EWK Needs and Priorities

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thanks to many people for useful discussions

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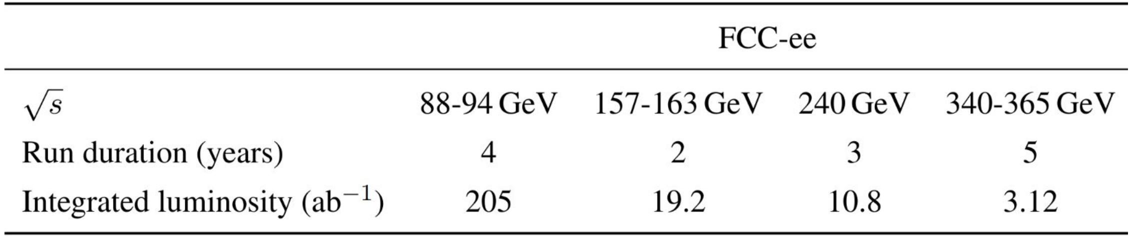
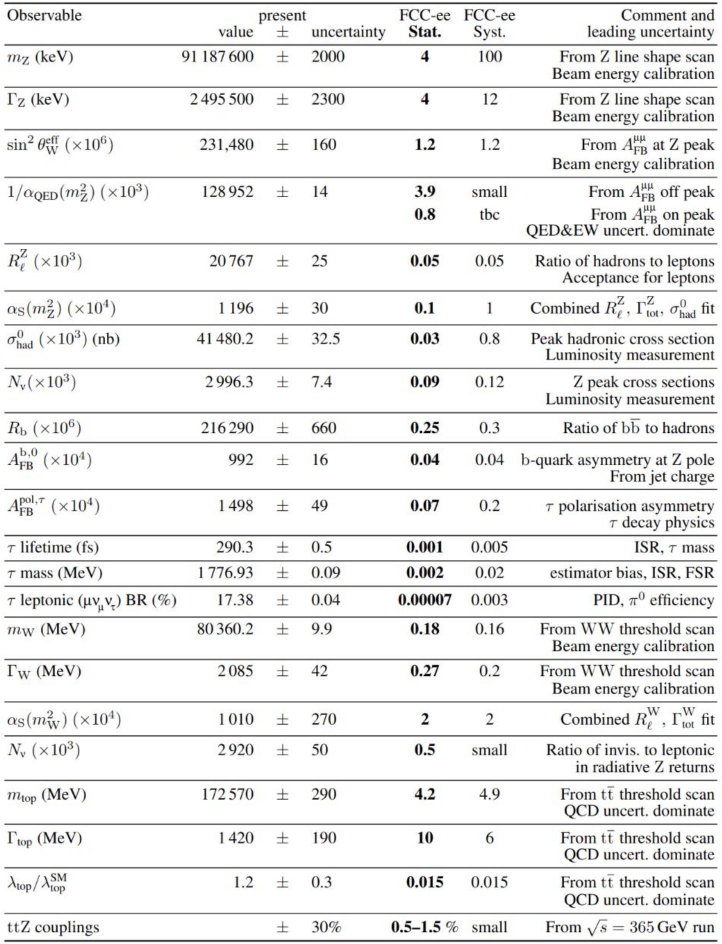
FCC Week 2025, Vienna, Austria

Introduction

- Tera-Z program provides up to 2 orders of magnitude improvement in measurements at the Z pole
- Statistical uncertainties will be tiny
- Self-calibrating measurements and in-situ calibration procedures are essential to control experimental systematics
- Significant theoretical challenges in some places



	FCC-ee			
$\sqrt{s}$	88-94 GeV	157-163 GeV	240 GeV	340-365 GeV
Run duration (years)	4	2	3	5
Integrated luminosity (ab^{-1})	205	19.2	10.8	3.12



Observable		present		FCC-ee	FCC-ee	Comment and
	value	±	uncertainty	**Stat.**	Syst.	leading uncertainty
m_Z (keV)	91 187 600	±	2000	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2 495 500	±	2300	**4**	12	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{\mathrm{eff}}$ ($\times 10^6$)	231,480	±	160	**1.2**	1.2	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)$ ($\times 10^3$)	128 952	±	14	**3.9** **0.8**	small tbc	From $A_{FB}^{\mu\mu}$ off peak From $A_{FB}^{\mu\mu}$ on peak QED&EW uncert. dominate
R_ℓ^Z ($\times 10^3$)	20 767	±	25	**0.05**	0.05	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_S(m_Z^2)$ ($\times 10^4$)	1 196	±	30	**0.1**	1	Combined R_ℓ^Z, Γ_{tot}^Z, σ_{had}^0 fit
σ_{had}^0 ($\times 10^3$) (nb)	41 480.2	±	32.5	**0.03**	0.8	Peak hadronic cross section Luminosity measurement
N_ν($\times 10^3$)	2 996.3	±	7.4	**0.09**	0.12	Z peak cross sections Luminosity measurement
R_b ($\times 10^6$)	216 290	±	660	**0.25**	0.3	Ratio of $b\bar{b}$ to hadrons
$A_{FB}^{b,0}$ ($\times 10^4$)	992	±	16	**0.04**	0.04	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{\mathrm{pol},\tau}$ ($\times 10^4$)	1 498	±	49	**0.07**	0.2	τ polarisation asymmetry τ decay physics
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.005	ISR, τ mass
τ mass (MeV)	1 776.93	±	0.09	**0.002**	0.02	estimator bias, ISR, FSR
τ leptonic ($\mu\nu_\mu\nu_\tau$) BR (%)	17.38	±	0.04	**0.00007**	0.003	PID, π^0 efficiency
m_W (MeV)	80 360.2	±	9.9	**0.18**	0.16	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2 085	±	42	**0.27**	0.2	From WW threshold scan Beam energy calibration
$\alpha_S(m_W^2)$ ($\times 10^4$)	1 010	±	270	**2**	2	Combined R_ℓ^W, Γ_{tot}^W fit
N_ν ($\times 10^3$)	2 920	±	50	**0.5**	small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	172 570	±	290	**4.2**	4.9	From $t\bar{t}$ threshold scan QCD uncert. dominate
Γ_{top} (MeV)	1 420	±	190	**10**	6	From $t\bar{t}$ threshold scan QCD uncert. dominate
$\lambda_{\mathrm{top}}/\lambda_{\mathrm{top}}^{\mathrm{SM}}$	1.2	±	0.3	**0.015**	0.015	From $t\bar{t}$ threshold scan QCD uncert. dominate
ttZ couplings		±	30%	**0.5–1.5 %**	small	From $\sqrt{s} = 365$ GeV run

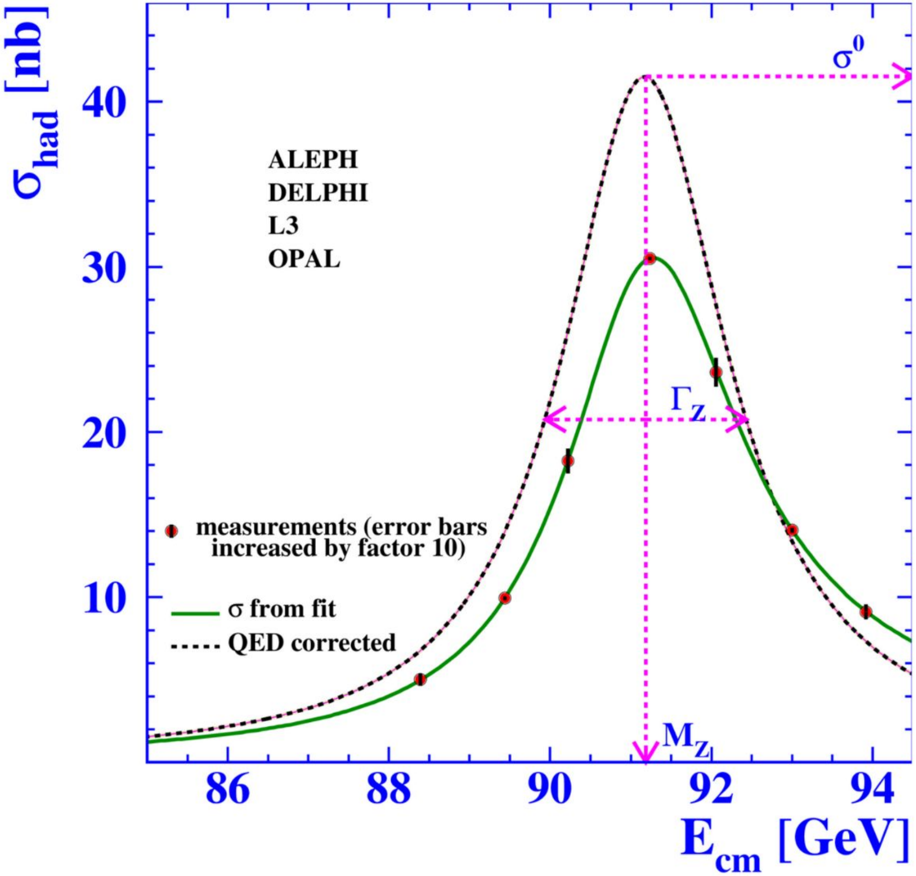
2505.00272 (FSR Volume 1)

Introduction

- This talk is NOT an exhaustive summary of the physics studies done so far
- Rather highlighting some general directions of work towards the pre-TDR phase, with some specific examples
- In general:
  - Targeted full-simulation studies for object performance, calibration workflows, more realistic systematic uncertainty models for the measurements
  - Try to optimize detector designs for small systematic uncertainty (not always the same as best efficiency, resolution, etc)
  - Identify possible systematic issues as early as possible which could be mitigated at the detector design level

Z-pole scan

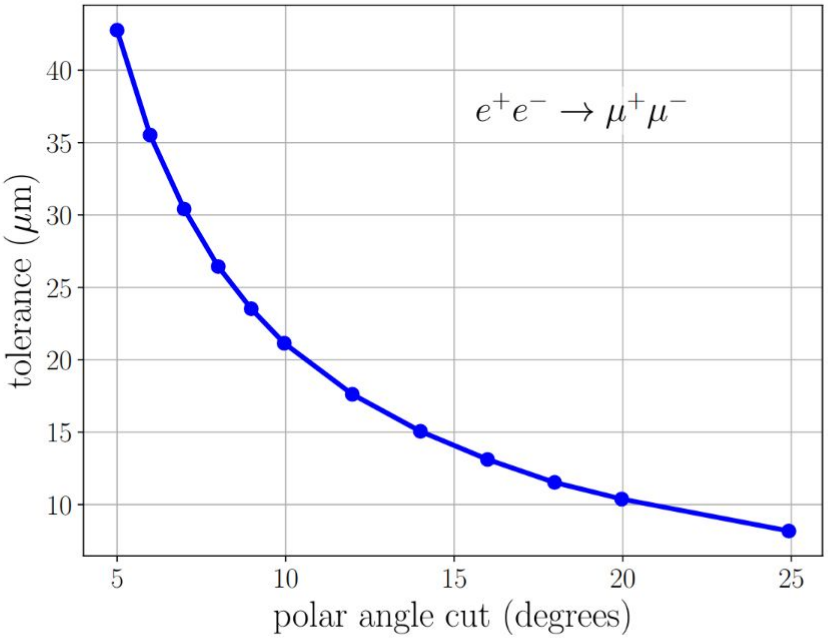
- Z mass and width determined from measured cross section vs Ecm
- Absolute energy scale nominally from resonant depolarization with estimated systematic uncertainty of 100 keV
    - Work ongoing to determine point to point calibration to much greater precision (see EPOL session tomorrow)
- Luminosity must be determined in-situ from e.g Bhabha scattering or diphoton production
- **Correlation structure of the uncertainty on both the beam energy and the measured cross sections critically impact the achievable precision on the mass and width**

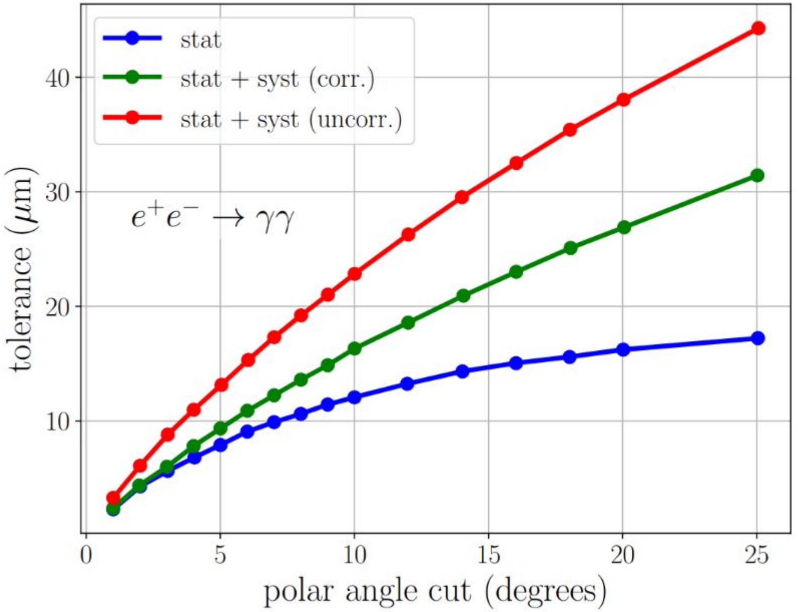


https://doi.org/10.1016/j.physrep.2005.12.006

Luminosity Measurement and Acceptance

A. Blondel, M. Dam https://repository.cern/records/f1fs5-0jr59

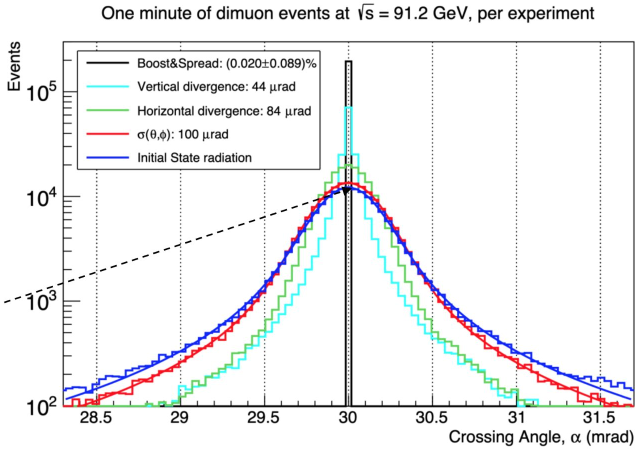


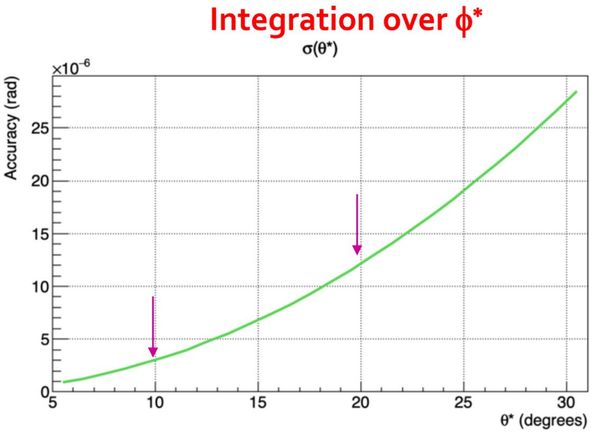


- Achieving target precision in acceptance systematics uncertainty of 10^-6 (10^-5) for dilepton (diphoton) events requires control over the radial position of the endcap calorimeter/tracking detector to O(10um)
- Electron-photon disambiguation is also crucial here

In-situ calorimeter acceptance determination

- Final state particle angles measured in tracker or with calorimeter can be used together with conservation of energy/momentum to determine the crossing angle (and longitudinal boost)
- Known crossing angle/boost can be used to calibrate angular measurements
- Angular calibration and crossing angle/boost can in principle be determined simultaneously to needed precision
  - **In situ calibration complements metrology, which can also be facilitated by detector design**
- N.b. angles are better measured than energy/momentum and are smeared symmetrically by radiative effects
  - To first order in a solenoidal field, polar angle is independent of the B-field and ionization losses while azimuthal angle still carries some dependency
  - But both angles are subject to “non-linearities”
- This needs to be studied in more realistic conditions
- Can never be fully decoupled from the tracking system since precise angle measurement of photons depends on vertex/beamspot position

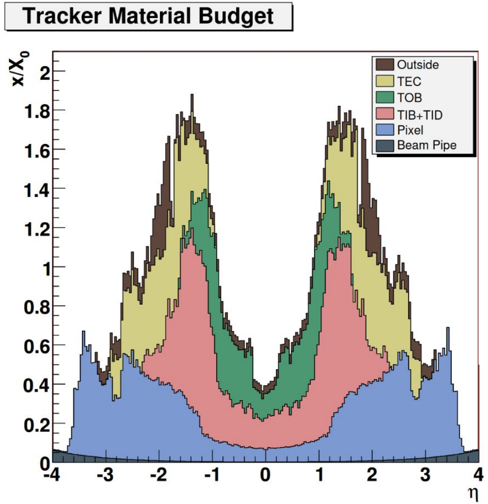




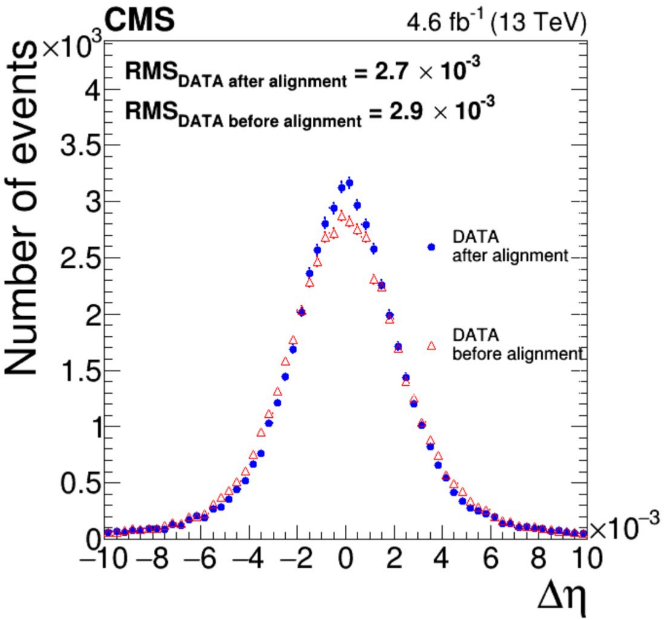
https://indico.cern.ch/event/1202105/contributions/5396834/attachments/2661280/4610775/AcceptanceDiPhoton_FCCWeek23.pdf (P. Janot, FCC Week 2023)

Aside: ECal-Tracker alignment in CMS

- CMS Ecal aligned with electron track-cluster matching to ~0.5 mrad (~1mm radial position)
- But with MUCH more material than proposed FCC-ee detectors and hence much more difficult electron track reconstruction



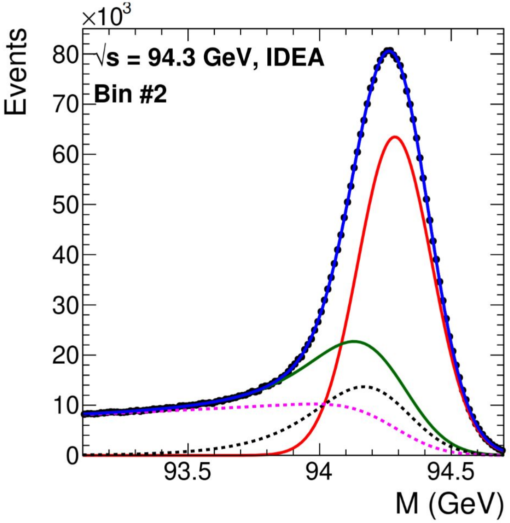
[JINST 3 (2008) S08004](https://doi.org/10.1088/1748-0221/3/08/S08004)

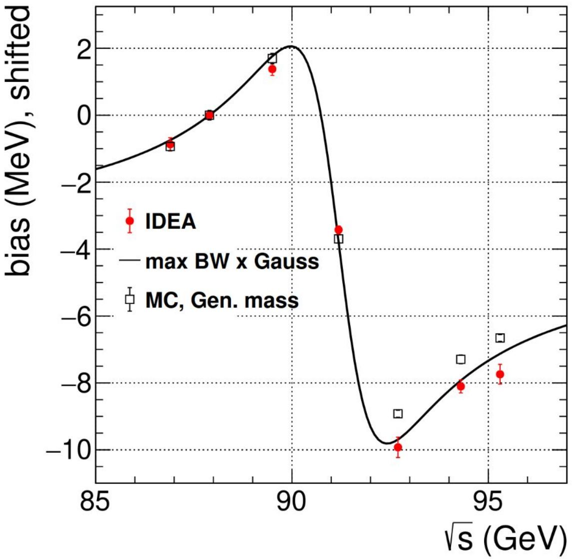


JINST 19 (2024) P09004

Point to point energy calibration/uncertainties

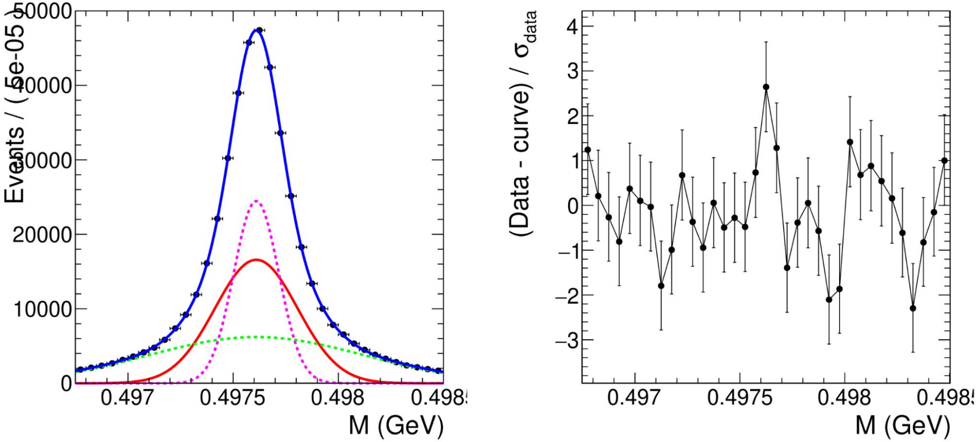
- Detailed study on constraining and/or cross-checking the point to point energy calibration with dimuon events to 20 keV -> 11 keV systematic uncertainty on Z width

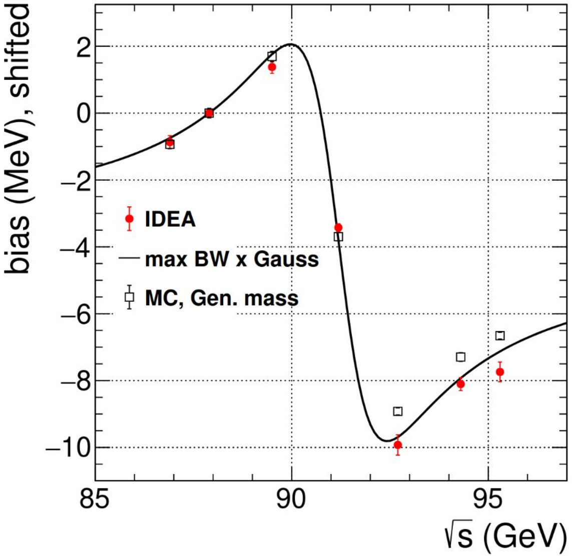




E. Perez, https://repository.cern/records/h34ka-06y15

Point to point energy calibration: Stability/Linearity

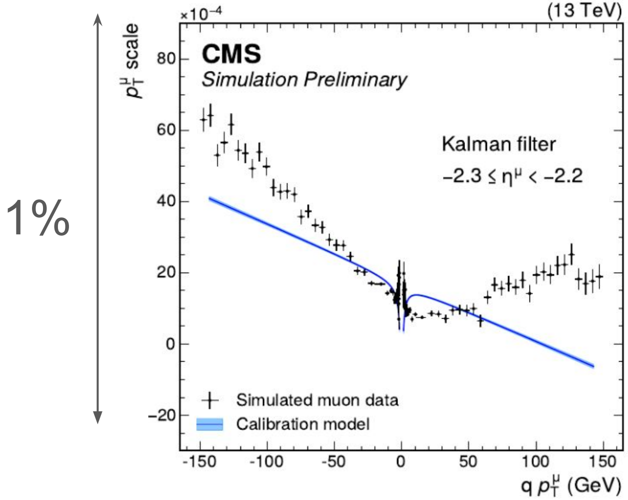




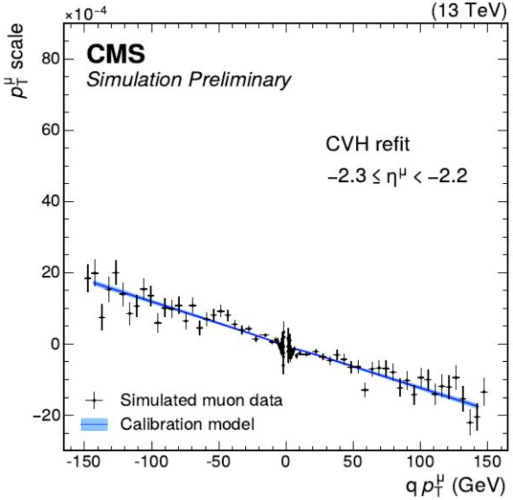
- Few 10^12 Ks->pi+ pi- from hadronic Z decays can be used to monitor stability of the momentum scale to the required 10^-7 level
    - Can this be complemented by NMR probes and/or monitoring of solenoid coil current?
- Strong requirements also on linearity (10^-7 momentum scale stability for average muon momentum between ~42 and 48 GeV)
- What is the limit on the absolute momentum scale calibration and what benefits would this bring in terms of redundancy, etc?
    - Ultimate limit for “external” momentum scale: 2 ppm precision on J/psi mass (measured from resonant depolarization at VEPP-4M), but still challenges from e.g. QED FSR modeling
    - FCC-ee beam energy calibration can also be “transferred” to an absolute momentum scale calibration

Tracking Linearity

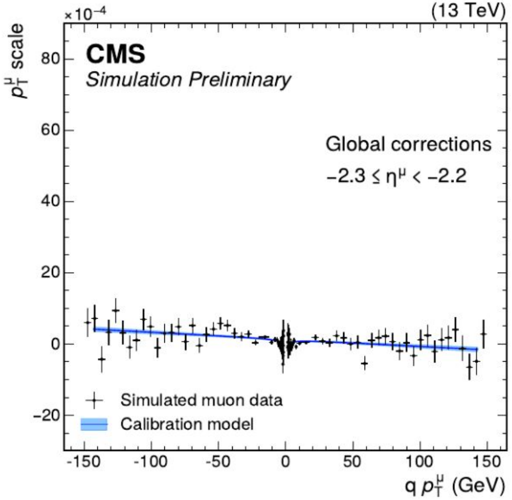
2412.13872



(a) Kalman Filter



(b) CVH Refit



(c) +global corrections

- Detailed study of momentum scale linearity in Silicon trackers in the context of the recent CMS mW measurement
- Calibration chain treats magnetic field and material corrections as part of the global alignment procedure
  - Eventually no distinction between (generalized) global alignment and “momentum scale calibration” if everything can be done consistently

Tracking Linearity

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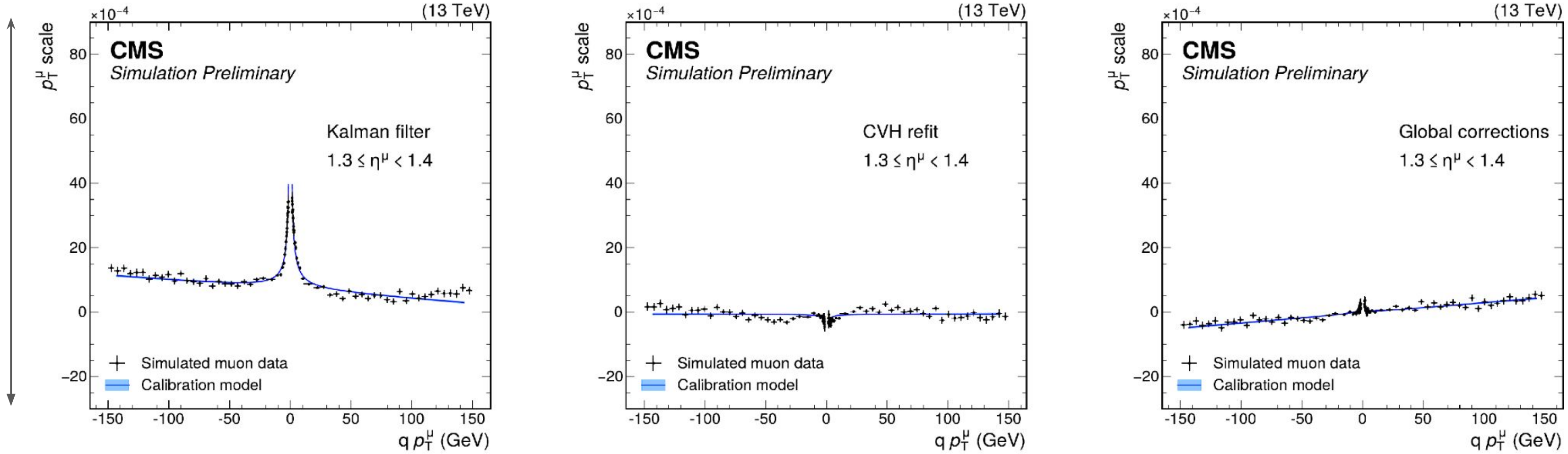

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(a) Kalman Filter (b) CVH Refit (c) +global corrections

- Detailed study of momentum scale linearity in Silicon trackers in the context of the recent CMS mW measurement
- Also recent paper with detailed study of CDF COT drift chamber:
  - A. Kotwal https://doi.org/10.1103/PhysRevResearch.7.013128

Tracking Linearity

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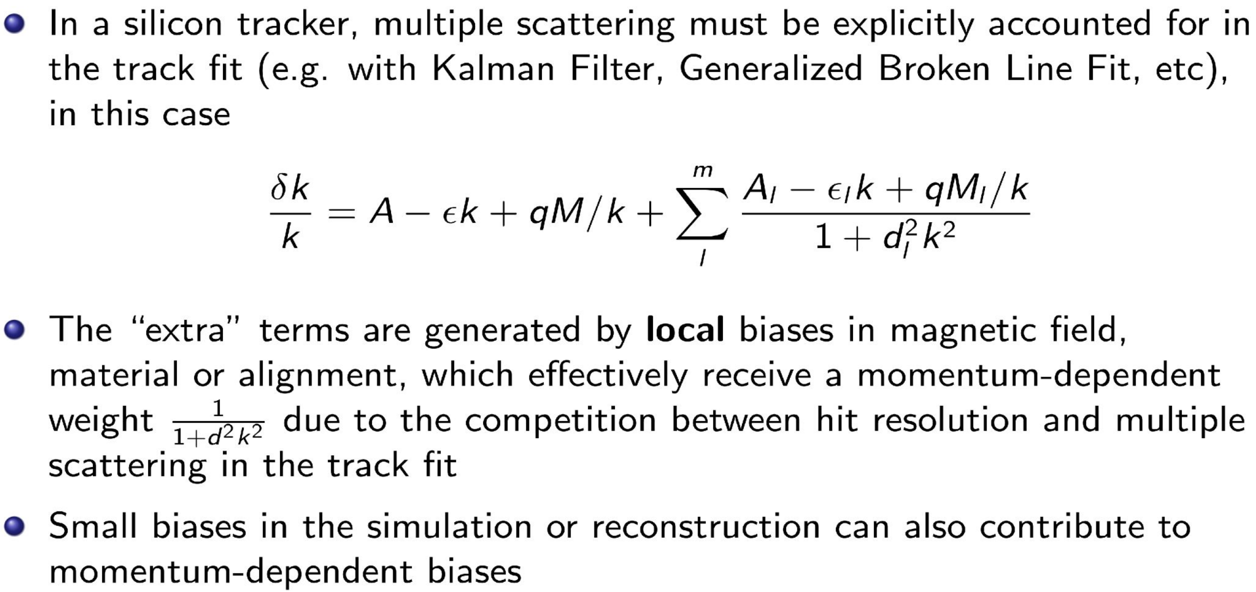


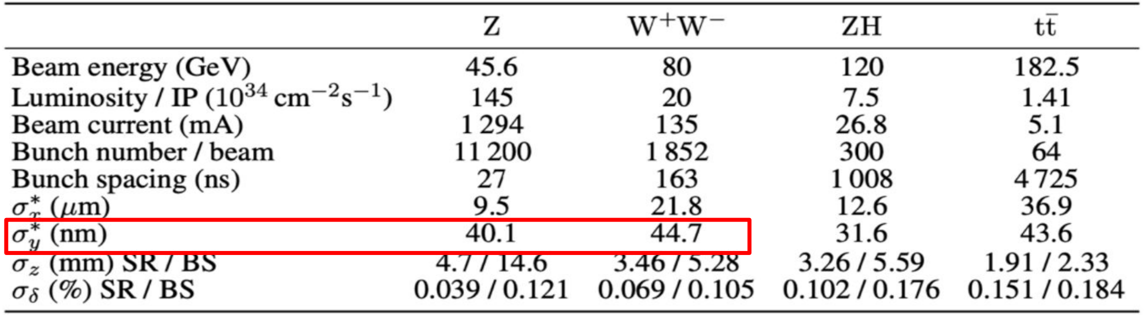
- In a silicon tracker, multiple scattering must be explicitly accounted for in the track fit (e.g. with Kalman Filter, Generalized Broken Line Fit, etc), in this case

$$\frac{\delta k}{k} = A - \epsilon k + qM/k + \sum_{l}^{m} \frac{A_l - \epsilon_l k + qM_l/k}{1 + d_l^2 k^2}$$

- The "extra" terms are generated by **local** biases in magnetic field, material or alignment, which effectively receive a momentum-dependent weight $\frac{1}{1+d^2k^2}$ due to the competition between hit resolution and multiple scattering in the track fit
- Small biases in the simulation or reconstruction can also contribute to momentum-dependent biases

- CMS is "worst case scenario" here with good single point resolution and >1 radiation length of material, but target precision for FCC-ee is much more stringent
- Mismodeling of e.g. magnetic field uniformity along track trajectory at 10^-5 or 10^-6 level could still cause issues -> to be studied in more detail

Luminous Region

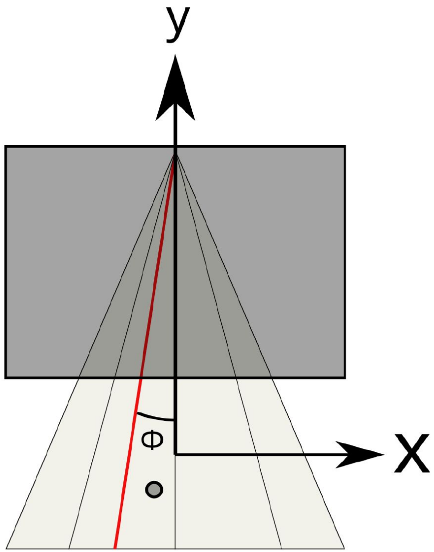


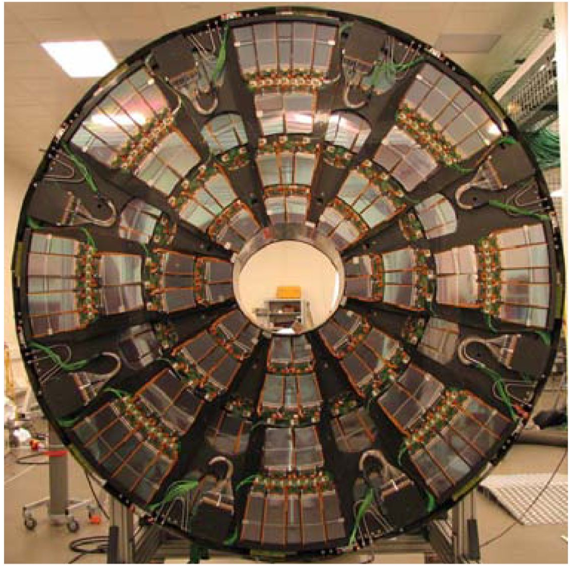
	Z	W^+W^-	ZH	$t\bar{t}$
Beam energy (GeV)	45.6	80	120	182.5
Luminosity / IP (10^{34} $\text{cm}^{-2}\text{s}^{-1}$)	145	20	7.5	1.41
Beam current (mA)	1 294	135	26.8	5.1
Bunch number / beam	11 200	1 852	300	64
Bunch spacing (ns)	27	163	1 008	4 725
σ_x^* (μm)	9.5	21.8	12.6	36.9
σ_y^* (nm)	40.1	44.7	31.6	43.6
σ_z (mm) SR / BS	4.7 / 14.6	3.46 / 5.28	3.26 / 5.59	1.91 / 2.33
σ_δ (%) SR / BS	0.039 / 0.121	0.069 / 0.105	0.102 / 0.176	0.151 / 0.184

- Beam is extremely narrow in vertical plane compared to vertex detector resolution
- If this is properly exploited can be very powerful for flavour tagging, tau reconstruction, etc
- Delicate:
    - Beamspot parameters have to be very accurately known, otherwise a 40nm constraint can introduce biases
    - Impact parameter resolution/flavour tagging efficiencies become azimuthally asymmetric
    - See also talk from S. Aumiller later
- In practice: Significant interplay of beam position, width, crossing angle, boost, energy spread and detector alignment
- Correlation of collision position/time and energy?

Aside: Radial alignment of tracker endcap

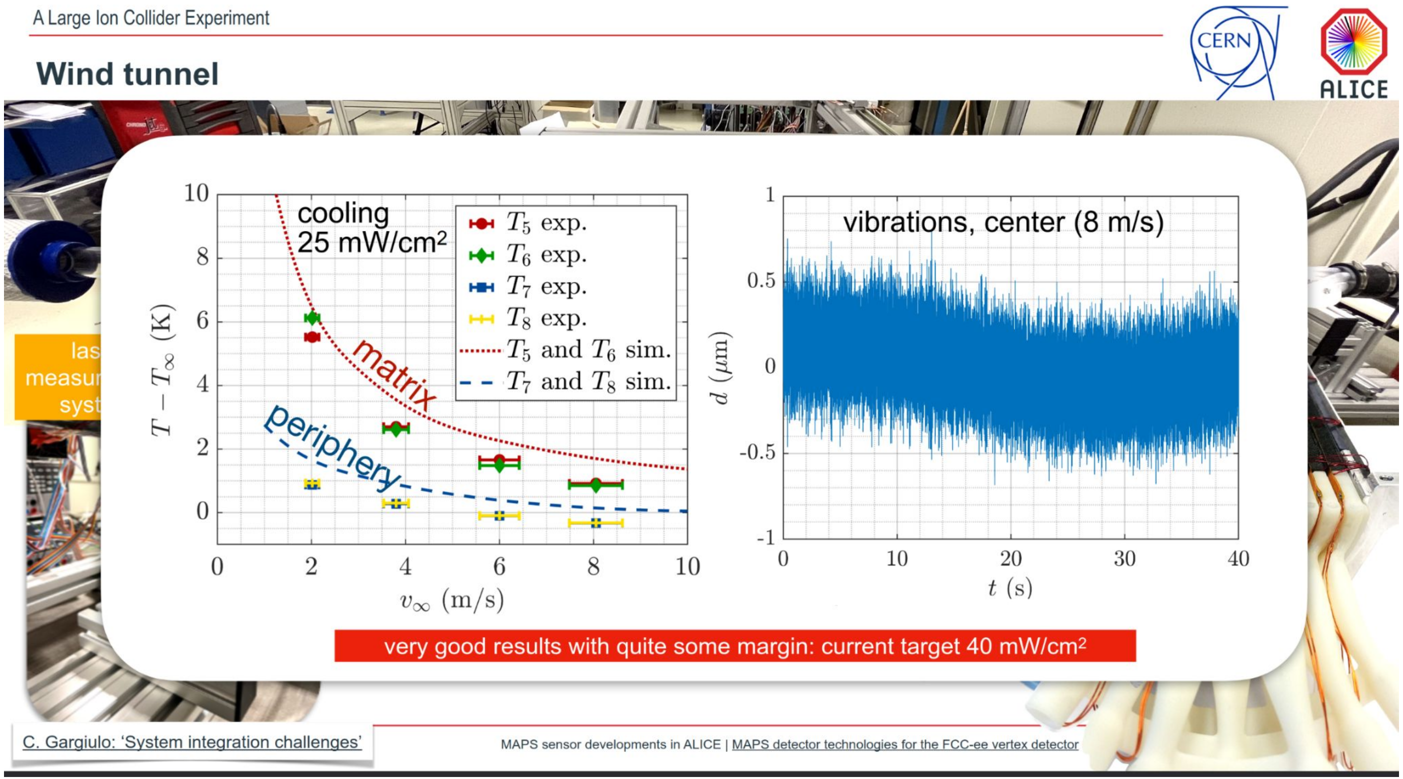
- Typical geometry for Silicon tracker endcap: Trapezoidal modules with radially projective strips
- Even with stereo angle modules, this configuration is NOT optimal for alignment precision in the radial direction as needed to define the acceptance (nearly parallel to the strips)
- Relevant for both all-silicon tracker or gas/straw trackers with silicon wrapper
- Consider alternatives?





JINST 3 (2008) S08004

ITS3 Experience


A Large Ion Collider Experiment

Wind tunnel

very good results with quite some margin: current target 40 mW/cm²

C. Gargiulo: 'System integration challenges'

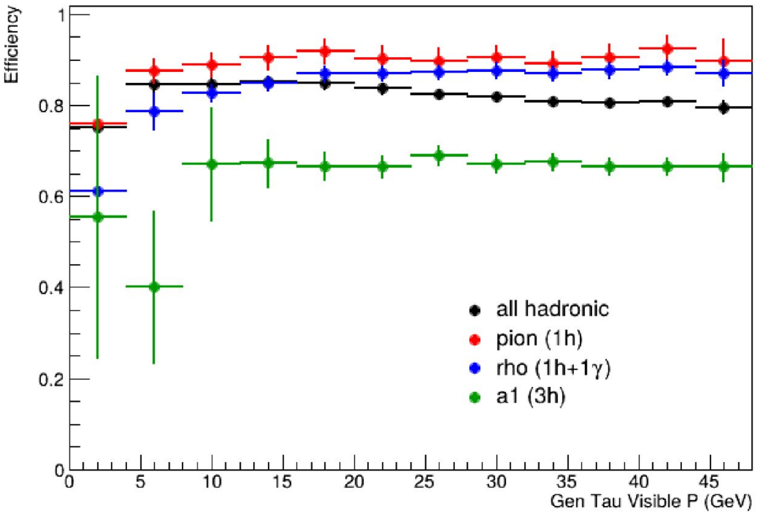
MAPS sensor developments in ALICE | MAPS detector technologies for the FCC-ee vertex detector

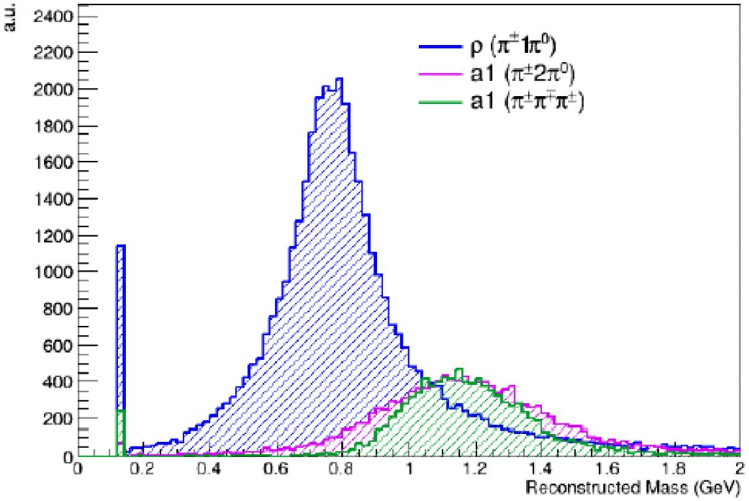
- Vibrations from air cooling of MAPS vertex detectors large enough to show up in hit residuals vs bunch crossing number?
- Time–dependent alignment?
- Pay close attention to possible deformations from ideal cylinder

Next steps: Alignment and Energy/Momentum Calibration

- Prototype (generalized) global alignment workflow useful to study interplay of luminous region parameterization/determination, detector alignment, B-field/momentum scale calibration/linearity/stability
- This is closely related to the key uncertainties for the Z lineshape scan and could give important feedback for detector design
- Sensitivity of AFB measurements to charge-dependent momentum biases from misalignment?
- Some synergy with ongoing efforts to measure mZ in ATLAS/CMS/LHCb
- IDEA is probably a good starting point since both gas and Si layers are included
    - Integration of alignment hooks into GenFit2?
    - Geant4e propagator needed?
- Basic simulation of cosmic muons also needed
    - Can likely adapt from LHC experiments
- Eventually will need to ensure that simulation/reconstruction can accommodate detector misalignment, deformations, wire sag, lorentz angle, dead channels, etc etc

More Fullsim studies: Tau reconstruction and polarization



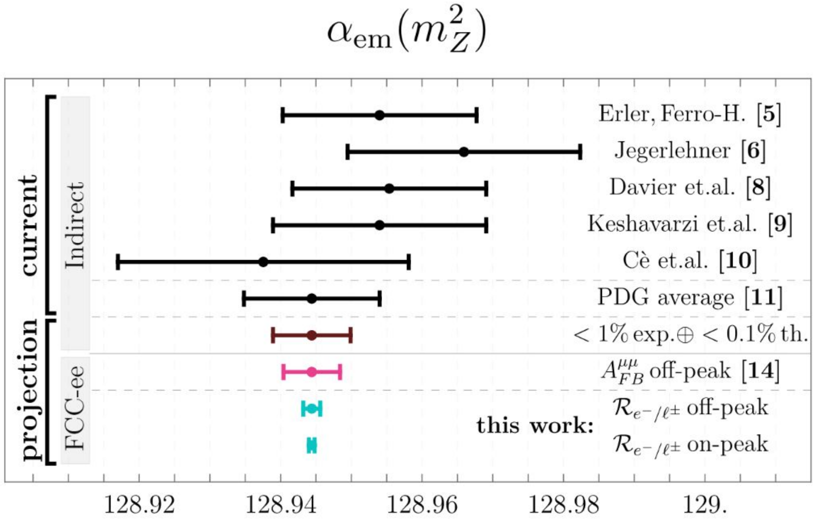


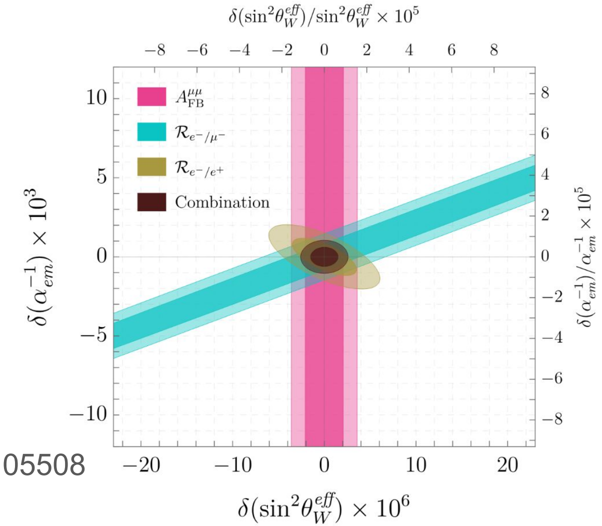
J. Alcaraz, M. Cepeda, D. Garcia,
https://repository.cern/records/69a4s-7vw37

- Important challenge for full-simulation studies: Huge number of events needed to match data statistics (8 million simulated Z->tau tau here compared to 10^11 expected in data)
- Will require significant streamlining of MC generation and data formats to optimize storage and IO footprint for massive samples and enable very high analysis event rates

alpha_em

- Recent proposal to measure alpha_em from ratio of electrons/positrons/muons (exploiting alpha_em dependence of t-channel vs s-channel contributions)
- Critically depends on controlling (differential) efficiency of muons vs electrons
- This is a possible candidate for a more detailed mock-up of the in-situ efficiency calibration procedure
    - Also some relation with in-situ flavour tagging calibration





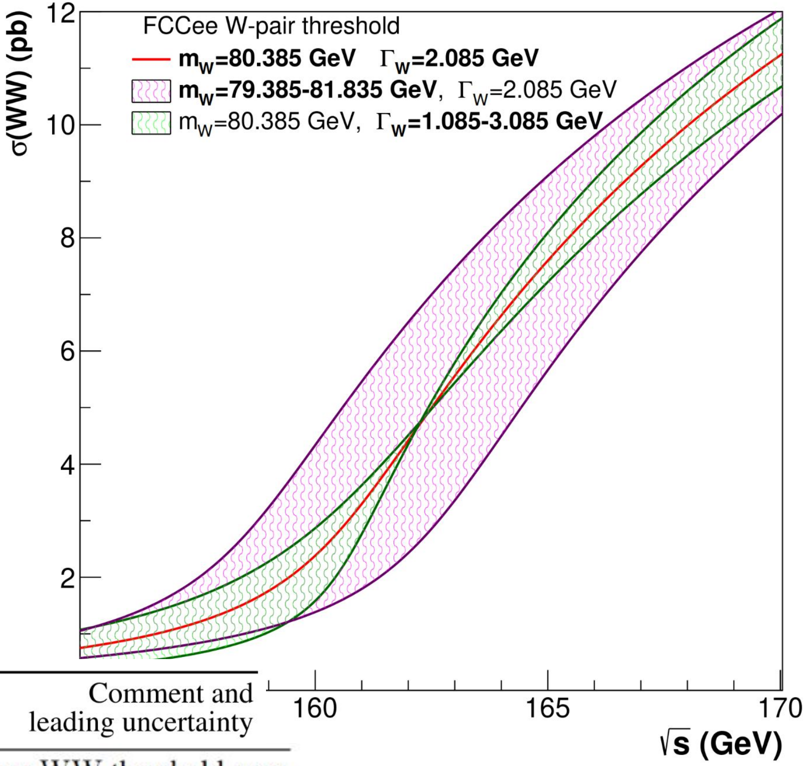
M. Riembau, 2501.05508

Theory Considerations

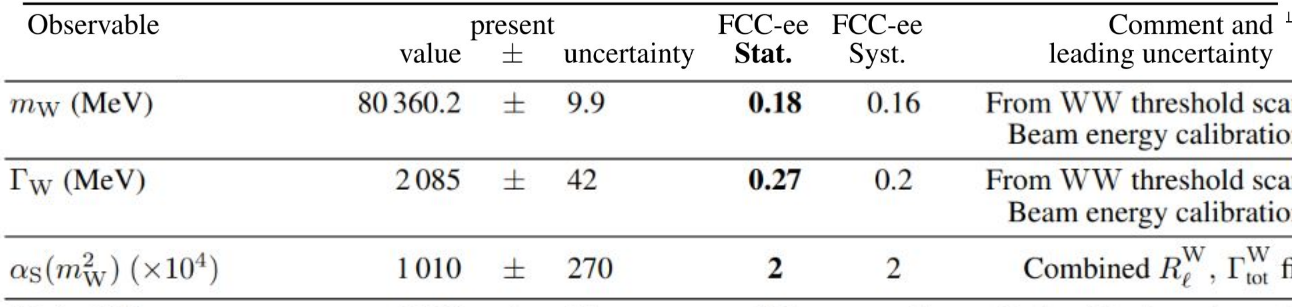
- Two related but complementary cases
  - Higher order EWK calculations needed to relate measured SM parameters
  - Calculations needed for cross section/observable predictions
    - Final state kinematic distributions
    - Cross section vs beam energy scans
      - Z pole (ISR is critical here)
      - WW threshold
      - ttbar threshold
    - Theory uncertainties will have to be interpreted together with statistical and experimental systematics
      - Understanding of correlations crucial
- General: Need to carefully keep track of theoretical assumptions for precision measurements
  - E.g. assumption of no flavour changing neutral currents for flavour tagging calibration

WW Threshold Scan

- Significant theory challenges here among others
    - Delicate matching of on and off-shell calculations
    - With current calculations, theory uncertainty at 3-5 MeV level -> order of magnitude improvement needed
- Even with increased calculation accuracy, how to estimate correlation structure of theory uncertainties? (correlated vs point-to-point)
- Can relevant theory uncertainties be partly constrained in-situ either from shape of cross section itself (more scan points) or other observables?
- Possible BSM effects on threshold cross section?



P. Azzurri 2107.04444



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$\alpha_S(m_W^2)$ ($\times 10^4$)	1 010	±	270	**2**	2	Combined R_ℓ^W, Γ_{tot}^W fit

Conclusions

- Significant amount of work has gone into estimating achievable precision for precision electroweak measurements at Z pole and WW threshold
- Moving into pre-TDR phase more realistic analysis and calibration workflows are needed to identify possible possible systematic limits which require more work/thought and/or which could be mitigated at the detector design level
- This will include further targeted use of full simulation with corresponding technical needs
    - Full simulation/reconstruction implementation for additional detector concepts (e.g. at least one with gaseous tracker)
    - Streamlining of workflows/data formats to enable scale-up in size of simulated samples where needed

Backup

mZ: Ultimate precision

- N.b the absolute reference scale ideally comes from J/psi (measured to very high precision with resonant depolarization in lower energy e+ e- collisions)

Resonance	PDG mass (GeV)	Relative uncertainty (ppm)
Z	91.188 +- 0.0020	22
J/psi	3.096900 +- 0.000006	2
Y(1s)	9.46040 +- 0.00010	11
Y(2s)	10.0234 +- 0.0005	50
Y(3s)	10.3551 +- 0.0005	48
B+-	5.27941 +- 0.00007	13
K0	0.4976111 +- 0.000013	26
D*+-	2.01026 +- 0.00005	24