# Particle Physics Lecture 5 - Experiments

# Content

- Last 4 weeks:
  - nuclear physics, particles & history
  - forces
  - symmetries
  - cross-sections and Feynman rules
- Today:
  - Particle detection
  - Modern particle experiments and open questions
- Next week:
  - Accelerators & ELSA tour
  - Mini-symposium

# Particle detection

#### How to detect particles?

• Charged particles:

• Neutral particles:

• Particles with short lifetime

### How to detect particles?

- Charged particles:
  - ionize the medium electromagnetic interaction

- Neutral particles:
  - force them to lose all their energy -> 'Calorimetry'
  - neutrino's: Large volume, low background, wait a long time...
- Particles with short lifetime
  - reconstruct decay products & 'track' them to a point of origin

#### First detectors

- Photographic plate: radiation creates 'blobs' [Curie]
- Used in balloon experiments for cosmic ray detection



• Can be used to measure 'intensity' after a certain time.

#### First detectors

- Spark chamber:
  - particles ionize gas between plates
  - plates are under +- high voltage

-> create 'lightning'

• Can see particles real-time



https://www.youtube.com/watch?v=DpW08xV3RI8

#### Bubble chamber



# Bubble chamber

- Supercooled gas
- Charged particles create 'condensation nuclei' —> tracks
- Can 'see' particle decays
- Can be used 'real-time'
- Can measure distances (in combination a with picture)
- With <u>magnetic field</u>: can calculate momentum
   qvB = mv<sup>2</sup>/R —> mv = qBR



Not automatic...

#### https://www.youtube.com/watch?v=rZR8cnF98ns

#### Scintillation detectors

 Particle passes through luminescent/phosphorescent material —> material gets excited, and then emits light (inorganic crystals, organic materials)





# Scintillation detectors

- Particle passes through luminescent/phosphorescent material —> material gets excited, and then emits light
- Capture light with PhotoMultiplier (PM) tube



- Detect current —> signal
- 'Cheap', efficient, but bulky



# Silicon detectors

- Silicon: <u>semiconductor</u>, and largely available
- Add <u>impurities</u> into lattice: introduce free charge carriers (now conducting, but material still electrically neutral!)



# Silicon detectors

- Add P- and N-type materials together: <u>PN junction</u>
  - System naturally reorders: non-conducting 'depletion region'.



# Silicon detectors

- Add P- and N-type materials together: <u>PN junction</u>
  System naturally reorders: non-conducting 'depletion region'.
- Enhance region by adding 'reverse bias voltage'
- If ionising particle passes through depletion region:
  - briefly becomes conducting again
  - electric 'signal' passes through.
- Enhance, shape, integrate, and readout!



- Very fast! High resolution 'pictures'!
- Expensive, not very radiation hard, and can be 'thick'

#### Gas detectors

#### • Idea:

Fill an area with gas, which traversing particles will ionize
 Find a way to detect these charges

• Geiger-Muller counter





Belle drift chamber, KEK, Tsukuba, Japan

• Charges 'drift' to detection plane under high electric fields



- Charges 'drift' to detection plane under high electric fields
- While they drift, charges undergo diffusion...



- Charges 'drift' to detection plane under high electric fields
- While they drift, charges undergo diffusion...
- Near the wire, the acceleration causes multiplication





- Charges 'drift' to detection plane under high electric fields
- While they drift, charges undergo diffusion...
- Near the wire, the acceleration causes multiplication
- Finally, the signal is caught by the anode



- z-location of charge = [drift time] x [drift velocity]
  —> constant E-field!
- Choice of drift gas important (Argon: ampl. CO<sub>2</sub>: quenching.)
- Radiation hard, 'cheap', and creates (x,y,z) point!
- Usually long drift time, and not great spacial resolution.



#### Straw tube tracker

- Create many little 'drift chambers' with one central wire
- 'Timing' measures distance from central wire



- 'Cheap' coverage of large areas, and good resolution (~100 um)
- Relatively 'thin', and small drift times (~50 ns)
- Only one 'hit' per straw possible: 0.5 cm vs 50 um (silicon)

# Detecting particle types

- So far: detecting the location of particles. What about ID?
  - Energy loss
  - Cherenkov radiation
  - Time-of-flight

# Energy loss

- 'stopping power', called dE/dx
  - Mostly through coulomb interactions with material
  - Ionisation of medium: drops as  $\sim 1/v^2$ . Bethe-Bloch equation:

$$-\left\langle \frac{dE}{dx}\right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2}\ln\frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

- at low momenta: nuclear effects
- at high momenta: radiation, brehmsstrahlung

#### http://pdg.lbl.gov/2009/reviews/rpp2009-rev-passage-particles-matter.pdf



Au+Al at \s<sub>NN</sub> = 3.5 GeV



Can detect by measuring the charge deposited (charge ~ E)



- Can detect by measuring the charge deposited (charge ~ E)
- By measuring the number of ionisation clusters



- Can detect by measuring the charge deposited (charge ~ E)
- By measuring the number of ionisation clusters
- Or by measuring the 'time over threshold' of the voltage/current



#### Cherenkov radiation

• if  $v > v_{wave}$  of medium: conic emission of waves





# Cherenkov radiation

- if  $v > v_{wave}$  of medium: conic emission of waves
- if  $v > c_{light}$  of medium: emission of Cherenkov light



#### Cherenkov radiation

- if  $v > v_{wave}$  of medium: conic emission of waves
- if  $v > c_{light}$  of medium: emission of Cherenkov light

 $\cos(\theta) = \frac{1}{n\beta}$ 



# Time-of-flight

• If momentum not too high: noticeable timing difference



# Time-of-flight

- If momentum not too high: noticeable timing difference
- Example: using the (~1 ns) timing of the LHCb straw tube tracker:



#### Calorimeters

- Neutral particles: no coulomb —> no charge deposits
  : neutrons, photons, pi0...
- Get their energy: Smash them into lead targets, and count what comes out



#### Calorimeters

- 'Shashlik' structure:
  - Heavy layer: ensures loss of energy
  - Sampling layer: measures traversing particles


#### Calorimeters

- 'Shashlik' structure:
  - Heavy layer: ensures loss of energy
  - Sampling layer: measures traversing particles (or pay a lot of money for lead-tungsten crystals)



events are distributed into distinct bands according to their mass. Wh are primarily is of hadron definition, it is worth noting that a d also be observed.

- 'Shashlik' structure:
   Heavy layer: ensures loss of energy
  - Sampling layer: measures the Versing for the son data, high statistics sam
- p and  $\bar{p}$  tracks are needed. The selection of such control samples must Energy resolution, which would other wise bias the result. The strategy emp through purely king matic selections independent of RICH information particles copiously produced and reconstructed at LHCb.
- The following decays, and their charge conjugates, are identified:  $D^{*+}$  - Stochastic term This ensemble of final states provides a complete types needed to comprehensively a constant left detectors hadron demonstrated in Fig. 15, the  $K_{\rm S}^0$ ,  $\Lambda$ , and D<sup>\*</sup> selections have extremely 1 While high purity samples of the control modes can be gathered th requirements alone, the residual backgrounds present within each must To distinguish background from signal, a likelihood technique, called  $_{s}$ ? Stochastichten warishower' fluctuations to particle  $K_S^0$ ,  $\Lambda$ ,  $D^0$  is used as the difference of the stochastic state of the stochastic st Constant terme callor at the RICH PID can be appreciated by considering the each track type from the control samples. Figures 16(a-c) show the corr in the 2D plane of  $\Delta \log \mathcal{L}(K - \pi)$  versus  $\Delta \log \mathcal{L}(p - \pi)$ . Each particl quadrant of the two dimensional  $\Delta \log \mathcal{L}$  space, and demonstrates the 🕸 Nikhef 🏷 Maastricht University

### Showers

- EM showers: pair production vs brehmsstrahlung
- Shower depth:  $X = X_0 \frac{\ln(E_0/E_c)}{\ln 2}$ 
  - X<sub>0</sub>: radiation length of material
  - $E_0/E_c$ : fraction of the two processes
- Hadronic showers: harder to predict. QCD...
- LHCb:
   EM Calo: a,b = 10%, 1.5%
   Had. Calo: a,b = 80%, 10%



# Considerations

Purpose of detector? Spend your money:

very good momentum resolution



Complete (4 pi) coverage



excellent vertex resolution





Ittle energy loss during travel





# Considerations

Purpose of detector? Spend your money:





 $\langle \bullet \rangle$  complete (4 pi) coverage (-> efficiency, closeness)



 $\langle \bullet \rangle$  excellent vertex resolution (-> good lifetime resolution)





Ittle energy loss during travel (-> no radiation loss)





# Considerations

Purpose of detector? Spend your money:

very good momentum resolution (strong magnet, small pixels)





excellent vertex resolution (very close to PV, small pixels)

very fast timing (expensive electronics & detectors)



Ittle energy loss during travel (thin detector technology)





good energy resolution (expensive calo crystals, small pixels)

# Summary

- There are various ways of detecting particles, each with its own advantages/disadvantages.
- Most accelerator-based experiments will have some form of tracking, a magnet, PID, and calorimetry
- A careful consideration is made for every detector setup, optimized for the corresponding physics program.

#### Jupyter challenge - Top 3:

Jacco	- chi2/ndf = 5.87,N(Bs) = 1.13 M
1)	- chi2/ndf = 5.52,N(Bs) = 1.92 M
2)	- chi2/ndf = 5.57,N(Bs) = 1.92 M
3)	- chi2/ndf = 5.96 ,N(Bs) = 0.3 M

#### Jupyter challenge - Top 3:

√(Bs) = 1.13 M	- chi2/ndf = 5.87	Jacco
√(Bs) = 1.13	- chi2/ndf = 5.87	Jacco

- 1) Nelson chi2/ndf = 5.52 , N(Bs) = 1.92 M
- 2) Francesco chi2/ndf = 5.57 , N(Bs) = 1.92 M
- 3) Hildebert chi2/ndf = 5.96, N(Bs) = 0.3 M

# Modern experiments

(note: cherry picked!)

# Big questions in physics

- What is dark matter?
- What is the mass of neutrinos?
- Where do the ultra high energy cosmic rays come from?
- Are protons unstable?
- Where did all the antimatter go?
- What happened during the big bang?
- Why is the Higgs mass so fine-tuned?
- Why are there (only) three generations?
- What is the top quark mass?

http://discovermagazine.com/2002/feb/cover

There is 'dark' mass in the universe, that affects gravitational pull
 Galaxy rotation curves



- There is 'dark' mass in the universe, that affects gravitational pull
  - Galaxy rotation curves
  - Gravitational microlensing



- There is 'dark' mass in the universe, that affects gravitational pull
  - Galaxy rotation curves
  - Gravitational microlensing
  - Peaks in power spectrum of cosmic microwave background (CMB)





- There is 'dark' mass in the universe, that affects gravitational pull
  - Galaxy rotation curves
  - Gravitational microlensing
  - Peaks in power spectrum of cosmic microwave background (CMB)

#### —> 1/4 of the energy content in our universe!



- WIMPs or MACHOs?
- Evidence favours DM particles. But what?
  - must be stable
  - must not interact via QED or QCD
  - lightest SUSY particle? sterile (right-handed) neutrino's?

- WIMPs or MACHOs?
- Evidence favours DM particles. But what?
  - must be stable
  - must not interact via QED or QCD
  - lightest SUSY particle? sterile (right-handed) neutrino's?
- 3 ways of searching:



• Liquid Xenon drift chamber ("Time Projection Chamber")





- Under a mountain in Gran Sasso, Italy, in an old mine
- Shielded by ultra pure water
- Two signals, S1 (light) and S2 (charge)
- Backgrounds: natural isotopes, cosmic radiation, neutrinos!
- Xenon nT upgrade: ~2020







# What is the mass of neutrinos?

- 1960: there is a ~50% deficit of electron-neutrinos from the sun
- Since 1998: Neutrinos change flavour on their way here!

$$P_{lpha 
ightarrow eta, lpha 
eq eta} = \sin^2(2 heta) \sin^2\left( egin{array}{c} \Delta m^2 L \ 4E \end{array} 
ight) ( ext{natural units})$$



# What is the mass of neutrinos?

- 1960: there is a ~50% deficit of electron-neutrinos from the sun
- Since 1998: Neutrinos change flavour on their way here!

$$P_{lpha
ightarroweta,lpha
eqeta}=\sin^2(2 heta)\sin^2\left(rac{\Delta m^2 L}{4E}
ight) ( ext{natural units})$$

• This means they must have mass!



# What is the mass of neutrinos?

- 1960: there is a ~50% deficit of electron-neutrinos from the sun
- Since 1998: Neutrinos change flavour on their way here!

$$P_{lpha
ightarroweta,lpha
eqeta}=\sin^2(2 heta)\sin^2\left(rac{\Delta m^2L}{4E}
ight) ext{(natural units)}$$

- This means they must have mass!
- Mass hierarchy of great importance to
  - Grand Unified Theories,
  - neutrinos are their own antiparticle?
  - types of elements produced in supernovae
  - potential 'CP-violation' or 'leptogenesis': is this why the antimatter disappeared?

# Super-Kamiokande



- 1km underground mount Ikeno -
- 40m diameter
- 50,000 ton of ultrapure water -
- 13,000 PM tubes \_

Upgrade: Hyper-Kamiokande: 2025

- Sources:
  - reactors
  - atmosphere
  - solar
  - ...?

# DUNE

- Long baseline neutrino experiment -
- FermiLab accelerator creates beam \_
- Travel 1300 km underground \_





# DUNE





# High-energy cosmic rays



# Pierre Auger observatory



https://arxiv.org/pdf/1709.07321.pdf

### Pierre Auger observatory



https://arxiv.org/pdf/1709.07321.pdf

### High-energy cosmic rays



• How to detect high energy, extragalactic neutrinos?

### IceCube



https://www.youtube.com/watch?v=OdWZA5UxmOk

#### IceCube

- 1 km3 covered with photomultipliers
- 1.5 2.5 km under the Antarctic ice
- 60 'DOMs' x 86 'strings'



#### IceCube

- 1 km3 covered with photomultipliers
- 1.5 2.5 km under the Antarctic ice
- 60 'DOMs' x 86 'strings'

-sources more data! le ~2025 stronomy

> Neutrino-Showers Neutrino-tracks Swift X-ray SLac Sources TeVCat

#### Abstract

A high-energy neutrino event detected by IceCube on 22 September 2017 was coincident in direction and time with a gamma-ray flare from the blazar TXS 0506+056. Prompted by this association, we investigated 9.5 years of IceCube neutrino observations to search for excess emission at the position of the blazar. We found an excess of high-energy neutrino events, with respect to atmospheric backgrounds, at that position between September 2014 and March 2015. Allowing for time-variable flux, this constitutes 3.5 $\sigma$  evidence for neutrino emission from the direction of TXS 0506+056, independent of and prior to the 2017 flaring episode. This suggests that blazars are identifiable sources of the high-energy astrophysical neutrino flux.

https://arxiv.org/abs/1602.03694

# **KM3NeT**

- Similar idea, using the mediterranean sea
- Currently under construction
- Nikhef: just received 12.3M investment





#### Mass hierarchy prospects

~2023: could be solved!



https://arxiv.org/pdf/1701.04078.pdf
#### Accelerator-based detectors

- Allows for continuous, systematic measurements
- Extremely high precision measurements (can build precision instrumentation around a fixed point!)
- A lot of data! (or "integrated Luminosity")



#### Accelerator-based detectors

- LHC: proton-proton collider
  - 13 TeV center-of-mass energy
  - 40 million 'bunch crossings' / second
  - -> sometimes with 20 collisions / 'bunch crossing'

Instantaneous luminosity ~  $2 \times 10^{34}$  / (cm<sup>2</sup> s).





#### Accelerator-based detectors

- Readout of detectors must be very, very fast (~25 ns)
- Equipment must be very radiation 'hard'
  : Few years of operation —> 35 kGy (= kJ/kg) for a single 'layer'
  : compare to yearly background dose: ~3 mSv
- Often: precision demanded which is not yet possible to build
- Data: ~1MB/'event' -> 40 TB /s ?? -> not possible?

#### Data size

- Zero-suppress raw data (no 0 and 1's, but build clusters)
- Only send relevant information: trigger interesting events

   high-performance, cutting edge algorithms
   Crucial: don't throw away new particles!
- Real data rate ~ 2 GB/s
- Still enough data to stack DVD's to mt. Blanc every year. (x1.5)



#### Data size

- Infrastructure: World-wide Computing Grid (LCG)
- Reconstructing data
- Simulating data
- User job processing





#### Welcome to the era of tera

## ATLAS / CMS







# ATLAS / CMS

- 'General purpose' detectors
- Collaborations: ~3000 people
- Main goals:
  - direct detection of new particles (SUSY)
  - measuring the top quark mass
  - Studying the Higgs boson properties

## ATLAS





# Higgs

- Various (production and) decay channels
- Discovered in 2012



# Higgs

- Looks like the SM Higgs boson... but:
- Only spin-0 particle observed so far! —> study properties!
- Coupling ~ mass —> our 'portal' to dark matter?
   —> measure the total decay width / lifetime!
- Is the potential really our V( $\phi$ ) ? —> measure  $\lambda$  : self-coupling!



#### SUSY search limits

ATLAS SUSY Searches* - 95% CL Lower Limits July 2018 ATLAS Preliminary $\sqrt{s}$ - 7, 8, 13 TeV											
	Model	$e, \mu, \tau, \gamma$	/ Jets	$E_{\rm T}^{\rm miss}$	∫£ <i>dı</i> [fl	Ma	ss limit		$\sqrt{s} = 7,81$	<mark>ΓeV</mark> √s = 13 TeV	Reference
e.	$\bar{g}\bar{q}, \bar{q} \rightarrow q \bar{d}_{1}^{0}$	0 mono-jet	2-8 jeta 1-3 jeta	Yes Yes	36.1 36.1		0.43	0.9	1.55	$\begin{array}{c} m(\tilde{E}_{1}^{\prime}){<}100~{\rm GeV} \\ m(j){<}m(\tilde{E}_{1}^{\prime}){=}3~{\rm GeV} \end{array}$	1712/02020 1711/03901
Inclusive Searche	88×3→9541	0	2-6 jels	Yes	36.1	jî Jî		Forbidden	2.0 0.95-1.6	m(ℓ_1)~200 GeV m(ℓ_1)=200 GeV	1715/02020 1715/02332
	33.3~9%(C)E	$3 a_{e}p_{e}$	4 ets 2 ets	Yes	36.1 36.1	8			1.85	$m(\hat{F}_1^{\prime})$ =300 GeV $m(\hat{g})$ - $m(\hat{F}_1^{\prime})$ =50 GeV	1708.08731 1505.11831
	ŝš. ž→φ2₩Z <b>Ž</b> 1	0 3 A.P	7-11 jets 4 jets	Ks	36.1 36.1	ž ž		0.98	1.8	m( $\hat{\epsilon}_1^2$ ) -:400 GeV m( $\hat{\epsilon}_1$ )200 GeV	1708.02794 1708.03731
	ss i ntt <sup>n</sup>	0-1 c.µ 3 c.µ	S∦ -1jels	Yes	36.1 36.1	an an			2.0	m(7))~300 GeV m(j) m(7))=300 GeV	1715.01901 1705.03731
3 <sup>14</sup> gen, sopania dreet produción	$\hat{b}_1\hat{b}_1, \hat{b}_1 {\rightarrow} bk_1^0/G_1^1$		Multiple Multiple Multiple		36.1 36.1 36.1	δι Forbleden δι δι	Forbiddon Forbiddon	0.9 0.58-0.82 0.7	n(31)	$\begin{array}{l} m[\tilde{x}_{1}^{0}]{=}300~{\rm GeV},~{\rm BH}[\tilde{x}_{1}^{0}]{=}1\\ m[\tilde{x}_{1}^{0}]{=}300~{\rm GeV},~{\rm BH}[\tilde{x}_{1}^{0}]{=}131[\tilde{x}_{1}^{0}]{=}2.5\\ {\rm CBD}~{\rm GeV},~m[\tilde{x}_{1}^{0}]{=}320~{\rm GeV},~{\rm BH}[\tilde{x}_{1}^{0}]{=}1\end{array}$	1708.02280, 1711.00001 1708.09266 1708.08731
	$\tilde{b}_1\tilde{b}_1,\tilde{t}_1\tilde{t}_1,M_2=2\times M_1$		Mutipie Mutipie		36.1 36.1	7, 7, Ferbialdan		0.7		$m(\tilde{k}_1^0)$ =50 GeV $m(\tilde{k}_1^0)$ =200 GeV	1703.04162, 1711.11520, 1706.02047 1703.04162, 1711.11520, 1706.02047
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1  ightarrow W \tilde{t}_1^{(2)}  ext{ or } \tilde{t}_1^{(2)}$ $\tilde{t}_1 \tilde{t}_1, \tilde{H}  ext{ LSP }$	024,9	0-2 jels/1-2. Multiple Multiple	0 Yes	36.1 36.1 36.1	Σ <sub>1</sub> Σ <sub>1</sub> Σ <sub>1</sub> Forbidden		1.0 0.4-0.9 0.6-0.8	mež) meži	$m(\tilde{c}_{1}^{0}) = 1 \text{ GeV}$ = 150 CeV, $m(\tilde{c}_{1}^{0}) = m(\tilde{c}_{1}^{0}) = 5 \text{ CeV}, \tilde{c}_{1} = \tilde{c}_{2}$ = 300 CeV, $m(\tilde{c}_{1}^{0}) = m(\tilde{c}_{1}^{0}) = 5 \text{ CeV}, \tilde{c}_{1} = \tilde{c}_{2}$	1508.06816, 1709.04188, 1711.11520 1.709.04183, 1711.11520 1.709.04183, 1711.11520
	$\tilde{r}_{1}\tilde{r}_{1}$ , Well-Tempered LSP		Multiple		36.1	ž <sub>1</sub>		0.48-0.84	$\mathbf{m}(\widehat{\mathbf{C}}_{i}^{n})$	=150 GeV, $\mathbf{n}(\hat{\mathbf{r}}_{1}^{n})$ - $\mathbf{n}(\hat{\mathbf{r}}_{1}^{n})$ =5 GeV, $l_{1} \approx l_{2}$	1709.04193, 1711.01620
	$T_1T_1, T_1 \rightarrow cT_1 / cc, c \rightarrow c\tilde{T}_1$	0 0	2: mono (ct	Yes Yes	96.1 36.1	2) 2) 2)	0.46 0.43	0.85		V:C 0= ( <sup>1</sup> , <sup>1</sup> )(m W:C (2= (2=(1, 1)) m(ℓ <sub>1</sub> , 1) m(ℓ <sub>1</sub> ) = 0 (2) m(ℓ <sub>1</sub> , 1) m(ℓ <sub>1</sub> )	1505/01649 1505/01649 1711/00001
	$\vec{t}_2 \vec{t}_2, \vec{t}_2 \rightarrow \vec{t}_1 + \hat{t}_1$	$1.2 c_{e} \mu$	4.5	Yes.	36.1	Z <sub>1</sub>		0.32-0.88		$m(\tilde{\xi}_{12}^{3})=0$ GeV, $m(\tilde{\chi}_{1})$ $m(\tilde{\chi}_{1}^{3})=180$ GeV	1705.03068
	${\hat x}_1^{\pm} {\hat x}_2^{\pm}$ via WZ	2-3 c. p 10. pp	- 2 J	\$ \$ \$	36.1 36.1	えた(死) (表) (表) (元) (元) (元)	0	0.6		$m(\hat{t}_1^0)=0$ $m(\hat{t}_1^0)=0$ GeV	1403.5594, 1506.02203 1712.00118
	$\mathcal{R}_{1}^{*}\mathcal{R}_{2}^{*}$ via $We$	101737100		Yes:	20.3	$\chi_{1}^{*} E_{2}^{0} = 0.26$				m(7)(-0	1501/07110
EW direct	$\mathcal{K}_{1}^{*}\mathcal{R}_{1}^{*}\mathcal{J}_{2}^{0}, \mathcal{K}_{1}^{*} \rightarrow \tilde{r}\nu(r\tilde{v}), \mathcal{K}_{2}^{0} \rightarrow \tilde{r}r(v\tilde{v})$	27	-	Yes	36.1	$\hat{x}_{0}^{*} \hat{x}_{0}^{*} $ $\hat{x}_{0}^{*} \hat{x}_{0}^{*} $ 0.22		0.76	$m(\tilde{\epsilon}_1^{-}),m)\tilde{\epsilon}_2$	$m(\tilde{k}_{1}^{0})=0, m(\tilde{x},\tilde{v})=0.5(m(\tilde{k}_{1}^{0})+m(\tilde{k}_{1}^{0}))$ >-100 GeV, $m(\tilde{x},\tilde{v})=0.5(m(\tilde{k}_{1}^{0})+m(\tilde{k}_{1}^{0}))$	170×07825 170×07625
	$\delta_{L,R}\delta_{L,R}$ , $\ell \rightarrow \ell \tilde{\chi}_1^{\prime}$	2 6.p 2 6.p	0 ≥ 1	Yes Yes	36.1 36.1	7 7 0.18	0.5			$\mathbf{m}(\widetilde{t}_1^*,\mathbf{m}(\widetilde{t}_1^2)) = 5 \ \mathrm{GeV}$	1603.02762 1712.08(19
	RR, R→MC/ZC	9 4 c.p	> 36 D	Yes Yes	36.1 36.1	й 0.13-0.23 Й 0.3		0.29-0.88		$\begin{array}{l} \mathrm{DR}(\tilde{T}_1^0 \rightarrow M_{\mathrm{CP}}^0 1) \\ \mathrm{SR}(\tilde{T}_1^0 \rightarrow M_{\mathrm{CP}}^0 1) \end{array}$	1508.04030 1504.03052
Long-lived particles	Direct $\mathcal{X}_1^* \mathcal{X}_1$ prod., long-lived $\tilde{\mathcal{X}}_1^*$	Disapp. trk	1 jel	Yee	36.1	<sup>j</sup> <sup>1</sup> / <sub>1</sub> 0.15	0.46			Pure Wino Fure Higgsino	1710.02118 .0TL-PHYS-PUB-2012-018
	Stable g R-hadron	SVP	Multiples		8.2	8			1.6		1605.06129
	Metassable g B nacimit, $g \rightarrow qy c_1$ CMSB, $\tilde{T}_1^0 \rightarrow \gamma \tilde{C}_2$ long-lived $\tilde{L}_2^0$	2 8	-	Yes	20.3	$\hat{x}_{1}^{2} = construction $	0.44		1/2 /	1-cr/∛i-c) rs. SPS8-model	1400 0042
	$gg; X_1^0 \rightarrow cov(e\mu\nu/\mu\mu\nu)$	displ. we $\langle \eta q \rangle$	44		20.8	2			1.3	$0 < cr(\tilde{z}_1^0) < 1000mm, rr(\tilde{z}_1^0) = 1  leV$	1504.06162
	$LFV \ \rho p {\rightarrow} \hat{\pi}_{\tau} + X, \hat{\pi}_{\tau} {\rightarrow} e \rho / e \tau / \rho \tau$	$e\mu_{s}er_{s}\mu_{r}$		•	3.2	20			1.9	$\lambda_{\rm AM}^{\prime}{=}0.11, \lambda_{\rm PO}{}_{\rm PO}{}_{\rm PO}{=}0.07$	1607.08079
	$\hat{\chi}_1^{\pm}\hat{\chi}_1^{\mp}/\hat{\chi}_2^0 \rightarrow WW/2DWW$	$4 < \mu$	0	Yee	36.1	$\hat{X}_{0,1}^{\pm} \hat{K}_{0,1}^{\pm} = [\hat{X}_{0,0} \neq 0, \hat{d}_{1,0} \neq 0]$		0.82	1.33	m(ℓ <sub>1</sub> <sup>0</sup> )=100 GeV	1504,03632
>	$\mathcal{R}h, \mathcal{Z} \rightarrow q q \mathcal{K}_1, \mathcal{K}_1 \rightarrow q q q$	0 4	Multiple	na -	30.1 30.1	X = [m(K)] 200 GeV, 1100 GeV] X = [4 <sup>2</sup> <sub>112</sub> =2e-4, 2e-6]		1,00	1.3 1.9	Longe A <sub>11,2</sub> m(\$ <sup>0</sup> / <sub>1</sub> )=200 GeV/ binc-like	1001.03550 ATLAS CONF 2018 008
đ	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow thr/\tilde{g} \rightarrow t\tilde{t}r^0, \tilde{X}^0_1 \rightarrow thr$		Multiple		36.1	$\hat{g} = \{\hat{g}_{j,k}^{*}, -1, 1 \in \mathbb{Z}\}$		_	1.0 2.1	$n(\hat{x}_{1}^{0})$ = 200 GeV, bine-like	ATLAS-CONT-AND HUS
	$\tilde{n}, \tilde{r} \rightarrow t \tilde{k}_1^0, \tilde{k}_1^0 \rightarrow t b s$		Multiple		36.1	8 [1 <sup>v</sup> <sub>22</sub> =24-5, 14-2]	0.55	1.05	1	$m(\tilde{\mathcal{R}}_{1}^{0})$ =200 GeV; bino-like	ATLAS-CONF-2019-009
	$T_1T_1, T_1 \rightarrow 0.8$ $T_1T_1, T_1 \rightarrow 0.8$	0 9,55	2 103 + 2 1 2 b		36.7	21 (05.34) 21	0.42 0		0.4-1.45	$0 \mathrm{B}(t_1 \! \rightarrow \! i_N) \tilde{v}_N (> \! 2 \mathrm{MS})$	1719/07171 1719/06644
-											
"Only pher	a selection of the available ma tomena is shown. Many of the	ass limits on limits are ba	new state ised on	501	$\mathbf{n}$	0				Mass scale [TeV]	
simplified models, c.f. refs. for the assumptions made.											

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/

#### SUSY search limits

ATLAS SUSY Searches* - 95% CL Lower Limits July 2018 Vs - 7, 8, 13 TeV											
	Model	$e, \mu, \tau, \gamma$	Jets	$E_{\rm T}^{\rm miss}$	∫£ <i>di</i> [fb	<sup>-1</sup> ] Mass limit $\sqrt{s} = 7, 8 \text{ TeV}$ $\sqrt{s} = 13 \text{ TeV}$	W.	Reference			
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q \tilde{d}_1^{\dagger}$	0 mono-jat	2-8 jota 1-3 jota	Yes Yes	36.1 36.1	φ         (2x, 0x Deget.)         0.9         1.55         m           φ         (1x, 0x Deget.)         0.43         0.71         m         m	n(ℓ_1)=100 GeV ((m)ℓ_1)=5 GeV	1712/02032 1711/03901			
Inclusive Searche	8∛. 3→q9ℓ <sup>0</sup>	0	2-6 jols	Yes	36.1	2.0 Farbidden 0.95-1.6	n( $\tilde{t}_{1}^{0}$ >.200 GeV n( $\tilde{t}_{1}^{0}$ =300 GeV	1712-02034 1712-02032			
	33.3~9%(C)E	3 n, p $\delta c, \mu \mu$	4 ets 2 ets	Ns	36.1 36.1	3 3 1.85 mG)	$n(\tilde{F}_{ij}^{A} \sim 100  {\rm GeV})$ $m(\tilde{F}_{ij}^{A}) = 50  {\rm GeV}$	1708.03731 1505.11981			
	ŝš. ž−φ2₩Z <b>Ž</b> 1	0 3 4. µ	7-11 jets -4 jets	Ks	36.1 36.1	ž 1.8 m ž 0.98 m(či-n	(k <sup>2</sup> ) ≪100 G/V #(k <sup>2</sup> )−200 G/V	1708.02794 1708.03731			
	$\mathfrak{g}\mathfrak{g}\mathfrak{g}\mathfrak{g}\mathfrak{g}\mathfrak{g}\mathfrak{g}\mathfrak{g}\mathfrak{g}\mathfrak{g}$	0-1 c.p 3 c.p	SA -1jels	Yes	36.1 36.1	3 3 1.25 n(s) n	n(F))~300 SeV x(F))=900 SeV	1711.01901 1705.03781			
3 <sup>14</sup> gen, souartis driest production	$\hat{b}_1\hat{b}_1, \hat{b}_1 \rightarrow b\ell_1^0/tT_1^1$		Multiple Multiple Multiple		36.1 36.1 36.1	$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	aV, BB(AT)(=1 )(=BB(2T))=0.5 CeV, BB(2T)(=1	1708523286, 1711.03001 1708.09256 1705.03731			
	$\tilde{b}_1\tilde{b}_1,\tilde{t}_1\tilde{t}_1,M_2=2\times M_1$		Multiple Multiple		36.1 36.1	7) 0.7 7) Ferbiadan 0.9	m(\$ <sup>2</sup> )(−50 GeV n(\$ <sup>2</sup> ))=200 GeV	1703.04162, 1711.11520, 1706.02247 1703.04162, 1711.11520, 1706.02247			
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1  ightarrow W \tilde{t}_1^{(2)}  ext{ or } \tilde{t}_1^{(2)}$ $\tilde{t}_1 \tilde{t}_1, \tilde{H} \text{ LSP }$	0-2 <i>4.</i> 9 0	-2 jets/1-2. Multiple Multiple	0 Yes	36.1 36.1 36.1	A         1.0           7,         0.4-0.9         m(?)-150Call, m(?)-m(?)           7,         Forbiddun         0.8-0.8         m(?)-150Call, m(?)-m(?)	m(2) <sup>1</sup> (−1 GeV (−5 GeV, i <sub>1</sub> ≈ i <sub>2</sub> , (−5 GeV, i <sub>1</sub> ≈ i <sub>2</sub> ,	1508.06516, 1709.04188, 1711, 11520 1.7069.04183, 1711, 11520 1.7069.04183, 1711, 11520			
	$\tilde{r}_{1}\tilde{r}_{1}$ , Well-Tempered LSP		Multiple		36.1	$t_1$ 0.48-0.84 $m(\tilde{r}_1^0)$ =150 GeV, $m(\tilde{r}_1^0)$ -m( $\tilde{r}_1^0$ )	$\pm 5$ GeV, $i_1 \sim i_2$ .	1709.04193, 1711.01020			
	$f_1 f_1, f_1 \rightarrow c \tilde{t}_1^{\prime \prime} / \tilde{c} c, \tilde{c} \rightarrow c \tilde{t}_1^{\prime \prime}$	۰ ٥	2: nono ist	Yee Yee	36.1 36.1	λ 0.85 λ 0.46 m(ζ./) λ 0.43 m(ζ./)	m( $\tilde{t}_{1}^{2}$ )=0.3cV m( $\tilde{t}_{1}^{2}$ )=0.3cV (m) $\tilde{t}_{1}^{2}$ )=0.3cV	1805/01649 1805/01649 1711/03001			
	$bb, b \rightarrow b + b$	1-2 c. g	4.5	Yes.	36.1	2	v(2)=180.30V	1705/05968			
	No. of the WZ	236.0		¥s.	35.1	11	m <sup>20</sup> 1-0	1403 5694, 1906,02203			
		se, pji	21	Yes	36.1	🌁 The search continues 👘 🤲	$m(\hat{k}_{1}^{0}) = 10 \text{ GeV}$	1712-00118			
s EW	$\hat{X}_{1}^{+}\hat{X}_{2}^{0}$ with $Wh$ $\hat{V}^{+}\hat{V}^{+}$ $\hat{V}^{0}$ $\hat{V}^{+}$ , where $\hat{V}^{0}$ , where $\hat{V}$	1017y/105		Yes Yes	20.3		m(ří)(=0 Starti <sup>2</sup> (= m)( <sup>2</sup> ()	1501.0710			
	$A[a](x_2,x_1 \neg \phi)(\phi)(x_2 \neg \phi)(\phi)$			1.52		$\hat{k}_{0}^{*}/\hat{k}_{0}^{*}$ 0.22 $m(\hat{k}_{1}^{*})m(\hat{k}_{1}^{*})-100$ GeV, $m(x, \hat{y})=0.5$	$i[m]\tilde{k}_{1}^{*}(+n)\tilde{k}_{1}^{*}()$	12050-0325			
	$\hat{c}_{L,R}\hat{c}_{L,R}, \hat{c} \rightarrow \hat{c}\hat{c}_{1}^{0}$	2 c.p	0 ≥ 1	Yos Yos	36.1 36.1	7 0.5 7 0.18 m(?)	$m(\tilde{r}_{1}^{0})=0$ $(m(\tilde{r}_{1}^{0})=5$ GeV	1803/02/62 1712/08119			
	ĤĤ, R→MG/ZC	9 4 с.р	> 38 0	Yos Yes	36.1 36.1	n         0.13-0.23         0.29-0.88         n           n         0.3         6         6	$\begin{array}{l} \mathrm{IR}(\widehat{T}_{j}^{0} \rightarrow M\widehat{c}) = 1 \\ \mathrm{IR}(\widehat{T}_{j}^{0} \rightarrow 2\widehat{C}) = 1 \end{array}$	1809.04030 1504.03602			
	Direct $\hat{\mathcal{X}}_1^* \hat{\mathcal{X}}_1$ prod., long lived $\hat{\mathcal{X}}_1^*$	Disapp. trk	1 jel	Yee	36.1	$\hat{x}_{\mu}^{\Lambda} = 0.46$ $\hat{x}_{\mu}^{\Lambda} = 0.15$	Pure Wino Pure Higgsho	1713.02118 XTI-PHYS-PUB-2017-019			
Pick Pick	Stable g R-hadron	SVP			8.2	8 1.6		1505.05129			
Long	Metastable $\hat{g} \in \mathbb{R}$ hadron, $\hat{g} \rightarrow q g \hat{k}^{0}_{1}$ CMSE $\hat{x}^{0}_{1} \rightarrow g \hat{x}^{0}_{2}$ is not lead $\hat{x}^{0}_{2}$	2 %	мары	West.	32.8	2 [19] = 100 m, 02 m] 1.6 2.4 T P <sup>4</sup> 0.44 1.5 2.5 2.5 1.5 1.5 1.5 1.5 1.5 1.5 1.5 1.5 1.5 1	a(∜](=100 GeV a, SDStandal	1210.24501, 16.24.24520			
	$\bar{g}\bar{g}, \tilde{\chi}^0_1 \rightarrow cev/epv/ppv$	displ.we/ap/pp			20.3	$\frac{1}{3}$ $\frac{1}{3}$ $\frac{1}{3}$ $\frac{1}{3}$ $\frac{1}{3}$	$m, m(\tilde{t}_1^0) = 1.16V$	1504.06162			
	$LFV(\rho p {\mapsto} i_\tau + X, i_\tau {\rightarrow} e \rho / e \tau / \rho \tau$	ey,et,or		•	3.2	2 <sub>μ</sub> . 1.9 J <sub>en</sub> =0.11, J	0.07 <sub>0000000000000000000000000000000000</sub>	1607.00079			
РV	$\hat{\chi}_1^{\pm} \hat{\chi}_1^{\mp} / \hat{\chi}_2^{0} \rightarrow WW/2DW m$	4 c. p	0	Yee	35.1	$\hat{x}_{0}^{*}/\hat{x}_{0}^{3} = [\hat{x}_{12} \neq 0, A_{12} \neq 0]$ 0.02 1.33	a(2)(=100/3±V	1504.03632			
	$R_{1}^{p}, 3 \rightarrow qq \ell_{1}^{r}, \ell_{1}^{r} \rightarrow qqq$	0 +4	Starge-Arje Multiple	na -	30.1 30.1	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	Carge A <sub>112</sub> CGeV, binc-like	1701.03550 ATLAS CONF 2018 008			
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow thr / \tilde{g} \rightarrow t\tilde{t}r^{0}_{1}, \tilde{x}^{0}_{1} \rightarrow thr$		Multiple		36.1	3 (X <sub>2</sub> =1,10/2) 1,0 2,1 n(X)(-201	GeV/bine-like	ATLAS-CONF-900 HIGH			
	$\vec{n}, \vec{r} \rightarrow t \vec{k}_1^0, \vec{k}_1^0 \rightarrow t b \tau$		Multiple		35.1	$\frac{1}{2} = [\Gamma_{g_1}^{\nu} - 2a - c_1 + a 2] = 0.55 = 1.05 = \pi (\hat{t}_1^{\nu}) - 2\pi i$	Ciel ( bind-like)	ATLAS-CONT-2019-009			
	$T_1(t_1, t_1) \rightarrow 0.8$ $T_1(t_1, t_1) \rightarrow 0.8$	20,0	2h 2h		36.7 36.1	<sup>2</sup> 1 <u>25</u> . <sup>λ+</sup> ] 0.42 0.61 ξ <sub>1</sub> 0.4-1.45 Πογ.		1710,07171 1710,06644			
-											
Conty a selection of the available mass limits on new states or 10 <sup>-4</sup> Mass scale [TeV]											
simplified models, c.f. refs. for the assumptions made.											

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/

# ALICE

- Studying heavy ion collisions
- Collaboration: ~1500 people



# ALICE

Trying to probe thermodynamics at the big bang:
 —> quark-gluon plasma



https://www.sciencedirect.com/science/article/pii/S2405428316300144

## LHCb

- 'B'-quark properties
- Collaboration: ~600 people



• downstream of the second of the s

Not so great calorimetry, lower pileup (= # PVs per bX)



# LHCb

- live event display: <u>https://lbevent.cern.ch/EventDisplay/index.html</u>
- live status display: <a href="https://op-webtools.web.cern.ch/vistar/vistars.php">https://op-webtools.web.cern.ch/vistar/vistars.php</a>



# LHCb

- LHCb's mission is to make extremely precise flavour measurements
   –> new particles could contribute to quantum loops
- If observation  $\neq$  SM prediction: new physics!
- Very rare decays
- (time-dependent) CP violation
- lifetimes, spectroscopy of new states (X-quarks, where X>3)





#### $B \longrightarrow mu mu$

- Very rare decay:  $\sim 10^{-9}$  !
- Very suppressed and only via quantum loops -> new particles!
- First observed in 2017
- Seems close to SM, but error still large



## CP violation

• Many modes measured. One exciting relic from ~2010 debunked!



# CP violation

- Many modes measured. One exciting relic from ~2010 debunked!
- Mostly consistent with standard model.



## Lepton non-universality

Standard model: coupling to all leptons is the same ('universal').
 —> Observe: ratio of (B —> D tau) / (B —> D mu): too high!



### Lepton non-universality

Standard model: coupling to all leptons is the same ('universal').
 —> transition of [b —> s mu+ mu-] / [b —> s e+ e-]: too low!



https://arxiv.org/pdf/1406.6482.pdf

## Lepton non-universality

- Both can be classified by the same type of 'new interactions'!
   'Combination' ~ 5 sigma?
- Potential explanation?
  - ~TeV scale Z' boson?
  - ~TeV LeptoQuark?

Then Atlas/CMS should see it soon!





https://cds.cern.ch/record/2270937/files/LHCb-PROC-2017-018.pdf http://benasque.org/2017lhc/talks\_contr/244\_NP-Kosnik.pdf

# Summary

- Many exciting fundamental questions
- Many recent high-profile results (and don't forget about the nobel prizes for the Higgs (2013), neutrino oscillations (2015))
- Well underway of shedding light on many mysteries
   —> Many new experiments being set up, within 5-10 years
- Era of multi-messenger astronomy is <u>now</u>!
- LHC: many interesting results, mostly statistically limited —> Upgrade of LHC detectors: 2018-2020, <u>will provide answers</u>
- These are **exciting times** to be a particle physicist!

# Big questions in physics

- What is dark matter?
- What is the mass of neutrinos?
- Where do the ultra high energy cosmic rays come from?
- Are protons unstable?
- Where did all the antimatter go?
- What happened during the big bang?
- Why is the Higgs mass so fine-tuned?
- Why are there (only) three generations?
- What is the top quark mass?

http://discovermagazine.com/2002/feb/cover

# Big questions in physics

- What is dark matter?
- What is the mass of neutrinos?
- Where c
- Are prot
- Where c
- What ha
- Why is t
- Why are
- What is



http://discovermagazine.com/2002/feb/cover