Emerging Emphases in High Energy Physics: A Theorist's Perspective

Biswarup Mukhopadhyaya
Indian Institute of Science Education and Research Kolkata

CHEP, IISc, August, 2024

There seems to be a little indecisiveness, because...

- .....

There seems to be a little indecisiveness, because...

- .....
- *No clear hint about physics beyond the standard model (BSM)*

There seems to be a little indecisiveness, because...

- *.....*
- *No clear hint about physics beyond the standard model (BSM)*
- *The 'Higgs and nothing' picture is not what we had expected.*
  Also, crucially, 'the Higgs' or 'a Higgs' ?

There seems to be a little indecisiveness, because...

- *.....*
- *No clear hint about physics beyond the standard model (BSM)*
- *The 'Higgs and nothing' picture is not what we had expected.*
  Also, crucially, 'the Higgs' or 'a Higgs' ?
- *The influx of new physics theories (SUSY, X-dim, GUT, 2HDM/alternative EWSB schemes...) has far outweighed the flow of supporting observations.*
  Data collected is voluminous but not sufficiently striking/time-tested.

- *Are we still under the spell of the revolutions (QM, STR/GTR) that swept us, starting from the* **'two clouds in the sky of physics,**, *noted by Lord Kelvin around 1900?*

- *Are we still under the spell of the revolutions (QM, STR/GTR) that swept us, starting from the* **'two clouds in the sky of physics,**, *noted by Lord Kelvin around 1900?*
- *True,*
  No. of theoretical proposals $>>$ **Amount of data**
  But, can it be taken in a positive spirit, rather than one of deprecation?

- *Are we still under the spell of the revolutions (QM, STR/GTR) that swept us, starting from the* **'two clouds in the sky of physics,**, *noted by Lord Kelvin around 1900?*
- *True,*
  No. of theoretical proposals $>>$ **Amount of data**
  But, can it be taken in a positive spirit, rather than one of deprecation?
- *Rather than having*
  One (or no) question $\longrightarrow$ **one theoretical model**,
  Haven't we started visualising
  Related observations $\longrightarrow$ **multiple theoretical issues?**,
  (especially, with AI/ML-aided tools and techniques)

At the low-energy end: dipole moments...

- $(g-2)_\mu$: *A clear deficit in SM contribution is claimed, by most-groups who estimate the HVP/LBL contribution based on the data-driven method.*
  As usual, many electroweak BSM contributions proposed over the years

At the low-energy end: dipole moments...

- $(g-2)_\mu$: *A clear deficit in SM contribution is claimed, by most-groups who estimate the HVP/LBL contribution based on the data-driven method.*
  As usual, many electroweak BSM contributions proposed over the years
- *Lattice-based estimates claim no discrepancy, though with larger error-bars.*

At the low-energy end: dipole moments...

- $(g-2)_\mu$: *A clear deficit in SM contribution is claimed, by most-groups who estimate the HVP/LBL contribution based on the data-driven method.*
  As usual, many electroweak BSM contributions proposed over the years
- *Lattice-based estimates claim no discrepancy, though with larger error-bars.*
- *The recent CMD3 results, however, claim much bigger contributions, and practically no deficit.*

At the low-energy end: dipole moments...

- $(g-2)_\mu$: *A clear deficit in SM contribution is claimed, by most-groups who estimate the HVP/LBL contribution based on the data-driven method.*
  As usual, many electroweak BSM contributions proposed over the years
- *Lattice-based estimates claim no discrepancy, though with larger error-bars.*
- *The recent CMD3 results, however, claim much bigger contributions, and practically no deficit.*
- *Resolution:*
  Awaits reduced uncertainty in lattice estimates.
  Also, consistency of data-driven estimates, contingent upon long-distance QCD.

At the low-energy end: dipole moments...

- $(g-2)_\mu$: *A clear deficit in SM contribution is claimed, by most-groups who estimate the HVP/LBL contribution based on the data-driven method.*
  As usual, many electroweak BSM contributions proposed over the years
- *Lattice-based estimates claim no discrepancy, though with larger error-bars.*
- *The recent CMD3 results, however, claim much bigger contributions, and practically no deficit.*
- *Resolution:*
  Awaits reduced uncertainty in lattice estimates.
  Also, consistency of data-driven estimates, contingent upon long-distance QCD.
- *BSM contributions: relevant, but may end up constraining scenarios.*
  On the whole, intertwined issues need to be addressed.

At the low-energy end: dipole moments...

- *Electric dipole moment of the neutron (EDMN):*
  The weak CP-violating (CKM) phase alone keeps the contribution low
  However, there are potential contributions from the chromo-electric dipole moment operator arising via a strong CPV phase.

At the low-energy end: dipole moments...

- *Electric dipole moment of the neutron (EDMN):*
  The weak CP-violating (CKM) phase alone keeps the contribution low
  However, there are potential contributions from the chromo-electric dipole moment operator arising via a strong CPV phase.
- *Some recent lattice estimates revisit the strong contribution (including the Weinberg three-gluon operator).*
  The strong phase may mount higher than the weak phase effect. (in spite of large uncertainties)
  (T. Bhattacharya et al., (2021,2022,2024))

At the low-energy end: dipole moments...

- *Electric dipole moment of the neutron (EDMN):*
  The weak CP-violating (CKM) phase alone keeps the contribution low
  However, there are potential contributions from the chromo-electric dipole moment operator arising via a strong CPV phase.
- *Some recent lattice estimates revisit the strong contribution (including the Weinberg three-gluon operator).*
  The strong phase may mount higher than the weak phase effect. (in spite of large uncertainties)
  (T. Bhattacharya et al., (2021,2022,2024))
- *Relates to the question:*
  Can the strong phase explain baryogenesis too?

  Again, connects long-distance QCD, weak vs strong CP-violation, and cosmology.

Around the TeV scale ...

- *We do not yet have decisive,* **correlated** *signals of any specific new physics signal (of SUSY, X-dim, GUT, LR-symmetry, 2HDM...) proposed so far*

Around the TeV scale ...

- *We do not yet have decisive,* **correlated** *signals of any specific new physics signal (of SUSY, X-dim, GUT, LR-symmetry, 2HDM...) proposed so far*
- *There is instead a* **somewhat healthy** *trend of going bottom-up, in a data-driven manner.*

  One of the biggest sources: what we think of as the Higgs particle

Around the TeV scale ...

- *We do not yet have decisive,* **correlated** *signals of any specific new physics signal (of SUSY, X-dim, GUT, LR-symmetry, 2HDM...) proposed so far*
- *There is instead a* **somewhat healthy** *trend of going bottom-up, in a data-driven manner.*

  One of the biggest sources: what we think of as the Higgs particle
- *In the past, While still undetected, this particle has fixed some issues like its own mass range in SM, MSSM, etc. What is needed now is some* **robust** *evidence of conflict/contradiction.*

Around the TeV scale ...

- *We do not yet have decisive,* **correlated** *signals of any specific new physics signal (of SUSY, X-dim, GUT, LR-symmetry, 2HDM...) proposed so far*
- *There is instead a* **somewhat healthy** *trend of going bottom-up, in a data-driven manner.*

  One of the biggest sources: what we think of as the Higgs particle
- *In the past, While still undetected, this particle has fixed some issues like its own mass range in SM, MSSM, etc. What is needed now is some* **robust** *evidence of conflict/contradiction.*
- *Currently, the BSM scenario that is pursued most is an extended EWSB sector.*

Not purely wishful thinking, because ...

- *An extended ESWB sector is likely to lie relatively close to the EWSB scale.*

Not purely wishful thinking, because ...

- *An extended ESWB sector is likely to lie relatively close to the EWSB scale.*
- *Vacuum stability + unitarity: More easily valid till high scales in, say, 2HDM as compared to the SM*

Not purely wishful thinking, because ...

- *An extended ESWB sector is likely to lie relatively close to the EWSB scale.*
- *Vacuum stability + unitarity: More easily valid till high scales in, say, 2HDM as compared to the SM*
- *An extended scalar sector is a better portal to dark matter/dark sector*

Not purely wishful thinking, because ...

- *An extended ESWB sector is likely to lie relatively close to the EWSB scale.*
- *Vacuum stability + unitarity: More easily valid till high scales in, say, 2HDM as compared to the SM*
- *An extended scalar sector is a better portal to dark matter/dark sector*
- *All these for parameter ranges where signals are observable at the HL-LHC*

Effective field theories ...

- *A perceived panacea (and justifiably)....*

Effective field theories ...

- *A perceived panacea (and justifiably)....*
- *SMEFT:*
  $\mathcal{L} = \mathcal{L}_{SM} + \Sigma \frac{c_j}{\Lambda^2} O_j^6 + \Sigma \frac{c_i}{\Lambda^4} O_i^8$

Effective field theories ...

- *A perceived panacea (and justifiably)....*
- *SMEFT:*
  $\mathcal{L} = \mathcal{L}_{SM} + \Sigma \frac{c_j}{\Lambda^2} O_j^6 + \Sigma \frac{c_i}{\Lambda^4} O_i^8$
- *HEFT:*
  $\mathcal{L} = ... + \frac{v^2}{4} F(h) Tr[(D_\mu U^\dagger)(D_\mu U)] + \frac{1}{2}(\partial_\mu h)^2 - V(h)$

  $F(h), V(h)$: *infinite series in* h/v, *with the Higgs field shifted w.r.t. vev*

  $U = exp(\tau_i \pi_i / v)$, $\pi_i (i = 1 - 3) =$ *goldstones,*
  $v =$ *Higgs vev*
  (Usually works for $v << \Lambda$, *the UV physics scale)*

Effective field theories ...

- *A perceived panacea (and justifiably)....*
- *SMEFT:*
  $\mathcal{L} = \mathcal{L}_{SM} + \Sigma \frac{c_j}{\Lambda^2} O_j^6 + \Sigma \frac{c_i}{\Lambda^4} O_i^8$
- *HEFT:*
  $\mathcal{L} = ... + \frac{v^2}{4} F(h) Tr[(D_\mu U^\dagger)(D_\mu U)] + \frac{1}{2}(\partial_\mu h)^2 - V(h)$

  $F(h), V(h)$: *infinite series in* h/v, *with the Higgs field shifted w.r.t. vev*

  $U = exp(\tau_i \pi_i / v)$, $\pi_i (i = 1 - 3) =$ *goldstones,*
  $v =$ *Higgs vev*
  (Usually works for $v << \Lambda$, *the UV physics scale)*
- *Procedure for working back to any proposed UV physics :*
  UV parameters matched with EFT parameters@Λ
  Evolved down to $v \longrightarrow$ *checked against measurements*
  $\longrightarrow$ *UV physics under probe*

Effective field theories ...

- *Many possible operators at any order*
  $\Rightarrow$ Large set (typically, $\sim 20 - 30$) to be selected for any relevant process.

  Sophisticated techniques based on Machine Learning are of great help

Effective field theories ...

- *Many possible operators at any order*
  $\Rightarrow$ Large set (typically, $\sim 20 - 30$) to be selected for any relevant process.

  Sophisticated techniques based on Machine Learning are of great help
- *A parallel feeder programme on possible UV physics warranted, with less bias towards 'lightness' of new particles.*

Effective field theories ...

- *Many possible operators at any order*
  $\Rightarrow$ Large set (typically, $\sim 20 - 30$) to be selected for any relevant process.

  Sophisticated techniques based on Machine Learning are of great help
- *A parallel feeder programme on possible UV physics warranted, with less bias towards 'lightness' of new particles.*
- *EFT will connect the UV world with top, Higgs and electroweak precision physics*

- *Sample UV scenarios, and the matching process have to be creative*

- *Sample UV scenarios, and the matching process have to be creative*
- *a la Dawson (2024), HEFT, for sample UV scenarios, admit non-unique matching*
  Such pitfalls require intensive investigations

- *Sample UV scenarios, and the matching process have to be creative*
- *a la Dawson (2024), HEFT, for sample UV scenarios, admit non-unique matching*
  Such pitfalls require intensive investigations
- *EFT mostly assumes that all unseen particles are at the UV scale Λ and above.*
  How to address scenarios where light degrees of freedom ($\lesssim v$) may exist and may be difficult to detect.
  (e.g. a light pseudoscalar/graviscalar)

- *Sample UV scenarios, and the matching process have to be creative*
- *a la Dawson (2024), HEFT, for sample UV scenarios, admit non-unique matching*
  Such pitfalls require intensive investigations
- *EFT mostly assumes that all unseen particles are at the UV scale Λ and above.*
  How to address scenarios where light degrees of freedom ($\lesssim v$) may exist and may be difficult to detect.
  (e.g. a light pseudoscalar/graviscalar)
- *Is there any alternative to the direct measurement of the Higgs self-coupling to the precision level of 1%?*
  (which may become the issue-clincher in 'the Higgs or a Higgs'?) (read SM or BSM)

‘Blessed are the poor in spirit, for theirs is the kingdom of heaven’...

- *Baryogenesis/leptogenesis: again, lots of models proposed, without much of* **new kind of data**

'Blessed are the poor in spirit, for theirs is the kingdom of heaven'...

- *Baryogenesis/leptogenesis: again, lots of models proposed, without much of* **new kind of data**
- *It is useful to probe if B/L violation is linked with the dark matter (DM) problem.*
  Asymmetric DM scenarios are suggestive, but concrete numerical predictions/checks awaited.

'Blessed are the poor in spirit, for theirs is the kingdom of heaven'...

- *Baryogenesis/leptogenesis: again, lots of models proposed, without much of* **new kind of data**
- *It is useful to probe if B/L violation is linked with the dark matter (DM) problem.*
  Asymmetric DM scenarios are suggestive, but concrete numerical predictions/checks awaited.
- *Gravitational wave: suggested as a source of particle physics information.*
  What is the wait period for some breakthrough?

JWST...

- *Details of inflation, dark energy .....*

JWST...

- *Details of inflation, dark energy .....*
- *Test for ΛCDM in small bright red galaxies at large redshift*

JWST...

- *Details of inflation, dark energy .....*
- *Test for ΛCDM in small bright red galaxies at large redshift*
- *Dark stars:* **made of** *H_2/He, powered by* **not** *nuclear fusion* **but** *DM annihilation.*
  Theoretical efforts may yield information re DM annihilation channels, upon their observation.

JWST...

- *Details of inflation, dark energy .....*
- *Test for ΛCDM in small bright red galaxies at large redshift*
- *Dark stars:* **made of** *H_2/He, powered by* **not** *nuclear fusion* **but** *DM annihilation.*
  Theoretical efforts may yield information re DM annihilation channels, upon their observation.
- **Einstein ring** *around the galaxy JWST-ER1g*
  (17 billion ly away, $\approx$ 10 billion years old)
  A pointer towards high-mass DM
  An impetus to theorists?

In the context of DM.....

- *Neutrino experiments: Super-K, ICECUBE, ICARUS, ANTARES...*

In the context of DM.....

- *Neutrino experiments: Super-K, ICECUBE, ICARUS, ANTARES...*
- *γ-ray experiments: HESS, CTEQ...*
  The high energy (read DM mass) end is especially open to studies

In the context of DM.....

- *Neutrino experiments: Super-K, ICECUBE, ICARUS, ANTARES...*
- *γ-ray experiments: HESS, CTEQ...*
  The high energy (read DM mass) end is especially open to studies
- *Detectability will improve, but revelations on the dynamics of DM particles may not come.*

In the context of DM.....

- *Neutrino experiments: Super-K, ICECUBE, ICARUS, ANTARES...*
- *γ-ray experiments: HESS, CTEQ...*
  The high energy (read DM mass) end is especially open to studies
- *Detectability will improve, but revelations on the dynamics of DM particles may not come.*
- *Radio signals from dwarf spheroidal galaxies (dSph): Has more serious dependence on DM dynamics, since that determines the intensity and energy profile of e^+e^- emitting radio synchrotron signals.*
  The Square Kilometer Array (SKA) telescope enables detection of $\gtrsim$ 5-10 TeV DM particles

In the context of DM.....

- *Neutrino experiments: Super-K, ICECUBE, ICARUS, ANTARES...*
- *γ-ray experiments: HESS, CTEQ...*
  The high energy (read DM mass) end is especially open to studies
- *Detectability will improve, but revelations on the dynamics of DM particles may not come.*
- *Radio signals from dwarf spheroidal galaxies (dSph): Has more serious dependence on DM dynamics, since that determines the intensity and energy profile of e^+e^- emitting radio synchrotron signals.*
  The Square Kilometer Array (SKA) telescope enables detection of $\gtrsim$ 5-10 TeV DM particles
- *Potential food for thought for DM theorists*

DM studies: some general bias and uncertainties....

- *Direct DM search: expected event rates are based on Maxwellian distribution—*
  no local fluctuation/clumping

DM studies: some general bias and uncertainties....

- *Direct DM search: expected event rates are based on Maxwellian distribution—*
  no local fluctuation/clumping

- *a few tens of GeV* $\lesssim$ *WIMP mass* $\lesssim$ *a few hundred GeV's*

DM studies: some general bias and uncertainties....

- *Direct DM search: expected event rates are based on Maxwellian distribution—*
  no local fluctuation/clumping
- *a few tens of GeV* $\lesssim$ *WIMP mass* $\lesssim$ *a few hundred GeV's*
- *Collider signals of DM* $\Rightarrow$ *MET*

DM studies: some general bias and uncertainties....

- *Direct DM search: expected event rates are based on Maxwellian distribution—*
  no local fluctuation/clumping
- *a few tens of GeV* $\lesssim$ *WIMP mass* $\lesssim$ *a few hundred GeV's*
- *Collider signals of DM* $\Rightarrow$ *MET*
- *The DM is* **stable**

DM studies: some general bias and uncertainties....

- *Direct DM search: expected event rates are based on Maxwellian distribution—*
  no local fluctuation/clumping
- *a few tens of GeV* $\lesssim$ *WIMP mass* $\lesssim$ *a few hundred GeV's*
- *Collider signals of DM* $\Rightarrow$ *MET*
- *The DM is* **stable**
- *DM annihilation/decay* $\Rightarrow$ *two-body final states*

DM studies: some general bias and uncertainties....

- *Direct DM search: expected event rates are based on Maxwellian distribution—*
  no local fluctuation/clumping
- *a few tens of GeV* $\lesssim$ *WIMP mass* $\lesssim$ *a few hundred GeV's*
- *Collider signals of DM* $\Rightarrow$ *MET*
- *The DM is* **stable**
- *DM annihilation/decay* $\Rightarrow$ *two-body final states*
- *For indirect signals, values of the relevant astrophysical parameters are in 'standard' ranges*

DM studies: some general bias and uncertainties....

- *Direct DM search: expected event rates are based on Maxwellian distribution—*
  no local fluctuation/clumping
- *a few tens of GeV* $\lesssim$ *WIMP mass* $\lesssim$ *a few hundred GeV's*
- *Collider signals of DM* $\Rightarrow$ *MET*
- *The DM is* **stable**
- *DM annihilation/decay* $\Rightarrow$ *two-body final states*
- *For indirect signals, values of the relevant astrophysical parameters are in 'standard' ranges*
- *Departure from the standard assumptions may alter DM search paradigms and also the standard conclusions*

With no assumption about DM annihilation BR, a WIMP DM can be anywhere between a few MeV and tens of TeV's...

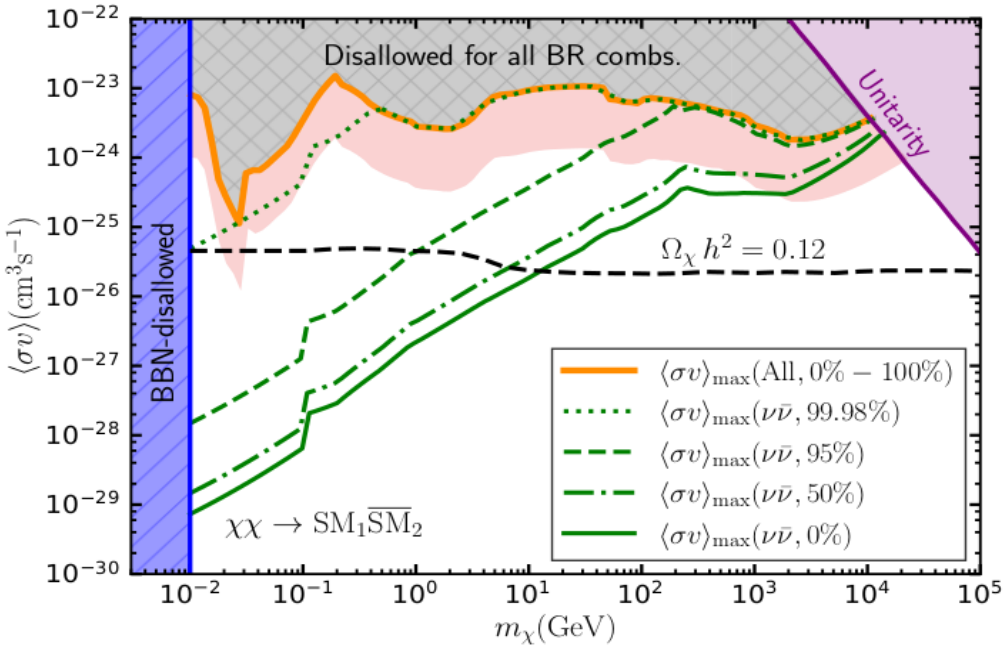

FIG. 4. For a single-component thermal WIMP, constituting all the observed DM, the orange line represents the BR-independent upper limit on total $\langle\sigma v\rangle$ (at 95% C.L.) and the light red band shows its variation with the astrophysical uncertainties, in the m_χ range 10 MeV - 100 TeV. The gray region is ruled out for all possible BR combinations, while, the blue region is disallowed by BBN [25, 26]. The purple and the black lines are the same as in Fig. 3. Variation of the maximum allowed total $\langle\sigma v\rangle$ with the BR attributed to $\nu\bar{\nu}$ are shown by the green lines. See the text for details.

From K. Dutta, A. Kar, A. Ghosh, BM (2022)

"To know, is to know that you know nothing ..."

Socrates