Flavour Physics at the FCC-ee

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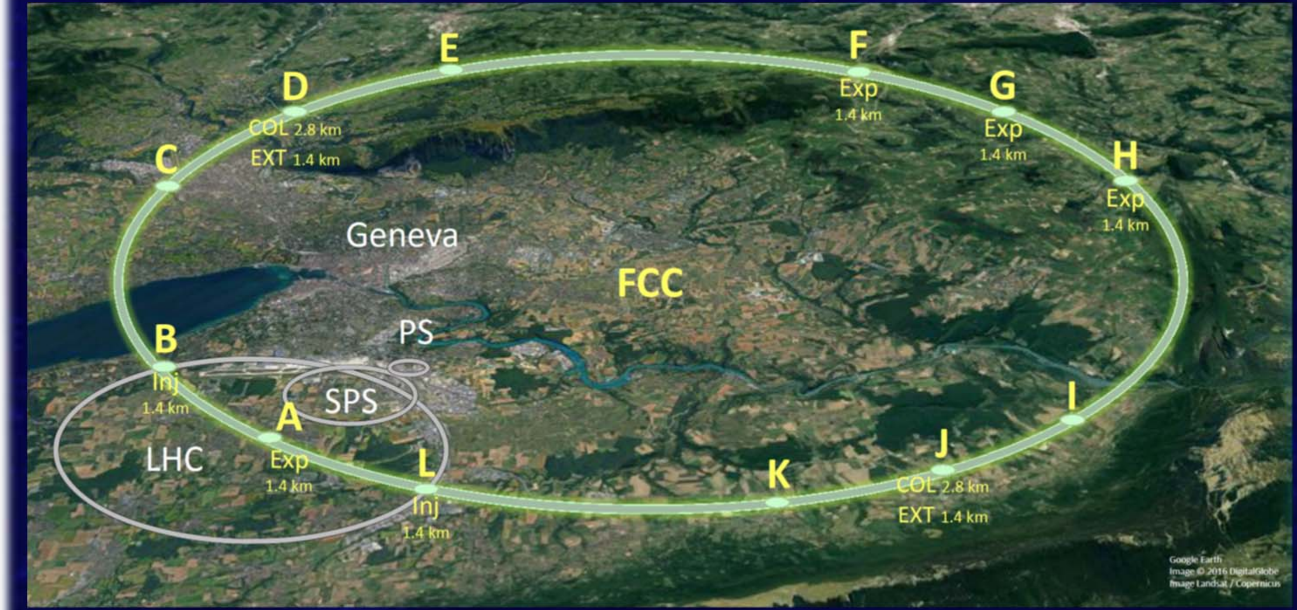
Epiphany 2018

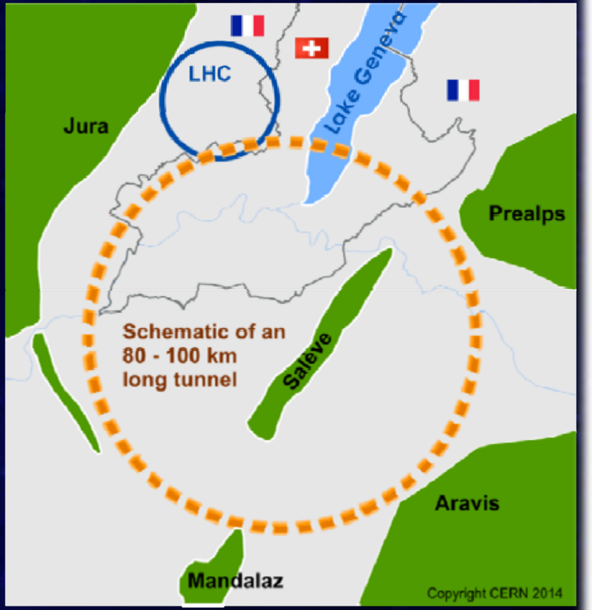
1. Future Circular Collider Project
2. FCC-ee Detector
3. Studies of B → K* ll decays
4. Searches for Z → l l’
5. Searches for Heavy Neutral Leptons
6. Summary

FCC – Future Circular Collider

- **FCC project – 100 km circular tunnel infrastructure in Geneve area**
  - ✓ **p-p collider:** FCC-hh – flagship, 100 TeV (16T magnets)
  - ✓ **e^--e^+ collider:** FCC-ee – potential first step, preceding the FCC-pp
  - ✓ **e-p collider:** FCC-he – additional option
- **Goal: CDR and cost review by the end of 2018**

→ **European Strategy for Particle Physics 2020**





FCC Collaboration

- 119 institutes
- 31 countries
- 25 industrial partners

fcc.web.cern.ch

EC
H2020

- **EuroCirCol project**
- **EASITrain ITN**

- **Poland @ FCC:**
  - ✓ Institute of Nuclear Physics PAN, Kraków
  - ✓ Silesia University, Katowice
  - ✓ Wroclaw University of Technology
  - ✓ Cracow University of Technology

FCC-ee Physics Programme

- **Collider:** two rings; four interaction points; flat beams; non-zero crossing angle, crab waist
- Four working points: $\sqrt{s} = M_Z$ $\sqrt{s} = M(WW)$ $\sqrt{s} = M(ZH)$ $\sqrt{s} = M(t\bar{t})$

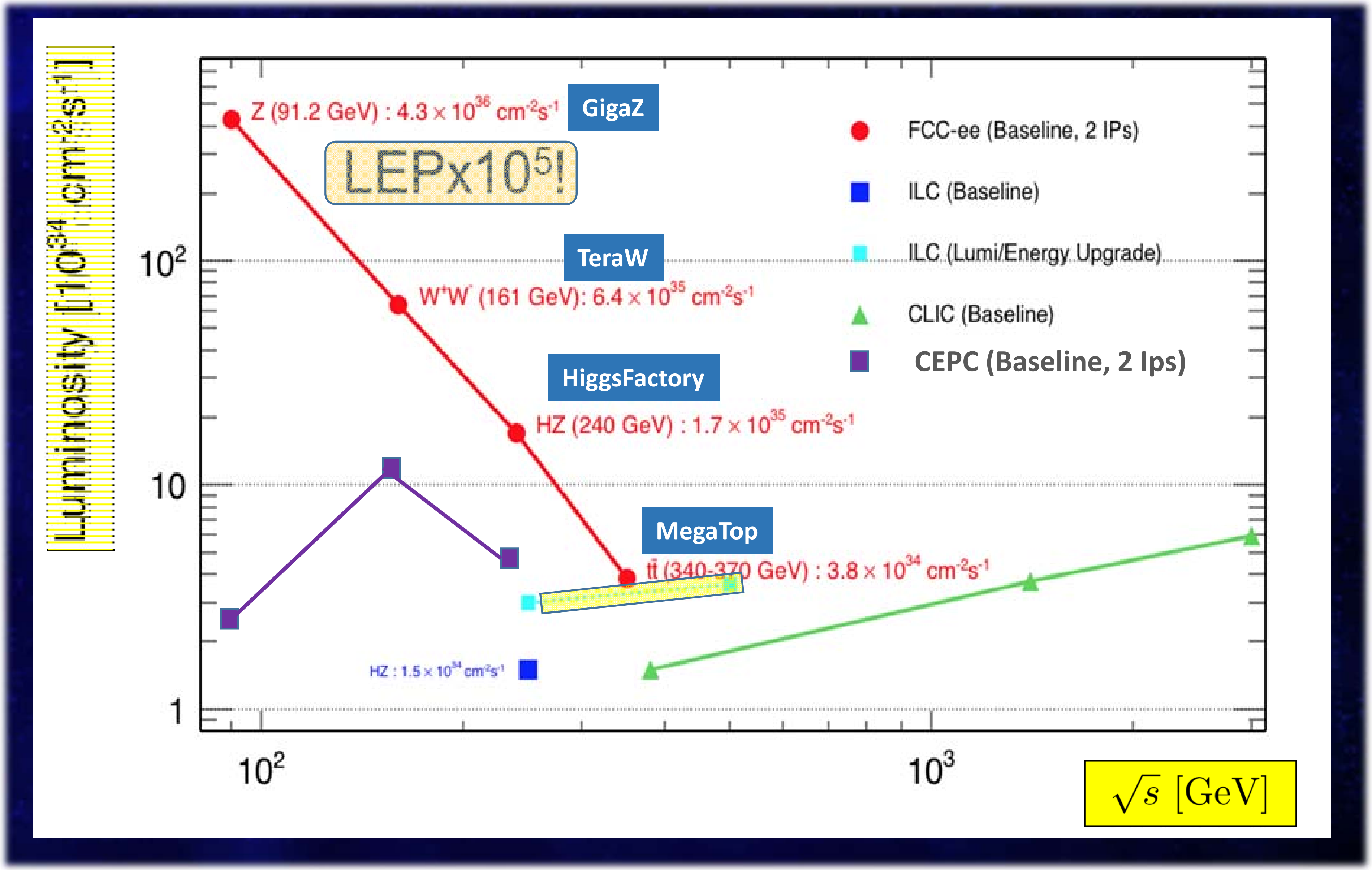
Parameter	**FCC-Z**	**FCC-WW**	**FCC-ZH**	**FCC-tt**	**LEP2**
E [GeV]	**45.6**	**80**	**120**	**182.5**	**104.5**
I [mA]	1390	147	29	5.4	4
No. Bunches/beam	16 640	2 000	393	39	4
Energy loss/turn [GeV]	0.036	0.34	1.72	9.21	3.34
Synchrotron power [MW]	100	100	100	100	22
RF Voltage [GV]	0.1	0.44	2.0	10.93	3.5
$\beta^*_{x/y}$ (mm)	150 / 0.8	200 / 1	300 / 1	1000 / 2	1500 / 50
ε_y / ε_x at collision	0.37	0.36	0.21	0.19	0.01
L (10^{34} cm^{-2}s^{-1})/IP	**230**	**32**	**8**	**1.5**	**0.012**
Statistics (4 expts)	10^{13} Z / 6yrs	3×10^{7} WW/2yr	10^{6} ZH/5yrs	10^{6} $t\bar{t}$ / 5yrs	

TeraZ **OkuW** **Higgs factory** **MegaTop**

LEP1 :

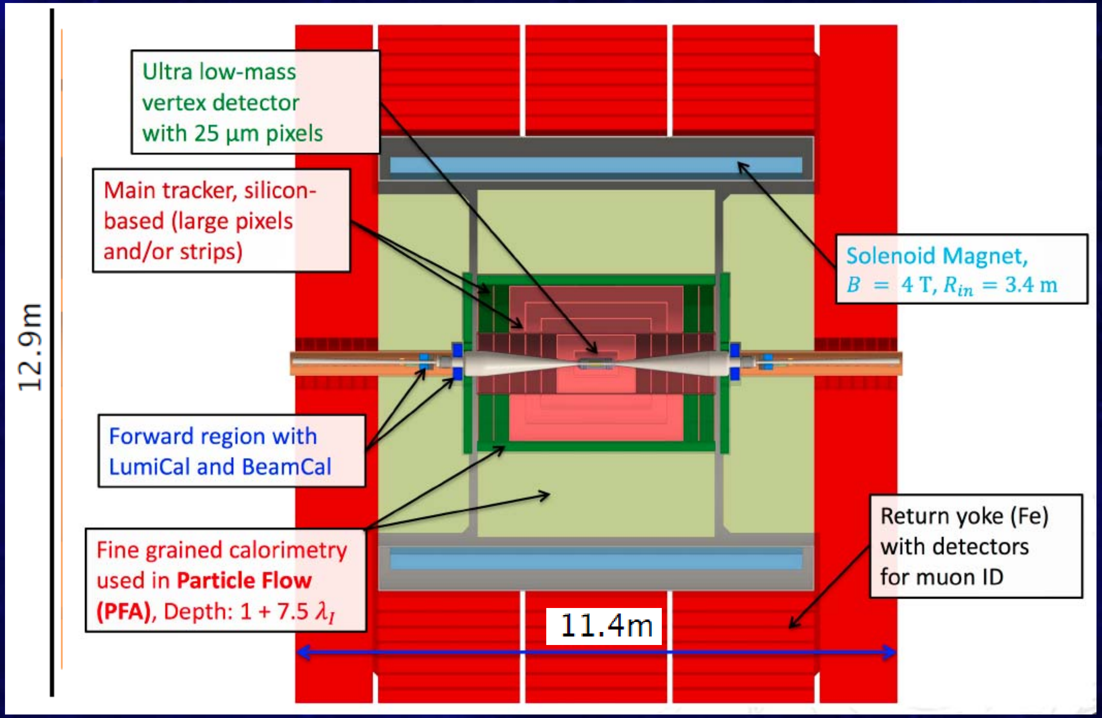
$2.1 \times 10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

Proposals for New e^+e^- Colliders:

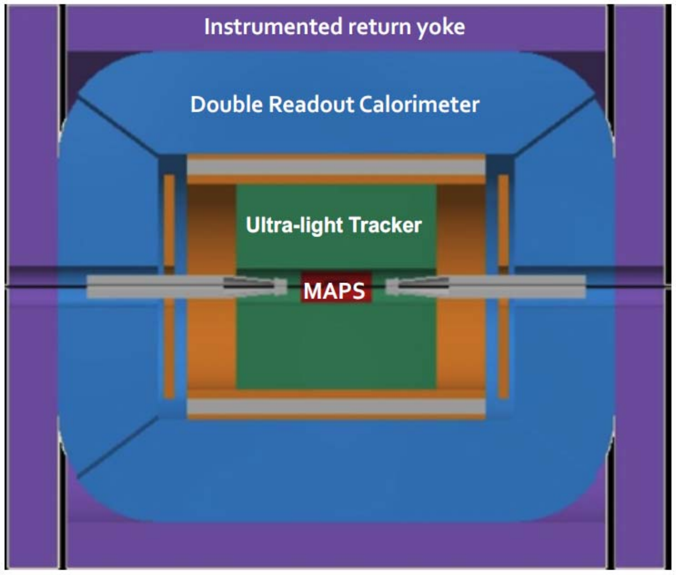


FCC-ee Detector

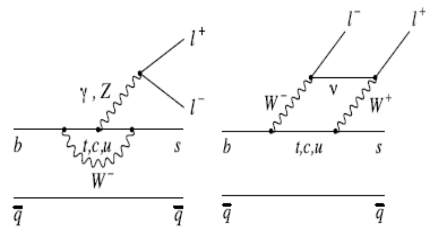
CLICdp inspired



IDEA

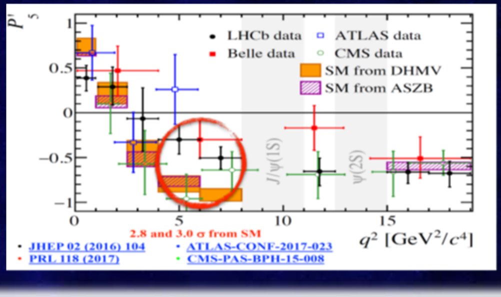


b→ s $l^+ l^-$ Transitions



Anomalies:

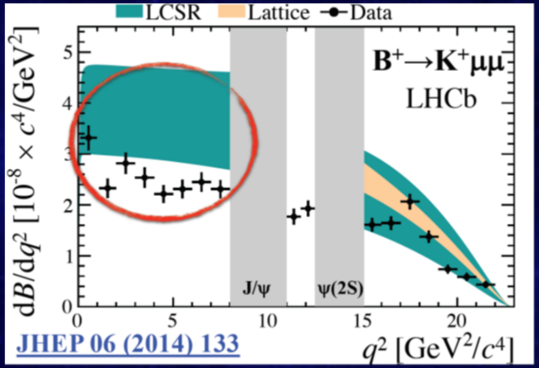
- **Angular analyses**



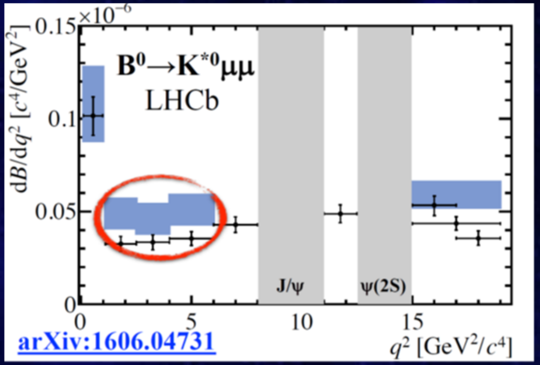
2.8 and 3.0 σ from SM

- JHEP 02 (2016) 104
- PRL 118 (2017)
- ATLAS-CONF-2017-023
- CMS-PAS-BPH-15-008

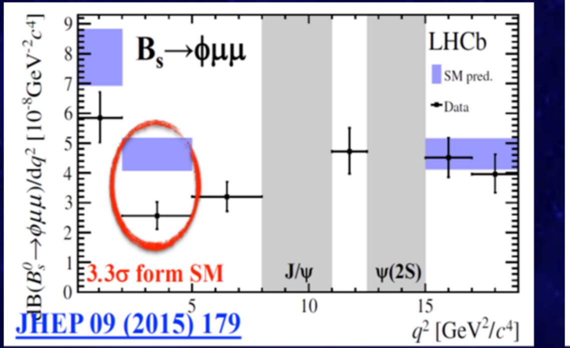
- **Differential branching fractions**



JHEP 06 (2014) 133

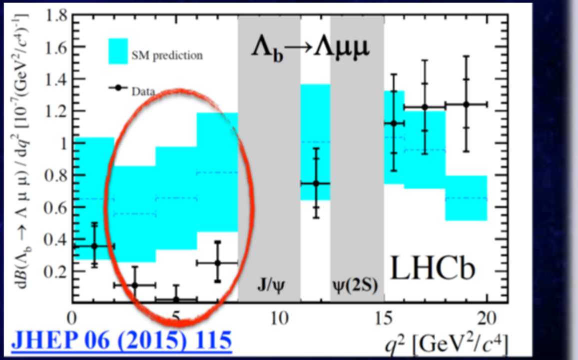


arXiv:1606.04731



3.3σ form SM

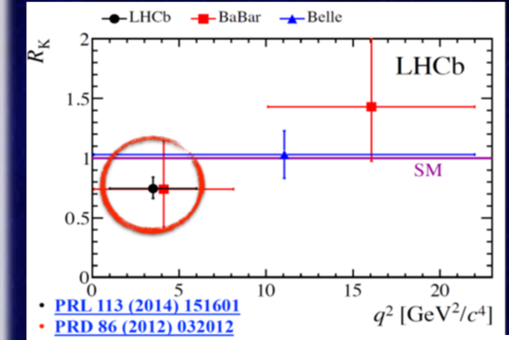
JHEP 09 (2015) 179



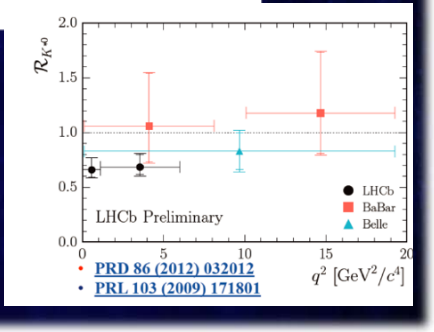
JHEP 06 (2015) 115

- **Lepton universality tests**

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



- PRL 113 (2014) 151601
- PRD 86 (2012) 032012
- PRL 103 (2009) 171801



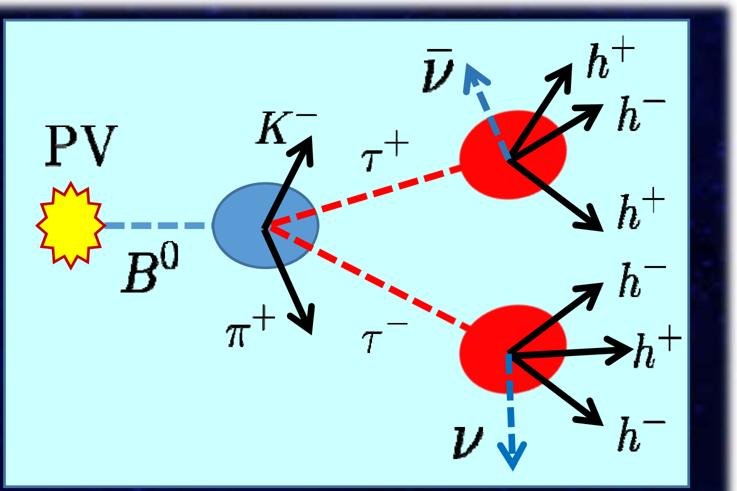
- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

- $B \to K^*\tau^+\tau^-$ (partial reconstruction)

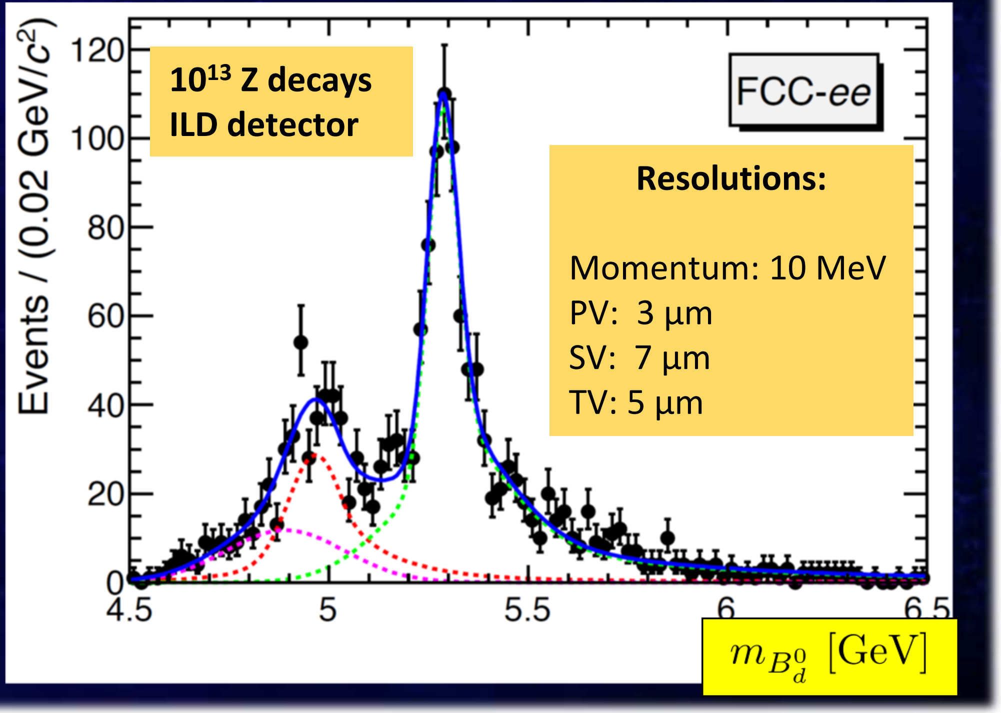
B→ K* $\tau^+ \tau^-$ Decays at FCC-ee

- Concentrate on τ decays to three prongs (τ → $a_1\nu$) – two neutrinos missing (6 d.o.f.)
- HOPEFULLY the secondary vertices of K*→ Kπ and τ provide sufficiently many constraints:
  - B flight distance - 2 d.o.f.
  - τ flight distance - 4 d.o.f.
  - τ masses - 2 d.o.f. (←Not all independent)

arXiv: 1705.11106 [hep-ex]



🟩 signal
🟥 $B_s \to D_s^+ D_s^- K^{*0}(892)$
🟪 $\bar{B}^0 \to D_s^+ K^{*0}(892)\tau^-\bar{\nu}_\tau$



10^{13} Z decays
ILD detector

Resolutions:

Momentum: 10 MeV
PV: 3 μm
SV: 7 μm
TV: 5 μm

- The crucial role of secondary and tertiary vertex resolution
- FCC-ee: 1000 signal events expected, assuming typical (ILD-like) detector and FCC-ee baseline luminosity
- Belle 2: 10 events expected
- → angular analysis feasible (?)

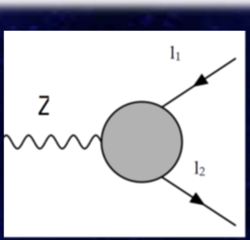
Studies of charged Lepton Flavour Violation (cLFV)

- Evidence for neutrino oscillations:
  ➔ at least two neutrinos are massive fermions AND (neutral) lepton flavour is not conserved

- So far there is no experimental evidence for **charged** Lepton Flavour Violation (cLFV)…

1. Search for cLFV in the decays of Z bosons

$Z \to ll',\ l \neq l',\ l, l' = e, \mu, \tau$

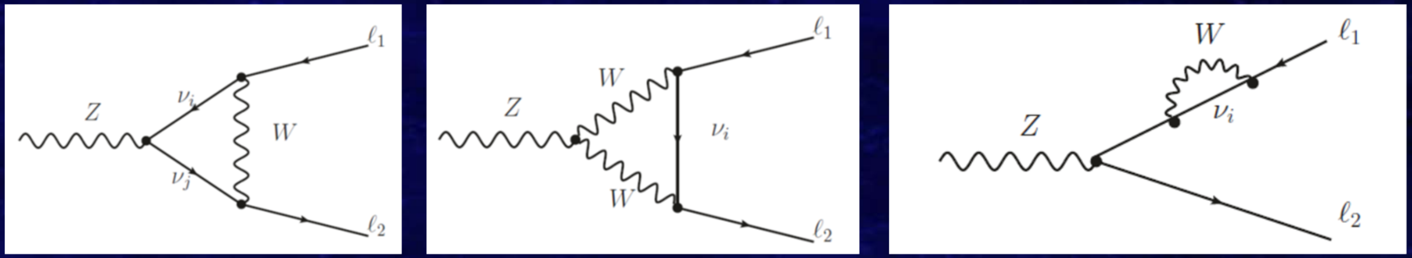


SM: Massless neutrinos: cLFV forbidden at any order of perturbation theory
Massive neutrinos: cLFV processes l➔l'γ present at the one-loop level but strongly suppressed by GIM

$$\mathrm{BR}(Z \to e^{\pm}\mu^{\mp}) \sim \mathrm{BR}(Z \to e^{\pm}\tau^{\mp}) \leq 10^{-60}$$

$$\mathrm{BR}(Z \to \mu^{\pm}\tau^{\mp}) \sim 10^{-54}$$

BSM: $BR(Z \to ll') \sim 10^{-9}$ - particularly for models with new sterile fermions



(ν are physical states, i= 3+N, N – numer of extra Majorana states)

Any observation of Z ➔ l l' would be a clear sign of New Physics

Studies of charged Lepton Flavour Violation (cLFV)

1. Search for cLFV in the decays of Z bosons

$Z \to ll',\ l \neq l',\ l,l' = e,\mu,\tau$

Expt:

$\mathrm{BR}(Z \to e^{\pm}\mu^{\mp}) < 7.5 \times 10^{-7}\ \mathrm{(ATLAS)}$ ATLAS: PRD 90 (2014) 0720210

$\mathrm{BR}(Z \to e^{\pm}\tau^{\mp}) \leq 9.8 \times 10^{-6}\ \mathrm{(LEP)}$ OPAL: Z.Phys C67 (1995) 555

$\mathrm{BR}(Z \to \mu^{\pm}\tau^{\mp}) \leq 1.2 \times 10^{-5}\ \mathrm{(LEP)}$ DELPHI: Z.Phys C73 (1997) 243

Sensitivity up to 10^{-9}-10^{-10}. The stringent constraints in μτ final state JHEP 04 (2015) 051

- ➔ Identify a clear τ decay in one hemisphere
- ➔ Look for „beam energy" e or μ in the opposite hemisphere

Backgrounds:

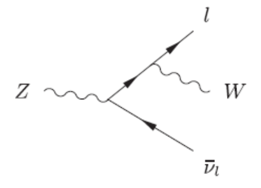
$\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau,\ \tau^- \to e^-\bar{\nu}_e\nu_\tau$ (two very soft neutrinos) depends strongly on energy-momentum resolution

$Z \to \tau^+\tau^-$

$Z \to q\bar{q}\ \mathrm{(low\ mult.)}$

$Z \to W^* l^- \nu,\ W^* \to \tau\bar{\nu}_\tau$

PR D93 (2016) 093005



Complementarity between FCC-ee and low energy cLFV searches (l'→ lγ, μ to e conversion…)

Studies of charged Lepton Flavour Violation (cLFV)

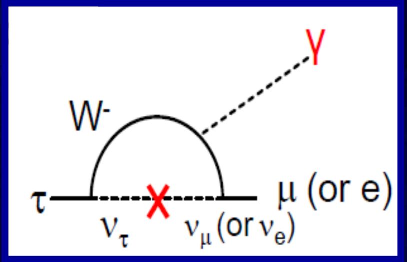
2. Search for cLFV in the decays of τ leptons

$\tau^- \to \mu^-\mu^+\mu^-$ $\tau^- \to \mu^-\gamma$

SM:

$$\mathrm{BR}(\tau \to \mu\gamma) \leq 10^{-40}$$

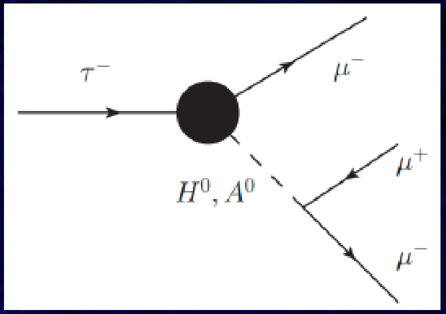
$$\mathrm{BR}(\tau \to \mu\mu\mu) = \frac{3\alpha_{em}}{32\pi}\left|\sum_{i=1}^{3} U^*_{\tau i} U_{\mu i} \frac{\Delta m^2_{i2}}{m^2_W}\right| \leq 10^{-40}$$



BSM:

$$BR(\tau \to \mu\mu\mu) < 10^{-9}$$

- particularly SUSY, Little Higgs, 4gen…)



Expt:

$\mathrm{Belle}: \ BR(\tau \to \mu\mu\mu) < 2.1 \times 10^{-8}$ PL B687 (2010) 139

$\mathrm{BaBar}: BR(\tau \to \mu\mu\mu) < 3.3 \times 10^{-8}$ PR D81 (2010) 11101

$\mathrm{LHCb}: BR(\tau \to \mu\mu\mu) < 4.6 \times 10^{-8}$ JHEP 1502 (2015) 121

- New Physics effects can be parametrized in a general way using the Effective Field Theory approach including beyond the Standard Model operators with different chirality structures (as in the LHCb analysis ; see ref above).

- This approach is integrated with the TAUOLA package (IFJ PAN) arXiv: 1609.04617 [hep-ph]

Sensitivity up to 10^{-12}

Belle2: sensitivity up to 10^{-10}

Heavy Neutral Leptons Searches

- The masses of light neutrinos are efficiently generated via the see-saw mechanism upon the inclusion of sterile right-handed neutrinos
- Example: Neutrino Minimal Standard Model (νMSM)

L.Canetti, M.Drewes, T.Frosard, M.Shaposhnikov,
Phys. Rev. D87 (9) (2013) 093006

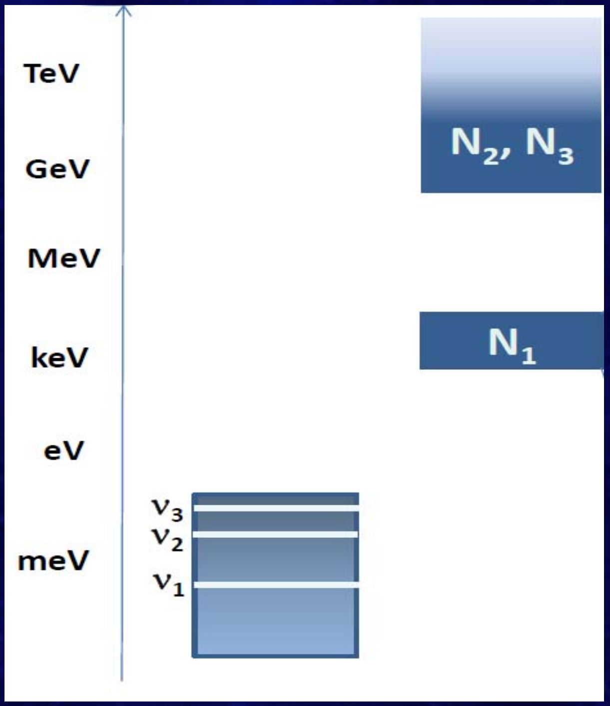
$I = \frac{1}{2}$

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$$

$I = 0$

$(e)_R$	$(\mu)_R$	$(\tau)_R$	$Q = -1$
$(\nu_e)_R \equiv N_1$	$(\nu_\mu)_R \equiv N_2$	$(\nu_\tau)_R \equiv N_3$	$Q = 0$

„sterile", HNL – Heavy Neutral Leptons



N_2, N_3 - can generate Baryon Asymmetry of the Universe (BAU) if $m_{N_2,N_3} > 140\ \mathrm{MeV}$

N_1 - DM candidate
Search for $N_1 \to \nu\gamma$

A "physical left-handed neutrino" produced e.g. in the Z^0 decay is a mixture of the light and heavy state $\nu_L = \nu\cos\theta + N\sin\theta$

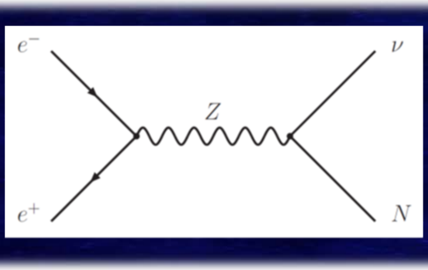
with the mixing angle $\theta \approx m_\nu / m_N$

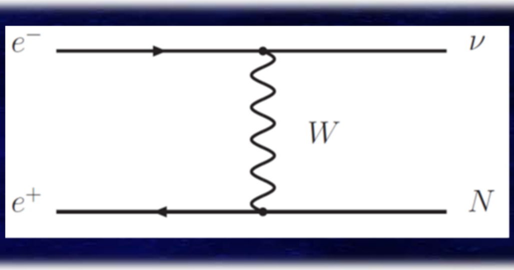
Constraints: $m_{N_1} \in (1 - 50)\ \mathrm{keV}$ $\theta \in (10^{-7} - 10^{-13})$ $\tau_{N_1} > \tau_{\mathrm{Universe}}$

HNL Production and Decay

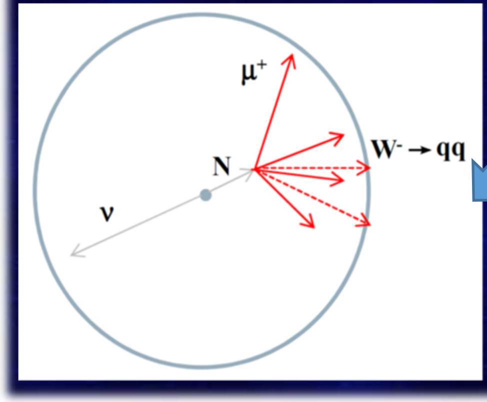
- **The HNL production**

$e^+e^- \to N\nu$





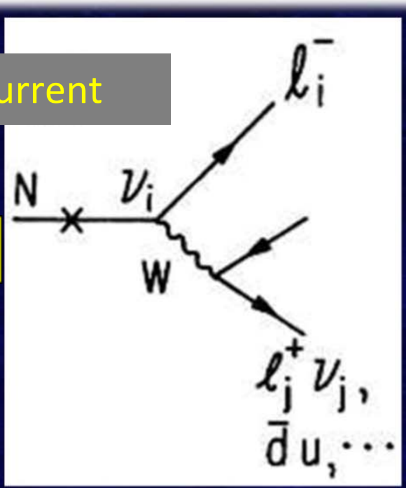
- The HNL decay



The Charged Current

$l_i^- l_j^+ \nu_j$

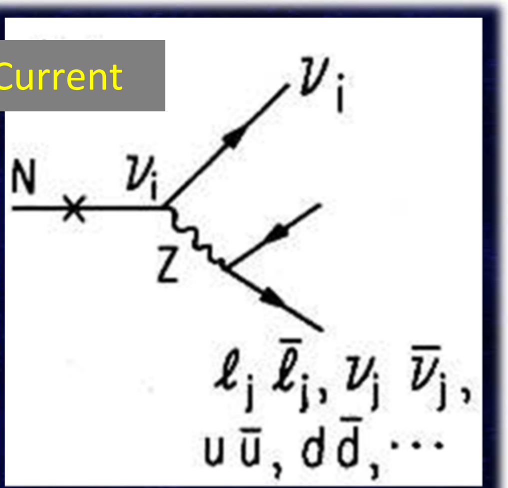
$l_i^- \bar{d}u, \ldots$



The Neutral Current

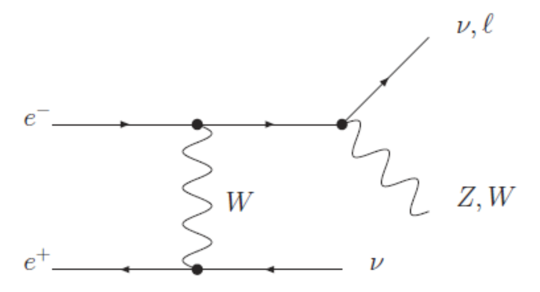
$\nu_i l_j^+ l_j^-$

$\nu_i u\bar{u}, \ldots$



- The background (4f)

$e^+e^- \to Z \to W^*W \to l\nu\ q\bar{q}'$



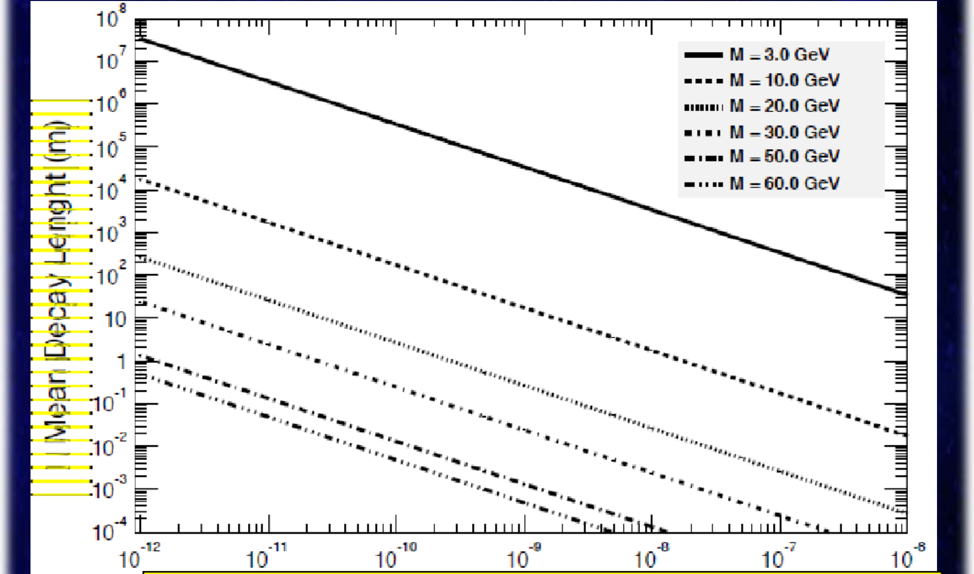
Absent for HNLs decaying with e.g. L ~ 1 m

HNL Production and Decay

- The average decay length of N:

$$\boxed{L \sim \frac{3\ [\mathrm{cm}]}{|U|^2 \cdot (m_N[\mathrm{GeV}])^6}}$$

A.Blondel et al., arXiv: 1411.5230 [hep-ex]



$$|U|^2 = |U_e|^2 + |U_\mu|^2 + |U_\tau|^2 \ (N-\nu \text{ couplings})$$

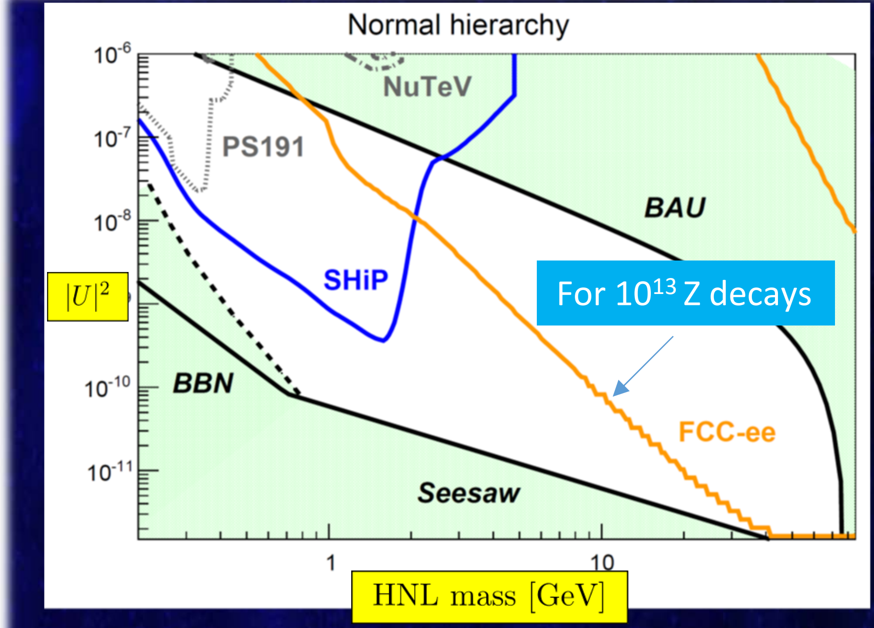
$$|U|^2 \propto \theta^2$$

$m_N \approx 50$ GeV

$m_\nu \approx 0.05$ GeV

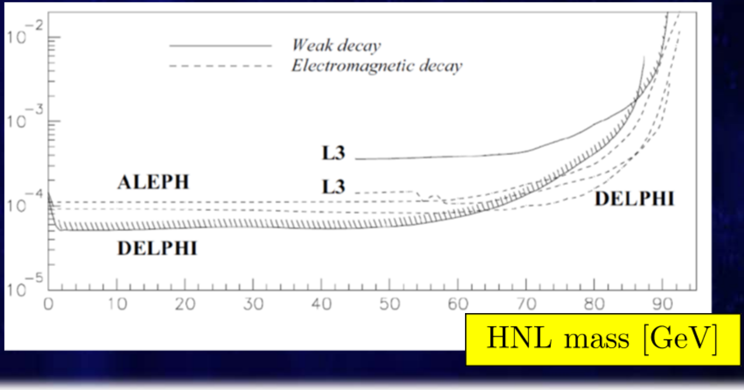
$|U|^2 \sim 10^{-12}$

$\Bigg\}$ Decay length ~1 m



For 10^{13} Z decays

- The sensitivity FCC-ee up to 10^{-12}
- The results of LEP searches: 10^{-4}



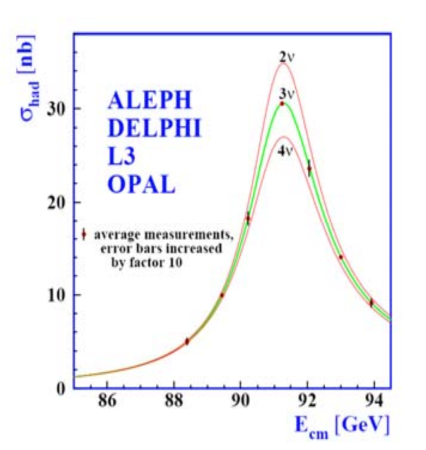
The Z Invisible Width
– Number of Light Neutrino Species

- **„Direct method”:** N_ν determined at LEP1 from the Z line-shape scan:

$$\Gamma_{tot} = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \sum_{i=1}^{5}\Gamma_{qq} + N_\nu\Gamma_{\nu\nu}$$

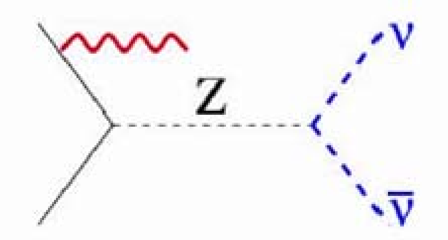
$$N_\nu = 2.984 \pm 0.008$$

2σ below 3.0



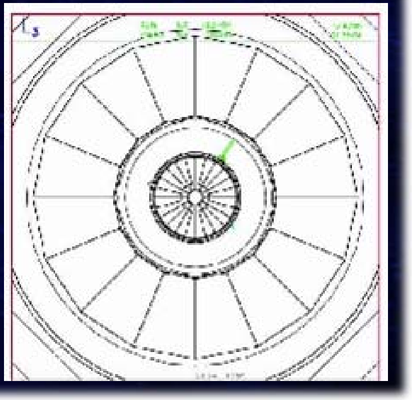
  - A hint of non-unitarity of the PMNS matrix?
  - Only small room for improvements: precision limited by the theoretical uncertainty on normalization, i.e. on small angle Bhabha cross section (0.0046 at LEP1).

- **Alternative „indirect method”:** $e^+e^- \to Z\gamma, \quad Z \to \nu\bar{\nu}$



  - Radiative return process from the higher masses than the Z resonance
  - Monophoton events (normalized to gamma-lepton-lepton events):

$$N_\nu = \left(\frac{e^+e^- \to \gamma Z_{\text{inv}}}{e^+e^- \to \gamma Z_{\text{lept}}}\right)^{\text{meas}} / \left(\frac{\Gamma_{\nu\bar{\nu}}}{\Gamma_{\text{lept}}}\right)^{\text{SM}}$$



- LEP1: $N_\nu = 2.92 \pm 0.05$ (statistics too scarse).
- Relatively small theoretical uncertainties.

- Photon selection common for both final states → cancellations of systematics.
- N_ν can be measured vs sqrt(s) → sensitivity to NP at high energy scales.

The Z Invisible Width
– Number of Light Neutrino Species

- Both methods are independent and complementary: data sets, systematics, theoretical input…
- Sensitivity

direct: $\Delta N_\nu = 0.00008(\mathrm{stat}) \pm 0.004(\mathrm{syst})$

indirect:

$\sqrt{s} = 161$ GeV — 1 year of running : 3×10^7 $\gamma Z(\mathrm{inv})$ evts — $\Delta N_\nu = 0.0011$

$\sqrt{s} = 240$ and 350 GeV — 5 years of running — $\Delta N_\nu = 0.0008$

$\sqrt{s} = 125$ GeV — 1 year of running — $\Delta N_\nu = 0.0004$

(opportunity to measure directly e^+e^- → H)

(stat)

(running parasitically)

Summary

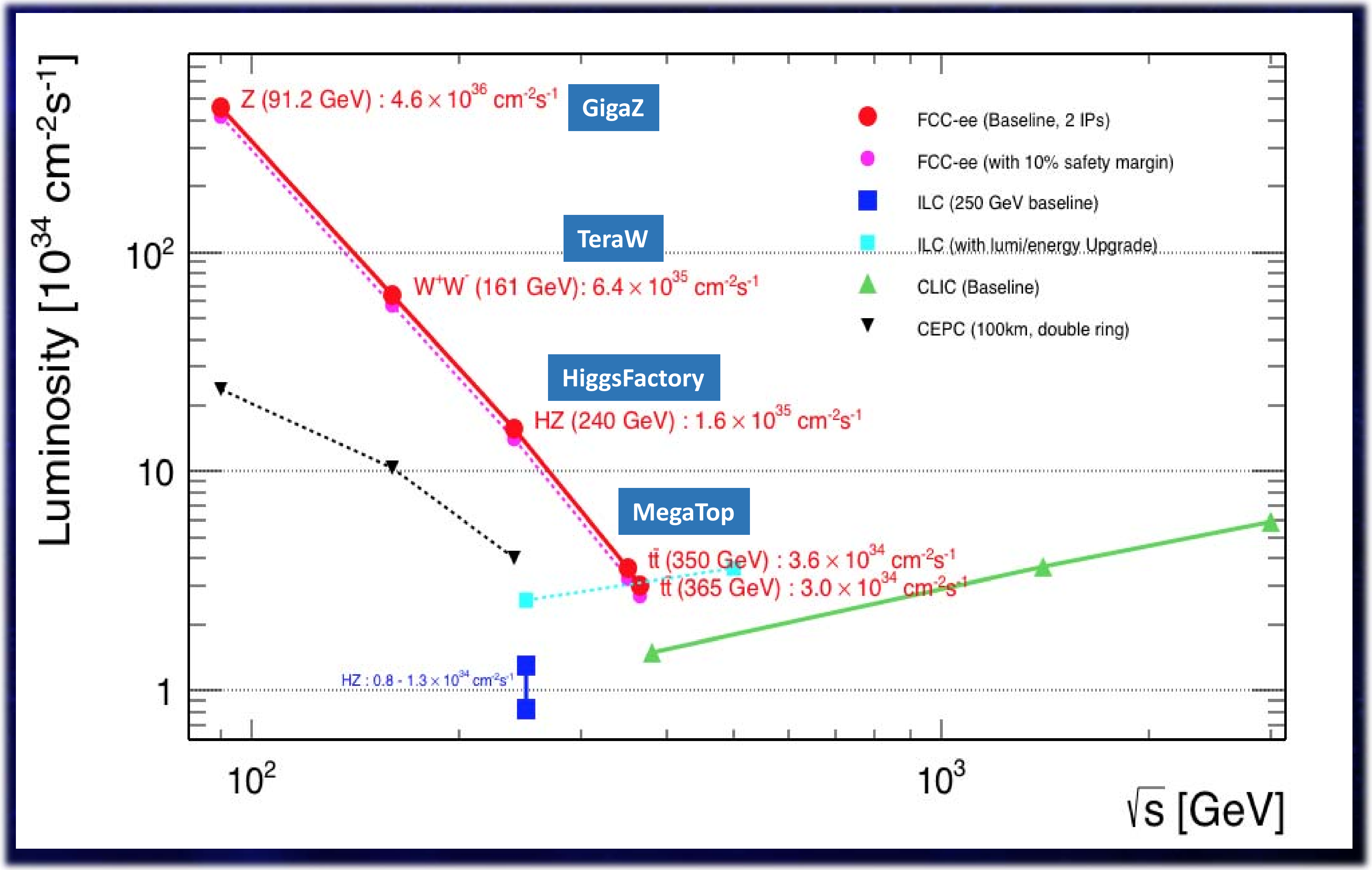
FCC-ee offers a vast potential for flavour physics studies,

in particular for the selected topics, discusses in this talk:

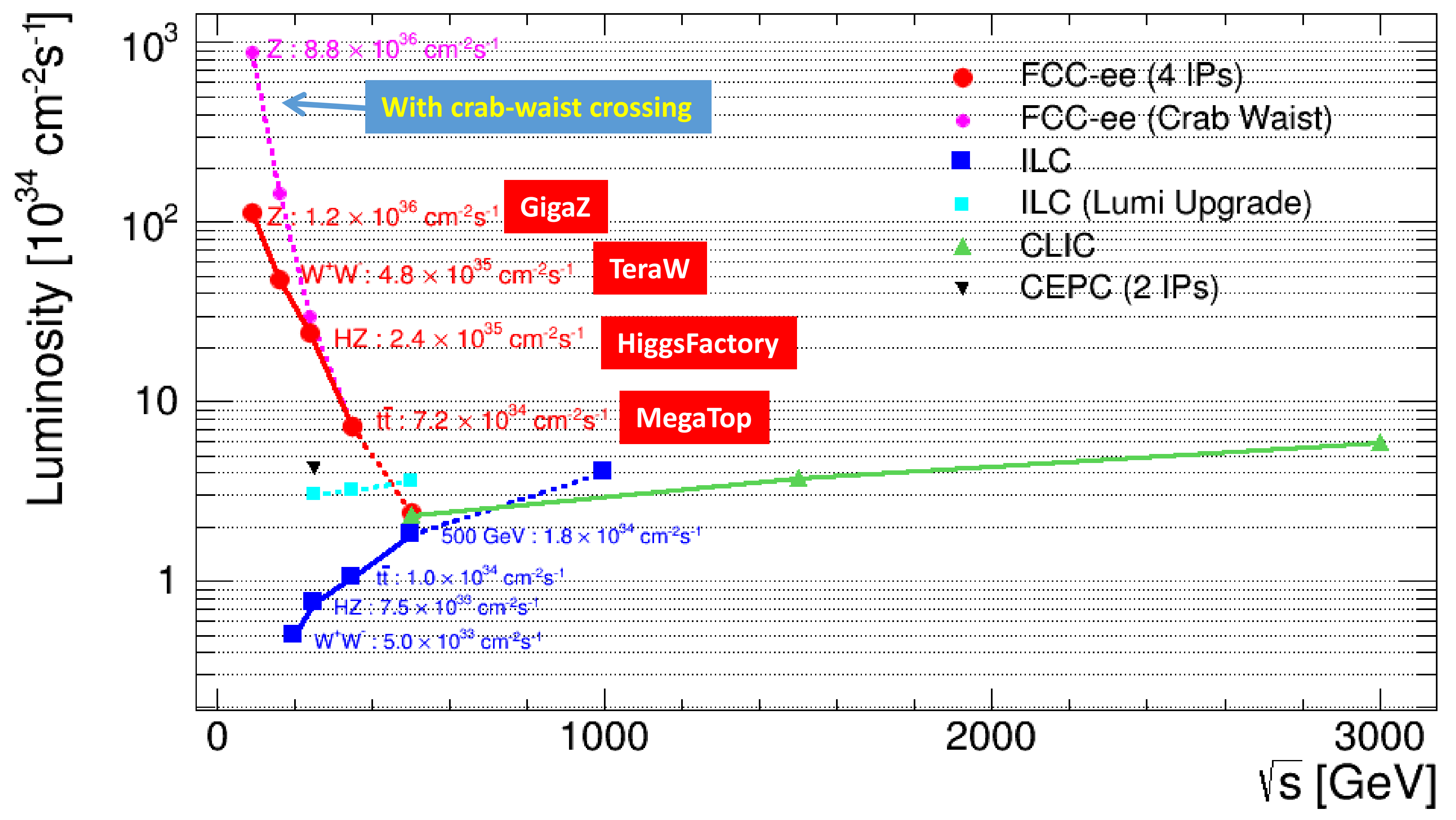
- Studies of B → K* ll decays
- Searches for Z → l l’
- Searches for Heavy Neutral Leptons

Spare Slides

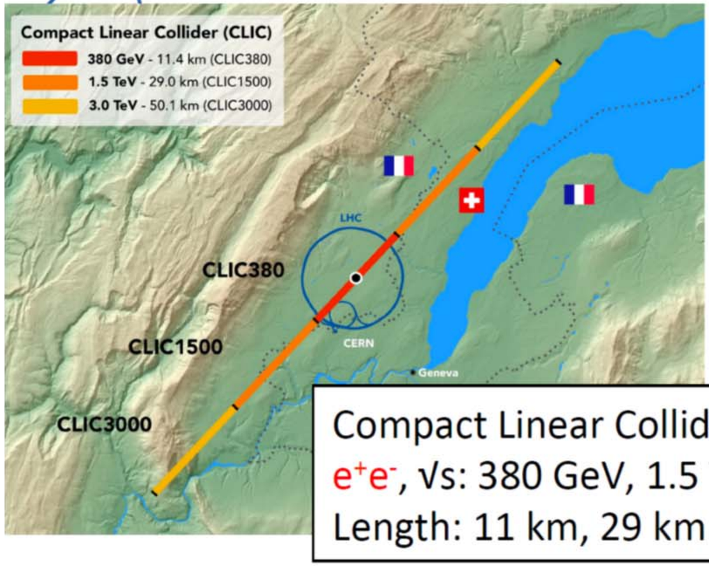
Proposals for New e^+e^- Colliders:



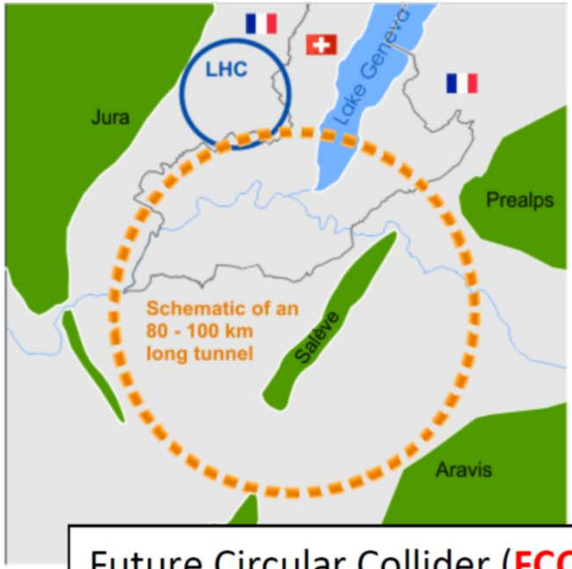
Proposals for New e^+e^- Colliders:



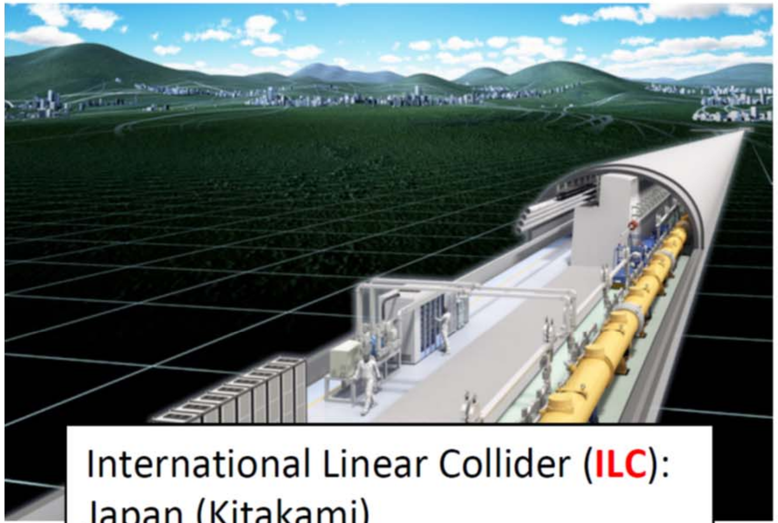
studies of high-energy e^+e^- colliders



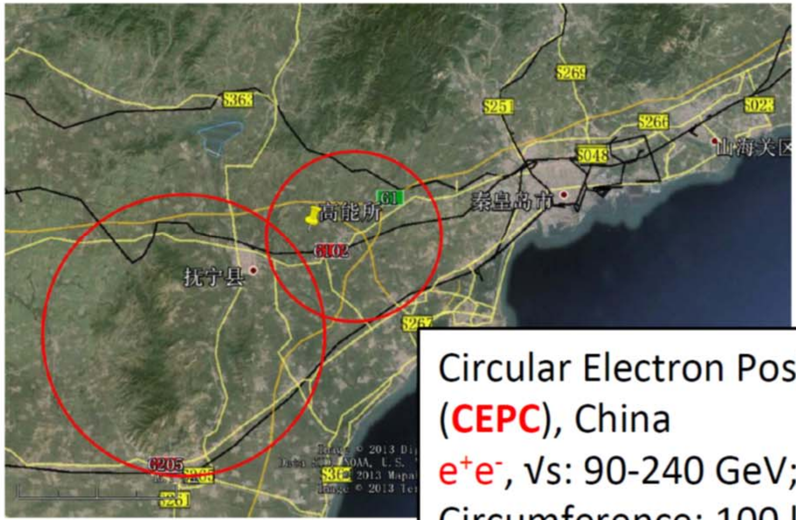
Compact Linear Collider (**CLIC**): CERN
e^+e^-, $\sqrt{s}$: 380 GeV, 1.5 TeV, 3 TeV
Length: 11 km, 29 km , 50 km



Future Circular Collider (**FCC-ee**): CERN
e^+e^-, $\sqrt{s}$: 90 - 350 GeV; FCC-hh pp
Circumference: 97.75 km



International Linear Collider (**ILC**):
Japan (Kitakami)
e^+e^-, $\sqrt{s}$: 250 – 500 GeV (1 TeV)
Length: 17 km, 31 km (50 km)



Circular Electron Positron Collider
(**CEPC**), China
e^+e^-, $\sqrt{s}$: 90-240 GeV; SPPC pp,
Circumference: 100 km

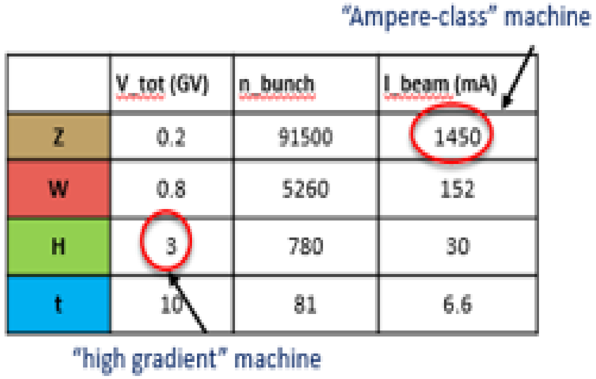
FCC-ee operation model

working point	luminosity/IP [10^{34} cm^{-2}s^{-1}]	total luminosity (2 IPs)/ yr	physics goal	run time [years]
Z first 2 years	100	26 ab^{-1}/year	**150 ab^{-1}**	**4**
Z later	200	52 ab^{-1}/year		
W	30	7.8 ab^{-1}/year	**10 ab^{-1}**	**1**
H	7.0	1.8 ab^{-1}/year	**5 ab^{-1}**	**3**
machine modification for RF installation & rearrangement: **1 year**				
top 1st year (350 GeV)	0.8	0.2 ab^{-1}/year	**0.2 ab^{-1}**	**1**
top later (365 GeV)	1.3	0.34 ab^{-1}/year	**1.5 ab^{-1}**	**4**

total program duration: 14 years ***- including machine modifications***

phase 1 (*Z*, *W*, *H*): 8 years, **phase 2 (top): 6 years**

FCC-ee RF staging scenario



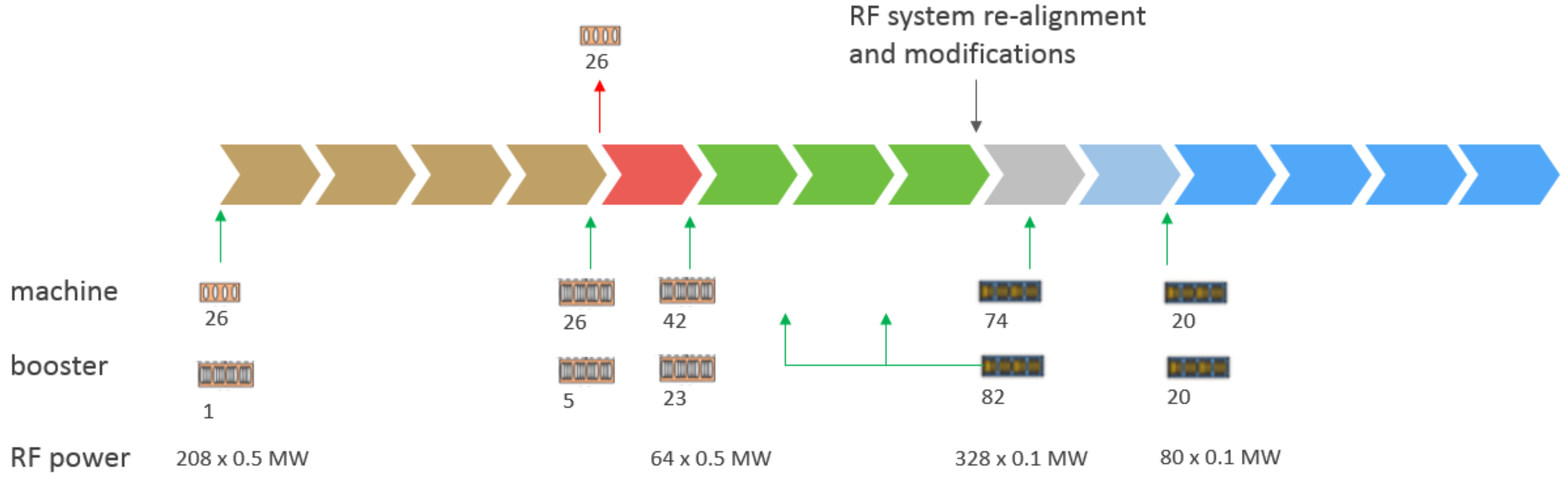
"Ampere-class" machine

	V_tot (GV)	n_bunch	I_beam (mA)
Z	0.2	91500	1450
W	0.8	5260	152
H	3	780	30
t	10	81	6.6

"high gradient" machine

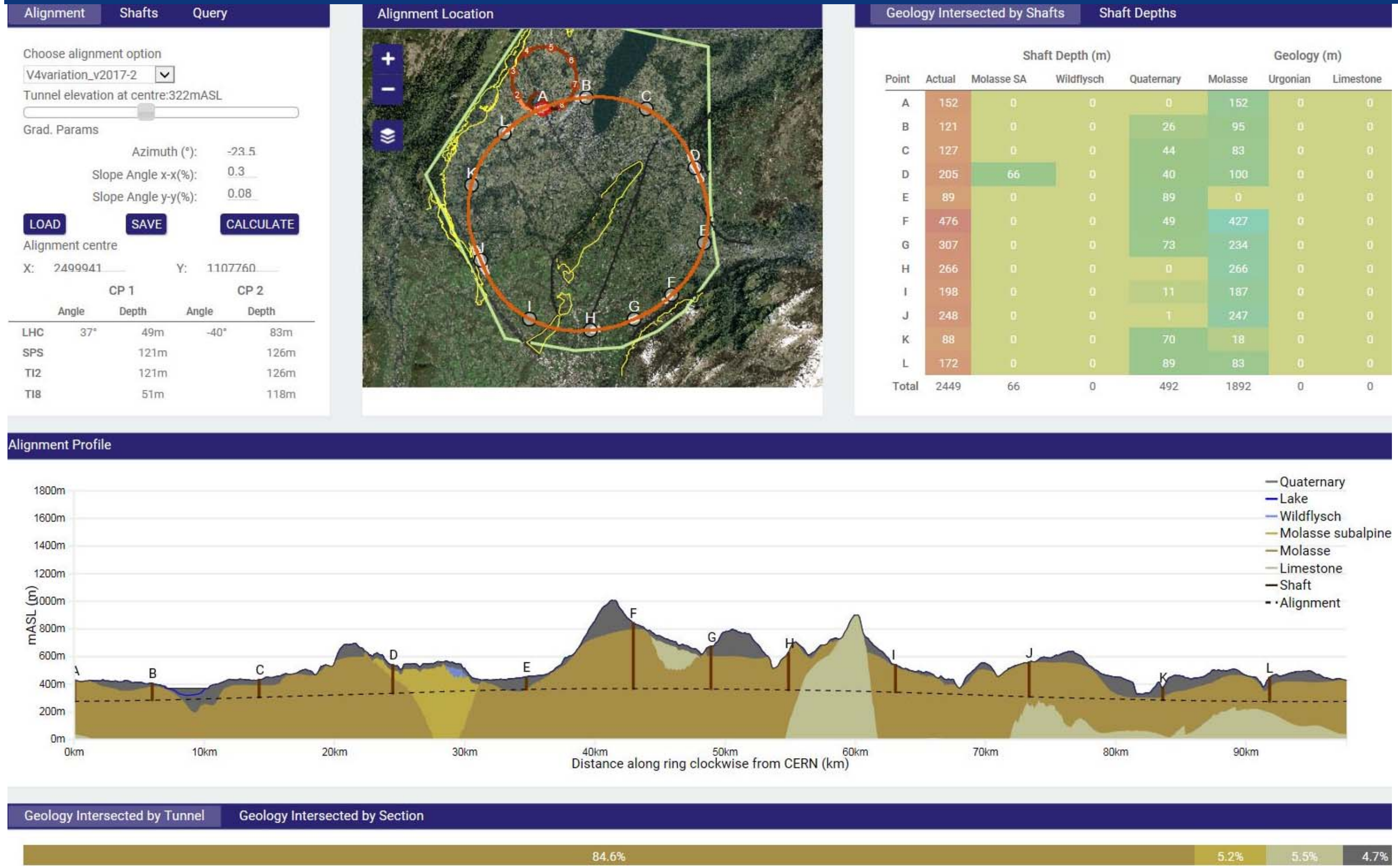
three sets of RF cavities to cover all options for FCC-ee & booster:

- **installation sequence comparable to LEP (≈ 30 CM/shutdown)**
- **high intensity (Z, FCC-hh): 400 MHz mono-cell cav, ~1 MW source**
- **higher energy (W, H, t): 400 MHz four-cell cavities (4/cryomodule)**
- **ttbar machine complement: 800 MHz five-cell cavities (4/cryom.)**



- LEP record: ~ 32 CM in one shutdown
- Possibly 1 year of long shutdown between ZH and ttbar operation.
- spread 800 MHz RF power & booster installation over the preceding shutdowns

CE tunnel implementation study



Choose alignment option: V4variation_v2017-2

Tunnel elevation at centre:322mASL

Grad. Params

Azimuth (°): -23.5

Slope Angle x-x(%): 0.3

Slope Angle y-y(%): 0.08

LOAD SAVE CALCULATE

Alignment centre

X: 2499941 Y: 1107760

	CP 1		CP 2	
	Angle	Depth	Angle	Depth
LHC	37°	49m	-40°	83m
SPS		121m		126m
TI2		121m		126m
TI8		51m		118m

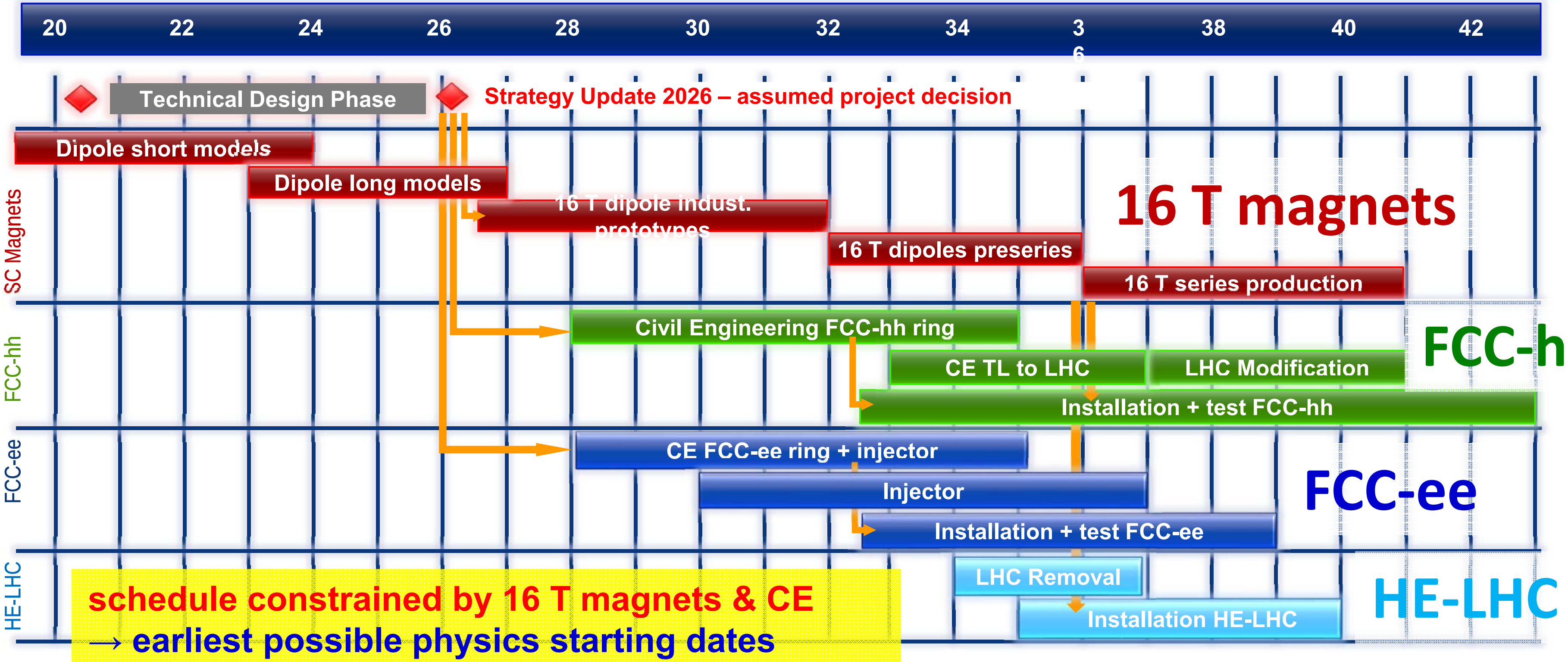
	Shaft Depth (m)				Geology (m)		
Point	Actual	Molasse SA	Wildflysch	Quaternary	Molasse	Urgonian	Limestone
A	152	0	0	0	152	0	0
B	121	0	0	26	95	0	0
C	127	0	0	44	83	0	0
D	205	66	0	40	100	0	0
E	89	0	0	89	0	0	0
F	476	0	0	49	427	0	0
G	307	0	0	73	234	0	0
H	266	0	0	0	266	0	0
I	198	0	0	11	187	0	0
J	248	0	0	1	247	0	0
K	88	0	0	70	18	0	0
L	172	0	0	89	83	0	0
Total	2449	66	0	492	1892	0	0

Optimisation criteria:
- tunneling rock type,
- shaft depth accessibility
- surface points, etc.

Tunneling:
- Molasse 90%,
- Limestone 5%,
- Moraines 5%

Implementation:
- 90-100 km fits well geological situation in Geneva basin
- Shallow variant, 30 m below lake-bed
- Connected with LHC or SPS

Technical Schedule for each the 3 Options



schedule constrained by 16 T magnets & CE

→ earliest possible physics starting dates

- **FCC-hh: 2043**
- **FCC-ee: 2039**
- **HE-LHC: 2040 (with HL-LHC stop LS5 / 2034)**

FCC = global “Swiss army knife” of colliders

global R&D effort

100 TeV *pp* collisions

heavy-ion collisions

technology available!

e$^+$e$^-$ H, Z, W, t factory

conceptual studies

γγ, polarized *p*, s-channel *H* prod.,

…, …

HE-LHC

global R&D effort

PoP exp’ts

gamma Factory

R&D effort

highest-energy *ep* & eA collider

fixed target programs

technology available

– frontier science for >100 years

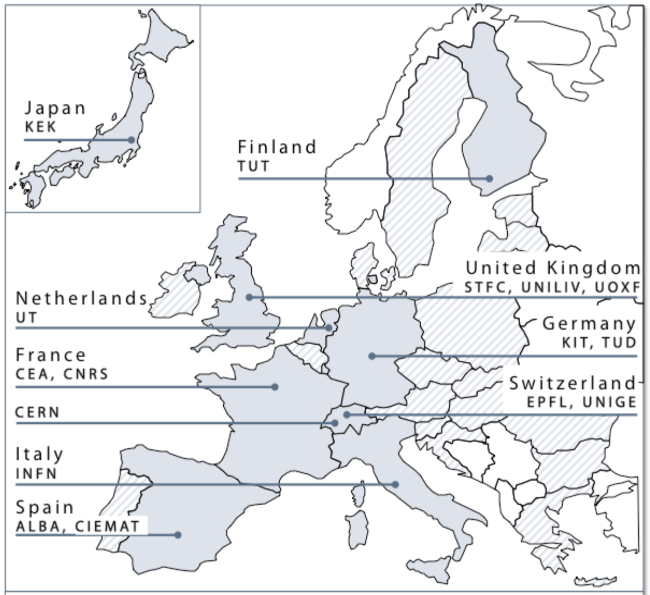
conceptual studies

tantalizing upgrade paths to 100 TeV μ$^+$μ$^-$ collider “FCC-μμ”

& exp’ts

EU H2020 Design Study EuroCirCol

UNIVERSITY OF TWENTE.
INFN
TAMPERE UNIVERSITY OF TECHNOLOGY
cea
cnrs dépasser les frontières
TECHNISCHE UNIVERSITÄT DARMSTADT
KIT Karlsruher Institut für Technologie



EuroCirCol consortium, federating 16 partners, 1 from Japan and 1 IEIO

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
CERN
UNIVERSITY OF LIVERPOOL
UNIVERSITY OF OXFORD
UNIVERSITÉ DE GENÈVE
ALBA
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
MANCHESTER 1824

European Union Horizon 2020 program

- **Support for FCC-hh study**
- **3 MEURO co-funding**
- **Started June 2015, ends in May 2019**

Scope:

FCC-hh collider

- **Optics Design (arc and IR)**
- **Cryogenic beam vacuum system design including beam tests at ANKA**
- **16 T dipole design, construction folder for demonstrator magnets**

EASITrain Marie Curie Training Network

FCC

EASITrain

European Advanced Superconductivity Innovation and Training Network

➢ **selected for funding by EC in May 2017, started 1 October 2017**

- SC wires at low temperatures for magnets (Nb_3Sn, MgB_2, HTS)
- Superconducting thin films for RF and beam screen (Nb_3Sn, Tl)
- Electrohydraulic forming for RF structures
- Turbocompressor for Nelium refrigeration
- Magnet cooling architectures

Horizon 2020 program

Funding for 15 Early Stage Researchers over 3 years & training

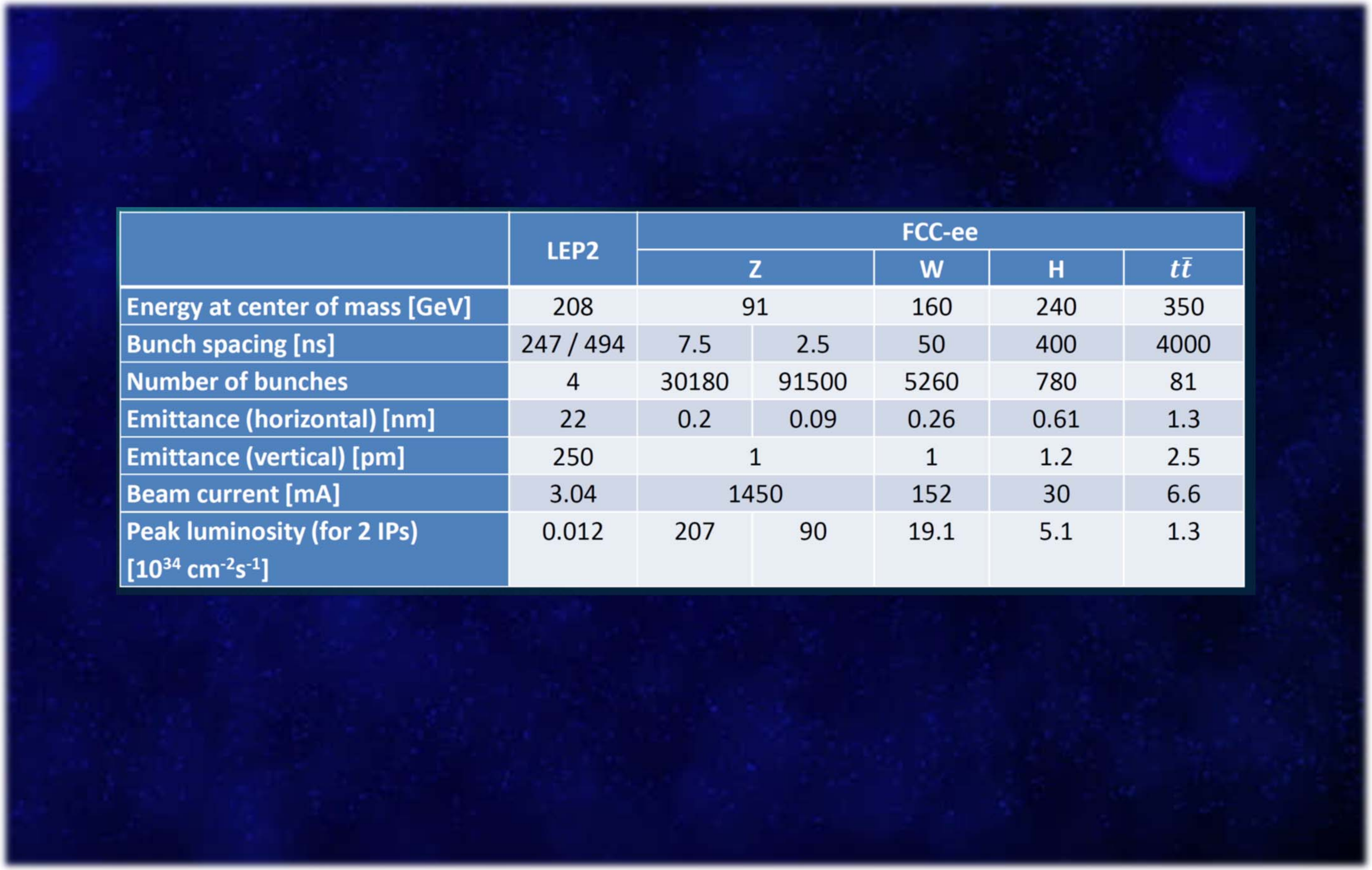
13 Beneficiaries

BRUKER
cea
Columbus Superconductors
HZB Helmholtz Zentrum Berlin
SPIN
Universität Stuttgart
INFN
TECHNISCHE UNIVERSITÄT DRESDEN
TU WIEN TECHNISCHE UNIVERSITÄT WIEN
UNIVERSITÄT SIEGEN
WU
I-CUBE
CERN

12 Partners

Bmax
ASG Superconductors
BILFINGER Babcock Noell GmbH
CemeCon The Tool Coating
IEEE Advancing Technology for Humanity
Cryotec IMPIANTI S.r.l.
MAN Diesel & Turbo
TERRA MATER Factual Studios
Red Bull MEDIA HOUSE
research instruments
SIGMAPHI
UNIVERSITÀ DEGLI STUDI DI GENOVA
AIR LIQUIDE

Outline



	LEP2	FCC-ee				
		Z		W	H	$t\bar{t}$
Energy at center of mass [GeV]	208	91		160	240	350
Bunch spacing [ns]	247 / 494	7.5	2.5	50	400	4000
Number of bunches	4	30180	91500	5260	780	81
Emittance (horizontal) [nm]	22	0.2	0.09	0.26	0.61	1.3
Emittance (vertical) [pm]	250	1		1	1.2	2.5
Beam current [mA]	3.04	1450		152	30	6.6
Peak luminosity (for 2 IPs) [10^{34} cm^{-2}s^{-1}]	0.012	207	90	19.1	5.1	1.3

FCC-ee collider parameters

parameter	Z	WW	H (ZH)	ttbar	
beam energy [GeV]	45	80	120	175	182.5
beam current [mA]	1390	147	29	6.4	5.4
no. bunches/beam	16640	2000	393	48	39
bunch intensity $[10^{11}]$	1.7	1.5	1.5	2.7	2.8
SR energy loss / turn [GeV]	0.036	0.34	1.72	7.8	9.21
total RF voltage [GV]	0.1	0.44	2.0	9.5	10.9
long. damping time [turns]	1281	235	70	23	20
horizontal beta* [m]	0.15	0.2	0.3	1	1
vertical beta* [mm]	0.8	1	1	2	2
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.34	1.45
vert. geom. emittance [pm]	1.0	1.0	1.3	2.7	2.7
bunch length with SR / BS [mm]	3.5 / 12.1	3.3 / 7.6	3.1 / 4.9	2.5 / 3.3	2.5 / 3.2
luminosity $[10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}]$	>200	>30	>7	>1.5	>1.3
beam lifetime rad Bhabha / BS [min]	70 / >200	500 / 20	42 / 20	39 / 24	39 / 25

FCC-ee operation model

working point	luminosity/IP [10^{34} cm^{-2}s^{-1}]	total luminosity (2 IPs)/ yr	physics goal	run time [years]
Z first 2 years	100	26 ab^{-1}/year	**150 ab^{-1}**	**4**
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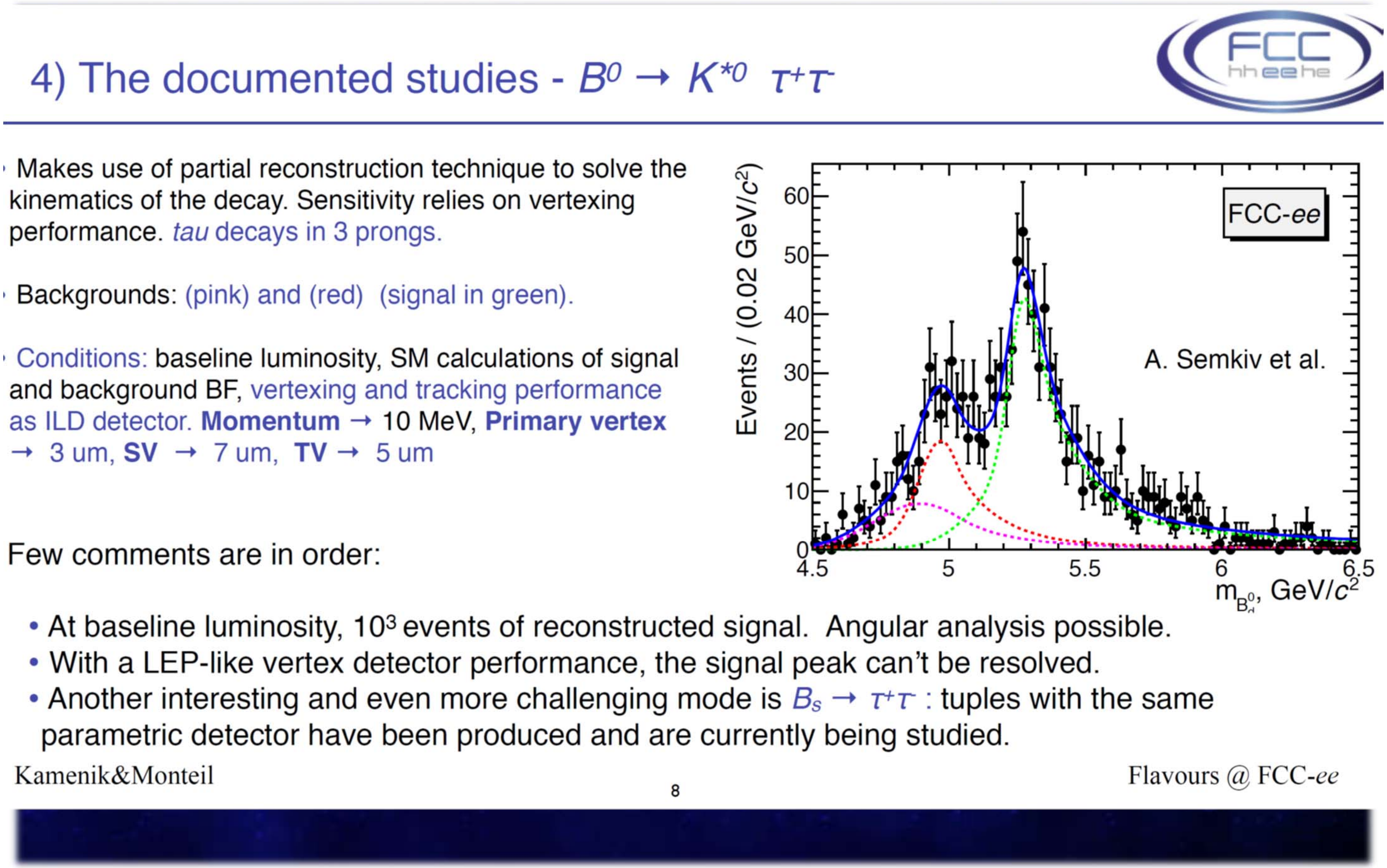
total program duration: 14 years - *including machine modifications*

phase 1 (*Z*, *W*, *H*): 8 years, phase 2 (top): 6 years

hadron collider parameters (*pp*)

parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1 (0.5)		2.2	(2.2) 1.15
bunch spacing [ns]	25 (12.5)		25 (12.5)	25
norm. emittance $\gamma\varepsilon_{x,y}$ [μm]	2.2 (1.1)		2.5 (1.25)	(2.5) 3.75
IP $\beta^*_{x,y}$ [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	5	30	28	(5) 1
peak #events / bunch Xing	170	1000 (500)	800 (400)	(135) 27
stored energy / beam [GJ]	8.4		1.4	(0.7) 0.36
SR power / beam [kW]	2400		100	(7.3) 3.6
transv. emit. damping time [h]	1.1		3.6	25.8
initial proton burn off time [h]	17.0	3.4	3.0	(15) 40

b→ s $l^+ l^-$ Transitions



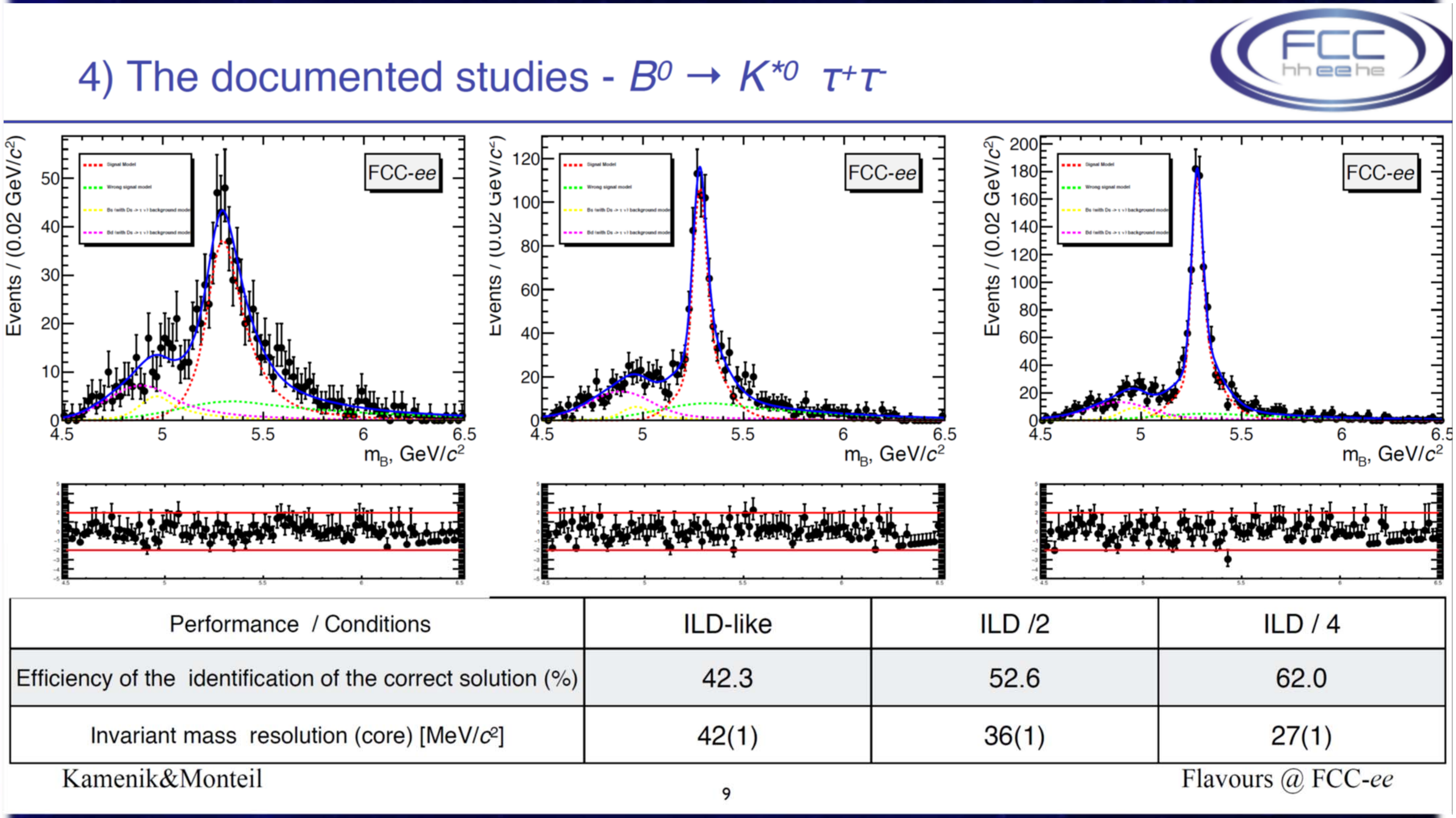
4) The documented studies - $B^0 \to K^{*0}\ \tau^+\tau^-$

- Makes use of partial reconstruction technique to solve the kinematics of the decay. Sensitivity relies on vertexing performance. *tau* decays in 3 prongs.
- Backgrounds: (pink) and (red) (signal in green).
- Conditions: baseline luminosity, SM calculations of signal and background BF, vertexing and tracking performance as ILD detector. **Momentum** → 10 MeV, **Primary vertex** → 3 um, **SV** → 7 um, **TV** → 5 um

Few comments are in order:

- At baseline luminosity, 10^3 events of reconstructed signal. Angular analysis possible.
- With a LEP-like vertex detector performance, the signal peak can't be resolved.
- Another interesting and even more challenging mode is $B_s \to \tau^+\tau^-$: tuples with the same parametric detector have been produced and are currently being studied.

$b \rightarrow s\, l^+ l^-$ Transitions



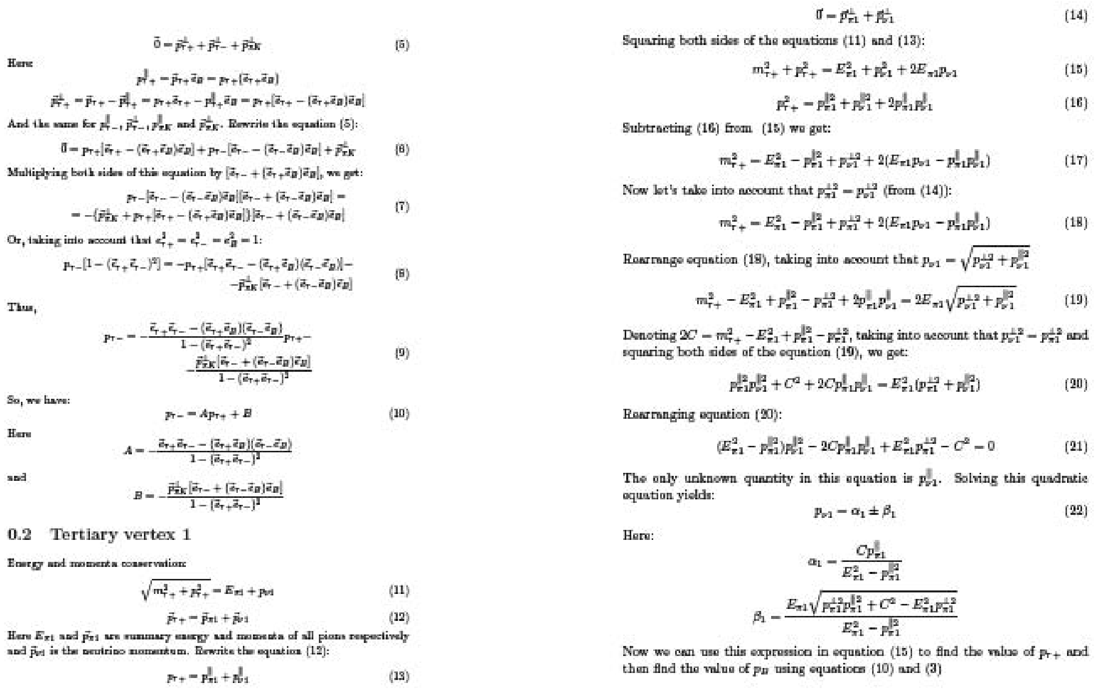
4) The documented studies - $B^0 \rightarrow K^{*0}\ \tau^+\tau^-$

Performance / Conditions	ILD-like	ILD /2	ILD / 4
Efficiency of the identification of the correct solution (%)	42.3	52.6	62.0
Invariant mass resolution (core) [MeV/c^2]	42(1)	36(1)	27(1)

Kamenik&Monteil

b→ s l^+ l^- Transitions

- The transition $B^0 \rightarrow K^{*0}\,\tau^+\tau^-$ can be fully solved. In equations:



$$\vec{0} = \vec{p}^{\perp}_{\tau+} + \vec{p}^{\perp}_{\tau-} + \vec{p}^{\perp}_{\pi K} \qquad (5)$$

Here:

$$p^{\parallel}_{\tau+} = \vec{p}_{\tau+}\vec{e}_B = p_{\tau+}(\vec{e}_{\tau+}\vec{e}_B)$$

$$\vec{p}^{\perp}_{\tau+} = \vec{p}_{\tau+} - \vec{p}^{\parallel}_{\tau+} = p_{\tau+}\vec{e}_{\tau+} - p^{\parallel}_{\tau+}\vec{e}_B = p_{\tau+}[\vec{e}_{\tau+} - (\vec{e}_{\tau+}\vec{e}_B)\vec{e}_B]$$

And the same for $p^{\parallel}_{\tau-}, \vec{p}^{\perp}_{\tau-}, p^{\parallel}_{\pi K}$ and $\vec{p}^{\perp}_{\pi K}$. Rewrite the equation (5):

$$\vec{0} = p_{\tau+}[\vec{e}_{\tau+} - (\vec{e}_{\tau+}\vec{e}_B)\vec{e}_B] + p_{\tau-}[\vec{e}_{\tau-} - (\vec{e}_{\tau-}\vec{e}_B)\vec{e}_B] + \vec{p}^{\perp}_{\pi K} \qquad (6)$$

Multiplying both sides of this equation by $[\vec{e}_{\tau-} + (\vec{e}_{\tau+}\vec{e}_B)\vec{e}_B]$, we get:

$$\begin{aligned} &p_{\tau-}[\vec{e}_{\tau-} - (\vec{e}_{\tau-}\vec{e}_B)\vec{e}_B][\vec{e}_{\tau-} + (\vec{e}_{\tau-}\vec{e}_B)\vec{e}_B] = \\ &= -(\vec{p}^{\perp}_{\pi K} + p_{\tau+}[\vec{e}_{\tau+} - (\vec{e}_{\tau+}\vec{e}_B)\vec{e}_B])[\vec{e}_{\tau-} + (\vec{e}_{\tau-}\vec{e}_B)\vec{e}_B] \end{aligned} \qquad (7)$$

Or, taking into account that $e^2_{\tau+} = e^2_{\tau-} = e^2_B = 1$:

$$\begin{aligned} p_{\tau-}[1 - (\vec{e}_{\tau+}\vec{e}_{\tau-})^2] = -p_{\tau+}[\vec{e}_{\tau+}\vec{e}_{\tau-} - (\vec{e}_{\tau+}\vec{e}_B)(\vec{e}_{\tau-}\vec{e}_B)] - \\ -\vec{p}^{\perp}_{\pi K}[\vec{e}_{\tau-} + (\vec{e}_{\tau-}\vec{e}_B)\vec{e}_B] \end{aligned} \qquad (8)$$

Thus,

$$\begin{aligned} p_{\tau-} = -\frac{\vec{e}_{\tau+}\vec{e}_{\tau-} - (\vec{e}_{\tau+}\vec{e}_B)(\vec{e}_{\tau-}\vec{e}_B)}{1 - (\vec{e}_{\tau+}\vec{e}_{\tau-})^2}p_{\tau+} - \\ -\frac{\vec{p}^{\perp}_{\pi K}[\vec{e}_{\tau-} + (\vec{e}_{\tau-}\vec{e}_B)\vec{e}_B]}{1 - (\vec{e}_{\tau+}\vec{e}_{\tau-})^2} \end{aligned} \qquad (9)$$

So, we have:

$$p_{\tau-} = Ap_{\tau+} + B \qquad (10)$$

Here

$$A = -\frac{\vec{e}_{\tau+}\vec{e}_{\tau-} - (\vec{e}_{\tau+}\vec{e}_B)(\vec{e}_{\tau-}\vec{e}_B)}{1 - (\vec{e}_{\tau+}\vec{e}_{\tau-})^2}$$

and

$$B = -\frac{\vec{p}^{\perp}_{\pi K}[\vec{e}_{\tau-} + (\vec{e}_{\tau-}\vec{e}_B)\vec{e}_B]}{1 - (\vec{e}_{\tau+}\vec{e}_{\tau-})^2}$$

0.2 Tertiary vertex 1

Energy and momenta conservation:

$$\sqrt{m^2_{\tau+} + p^2_{\tau+}} = E_{\pi 1} + p_{\nu 1} \qquad (11)$$

$$\vec{p}_{\tau+} = \vec{p}_{\pi 1} + \vec{p}_{\nu 1} \qquad (12)$$

Here $E_{\pi 1}$ and $\vec{p}_{\pi 1}$ are summary energy and momenta of all pions respectively and $\vec{p}_{\nu 1}$ is the neutrino momentum. Rewrite the equation (12):

$$p_{\tau+} = p^{\parallel}_{\pi 1} + p^{\parallel}_{\nu 1} \qquad (13)$$

$$\vec{0} = \vec{p}^{\perp}_{\pi 1} + \vec{p}^{\perp}_{\nu 1} \qquad (14)$$

Squaring both sides of the equations (11) and (13):

$$m^2_{\tau+} + p^2_{\tau+} = E^2_{\pi 1} + p^2_{\nu 1} + 2E_{\pi 1}p_{\nu 1} \qquad (15)$$

$$p^2_{\tau+} = p^{\parallel 2}_{\pi 1} + p^{\parallel 2}_{\nu 1} + 2p^{\parallel}_{\pi 1}p^{\parallel}_{\nu 1} \qquad (16)$$

Subtracting (16) from (15) we get:

$$m^2_{\tau+} = E^2_{\pi 1} - p^{\parallel 2}_{\pi 1} + p^{\perp 2}_{\nu 1} + 2(E_{\pi 1}p_{\nu 1} - p^{\parallel}_{\pi 1}p^{\parallel}_{\nu 1}) \qquad (17)$$

Now let's take into account that $p^{\perp 2}_{\pi 1} = p^{\perp 2}_{\nu 1}$ (from (14)):

$$m^2_{\tau+} = E^2_{\pi 1} - p^{\parallel 2}_{\pi 1} + p^{\perp 2}_{\pi 1} + 2(E_{\pi 1}p_{\nu 1} - p^{\parallel}_{\pi 1}p^{\parallel}_{\nu 1}) \qquad (18)$$

Rearrange equation (18), taking into account that $p_{\nu 1} = \sqrt{p^{\perp 2}_{\nu 1} + p^{\parallel 2}_{\nu 1}}$

$$m^2_{\tau+} - E^2_{\pi 1} + p^{\parallel 2}_{\pi 1} - p^{\perp 2}_{\pi 1} + 2p^{\parallel}_{\pi 1}p^{\parallel}_{\nu 1} = 2E_{\pi 1}\sqrt{p^{\perp 2}_{\nu 1} + p^{\parallel 2}_{\nu 1}} \qquad (19)$$

Denoting $2C = m^2_{\tau+} - E^2_{\pi 1} + p^{\parallel 2}_{\pi 1} - p^{\perp 2}_{\pi 1}$, taking into account that $p^{\perp 2}_{\nu 1} = p^{\perp 2}_{\pi 1}$ and squaring both sides of the equation (19), we get:

$$p^{\parallel 2}_{\pi 1}p^{\parallel 2}_{\nu 1} + C^2 + 2Cp^{\parallel}_{\pi 1}p^{\parallel}_{\nu 1} = E^2_{\pi 1}(p^{\perp 2}_{\pi 1} + p^{\parallel 2}_{\nu 1}) \qquad (20)$$

Rearranging equation (20):

$$(E^2_{\pi 1} - p^{\parallel 2}_{\pi 1})p^{\parallel 2}_{\nu 1} - 2Cp^{\parallel}_{\pi 1}p^{\parallel}_{\nu 1} + E^2_{\pi 1}p^{\perp 2}_{\pi 1} - C^2 = 0 \qquad (21)$$

The only unknown quantity in this equation is $p^{\parallel}_{\nu 1}$. Solving this quadratic equation yields:

$$p_{\nu 1} = \alpha_1 \pm \beta_1 \qquad (22)$$

Here:

$$\alpha_1 = \frac{Cp^{\parallel}_{\pi 1}}{E^2_{\pi 1} - p^{\parallel 2}_{\pi 1}}$$

$$\beta_1 = \frac{E_{\pi 1}\sqrt{p^{\perp 2}_{\pi 1}p^{\parallel 2}_{\pi 1} + C^2 - E^2_{\pi 1}p^{\perp 2}_{\pi 1}}}{E^2_{\pi 1} - p^{\parallel 2}_{\pi 1}}$$

Now we can use this expression in equation (15) to find the value of $p_{\tau+}$ and then find the value of p_B using equations (10) and (3)

A. Semkiv et al.

- Nothing complicated but quite ... cumbersome.

- This can be generalized even to decays where the secondary vertex is NOT reconstructed. Thinking of $B^0_s \rightarrow \tau^+\tau^-$ for instance.

b→ s $l^+ l^-$ Transitions

$$R_K^{\ell\ell'} = \frac{\mathrm{BR}(B \to K\ell^+\ell^-)_{[q_1^2,q_2^2]}}{\mathrm{BR}(B \to K\ell'^+\ell'^-)_{[q_1^2,q_2^2]}}$$

$$R_K^{\mu e} = \frac{\mathrm{BR}(B \to K\mu^+\mu^-)_{[1,6]}}{\mathrm{BR}(B \to Ke^+e^-)_{[1,6]}} = 1.00023 \pm 0.00063$$

$$R_K^{\tau e} = \frac{\mathrm{BR}(B \to K\tau^+\tau^-)_{[14.18,\mathrm{max}]}}{\mathrm{BR}(B \to Ke^+e^-)_{[14.18,\mathrm{max}]}} = 1.161 \pm 0.040$$

$$R_K^{\tau\mu} = \frac{\mathrm{BR}(B \to K\tau^+\tau^-)_{[14.18,\mathrm{max}]}}{\mathrm{BR}(B \to K\mu^+\mu^-)_{[14.18,\mathrm{max}]}} = 1.158 \pm 0.039$$

(Bouchard et al. 1306.0434)

only very few results from direct searches for rare B decays with taus in the final state are available

- strongest current bound (BaBar, PoS ICHEP 2010, 234)

$$\mathrm{BR}(B \to K\tau^+\tau^-)_{[14.23,\mathrm{max}]} < 3.3 \times 10^{-3}$$

- expected sensitivity at Belle II to BRs of $O(10^{-4}) \sim O(10^{-5})$

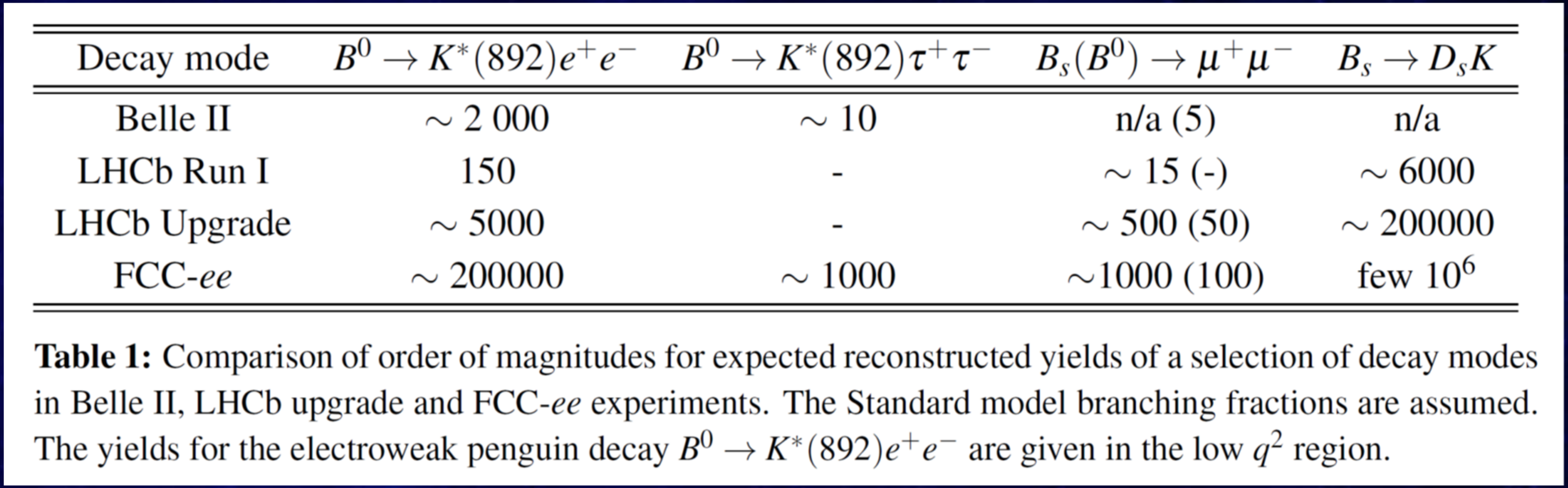
indirect constraints (model-dependent) from $B \to K^{(*)}\nu\bar{\nu}$

- strongest current bound (BaBar, PRD 87, 112005 (2013))

$$\mathrm{BR}(B \to K\nu\bar{\nu}) < 1.7 \times 10^{-5}$$

- expect order of magnitude better sensitivity at Belle II
- constraints from $B \to K\nu\bar{\nu}$ can be avoided if e.g. only right handed taus involved

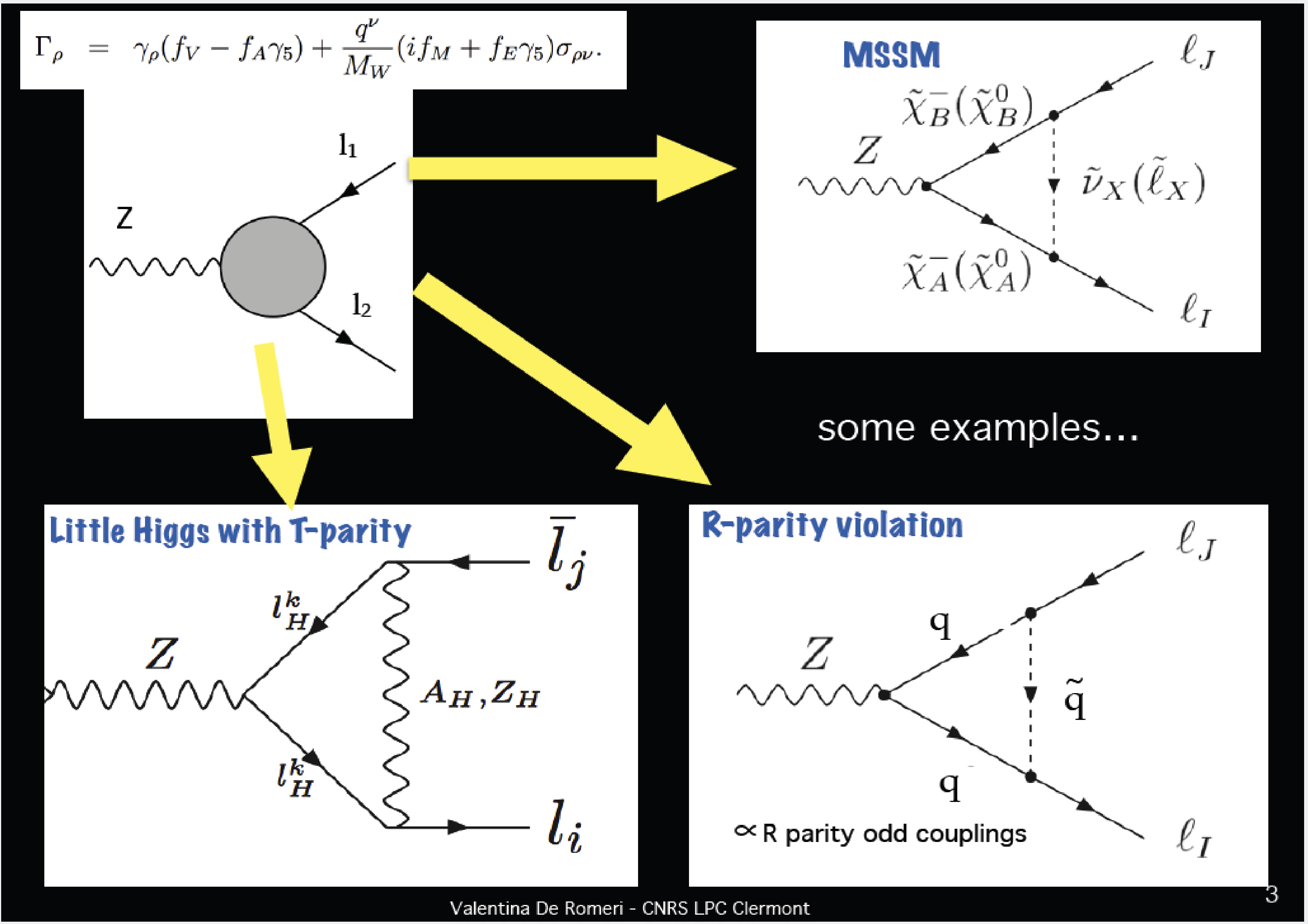
$b \to s\ l^+ l^-$ Transitions



Decay mode	$B^0 \to K^*(892)e^+e^-$	$B^0 \to K^*(892)\tau^+\tau^-$	$B_s(B^0) \to \mu^+\mu^-$	$B_s \to D_s K$
Belle II	$\sim$ 2 000	$\sim$ 10	n/a (5)	n/a
LHCb Run I	150	-	$\sim$ 15 (-)	$\sim$ 6000
LHCb Upgrade	$\sim$ 5000	-	$\sim$ 500 (50)	$\sim$ 200000
FCC-*ee*	$\sim$ 200000	$\sim$ 1000	$\sim$1000 (100)	few 10^6

Table 1: Comparison of order of magnitudes for expected reconstructed yields of a selection of decay modes in Belle II, LHCb upgrade and FCC-*ee* experiments. The Standard model branching fractions are assumed. The yields for the electroweak penguin decay $B^0 \to K^*(892)e^+e^-$ are given in the low q^2 region.

cLFV



$$\Gamma_\rho \;=\; \gamma_\rho(f_V - f_A\gamma_5) + \frac{q^\nu}{M_W}(i f_M + f_E\gamma_5)\sigma_{\rho\nu}.$$

MSSM

some examples…

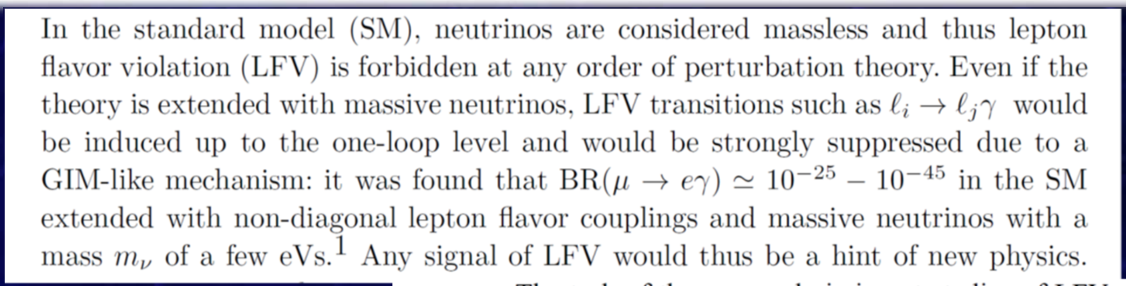
Little Higgs with T-parity

R-parity violation

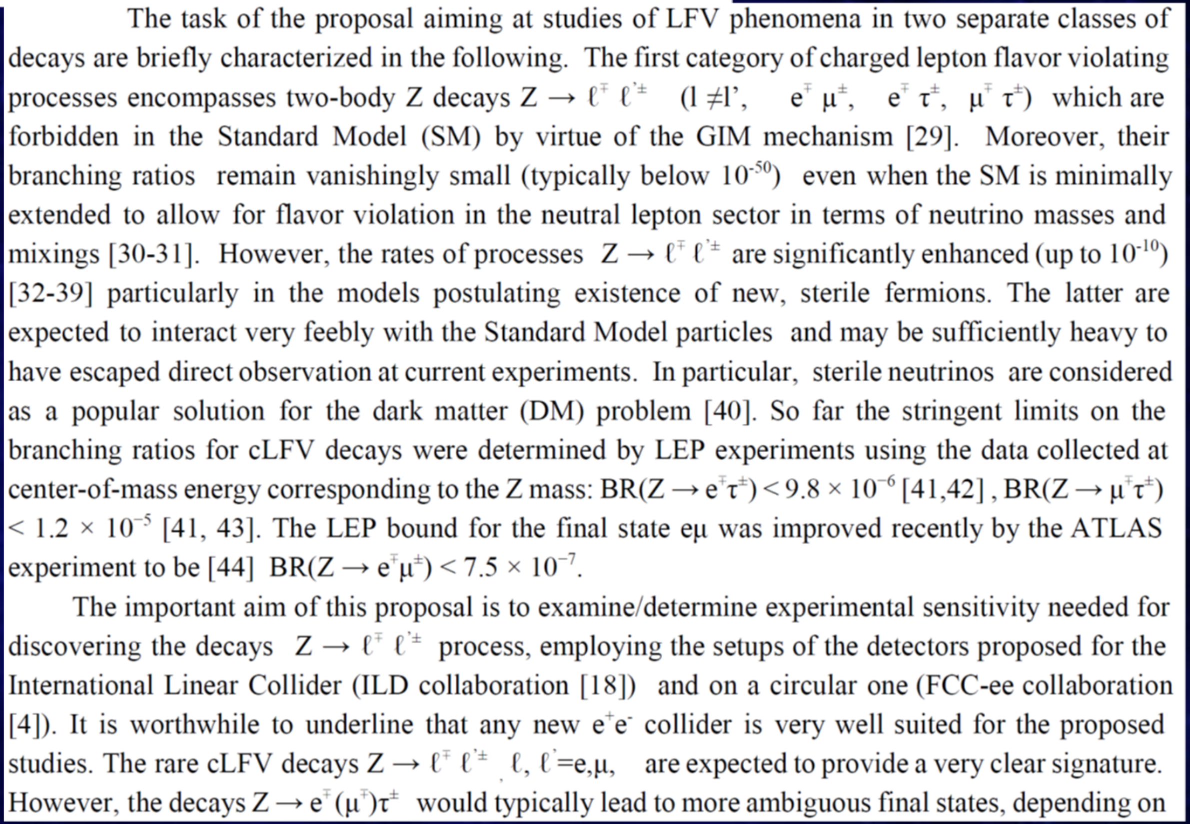
∝ R parity odd couplings

Valentina De Romeri - CNRS LPC Clermont

cFLV

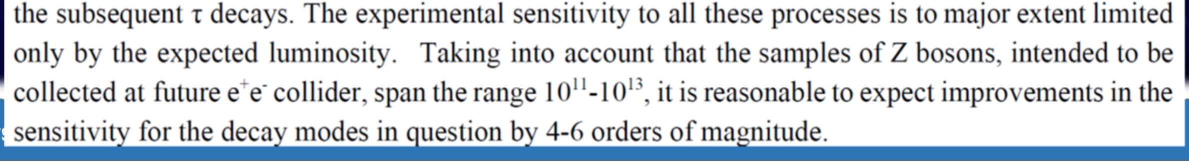


In the standard model (SM), neutrinos are considered massless and thus lepton flavor violation (LFV) is forbidden at any order of perturbation theory. Even if the theory is extended with massive neutrinos, LFV transitions such as $\ell_i \to \ell_j \gamma$ would be induced up to the one-loop level and would be strongly suppressed due to a GIM-like mechanism: it was found that $\mathrm{BR}(\mu \to e\gamma) \simeq 10^{-25} - 10^{-45}$ in the SM extended with non-diagonal lepton flavor couplings and massive neutrinos with a mass m_ν of a few eVs.[1] Any signal of LFV would thus be a hint of new physics.



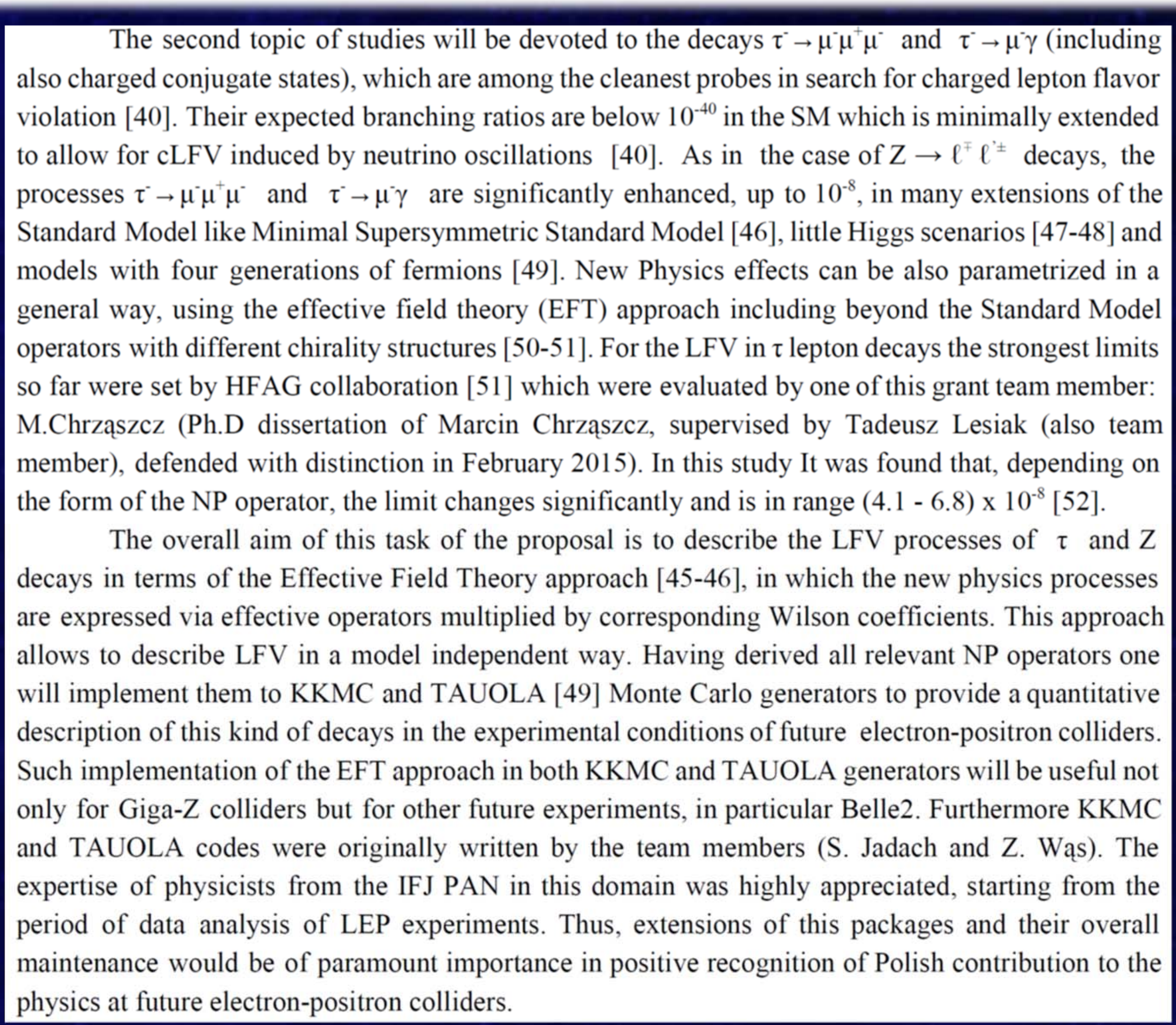
The task of the proposal aiming at studies of LFV phenomena in two separate classes of decays are briefly characterized in the following. The first category of charged lepton flavor violating processes encompasses two-body Z decays $Z \to \ell^{\mp} \ell'^{\pm}$ ($l \neq l'$, $e^{\mp}\mu^{\pm}$, $e^{\mp}\tau^{\pm}$, $\mu^{\mp}\tau^{\pm}$) which are forbidden in the Standard Model (SM) by virtue of the GIM mechanism [29]. Moreover, their branching ratios remain vanishingly small (typically below 10^{-50}) even when the SM is minimally extended to allow for flavor violation in the neutral lepton sector in terms of neutrino masses and mixings [30-31]. However, the rates of processes $Z \to \ell^{\mp} \ell'^{\pm}$ are significantly enhanced (up to 10^{-10}) [32-39] particularly in the models postulating existence of new, sterile fermions. The latter are expected to interact very feebly with the Standard Model particles and may be sufficiently heavy to have escaped direct observation at current experiments. In particular, sterile neutrinos are considered as a popular solution for the dark matter (DM) problem [40]. So far the stringent limits on the branching ratios for cLFV decays were determined by LEP experiments using the data collected at center-of-mass energy corresponding to the Z mass: $\mathrm{BR}(Z \to e^{\mp}\tau^{\pm}) < 9.8 \times 10^{-6}$ [41,42] , $\mathrm{BR}(Z \to \mu^{\mp}\tau^{\pm}) < 1.2 \times 10^{-5}$ [41, 43]. The LEP bound for the final state eμ was improved recently by the ATLAS experiment to be [44] $\mathrm{BR}(Z \to e^{\mp}\mu^{\pm}) < 7.5 \times 10^{-7}$.

The important aim of this proposal is to examine/determine experimental sensitivity needed for discovering the decays $Z \to \ell^{\mp} \ell'^{\pm}$ process, employing the setups of the detectors proposed for the International Linear Collider (ILD collaboration [18]) and on a circular one (FCC-ee collaboration [4]). It is worthwhile to underline that any new e^+e^- collider is very well suited for the proposed studies. The rare cLFV decays $Z \to \ell^{\mp} \ell'^{\pm}$ $\ell, \ell'=e,\mu$, are expected to provide a very clear signature. However, the decays $Z \to e^{\mp}(\mu^{\mp})\tau^{\pm}$ would typically lead to more ambiguous final states, depending on



the subsequent τ decays. The experimental sensitivity to all these processes is to major extent limited only by the expected luminosity. Taking into account that the samples of Z bosons, intended to be collected at future e^+e^- collider, span the range 10^{11}-10^{13}, it is reasonable to expect improvements in the sensitivity for the decay modes in question by 4-6 orders of magnitude.

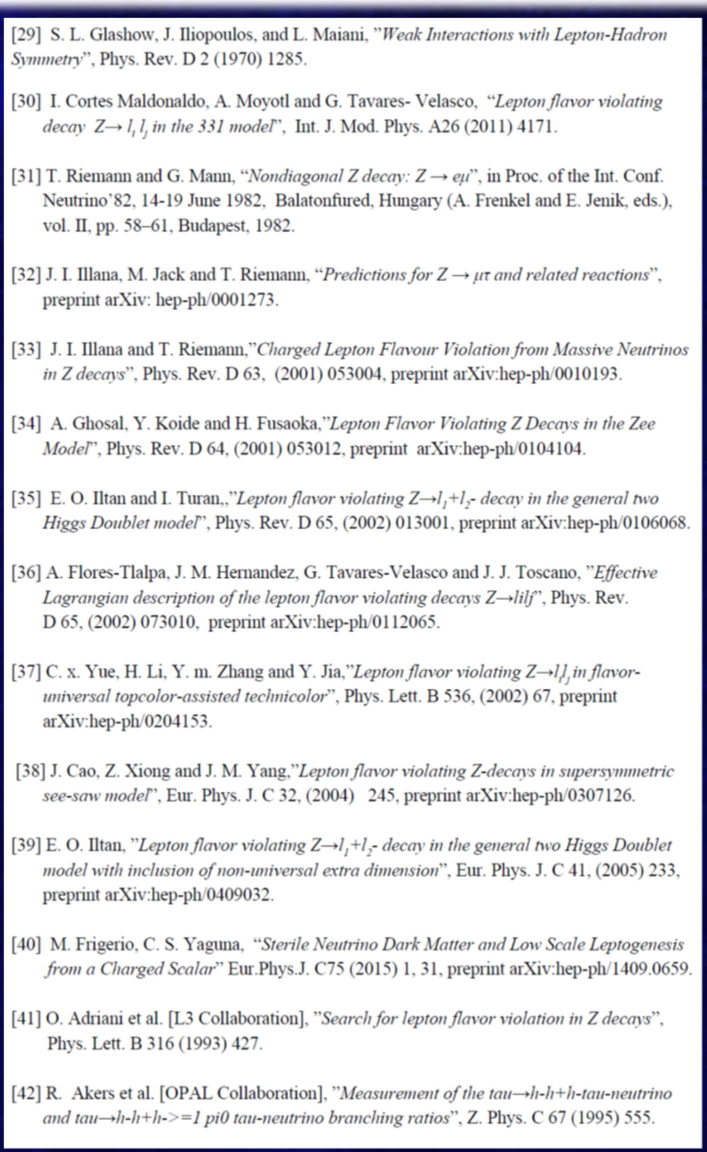
cLFV



The second topic of studies will be devoted to the decays $\tau^- \to \mu^-\mu^+\mu^-$ and $\tau^- \to \mu^-\gamma$ (including also charged conjugate states), which are among the cleanest probes in search for charged lepton flavor violation [40]. Their expected branching ratios are below 10^{-40} in the SM which is minimally extended to allow for cLFV induced by neutrino oscillations [40]. As in the case of $Z \to \ell^{\mp}\ell'^{\pm}$ decays, the processes $\tau^- \to \mu^-\mu^+\mu^-$ and $\tau^- \to \mu^-\gamma$ are significantly enhanced, up to 10^{-8}, in many extensions of the Standard Model like Minimal Supersymmetric Standard Model [46], little Higgs scenarios [47-48] and models with four generations of fermions [49]. New Physics effects can be also parametrized in a general way, using the effective field theory (EFT) approach including beyond the Standard Model operators with different chirality structures [50-51]. For the LFV in τ lepton decays the strongest limits so far were set by HFAG collaboration [51] which were evaluated by one of this grant team member: M.Chrząszcz (Ph.D dissertation of Marcin Chrząszcz, supervised by Tadeusz Lesiak (also team member), defended with distinction in February 2015). In this study It was found that, depending on the form of the NP operator, the limit changes significantly and is in range (4.1 - 6.8) x 10^{-8} [52].

The overall aim of this task of the proposal is to describe the LFV processes of τ and Z decays in terms of the Effective Field Theory approach [45-46], in which the new physics processes are expressed via effective operators multiplied by corresponding Wilson coefficients. This approach allows to describe LFV in a model independent way. Having derived all relevant NP operators one will implement them to KKMC and TAUOLA [49] Monte Carlo generators to provide a quantitative description of this kind of decays in the experimental conditions of future electron-positron colliders. Such implementation of the EFT approach in both KKMC and TAUOLA generators will be useful not only for Giga-Z colliders but for other future experiments, in particular Belle2. Furthermore KKMC and TAUOLA codes were originally written by the team members (S. Jadach and Z. Wąs). The expertise of physicists from the IFJ PAN in this domain was highly appreciated, starting from the period of data analysis of LEP experiments. Thus, extensions of this packages and their overall maintenance would be of paramount importance in positive recognition of Polish contribution to the physics at future electron-positron colliders.

cLFV



[29] S. L. Glashow, J. Iliopoulos, and L. Maiani, "*Weak Interactions with Lepton-Hadron Symmetry*", Phys. Rev. D 2 (1970) 1285.

[30] I. Cortes Maldonaldo, A. Moyotl and G. Tavares- Velasco, "*Lepton flavor violating decay $Z\to l_i l_j$ in the 331 model*", Int. J. Mod. Phys. A26 (2011) 4171.

[31] T. Riemann and G. Mann, "*Nondiagonal Z decay: $Z\to e\mu$*", in Proc. of the Int. Conf. Neutrino'82, 14-19 June 1982, Balatonfured, Hungary (A. Frenkel and E. Jenik, eds.), vol. II, pp. 58–61, Budapest, 1982.

[32] J. I. Illana, M. Jack and T. Riemann, "*Predictions for $Z\to\mu\tau$ and related reactions*", preprint arXiv: hep-ph/0001273.

[33] J. I. Illana and T. Riemann,"*Charged Lepton Flavour Violation from Massive Neutrinos in Z decays*", Phys. Rev. D 63, (2001) 053004, preprint arXiv:hep-ph/0010193.

[34] A. Ghosal, Y. Koide and H. Fusaoka,"*Lepton Flavor Violating Z Decays in the Zee Model*", Phys. Rev. D 64, (2001) 053012, preprint arXiv:hep-ph/0104104.

[35] E. O. Iltan and I. Turan,,"*Lepton flavor violating $Z\to l_1+l_2$- decay in the general two Higgs Doublet model*", Phys. Rev. D 65, (2002) 013001, preprint arXiv:hep-ph/0106068.

[36] A. Flores-Tlalpa, J. M. Hernandez, G. Tavares-Velasco and J. J. Toscano, "*Effective Lagrangian description of the lepton flavor violating decays Z→lilj*", Phys. Rev. D 65, (2002) 073010, preprint arXiv:hep-ph/0112065.

[37] C. x. Yue, H. Li, Y. m. Zhang and Y. Jia,"*Lepton flavor violating $Z\to l_i l_j$ in flavor-universal topcolor-assisted technicolor*", Phys. Lett. B 536, (2002) 67, preprint arXiv:hep-ph/0204153.

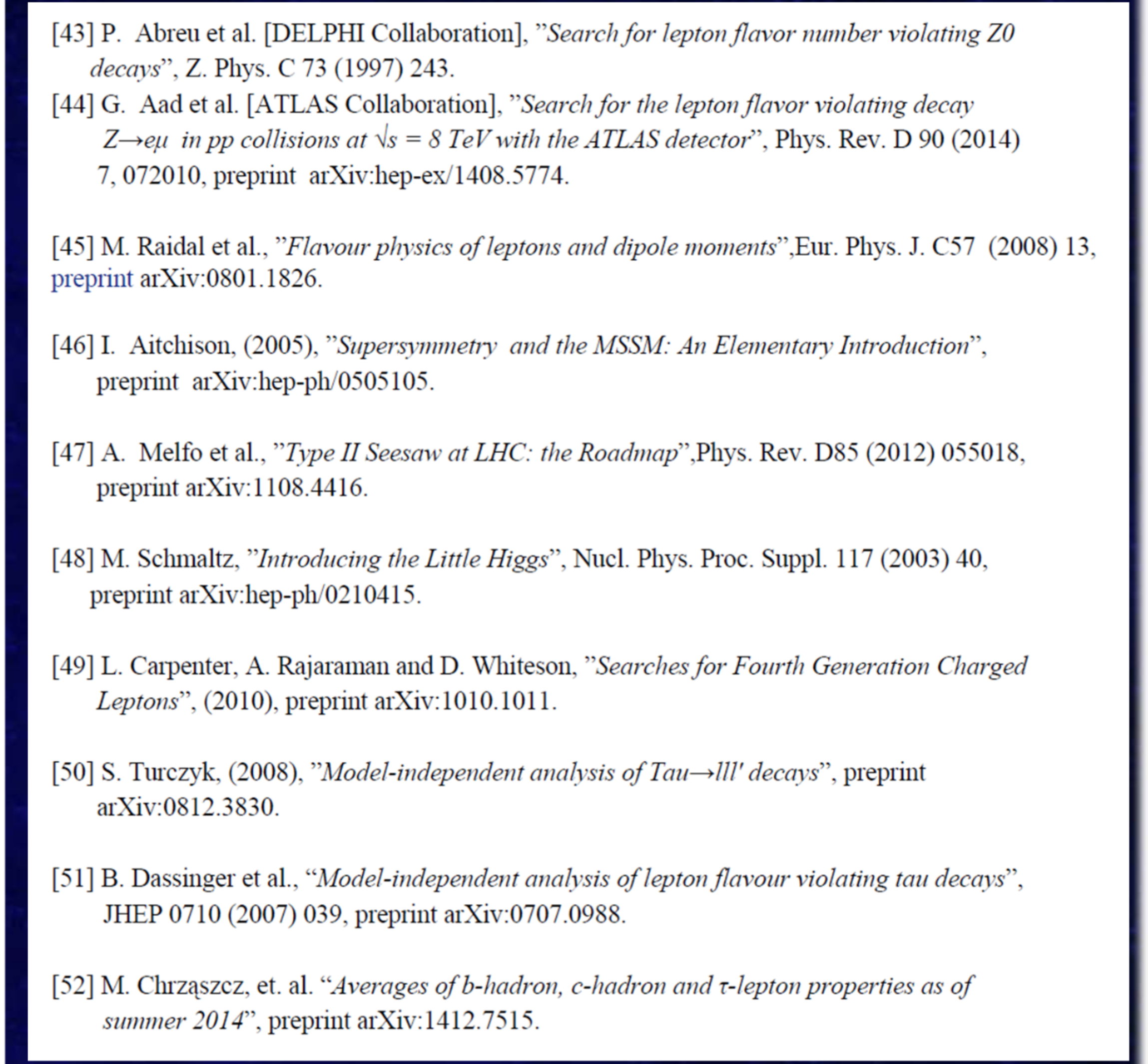
[38] J. Cao, Z. Xiong and J. M. Yang,"*Lepton flavor violating Z-decays in supersymmetric see-saw model*", Eur. Phys. J. C 32, (2004) 245, preprint arXiv:hep-ph/0307126.

[39] E. O. Iltan, "*Lepton flavor violating $Z\to l_1+l_2$- decay in the general two Higgs Doublet model with inclusion of non-universal extra dimension*", Eur. Phys. J. C 41, (2005) 233, preprint arXiv:hep-ph/0409032.

[40] M. Frigerio, C. S. Yaguna, "*Sterile Neutrino Dark Matter and Low Scale Leptogenesis from a Charged Scalar*" Eur.Phys.J. C75 (2015) 1, 31, preprint arXiv:hep-ph/1409.0659.

[41] O. Adriani et al. [L3 Collaboration], "*Search for lepton flavor violation in Z decays*", Phys. Lett. B 316 (1993) 427.

[42] R. Akers et al. [OPAL Collaboration], "*Measurement of the tau→h-h+h-tau-neutrino and tau→h-h+h->=1 pi0 tau-neutrino branching ratios*", Z. Phys. C 67 (1995) 555.



[43] P. Abreu et al. [DELPHI Collaboration], "*Search for lepton flavor number violating Z0 decays*", Z. Phys. C 73 (1997) 243.

[44] G. Aad et al. [ATLAS Collaboration], "*Search for the lepton flavor violating decay $Z\to e\mu$ in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*", Phys. Rev. D 90 (2014) 7, 072010, preprint arXiv:hep-ex/1408.5774.

[45] M. Raidal et al., "*Flavour physics of leptons and dipole moments*",Eur. Phys. J. C57 (2008) 13, preprint arXiv:0801.1826.

[46] I. Aitchison, (2005), "*Supersymmetry and the MSSM: An Elementary Introduction*", preprint arXiv:hep-ph/0505105.

[47] A. Melfo et al., "*Type II Seesaw at LHC: the Roadmap*",Phys. Rev. D85 (2012) 055018, preprint arXiv:1108.4416.

[48] M. Schmaltz, "*Introducing the Little Higgs*", Nucl. Phys. Proc. Suppl. 117 (2003) 40, preprint arXiv:hep-ph/0210415.

[49] L. Carpenter, A. Rajaraman and D. Whiteson, "*Searches for Fourth Generation Charged Leptons*", (2010), preprint arXiv:1010.1011.

[50] S. Turczyk, (2008), "*Model-independent analysis of Tau→lll' decays*", preprint arXiv:0812.3830.

[51] B. Dassinger et al., "*Model-independent analysis of lepton flavour violating tau decays*", JHEP 0710 (2007) 039, preprint arXiv:0707.0988.

[52] M. Chrząszcz, et. al. "*Averages of b-hadron, c-hadron and τ-lepton properties as of summer 2014*", preprint arXiv:1412.7515.

cLFV – EFT approach

cLFV resulting from BSM theories can de described in a model independent way in terms of the following dimension six operators:

$$
\begin{aligned}
O_1 &= (\bar{L}\gamma_\mu L)(\bar{L}\gamma^\mu L),\\
O_2 &= (\bar{L}\tau^a\gamma_\mu L)(\bar{L}\tau^a\gamma^\mu L),\\
O_3 &= (\bar{R}\gamma_\mu R)(\bar{R}\gamma^\mu R),\\
O_4 &= (\bar{R}\gamma_\mu R)(\bar{L}\gamma^\mu L),\\
R_1 &= g'(\bar{L}H\sigma_{\mu\nu}R)B^{\mu\nu},\\
R_2 &= g(\bar{L}\tau^a H\sigma_{\mu\nu}R)W^{\mu\nu}.
\end{aligned}
$$

$$R_e = \frac{1-\gamma_5}{2}\begin{pmatrix}0\\ \psi_e\end{pmatrix},\ R_\mu = \frac{1-\gamma_5}{2}\begin{pmatrix}0\\ \psi_\mu\end{pmatrix},\ R_\tau = \frac{1-\gamma_5}{2}\begin{pmatrix}0\\ \psi_\tau\end{pmatrix}$$

As defined above, $B_{\mu\nu}$ and $W_{\mu\nu,a}$ are the electroweak gauge fields, g and g' are the coupling constants of $SU(2)_L$ and $U(1)_Y$, H denotes the matrix of Higgs fields, $L(R)$ are the left(right)-handed fields and $\sigma^{\mu,\nu} = \frac{i}{4}[\gamma^\mu,\gamma^\nu]$.

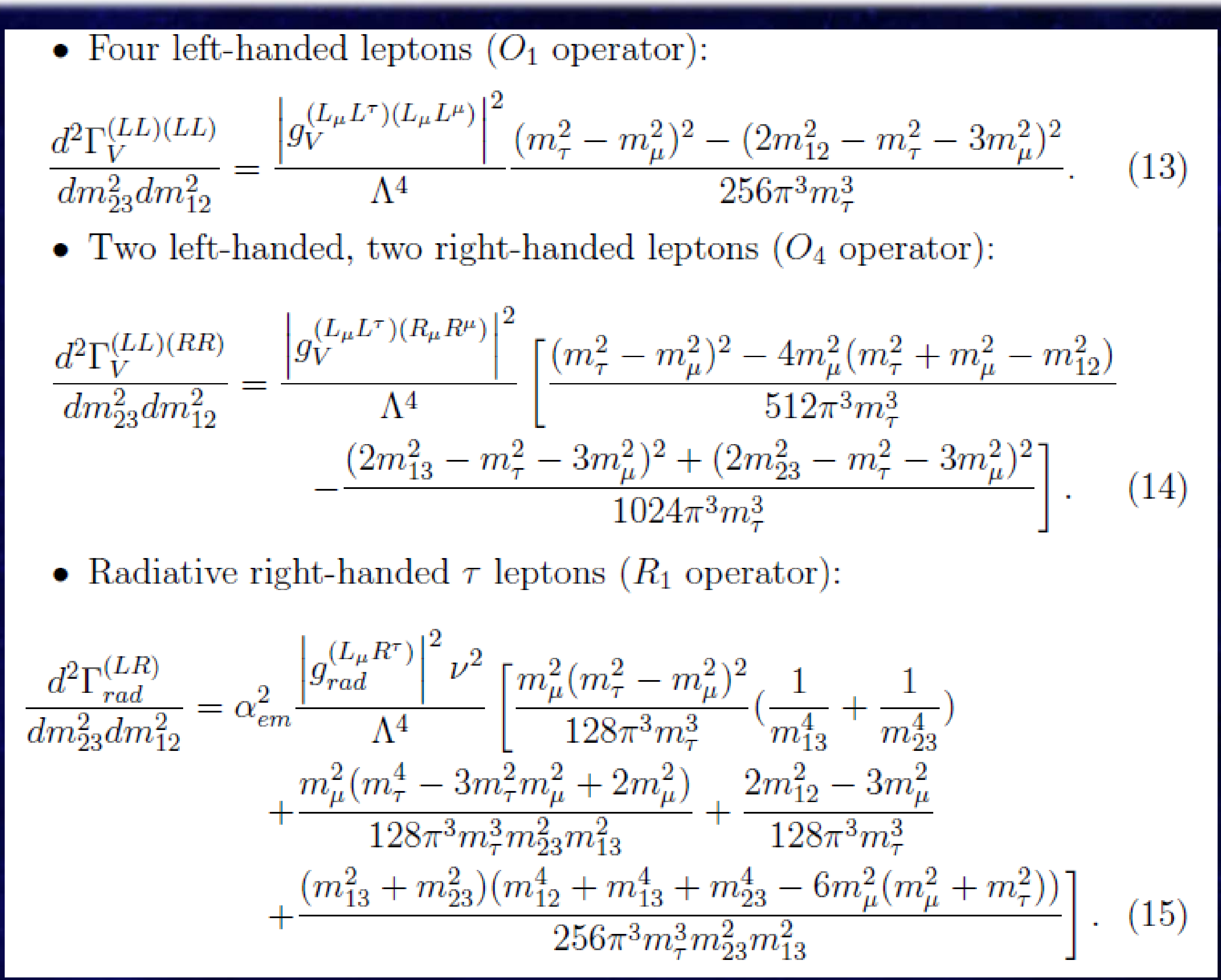
The respective decay widths cab v=be presented in the form of Dalitz distributions

They were derived in the following five cases corresponding to different lepton chirality structures

(The following dimuon masses are defined:

$$m^2_{--} = m^2_{12} = (p_{\mu^-} + p'_{\mu^-})^2, \qquad m^2_{+-} = m^2_{23} = (p'_{\mu^-} + p_{\mu^+})^2,$$
$$m^2_{13} = m^2_\tau + 3m^2_\mu - m^2_{--} - m^2_{+-},$$

cLFV – EFT approach



- Four left-handed leptons (O_1 operator):

$$\frac{d^2\Gamma_V^{(LL)(LL)}}{dm_{23}^2 dm_{12}^2} = \frac{\left|g_V^{(L_\mu L^\tau)(L_\mu L^\mu)}\right|^2}{\Lambda^4} \frac{(m_\tau^2 - m_\mu^2)^2 - (2m_{12}^2 - m_\tau^2 - 3m_\mu^2)^2}{256\pi^3 m_\tau^3}. \qquad (13)$$

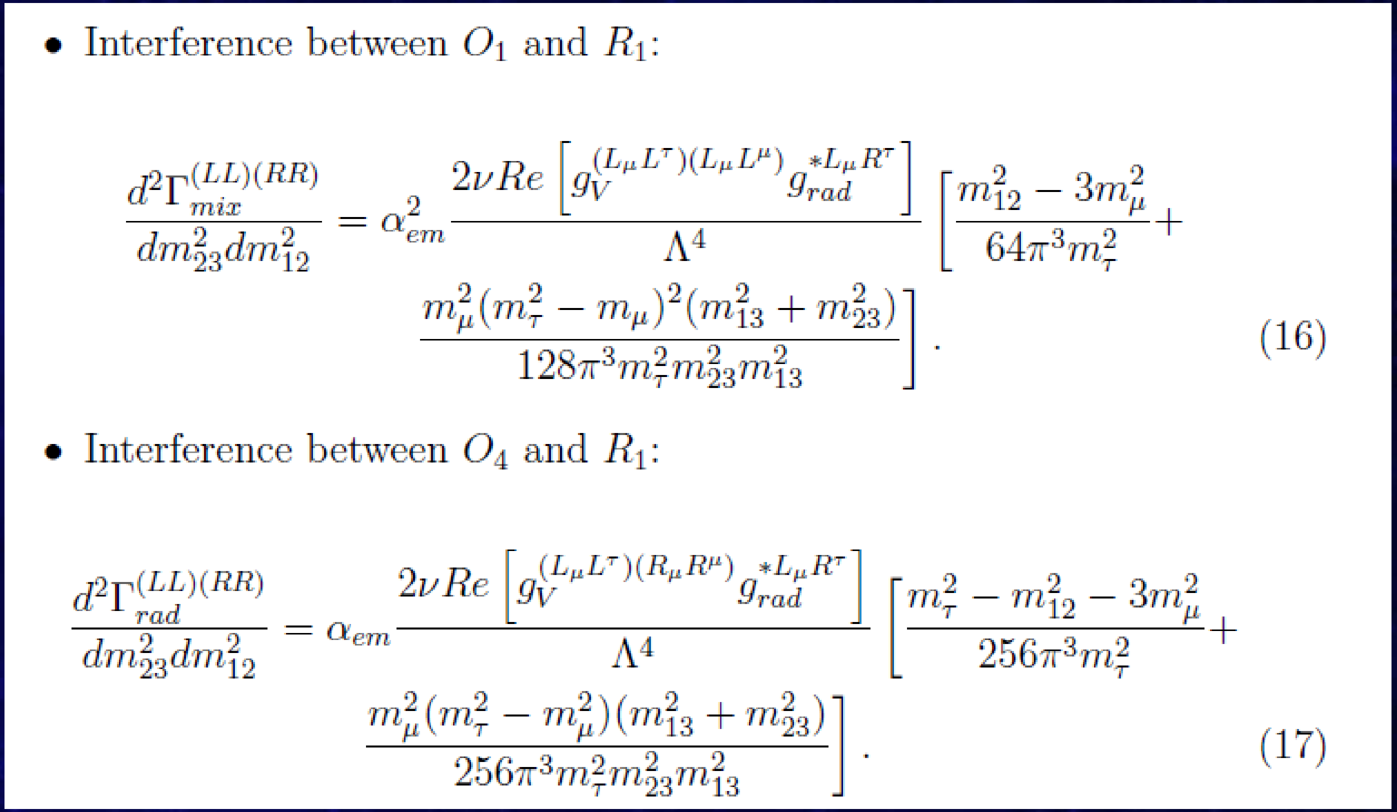
- Two left-handed, two right-handed leptons (O_4 operator):

$$\frac{d^2\Gamma_V^{(LL)(RR)}}{dm_{23}^2 dm_{12}^2} = \frac{\left|g_V^{(L_\mu L^\tau)(R_\mu R^\mu)}\right|^2}{\Lambda^4} \left[\frac{(m_\tau^2 - m_\mu^2)^2 - 4m_\mu^2(m_\tau^2 + m_\mu^2 - m_{12}^2)}{512\pi^3 m_\tau^3} - \frac{(2m_{13}^2 - m_\tau^2 - 3m_\mu^2)^2 + (2m_{23}^2 - m_\tau^2 - 3m_\mu^2)^2}{1024\pi^3 m_\tau^3}\right]. \qquad (14)$$

- Radiative right-handed τ leptons (R_1 operator):

$$\frac{d^2\Gamma_{rad}^{(LR)}}{dm_{23}^2 dm_{12}^2} = \alpha_{em}^2 \frac{\left|g_{rad}^{(L_\mu R^\tau)}\right|^2 \nu^2}{\Lambda^4} \left[\frac{m_\mu^2(m_\tau^2 - m_\mu^2)^2}{128\pi^3 m_\tau^3}\left(\frac{1}{m_{13}^4} + \frac{1}{m_{23}^4}\right) + \frac{m_\mu^2(m_\tau^4 - 3m_\tau^2 m_\mu^2 + 2m_\mu^2)}{128\pi^3 m_\tau^3 m_{23}^2 m_{13}^2} + \frac{2m_{12}^2 - 3m_\mu^2}{128\pi^3 m_\tau^3} + \frac{(m_{13}^2 + m_{23}^2)(m_{12}^4 + m_{13}^4 + m_{23}^4 - 6m_\mu^2(m_\mu^2 + m_\tau^2))}{256\pi^3 m_\tau^3 m_{23}^2 m_{13}^2}\right]. \qquad (15)$$

cLFV – EFT approach

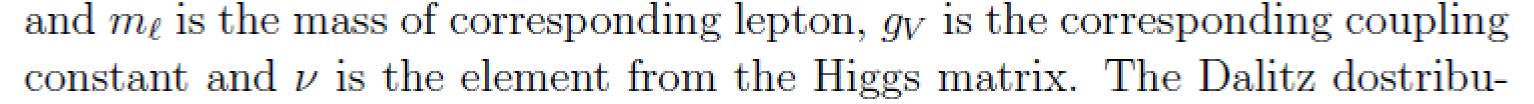


- Interference between O_1 and R_1:

$$\frac{d^2\Gamma^{(LL)(RR)}_{mix}}{dm^2_{23}dm^2_{12}} = \alpha^2_{em}\frac{2\nu Re\left[g_V^{(L_\mu L^\tau)(L_\mu L^\mu)}\, g_{rad}^{*L_\mu R^\tau}\right]}{\Lambda^4}\left[\frac{m^2_{12}-3m^2_\mu}{64\pi^3 m^2_\tau}+\frac{m^2_\mu(m^2_\tau-m_\mu)^2(m^2_{13}+m^2_{23})}{128\pi^3 m^2_\tau m^2_{23} m^2_{13}}\right]. \tag{16}$$

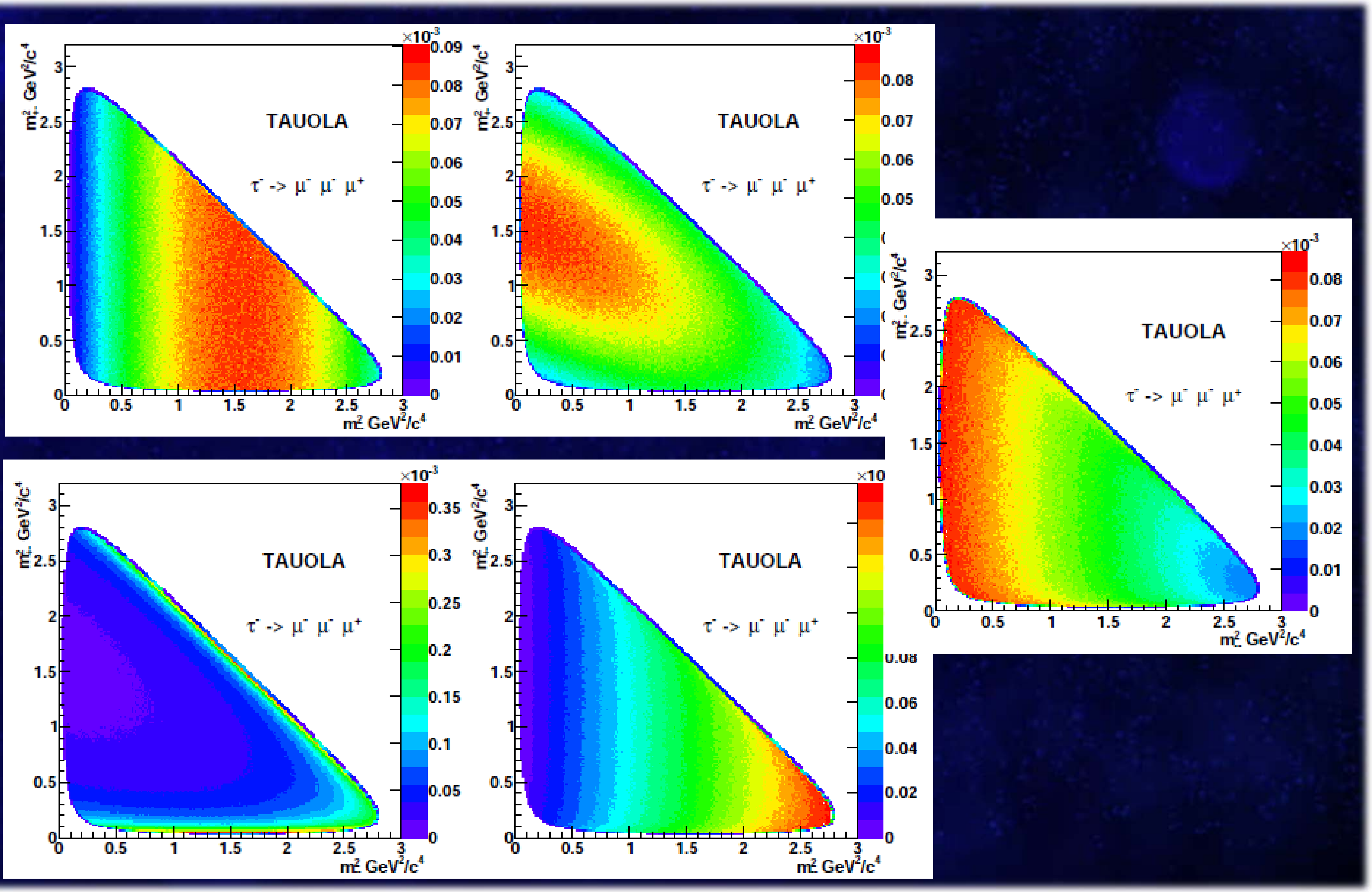
- Interference between O_4 and R_1:

$$\frac{d^2\Gamma^{(LL)(RR)}_{rad}}{dm^2_{23}dm^2_{12}} = \alpha_{em}\frac{2\nu Re\left[g_V^{(L_\mu L^\tau)(R_\mu R^\mu)}\, g_{rad}^{*L_\mu R^\tau}\right]}{\Lambda^4}\left[\frac{m^2_\tau-m^2_{12}-3m^2_\mu}{256\pi^3 m^2_\tau}+\frac{m^2_\mu(m^2_\tau-m^2_\mu)(m^2_{13}+m^2_{23})}{256\pi^3 m^2_\tau m^2_{23} m^2_{13}}\right]. \tag{17}$$



and m_ℓ is the mass of corresponding lepton, g_V is the corresponding coupling constant and ν is the element from the Higgs matrix. The Dalitz dostribu-

cLFV – EFT approach



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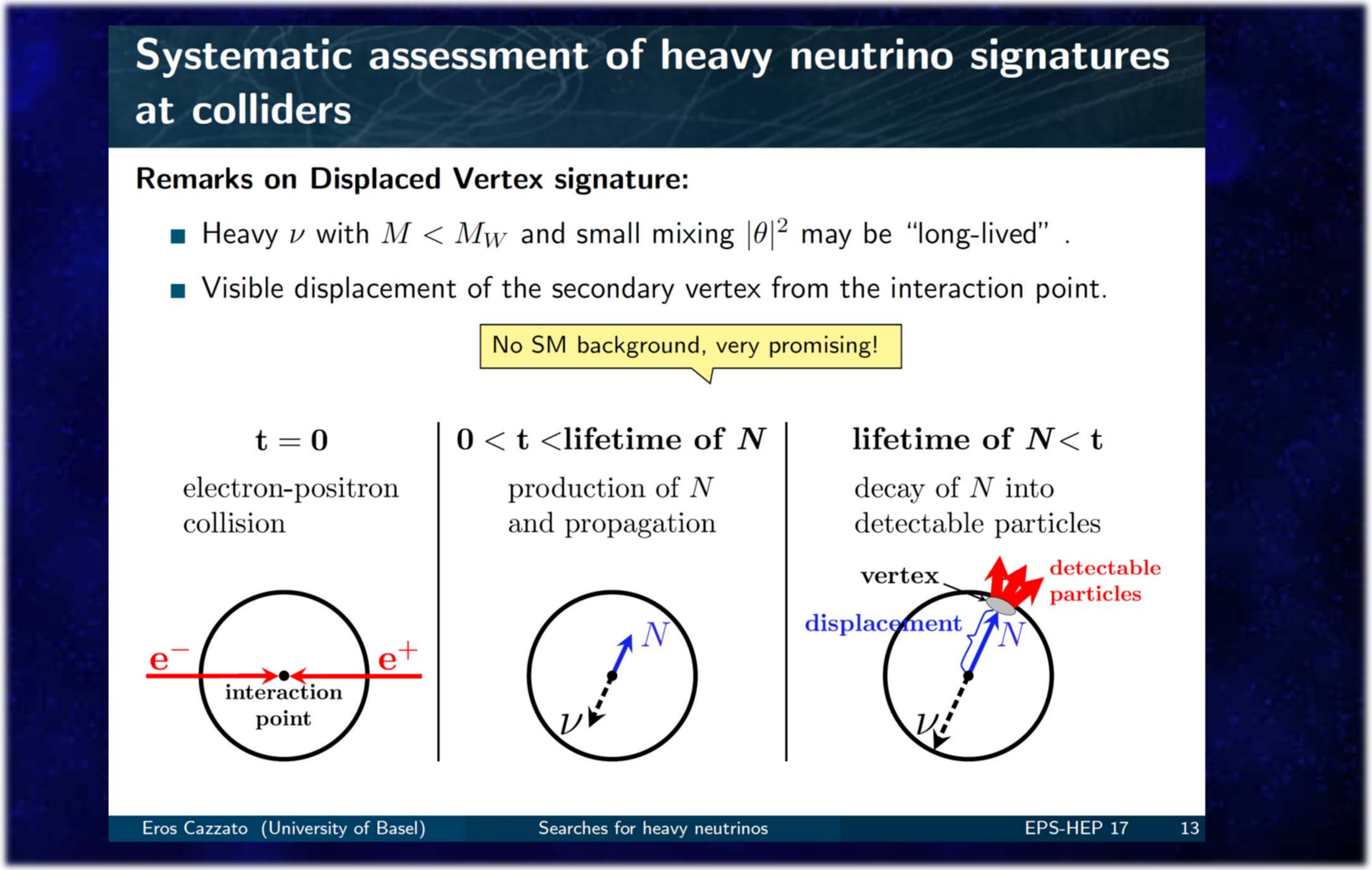

Systematic assessment of heavy neutrino signatures at colliders

Remarks on Displaced Vertex signature:

- Heavy ν with $M < M_W$ and small mixing $|\theta|^2$ may be “long-lived” .
- Visible displacement of the secondary vertex from the interaction point.

No SM background, very promising!

Eros Cazzato (University of Basel) Searches for heavy neutrinos EPS-HEP 17 13

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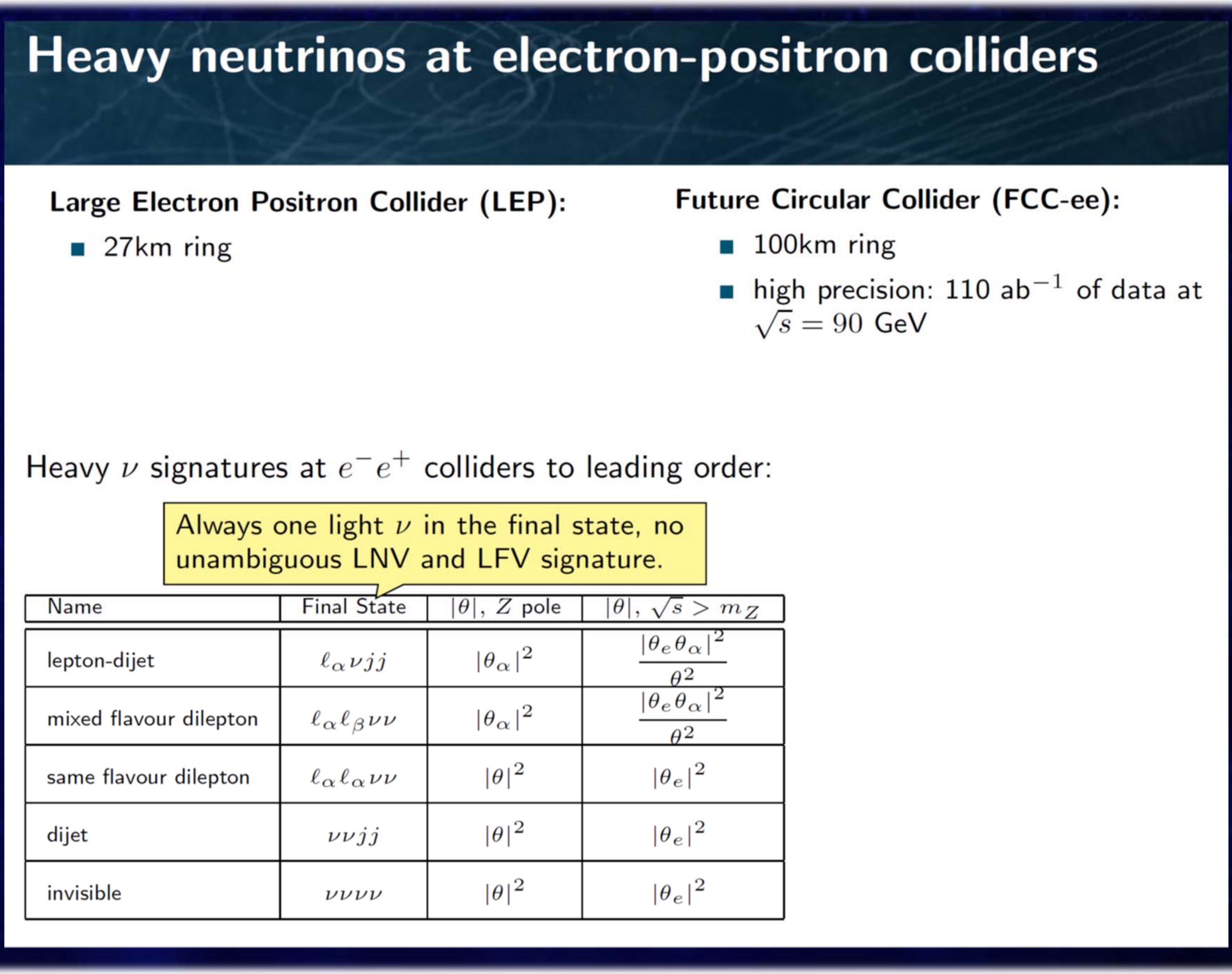

Heavy neutrinos at electron-positron colliders

Large Electron Positron Collider (LEP):

- 27km ring

Future Circular Collider (FCC-ee):

- 100km ring
- high precision: 110 ab^{-1} of data at $\sqrt{s} = 90$ GeV

Heavy ν signatures at $e^- e^+$ colliders to leading order:

Always one light ν in the final state, no unambiguous LNV and LFV signature.

Name	Final State	$\lvert\theta\rvert$, Z pole	$\lvert\theta\rvert$, $\sqrt{s} > m_Z$
lepton-dijet	$\ell_\alpha \nu jj$	$\lvert\theta_\alpha\rvert^2$	$\frac{\lvert\theta_e \theta_\alpha\rvert^2}{\theta^2}$
mixed flavour dilepton	$\ell_\alpha \ell_\beta \nu\nu$	$\lvert\theta_\alpha\rvert^2$	$\frac{\lvert\theta_e \theta_\alpha\rvert^2}{\theta^2}$
same flavour dilepton	$\ell_\alpha \ell_\alpha \nu\nu$	$\lvert\theta\rvert^2$	$\lvert\theta_e\rvert^2$
dijet	$\nu\nu jj$	$\lvert\theta\rvert^2$	$\lvert\theta_e\rvert^2$
invisible	$\nu\nu\nu\nu$	$\lvert\theta\rvert^2$	$\lvert\theta_e\rvert^2$

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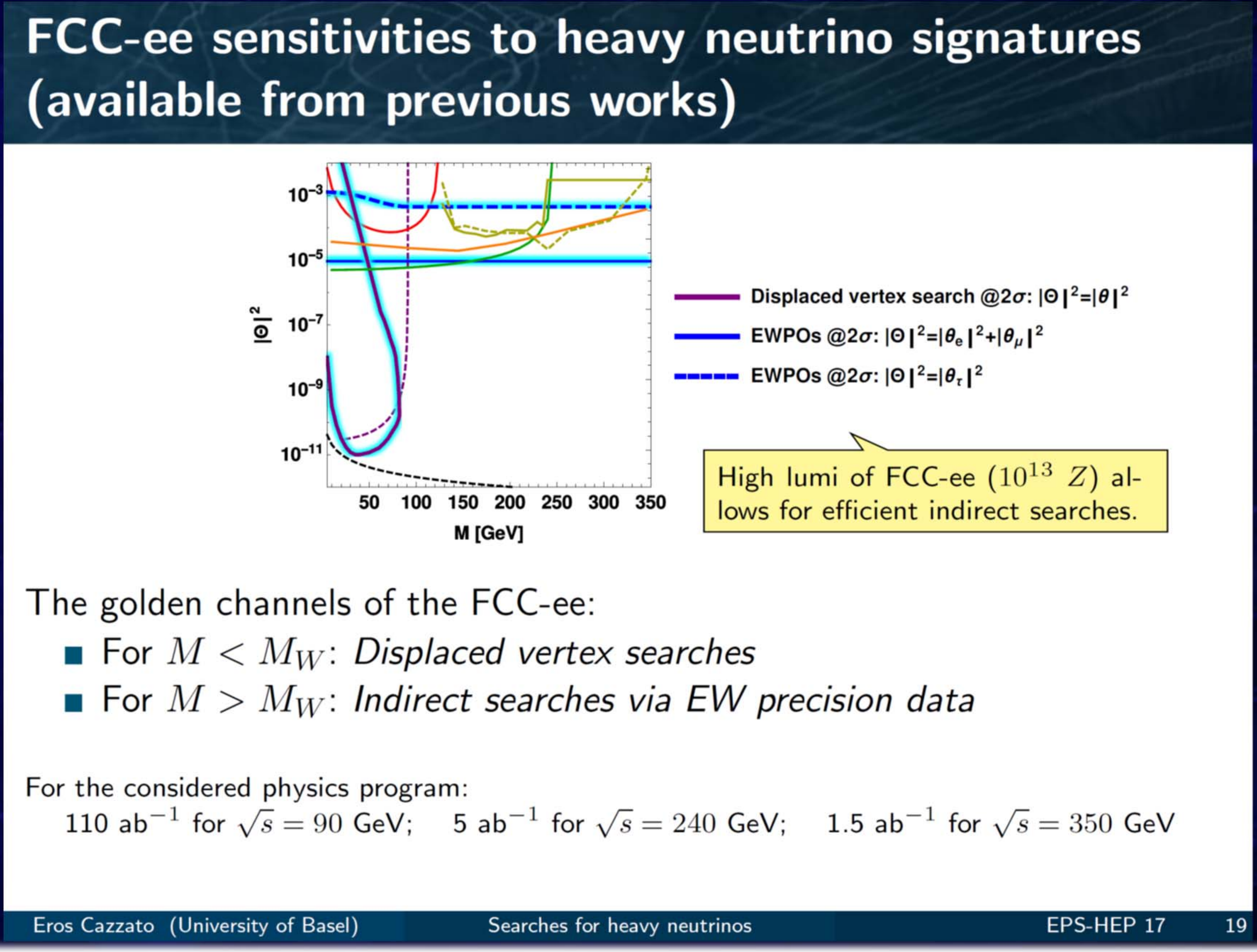

FCC-ee sensitivities to heavy neutrino signatures (available from previous works)

High lumi of FCC-ee (10^{13} Z) allows for efficient indirect searches.

The golden channels of the FCC-ee:

- For $M < M_W$: *Displaced vertex searches*
- For $M > M_W$: *Indirect searches via EW precision data*

For the considered physics program:
110 ab^{-1} for $\sqrt{s} = 90$ GeV; 5 ab^{-1} for $\sqrt{s} = 240$ GeV; 1.5 ab^{-1} for $\sqrt{s} = 350$ GeV

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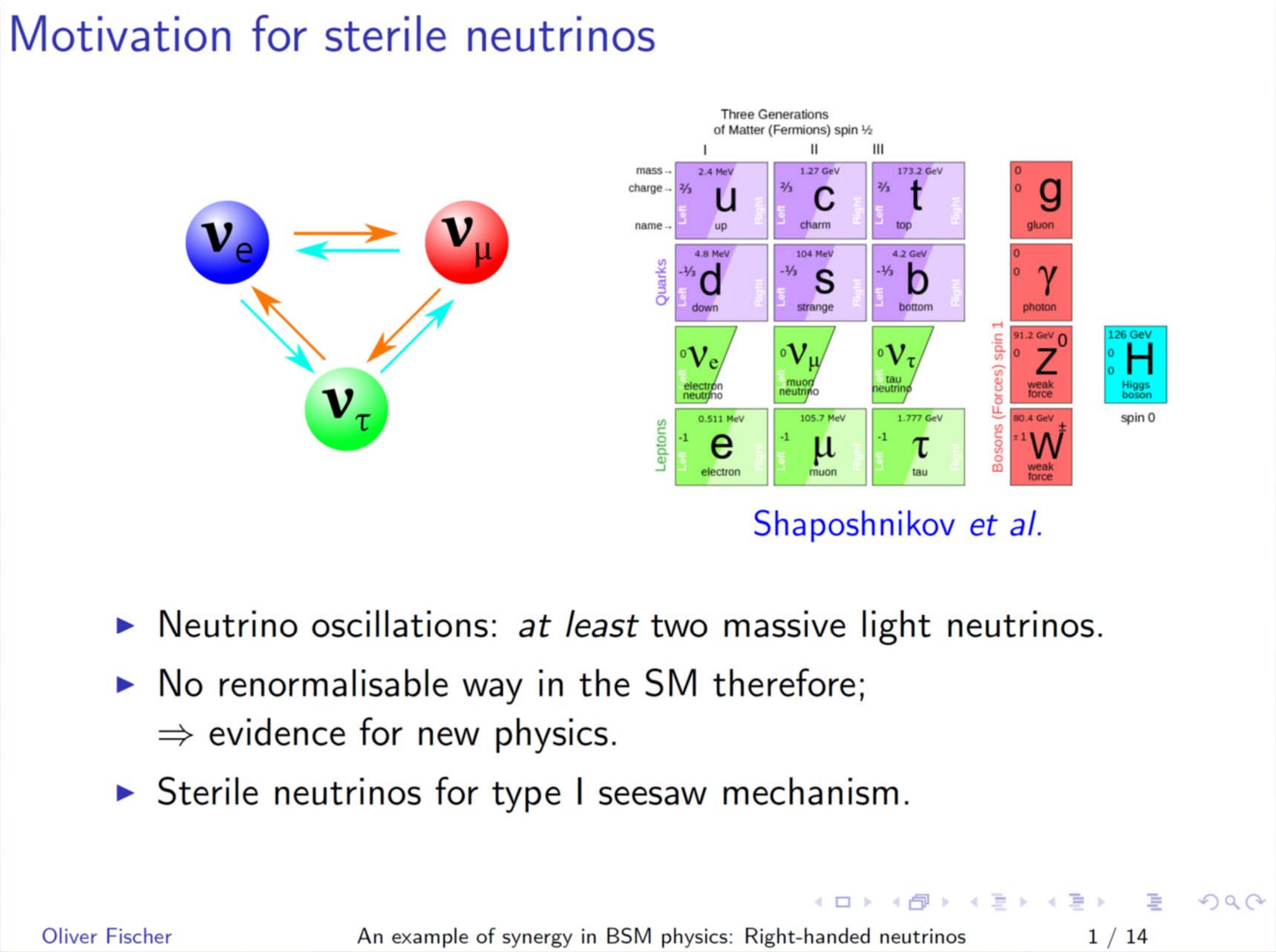

Motivation for sterile neutrinos

Shaposhnikov *et al.*

- Neutrino oscillations: *at least* two massive light neutrinos.
- No renormalisable way in the SM therefore;
  ⇒ evidence for new physics.
- Sterile neutrinos for type I seesaw mechanism.

Oliver Fischer An example of synergy in BSM physics: Right-handed neutrinos 1 / 14

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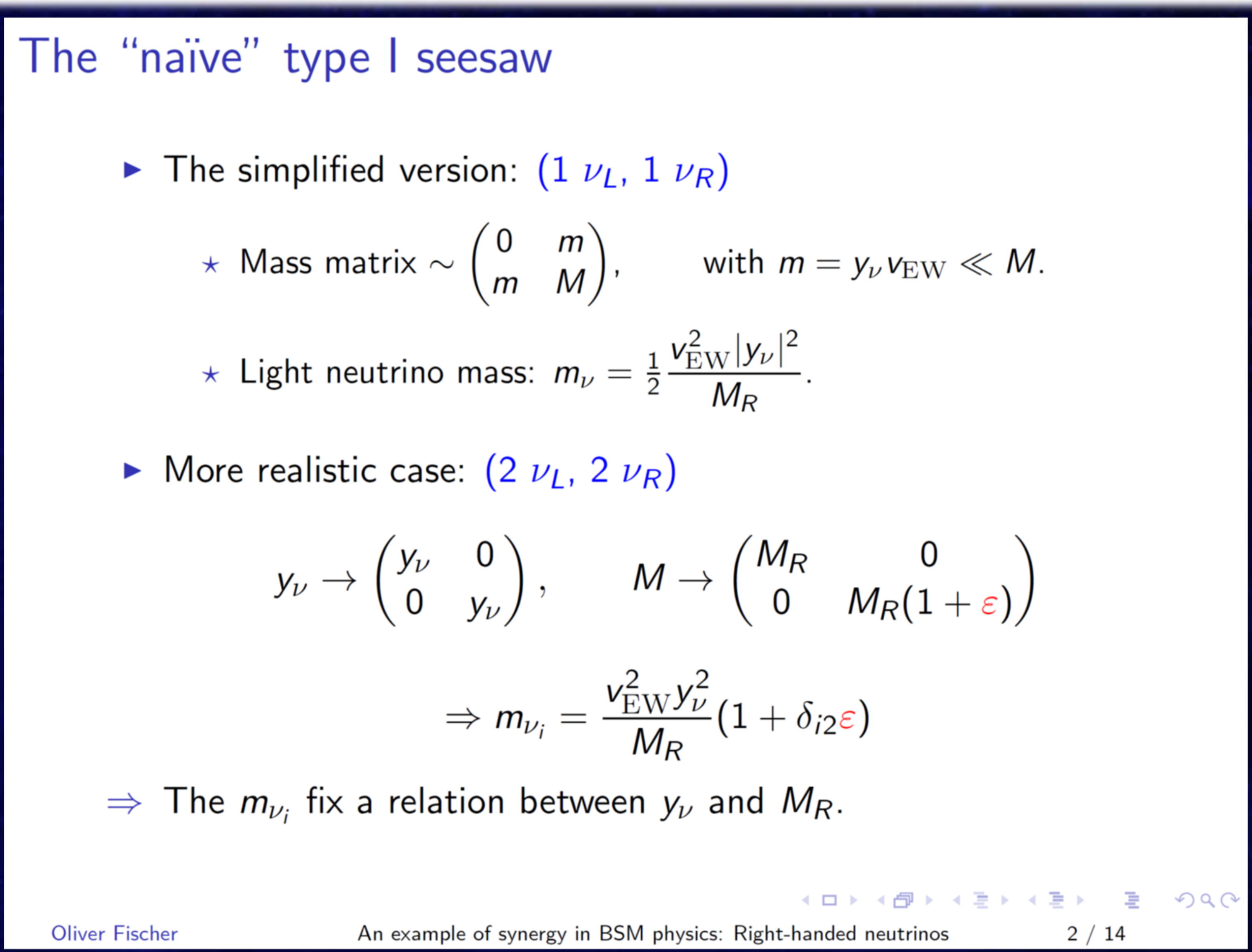

The “naïve” type I seesaw

- The simplified version: $(1\ \nu_L,\ 1\ \nu_R)$
  - ⋆ Mass matrix $\sim \begin{pmatrix} 0 & m \\ m & M \end{pmatrix}$, with $m = y_\nu v_{\mathrm{EW}} \ll M$.
  - ⋆ Light neutrino mass: $m_\nu = \frac{1}{2}\frac{v_{\mathrm{EW}}^2 |y_\nu|^2}{M_R}$.
- More realistic case: $(2\ \nu_L,\ 2\ \nu_R)$

$$y_\nu \to \begin{pmatrix} y_\nu & 0 \\ 0 & y_\nu \end{pmatrix}, \qquad M \to \begin{pmatrix} M_R & 0 \\ 0 & M_R(1+\varepsilon) \end{pmatrix}$$

$$\Rightarrow m_{\nu_i} = \frac{v_{\mathrm{EW}}^2 y_\nu^2}{M_R}(1 + \delta_{i2}\varepsilon)$$

$\Rightarrow$ The m_{ν_i} fix a relation between y_ν and M_R.

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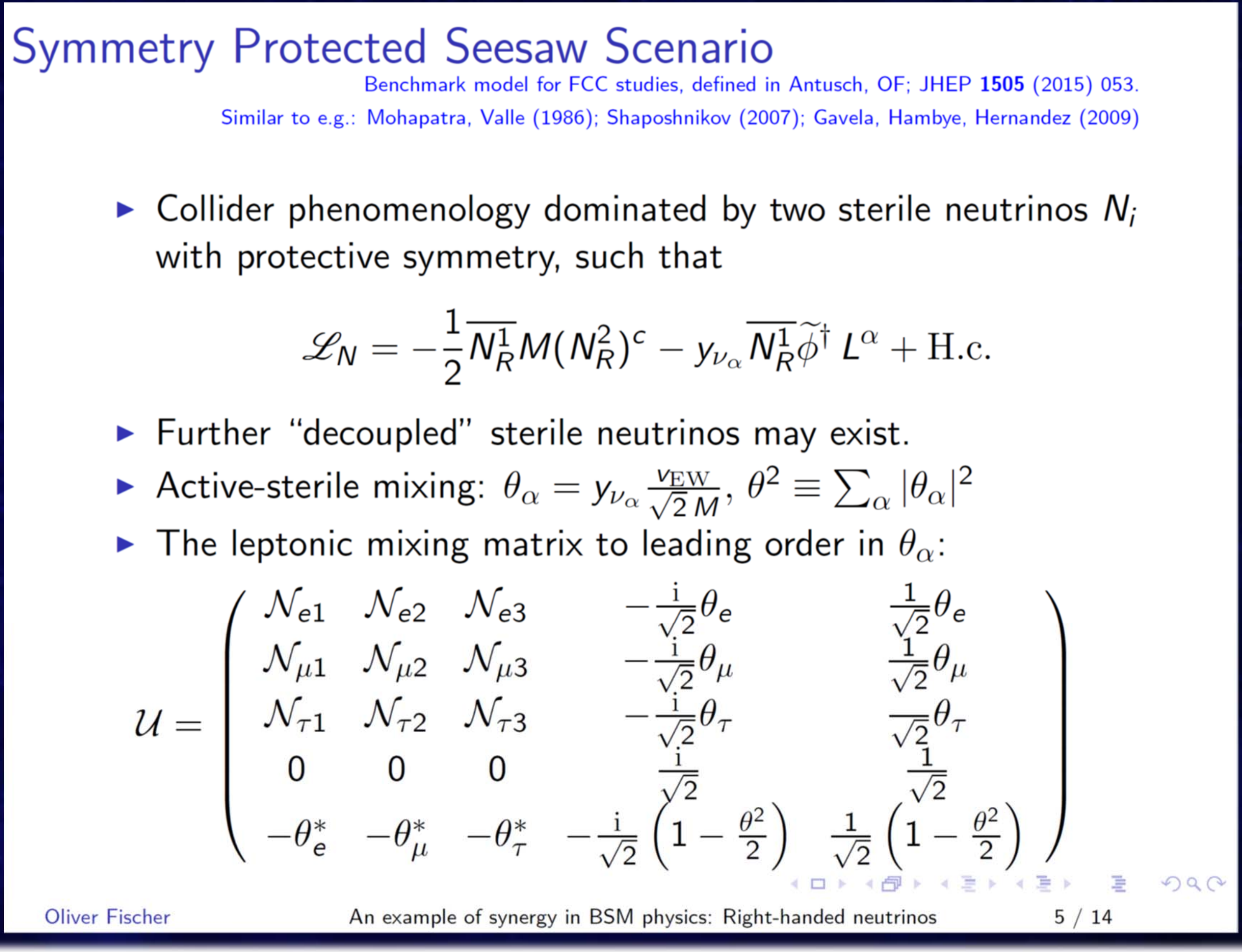

Symmetry Protected Seesaw Scenario

Benchmark model for FCC studies, defined in Antusch, OF; JHEP **1505** (2015) 053.

Similar to e.g.: Mohapatra, Valle (1986); Shaposhnikov (2007); Gavela, Hambye, Hernandez (2009)

- Collider phenomenology dominated by two sterile neutrinos N_i with protective symmetry, such that

$$\mathscr{L}_N = -\frac{1}{2}\overline{N_R^1} M (N_R^2)^c - y_{\nu_\alpha}\overline{N_R^1}\widetilde{\phi}^\dagger L^\alpha + \mathrm{H.c.}$$

- Further "decoupled" sterile neutrinos may exist.
- Active-sterile mixing: $\theta_\alpha = y_{\nu_\alpha}\frac{v_{\mathrm{EW}}}{\sqrt{2}\,M}$, $\theta^2 \equiv \sum_\alpha |\theta_\alpha|^2$
- The leptonic mixing matrix to leading order in θ_α:

$$\mathcal{U} = \begin{pmatrix} \mathcal{N}_{e1} & \mathcal{N}_{e2} & \mathcal{N}_{e3} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_e & \frac{1}{\sqrt{2}}\theta_e \\ \mathcal{N}_{\mu 1} & \mathcal{N}_{\mu 2} & \mathcal{N}_{\mu 3} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_\mu & \frac{1}{\sqrt{2}}\theta_\mu \\ \mathcal{N}_{\tau 1} & \mathcal{N}_{\tau 2} & \mathcal{N}_{\tau 3} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_\tau & \frac{1}{\sqrt{2}}\theta_\tau \\ 0 & 0 & 0 & \frac{\mathrm{i}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -\theta_e^* & -\theta_\mu^* & -\theta_\tau^* & -\frac{\mathrm{i}}{\sqrt{2}}\left(1-\frac{\theta^2}{2}\right) & \frac{1}{\sqrt{2}}\left(1-\frac{\theta^2}{2}\right) \end{pmatrix}$$

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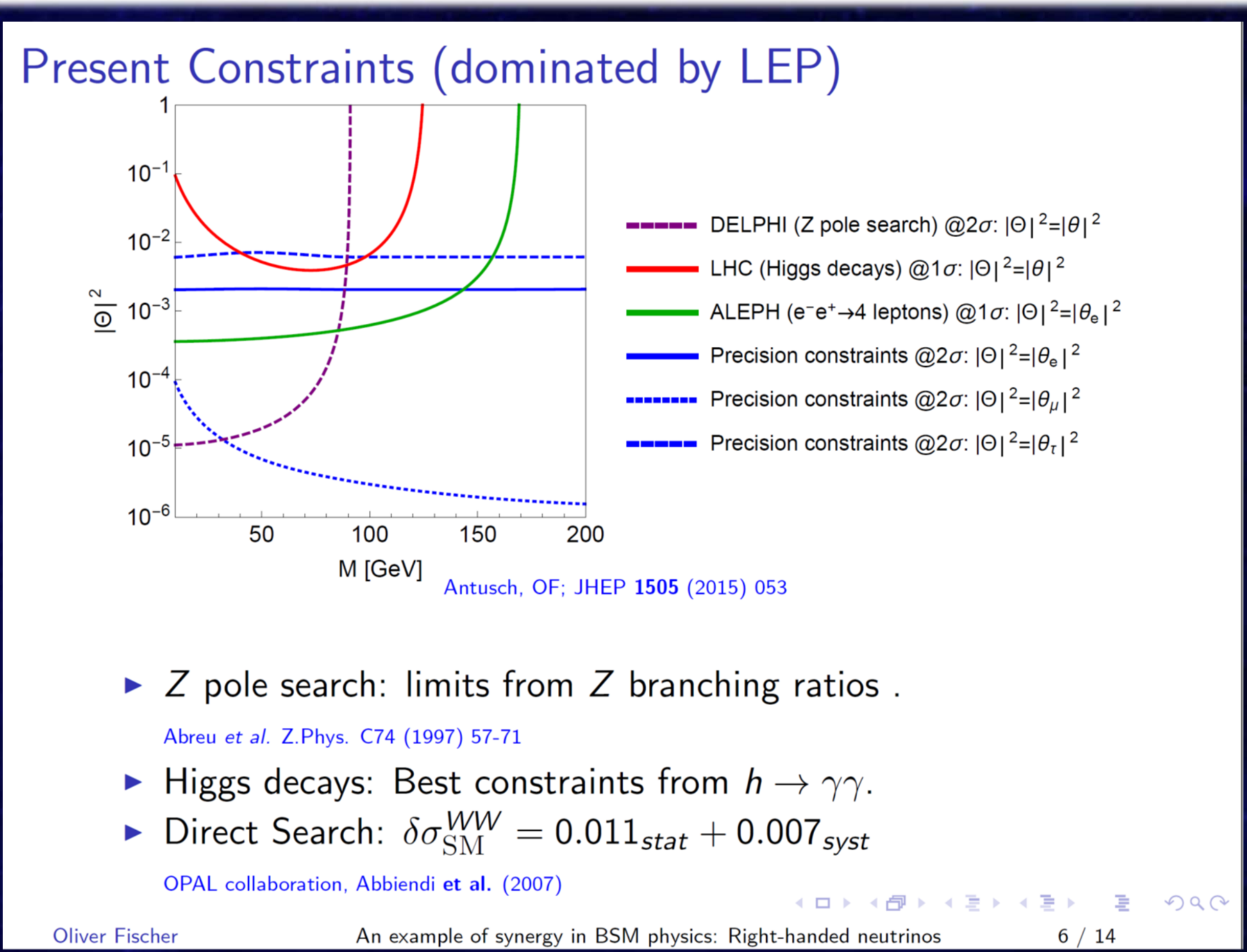

Present Constraints (dominated by LEP)

Antusch, OF; JHEP **1505** (2015) 053

- Z pole search: limits from Z branching ratios .

  Abreu *et al.* Z.Phys. C74 (1997) 57-71
- Higgs decays: Best constraints from $h \to \gamma\gamma$.
- Direct Search: $\delta\sigma_{\mathrm{SM}}^{WW} = 0.011_{stat} + 0.007_{syst}$

  OPAL collaboration, Abbiendi **et al.** (2007)

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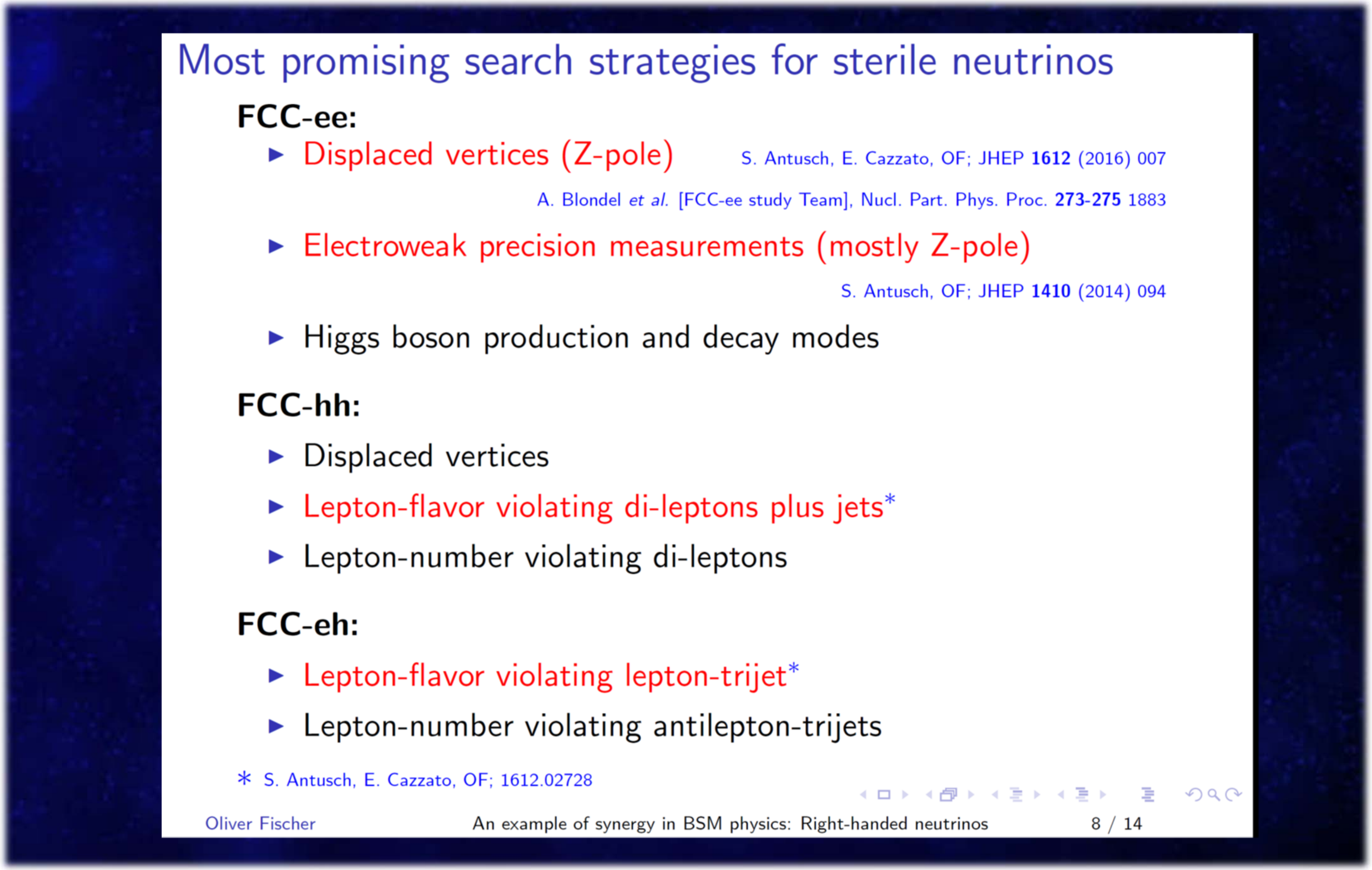


Most promising search strategies for sterile neutrinos

FCC-ee:

- Displaced vertices (Z-pole) S. Antusch, E. Cazzato, OF; JHEP **1612** (2016) 007
  A. Blondel *et al.* [FCC-ee study Team], Nucl. Part. Phys. Proc. **273-275** 1883
- Electroweak precision measurements (mostly Z-pole)
  S. Antusch, OF; JHEP **1410** (2014) 094
- Higgs boson production and decay modes

FCC-hh:

- Displaced vertices
- Lepton-flavor violating di-leptons plus jets*
- Lepton-number violating di-leptons

FCC-eh:

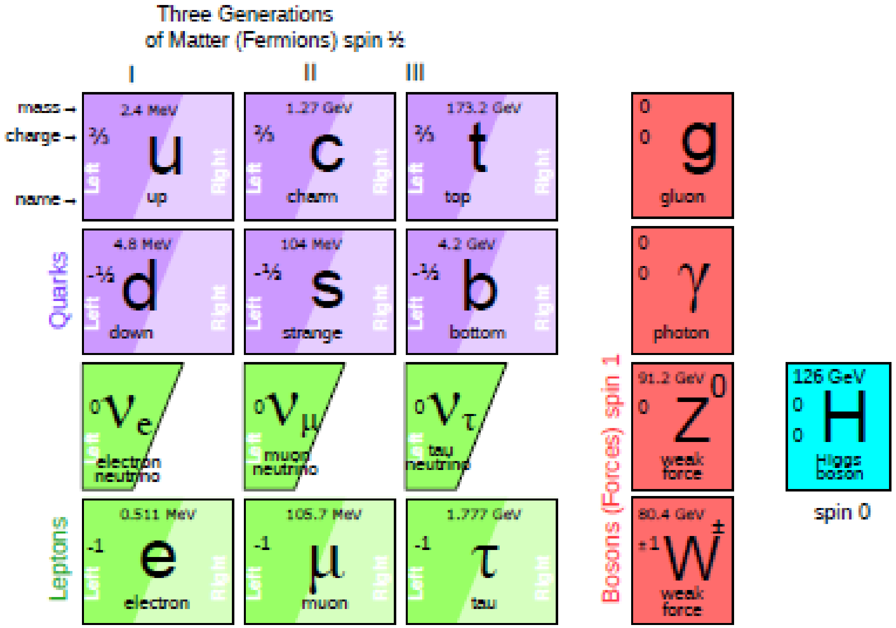
- Lepton-flavor violating lepton-trijet*
- Lepton-number violating antilepton-trijets

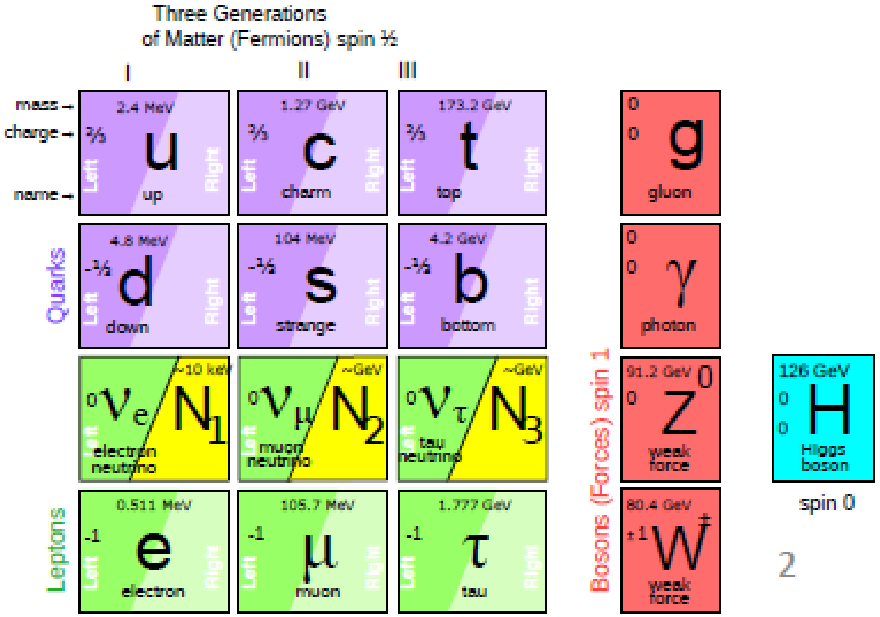
* S. Antusch, E. Cazzato, OF; 1612.02728

Oliver Fischer An example of synergy in BSM physics: Right-handed neutrinos 8 / 14

THE STANDARD MODEL IS COMPLETE .....

But at least 3 pieces are still missing





neutrinos have mass...

and this very probably implies new degrees of freedom

➔ Right-Handed, Almost «Sterile» (*very* small couplings) Neutrinos completely unknown masses (meV to ZeV), nearly impossile to find.

.... but could perhaps explain all: DM, BAU,ν-masses

Search for heavy neutral leptons

search $e^+ e^- \rightarrow \nu N$

$N \rightarrow \nu(\gamma/Z)^* \rightarrow$ monojet

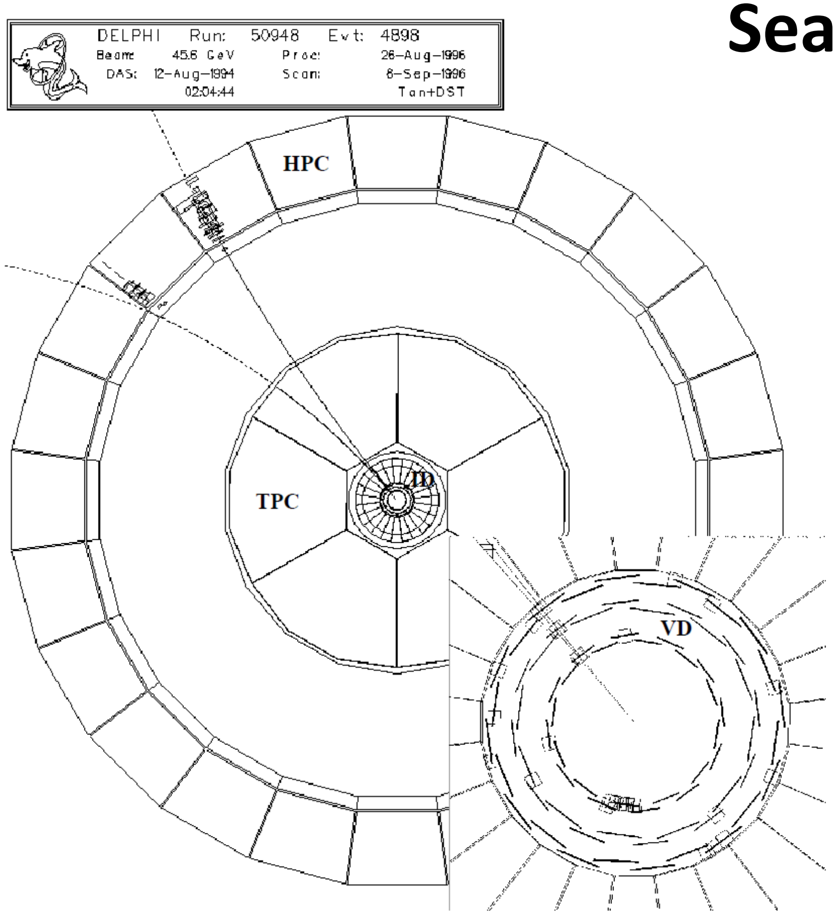
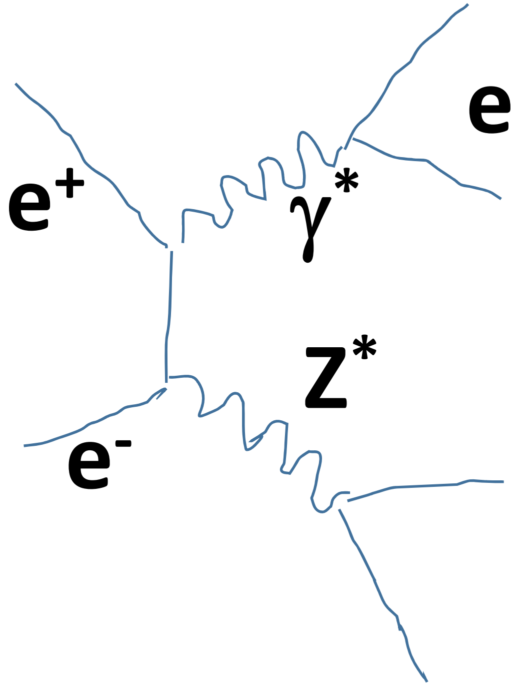


Fig. 3. Surviving event in the monojet search. It has an invariant mass of 300 MeV/c^2 and a missing p_t of 6 GeV/c and is probably an $e^+e^- \rightarrow e^+e^-\nu\bar{\nu}$ interaction

Find: one event in 4×10^6Z:



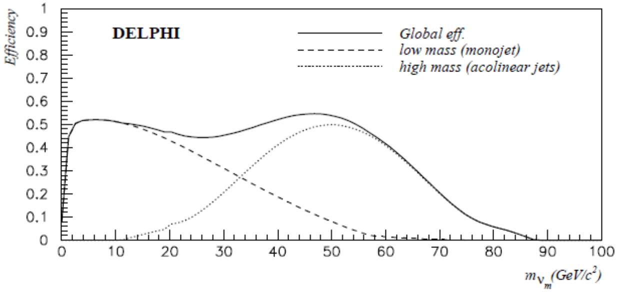
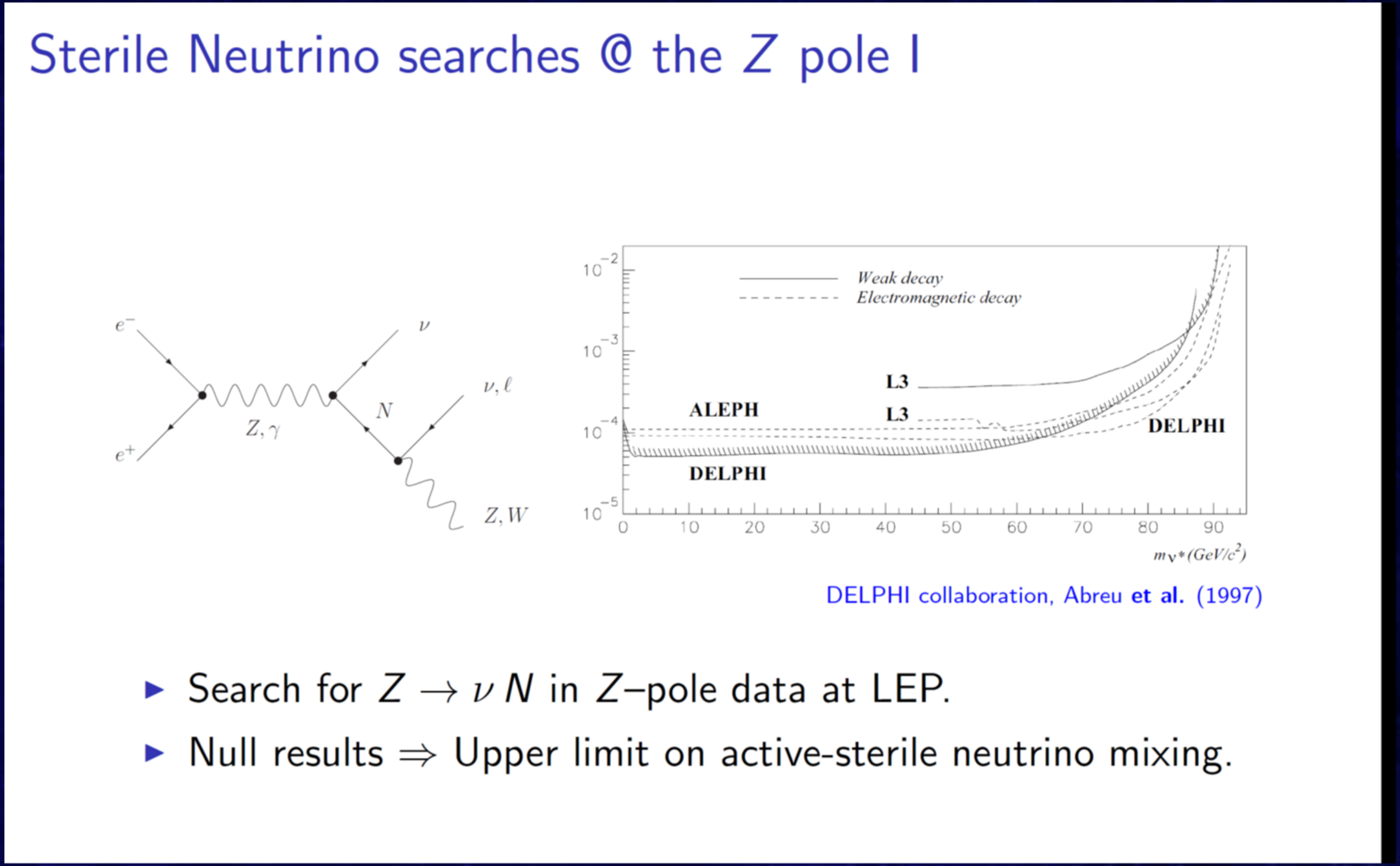


Fig. 4. Efficiency of the monojet search (Sect. 3) and the acollinear jets search (Sect. 4). The *full curve* shows the efficiency of the two searches combined

HNL



Sterile Neutrino searches @ the Z pole I

DELPHI collaboration, Abreu **et al.** (1997)

- Search for $Z \to \nu\, N$ in Z–pole data at LEP.
- Null results $\Rightarrow$ Upper limit on active-sterile neutrino mixing.

HNL

Search for Sterile Neutrinos at FCC-ee

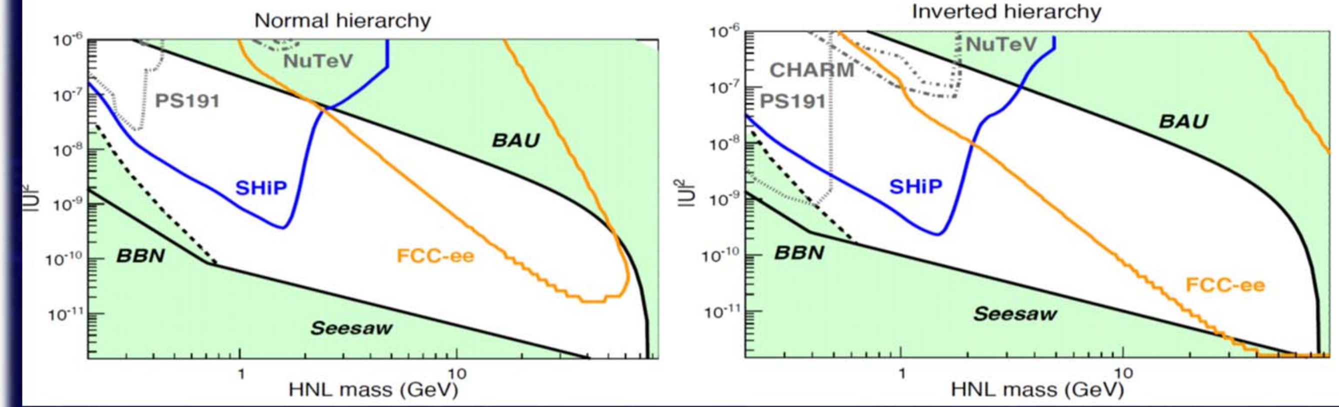
- **Number of neutrino families from LEP Nν=2.984±0.008**
  - potential to improve to ±0.001 using e+e—>Zγ (not enough statistics at LEP)
- **Search for sterile neutrinos in Z decays:**

$$\boxed{Z \rightarrow N\nu_i,\ \text{with } N \rightarrow W^{*}l \text{ or } Z^{*}\nu_j}$$

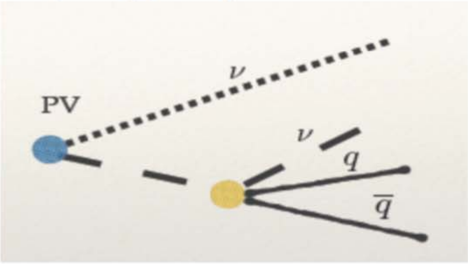
  - Number of events depends on mixing between N and ν, and m_N

$N_\nu \sim \sigma(e^+e^- \rightarrow \nu\bar{\nu}\gamma) \,/\, 2\sigma(e^+e^- \rightarrow \mu^+\mu^-\gamma)$

arXiv:1411.5230

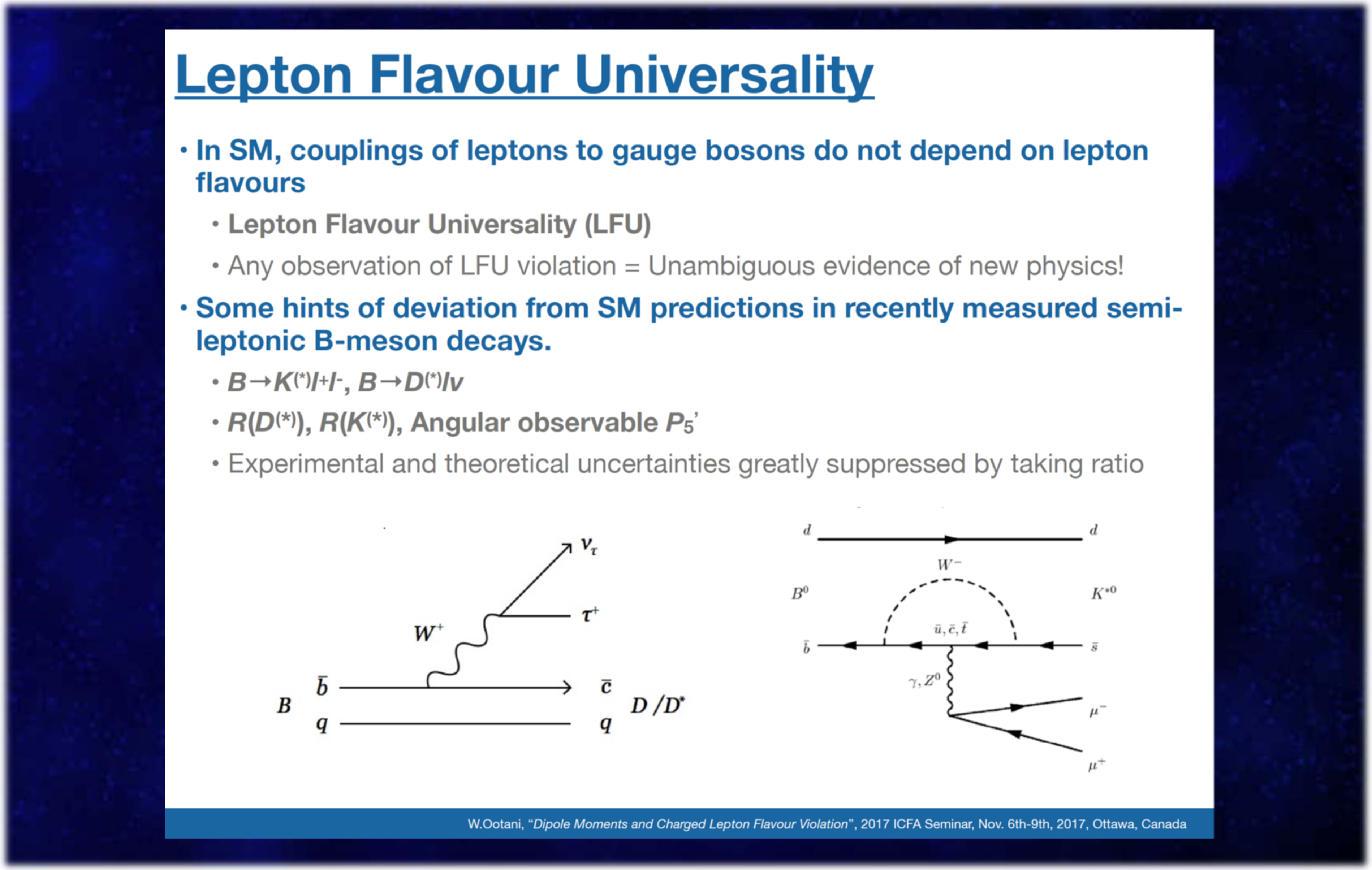


(Very) Displaced SV



two plots correspond to different luminosity and detector size

Lepton Flavour Universality Violation

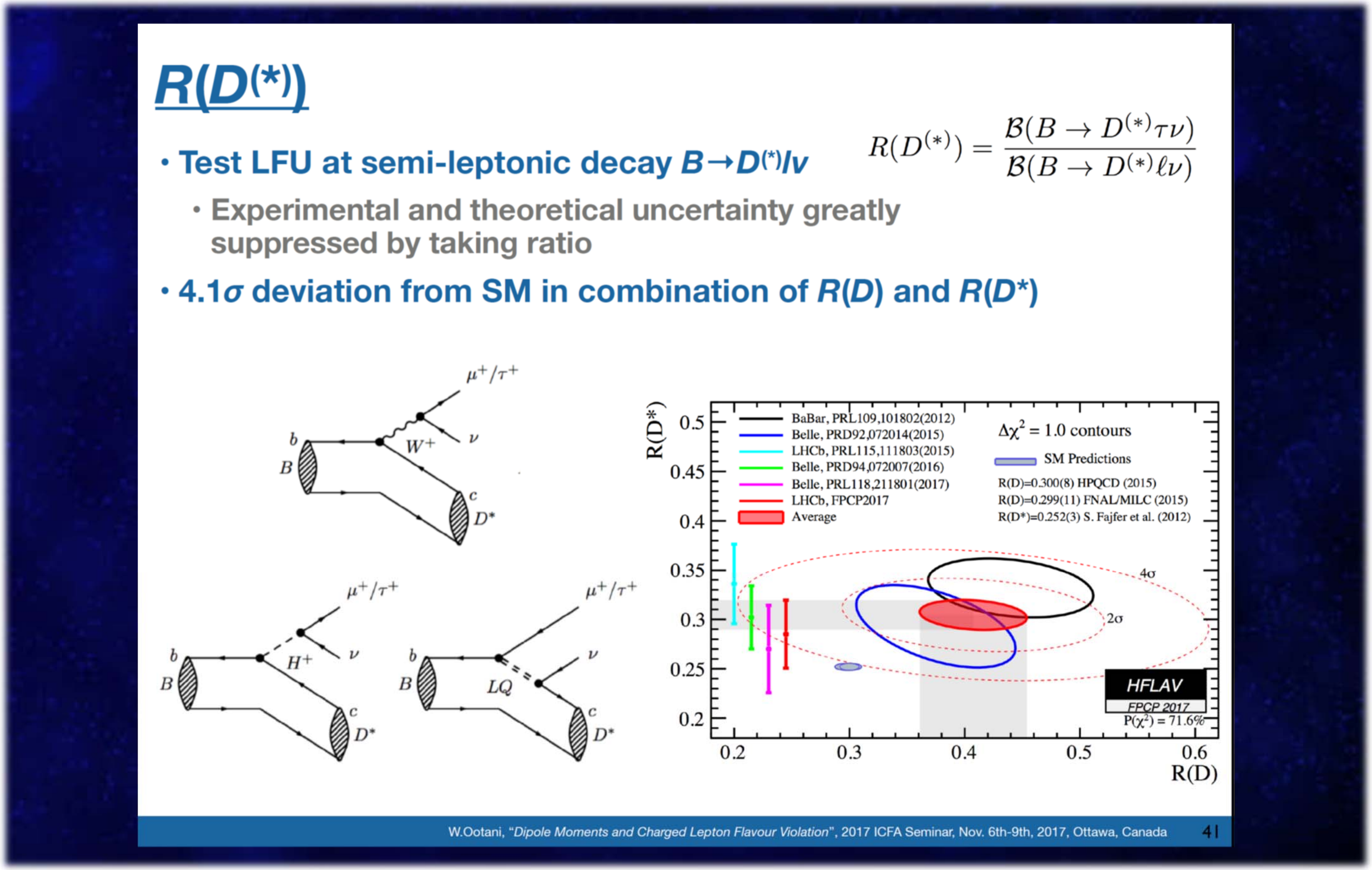


Lepton Flavour Universality

- **In SM, couplings of leptons to gauge bosons do not depend on lepton flavours**
  - **Lepton Flavour Universality (LFU)**
  - Any observation of LFU violation = Unambiguous evidence of new physics!
- **Some hints of deviation from SM predictions in recently measured semi-leptonic B-meson decays.**
  - $B \to K^{(*)} l^+ l^-$, $B \to D^{(*)} l \nu$
  - $R(D^{(*)})$, $R(K^{(*)})$, **Angular observable** P_5'
  - Experimental and theoretical uncertainties greatly suppressed by taking ratio

W.Ootani, "*Dipole Moments and Charged Lepton Flavour Violation*", 2017 ICFA Seminar, Nov. 6th-9th, 2017, Ottawa, Canada

Lepton Flavour Universality Violation



R(D(*))

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

- **Test LFU at semi-leptonic decay *B→D(*)lv***
  - Experimental and theoretical uncertainty greatly suppressed by taking ratio
- **4.1*σ* deviation from SM in combination of *R(D)* and *R(D*)***

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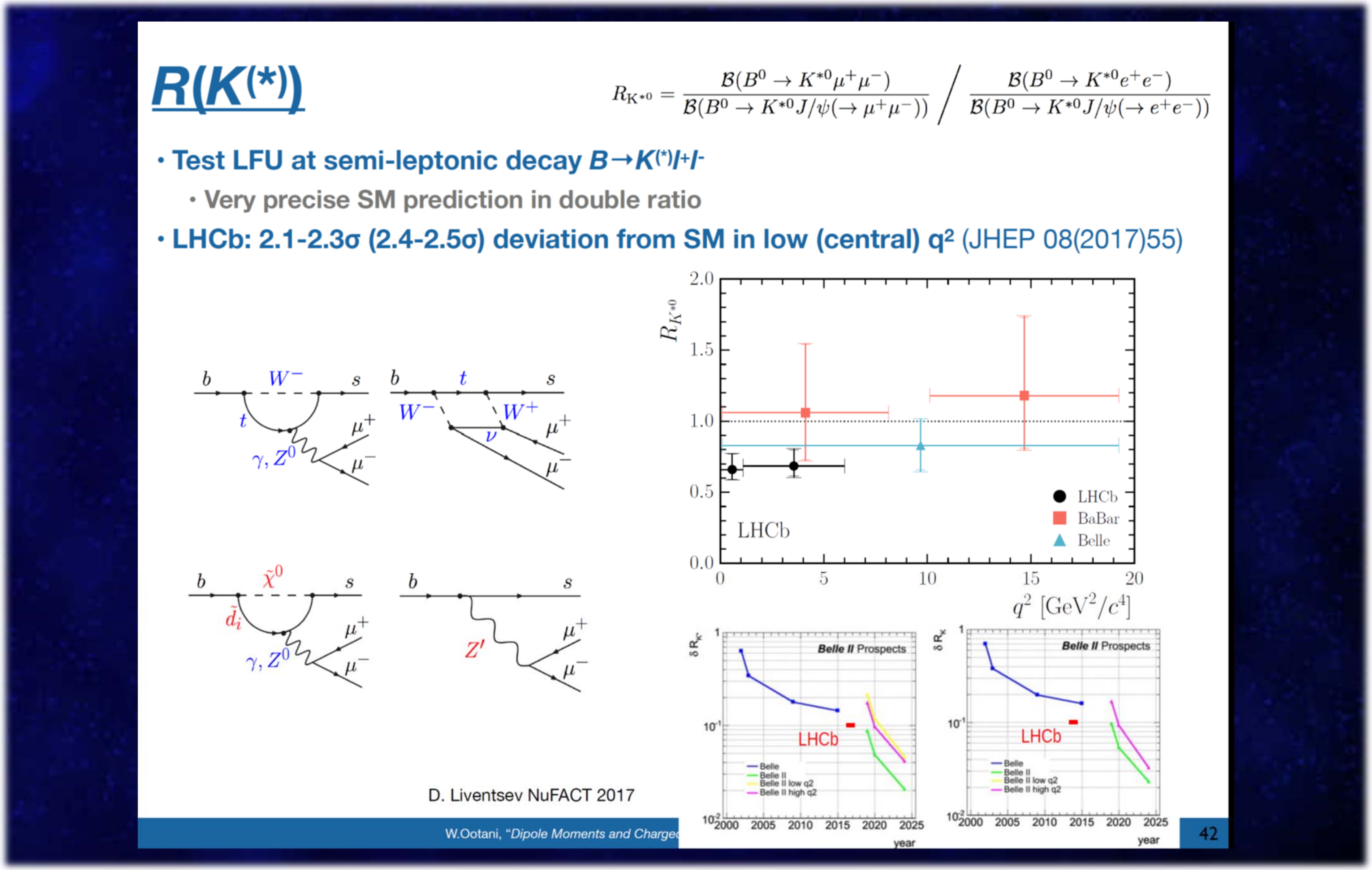
Lepton Flavour Universality Violation



R(K(*))

$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

- **Test LFU at semi-leptonic decay $B\to K^{(*)}l^+l^-$**
  - **Very precise SM prediction in double ratio**
- **LHCb: 2.1-2.3σ (2.4-2.5σ) deviation from SM in low (central) q²** (JHEP 08(2017)55)

D. Liventsev NuFACT 2017

W.Ootani, "Dipole Moments and Charged

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