S. Muanza, CPPM Marseille, CNRS-IN2P3

Introduction to Supersymmetry

PART II

Experimental Searches

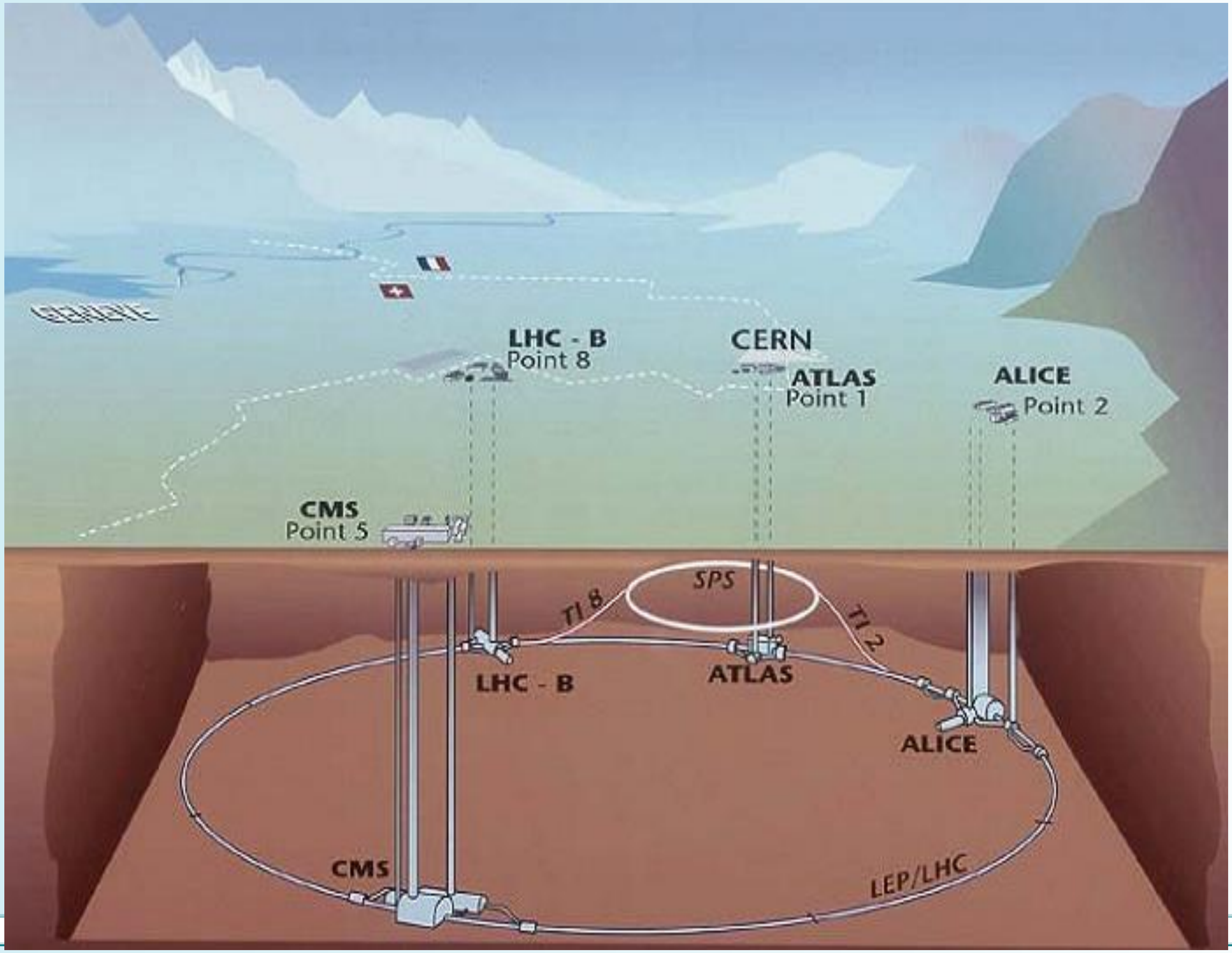
LHC

Personal Bias: I'll present results from the ATLAS experiment

LHC
- Experiments -

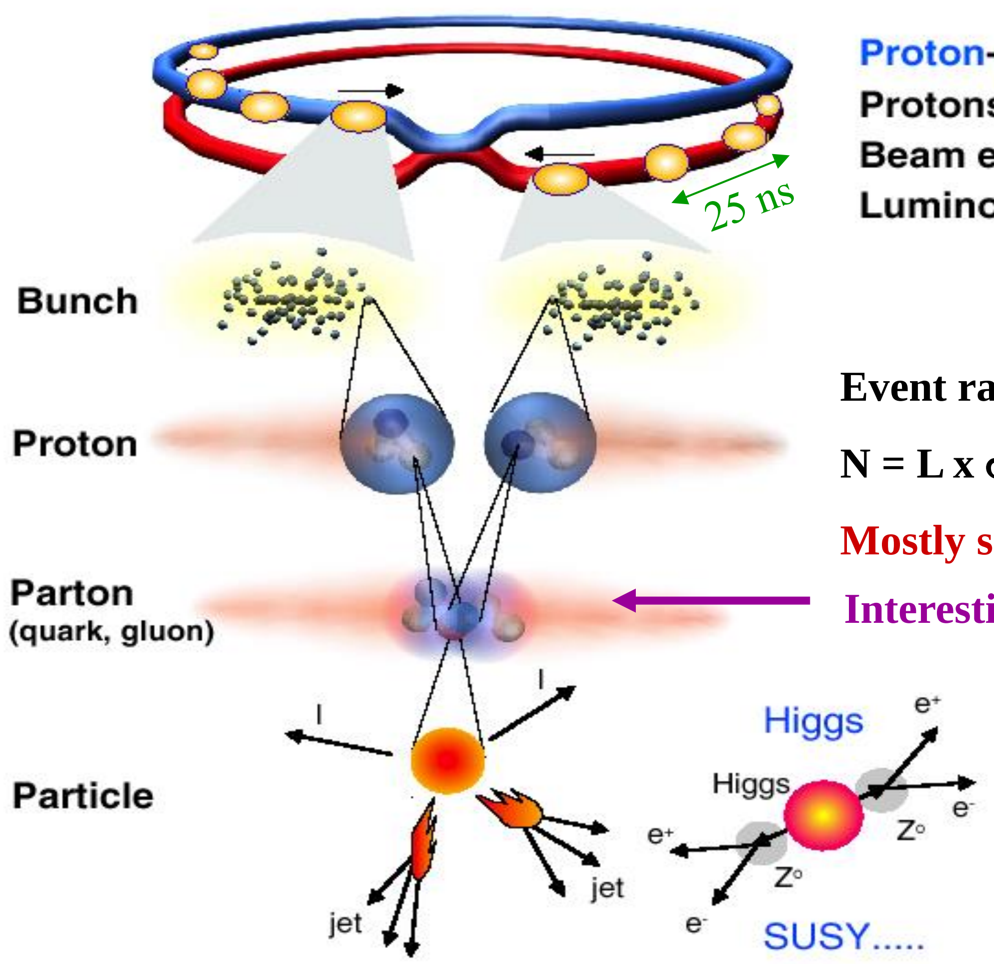
3 Experiments can carry SUSY searches:

- Direct: ATLAS & CMS
- Indirect: LHCb



LHC
- Nominal Features -

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:

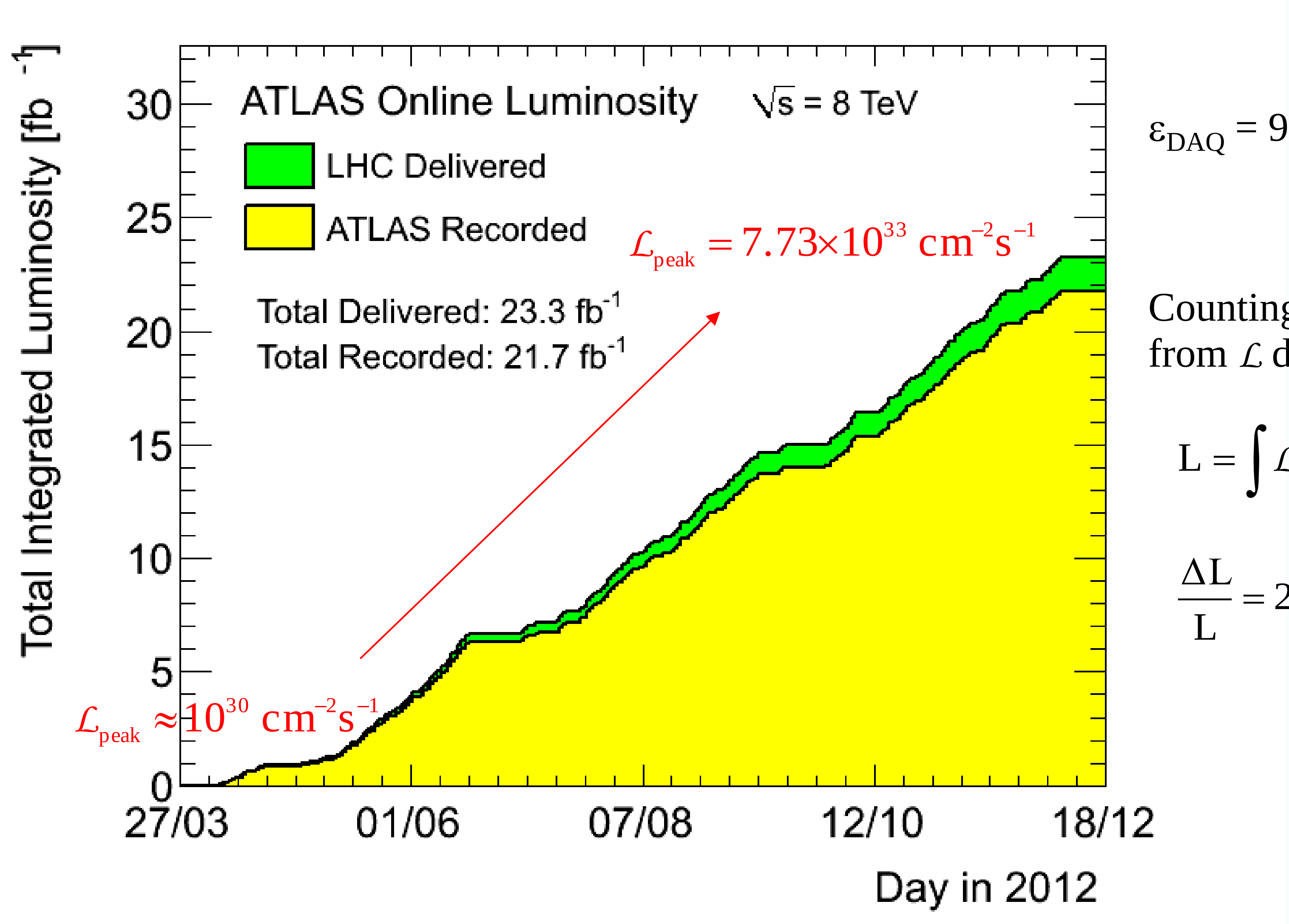
N = L x σ (pp) ≈ 10^9 interactions/s

Mostly soft (low p_T) events

Interesting hard (high-p_T) events are rare

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

LHC
- 2012 Integrated Luminosity -



$\mathcal{L}_{\text{peak}} \approx 10^{30}\ \text{cm}^{-2}\text{s}^{-1}$

$\mathcal{L}_{\text{peak}} = 7.73 \times 10^{33}\ \text{cm}^{-2}\text{s}^{-1}$

$\varepsilon_{\text{DAQ}} = 95.3\%$

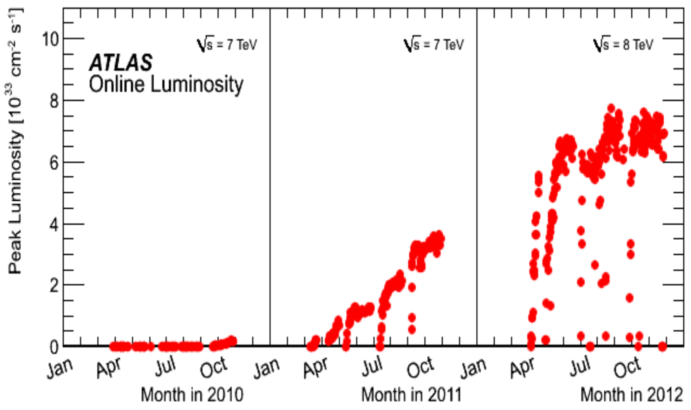
Counting rate from $\mathcal{L}$ detectors

$$L = \int \mathcal{L} dt$$

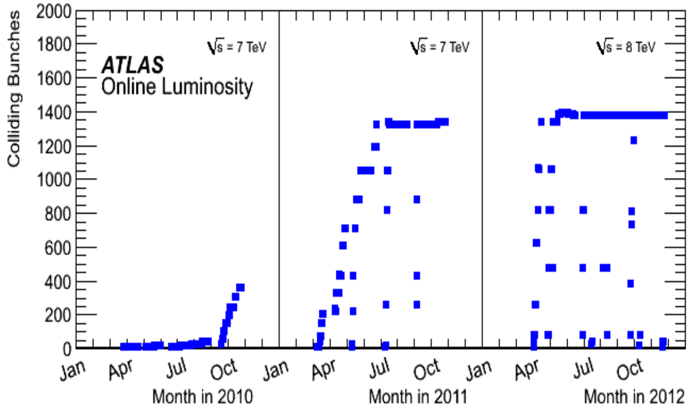
$$\frac{\Delta L}{L} = 2.8\%$$

Data Taking Conditions

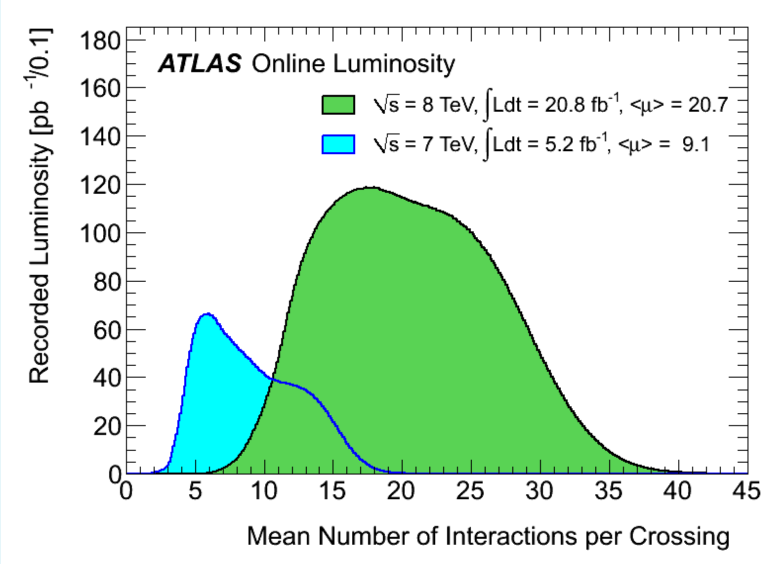
Evolution of the instantaneous luminosity



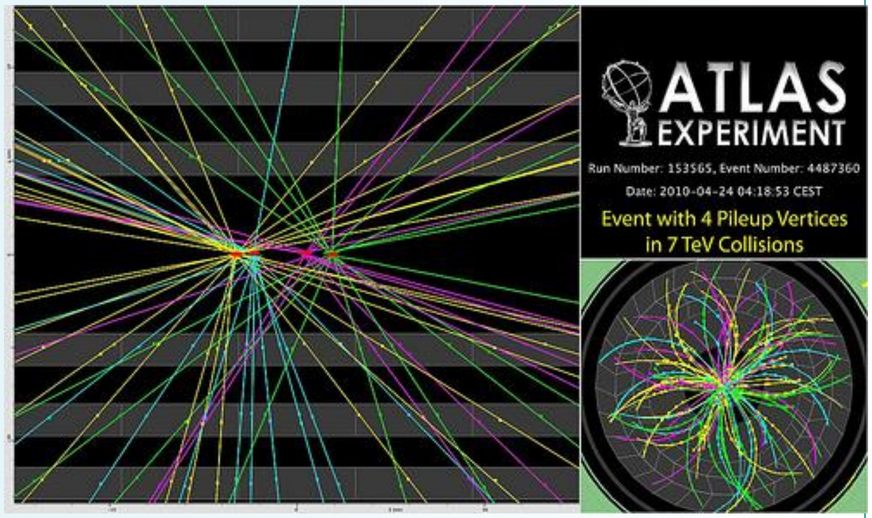
Evolution of the nber of p bunches



<Nber> of collisions per bunch crossing

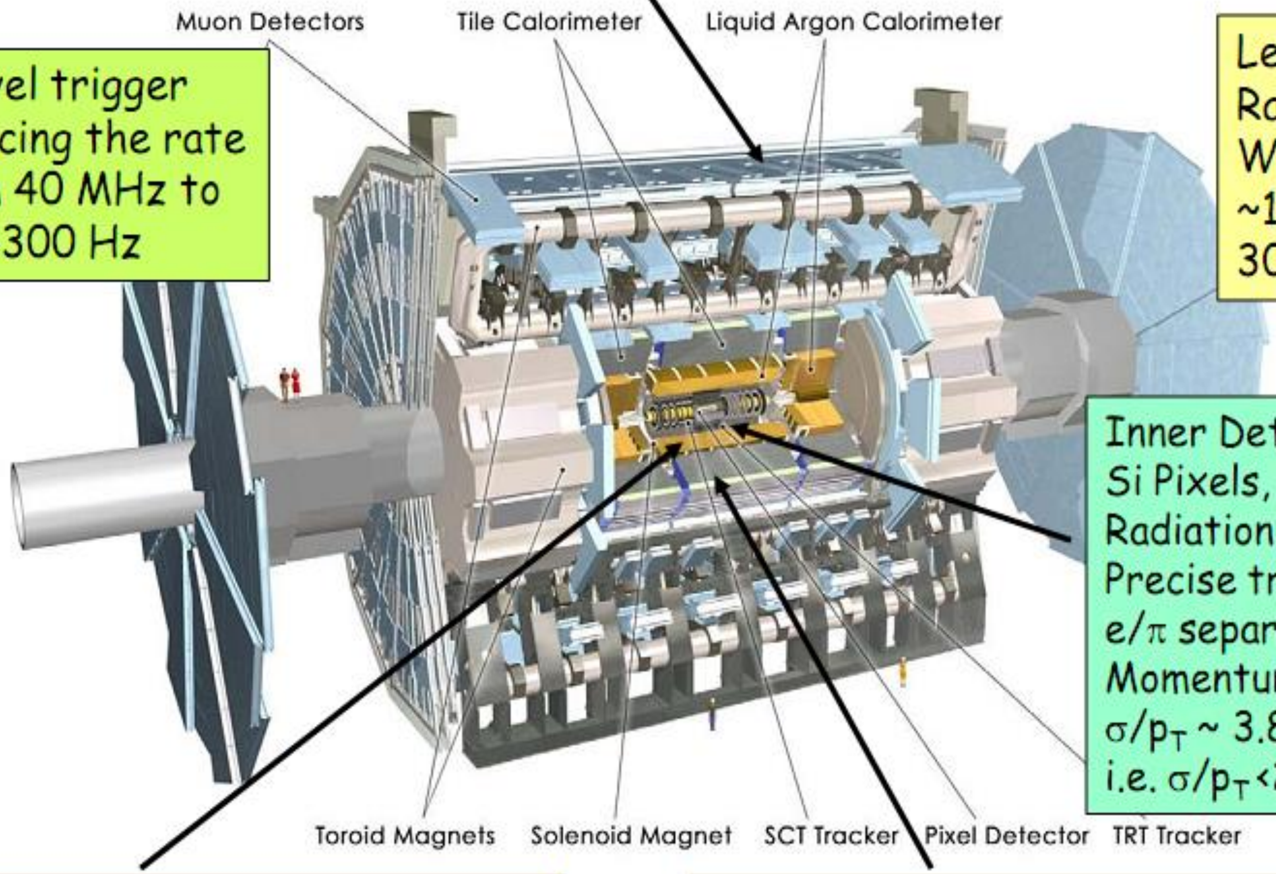


A Multiple pp Collision



The ATLAS detector

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to $E_\mu \sim 1$ TeV



3-level trigger
reducing the rate
from 40 MHz to
200-300 Hz

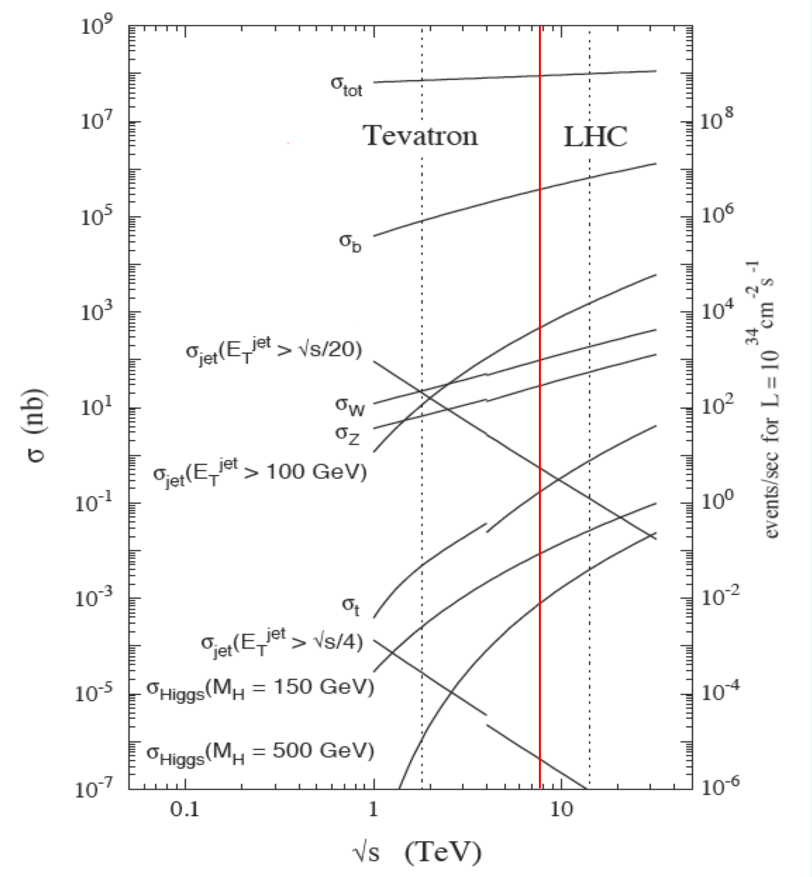
Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
$\sim10^8$ electronic channels
3000 km of cables

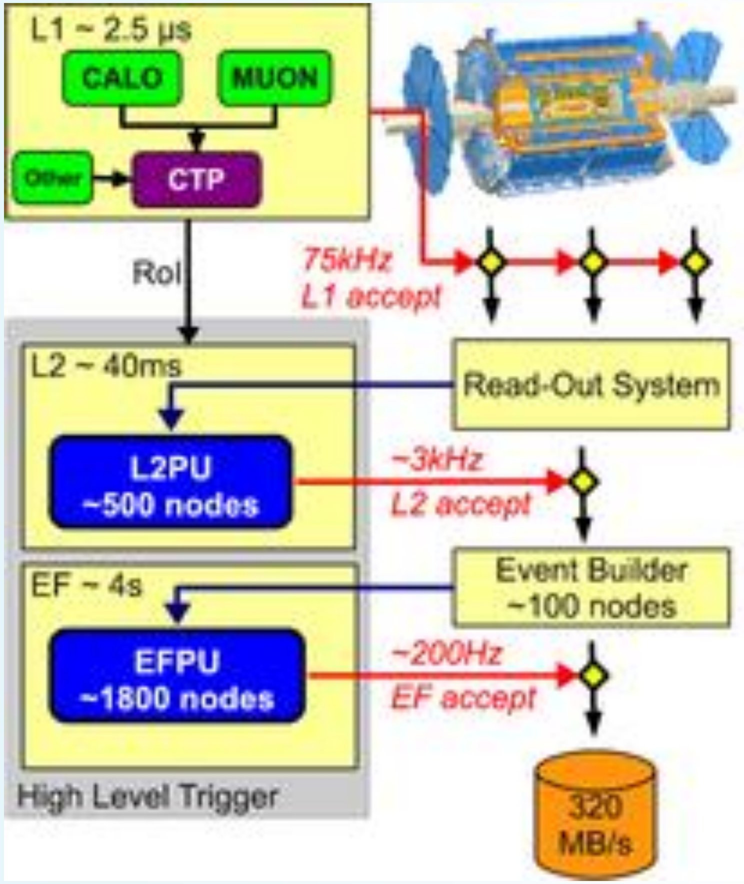
Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition
Radiation detector (straws)
Precise tracking and vertexing,
e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\, p_T(\text{GeV}) \oplus 0.015$
i.e. $\sigma/p_T<2\%$ for pt < 35 GeV

EM calorimeter (($|\eta|<3.2$):
Pb-LAr Accordion; e/γ trigger,
identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

Analyses: Higgs Searches
- Trigger: On-Line Selection -





$$\boxed{H \rightarrow \gamma\gamma}$$

$$\text{Single } \gamma : p_T(\gamma\gamma > 60\ \text{GeV}$$

$$\text{Double } \gamma : \begin{cases} p_T(\gamma\gamma > 20\ \text{GeV} \\ \text{Isolation} \end{cases}$$

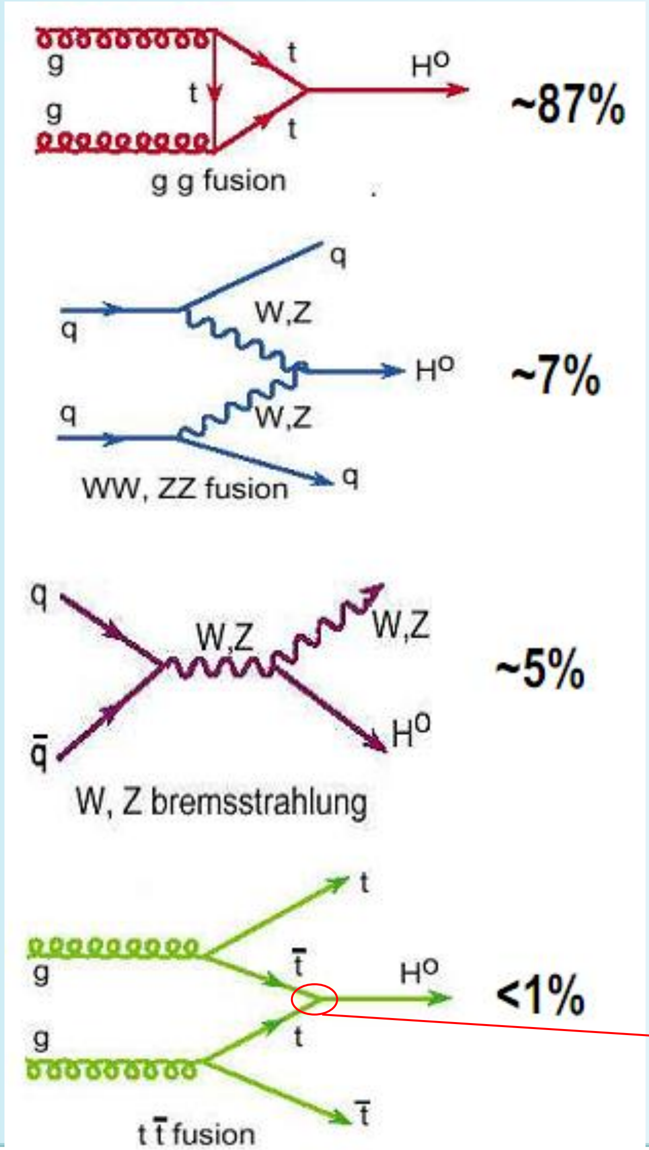
$$\boxed{H \rightarrow 4\ell^\pm}$$

$$\text{Single } \ell^\pm : \begin{cases} p_T(\mu^\pm) > 18\ \text{GeV} \\ p_T(e^\pm) > 22\ \text{GeV} \end{cases}$$

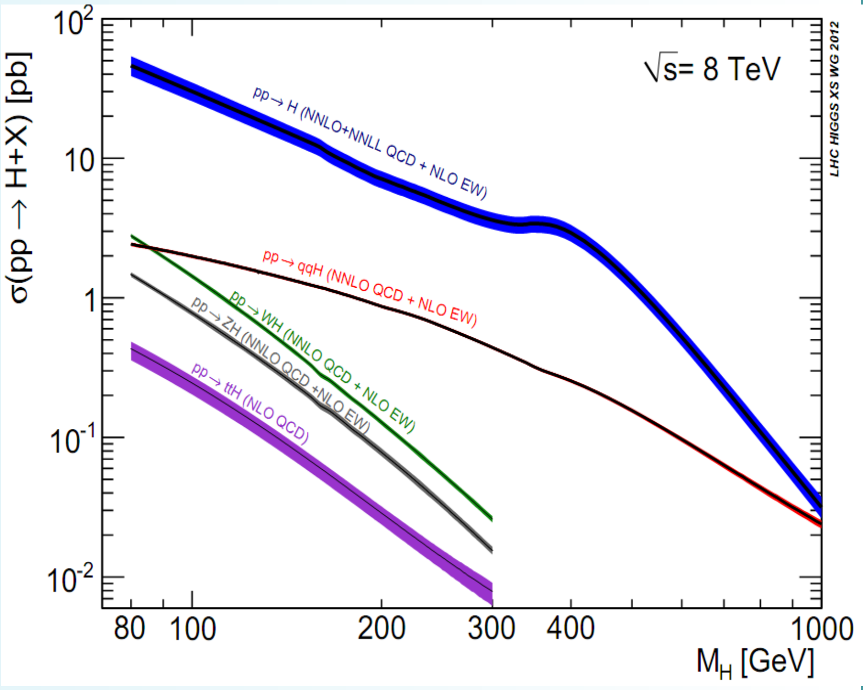
$$\text{Double } \ell^\pm : \begin{cases} p_T(\mu^\pm) > 10\ \text{GeV} \\ p_T(e^\pm) > 12\ \text{GeV} \end{cases}$$

Production Mechanisms

LO Feynman Diagrams



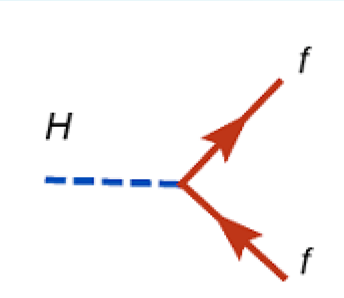
Cross Sections



Unique opportunity to measure the top Yukawa coupling!

Decay Modes

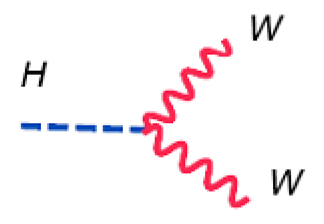
LO Feynman Diagrams



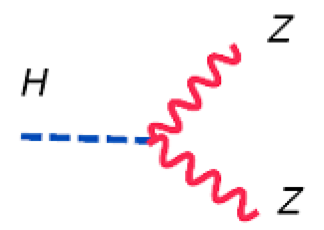
$b\bar{b}$ $\approx 58\%$

$c\bar{c}$ $\approx 3\%$

$\tau^+\tau^-$ $\approx 6\%$

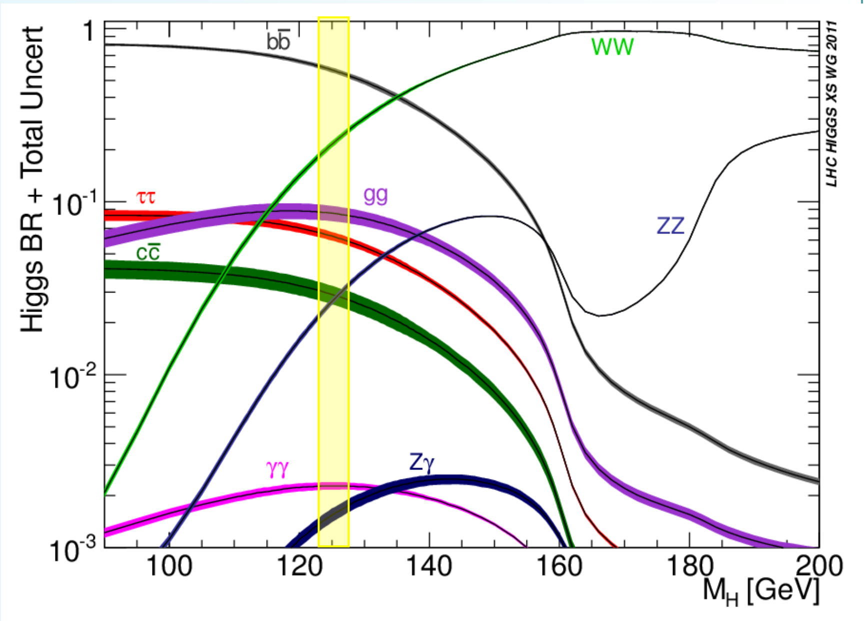


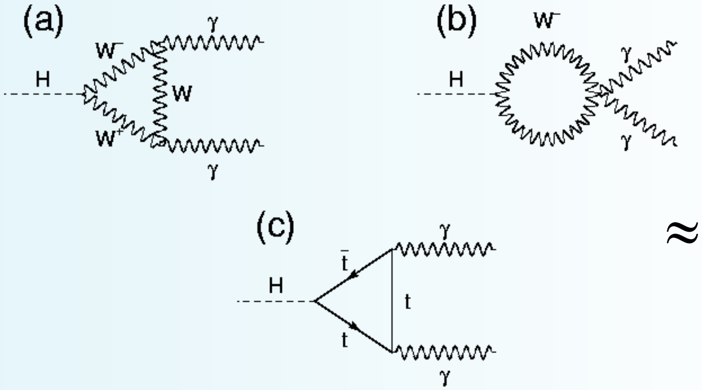
$\approx 22\%$



$\approx 3\%$

Branching Ratios





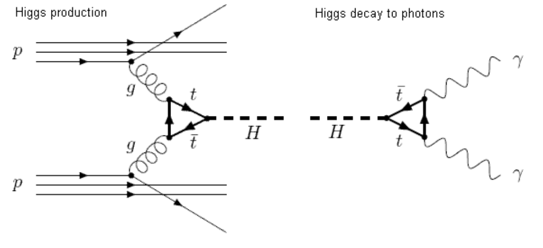
$\approx 0.3\%$

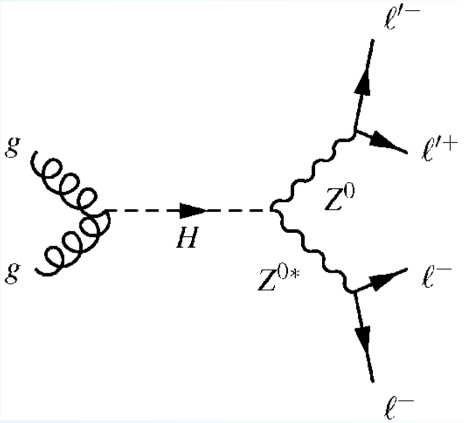
Search Topologies
- 2 Examples -

2 photons

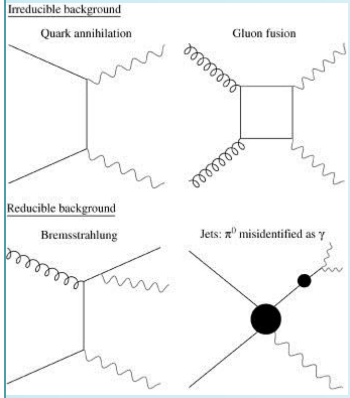
4 charged leptons

Signal

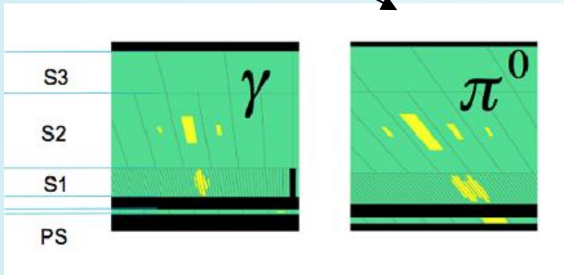




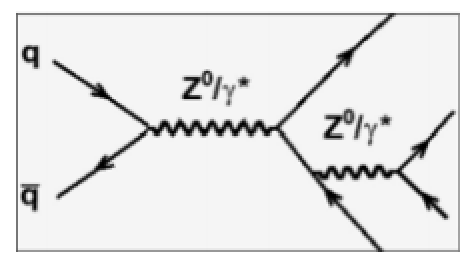
Background



$\pi^0 \rightarrow \gamma\gamma$



Irreducible:



Reducible: Z+bb, tt+jets

Analyses
- Offline Selection -

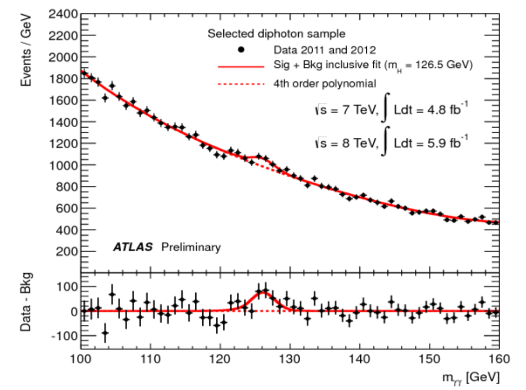
- Events read from tape
- Improved signal vs background separation

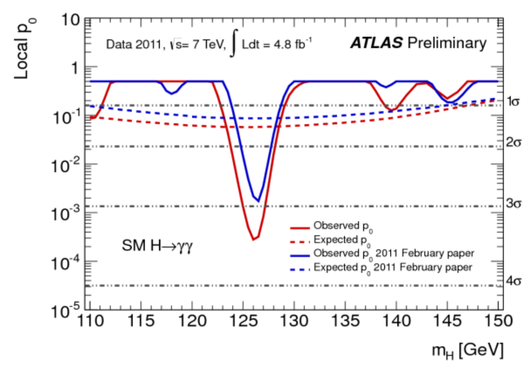
$p_T(\gamma_1) > 40\ \text{GeV}$

$p_T(\gamma_2) > 30\ \text{GeV}$

$|\eta(\gamma)| < 2.37$

Isolation





$p_T(\ell^\pm) > 20, 15, 10, 7\ (6)\ \text{GeV}$

$|\eta(e^\pm)| < 2.47$

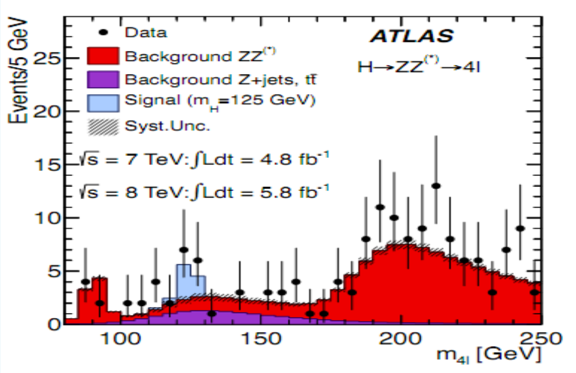
$|\eta(\mu^\pm)| < 2.7$

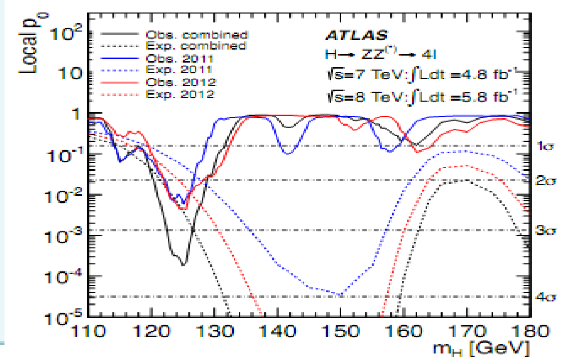
Isolation

$50 < M(\ell_1^\pm, \ell_2^\pm) < 106\ \text{GeV}$

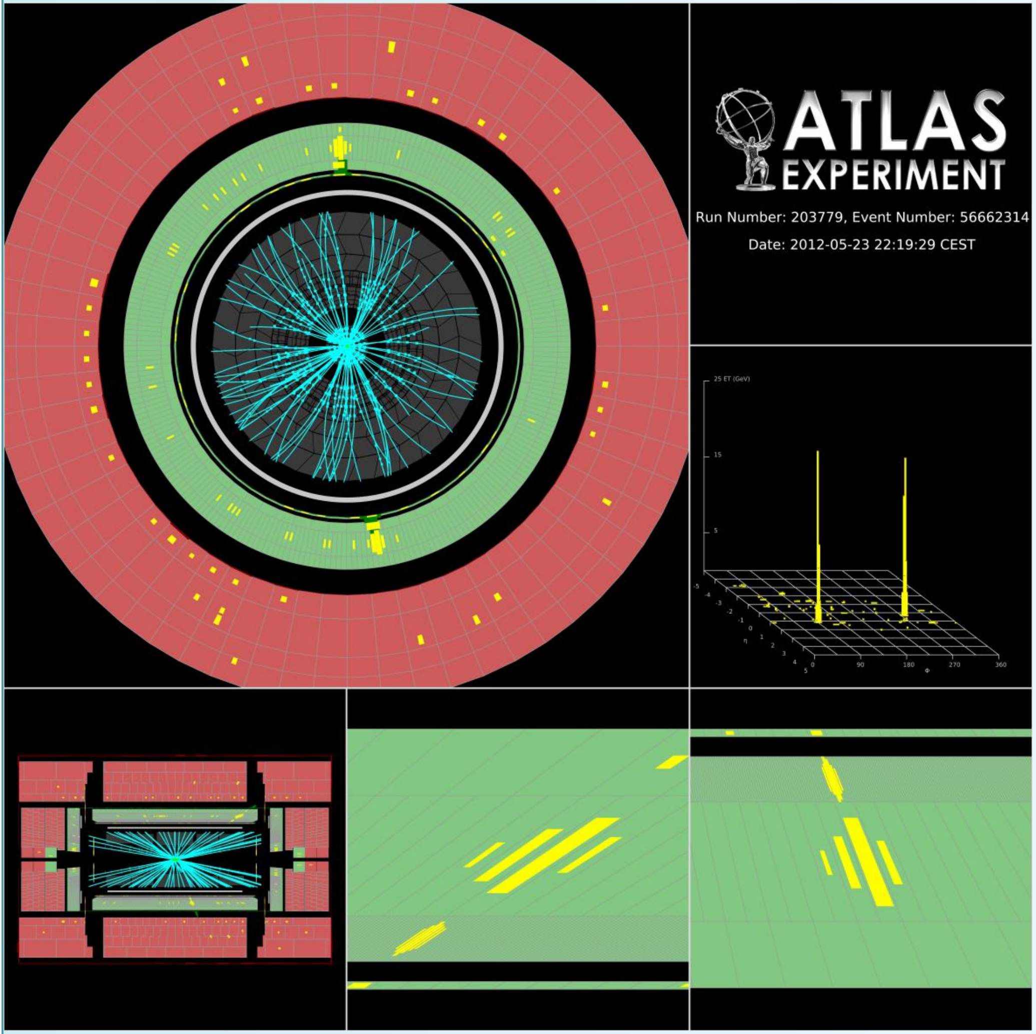
$M(\ell_3^\pm, \ell_4^\pm) < 115\ \text{GeV}$

$M(\ell_3^\pm, \ell_4^\pm) \subset [17.5, 50]\ \text{GeV}$





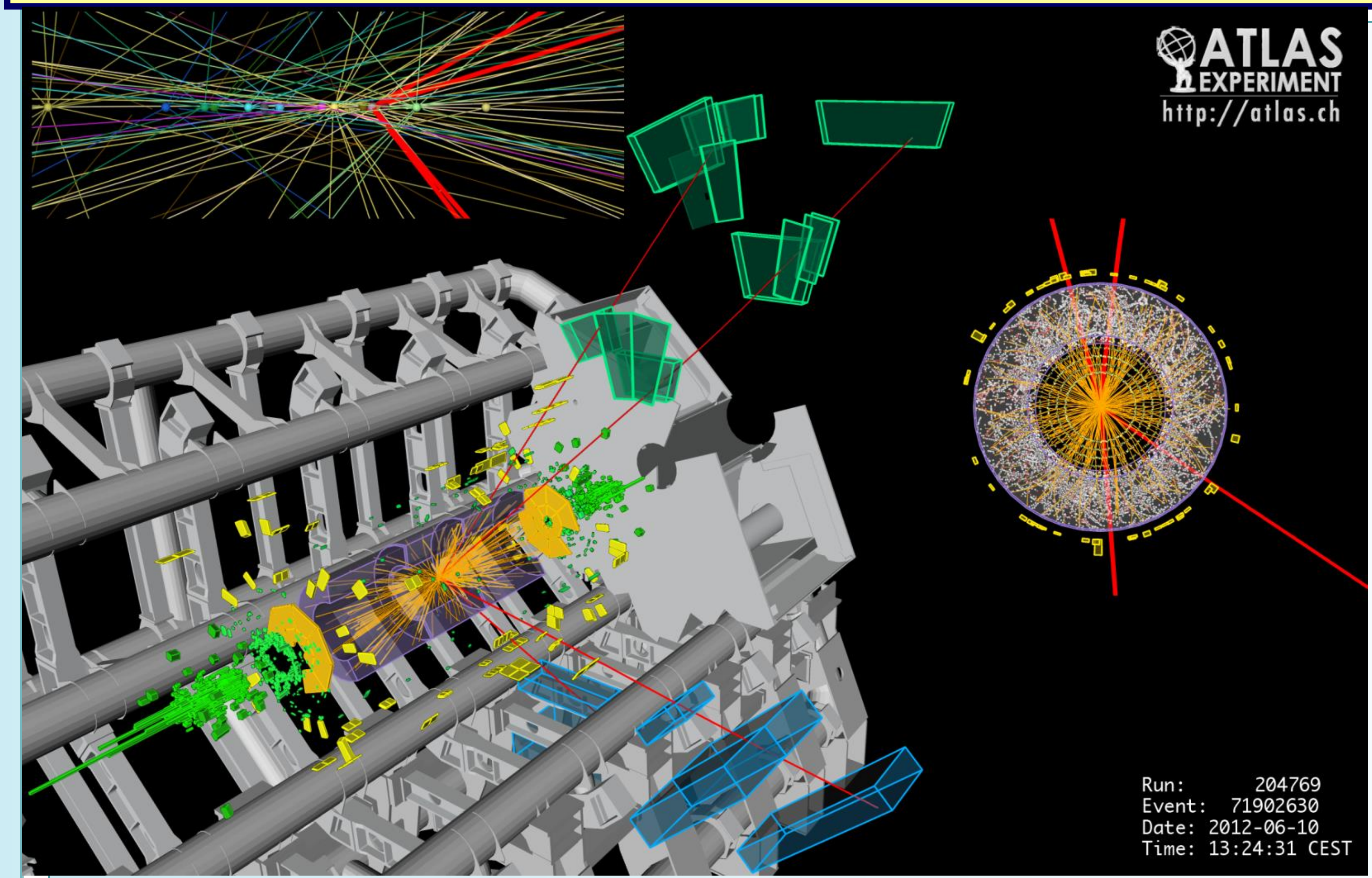
ATLAS Candidates (1)



$H \to \gamma\gamma$

Photon candidates are unconverted.
Event number: 56662314
Run: 203779 at sqrt(s) = 8 TeV
γ_1: pT = 62.2 GeV and η = 0.39
γ_2: pT = 55.5 GeV and η = 1.18
M($\gamma\gamma$) = 126.9 GeV

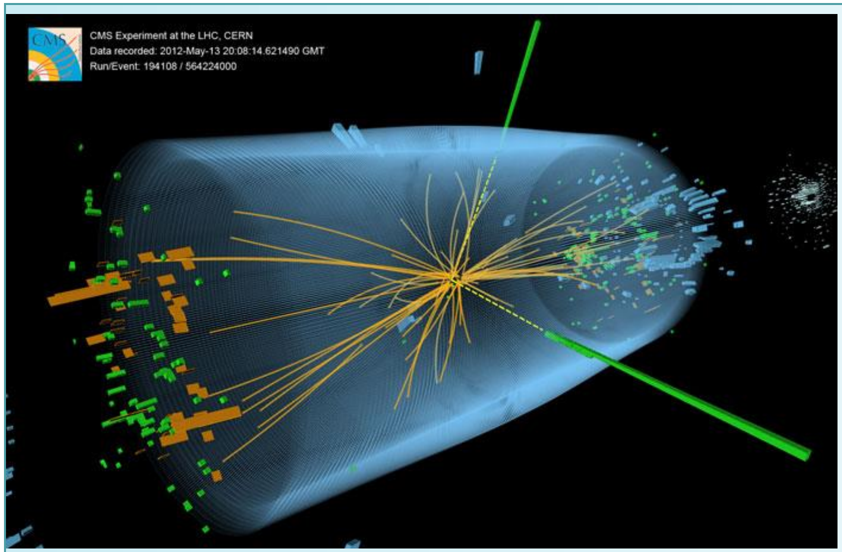
ATLAS Candidates (2)



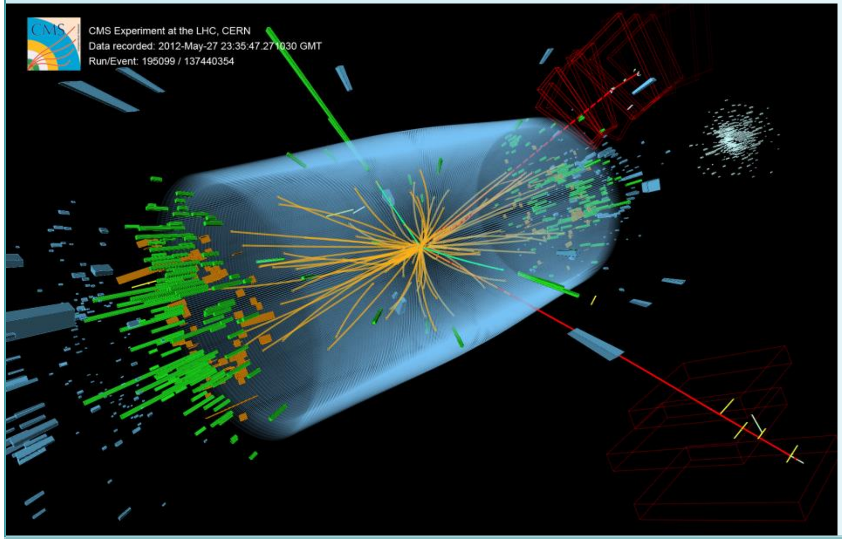
$$H \to ZZ \to \mu^+ \mu^- \mu^+ \mu^-$$

EventNumber: 71902630
RunNumber: 204769
M(4μ)=125.1 GeV
M_{12}=86.3 GeV, M_{34}=31.6 GeV
μ_1: pT=36.1 GeV, η=1.29, ϕ=1.33
μ_2: pT=47.5 GeV, η=0.69, ϕ=–1.65
μ_3: pT=26.4 GeV, η=0.47, ϕ=–2.51
μ_4: pT=71.7 GeV, η=1.85, ϕ=1.65

CMS Candidates

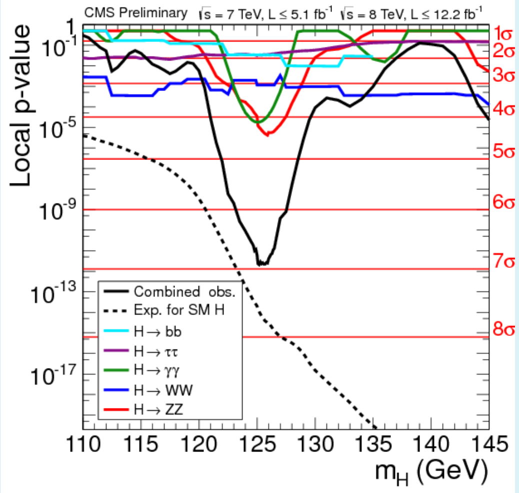


$H \rightarrow \gamma\gamma$

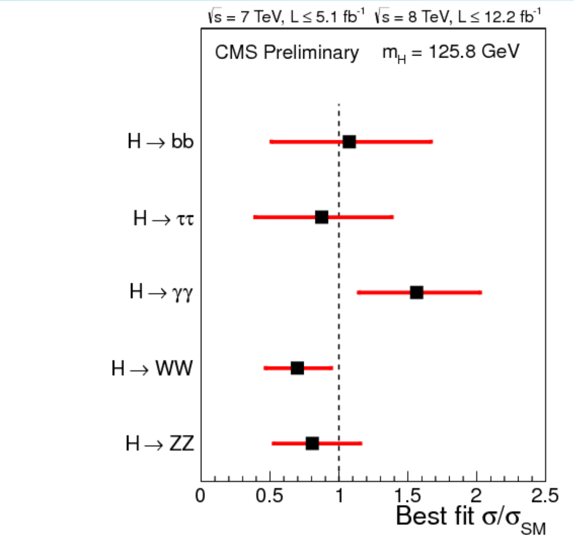


$H \rightarrow ZZ \rightarrow e^+e^-\mu^+\mu^-$

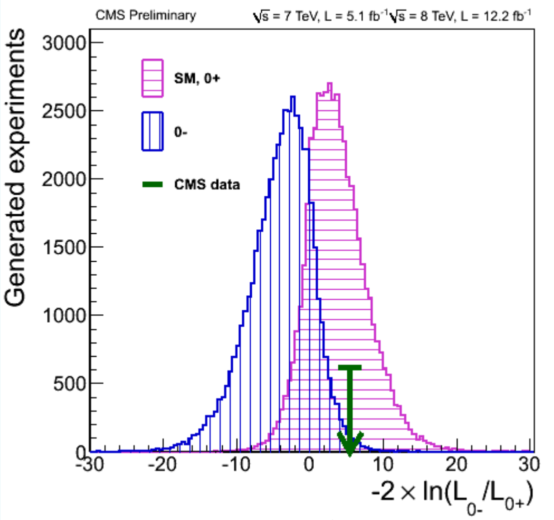
Recent CMS Results
- HCP2012, 12-16 Nov 2012 -



Confirmation of the dicovery



Signal strength by channel



Parity

SUSY Interpretation of a Higgs Signal (1)

- Modified Couplings:

$$\boxed{\begin{aligned}\sigma_{\mathrm{hZ}} &= \sin^2(\beta-\alpha)\ \sigma^{SM}_{\mathrm{HZ}} \\ \sigma_{\mathrm{hA}} &= \cos^2(\beta-\alpha)\bar{\lambda}\ \sigma^{SM}_{\mathrm{HZ}}\end{aligned}}$$

$$\bar{\lambda} = \lambda^{3/2}_{\mathrm{Ah}}/[\lambda^{1/2}_{\mathrm{Zh}}(12M^2_{\mathrm{Z}}/s+\lambda_{\mathrm{Zh}})]$$

$$\lambda_{ij} = [1-(m_i+m_j)^2/s][1-(m_i-m_j)^2/s]$$

- Decoupling Limit:

$M_{H^0} \approx M_{A^0} \approx M_{H^\pm} >> M_{Z^0}, M_{h^0}$ => h^0 is light and has SM-like couplings

Realized in practice when: $\sin^2(\beta-\alpha) \geq 0.95$

- Additional contribution to loops:

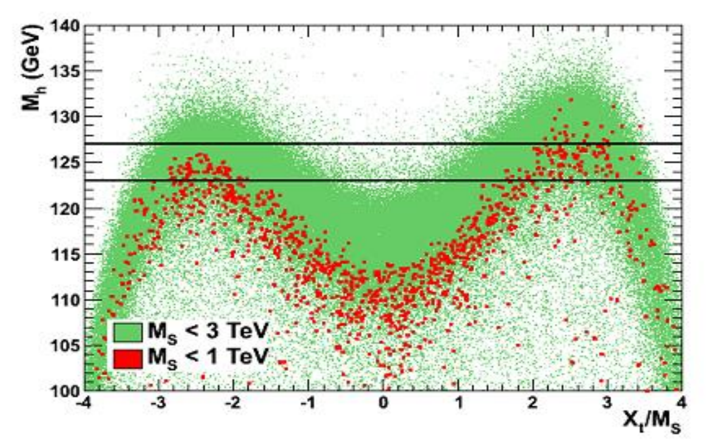
could make differences in h^0 BRs and explain the currently observed tensions between the decay channels

SUSY Interpretation of a Higgs Signal (1)

- Large Mixing in Stop Sector:

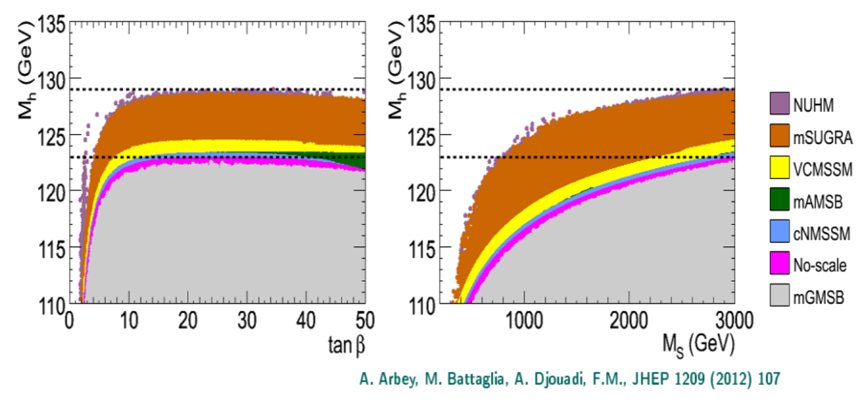
$$M_{h^0} = M_Z|\cos 2\beta| + \frac{3\overline{m}_t^4}{2\pi^2 v^2 \sin^2\beta}\left[\mathrm{Log}\frac{M_S^2}{\overline{m}_t^2} + \frac{X_t^2}{2M_S^2}\left(1-\frac{X_t^2}{6M_S^2}\right)\right]$$

$$\begin{cases} M_S = \sqrt{M_{\tilde{t}_1}\cdot M_{\tilde{t}_2}} \\ X_t = A_t - \dfrac{\mu}{\tan\beta} \end{cases}$$

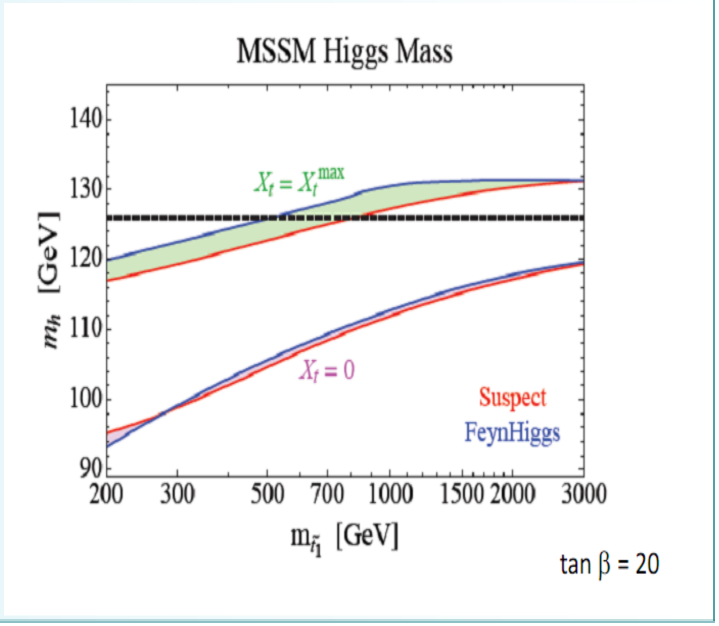


Max. Mixing:

$$X_t = \sqrt{6}\cdot M_S$$

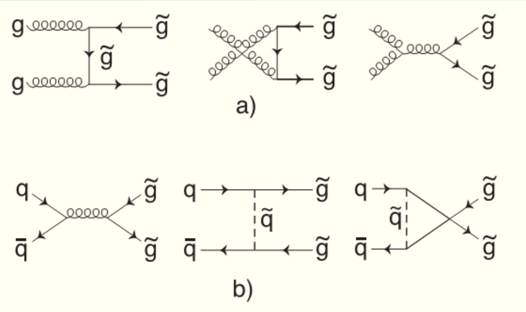


A. Arbey, M. Battaglia, A. Djouadi, F.M., JHEP 1209 (2012) 107

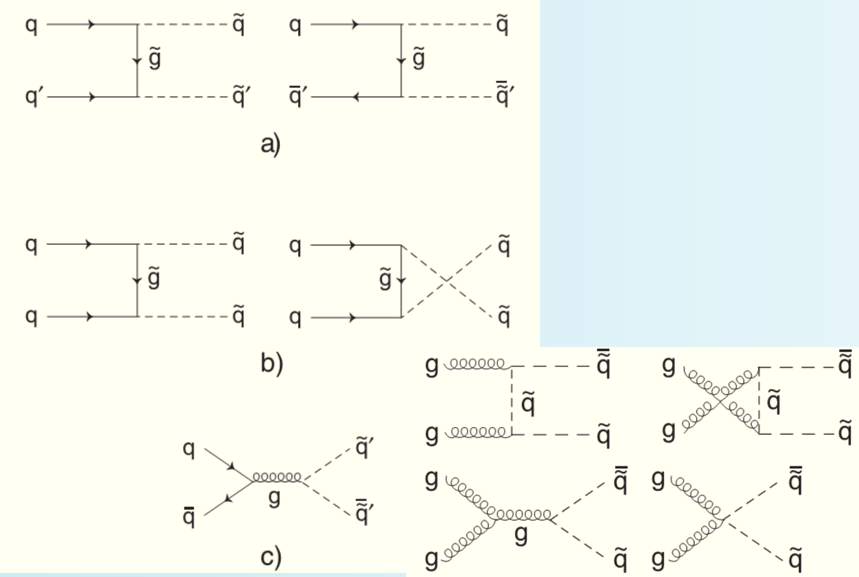


SUSY Searches
- Production Mechanisms (1) -

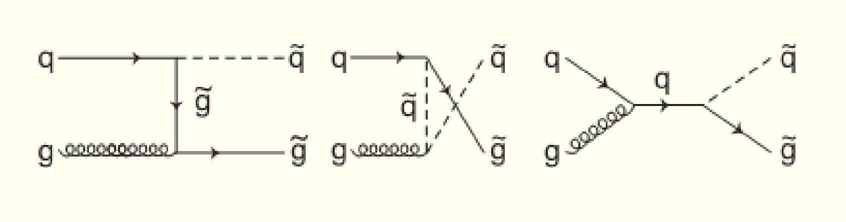
- How are these Sparticles produced?
  - Gluino pairs:



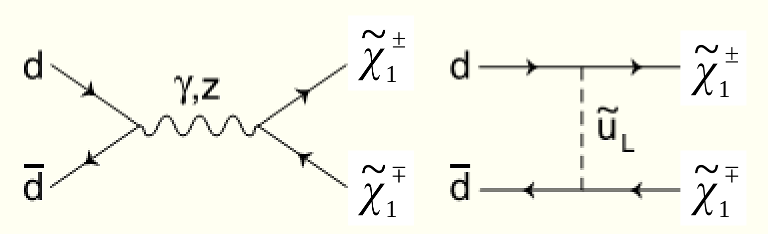
  - Squark pairs:



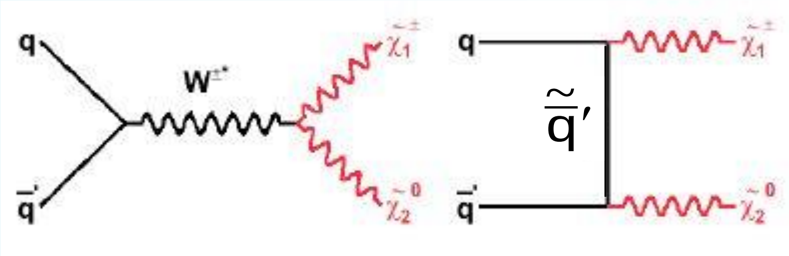
  - Gluino+Squark pairs:



  - Chargino pairs:

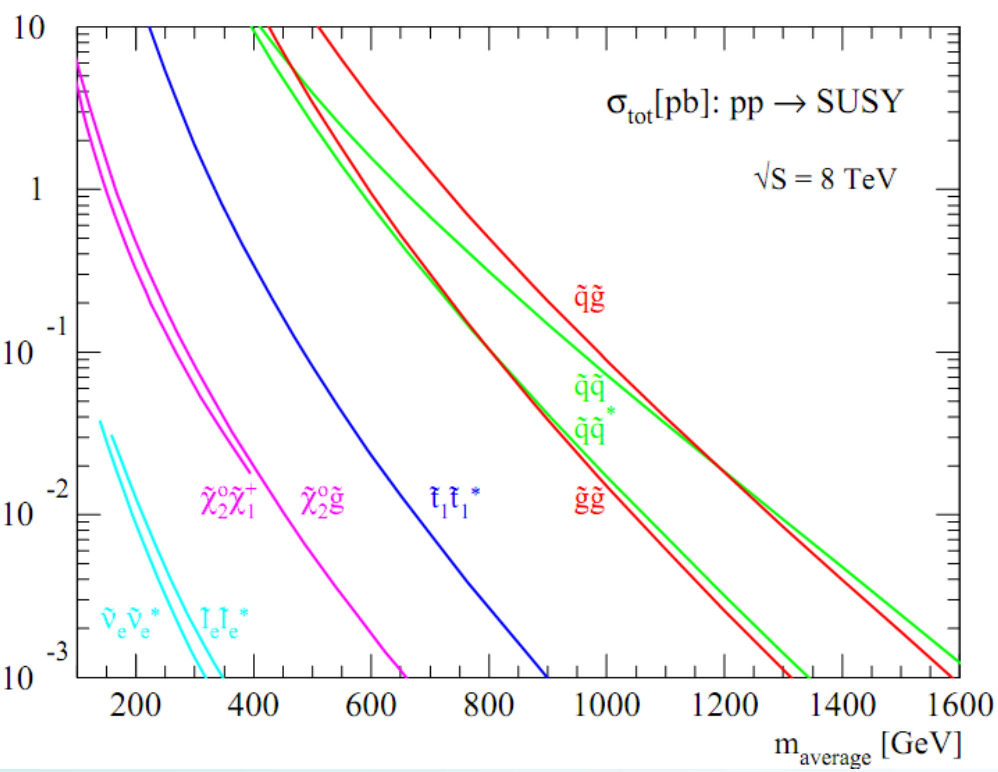


  - Chargino+Neutralino pairs:



SUSY Searches
- Production Mechanisms (2) -

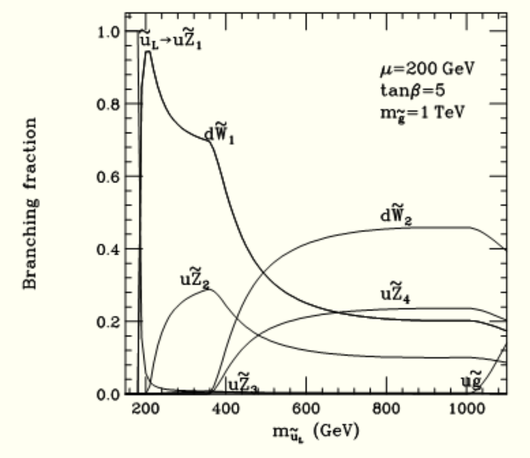
- What are the cross sections?

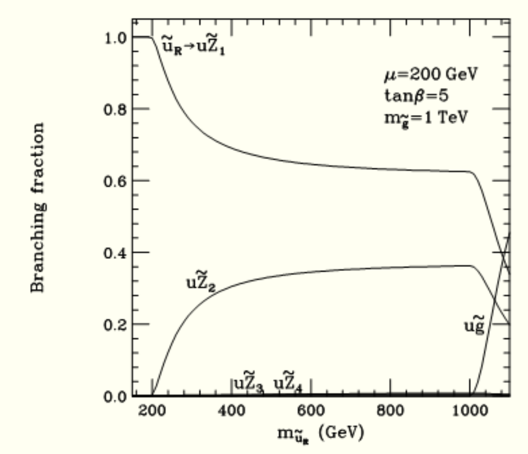


- Obtained with Prospino (include NLO-QCD corrections)
- They determine which Sparticles are accessible and the hierarchy in their search

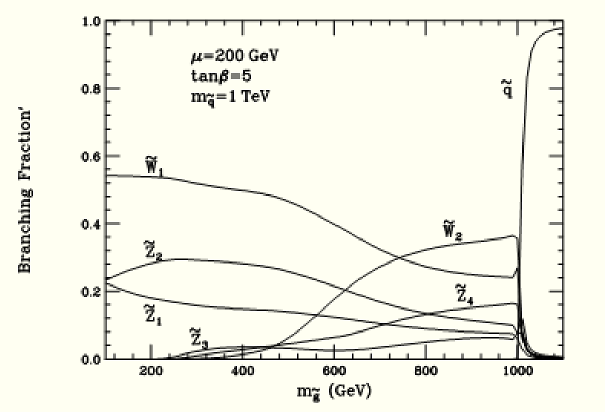
SUSY Searches
- Decay Modes -

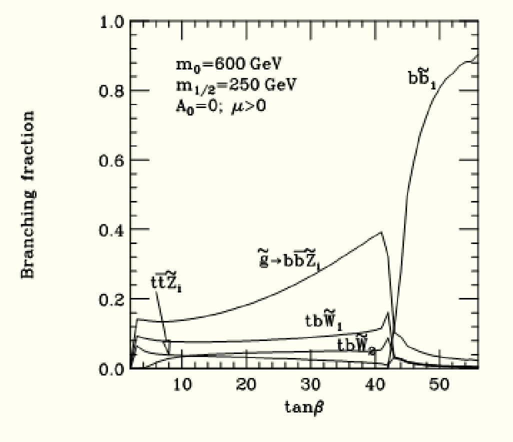
- How do these Sparticles decay?
- Squarks:





- Gluinos:

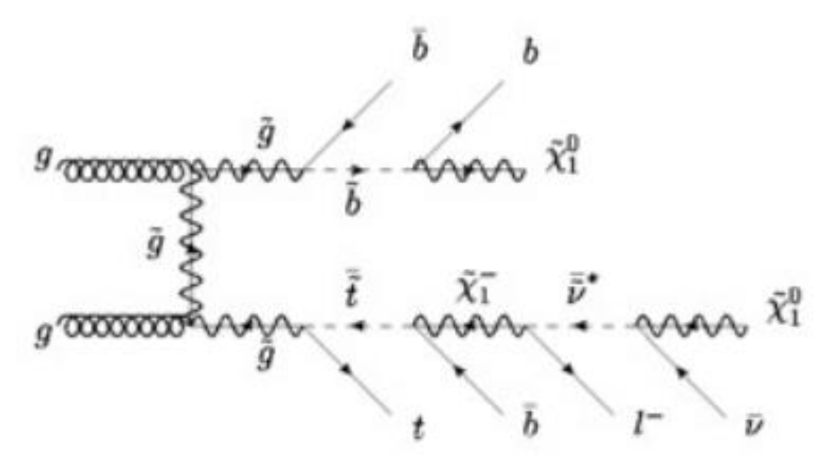




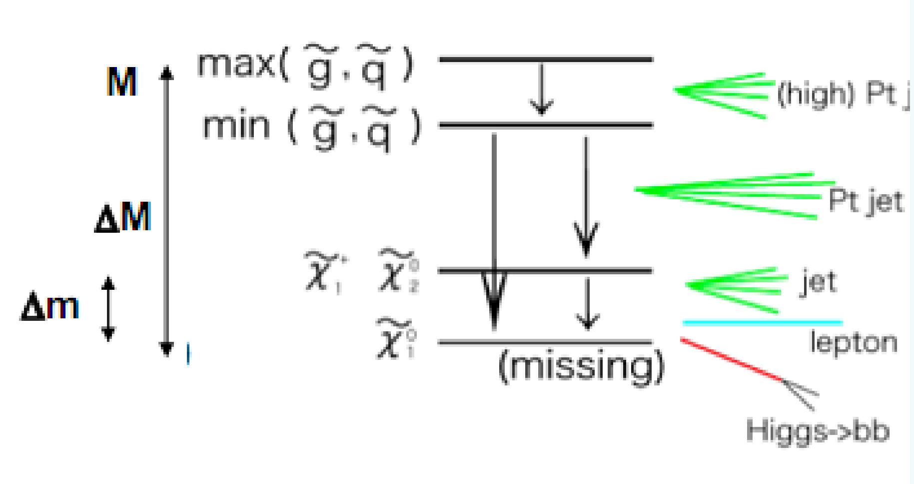
- Search topologies are chosen wrt to some decay chains
- In RPC searches the phase space is limited by a ΔM

SUSY Searches
- Decay Modes -

- What are the serach topologies?



multi-Jets + n leptons + E_T^{miss}



Analysis Tools
- Kinematic Variables -

- Pseudo-rapidity: $$\eta = -\mathrm{Log}\left(\tan\frac{\theta}{2}\right)$$

- Angular distance in space: $$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2}$$

- Missing Transverse Energy:

$$\begin{cases} -p_x^{miss} = \sum_{objects} p_x(\text{reco'd object}) + p_x(\text{non-associated cells}) \\ -p_y^{miss} = \sum_{objects} p_y(\text{reco'd object}) + p_y(\text{non-associated cells}) \end{cases}$$

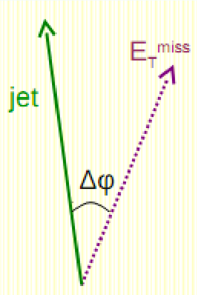
$$\boxed{|\vec{\not p}| = \not E_T = E_T^{miss} = \sqrt{(p_x^{miss})^2 + (p_y^{miss})^2}}$$

- Total Transverse Energy:

It's a scalar sum $$\boxed{H_T = \sum_{i=1}^{N_{obj}} p_T^{(i)}}$$

- $\Delta\phi(\text{jets}, E_T^{miss})$:

Lower bound helps reduce E_T^{miss} from jets mis-measurements



Analysis Tools
- Anti-k_T Jets -

- Definition: It's a recombination algorithm
- Properties:
  - it is IR-safe
  - it can easily be implemented in theoretical or experimental analyses
  - it can be defined at any order of the perturbation theory
- Description:
  - Recombines successively closest pairs

$$d_{ij} = \min[k_T^{2p}(i), k_T^{2p}(j)] \cdot R_{ij}^2 \qquad R_{ij}^2 = (\Delta y_{ij})^2 + (\Delta \varphi_{ij})^2$$

$$\begin{cases} p = 1:\ k_T \text{ algorithm} \longrightarrow & \text{area fluctuates and depends on } p_T \\ p = 0:\ \text{Aachen/Cambrigde algorithm} \longrightarrow & \text{area fluctuates, depends less on } p_T \\ p = -1:\ \text{anti}-k_T \text{ algorithm} \longrightarrow & \text{constant area (circular jets)} \end{cases}$$

- Implementation: http://www.fastjet.fr

Analysis Tools
- Kinematic Variables -

- Effective Mass:
  - sensitive to $\sqrt{\hat{s}}$

$$M_{\rm eff} \equiv \underbrace{\sum_{i=1}^{n} |\mathbf{p}_{\rm T}^{(i)}|}_{H_T} + E_{\rm T}^{\rm miss}$$

- Stransverse mass:
  - lower bound on mass of particle decaying semi-invisibly

$$m_{\rm T2}\left(\mathbf{p}_{\rm T}^{(1)}, \mathbf{p}_{\rm T}^{(2)}, \not{\mathbf{p}}_{\rm T}\right) \equiv \min_{\not{\mathbf{q}}_{\rm T}^{(1)}+\not{\mathbf{q}}_{\rm T}^{(2)}=\vec{E}_{\rm T}^{\rm miss}} \left\{\max\left(m_{\rm T}\left(\mathbf{p}_{\rm T}^{(1)}, \not{\mathbf{q}}_{\rm T}^{(1)}\right), m_{\rm T}\left(\mathbf{p}_{\rm T}^{(2)}, \not{\mathbf{q}}_{\rm T}^{(2)}\right)\right)\right\}$$

visible

invisible

where

$$m_{\rm T}^2\left(\mathbf{p}_{\rm T}^{(i)}, \not{\mathbf{q}}_{\rm T}^{(i)}\right) \equiv 2|\mathbf{p}_{\rm T}^{(i)}||\not{\mathbf{q}}_{\rm T}^{(i)}| - 2\mathbf{p}_{\rm T}^{(i)} \cdot \not{\mathbf{q}}_{\rm T}^{(i)}$$

(usual transverse mass)

- Contransverse mass:
  - useful for identical parent particles decay semi-invisibly

$$M_{CT}(j1, j2) = \sqrt{[E_T(j_1) + E_T(j_2)]^2 - [\vec{p}_T(j_1) - \vec{p}_T(j_2)]^2}$$

SUSY → Multijets+mET (1)

$\sqrt{s} = 7\,\mathrm{TeV}$

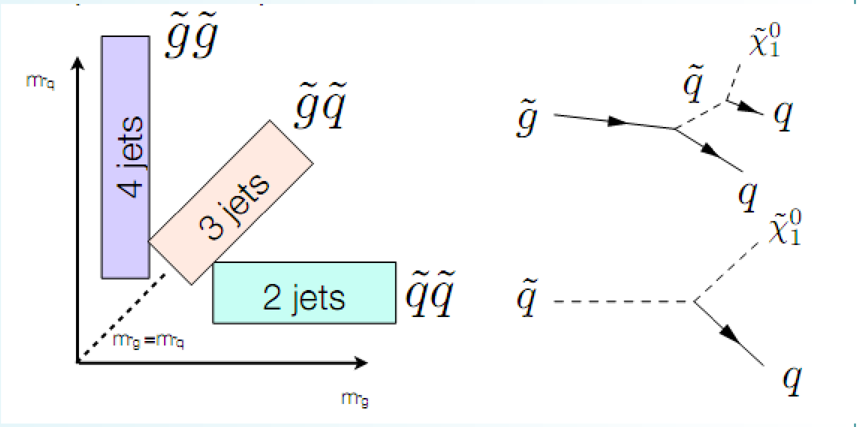
L=1.04 fb^{-1}

Dataset:
- 2011 p+p collisions

Trigger:
- LVL1: multijets
- HLT: 5j55 or 6j45
- Performance: ε=99%

Data Quality:
- Remove bad $\mathcal{L}$ blocks
- Remove evts w/ bad jets
- Reject evts w/ cosmics or noise

Object ID:
- Jets:
  - anti-k_T, ΔR=0.4
  - $p_T > 20$ GeV
  - $|\eta|<2.5$
- e: medium, $p_T > 20$ GeV, $|\eta|<2.47$
- e isolation: H_T(tracks) (ΔR=0.2)<10% p_T(e)
- μ: matched, $p_T > 20$ GeV, $|\eta|<2.4$
- μ isolation: H_T(tracks) (ΔR=0.2)<1.8GeV
- Veto isolated e or μ



SUSY → Jets+mET (3)

Main Background Processes:

- Z+jets: especially Z(→νν)+jets
- W+jets: especially W(→τν)+jets or W(→e/μν)+jets w/ missed e/μ
- QCD multijet

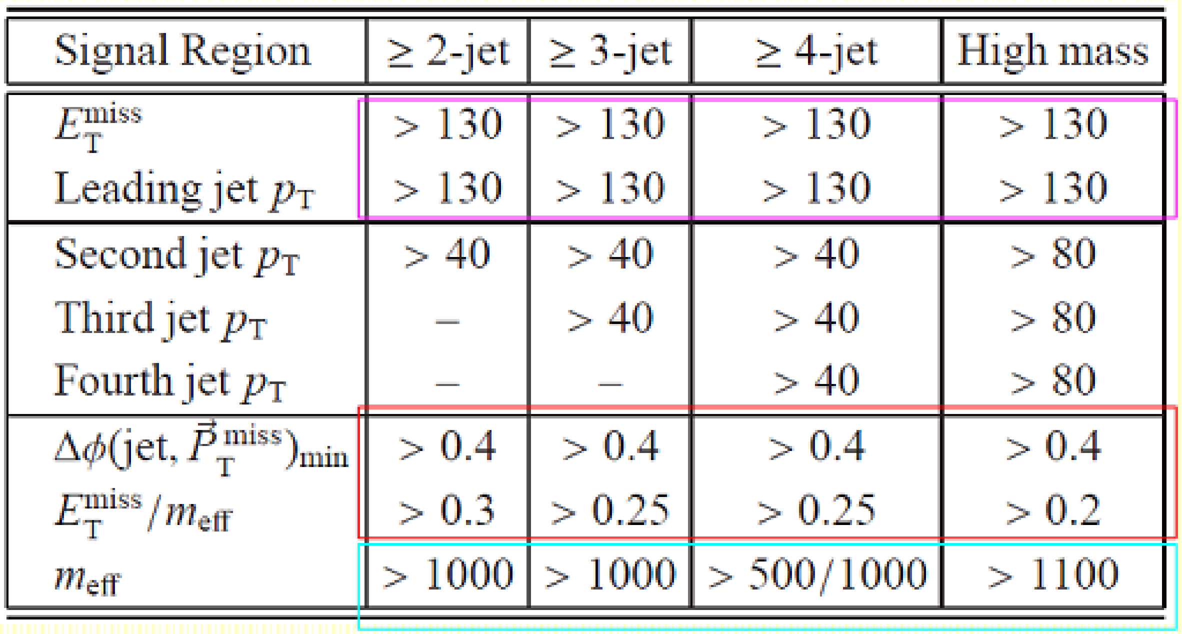
Background Estimation:

- Evaluate each process in a « Control Region » (5 CRs x 5 SRs)
- Extrapolate the CR to SR using transfer factors:

Estimate Signal Sensitivity:

- Profile log-likelihood fit (with correlated systematic uncertainties and CRs cross-contamination)

SUSY → Jets+mET (3)



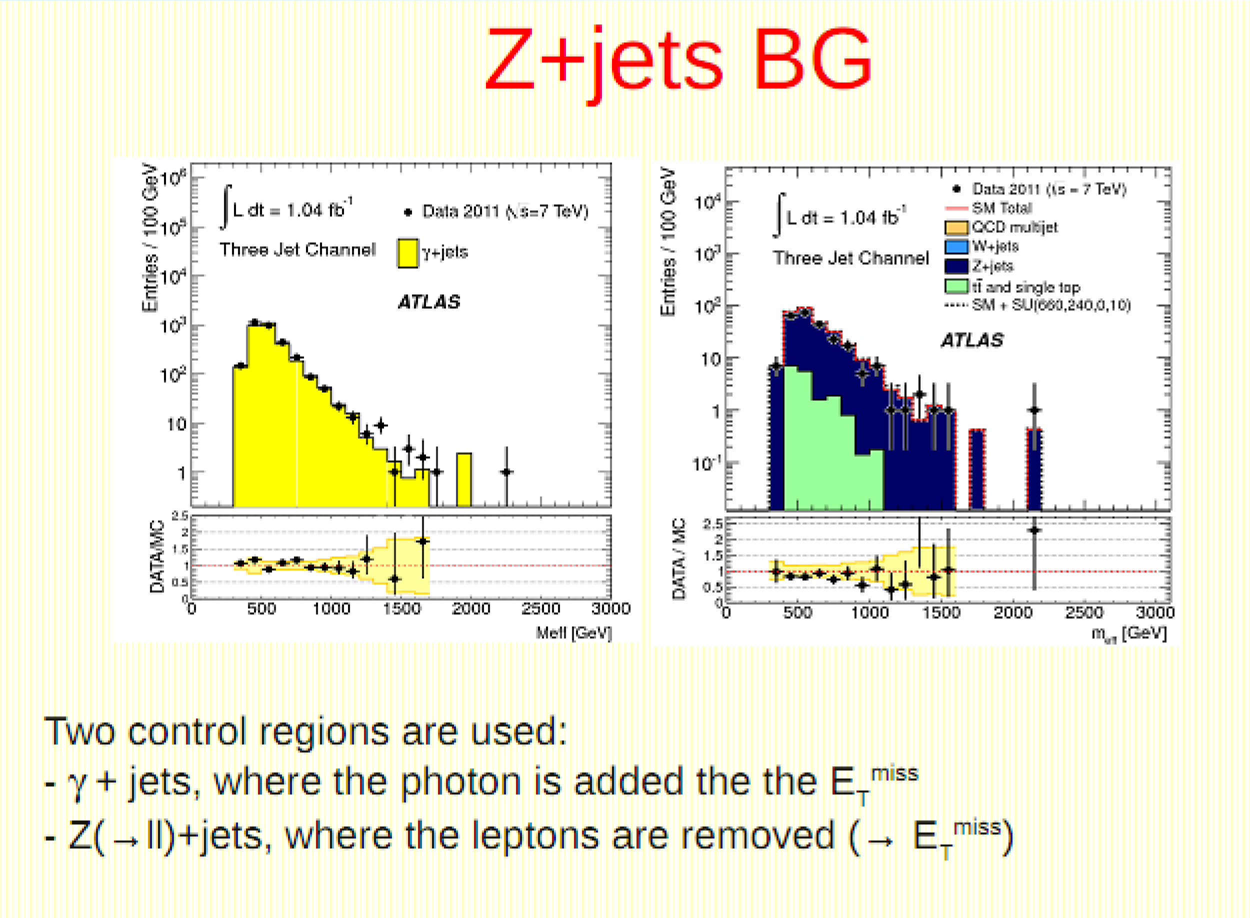
Signal Region	$\geq$ 2-jet	$\geq$ 3-jet	$\geq$ 4-jet	High mass
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 130	> 130	> 130	> 130
Leading jet p_{T}	> 130	> 130	> 130	> 130
Second jet p_{T}	> 40	> 40	> 40	> 80
Third jet p_{T}	–	> 40	> 40	> 80
Fourth jet p_{T}	–	–	> 40	> 80
$\Delta\phi(\mathrm{jet}, \vec{P}_{\mathrm{T}}^{\mathrm{miss}})_{\mathrm{min}}$	> 0.4	> 0.4	> 0.4	> 0.4
$E_{\mathrm{T}}^{\mathrm{miss}} / m_{\mathrm{eff}}$	> 0.3	> 0.25	> 0.25	> 0.2
m_{eff}	> 1000	> 1000	$> 500/1000$	> 1100

Trigger requirements

Reject the QCD BG

Optimize for SUSY

SUSY → Jets+mET (3)



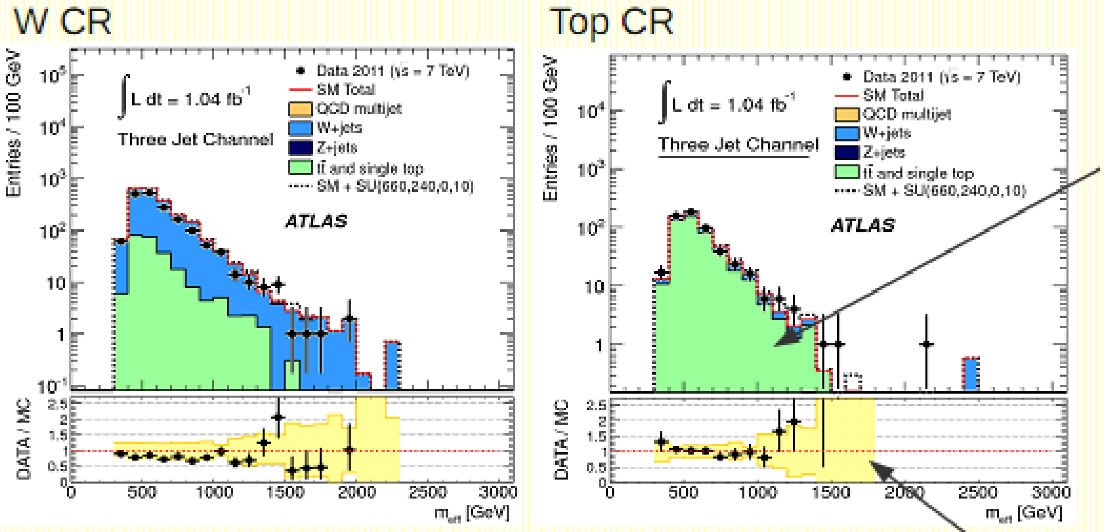
Z+jets BG

Two control regions are used:

- γ + jets, where the photon is added the the E_T^{miss}
- Z(→ ll)+jets, where the leptons are removed (→ E_T^{miss})

SUSY → Jets+mET (3)

W+jets and top BG



MC normalized to luminosity

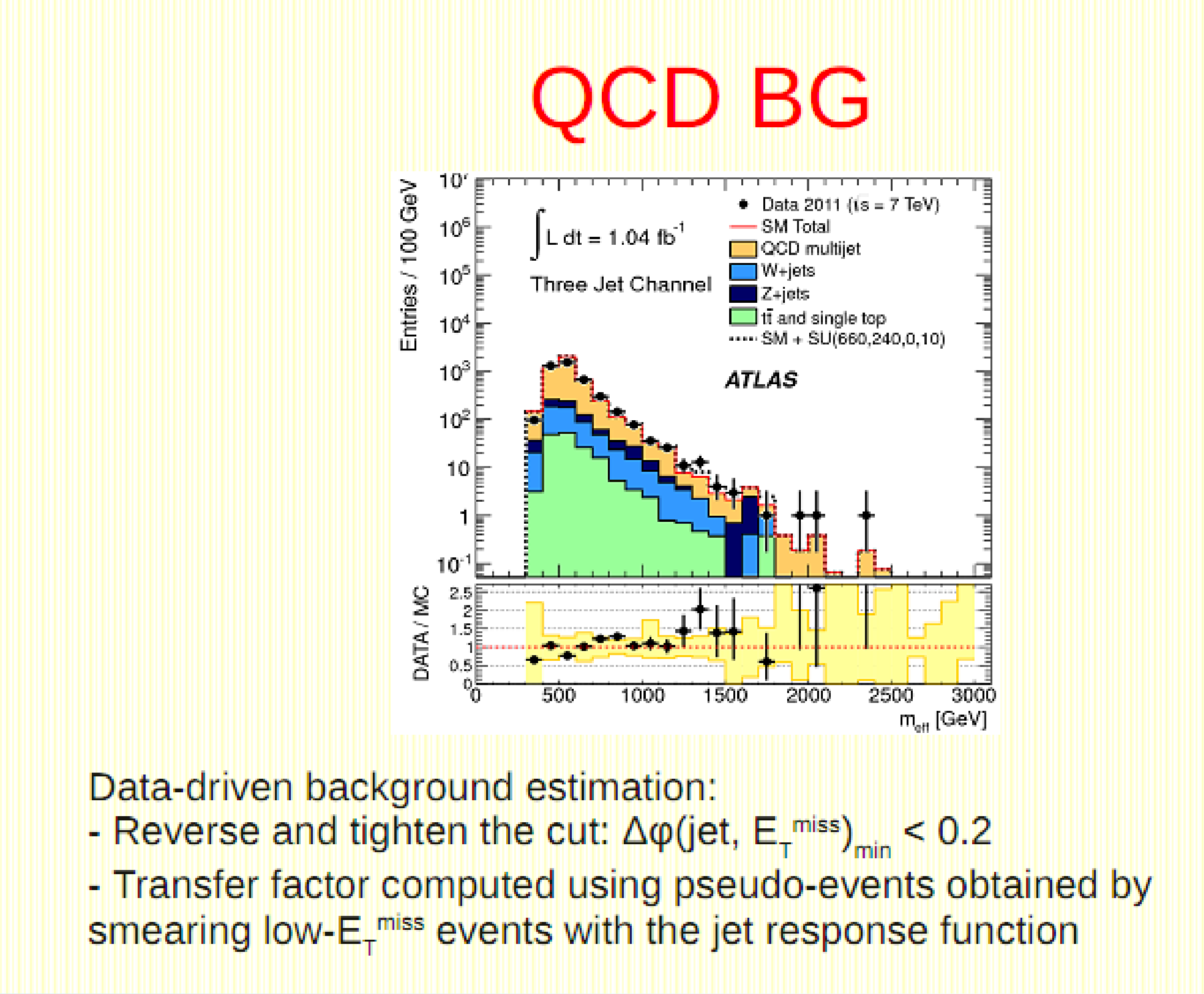
JES, JER, MC stat uncert.

- Select 1-lepton events with 30 < m_T < 100 GeV

- Split the top from W by asking for no b-tagged jet (W) or at least one b-tagged jet (top)

- Treat the lepton as a jet (for MET calculations, Meff, jet cuts...)

SUSY → Jets+mET (3)

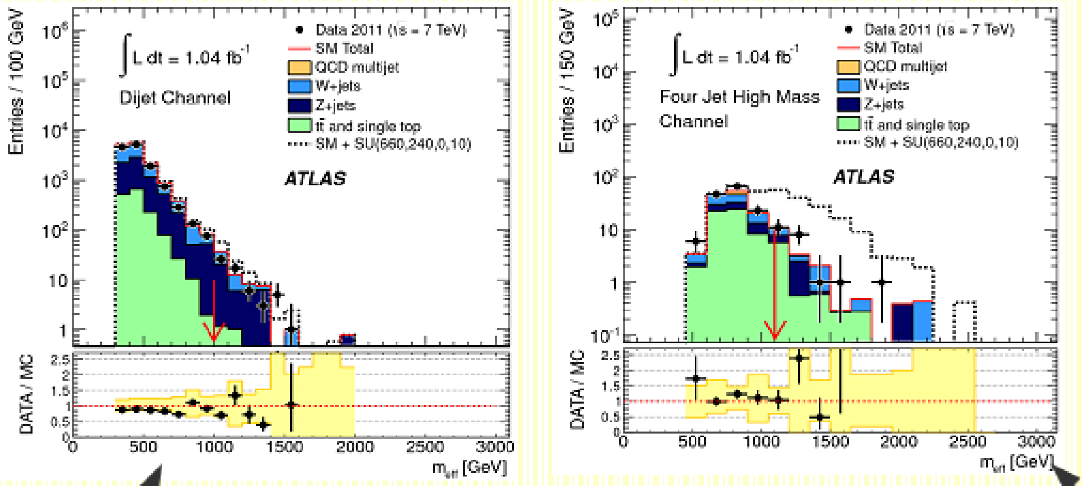


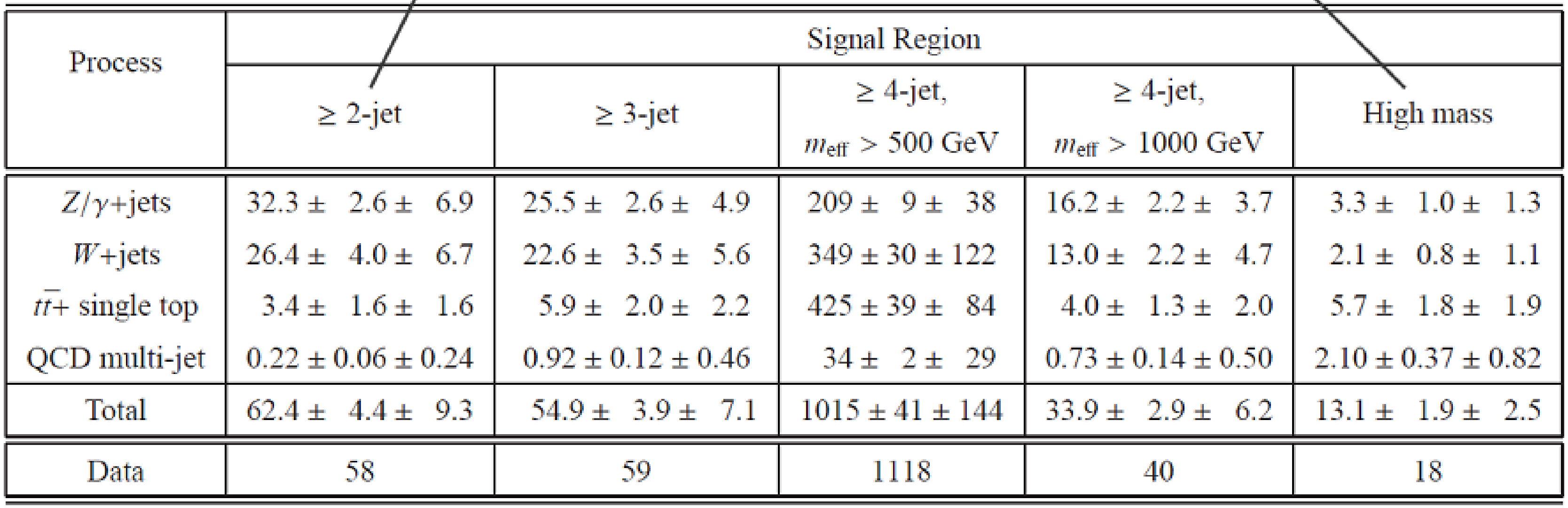
QCD BG

Data-driven background estimation:

- Reverse and tighten the cut: $\Delta\varphi(\mathrm{jet}, E_T^{\mathrm{miss}})_{\mathrm{min}} < 0.2$
- Transfer factor computed using pseudo-events obtained by smearing low-E_T^{miss} events with the jet response function

SUSY → Jets+mET (3)



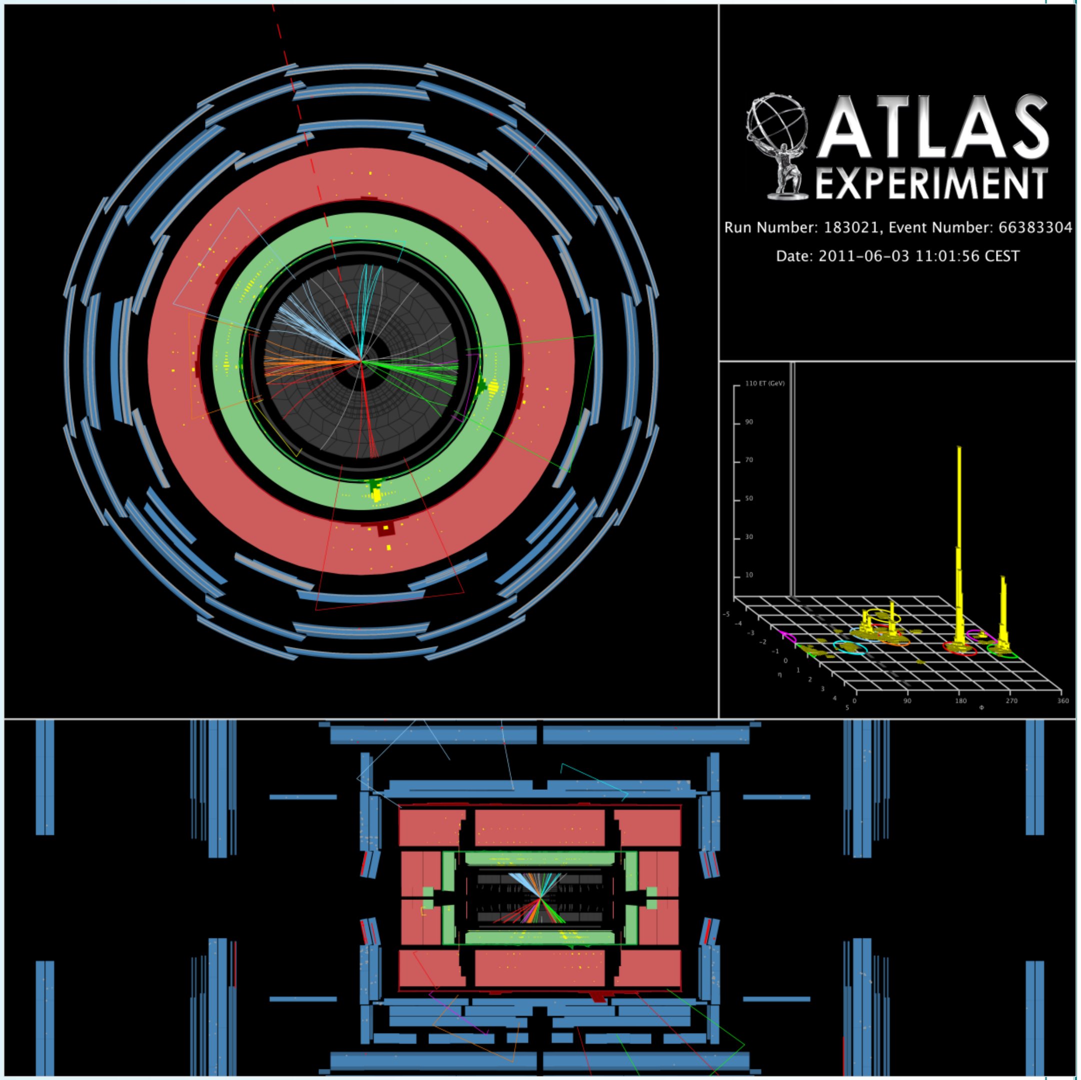


<table>
<tr><th rowspan="2">Process</th><th colspan="5">Signal Region</th></tr>
<tr><th>≥ 2-jet</th><th>≥ 3-jet</th><th>≥ 4-jet,
$m_{\mathrm{eff}} > 500$ GeV</th><th>≥ 4-jet,
$m_{\mathrm{eff}} > 1000$ GeV</th><th>High mass</th></tr>
<tr><td>Z/γ+jets</td><td>32.3 ± 2.6 ± 6.9</td><td>25.5 ± 2.6 ± 4.9</td><td>209 ± 9 ± 38</td><td>16.2 ± 2.2 ± 3.7</td><td>3.3 ± 1.0 ± 1.3</td></tr>
<tr><td>W+jets</td><td>26.4 ± 4.0 ± 6.7</td><td>22.6 ± 3.5 ± 5.6</td><td>349 ± 30 ± 122</td><td>13.0 ± 2.2 ± 4.7</td><td>2.1 ± 0.8 ± 1.1</td></tr>
<tr><td>$t\bar{t}$+ single top</td><td>3.4 ± 1.6 ± 1.6</td><td>5.9 ± 2.0 ± 2.2</td><td>425 ± 39 ± 84</td><td>4.0 ± 1.3 ± 2.0</td><td>5.7 ± 1.8 ± 1.9</td></tr>
<tr><td>QCD multi-jet</td><td>0.22 ± 0.06 ± 0.24</td><td>0.92 ± 0.12 ± 0.46</td><td>34 ± 2 ± 29</td><td>0.73 ± 0.14 ± 0.50</td><td>2.10 ± 0.37 ± 0.82</td></tr>
<tr><td>Total</td><td>62.4 ± 4.4 ± 9.3</td><td>54.9 ± 3.9 ± 7.1</td><td>1015 ± 41 ± 144</td><td>33.9 ± 2.9 ± 6.2</td><td>13.1 ± 1.9 ± 2.5</td></tr>
<tr><td>Data</td><td>58</td><td>59</td><td>1118</td><td>40</td><td>18</td></tr>
</table>

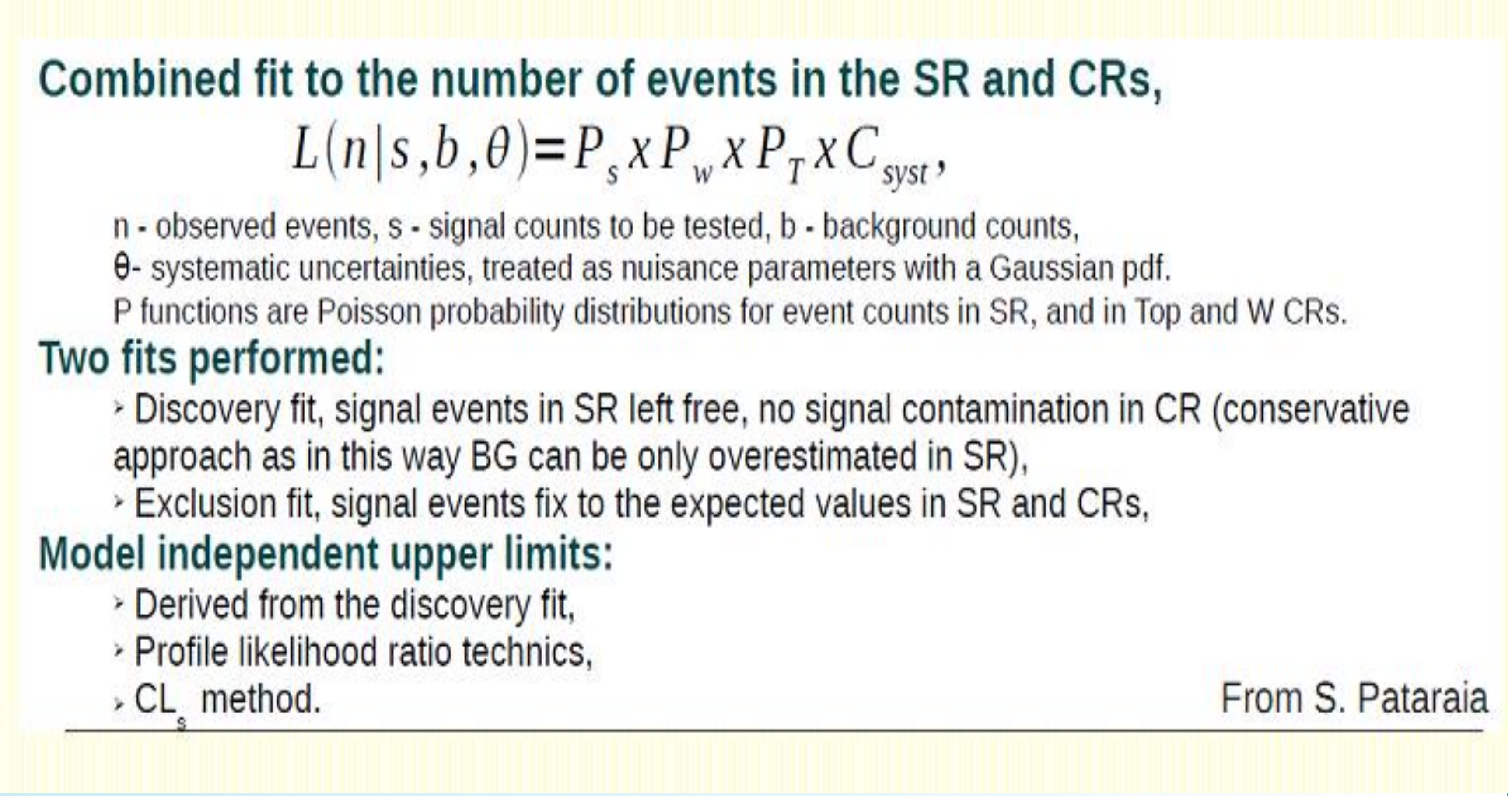
95% CL limits on cross section · acceptance · efficiency:
22 fb, 25 fb, 429 fb, 27 fb and 17 fb

SUSY → Jets+mET (3)

Event w/ highest meff found
5 jets with pt > 40 GeV:
pt = 528, 418, 233, 171, 42 GeV
met = 460 GeV
meff =1810 GeV (4 leading jets)



SUSY → Jets+mET (3)



Combined fit to the number of events in the SR and CRs,

$$L(n|s,b,\theta)=P_s \, x \, P_w \, x \, P_T \, x \, C_{syst},$$

n - observed events, s - signal counts to be tested, b - background counts,
θ- systematic uncertainties, treated as nuisance parameters with a Gaussian pdf.
P functions are Poisson probability distributions for event counts in SR, and in Top and W CRs.

Two fits performed:

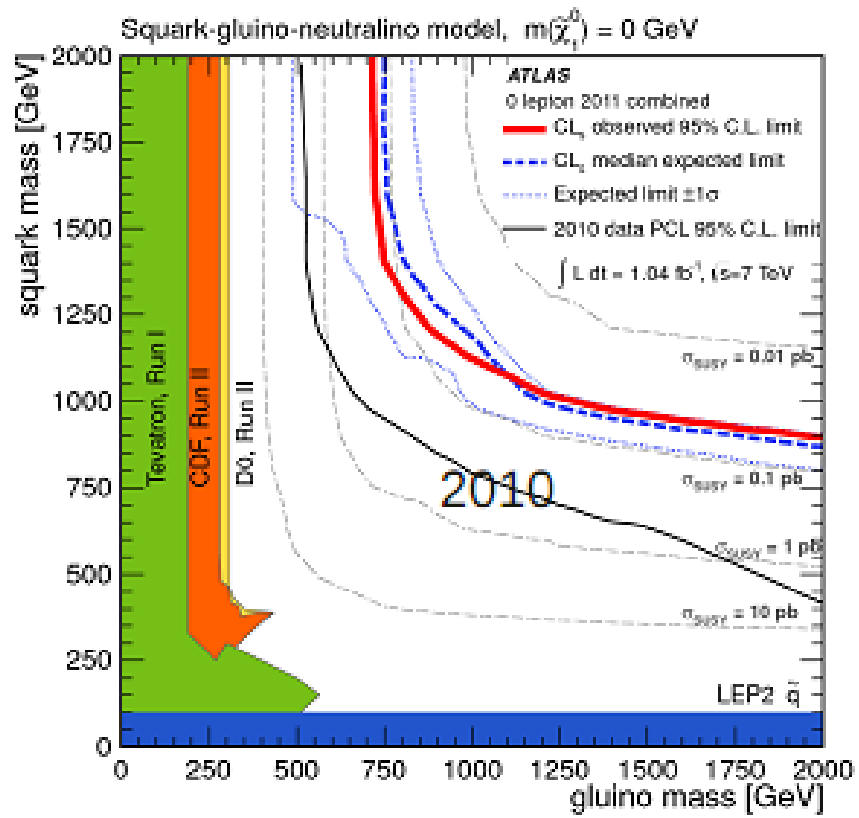
- Discovery fit, signal events in SR left free, no signal contamination in CR (conservative approach as in this way BG can be only overestimated in SR),
- Exclusion fit, signal events fix to the expected values in SR and CRs,

Model independent upper limits:

- Derived from the discovery fit,
- Profile likelihood ratio technics,
- CL_s method.

From S. Pataraia

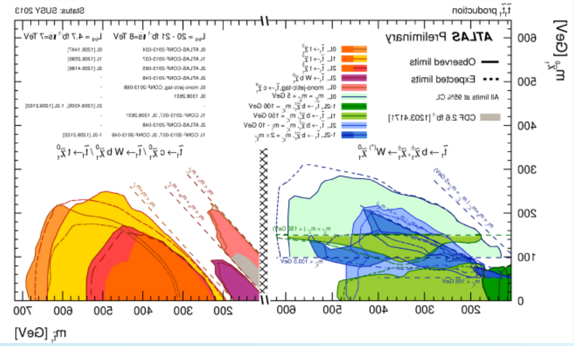
SUSY → Jets+mET (3)

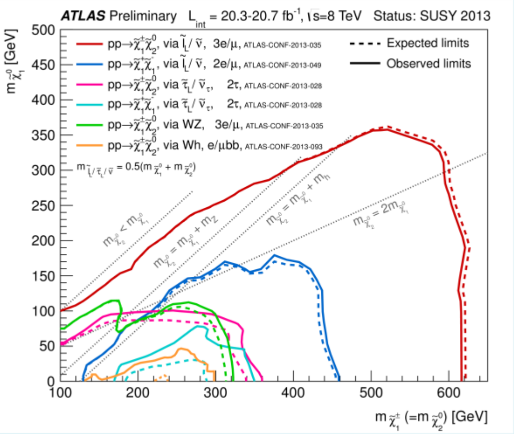


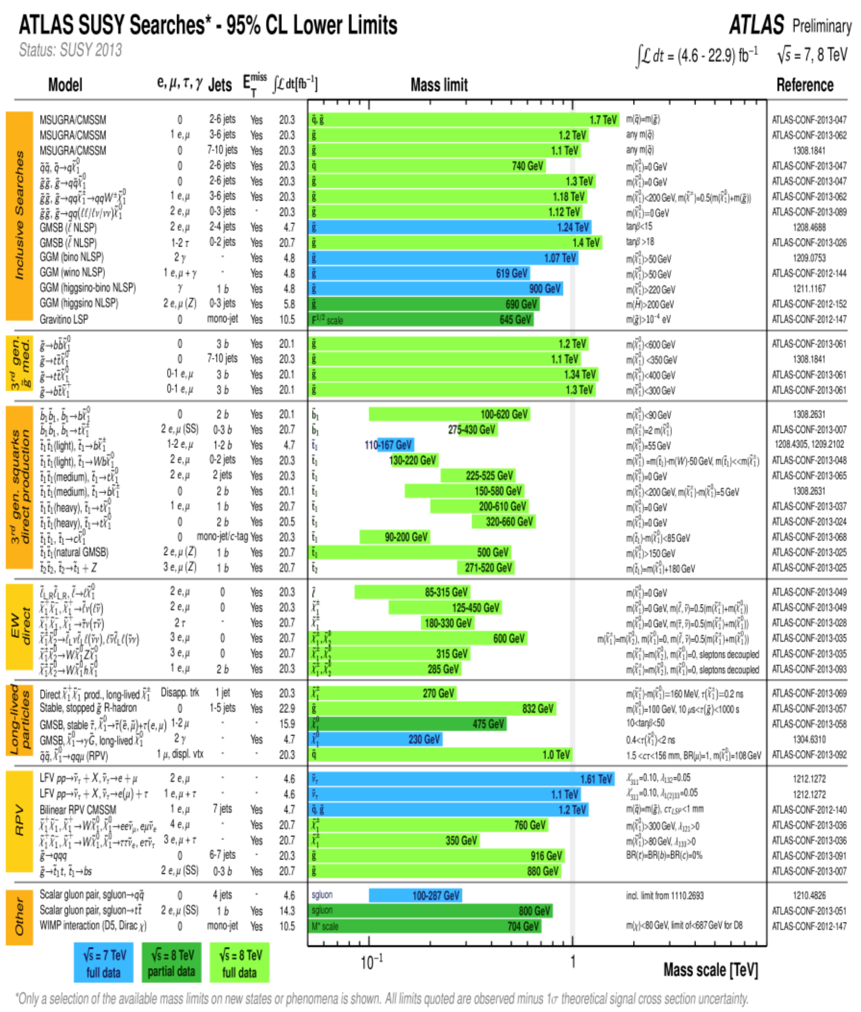
→ gluino and squark masses below 700 GeV and 875 GeV are excluded (for squark or gluino masses below 2 TeV)

→ limit at 1075 GeV for equal mass squarks and gluinos

SUSY Searches
- ATLAS Summary -







ATLAS SUSY Searches* - 95% CL Lower Limits

Status: SUSY 2013

ATLAS Preliminary

$\int \mathcal{L}\,dt = (4.6 - 22.9)\ \text{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

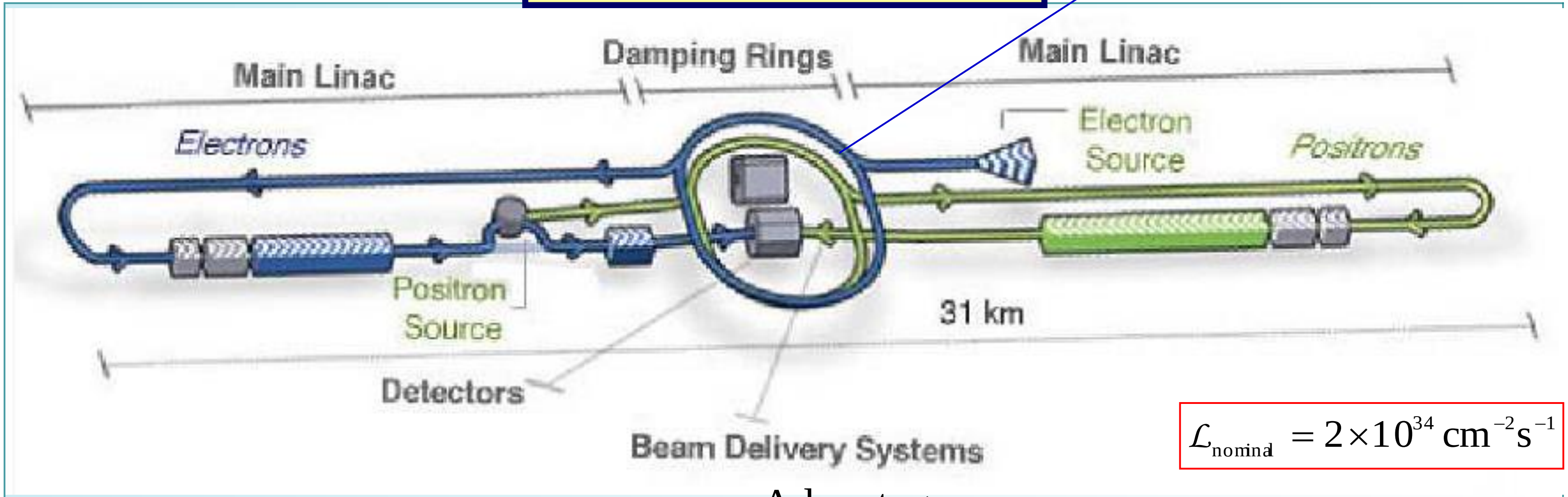
	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\,dt[\text{fb}^{-1}]$	Mass limit			Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde q, \tilde g$	1.7 TeV	$m(\tilde q)=m(\tilde g)$	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.3	$\tilde g$	1.2 TeV	any $m(\tilde q)$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde g$	1.1 TeV	any $m(\tilde q)$	1308.1841
	$\tilde q\tilde q, \tilde q \to q\tilde\chi_1^0$	0	2-6 jets	Yes	20.3	$\tilde q$	740 GeV	$m(\tilde\chi_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde g\tilde g, \tilde g \to q\bar q\tilde\chi_1^0$	0	2-6 jets	Yes	20.3	$\tilde g$	1.3 TeV	$m(\tilde\chi_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde g\tilde g, \tilde g \to qq\tilde\chi_1^\pm \to qqW^\pm\tilde\chi_1^0$	1 e,μ	3-6 jets	Yes	20.3	$\tilde g$	1.18 TeV	$m(\tilde\chi_1^0)$<200 GeV, $m(\tilde\chi^\pm)=0.5(m(\tilde\chi_1^0)+m(\tilde g))$	ATLAS-CONF-2013-062
	$\tilde g\tilde g, \tilde g \to qq(\ell\ell/\ell\nu/\nu\nu)\tilde\chi_1^0$	2 e,μ	0-3 jets	-	20.3	$\tilde g$	1.12 TeV	$m(\tilde\chi_1^0)$=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde\ell$ NLSP)	2 e,μ	2-4 jets	Yes	4.7	$\tilde g$	1.24 TeV	$\tan\beta$<15	1208.4688
	GMSB ($\tilde\ell$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde g$	1.4 TeV	$\tan\beta$ >18	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	-	Yes	4.8	$\tilde g$	1.07 TeV	$m(\tilde\chi_1^0)$>50 GeV	1209.0753
	GGM (wino NLSP)	1 $e,\mu+\gamma$	-	Yes	4.8	$\tilde g$	619 GeV	$m(\tilde\chi_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde g$	900 GeV	$m(\tilde\chi_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde g$	690 GeV	$m(\tilde H)$>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale	645 GeV	$m(\tilde g)>10^{-4}$ eV	ATLAS-CONF-2012-147
3^{rd} gen. $\tilde g$ med.	$\tilde g \to b\bar b\tilde\chi_1^0$	0	3 b	Yes	20.1	$\tilde g$	1.2 TeV	$m(\tilde\chi_1^0)$<600 GeV	ATLAS-CONF-2013-061
	$\tilde g \to t\bar t\tilde\chi_1^0$	0	7-10 jets	Yes	20.3	$\tilde g$	1.1 TeV	$m(\tilde\chi_1^0)$ <350 GeV	1308.1841
	$\tilde g \to t\bar t\tilde\chi_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde g$	1.34 TeV	$m(\tilde\chi_1^0)$<400 GeV	ATLAS-CONF-2013-061
	$\tilde g \to b\bar t\tilde\chi_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde g$	1.3 TeV	$m(\tilde\chi_1^0)$<300 GeV	ATLAS-CONF-2013-061
3^{rd} gen. squarks direct production	$\tilde b_1\tilde b_1, \tilde b_1 \to b\tilde\chi_1^0$	0	2 b	Yes	20.1	$\tilde b_1$	100-620 GeV	$m(\tilde\chi_1^0)$<90 GeV	1308.2631
	$\tilde b_1\tilde b_1, \tilde b_1 \to t\tilde\chi_1^\pm$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde b_1$	275-430 GeV	$m(\tilde\chi_1^\pm)=2\,m(\tilde\chi_1^0)$	ATLAS-CONF-2013-007
	$\tilde t_1\tilde t_1$(light), $\tilde t_1 \to b\tilde\chi_1^\pm$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde t_1$	110-167 GeV	$m(\tilde\chi_1^0)$=55 GeV	1208.4305, 1209.2102
	$\tilde t_1\tilde t_1$(light), $\tilde t_1 \to Wb\tilde\chi_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde t_1$	130-220 GeV	$m(\tilde\chi_1^0) = m(\tilde t_1)-m(W)-50$ GeV, $m(\tilde t_1)<<m(\tilde\chi_1^\pm)$	ATLAS-CONF-2013-048
	$\tilde t_1\tilde t_1$(medium), $\tilde t_1 \to t\tilde\chi_1^0$	2 e,μ	2 jets	Yes	20.3	$\tilde t_1$	225-525 GeV	$m(\tilde\chi_1^0)$=0 GeV	ATLAS-CONF-2013-065
	$\tilde t_1\tilde t_1$(medium), $\tilde t_1 \to b\tilde\chi_1^\pm$	0	2 b	Yes	20.1	$\tilde t_1$	150-580 GeV	$m(\tilde\chi_1^0)$<200 GeV, $m(\tilde\chi_1^\pm)-m(\tilde\chi_1^0)$=5 GeV	1308.2631
	$\tilde t_1\tilde t_1$(heavy), $\tilde t_1 \to t\tilde\chi_1^0$	1 e,μ	1 b	Yes	20.7	$\tilde t_1$	200-610 GeV	$m(\tilde\chi_1^0)$=0 GeV	ATLAS-CONF-2013-037
	$\tilde t_1\tilde t_1$(heavy), $\tilde t_1 \to t\tilde\chi_1^0$	0	2 b	Yes	20.5	$\tilde t_1$	320-660 GeV	$m(\tilde\chi_1^0)$=0 GeV	ATLAS-CONF-2013-024
	$\tilde t_1\tilde t_1, \tilde t_1 \to c\tilde\chi_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde t_1$	90-200 GeV	$m(\tilde t_1)-m(\tilde\chi_1^0)$<85 GeV	ATLAS-CONF-2013-068
	$\tilde t_1\tilde t_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.7	$\tilde t_1$	500 GeV	$m(\tilde\chi_1^0)$>150 GeV	ATLAS-CONF-2013-025
	$\tilde t_2\tilde t_2, \tilde t_2 \to \tilde t_1 + Z$	3 e,μ (Z)	1 b	Yes	20.7	$\tilde t_2$	271-520 GeV	$m(\tilde t_1)=m(\tilde\chi_1^0)$+180 GeV	ATLAS-CONF-2013-025
EW direct	$\tilde\ell_{L,R}\tilde\ell_{L,R}, \tilde\ell \to \ell\tilde\chi_1^0$	2 e,μ	0	Yes	20.3	$\tilde\ell$	85-315 GeV	$m(\tilde\chi_1^0)$=0 GeV	ATLAS-CONF-2013-049
	$\tilde\chi_1^+\tilde\chi_1^-, \tilde\chi_1^+ \to \tilde\ell\nu(\ell\tilde\nu)$	2 e,μ	0	Yes	20.3	$\tilde\chi_1^\pm$	125-450 GeV	$m(\tilde\chi_1^0)$=0 GeV, $m(\tilde\ell,\tilde\nu)=0.5(m(\tilde\chi_1^\pm)+m(\tilde\chi_1^0))$	ATLAS-CONF-2013-049
	$\tilde\chi_1^+\tilde\chi_1^-, \tilde\chi_1^+ \to \tilde\tau\nu(\tau\tilde\nu)$	2 τ	-	Yes	20.7	$\tilde\chi_1^\pm$	180-330 GeV	$m(\tilde\chi_1^0)$=0 GeV, $m(\tilde\tau,\tilde\nu)=0.5(m(\tilde\chi_1^\pm)+m(\tilde\chi_1^0))$	ATLAS-CONF-2013-028
	$\tilde\chi_1^\pm\tilde\chi_2^0 \to \tilde\ell_L\nu\tilde\ell_L\ell(\tilde\nu\nu), \ell\tilde\nu\tilde\ell_L\ell(\tilde\nu\nu)$	3 e,μ	0	Yes	20.7	$\tilde\chi_1^\pm, \tilde\chi_2^0$	600 GeV	$m(\tilde\chi_1^\pm)=m(\tilde\chi_2^0)$, $m(\tilde\chi_1^0)$=0, $m(\tilde\ell,\tilde\nu)=0.5(m(\tilde\chi_1^\pm)+m(\tilde\chi_1^0))$	ATLAS-CONF-2013-035
	$\tilde\chi_1^\pm\tilde\chi_2^0 \to W\tilde\chi_1^0 Z\tilde\chi_1^0$	3 e,μ	0	Yes	20.7	$\tilde\chi_1^\pm, \tilde\chi_2^0$	315 GeV	$m(\tilde\chi_1^\pm)=m(\tilde\chi_2^0)$, $m(\tilde\chi_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-035
	$\tilde\chi_1^\pm\tilde\chi_2^0 \to W\tilde\chi_1^0 h\tilde\chi_1^0$	1 e,μ	2 b	Yes	20.3	$\tilde\chi_1^\pm, \tilde\chi_2^0$	285 GeV	$m(\tilde\chi_1^\pm)=m(\tilde\chi_2^0)$, $m(\tilde\chi_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-093
Long-lived particles	Direct $\tilde\chi_1^+\tilde\chi_1^-$ prod., long-lived $\tilde\chi_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde\chi_1^\pm$	270 GeV	$m(\tilde\chi_1^\pm)-m(\tilde\chi_1^0)$=160 MeV, $\tau(\tilde\chi_1^\pm)$=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde g$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde g$	832 GeV	$m(\tilde\chi_1^0)$=100 GeV, 10 μs<$\tau(\tilde g)$<1000 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde\tau$, $\tilde\chi_1^0 \to \tilde\tau(\tilde e,\tilde\mu)+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde\chi_1^0$	475 GeV	10<$\tan\beta$<50	ATLAS-CONF-2013-058
	GMSB, $\tilde\chi_1^0 \to \gamma\tilde G$, long-lived $\tilde\chi_1^0$	2 γ	-	Yes	4.7	$\tilde\chi_1^0$	230 GeV	0.4<$\tau(\tilde\chi_1^0)$<2 ns	1304.6310
	$\tilde q\tilde q, \tilde\chi_1^0 \to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde q$	1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, $m(\tilde\chi_1^0)$=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp \to \tilde\nu_\tau + X, \tilde\nu_\tau \to e + \mu$	2 e,μ	-	-	4.6	$\tilde\nu_\tau$	1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp \to \tilde\nu_\tau + X, \tilde\nu_\tau \to e(\mu) + \tau$	1 $e,\mu+\tau$	-	-	4.6	$\tilde\nu_\tau$	1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	1 e,μ	7 jets	Yes	4.7	$\tilde q, \tilde g$	1.2 TeV	$m(\tilde q)=m(\tilde g)$, $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
	$\tilde\chi_1^+\tilde\chi_1^-, \tilde\chi_1^+ \to W\tilde\chi_1^0, \tilde\chi_1^0 \to ee\tilde\nu_\mu, e\mu\tilde\nu_e$	4 e,μ	-	Yes	20.7	$\tilde\chi_1^\pm$	760 GeV	$m(\tilde\chi_1^0)$>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde\chi_1^+\tilde\chi_1^-, \tilde\chi_1^+ \to W\tilde\chi_1^0, \tilde\chi_1^0 \to \tau\tau\tilde\nu_e, e\tau\tilde\nu_\tau$	3 $e,\mu+\tau$	-	Yes	20.7	$\tilde\chi_1^\pm$	350 GeV	$m(\tilde\chi_1^0)$>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde g \to qqq$	0	6-7 jets	-	20.3	$\tilde g$	916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde g \to \tilde t_1 t, \tilde t_1 \to bs$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde g$	880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon pair, sgluon→$q\bar q$	0	4 jets	-	4.6	sgluon	100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon→$t\bar t$	2 e,μ (SS)	1 b	Yes	14.3	sgluon	800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale	704 GeV	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

$$\left\{\begin{array}{l} M_{\tilde q} > 1.7\,\text{TeV}\ (M_{\tilde g} = M_{\tilde q}, \text{light } \tilde\chi_1^0) \\ M_{\tilde g} > 1.18\,\text{TeV}\ (M_{\tilde q} < 2\,\text{TeV}, \text{light } \tilde\chi_1^0) \end{array}\right.$$

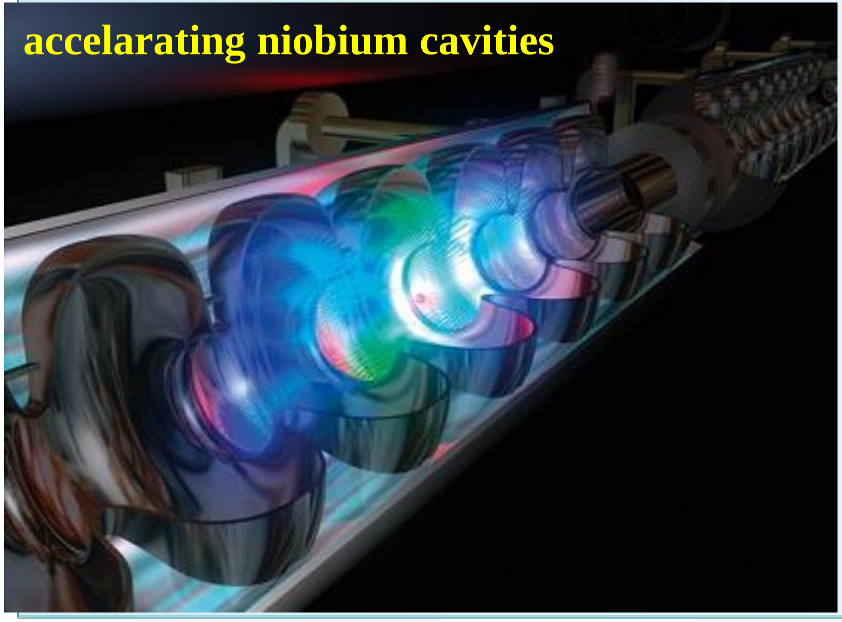
II. ILC

Main Features



structures the beam bunches

$\mathcal{L}_{\text{nominal}} = 2 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$



accelarating niobium cavities

Advantages:

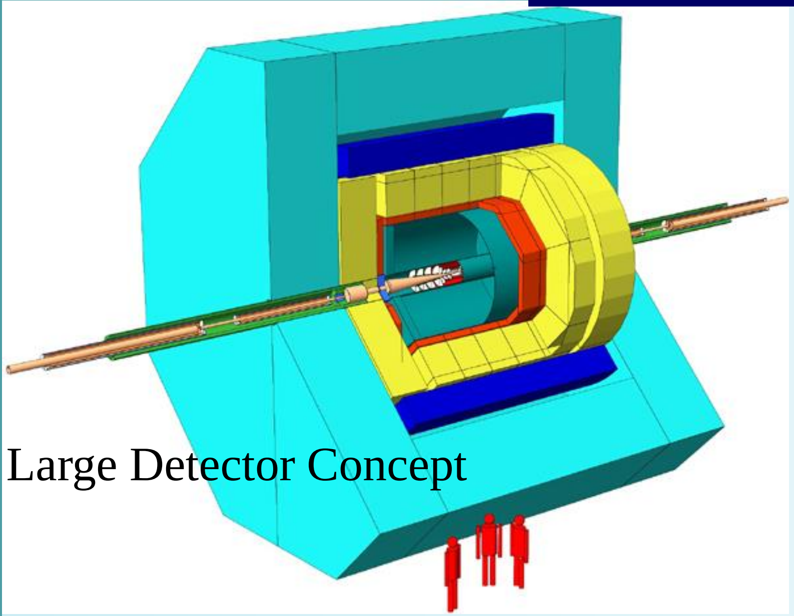
Very clean and flexible environment:

- tuneable E: $M_Z \leq \sqrt{s} \leq 500\ GeV$ (Phase I: ~500 fb^{-1})
  $M_Z \leq \sqrt{s} \leq 1 TeV$ (Upgrade → Phase II)
- polarized beams: $P(e^-) \leq 80\%$
  $P(e^+) \leq 50\%$
- low rate: 15-30 kHz
- sensitivity to virtual effects

Drawbacks:

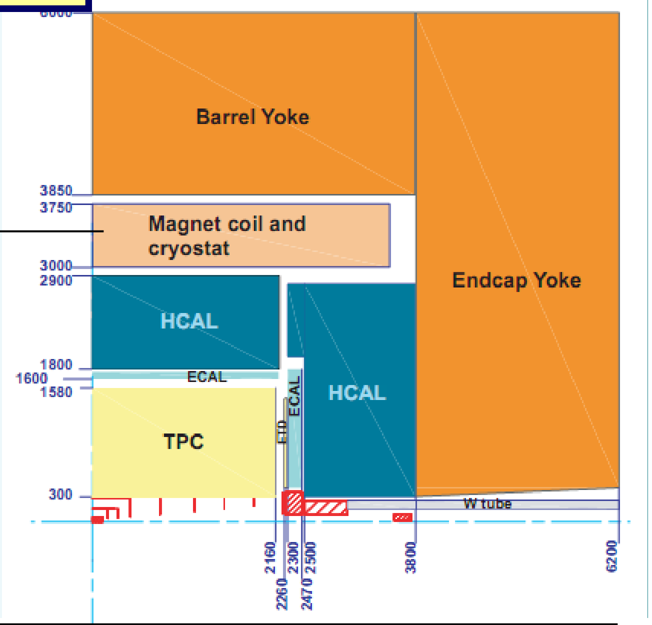
- large γγ background (0.1 evt / bunch X)
  - 10% evts w/ $\sqrt{s'} < \sqrt{s}$
  - monitor accolinearity of Bhabha's to estimate $\sqrt{s'}$

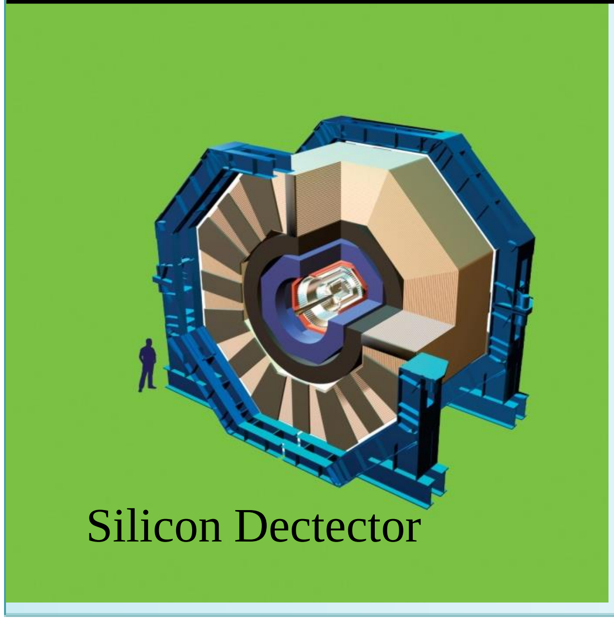
Detector Concepts (1)



Large Detector Concept

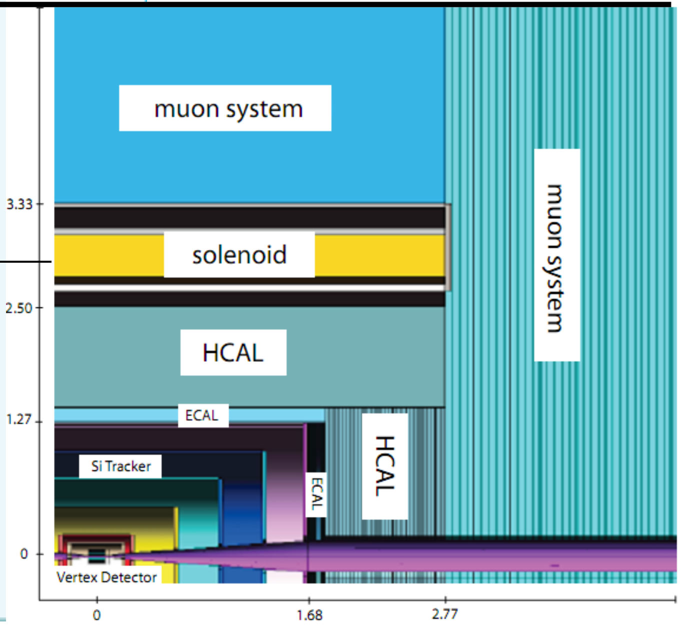
B=4 T



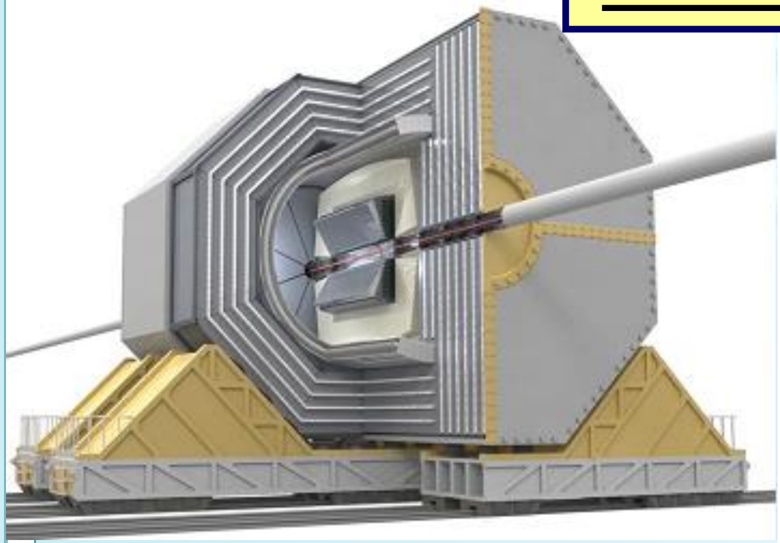


Silicon Dectector

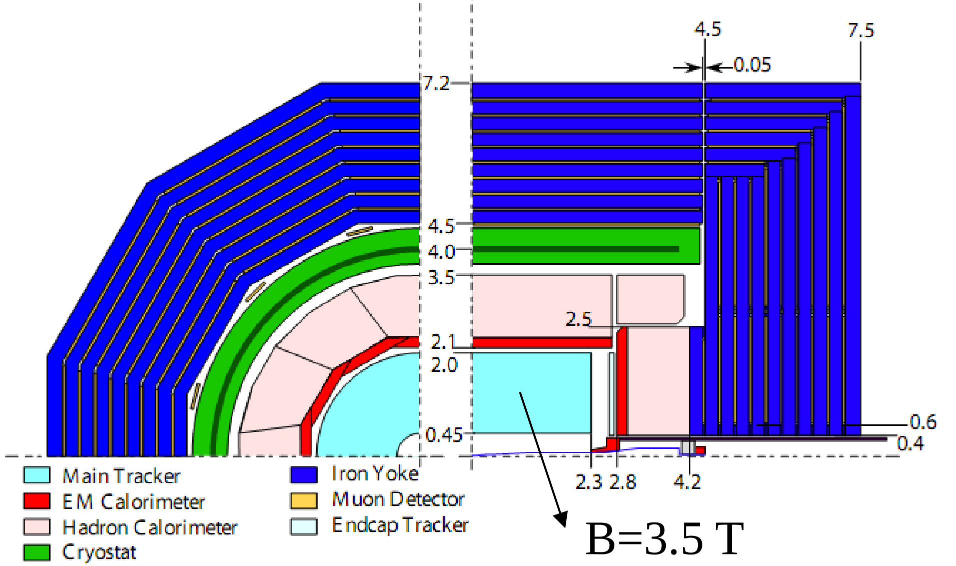
B=5 T



Detector Concepts (2)



Global Detector Concept



- 🟦 Main Tracker
- 🟥 EM Calorimeter
- ▨ Hadron Calorimeter
- 🟩 Cryostat
- 🟦 Iron Yoke
- 🟨 Muon Detector
- ☐ Endcap Tracker

« Triggerless Mode » Collider:

•Low rate enables:

- No hardware trigger
- Just a software-based trigger for loose filtering

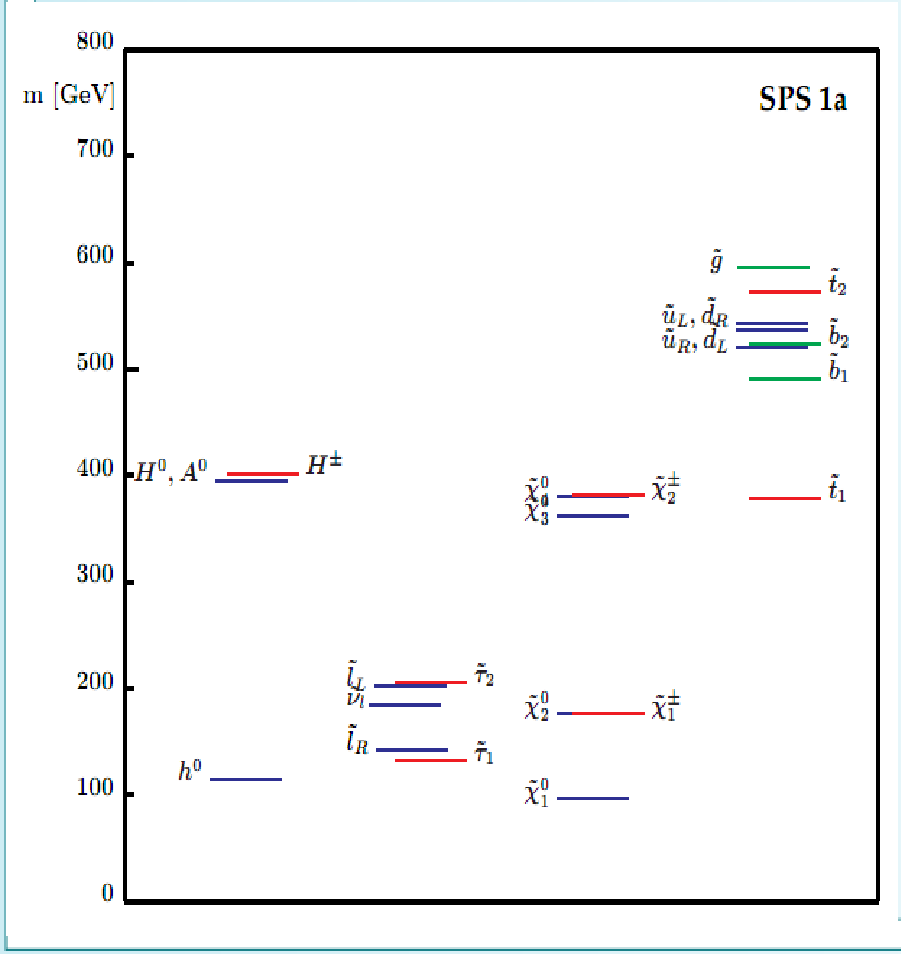
Typical Requirements:

- Inner Tracking:
  - Vertex Detector: $\sigma(1/p_T) \leq 5\times10^{-5}\, p_T$
  - Outer Tracking: $\sigma_{IP} = 5\mu m \oplus 10\,\mu m \cdot \sin^{3/2}\theta$
- Calorimetry:
  - EM: $\dfrac{\sigma_E}{E} = \dfrac{17\%}{\sqrt{E}}$
  - Jets: $\dfrac{\sigma_E}{E} = \dfrac{30\%}{\sqrt{E}}$

SUSY Benchmark

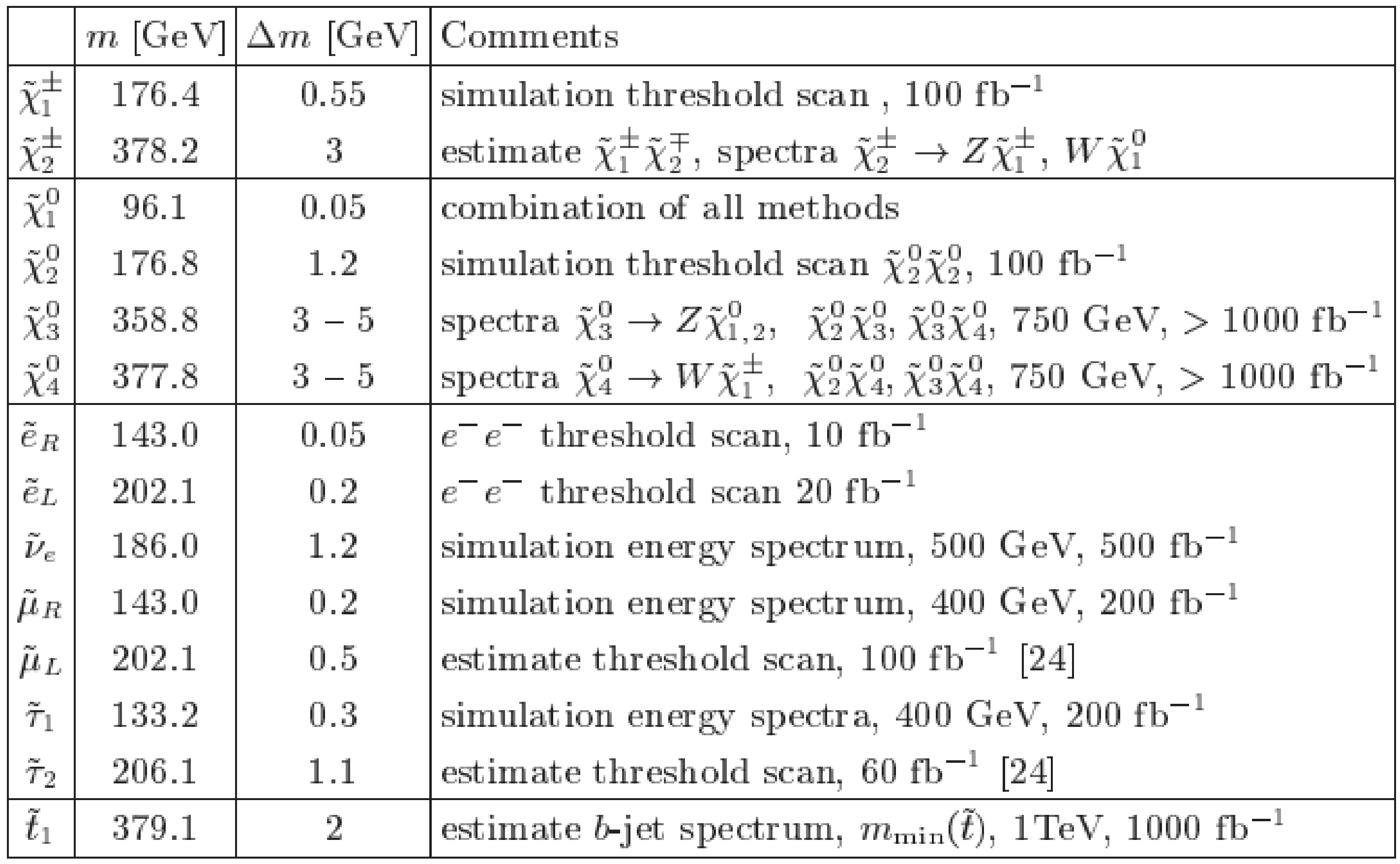
SPS1a:

- Old SUSY benchmark in the bulk region
- Outside the recent allowed region from WMAP



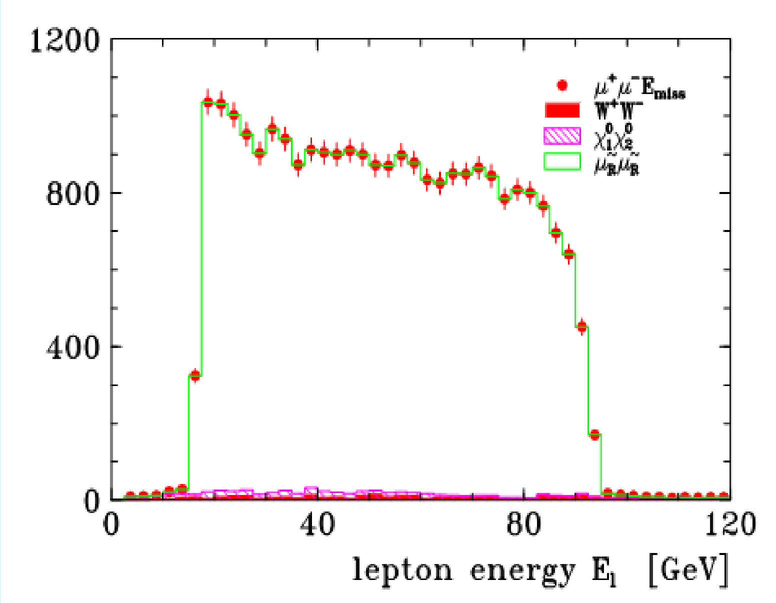
$$\begin{cases} m_0 = 100\text{GeV} \\ \text{m}_{1/2} = 250\text{GeV} \\ \text{A}_0 = \text{-}100\text{GeV} \\ \tan\beta = 10 \\ \mu > 0 \end{cases}$$

SUSY Measurements



	m [GeV]	Δm [GeV]	Comments
$\tilde{\chi}_1^\pm$	176.4	0.55	simulation threshold scan , 100 fb^{-1}
$\tilde{\chi}_2^\pm$	378.2	3	estimate $\tilde{\chi}_1^\pm \tilde{\chi}_2^\mp$, spectra $\tilde{\chi}_2^\pm \to Z\tilde{\chi}_1^\pm, W\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$	96.1	0.05	combination of all methods
$\tilde{\chi}_2^0$	176.8	1.2	simulation threshold scan $\tilde{\chi}_2^0 \tilde{\chi}_2^0$, 100 fb^{-1}
$\tilde{\chi}_3^0$	358.8	3 – 5	spectra $\tilde{\chi}_3^0 \to Z\tilde{\chi}_{1,2}^0$, $\tilde{\chi}_2^0 \tilde{\chi}_3^0$, $\tilde{\chi}_3^0 \tilde{\chi}_4^0$, 750 GeV, $>$ 1000 fb^{-1}
$\tilde{\chi}_4^0$	377.8	3 – 5	spectra $\tilde{\chi}_4^0 \to W\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0 \tilde{\chi}_4^0$, $\tilde{\chi}_3^0 \tilde{\chi}_4^0$, 750 GeV, $>$ 1000 fb^{-1}
$\tilde{e}_R$	143.0	0.05	$e^- e^-$ threshold scan, 10 fb^{-1}
$\tilde{e}_L$	202.1	0.2	$e^- e^-$ threshold scan 20 fb^{-1}
$\tilde{\nu}_e$	186.0	1.2	simulation energy spectrum, 500 GeV, 500 fb^{-1}
$\tilde{\mu}_R$	143.0	0.2	simulation energy spectrum, 400 GeV, 200 fb^{-1}
$\tilde{\mu}_L$	202.1	0.5	estimate threshold scan, 100 fb^{-1} [24]
$\tilde{\tau}_1$	133.2	0.3	simulation energy spectra, 400 GeV, 200 fb^{-1}
$\tilde{\tau}_2$	206.1	1.1	estimate threshold scan, 60 fb^{-1} [24]
$\tilde{t}_1$	379.1	2	estimate b-jet spectrum, $m_{\min}(\tilde{t})$, 1TeV, 1000 fb^{-1}

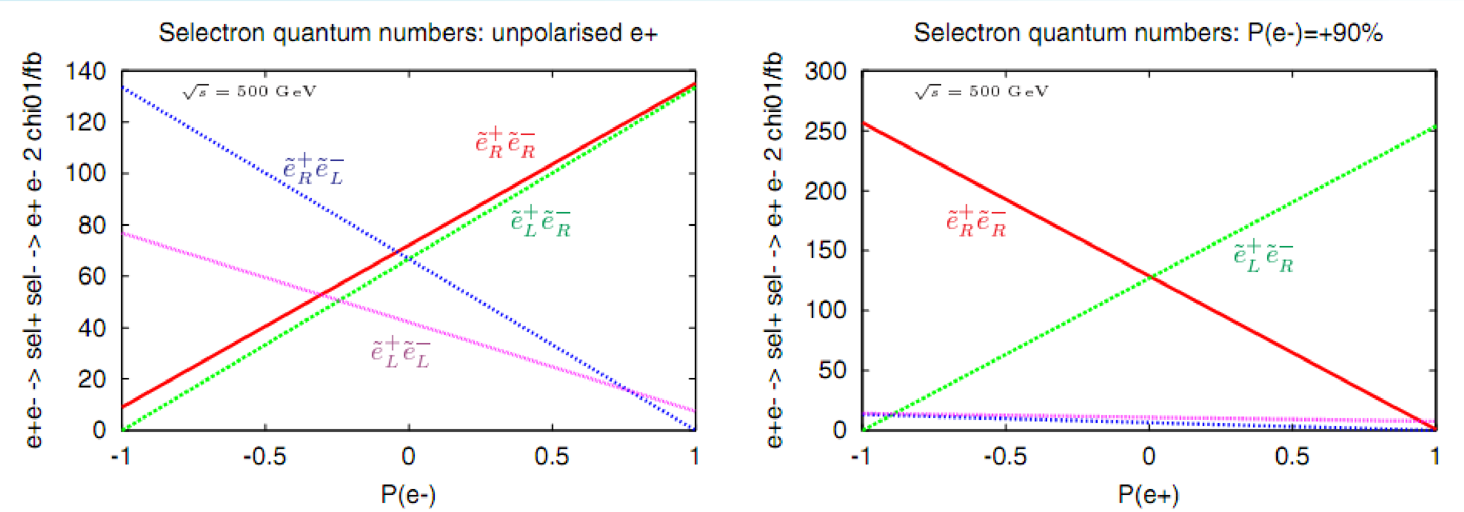
Thresholds & Edges Measurements



$$e^-_R e^+_L \to \tilde\mu^+_R \tilde\mu^-_L \to \mu^+\mu^-\tilde\chi^0_1\tilde\chi^0_1$$

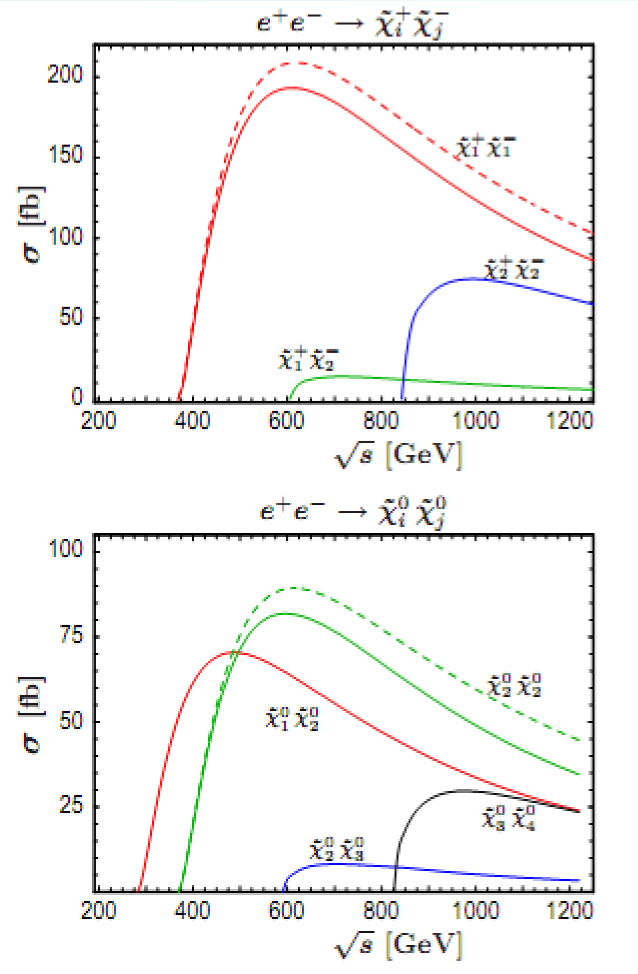
L=200 fb^{-1}

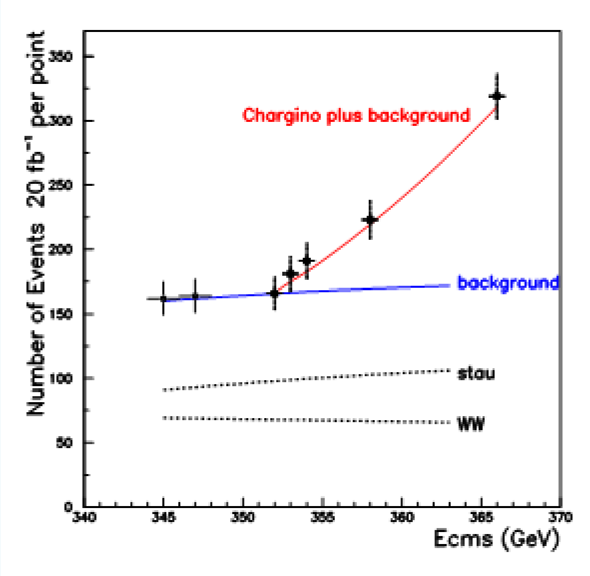
Beam Polarization



Threshold Scans

Sharp production thresholds => E scan gives good sensitivity M(FS)



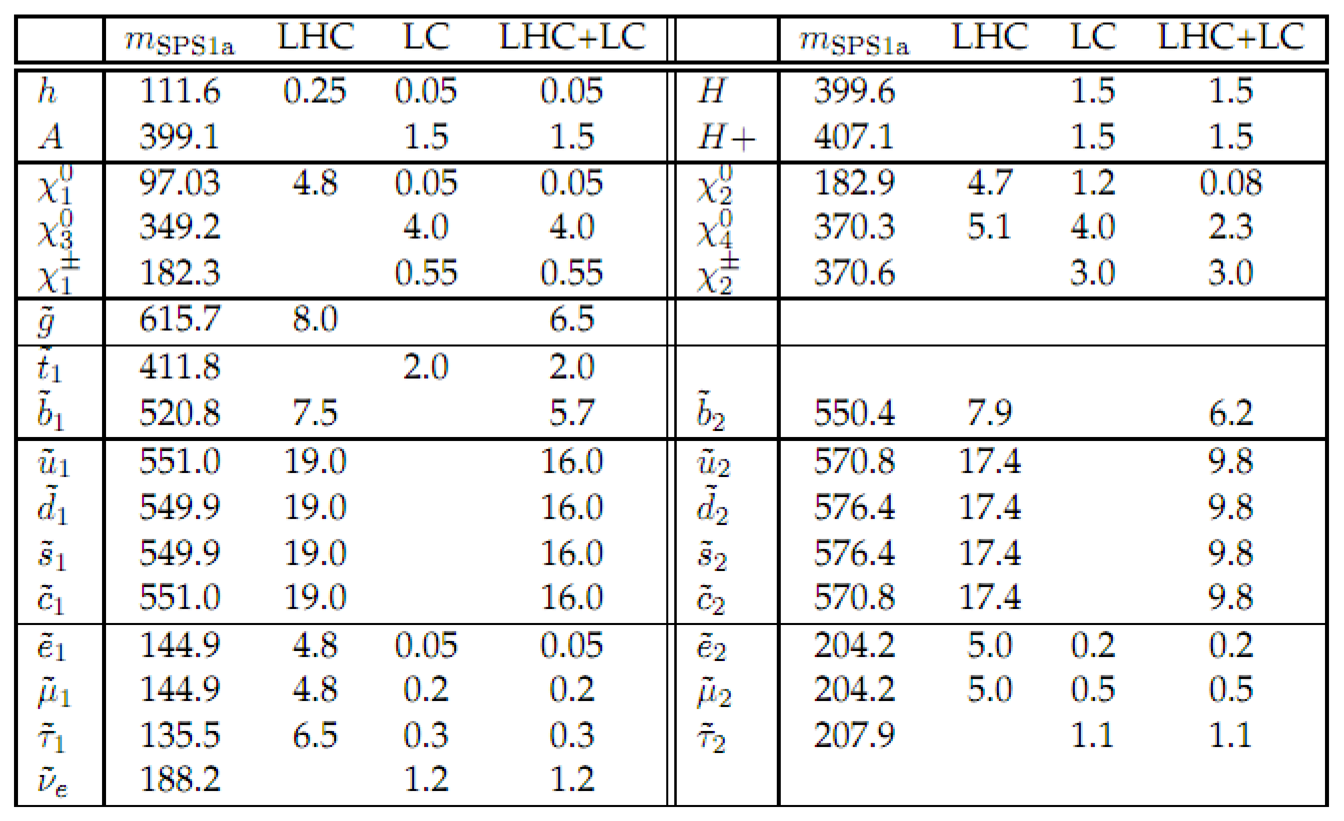


$$e_R^+ e_L^- \to \tilde\chi_1^\pm \tilde\chi_1^\mp \to \tau^+ \tau^- \nu_\tau \bar\nu_\tau \tilde\chi_1^0 \tilde\chi_1^0$$

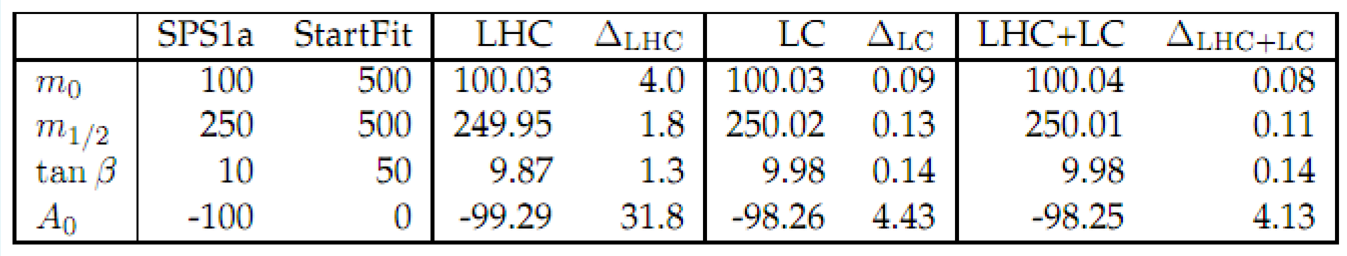
L=100 fb^{-1}

mSUGRA Fit

SFitter



	m_{SPS1a}	LHC	LC	LHC+LC		m_{SPS1a}	LHC	LC	LHC+LC
h	111.6	0.25	0.05	0.05	H	399.6		1.5	1.5
A	399.1		1.5	1.5	$H+$	407.1		1.5	1.5
χ_1^0	97.03	4.8	0.05	0.05	χ_2^0	182.9	4.7	1.2	0.08
χ_3^0	349.2		4.0	4.0	χ_4^0	370.3	5.1	4.0	2.3
$\chi_1^\pm$	182.3		0.55	0.55	$\chi_2^\pm$	370.6		3.0	3.0
$\tilde{g}$	615.7	8.0		6.5					
$\tilde{t}_1$	411.8		2.0	2.0					
$\tilde{b}_1$	520.8	7.5		5.7	$\tilde{b}_2$	550.4	7.9		6.2
$\tilde{u}_1$	551.0	19.0		16.0	$\tilde{u}_2$	570.8	17.4		9.8
$\tilde{d}_1$	549.9	19.0		16.0	$\tilde{d}_2$	576.4	17.4		9.8
$\tilde{s}_1$	549.9	19.0		16.0	$\tilde{s}_2$	576.4	17.4		9.8
$\tilde{c}_1$	551.0	19.0		16.0	$\tilde{c}_2$	570.8	17.4		9.8
$\tilde{e}_1$	144.9	4.8	0.05	0.05	$\tilde{e}_2$	204.2	5.0	0.2	0.2
$\tilde{\mu}_1$	144.9	4.8	0.2	0.2	$\tilde{\mu}_2$	204.2	5.0	0.5	0.5
$\tilde{\tau}_1$	135.5	6.5	0.3	0.3	$\tilde{\tau}_2$	207.9		1.1	1.1
$\tilde{\nu}_e$	188.2		1.2	1.2					



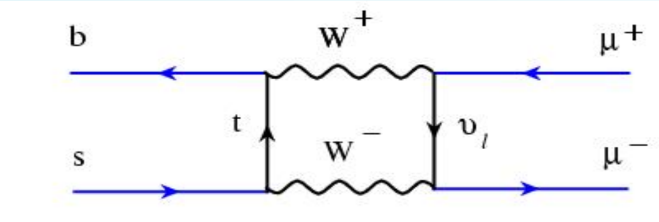
	SPS1a	StartFit	LHC	Δ_{LHC}	LC	Δ_{LC}	LHC+LC	$\Delta_{\mathrm{LHC+LC}}$
m_0	100	500	100.03	4.0	100.03	0.09	100.04	0.08
$m_{1/2}$	250	500	249.95	1.8	250.02	0.13	250.01	0.11
$\tan\beta$	10	50	9.87	1.3	9.98	0.14	9.98	0.14
A_0	-100	0	-99.29	31.8	-98.26	4.43	-98.25	4.13

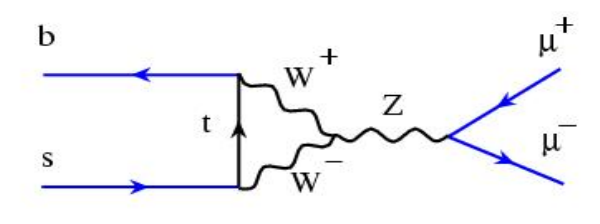
III. Indirect Accelerator Constraints

Hereafter I describe some virtual effects measured at accelerators that indirectly constrain SUSY:

- $a_\mu = 1/2(g-2)_\mu$
- $b \rightarrow s\gamma$ (not covered today)
- $B_s \rightarrow \mu^+\mu^-$,…

$B_s \to \mu^+\mu^-$ (1)



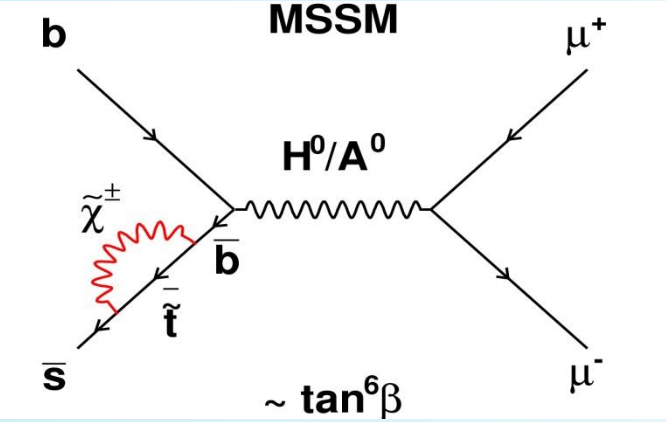


- In SM $B_s \to \mu^+\mu^-$ is suppressed (need FCNC)

SM predicts $BR(B_s \to \mu^+\mu^-) = (3.35 \pm 0.32)\times 10^{-9}$

Ref: M. Blanke et al., JHEP 0610 (2006) 003

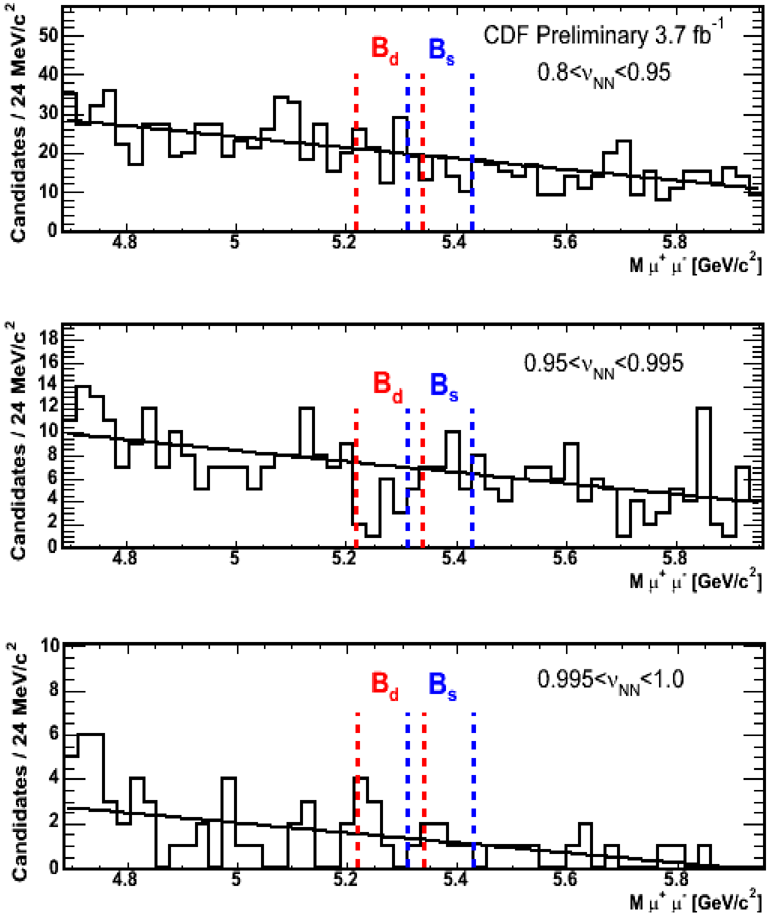
- SUSY can enhance BR by 1 order of magnitude



$$i\mathcal{M} \propto \frac{M_\mu}{M^2_{A^0}} \tan^3\beta$$

A key early measurement for LHC

$B_s \to \mu^+\mu^-$ (2)



CDF Result: No excess seen

L=3.7 fb^{-1}

$$\begin{cases} BR(B_s \to \mu^+\mu^-) < 4.3\text{x}10^{-8}\ (95\%\,CL) \\ BR(B_d \to \mu^+\mu^-) < 7.6\text{x}10^{-9}\ (95\%\,CL) \end{cases}$$

Aug 2009

D0 Result: No excess seen

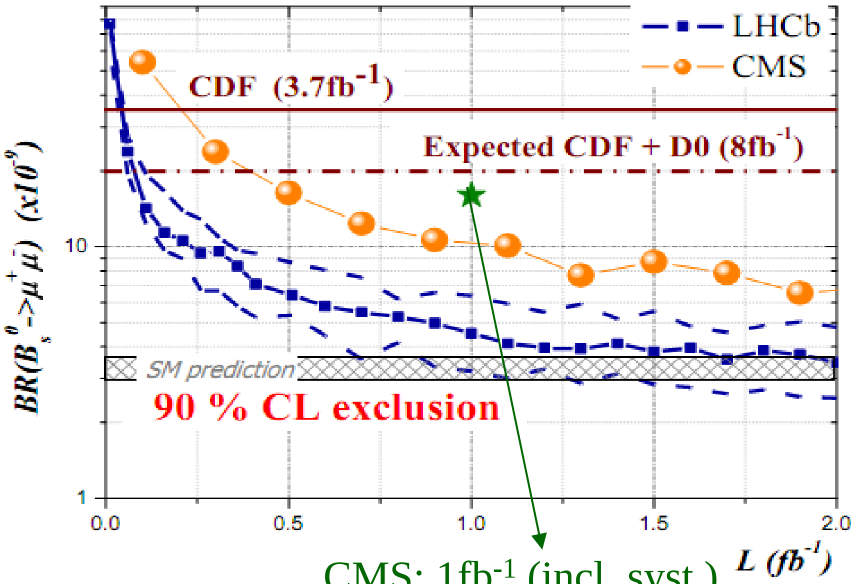
L=6.1 fb^{-1}

$$BR(B_s \to \mu^+\mu^-) < 5.1\text{x}10^{-8}\ (95\%\,CL)$$

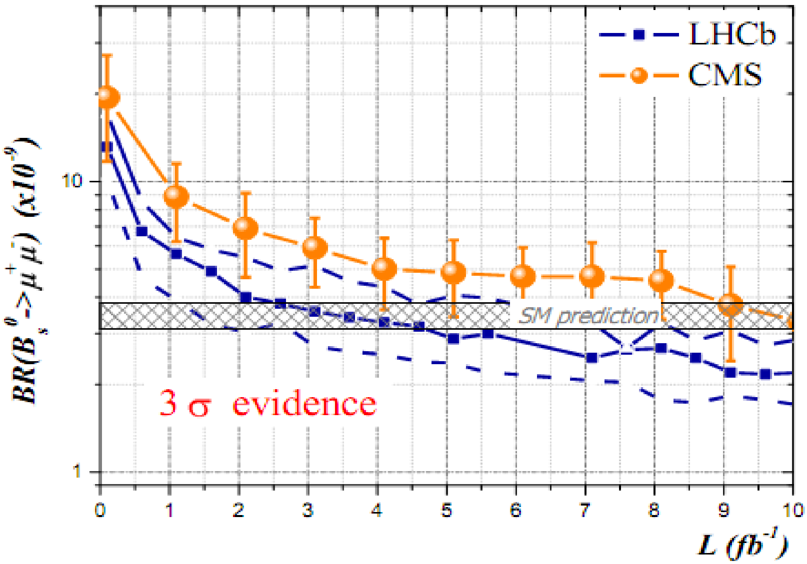
Jun 2010

$B_s \to \mu^+\mu^-$ (3)

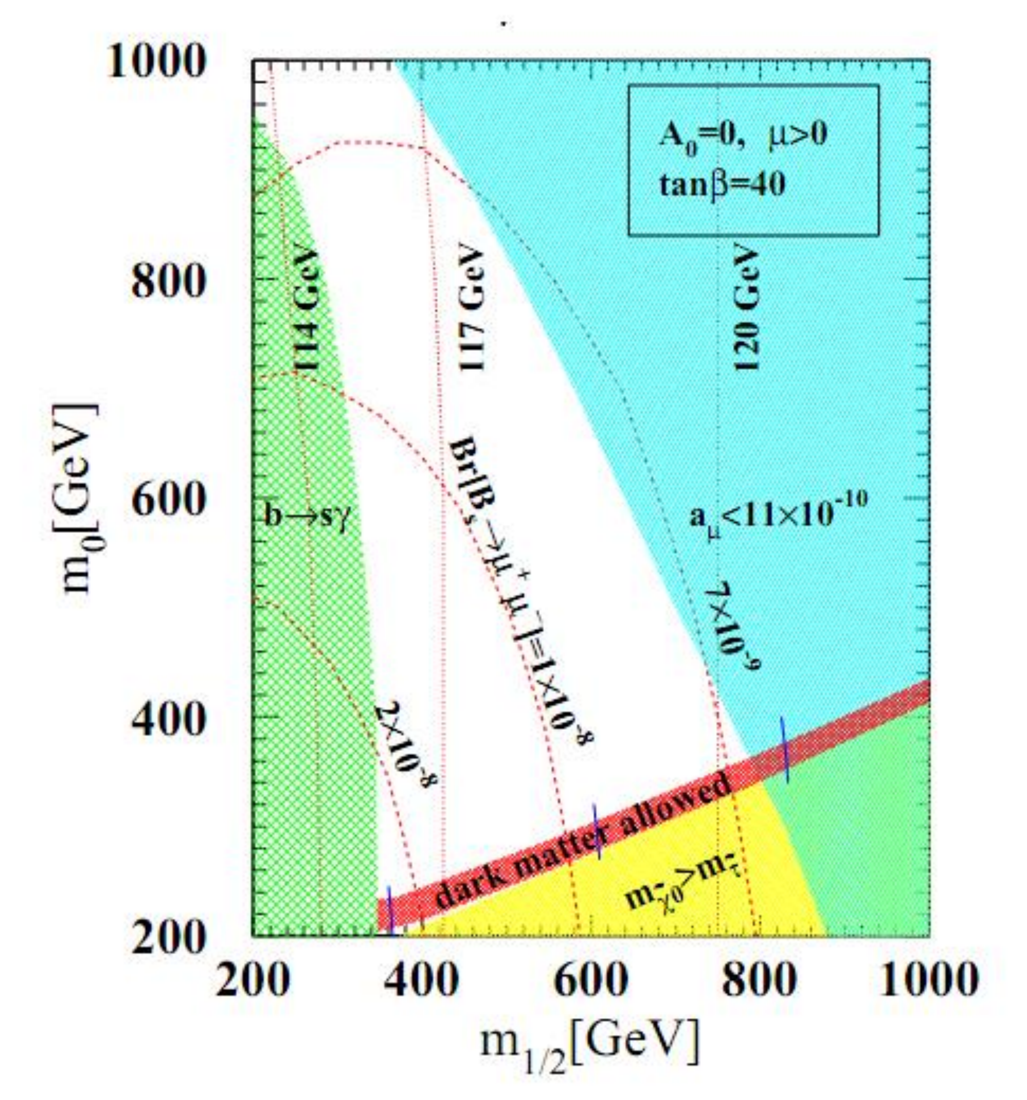
- ATLAS & CMS:
  - $|\eta_\mu|<2.5$, $\mathcal{L}=10^{32\text{-}33}$ cm^{-2}s^{-1}
  - Single & di-muon triggers
- LHCb:
  - $1.9<|\eta_\mu|<2.5$, $\mathcal{L}=2\text{x}10^{32}$ cm^{-2}s^{-1}
  - Low p_T trigger (sensitivity to σ_{bb} 2.3 larger than ATLAS & CMS)
- Evt Selection:
  - based upon several variables, including $M_{\mu\mu}$
  - mass resolutions: 90 MeV (ATLAS), 53 MeV (CMS), 22 MeV (LHCb)



CMS: 1fb^{-1} (incl. syst.)

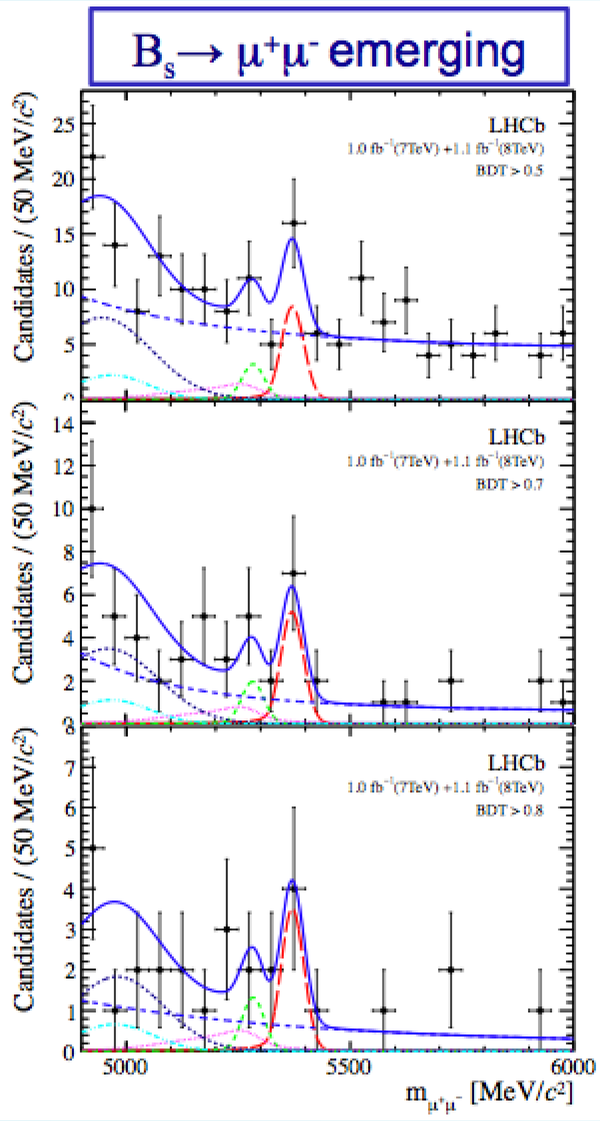


$B_s \to \mu^+\mu^-$ (3)



1000
800
600
400
200
200
400
600
800
1000
m_0[GeV]
$m_{1/2}$[GeV]
A_0=0, μ>0
tanβ=40
114 GeV
117 GeV
120 GeV
b→sγ
$Br[B_s \to \mu^+\mu^-]=1\times10^{-8}$
2×10^{-8}
7×10^{-9}
$a_\mu<11\times10^{-10}$
dark matter allowed
$m_{\tilde\chi^0} > m_{\tilde\tau}$

$B_s \to \mu^+\mu^-$ (4)
- Epilogue -



- LHCb: Finally observed this rare DK mode!
  - 2011 & 2012 Datasets:
    - resp. 1.0 & 1.1 fb^{-1}
    - resp. 7 TeV & 8 TeV

$$\boxed{BR(B_s \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2})\text{x}\,10^{-9}}$$

- Fittino:
  - It was already shown based on the 7 TeV LHCb that the NUHM1 models fit better this data and the 126 GeV Higgs constraint than the CMSSM

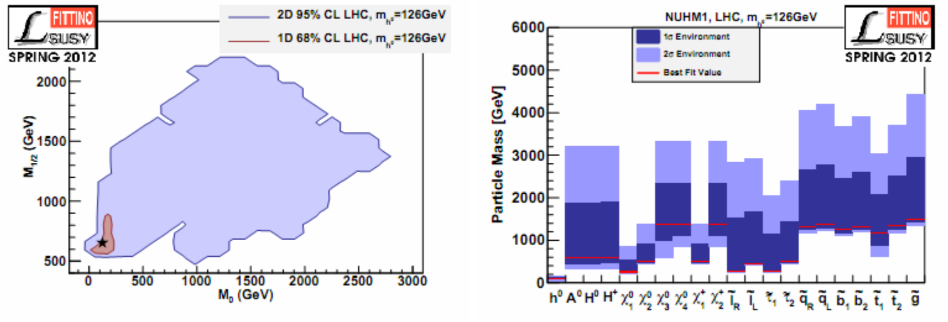


Figure 6: Left: Parameter distributions for the LHC+m_h fit of the NUHM1 with the 1-dimensional 1σ in red and the 2-dimensional 2σ in blue, and the best fit point marked by a star. Right: predicted distribution of sparticle and Higgs boson masses from the LHC + m_h fit of the NUHM1.

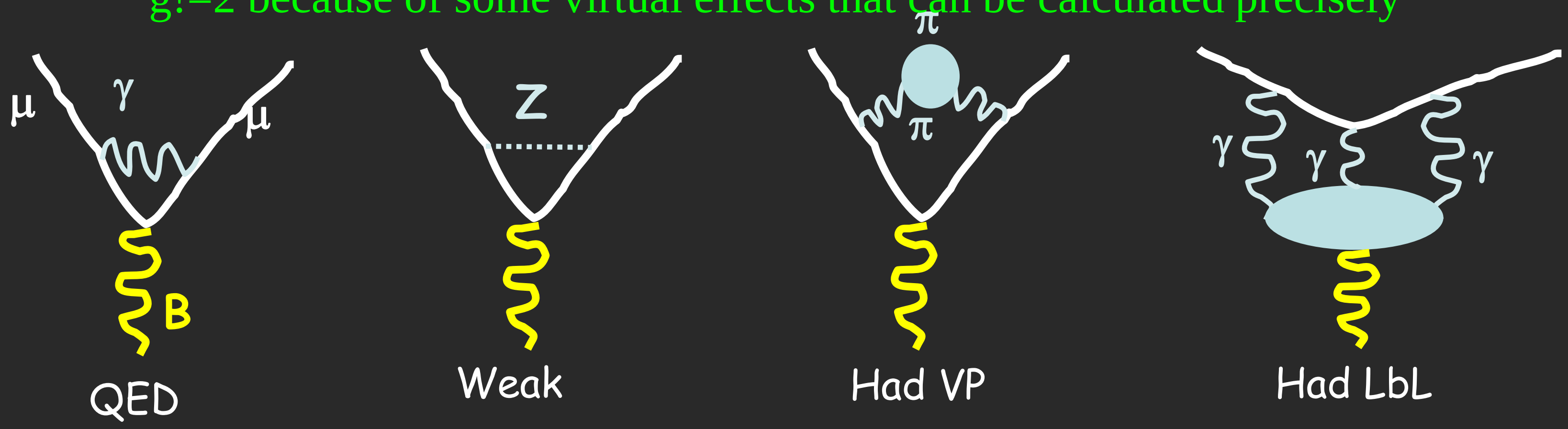
$a_\mu = 1/2(g-2)_\mu$ (1)
- Introduction -

- Magnetic dipole moment:
  - Charged particle w/ circular trajectory: $\vec{\mu}_L = \frac{e}{2mc}\vec{L}$ w/ $\vec{L} = \vec{r} \wedge \vec{p}$
  - This is due to spin: $\vec{\mu} = g_\ell \frac{e\hbar}{2m_\ell c}\vec{S}$
  - Dirac's theory predicts: $g_\ell = 2$
  - Precision measurements slightly differ: $g_\ell \approx 2.0024$
  - Anomalous magnetic moment: $a_\mu = \frac{1}{2}(g_\mu - 2)$
  - Measure it in: $\pi^{\pm} \to \mu^{\pm} + \nu_\mu$

    $e^{\pm} + \nu_e + \nu_\mu \hookleftarrow$
    - where muons are polarized
    - and decay to electrons carrying muon spin direction

$a_\mu = 1/2(g-2)_\mu$
- Theoretical Predictions -

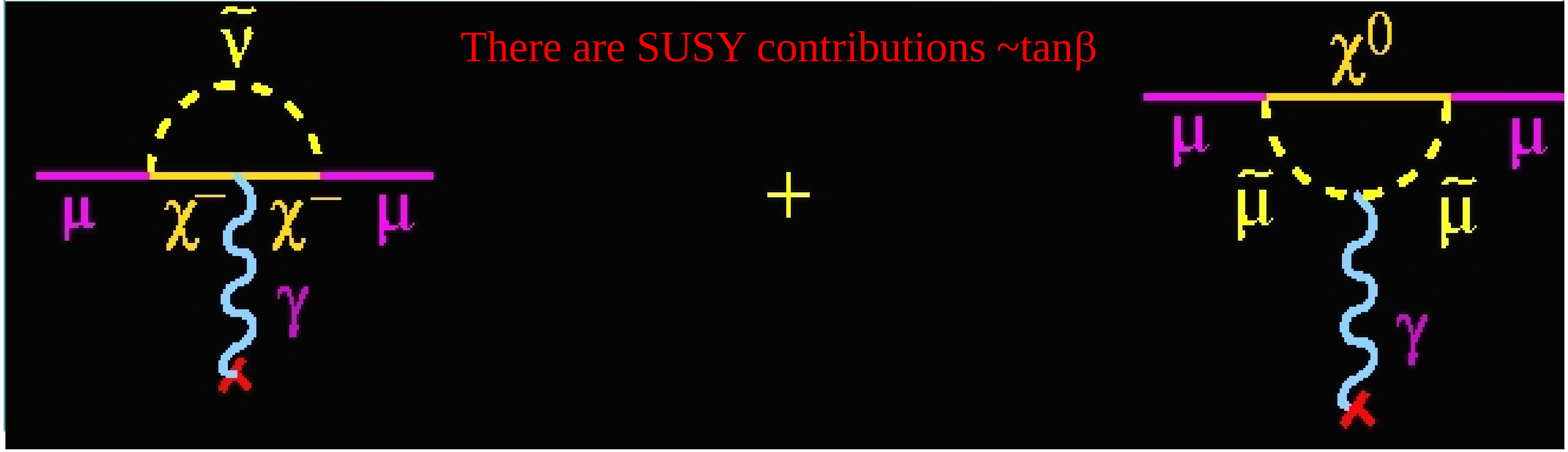
g!=2 because of some virtual effects that can be calculated precisely



Full: up-to 4-loops
Partial: 5-loop

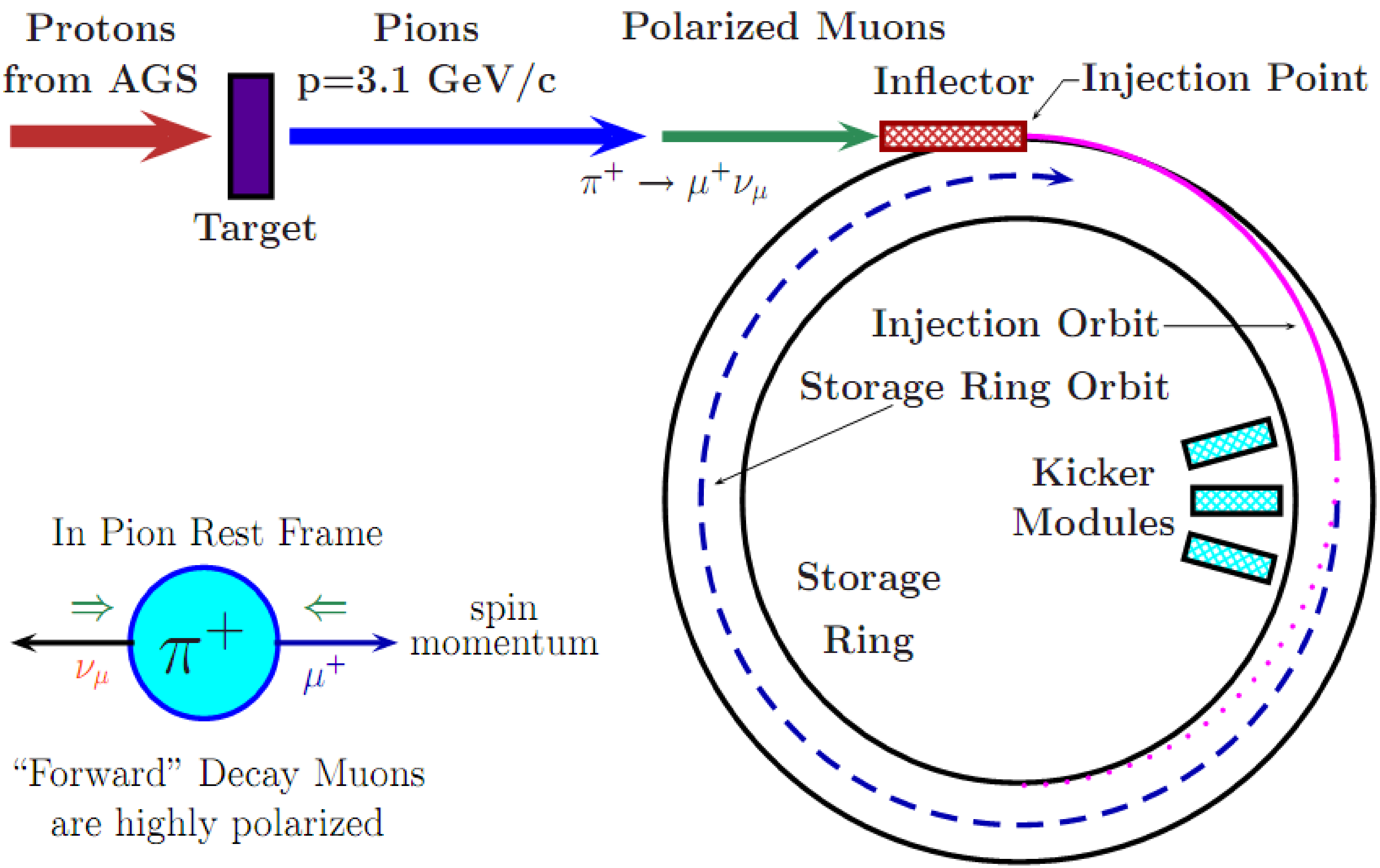
Full: up-to 2-loops

There are SUSY contributions ~tanβ



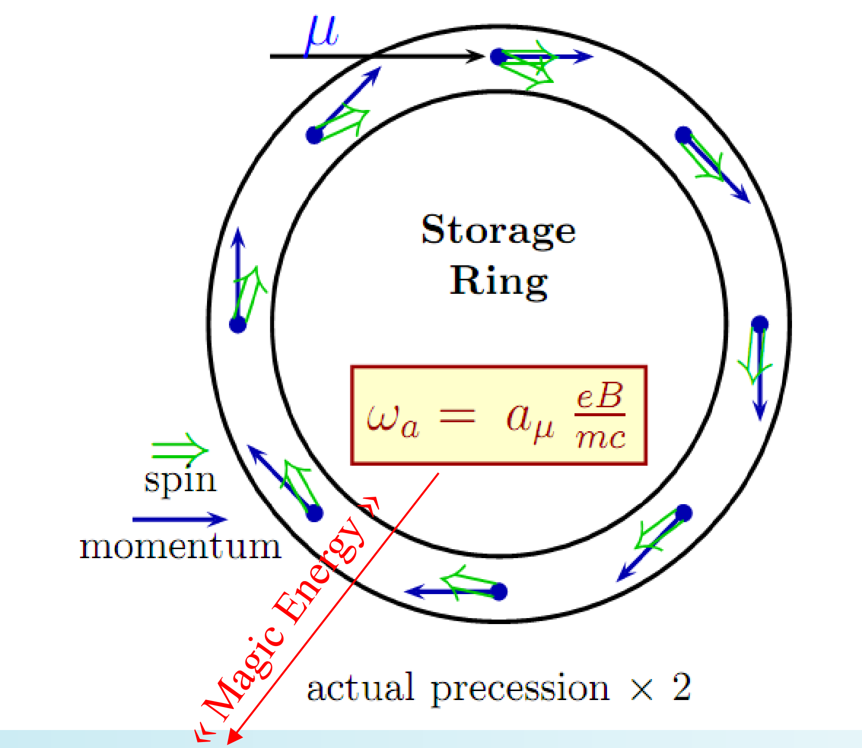
$a_\mu = 1/2(g-2)_\mu$
- Experimental Setup -

E821 at BNL (1998-2001)



"Forward" Decay Muons are highly polarized

$a_\mu = 1/2(g-2)_\mu$
- Measurement Technique -



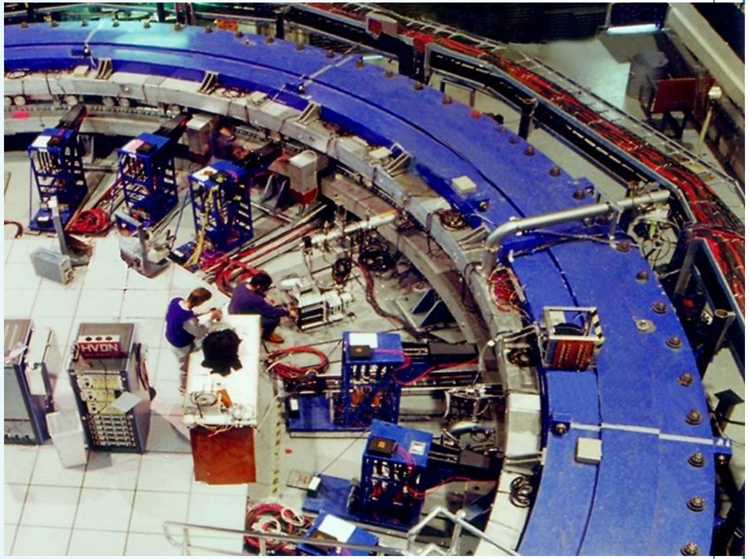
$p(\mu^\pm) = 3.094 GeV$

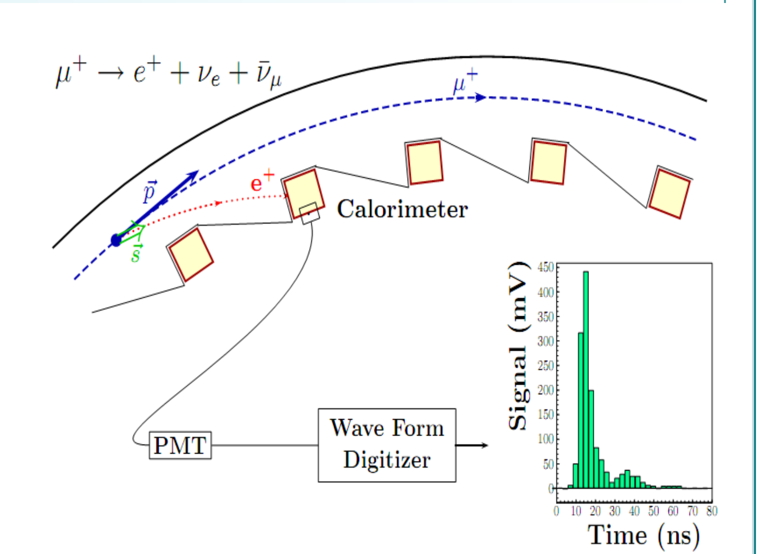
$R = 7.112 m$

$B = 1.45 T$ (constant)

Larmor Precession angle: $\approx 12°$

Larmor Precession frequency: ω_a





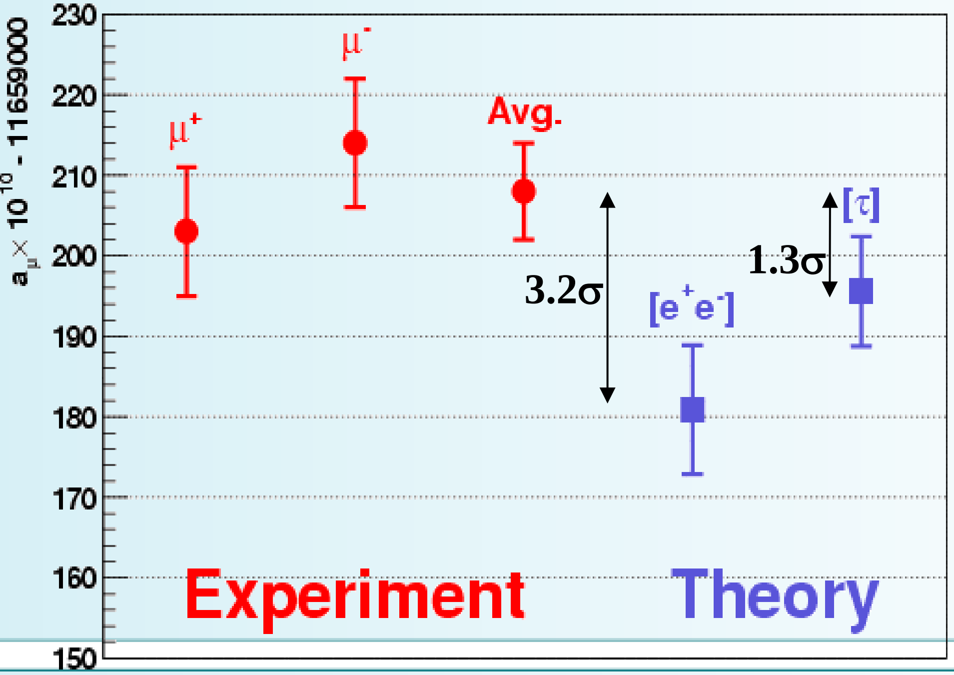
$a_\mu = 1/2(g-2)_\mu$
- Final Results -

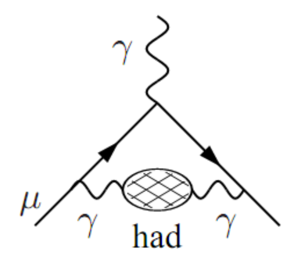
One of the most precise measurements in particle physics: 0.54 ppm !

$$a_\mu^{\text{exp}} = 1.16592080(63) \times 10^{-3}$$

$$a_\mu^{\text{the}} = 1.16591793(68) \times 10^{-3}$$

Ref: G.W. Bennett et al., PRD73 (2006) 072003





LO hadronic vacuum polarization

Detailed Outline

I. SUSY Dark Matter

- Evidence for Dark Matter
- Candidate Particles
- Cosmological Constraints
- Direct Detection
- Indirect Detection (Not covered today)

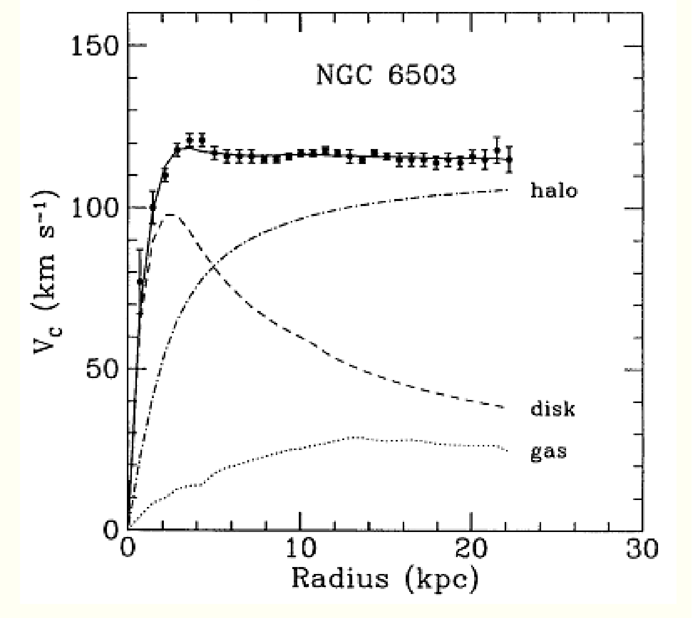
II. SUSY Global Fits

Evidence for Dark Matter

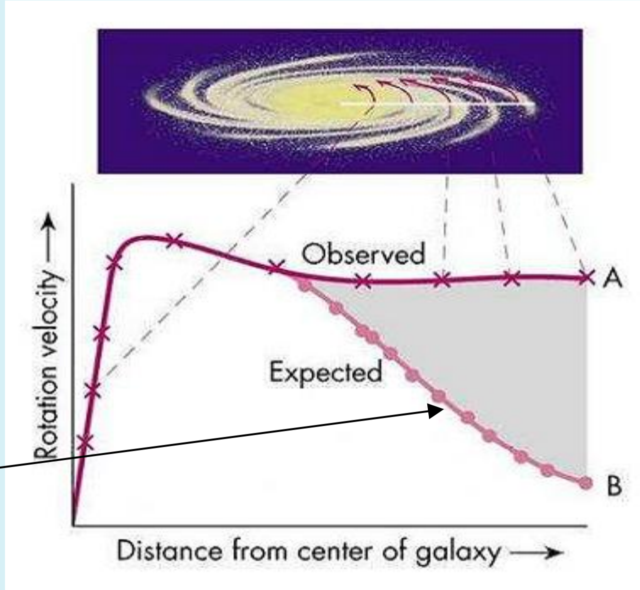
- Spiral galaxy rotation curves are incompatible w/ only visible matter contributions

Ref: F. Zwicky, Helv Phys Acta 6(2) (1933) 110-127

Galaxy Rotaion Curve



$$v = \sqrt{\frac{GM(r)}{r}}$$



- Other indications:
  - Clusters and Super-Clusters (gravitational lensing, X-rays,…)
  - Large Scale Structures (formation)
  - …

Main Properties of Dark Matter

- Its composition cannot be explained by SM particles

- Features of the « Usual Suspect »:
  - Massive: compatible w/ measured Ω_m, « Cold Dark Matter »: $\beta < 0.1$
  - No electric charge (Dark)
  - No color charge (no bound states found in exotic nuclei or atoms)
  - Only interactions: Weak & Gravitational
  - So-called WIMP: « Weakly Interacting Massive Particle »

Dark Matter Candidates

- SM Particles:
  - Neutrinos:
    - Hot Dark Matter (β>0.95): not suitable to explain properties of galaxies

- SUSY Particles:
  - Gravitino: when LSP: in general too light => Hot Dark Matter
  - Sneutrino: large annihilation σ (=> mass > 500 GeV), too σ_{el}(sneutrino+N)~O(fb)
  - Lightest Neutralino: ideal candidate
  - or even Axion, Axino (SO(10)-inspired)

- Other BSM candidates:
  - LKP (ED), LTP (LH), branons, black holes,…

Universe Expansion

Density for species i

$$\Omega_i \equiv \frac{\rho_i}{\rho_c}$$

Critical density

$$\rho_c \equiv \frac{3H^2}{8\pi G_N}$$

$$\rho_C \approx 1.88 \times 10^{-29} h^2 \cdot g \cdot cm^{-3}$$

$$H \approx 71\ \mathrm{km \cdot s^{-1} \cdot Mpc^{-1}}$$

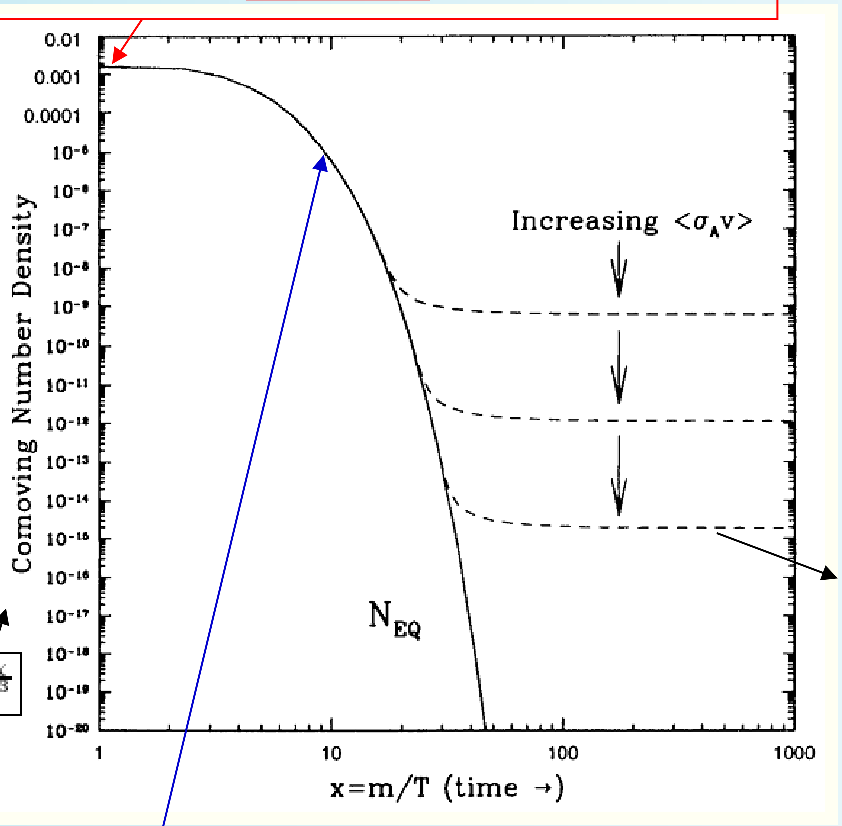
(Hubbleparam. today)

$\rho < \rho_c$	$\Omega < 1$	$k = -1$	Open
$\rho = \rho_c$	$\Omega = 1$	$k = 0$	Flat
$\rho > \rho_c$	$\Omega > 1$	$k = 1$	Closed

Dark Matter Relic Density

$\tilde{\chi}_1^0 + \tilde{\chi}_1^0 \leftrightarrow f + \bar{f}$ thermal equilibrium

$T \gg m_\chi$ $\quad n_\chi \propto T^3$ (hot universe)



$f_\chi = \frac{n_\chi}{T^3}$

freeze-out:
interaction rate <
expansion rate

$T \ll m_\chi$ $\quad n_\chi \propto \exp^{-m_\chi/T}$ (universe cools down)

Boltzmann equation

$$\frac{dn}{dt} = -3Hn - \langle \sigma_{annih} v_{rel} \rangle (n^2 - n_{equil}^2)$$

decrease due
to expansion

variation due to annihil.
into SM particles

- n: actual neutralino density
- n_{equil}: neutralino density at thermal equilibrium
- σ_{annih}: annihiliation cross section
- v_{rel}: relative velocity

solution

$$\Omega_\chi h^2 = \frac{m_\chi n_\chi}{\rho_c} \simeq \frac{3 \times 10^{-27} cm^3/s}{\langle \sigma_{ann} v \rangle}$$

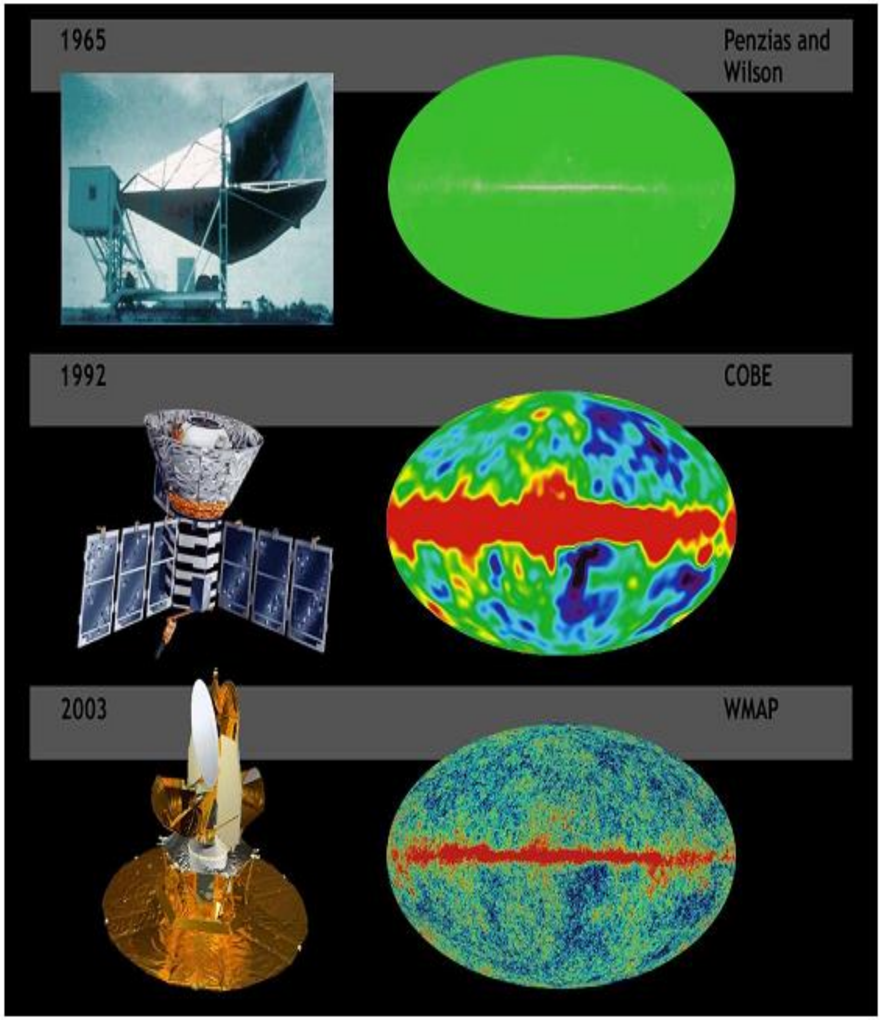
w/ WMAP =>

$\langle \sigma_{ann} v \rangle \simeq 3\times10^{-26}$ cm³/s

typical for weak interactions!

Cosmic Microwave Background

- Very isotropical photon radiation at T = 2.7°K
- Relic radiation from the Big Bang
- Predicted by G. Gamow, R. Alpher, R. Herman, in 1948



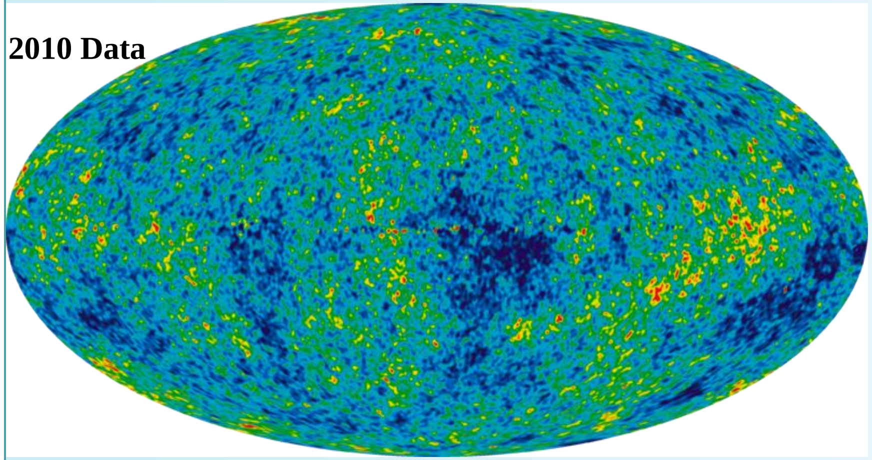
Discovered in 1964
Using a radio-telescope

COBE: « COsmic Background Explorer »
Satellite exp^{t} launched in 19??

WMAP: « Wilkinson Microwave Anisotropy Probe »
Satellite expt launched in 2001

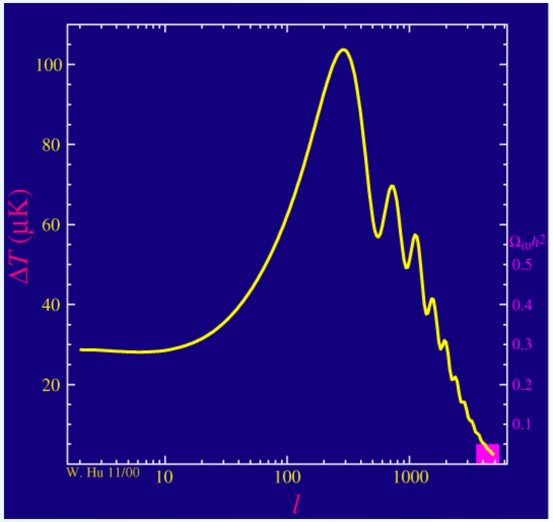
← Need accuracy of $\Delta T/T \sim 10^{-5}$

Cosmology Precision Measurements



Anisotropies measured by the WMAP satellite exp^t

Ref: C.L. Bennett et al., Astrophys J Suppl 148 (2003) 1

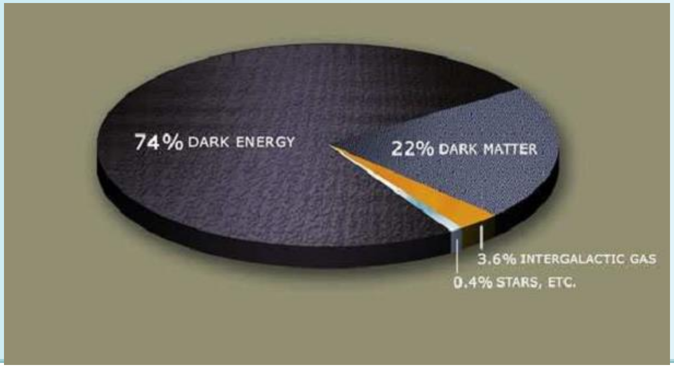


CMB: Angular Power Spectrum

Positions & rel. heights of acoustic peaks

=> infos about geometry & composition of the universe

Combined w/ other measurements (supernovae, galaxy clusters,...):



$$\begin{cases} \Omega_{baryon} h^2 = 0.02267 \begin{cases} +0.00058 \\ -0.00059 \end{cases} \\ \Omega_{\Lambda} h^2 = 0.726 \pm 0.015 \\ \Omega_{\nu} h^2 \approx 0.005 \end{cases}$$

$$\Omega_{CDM} h^2 = \Omega_{Matter} h^2 - \Omega_{Baryon} h^2 = 0.1126 \begin{cases} +0.0081\ (0.0161) \\ -0.0090\ (0.0181) \end{cases}$$

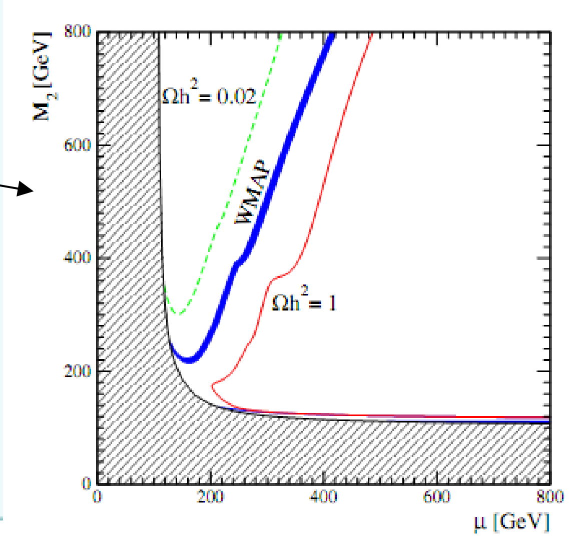
68%CL 95%CL

=> $\boxed{\Omega_{\tilde{\chi}_1} h^2 < 0.129}$ 95%CL

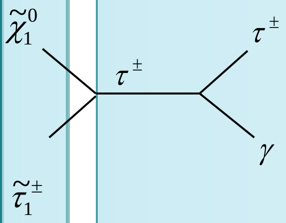
Impact on Dark Matter Candidates

- Bad candidates:
  - Neutrinos:
    - WMAP constraint: $\Omega_\nu h^2 < 0.0076$ => $\sum m_\nu \lesssim 0.7 \text{ eV}$

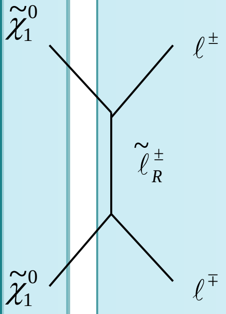
- Still possible candidates:
  - NUHM1: SO(10)-inspired
    - $m(\Phi) > m_0$ => higgsino DM irresp. $m_{1/2}$ & m_0
  - $m(\Phi) < 0$ => A-funnel for any tanβ
  - NUHM2: light squarks, m(seL) < m(seR), SU(5)-inspired
  - NUGAMA, NMSSM,…



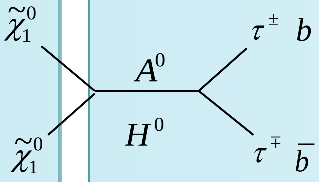
ATLAS SUSY Benchmarks
- Old WMAP -



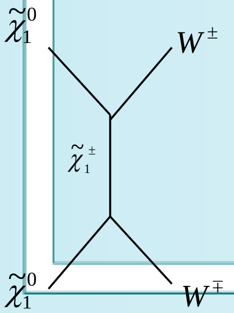
- light $\tilde{\tau}_1^{\pm}$
- in equilibrium w/ LSP
- heavy bino LSP



- bino LSP
- light $\tilde{\ell}_R^{\pm}$
- (g-2) ok, FCNC risky

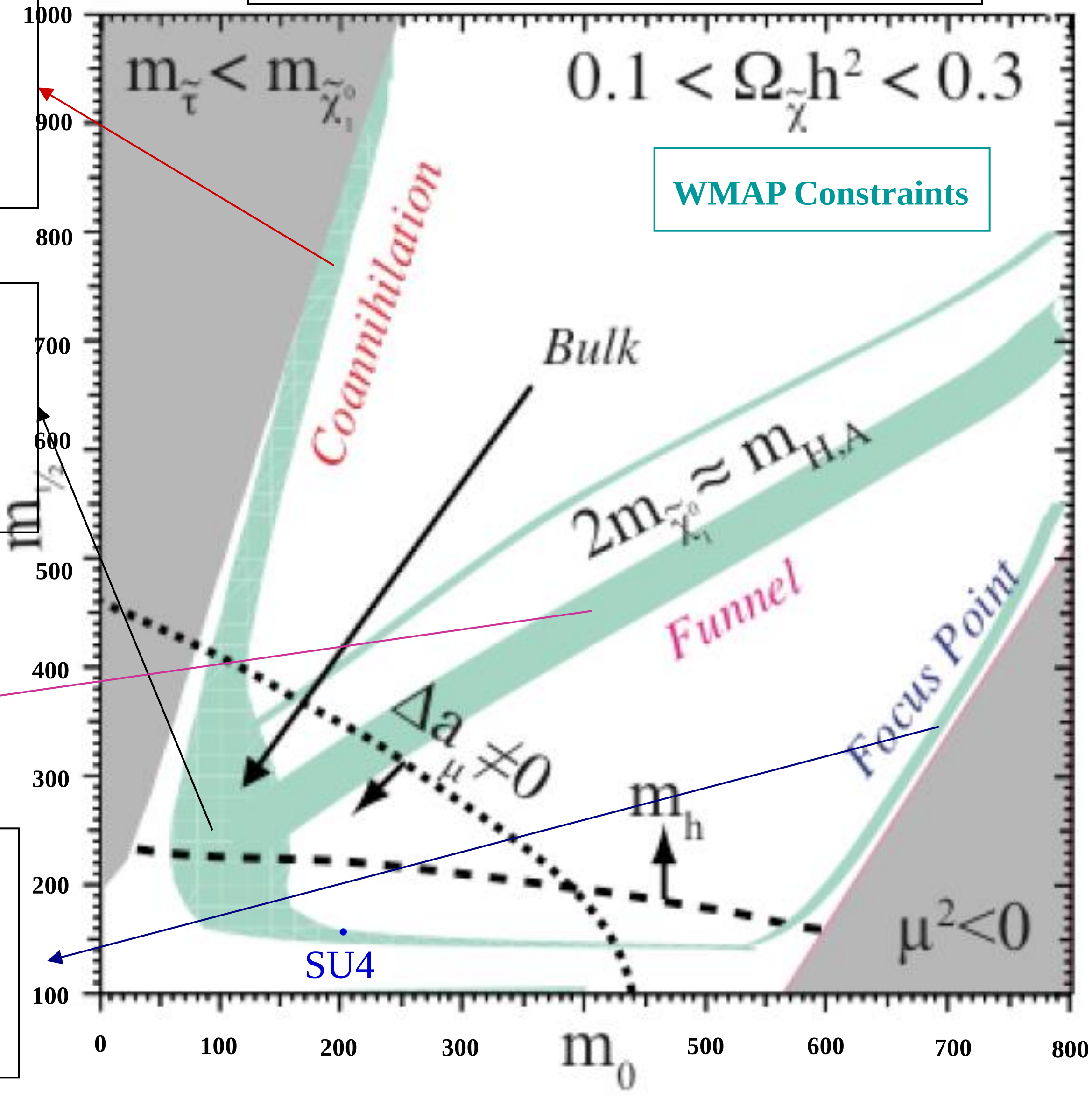


- H, A poles
- large tanb
- heavy bino LSP

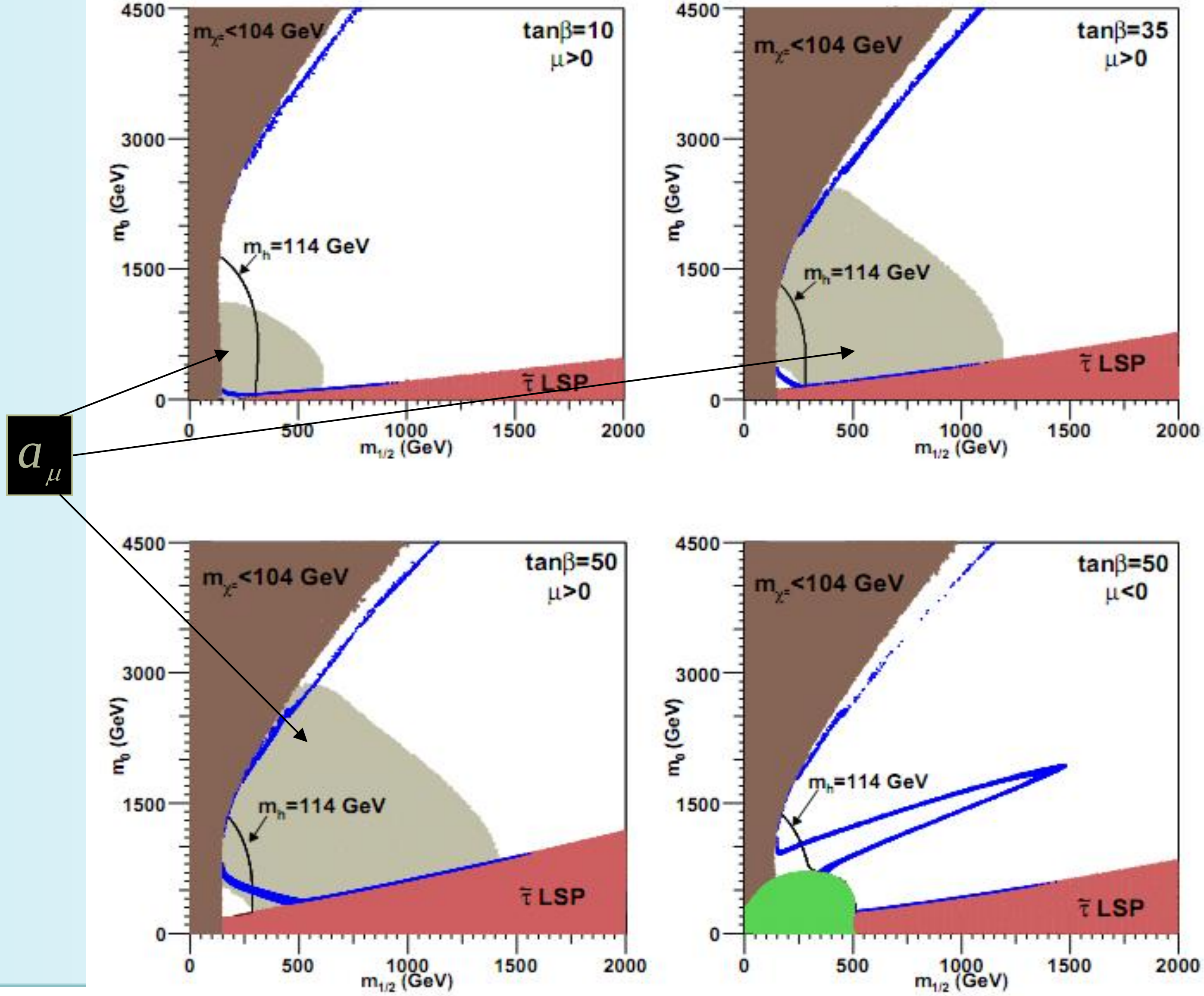


- large m_0, small $|\mu|$
- light higgsino LSP
- heavy $\tilde{\ell}_R^{\pm}$

Isajet 7.71, m(top)=175 GeV, Large tan β, μ>0



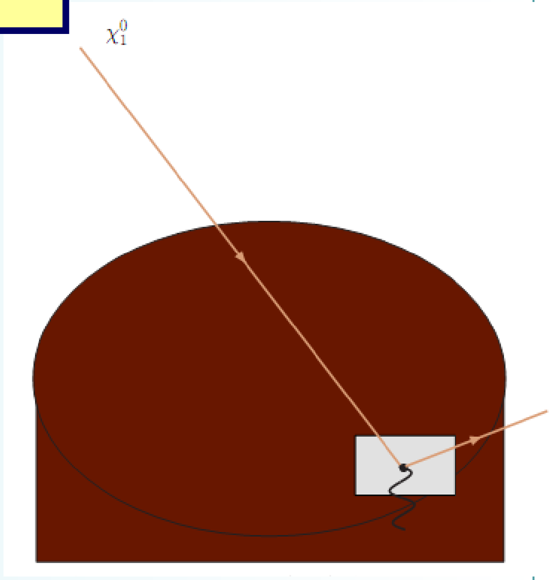
ATLAS SUSY Benchmarks
- Latest WMAP -



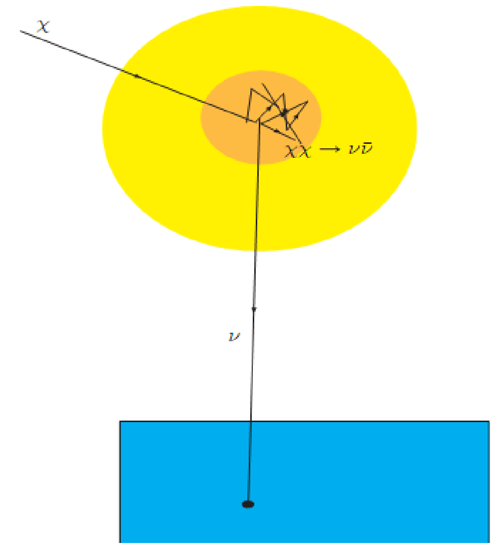
a_μ

Dark Matter Searches
- Two Methods -

- Direct Detection:
  - Principle: look for DM+N interactions
  - Completed Expts:
    - DAMA, CDMS, CRESST-I, MAC-He3, EDELWEISS-I, MAC-He3, SIMPLE, XENON10, ZEPLIN-I&II
  - Ongoing Expts:
    - ArDM, CDMS-II, CLEAN-DEAP, COUP, CRESST-II, DAMA-LIBRA, EDELWEISS-II, LUX, TEXONO, WARP, XENON100, ZEPLIN-III
  - Future Expts:
    - EURECA, LUX-20T, Super-CDMS



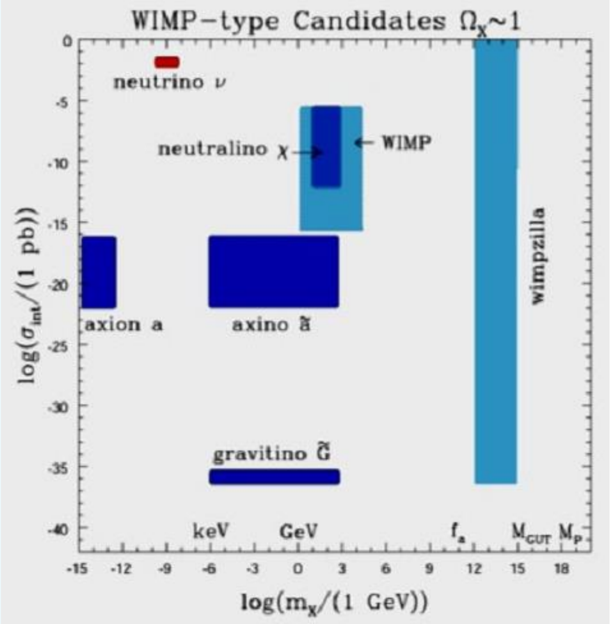
- Indirect Detection:
  - Principle:
    - look for SM particles produced through DM annihilation processes
    - Searches Particles: e^-, e^+, γ-rays, ν, $\bar{p}$
  - Expts:
    - AMANDA, ANTARES, KM3NET, AUGER, GLAST, HESS, ICECUBE, SUPER-K

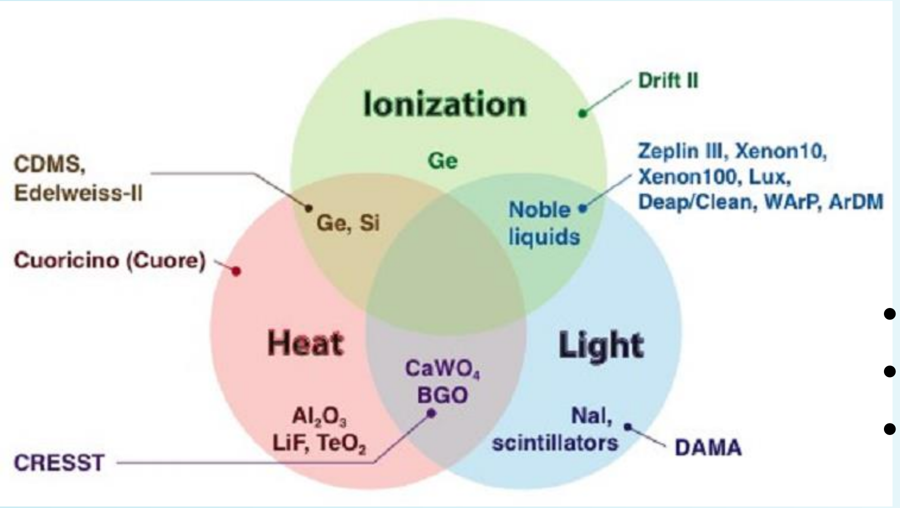


Dark Matter Searches - Direct Detection (1) -

Search Hypotheses

1. DM forms a static halo in the galactic rest frame
   - The sun rotates at 230 km/s around the galactic center
   - The earth rotates at (230+/-15) km/s => annual modulation
2. DM elastically scatters on ordinary matter
3. 10 GeV < m(WIMP) < 10 TeV
   => nuclear recoil E: 1-100 keV

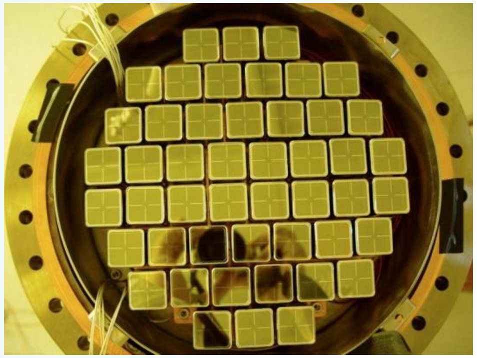




- Heat: phonons in crystaline lattice structure
- Ionization: free electrons in materials
- Light: scintillation in materials

Dark Matter Searches
- Direct Detection (2) -

XENON-100 Experiment

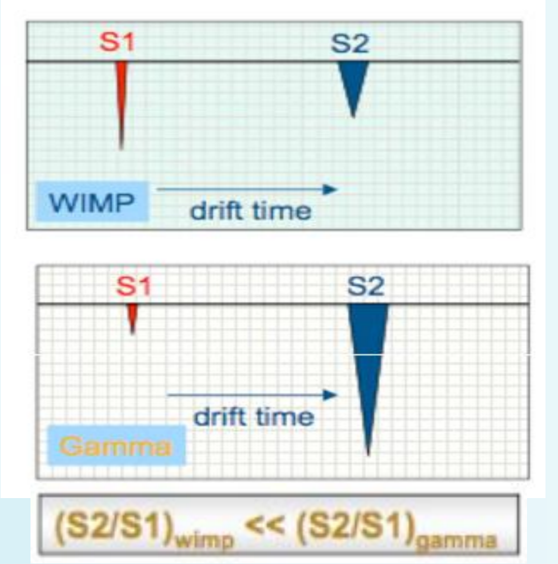


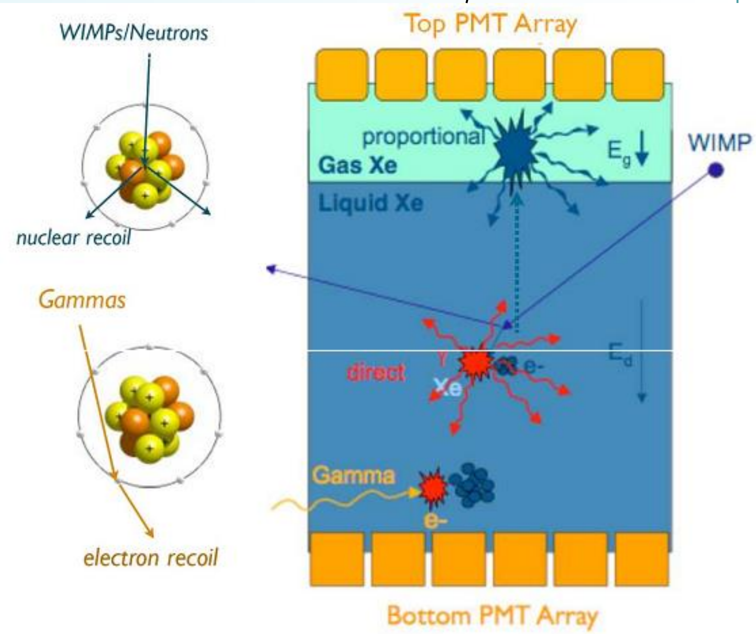
- Location:
  - LN Gran Sasso

- Detection Technique:
  - dual phase Xe detector + PMTs
  - prompt scintillation in liquid
  - ionization => proportional scintillation in gas
  - Phase I (05-07): 10 kg target mass
  - Phase II (08-10): 100 kg target mass, bkgd/100

- Data samples:
  - 190.4 kg-day

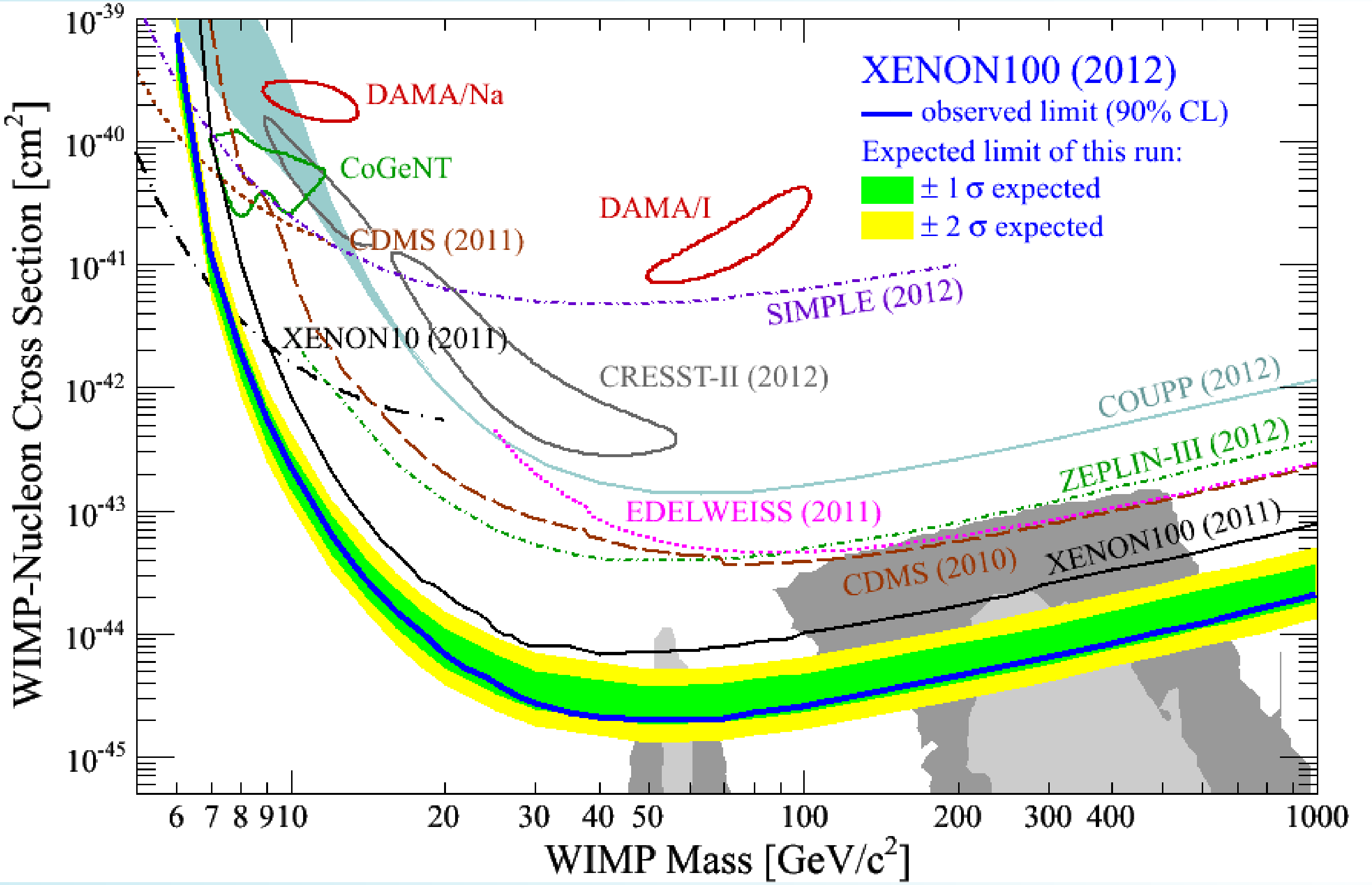
- S1: scintillation in LXe (bottom)
- S2: top ionization in GXe (top)





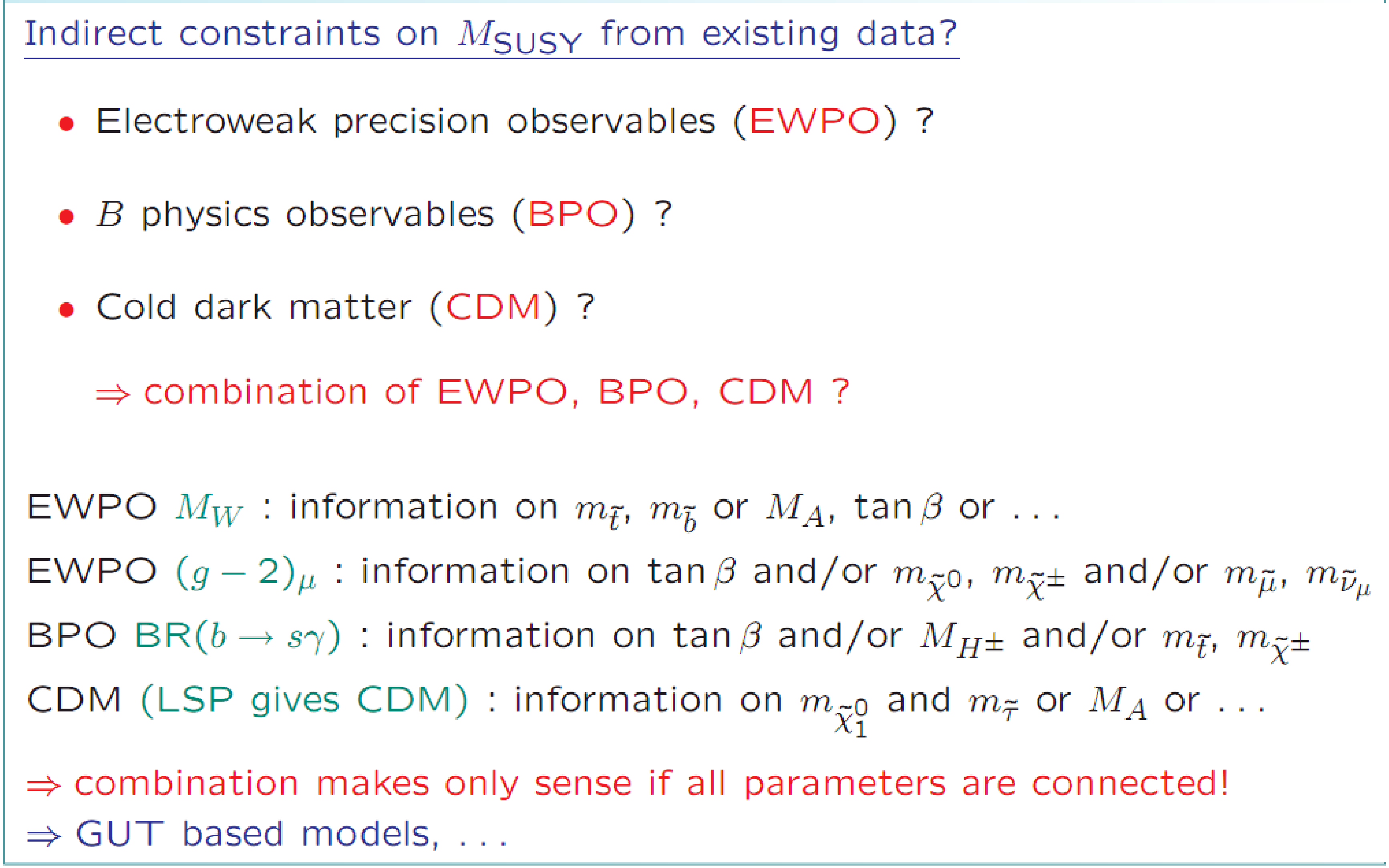
Dark Matter Searches
- Direct Detection (3) -

XENON-100 Results



SUSY Global Fits (1)

- Versions of SUSY filts that include the non-accelerator constraints



Indirect constraints on M_{SUSY} from existing data?

- Electroweak precision observables (EWPO) ?
- B physics observables (BPO) ?
- Cold dark matter (CDM) ?

$\Rightarrow$ combination of EWPO, BPO, CDM ?

EWPO M_W : information on $m_{\tilde t}$, $m_{\tilde b}$ or M_A, $\tan\beta$ or . . .

EWPO $(g-2)_\mu$: information on $\tan\beta$ and/or $m_{\tilde\chi^0}$, $m_{\tilde\chi^\pm}$ and/or $m_{\tilde\mu}$, $m_{\tilde\nu_\mu}$

BPO $\text{BR}(b \to s\gamma)$: information on $\tan\beta$ and/or $M_{H^\pm}$ and/or $m_{\tilde t}$, $m_{\tilde\chi^\pm}$

CDM (LSP gives CDM) : information on $m_{\tilde\chi^0_1}$ and $m_{\tilde\tau}$ or M_A or . . .

$\Rightarrow$ combination makes only sense if all parameters are connected!

$\Rightarrow$ GUT based models, . . .

SUSY Global Fits (2)

χ^2 calculation:

→ global χ^2 likelihood function
combines all theoretical predictions with experimental constraints:

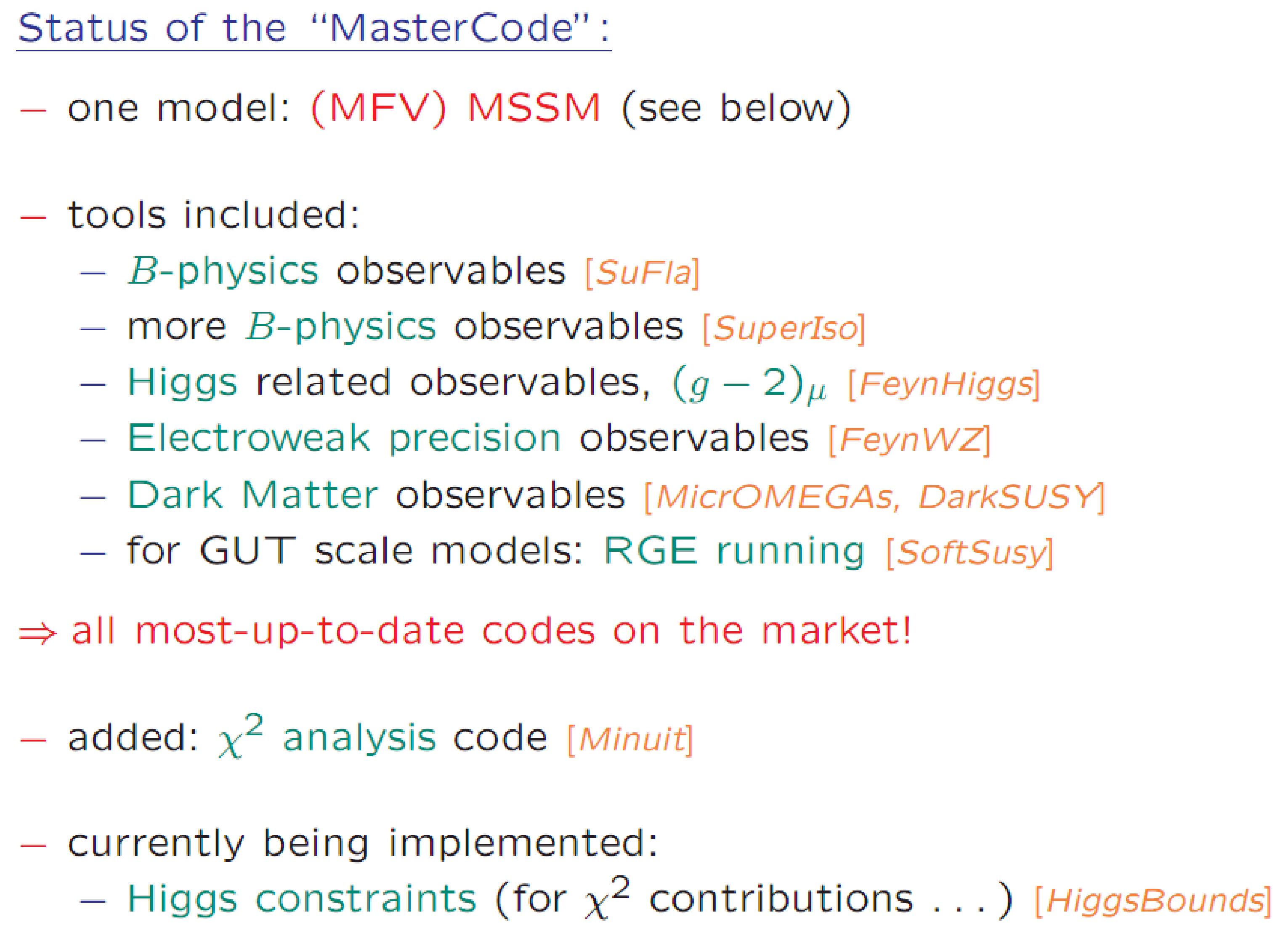
$$\chi^2 = \sum_i^N \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2} + \sum_i^M \frac{(f_{\mathrm{SM}_i}^{\mathrm{obs}} - f_{\mathrm{SM}_i}^{\mathrm{fit}})^2}{\sigma(f_{\mathrm{SM}_i})^2}$$

N: number of observables studied
M: SM parameters: $\Delta\alpha_{\mathrm{had}}, m_t, M_Z$
C_i: experimentally measured value (constraint)
P_i: MSSM parameter-dependent prediction for the corresponding constraint

Assumption: measurements are uncorrelated - fulfilled to a high degree

SUSY Global Fits (3)

- Tools: http://www.cern.ch/matsercode



Status of the "MasterCode":

- one model: (MFV) MSSM (see below)
- tools included:
  - B-physics observables [*SuFla*]
  - more B-physics observables [*SuperIso*]
  - Higgs related observables, $(g-2)_\mu$ [*FeynHiggs*]
  - Electroweak precision observables [*FeynWZ*]
  - Dark Matter observables [*MicrOMEGAs, DarkSUSY*]
  - for GUT scale models: RGE running [*SoftSusy*]

⇒ all most-up-to-date codes on the market!

- added: χ^2 analysis code [*Minuit*]
- currently being implemented:
  - Higgs constraints (for χ^2 contributions . . .) [*HiggsBounds*]

SUSY Global Fits (4)

Best-fit points:

CMSSM:

$m_{1/2} = 310$ GeV, $m_0 = 60$ GeV, $A_0 = 130$ GeV,

$\tan\beta = 11$, $\mu = 400$ GeV, $M_A = 450$ GeV

$\chi^2/N_{\mathrm{dof}} = 20.6/19$ (36 % probability)

$\Rightarrow$ very similar to SPS 1a :-)

NUHM1:

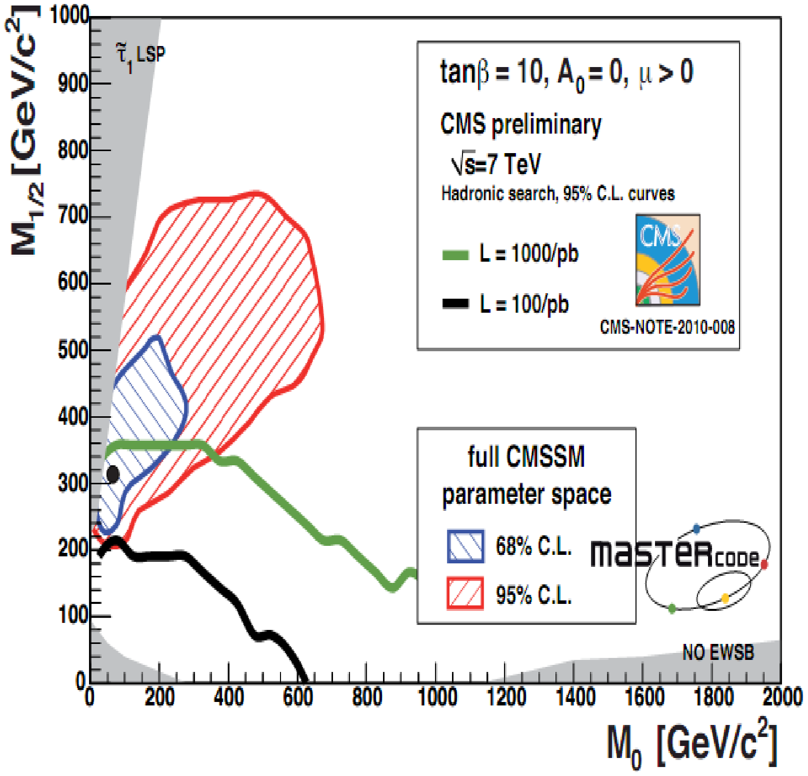
$m_{1/2} = 270$ GeV, $m_0 = 150$ GeV, $A_0 = -1300$ GeV,

$\tan\beta = 11$, $\mu = 1140$ GeV, $M_A = 310$ GeV

(similar probability)

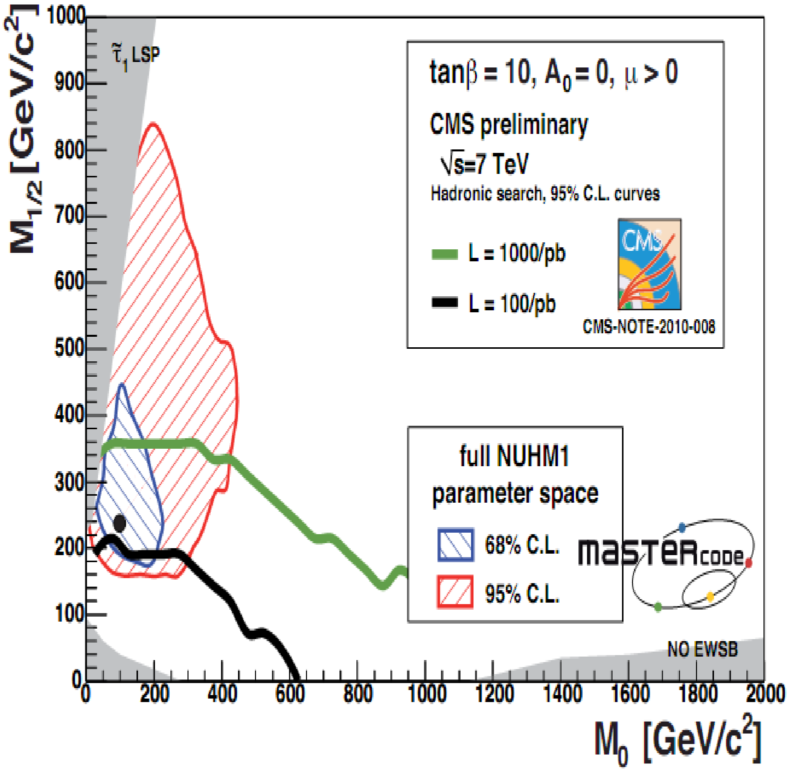
SUSY Global Fits (5)

LHC (CMS) ⊕ CMSSM analysis:



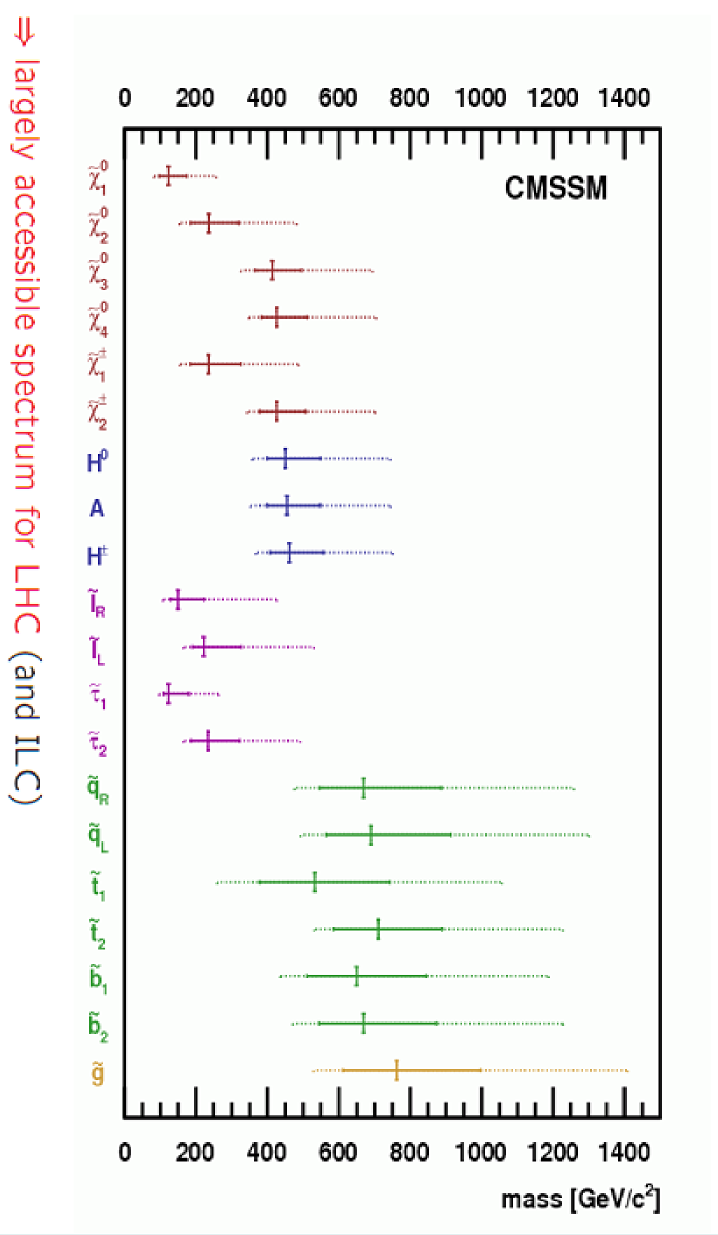
⇒ best-fit point and part of 68% C.L. are can be tested in 2011

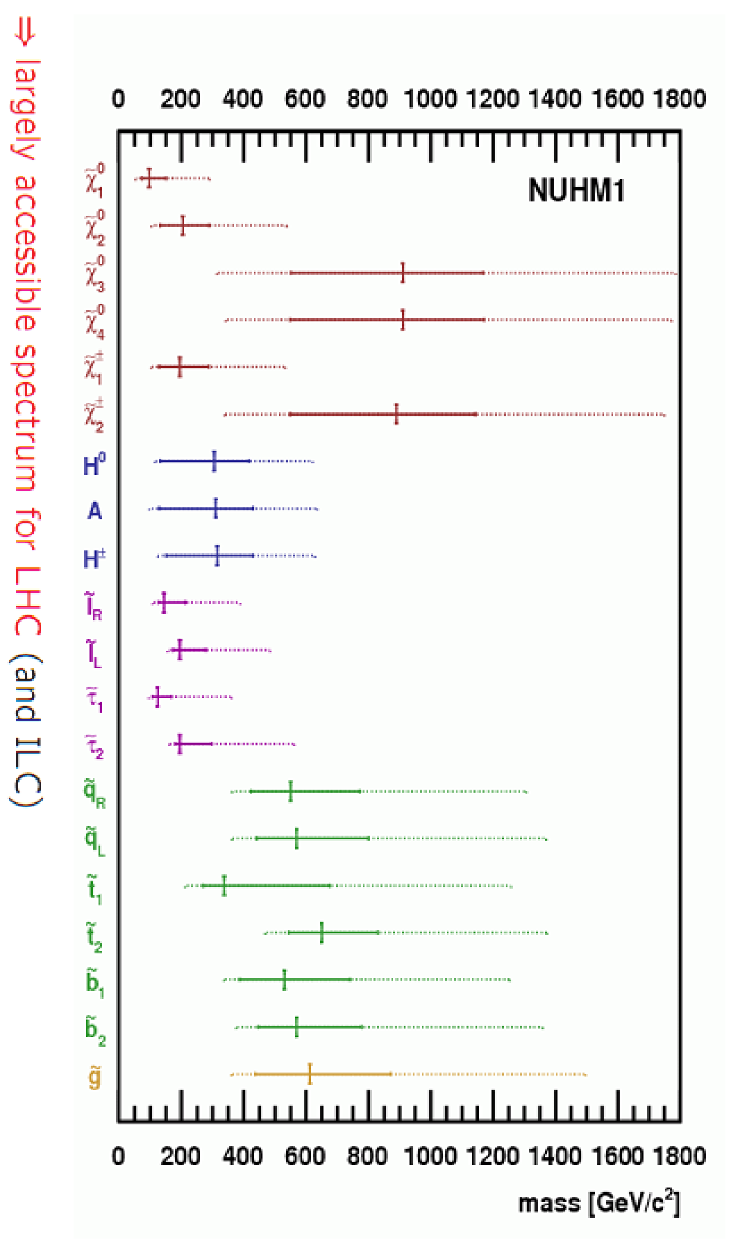
LHC (CMS) ⊕ NUHM1 analysis:



⇒ best-fit point and part of 68% C.L. are can be tested in 2011

SUSY Global Fits (6)





BACK-UP