SUSY Searches at Collider Experiments

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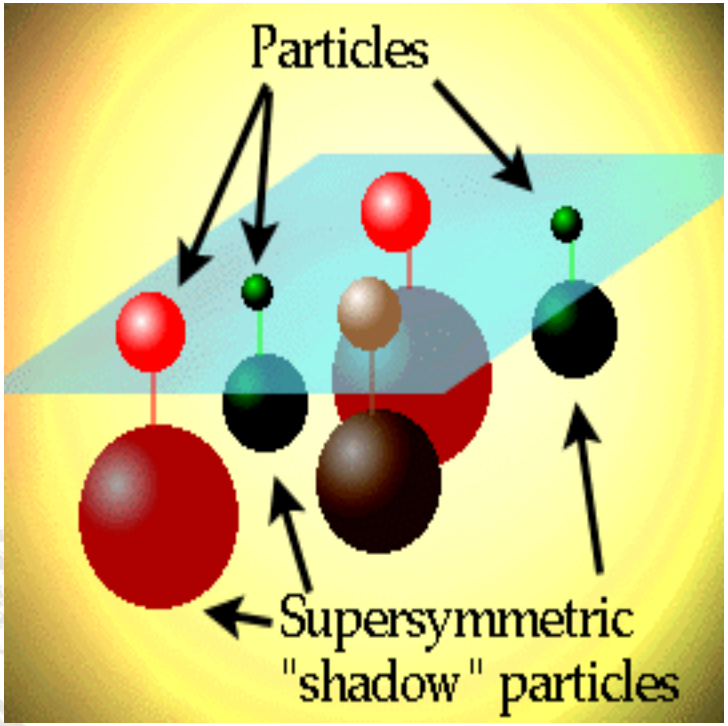
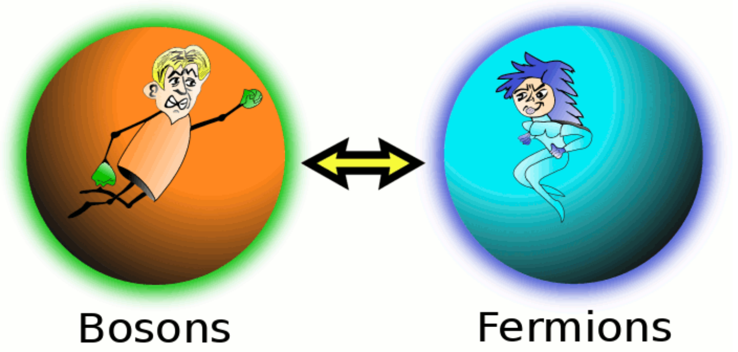


(Julius Wess and Bruno Zumino, 1974)



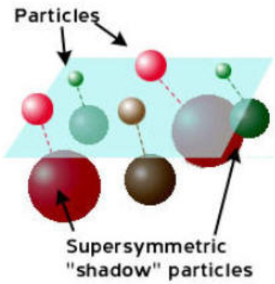
中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

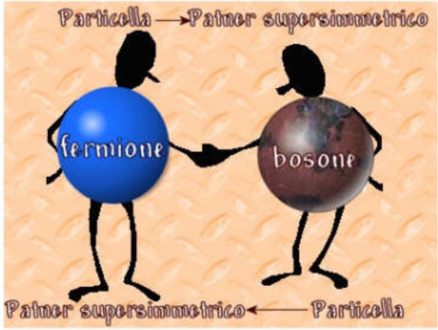
Outline

- SUSY Introduction
- The LHC and ATLAS
- SUSY search strategy

… Coffee Break …

- Overview of SUSY search results
- Outlook





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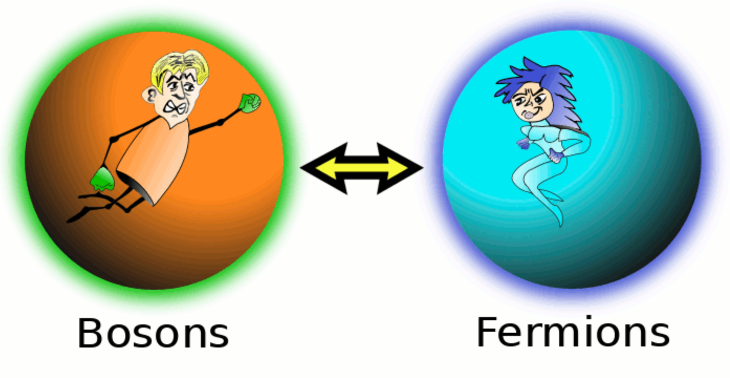
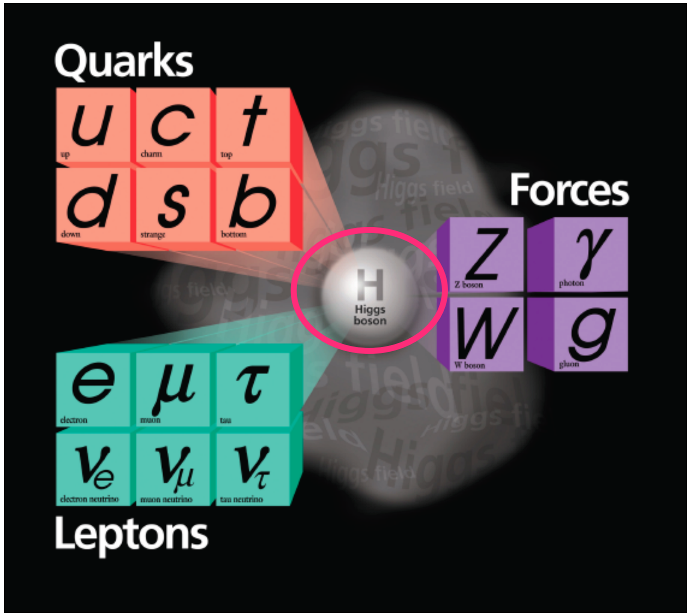
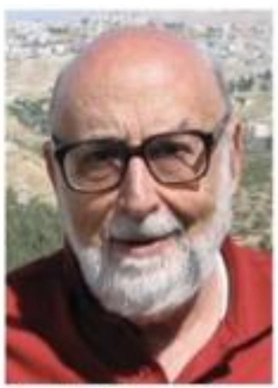


SM and Beyond





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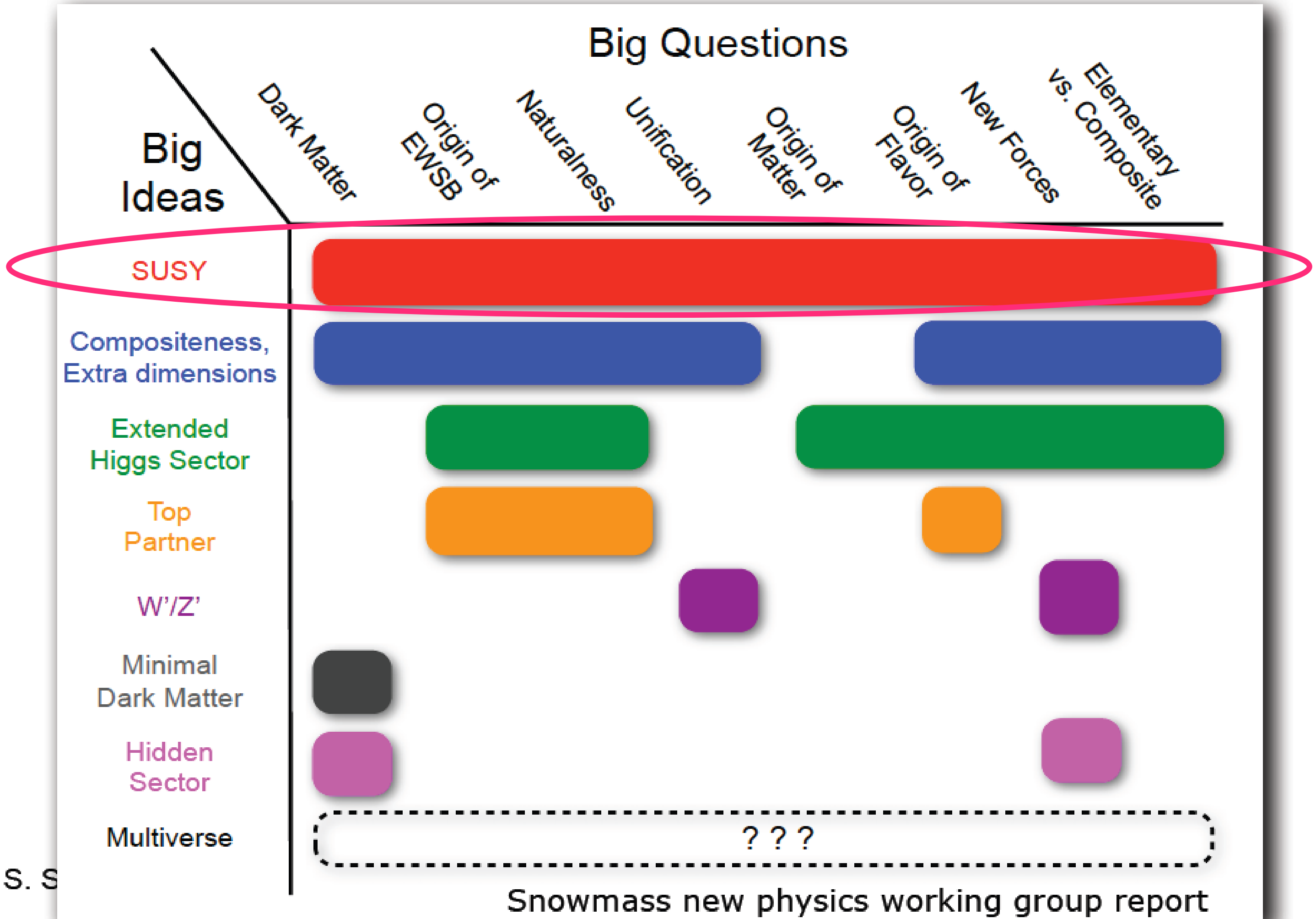
François Englert

Photo: G-M Greuel via Wikimedia Commons

Peter W. Higgs

- Higgs boson observed, SM fits the experimental data very well ➔ big success in EW scale
- While has problem in Planck scale:
  - 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**

New Physics beyond the SM



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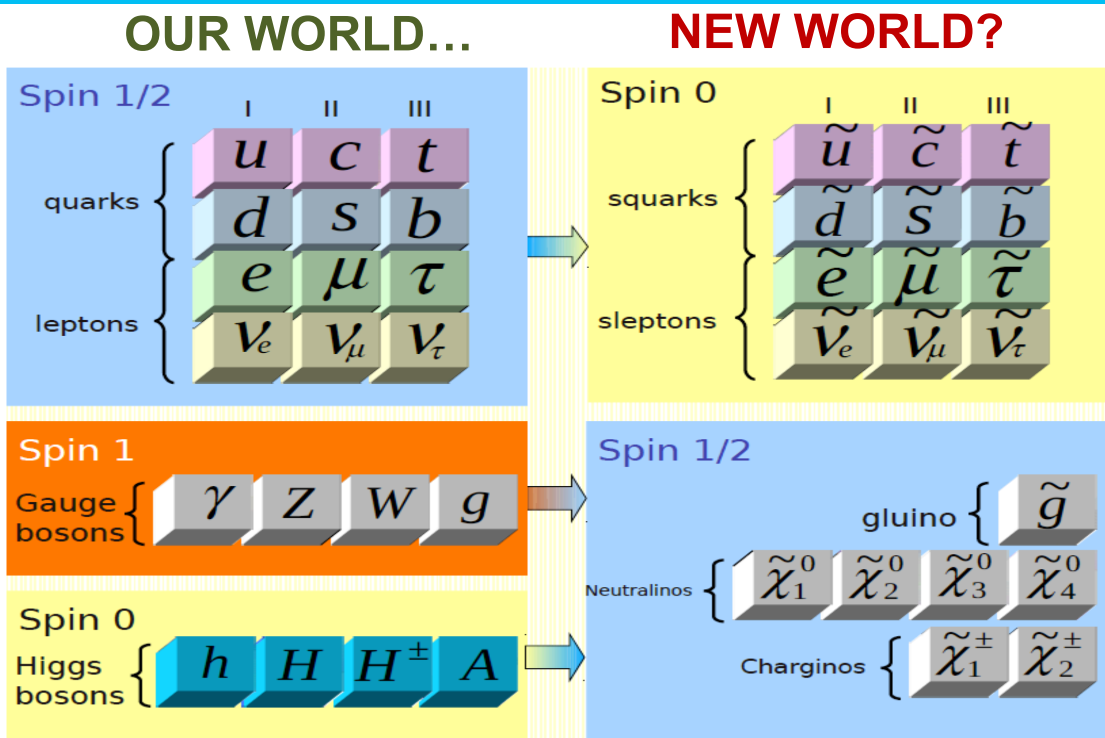
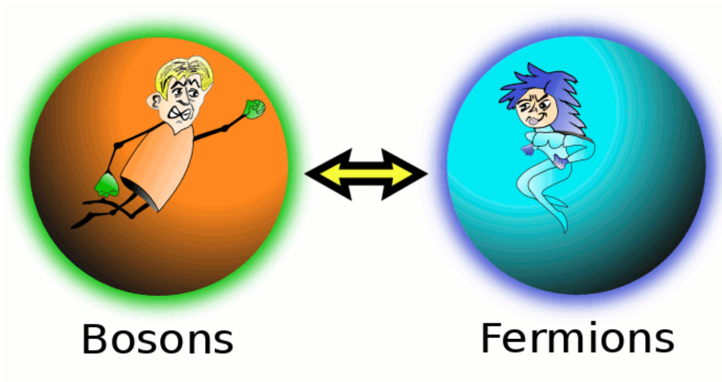
SUSY Introduction



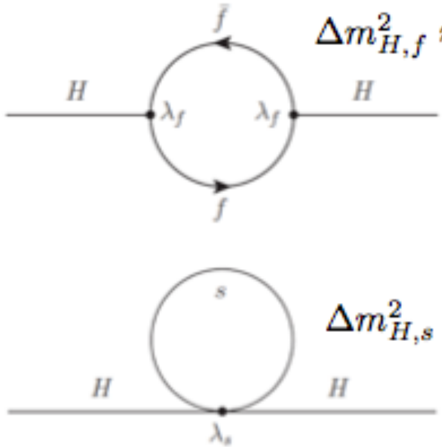


Q |boson> = |fermion>
Q |fermion> = |boson>

- A symmetry which unified fermions (mater) and bosons (forces)
- A more fundamental theory： compatible with SM in EW scale, solve most problems in Planck scale
- Good candidate for Dark Matter

SUSY Introduction

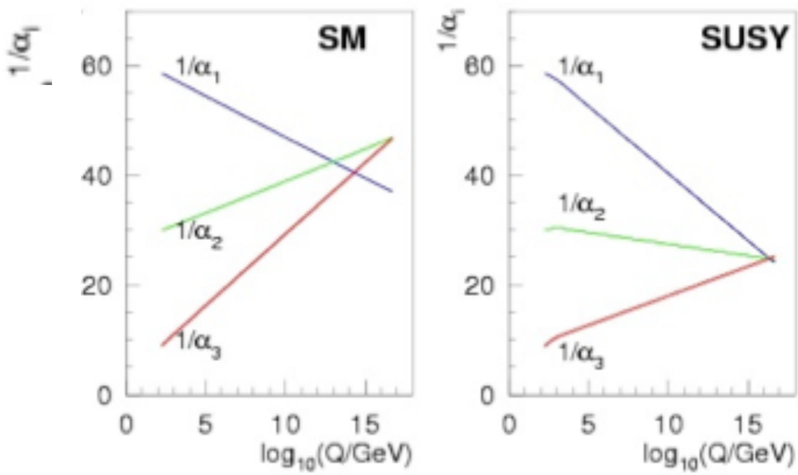
- **Solve hierarchy problem** without "fine tuning"
  - SUSY contributions to Higgs mass cancel SM contributions



$$\Delta m^2_{H,f} \approx -\frac{\lambda_f^2}{8\pi^2}\Lambda^2_{\mathrm{UV}}$$

$$\Delta m^2_{H,s} \approx \frac{\lambda_s}{16\pi^2}\Lambda^2_{\mathrm{UV}}$$

- **Unification of gauge couplings**
  - New particle content changes running of couplings



- **Provide Dark Matter candidate**
  - Lightest SUSY particle (LSP) can be stable and only weekly interacting

Some of the arguments are most convincing for SUSY particles at ~TeV scale

Dark Matter寻找与SUSY寻找的关系

- 只要dark matter不仅仅是引力相互作用现象，它都将可能在LHC实验中表现为large missing Et 现象
- R宇称守恒SUSY寻找包括了各种large missing Et的topology.
- 因此，即使SUSY理论不一定正确，但是dark matter的large missing Et 信号一定会在SUSY寻找中显示。

→超对称粒子的寻找不仅对寻找超对称粒子本身有重要意义，也对寻找暗物质实验证据具有重要意义

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大型强子对撞机（LHC）
位于欧洲核子研究中心（CERN）

- 周长27km，跨越瑞士法国国境，总投资40亿美元
- 世界能量最高最大的加速器，质心系能量14TeV（14×10^{12}eV）

ATLAS and CMS detector @ LHC

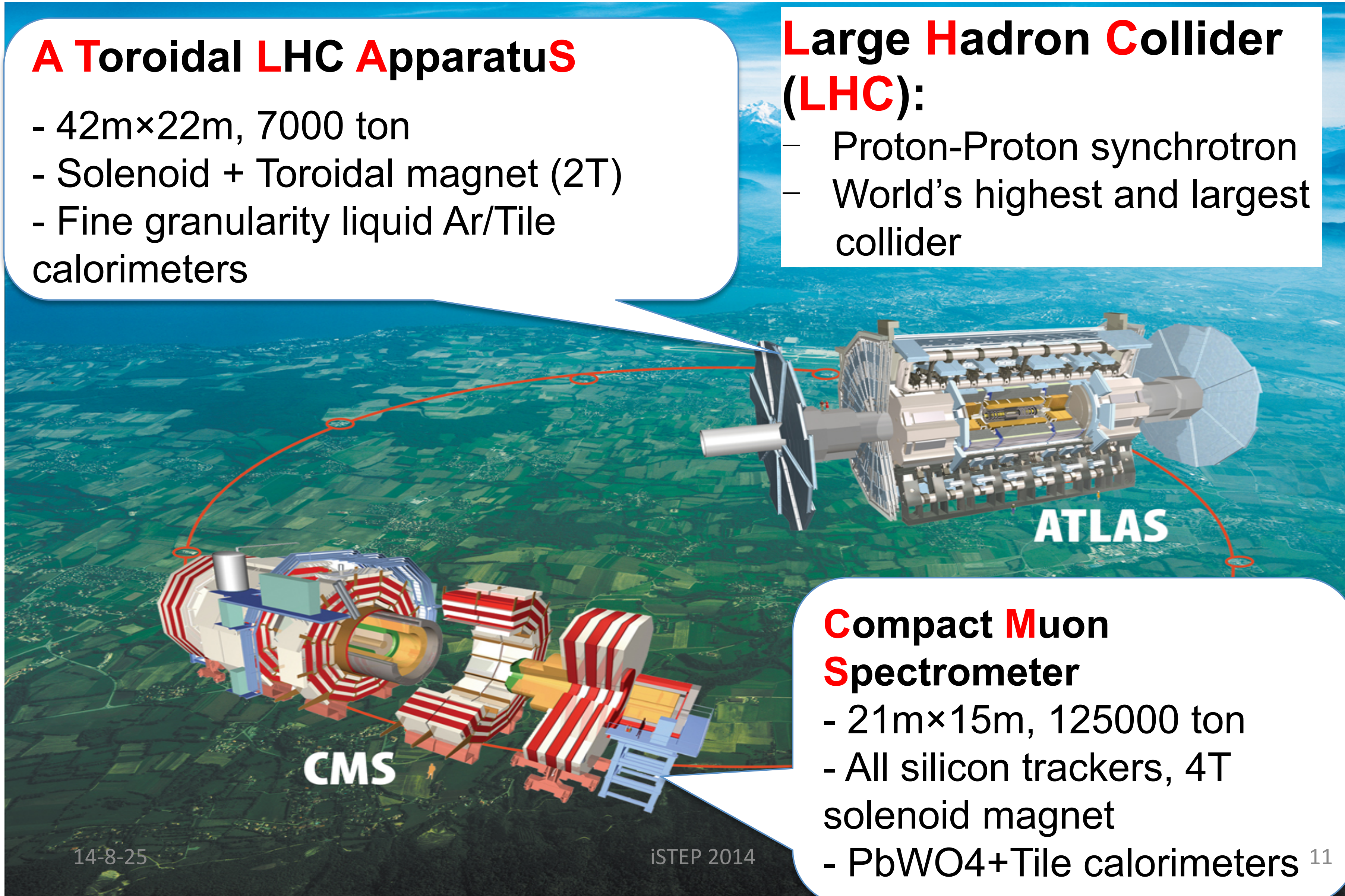
ATLAS and CMS: two multi-purpose detectors @LHC

A Toroidal LHC ApparatuS

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

Large Hadron Collider (LHC):

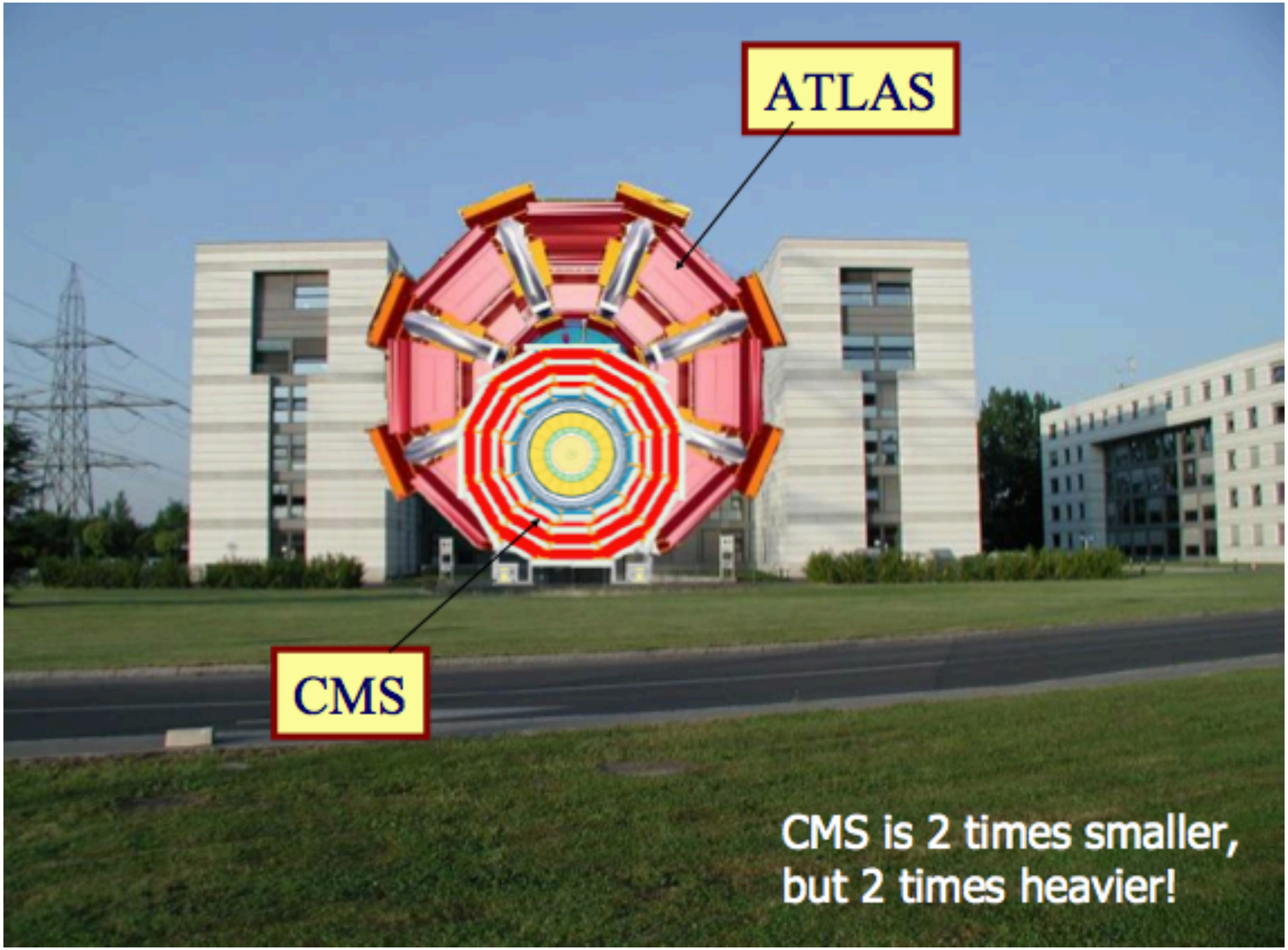
- Proton-Proton synchrotron
- World's highest and largest collider



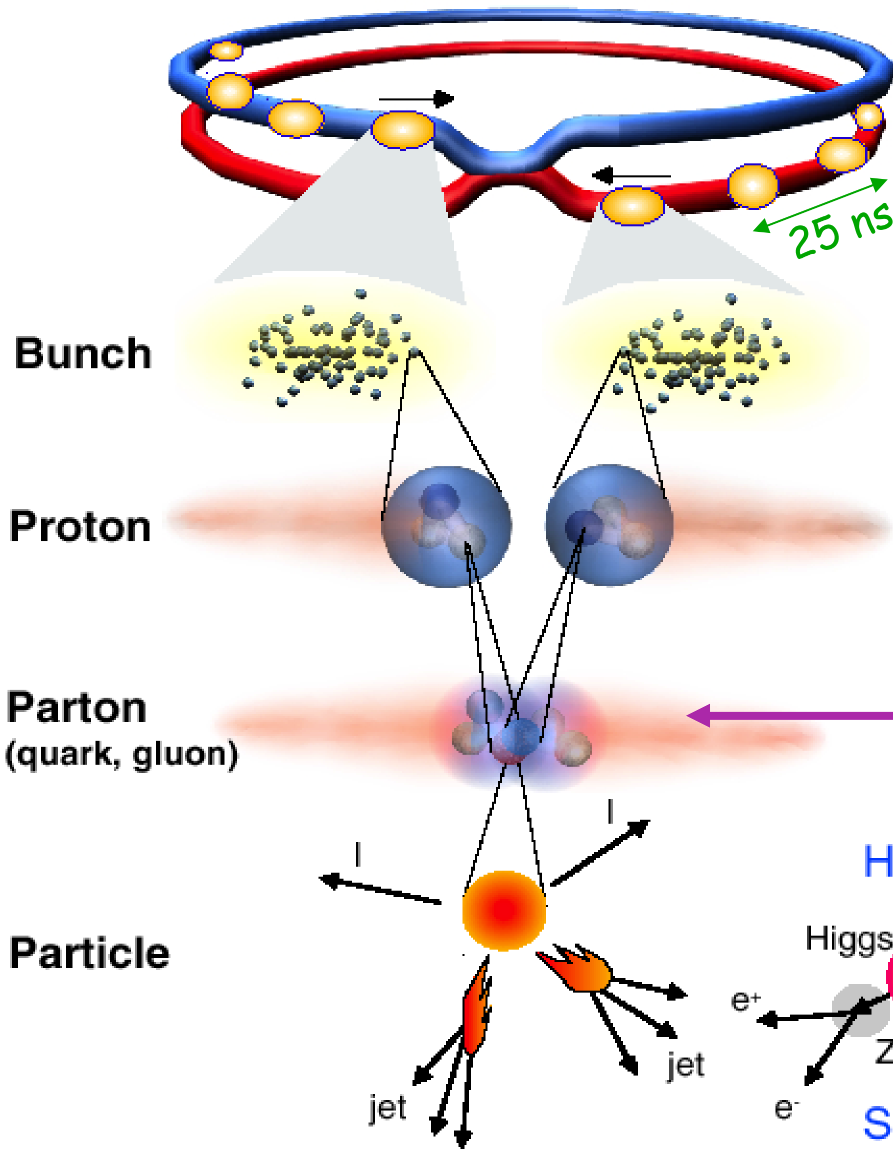
Compact Muon Spectrometer

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

ATLAS and CMS



Collisions at LHC



Proton-Proton

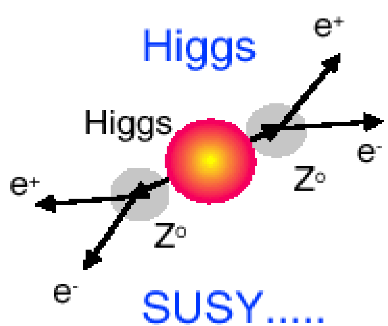
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}

Event rate:

N = L x σ (pp) $\approx$ 10^9 interactions/s

Mostly soft (low p_T) events

Interesting hard (high-p_T) events are rare

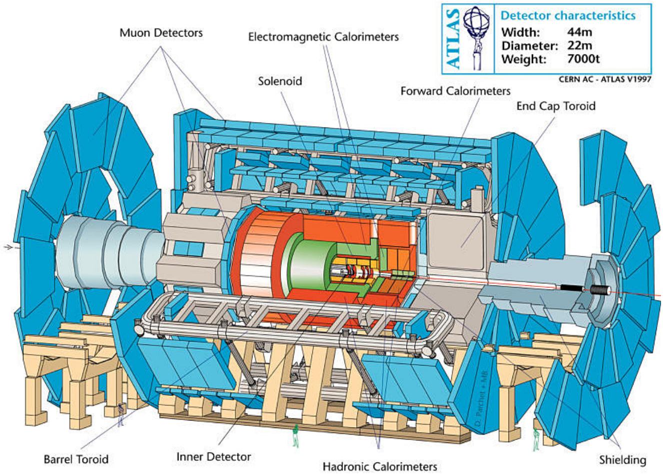


Selection of 1 in 10,000,000,000,000

→ very powerful detectors needed

Detector requirements

- Excellent position and momentum resolution in central tracker
  - b-jets, taus
- Excellent ECAL performance
  - electrons, photons
  - good granularity (energy and position



- Good HCAL performance
  - jets, Etmiss (neutrinos, SUSY stable LSP, etc)
  - good granularity (energy and position measurements)
  - good η coverage (hermeticity for Etmiss measurements)
- Excellent muon identification and momentum resolution
  - from "combined" muons in external spectrometer + central tracker

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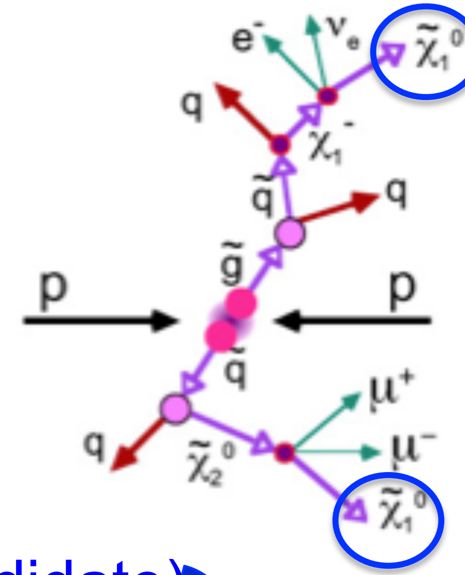
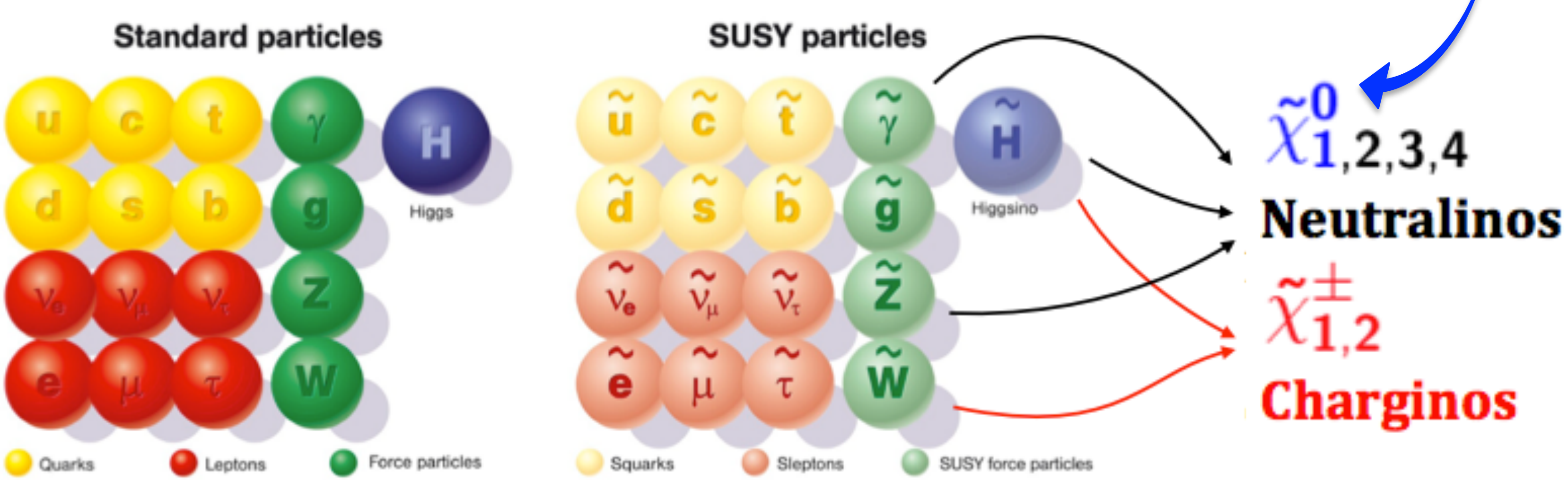
SUSY Signature

- Conserved R parity (originally introduced for stability of proton, R=+1 for SM, -1 for SUSY)

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

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



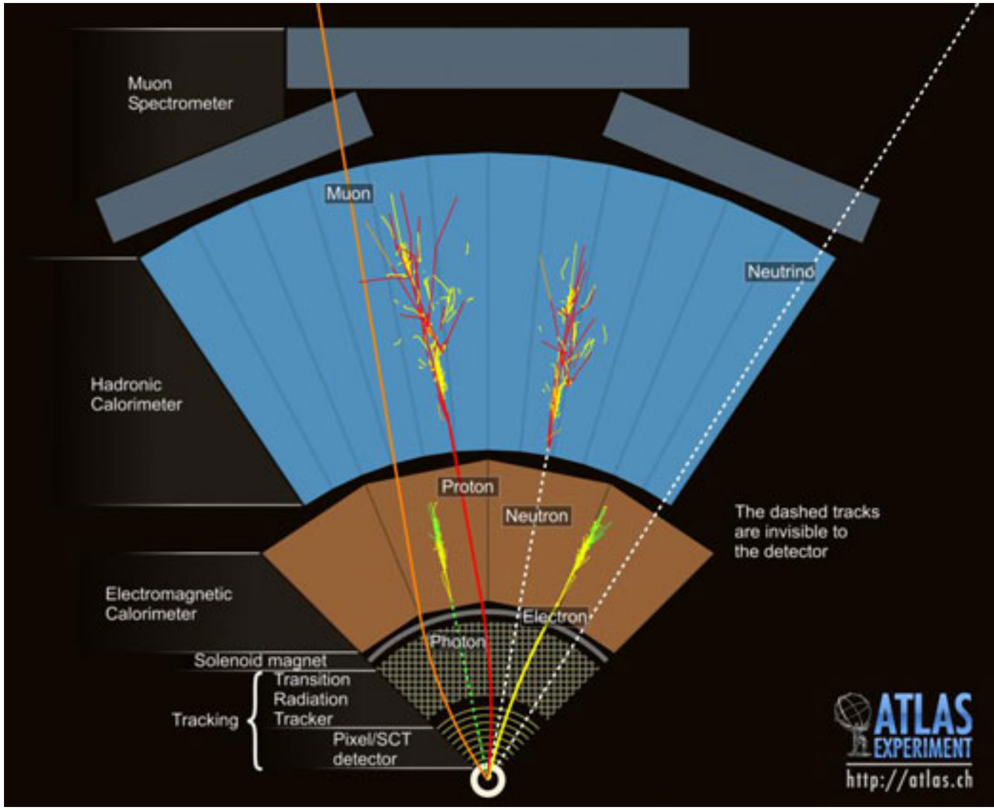


Minimal Supersymmetric Standard Model

Standard Model Particles and Fields		Supersymmetric Partners: Interaction Eigenstates		Supersymmetric Partners: 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**		

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

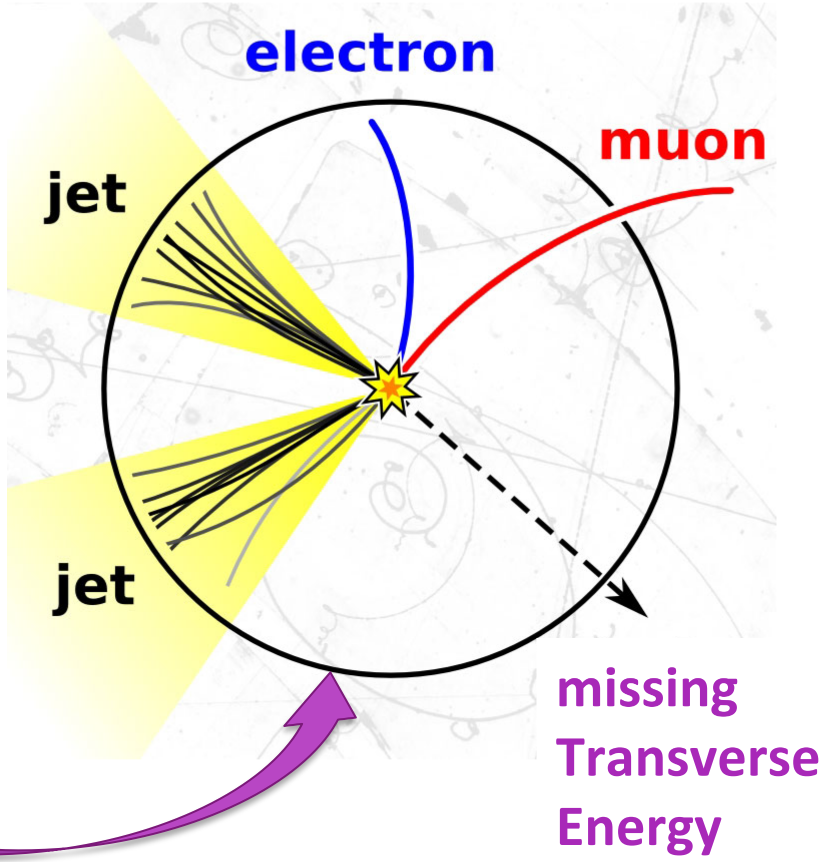


MET: Missing Transverse Energy

- 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**

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



Why do we need SUSY models?

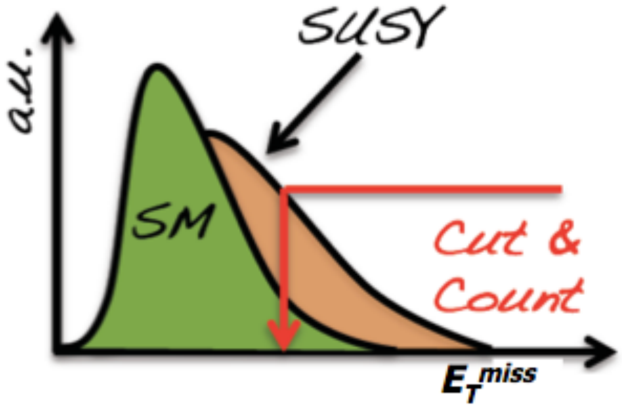
- Different masses – different phase space – different search region – different final state particles to search for...
- We need some model for signal region definition and optimization …
- If we don't see anything, we (the experimentalists) also like to set limits, and limits can only be set on certain models...

SUSY models: good sale in market

- Simplified Models:
  - Not really a model (Br~100%, most masses fixed at high scales)
  - Important tool for interpretation
- Phenomenological MSSM:
  - 19 free parameters
    - ✓ M1,M2,M3
    - ✓ tan β, μ and m_A
    - ✓ 10 sfermion mass parameters
    - ✓ A_t, A_b and A_τ
  - pMSSM captures "most" of phenomenologic features of R-parity conserving MSSM
  - Comprehensive and computationally realistic approximation of the MSSM with neutralino LSP

SUSY Search Strategy

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

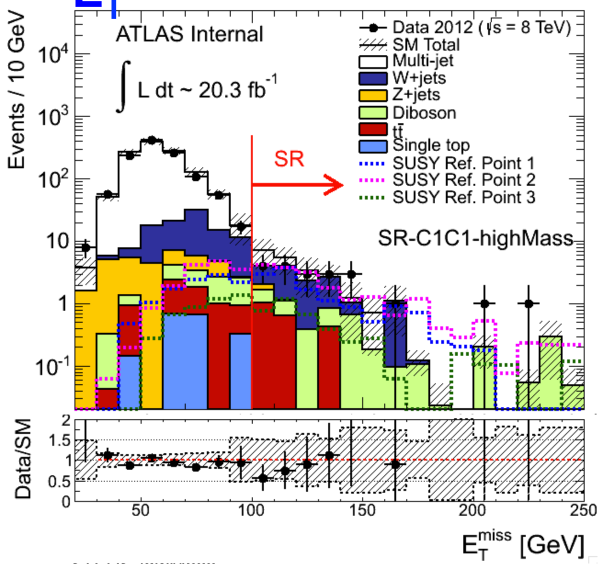


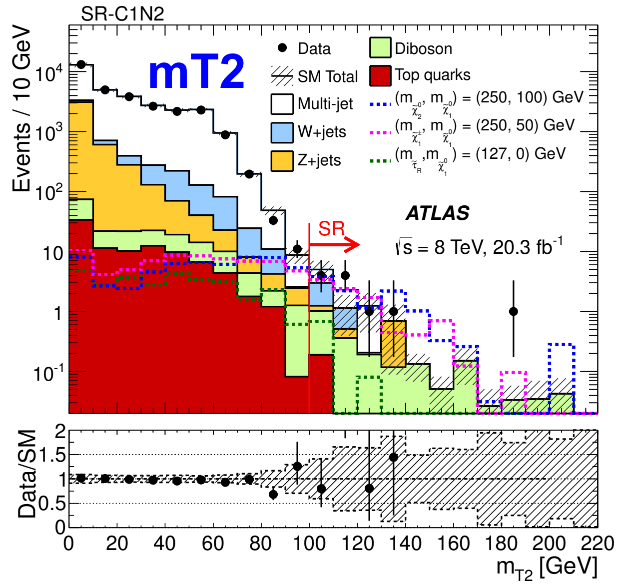
- **SUSY sensitive variables:** Try to establish excess of events in some sensitive kinematic distribution

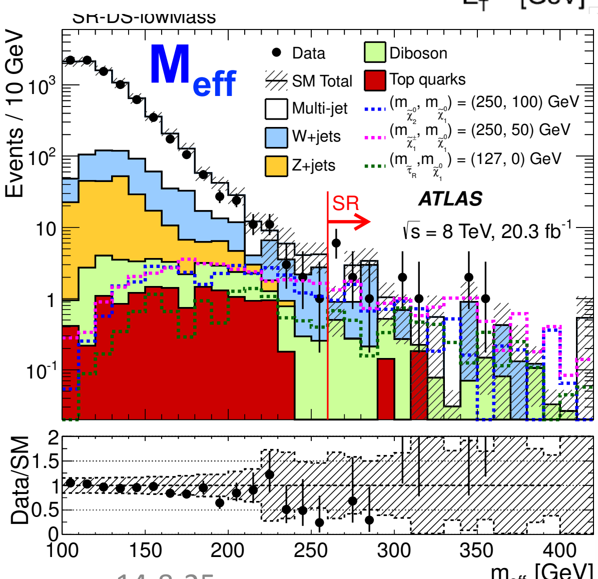
- **SM background:** the discovery of new physics can only be claimed when SM backgrounds are understood well or under control
  - Background estimation should better be estimated from data (use **Data-Driven Method**) because of imperfect knowledge of underlying event, parton showering, parton distribution functions, limited MC statistics …

SUSY Sensitive Variables

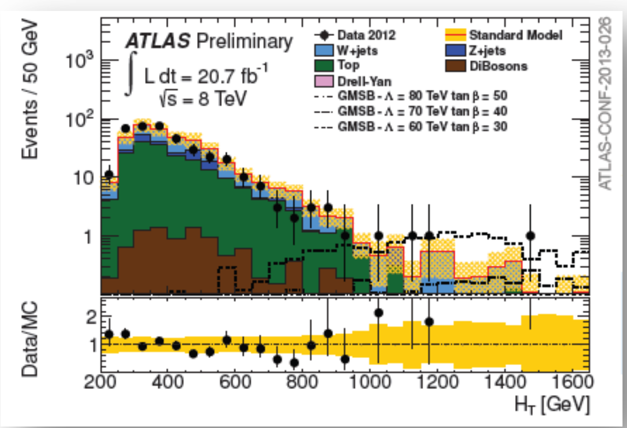
E_T^{miss}







HT



- Missing ET (E_T^{miss})
- Effective mass (M_{eff})

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

- mT2

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

- HT

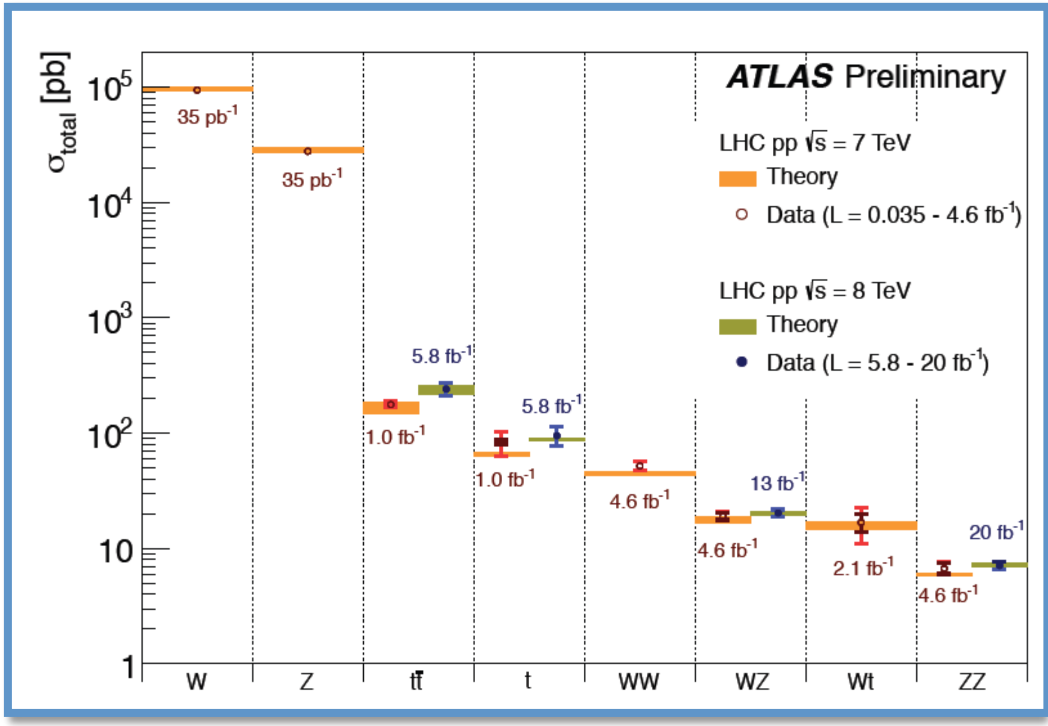
$$H_T = \sum p_T^l + \sum p_T^{jet}$$

- Many others …

SM Background

- SM bkgs: multi-jets, top, bosons (W,Z), dibosons (WW,WZ,ZZ), tribosons, Higgs
  - SM bgs understood very well
- BG estimation strategy:
  - Dominant systematics: data-driven method
  - sub-dominant BG: MC estimation

SM "backgrounds"– the big picture



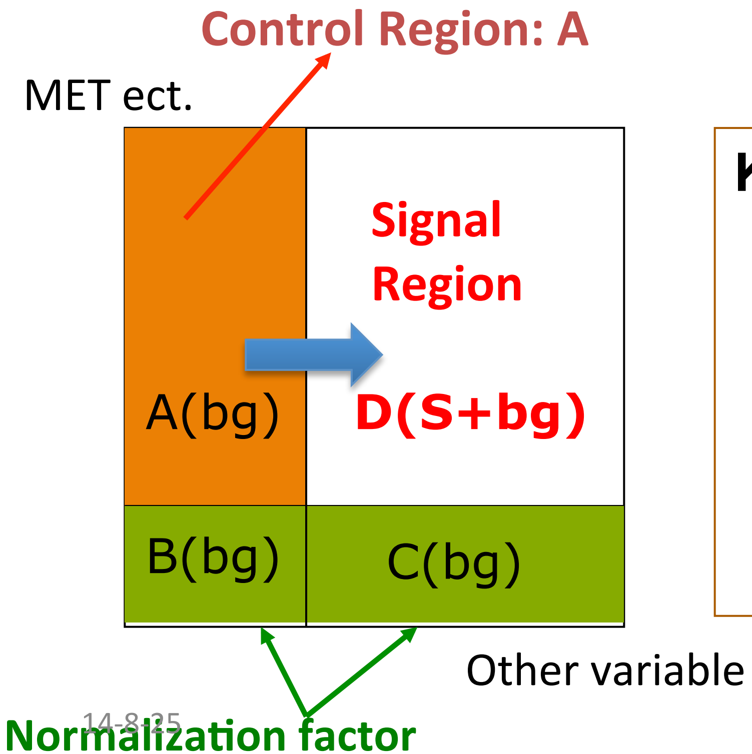
Data-Driven-Method (ABCD method)

One approach to data-driven bg ***estimation*** is to use uncorrelated model-independent variables to *extrapolate* the background from a background-dominated control region A to the signal region D.

N_bg in signal region D = A*(C/B)

Control Sample

Normalize Factor

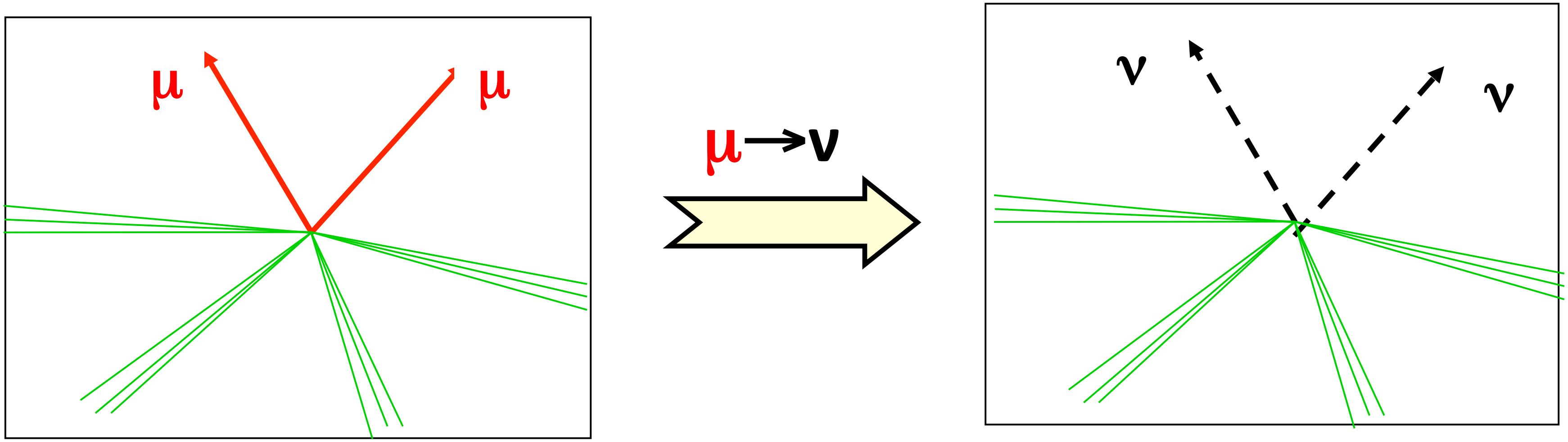


Key points:

- **The two variables** should have good discrepancy and uncorrelated
- **Control Sample selection(A)**: enough statistics; lower susy contamination; good purity

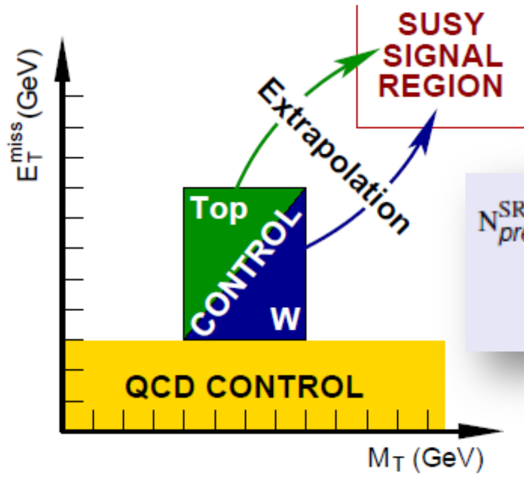
Data-Driven-Method (Replacement Method)

- Many other DDM, while based on ABCD method: e.g. replacement method, Matrix Method, simultaneously fit method …
- one example: Z➔νν estimated from Z➔μμ (replacement method)
  - **A method to get a control sample:**
    - **Seed Sample: reconstructed Z→ee or Z→μμ events**
    - **Replacement: replace charged leptons by neutrinos (E_T^{miss} is estimated by $p_T^{(Z)}$)**
    - **Apply corrections for lepton efficiency (from data) and acceptance (from MC)**
  - **Derive Z➔νν MET distribution (shape from Zmm, TF from low MET region)**



Data-Driven-Method (others)

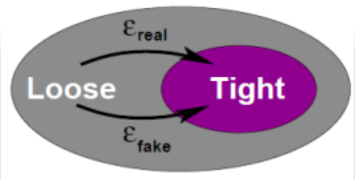
- ☐ ***Simultaneous fit* method**
- ☐ **Matrix Method**
- ☐ ……



$$N^{SR}_{pred_j} = (N^{CR_i}_{data} - N^{CR_i}_{other\ bkg}) \times \frac{N_{pred}(MC^j, SR)}{N_{pred}(MC^j, CR_i)}$$

$$= (N^{CR_i}_{data} - N^{CR_i}_{other\ bkg}) \times C^j_{CR_i \to SR}$$

$$\text{QCD BG} = \frac{1}{1/\epsilon_{fake} - 1/\epsilon_{real}} \cdot N_{fail} - \frac{1/\epsilon_{real} - 1}{1/\epsilon_{fake} - 1/\epsilon_{real}} \cdot N_{pass}$$



N_{pass}: Events passing the signal selection cuts (*tight*)

N_{fail}: Events satisfying relaxed lepton isolation criteria but not passing the signal selection cuts (*loose-but-not-tight*)

ϵ_{real}: Probability that a loose non-QCD event passes also the tight selection cuts

ϵ_{fake}: Probability that a loose QCD event passes also the tight selection cuts

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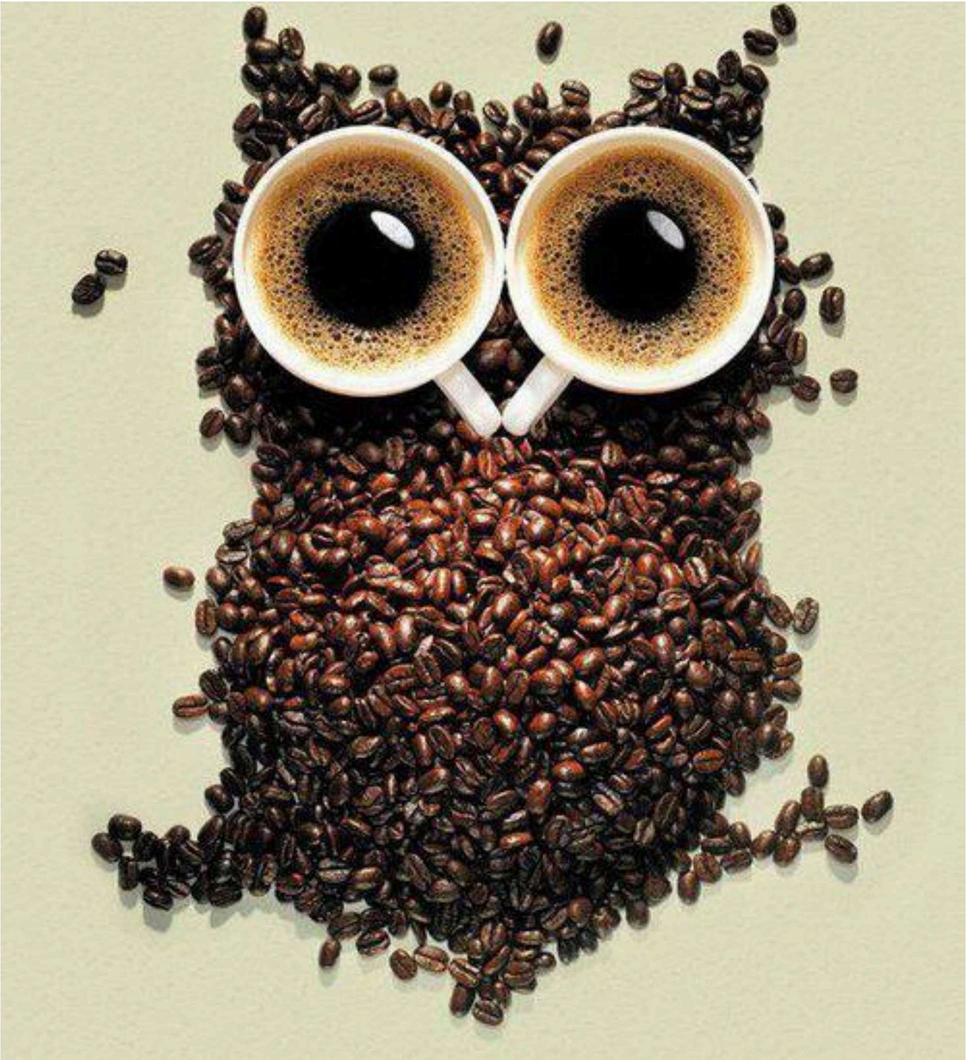

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SUSY Searches @ LHC

Strong production: gluino pair, gluino-squark and squark pair (include **3rd generation**) production

1）Generic signatures :

Multi -jets + n_lepton/n_photon(n=0,1, ≥2) + large E_T^{miss} (0L,**>=1 L**)

2）large xs, but heavy SUSY mass scale

Final states:

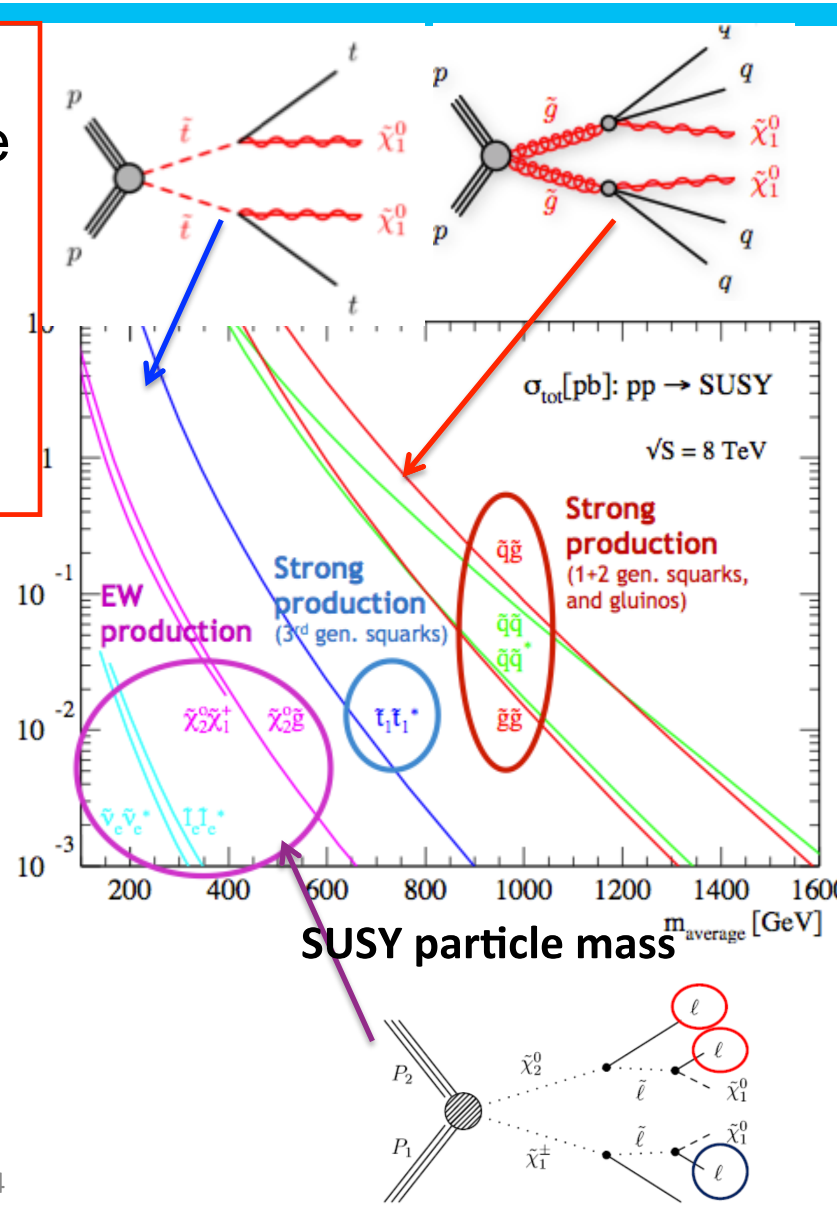
n_jets + n_leptons/n_photons + *large E_T^{miss}* (n≥0)

Weak production: direct gaugino/slepton production

1）Generic signatures:

low–jet multiplicity + ≥ 2leptons + large E_T^{miss} (2/3/4L, **>=2tau**)

2）low xs, but small SUSY mass scale



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Weak production: direct gaugino/slepton production

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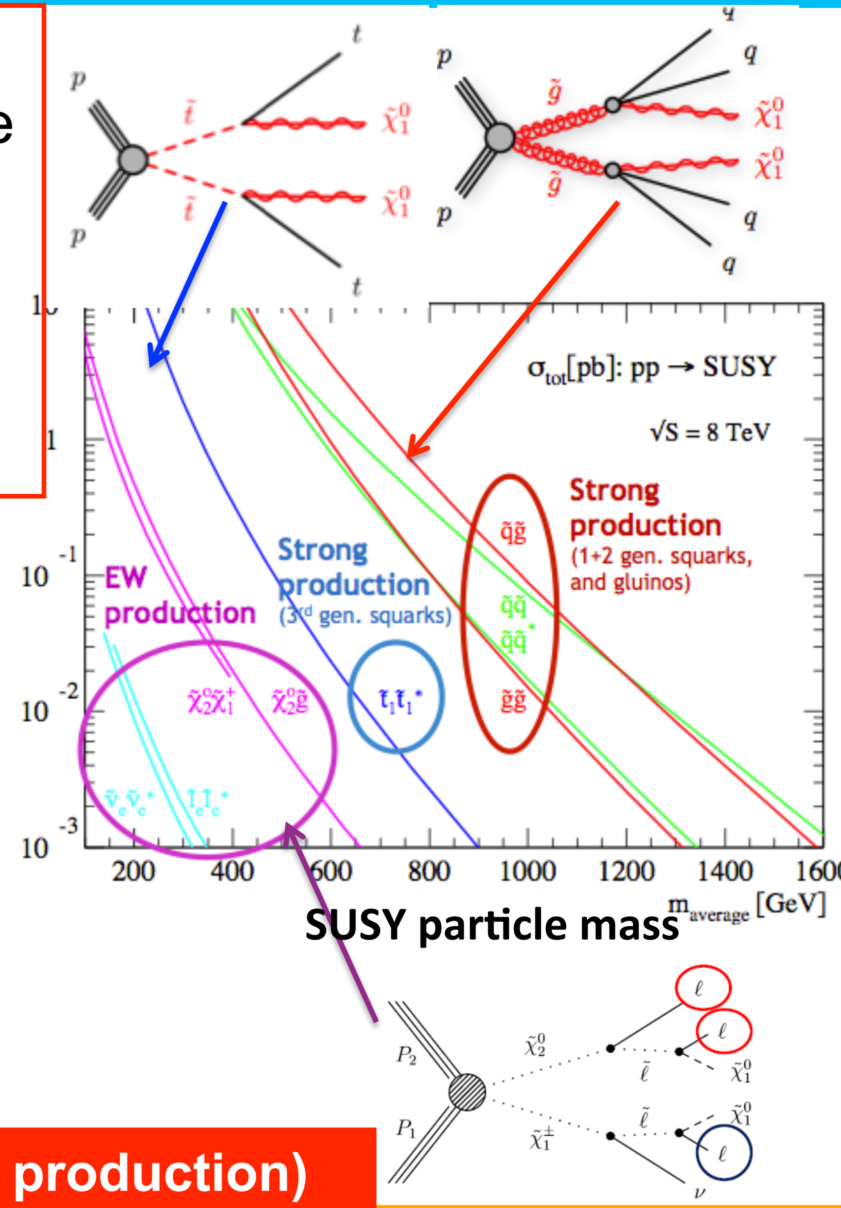
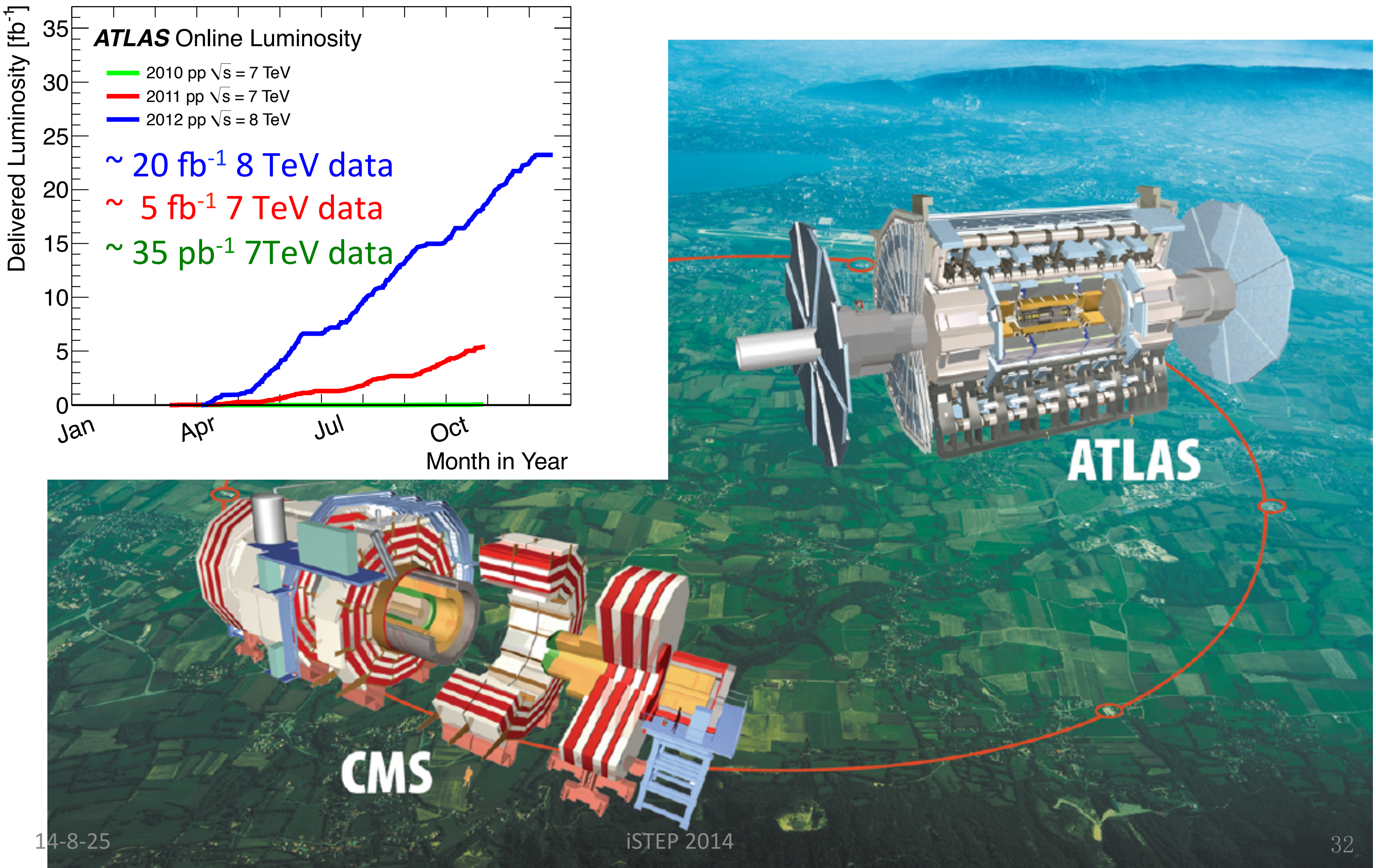
E.g.: >=2tau + MET (direct gaugino/stau production)



Since 2010, ATLAS&CMS have invested huge efforts in SUSY search @LHC : Great Luminosity recorded

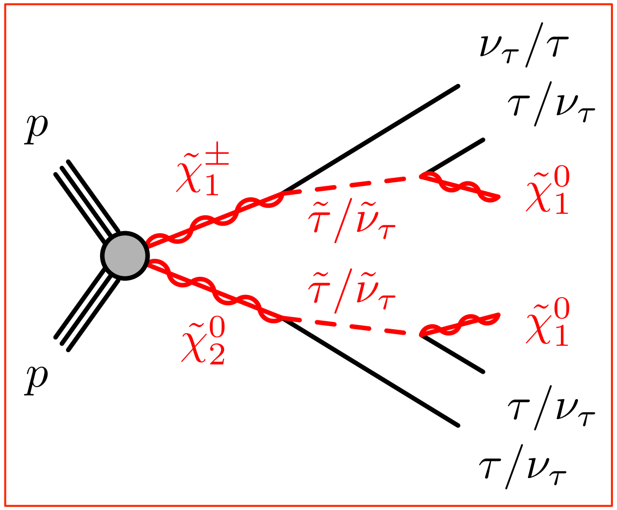


Analysis Procedure

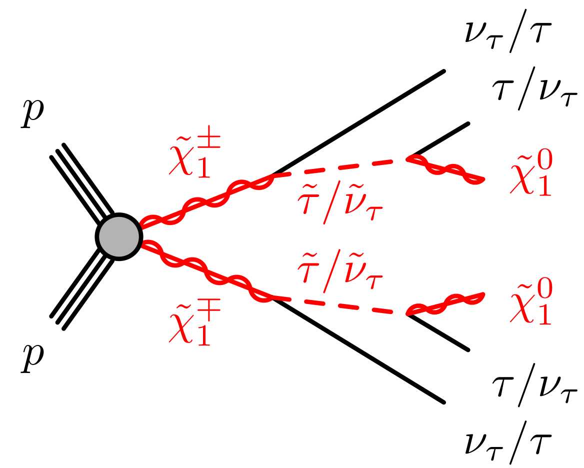
- Pre-selection: select good objects (e, mu, tau, jet, …), apply trigger depending on analysis, remove bad events (bad runs, not from pp collisions, in transition region …)
- SR definition and optimization
  - Define signal regions based on decay topologies occurring in generic models
  - Set final cut on discriminating variables (e.g. M_{eff}) to optimize sensitivity to reference models with appropriate mass scale
- SM Background estimations (data-driven + MC)
- Compare SM predictions with data
- If no excess, interpret results in different SUSY models

Signal Grids

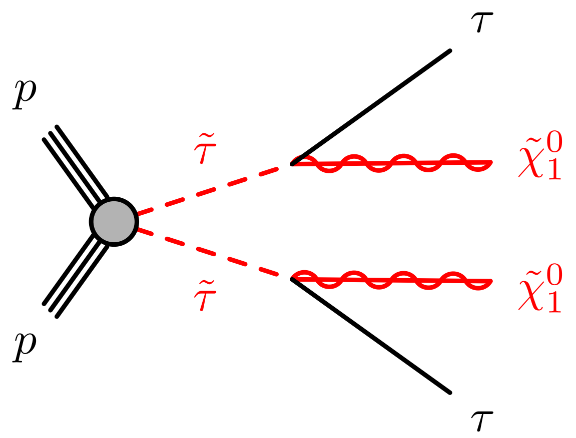
E.g.: >=2tau + MET (direct gaugino/stau production)



3tau + MET



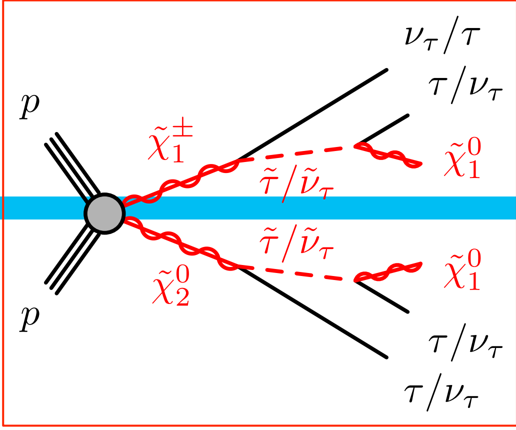
2tau + MET



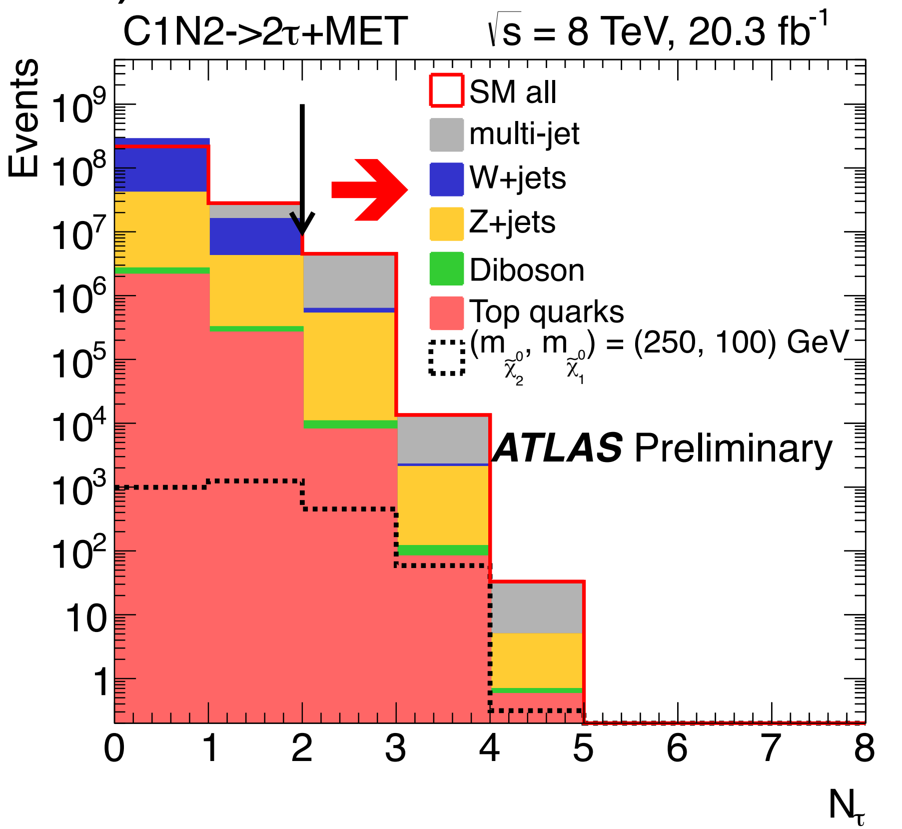
2tau + MET

- Final states: >= 2tau + MET (e.x.: C1N2)
- Only consider tau decay hadronically (e, mu vetoed)
- Results published in arXiv:1407.0350
- **Assuming selectron and smuon are heavy, only stau is light, which is sensitive for light stau model**

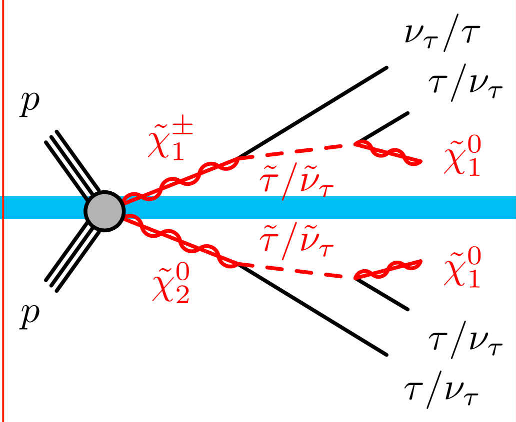
Signal Region Definition



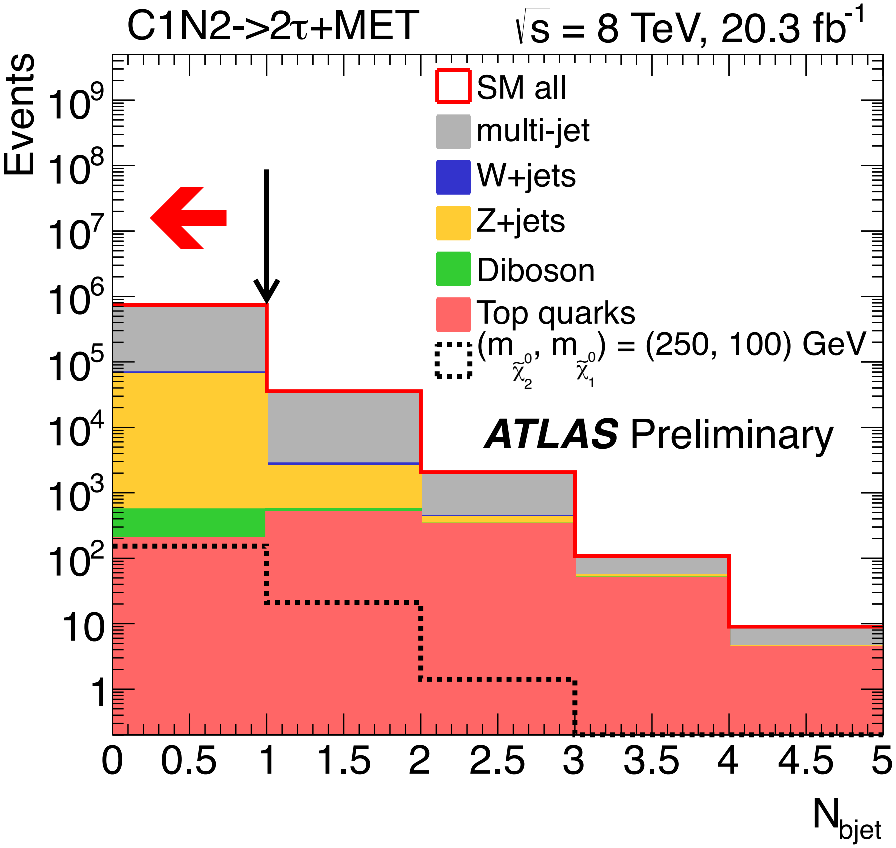
- Final states: >=2tau +MET
- **Trigger**: di-tau trigger (only select interested events with at least 2 taus)
- At least **2 OS taus** (e, mu veto)



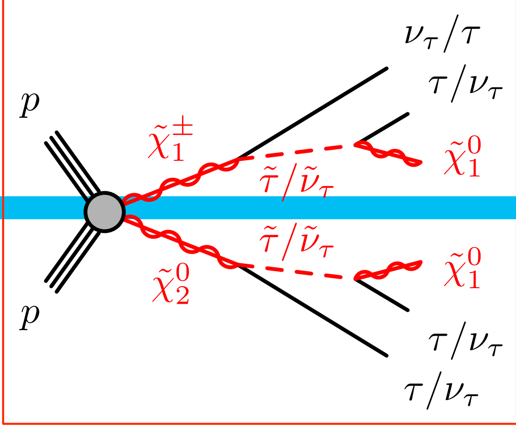
Signal Region Definition



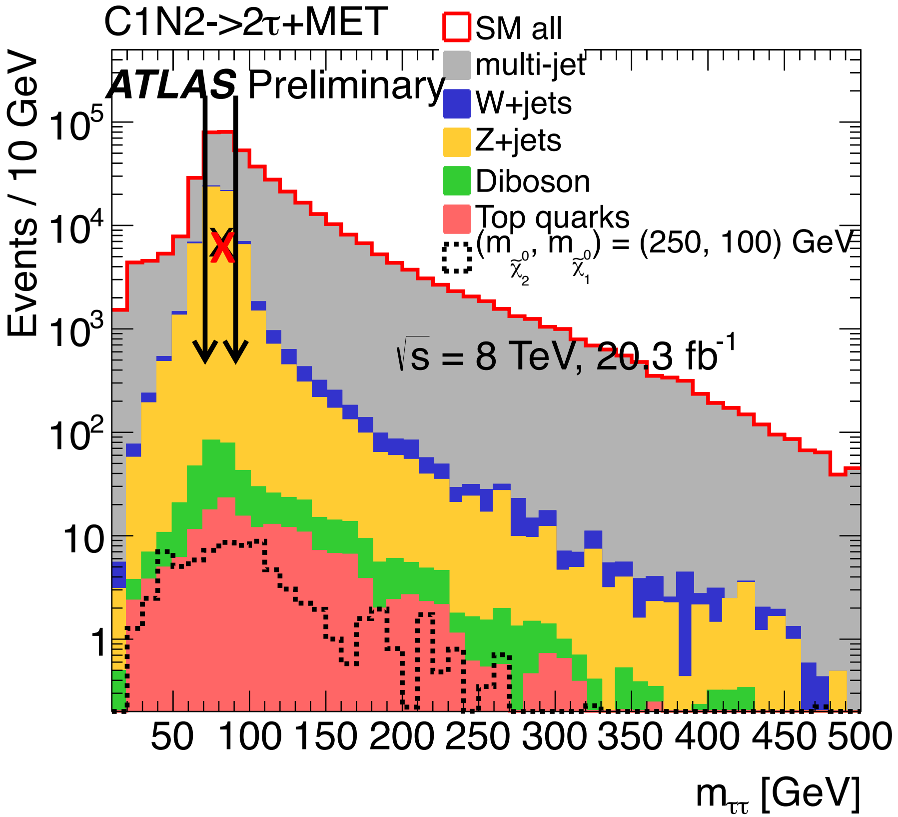
- Final states: >=2tau +MET
- **Trigger**: di-tau trigger (only select interested events with at least 2 taus)
- At least **2 OS taus** (e, mu veto
- **bjet veto (Nbjet =0)**
  - suppress top, cover signal events with ISR jet



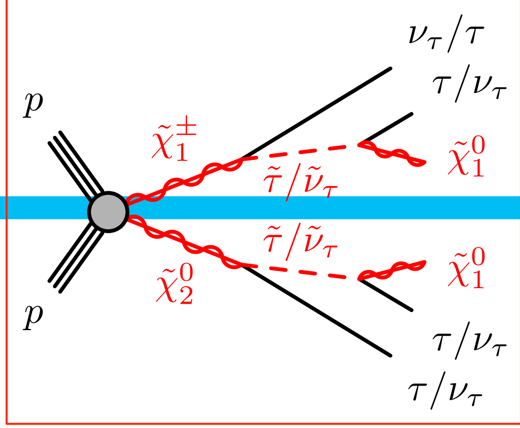
Signal Region Definition



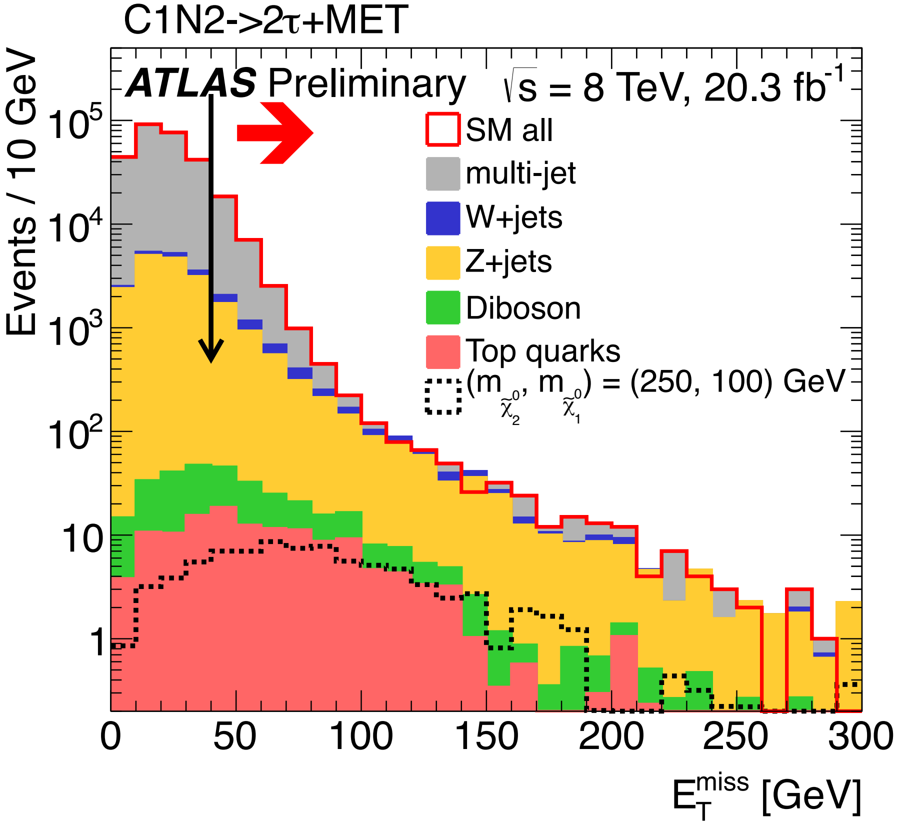
- Final states: >=2tau +MET
- **Trigger**: di-tau trigger (only select interested events with at least 2 taus)
- At least **2 OS taus** (e, mu veto)
- **bjet veto (Nbjet =0)**
  - suppress top, cover signal events with ISR jet
- **Z-veto**: suppress Z+jets BGs



Signal Region Definition



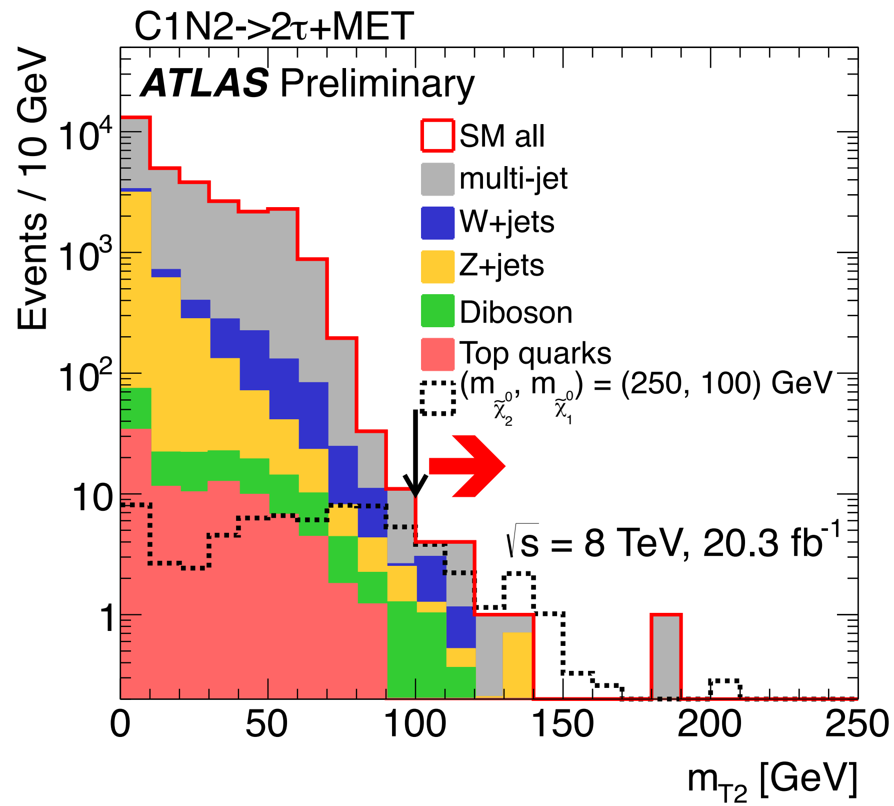
- Final states: >=2tau +MET
- **Trigger**: di-tau trigger (only select interested events with at least 2 taus)
- At least **2 OS taus** (e, mu veto)
- **bjet veto (Nbjet =0)**
  - suppress top, cover signal events with ISR jet
- **Z-veto**: suppress Z+jets BGs
- **MET>40 GeV**: suppress QCD/Z



Signal Region Definition

SR-C1N2
≥ 2 OS taus b-jet veto Z-veto $E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV $m_{\mathrm{T2}} > 100$ GeV

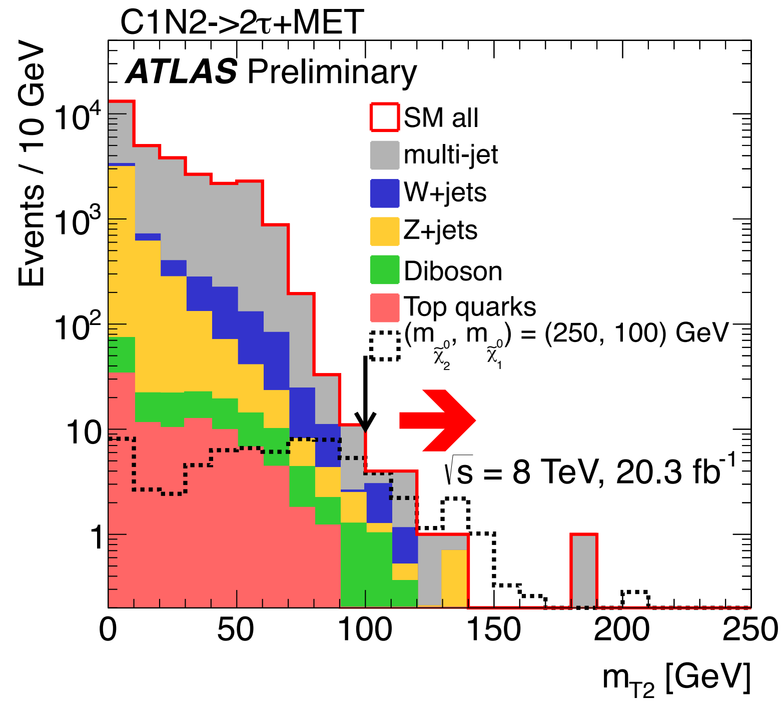
- Final states: >=2tau +MET
- **Trigger**: di-tau trigger (only select interested events with at least 2 taus)
- At least **2 OS taus** (e, mu veto)
- **bjet veto (Nbjet =0)**
  - suppress top, cover signal events with ISR jet
- **Z-veto**: suppress Z+jets BGs
- **MET>40 GeV**: suppress QCD/Z
- **MT2>100 GeV**: further suppress all SM BGs and enhance SUSY sensitivity



Background Composition

SR-C1N2
≥ 2 OS taus
b-jet veto
Z-veto
$E_T^{miss} > 40$ GeV
$m_{T2} > 100$ GeV

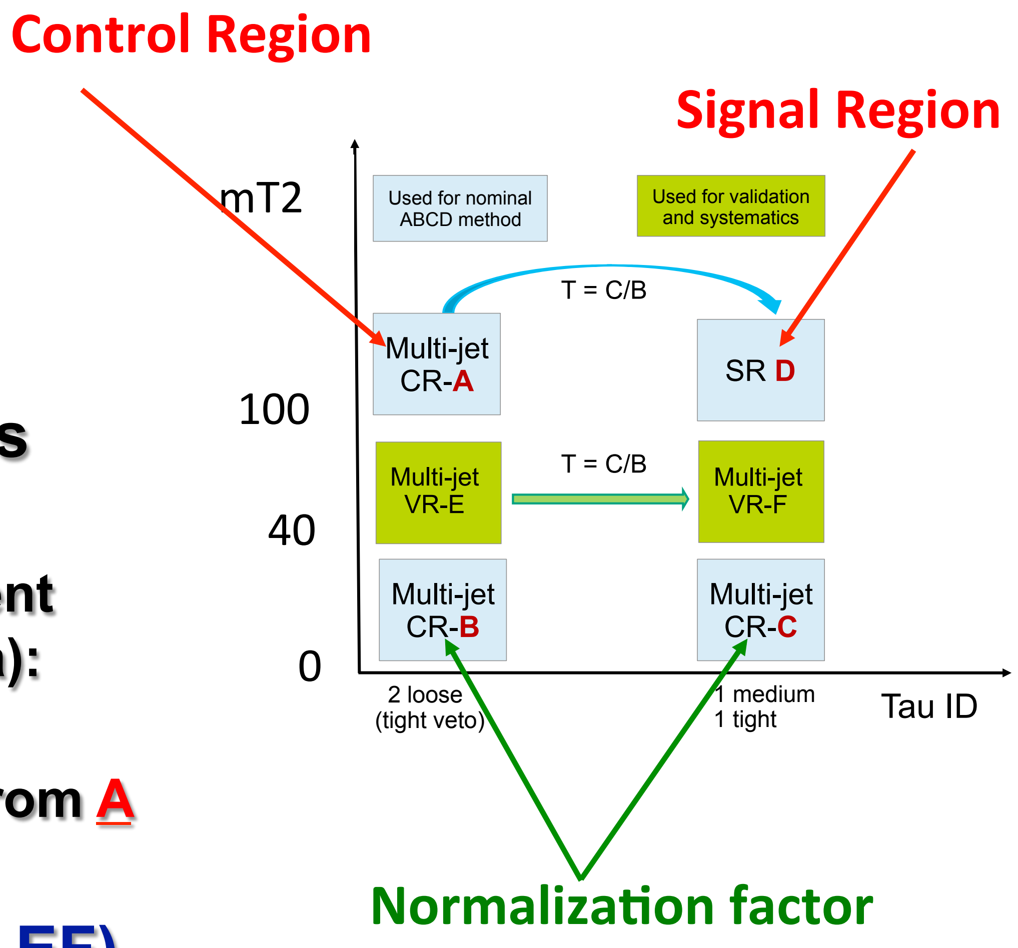
SM process	SR-C1N2
top	0.2 ± 0.2
Z+jets	1.0 ± 0.6
diboson	2.2 ± 0.5
W+jets	2.4 ± 1.3
multi-jet	2.3 ± 1.4
SM total	8.1 ± 2.1



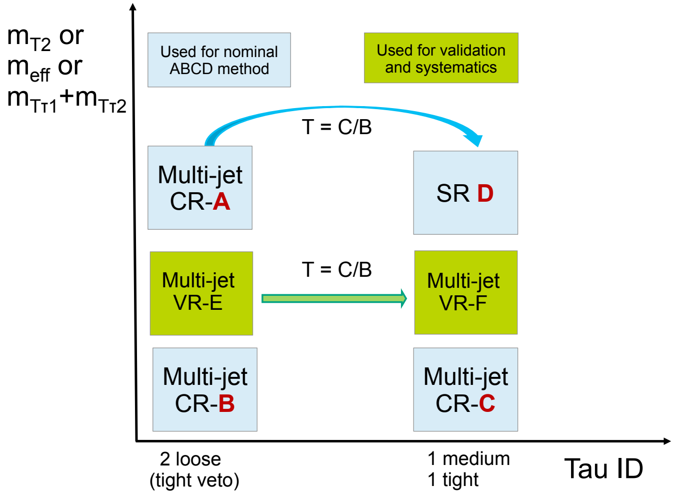
- Dominant Background: multi-jet, W+jets and diboson
- **multi-jet BG: ABCD data-driven method**
- **Others: MC prediction**

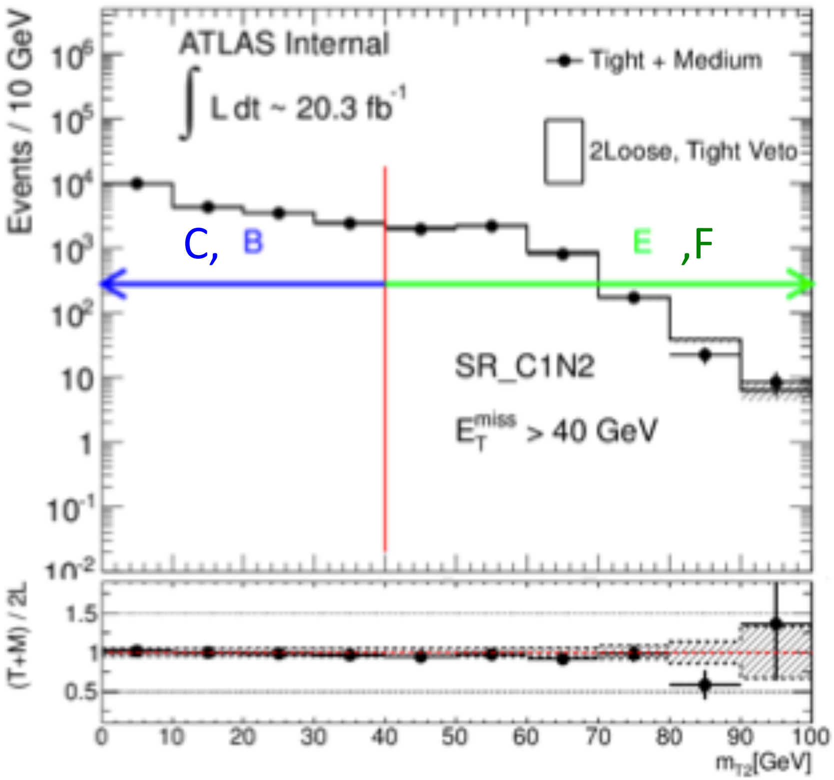
Fake tau BG estimation：ABCD method

- Two weak correlated Variables:
  - X-axis: TauID
  - Y-axis: mT2
- Signal Region
  - SR D
- Baseline Control Regions
  - QCD+W CR-A/B/C
  - TF obtained from QCD event (low mT2 region from Data): TF=C/B
  - Extrapolation performed from A to D through TF
- Validation Region (W VR-EF)



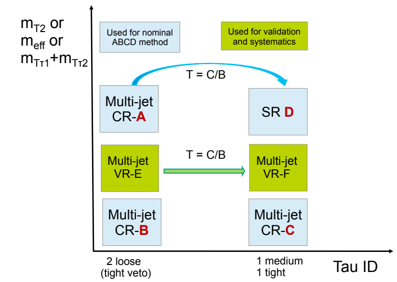
ABCD method check:
- Correlation between TauID and mT2





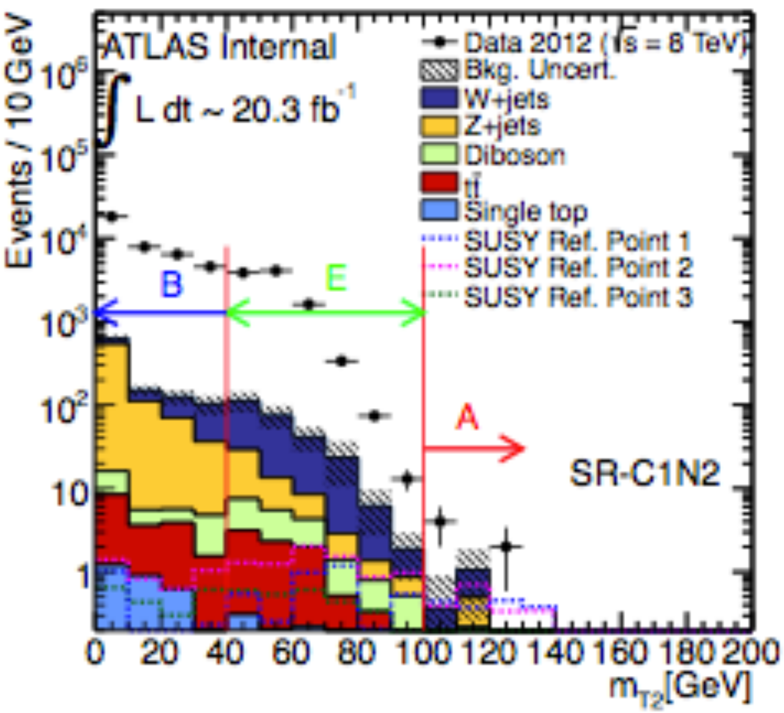
- **No strong correlation between TauID and Mt2.**
- **The residual correlation is estimated as systematic uncertainty using validation region E,F.**

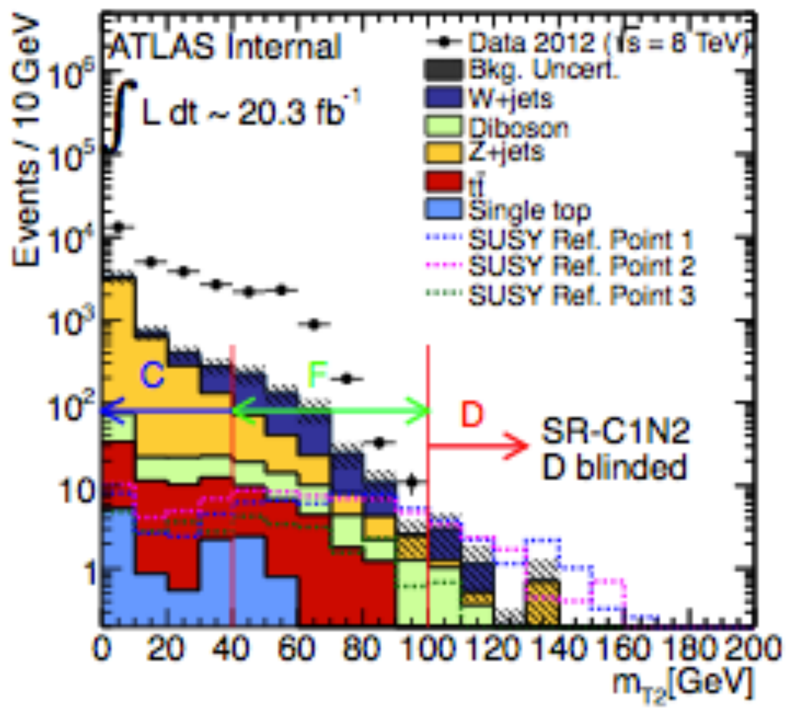
ABCD method check:
- purity of multi-jet in CRs



2LooseTauID, TightTauVeto
CR-A,B VR-E

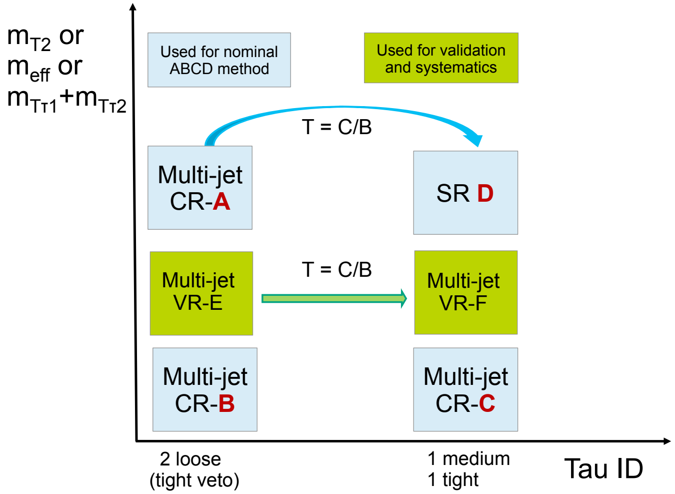
1TightTau+1MediumTau
CR-C, SR-D,VR-F





- In fake tau BG CR, QCD purity is high.
- Non-fake tau BGs in CR has been subtracted using MC and taken into account as syst.

Fake Tau BGs Estimation: Results

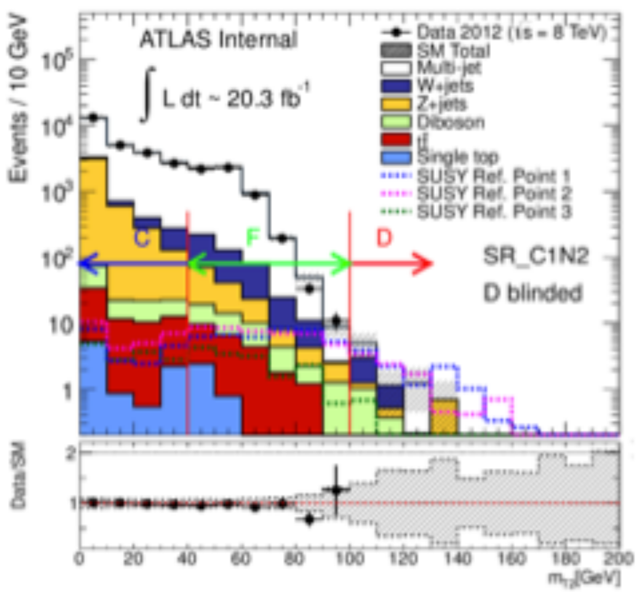


- D = A * T (T=C/B)

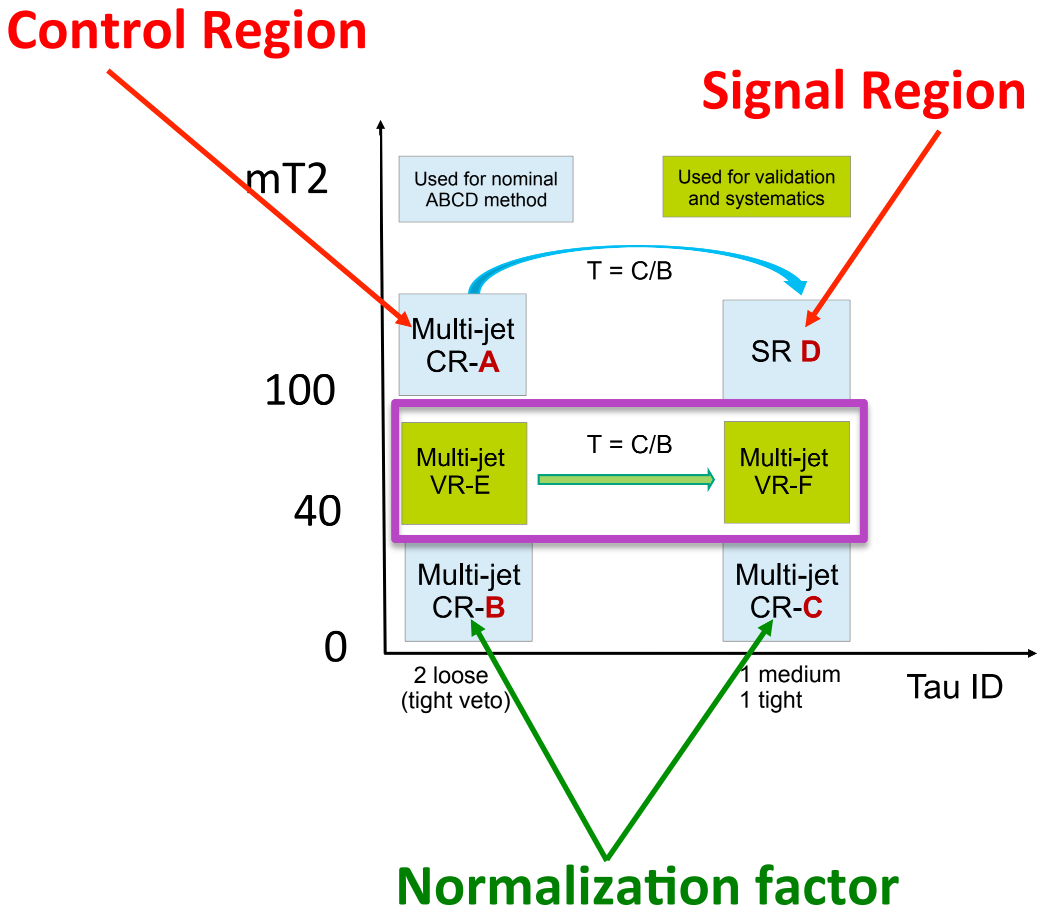
		region A	region B	region C	$\mathcal{T} = C/B$	multi-jet in SR
SR-C1N2	Data	6	36907	24601	0.554 ± 0.031	2.3 ± 1.4
	Z+jets	0.3 ± 0.15	726 ± 261	3981 ± 1060		
	W+jets	1.0 ± 0.4	252 ± 82	587 ± 182		
	diboson	0.5 ± 0.26	14.6 ± 4.8	72± 20		
	top	0.1 ± 0.06	17.3 ± 6.1	68.0 ± 22.3		
	multi-jet	4.1 ± 2.5	35897 ± 334	19893 ± 1087		
	Ref. Point 1	1.9 ± 0.85	1.4 ± 0.7	17.8 ± 6.2		

ABCD method validation

multi-jet-VR	C1N2
Data	5585
SM total	5844 ± 338
multi-jet	5374 ± 322
top	23.9 ± 10.1
W+jets	322 ± 93.2
Z+jets	97 ± 39.4
diboson	27.2 ± 7.6



F = E * T (T=C/B)



systematics

Systematics from MC prediction

PDF
other theory uncer. down
other theory uncer. up
lumi
TESDOWN
TESUP
TEVSFDOWN
TEVSFUP
TEVSFDOWN
TEVSFUP
TFAKESFDOWN
TFAKESFUP
TIDSFDOWN
TIDSFUP
TTRIGSFDOWN
TTRIGSFUP
BJETDOWN
BJETUP
CJETDOWN
CJETUP
MistagDOWN
MistagUP
PILEUPDOWN
PILEUPUP
JERR
JESM
JESP
MET_RESOST
MET_SCALESTDOWN
MET_SCALESTUP

Theory syst.

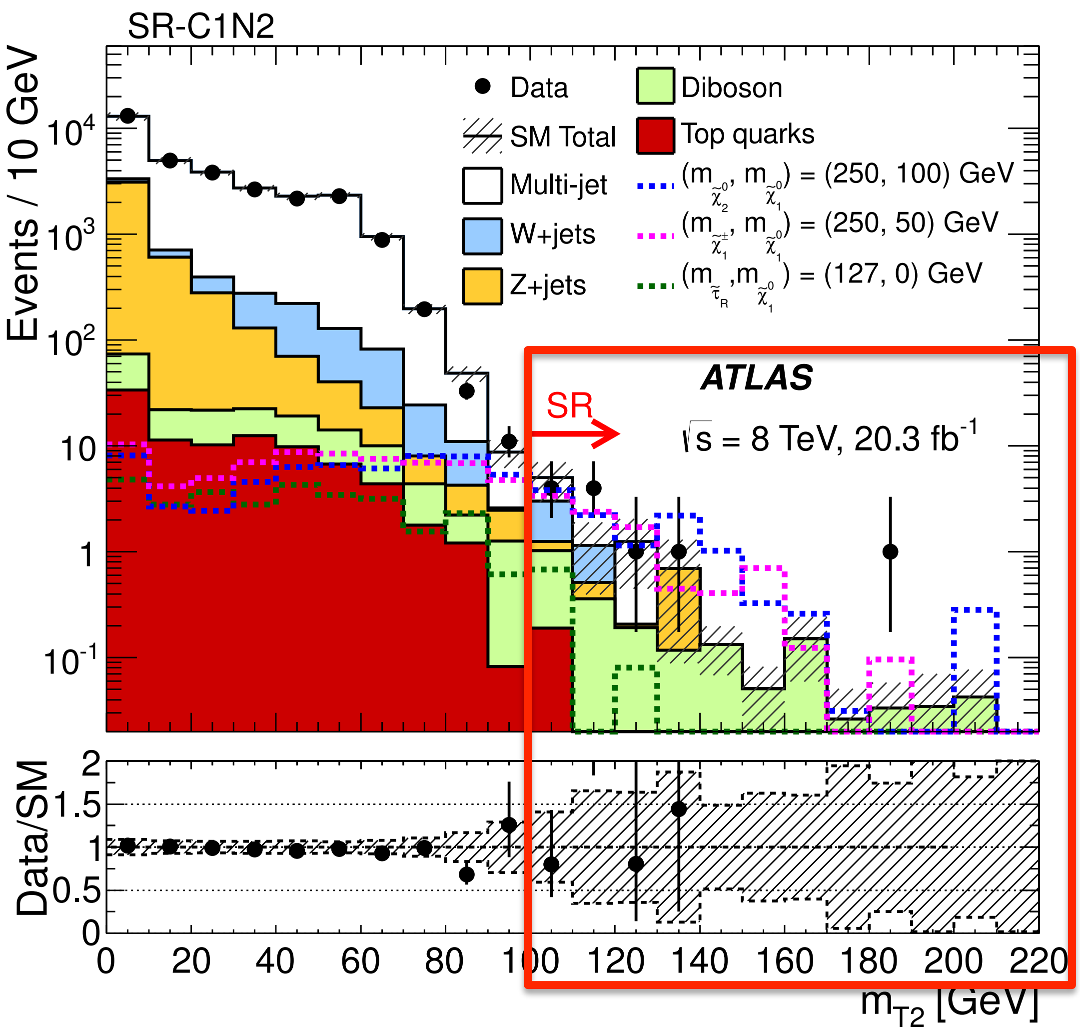
experimental syst.

Systematics from ABCD method:
Fake tau BG (multi-jet BG) systematics

Systematic Source
Correlation
Non-multi-jet subtraction in Region A
Non-multi-jet subtraction in Region B
Non-multi-jet subtraction in Region C
Number of events in Region A
Number of events in Regions C and B

Results

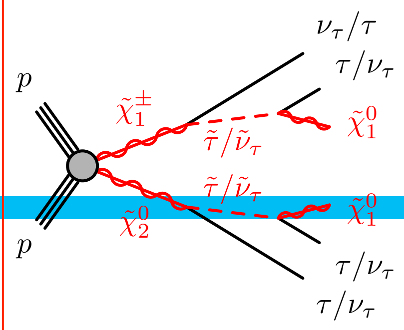
SR-C1N2
≥ 2 OS taus
b-jet veto
Z-veto
$E_T^{miss} > 40$ GeV
$m_{T2} > 100$ GeV

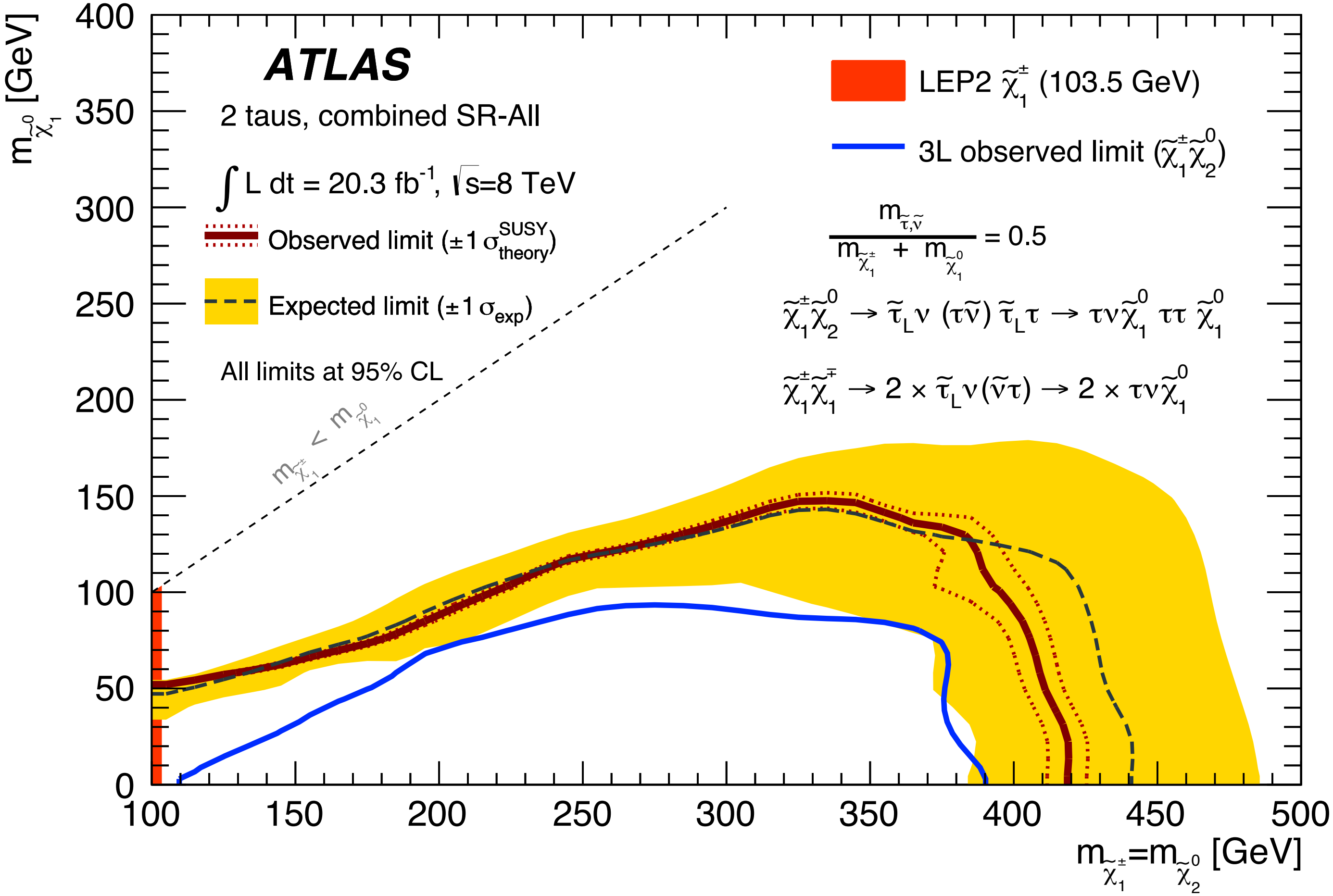


SM process	SR-C1N2
Top	0.30 ± 0.19
Z+jets	0.9 ± 0.5
W+jets	2.2 ± 0.8
Diboson	2.2 ± 0.9
Multi-jet	2.3 ± 2.0
SM total	7.9 ± 2.4
Observed	11
Ref. point 1	11.3 ± 2.8
Ref. point 2	9.2 ± 2.1
Ref. point 3	0.8 ± 0.5

- ***No significant excess…***
- ***Set limit …***

Exclusion Limits: simplified model



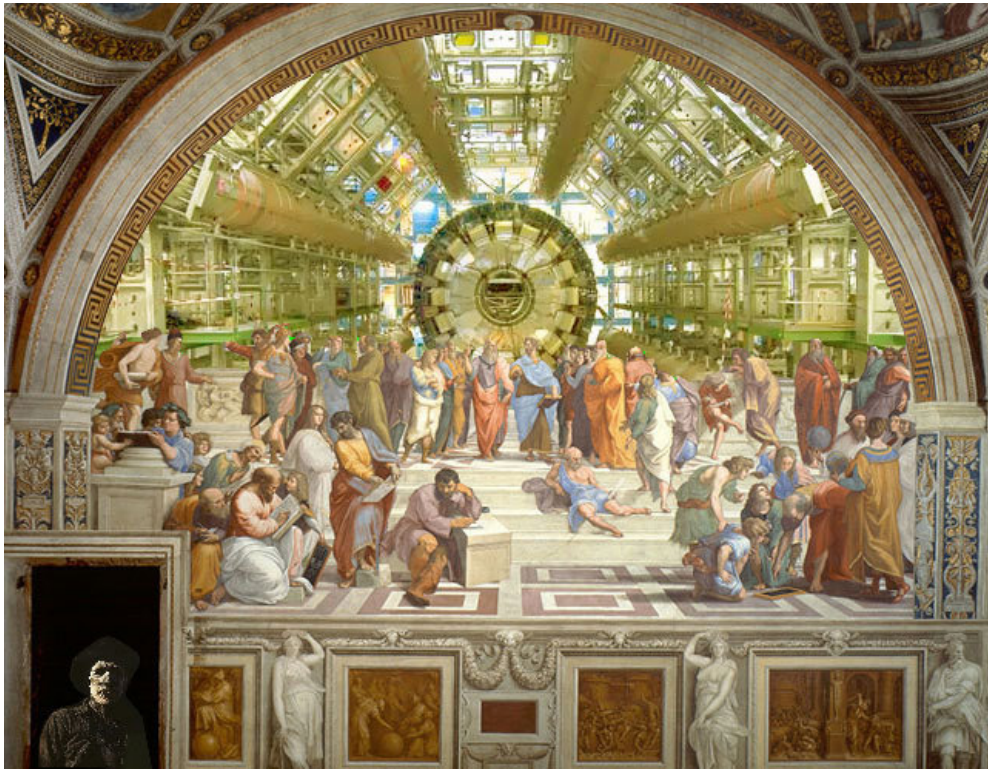


Outline

- SUSY Introduction
- The LHC and ATLAS
- SUSY search strategy

… Coffee Break …

- Overview of SUSY search results
- ➔Outlook🡐



Outlook

- High energy running in 2015 will significantly increase our sensitivity to many SUSY scenarios, especially cover difficult SUSY regions

- Ready for new physics !!!


Exciting times are ahead of us!
Thank You !
Urbi et Orbi

LHC roadmap

2015-2017: 100 fb^{-1}, ~ 1* 10 ^{34} $cm^{-1}s^{-1}$ (LS1)
2020-2022: 300 fb^{-1}, ~ 2* 10 ^{34} $cm^{-1}s^{-1}$ (LS2)
2026-2035: 3000 fb^{-1}, ~ 5* 10 ^{34} $cm^{-1}s^{-1}$ (LS3)

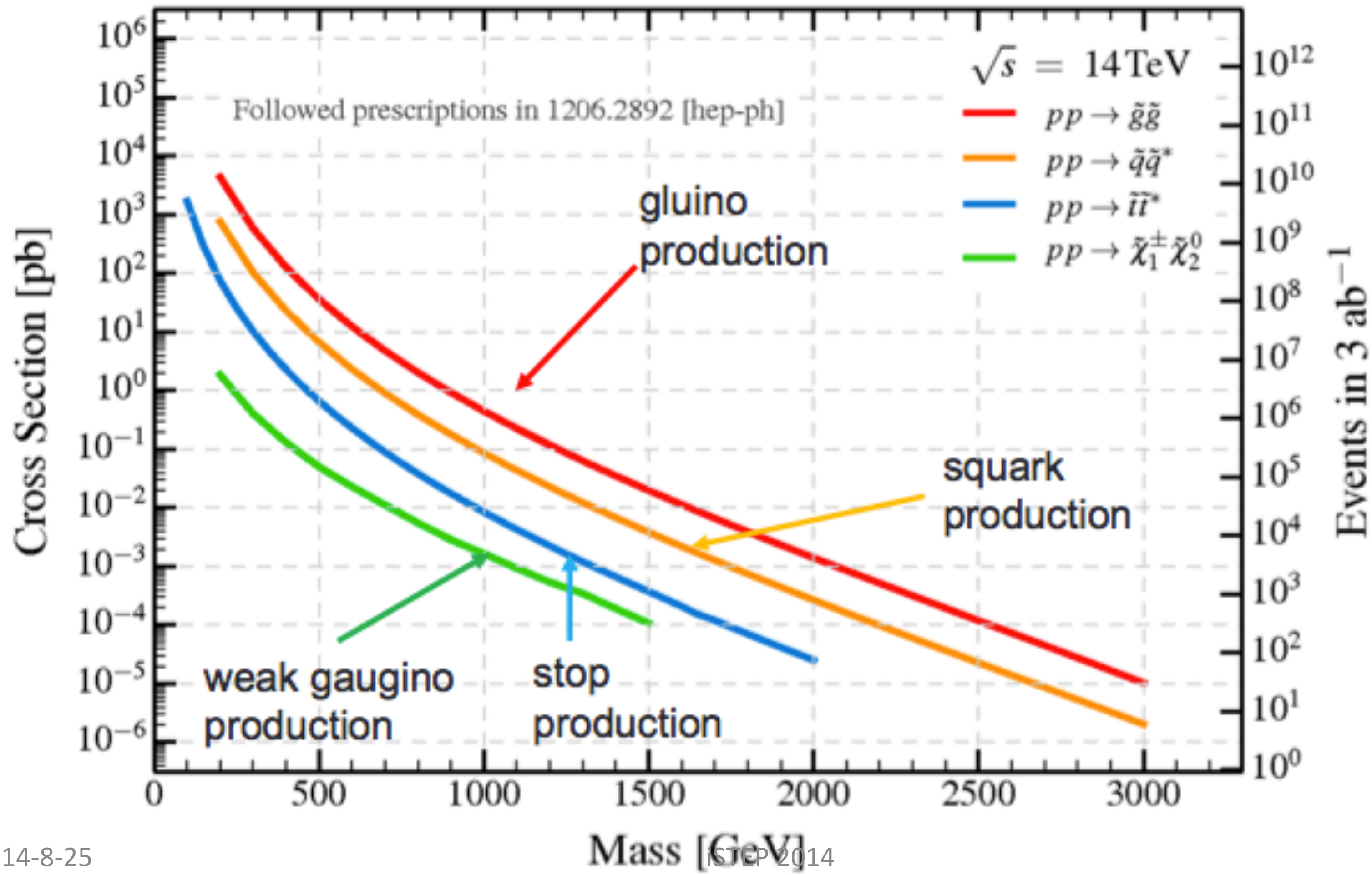
update - December 2013

2009		LHC startup, √s 900 GeV	
2010–2012		√s=7+8 TeV, L~6x10^{33}cm^{-2}s^{-1}, bunch spacing 50ns	Run 1, ~25 fb^{-1}
2013–2014	LS1	Go to design energy, nominal luminosity - Phase 0	
2015–2018		√s=13~14 TeV, L~1x10^{34}cm^{-2}s^{-1}, bunch spacing 25ns	Run 2, ~75-100 fb^{-1}
2019	LS2	Injector + LHC Phase I upgrade to ultimate design luminosity	
2020–2022		√s=14 TeV, L~2x10^{34}cm^{-2}s^{-1}, bunch spacing 25ns	Run 3, ~350 fb^{-1}
2023–2025	LS3	HL-LHC Phase II upgrade: Interaction Region, crab cavities?	
… 2035?		√s=14 TeV, L~5x10^{34}cm^{-2}s^{-1}, luminosity levelling	~3000 fb^{-1}

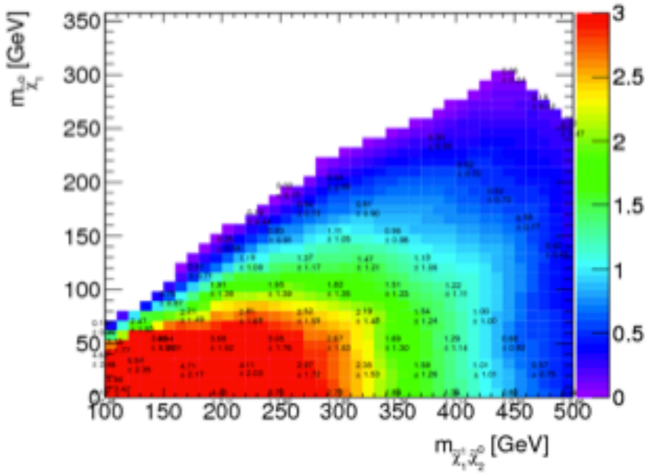
From LHCC Open meeting, 03.12.2013

SUSY Search at HL-LHC

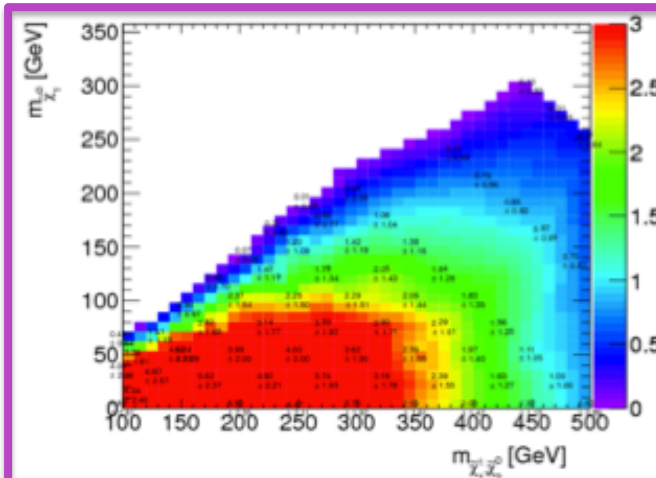
- Limits set by Run-1 LHC: $m_{\tilde{q}} < 0.7$ TeV, $m_{\tilde{g}} < 1.3$ TeV
- Less stringent limits on sleptons, 3rd generation squark, weak gauginos
  - → Accessible at HL-LHC



mT2 Optimization

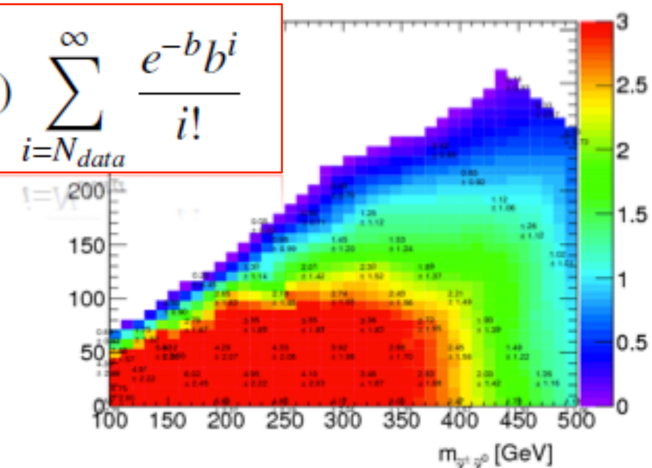


(a) $\not{E}_T$ > 40 GeV, m_{T2}> 90 GeV



(b) $\not{E}_T$ > 40 GeV, m_{T2}> 100 GeV

$$p \propto \int_0^\infty db\, G(b; N_b, \delta b) \sum_{i=N_{data}}^{\infty} \frac{e^{-b} b^i}{i!}$$



(c) $\not{E}_T$ > 40 GeV, m_{T2}> 110 GeV

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

Simultaneous fit II

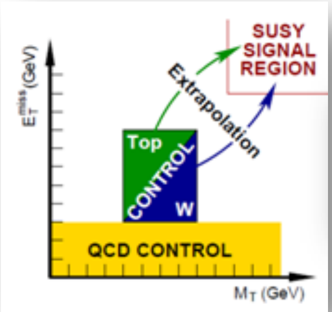
- Input: Probability density function (Signal and background are described by a binned PDF in CRs, SRs and VRs -- technically it is implemented by a collection of histograms).
  - The number of observed events (described using a Poisson)
  - The ttbar and W(Z)+jets backgrounds: MC prediction
    - →samples of all fit regions are scaled by "free parameters" mu_wz/ mu_top (un-constrained scaling factors) to get an overall normalization.
  - The QCD multi-jet background estimate: data-driven prediction
    - →only allowed to vary within its uncertainties in the fit.
  - Smaller backgrounds as single top, dibosons and ttbar+vector boson: MC prediction.
    - →only allowed to vary within uncertainties.
  - Signal samples of fit regions are scaled by "free parameter" mu_SIG.
  - Statistical and systematic uncertainties are included as nuisance parameters, typically constrained by a Gaussian. Correlations between the systematics are considered.

- The product of the various PDF forms the likelihood.
- The fit maximizes the likelihood by adjusting parameters→ the optimal value/error of the free parameters and nuisance parameters are determined simultaneously when the PDF is fitted to Data.

背景联合拟合

- 技术主旨：本底在背景区域具有较高的统计量。通过联合拟合背景区域CR与信号区域SR，有效提高信号区域中本底估计的可信度。该技术被SUSY各个分析广泛使用。

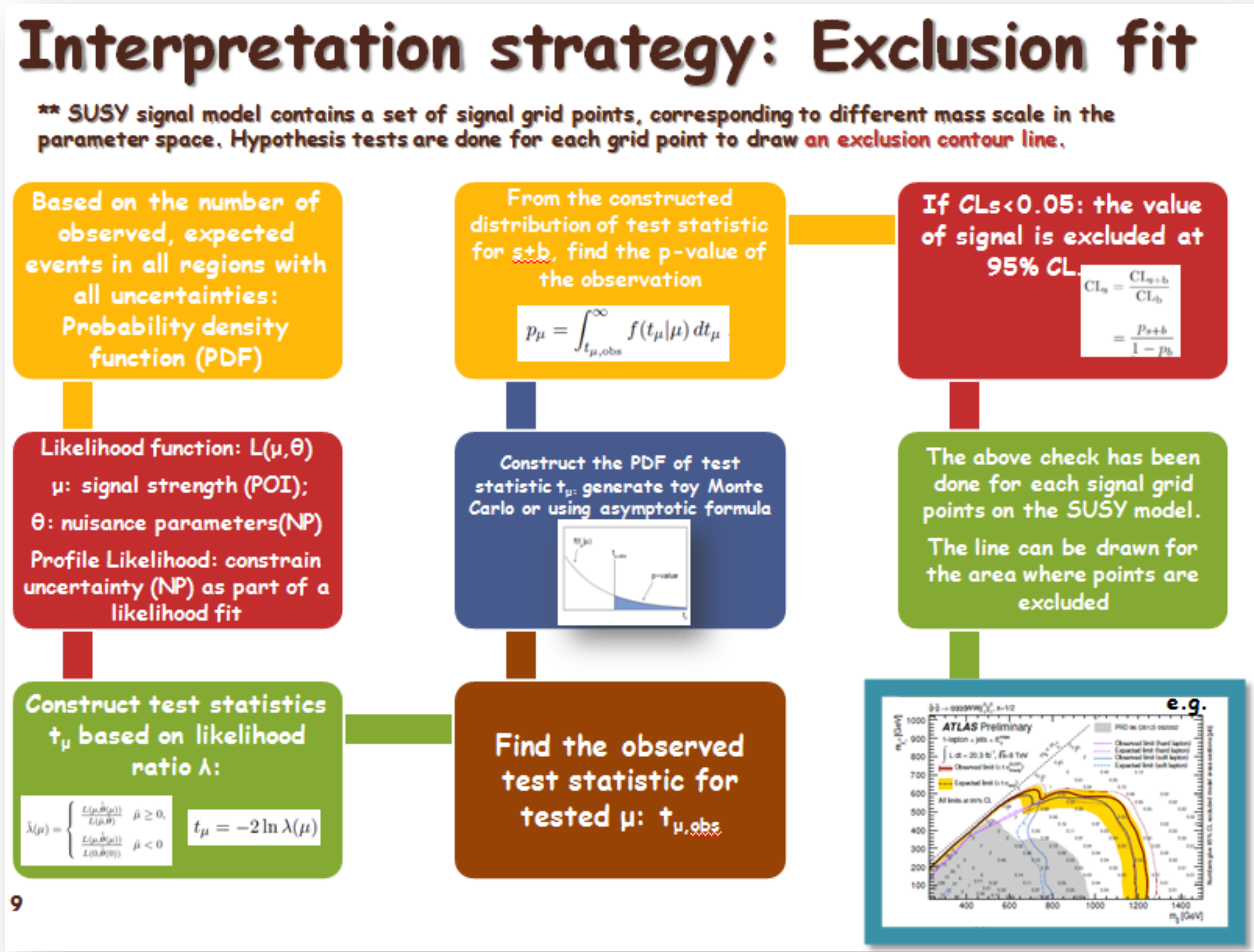
- 具体方案：优化似然函数（Profile Likelihood）：
  - 考虑各区域中观测值，背景估算值，误差及其关联
  - 主要本底在拟合中可自由浮动
  - 误差在拟合中为nuisance parameters



- 不同拟合类型：
  - Background-only/仅背景拟合:在验证区域检验拟合。
  - Discovery/发现拟合:与模型无关Non-SM信号强度上限。
  - Exclusion/排除拟合:不同信号模型的SUSY信号排除上限。

统计分析

- 扫描SUSY信号二维参量空间
- 基于似然函数建立test statistic, 通过假设检验获得CLs
- 判定信号是否在相应置信度被排除
- 给出信号排除区域图



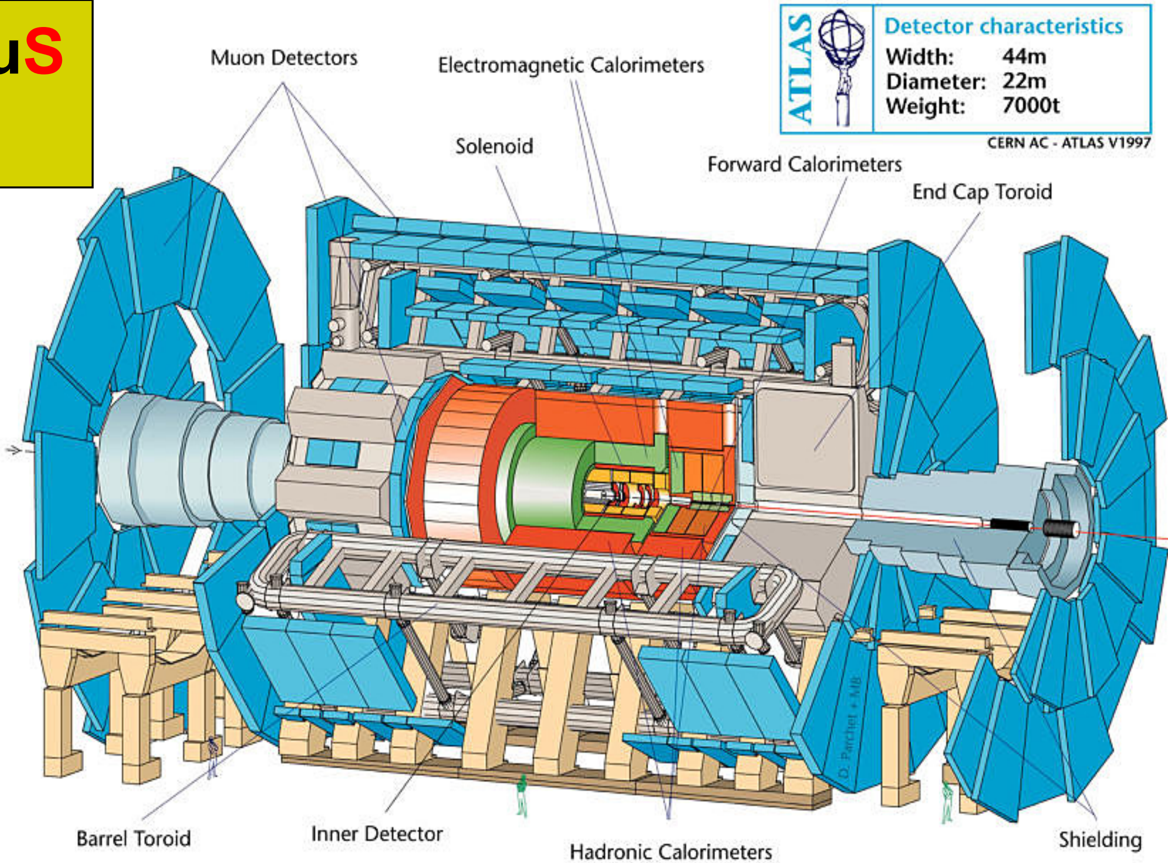
Minimal Supersymmetric Standard Model

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		

A Toroidal LHC ApparatuS

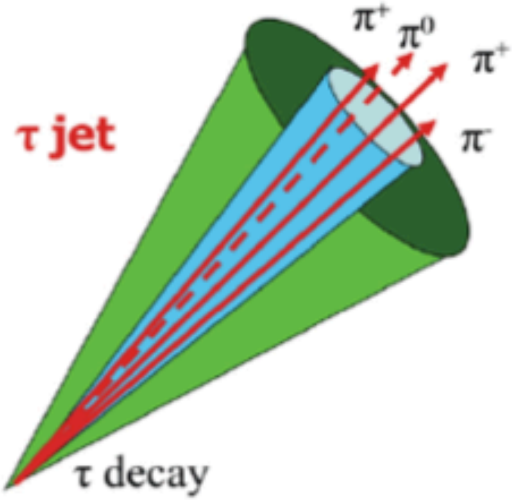
- 42m×22m, 7000 ton

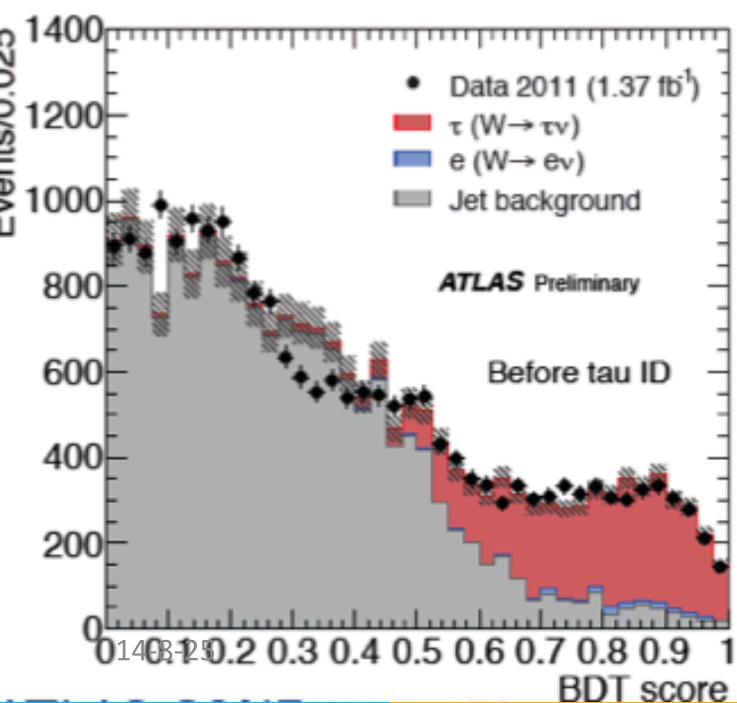
- Inner Detector (2T solenoid, |η|<2.5):
  $\sigma_{p_T}/p_T \;\square\; 0.05\%/GeV \times p_T \oplus 1\%$
- Calorimetry:
  * electromagnetic, |η|<3.2
    $\sigma_E/E \;\square\; 10\,\%\sqrt{GeV}/\sqrt{E} \oplus 0\%$
  * hadronic (central, |η|<1.7)
    $\sigma_E/E \;\square\; 50\,\%\sqrt{GeV}/\sqrt{E} \oplus 3\%$
  * hadronic (endcaps, 1.7<|η|<3.2)
    $\sigma_E/E \;\square\; 60\,\%\sqrt{GeV}/\sqrt{E} \oplus 3\%$
  * hadronic (forward, 3.2<|η|<4.9)
    $\sigma_E/E \;\square\; 100\,\%\sqrt{GeV}/\sqrt{E} \oplus 5\%$
- Muon system (~4T toroid, |η|<2.7):
  $\sigma_{p_T}/p_T \;\square\; 10\%$ for $p_T(\mu) \approx 1$ TeV/c



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

Hadronic Taus



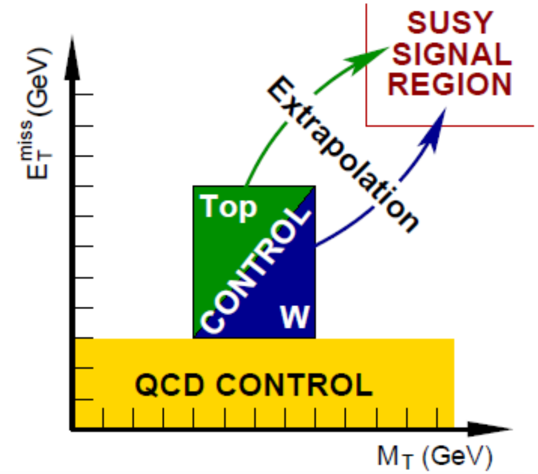


- Tau decays:
  - Leptonic (35%): $\tau \to \nu_\tau \ell \bar{\nu}_\ell$
  - Hadronic (65%): decay to one or three charged pions, neutrinos and π^0's
- Need to separate τ's from hadronic jets:
  - τ decay tends to be well collimated
  - Large electromagnetic component from $\pi^0 \to \gamma\gamma$ decay

Tau Object

- ▷ $p_T > 20$ GeV, $|\eta| < 2.5$
- ▷ 1 or 3 tracks with total charge ± 1
- ▷ Boosted decision tree (BDT) using variables sensitive to the longitudinal and transverse shower shape
- ▷ Working points:
  - **Loose:** efficiency: 60%; jet rejection: 20-50
  - **Tight:** efficiency: 30-50%; jet rejection: 30-200

Data-Driven-Method (simultaneously fit)



- Background estimates in SRs are obtained by a ***simultaneous fit*** in each channel based on the **profile likelihood method**.
  - Fit for all BG-CRs
- Comments:
  - Shape from MC (CR), NF from fit
  - Advantage:
    - Considered correlations between different BG CRs and VRs, SRs;
    - considered correlated syst. from detector
  - Disadvantage: shape is depending on MC (semi-data-driven method)

$$N^{SR}_{pred_j} = (N^{CR_j}_{data} - N^{CR_j}_{other\ bkg}) \times \frac{N_{pred}(MC^j, SR)}{N_{pred}(MC^j, CR_j)}$$

$$= (N^{CR_j}_{data} - N^{CR_j}_{other\ bkg}) \times C^j_{CR_j \to SR}$$

Normalization factor (NF)