超标准模型物理 BSM

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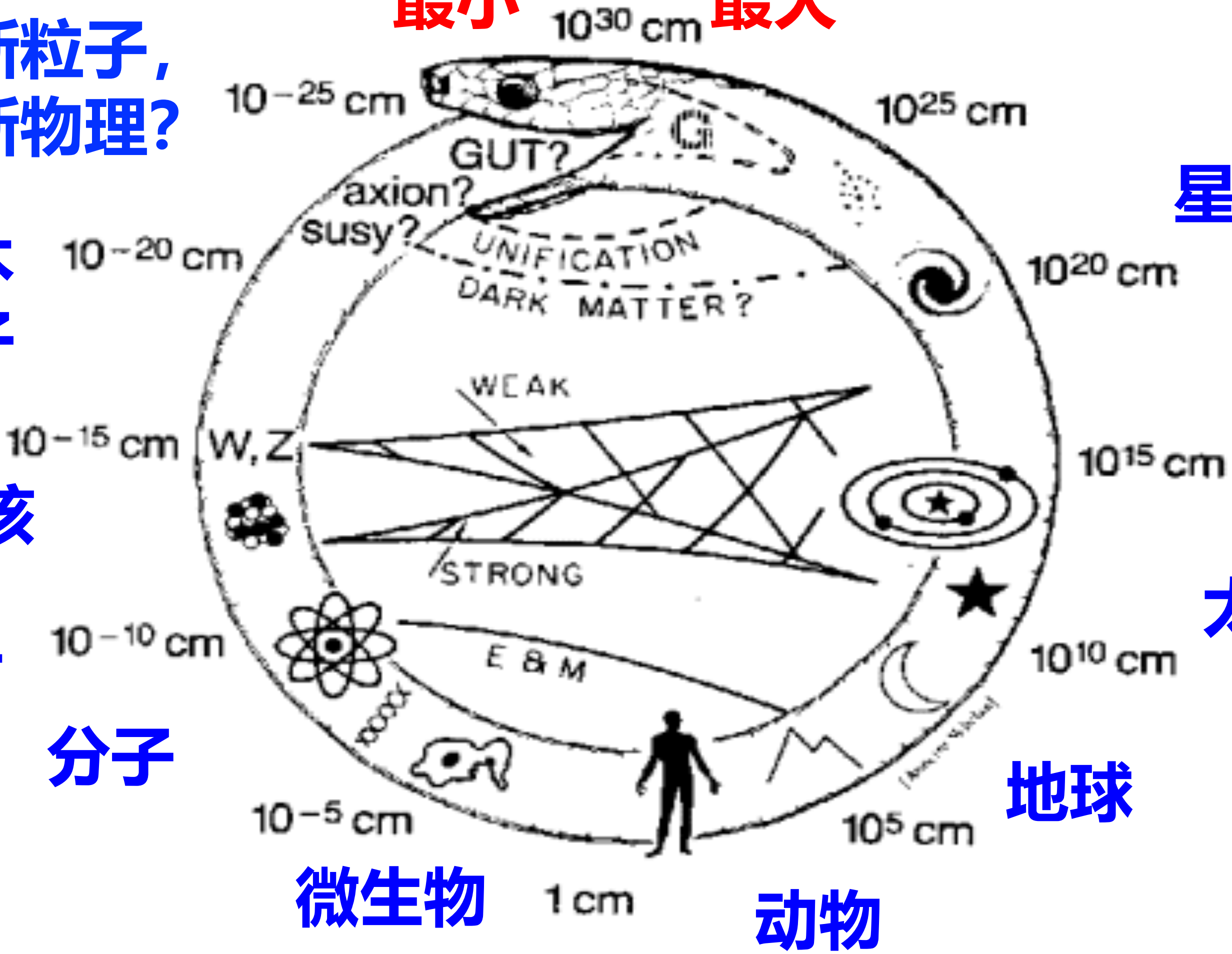
Chinese Academy of Sciences

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

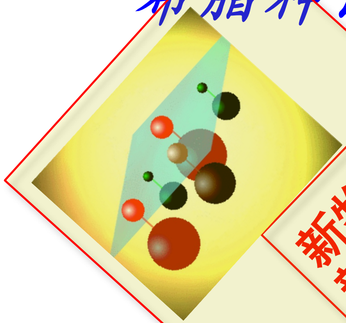
分子

地球

微生物

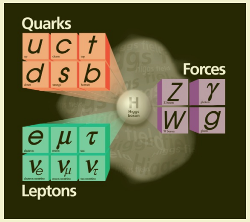
动物

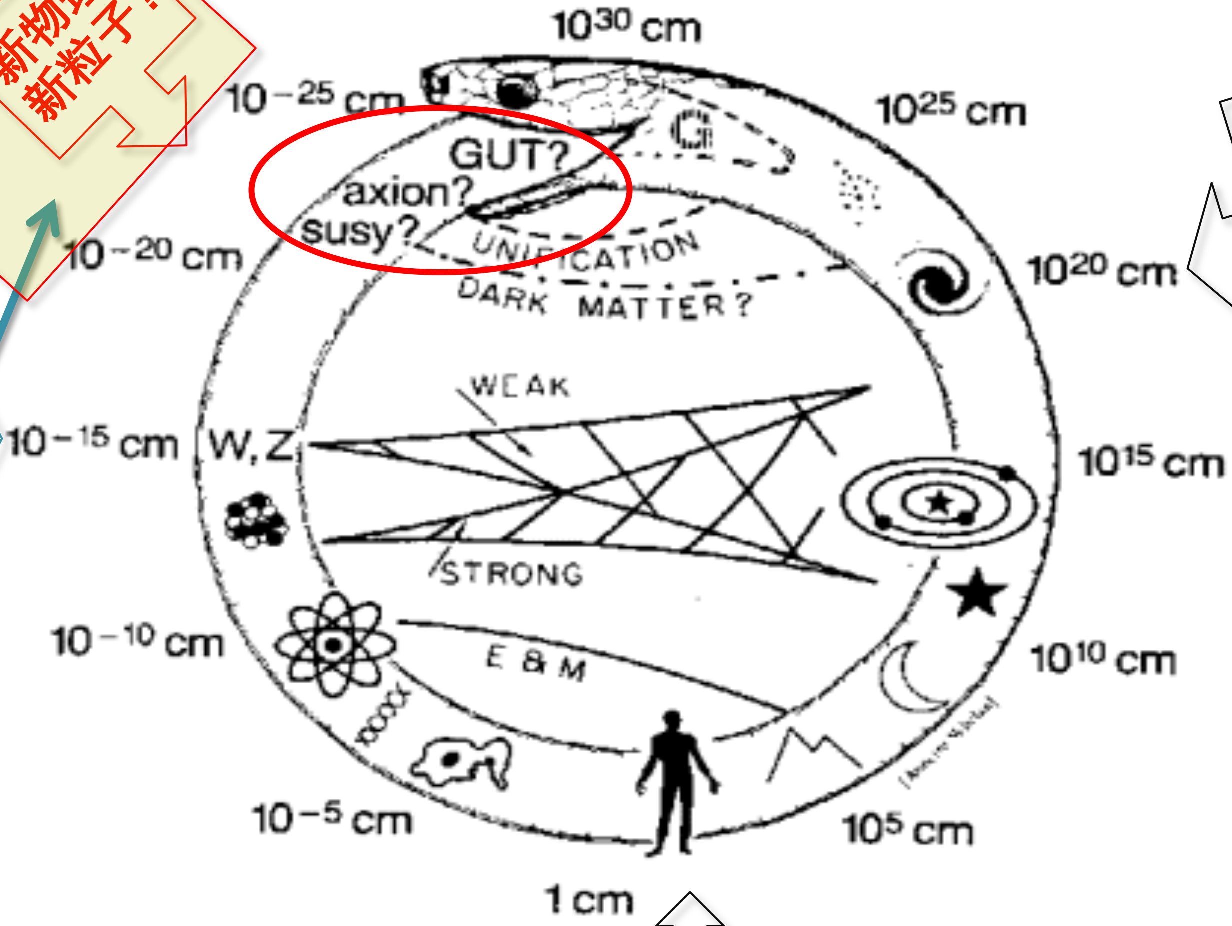
希腊神话中的怪物"Uroboros"与格拉肖的"宇宙圈"



新物理，新粒子？

粒子"微观世界"，强弱相互作用主导，理论模型是标准模型

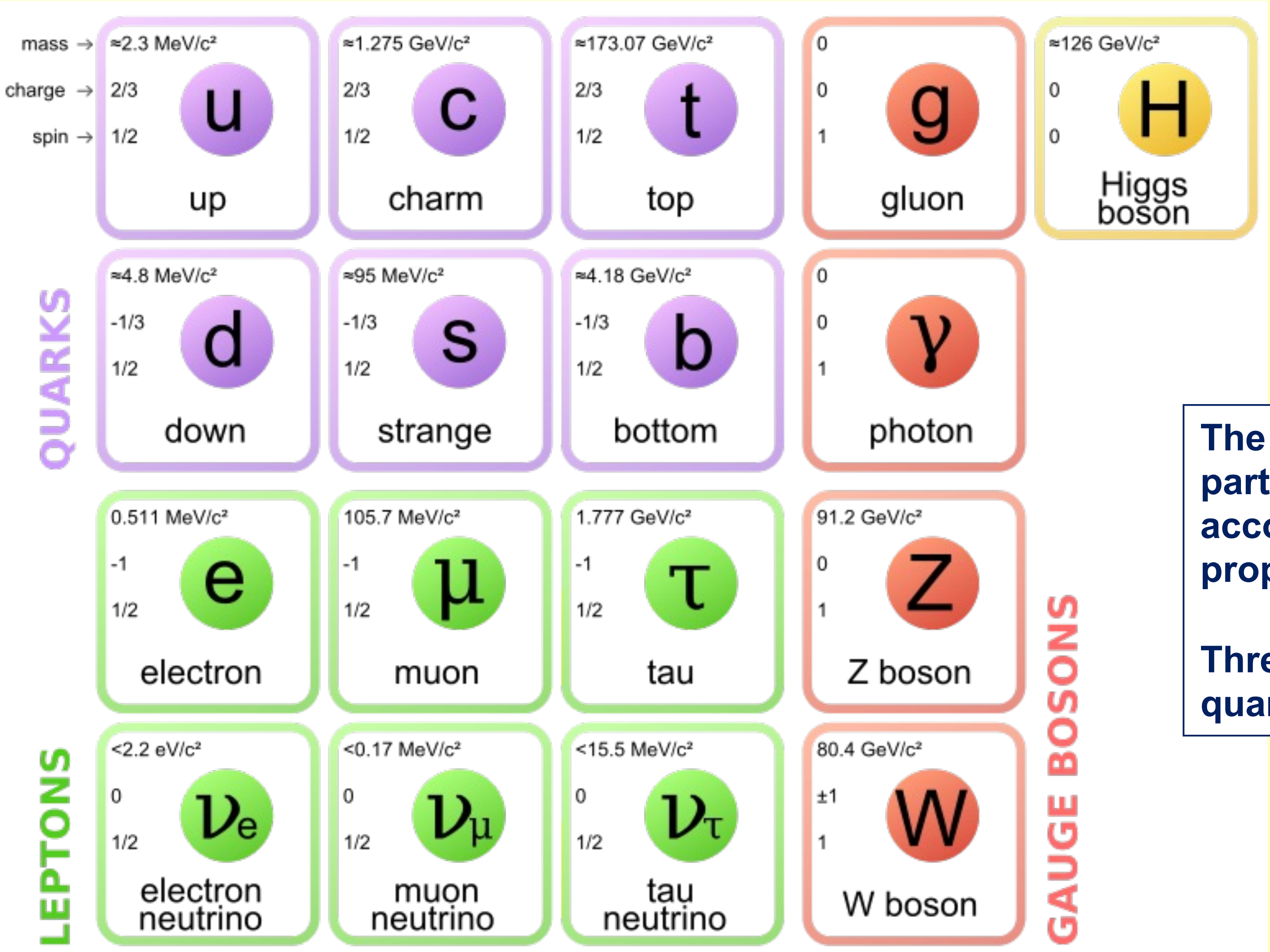




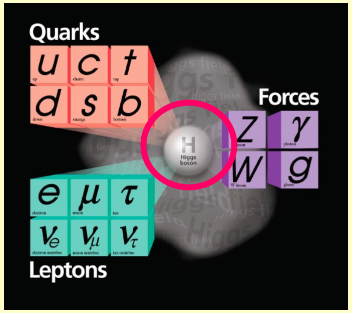
引力主导，爱因斯坦的广义相对论

引力和电磁力占主导地位

Standard Model of Elementary Particles



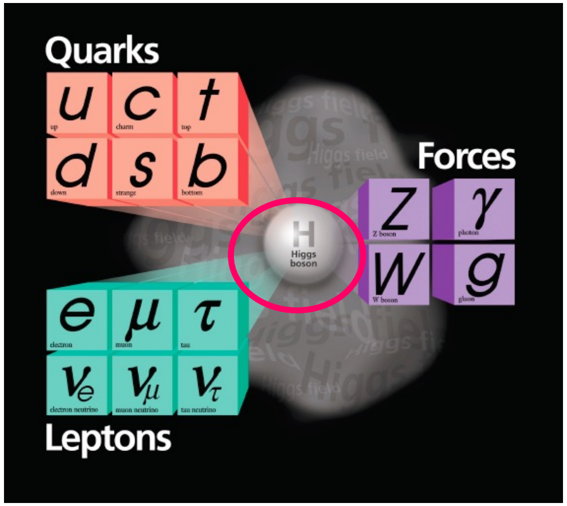
mass → charge → spin →	≈2.3 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c^2 0 0 H Higgs boson
QUARKS	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	
	0.511 MeV/c^2 -1 1/2 e electron	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	



The elementary particles arranged according to their properties

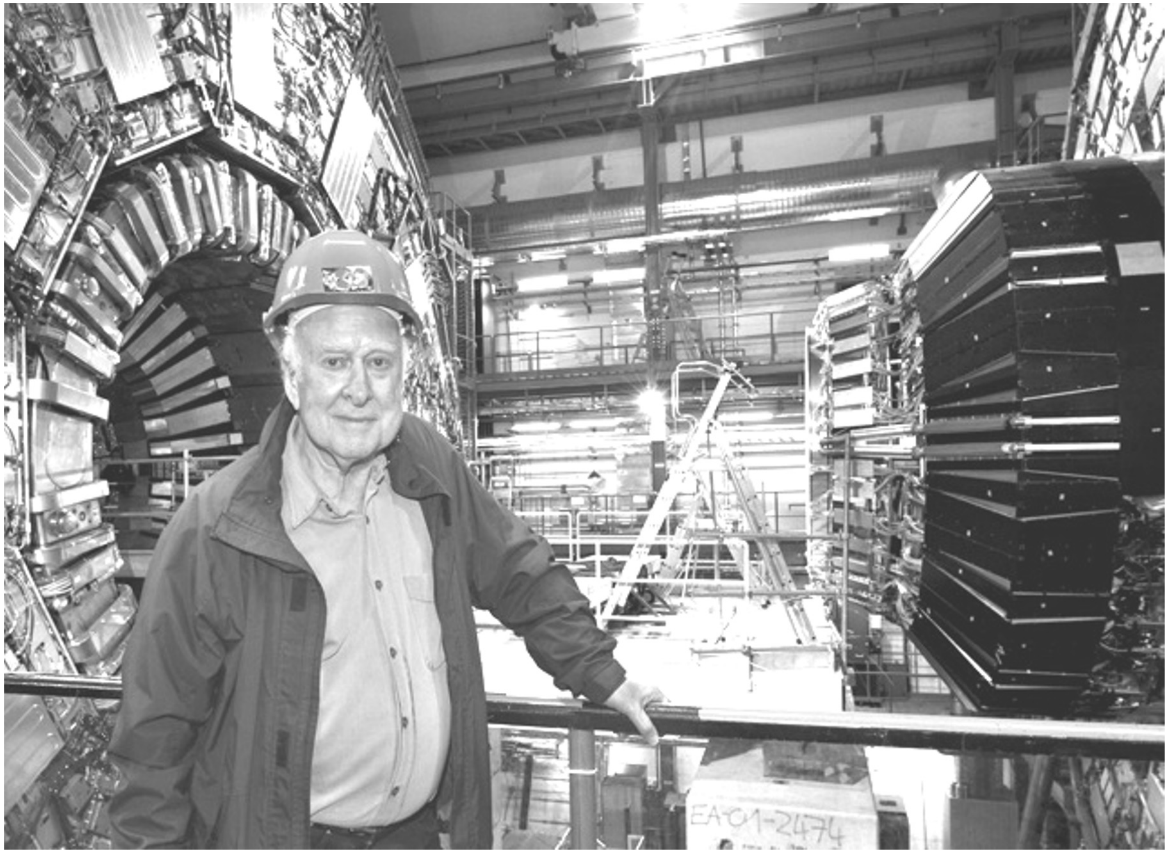
Three families of quarks and leptons

← *Fermionen* → ← *Bosonen* →



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

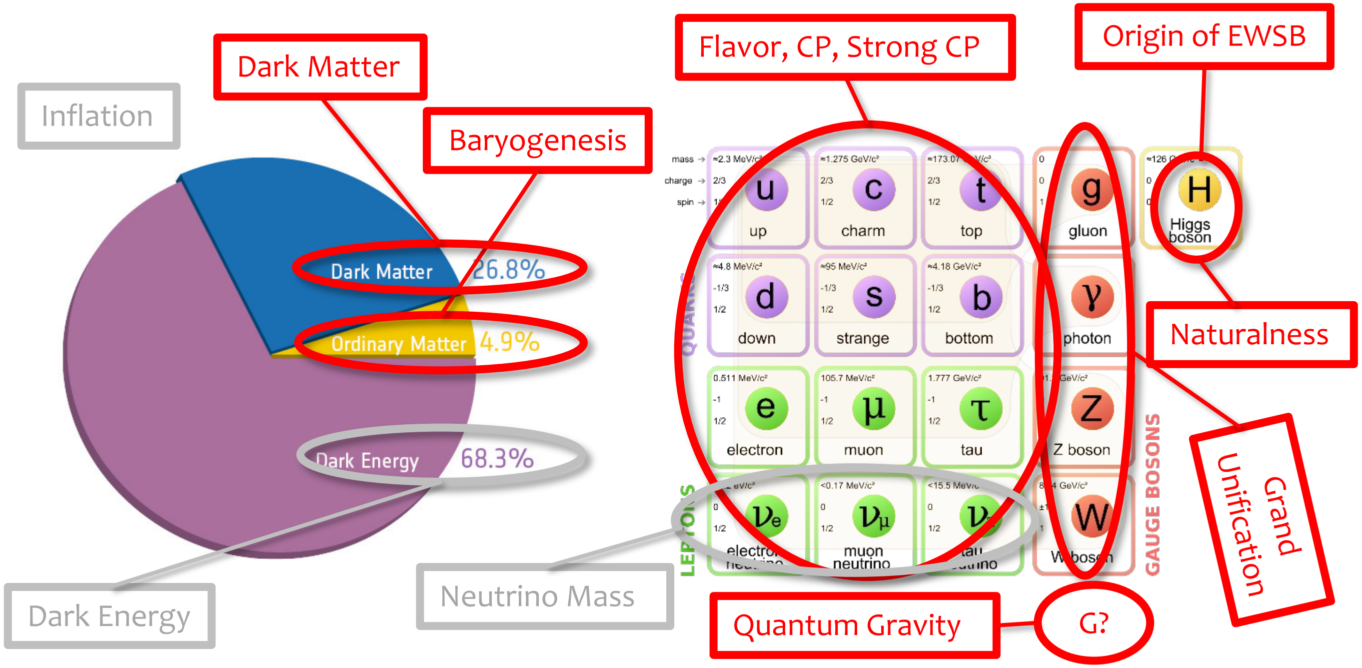
The Nobel Prize in Physics 2013
François Englert, Peter Higgs



P. Higgs at CMS

- **Many big questions not answered by SM !**
  - Naturalness and “hierarchy” problem
  - Unification of gauge coupling
  - Dark Matter
  - ……

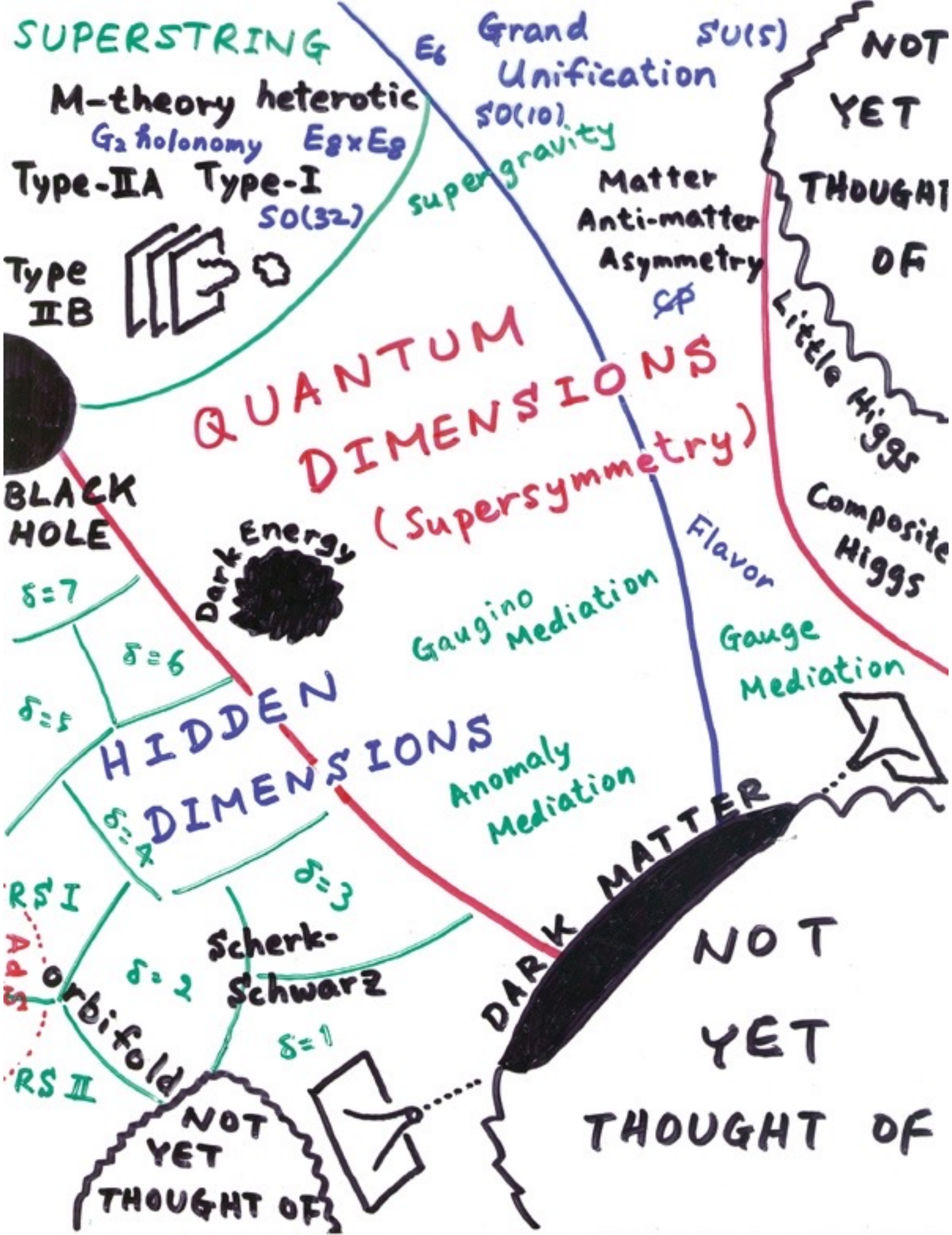
- Need a more fundamental theory of which SM is only a low-energy approximation ➔ **New Physics**



Exploration at energy frontier

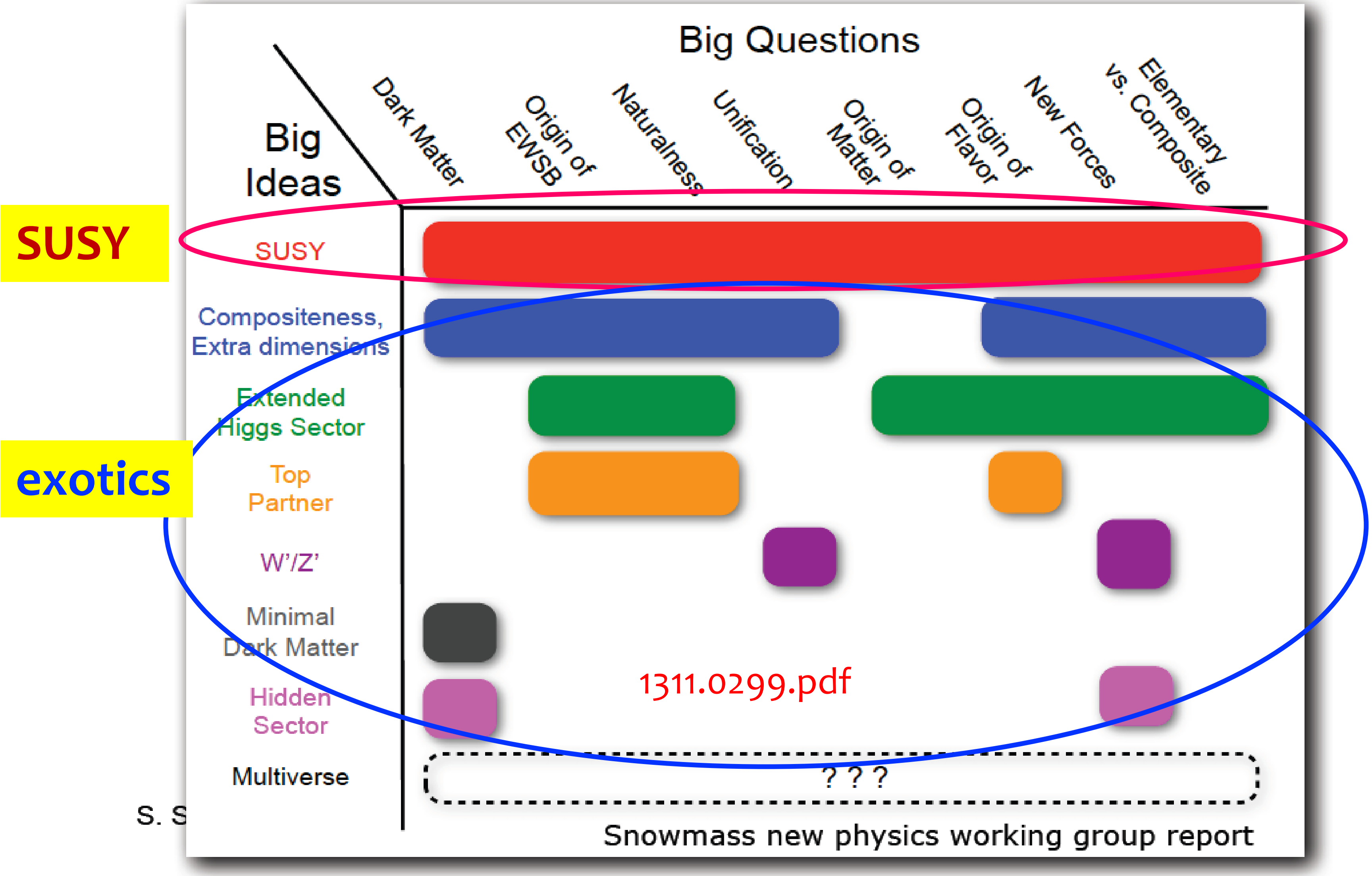
P. Higgs at CMS

Picture modified from Jonathan Feng at 2017 ICFA Seminar


SUPERSTRING
M-theory
G₂ holonomy
heterotic
E₈×E₈
Type-IIA
Type-I
SO(32)
Type IIB
BLACK HOLE
E₆
Grand Unification
SU(5)
SO(10)
Supergravity
Matter Anti-matter Asymmetry
CP
NOT YET THOUGHT OF
Little Higgs
Composite Higgs
QUANTUM DIMENSIONS
(Supersymmetry)
Dark Energy
Flavor
Gaugino Mediation
Gauge Mediation
δ=7
δ=6
δ=5
δ=4
δ=3
δ=2
δ=1
HIDDEN DIMENSIONS
Anomaly Mediation
RS I
AdS
orbifold
RS II
Scherk-Schwarz
DARK MATTER
NOT YET THOUGHT OF
NOT YET THOUGHT OF

BSM ideas

New Physics beyond the SM



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	? ? ?							

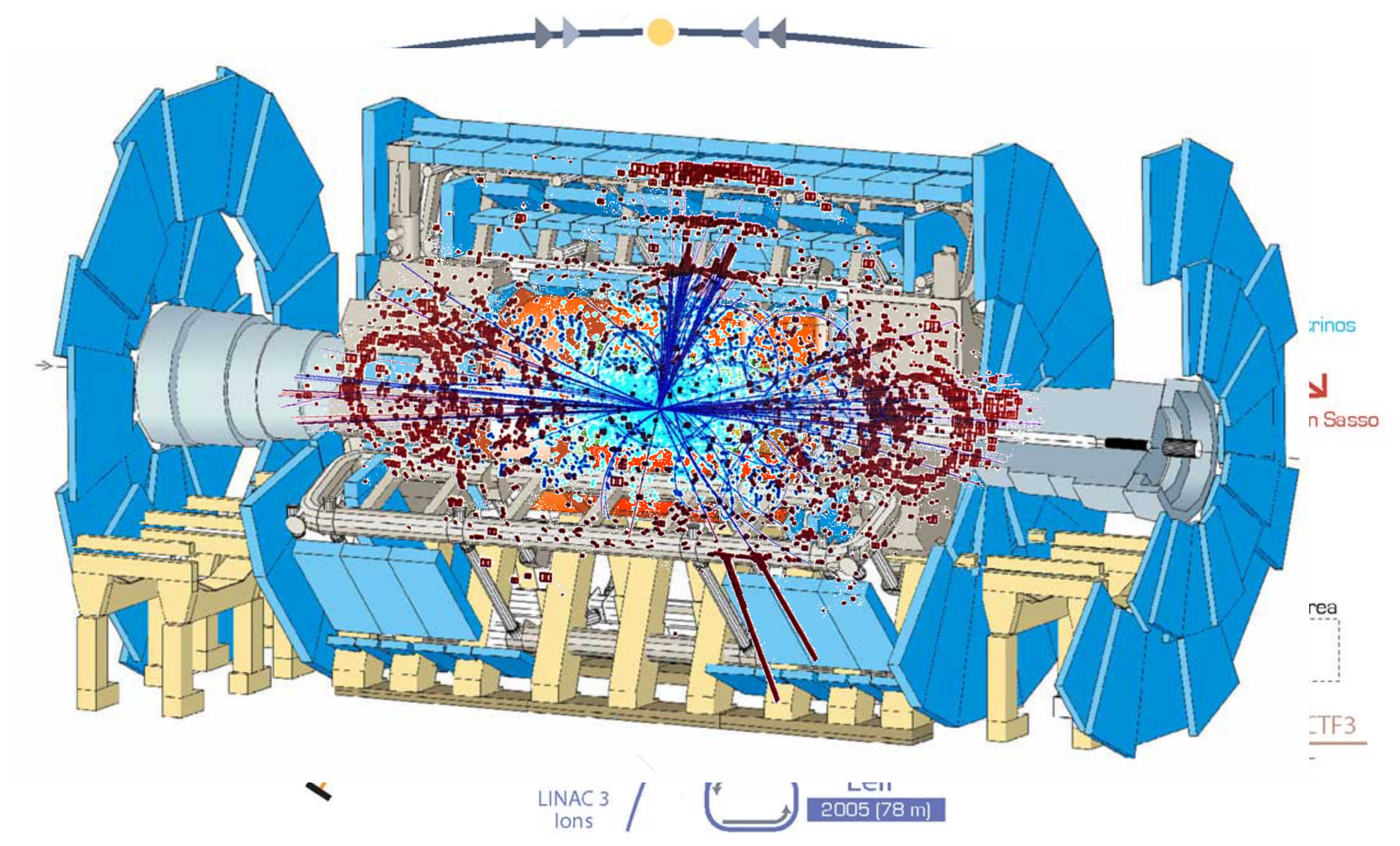
Snowmass new physics working group report

LHC & ATLAS/CMS detectors

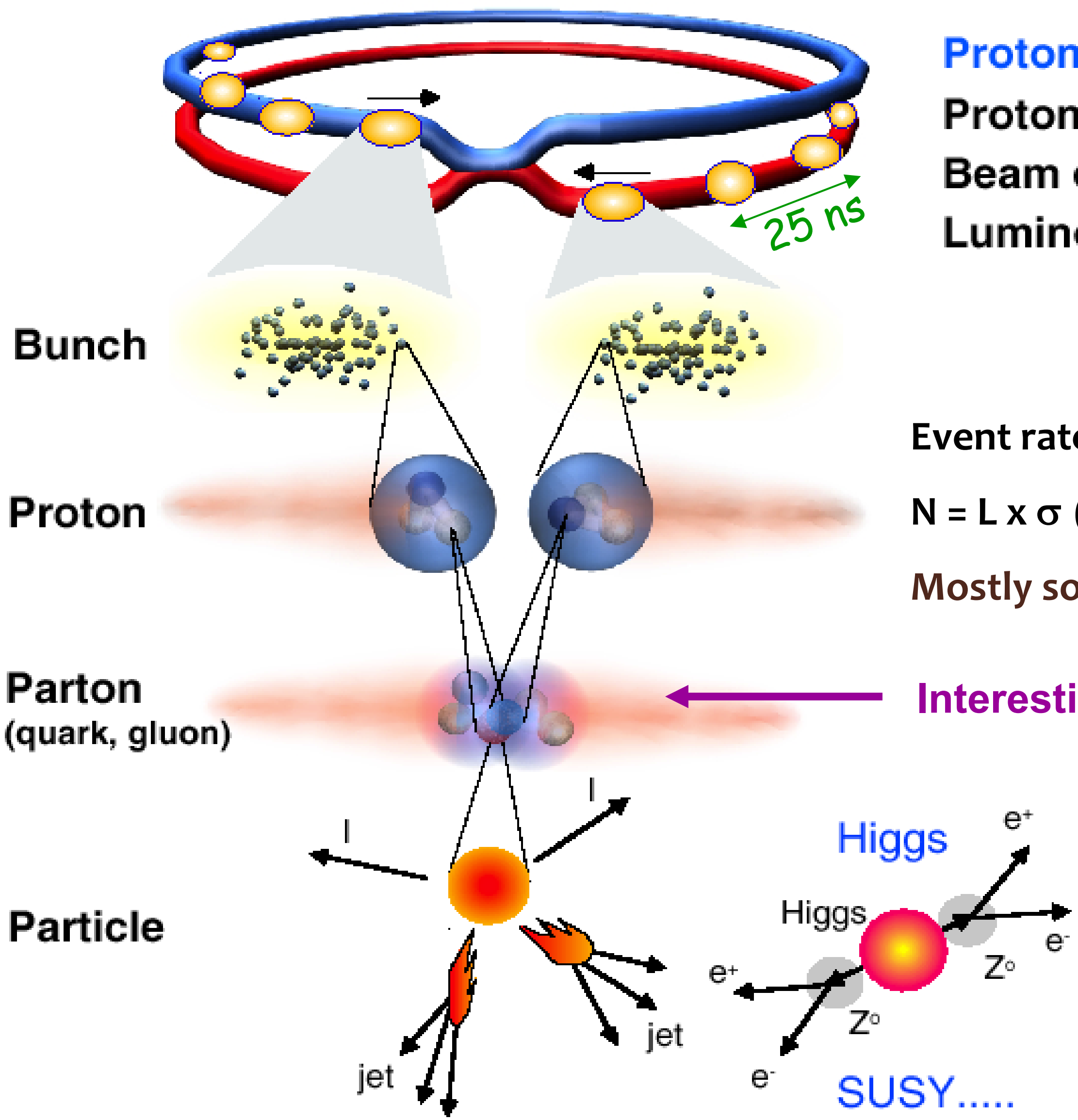
LHC 大型强子对撞机

- 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 ($7x10^{12}$ eV)
Luminosity	10^{34} cm^{-2} s^{-1}

Event rate:

N = L x σ (pp) ≈ 10^9 interactions/s

Mostly soft (low p_T) events

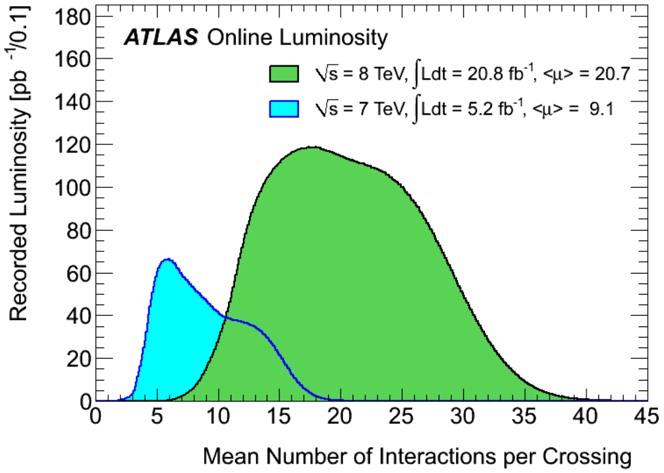
Interesting hard (high-p_T) events are rare

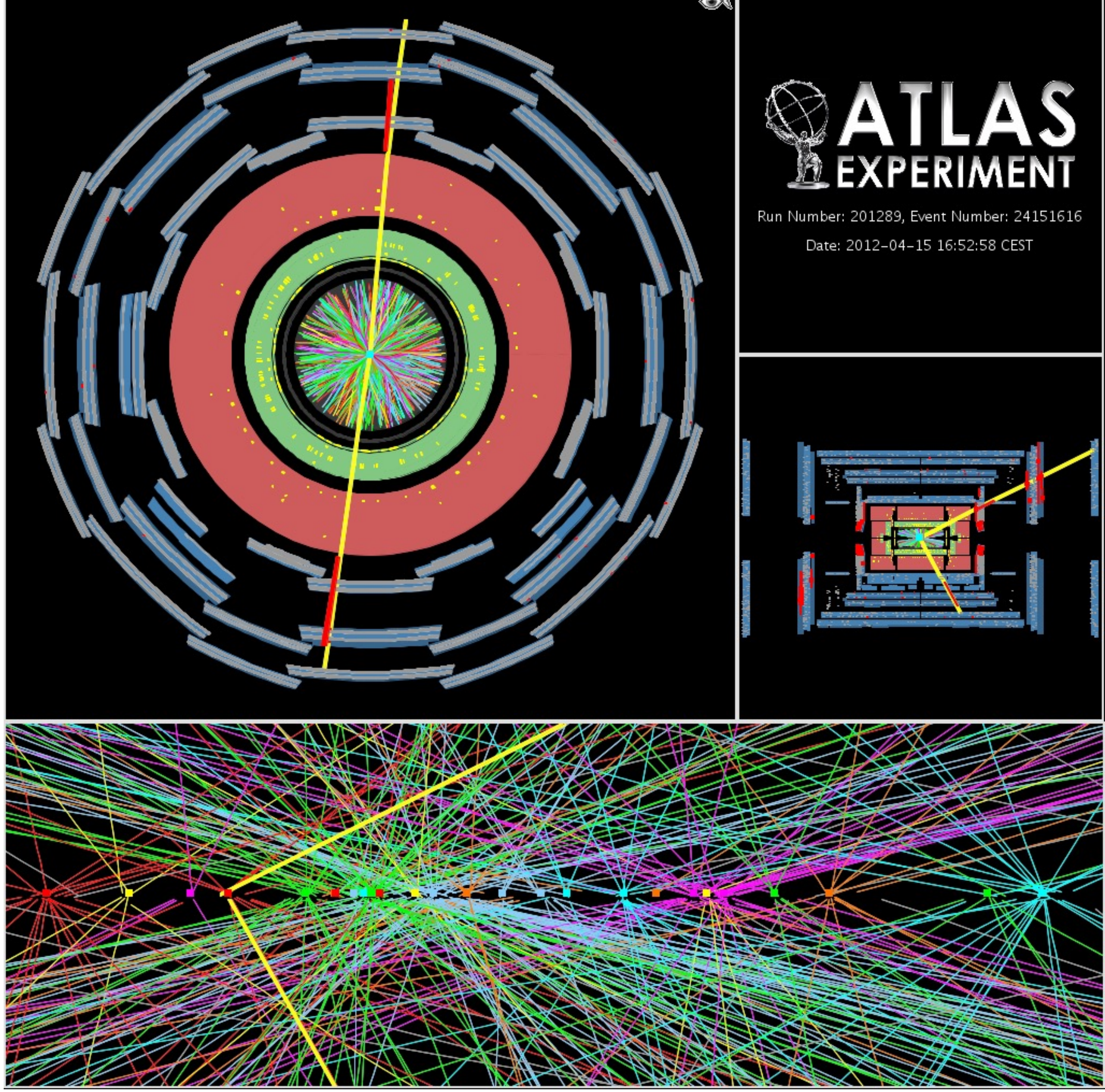
Selection of 1 in 10,000,000,000,000

→ **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

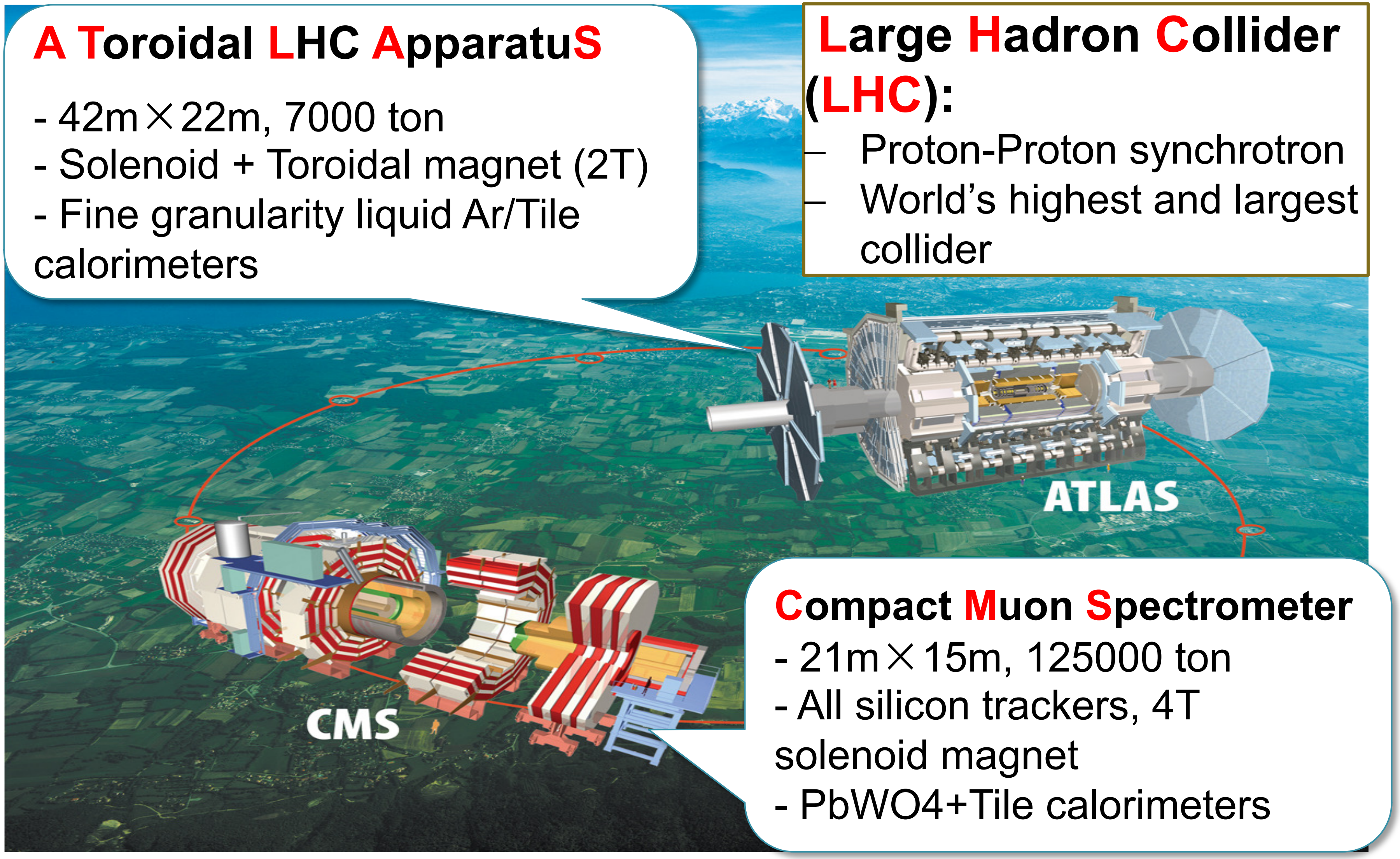




Inner Detector for a Z → μμ event with 25 primary vertices

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

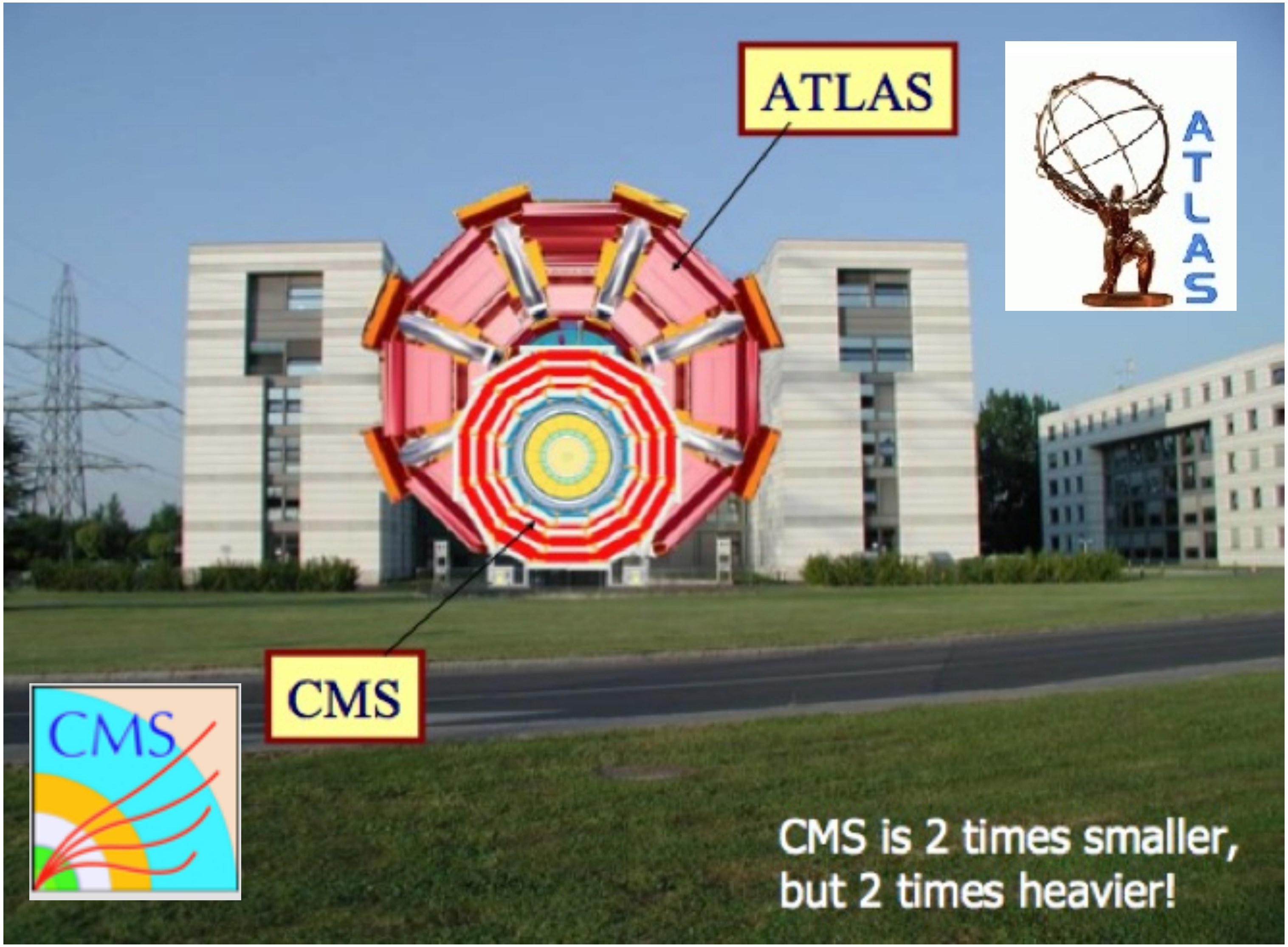
Large Hadron Collider (LHC):

- 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



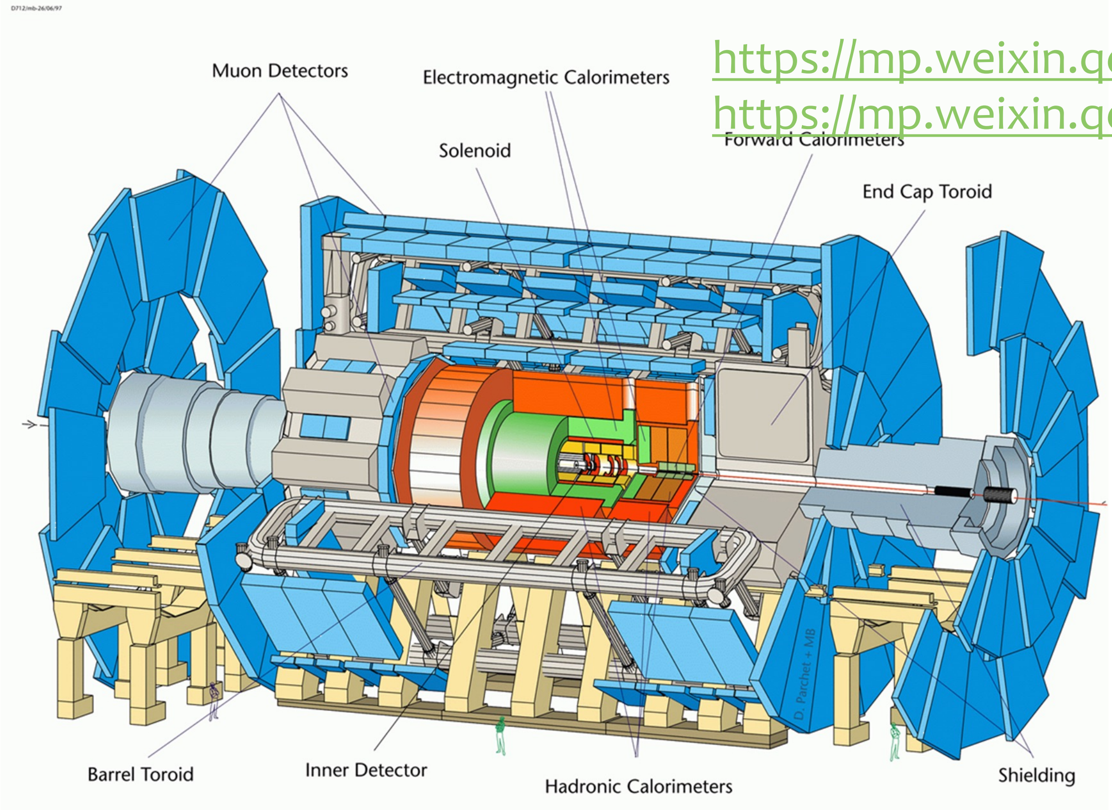
CMS is 2 times smaller,
but 2 times heavier!

https://mp.weixin.qq.com/s/_UtuSypTu1Dl1lnDuo6VTw
https://mp.weixin.qq.com/s/cJ6J3M-y36qNMicy7-jVQw

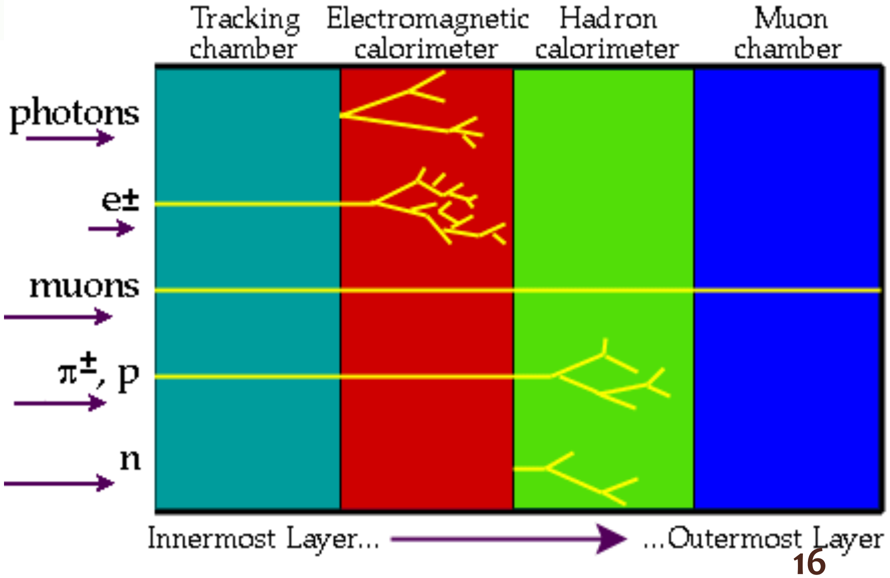
ATLAS

A Toroidal LHC ApparatuS

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~ 10^8 electronic channels
~ 3000 km of cables

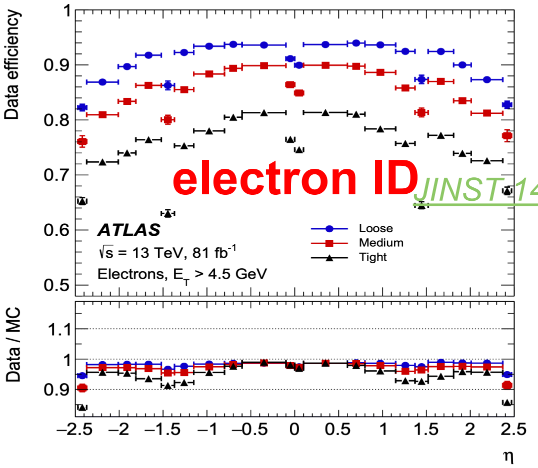


- **Tracking ($|\eta|<2.5$, B=2T) :**
  - **Si pixels and strips**
  - **Transition Radiation Detector (e/π separation)**
- **Calorimetry ($|\eta|<5$) :**
  - **EM : Pb-LAr**
  - **HAD: Fe/scintillator (central), Cu/W-LAr (fwd)**
- **Muon Spectrometer ($|\eta|<2.7$) :**
  - **air-core toroids with muon chambers**



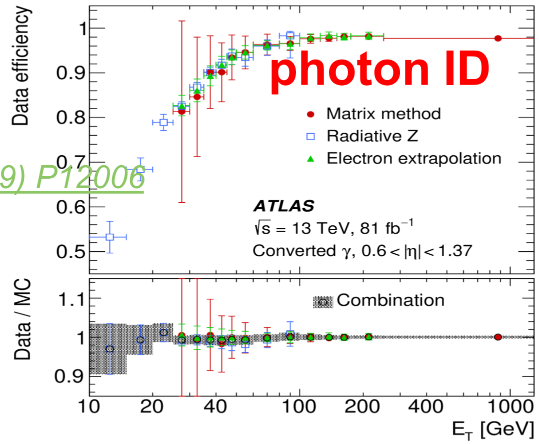
Excellent detector performance

- Thanks excellent understanding of detector performance, and development of rec. and ID algorithms
- **Precision object performance :** el-ID<1% (pt~30-250GeV), mu-ID<0.1% (pt~10-150 GeV), JES unc. ~1% (pt~100-1000GeV)

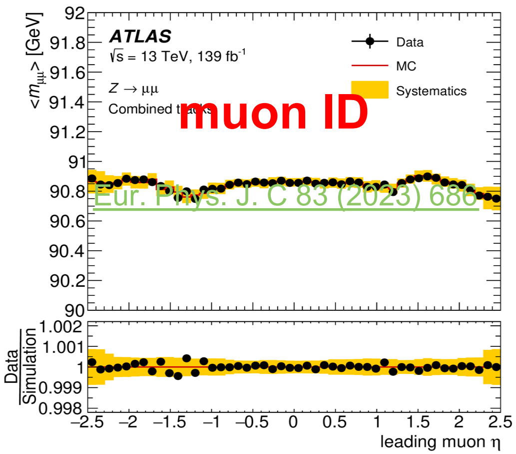


electron ID

JINST 14 (2019) P12006

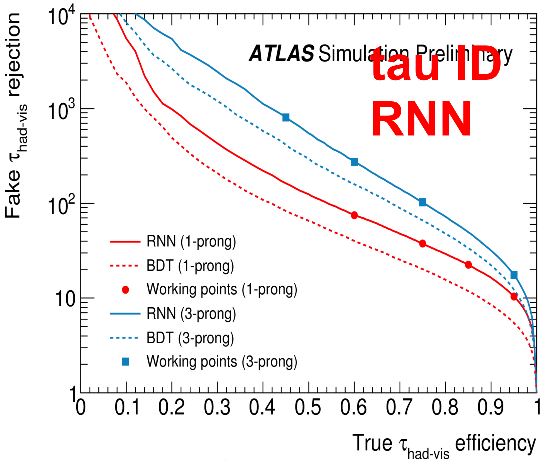


photon ID



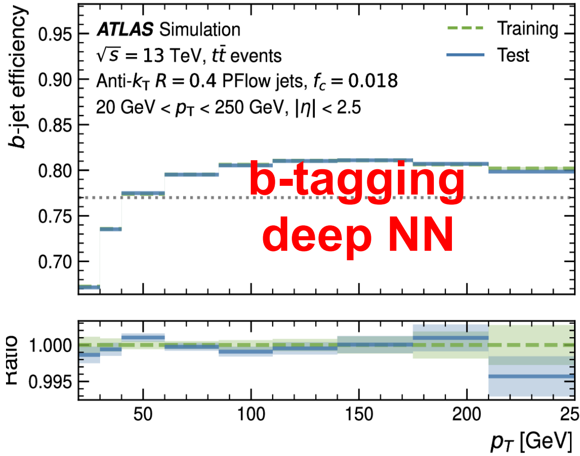
muon ID

Eur. Phys. J. C 83 (2023) 686



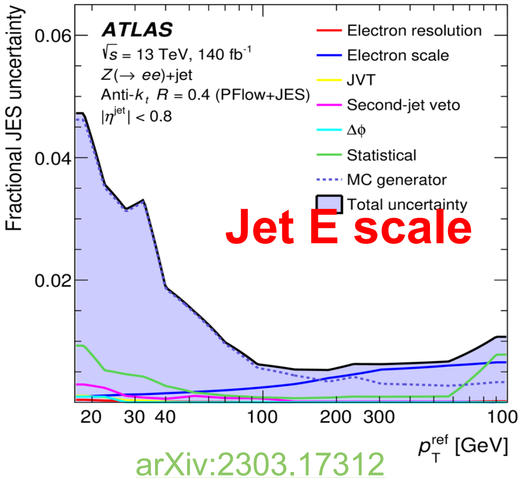
tau ID RNN

ATL-PHYS-PUB-2019-033



b-tagging deep NN

Eur. Phys. J. C 83 (2023) 681



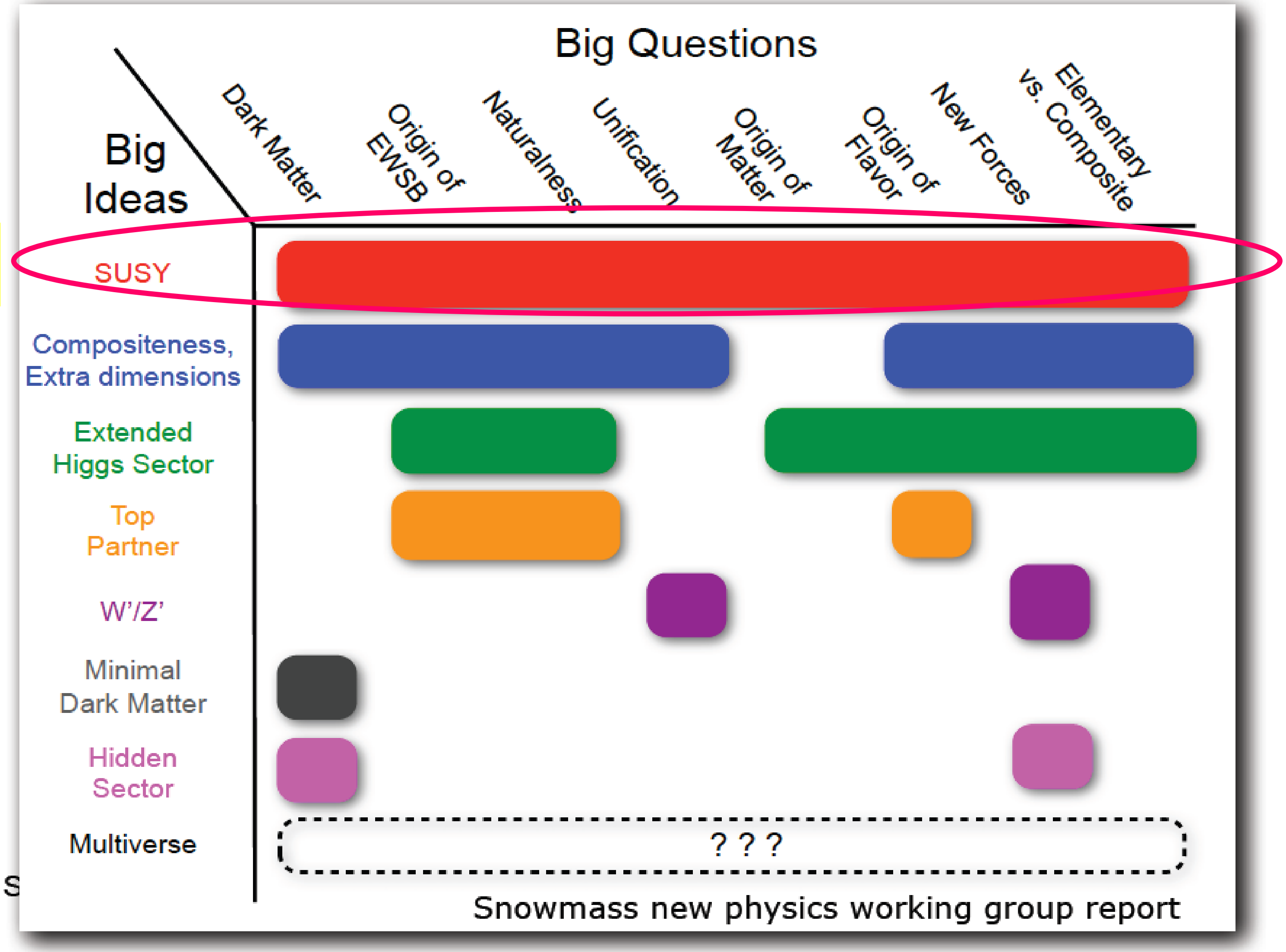
Jet E scale

arXiv:2303.17312

BSM Searches @ LHC

New Physics beyond the SM

SUSY

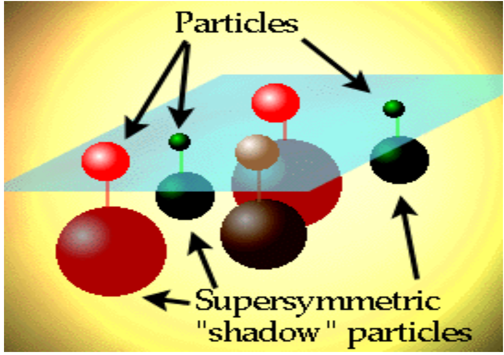


Snowmass new physics working group report

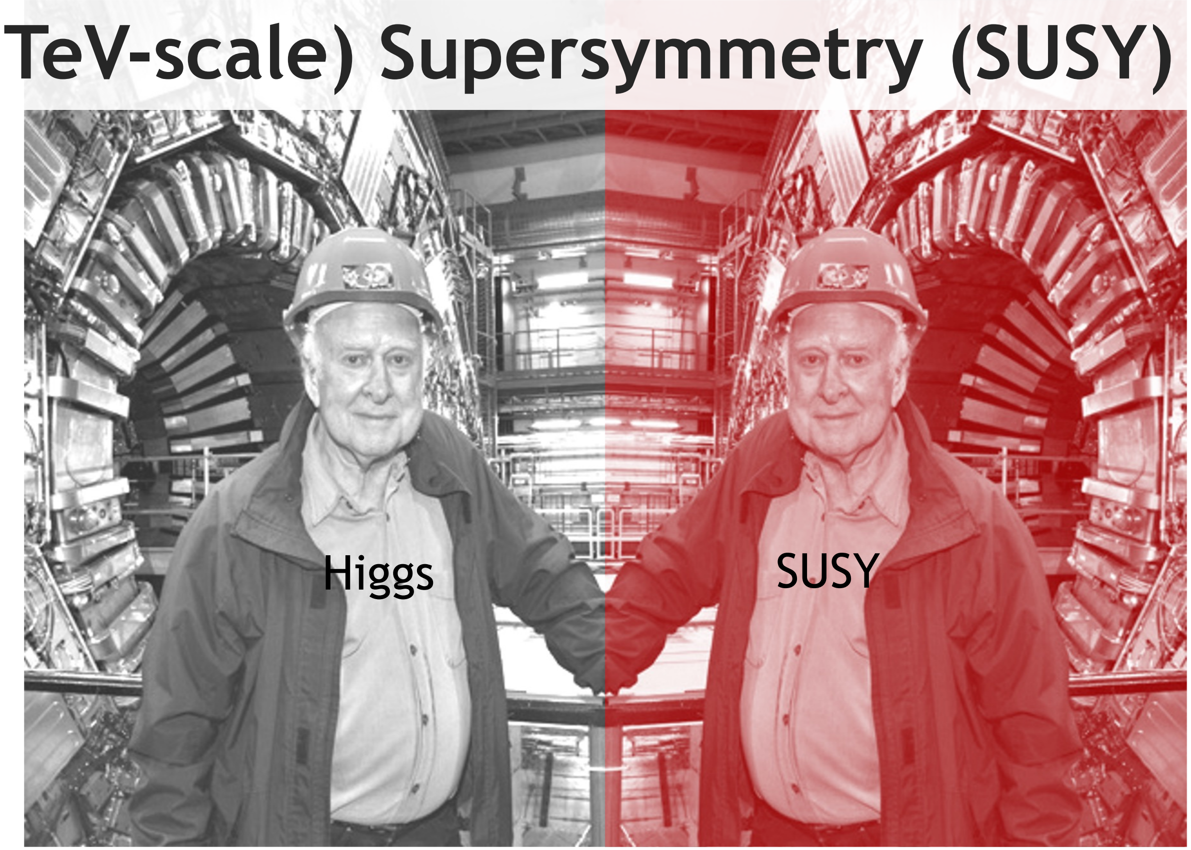
S. S

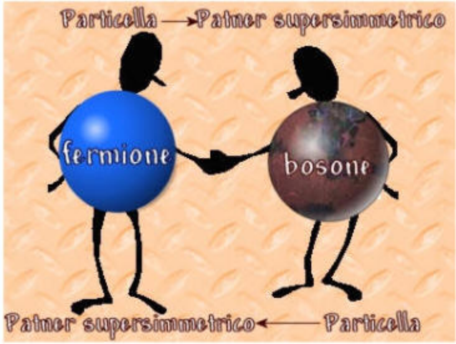
What is SUSY?

How SUSY do help?

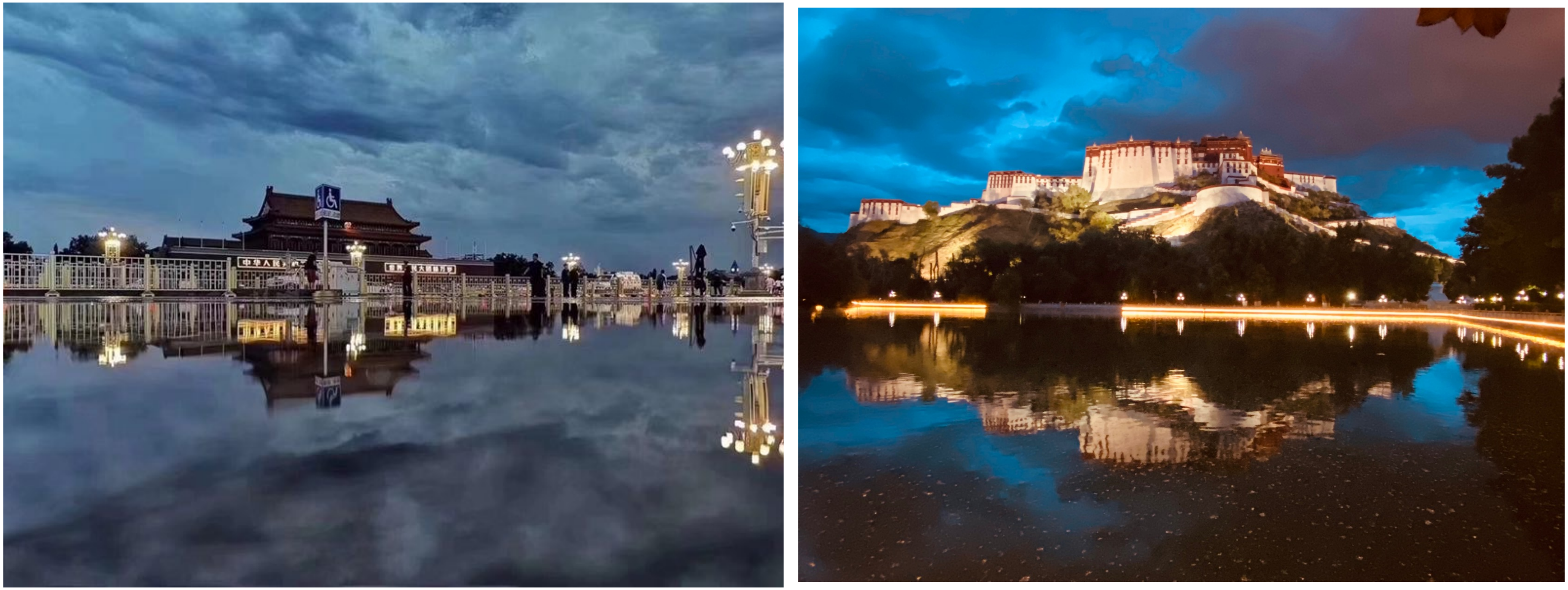


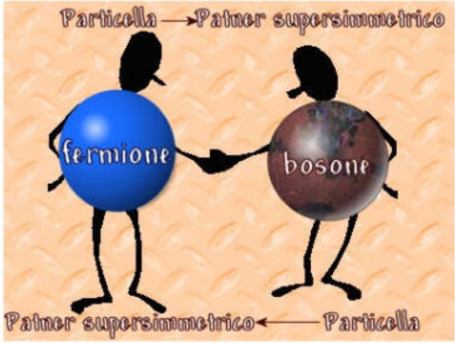
(TeV-scale) Supersymmetry (SUSY)



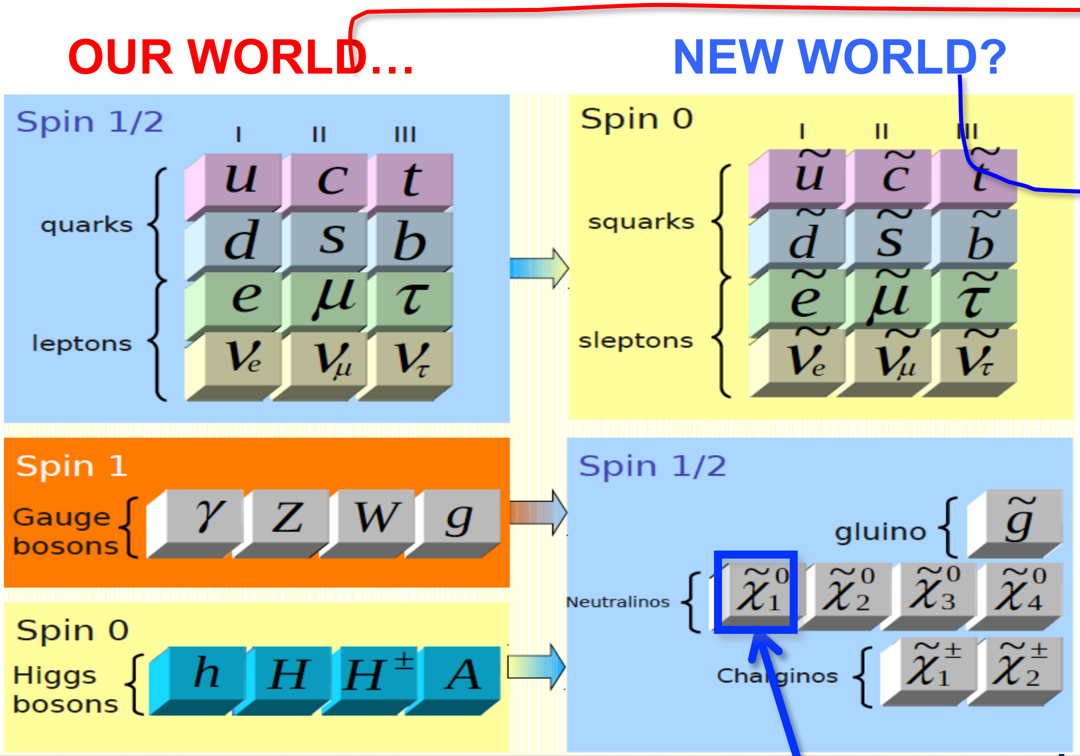


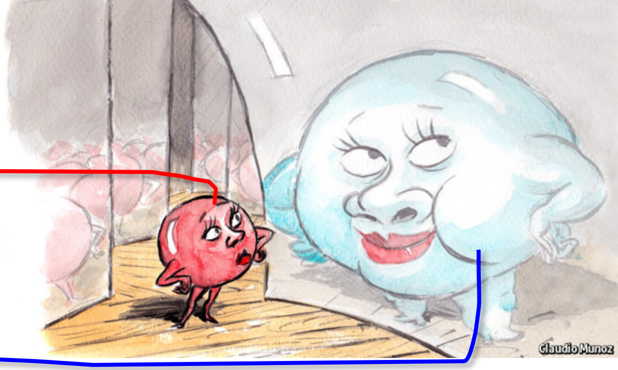
P. Higgs at CMS



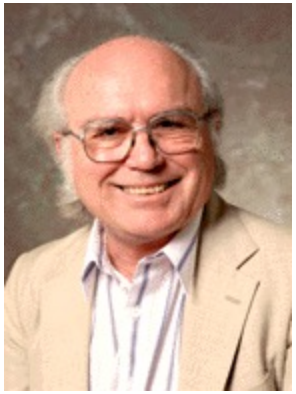

Particella → Patner supersimmetrico
fermione
bosone
Patner supersimmetrico ← Particella

SUSY Introduction





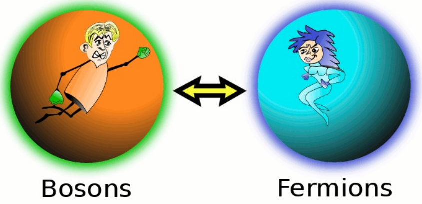
Julius Wess
(1934 – 2007)



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>

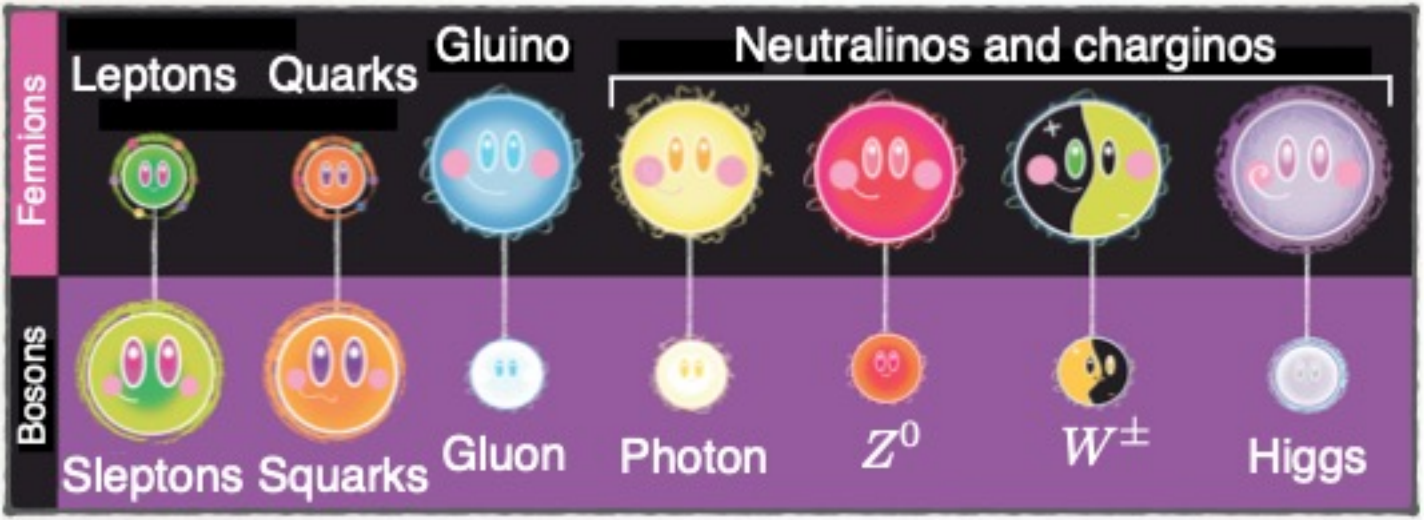
Spin differ by 1/2

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**		

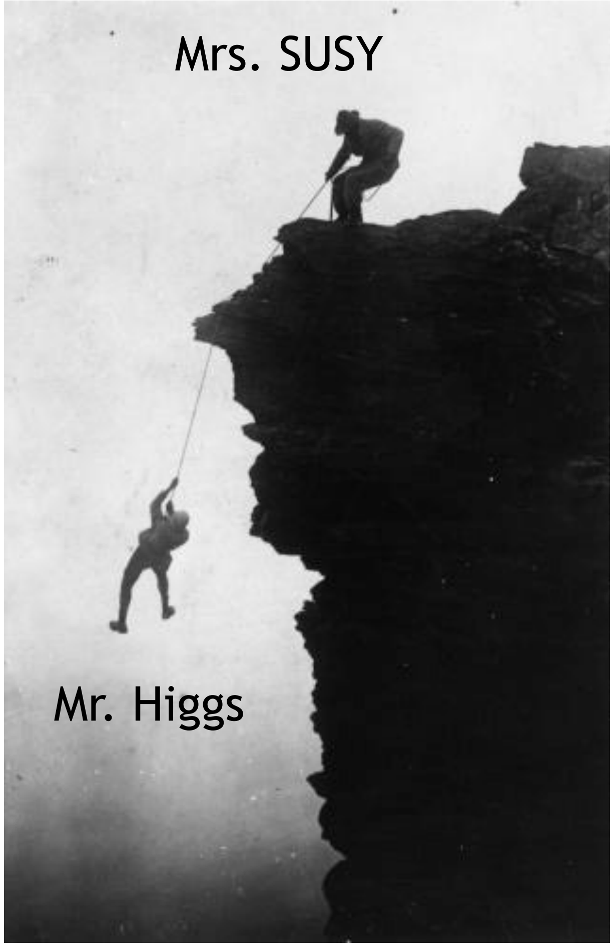
Minimal Supersymmetric Standard Model

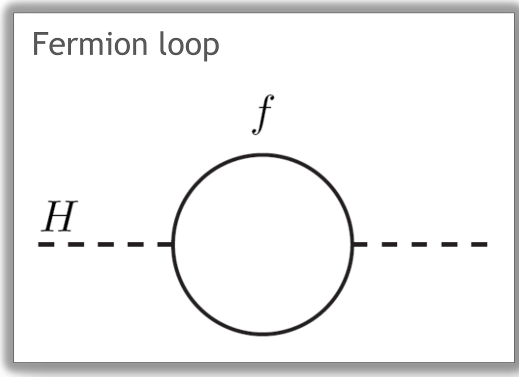
Standard Model Particles and Fields		Supersymmetric Partners			
		Interaction Eigenstates		Mass Eigenstates	
Symbol	**Name**	**Symbol**	**Name**	**Symbol**	**Name**
$q = u, a$					**quark**
$l =$					**epton**
$l = \nu$					**eutrino**
					luino
W					
H_u^+					**argino**
B	B-field	$\widetilde{B}$	**bino**	$\widetilde{\chi}^0_{1,2,3,4}$	**neutralino**
W^0	W0-field	$\widetilde{W}^0$	**wino**		
H_u^0, H_d^0	neutral Higgs boson	$\widetilde{H}_u^0, \widetilde{H}_d^0$	**neutral higgsino**		

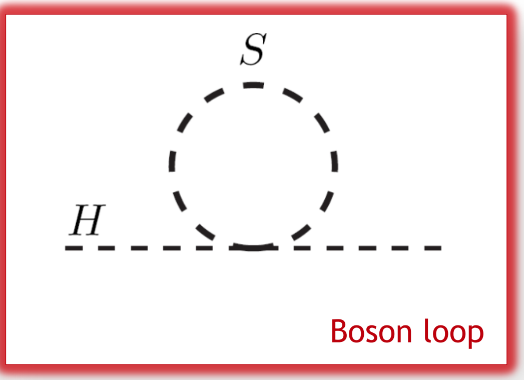


SUSY Introduction

- **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

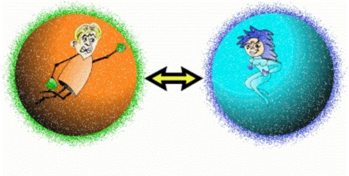




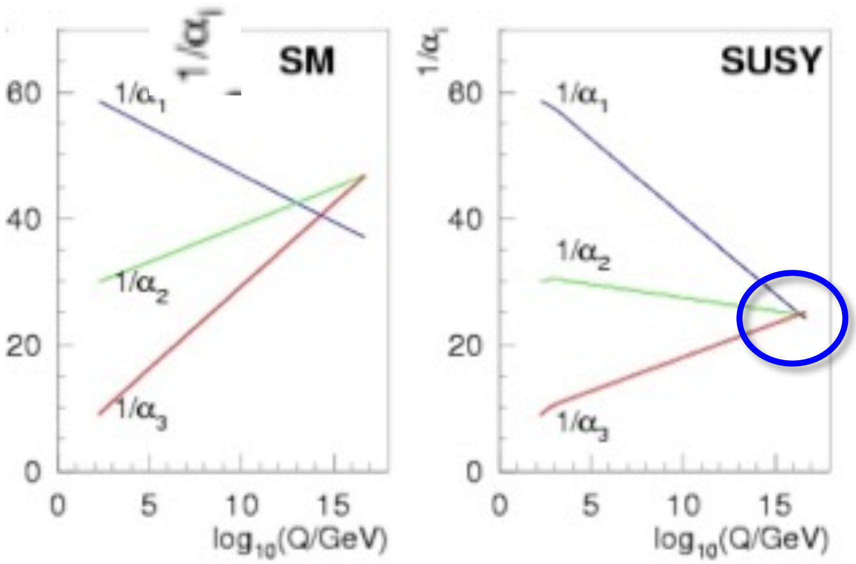


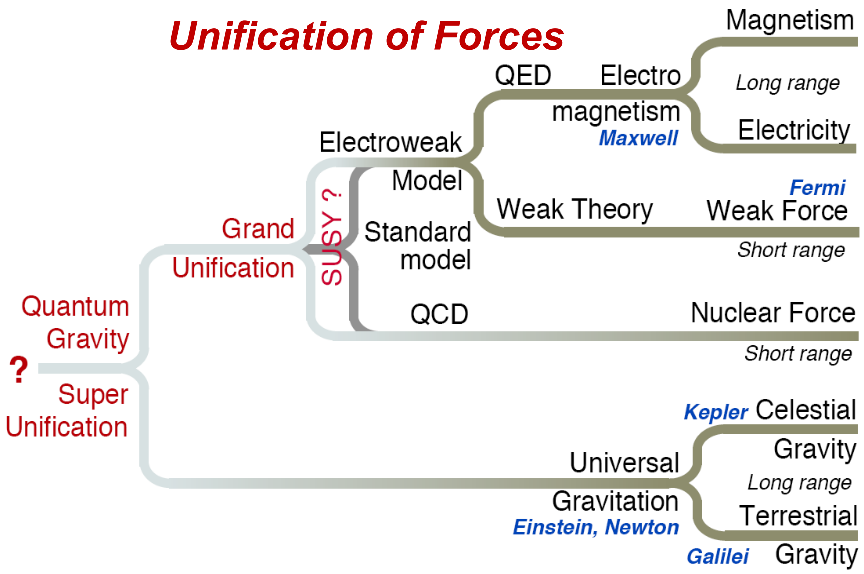
$$M_h^2 = M_{h,tree}^2 + \Delta M_h; \qquad SM: \Delta M_h \sim \Lambda^2; \qquad SUSY: \Delta M_h \sim m_{soft}^2 \log(\Lambda / m_{soft})$$

SUSY Introduction



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



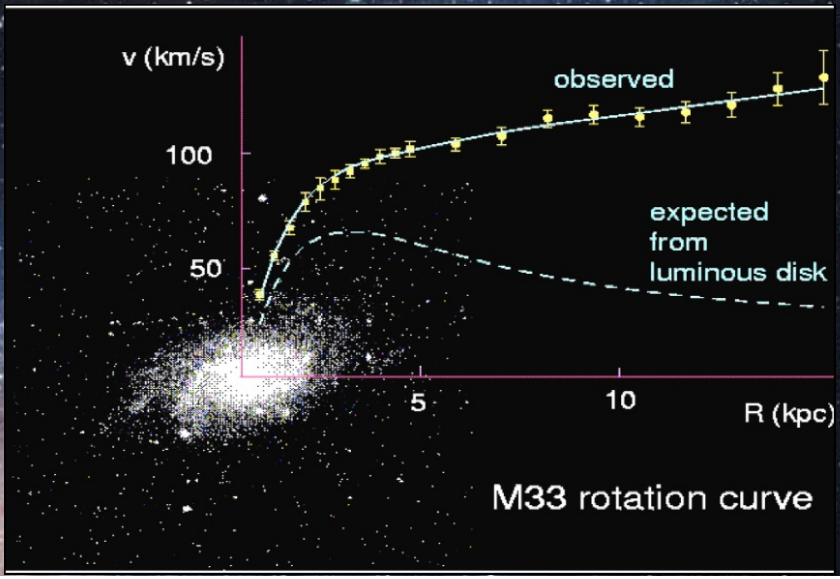


Unification of Forces

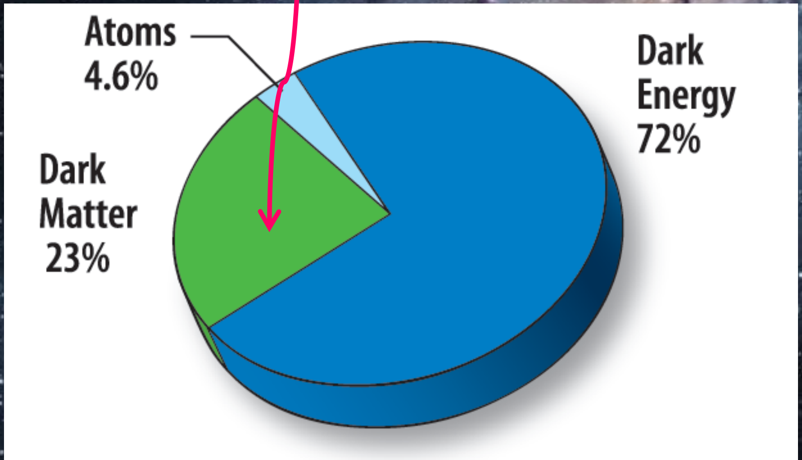
Magnetism
Long range
Electricity
QED Electro magnetism
Maxwell
Electroweak
Model
Weak Theory
Fermi
Weak Force
Short range
Grand Unification
SUSY ?
Standard model
QCD
Nuclear Force
Short range
Quantum Gravity
?
Super Unification
Kepler Celestial Gravity
Long range
Universal Gravitation
Einstein, Newton
Terrestrial
Galilei Gravity

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

How to hunt SUSY?

(TeV-scale) Supersymmetry (SUSY)

P. Higgs at CMS

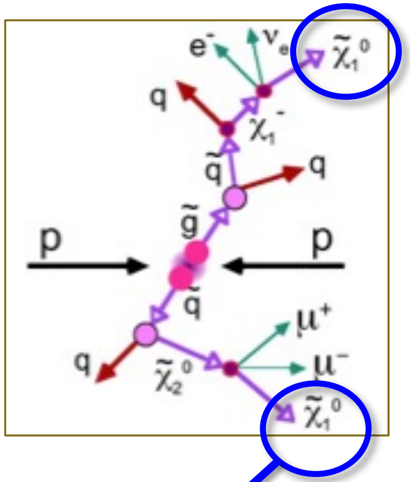
How do we start? - SUSY Signature

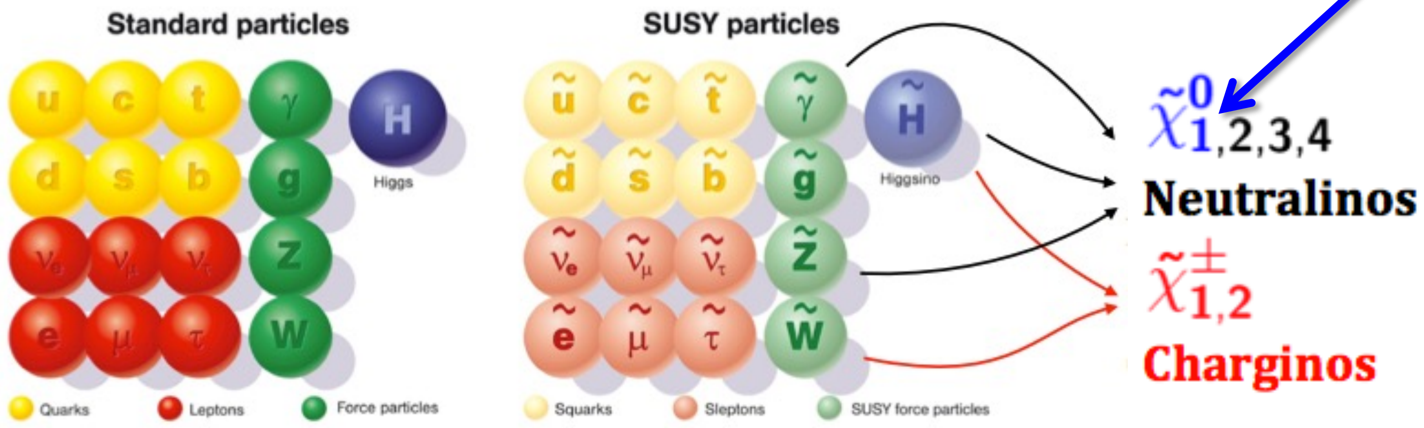
- **Conserved R parity** (originally introduced for stability of proton)

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

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)**

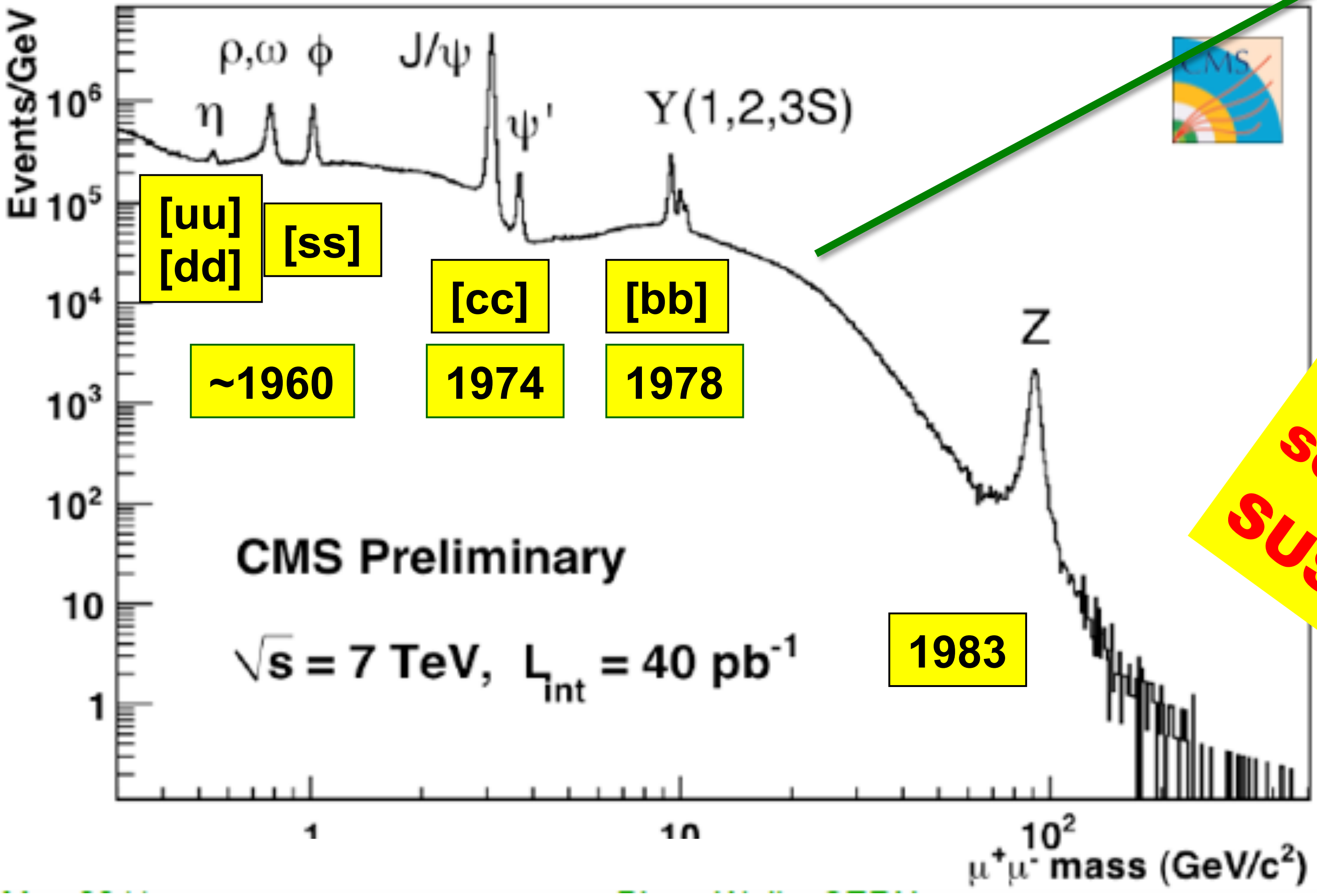




How do we search for SUSY?

Not like general particles with peak in mass spectrum ☹

2010



[uu]
[dd]

[ss]

[cc]

[bb]

~1960

1974

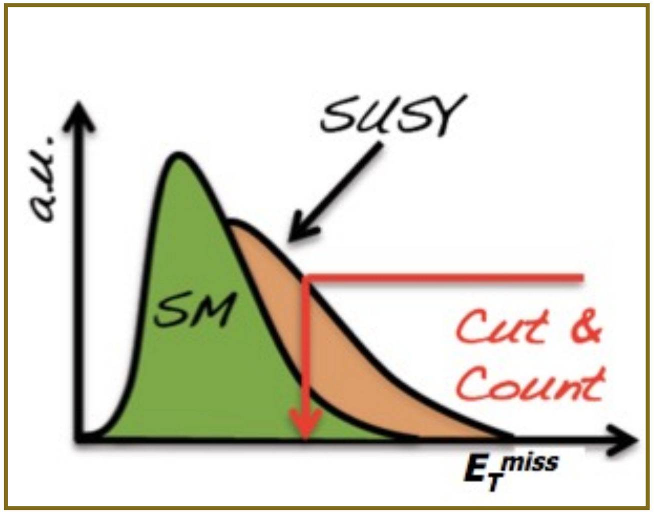
1978

1983

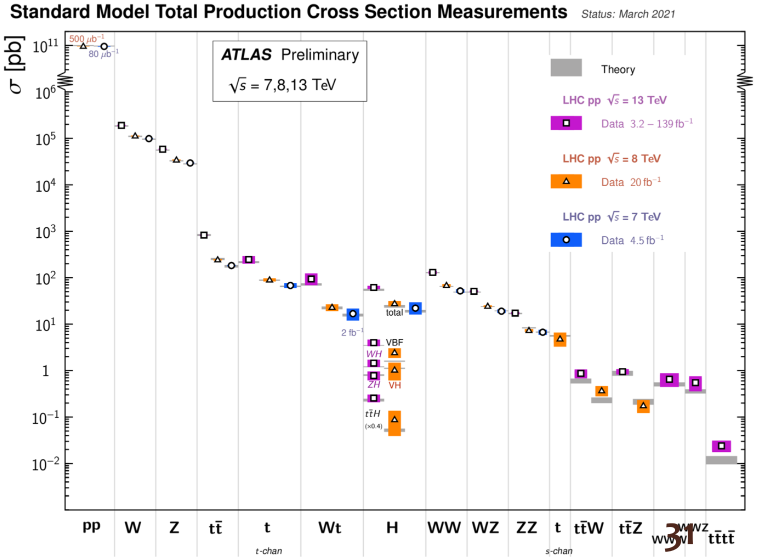
How do we search for SUSY?

How do we search for SUSY?

- **SUSY search strategy:** search for deviation from SM 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.

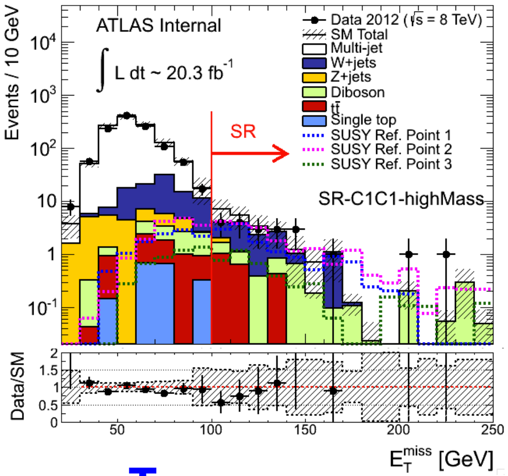


SM "backgrounds"– the big picture

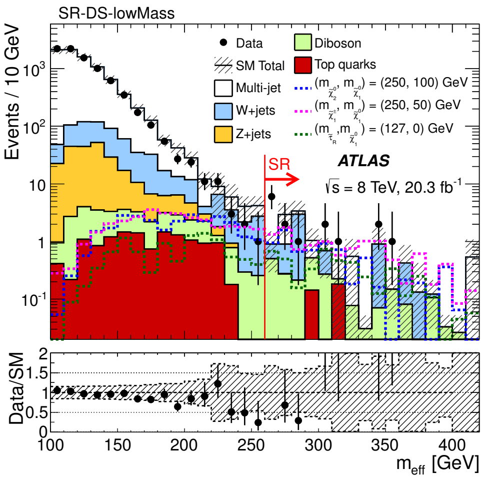


SUSY Sensitive Variables

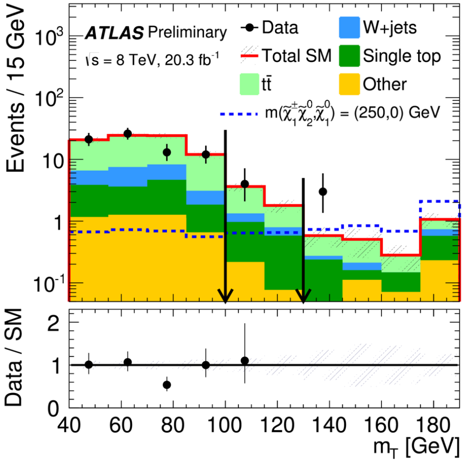
E_T^{miss}



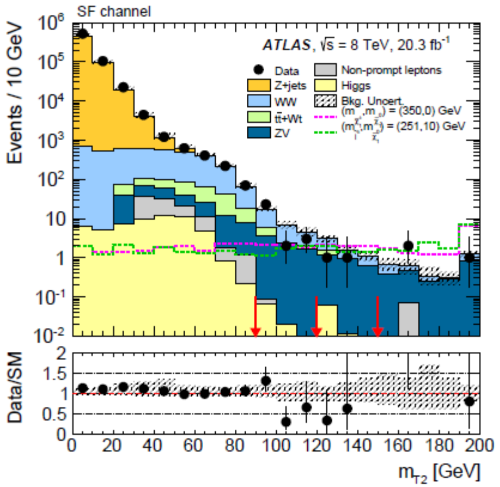
M_{eff}



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}**)

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

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

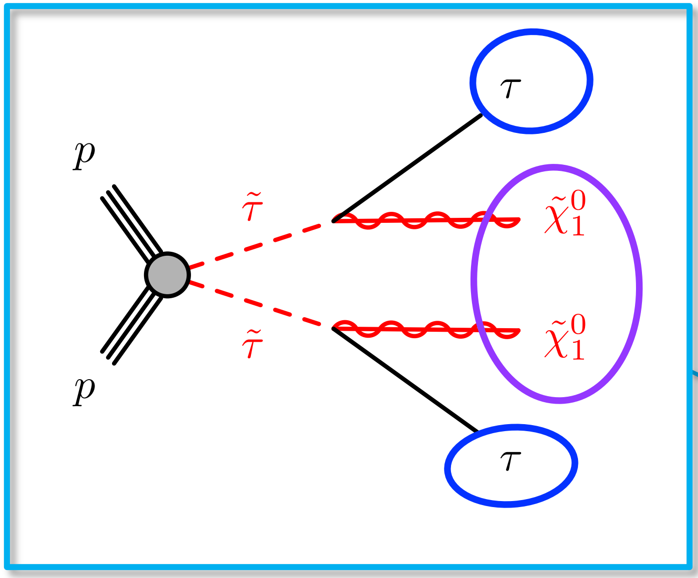
$$m_{T2} = \min_{\mathbf{q}_T}\left[\max\left(m_T(\mathbf{p}_T^{\ell 1},\mathbf{q}_T), m_T(\mathbf{p}_T^{\ell 2},\mathbf{p}_T^{\text{miss}} - \mathbf{q}_T)\right)\right]$$

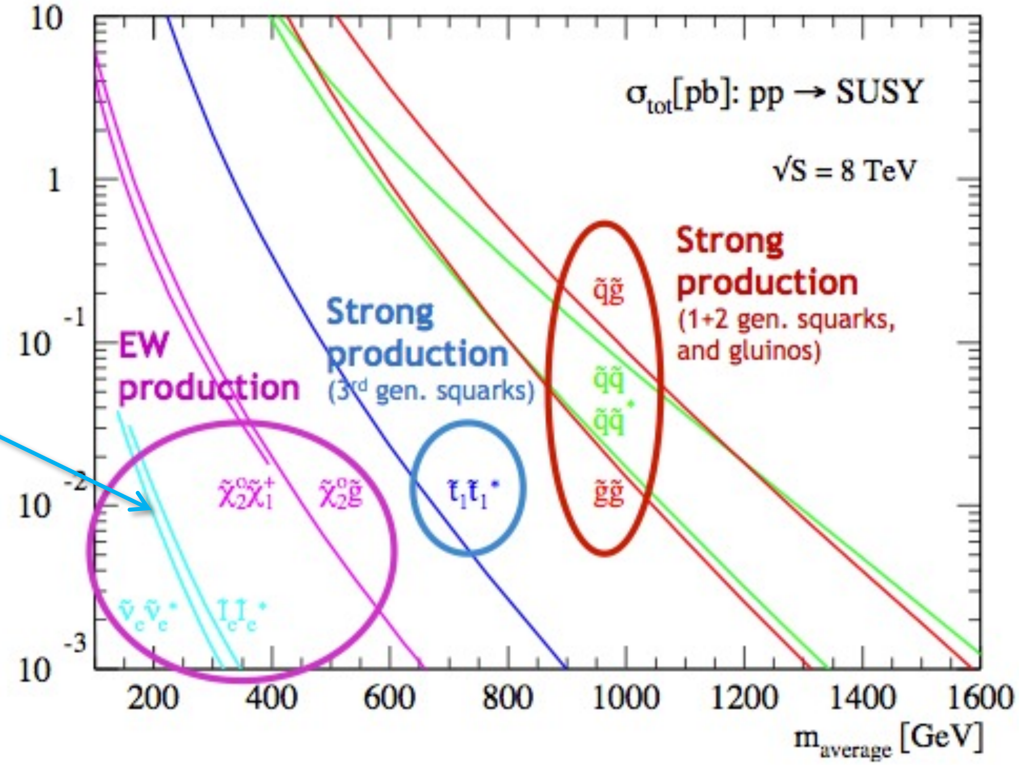
- Many others …

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



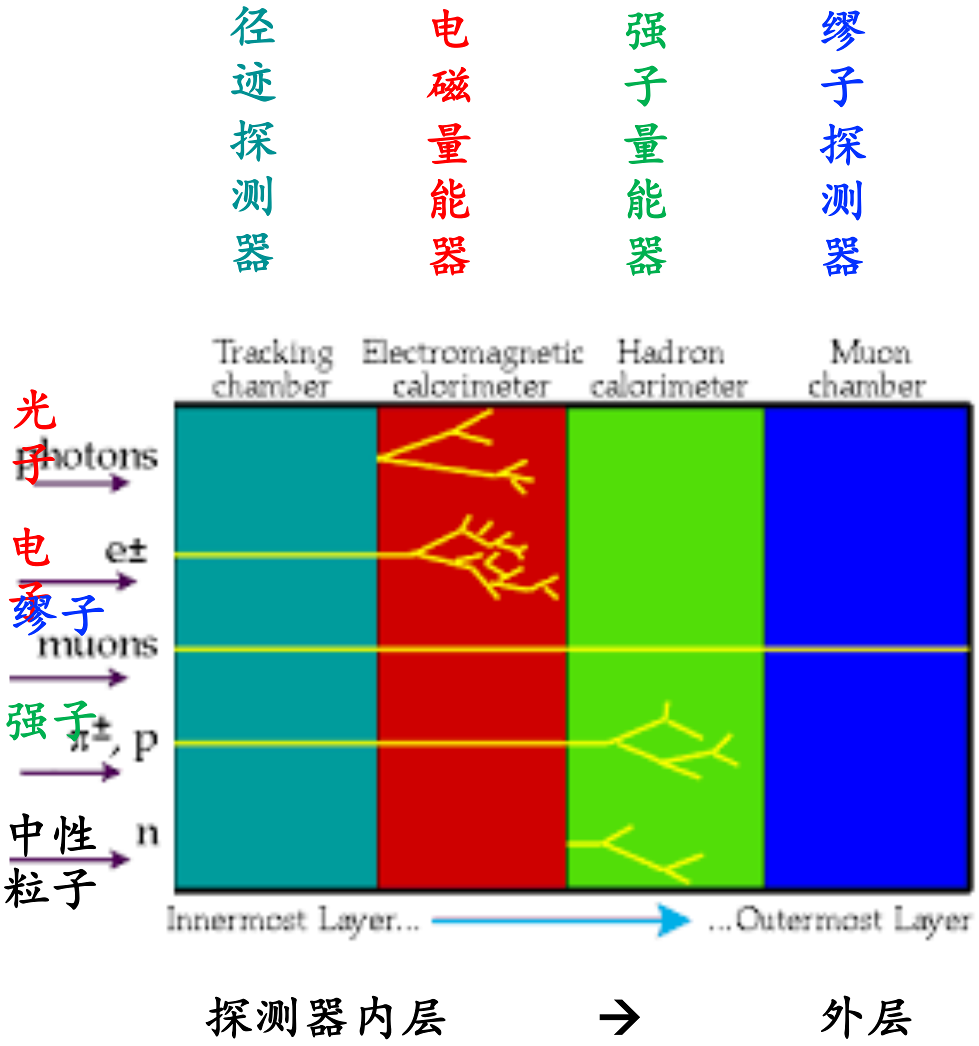


Final states:

2 tau + large E_T^{miss}

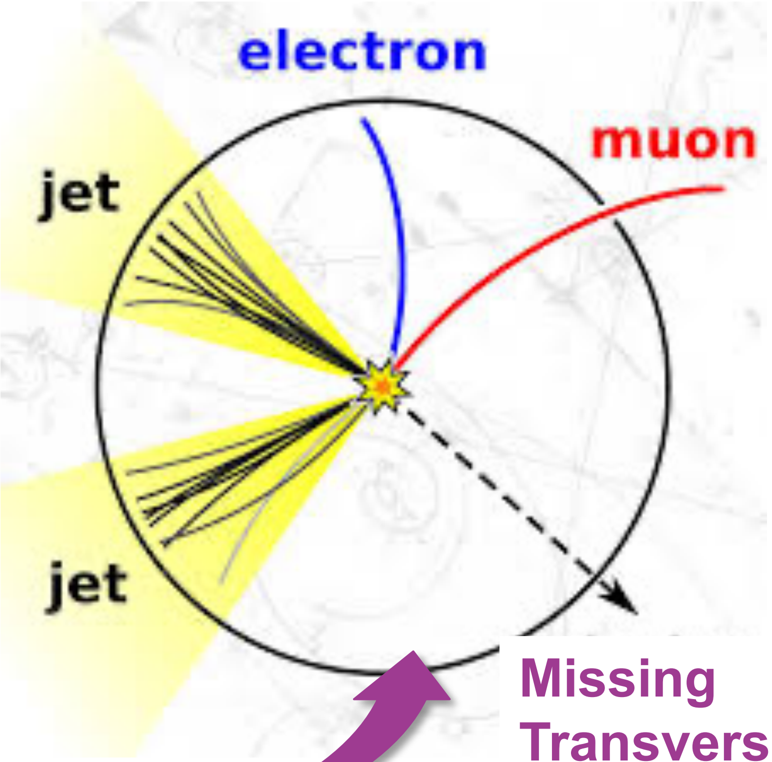
2: Pre-selection Reconstructed Objects

- 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

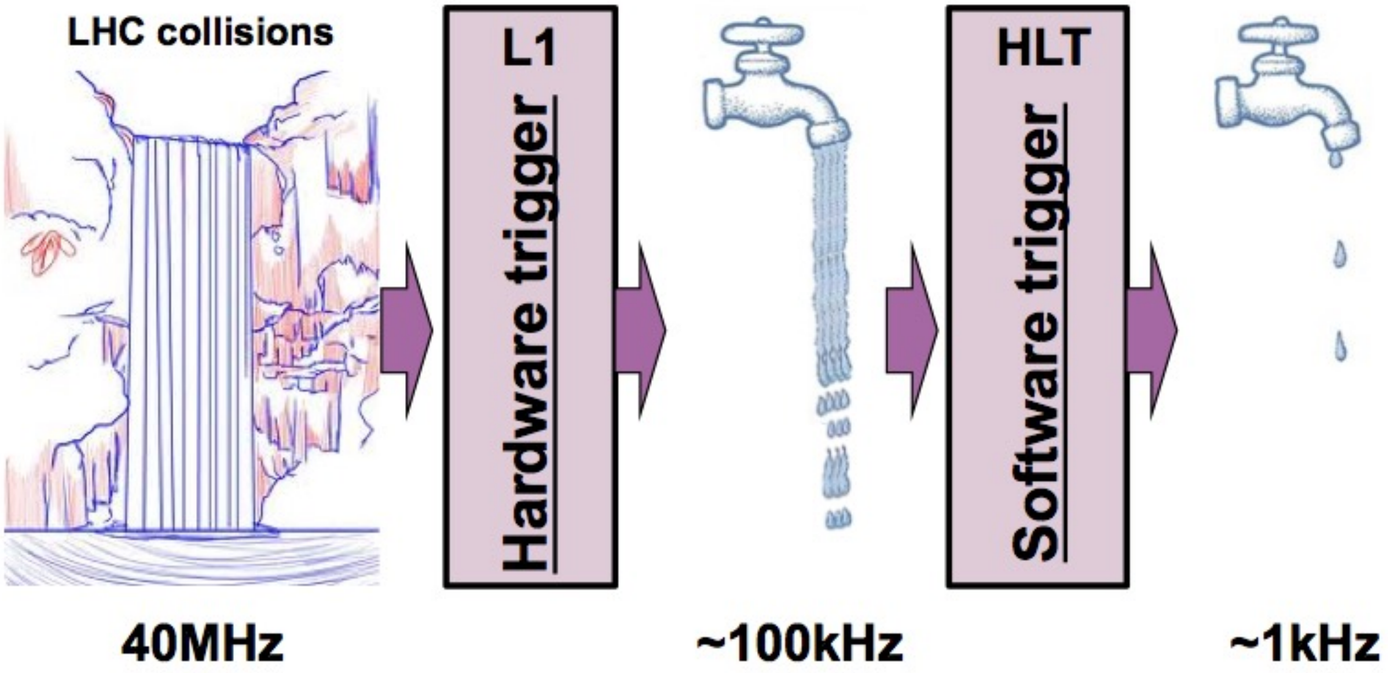
- At the LHC an unknown proportion of the energy of the colliding protons escapes down the beam-pipe
- Invisible particles (neutrinos, neutralinos?) are created their momentum can be constrained in **the plane transverse to the beam direction**



Missing Transverse Energy

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

Triggering on Physics



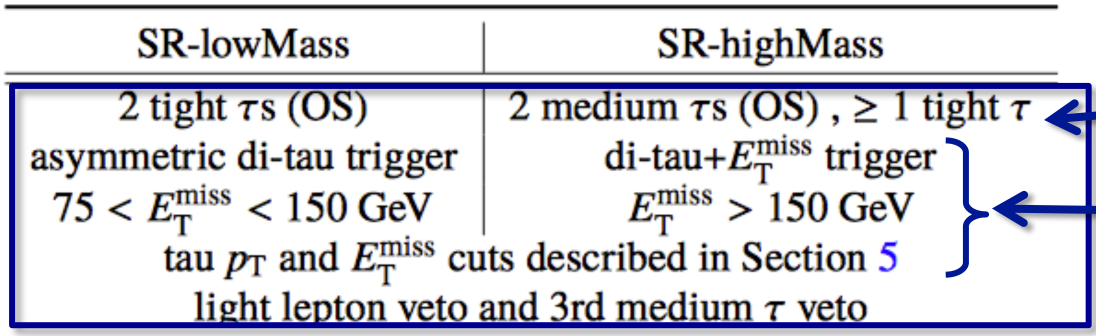
- Apply trigger depending on analysis
- Only pick up what we are interested events
- 2tau or 2tau+MissingET trigger used here

Final states: 2 tau + large E_T^{miss}

ATLAS-CONF-2019-018

3: SR definition and optimization

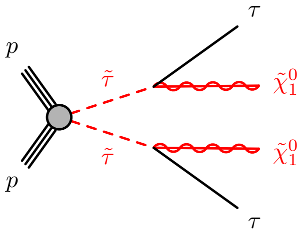
Table 1: Summary of selection requirements for the signal regions.



SR-lowMass	SR-highMass
2 tight τs (OS)	2 medium τs (OS) , $\geq$ 1 tight τ
asymmetric di-tau trigger	di-tau+$E_{\mathrm{T}}^{\mathrm{miss}}$ trigger
$75 < E_{\mathrm{T}}^{\mathrm{miss}} < 150$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV
tau p_{T} and $E_{\mathrm{T}}^{\mathrm{miss}}$ cuts described in Section 5	
light lepton veto and 3rd medium τ veto	

taus

Trigger

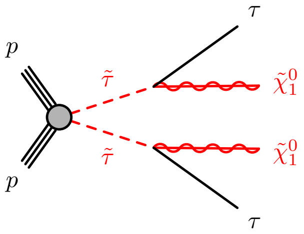


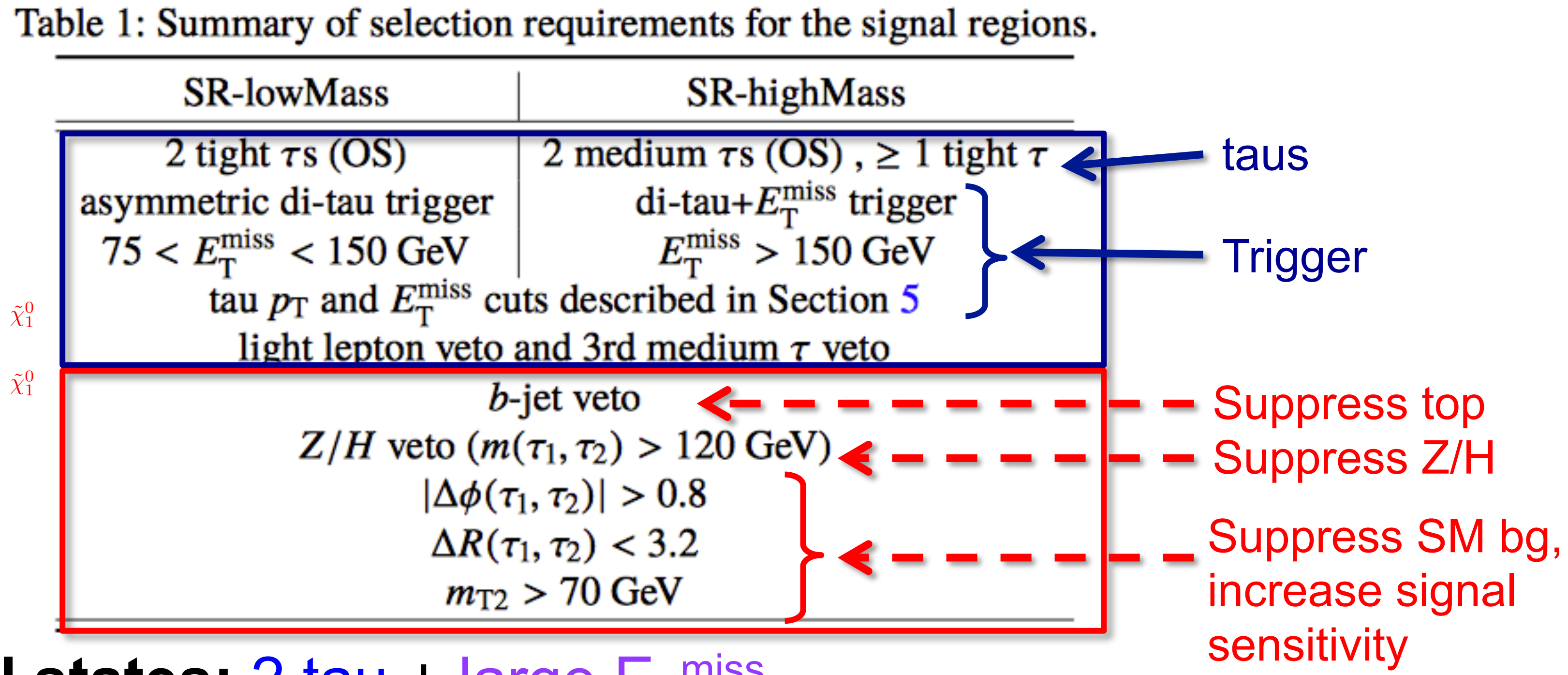
Final states: 2 tau + large E_T^{miss}

- According to signal signature, select interested final states objects: tau and MET requirement

ATLAS-CONF-2019-018

3: SR definition and optimization





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2 tight τs (OS)	2 medium τs (OS) , $\geq$ 1 tight τ
asymmetric di-tau trigger	di-tau+E_T^{miss} trigger
$75 < E_T^{miss} < 150$ GeV	$E_T^{miss} > 150$ GeV
tau p_T and E_T^{miss} cuts described in Section 5	
light lepton veto and 3rd medium τ veto	
b-jet veto	
Z/H veto ($m(\tau_1, \tau_2) > 120$ GeV)	
$\lvert\Delta\phi(\tau_1, \tau_2)\rvert > 0.8$	
$\Delta R(\tau_1, \tau_2) < 3.2$	
$m_{T2} > 70$ GeV	

taus

Trigger

Suppress top

Suppress Z/H

Suppress SM bg, increase signal sensitivity

Final states: 2 tau + large E_T^{miss}

- According to signal signature, select interested final states objects: tau and MET requirement

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

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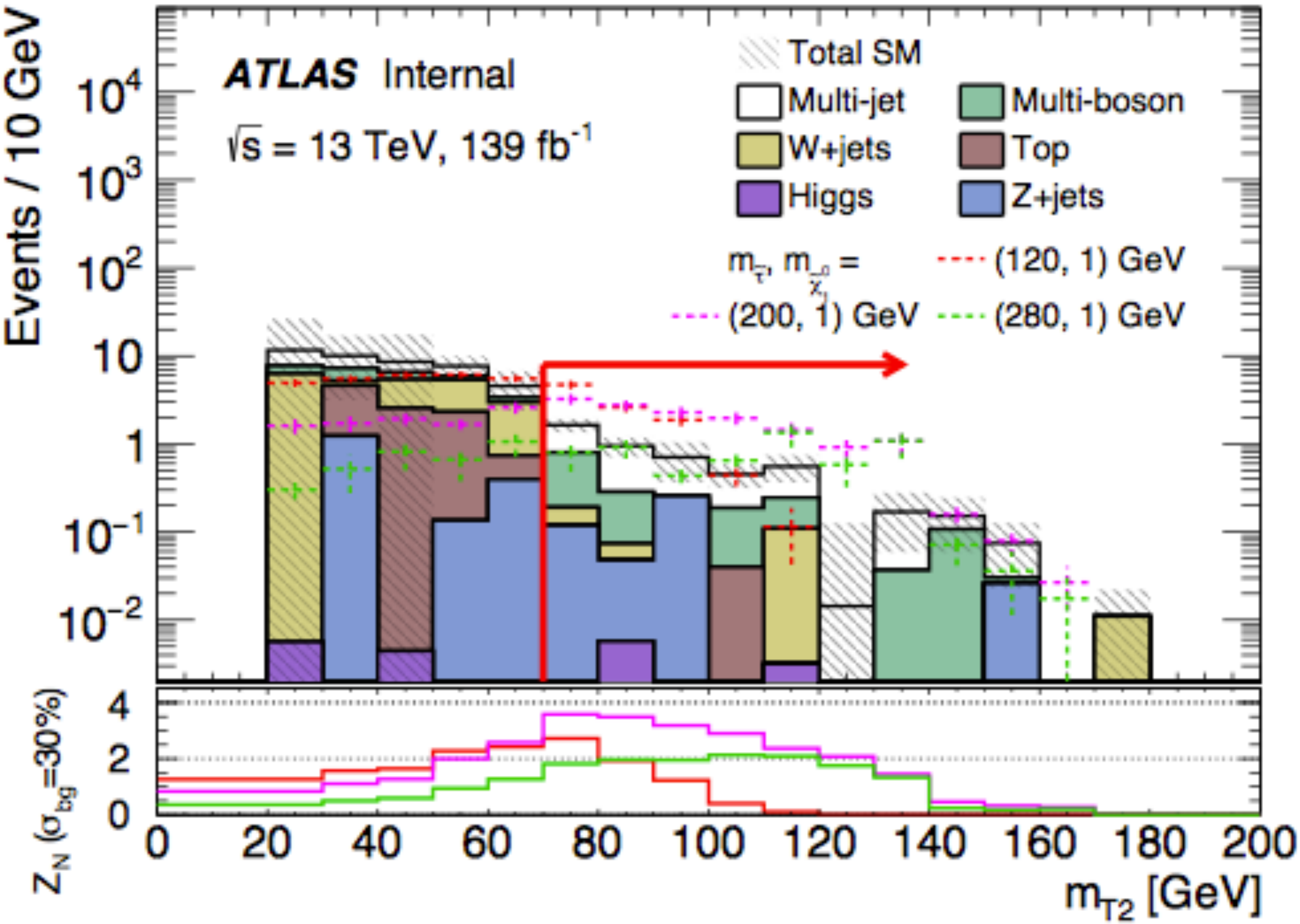
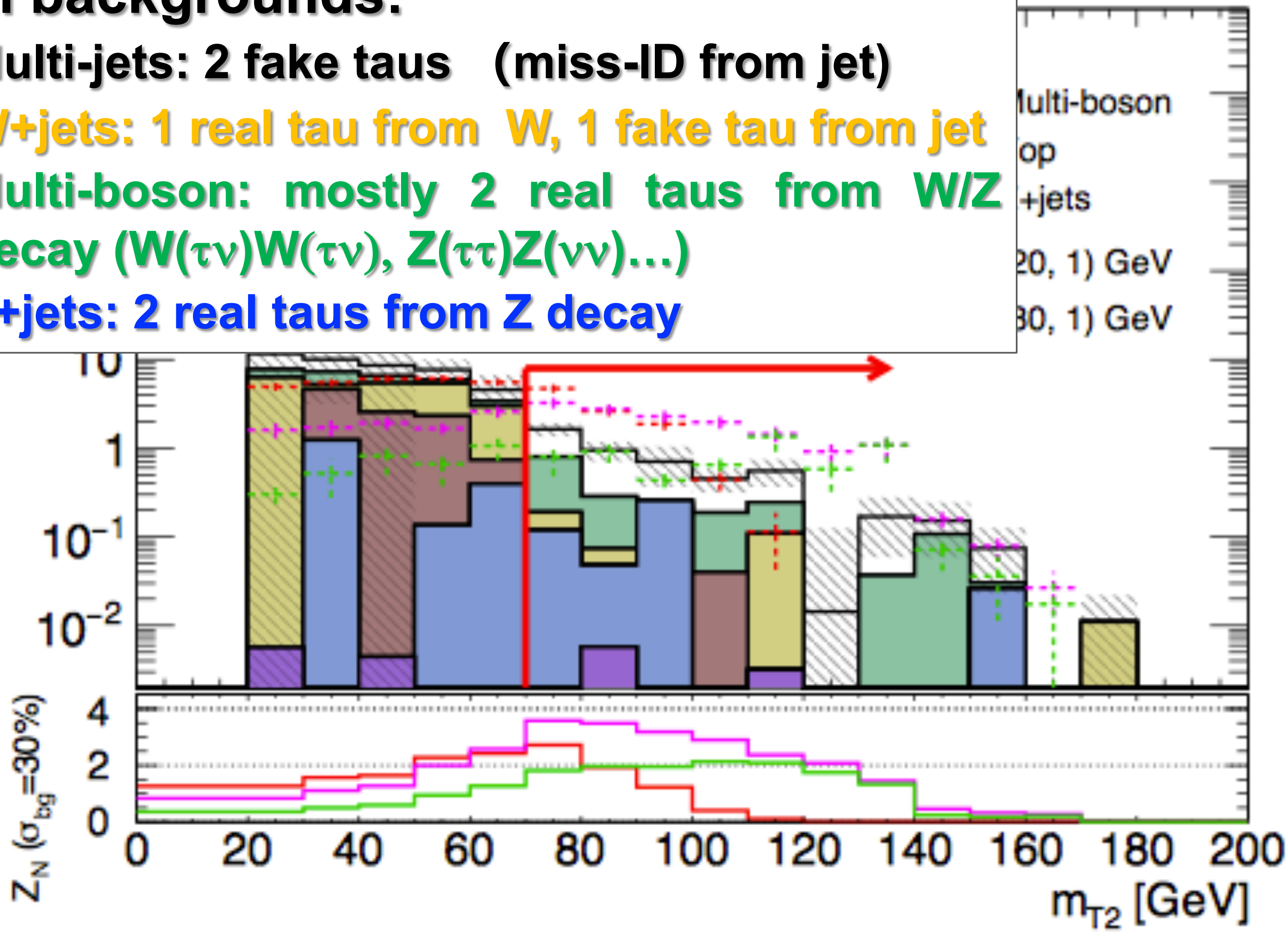
3: SR definition and optimization



3: SR definition and optimization

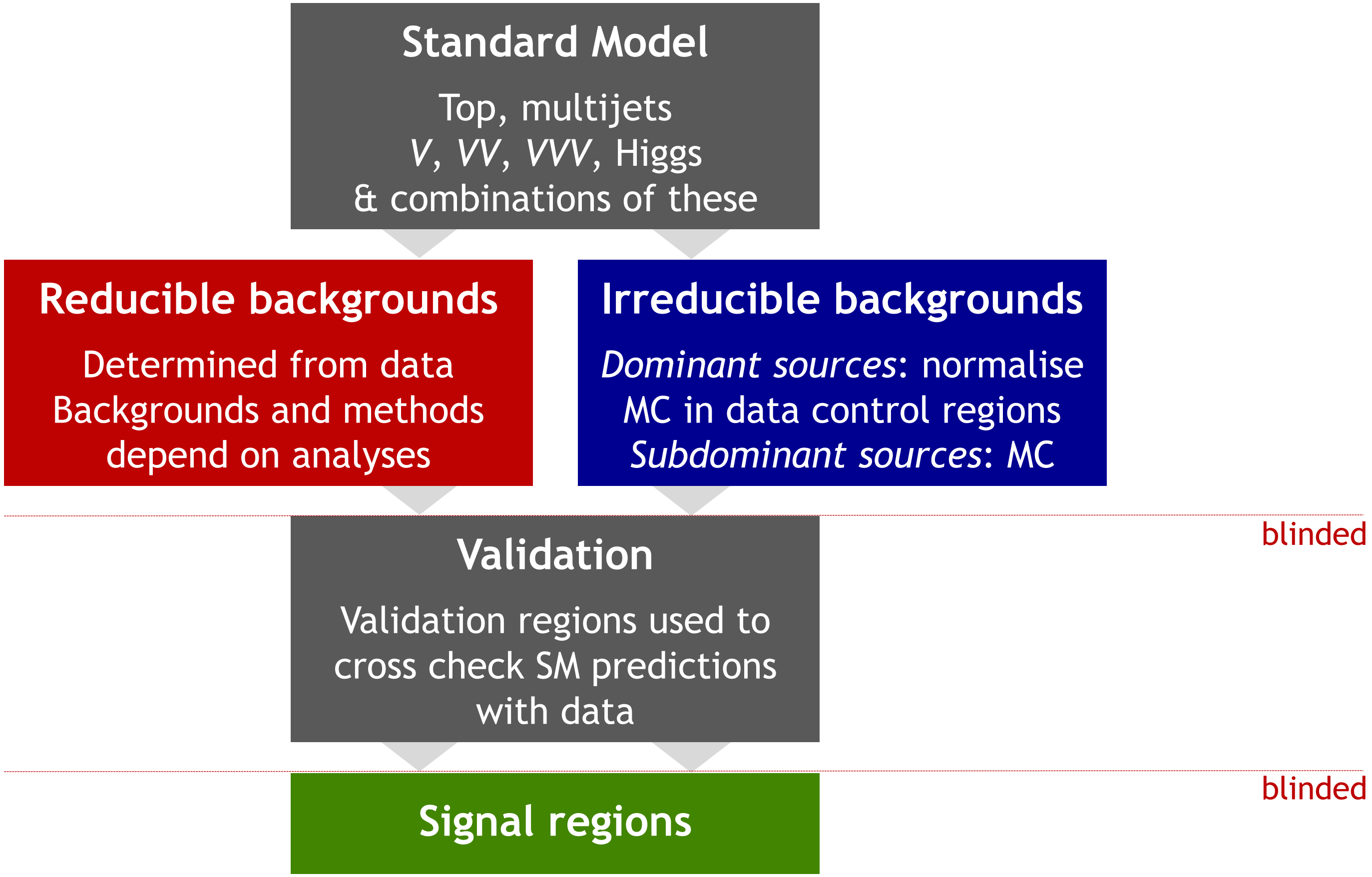


Main backgrounds:

- **Multi-jets: 2 fake taus (miss-ID from jet)**
- **W+jets: 1 real tau from W, 1 fake tau from jet**
- **Multi-boson: mostly 2 real taus from W/Z decay ($W(\tau\nu)W(\tau\nu)$, $Z(\tau\tau)Z(\nu\nu)$…)**
- **Z+jets: 2 real taus from Z decay**

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

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
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Reducible backgrounds

Determined from data
Backgrounds and methods
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Validation

Validation regions used to
cross check SM prediction
with data

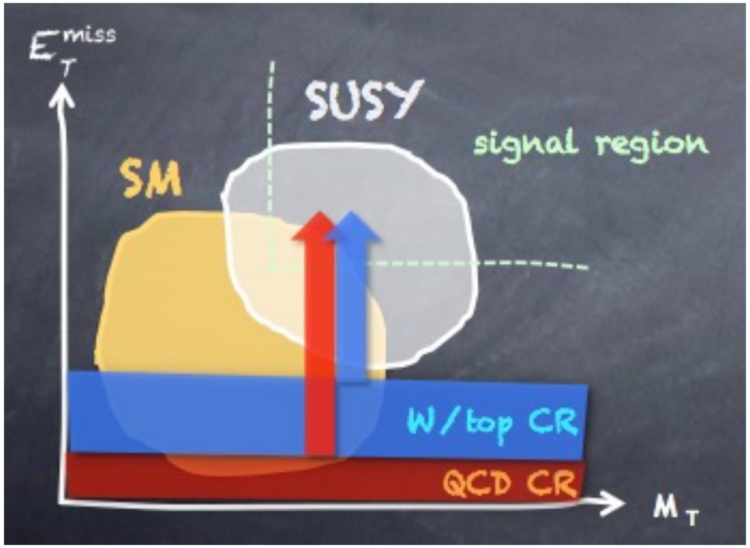
Signal regions

- **Multijet background**: "ABCD method" or fake factor 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

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

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

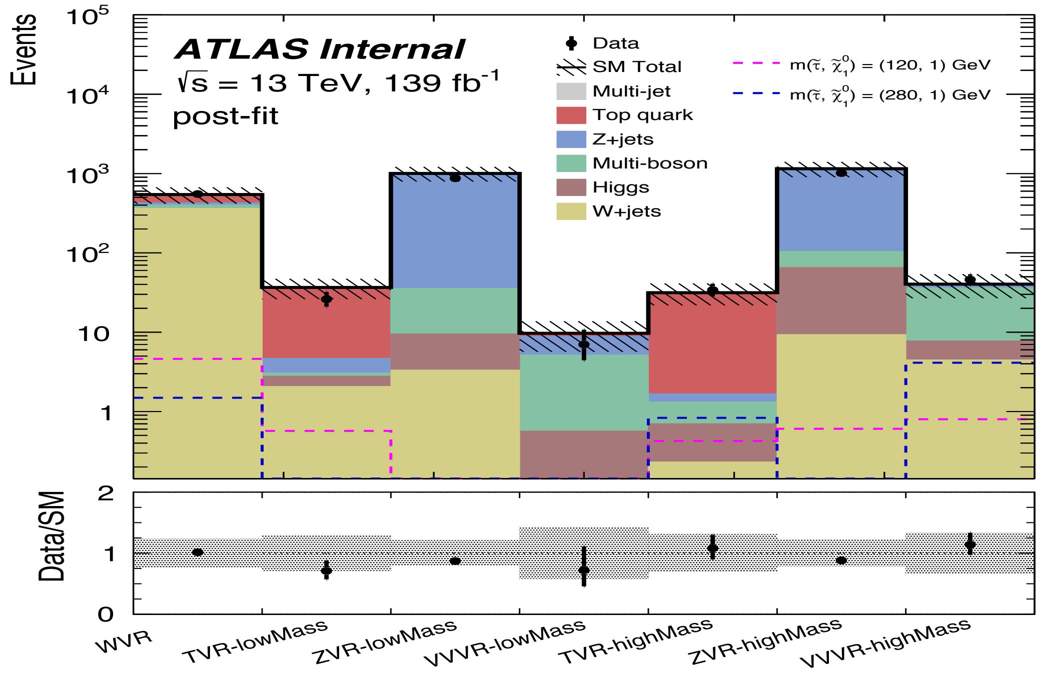
Validation regions used to cross check SM predictions with data

Signal regions

+ MC)

SU e SM

BC



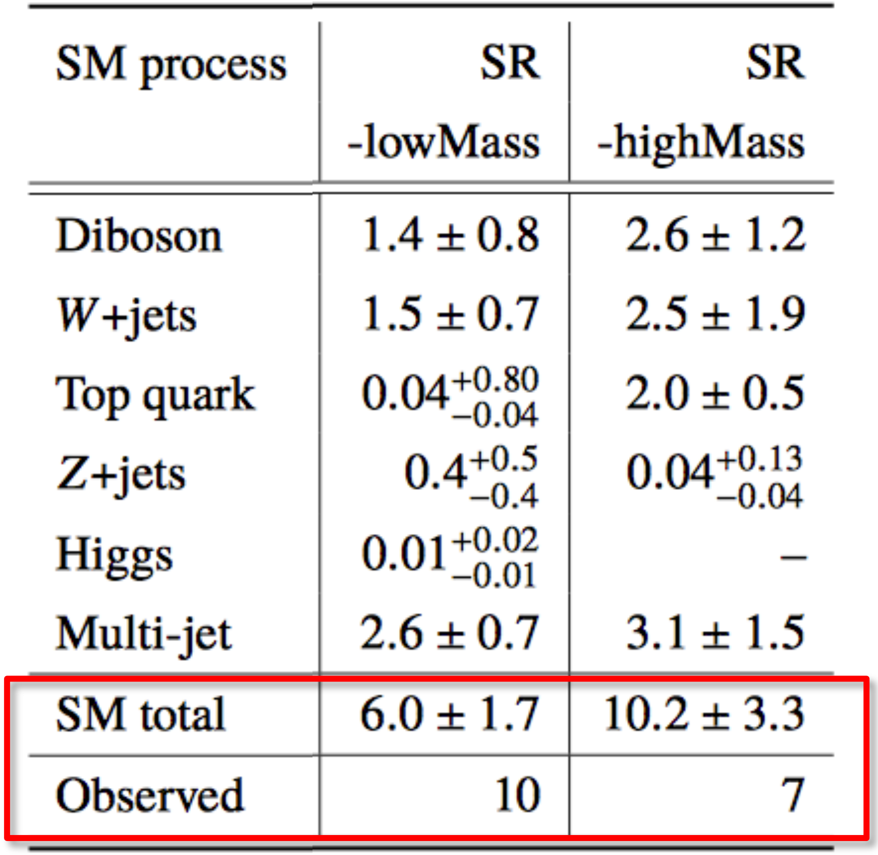
Determined from data
Backgrounds and meth
depend on analyses

ant sources: normalise
data control regions
subdominant sources: MC

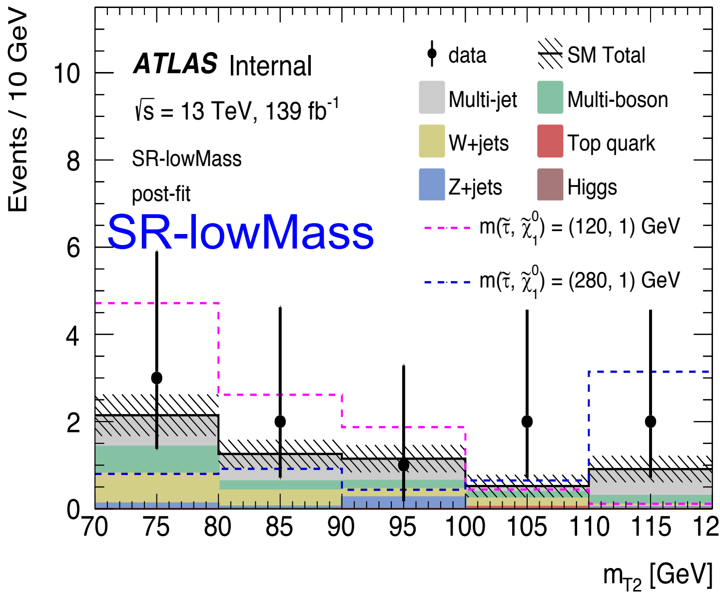
Validation

Validation regions used to cross check SM predictions with data

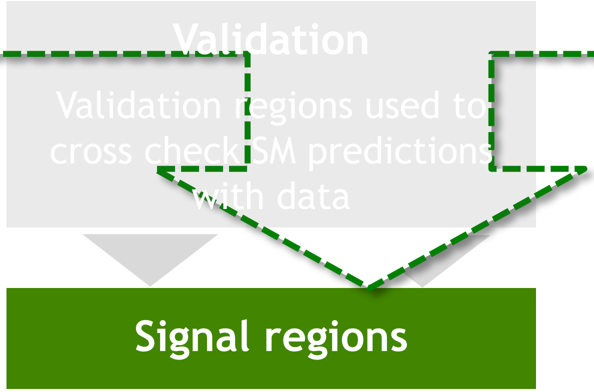
Signal regions



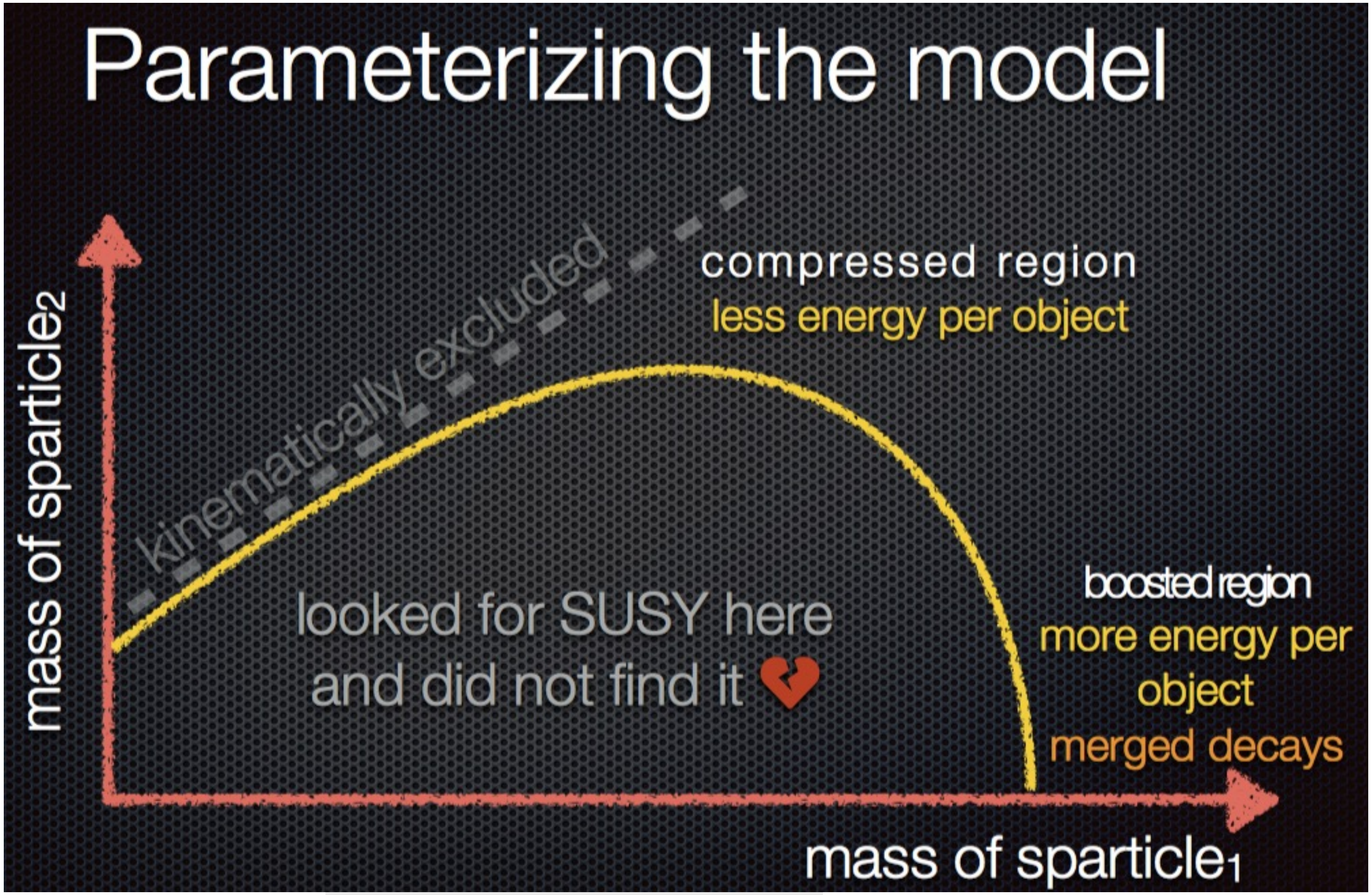
SM process	SR -lowMass	SR -highMass
Diboson	1.4 ± 0.8	2.6 ± 1.2
W+jets	1.5 ± 0.7	2.5 ± 1.9
Top quark	$0.04^{+0.80}_{-0.04}$	2.0 ± 0.5
Z+jets	$0.4^{+0.5}_{-0.4}$	$0.04^{+0.13}_{-0.04}$
Higgs	$0.01^{+0.02}_{-0.01}$	–
Multi-jet	2.6 ± 0.7	3.1 ± 1.5
SM total	6.0 ± 1.7	10.2 ± 3.3
Observed	10	7



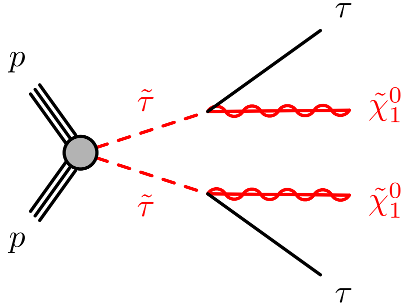
- No significant excess except for SR-lowMass

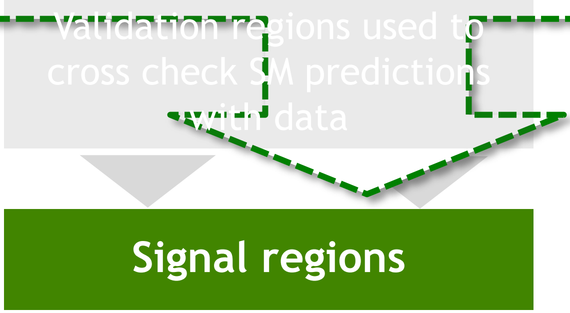


5: Compare SM predictions with data



Parameterizing the model

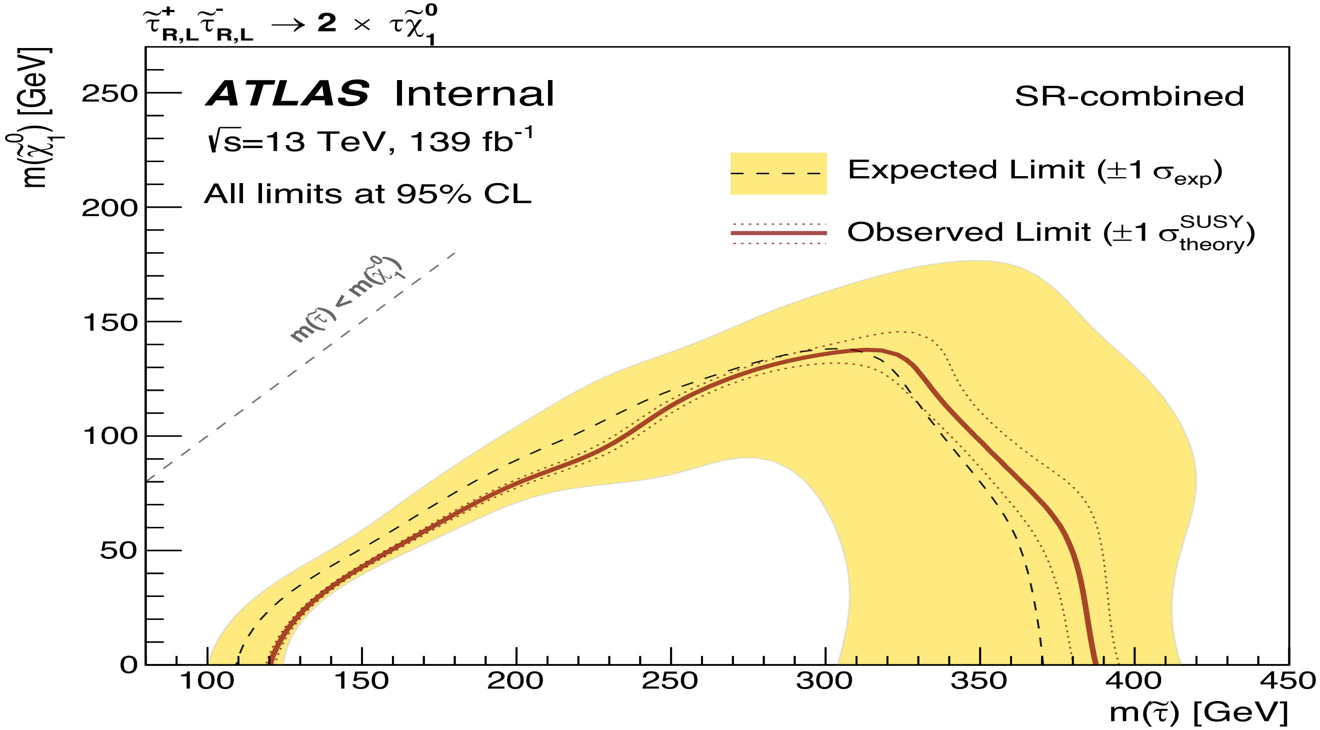




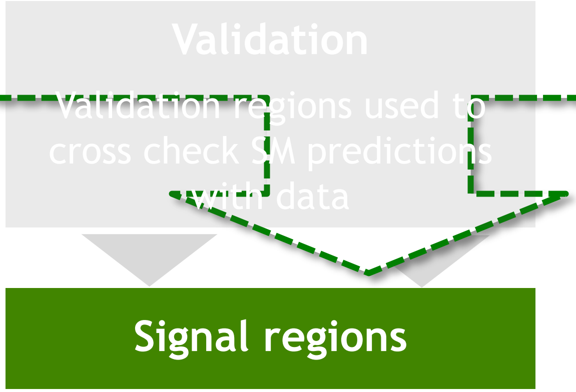
Validation regions used to cross check SM predictions with data

Signal regions

6: Interpretations



- excludes **stau masses** between **120-390 GeV**



Validation

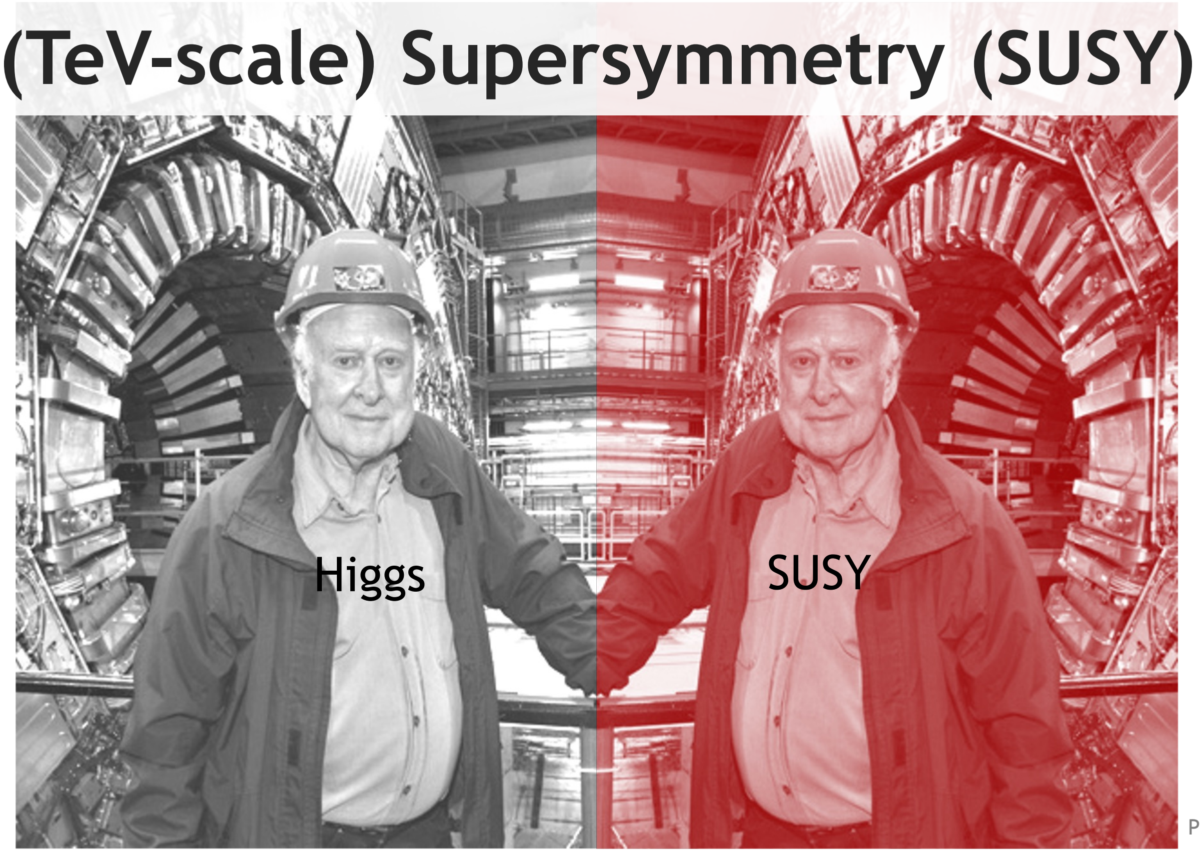
Validation regions used to cross check SM predictions with data

Signal regions

6: Interpretations

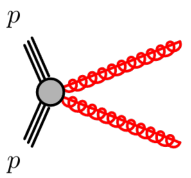
SUSY search results @ LHC

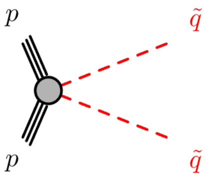
ATLAS public link
CMS public link

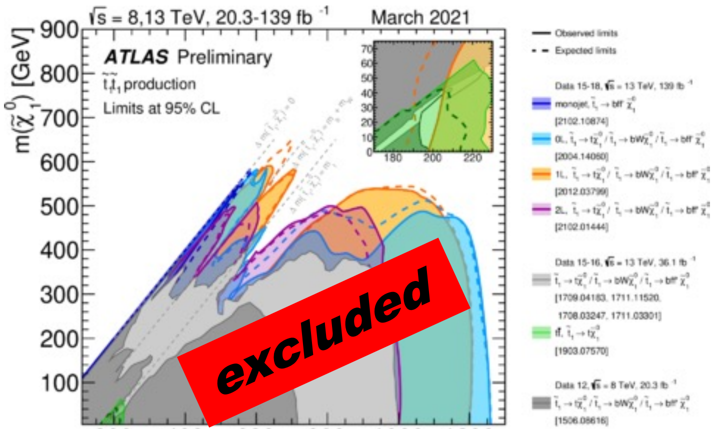


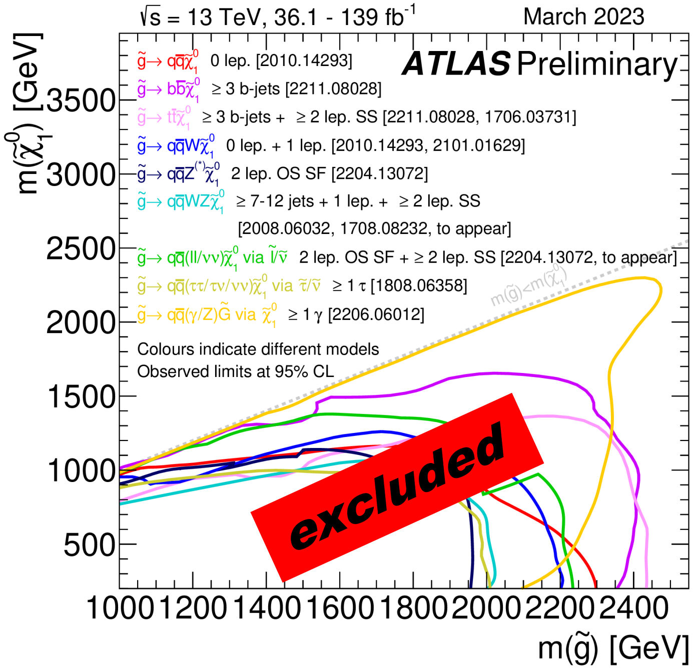
P. Higgs at CMS

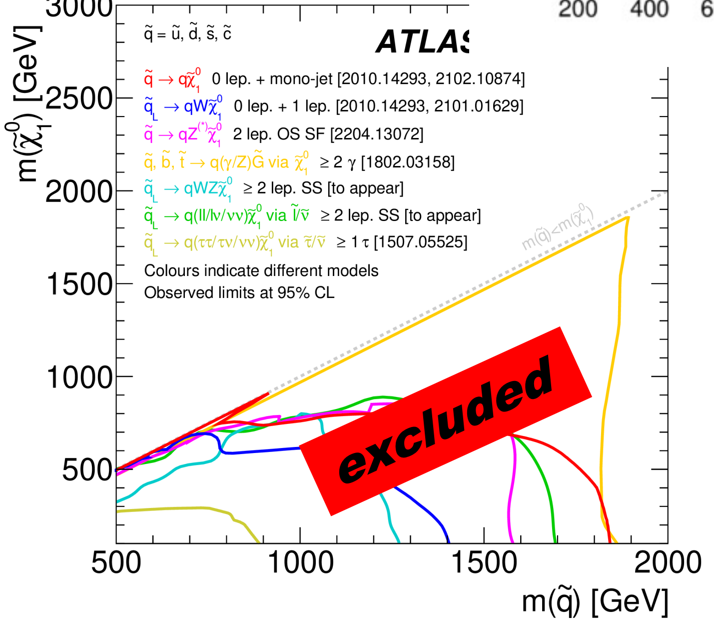
Gluino & squarks

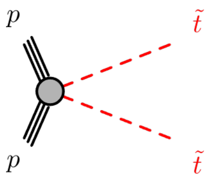












In **simplified model approach** (depending on decay mode and/or mass splittings):

- M(~g) < O (1.9 TeV) – O (2.4 TeV) @95% CL
- M(~q) < O (1.4 TeV) – O (1.85 TeV) @95% CL
- M(~t/~b) < O (0.7 TeV) – O (1.25/1.35 TeV) @95% CL

New: Gbb, Gtt, SS

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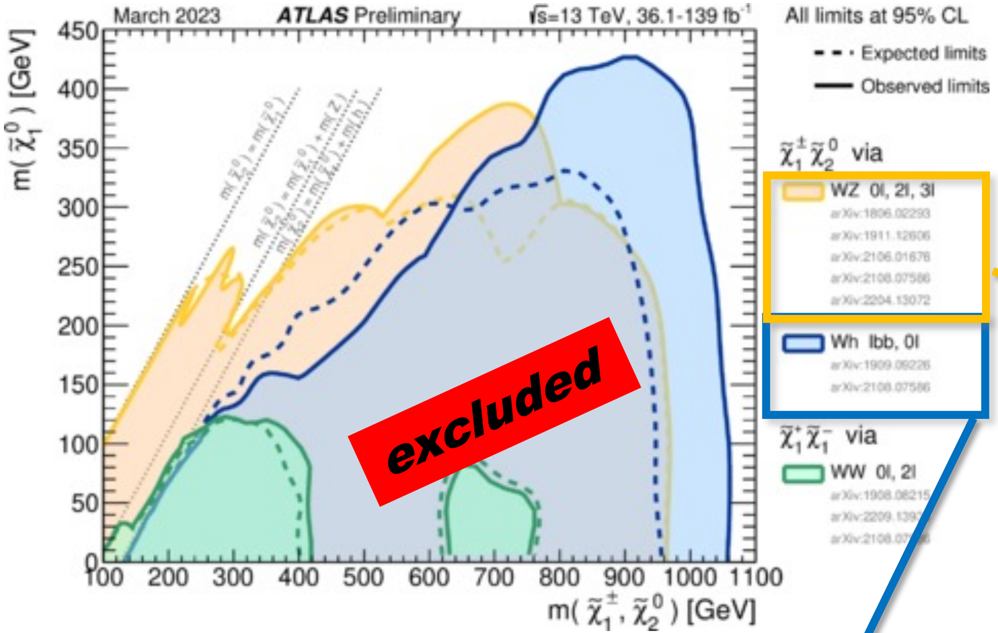
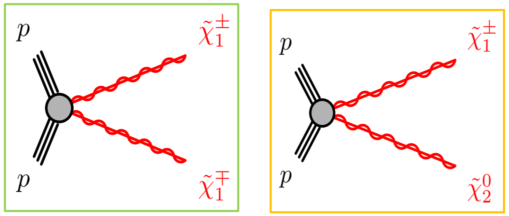
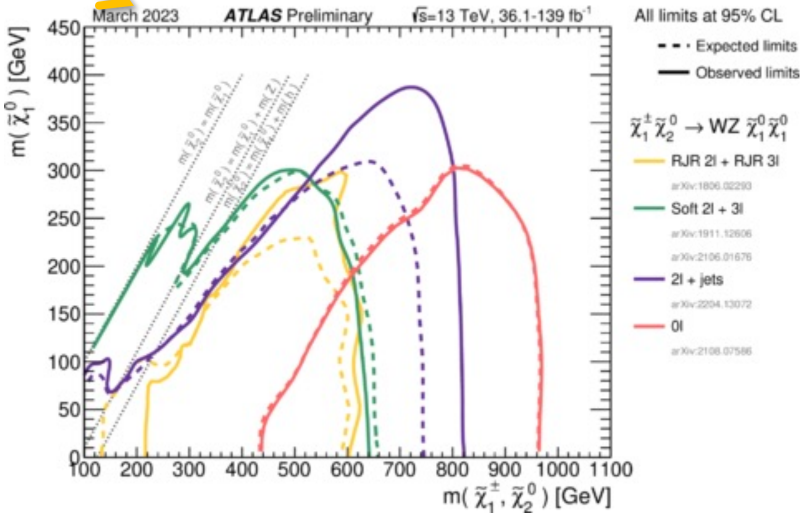
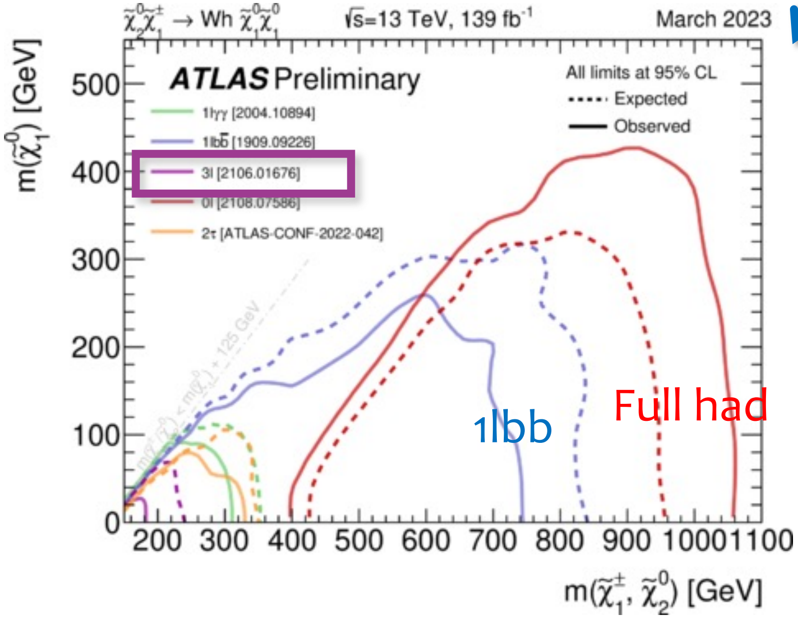
Electroweakinos

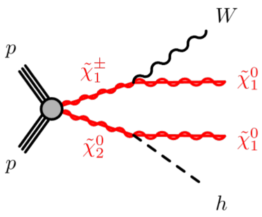




C1C1 (C1N2) production:
via WW (WZ/Wh) decay (upto 1.05 TeV)
via ~l decay (up to 1.0-1.1 TeV)







Sleptons

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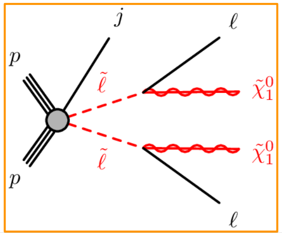
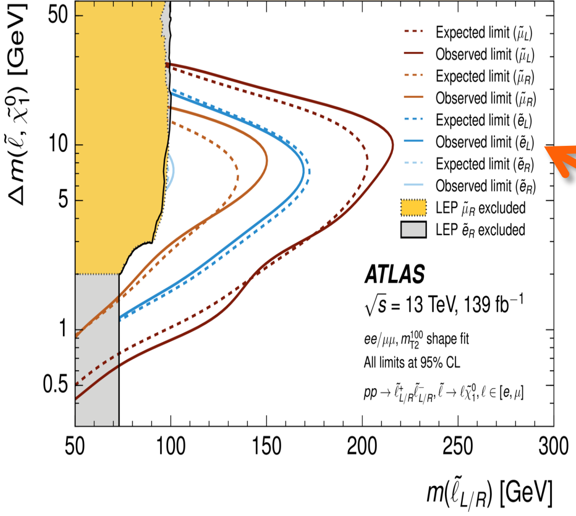
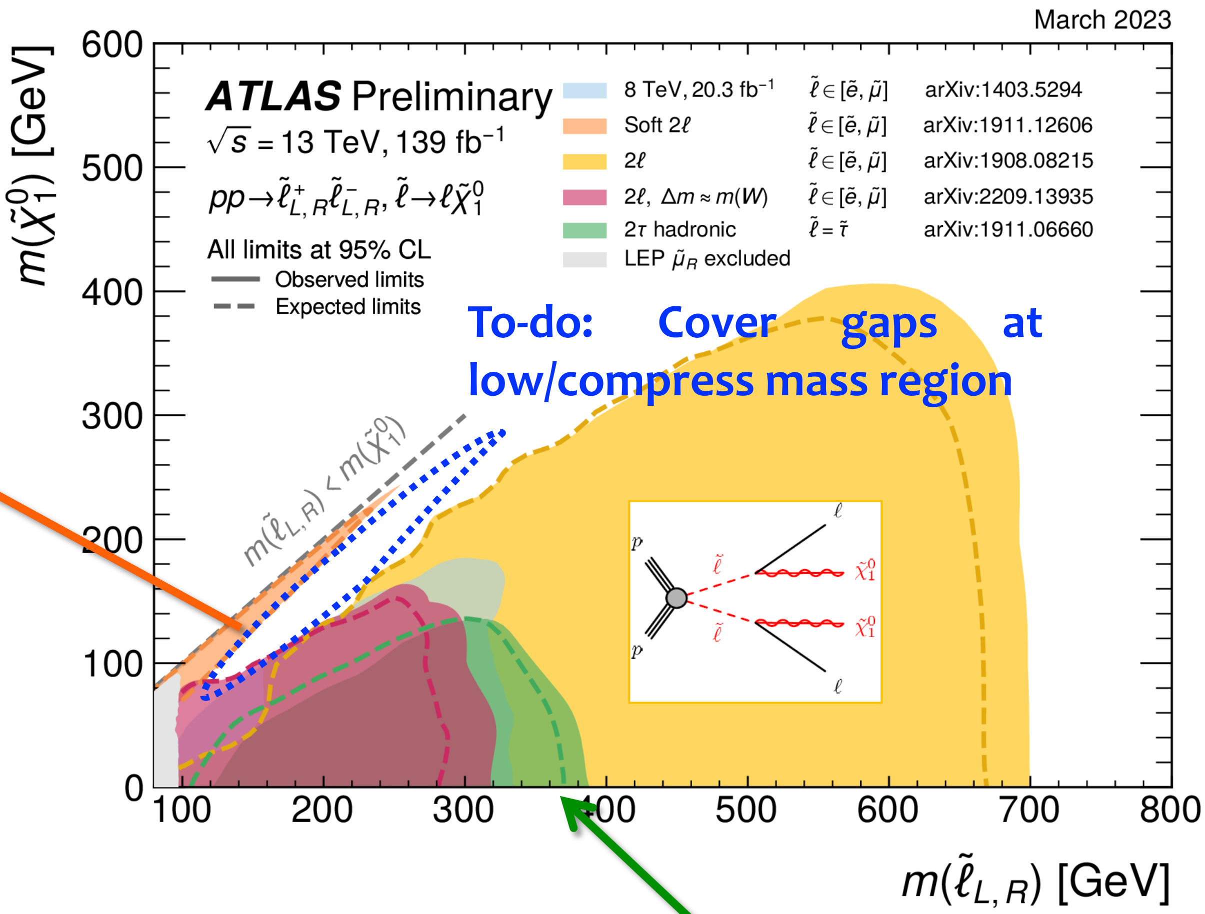






To-do: Cover gaps at low/compress mass region

Stau updated

Limits maybe different in case of cascade decays of the sleptons into lighter electroweakino states

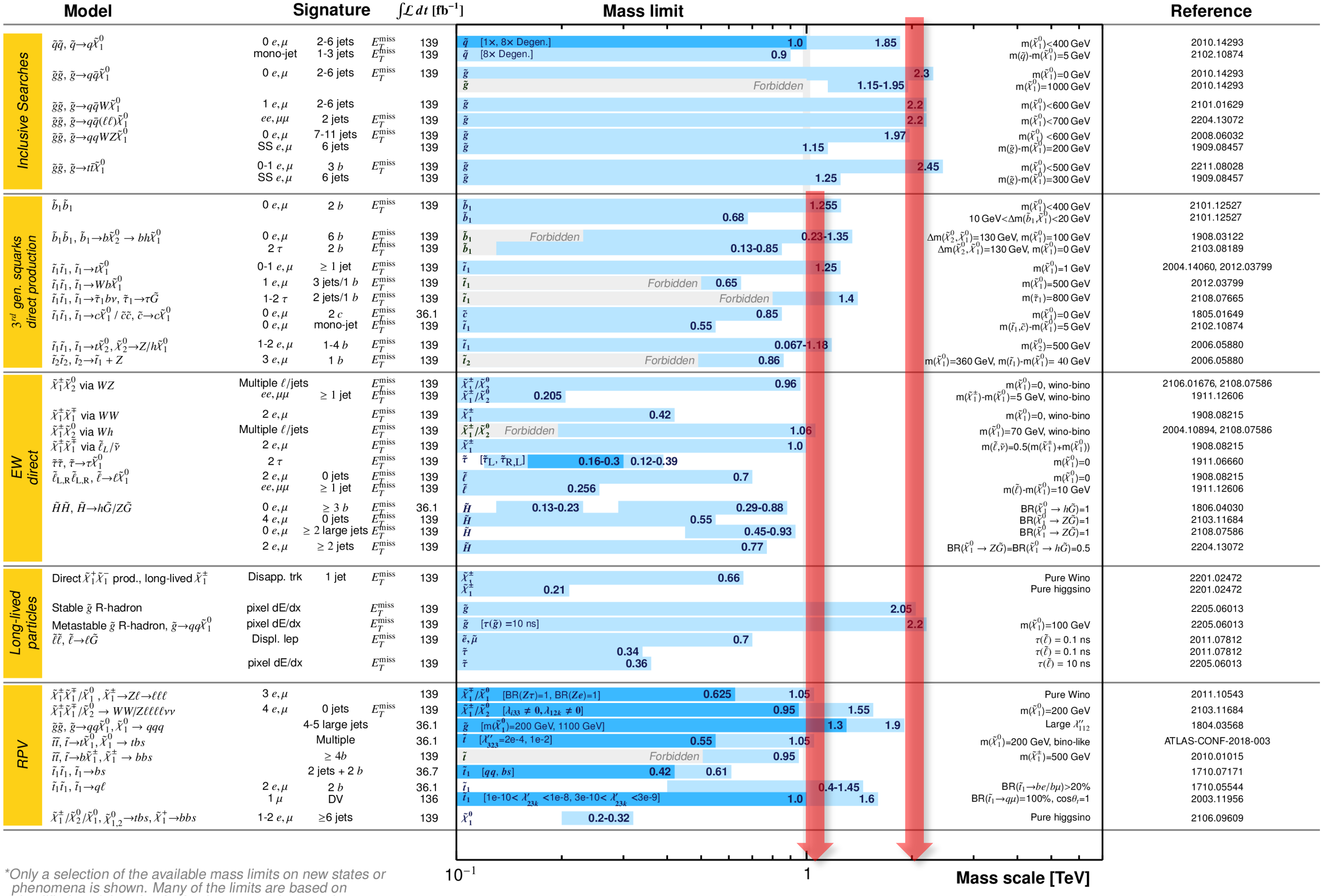
ATL-PHYS-PUB-2023-005

ATLAS SUSY Searches* - 95% CL Lower Limits

March 2023

ATLAS Preliminary

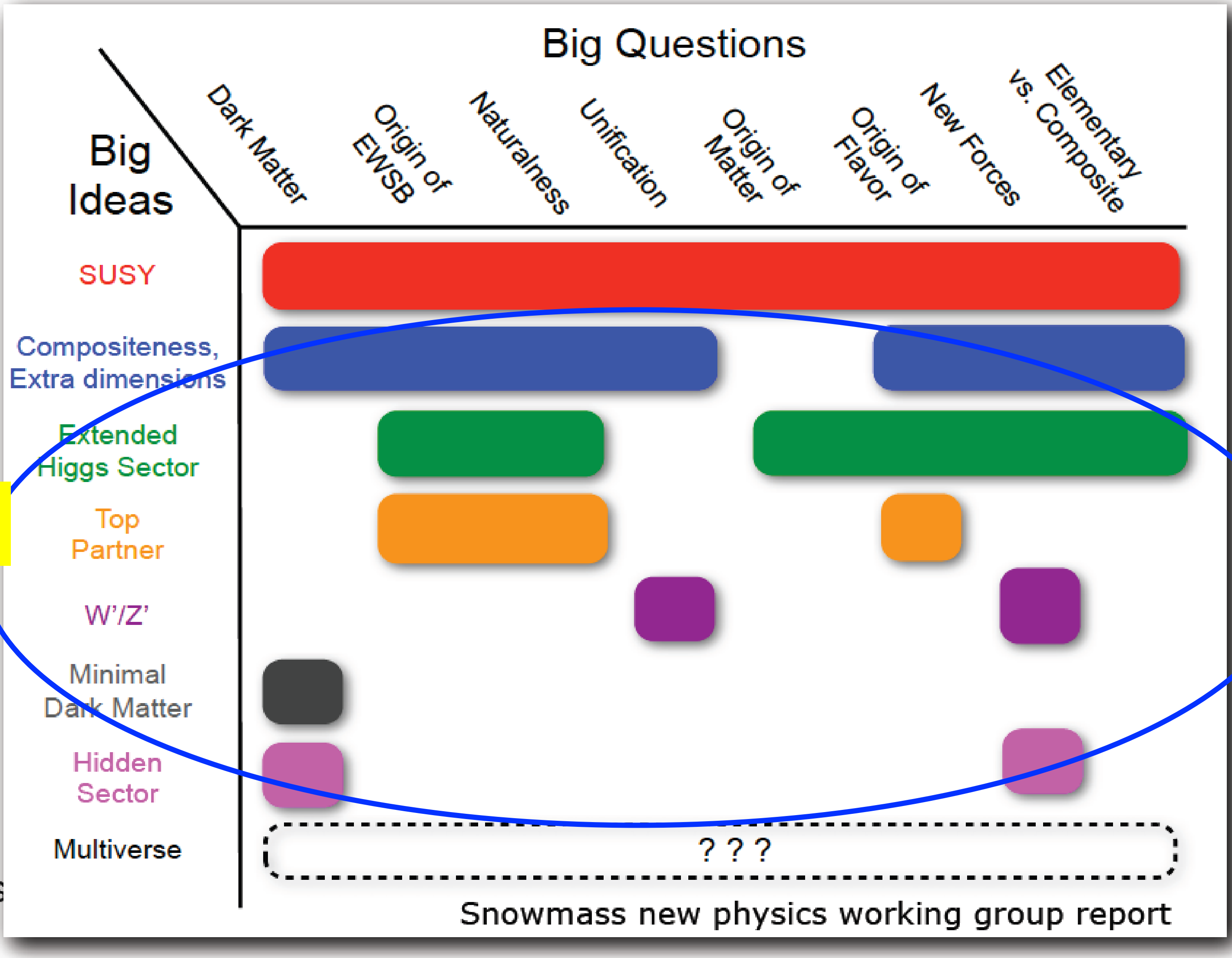
$\sqrt{s}$ = 13 TeV



	Model	Signature			$\int\mathcal{L}\,dt$ [fb^{-1}]	Mass limit				Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	0 e,μ	2-6 jets	E_T^{miss}	139	$\tilde{q}$	[1×, 8× Degen.]	1.0 1.85	m($\tilde{\chi}^0_1$)<400 GeV	2010.14293
		mono-jet	1-3 jets	E_T^{miss}	139	$\tilde{q}$	[8× Degen.]	0.9	m($\tilde{q}$)-m($\tilde{\chi}^0_1$)=5 GeV	2102.10874
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0 e,μ	2-6 jets	E_T^{miss}	139	$\tilde{g}$		2.3	m($\tilde{\chi}^0_1$)=0 GeV	2010.14293
						$\tilde{g}$	Forbidden	1.15-1.95	m($\tilde{\chi}^0_1$)=1000 GeV	2010.14293
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}W\tilde{\chi}^0_1$	1 e,μ	2-6 jets		139	$\tilde{g}$		2.2	m($\tilde{\chi}^0_1$)<600 GeV	2101.01629
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}^0_1$	$ee,\mu\mu$	2 jets	E_T^{miss}	139	$\tilde{g}$		2.2	m($\tilde{\chi}^0_1$)<700 GeV	2204.13072
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}^0_1$	0 e,μ	7-11 jets	E_T^{miss}	139	$\tilde{g}$		1.97	m($\tilde{\chi}^0_1$) <600 GeV	2008.06032
		SS e,μ	6 jets		139	$\tilde{g}$		1.15	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=200 GeV	1909.08457
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	E_T^{miss}	139	$\tilde{g}$		2.45	m($\tilde{\chi}^0_1$)<500 GeV	2211.08028
		SS e,μ	6 jets		139	$\tilde{g}$		1.25	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=300 GeV	1909.08457
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e,μ	2 b	E_T^{miss}	139	$\tilde{b}_1$		1.255	m($\tilde{\chi}^0_1$)<400 GeV	2101.12527
						$\tilde{b}_1$		0.68	10 GeV<Δm($\tilde{b}_1$,$\tilde{\chi}^0_1$)<20 GeV	2101.12527
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_2\to bh\tilde{\chi}^0_1$	0 e,μ	6 b	E_T^{miss}	139	$\tilde{b}_1$	Forbidden	0.23-1.35	Δm($\tilde{\chi}^0_2$,$\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=100 GeV	1908.03122
		2 τ	2 b	E_T^{miss}	139	$\tilde{b}_1$		0.13-0.85	Δm($\tilde{\chi}^0_2$,$\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=0 GeV	2103.08189
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}^0_1$	0-1 e,μ	$\geq$ 1 jet	E_T^{miss}	139	$\tilde{t}_1$		1.25	m($\tilde{\chi}^0_1$)=1 GeV	2004.14060, 2012.03799
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}^0_1$	1 e,μ	3 jets/1 b	E_T^{miss}	139	$\tilde{t}_1$	Forbidden	0.65	m($\tilde{\chi}^0_1$)=500 GeV	2012.03799
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to\tilde{\tau}_1 b\nu$, $\tilde{\tau}_1\to\tau\tilde{G}$	1-2 τ	2 jets/1 b	E_T^{miss}	139	$\tilde{t}_1$	Forbidden	1.4	m($\tilde{\tau}_1$)=800 GeV	2108.07665
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}^0_1$	0 e,μ	2 c	E_T^{miss}	36.1	$\tilde{c}$		0.85	m($\tilde{\chi}^0_1$)=0 GeV	1805.01649
		0 e,μ	mono-jet	E_T^{miss}	139	$\tilde{t}_1$		0.55	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}^0_1$)=5 GeV	2102.10874
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}^0_2$, $\tilde{\chi}^0_2\to Z/h\tilde{\chi}^0_1$	1-2 e,μ	1-4 b	E_T^{miss}	139	$\tilde{t}_1$		0.067-1.18	m($\tilde{\chi}^0_2$)=500 GeV	2006.05880
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ	1 b	E_T^{miss}	139	$\tilde{t}_2$	Forbidden	0.86	m($\tilde{\chi}^0_1$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)= 40 GeV	2006.05880
EW direct	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via WZ	Multiple ℓ/jets		E_T^{miss}	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$		0.96	m($\tilde{\chi}^0_1$)=0, wino-bino	2106.01676, 2108.07586
		$ee,\mu\mu$	$\geq$ 1 jet	E_T^{miss}	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$		0.205	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=5 GeV, wino-bino	1911.12606
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via WW	2 e,μ		E_T^{miss}	139	$\tilde{\chi}^\pm_1$		0.42	m($\tilde{\chi}^0_1$)=0, wino-bino	1908.08215
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via Wh	Multiple ℓ/jets		E_T^{miss}	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	Forbidden	1.06	m($\tilde{\chi}^0_1$)=70 GeV, wino-bino	2004.10894, 2108.07586
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		E_T^{miss}	139	$\tilde{\chi}^\pm_1$		1.0	m($\tilde{\ell}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	1908.08215
	$\tilde{\tau}\tilde{\tau}$, $\tilde{\tau}\to\tau\tilde{\chi}^0_1$	2 τ		E_T^{miss}	139	$\tilde{\tau}$	[$\tilde{\tau}_L$, $\tilde{\tau}_{R,L}$]	0.16-0.3 0.12-0.39	m($\tilde{\chi}^0_1$)=0	1911.06660
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0 jets	E_T^{miss}	139	$\tilde{\ell}$		0.7	m($\tilde{\chi}^0_1$)=0	1908.08215
		$ee,\mu\mu$	$\geq$ 1 jet	E_T^{miss}	139	$\tilde{\ell}$		0.256	m($\tilde{\ell}$)-m($\tilde{\chi}^0_1$)=10 GeV	1911.12606
	$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	$\geq$ 3 b	E_T^{miss}	36.1	$\tilde{H}$		0.13-0.23 0.29-0.88	BR($\tilde{\chi}^0_1\to h\tilde{G}$)=1	1806.04030
		4 e,μ	0 jets	E_T^{miss}	139	$\tilde{H}$		0.55	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1	2103.11684
		0 e,μ	$\geq$ 2 large jets	E_T^{miss}	139	$\tilde{H}$		0.45-0.93	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1	2108.07586
		2 e,μ	$\geq$ 2 jets	E_T^{miss}	139	$\tilde{H}$		0.77	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=BR($\tilde{\chi}^0_1\to h\tilde{G}$)=0.5	2204.13072
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	E_T^{miss}	139	$\tilde{\chi}^\pm_1$		0.66	Pure Wino	2201.02472
						$\tilde{\chi}^\pm_1$		0.21	Pure higgsino	2201.02472
	Stable $\tilde{g}$ R-hadron	pixel dE/dx		E_T^{miss}	139	$\tilde{g}$		2.05		2205.06013
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}^0_1$	pixel dE/dx		E_T^{miss}	139	$\tilde{g}$	[$\tau(\tilde{g})$ =10 ns]	2.2	m($\tilde{\chi}^0_1$)=100 GeV	2205.06013
	$\tilde{\ell}\tilde{\ell}$, $\tilde{\ell}\to\ell\tilde{G}$	Displ. lep		E_T^{miss}	139	$\tilde{e},\tilde{\mu}$		0.7	$\tau(\tilde{\ell})$ = 0.1 ns	2011.07812
						$\tilde{\tau}$		0.34	$\tau(\tilde{\ell})$ = 0.1 ns	2011.07812
		pixel dE/dx		E_T^{miss}	139	$\tilde{\tau}$		0.36	$\tau(\tilde{\ell})$ = 10 ns	2205.06013
RPV	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_1$, $\tilde{\chi}^\pm_1\to Z\ell\to\ell\ell\ell$	3 e,μ			139	$\tilde{\chi}^\mp_1/\tilde{\chi}^0_1$	[BR($Z\tau$)=1, BR(Ze)=1]	0.625 1.05	Pure Wino	2011.10543
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	E_T^{miss}	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	[$\lambda_{i33}\neq 0,\lambda_{12k}\neq 0$]	0.95 1.55	m($\tilde{\chi}^0_1$)=200 GeV	2103.11684
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to qqq$		4-5 large jets		36.1	$\tilde{g}$	[m($\tilde{\chi}^0_1$)=200 GeV, 1100 GeV]	1.3 1.9	Large λ''_{112}	1804.03568
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to tbs$		Multiple		36.1	$\tilde{t}$	[λ''_{323}=2e-4, 1e-2]	0.55 1.05	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to b\tilde{\chi}^\pm_1$, $\tilde{\chi}^\pm_1\to bbs$		$\geq 4b$		139	$\tilde{t}$	Forbidden	0.95	m($\tilde{\chi}^\pm_1$)=500 GeV	2010.01015
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$	[qq, bs]	0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to q\ell$	2 e,μ	2 b		36.1	$\tilde{t}_1$		0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde{t}_1$	[1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9]	1.0 1.6	BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1	2003.11956
	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2/\tilde{\chi}^0_1$, $\tilde{\chi}^0_{1,2}\to tbs$, $\tilde{\chi}^+_1\to bbs$	1-2 e,μ	$\geq$6 jets		139	$\tilde{\chi}^0_1$		0.2-0.32	Pure higgsino	2106.09609

*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



Big Questions

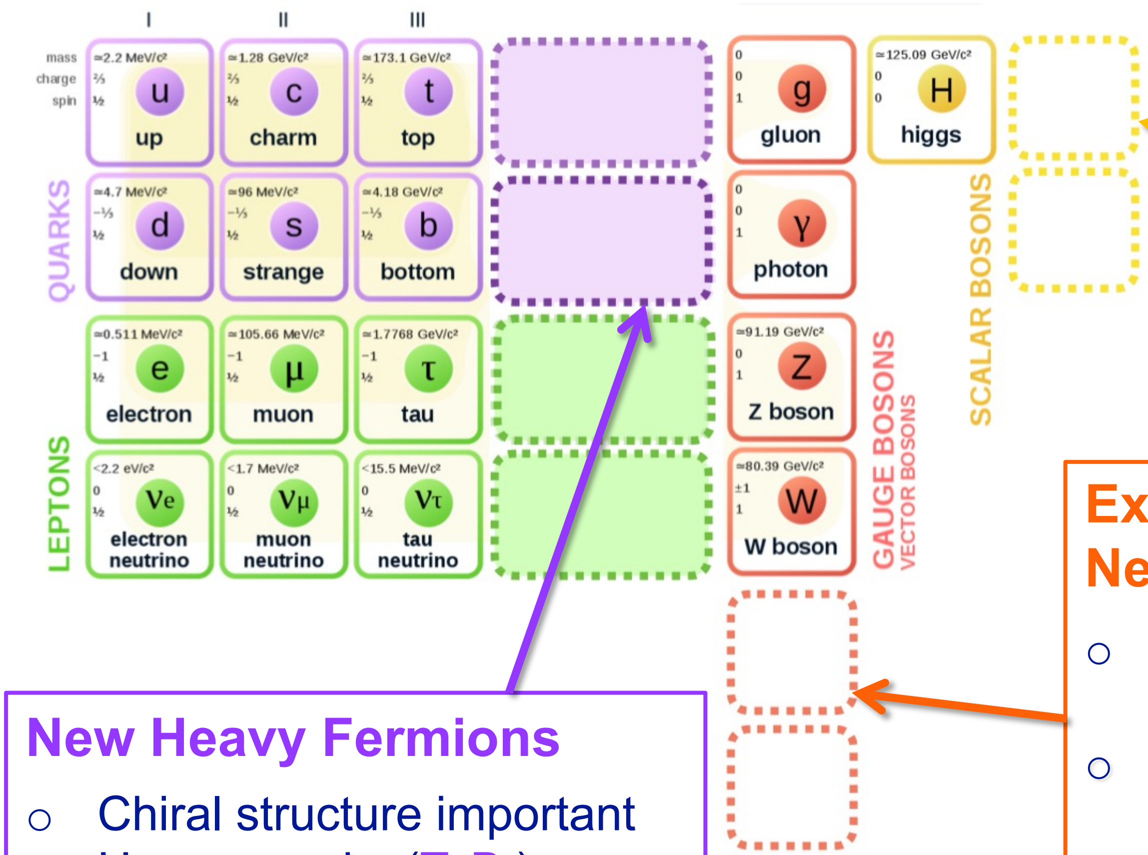
Big Ideas	Dark Matter	Origin of EWSB	Naturalness	Unification	Origin of Matter	Origin of Flavor	New Forces	Elementary vs. Composite
SUSY	■	■	■	■	■	■	■	■
Compositeness, Extra dimensions	■	■	■	■		■	■	■
Extended Higgs Sector		■	■		■	■	■	■
Top Partner		■	■			■		
W'/Z'				■			■	
Minimal Dark Matter	■					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

Snowmass new physics working group report

exotics

S. S

Exotics - various extension of SM



Additional Scalar States

- ○ A common feature in SUSY models
- ○ Mixing with Higgs

Extended Gauge Sector / New bosons

- ○ Extra dimension models (V KK,GKK, …)
- ○ Grand unification theories (leptoquarks, …)
- ○ Technicolor, composite Higgs (W’, Z’,…)

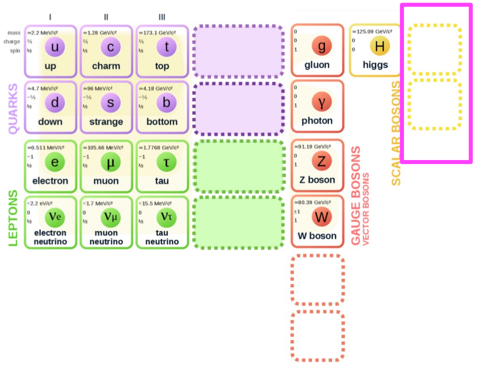
New Heavy Fermions

- ○ Chiral structure important
- ○ Heavy quarks (T, B)
- ○ Excited fermion (q*,l*,v* …)

Compositeness

- ○ New forces/particles integrate out at low energies (SM)

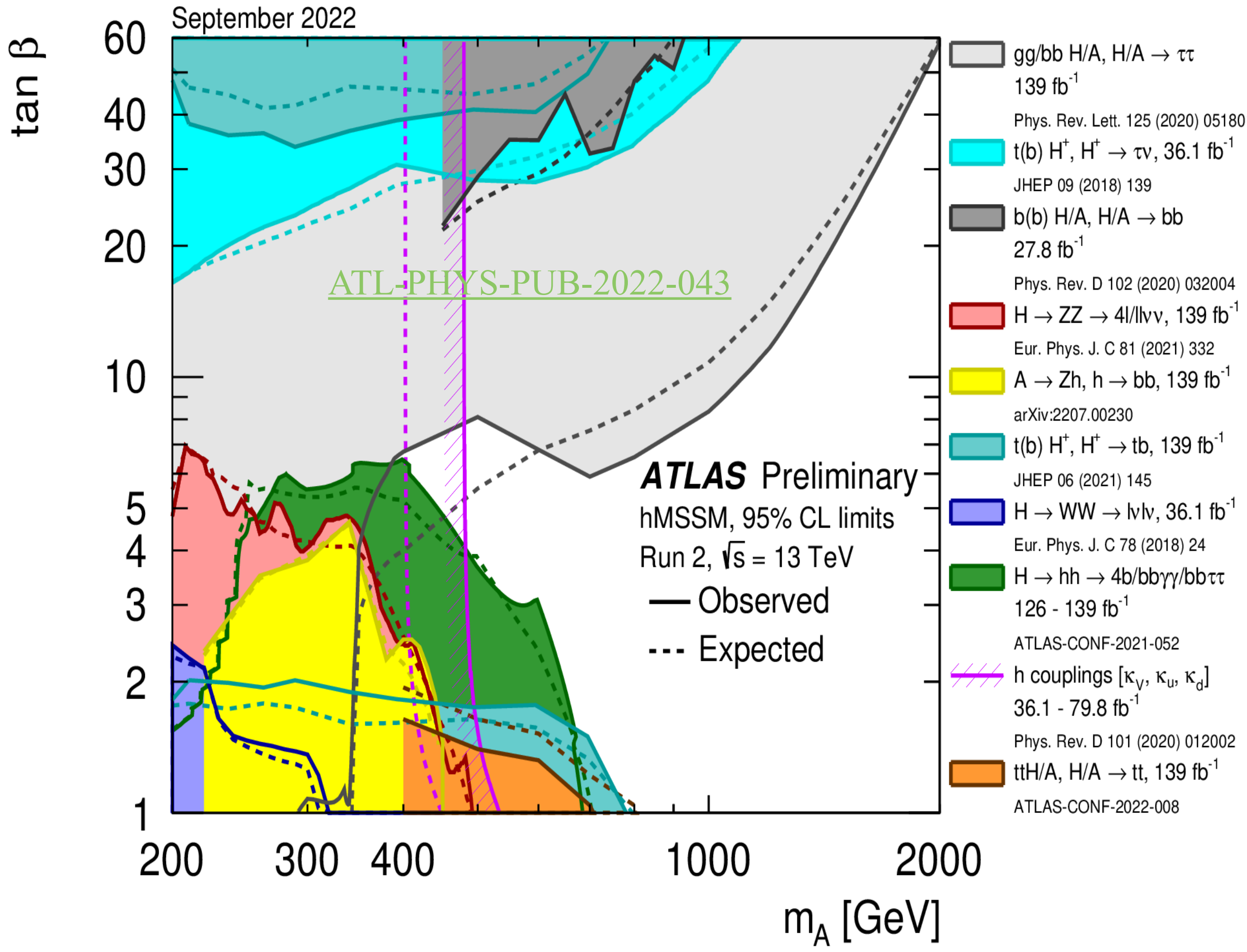
Extended Higgs sector – BSM Higgs



Many models: MSSM, 2HDM, etc.

☞ **Benchmark models: MSSM-like**

- **5 Higgs bosons:** h, H, A, $H^{\mp}$
- **2 free parameters at tree level:** m_A, tan $\beta = \nu_u/\nu_d$



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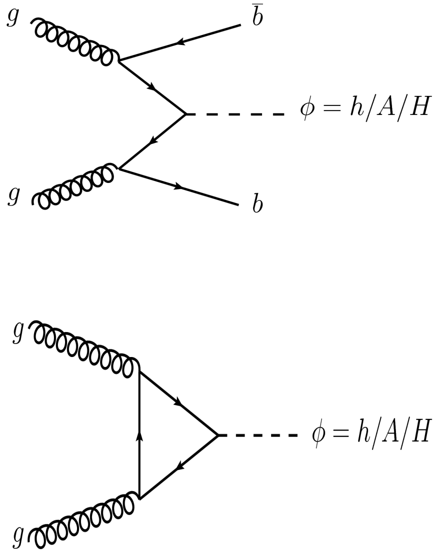
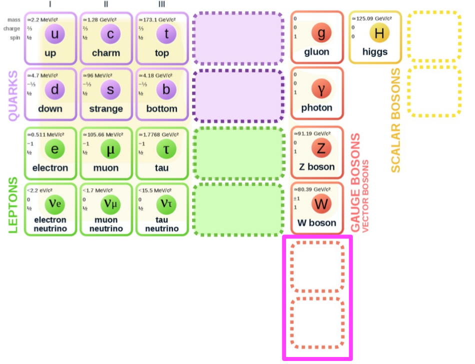
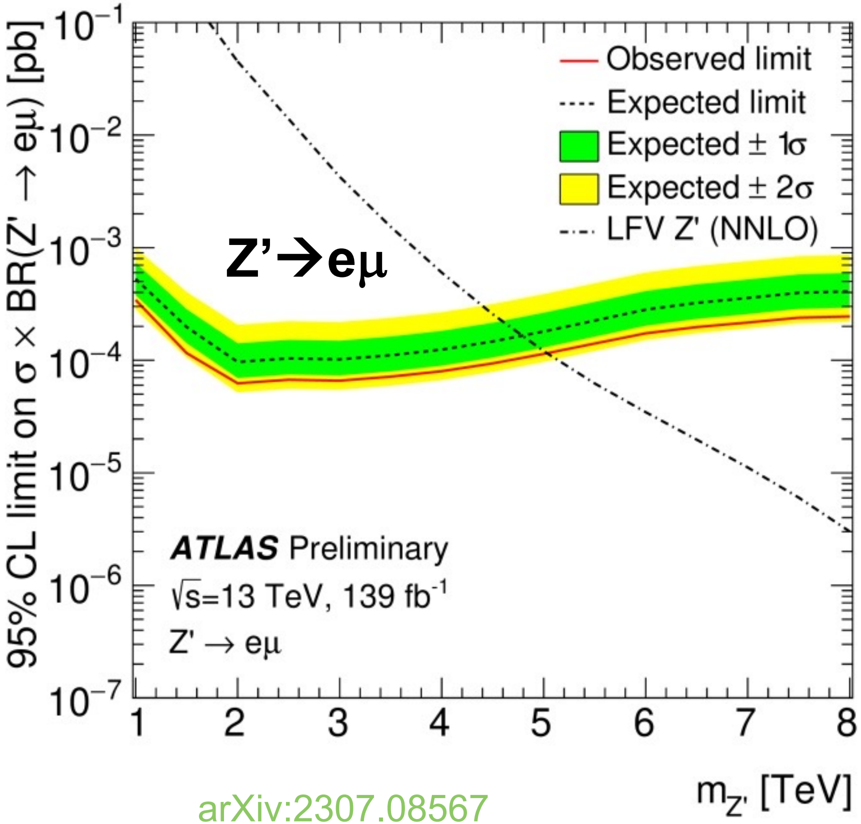


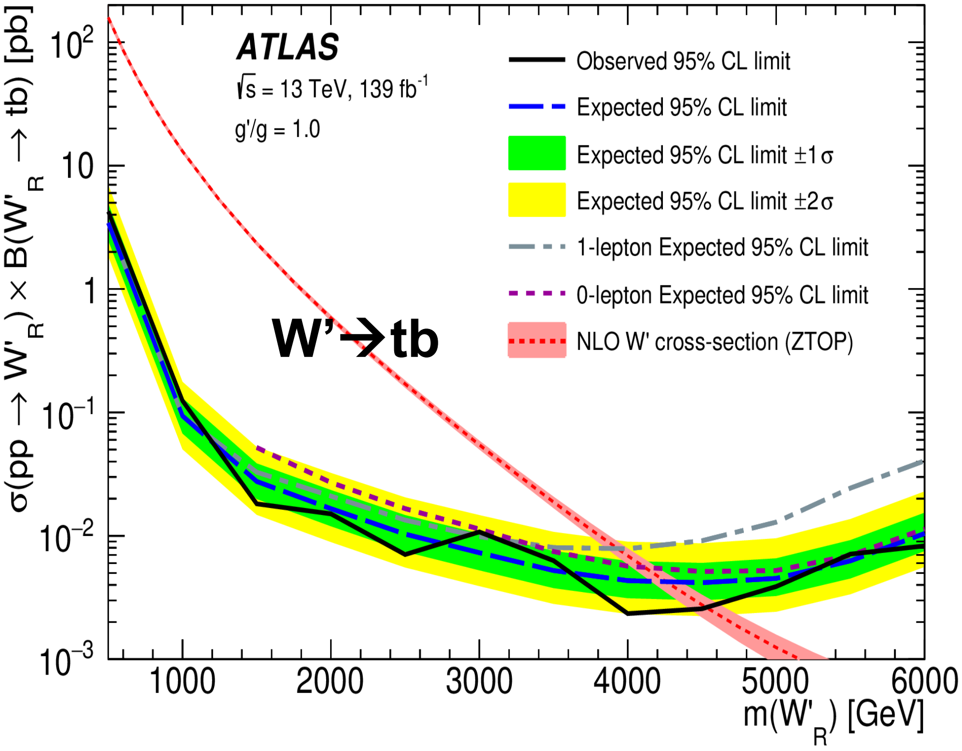
Extended gauge sector – Resonance (ff)



- **Predicted by many BSM models:**
  - ED (Randall-Sundrum (RS) Graviton), Heavy Vector Triplet (HVT: W′, Z′), DM mediator, …



arXiv:2307.08567



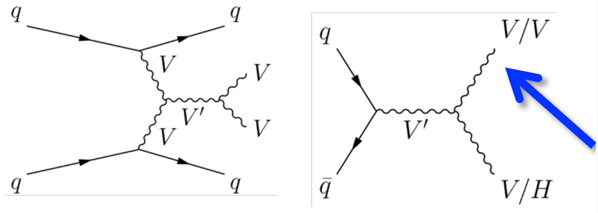
2308.08521

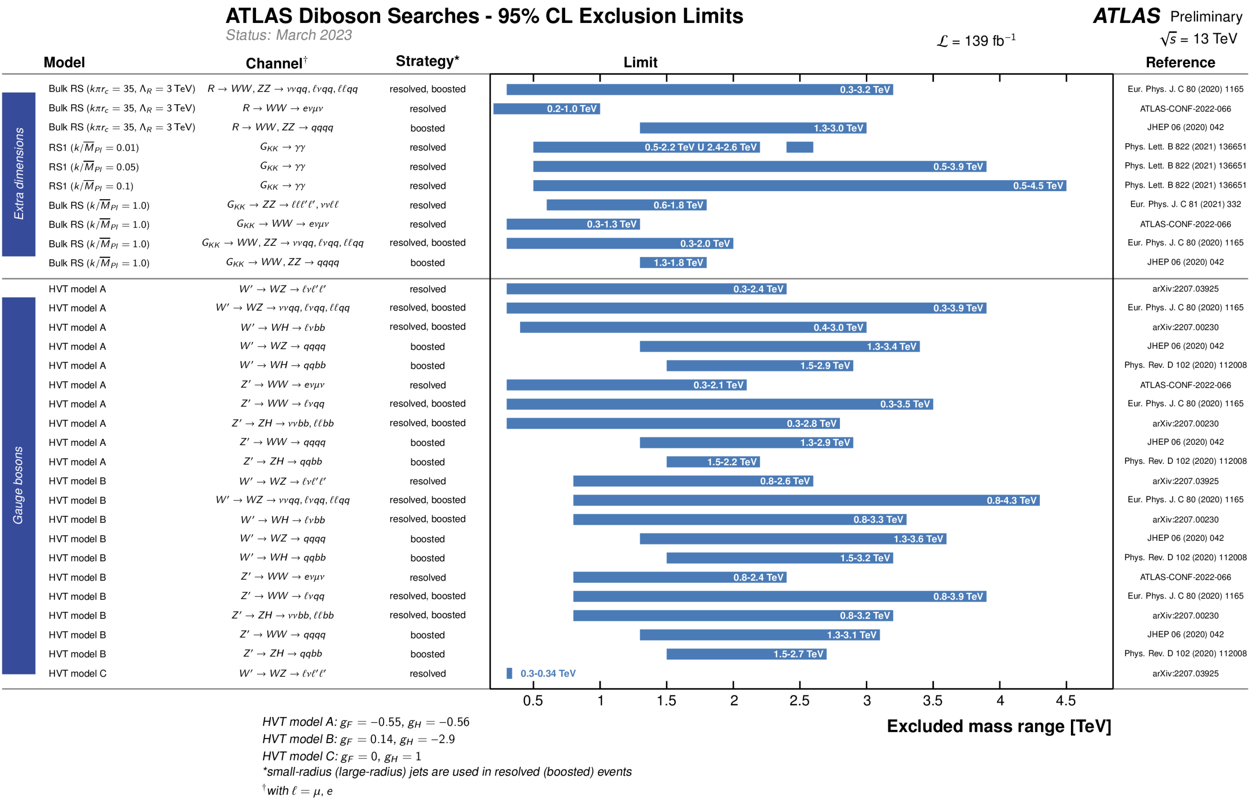
Extended gauge sector – Resonance (VV)

- **Predicted by many BSM models:**
  - ED (Randall-Sundrum (RS) Graviton), Heavy Vector Triplet (HVT: W′, Z′), DM mediator, …

- Spin-2 bulk **RS Graviton** $G_{KK} \to WW/ZZ$

- Heavy Vector Triplet **(HVT)**





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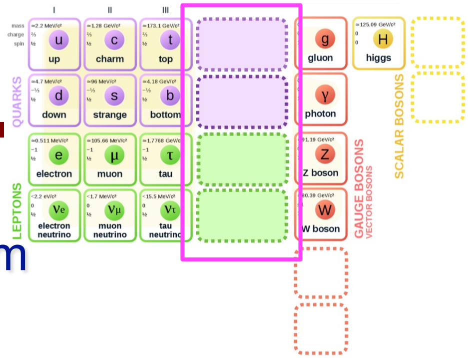
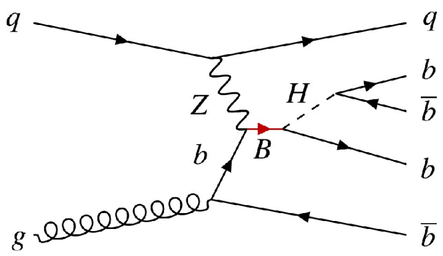
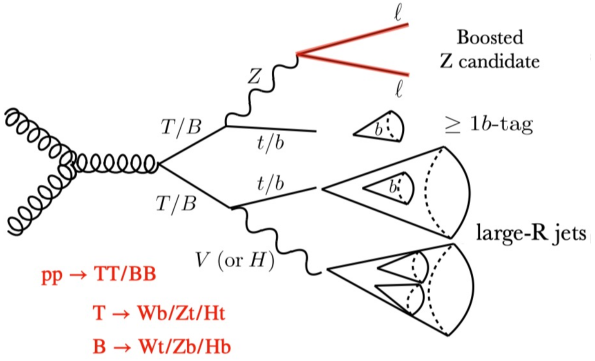
Extended fermion sector



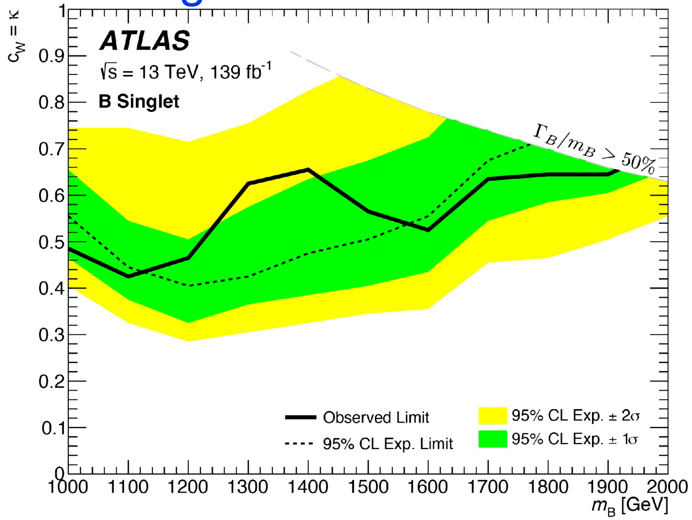
- Heavy Vector-like fermions (T, B, Tau …)
  - New heavy partner of top in loop to solve hierarchy problem
  - constraints on Singlet/Doublet BB, TT: 1.2-1.4 TeV
- Excited fermion (q*,l*,v* …)

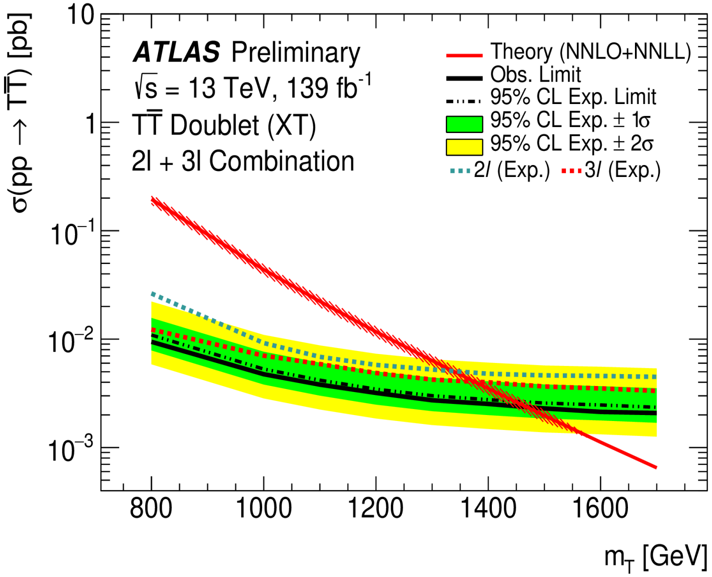




Singlet B

Double TT





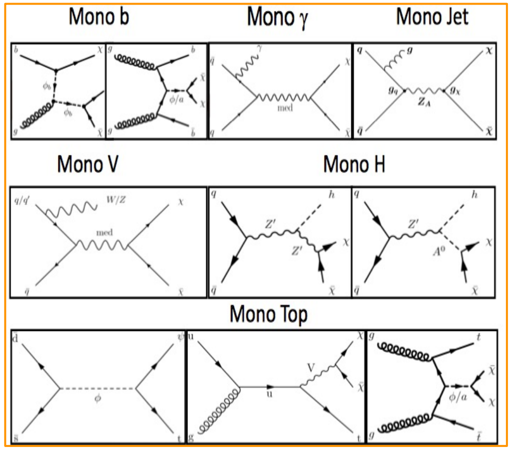
arXiv:2308.02595

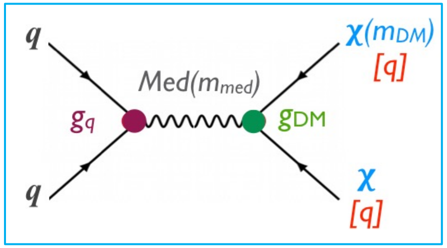
DM search at colliders

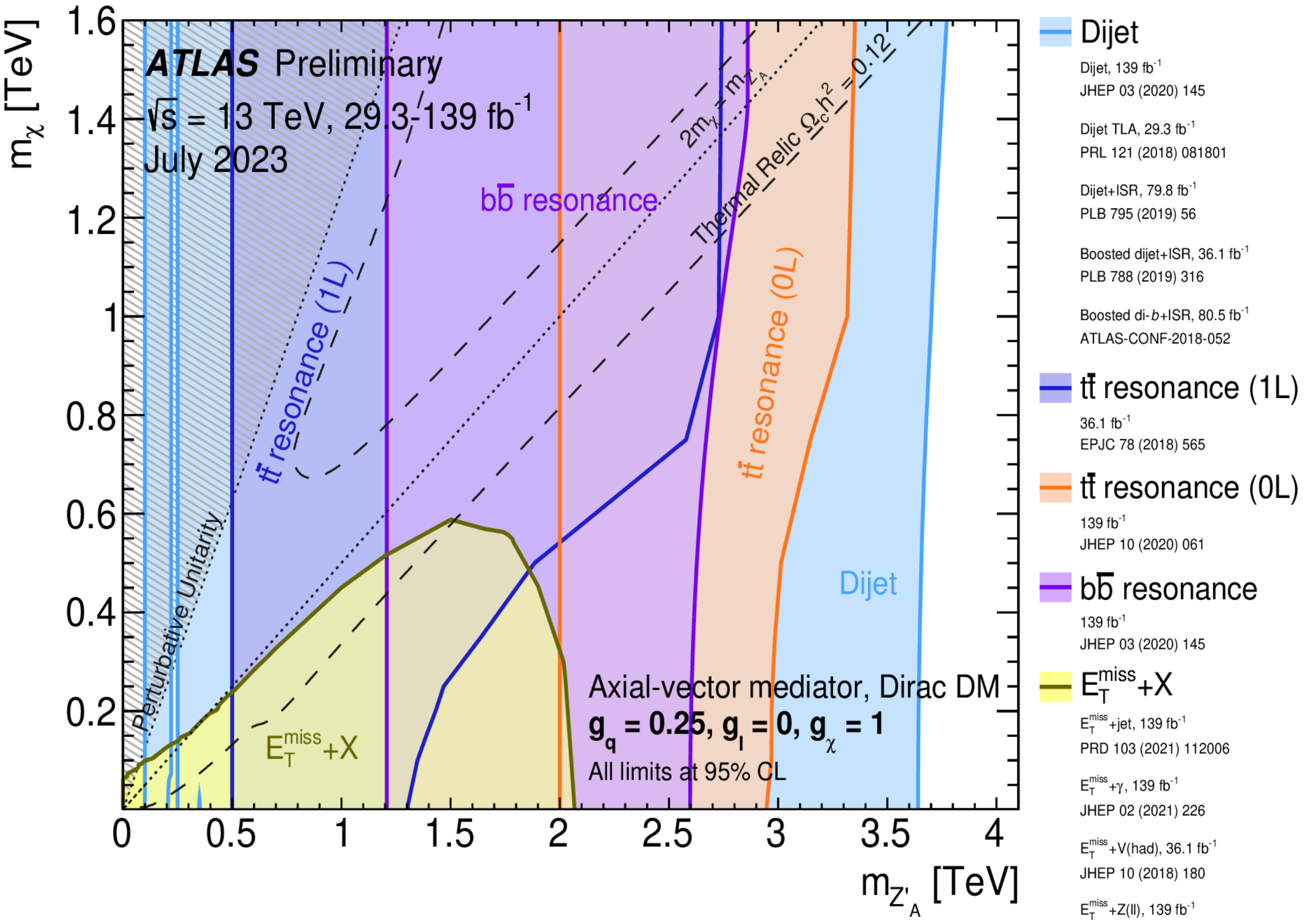
SUSY, Higgs portal DM,
simplified models,…

- **Simplified models**
  (mono-X, mediator)

ATL-PHYS-PUB-2023-018





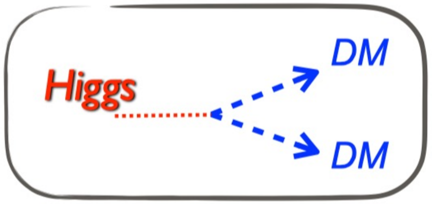


DM search at colliders

SUSY, Higgs portal DM, simplified models,…

Higgs portal DM:

Direct coupling H-DM will enhance H invisible decays (SM ~0.1%)



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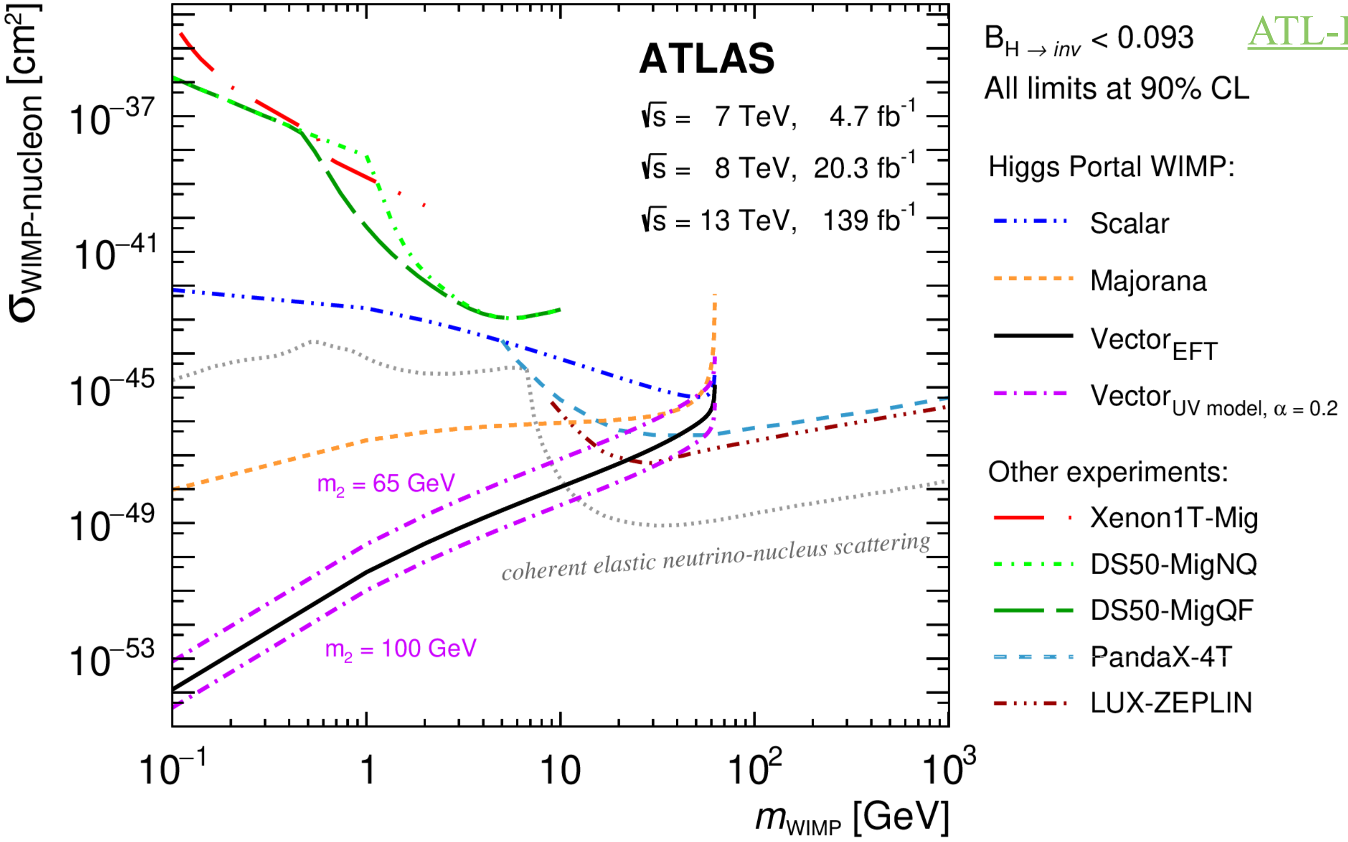


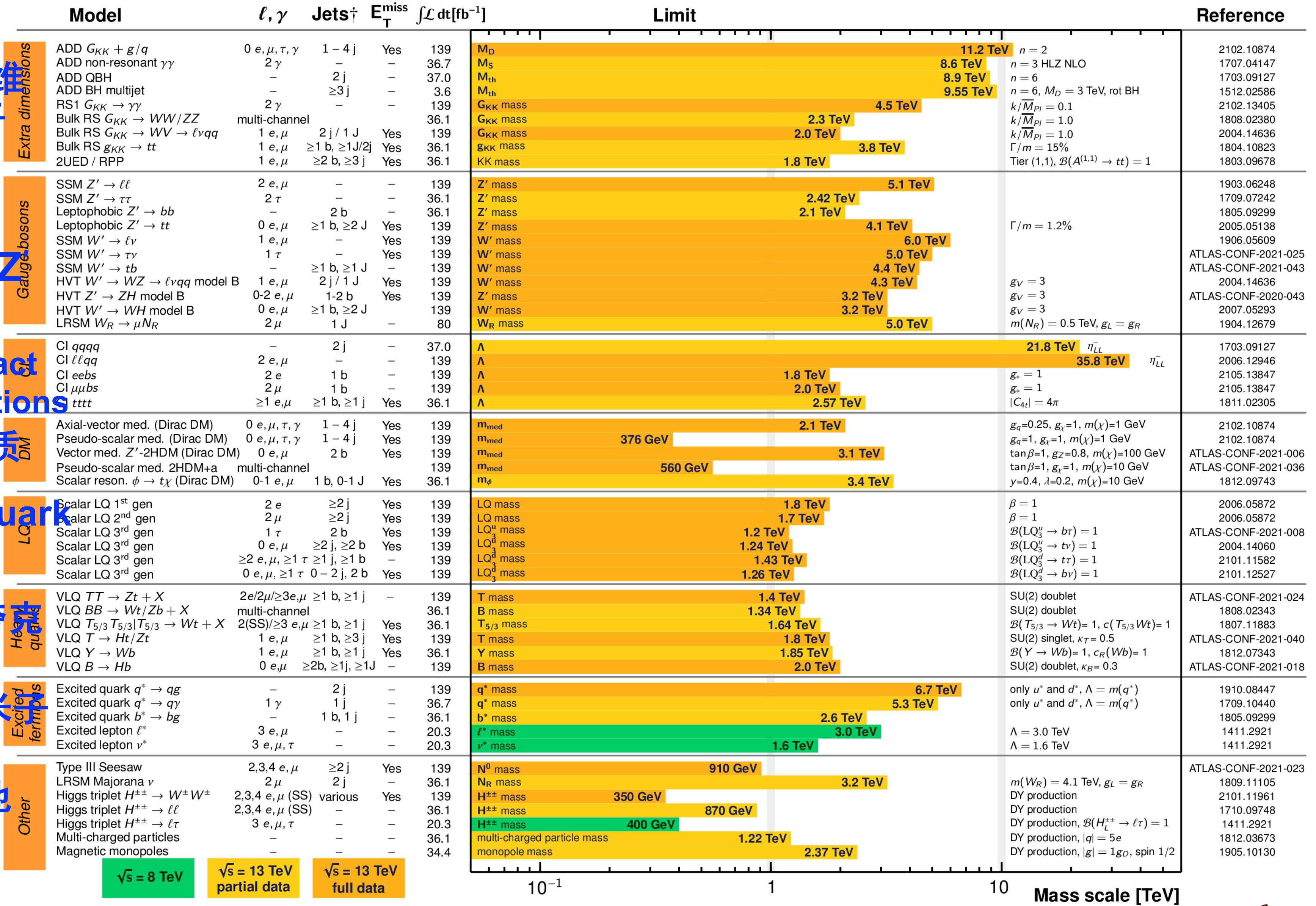
The combination of results (all H prod.) translated into xSec limit

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: July 2021

ATLAS Preliminary

$\int\mathcal{L}\,dt = (3.6 - 139)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ 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 $G_{KK} + g/q$	$0\ e, \mu, \tau, \gamma$	1 – 4 j	Yes	139	🟧 M_D	11.2 TeV	$n = 2$	2102.10874
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	36.7	🟨 M_S	8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	🟨 M_{th}	8.9 TeV	$n = 6$	1703.09127
	ADD BH multijet	–	≥3 j	–	3.6	🟨 M_{th}	9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	$2\ \gamma$	–	–	139	🟧 G_{KK} mass	4.5 TeV	$k/\overline{M}_{Pl} = 0.1$	2102.13405
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	🟨 G_{KK} mass	2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \to WV \to \ell\nu qq$	$1\ e, \mu$	2 j / 1 J	Yes	139	🟧 G_{KK} mass	2.0 TeV	$k/\overline{M}_{Pl} = 1.0$	2004.14636
	Bulk RS $g_{KK} \to tt$	$1\ e, \mu$	≥1 b, ≥1J/2j	Yes	36.1	🟨 g_{KK} mass	3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	$1\ e, \mu$	≥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 $Z' \to \ell\ell$	$2\ e, \mu$	–	–	139	🟧 Z' mass	5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	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 $Z' \to tt$	$0\ e, \mu$	≥1 b, ≥2 J	Yes	139	🟧 Z' mass	4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	139	🟧 W' mass	6.0 TeV		1906.05609
	SSM $W' \to \tau\nu$	$1\ \tau$	–	Yes	139	🟧 W' mass	5.0 TeV		ATLAS-CONF-2021-025
	SSM $W' \to tb$	–	≥1 b, ≥1 J	–	139	🟧 W' mass	4.4 TeV		ATLAS-CONF-2021-043
	HVT $W' \to WZ \to \ell\nu qq$ model B	$1\ e, \mu$	2 j / 1 J	Yes	139	🟧 W' mass	4.3 TeV	$g_V = 3$	2004.14636
	HVT $Z' \to ZH$ model B	0-2 e, μ	1-2 b	Yes	139	🟧 Z' mass	3.2 TeV	$g_V = 3$	ATLAS-CONF-2020-043
	HVT $W' \to WH$ model B	$0\ e, \mu$	≥1 b, ≥2 J		139	🟧 W' mass	3.2 TeV	$g_V = 3$	2007.05293
	LRSM $W_R \to \mu N_R$	$2\ \mu$	1 J	–	80	🟨 W_R mass	5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	🟨 Λ	21.8 TeV	η_{LL}^-	1703.09127
	CI $\ell\ell qq$	$2\ e, \mu$	–	–	139	🟧 Λ	35.8 TeV	η_{LL}^-	2006.12946
	CI $eebs$	$2\ e$	1 b	–	139	🟧 Λ	1.8 TeV	$g_* = 1$	2105.13847
	CI $\mu\mu bs$	$2\ \mu$	1 b	–	139	🟧 Λ	2.0 TeV	$g_* = 1$	2105.13847
	CI $tttt$	≥1 e,μ	≥1 b, ≥1 j	Yes	36.1	🟨 Λ	2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	1811.02305
DM	Axial-vector med. (Dirac DM)	$0\ e, \mu, \tau, \gamma$	1 – 4 j	Yes	139	🟧 m_{med}	2.1 TeV	g_q=0.25, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Pseudo-scalar med. (Dirac DM)	$0\ e, \mu, \tau, \gamma$	1 – 4 j	Yes	139	🟧 m_{med}	376 GeV	g_q=1, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Vector med. Z'-2HDM (Dirac DM)	$0\ e, \mu$	2 b	Yes	139	🟧 m_{med}	3.1 TeV	$\tan\beta$=1, g_Z=0.8, $m(\chi)$=100 GeV	ATLAS-CONF-2021-006
	Pseudo-scalar med. 2HDM+a	multi-channel			139	🟧 m_{med}	560 GeV	$\tan\beta$=1, g_χ=1, $m(\chi)$=10 GeV	ATLAS-CONF-2021-036
	Scalar reson. $\phi \to t\chi$ (Dirac DM)	0-1 e, μ	1 b, 0-1 J	Yes	36.1	🟨 m_ϕ	3.4 TeV	y=0.4, λ=0.2, $m(\chi)$=10 GeV	1812.09743
LQ	Scalar LQ 1st gen	$2\ e$	≥2 j	Yes	139	🟧 LQ mass	1.8 TeV	$\beta = 1$	2006.05872
	Scalar LQ 2nd gen	$2\ \mu$	≥2 j	Yes	139	🟧 LQ mass	1.7 TeV	$\beta = 1$	2006.05872
	Scalar LQ 3rd gen	$1\ \tau$	2 b	Yes	139	🟧 LQ_3^u mass	1.2 TeV	$\mathcal{B}(\mathrm{LQ}_3^u \to b\tau) = 1$	ATLAS-CONF-2021-008
	Scalar LQ 3rd gen	$0\ e, \mu$	≥2 j, ≥2 b	Yes	139	🟧 LQ_3^u mass	1.24 TeV	$\mathcal{B}(\mathrm{LQ}_3^u \to t\nu) = 1$	2004.14060
	Scalar LQ 3rd gen	≥2 e, μ, ≥1 τ	≥1 j, ≥1 b	–	139	🟧 LQ_3^d mass	1.43 TeV	$\mathcal{B}(\mathrm{LQ}_3^d \to t\tau) = 1$	2101.11582
	Scalar LQ 3rd gen	$0\ e, \mu$, ≥1 τ	0 – 2 j, 2 b	Yes	139	🟧 LQ_3^d mass	1.26 TeV	$\mathcal{B}(\mathrm{LQ}_3^d \to b\nu) = 1$	2101.12527
Heavy quarks	VLQ $TT \to Zt + X$	$2e/2\mu/{\geq}3e,\mu$	≥1 b, ≥1 j	–	139	🟧 T mass	1.4 TeV	SU(2) doublet	ATLAS-CONF-2021-024
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	🟨 B mass	1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3}\lvert T_{5/3} \to Wt + X$	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	1807.11883
	VLQ $T \to Ht/Zt$	$1\ e, \mu$	≥1 b, ≥3 j	Yes	139	🟧 T mass	1.8 TeV	SU(2) singlet, κ_T= 0.5	ATLAS-CONF-2021-040
	VLQ $Y \to Wb$	$1\ e, \mu$	≥1 b, ≥1 j	Yes	36.1	🟨 Y mass	1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb$	$0\ e,\mu$	≥2b, ≥1j, ≥1J	–	139	🟧 B mass	2.0 TeV	SU(2) doublet, κ_B= 0.3	ATLAS-CONF-2021-018
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	139	🟧 q^* mass	6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \to q\gamma$	$1\ \gamma$	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^*	$3\ e, \mu$	–	–	20.3	🟩 ℓ^* mass	3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	$3\ e, \mu, \tau$	–	–	20.3	🟩 ν^* mass	1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	2,3,4 e, μ	≥2 j	Yes	139	🟧 N^0 mass	910 GeV		ATLAS-CONF-2021-023
	LRSM Majorana ν	$2\ \mu$	2 j	–	36.1	🟨 N_R mass	3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to W^\pm W^\pm$	2,3,4 e, μ (SS)	various	Yes	139	🟧 $H^{\pm\pm}$ mass	350 GeV	DY production	2101.11961
	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 $H^{\pm\pm} \to \ell\tau$	$3\ e, \mu, \tau$	–	–	20.3	🟩 $H^{\pm\pm}$ mass	400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Multi-charged particles	–	–	–	36.1	🟨 multi-charged particle mass	1.22 TeV	DY production, $\lvert q\rvert = 5e$	1812.03673
	Magnetic monopoles	–	–	–	34.4	🟨 monopole mass	2.37 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1905.10130

🟩 $\sqrt{s}$ = 8 TeV 🟨 $\sqrt{s}$ = 13 TeV partial data 🟧 $\sqrt{s}$ = 13 TeV full data

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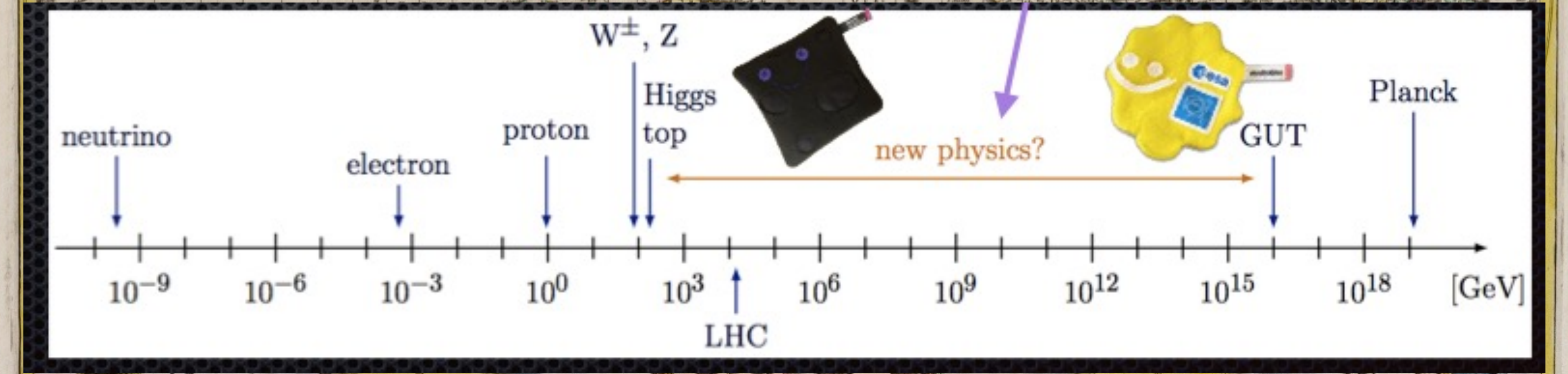
*Only a selection of the available mass limits on new states or phenomena is shown.

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

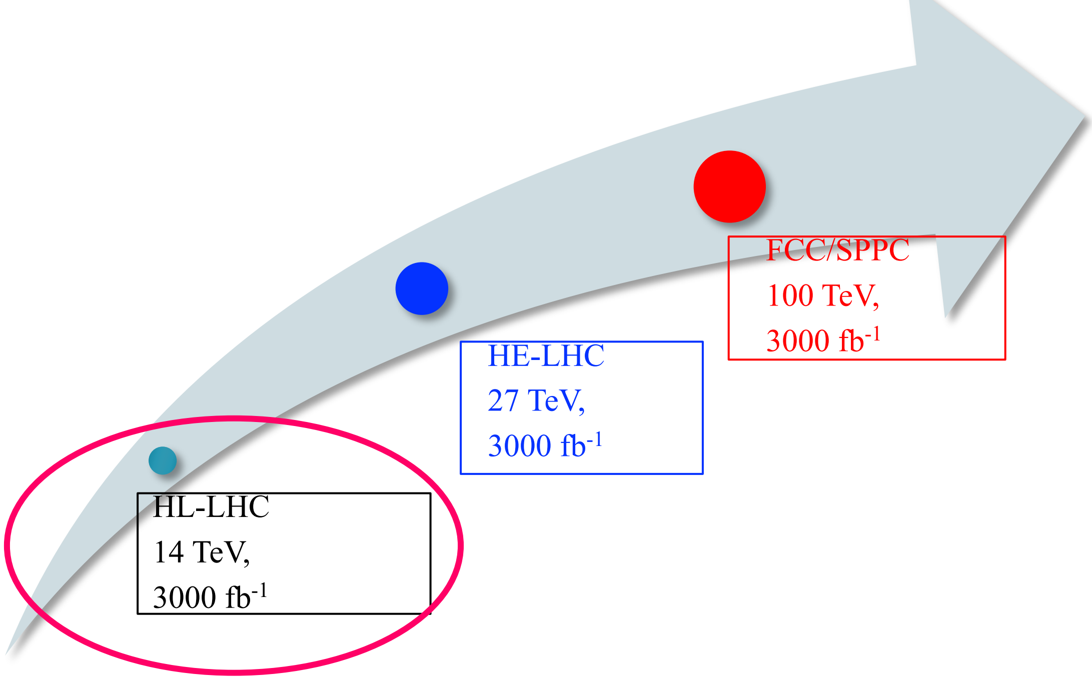
The journey into new physics territory has just only begun, and for sure, exciting times are ahead of us! (only ~5% dataset ready)



J Blaeu 1664

Prospects at Future Proton colliders

Future Proton Colliders



- **Long term prospects for 2 more collider scenarios have been studied (14, 27, 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**

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

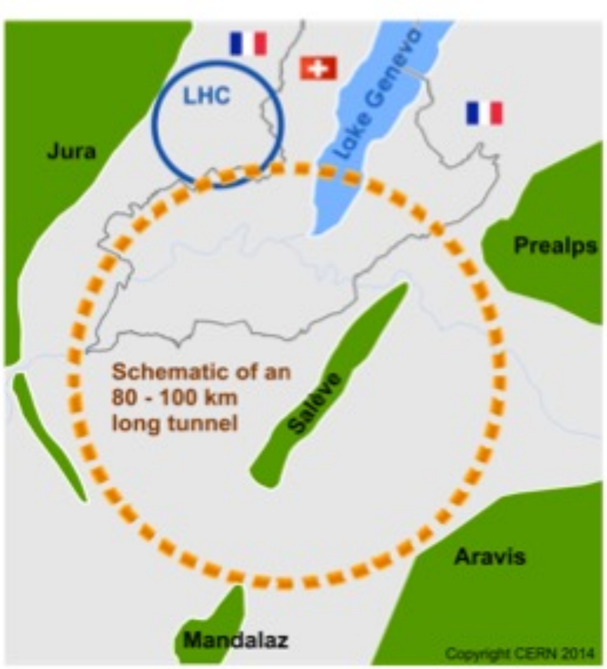
HL-LHC: E_{CM} = 14 TeV, 3 ab^{-1}, 2026~2035… (formally approved as *project* by CERN council last week)

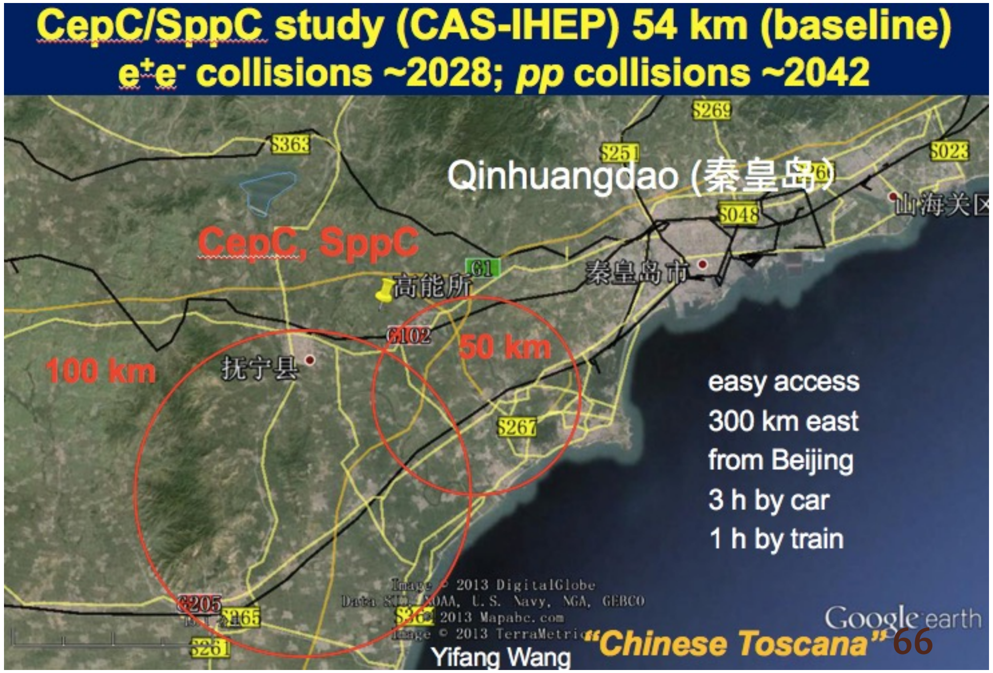
Future Circular Collider FCC-hh (CERN):

- E_{CM} ~ 100 TeV in 100 km ring, $L \sim 2 \times 10^{35}$ $s^{-1}cm^{-2}$
- ~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, $L \sim 1 \times 10^{35}$ $s^{-1}cm^{-2}$
- Requires very high gradient dipole magnets ~ 20 T
- Possible start of physics ~ 2042



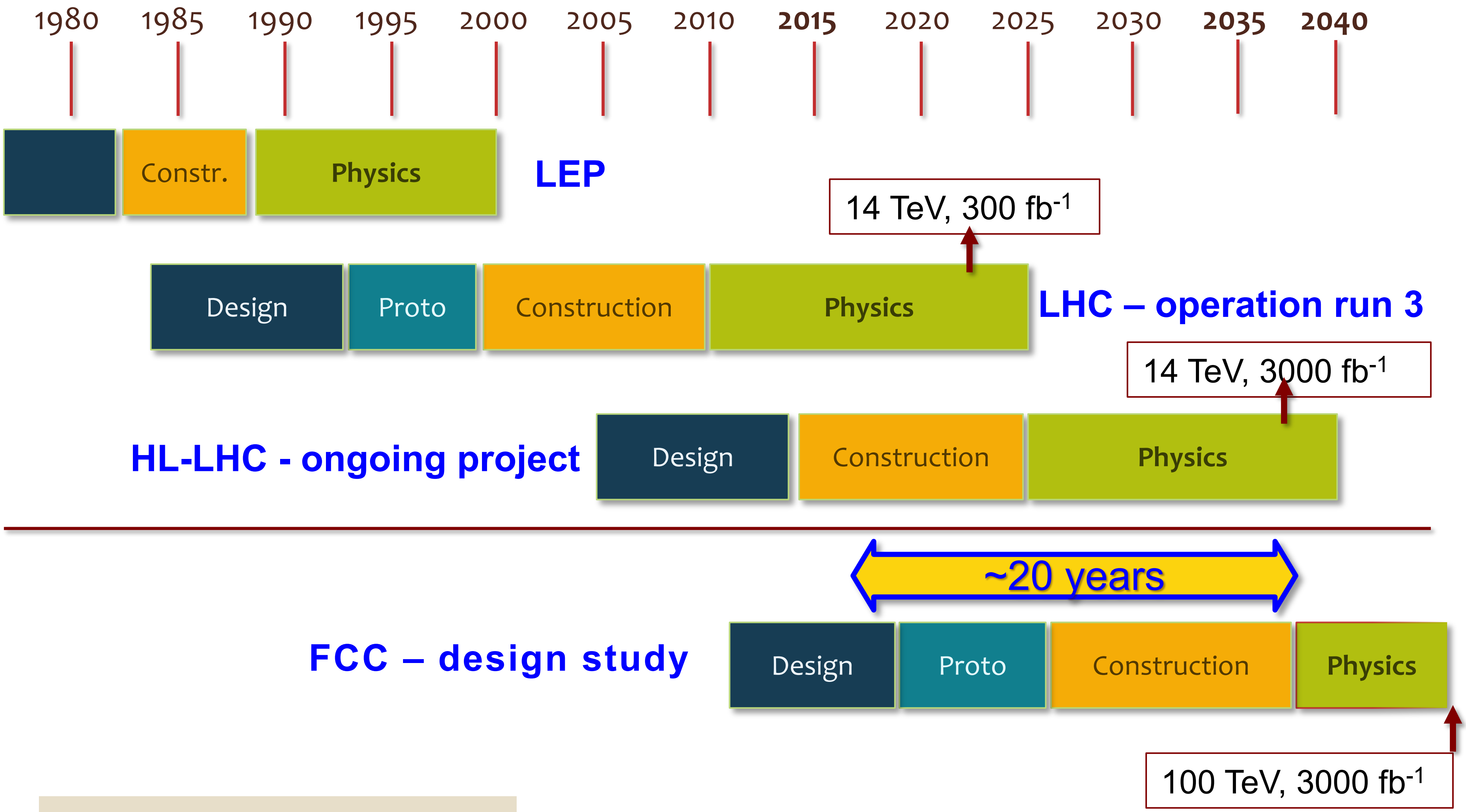

CepC/SppC study (CAS-IHEP) 54 km (baseline)
e^+e^- collisions ~2028; *pp* collisions ~2042

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

Yifang Wang

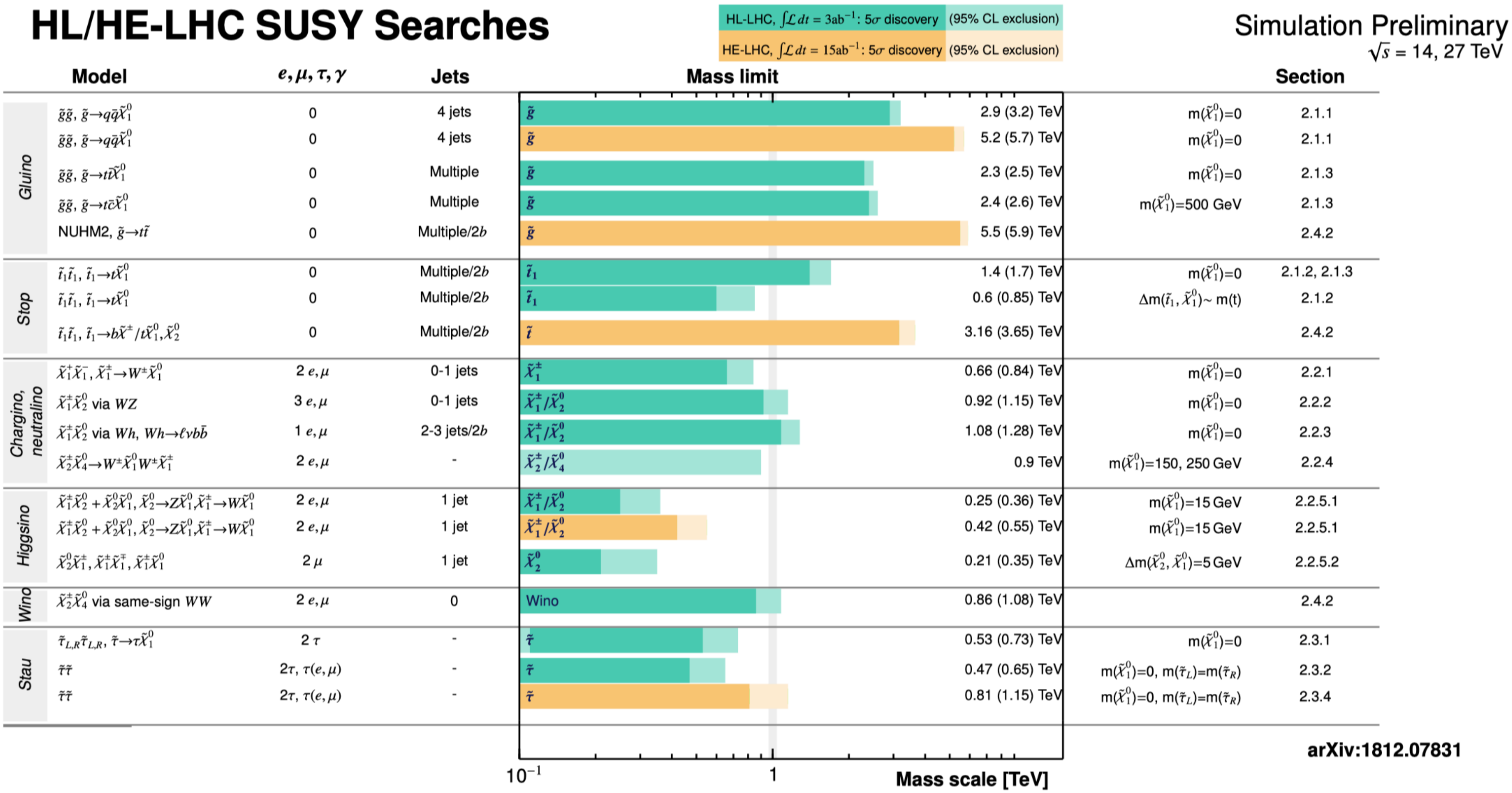
“Chinese Toscana”

CERN Circular Colliders & FCC

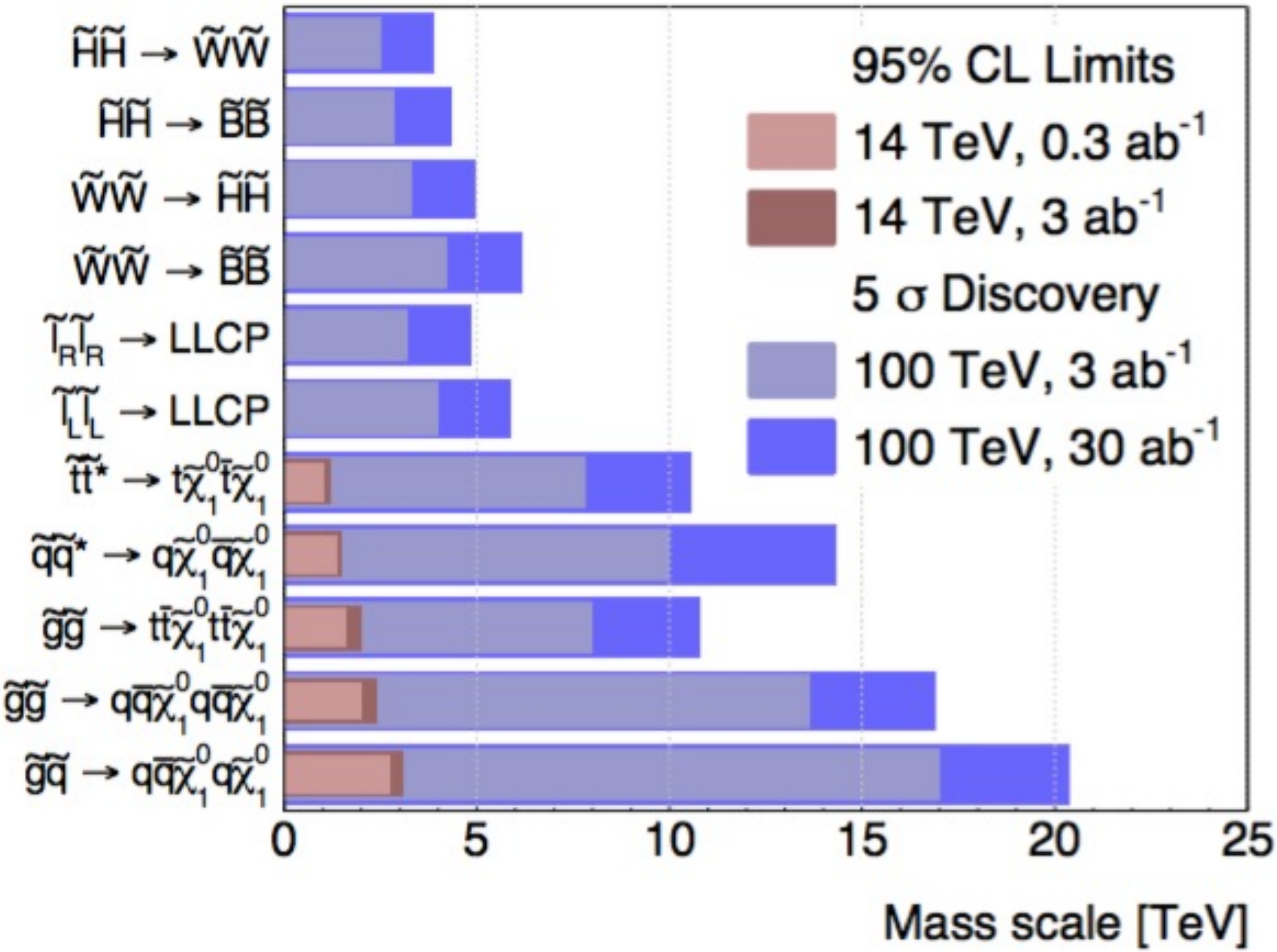


See Michael's talk

Prospects at HL/HE-LHC (summary)



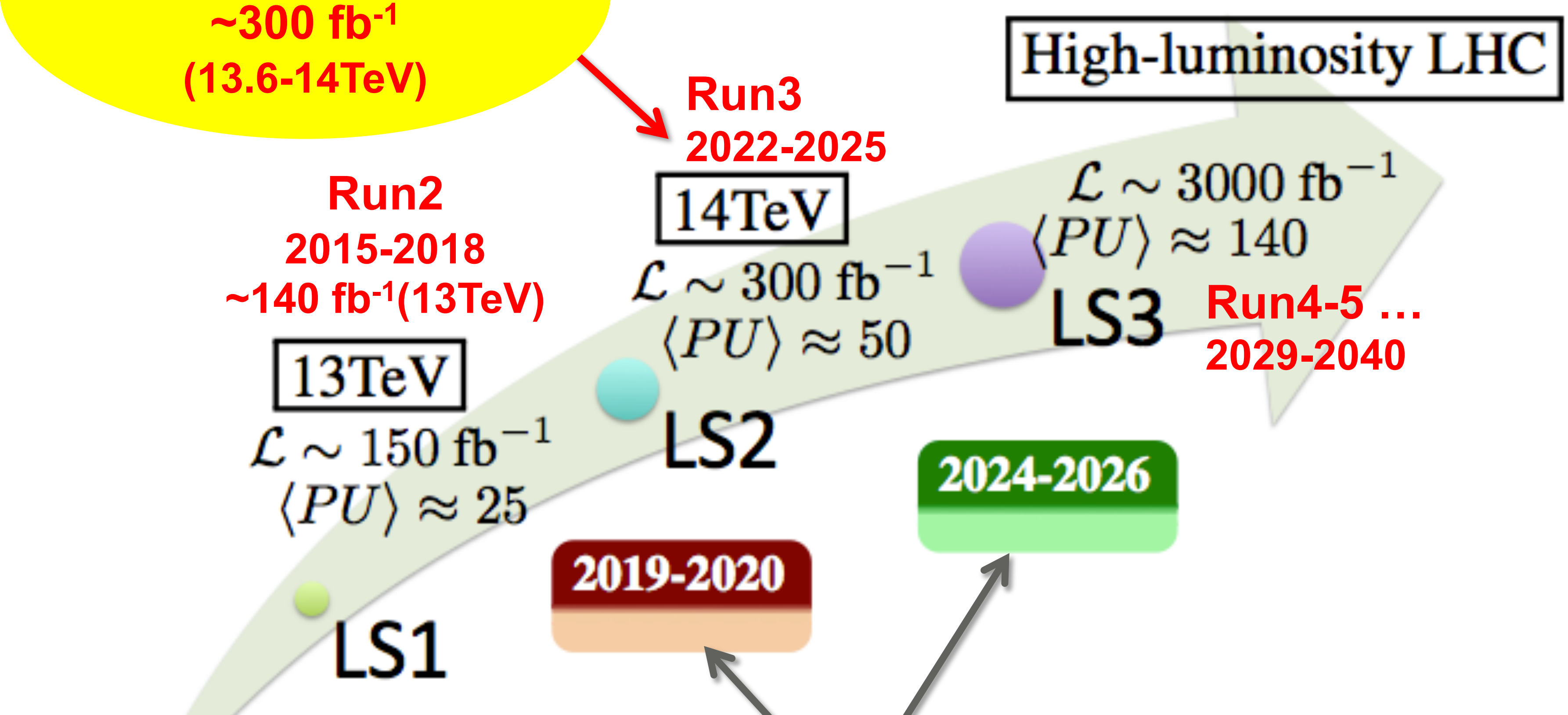
- **In most BSM scenarios, we expect the HL-LHC will increase the present reach in mass and coupling by 20 – 50% (half Run-2 data)**
- **If there are some excess, will move to HE-LHC with double sqrt{s}**


$\tilde{H}\tilde{H} \to \tilde{W}\tilde{W}$
$\tilde{H}\tilde{H} \to \tilde{B}\tilde{B}$
$\tilde{W}\tilde{W} \to \tilde{H}\tilde{H}$
$\tilde{W}\tilde{W} \to \tilde{B}\tilde{B}$
$\tilde{l}_R\tilde{l}_R \to$ LLCP
$\tilde{l}_L\tilde{l}_L \to$ LLCP
$\tilde{t}\tilde{t}^* \to t\tilde{\chi}_1^0\bar{t}\tilde{\chi}_1^0$
$\tilde{q}\tilde{q}^* \to q\tilde{\chi}_1^0\bar{q}\tilde{\chi}_1^0$
$\tilde{g}\tilde{g} \to t\bar{t}\tilde{\chi}_1^0 t\bar{t}\tilde{\chi}_1^0$
$\tilde{g}\tilde{g} \to q\bar{q}\tilde{\chi}_1^0 q\bar{q}\tilde{\chi}_1^0$
$\tilde{g}\tilde{q} \to q\bar{q}\tilde{\chi}_1^0 q\tilde{\chi}_1^0$
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]

New World !!!

The results are based on 36-140 fb^{-1} @ 13 TeV (RUN2 2015-2018) <5% of total

We are here :
2022-2025:
~300 fb^{-1}
(13.6-14TeV)



High-luminosity LHC

Run1

8TeV

2010-2012
~25 fb^{-1}

Run2
2015-2018
~140 fb^{-1}(13TeV)

13TeV

$\mathcal{L} \sim 150\ \text{fb}^{-1}$
$\langle PU \rangle \approx 25$

Run3
2022-2025

14TeV

$\mathcal{L} \sim 300\ \text{fb}^{-1}$
$\langle PU \rangle \approx 50$

$\mathcal{L} \sim 3000\ \text{fb}^{-1}$
$\langle PU \rangle \approx 140$

Run4-5 …
2029-2040

LS1

LS2

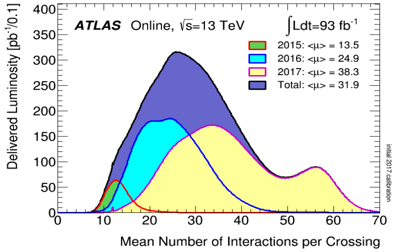
LS3

2013-2014

2019-2020

2024-2026

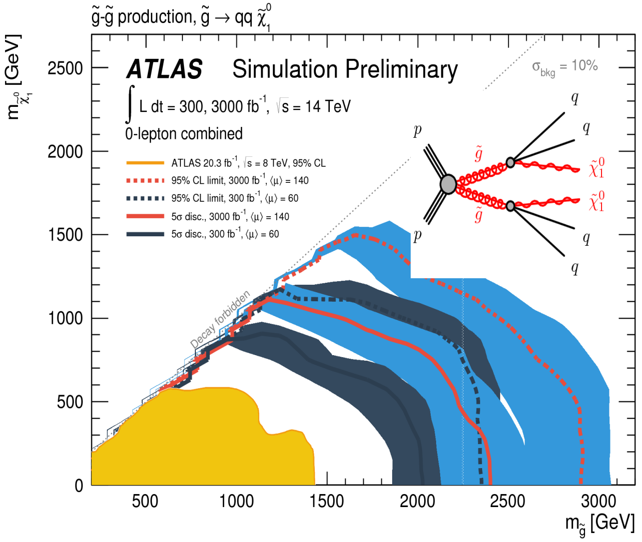
Long Stop

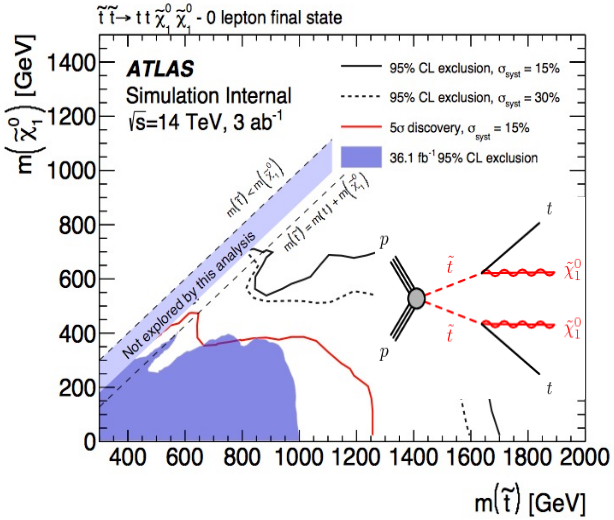


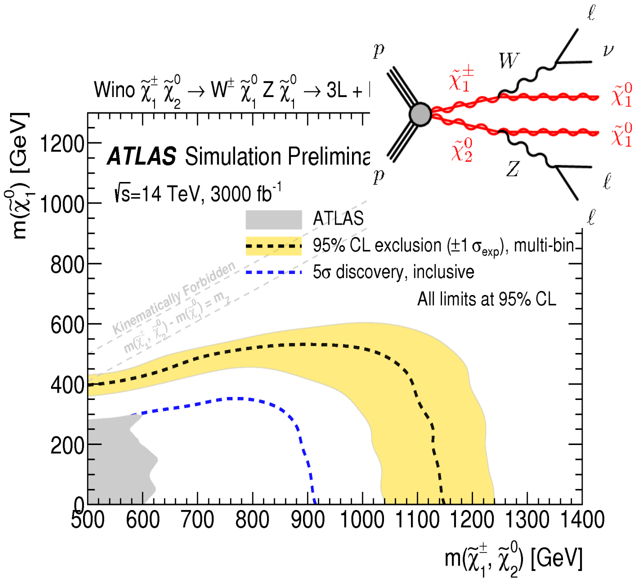
Prospects at HL-LHC (summary)

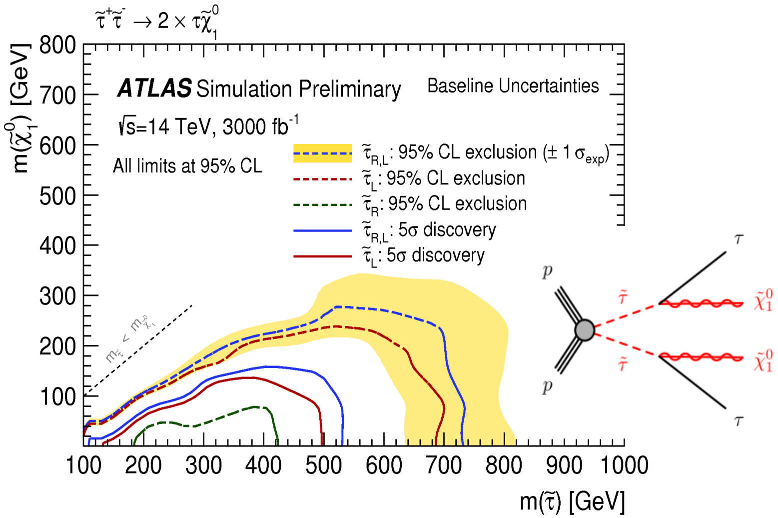
Discovery potential with 3000 fb^{-1}@14TeV

Gluinos ~ 2.5 TeV; Stop ~ 1.2 TeV ; EWKinos ~ 0.9 TeV; Staus ~ 0.5 TeV









In most BSM scenarios, we expect the HL-LHC will increase the present reach in mass and coupling by 20 – 50% and potentially discover new physics that is currently unconstrained.

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

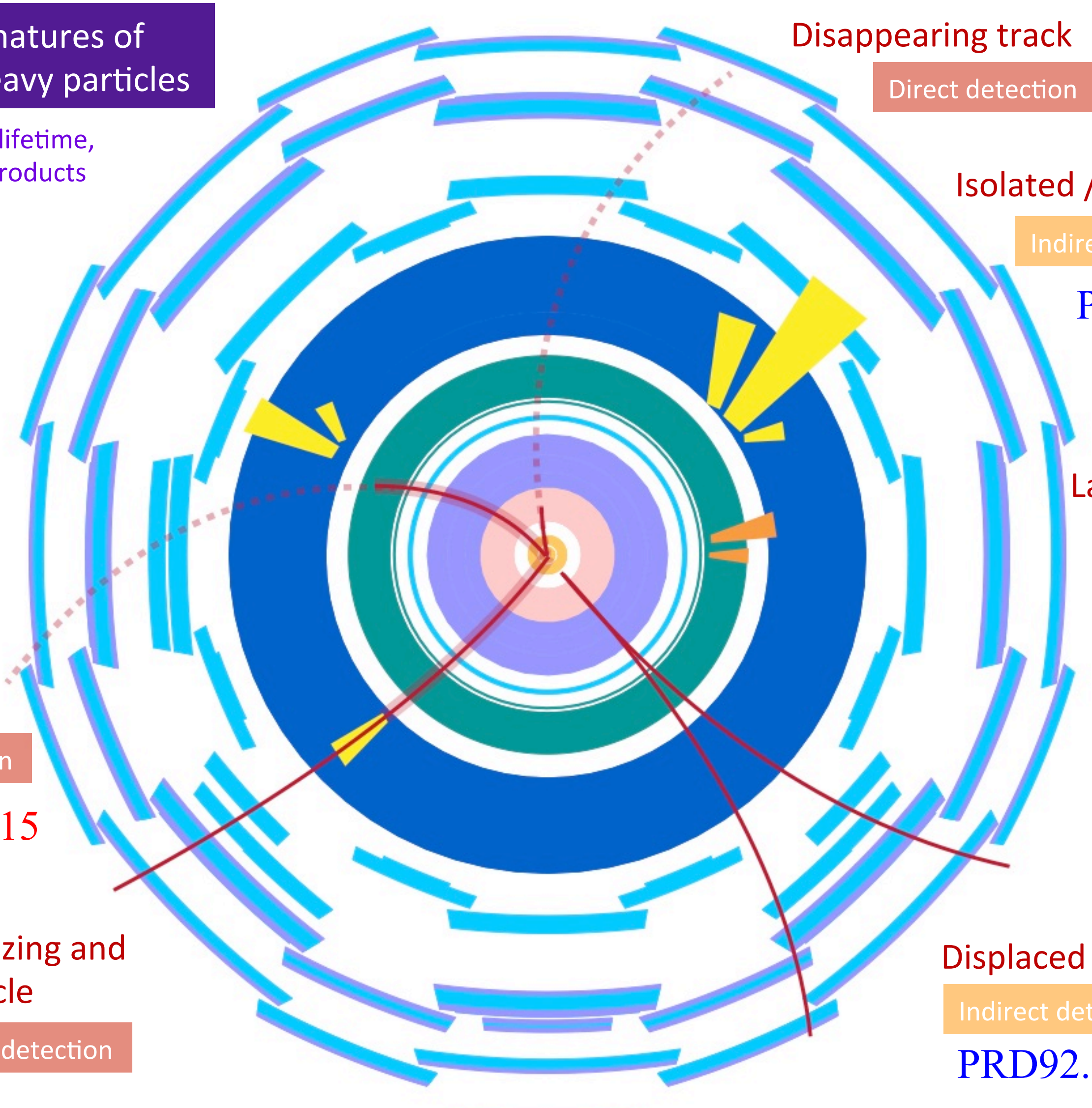
The Intensity Frontier

The Cosmic Frontier

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

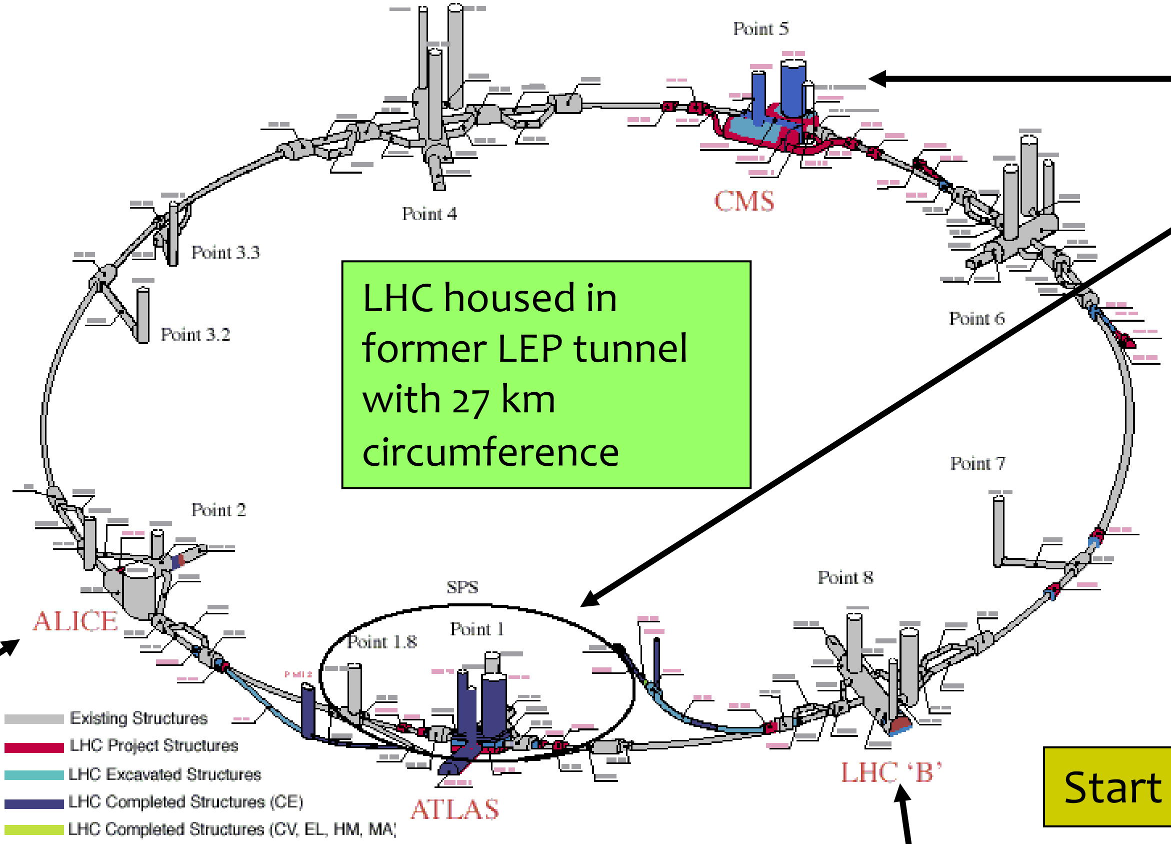
Indirect detection

PRD92.072004

LHC

pp

- $\sqrt{s}$ = 14 TeV (7 times higher than Tevatron/Fermilab)
  → search for new massive particles up to m ~ 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

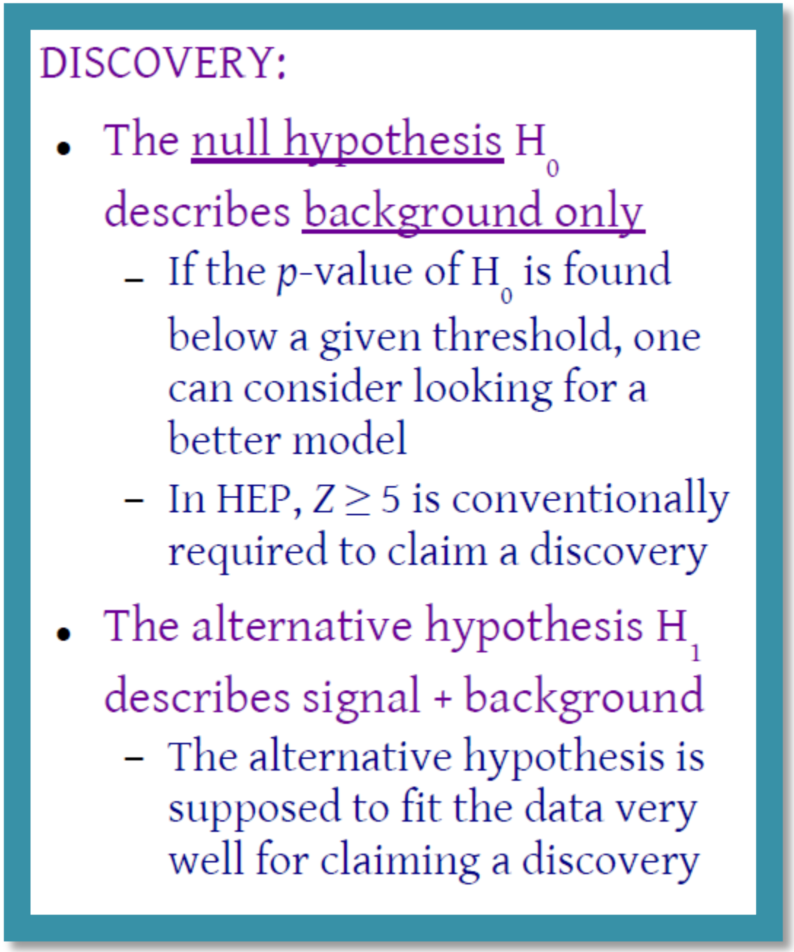
ALICE :
heavy ions

LHCb :
pp, B-physics

Start : Winter 2009

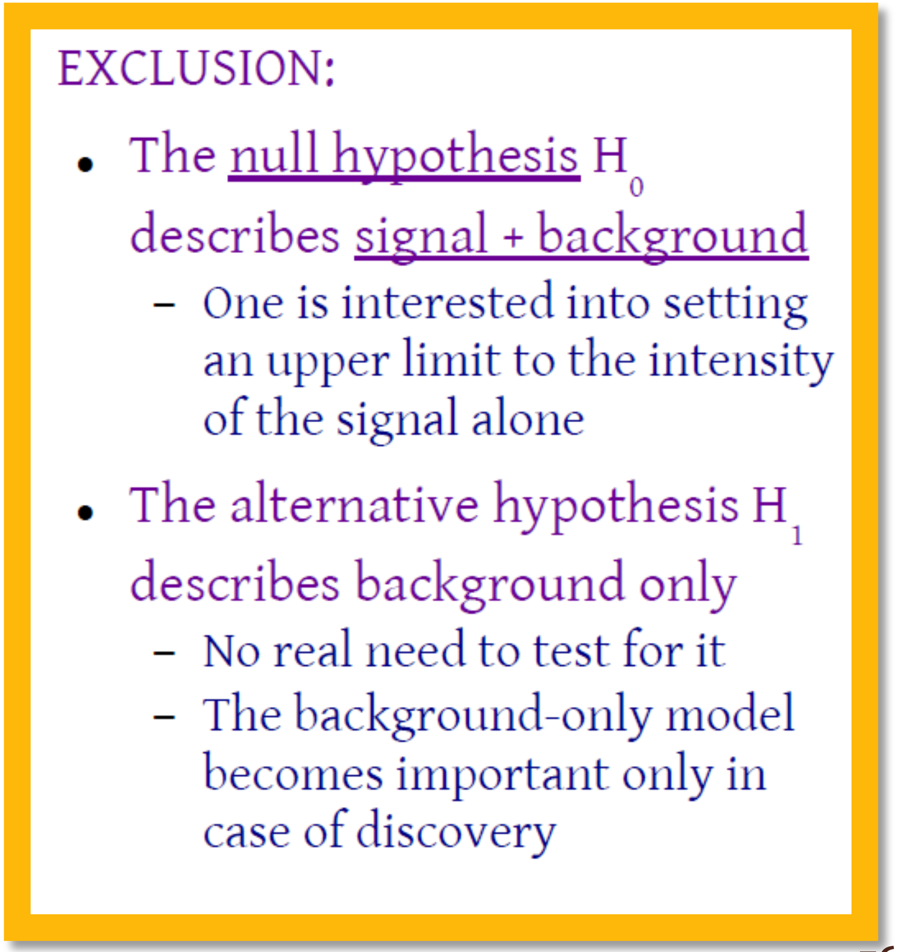
Discovery and exclusion

- 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

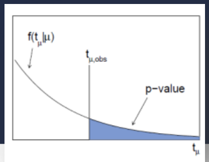
Construct test statistics t_μ based on likelihood ratio λ:

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

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

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

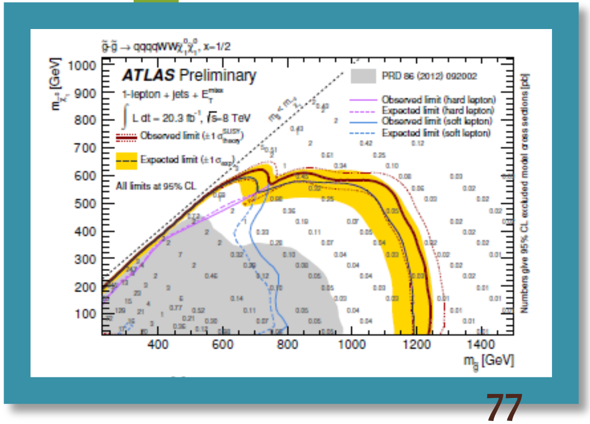
$$p_\mu = \int_{t_{\mu,\mathrm{obs}}}^{\infty} f(t_\mu|\mu)\, dt_\mu$$

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

$$\mathrm{CL_s} = \frac{\mathrm{CL_{s+b}}}{\mathrm{CL_b}} = \frac{p_{s+b}}{1-p_b}$$

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.

The Higgs mechanism, an analogy…

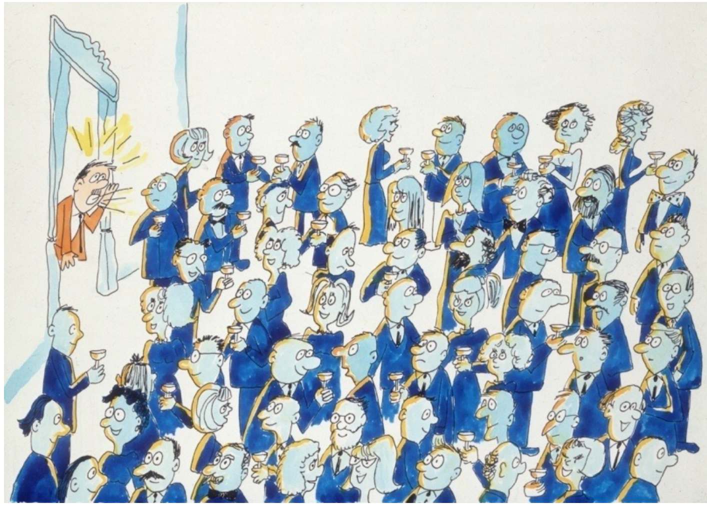
D. Miller
(UC London)

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...

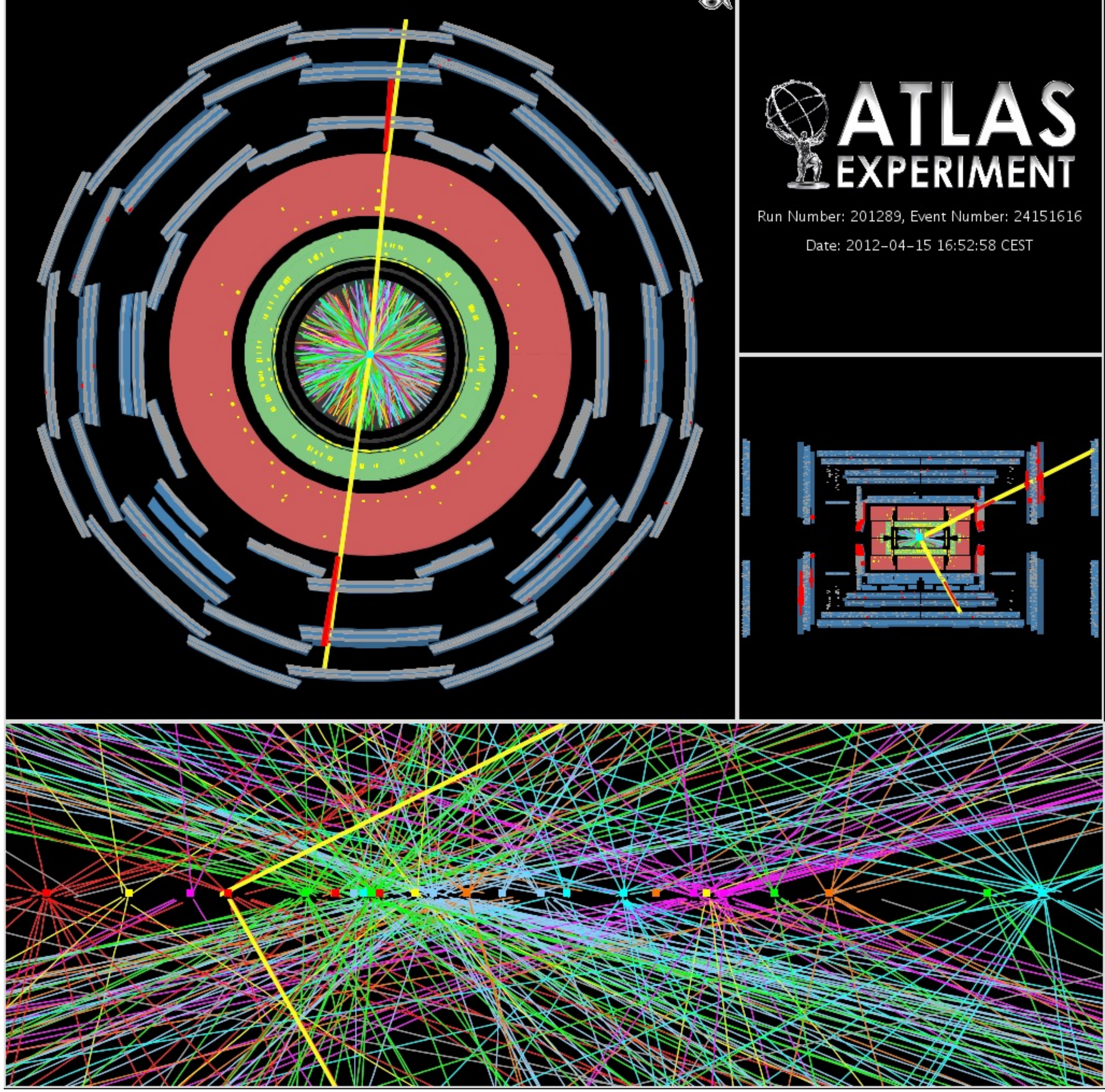


Somebody whispers a rumour into the room...

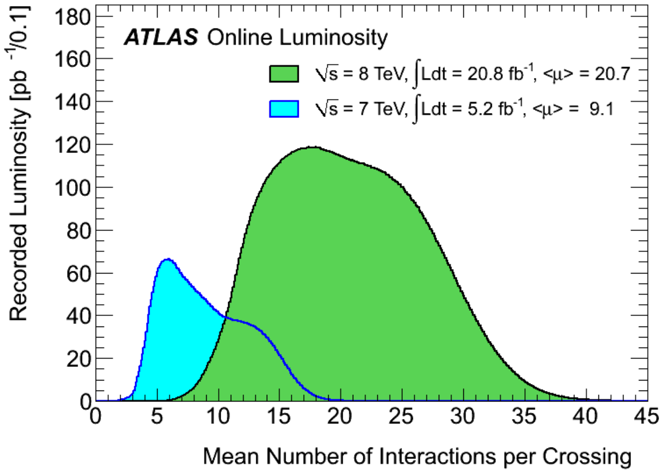
... and the field starts to get excited and interact with itself giving birth to a massive particle

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

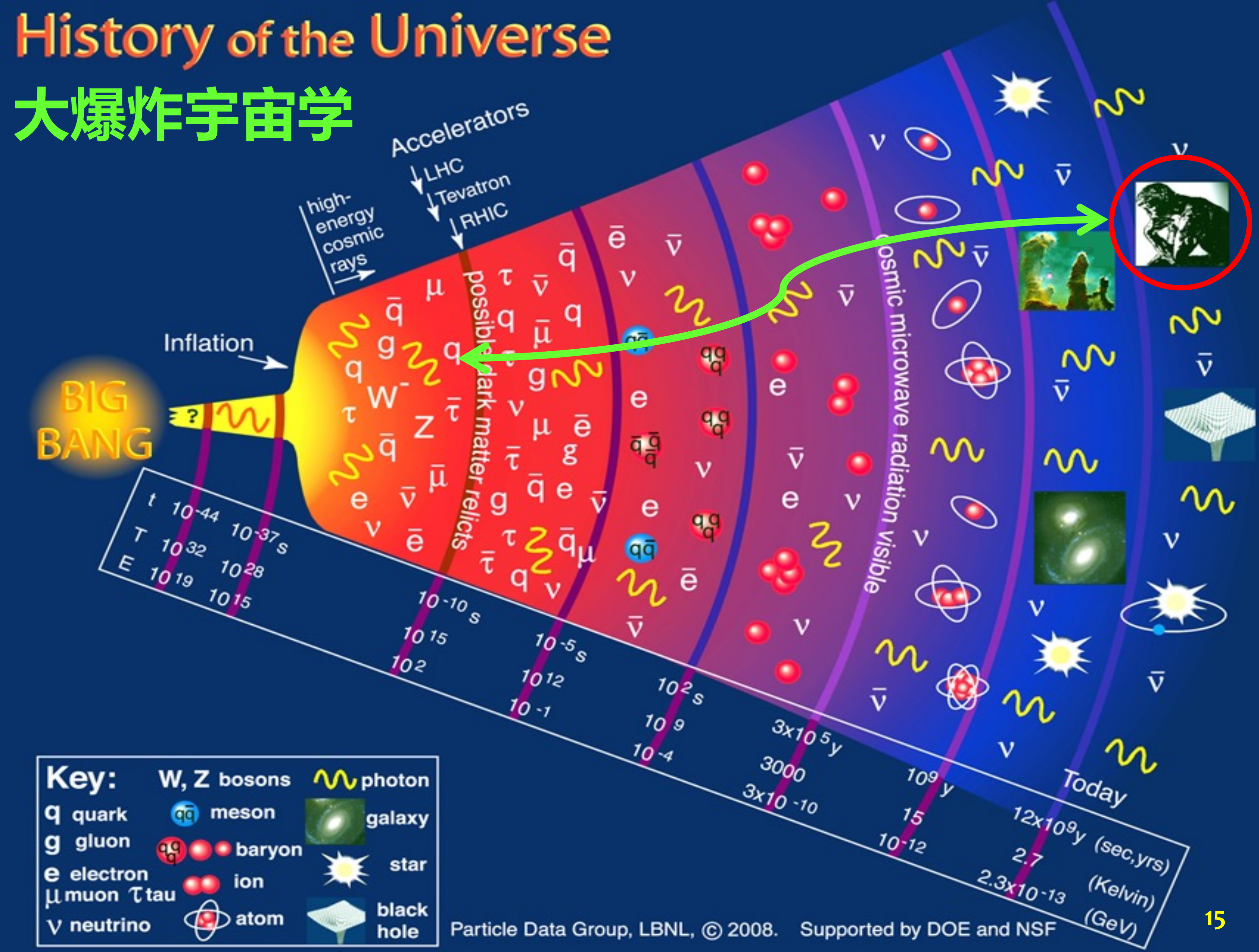
- Trigger
- Pile-up
- Maintain accuracy of the the measurements in this environment



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

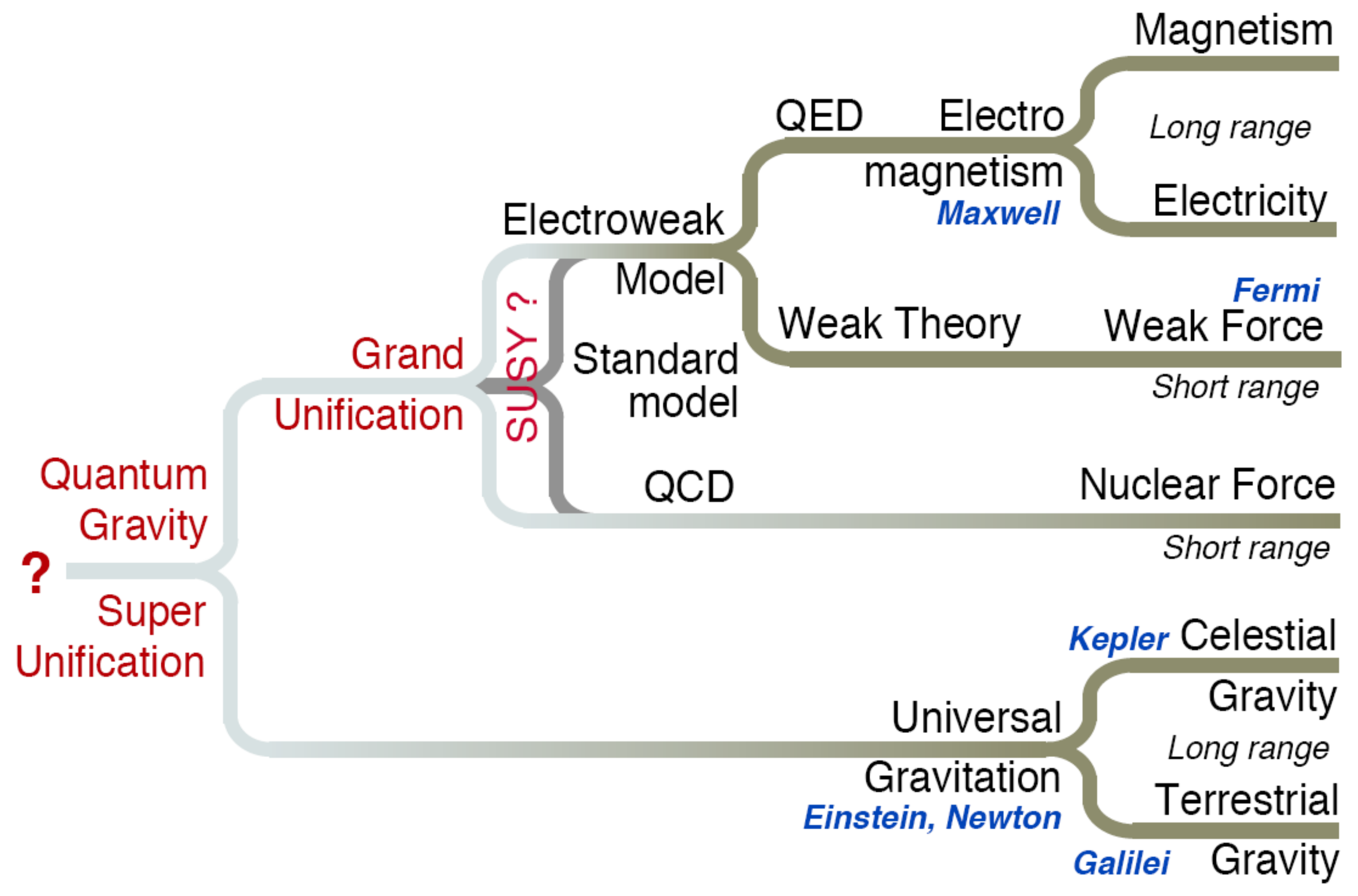


大爆炸宇宙学

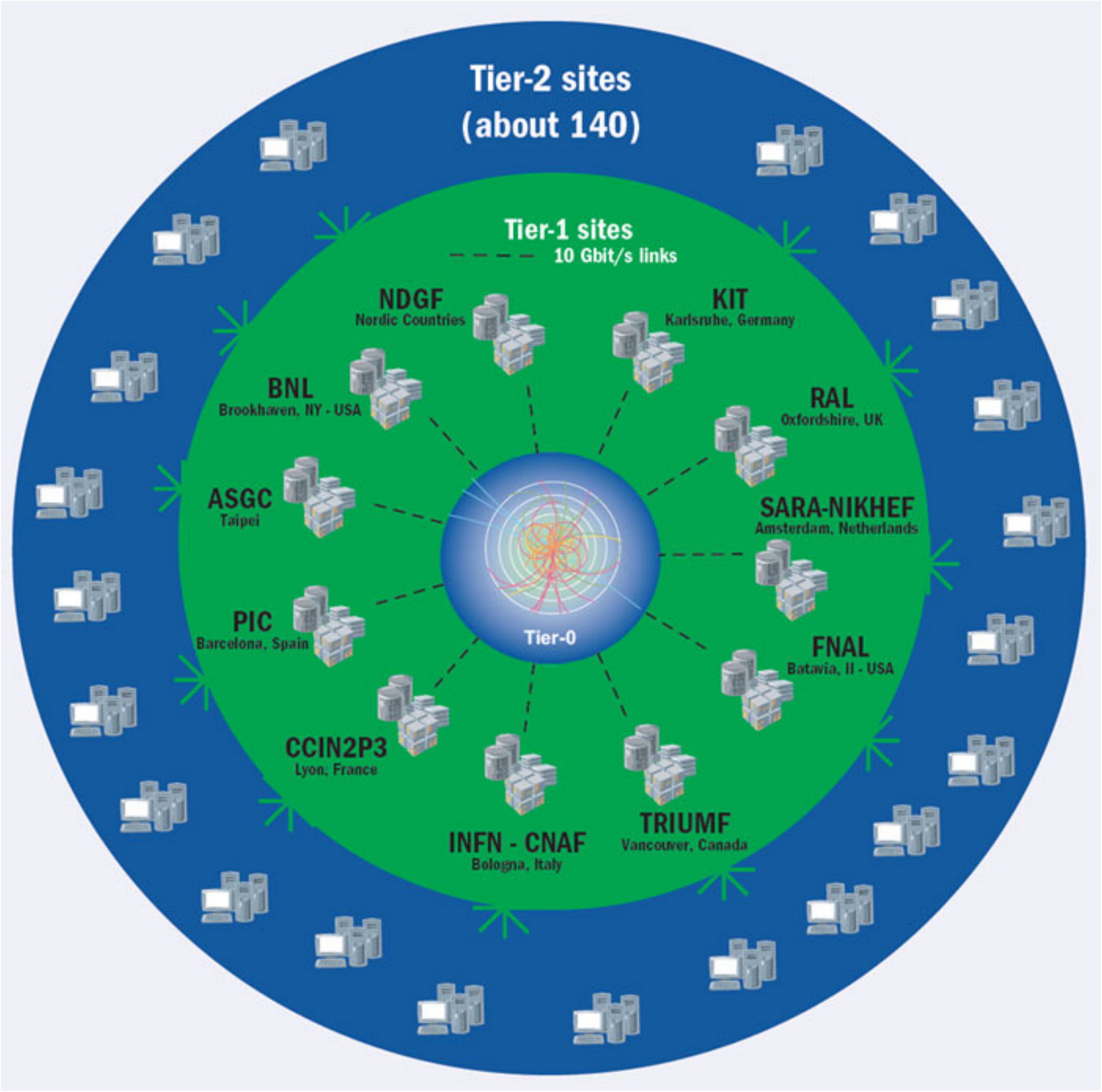


Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

Unification of Forces



The Worldwide LHC Computing Grid (WLCG)



WLCG
Worldwide LHC Computing Grid

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 …