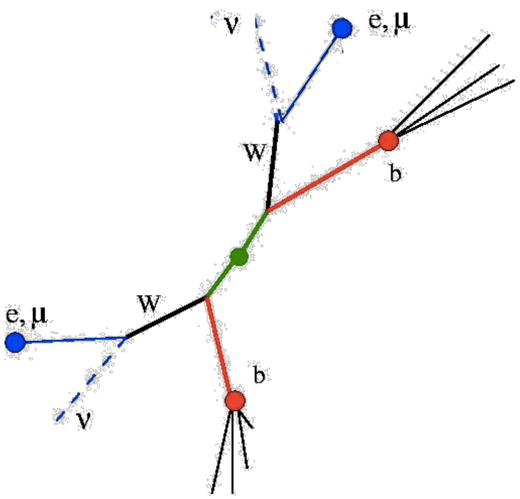
Top physics

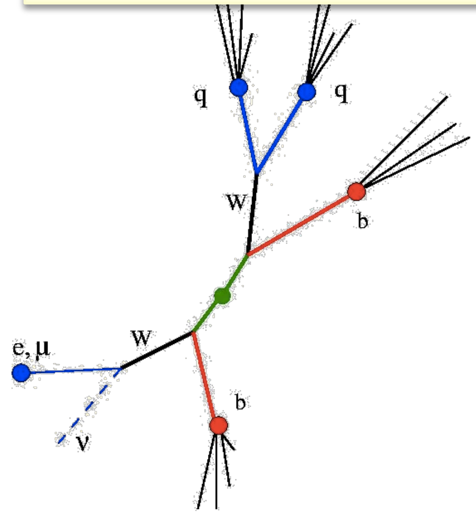
The top

- **If the J/ψ, Y, W and Z are standard candles, then the top is a candelabra***
  - **Leptons, missing E_T, additional jets; and b-tagging**
  - **Analysis requires all that has gone into the W and Z, plus increased QCD background (because of higher jet multiplicity).**
    - **Plus interplay with W/Z+jets production**

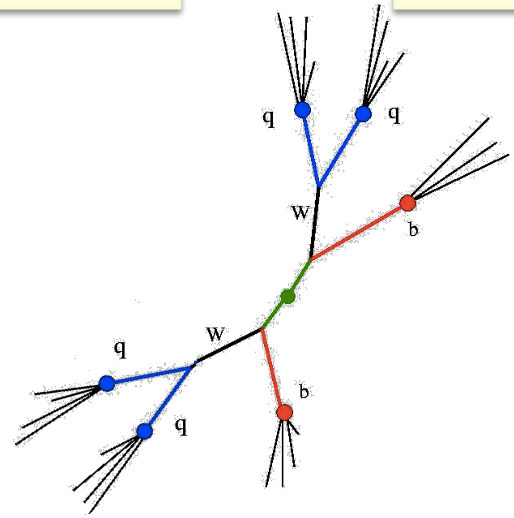
Dilepton: cleanest but Br~4/81



1-lepton: semi-clean; Br~8/27



0-lepton: not-clean; Br~4/9

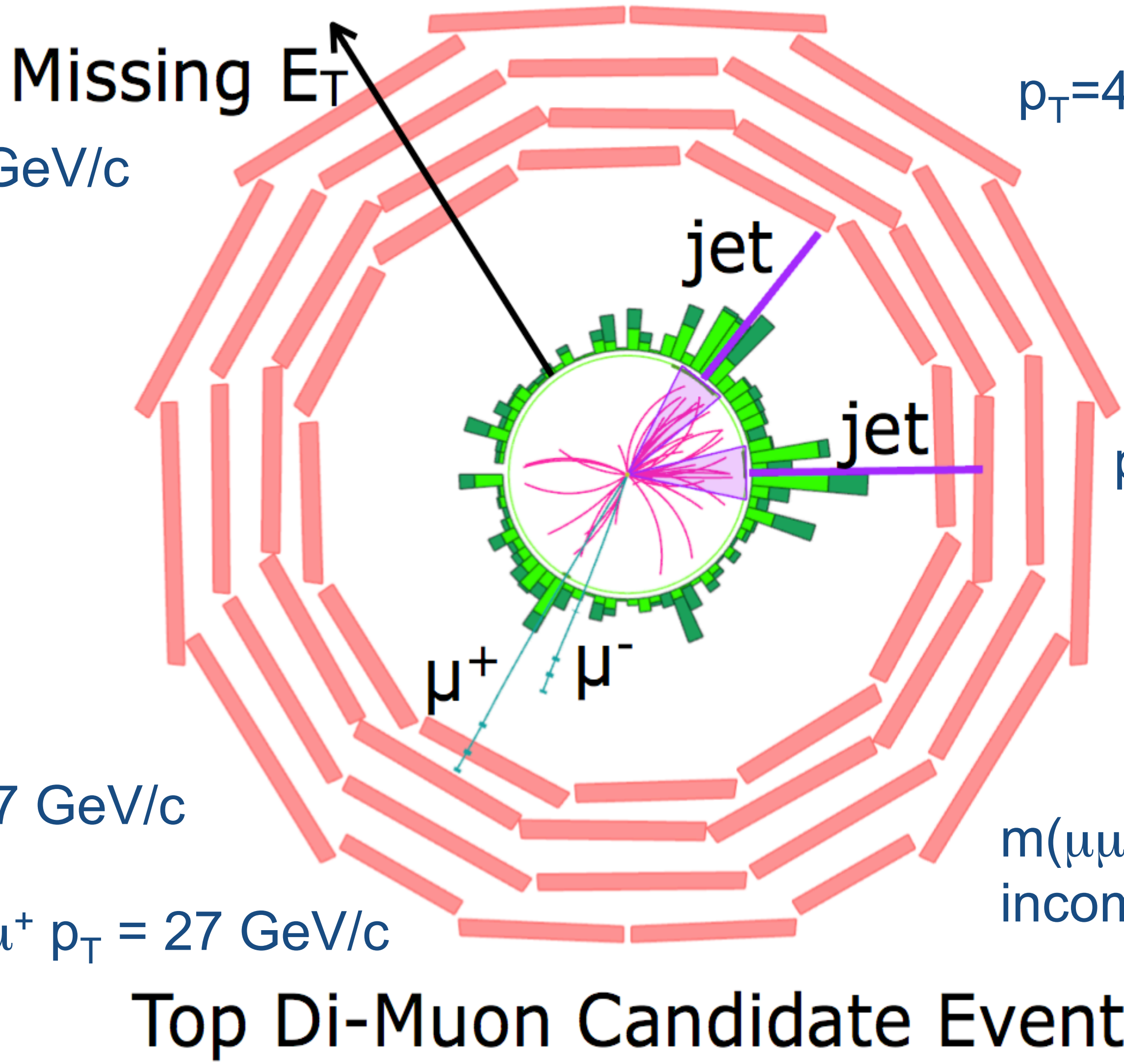


***: first heard this from Ken Bloom, U of Nebraska**

top quark candidates: dilepton

MET= 57 GeV/c

p_T=45 GeV/c



p_T = 56 GeV/c

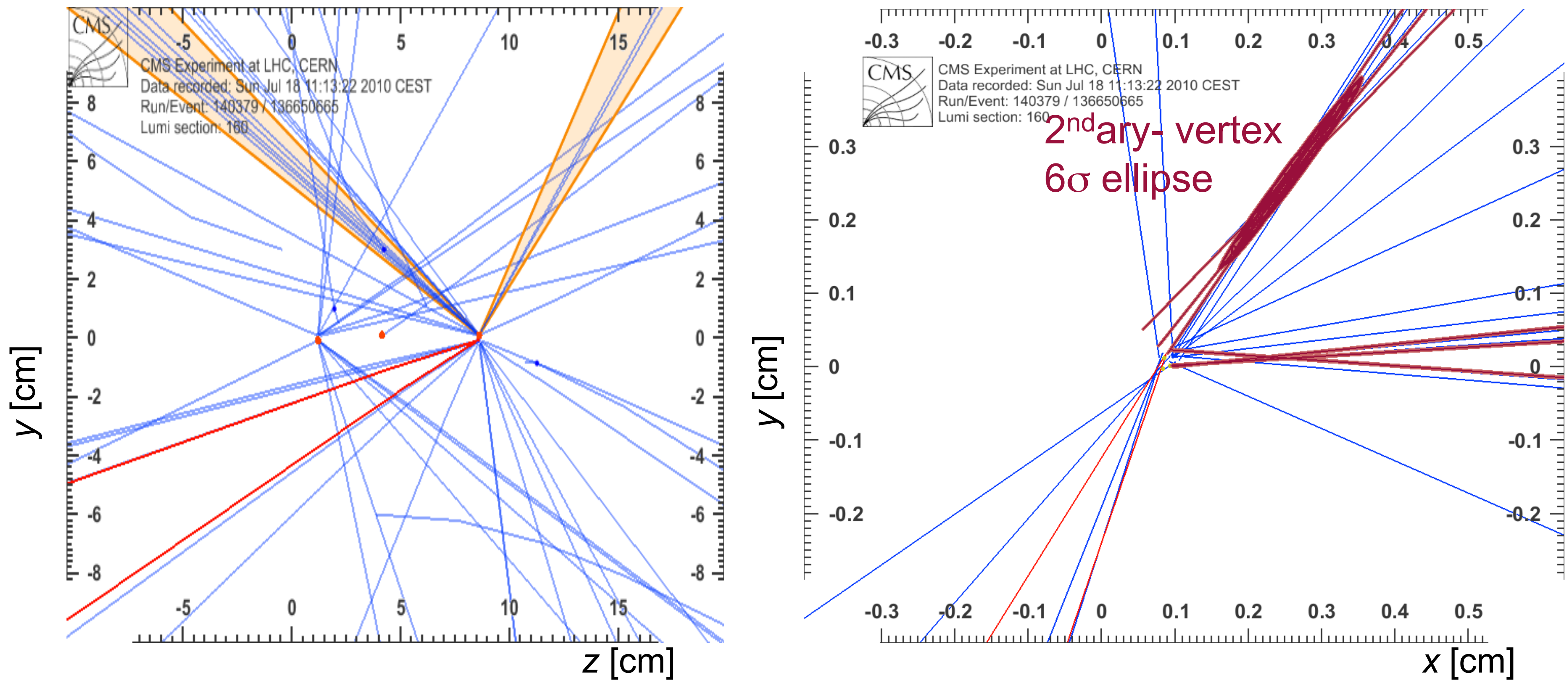
μ^- p_T = 57 GeV/c

μ^+ p_T = 27 GeV/c

m(μμ) = 26 GeV/c^2
incompatible with Z

top quark candidates: dilepton (cntd)

- **In addition: the two jets have good/clear *b*-tags**
- **Important cross check: muons and jets coming from the same interaction vertex.**

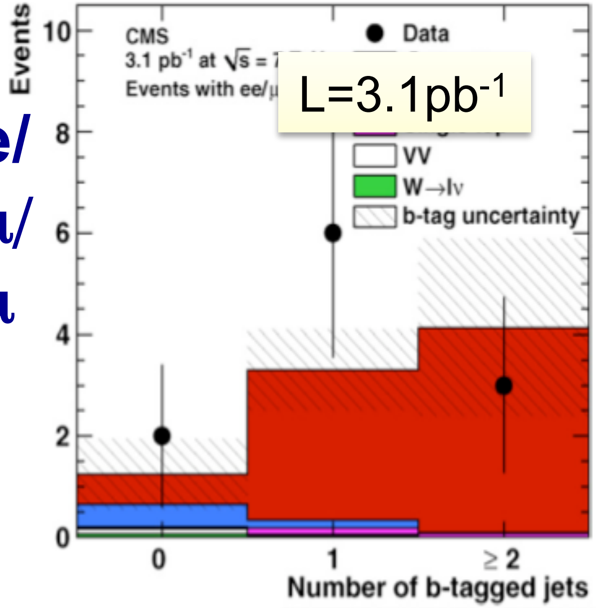


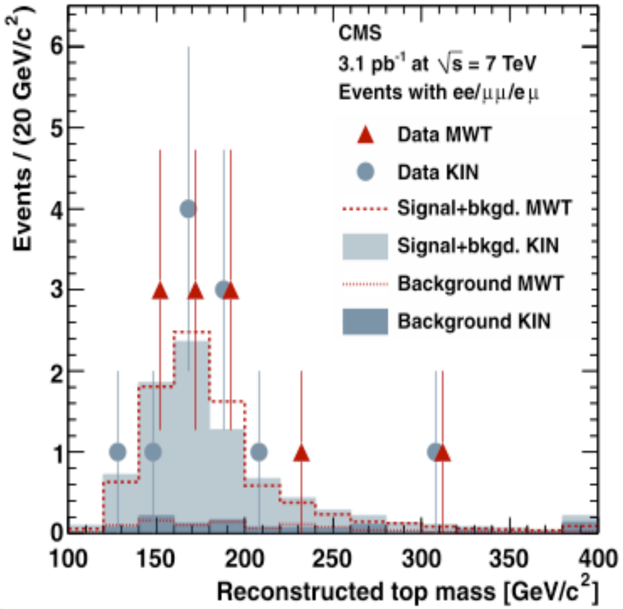
Top in dileptons+jets

- **Full selection applied;**
  - **Z-bosonVeto, $|M(\ell\ell)-M_Z|>15$ GeV**
  - **ME_T >30 (20) GeV in ee,μμ,(eμ); N(jets)≥2**

arXiv:1010.5994

ee/ eμ/ μμ





Source	Number of events
Expected $t\bar{t}$	7.7 ± 1.5
Dibosons (VV)	0.13 ± 0.07
Single top (tW)	0.25 ± 0.13
Drell-Yan $Z/\gamma^* \to \tau^+\tau^-$	0.18 ± 0.09
Drell-Yan $Z/\gamma^* \to e^+e^-, \mu^+\mu^-$	$1.4 \pm 0.5 \pm 0.5$
Events with non-W/Z leptons	$0.1 \pm 0.5 \pm 0.3$
Total backgrounds	2.1 ± 1.0
Expected total, including $t\bar{t}$	9.8 ± 1.8
Data	11

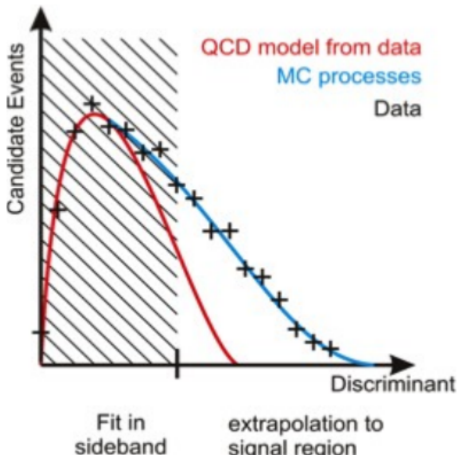
Cross section measurement:

$\sigma(pp \to tt + X)$ = 194±72(stat)±24(syst)±21(lumi) pb.
NLO prediction: 158±24 pb – for m_t = 172.5 GeV/c^2

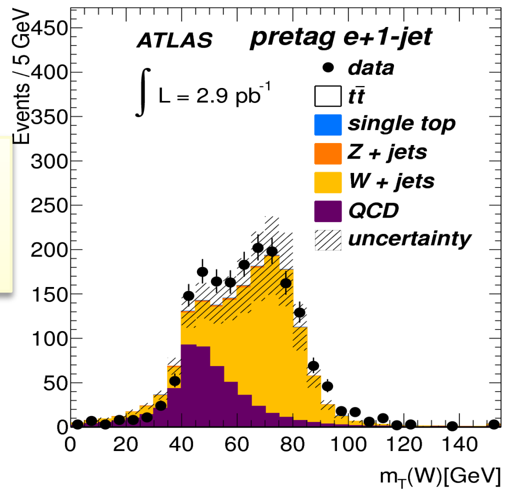
Top cross section (bkg estimate example)

- **First: bkg from QCD**

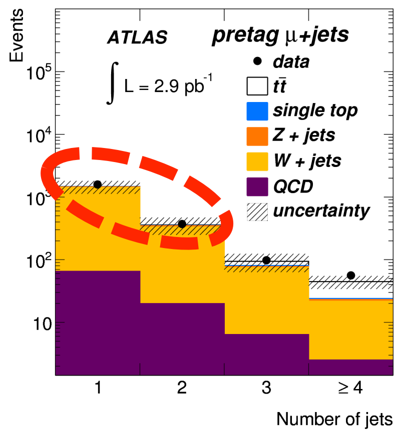
à la W+jet cross section: fit E_T^{miss} to 2 templates:
fake/non-prompt (from data: loose)
prompt leptons (signal, W+jets) from simulation



X-check on $M_T(W)$



- **Then: W+jets**
  - **Measure in Nj=1,2**



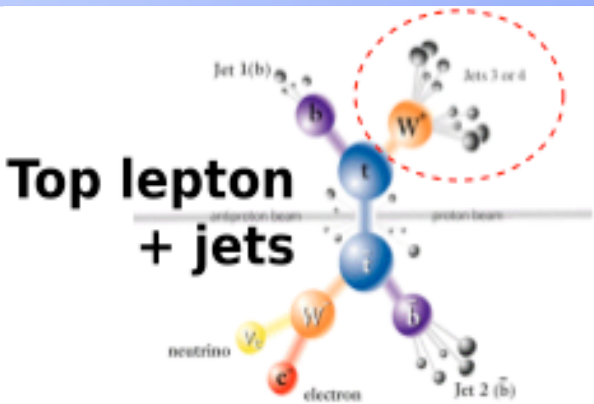
  - **then "Behrends scaling" to get Nj=4**
  - **Then simu to get btag fraction**

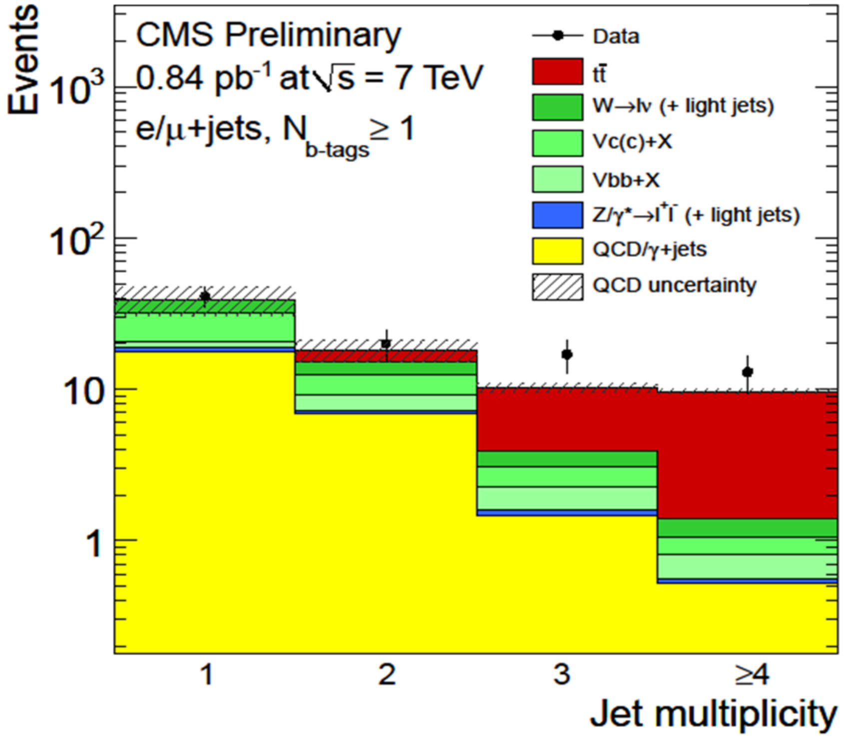
$$W^{\geq 4\text{-jet}}_{\text{pre-tag}} = W^{2\text{-jet}}_{\text{pre-tag}} \cdot \sum_{n=2}^{\infty} (W^{2\text{-jet}}_{\text{pre-tag}} / W^{1\text{-jet}}_{\text{pre-tag}})^n$$

$$W^{\text{tagged}-\geq 4\text{jet}} = W^{\text{pretag}-\geq 4\text{jet}} \cdot f^{\geq 4-\text{jet}}_{\text{tagged}}$$

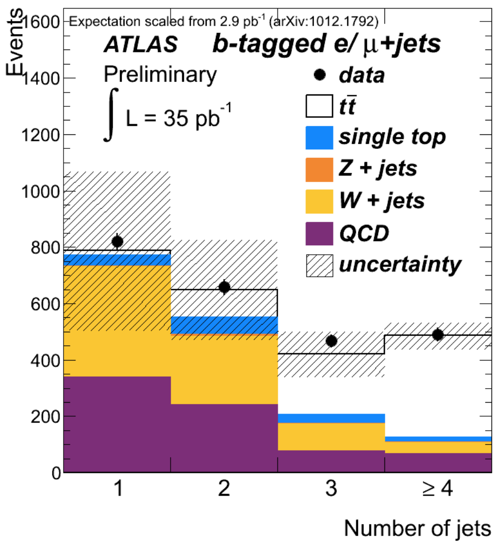
Top in lepton+jets

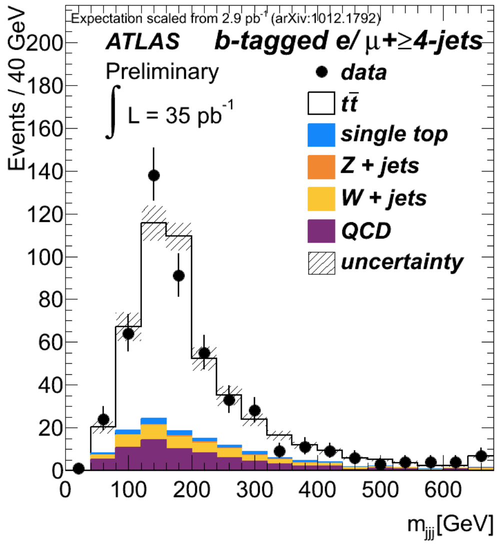
- **Require ≥1 secondary vertex tag with ≥2 tracks;**
  - **~50% efficiency ~1% fake rate**
- **N(jets)≥3**
  - **30 signal evts over estimated bkg of 5.3**
- **t-tbar rate consistent with NLO cross section**
  - **Systematic uncertainties**
    - **Expt: JES, b-tagging**
    - **The: scale, PDF, hadronization modeling**





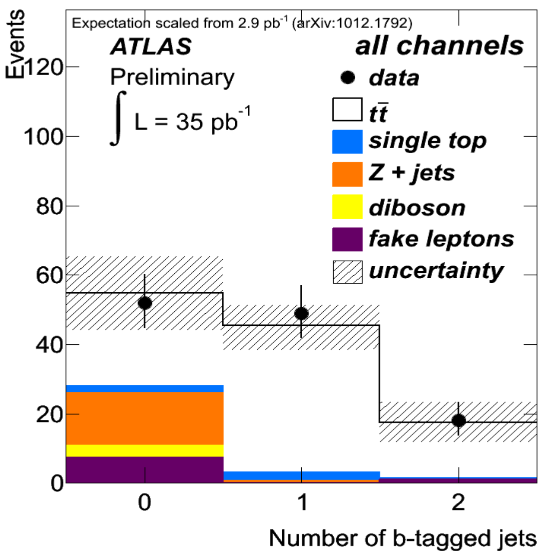
Top production in ATLAS

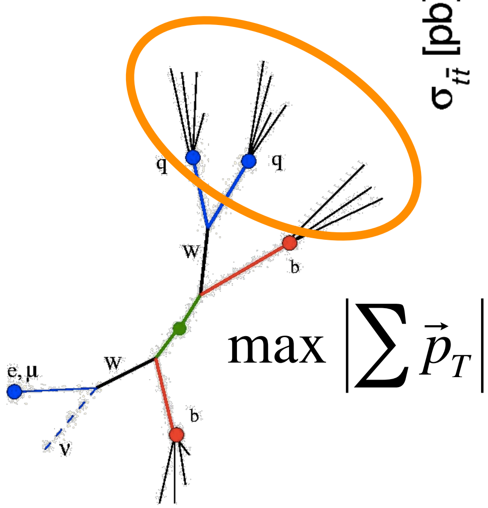


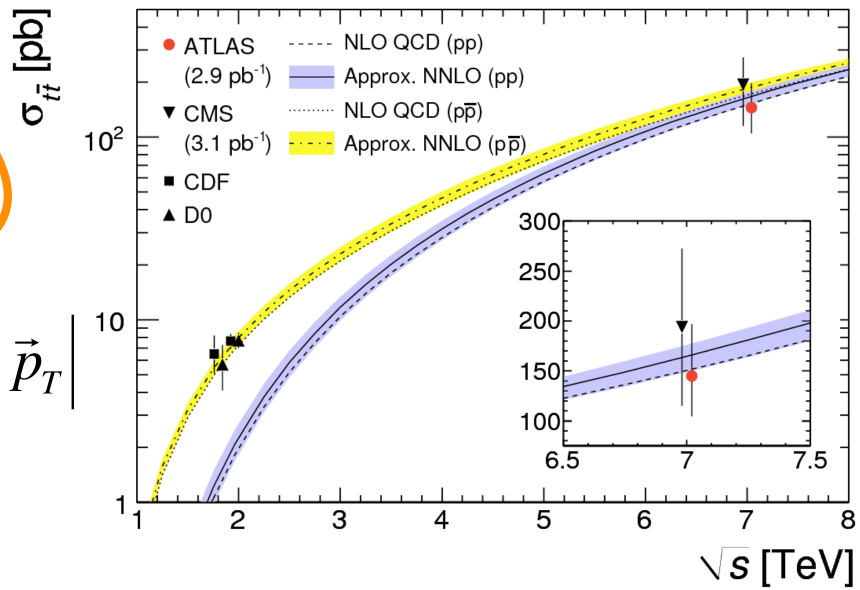


$p_T(e/\mu)>20$ GeV, $|\eta|<2.5$
$p_T(jet)>25$ GeV, $|\eta|<2.8$
Use W+jet xsec to extrapolate bkg in +4jet bin

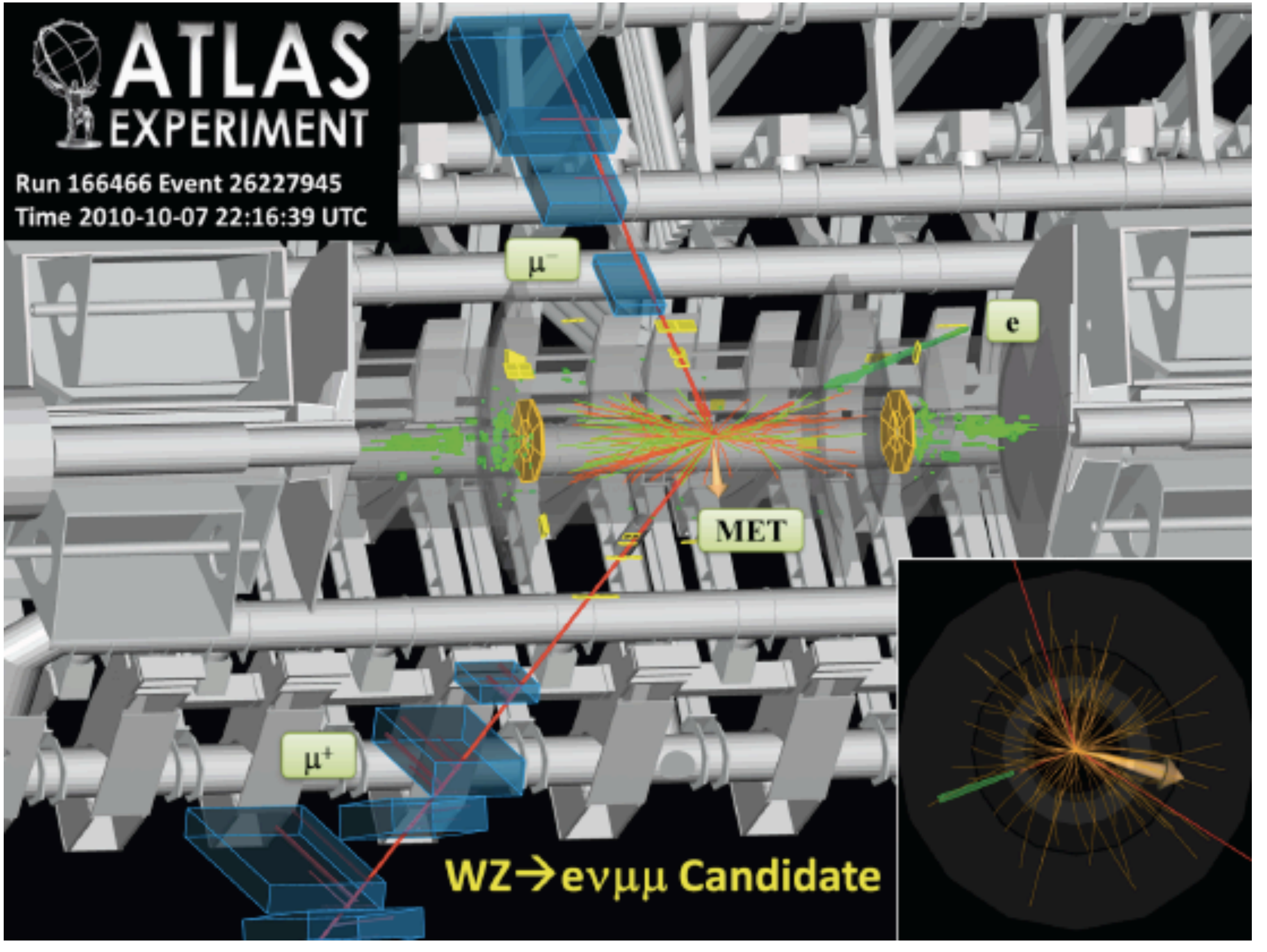
arXiv:1012.1792





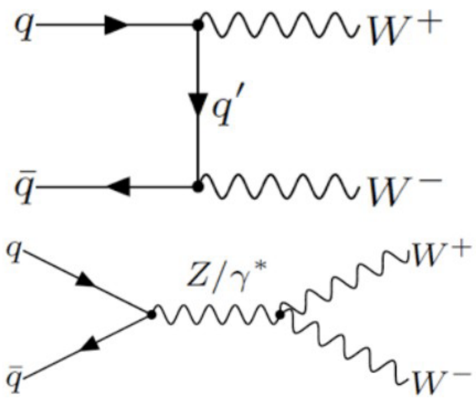


WZ production (?)



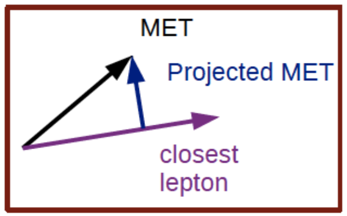
WW production

- **Last SM measurement before getting to the level needed for the Higgs search**
  - **Also probe for physics BSM (VVV vertex)**
- **Two high-P_T (20 GeV, |η|<2.4/2.5) isolated leptons (ee, $e\mu$, $\mu\mu$)**
  - **Bkgs: top, Drell-Yan (mainly Z)**
    - **Z-mass veto (15 GeV around Z)**
    - **M(ll)>12 GeV (low-M resonances)**
    - **No 3rd lepton (P_T>10)**
    - **Jets counted: P_T>25, |η|<5.0**

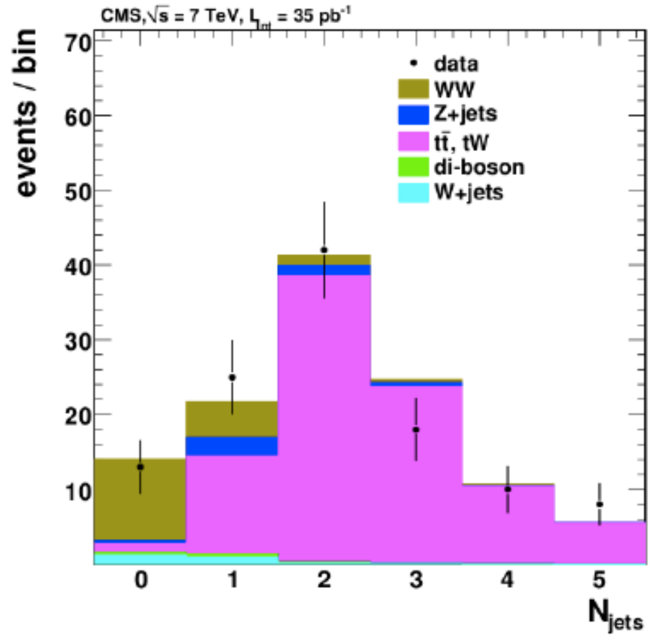


$$\Delta\phi_{min} = min(\Delta\phi(\ell_1, E_T^{miss}), \Delta\phi(\ell_2, E_T^{miss}))$$

Projected MET (against Z→ττ, ll):



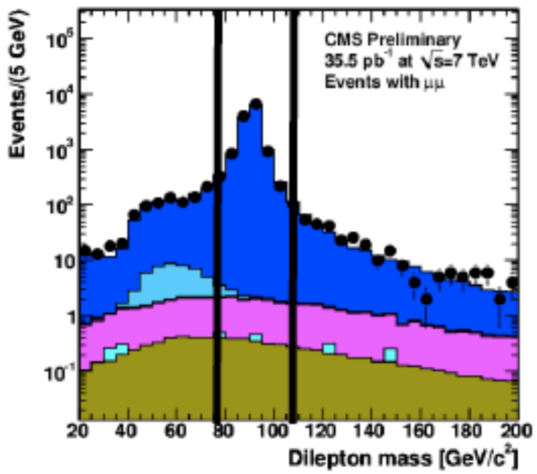
pMET>35 (ee,$\mu\mu$)
pMET>20 ($e\mu$)



WW production

- **Data-driven bkgs – example:**

Process	Events
W+jets + QCD	$1.7 \pm 0.4 \pm 0.7$
$t\bar{t} + tW$	$0.77 \pm 0.05 \pm 0.77$
$W\gamma$	$0.31 \pm 0.04 \pm 0.05$
$Z + WZ + ZZ \to e^+e^- / \mu^+\mu^-$	$0.2 \pm 0.2 \pm 0.3$
$WZ + ZZ$, not from Z	$0.22 \pm 0.01 \pm 0.04$
$Z \to \tau^+\tau^-$	$0.09 \pm 0.05 \pm 0.09$
Total	$3.29 \pm 0.45 \pm 1.09$



$$\sigma = \frac{N_{data} - N_{bkg}}{\epsilon \mathcal{L} BR(W \to \ell\nu)^2}$$

$$\Delta\sigma = \frac{\sqrt{N_{data}}}{\epsilon\mathcal{L}} \oplus \frac{\Delta N_{bkg}}{\epsilon\mathcal{L}} \oplus \frac{\Delta\epsilon}{\epsilon}\sigma \oplus \frac{\Delta\mathcal{L}}{\mathcal{L}}\sigma$$

variable	value	uncertainty
N_{data}	13	—
N_{bkg}	3.29	1.18
ϵ (%)	6.34	0.46
$\mathcal{L}$ (pb)	35.5	3.9
$BR(W \to l\nu)$	0.1080	0.0009

$$\sigma_{WW} = 41.1 \pm 15.3(\text{stat}) \pm 5.8(\text{syst}) \pm 4.5(\text{lumi})\ \text{pb}$$

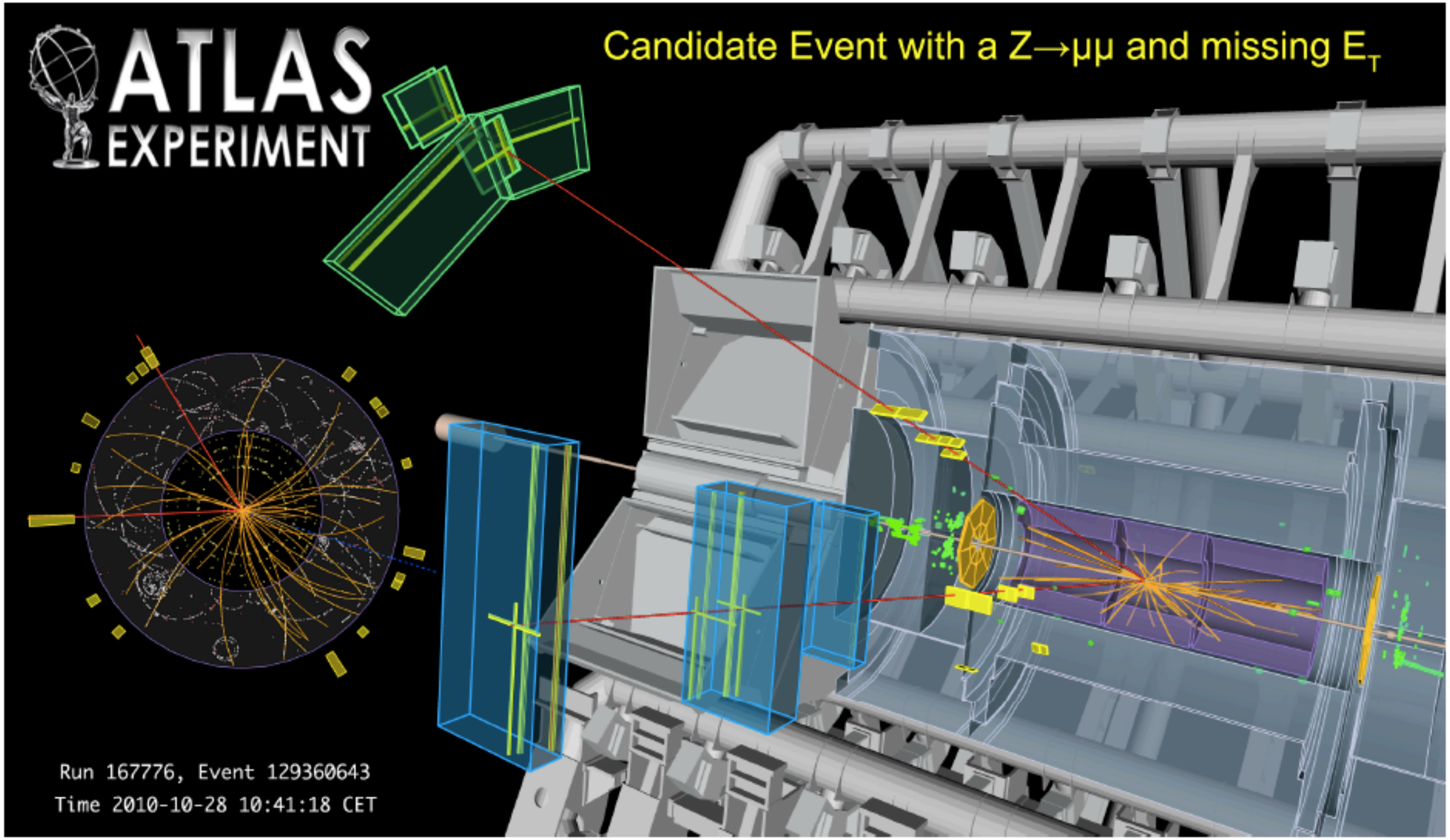
$$\sigma_{\text{NLO}} = 43.0 \pm 2.0\ \text{pb}$$

$$(\sigma_{\text{ww}}/\sigma_W) \times 10^4 = 4.46 \pm 1.66 \pm 0.64$$

$$(\sigma_{\text{ww}}/\sigma_W) \times 10^4{}_{NLO} = 4.45 \pm 0.30$$

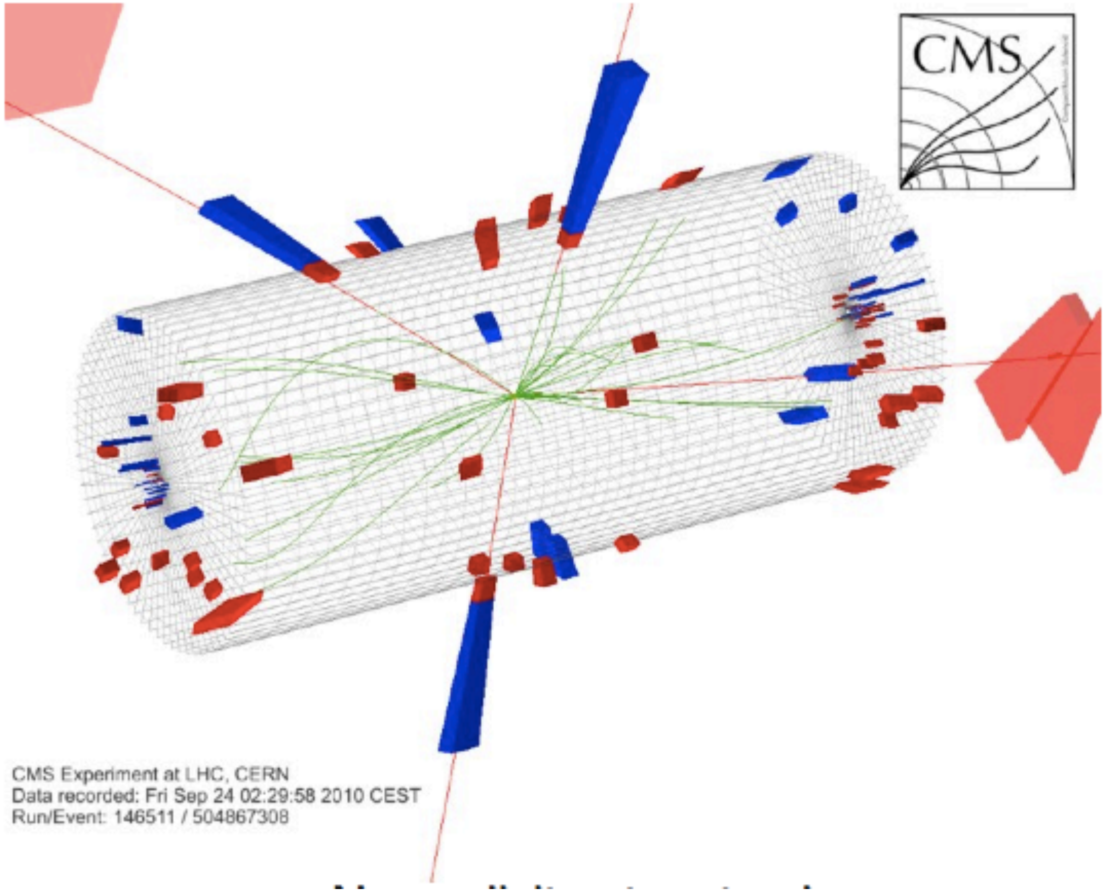
ZZ (?) $\rightarrow \mu^+\mu^-\nu\nu$

$m_{\mu\mu}$ 94 GeV, E_T^{miss} = 161 GeV



(H?)→ZZ→$\mu^+\mu^-\mu^+\mu^-$

- **CMS has a spectacular (and very rare indeed) event**



If beauty applies to events: a beautiful ZZ event (from someone's decay?)

Muons (p_T [GeV], η, φ [rad])

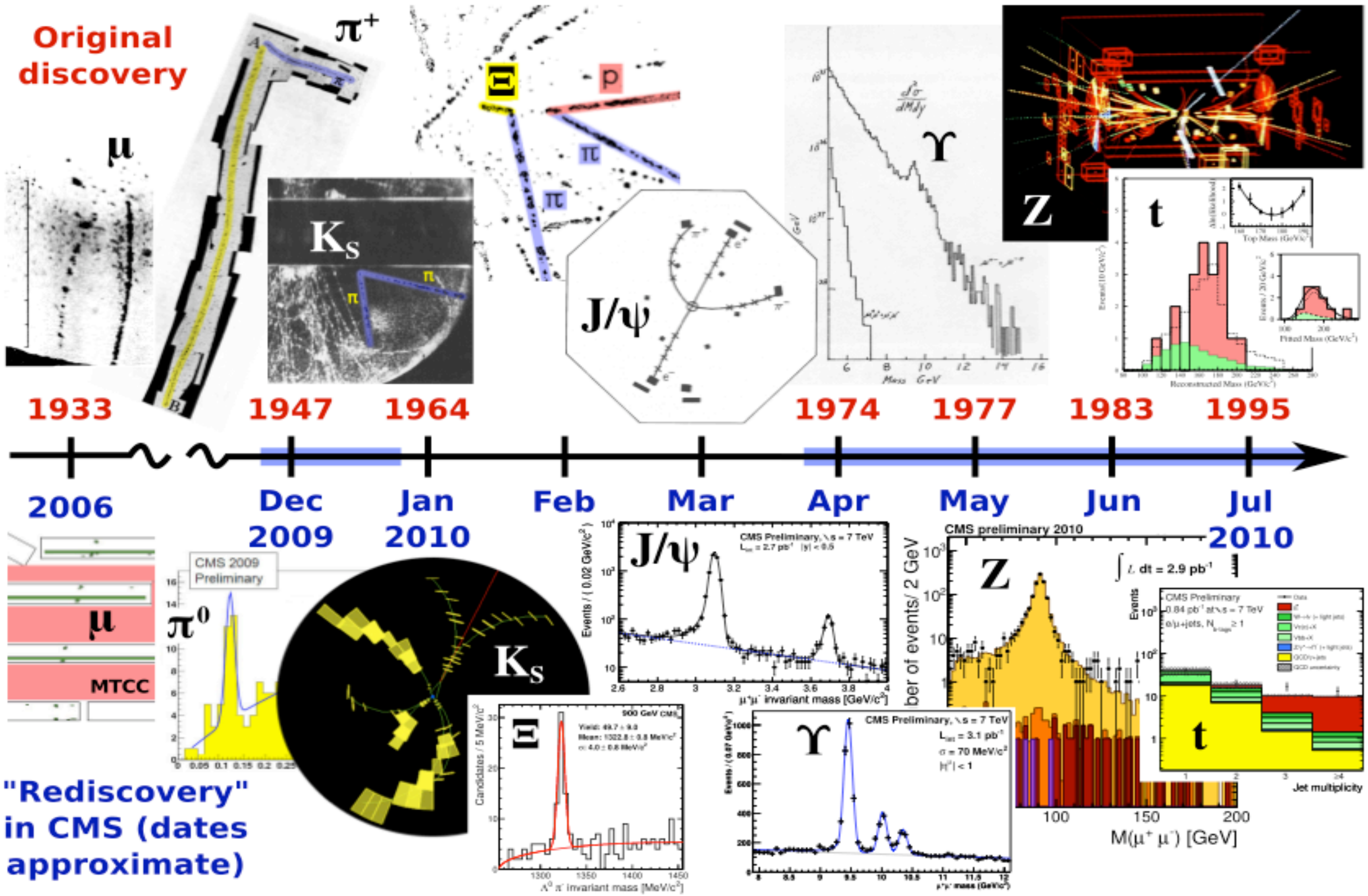
μ_0^-(48.1422, -0.412532,-1.92555)
μ_1^+(43.4421, 0.204654, 1.79493)
μ_2^+(25.8769, -0.782084, 0.774588)
μ_3^-(19.5646, 2.01112, -0.980597)

Invariant Masses

$\mu_0 + \mu_1$: 92.15 GeV (total(Z) p_T 26.5 GeV, ϕ -3.03),
$\mu_2 + \mu_3$: 92.24 GeV (total(Z) p_T 29.4 GeV, ϕ +.06),
$\mu_0 + \mu_2$: 70.12 GeV (total p_T 27 GeV),
$\mu_3 + \mu_1$: 83.1 GeV (total p_T 26.1 GeV).

Invariant Mass of 4μ: 201 GeV

Around the standard model in 7 months



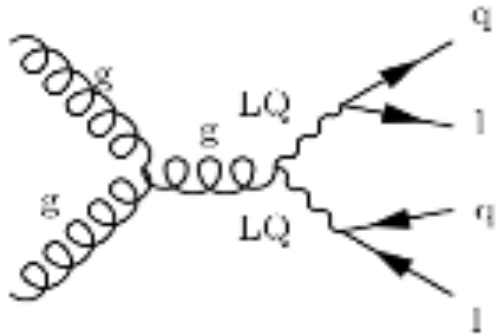
Searches for signs of exotic New Physics

Many (many) possibilities

- **Exotica:**
  - Leptoquarks
  - New gauge bosons (W', Z')
    - New resonances (W-Z-like)
  - Fourth generation (b')
  - Organic, Non-Accreting, Friendly, Evaporating Microscopic Off-White Cavities (name introduced by Greg Landsberg; old name: black holes)
  - Universal Extra dimensions (diphotons)
- **Supersymmetry**
  - Squarks and gluinos
    - Decays into jets and MET (more mSUGRA like)
    - Decays into photons (GMSB)
- **SUSY-based exotica:**
  - Long-lived particles

Leptoquarks (I)

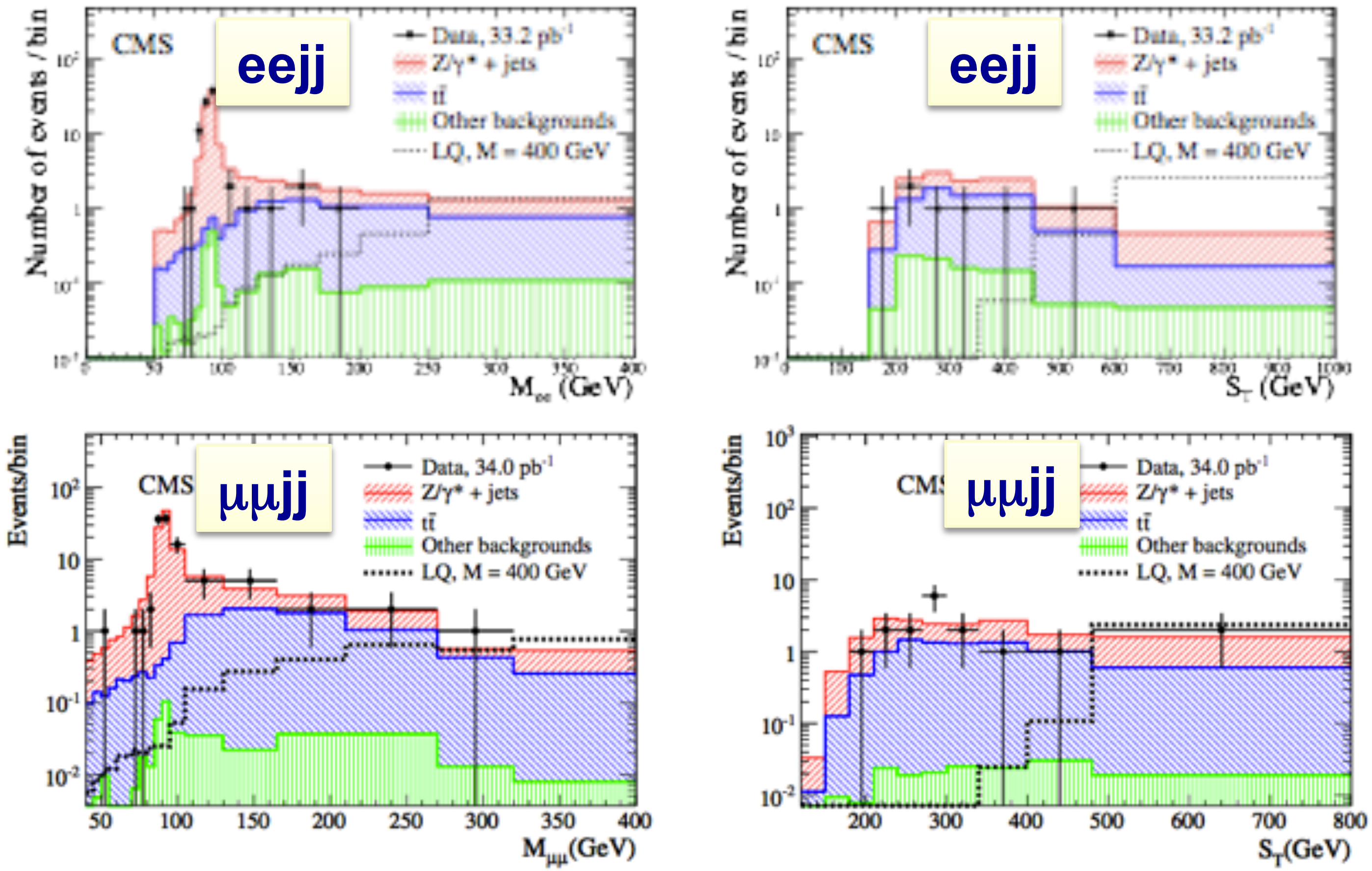
- **As name implies, they are both "leptons" and "quarks": i.e. carry baryon and lepton number – & color (large σ!)**
  - **GUT-inspired models, with (hypothetical) proton decay acting as one of the main motivations**
  - **Decay: into ℓq (branching ratio β) and νq (BR=1-β)**
  - **A leptoquark for each generation; cross-couplings FCNC constraints.**
    - **In general: assume decays to one lepton only; searches usually carried out independently for each generation**
      - **Easier searches (e/μ): first two generations, LQ1 and LQ2**
- **Pair-produced (gluon fusion) final state: dileptons & jets look for: peak in mass(ℓq)**



Leptoquarks (II)

- **Main irreducible bkg: DY+jets; 2nd: top production**
  - In situ Z+jets measurement + measured top cross section in the dilepton channel to estimate both bkgs

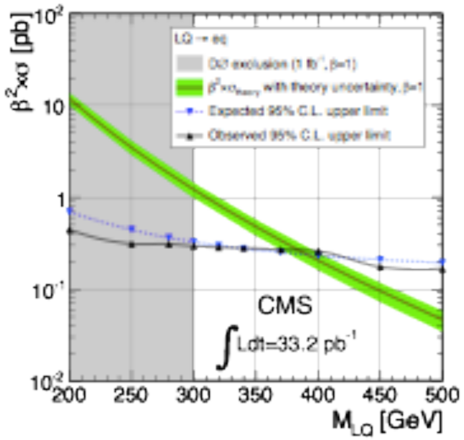
- DY+jets normalized to Z+jets (control region)
- anti-Z cut
- optimize S_T cut (mass-dependent)

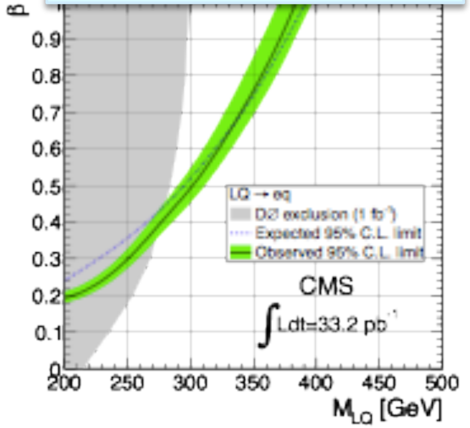


Leptoquarks: limits

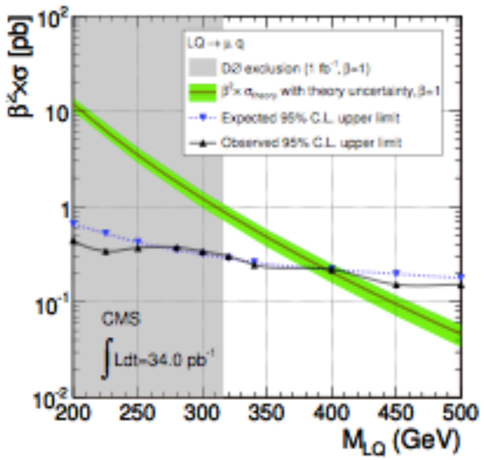
- **LQ1: S_T> 340-660 GeV for M_{LQ1} = 200-500 GeV, 2-0 events observed; consistent with bkg estimate**
- **LQ2: S_T > 310-700 GeV for M_{LQ2} = 200-500 GeV, 5-0 events observed; consistent with bkg estimate**

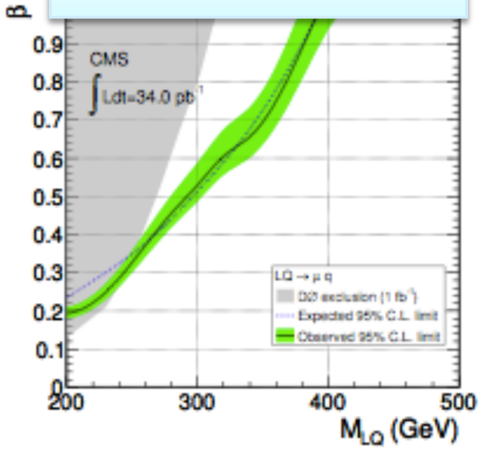
arXiv:1012.4031





arXiv:1012.4033

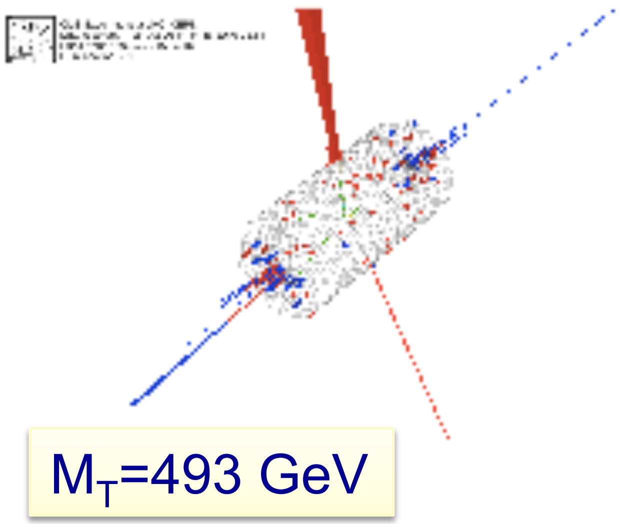


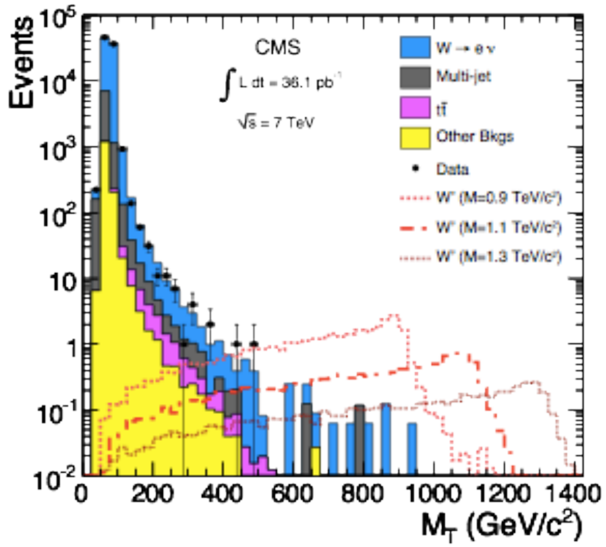


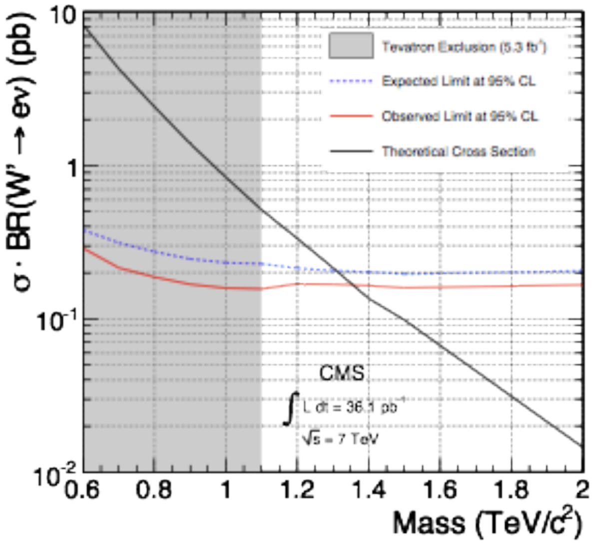
Limit for β=1	Limit on M(LQ1) [GeV]	Limit on M(LQ2) [GeV]
Tevatron	299	316
LHC	384 (exp: 391)	394 (exp: 394)

Search for W′

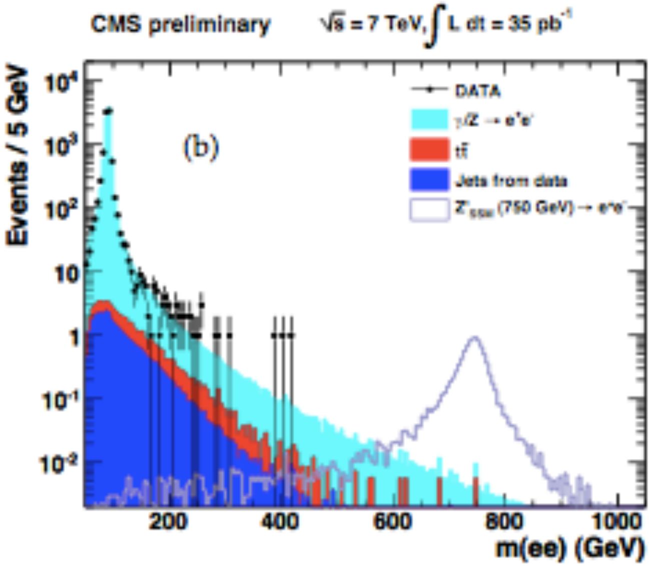
- **Main bkgs: W* (high-mass tail of B-W) and QCD; estimated via template method**
  - **Mass-dependent selection:**
    - **M_T > 400-675 GeV for M(W′) = 0.6-2.0 TeV; 2-0 events observed**
  - **M(W′) > 1.36 TeV (eν); well beyond Tevatron limit: 1.12 TeV [CDF@5.3 fb^{-1}, arXiv:1012.5145]**

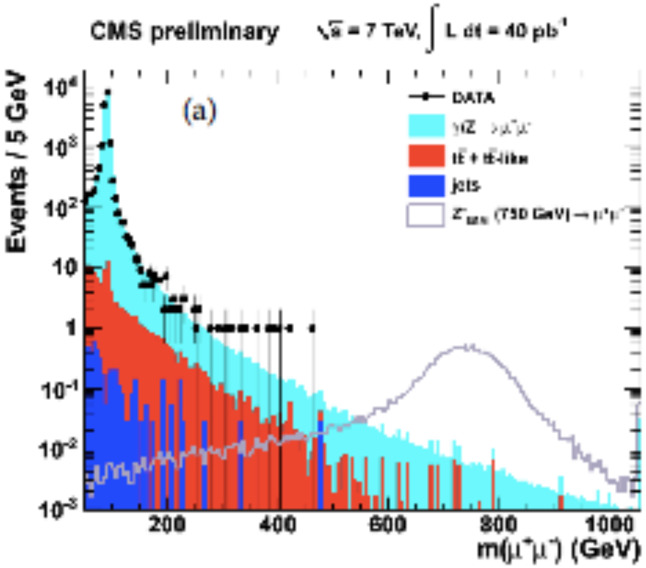


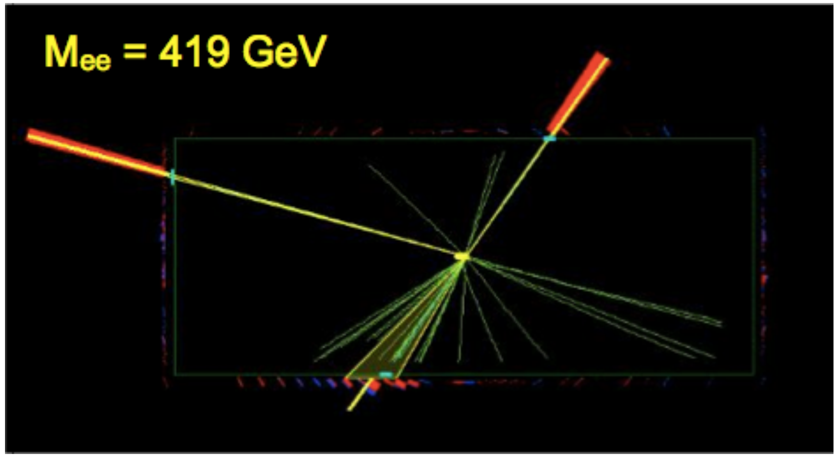




Search for Z'

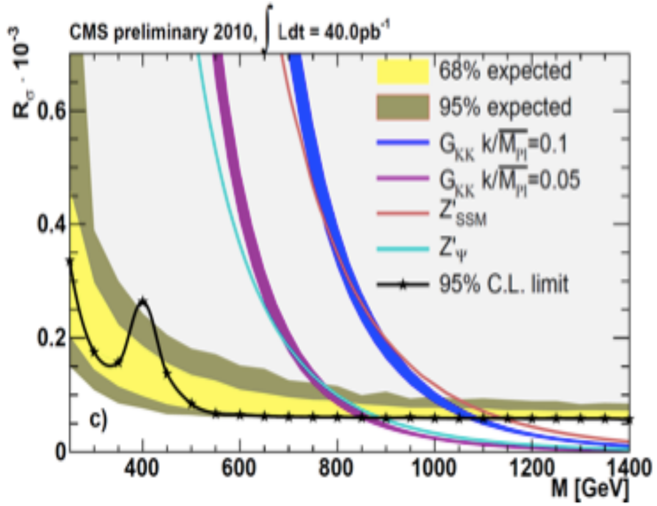






- **Coherent ee and μμ analyses**
  - **Require +/– for muons; not for elecs**

Main bkgs: Drell-Yan (by far) + top
Top estimated from e-μ events



Tevatron search for Z'

- **Very recent Tevatron update (Jan 24)**
  - **CDF, 4.6 fb^{-1}**
  - **Dimuon channel**
  - **Limit for a Z' with SM-like couplings:**

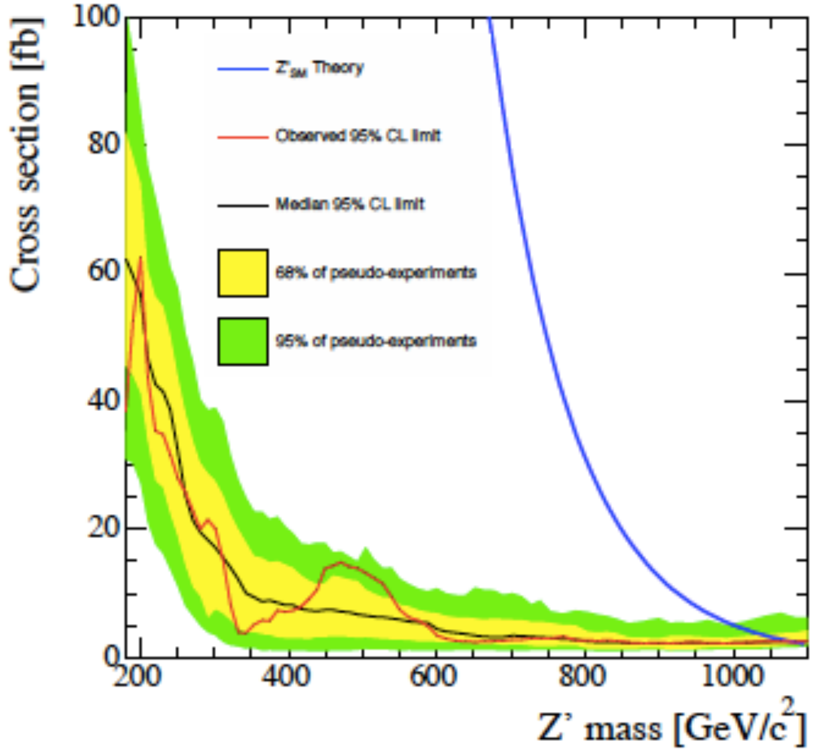


TABLE I: Mass limits on specific spin-1 Z' models [12] in data with 4.6 fb^{-1} of integrated luminosity at 95% confidence level.

Model	Z'_l	Z'_{sec}	Z'_N	Z'_ψ	Z'_χ	Z'_η	Z'_{SM}
Mass Limit (GeV/c^2)	817	858	900	917	930	938	1071

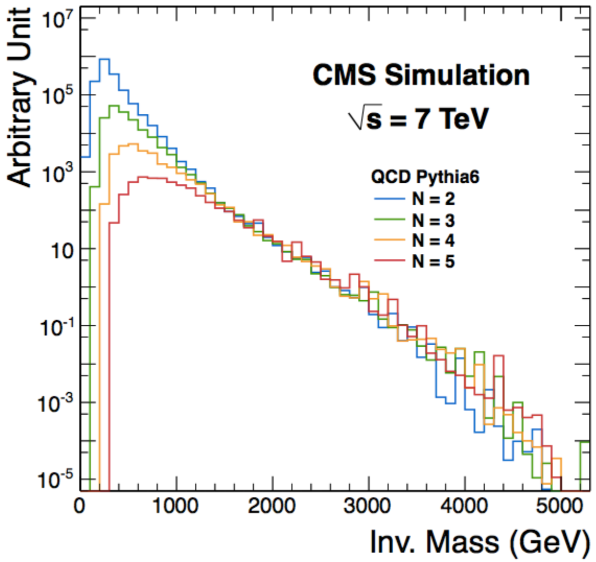
Search for BHs

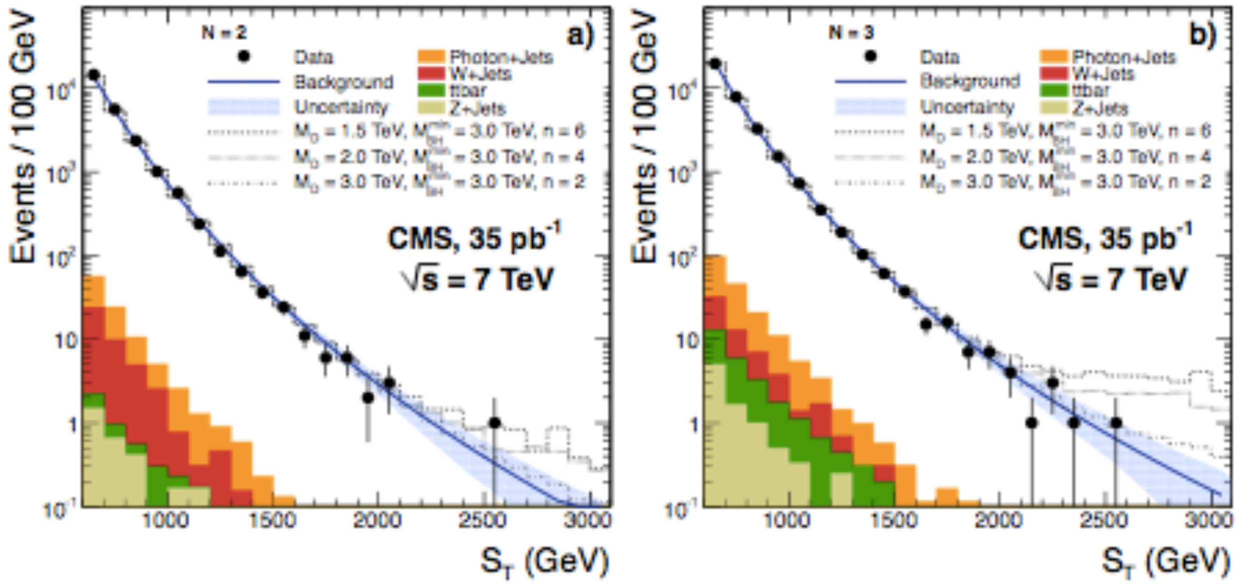
- **THE signature of low-scale quantum gravity (M_D << M_{Pl})**
  - BH formation when the two colliding partons have distance smaller than R_s,, the Schwarzschild radius corresponding to their invariant mass
  - Cross section from geometry: $\sigma = \pi R_S^2 \sim TeV^{-2}$ (up to ~100 pb!)
- **BHs decay instantaneously via Hawking evaporation emitting "democratically" a large number of energetic quarks, gluons, leptons, photons, W/Z, h, etc.**
  - Contrary to SUSY, expect ~ small MET (this: model-dependent)
- **In practice: CHARYBDIS 2 and BlackMax generators**
  - Original papers [Dimopoulos & Landsberg, PRL 87, 161602 (2001); Giddings & Thomas, PRD 65, 050610 (2002)],
  - Plus: [partial] grey-body factors, spinning Kerr black holes, formation of a stable non-interacting remnant, etc.
  - Caveat: semi-classical approximation; expected to be modified for BH masses <~ $5M_D$

Search for BHs

arXiv:1012.3375

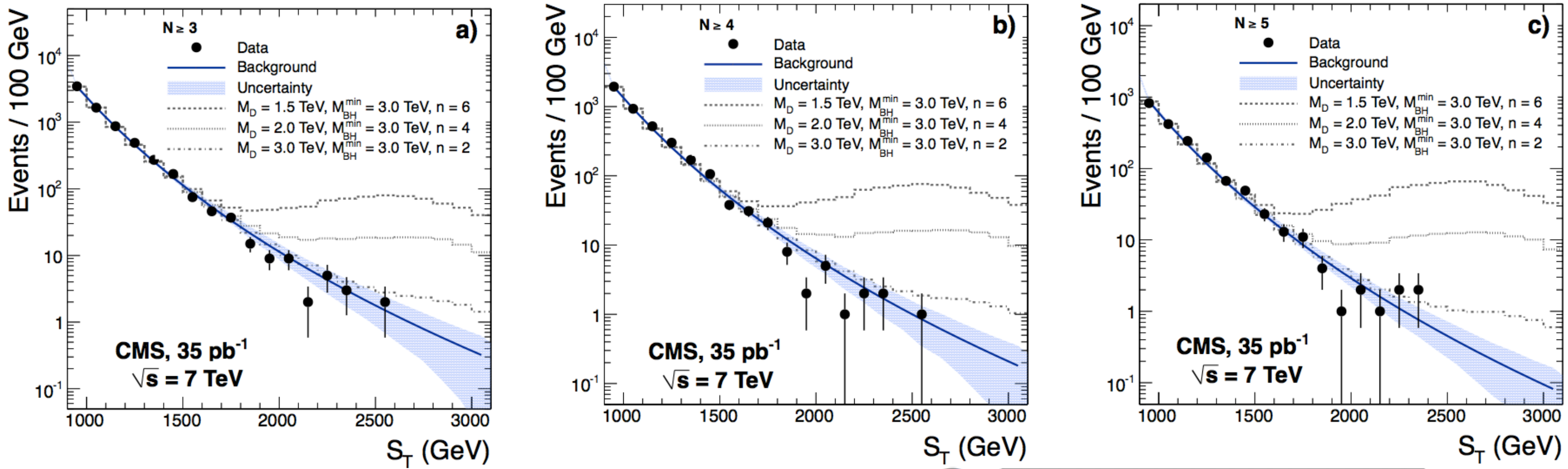
- **Expect lots of activity in the event, so**
  - Use S_T = Sum E_T of all objects (including ME_T) with E_T>50 GeV.
    - Great for avoiding pileup (in the future as well)
- **Key observation for search: S_T-invariance of final state multiplicity. Expecteded for Mass, but ST?**
  - A posteriori wisdom: FSR/ISR collinear do not affect ST a lot



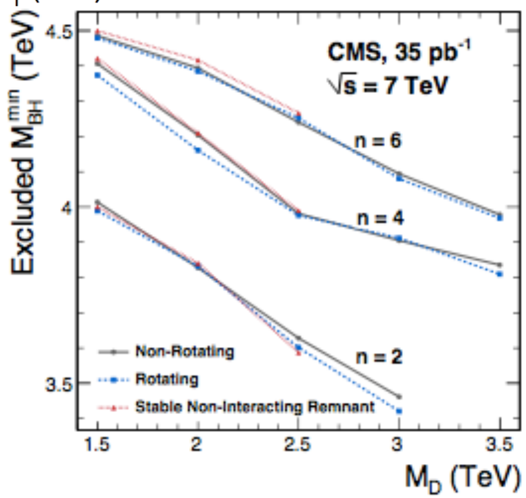


Search for BHs

- **Use N=2 shape (with uncertainties) to fit higher multiplicities – where signal more prominent**



No excess, so set limits on minimum M_{BH} of 3.5-4.5 TeV (semi-classical approximation)



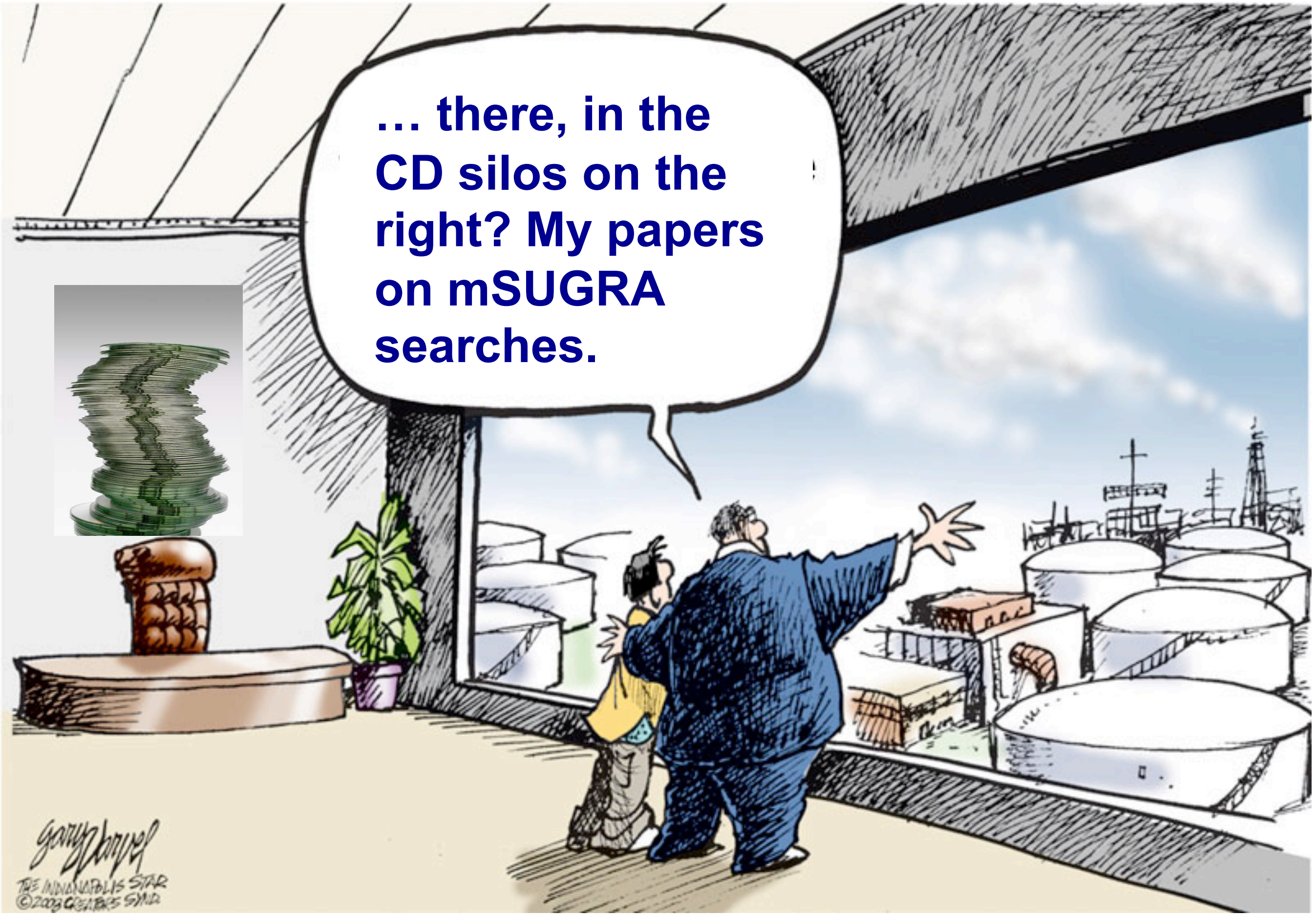
Supersymmetry

SUSY: view in the 80's (and 90's)

"One day, all of these will be SUSY phenomenology papers."

SUSY: modern-day view

SUSY space remains huge



Towards a search for SUSY signatures

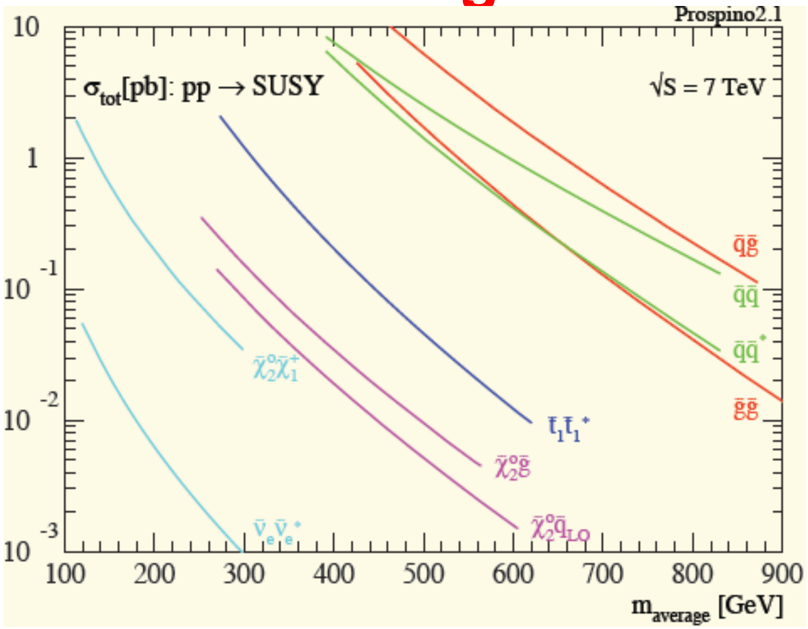
- SUSY is actually quite predictive: it specifies the spins and couplings of the superpartners
  - Unfortunately, it tells us nothing about the masses
    - For this depends on the SUSY breaking mechanism
  - End result: large space of signatures, depended on models
  - Two sobering papers (read for academic purposes…):
    - arXiv:1009.2539: "Supersymmetry Without Prejudice at the LHC"; J.Conley, J.Gainer, J.L. Hewett, M.P.Le, T.G.Rizzo
    - arXiv:1008.2483: "How to look for supersymmetry under the lamppost at the LHC"; P.Konar, K.Matchev, M.Park, G.Sarangi
- E.g. 2nd: agnostic approach. Consider all possible mass hierarchies: there are 9! = 362880 of them

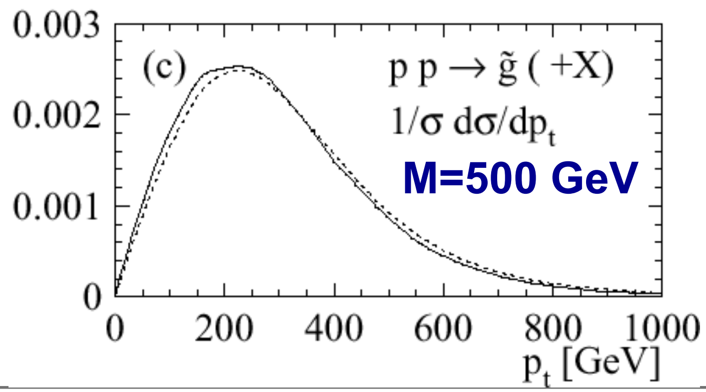
$\tilde{u}_L, \tilde{d}_L$	$\tilde{u}_R$	$\tilde{d}_R$	$\tilde{e}_L, \tilde{\nu}_L$	$\tilde{e}_R$	$\tilde{h}^{\pm}, \tilde{h}^0_u, \tilde{h}^0_d$	$\tilde{b}^0$	$\tilde{w}^{\pm}, \tilde{w}^0$	$\tilde{g}$
Q	U	D	L	E	H	B	W	G
M_Q	M_U	M_D	M_L	M_E	M_H	M_B	M_W	M_G

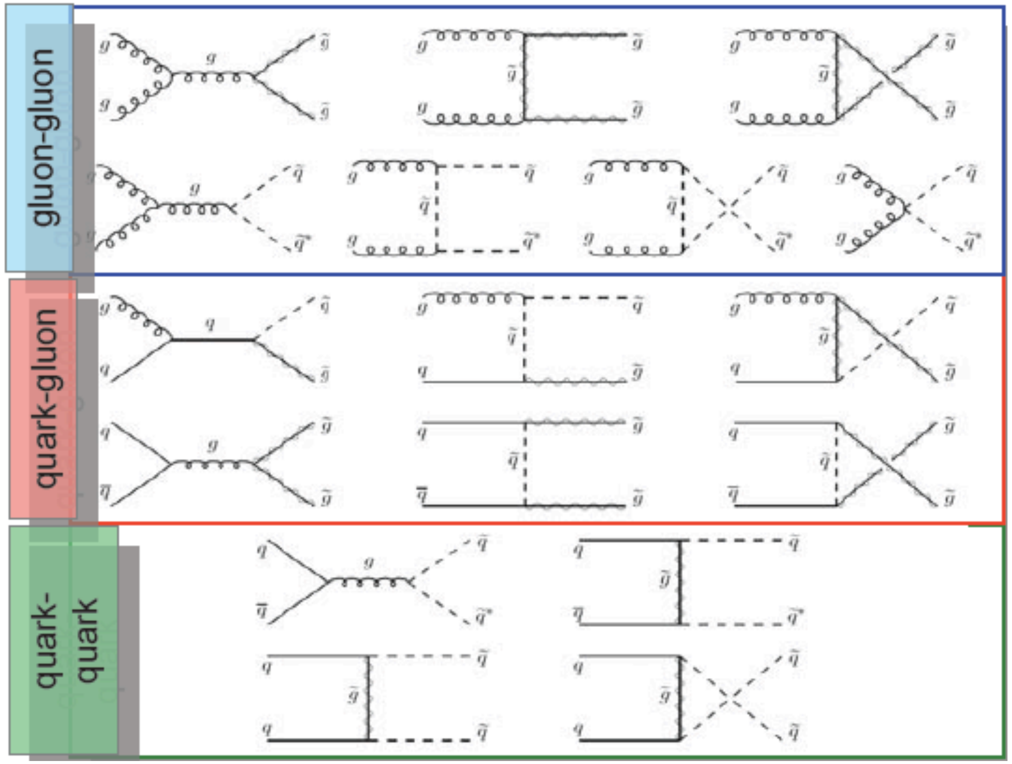
  - CHAMPs: 8! (40,320) cases, LSP=eR (charged, color-neutral); signature: CHAMP (independently of hierarchy)
  - R-hadrons: 4x8! (161,280) cases, LSP=colored object; again, independent of hierarchy
  - MET: 4x8! (161,280) cases, LSP=weakly-interacting, neutral particle; phenomenology depends crucially on mass hierarchy

SUSY: what we know

- **Squarks and gluinos: colored: large σ**







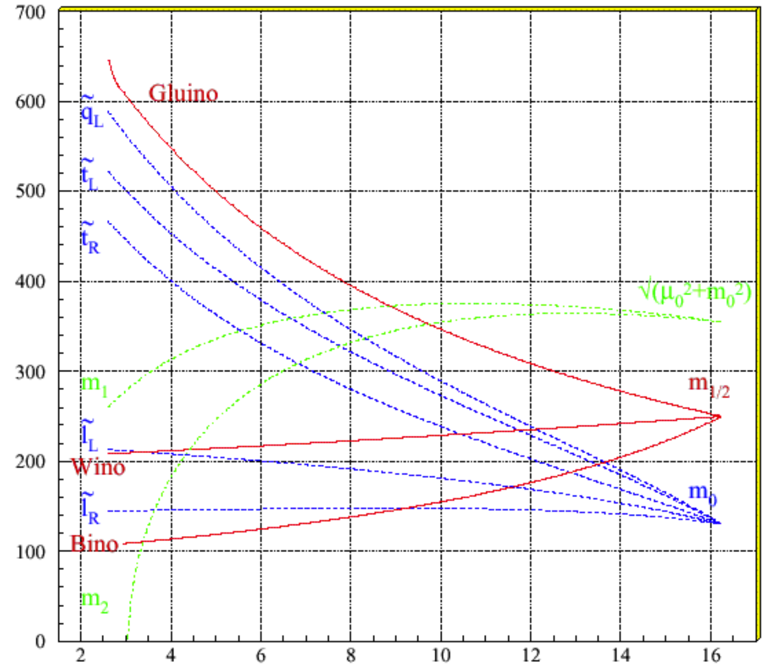
Several high-P_T jets; high MET (R_p conservation); possibly lepton and b-rich

SUSY: what we don't know (breaking)

- **Huge number of theoretical models**
  - Very complex analysis; MSSM-124. Hard work to study particular scenario
    - assuming it is available in an event generator (!)
  - To reduce complexity we have to choose some "reasonable", "typical" models; use a theory of dynamical SYSY breaking
    - mSUGRA (gravity-mediated)
    - GMSB (gauge-mediated)
    - AMSB (anomaly-mediated; studied in less detail)
  - Model determines phenomenology (masses, decays, signals)

CMSSM (based on mSUGRA)

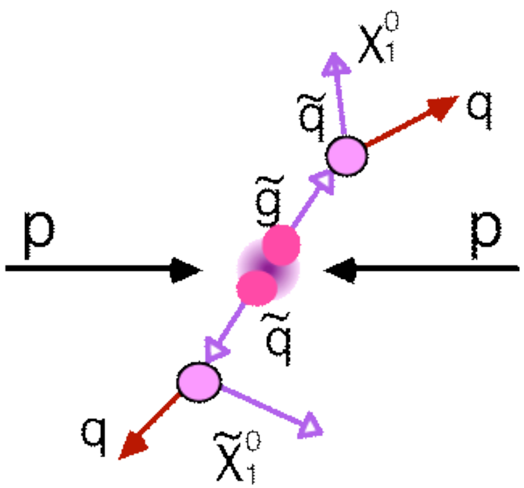
- **Five parameters**
- **GUT scale:**
  - **Common scalar masses (m_0)**
  - **Common gaugino masses ($m_{1/2}$)**
  - **All tri-linear Higgs-sfermion-sfermion couplings A_0**
- **Low-energy:**
  - **tanβ and sign(μ)**
- **Full "particle table" predicted**
  - **26 RGE's solved iteratively: run masses down to EWK scale**
  - **Branch: R_{parity} (non)conservation**
  - **Extensions: relax GUT assumptions (add parameters)**

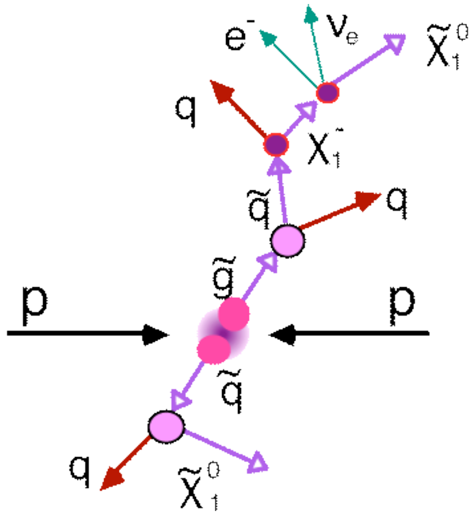


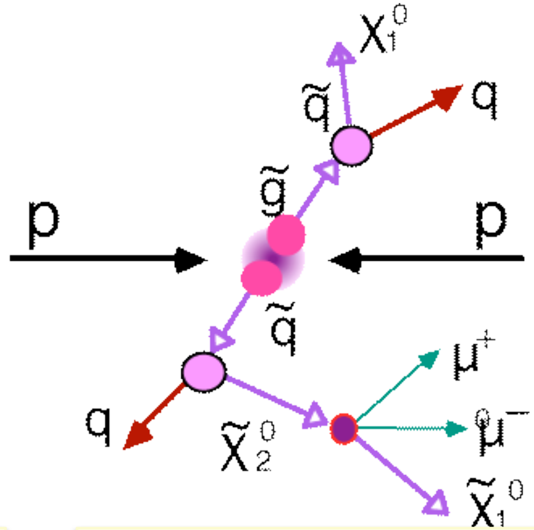
M(squark): large increase (due to α_3)
M(slepton): small increase (due to α_1, α_2)
Gauginos: gluino fast-rising; B-ino, W-ino mass decreases
Mixing → charginos (2) & neutralinos (4)
Higgs: strong top coupling drives $\mu^2<0$;
Symmetry Breaking mechanism arises naturally in mSUGRA(!)

SUSY: signatures and bkgs

- **Searches distinguished by the number of leptons**
  - In all cases, demand "(high-P_T) jets + (high) ME_T"
  - 0ℓ (all-hadronic); 1ℓ; 2ℓ (and break down into OS and SS)







QCD multijets $Z(\rightarrow\nu\nu)$+ jets (W,t)+jets; $W\rightarrow\tau\nu$	QCD: small $W/Z(\rightarrow\ell\nu)$+jets $t(\rightarrow\ell\nu)$+jets	$W/Z(\rightarrow\ell\nu)$+jets WW, WZ $tt(\rightarrow\ell\ell\nu)$+jets

SUSY: jets+ME_T

- **Strongly-produced squarks and gluinos with M>400 GeV**
  - Decaying into SM particles (e.g. quarks) plus LSP; either directly or after a long chain
  - Huge background from QCD (several orders of magnitude).
  - Strategy: use kinematics (α_T) to reduced it to negligible level, then tackle next bkg
    - Veto leptons to avoid EWK backgrounds with MET arising from neutrinos
    - Largest remaining bkgs: Z ($\rightarrow\nu\nu$)+jets, W($\rightarrow\ell\nu$)+jets, t-tbar

α_T for 2 jets:

$$\alpha_T = \frac{E_{T2}}{M_T} \leq 0.5$$

Expectation for QCD: $\alpha_T = 0.5$
Jet mismeasurements: $\alpha_T < 0.5$

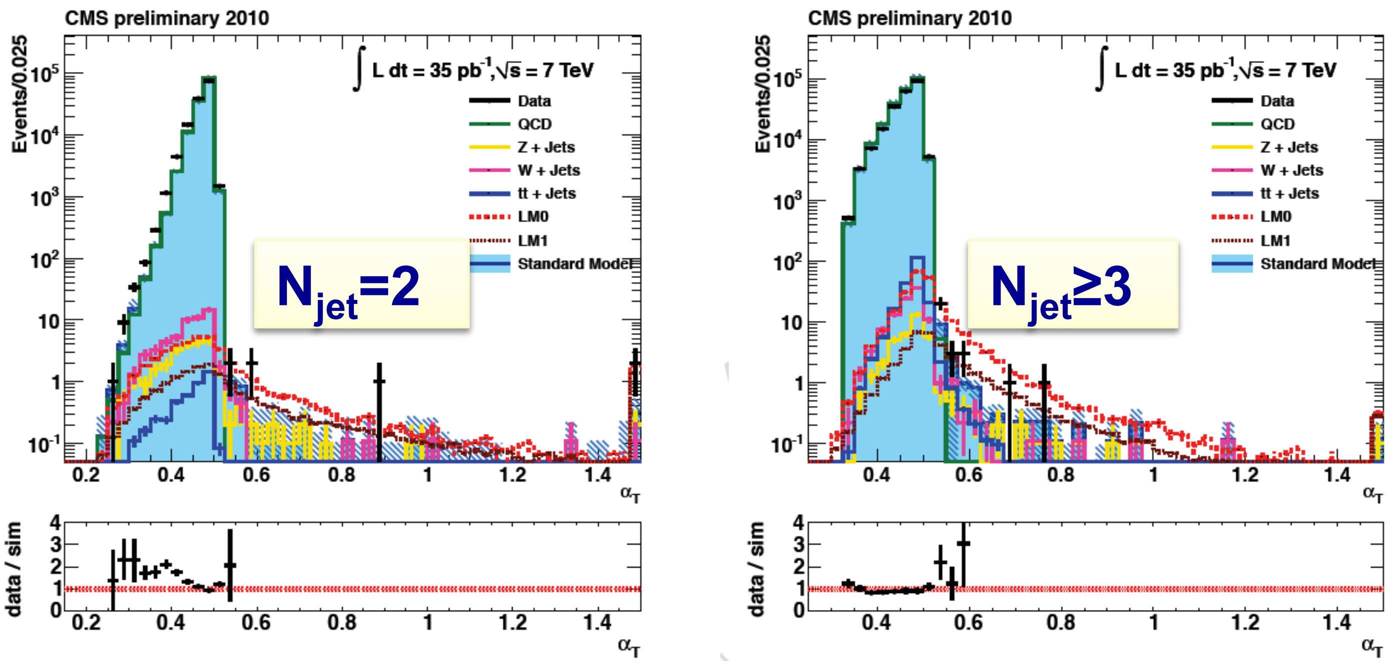
α_T for n jets:

$$\alpha_T = \frac{1}{2}\frac{H_T - \Delta H_T}{M_T}$$

(form two pseudo-jets – defined by balance in "pseudo-jet" $H_T = \Sigma E_T$)

SUSY: jets+ME_T

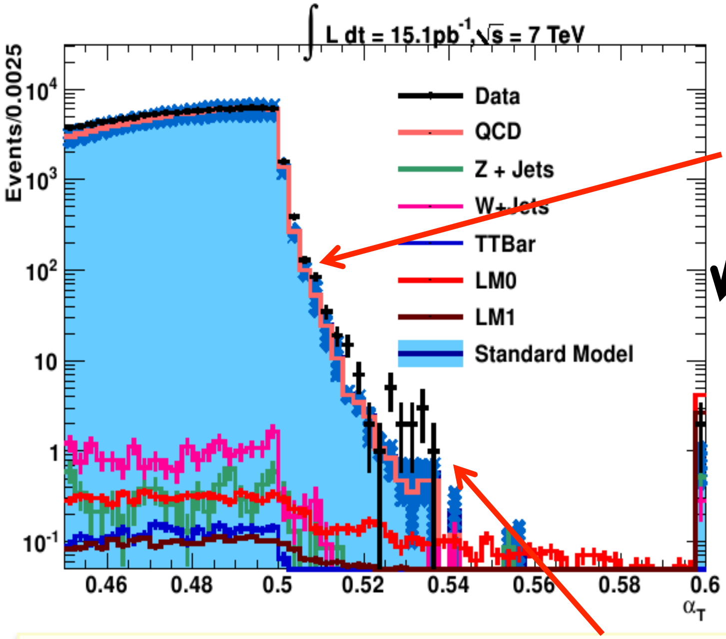
- **Apply a cut at α_T>0.55, QCD → negligible**



- **For remaining bkgs (estimate): data-driven methods**
  - **Direct estimate of EWK bkg using W+jets (for W & top) and γ +jet (for Z(→νν)+jets)**
  - **Inclusive estimate using extrapolation from lower-H_T (where SUSY is negligible)**

SUSY: jets+MET; Killing QCD with α_T

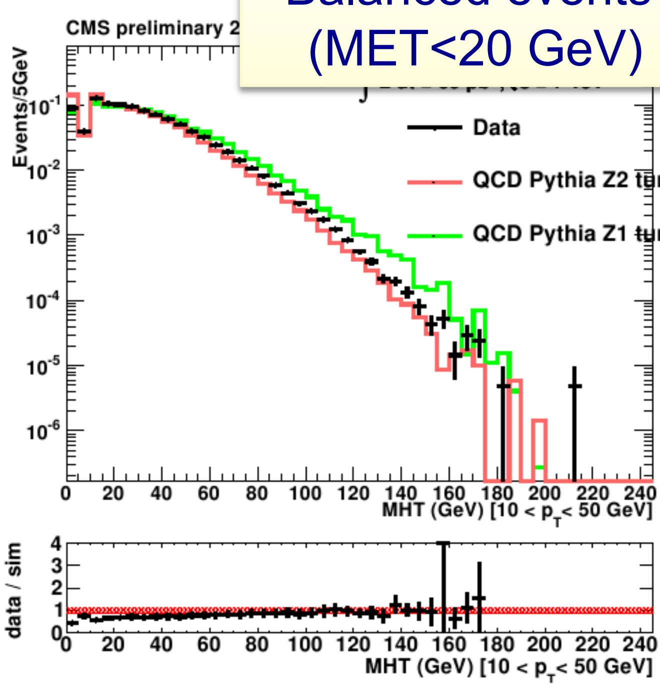
- **Spill-over in α_T>0.5 from:**
  - **Processes with genuine MET (EWK, TOP, and SUSY ☺)**
  - **Some remnant QCD**



Core of resolution function:
Jet loss
(min p_T cut on jets)

Tail of resolution function:
Catastrophic mismeasurement
of a jet: protect by avoiding holes

Balanced events
(MET<20 GeV)



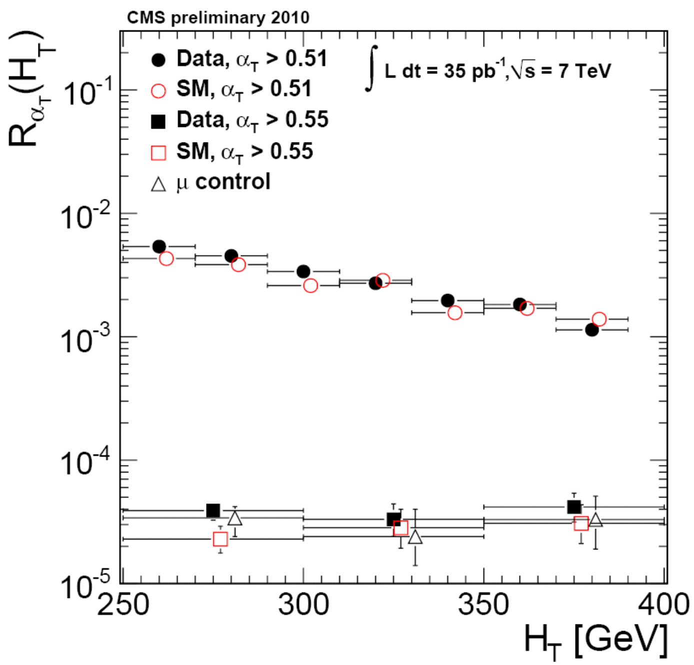
$$R_{MHT} = \frac{MH_T\left(p_T\left(jet\right) > 50\right)}{MH_T\left(p_T\left(jet\right) > 30\right)} < 1.25$$

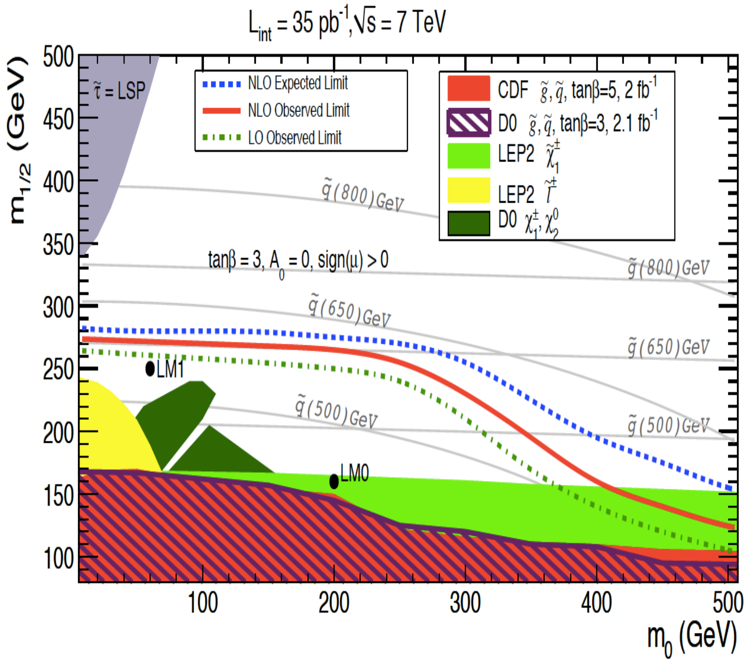
SUSY: jets+ME_T

- **13 events observed, consistent with bkg estimates**

N_{jet}	$N^{Data}_{predicted}$	$N^{Data}_{observed}$	$N^{SM}_{predicted}$	$N^{SM}_{observed}$
2	$4.88 \pm^{4.65}_{3.37}$	5	$2.79 \pm^{3.05}_{2.1}$	2.8 ± 0.5
≥ 3	$5.55 \pm^{3.59}_{2.82}$	9	$7.7 \pm^{5.04}_{3.91}$	6.3 ± 0.7
≥ 2	$9.43 \pm^{4.8}_{3.97}$	13	$10.3 \pm^{5.57}_{4.52}$	9.1 ± 0.9

- **So set limits; already with 35 pb^{-1}: significant extension of previous (Tevatron+LEP) reach**



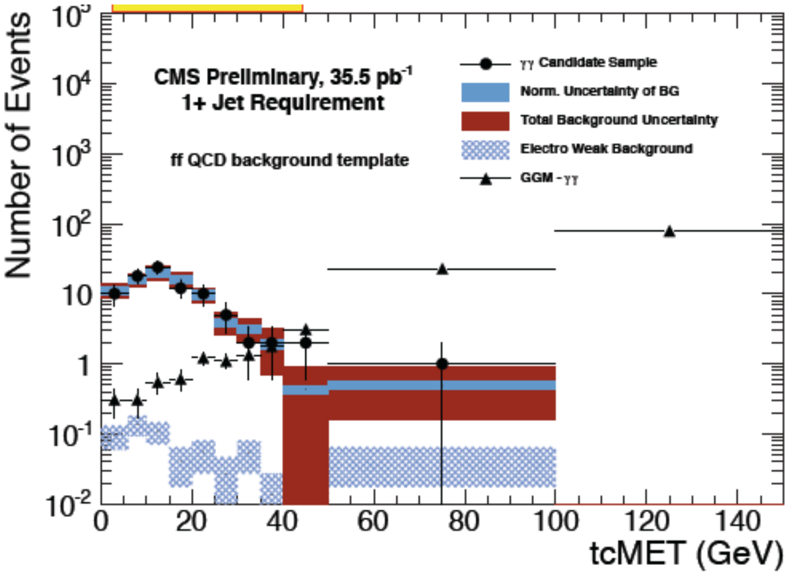


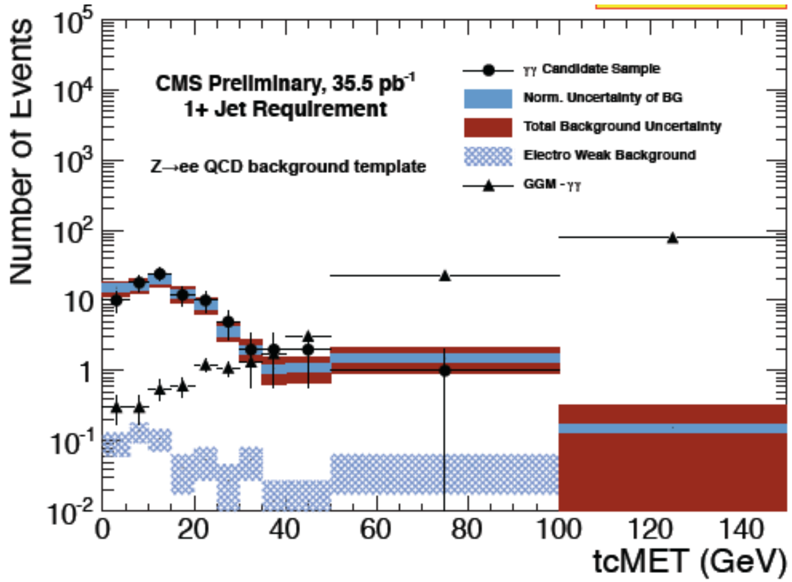
SUSY GMSB search: diphotons (I)

- **GMSB: just as good a SUSY; solves all issues that SUSY is good for: hierarchy; unification at GUT scales; also (for very long-lived LSP, also DM)**
- **Assumes SUSY broken at large scale in sector containing non-SM (heavy) particles**
  - **This sector couples to SM via "messengers" of mass M**
  - **Loops involving messengers → mass to s-partners**
    - **Advantage of model; mass from gauge interactions → no FCNC (can cause problems in mSUGRA)**
- **Phenomenology: LSP is gravitino ($\tilde{G}$)**
  - **SUGRA: M(G)~*O*(1)TeV → irrelevant to phenomenology**
  - **GMSB: NSLP decays to $\tilde{G}$; unstable → NLSP can be charged**
    - **Lifetime of NLSP "free": *O*(μm) < cτ < *O*(km)**
  - **Neutral NLSP: decays to γ, Z^0, h^0;**
  - **Charged NLSP: $\tilde{\ell}_R$;**
    - **low tanβ: degenerate $\tilde{e}_R,\tilde{\mu}_R,\tilde{\tau}_R$; high tanβ: $\tilde{\tau}_R$ is lightest slepton, others decay to it**
- **Good signature: photons + MET +jet(s)**

SUSY GMSB search: diphotons (II)

- Demand two photons + jet (kill beam halo)
- Bkg: jets; γ+jet; W+γ; W+jet (and jet $\rightarrow$ γ; "fake")
- Two data-driven bkg estimates to get ME_T tail (dominated by hadronic recoil):
  - Z$\rightarrow$ee events (not applying tracking to e's)
  - Loose photon-ID (so picking up jets); gives "fake-fake" bkg. Normalize to diEM p_T; spectrum to data (at low p_T)
    - Since γ+jet same shape as jet+jet, estimate includes "real-fake"

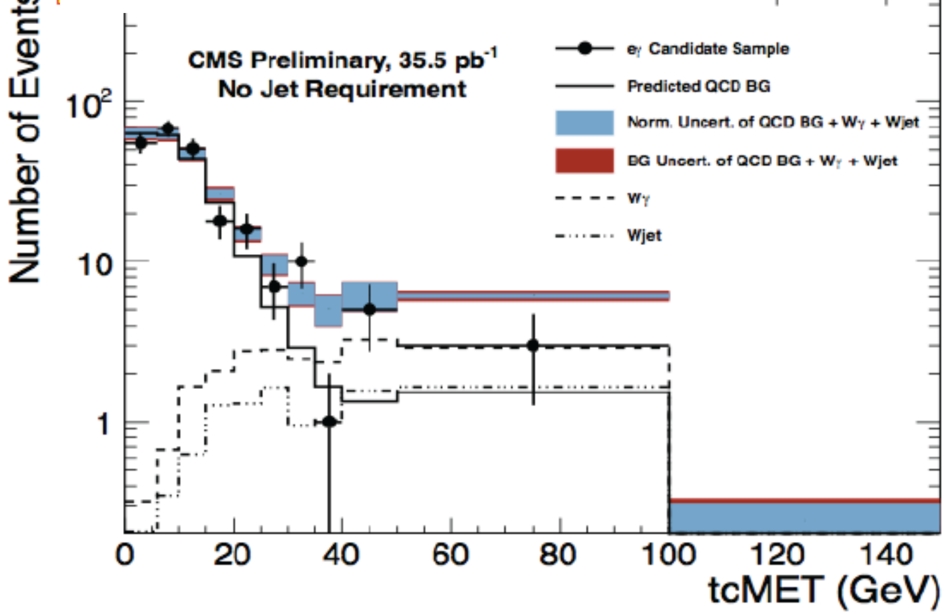




SUSY GMSB search: diphotons (III)

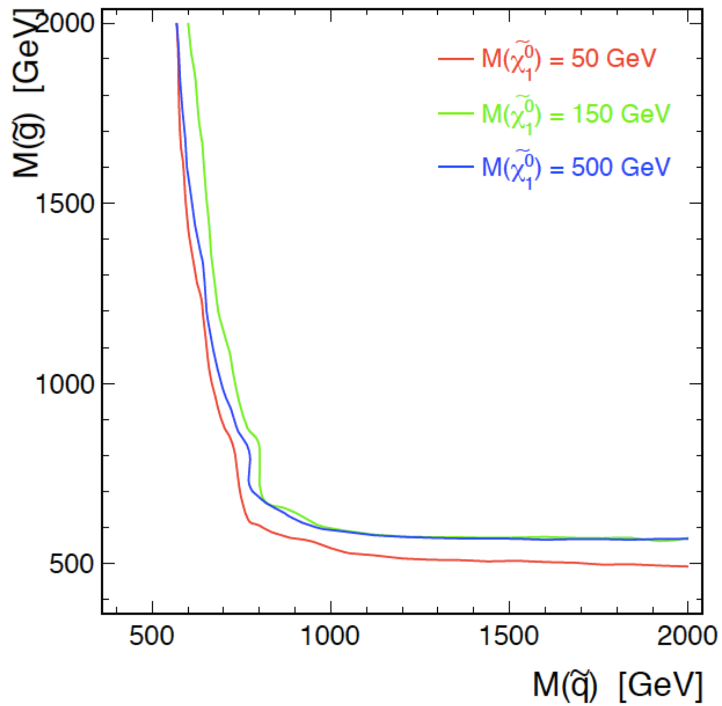
- **Also important: demonstrate that signal would be visible**
  - **Use eγ sample (from W+γ)**

35 GeV	9	3.4 ± 0.4	12.7
40 GeV	8	2.0 ± 0.2	9.6
50 GeV	3	0.9 ± 0.1	4.5



No excess over bkg estimate → limits

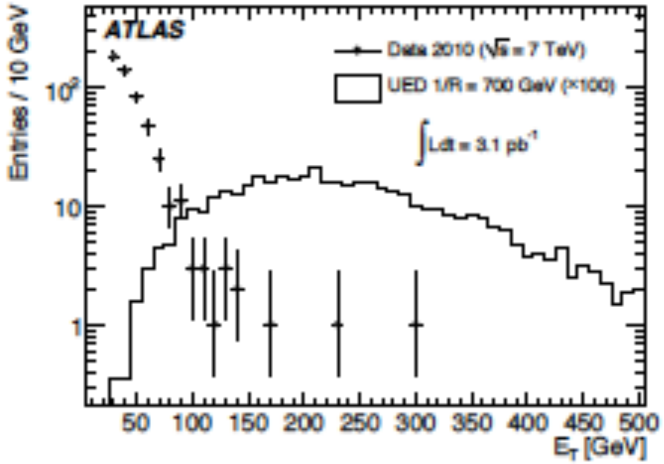
For equal squark and gluino masses the limits are 740, 800 GeV, and 780 GeV

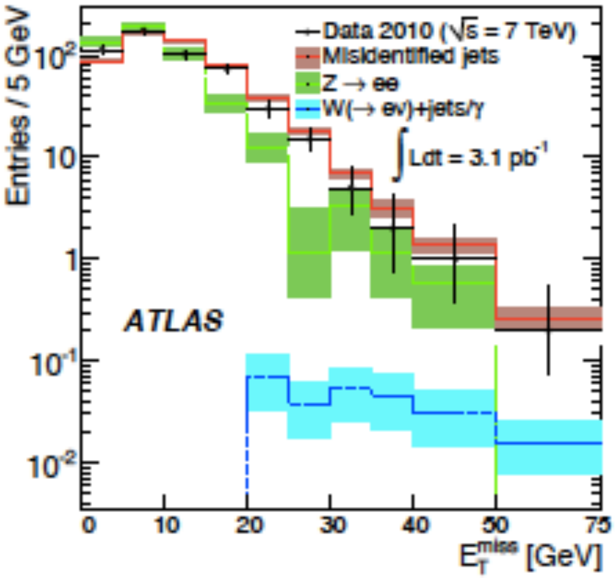


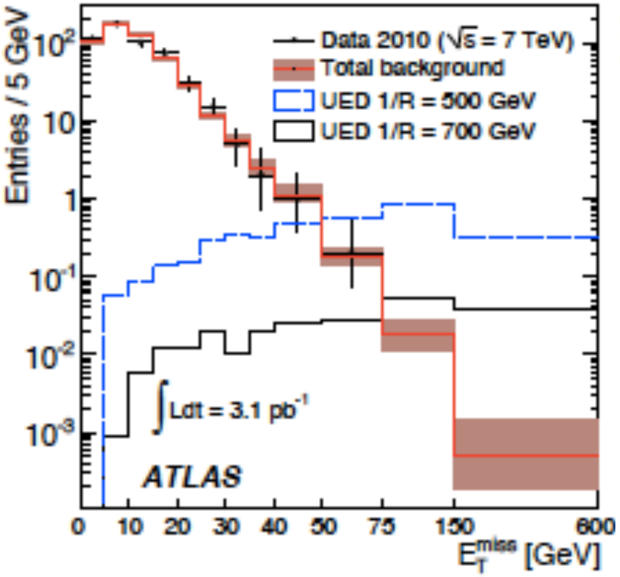
Universal Extra Dimensions

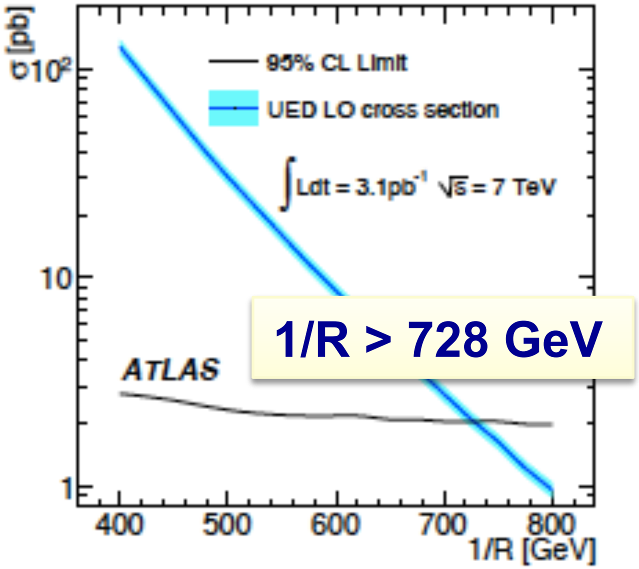
- **Two-photon search + MET**
  - **Same analysis [as GMSB search]**

E_T^{miss} range (GeV)	Data events	Predicted background events Total	QCD	$W(\to e\nu)$ + jets/γ
0 - 20	465	465.0 ± 9.1	465.0 ± 9.1	-
20 - 30	45	40.5 ± 2.2	40.41 ± 2.17	0.11 ± 0.07
30 - 50	9	10.3 ± 1.3	10.13 ± 1.30	0.16 ± 0.10
50 - 75	1	0.93 ± 0.23	0.85 ± 0.23	0.08 ± 0.05
> 75	0	0.32 ± 0.16	0.28 ± 0.15	0.04 ± 0.03









1/R > 728 GeV

Heavy Stable Charged Particles

- **They appear in numerous SM extensions:**
  - SUSY (split SUSY: gluinos much lighter than squarks → long lifetime; GMSG models: stau NLSP, decaying via gravitational coupling only; light stop with only a limited number of decay modes)
  - Other: hidden valleys; GUTs; …
- **Two types of signatures:**
  - MIP: HSCP passes through tracker & muon chambers
  - Strongly interacting: R-hadrons traversing material can flip Q or become neutral (for example in gluino hadronization). Majority would not reach muon chambers
- **Analyses**
  - dE/dx: Massive, charged particles traversing detector: highly ionizing tracks in tracker and possibly muon systems
  - (Out-of-time) Jet: particles stopping in the detector and decaying – possibly out-of-time with the collisions
- **Complementary signatures: jet analysis sensitive to slow particles; dE/dx search needs higher β (min-P_T requirement)**

Heavily ionizing tracks

- **Mass estimate from approximate Bethe-Bloch:**

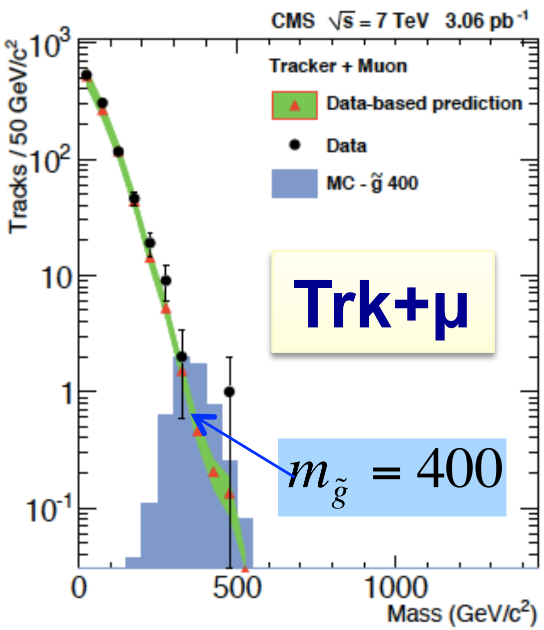
$$I_h = K\frac{m^2}{p^2} + C$$

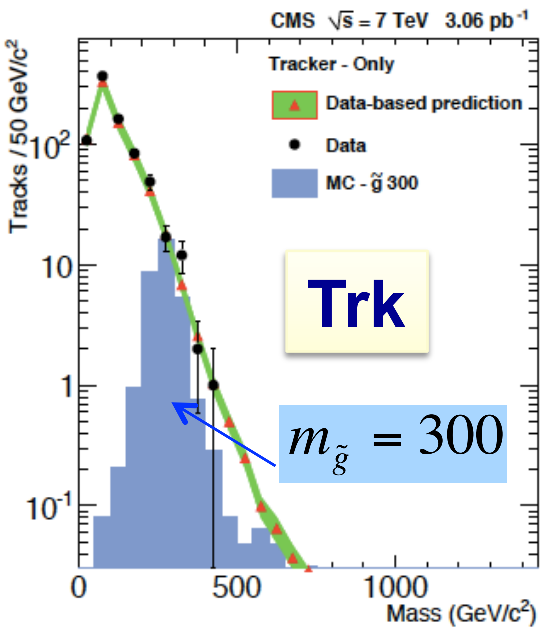
K=2.58 MeV c^2/cm
C=2.56 MeV/cm

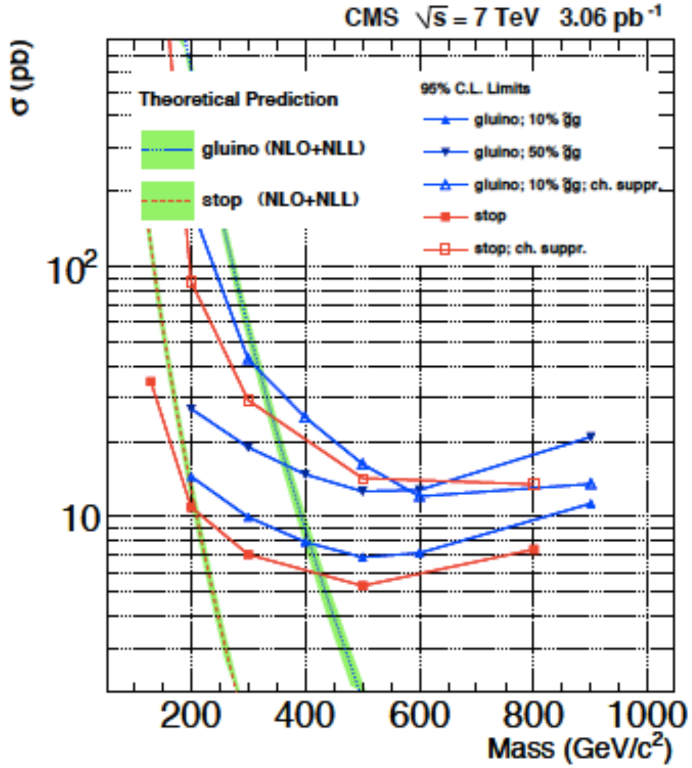
  - **K and C determined from proton data**
    - **Mass resolution: 12% at 300 GeV**

- **Cut on I_{AS} (MIP compatibility) & p_T (I_{AS}, p_T: uncorrelated)**

$$\textbf{Bkg} = \frac{(\#\text{pass } I_{AS} \text{ only})(\#\text{pass } p_T \text{ only})}{\#\text{Fail } I_{AS} \cap p_T}$$



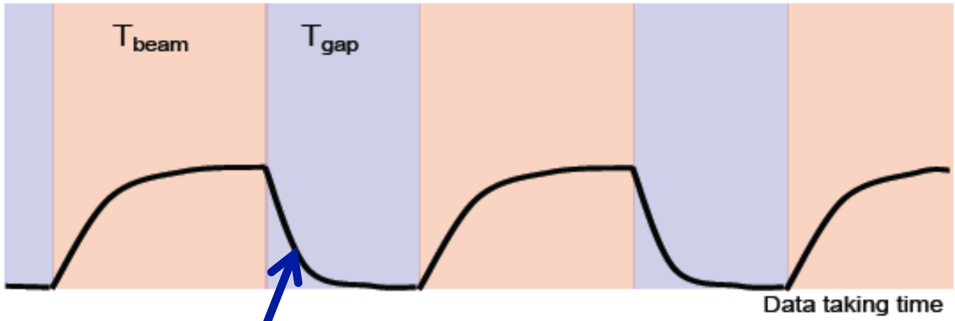




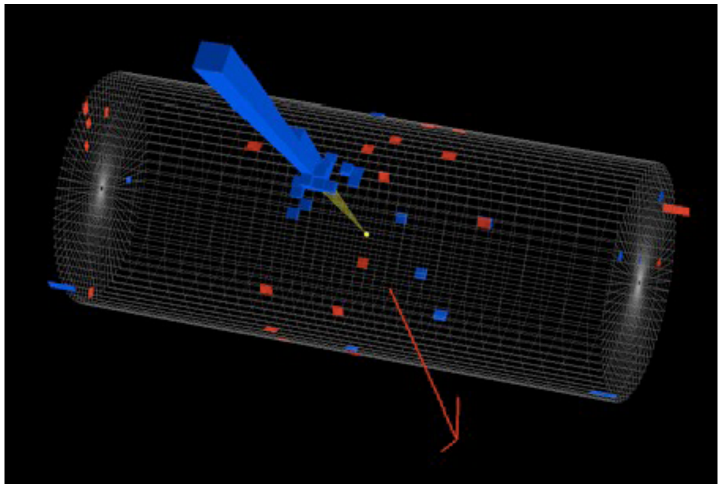
Stopped gluinos (I)

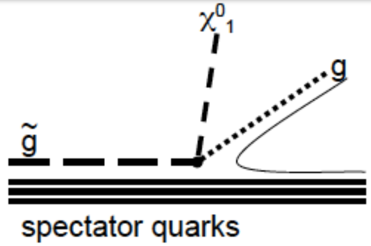
- **Slow (β < 0.4) long-lived gluinos hadronize into and then stop in the dense material of the CMS detector**
  - **Their number builds up with luminosity:**

They then decay μs, s or day(s) later. Their decay:

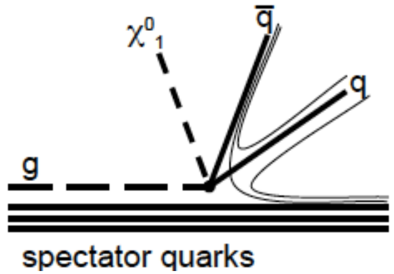


Spectacular jets in the absence of beam





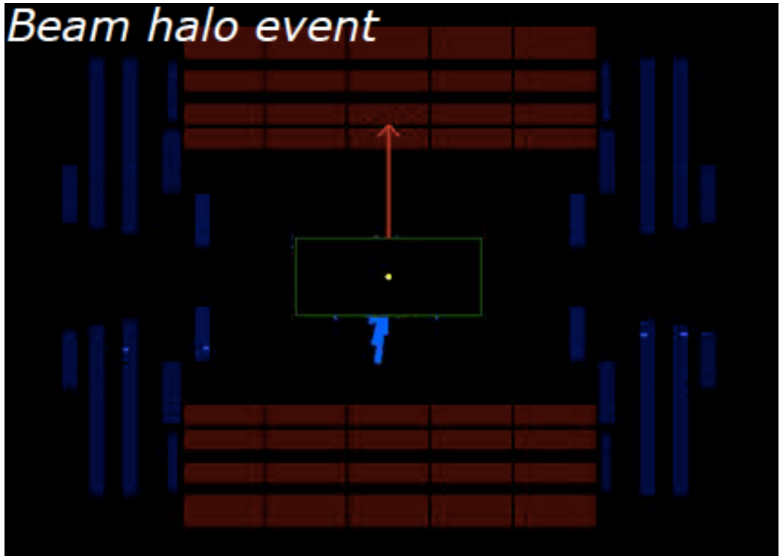
$$\Delta^{++}_{\tilde{g}} \rightarrow \tilde{g}\, u(uu) \rightarrow g\, \chi^0_1\, u(uu)$$

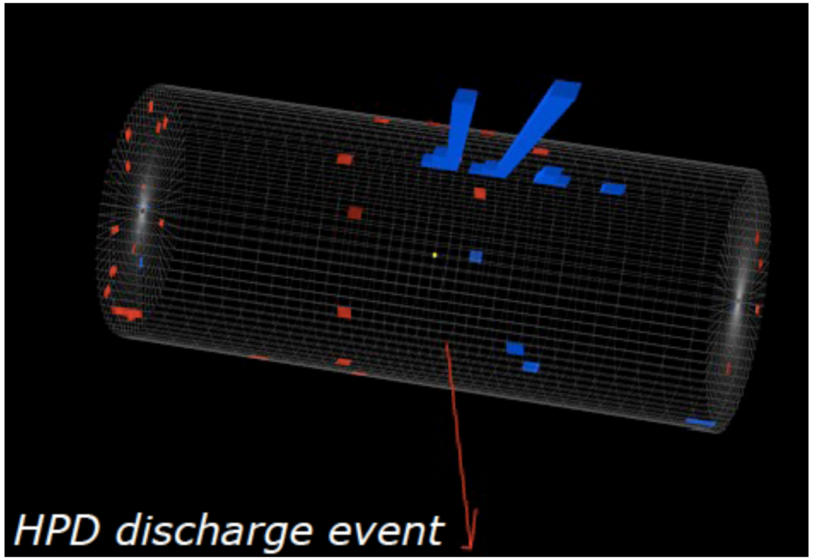


$$\Delta^{++}_{\tilde{g}} \rightarrow \tilde{g}\, u(uu) \rightarrow q\bar{q}\, \chi^0_1\, u(uu)$$

Stopped gluinos (II)

- **Special trigger: no-beam .AND. BPTX (anticoincidence)**
  - Was run also after the end of fills (to reach long lifetimes)
- **Main background: cosmic rays, beam halo, HCAL noise**



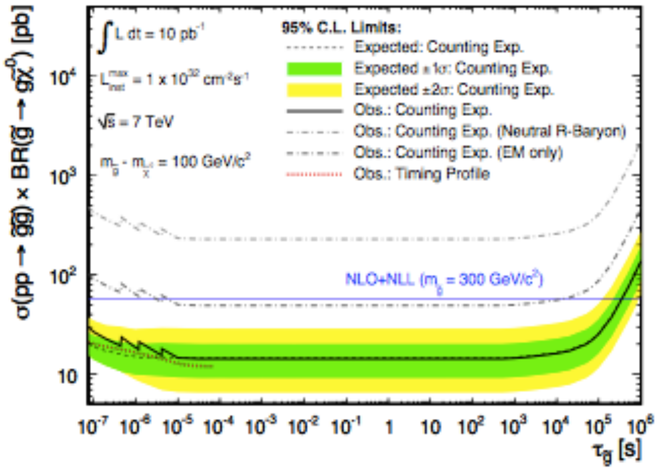


  - Select against them (e.g. HCAL noise: jets not at same phi). Finally: signal shape (electronics): use ratio of energy in BX+1/BX and BX+2/BX+1

Stopped gluinos (III)

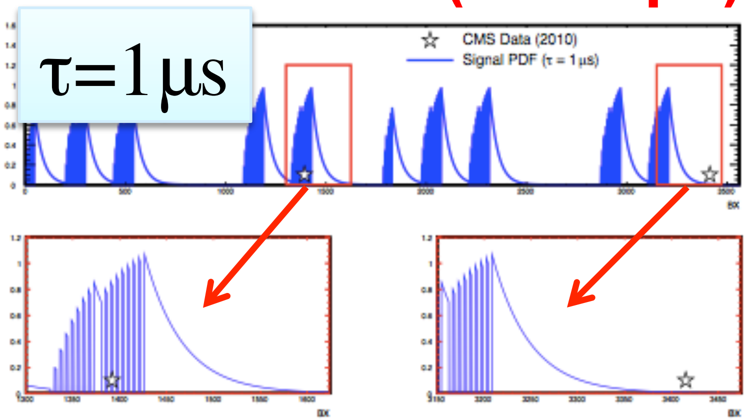
- **Search carried out for different lifetimes ($\Delta t=1.26\ \tau_g$)**

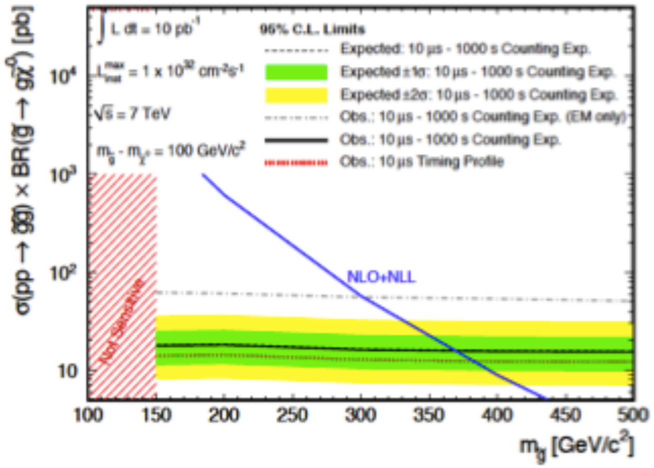
Lifetime [s]	Expected Background (± stat. ± syst.)	Observed
1×10^{-7}	$0.8\pm0.2\pm0.2$	2
1×10^{-6}	$1.9\pm0.4\pm0.5$	3
1×10^{-5}	$4.9\pm1.0\pm1.3$	5
1×10^{6}	$4.9\pm1.0\pm1.3$	5



- **Also look at time structure (τ<100μs)**

Given τ hypothesis: calculate PDF for signal evt time, using lumi profile; bkg: flat



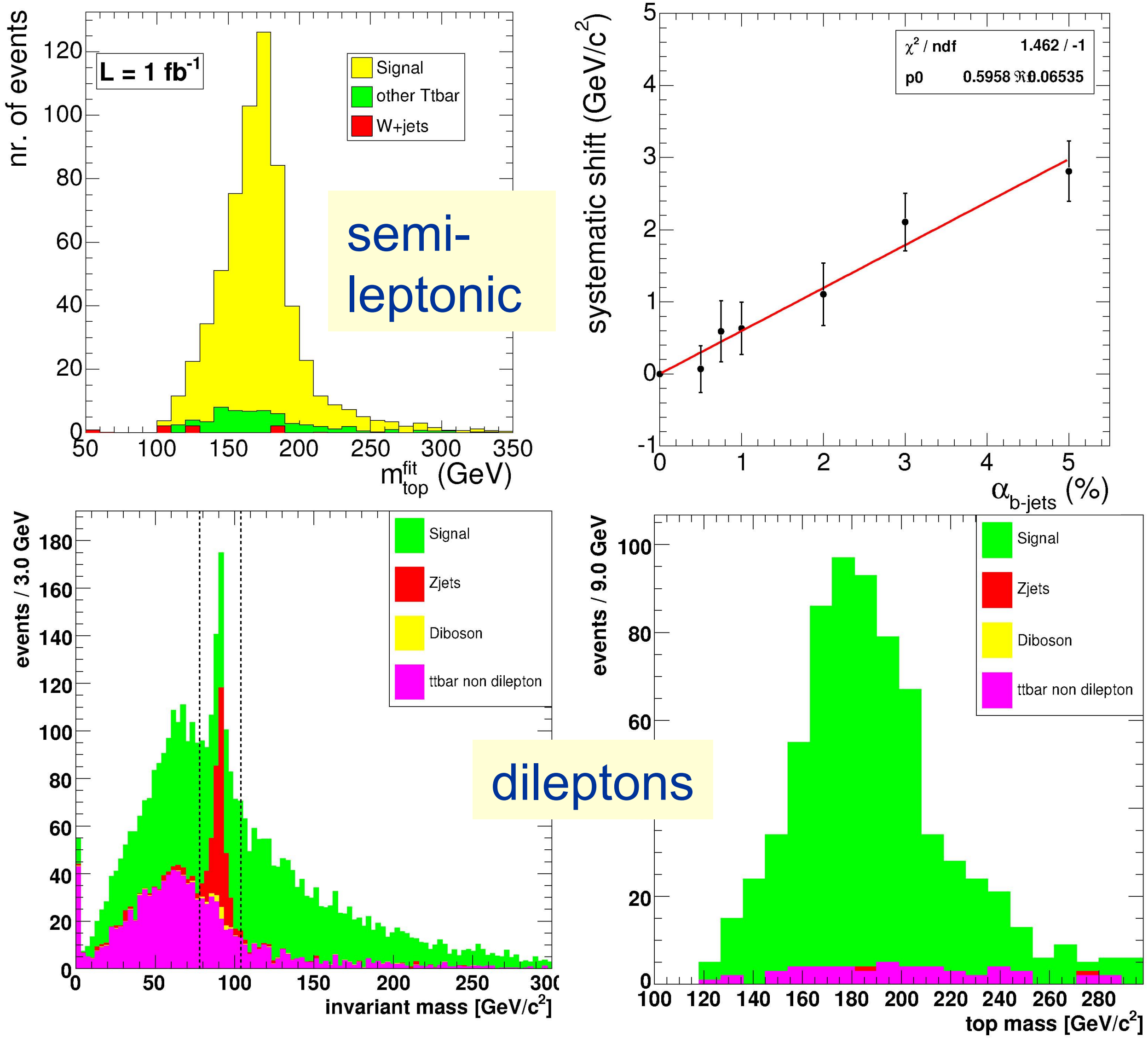


- **Fix $m_{\tilde{g}}-M_{\tilde{\chi}^0}$=100 GeV (efficient trig/jet)**
- **Counting experiment: *exclude $m_{\tilde{g}}$ < 370 GeV***

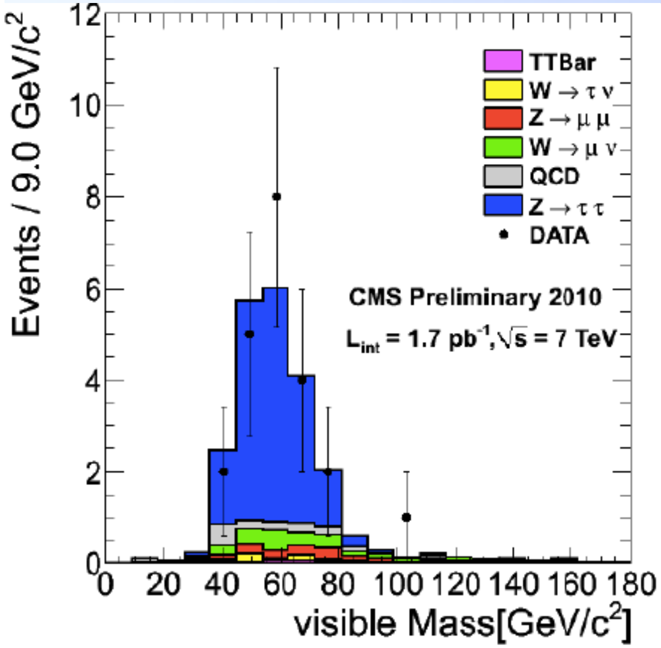
Physics with
100pb^{-1} – (2-5)000 pb^{-1}

Top physics with 1 fb^{-1}

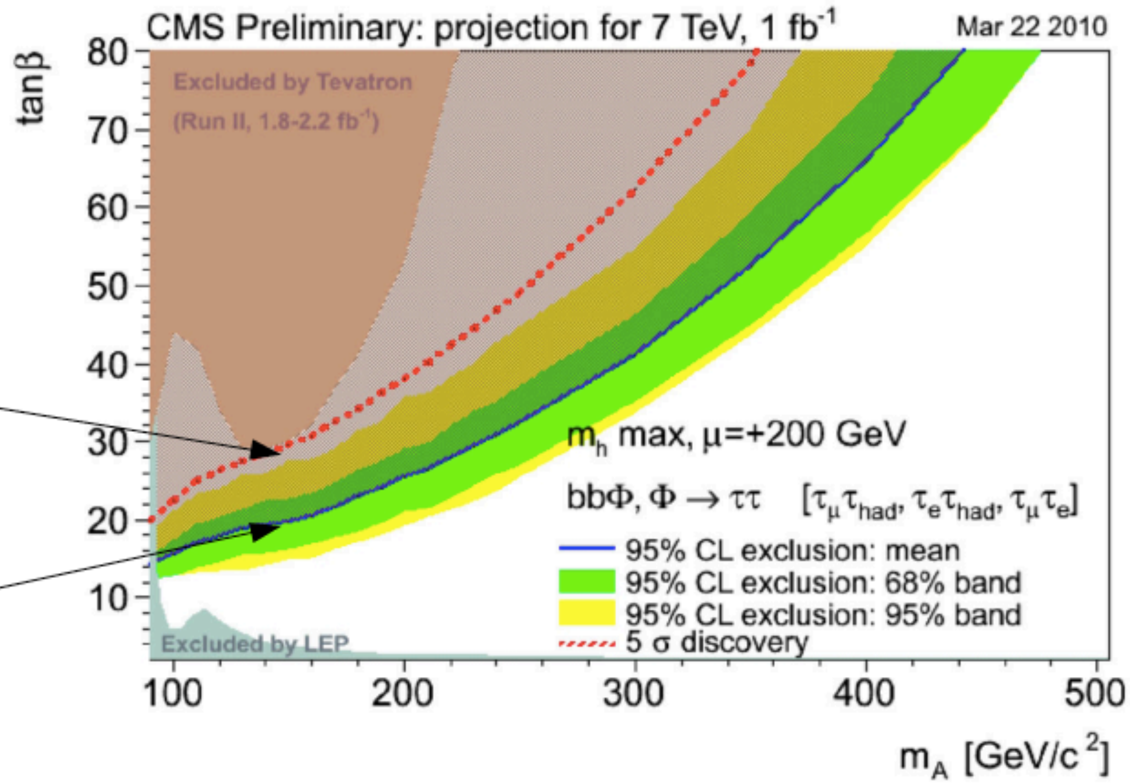
- **Observation of the top quark: demonstration that ALL of CMS works**
- **Understanding of top quark production: key element in searches for new physics**
    - **di-top (resonance) search**
    - **ds/dMtt…**
    - **Mass measurement**



SUSY Higgs



- Current $Z \to \tau\tau \to \mu + \tau$-jet signal used to "calibrate" expectations for $A/H \to \tau\tau \to \mu + \tau$-jet
  - Significant reach with $1 fb^{-1}$:



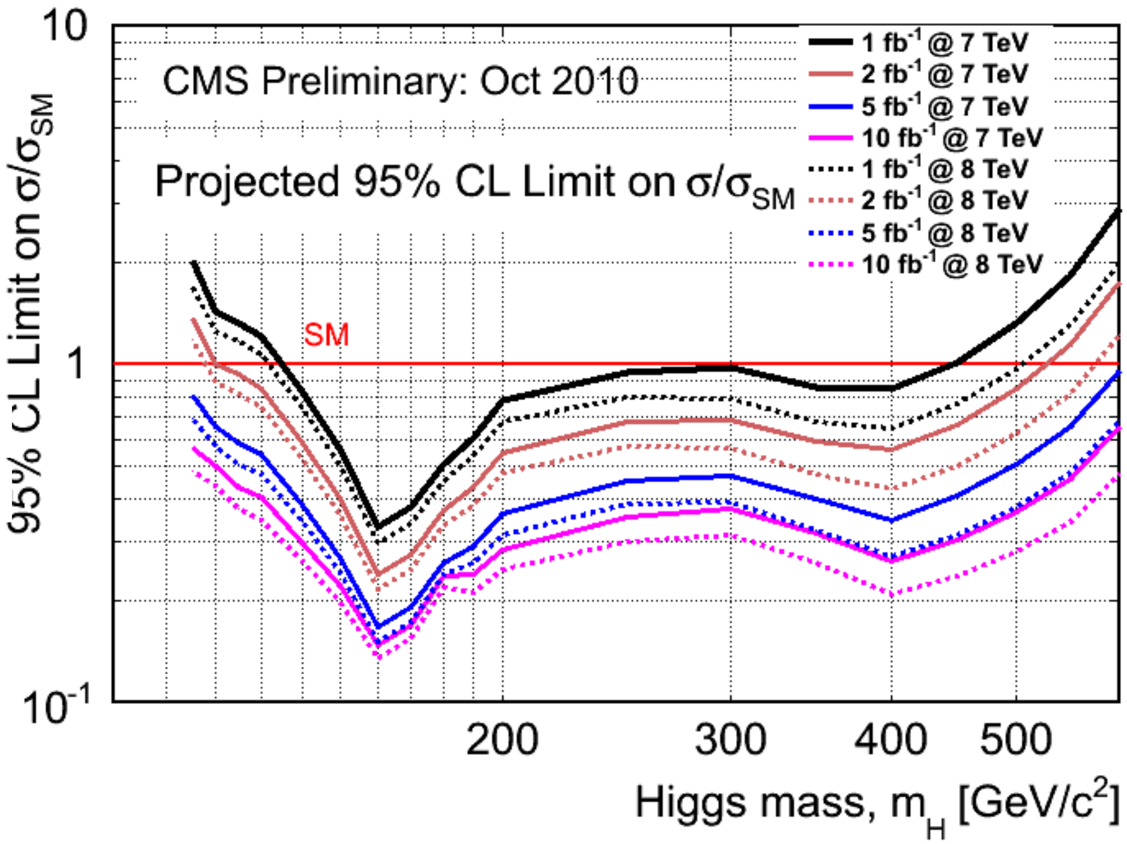
At low M_A $\tan\beta<20$ — discovery

At low M_A $\tan\beta<15$ — exclusion

The (SM) Higgs…

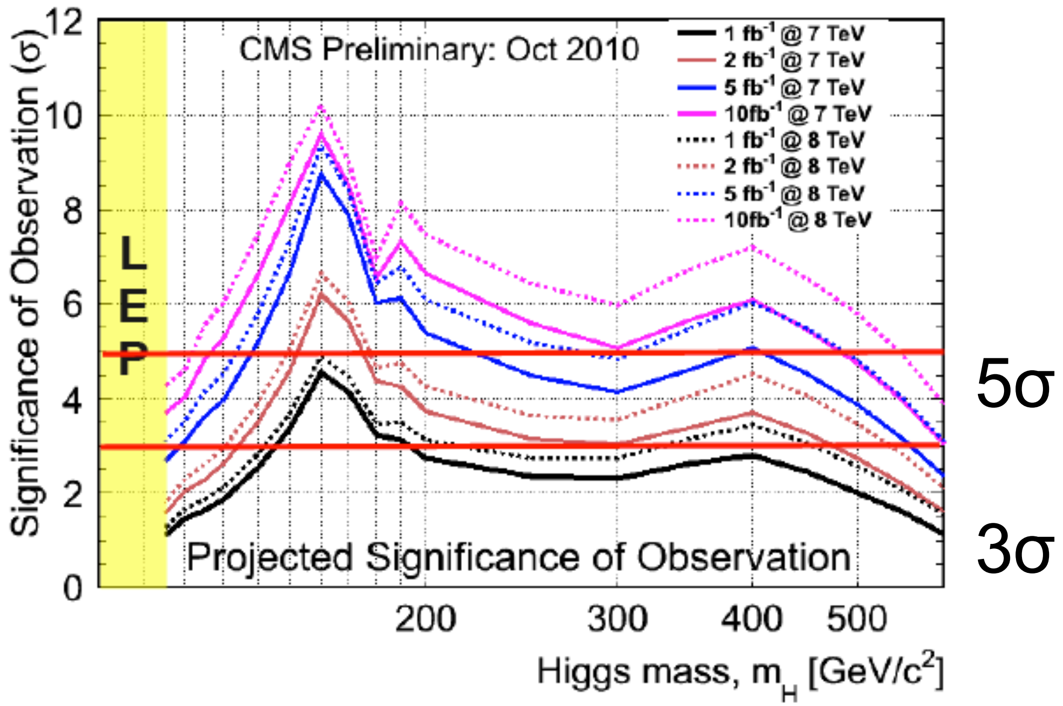
- **Combining all modes: search essentially complete with 5-10 fb^{-1}**
  - **Can certainly exclude it at 95%CL throughout the “relevant” region**
  - **Also 3σ effects**

7 TeV		8 TeV	
——	1 fb^{-1}	- - -	1 fb^{-1}
——	2 fb^{-1}	- - -	2 fb^{-1}
——	5 fb^{-1}	- - -	5 fb^{-1}
——	10 fb^{-1}	- - -	10 fb^{-1}

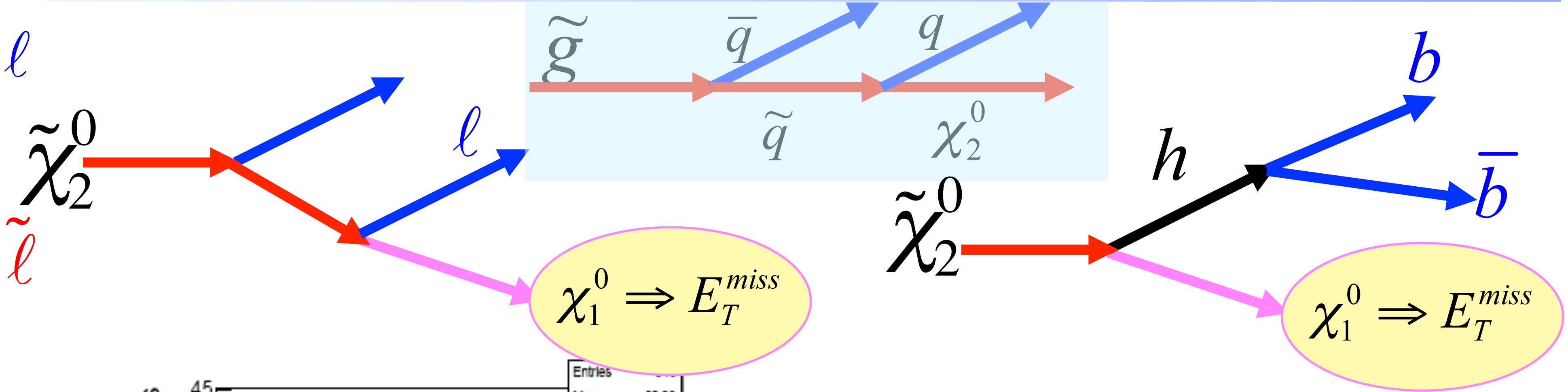


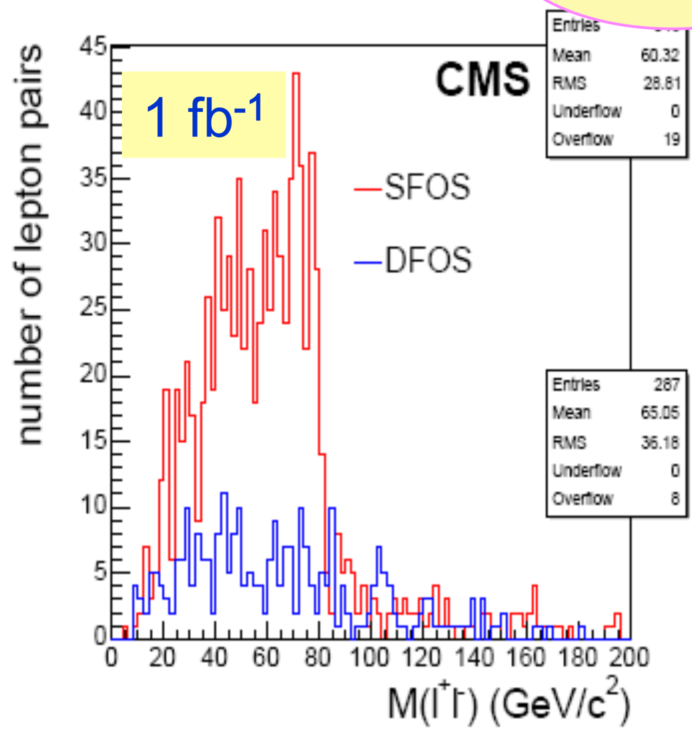
The (SM) Higgs (III)

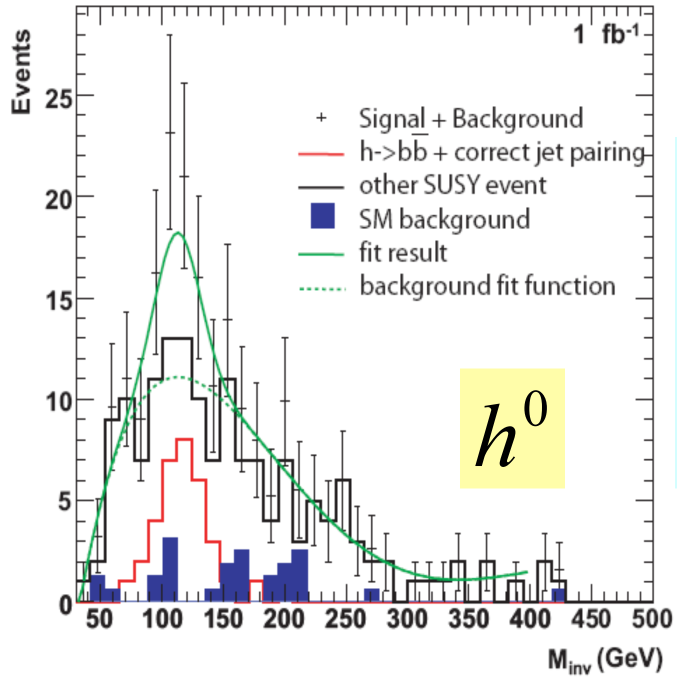
- **Discovery (aka 5σ) bottom line:**
  - **No discovery with 1fb^{-1}. Firm observation with 5 fb^{-1}: in the range 140-230 GeV**
  - **With two experiments: lower end: add ~10 GeV; upper end: ~500 GeV**



SUSY signals (cascades)







Can be discovery channel for the Higgs

Summary

Summary

- LHC and experiments' startup at 7 TeV impressive
  - By now the detectors are fully ready scientific instruments: physics-producing engines
- With ~40pb^{-1} the LHC has observed all particles of the standard model (save for neutrinos)
  - Solid basis for understanding the "background" to searches at higher mass and transverse energy scales
- Searches have started; several analyses in place
  - Proof-of-principle; even more: reach exceeds Tevatron
  - Just need more data
- With 1fb^{-1} we enter the Higgs discovery era. With a few fb^{-1}: firm discovery
  - "SUSY" explorable over very large area with 1fb^{-1}; possible new resonances. Very large reach for other new physics.
- And of course, if history is a guide, we will find the unexpected. The journey has only just started!

Acknowledgements

- **Many thanks to the following individuals for lecture material and very valuable information:**

  Nikos Varelas; Greg Landsberg; Tejinder Virdee; Sridhara Dasu; Andreas Schopper; Leandro Nisati