Assortment of Di-Lepton Signatures and Physics Beyond the Standard Model

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Contents

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- Opposite-Sign, Same-Flavor, Resonance Structure
  - Z' - new vector boson:
    - GUT remnant?
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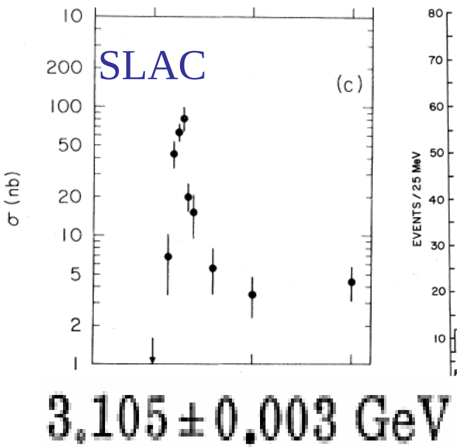
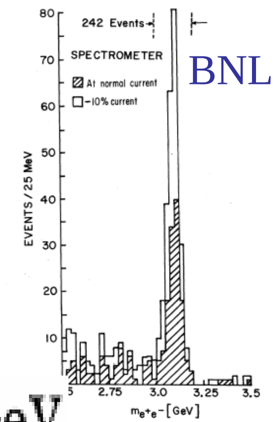
- Same-Sign/Opposite Sign + Missing Energy,or/and Jets
  - Supersymmetry production, limits, inclusive, exclusive searches
  - Probing the Majoranna nature of gauginos.
  - Spin information through dilepton angular correlations.
- Tri-Lepton
- Lepton Jets
  - Exotic type of structures involving highly collimated lepton jets.

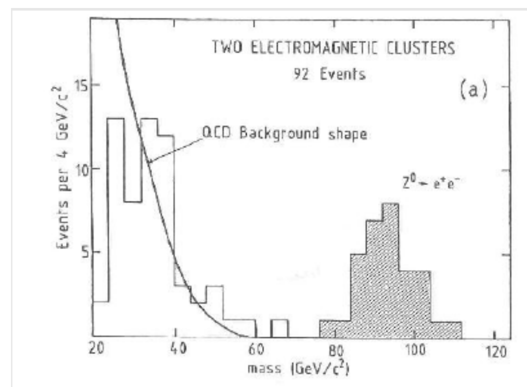
The Di-lepton Historic Road map…

J/Psi ->ll 1974

X-> ll+J+$\not{E}$ 20(1/0)4 ???

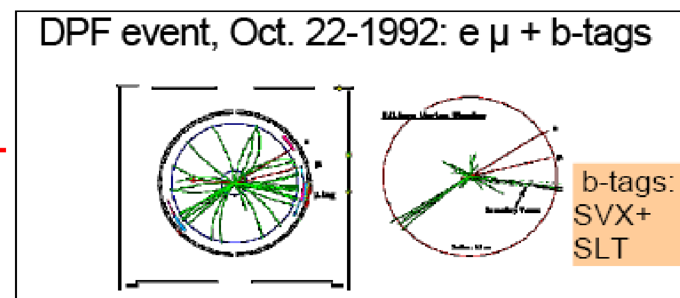






Z->ll 1984

May 1983
the Z boson was
discovered



March 1995

ttb-> ll+J+$\not{E}$ 1994

CDF M_{top}=176 ± 8 ± 10 GeV/c^2

DØ M_{top}=199 ± 20 ± 22 GeV/c^2

average: M_{top} = 180 ± 12 GeV/c^2

CDF published
"first evidence of top quark production
In ppb = 1.8TeV with 19.3pb-1"

M_{top} = $174 \pm 10^{+13}_{-12}$ GeV/c^2

Z' Origins

1) GUTs scenarios often give extra factors of U(1)

- The LRM, based on the low-energy gauge group

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L},$$

can arise from an SO(10) or E6 GUT.

1) E6 Grand Unified Theories

$$E_6 \rightarrow SO(10) \times U(1)_\psi \rightarrow SU(5) \times U(1)_\chi \times U(1)_\psi$$

$$G = U(1)_\theta = c_\theta U(1)_\psi - s_\theta U(1)_\chi$$

At TeV scale

model	ψ	χ	η	I
θ	0	-90^o	37.76^o	-52.24^o

- KK-like theories with extra-dimensions give vector-boson (excited modes) excitation of the SM gauge-bosons (zero modes).

- Little Higgs theories have partners for the Z and W's (assume no T-parity, or otherwise Z' can not decay to dilepton).

- SUSY with R-parity breaking,

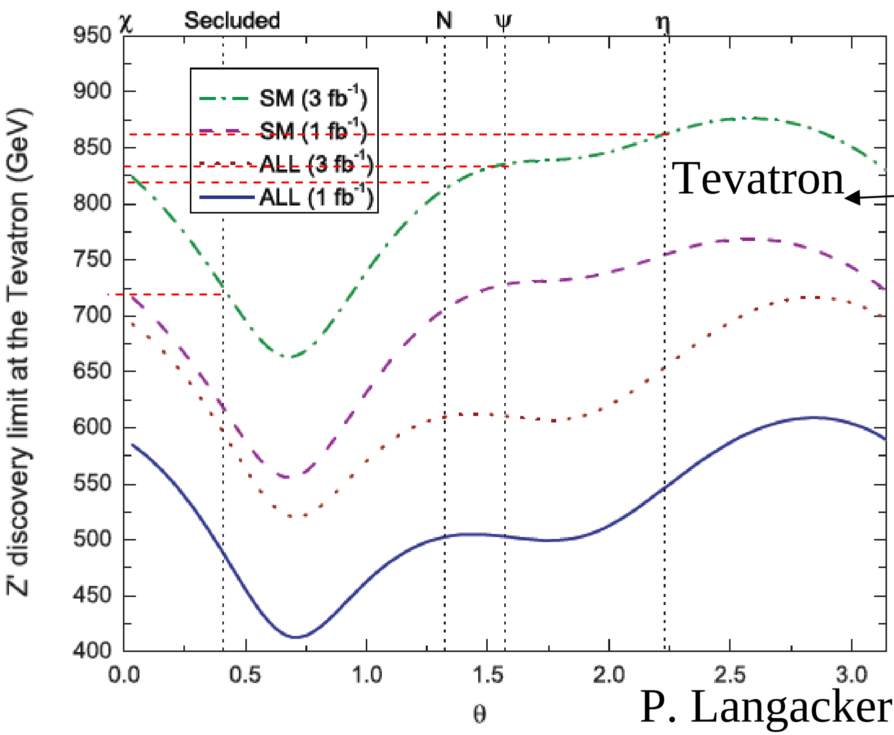
Constraints from Colliders

	ρ_0 free	$\rho_0 = 1$	$\sin\theta$ ($\rho_0 = 1$)	Indirect Searches (GeV)	Direct Searches (GeV)	
					e^+e^- Colliders	p^+p^- Colliders
χ	551	545	$(-0.0020) - (+0.0015)$	680	781	864
ψ	151	146	$(-0.0013) - (+0.0024)$	481	366	853
η	379	365	$(-0.0062) - (+0.0011)$	619	515	933
LR	570	564	$(-0.0009) - (+0.0017)$	804	518	630
sequential	822	809	$(-0.0041) - (+0.0003)$	1787	1018	966

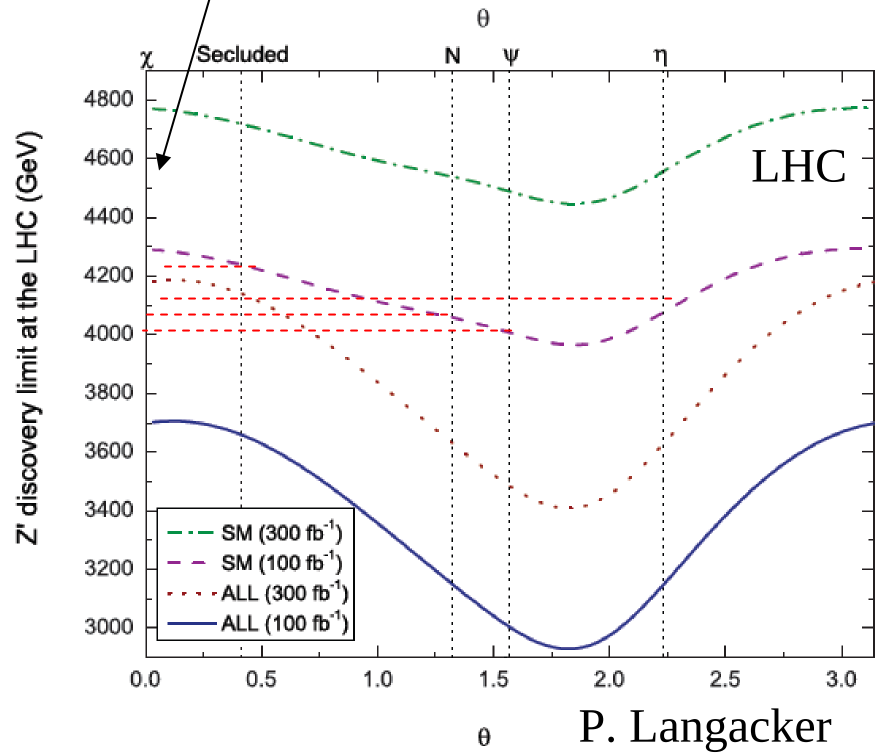
P. Langacker , T. Rizzo
CDF,D0,LEP

95% CL lower limits on various extra Z' gauge boson masses (GeV) and 90% CL ranges for the mixing sinθ from precision electroweak data (columns 2-4), Tevatron searches (assuming decays into SM particles only), and LEP 2.

Tevatron and LHC Sensitivity



Z’ decays into SM fermions only

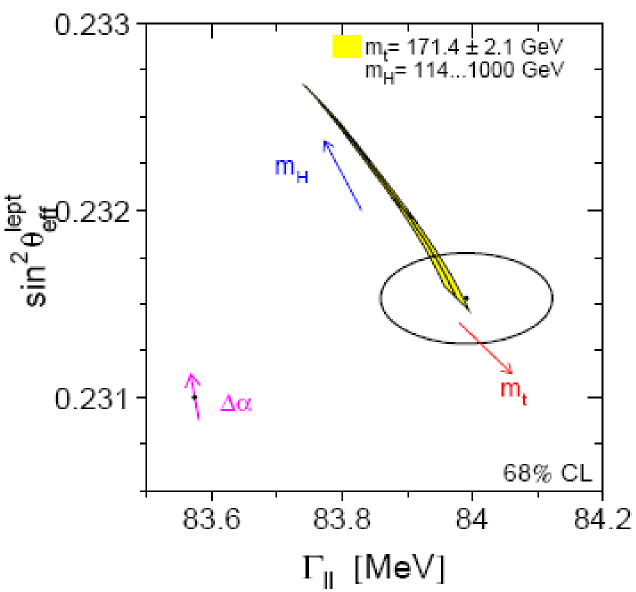


Discovery limits for an E6 Z’ mass as a function of θ_{E6} model requiring to a total of 10 (ll=e,mu) events

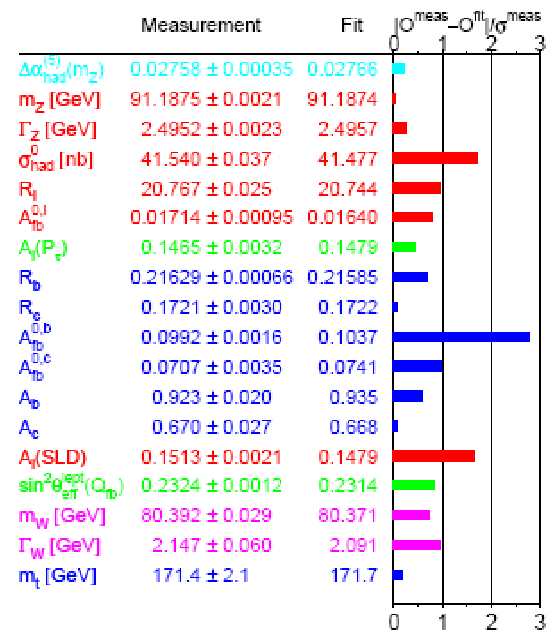
Present Constraints on Z-Z’

$$\mathcal{L}_K = -\frac{1}{4}W^a_{\mu\nu}W^{\mu\nu}_a - \frac{1}{4}\tilde{B}_{\mu\nu}\tilde{B}^{\mu\nu} - \frac{1}{4}\tilde{Z}'_{\mu\nu}\tilde{Z}'^{\mu\nu} - \frac{\sin\chi}{2}\tilde{Z}'_{\mu\nu}\tilde{B}^{\mu\nu}$$

$$\sum_i \left[\left(\frac{g_L}{c_w} T_{3L} Z + g_{Z'} T' Z'\right) v_{D_i} \right]^2 + \sum_j \left[g_{Z'} T' v_{S_j} Z' \right]^2$$

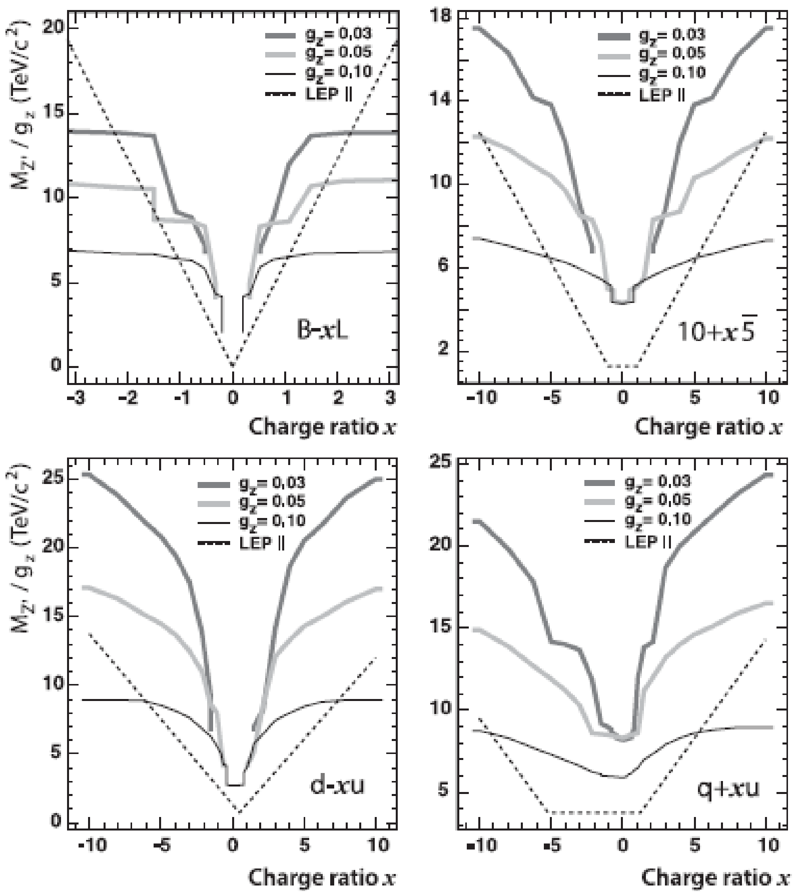


Limit $\phi < 10^{-3}$



Summer 2009 results from LEPEWKWG

Limits on the U(1)' charges

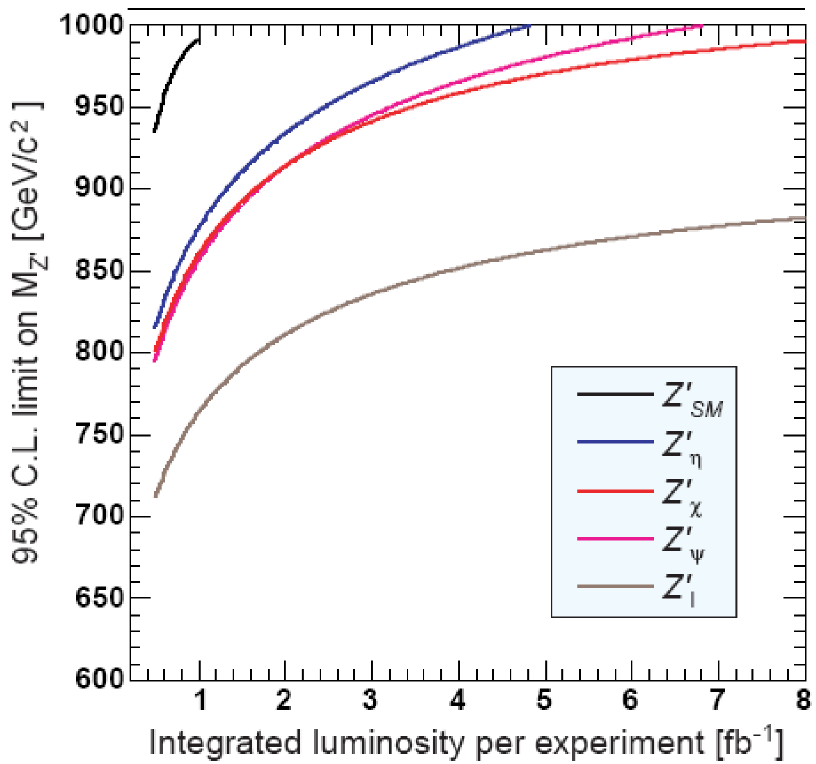


Exclusion limits (450 pb-1)on four sets of *U*(1) charges from CDF z→ee and the LEP-II experiments

fermion	$U(1)_{B-xL}$	$U(1)_{10+x\bar{5}}$	$U(1)_{d-xu}$	$U(1)_{q+xu}$
(u_L, d_L)	$1/3$	$1/3$	0	$1/3$
u_R	$1/3$	$-1/3$	$-x/3$	$x/3$
d_R	$1/3$	$-x/3$	$1/3$	$(2-x)/3$
(ν_L, e_L)	$-x$	$x/3$	$(-1+x)/3$	-1
e_R	$-x$	$-1/3$	$x/3$	$-(2+x)/3$

PDG

Tevatron Projection for Z→ee



Rapidity falling pdf
Leaves the m>TeV
for LHC

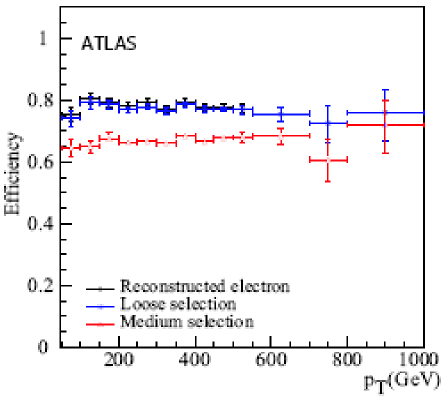
T. Rizzo

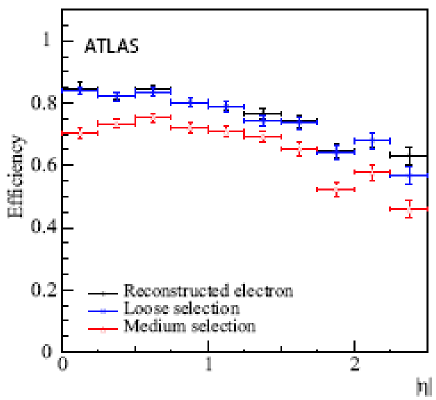
Extrapolation of the Z' reach for a number of different models at the Tevatron as the integrated luminosity increases. Results from CDF and D0 are combined.

Experimental Tasks

- Lepton reconstruction
- ElectronID
  - 150 < Et <700 GeV, barrel and endcap regions is (89.4 ⊕ 0.1)% and (88.1 ⊕ 0.1)% [CMS] (
  - Loose selection ~ 65 – 80% [ATLAS]
- Muon Id
  - 98% [CMS,ATLAS]
- Lepton Efficiency from data
- Energy resolution Barrel (~1%) EndCap (~5%)
  - Calorimeter response (Algorithm) , Saturation (few percent)
  - Mass resolution <1% at TeV
- Energy scale calibration
  - Intercalibration (test beam ,cosmic) ~few percent [CMS] 1% [ATLAS]
- Charge misID   1% -> 5% 1TeV

Lepton performance

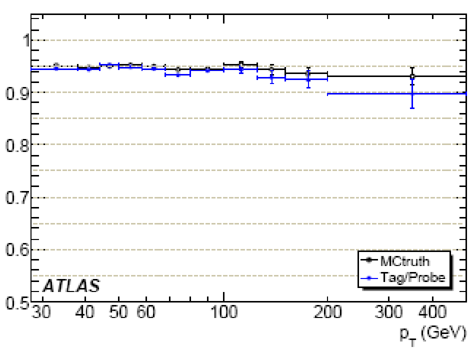




Electron Efficiency

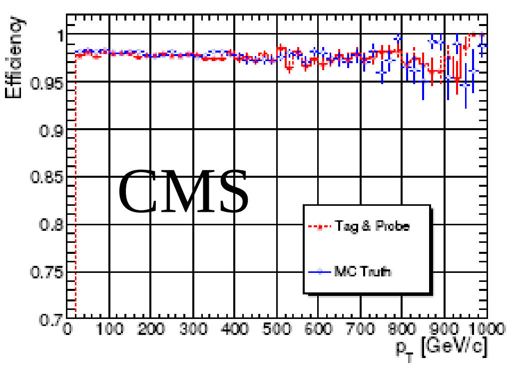
CMS

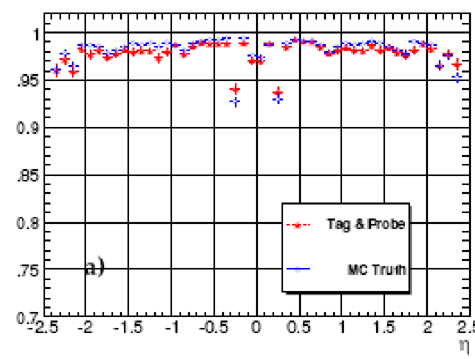
	Barrel		Endcap	
	$Z \to ee$	jet bg.	$Z \to ee$	jet bg.
efficiencies	$93.9 \pm 0.1\%$	–	$94.3 \pm 0.2\%$	–
rejection power	–	$99.8 \pm 0.1\%$	–	$98.4 \pm 0.4\%$



Eff_mu
95-98%

CMS





Muon Efficiency

An arbitrary large-statistics combination of high-mass Drell-Yan dimuon samples is used.

Tag & Prob

T&P is a standard method to measure efficiency in a data driven using technique

Tag : An object that passes a set of very tight selection

Probe: An object that depends on the specifics of the selection criterion being examined.

$$\varepsilon = \frac{P_{\mathrm{pass}}}{P_{\mathrm{all}}},$$

P_{pass} is the number of probes passing the selection criteria
P_{all} is the total number of probes counted using the resonance.

Z' Efficiency

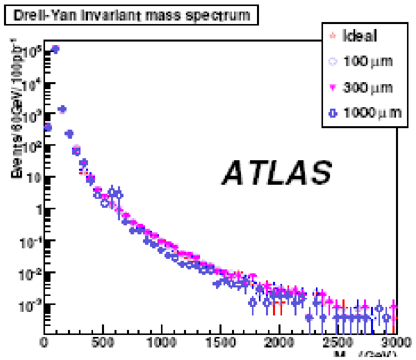
The electron identification efficiency cannot be directly determined at the energies in the region where searches for new physics will take place.

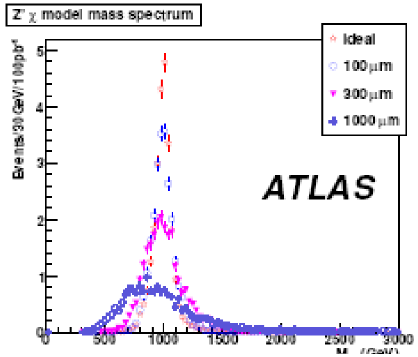
- Two methods have being devised both utilize the large number of events at the Z resonance

However

- One depends on Monte Carlo simulation information to extrapolate to the region of interest
- The second uses higher energy events in the DY tail using events closer to the energies of interest, but having limited statistics and having to suppress sources of fake electrons.

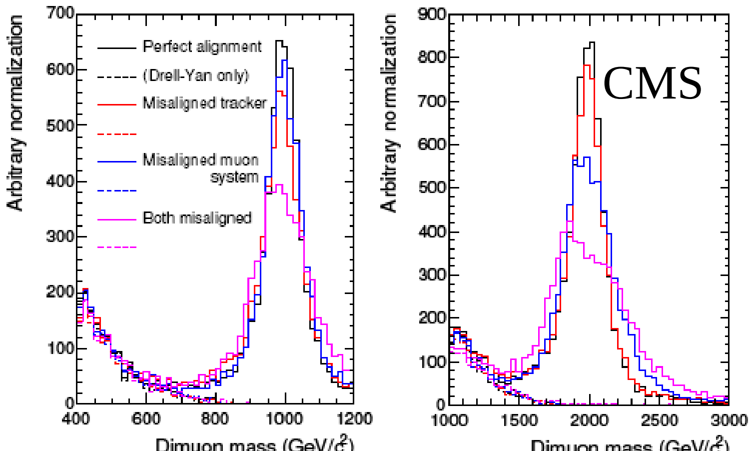
Mis-alignment





Misalignment (μm)	Ideal	40	100	200	300	500	700	1000
Relative efficiency	0.984	0.984	0.984	0.98	0.973	0.948	0.918	0.877

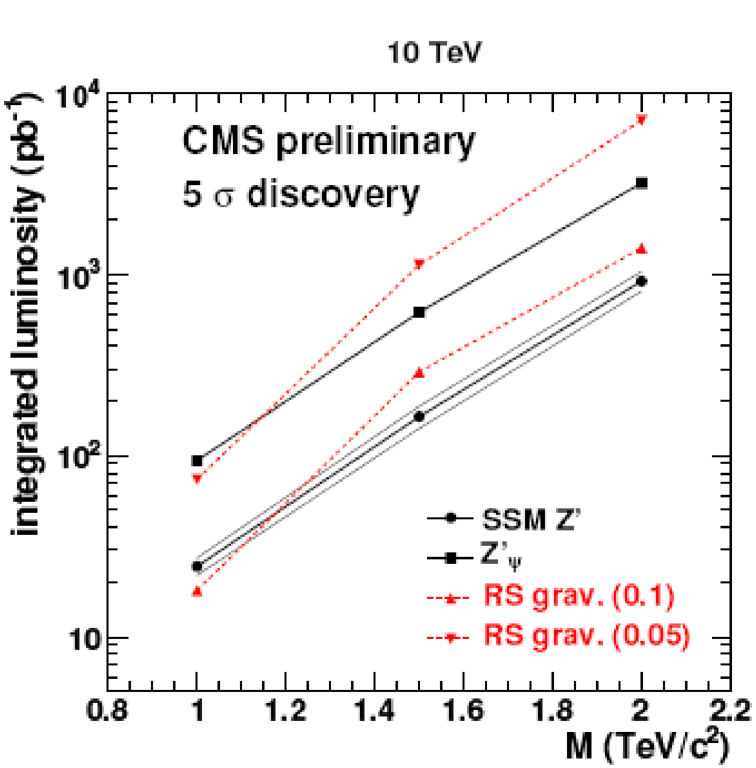
The DY background
Is largely unaffected



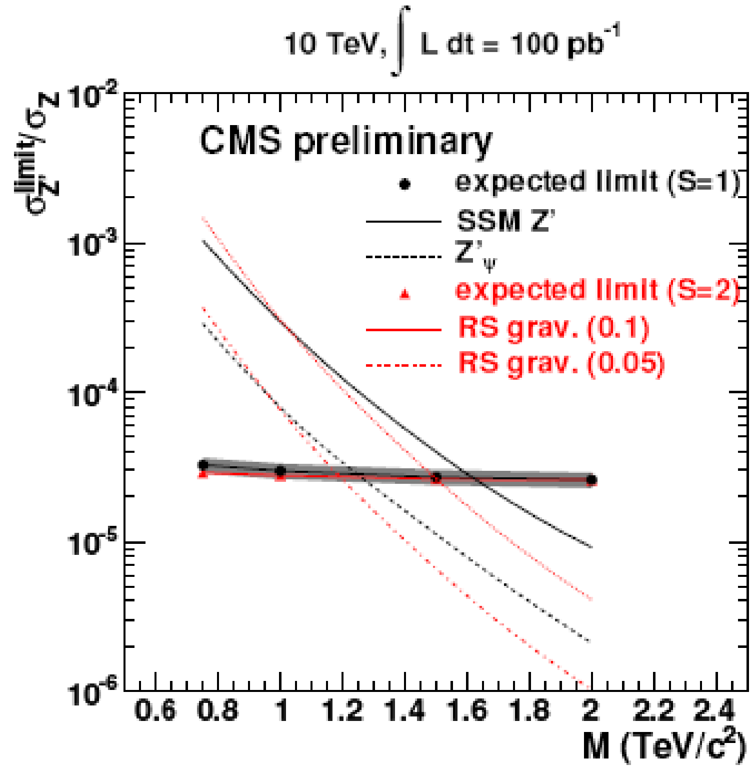
Mass resolution 7-8% 10%

Z'->ee Mass Discovery and Exclusion

CMS



(a)

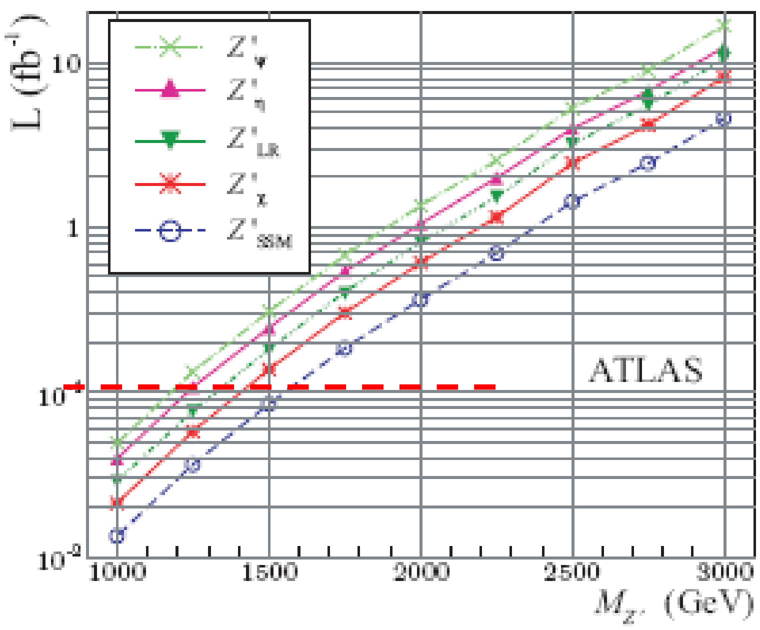


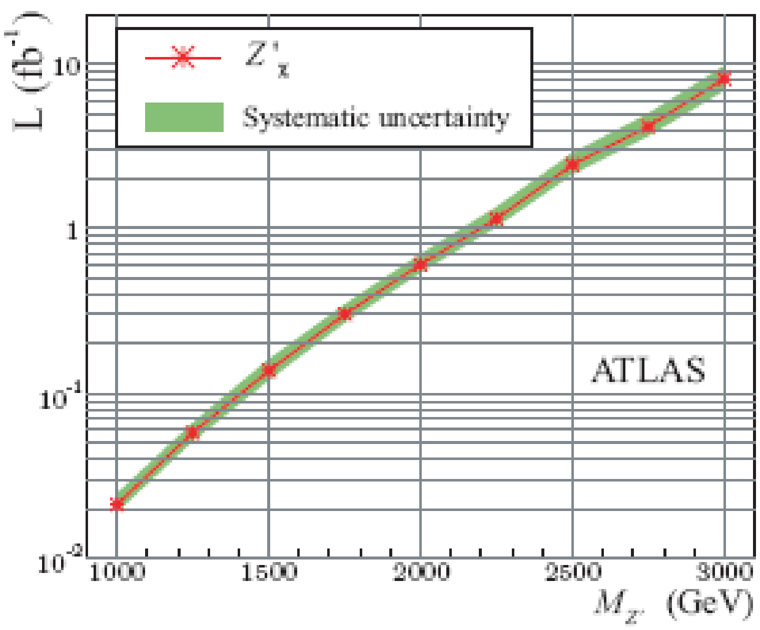
(b)

$1.37\ TeV/c^2 < Z_{SSM}$
$1.02\ TeV/c^2 < Z_{\psi}$
$1.31\ TeV/c^2 < Z_{RS}$ c=0.1
$1.06\ TeV/c^2 < Z_{RS}$ c=0.01

$1.59\ TeV/c^2 < Z_{SSM}$
$1.26\ TeV/c^2 < Z_{\psi}$
$1.49\ TeV/c^2 < Z_{RS}$ c=0.1
$1.21\ TeV/c^2 < Z_{RS}$ c=0.01

Discovery Reach Z'->ee [ATLAS]





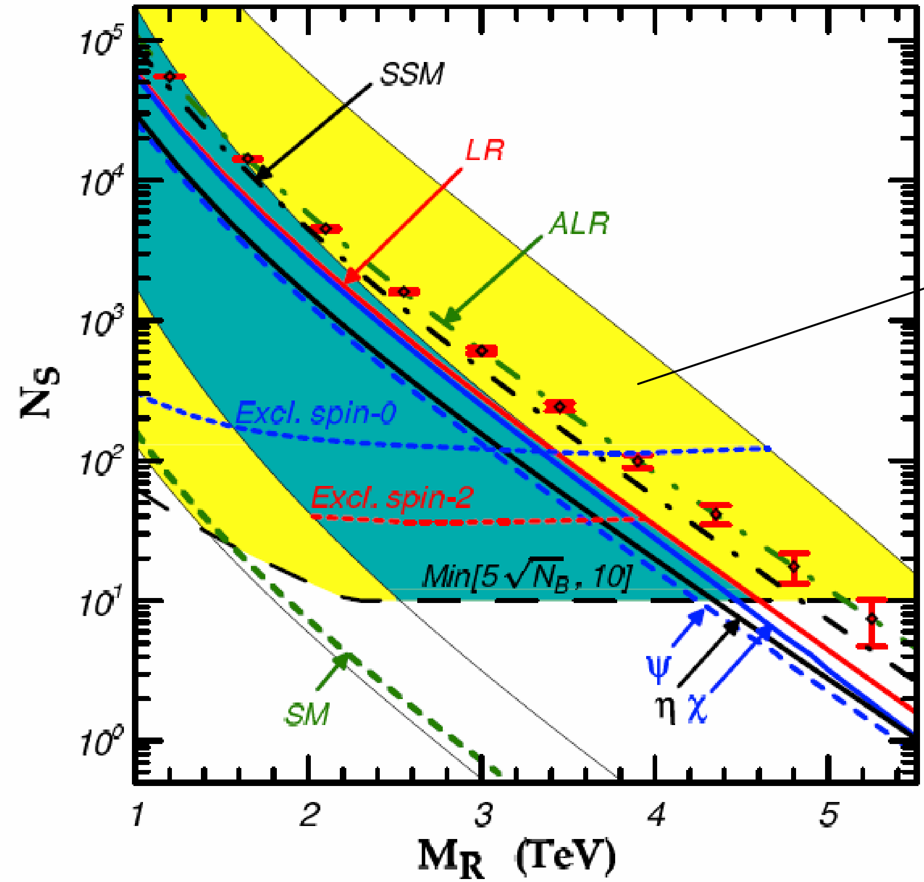
Which Z'?

After discovery and identification, one should attempt to measure the coupling to the different SM species. Knowledge of the coupling may help decipher which Z' is it (GUT, KK, LH. . .)

1. Observation
2. Rate
3. Spin
4. F_FB
5. Rapidity distribution
6. Couplings $\sigma_{z'}^{l}\Gamma_{z'} = \sigma_{z'}\Gamma_{l}$

Z' Rate

$$pp \to R \to l^+l^- + X \ (l = e, \mu)$$



sneutrino signature space

$$q\bar{q} \to \tilde{\nu} \to l^+l^-$$

$$q\bar{q} \to \gamma, Z \to l^+l^-$$

$$q\bar{q} \to G \to l^+l^-$$

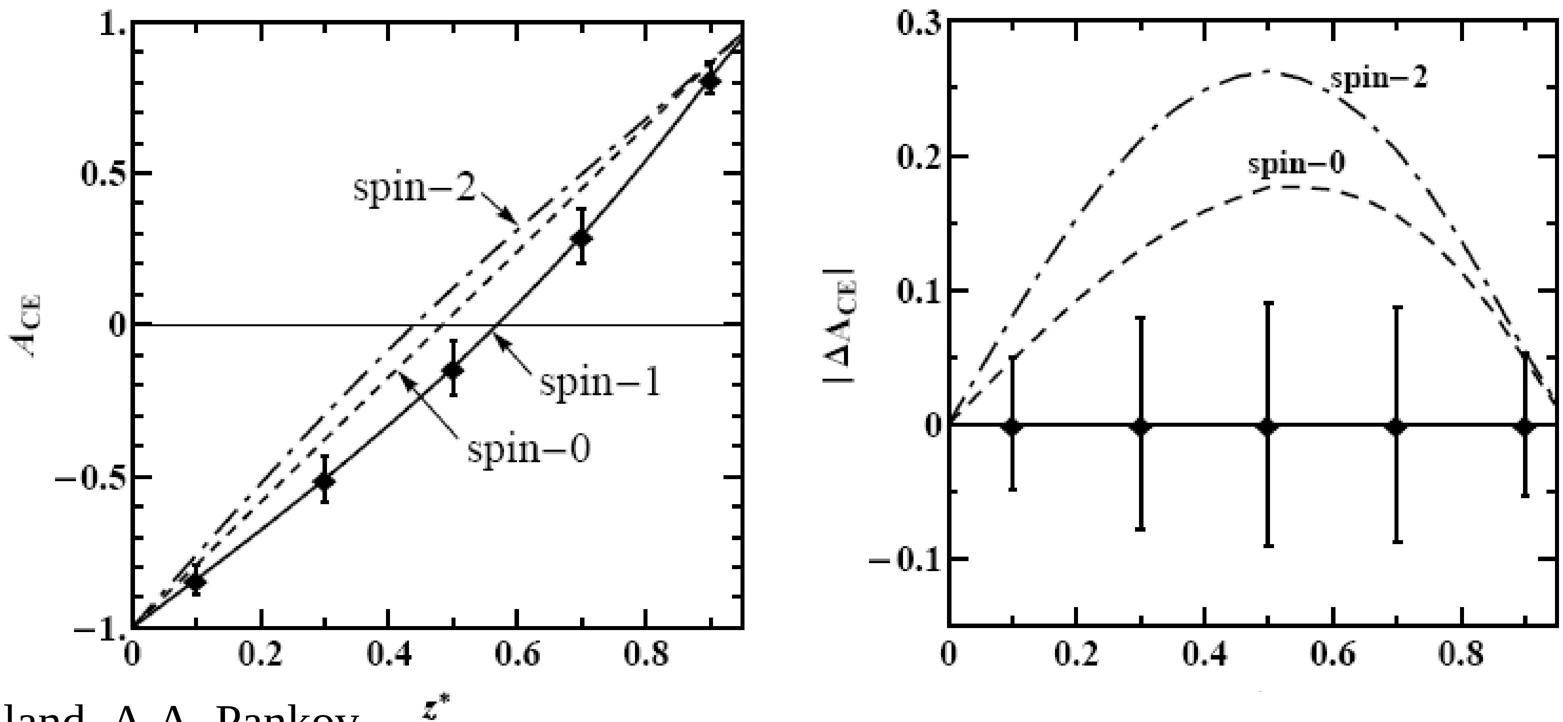
$$gg \to G \to l^+l^-$$

P. Osland, A.A. Pankov
N. Paver, A.V. Tsytrinoy

Expected number of resonance (signal) events at the LHC with Lint = 100 fb-1

Z' Spin

$$A_{\rm CE}(M_R) = \frac{\sigma_{\rm CE}(R_{ll})}{\sigma(R_{ll})}, \quad \text{with} \quad \sigma_{\rm CE}(R_{ll}) \equiv \left[\int_{-z^*}^{z^*} - \left(\int_{-z_{\rm cut}}^{-z^*} + \int_{z^*}^{z_{\rm cut}}\right)\right] \frac{d\sigma(R_{ll})}{dz}\, dz.$$



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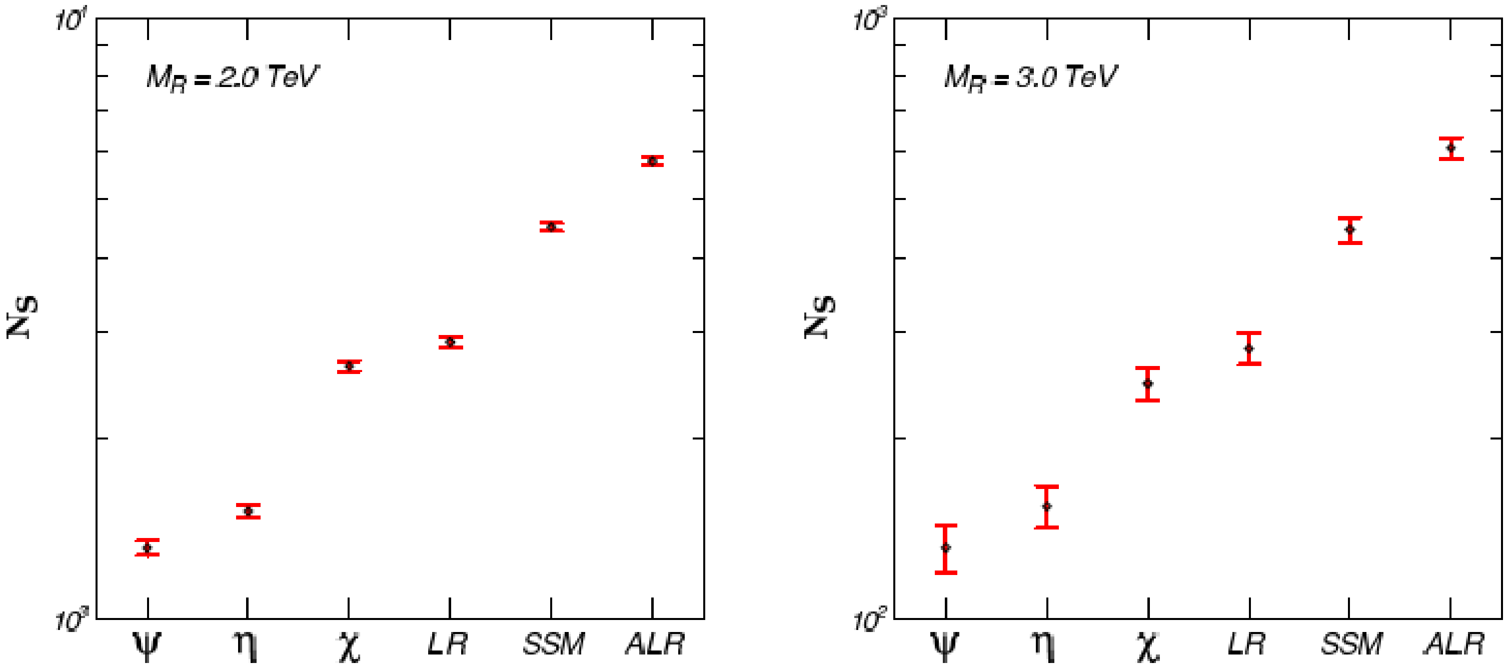
$$\Delta A^S_{\rm CE} = A^S_{\rm CE} - A^V_{\rm CE} \qquad \Delta A^G_{\rm CE} = A^G_{\rm CE} - A^V_{\rm CE}.$$

Differentiating Z’ Models



The error bars show the 1-⇔ statistical uncertainty at 100 fb□1 of integrated luminosity.

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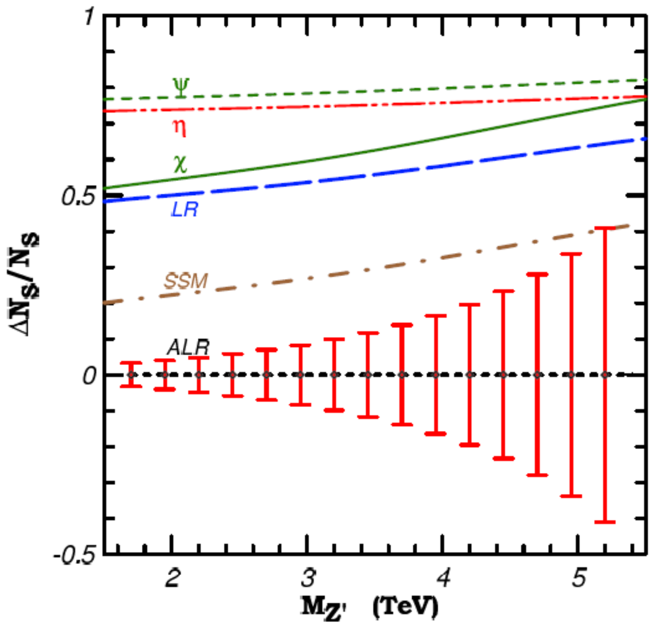
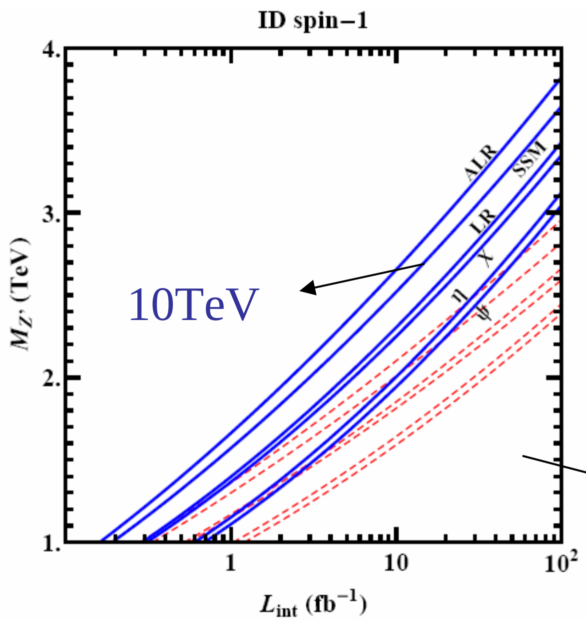
Differentiating Z’ Models





$$\frac{\Delta N_S}{N_S} = \frac{N_S(Z') - N_S(Z'_{\rm ALR})}{N_S(Z'_{\rm ALR})}. \quad \chi^2 = \left(\frac{\Delta N_S}{\delta N_S}\right)^2$$

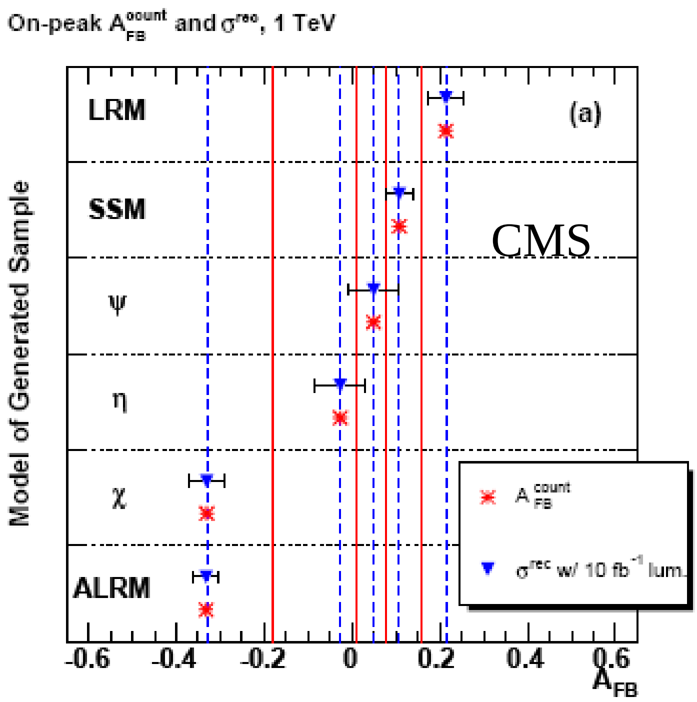
P. Osland, A.A. Pankov
N. Paver, A.V. Tsytrinoy

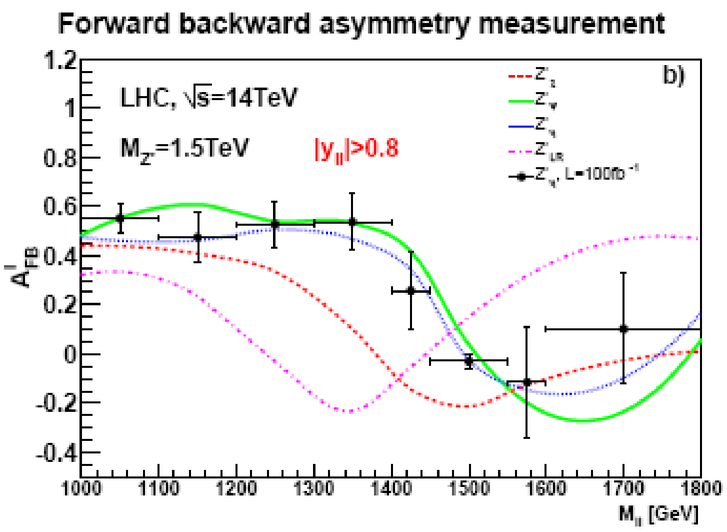
Distinguish between models
Based on statistics Lint = 100 bf-1

Spin-determination reach as a function of integrated luminosity

A_FB to Probe the Model

$$\frac{d\sigma}{d\cos\theta^\star} \propto \frac{3}{8}(1+\cos^2\theta^\star) + A_{FB}\cos\theta^\star$$





T. Rizzo

100fb-1

Supersymmetry (di-lepton)

Sparticles limits

Relevant cross-section (early discovery?)

Survey of signatures for early running

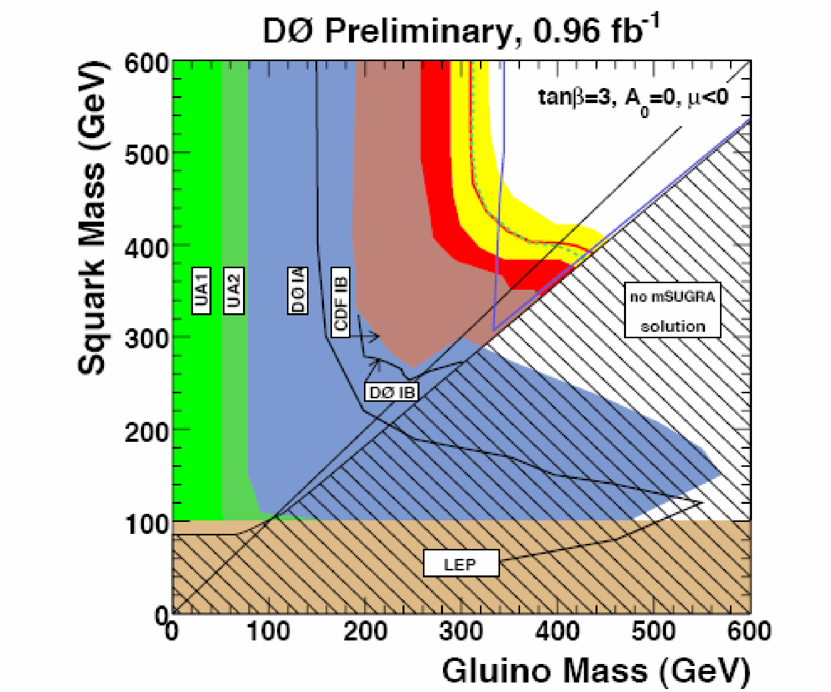
Highlight from specific studies

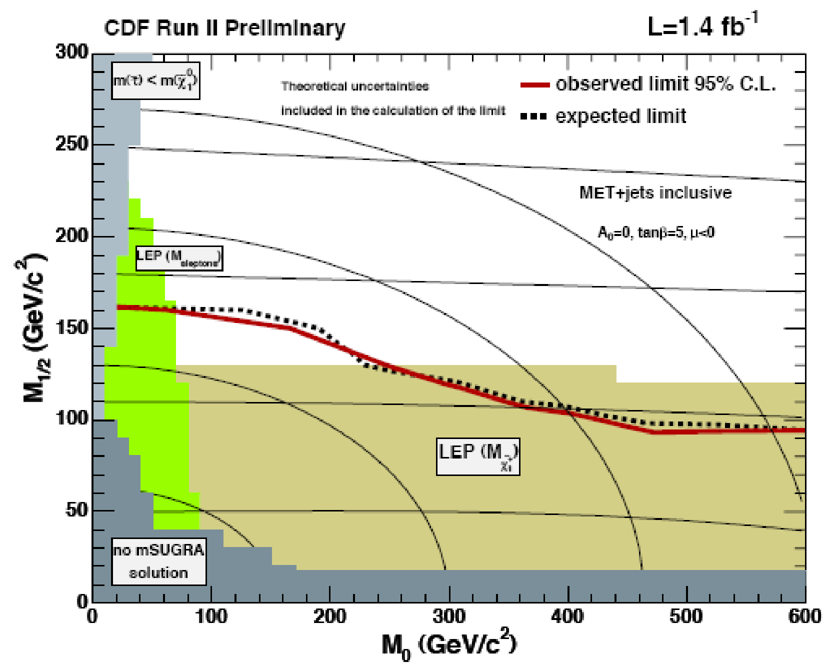
- Dileptons + Missing energy signals
- Dilepton + Jest + MET

How can we find out about

- The sparticles scale
- Spin
- Couplings

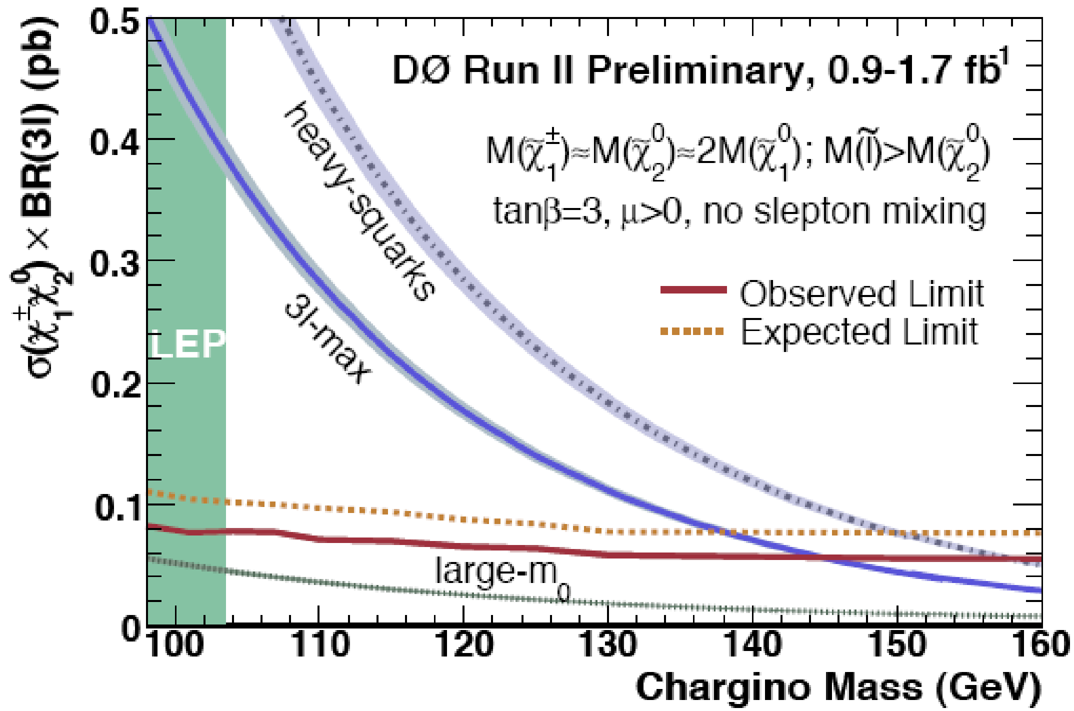
Constraints from Colliders





D0 1 fb-1, excludes $m\tilde{q} < 375$ GeV,
$m\tilde{g} < 289$ GeV, 1 fb-1, excludes $m\tilde{q} < 375$ GeV,
$m\tilde{g} < 289$ GeV,

Chargino : 3lepton+MET



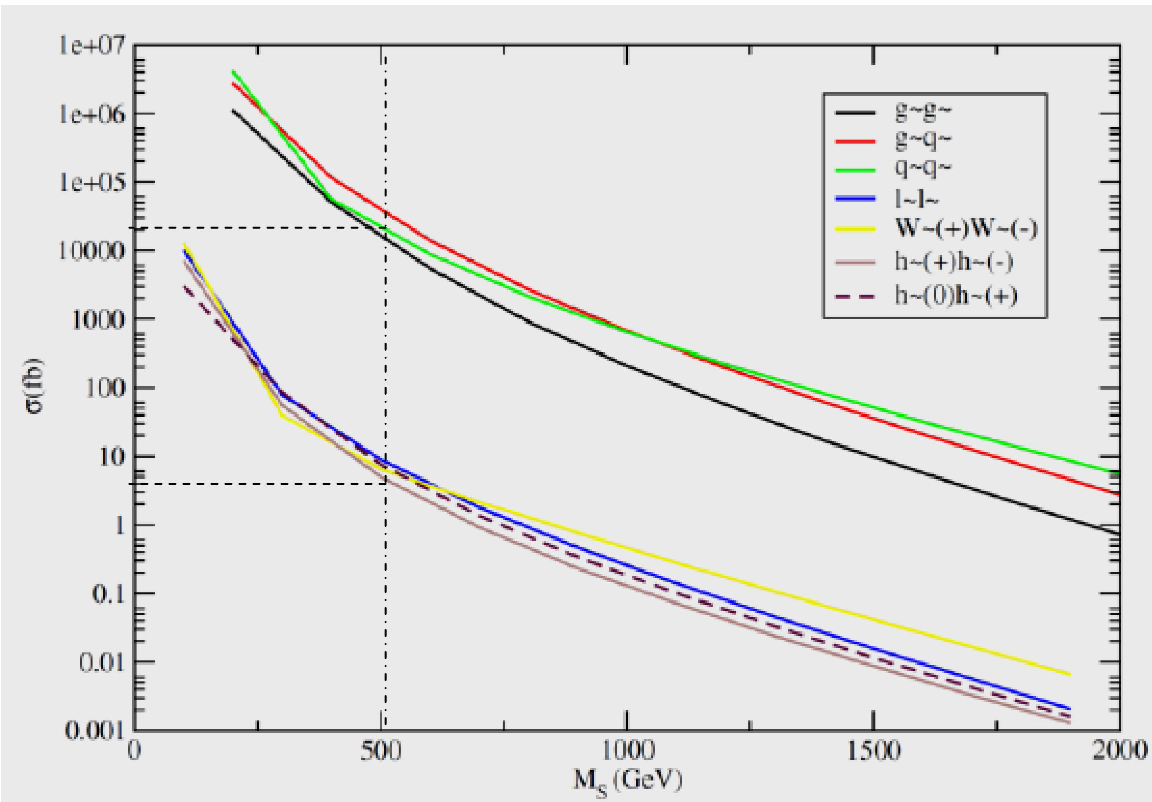
Chargino mass
CDF 1.1fb-1
>129GeV
M0=70

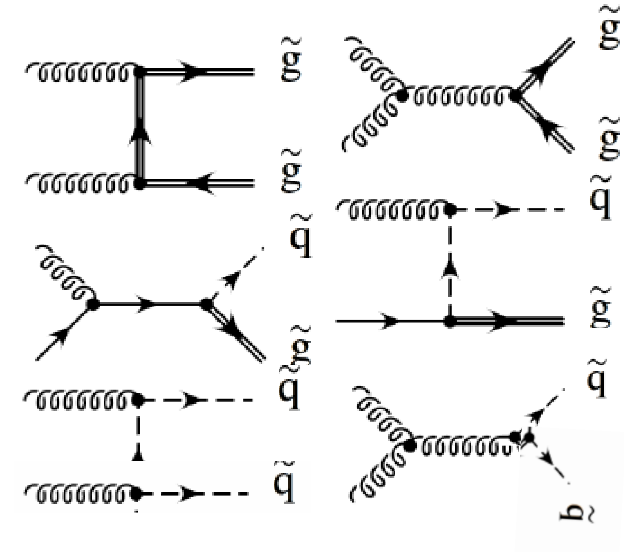
D0 0.9-1.7fb-1
>145GeV
M0 is such that
N2<slepton

$\tan\beta = 3$ and $\mu > 0$, and A0 so that no stau mixing

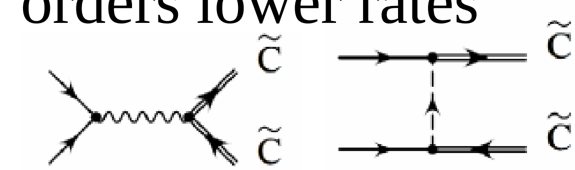
Super Partner Production

Colored vs. Uncolored production at LHC





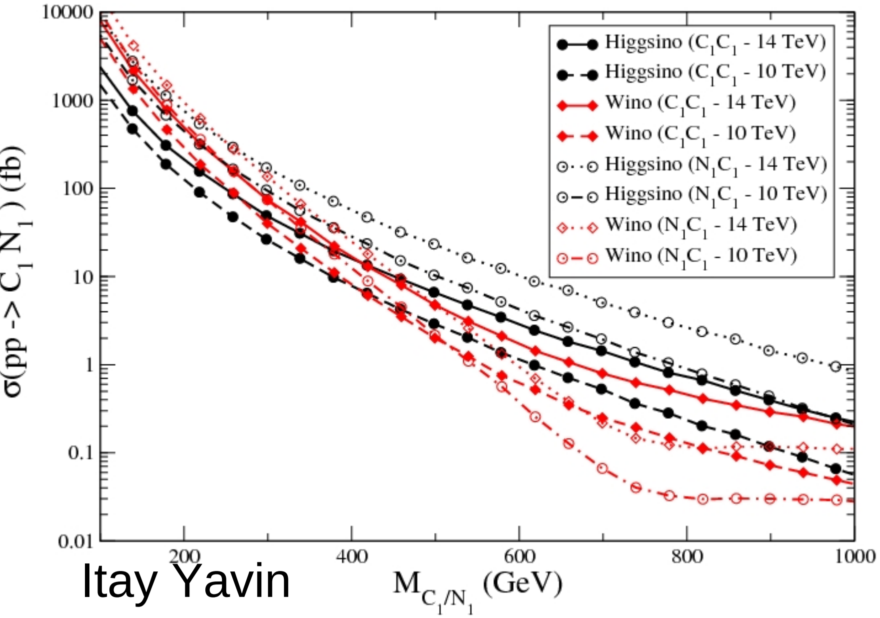
Weak coupling – 2-3 orders lower rates



LianTao Wang

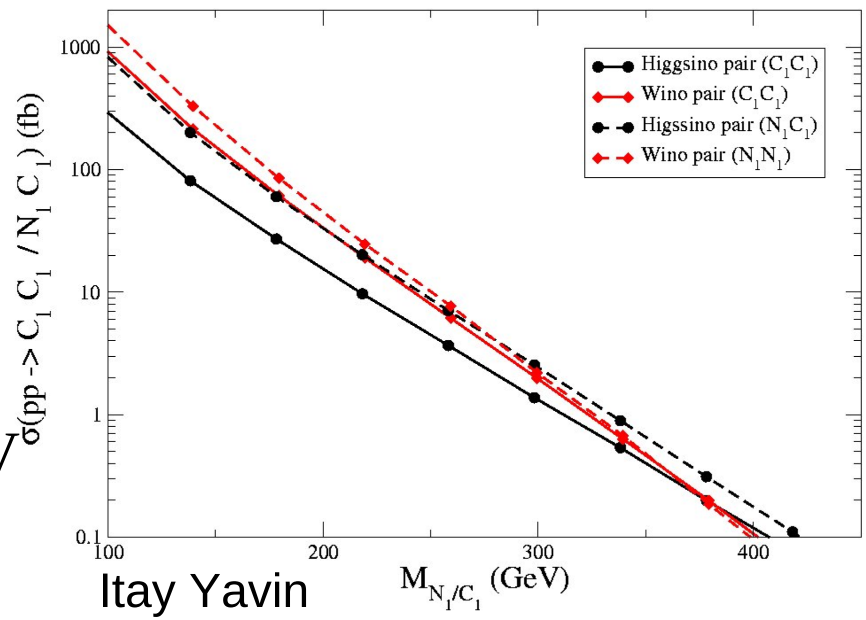
Chargino Neutralino Production

LHC



Itay Yavin

Tevatron

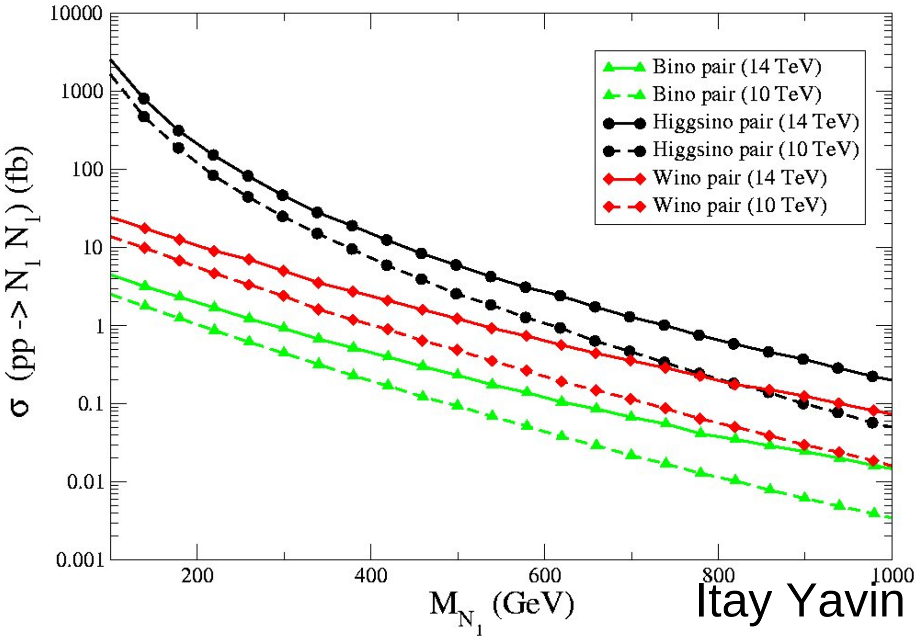


Itay Yavin

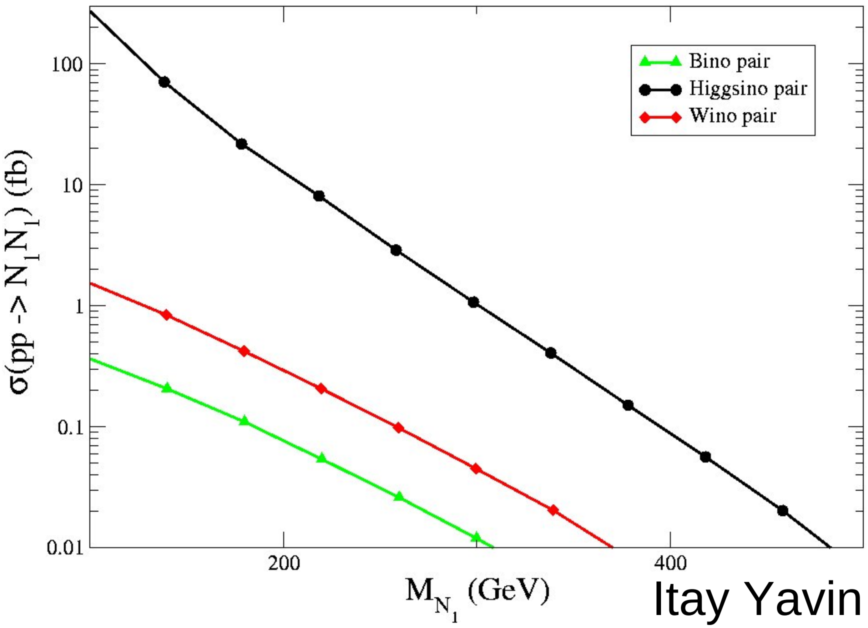
Note: Squark mass of 750 GeV
the rest decouple

Neutralino Production

LHC

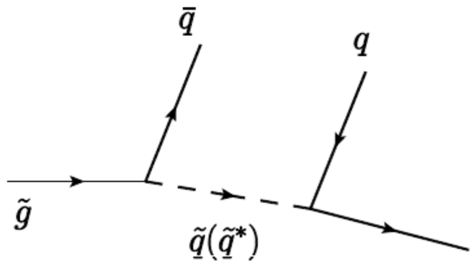


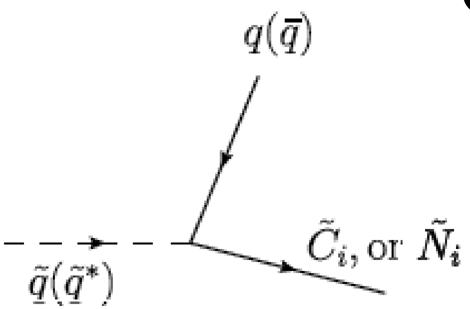
Tevatron



Sparticle Decays

QCD

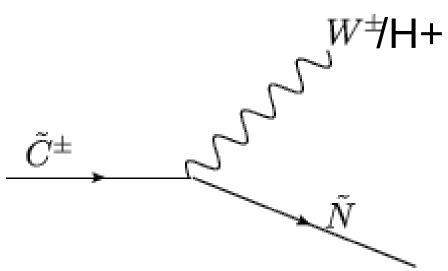


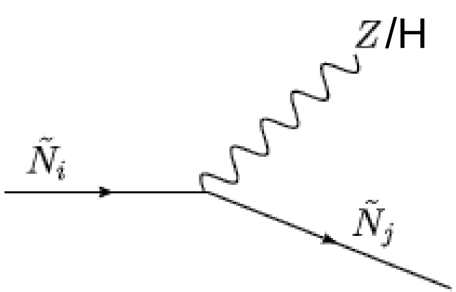


Gluino→Squark+Jet

Squark→ Gluino + Jet→ off shell squark + 2 Jet

EWK

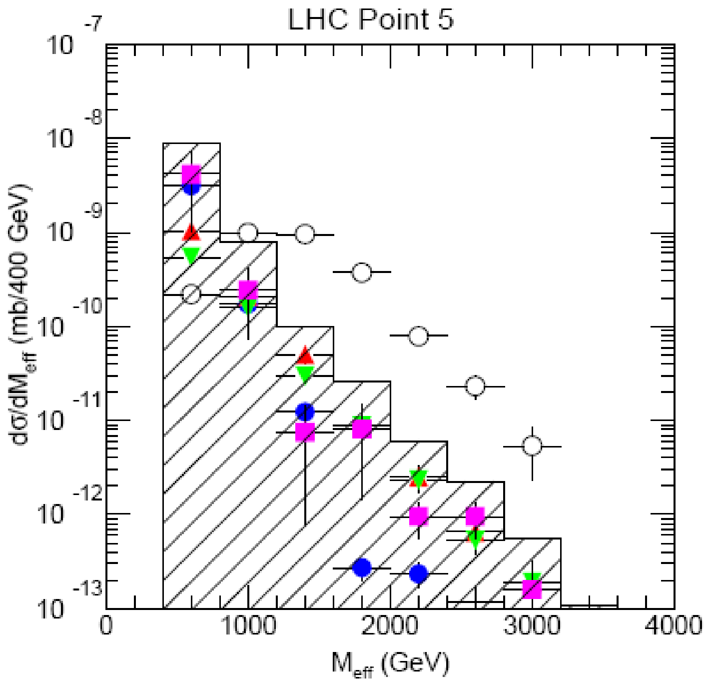


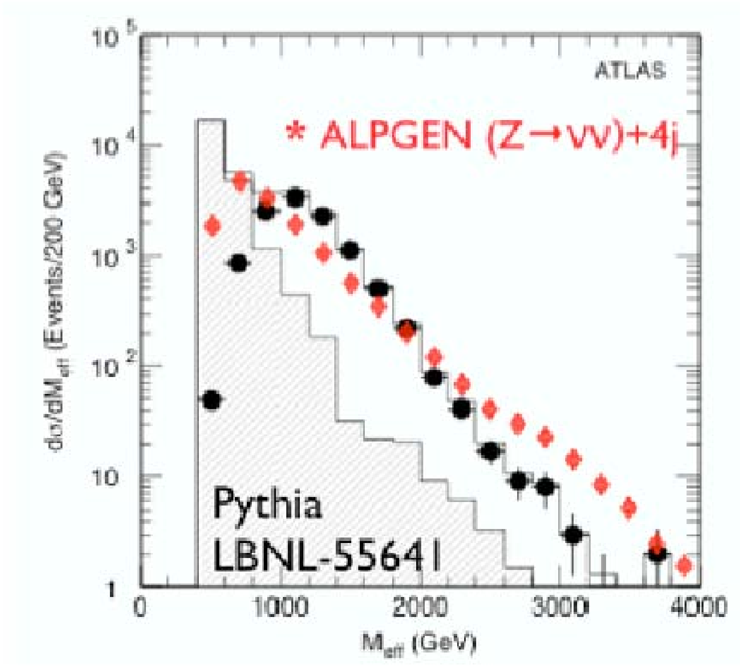


Dilepton SUSY Signatures

Inclusive Search

Watch out !!!



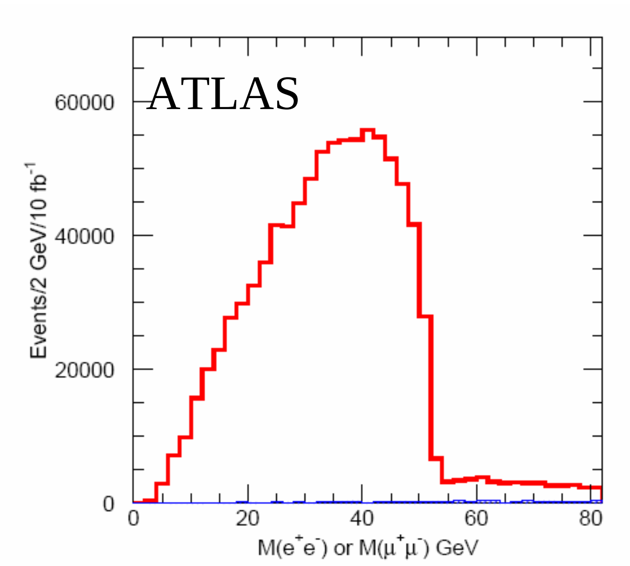


Dilepton SUSY Signatures

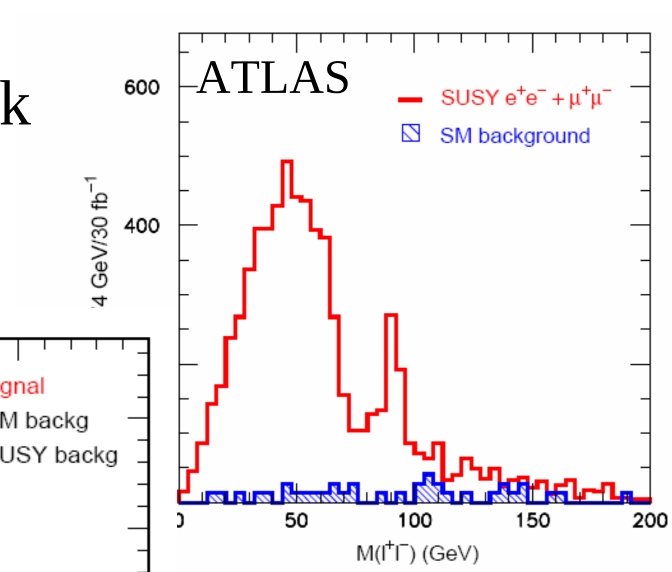
Exclusive Search

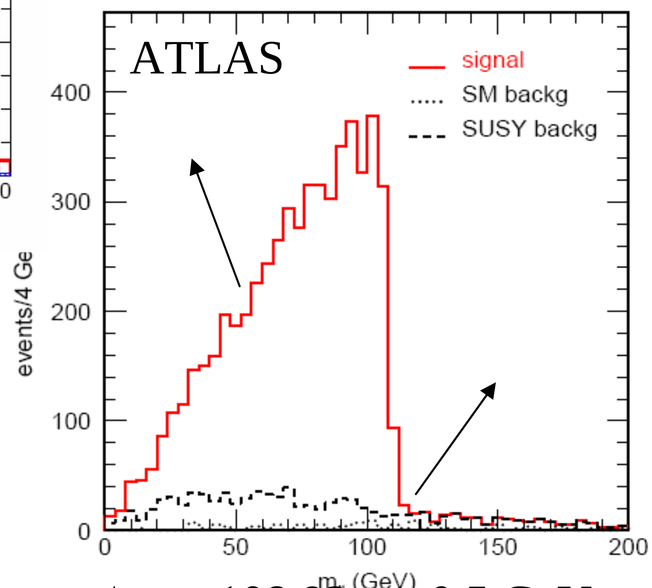
The decay involves usually

- $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 l^+ l^-$;
- $\tilde{\chi}_2^0 \to \tilde{l}^{\pm} l^{\mp} \to \tilde{\chi}_1^0 l^+ l^-$;
- $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h \to \tilde{\chi}_1^0 b\bar{b}$.



Gaugino>squark
Light sleptons





Light neutralino

Δm = 52.47 +/- 0.05 GeV

Δm = 108.93 +/- 0.5 GeV

Light neutralino
and heavy sleptons

Δm = 68.13 +/- 0.5 +007 GeV

Experimentally

Systematics:

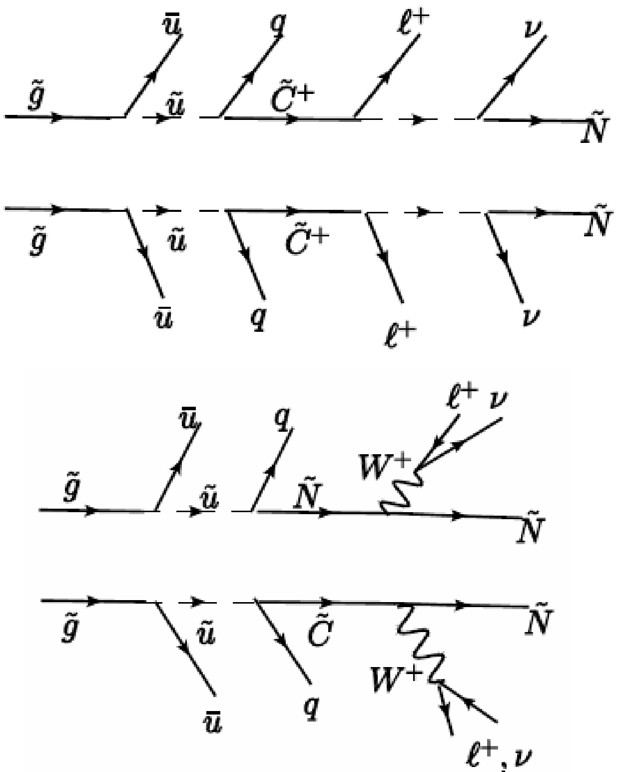
- Impact of the acceptance
- Resolution effects
- Pileup
- QCD background Model
- Background subtractions

Interesting vars:

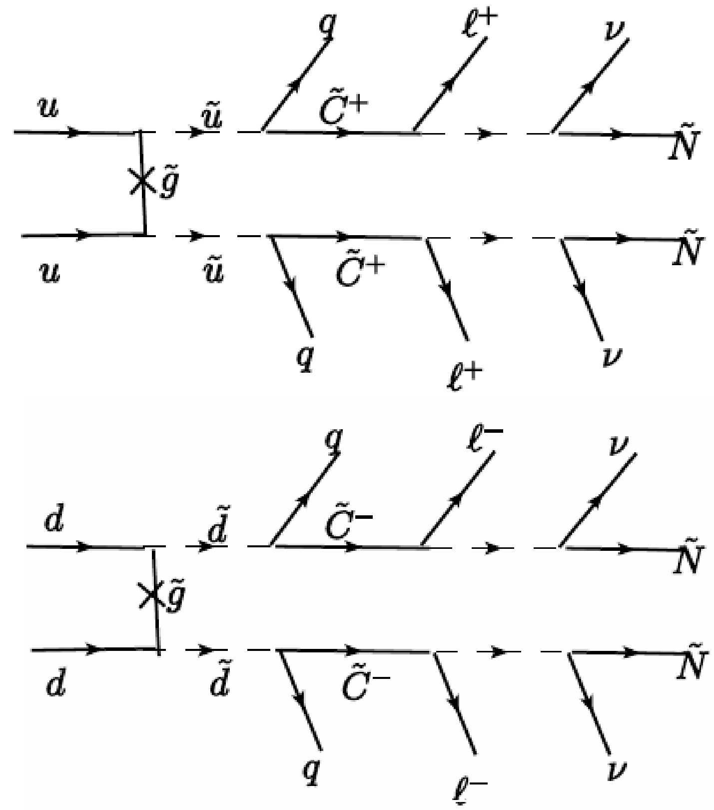
- Pt2/Pt1
- Pt_ll
- Kinematic End points

Same Sign Di-Leptons (Majorana Gaugino)

Gluino Production



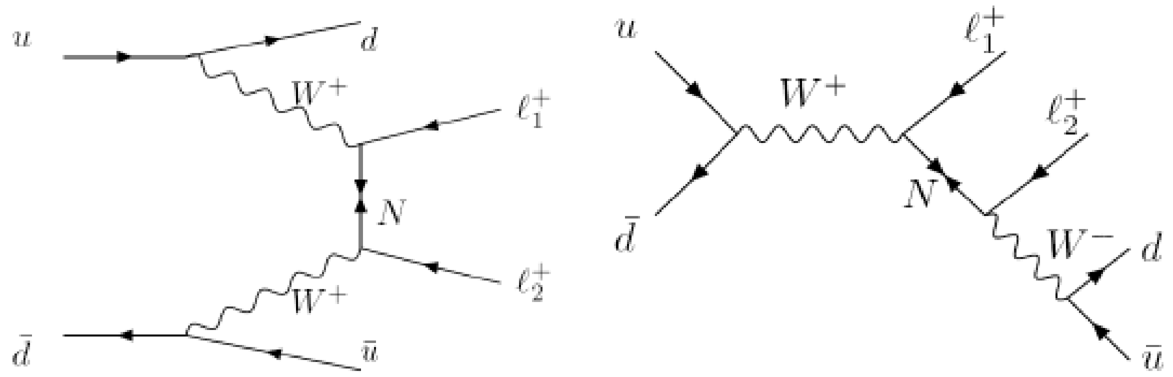
Same Sign Squarks



Or Gluino squark production

Same-Sign Dilepton (Majorana neutrino)

VBF



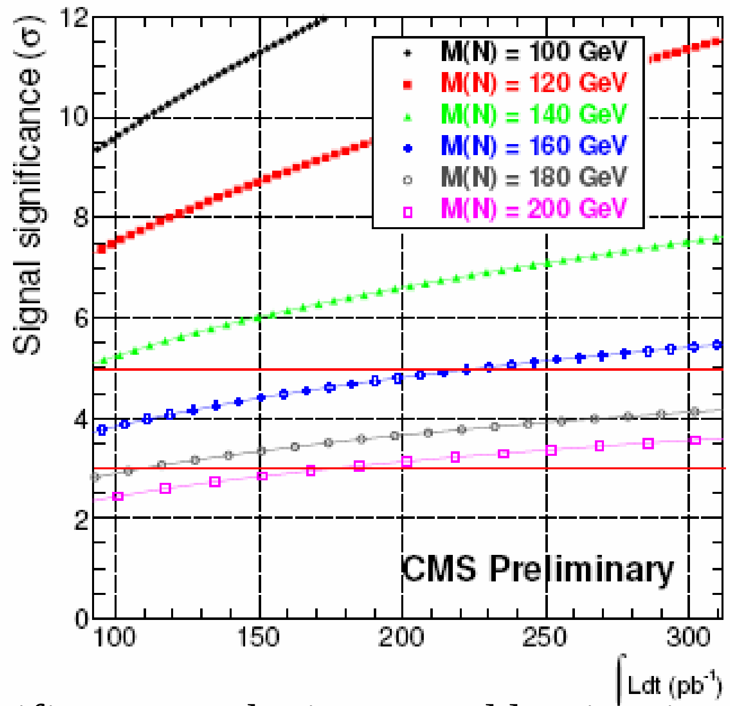
Virtual W decay

The cross section for this process is suppressed by $|V_{Nl}|^4$.

Tao Han et al

M_N	Cross-section (pb)	Event Rate (100 pb^{-1})
100 GeV	3.17	317
120 GeV	1.24	124
140 GeV	0.632	63.2
160 GeV	0.362	36.2
180 GeV	0.227	22.7
200 GeV	0.152	15.2

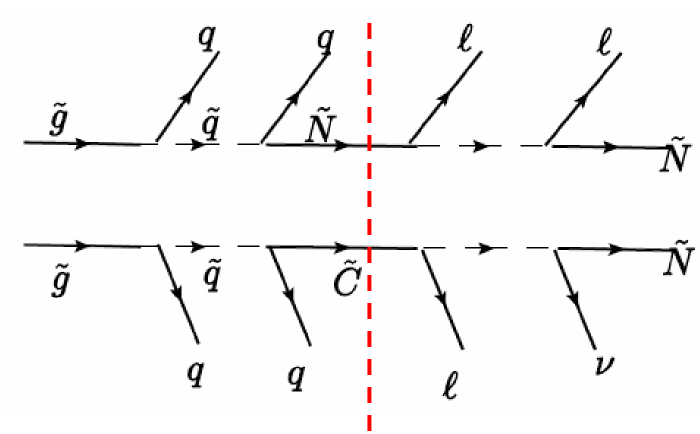
Background	Cross-Section (pb)	Event Rate (100 pb^{-1})
WW	74	7400
ZZ	10.5	1050
tW	32	3200
WZ	32	3200
Triple W/Z	0.071	7.1
Drell-Yan $M_{\mu\mu} > 200$ GeV	1.5	150
$Z(\mu\mu)$ + jets	657	65700
$Z(\tau\tau)$	1086	108600
VQQ (V=W/Z Q=b/c)	289	28900
$t\bar{t}$	414	41400

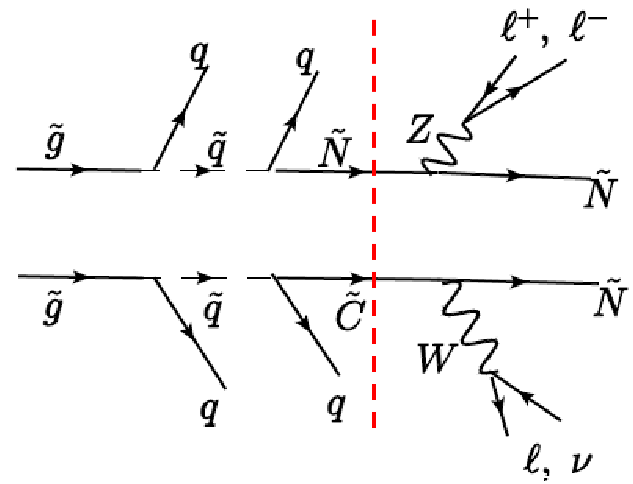


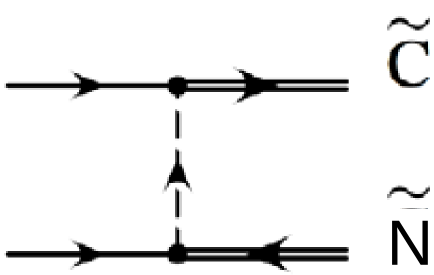
$$\sqrt{s} = 10 TeV$$

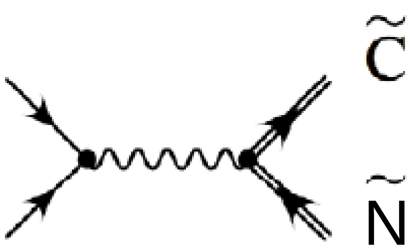
The discovery significance vs the integrated luminosity for several masses within the region studied. The 3σ and 5σ lines are shown in red.The significance values below 100 pb^{-1} do not include the increased uncertainties in the measurements; therefore, we don't assume the significance values for that region to be valid for discovery.

3 Lepton Signature ? 3lepton+MET



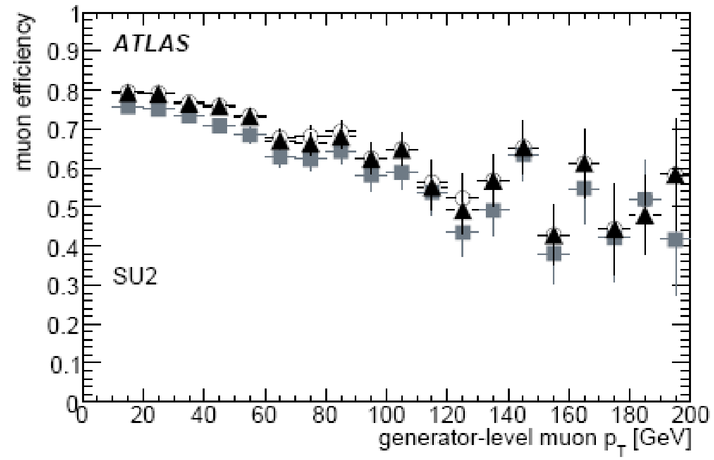


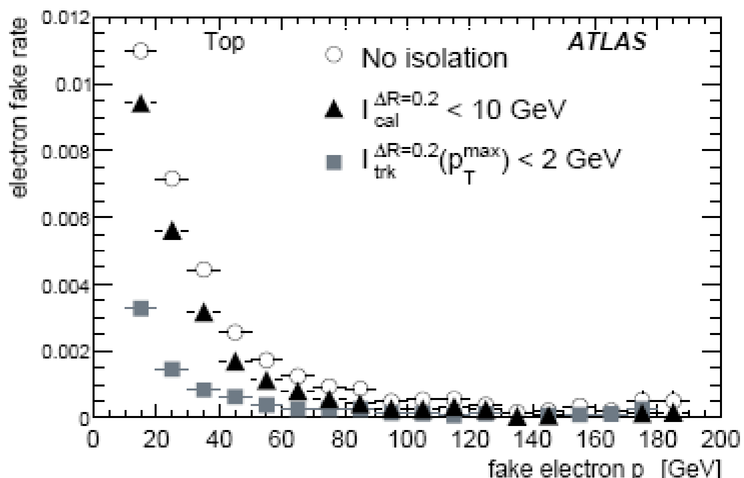




With production Mechanism or heavier sparticles

1. At least 1 pair of OSSF leptons
2. At least 3 leptons
3. $Pt_{track\,\max}^{\Delta R=0.2}$ <2GeV electrons, $Pt_{track\,\max}^{\Delta R=0.2}$ <1GeV muons
4. No OSSF inv mass in range 81.2GeV < M_{OSSF} <102.2GeV
5. Et^{miss} >30GeV
6. Optional – no Jet with Pt>20GeV



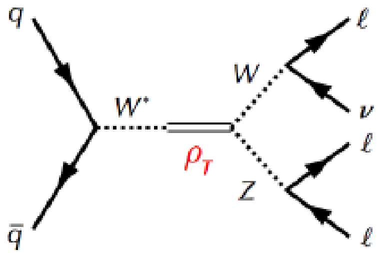


Source	Uncertainty	
	No jet veto	With jet veto
Background production rates	0.8%	1.9%
Lepton Efficiency	2.3%	2.3%
Fakes ($R_{b \to \ell}$)	4.0%	1.2%
Hadronic energy scale	–	1.8%
Missing energy scale	1.5%	1.0%
Total systematic	4.9%	3.8%
Statistical	3.7%	6.9%
Statistical + Systematic	6.2%	7.9%

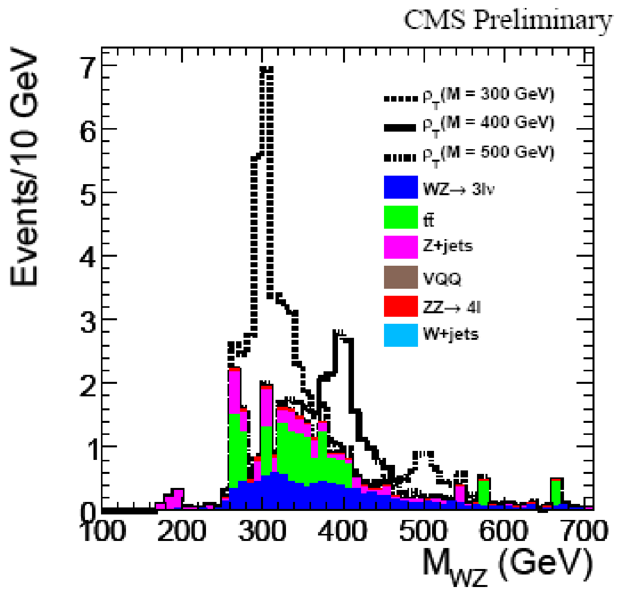
	SU1	SU2	SU3	SU4	SU8	SU2χ	SU3χ	SU2+JV	SU3+JV
$\mathscr{S}$, 10 fb^{-1}	7.7	5.9	17.2	69.3	1.9	3.3	1.6	1.9	1.4
$\int dt\, \mathscr{L}$ for 5σ	4.2	7.1	0.8	0.1	70.5	22.4	92.9	66.9	119.3

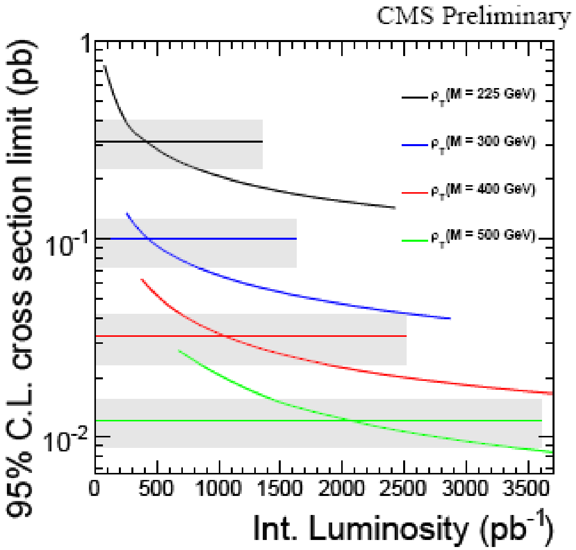
Discovery potential, and integrated luminosity required for 5s discovery.

3 Lepton +MET



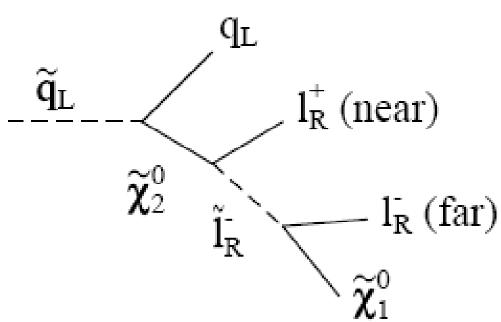
WTC Model



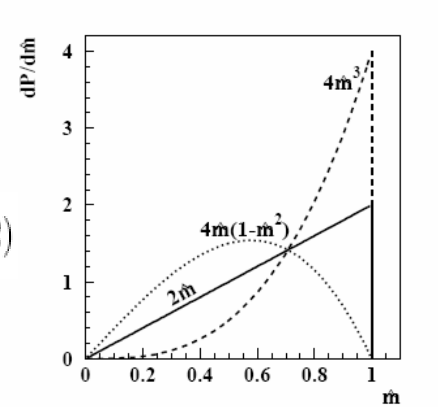


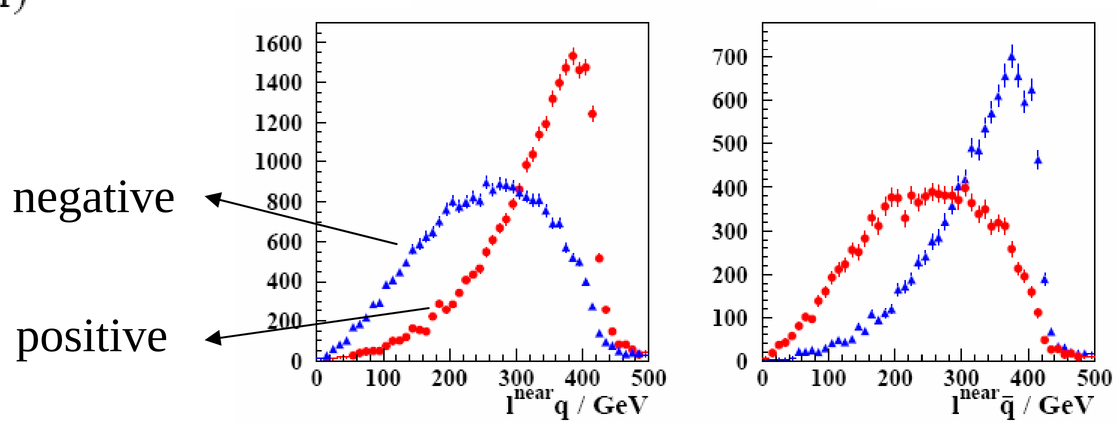
Spin Measurements of SUSY particles

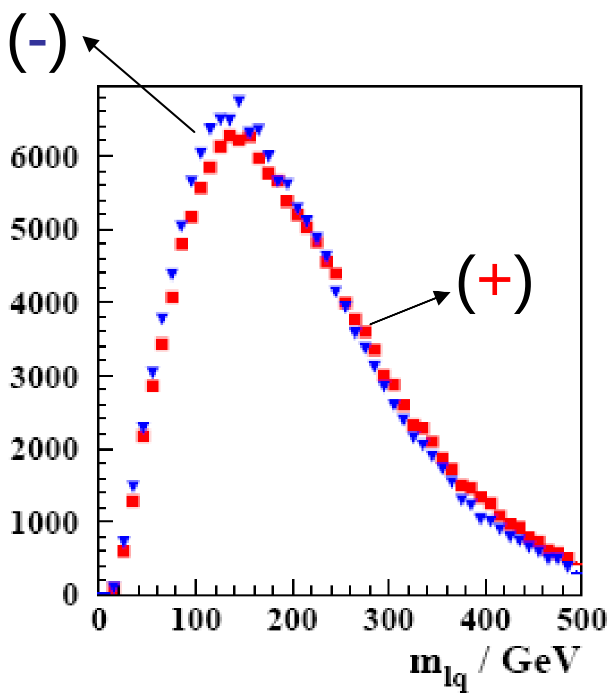
Use of angular distribution is sparticle decays lead to charge asymmetry in lepton-jet invariant mass distribution



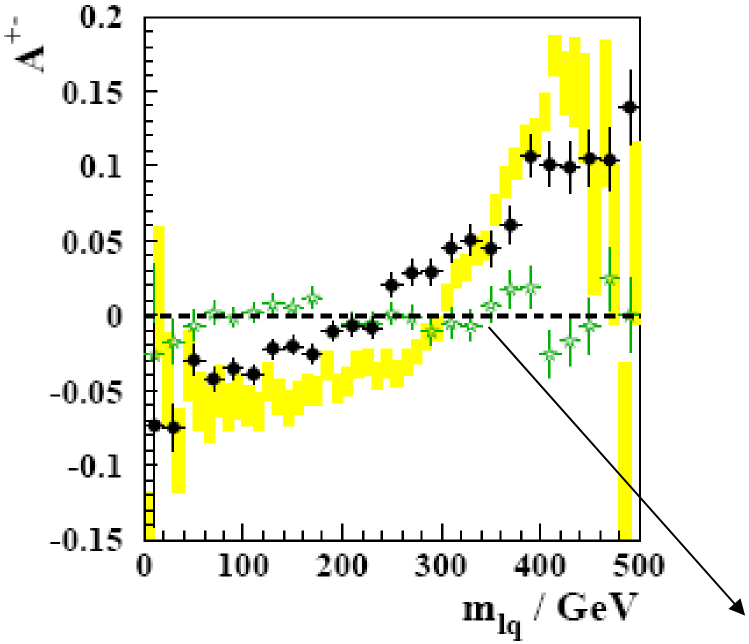
$$\hat{m} = \sin(\theta^*/2)$$







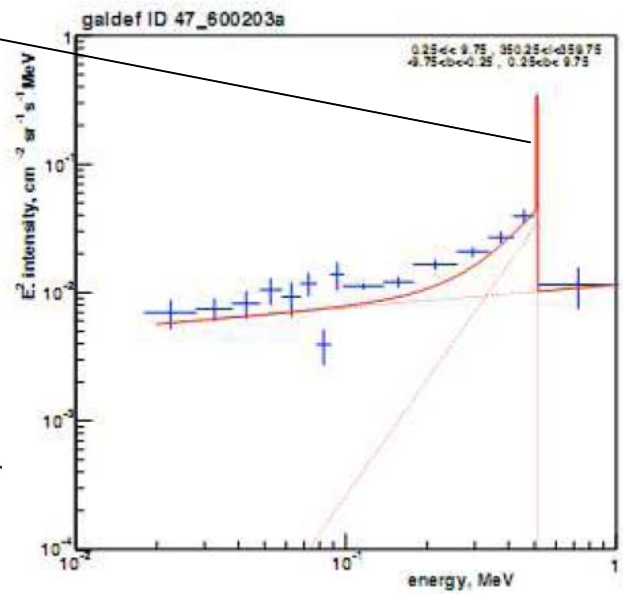
$$A^{+-} \equiv \frac{s^{+} - s^{-}}{s^{+} + s^{-}} \qquad s^{\pm} = \frac{d\sigma}{d(m_{l^{\pm}q})}$$



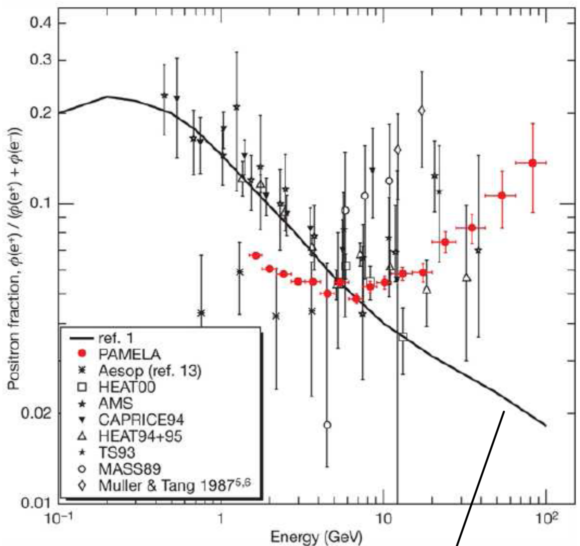
Phase Space

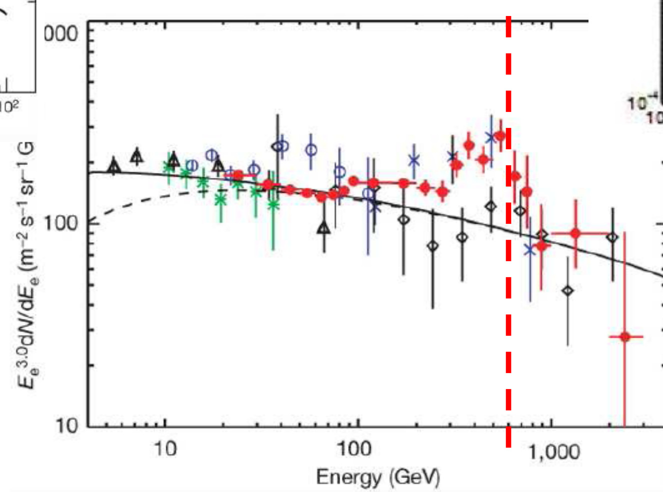
Experimental Motivation for Unifying DM

Galactic center



ATIC/PPB





PAMELA

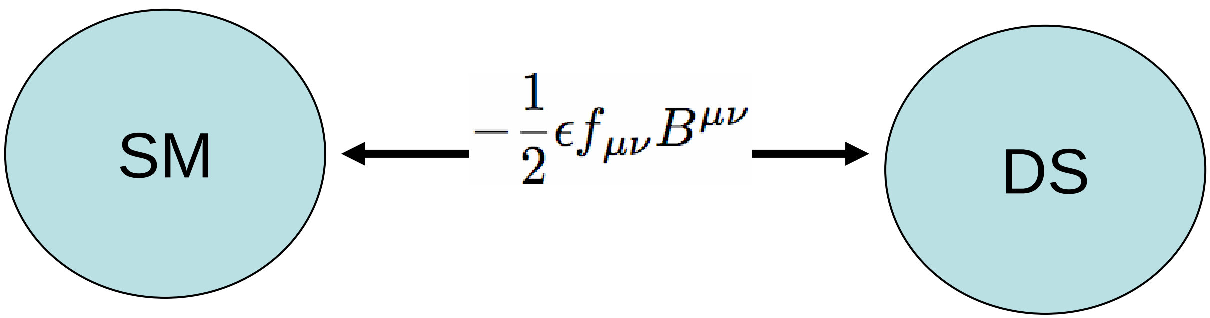
INTEGRAL

Theory: secondary production of positrons from propagation of cosmic rays,

New Sector

Consider another sector, charged under some new U'(1), which couples very weakly to the SM via kinetic mixing with hypercharge only.

N. Arkani Hamed
D. FinkBeiner
T. Slatyer
N. Weiner
Itay Yavin
LianTao Wang



$$\mathcal{L}_{\rm SM} = \ldots$$

http://pdg.lbl.gov

$$\mathcal{L}_{\rm DS} \supset i\bar{\chi}\gamma^{\mu}D_{\mu}\chi + M\bar{\chi}\chi$$

$$-\frac{1}{4}f_{\mu\nu}f^{\mu\nu} + \frac{1}{2}m^2 b_{\mu}b^{\mu}$$

$$+|D_{\mu}h_i|^2 - V(h_i)$$

$M \sim \text{TeV}$

$m \sim \text{GeV}$

Direct Production

Producing directly the heavy dark matter particle is going to be difficult. But, the lighter portion of the dark spectrum can be produced and investigated!!!

$$-\frac{1}{2}\epsilon f_{\mu\nu}B^{\mu\nu} \quad \rightarrow \quad \epsilon\cos\theta_w\ b_\mu J^\mu_{\rm em} + \epsilon\sin\theta_w Z_\mu J^\mu_{\rm dark}$$

So,

1) The dark photon, couples to electromagnetic charge!

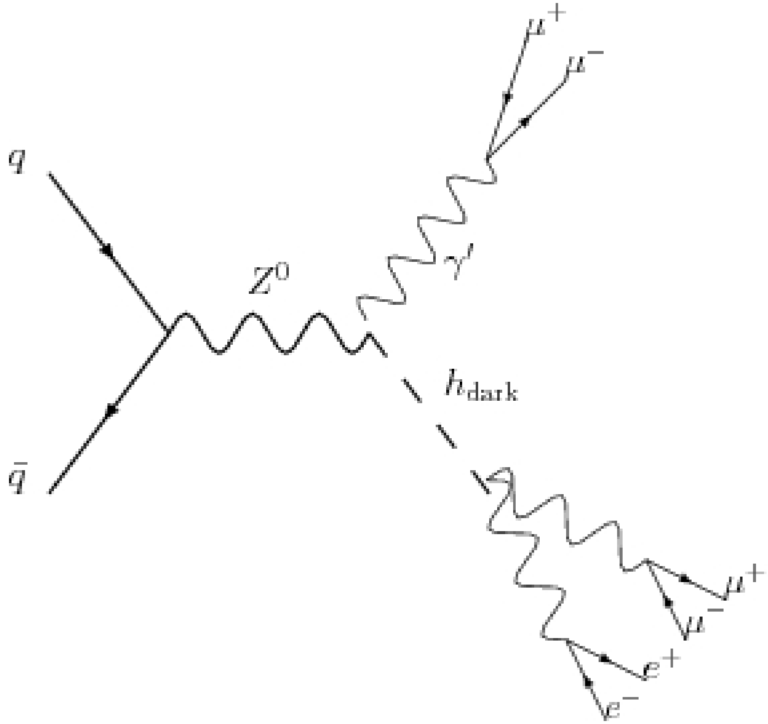
2) The Z^0 vector-boson couples to the dark current!

If supersymmetry is only softly broken in the dark sector, then we also couple to the dark higgsinos:

$$\mathcal{L}_{\rm susy} \supset \epsilon\lambda_{\tilde{B}}\tilde{J}_{\rm dark}$$

Rare Z Decay

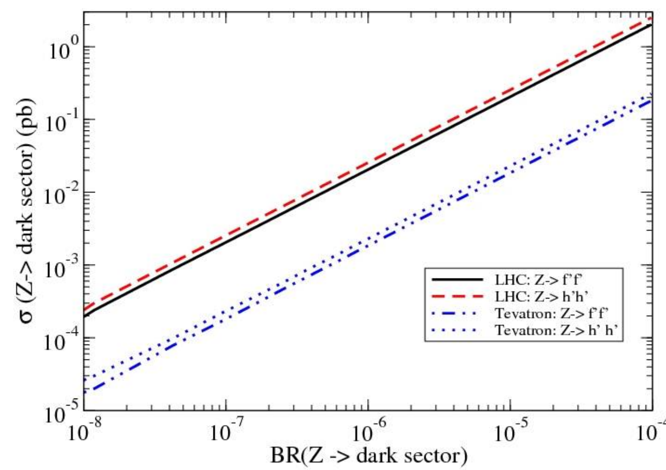
The neutral vector-boson couples directly to the dark current. Therefore, the dark higgses and can be directly produced:



Lepton Jets - A collimated collection of energetic leptons with a small opening angle.

$$\theta \sim \frac{m}{E}$$

θ



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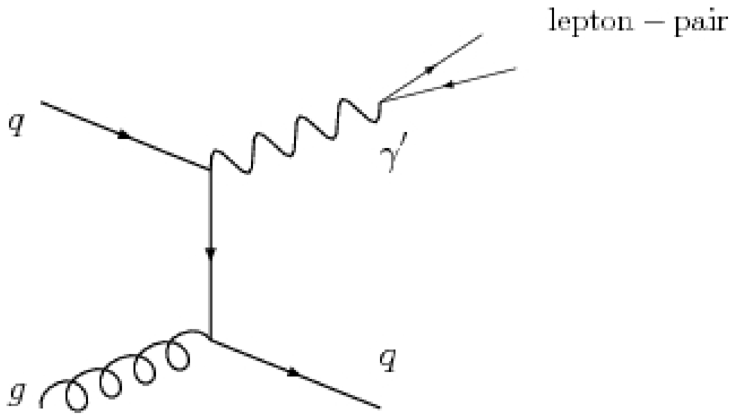
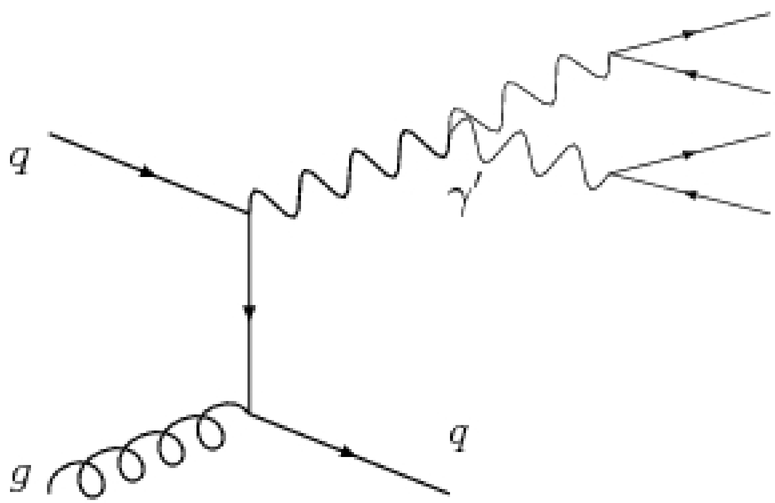
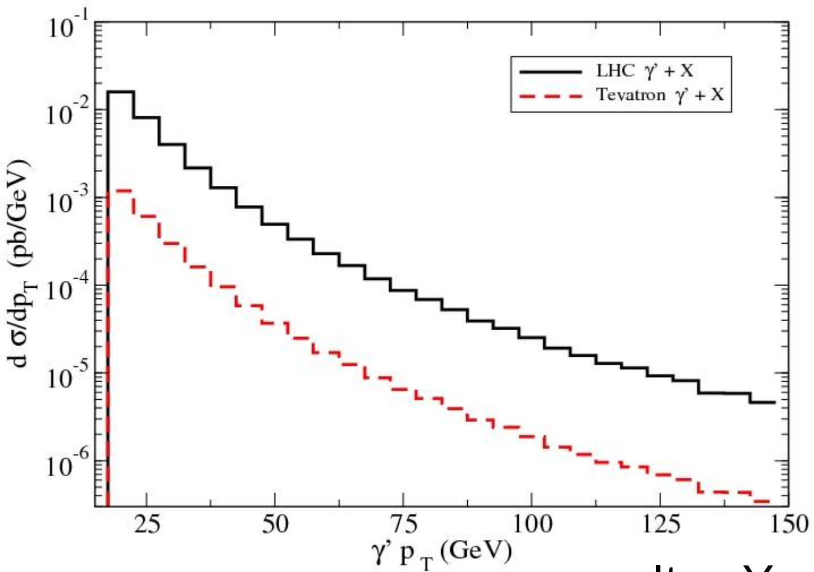
Prompt Dark Photon

Since it couples to electromagnetic current, the dark photon couples to the constituent quarks. It can be produced in analogy with prompt photon production:







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May act as a good benchmark against which to test detector performance.

Conclusions

Di-lepton is the smoking gun of new physics in LHC

Both CMS and ATALS demonstrate excellent lepton ID

A large number of topologies is still waiting to be covered

If history repeats itself, we expect di-lepton +X
Channel to reveal to us another secret from BSM in LHC

I would like to thank Meenakshi Narain and Yasunori Nomura for the kind invitation and Itay Yavin for his contribution and many interesting discussions.

- BACKUP

Additional Z bosons

Z'_{SM} with standard couplings

Mass $m >$ 923 GeV, CL = 95% ($p\overline{p}$ direct search)

Mass $m >$ 1500 GeV, CL = 95% (electroweak fit)

Z_{LR} of $\mathrm{SU(2)}_L \times \mathrm{SU(2)}_R \times \mathrm{U(1)}$ (with $g_L = g_R$)

Mass $m >$ 630 GeV, CL = 95% ($p\overline{p}$ direct search)

Mass $m >$ 860 GeV, CL = 95% (electroweak fit)

Z_χ of $\mathrm{SO(10)} \rightarrow \mathrm{SU(5)} \times \mathrm{U(1)}_\chi$ (with $g_\chi = e/\cos\theta_W$)

Mass $m >$ 822 GeV, CL = 95% ($p\overline{p}$ direct search)

Mass $m >$ 781 GeV, CL = 95% (electroweak fit)

Z_ψ of $E_6 \rightarrow \mathrm{SO(10)} \times \mathrm{U(1)}_\psi$ (with $g_\psi = e/\cos\theta_W$)

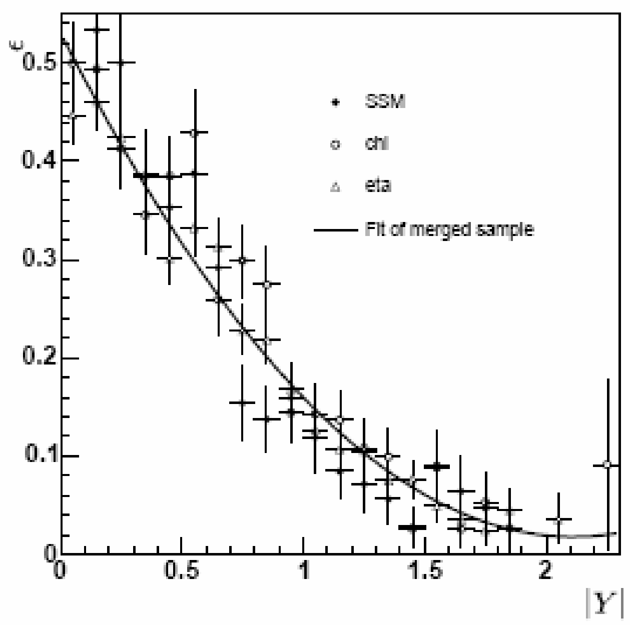
Mass $m >$ 822 GeV, CL = 95% ($p\overline{p}$ direct search)

Mass $m >$ 475 GeV, CL = 95% (electroweak fit)

Z_η of $E_6 \rightarrow \mathrm{SU(3)} \times \mathrm{SU(2)} \times \mathrm{U(1)} \times \mathrm{U(1)}_\eta$ (with $g_\eta = e/\cos\theta_W$)

Mass $m >$ 891 GeV, CL = 95% ($p\overline{p}$ direct search)

Mass $m >$ 619 GeV, CL = 95% (electroweak fit)



(a) $0.8\,TeV < \sqrt{s'} < 1.4\,TeV$