Prospects for Future Collider Physics

What is the Higgs boson trying to tell us?
Is supersymmetry waiting?
Can LHC Run 2 find it?
What if X(750) exists?
Sphalerons?

John Ellis
Higgs Mass Measurements

- ATLAS + CMS ZZ* and γγ final states

One thing we have!

125.09 ± 0.21 (stat) ± 0.11 (syst)

- Statistical uncertainties dominate
- Allows precision tests
- Crucial for stability of electroweak vacuum
Elementary Higgs or Composite?

- Higgs field: \( \langle 0 | H | 0 \rangle \neq 0 \)
- Quantum loop problems

\( m_h^2 \sim (200 \text{ GeV})^2 \)

- Cut-off \( \Lambda \sim 1 \text{ TeV} \) with Supersymmetry?
- Cutoff \( \Lambda = 10 \text{ TeV} \)

- Fermion-antifermion condensate
- Just like QCD, BCS superconductivity
- Top-antitop condensate? needed \( m_t > 200 \text{ GeV} \)

New technicolour force?
- Heavy scalar resonance?
- Little Higgs, …
- Re-awakened by \( X(750) \)?
Why is there Nothing rather than Something?

- Higher-dimensional operators as relics of higher-energy physics, e.g., dimension 6:

\[ \mathcal{L}_{\text{eff}} = \sum_{n} \frac{f_n}{\Lambda^2} \mathcal{O}_n \]

- Operators constrained by SU(2) \times U(1) symmetry:

\[
\mathcal{L} \supset \frac{\bar{c}_H}{2v^2} \partial^\mu [\Phi^\dagger \Phi] \partial_\mu [\Phi^\dagger \Phi] + \frac{g'^2}{m_W^2} \Phi^\dagger \Phi B_{\mu\nu} B^{\mu\nu} + \frac{g_s^2}{m_W^2} \Phi^\dagger \Phi G^a_{\mu\nu} G^{\mu\nu}_a \\
+ \frac{2ig}{m_W^2} \bar{c}_{HW} [D^\mu \Phi^\dagger T_{2k} D^\nu \Phi] W^k_{\mu\nu} + \frac{ig'}{m_W^2} \bar{c}_{HB} [D^\mu \Phi^\dagger D^\nu \Phi] B_{\mu\nu} \\
+ \frac{ig}{m_W^2} \bar{c}_W [\Phi^\dagger T_{2k} \overleftrightarrow{D}^\mu \Phi] D^\nu W^k_{\mu\nu} + \frac{ig'}{2m_W^2} \bar{c}_B [\Phi^\dagger \overleftrightarrow{D}^\mu \Phi] \partial^\nu B_{\mu\nu} \\
+ \frac{\bar{c}_t}{v^2} y_t \Phi^\dagger \Phi \Phi^\dagger \cdot \bar{Q}_L t_R + \frac{\bar{c}_b}{v^2} y_b \Phi^\dagger \Phi \Phi \cdot \bar{Q}_L b_R + \frac{\bar{c}_\tau}{v^2} y_\tau \Phi^\dagger \Phi \Phi \cdot \bar{L}_L \tau_R
\]

- Constrain with precision EW, Higgs data, TGCs ...
Global Fits including LHC TGCs

- Higgs production
- LHC Triple-gauge couplings
- Global combination
- Individual operators
Projected $e^+e^-$ Colliders: Luminosity vs Energy

Updated from TLEP physics study group: arXiv:1308.6176
• **LHC constraints**

• **FCC-ee constraints**: see $\Lambda \sim 10$ TeV?
• Shadings:
  – With/without theoretical uncertainties in EWPTs

• Shadings of green:
  – Effect of including TGCs at ILC

**FCC-ee Higgs & TGC Measurements**

**EWPTs and Higgs**

**Higgs and TGCs**
• «Empty» space is unstable
• Dark matter
• Origin of matter
• Masses of neutrinos
• Hierarchy problem
• Inflation
• Quantum gravity
• ...

The Standard Model
What lies beyond the Standard Model?

Supersymmetry

• Stabilize electroweak vacuum
• Successful prediction for Higgs mass
  – Should be < 130 GeV in simple models
• Successful predictions for couplings
  – Should be within few % of SM values
• Naturalness, GUTs, string, …, dark matter

New motivations
From LHC Run 1
Theoretical Constraints on Higgs Mass

- Large $M_h \rightarrow$ large self-coupling $\rightarrow$ blow up at low energy scale $\Lambda$ due to renormalization.

- Small: renormalization due to $t$ quark drives quartic coupling $< 0$ at some scale $\Lambda \rightarrow$ vacuum unstable.

- Vacuum could be stabilized by Supersymmetry.

\[ \lambda(Q) = \lambda(v) - \frac{3m_t^4}{2\pi^2v^4} \log \frac{Q}{v} \]

Instability @ $10^{11.1 \pm 1.3}$ GeV

Degrassi, Di Vita, Elias-Miro, Giudice, Isodori & Strumia, arXiv:1205.6497
Vacuum Instability in the Standard Model

- Very sensitive to $m_t$ and $\Lambda_H$

- Instability scale:

\[
\log_{10}\left(\frac{\Lambda}{\text{GeV}}\right) = 11.3 + 1.0\left(\frac{M_h}{\text{GeV}} - 125.66\right) - 1.2\left(\frac{M_t}{\text{GeV}} - 173.10\right) + 0.4\frac{\alpha_3(M_Z) - 0.1184}{0.0007}
\]

- World average
- New D0
- New ATLAS
- New CMS

$\mathbf{m_t = 173.3 \pm 1.0 \text{ GeV} \Rightarrow \log_{10}(\Lambda/\text{GeV}) = 11.1 \pm 1.3}$
How to Stabilize a Light Higgs Boson?

• Top quark destabilizes potential: introduce stop-like scalar:
  \[ \mathcal{L} \supset M^2 |\phi|^2 + \frac{M_0}{v^2} |H|^2 |\phi|^2 \]
  
• Can delay collapse of potential:
• But new coupling must be fine-tuned to avoid blow-up:
• Stabilize with new fermions:
  – just like Higgsinos
• Very like Supersymmetry!
PLETHORA OF MODELS CONSISTENT WITH DATA, MANY OF THEM NATURAL. WHERE DOES THE DATA POINT US?
MasterCode

- Combines diverse set of tools
  - different codes: all state-of-the-art
    - Electroweak Precision (FeynWZ)
    - Flavour (SuFla, micrOMEGAs)
    - Cold Dark Matter (DarkSUSY, micrOMEGAs)
    - Other low energy (FeynHiggs)
    - Higgs (FeynHiggs)
  - different precisions (one-loop, two-loop, etc)
  - different languages (Fortran, C++, English, German, Italian, etc)
  - different people (theorists, experimentalists)
- Compatibility is crucial! Ensured by
  - close collaboration of tools authors
  - standard interfaces

Model parameters: e.g. m0, 1/2, A0, tanβ, etc

Spectrum calculators
- SoftSUSY
- SuSpect

SLHA

Predictors
- Higgs Sector
  - FeynHiggs
- Flavour Phys.
  - SuFla
  - MicrOMEGAs
- EWK Phys.
  - FeynWZ

LHC (FastLim, Atom, Scorpion)

Predictions

Expt. Data

E. Bagnaschi, O. Buchmüller, R. Cavanaugh, M. Citron, A. De Roeck, M.J. Dolan, J.E., H. Flächer, S. Heinemeyer, G. Isidori, D. Martinez Santos, K.A. Olive, K. Sakurai, G. Weiglein
• Universal soft supersymmetry breaking at input GUT scale?
  – For gauginos and all scalars: CMSSM
  – Non-universal Higgs masses: NUHM1,2
• **Strong pressure from LHC (p ~ 0.1)**
• Treat soft supersymmetry-breaking masses as phenomenological inputs at EW scale
  – pMSSMn (n parameters)
  – With universality motivated by upper limits on flavour-changing neutral interactions: pMSSM10
• **Less strongly constrained by LHC (p ~ 0.3)**
Fit to Constrained MSSM (CMSSM)

2012 ATLAS + CMS with 20/fb of LHC Data

Allowed region extends to large $m_0$

$p$-value of simple models $\sim 10\%$ (also SM)

Buchmueller, JE et al: arXiv:1312.5250
Constrained MSSM (CMSSM)

LHC MET searches

Contributions to global $\chi^2$ from different observables
Dark Matter Density Mechanisms

2012 ATLAS + CMS with 20/fb of LHC Data

- $\tilde{\tau}_1$ coannihilation (pink): \( \frac{m_{\tilde{\tau}_1}}{m_{\tilde{\chi}_1^0}} - 1 < 0.15 \),
- A/H funnel (blue): \( \frac{|M_A|}{2m_{\tilde{\chi}_1^0}} - 1 < 0.2 \),
- $\tilde{\chi}_1^\pm$ coannihilation (green): \( \frac{m_{\tilde{\chi}_1^\pm}}{m_{\tilde{\chi}_1^0}} - 1 < 0.1 \),
- $\tilde{t}_1$ coannihilation (grey): \( \frac{m_{\tilde{t}_1}}{m_{\tilde{\chi}_1^0}} - 1 < 0.2 \).

Buchmueller, JE et al: arXiv:1312.5250

Estimated reach with Run 2 of the LHC

Current LHC reach
Measuring the CMSSM with the LHC

Buchmueller, JE et al: arXiv:1505.04702
Dark Matter in CMSSM, NUHM1/2, pMSSM10

Estimated future LHC reach

Current LHC reach

Bagnaschi, JE et al: arXiv:1508.01173
Long-Lived Stau in CMSSM, NUHM?

Possible if $m_{\text{stau}} - m_{\text{LSP}} < m_\tau$

Generic possibility in CMSSM, NUHM
(stau coannihilation region)

- $\tau_{\text{stau}} > 10^3 \text{ s}$ gives problems with nucleosynthesis
- $\tau_{\text{stau}} > 10^{-7} \text{ s}$ gives separated vertex signature for $\tau$-like decays

Bagnaschi, JE et al: arXiv:1508.01173
Phenomenological MSSM (pMSSM10)

LHC MET searches

De Vries, JE et al: arXiv:1504.03260

Contributions to global $\chi^2$ from different observables

3 gaugino masses: $M_{1,2,3}$
2 squark masses: $m_{\tilde{q}_1} = m_{\tilde{q}_2} \neq m_{\tilde{q}_3}$
1 slepton mass: $m_{\tilde{\ell}}$
1 trilinear coupling: $A$
Higgs mixing parameter: $\mu$
Pseudoscalar Higgs mass: $M_A$
Ratio of vevs: $\tan \beta$

De Vries, JE et al: arXiv:1504.03260
Anomalous Magnetic Moment of Muon

2012 ATLAS + CMS with 20/fb of LHC Data

\[ g_\mu - 2 \text{ anomaly} \]

Cannot be explained by models with GUT-scale unification

Can be explained in pMSSM10

\[ \Delta \left( \frac{g-2}{2} \right) \]

pMSSM10 can explain experimental measurements of \( g_\mu - 2 \)

De Vries, JE et al: arXiv:1504.03260
Fits to Supersymmetric Models

2012 ATLAS + CMS with 20/fb of LHC Data

Gluino mass

Reach of LHC at High luminosity

De Vries, JE et al: arXiv:1504.03260

Favoured values of gluino mass also significantly above pre-LHC, > 1.2 TeV
Fits to Supersymmetric Models

2012 ATLAS + CMS with 20/fb of LHC Data

Stop mass

Remaining possibility of a light “natural” stop weighing ~ 400 GeV

De Vries, JE et al: arXiv:1504.03260
2012 ATLAS + CMS with 20/fb of LHC Data

Reach of chargino + b searches

Reach of LSP + top searches

Part of region of light "natural" stop weighing ~ 400 GeV can be covered

pMSSM10

De Vries, JE et al: arXiv:1504.03260
Why we are so excited by Run 2

- 2015 luminosity already explores new physics
Prospects for SUSY Searches

- Different models, various dark matter mechanisms

| DM mechanism | Exp’t | CMSSM | NUHM1 | NUHM2 | pMSSM10 |
|--------------|------|-------|-------|-------|---------|
| $\tilde{\tau}_1$ coann. | LHC | ✓ $E_T$, ✓ LL | ✓ $E_T$, ✓ LL | ✓ $E_T$, ✓ LL | ✓ $E_T$, × LL |
| DM | ✓ | ✓ | ✓ | ✓ | ✓ |
| $\tilde{\chi}_1^\pm$ coann. | LHC | – | × | × | (✓ $E_T$) |
| DM | – | ✓ | ✓ | ✓ | |
| $t_1$ coann. | LHC | – | – | ✓ $E_T$ | – |
| DM | – | – | ✓ | – | – |
| $A/H$ funnel | LHC | ✓ $A/H$ | ✓ $A/H$ | ✓ $A/H$ | – |
| DM | ✓ | ✓ | ✓ | – | – |
| Focus point | LHC | (✓ $E_T$) | – | – | – |
| DM | ✓ | – | – | – | – |
| $h, Z$ funnels | LHC | – | – | – | (✓ $E_T$) |
| DM | – | – | – | – | |

- No guarantees, but good prospects

Bagnaschi, JE et al: arXiv:1508.01173
Squark-Gluino Plane

Discover 12 TeV squark, 16 TeV gluino @ 5σ
“Who ordered that”

He was talking about the muon …
Reported on Tuesday, Dec. 15

- Peaks in $\gamma\gamma$ invariant mass distributions
- Possible new particle X with mass $\sim 750$ GeV decaying into 2 photons
Global Analysis of $X$ Signal

- Assume scalar/pseudoscalar (angular distribution?)
- Combined analysis of CMS and ATLAS data

Some tension between data from Run 1 and Run 2?

JE, S.Ellis, Quevillon, Sanz & You, arXiv:1512.05327
X Decays?

- Decay to $\gamma\gamma$ via anomalous triangle diagrams
- Probably also production via gluon fusion
- Loops need heavy particles, $m > 350 \text{ GeV}$
- Can’t be 4th generation/minimal supersymmetry
- Single vector-like quark enough, could be more
  - 1: Single VL quark, cf, $t_R$
  - 2: Doublet of VL quarks, cf, $q_L$
  - 3: Doublet + 2 singlets, cf, $q_L, t_R, b_R$
  - 4: Complete VL generation, including leptons
- Assume $gg$ decays dominant

JE, S. Ellis, Quevillon, Sanz & You, arXiv:1512.05327
Scalar/Pseudoscalar Models for X

- Required X couplings $\lambda$ to heavy fermions in different models
- Black line = best fit
  - Band = 1 $\sigma$
  - Perturbative limit
  - Neutral fermion could be dark matter

JE, S.Ellis, Quevillon, Sanz & You, arXiv:1512.05327
**How to Probe Possible Models?**

- Other possible decay modes

| Model | $Tr[Y^2]$ | $Tr[D(r)^2]$ | $BR(X \rightarrow gg)$ | $BR(X \rightarrow Z\gamma)$ | $BR(X \rightarrow ZZ)$ | $BR(X \rightarrow W^{\pm}W^{\mp})$ |
|-------|------------|--------------|-------------------------|-----------------------------|------------------------|-----------------------------|
| 1     | 8/3        | 0            | 180                     | 1.2                        | 0.090                  | 0                          |
| 2     | 1/3        | 3            | 460                     | 10                         | 9.1                    | 61                         |
| 3     | 11/3       | 3            | 460                     | 1.1                        | 2.8                    | 15                         |
| 4     | 20/3       | 4            | 180                     | 0.46                       | 2.1                    | 11                         |
| Current limit |               | $\sim 2 \times 10^4$ | 7                        | 13                         | 46                     |

- Predictions $\leq$ experimental limits
- Potentially accessible to experiment
- Also look for heavy fermions!
- **Work for a generation – if X particle exists!**
- **Will know in 2016**

JE, S.Ellis, Quevillon, Sanz & You, arXiv:1512.05327
Scalar/Pseudoscalar Models for X

- What if $\Gamma_X = 45$ GeV?
- Required $X$ couplings $\lambda$ to heavy fermions in different models
- Black line = best fit
- Green band = 1 $\sigma$
- Perturbative limit
- More fermions in loops?

JE, S.Ellis, Quevillon, Sanz & You, arXiv:1512.05327
Possible Future X Signal

- Assuming production by gluon-gluon fusion
- Normalized to $\sigma B(\gamma\gamma) = 6$ fb

PDF, ren’\textsuperscript{\textprime}n scale uncertainties @ 100 TeV $\sim$ 30%

Djouadi, JE, Godbole, Quevillon, arXiv:1601.03696
\[ \gamma \gamma \rightarrow X \text{ Signal at } e^+e^- \text{ Collider} \]

- For \( \sigma_B(\gamma \gamma) = 6 \text{ fb} \), assuming \( X \rightarrow gg \) dominant

- Centre-of-mass energy \( \sim 1 \text{ TeV} \) preferred!

Djouadi, JE, Godbole, Quevillon. arXiv:1601.03696
Cross Sections for Vector-Like Q

- Pair-production at LHC, future circular colliders

- Present lower mass limit $\sim 800$ GeV

Djouadi, JE, Godbole, Quevillon.
arXiv:1601.03696
Cross Sections for Vector-Like L

- Pair-production at LHC, future circular colliders
  - Present mass limit < 400 GeV

Djouadi, JE, Godbole, Quevillon, arXiv:1601.03696
Single Vector-Like Q, L Production

- Single production at LHC, future circular colliders

- Assuming mixing angle with light fermions $\xi = 0.1$

Djouadi, J. E., Godbole, Q. Quevillon.

arXiv:1601.03696

$\sigma(pp \rightarrow \bar{\mathbb{N}})$ [pb]

$\sigma(pp \rightarrow \bar{q}Q)$ [pb]

$\sqrt{s} = 8, 13, 14, 33, 100$ TeV

$\xi = 0.1$
Model 1: Single VL quark, \( c_f, t_R \)
- Non-perturbative coupling required

Model 2: Doublet of VL quarks, \( c_f, q_L \)
- Non-perturbative coupling favoured

Model 3: Doublet + 2 singlets, \( c_f, q_L, t_R, b_R \)
- Perturbative range covered by LHC

Model 4: Complete VL generation, including leptons
- Covering perturbative range needs higher energy

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### Table: Sensitivity to Vector-Like Q, L

| Model | \( \text{Vector-like quark mass sensitivity} \) | \( \text{Vector-like lepton mass sensitivity} \) |
|-------|-----------------------------------------------|-----------------------------------------------|
|       | \( 100 \text{fb}^{-1} \) \( 300 \text{fb}^{-1} \) \( 300 \text{fb}^{-1} \) \( 20 \text{ab}^{-1} \) | \( 100 \text{fb}^{-1} \) \( 300 \text{fb}^{-1} \) \( 300 \text{fb}^{-1} \) \( 20 \text{ab}^{-1} \) |
| 1     | 1.4 1.7 3.1 11.7 | - |
| 2     | 1.5 1.8 3.4 12.7 | - |
| 3     | 1.6 2.0 3.7 13.7 | 0.56 0.73 1.7 5.3 |
| 4     | 1.6 2.0 3.7 13.7 | 0.56 0.73 1.7 5.3 |

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Djouadi, JE, Godbole, Quevillon, arXiv:1601.03696
Alternative Higgs Doublet Scenario

• After singlet, doublet?
• Heavy Higgses in 2 Higgs doublet model: $\Phi = H, A$
• Nearly degenerate in many versions, e.g., SUSY
• Expect $t\bar{t}$ decays to dominate
• Can accommodate $\Gamma_\Phi \sim 45$ GeV (ATLAS)
• Need larger enhancement of loops compared to singlet model

• Rich bosonic phenomenology

Djouadi, JE, Godbole, Quevillon, arXiv:1601.03696
Φ = H, A Decays in Doublet Model

- Dependences on tan β of branching ratios, Γ_Φ

- Prefer tan β ~ 1
- Dominant Φ decays to t tbar

Djouadi, JE, Godbole, Quevillon. arXiv:1601.03696
Lineshape in $pp$ Collisions

- $+\text{MSSM: } \tan \beta = 1$
- $M_H - M_A \sim 15 \text{ GeV}$
- $\Gamma_H, \Gamma_A \sim 32, 35 \text{ GeV}$
- $\sigma_B(A \rightarrow \gamma\gamma) = 2 \times \sigma_B(H \rightarrow \gamma\gamma)$
- Asymmetric
  - ‘Breit-Wigner’
- Resolvable?

Djouadi, JE, Godbole, Quevillon, arXiv:1601.03696
Fermion Loop Form Factors

- Triangle diagrams suppressed for small $M_F$

- Enhanced if $m_F \sim M_\Phi/2$

Djouadi, JE, Godbole, Quevillon, arXiv:1601.03696
Obtaining Loop Enhancement

- Need loop enhancement \( \sim 500 \) if \( \Gamma \sim 45 \) GeV
- Vector-like generation of quarks and leptons
- 3 doubly-charged leptons
- 3 pairs of vector-like leptons

Djouadi, JE, Godbole, Quevillon, arXiv:1601.03696
Possible $\Phi = H, A$ Signals

- Normalized to $\sigma_B(\gamma\gamma) = 6$ fb @ 13 TeV

Djouadi, JE, Godbole, Quevillon, arXiv:1601.03696
Possible $H^\pm$ Signals

- @ 14, 100 TeV for varying $M_{H^\pm} \neq M_{\Phi}$ in general
\( \gamma \gamma \rightarrow \Phi \rightarrow t\bar{t} \)

- For \( \sigma_B(\gamma \gamma) = 6 \text{ fb} \), assuming \( \Gamma(\Phi=H,A) = 45 \text{ GeV} \)
- \( e^+e^- \) centre-of-mass energy \( \sim 1 \text{ TeV} \)

Djouadi, JE, Godbole, Quevillon, arXiv:1601.03696
“Plus un fait est extraordinaire, plus il a besoin d’être appuyé de fortes preuves”

Laplace, 1812

“The more extraordinary a claim, the stronger the proof required to support it.”
Higgs champagne in Singapore
Search for Sphalerons in $pp$ Collisions

- Used to think sphaleron transitions very suppressed
- Challenged by Tye & Wong
- Recall periodic potential, construct Bloch wave
\[
\left( -\frac{1}{2m} \frac{\partial^2}{\partial Q^2} + V(Q) \right) \Psi(Q) = E\Psi(Q)
\]
\[
V(Q) \simeq 4.75 \left( 1.31 \sin^2(Qm_W) + 0.60 \sin^4(Qm_W) \right) \text{TeV}
\]
- Enhanced transition rate below/above $E_{\text{Sph}} \sim 9$ TeV
\[
\sigma(\Delta n = \pm 1) \propto \exp \left( c \frac{4\pi}{\alpha_W} S(E) \right) \\
S(E) = (1 - a)\hat{E} + a\hat{E}^2 - 1 \quad \text{for} \quad 0 \leq \hat{E} \leq 1
\]
- Estimated transition rate: unknown prefactor $p$
\[
\sigma(\Delta n = \pm 1) = \frac{p}{m_W^2} \sum_{ab} \int dE \frac{d\mathcal{L}_{ab}}{dE} \exp \left( c \frac{4\pi}{\alpha_W} S(E) \right)
\]

arXiv:1505.03690
Sphaleron Transitions

- Final-state invariant mass distribution @ LHC
  - Including different parton processes

JE, Sakurai, arXiv:1601.03654
Sphaleron Transitions

• Growth of cross section with energy, if $p$ constant

• For different sphaleron masses (9 TeV expected)

• Normalization $p$ poorly known

JE, Sakurai, arXiv:1601.03654
Sphaleron Transitions

- Mass distributions in sphaleron-induced transitions

- Reduced by neutrino emission, etc.

- Broader mass distributions at higher energies

JE, Sakurai, arXiv:1601.03654
Sphaleron Transitions

- Properties of $\Delta n = \pm 1$ 10- and 14-particle final states

- Relatively spherical, plentiful tops

JE, Sakurai, arXiv:1601.03654
Sphaleron Transitions

- Energy dependence of 10-particle final states

- Events with plenty of missing $E_T$
Comparison with Black Hole Search

- Data from ATLAS search with 3/fb @ 13 TeV

- Expect plenty of events with large missing $H_T$
Constraint from Black Hole Search

- High acceptance for 10-particle final states of ATLAS search with 3/fb @ 13 TeV
- Exclude $p \sim 0.3$ for expected $E_{\text{Sph}} = 9$ TeV
- Stronger constraint for 14-particle final states

JE, Sakurai, arXiv:1601.03654
Rumours of the death of SUSY are exaggerated – Still the best framework for TeV-scale physics
Still the best candidate for cold dark matter
Simple models (CMSSM, etc.) under pressure – More general models quite healthy
Good prospects for LHC Run 2 and for direct dark matter detection – no guarantees!
Whole new world if X(750) is real!
Think again about sphalerons!