Summary / Prospects / Physics Case
Electroweak, QCD, Heavy Flavour

Joint **FCC France-Italy, Lyon**
— November, 2022

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Presentations at this workshop

This summary based on the following presentations

Overview of Theory
Fulvio Piccinini (Pavia)

Overview of Software and Physics
Patricia Azzi (Padova/CERN)

Overview of Detector Concepts
Didier Contardo (IP2I Lyon)

Forward-Backward Asymmetries
Giovanni Guerrieri (Trieste)

$b \to s\tau^+\tau^-$
Tristan Miralles (LPC Clermont)

$B_s \to D_sK$ benchmark with IDEA
Giulio Mezzadri (Ferrara)

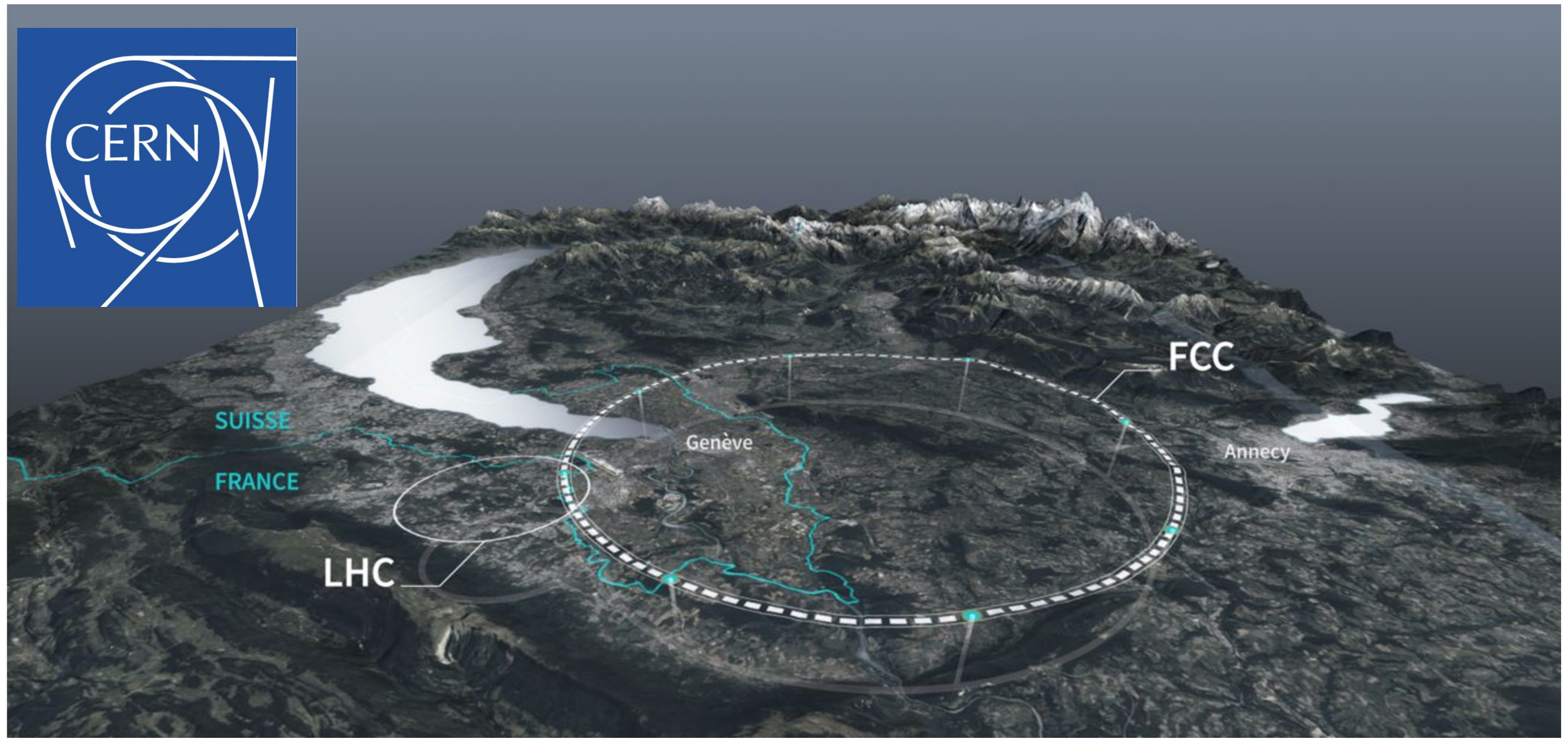
Prospect for tau measurements
Alberto Lusiani (Pisa)

Top-beauty synergies @ FCC-ee
Lars Röhrig (TU Dortmund, LPC Clermont)

Vector Boson Scattering at FCC-hh
Isaac Ehel (LLR)

FCC: Future Circular ColliderS

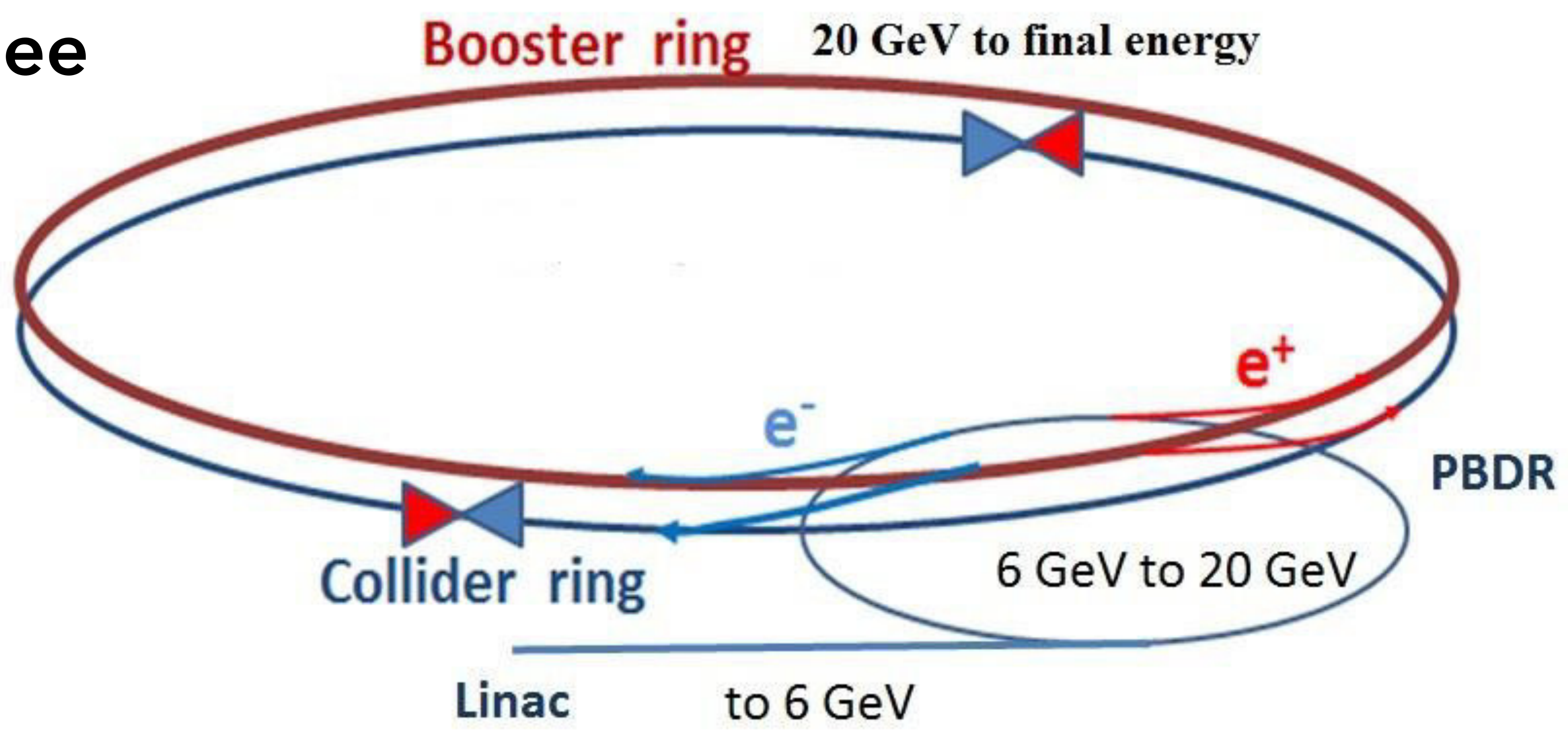
see presentation by Frank Zimmermann



100-km tunnel in Geneva area, 100-300 m underground, 8 sites

	$\sqrt{s}$	$\mathscr{L}$ ($cm^{-2}s^{-1}$)	first beams (technically)	tunnel
FCC-ee	90-365 GeV	$200\text{-}1.5\times10^{34}$	2039	100-km
FCC-eh	3.5 TeV	1.5×10^{34}	2043	
FCC-hh	100 TeV	3×10^{35}	2043	

FCC-ee



RF system: high-current → high gradient

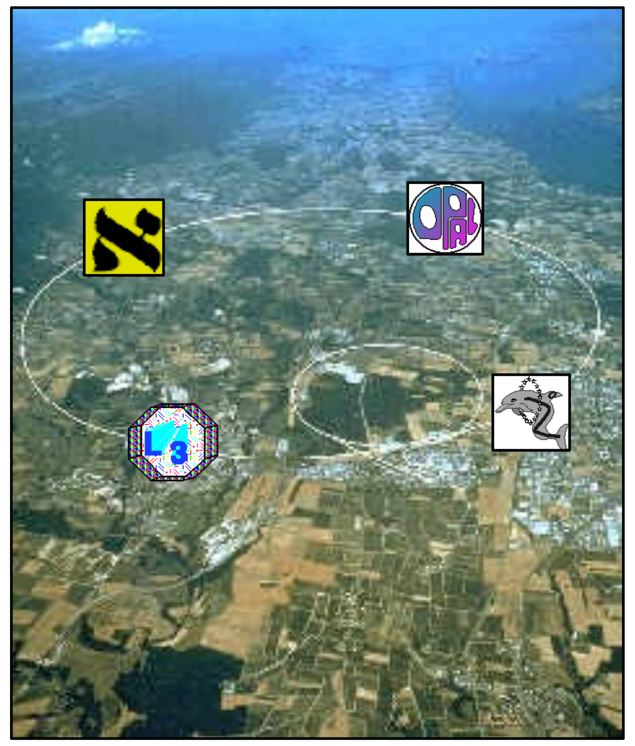
	V_{rf} [GV]	#bunches	I_{beam} [mA]
Z	0,1	16640	**1390**
WW	0,44	2000	147
ZH	2,0	393	29
top	**10,9**	48	5,4

Reminder: Physics at the Z-Pole

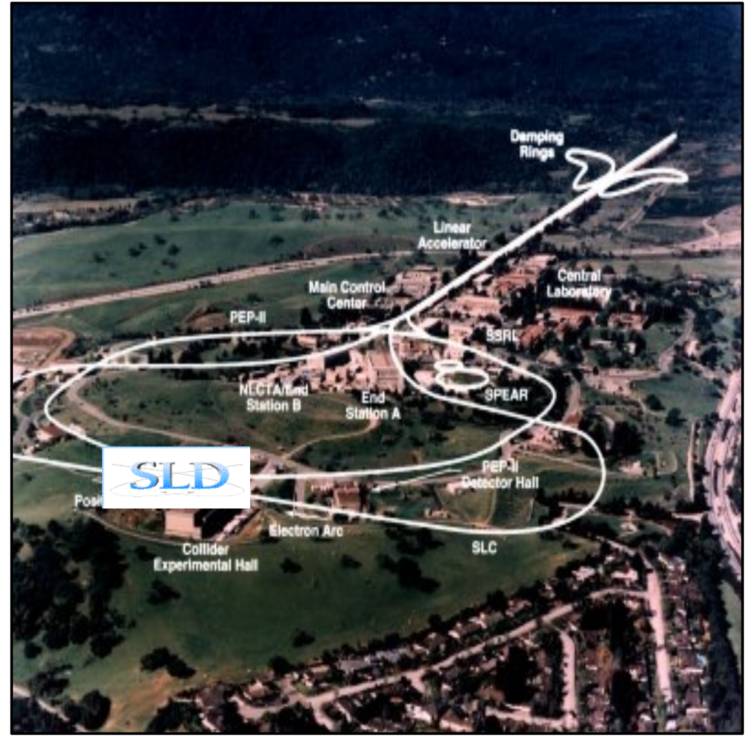
e^+e^- colliders $\sqrt{s}$ = 91 GeV

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!

LEP1 legacy

M_Z = 91187.5 ± 2.1 MeV
Γ_Z = 2495.2 ± 2.3 MeV

from Z line shape

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

from LR and FB asymmetries
(tension "leptons" vs "quarks")

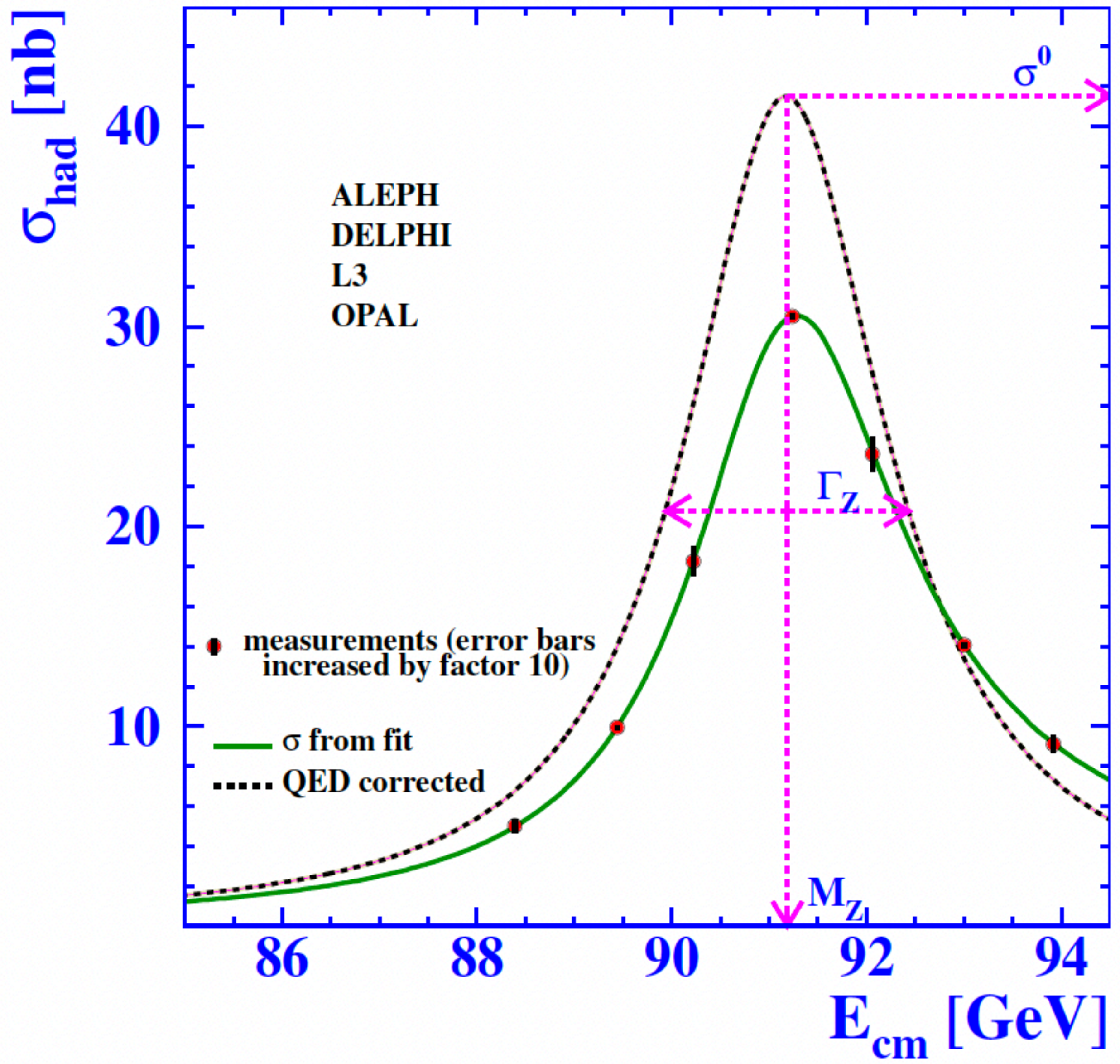
α_s = 0.1190 ± 0.0025

from multi-jets

N_ν = 2.9840 ± 0.0082

from peak cross -section and ratio of partial widths
(2σ deficit)

$e^+e^- \rightarrow Z \rightarrow$ hadrons



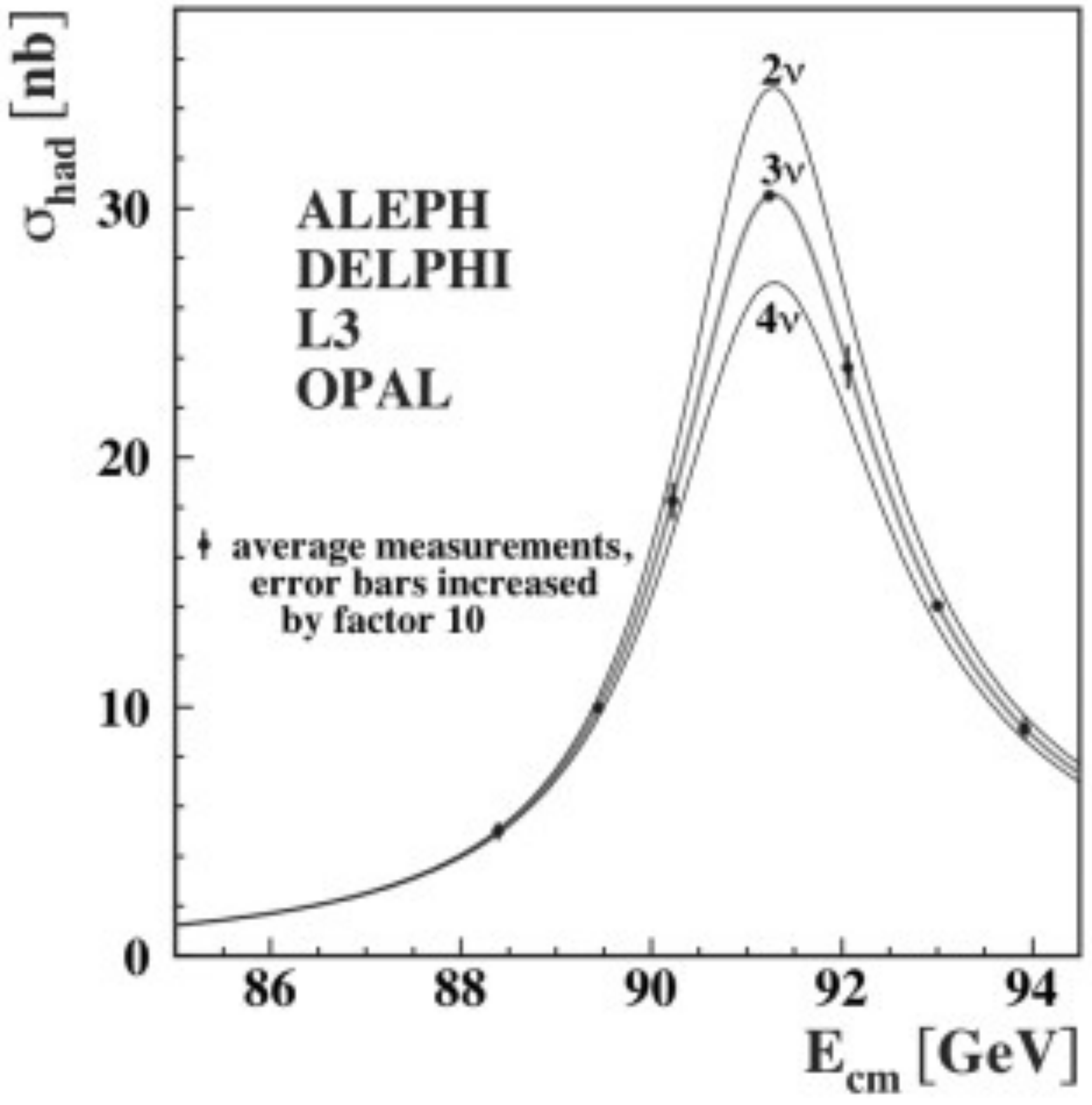
see presentation by
F. Puccinini

A By-Product of FCC-ee Studies

A recent LEP **luminosity update** confirms $N_\nu = 3$ *active neutrinos*

$$\sigma^0_{\text{had}} = \frac{N_{\text{had}}}{L}$$

Luminosity: dominant source of uncertainty in σ_{had}^0 and N_ν



Including **corrections** due to the beam-beam effect, and updating theoretical calculation the Bhabha scattering cross-section, the long-standing LEP 2σ deficit is gone

from $N_\nu = 2.9840 \pm 0.0082$

to $N_\nu = 2.9963 \pm 0.0074$

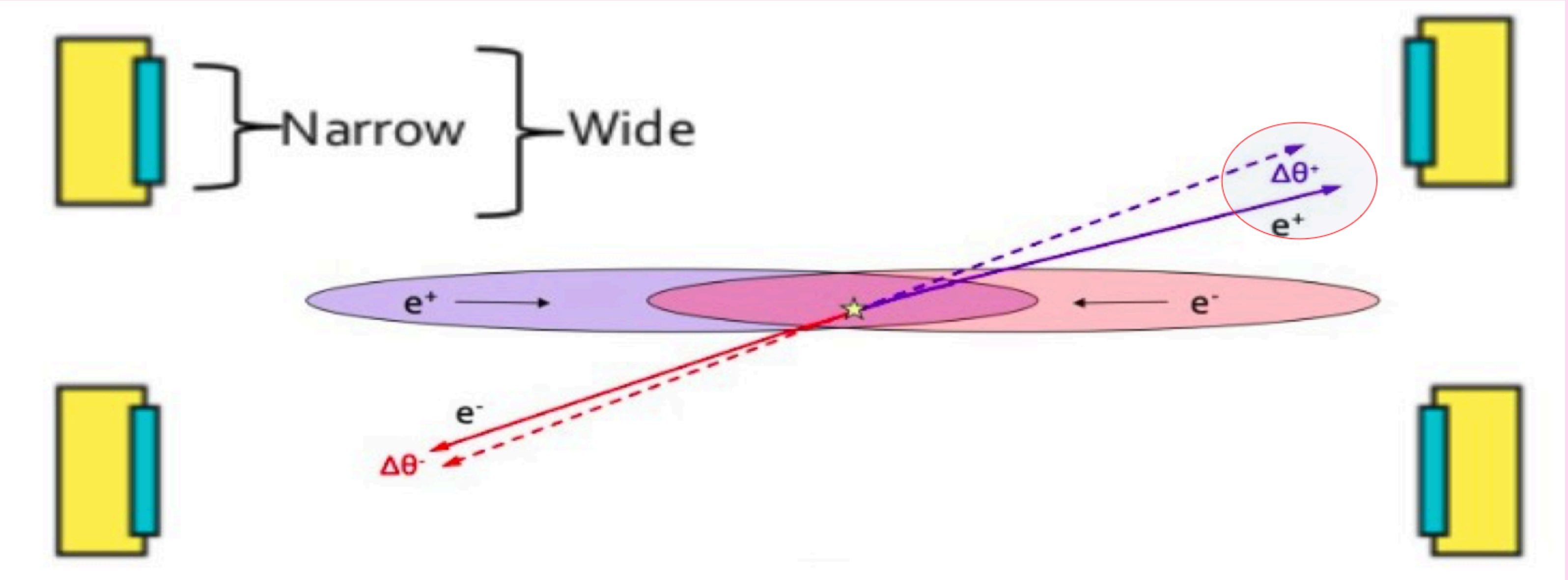
- $\sigma^0_{\text{had}} = 41.4737 \pm 0.0326$ nb
- $\Gamma_Z = 2.4955 \pm 0.0023$ GeV

arXiv:1908.01704

arXiv:1912.02067

Y.Voutsinas at Moriond EW 2021

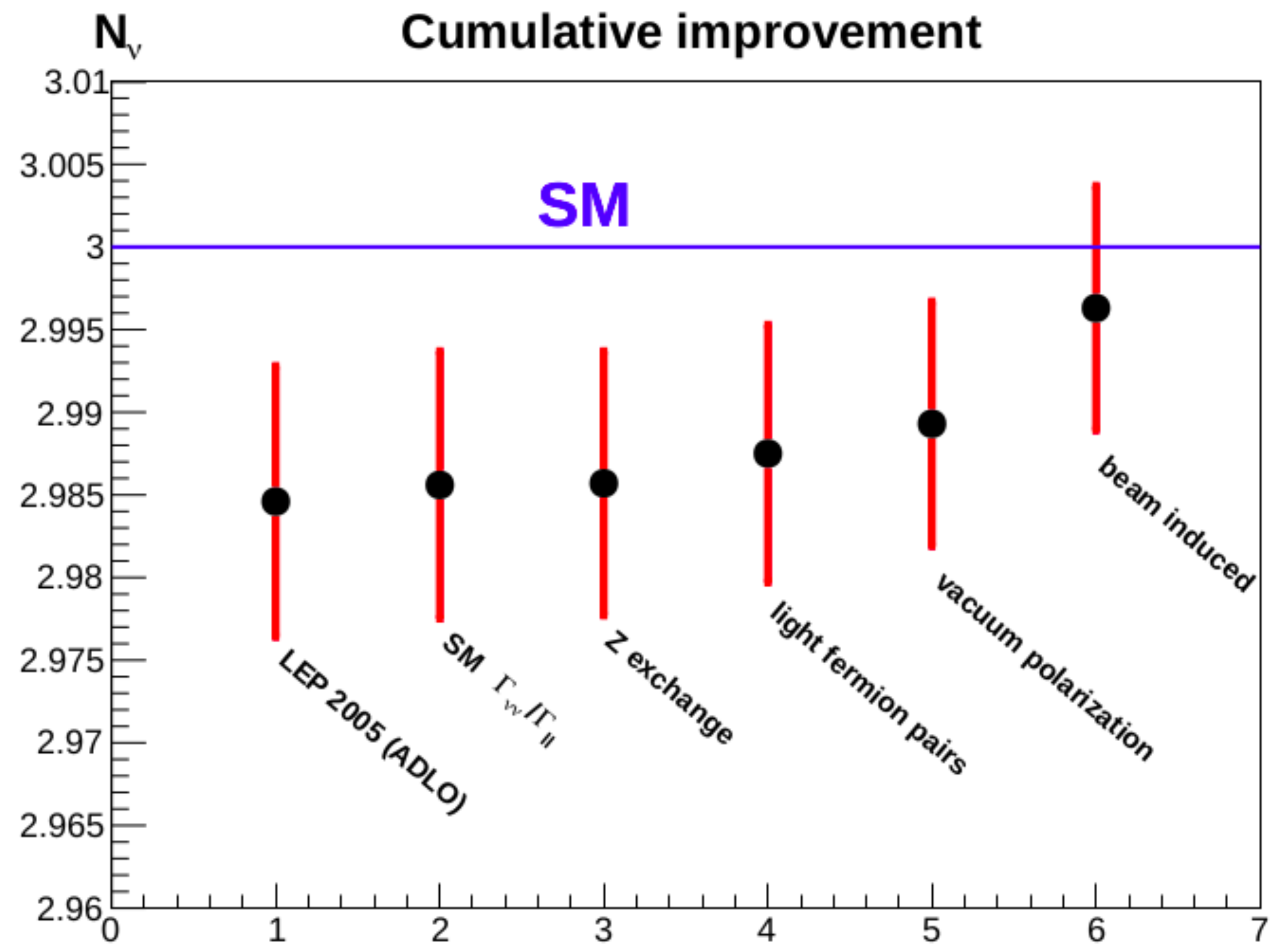
Luminosity from small-angle Bhabha scattering rate



scattered electrons are focused by the field of the opposite bunch

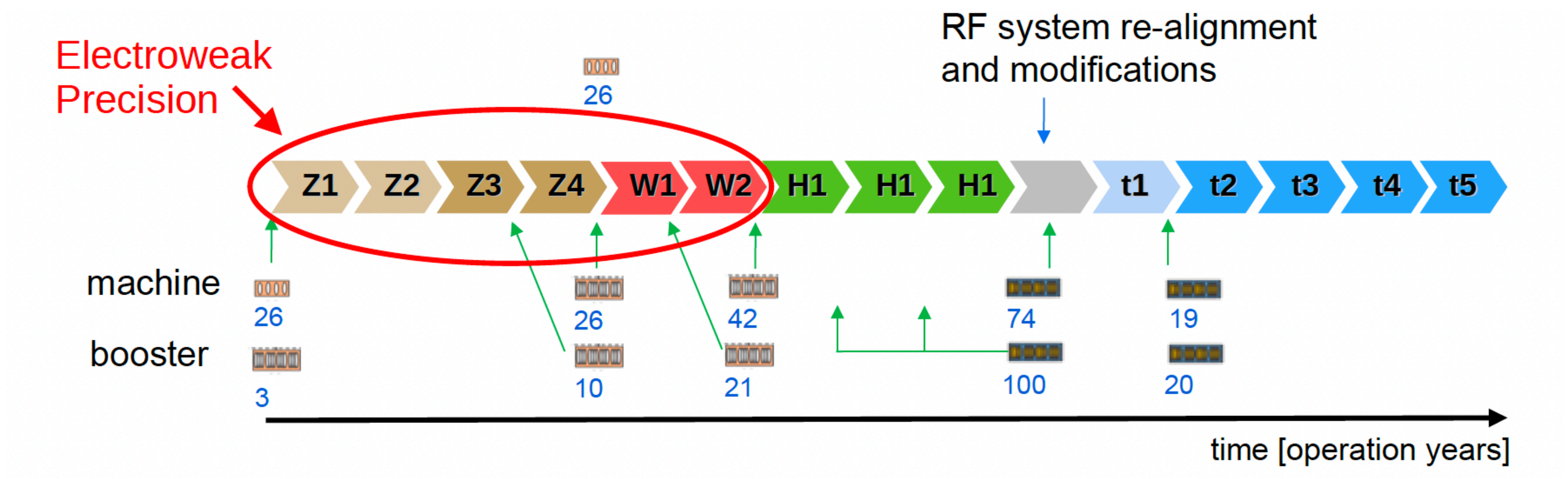
LEP-1
- beam-beam bias: −0.1%
- theory ±0.061%
- exp ±0.034%

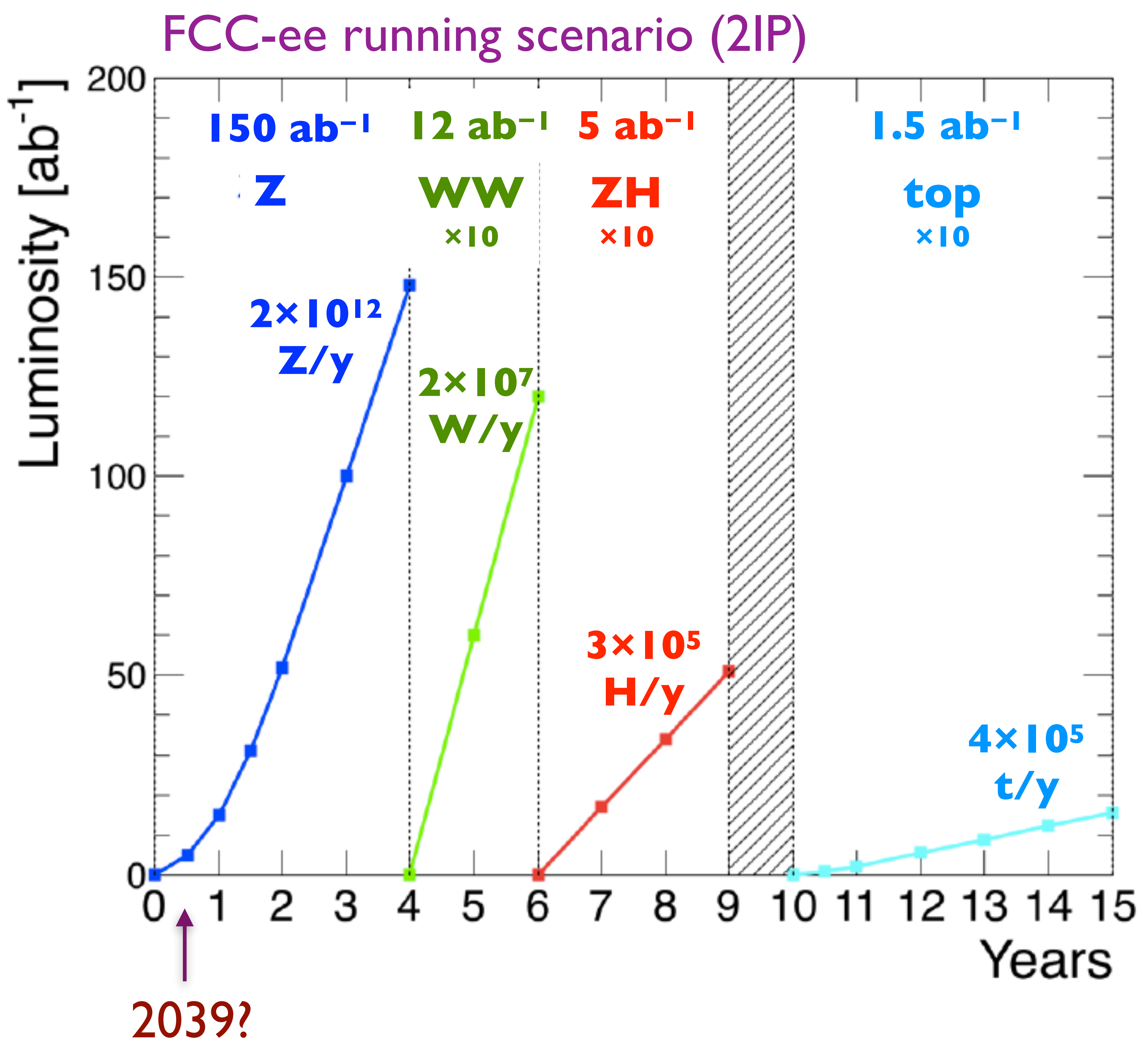
FCC-ee
- beam-beam bias: −0.2%
- $\Delta L/L = 10^{-4}$
- **luminometer**: extremely accurate mechanical construction, at $\mathcal{O}$(few μm)



theory improvements

FCC-ee: e^+e^- Circular Collider





With respect to LEP

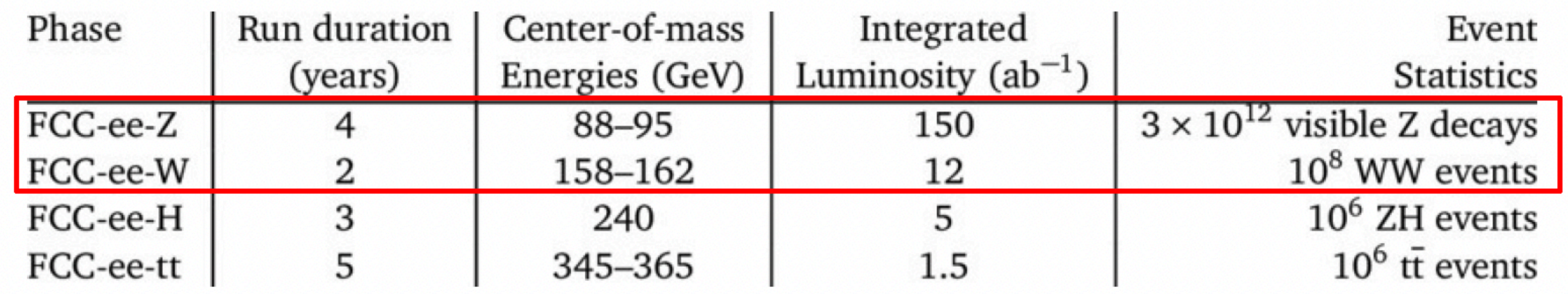
- LEP dataset = a few minutes of FCC-ee
- 3 orders of magnitude in statistical uncertainties
- About a million times LEP for precision measurements
- Goal: limit the systematic uncertainties within a factor of 10 of the statistical

Key elements

- Knowledge of center-of-mass energy
  - 100 keV at the Z, 300 keV at the WW threshold
- Knowledge of the luminosity
- Control of acceptance and efficiency
  - Detector fiducial volume
  - Detector simulations
- Control of backgrounds
- Theory predictions (signal and backgrounds)
  - Monte-Carlo simulations

FCC-ee as electroweak and flavour factory

Data taking plan



Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics
FCC-ee-Z	4	88–95	150	3×10^{12} visible Z decays
FCC-ee-W	2	158–162	12	10^8 WW events
FCC-ee-H	3	240	5	10^6 ZH events
FCC-ee-tt	5	345–365	1.5	10^6 $t\bar{t}$ events

Huge statistics at the Z pole

- 150 fb^{-1} in 4 years
- > 3×10^{12} Z decays (LEP/ADLO: 20×10^6)

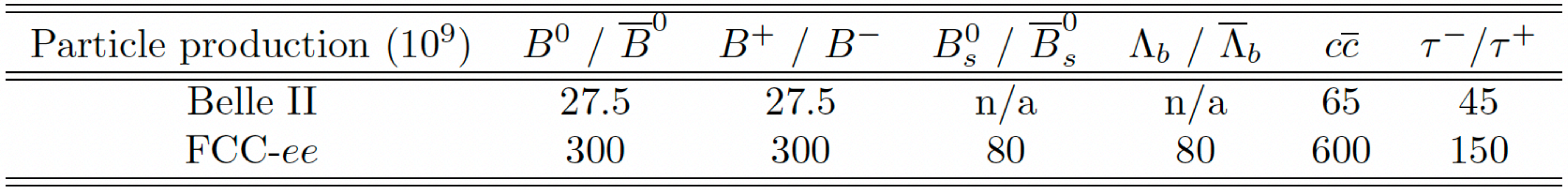
Tera Z (> 3×10^{12} Z decays, around Z pole)

- Z mass → precision EWK fit
- Z width → EWK radiative corrections
- $\sigma^0_{\rm had}$, peak cross section → invisible width, N_ν
- $R^0_\ell = \Gamma_{\rm had}/\Gamma_\ell$ → lepton couplings, $\alpha_s(m^2_Z)$
- $A_{\rm FB}(\mu\mu)$ → lepton couplings, $\sin^2\theta^{\rm eff}_W$, $\alpha_{\rm QED}(m^2_Z)$
- $A_{\rm FB}(\rm b, c)$, $R^0_{\rm b,c}$ → quark couplings
- tau polarisation → lepton coupling universality, $\sin^2\theta^{\rm eff}_W$

Oku WW (10^8 WW, around WW threshold)

- W mass → precision EWK fit
- W width → direct measurement
- $R^{\rm W}_\ell = \Gamma_{\rm had}/\Gamma_\ell$ → $\alpha_s(m^2_Z)$
- limits on anomalous triple and quartic gauge couplings

And also, Z pole = ultimate
beauty, charm and tau factory



Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B^0_s / $\overline{B}^0_s$	Λ_b / $\overline{\Lambda}_b$	$c\bar{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	300	300	80	80	600	150

and about 4.10^9 B_c mesons

Physics with > 3×10^{12} Z Bosons

FCC-ee

EWPOs
Goal: 20 to 100 better
precision than LEP

from
FCC-ee Snowmass

observable	present value	FCC-ee stat syst	from	main source of systematics
M_Z (MeV)	91186.7 ± **2.2**	**0.004** ± **0.100**	Z line shape	beam energy calibration
Γ_Z (MeV)	2495.2 ± **2.3**	**0.004** ± **0.025**		
$\sin^2\theta_{eff}$ ($\times10^6$)	231530 ± **160**	**2** ± **2.4**	$A_{FB}^{\mu,0}$	
$A_{FB}^{b,0}$ ($\times10^4$)	992 ± **16**	**0.02** ± **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**	**3** ± **<1**	A_{FB}^{μ} off-peak	
σ_{had}^0 (pb)	41541 ± **37**	**0.1** ± **4**	peak cross-sections	luminosity measurement
N_ν ($\times10^4$)	29960 ± **82**	**0.05** ± **10**		

- **$\sqrt{s}$ calibration** by RDP
    - $\Delta E/E \sim \mathcal{O}(10^{-6})$
    - 100 (300) 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})

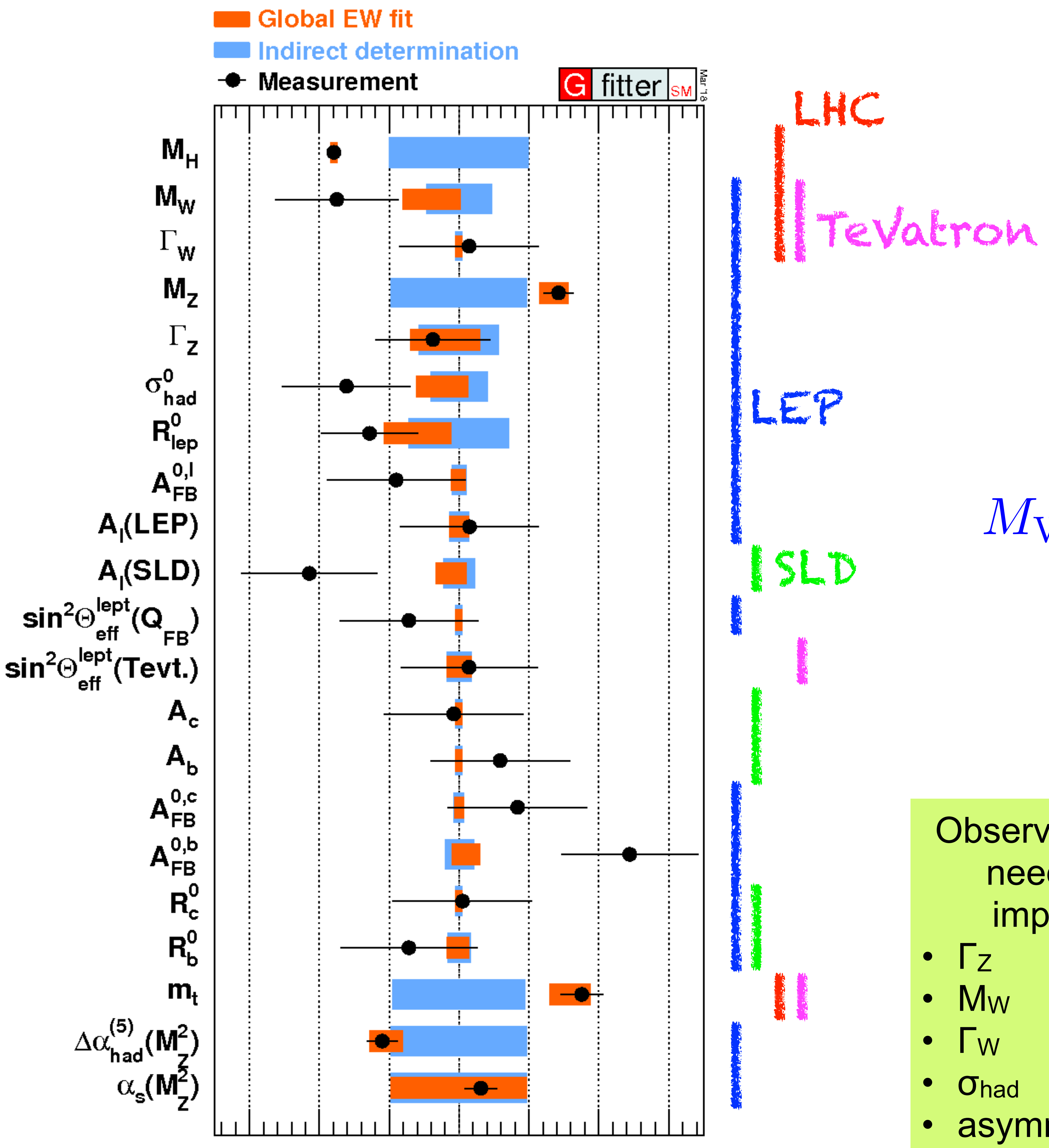
From **asymmetries** and **partial width** measurements, improvement by 1 to 2 orders of magnitude on Z vector and axial-vector couplings to leptons (e, μ and τ) and quarks (b and c)

- virtually infinite statistics
  → 20 years to work on systematics!
- already huge jump in precision after 2 years, > 10^{11} Z decays (= CEPC)

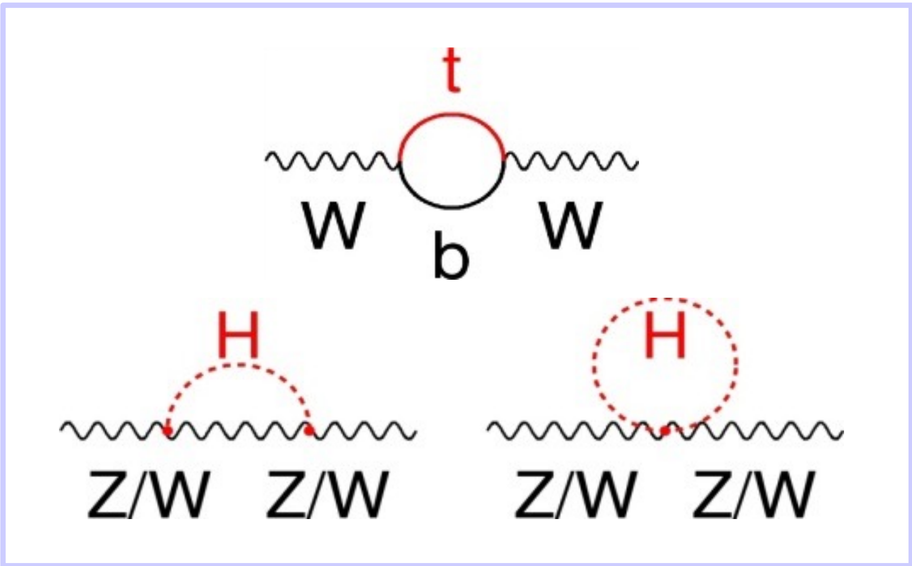
FCC-ee will require pushing **theory uncertainty** down by at least a factor of 10 on cross sections and even more on A_{FB} w.r.t LEP [FP]

The Electroweak Fit

see presentation by Fulvio Piccinini



p-value Prob(χ^2_{min},15) = 0.23



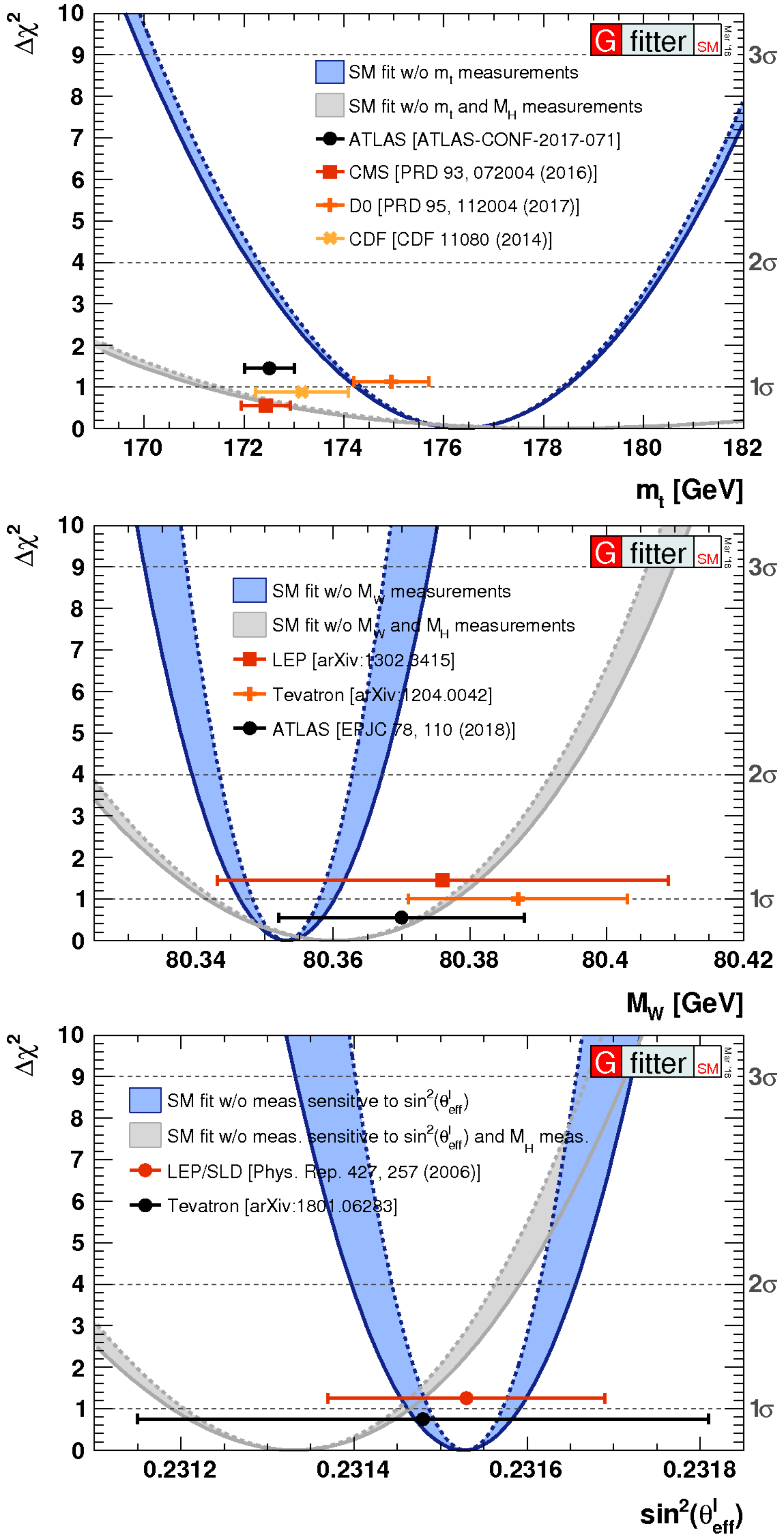
$$M_W{}^2 = (1+\Delta\rho) M_Z{}^2 (1-\sin^2\theta_{\rm eff})$$

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

(of order 1%)

Observables that need to be improved:

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



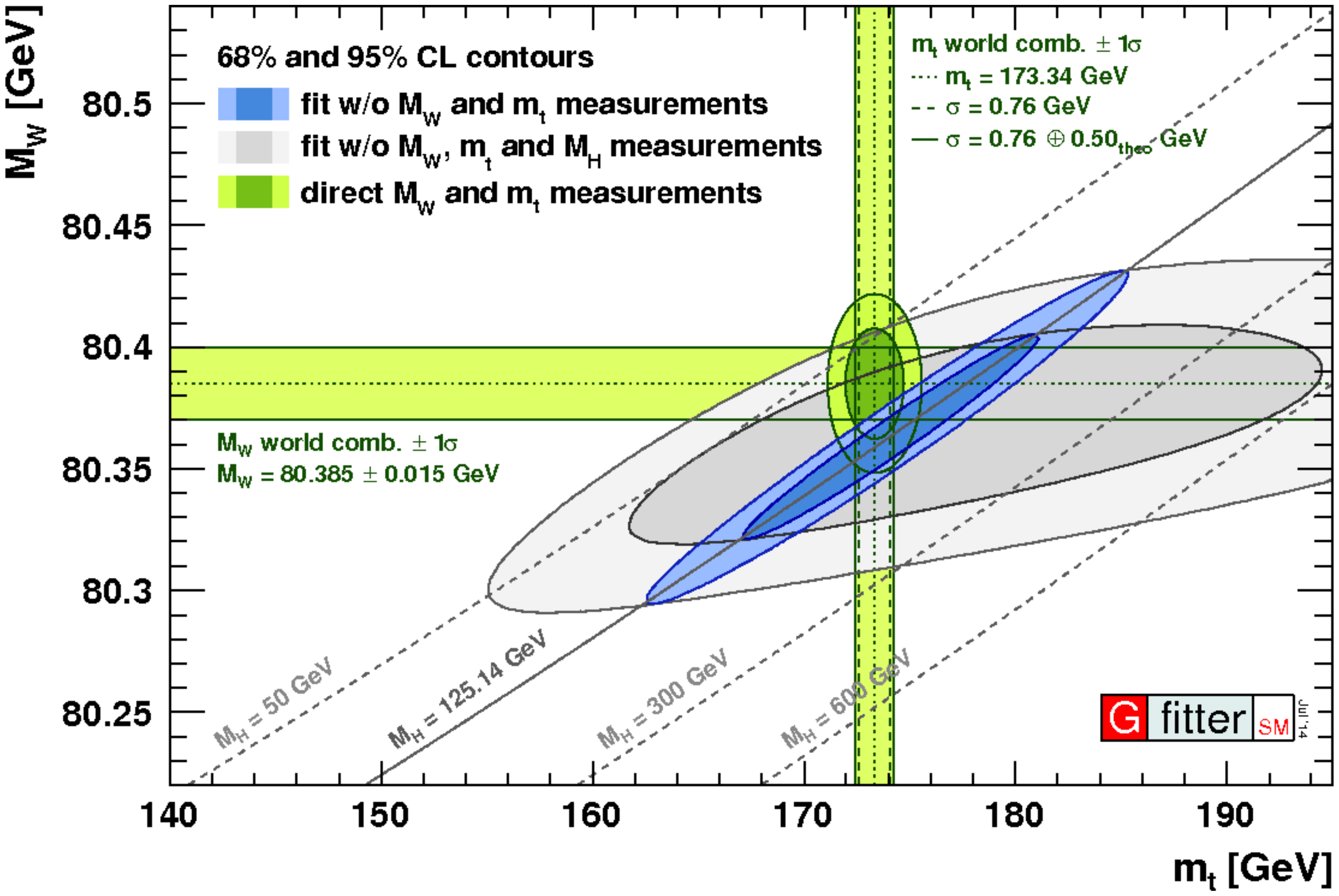
m_t

M_W

$\sin^2\theta^{eff}$

The Electroweak Fit

see presentation by Fulvio Piccinini

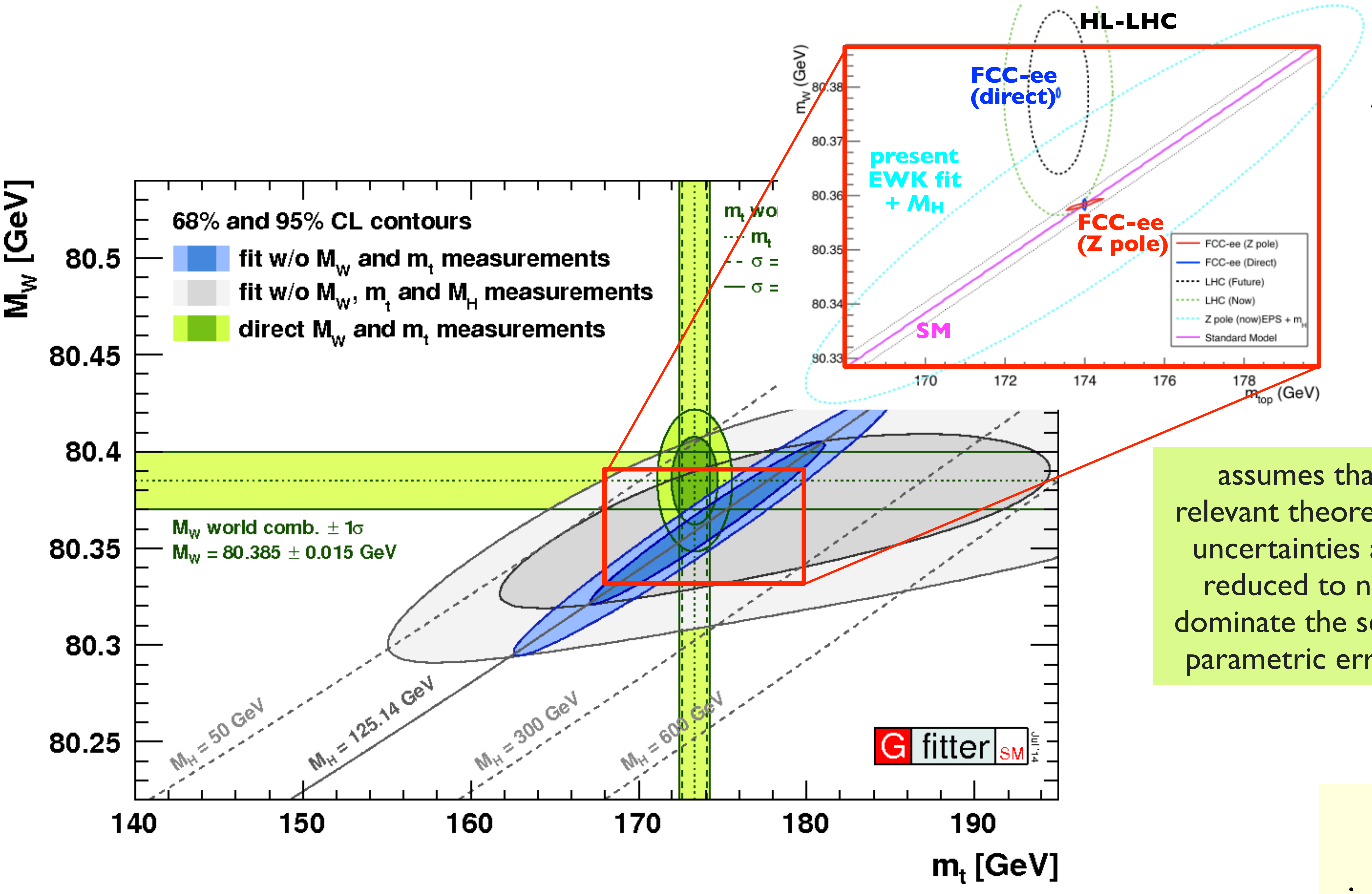


Successful experimental strategy

- precision at e^+e^- machines
- discoveries at hadron machines

The Ultimate Electroweak Fit

see presentation by Fulvio Piccinini



FCC-ee CDR (2018)

Main ingredients

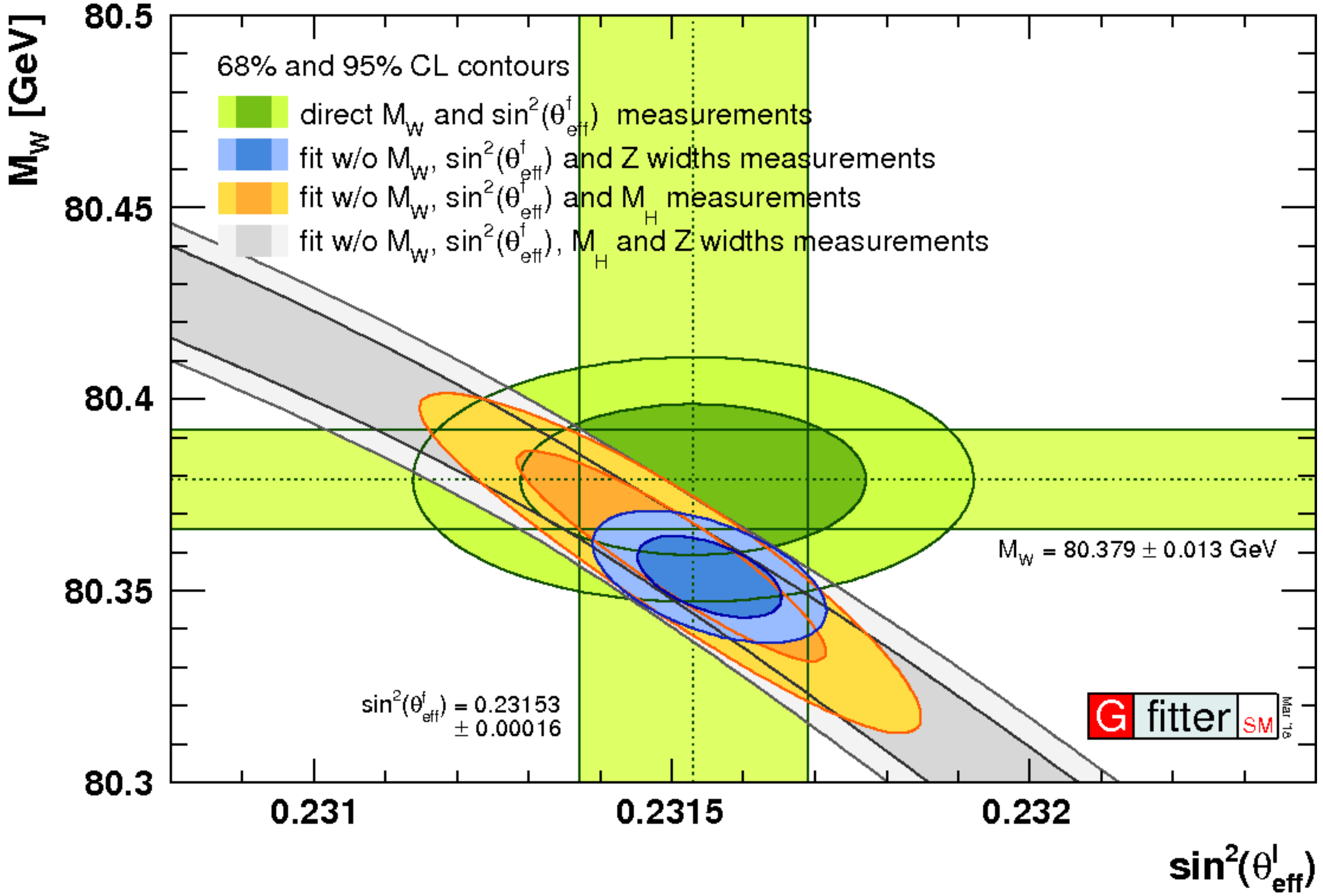
- effective weak mixing angle
- mass of the W boson
- width of the W boson
- mass of the top quark
- (mass of the Higgs boson)

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

Through SMEFT probes energy scales in the Λ>20 TeV range for certain NP operators

The Electroweak Fit

see presentation by Fulvio Piccinini



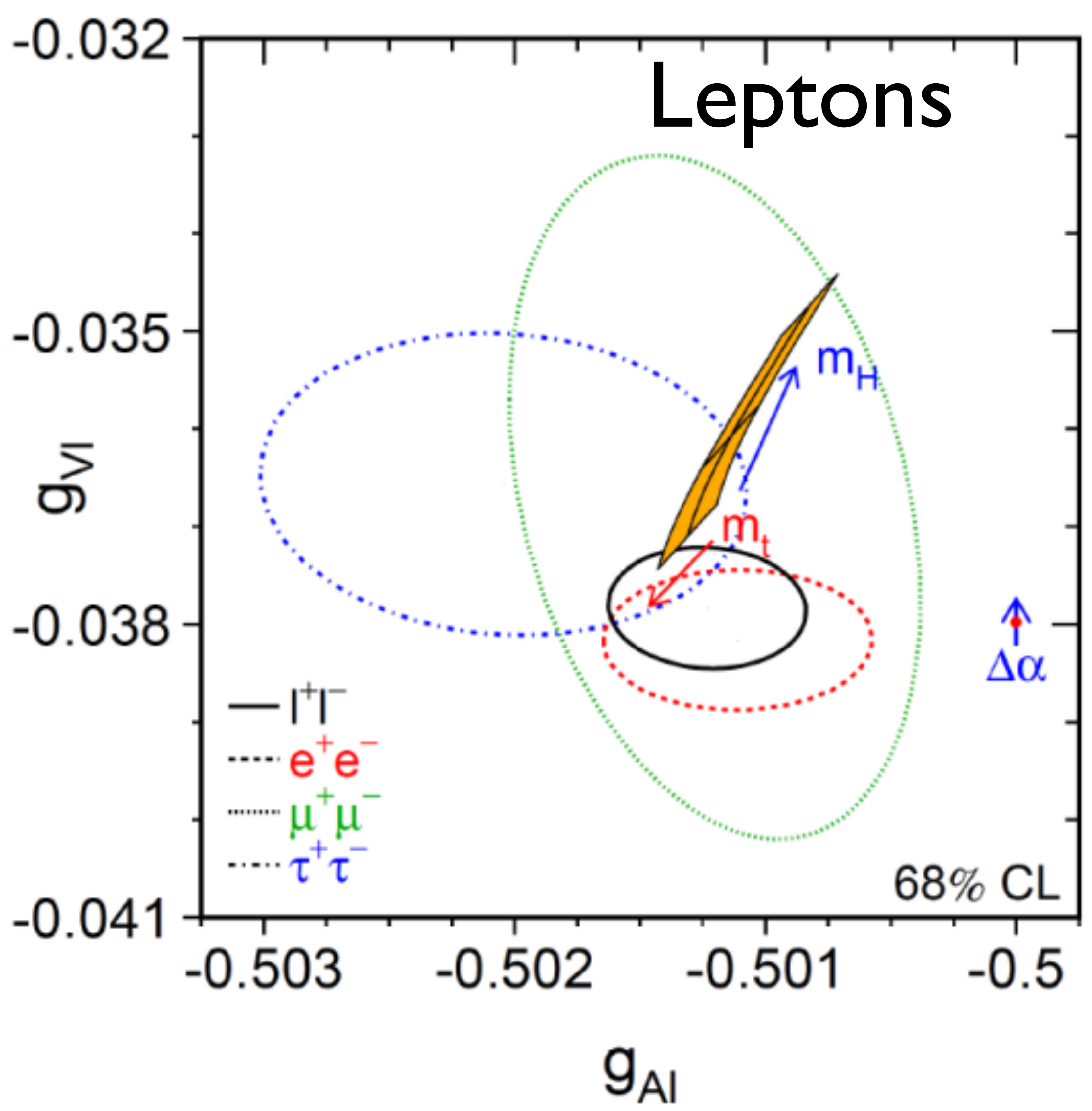
Projection of the electroweak fit, showing M_W versus $\sin 2\theta^{\ell}_{eff}$

Left-Right Asymmetries

Effective vector and axial-vector couplings

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

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

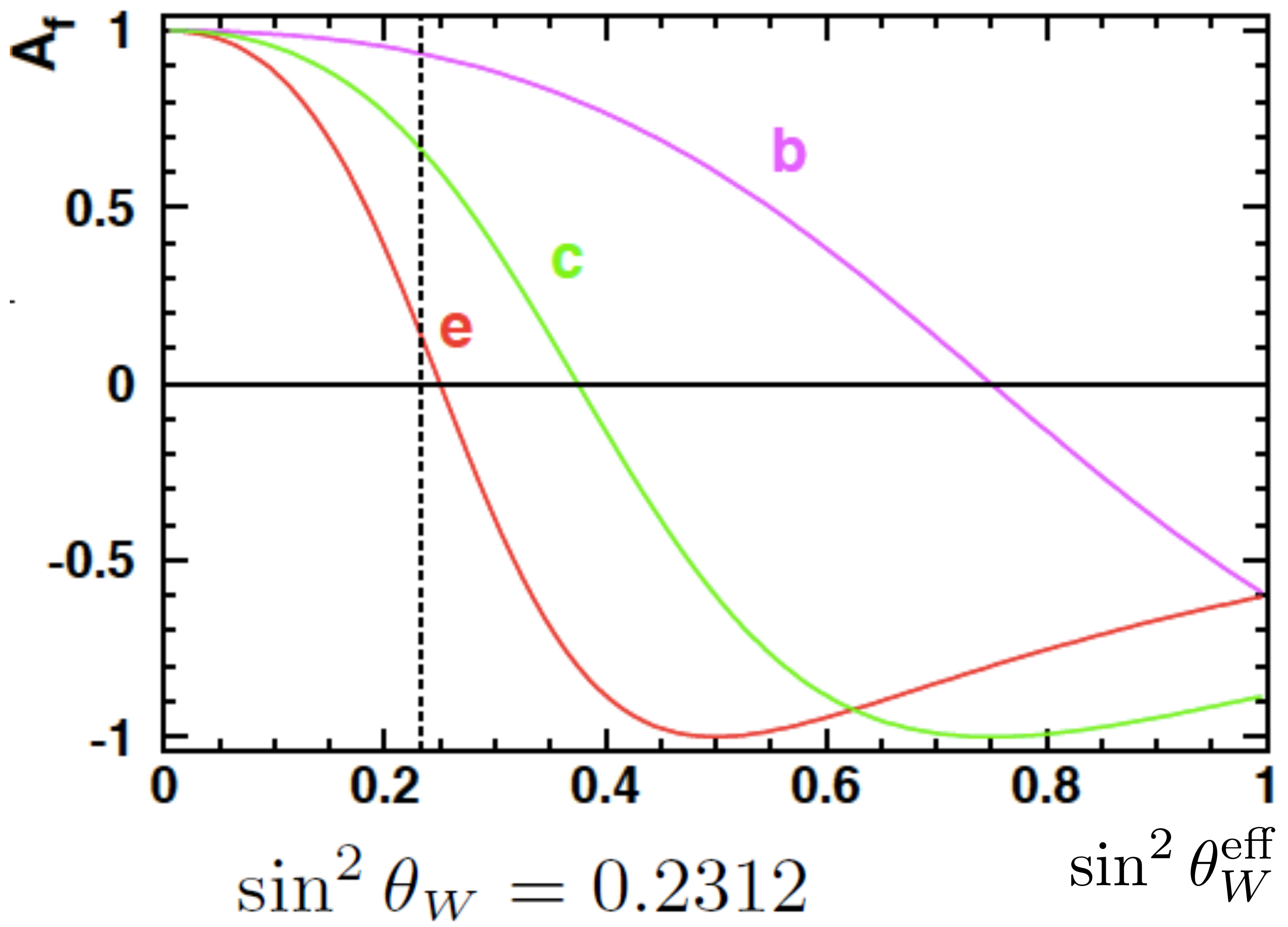


Asymmetry in left- and right-handed couplings

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

Depends on vector to axial-vector ratios

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



$\sin^2\theta_W = 0.2312$

possibility of longitudinal beam polarisation in FCC-ee being studied (would reduce luminosity)

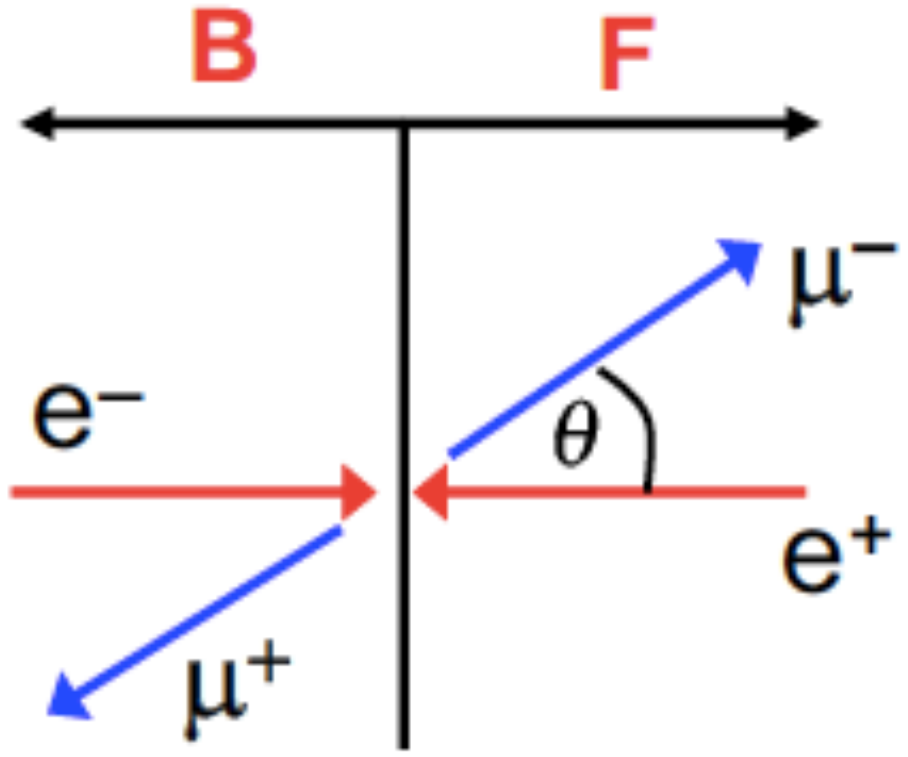
Left-right asymmetries can be measured at the Z pole with longitudinally polarised beams (i.e., at SLD, ILC)

Forward-Backward Asymmetries

With unpolarised beams

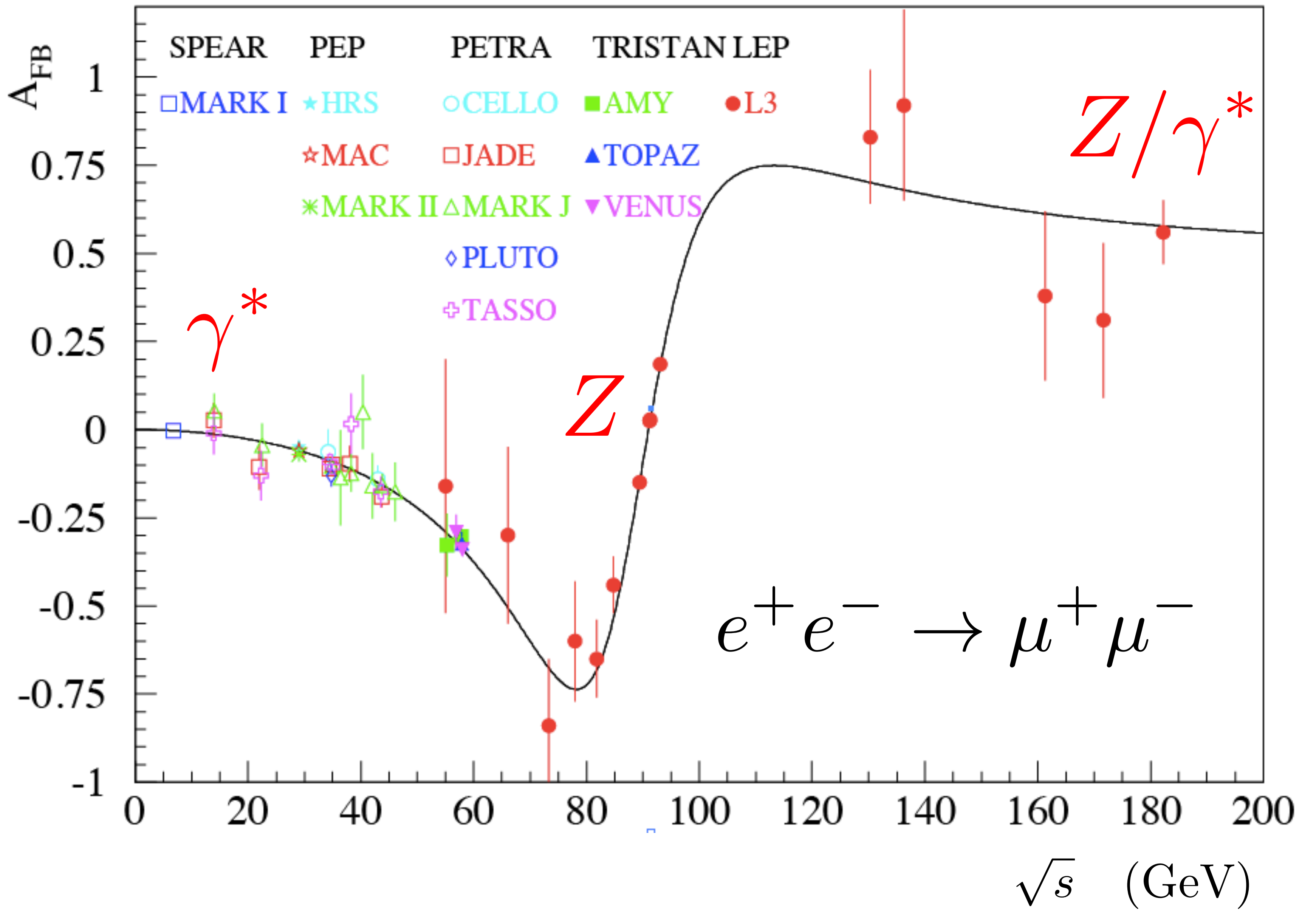
FB Asymmetry

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

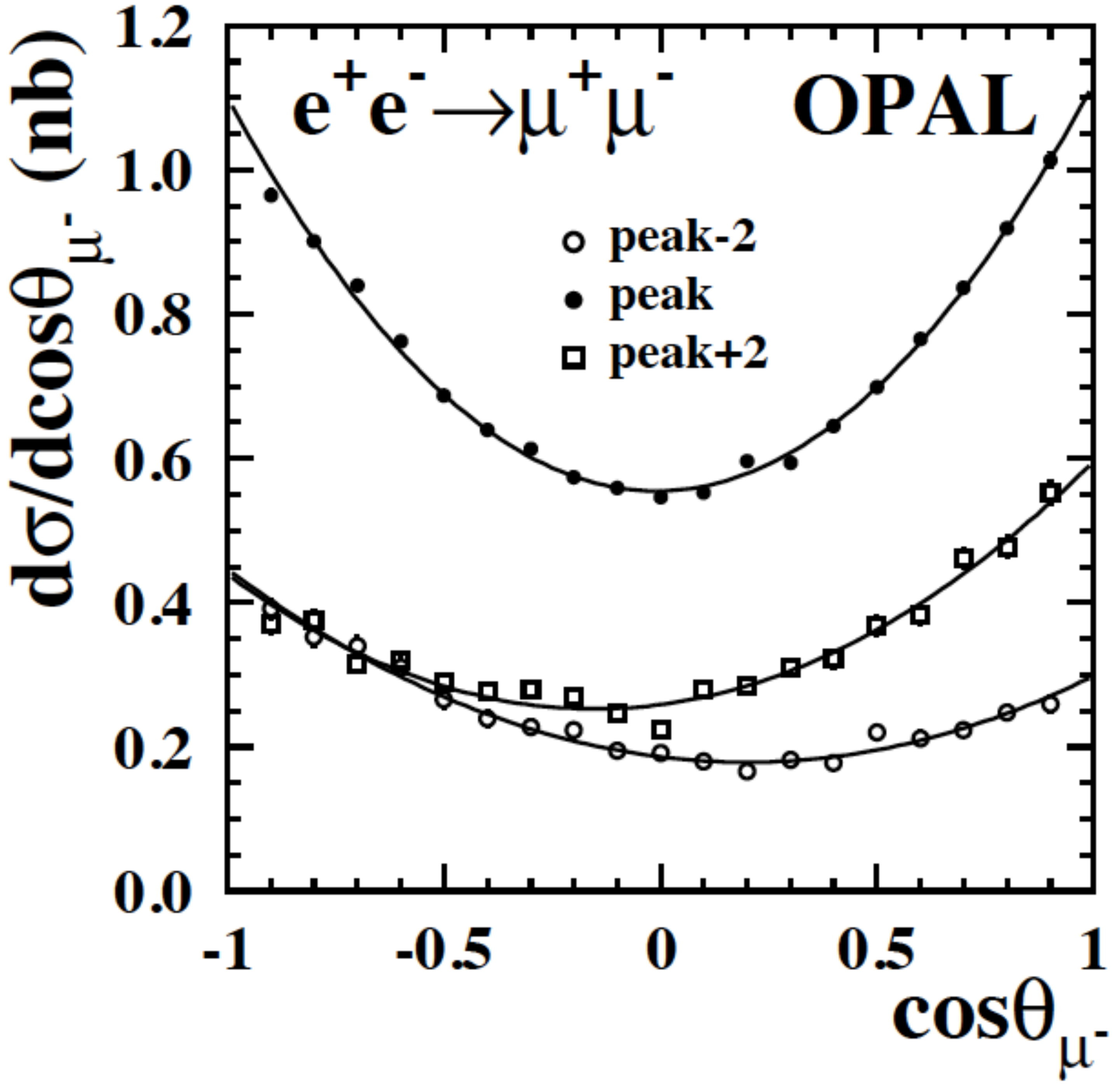


$$\frac{d\sigma}{d\cos\theta} \propto 1 + \cos^2\theta + \frac{3}{8} A_{\mathrm{FB}} \cos\theta$$

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

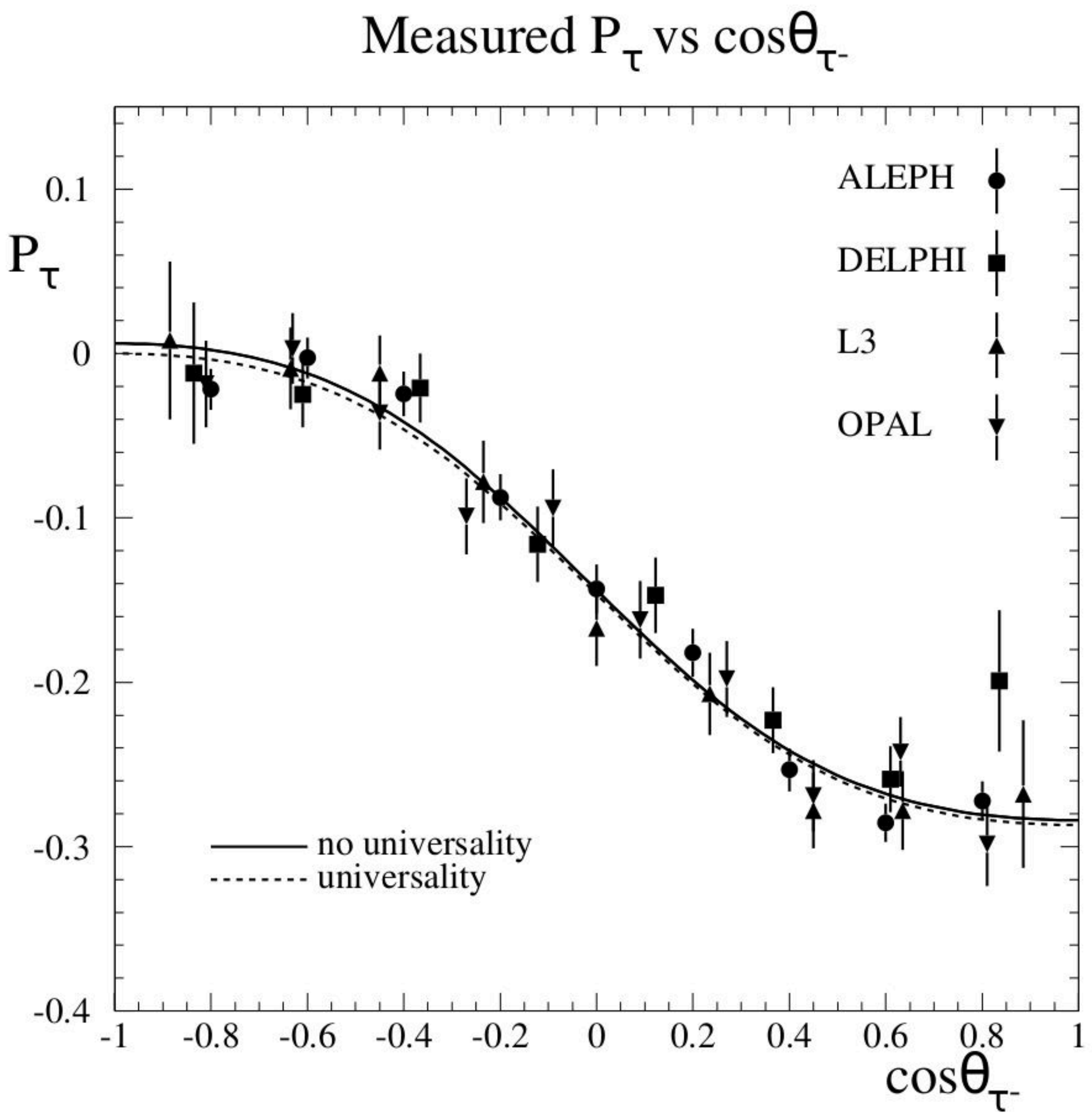


√s dependance due to interference between the Z and the photon exchange



Tau polarisation

see presentation by Alberto Lusiani



angle τ− with respect to e⁻ beam

Disentangle left-right asymmetries for electrons and taus

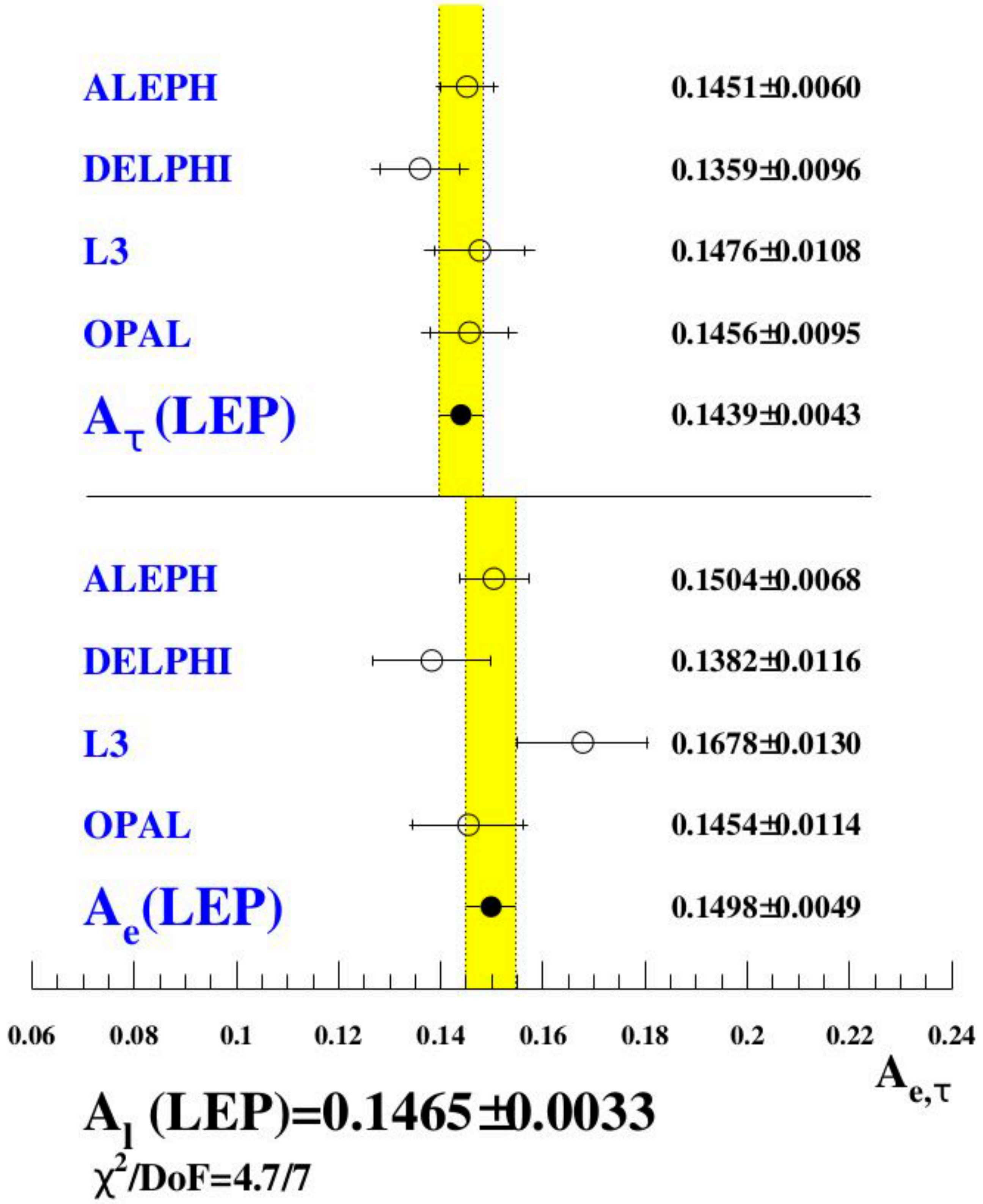
$$P(\cos\theta) = \frac{\mathcal{A}_\tau(1+\cos^2\theta) + 2\mathcal{A}_e\cos\theta}{(1+\cos^2\theta) + 2\mathcal{A}_e\mathcal{A}_\tau\cos\theta}$$

Forward/backward tau polarisation asymmetry provides a measurement of electron LR asymmetry (= Z polarisation)

$$P_\tau^{\mathrm{FB}} = -\frac{4}{3}\mathscr{A}_e$$

LEP1 legacy

Provides best Ae and Aτ



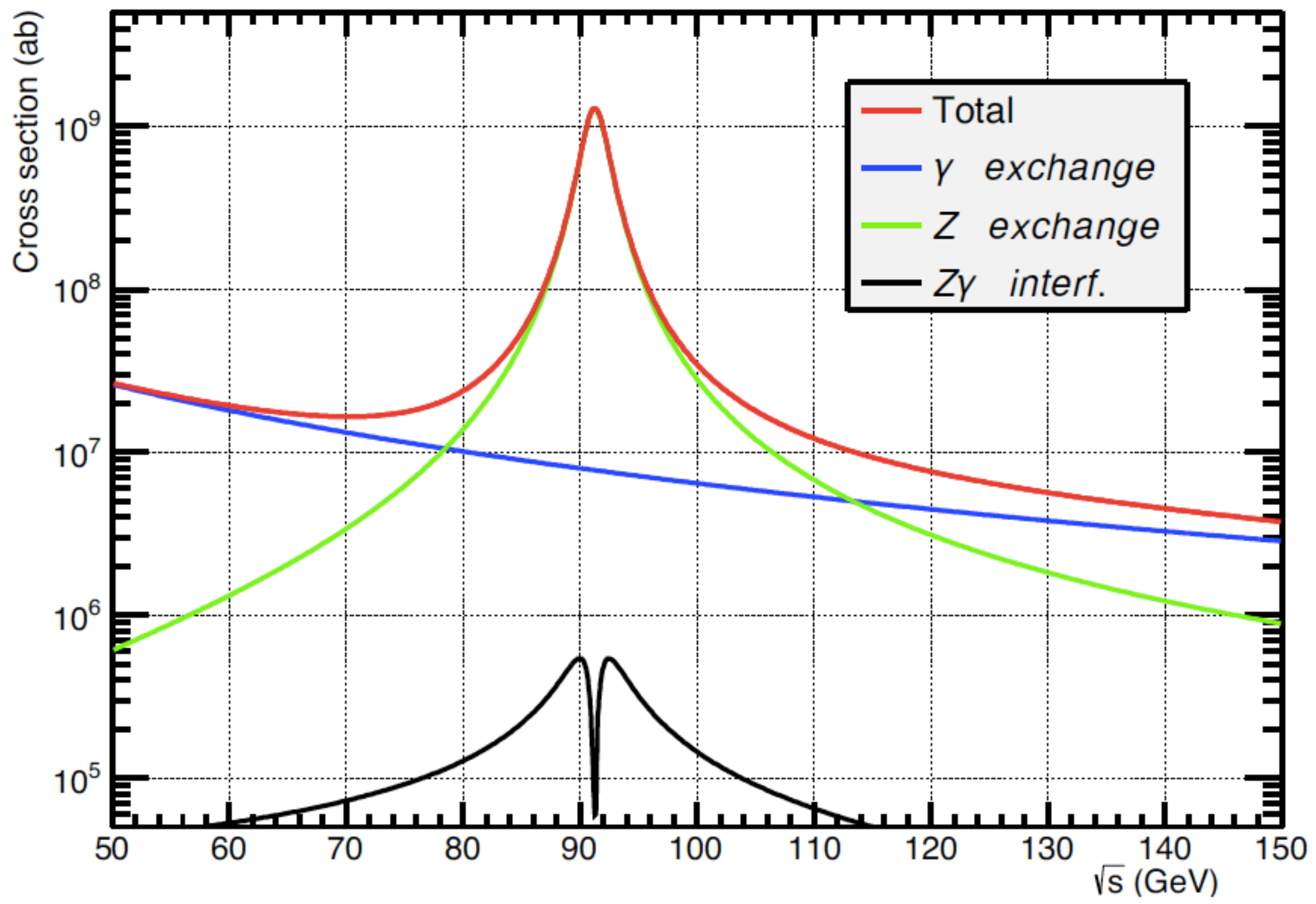
LEP among dominant systematics
- beam energy
- non-tau backgrounds

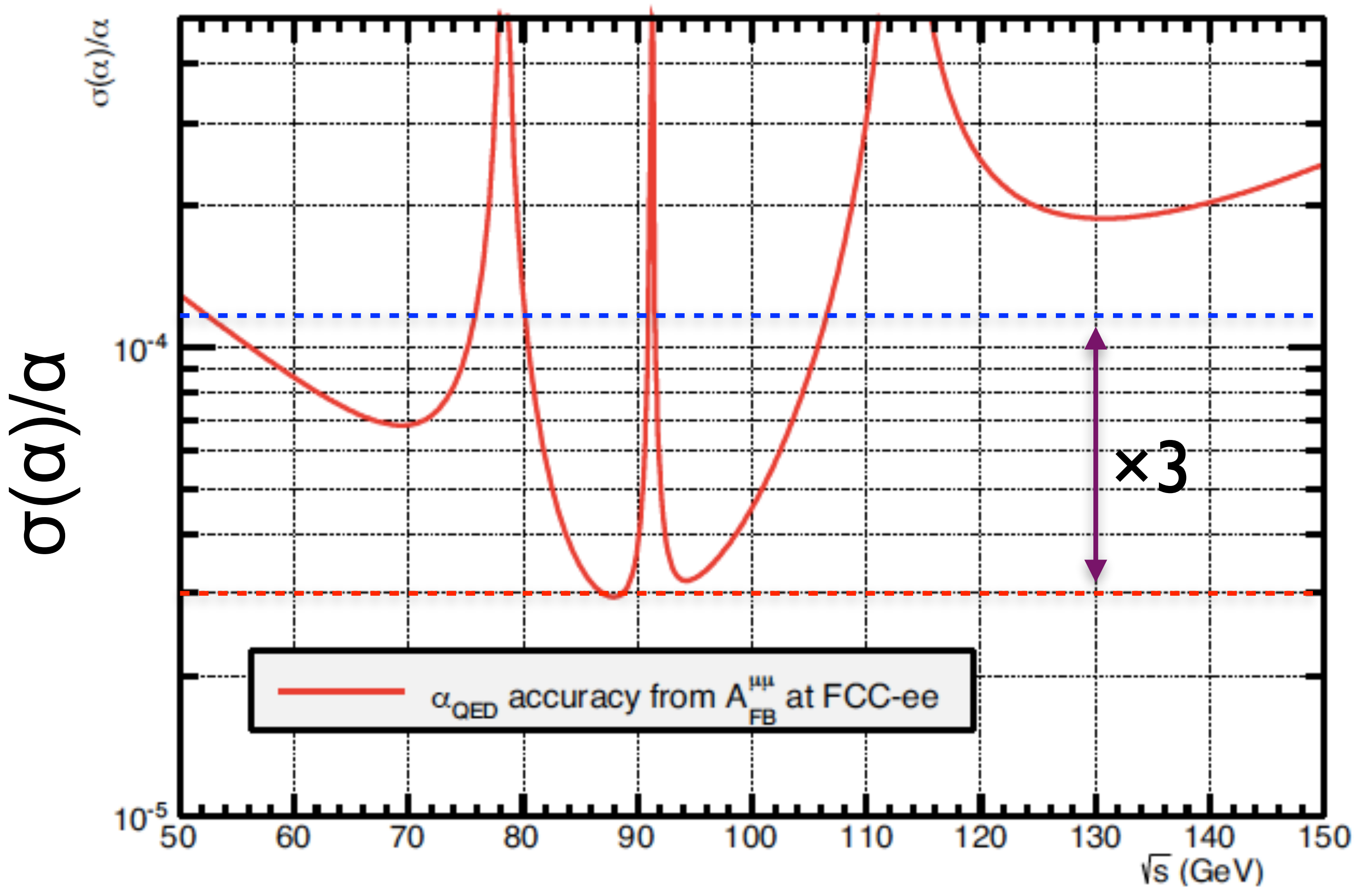
FCC-ee
- beam energy uncertainty negligible
- much control of tau backgrounds thanks to huge statistics of control samples
- goal: one order of magnitude reduction wrt to LEP → stat+sys: 0.0003

Uncertainties on tau polarisation may limit coupling and LR asymmetries meas.

$A_{FB}(\mu)$ and QED coupling constant

P. Janot, JHEP 02 (2016) 053





one year of running at any given √s

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

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

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

$1/\alpha(M_Z^2)$ at the **4×10^{-5}** level

from 40 fb^{-1} at ±3 GeV of Z pole

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

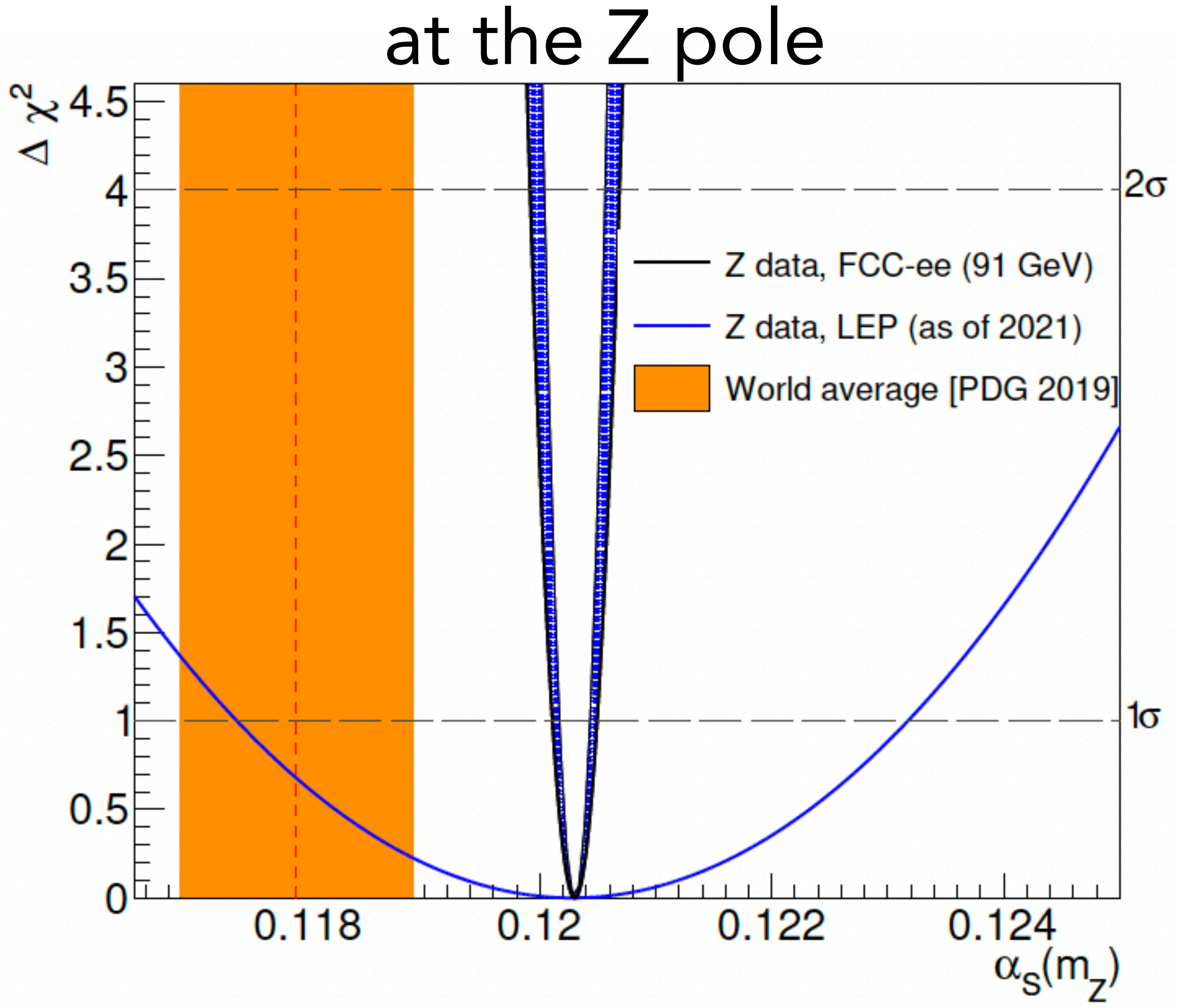
Price to pay:
sizeable part (one third ?) of the time
off-peak

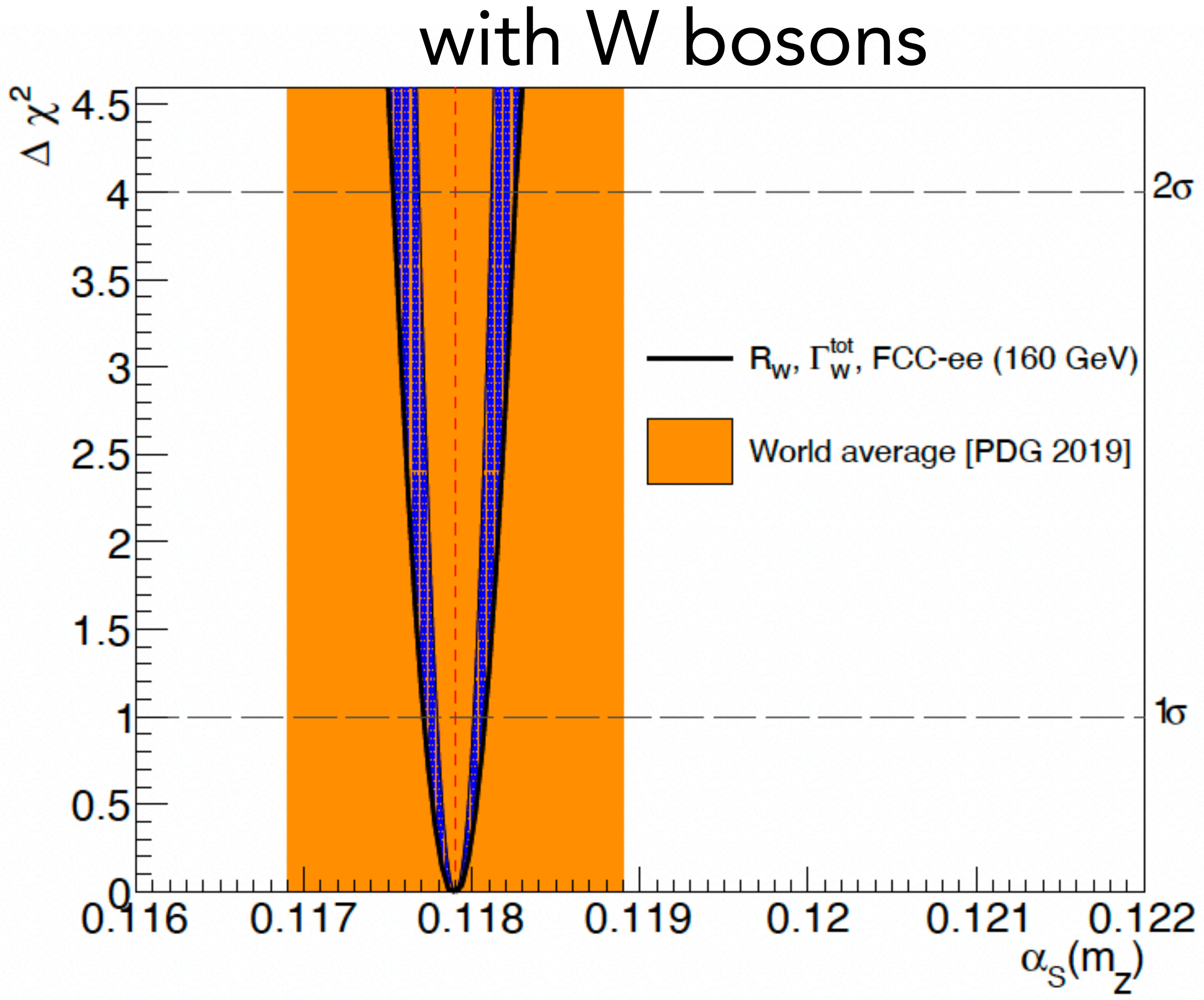
computation of missing EW higher-order corrections is still needed

QCD studies at FCC-ee

Strong coupling constant

[arXiv:2005.04545](https://arxiv.org/abs/2005.04545)





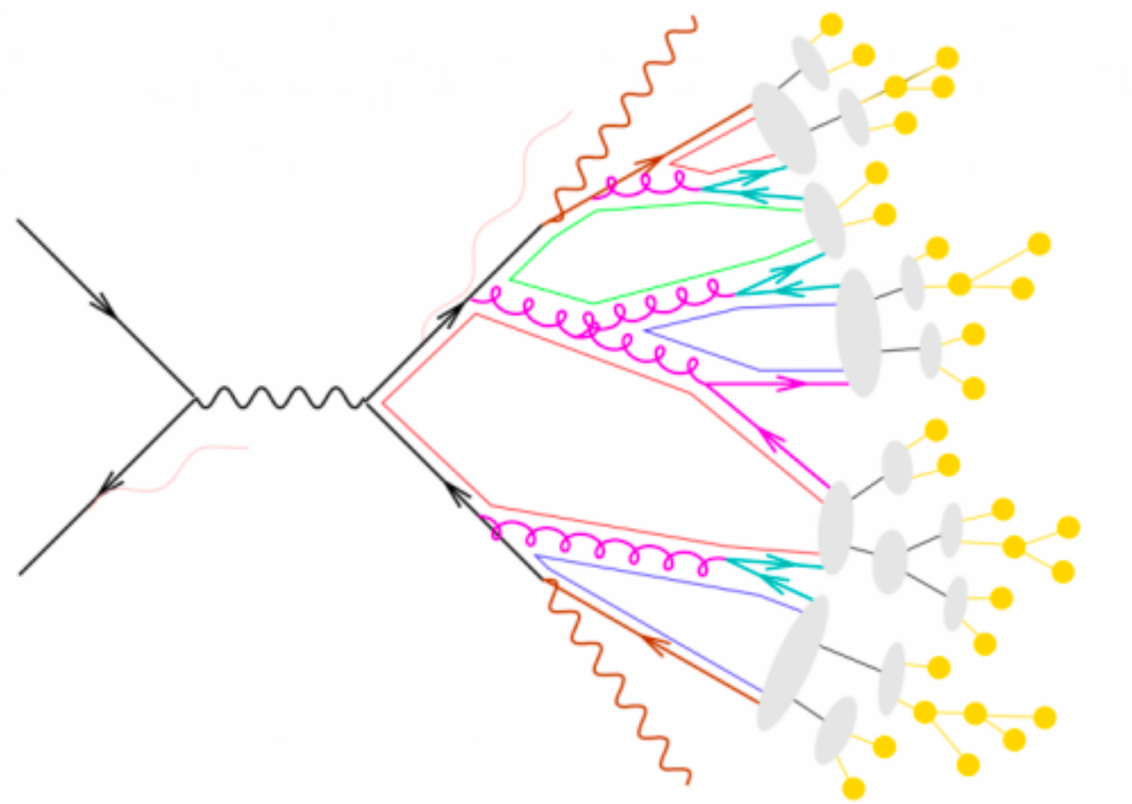
3.5×10^{12} hadronic Z decays!

$\alpha_s(m_Z^2)$ with uncertainty 0.00015 from event shape observables (current accuracy: ±0.85%)

Also:

- tau decays (current unc.: 1.6%)
- jet production rates and event shapes

Very rich program of QCD measurements



Enormous multi-jet data sample

- Understanding of parton showers
- higher-order logarithmic resummations
- hadronisation and nonperturbative phenomena, soft and collinear emissions
- phenomenological and/or analytic models
- etc.

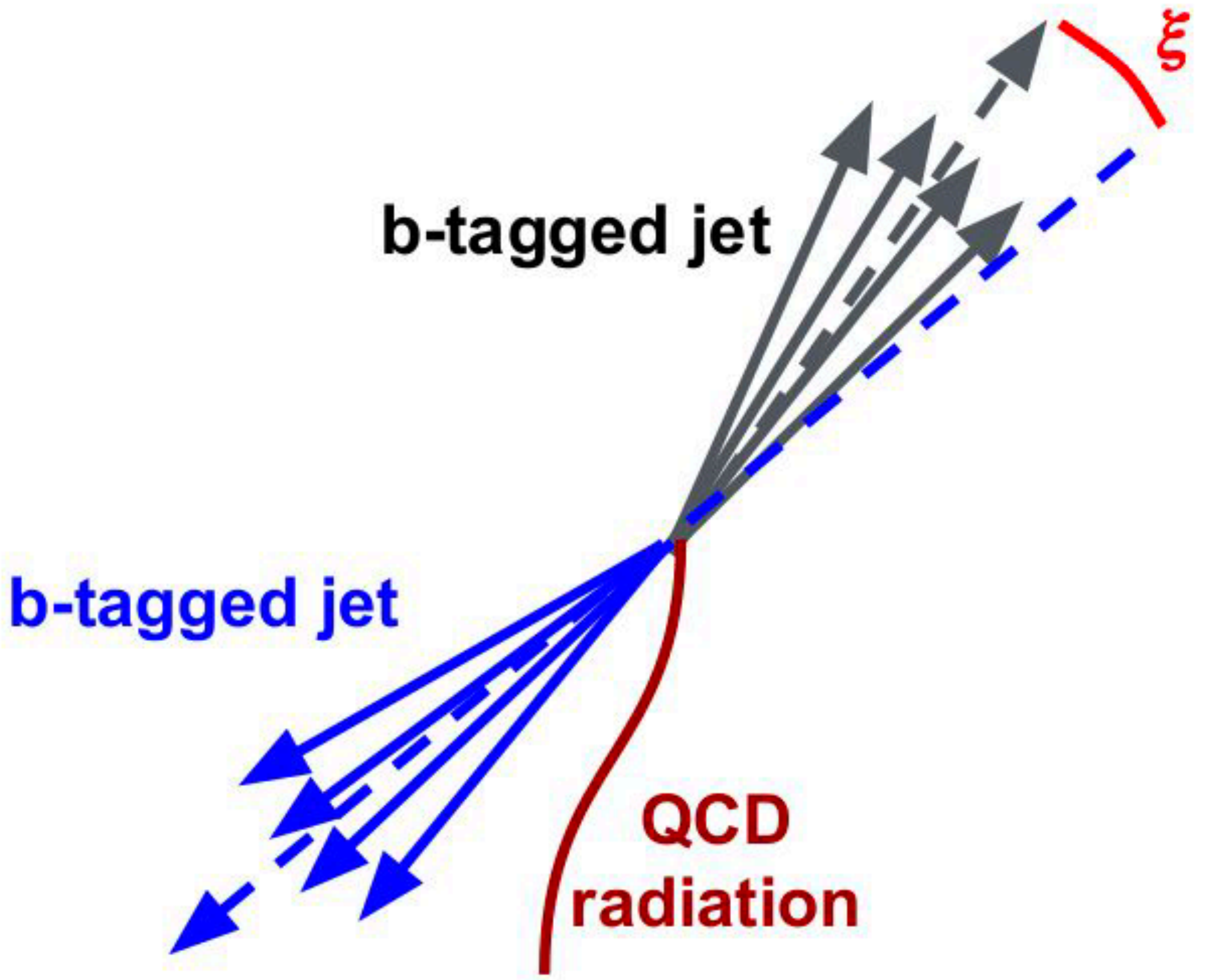
Factors up to 10 improvements with respect to the current **state-of-the-art in the theoretical uncertainties** of the calculations of the partial and total widths of the W and Z bosons will be needed (higher-order QCD and mixed QCD+EWK calculations)

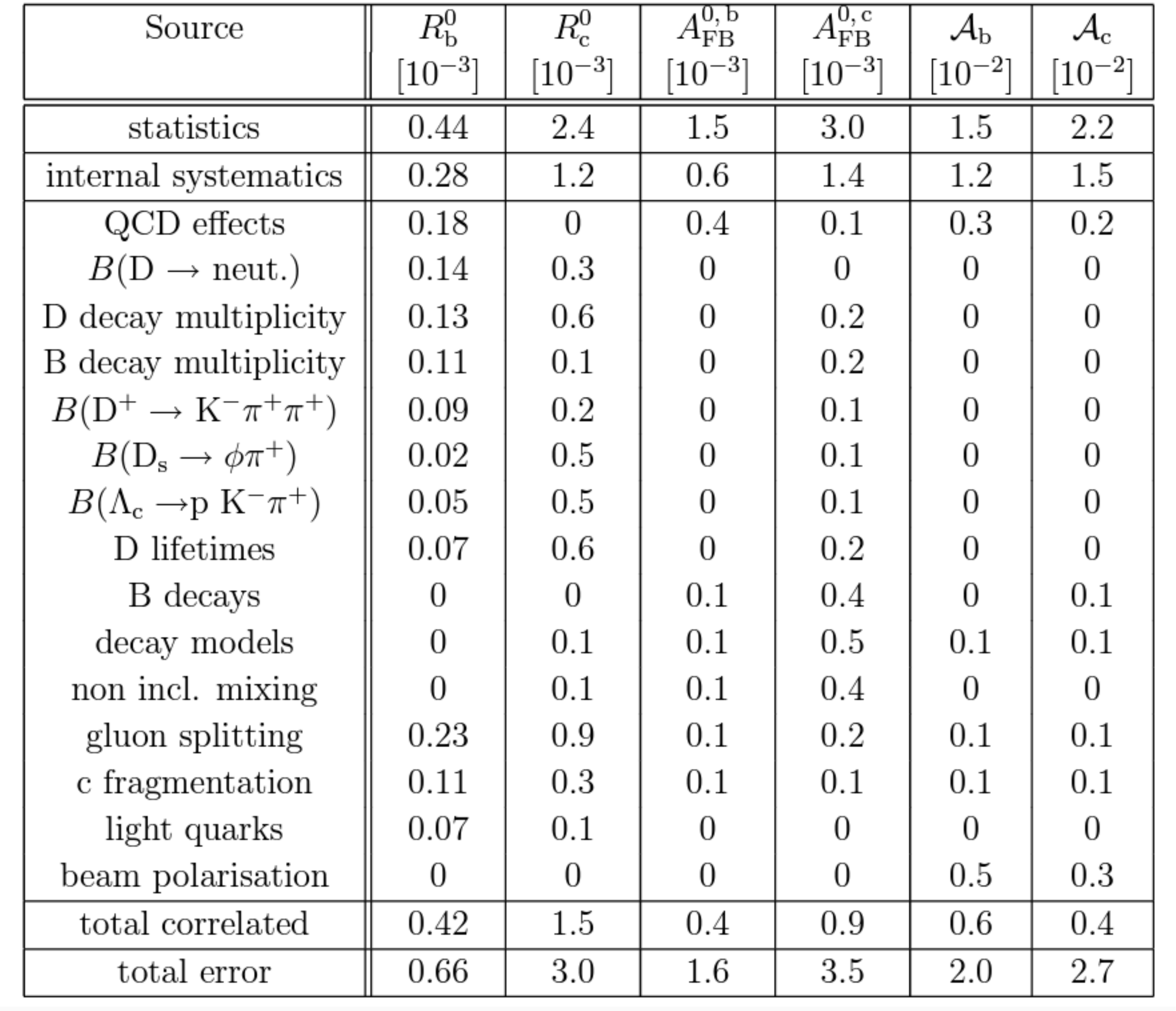
QCD: main source of uncertainty in FB asymmetry of b quarks (2.4σ)

AFB(b)

see presentation by Giovanni Guerrieri

- QCD corrections are a dominant source of correlated systematics between measurements
- QCD corrections and associated uncertainties can be reduced significantly thanks to acolinearity cuts
- much improved b/c jet tagging
- huge samples to control gluon splitting
- use of exclusive B decay samples





Source	R_b^0 [10^{-3}]	R_c^0 [10^{-3}]	$A_{FB}^{0,b}$ [10^{-3}]	$A_{FB}^{0,c}$ [10^{-3}]	$\mathcal{A}_b$ [10^{-2}]	$\mathcal{A}_c$ [10^{-2}]
statistics	0.44	2.4	1.5	3.0	1.5	2.2
internal systematics	0.28	1.2	0.6	1.4	1.2	1.5
QCD effects	0.18	0	0.4	0.1	0.3	0.2
$B(\mathrm{D} \to \text{neut.})$	0.14	0.3	0	0	0	0
D decay multiplicity	0.13	0.6	0	0.2	0	0
B decay multiplicity	0.11	0.1	0	0.2	0	0
$B(\mathrm{D}^+ \to \mathrm{K}^-\pi^+\pi^+)$	0.09	0.2	0	0.1	0	0
$B(\mathrm{D_s} \to \phi\pi^+)$	0.02	0.5	0	0.1	0	0
$B(\Lambda_c \to \mathrm{p\,K}^-\pi^+)$	0.05	0.5	0	0.1	0	0
D lifetimes	0.07	0.6	0	0.2	0	0
B decays	0	0	0.1	0.4	0	0.1
decay models	0	0.1	0.1	0.5	0.1	0.1
non incl. mixing	0	0.1	0.1	0.4	0	0
gluon splitting	0.23	0.9	0.1	0.2	0.1	0.1
c fragmentation	0.11	0.3	0.1	0.1	0.1	0.1
light quarks	0.07	0.1	0	0	0	0
beam polarisation	0	0	0	0	0.5	0.3
total correlated	0.42	1.5	0.4	0.9	0.6	0.4
total error	0.66	3.0	1.6	3.5	2.0	2.7

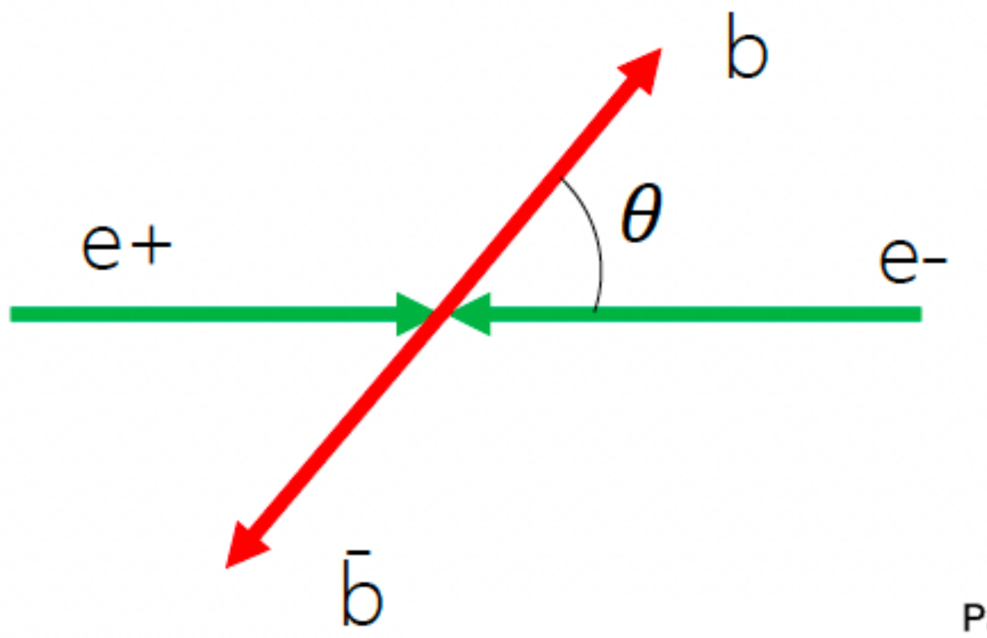
arXiv:2010.08604

arXiv:2011.00530

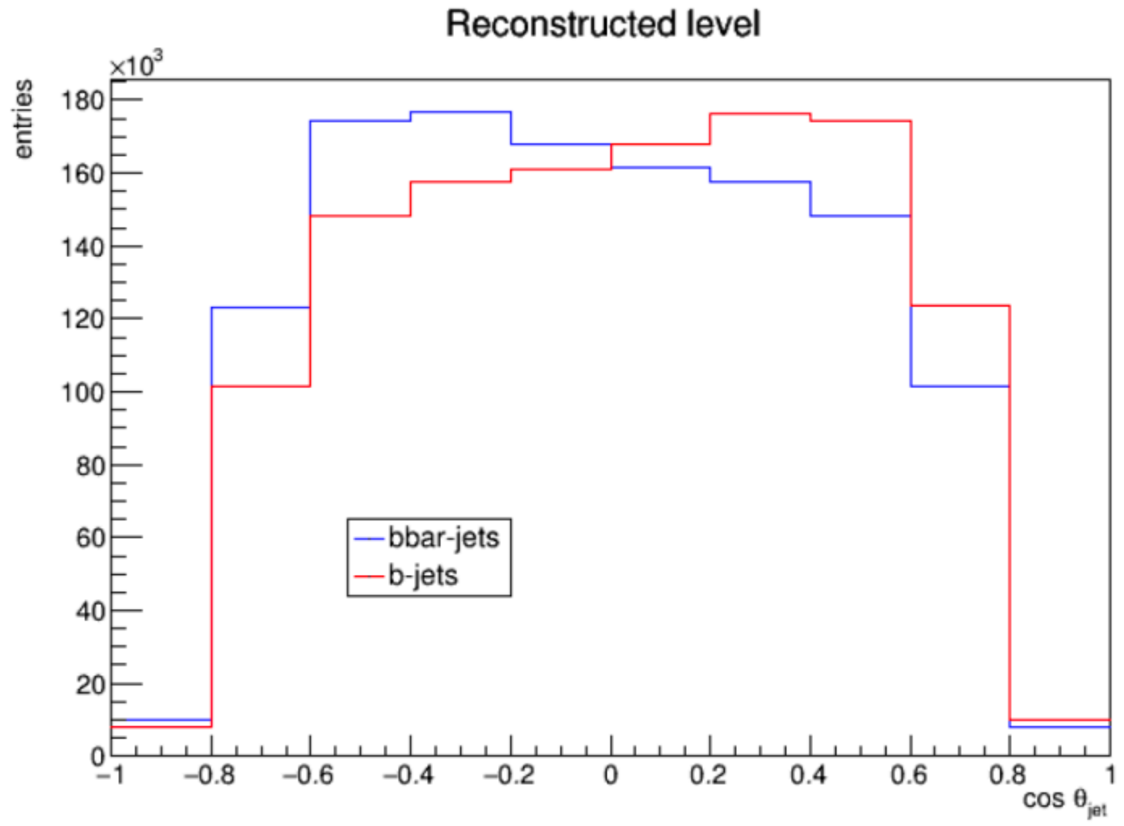
Forward-backward asymmetries at FCC-ee

see presentation by Giovanni Guerrieri

Difficulty: quark-antiquark discrimination
→ two approches are extensively studied

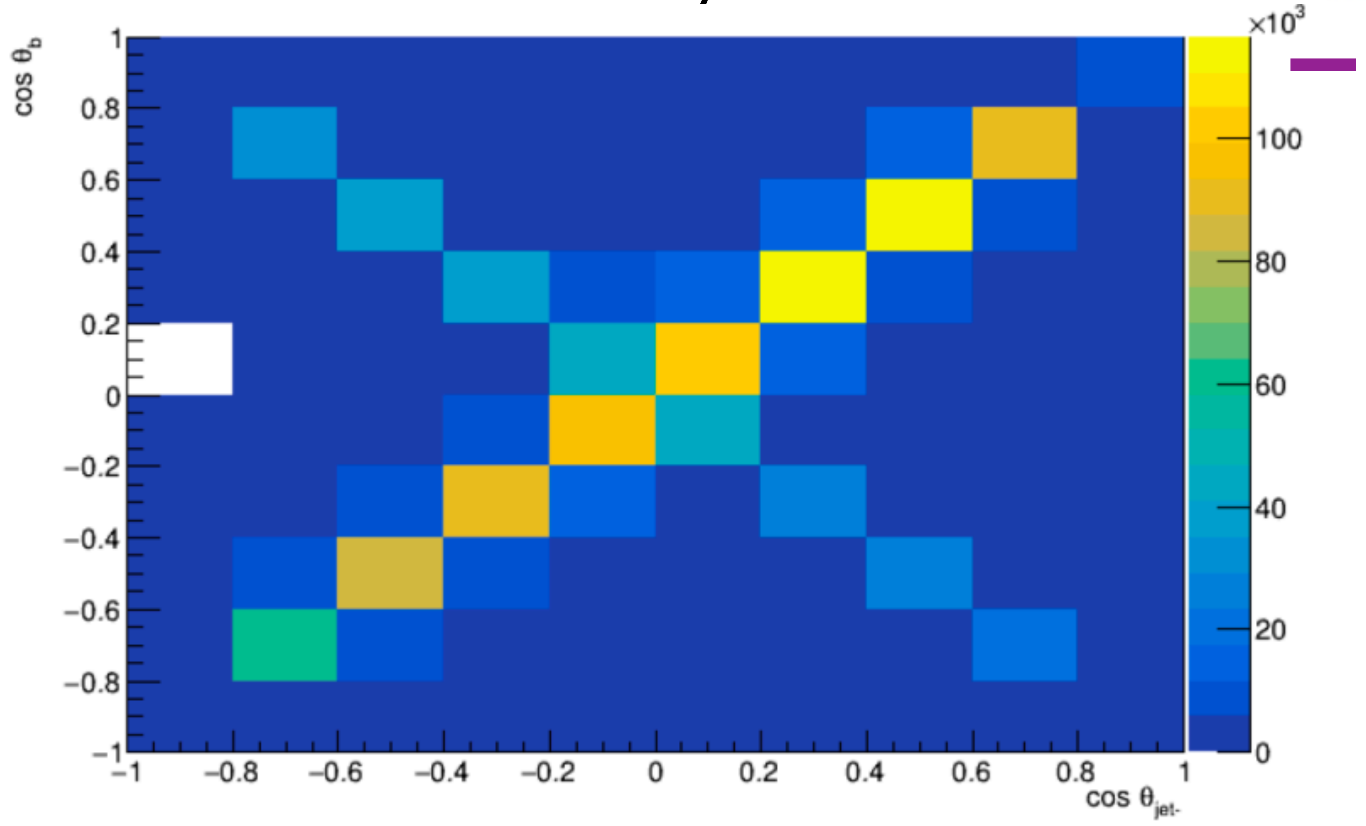


Jet charge study



×

unfolding with 10x10 matrix
and efficiency correction



$^{-1}$

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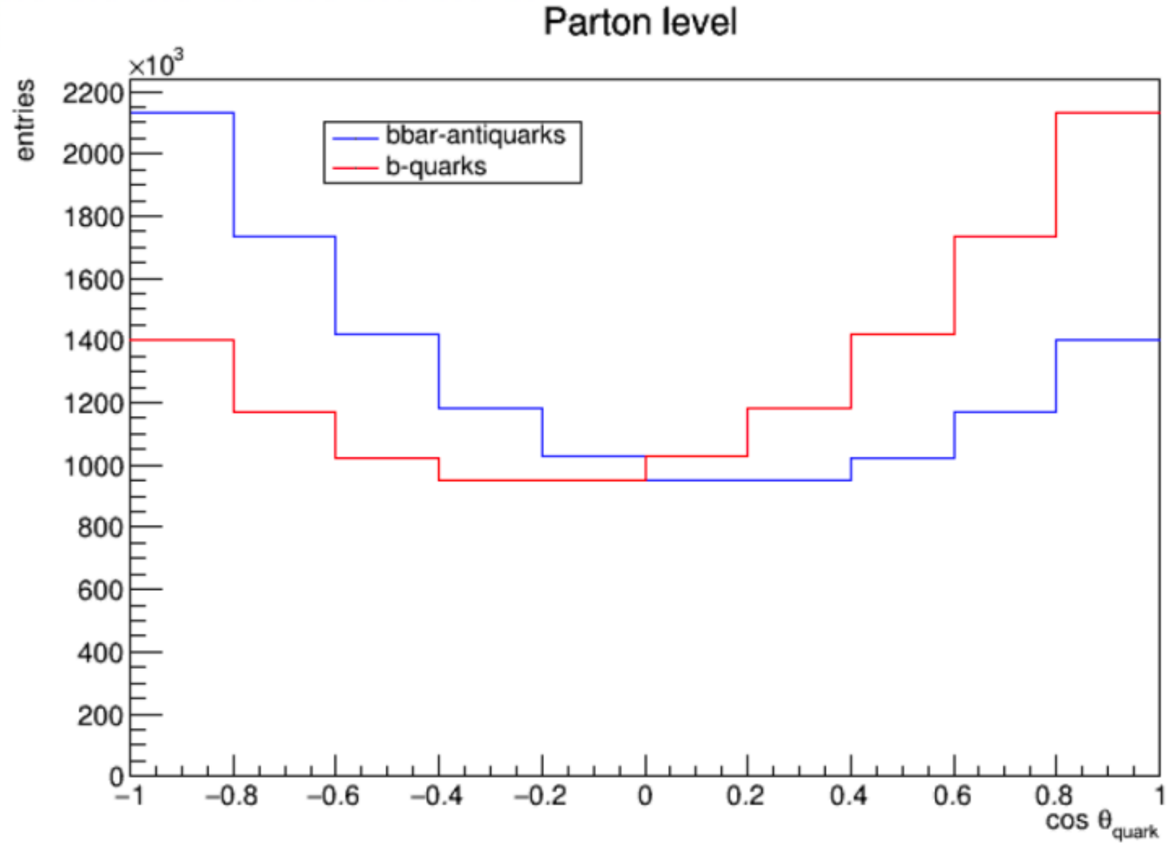


~~Soft~~ lepton study

In both cases, stat uncertainty:
- 1.4 fb^{-1}: ±0.1%
- 150 fb^{-1}: ±0.01%

Expected dominant systematics
- modelling of b fragmentation (~5%)
- FS QCD radiation effects
- B-hadron decay modelling
- b-tagging efficiency

Very promising
- analysis workflows in place
- unfolding machinery in place

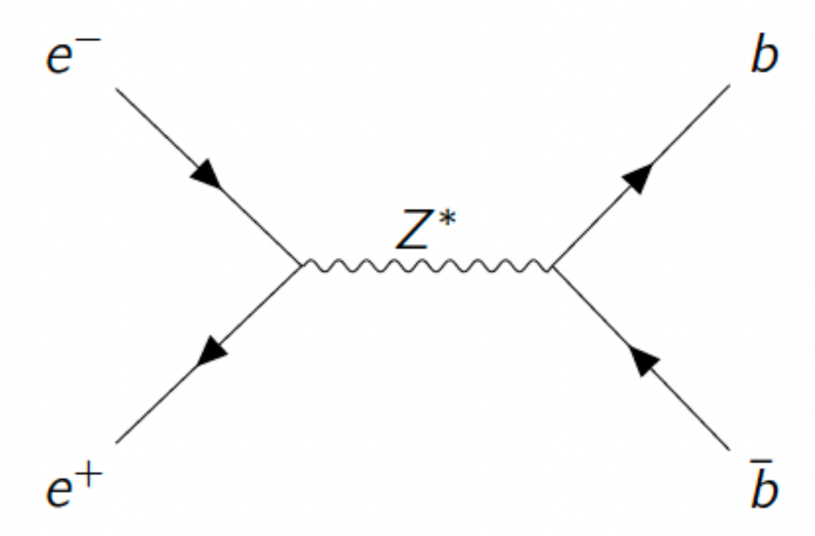
Next steps
- reproduce LEP results
- improve systematics

$$A_{FB}^{0,b} = 0.09410 \pm 0.00001(\text{stat}) \pm 0.00450(\text{syst})$$

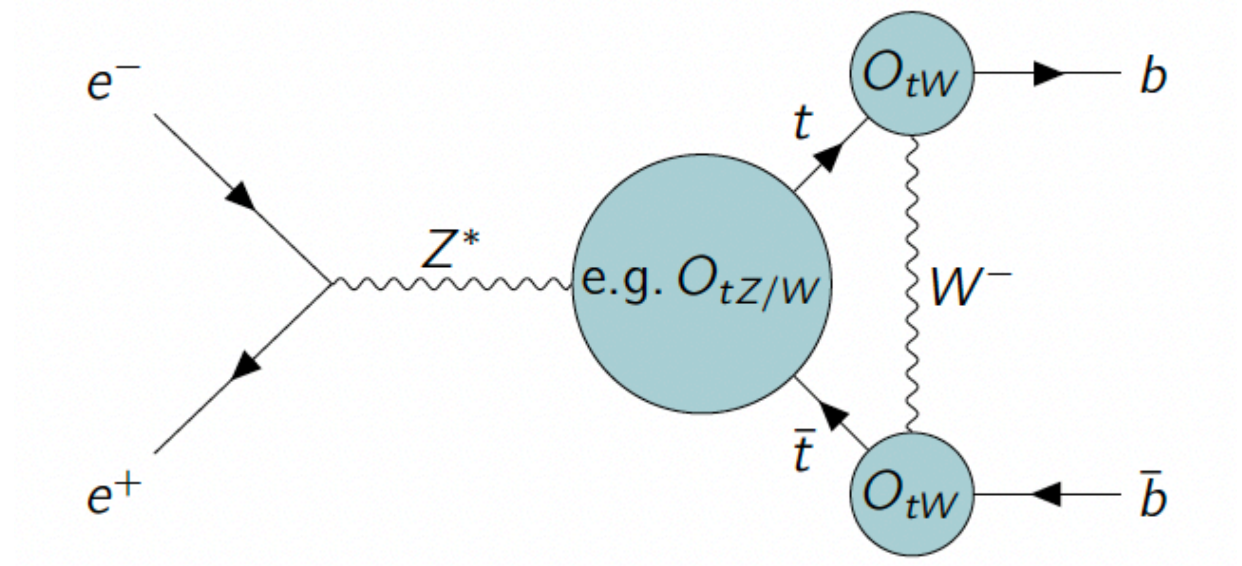
Measurement at the Z pole: R_b

see presentation by Lars Röhrig

Novel b-hadron double tagging technique for R_b determination

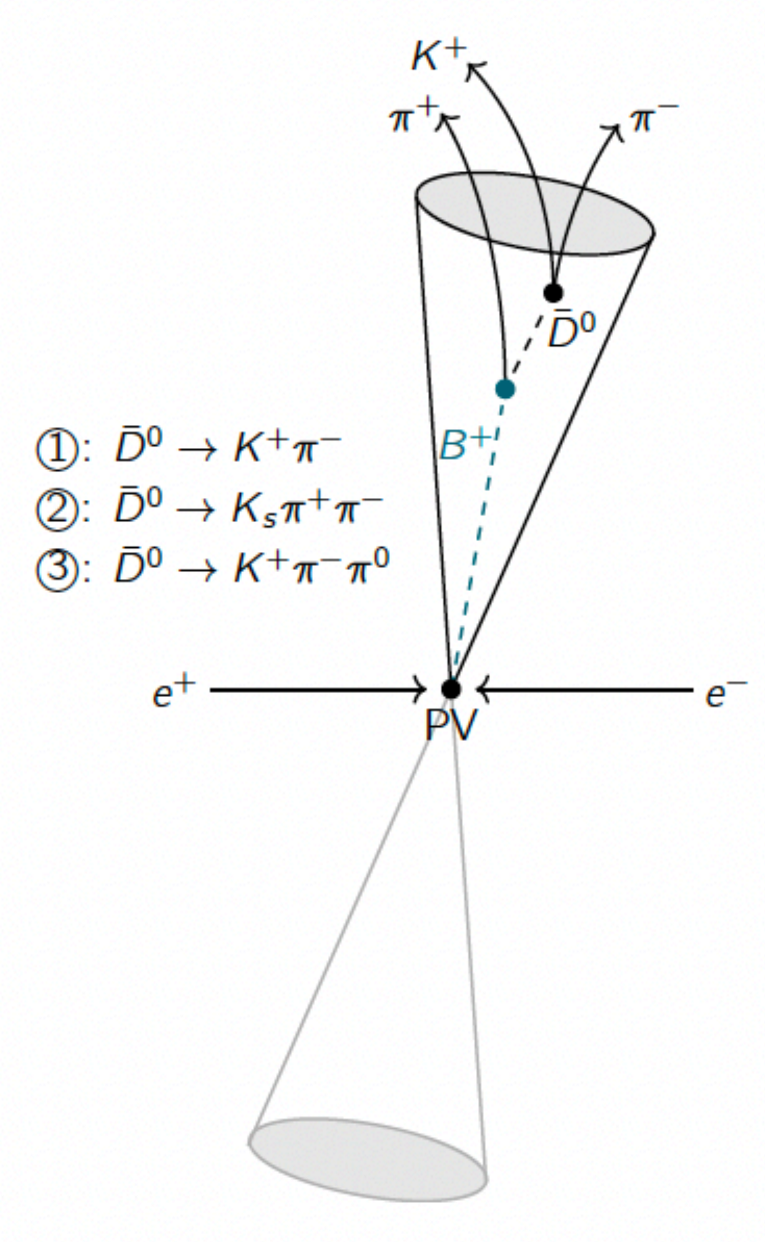


Tree-level contribution.



Zbb-vertex correction, contribution ≈ 1 %.

LEP measurement dominated by
- udsc background
- MC statistics



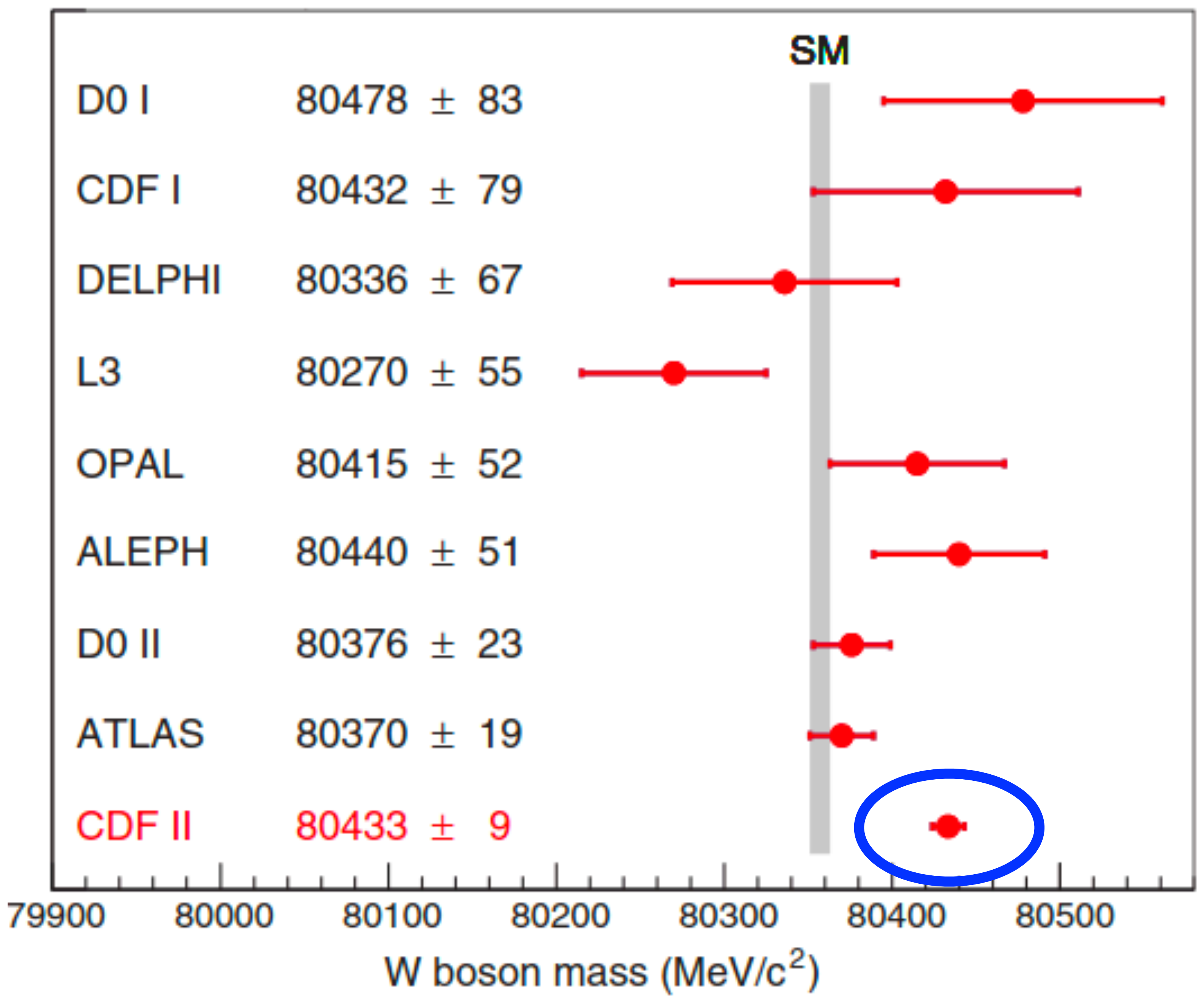
New hemisphere tagging
- select hemisphere with exclusive B-hadron tag
- purity close to 100%
- efficiency of order 1%
- → statistical unc. of order 5 10^{-5} (=LEPx20)
- hemisphere correlation unc. much reduced

Next steps
- estimate purity of exclusive hemisphere tagging
- check than 1% efficiency is possible
- fully charged B decays
- decays with K_S^0 or π^0 in the FS
- → requirements on tracking and calorimetry
- similar work to be developed for A_{FB}^b

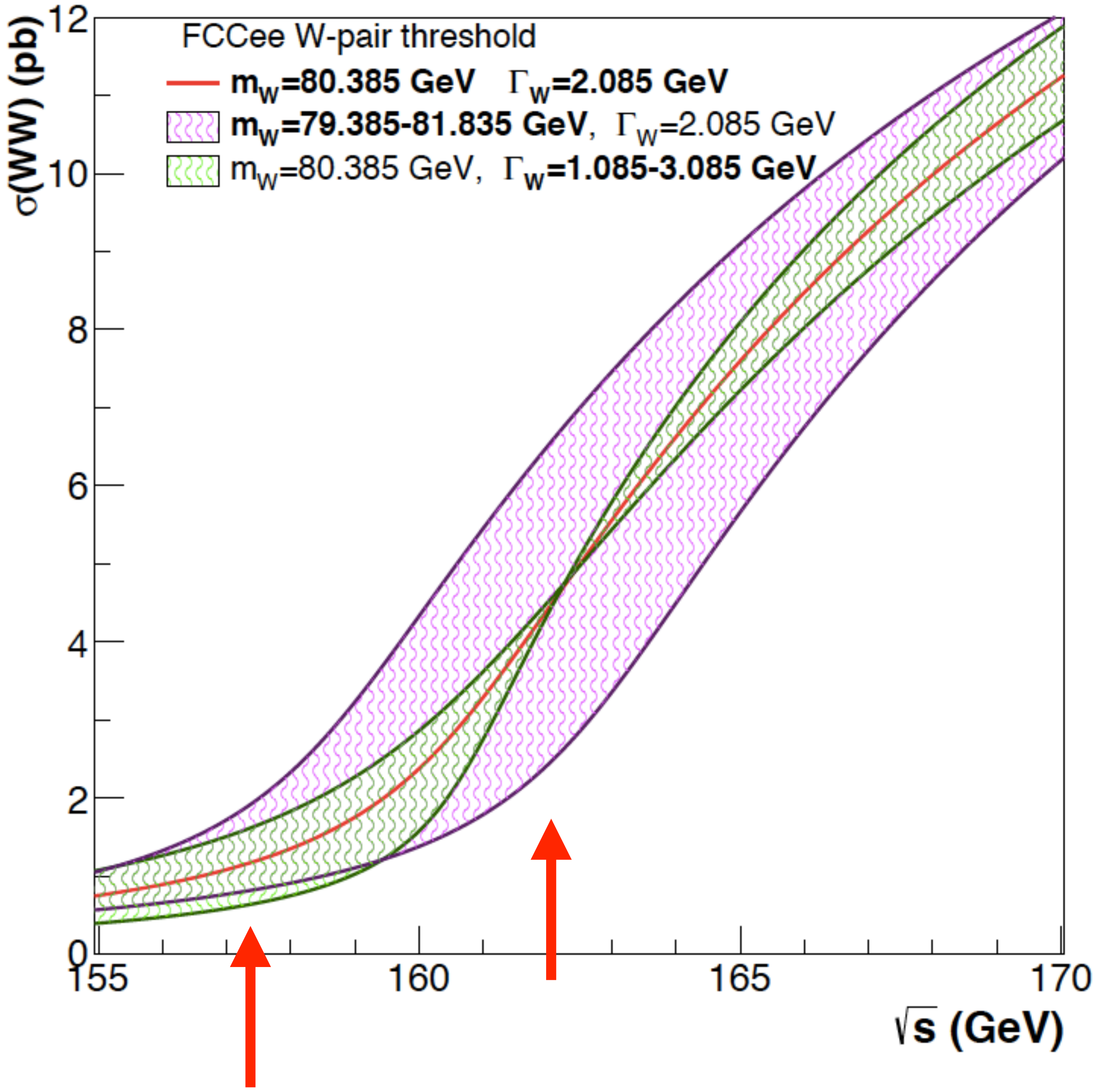
synergy with previous talk!

WW threshold and above

W mass: very hot topic!



At threshold, unpolarised



FCC-ee target

- $\Delta M_W = 0.4\ (0.25 \oplus 0.3)$ MeV
- $\Delta \Gamma_W = 1.5\ (1.2 \oplus 0.3)$ MeV

Above threshold

- 1000 times LEP-2 statistics

V_{cb} from WW (10^8 WW pairs)

- W → sc ~ W → du 127M
- W → su ~ W → dc 6.8M
- W → bu 1.7k
- W → bc 250k

Current precision on V_{cb}: 1.5%

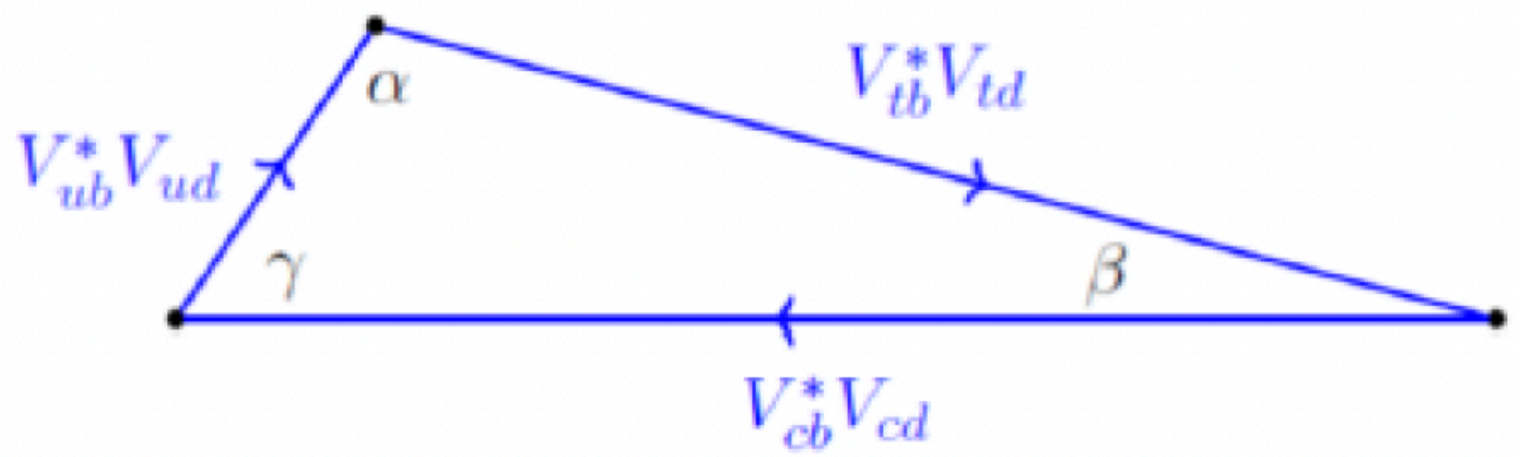
FCC-ee

Study in progress, hope to reach better than 0.5%

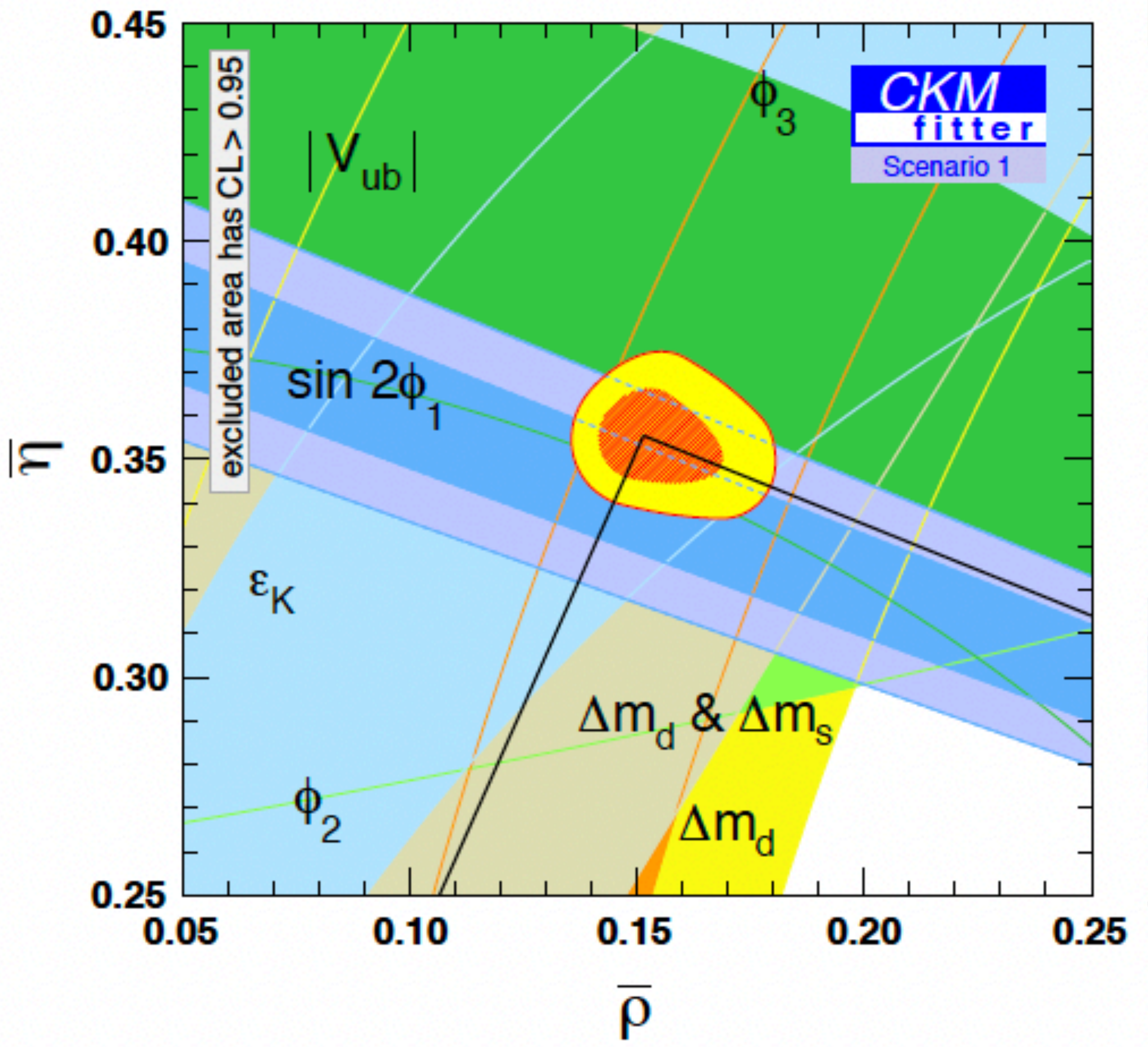
CKM measurements

see presentation by Giulio Mezzadri

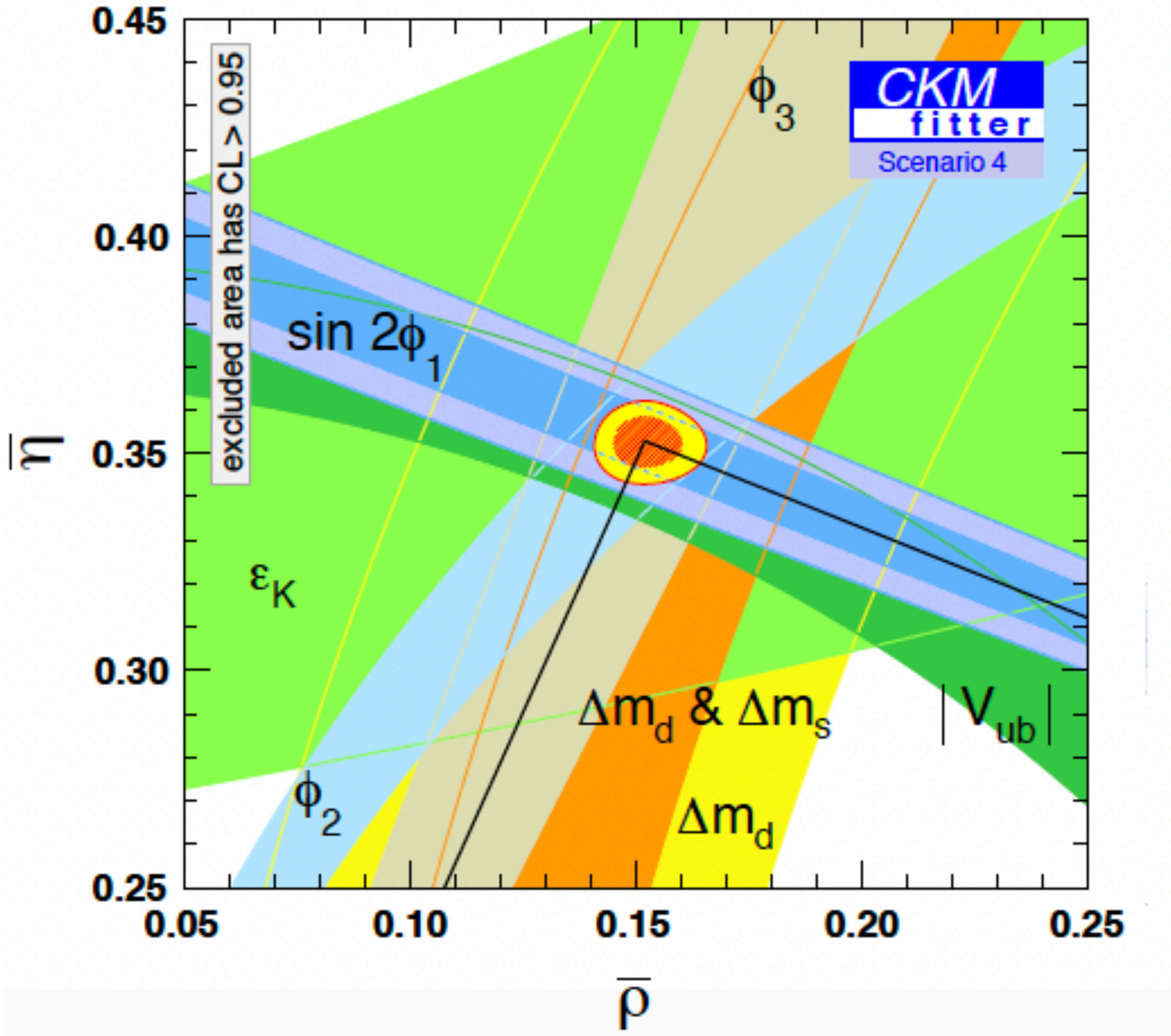
Unitarity Triangle



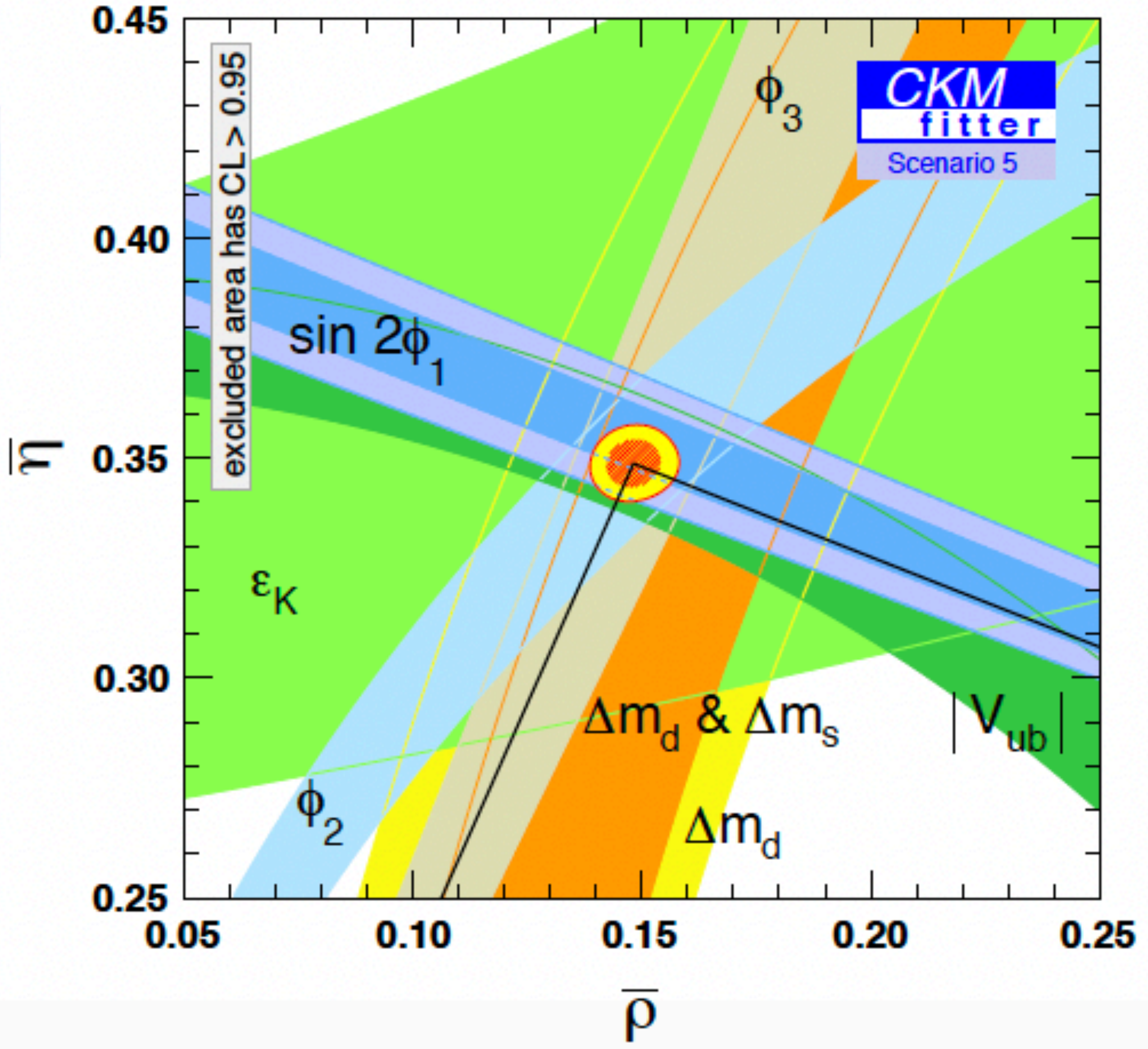
Now



$50\ ab^{-1}$ Belle II



$50\ ab^{-1}$ Belle II + LHCb



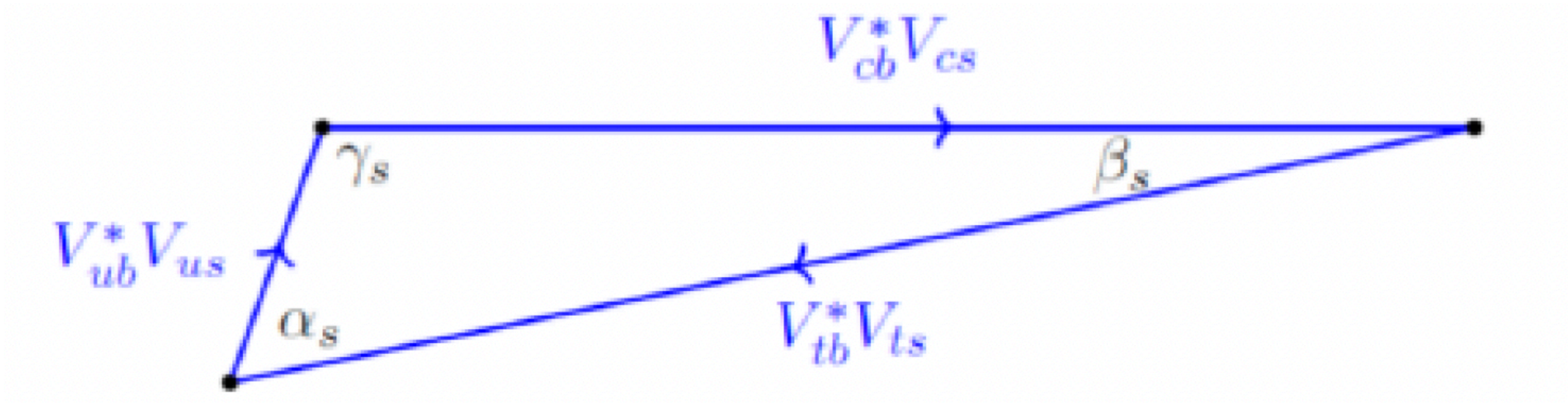
At the end of HL-LHC, γ will be known with about 1 deg uncertainty

FCC-ee can improve this uncertainty by a factor of 2, with decays such as B → DK

B → DK
arXiv:2107.05311

The “flat” triangle UT_{sb}

see presentation by Giulio Mezzadri



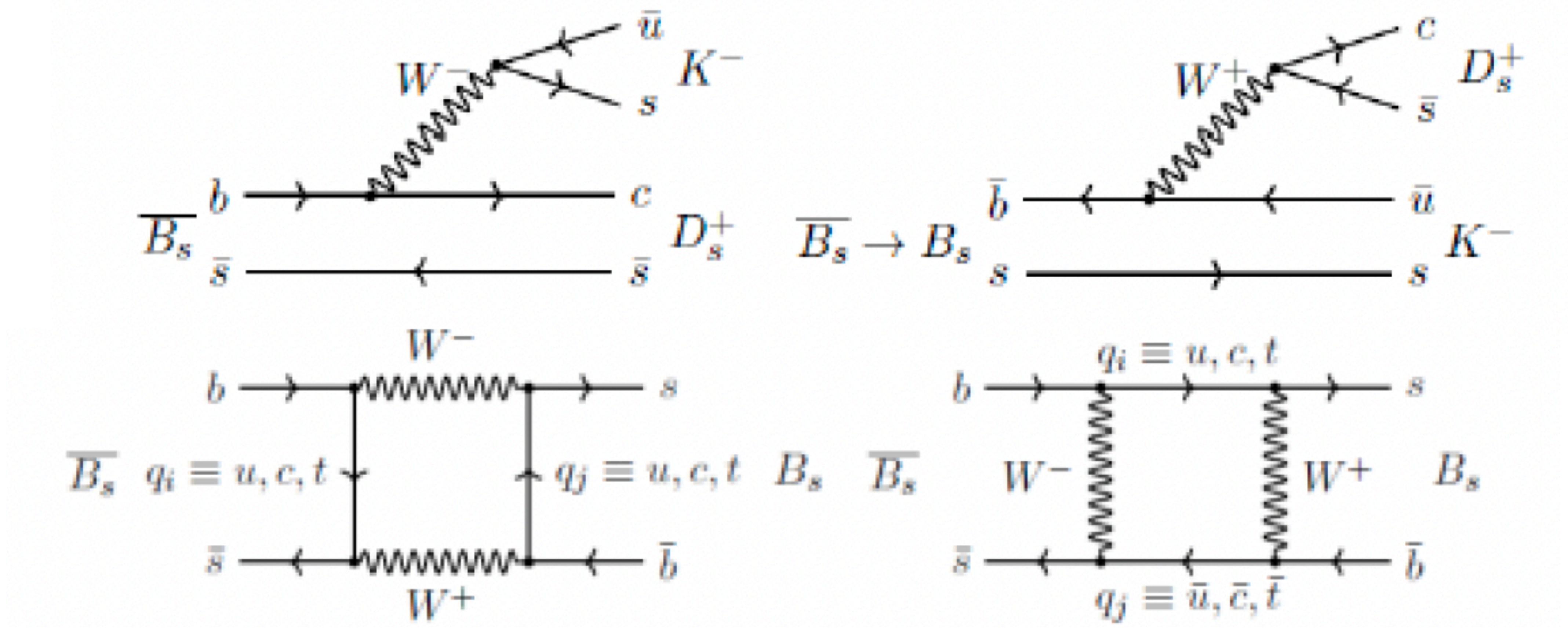
$(\alpha_s, \beta_s, \gamma_s) \sim (1.2; 0.02; 1.9)$

All the angles of the “flat” unitarity triangle UT_{sb} can be determined directly with high accuracy

- $B_s \to D_sK$ $\pi - (\alpha_s - \beta_s)$
- $B_s \to J/\Phi\psi$ $\pi + 2\beta_s$
- $B_u \to D^0K$ $\pi + \gamma_s$

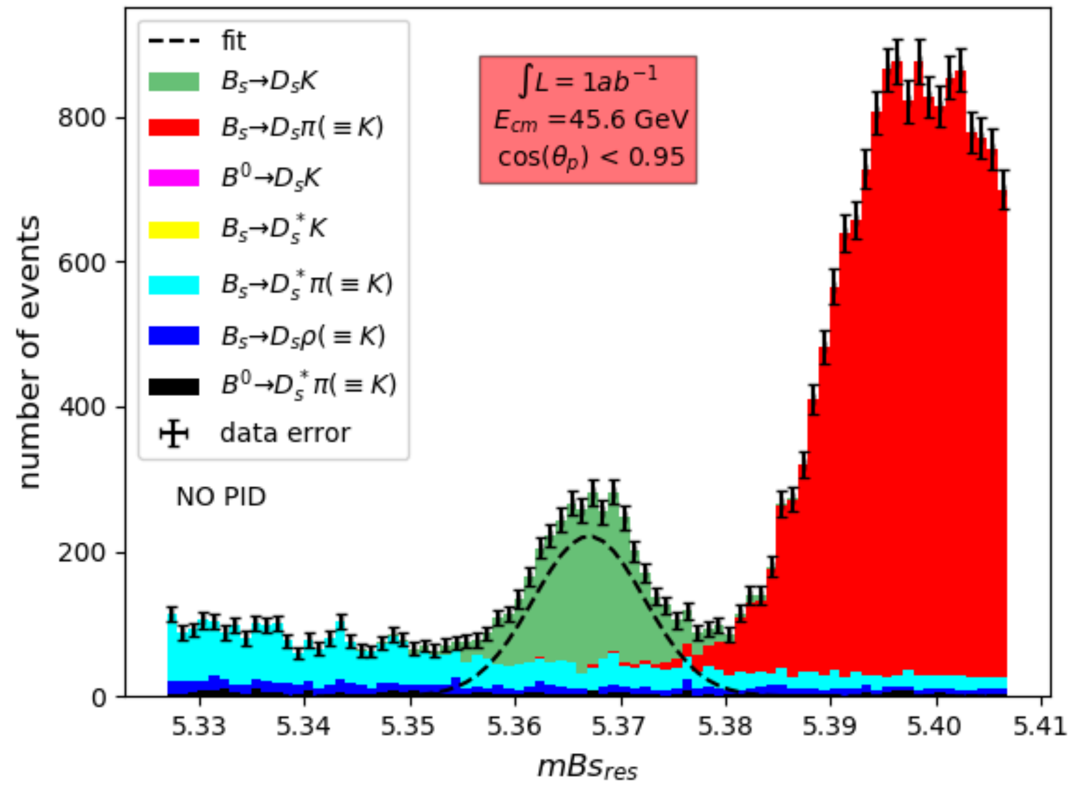
R. Aleksan et al.
$B_s \longrightarrow D_sK$
arXiv:2107.02002

Mixing-induced CP violation in time-dependent $B_s \to D_sK$

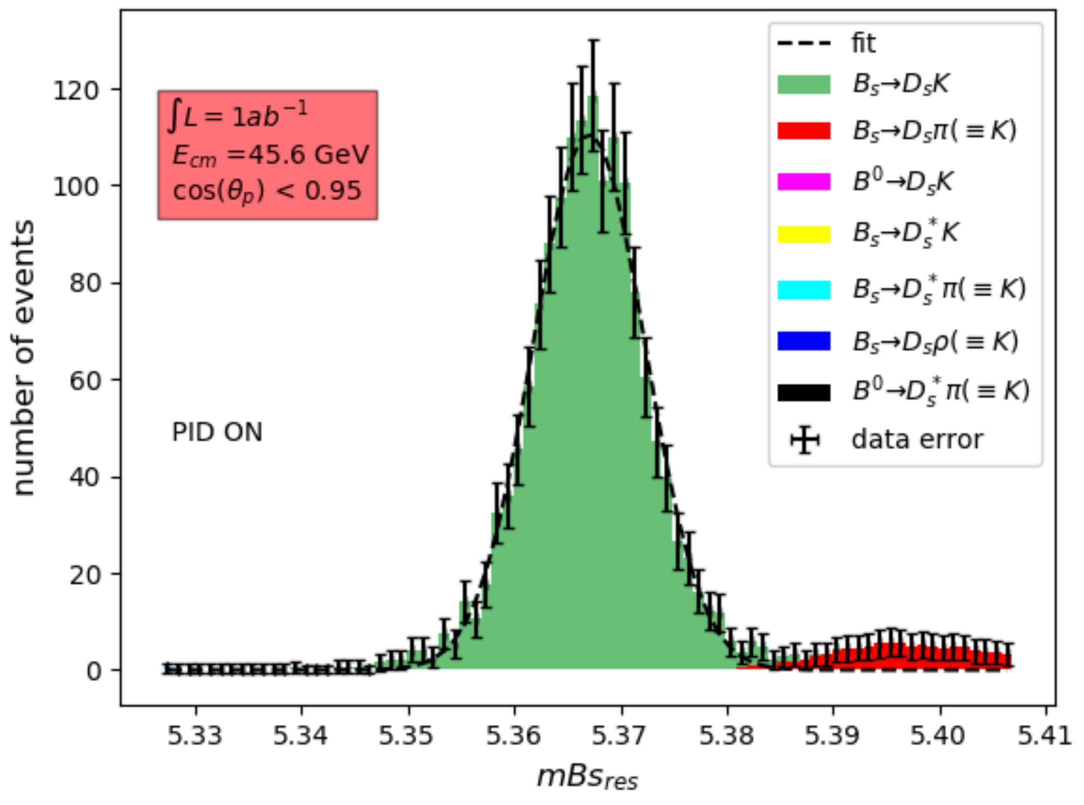


$B_s \longrightarrow \phi\phi$
arXiv:2205.07823

without PID



wit PID



The guiding light analysis…

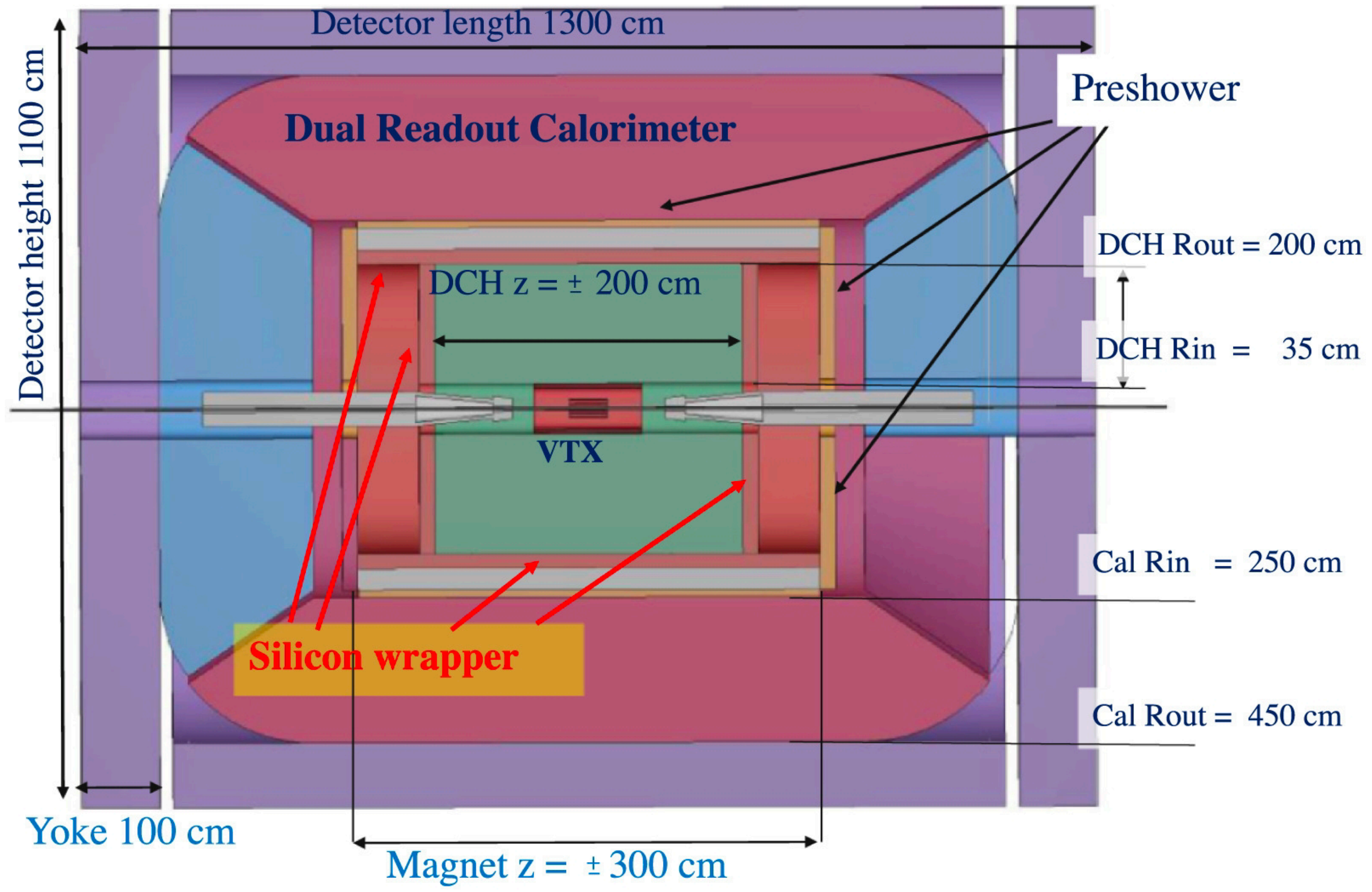
Fast simulation of $B_s \to D_s K$ benchmark

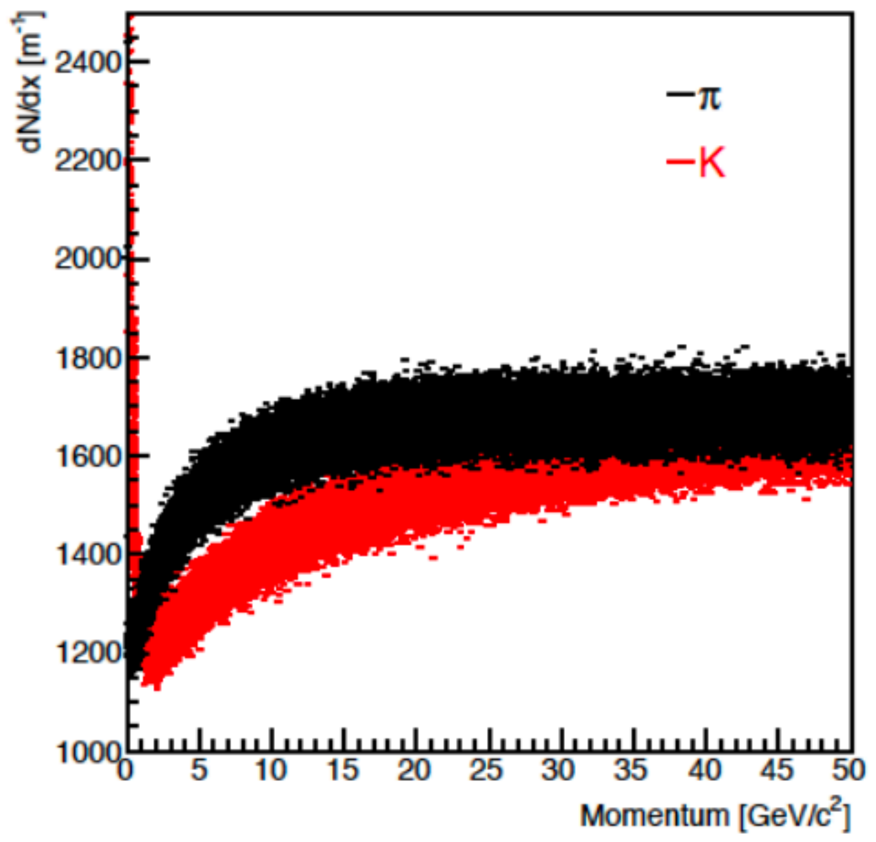
see presentation by Giulio Mezzadri

Ds→ Φπ + bachelor K, with Φ → KK

First fast IDEA simulation of this mode (DELPHES)

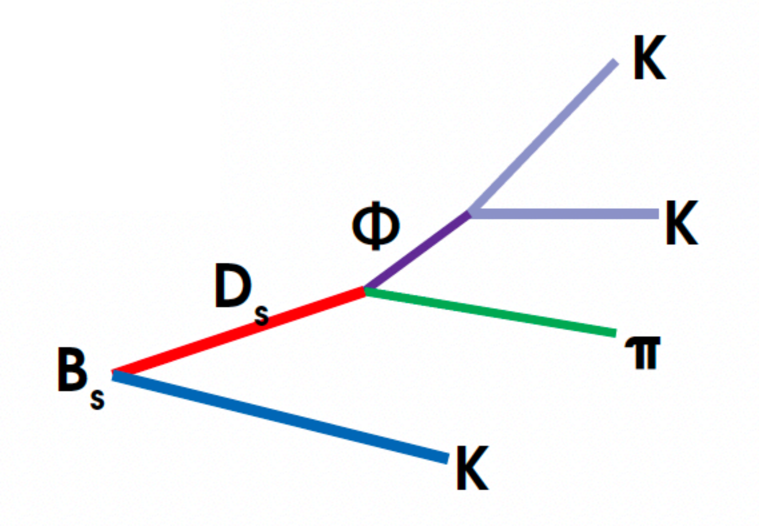
- tools tested and ready for more complex analyses
- a new version of the vertexing code now available

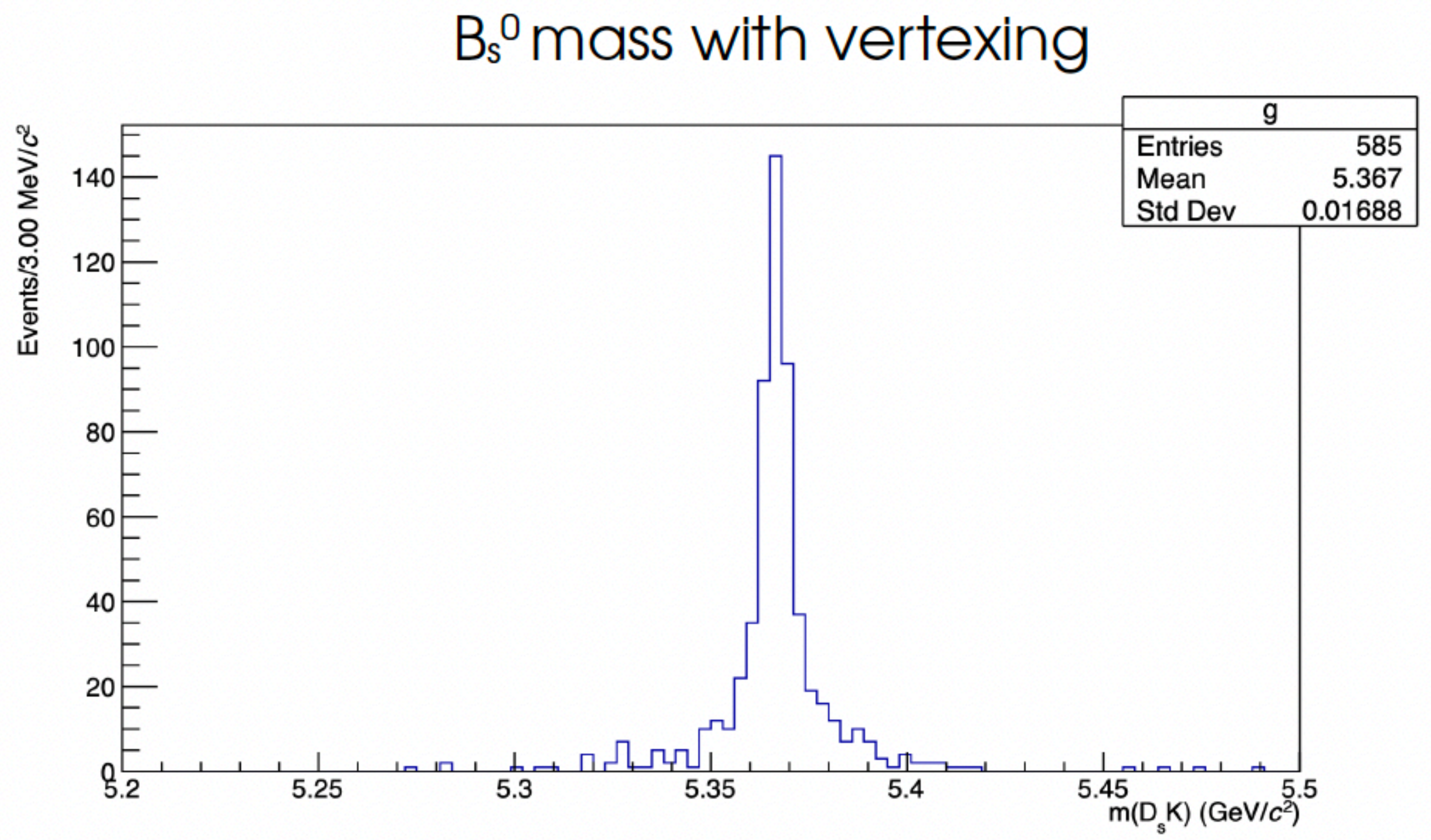


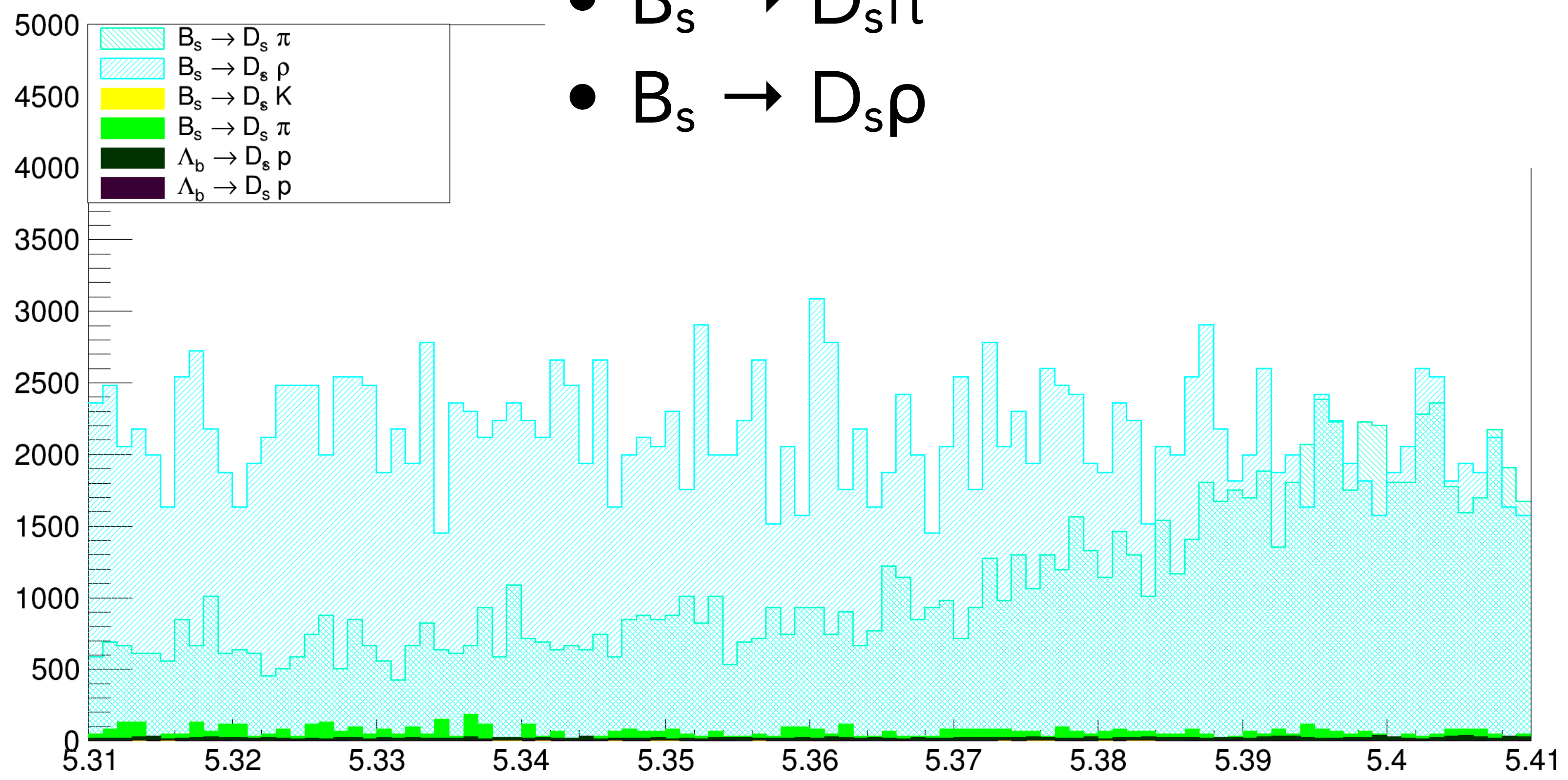


Study in a preliminary stage

- good reconstruction of B_s candidate mass, vertexing with covariance matrix
- systematic studies with truth matching
- first look at PID (cluster counting)
- first study of combinatorial from some of the main B_s backgrounds







main backgrounds:

- $B_s \to D_s\pi$
- $B_s \to D_s\rho$

next steps

- reproduce results of guiding analysis
- final states with neutrals

Need to distinguish from $B_s \to D_s\pi$

Importance of K/π identification

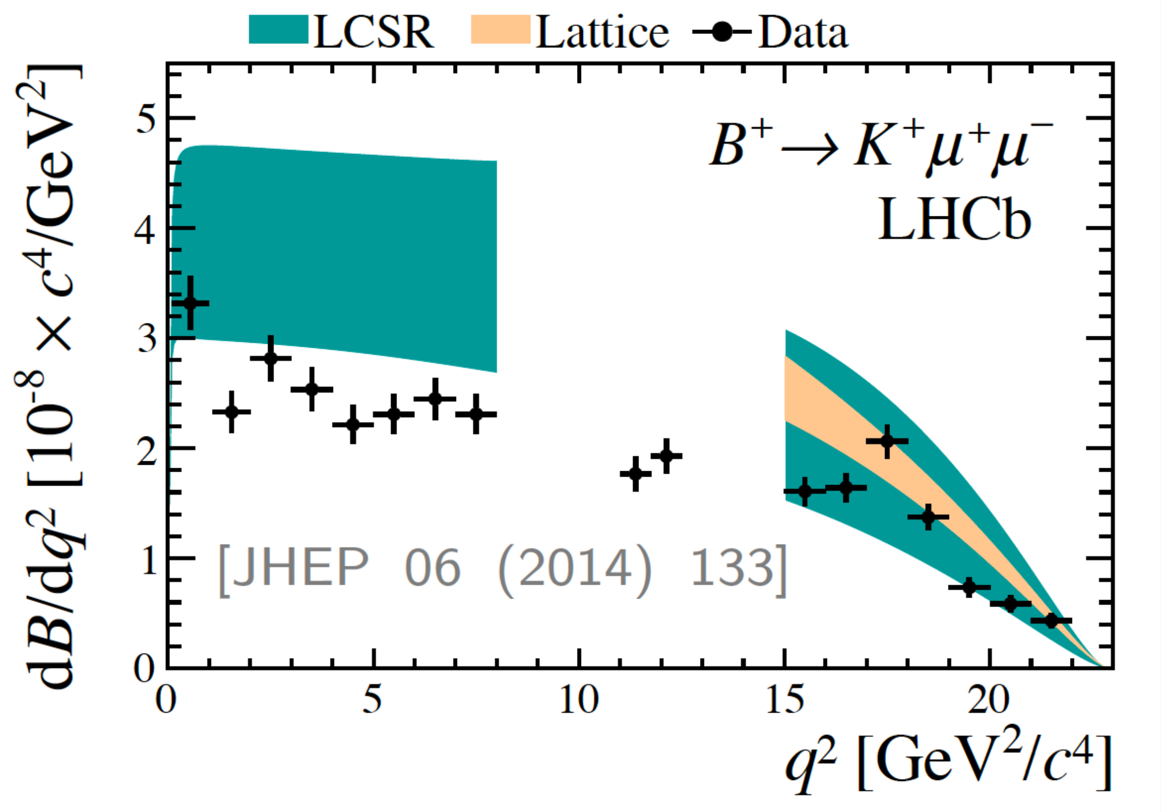
Flavour anomalies

Over the years LHCb has reported or confirmed intriguing flavour anomalies, some of which hint at deviations from Lepton Flavour University (LFU)

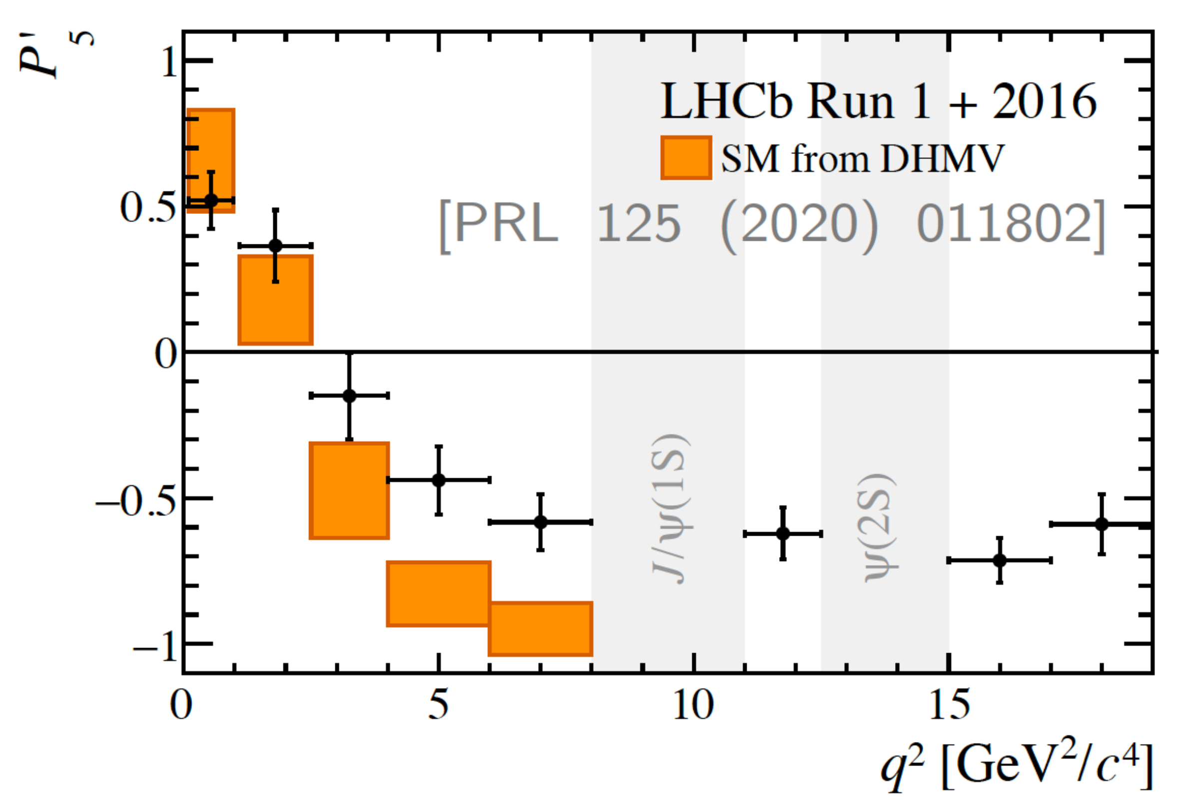
LFU in the SM: universal electroweak gauge interactions to e, μ and τ leptons

In b → $s\ell^+\ell^-$ transitions

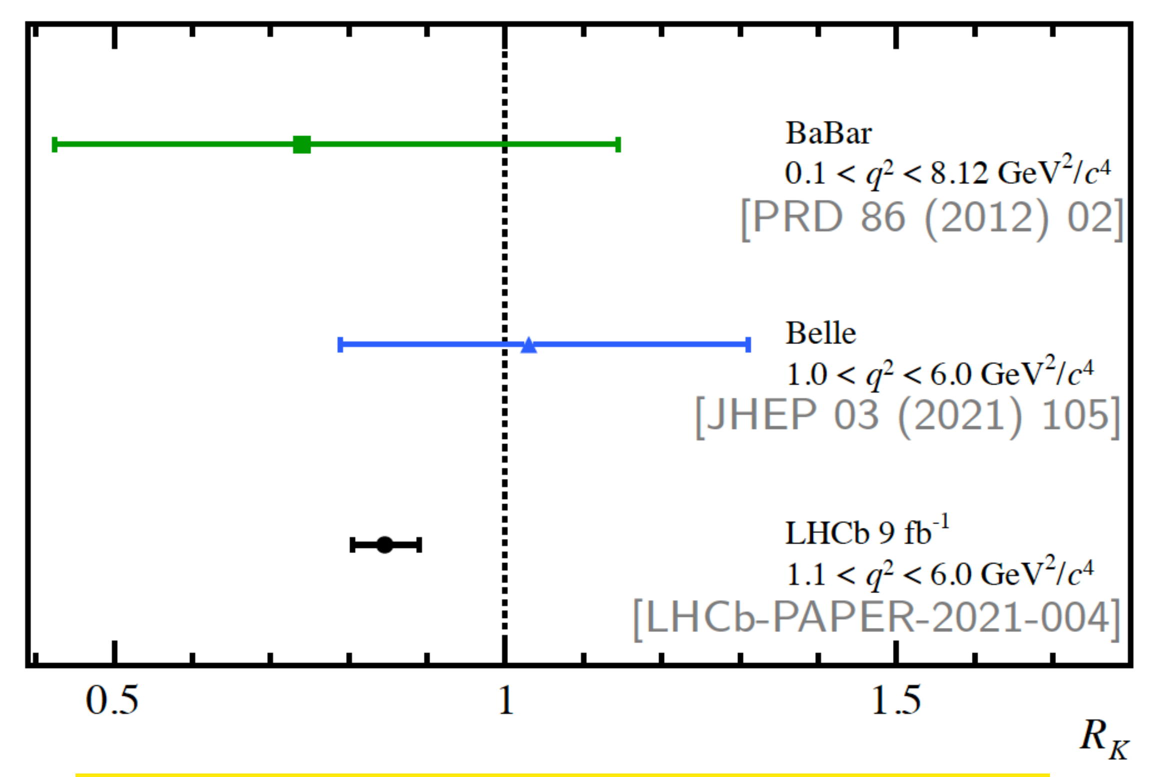
- Branching fractions
- Angular analyses
- Test of LFU involving μ/e ratios $R(K^{(*)})$: $B\to K^{(*)}\mu^+\mu^-/B\to K^{(*)}e^+e^-$



[JHEP 06 (2014) 133]



[PRL 125 (2020) 011802]



[PRD 86 (2012) 02]

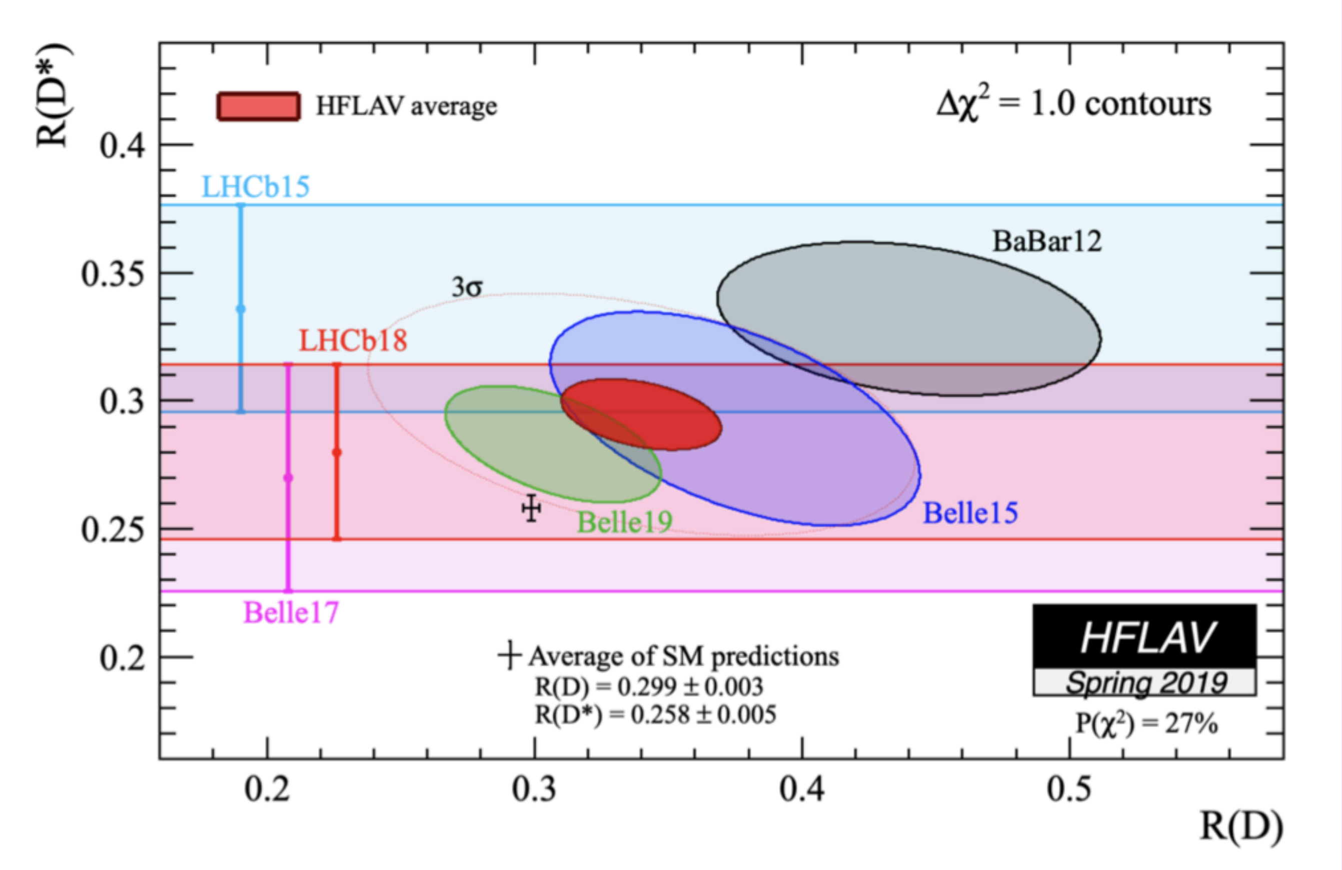
[JHEP 03 (2021) 105]

[LHCb-PAPER-2021-004]

3.1σ deviation from SM

In b → $c\ell\nu$ transitions

- tests of LFU involving τ/μ ratios $R(D^{(*)})$: $B\to D^{(*)}\tau\nu\ /\ B\to D^{(*)}\mu\nu$



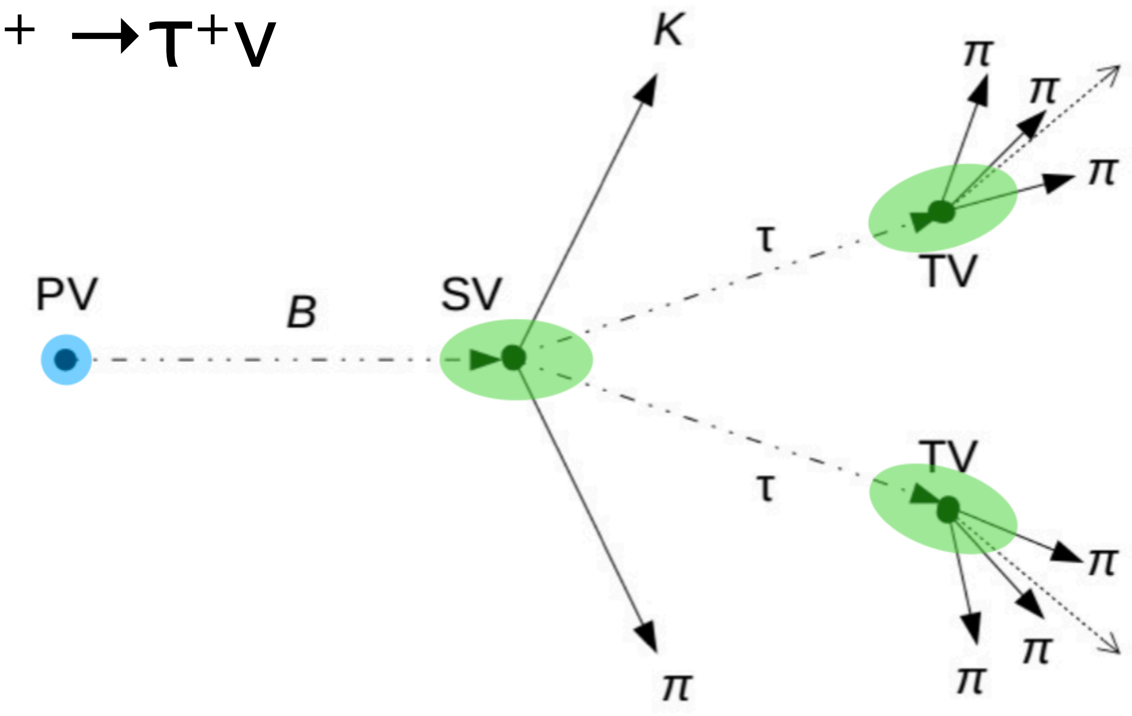
LHCb has presented several new results based on their full Run-2 dataset

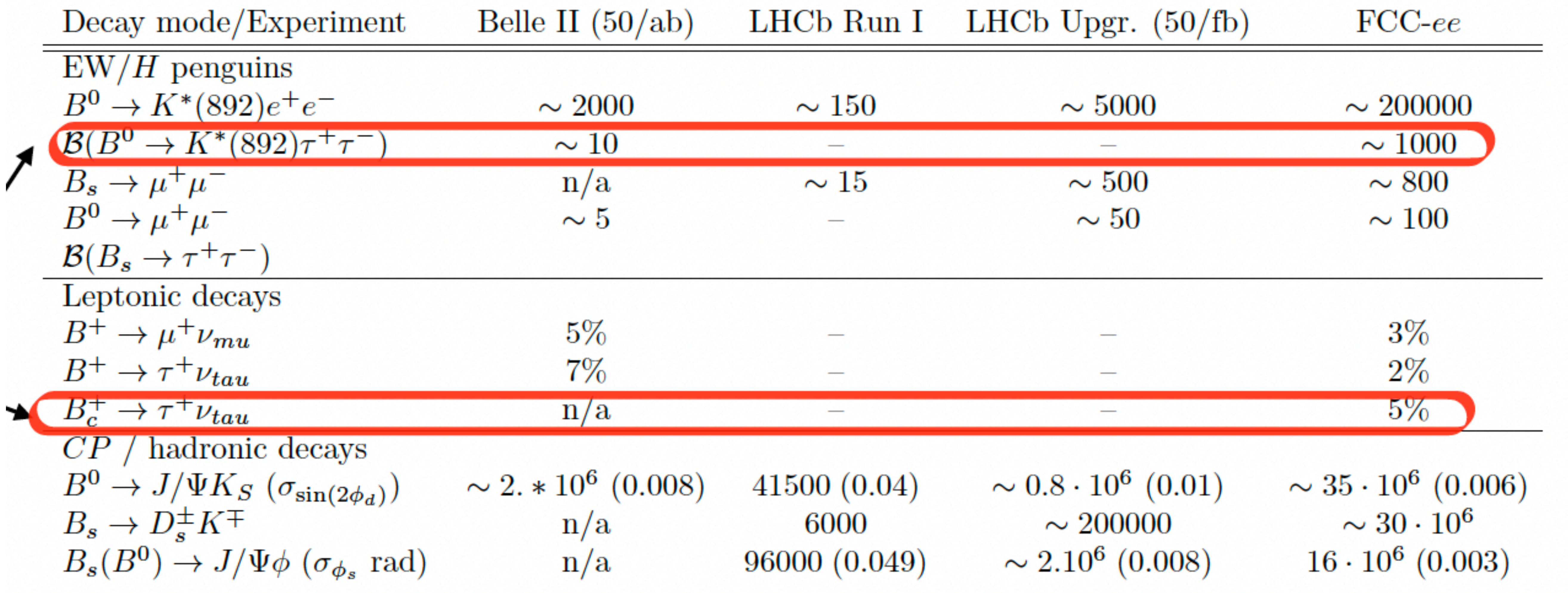
Study of B_s to $K^*\tau\tau$ at FCC-ee

see presentation by Tristan Miralles

Importance of final states with tau leptons

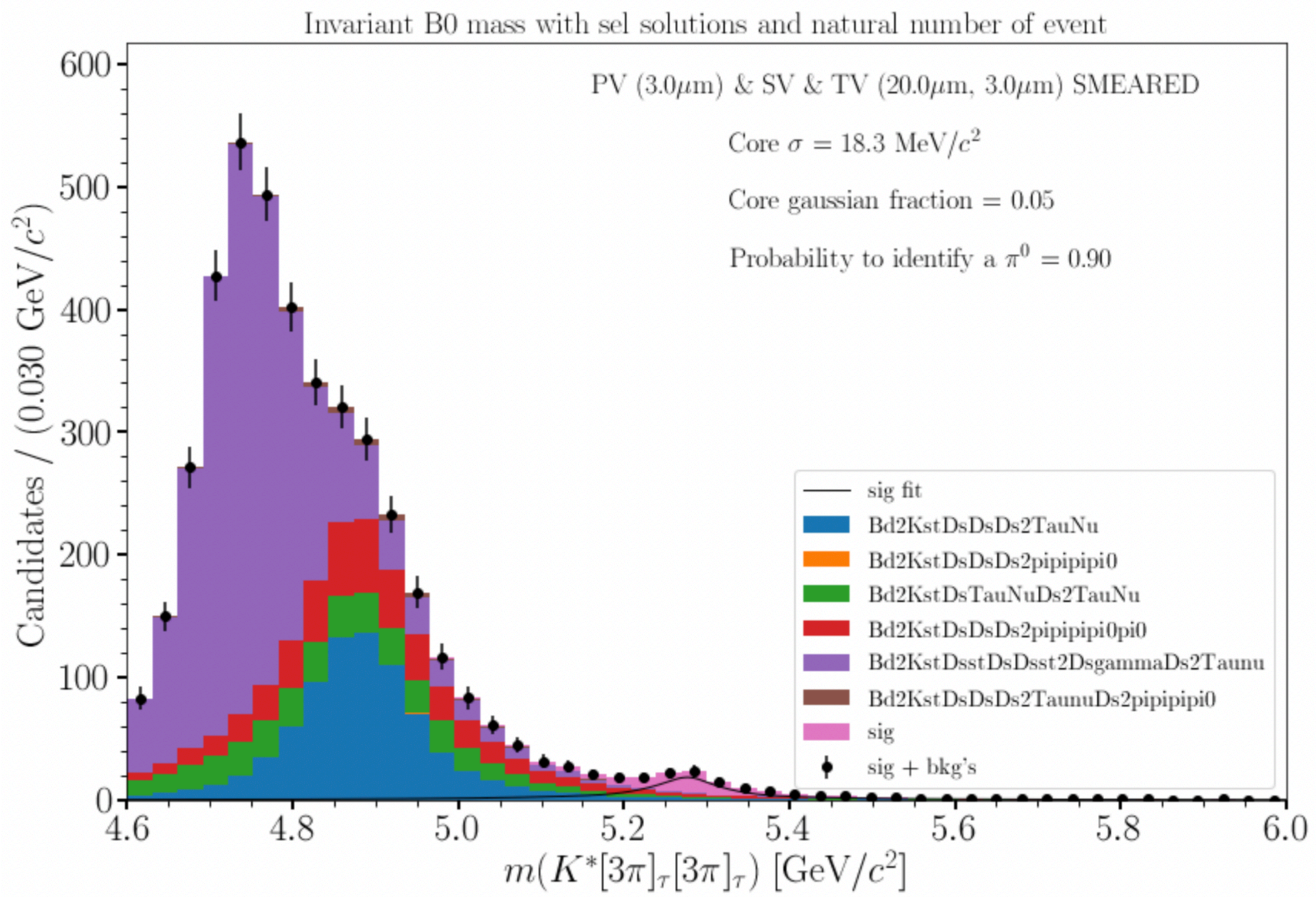
- B → K* τ+τ−,
- V_{cb} from $B_c^+ \to \tau^+\nu$



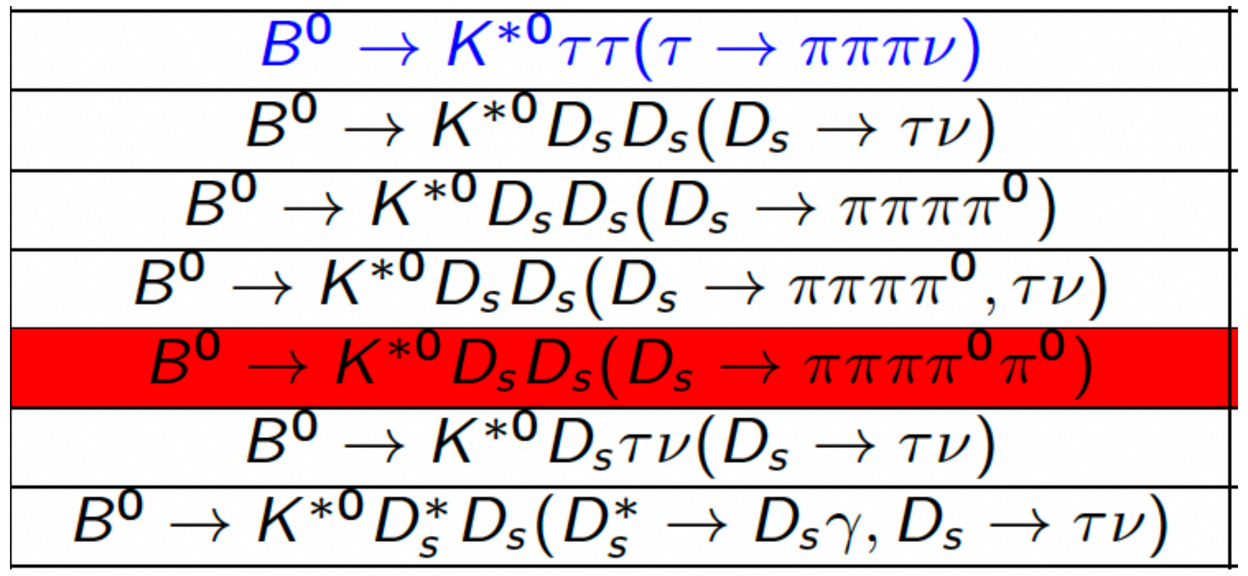


Decay mode/Experiment	Belle II (50/ab)	LHCb Run I	LHCb Upgr. (50/fb)	FCC-ee
EW/H penguins				
$B^0 \to K^*(892)e^+e^-$	~ 2000	~ 150	~ 5000	~ 200000
$\mathcal{B}(B^0 \to K^*(892)\tau^+\tau^-)$	~ 10	–	–	~ 1000
$B_s \to \mu^+\mu^-$	n/a	~ 15	~ 500	~ 800
$B^0 \to \mu^+\mu^-$	~ 5	–	~ 50	~ 100
$\mathcal{B}(B_s \to \tau^+\tau^-)$				
Leptonic decays				
$B^+ \to \mu^+\nu_{mu}$	5%	–	–	3%
$B^+ \to \tau^+\nu_{tau}$	7%	–	–	2%
$B_c^+ \to \tau^+\nu_{tau}$	n/a	–	–	5%
CP / hadronic decays				
$B^0 \to J/\Psi K_S$ ($\sigma_{\sin(2\phi_d)}$)	$\sim 2. * 10^6$ (0.008)	41500 (0.04)	$\sim 0.8 \cdot 10^6$ (0.01)	$\sim 35 \cdot 10^6$ (0.006)
$B_s \to D_s^\pm K^\mp$	n/a	6000	~ 200000	$\sim 30 \cdot 10^6$
$B_s(B^0) \to J/\Psi\phi$ (σ_{ϕ_s} rad)	n/a	96000 (0.049)	$\sim 2.10^6$ (0.008)	$16 \cdot 10^6$ (0.003)

Reconstruction method fully validated with simulated signal events



Extensive study of backgrounds



$B^0 \to K^{*0}\tau\tau(\tau \to \pi\pi\pi\nu)$
$B^0 \to K^{*0}D_sD_s(D_s \to \tau\nu)$
$B^0 \to K^{*0}D_sD_s(D_s \to \pi\pi\pi\pi^0)$
$B^0 \to K^{*0}D_sD_s(D_s \to \pi\pi\pi\pi^0, \tau\nu)$
$B^0 \to K^{*0}D_sD_s(D_s \to \pi\pi\pi\pi^0\pi^0)$
$B^0 \to K^{*0}D_s\tau\nu(D_s \to \tau\nu)$
$B^0 \to K^{*0}D_s^*D_s(D_s^* \to D_s\gamma, D_s \to \tau\nu)$

$D_s \to 3\pi 2\pi^0$ = overwhelming

- need to identify π^0 from η/ω

$D_s \to \tau\pi$

- can be reduced with a 2D cut in the plane of p_τ cuts

Tau Physics

see presentation by Alberto Lusiani

150 billion τ+τ− pairs at the Z pole (=3 times Belle-2), with a boost of 25

tau polarisation

- τ and e chiral coupling asymmetries
- decays
  - τ → eνν and τ → μνν
  - τ → hν, h = π, K (1-prong)
  - τ → $\pi\pi^0\nu$
  - 3-prong, 5-prong…
- for each mode: kin. variables with various sensitivities to polarisation
  - clean separation between modes required
  - π^0 measurements essential

Mass

- pseudo-mass method
- current: 10^{-4} relative (Belle)
- 3-prong decays
  - momentum of 3-prong system and ~~beam energy~~
- control sample: Z → J/ψX

Estimate of V_{us} and first row unitarity test

- τ → X_s ν
- τ → K
- τ → K / τ → π

Tau spectral functions

- more favourable at Z peak
- rare decay modes
- complex analyses, need manpower and MC

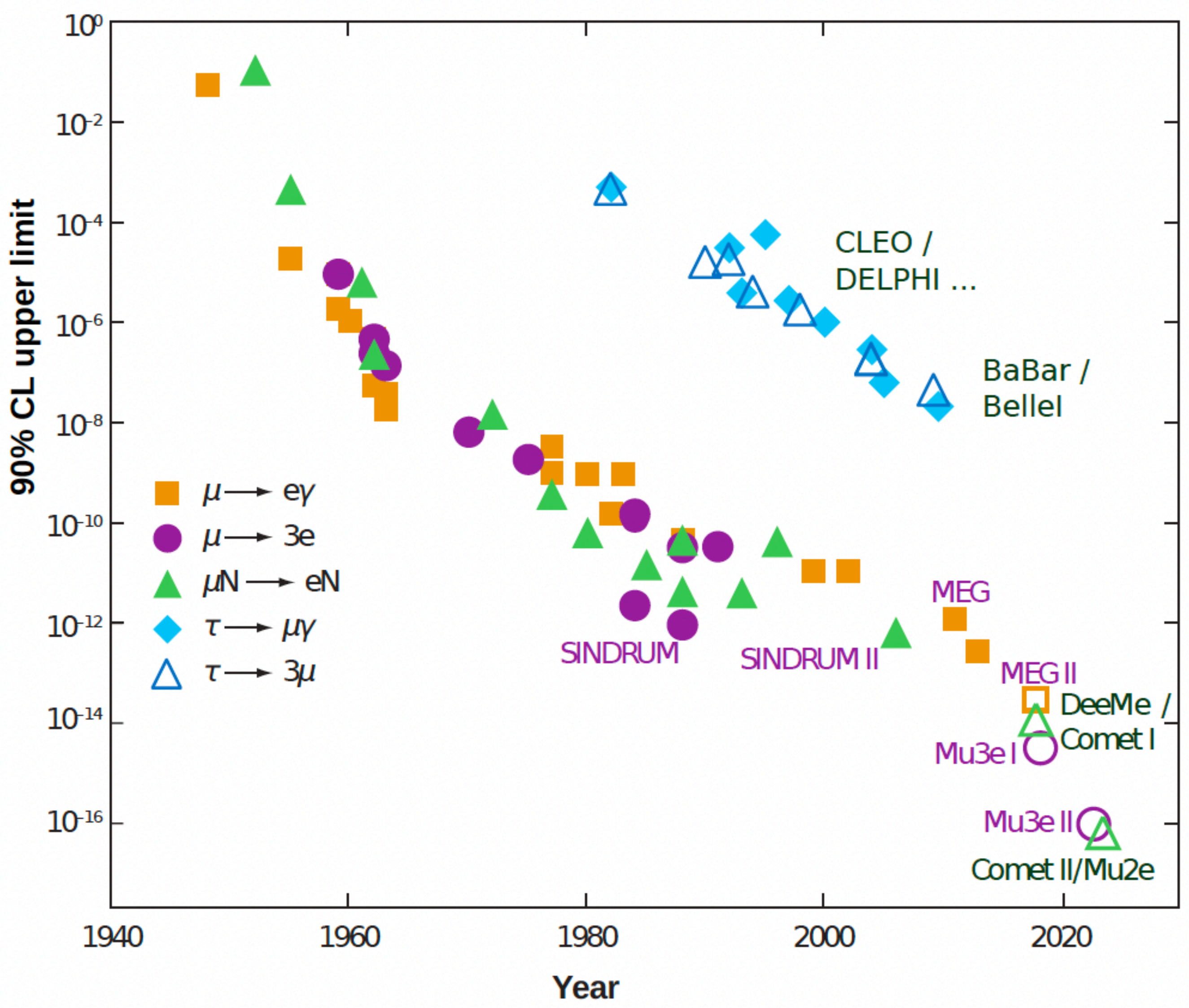
Lifetime

- statistical uncertainty at 10^{-5} level
- flight distance 2.2 mm
- strong requirements on VDet construction and alignement
- target impact parameter resolution 3 μm (factor of 5 wrt LEP)
  - enormous control samples

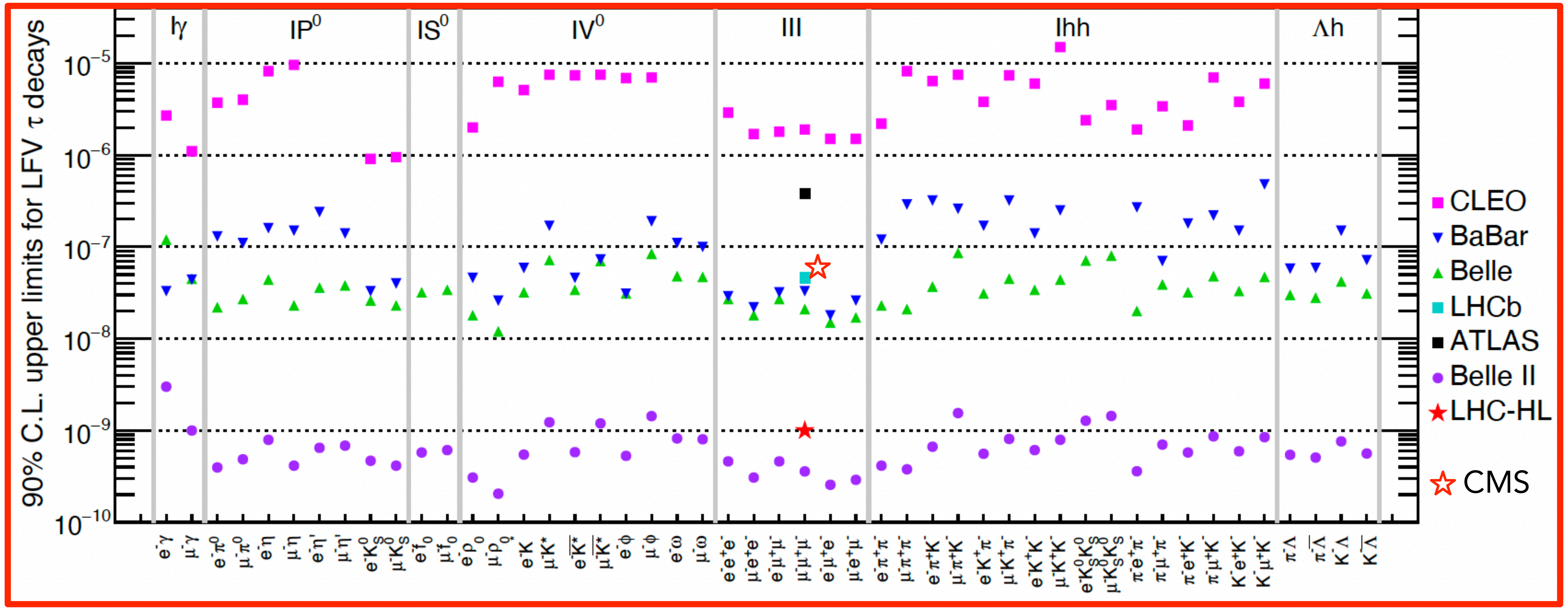
Search for LFV decays

see presentation by Alberto Lusiani

LFV searches vigorously pursued



Updated from W.J. Marciano, T. Mori and J.M. Roney, Ann.Rev.Nucl.Part.Sci. 58, 315 (2008)



HL-LHC can do well for τ → 3μ

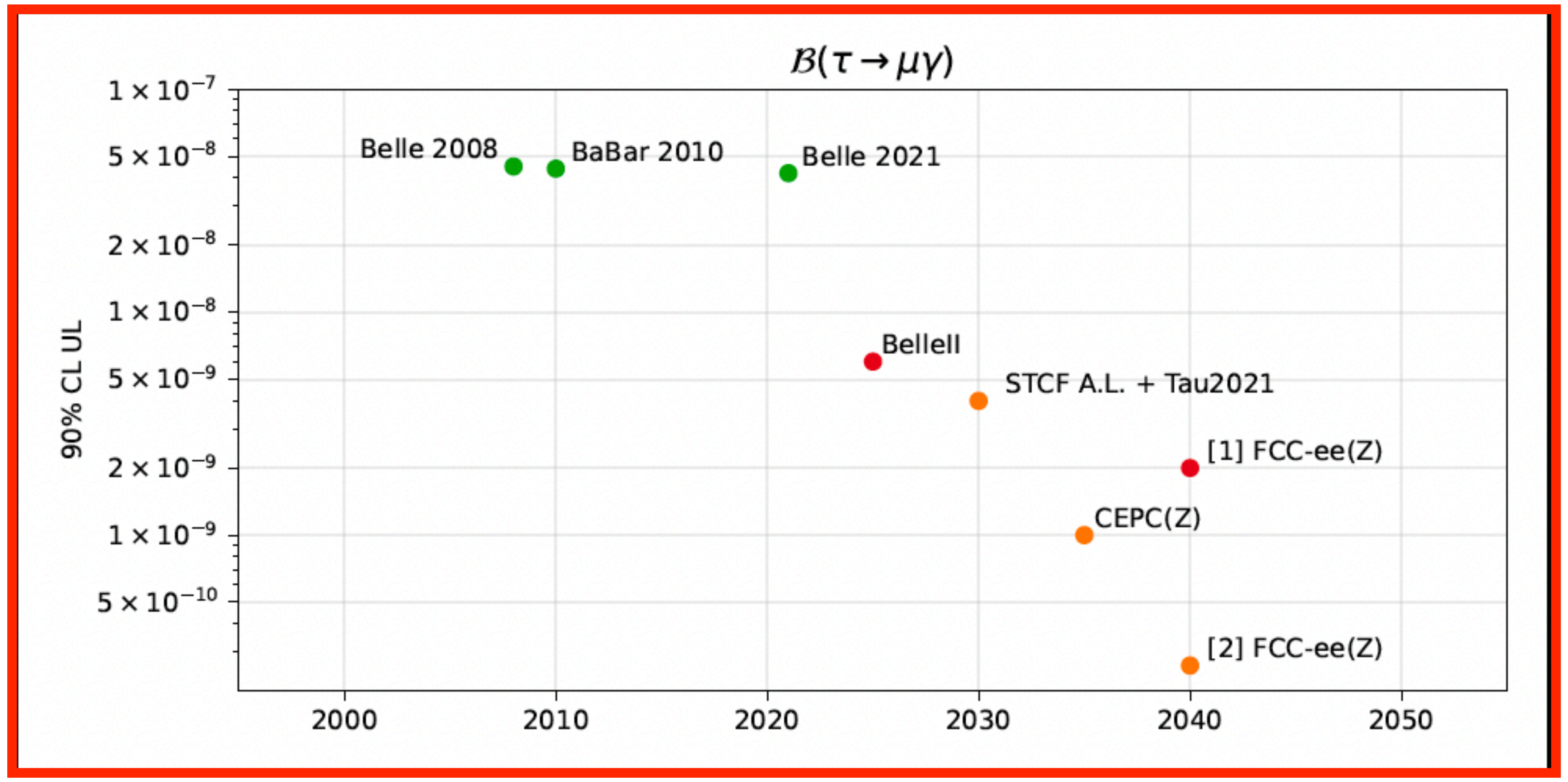
- muon LFV more powerful
- tau LFV has more channels
  - discrimination of NP models
  - more powerful for specific models

Search for LFV decays

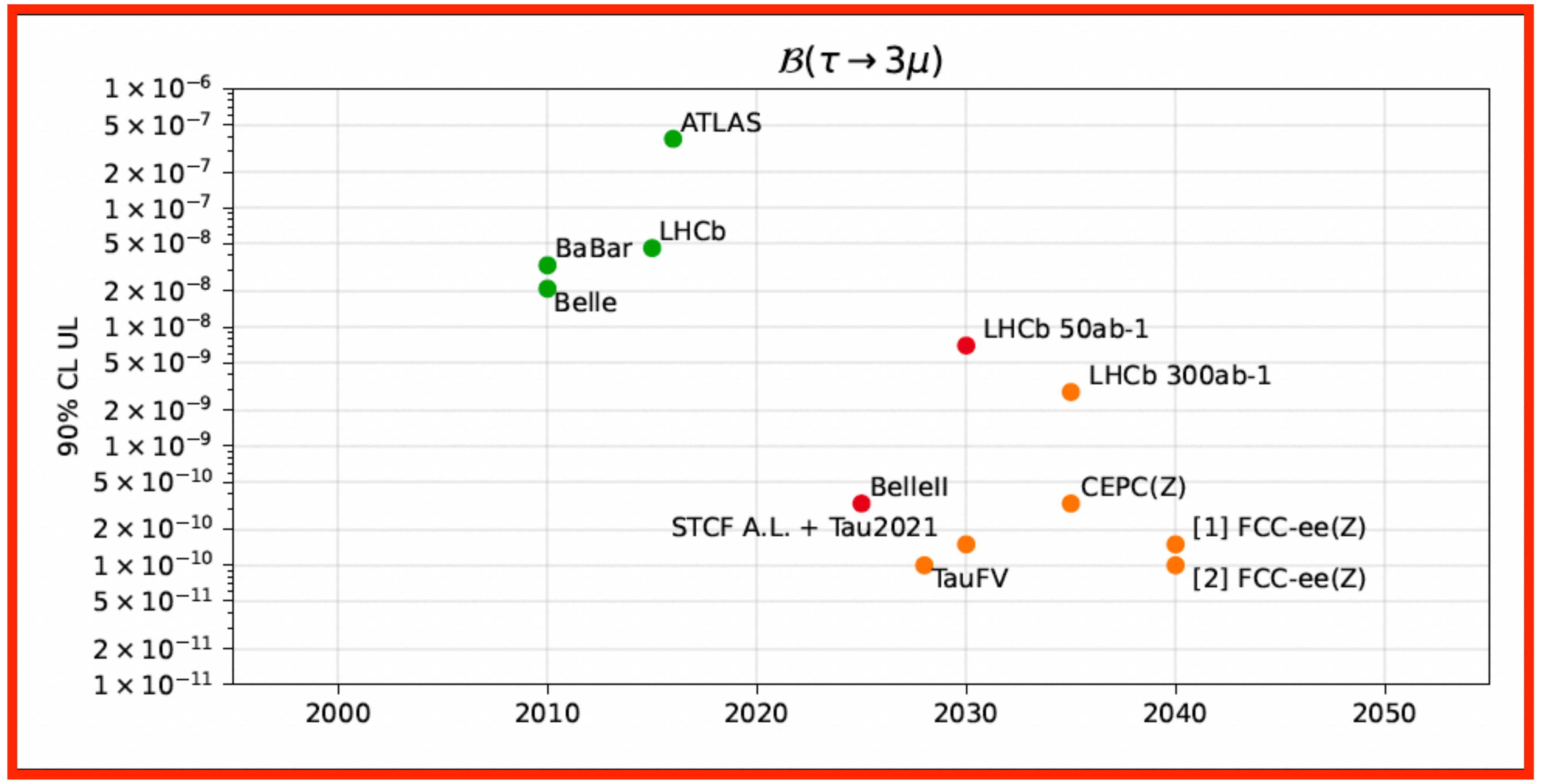
see presentation by Alberto Lusiani

FCC-ee
- no extensive simulation studies yet
- existing MC simulation technology seems sufficient [AL]

Estimates
- from extrapolations, with reasonable hypotheses
- with (improbable) background free assumption



[1] M. Dam, 2% of FCC stat
[2] M. Dam, with long-segmented xtal ECAL



[1] Alberto's guestimate
[2] M. Dam, TAU2021

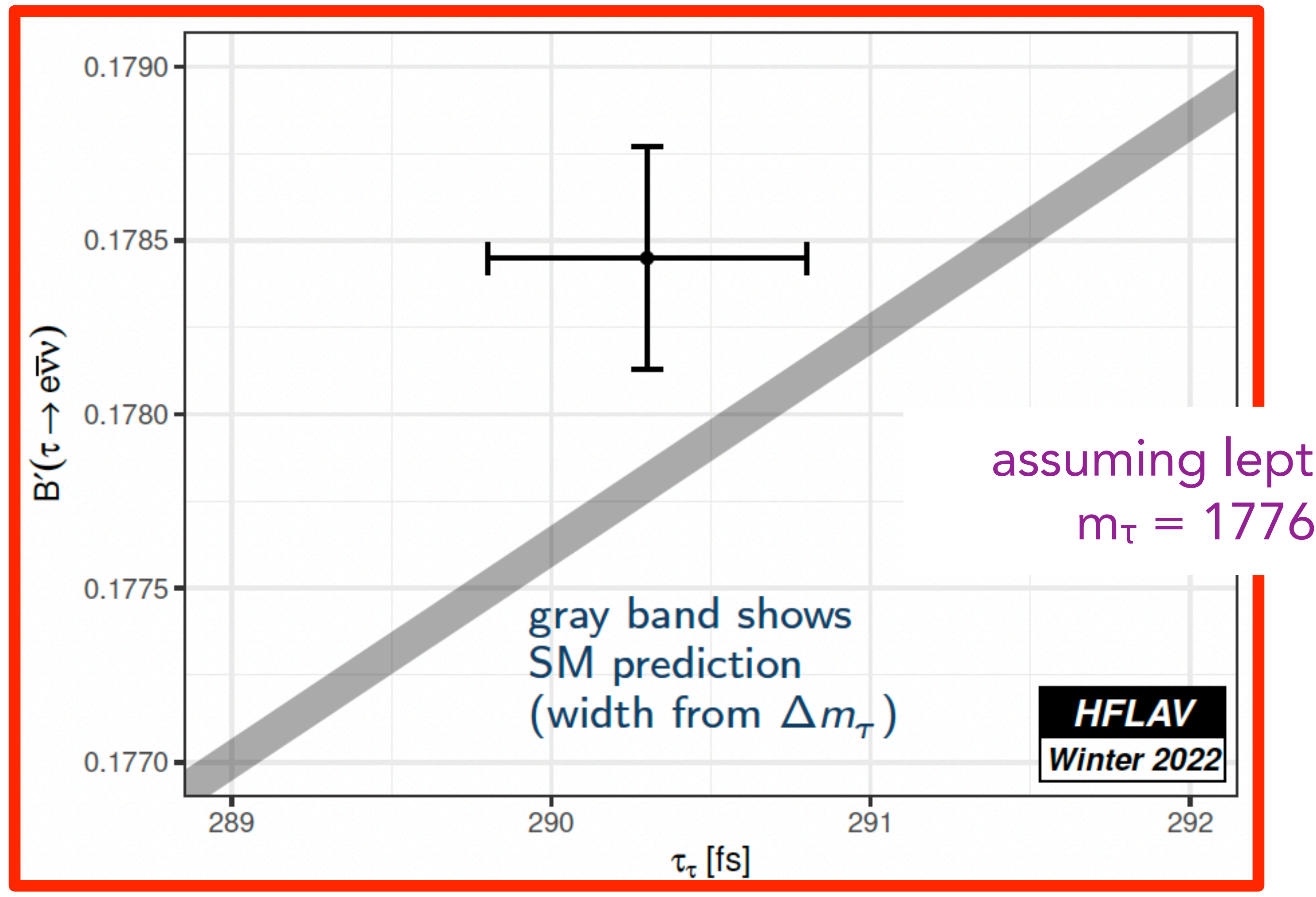
$\tau \to \mu\gamma$ improves with
- EM energy res. and granularity
- muon ID

$\tau \to \mu\gamma$ improves with
- tracking & vertexing
- muon ID

Bottom line
- FCC-ee/CEPC competitive with Belle-2 and future TCF

Lepton flavour universality test

see presentation by Alberto Lusiani



gray band shows SM prediction (width from Δm_τ)

assuming lepton universality with m_τ = 1776.86 ± 0.12 MeV

$B'(\tau \to e\nu\nu)$ = average of $B(\tau \to e\nu\nu)$

$B(\tau \to \nu\nu).f_{\tau e}/f_{\tau\mu}$

m_τ

- systematic from pseudo-mass modelling
- improve using 5-prong decays?

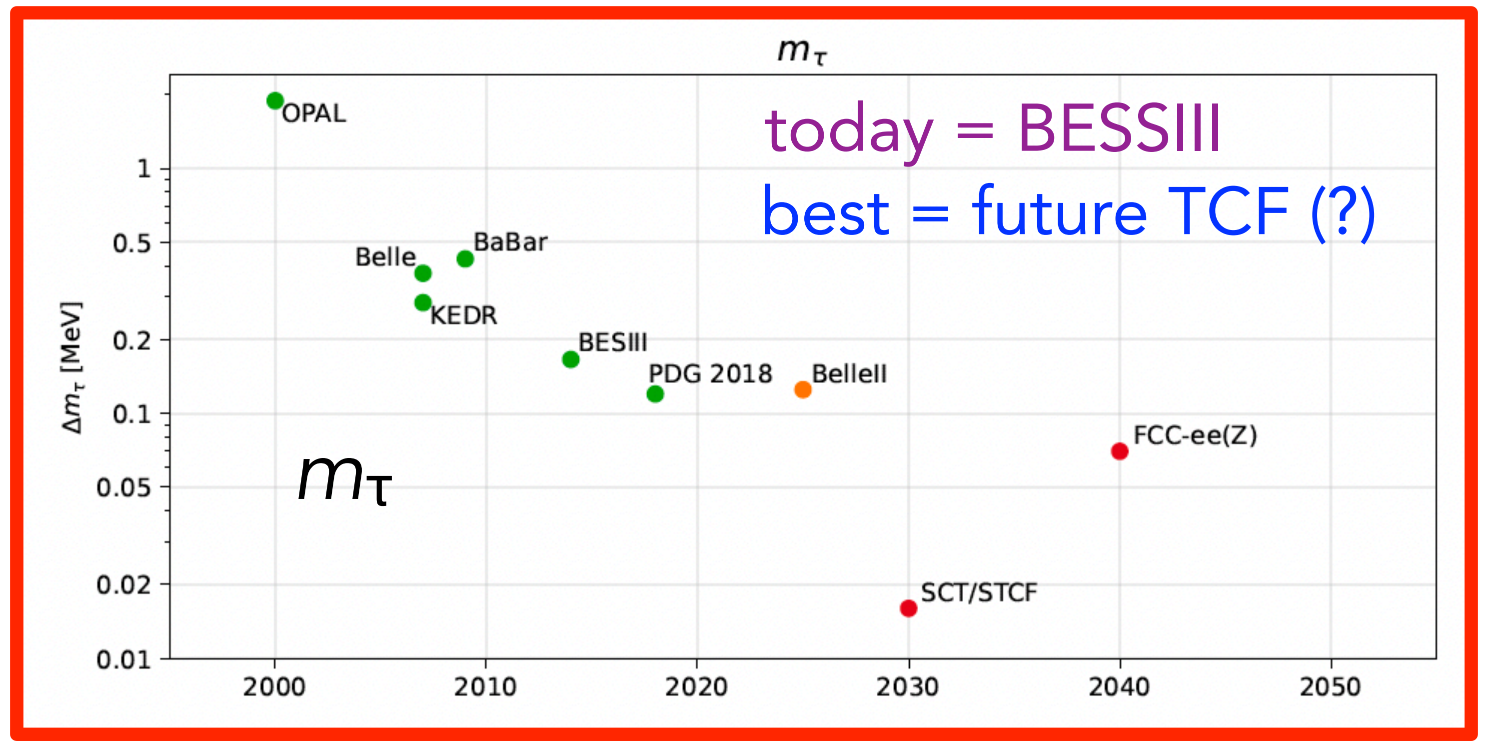
FCC-ee

τ_τ

- limiting systematic: length scale of VDet

$B(\tau \to \ell\nu\nu)$

- guestimate from ALEPH extrapolation

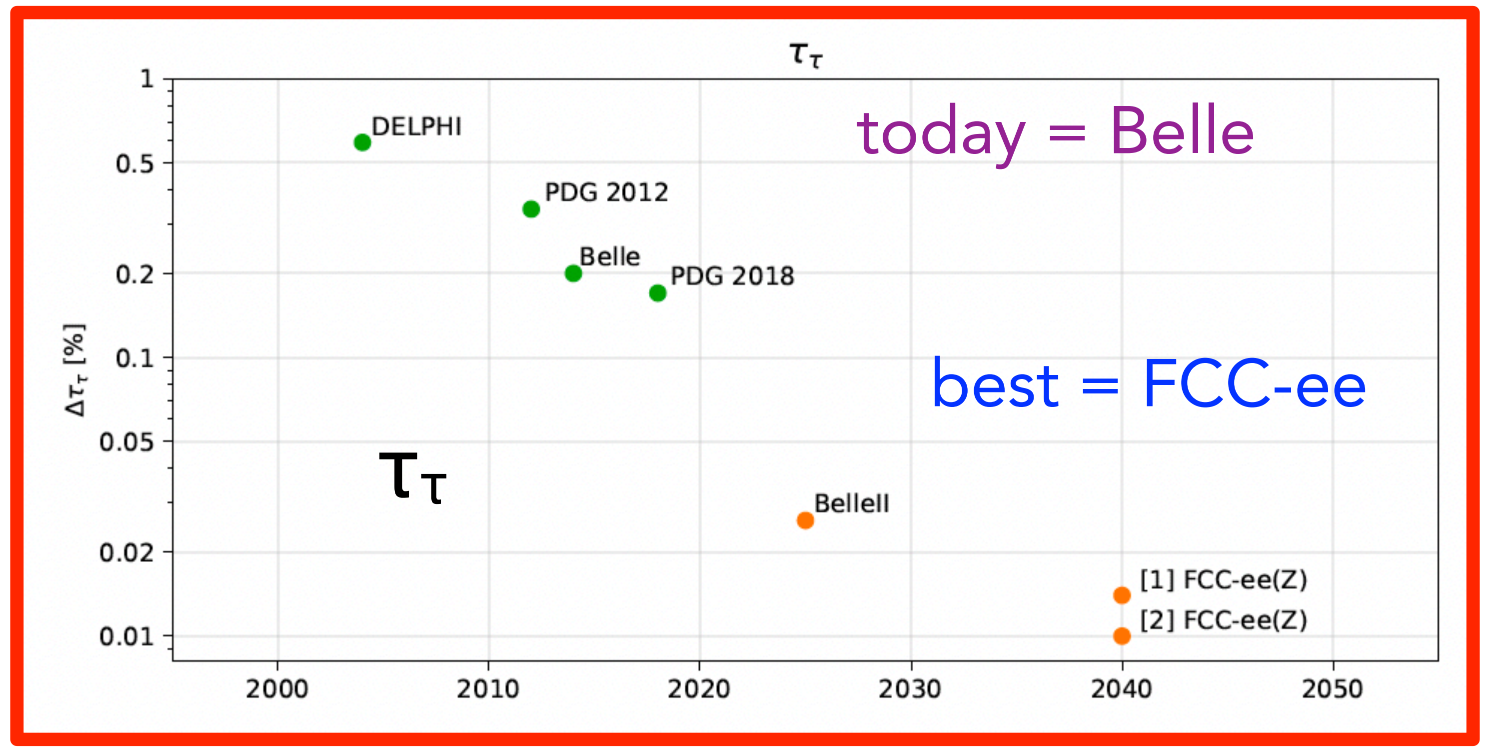


today = BESSIII

best = future TCF (?)

m_τ

x2

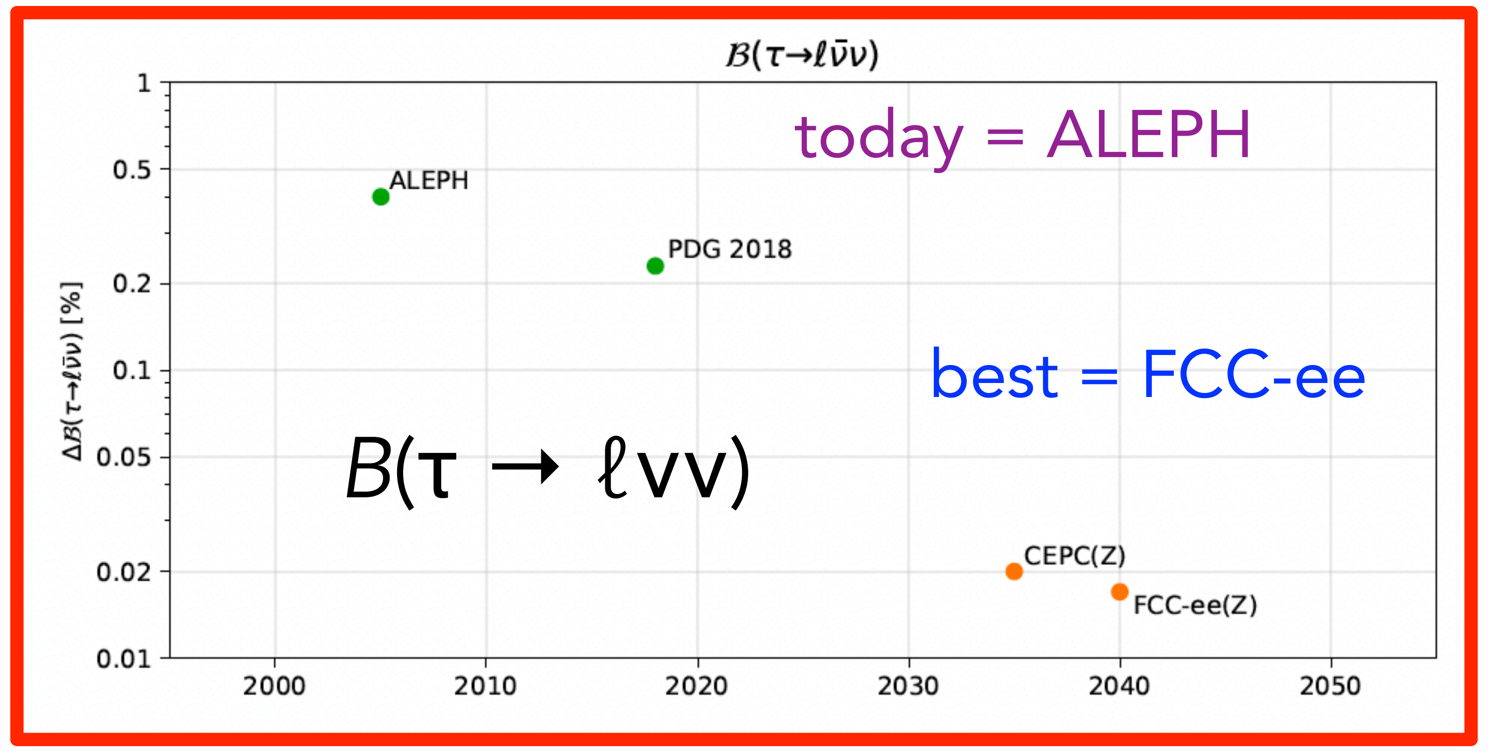


today = Belle

best = FCC-ee

τ_τ

x10



today = ALEPH

best = FCC-ee

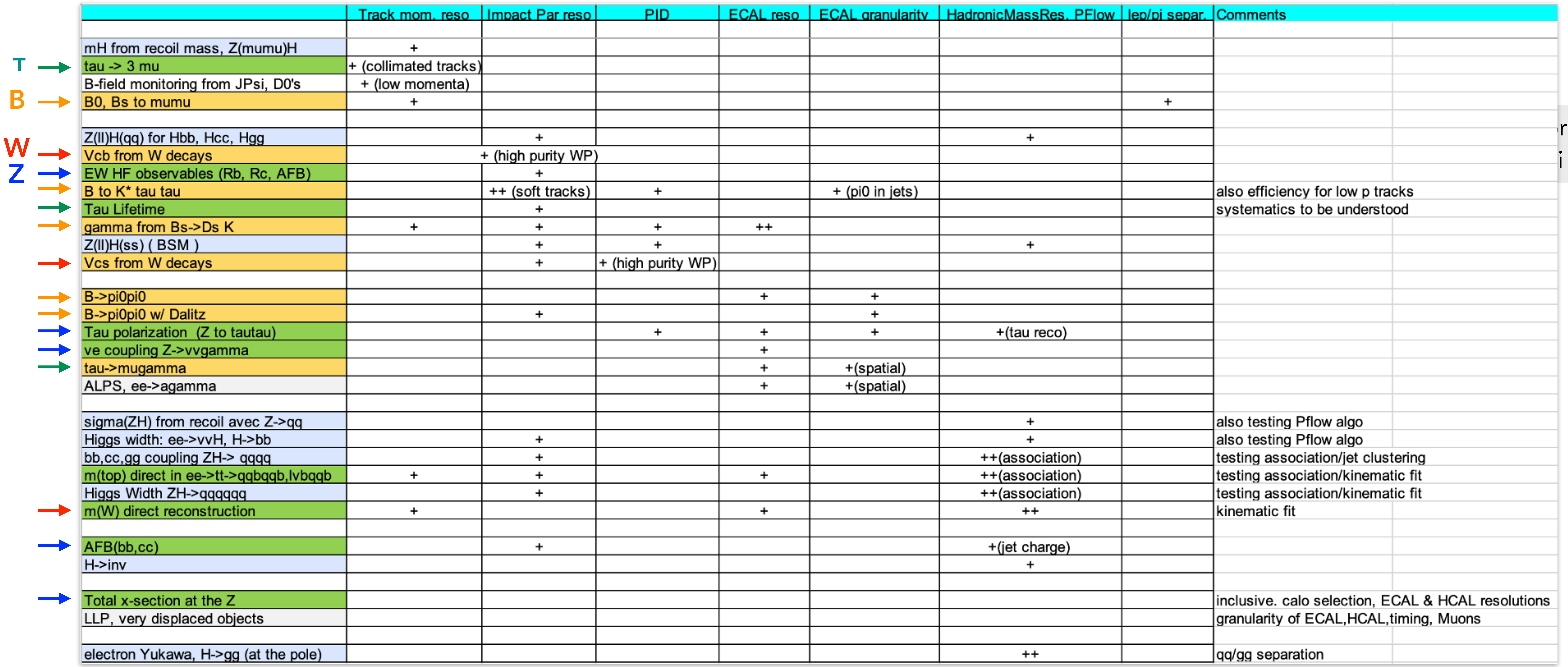
$B(\tau \to \ell\nu\nu)$

x10

Expect **huge improvement** on this powerful LFU test

FCC-ee detector requirements

see presentation by Patricia Azzi
see presentation by Didier Contardo



	Track mom. reso	Impact Par reso	PID	ECAL reso	ECAL granularity	HadronicMassRes. PFlow	lep/pi separ.	Comments
mH from recoil mass, Z(mumu)H	+							
tau -> 3 mu	+ (collimated tracks)							
B-field monitoring from JPsi, D0's	+ (low momenta)							
B0, Bs to mumu	+						+	
Z(ll)H(qq) for Hbb, Hcc, Hgg		+				+		
Vcb from W decays		+ (high purity WP)						
EW HF observables (Rb, Rc, AFB)		+						
B to K* tau tau		++ (soft tracks)	+		+ (pi0 in jets)			also efficiency for low p tracks
Tau Lifetime		+						systematics to be understood
gamma from Bs->Ds K	+	+	+	++				
Z(ll)H(ss) (BSM)		+	+			+		
Vcs from W decays		+	+ (high purity WP)					
B->pi0pi0				+	+			
B->pi0pi0 w/ Dalitz		+			+			
Tau polarization (Z to tautau)			+	+	+	+(tau reco)		
ve coupling Z->vvgamma				+				
tau->mugamma				+	+(spatial)			
ALPS, ee->agamma				+	+(spatial)			
sigma(ZH) from recoil avec Z->qq						+		also testing Pflow algo
Higgs width: ee->vvH, H->bb		+				+		also testing Pflow algo
bb,cc,gg coupling ZH-> qqqq		+				++(association)		testing association/jet clustering
m(top) direct in ee->tt->qqbqqb,lvbqqb	+	+		+		++(association)		testing association/kinematic fit
Higgs Width ZH->qqqqqq		+				++(association)		testing association/kinematic fit
m(W) direct reconstruction	+			+		++		kinematic fit
AFB(bb,cc)		+				+(jet charge)		
H->inv						+		
Total x-section at the Z								inclusive. calo selection, ECAL & HCAL resolutions
LLP, very displaced objects								granularity of ECAL,HCAL,timing, Muons
electron Yukawa, H->gg (at the pole)						++		qq/gg separation

resentations by
i & D. Contardo

Many specific challenges for Z pole data taking

- over 100 kHz event rate: storage and processing!
- extreme constraints on **luminometer mechanical accuracy** and alignement
- extreme control on **acceptance** of central tracking and calorimetry

Also

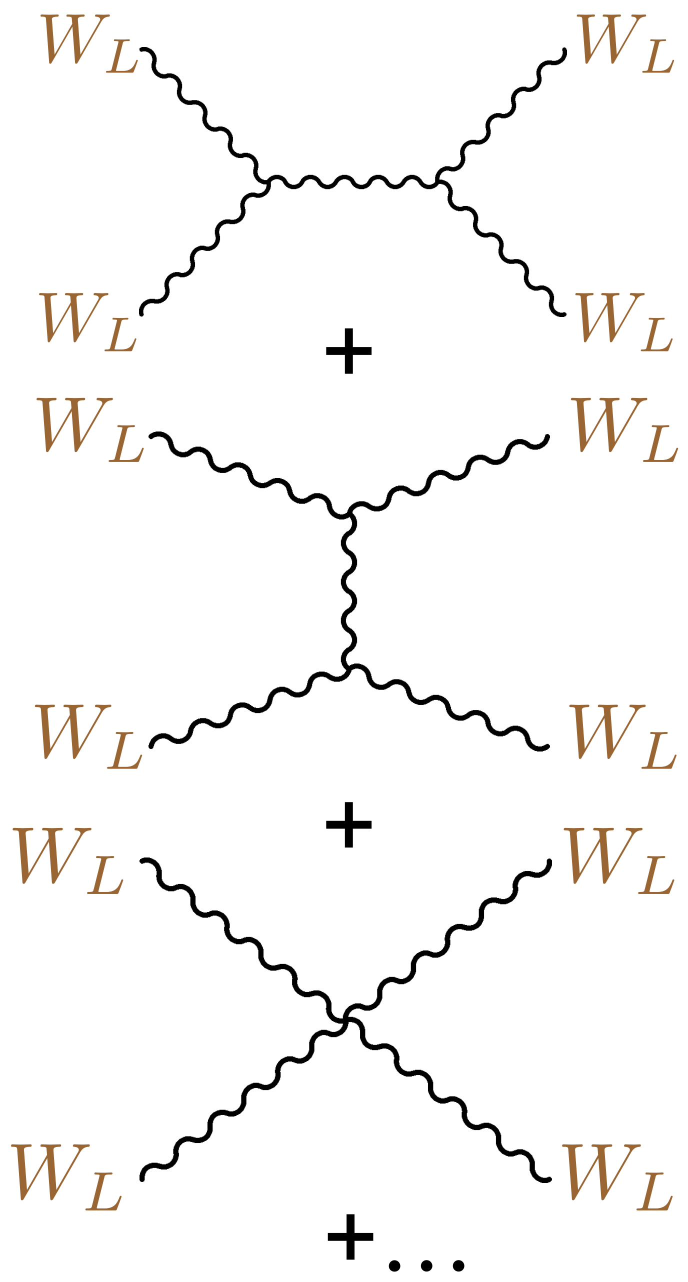
- b, c jet-tagging, b-flavour tagging
- K/π separation over wide range
- π^0 ($\Delta E/E < 5\%/\sqrt{E}$), K_S^0 reconstruction

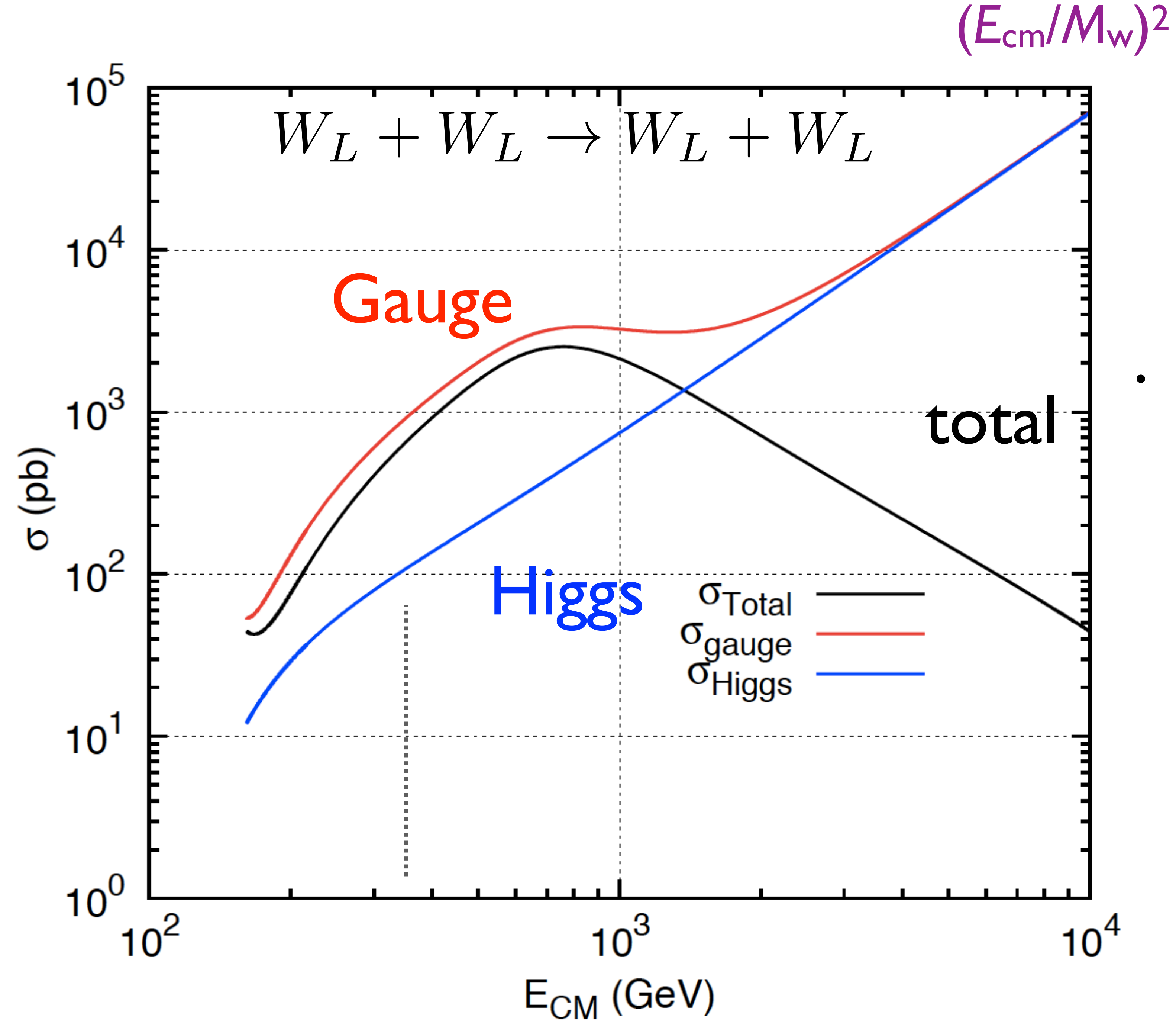
Unitarity and the Higgs Boson

see presentation by Isaac Ehel

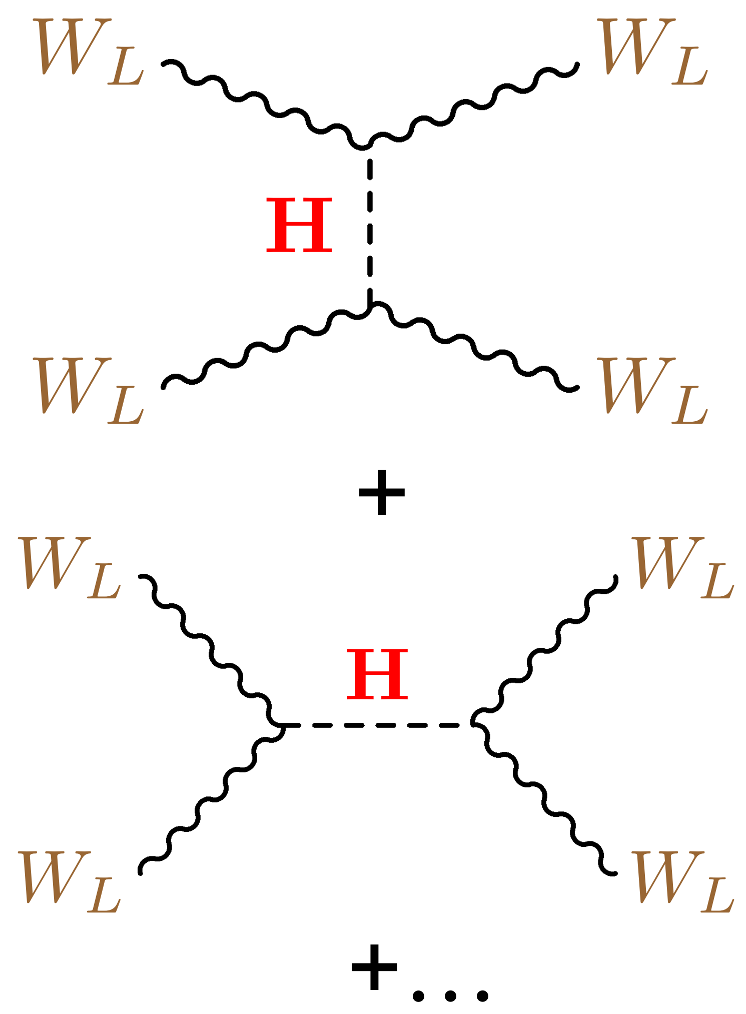
In the SM, the Higgs boson “unitarises” the longitudinal W scattering amplitudes

Gauge





Higgs



With the Higgs: **exact** cancellation of the **unitarity-violating** E^2 dependance of the scattering cross section at high energy

Elucidation of the EWSB sector

- probe SM in regime where the EW symmetry is restored ($\sqrt{s} \gg v = 246$ GeV) by studying longitudinal gauge boson scattering in the 1-5 TeV energy range

Crucial closure test of the SM

- either the Higgs regularises the theory fully
- or New Physics shows up a the TeV scale
  - anomalous TGCs and QGCs
  - new Higgs or gauge particles

FCC-hh

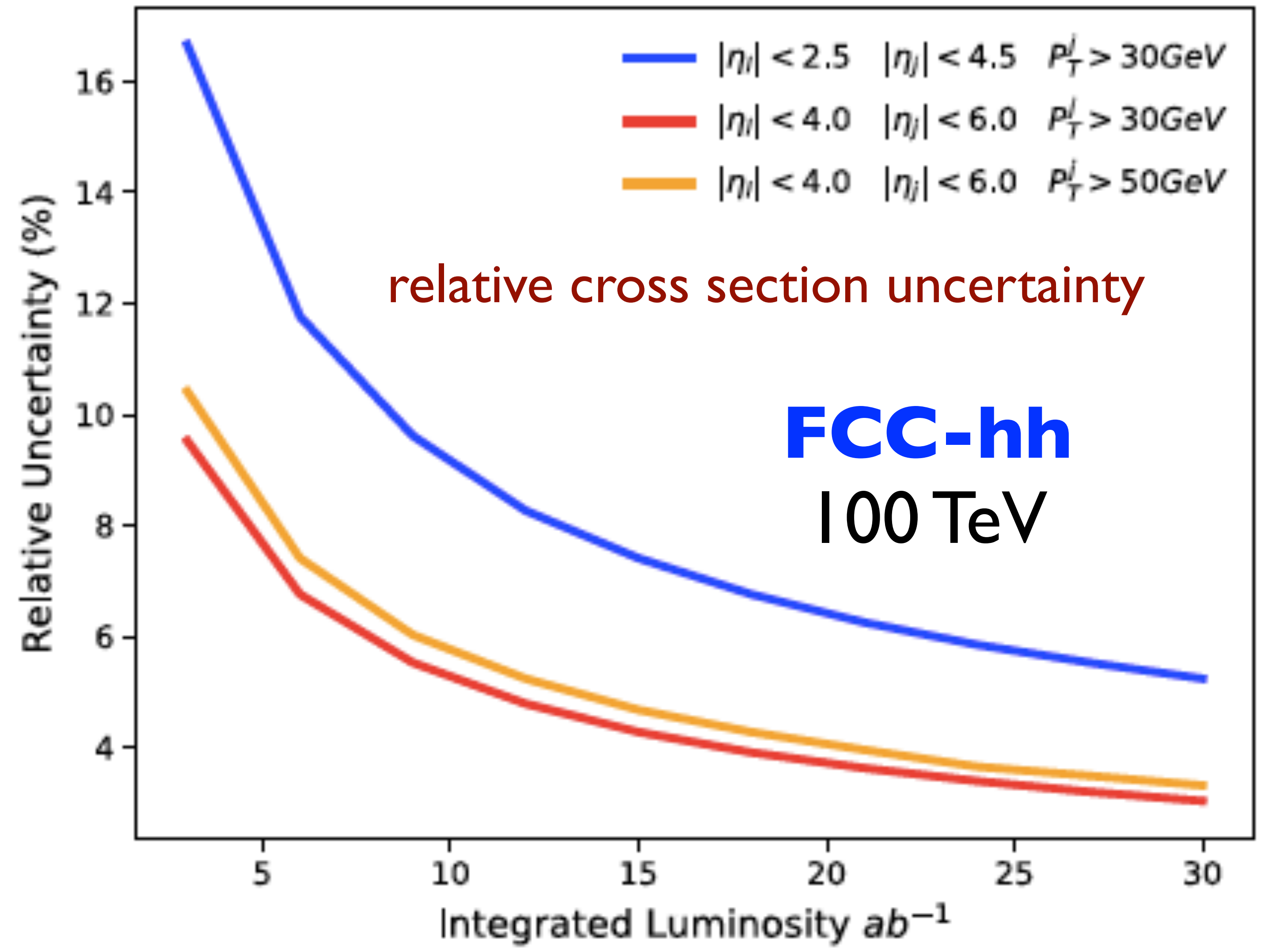
see presentation by Isaac Ehel

Scattering of longitudinal vector bosons (VBS)

- sensitive to the relation between gauge couplings and the VVH coupling
- large QCD and EWK backgrounds
- two jets at large backward and forward rapidities
- azimuthal correlations between the two leptons

A precise measurement necessitates
leptons down to |η| = 4 and
jets down to |η| = 6
in conditions of 1000 pile-up events!

VBS $W_L W_L$ same sign



relative cross section uncertainty

FCC-hh
100 TeV

Measurements of longitudinal-VBS processes are essential to studying the BEH-Mechanism, and a prime place to determine precise Higgs couplings at high energies

Longitudinally-polarised ZZ scattering

see presentation by Isaac Ehel

Feasibility study

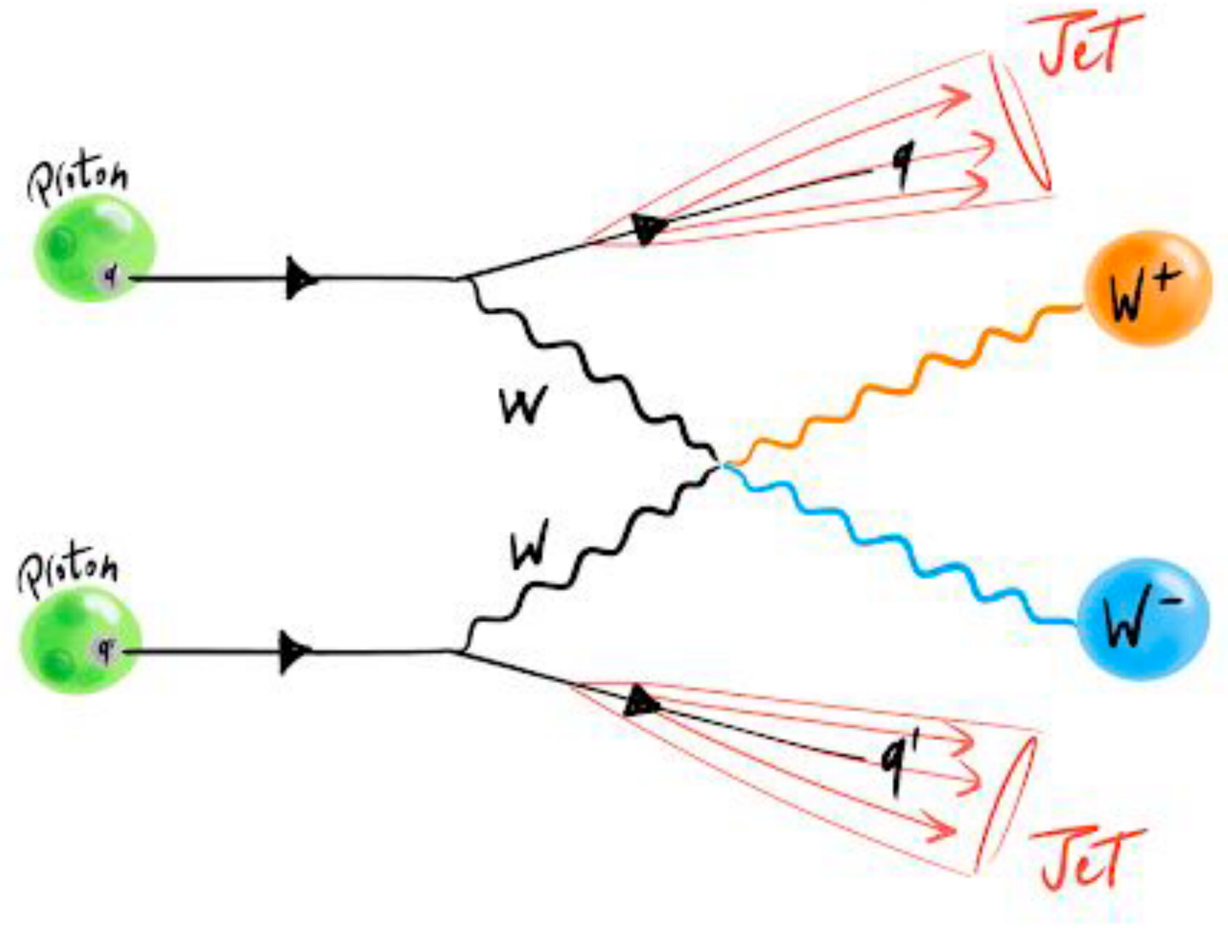
Using MadGraph5_aMC@NLO

Unpolarised cross sections pp→ VVqq → 4ℓqq

fb	14 TeV	27 TeV	ratio	100 TeV	ratio
$W^+W^+ + W^-W^-$	39.9	127.0	3.2	818.0	20.5
$W^+Z + W^-Z$	8.1	26.6	3.2	177.6	22.5
ZZ	**0.7**	**2.2**	**3.4**	**15.6**	**24.0**

Polarised cross sections pp→ VVqq → 4ℓqq

fb	14 TeV	27 TeV	ratio	100 TeV	ratio
$W^+W^+ + W^-W^-$	1.3	4.2	3.0	19.4	14.9
$W^+Z + W^-Z$	0.4	1.4	3.2	8.7	22.5
ZZ	**0.04**	**0.13**	**3.4**	**0.86**	**22.6**



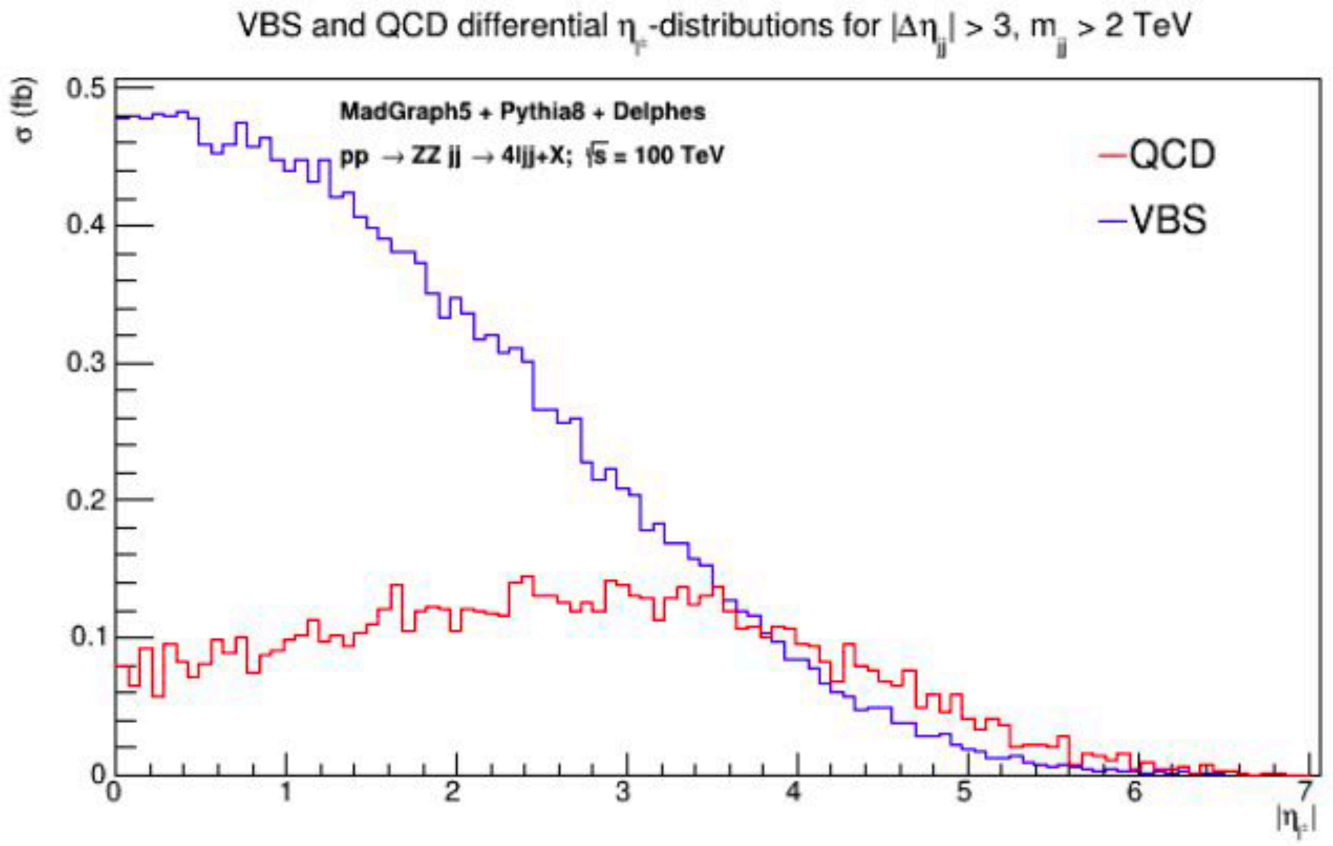
Longitudinally polarised VBS cross sections: consistent gain of 3 (20) across all channels for 27 (100) TeV center of mass energy.

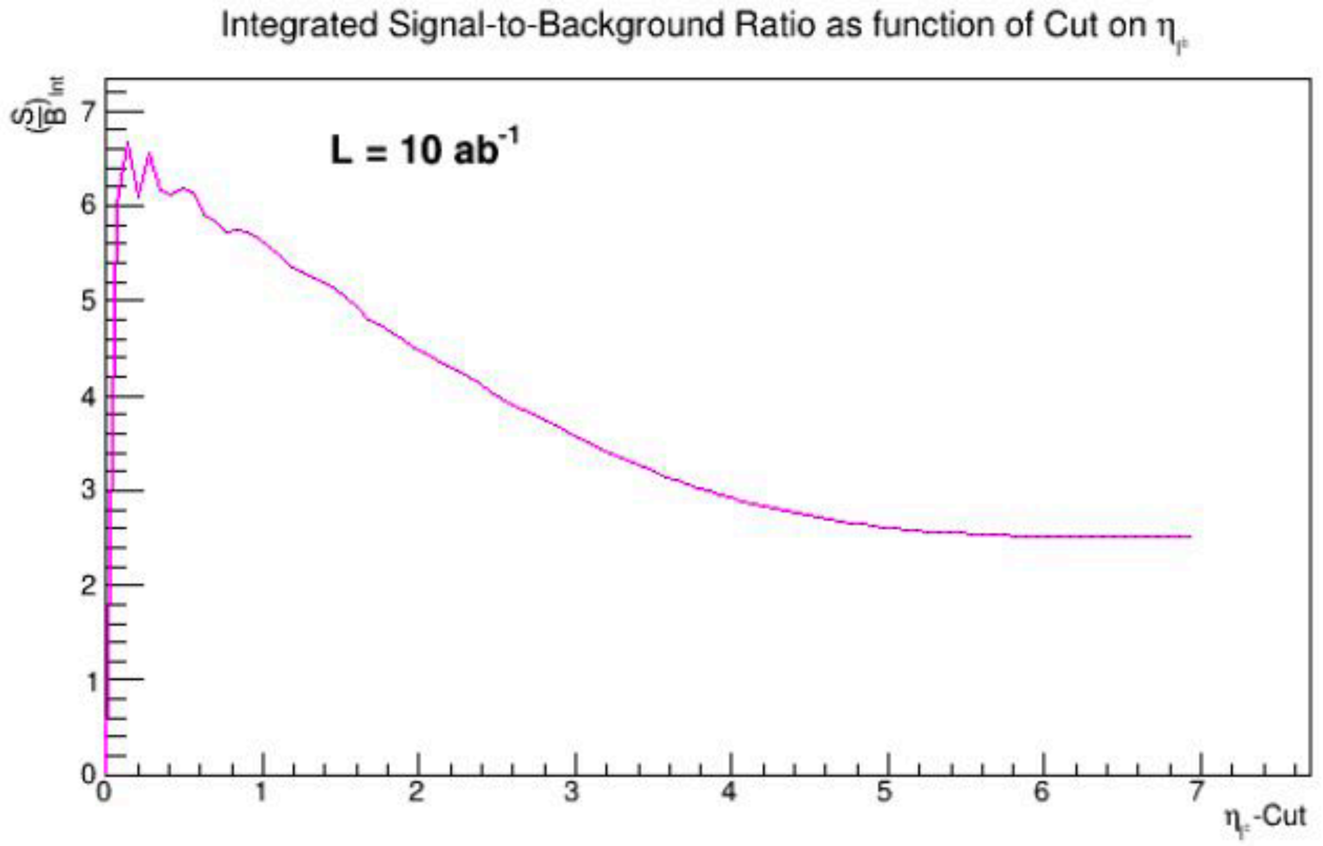
Longitudinally-polarised ZZ scattering

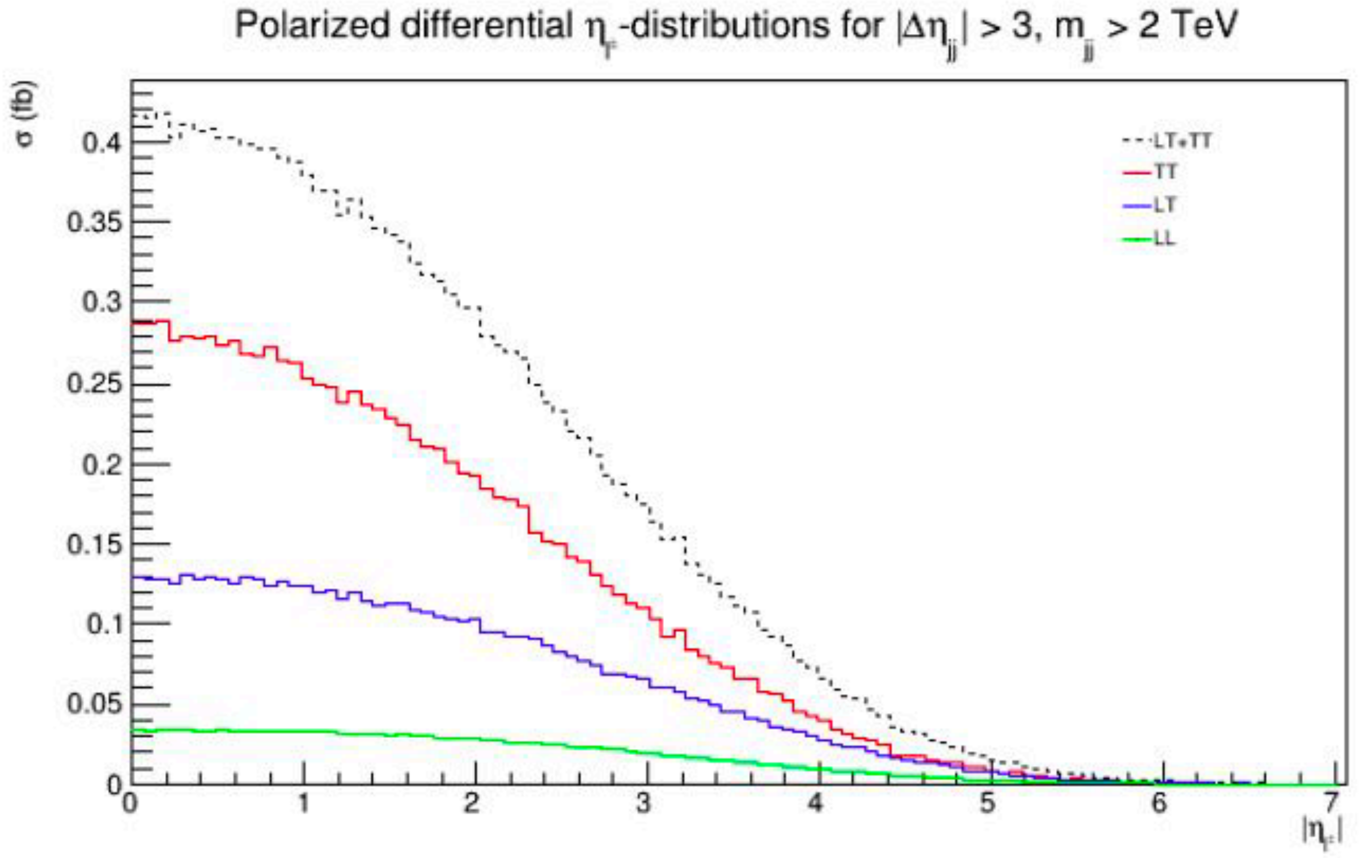
see presentation by Isaac Ehel

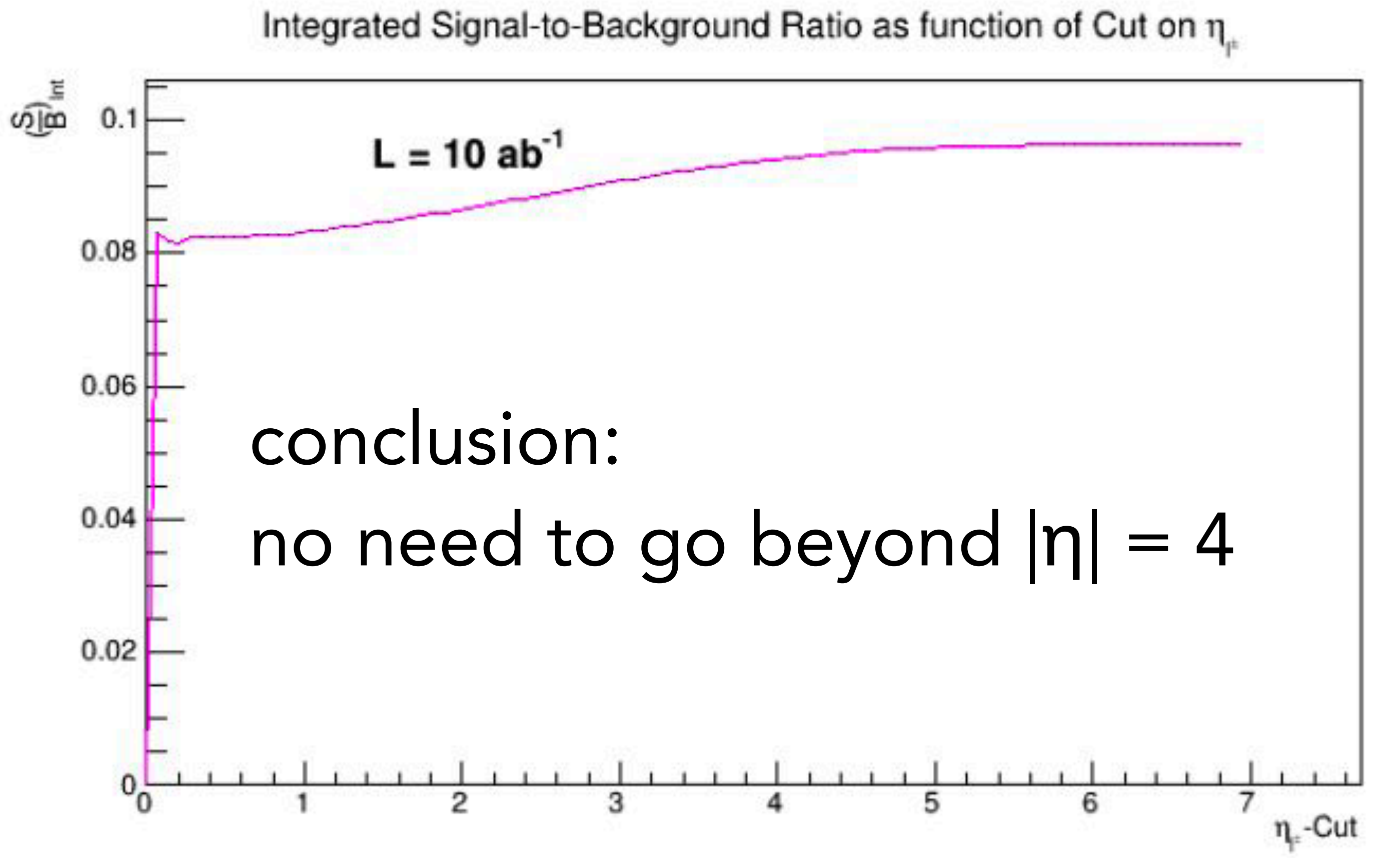
Feasibility study

Using Delphes simulation


VBS and QCD differential η_l-distributions for $|\Delta\eta_{jj}| > 3$, $m_{jj} > 2$ TeV


Integrated Signal-to-Background Ratio as function of Cut on η_l


Polarized differential η_l-distributions for $|\Delta\eta_{jj}| > 3$, $m_{jj} > 2$ TeV


Integrated Signal-to-Background Ratio as function of Cut on η_l

conclusion:
no need to go beyond |η| = 4

max pseudo rapidity of leptons →

Backgrounds: QCD-induced processes
Optimisation: 2 TeV cut on dijet mass and 3 on jet rapidity separation

Very promising study that demonstrates possibility of

- separation of VBS and QCD events
- separation of polarisation states in ZZ scattering

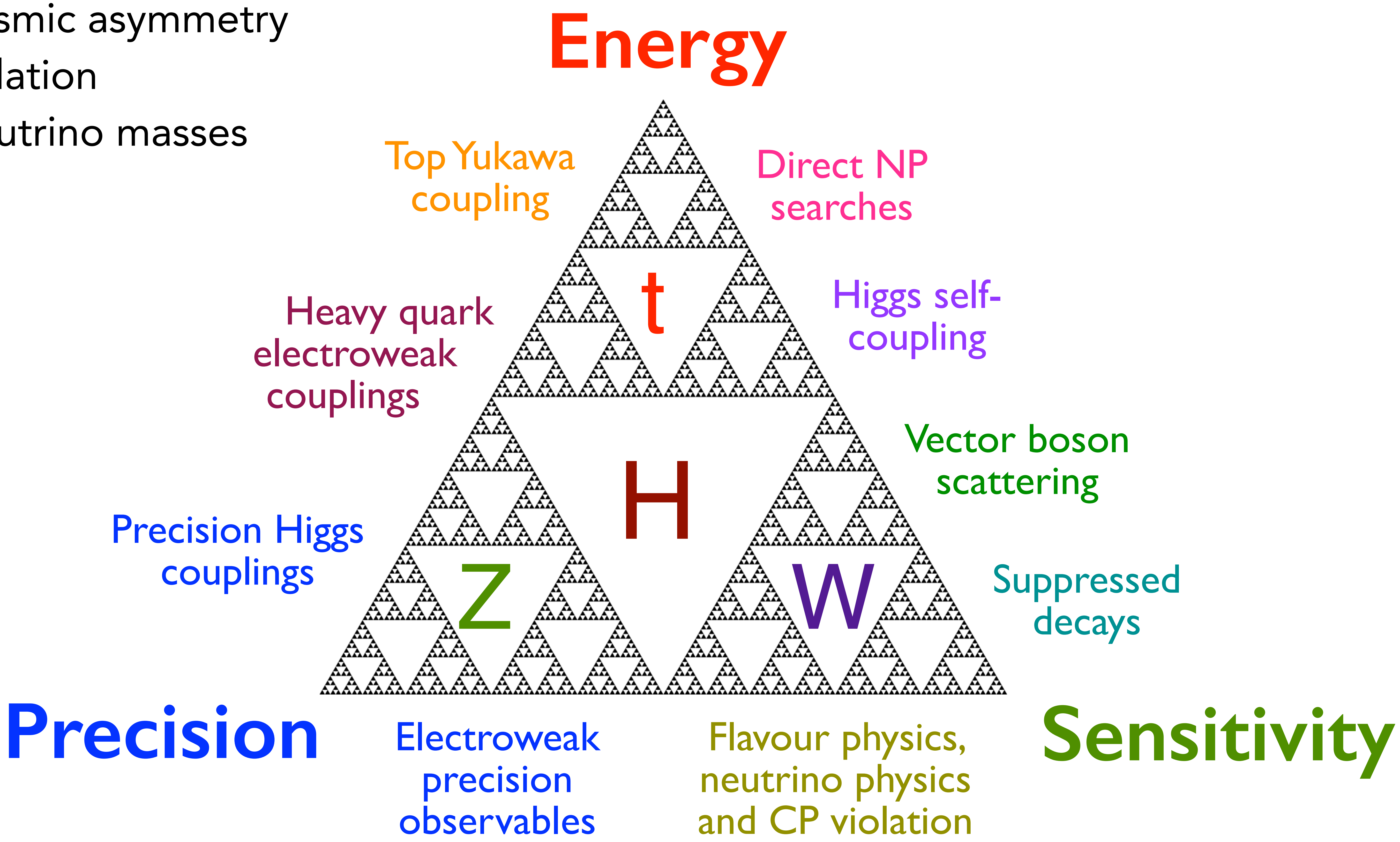
En guise de conclusion

Known departures from SM
- dark matter / energy
- cosmic asymmetry
- inflation
- neutrino masses

Where is New Physics?
- within LHC reach but elusive?
- beyond LHC energy reach?

…there is no experiment/facility, proposed or conceivable (…) which can guarantee discoveries beyond the SM, and answers to the big questions of the field

M. Mangano



FCC programme after HL-LHC

FCC-ee is
- the **unique opportunity** to study *with the highest possible precision* the **four most massive elementary particles**, W, Z, H and t, four pillars of the SM which are at the **heart of the electroweak symmetry breaking mechanism**
- a **necessary and indispensable step** towards the highest energies in proton-proton collisions: **FCC-hh**

Thank you to the EWK/flavour speakers in physics parallel sessions

- great talks!
- all errors in this summary talk are mine

Thank you to the organisers and all the participants for this nice workshop!

Future e^+e^- Colliders: Pros & Cons

	Circular Colliders (FCC-ee)		Linear Colliders (ILC)	
	pros	cons	pros	cons
$\sqrt{s}$		• **limited by synchrotron radiation** (SR), which increases as E^4_{beam}/R • 100 km → 365 GeV max	• **extendable in energy** • large potential $\sqrt{s}$ reach 250→500→1000 GeV (access to ttH, ZHH, Hee)	• running at $\sqrt{s}$ smaller than 250 GeV would require optimisation
beam-strahlung		• **strong**: affects beam lifetime (typically 30 min.) • **top-up injection** needed to compensate for fast $\mathscr{L}$ burn-off		• **strong** due to beam size at interaction point (IP) • increasing with energy
energy spread	• **small energy spread** (<0.1% at 240 GeV) • with top-up injection: **mean $\mathscr{L}$ = 95% of peak**			• **larger energy spread** (86% within 1% of nominal at 250 GeV)
lumi	• **high-lumi** obtained with **large number of bunches** • **increasing at lower $\sqrt{s}$** due to less SR (spare RF used to accelerate more bunches) • **crab waist** scheme • **several interaction regions** possible	• **limited by SR power** at higher energies	• **high-lumi** obtained with **nanometer-size beams** • **increasing naturally with energy** thanks to beam dynamics at IP • **luminosity upgrade** (1312 → 2625 bunches)	• **low repetition rate** • **only one interaction region** (ILD and SLD detectors in push-pull)
L-polar		• **no L-polarisation**, except perhaps at Z peak	• **e^- beam: ±80%** • **e^+ beam: ±30% (±60%)**	
misc	• precise E_{beam} from **resonant depolarisation** (Z peak and WW threshold)		• nm-beams at IP allow for **very small beam pipe** (superior for b/c tagging)	

Detector Concepts

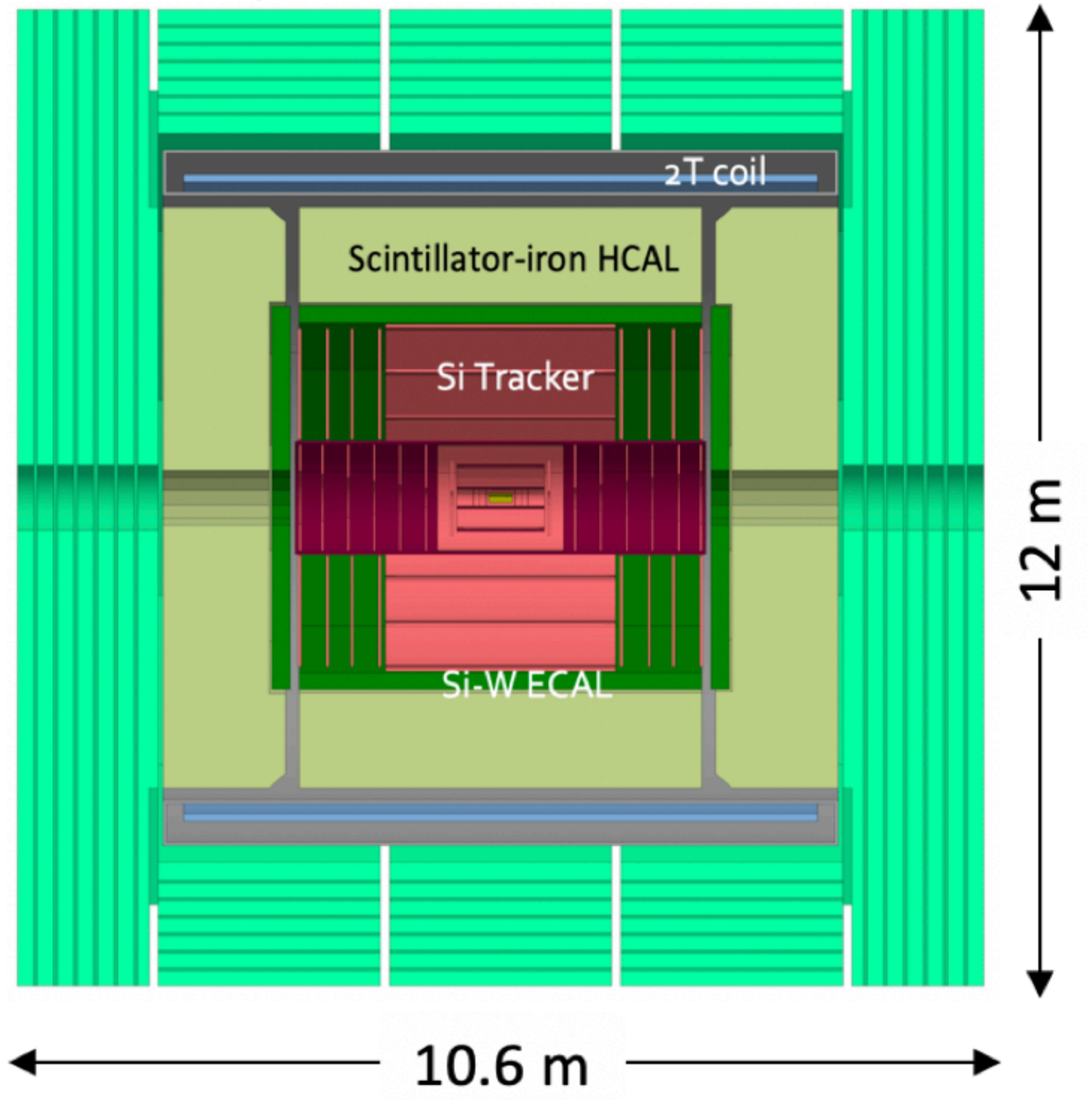
see presentation by Didier Contardo

FCC-ee detector concepts
- CLD: inspired from CLIC detector
- IDEA: from present state-of-the-art

2 or 4 IPs?

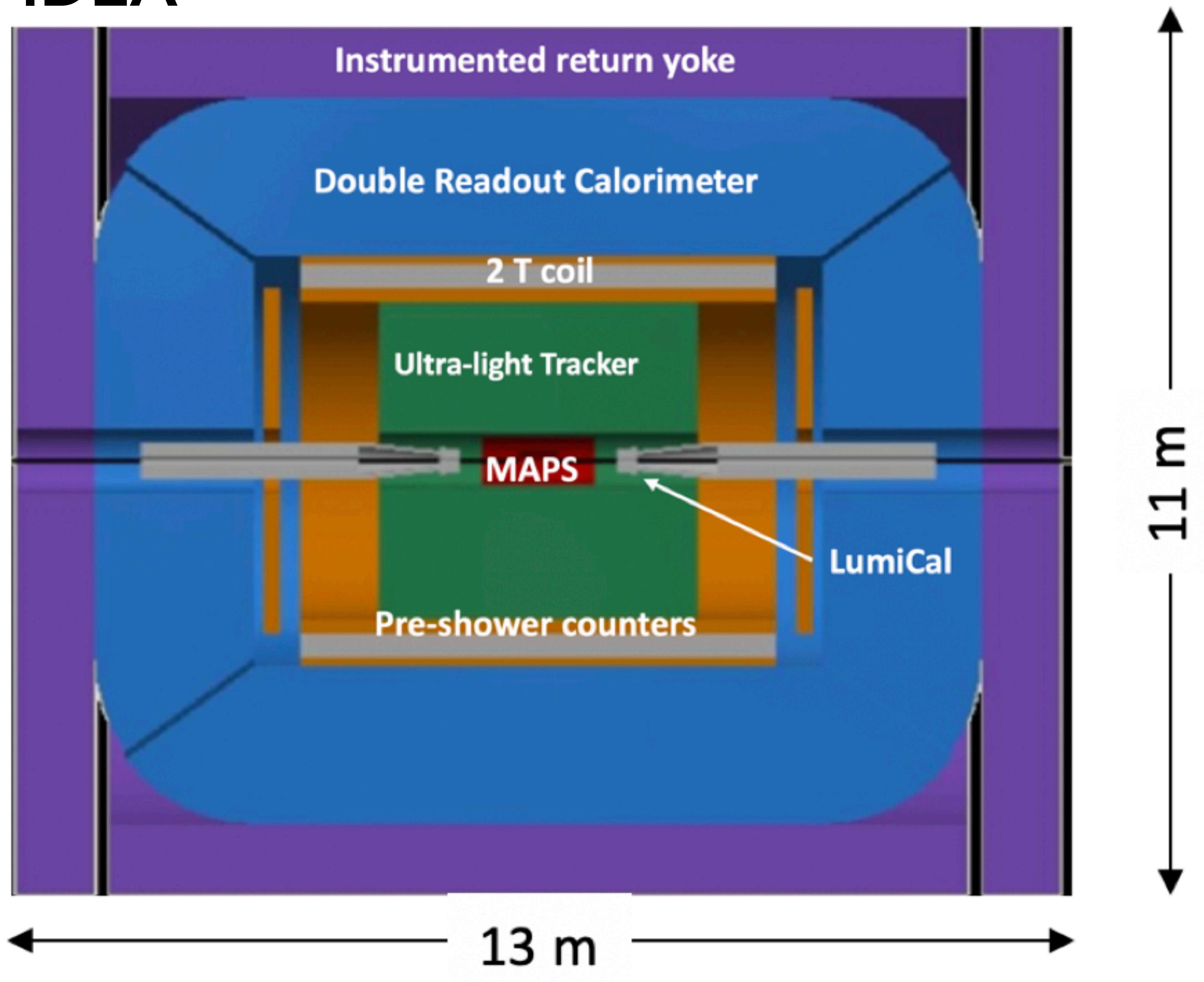
other concepts under study, *e.g.*

CLD (inspired from CLIC detector)



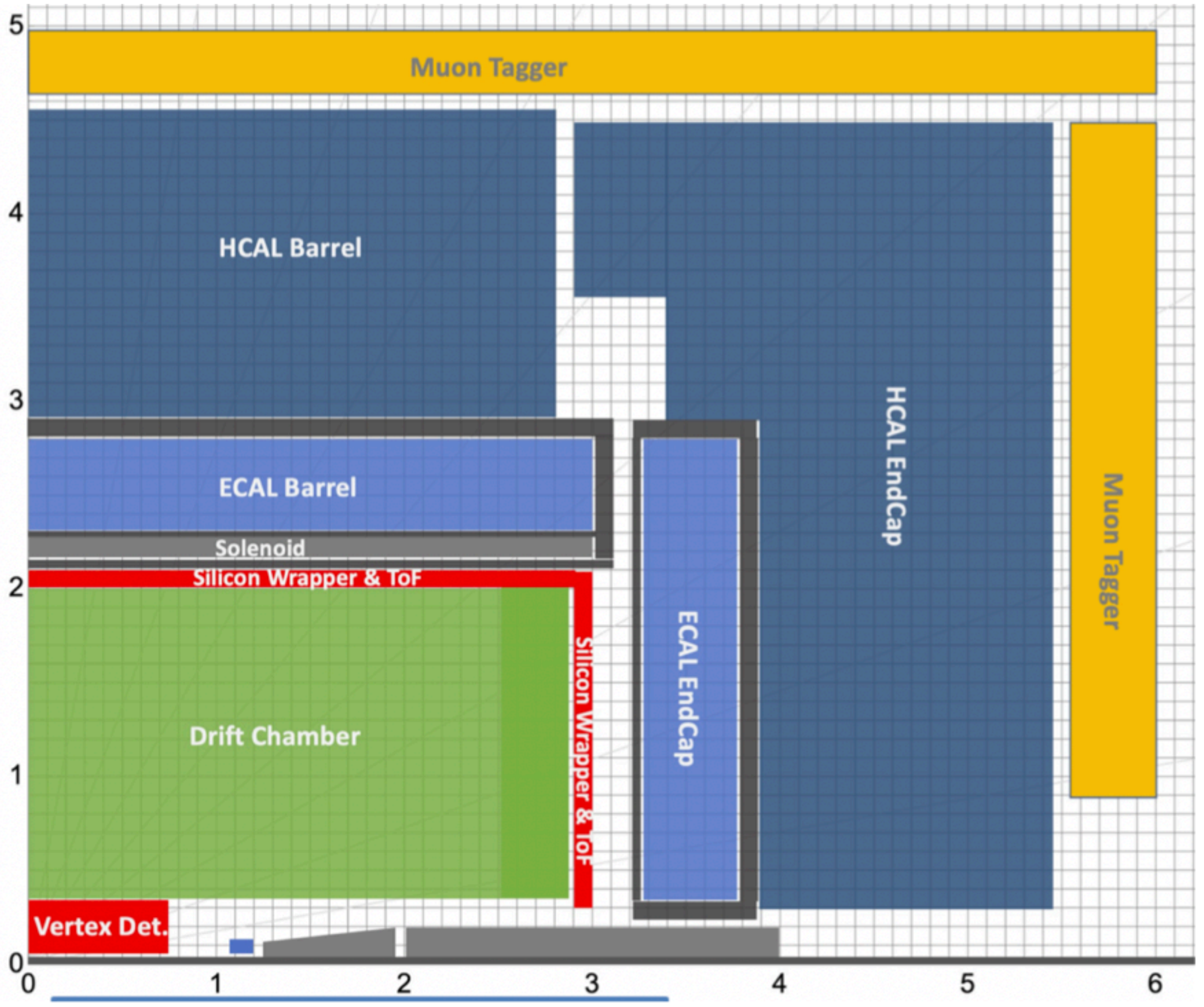
- All silicon tracker
- PID with compact RICH/SiPMs?
- CALICE-like calo (W/Si, W/scint+SiPMs)
- coil outside calorimeters

IDEA



- MAPs + extremely transparent drift chamber
- PID exploiting cluster counting
- timing layer + crystals + dual readout?
- coil between ECAL and HCAL?

Noble Liquid ECAL



- Vertex detector + drift chamber
- PID with TOF
- Fined-grained LAr/Pb
- coil inside calorimeters

excellent momentum resolution

high hermiticity

high granularity

high separation power

dedicated PID?

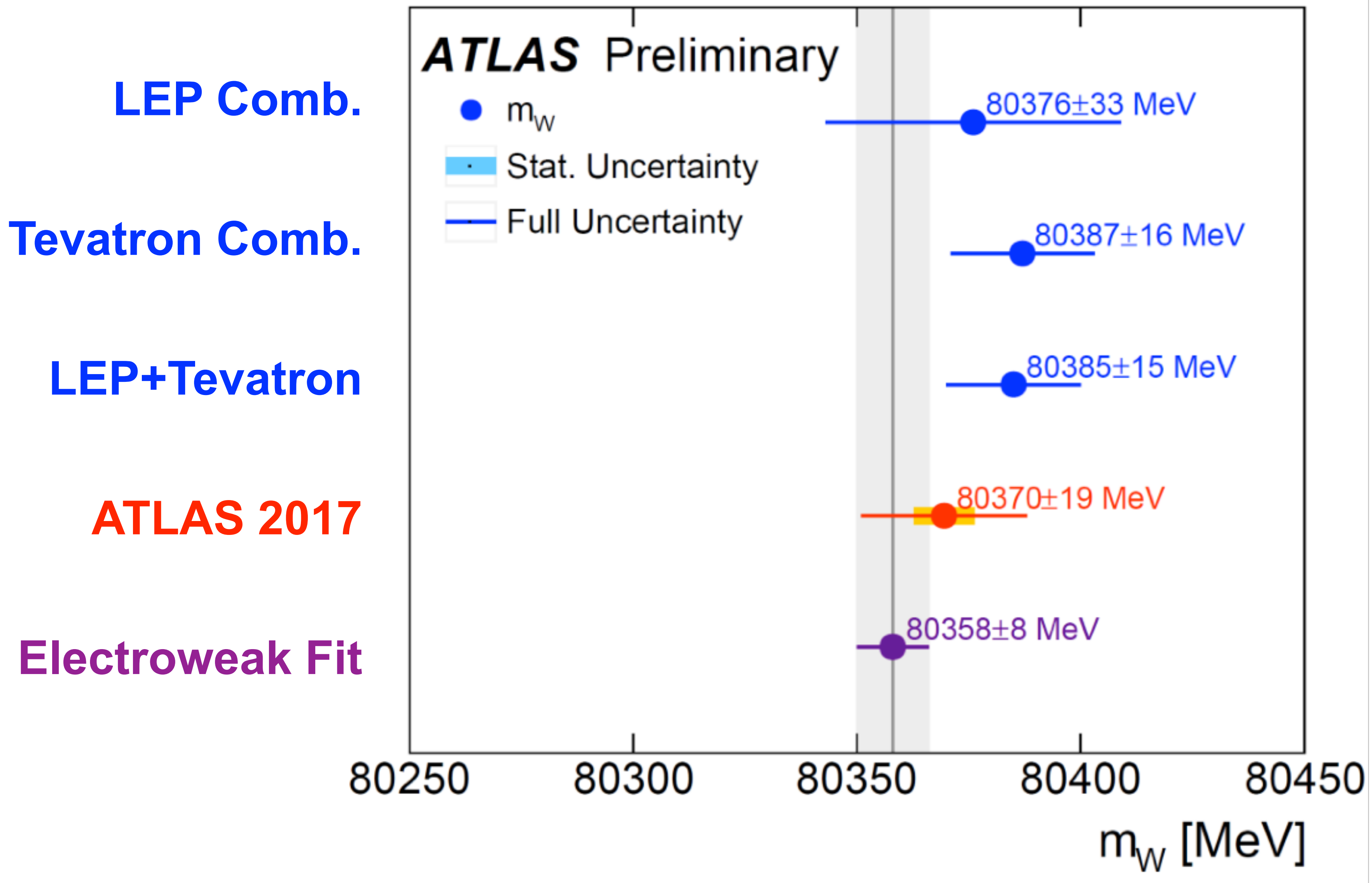
EM energy resolution?

Luminosity → B field limited to 2T

M_W : Parametric Errors

Experimental

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



Electroweak Fit

$M_\mathrm{W} = 80.3584 \text{ GeV} \qquad \pm\ 8.0 \text{ MeV}$ ●

$\pm\, (\delta M_\mathrm{W})_\mathrm{th} \qquad 4.0 \text{ MeV}$ ●

$\pm\, (\delta M_\mathrm{W})_\mathrm{top} \qquad (\delta M_\mathrm{top}/0.76 \text{ GeV}) \times 5.5 \text{ MeV}$ ●

$\pm\, (\delta M_\mathrm{W})_\mathrm{H} \qquad (\delta M_\mathrm{H}/0.24 \text{ GeV}) \times 0.1 \text{ MeV}$ ●

$\pm\, (\delta M_\mathrm{W})_\mathrm{Z} \qquad (\delta M_\mathrm{Z}/2.1 \text{ MeV}) \times 2.5 \text{ MeV}$ ●

$\pm\, (\delta M_\mathrm{W})_\alpha \qquad (\delta\alpha/10^{-4}) \times 1.8 \text{ MeV}$ ●

$\pm\, (\delta M_\mathrm{W})_{\alpha_s} \qquad (\delta\alpha_s/3{\times}10^{-3}) \times 2.0 \text{ MeV}$ ●

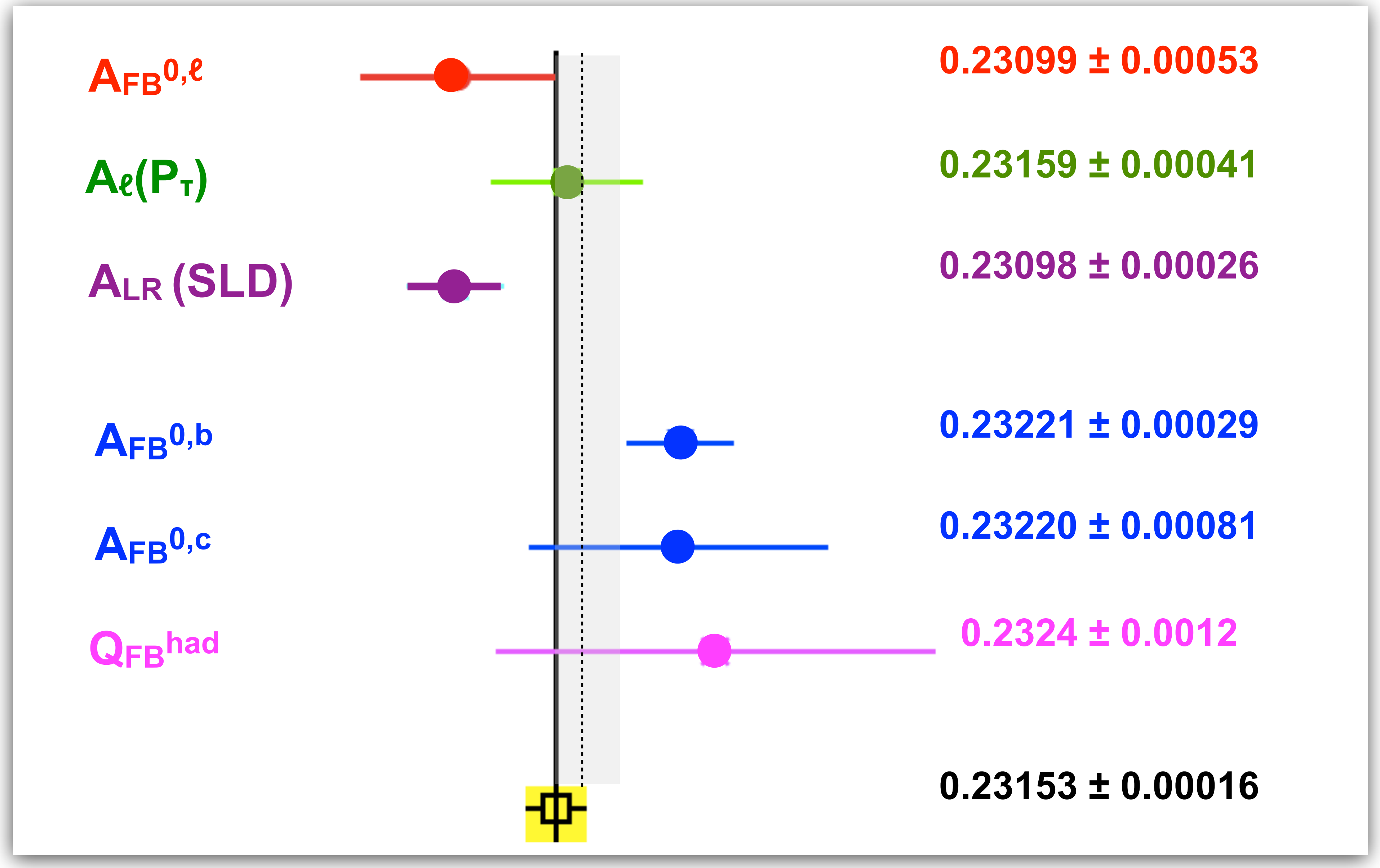
Main parametric errors:

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

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

Experimental

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



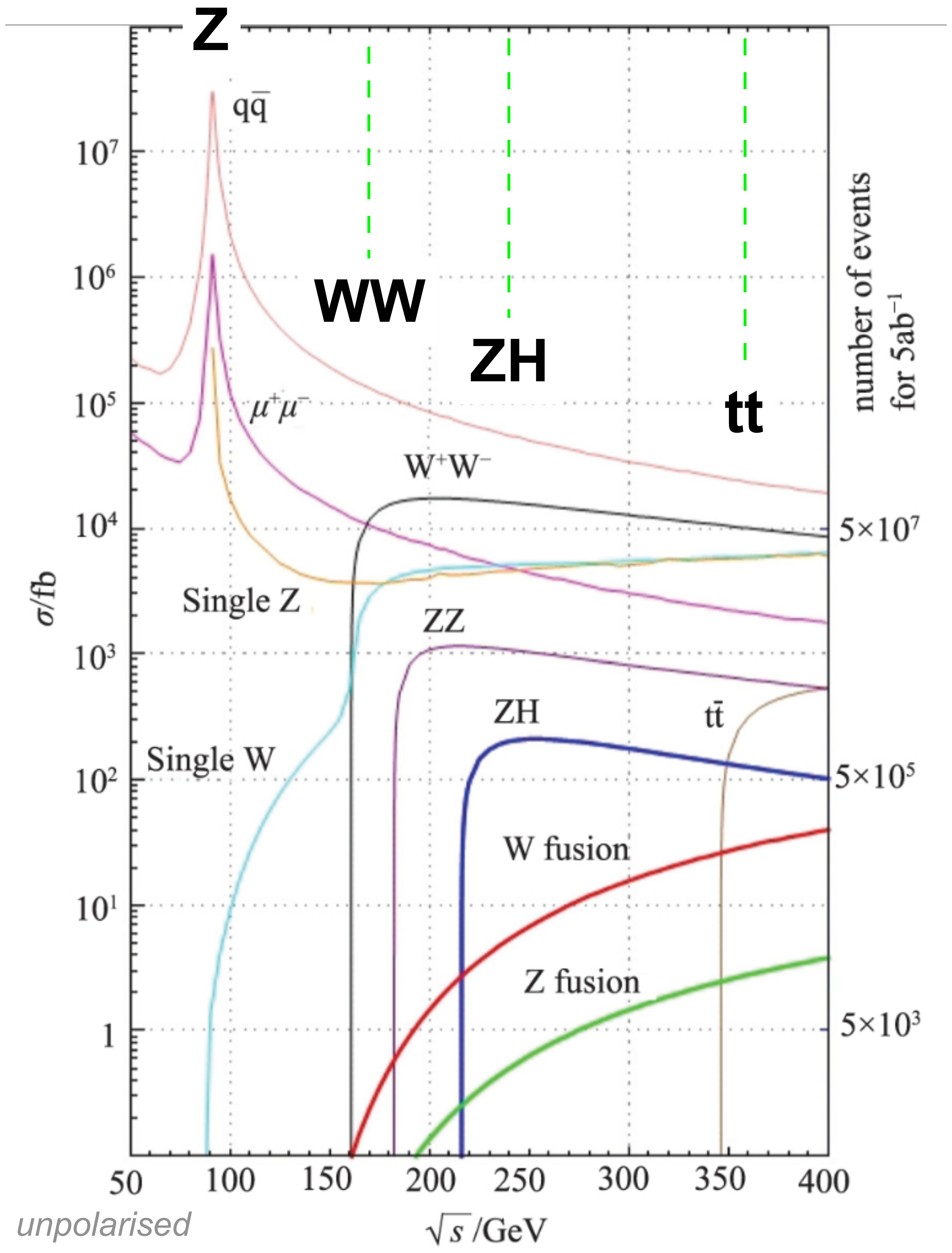
Electroweak Fit

$$\begin{aligned}
\sin^2\theta^{\ell}_{\rm eff} = \;& 0.231488 && \pm\, 7.0\times10^{-5} && \bullet \\
& \pm(\delta\sin^2\theta^{\rm eff}_{\rm W})_{\rm th} && 4.7\times10^{-5} && \bullet \\
& \pm(\delta\sin^2\theta^{\rm eff}_{\rm W})_{\rm top} && (\delta M_{\rm top}/0.76\ {\rm GeV})\times 2.9\times10^{-5} && \bullet \\
& \pm(\delta\sin^2\theta^{\rm eff}_{\rm W})_{\rm H} && (\delta M_{\rm H}/0.24\ {\rm GeV})\times 0.1\times10^{-5} && \bullet \\
& \pm(\delta\sin^2\theta^{\rm eff}_{\rm W})_{\rm Z} && (\delta M_{\rm Z}/2.1\ {\rm MeV})\times 1.5\times10^{-5} && \bullet \\
& \pm(\delta\sin^2\theta^{\rm eff}_{\rm W})_{\alpha} && (\delta\alpha/10^{-4})\times 3.5\times10^{-5} && \bullet \\
& \pm(\delta\sin^2\theta^{\rm eff}_{\rm W})_{\alpha_s} && (\delta\alpha_s/3\times10^{-3})\times 1.0\times10^{-5} && \bullet
\end{aligned}$$

Main parametric errors:

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

Cross Sections in e^+e^-



unpolarised

At Z pole		
• $e^+e^- \to Z$	**30 nb**	
At WW threshold		
• $e^+e^- \to W^+W^-$	**0-12 pb**	
At $\sqrt{s}$ = 250 GeV		
• $e^+e^- \to ZH$	**200 fb**	*(Higsstrahlung)*
• $e^+e^- \to H\nu\nu$	**8 fb**	*(W fusion)*
Cross sections decreasing as 1/s:		
• $e^+e^- \to qq(\gamma)$	**60 pb**	*(incl. Z return)*
• $e^+e^- \to W^+W^-$	**16 pb**	
• $e^+e^- \to ZZ$	**1 pb**	
Slowly increasing cross sections:		
• $\gamma\gamma \to qq, \ell\ell$	**30 pb**	*(m > 30 GeV)*
• $e\gamma \to Ze$	**3.8 pb**	
• $e\gamma \to W\nu$	**1.5 pb**	*(WWγ)*
• $ee \to Z\nu\nu$	**32 fb**	*(WWZ)*
At $\sqrt{s}$ = 380 GeV		
• $e^+e^- \to tt$	**500 fb**	
• $e^+e^- \to ZH$	**100 fb**	
• $e^+e^- \to H\nu\nu$	**40 fb**	

Physics at e^+e^- Colliders

$\sqrt{s}$	Processes	Physics Goals	Observables
91 GeV	• $e^+e^- \to Z$	ultra-precision EW physics	$\sin^2\theta_{eff}$ M_Z, Γ_Z, N_ν α, α_S
125 GeV	• $e^+e^- \to H$	*limit on s-channel H production?*	y_e
160 GeV	• $e^+e^- \to W^+W^-$	ultra-precision W mass	M_W, Γ_W
>160 GeV	• $e^+e^- \to W^+W^-$ • $e^+e^- \to qq, \ell\ell\ (\gamma)$	precision W mass and couplings precision EW (incl. Z return)	M_W, aTGC N_ν
250 GeV	• $e^+e^- \to ZH$	ultra-precision Higgs mass precision Higgs couplings	M_H κ_V, κ_f, Γ_H
360 GeV	• $e^+e^- \to tt$	ultra-precision top mass	M_{top}
>360 GeV	• $e^+e^- \to tt$ • $e^+e^- \to ZH$ • $e^+e^- \to H\nu\nu$	precision top couplings precision Higgs couplings	
500+ GeV	• $e^+e^- \to ttH$ • $e^+e^- \to ZHH$ • $e^+e^- \to Z' \to ff$ • $e^+e^- \to XX$ • $e^+e^- \to AH, H^+H^-$	Higgs coupling to top Higgs self-coupling search for heavy Z' bosons search for supersymmetry (SUSY) search for new Higgs bosons	y_{top} λ_{HHH}