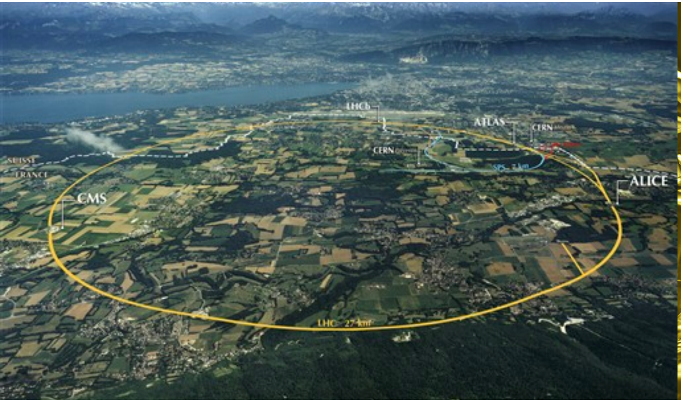
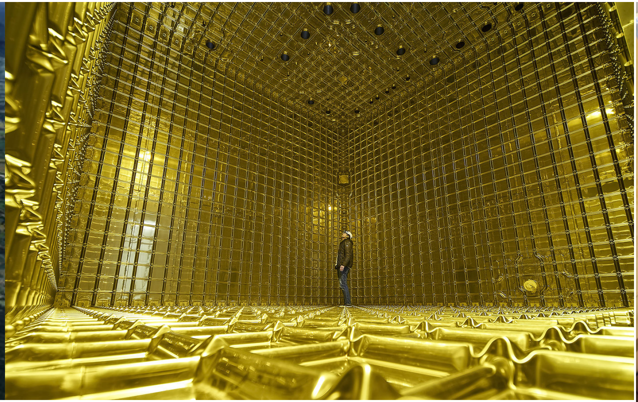
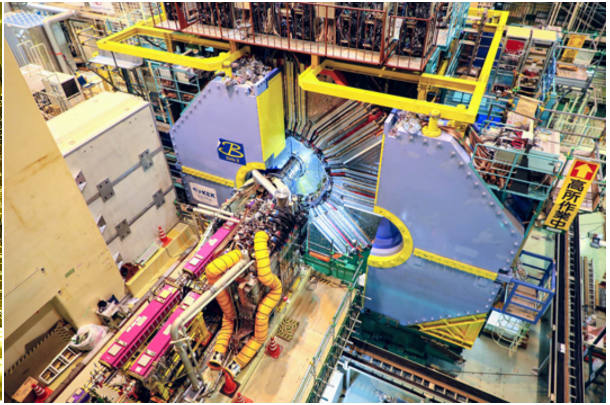
Particle Physics Highlights and Challenges

Beate Heinemann

DESY and Albert-Ludwigs-Universität Freiburg







HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

ECFA
NuPECC
ApPEC

JENAS-2019
Joint ECFA-NuPECC-ApPEC Seminar
October 14-16, 2019 - LAL Orsay, France

Outline

(personal selection of material)

- Electroweak Physics
- Strong Interactions
- Flavour Physics
- Neutrino Physics
- Dark Matter and Dark Sectors
- Hierarchy Problem

CERN-ESU-004
30 September 2019

Physics Briefing Book

Input for the European Strategy for Particle Physics Update 2020

Electroweak Physics: Richard Keith Ellis[1], Beate Heinemann[2,3] *(Conveners)*
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Neutrino Physics & Cosmic Messengers: Stan Bentvelsen[45], Marco Zito[46,47] *(Conveners)*
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Beyond the Standard Model: Gian F. Giudice[20], Paris Sphicas[20,52] *(Conveners)*
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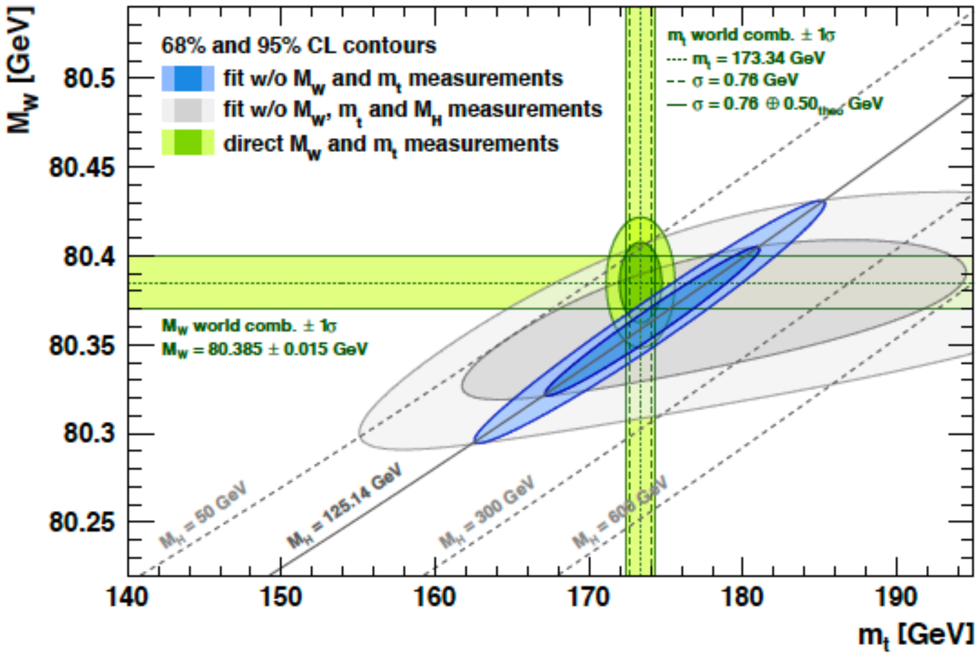
Editors: Halina Abramowicz[71], Roger Forty[20], and the Conveners

Material based largely on Physics Briefing Book of European Strategy for Particle Physics Update 2020, released on Oct. 2nd 2019

Electroweak Interactions

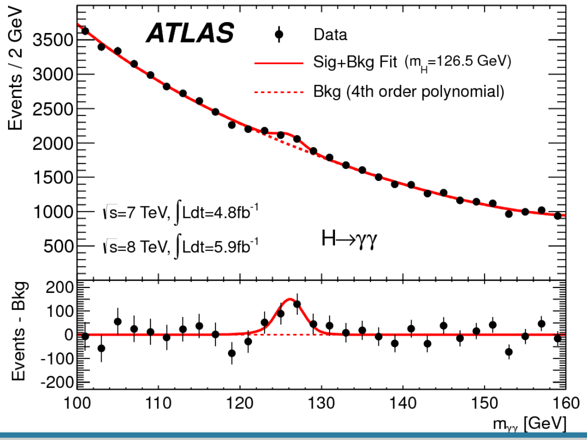
- Discovered mechanism to break electroweak symmetry
  - Higgs mechanism
- Provides technical solution but very unsatisfactory
- Higgs sector contains 15 ad-hoc parameters
  - Only 3 in gauge sector!

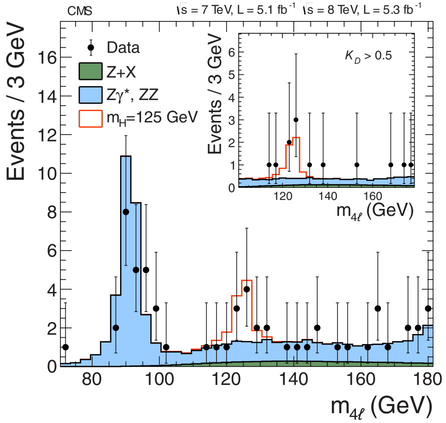


G. Giudice: *"Essentially all problems or unsatisfactory aspects of the Standard Model are ultimately related to the structure of Higgs interactions"*

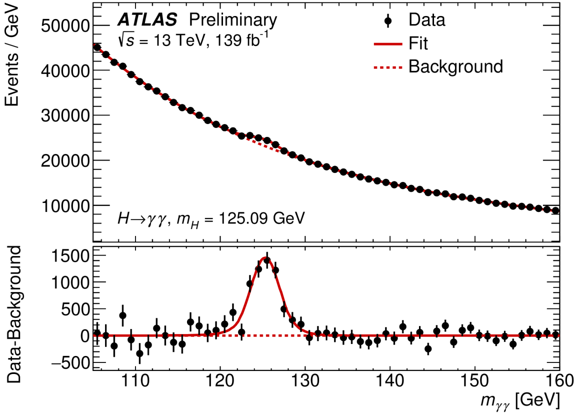
Higgs Boson: 2012 vs 2019

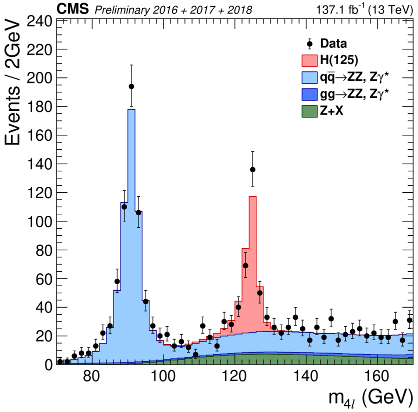
July 2012:
~10 fb^{-1}
@7-8 TeV



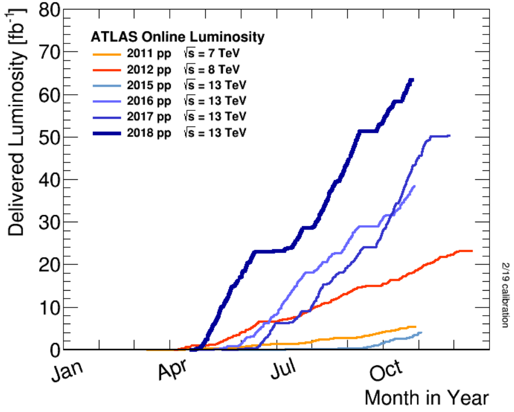


Today:
~140 fb^{-1}
@13 TeV

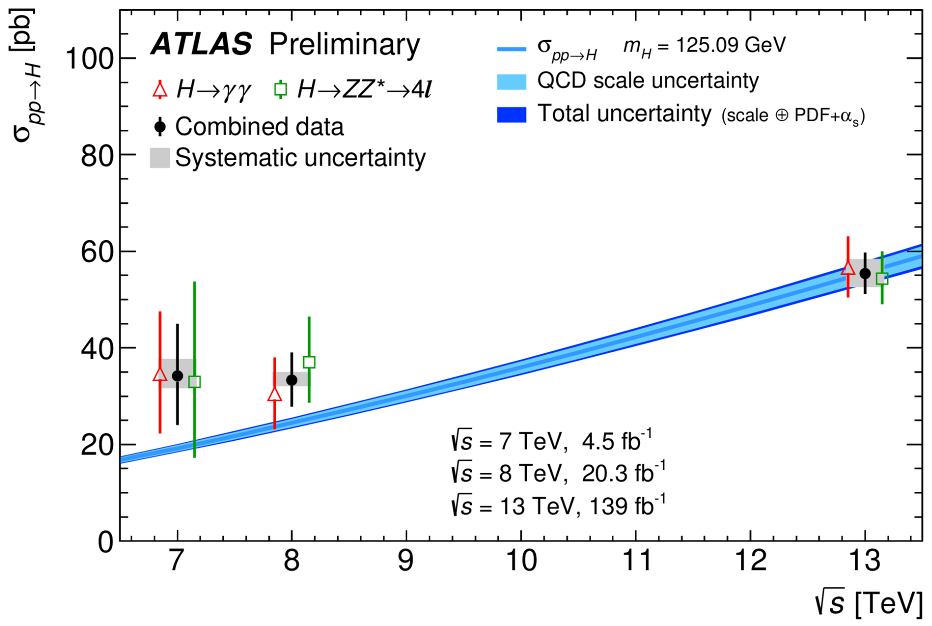


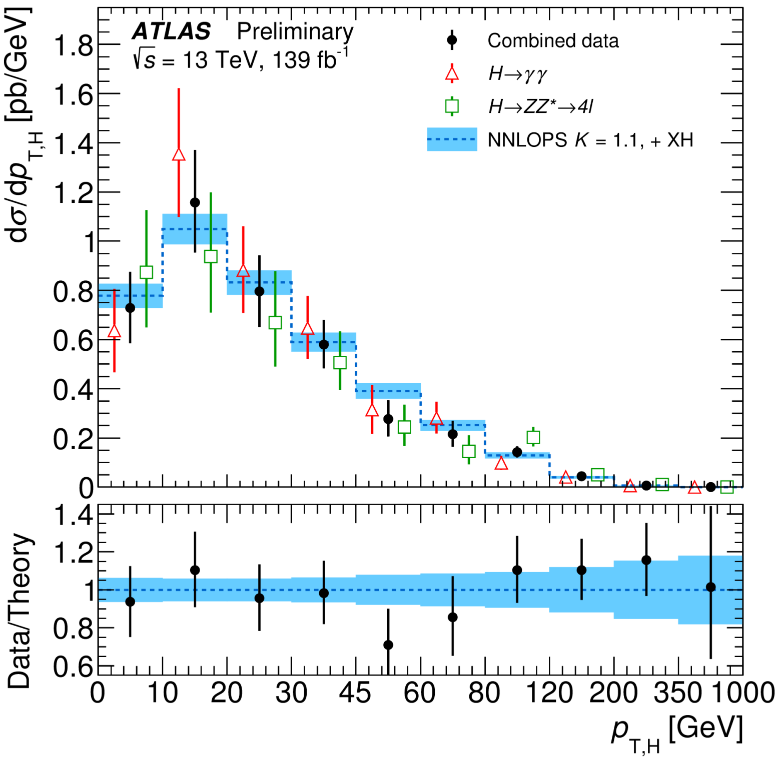


LHC luminosity



Differential H Cross Section Measurements





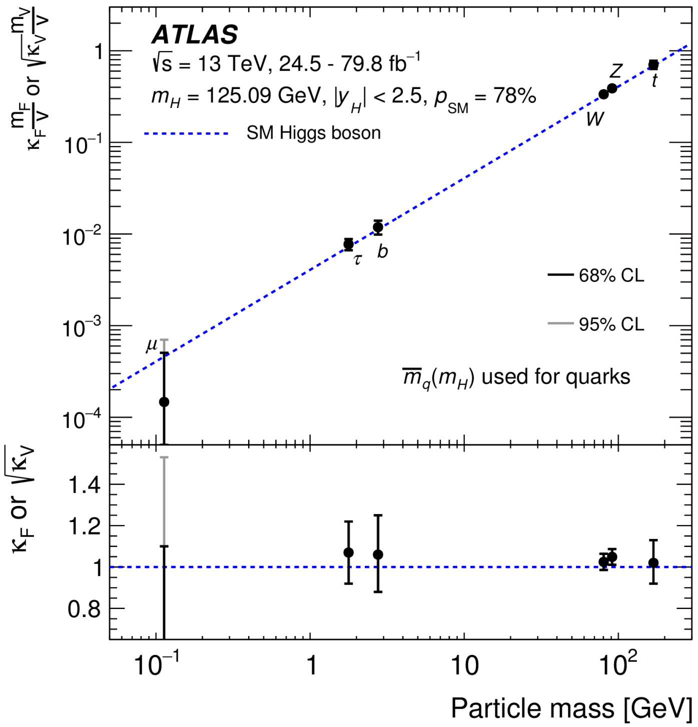
σ_{data}=55.4±4.3 pb

σ_{SM} =55.6±2.5 pb (87% ggF, N^{3}LO and NLO EWK)

Higgs Couplings Today

Parameter	Result
κ_Z	1.10 ± 0.08
κ_W	1.05 ± 0.08
κ_b	$1.06^{+0.19}_{-0.18}$
κ_t	$1.02^{+0.11}_{-0.10}$
κ_τ	1.07 ± 0.15
κ_μ	< 1.53 at 95% CL

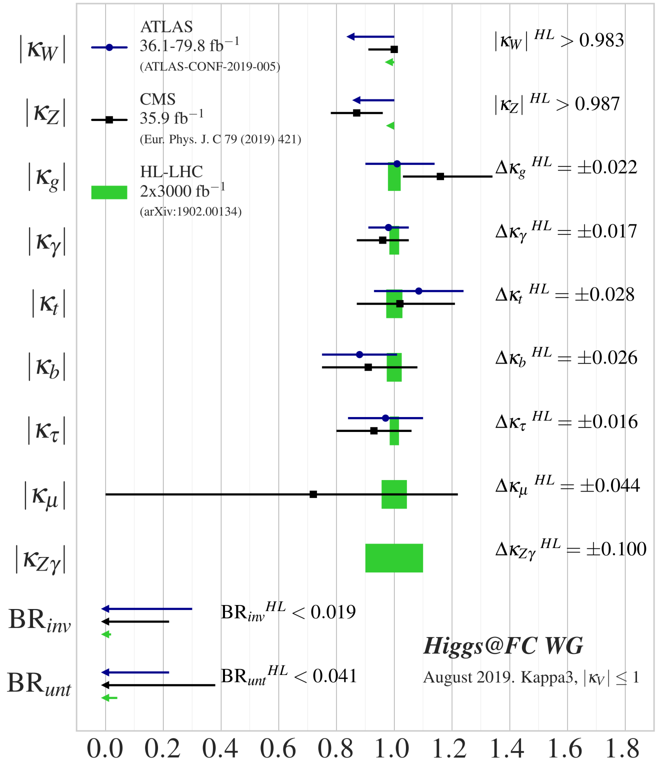
assumes BR_{BSM}=0



- Gauge bosons and 3rd gen fermions: δ≈10-20%

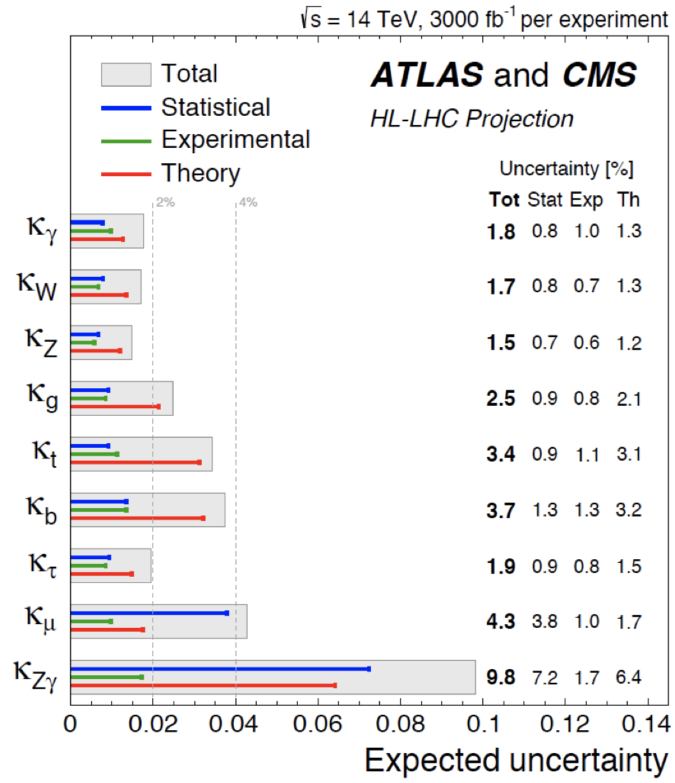
Current Results vs High-Luminosity LHC

LHC now vs HL-LHC



10%

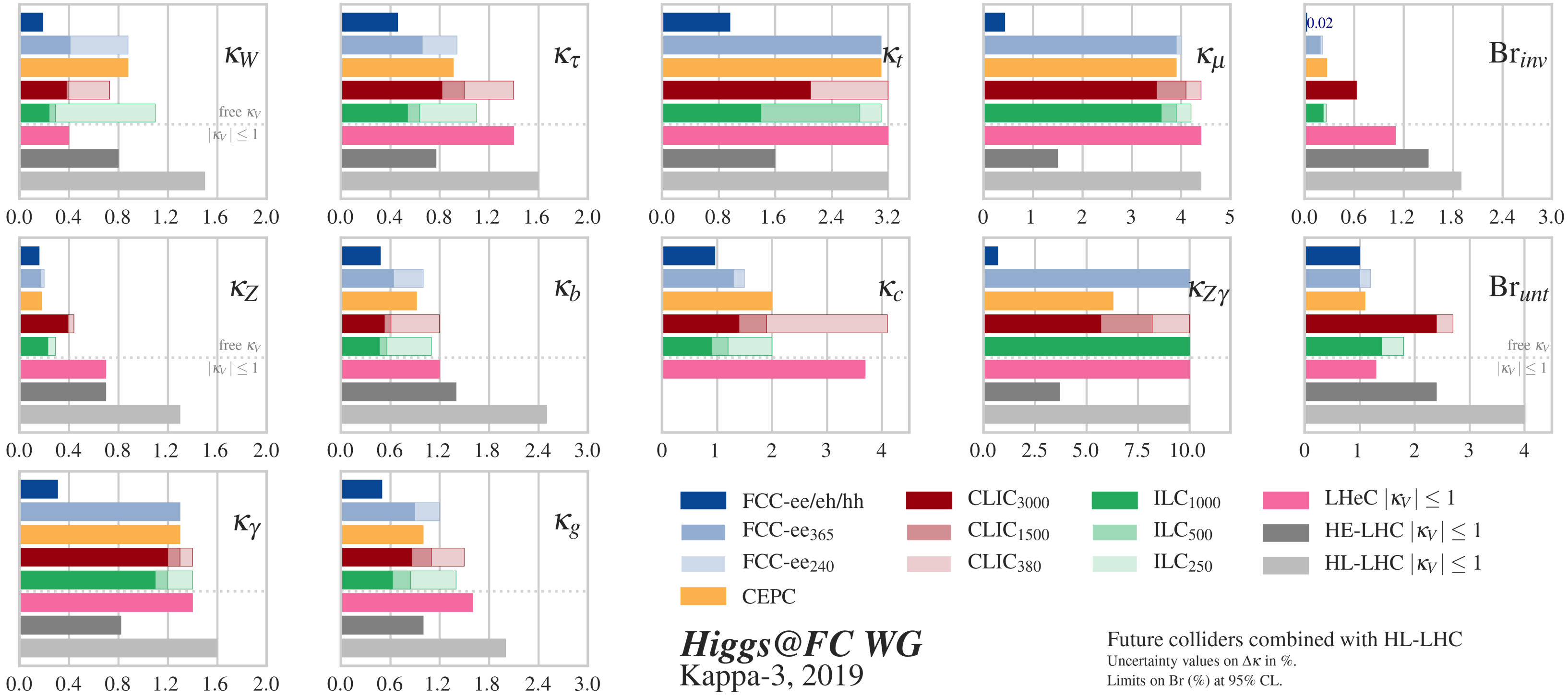
High Luminosity LHC (HL-LHC)



10%

Comparison of Future Colliders

arXiv:1905.03764



Requires also significant improvements in theoretical calculations

of "largely" improved H couplings (EFT)

NB: number of seconds/year differs: ILC 1.6×10^7, FCC-ee & CLIC: 1.2×10^7, CEPC: 1.3×10^7

		Factor ≥2	Factor ≥5	Factor ≥10	Years from T_0
Initial run	CLIC380	9	6	4	7
	FCC-ee240	10	8	3	9
	CEPC	10	8	3	10
	ILC250	10	7	3	11
2nd/3rd Run ee	FCC-ee365	10	8	6	15
	CLIC1500	10	7	7	17
	HE-LHC	1	0	0	20
	ILC500	10	8	6	22
hh	CLIC3000	11	7	7	28
ee,eh & hh	FCC-ee/eh/hh	12	11	10	>50

13 quantities in total

of "largely" improved H couplings (EFT)

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ee,eh & hh	FCC-ee/eh/hh	12	11	10	>50

13 quantities in total

About half the couplings improved by factor 5 already in initial run

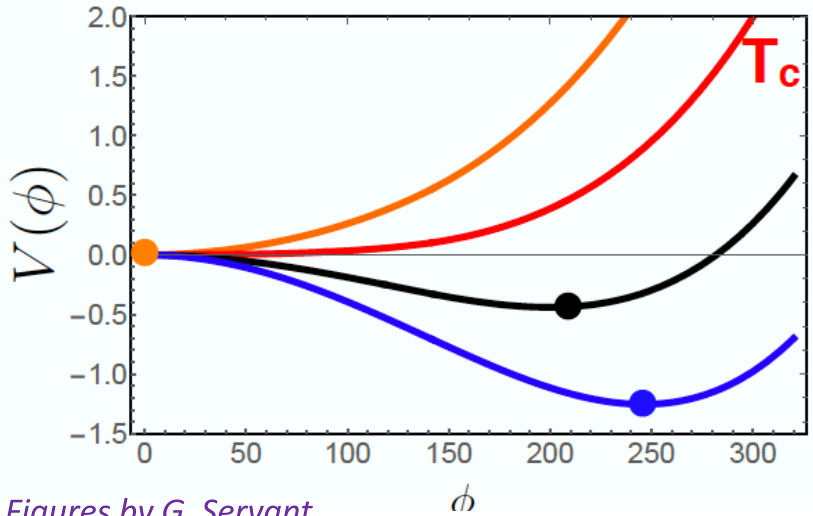
Electroweak potential

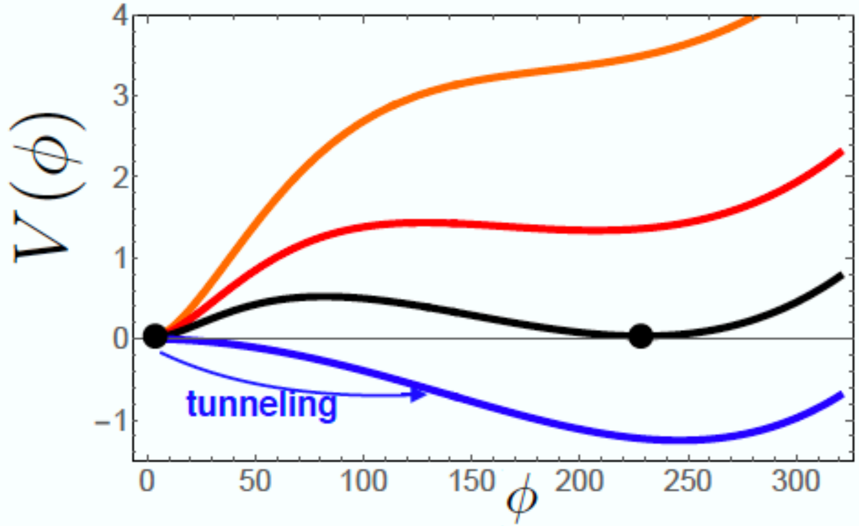
Standard Model

- Electroweak phase transition (EWPT) is a "smooth crossover"
- Electroweak symmetry restored for $T \geq T_C = 130$ GeV

Alternative idea

- Electroweak phase transition via tunneling: 1st order transition
  - Two phases co-exist
- Electroweak baryogenesis possible if strong 1st order transition $\frac{v(T_{\rm pt})}{T_{\rm pt}} \gtrsim 1.0$





Figures by G. Servant

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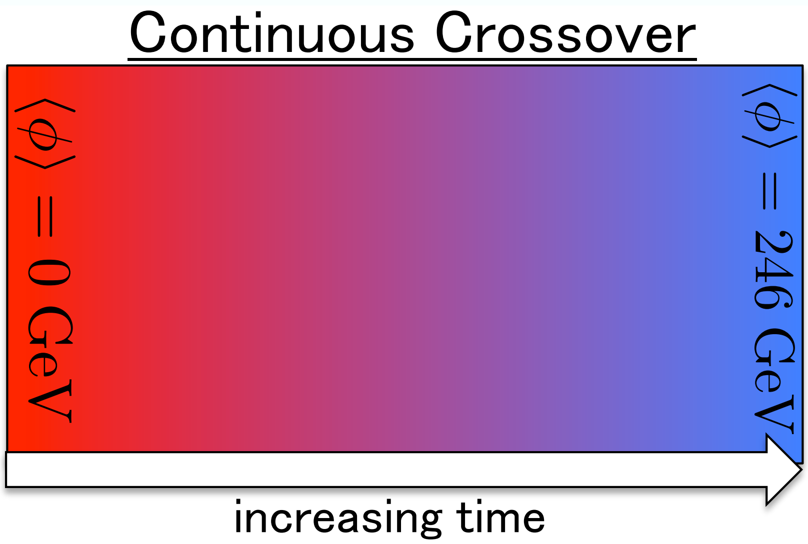
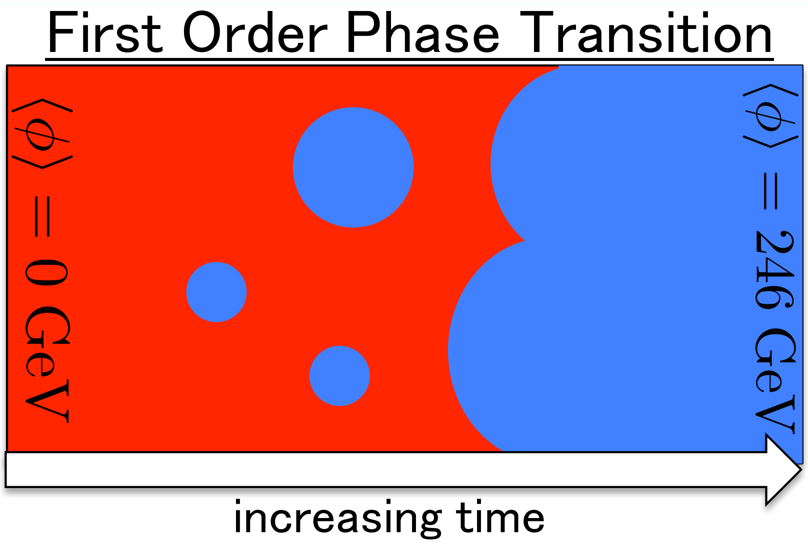
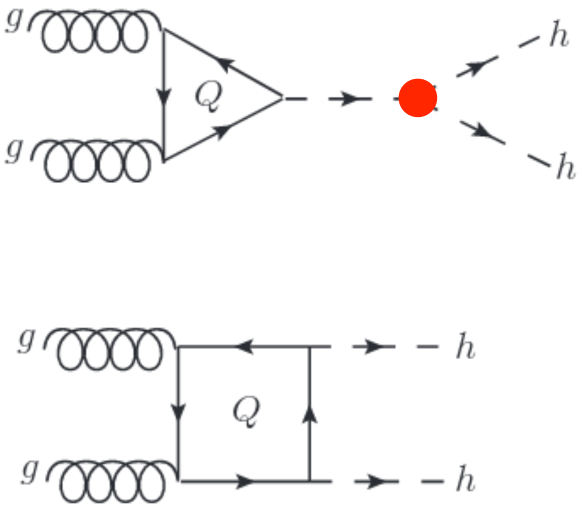
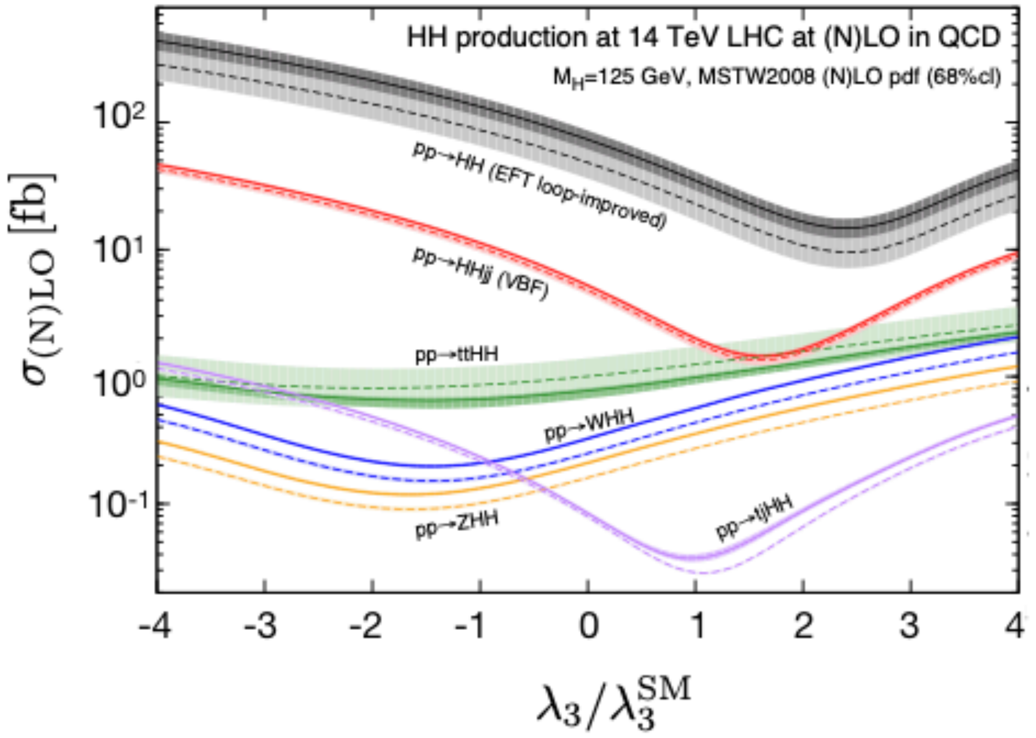




Measuring the Higgs self-coupling: LHC

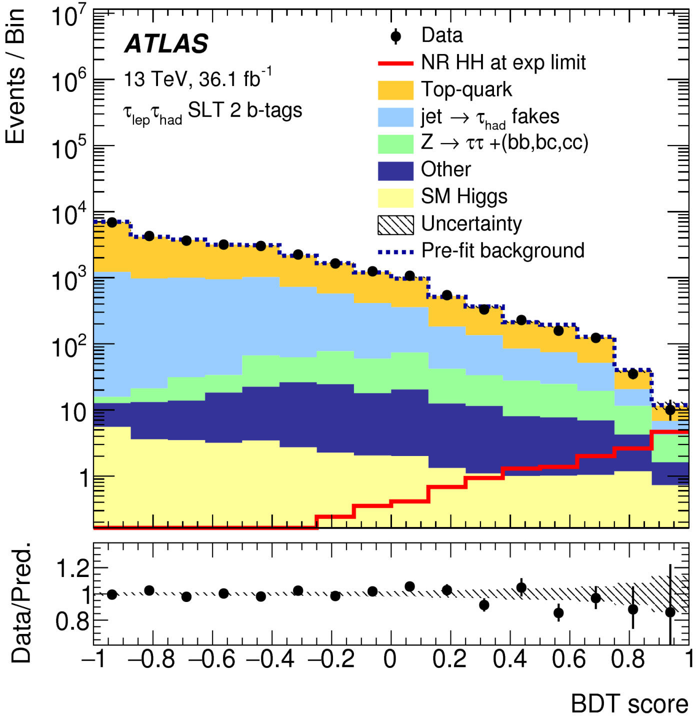
Hadron collider



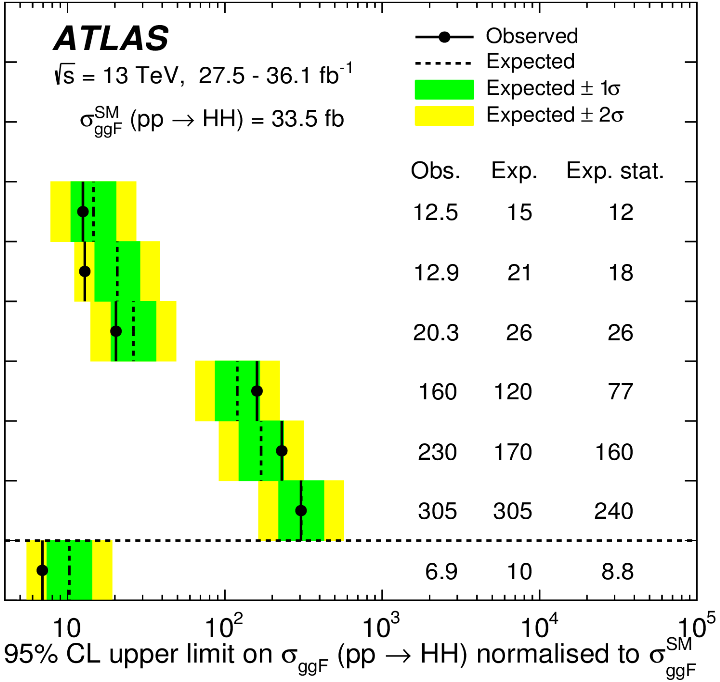


Di-Higgs Production: LHC results

HH→bbττ search result



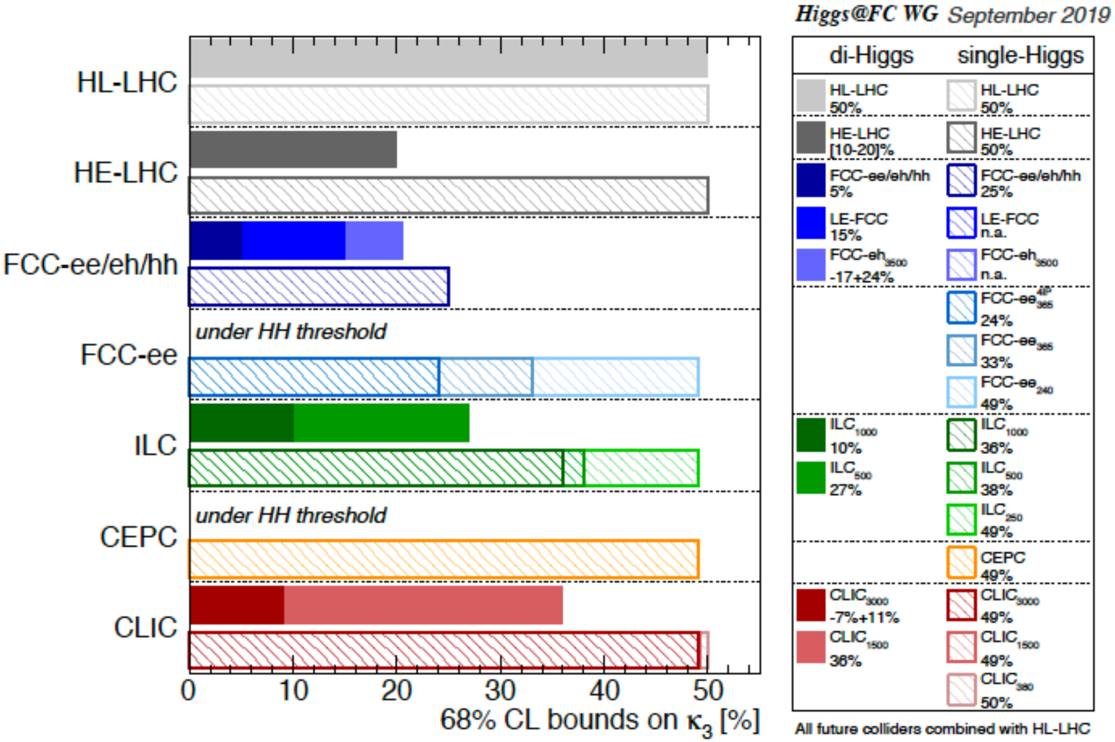
HH analyses combined



	Obs.	Exp.	Exp. stat.
HH→ $b\bar{b}\tau^+\tau^-$	12.5	15	12
HH→ $b\bar{b}b\bar{b}$	12.9	21	18
HH→ $b\bar{b}\gamma\gamma$	20.3	26	26
HH→ $W^+W^-W^+W^-$	160	120	77
HH→ $W^+W^-\gamma\gamma$	230	170	160
HH→ $b\bar{b}W^+W^-$	305	305	240
Combined	6.9	10	8.8

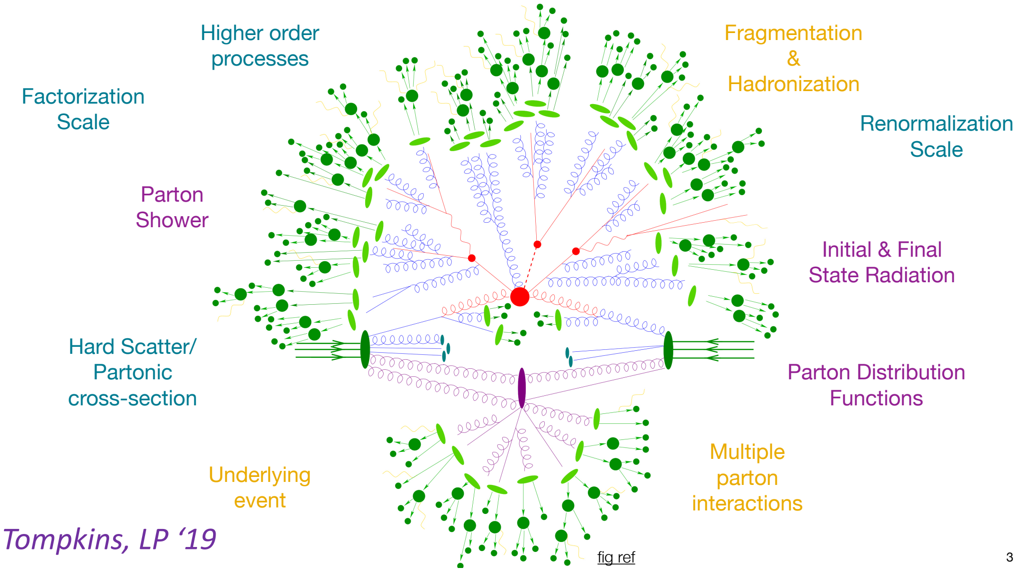
=> Upper limit at 95% CL: 6.9 x σ_{SM} => $-5<\kappa_\lambda<12$

Sensitivity to κ_λ: future colliders



- HL-LHC: ~50%
  - Already relevant for EWPT!
- Future high-energy colliders: ~5-10%

The Strong Interaction



L. Tompkins, LP '19

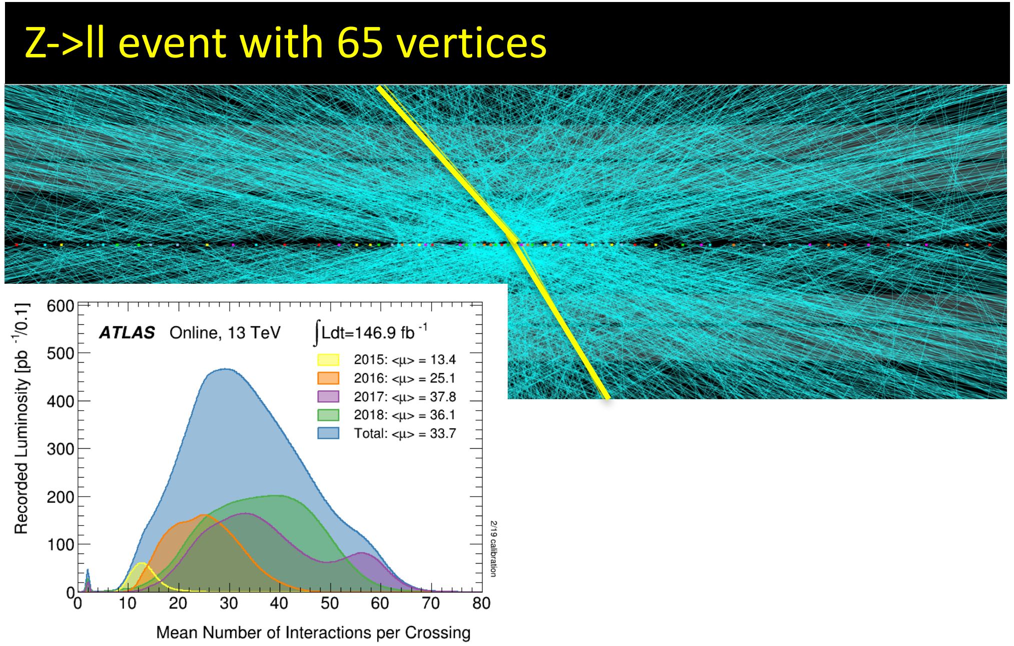
Conceptional aspects of QCD (closely related to nuclear physics)

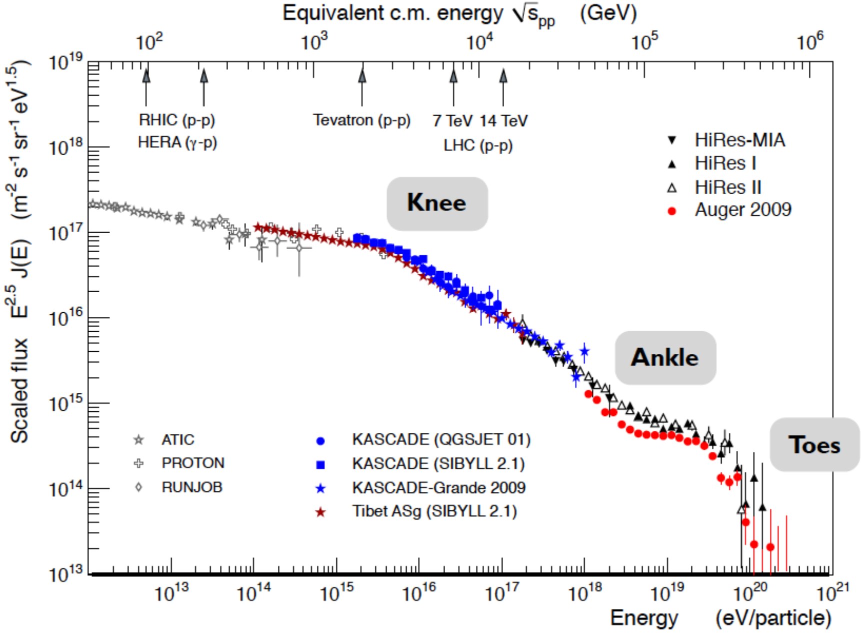
- Long-distance phenomena (e.g. confinement)
- Collective behaviour at high temperatures or densities
- Transition of high to low energies (e.g. hadronisation)

Practical aspects of QCD predictions

- **Soft interactions** constitute "noise" in high-pileup environment
- Parton flux in proton determined by **parton distribution functions (PDFs)**
- **Strong coupling constant** governs rate jet production at pp collider
- Precise predictions at hadron colliders require ever **higher order calculations**

Soft QCD processes



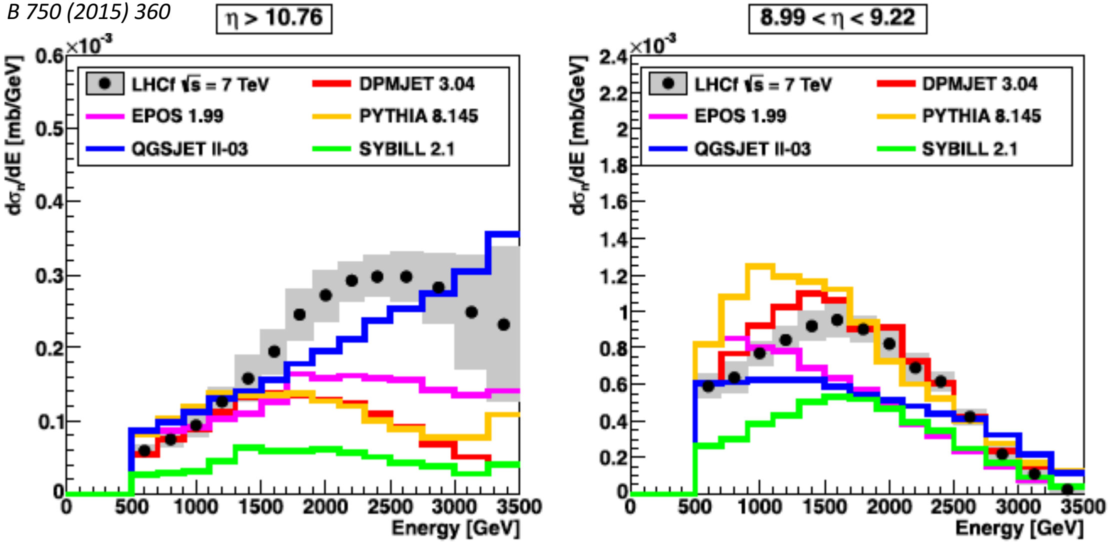


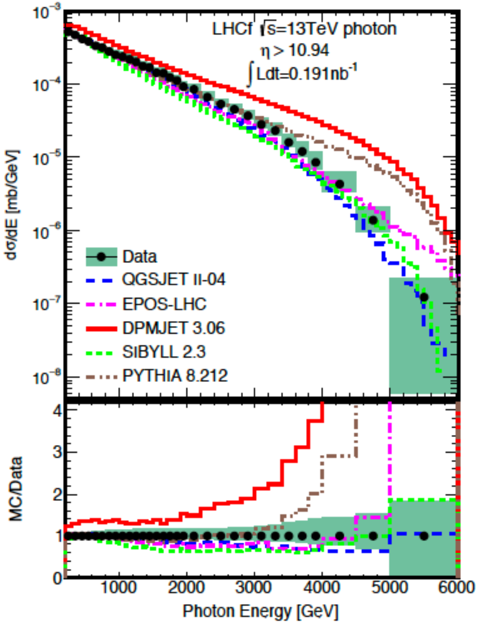
Relevant for understanding of pileup at LHC, for high energy astrophysics and for non-pertubative calculations

Neutral particles: forward n and γ production

Phys. Lett. B 780 (2018) 233

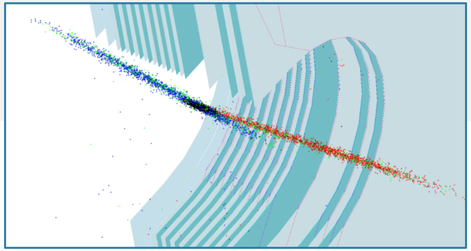
Phys. Lett. B 750 (2015) 360





- LHCf: dedicated experiment measuring production of neutral particles in forward direction
- Data measurements discriminate between different models

Anti-proton production in p-He collisions

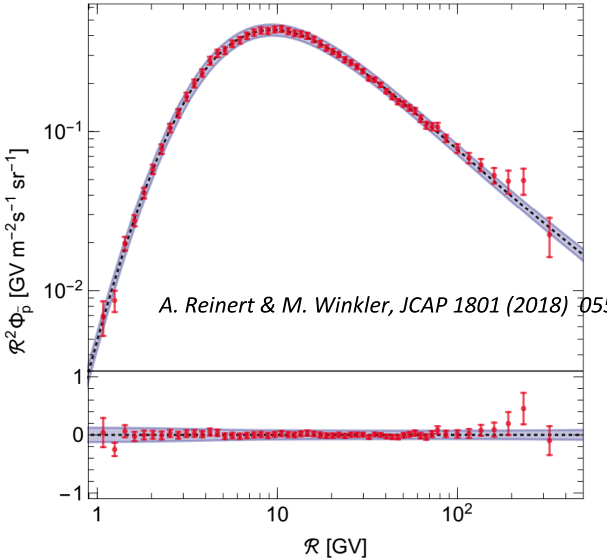


AMS and PAMELA spectrometers measure fraction of antiprotons in space

- Indirect probe for dark matter annihiliation
- Uncertainties on antiproton cross sections in pp and pHe collisions important

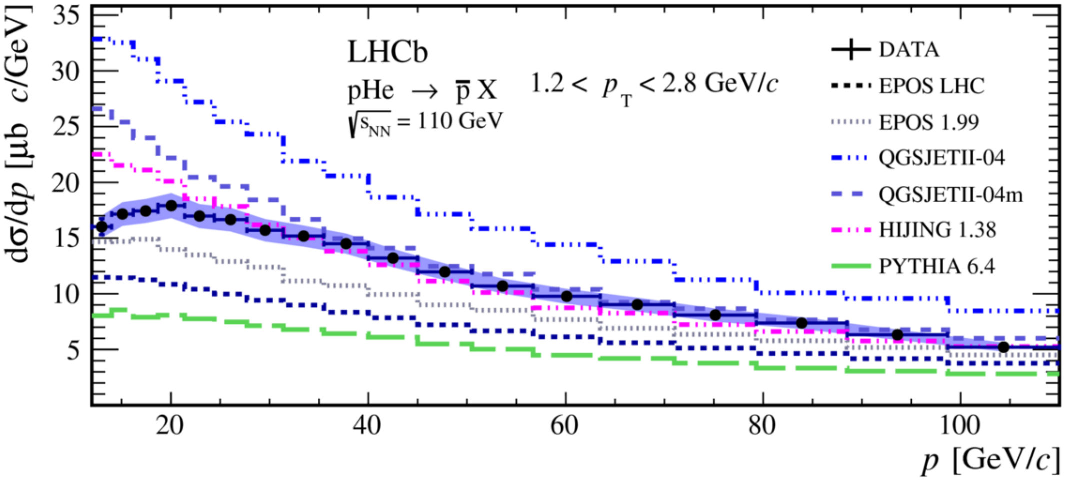
LHCb uses fixed-target mode (p+He gas) to measure antiproton production in pHe collisions

AMS data, M. Aguilar et al., PRL 113 (2014).



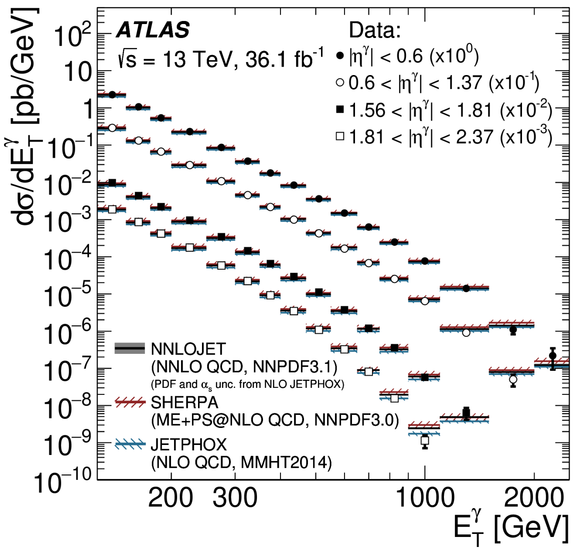
A. Reinert & M. Winkler, JCAP 1801 (2018) 055

LHCb, arXiv:1808.06127



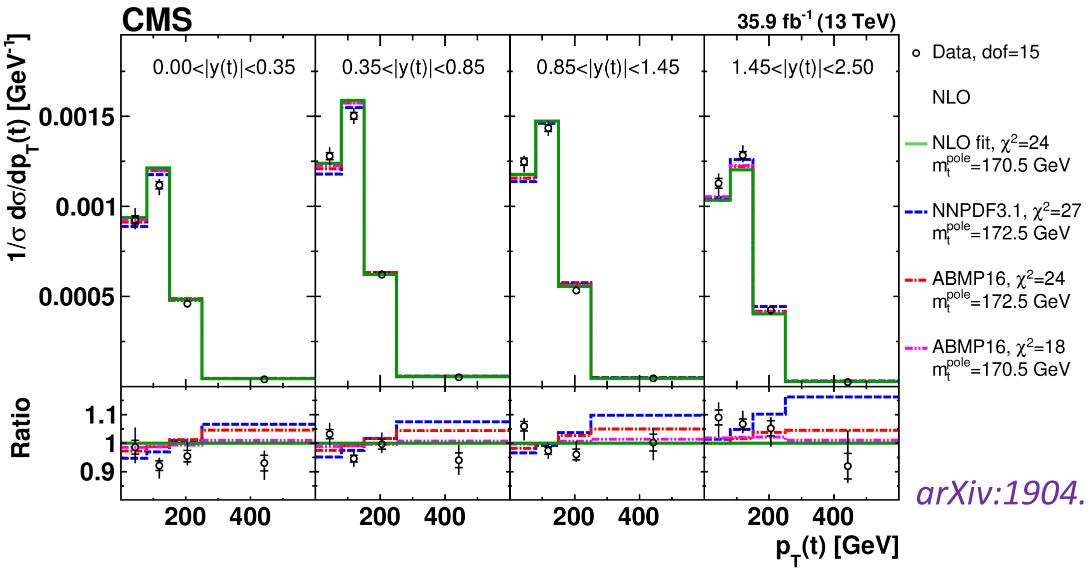
Perturbative QCD at the LHC

$pp \rightarrow \gamma + \text{jets}$



arXiv:1908.02746

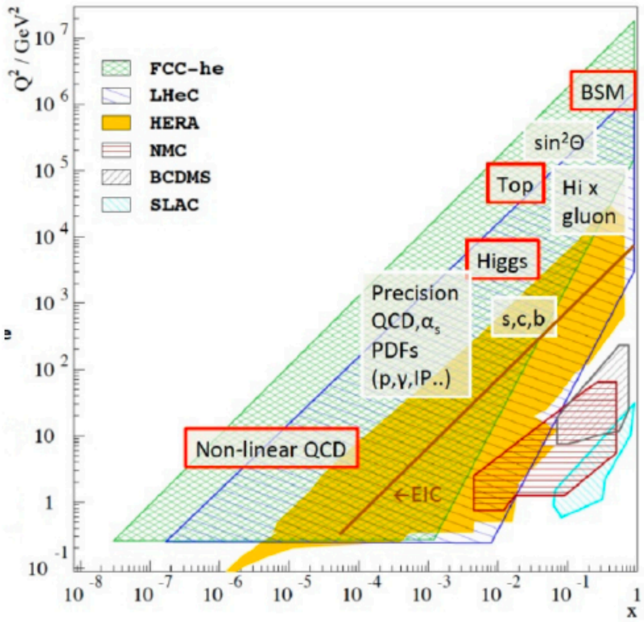
$pp \rightarrow t\bar{t} + X$

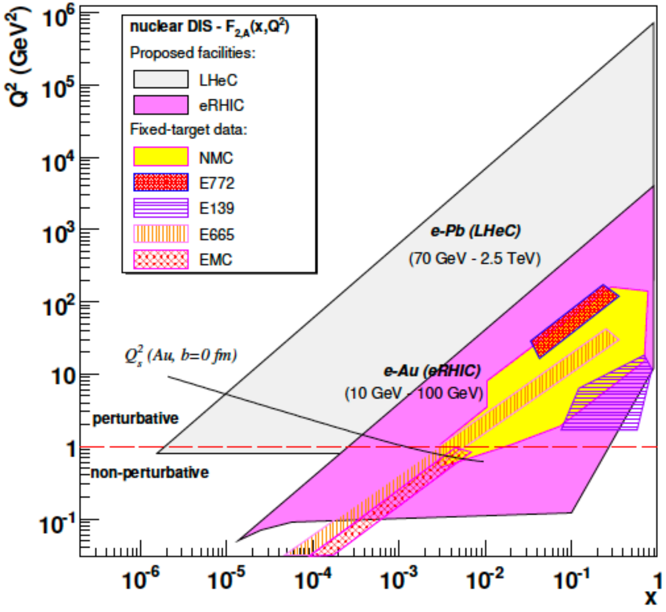


arXiv:1904.05237

- Multi-differential measurements of QCD production processes
  - Test MC generators and higher order QCD calculations (NNLO+beyond)
  - Determine strong coupling constant α_s and/or parton distribution functions

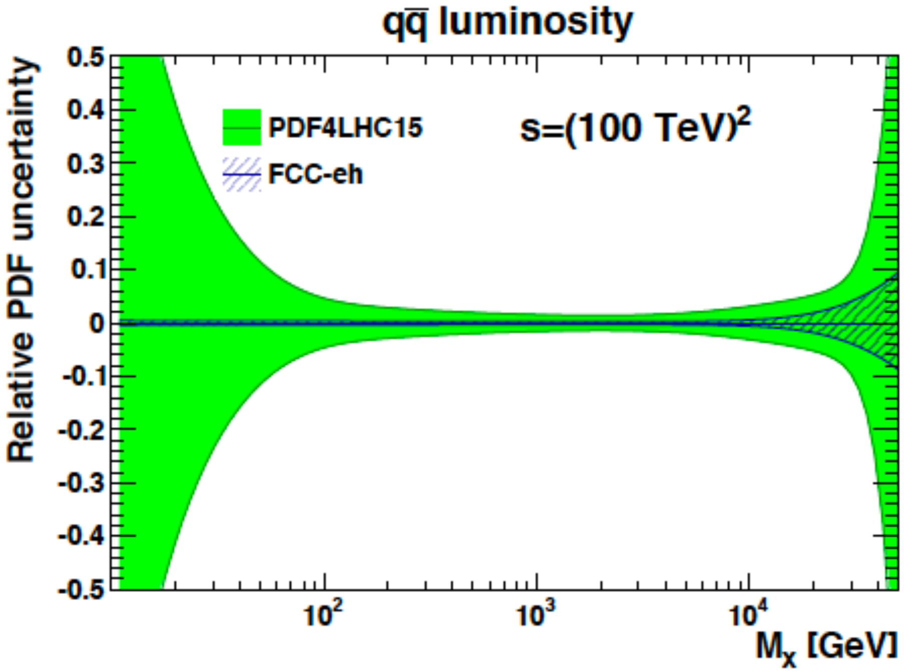
Parton distribution functions





- Full exploitation of pp data requires precise knowledge of PDFs
  - New ep colliders (LHeC, EIC, FCC-eh) can provide important input

Parton distribution functions



- Full exploitation of pp data requires precise knowledge of PDFs
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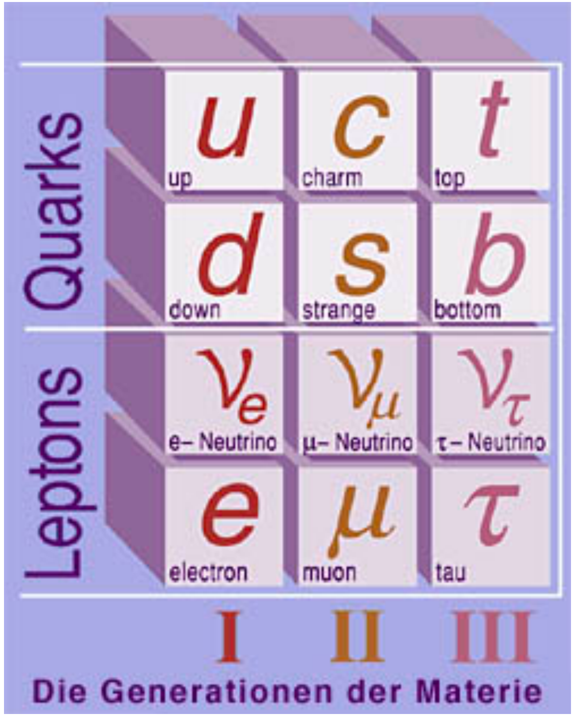
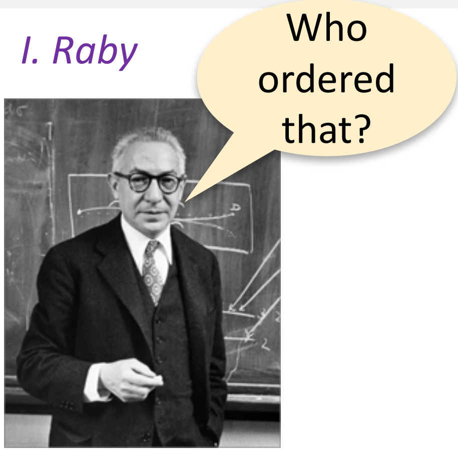
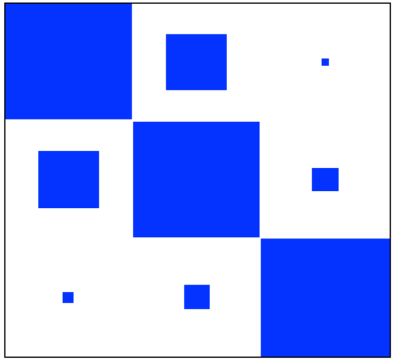
Flavour Physics



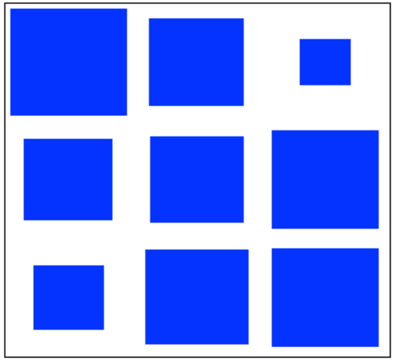
I. Raby



Quark mixing



Neutrino mixing



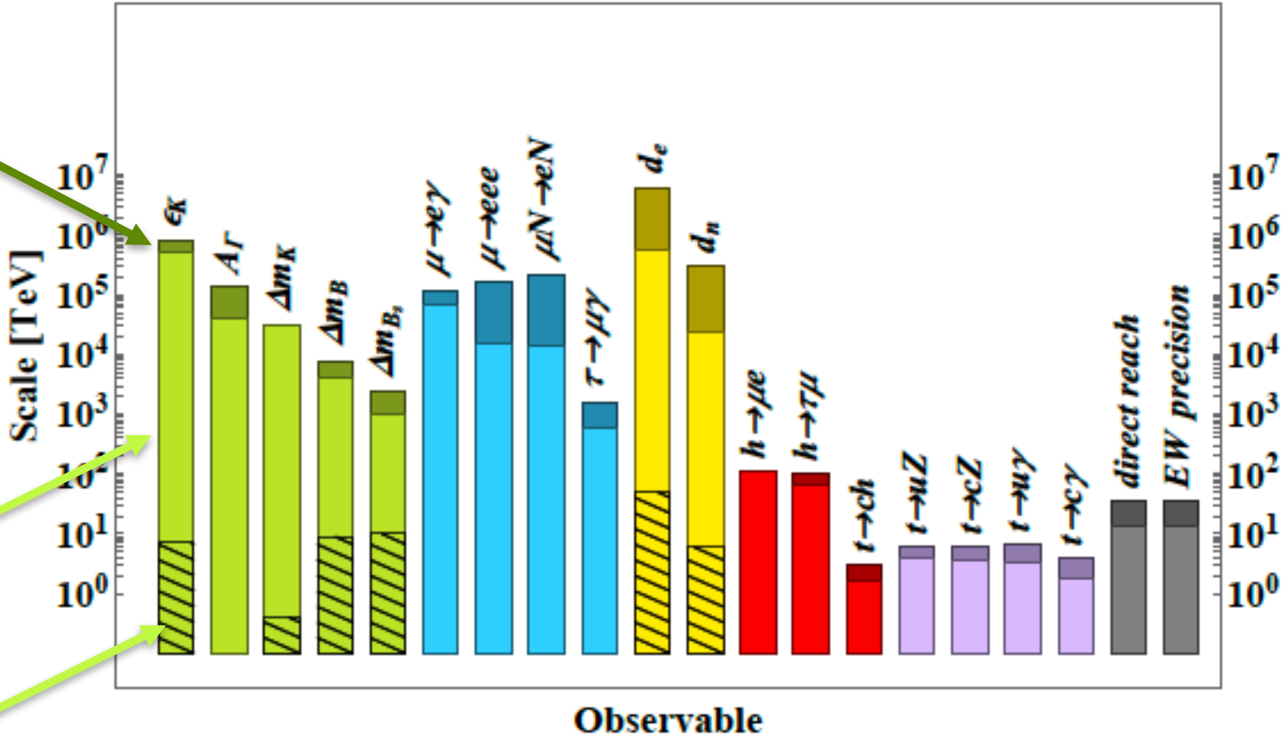
- Flavour puzzle today *(adapted from Y. Nir):*
  - Why is there so much structure in the quark sector?
  - Why is there no structure in the neutrino sector?
  - Why are there no flavor-changing neutral currents?
- What is source of CP violation explaining lack of anti-matter?
- Flavour is also excellent probe of high-scale physics
  - New physics tends to break accidental symmetries of SM

Flavour: New Physics Sensitivities

Future sensitivity: g=1

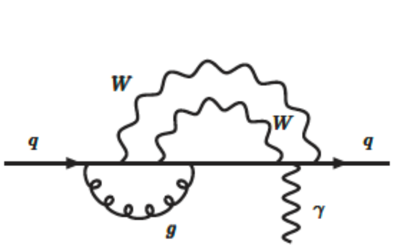
Current sensitivity: g=1

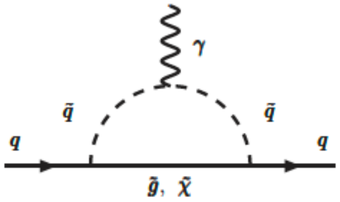
Current sensitivity: MFV

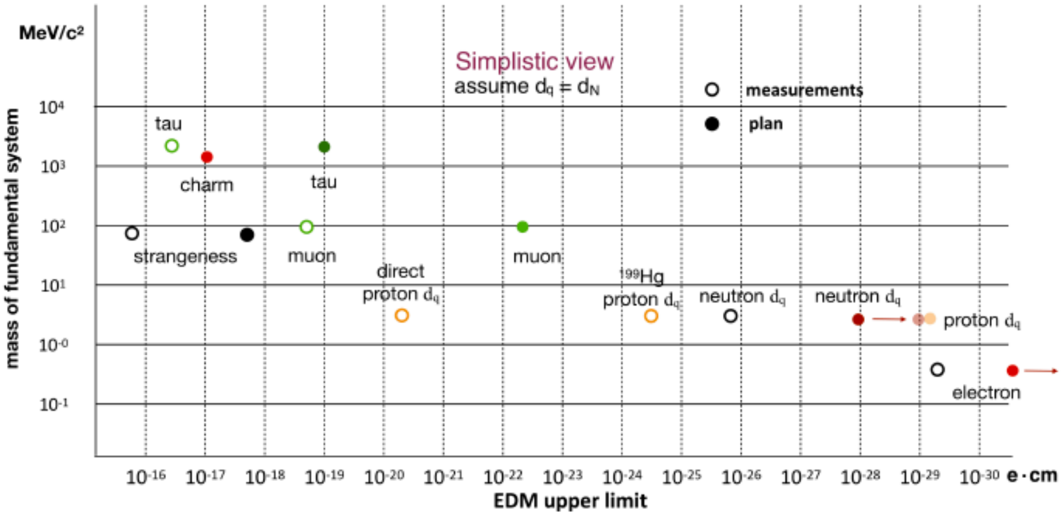


Electric Dipole Moment

“Has killed more SUSY models than anything else” *(I. Hinchliffe)*







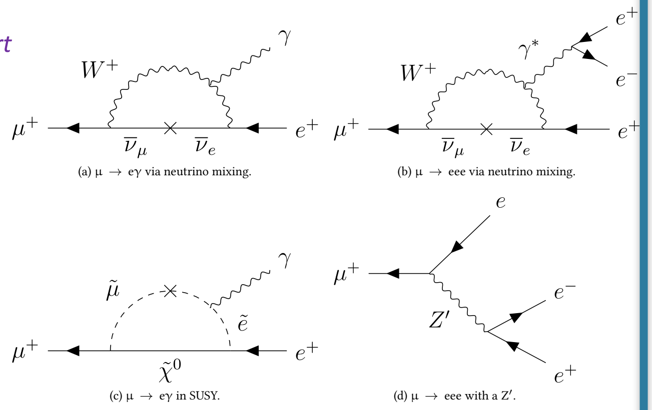
- Current limits: 3.6×10^{-26} for neutron, 1.1×10^{-29} for electron
  - Lepton and quark EDMs are complementary tests of new physics
- Advancements planned in future experiments: factors ~10-1000
- Observation would be clear evidence for new physics

Lepton Flavour Violation: $\mu \to e$ and $\tau \to \ell$

Figures from A-K Perrevoort

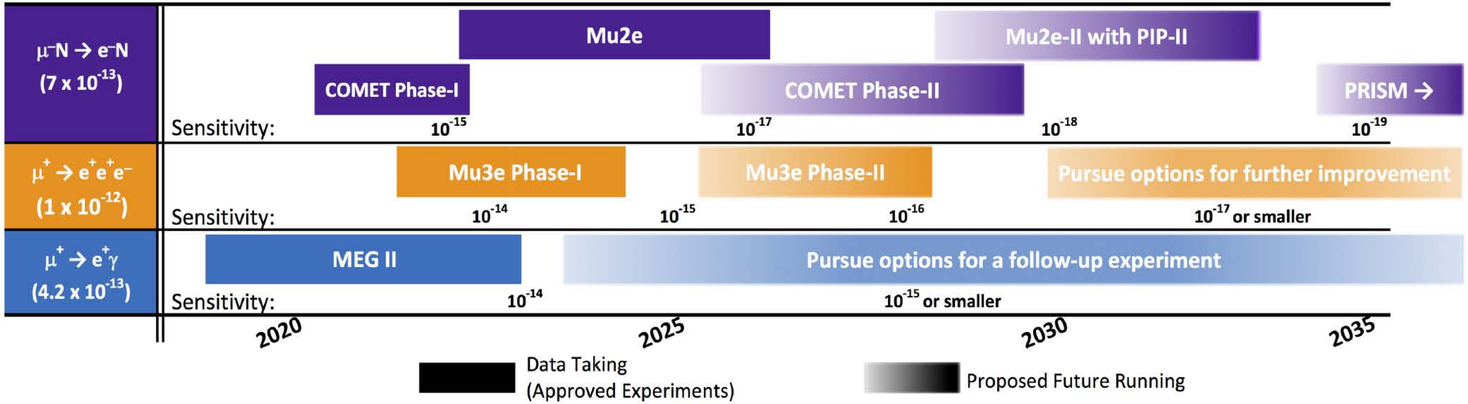
SM: BR<10^{-54}

BSM

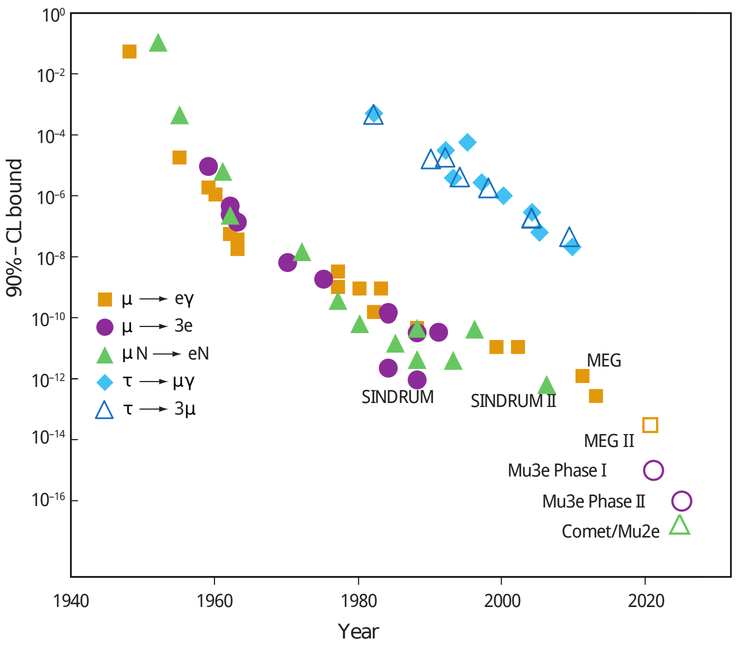


Several dedicated experiments coming online in near future for $\mu \to e$ decay or transition in Europe, US and Japan

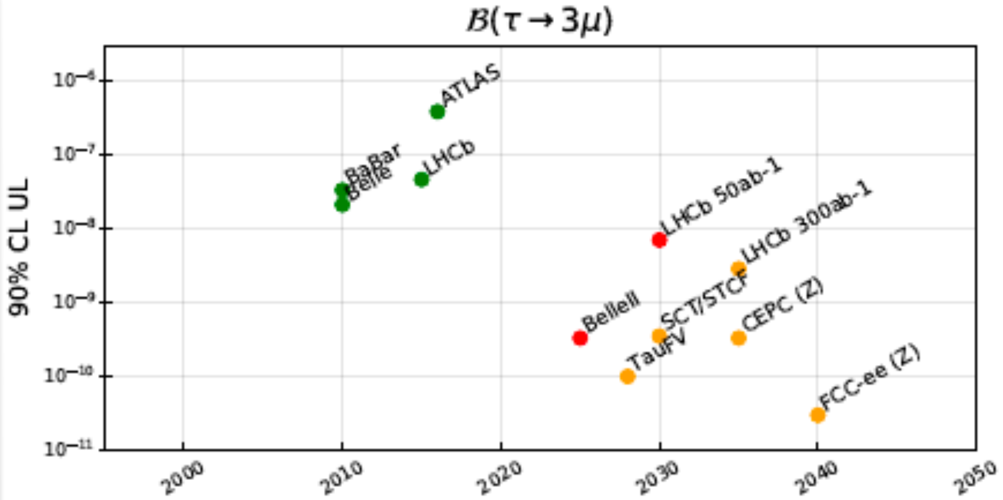
Searches for Charged-Lepton Flavor Violation in Experiments using Intense Muon Beams 1812.06540



Lepton Flavour Violation: $\mu \rightarrow eX$ and $\tau \rightarrow \ell X$



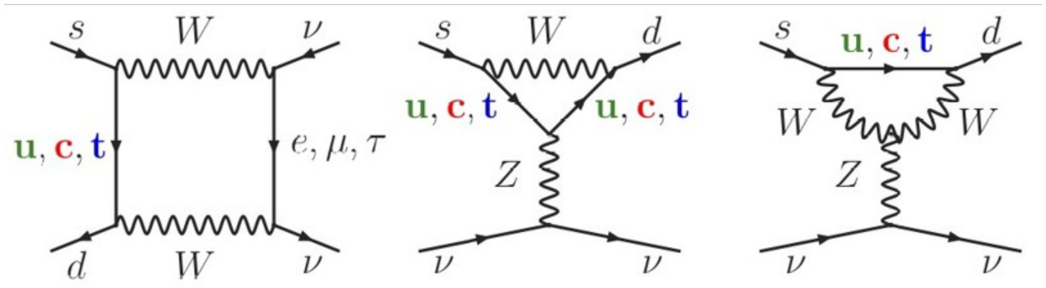
Muons: Expect to improve sensitivity by factor 10^4!

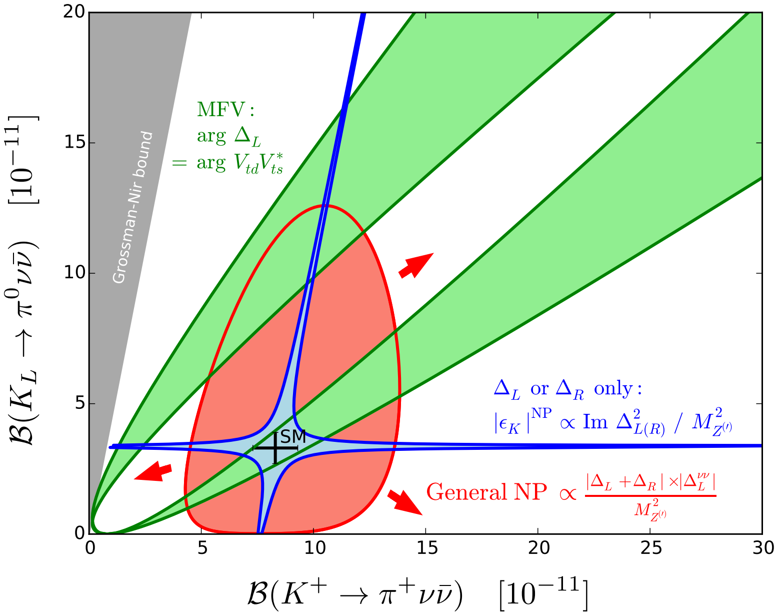


Taus:

- Next decade (LHCb, Belle-II): ~10^2
- Beyond next decade (Tera-Z): ~10^3

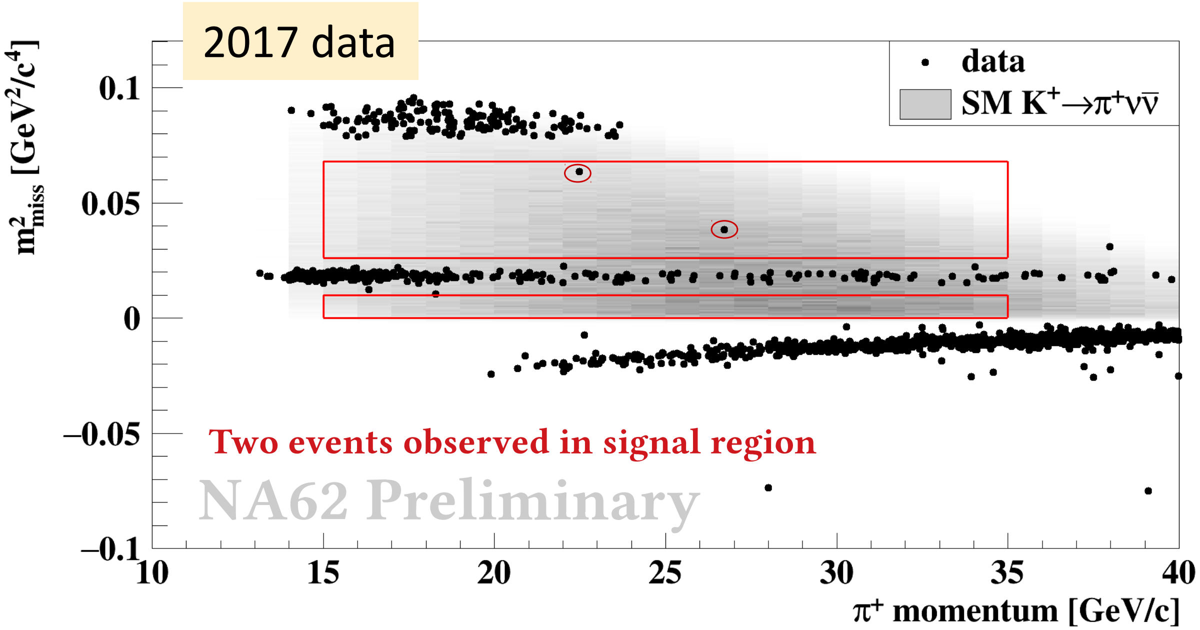
Rare Kaon decays





- Charged and neutral kaon decays important probe of new physics
- Major focus: $K^+ \to \pi^+ \nu\bar{\nu}$ (NA62) and $K_L^0 \to \pi^0 \nu\bar{\nu}$ (KOTO, KLEVER)

Recent Result by NA62



2016+2017 data

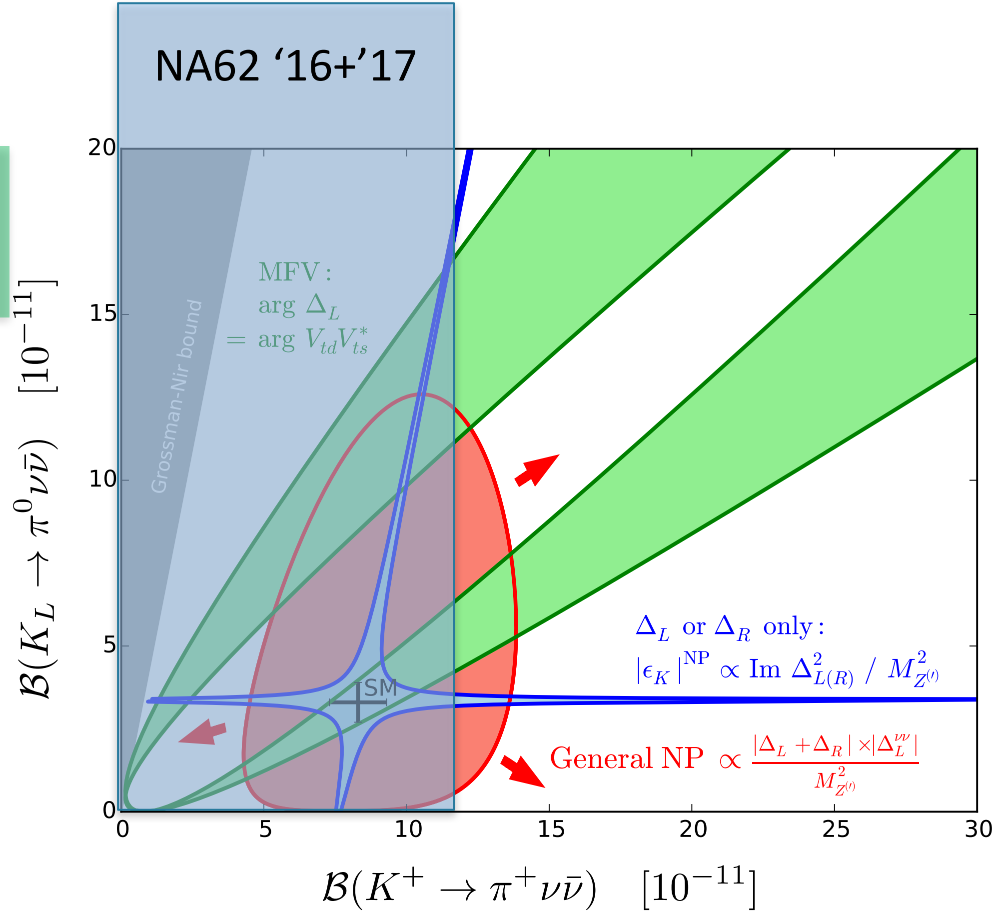
- $N_{data}=3$
- $N_{background}= 1.65\pm0.31$

$$BR(K^+ \to \pi^+ \nu\nu) < 1.85 \times 10^{-10} \ @ \ 90\ \%\ CL$$

$$BR(K^+ \to \pi^+ \nu\nu) = 0.47^{+0.72}_{-0.47} \times 10^{-10}$$

Future Prospects

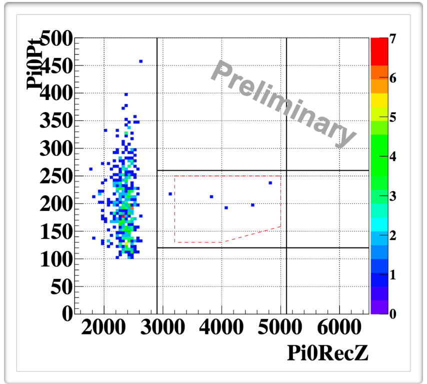
KOTO '15 limit:
BR<3x10^{-9}

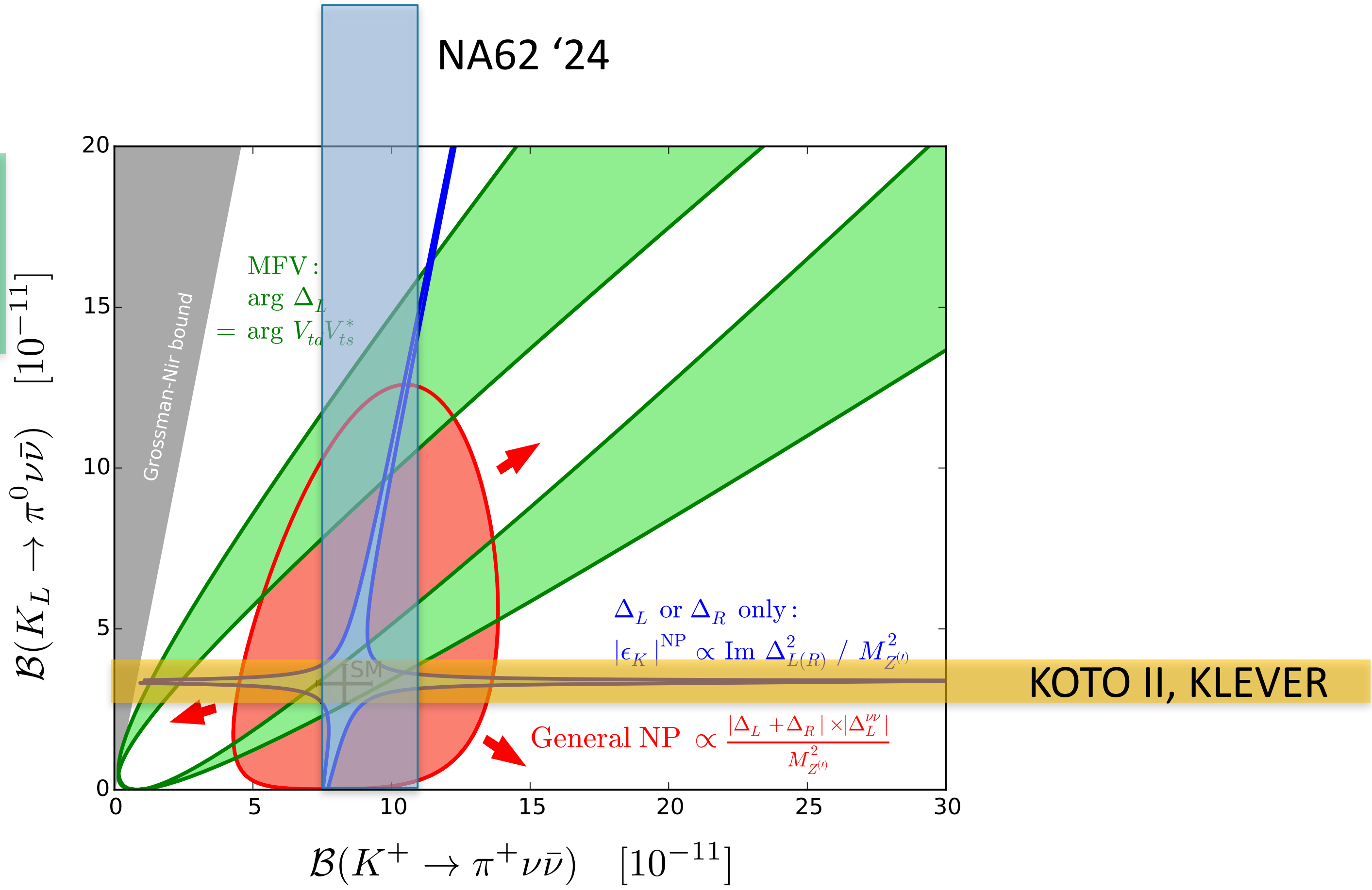


Future Prospects

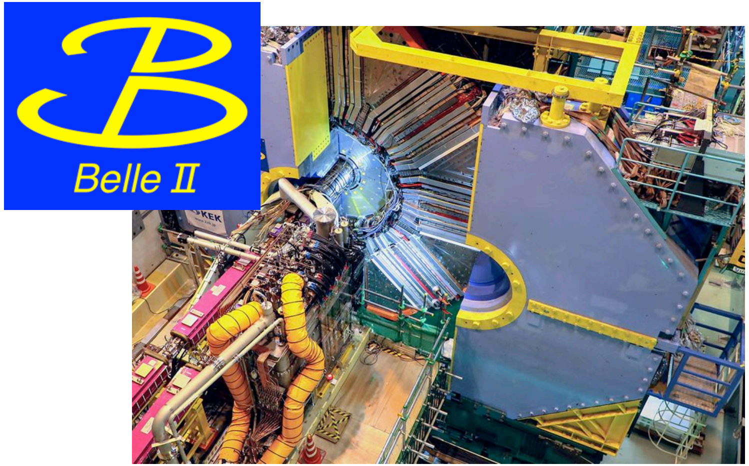
KOTO '16-'18
- sensitivity 7×10^{-10}
- 4 events obs.

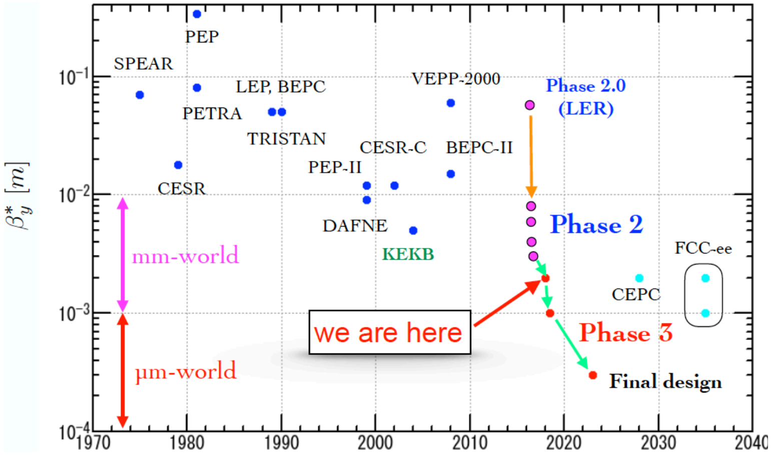
KOTO



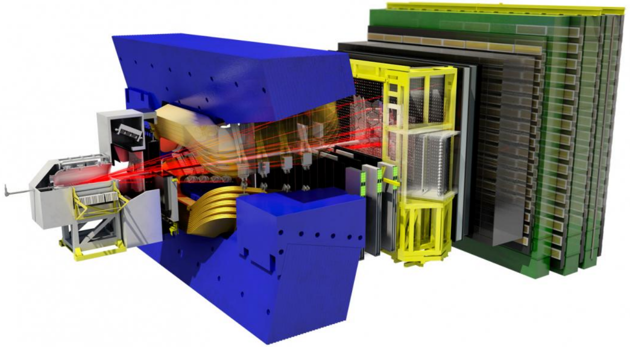


Heavy Flavour





- Major improvements in the next decade expected
  - Super-KEKB and Belle-II
    - Data taking started: towards lumi goal
  - LHCb detector upgrade

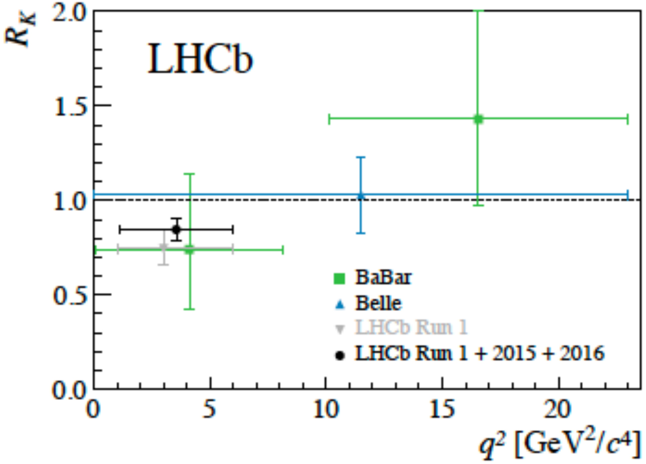


Anomalies in flavour physics

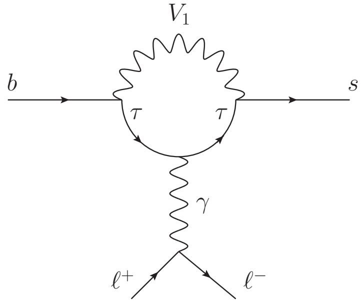
- Lepton flavour violation probes in B-decays

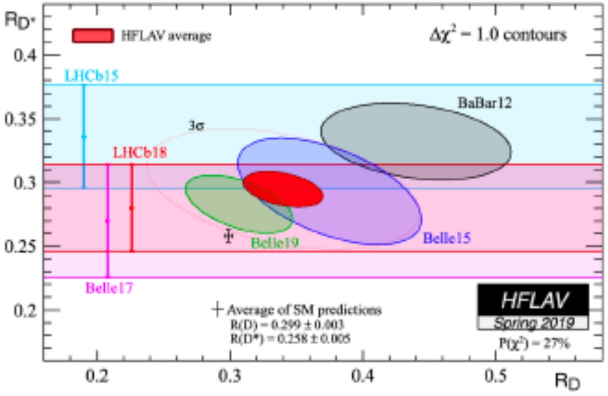
- Define:

$$R_H = \frac{\displaystyle\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{\mathrm{d}\Gamma[B\to H\mu^+\mu^-]}{\mathrm{d}q^2}\mathrm{d}q^2}{\displaystyle\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{\mathrm{d}\Gamma[B\to He^+e^-]}{\mathrm{d}q^2}\mathrm{d}q^2}$$

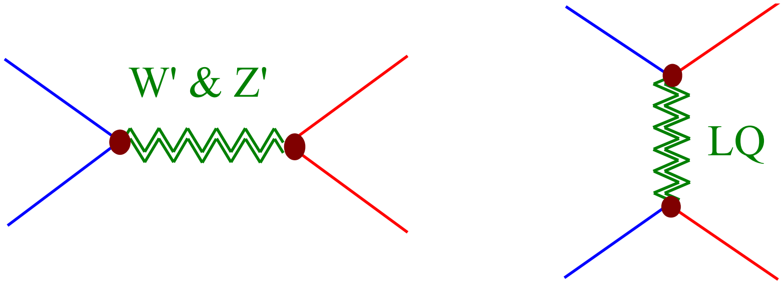


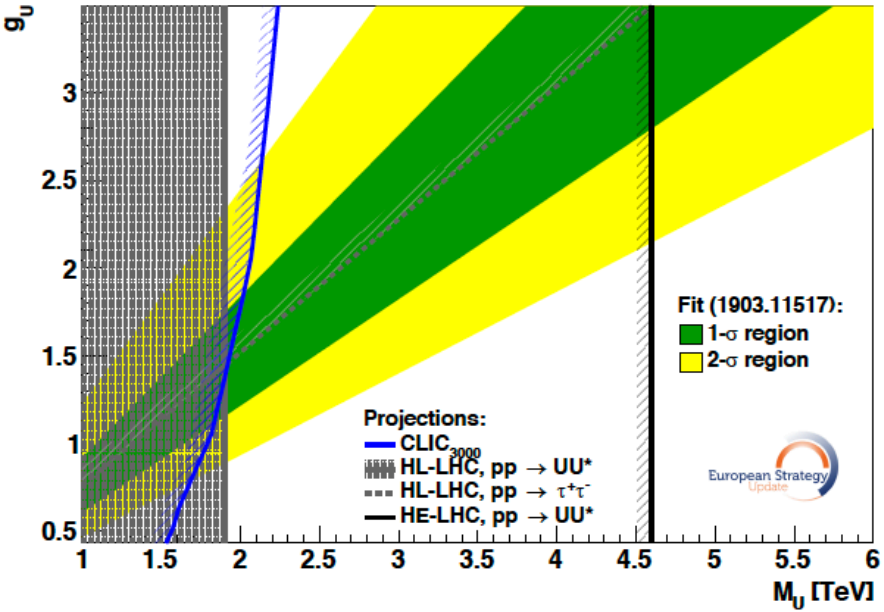
- Several BSM explanations proposed, e.g.
  - Leptoquarks
  - Z' with LFV couplings





Is flavour anomaly explained by leptoquark or Z'?



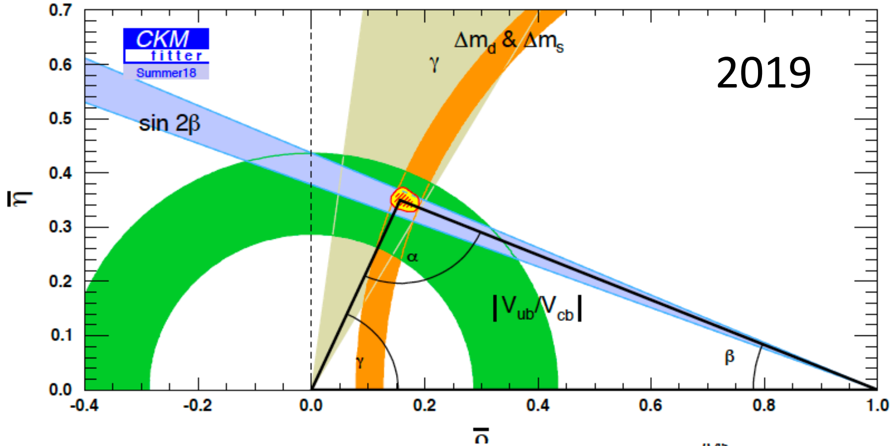


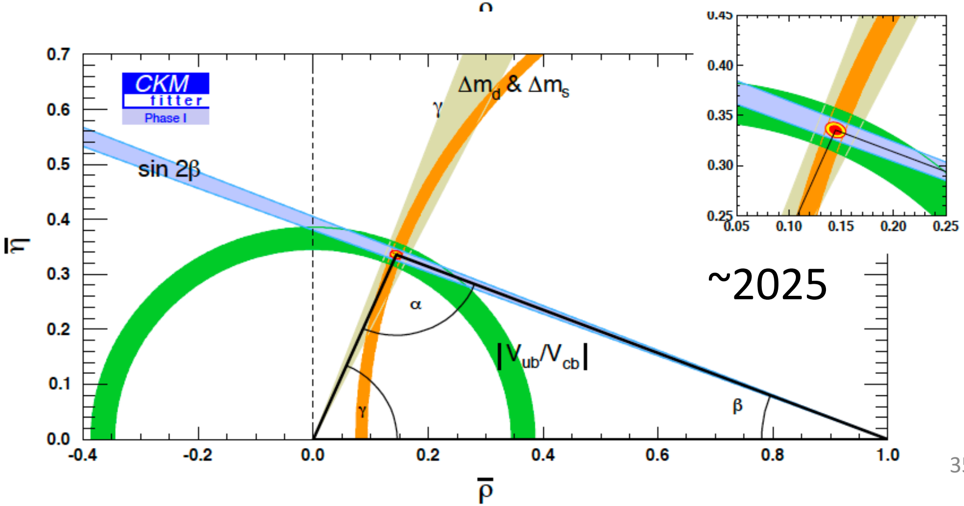
Complementary: direct searches at hadron colliders

CKM Unitarity Triangle

Expect huge improvements in parameters of CKM unitarity triangle by ~2025

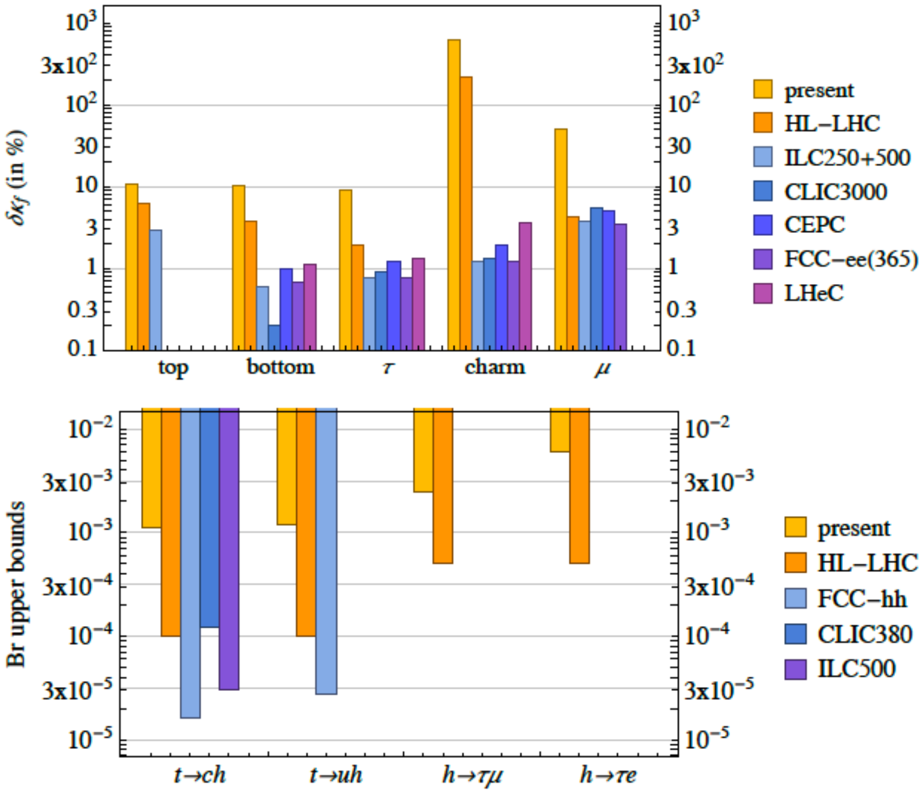
- Even higher precision expected by ~2035





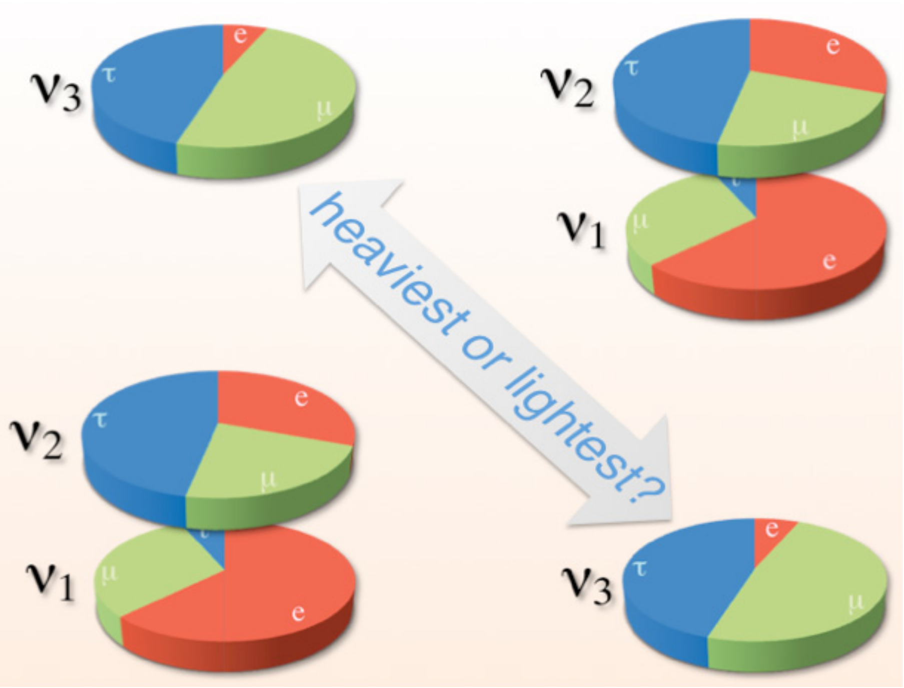
Can Higgs tell us about Flavour?

- Higgs is the only boson that cares about flavour!
  - Could it tell us something?
- Fermion couplings
  - 3rd generation observed
    - Now: 10% precision
    - Future colliders: ~1% precision
  - 2nd generation:
    - Muons: HL-LHC
    - Charm: requires new collider
  - 1st generation: very difficult
  - LFV couplings
    - HL-LHC sensitivity 10^{-3}-10^{-4}

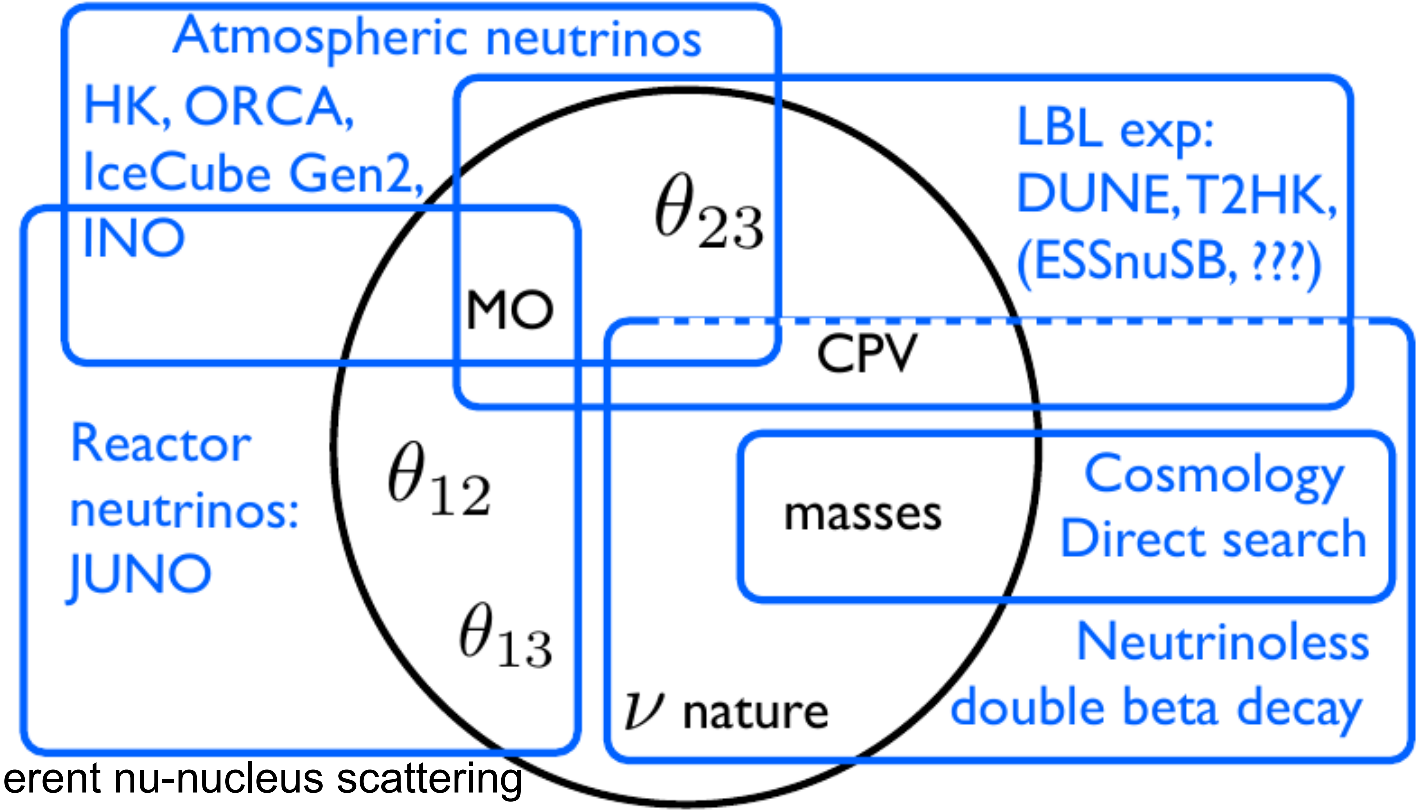


Neutrinos: Many Questions

- What is the mass ordering?
- Is CP violated?
- What is the absolute mass scale?
- Are neutrinos Dirac or Majorana particles?
- Are there heavy neutrinos?
- …



Tackling the neutrino sector experimentally



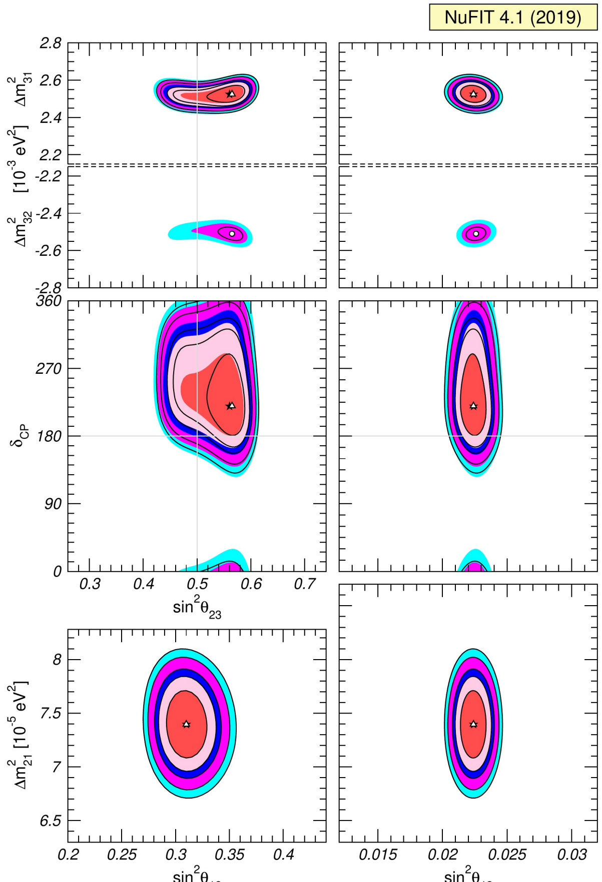
Coherent nu-nucleus scattering

S. Pascoli Granada 2019

Fit to World Neutrino data

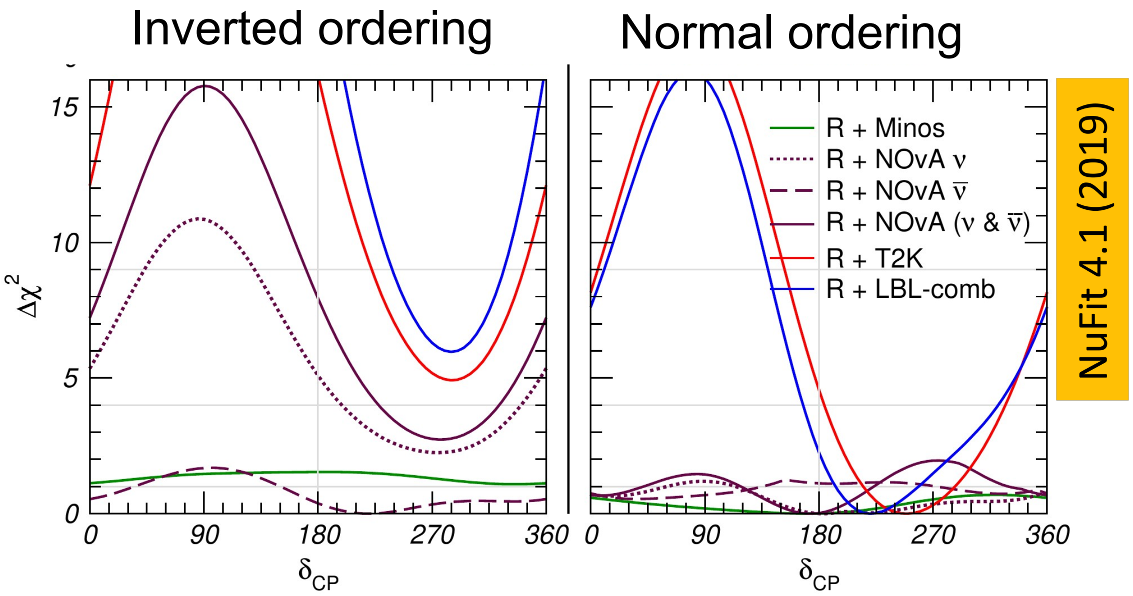
6 free parameters in fit

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 10.4$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.75}$	$31.61 \to 36.27$
	$\sin^2\theta_{23}$	$0.563^{+0.018}_{-0.024}$	$0.433 \to 0.609$	$0.565^{+0.017}_{-0.022}$	$0.436 \to 0.610$
	$\theta_{23}/^\circ$	$48.6^{+1.0}_{-1.4}$	$41.1 \to 51.3$	$48.8^{+1.0}_{-1.2}$	$41.4 \to 51.3$
	$\sin^2\theta_{13}$	$0.02237^{+0.00066}_{-0.00065}$	$0.02044 \to 0.02435$	$0.02259^{+0.00065}_{-0.00065}$	$0.02064 \to 0.02457$
	$\theta_{13}/^\circ$	$8.60^{+0.13}_{-0.13}$	$8.22 \to 8.98$	$8.64^{+0.12}_{-0.13}$	$8.26 \to 9.02$
	$\delta_{CP}/^\circ$	221^{+39}_{-28}	$144 \to 357$	282^{+23}_{-25}	$205 \to 348$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.528^{+0.029}_{-0.031}$	$+2.436 \to +2.618$	$-2.510^{+0.030}_{-0.031}$	$-2.601 \to -2.419$



I. Esteban et al., see 1811.05487

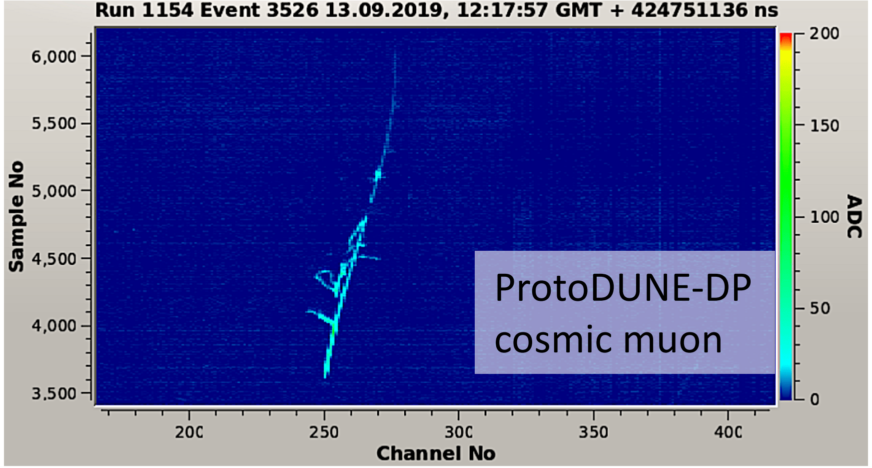
CP violation and Mass Ordering



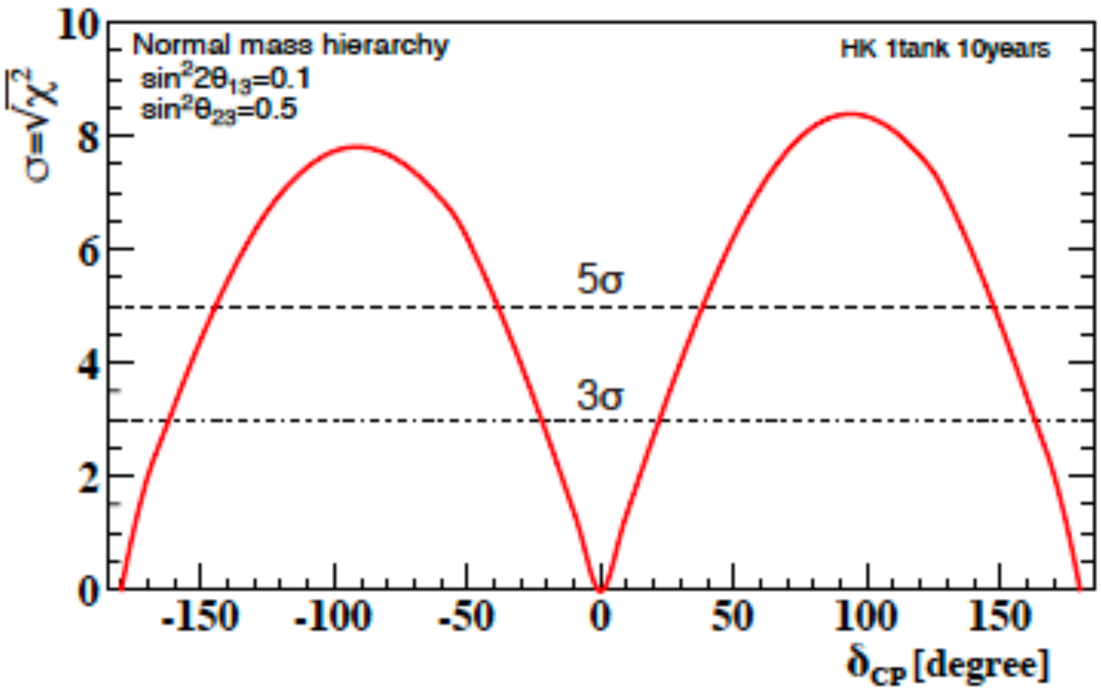
- Mass ordering
  - Combined T2K & Nova data prefer normal ordering (~3σ)
- CP violation:
  - CP violation ($\delta_{CP} \neq 180°$) favoured by T2K data (~2σ)
  - NOVA data show no preference

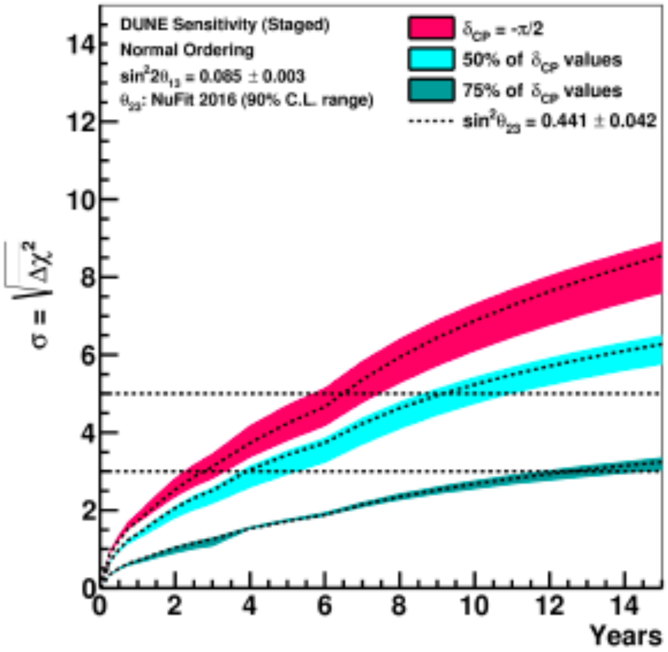
Construction of future Long Baseline Experiments

- CERN neutrino platform plays pivotal role
  - Test & understand protoDUNE single- and dual-phase detectors
  - Critical input for TDRs
- Hyper-K construction starting in 2020



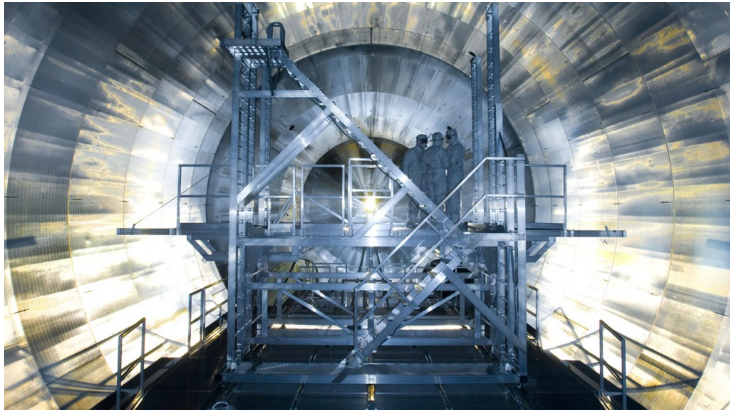
Sensitivity of future experiments

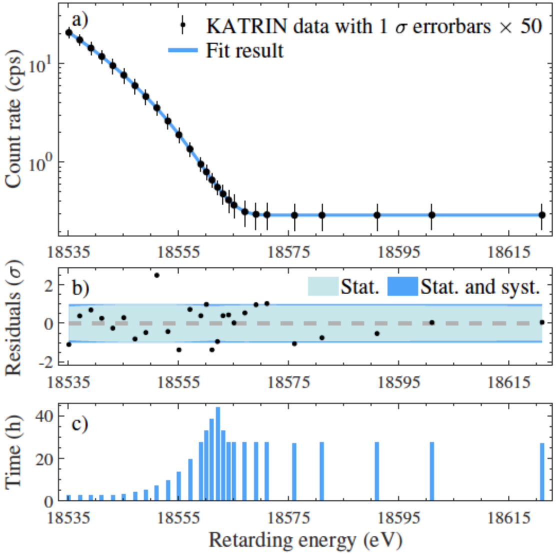




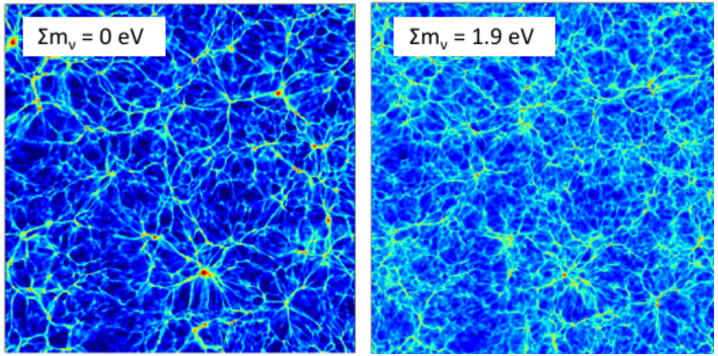
Different technologies of Hyper-K and DUNE (Water Cherenkov vs LAr TPC)
=> somewhat complementary

Absolute Neutrino Mass Scale

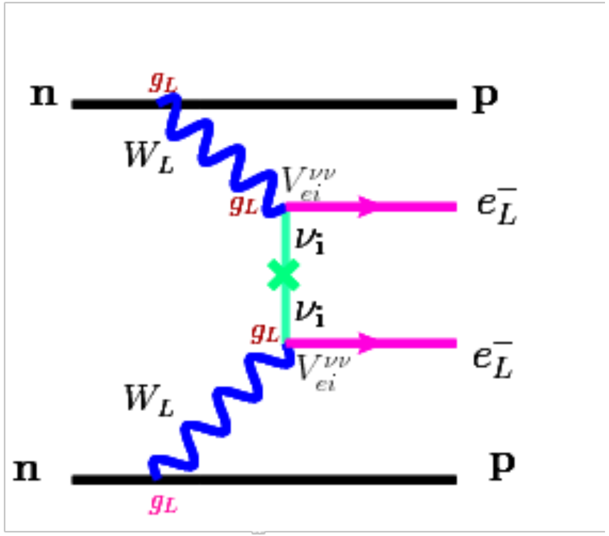


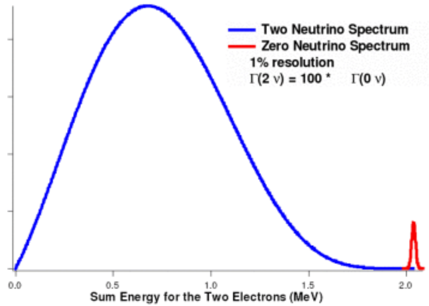


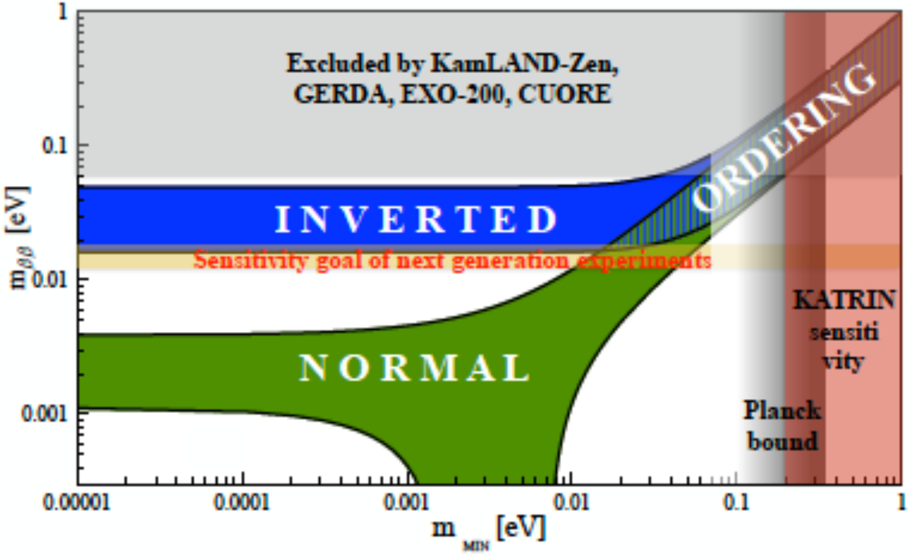
- First results from KATRIN (Sept. 2019)
  - Upper limit: m_e<1.1 eV @ 90% CL
    - Based on 28 days of data taking
  - 5y sensitivity: m_e<0.2 eV
- Future cosmology missions (Euclid, DESI) will also have sensitivity



Is the neutrino its own anti-particle?

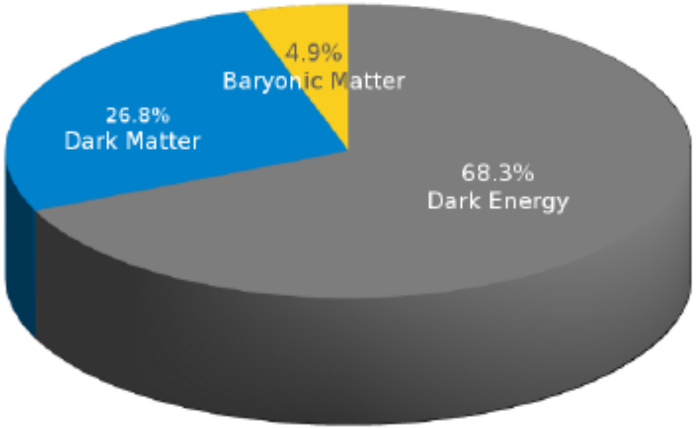




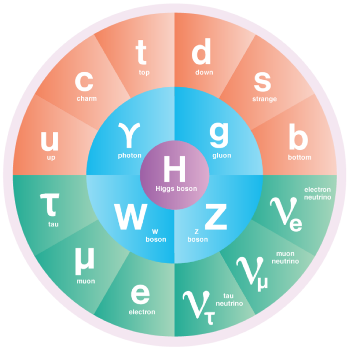


- Several experiments of next generation planned
- Should probe inverted hierarchy allowed region

Dark Sector

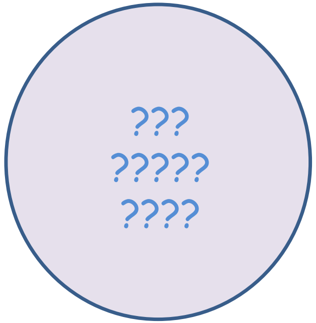


Visible sector



Zoo of particles
w/structure
$SU(3)_c x\ SU(2)_L\ x\ U(1)_Y$

Dark sector



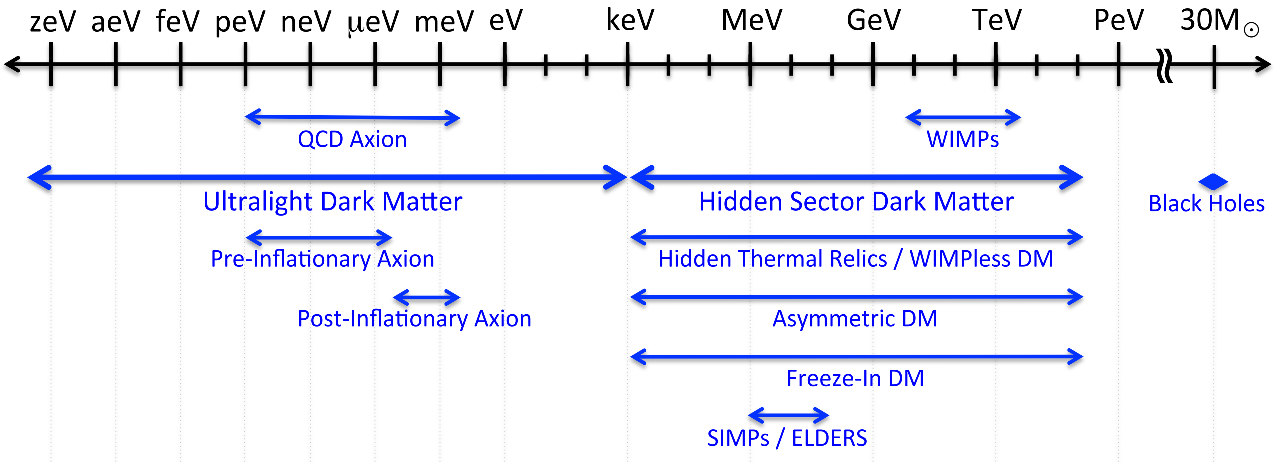
Why not in the
dark sector too?
New gauge symmetries?

Y. Hochberg, LP '19

Dark Sector

Dark Matter Candidates: Very little clue on mass scales

Too small mass
⇒ won't "fit"
in a galaxy!

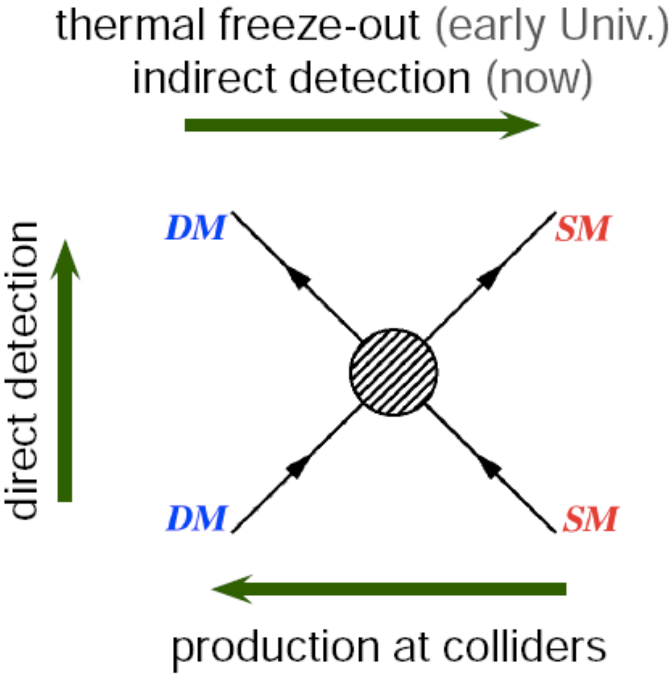


From MACHOs
searches

graphics by M. Carena

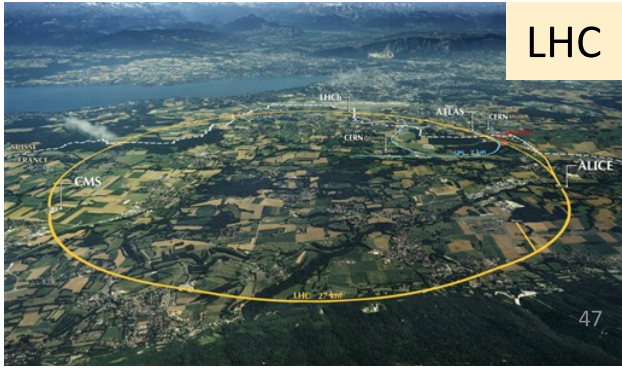
How to search for WIMPs?

XENON1T in Gran Sasso

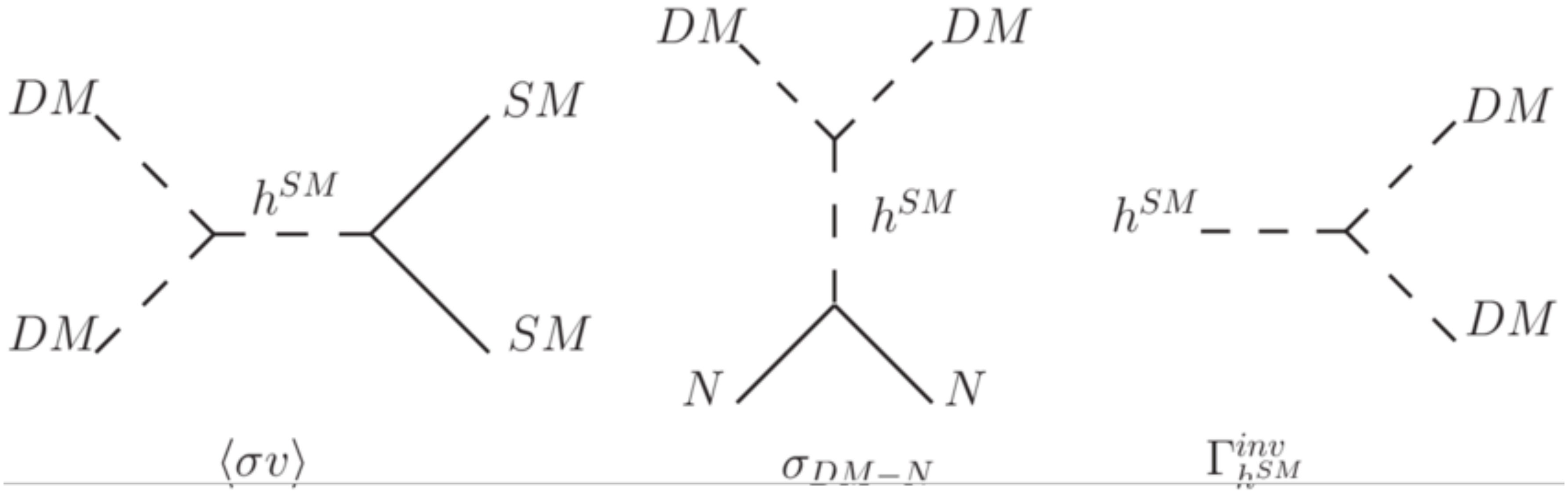


AMS satellite

LHC



Dark Matter processes with Higgs



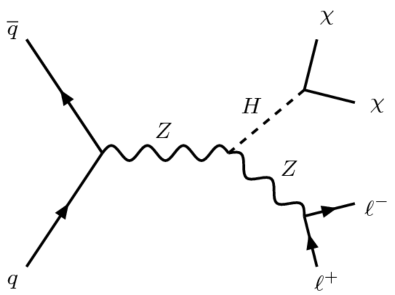
DM annihilation early Universe & satellites

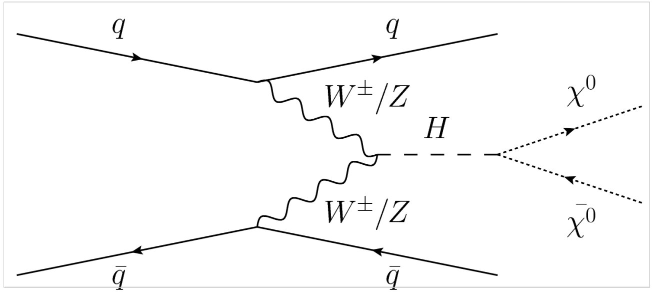
DM-N Scattering (XENON1T etc.)

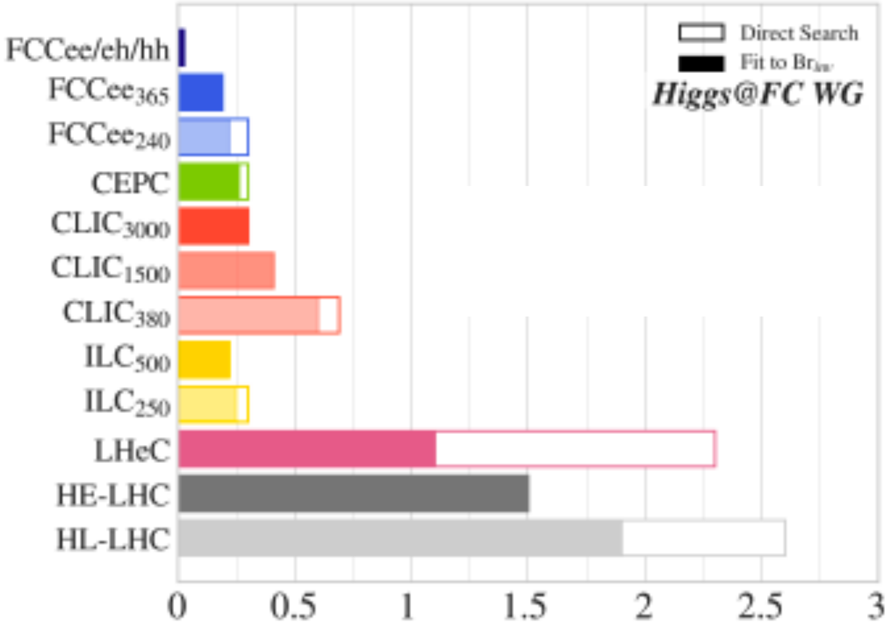
DM production early Universe & LHC

"Invisible" Higgs decays?

- Does dark matter (χ) interact with the Higgs?
  - Higgs can decay to dark matter candidates if $m_H > 2\ m_\chi$





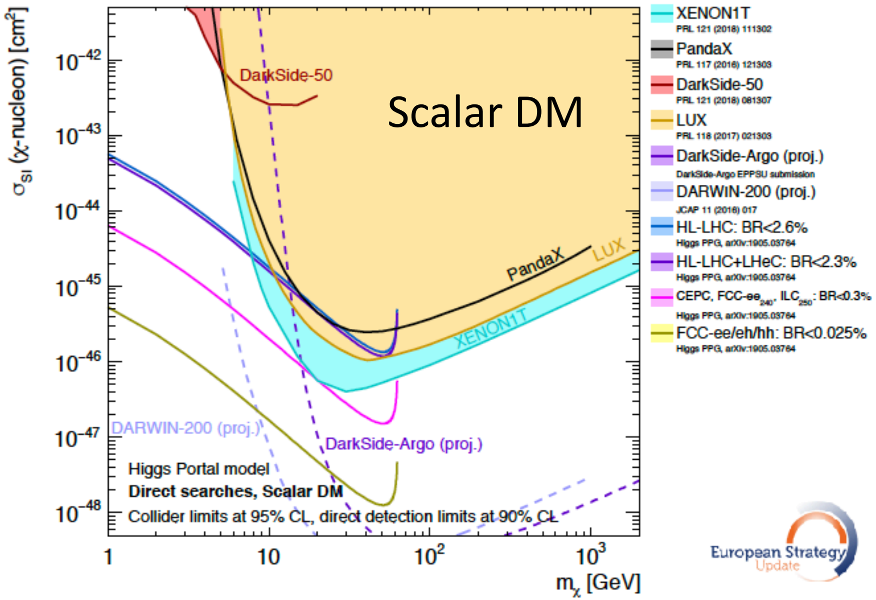


Comparing direct detection and Higgs constraints

Dark Matter can be scalar, vector or fermion:

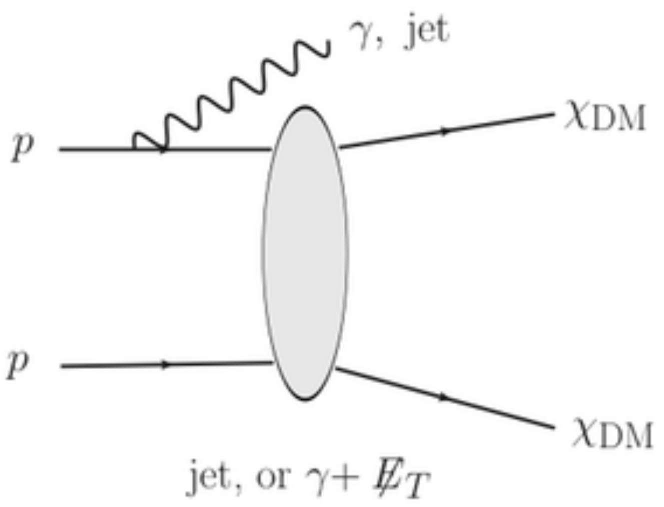
$$\mathrm{BR}_{\chi}^{\mathrm{inv}} \equiv \frac{\Gamma(H \to \chi\chi)}{\Gamma_H^{\mathrm{SM}} + \Gamma(H \to \chi\chi)} = \frac{\sigma_{\chi p}^{\mathrm{SI}}}{\Gamma_H^{\mathrm{SM}}/r_\chi + \sigma_{\chi p}^{\mathrm{SI}}}$$

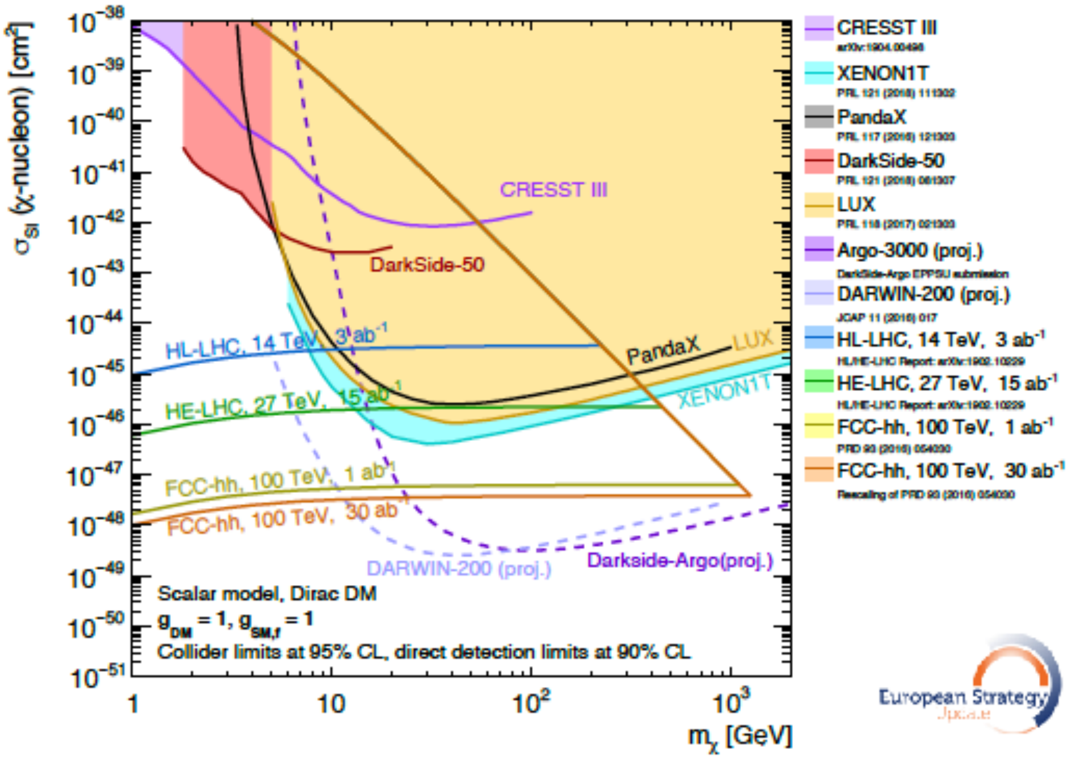
with $r_\chi = \Gamma(H \to \chi\chi)/\sigma_{\chi p}^{\mathrm{SI}}$



- Approaches are complementary
  - Higgs more sensitive at low mass, direct detection more sensitive at high mass
- Comparison is mode—dependent
  - This is good: if we see signal we will learn physics from it!

Monojet search





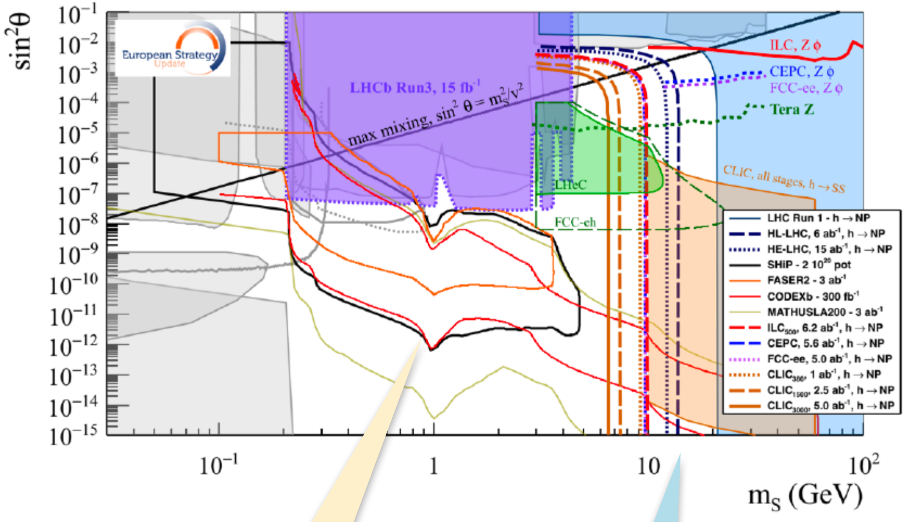
European Strategy Update

Can fully probe thermal WIMP with FCC-hh

Other Dark(ish) Particles: FIPs

Feebly interacting particles (FIPs)

Portal	Coupling
Vector (Dark Photon, A_μ)	$-\frac{\varepsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Scalar (Dark Higgs, S)	$(\mu S + \lambda_{HS} S^2) H^\dagger H$
Fermion (Sterile Neutrino, N)	$y_N LHN$
Pseudo-scalar (Axion, a)	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$



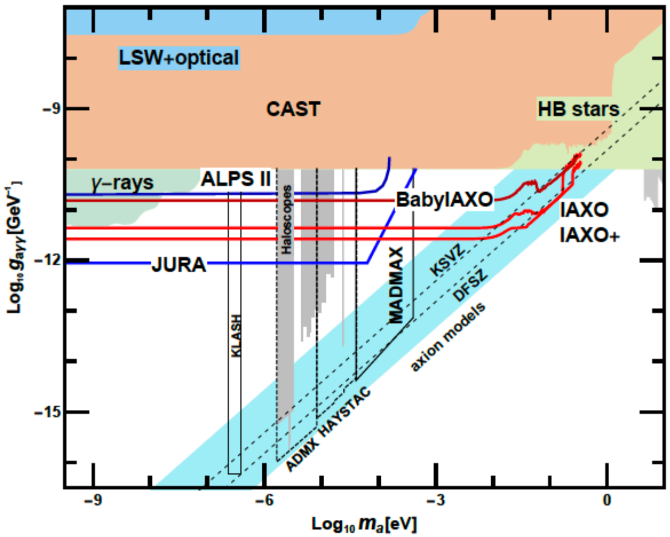
Beam dump

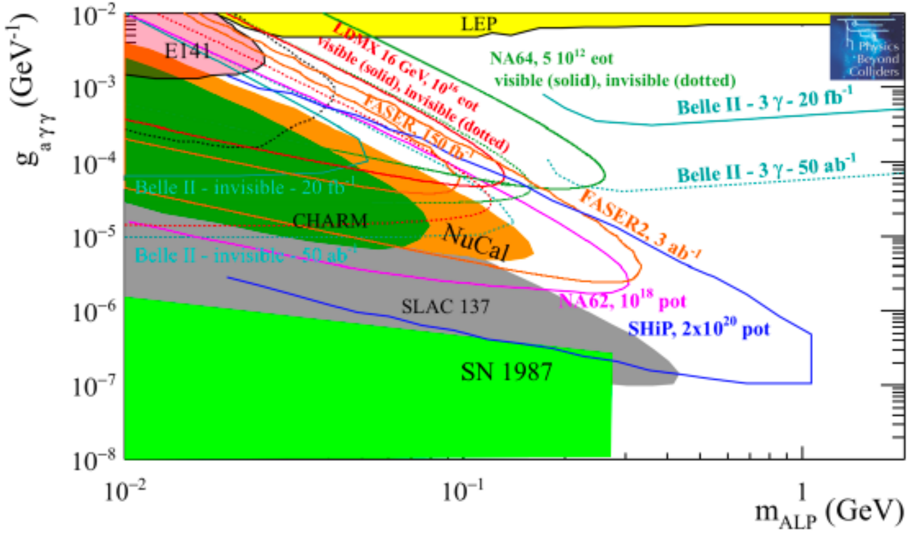
H →untagged

- Scalar portal very interesting!
  - Electroweak phase transition
  - Dark matter
  - Finetuning problem

Axion-Like Particles (ALPs)

- Axion originally proposed as solution to strong CP problem (Peccei, Quinn)
  - Could also be relevant for Dark Matter, stellar evolution..
- Many complementary searches for Axion-Like Particles
  - Dedicated experiments (ALPS, CAST, IAXO), beam dump facilities (e.g. SHiP) and colliders





Is our world natural?

- Large quantum corrections to Higgs mass:

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}[\Lambda_{UV}^2 + ...].$$ ~ M_{Pl}^2 if no new physics with $\Lambda<M_{Pl}$

- Unnatural that $m_H \ll \Lambda_{NP}$ => *"hierarchy problem"*

- Quantify: $$\varepsilon \equiv \frac{m_H^2}{(\Delta m_H)^2}$$

Method	Dependence	Current Constraint
Direct searches: soft models	$\Delta m_H^2 \sim m_T^2$	$\varepsilon \lesssim 1\%$
Direct searches: super-soft models	$\Delta m_H^2 \sim 3y_t^2/(4\pi^2)m_T^2$	$\varepsilon \lesssim 10\%$
Direct searches: hyper-soft models	$\Delta m_H^2 \sim 3\lambda_h/(16\pi^2)m_T^2$	$\varepsilon \lesssim 100\%$
Higgs couplings	$m_H^2/\Delta m_H^2 \sim \delta g_h/g_h$	$\varepsilon \lesssim 10\%$
Oblique parameters (CH models)	$m_H^2/\Delta m_H^2 \sim \delta O \times 3$	$\varepsilon \lesssim 30\%$
Oblique parameters (SUSY models)	$m_H^2/\Delta m_H^2 \sim \delta O \times 10^3$	n.a.

Simplicity vs Naturalness

R. Rattazzi

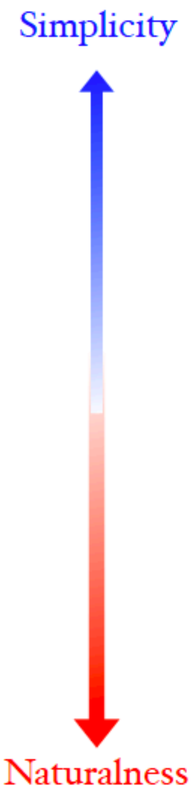
The two Chief Systems

I. The SM is valid up to $\Lambda_{UV} \gg TeV$

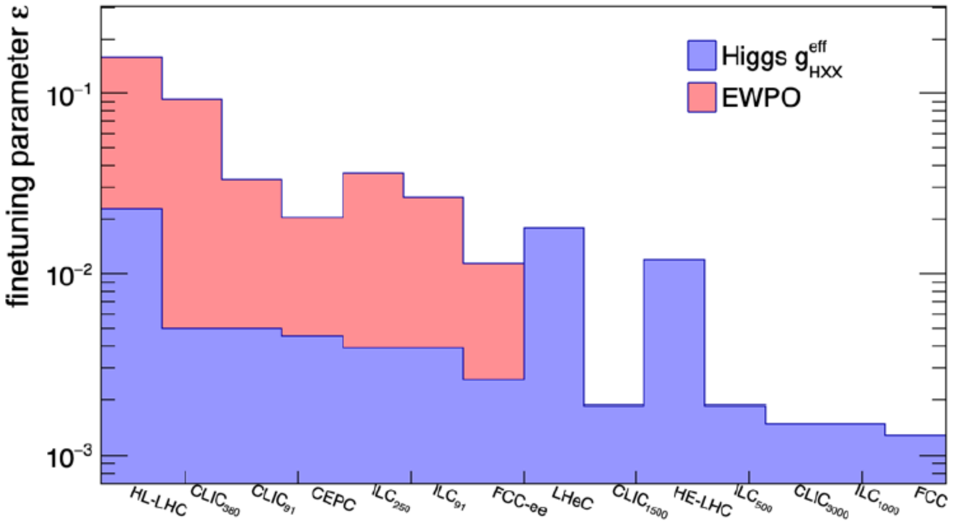
- B, L and Flavor: beautifully in accord with observation
- Higgs mass & C.C. hierarchy point beyond naturalness
  - multiverse
  - cosmological relaxation, Nnaturalness, ...
  - failure of EFT ideology (UV/IR connection)

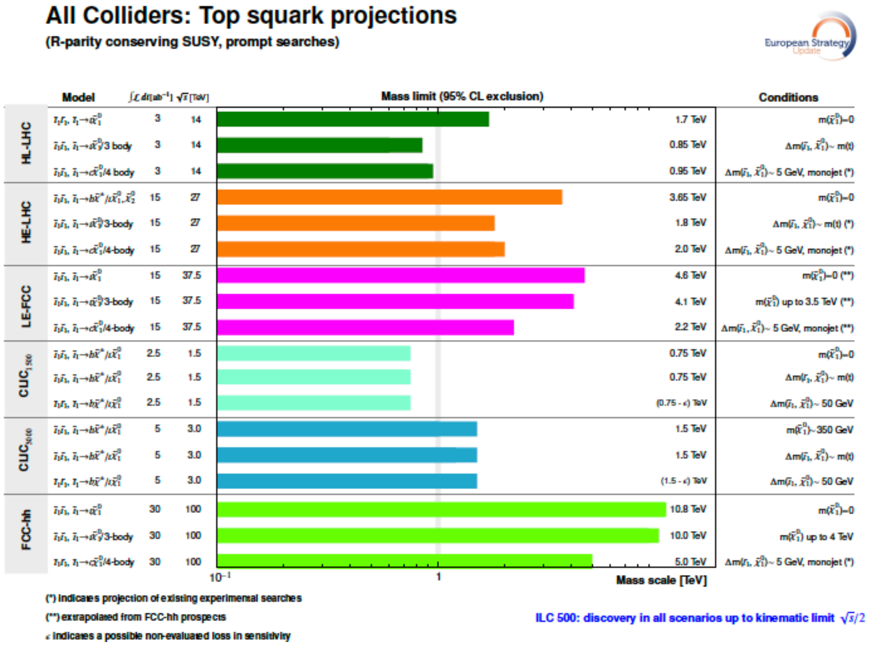
II. Naturalizing New Physics appears at $\Lambda_{UV} \sim 1\,\text{TeV}$

- Constraints on B, L, Flavor & CP met by clever model building



Is our world natural?

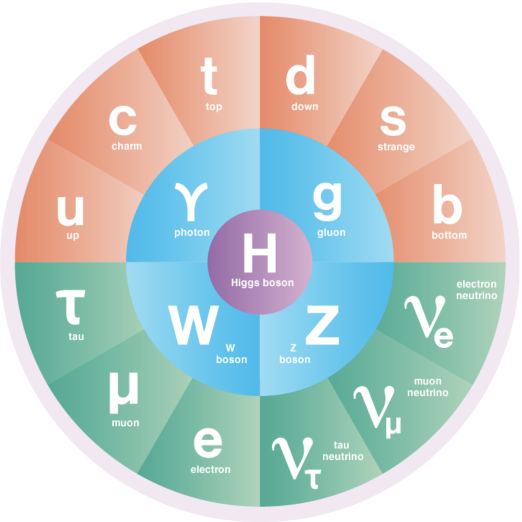


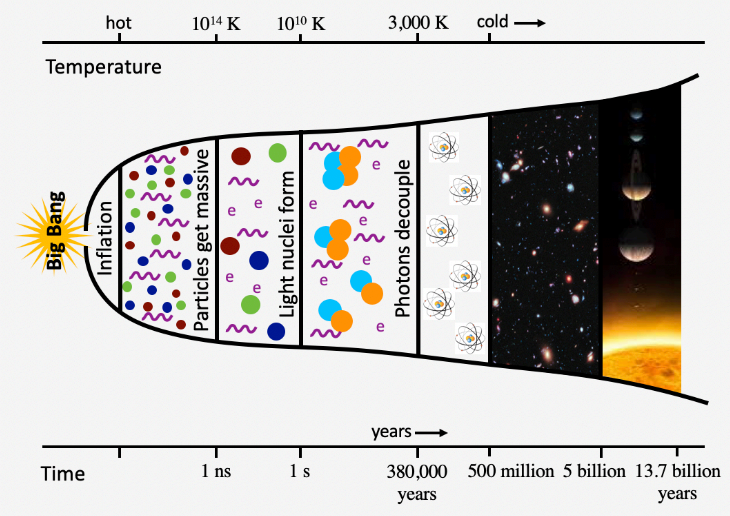


- Will probe naturalness to levels of 10^{-3} with Higgs couplings
  - Down to 10^{-2}-10^{-4} with direct searches

Conclusions

- Amazingly exciting world of particle physics
  - So many questions… so many experiments to do…so many challenges!
- Hard to know where the next breakthrough is….
  - But let's break through … even if it is difficult… and takes a while!





from Selya Ipek

Conclusions

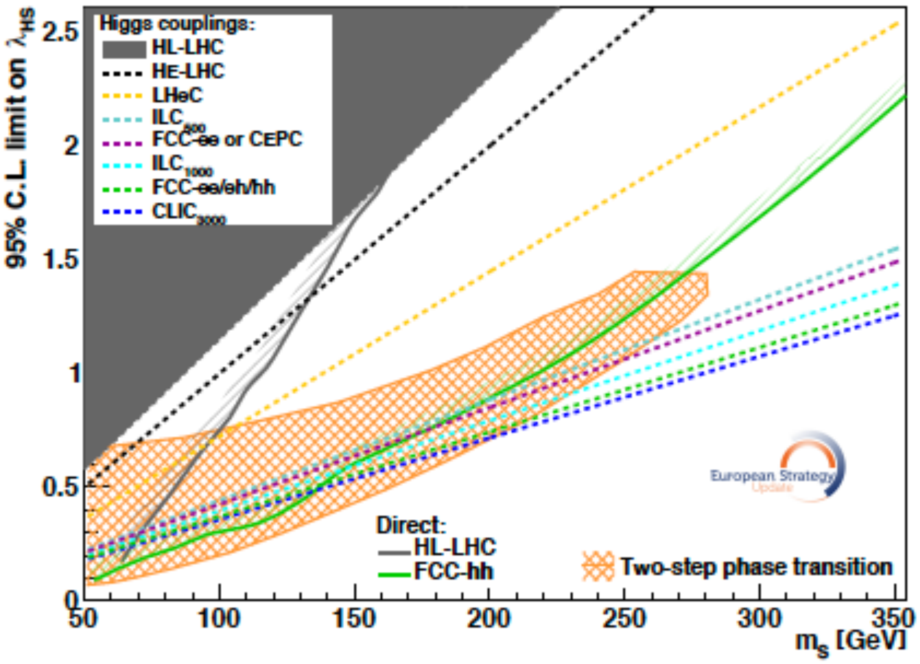
- Amazingly exciting world of particle physics
  - So many questions… so many experiments to do…so many challenges!
- Hard to know where the next breakthrough is….
  - But let's break through … even if it is difficult… and takes a while!

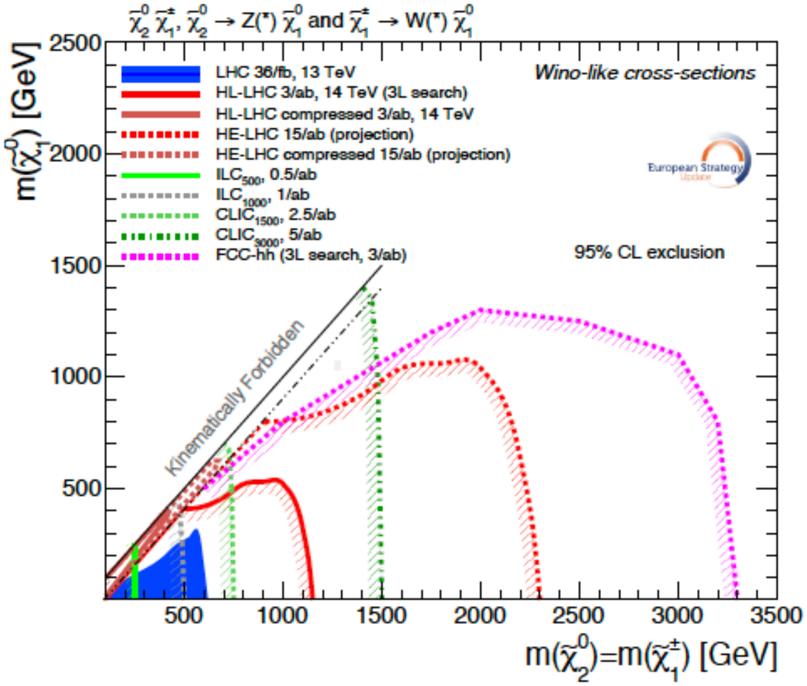
Eliud Kipchoge, Oct. 12th 2019
"No human is limited"

Backup

Is there a Singlet?

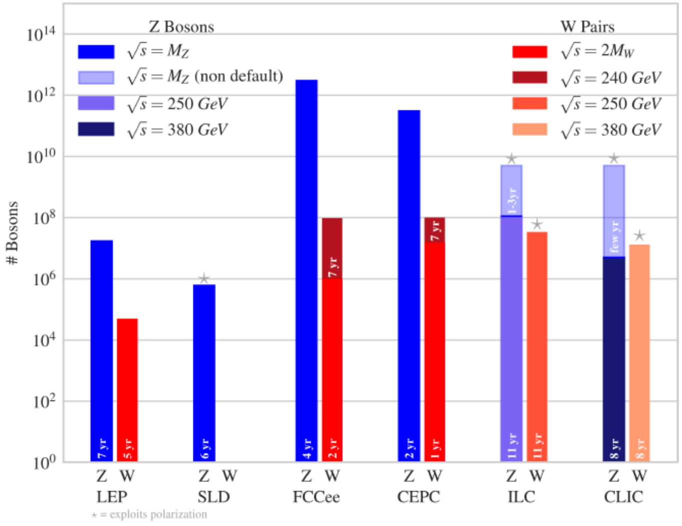
- Scalar singlet
  - May or may not mix with H boson
  - Mass below or above m_H
- Could address several questions:
  - Order of electroweak phase transition
  - Dark matter
  - …
- Future experiments will probe very interesting parameter space

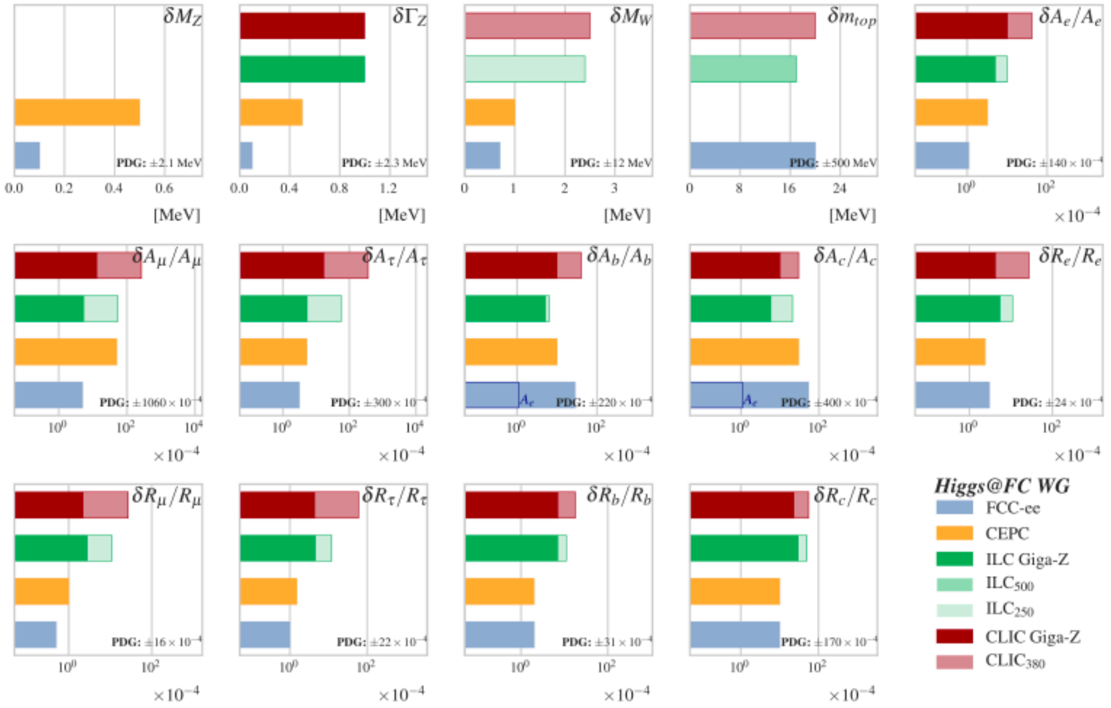




$\tilde{\chi}_2^0\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0 \rightarrow Z(^*)\,\tilde{\chi}_1^0$ and $\tilde{\chi}_1^\pm \rightarrow W(^*)\,\tilde{\chi}_1^0$
LHC 36/fb, 13 TeV
HL-LHC 3/ab, 14 TeV (3L search)
HL-LHC compressed 3/ab, 14 TeV
HE-LHC 15/ab (projection)
HE-LHC compressed 15/ab (projection)
ILC_{500}, 0.5/ab
ILC_{1000}, 1/ab
$CLIC_{1500}$, 2.5/ab
$CLIC_{3000}$, 5/ab
FCC-hh (3L search, 3/ab)
Wino-like cross-sections
European Strategy Update
95% CL exclusion
Kinematically Forbidden
$m(\tilde{\chi}_1^0)$ [GeV]
$m(\tilde{\chi}_2^0)=m(\tilde{\chi}_1^\pm)$ [GeV]

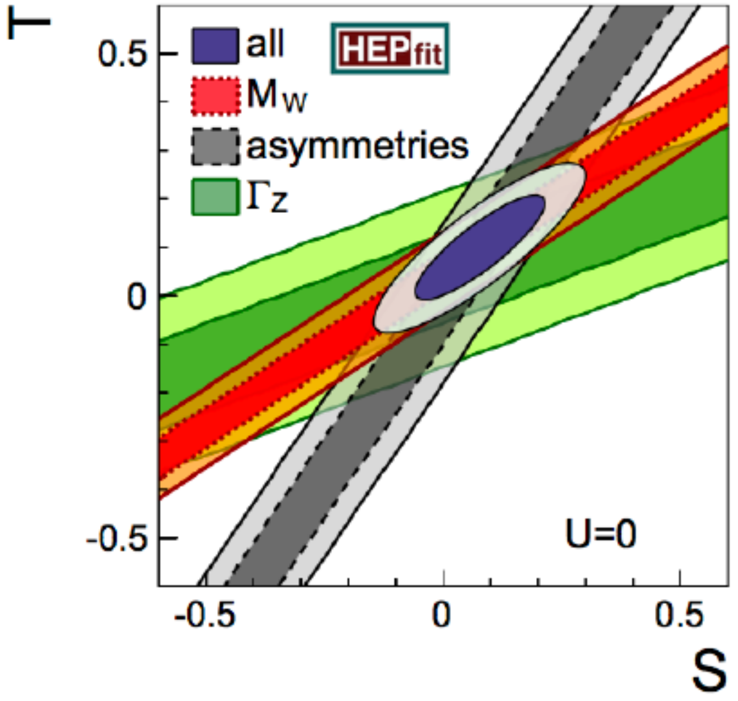
Electroweak Precision Data

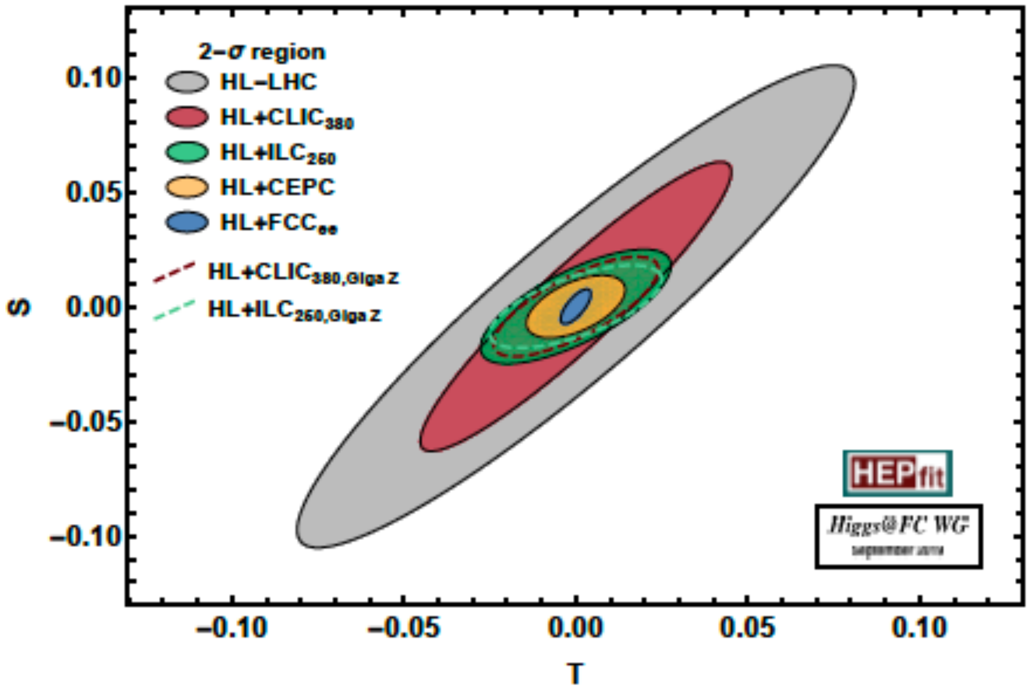




Huge improvements with future e+e- colliders ("Tera-Z")

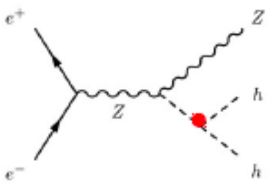
S and T parameters

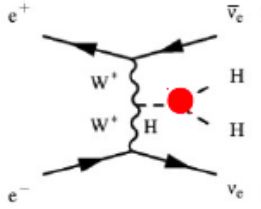


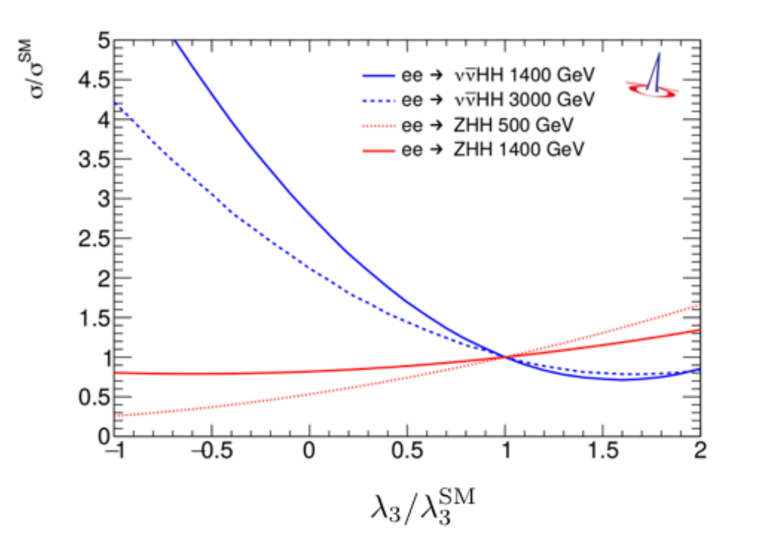


Measurement of Higgs Self-Coupling: Lepton Colliders

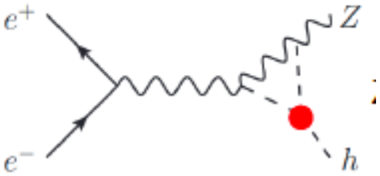
- Di-Higgs processes at lepton colliders
  - ZHH or VBF production complementary



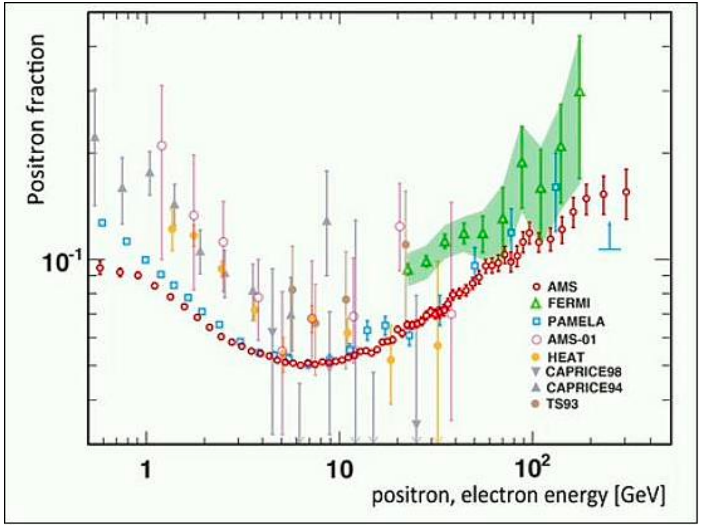


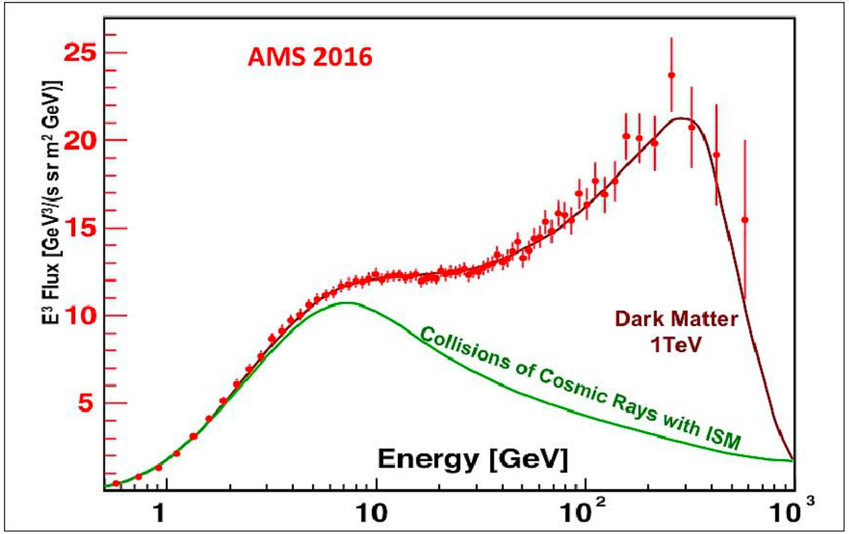


- Single-Higgs production sensitive through loop effects, e.g. for $\boldsymbol{\kappa_\lambda = 2}$:
  - Hadron colliders: ~3%
  - Lepton colliders: ~1%



AMS positron flux

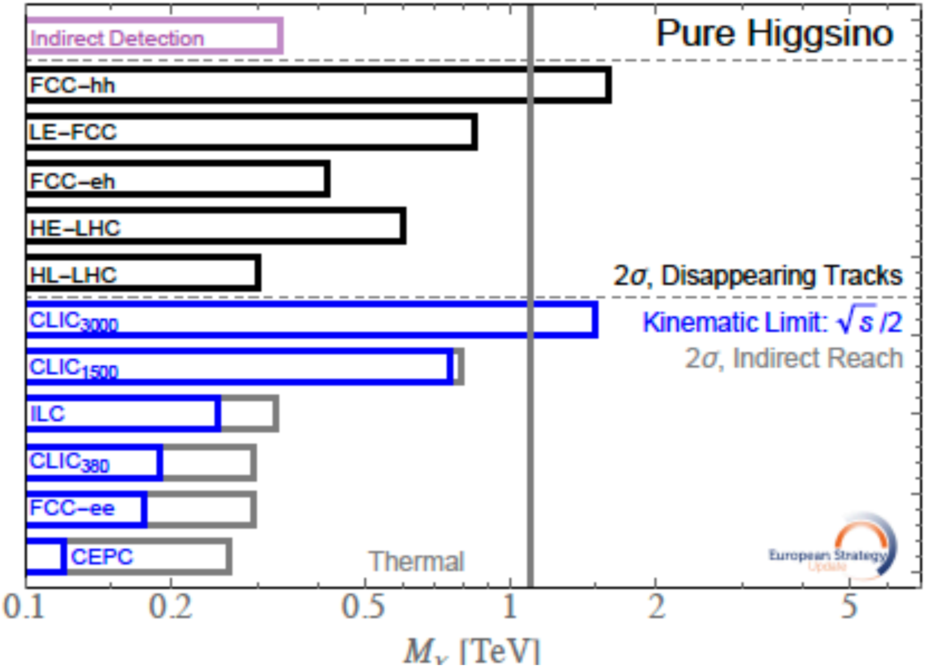


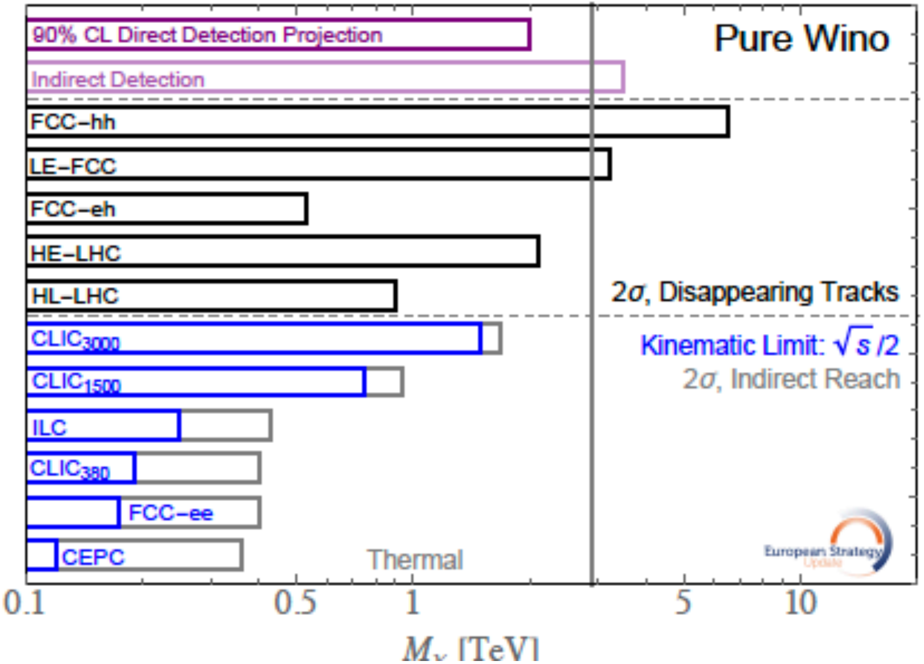


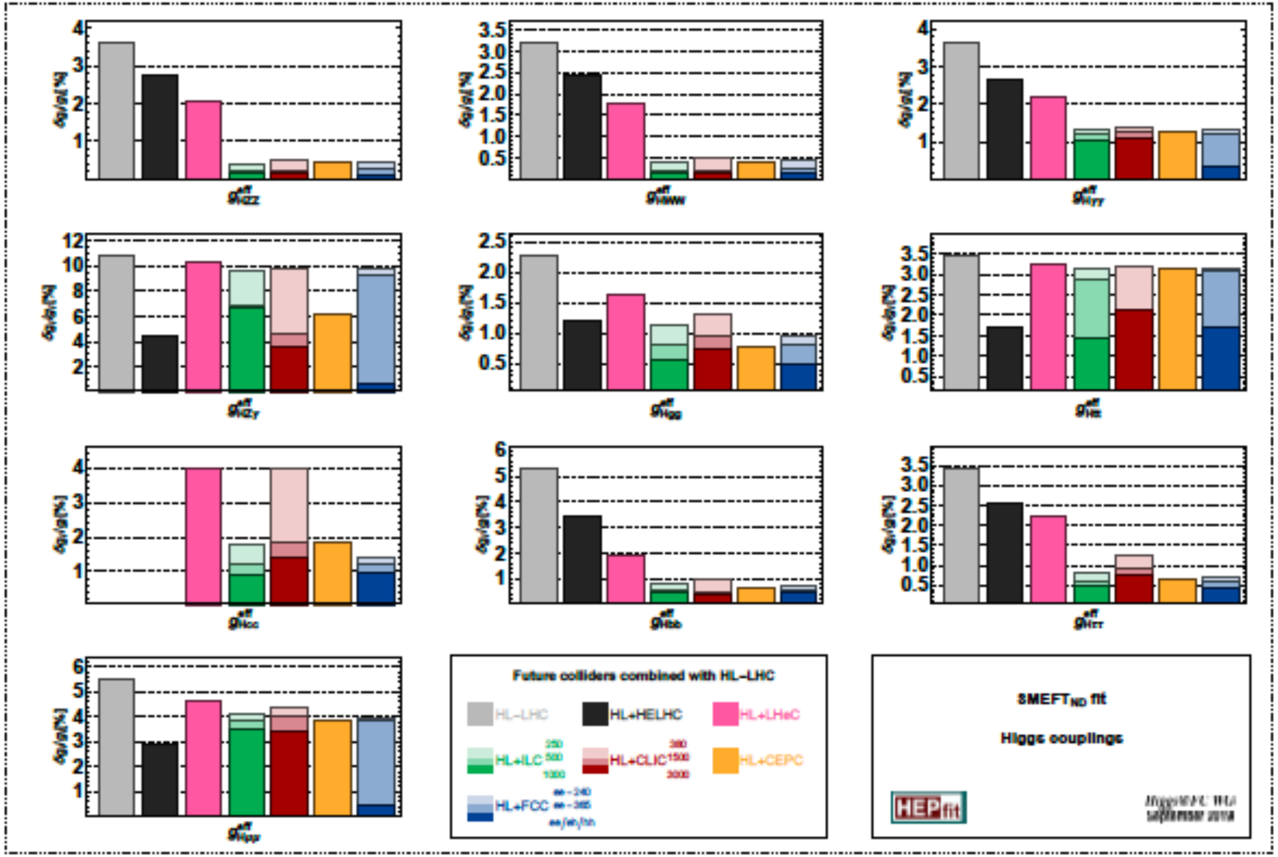
J. Kopp, Phys.Rev. D88 (2013) 076013

- AMS sees increase in positron flux as function of energy
- One possible explanation: DM annihilation to $\boldsymbol{\tau^+\tau^-}$ or $\boldsymbol{\mu^+\mu^-}$ pairs
  - These subsequently decay to electrons
- Another explanation: astrophysical sources, e.g. pulsars

Dark Matter searches compared






Future colliders combined with HL-LHC
HL-LHC
HL+HELHC
HL+LHeC
HL+ILC
HL+CLIC
HL+CEPC
HL+FCC
SMEFT$_{ND}$ fit
Higgs couplings
HEPfit

Comparing direct detection and Higgs constraints

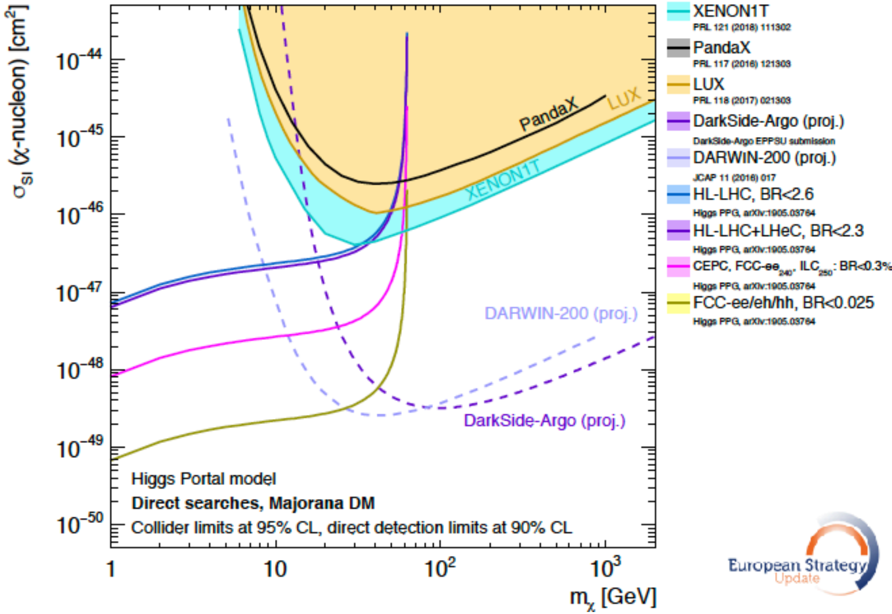
Dark Matter can be scalar, vector or fermion:

Scalar: $$\Delta\mathcal{L}_S = -\frac{1}{2}m_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{hSS} H^\dagger H S^2 \,,$$

Vector: $$\Delta\mathcal{L}_V = \frac{1}{2}m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{4}\lambda_{hVV} H^\dagger H V_\mu V^\mu ,$$

Fermion: $$\Delta\mathcal{L}_f = -\frac{1}{2}m_f f f - \frac{1}{4}\frac{\lambda_{hff}}{\Lambda} H^\dagger H f f + \text{h.c.} \,. \qquad (5)$$

$$\mathrm{BR}_\chi^{\mathrm{inv}} \equiv \frac{\Gamma(H\to\chi\chi)}{\Gamma_H^{\mathrm{SM}} + \Gamma(H\to\chi\chi)} = \frac{\sigma_{\chi p}^{\mathrm{SI}}}{\Gamma_H^{\mathrm{SM}}/r_\chi + \sigma_{\chi p}^{\mathrm{SI}}}$$



With $$r_\chi = \Gamma(H\to\chi\chi)/\sigma_{\chi p}^{\mathrm{SI}}$$

Let there be a singlet

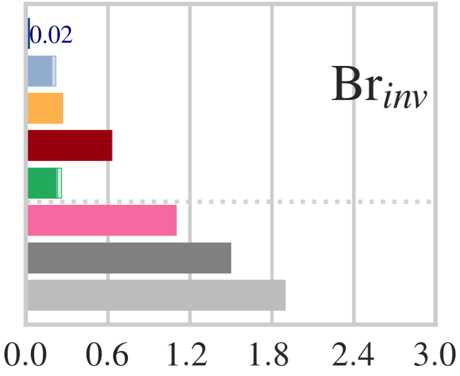
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu S)(\partial^\mu S) - \frac{m_s^2}{2}S^2 - \frac{a_s}{3}S^3 - \frac{\lambda_s}{4}S^4 - \lambda_{hs}\Phi^\dagger\Phi S^2 - 2a_{hs}\Phi^\dagger\Phi S \quad \langle\Phi\rangle = (0, v/\sqrt{2}), \quad \langle S\rangle = v_s$$

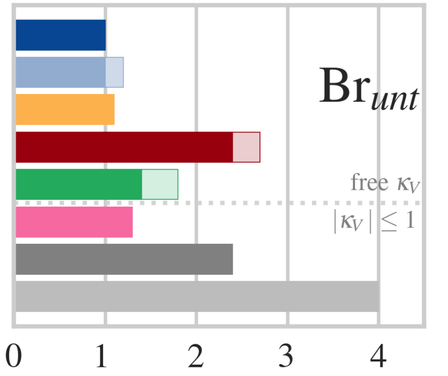
Mixing between S and H:

$$\sin 2\theta = \frac{4v(a_{hs} + \lambda_{hs}v_s)}{M_h^2 - M_s^2}$$

Z_2 symmetry: $a_{hs} = v_s = 0$

=> No mixing between H and S





If $M_S < M_H/2$ => H→SS decay possible

- Z_2 symmetry: $S \rightarrow$ invisibly
- $\sin\theta \neq 0$:
  - $S \rightarrow f\bar{f}$ with $y_{f,S} = \sin\theta\, y_{f,H}$ => direct searches
  - $S \rightarrow$ undetected is also sensitive in global fit

Let there be a singlet

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu S)(\partial^\mu S) - \frac{m_s^2}{2}S^2 - \frac{a_s}{3}S^3 - \frac{\lambda_s}{4}S^4 - \lambda_{hs}\Phi^\dagger\Phi S^2 - 2a_{hs}\Phi^\dagger\Phi S$$

$$\langle\Phi\rangle = (0, v/\sqrt{2}), \quad \langle S\rangle = v_s$$

Mixing between S and H:

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Z_2 symmetry: $a_{hs} = v_s = 0$

=> No mixing between H and S

If $M_S > M_H/2$ and $\sin\theta \neq 0$

- all H couplings modified => BR unaffected
- Total production cross section modified

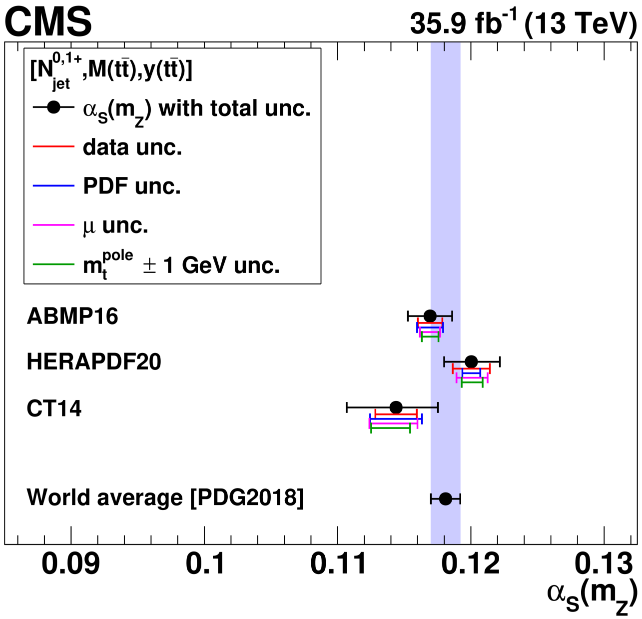
$$\mu_i^f \approx \cos^2\theta.$$

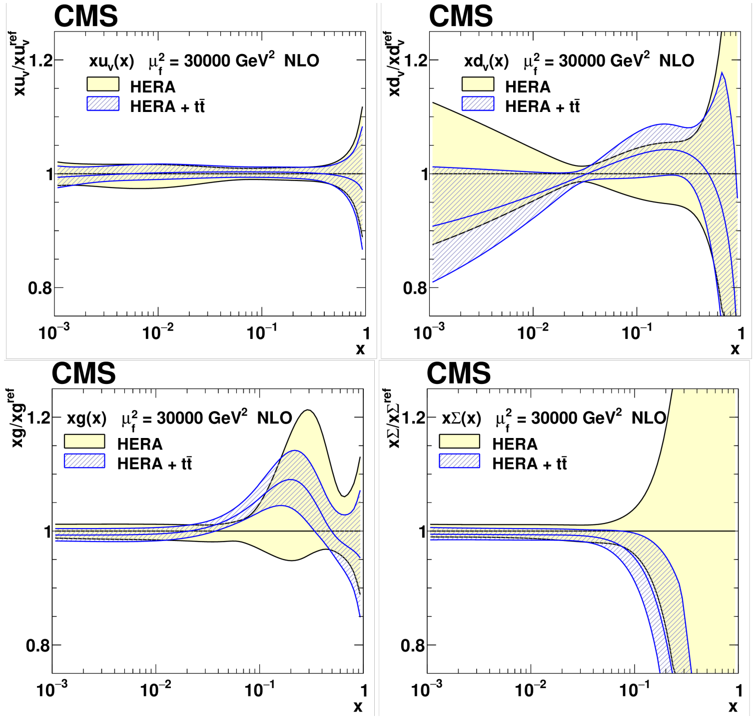
For 1st order ewk phase transition (Katz, Perelstein, arXiv:1401.1827): $\mu_i^f - 1 \gtrsim 0.6\%.$

	Δμ (%)
now	7.8
HL-LHC	1.5-3
ILC	0.7
FCC-ee	0.5
CLIC	0.24

Perturbative QCD at the LHC

arXiv:1904.05237





- Important consistency check
  - Actually some tension between tt data and other data seen in QCD fits

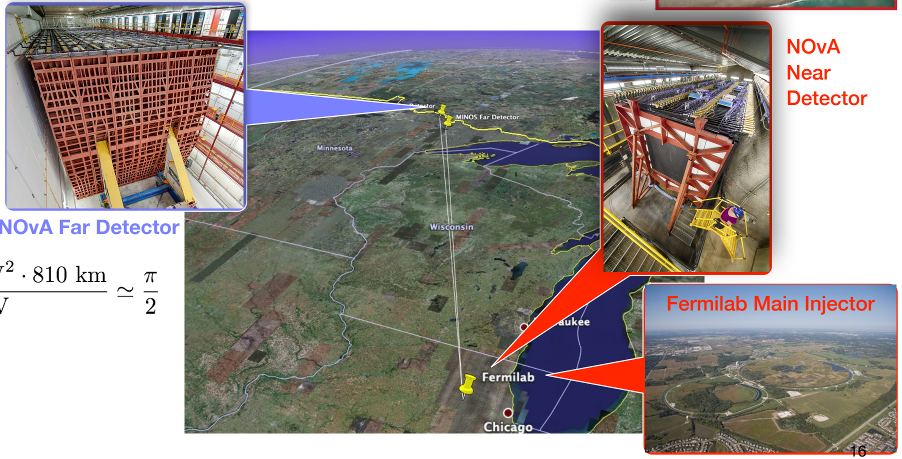
Long-Baseline Experiments in Japan and USA

T2K

$E_\nu \simeq 0.7$ GeV,

$$\Delta \equiv \frac{1.27 \cdot 0.0025\ \mathrm{eV}^2 \cdot 295\ \mathrm{km}}{0.7\ \mathrm{GeV}} \simeq \frac{\pi}{2}$$

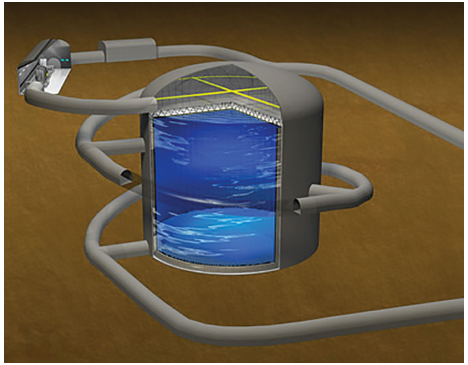
NOvA



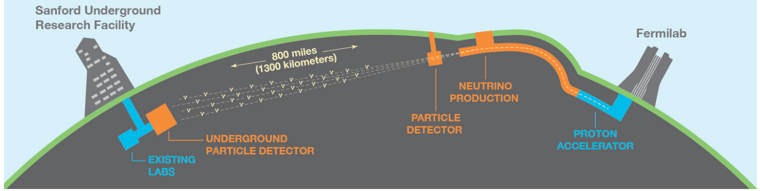
$E_\nu \simeq 2$ GeV,

$$\Delta \equiv \frac{1.27 \cdot 0.0025\ \mathrm{eV}^2 \cdot 810\ \mathrm{km}}{2\ \mathrm{GeV}} \simeq \frac{\pi}{2}$$

Hyper-Kamiokande



LBNF beamline => DUNE



LHC Roadmap

2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
….
2037

Run 1: $\sqrt{s}$=7-8 TeV, $\int$**Ldt=25 fb**$^{-1}$, pileup $\mu \approx 20$

LS1: phase 0 upgrade

Run 2: $\sqrt{s} \approx 13$ TeV, $\int$**Ldt≈120 fb**$^{-1}$, $\mu \approx 43$

We are here!

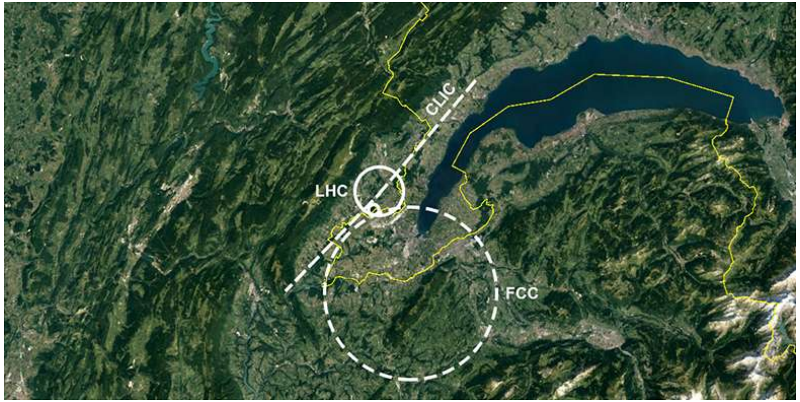
LS2: phase 1 upgrade

Run 3: $\sqrt{s} \approx 14$ TeV, $\int$**Ldt≈350 fb**$^{-1}$, μ=50-80

LS3: phase 2 upgrade

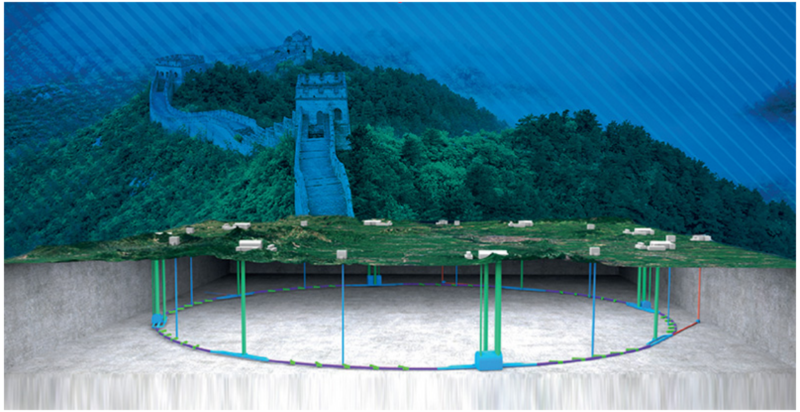
HL-LHC: $\sqrt{s} \approx 14$ TeV, $\int$**Ldt≈3000 fb**$^{-1}$, $\mu \approx 140$-200

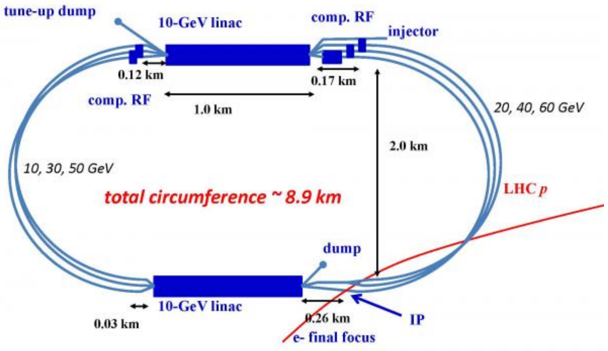
Future Colliders



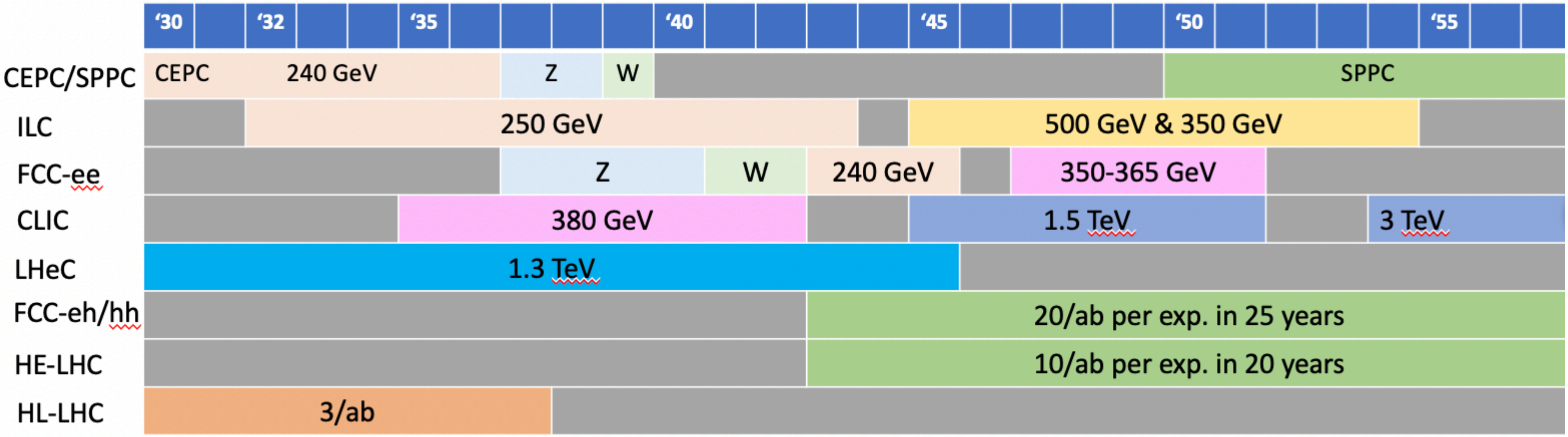
Proposed colliders:

- Linear e+e-: ILC, CLIC
- Circular e+e-: FCC-ee, CePC
- pp: HE-LHC, FCC-hh, SppC
- ep: LHeC, FCC-eh



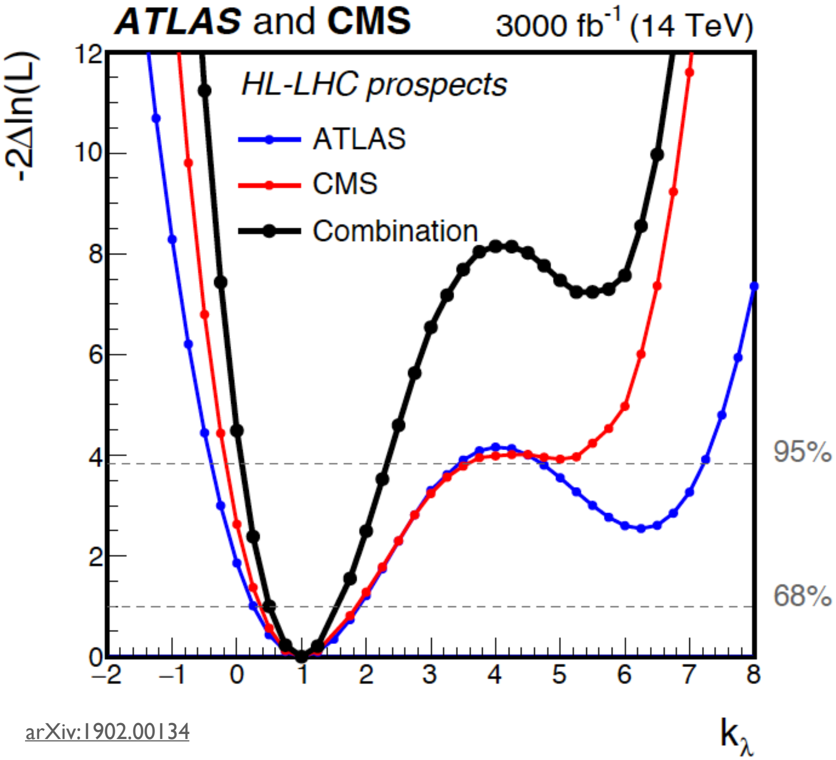


Future Colliders: √s and tentative timescales



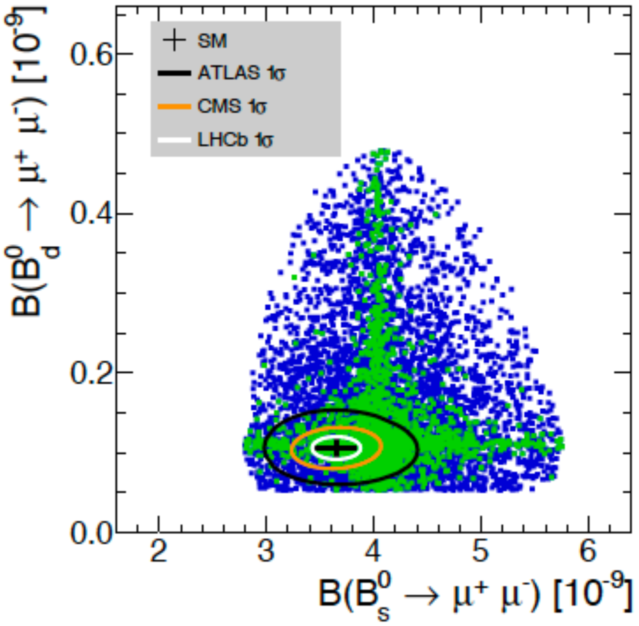
Sensitivity to κ_λ at HL-LHC

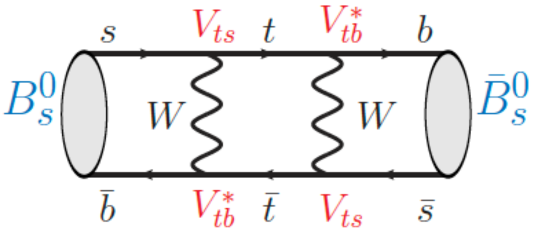
- 50% sensitivity at HL-LHC….
- Sensitivity very relevant for probing order of phase transition!

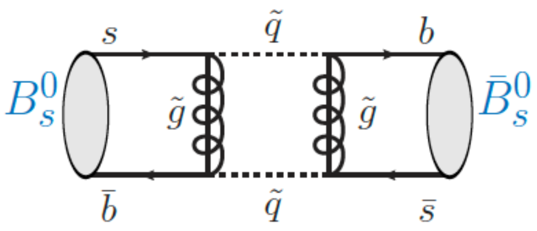


arXiv:1902.00134

New physics with heavy quarks





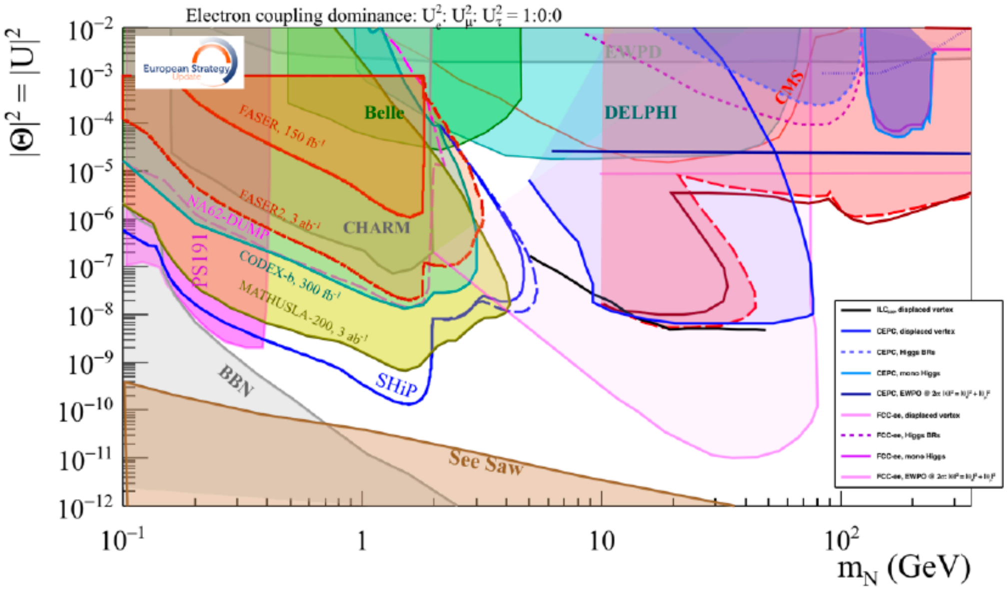


Sensitive to many models of new physics

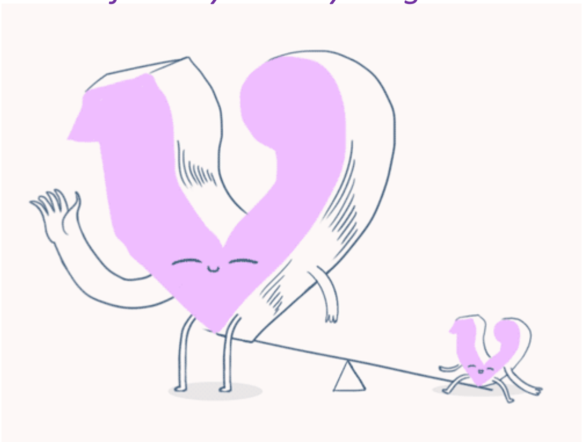
What about right-handed neutrinos

Minkowski (77); Gell-Mann, Ramond, Slansky; Yanagida; Glashow; R. N. M., Senjanovic (1979)

- *Seesaw mechanism* could explain $m_\nu \ll m_e$
- Requires heavy RH neutrino: $M_R/g \gg v$
  - typically at GUT scale but could be lower but could be lower if g very small

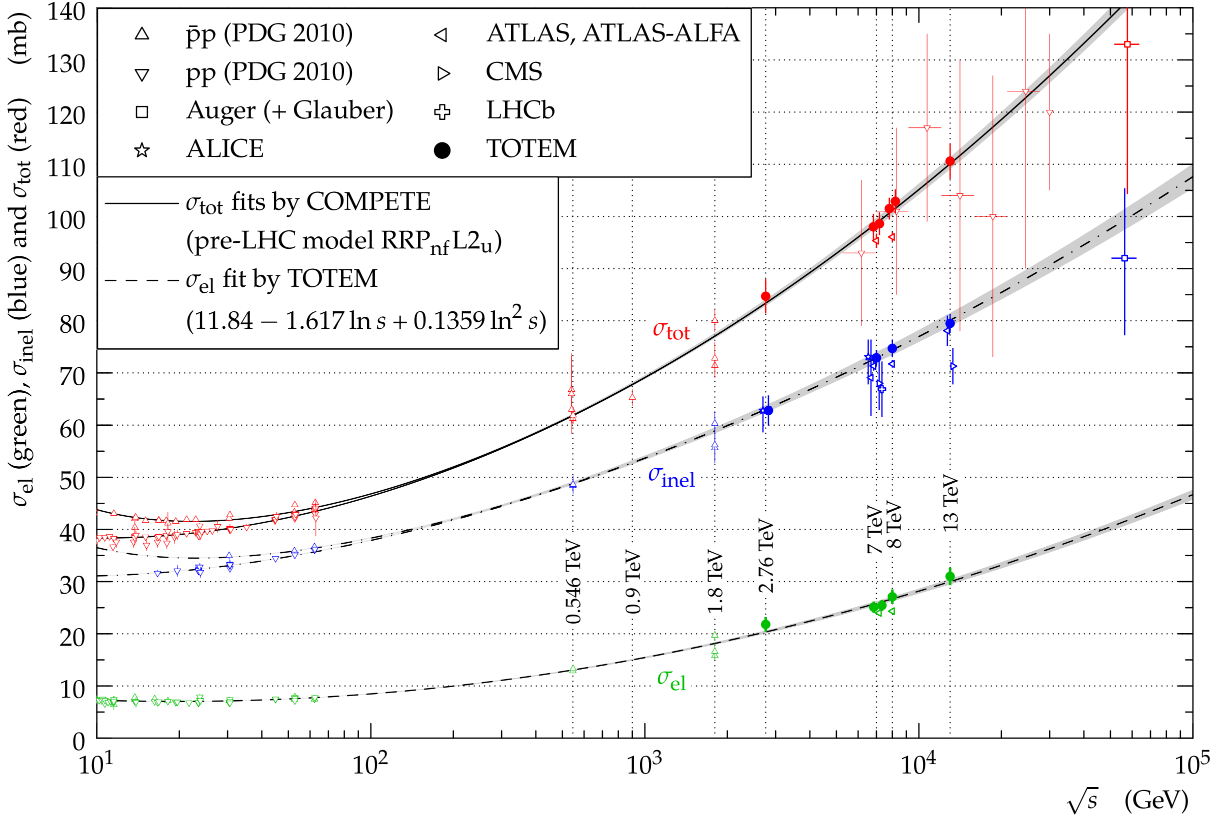


from Symmetry magazine



Probed by e.g. beam dump & collider experiments

Total, Inelastic and Elastic Cross Sections



arXiv:1712.06153 and refs therein