Experimental status and future colliders opportunities

Fulvio Piccinini

International School on future colliders, Pisa

Pisa, 17-21 September 2018

The paradigm: Standard Model (1967)

VOLUME 19, NUMBER 21 PHYSICAL REVIEW LETTERS 20 NOVEMBER 1967

[11] In obtaining the expression (11) the mass difference between the charged and neutral has been ignored.

[12] M. Ademollo and R. Gatto, Nuovo Cimento 44A, 282 (1966); see also J. Pasupathy and R. E. Marshak, Phys. Rev. Letters 17, 888 (1966).

[13] The predicted ratio [eq. (12)] from the current algebra is slightly larger than that (0.23%) obtained from the ρ-dominance model of Ref. 2. This seems to be true also in the other case of the ratio $\Gamma(\eta\rightarrow\pi^+\pi^-\gamma)/\Gamma(\gamma\gamma)$ calculated in Refs. 12 and 14.

[14] L. M. Brown and P. Singer, Phys. Rev. Letters 8, 460 (1962).

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons

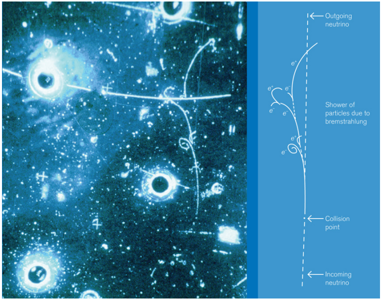
and on a right-handed singlet

$$R \equiv [\tfrac12(1-\gamma_5)]e. \qquad (2)$$

$$\mathcal{L} = -\tfrac14(\partial_\mu \vec{A}_\nu - \partial_\nu \vec{A}_\mu + g\vec{A}_\mu \times \vec{A}_\nu)^2 - \tfrac14(\partial_\mu B_\nu - \partial_\nu B_\mu)^2 - \bar{R}\gamma^\mu(\partial_\mu - ig'B_\mu)R - L\gamma^\mu(\partial_\mu ig\vec{t}\cdot\vec{A}_\mu - i\tfrac12 g'B_\mu)L$$

$$-\tfrac12|\partial_\mu\varphi - ig\vec{A}_\mu\cdot\vec{t}\varphi + i\tfrac12 g'B_\mu\varphi|^2 - G_e(\bar{L}\varphi R + \bar{R}\varphi^\dagger L) - M_1{}^2\varphi^\dagger\varphi + h(\varphi^\dagger\varphi)^2. \qquad (4)$$

1973: neutral currents



$\nu e \rightarrow \nu e$ at bubble chamber **Gargamelle**, CERN, 1973

In the following years colliders were fundamental in establishing the SM particle content

Consistent extension to the quark sector

PHYSICAL REVIEW D VOLUME 2, NUMBER 7 1 OCTOBER 1970

Weak Interactions with Lepton-Hadron Symmetry*

S. L. Glashow, J. Iliopoulos, and L. Maiani†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139

(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

- prediction of a fourth quark (“charm”) $\Longrightarrow$ 1974: discovery

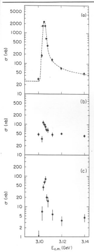


FIG. 1. Cross section versus energy for (a) multi-hadron final states, (b) e^+e^- final states, and (c) $\mu^+\mu^-$, ... and K^+K^- final states. The curve in (a) is the expected shape of a δ-function resonance folded with the Gaussian energy spread of the beams and including ...

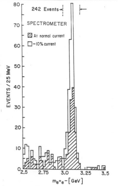
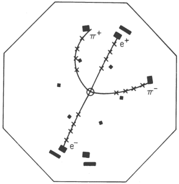
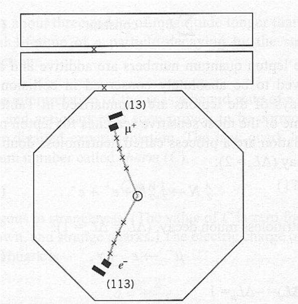


FIG. 2. Mass spectrum showing the existence of J. ...sults from two spectrometer settings are plotted ...wing that the peak is independent of spectrometer ...rents. The run at reduced current was taken two ...nths later than the normal run.

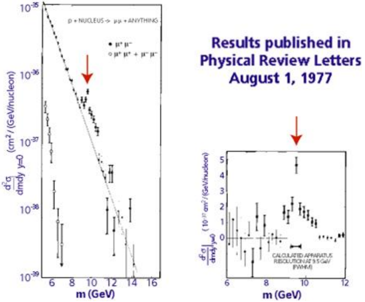


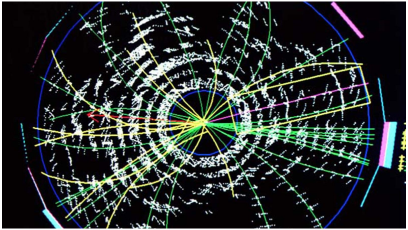


$$e^+ \; e^- \to \tau^+ \; \tau^-$$

$$\tau^- \to e^- \; \overline{\nu}_e \; \nu_\tau$$

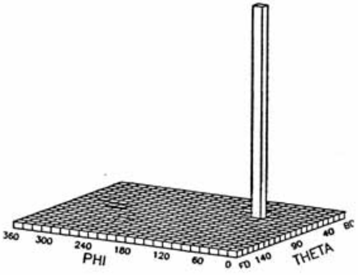
$$\tau^+ \to \mu^+ \; \nu_\mu \; \overline{\nu}_\tau$$

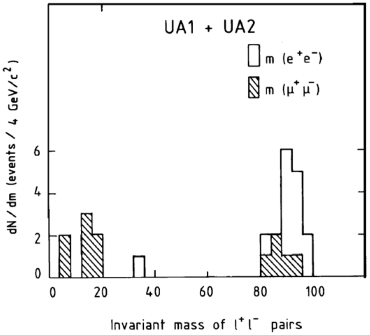




1995, $p\bar{p}$ collisions ($\sqrt{s} \sim 1.8$ TeV)
at Tevatron, Fermilab

1983: W and Z^0 vector bosons



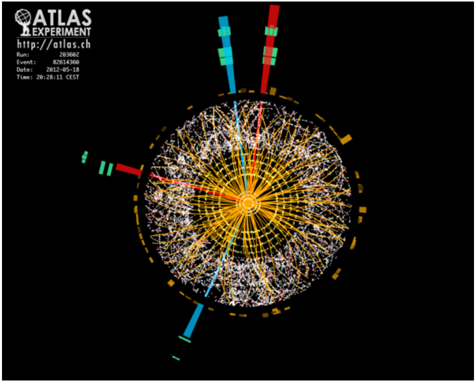


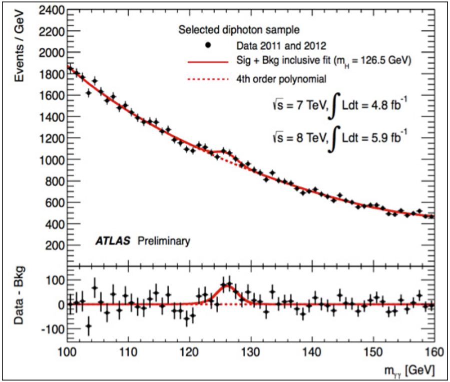
UA1 and **UA2** experiments at SPS collider $\sqrt{s} \sim 600$ GeV, Cern, 80s.

Decay $W \to \ell\nu$ and $Z^0 \to l^+l^-$ in $p\bar{p}$ collisions

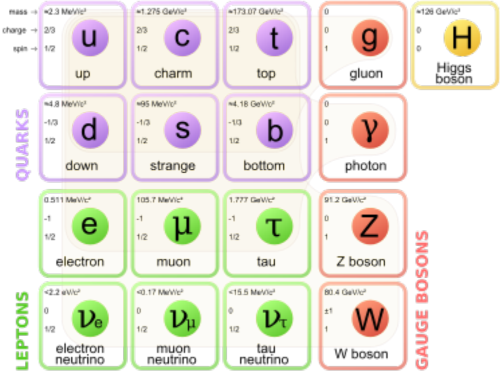
Higgs boson: last SM ingredient, LHC (2012)

- Confirmation in two Higgs decay channel:
  - photon pair
  - 4 leptons (e.g. $e^+e^-\mu^+\mu^-$)





SM in a picture



- in the process of discovering the SM particles, a crucial point has been to have colliders of increasing energy
- During last three decades the SM has been tested to high level of precision by means of (leptonic and hadronic) colliders

First collider ever built: AdA, LNF (Italy)

- VEP-1 collider, Novosibirsk (Russia)
- Princeton-Stanford Colliding Beam Experiment, Stanford (USA)

Relevant parameters for collider maximum energy

- energy loss by sincrotron radiation of charged particles bent by a magnetic field

$$\Delta E \sim \left(\frac{E}{m}\right)^4 \times \frac{1}{R}$$

  - limiting factor for e^+e^- collider. E.g. at LEP @$\sqrt{s} = 210$ GeV

$$E_{\mathrm{beam}} = 105\ \mathrm{GeV} \Longrightarrow P \sim 22\ \mathrm{MW} \to 800\ \frac{\mathrm{W}}{\mathrm{m}}$$

  - for comparison, proton beam at LHC of 6.5 TeV $\Longrightarrow P \sim 0.2$ W/m
- achievable magnetic field in dipoles with available technologies

$$E_{\mathrm{beam(TeV)}} = 0.3 R(\mathrm{km}) B(\mathrm{Tesla})$$

  - main limiting factor in pushing up LHC energy
- achievable accelerating e.m. field gradient G on a distance l

$$E = eGl$$

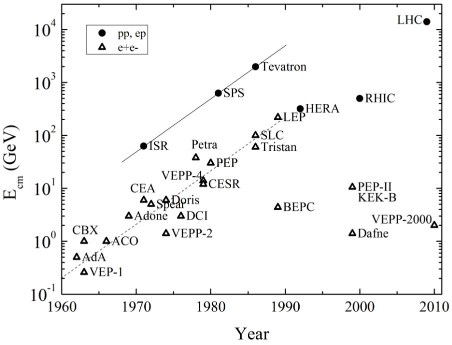
Other relevant parameter: luminosity

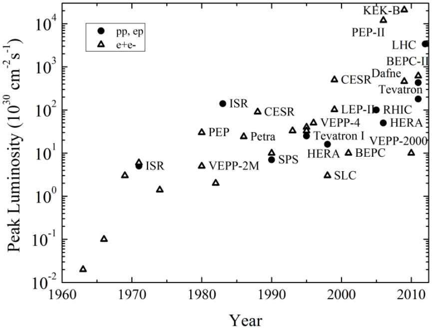
$$
\begin{aligned}
\frac{dN_{\rm exp}}{dt} &= \mathcal{L}\sigma \\
\mathcal{L} &= f\frac{N_1 N_2}{A} \\
f &= \text{collision frequency} \\
N_i &= \text{particles in colliding bunches} \\
A &= \text{effective overlap area of the beams}
\end{aligned}
$$

- time integrated luminosity $L \Longrightarrow$ total number of collected events

see lectures by F. Zimmermann

Time evolution of maximum energy and luminosity



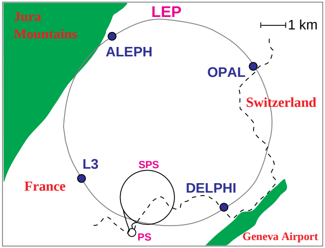


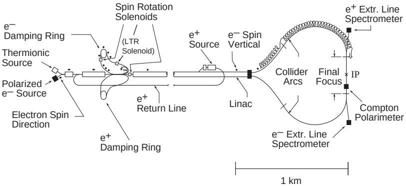
V.D. Shiltsev, arXiv:1205.3087

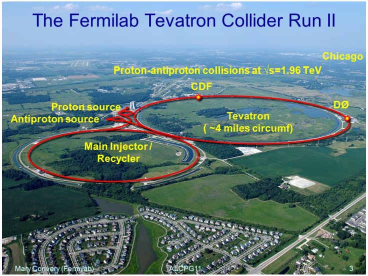
Leptonic vs hadronic colliders

- e^+e^- colliders: pointlike electrons $\Longrightarrow$ clean signatures in the detectors
  - center of mass energy known with good precision
  - reliable perturbative theoretical predictions (ew interactions)
  - **ideal machines for precision studies**
  - limited by sincrotron radiation in maximum achievable energy
- $pp/p\bar{p}$ colliders: protons are composite hadrons $\Longrightarrow$ at large four-momentum transfers the collisions between quarks and gluons
  - potential contamination from underlying event (interaction between the beam remnants)
  - large backgrounds from QCD processes
    - $\alpha_s > \alpha_{em}$ and gluons interact only through QCD
  - center of mass energy accessible through PDF's which need input from experimental data
  - interesting hard scattering energy lower than nominal c.m. energy
  - typically less precise theoretical predictions
  - almost absence of sincrotron radiation $\Longrightarrow$ **ideal discovery machines**

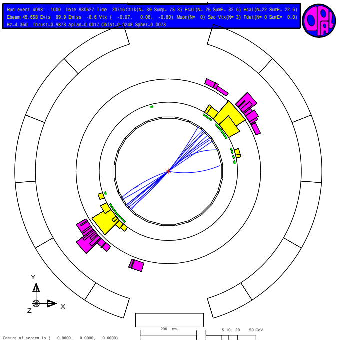
'89-2001: LEP1-2; '92-'98: SLC; '86-2011: Tevatron

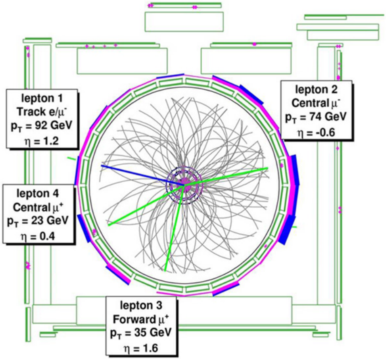






events at LEP and Tevatron

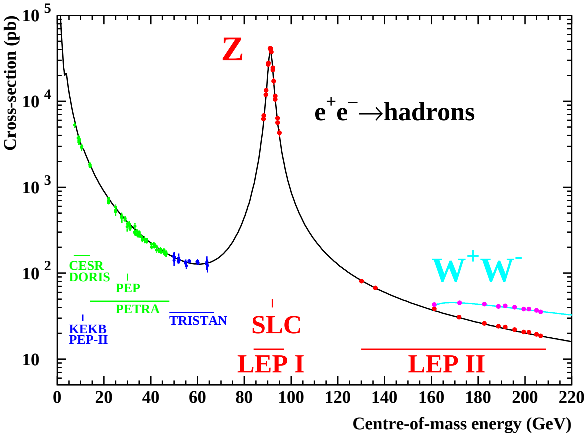




$e^+e^- \to Z \to q\bar{q} \to 2$ jets

$p\bar{p} \to ZZ \to \mu^+\mu^-\mu^+\mu^-$

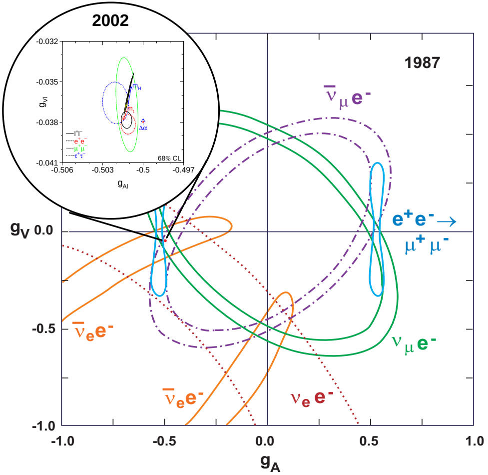
SM tested up to ~ 200 GeV



- precision $\mathcal{O}(0.1\%)$ measurements of the processes $e^+e^- \to f\bar{f}$
- $\mathcal{O}(1\%)$ for the processes $e^+e^- \to WW/ZZ \to 4$ fermions

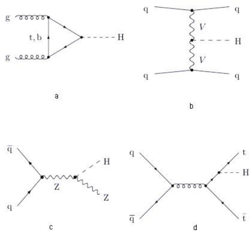
Z couplings to fermions

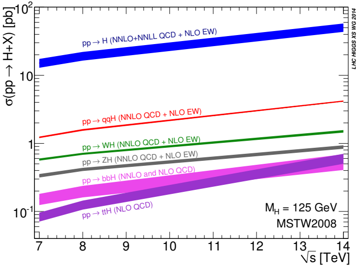
- $\mathcal{L}_{\text{int}} = J^\mu Z^0_\mu, \qquad J^\mu \sim \bar{\psi}\gamma^\mu(g_V - g_A\gamma_5)\psi$

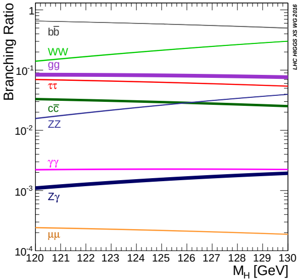


- strong constraints on physics beyond SM

2012 –: discovery and study of the Higgs at the LHC

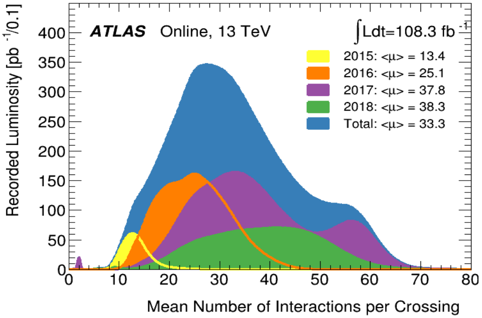




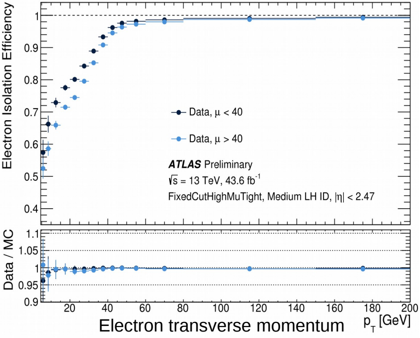


Pileup at LHC

Interactions per bunch per crossing:

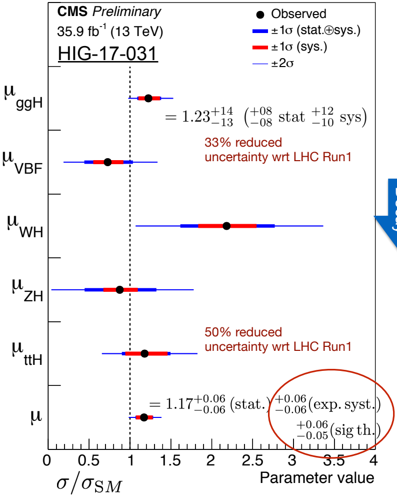


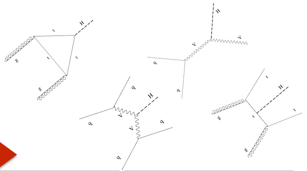
Electron isolation efficiency:



talk by T. Carli, ICHEP 2018, Seoul

Higgs Properties





Production

Decay

	ggF	VBF	VH	ttH
H→ZZ→4l	●	●	●	●
H→γγ	●	●	●	●
H→WW	●	●	●	●
H→bb	●		●	●
H→ττ	●	●		●
H→μμ	●	●		
H→inv	●	●	●	

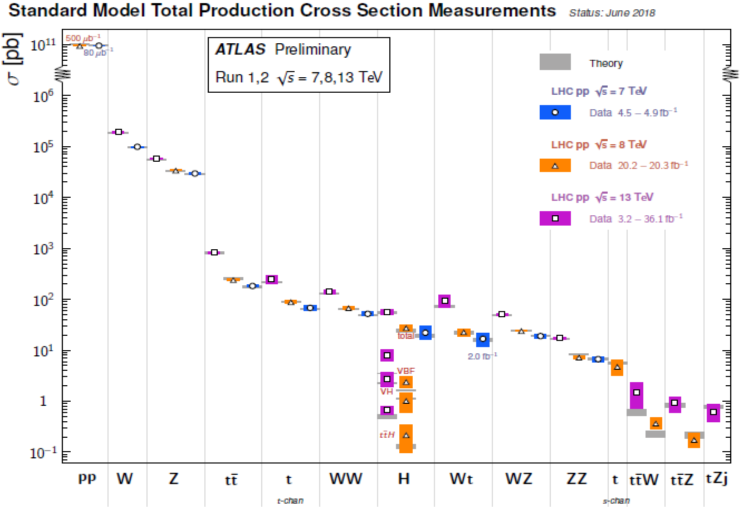
Total of 250 even categories

$$BF(H \to \text{inv.}) < 22\%\,@\,95\%\,\text{C.L.}$$

- Nearing theory-limited territory with just 2016 data

talk by S. Rahatlou, ICHEP 2018, Seoul

Measurements overview



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Measurements of electroweak parameters

New

Measurement of electroweak mixing angle:

Drell-Yan cross-section qq→Z→ll expanded as sum of 9 harmonic polynomials (NNLO QCD).
In LO QCD (Z-boson rest frame):

A_4 (and A_3) sensitive to weak mixing angle

$$\frac{d\sigma}{dy^{\ell\ell}\, dm^{\ell\ell}\, d\cos\theta} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dy^{\ell\ell}\, dm^{\ell\ell}}\left\{(1+\cos^2\theta) + A_4 \cos\theta\right\}$$

A_4 measured using two leptons |η|<2.4 (cc)
and at least one forward electron 2.5<|η|<4.6 (cf).
Using 8 TeV data (2012).

Result from likelihood fit:

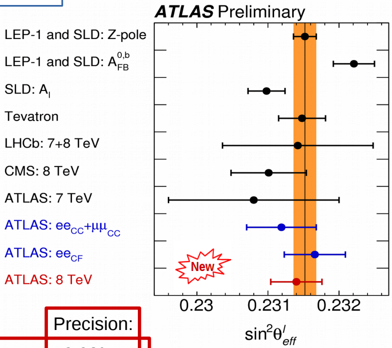
$$\sin^2\theta^l_{eff} = 0.23140 \pm 0.00036$$

Uncertainty break-down:

$$0.00021\,(stat) \pm 0.00024\,(PDF) \pm 0.00016\,(syst)$$

Main limitation knowledge initial quark direction.

ATLAS-CONF-2018-037



0.15% precision

Other recent electroweak measurements:

			Precision:
W-mass:	80370 +- 19 MeV	EPJ C78 (2018) 110	~0.02%
Higgs mass:	124970 +- 240 MeV	arXiv:1806.00242	~0.2%
Top-mass:	172510 +- 500 MeV	ATLAS-CONF-2017-071	~0.3%

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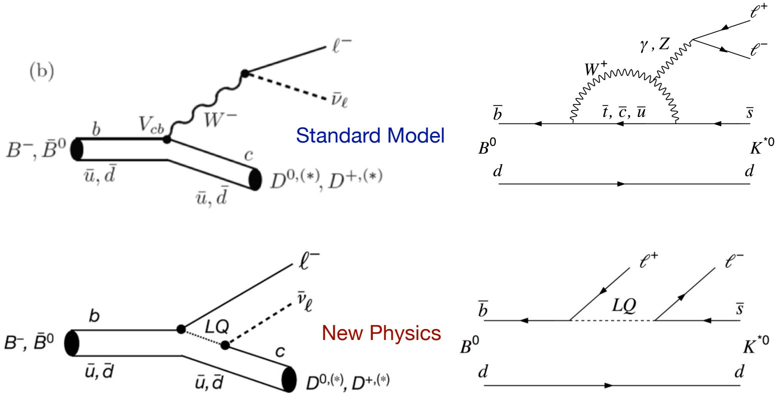
Any hint of discrepancy between data and SM?

- Up to now all direct searches at LHC of new particles has given negative results, putting lower limits on the coupling-mass ratio g/M
- however some puzzling data at low energy
  - from LHCb data
  - from the anomalous magnetic moment of the muon



LEPTON FLAVOR UNIVERSALITY

INDIRECT NEW PHYSICS

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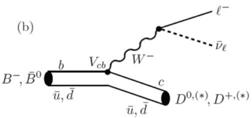
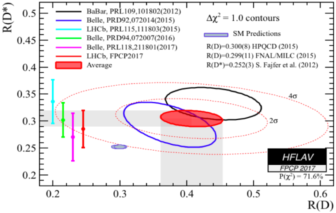
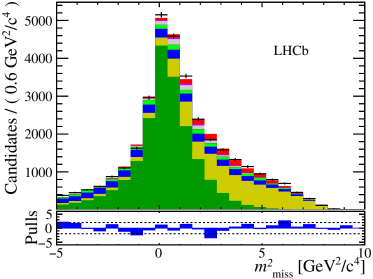
ANOMALIES AT TREE LEVEL

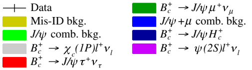


$$R(D^*) = \frac{BF(B \to D^* \tau \nu)}{BF(B \to D^* \mu \nu)}$$



- Extending study of tree-level anomalies to B_c sector with J/psi





SM prediction: 0.25-0.28

$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_\mu)}$$
$$= 0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{syst})$$

$B_c^+ \to J/\psi$ form factors

PRD 97 (2018) 072013,
PRL 120 (2018) 121801,
Run 1, 3 fb^{-1}

Shahram Rahatlou, Roma Sapienza & INFN

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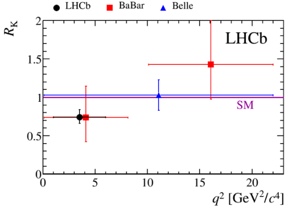
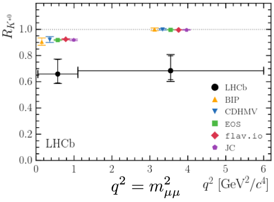
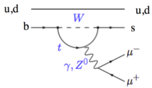
ANOMALIES IN PENGUINS

PRL 113 (2014) 151601, JHEP 08 (2017) 055, Run 1 data, 3 fb^{-1}





muons / electrons [b → s]



$$R_K = \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)}$$

Analogously: R_{K^*}

- Discrepancies in b →sll transitions at BaBar, Belle, and LHCb
  - Differential branching fractions
- Analysis with Run2 data underway at LHCb
  - challenging precision analysis over multi-year data sample
  - Also adding new final states, e.g. $B_s \to \phi\, l^+ l^-$
- Plan to perform measurement at CMS with improved low-momentum electron reconstruction

Shahram Rahatlou, Roma Sapienza & INFN

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status of $a_\mu = (g-2)/2$

- E821@BNL measurement with an error of 0.54 ppm

$$a_\mu^{\rm exp} = 116592089(63) \times 10^{-11}$$

G.W. Bennet et al. (Muon (g-2)), Phys. Rev. **D73** (2006) 072003

- Error reduction by about a factor of 4 in few years with E989@FNAL

R.M. Carey et al., (2009), Fermilab-Proposal-0989

- E34@JPARC can later
cross-check the E989 result with a completely independent method

J. Imazato, Nucl. Phys. Proc. Suppl. 129 (2004) 81, J-PARC Proposal

- Theoretical prediction

F. Jegerlehner, MITP Workshop, 19-23 February 2018, Mainz

$$a_\mu^{\rm SM} = 116591783(35) \times 10^{-11}$$

- $\Delta({\rm Th} - {\rm Exp}) = -306 \pm 72$ $\sim 4\sigma$ deviation

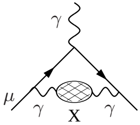
  - New Physics?
  - systematics of the measurement?

- QED perturbative corrections known up to 4 loops plus 5 loops partial calculation: $a_\mu^{\rm QED} = 116584718.86(30) \times 10^{-11}$
  $\sim 99.99\%$ of the total

T. Aoyama, M. Hayakawa, T. Kinoshita; S. Laporta, E. Remiddi; M. Passera

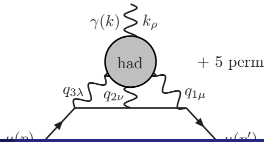
- $a_\mu^{\rm HLO} = 6894.6(32.5) \times 10^{-11} \Longrightarrow$ largest source of uncertainty

F. Jegerlehner, MITP Workshop, 19-23 February 2018, Mainz



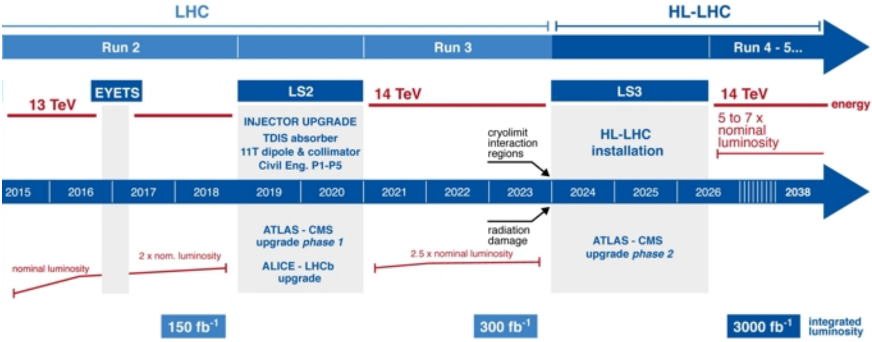
- Hadronic light-by-light: $a_\mu^{\rm LxL} = 103.4(28.8) \times 10^{-11}$

F. Jegerlehner, MITP Workshop, 19-23 February 2018, Mainz



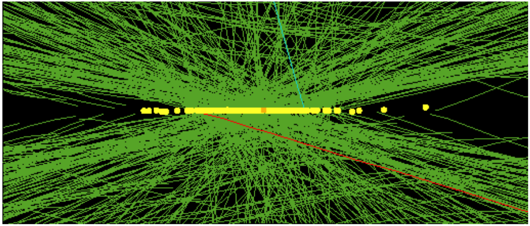
$+$ 5 permutations of the q_i

The (approved) future of LHC



main issues at HL-LHC

- increase of pile-up, up to $<\mu>\sim 140$ (n. of interaction per crossing)



CMS-TDR-15-02, LHCC-P-008

- damage to detector components from large radiation dose

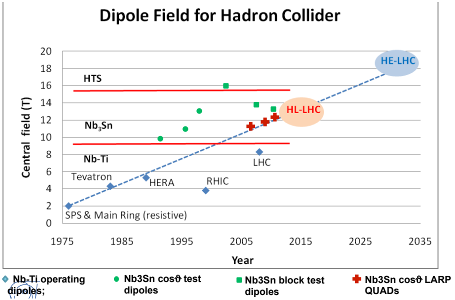
$\Longrightarrow$

- upgrades needed for detector hardware, trigger, DAQ, software and computing

see lectures by S. Vallecorsa and M. Selvaggi

What next after HL-LHC?
without a clearcut clue on the next relavant scale

- **push the energy frontier as much as we can**
- consistently with the (today) conceivable technological progress



L. Rossi, INFN EU Strategy Meeting, 6-7 September 2018, Roma, Italy

- in a complementary way, **precision machine** where to study Higgs couplings (and also electroweak physics) with great accuracy, looking for discrepancies with SM theory predictions

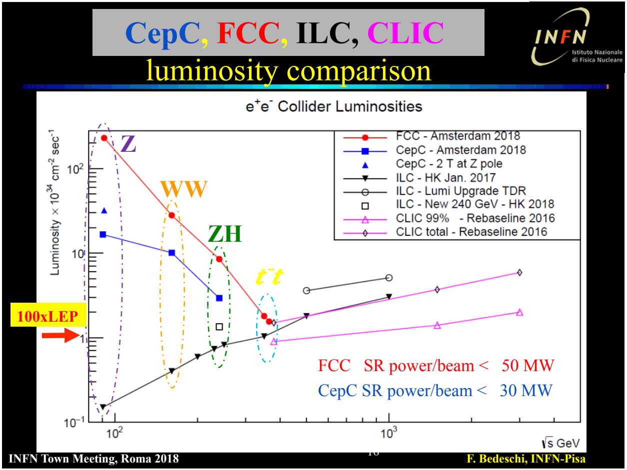
existing projects under study

- Europe (CERN)
  - **HE-LHC**: pp collider at $\sqrt{s} \simeq 27 - 30$ TeV, in the same tunnel as LHC, by using new dipoles giving 16-20 Tesla magnetic field
  - **FCC**
    - FCC-hh: pp collider at $\sqrt{s} \simeq 100$ TeV, within a 100 Km tunnel
    - FCC-ee: very high luminosity e^+e^- machine within the 100 Km tunnel, from the Z boson mass to the $t\bar{t}$ threshold
    - FCC-he: pe collider (50 TeV proton beam and 60 GeV electron beam)
  - **CLIC**: e^+e^- linear collider reaching the multi-TeV energy scale
- China
  - **CEPC**: similar to FCC-ee, with less lumi performance and maximum $\sqrt{s} \sim 240$ GeV
  - **SppC**: similar to FCC-hh
- Japan
  - **ILC**: linear e^+e^- collider, c.m. energy from 250 GeV up to 1 TeV

lectures by M.L. Mangano, W. Riegler and F. Zimmermann on pp colliders

lectures by F.P., J. Guimaraes da Costa and F. Zimmermann on e^+e^- colliders

luminosity comparison among lepton colliders

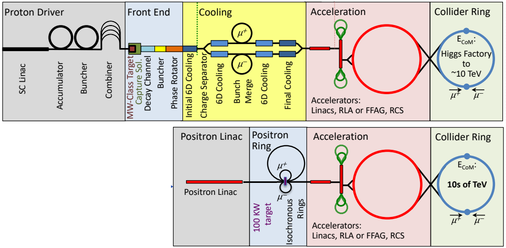


F. Bedeschi, INFN EU Strategy Meeting, 6-7 September 2018, Roma, Italy

$\mu^+\mu^-$ collider

- $m_\mu \sim 200 m_e \Longrightarrow$ bremsstrahlung would be suppressed w.r.t. a circular e^+e^- collider by a factor $(m_e/m_\mu)^4$
- μ lifetime $\sim 2.2\mu$s but longer when accelerated
- it would enable
    - direct Higgs resonance production
    - multi-TeV "compact" leptonic collider

lecture by A. Wulzer



M.E. Biagini, INFN EU Strategy Meeting, 6-7 September 2018, Roma, Italy

lecture by P. Raimondi

Last but not least: new acceleration techniques

- Current acceleration techniques are based on RF fields $f \sim 10 - 30$ GHz, which allow field gradients of the order of 100 MV/m
- ongoing studies on new more effective techniques
  - acceleration in dielectric structures $\Longrightarrow \sim 1 - 3$ GV/m
  - acceleration in ionized plasma $\Longrightarrow \sim 30 - 100$ GV/m
  - acceleration in solid crystals $\Longrightarrow \sim 0.1 = 10$ TV/m

lecture by M. Ferrario