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Physics Beyond the Standard Model

Part II: Introduction to Experimental Searches

Apologies for not acknowledging authors of the illustrations

Outline

PART I: BSM Searches at Accelerator Facilities

PART II: BSM Searches without Accelerators

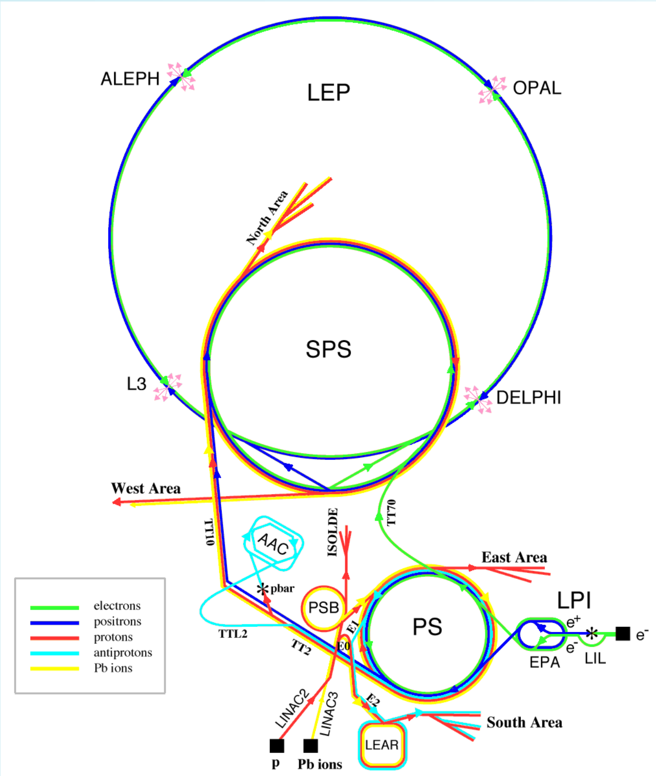
2

PART I: BSM Searches at Accelerator Facilities

3

« Large Electron Positron » Collider

- Amongst the large variety of colliders, I'll describe the 2 biggest: LEP former CERN e^+e^- collider (1989-2001) and LHC, CERN current pp collider (2009-present)
- LEP:
  - 27 km in circumference
  - 100 m underground swiss-french border
  - LEP1 (1989-1996): $\sqrt{s} = m_Z$ (18 million Z^0 produced)
  - LEP2 (1998-2001): $161 \leq \sqrt{s} \leq 209$ GeV
  - 4 Experiments: ALEPH, DELPHI, L3, OPAL



RF Cavity (in straight sections!)

Impressive size

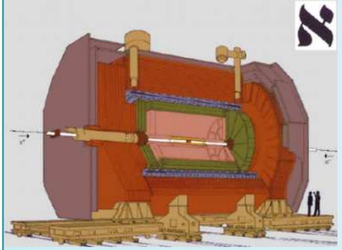
LEP Characteristics

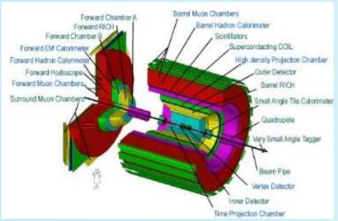
- e^+e^- Collider
- Diameter: 8.5 km
- LEP 2:
  - Bunch spacing: $\Delta t_X = 270$ ns
  - Instantaneous luminosity: $\mathcal{L} = 10^{31\text{-}32}$ cm^{-2}s^{-1}
  - Beam energy spread: $\frac{\Delta E_B}{E_B} = 1.5 \times 10^{-4}$
  - Crossing angle: $\alpha_X = 0.5$ mrad
  - Integrated luminosity delivered to L3 experiment:

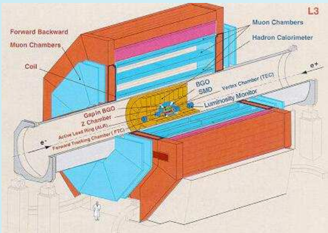
$\sqrt{s}$ (GeV)	$\int \mathcal{L}dt$ (pb^{-1}) (Delivered to L3)
189	176.4
192	29.8
196	84.1
200	83.3
202	37.1
202-206	145.3
206-209	72.0

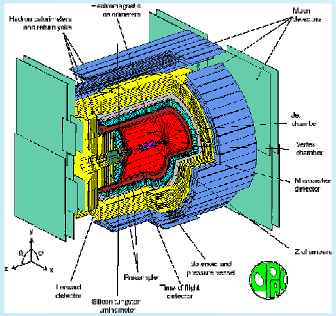
L3 Detector

ADLO

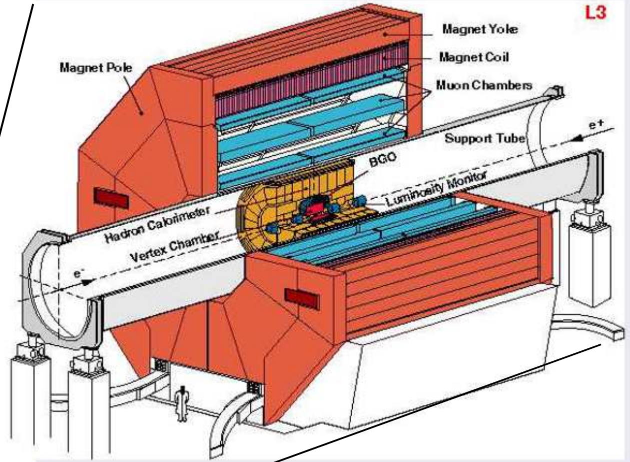








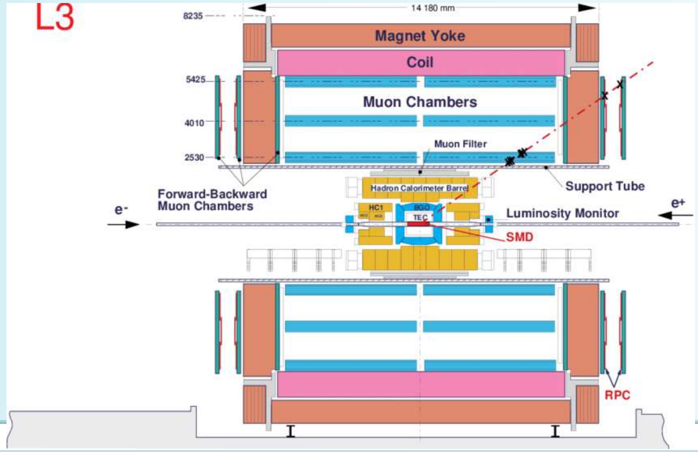
Description

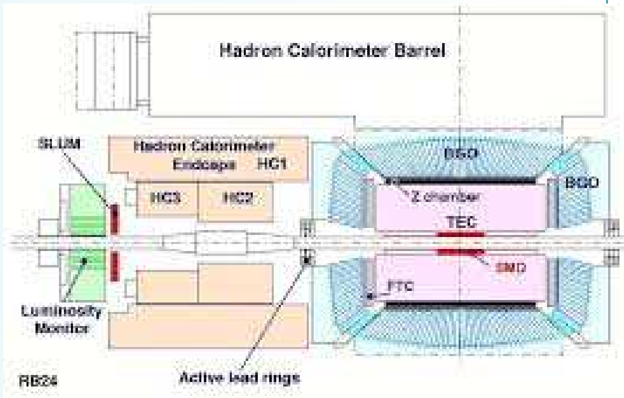


- Solenoid: B = 0.51 T
- Toroid: B = 1.24 T

Performance

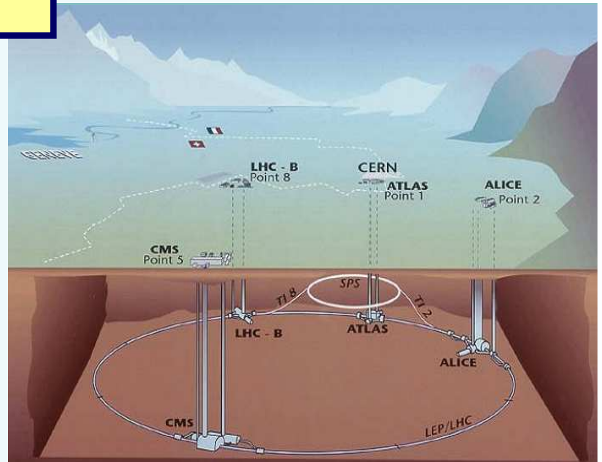
- Tracking:
  - $\sigma_{r\phi} = (7_{SMD}/50_{TEC})\ \mu m$
  - $\sigma_{rz} = (14_{SMD}/320_{TEC})\ \mu m$
  - $(\frac{\sigma_{p_T}}{p_T})^{TEC}_{p_T=50\ GeV} = 1.5\%$
- Calorimeters:
  - EM: $\frac{\sigma_E}{E} = \frac{2.8\%}{\sqrt{E}} \oplus \frac{0.08\%}{E} \oplus 0.4\%$
  - Jets: $\frac{\sigma_E}{E} = \frac{55\%}{\sqrt{E}} \oplus 5\%$
- Muon:
  - C: $\frac{\sigma_p}{p} = 2.5\%$ (45 GeV)
  - E-C: $\frac{\sigma_p}{p} = 5 - 25\%$
  - FWD: $\frac{\sigma_p}{p} = 35\%$



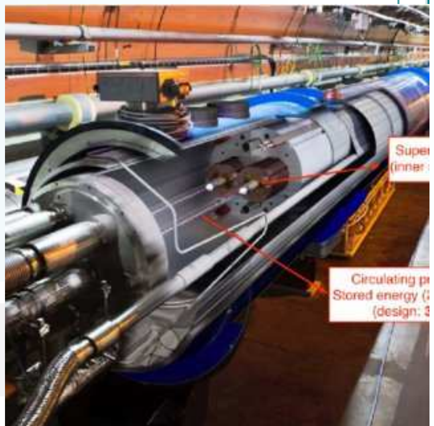


LHC Characteristics

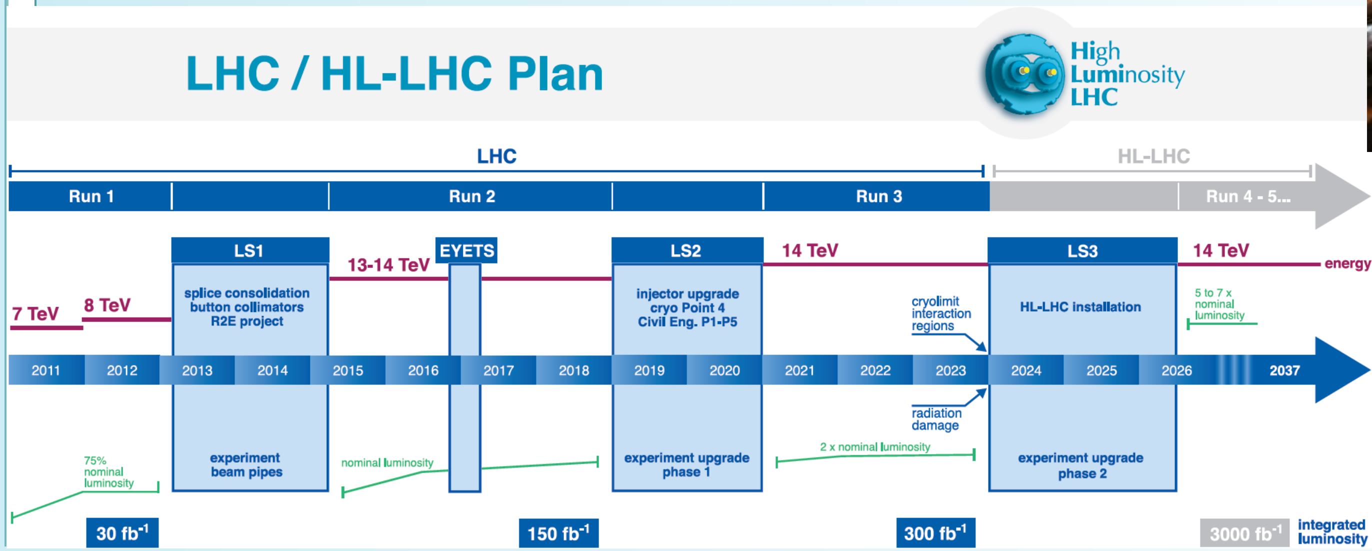
- p+p / p+Pb / Pb+Pb Collider
- Diameter: 8.5 km (same tunnel as LEP)
- Beam energy spread: $\frac{\Delta E_B}{E_B} = 1.11 \times 10^{-4}$
- Crossing angle: $\alpha_X = 285\ \mu\text{rad}$



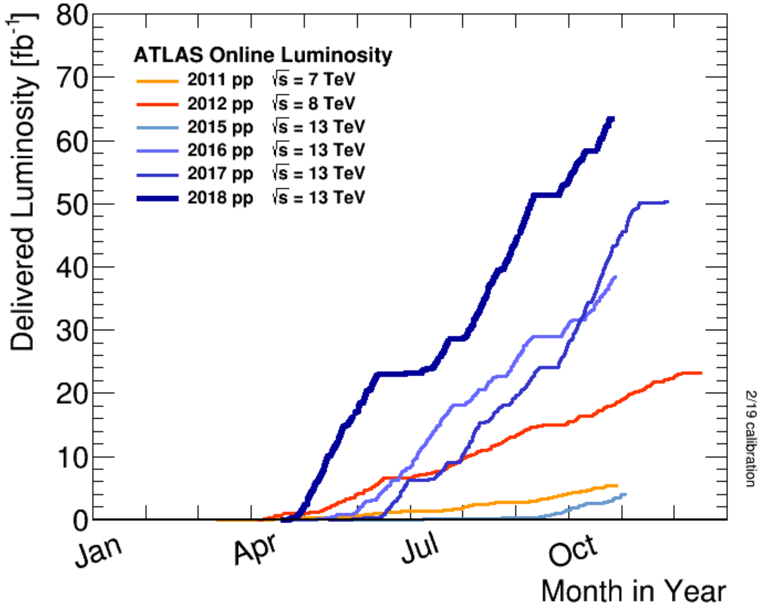
Phase	Period	$\sqrt{s}$ [TeV]	Δt_X [ns]	L [$cm^{-2}s^{-1}$]	L [fb^{-1}]
Run 1	2010-2011	7	150 ↘ 50	2-4 x 10^{33}	5
	2012	8	50	8 x 10^{33}	20
Run 2	2015-2018	13	50 ↘ 25	2 x10^{34}	140
Run 3	2021-2013	14	25	2 x10^{34}	150

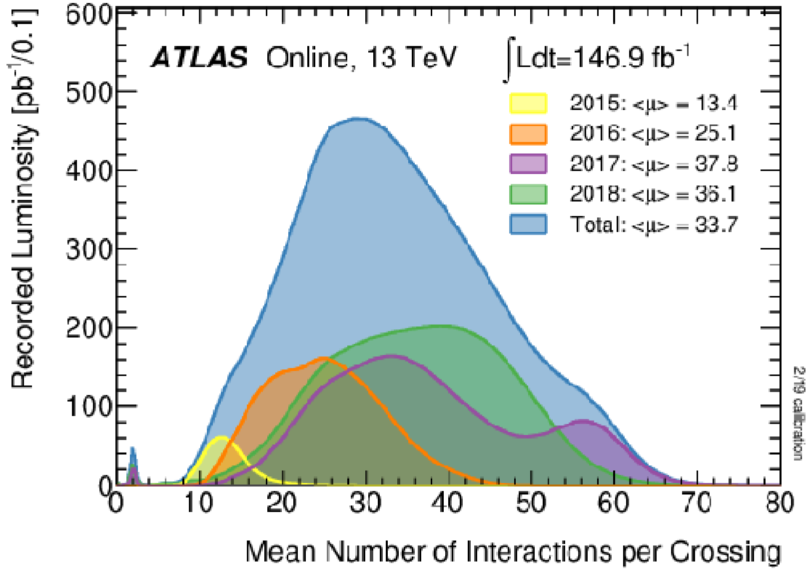


Bending SC dipole (B=8.33 T)

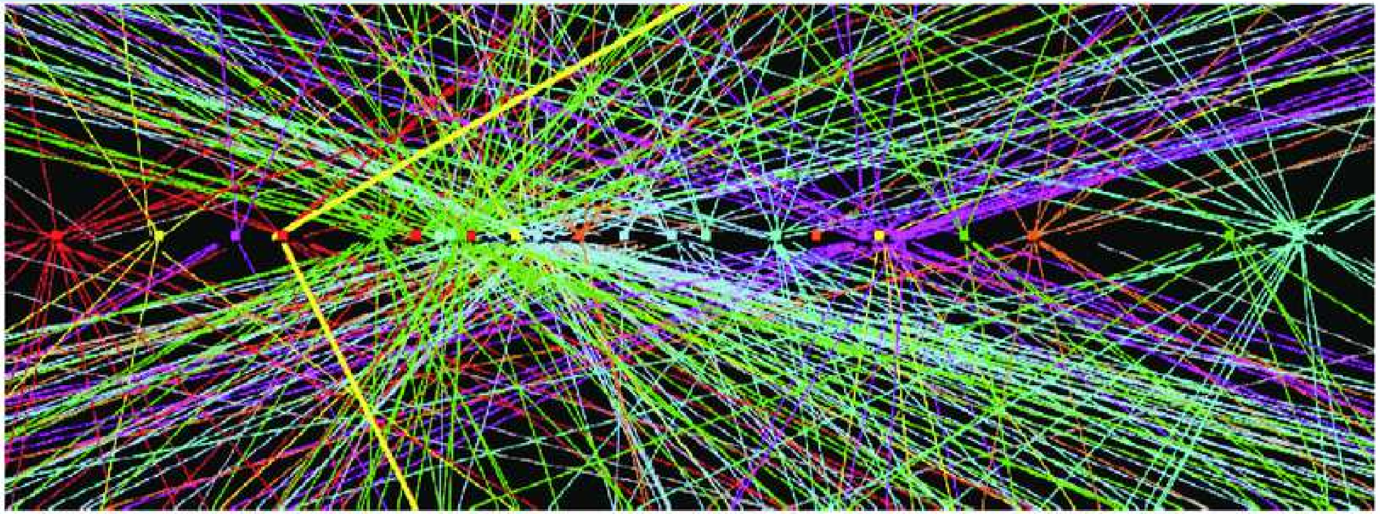


LHC Pile-Up

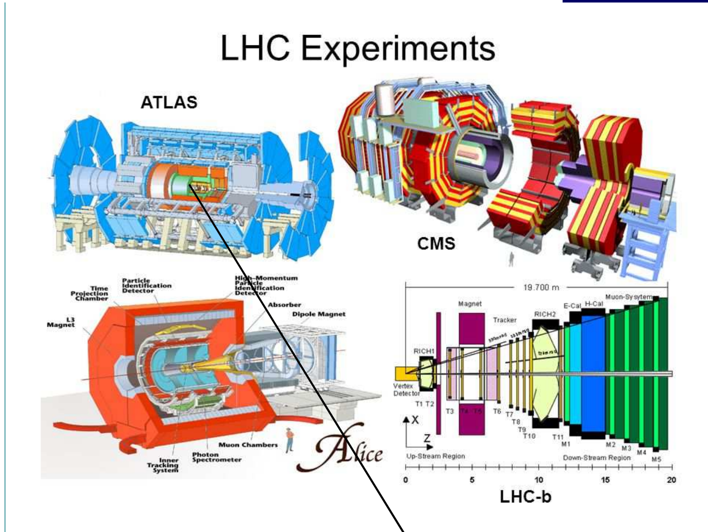


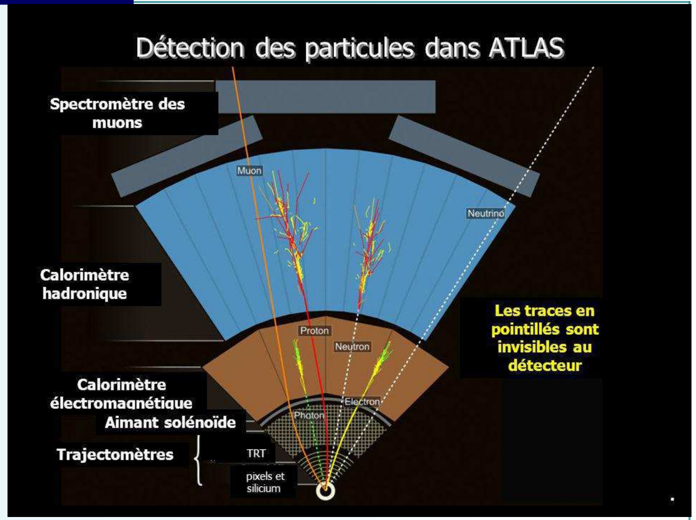


Run 1: $Z \rightarrow e^{+}e^{-}$ candidate with 19 events P.U.

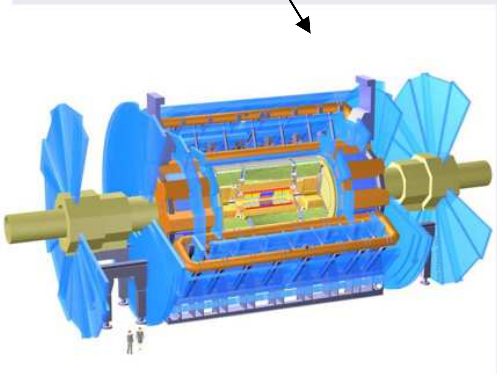


LHC Detectors





Description

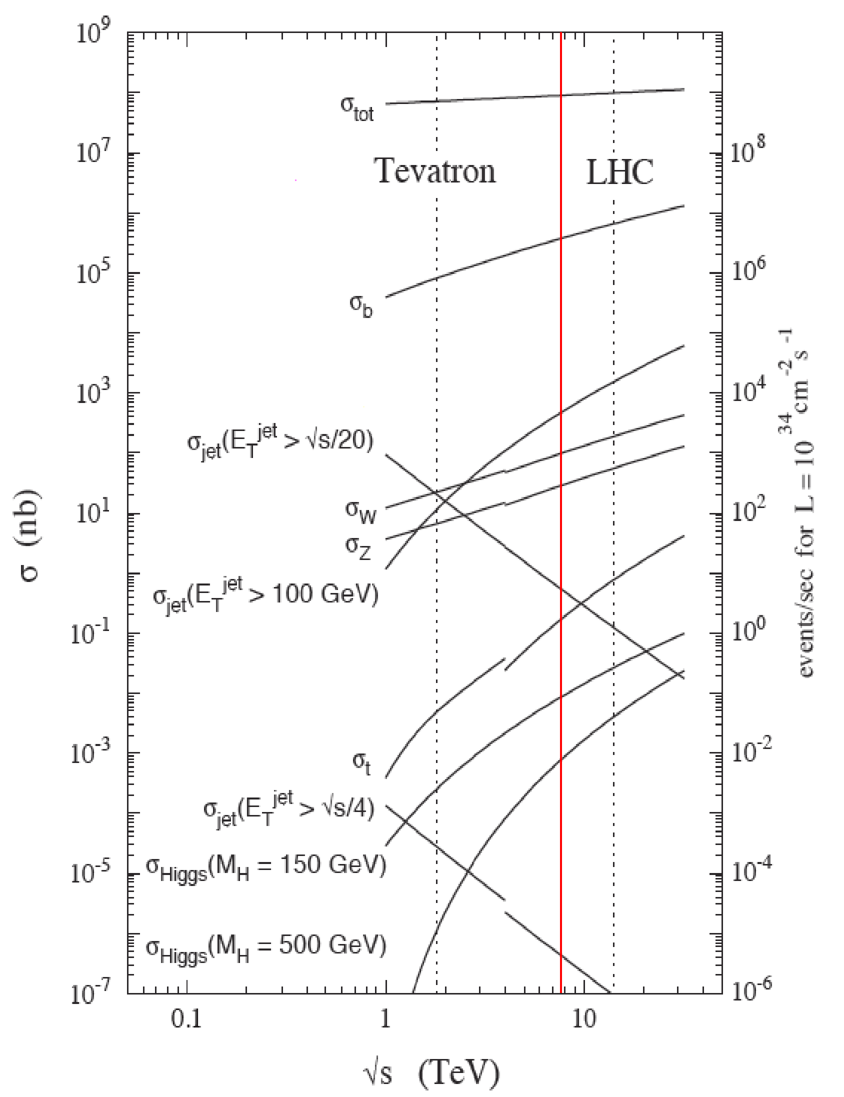


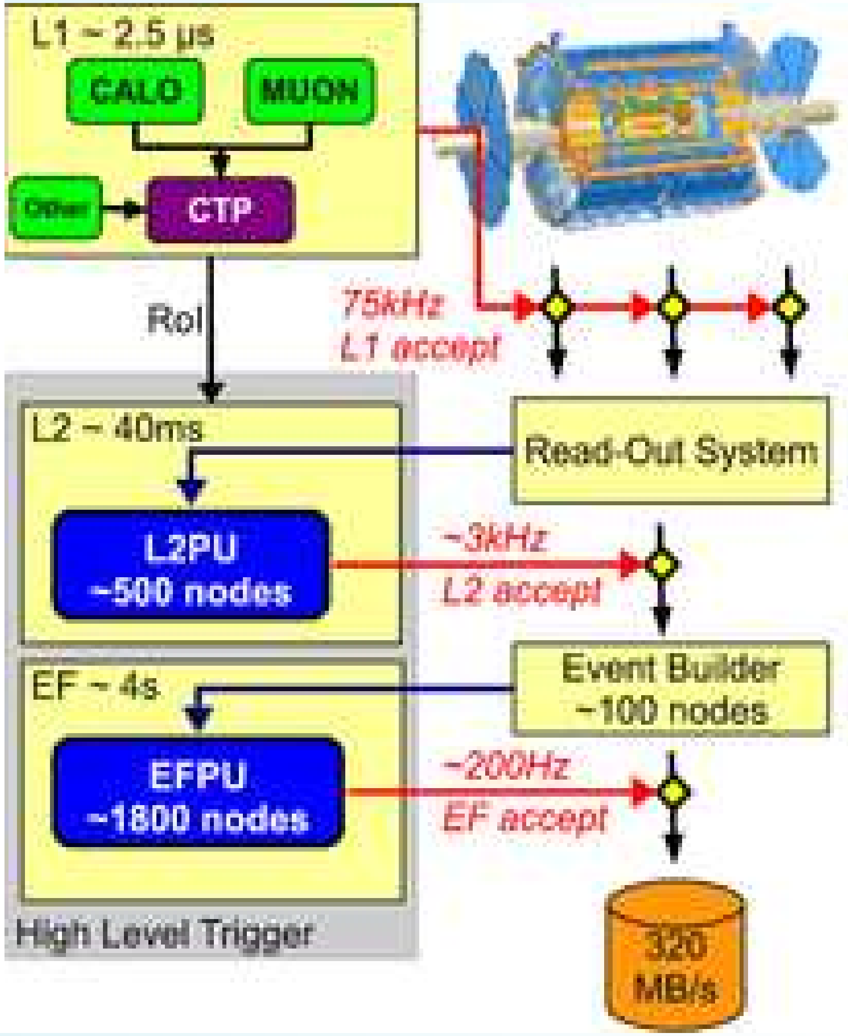
- Solenoid: B = 2 T
- Toroid: B = 3.9-4.1 T ($\int B \cdot dl = 2.0\text{-}7.5\, T \cdot m$)

Performance

- Tracking:
  - $\frac{\sigma_{p_T}}{p_T} = (0.05 \times p_T \oplus 1.0)\%$
  - $\sigma_{d_0} = (10 \oplus \frac{140}{p_T})\mu m$
- Calorimeters:
  - EM: $\frac{\sigma_E}{E} = \frac{10.1\%}{\sqrt{E}} \oplus 0.17\%$
  - Jets: $\frac{\sigma_E}{E} = \frac{52.1\%}{\sqrt{E}} \oplus 3.0\% \oplus \frac{1.59\%}{E}$
  - $\not{E}_T$: $\sigma_{\not{E}_T} = 0.48 \times \sqrt{H_T}$
- Muon:
  - $p_T = 50$ GeV: $\frac{\sigma_{p_T}}{p_T} = 2\%$
  - $p_T = 1$ TeV: $\frac{\sigma_{p_T}}{p_T} = 10\%$

Trigger: On-Line Selection



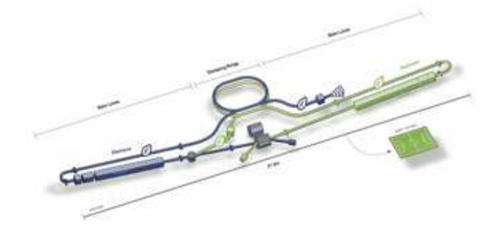


Panorama of Future Colliders

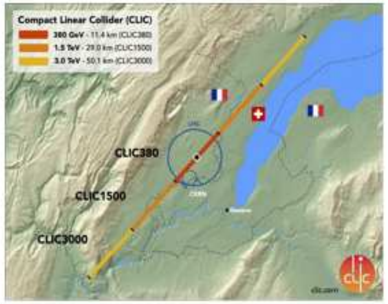
Linear

Circular

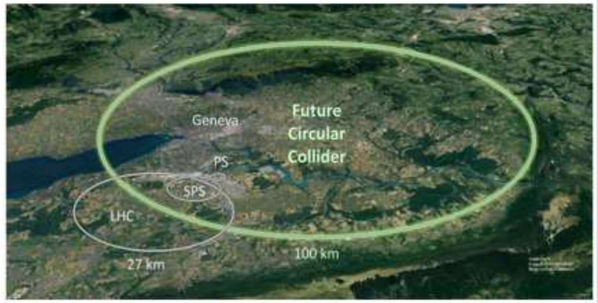
ILC, Japan



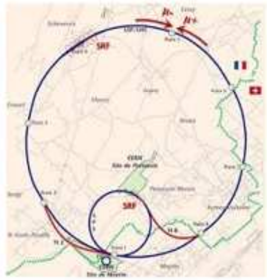
CLIC, CERN



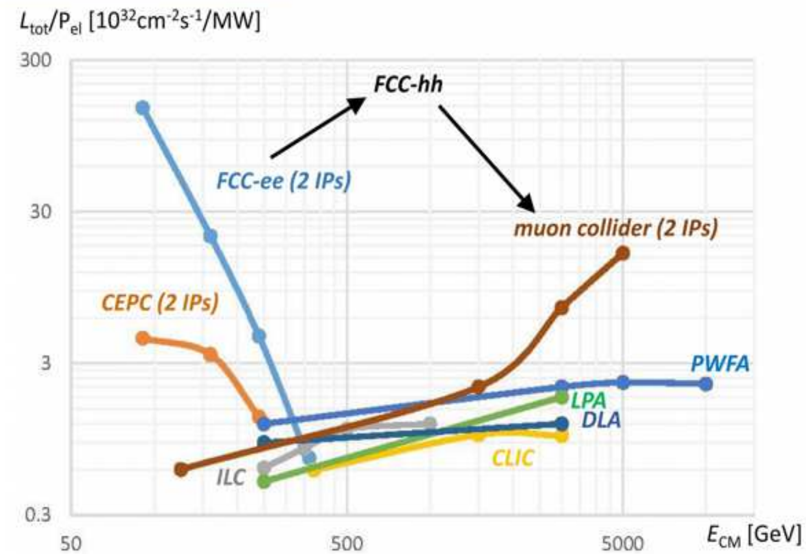
FCC, CERN



CEPC & SPPS, China



Muon Collider, CERN



Search Instruments

Accelerators

- Instruments of the ENERGY LENS: they provide the high momentum to probe matter at short distances

Main Features

- CoM Energy
  - Fixed target: $\sqrt{s} = \sqrt{2mE_B}$
  - Collider: $\sqrt{s} = 2E_B$
- Luminosity:
  - Instantaneous: $\mathcal{L} = \frac{f \cdot N^2}{4\pi \cdot \sigma_x \cdot \sigma_y}$
  - Integrated: $L = \int \mathcal{L} \cdot dt$
  - Event Rate: $R = \mathcal{L} \cdot \sigma$
  - Number of Events: $N = L \cdot \sigma$

Detectors

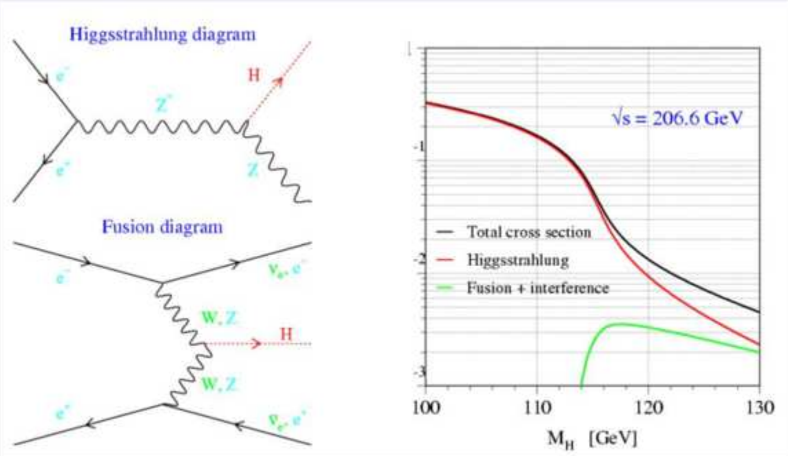
- 2 Types:
  - Trackers: low density materials (hits), small perturbation of trajectories, work for charged (or converted particles)
  - Calorimeters: dense materials (showers) to absorb the full E of the particles ($e^{+/-}$, γ, hadrons)
- Figures of merit:
  - Resolutions
  - Granularity
  - Hermiticity (Forward Calorimeters)
  - Trigger (Hadron Colliders)

Search for Higgs Boson at LEP2

- Relevant Models: SM, GUT, SUSY

Production Mechanisms

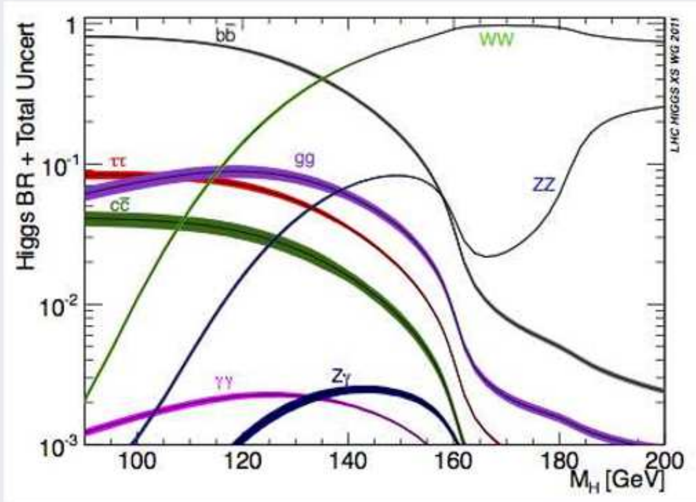
- Higgs-strahlung: $M_H \leq \sqrt{s} - M_Z$
- VBF: beyond this kinematical limit
- $\sigma(e^+e^- \rightarrow HZ) \approx 100$ fb, for
  - $\sqrt{s} = 209$ GeV
  - $M_H = 115$ GeV



Decay Modes

For $M_H = 115$ GeV,

- $BR(H \rightarrow b\bar{b}) = 73.6\%$
- b-tagging is crucial



Search for Higgs Boson at LEP2

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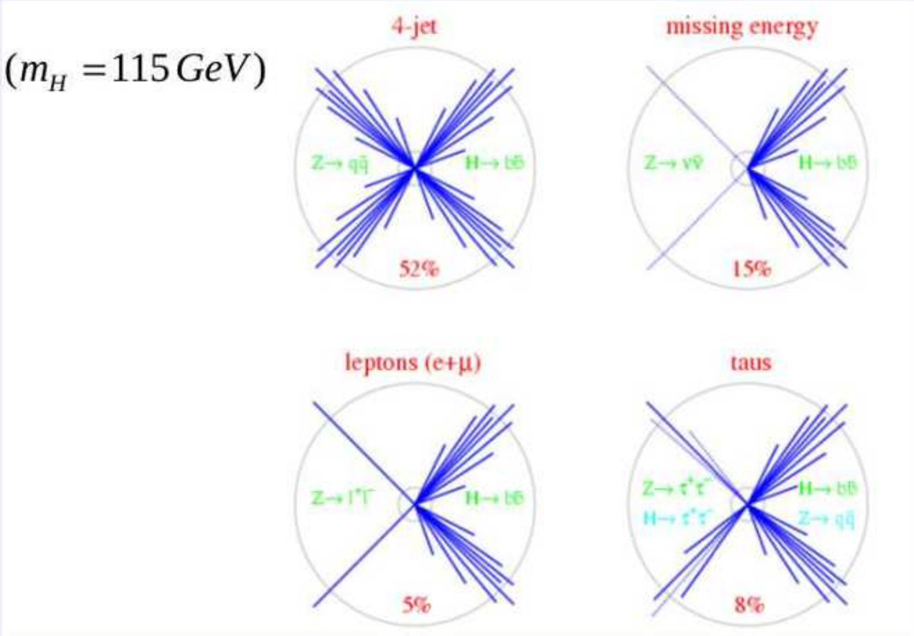
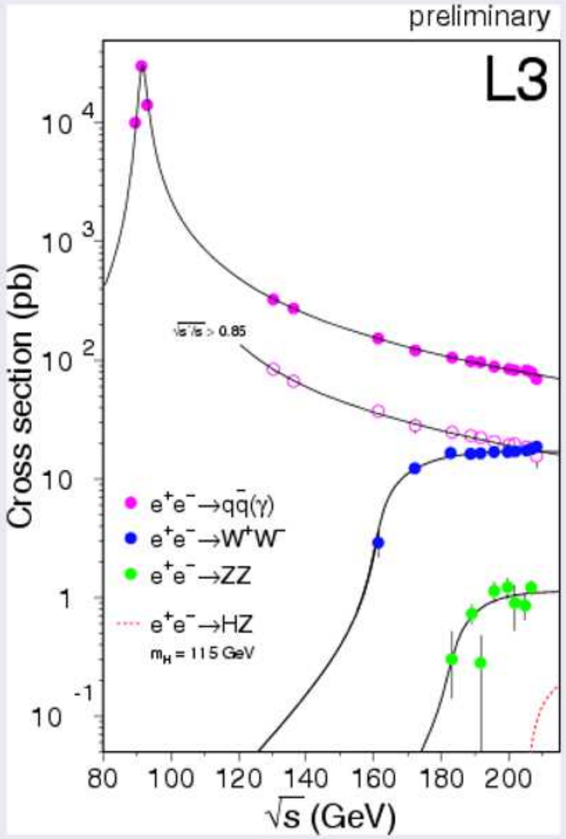
Search Topologies



Background Processes



Search for Higgs Boson at LEP2

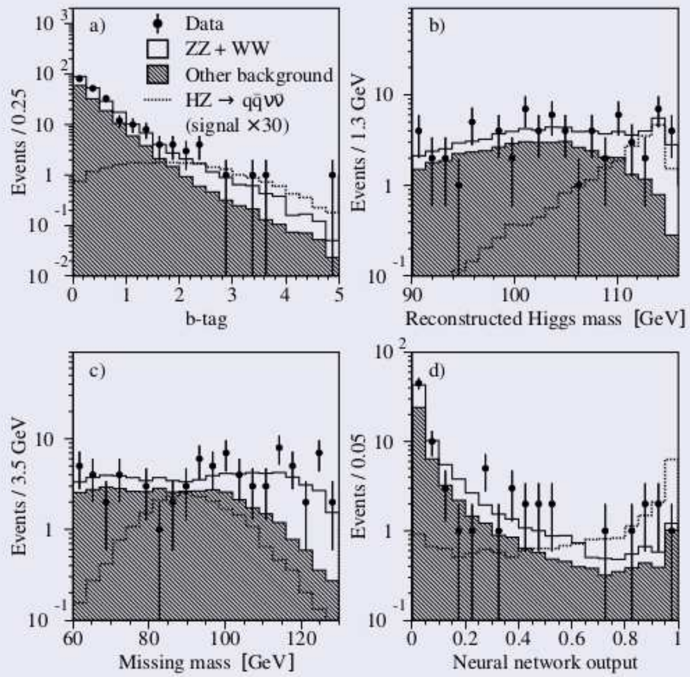
- Relevant Models: SM, GUT, SUSY

$H(\to b\bar{b}) + Z(\to \nu\bar{\nu})$ Channel (Evt Selection)

- Preselection:
  topology, high $M(b\bar{b})$ & high $\not{M}$, small acollinearity,...
- Kinematic Fit:
  - $M_H^{4C} = M(b\bar{b})$ such that $\not{M} \approx M_Z$
- Main discriminant:
  Neural Network $\longleftarrow$
  Inputs(kinematics,b-tagging)
- Final discriminant:
  Combination of NN & M_H^{4C}

$H(\to b\bar{b}) + Z(\to \nu\bar{\nu})$ Channel (Evt Yields)

Distr. before the final selection shown for:
$\sqrt{s} > 206$ GeV, $M_H = 115$ GeV, $S(\times 30)$

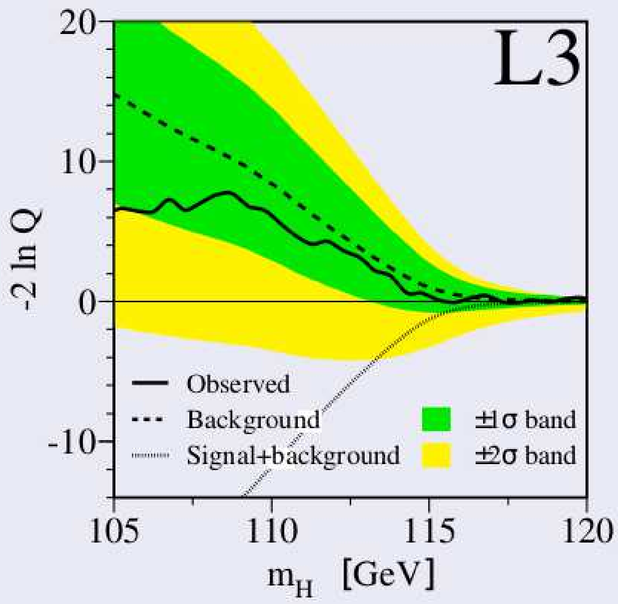


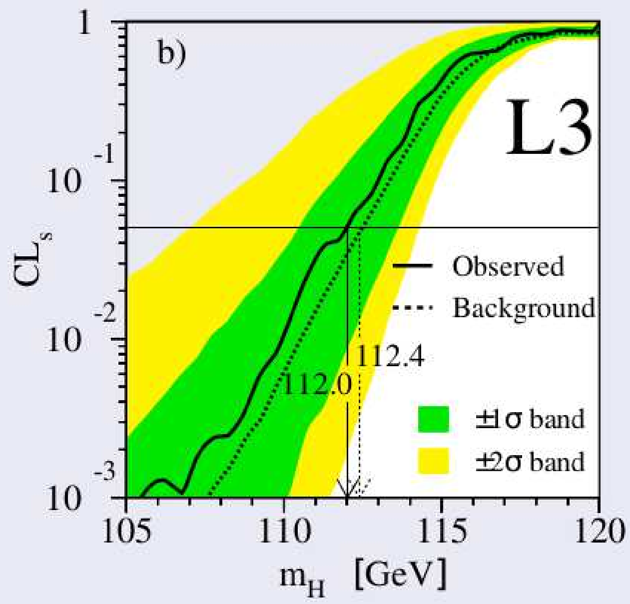
Search for Higgs Boson at LEP2

- Relevant Models: SM, GUT, SUSY

L3 Exclusion Limit

- Final Selection: $N_{Obs} = 5,\ N_B = 3.3,\ N_S = 0.66$
- Systematic uncert.:
  - $3 - 6\%$ (S), $6 - 15\%$ (B)
  - Main sources: b-tagging, MC stat.



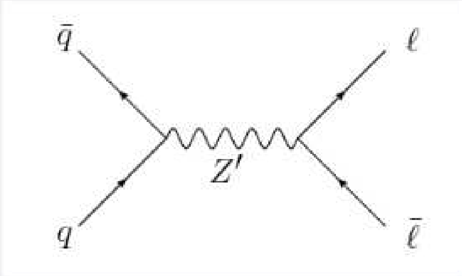


- MSSM Interpretation: Comb. hZ & hA analyses ($\sigma_{hZ} = sin^2(\beta - \alpha) \cdot \sigma_{HZ}$)

Search for Z'

- Relevant Models: GUT or RS Extra Dimensions

Search for Z': Principles



- Event Topology: "Charged dilepton" ($\ell = e/\mu$), i.e. all visible decay products
- Distinctive feature: signal peaks at $M_{\ell^+\ell^-} \approx M_{Z'}$ over a smooth background (search for resonance)
- Mass reconstruction:
  - Easy if FS is only made of visible decay products
  - In this case, one can rely exclusively on the Final State (FS)!
  - Invariant mass for N-body decay:

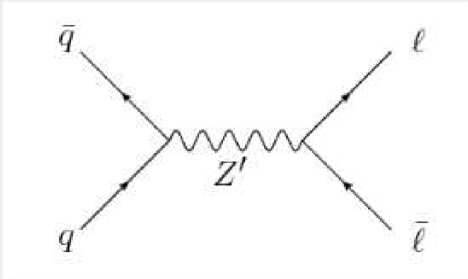
$$M = \sqrt{\left(\sum_{i=1}^{N} E_i\right)^2 - \left(\sum_{i=1}^{N} \vec{p}_i\right)^2} \quad (1.a.)$$

  - Ref: A. Einstein, Ann. d. Phys., vol.18, n13 (1905) 639-641
  - Comments:
    - Full Lorentz invariant
    - This is how the Z mass is measured at collider experiments

Search for Z'

- Relevant Models: GUT or RS Extra Dimensions

Search for Z': Principles



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- Mass reconstruction:
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  - In this case, one can rely exclusively on the Final State (FS)!
  - Invariant mass for 2-body decay:

$$M = \sqrt{2E_{\ell^+}E_{\ell^-}\left[1 - cos(\alpha_{\ell^+,\ell^-})\right]} \quad (1.b.)$$

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    - Full Lorentz invariant
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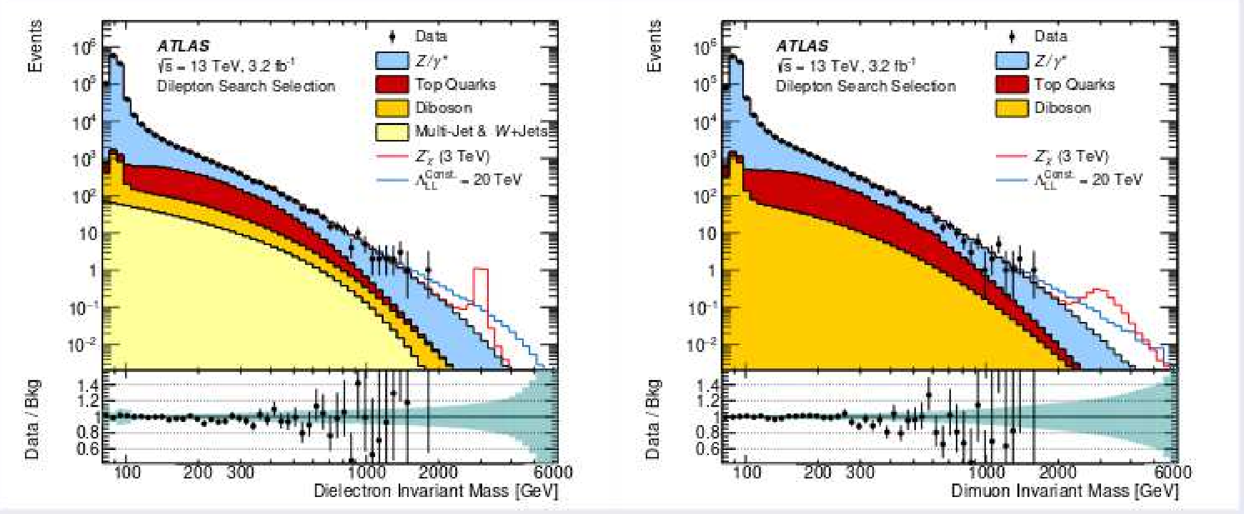
Search for Z'

- Relevant Models: GUT or RS Extra Dimensions

Search for Z': Typical Analysis $\longrightarrow$ Ref: arXiv:1607.03669 [hep-ex]

- Event Topology: "Charged dilepton" ($\ell = e/\mu$)
- Main background process: $q\bar{q} \to \gamma^*/Z^* \to \ell^+\ell^-$ (aka Drell-Yan production)
- Data sample: $\int \mathcal{L}dt = 3.2\ fb^{-1}$ of ATLAS pp collisions at $\sqrt{s} = 13$ TeV (2015)
- Event Selection:
  - Trigger: di-electron with $p_T(e^\pm) > 17$ GeV & single muon with $p_T(\mu^\pm) > 26/50$ GeV
  - Offline: 2 OS-SF isolated leptons with $p_T > 30$ GeV
- Final discriminant: Dilepton Mass
- Sensitivity to signal: depends crucially on
  - Signal natural width: $\Gamma_{Z'}$ (model dependent)
  - Dilepton mass resolution: mainly resulting from $\frac{\sigma_E}{E}(e^\pm)$ or $\frac{\sigma_p}{p}(\mu^\pm)$



Search for Z'

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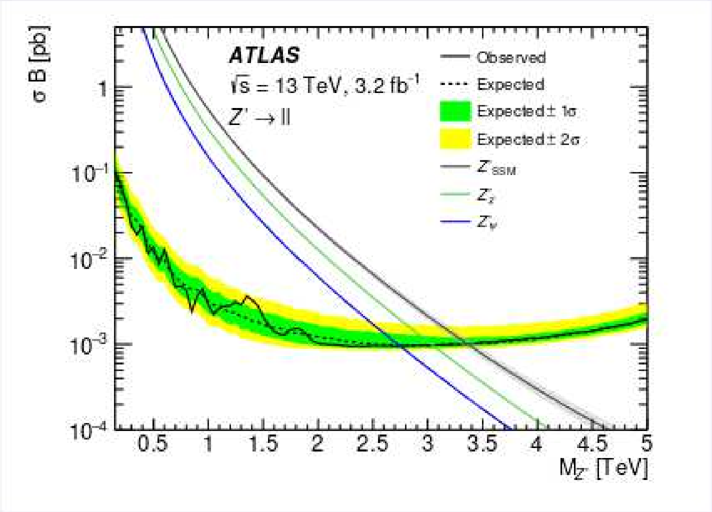
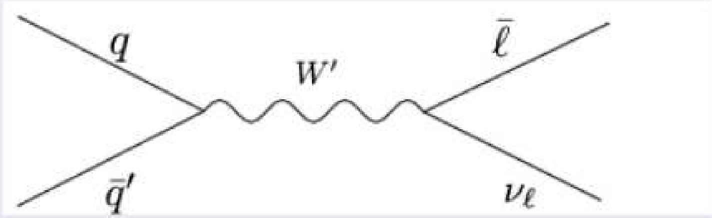


Search for W’

- Relevant Models: GUT

Search for W': Principles (1)



- Event Topology: $1\ell^{\pm} + \not{E}_T$
- Distinctive feature: signal displays a Jacobian peak at $M_T \approx M_{W'}$ over a smooth background (search for resonance)
- Mass reconstruction:
  - More complicated:
    - Can measure the full $4-p$ of the charged lepton
    - But ν escapes detection $\Rightarrow$ both $E(\nu)$ and $p_z(\nu)$ are unkown!
    - Full event reconstruction: not possible!
  - Transverse mass for N-body decay:

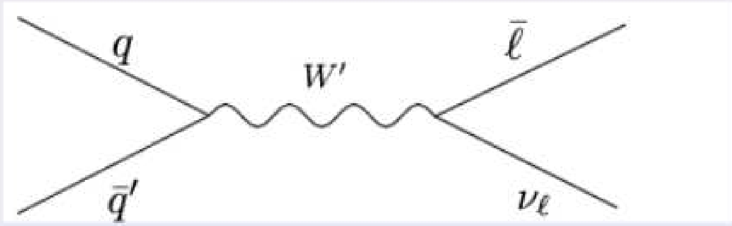
$$M_T = \sqrt{\left(\sum_{i=1}^{N} E_{T_i}\right)^2 - \left(\sum_{i=1}^{N} \vec{p}_{T_i}\right)^2} \quad (2.a.)$$

  - Ref: V. Barger et al., Z.Phys. C21 (1983) 99
  - Comments:
    - Not fully Lorentz invariant (only along longitudinal boosts)
    - This is how the W mass is measured at hadron collider experiments

Search for Z'

- Relevant Models: GUT or RS Extra Dimensions

Search for W': Principles (1)



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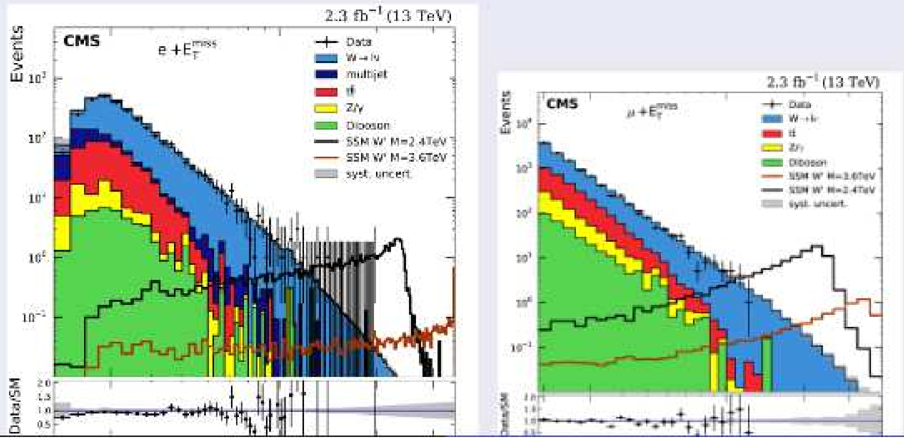
Search for W’

- Relevant Models: GUT or RS Extra Dimensions

Search for W': Typical Analysis $\longrightarrow$ Ref: arXiv:1612.09274 [hep-ex]

- Event Topology: $\ell = e/\mu + \not{E}_T$
- Main background process: $q\bar{q} \rightarrow W^* \rightarrow \ell^{\pm}\nu$ (aka Drell-Yan production)
- Data sample: $\int \mathcal{L}dt = \ fb^{-1}$ of CMS pp collisions at $\sqrt{s} = 13$ TeV (201?)
- Event Selection:
  - Trigger: 1 $e^{\pm}$ w/ $p_T(e^{\pm}) > 105/115$ GeV or 1 $\mu^{\pm}$ w/ $p_T(\mu^{\pm}) > 45/50$ GeV
  - Offline: 1 isolated $e^{\pm}/\mu^{\pm}$ (reject events w/ 2 leptons), $0.4 < \frac{p_T(\ell^{\pm})}{\not{E}_T} < 1.5$
- Final discriminant: Transverse Mass
- Sensitivity to signal: depends crucially on
  - Signal natural width: $\Gamma_{W'}$ (model dependent)
  - Transverse mass resolution: resulting from $\frac{\sigma_E}{E}(e^{\pm})$ or $\frac{\sigma_p}{p}(\mu^{\pm})$ and $\frac{\sigma_{\not{E}_T}}{\not{E}_T}$

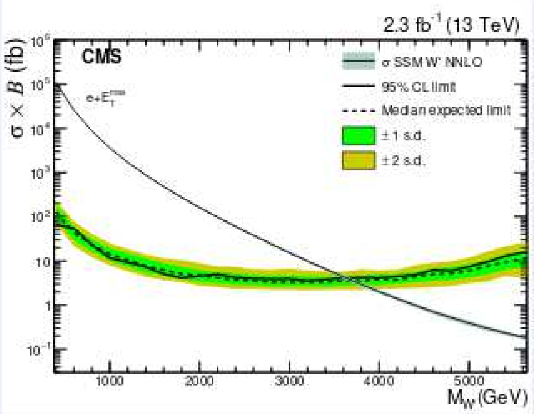


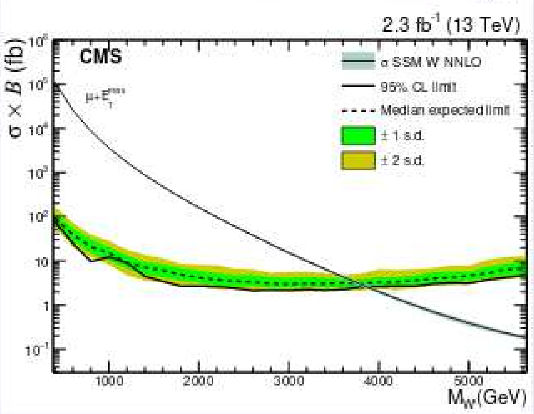
Search for W'

- Relevant Models: GUT or RS Extra Dimensions

Search for W': Typical Analysis $\longrightarrow$ Ref: arXiv:1612.09274 [hep-ex]

- Event Topology: $\ell = e/\mu + \not{E}_T$
- Main background process: $q\bar{q} \to W^* \to \ell^\pm \nu$ (aka Drell-Yan production)
- Data sample: $\int \mathcal{L}dt = \ fb^{-1}$ of CMS pp collisions at $\sqrt{s} = 13$ TeV (201?)
- Event Selection:
  - Trigger: 1 $e^\pm$ w/ $p_T(e^\pm) > 105/115$ GeV or 1 $\mu^\pm$ w/ $p_T(\mu^\pm) > 45/50$ GeV
  - Offline: 1 isolated $e^\pm/\mu^\pm$ (reject events w/ 2 leptons), $0.4 < \frac{p_T(\ell^\pm)}{\not{E}_T} < 1.5$
- Final discriminant: Transverse Mass
- Sensitivity to signal: depends crucially on
  - Signal natural width: $\Gamma_{W'}$ (model dependent)
  - Transverse mass resolution: resulting from $\frac{\sigma_E}{E}(e^\pm)$ or $\frac{\sigma_p}{p}(\mu^\pm)$ and $\frac{\sigma_{\not{E}_T}}{\not{E}_T}$





Search for W'

- Relevant Models: GUT or RS Extra Dimensions

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- Event Topology: $\ell = e/\mu + \not{E}_T$
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  - Offline: 1 isolated $e^{\pm}/\mu^{\pm}$ (reject events w/ 2 leptons), $0.4 < \frac{p_T(\ell^{\pm})}{\not{E}_T} < 1.5$
- Final discriminant: Transverse Mass
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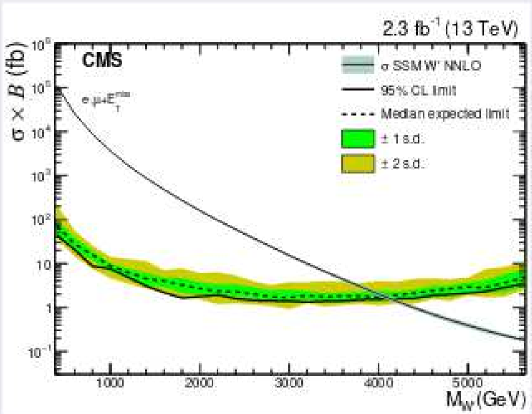
  - Transverse mass resolution: resulting from $\frac{\sigma_E}{E}(e^{\pm})$ or $\frac{\sigma_p}{p}(\mu^{\pm})$ and $\frac{\sigma_{\not{E}_T}}{\not{E}_T}$

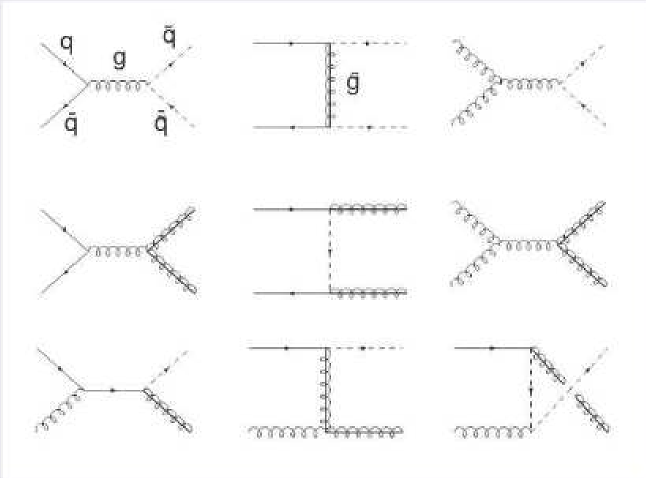


SUSY: Production Processes

- Relevant Models: SUSY, SUSY GUT, SuperString / M-Theory

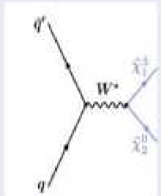
SUSY Strong Production at LHC

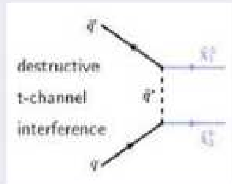
- Shortname: "SUSY QCD"
- Sparticles:
  - 1^{st}& 2^{nd} generation squarks $\tilde{q}$: scalar u, scalar s,...
  - 3^{rd} generation squarks $\tilde{Q}$: stops $(\tilde{t}_{1,2})$, sbottoms $(\tilde{b}_{1,2})$
  - gluinos $\tilde{g}$
- Cross section: $\sigma(pp \to \tilde{q}\tilde{q}/\tilde{q}\tilde{g}/\tilde{g}\tilde{g})_{LO} \propto \alpha_3^2$

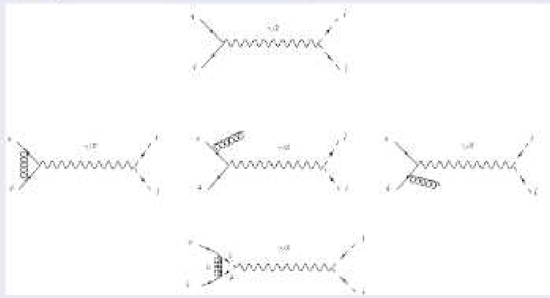


SUSY EWK Production at LHC

- Shortname: "SUSY EWK"
- Sparticles:
  - sleptons:
    charged (staus, smuons, selectrons $\tilde{\ell}^{\pm}$
    neutral (sneutrinos $\tilde{\nu}$)
  - "electroweakinos":
    charginos $\tilde{\chi}^{\pm}_{1,2}$
    neutralinos $\tilde{\chi}^{0}_{1,2,3,4}$
- Cross section:
  $\sigma(pp \to \tilde{\ell}^{\pm}\tilde{\nu}/\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0)_{LO} \propto \alpha_2^2$

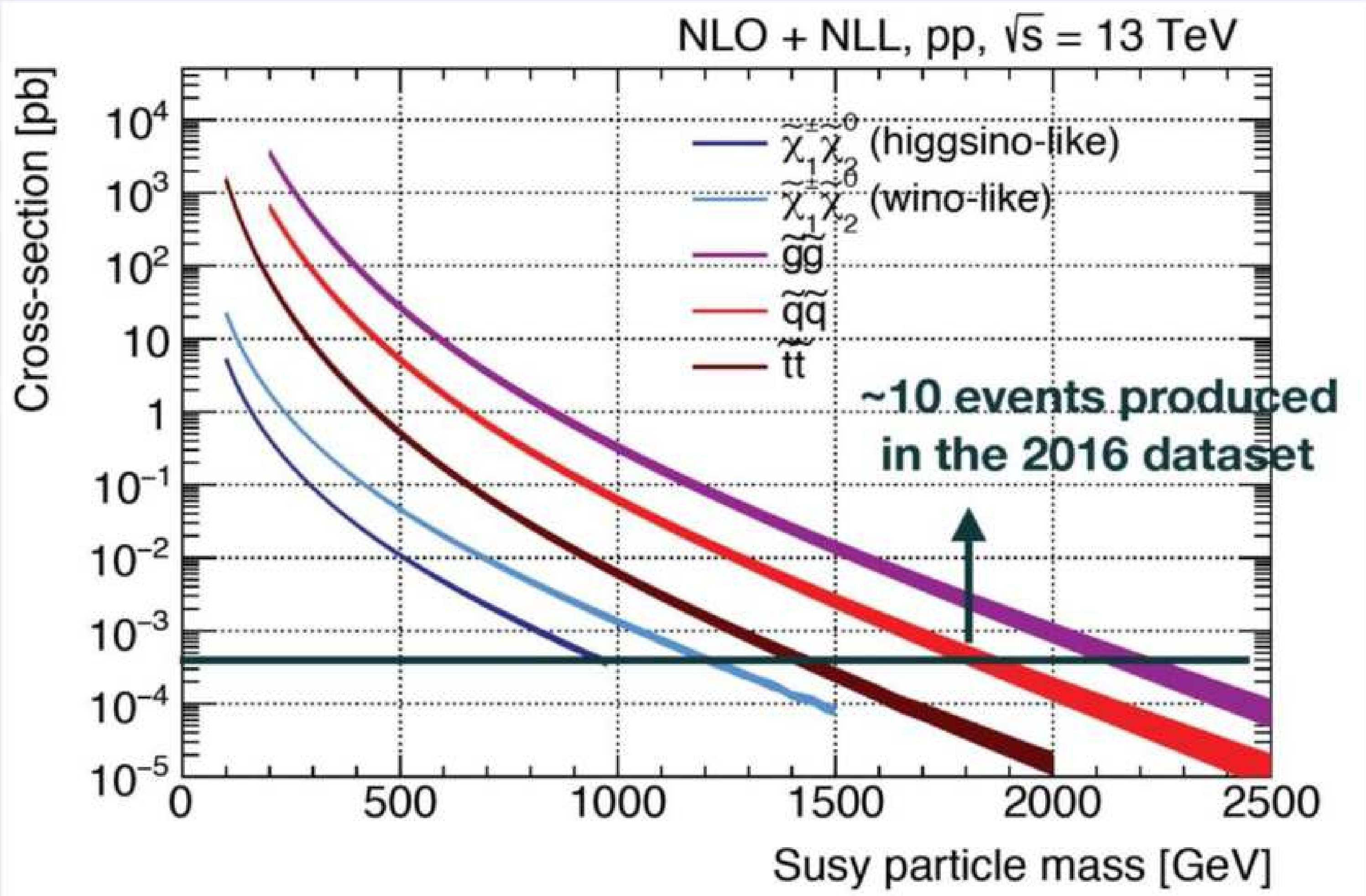




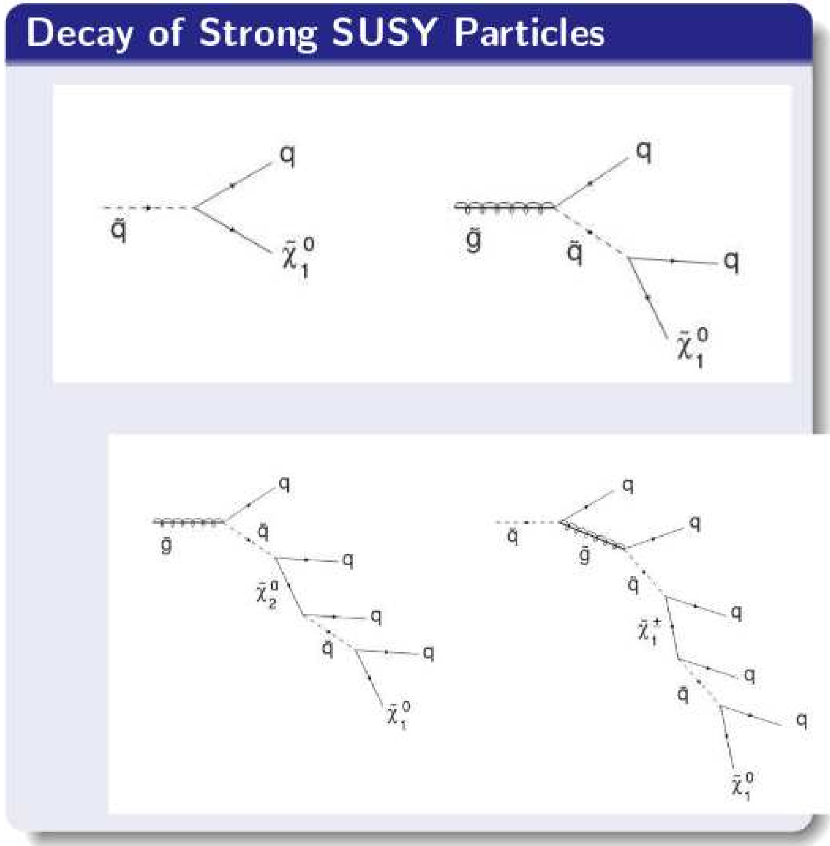


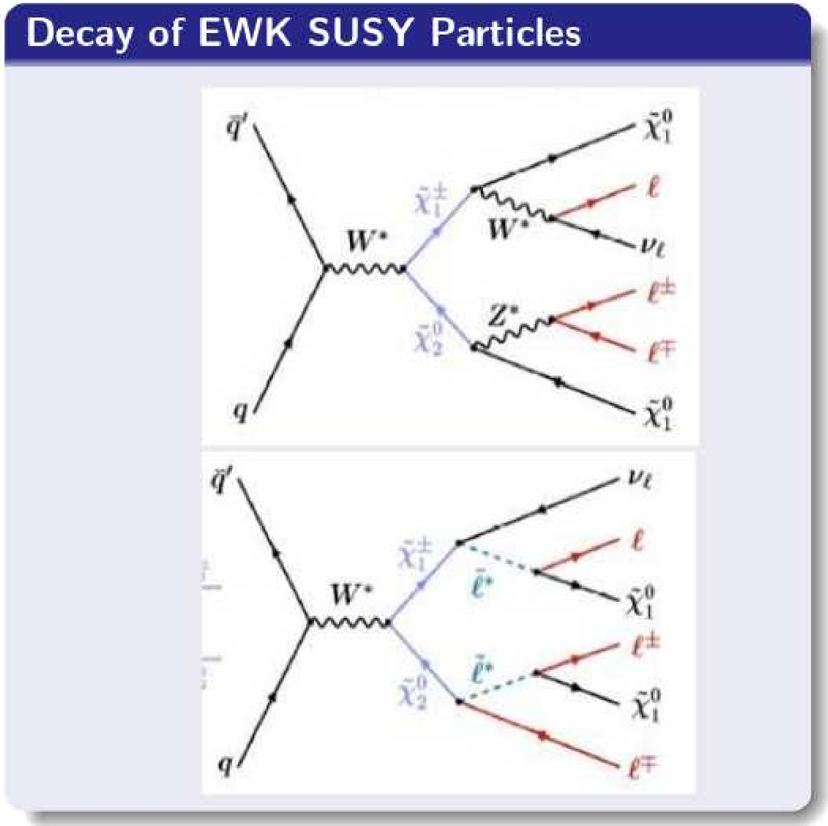
SUSY: Production Cross Sections

- State-of-the-art theory prediction:
  - Matrix Elements (MEs): σ_{NLO} (Next-to-Leading Order: "1-loop" QCD corrections)
  - Resummation: σ_{NLL} (Next-to-Leading Logs)



SUSY: Decay Modes

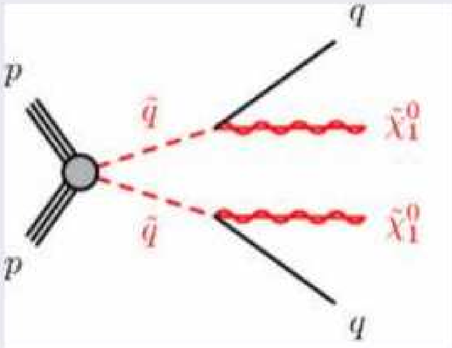


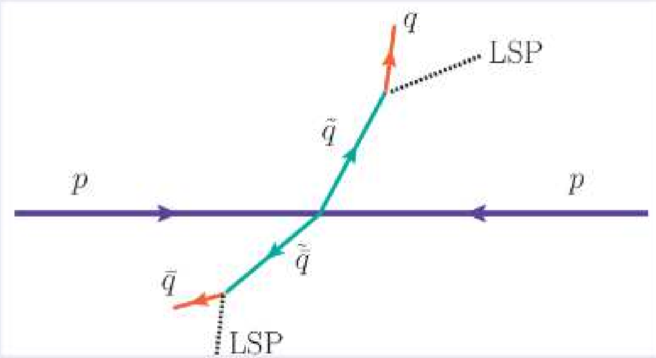


SUSY: from Decays to Search Topologies

Relation between Decay Chain & Search Topology

- Simple example:
  squarks pair production searched for in the acoplanar $2j + \not{E}_T$ event topology



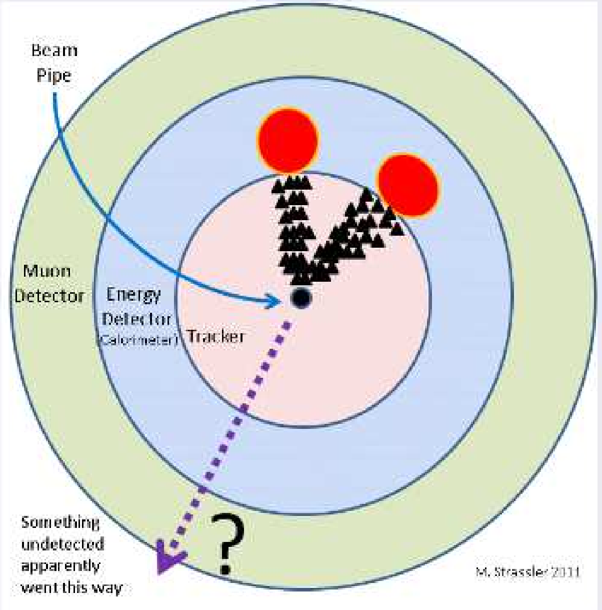


- General case: $(n)j + (m)\ell^{\pm} + (p)\gamma + \not{E}_T$ event topology
  - w/ different the jets flavours: $b-jets$, $c-jets$, $\tau-jets$, $LF-jets$ (LF: u/d/s/g)
  - $\ell^{\pm}$ stands for $e^{\pm}$ or $\mu^{\pm}$

SUSY: Search Topologies

Relation between Decay Chain & Search Topology

- Simple example:
  squarks pair production searched for in the acoplanar $2j + \not{E}_T$ event topology

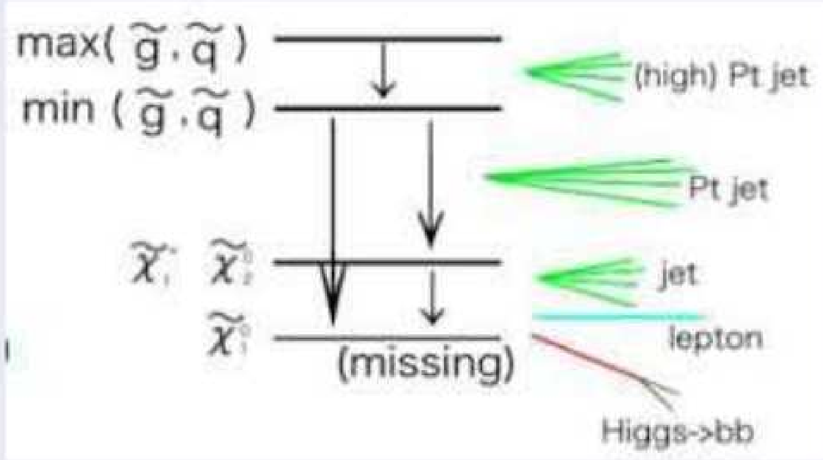


- General case: $(n)j + (m)\ell^{\pm} + (p)\gamma + \not{E}_T$ event topology
  - w/ different the jets flavours: $b-jets$, $c-jets$, $\tau-jets$, $LF-jets$ (LF: u/d/s/g)
  - $\ell^{\pm}$ stands for $e^{\pm}$ or $\mu^{\pm}$

SUSY: Phase Space in Decay Chains

Relation between Decay Chain & Search Topology

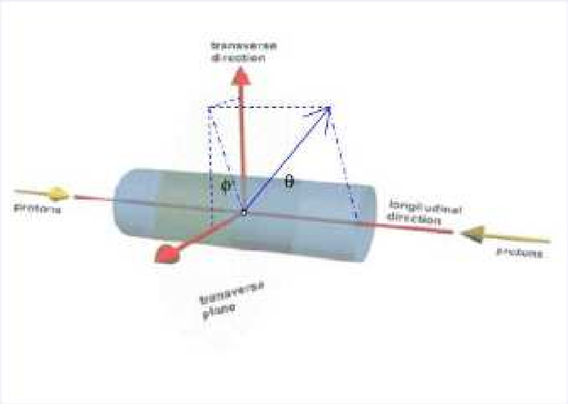
- Simple example:
  squarks pair production searched for in the acoplanar $2j + \not{E}_T$ event topology
- General case: $(n)j + (m)\ell^{\pm} + (p)\gamma + \not{E}_T$ event topology
  - w/ different the jets flavours: $b - jets$, $c - jets$, $\tau - jets$, $LF - jets$ (LF: u/d/s/g)
  - $\ell^{\pm}$ stands for $e^{\pm}$ or $\mu^{\pm}$



SUSY: Basic Analysis Variables

Search for squarks & gluinos: Specific Variables

- Event Topology: products$(n)j + (m)\ell^{\pm} + \not{E}_T$ ($p \neq 0$ for GMSB)
- No obvious distinctive features over the large QCD background
- Usual Angular Variables:



$$\begin{cases} y = \frac{1}{2} Log \frac{(E+p_z)}{(E-p_z)} \\ \eta = -Log\left(tan\frac{\theta}{2}\right) \\ \Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \\ \Delta\phi_{min}(jets, \not{E}_T) \end{cases} \quad (8)$$

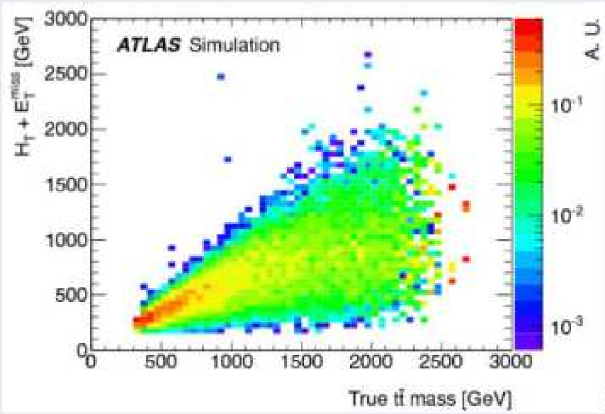
SUSY: Effective Mass

Search for squarks & gluinos: Specific Variables

- Effective Mass:

$$M_{eff} = \sum_{i=1}^{N} p_{T_i}^{jets} + p_{T_i}^{leptons} + \not{E}_T \quad (9)$$

  - Not Lorentz invariant
  - But, sensitive to mass scale
    - $pp \to \tilde{g} + \tilde{q}$: $M_{eff}\, Min(M_{\tilde{g}}, M_{\tilde{q}})$
  - Yet, not precise and slightly biased
  - Ref: F. Paige, in A. Bartl et al., Proc. of Snowmass (1996) 693, [hep-ph/9612359]
  - Ref: F. Paige, in I. Hinchliffe et al., Phys. Rev. D55 (1997) 5520, [hep-ph/9610544]

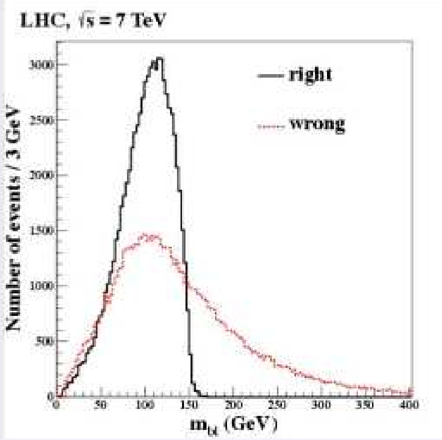


Search for $Z' \to t\bar{t}$

SUSY: Stransverse Mass

Search for squarks & gluinos: Specific Variables

- Stransverse Mass:
  - Partly Lorentz invariant (only along longitudinal boosts)
  - Sensitive to mass difference
  - In practice end-points are difficult to measure (smearing, background, pile-up,...)
  - Ref: C. Lester, D. Summers, Phys. Lett. B463 (1999) 99-103, arXiv:9906349



$t\bar{t}$ dilepton channel

$$M_{T2}\left[vis^{(A)}, vis^{(B)}|M_\chi^{trial}\right] =$$

$$\min_{\vec{\not{E}}_T=\vec{\not{E}}_T^{(A)}+\vec{\not{E}}_T^{(B)}} Max\left[M_T(\vec{p}_T^{vis(A)}, \vec{\not{E}}_T^{(A)}|M_\chi^{trial}), M_T(\vec{p}_T^{vis(B)}, \vec{\not{E}}_T^{(B)}|M_\chi^{trial})\right] \quad (10)$$

$$M_T^{2(A)} = M^{2(A)} + M^{2(\chi A)} + 2\left[E_T^{(A)}E_T^{(\chi A)} - \vec{p}_T^{(A)}\vec{p}_T^{(\chi A)}\right] \quad (11)$$

$M_{T2} \leq M_{Parent}$ and $M_{T2}^{Edge} \approx M_{Parent}$

(provided $M_\chi = M_{\tilde{\chi}_1^0}$)(12)

SUSY: Stransverse Mass

Search for squarks & gluinos: Specific Variables

- Stransverse Mass:
  - Partly Lorentz invariant (only along longitudinal boosts)
  - Sensitive to mass difference
  - In practice end-points are difficult to measure (smearing, background, pile-up,...)
  - Ref: C. Lester, D. Summers, Phys. Lett. B463 (1999) 99-103, arXiv:9906349

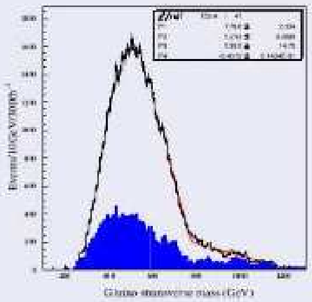
$$M_{T2}\left[vis^{(A)}, vis^{(B)}|M_{\chi}^{trial}\right] =$$

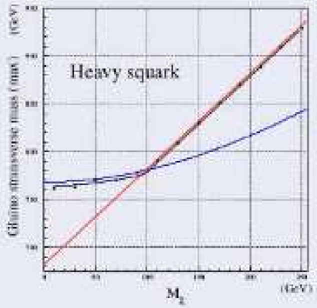
$$\min_{\vec{\not{E}}_T=\vec{\not{E}}_T^{(A)}+\vec{\not{E}}_T^{(B)}} Max\left[M_T(\vec{p}_T^{vis(A)}, \vec{\not{E}}_T^{(A)}|M_{\chi}^{trial}), M_T(\vec{p}\right)$$

$$M_T^{2(A)} = M^{2(A)}+M^{2(\chi A)}+2\left[E_T^{(A)}E_T^{(\chi A)} - \vec{p}_T^{(A)}\vec{p}_T^{(\chi A)}\right] \quad (11)$$

$M_{T2} \leq M_{Parent}$ and $\mathrm{M}_{\mathrm{T2}}^{\mathrm{Edge}} \approx \mathrm{M}_{\mathrm{Parent}}$

(provided $\mathrm{M}_{\chi} = M_{\tilde{\chi}_1^0}$)(12)





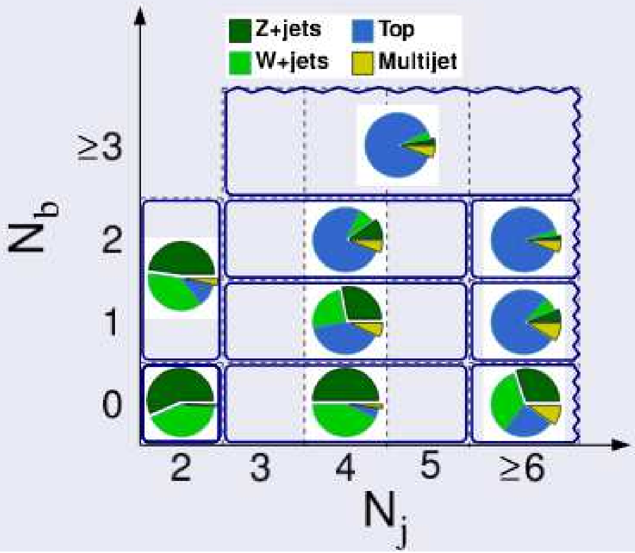
Properteis of Stransverse Mass

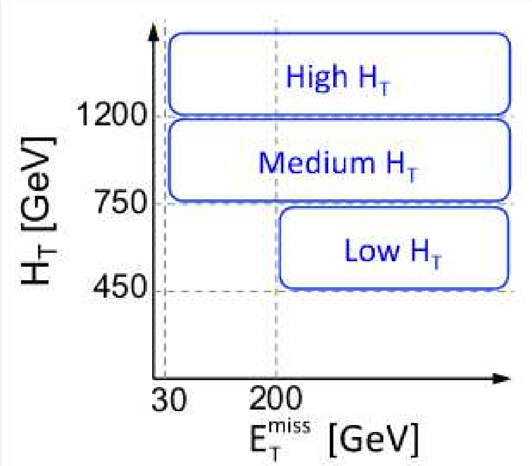
SUSY: Search in Jets+mET Topology

Search for squarks and gluinos: Typical M_{T2}-based Search

Ref: arXiv:1502.04358 [hep-ex]

- Event Topology: "$(n_{LF})j + (n_b)j + (0)\ell^{\pm}\not{E}_T$"
- Main background process: $Z(\to \nu\bar{\nu}) + jets$, $W^{\pm}(\to \ell^{\pm}\nu) + jets$, $t\bar{t}$ and QCD
- Data sample: $\int \mathcal{L}dt = 19.5\ fb^{-1}$ of CMS pp collisions at $\sqrt{s} = 8$ TeV (2012)
- Event Selection: $H_T = \sum_{i=1}^{N_j} p_{T_i}$
  - Trigger: $H_T > 650$ GeV OR $\not{E}_T > 150$ GeV OR $H_T > 350$ GeV& $\not{E}_T > 100$ GeV
  - Offline: 2 jets with $p_T > 100$ GeV and $|\eta| < 3.0$
    $H_T > 750$ GeV, OR $H_T > 450$ GeV, AND $\not{E}_T > 200$ GeV
    suppress QCD: $\Delta\phi_{min}(jets, \not{E}_T) > 0.3$ rad
- Final discriminant: events are clustered into 2 fat jets, $M_{T2} > 100 - 200$ GeV





SUSY: Search in Jets+mET Topology

Search for squarks and gluinos: Typical M_{T2}-based Search $\longrightarrow$ Link

- Event Topology: "$(n_{LF})j + (n_b)j + (0)\ell^{\pm} \not{E}_T$"
- Main background process: $Z(\to \nu\bar{\nu}) + jets$, $W^{\pm}(\to \ell^{\pm}\nu) + jets$, $t\bar{t}$ and QCD
- Data sample: $\int \mathcal{L}dt = 19.5\ fb^{-1}$ of CMS pp collisions at $\sqrt{s} = 8$ TeV (2012)
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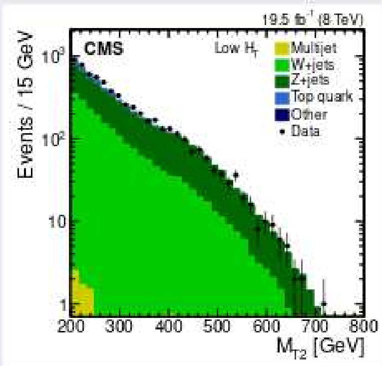
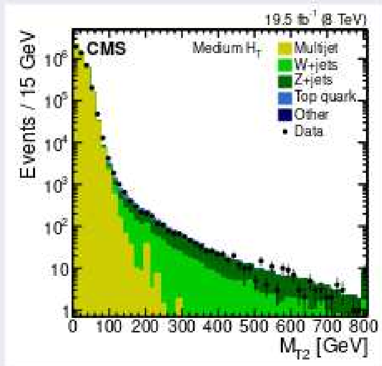
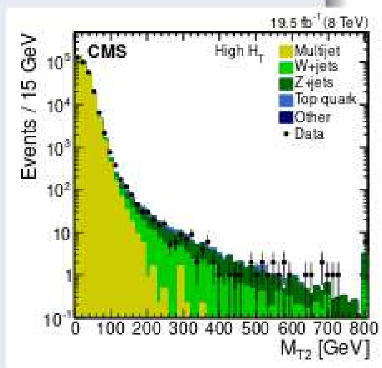


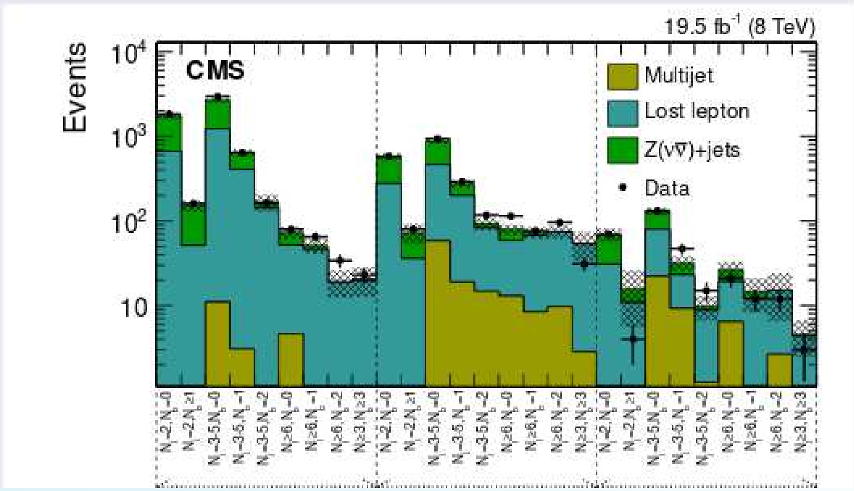




SUSY: Search in Jets+mET Topology

Search for squarks and gluinos: Typical M_{T2}-based Search $\longrightarrow$ Link

- Event Topology: "$(n_{LF})j + (n_b)j + (0)\ell^{\pm}\not{E}_T$"
- Main background process: $Z(\rightarrow \nu\bar{\nu}) + jets$, $W^{\pm}(\rightarrow \ell^{\pm}\nu) + jets$, $t\bar{t}$ and QCD
- Data sample: $\int \mathcal{L}dt = 19.5\ fb^{-1}$ of CMS pp collisions at $\sqrt{s} = 8$ TeV (2012)
- Event Selection: $H_T = \sum_{i=1}^{N_j} p_{T_i}$
  - Trigger: $H_T > 650$ GeV OR $\not{E}_T > 150$ GeV OR $H_T > 350$ GeV& $\not{E}_T > 100$ GeV
  - Offline: 2 jets with $p_T > 100$ GeV and $|\eta| < 3.0$
    $H_T > 750$ GeV, OR $H_T > 450$ GeV, AND $\not{E}_T > 200$ GeV
    suppress QCD: $\Delta\phi_{min}(jets, \not{E}_T) > 0.3$ rad
- Final discriminant: events are clustered into 2 fat jets, $M_{T2} > 100 - 200$ GeV



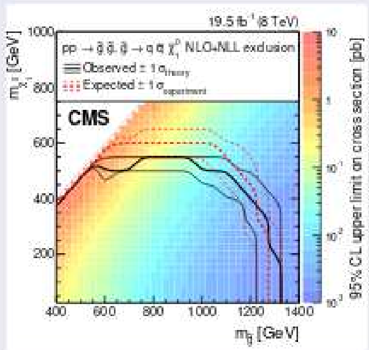
SUSY: Limits in Jets+mET Topology

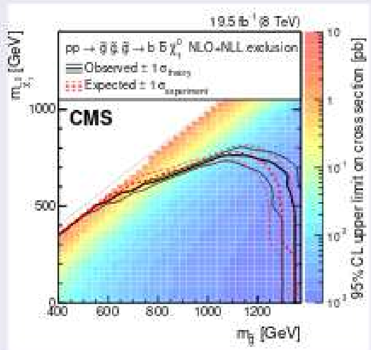
Search for squarks and gluinos: Typical M_{T2}-based Search $\longrightarrow$ Link

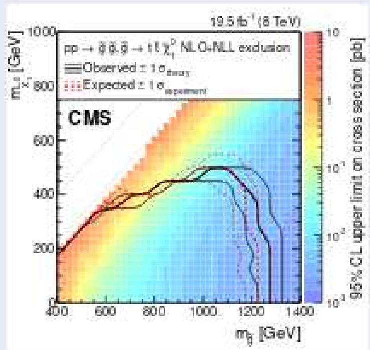
- Event Topology: "$(n_{LF})j + (n_b)j + (0)\ell^{\pm}\not{E}_T$"
- Main background process: $Z(\rightarrow \nu\bar{\nu}) + jets$, $W^{\pm}(\rightarrow \ell^{\pm}\nu) + jets$, $t\bar{t}$ and QCD
- Data sample: $\int \mathcal{L}dt = 19.5\ fb^{-1}$ of CMS pp collisions at $\sqrt{s} = 8$ TeV (2012)
- Event Selection: $H_T = \sum_{i=1}^{N_j} p_{T_i}$
  - Trigger: $H_T > 650$ GeV OR $\not{E}_T > 150$ GeV OR $H_T > 350$ GeV& $\not{E}_T > 100$ GeV
  - Offline: 2 jets with $p_T > 100$ GeV and $|\eta| < 3.0$

    $H_T > 750$ GeV, OR $H_T > 450$ GeV, AND $\not{E}_T > 200$ GeV

    suppress QCD: $\Delta\phi_{min}(jets, \not{E}_T) > 0.3$ rad
- Final discriminant: events are clustered into 2 fat jets, $M_{T2} > 100 - 200$ GeV







SUSY: Dilepton Edge (1/2)

Search for Direct Production of Electroweakinos: Specific Variables

- Dilpeton Mass Edge:
  - Lorentz invariant
  - Sensitive to mass difference
  - Very accurate
    - $pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to 3\ell^{\pm} + \not{E}_T$
    - 2-body DK:

$$M_{\ell^+\ell^-}^{max} = M_{\tilde{\chi}_2^0} \times \sqrt{\left(1 - \frac{M^2_{\tilde{\ell}_2^{\pm}}}{M^2_{\tilde{\chi}_2^0}}\right)\left(1 - \frac{M^2_{\tilde{\chi}_1^0}}{M^2_{\tilde{\ell}_2^{\pm}}}\right)} \quad (13)$$

    - 3-body DK:

$$M_{\ell^+\ell^-}^{max} = M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0} \quad (14)$$

  - Ref: H. Baer et al., Phys. Rev. D 50 (1994) 4508 [hep-ph/9404212]

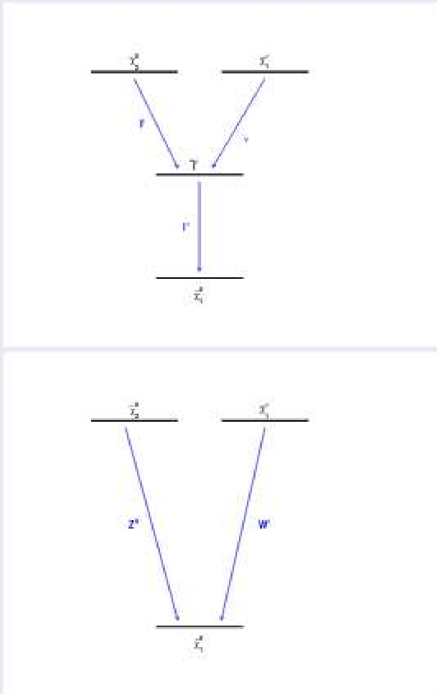


Figure: $\tilde{\chi}_2^0$ 2-body (top) and 3-body (bottom) leptonic decay

SUSY: Dilepton Edge (2/2)

Search for Direct Production of Electroweakinos: Specific Variables

- Dilpeton Mass Edge:
  - Lorentz invariant
  - Sensitive to mass difference
  - Very accurate
    - $pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to 3\ell^{\pm} + \not{E}_T$
    - 2-body DK:

$$M_{\ell^+\ell^-}^{max} = M_{\tilde{\chi}_2^0} \times \sqrt{\left(1 - \frac{M^2_{\tilde{\ell}_2^{\pm}}}{M^2_{\tilde{\chi}_2^0}}\right)\left(1 - \frac{M^2_{\tilde{\chi}_1^0}}{M^2_{\tilde{\ell}_2^{\pm}}}\right)} \quad (13)$$

    - 3-body DK:

$$M_{\ell^+\ell^-}^{max} = M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0} \quad (14)$$

- Ref: H. Baer et al., Phys. Rev. D 50 (1994) 4508 [hep-ph/9404212]

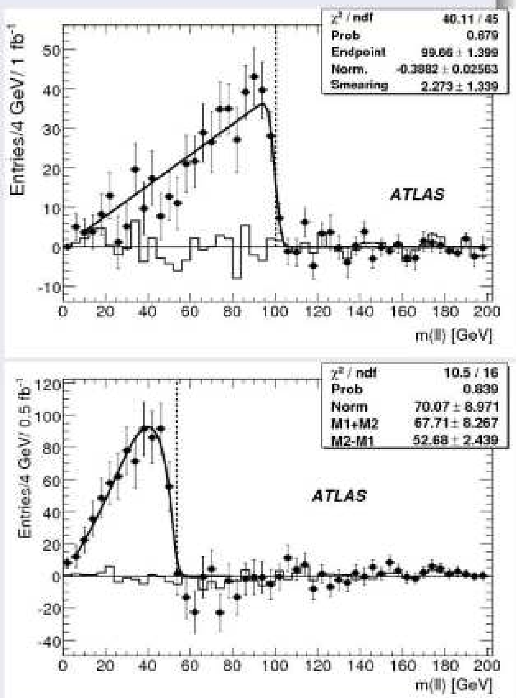
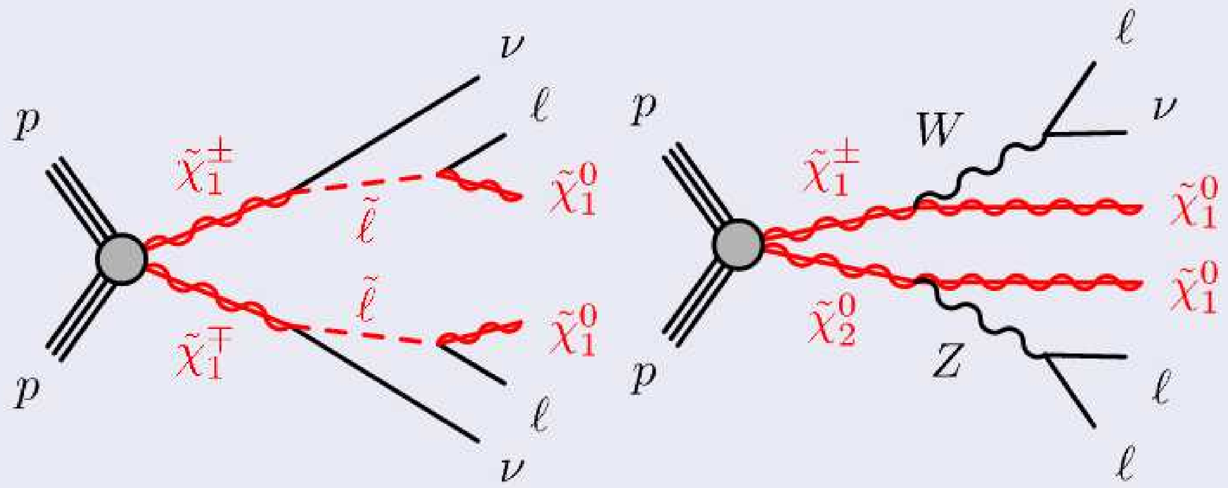


Figure: $\tilde{\chi}_2^0$ 2-body (top) and 3-body (bottom) leptonic decay

SUSY: EWK Production Mechanisms

- Search for EWK SUSY particles with first data of ATLAS Run 2
- Dataset: 2015-2016
- Center-of-mass energy: 13 TeV
- Integrated luminosity: 36.1 fb^{-1}

Search for chargino-neutralino pairs: Typical Search $\longrightarrow$ Ref: arXiv:1803.02762 [hep-ex]



SUSY: Search in Trilepton Topology

Search for chargino-neutralino pairs: Typical Search ⟶ Ref: arXiv:1803.02762 [hep-ex]

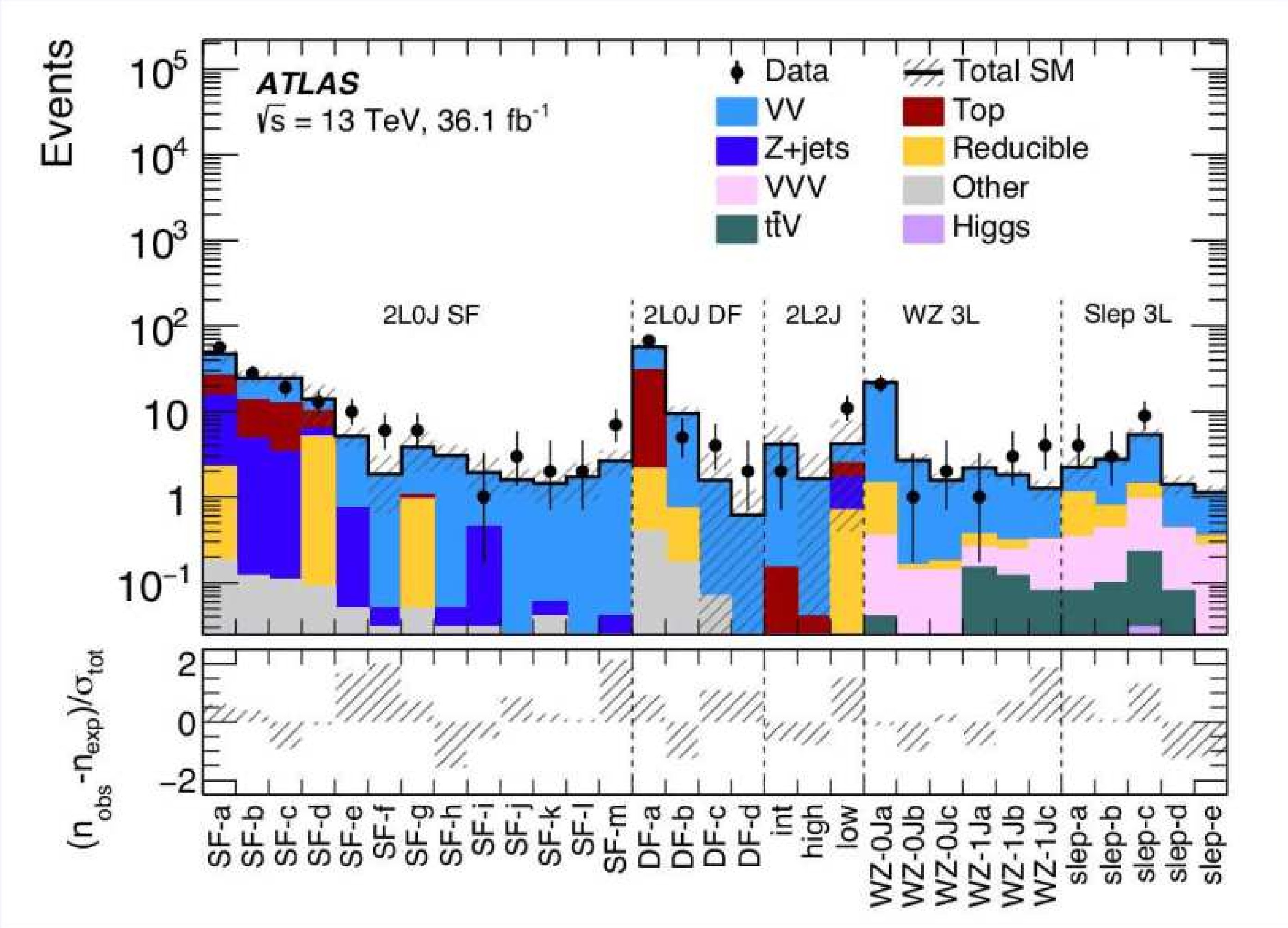
- Event Topology: "$3\ell^{\pm} + \not{E}_T$"
- Main background process: $W^{\pm}(\to \ell^{\pm}\nu) + Z(\to \ell^{+}\ell^{-})$
- Data sample: $\int \mathcal{L}dt = 36.1\ fb^{-1}$ of ATLAS pp collisions at $\sqrt{s} = 13$ TeV (2015-2016)
- Event Selection:
  - Trigger: dilepton
  - Offline:

3ℓ exclusive signal region definitions

m_{SFOS} [GeV]	$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$p_{\mathrm{T}}^{\ell_3}$ [GeV]	$n_{\text{non-}b\text{-tagged jets}}$	$m_{\mathrm{T}}^{\mathrm{min}}$ [GeV]	$p_{\mathrm{T}}^{\ell\ell\ell}$ [GeV]	$p_{\mathrm{T}}^{\mathrm{jet1}}$ [GeV]	Bins
<81.2	> 130	20–30 > 30		> 110			SR3-slep-a SR3-slep-b
>101.2	> 130	20–50 50–80 > 80		> 110			SR3-slep-c SR3-slep-d SR3-slep-e
81.2–101.2	60-120 120–170 > 170		0	> 110			SR3-WZ-0Ja SR3-WZ-0Jb SR3-WZ-0Jc
81.2-101.2	120–200 > 200	> 35	≥ 1	> 110 110–160 > 160	< 120	> 70	SR3-WZ-1Ja SR3-WZ-1Jb SR3-WZ-1Jc

SUSY

Search for chargino-neutralino pairs: Typical Search ⟶ Ref: arXiv:1803.02762 [hep-ex]

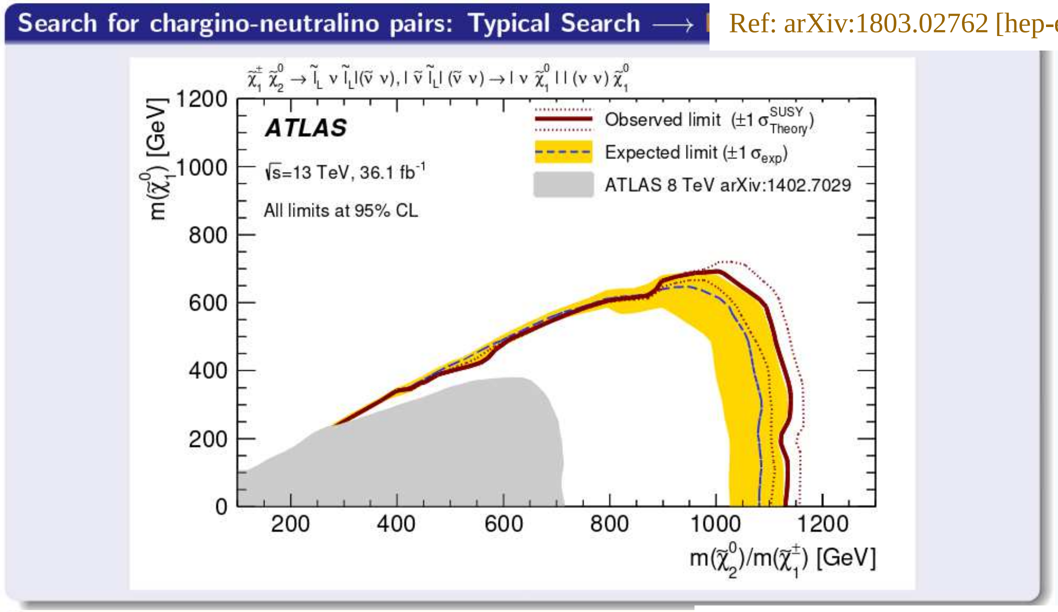


SUSY

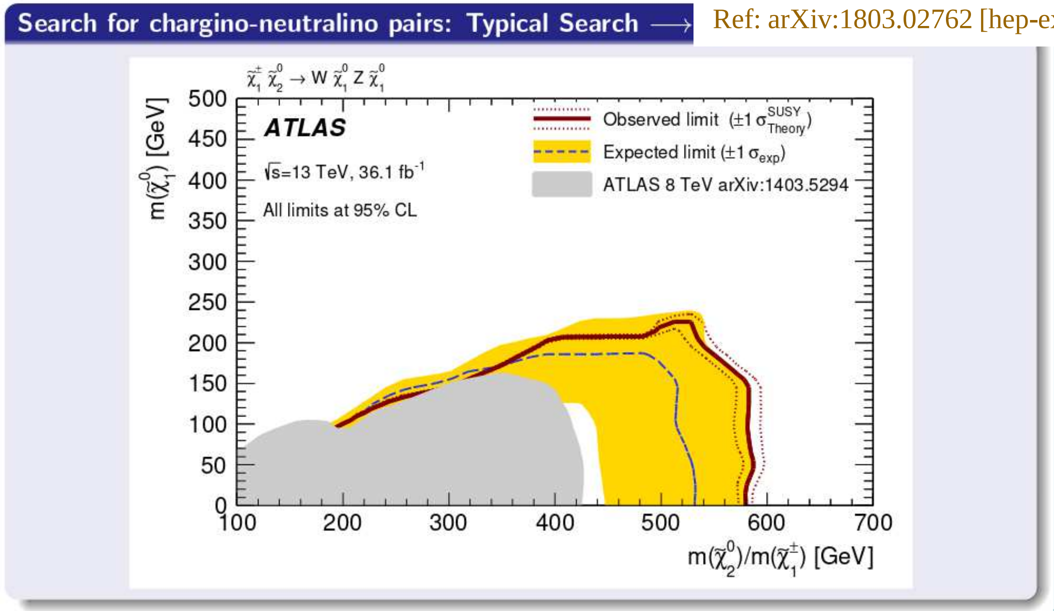
Search for chargino-neutralino pairs: Typical Search $\longrightarrow$ Ref: arXiv:1803.02762 [hep-ex]

Signal channel	Region	N_{obs}	N_{exp}	$\langle\epsilon\sigma\rangle^{95}_{obs}$[fb]	S^{95}_{obs}	S^{95}_{exp}	$p(s{=}0)$	Z
2ℓ+0jets	DF-100	78	68 ± 7	0.88	32	27^{+11}_{-8}	0.22	0.77
	DF-150	11	11.5 ± 3.1	0.32	11.4	12^{+5}_{-4}	0.5	0
	DF-200	6	2.1 ± 1.9	0.33	12.0	$10.3^{+2.9}_{-1.9}$	0.06	1.5
	DF-300	2	0.6 ± 0.6	0.18	6.6	$5.6^{+1.1}_{-0.9}$	0.10	1.3
	SF-loose	153	133 ± 22	2.02	73	53^{+21}_{-16}	0.16	1.0
	SF-tight	9	9.8 ± 2.9	0.29	10.5	12^{+4}_{-3}	0.5	0
2ℓ+jets	SR2-int	2	$4.1^{+2.6}_{-1.8}$	0.13	4.5	$5.6^{+2.2}_{-1.4}$	0.5	0
	SR2-high	0	$1.6^{+1.6}_{-1.1}$	0.09	3.1	$3.1^{+1.4}_{-0.1}$	0.5	0
	SR2-low	11	$4.2^{+3.4}_{-1.6}$	0.43	15.7	12^{+4}_{-2}	0.06	1.6
3ℓ	WZ-0Ja	21	21.7 ± 2.9	0.35	12.8	14^{+3}_{-5}	0.5	0
	WZ-0Jb	1	2.7 ± 0.5	0.10	3.7	$4.6^{+2.1}_{-0.9}$	0.5	0
	WZ-0Jc	2	1.6 ± 0.3	0.13	4.8	$4.1^{+1.7}_{-0.7}$	0.28	0.57
	WZ-1Ja	1	2.2 ± 0.5	0.09	3.2	$4.5^{+1.6}_{-1.3}$	0.5	0
	WZ-1Jb	3	1.8 ± 0.3	0.16	5.6	$4.3^{+1.7}_{-0.9}$	0.18	0.91
	WZ-1Jc	4	1.3 ± 0.3	0.20	7.2	$4.2^{+1.7}_{-0.4}$	0.03	1.8
	slep-a	4	2.2 ± 0.8	0.19	6.8	$4.7^{+2.3}_{-0.5}$	0.23	0.72
	slep-b	3	2.8 ± 0.4	0.14	5.2	$5.1^{+1.9}_{-1.2}$	0.47	0.08
	slep-c	9	5.4 ± 0.9	0.29	10.5	$6.8^{+2.9}_{-1.3}$	0.09	1.4
	slep-d	0	1.4 ± 0.4	0.08	3.0	$3.6^{+1.2}_{-0.6}$	0.5	0
	slep-e	0	1.1 ± 0.2	0.09	3.3	$3.6^{+1.3}_{-0.5}$	0.5	0

SUSY



Ref: arXiv:1803.02762 [hep-ex]



Ref: arXiv:1803.02762 [hep-ex]

Latest SUSY Results from LHC

ATLAS

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

CMS

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

Search for Large Extra Dimensions

- Search for monojets with first data of ATLAS Run 2 (Ref: arXiv:1711.03301 [hep-ex])
- Dataset: 2015-2016
- Center-of-mass energy: 13 TeV
- Integrated luminosity: 36.1 fb^{-1}

- Triggers: $\not{E}_T > 90\,\text{GeV}$

- Offline Event Selection:

$$1 \leq N_{jets} \leq 4$$

$$\begin{cases} p_T(j_1) > 250\,\text{GeV} \\ |\eta(j_1)| < 2.4 \end{cases}$$

$$\begin{cases} p_T(j_{2,3,4}) > 30\,\text{GeV} \\ |\eta(j_{2,3,4})| < 2.8 \end{cases}$$

$$\begin{cases} \not{E}_T > 250\,\text{GeV} \\ \Delta\varphi[\vec{p}_T(\text{jets}), \vec{\not{E}}_T] > 0.4 \end{cases}$$

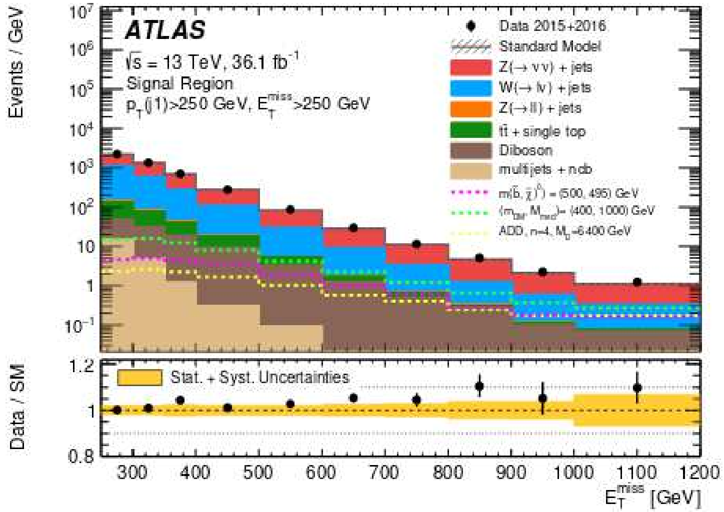
Reject events w/ isolated leptons:

$$\begin{cases} p_T(e^{\pm}) > 20\,\text{GeV} \\ |\eta(e^{\pm})| < 2.47 \end{cases} \qquad \begin{cases} p_T(\mu^{\pm}) > 10\,\text{GeV} \\ |\eta(\mu^{\pm})| < 2.5 \end{cases}$$

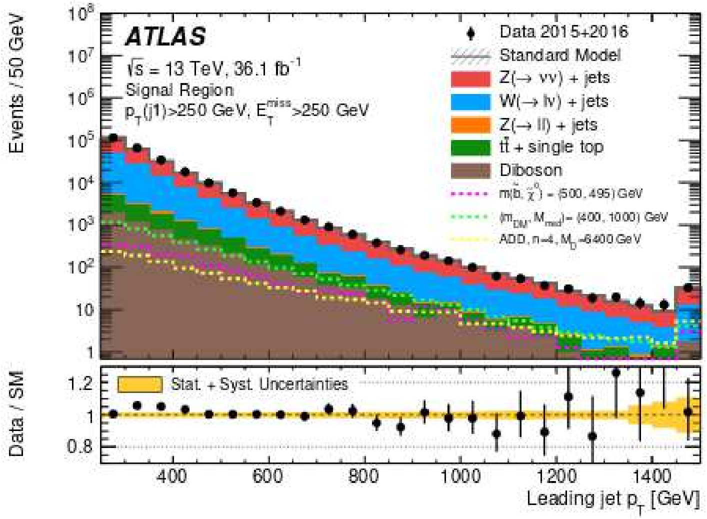
- Signal Regions:

Inclusive (IM)	IM1	IM2	IM3	IM4	IM5	IM6	IM7	IM8	IM9	IM10
E_T^{miss} [GeV]	>250	>300	>350	>400	>500	>600	>700	>800	>900	>1000
Exclusive (EM)	EM1	EM2	EM3	EM4	EM5	EM6	EM7	EM8	EM9	EM10
E_T^{miss} [GeV]	250–300	300–350	350–400	400–500	500–600	600–700	700–800	800–900	900–1000	>1000

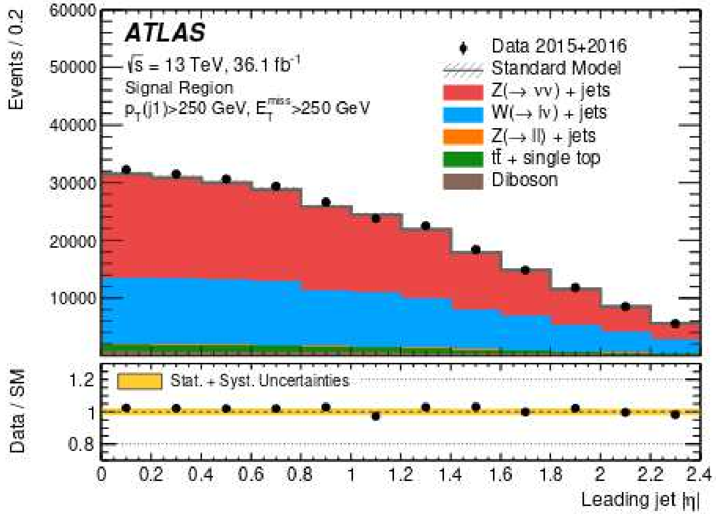
Search for Large Extra Dimensions



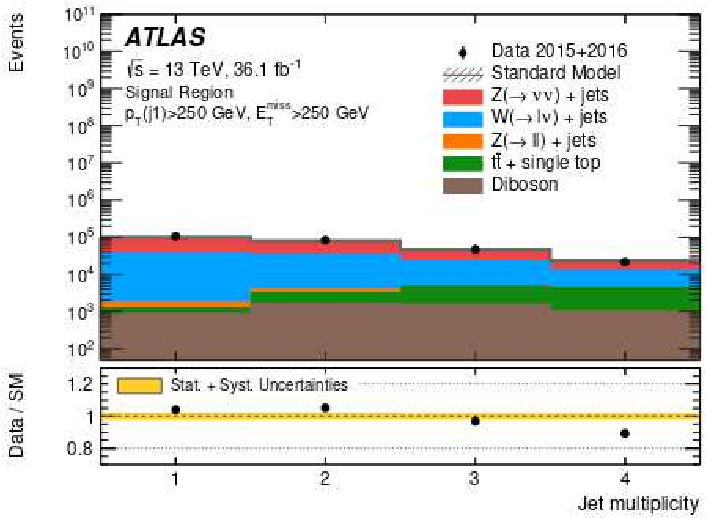
(a)



(b)



(c)



(d)

Search for Large Extra Dimensions

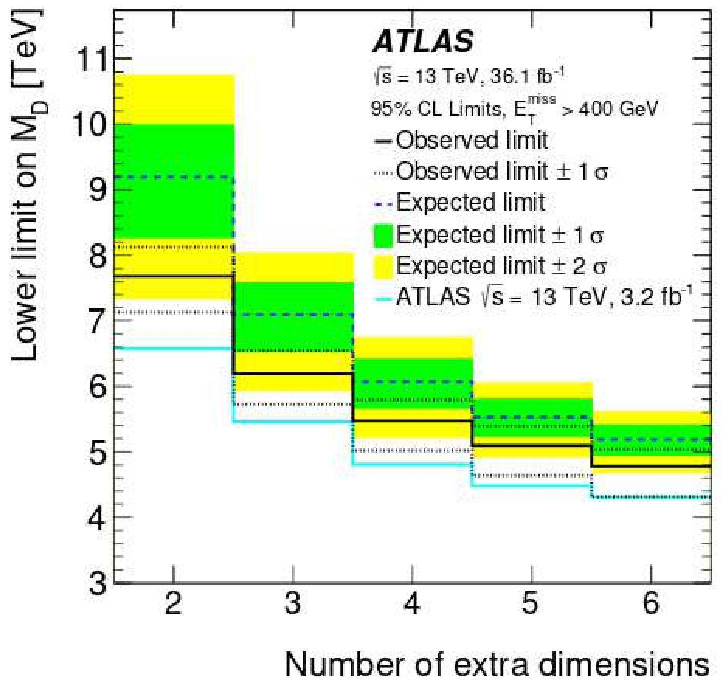
Exclusive Signal Region	EM2	EM4	EM6	EM8	EM9
Observed events (36.1 fb^{-1})	67475	27843	2975	512	223
SM prediction	67100 ± 1400	27640 ± 610	2825 ± 78	463 ± 19	213 ± 9
$W(\to e\nu)$	5510 ± 140	1789 ± 59	147 ± 9	18 ± 1	8 ± 1
$W(\to \mu\nu)$	6120 ± 200	2021 ± 82	173 ± 9	21 ± 5	11 ± 1
$W(\to \tau\nu)$	13680 ± 310	4900 ± 110	397 ± 11	55 ± 5	29 ± 2
$Z/\gamma^*(\to e^+e^-)$	0.03 ± 0	0.02 ± 0.02	–	–	–
$Z/\gamma^*(\to \mu^+\mu^-)$	167 ± 8	36 ± 2	2.0 ± 0.2	0.4 ± 0.1	0.5 ± 0.1
$Z/\gamma^*(\to \tau^+\tau^-)$	185 ± 6	68 ± 4	5.1 ± 0.3	0.3 ± 0.1	0.31 ± 0.04
$Z(\to \nu\bar{\nu})$	37600 ± 970	17070 ± 460	1933 ± 57	337 ± 12	153 ± 7
$t\bar{t}$, single top	2230 ± 200	848 ± 86	43 ± 6	4 ± 1	1.3 ± 0.4
Diboson	1327 ± 90	874 ± 64	124 ± 16	26 ± 5	10 ± 2
Multijet background	170 ± 160	13 ± 13	1 ± 1	1 ± 1	0.1 ± 0.1
Non-collision background	71 ± 71	18 ± 18	–	–	–

Inclusive Signal Region			Exclusive Signal Region		
Region	Predicted	Observed	Region	Predicted	Observed
IM1	245900 ± 5800	255486	EM1	111100 ± 2300	111203
IM2	138000 ± 3400	144283	EM2	67100 ± 1400	67475
IM3	73000 ± 1900	76808	EM3	33820 ± 940	35285
IM4	39900 ± 1000	41523	EM4	27640 ± 610	27843
IM5	12720 ± 340	13680	EM5	8360 ± 190	8583
IM6	4680 ± 160	5097	EM6	2825 ± 78	2975
IM7	2017 ± 90	2122	EM7	1094 ± 33	1142
IM8	908 ± 55	980	EM8	463 ± 19	512
IM9	464 ± 34	468	EM9	213 ± 9	223
IM10	238 ± 23	245	EM10	226 ± 16	245

Search for Large Extra Dimensions

ADD Model Limits on M_D (95% CL)			
	Expected [TeV]	Observed [TeV]	Observed (damped) [TeV]
$n = 2$	$9.2^{+0.8}_{-1.0}$	$7.7^{+0.4}_{-0.5}$	7.7
$n = 3$	$7.1^{+0.5}_{-0.6}$	$6.2^{+0.4}_{-0.5}$	6.2
$n = 4$	$6.1^{+0.3}_{-0.4}$	$5.5^{+0.3}_{-0.5}$	5.5
$n = 5$	$5.5^{+0.3}_{-0.3}$	$5.1^{+0.3}_{-0.5}$	5.1
$n = 6$	$5.2^{+0.2}_{-0.3}$	$4.8^{+0.3}_{-0.5}$	4.8

- Main Systematic Uncertainties :
  - Integrated luminosity: ΔL/L=3.2%
  - JES, JER, mET scale: 0.5% < ΔB/B < 5.3%
    (IM1) (IM10)
  - Total uncertainty: 2.4% < ΔB/B < 9.7%
    (IM1) (IM10)



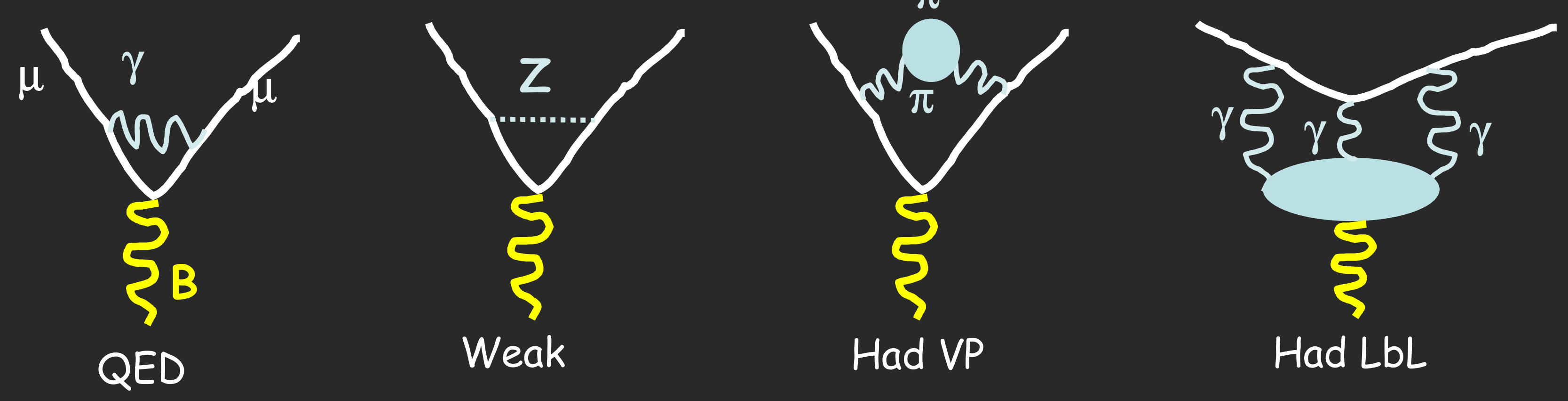
Muon Anomalous Magnetic Moment - Introduction -

- Magnetic dipole moment:
  - Charged particle w/ circular trajectory: $\vec{\mu}_L = \frac{e}{2mc}\vec{L}$ with $\vec{L} = \vec{r}\times\vec{p}$
  - 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

Muon Anomalous Magnetic Moment
- Theoretical Predictions -

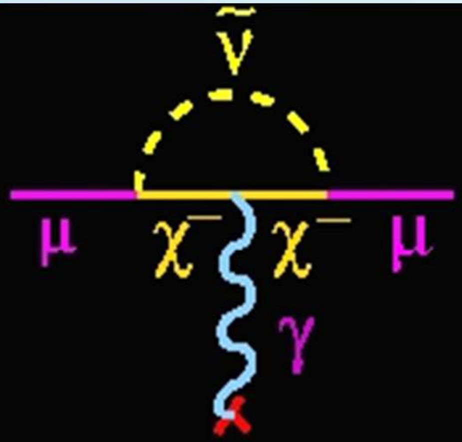
g!=2 because of some virtual effects that can be calculated precisely



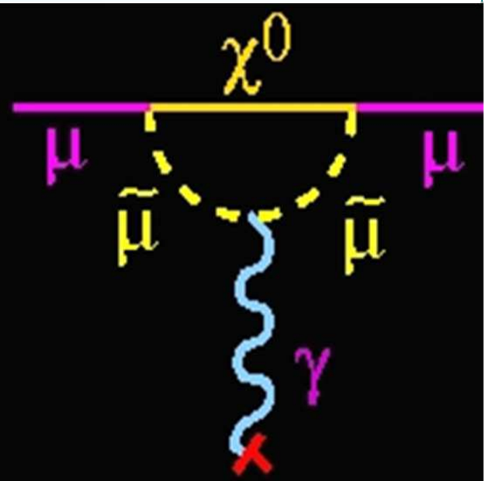
Full: up-to 4-loops
Partial: 5-loop

Full: up-to 2-loops

There are SUSY contributions ~tanβ

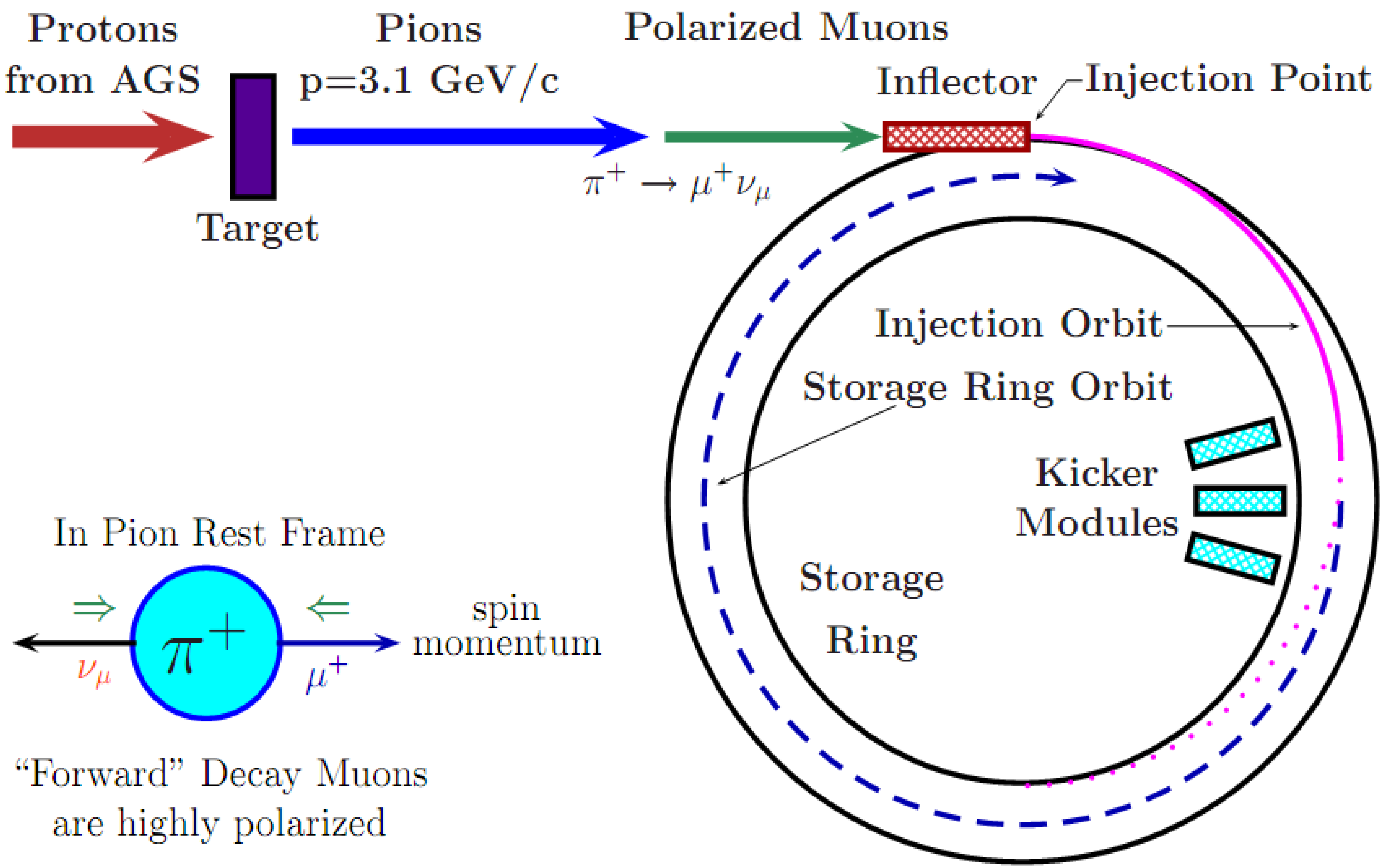


+

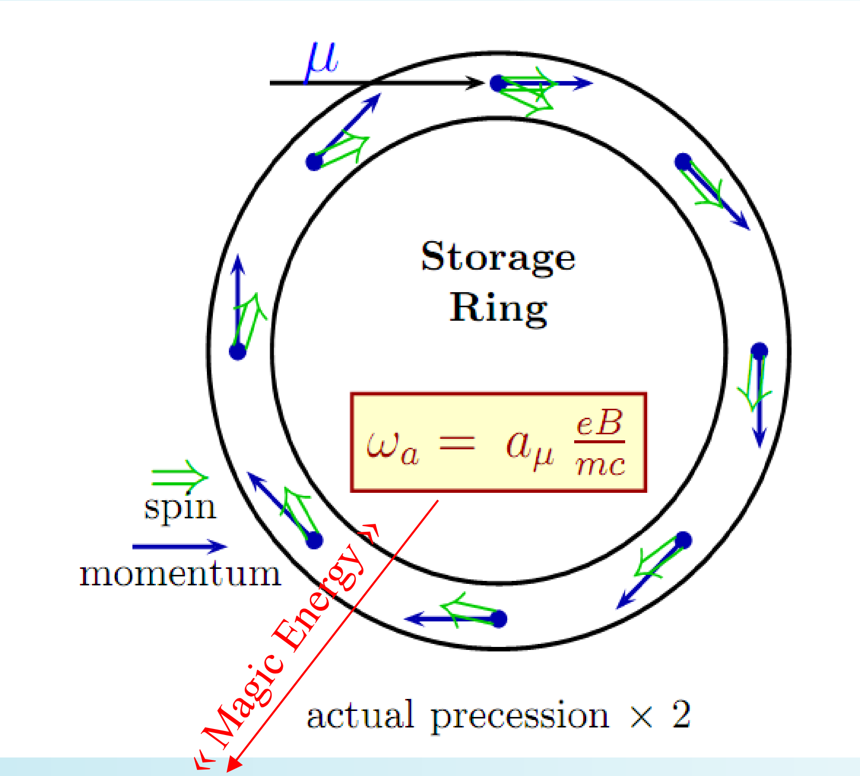


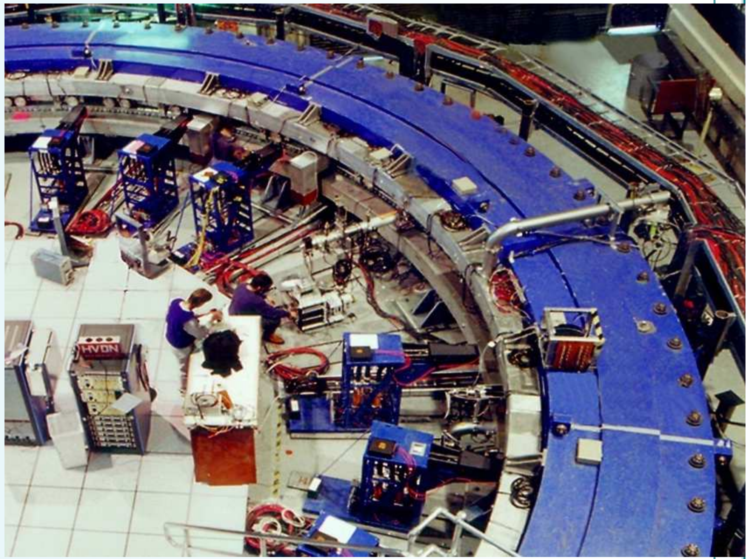
Muon Anomalous Magnetic Moment
- Experimental Setup -

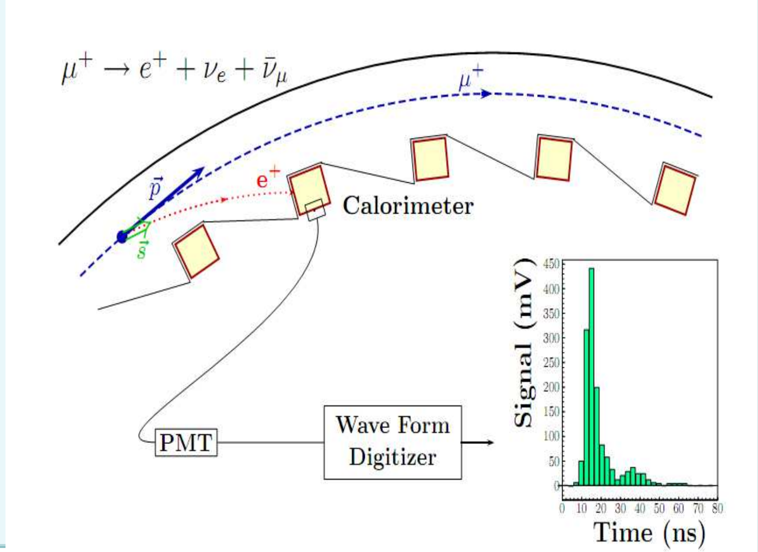
E821 at BNL (1998-2001)



Muon Anomalous Magnetic Moment
- Measurement Technique -







$p(\mu^{\pm}) = 3.094\,GeV$

Larmor Precession angle : $\approx 12°$

$R = 7.112\,m$

Larmor Precession frequency : ω_a

$B = 1.45\,T$ (constant)

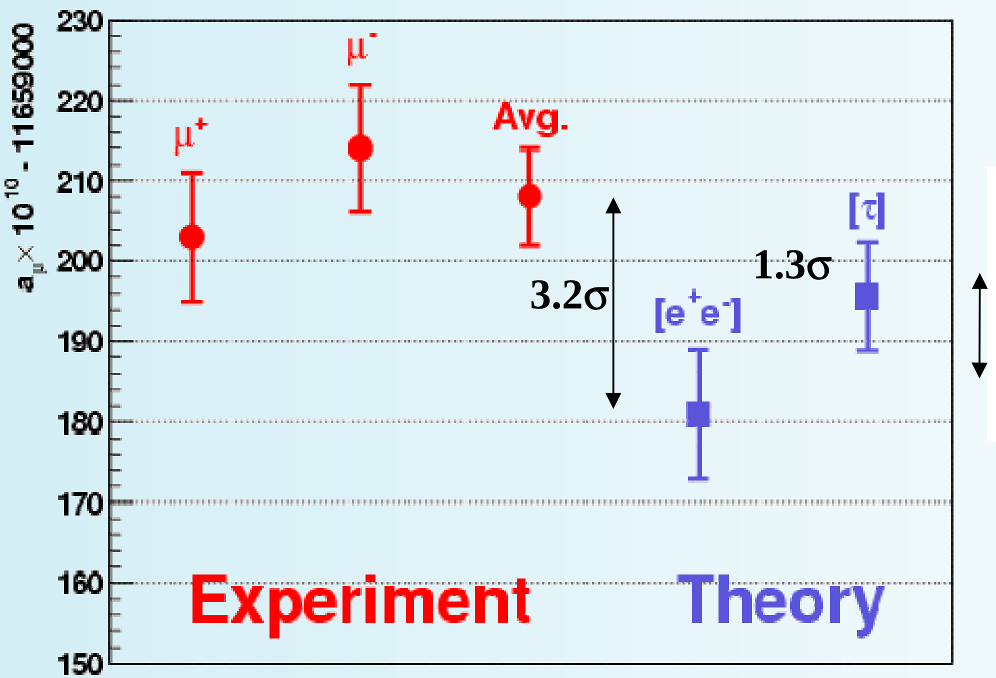
Muon Anomalous Magnetic Moment
- Final Results -

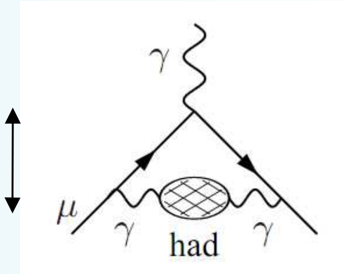
One of the most precise measurements in particle physics: 0.54 ppm !

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

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

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





LO hadronic
vacuum polarization

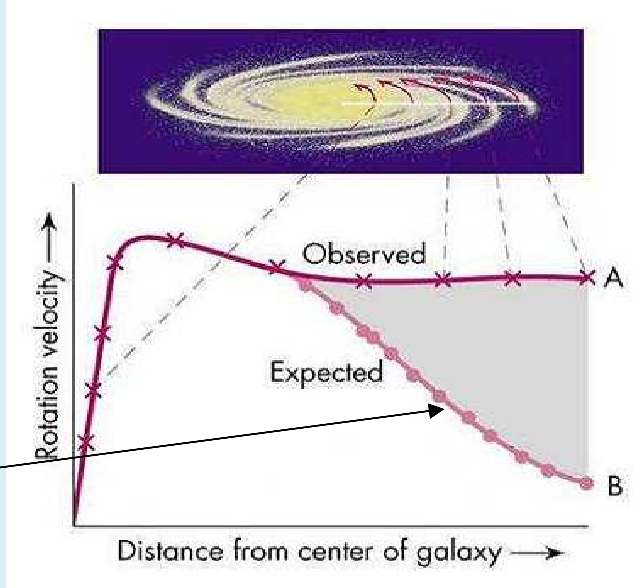
PART II: BSM Searches without Accelerators

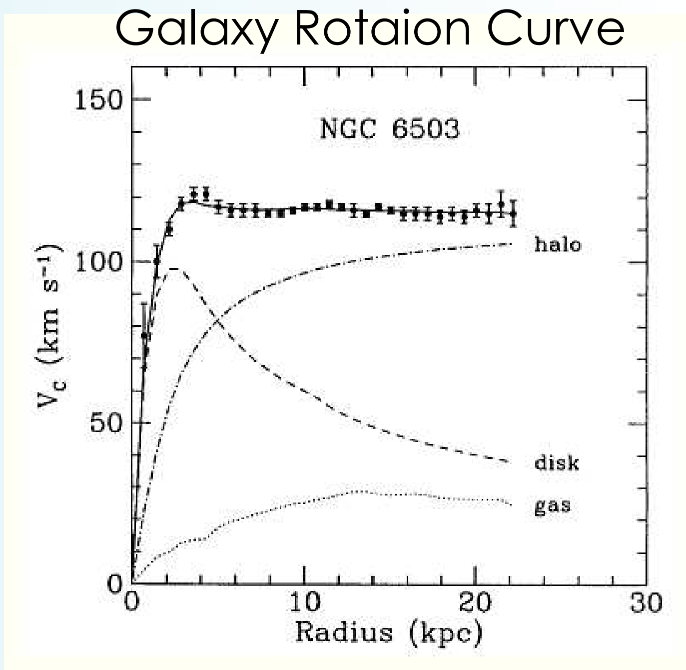
Evidence for Dark Matter

• Spiral galaxy rotation curves are incompatible with only visible matter contributions

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

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





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

Universe Expansion

Density for species i

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

Critical density

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

$$\rho_C \approx 1.88\times10^{-29} h^2 \cdot g \cdot cm^{-3}$$

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

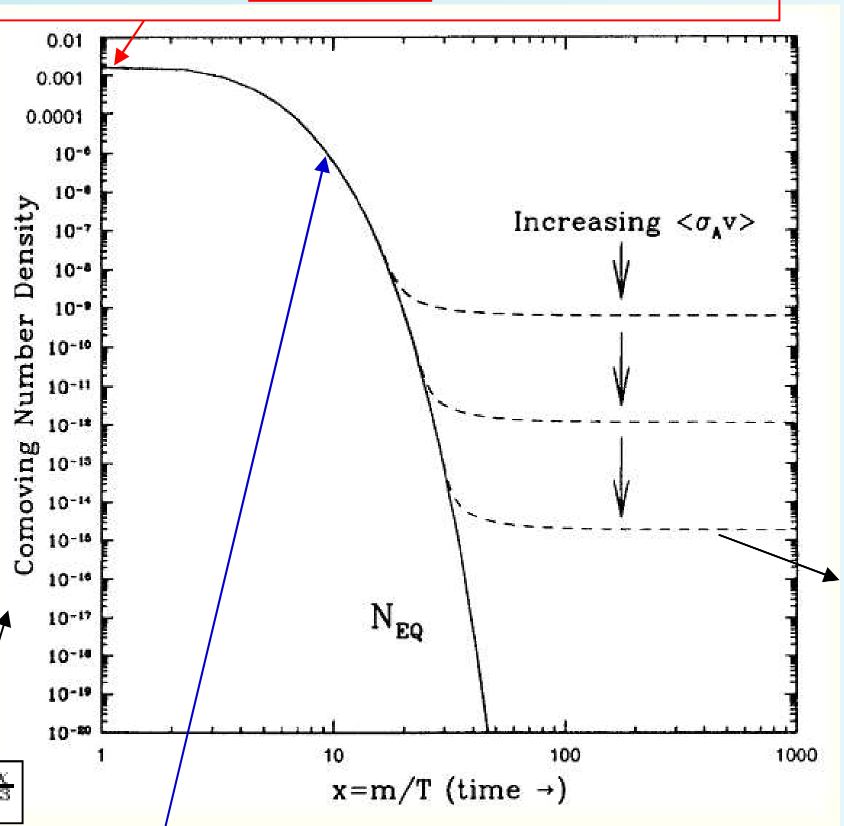
(Hubble param. today)

$\rho < \rho_c$	$\Omega < 1$	$k = -1$	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

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



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

freeze-out: interaction rate < expansion rate

$T \ll m_\chi$ $n_\chi \propto \exp^{-m_\chi/T}$ (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}: neutralinos annihiliation cross section
- v_{rel}: relative velocity

solution

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

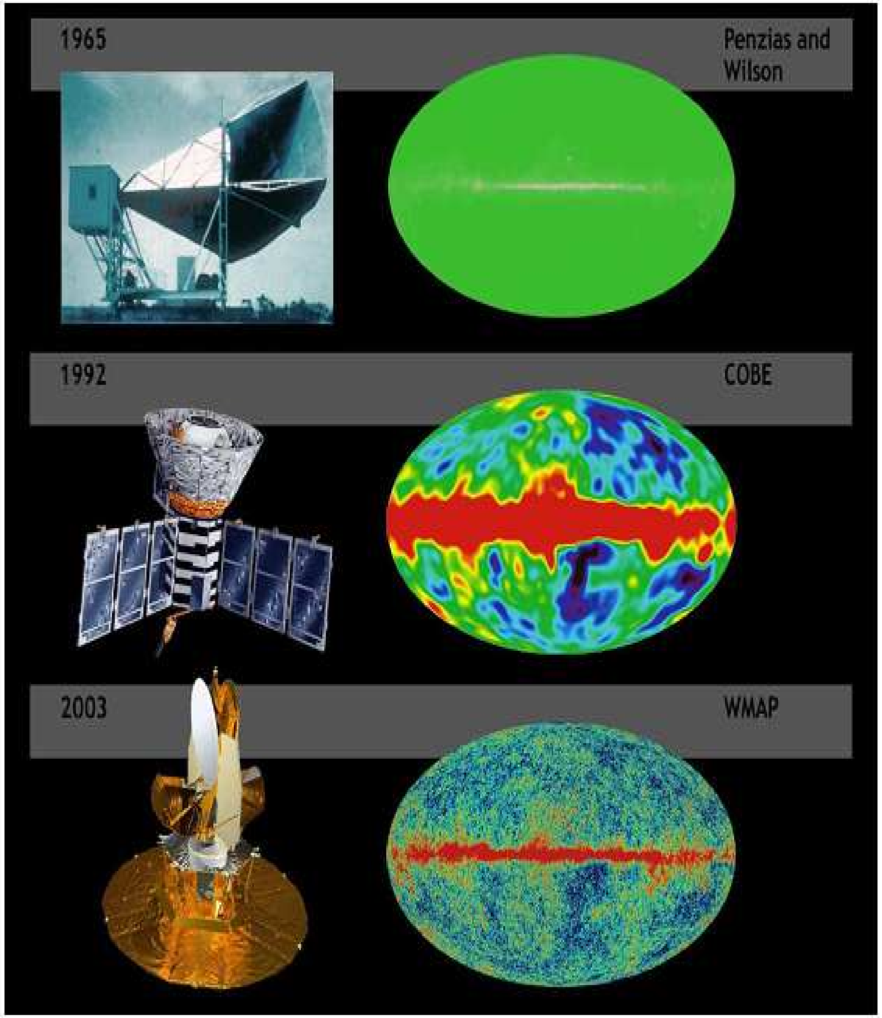
with WMAP =>

$\langle \sigma_{ann} v \rangle \simeq 3 \times 10^{-26}\ \mathrm{cm^3/s}$

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



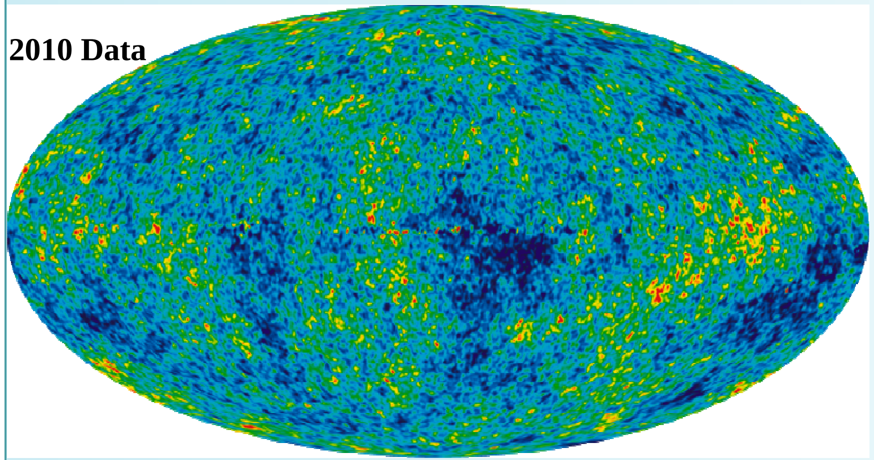
Discovered in 1964
Using a radio-telescope

COBE: « COsmic Background Explorer »
Satellite expt launched in 19??

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

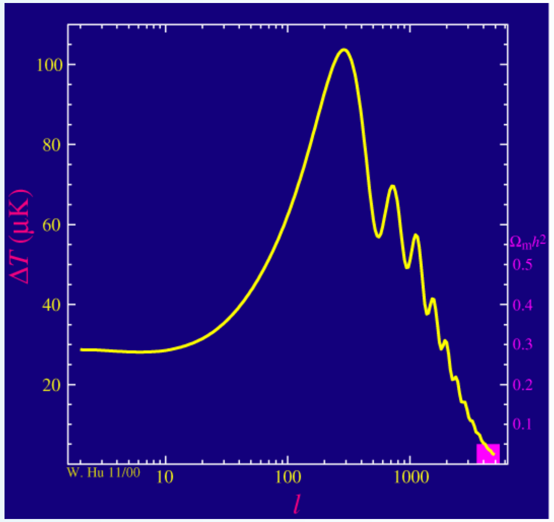
← Need accuracy of $\Delta T/T \sim 10^{-5}$

Cosmology Precision Measurements



Anisotropies measured by the WMAP satellite exp[t]

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



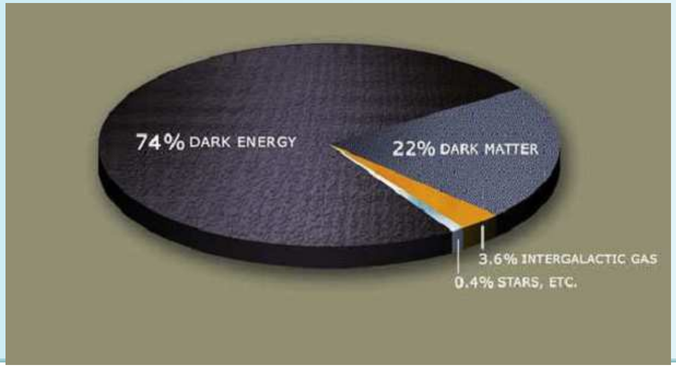
CMB: Angular Power Spectrum

Positions & rel. heights of acoustic peaks

=> infos about geometry & composition of the universe

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

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



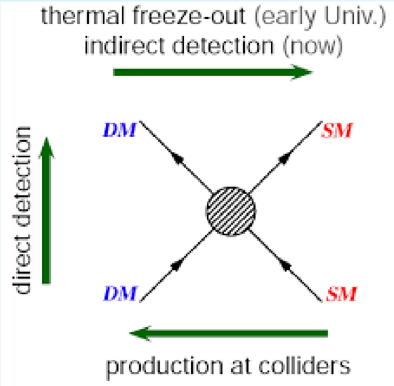
$$\Omega_{DM} h^2 = \Omega_{Matt.} h^2 - \Omega_{Baryon} h^2 = 0.1126 \begin{cases} +0.0081 (0.0161) \\ -0.0090 (0.0181) \end{cases}$$

68% CL 95% CL

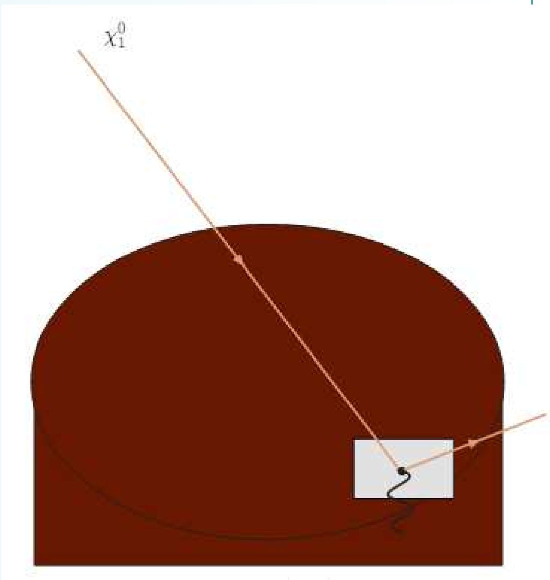
=> $\Omega_{\tilde{\chi}_1} h^2 < 0.129$ 95% CL

Dark Matter Searches
- Complementary Methods -

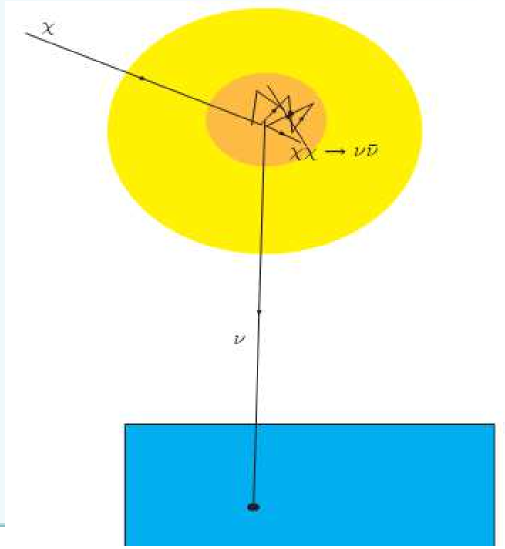
• Mandelstam Crossing:



• Direct Detection:
  - Principle: look for DM+N interactions
  - Expts:
    - LUX, XENON, DarkSide



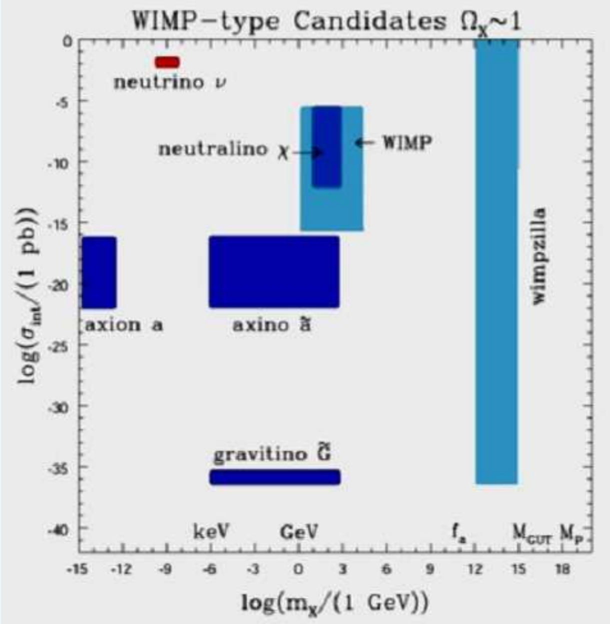
• Indirect Detection:
  - Principle:
    - look for SM particles produced through DM annihilation processes
    - Searches Particles: e^-, e^+, γ-rays, ν, p
  - Expts:
    - AMANDA, ANTARES, KM3NET, AUGER, GLAST, HESS, ICECUBE, SUPER-K, CTA

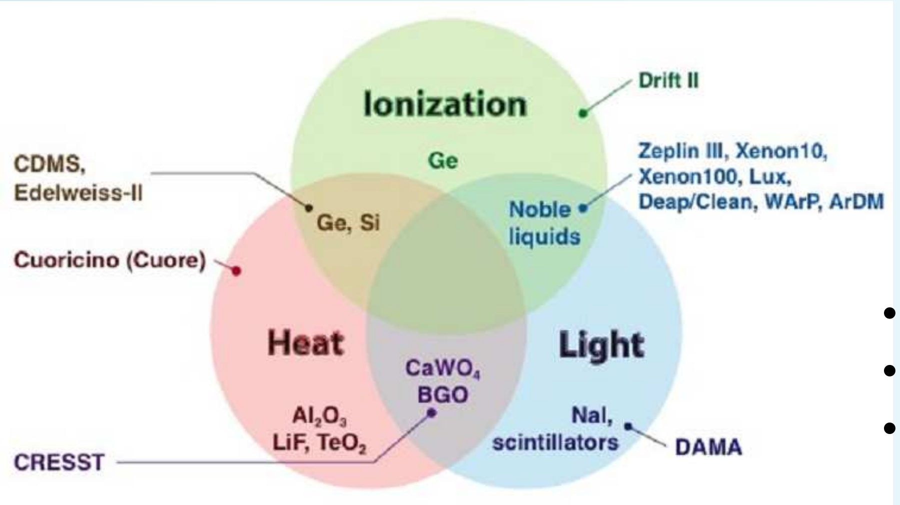


Dark Matter Searches
- Direct Detection (1/3) -

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

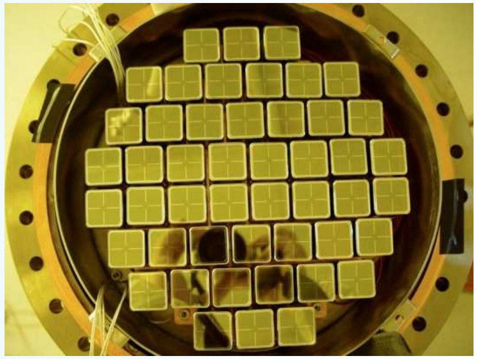




- Heat: phonons in crystaline lattice structure
- Ionization: free electrons in materials
- Light: scintillation in materials

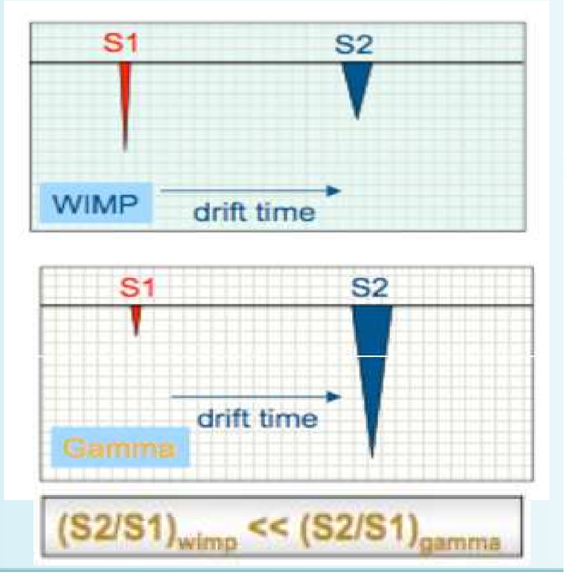
Dark Matter Searches
- Direct Detection (2/3) -

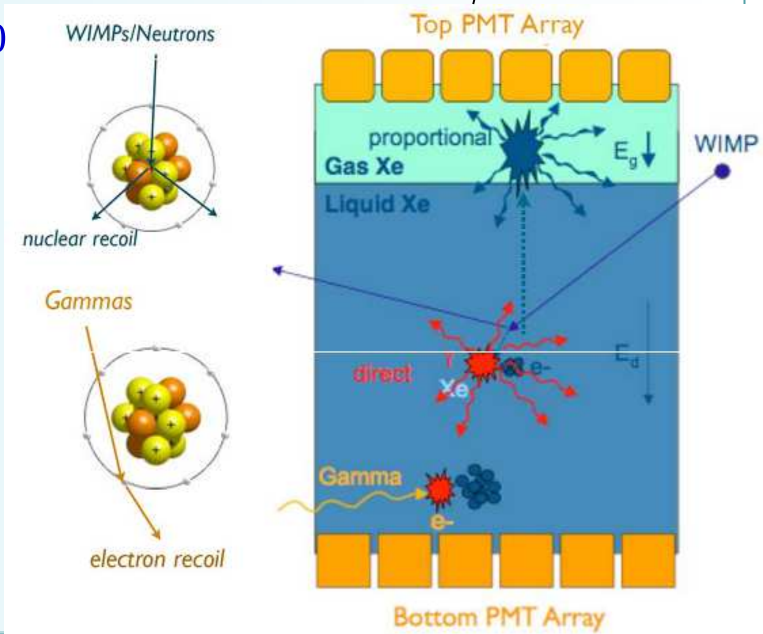
XENON-100 Experiment



• 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



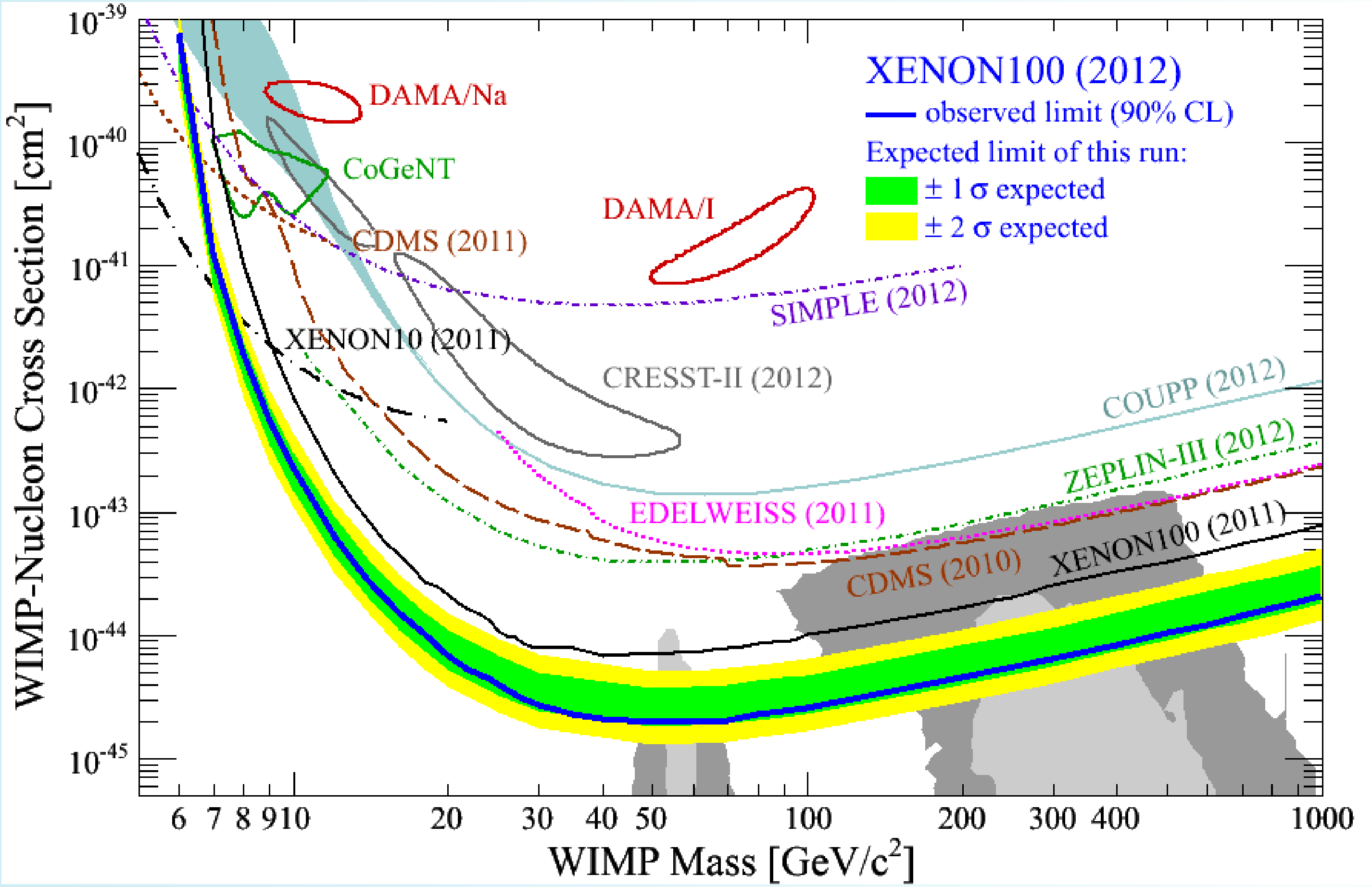


• Data samples:
  • 190.4 kg-day

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

Dark Matter Searches
- Direct Detection (3/3) -

XENON-100 Results



BACK-UP

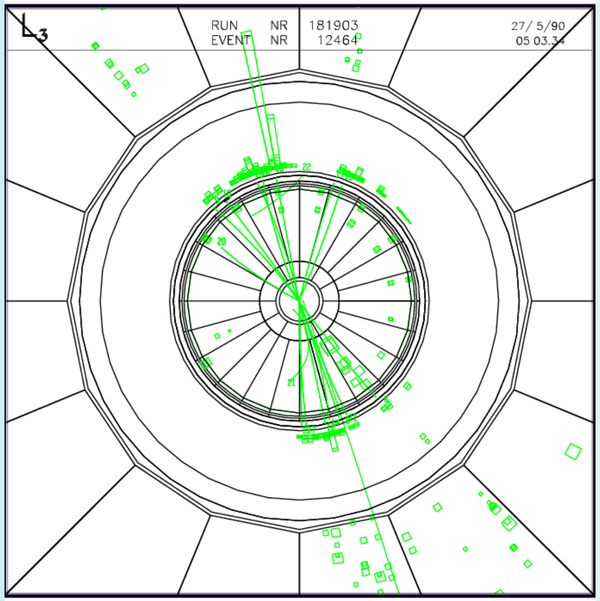
Search Instruments

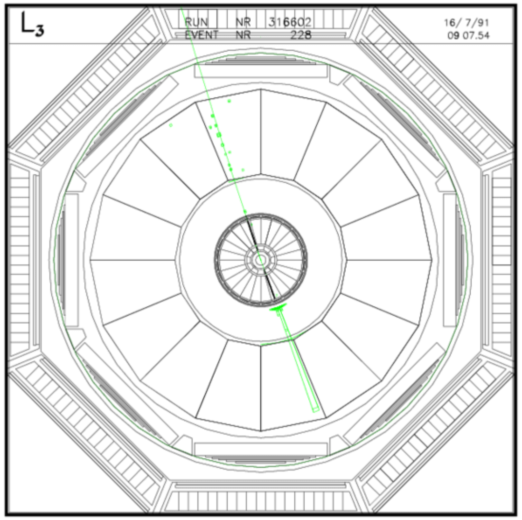
- Characteristics of LEP / LHC tunnel

$$B\,\rho\left[\mathrm{T\,m}\right] = 3.3356\ p_0\left[\mathrm{GeV/c}\right]$$

	LEP	LHC
ρ [m]	3096.175	2803.95
p_0 [GeV/c]	104	7000
B [T]	0.11	8.33

L3 Detector





r 5: Event Selection