科创计划-新物理2023

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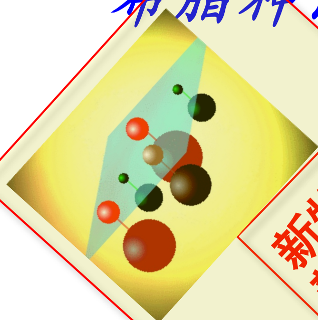
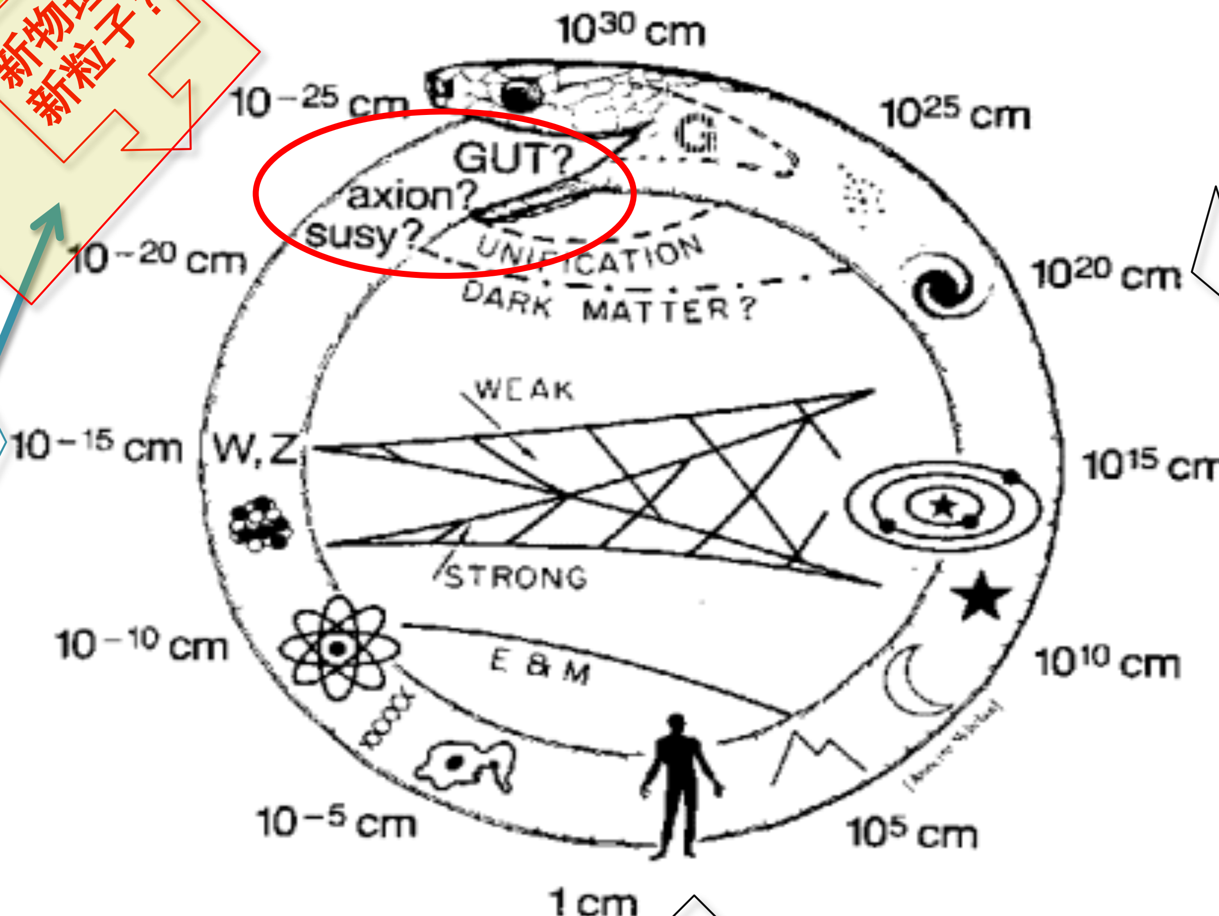
科创计划项目简介

1. **项目简介及预期目标：** 目前比较成功的粒子物理标准模型依然存在一系列问题，比如无法解释中微子质量、暗物质，不能统一几种相互作用等，因而超出标准模型的新物理研究一直是粒子物理研究的热点，也是世界上能量最高的大型强子对撞机LHC的热门课题。本项目拟利用LHC上的ATLAS实验数据开展相关的新物理寻找的实验研究，比如暗物质、长寿命粒子、超对称粒子等。
2. **使用的实验方法、仪器设备、数据软件等：** 本项目将使用ATLAS实验数据和分析软件，利用C++和Root等进行物理分析。
3. **对学生专业知识背景等方面的要求**：要求学生具有大学物理基础，一定的python和C++程序的基础，对粒子物理和机器学习有一定兴趣。
4. **预期项目成果和收获：** 学会高能物理数据分析的基本方法和技巧，得到初步的物理分析结果。

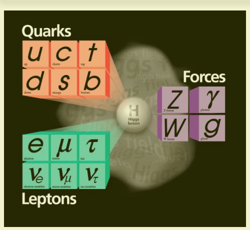
希腊神话中的怪物“Uroboros”与格拉肖的“宇宙圈”



新物理，新粒子？

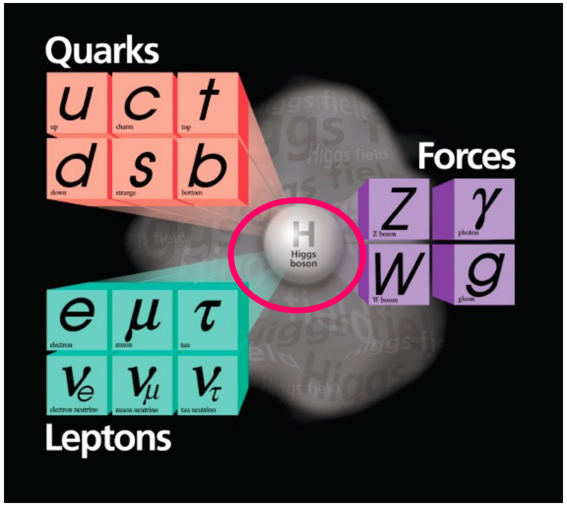


粒子“微观世界”，强弱相互作用主导，理论模型是标准模型

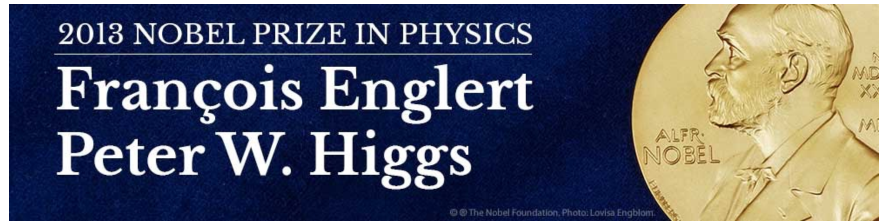


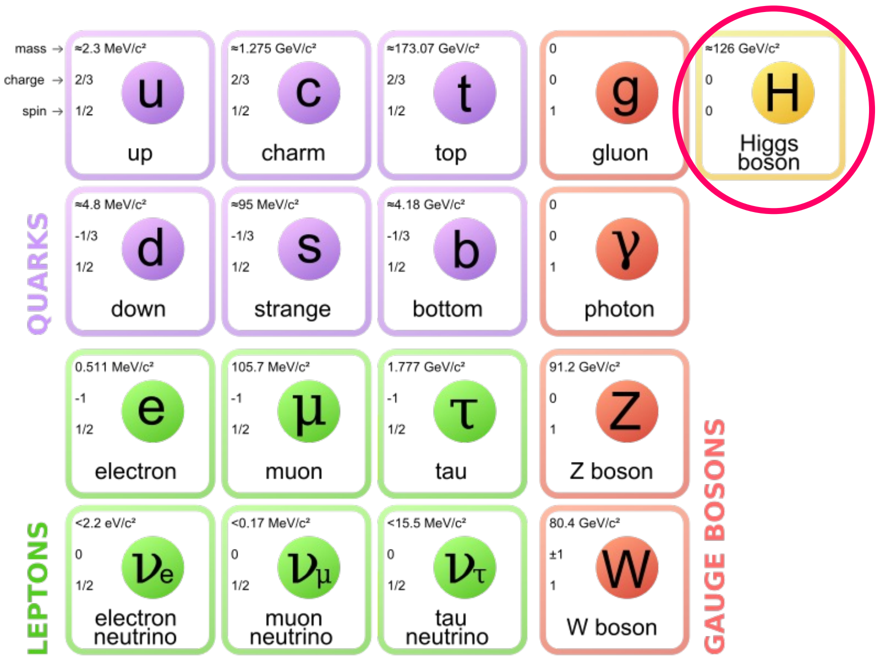
引力主导，爱因斯坦的广义相对论

引力和电磁力占主导地位



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





Fermionen ***Bosonen***

P. Higgs at CMS

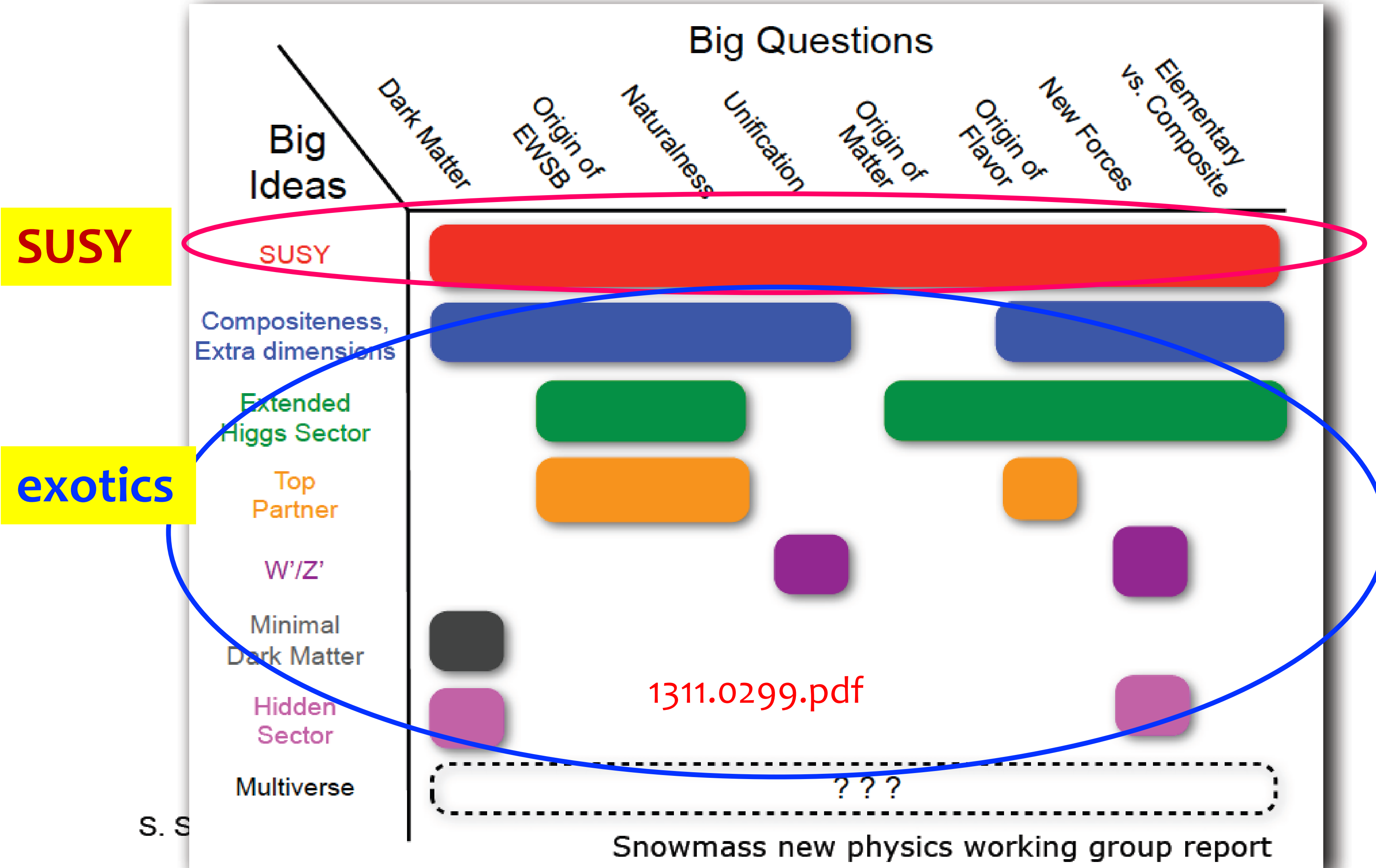
- Need a more **fundamental theory** of which SM is only a low-energy approximation → **New Physics**

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

Unfortunately, there is a problem with the Higgs!

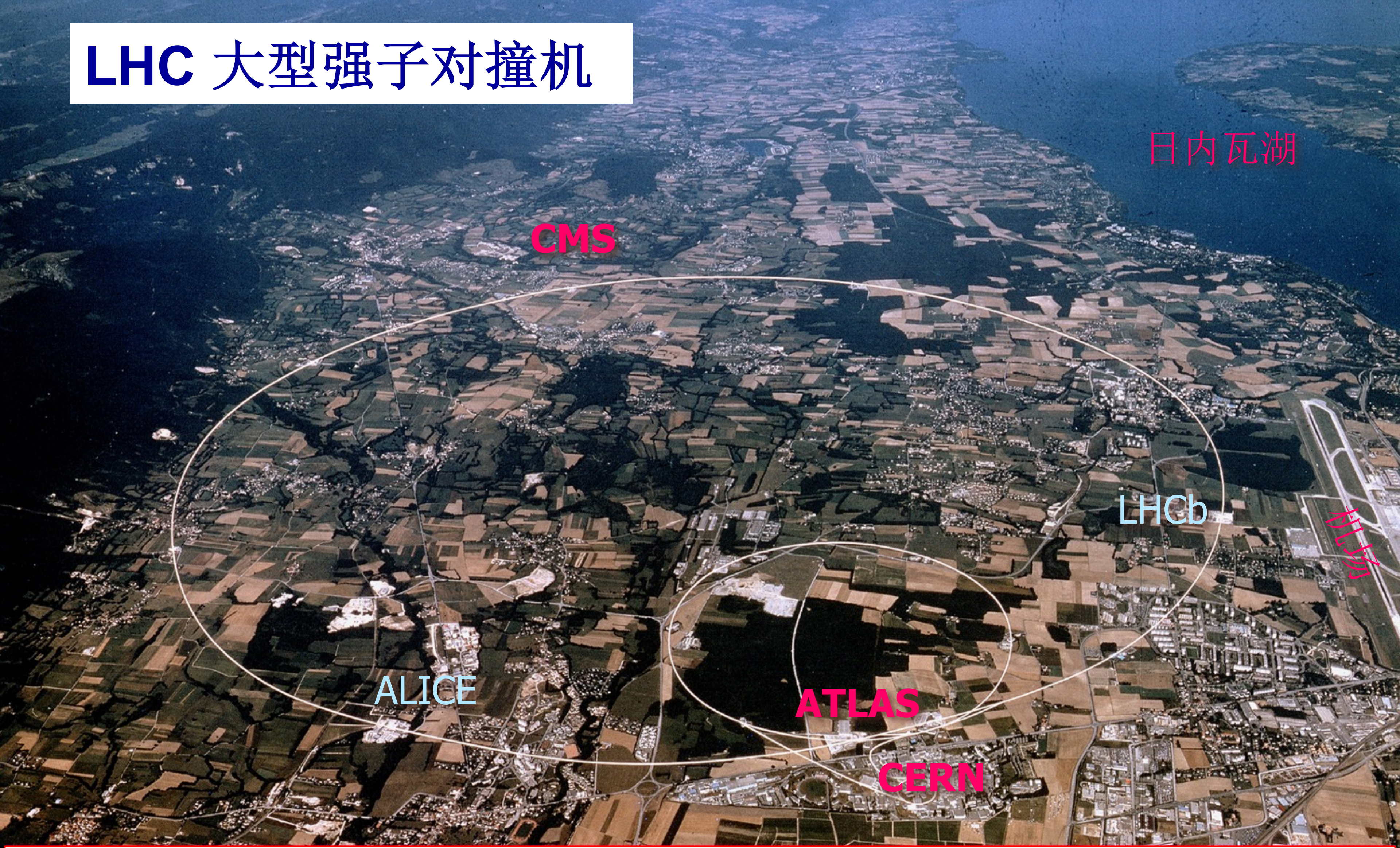
P. Higgs at CMS

New Physics beyond the SM



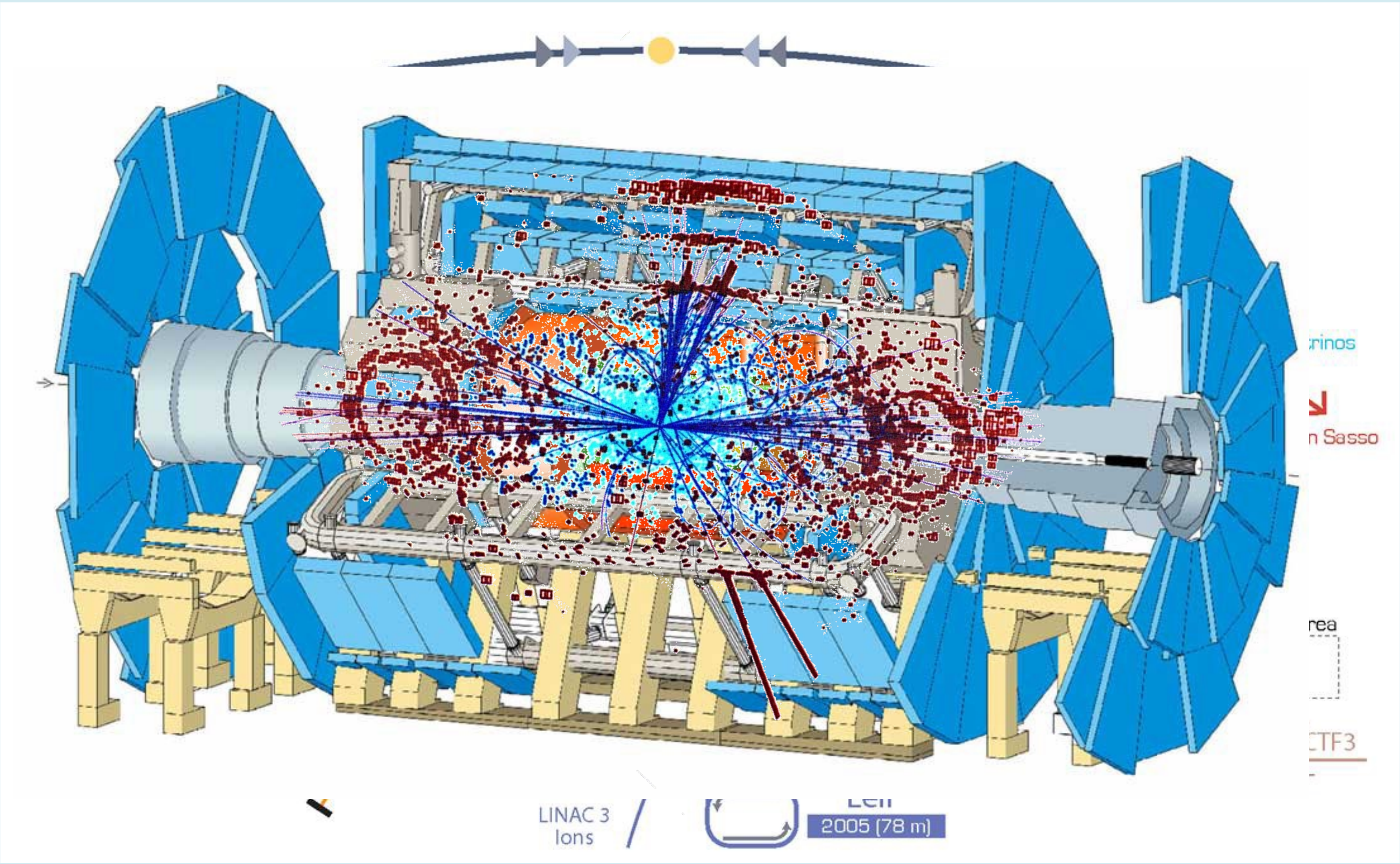
LHC & ATLAS/CMS detectors

LHC 大型强子对撞机

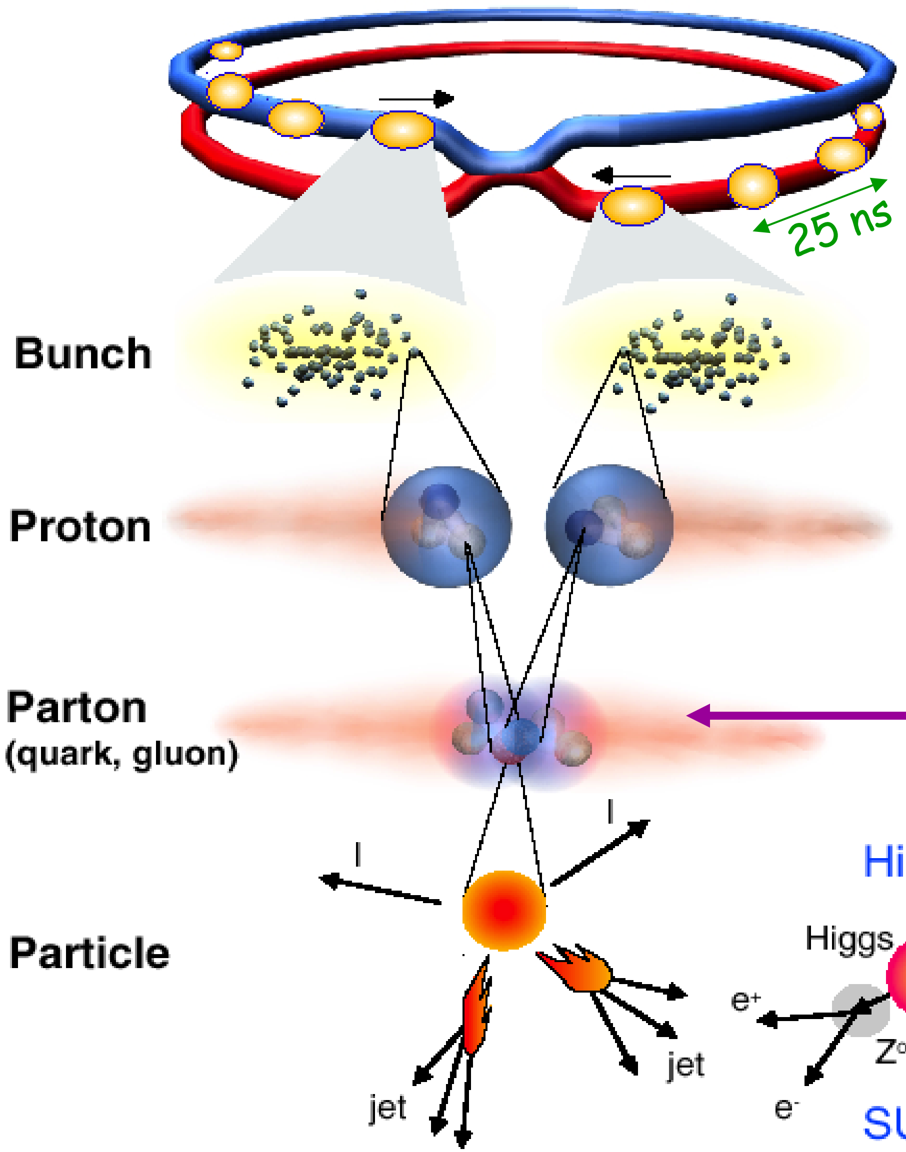


- 周长 27 公里，隧道深100米，跨越瑞士法国国境
- 世界最大，能量最高的加速器，进行最前沿的粒子物理研究
- **质心系能量14TeV** (Tevatron的7倍)，可以发现**5TeV**以下的**较重的新粒子**
- **积分亮度10^{34} cm^{-2} s^{-1}** (Tevatron 的100倍)，可以发现微小衰变截面的**稀有事例**

CERN’s particle accelerator chain



Collisions at LHC



Proton-Proton

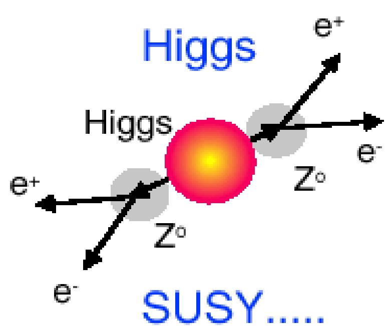
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}

Event rate:

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

Mostly soft (low p_T) events

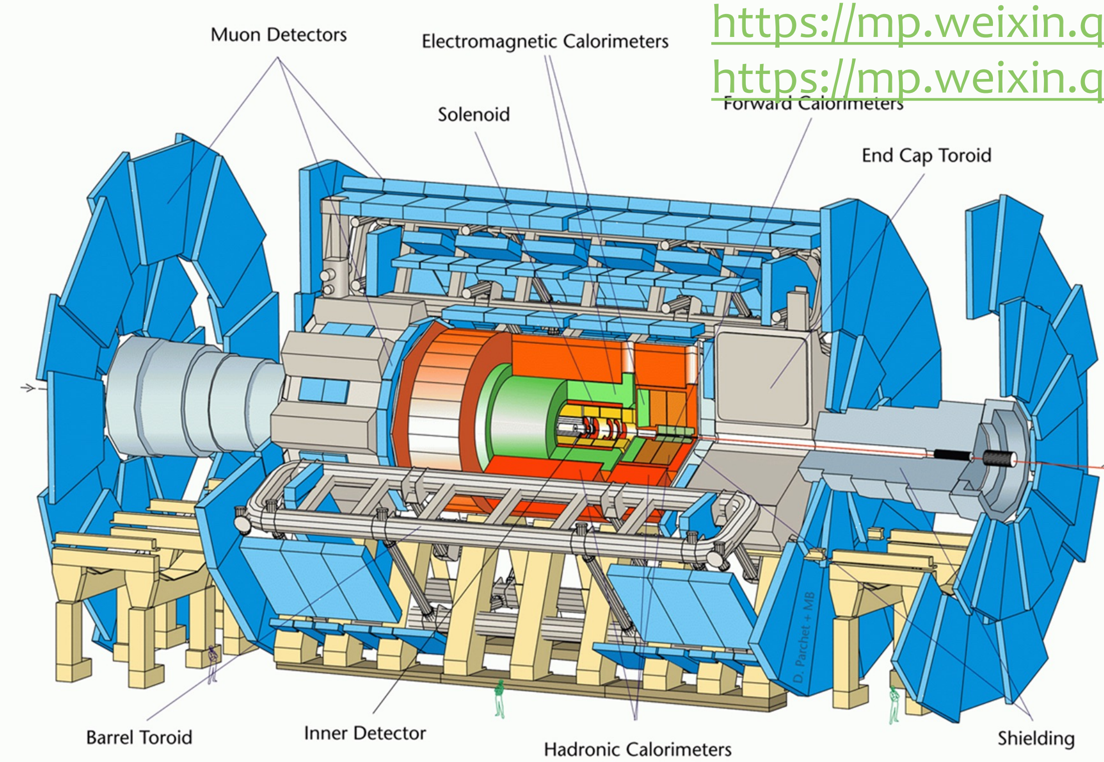
Interesting hard (high-p_T) events are rare



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

→ very powerful detectors needed

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

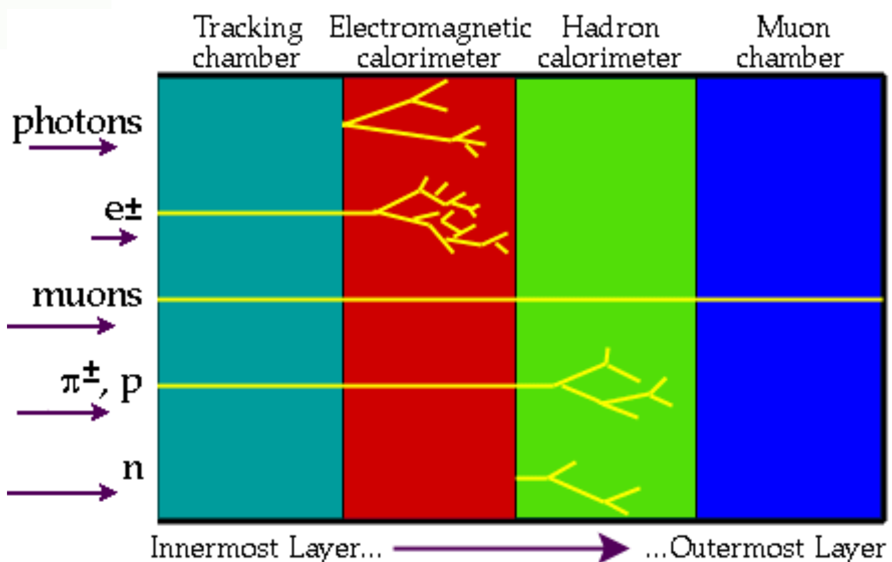


ATLAS

A Toroidal LHC ApparatuS

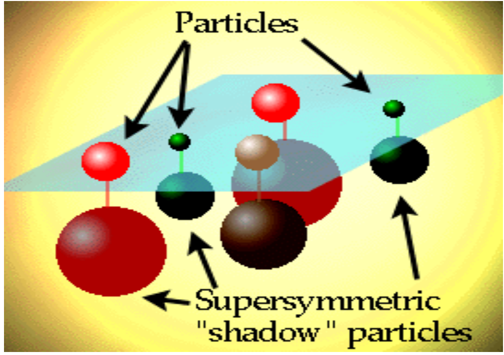
Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~ 10^8 electronic channels
~ 3000 km of cables

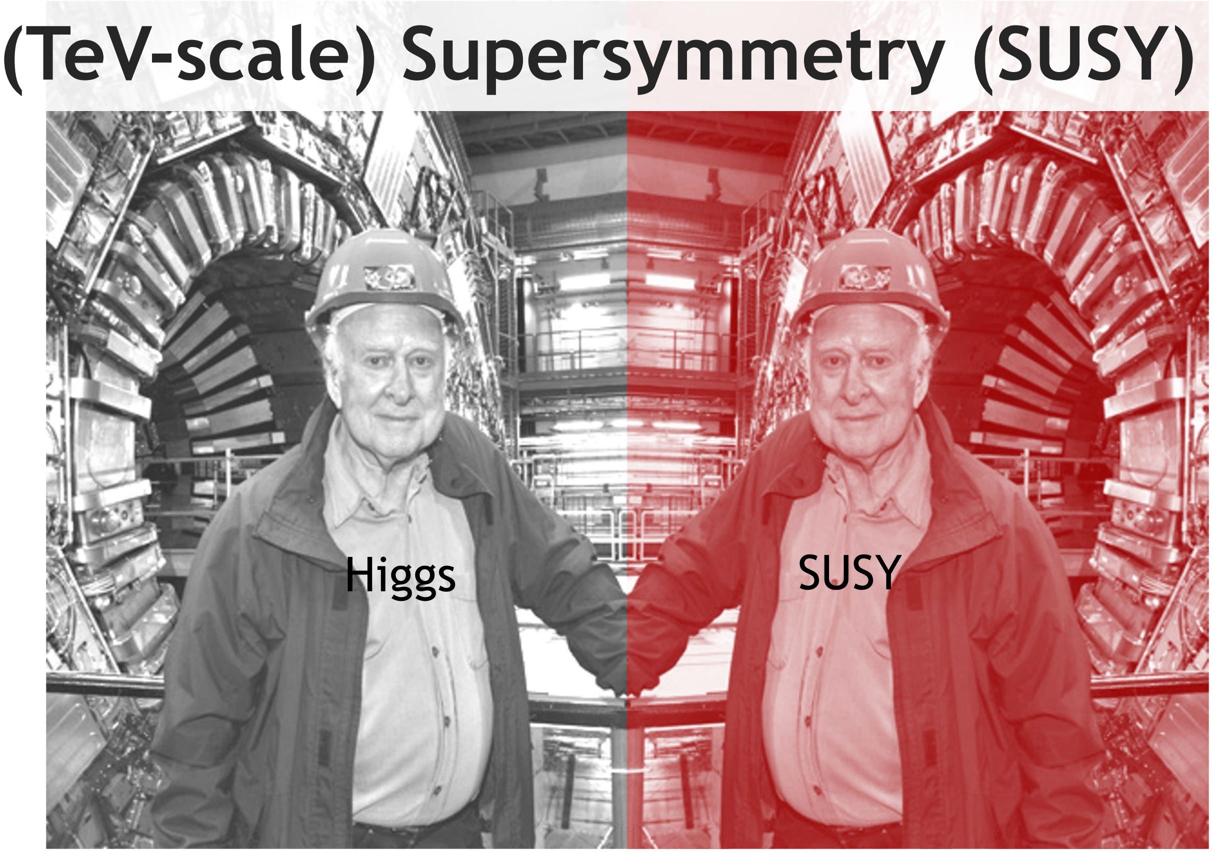
- **Tracking (|η|<2.5, B=2T) :**
  - **Si pixels and strips**
  - **Transition Radiation Detector (e/π separation)**
- **Calorimetry (|η|<5) :**
  - **EM : Pb-LAr**
  - **HAD: Fe/scintillator (central), Cu/W-LAr (fwd)**
- **Muon Spectrometer (|η|<2.7) :**
  - **air-core toroids with muon chambers**



What is SUSY?

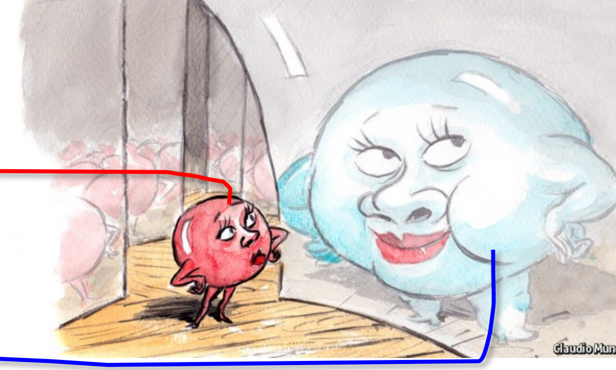
How SUSY do help?



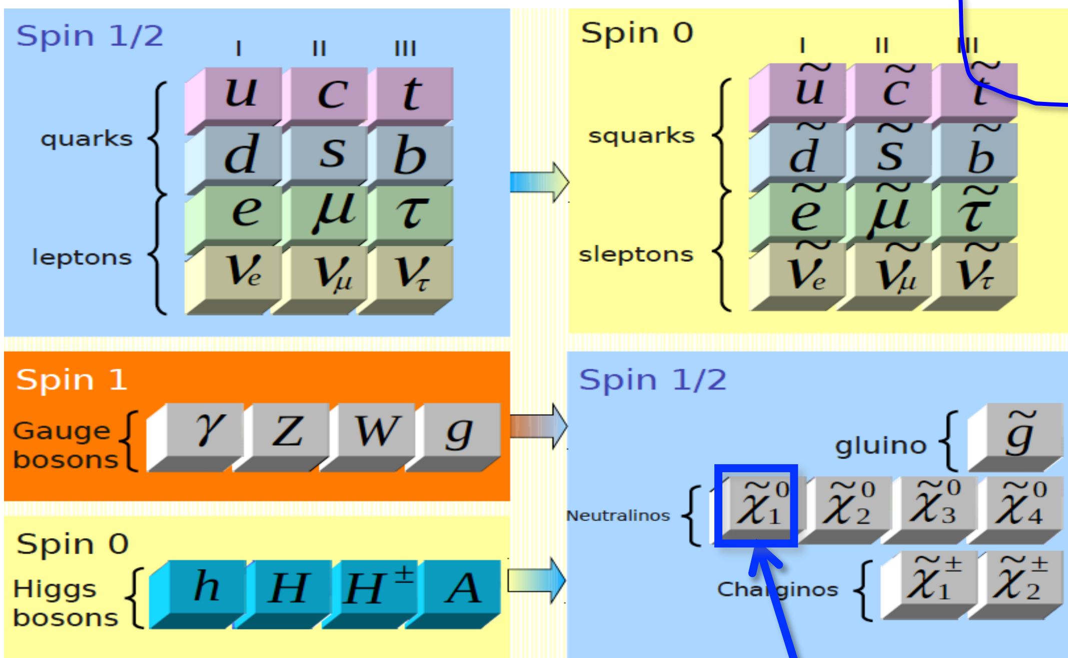


P. Higgs at CMS

SUSY Introduction



OUR WORLD… **NEW WORLD?**

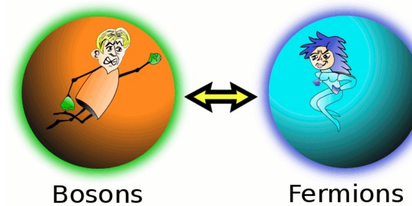


Julius Wess (1934 – 2007)

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>

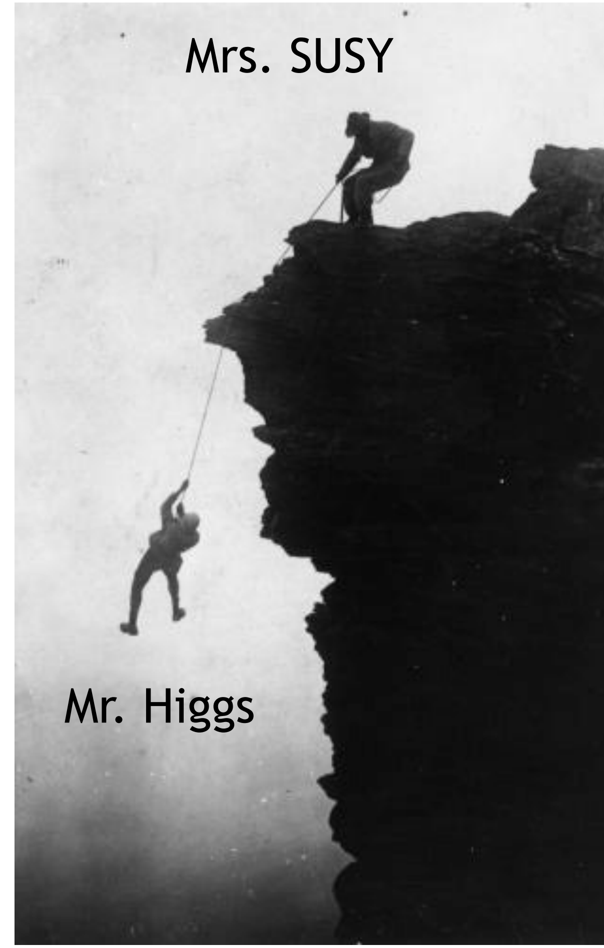
Spin differ by 1/2

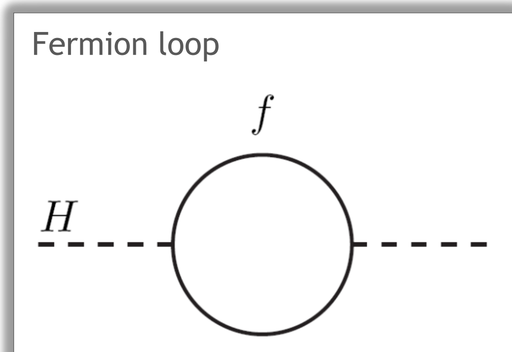
Minimal Supersymmetric Standard Model

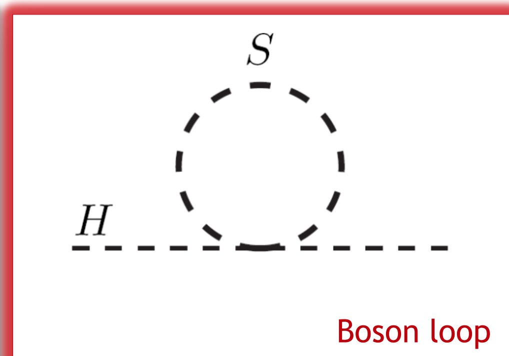
Standard Model Particles and Fields		Supersymmetric Partners			
		Interaction Eigenstates		Mass Eigenstates	
Symbol	Name	Symbol	Name	Symbol	Name
$q = u, d, c, s, t, b$	quark	$\tilde{q}_L, \tilde{q}_R$	**squark**	$\tilde{q}_1, \tilde{q}_2$	**squark**
$l = e, \mu, \tau$	lepton	$\tilde{l}_R, \tilde{l}_L$	**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	W^0-field	$\tilde{W}^0$	**wino**		
H_u^0, H_d^0	neutral Higgs boson	$\tilde{H}_u^0, \tilde{H}_d^0$	**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

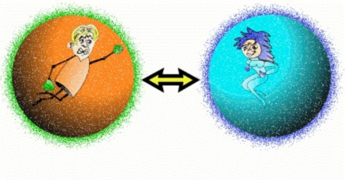




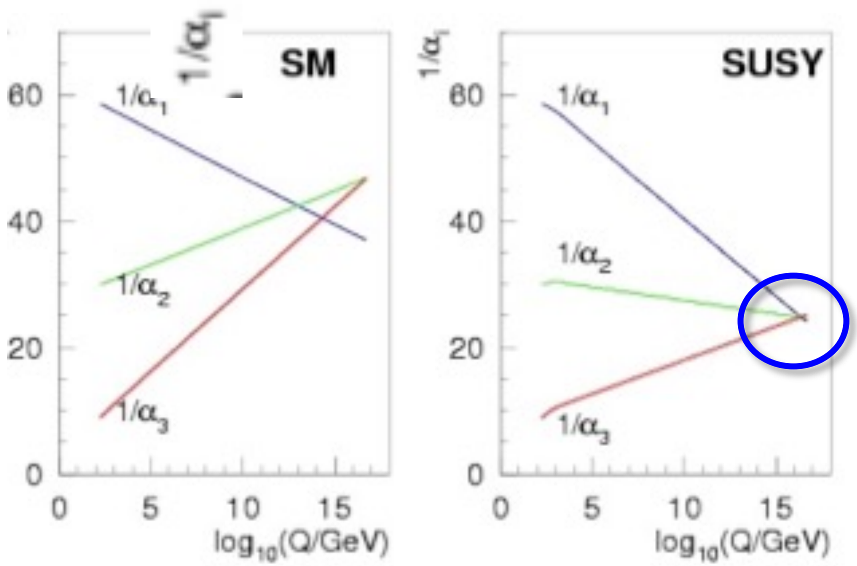


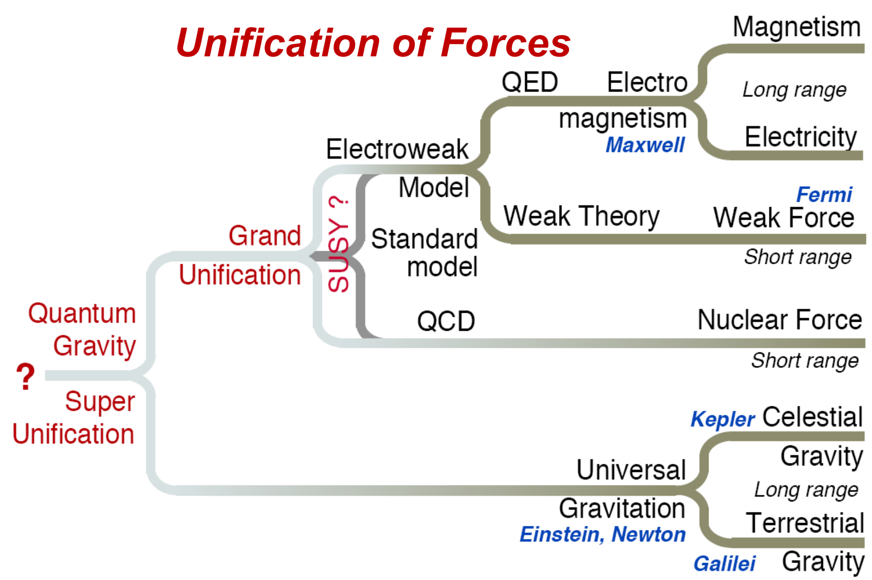
$$M_h^2 = M_{h,tree}^2 + \Delta M_h; \qquad SM : \Delta M_h \sim \Lambda^2; \qquad SUSY : \Delta M_h \sim m_{soft}^2 \log(\Lambda / m_{soft})$$

SUSY Introduction



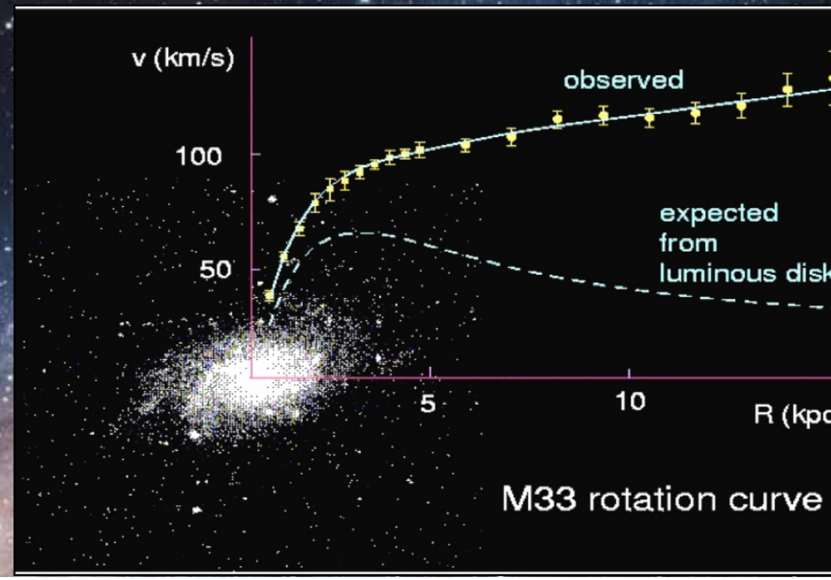
- **Unification of gauge couplings**
  - New particle content changes running of couplings
  - Requires SUSY masses below few TeV





Provide Dark Matter candidate

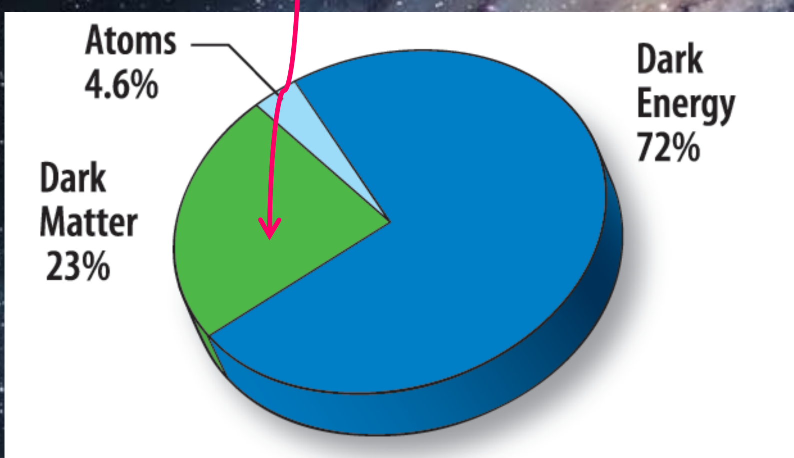
天文学家发现宇宙中很大一部分是我们看不见的 暗物质 （明物质只占4.6%）



Provide perfect dark mater candidate - WIMP(lightest neutralino in R-parity conserving models)

- ❑ stable
- ❑ electrically neutron
- ❑ same density as DM

‘Supersymmetric’ particles ?



$0.094 < \Omega_{CDM}h^2 < 0.136$ (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

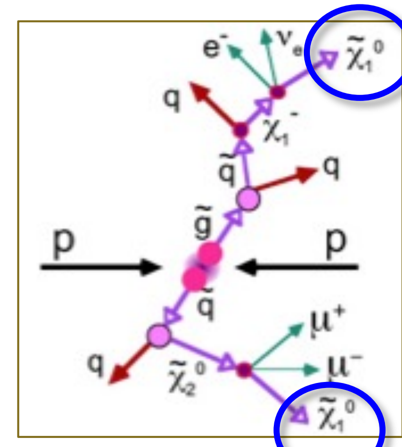
How do we start? - SUSY Signature

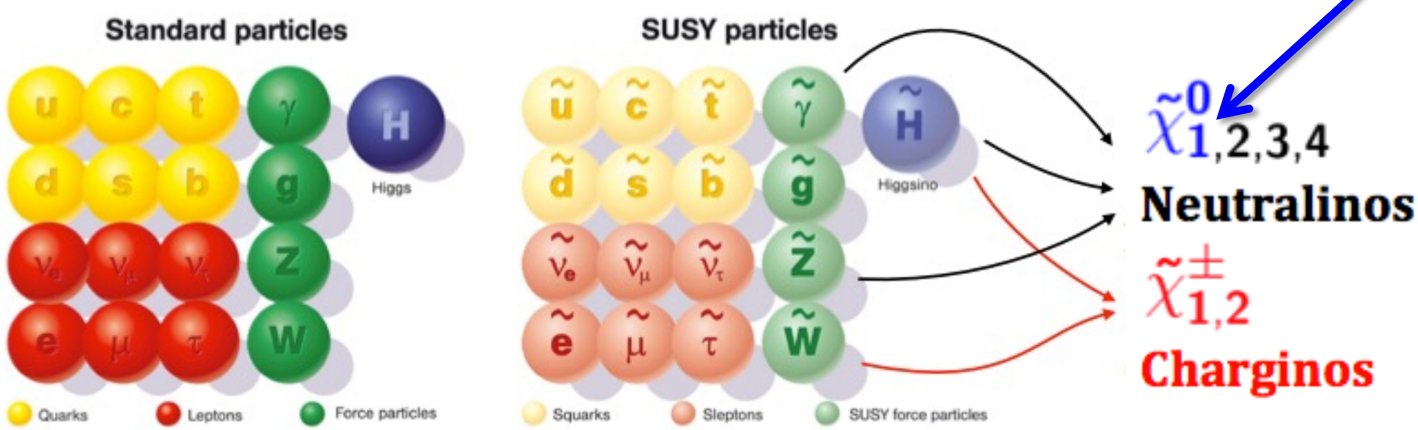
- **<u>Conserved R parity</u>** (originally introduced for stability of proton)

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

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

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

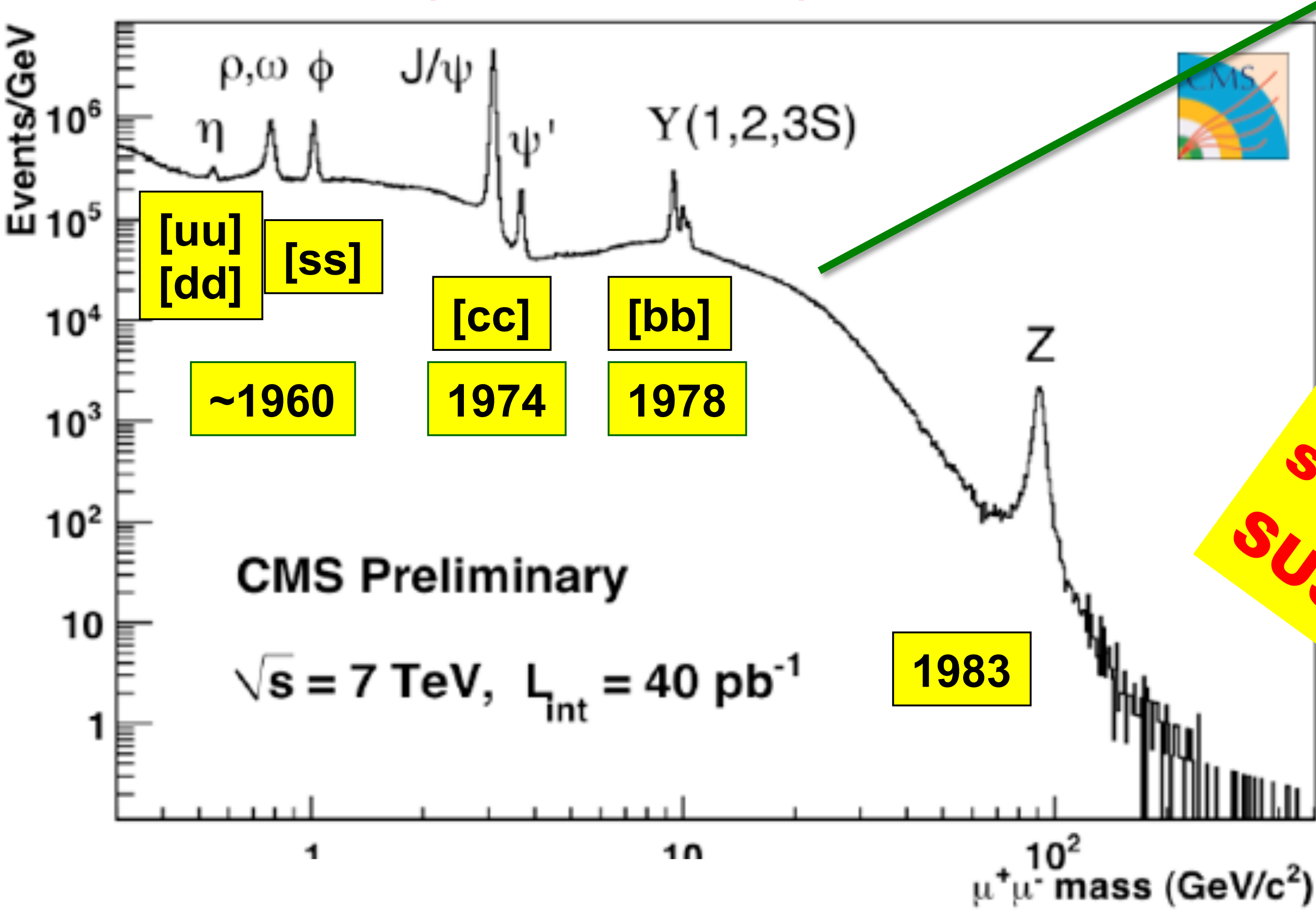




How do we search for SUSY?

2010

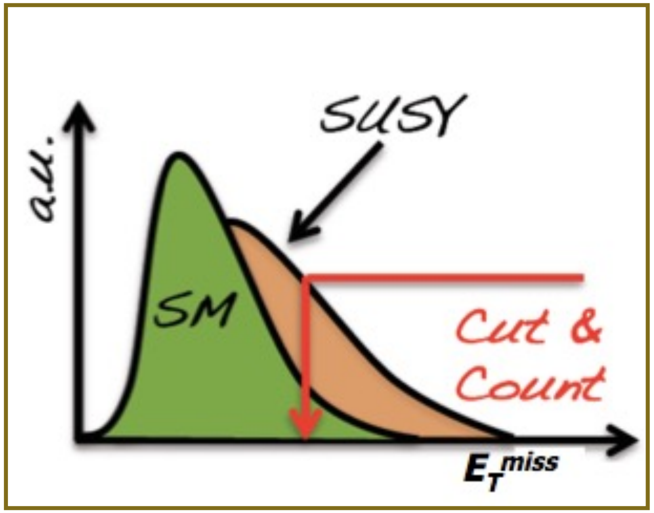
Not like general particles with peak in mass spectrum ☹



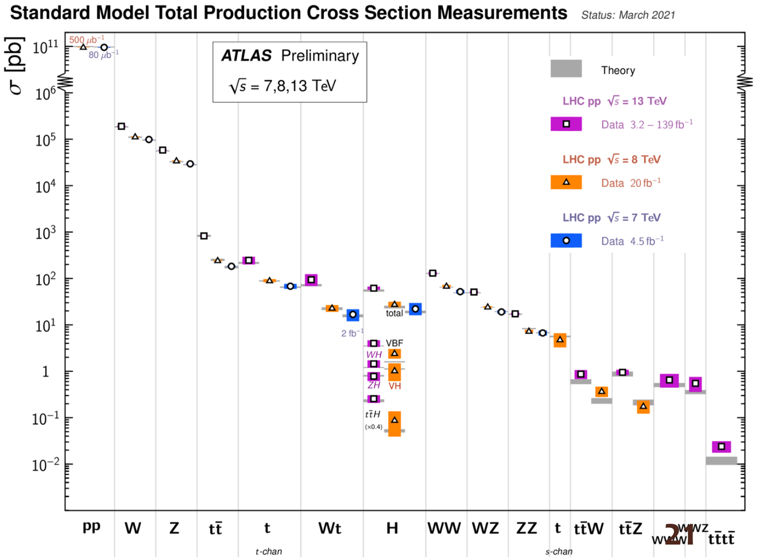
How do we search for SUSY?

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.

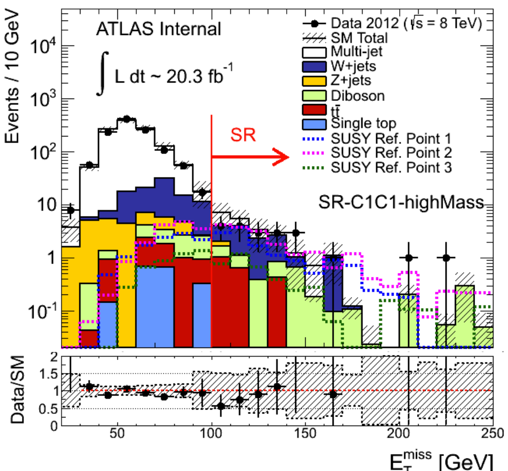


SM "backgrounds"– the big picture

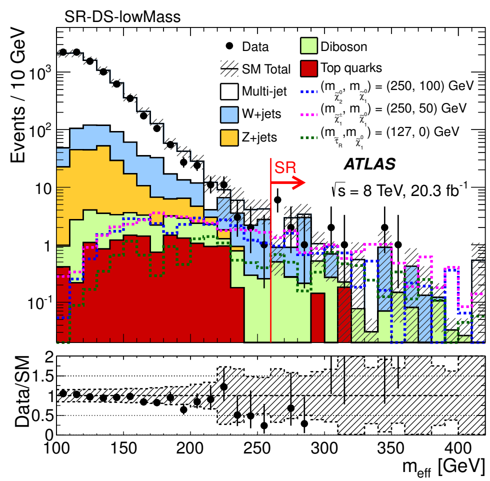


SUSY Sensitive Variables

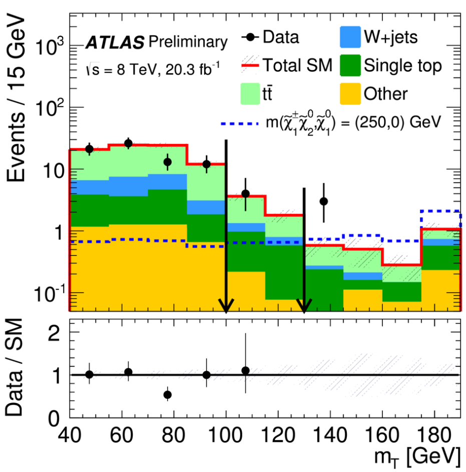
E_T^{miss}



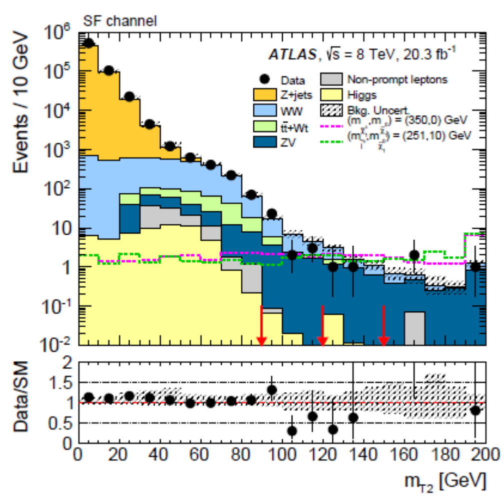
M_{eff}



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}**)

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

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

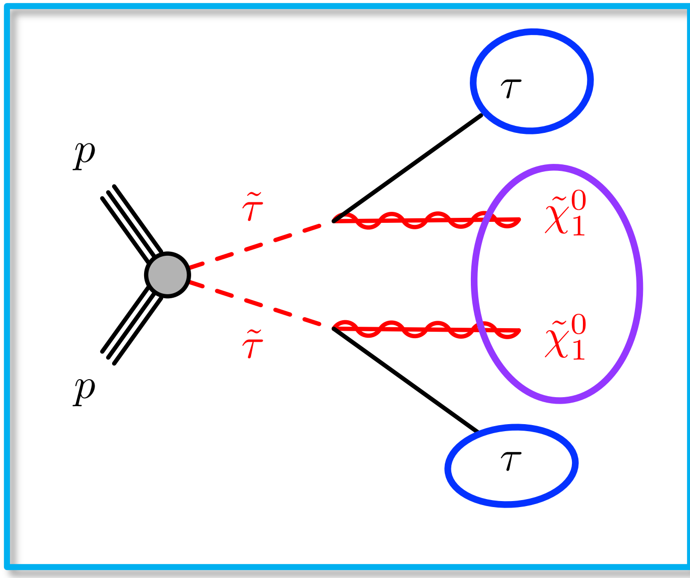
$$m_{\rm T2} = \min_{\mathbf{q}_{\rm T}}\left[\max\left(m_{\rm T}(\mathbf{p}_{\rm T}^{\ell 1}, \mathbf{q}_{\rm T}), m_{\rm T}(\mathbf{p}_{\rm T}^{\ell 2}, \mathbf{p}_{\rm T}^{\rm miss} - \mathbf{q}_{\rm T})\right)\right]$$

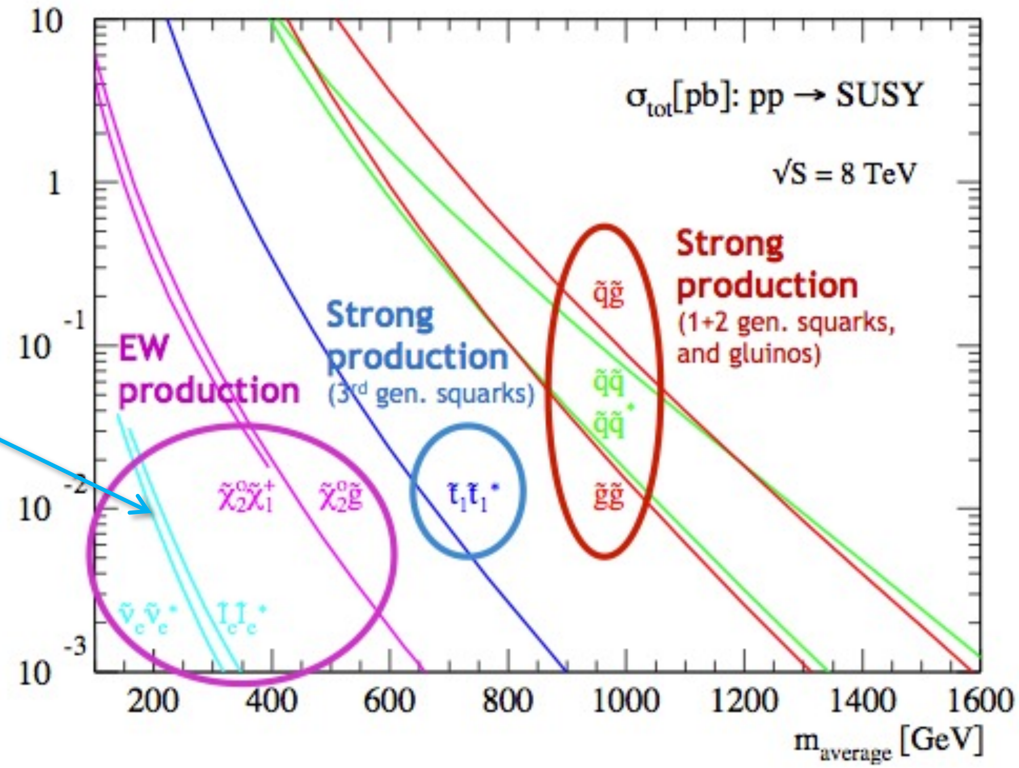
- Many others …

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



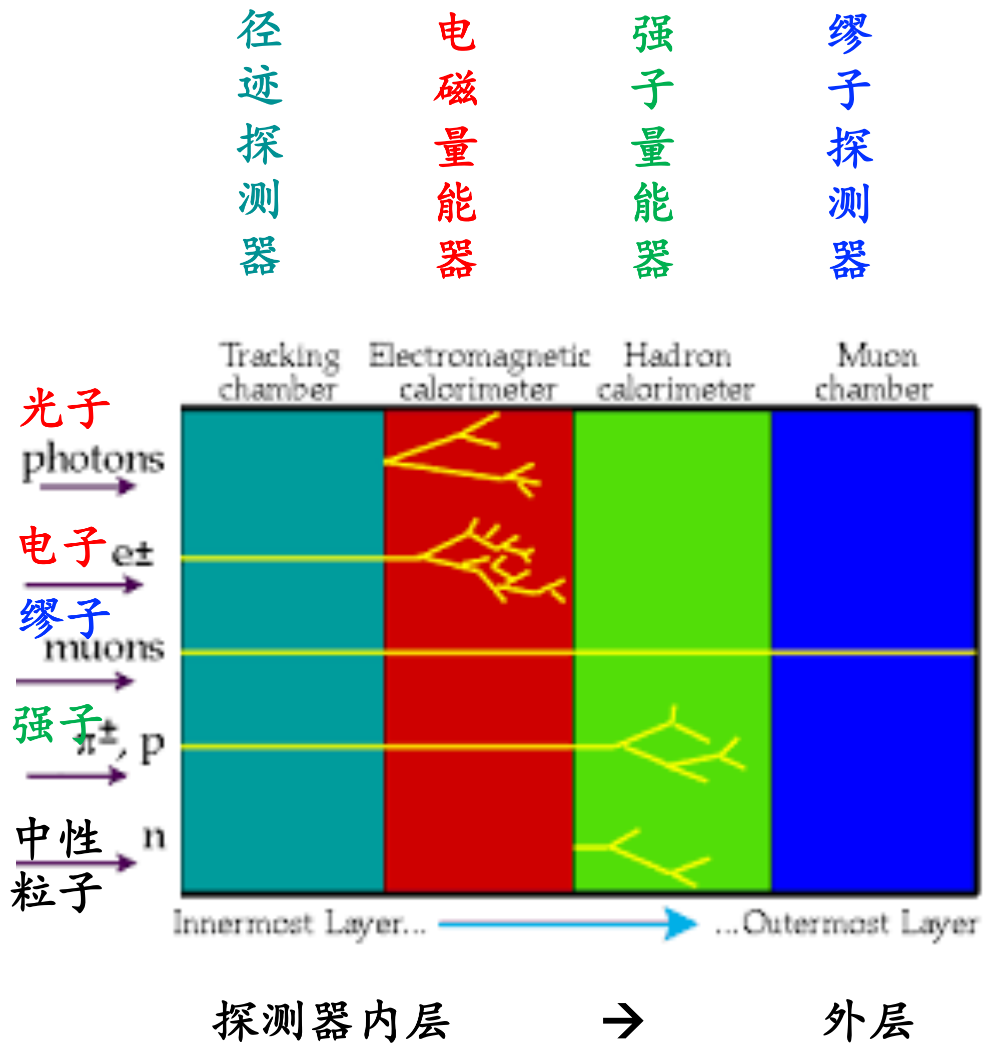


Final states:

2 tau + large E_T^{miss}

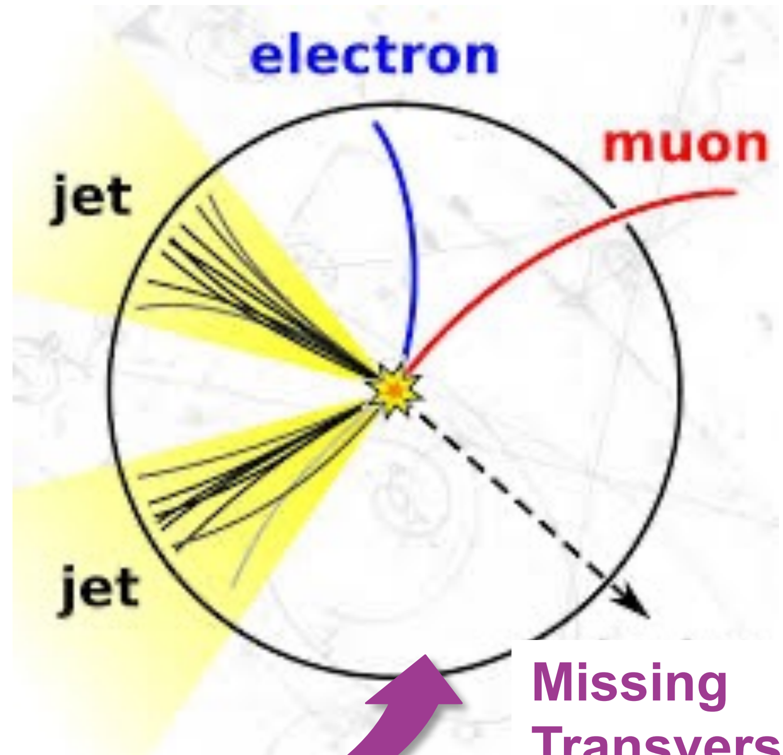
2: Pre-selection Reconstructed Objects

- 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

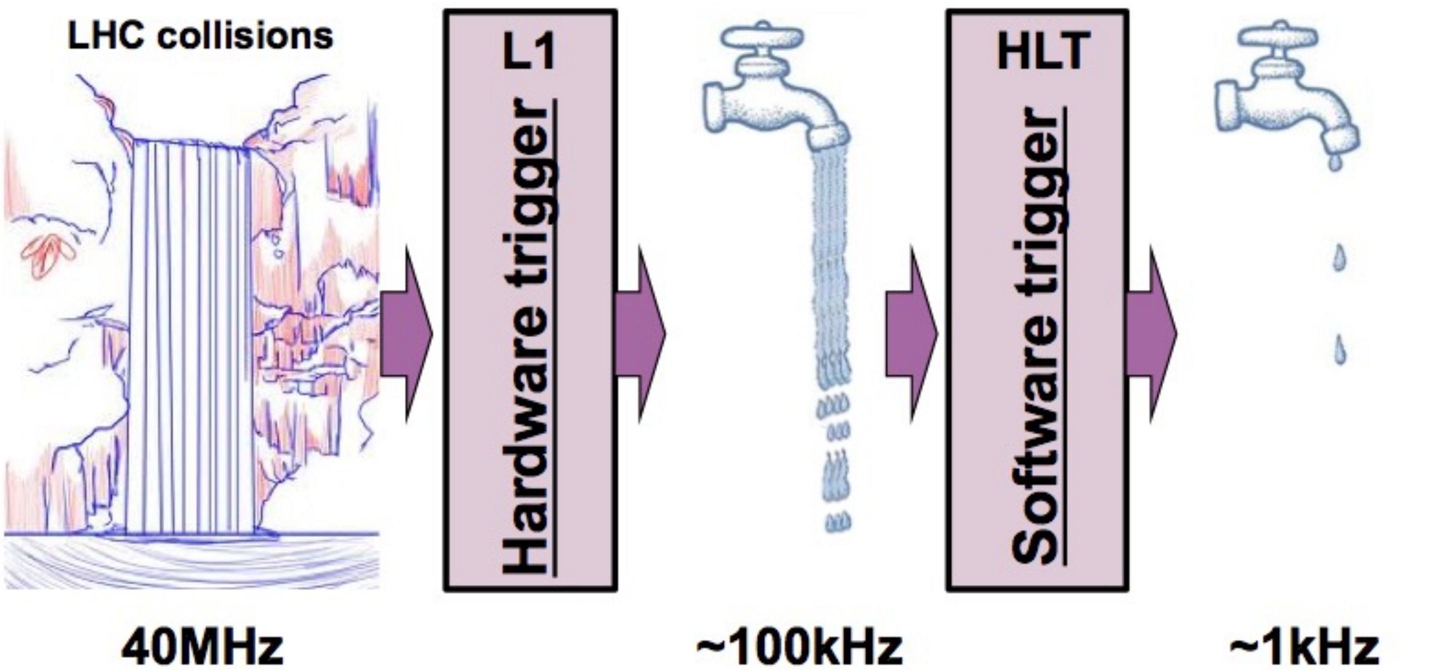
- At the LHC an unknown proportion of the energy of the colliding protons escapes down the beam-pipe
- Invisible particles (neutrinos, neutralinos?) are created their momentum can be constrained in **the plane transverse to the beam direction**



Missing Transverse Energy

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

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}

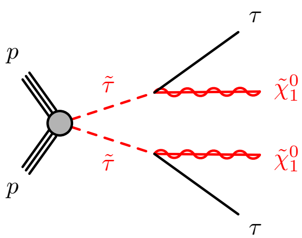
3: SR definition and optimization

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

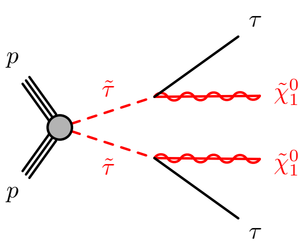
Trigger



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

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

3: SR definition and optimization



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tau p_{T} and $E_{\mathrm{T}}^{\mathrm{miss}}$ 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)	
$\lvert\Delta\phi(\tau_1, \tau_2)\rvert > 0.8$	
$\Delta R(\tau_1, \tau_2) < 3.2$	
$m_{\mathrm{T2}} > 70$ GeV	

taus

Trigger

Suppress top

Suppress Z/H

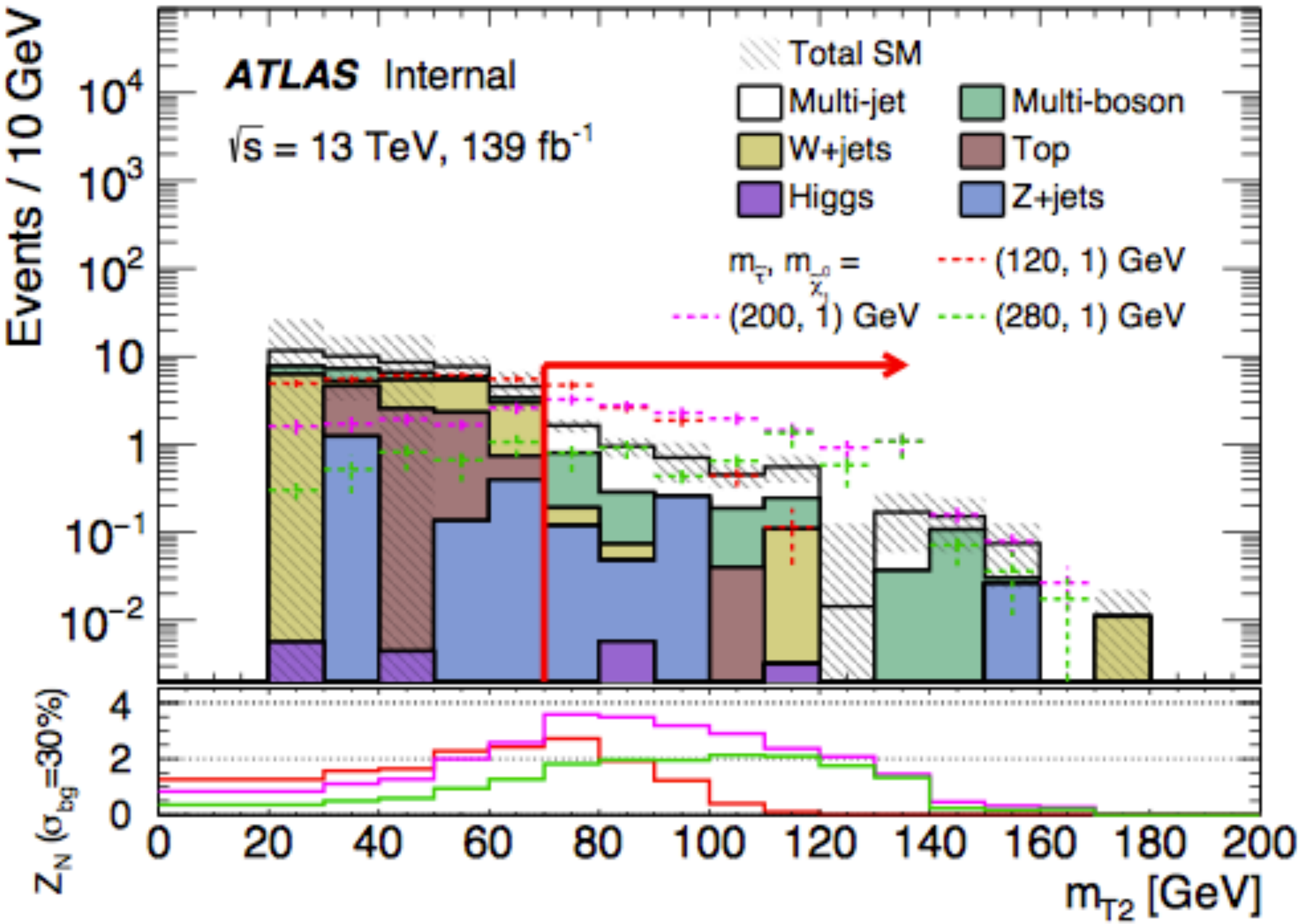
Suppress SM bg, increase signal sensitivity

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

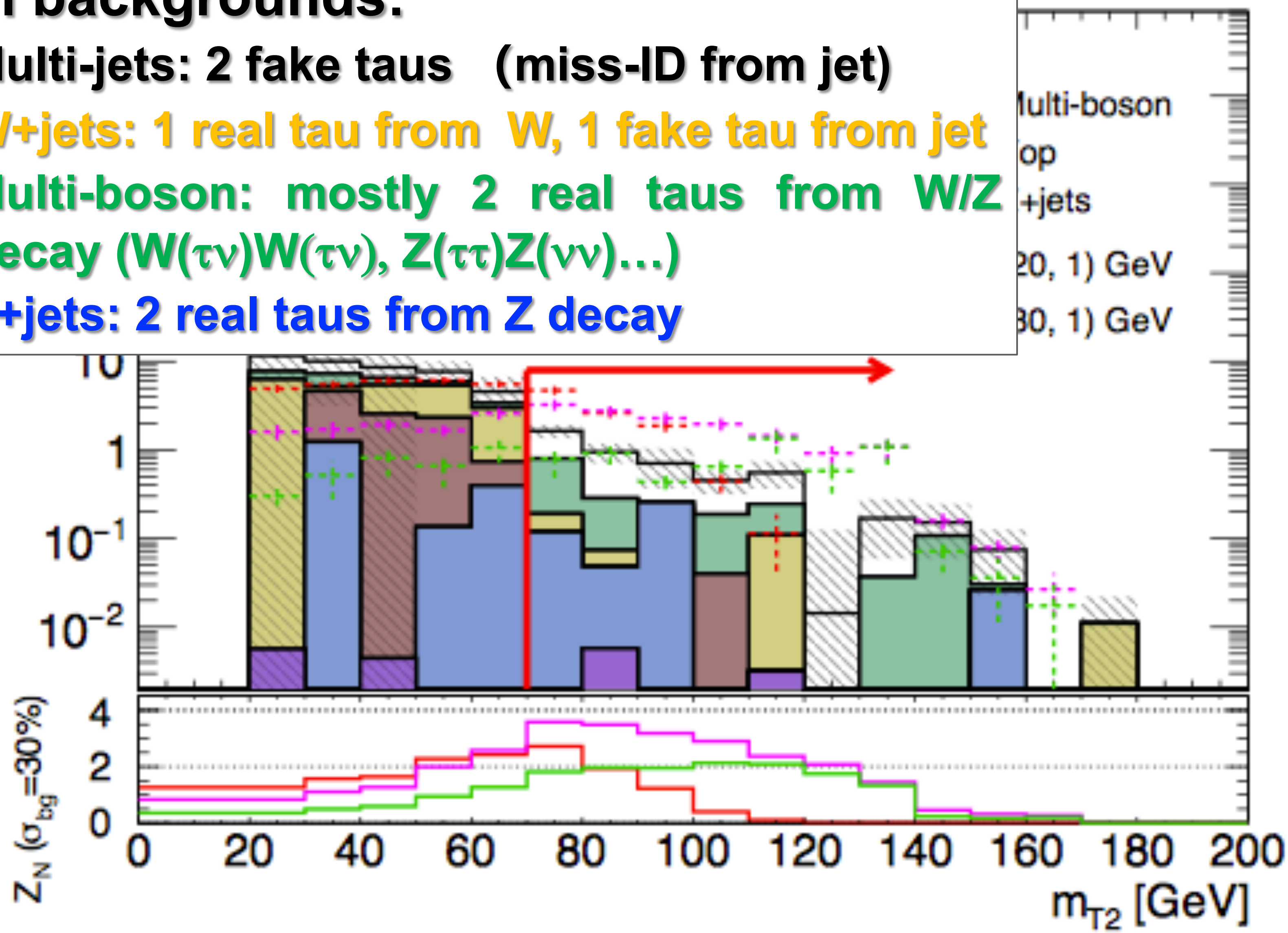
3: SR definition and optimization



3: SR definition and optimization

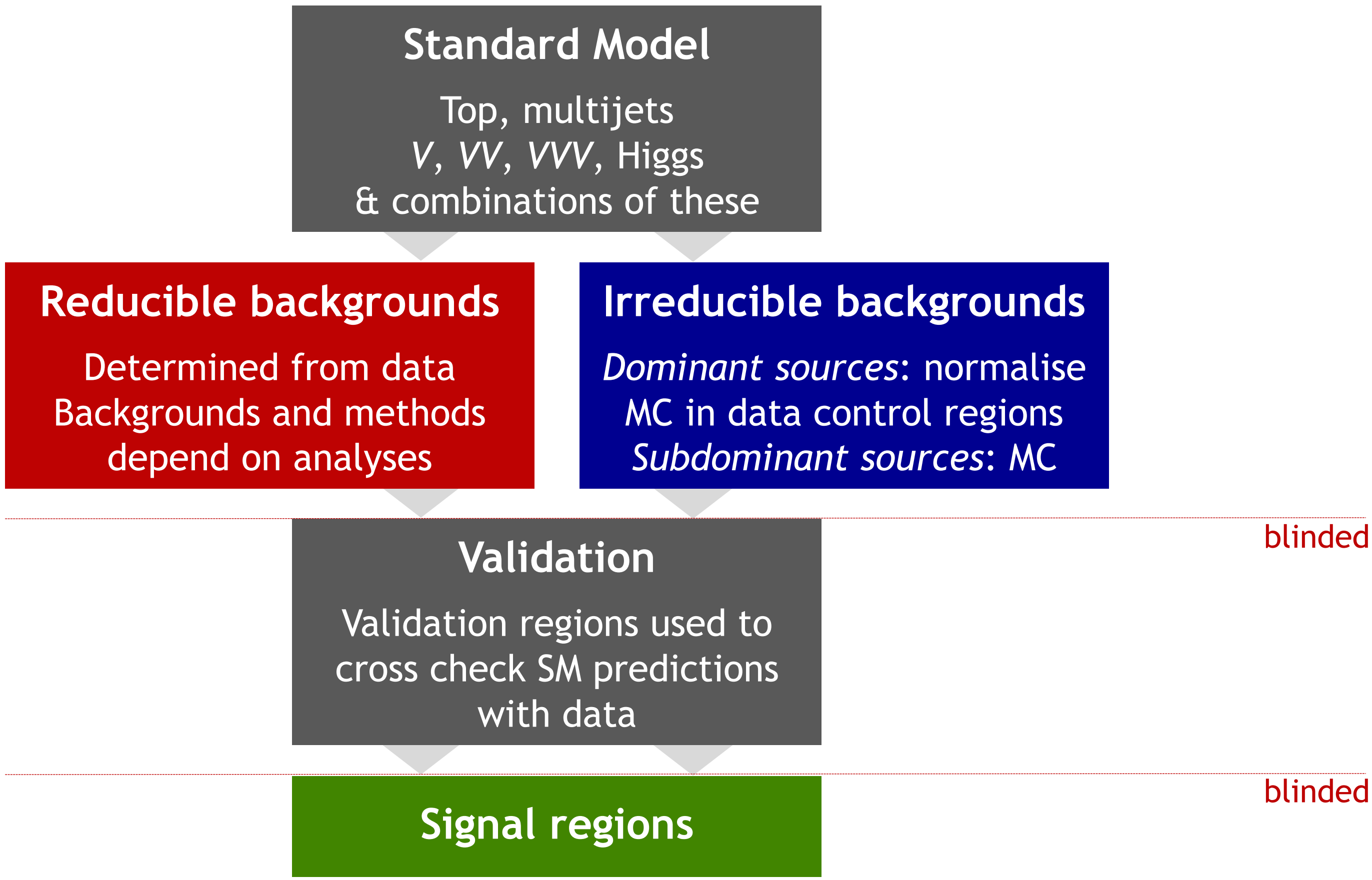
Main backgrounds:

- **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(τν)W(τν), Z(ττ)Z(νν)…)**
- **Z+jets: 2 real taus from Z decay**



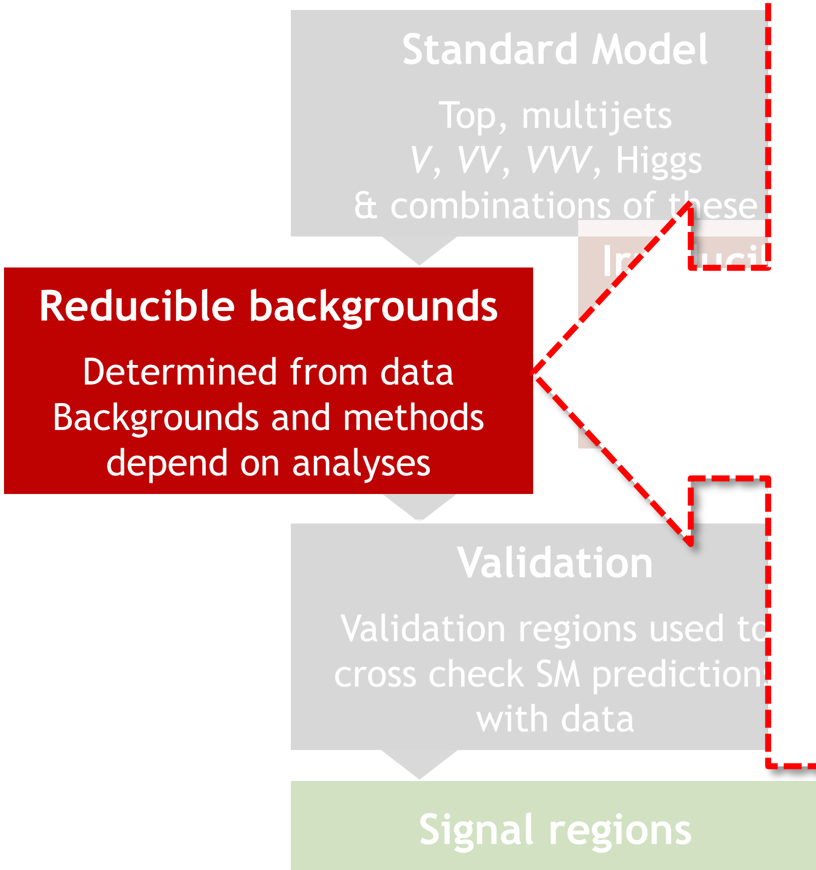
4: SM Background estimations (data-driven + MC)

SUSY searches rely primarily on the understanding of the SM BG



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

SUSY searches rely primarily on the understanding of the SM BG

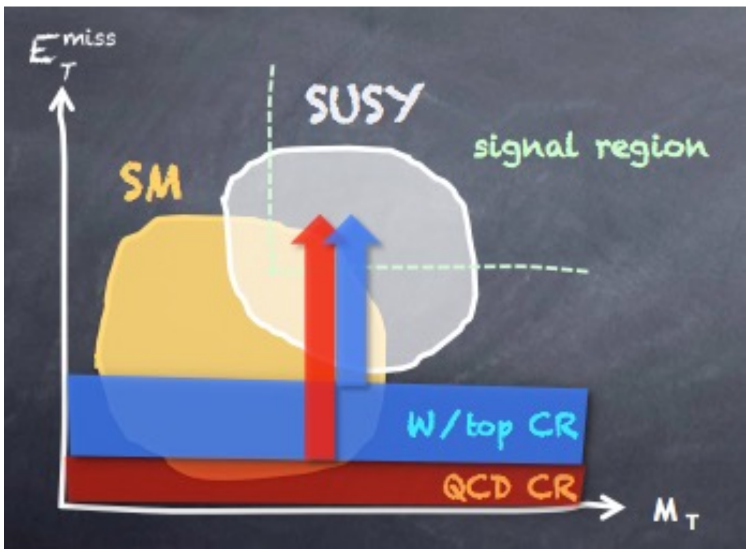


- **Multijet background**: "ABCD method" or fake factor method
- **Fake leptons or heavy-flavour jets** determined with "matrix method" in different-purity samples using "real" and "fake" probabilities measured in data.
- **Charge flip rate** measured in Z events

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

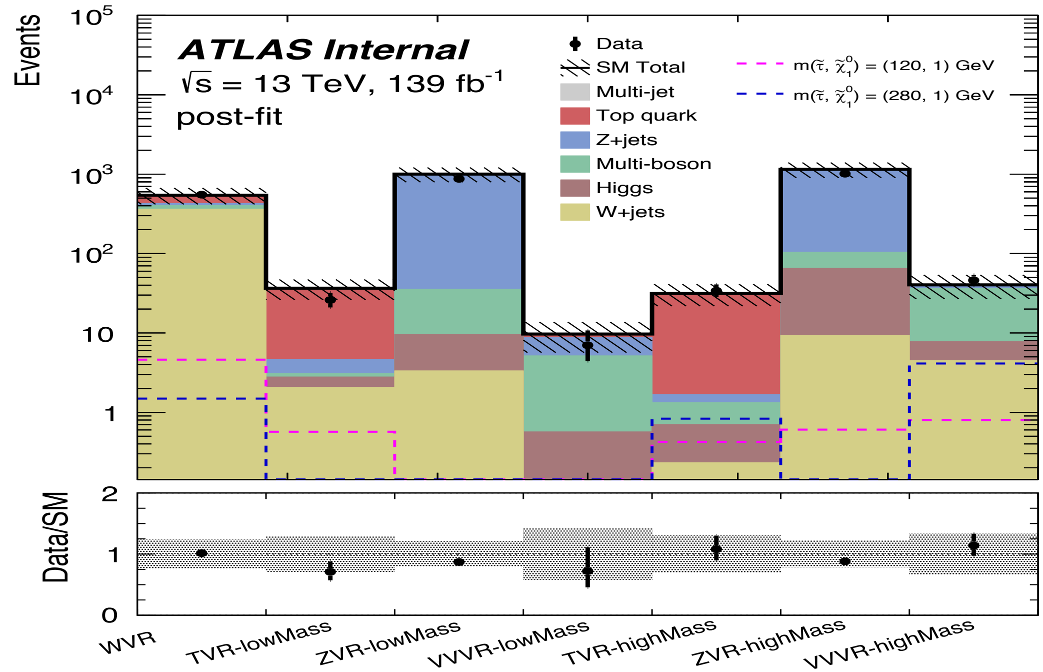
Validation regions used to cross check SM predictions with data

Signal regions

+ MC)

SU ... e SM

BC



Determined from data
Backgrounds and meth...
depend on analyses

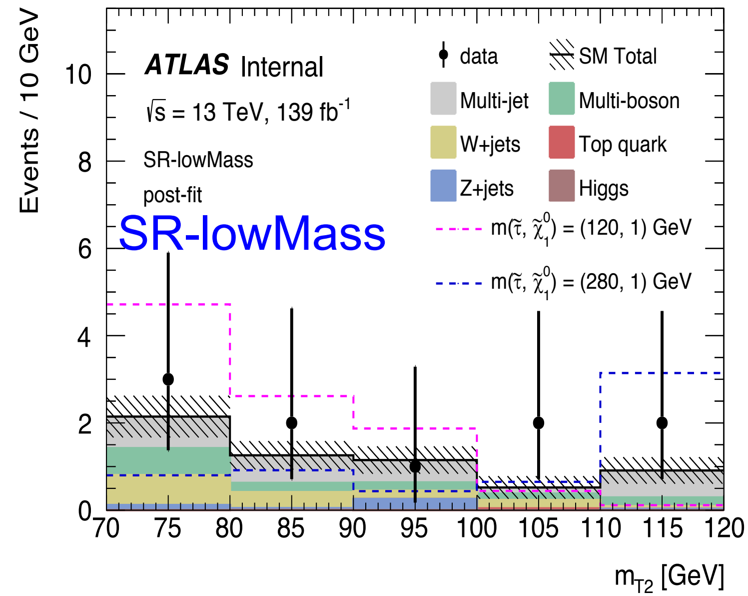
...ant sources: normalise
...data control regions
...subdominant sources: MC

Validation

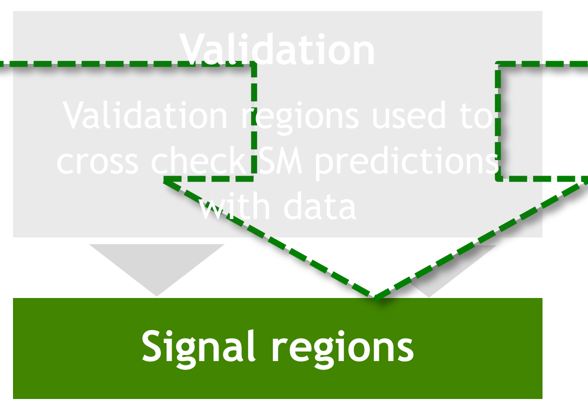
Validation regions used to cross check SM predictions with data

Signal regions

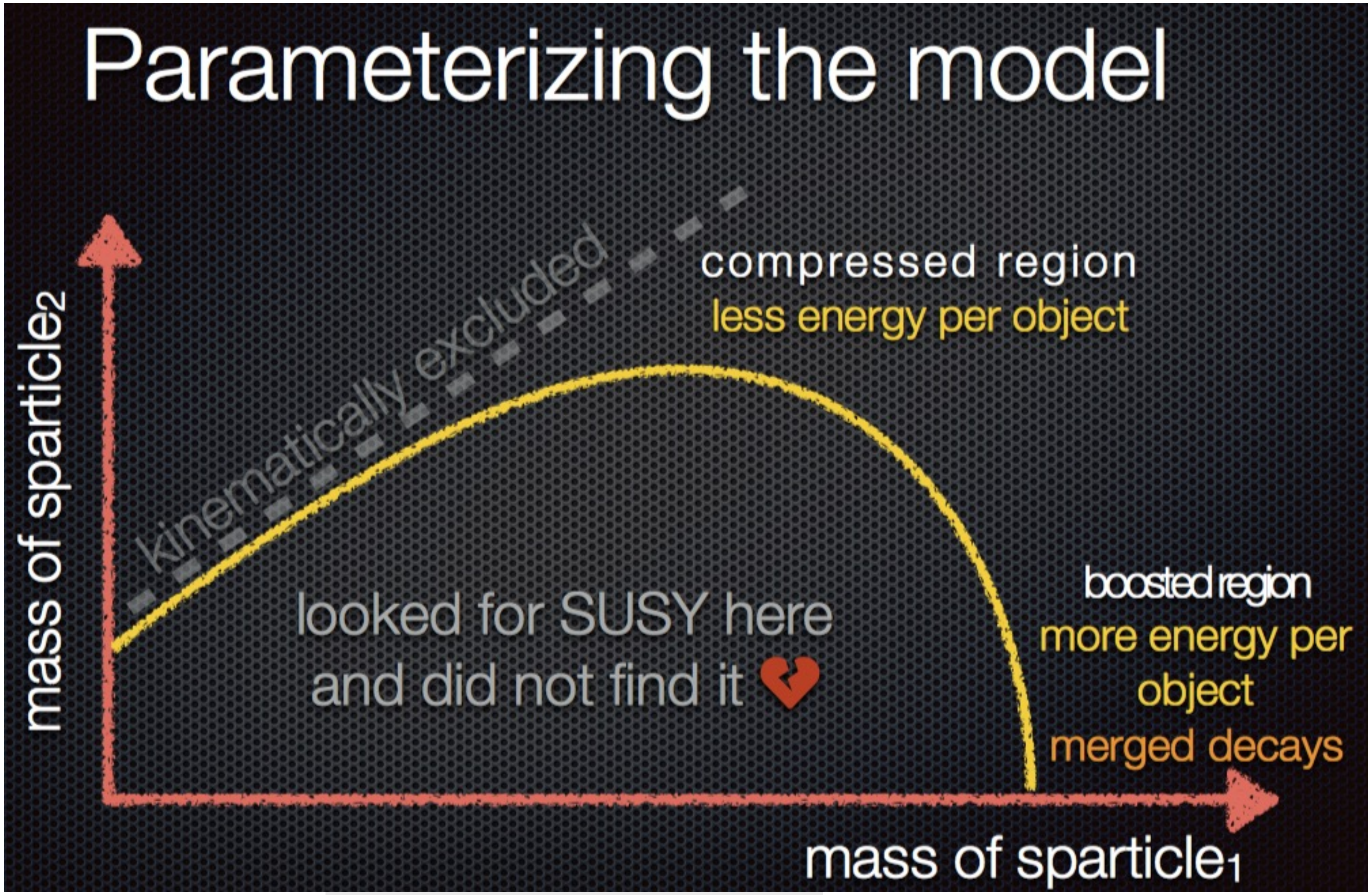
SM process	SR -lowMass	SR -highMass
Diboson	1.4 ± 0.8	2.6 ± 1.2
W+jets	1.5 ± 0.7	2.5 ± 1.9
Top quark	$0.04^{+0.80}_{-0.04}$	2.0 ± 0.5
Z+jets	$0.4^{+0.5}_{-0.4}$	$0.04^{+0.13}_{-0.04}$
Higgs	$0.01^{+0.02}_{-0.01}$	–
Multi-jet	2.6 ± 0.7	3.1 ± 1.5
SM total	6.0 ± 1.7	10.2 ± 3.3
Observed	10	7

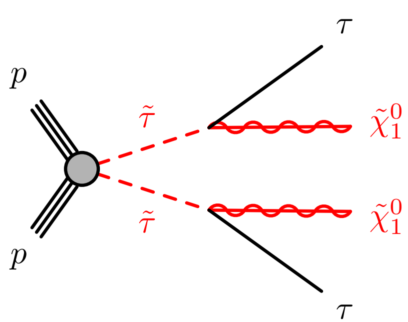


- No significant excess except for SR-lowMass



5: Compare SM predictions with data

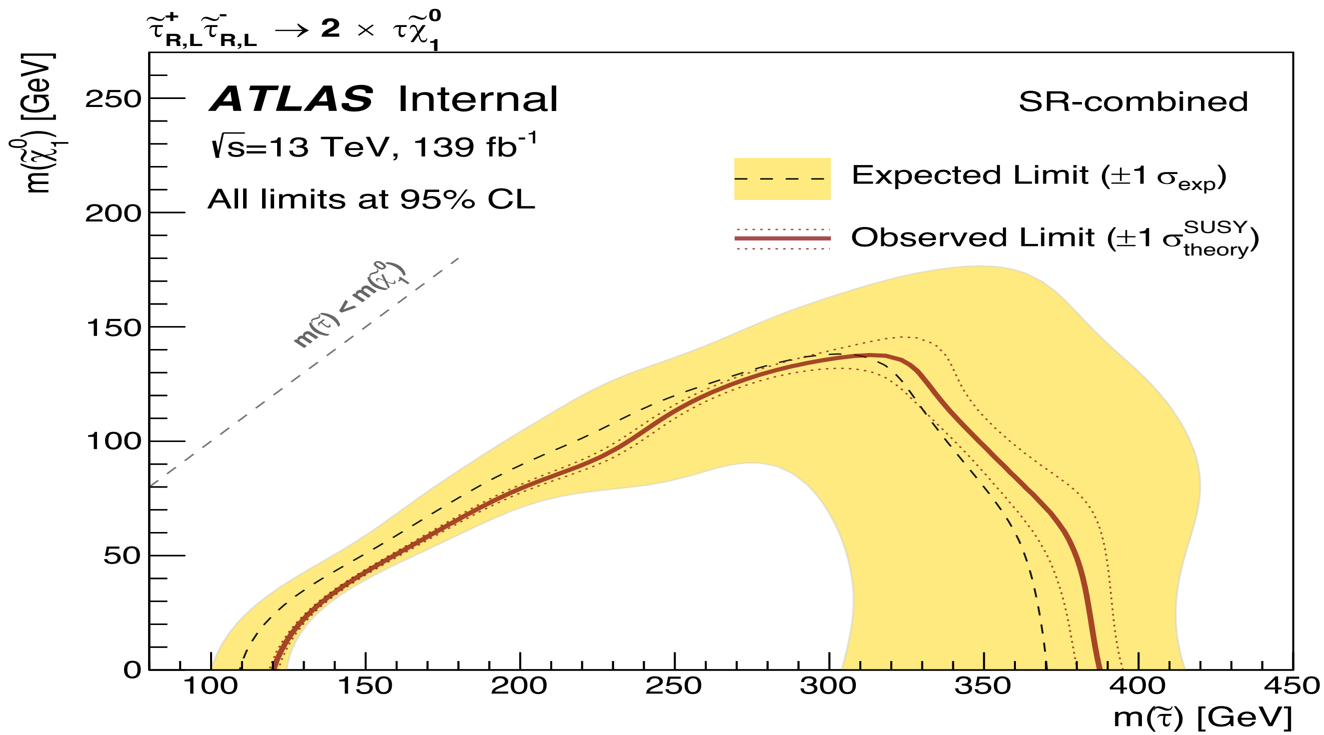




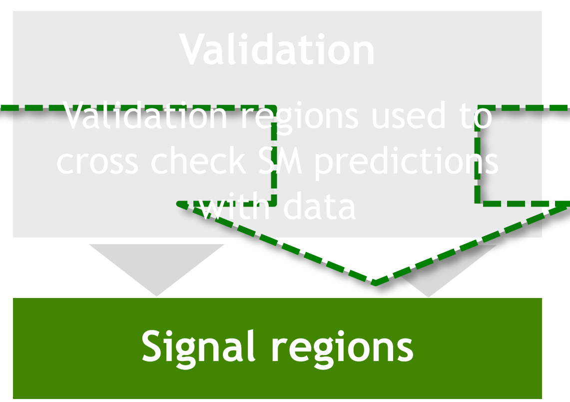
Validation regions used to cross check SM predictions with data

Signal regions

6: Interpretations



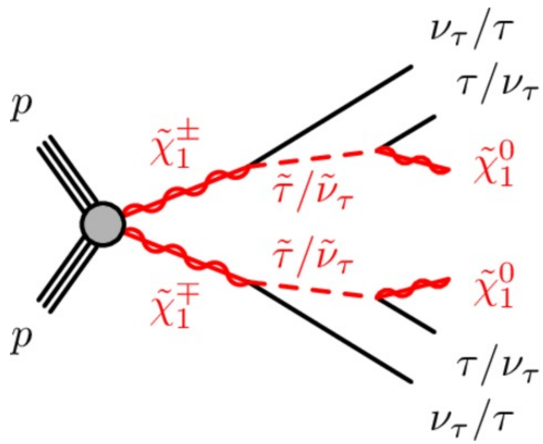
- excludes **stau masses** between **120-390 GeV**



6: Interpretations

Todo list:

- 阅读相关资料 （1-2礼拜）
- 申请计算机账号，熟悉计算环境，熟悉本底样本和信号样本，会提交作业（1-2礼拜）
- 看一下整个流程的cutflow（1-2礼拜）
- 初选（只看low-mass信号区，add asymmetric ditau trigger with tau-pt & met cut， 选择==2 medium tau）之后的kinematic distributions，通过信号和本底的分布，看哪些变量可以很好的区分信号和本底 （tau1_pt，eta，phi； tau2_pt,eta,phi;N_(medium tau)；N_(tight tau)；N_jets；N_bjets；MET； m(tau1,tau2)； DeltaPhi(tau1, tau2)； DeltaEta(tau1,tau2)；DeltaR(tau1,tau2)；mT_tau1；mT_tau2；Meff；mT2 ）（1-2礼拜）
- 初选后真实数据和本底的上述kinematic distributions，看一下MC modeling的情况 （1-2礼拜）
- 只用本底和信号样本，在初选的基础上，b-jet veto，DeltaPhi cut，m(tau1,tau2)cut，met cut一次加一个，看看该cut主要去除什么本底，理解信号区优化的目的和策略（1-2礼拜）
- Plot mT2 N-1 distribution, including Zn as a function of mT2, give a reasonable mT2 cut for signal region definition. （1-2礼拜）
- 后面看情况而定



SR-C1C1-LM	SR-C1N2OS-LM	SR-C1N2SS-LM
= 2 "medium" τ (OS)	$\geq$ 2 "medium" τ (OS)	$\geq$ 2 "medium" τ (SS)
$\geq$ 1 "tight" τ		-
asymmetric di-tau trigger		
$E_T^{miss} < 150$ GeV		
b-jet veto		
-	$N_{jets} < 3$	
$\lvert\Delta\phi(\tau_1, \tau_2)\rvert > 1.6$	-	$\lvert\Delta\phi(\tau_1, \tau_2)\rvert > 1.5$
Z/h veto ($m(\tau_1, \tau_2) > 120$ GeV)		-
$E_T^{miss} > 60$ GeV		$m_{Tsum} > 200$ GeV
$m_{T2} > 80$ GeV	$m_{T2} > 70$ GeV	$m_{T2} > 80$ GeV

申请高能所atlas账号:

- **Tutorials and materials:**
  - 高能所计算环境使用手册：http://afsapply.ihep.ac.cn/cchelp/zh/
  - IHEP School of Computing 2020 : https://indico.ihep.ac.cn/event/12060/timetable/#20200824
  - ATLAS Computing tutorial : https://twiki.cern.ch/twiki/pub/AtlasProtected/ChinaIhepAtlasGroup/ATLAS_2016English.pdf
  - HTCondor_Manual-ATLAS: https://twiki.cern.ch/twiki/pub/AtlasProtected/ChinaIhepAtlasGroup/HTCondor_Manual-ATLAS_English.pdf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