BSM SEARCHES @ LHC

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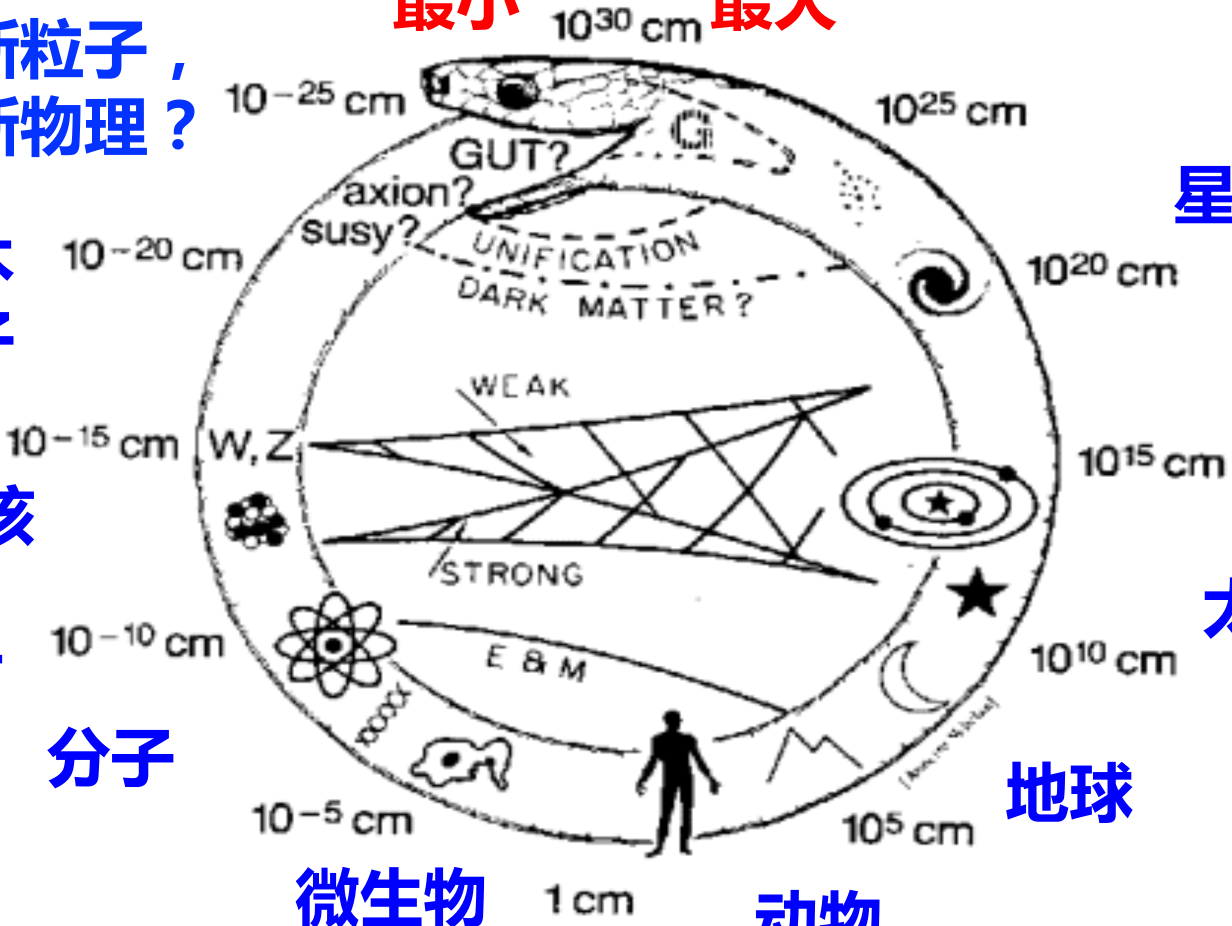
Institute of High Energy Physics Chinese Academy of Sciences

希腊神话中的怪物“Uroboros”与格拉肖的“宇宙圈”



最小 **最大**

新粒子，
新物理？

星系

基本粒子

太阳系

原子核

太阳

原子

分子

地球

微生物

动物

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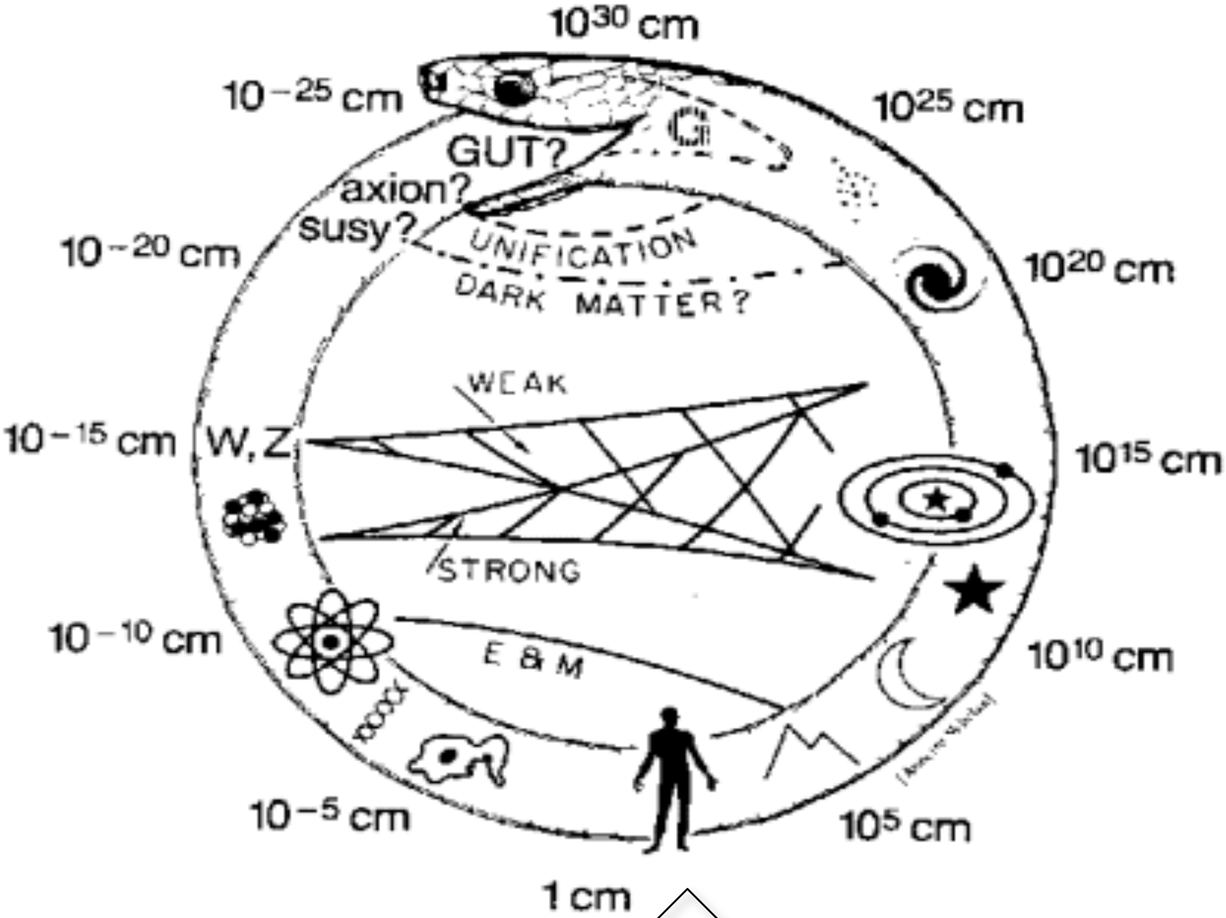

引力和电磁力占主导地位

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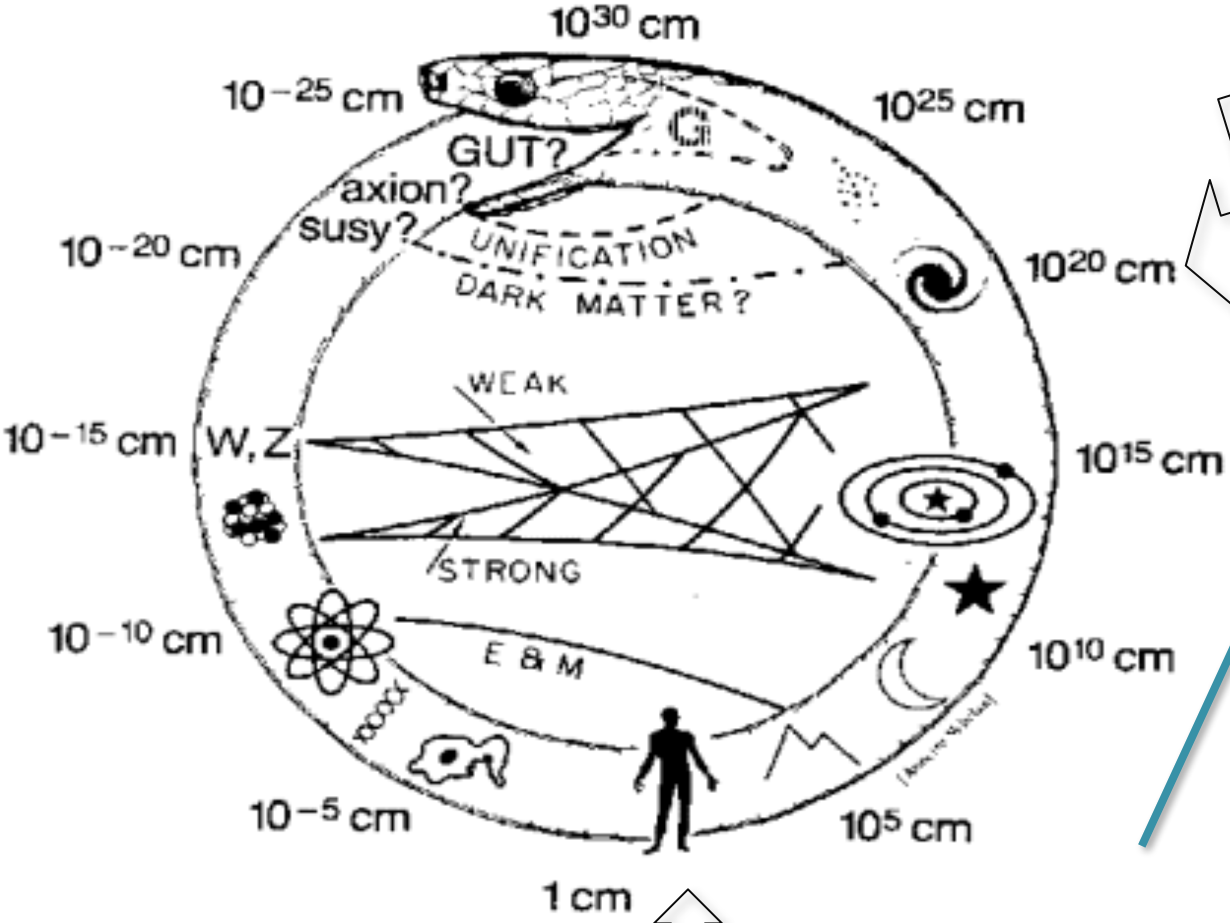

引力主导，爱因斯坦的广义相对论

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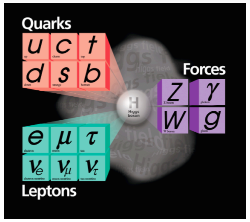
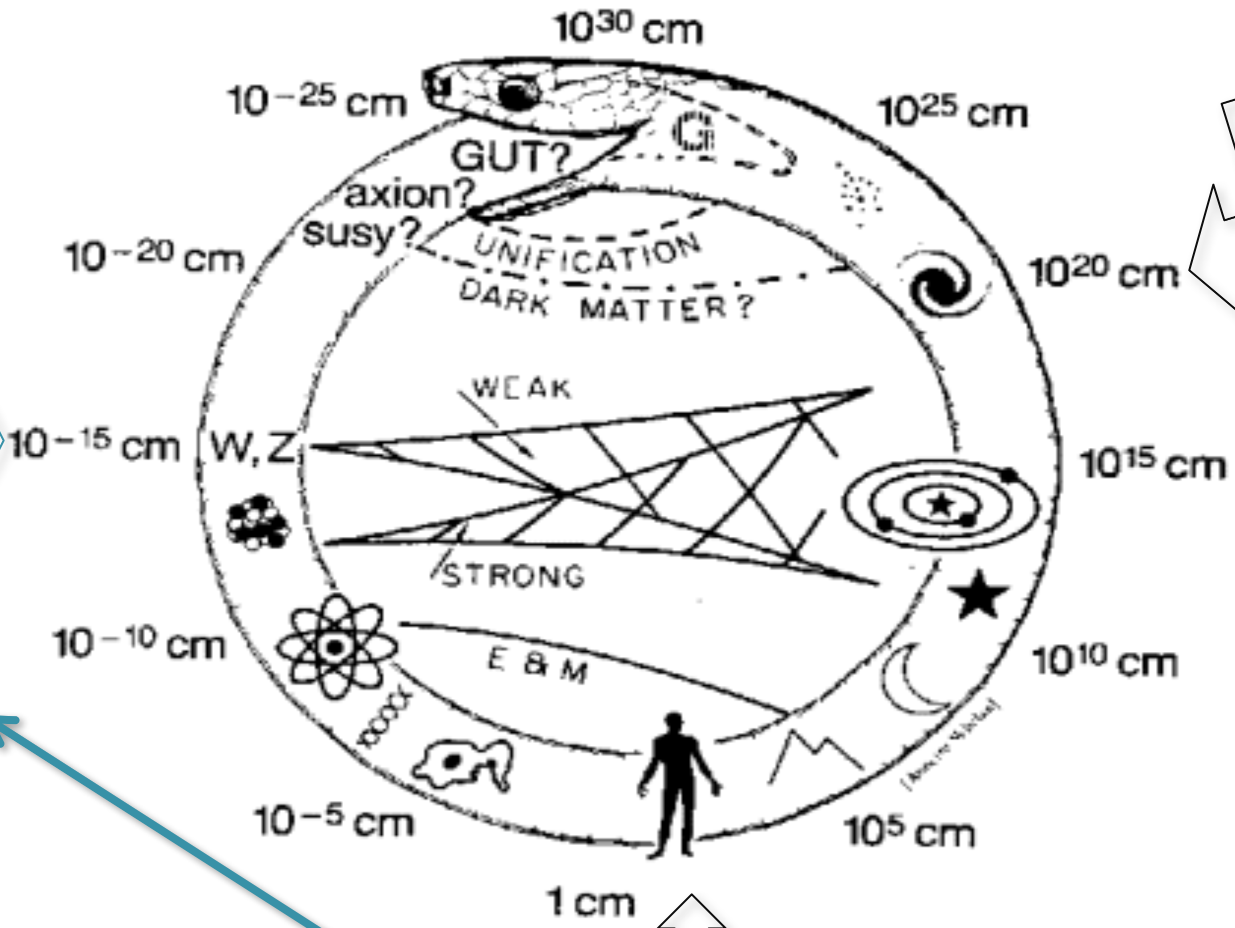
粒子“微观世界”，**强弱相互作用**主导，理论模型是**标准模型**





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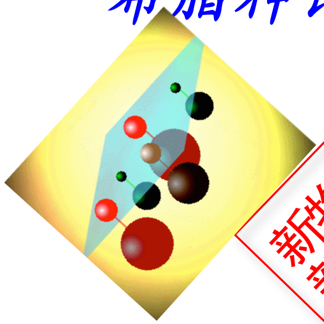

新物理，新粒子？

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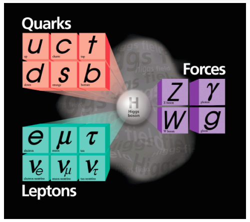

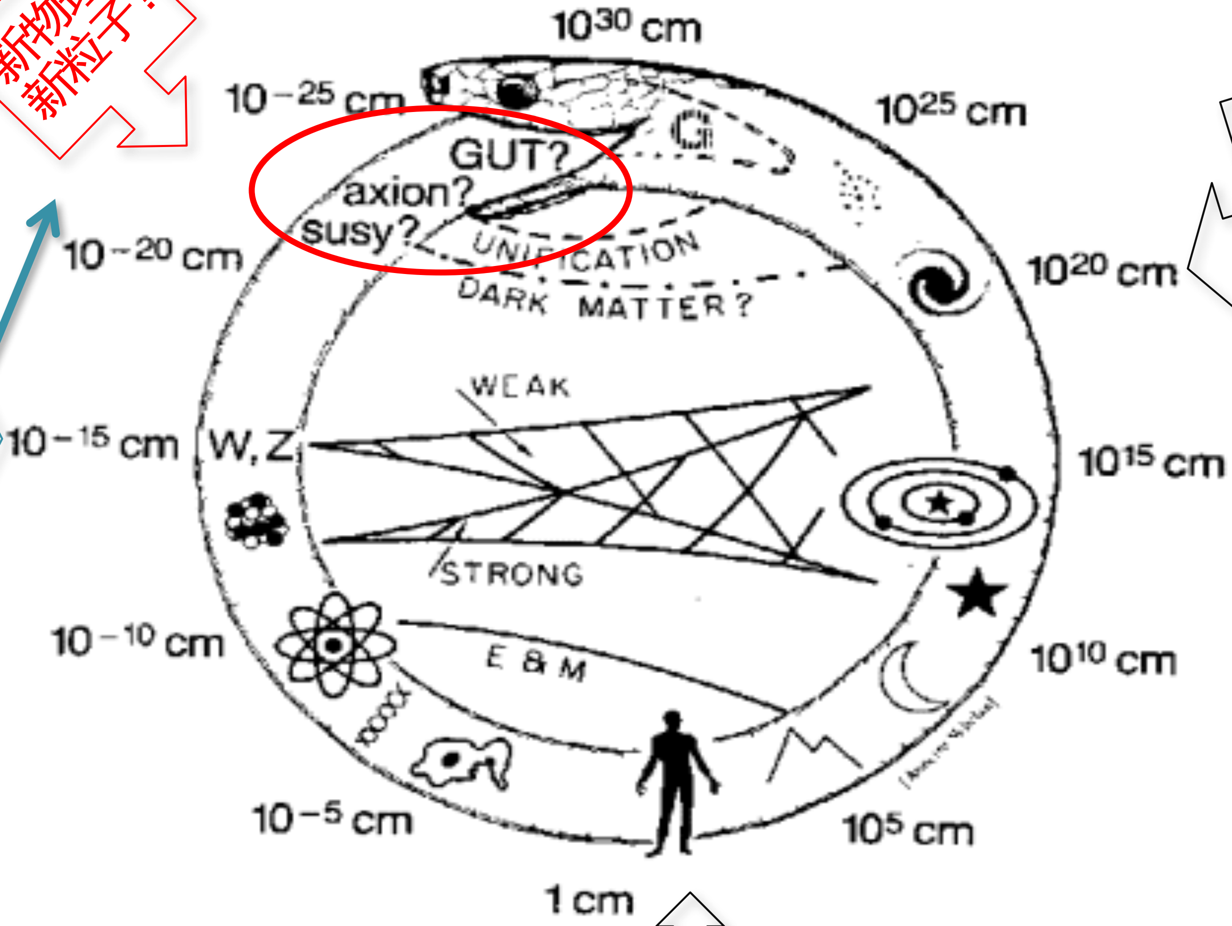

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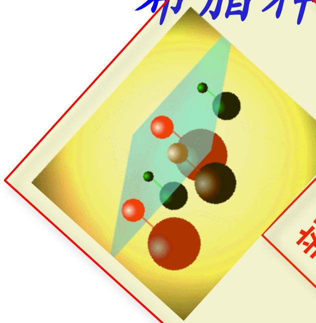

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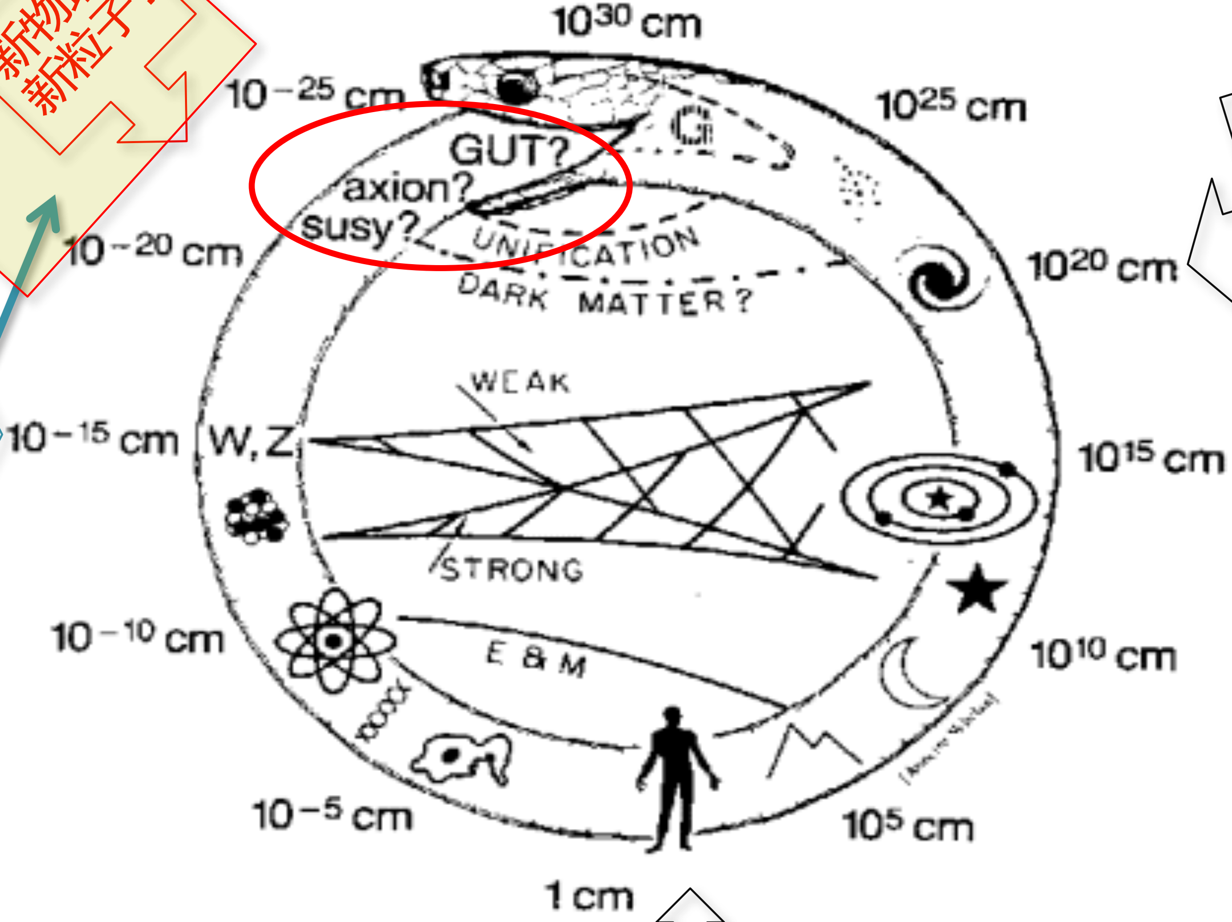

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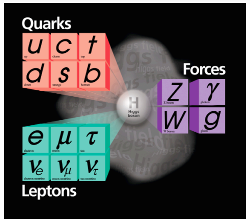

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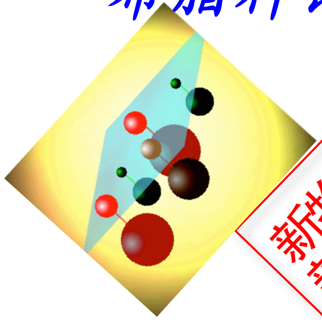

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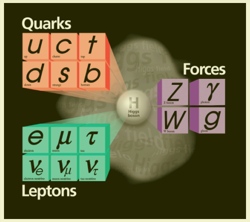

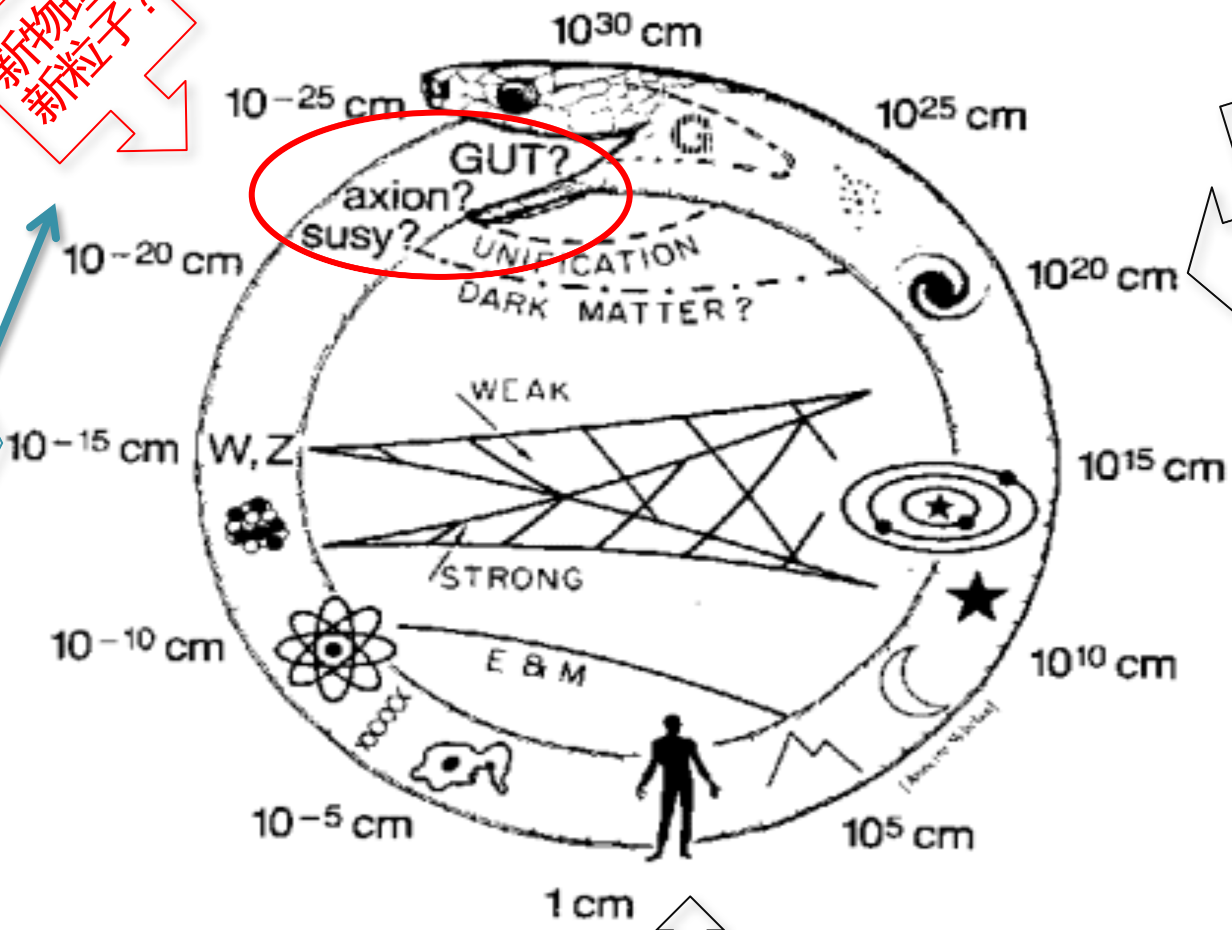

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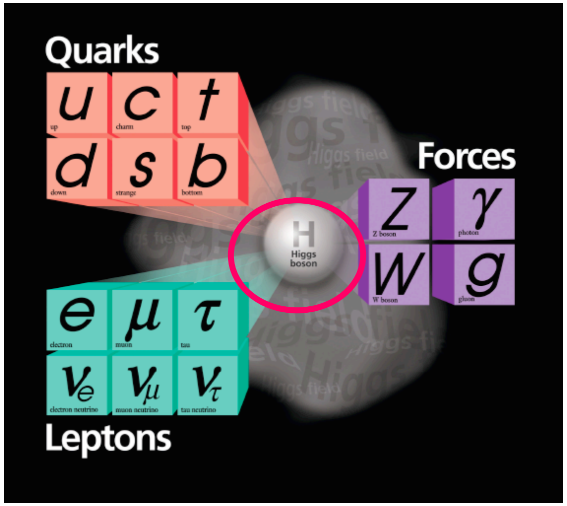
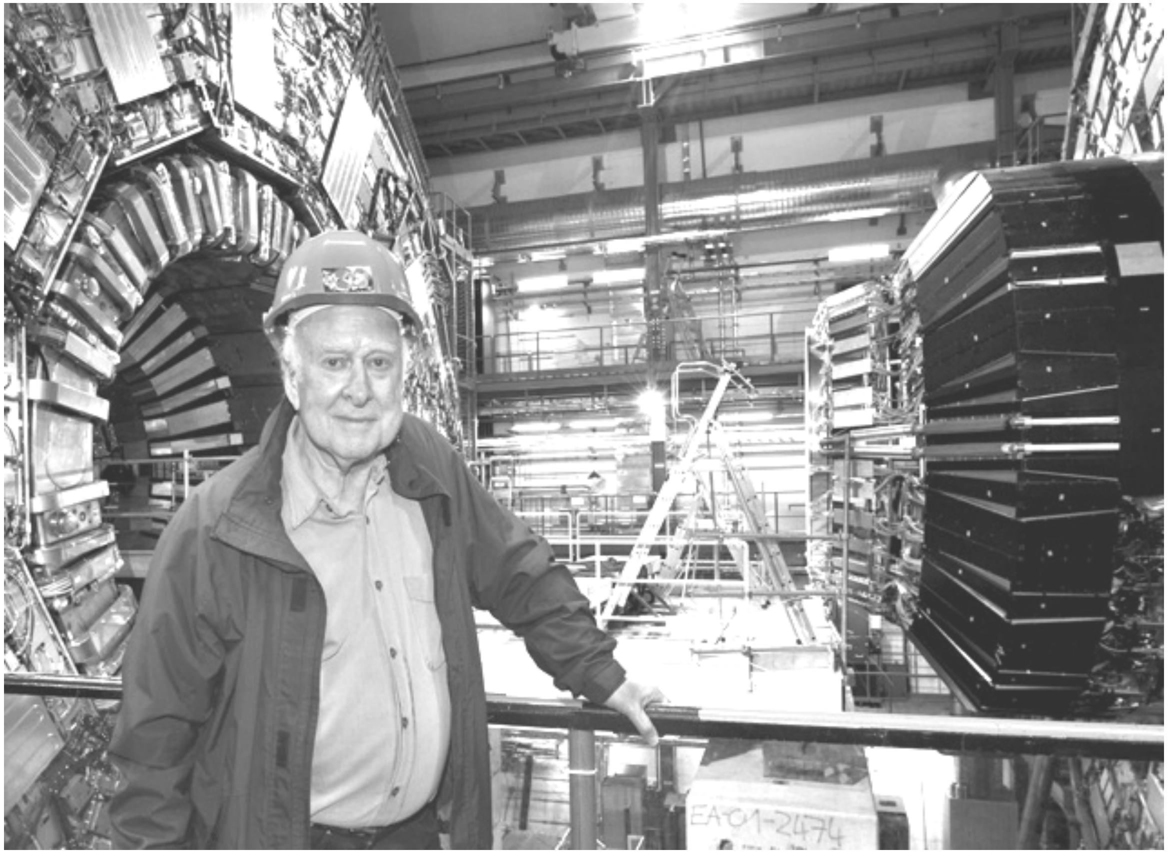


- Higgs boson observed, SM is complete. SM fits the experimental data very well ➔ big success in EW scale

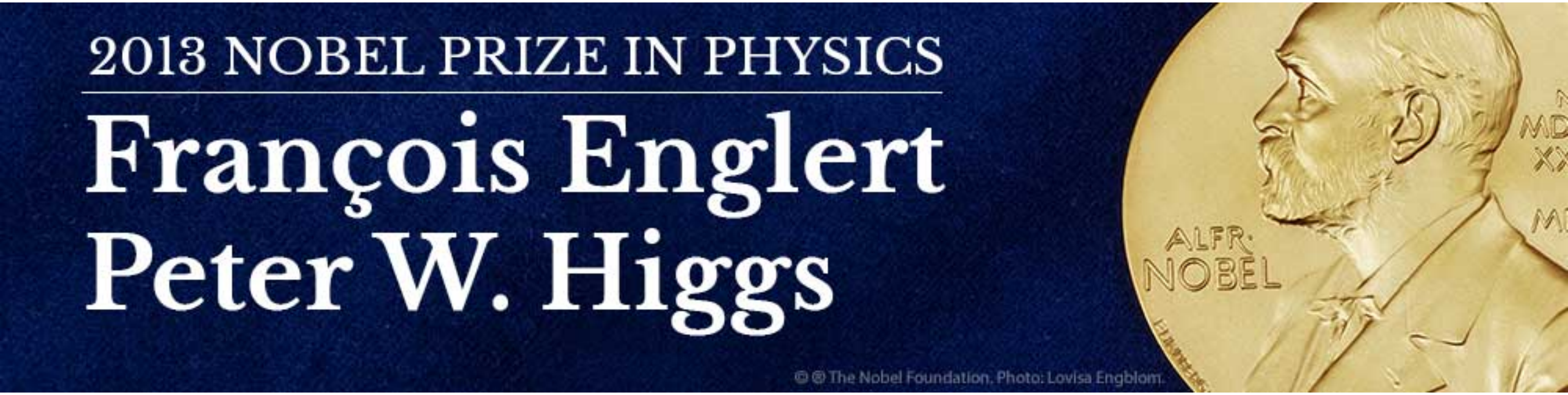
The Nobel Prize in Physics 2013
François Englert, Peter Higgs


P. Higgs at CMS

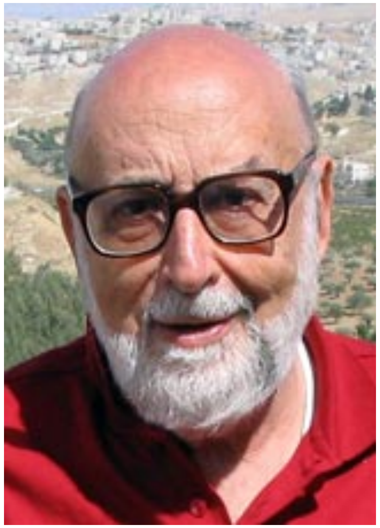
Very happy faces after the announcement of the discovery on 4th July 2012 at CERN and at ICHEP Melbourne

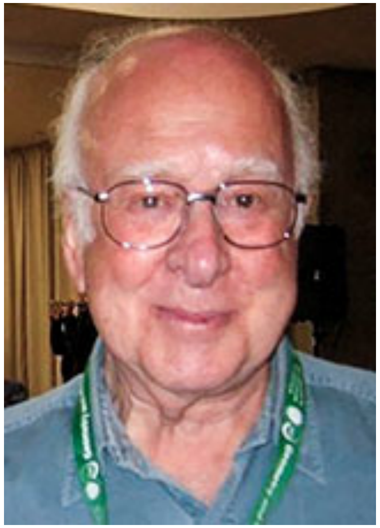
ICHEP2012
Melbourne

Announced on 8th October and celebrated on 10th December 2013:



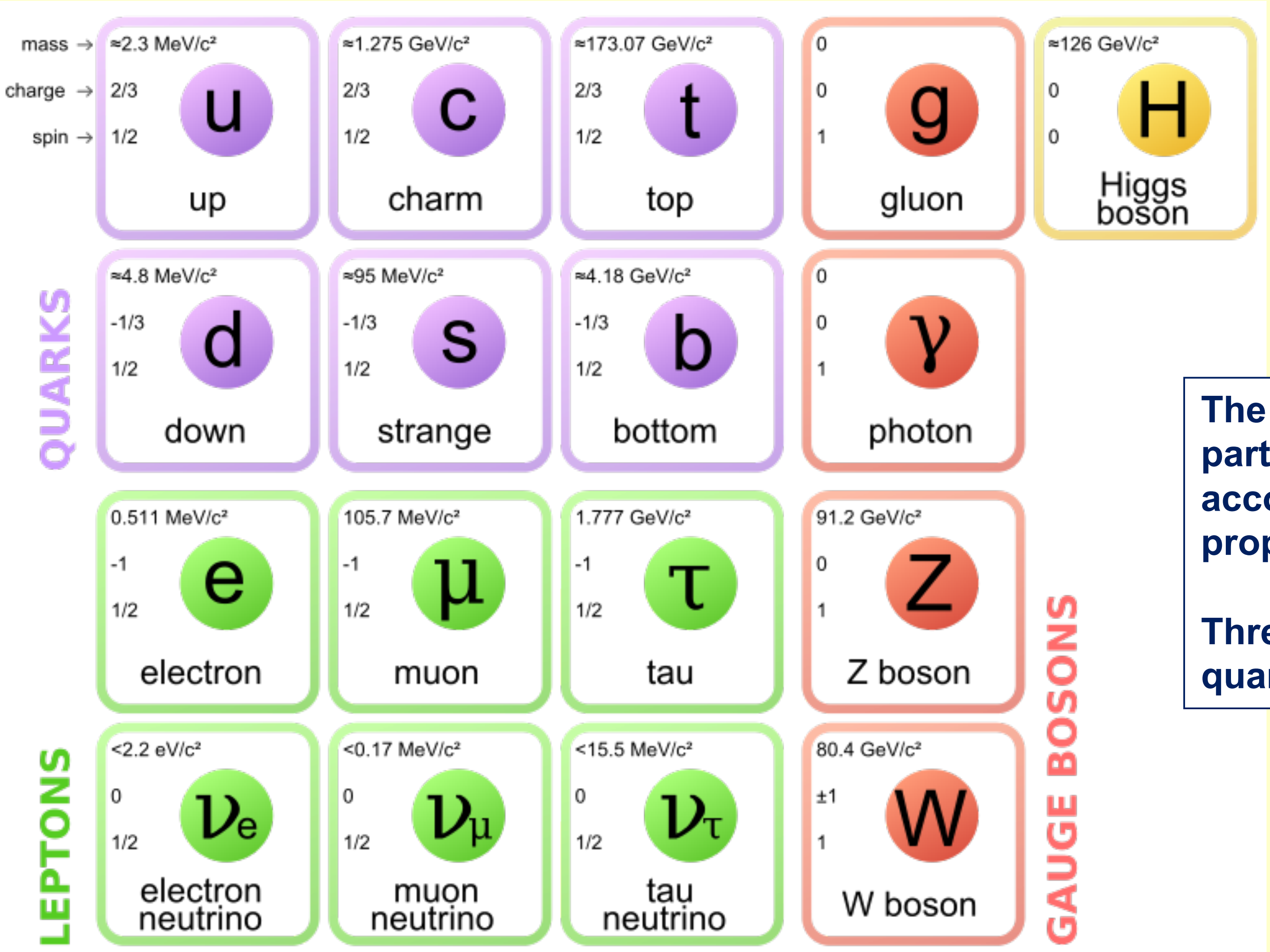
© ® The Nobel Foundation. Photo: Lovisa Engblom.





"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Standard Model of Elementary Particles



mass → charge → spin →	≈2.3 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c^2 0 0 H Higgs boson
QUARKS	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	
	0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	91.2 GeV/c^2 0 1 Z Z boson	GAUGE BOSONS
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	80.4 GeV/c^2 ±1 1 W W boson	

← *Fermionen* → ← *Bosonen* →

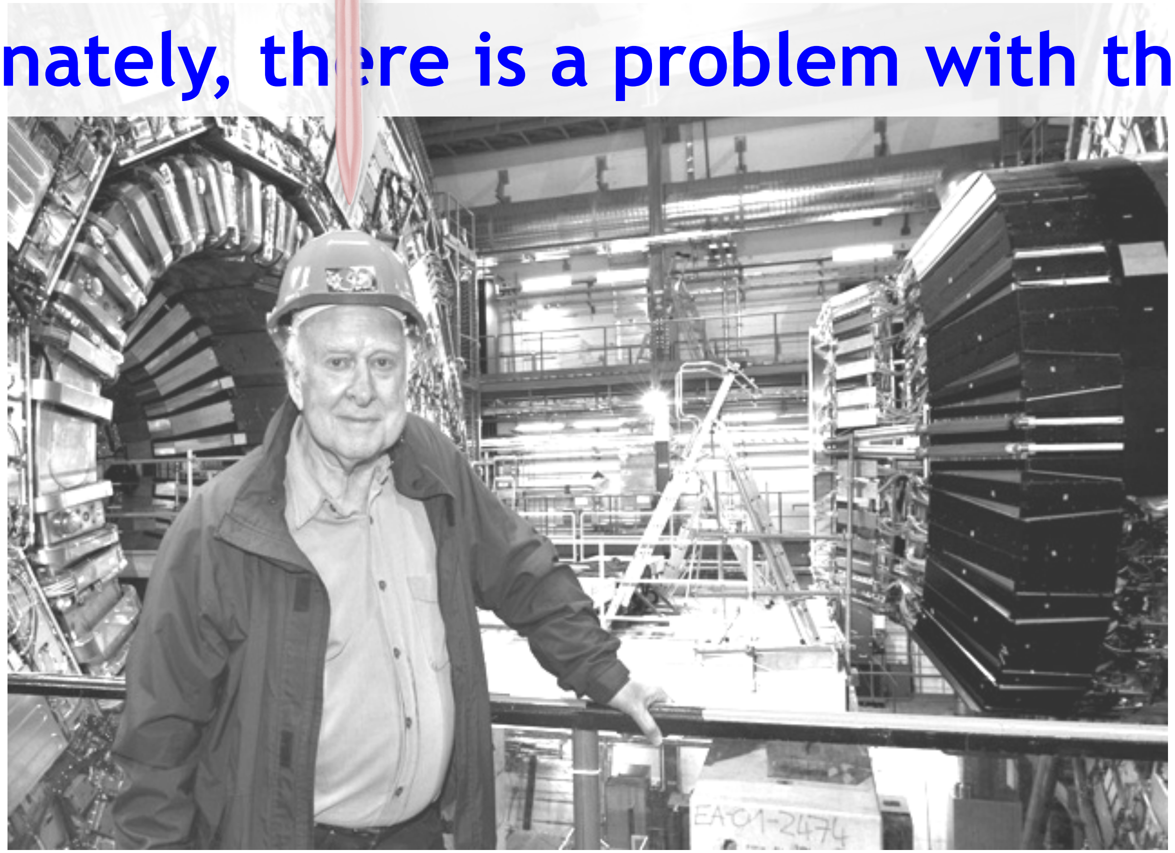
The elementary particles arranged according to their properties

Three families of quarks and leptons

- Need a more fundamental theory of which SM is only a low-energy approximation ➔ **New Physics**

- **While has problem in Planck scale:**
  - Naturalness and “hierarchy” problem
  - Unification of gauge coupling
  - Dark Matter
  - ……

Unfortunately, there is a problem with the Higgs!

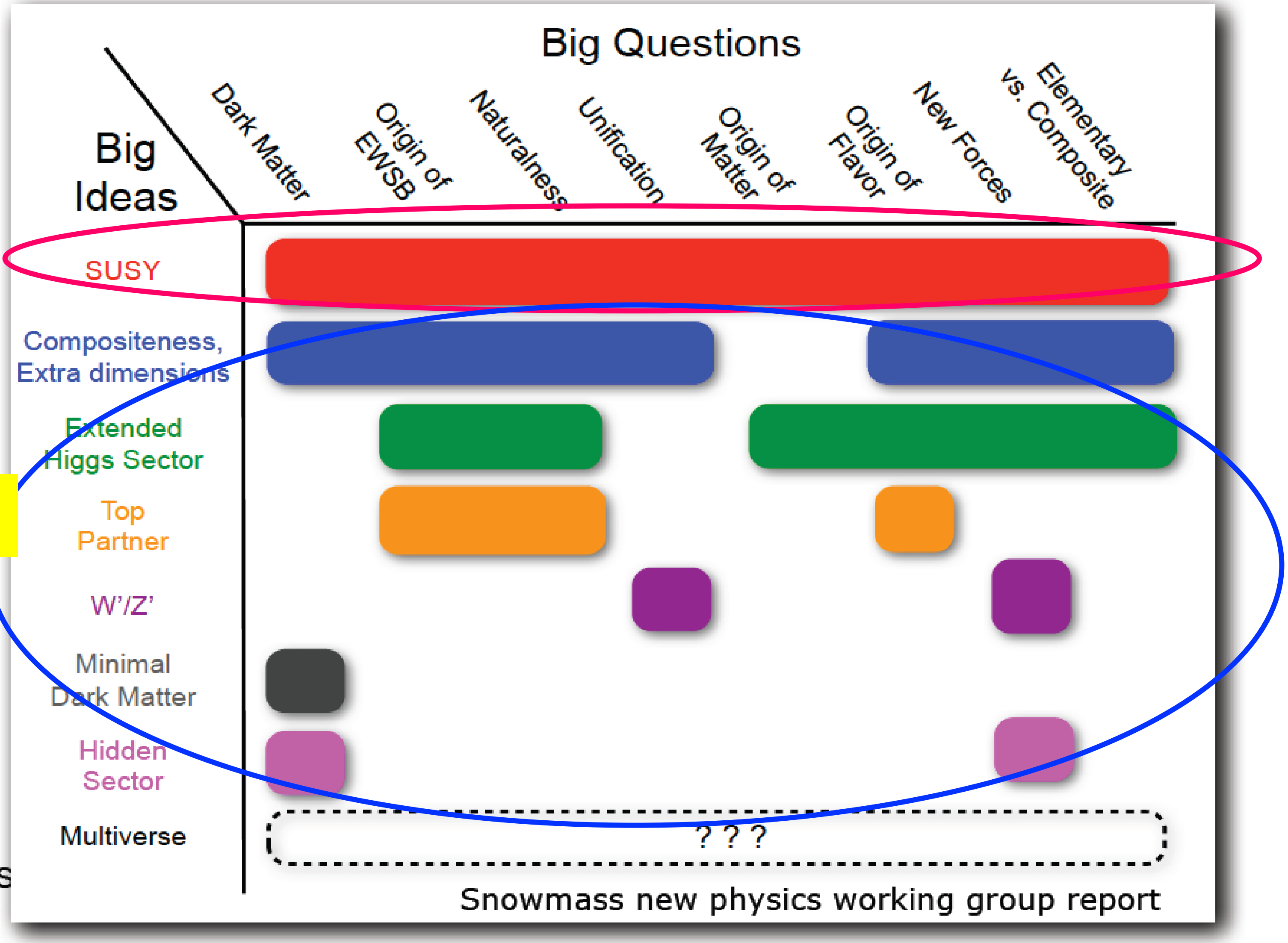


P. Higgs at CMS

New Physics beyond the SM

SUSY

exotics

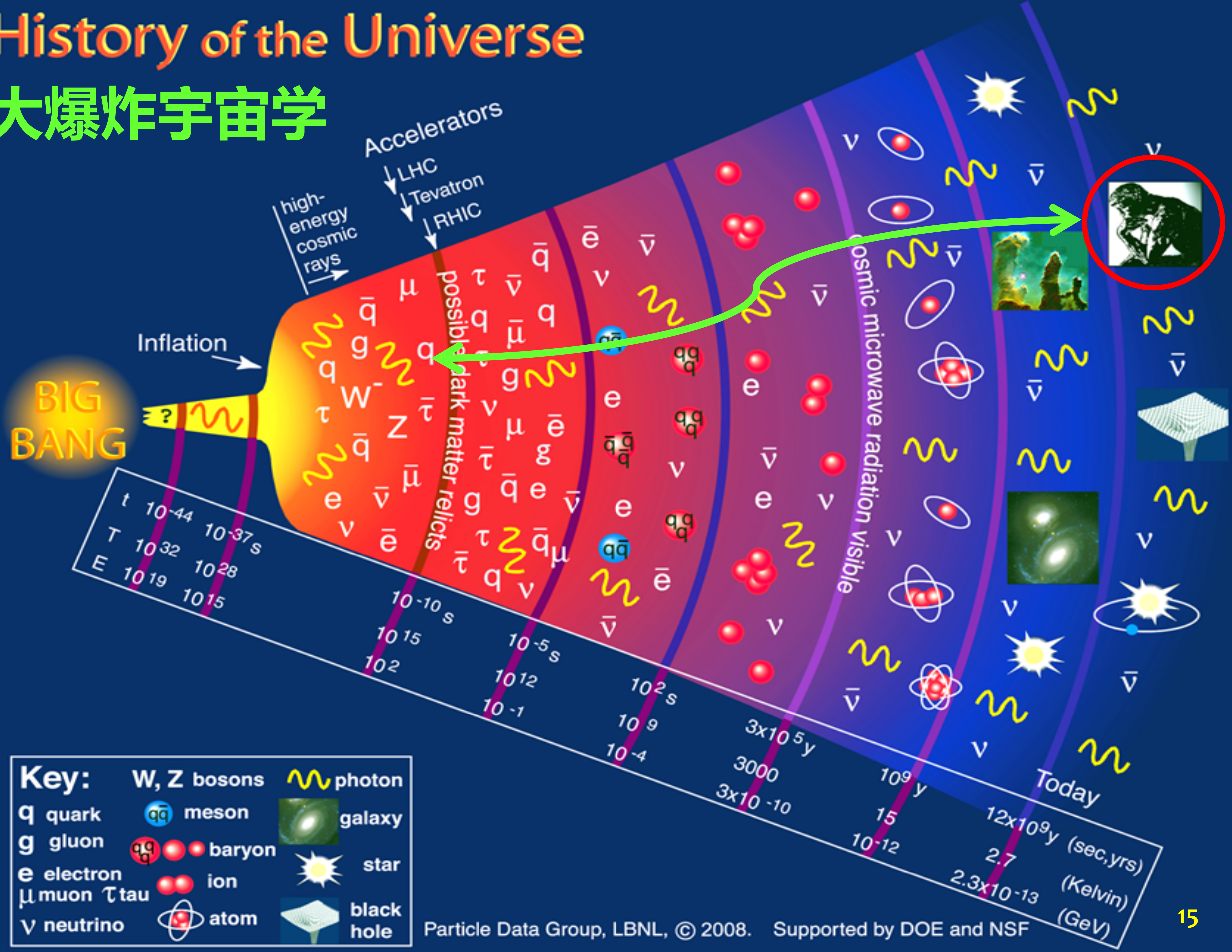


Snowmass new physics working group report

S. S

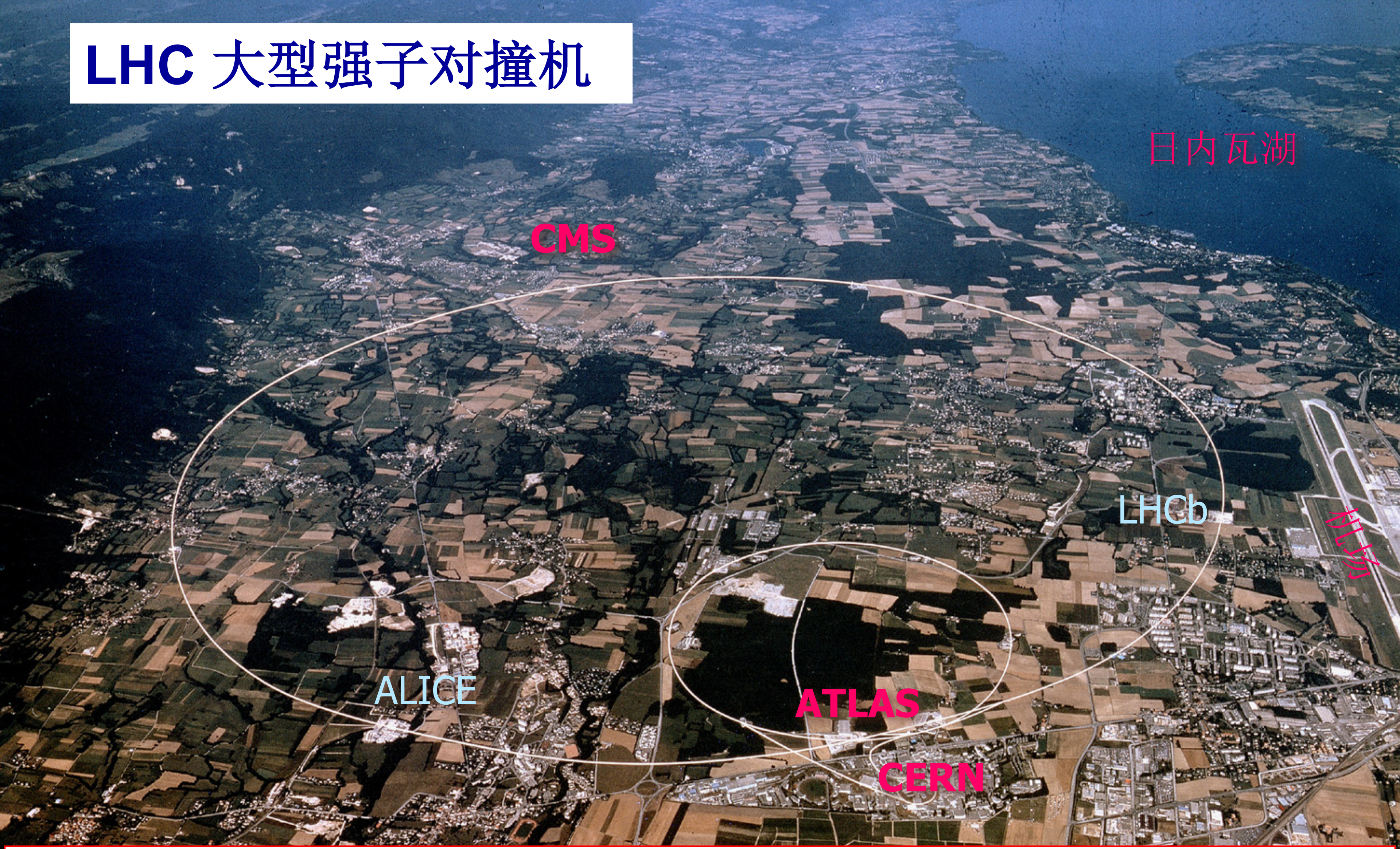
History of the Universe

大爆炸宇宙学



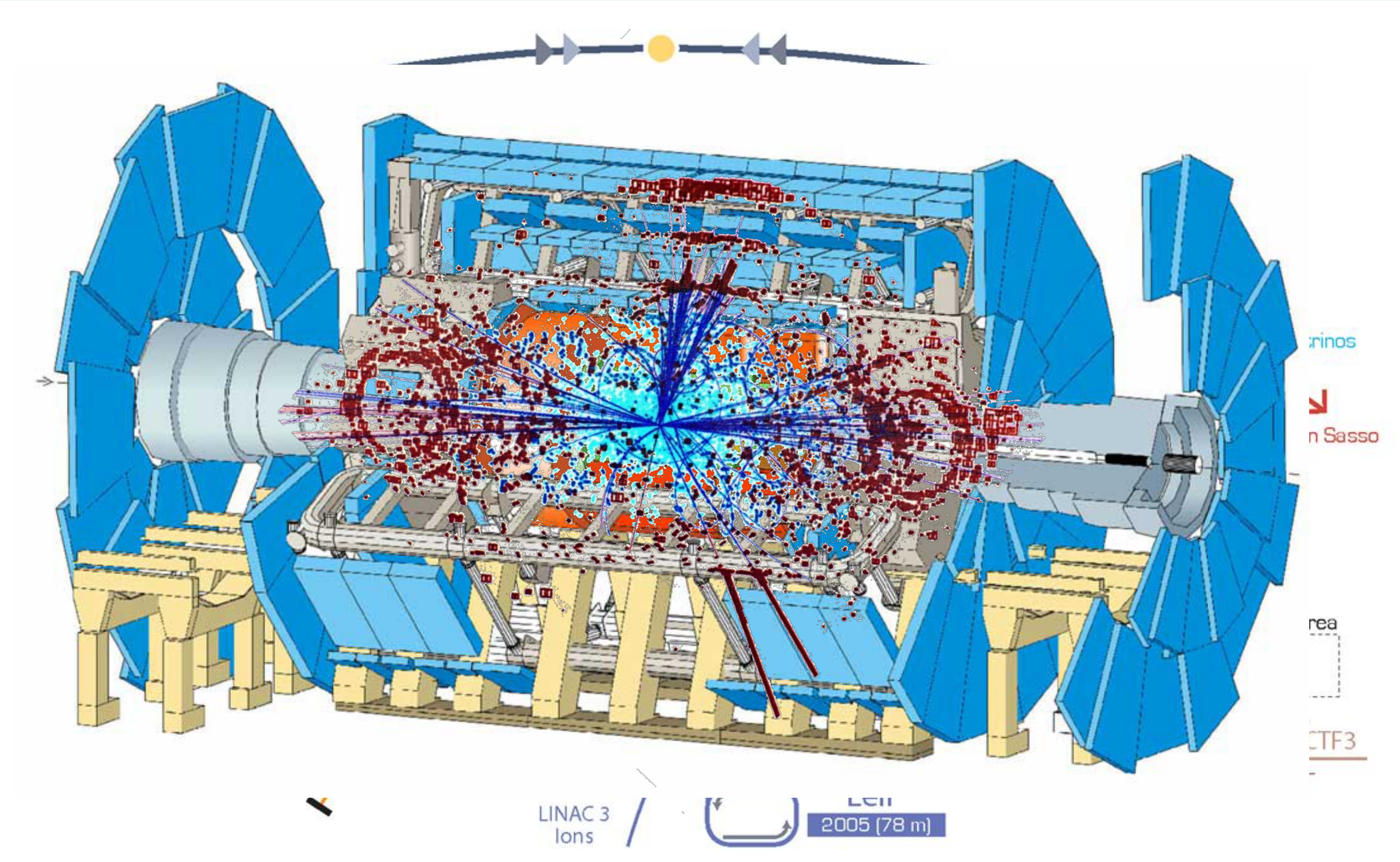
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

LHC 大型强子对撞机

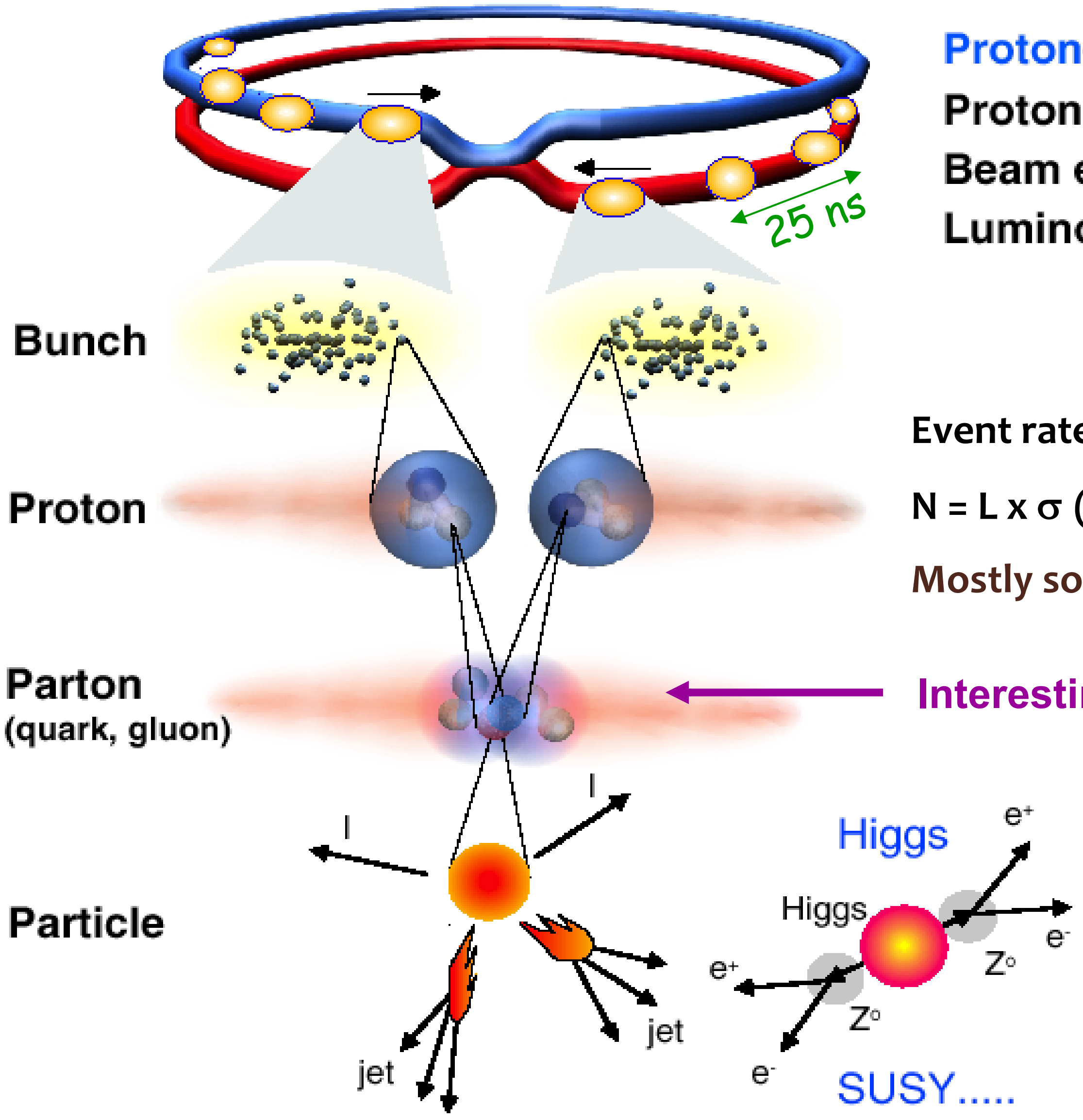


- 周长 **27** 公里，隧道深**100**米，跨越瑞士法国国境
- 世界最大，能量最高的加速器，进行最前沿的粒子物理研究
- **质心系能量14TeV** (Tevatron的7倍)，**可以发现5TeV以下的较重的新粒子**
- **积分亮度10^{34} cm^{-2} s^{-1}** (Tevatron 的100倍)，可以发现微小衰变截面的**稀有事例**

CERN’s particle accelerator chain



Collisions at LHC



Proton-Proton

Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}

Event rate:

$N = L \times \sigma\,(pp) \approx 10^9$ interactions/s

Mostly soft (low p_T) events

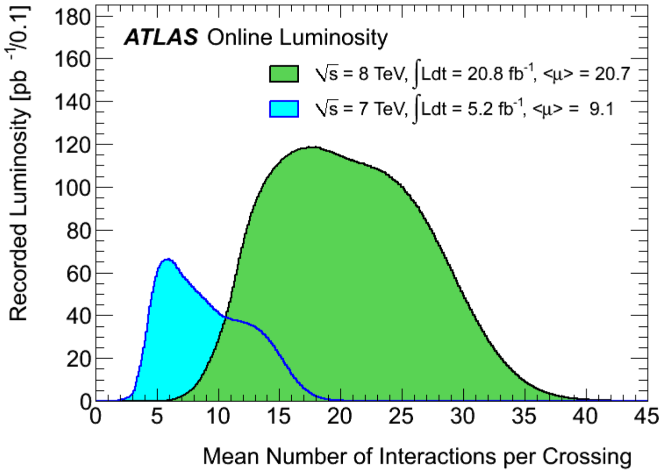
Interesting hard (high-p_T) events are rare

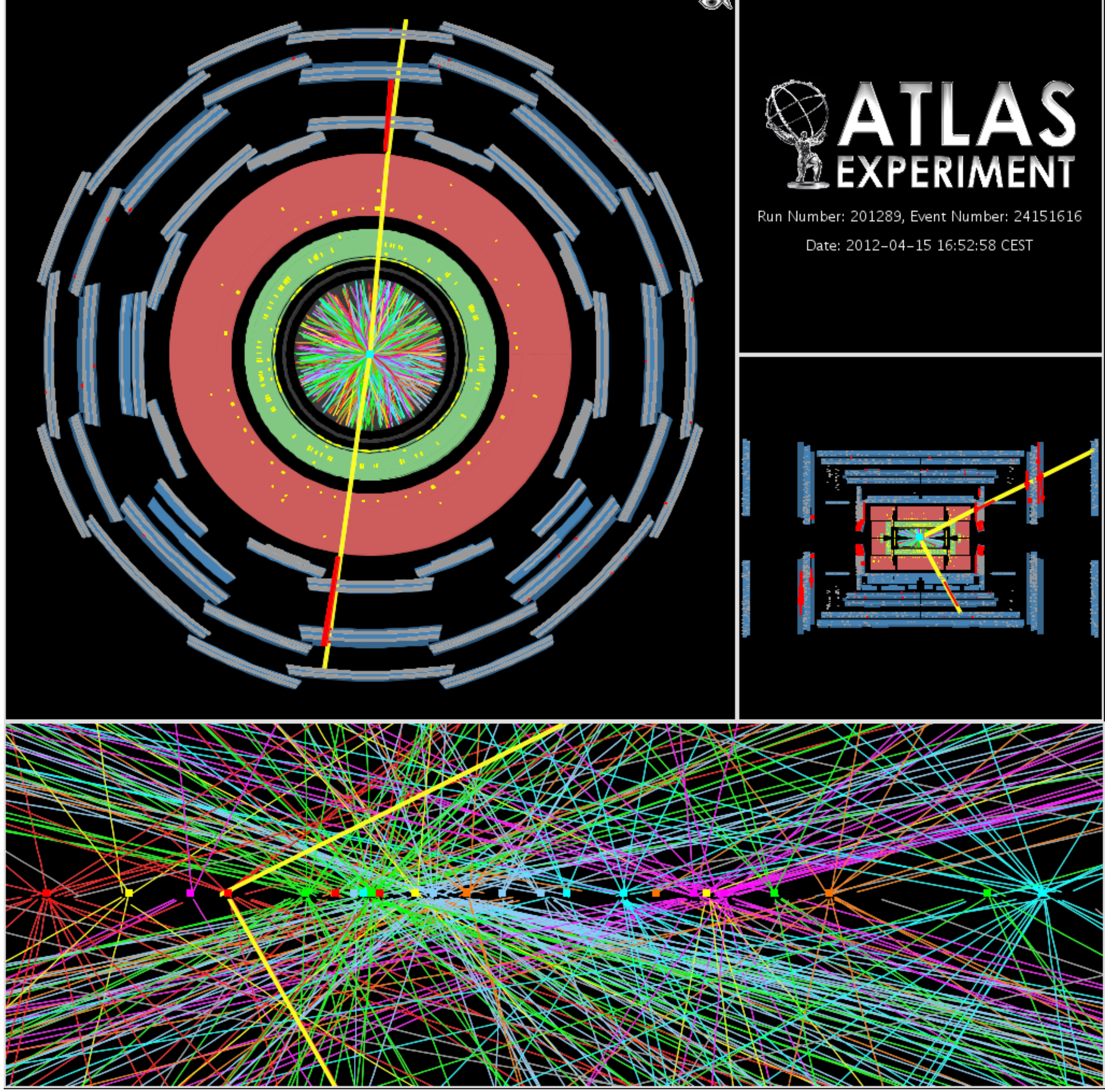
Selection of 1 in 10,000,000,000,000

→ very powerful detectors needed

Excellent LHC performance is a (nice) challenge for the experiment:

- **Trigger**
- **Pile-up**
- **Maintain accuracy of the the measurements in this environment**

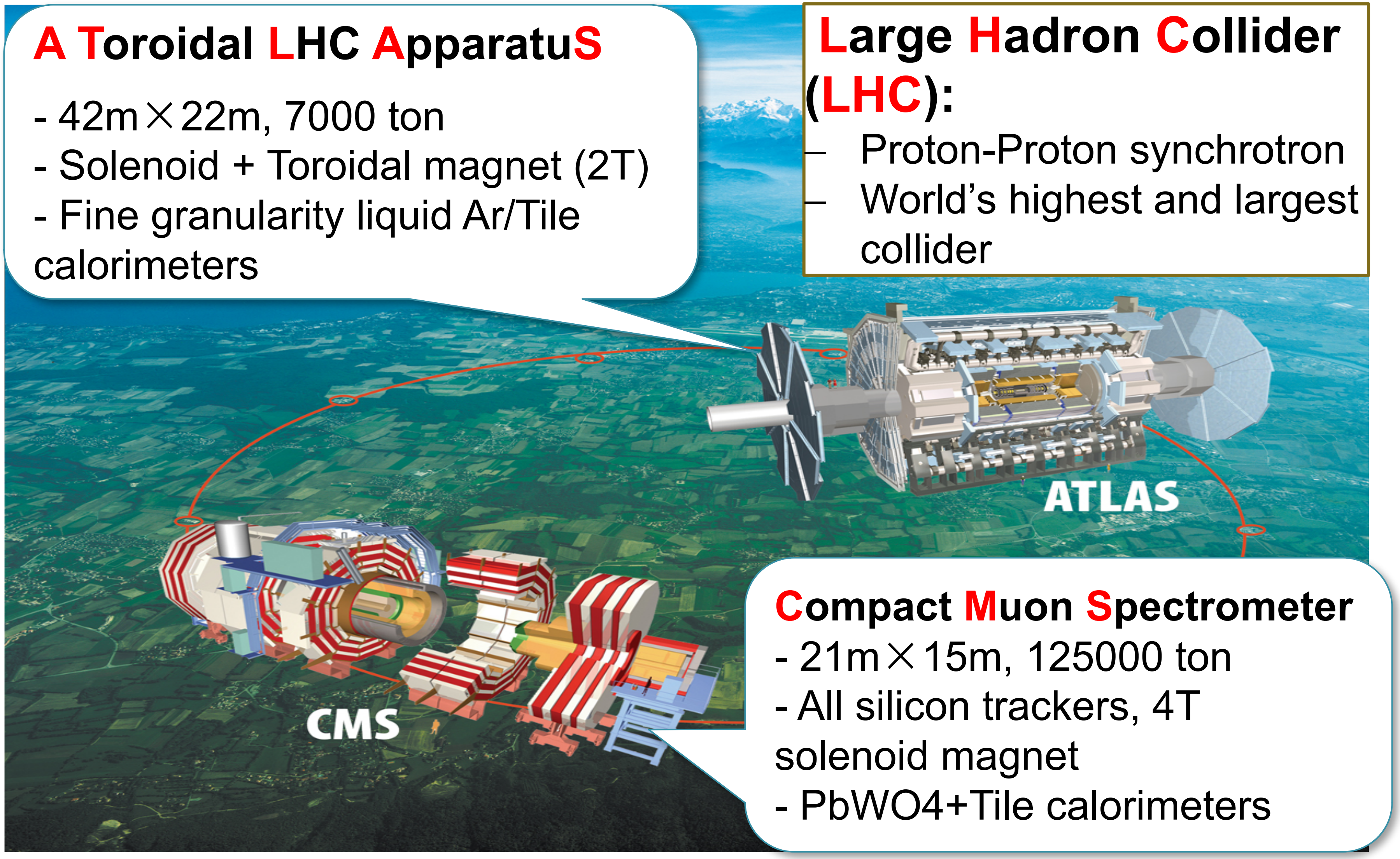




Inner Detector for a Z → μμ event with 25 primary vertices

ATLAS and CMS detector @ LHC

ATLAS and CMS: two multi-purpose detectors @LHC



A Toroidal LHC ApparatuS

- 42m×22m, 7000 ton
- Solenoid + Toroidal magnet (2T)
- Fine granularity liquid Ar/Tile calorimeters

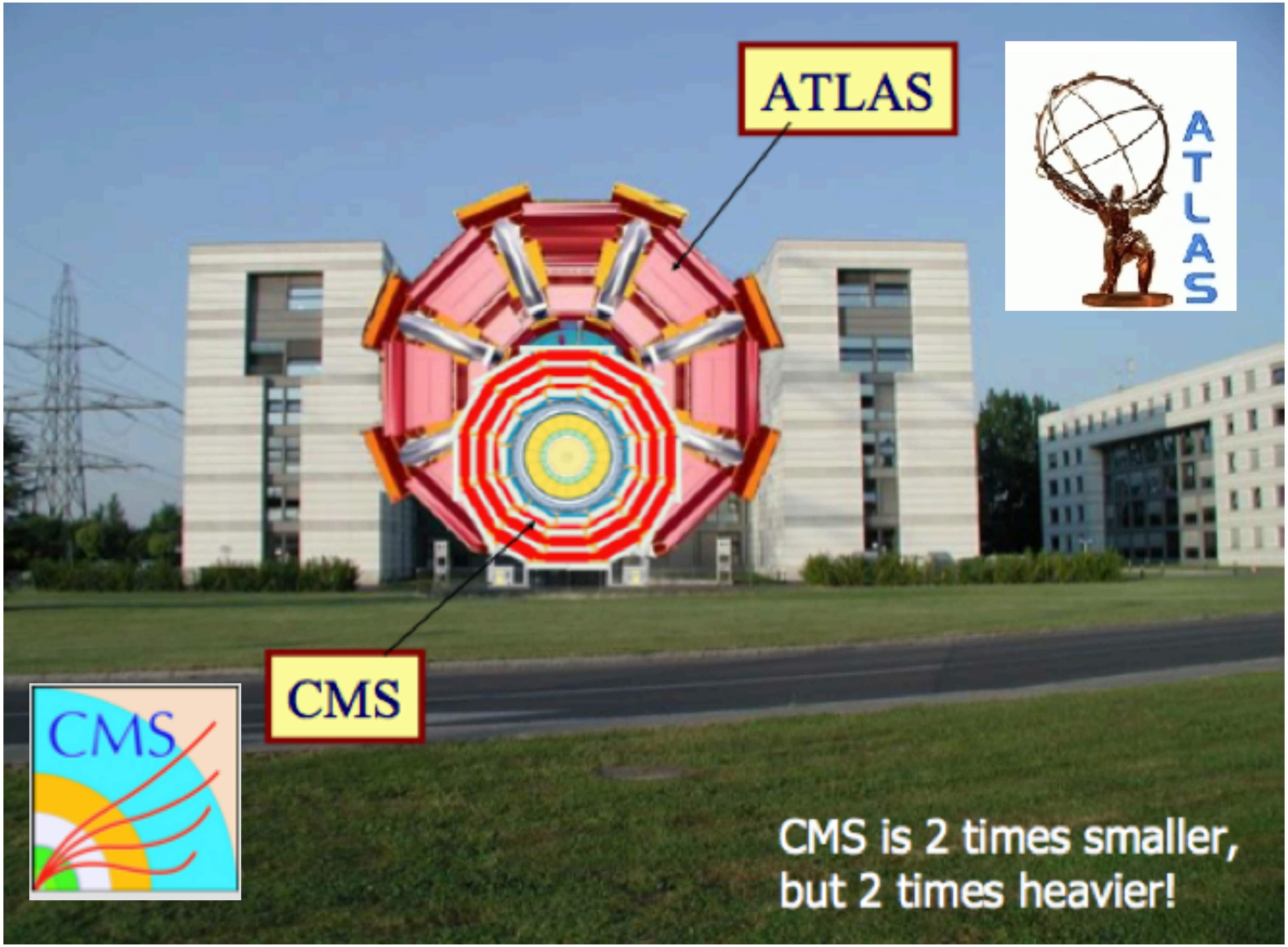
Large Hadron Collider (LHC):

- Proton-Proton synchrotron
- World’s highest and largest collider

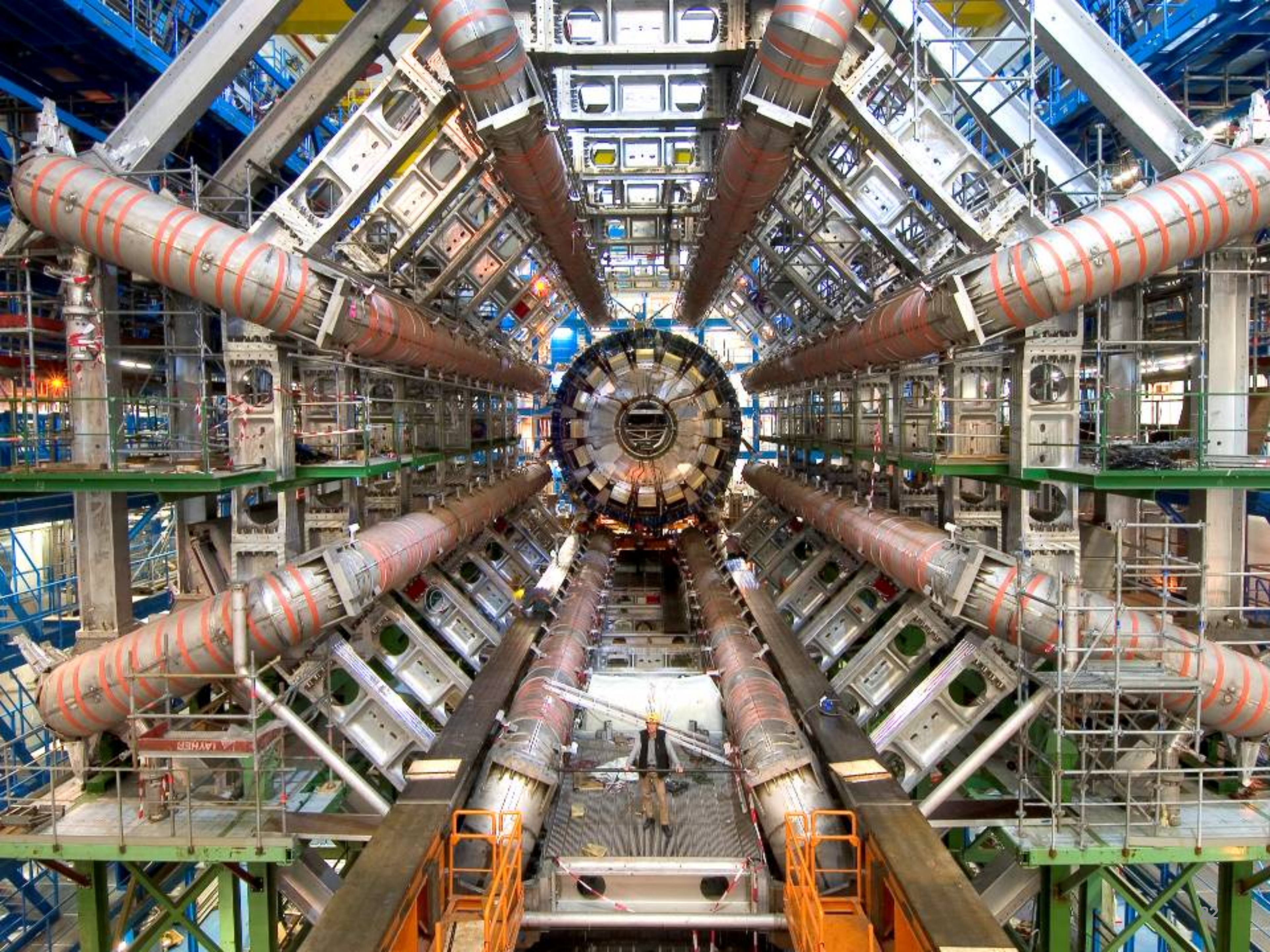
Compact Muon Spectrometer

- 21m×15m, 125000 ton
- All silicon trackers, 4T solenoid magnet
- PbWO4+Tile calorimeters

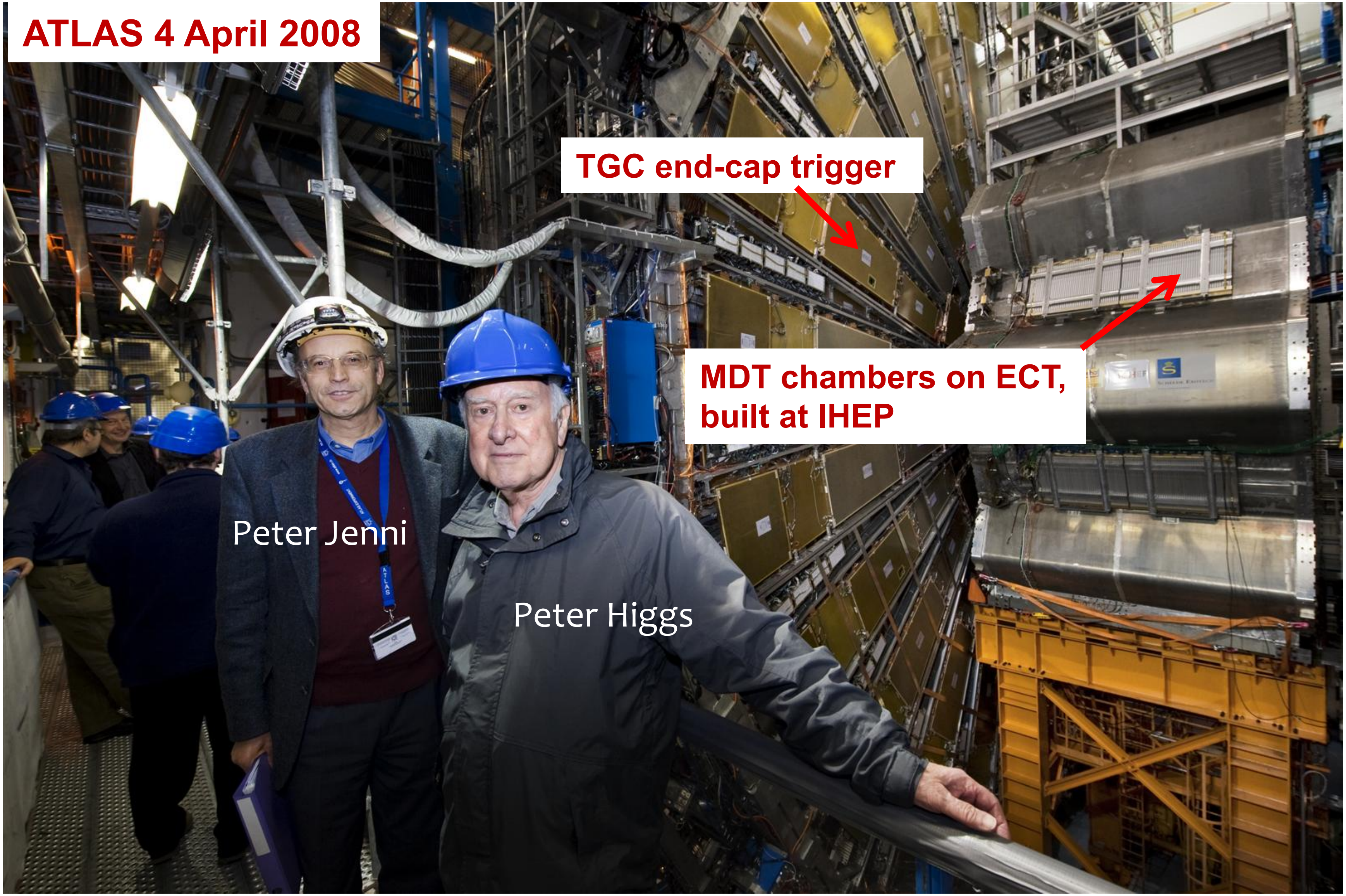
ATLAS and CMS



CMS is 2 times smaller, but 2 times heavier!



Chinese muon chambers installed in the ATLAS detector



ATLAS 4 April 2008

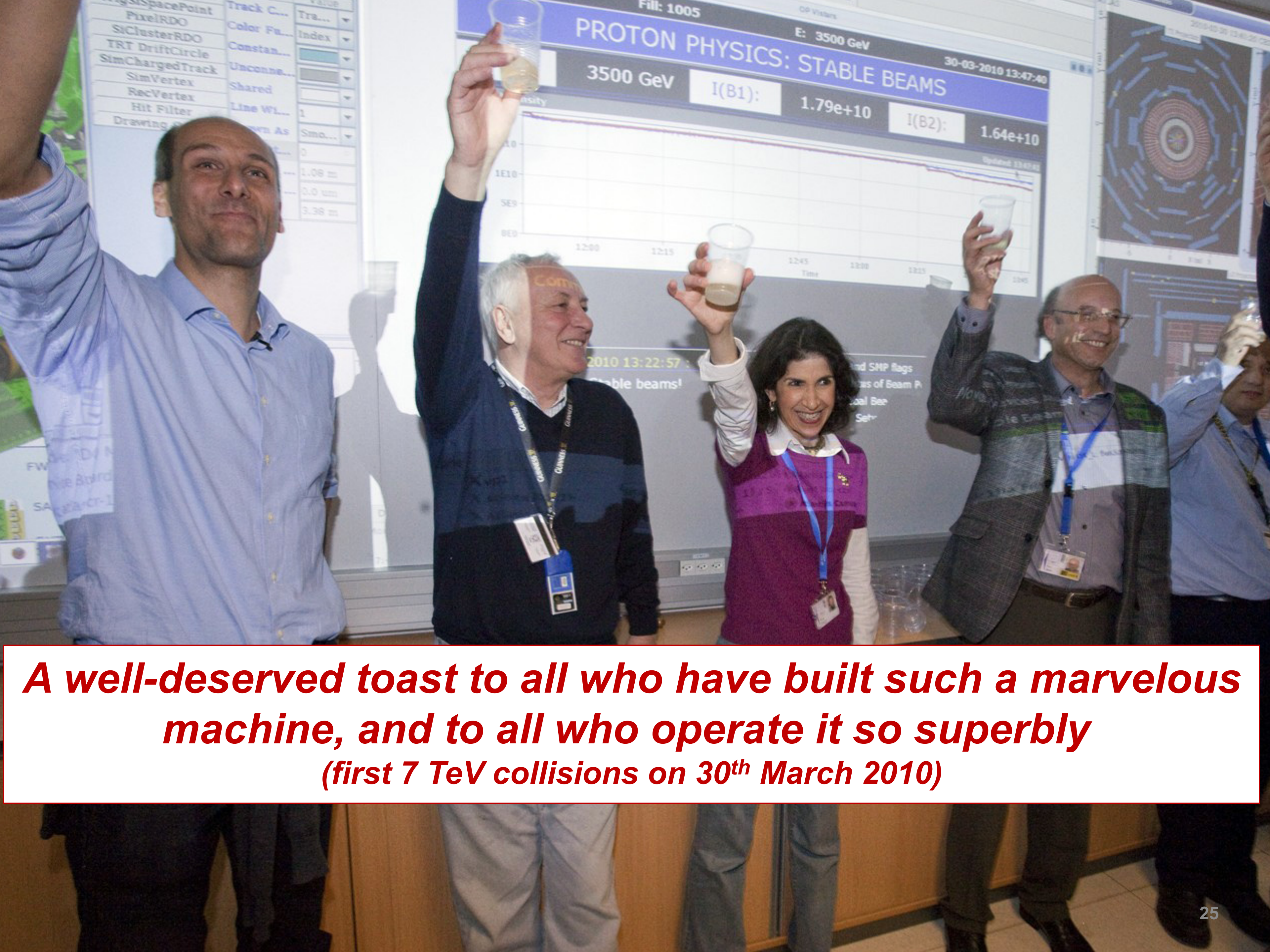
TGC end-cap trigger

MDT chambers on ECT, built at IHEP

Peter Jenni

Peter Higgs

The joy in the ATLAS Control Room when the first LHC beam collided on November 23rd, 2009....

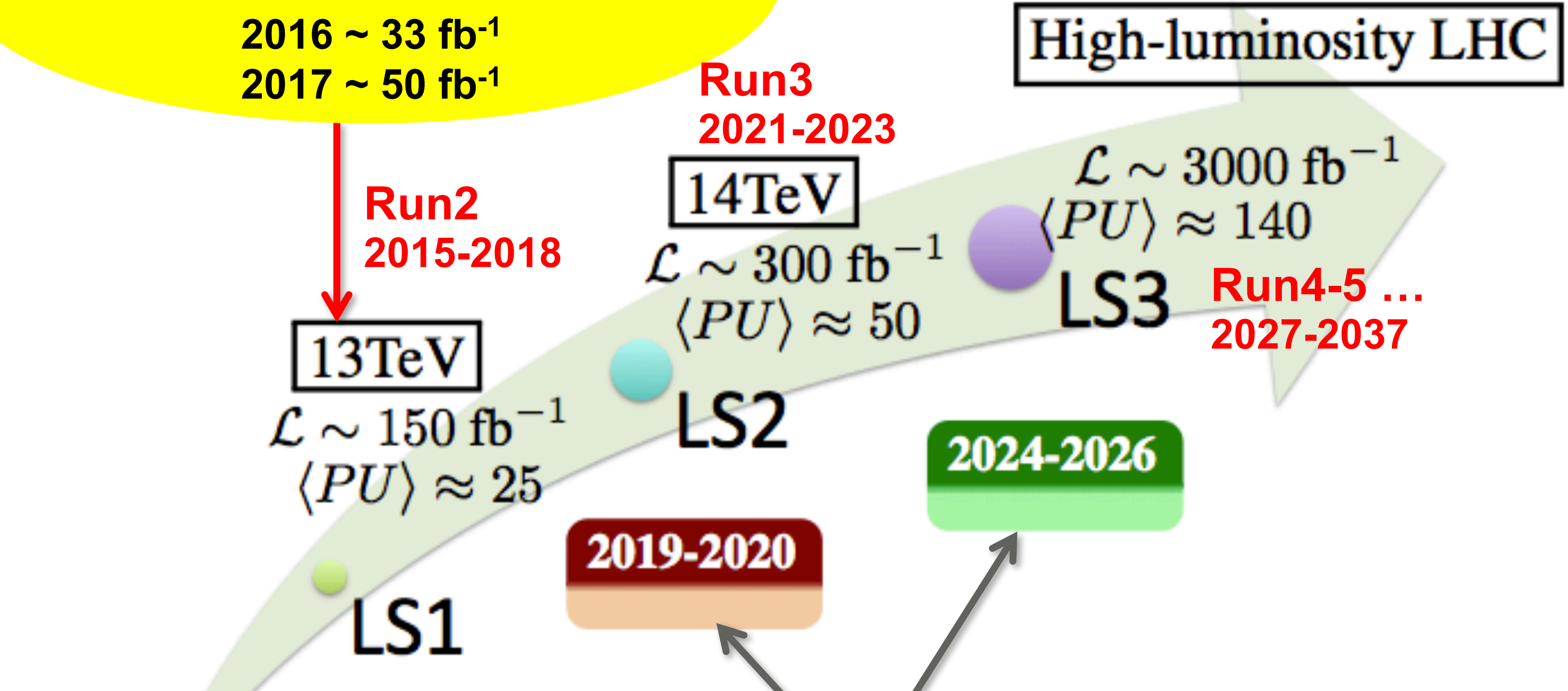


A well-deserved toast to all who have built such a marvelous machine, and to all who operate it so superbly

(first 7 TeV collisions on 30th March 2010)

We are here :
2015-2017: ~80 fb^{-1}(13TeV)
2015 ~ 3 fb^{-1}
2016 ~ 33 fb^{-1}
2017 ~ 50 fb^{-1}

The results are based on 36-80 fb^{-1} @ 13 TeV (RUN2 2015-2017) ~ 2-3% of total



Run1

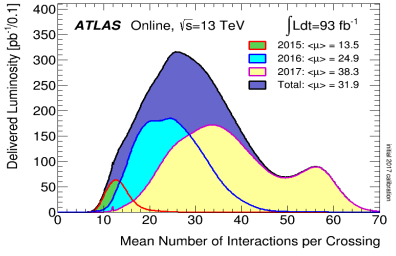
2010-2012
~25 fb^{-1}

Run2
2015-2018

Run3
2021-2023

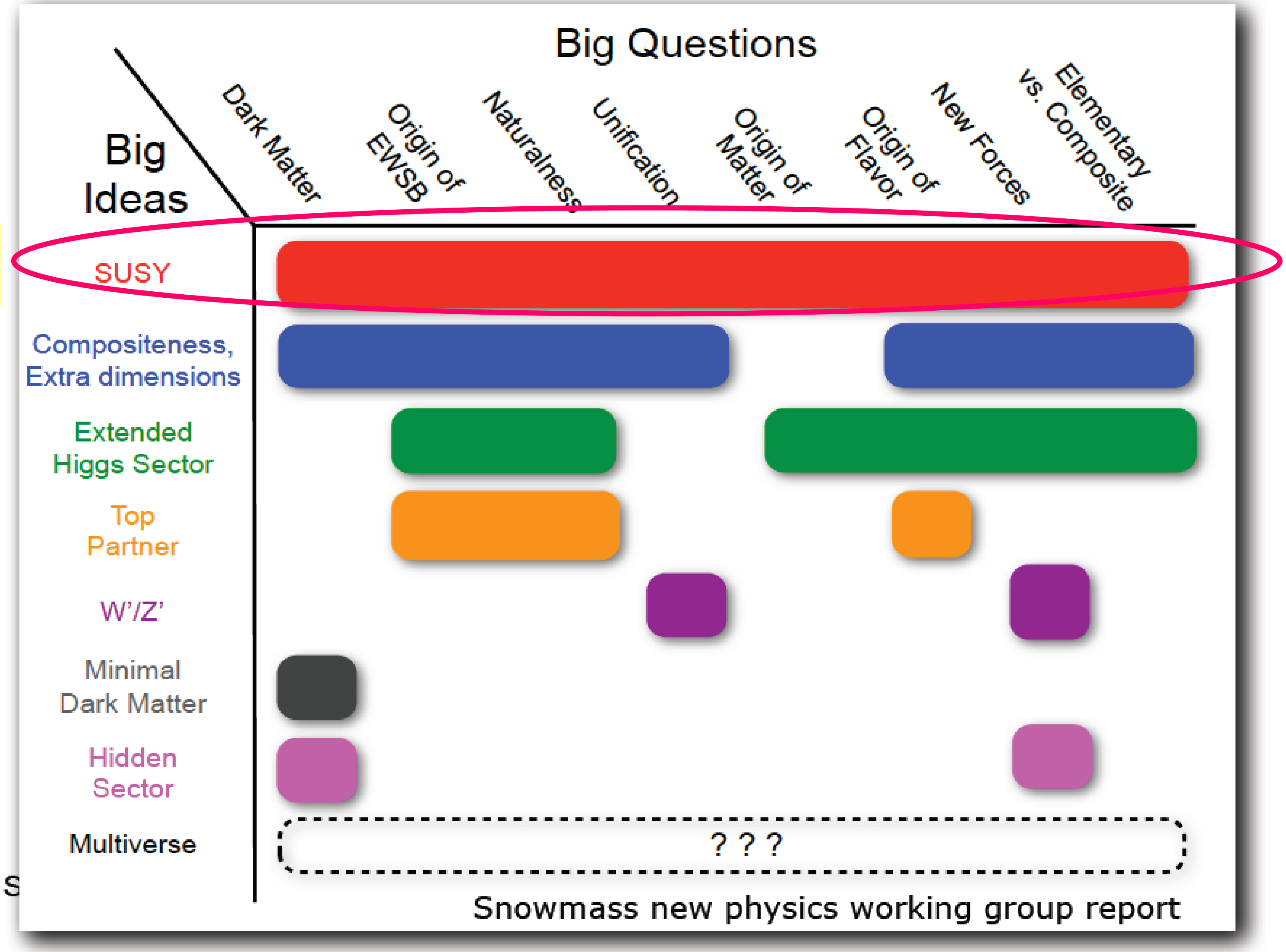
Run4-5 …
2027-2037

Long Stop



New Physics beyond the SM

SUSY



Big Questions

Big Ideas	Dark Matter	Origin of EWSB	Naturalness	Unification	Origin of Matter	Origin of Flavor	New Forces	Elementary vs. Composite
SUSY	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
Compositeness, Extra dimensions	🟦	🟦	🟦	🟦		🟦	🟦	🟦
Extended Higgs Sector		🟩	🟩		🟩	🟩	🟩	🟩
Top Partner		🟧	🟧			🟧		
W'/Z'				🟪			🟪	
Minimal Dark Matter	⬛							
Hidden Sector	🟪						🟪	
Multiverse	? ? ?							

Snowmass new physics working group report

S. S

SUSY search at colliders (mainly at LHC)

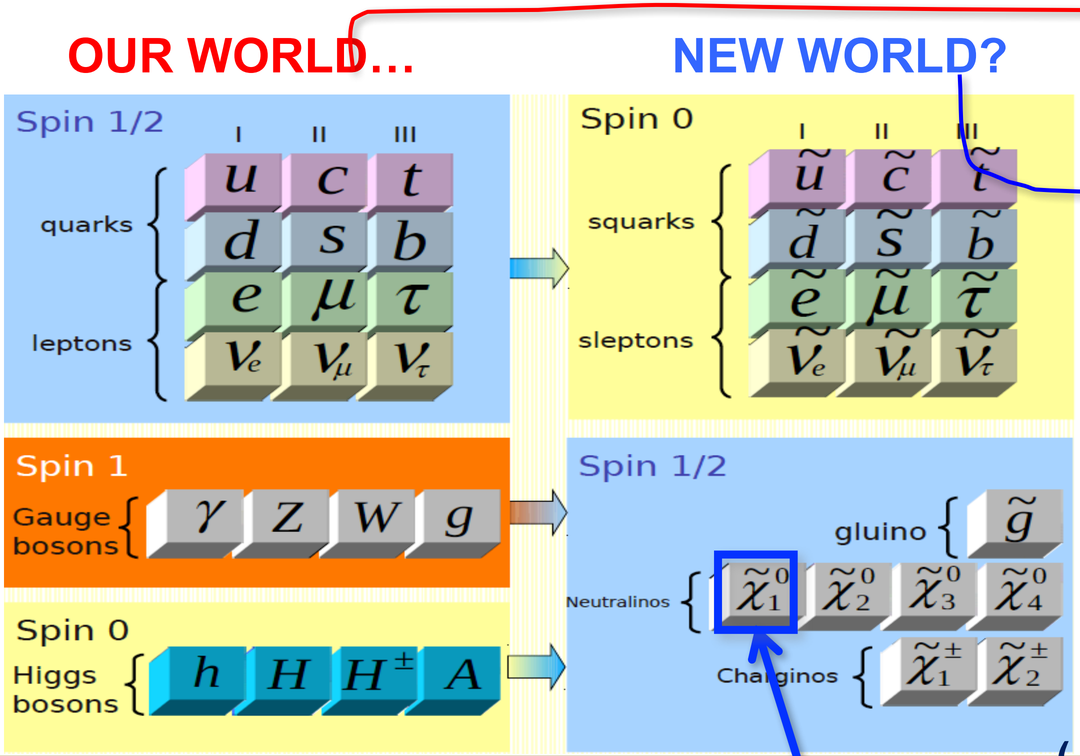
What is SUSY?

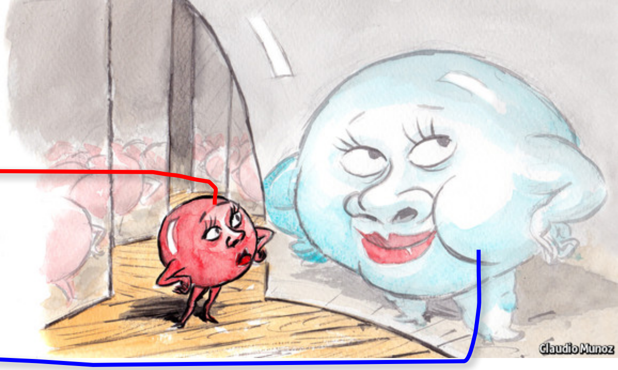
How SUSY do help?

(TeV-scale) Supersymmetry (SUSY)

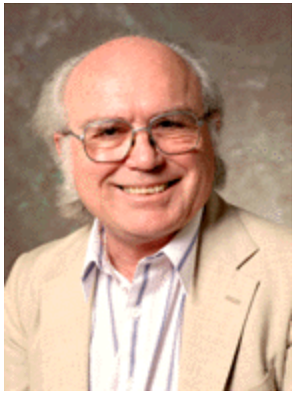
P. Higgs at CMS

SUSY Introduction





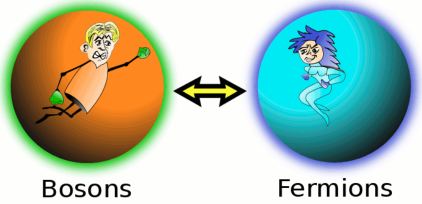
Julius Wess
(1934 – 2007)



Bruno Zumino
(1923 – 2014)

(Julius Wess and Bruno Zumino, 1974)

- ❑ **Establishes a symmetry between fermions (matter) and bosons (forces)**
- ❑ **Motivation:**
  - ○ **Unification (fermions-bosons, matter-forces)**
  - ○ **Solves some deep problems of the SM**
  - ○ **Provide Dark Matter candidate**
  - ○ **……**

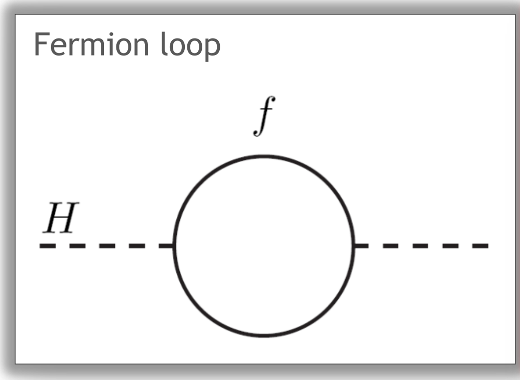


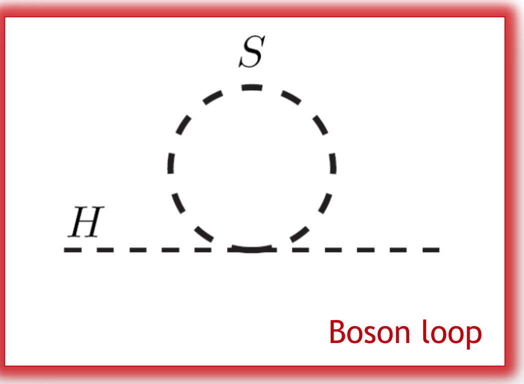
Q |boson> = |fermion>
Q |fermion> = |boson>

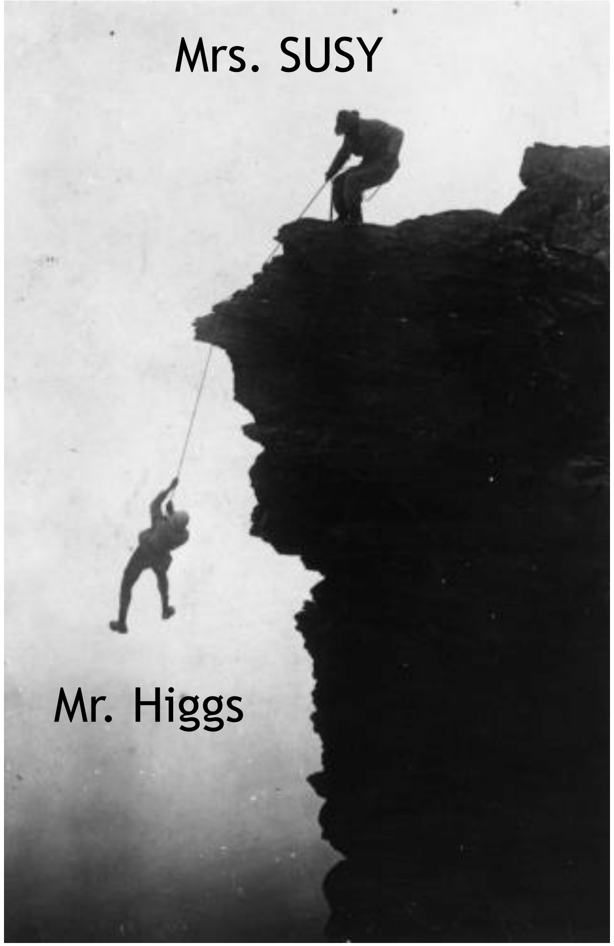
Spin differ by 1/2

SUSY Introduction

- **Solve hierarchy problem** without "fine tuning"
  - Fermion and boson loops contribute with **different signs** to the Higgs radiative corrections
  - Supersymmetric partner contributions to Higgs mass **cancel** SM contributions

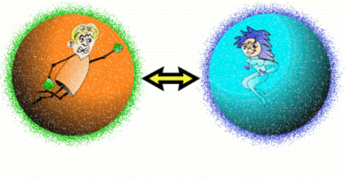




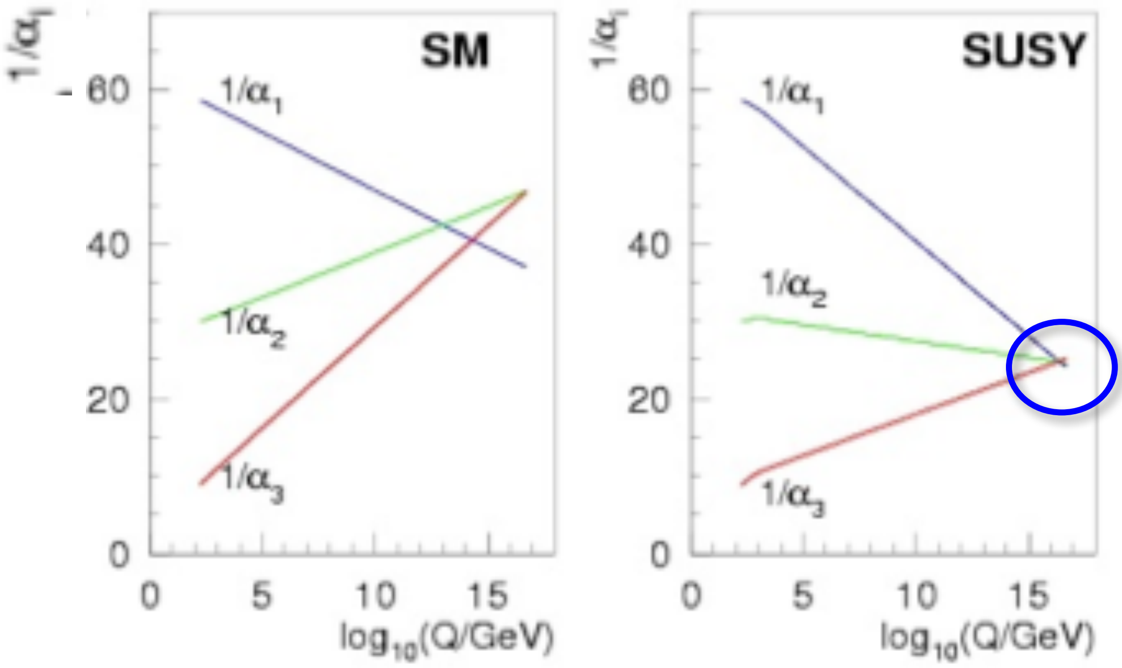


$$M_h^2 = M_{h,tree}^2 + \Delta M_h; \qquad SM: \Delta M_h \sim \Lambda^2; \qquad SUSY: \Delta M_h \sim m_{soft}^2 \log(\Lambda / m_{soft})$$

SUSY Introduction

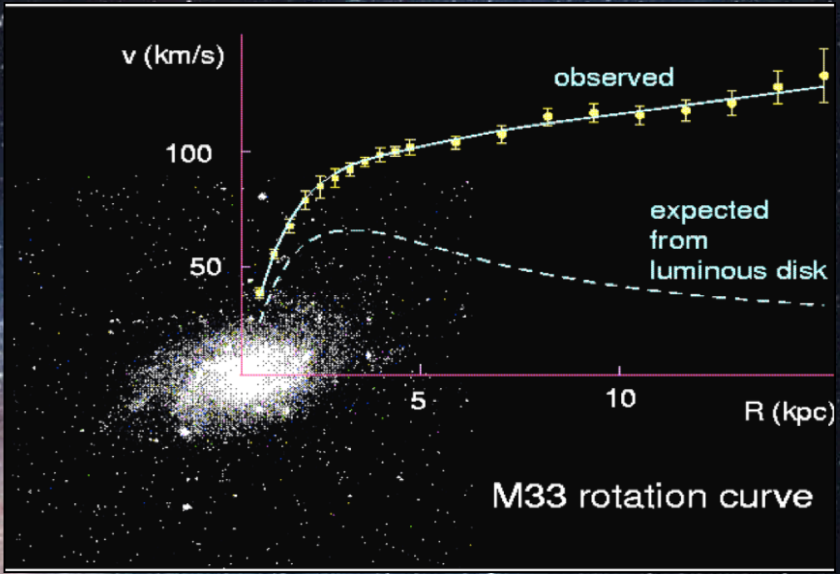


- ☐ **Unification of gauge couplings**
  - New particle content changes running of couplings
  - requires SUSY masses below few TeV

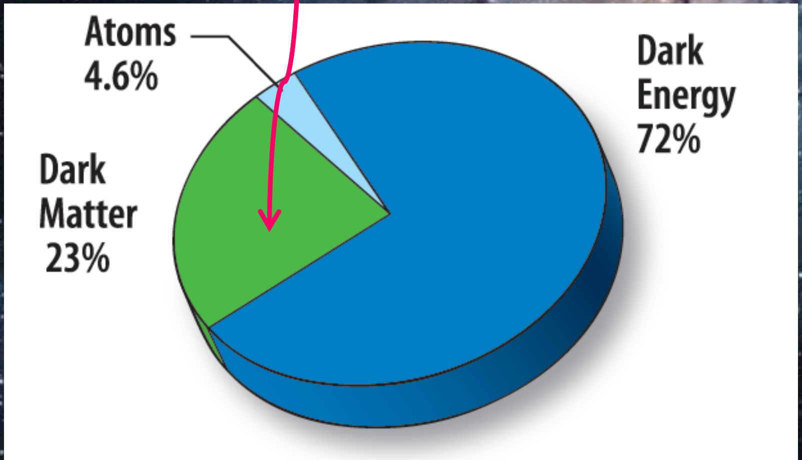


Provide Dark Matter candidate

天文学家发现宇宙中很大一部分是我们看不见的暗物质（明物质只占4.6%）



‘Supersymmetric’ particles ?



- **Provide perfect dark mater candidate - WIMP**(lightest neutralino in R-parity conserving models)
  - ❑ stable
  - ❑ electrically neutron
  - ❑ same density as DM

$0.094 < \Omega_{CDM}h^2 < 0.136$ **(95% CL)**

→ 通过寻找SUSY，可以为暗物质寻找提供实验证据！

How to hunt SUSY?

(TeV-scale) Supersymmetry (SUSY)

P. Higgs at CMS

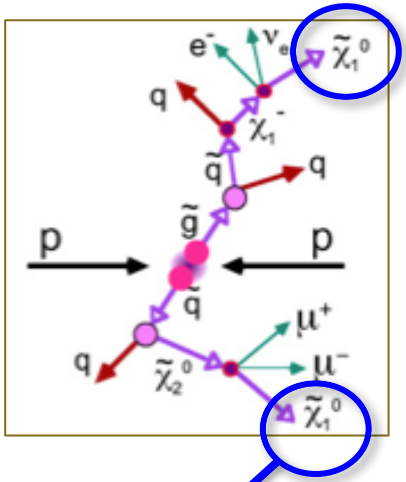
How do we start? - SUSY Signature

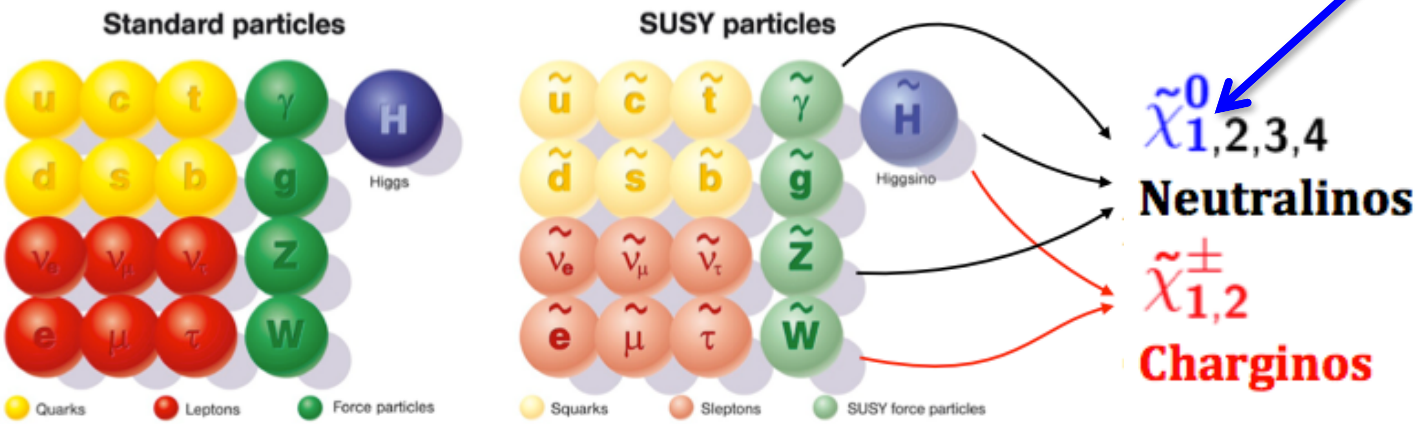
- **Conserved R parity** (originally introduced for stability of proton)

$$R = (-1)^{3(B-L)+2S}$$

R=+1 (SM)
R=-1 (SUSY)

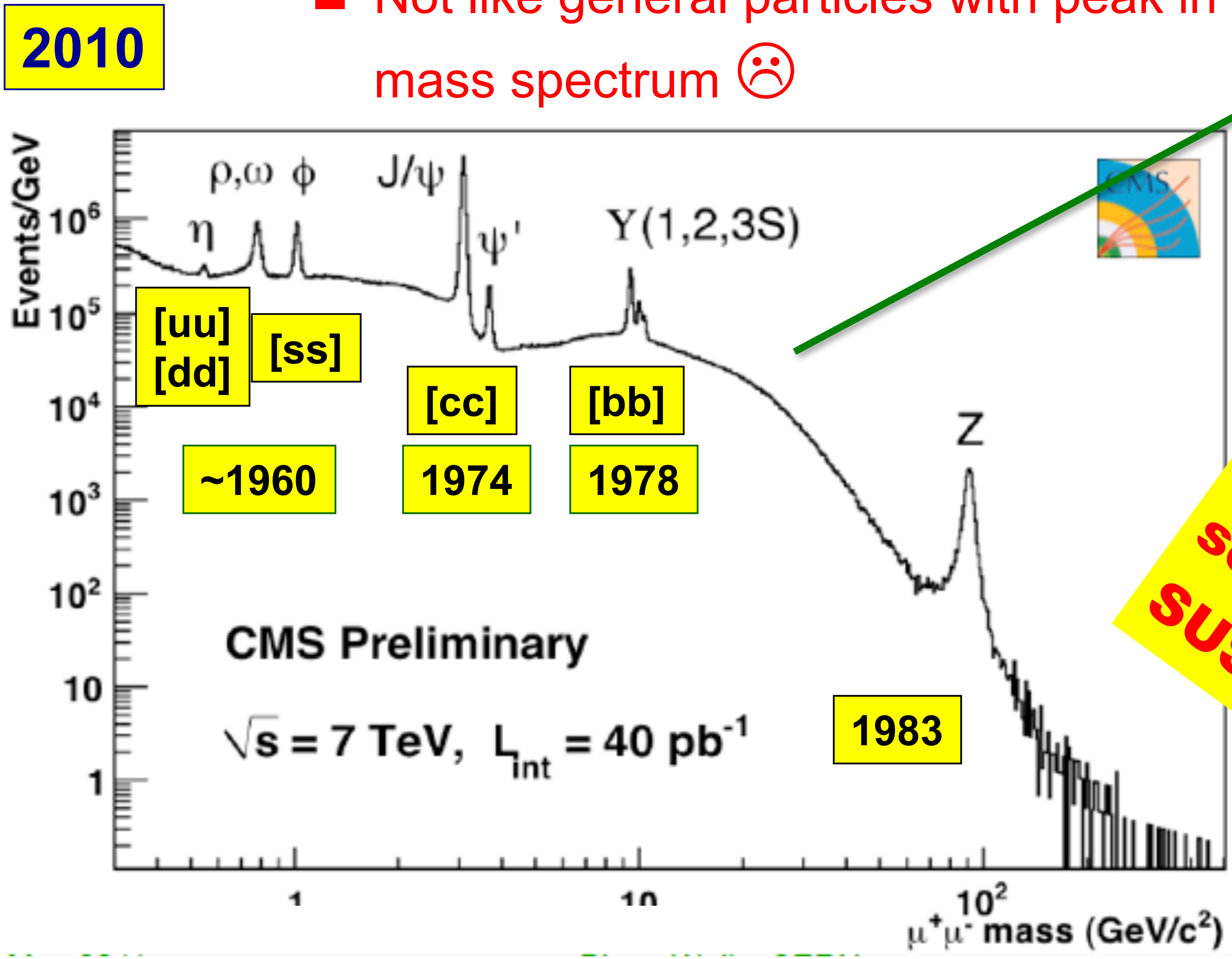
  - SUSY particles produced/annihilated in pairs
  - Lightest SUSY particle (LSP) stable (DM candidate)
  - Typical signature: jets/leptons/photons + **MET** **(key signature: large MET)**

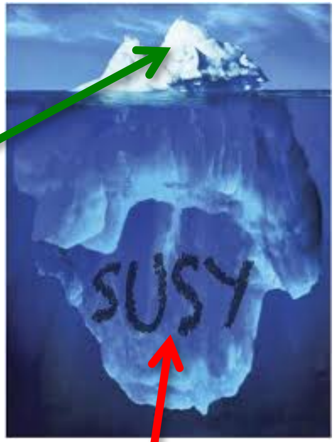




How do we search for SUSY?

- Not like general particles with peak in mass spectrum ☹

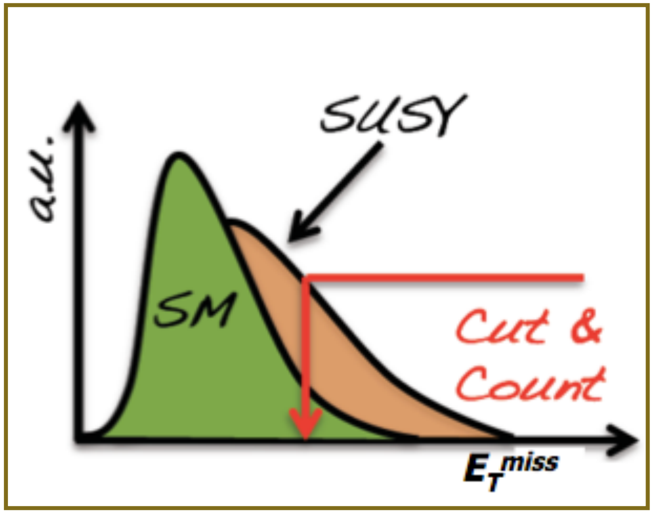




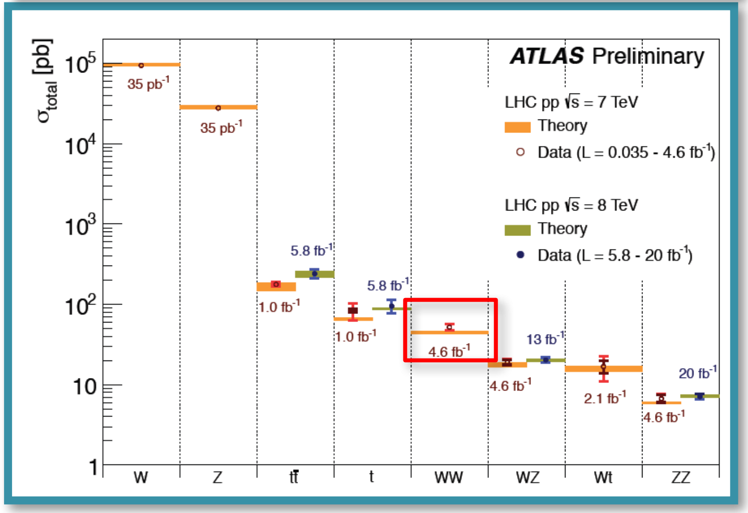
How do we search for SUSY?

How do we search for SUSY?

- **SUSY search strategy:** search for <u>deviation from SM</u> from the tails
- **SUSY sensitive variables:** Try to establish excess of events in some sensitive kinematic distribution
- **SM background:** the discovery of new physics can only be claimed when SM backgrounds are understood well or under control
  - SM bgs understood very well ☺
  - No hints for new physics ☹
  - Slightly overshoot in WW cross section, but consistent with NNLO xsec.

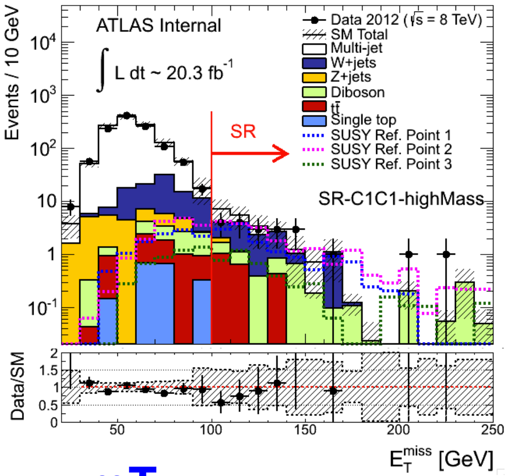


SM "backgrounds"– the big picture

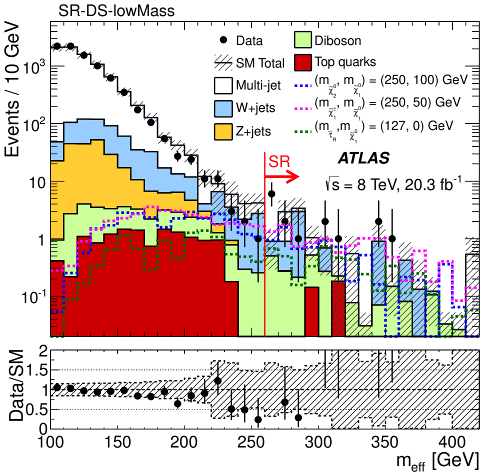


SUSY Sensitive Variables

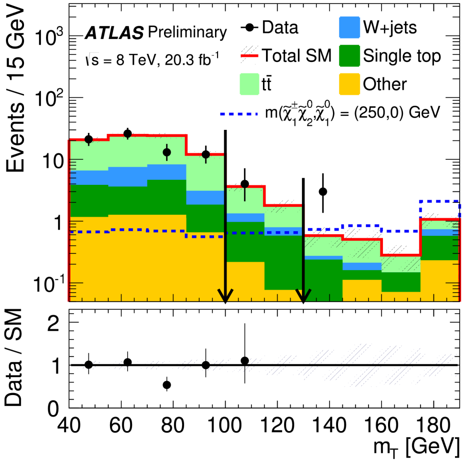
E_T^{miss}



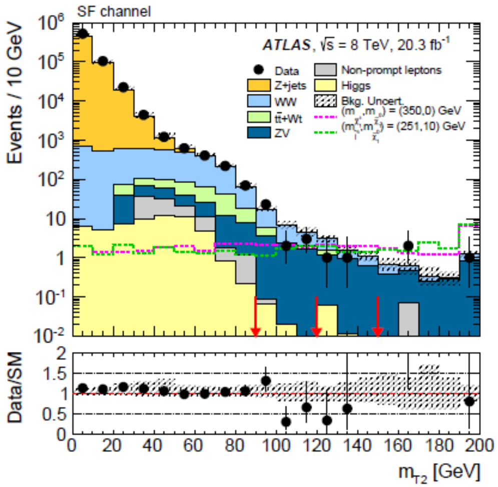
M_{eff}



mT



mT2



- **E_T^{miss}** from escaping LSP, to suppress bg from mis-measured jets and oth. SM BG
- Related to the sparticle mass scale, like effective mass (**M_{eff}**)

$$M_{\text{eff}} \equiv \sum_{i=1}^{N_{\text{jets}}} p_{\text{T}}^{\text{jet},i} + \sum_{j=1}^{N_{\text{lep}}} p_{\text{T}}^{\text{lep},j} + E_{\text{T}}^{\text{miss}}$$

- **mT, mT2** (stransverse mass): suppress BG with Ws

$$m_{\text{T2}} = \min_{\mathbf{q}_{\text{T}}}\left[\max\left(m_{\text{T}}(\mathbf{p}_{\text{T}}^{\ell 1}, \mathbf{q}_{\text{T}}), m_{\text{T}}(\mathbf{p}_{\text{T}}^{\ell 2}, \mathbf{p}_{\text{T}}^{\text{miss}} - \mathbf{q}_{\text{T}})\right)\right]$$

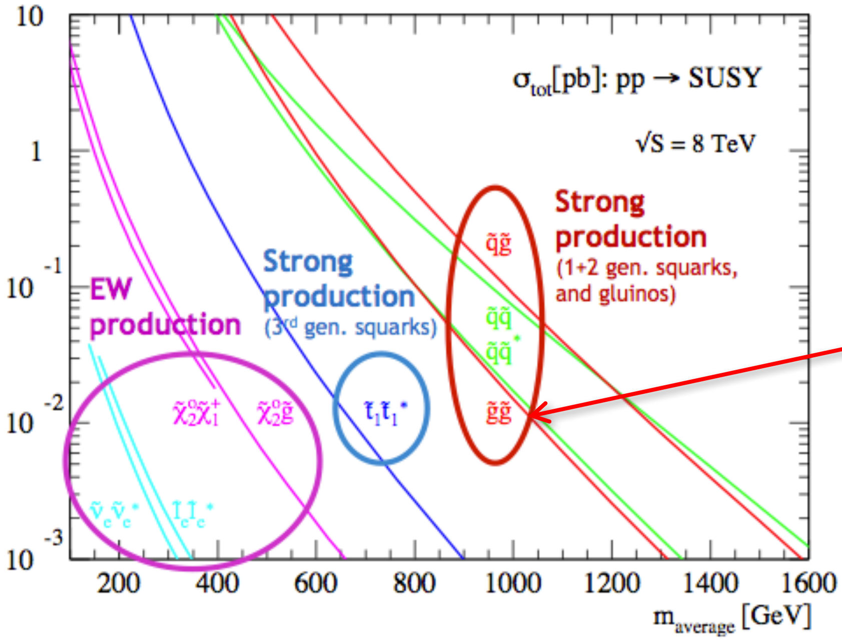
- Many others …

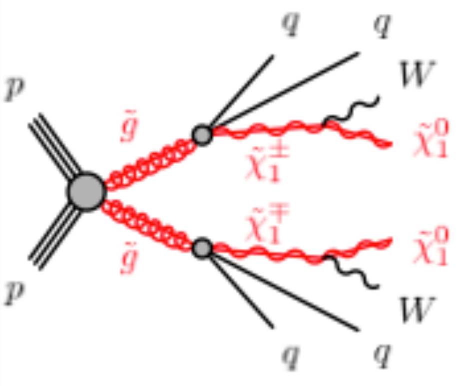
How do we search for SUSY?

-Analysis Procedure (similar for exotics)

1. **Be aware of SUSY signature, design signal grid**
2. **Pre-selection**: select good objects (e, mu, tau, jet, ...), apply trigger depending on analysis, remove bad events (bad runs, not from pp collisions, in transition region ...)
3. **SR definition and optimization**
   - **Define signal regions** based on decay topologies occurring in generic models
   - **Set final cut** on **discriminating variables** (e.g. Meff) to optimize sensitivity to reference models with appropriate mass scale
4. **SM Background estimations (data-driven + MC)**
5. **Compare SM predictions with data**
6. **If no excess, interpret results in different SUSY models**

1. Be aware of SUSY signature, design signal grid





gluinos decaying via charginos

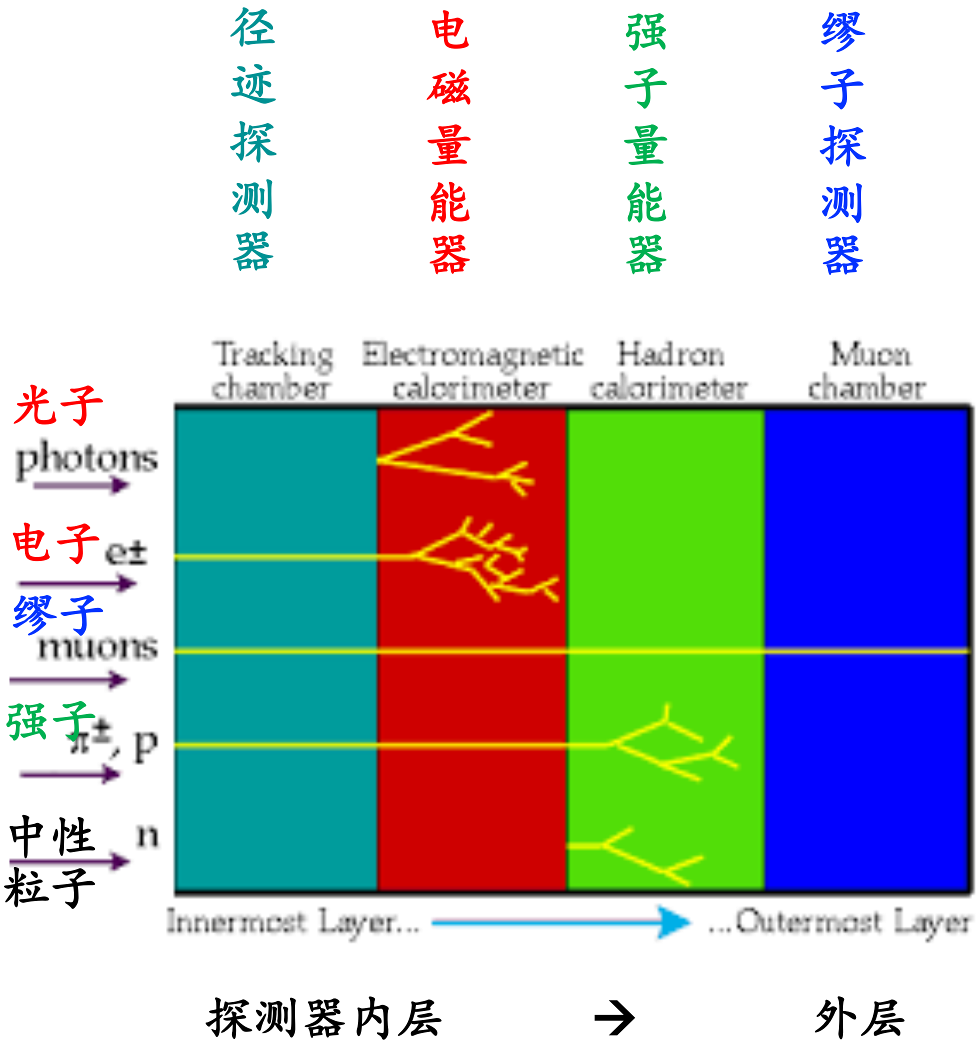
W → l nu
→ qq

Final states:

≥ 1 lepton + multi-jets + large E_T^{miss}

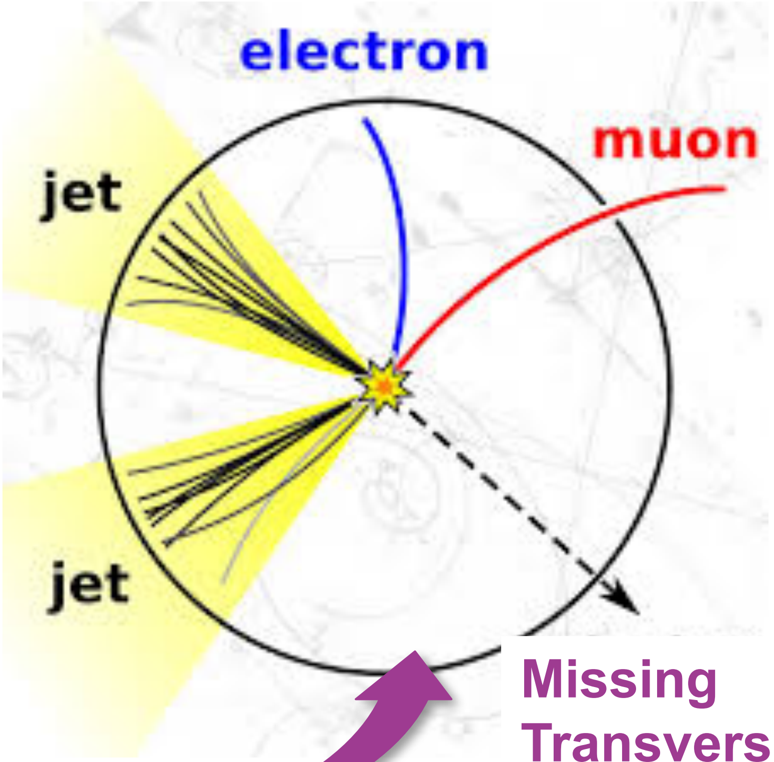
2: Pre-selection Reconstructed Objects

- Photons: no track but energy in el-m (and not in the hadronic) calorimeter
- Electrons: track and energy in el-m (and not in the hadronic) calorimeter
- Muons: track in inner tracker and muon chamber
- Jets: cluster in hadronic calorimeter



MET: Missing Transverse Energy

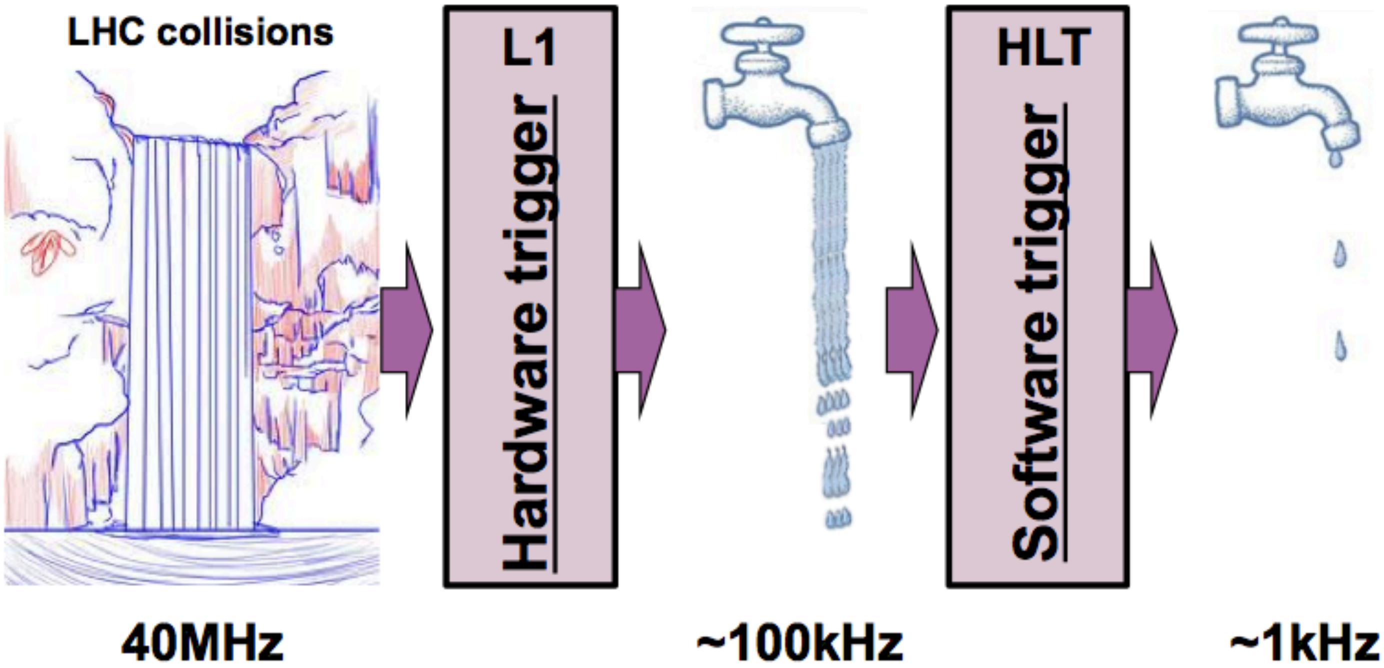
- At the LHC an unknown proportion of the energy of the colliding protons escapes down the beam-pipe
- Invisible particles (neutrinos, neutralinos?) are created their momentum can be constrained in **the plane transverse to the beam direction**



Missing Transverse Energy

$$E_T^{\text{miss}} = -\sum_i p_T(i)$$

Triggering on Physics

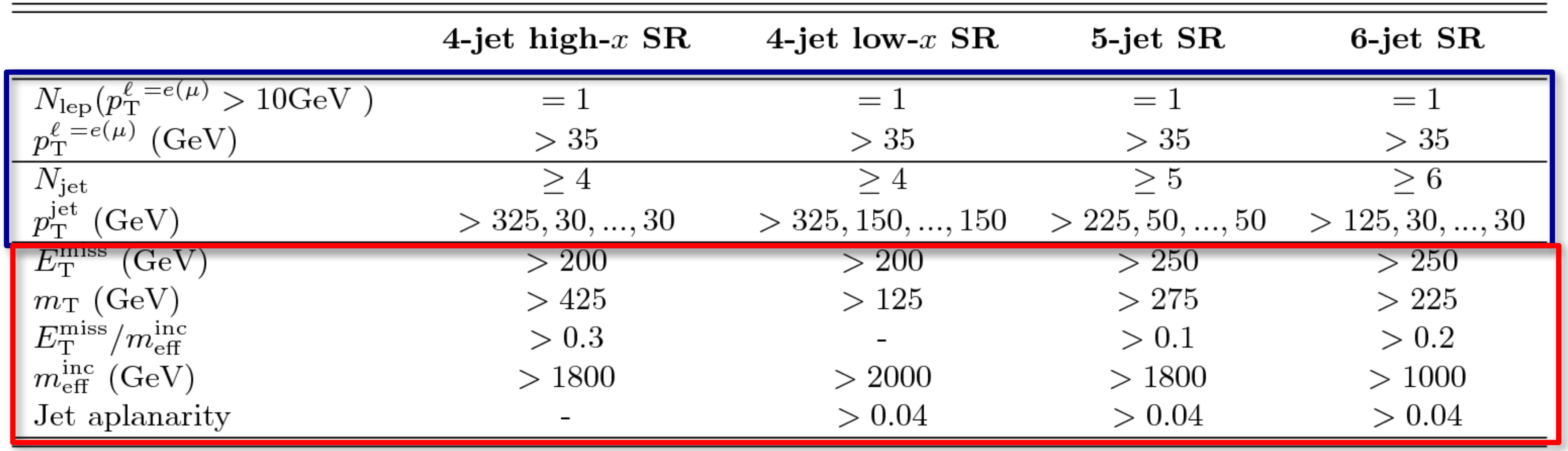


- Apply trigger depending on analysis
- Only pick up what we are interested events
- MissingET trigger used here

Final states: ≥ 1 lepton + multi-jets + large E_T^{miss}

3: SR definition and optimization

arXiv:1605.04285



	4-jet high-x SR	4-jet low-x SR	5-jet SR	6-jet SR
$N_{\text{lep}}(p_{\text{T}}^{\ell=e(\mu)} > 10\text{GeV})$	$= 1$	$= 1$	$= 1$	$= 1$
$p_{\text{T}}^{\ell=e(\mu)}$ (GeV)	> 35	> 35	> 35	> 35
N_{jet}	≥ 4	≥ 4	≥ 5	≥ 6
$p_{\text{T}}^{\text{jet}}$ (GeV)	$> 325, 30, ..., 30$	$> 325, 150, ..., 150$	$> 225, 50, ..., 50$	$> 125, 30, ..., 30$
$E_{\text{T}}^{\text{miss}}$ (GeV)	> 200	> 200	> 250	> 250
m_{T} (GeV)	> 425	> 125	> 275	> 225
$E_{\text{T}}^{\text{miss}}/m_{\text{eff}}^{\text{inc}}$	> 0.3	-	> 0.1	> 0.2
$m_{\text{eff}}^{\text{inc}}$ (GeV)	> 1800	> 2000	> 1800	> 1000
Jet aplanarity	-	> 0.04	> 0.04	> 0.04

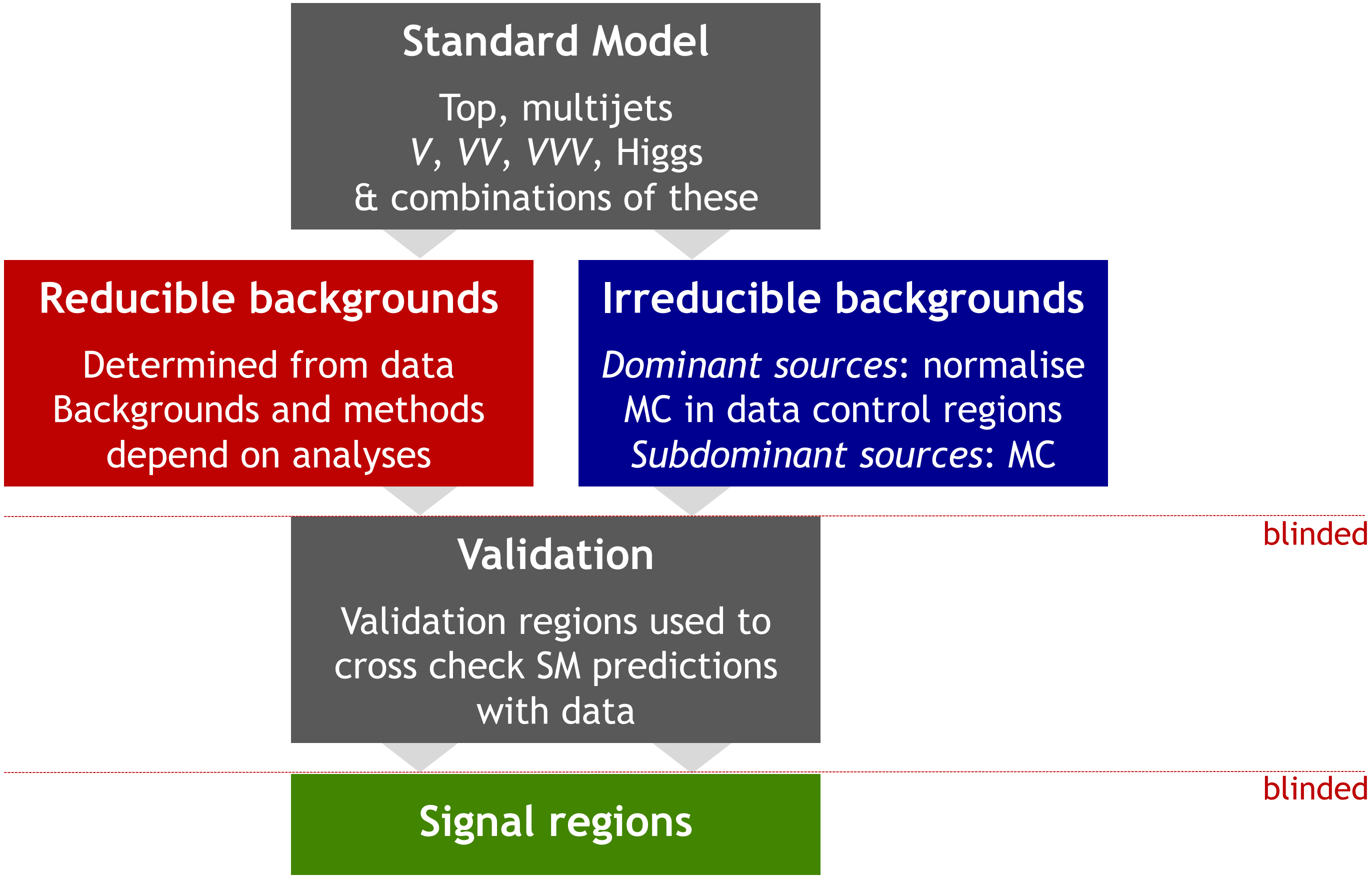
Final states: ≥ 1 lepton + multi-jets + large E_T^{miss}

- According to signal signature, select interested final states objects: number of jets, leptons requirement

- Suppress background using SUSY discriminating variables
- The cuts are from optimization with signal significance

4: SM Background estimations (data-driven + MC)

SUSY searches rely primarily on the understanding of the SM BG



Standard Model

Top, multijets
V, *VV*, *VVV*, Higgs
& combinations of these

Reducible backgrounds

Determined from data
Backgrounds and methods depend on analyses

Irreducible backgrounds

Dominant sources: normalise MC in data control regions
Subdominant sources: MC

blinded

Validation

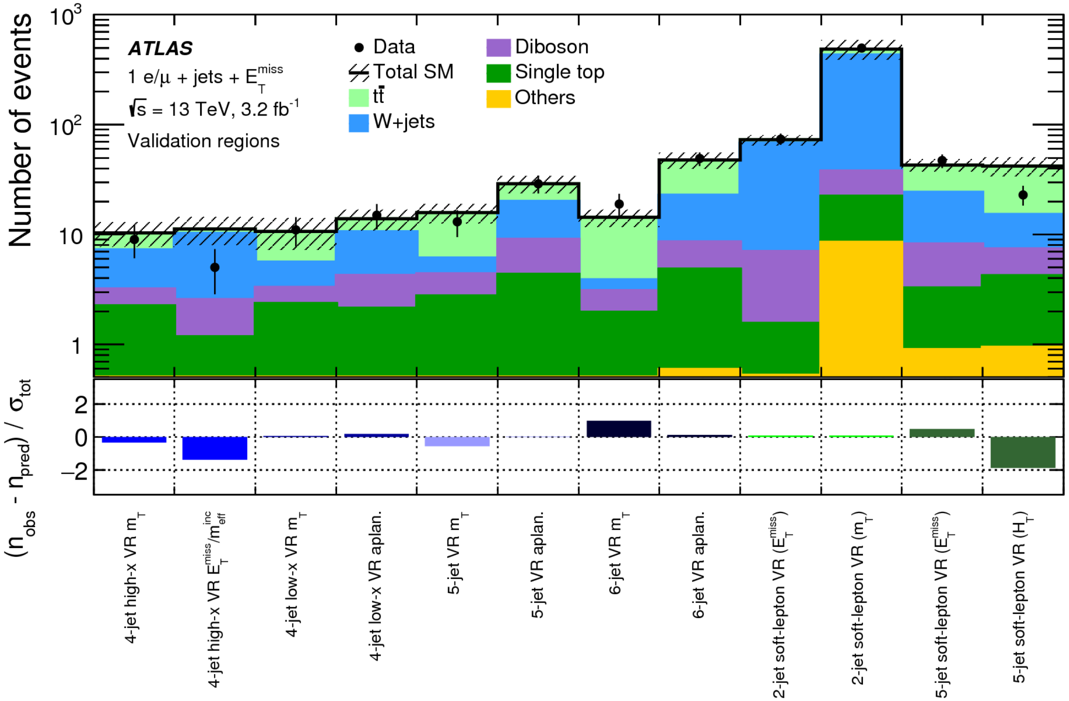
Validation regions used to cross check SM predictions with data

blinded

Signal regions

SU e SM

B



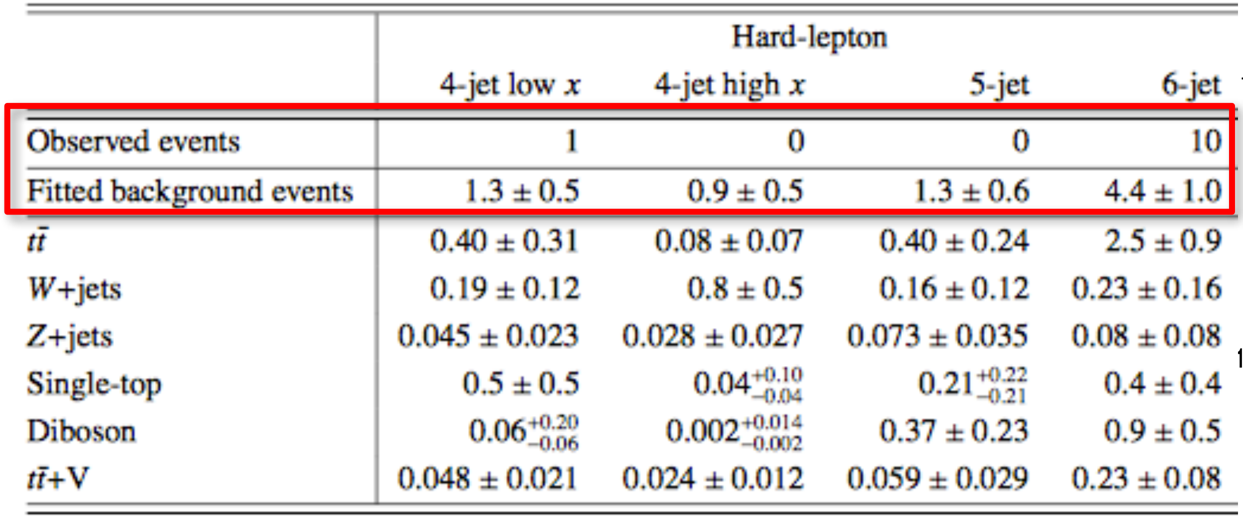
Determined from data
Backgrounds and meth
depend on analyses

ant sources: normalise
data control regions
subdominant sources: MC

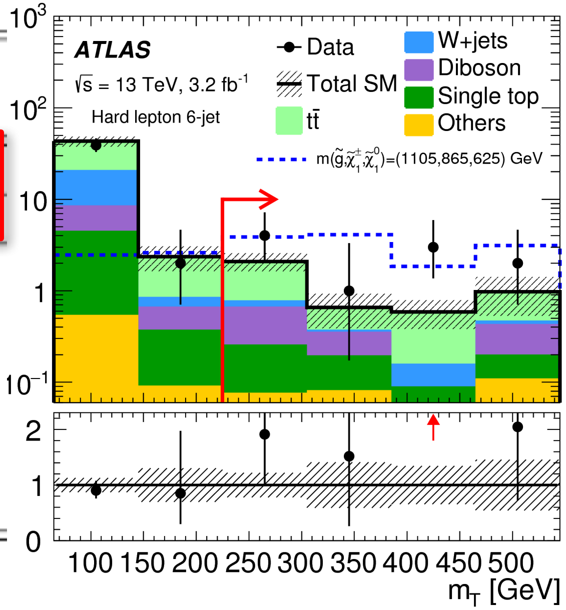
Validation

Validation regions used to cross check SM predictions with data

Signal regions

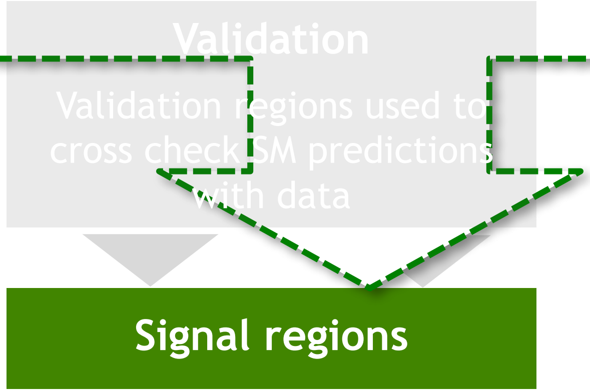


	Hard-lepton			
	4-jet low *x*	4-jet high *x*	5-jet	6-jet
Observed events	1	0	0	10
Fitted background events	1.3 ± 0.5	0.9 ± 0.5	1.3 ± 0.6	4.4 ± 1.0
$t\bar{t}$	0.40 ± 0.31	0.08 ± 0.07	0.40 ± 0.24	2.5 ± 0.9
W+jets	0.19 ± 0.12	0.8 ± 0.5	0.16 ± 0.12	0.23 ± 0.16
Z+jets	0.045 ± 0.023	0.028 ± 0.027	0.073 ± 0.035	0.08 ± 0.08
Single-top	0.5 ± 0.5	$0.04^{+0.10}_{-0.04}$	$0.21^{+0.22}_{-0.21}$	0.4 ± 0.4
Diboson	$0.06^{+0.20}_{-0.06}$	$0.002^{+0.014}_{-0.002}$	0.37 ± 0.23	0.9 ± 0.5
$t\bar{t}$+V	0.048 ± 0.021	0.024 ± 0.012	0.059 ± 0.029	0.23 ± 0.08



- No significant excess except for 6jet-SR

arXiv:1605.04285

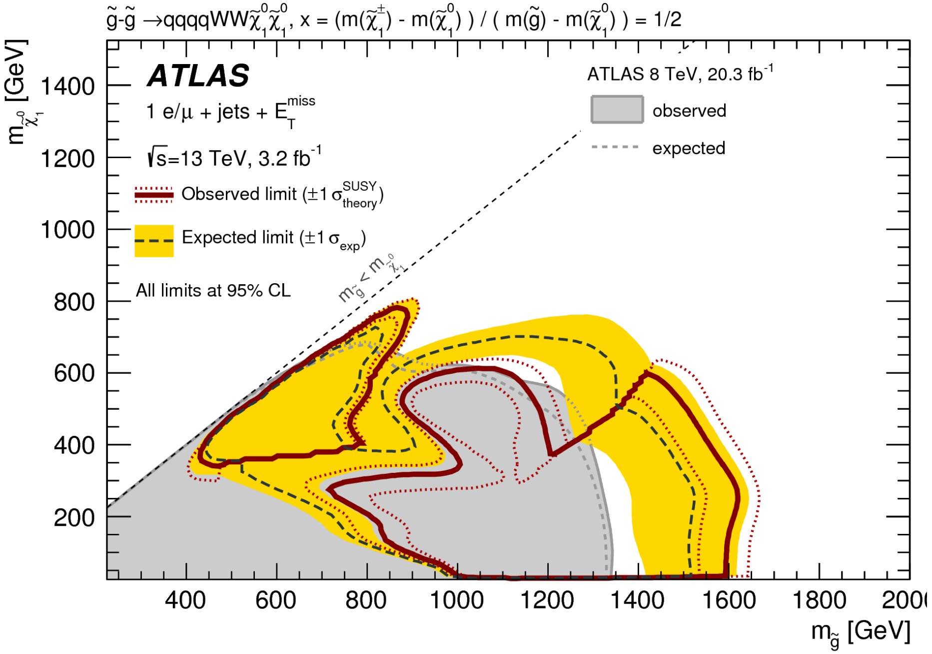


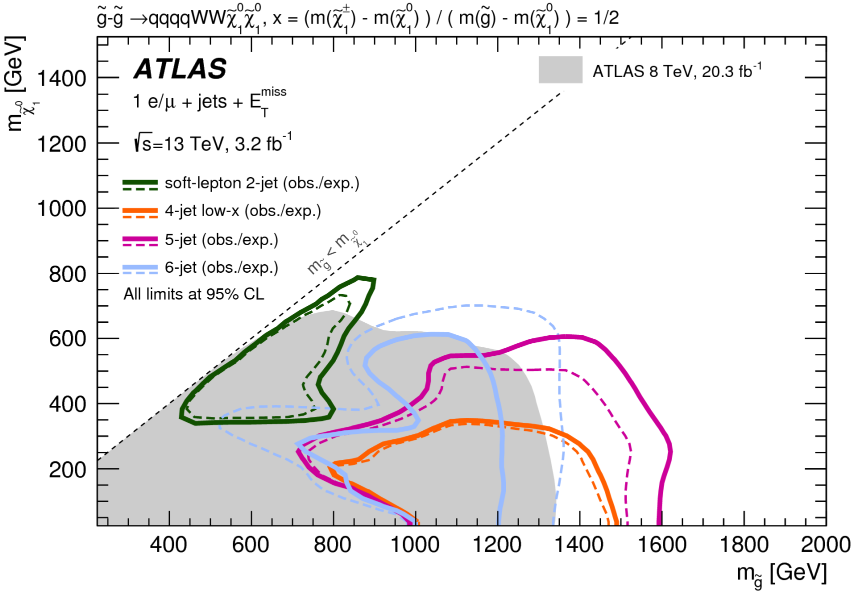
Validation

Validation regions used to cross check SM predictions with data

Signal regions

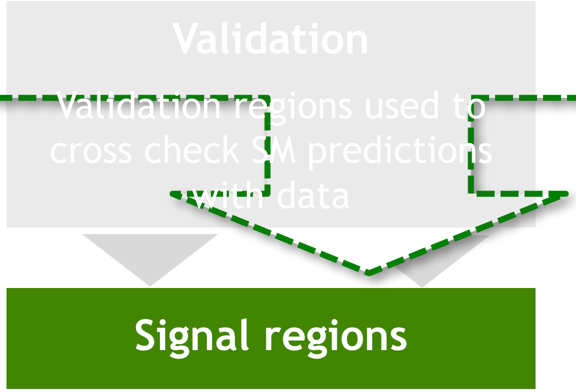
5: Compare SM predictions with data





arXiv:1605.04285

- excludes **gluino masses** up to **1.6 TeV**



Validation

Validation regions used to cross check SM predictions with data

Signal regions

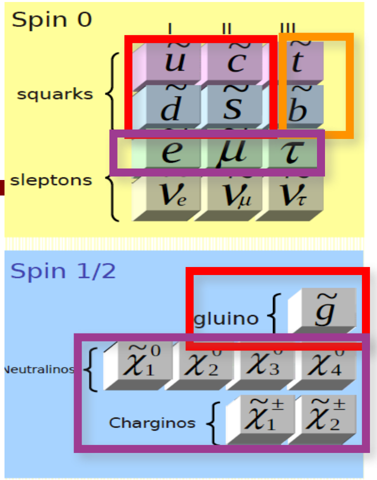
6: Interpretations

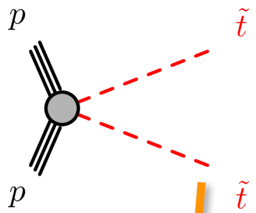
SUSY search results @ LHC and prospects at future colliders

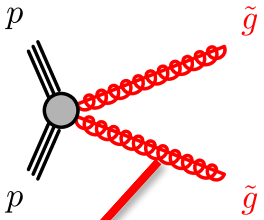
(TeV-scale) Supersymmetry (SUSY)

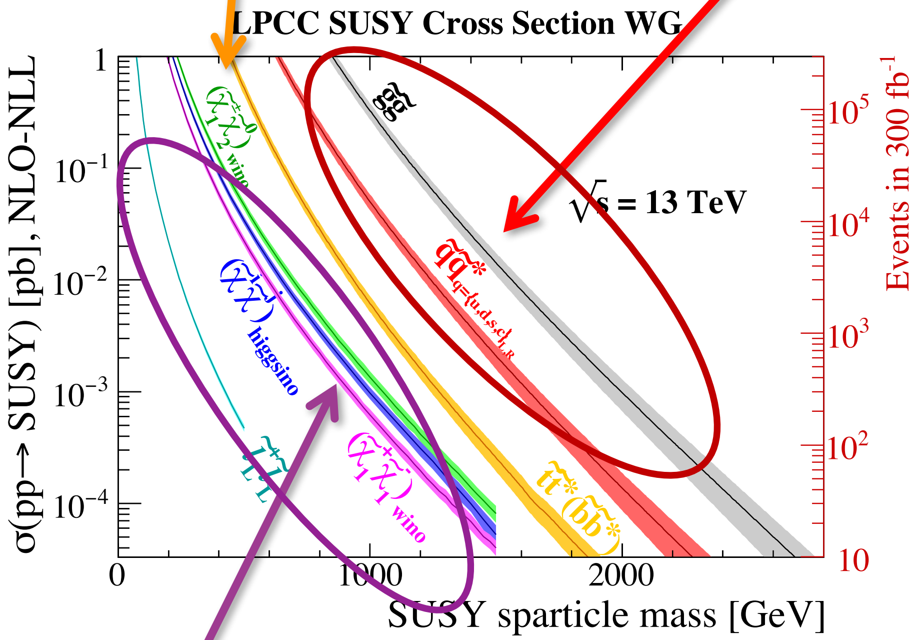
P. Higgs at CMS

SUSY Search @ LHC

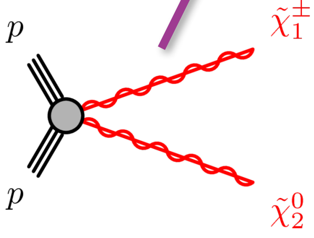








https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections arXiv:1407.5066



ATLAS public link
CMS public link

Strong production:

- ❑ targeting gluinos and 1st and 2nd generation squarks
- ❑ by far largest cross-sections

3rd generation:

- ❑ targeting stop and sbottoms
- ❑ Should be lowest mass squarks for naturalness reasons

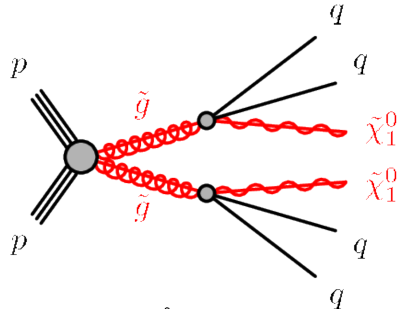
Electroweak production:

- ❑ targeting Electroweakinos, sleptons
- ❑ Lowest mass sparticles, clean signature

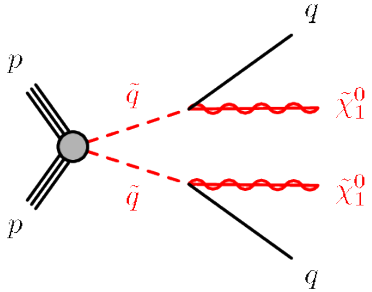
RPV/LL:

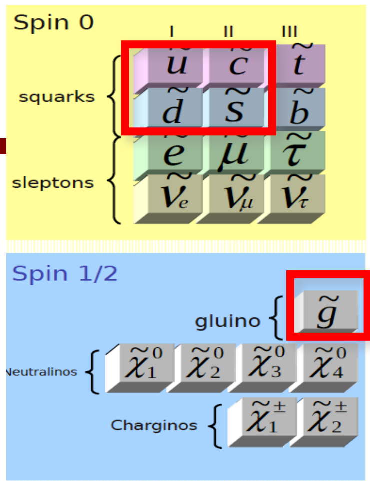
- ❑ targeting R-parity violating models and long lived sparticles
- ❑ More exotic models

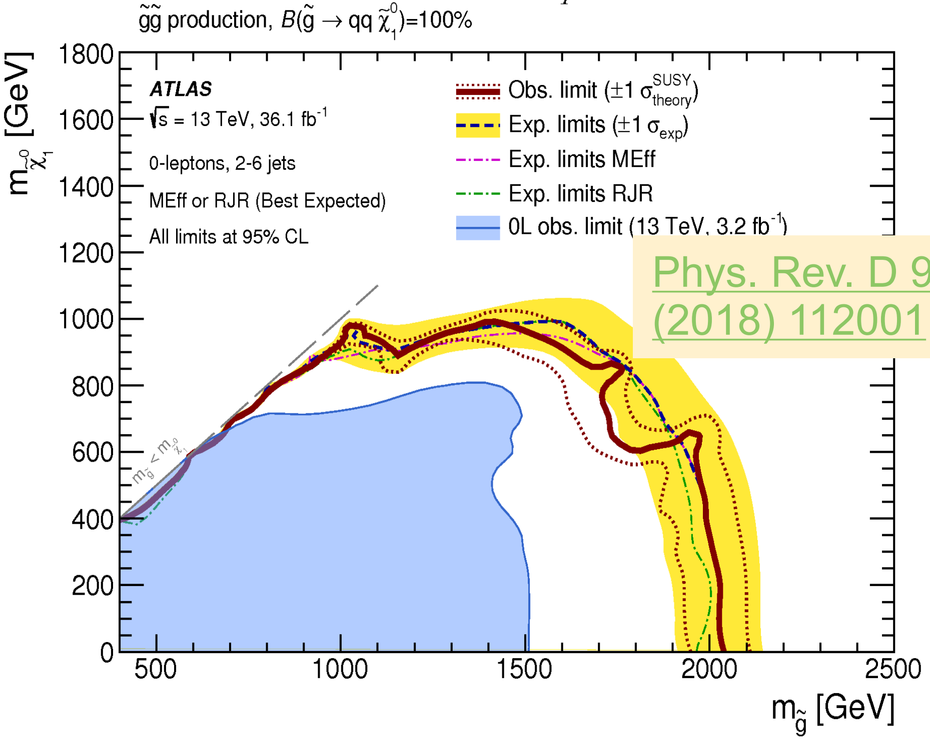
squark & gluino search (all had.)



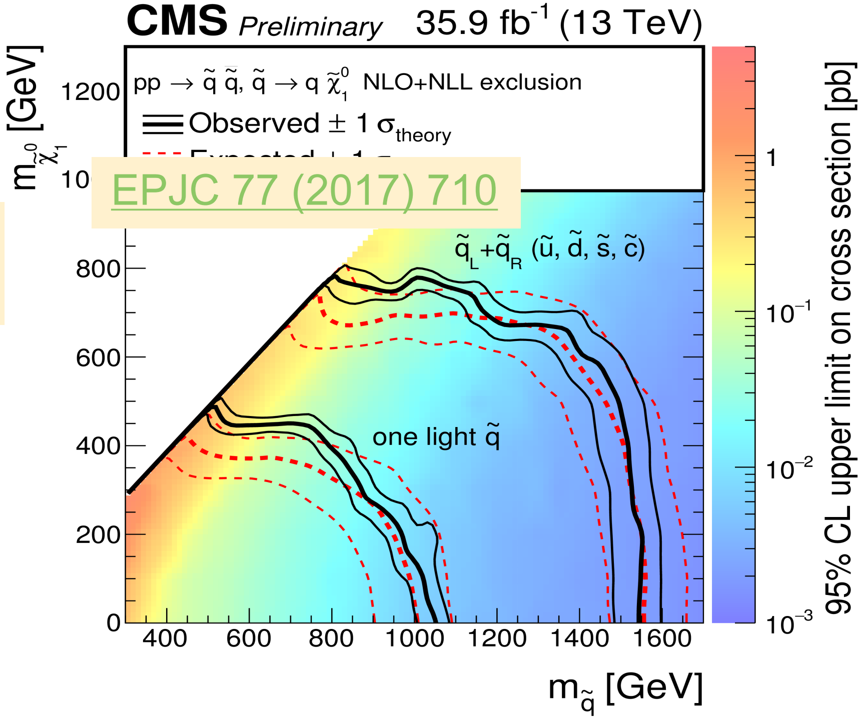
Signal: jets and missing energy







Phys. Rev. D 97 (2018) 112001

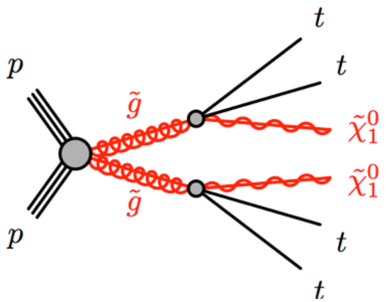


EPJC 77 (2017) 710

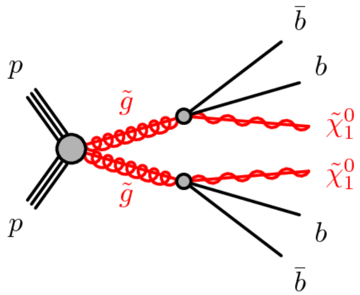
Corresponding sparticle mass limits for **BF=100%**:

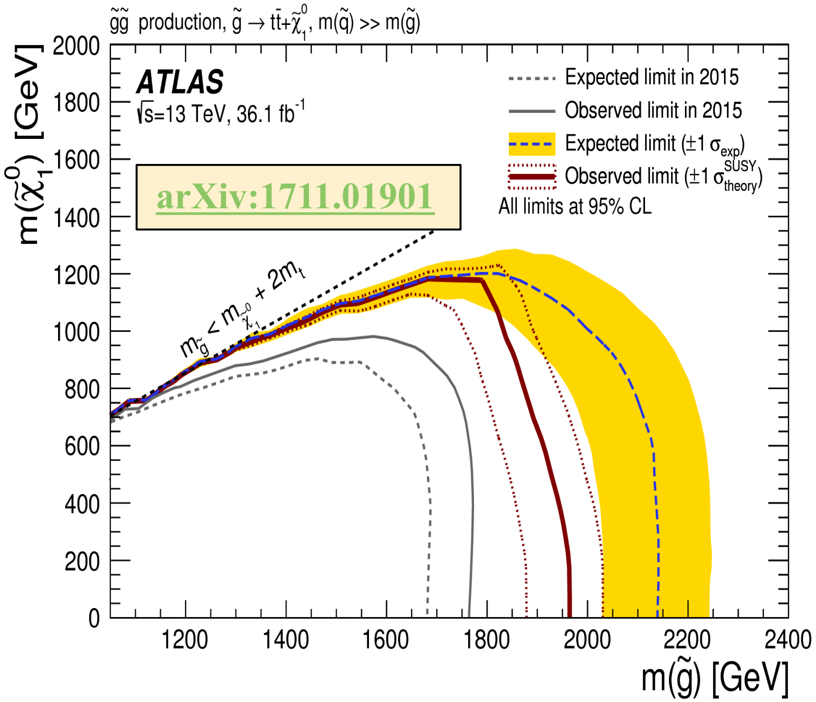
- Squarks: up to 1.55 TeV assuming 8-fold squark degeneracy
- Gluinos: up to 2.05 TeV with neutralinos up to 1.1 TeV

Gluino decays to 3rd Gen. squarks

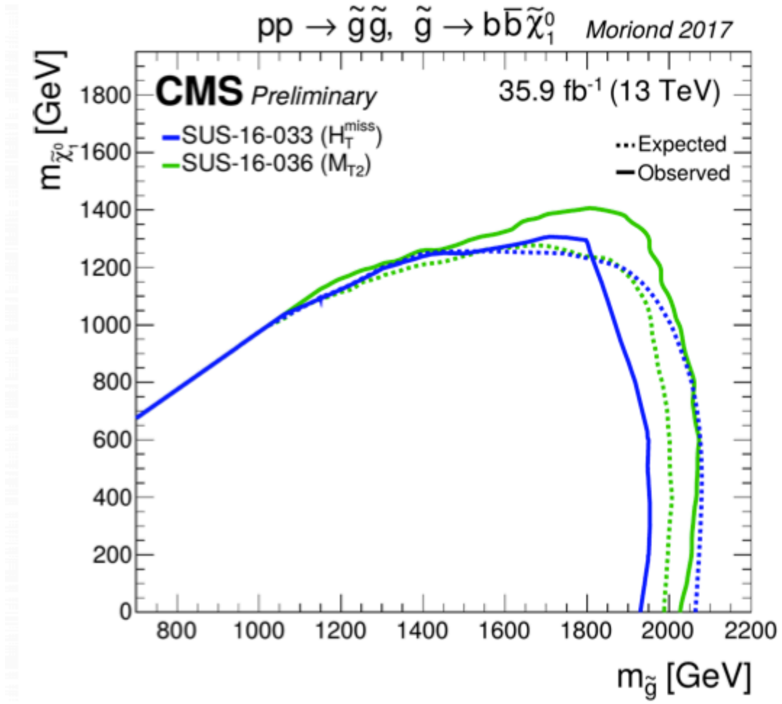


Signal: 4b-jets (right) up to 4 top quarks (left)





arXiv:1711.01901

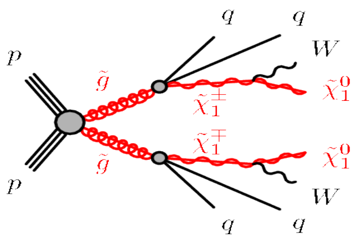


Corresponding sparticle mass limits for **BF=100%**:

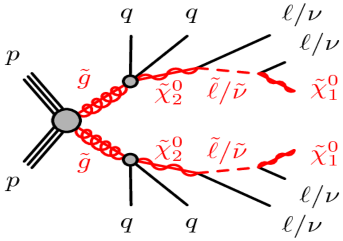
- Gtt: Gluinos up to 1.97 TeV with neutralinos up to 1.19 TeV
- Gbb: Gluinos up to 2.05 TeV with neutralinos up to 1.2 TeV

Multi-step decays

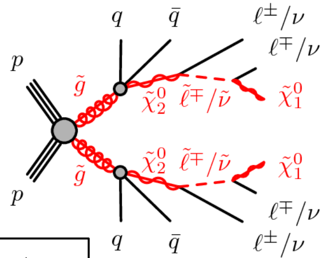
Signal: 1 or 2/3 leptons, jets and MET



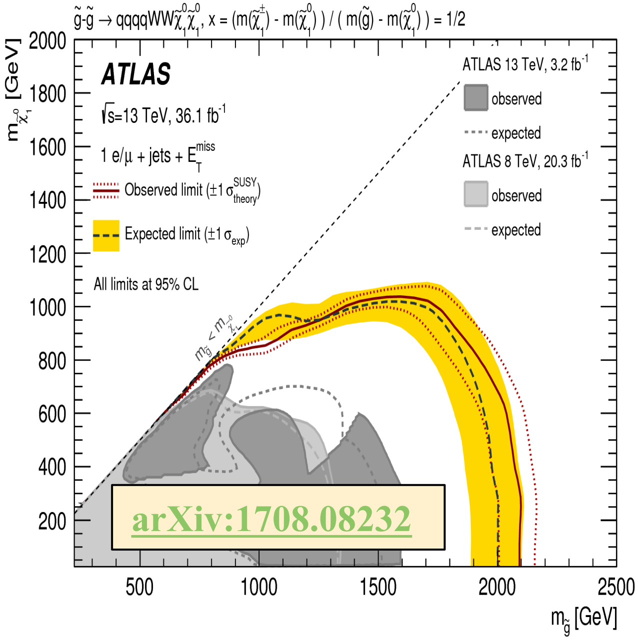
Single lept.



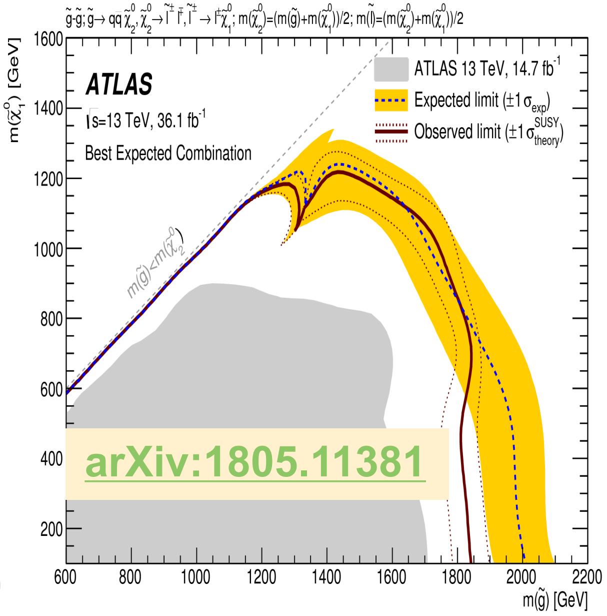
OS Di-lept.



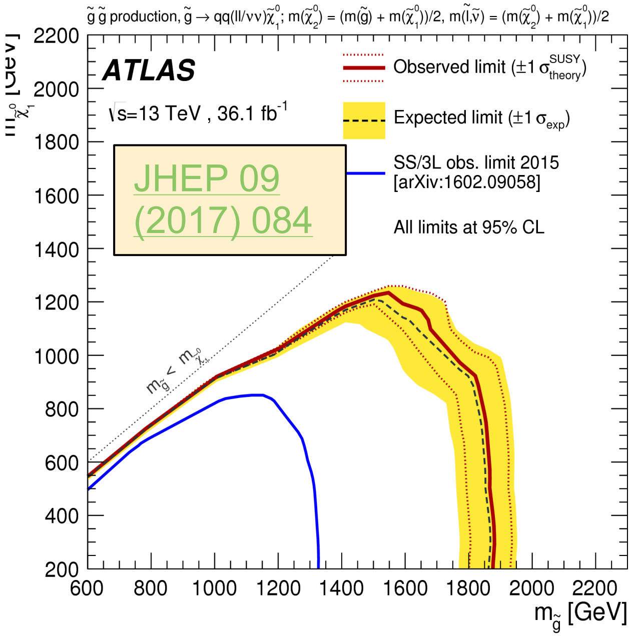
SS Di-lept.



arXiv:1708.08232



arXiv:1805.11381

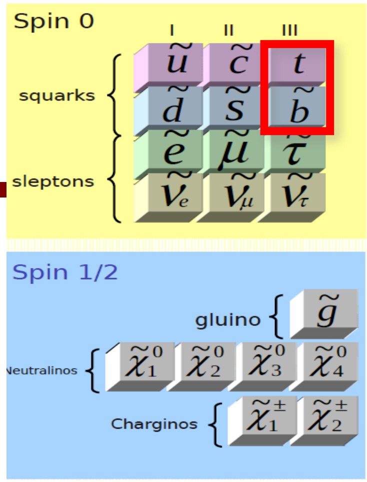


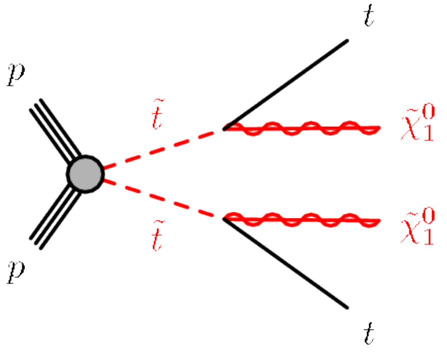
JHEP 09 (2017) 084

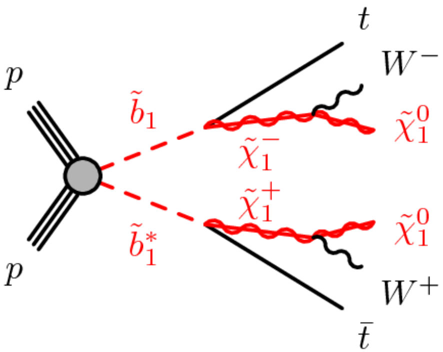
Corresponding sparticle mass limits for **BF=100%**:

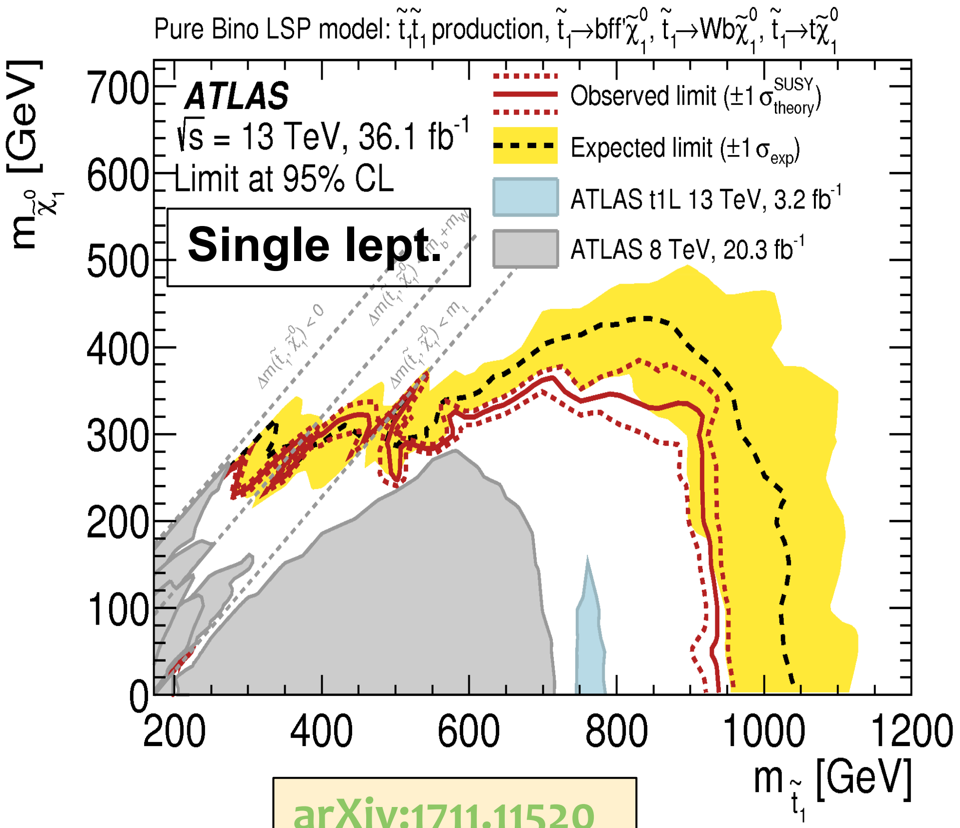
- Gluino mass up to 1.8-2 TeV, LSP up to 1-1.2 TeV

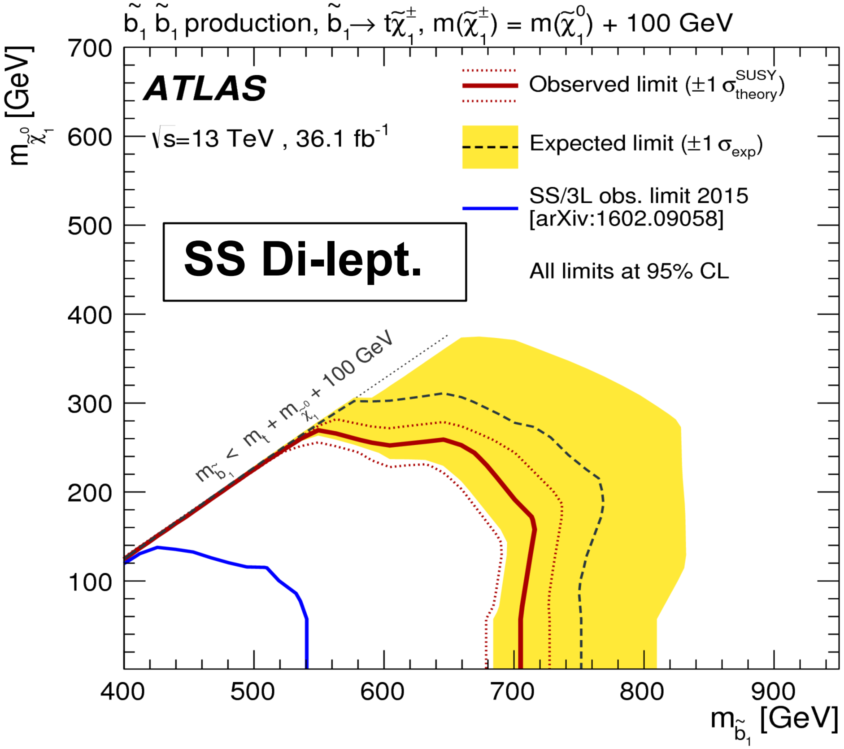
3rd Generation: stop/sbottom (leptonic)







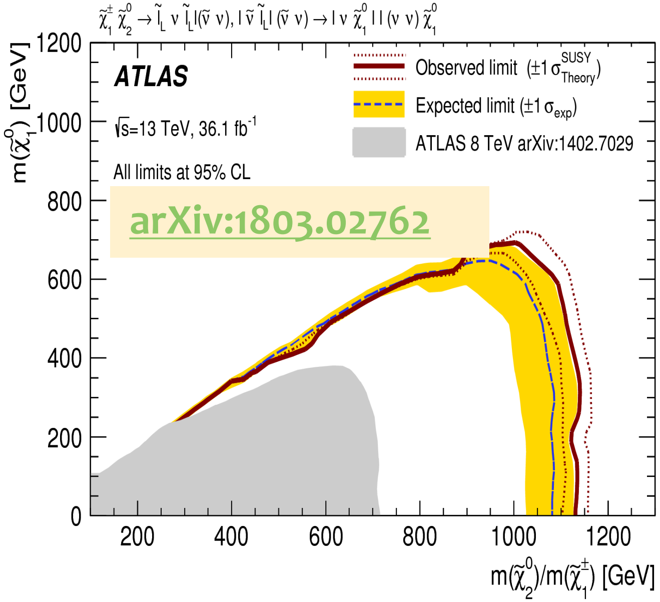




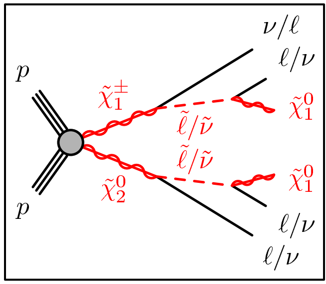
arXiv:1711.11520

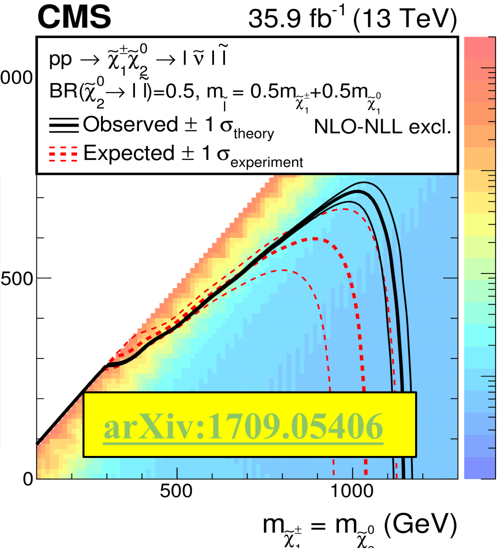
JHEP 09 (2017) 084

Gaugino search: via slepton decay (2l/3l)

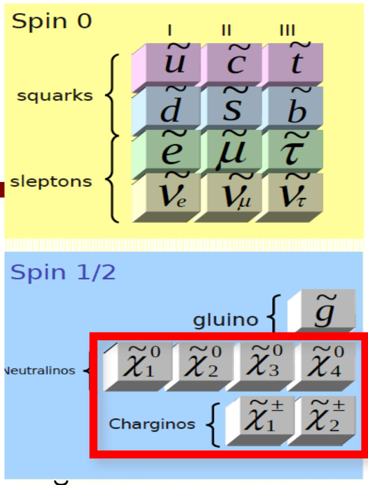


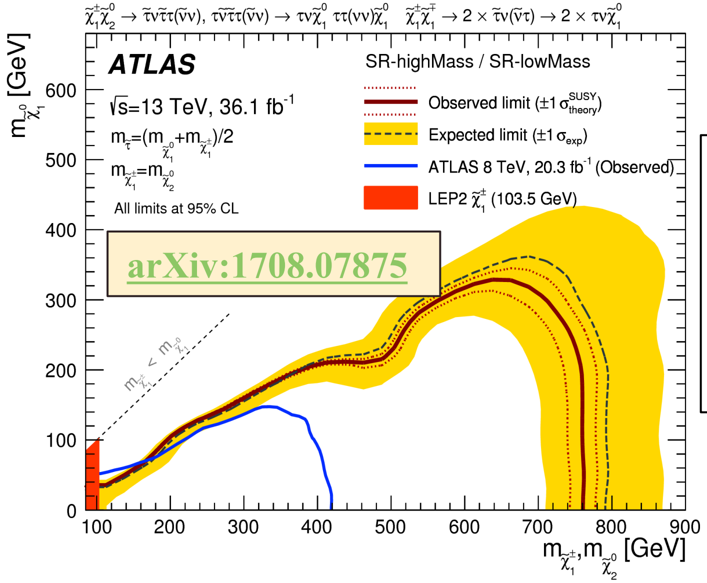
arXiv:1803.02762



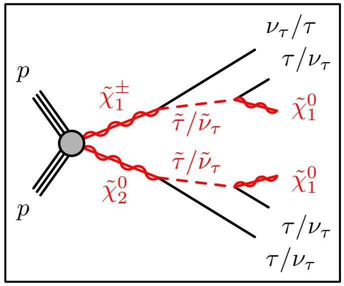


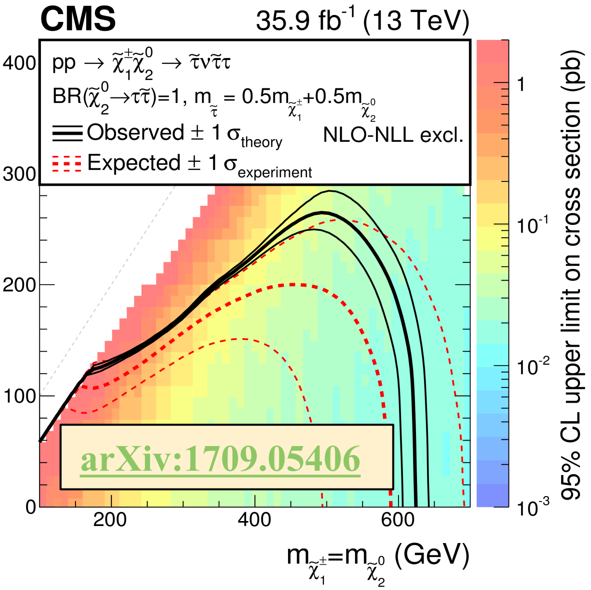
arXiv:1709.05406





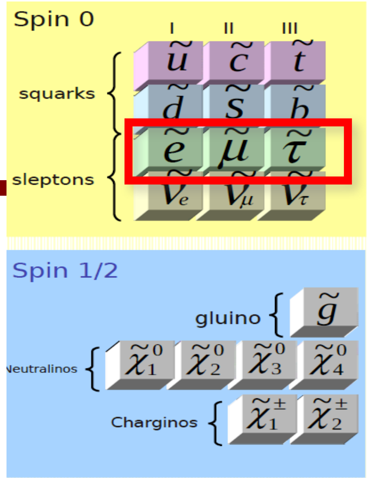
arXiv:1708.07875

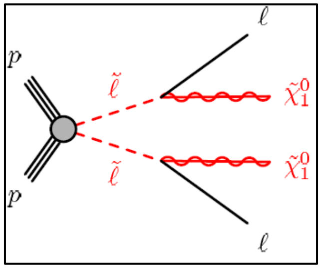


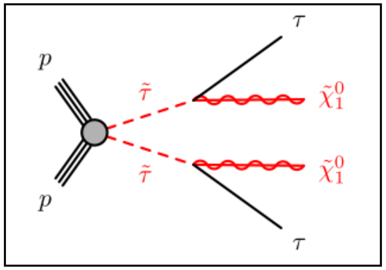


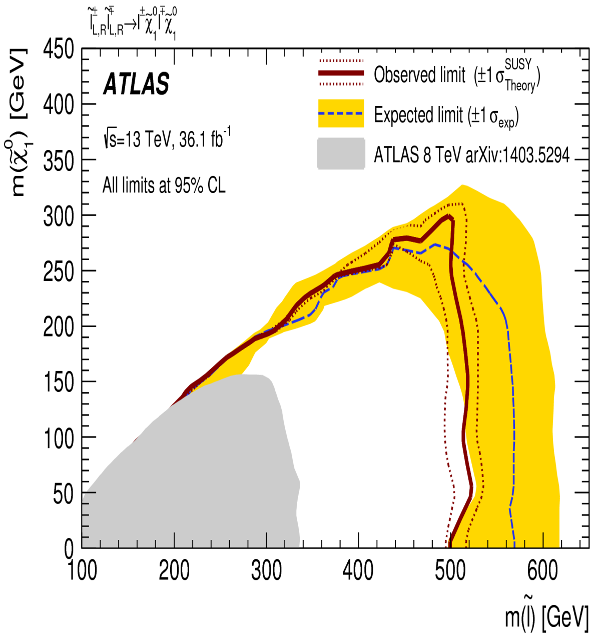
arXiv:1709.05406

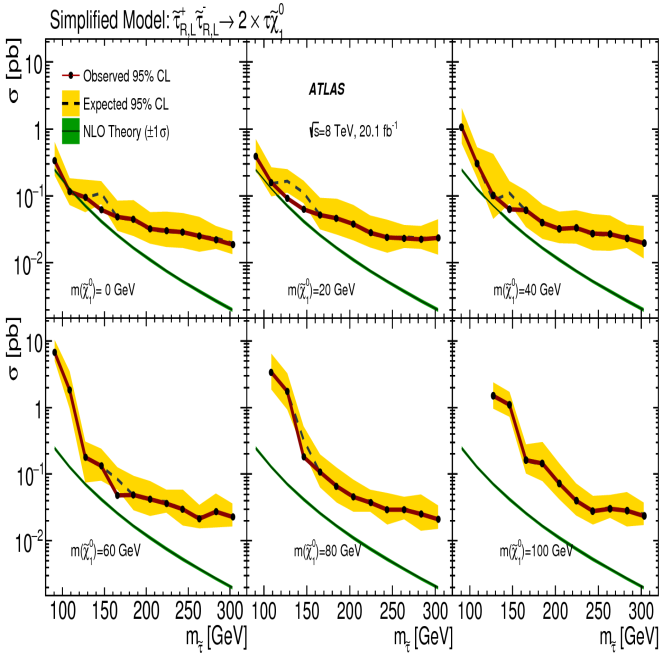
Slepton search

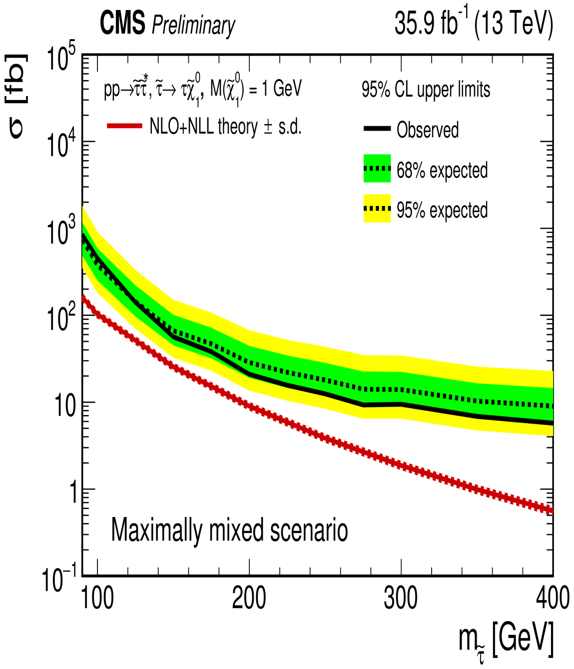












arXiv:1803.02762

Phys. Rev. D 93, 052002 (2016)

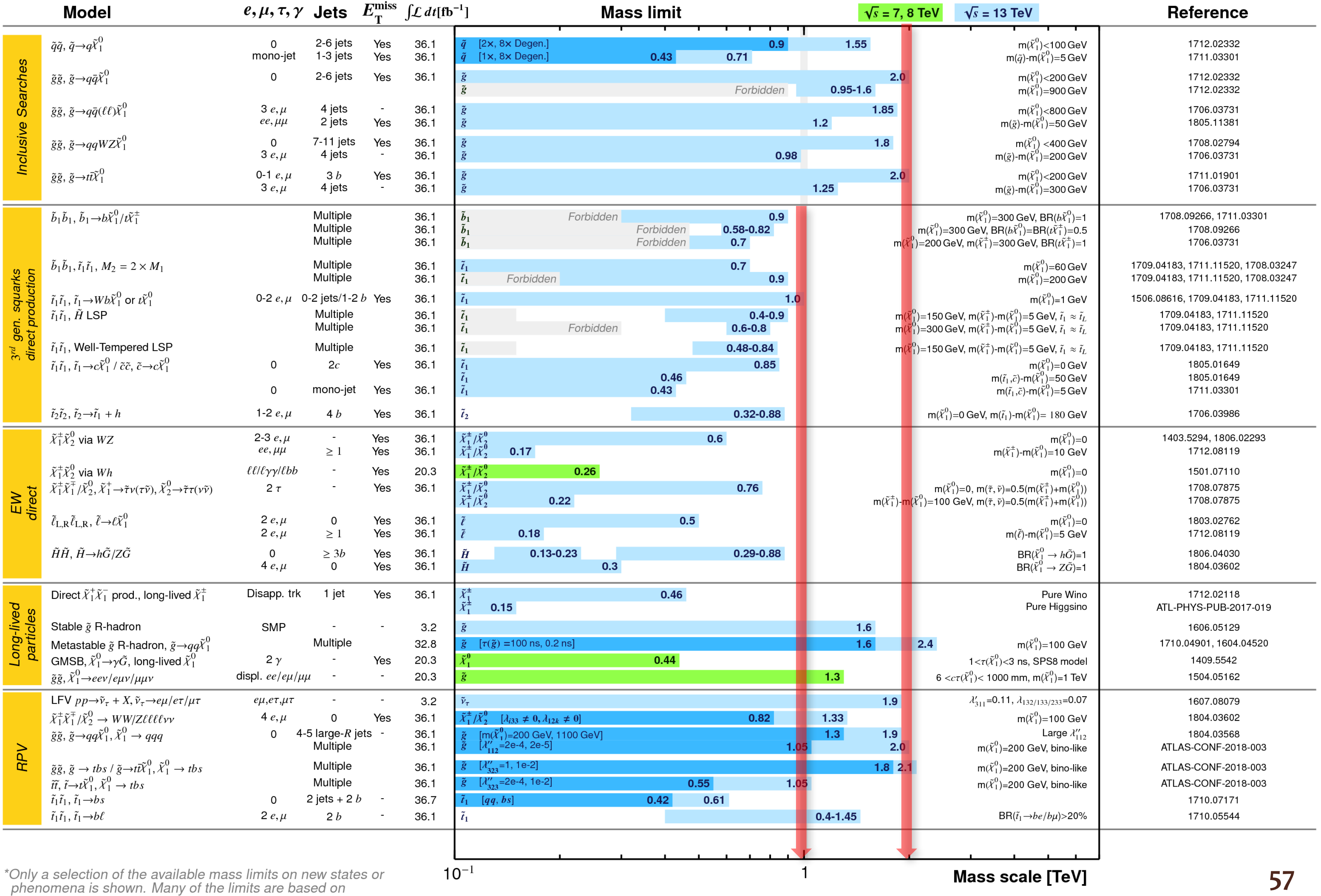
CMS-PAS-SUS-17-003

ATLAS SUSY Searches* - 95% CL Lower Limits

July 2018

ATLAS Preliminary

$\sqrt{s}$ = 7, 8, 13 TeV

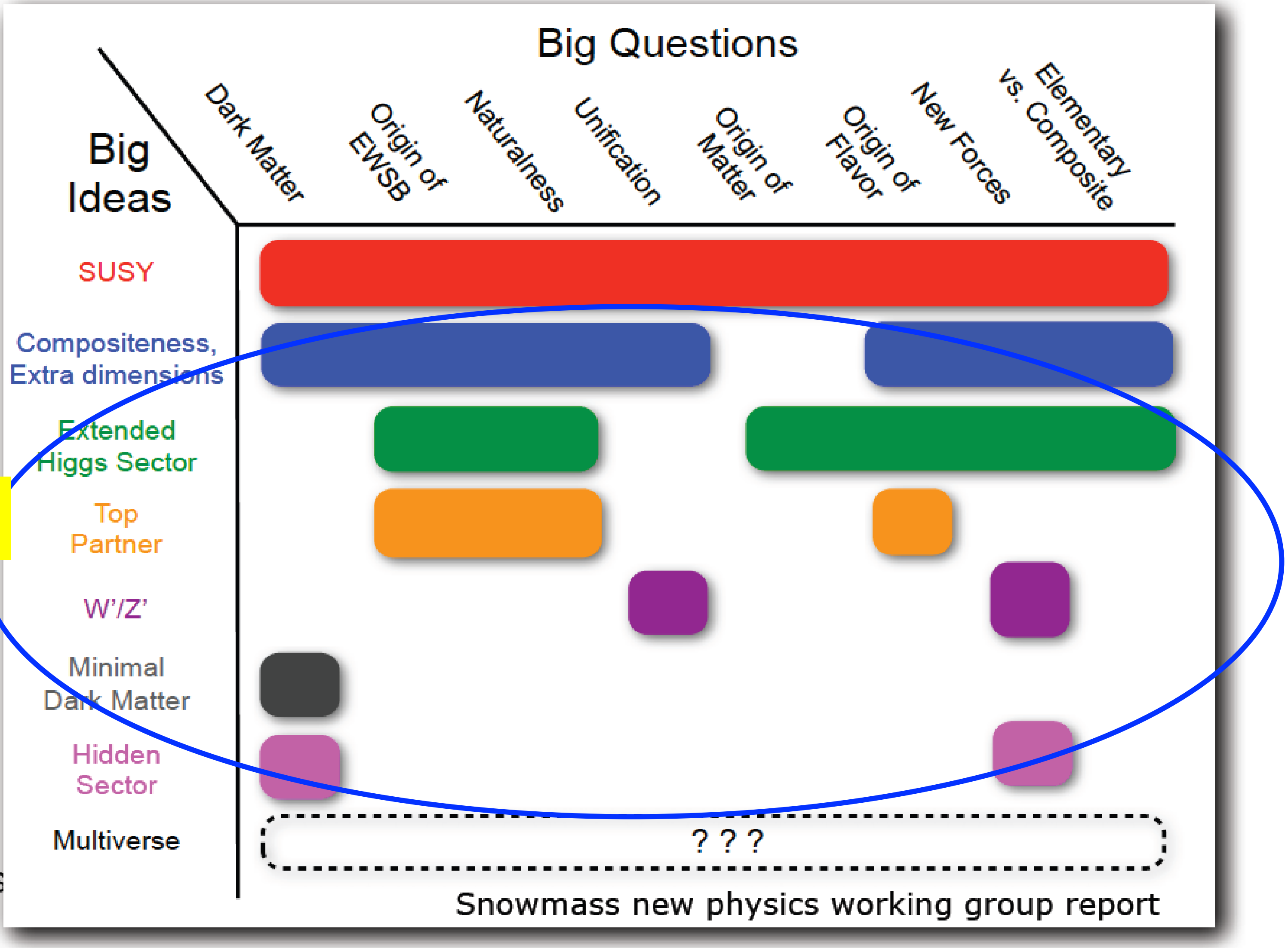


	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit			Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{q}$	[2×, 8× Degen.] 0.9 1.55	m($\tilde{\chi}_1^0$)<100 GeV	1712.02332
		mono-jet	1-3 jets	Yes	36.1	$\tilde{q}$	[1×, 8× Degen.] 0.43 0.71	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$	2.0	m($\tilde{\chi}_1^0$)<200 GeV	1712.02332
						$\tilde{g}$	Forbidden 0.95-1.6	m($\tilde{\chi}_1^0$)=900 GeV	1712.02332
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	3 e,μ	4 jets	-	36.1	$\tilde{g}$	1.85	m($\tilde{\chi}_1^0$)<800 GeV	1706.03731
		$ee,\mu\mu$	2 jets	Yes	36.1	$\tilde{g}$	1.2	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=50 GeV	1805.11381
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qqWZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	$\tilde{g}$	1.8	m($\tilde{\chi}_1^0$) <400 GeV	1708.02794
		3 e,μ	4 jets	-	36.1	$\tilde{g}$	0.98	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=200 GeV	1706.03731
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	36.1	$\tilde{g}$	2.0	m($\tilde{\chi}_1^0$)<200 GeV	1711.01901
		3 e,μ	4 jets	-	36.1	$\tilde{g}$	1.25	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=300 GeV	1706.03731
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\rightarrow b\tilde{\chi}_1^0/t\tilde{\chi}_1^\pm$		Multiple		36.1	$\tilde{b}_1$	Forbidden 0.9	m($\tilde{\chi}_1^0$)=300 GeV, BR($b\tilde{\chi}_1^0$)=1	1708.09266, 1711.03301
			Multiple		36.1	$\tilde{b}_1$	Forbidden 0.58-0.82	m($\tilde{\chi}_1^0$)=300 GeV, BR($b\tilde{\chi}_1^0$)=BR($t\tilde{\chi}_1^\pm$)=0.5	1708.09266
			Multiple		36.1	$\tilde{b}_1$	Forbidden 0.7	m($\tilde{\chi}_1^0$)=200 GeV, m($\tilde{\chi}_1^\pm$)=300 GeV, BR($t\tilde{\chi}_1^\pm$)=1	1706.03731
	$\tilde{b}_1\tilde{b}_1, \tilde{t}_1\tilde{t}_1$, $M_2 = 2\times M_1$		Multiple		36.1	$\tilde{t}_1$	0.7	m($\tilde{\chi}_1^0$)=60 GeV	1709.04183, 1711.11520, 1708.03247
			Multiple		36.1	$\tilde{t}_1$	Forbidden 0.9	m($\tilde{\chi}_1^0$)=200 GeV	1709.04183, 1711.11520, 1708.03247
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	36.1	$\tilde{t}_1$	1.0	m($\tilde{\chi}_1^0$)=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, $\tilde{H}$ LSP		Multiple		36.1	$\tilde{t}_1$	0.4-0.9	m($\tilde{\chi}_1^0$)=150 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
			Multiple		36.1	$\tilde{t}_1$	Forbidden 0.6-0.8	m($\tilde{\chi}_1^0$)=300 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, Well-Tempered LSP		Multiple		36.1	$\tilde{t}_1$	0.48-0.84	m($\tilde{\chi}_1^0$)=150 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}$, $\tilde{c}\rightarrow c\tilde{\chi}_1^0$	0	2c	Yes	36.1	$\tilde{t}_1$	0.85	m($\tilde{\chi}_1^0$)=0 GeV	1805.01649
						$\tilde{t}_1$	0.46	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=50 GeV	1805.01649
		0	mono-jet	Yes	36.1	$\tilde{t}_1$	0.43	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\rightarrow\tilde{t}_1 + h$	1-2 e,μ	4 b	Yes	36.1	$\tilde{t}_2$	0.32-0.88	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)= 180 GeV	1706.03986
EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ	2-3 e,μ	-	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	0.6	m($\tilde{\chi}_1^0$)=0	1403.5294, 1806.02293
		$ee,\mu\mu$	≥ 1	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	0.17	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=10 GeV	1712.08119
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh	$\ell\ell/\ell\gamma\gamma/\ell bb$	-	Yes	20.3	🟩 $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	0.26	m($\tilde{\chi}_1^0$)=0	1501.07110
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0$, $\tilde{\chi}_1^+\rightarrow\tilde{\tau}\nu(\tau\tilde{\nu})$, $\tilde{\chi}_2^0\rightarrow\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	0.76	m($\tilde{\chi}_1^0$)=0, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1708.07875
						$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	0.22	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=100 GeV, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1708.07875
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\rightarrow\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	36.1	$\tilde{\ell}$	0.5	m($\tilde{\chi}_1^0$)=0	1803.02762
		2 e,μ	≥ 1	Yes	36.1	$\tilde{\ell}$	0.18	m($\tilde{\ell}$)-m($\tilde{\chi}_1^0$)=5 GeV	1712.08119
	$\tilde{H}\tilde{H}$, $\tilde{H}\rightarrow h\tilde{G}/Z\tilde{G}$	0	$\geq 3b$	Yes	36.1	$\tilde{H}$	0.13-0.23 0.29-0.88	BR($\tilde{\chi}_1^0 \rightarrow h\tilde{G}$)=1	1806.04030
		4 e,μ	0	Yes	36.1	$\tilde{H}$	0.3	BR($\tilde{\chi}_1^0 \rightarrow Z\tilde{G}$)=1	1804.03602
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^\pm$	0.46	Pure Wino	1712.02118
						$\tilde{\chi}_1^\pm$	0.15	Pure Higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron	SMP	-	-	3.2	$\tilde{g}$	1.6		1606.05129
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\rightarrow qq\tilde{\chi}_1^0$		Multiple		32.8	$\tilde{g}$	[$\tau(\tilde{g})$ =100 ns, 0.2 ns] 1.6 2.4	m($\tilde{\chi}_1^0$)=100 GeV	1710.04901, 1604.04520
	GMSB, $\tilde{\chi}_1^0\rightarrow\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	🟩 $\tilde{\chi}_1^0$	0.44	1<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\rightarrow ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	🟩 $\tilde{g}$	1.3	6 <$c\tau(\tilde{\chi}_1^0)$< 1000 mm, m($\tilde{\chi}_1^0$)=1 TeV	1504.05162
RPV	LFV $pp\rightarrow\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\rightarrow e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$	1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0 \rightarrow WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	[$\lambda_{i33} \neq 0, \lambda_{12k} \neq 0$] 0.82 1.33	m($\tilde{\chi}_1^0$)=100 GeV	1804.03602
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \rightarrow qqq$	0	4-5 large-R jets	-	36.1	$\tilde{g}$	[m($\tilde{\chi}_1^0$)=200 GeV, 1100 GeV] 1.3 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde{g}$	[λ''_{112}=2e-4, 2e-5] 1.05 2.0	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow tbs$ / $\tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \rightarrow tbs$		Multiple		36.1	$\tilde{g}$	[λ''_{323}=1, 1e-2] 1.8 2.1	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\rightarrow t\tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \rightarrow tbs$		Multiple		36.1	$\tilde{g}$	[λ''_{323}=2e-4, 1e-2] 0.55 1.05	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow bs$	0	2 jets + 2 b	-	36.7	$\tilde{t}_1$	[qq, bs] 0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow b\ell$	2 e,μ	2 b	-	36.1	$\tilde{t}_1$	0.4-1.45	BR($\tilde{t}_1\rightarrow be/b\mu$)>20%	1710.05544

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

New Physics beyond the SM

exotics



Snowmass new physics working group report

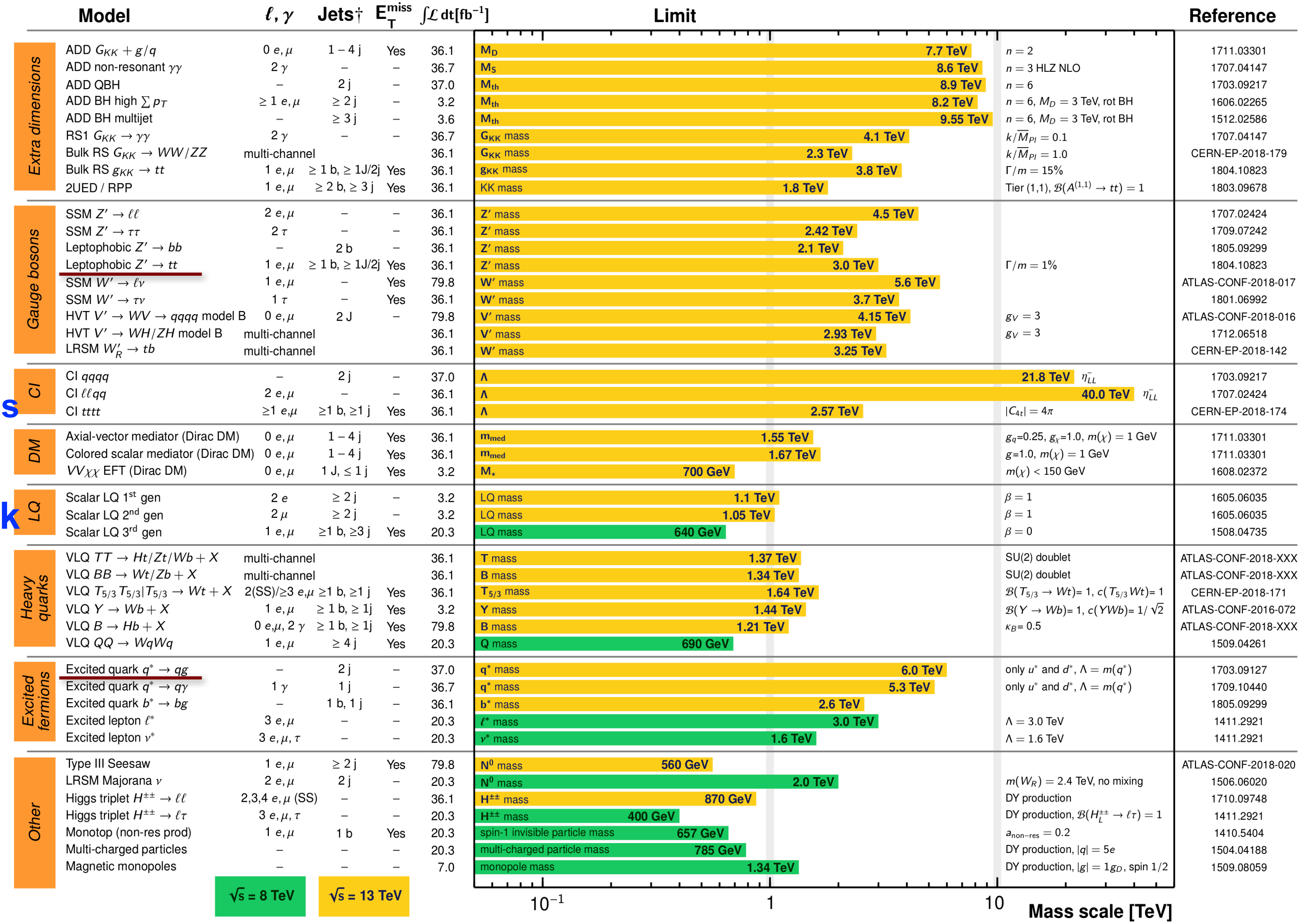
S. S

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2018

ATLAS Preliminary

$\int\mathcal{L}\,dt = (3.2 - 79.8)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV



额外维粒子

W', Z'

Contact interactions

暗物质

leptoquark

额外夸克

重费米子

其他

	Model	ℓ,γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Limit			Reference
Extra dimensions	ADD $G_{KK}+g/q$	0 e,μ	1 – 4 j	Yes	36.1	🟨 M_D	7.7 TeV	$n=2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	🟨 M_S	8.6 TeV	$n=3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	🟨 M_{th}	8.9 TeV	$n=6$	1703.09217
	ADD BH high $\sum p_T$	≥ 1 e,μ	≥ 2 j	–	3.2	🟨 M_{th}	8.2 TeV	$n=6$, $M_D=3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	🟨 M_{th}	9.55 TeV	$n=6$, $M_D=3$ TeV, rot BH	1512.02586
	RS1 $G_{KK}\to\gamma\gamma$	2 γ	–	–	36.7	🟨 G_{KK} mass	4.1 TeV	$k/\overline{M}_{Pl}=0.1$	1707.04147
	Bulk RS $G_{KK}\to WW/ZZ$	multi-channel			36.1	🟨 G_{KK} mass	2.3 TeV	$k/\overline{M}_{Pl}=1.0$	CERN-EP-2018-179
	Bulk RS $g_{KK}\to tt$	1 e,μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 g_{KK} mass	3.8 TeV	$\Gamma/m=15\%$	1804.10823
	2UED / RPP	1 e,μ	≥ 2 b, ≥ 3 j	Yes	36.1	🟨 KK mass	1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)}\to tt)=1$	1803.09678
Gauge bosons	SSM $Z'\to\ell\ell$	2 e,μ	–	–	36.1	🟨 Z' mass	4.5 TeV		1707.02424
	SSM $Z'\to\tau\tau$	2 τ	–	–	36.1	🟨 Z' mass	2.42 TeV		1709.07242
	Leptophobic $Z'\to bb$	–	2 b	–	36.1	🟨 Z' mass	2.1 TeV		1805.09299
	Leptophobic $Z'\to tt$	1 e,μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 Z' mass	3.0 TeV	$\Gamma/m=1\%$	1804.10823
	SSM $W'\to\ell\nu$	1 e,μ	–	Yes	79.8	🟨 W' mass	5.6 TeV		ATLAS-CONF-2018-017
	SSM $W'\to\tau\nu$	1 τ	–	Yes	36.1	🟨 W' mass	3.7 TeV		1801.06992
	HVT $V'\to WV\to qqqq$ model B	0 e,μ	2 J	–	79.8	🟨 V' mass	4.15 TeV	$g_V=3$	ATLAS-CONF-2018-016
	HVT $V'\to WH/ZH$ model B	multi-channel			36.1	🟨 V' mass	2.93 TeV	$g_V=3$	1712.06518
	LRSM $W'_R\to tb$	multi-channel			36.1	🟨 W' mass	3.25 TeV		CERN-EP-2018-142
CI	CI $qqqq$	–	2 j	–	37.0	🟨 Λ	21.8 TeV	η_{LL}^{-}	1703.09217
	CI $\ell\ell qq$	2 e,μ	–	–	36.1	🟨 Λ	40.0 TeV	η_{LL}^{-}	1707.02424
	CI $tttt$	≥1 e,μ	≥1 b, ≥1 j	Yes	36.1	🟨 Λ	2.57 TeV	$\|C_{4t}\|=4\pi$	CERN-EP-2018-174
DM	Axial-vector mediator (Dirac DM)	0 e,μ	1 – 4 j	Yes	36.1	🟨 m_{med}	1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi)=1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e,μ	1 – 4 j	Yes	36.1	🟨 m_{med}	1.67 TeV	g=1.0, $m(\chi)=1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	0 e,μ	1 J, ≤ 1 j	Yes	3.2	🟨 M_*	700 GeV	$m(\chi)<150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	🟨 LQ mass	1.1 TeV	$\beta=1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	🟨 LQ mass	1.05 TeV	$\beta=1$	1605.06035
	Scalar LQ 3rd gen	1 e,μ	≥1 b, ≥3 j	Yes	20.3	🟩 LQ mass	640 GeV	$\beta=0$	1508.04735
Heavy quarks	VLQ $TT\to Ht/Zt/Wb+X$	multi-channel			36.1	🟨 T mass	1.37 TeV	SU(2) doublet	ATLAS-CONF-2018-XXX
	VLQ $BB\to Wt/Zb+X$	multi-channel			36.1	🟨 B mass	1.34 TeV	SU(2) doublet	ATLAS-CONF-2018-XXX
	VLQ $T_{5/3}T_{5/3}\|T_{5/3}\to Wt+X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	🟨 $T_{5/3}$ mass	1.64 TeV	$\mathcal{B}(T_{5/3}\to Wt)$= 1, $c(T_{5/3}Wt)$= 1	CERN-EP-2018-171
	VLQ $Y\to Wb+X$	1 e,μ	≥ 1 b, ≥ 1j	Yes	3.2	🟨 Y mass	1.44 TeV	$\mathcal{B}(Y\to Wb)$= 1, $c(YWb)$= $1/\sqrt{2}$	ATLAS-CONF-2016-072
	VLQ $B\to Hb+X$	0 e,μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	🟨 B mass	1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-XXX
	VLQ $QQ\to WqWq$	1 e,μ	≥ 4 j	Yes	20.3	🟩 Q mass	690 GeV		1509.04261
Excited fermions	Excited quark $q^*\to qg$	–	2 j	–	37.0	🟨 q^* mass	6.0 TeV	only u^* and d^*, $\Lambda=m(q^*)$	1703.09127
	Excited quark $q^*\to q\gamma$	1 γ	1 j	–	36.7	🟨 q^* mass	5.3 TeV	only u^* and d^*, $\Lambda=m(q^*)$	1709.10440
	Excited quark $b^*\to bg$	–	1 b, 1 j	–	36.1	🟨 b^* mass	2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e,μ	–	–	20.3	🟩 ℓ^* mass	3.0 TeV	$\Lambda=3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e,μ,τ	–	–	20.3	🟩 ν^* mass	1.6 TeV	$\Lambda=1.6$ TeV	1411.2921
Other	Type III Seesaw	1 e,μ	≥ 2 j	Yes	79.8	🟨 N^0 mass	560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 e,μ	2 j	–	20.3	🟩 N^0 mass	2.0 TeV	$m(W_R)=2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm}\to\ell\ell$	2,3,4 e,μ (SS)	–	–	36.1	🟨 $H^{\pm\pm}$ mass	870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm}\to\ell\tau$	3 e,μ,τ	–	–	20.3	🟩 $H^{\pm\pm}$ mass	400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm}\to\ell\tau)=1$	1411.2921
	Monotop (non-res prod)	1 e,μ	1 b	Yes	20.3	🟩 spin-1 invisible particle mass	657 GeV	$a_{\mathrm{non-res}}=0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	🟩 multi-charged particle mass	785 GeV	DY production, $\|q\|=5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	🟩 monopole mass	1.34 TeV	DY production, $\|g\|=1g_D$, spin 1/2	1509.08059

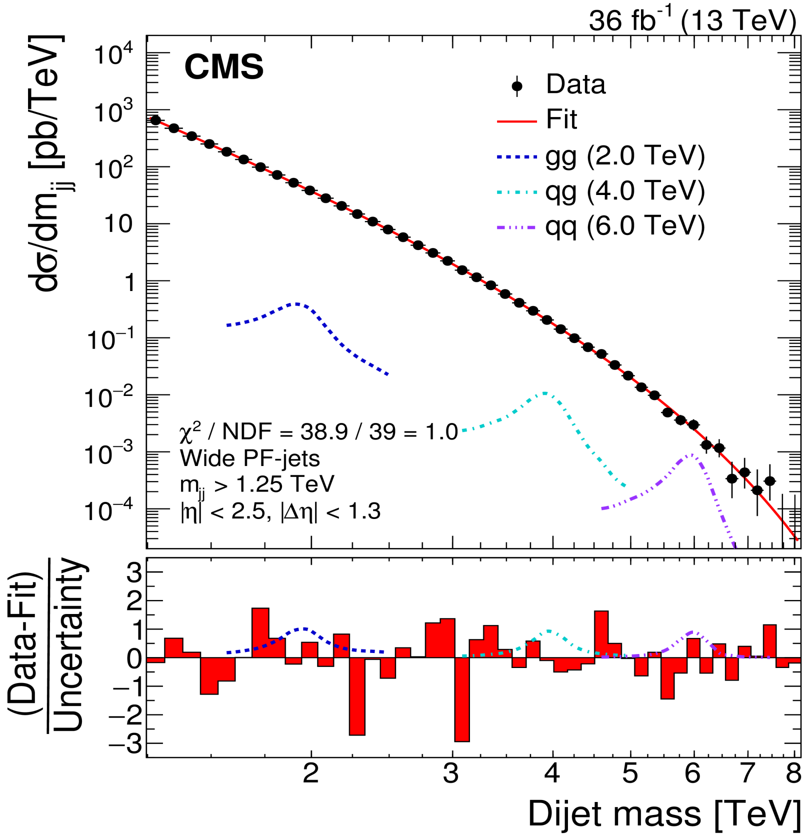
🟩 $\sqrt{s}$ = 8 TeV 🟨 $\sqrt{s}$ = 13 TeV

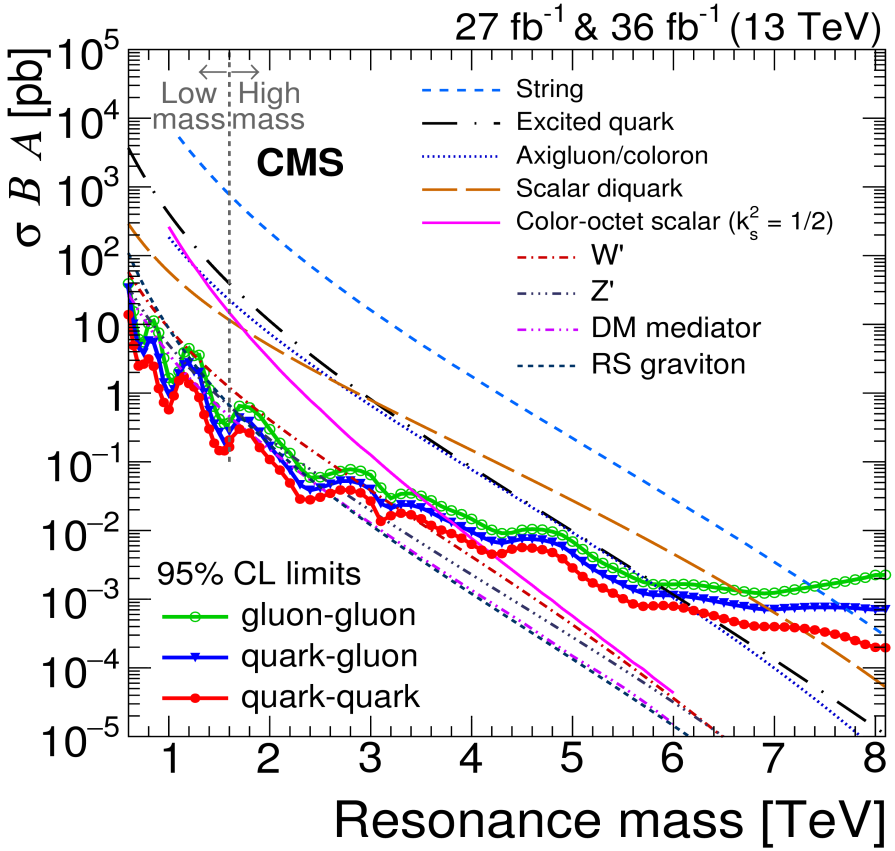
*Only a selection of the available mass limits on new states or phenomena is shown.

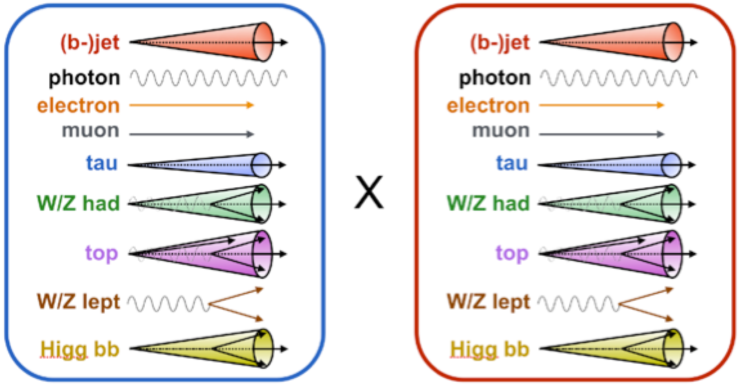
†Small-radius (large-radius) jets are denoted by the letter j (J).

Resonance (di-jet)

EXO-16-056





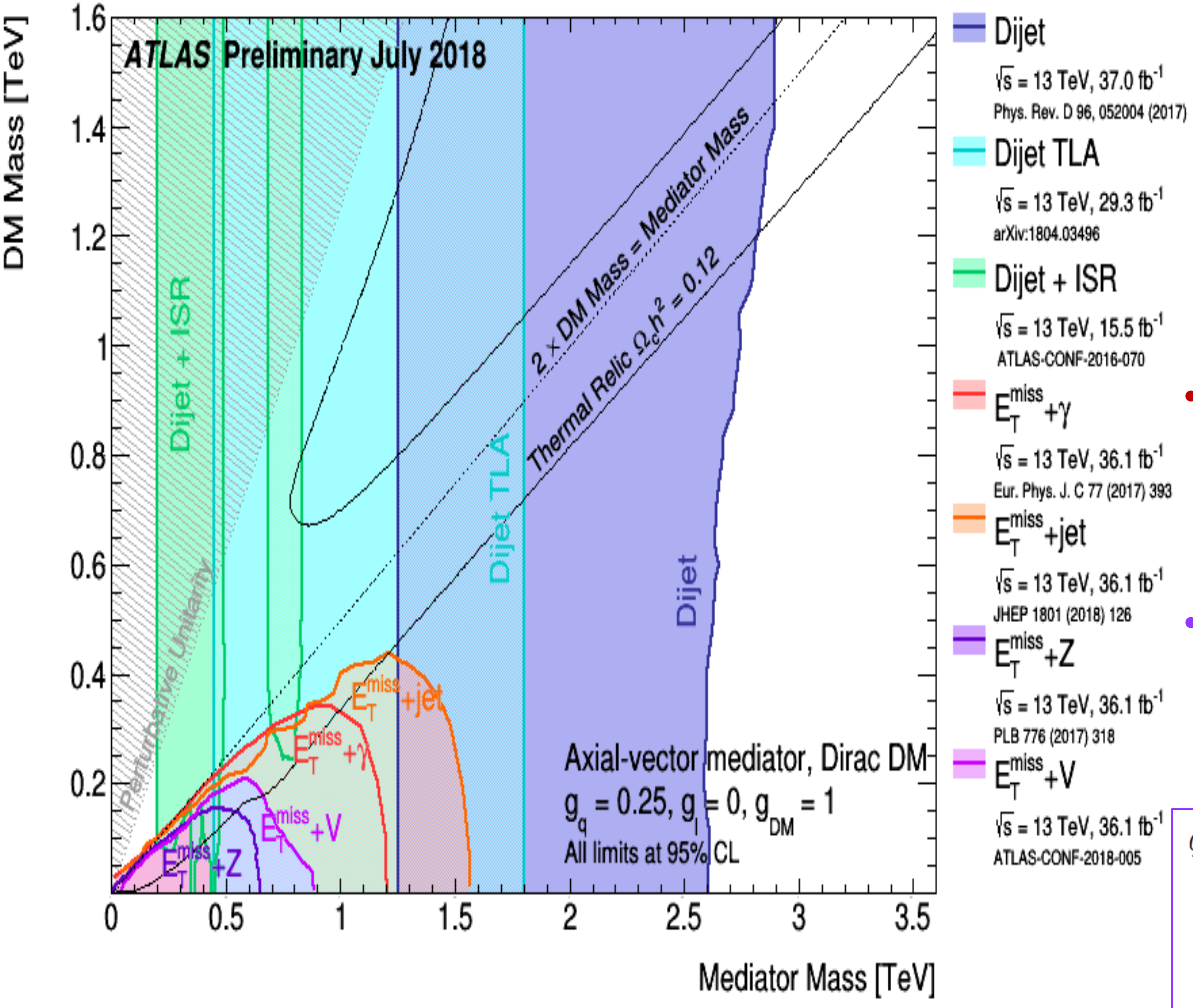


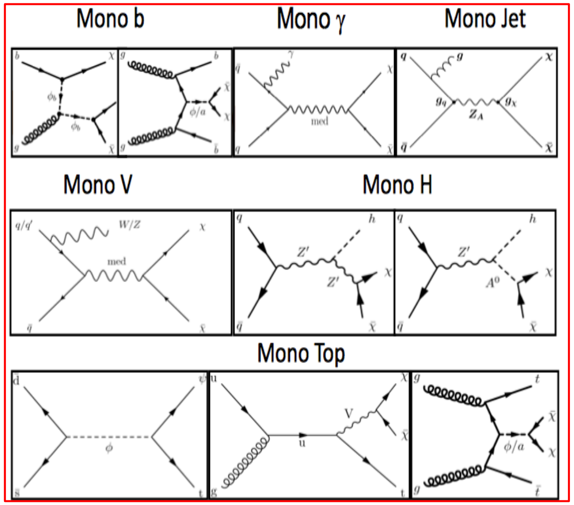
Results interpreted in many models e.g.:

- String resonance ~ 7.7 TeV
- Excited quark ~ 6 TeV
- W' ~ 3.3 TeV
- Z' ~ 2.7 TeV

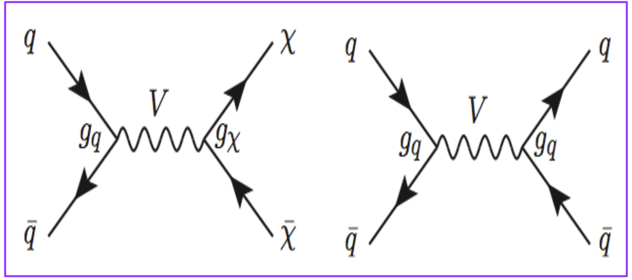
Dark Matter （暗物质）

Searches with MET+X or mediator

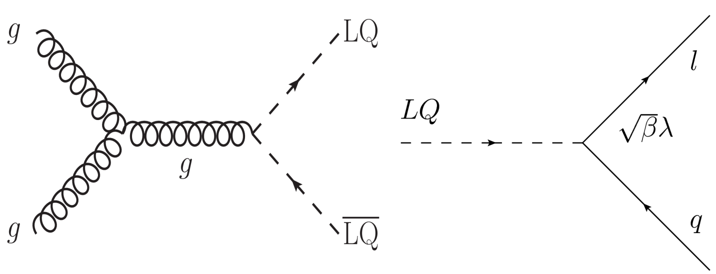




- **Searches in the Mono-X final states: Many models constrained up to 1-2 TeV**
- **Searches also in the Di-Jet final states exclude up to 2.6 TeV for almost whole DM range**



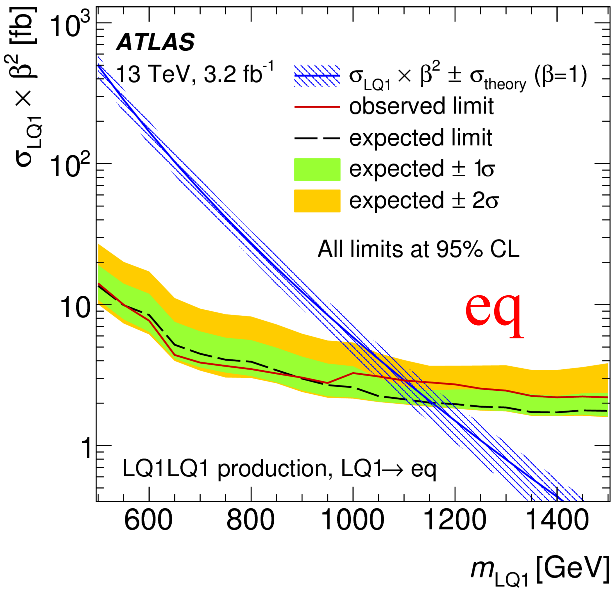
Leptoquarks

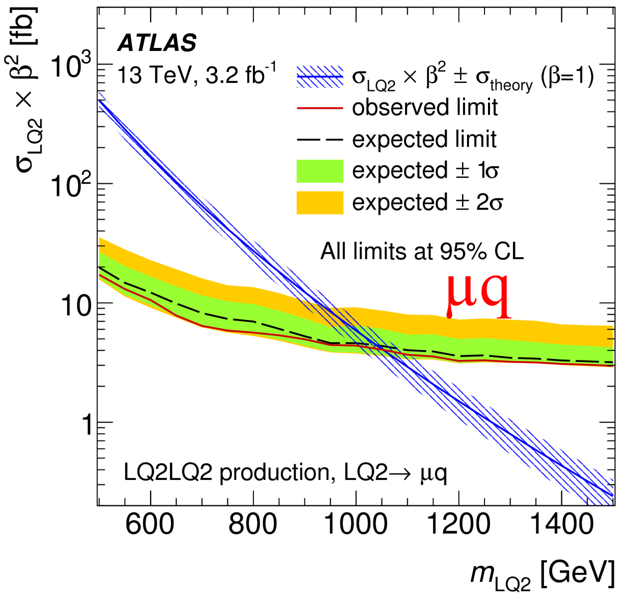


- **Leptoquarks (LQs) arise in many models, such as grand unified theories, compositeness models and superstring theories.**
- **LQs: carry colour charge, fractional electric charge, and both lepton and baryon quantum numbers.**
- **If exist, decay into a lepton and a quark. Search for resonance of lepton+jet in experiment.**

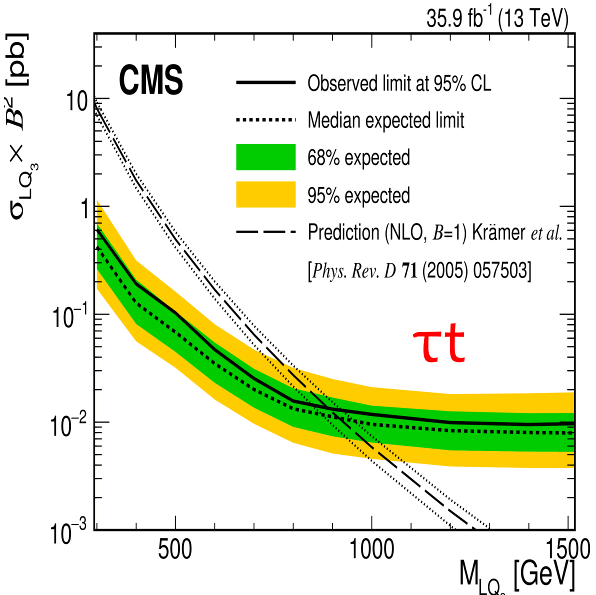
- **m(LQ1,LQ2) > 1.1TeV**
- **m(LQ3) > 0.9 TeV**

New J. Phys. 18 (2016) 093016





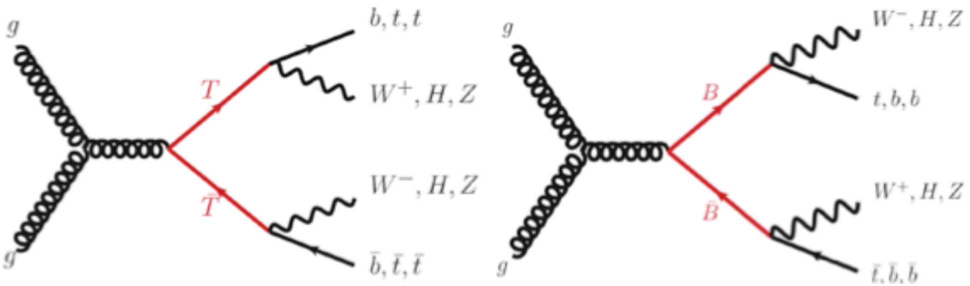
CMS-PAS-B2G-16-028



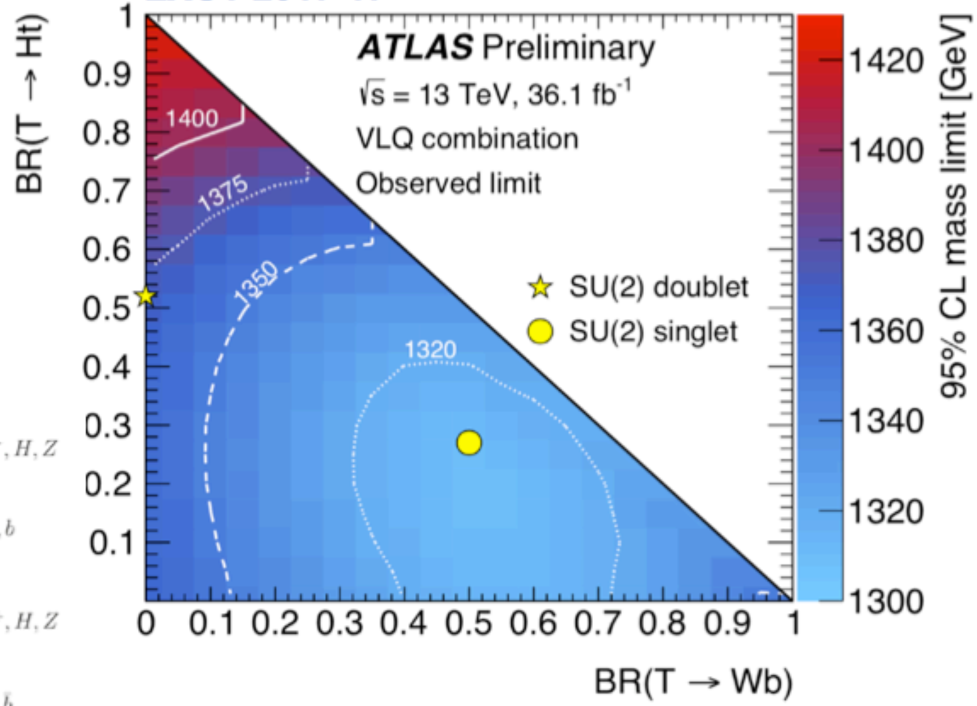
No significant excess observed in 2~36fb -1 . Results in terms of β = BR(LQ→lq)

Heavy quarks (额外夸克)

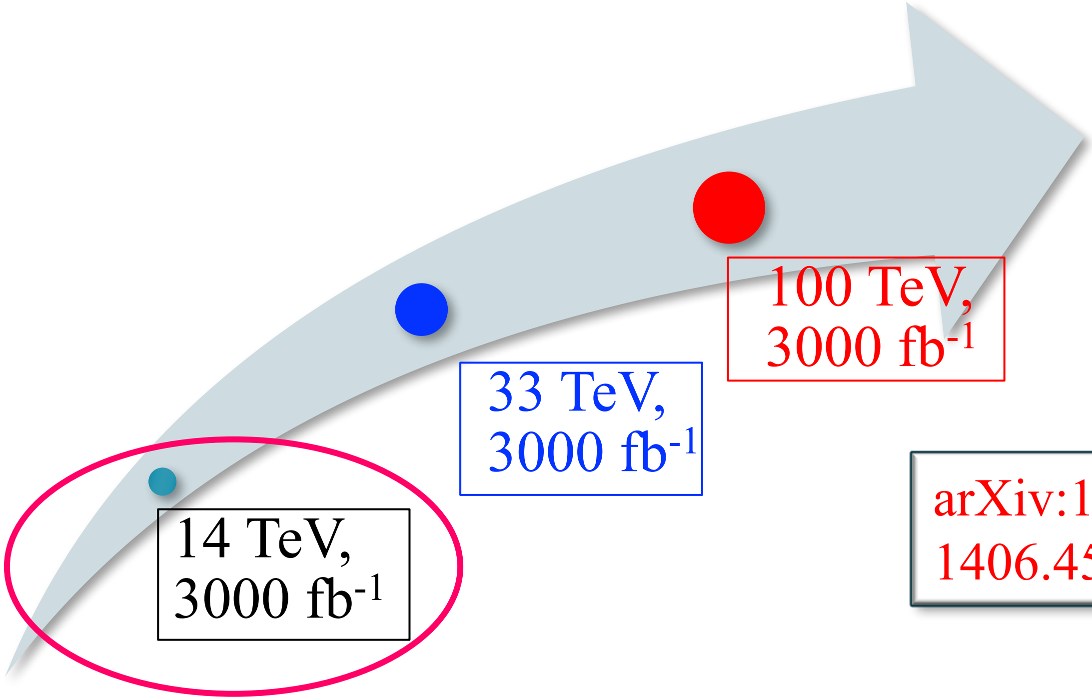
- **Vector-like T quark models solve hierarchy problem**
  - new heavy partner of top in loop
- Search of **T (q=2/3) and B (q=-1/3)** VLQ decaying to **W,H,Z and t,b** produced in **pairs**
- Recent **combination of 7 final states** (H(bb)t, W(lv)b, W(lv)t, Z(vv)t, Z(ll)t/b, trilepton/same-sign dilepton, fully hadronic)
- **Limits at the level of 1.3-1.4 TeV**



EXOT-2017-17



Prospects at Future Collider



14 TeV, 3000 fb^{-1}

33 TeV, 3000 fb^{-1}

100 TeV, 3000 fb^{-1}

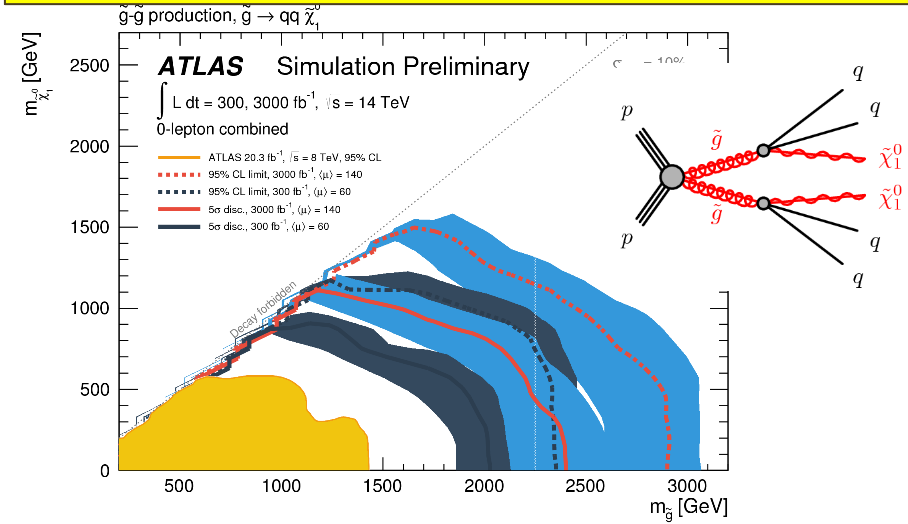
arXiv:1311.6480, 1406.4512, 1410.6287

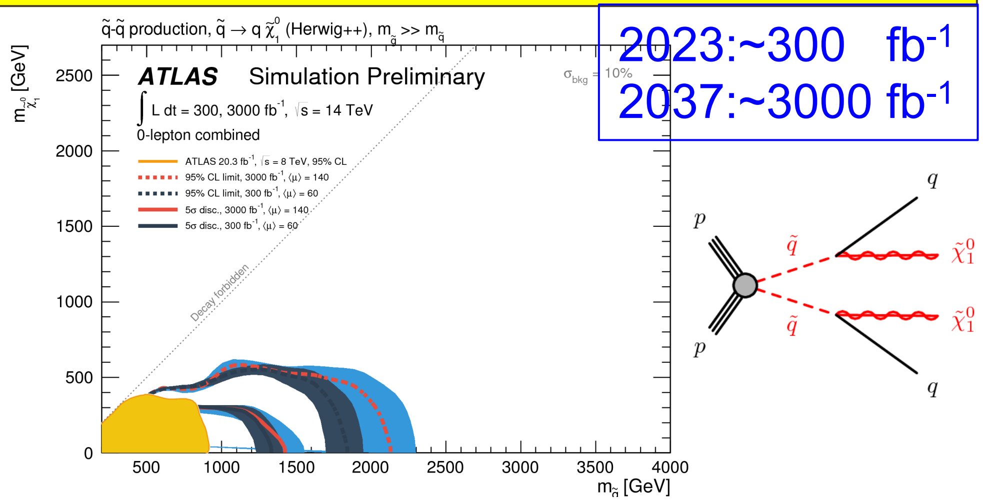
- **Long term prospects for 2 more collider scenarios have been studied (14, 33, 100 TeV @3000 fb^{-1})**
- **Use same search strategy as 8-13TeV @LHC**
- **Use simple analysis strategies, assume 20% syst. uncertainty, avoid assumption on detector design, pileup sensitivity, etc**

Prospects at HL-LHC

ATL-PHYS-PUB-2014-010

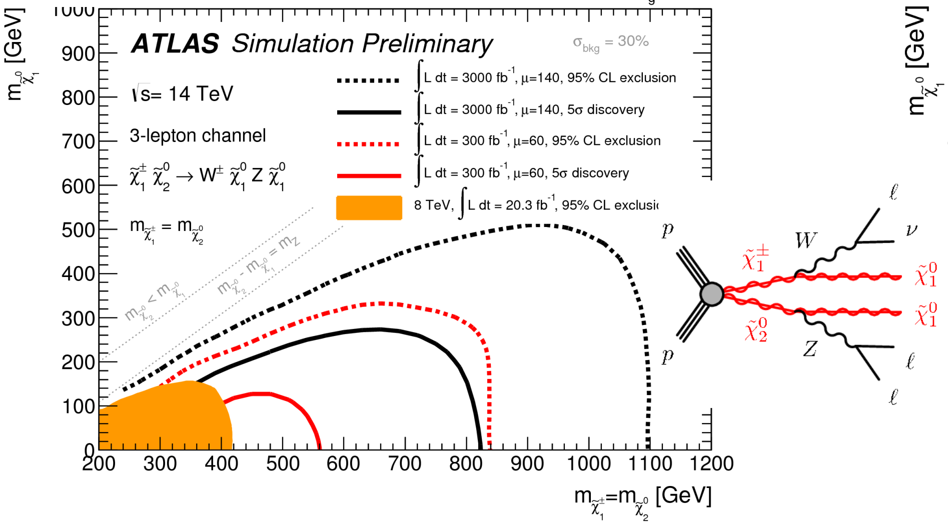
- ❑ ATLAS studied long term prospects for the (HL-)LHC with 300, 3000 fb^{-1}@14TeV
- ❑ **Discovery potential up to 2.5 TeV gluinos, 1.3 TeV squarks/sbottom and 800 GeV Electroweakinos, 500 GeV stau with 3000 fb^{-1}.**

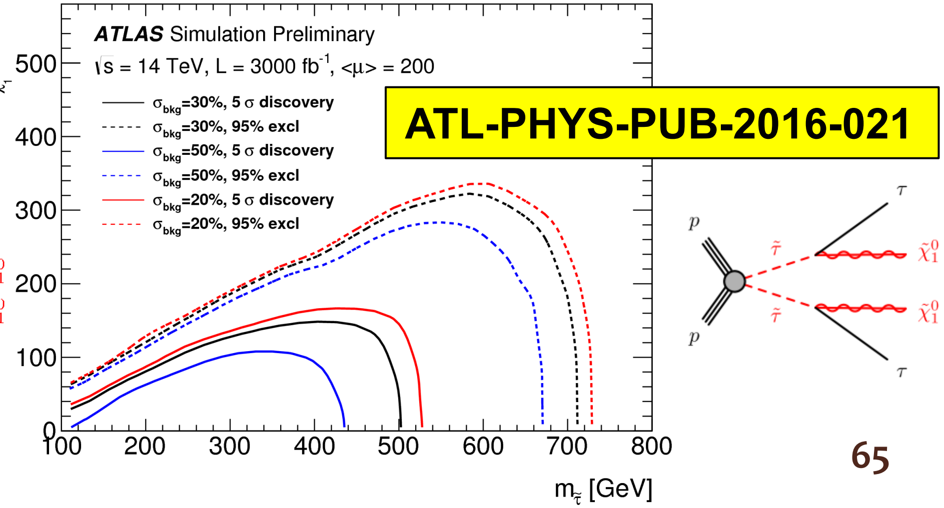




2023:~300 fb^{-1}

2037:~3000 fb^{-1}

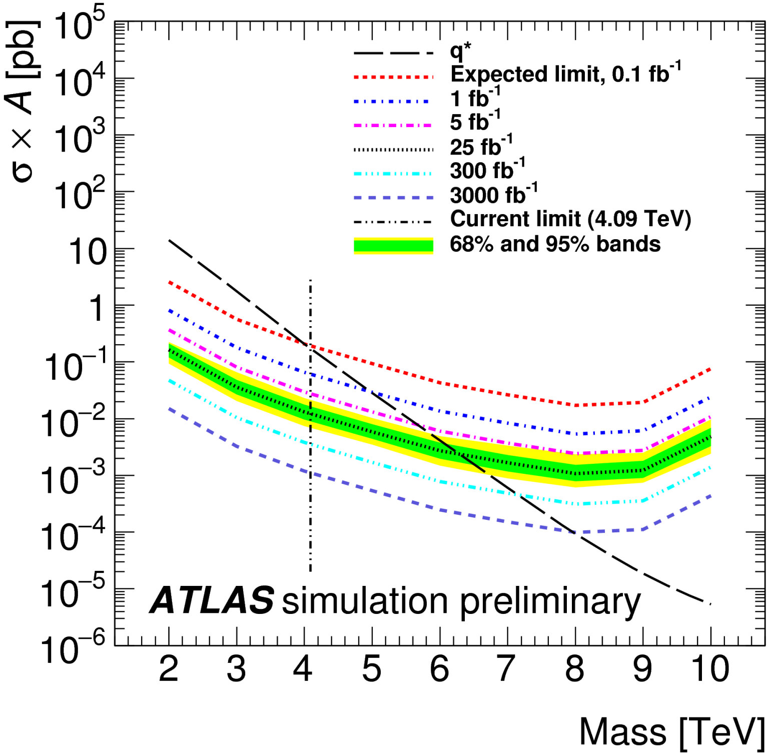




ATL-PHYS-PUB-2016-021

Prospects at HL-LHC

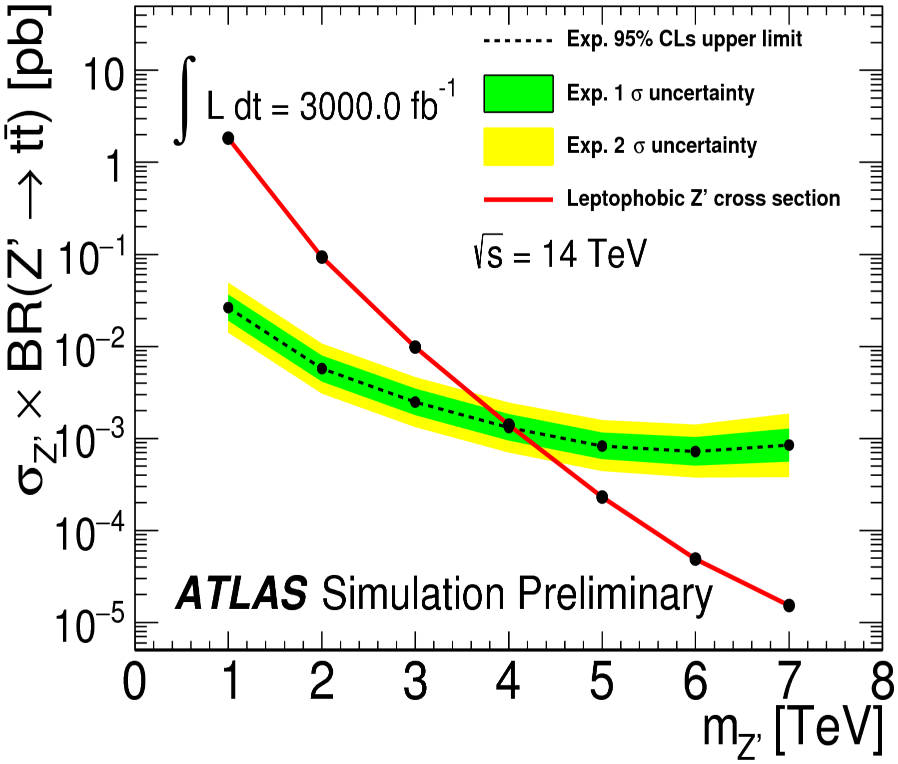
ATL-PHYS-PUB-2015-004



Exited quark q*→qg: di-jet

6→8 TeV

ATL-PHYS-PUB-2017-002



Z'→ttbar

3→4 TeV

Future hadron collider projects in a nutshell -- The next discovery machine

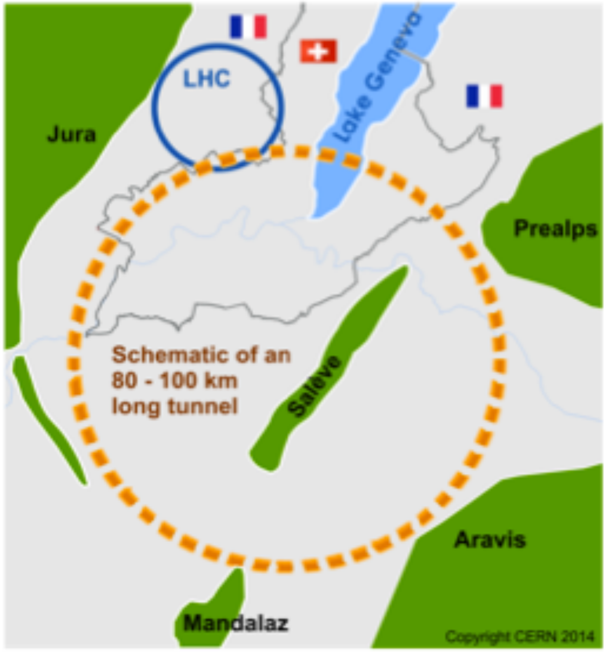
HL-LHC: E_{CM} = 14 TeV, 3 ab^{-1}, 2026~2035… (formally approved as *project* by CERN council last week)

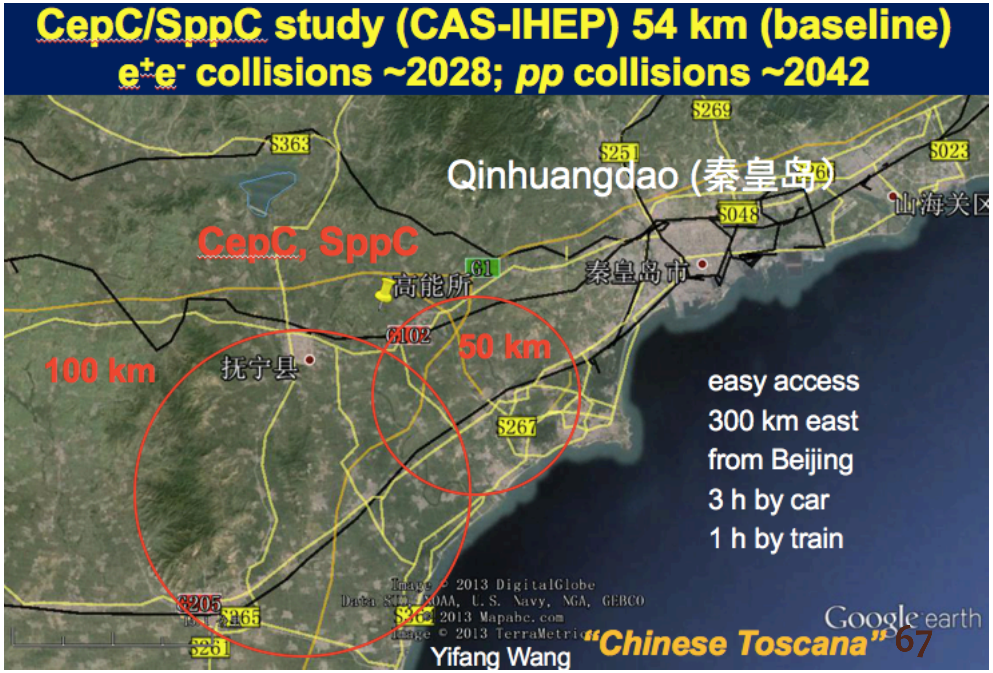
Future Circular Collider FCC-hh (CERN):

- E_{CM} ~ 100 TeV in 100 km ring, L ~ 2 × 10^{35} $s^{-1}cm^{-2}$
- ~16 T magnets, possibly HE-LHC (E_{CM} ~ 28 TeV) as intermediate stage
- Huge detectors for muon p_T measurement
- Possible start of physics ~ 2035

SppC (China):

- E_{CM} ~ 71 TeV in 55 km ring, L ~ 1 × 10^{35} $s^{-1}cm^{-2}$
- Requires very high gradient dipole magnets ~ 20 T
- Possible start of physics ~ 2042



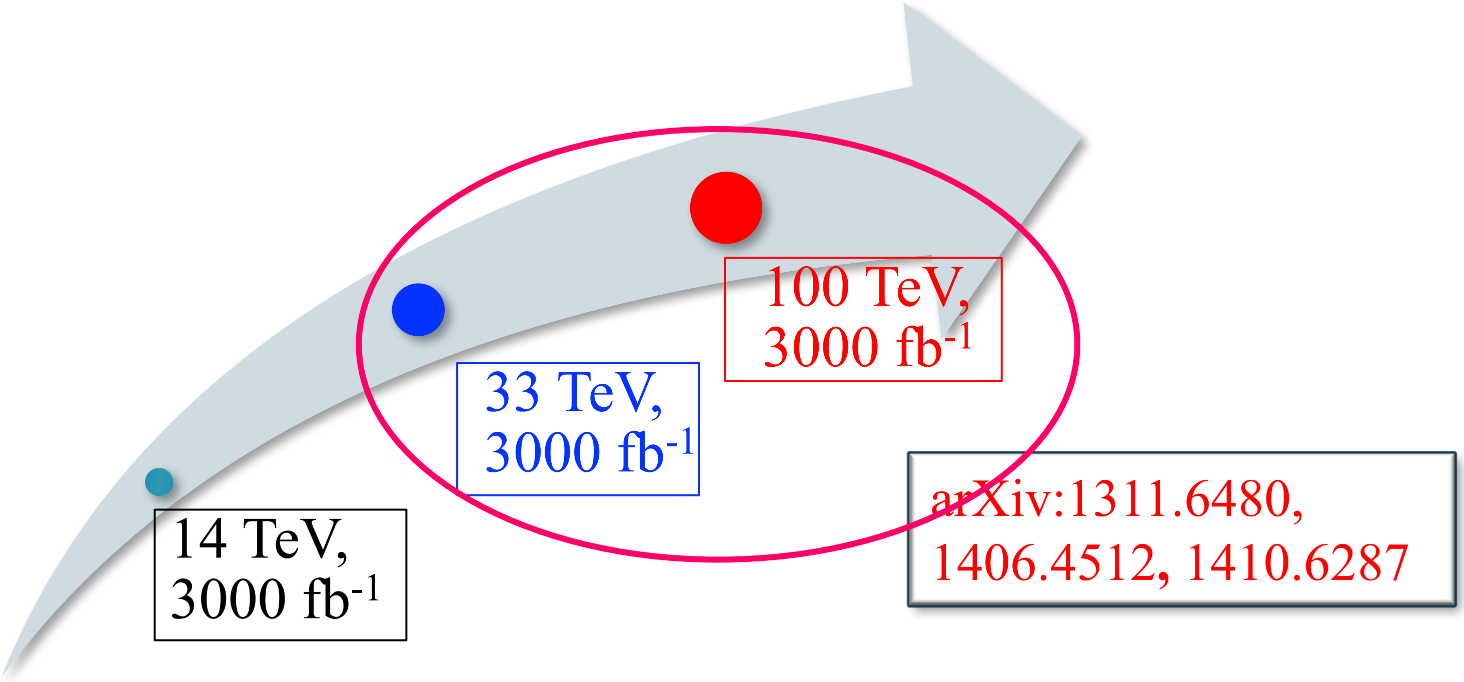

CepC/SppC study (CAS-IHEP) 54 km (baseline)
e^+e^- collisions ~2028; *pp* collisions ~2042

easy access
300 km east
from Beijing
3 h by car
1 h by train

Yifang Wang

"Chinese Toscana"

Prospects at Future Collider



14 TeV, 3000 fb^{-1}

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100 TeV, 3000 fb^{-1}

arXiv:1311.6480, 1406.4512, 1410.6287

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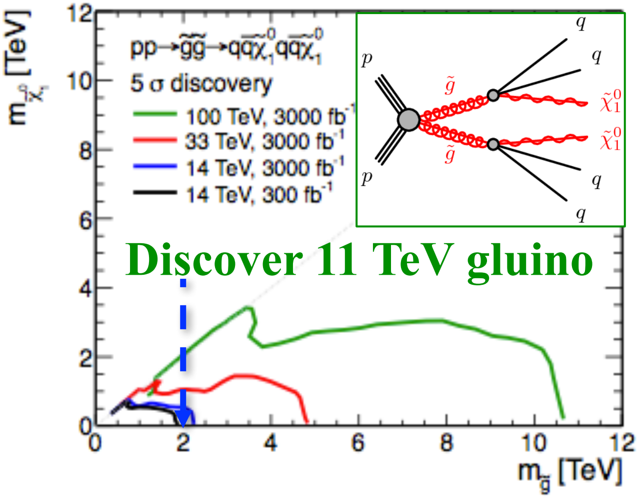
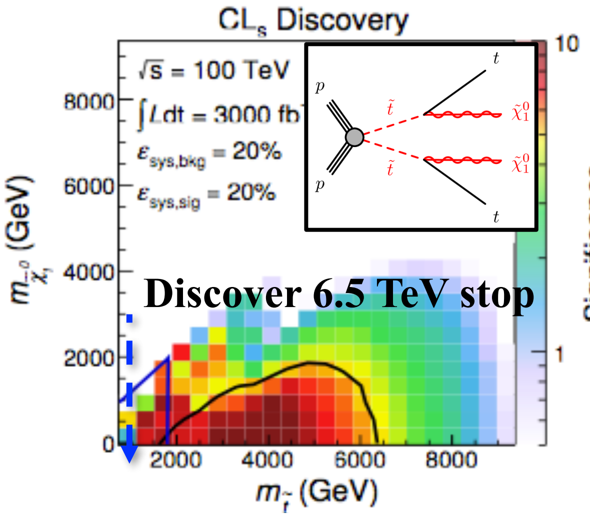
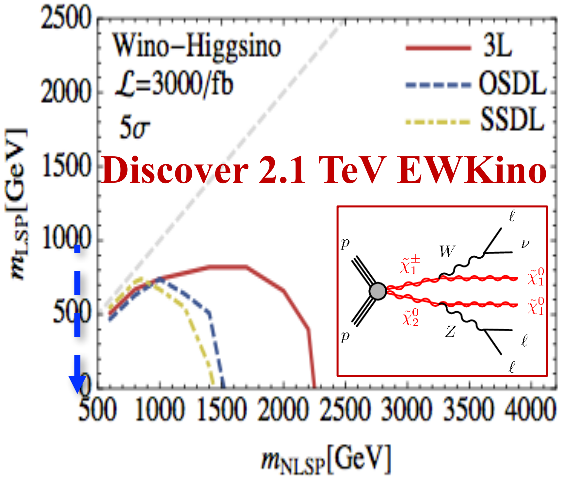
- **Use same search strategy as 8-13TeV @LHC**
- **Use simple analysis strategies, assume 20% syst. uncertainty, avoid assumption on detector design, pileup sensitivity, etc**

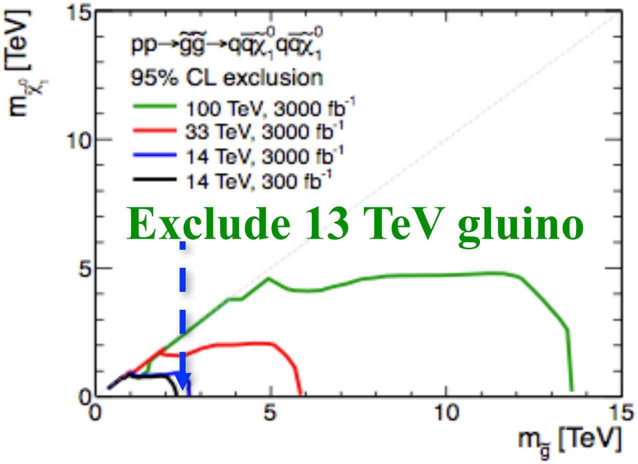
Prospects at Future Collider

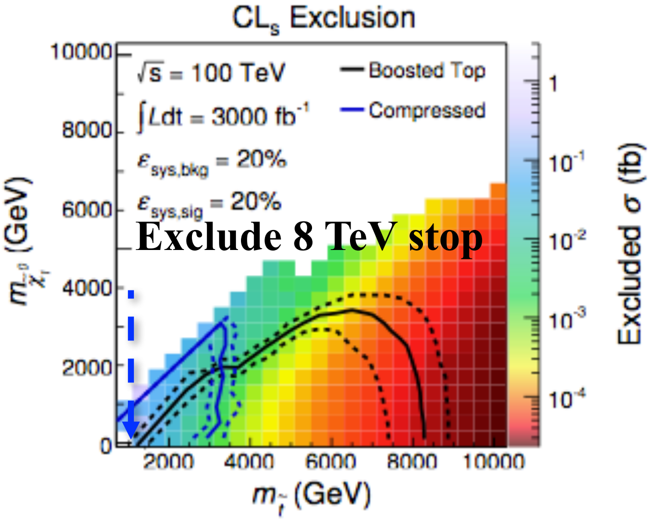
- ☐ **Discovery potential (exclusion) up to 11(13) TeV gluinos, 6.5(8) TeV squarks/sbottom and 2.1(3.2) TeV Electroweakinos.**

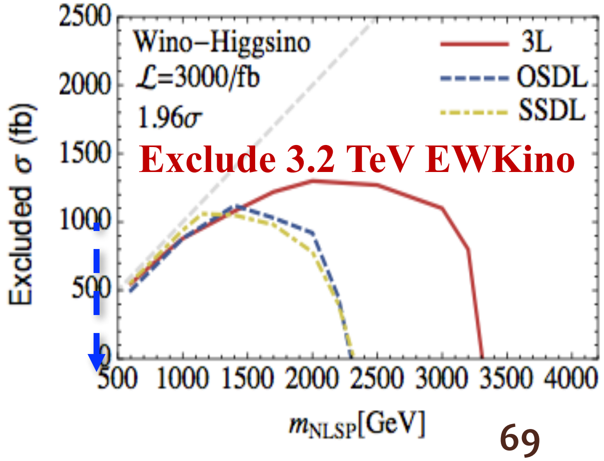

Discover 11 TeV gluino

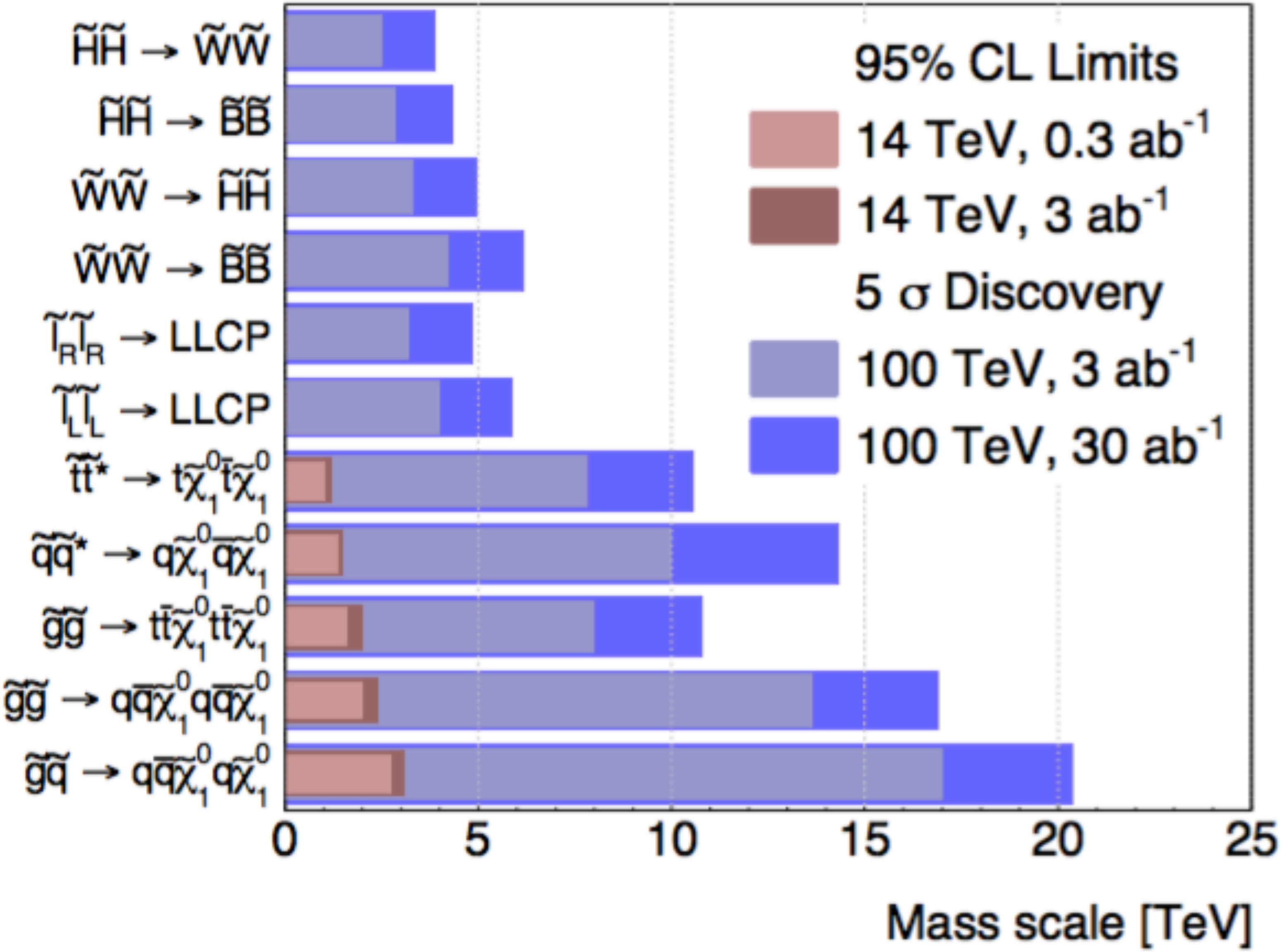

Discover 6.5 TeV stop


Discover 2.1 TeV EWKino


Exclude 13 TeV gluino


Exclude 8 TeV stop


Exclude 3.2 TeV EWKino

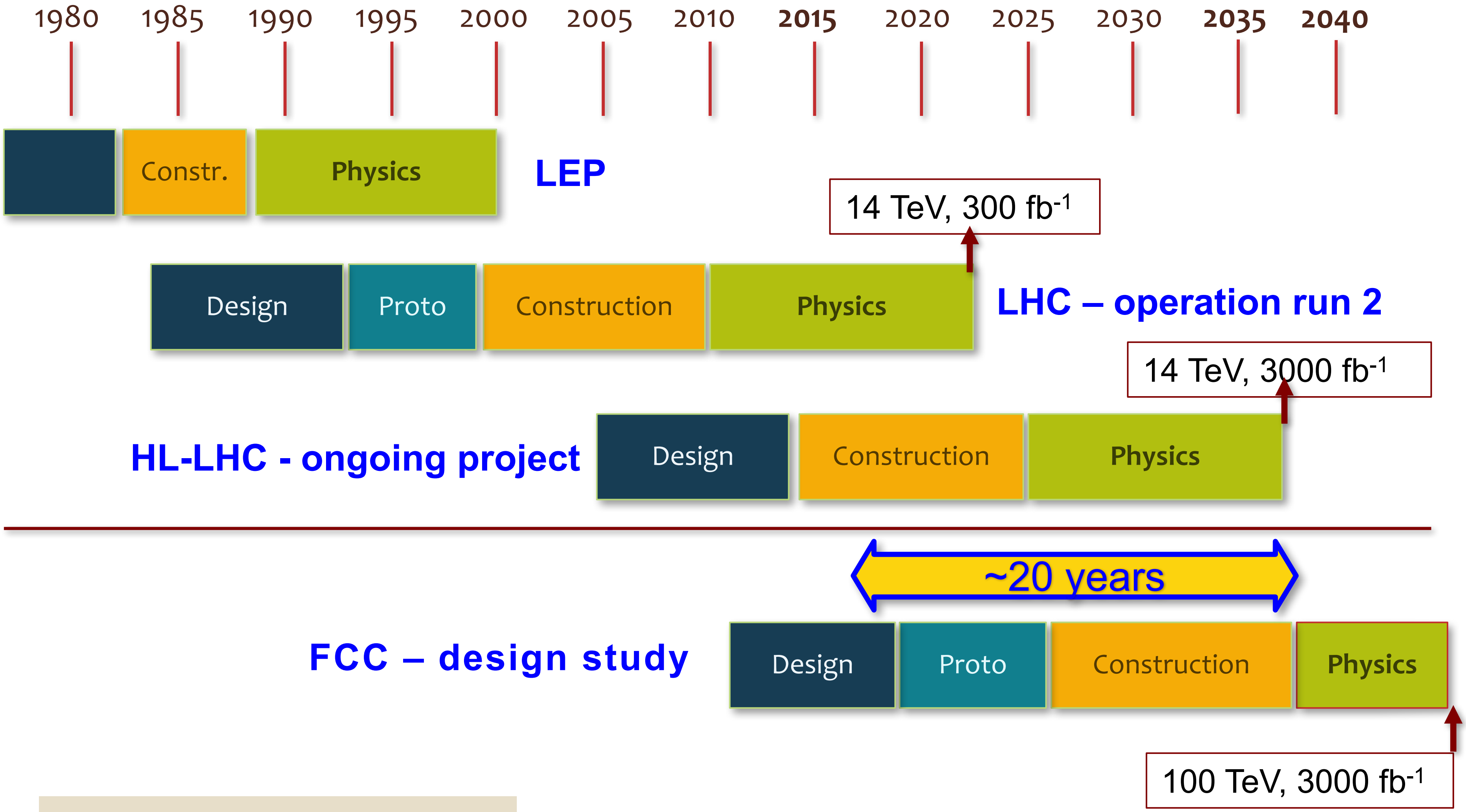

$\tilde{H}\tilde{H} \rightarrow \tilde{W}\tilde{W}$
$\tilde{H}\tilde{H} \rightarrow \tilde{B}\tilde{B}$
$\tilde{W}\tilde{W} \rightarrow \tilde{H}\tilde{H}$
$\tilde{W}\tilde{W} \rightarrow \tilde{B}\tilde{B}$
$\tilde{l}_R\tilde{l}_R \rightarrow$ LLCP
$\tilde{l}_L\tilde{l}_L \rightarrow$ LLCP
$\tilde{t}\tilde{t}^* \rightarrow t\tilde{\chi}_1^0\bar{t}\tilde{\chi}_1^0$
$\tilde{q}\tilde{q}^* \rightarrow q\tilde{\chi}_1^0\bar{q}\tilde{\chi}_1^0$
$\tilde{g}\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0 t\bar{t}\tilde{\chi}_1^0$
$\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0 q\bar{q}\tilde{\chi}_1^0$
$\tilde{g}\tilde{q} \rightarrow q\bar{q}\tilde{\chi}_1^0 q\tilde{\chi}_1^0$
95% CL Limits
14 TeV, 0.3 ab^{-1}
14 TeV, 3 ab^{-1}
5 σ Discovery
100 TeV, 3 ab^{-1}
100 TeV, 30 ab^{-1}
0
5
10
15
20
25
Mass scale [TeV]

The journey into new physics territory has just only begun, and for sure, exciting times are ahead of us!

J.Blaeu 1664

New World !!!

CERN Circular Colliders & FCC



1980 1985 1990 1995 2000 2005 2010 **2015** 2020 2025 2030 **2035** **2040**

Constr. | Physics — **LEP**

14 TeV, 300 fb^{-1}

Design | Proto | Construction | Physics — **LHC – operation run 2**

14 TeV, 3000 fb^{-1}

HL-LHC - ongoing project — Design | Construction | Physics

~20 years

FCC – design study — Design | Proto | Construction | Physics

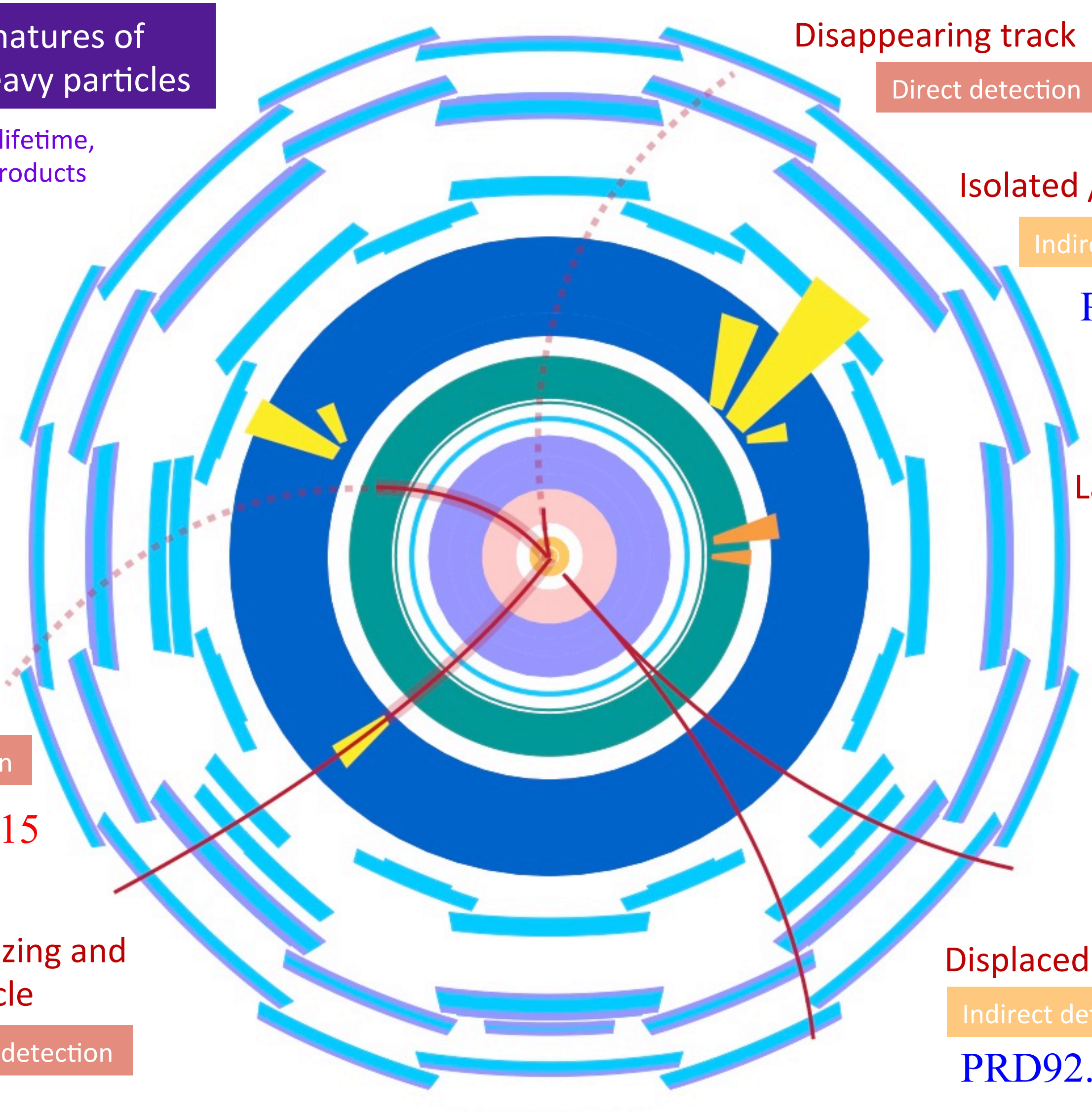
100 TeV, 3000 fb^{-1}

See Michael's talk

Long-Lived particles in SUSY

Detector signatures of long-lived heavy particles

depends on LLP lifetime, mass, & decay products



Disappearing track

Direct detection

PRD88.112006

Isolated / late jets

Indirect detection

PRD88.112003

Late photons

Indirect detection

PRD90.112005

Highly ionizing particle

Direct detection

PRD93.112015

Highly ionizing and slow particle

Direct detection

PLB(2016)647-665

Displaced vertex

Indirect detection

PRD92.072004

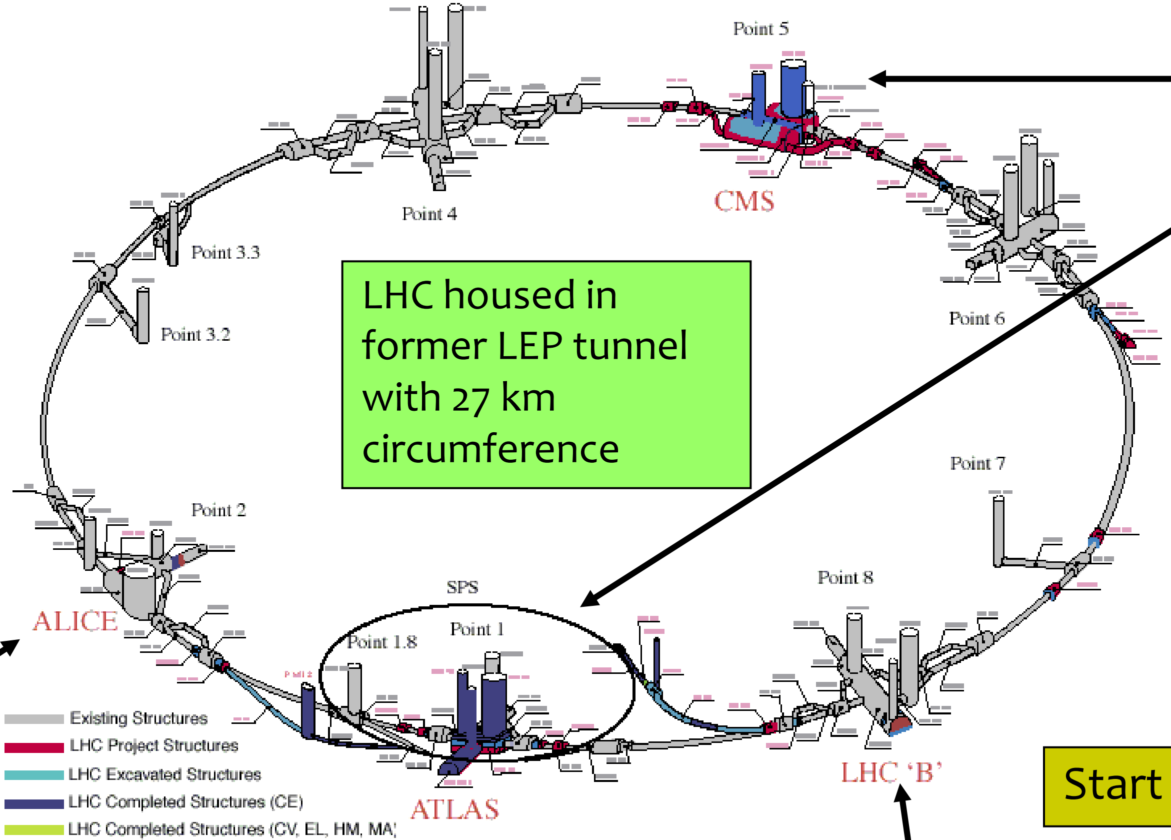
Minimal Supersymmetric Standard Model

Standard Model Particles and Fields		Supersymmetric Partners			
		Interaction Eigenstates		Mass Eigenstates	
Symbol	Name	Symbol	Name	Symbol	Name
$q = u, d, c, s, t, b$	quark	$\tilde{q}_L, \tilde{q}_R$	**squark**	$\tilde{q}_1, \tilde{q}_2$	**squark**
$l = e, \mu, \tau$	lepton	$\tilde{l}_R, \tilde{l}_L$	**slepton**	$\tilde{l}_1, \tilde{l}_2$	**slepton**
$l = \nu_e, \nu_\mu, \nu_\tau$	neutrino	$\tilde{\nu}$	**sneutrino**	$\tilde{\nu}$	**sneutrino**
g	gluon	$\tilde{g}$	**gluino**	$\tilde{g}$	**gluino**
$W^\pm$	W-boson	$\tilde{W}^\pm$	**wino**	$\tilde{\chi}^\pm_{1,2}$	**chargino**
H_u^+, H_d^-	charged Higgs boson	$\tilde{H}_u^+, \tilde{H}_d^-$	**charged higgsino**		
B	B-field	$\tilde{B}$	**bino**	$\tilde{\chi}^0_{1,2,3,4}$	**neutralino**
W^0	W⁰-field	$\tilde{W}^0$	**wino**		
H_u^0, H_d^0	neutral Higgs boson	$\tilde{H}_u^0, \tilde{H}_d^0$	**neutral higgsino**		

LHC

pp

- $\sqrt{s} = 14$ TeV (7 times higher than Tevatron/Fermilab)
  → search for new massive particles up to $m \sim 5$ TeV
- $L_{design} = 10^{34}\ cm^{-2}\ s^{-1}$ (>10^2 higher than Tevatron/Fermilab)
  → search for rare processes with small σ ($N = L\sigma$)



LHC housed in former LEP tunnel with 27 km circumference

ATLAS and CMS :
pp, general purpose

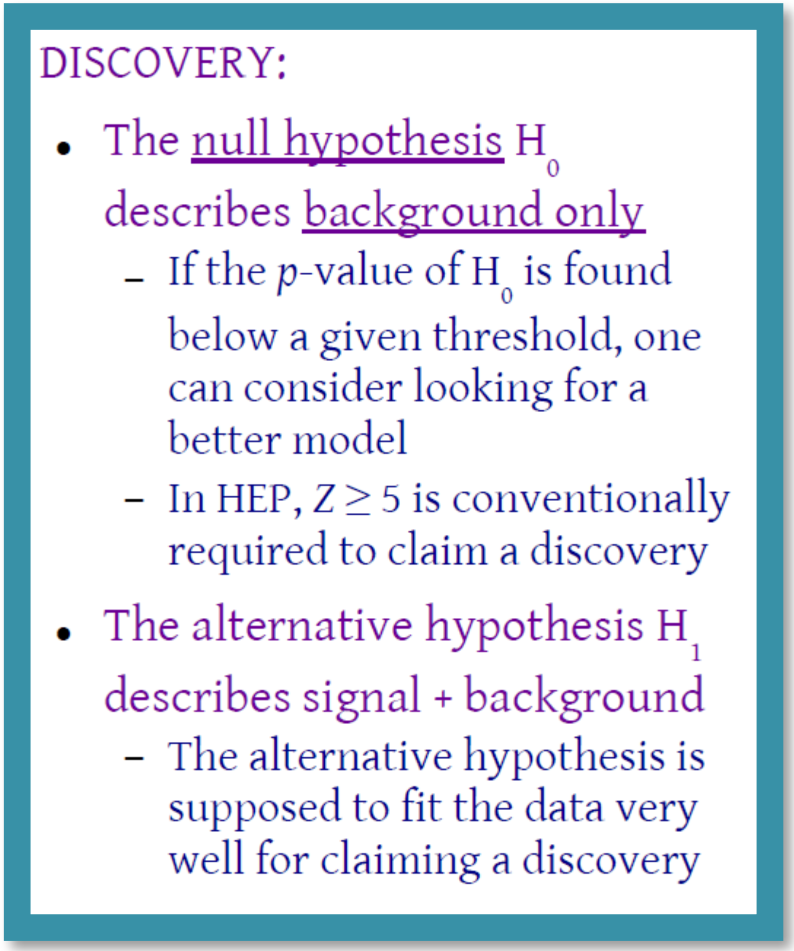
ALICE :
heavy ions

LHCb :
pp, B-physics

Start : Winter 2009

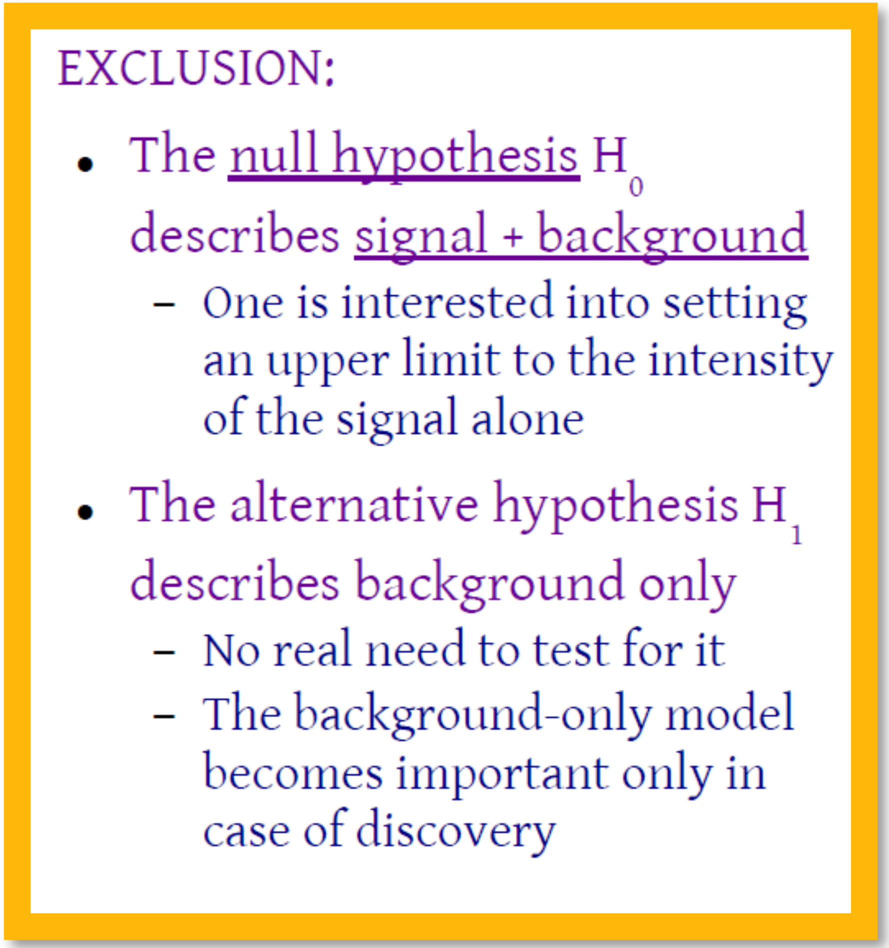
Discovery and exclusion

- P-value=probability that result is as/less compatible with the hypothesis



DISCOVERY:

- The null hypothesis H_0 describes background only
  - If the *p*-value of H_0 is found below a given threshold, one can consider looking for a better model
  - In HEP, $Z \geq 5$ is conventionally required to claim a discovery
- The alternative hypothesis H_1 describes signal + background
  - The alternative hypothesis is supposed to fit the data very well for claiming a discovery



EXCLUSION:

- The null hypothesis H_0 describes signal + background
  - One is interested into setting an upper limit to the intensity of the signal alone
- The alternative hypothesis H_1 describes background only
  - No real need to test for it
  - The background-only model becomes important only in case of discovery

Interpretation strategy

Based on the number of observed, expected events in all regions with all uncertainties: Probability density function (PDF)

Likelihood function: L(μ,θ)

μ: signal strength (POI);

θ: nuisance parameters(NP)

Profile Likelihood: constrain uncertainty (NP) as part of a likelihood fit

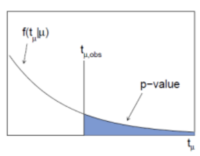
Construct test statistics t_μ based on likelihood ratio λ:

$$\tilde{\lambda}(\mu) = \begin{cases} \frac{L(\mu,\hat{\hat{\theta}}(\mu))}{L(\hat{\mu},\hat{\theta})} & \hat{\mu} \geq 0, \\ \frac{L(\mu,\hat{\hat{\theta}}(\mu))}{L(0,\hat{\hat{\theta}}(0))} & \hat{\mu} < 0 \end{cases}$$

$$t_\mu = -2\ln\lambda(\mu)$$

Find the observed test statistic for tested μ: $t_{\mu,obs}$

Construct the PDF of test statistic t_μ: generate toy Monte Carlo or using asymptotic formula



From the constructed distribution of test statistic for s+b, find the p-value of the observation

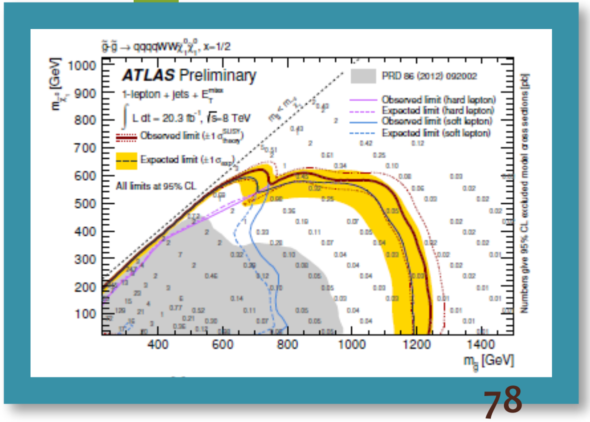
$$p_\mu = \int_{t_{\mu,\text{obs}}}^{\infty} f(t_\mu|\mu)\, dt_\mu$$

If CLs<0.05: the value of signal is excluded at 95% CL……….

$$\text{CL}_\text{s} = \frac{\text{CL}_\text{s+b}}{\text{CL}_\text{b}} = \frac{p_{s+b}}{1-p_b}$$

The above check has been done for each signal grid points on the SUSY model.

The line can be drawn for the area where points are excluded

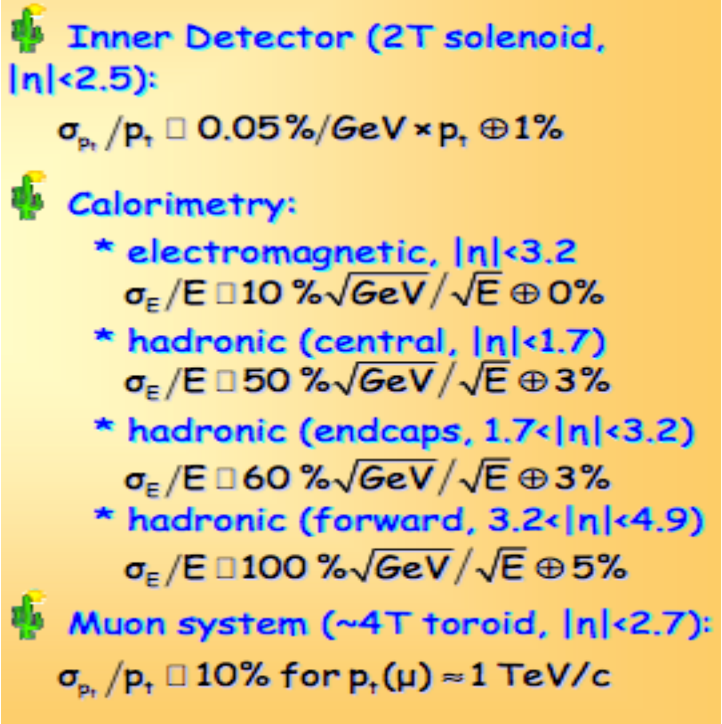


Simultaneous fit

- Background estimates in SRs are obtained by a *simultaneous fit* in each channel based on the profile likelihood method. Three dedicated fit for different purpose…
  - **Background-only fit**
    - Fit for all CRs, excluding SRs.
      - Get background-only estimates.
      - Also extrapolate to VRs (non used in fit, only for cross-check) and SRs.
  - **Discovery fit**
    - Fit for all CRs and SRs.
    - Signal contamination is turned off in CRs and set as a dummy number 1 in SR (so, the fitted non-SM signal strength = the excess in Nevents of SR)
      - Get model-independent upper limit on signal in SR.
  - **Exclusion fit**
    - Fit for all CRs and SRs.
    - Signal is turned on in all regions, according to model-dependent prediction.
      - Got signal model-dependent exclusion from all CRs+SRs →final exclusion contours for SUSY model
- The basic strategy is to share background information in all regions (CR,SR,VR). The background parameters are predominantly constrained by CRs with large statistics, which in turn reduces the impact of uncerts in SR.

A Toroidal LHC ApparatuS

- 42m×22m, 7000 ton



Inner Detector (2T solenoid, |η|<2.5):

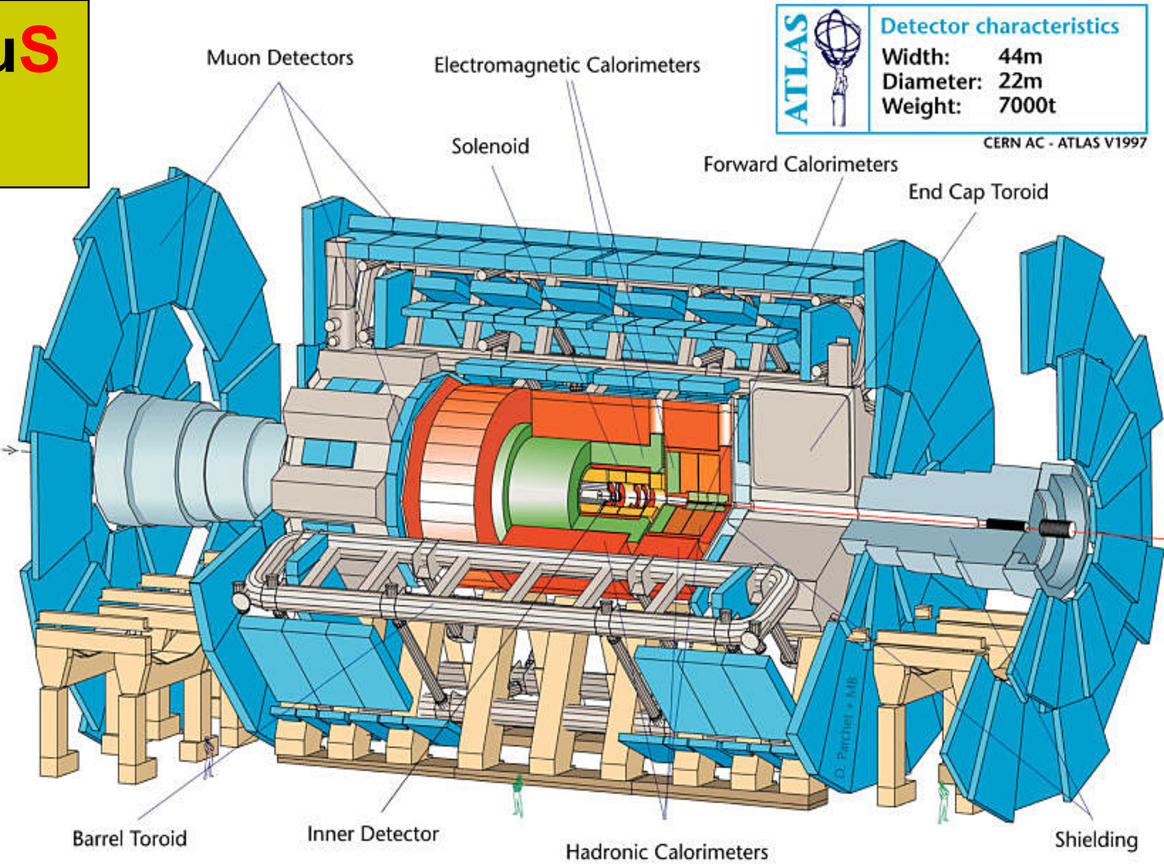
$\sigma_{p_t}/p_t \;\square\; 0.05\%/GeV \times p_t \oplus 1\%$

Calorimetry:

- * electromagnetic, |η|<3.2
  $\sigma_E/E \;\square\; 10\,\%\sqrt{GeV}/\sqrt{E} \oplus 0\%$
- * hadronic (central, |η|<1.7)
  $\sigma_E/E \;\square\; 50\,\%\sqrt{GeV}/\sqrt{E} \oplus 3\%$
- * hadronic (endcaps, 1.7<|η|<3.2)
  $\sigma_E/E \;\square\; 60\,\%\sqrt{GeV}/\sqrt{E} \oplus 3\%$
- * hadronic (forward, 3.2<|η|<4.9)
  $\sigma_E/E \;\square\; 100\,\%\sqrt{GeV}/\sqrt{E} \oplus 5\%$

Muon system (~4T toroid, |η|<2.7):

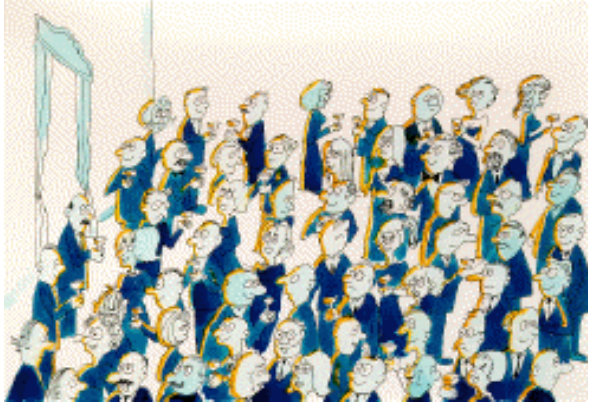
$\sigma_{p_t}/p_t \;\square\; 10\%$ for $p_t(\mu) \approx 1$ TeV/c



- **Inner Detector:** Highly segmented silicon strips, determine very accurately charged particles trajectories
- **Solenoid Magnet:** Solenoid coil that generates a 2T magnetic field in the region of the Inner Detector
- **Electromagnetic Calorimeter:** Electron and photon energies are measured through electromagnetic showers
- **Hadronic Calorimeter:** Hadrons interact with dense material and produce a shower of charged particles
- **Toroid Magnets:** 8 toroidal coils that create a 0,4T magnetic field in the area of the Muon Spectrometer
- **Muon Spectrometer:** Muons traverse the rest of the detector and are measured in its outer layers

The Higgs mechanism, an analogy...

D. Miller
(UC London)



The Higgs field fills all space

A ‘particle’ that moves in the Higgs field ...

... moves slower the more it attract attention (interacts with the Higgs field, generating its mass, the larger, the stronger its interactions...)

The Higgs particle, an analogy...

Somebody whispers a rumour into the room...

... and the field starts to get excited and interact with itself giving birth to a massive particle

SM Background Estimation

SUSY searches rely primarily on the understanding of the SM BG

Standard Model

Top, multijets
V, *VV*, *VVV*, Higgs
& combinations of these

Reducible backgrounds

Determined from data
Backgrounds and methods depend on analyses

Validation

Validation regions used to cross check SM prediction with data

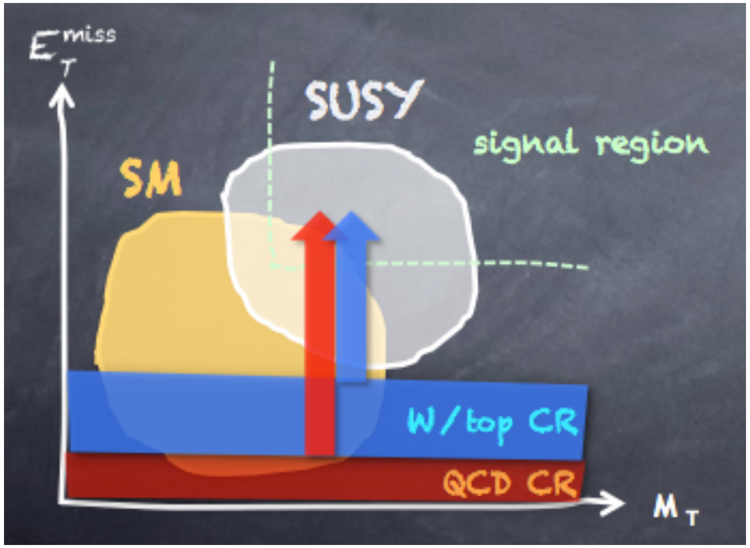
Signal regions

- **Multijet background**: “ABCD method” or jet smearing method
- **Fake leptons or heavy-flavour jets** determined with “matrix method” in different-purity samples using “real” and “fake” probabilities measured in data.
- **Charge flip rate** measured in *Z* events

SM Background Estimation

SUSY searches rely primarily on the understanding of the SM BG

Normalise MC prediction in SRs using dedicated CRs → transfer factor: *T*



Standard Model

Top, multijets
V, *VV*, *VVV*, Higgs
& combinations of these

Irreducible backgrounds

Dominant sources: normalise MC in data control regions
Subdominant sources: MC

Validation

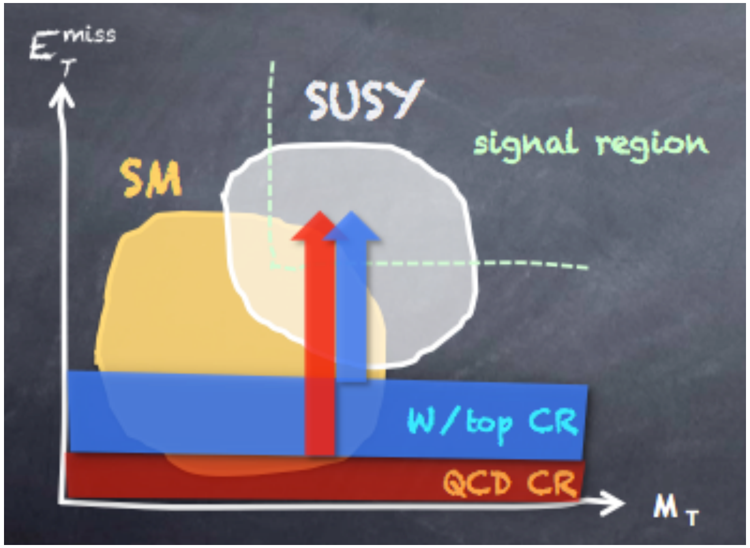
Validation regions used to cross check SM predictions with data

Signal regions

SM Background Es

SUSY searches rely primarily on the u
BG

Normalise MC prediction in SRs using dedicated CRs → transfer factor: ***T***



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V, *VV*, *VV*
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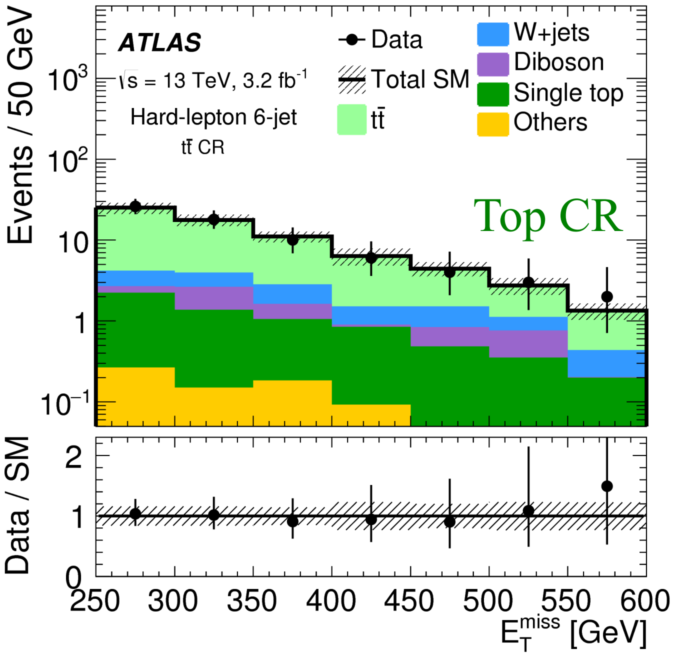
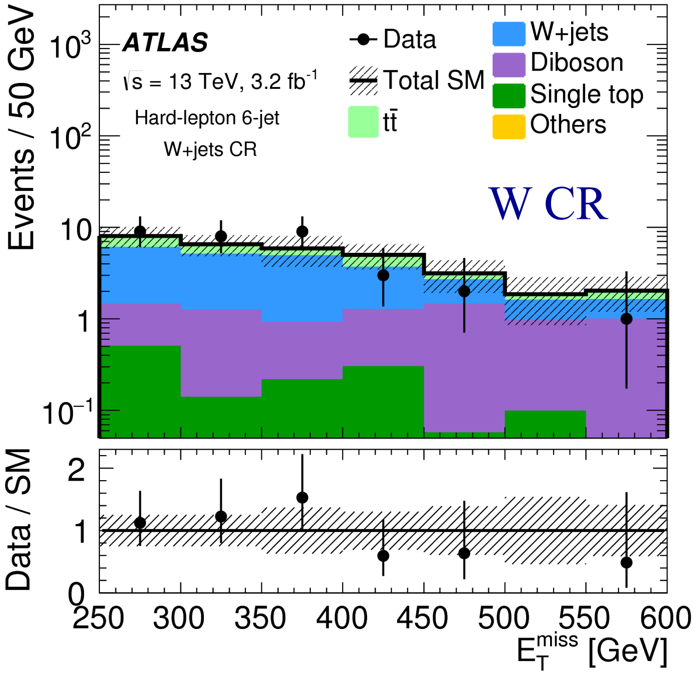




基础物理学的三大前沿

The Energy Frontier

质量起源

物质-反物质不对称

暗物质

宇宙起源

自然力的统一

新物理

中微子振荡

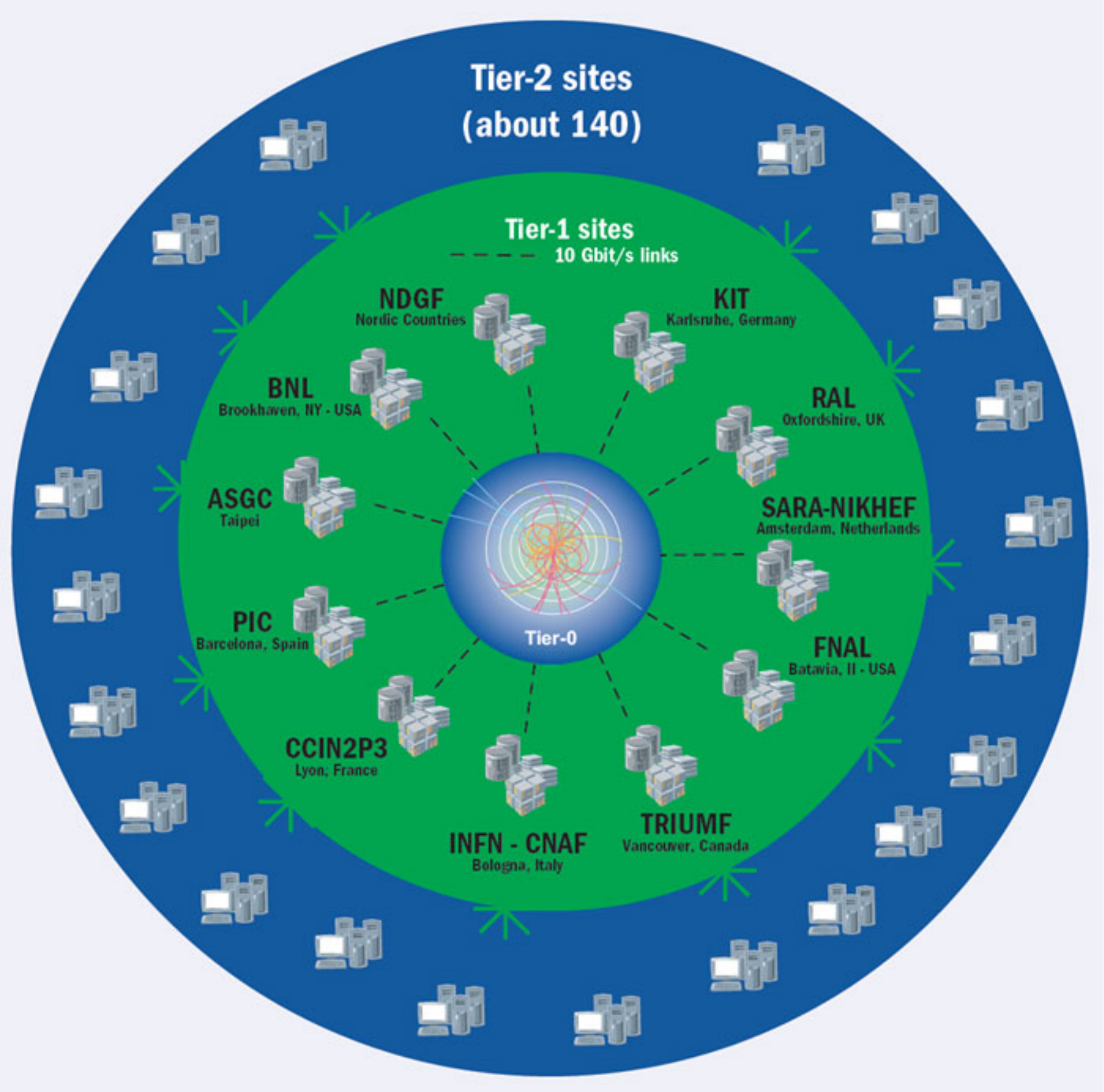
暗能量

质子衰变

The Intensity Frontier

The Cosmic Frontier

The Worldwide LHC Computing Grid (WLCG)



Tier-0 (CERN):
- Data recording
- Initial data reconstruction
- Data distribution

Tier-1 (12 centres):
- Permanent storage
- Re-processing
- Analysis
- Simulation

Tier-2 (68 federations of >100 centres):
- Simulation
- End-user analysis

SUSY models: good sale in market

- **Simplified Models:**
  - Not really a model (Br~100%, most masses fixed at high scales)
  - Important tool for signal region optimization & interpretation

- **Phenomenological models:**
  - ☐ pMSSM: captures “most” of phenomenologic features of R-parity conserving MSSM
    - 19 free parameters: M1,M2,M3 ; tan β, μ and $m_{A;}$ 10 sfermion mass parameters; A_t, A_b and A_T
    - Comprehensive and computationally realistic approximation of the MSSM with neutralino LSP
  - ☐ GGM (gravitino)

- **Complete SUSY models**: mSUGRA, GMSB …