Electroweak studies within Snowmass 2021

A. Freitas
University of Pittsburgh

`snowmass21.org/energy/ewk`

0. Snowmass 2021 structure

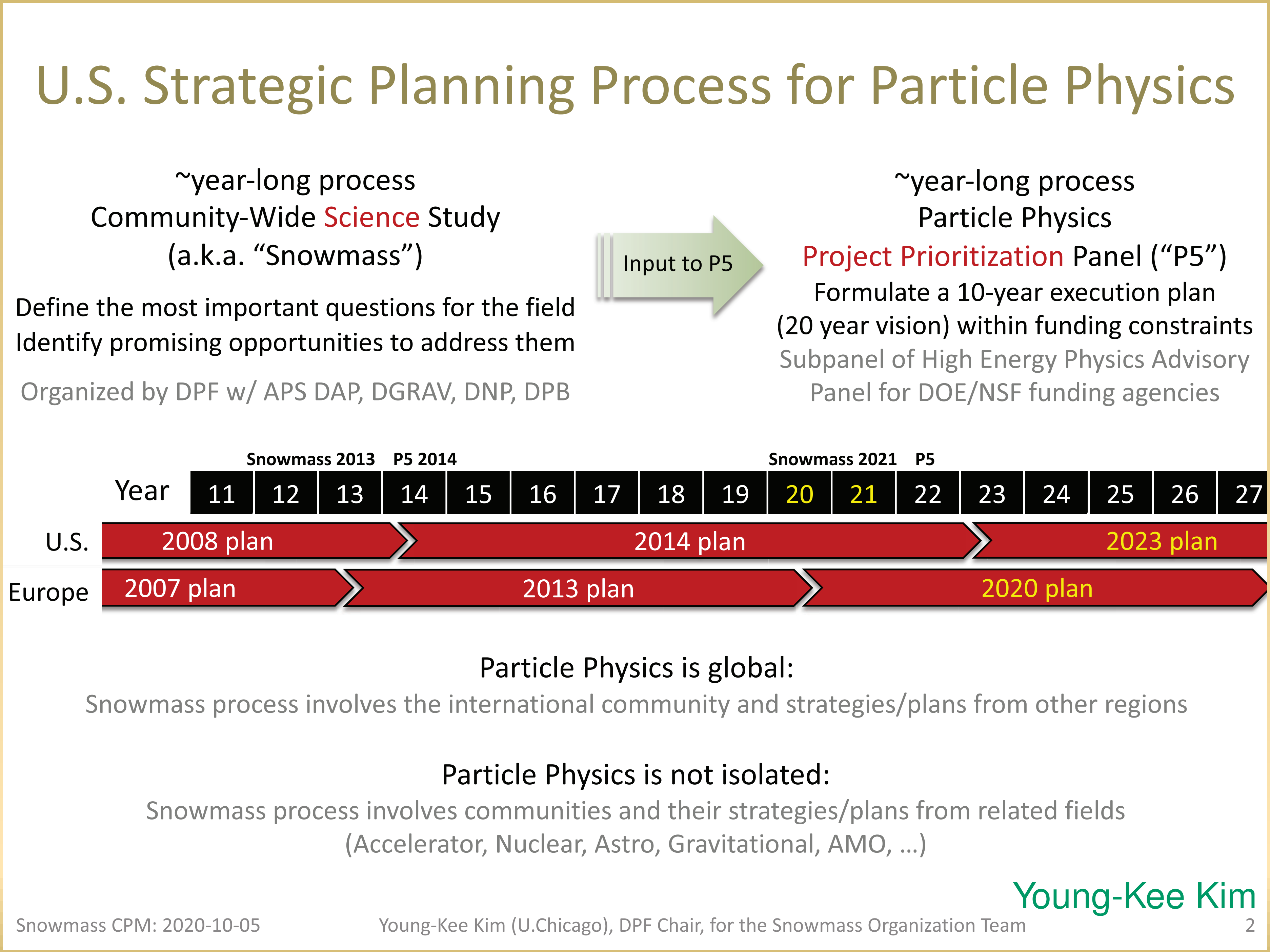
1. Electroweak precision tests

2. High-energy multi-boson production and VBS

3. Global SMEFT fits

Slide material from Aram Apyan, Pietro Govoni, Young-Kee Kim, Zhijun Liang, Alessandro Tricoli, Daniel Wiegand

Snowmass 2021 structure



U.S. Strategic Planning Process for Particle Physics

~year-long process
Community-Wide Science Study
(a.k.a. "Snowmass")

Define the most important questions for the field
Identify promising opportunities to address them

Organized by DPF w/ APS DAP, DGRAV, DNP, DPB

Input to P5

~year-long process
Particle Physics
Project Prioritization Panel ("P5")
Formulate a 10-year execution plan
(20 year vision) within funding constraints
Subpanel of High Energy Physics Advisory
Panel for DOE/NSF funding agencies

Particle Physics is global:
Snowmass process involves the international community and strategies/plans from other regions

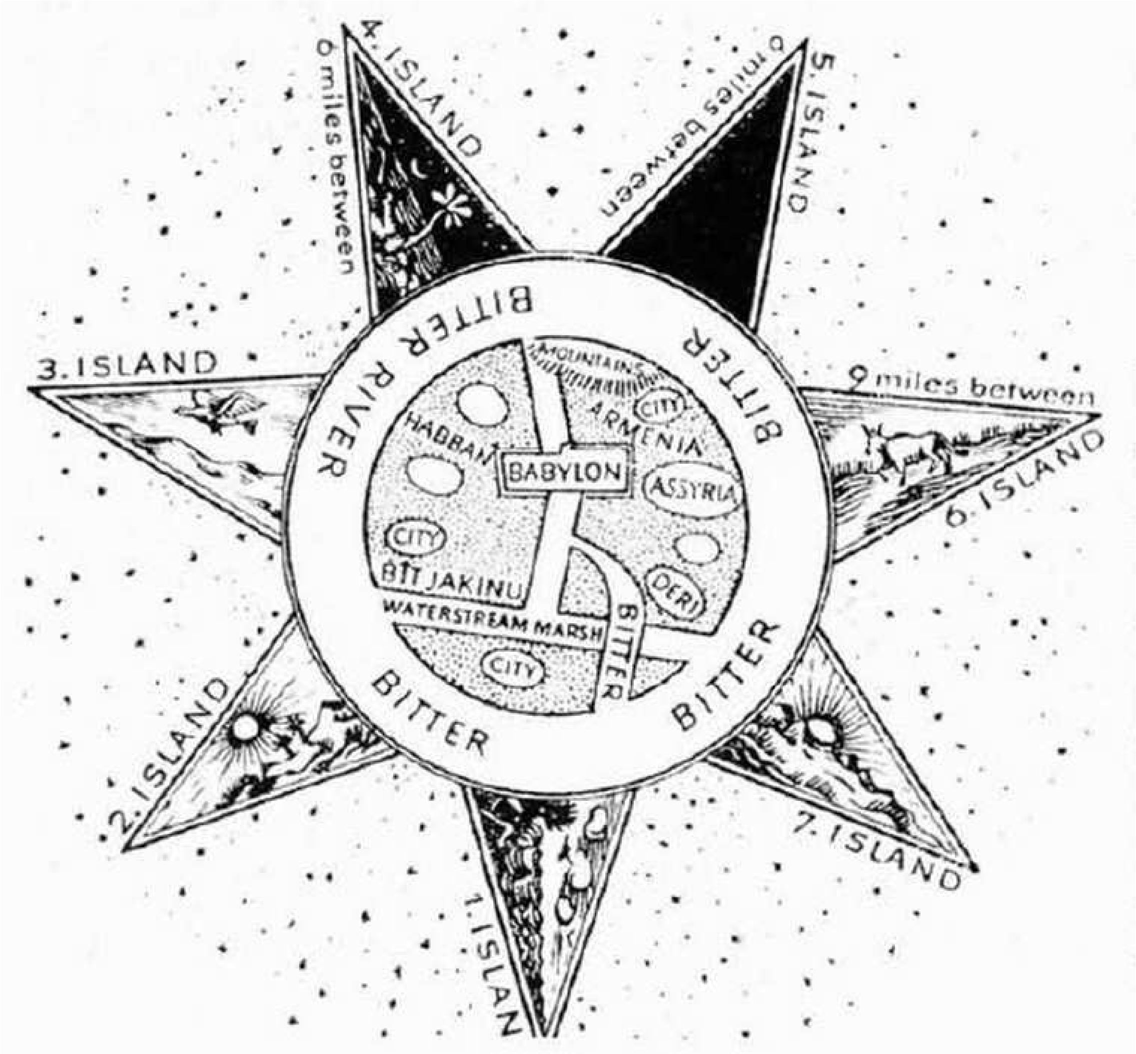
Particle Physics is not isolated:
Snowmass process involves communities and their strategies/plans from related fields
(Accelerator, Nuclear, Astro, Gravitational, AMO, …)

Young-Kee Kim

Snowmass CPM: 2020-10-05 Young-Kee Kim (U.Chicago), DPF Chair, for the Snowmass Organization Team 2

Snowmass 2021 structure

Frontiers:



Snowmass 2021 structure

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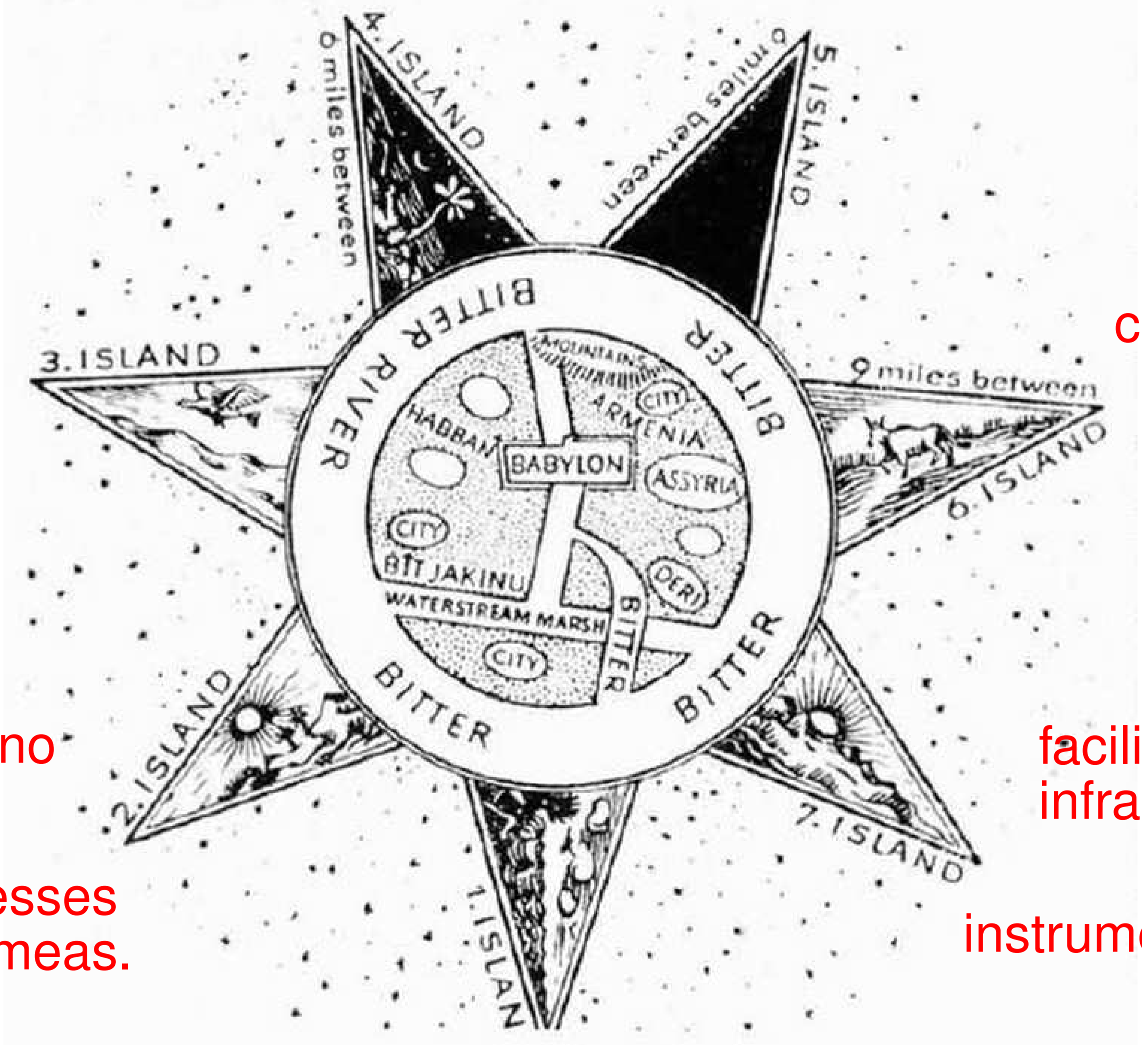


cosmic

theory

energy

computing

community

neutrino

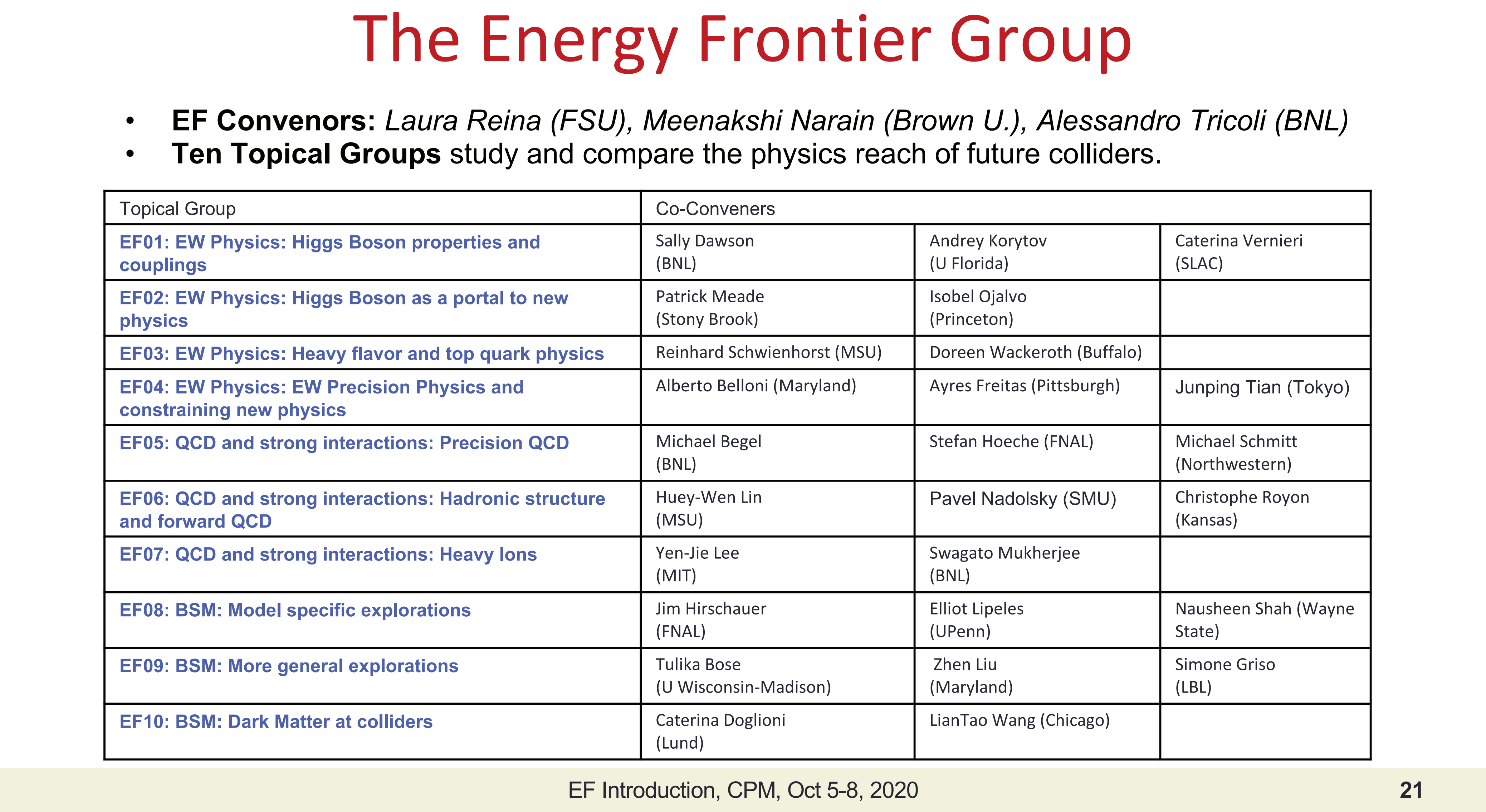
facilities &
infrastructure

rare processes
and prec. meas.

instrumentation

accelerator

Energy Frontier groups

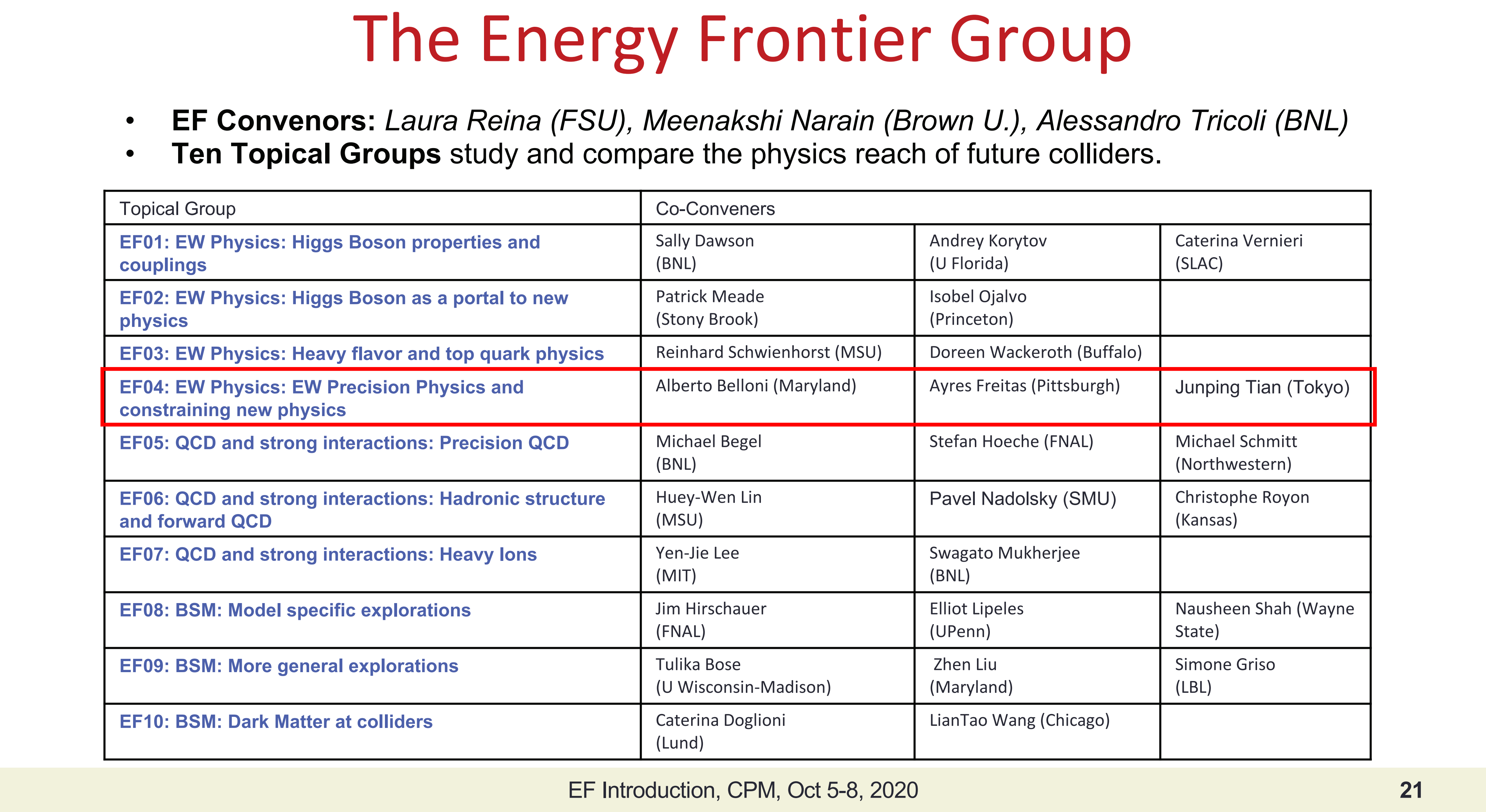


The Energy Frontier Group

- **EF Convenors:** *Laura Reina (FSU), Meenakshi Narain (Brown U.), Alessandro Tricoli (BNL)*
- **Ten Topical Groups** study and compare the physics reach of future colliders.

Topical Group	Co-Conveners		
EF01: EW Physics: Higgs Boson properties and couplings	Sally Dawson (BNL)	Andrey Korytov (U Florida)	Caterina Vernieri (SLAC)
EF02: EW Physics: Higgs Boson as a portal to new physics	Patrick Meade (Stony Brook)	Isobel Ojalvo (Princeton)	
EF03: EW Physics: Heavy flavor and top quark physics	Reinhard Schwienhorst (MSU)	Doreen Wackeroth (Buffalo)	
EF04: EW Physics: EW Precision Physics and constraining new physics	Alberto Belloni (Maryland)	Ayres Freitas (Pittsburgh)	Junping Tian (Tokyo)
EF05: QCD and strong interactions: Precision QCD	Michael Begel (BNL)	Stefan Hoeche (FNAL)	Michael Schmitt (Northwestern)
EF06: QCD and strong interactions: Hadronic structure and forward QCD	Huey-Wen Lin (MSU)	Pavel Nadolsky (SMU)	Christophe Royon (Kansas)
EF07: QCD and strong interactions: Heavy Ions	Yen-Jie Lee (MIT)	Swagato Mukherjee (BNL)	
EF08: BSM: Model specific explorations	Jim Hirschauer (FNAL)	Elliot Lipeles (UPenn)	Nausheen Shah (Wayne State)
EF09: BSM: More general explorations	Tulika Bose (U Wisconsin-Madison)	Zhen Liu (Maryland)	Simone Griso (LBL)
EF10: BSM: Dark Matter at colliders	Caterina Doglioni (Lund)	LianTao Wang (Chicago)	

Energy Frontier groups



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EF Introduction, CPM, Oct 5-8, 2020 **21**

Timeline

Snowmass Timeline in 2022 (Preliminary)

Developing Key Questions

Reports

Time

Snowmass Key Questions

Frontier #1 Key Questions

Frontier #10 Key Questions

TG #1 Key Questions

TG #2 Key Questions

...

TG #N Key Questions

TG #1 Key Questions

TG #2 Key Questions

...

TG #N Key Questions

Contributed Papers (deadline – to be determined)

Snowmass Report

Frontier Reports

TG Reports

October

September

August

July (CSS)

June

May

April

March

February

January

Electroweak precision tests

Open questions of the Standard Model:

- Is the Higgs boson part of a more complex sector?
- Is there an extended/unified symmetry group?
- What is dark matter?
- Why is there more matter than anti-matter in the universe?
- ...

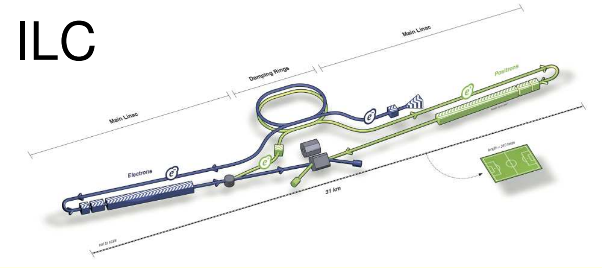
→ **Physics beyond the Standard Model**

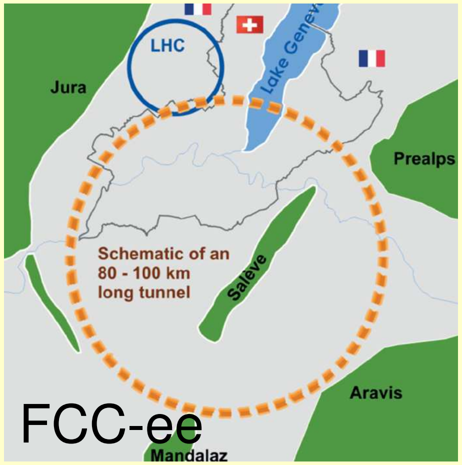
→ Direct searches at high-energy colliders (LHC)

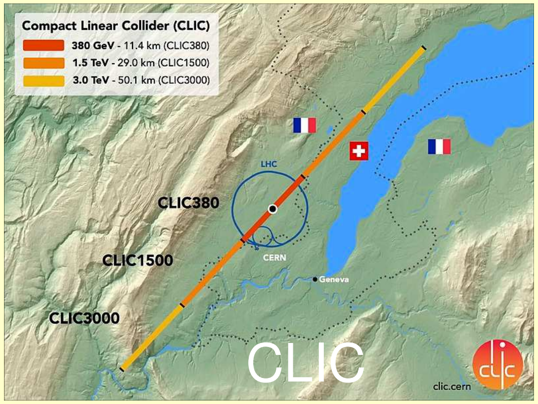
→ Astro-physics searches (e.g. DM direct / indirect detection)

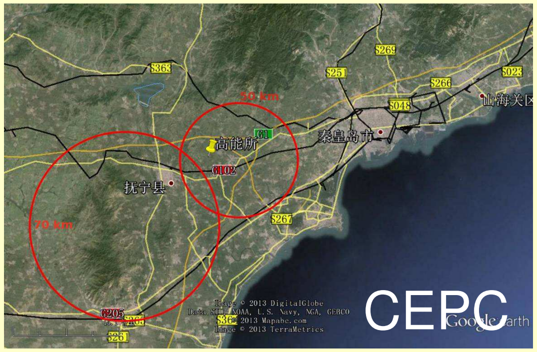
→ Indirect evidence from precision measurements

Electroweak precision tests at future colliders









- circular colliders: high-lumi run at $\sqrt{s} \sim M_Z$
- linear colliders: radiative return $e^+e^- \to \gamma Z$

$\sqrt{s}$	M_Z	$2M_W$	240–250 GeV	350–380 GeV
ILC	*100 fb^{-1}*	*500 fb^{-1}*	2 ab^{-1}	200 fb^{-1} (10 pts.)
CLIC	–	–	–	1 ab^{-1}
FCC-ee	230 ab^{-1}	10 ab^{-1} (2 pts.)	irrel. for EW phys.	200 fb^{-1} (8 pts.)
CEPC	45 ab^{-1}	2.6 ab^{-1} (3 pts.)	irrel. for EW phys.	–

Electroweak precision tests at future colliders

Anticipated precison for EWPOs:

Quantity	current	ILC*	CLIC*	FCC-ee†	CEPC†
M_Z [MeV]	2.1	–	–	0.1	0.5
Γ_Z [MeV]	2.3	–	–	0.1	0.5
M_W [MeV]	12	2.5	?	0.7	1.0
$\sin^2\theta^\ell_{\rm eff}$ $[10^{-5}]$	14	2	7.8	0.5	2.3
$R_b = \Gamma^b_Z/\Gamma^{\rm had}_Z$ $[10^{-5}]$	66	23	38	6	4.3

- Can be optimized with different run scenarios

  † Measurements at $\sqrt{s} \sim M_Z$ and $\sqrt{s} \sim 2M_W$

  * Measurements at $\sqrt{s} \sim 250/380$ GeV, using $ee \to \gamma Z$

- Polarized beams at ILC (P_{e^-}=0.8, P_{e^+}=0.8) and CLIC (P_{e^-}=0.8)

Electroweak precision tests at future colliders

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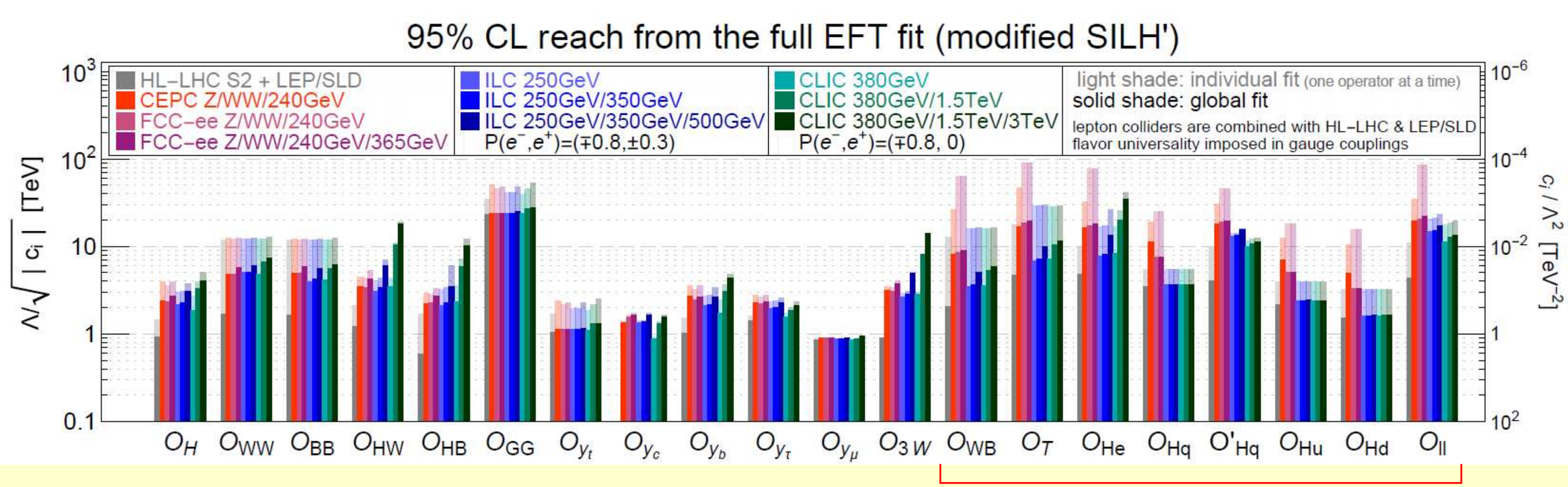


de Blas, Durieux, Grojean, Gu, Paul '19

Future colliders: Open questions

- Evaluate systematic uncertainties with full simulation (b-tagging hemisphere correlations, particle ID, lepton charge, τ lifetime)
- Some measurements appear systematic limited, but historically systematic effects are often overestimated during design stage
- How much can be gained for EWPOs by running ILC at $\sqrt{s} \sim M_Z$ compared to $\sqrt{s} \geq 250$ GeV (using rad. return)?
- For lin. coll.: Can one use $J/\psi \to \mu^+\mu^-$ to calibrate energy? ($\delta M_{J/\psi}/M_{J/\psi} \sim 2 \times 10^{-6}$ compared to $\delta M_Z/M_Z \sim 2 \times 10^{-5}$)
- Need improved theory calculations (at least 2-loop for $2 \to 2$ and 3/4-loop for Z production and decay)
- Is SMEFT always an appropriate language to parametrize devations from SM? What do we learn about specific BSM models?
- Can we disentangle degeneracies in the SMEFT parameter space with νp, ep and eN scattering experiments?

Future theory projections

Freitas, Heinemeyer, et al. '19

Quantity	FCC-ee	CEPC	current theory*	projected theory†
Γ_Z [MeV]	0.1	0.5	0.4	0.15
M_W [MeV]	0.7	1.0	4	1
$\sin^2\theta^\ell_{\rm eff}$ [10^{-5}]	0.5	2.3	4.5	1.5
$R_b = \Gamma^b_Z/\Gamma^{\rm had}_Z$ [10^{-5}]	6	4.3	11	5

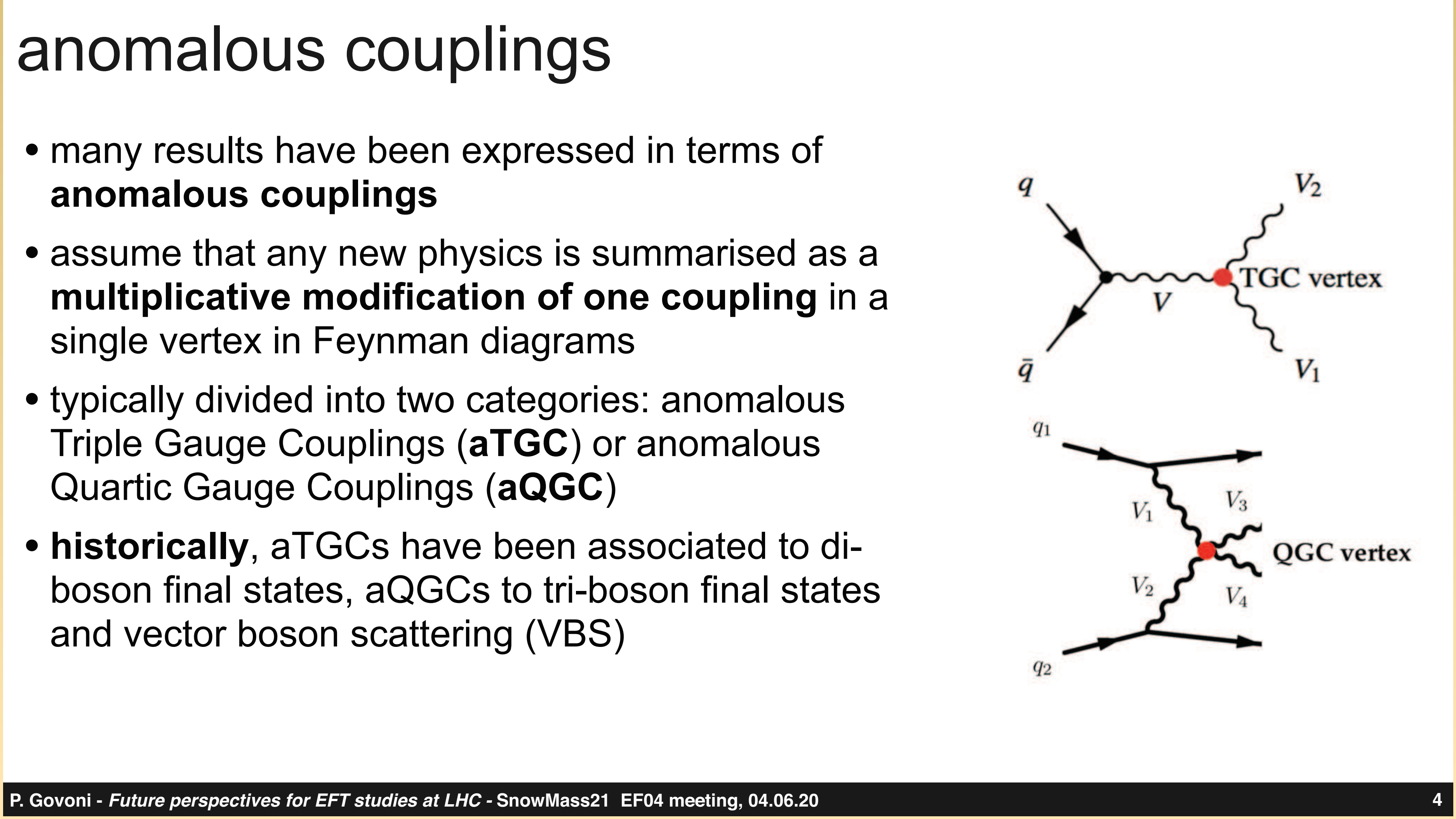
* **Current state-of-art:** full two-loop + leading 3-loop

† **Future scenario:** $\mathcal{O}(\alpha\alpha_s^2)$, $\mathcal{O}(N_f\alpha^2\alpha_s)$, $\mathcal{O}(N_f^2\alpha^2\alpha_s)$ + leading 4-loop

(N_f^n = at least n closed fermion loops)

Higher-energy multi-boson production and VBS

Multi-boson production at hadron colliders



anomalous couplings

- many results have been expressed in terms of **anomalous couplings**
- assume that any new physics is summarised as a **multiplicative modification of one coupling** in a single vertex in Feynman diagrams
- typically divided into two categories: anomalous Triple Gauge Couplings (**aTGC**) or anomalous Quartic Gauge Couplings (**aQGC**)
- **historically**, aTGCs have been associated to di-boson final states, aQGCs to tri-boson final states and vector boson scattering (VBS)

P. Govoni - *Future perspectives for EFT studies at LHC* - SnowMass21 EF04 meeting, 04.06.20

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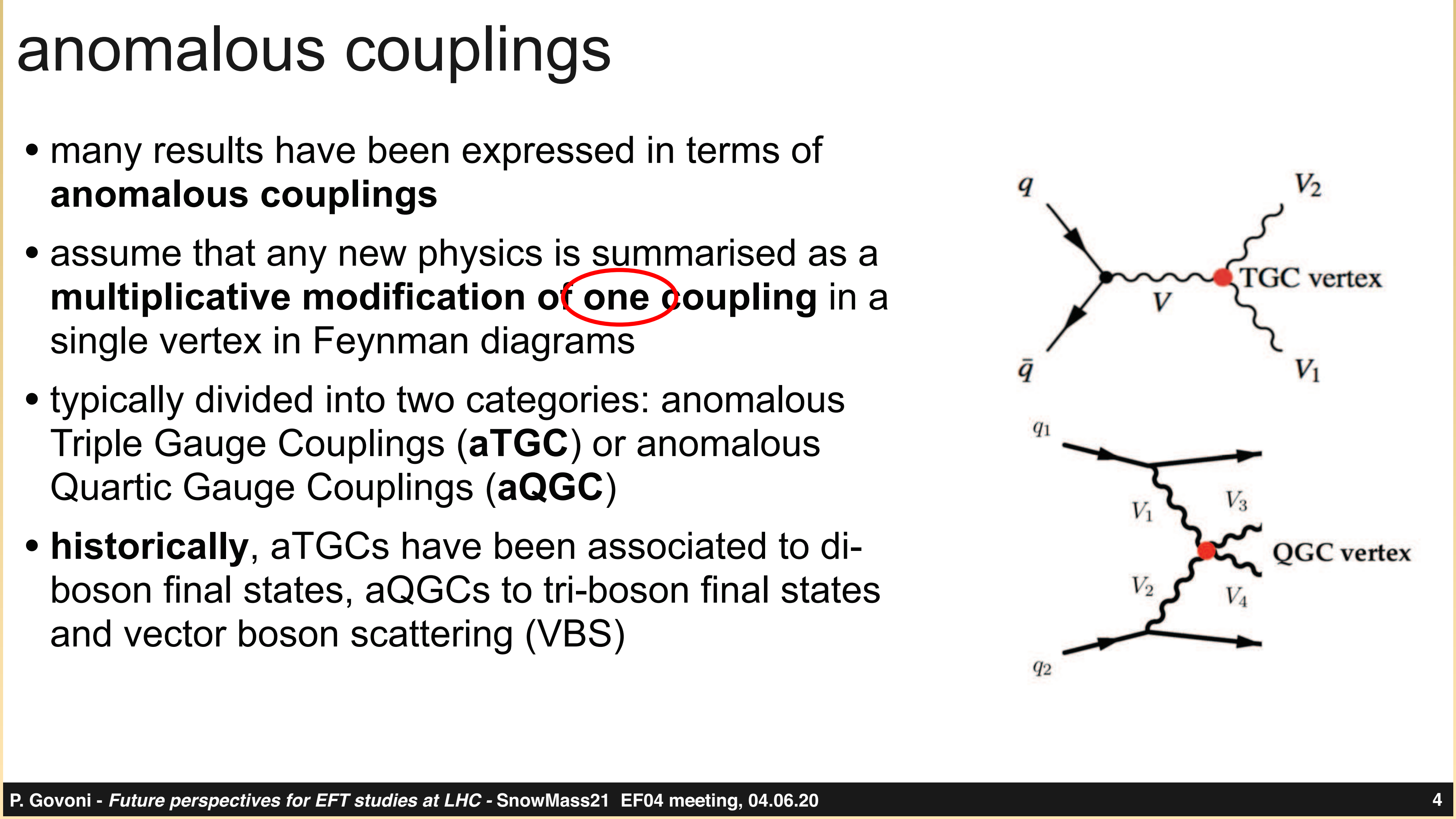
Multi-boson production at hadron colliders



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P. Govoni - *Future perspectives for EFT studies at LHC* - SnowMass21 EF04 meeting, 04.06.20 4

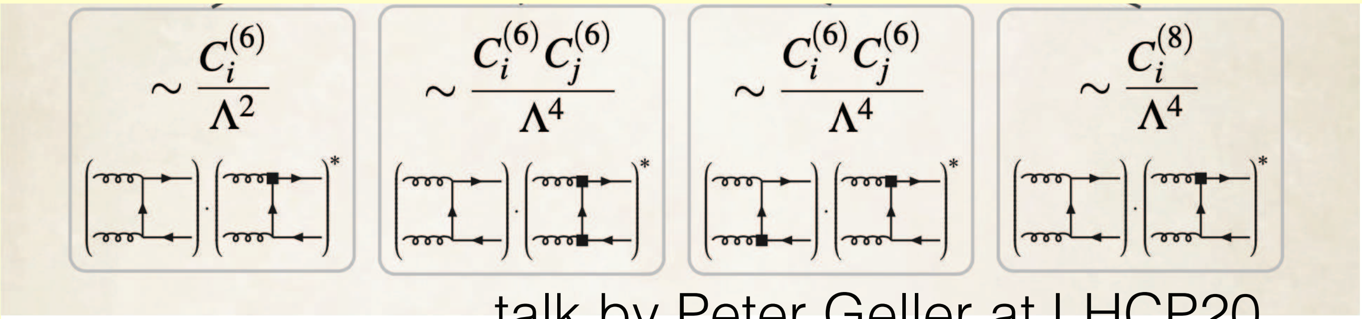
Future VBS studies

Parameterize aGC in terms of SMEFT operators

- Which SMEFT basis to use? [to combine different channels and experiments]
- EFT contributions in PDF fits? [otherwise may absorb new phys. in proton structure]
- Putting constraints on multi-dim. space of Wilson coefficients is expensive in terms of MC generation [is it ok to simply use event weights?]

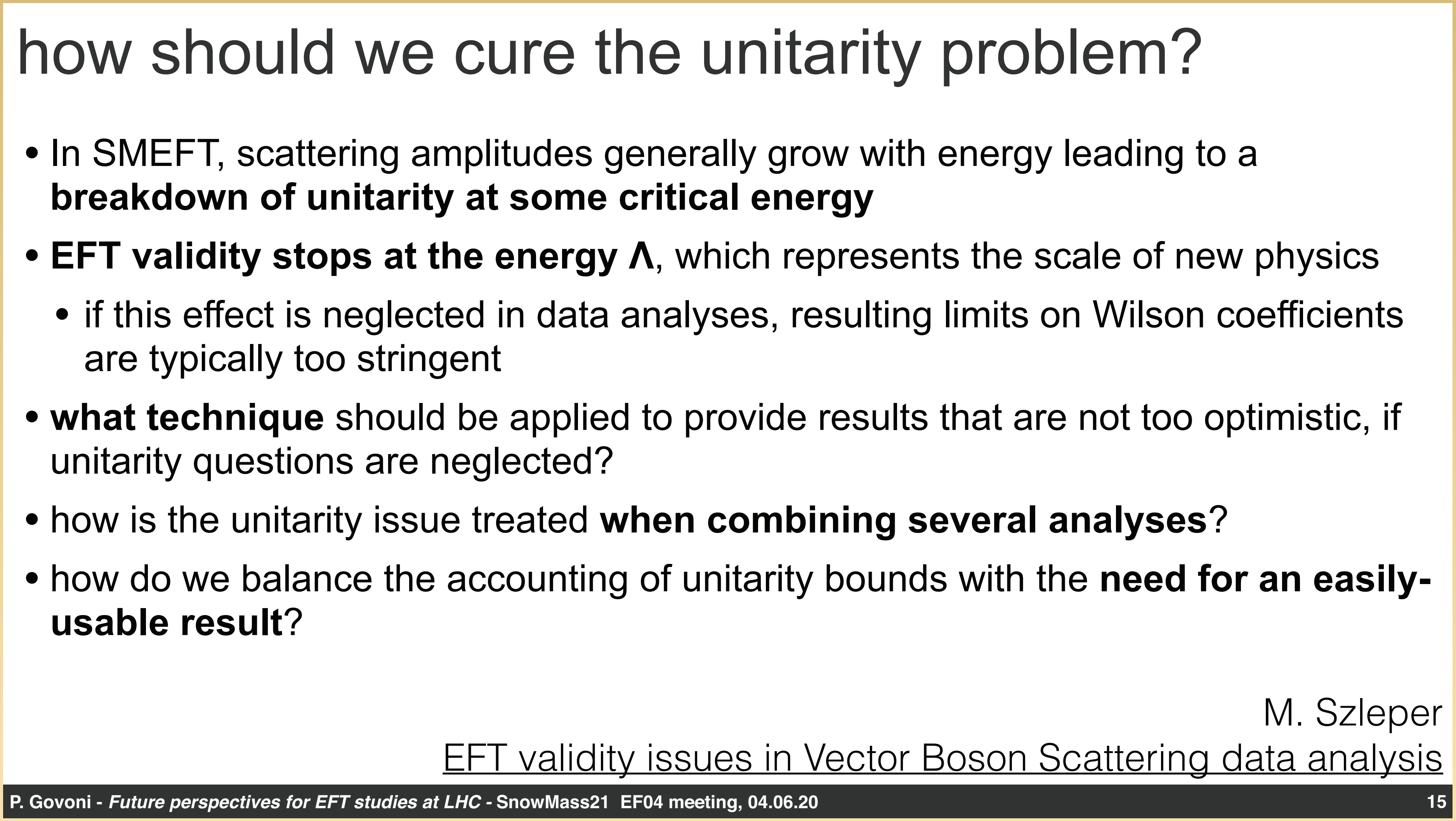
$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \underbrace{\frac{1}{\Lambda^2}\mathcal{L}_6}_{\text{state of art for global fits}} + \frac{1}{\Lambda^3}\mathcal{L}_7 + \underbrace{\frac{1}{\Lambda^4}\mathcal{L}_8}_{\text{needed for some aQGC}}$$

(When) should we mix dim-6 and dim-8 operators in the fits? How?



talk by Peter Geller at LHCP20

EFT validity



how should we cure the unitarity problem?

- In SMEFT, scattering amplitudes generally grow with energy leading to a **breakdown of unitarity at some critical energy**
- **EFT validity stops at the energy Λ**, which represents the scale of new physics
  - if this effect is neglected in data analyses, resulting limits on Wilson coefficients are typically too stringent
- **what technique** should be applied to provide results that are not too optimistic, if unitarity questions are neglected?
- how is the unitarity issue treated **when combining several analyses**?
- how do we balance the accounting of unitarity bounds with the **need for an easily-usable result**?

M. Szleper
EFT validity issues in Vector Boson Scattering data analysis

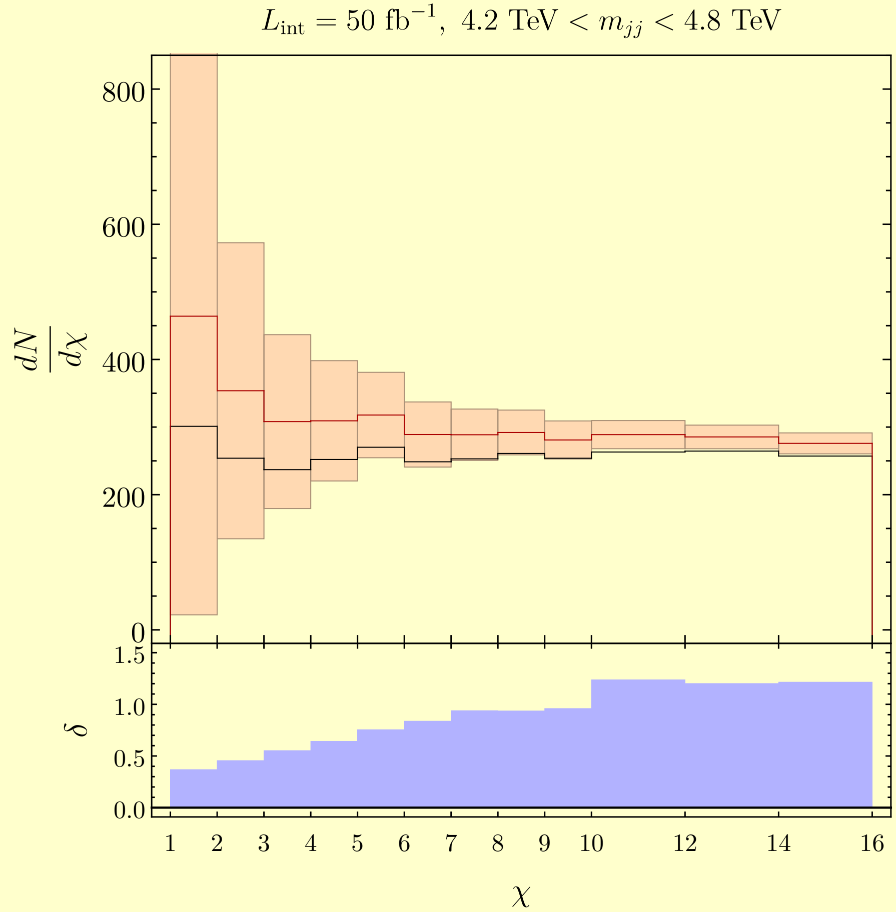
EFT validity

Proposal: Use dim6^2 as proxy for theory error and (unknown) dim8

Alte, König, Shepherd ’17,18

Sample pheno study for di-jet prod.:

$\chi = \exp(|y_1 - y_2|)$



Multi-boson production at lepton colliders

CLIC: e^+e^- with up to 3 TeV
μCol: $\mu^+\mu^-$ with up to 30 TeV

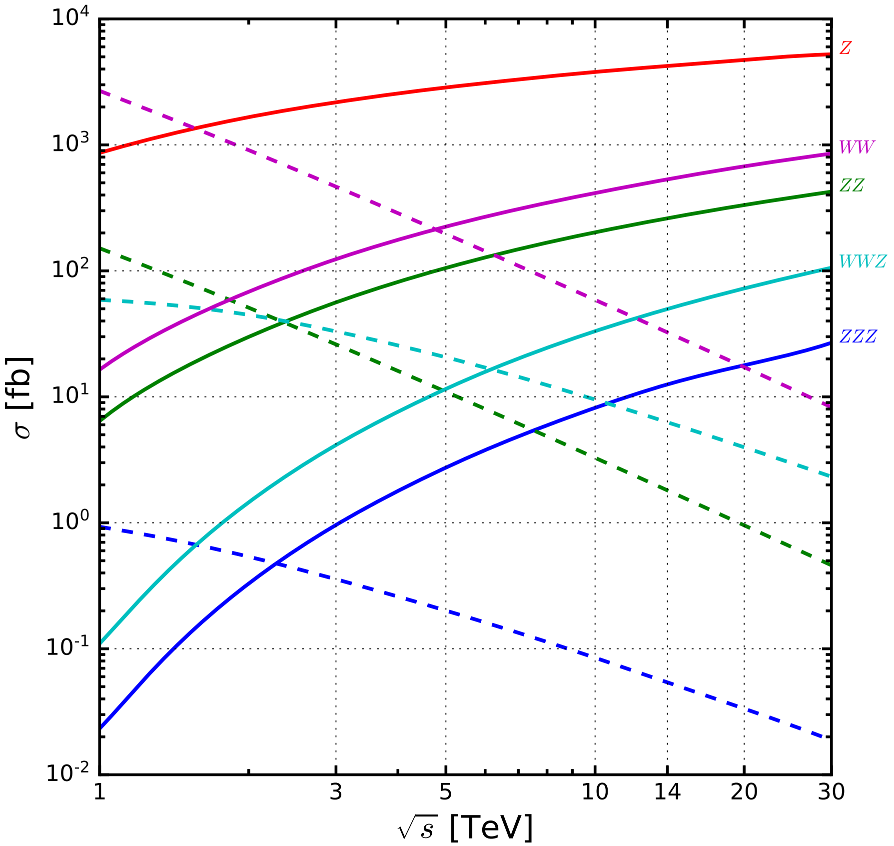
VBF/VBS dominates at $\sqrt{s} \gtrsim$ few TeV

EW PDFs provide good approx.
(prob. for "finding" W/Z in e/μ)

Can be computed perturbatively,
but resums $\log(s/M_V^2)$

Also may need **EW parton shower** for final states

Costantini et al. '20

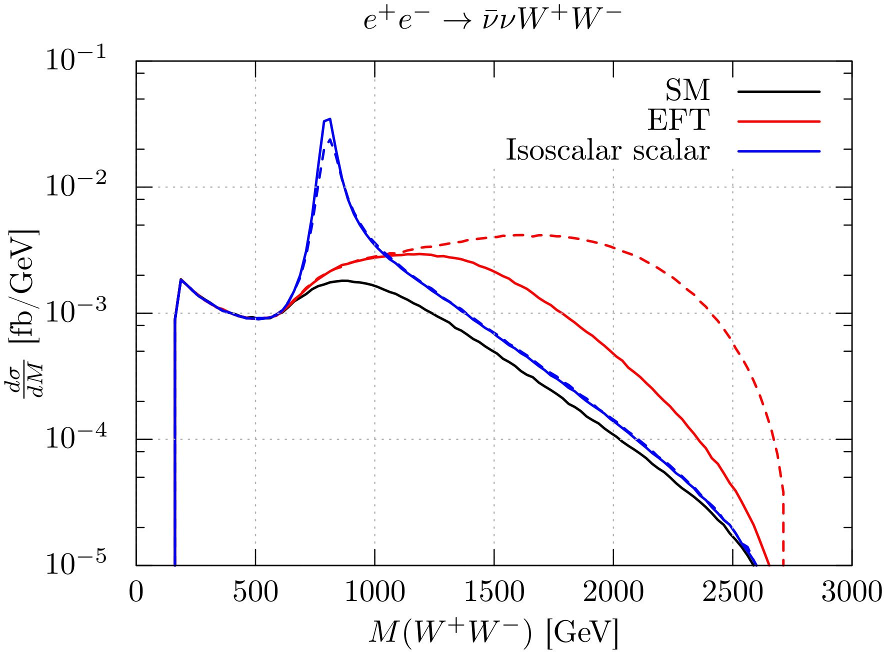


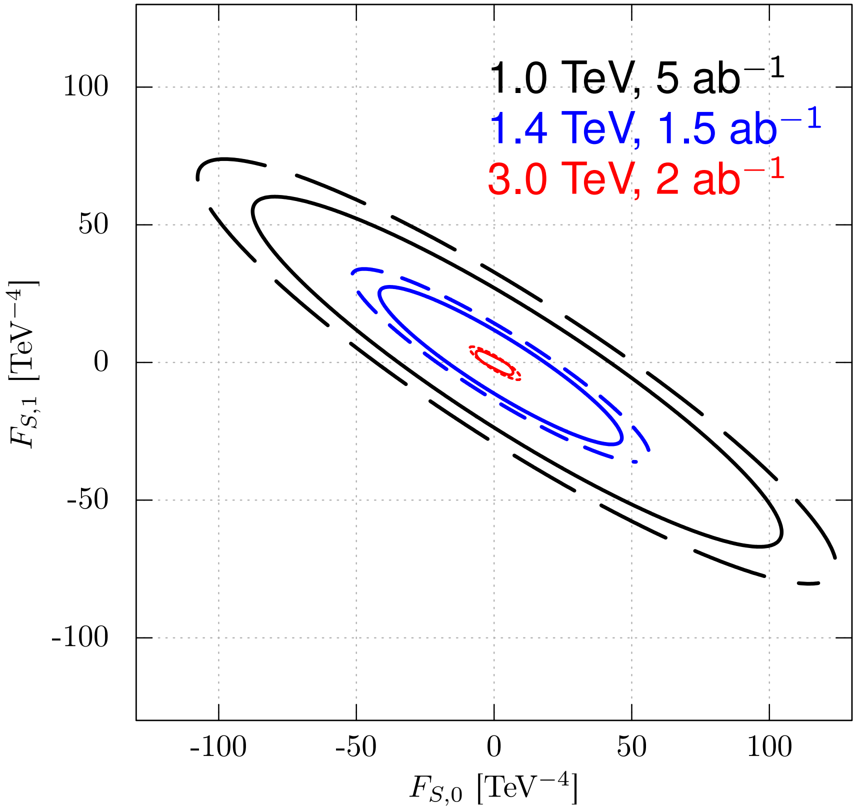
EFT validity

Sensitivity to new physics in VBS at CLIC:
EFT scale $\Lambda \lesssim 1$ TeV

→ EFT breaks down (need full model)

Fleper, Kilian, Reuter, Sekulla ’16





$$\mathcal{L}_{S,0} = F_{S,0}\,\mathrm{tr}\left[(\mathbf{D}_\mu\mathbf{H})^\dagger(\mathbf{D}_\nu\mathbf{H})\right]\,\mathrm{tr}\left[(\mathbf{D}^\mu\mathbf{H})^\dagger(\mathbf{D}^\nu\mathbf{H})\right]$$

$$\mathcal{L}_{S,1} = F_{S,1}\,\mathrm{tr}\left[(\mathbf{D}_\mu\mathbf{H})^\dagger(\mathbf{D}^\mu\mathbf{H})\right]\,\mathrm{tr}\left[(\mathbf{D}_\nu\mathbf{H})^\dagger(\mathbf{D}^\nu\mathbf{H})\right]$$

Global SMEFT fits

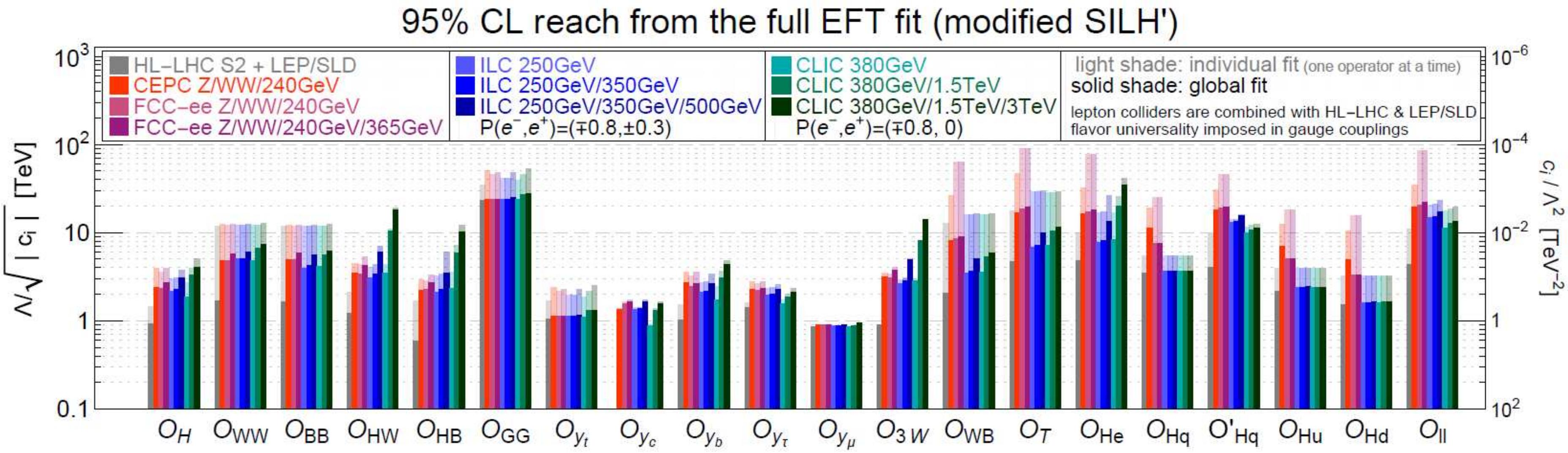
- Higher-dim. ops. constructed with SM fields

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{c_{\nu m}}{\Lambda}\mathcal{O}_{\nu m} + \frac{1}{\Lambda^2}\sum_i c_i \mathcal{O}_i^{(6)} + \ldots$$

- Present exp. data with minimal model assumption; Framework for comparing experiments

- More operators than observables
  → Need to make assumptions, e.g. U(3) or U(2) flavor universality

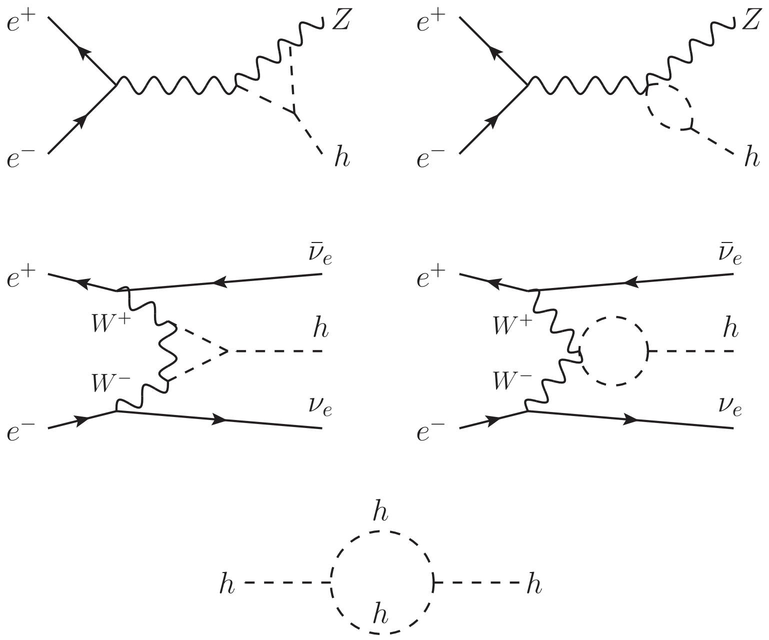
- Correlations between sectors (e.g. Higgs and EW)

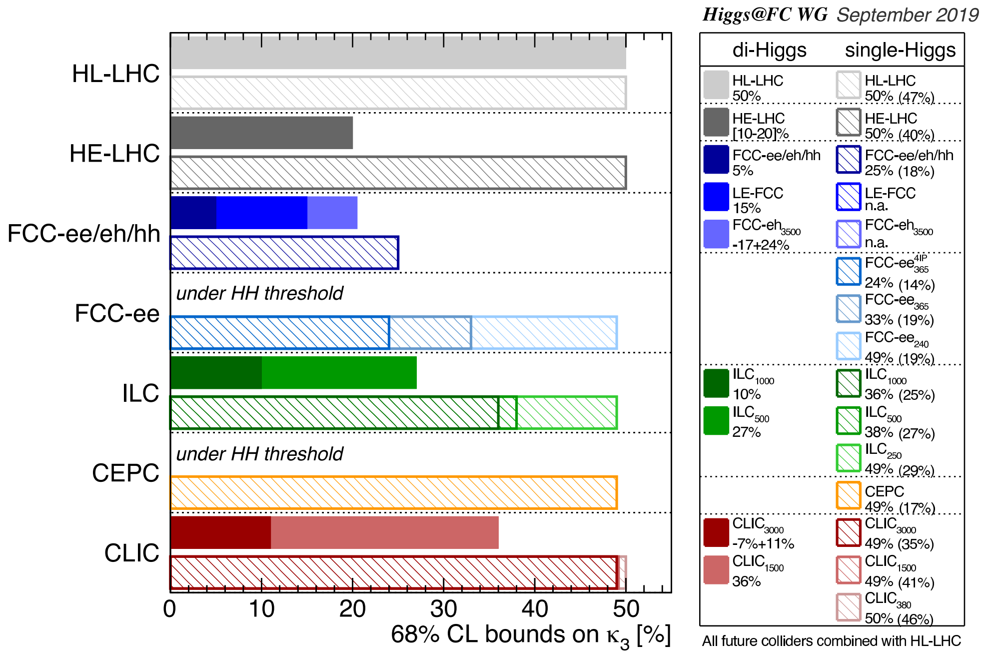


de Blas, Durieux, Grojean, Gu, Paul ’19

Higgs self-coupling

HH production vs. loop effects



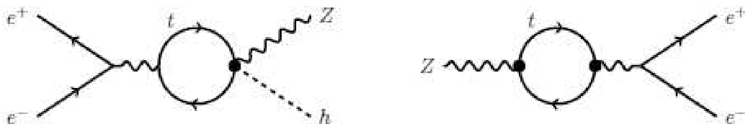


de Blas et al. ’19

- Spoiled by other loop effects?

Top operators

Top higher-dim. operators in loop diagrams:



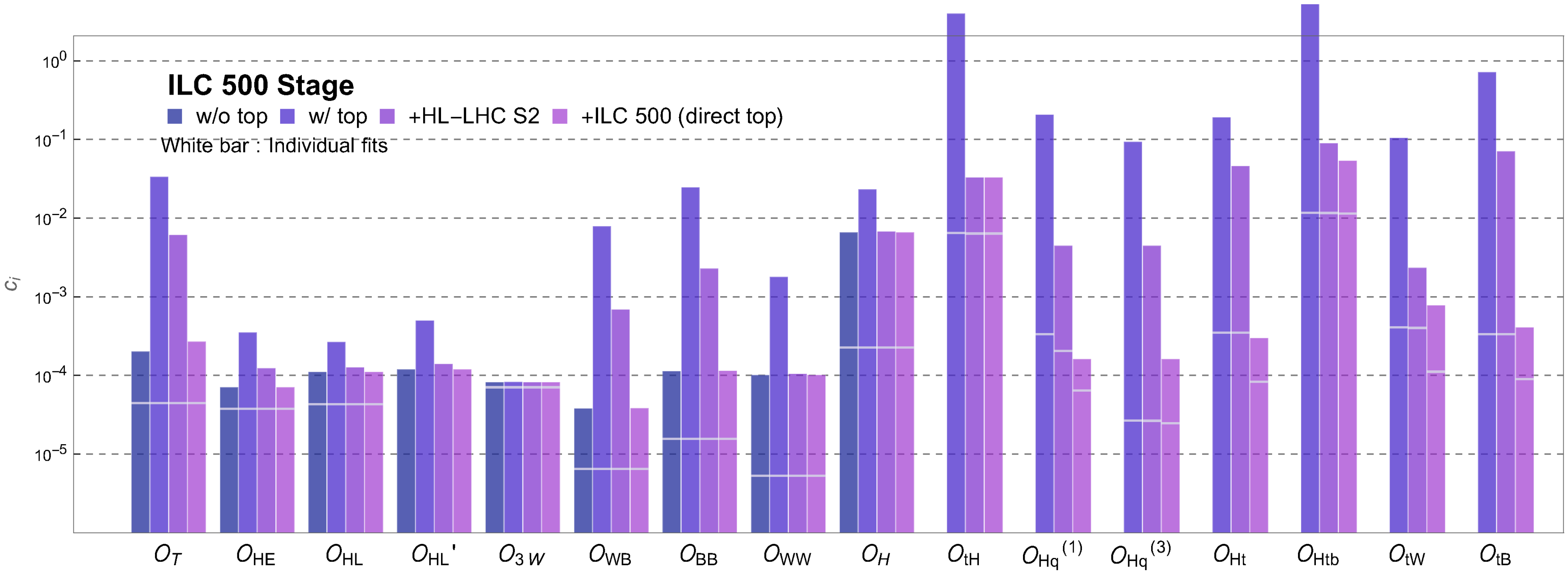
$$\mathcal{O}_{tH} = (\Phi^\dagger\Phi)(\bar{Q}t\tilde{\Phi}), \qquad \mathcal{O}^{(1)}_{Hq} = (\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{Q}\gamma^\mu Q),$$

$$\mathcal{O}^{(3)}_{Hq} = (\Phi^\dagger i \overleftrightarrow{D}^a_\mu \Phi)(\bar{Q}\gamma^\mu \tau^a Q), \qquad \mathcal{O}_{Ht} = (\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{t}\gamma^\mu t),$$

$$\mathcal{O}_{Htb} = (\tilde{\Phi}^\dagger i D_\mu \Phi)(\bar{t}\gamma^\mu b),$$

$$\mathcal{O}_{tW} = (\bar{Q}\sigma^{\mu\nu}t)\tau^a\tilde{\Phi}W^a_{\mu\nu}, \qquad \mathcal{O}_{tB} = (\bar{Q}\sigma^{\mu\nu}t)\tilde{\Phi}B_{\mu\nu},$$

Jung, Lee, Perell, Tian, Vos ’20



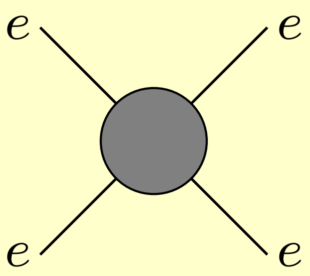
Global SMEFT fits: Open questions

- Full and consistent treatment of all ops. in VV prod ?
- Include Γ_H as free parameter (from exotic BSM decay channels) ?
- How to include EFT validity constraints; theory errors ?
- Include 4-fermion operators (e.g. from EW 2→2 processes) ?
- Include $\not{C}\!\not{P}$ operators (and $\not{C}\!\not{P}$ observables) ?
- SMEFT contributions in backgrounds and PDF fits?
- Impact of low-energy experiments and lepton-hadron colliders ?

Low-energy PV: EFT interpretation

4-lepton operator

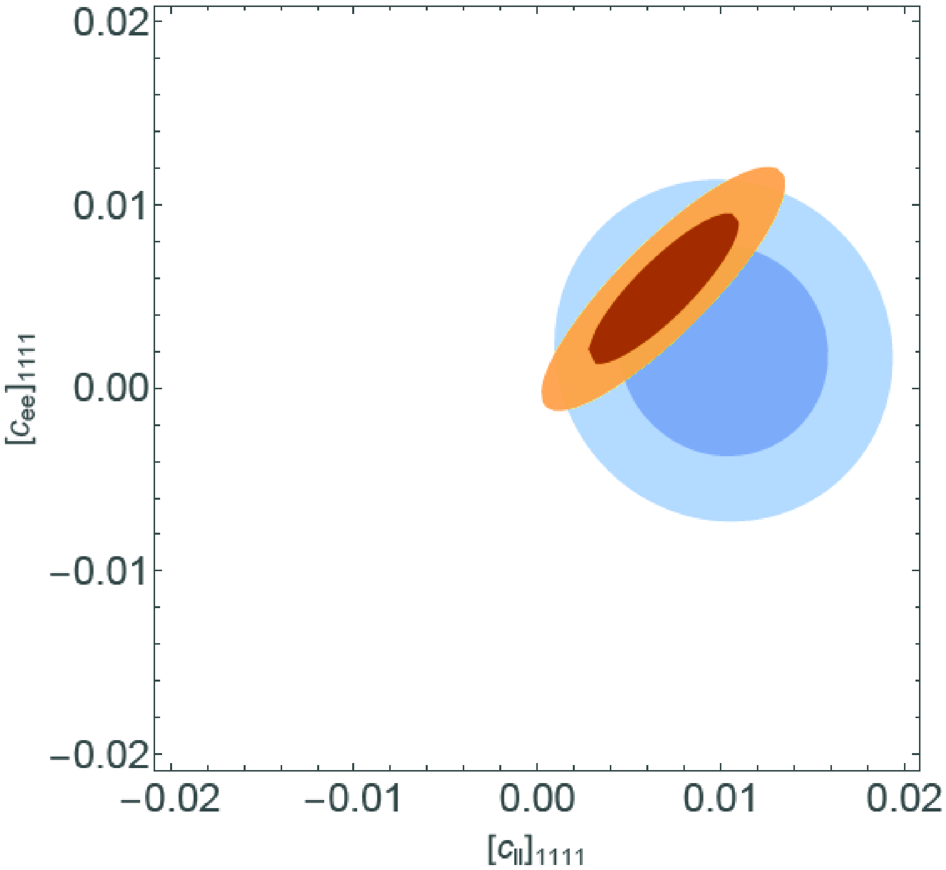
$$\frac{4\pi}{\Lambda^2}\,[\bar{e}\gamma^\mu\gamma_5 e]\,[\bar{e}\gamma_\mu e]$$



E158: $\Lambda \lesssim 17$ TeV

MOLLER: $\Lambda \lesssim 39$ TeV

Erler, Horowitz, Mantry, Souder '14



Falkowski, Gonzalez-Alonso, Mimouni '17
Falkowski et al. '18

$$\frac{c_{ee}}{v^2}\,[\bar{e}\gamma^\mu P_R e]\,[\bar{e}\gamma_\mu P_R e]$$

$$\frac{c_{\ell\ell}}{v^2}\,[\bar{e}\gamma^\mu P_L e]\,[\bar{e}\gamma_\mu P_L e]$$

Electron-Ion Collider (EIC)

DY+EIC: Best Bounds Yet

Fitting Methodology (68% CL):

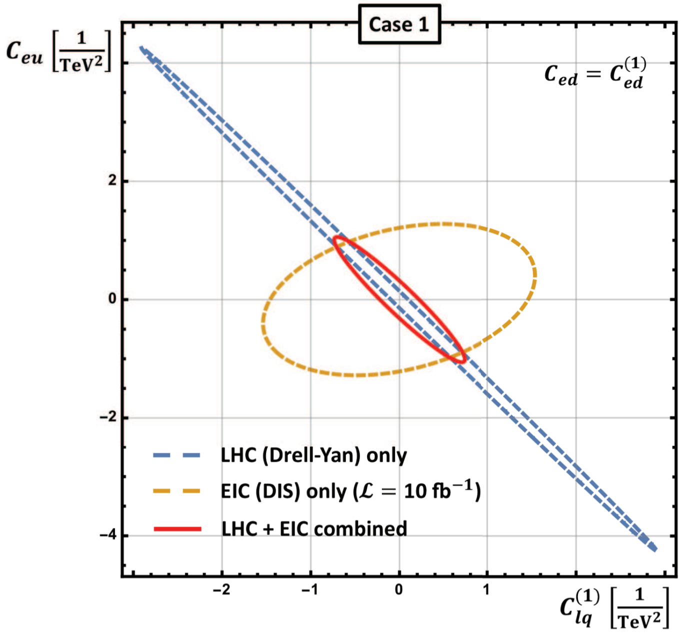
For EIC/DIS:
- Integrate over (x, Q^2) bins
- Assume uncorrelated errors
- $\Delta\sigma_{SMFT}$ measures deviation from SM

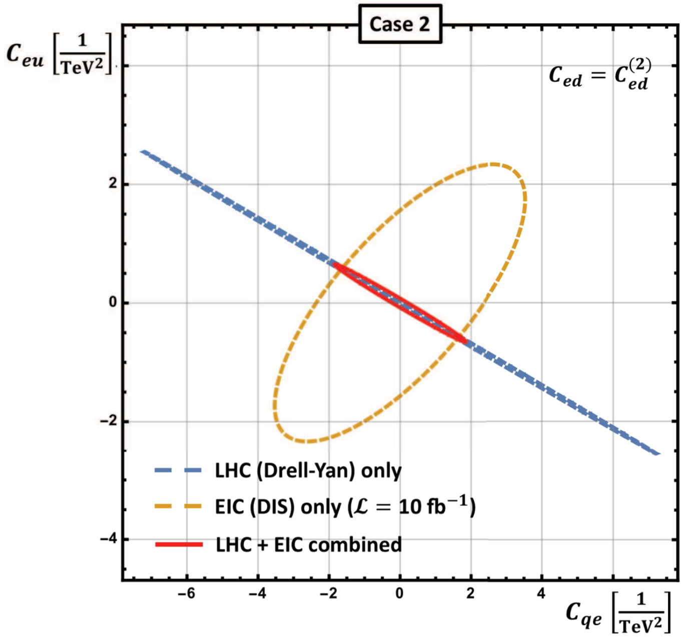
For LHC/DY:
- Integrate over m_{ll} bins
- Error Correlation from *ATLAS*
- Data deviation from SM

ATLAS Collab. (1606.01736)

Define χ^2 test statistic (DIS case):

$$\chi^2 = \sum_{\text{Bins}} \sum_{\text{Pol}/\pm} \left(\frac{\Delta\sigma_{SMFT}}{\Delta\sigma_{Err}}\right)^2$$





Be involved!

SM input parameters

- $M_{\mathsf{Z}},\ \Gamma_{\mathsf{Z}}$: From $\sigma(\sqrt{s})$ lineshape
- m_{t}: Current status $\delta m_{\mathsf{t}} \sim 0.4$ GeV at LHC
  $\rightarrow$ Additional theory uncertainties?

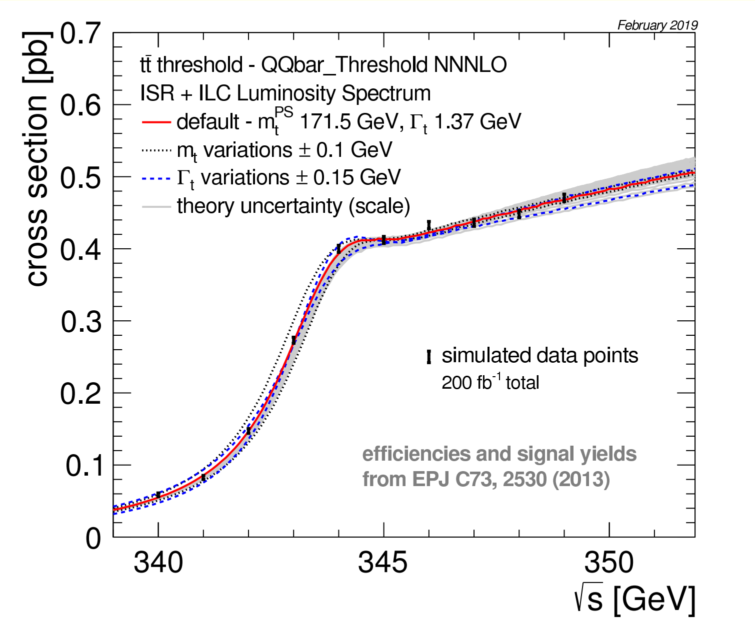
PDG '18

Butenschoen et al. '16

Ferrario Ravasio, Nason, Oleari '18

From $e^+e^- \rightarrow t\bar{t}$ at $\sqrt{s} \sim 350$ GeV:

$\delta m_{\mathsf{t}} \lesssim 50$ MeV



Simon '19

SM input parameters

- M_Z, Γ_Z: From $\sigma(\sqrt{s})$ lineshape
- m_t: Current status $\delta m_t \sim 0.4$ GeV at LHC — PDG '18

  $\rightarrow$ Additional theory uncertainties? — Butenschoen et al. '16

  Ferrario Ravasio, Nason, Oleari '18

  From $e^+e^- \rightarrow t\bar{t}$ at $\sqrt{s} \sim 350$ GeV:

  $\delta m_t \lesssim 50$ MeV
- m_b, m_c: From quarkonia spectra using Lattice QCD

  $\delta m_b^{\overline{\text{MS}}} \sim 30$ MeV, $\delta m_b^{\overline{\text{MS}}} \sim 25$ MeV — LHC HXSWG '16

  $\rightarrow$ estimated improvements $\delta m_b^{\overline{\text{MS}}} \sim 13$ MeV, $\delta m_b^{\overline{\text{MS}}} \sim 7$ MeV

  Lepage, Mackenzie, Peskin '14

SM input parameters

- α_{s}:
  - Most precise determination using Lattice QCD:

    $\alpha_{\mathsf{s}} = 0.1185 \pm 0.0008$ ALPHA '17

    $\alpha_{\mathsf{s}} = 0.1172 \pm 0.0011$ Zafeiropoulos et al. '19

  - e^+e^- event shapes and DIS: $\alpha_{\mathsf{s}} \sim 0.114$

    Alekhin, Blümlein, Moch '12; Abbate et al. '11; Gehrmann et al. '13

    → Subject to sizeable non-pertubative power corrections

    → Systematic uncertainties in power corrections?

  - Electroweak precision ($R_\ell = \Gamma_{\mathsf{Z}}^{\mathsf{had}}/\Gamma_{\mathsf{Z}}^{\ell}$):

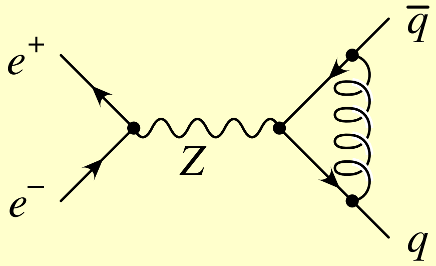
    $\alpha_{\mathsf{s}} = 0.120 \pm 0.003$ PDG '18

    → No (negligible) non-perturbative QCD effects

    FCC: $\delta R_\ell \sim 0.001$

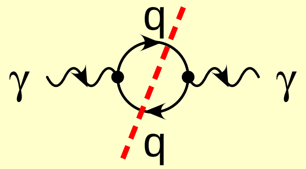
    $\Rightarrow \quad \delta\alpha_{\mathsf{s}} < 0.0002$ (subj. to theory error)

    Caviat: R_ℓ could be affected by new physics



SM input parameters

- $\Delta\alpha \equiv 1 - \frac{\alpha(0)}{\alpha(M_\mathrm{Z})} \approx 0.059 = 0.0315_\mathrm{lept} + 0.0276_\mathrm{had}$

  Hadronic effects from $e^+e^- \to$ had. data

  Last 5 years: new data from BaBar, VEPP, BES
  $\to$ Robust precision $\sim 10^{-4}$

  Davier et al. '17,19; Jegerlehner '17
  Keshavarzi, Nomura, Teubner '18

  With future data from BES, VEPP, Belle and improvements in QCD:
  $\delta(\Delta\alpha) \sim 5 \times 10^{-5}$

  Jegerlehner '19

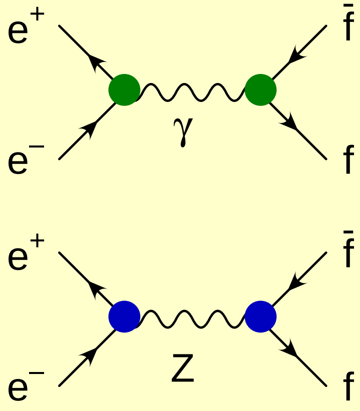
- Direct determination from $e^+e^- \to \mu^+\mu^-$ off the Z peak

  Janot '15

  (i.e. $A_\mathrm{FB}^{\mu\mu}$ at $\sqrt{s} \sim 88$ GeV and $\sqrt{s} \sim 95$ GeV)
  $\to \delta_\mathrm{th}(\Delta\alpha_\mathrm{had}) \sim 3 \times 10^{-5}$

  $$\sigma \propto (|g_\mathrm{V}^\ell|^2 + |g_\mathrm{A}^\ell|^2)^2 + (s - M_\mathrm{Z}^2)\,\alpha(M_\mathrm{Z})\underset{\substack{\uparrow\\ \text{determine}\\ \text{from Z pole}}}{|g_\mathrm{V}^\ell|^2} + \ldots$$

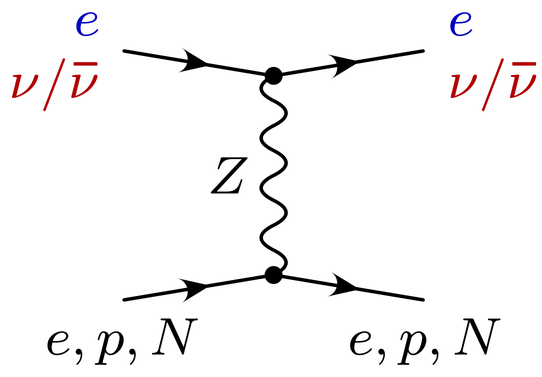
  $\to$ Requires multi-loop theory calculations

Low-energy parity violation

- Polarized ee, ep, ed scattering ($Q_W(e)$, $Q_W(p)$, eDIS)
  E158 '05; Qweak '17; JLab Hall A '13
- $\nu N/\bar{\nu}N$ scattering NuTeV '02
- Atomic parity violation ($Q_W(^{133}\text{Cs})$) Wood et al. '97 Guéna, Lintz, Bouchiat '05

→ Test of running $\overline{\text{MS}}$ weak mixing angle $\sin^2\bar{\theta}(\mu)$



$$g_{\text{AV}}^{ef}\,[\bar{e}\gamma^\mu\gamma_5 e]\,[\bar{f}\gamma_\mu f]$$
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$$g_{\text{AV}}^{ef} = \frac{1}{2} - 2|Q_f|\sin^2\bar{\theta}(\mu)$$
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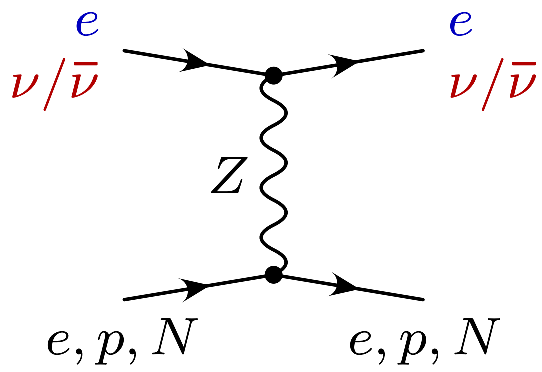
- Future experiments:

  MOLLER (ee), P2, SoLID (ep)



$$g^{ef}_{\text{AV}} \, [\bar{e}\gamma^{\mu}\gamma_5 e] \, [\bar{f}\gamma_{\mu} f]$$
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