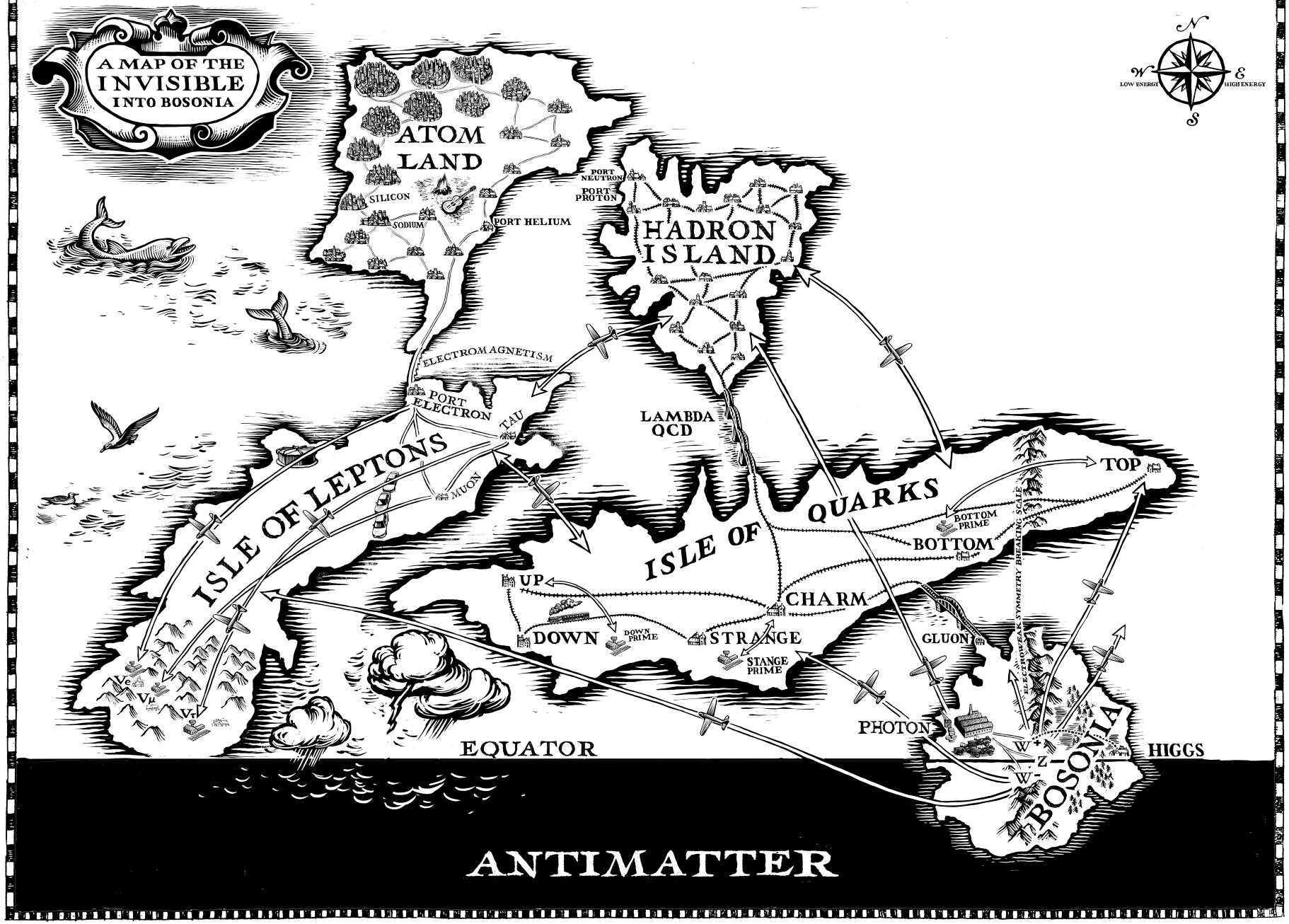
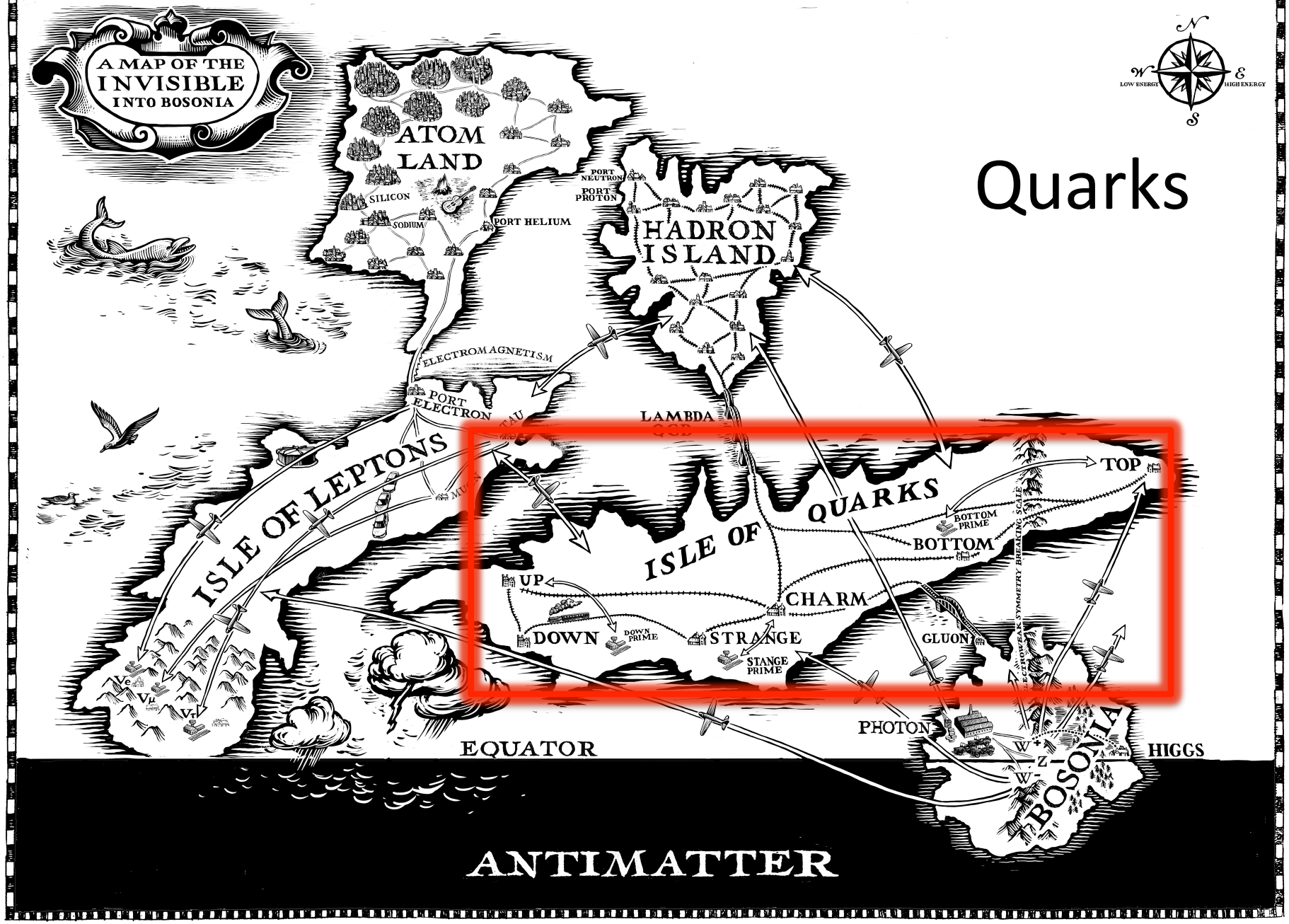
The Standard model
Day 3

Jon Butterworth


A MAP OF THE INVISIBLE INTO BOSONIA
N
W
E
S
LOW ENERGY
HIGH ENERGY
ATOM LAND
SILICON
SODIUM
PORT HELIUM
PORT NEUTRON
PORT PROTON
HADRON ISLAND
ELECTROMAGNETISM
PORT ELECTRON
TAU
MUON
ISLE OF LEPTONS
LAMBDA QCD
ISLE OF QUARKS
TOP
BOTTOM PRIME
BOTTOM
UP
CHARM
DOWN
DOWN PRIME
STRANGE
STANGE PRIME
GLUON
ELECTROWEAK SYMMETRY BREAKING SCALE
PHOTON
W+
Z
W-
BOSONIA
HIGGS
EQUATOR
ANTIMATTER


A MAP OF THE INVISIBLE INTO BOSONIA
ATOM LAND
SILICON
SODIUM
PORT HELIUM
PORT NEUTRON
PORT PROTON
HADRON ISLAND
ELECTROMAGNETISM
PORT ELECTRON
LAMBDA
ISLE OF LEPTONS
ISLE OF QUARKS
TOP
BOTTOM PRIME
BOTTOM
UP
CHARM
DOWN
DOWN PRIME
STRANGE
STANGE PRIME
GLUON
ELECTROWEAK SYMMETRY BREAKING SCALE
PHOTON
W+
Z
W-
BOSONIA
HIGGS
EQUATOR
ANTIMATTER
N
W
E
S
LOW ENERGY
HIGH ENERGY

Quarks

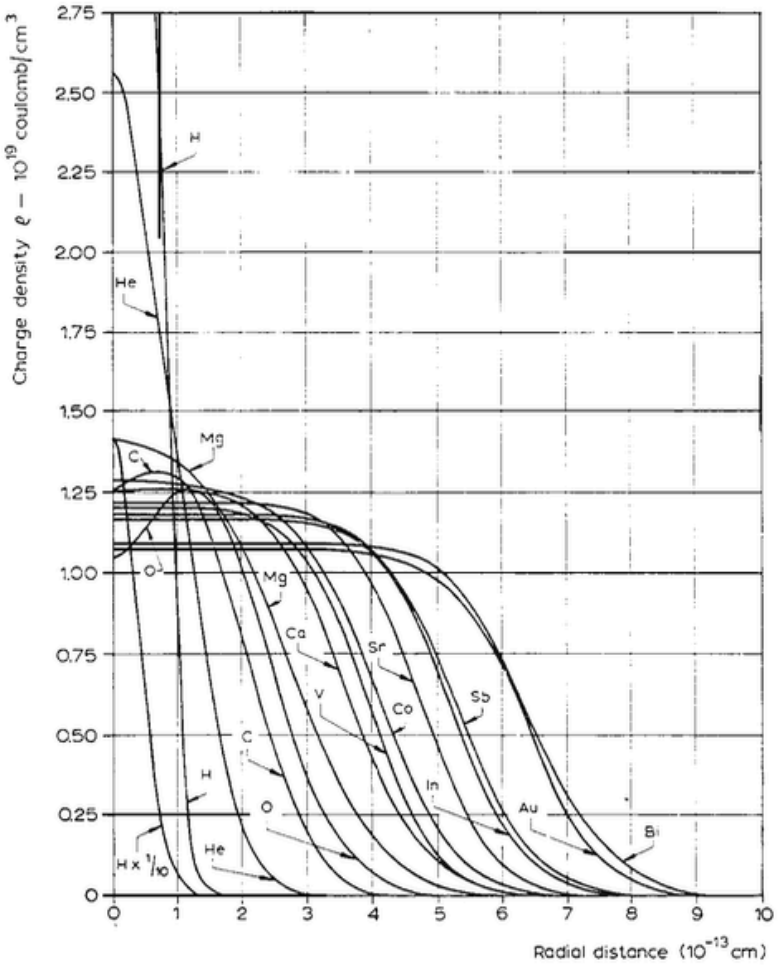
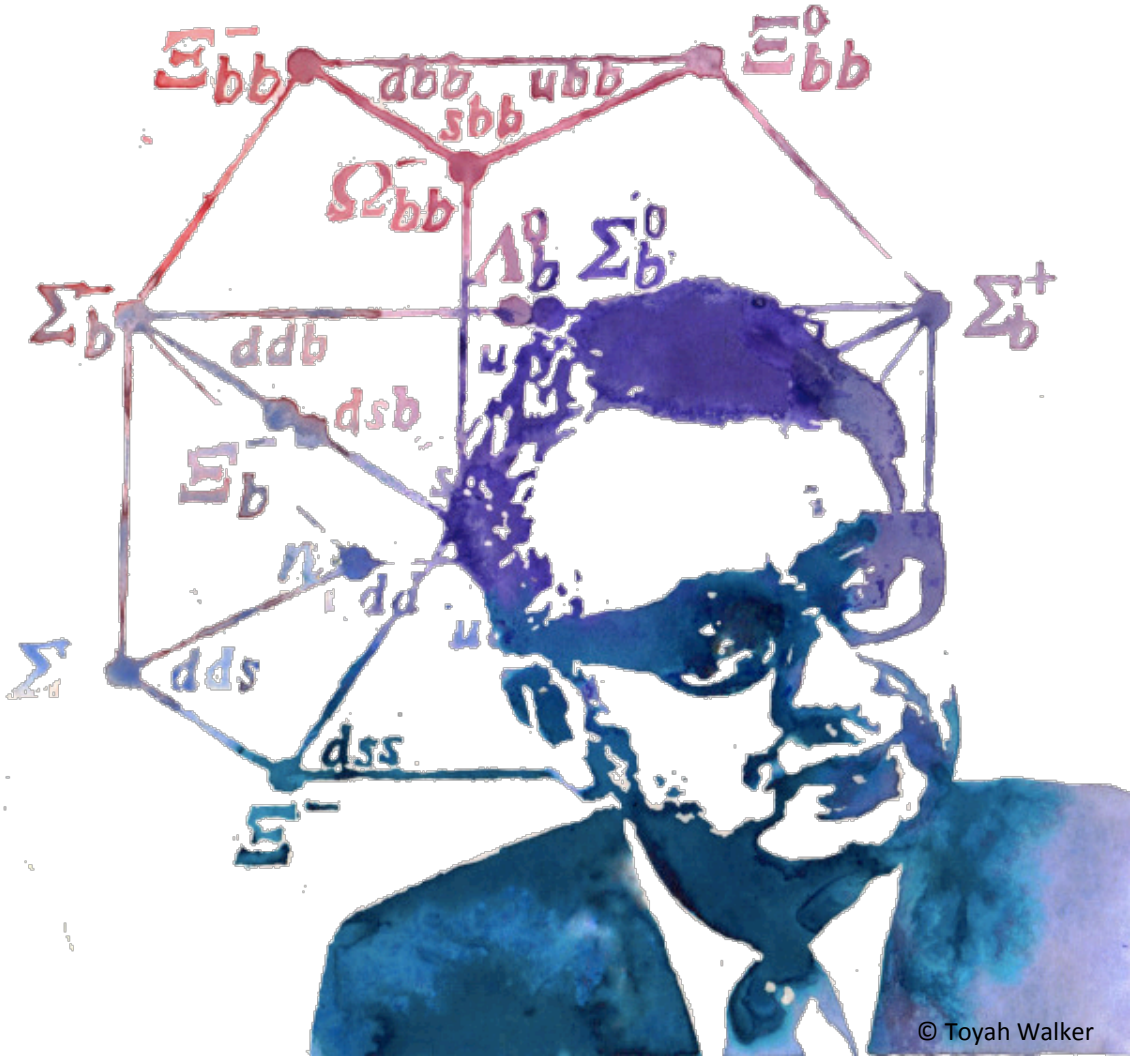
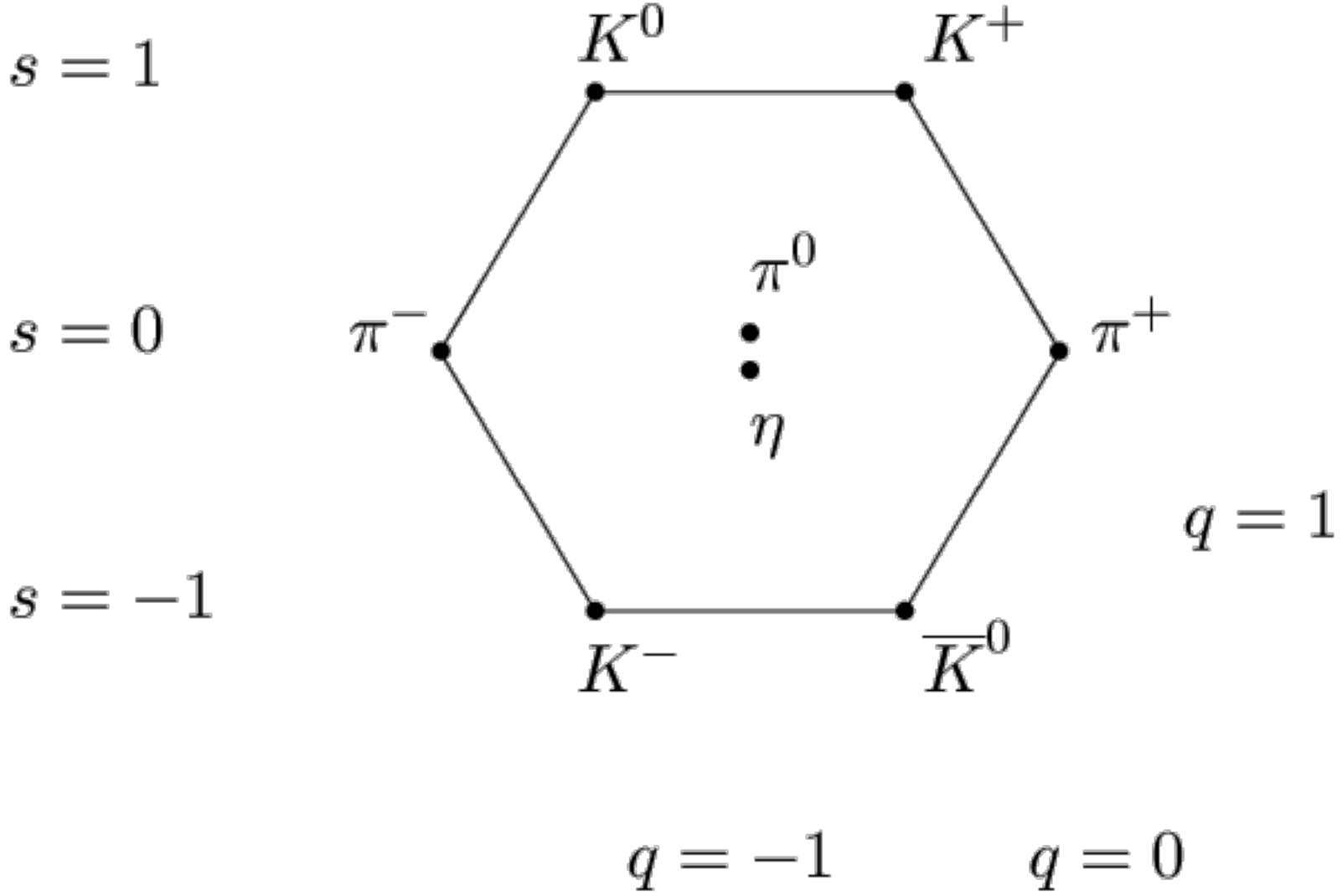


Fig. 8. This figure gives a summary of the approximate charge density distributions found for various nuclei studied by electron-scattering methods. The central densities are the least well determined positions of the curves. Note, however, the large disparity between the *average* central densities of the proton and all other nuclei. The alpha particle (^{4}He) is also a unique case and exhibits a much larger central density than all heavier nuclei.

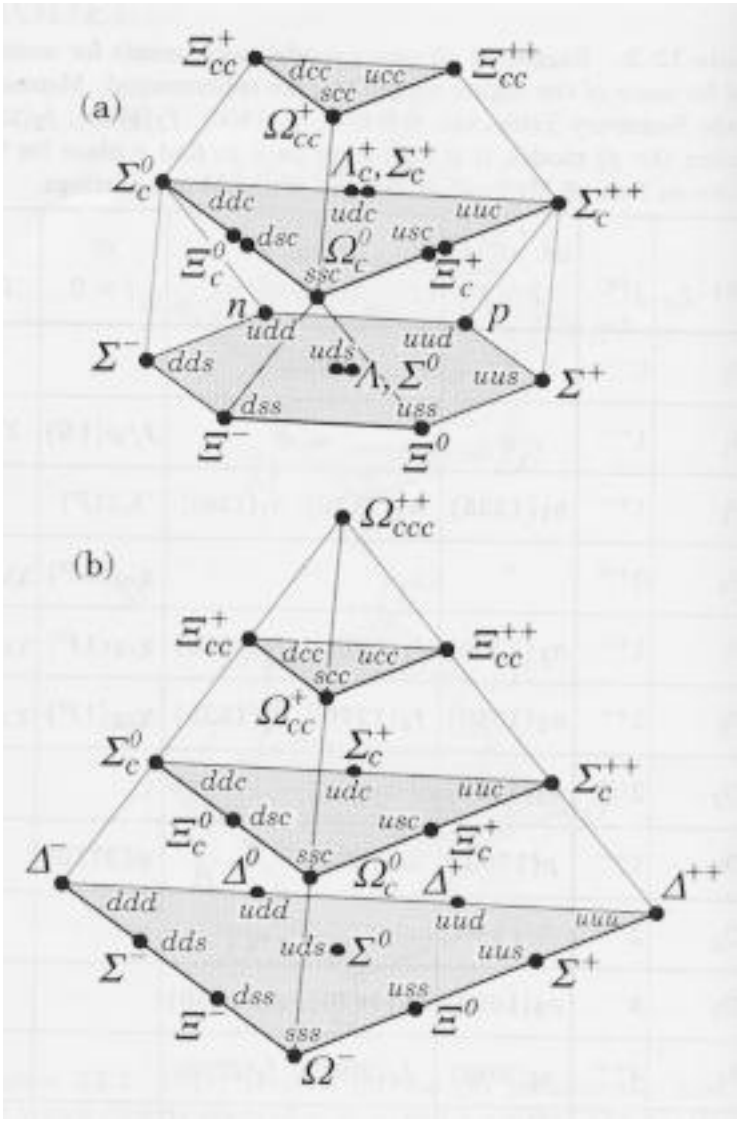
The “Eightfold Way”



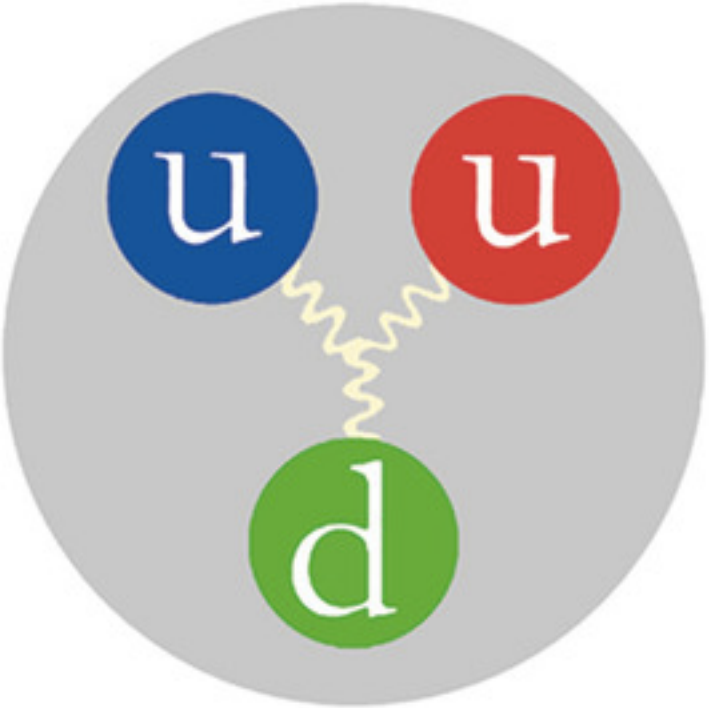
The “Eightfold Way”



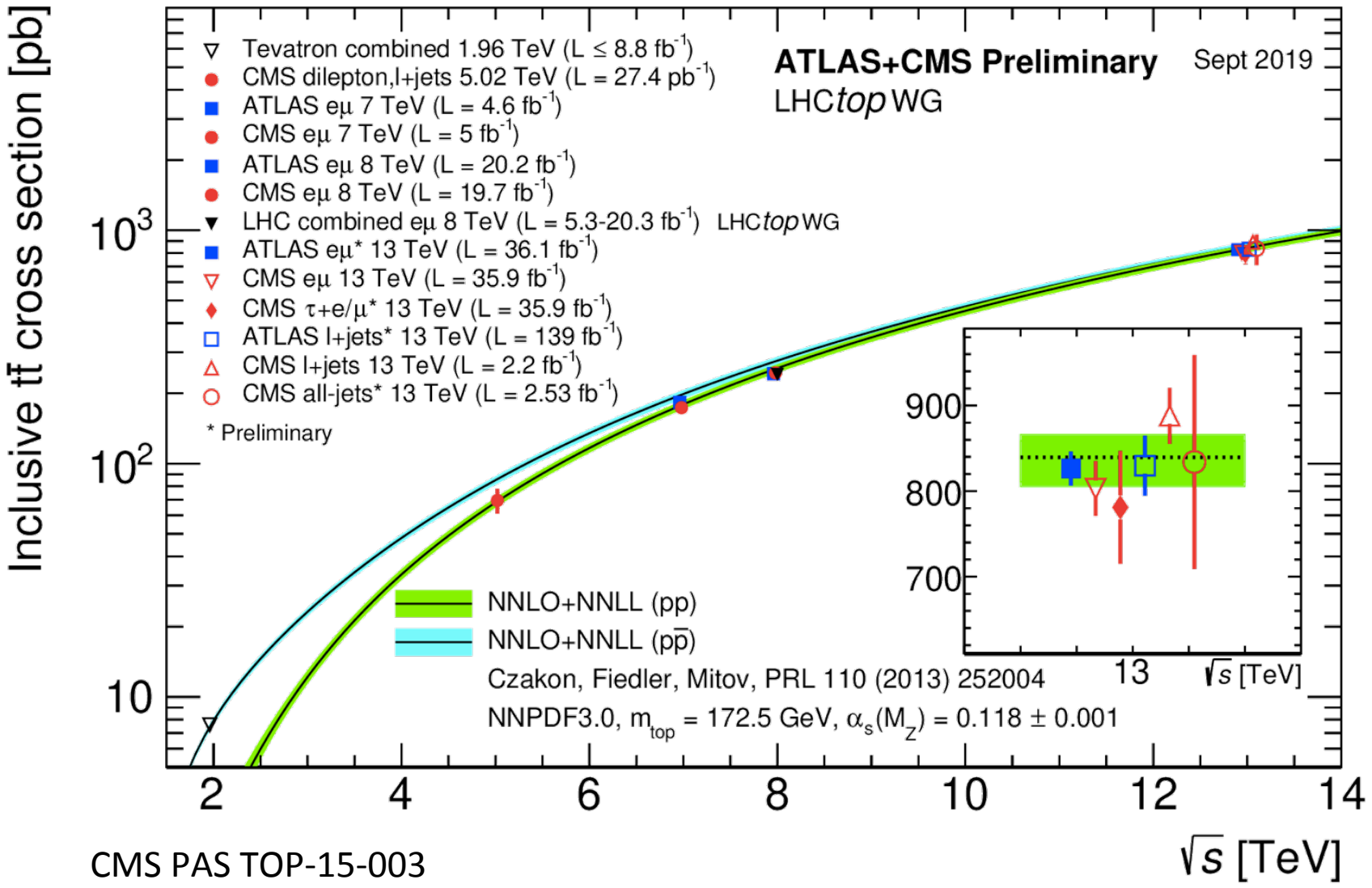
The n-fold Way?



Quark Colour and Flavour

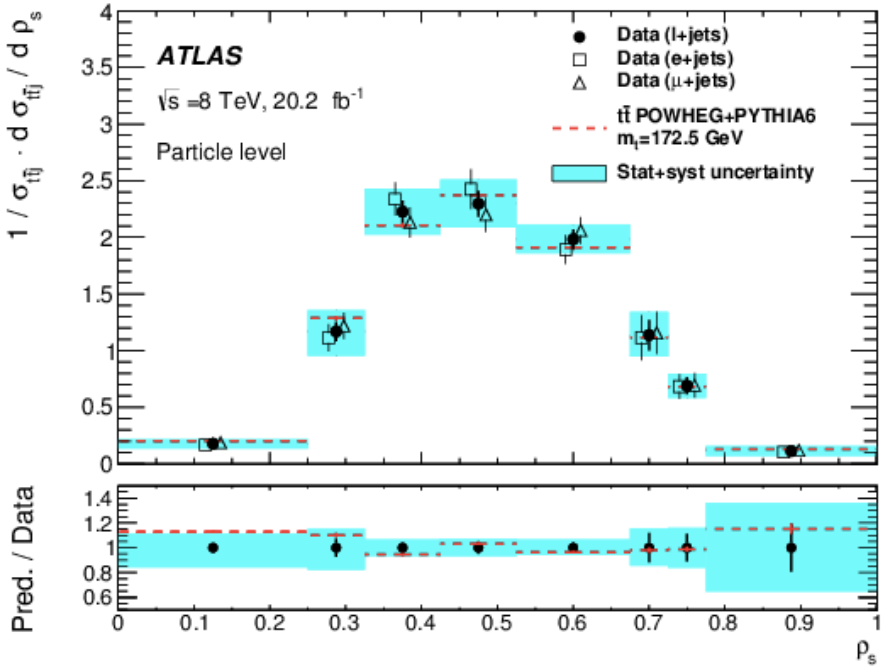


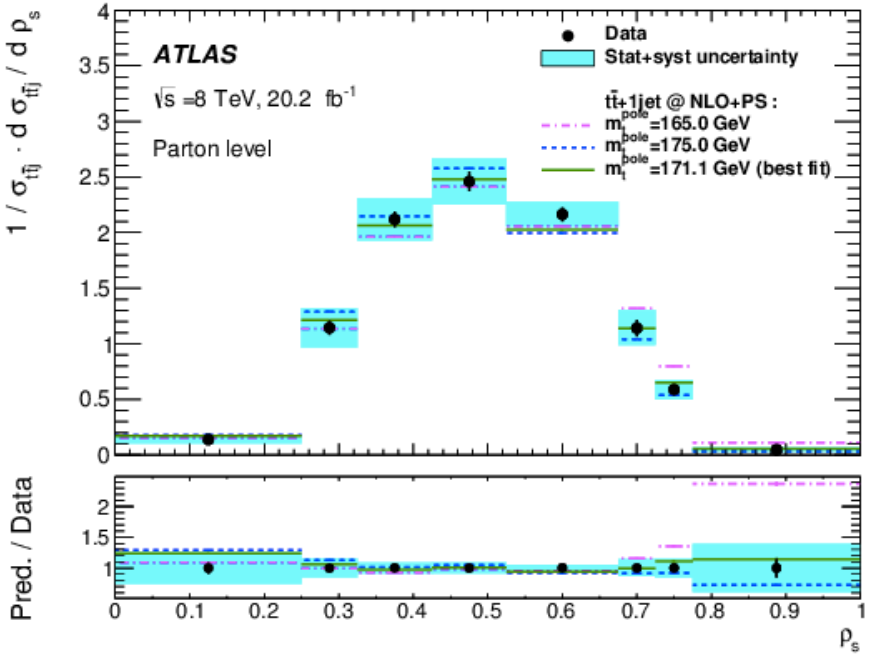
proton



CMS PAS TOP-15-003

The mass of the only free quark





$\rho_s = 2m_0/m_{t\bar{t}+1\text{-jet}}$

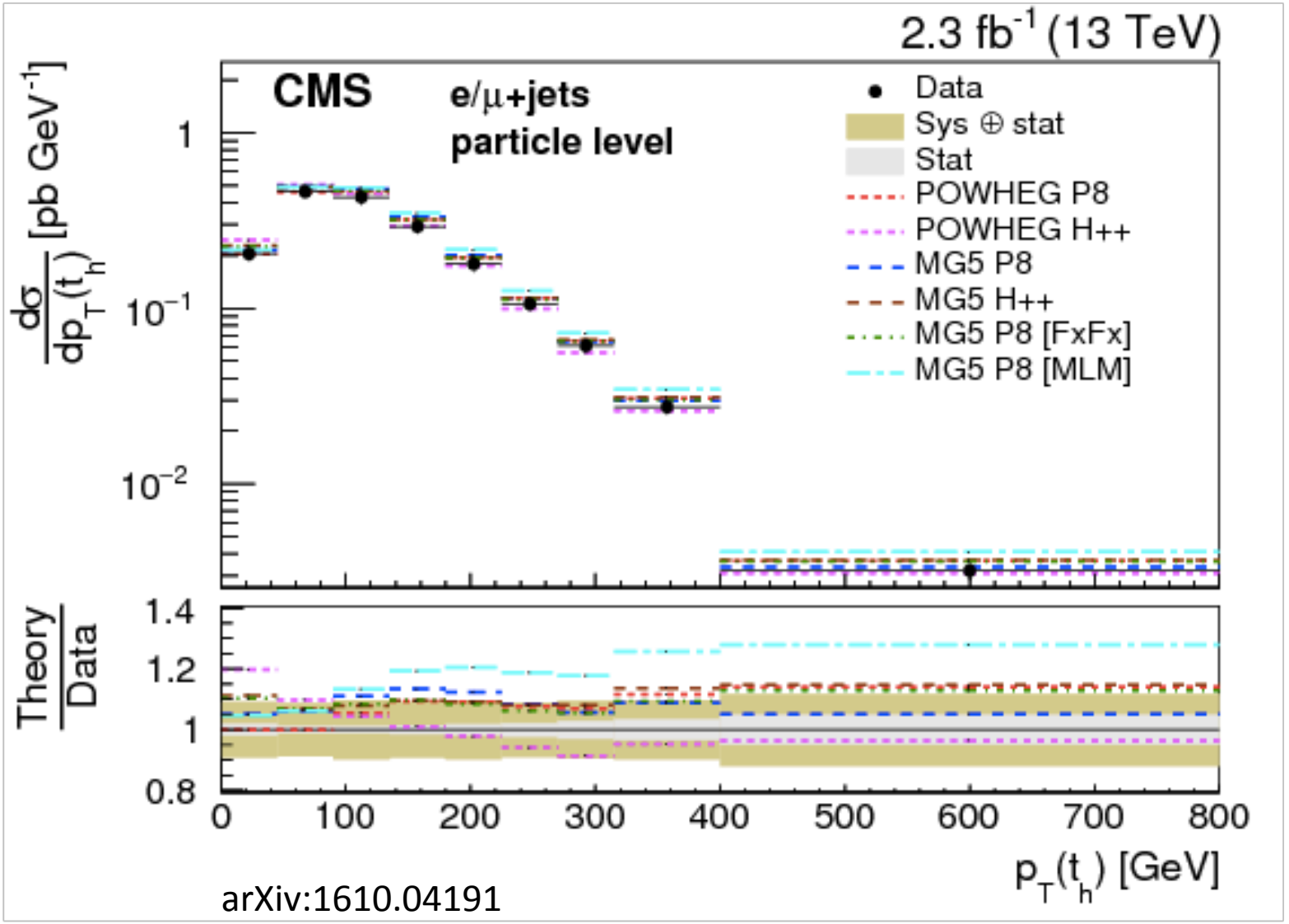
The value obtained for the pole-mass scheme is:

$$m_t^{\text{pole}} = 171.1 \pm 0.4\ (\text{stat}) \pm 0.9\ (\text{syst})\ ^{+0.7}_{-0.3}\ (\text{theo})\ \text{GeV}.$$

The extracted value in the running-mass scheme is:

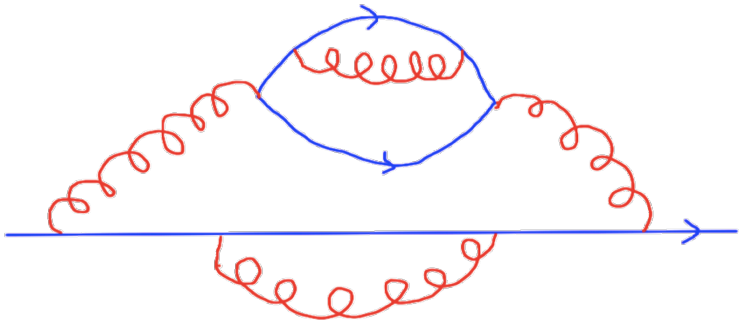
$$m_t(m_t) = 162.9 \pm 0.5\ (\text{stat}) \pm 1.0\ (\text{syst})\ ^{+2.1}_{-1.2}\ (\text{theo})\ \text{GeV}.$$

arXiv:1905.02302

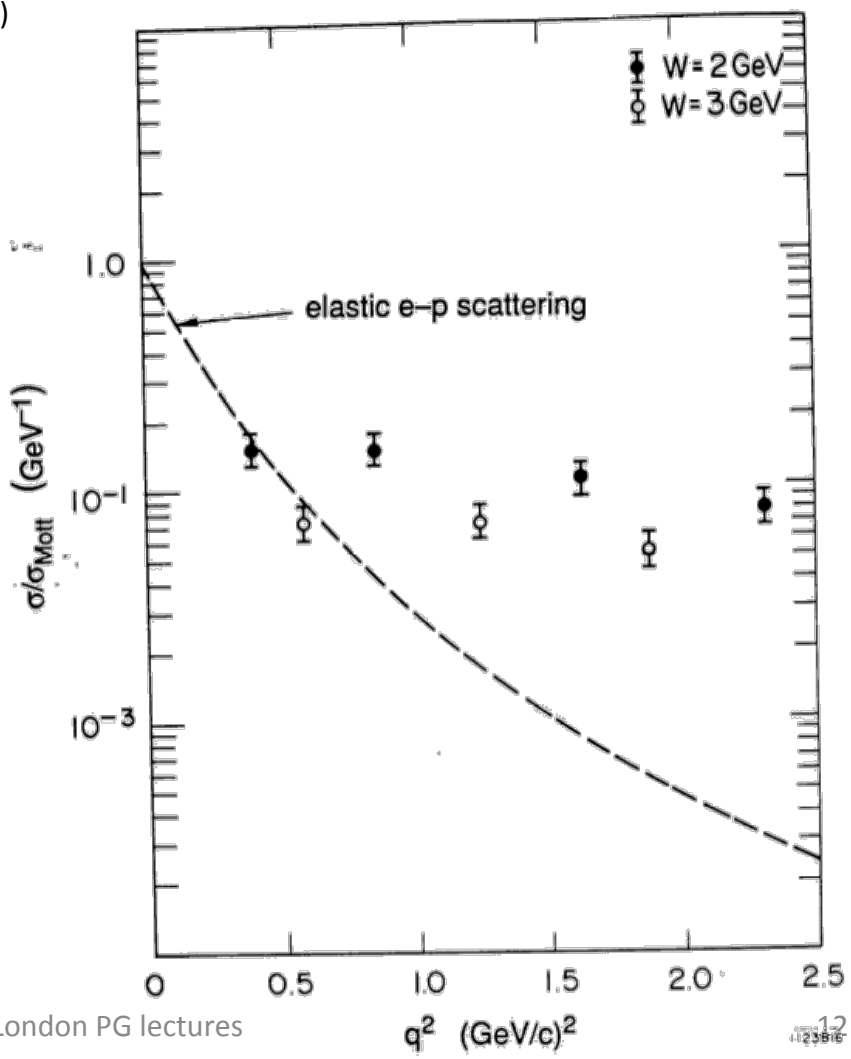

2.3 fb-1 (13 TeV)
CMS
e/μ+jets
particle level
Data
Sys ⊕ stat
Stat
POWHEG P8
POWHEG H++
MG5 P8
MG5 H++
MG5 P8 [FxFx]
MG5 P8 [MLM]
dσ/dpT(th) [pb GeV-1]
Theory/Data
pT(th) [GeV]
arXiv:1610.04191

Deep Inelastic Scattering

Freedom inside the proton: scaling, and violations

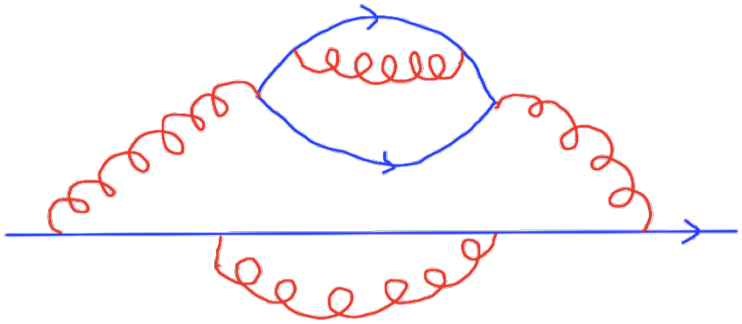


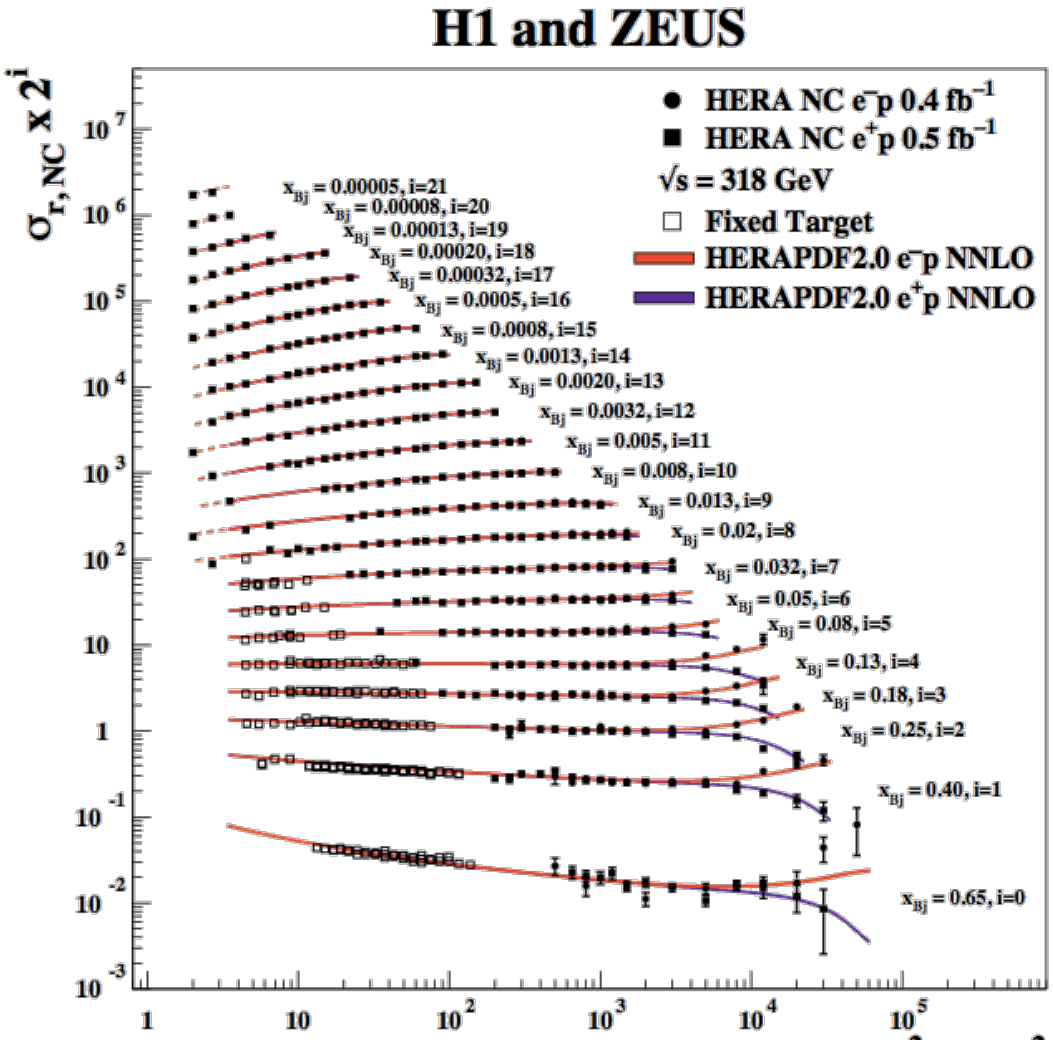
J. I. Friedman and H. W. Kendall, Ann. Rev. Nucl. Sci. 22, 203 (1972) (SLAC)



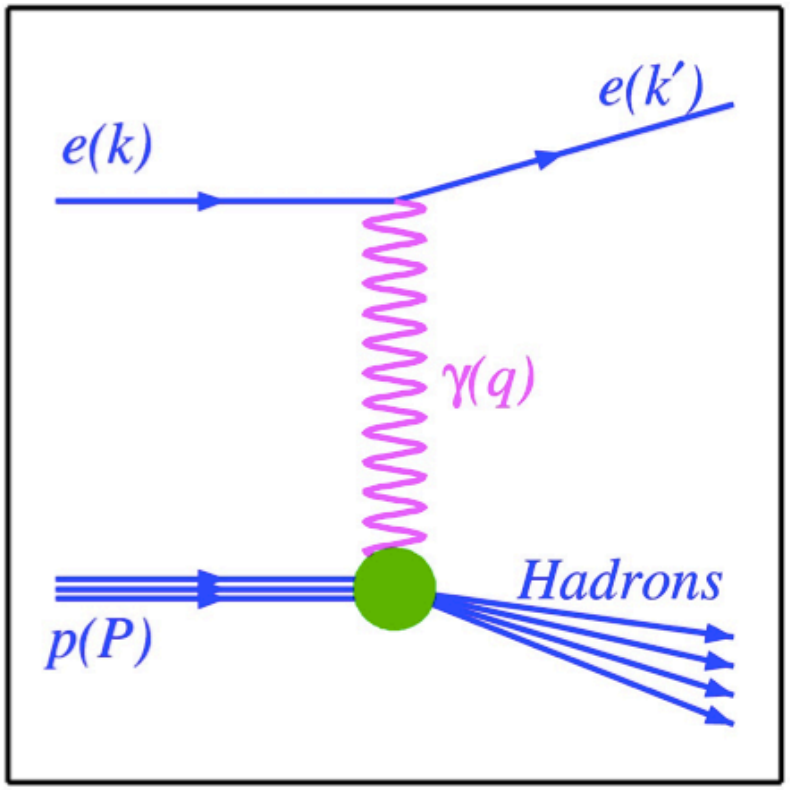
Deep Inelastic Scattering

Freedom inside the proton: scaling, and violations

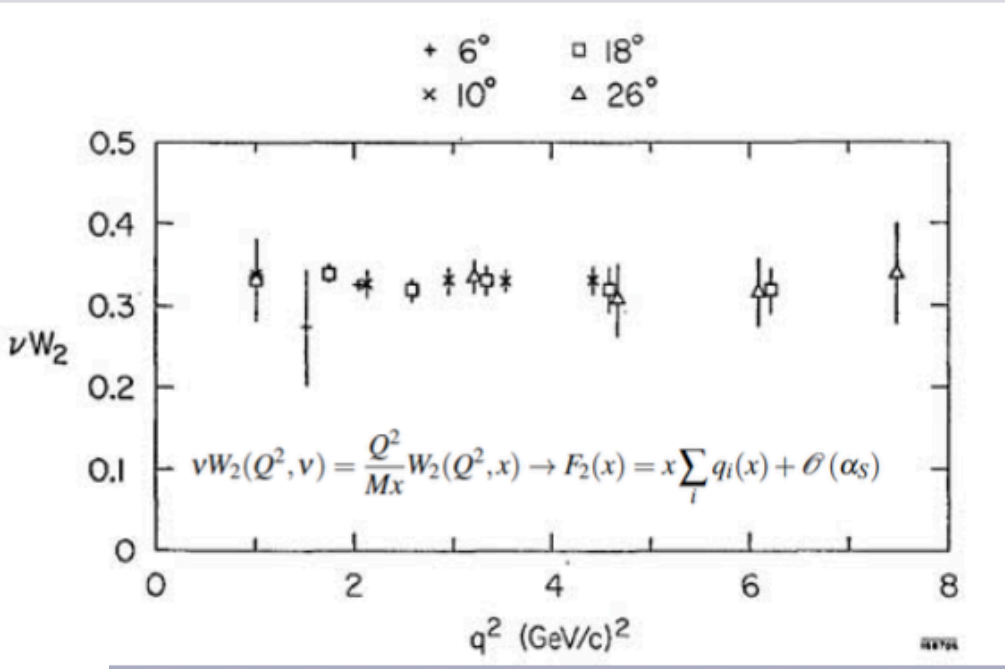




Deep Inelastic Scattering



$$x_{\mathrm{Bj}} = \frac{Q^2}{2\,p\cdot q}, \quad Q^2 = -q^2 \quad y = \frac{q\cdot p}{k\cdot p}$$

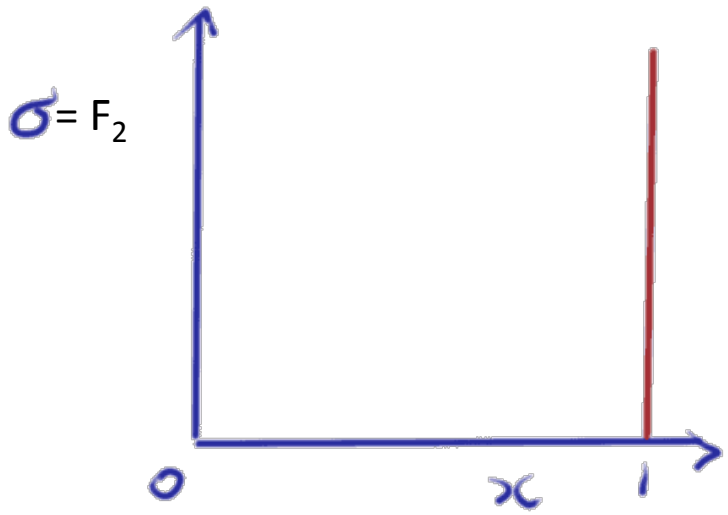


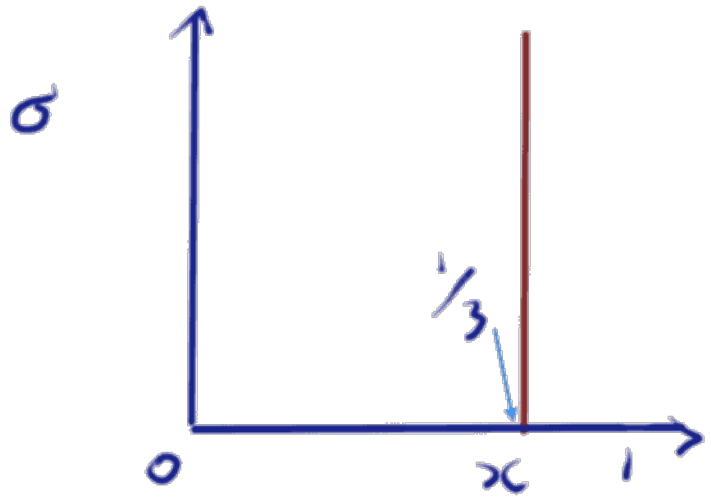
$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2 Y_+}{xQ^4} F_2(x,Q^2)(1-\delta_{_L}-\delta_3)(1+\delta_r)$$

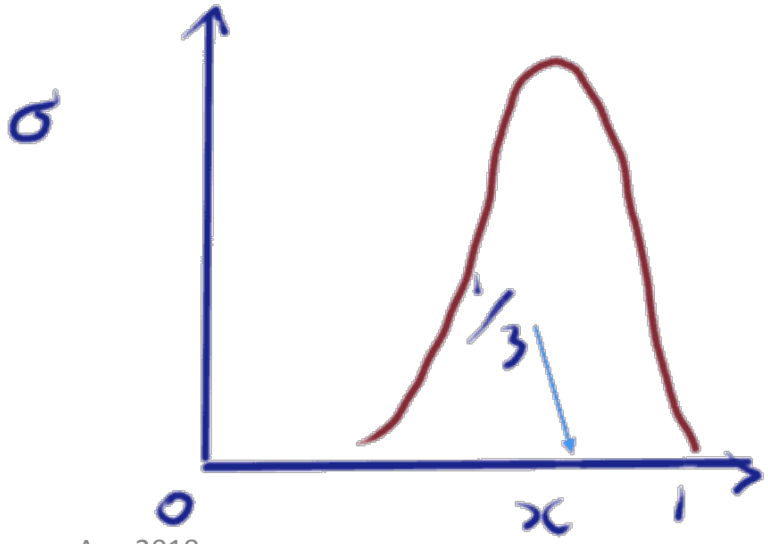
$$Y_\pm = 1 \pm (1-y)^2$$

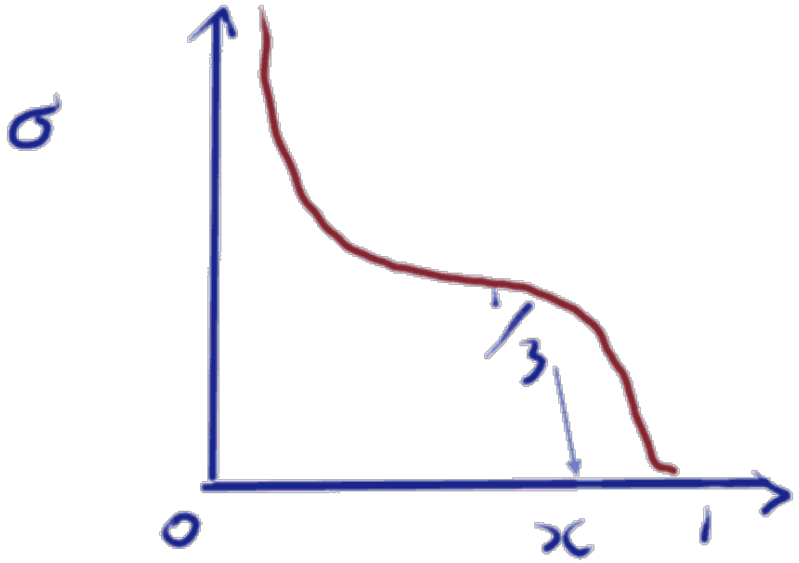
Part of Slide from Juan Rojo

From Proton to PDF

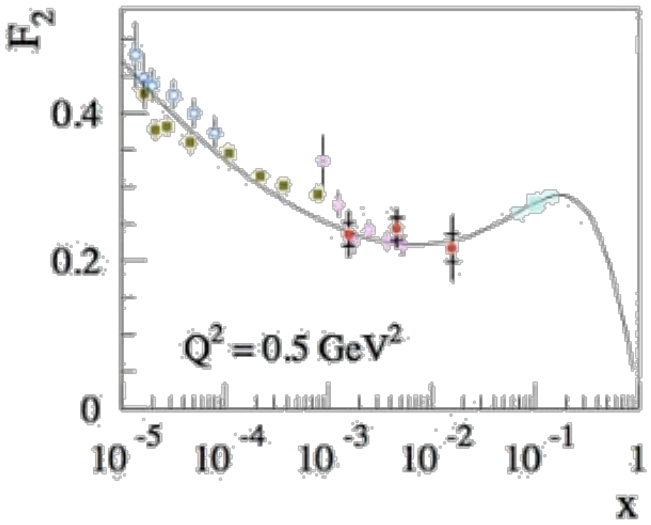


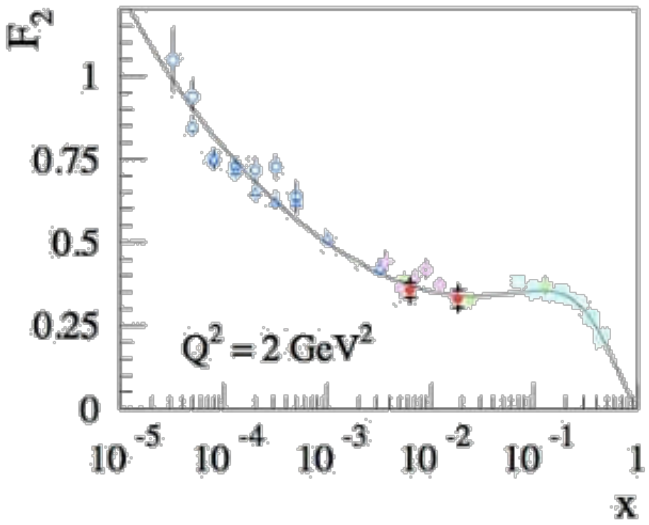


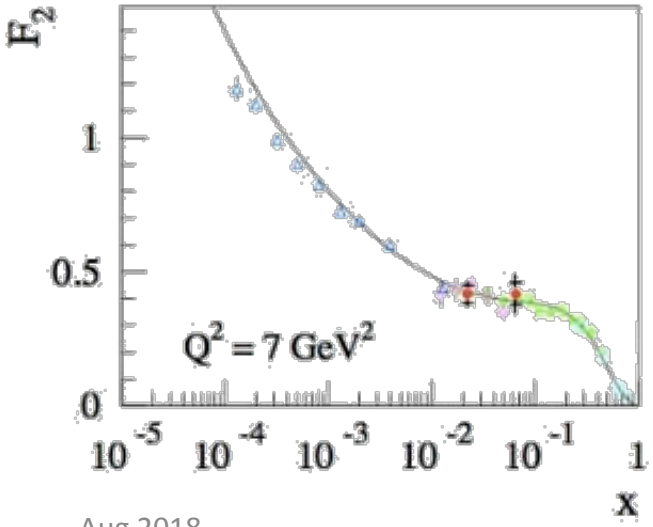


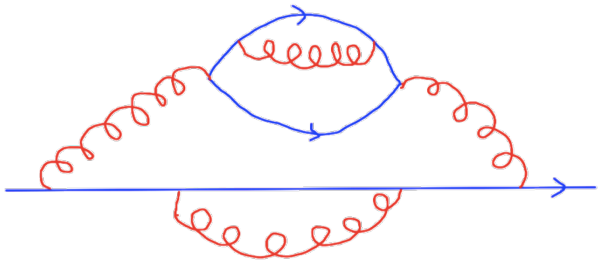


From Proton to PDF

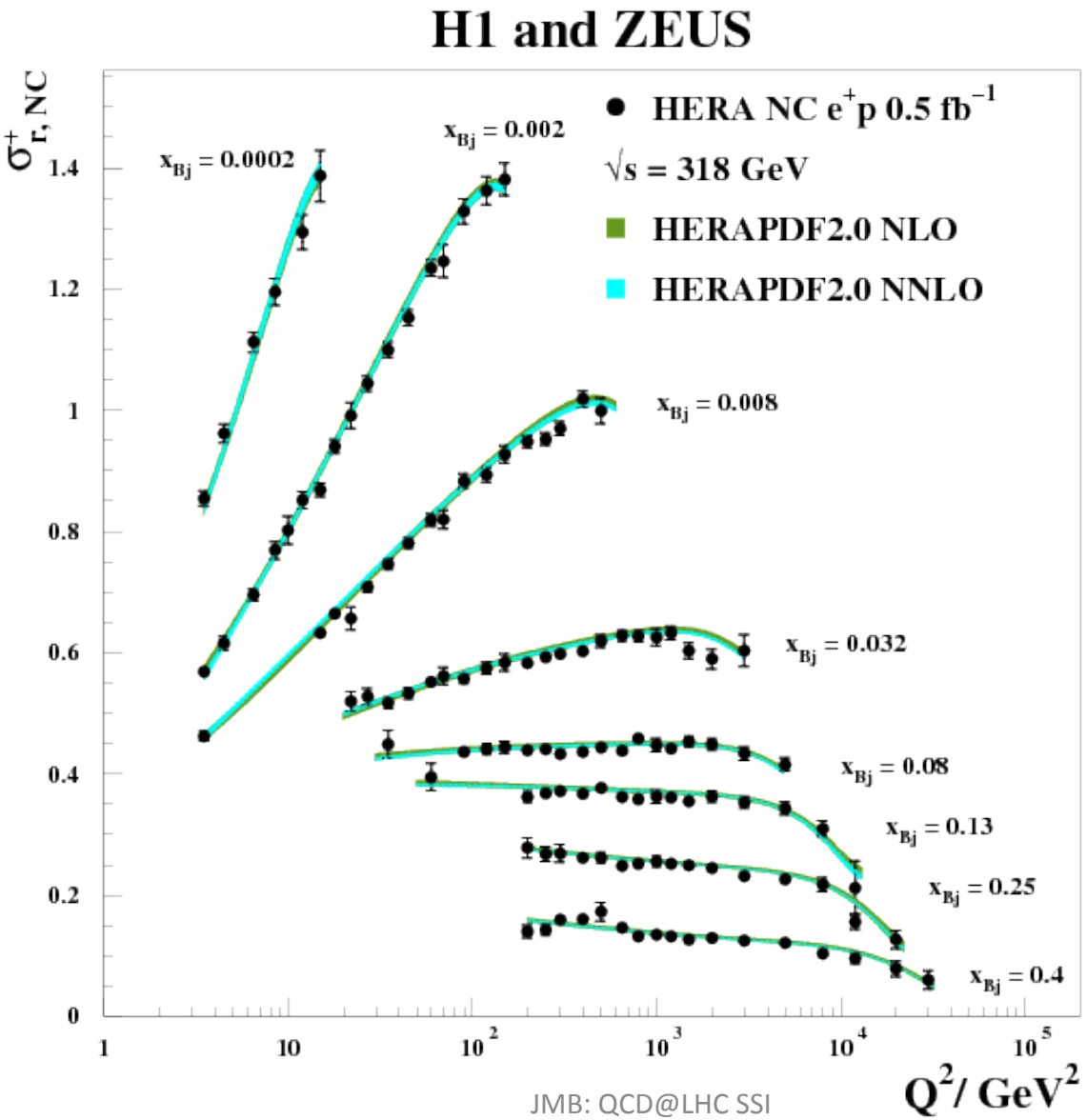




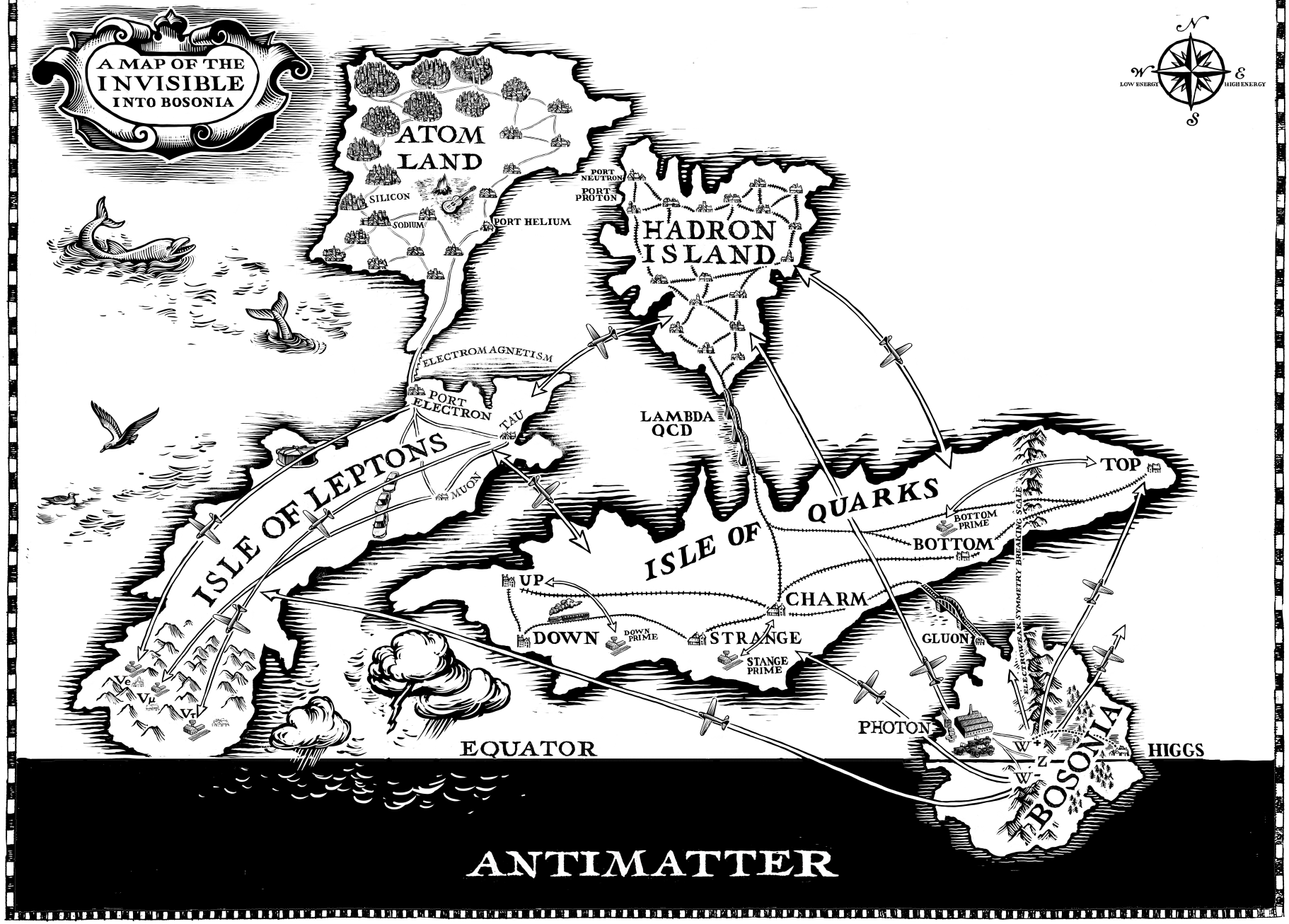


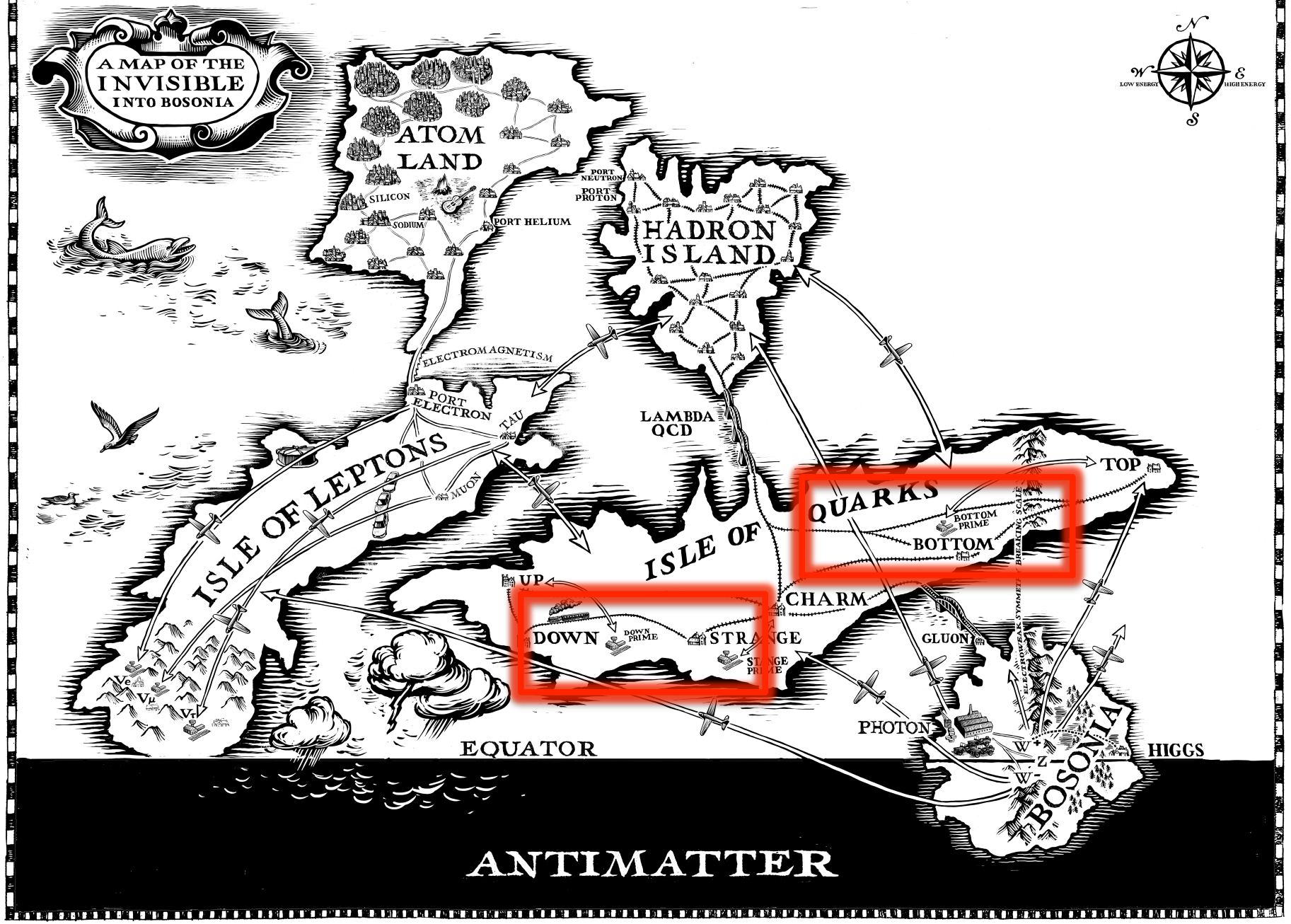


Scaling and Scaling Violations



arXiv:1607.00790


A MAP OF THE INVISIBLE INTO BOSONIA
N
W
E
S
LOW ENERGY
HIGH ENERGY
ATOM LAND
SILICON
SODIUM
PORT HELIUM
PORT NEUTRON
PORT PROTON
HADRON ISLAND
ELECTROMAGNETISM
PORT ELECTRON
TAU
MUON
ISLE OF LEPTONS
LAMBDA QCD
ISLE OF QUARKS
TOP
BOTTOM PRIME
BOTTOM
UP
CHARM
DOWN
DOWN PRIME
STRANGE
STANGE PRIME
GLUON
ELECTROWEAK SYMMETRY BREAKING SCALE
PHOTON
W+
Z
W-
BOSONIA
HIGGS
EQUATOR
ANTIMATTER


A MAP OF THE INVISIBLE INTO BOSONIA
N
W
E
S
LOW ENERGY
HIGH ENERGY
ATOM LAND
SILICON
SODIUM
PORT HELIUM
PORT NEUTRON
PORT PROTON
HADRON ISLAND
ELECTROMAGNETISM
PORT ELECTRON
TAU
MUON
ISLE OF LEPTONS
LAMBDA QCD
ISLE OF
QUARKS
TOP
BOTTOM PRIME
BOTTOM
UP
CHARM
DOWN
DOWN PRIME
STRANGE
STRANGE PRIME
GLUON
PHOTON
ELECTROWEAK SYMMETRY BREAKING SCALE
W+
Z
W-
BOSONIA
HIGGS
EQUATOR
ANTIMATTER

Quark mixing and CP violation

- The weak eigenstates of quarks are not the mass eigenstates: weak interaction mediates mixing, and thus CP violation

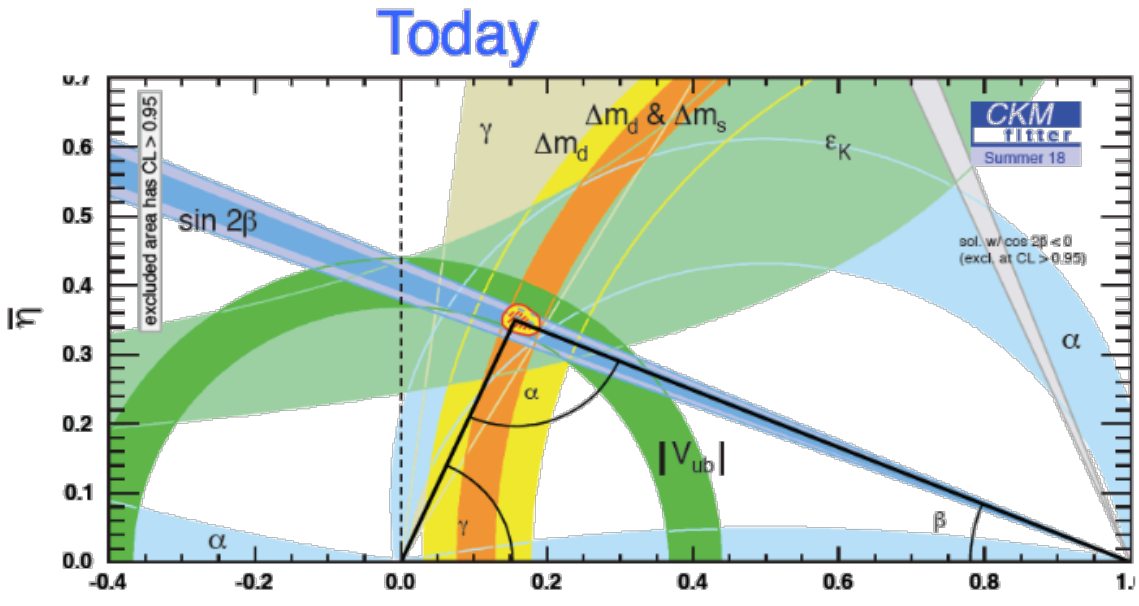
$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}.$$

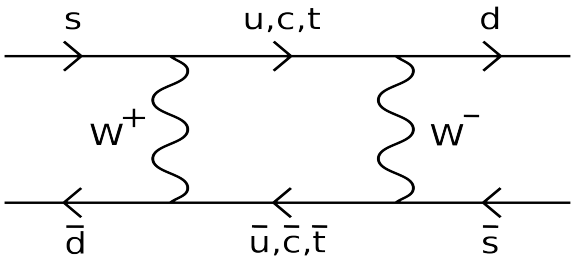
Quark mixing and CP violation

- The weak eigenstates of quarks are not the mass eigenstates: weak interaction mediates mixing, and thus CP violation
- All measurements & constraints consistent with SM unitary mixing matrix

$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97446 \pm 0.00010 & 0.22452 \pm 0.00044 & 0.00365 \pm 0.00012 \\ 0.22438 \pm 0.00044 & 0.97359^{+0.00010}_{-0.00011} & 0.04214 \pm 0.00076 \\ 0.00896^{+0.00024}_{-0.00023} & 0.04133 \pm 0.00074 & 0.999105 \pm 0.000032 \end{pmatrix}$$

← *From A Zoccoli, ESPP update, Granada*





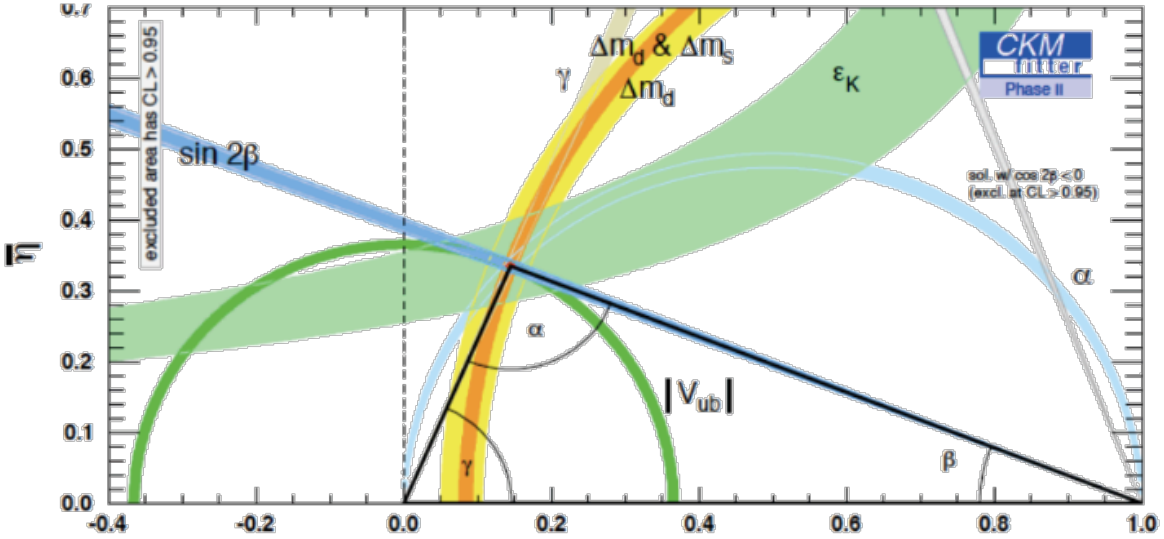
Quark mixing and CP violation

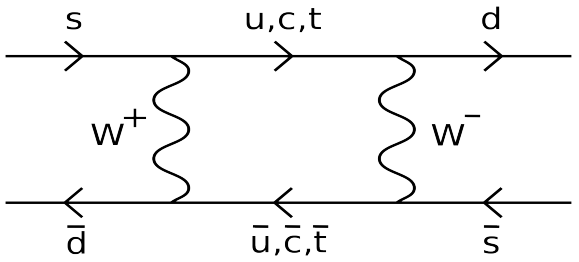
- The weak eigenstates of quarks are not the mass eigenstates: weak interaction mediates mixing, and thus CP violation
- All measurements & constraints consistent with SM unitary mixing matrix

$$V_{\rm CKM} = \begin{pmatrix} 0.97446 \pm 0.00010 & 0.22452 \pm 0.00044 & 0.00365 \pm 0.00012 \\ 0.22438 \pm 0.00044 & 0.97359^{+0.00010}_{-0.00011} & 0.04214 \pm 0.00076 \\ 0.00896^{+0.00024}_{-0.00023} & 0.04133 \pm 0.00074 & 0.999105 \pm 0.000032 \end{pmatrix}$$

← *From A Zoccoli, ESPP update, Granada*

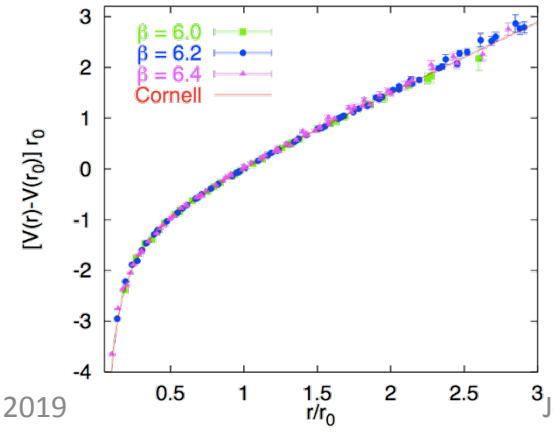
End of HL-LHC: Belle II + LHCb Upgrade II

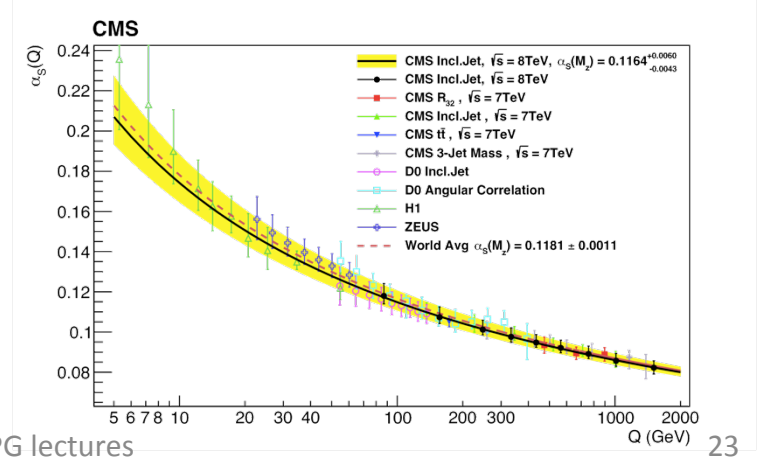




Quark Masses

Generation	Particle	Mass	Q/e	S	C	$\tilde{B}$	T
1	u_r, u_b, u_g	1.7 to 3.1 MeV	2/3	0	0	0	0
	d_r, d_b, d_g	4.1 to 5.7 MeV	-1/3	0	0	0	0
2	c_r, c_b, c_g	1.15 to 1.35 GeV	2/3	0	1	0	0
	s_r, s_b, s_g	80 to 130 MeV	-1/3	-1	0	0	0
3	t_r, t_b, t_g	172 to 174 GeV	2/3	0	0	0	1
	b_r, b_b, b_g	4 to 5 GeV	-1/3	0	0	-1	0



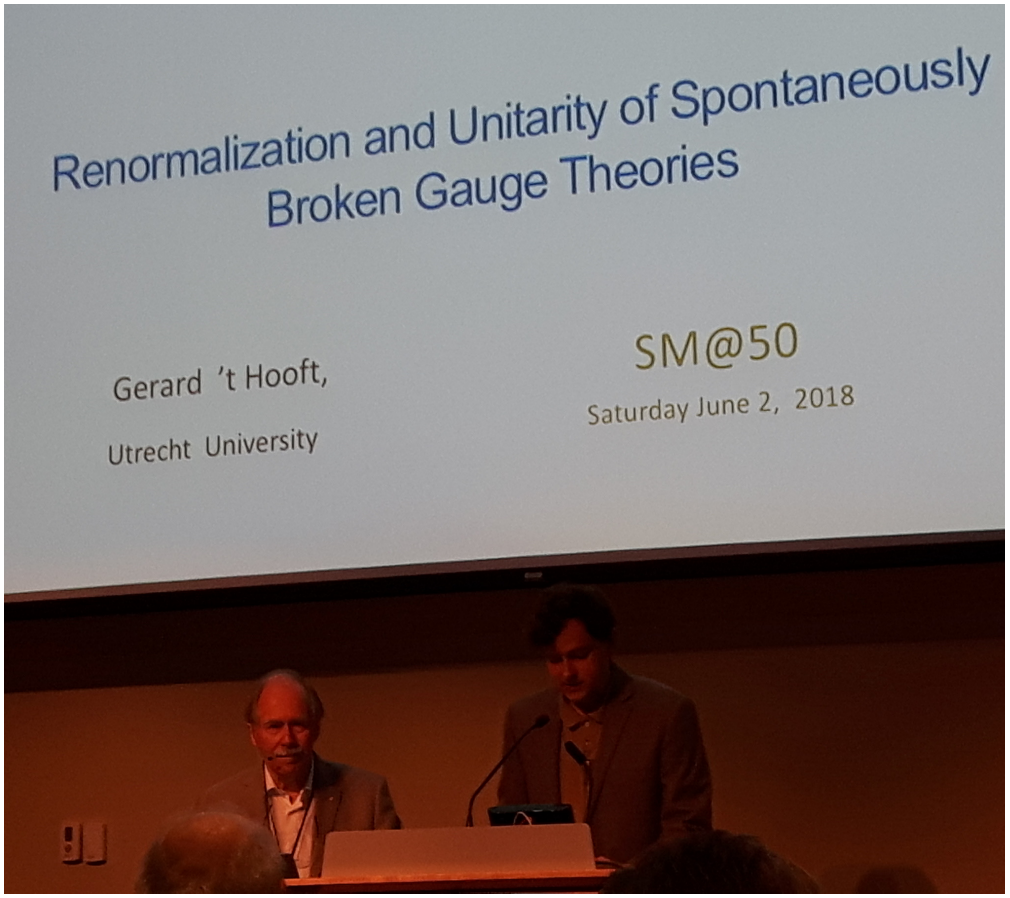


Course Outline

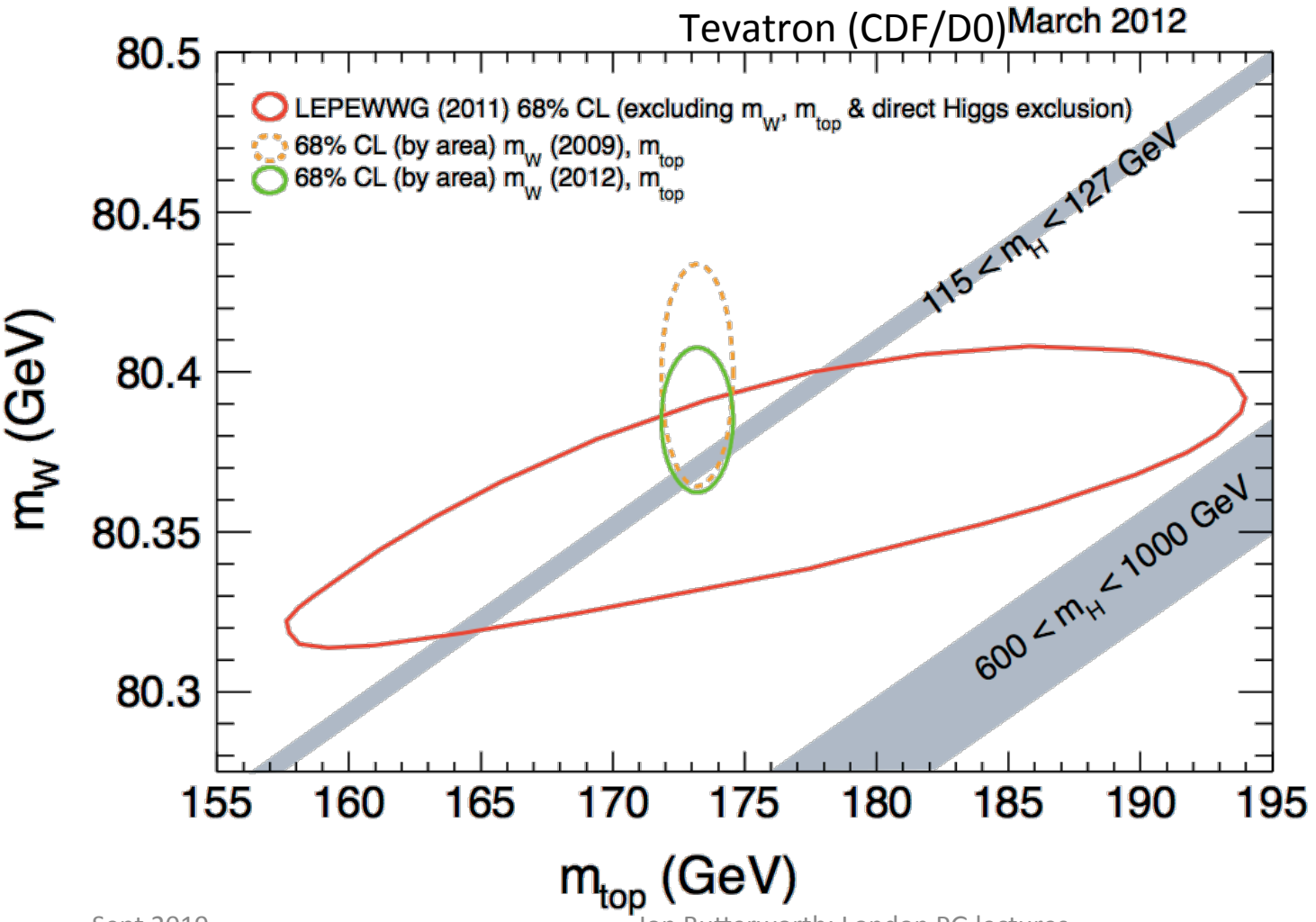
- Introduction: Matter and Forces
- Matter particles: fermionic content of the SM
- Renormalization and the Higgs sector
- Gravity
- Experimental concepts
- Special Relativity
- Relativistic Quantum Mechanics
- Towards Quantum Field Theory
- Calculating a cross section
- …over to Robert.
- QCD & Electroweak collider phenomenology

Renormalization, and the Higgs sector of the Standard Model

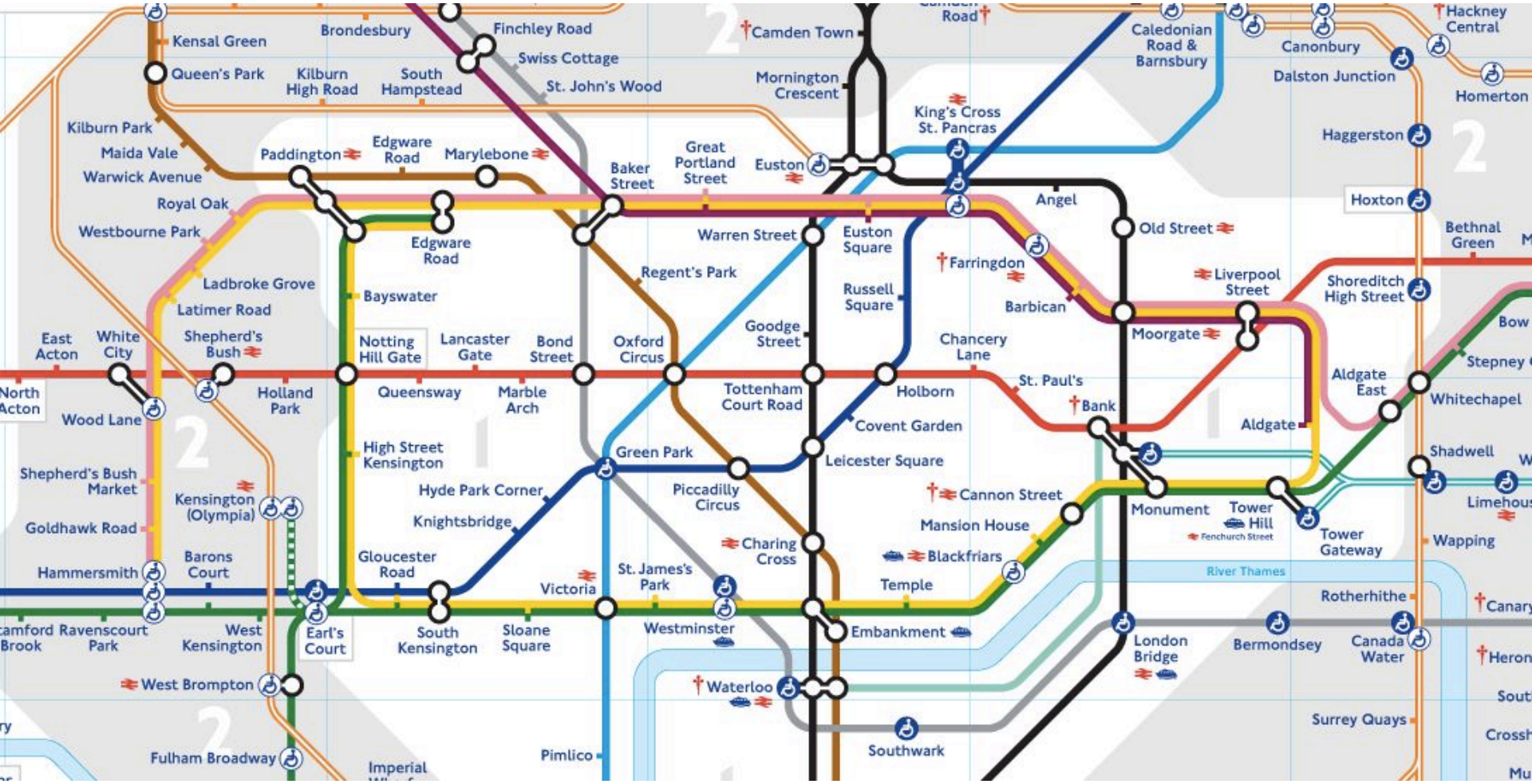
Renormalization, and the Higgs sector of the Standard Model

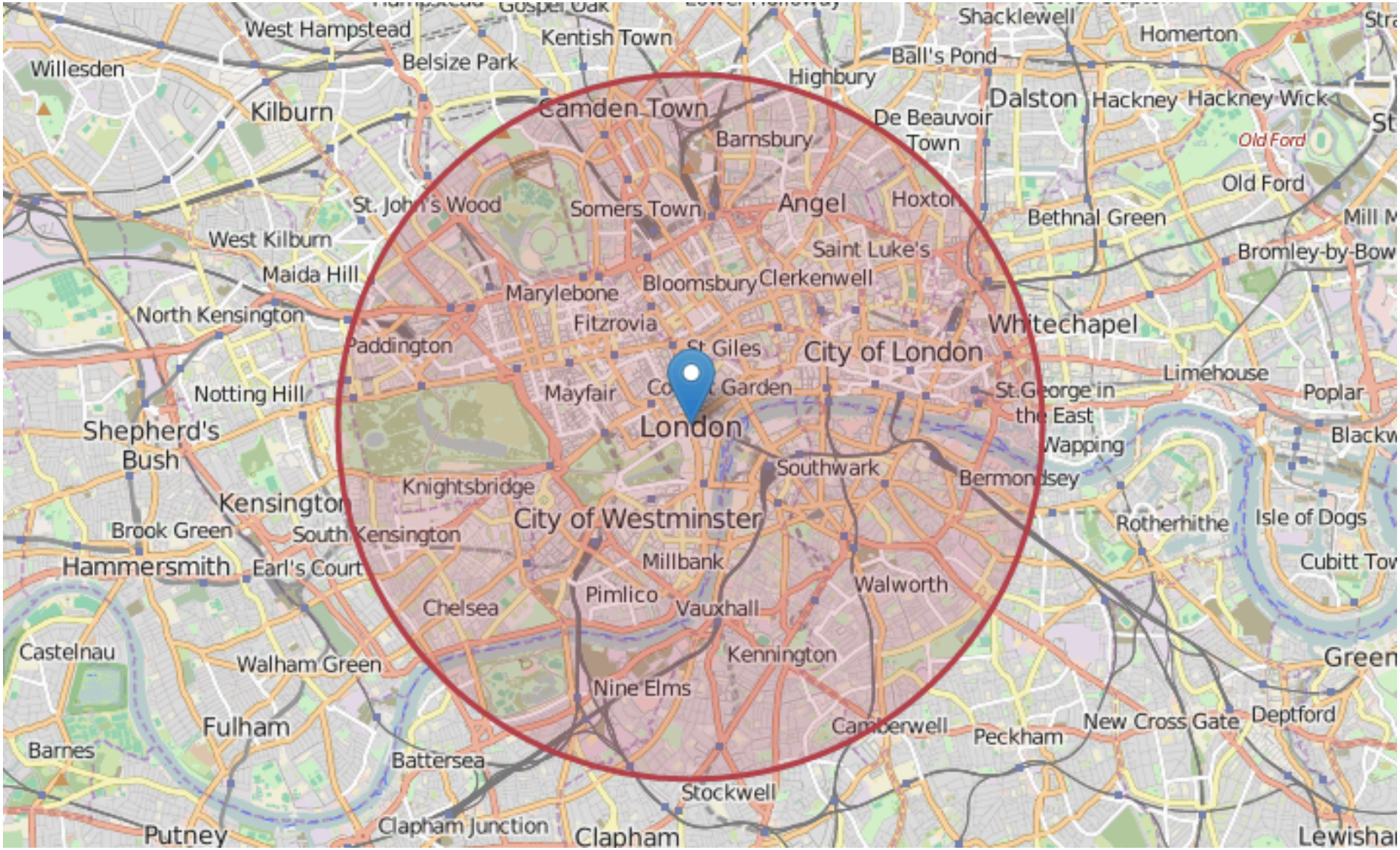


Electroweak symmetry breaking

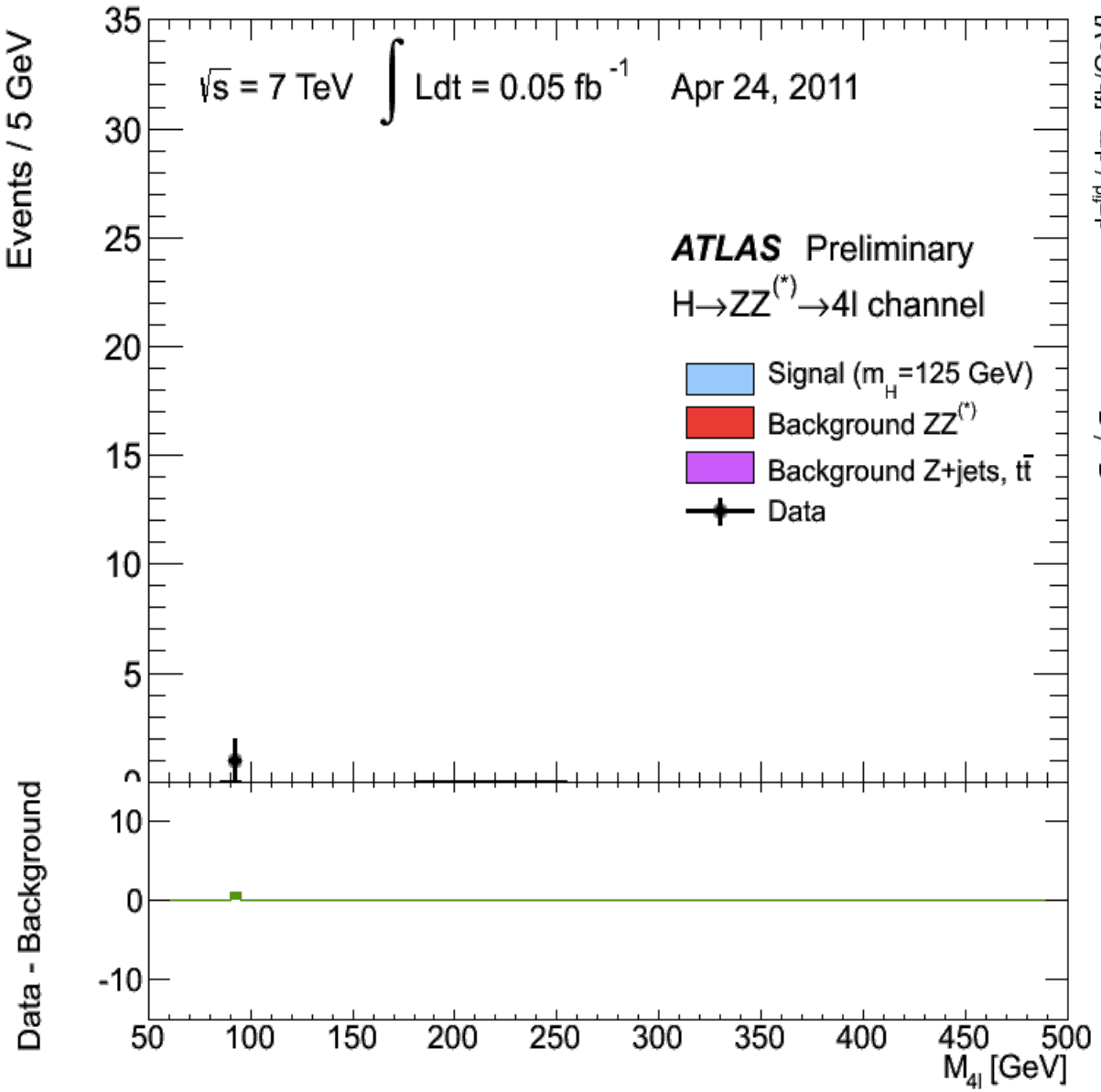


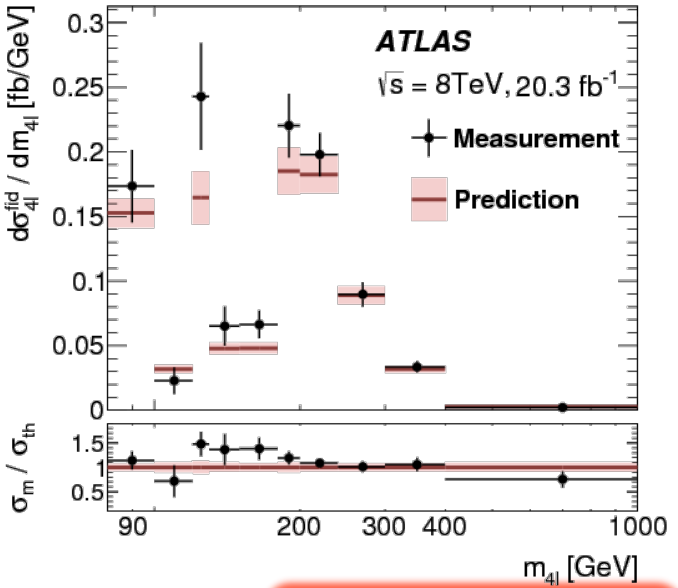

LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SUISSE
FRANCE
SPS 7 km
ALICE
CMS
LHC 27 km


Kensal Green
Brondesbury
Finchley Road
Swiss Cottage
Queen's Park
Kilburn High Road
South Hampstead
St. John's Wood
Camden Town
Mornington Crescent
Caledonian Road & Barnsbury
Canonbury
Dalston Junction
Hackney Central
Homerton
Kilburn Park
Maida Vale
Warwick Avenue
Paddington
Edgware Road
Marylebone
Baker Street
Great Portland Street
Euston
King's Cross St. Pancras
Haggerston
Royal Oak
Westbourne Park
Edgware Road
Warren Street
Euston Square
Angel
Hoxton
Bethnal Green
Ladbroke Grove
Latimer Road
Bayswater
Regent's Park
Russell Square
Farringdon
Old Street
Liverpool Street
Shoreditch High Street
Barbican
East Acton
White City
Shepherd's Bush
Notting Hill Gate
Lancaster Gate
Bond Street
Oxford Circus
Goodge Street
Chancery Lane
Moorgate
Bow
Stepney
North Acton
Wood Lane
Holland Park
Queensway
Marble Arch
Tottenham Court Road
Holborn
St. Paul's
Bank
Aldgate East
Whitechapel
Aldgate
High Street Kensington
Green Park
Covent Garden
Leicester Square
Shadwell
Shepherd's Bush Market
Kensington (Olympia)
Hyde Park Corner
Piccadilly Circus
Cannon Street
Monument
Tower Hill
Fenchurch Street
Tower Gateway
Limehouse
Goldhawk Road
Knightsbridge
Mansion House
Wapping
Hammersmith
Barons Court
Gloucester Road
Charing Cross
Blackfriars
River Thames
Victoria
St. James's Park
Temple
Rotherhithe
Canary
Ravenscourt Park
West Kensington
Earl's Court
South Kensington
Sloane Square
Westminster
Embankment
London Bridge
Bermondsey
Canada Water
Heron
West Brompton
Waterloo
Surrey Quays
Fulham Broadway
Pimlico
Southwark
Imperial

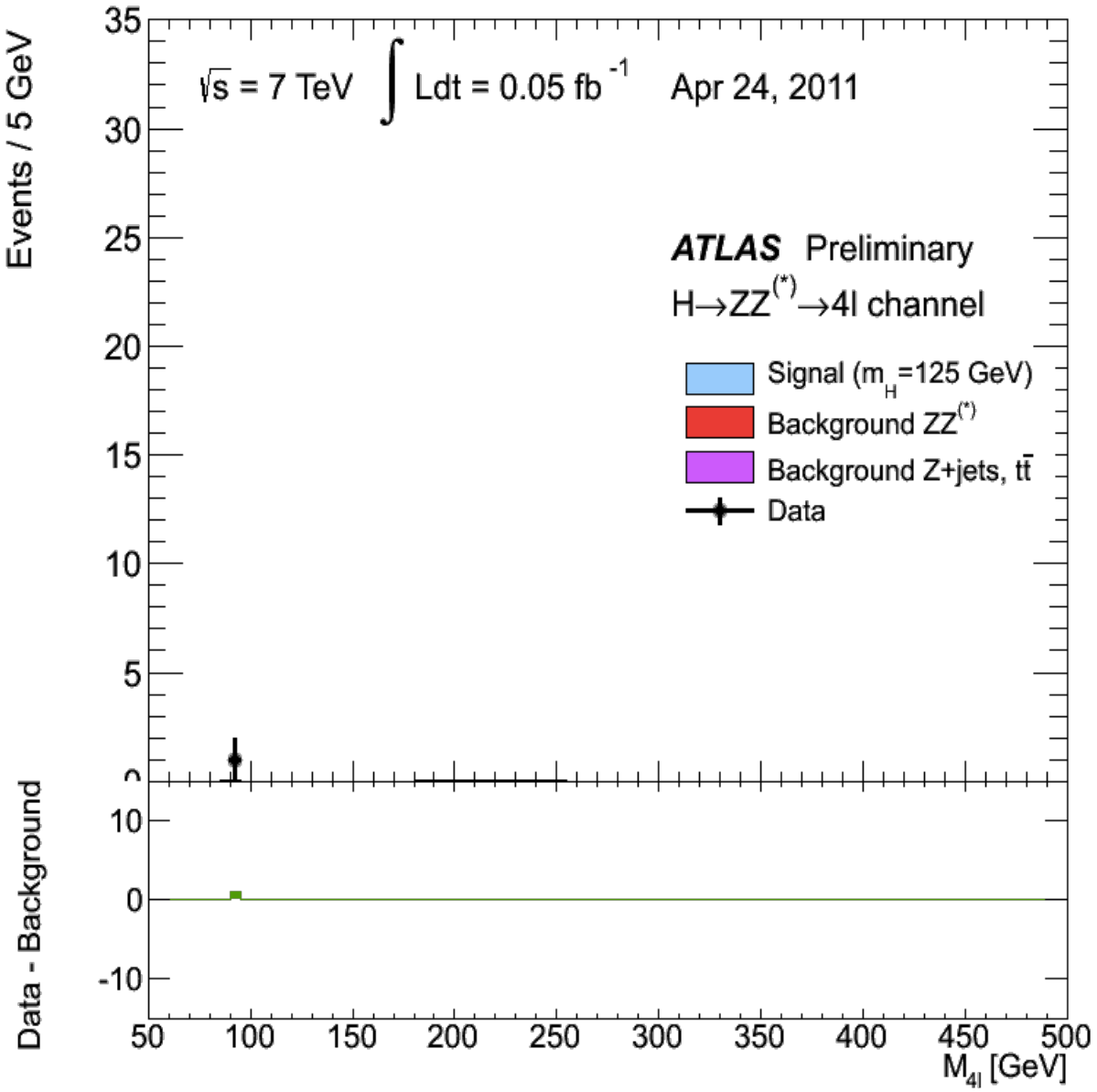


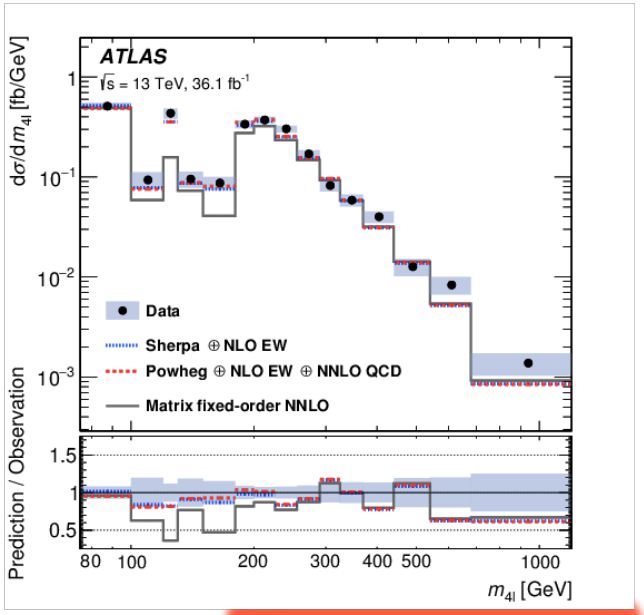
https://natronics.github.io/science-hack-day-2014/lhc-map/


Events / 5 GeV
√s = 7 TeV ∫ Ldt = 0.05 fb-1 Apr 24, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (mH=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Data - Background
M4l [GeV]

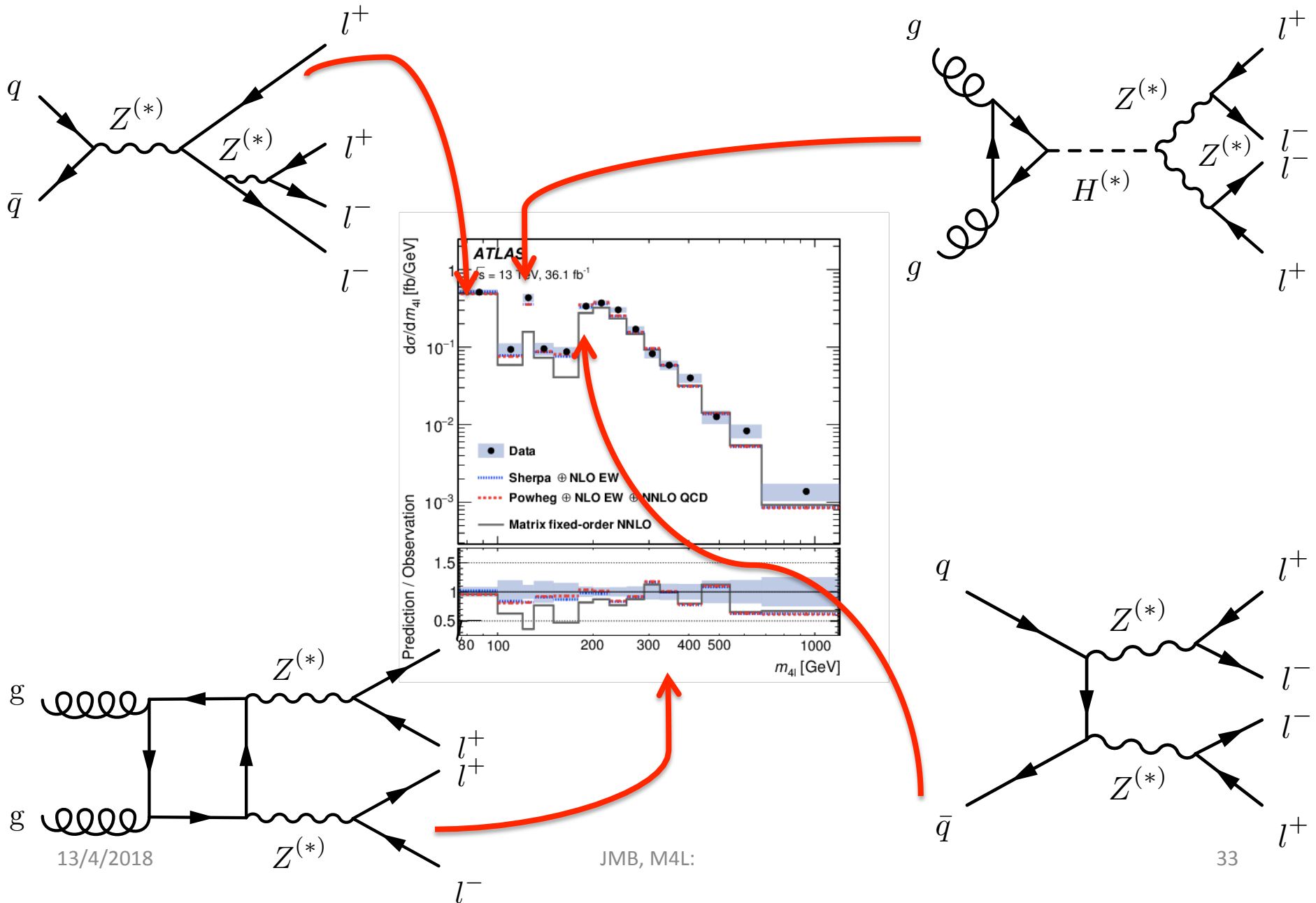

ATLAS
√s = 8TeV, 20.3 fb-1
Measurement
Prediction
dσ4lfid / dm4l [fb/GeV]
σm / σth
m4l [GeV]

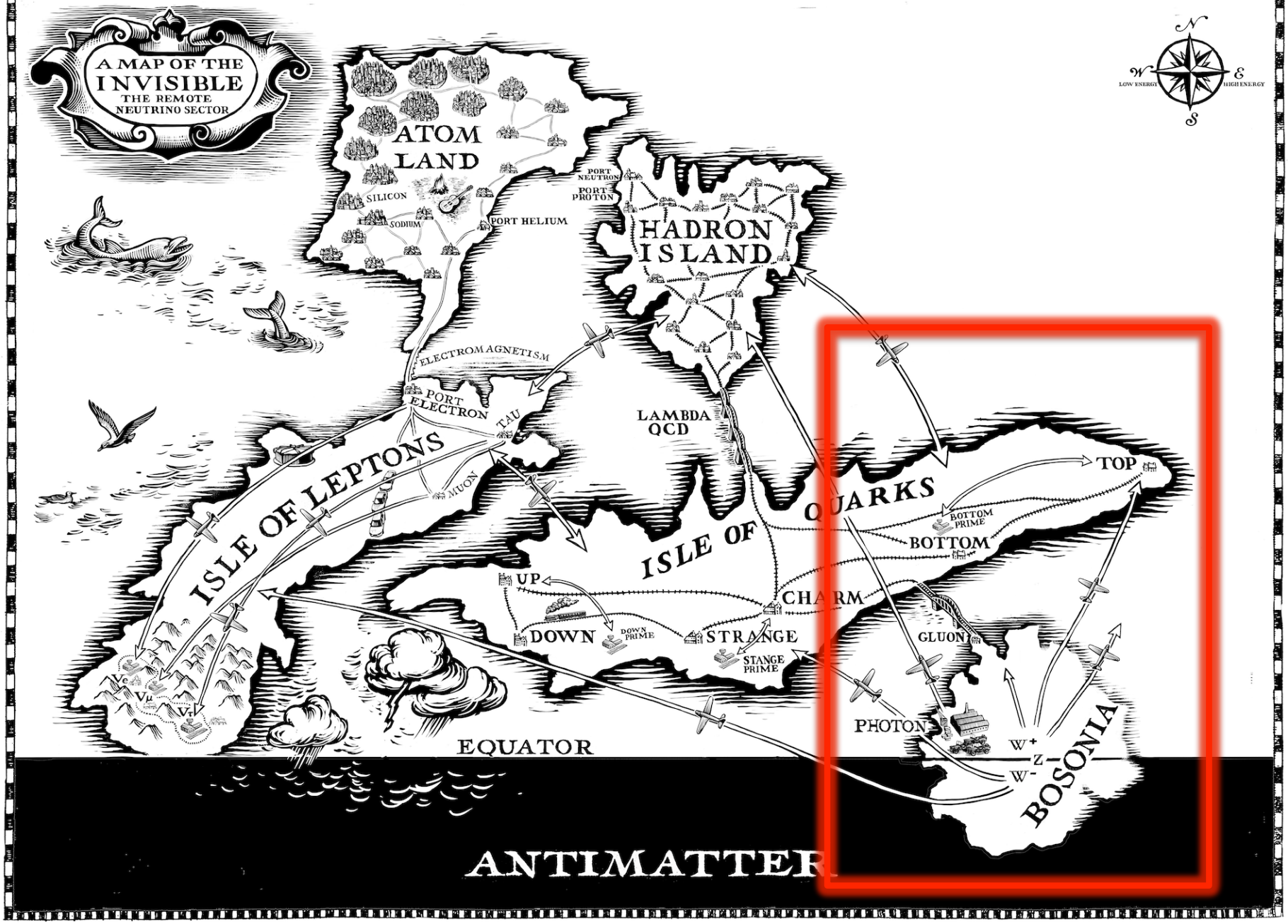

QUARKS
TOP
BOTTOM
GLUON
PHOTON
W+
Z
W-
BOSONIA

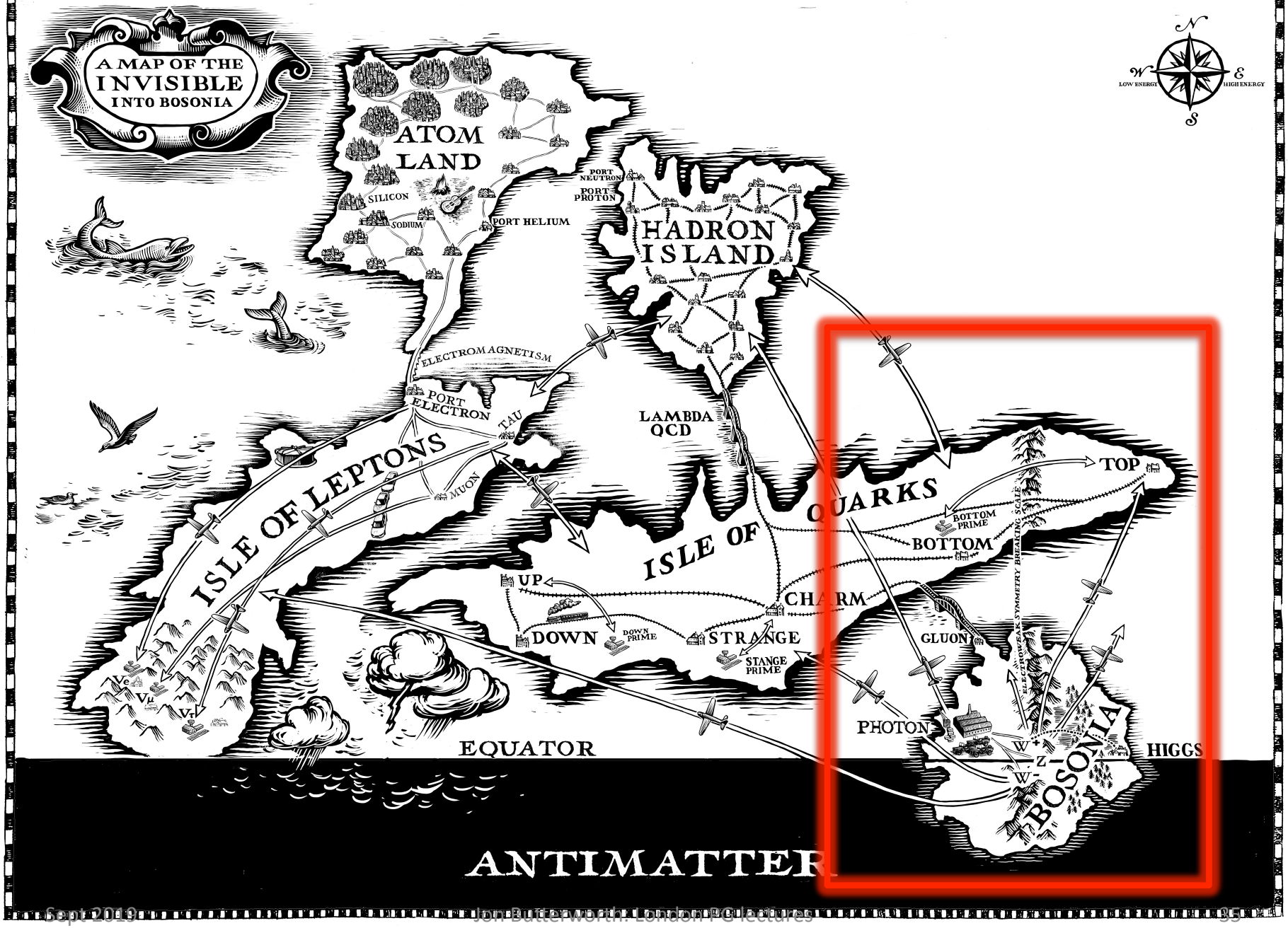

Events / 5 GeV
√s = 7 TeV ∫ Ldt = 0.05 fb⁻¹ Apr 24, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (m_H=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Data - Background
M_4l [GeV]


ATLAS
√s = 13 TeV, 36.1 fb⁻¹
dσ/dm_4l [fb/GeV]
Data
Sherpa ⊕ NLO EW
Powheg ⊕ NLO EW ⊕ NNLO QCD
Matrix fixed-order NNLO
Prediction / Observation
m_4l [GeV]

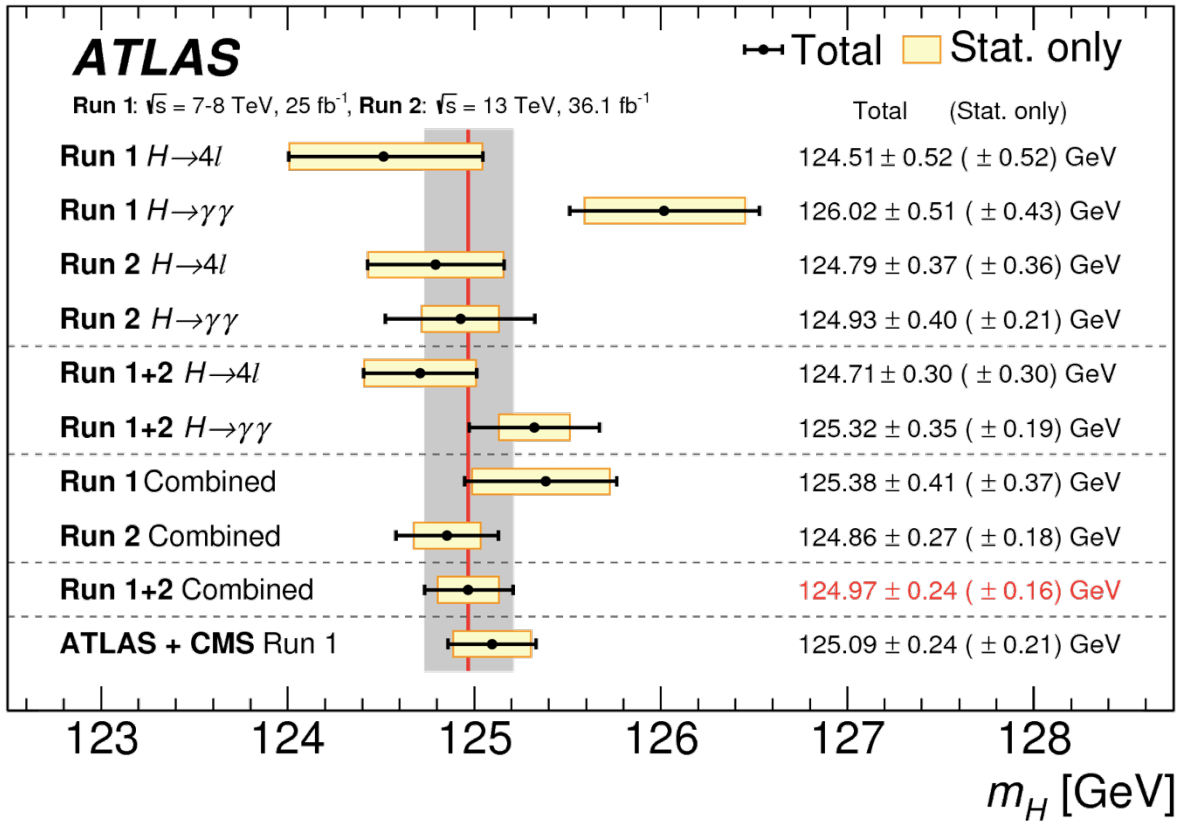

TOP
BOTTOM
GLUON
PHOTON
BOSONIA

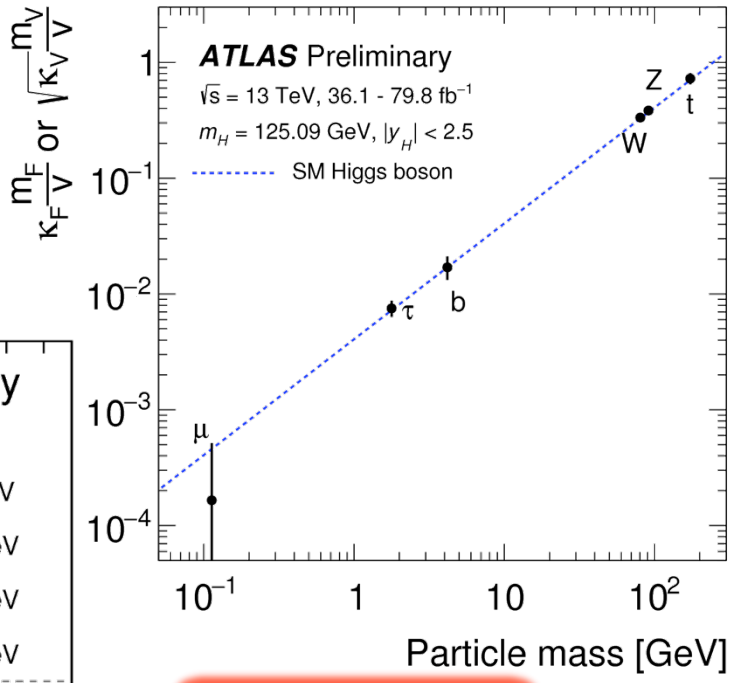

q
$\bar{q}$
$Z^{(*)}$
$Z^{(*)}$
l^+
l^+
l^-
l^-
g
g
$H^{(*)}$
$Z^{(*)}$
$Z^{(*)}$
l^+
l^-
l^-
l^+
ATLAS
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
$d\sigma/dm_{4l}$ [fb/GeV]
Data
Sherpa ⊕ NLO EW
Powheg ⊕ NLO EW ⊕ NNLO QCD
Matrix fixed-order NNLO
Prediction / Observation
m_{4l} [GeV]
g
g
$Z^{(*)}$
$Z^{(*)}$
l^+
l^+
l^-
q
$\bar{q}$
$Z^{(*)}$
$Z^{(*)}$
l^+
l^-
l^-
l^+


A MAP OF THE
INVISIBLE
THE REMOTE
NEUTRINO SECTOR
N
W
E
S
LOW ENERGY
HIGH ENERGY
ATOM
LAND
SILICON
SODIUM
PORT HELIUM
PORT
NEUTRON
PORT
PROTON
HADRON
ISLAND
ELECTROMAGNETISM
PORT
ELECTRON
TAU
MUON
LAMBDA
QCD
ISLE OF LEPTONS
ISLE OF QUARKS
TOP
BOTTOM
PRIME
BOTTOM
UP
CHARM
DOWN
DOWN
PRIME
STRANGE
STANGE
PRIME
GLUON
PHOTON
W+
Z
W-
BOSONIA
EQUATOR
ANTIMATTER


A MAP OF THE INVISIBLE INTO BOSONIA
N
W
E
S
LOW ENERGY
HIGH ENERGY
ATOM LAND
SILICON
SODIUM
PORT HELIUM
PORT NEUTRON
PORT PROTON
HADRON ISLAND
ELECTROMAGNETISM
PORT ELECTRON
TAU
MUON
ISLE OF LEPTONS
LAMBDA QCD
ISLE OF QUARKS
TOP
BOTTOM PRIME
BOTTOM
UP
CHARM
DOWN
DOWN PRIME
STRANGE
STANGE PRIME
GLUON
ELECTROWEAK SYMMETRY BREAKING SCALE
PHOTON
W+
Z
W-
BOSONIA
HIGGS
EQUATOR
ANTIMATTER

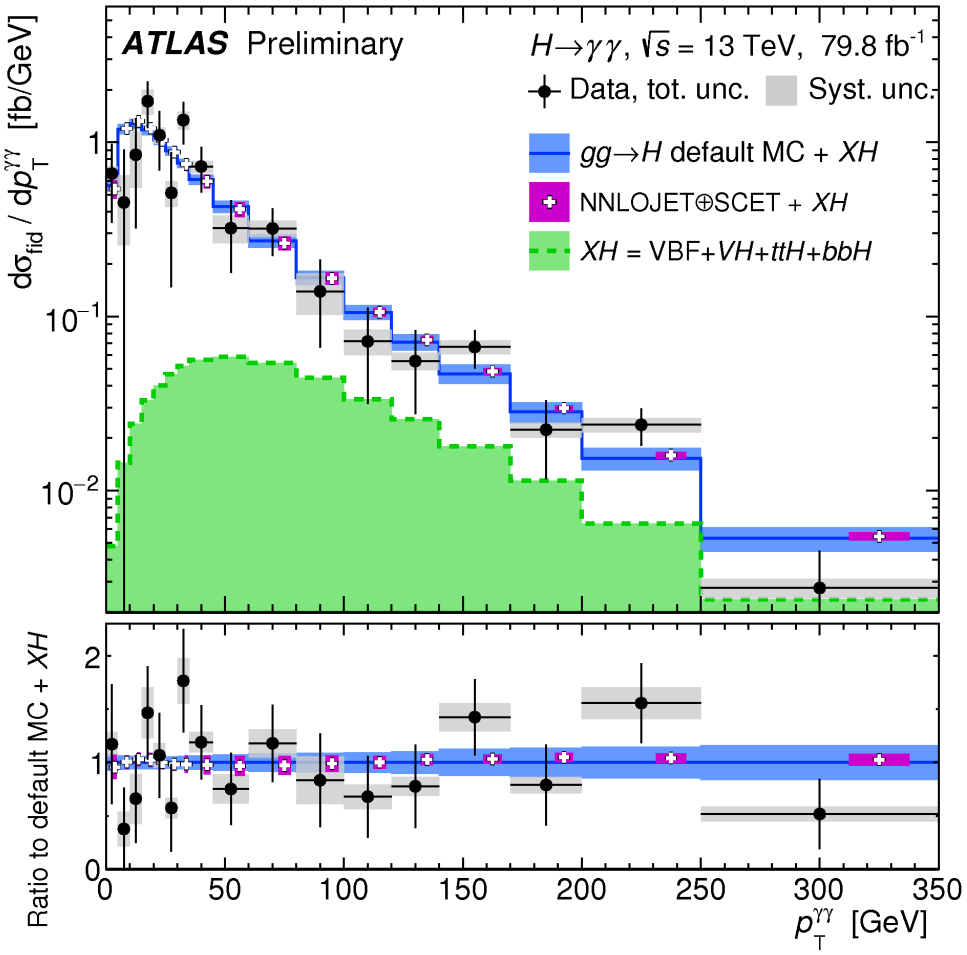
Precision Higgs

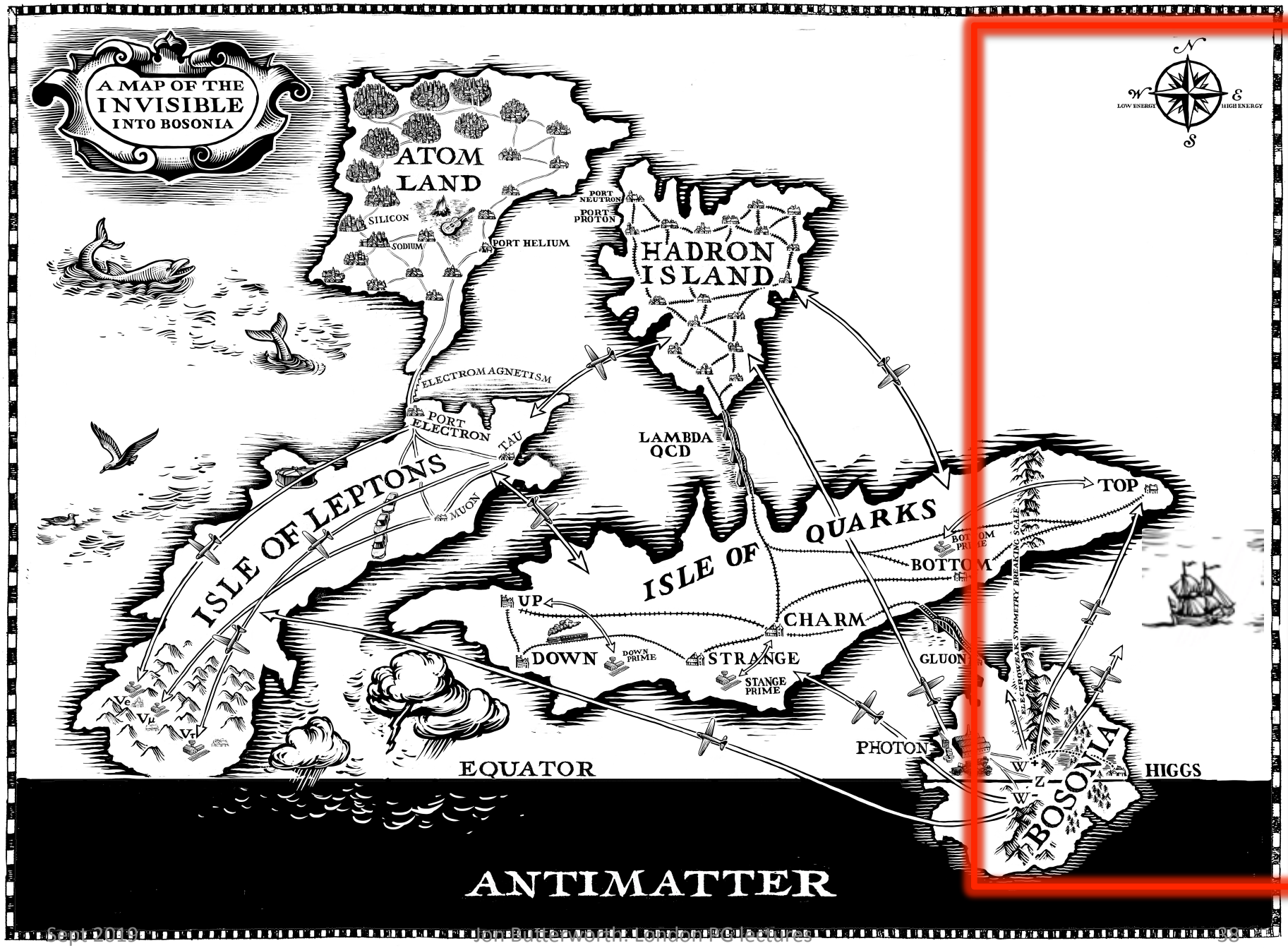




To the TeV scale and beyond…

- Into the unknown…
  - Well-defined, precise measurements and calculations.
  - High multiplicities
  - High boosts, even for electroweak-scale objects




A MAP OF THE INVISIBLE INTO BOSONIA
ATOM LAND
SILICON
SODIUM
PORT HELIUM
PORT NEUTRON
PORT PROTON
HADRON ISLAND
ELECTROMAGNETISM
PORT ELECTRON
TAU
MUON
ISLE OF LEPTONS
LAMBDA QCD
ISLE OF QUARKS
TOP
BOTTOM
UP
CHARM
DOWN
DOWN PRIME
STRANGE
STANGE PRIME
GLUON
PHOTON
EQUATOR
HIGGS
BOSONIA
ELECTROWEAK SYMMETRY BREAKING SCALE
LOW ENERGY
HIGH ENERGY
N
W
E
S
ANTIMATTER