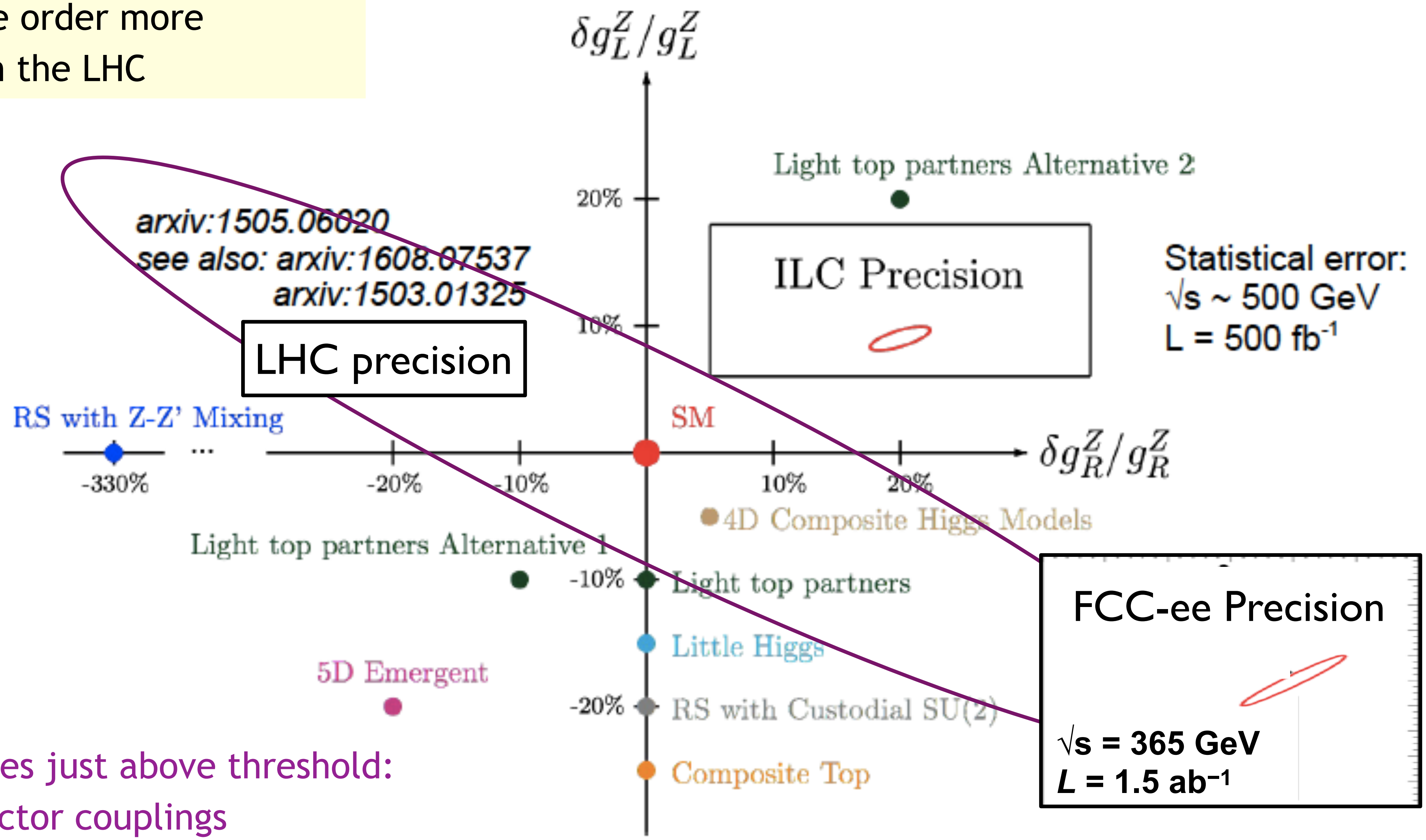
FCC-ee 2.4 ab^{-1}@365 GeV
- compensates lack of polarisation with statistics (one million tt events)
- final state polarisation extracted statistically from 2D energy/angular distribution of the lepton (polarisation transferred through the V−A decay of t →Wb)



P. Janot, JHEP 04 (2015) 182

Top Quark: Sensitivity to NP

e⁺e⁻ machines (ILC, CLIC, FCC-ee)
☛ more than one order more precise than the LHC



Limitation at energies just above threshold:
- vanishing axial-vector couplings
- large QCD uncertainties

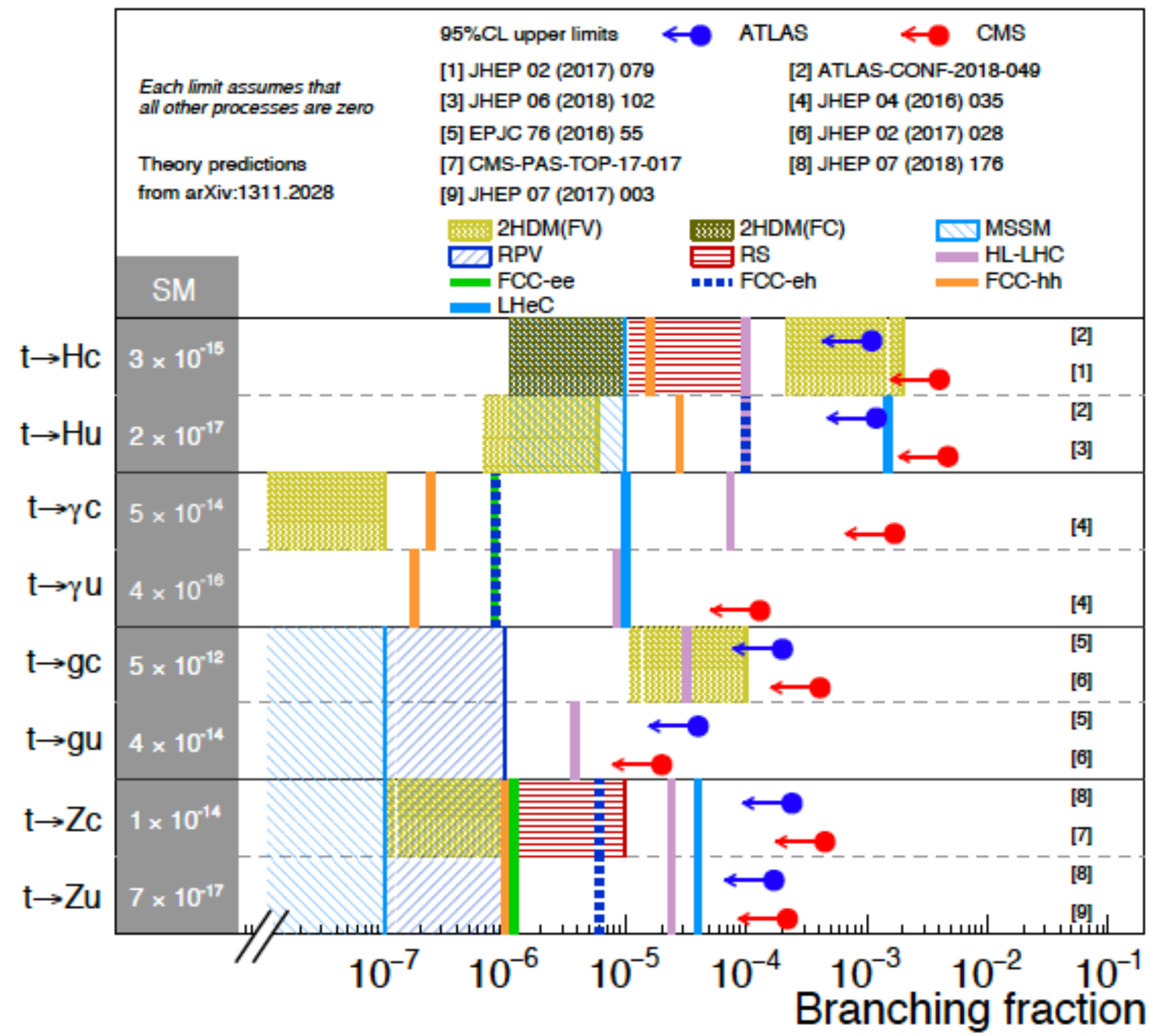
ILC optimal energy: √s ~ 500 GeV

Top Flavour Changing Neutral Currents

FCNC is a process where the top does not decay through CC ($t \to b$ with exchange of a W) but through NC ($t \to c, u$, with exchange of g, γ, Z or H)

- highly-suppressed in the SM
- can be enhanced by new physics

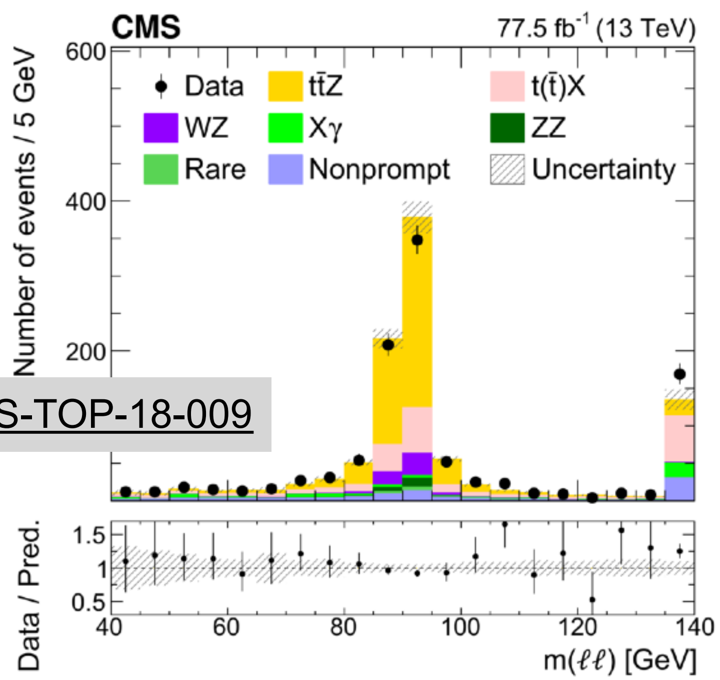
	SM	2HDM	MSSM
$t \to cg$	5×10^{-12}	$10^{-8} - 10^{-4}$	$10^{-7} - 10^{-6}$
$t \to cZ$	1×10^{-14}	$10^{-10} - 10^{-6}$	$10^{-7} - 10^{-6}$
$t \to c\gamma$	5×10^{-14}	$10^{-9} - 10^{-7}$	$10^{-9} - 10^{-8}$
$t \to cH$	3×10^{-15}	$10^{-5} - 10^{-3}$	$10^{-9} - 10^{-5}$



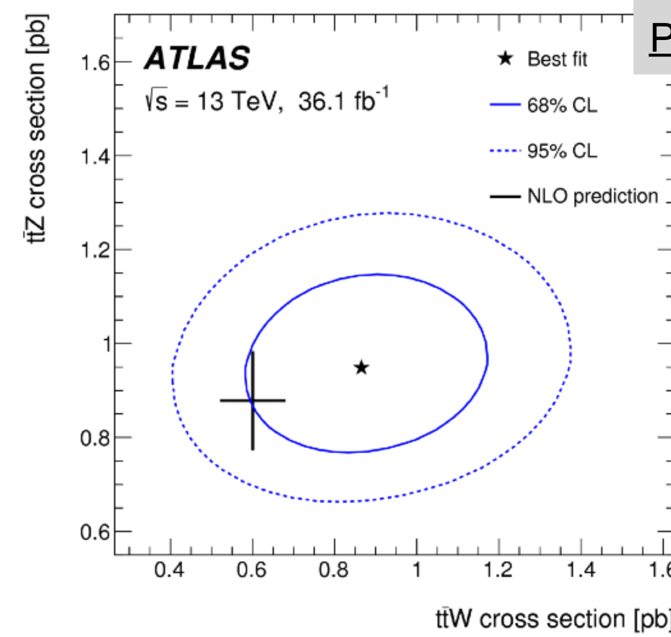
- ➠ FCC-hh: best reach due to the huge statistics available (10^{12} top quarks!)
- ➠ Exploiting boosted topologies allows to compensate large pileup (> 500)

Tops + (multi) Bosons, (multi) Tops

☛ $t\bar{t}W$ and $t\bar{t}Z$ production observed at LHC Run-II



CMS-TOP-18-009

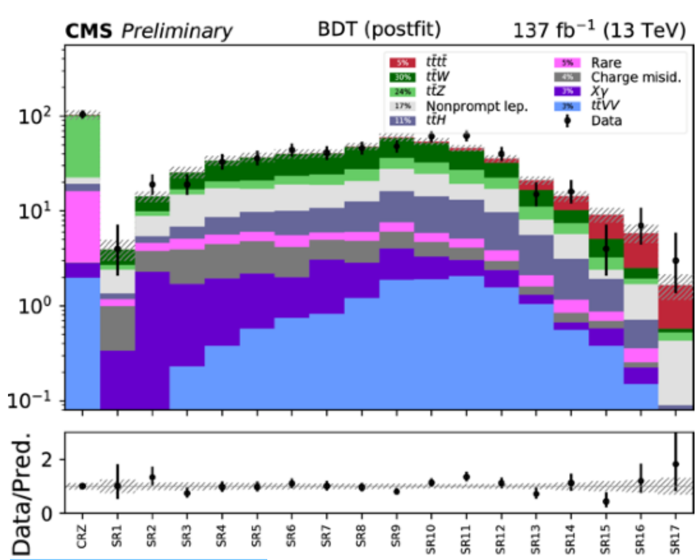


PRD 99 (2019) 072009

HL-LHC

- 10 to 100 more statistics

☛ 4-top production

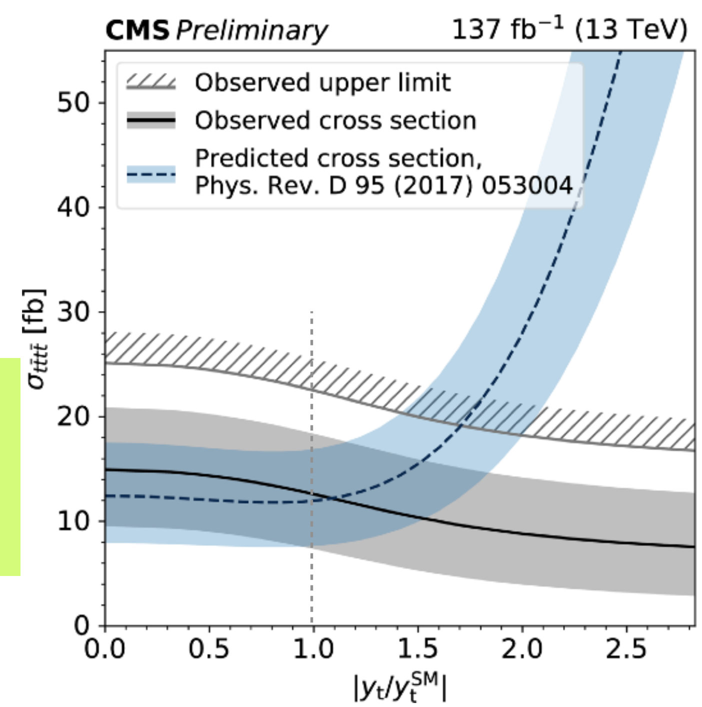


2.6 (2.7) σ

CMS-PAS-TOP-18-003

(almost) observed at LHC Run-II

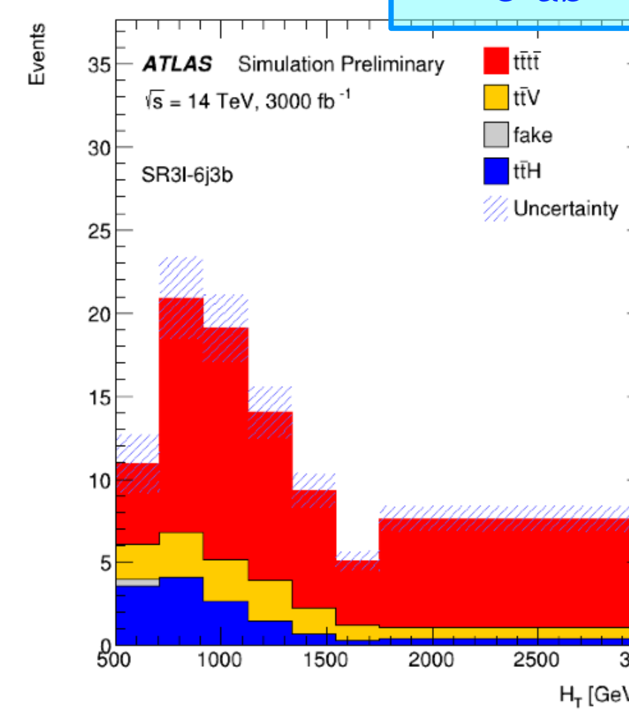
a way to probe the top Yukawa



obs. x-sect. (y_t/y_t^{SM} = 1): $12.6_{-5.2}^{+5.8}$ fb

SM: $12.0_{-2.5}^{+2.2}$ fb

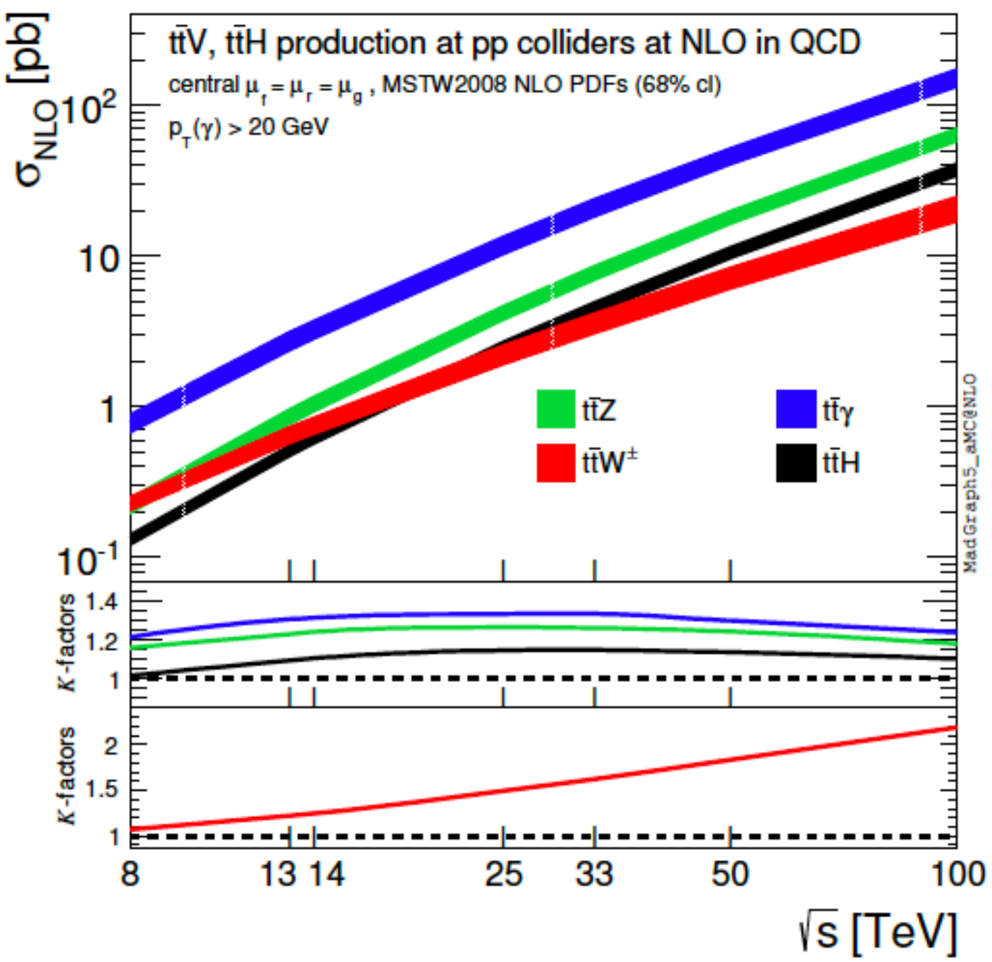
ATLAS HL-LHC
14 TeV
3 ab⁻¹

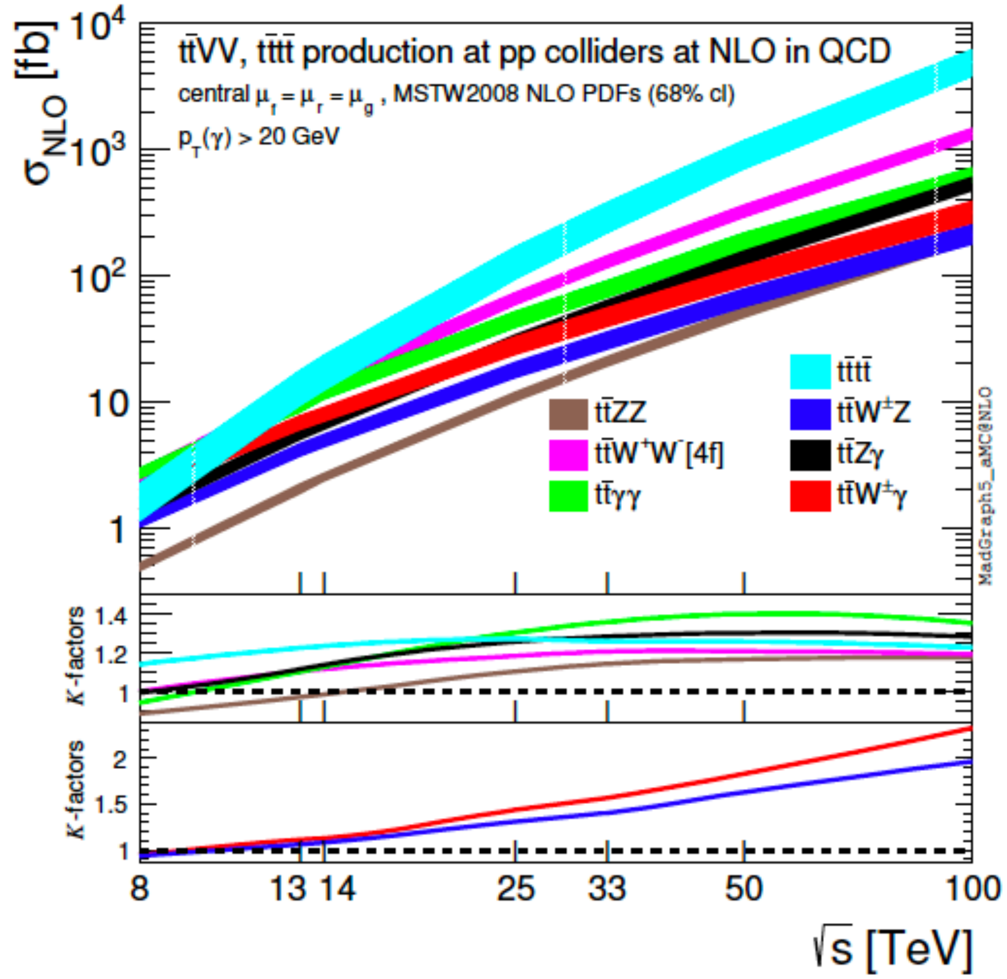


ATL-PHYS-PUB-2018-047

Tops + (multi) Bosons at FCC-hh

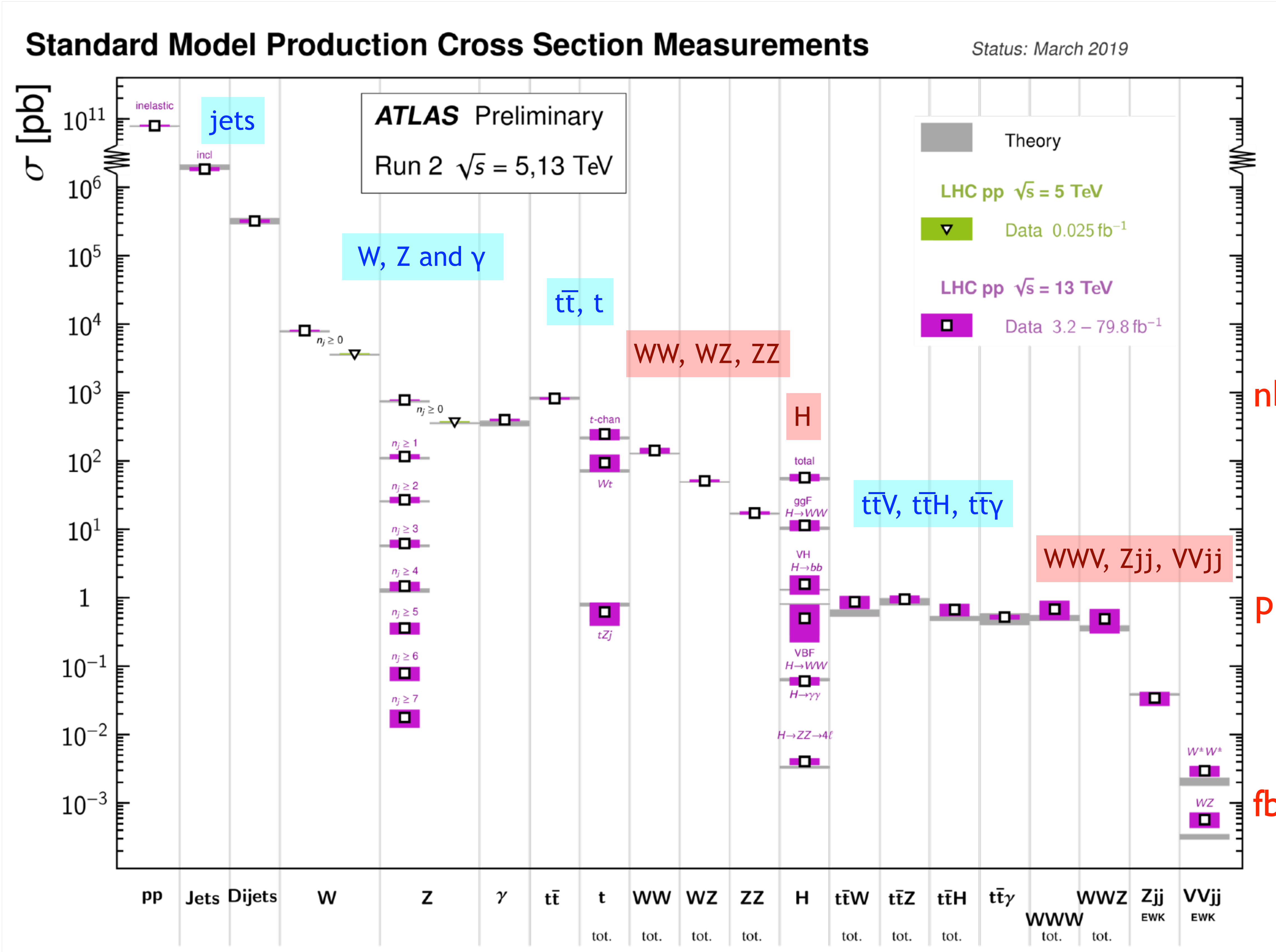
HL-LHC (→ HE-LHC) → FCC-hh
➠ huge increase in statistics





F. Maltoni et al.
arxiv:1507.05640

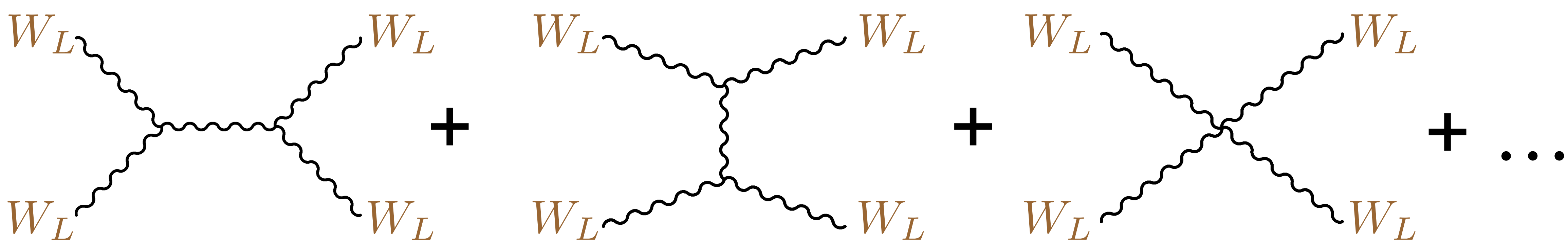
Summary of SM x-Sections at LHC



Unitarity and the Higgs Boson

Difference between massive and massless boson = longitudinal polarisation

Very relativistic massive bosons are dominated by their longitudinal polarisation

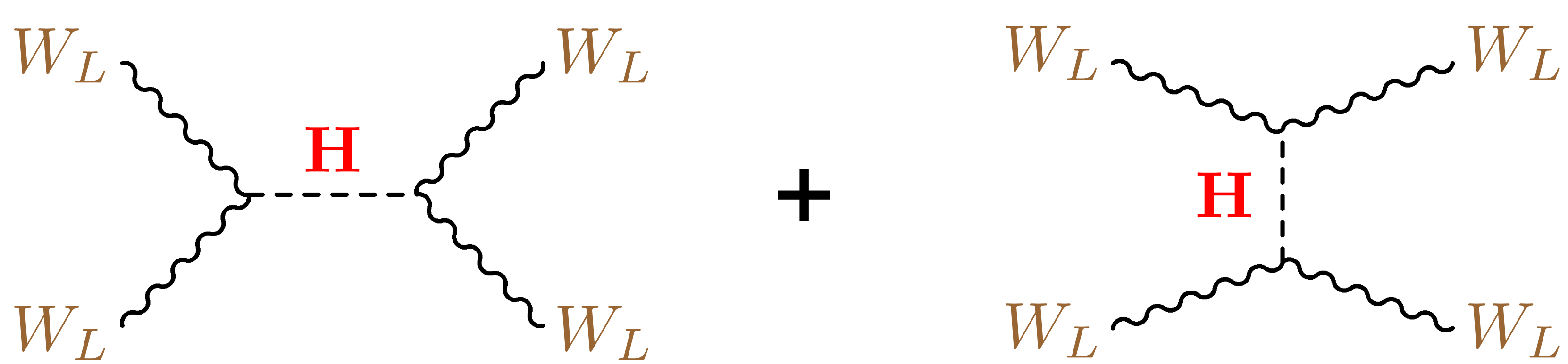


Longitudinal scattering amplitudes grow as CM energy increases

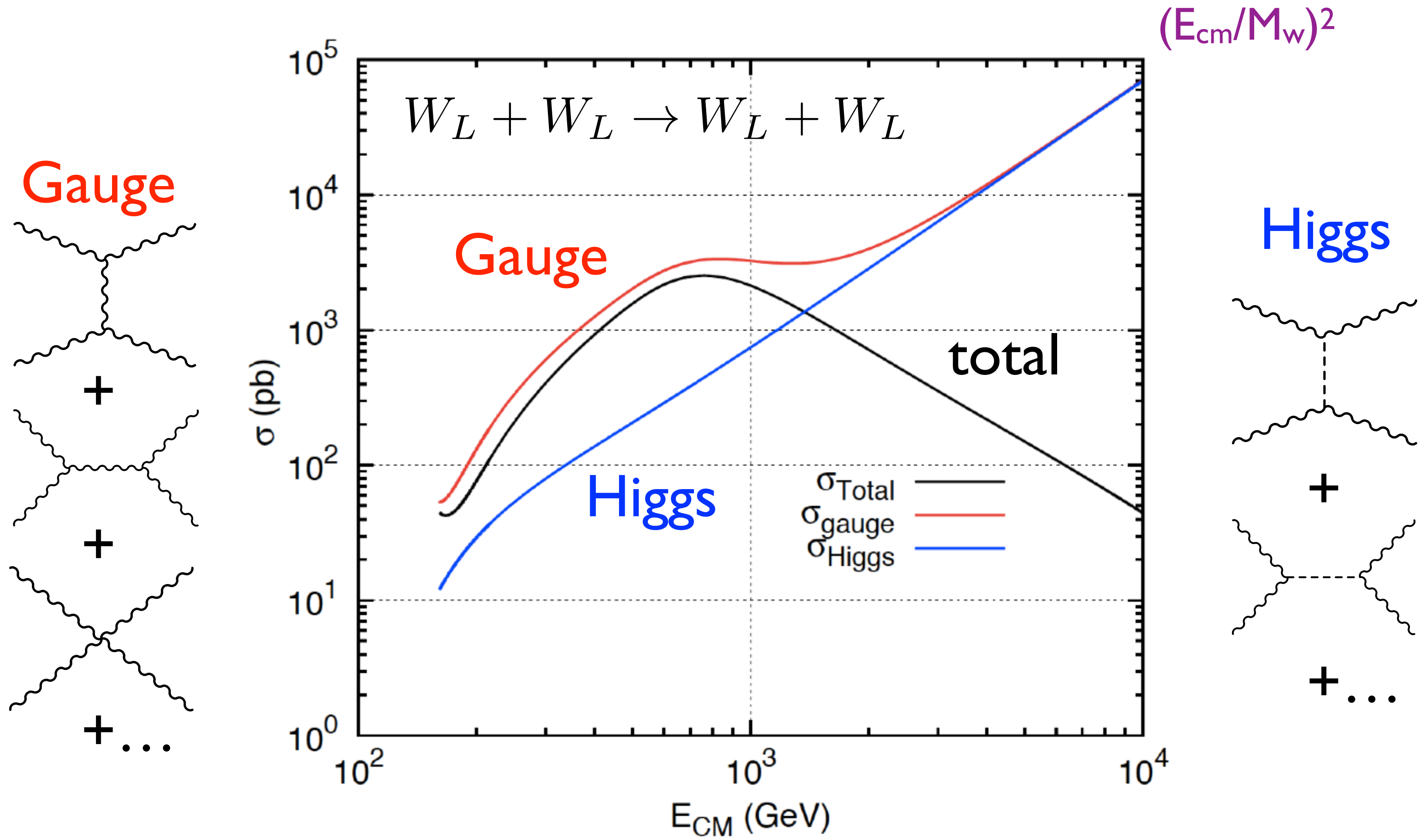
... and eventually violate *unitarity*

In the SM, the Higgs boson "unitarises" the longitudinal scattering amplitudes

(*unitarity* means "sum of probabilities of all processes equals one")

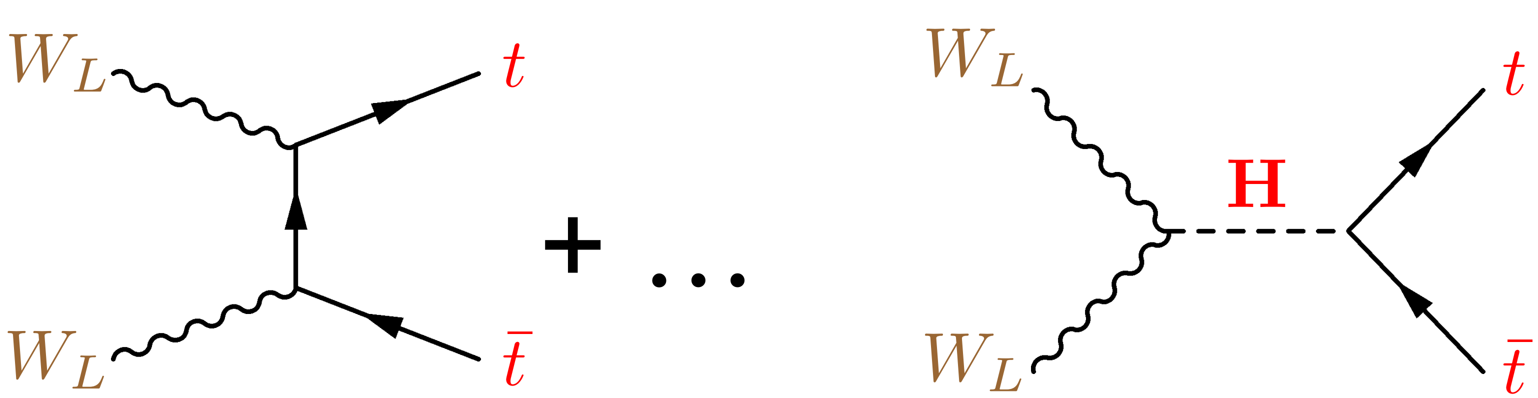


Unitarity and the Higgs Boson



The Higgs boson contribution cancels exactly the E^2 dependance of the cross section at high energy

Similarly the process $W_L W_L \to t\bar{t}$



...is "unitarised" by Higgs boson exchange

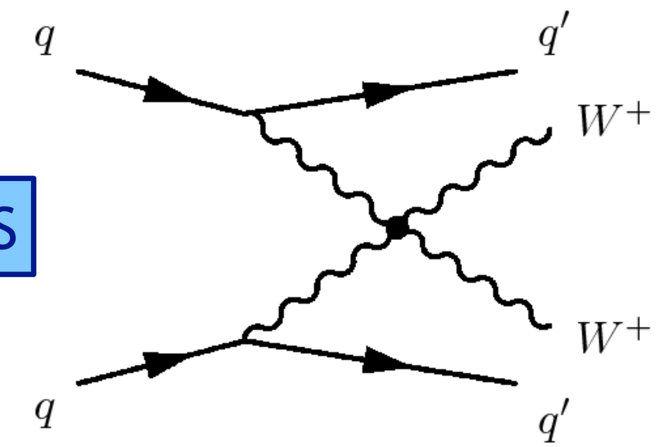
Unitarity is preserved if and only if all Higgs couplings are exactly those predicted by the SM

cf. N. Arkani-Hamed :"Inevitability of Physical Laws: Why the Higgs Boson Has to Exist"

Elucidating the EWSB Sector

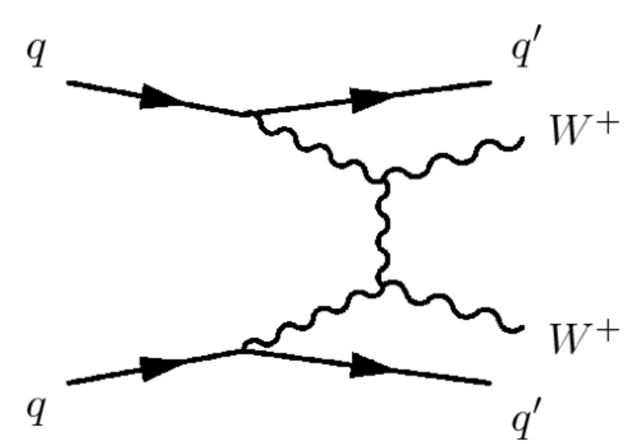
➠ probe longitudinal gauge boson scattering in regime where the EW symmetry is restored ($\sqrt{s} \gg 246$ GeV)

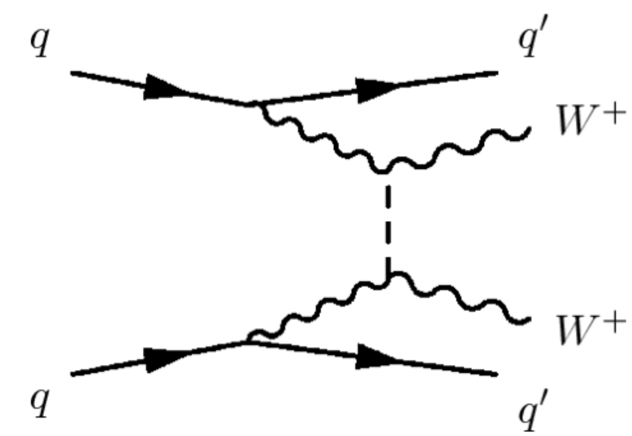
Crucial closure test of the SM
- either the Higgs regularises the theory fully
- or New Physics must show up a the TeV scale



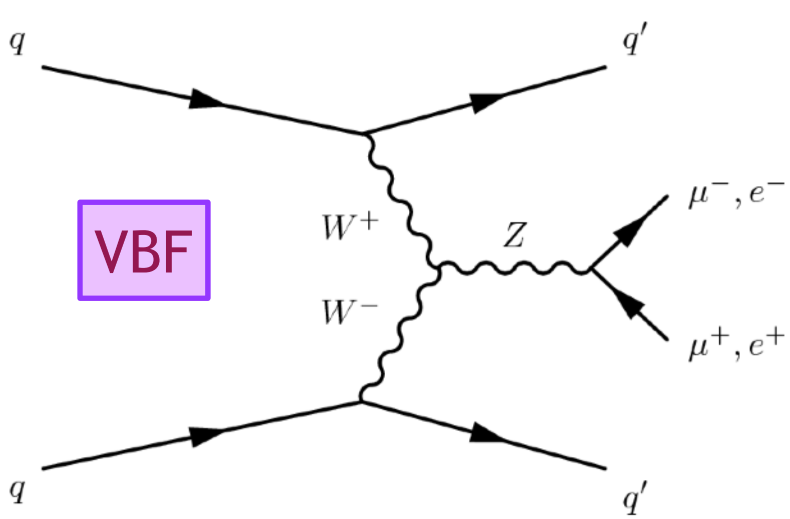
VBS

Dibosons & Vector Boson Fusion (VBF)
➠ anomalous Triple Gauge Couplings (aTGC)
Tribosons & Vector Boson Scattering (VBS)
➠ anomalous Quartic Gauge Couplings (aQGC)



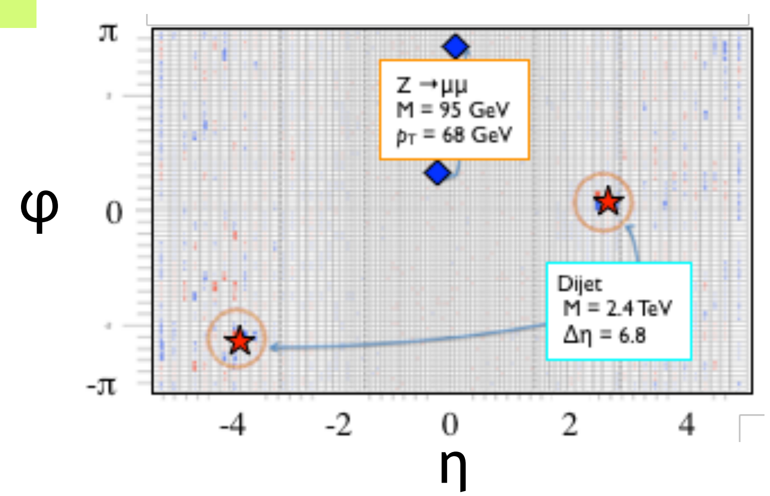


VBF



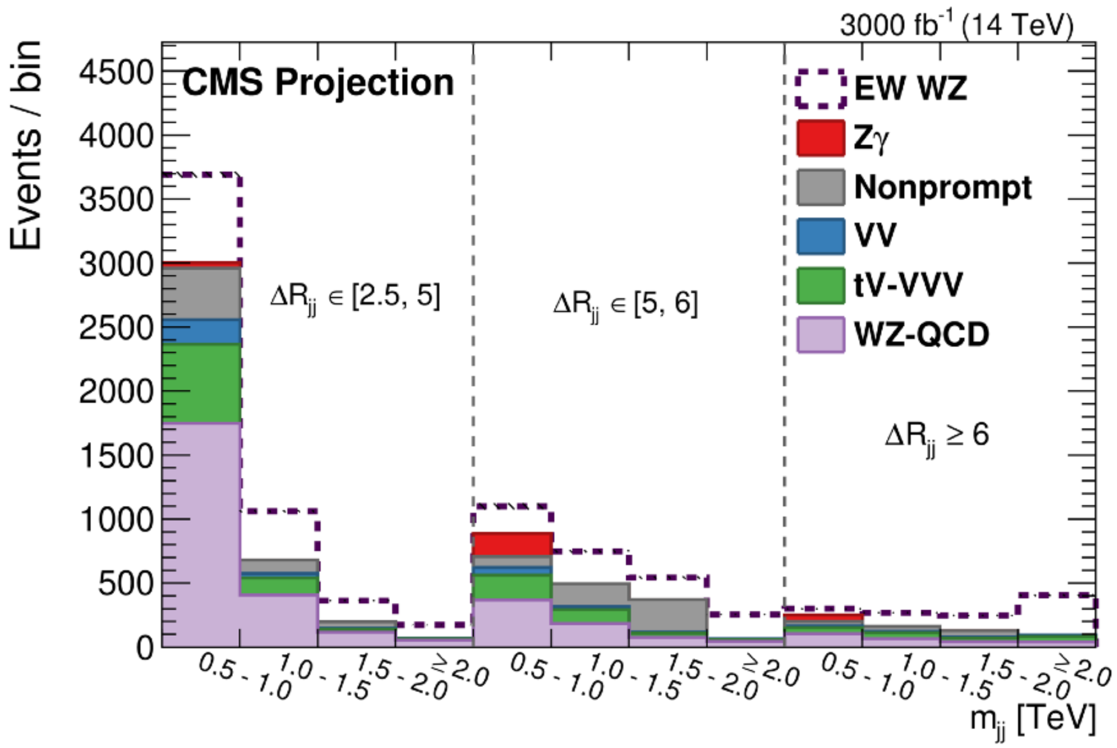
EWK production of the Z boson already seen at LHC Run-II

Common features:
- two hard high-rapidity jets
- large di-jet invariant mass (set by the mass scale of the scattered vector bosons)



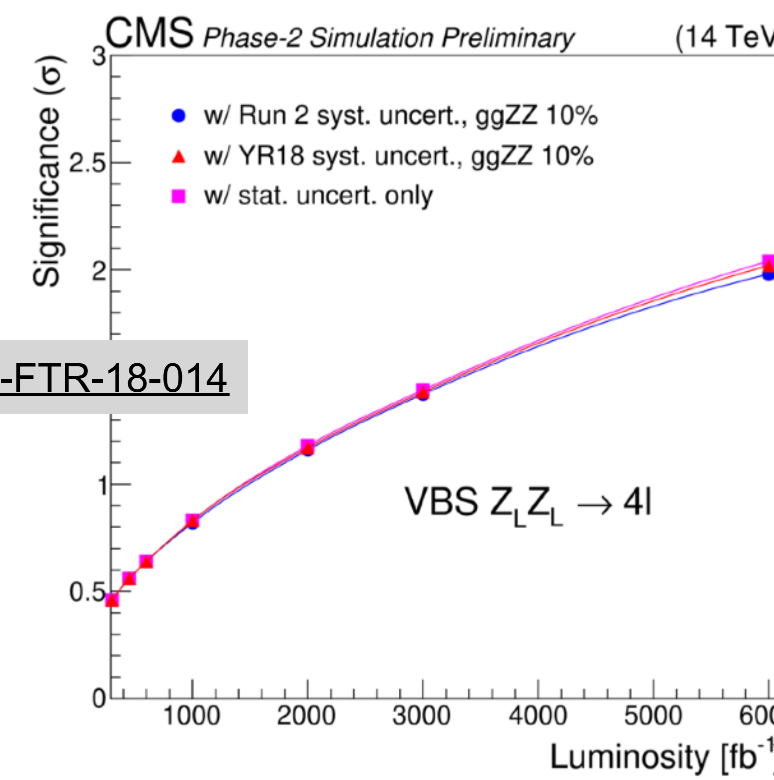
di-jet angular distance
$\Delta R^2 = \sqrt{(\Delta\varphi^2 + \Delta\eta^2)}$

VBS Expectations at HL/HE-LHC



VBS x-sections at HL-LHC

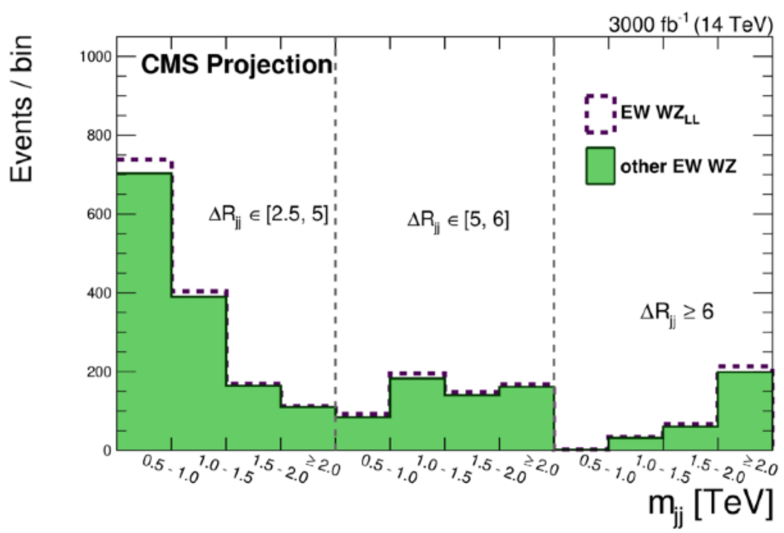
- > 5-σ observations for W^+W^+, WZ, WV, ZZ
- precision in the 6-10% range
- differential x-sections for ZZ

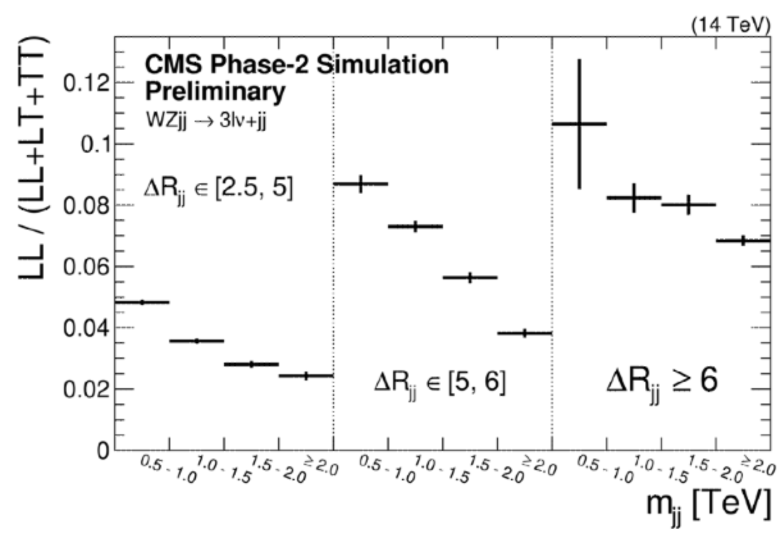


!!!

CMS-PAS-FTR-18-014

Separation of the LL component (~5%)





- expect > 3σ for $W_L W_L$ fraction by combining ATLAS and CMS at HL-LHC
- 5σ for $Z_L Z_L$ fraction at HE-LHC

CMS-PAS-FTR-18-038

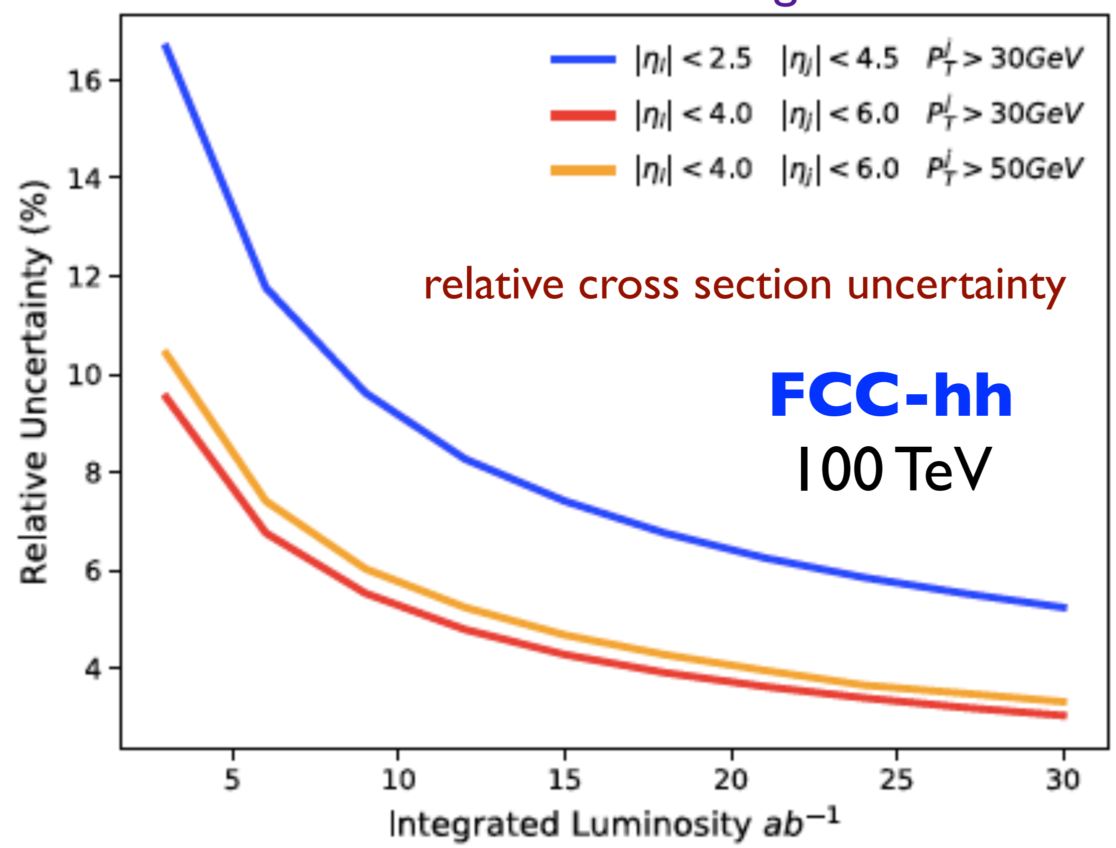
VBS Expectactions at FCC-hh

Extraction of the same-sign $W_L W_L$ signal requires removal of large QCD backgrounds (VV+jets) and separation of large EW background from transverse-boson scattering

- ➟ two forward jets with large rapidity separation
- ➟ large dilepton mass
- ➟ LL component from azimuthal correlations between leptons

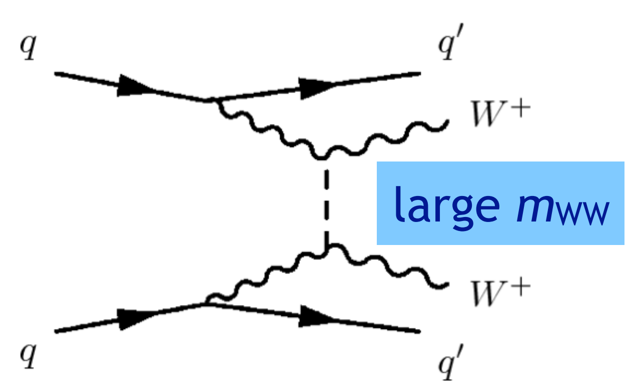
VBS process set strong constraints on the design for FCC-hh detectors

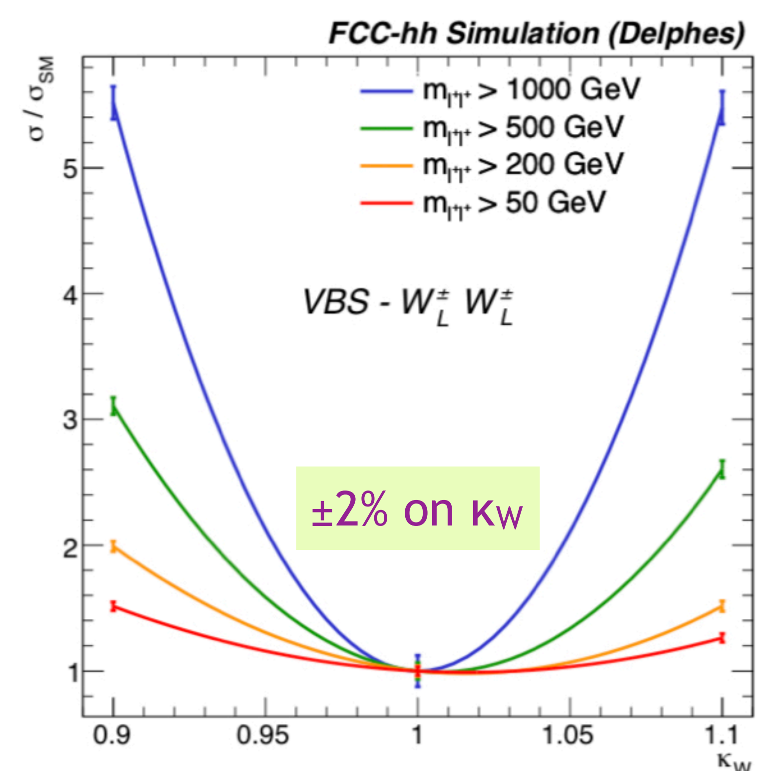
VBS $W_L W_L$ same sign

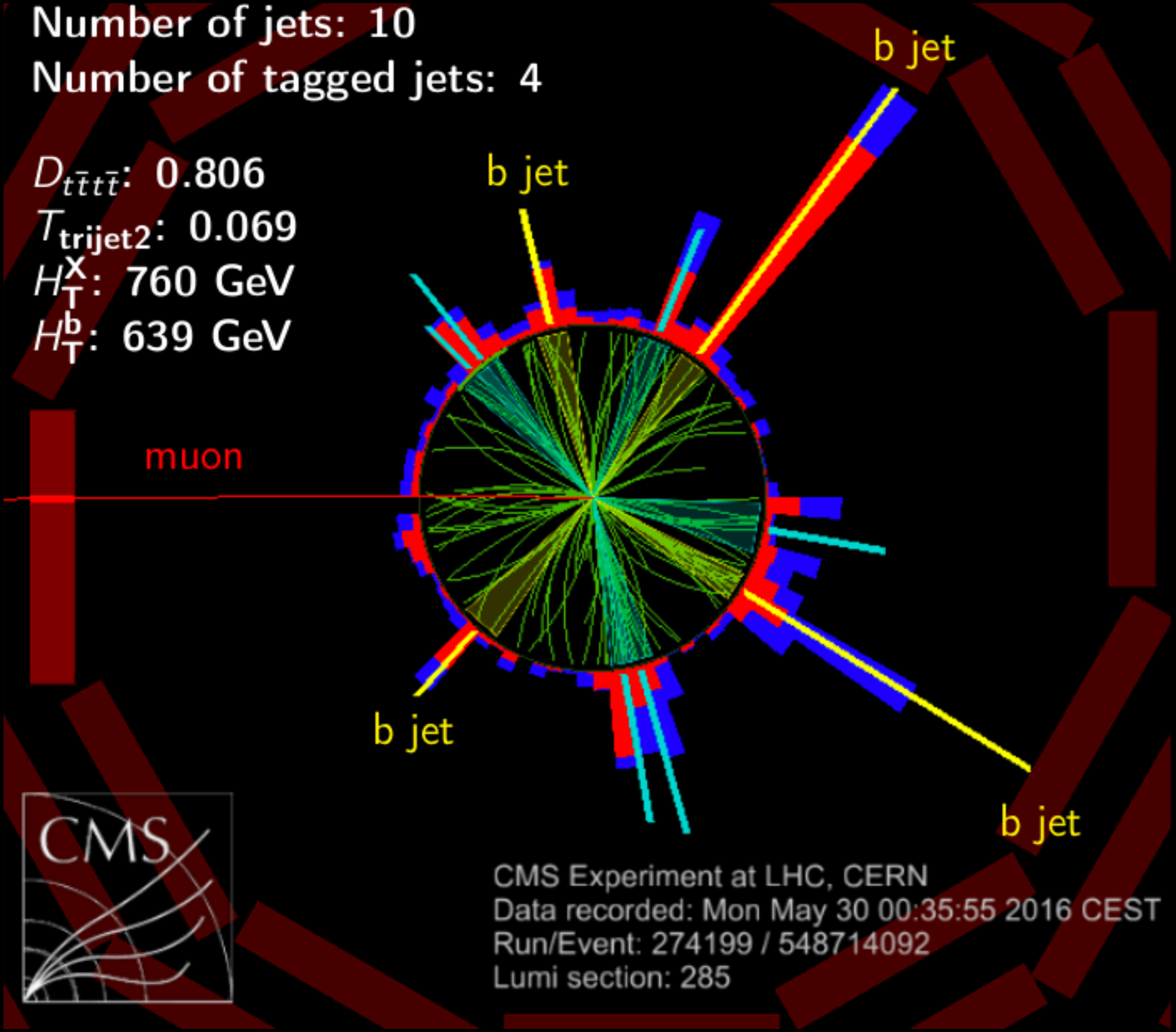


A precise measurement (3-4% precision) necessitates
leptons down to $|\eta| = 4$ and
jets down to $|\eta| = 6$
in conditions of 1000 pile-up events!

➟ constraints on κ_W
for various cuts on $m_{\ell\ell}$







A 4-top candidate event in CMS