Searches for Exotic Particles with the CMS Detector

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Outline

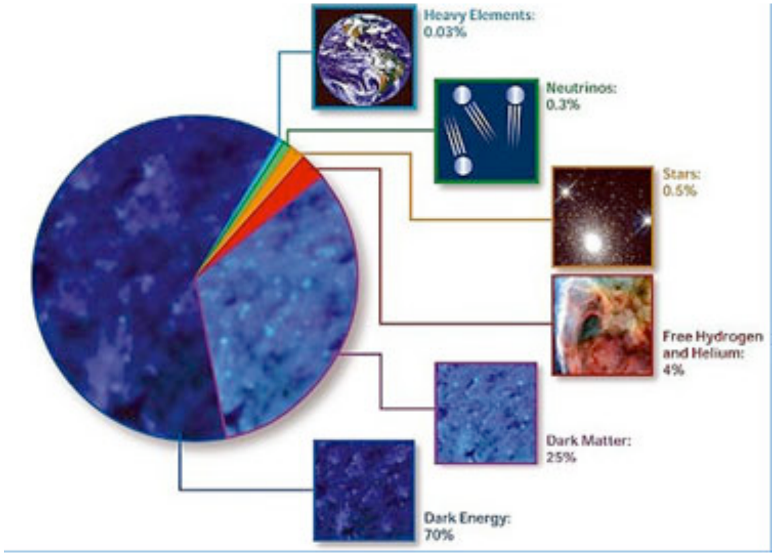
- Some pontification for the young in the audience
- The CMS detector and possible run scenarios
- The Standard Model at the LHC
- Models of exotic physics
- Di-object searches
- Heavy stable charged particles

Discover what?

An exciting time, as there are so very many questions:

Questions of the standard model

- What causes electroweak symmetry breaking?
- Where is the higgs?
- Why is it light?
- Why is there so much more matter than antimatter in the universe??



Question from cosmology

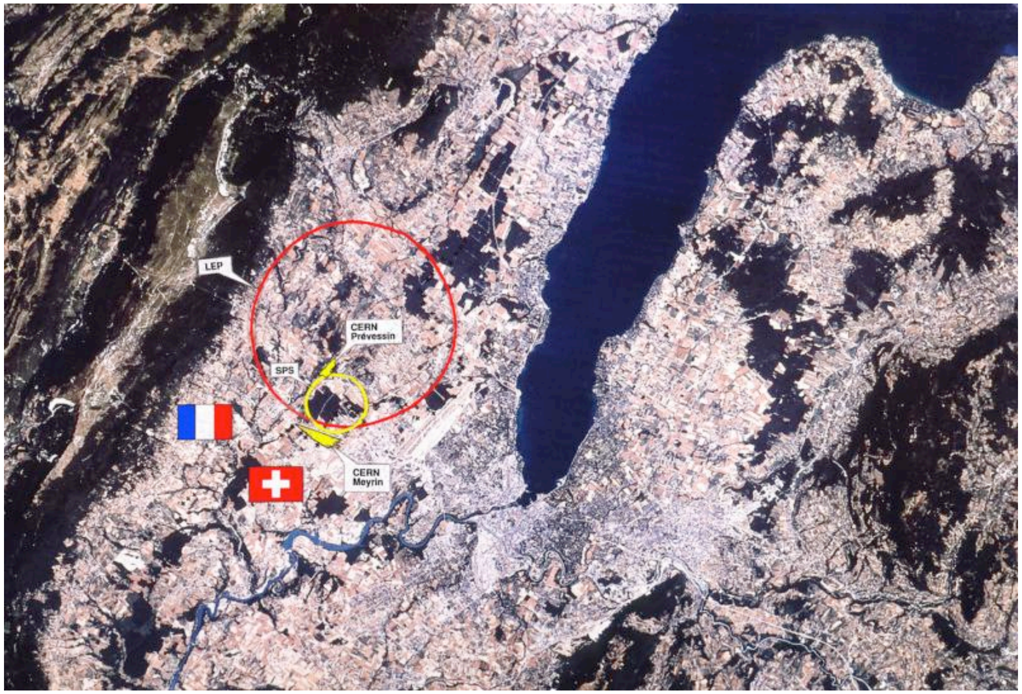
- Where is the dark matter particle?
- What is dark energy?

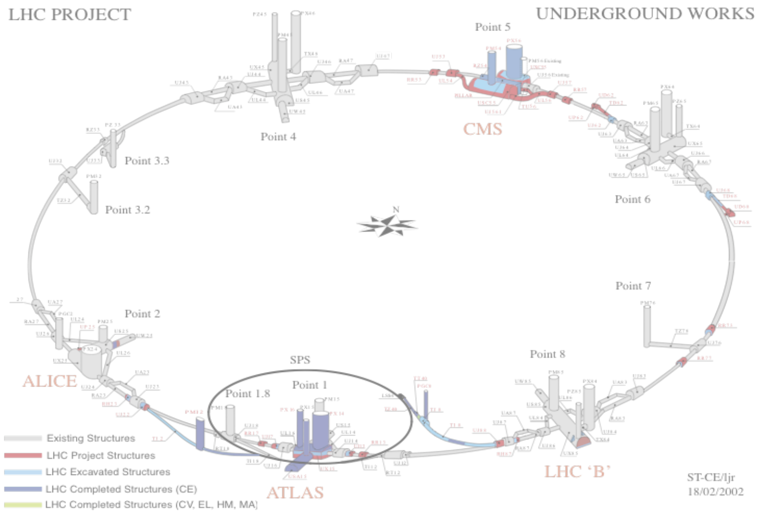
And Beyond

- Why do the fermions have such different masses?
- Why are neutrinos so light?
- Why are neutrinos not masses?
- Do the forces unify at a high energy scale?

etc. etc. etc.

Our new tool





- **pp $\sqrt{s}$ =14 TeV L=10^{34} cm^{-2} s^{-1}=10 μb^{-1}MHz (0.6A, 4μm)**
- **crossing rate 40 MHz (25 ns)**
- **circumference of 27 km (16.8 miles)**
- **Cost of about $3B?** **(depending on accounting method, conversion rate, etc)**
- 7 TeV (factor 3.5 higher than Tevatron)

Discovery at the LHC

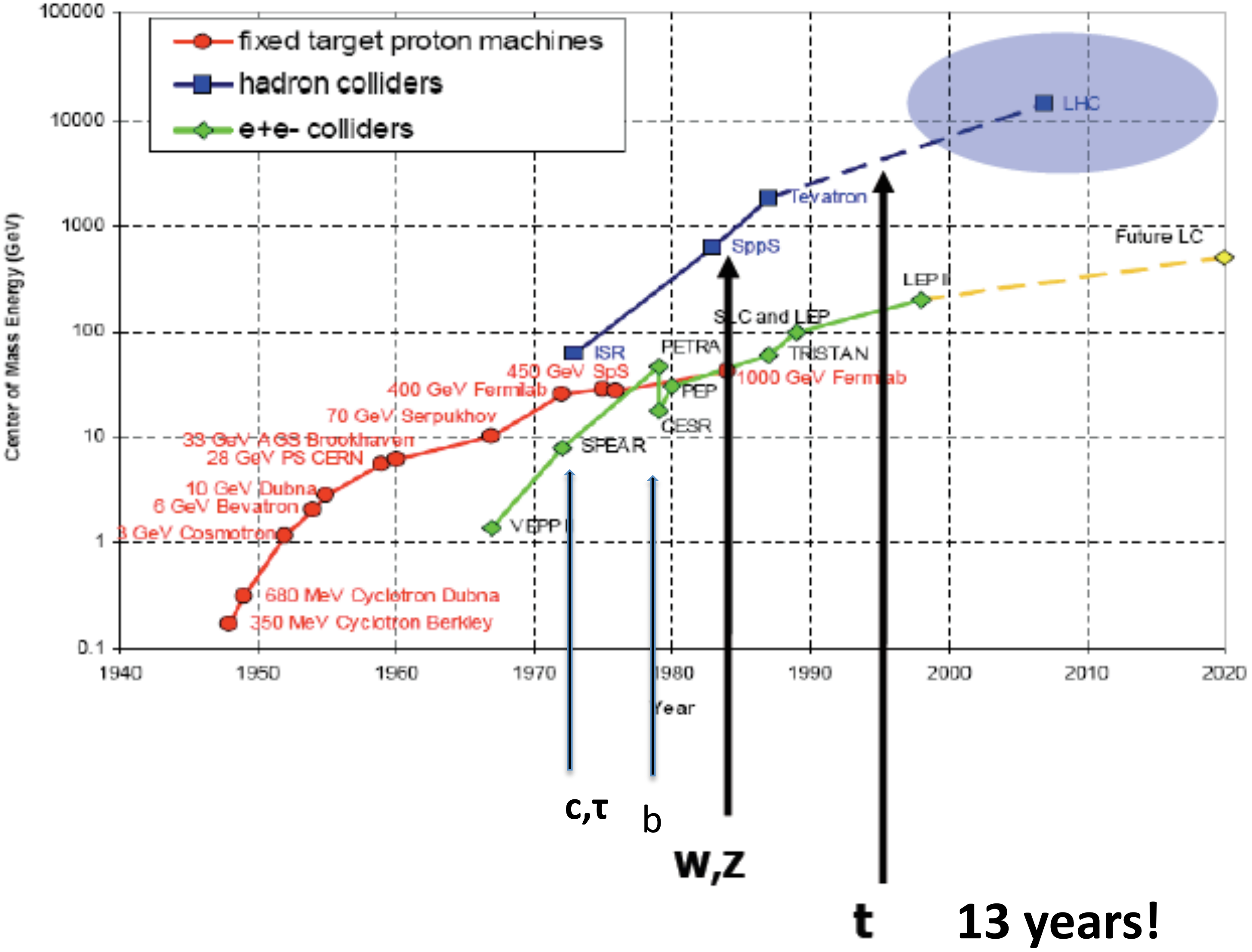
The LHC represents a new energy threshold.
Once we turn on, it should be simple to discover new particles, right?

LO description of a new particle search

- think about what distinguishes your signal from background
- design some variable or combination of variables (boosted decision tree, NN, etc) that maximizes the differences
- cut away most of your background using some criteria that optimizes significance
- estimate the remaining number of SM events (production cross section, BR, acceptance, efficiencies)
- see how many pass and feed that and your estimated background to RooStat and see what you got

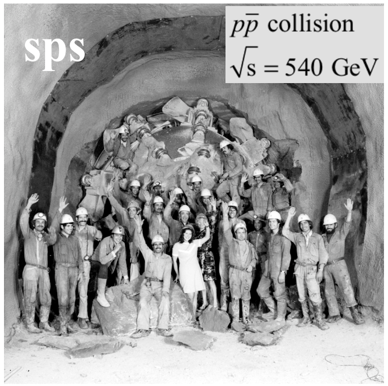
Is it really that simple?

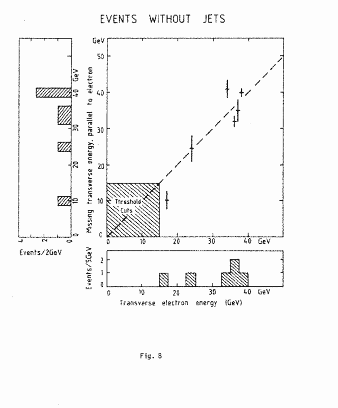
It’s been a long time

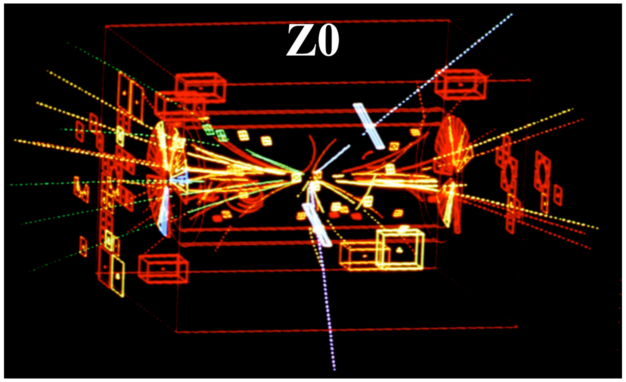


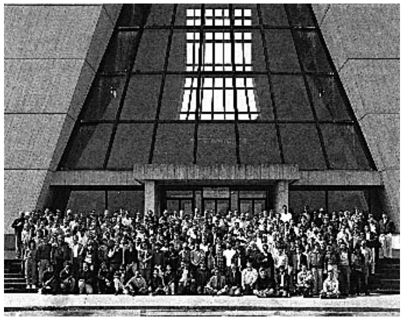
13 years!

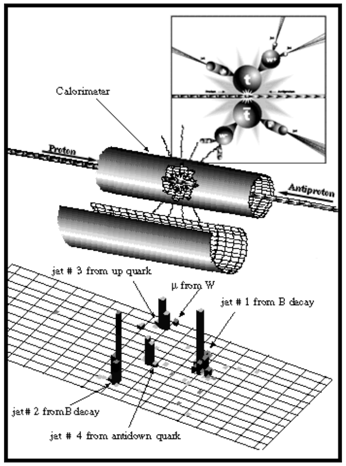
Very Different?









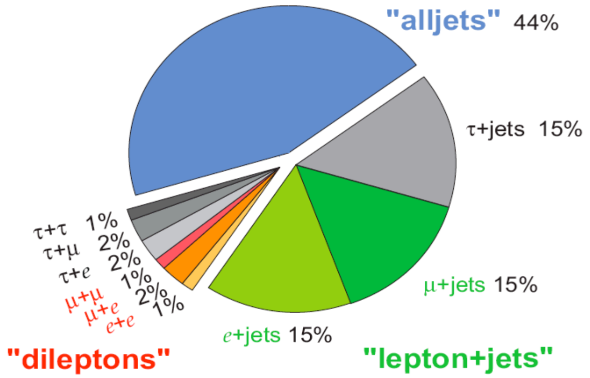


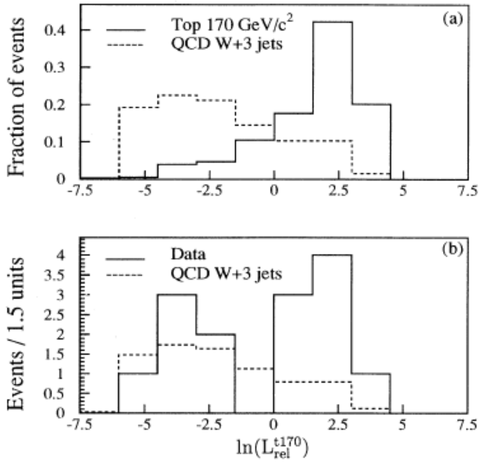
The SppS turned on at 1% of final instantaneous luminosity in 1983, but in the first run of a few months discovered the W with 8 events.

Tevatron turned on in 1987. Top discovered 8 years later.

Actually had a lot in common

- ALL properties of the signal tightly constrained by standard model
- Signal shows up in multiple channels
- with **FIXED RELATIONSHIPS**
- not only does the background agree with the background prediction, but **THE SIGNAL AGREES WITH THE SIGNAL PREDICTION**
- searches are easy (in principal) to design (optimize s/root(b), and it's (relatively) easy to interpret the results





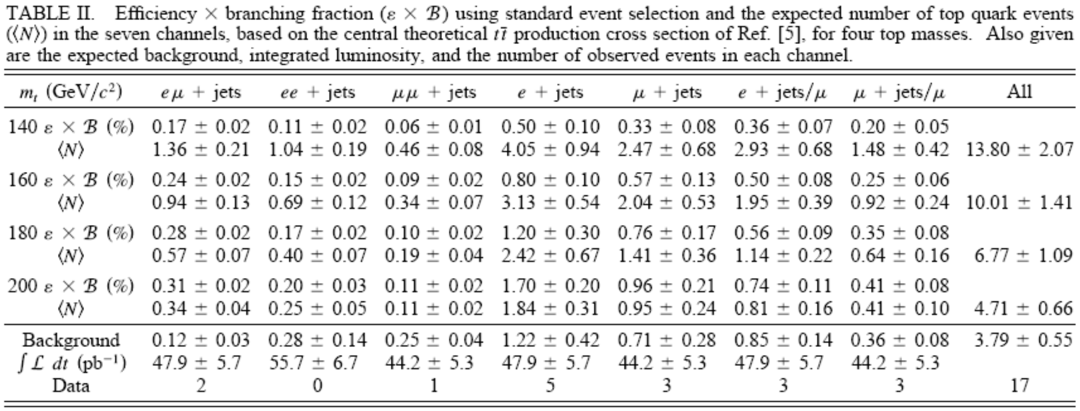
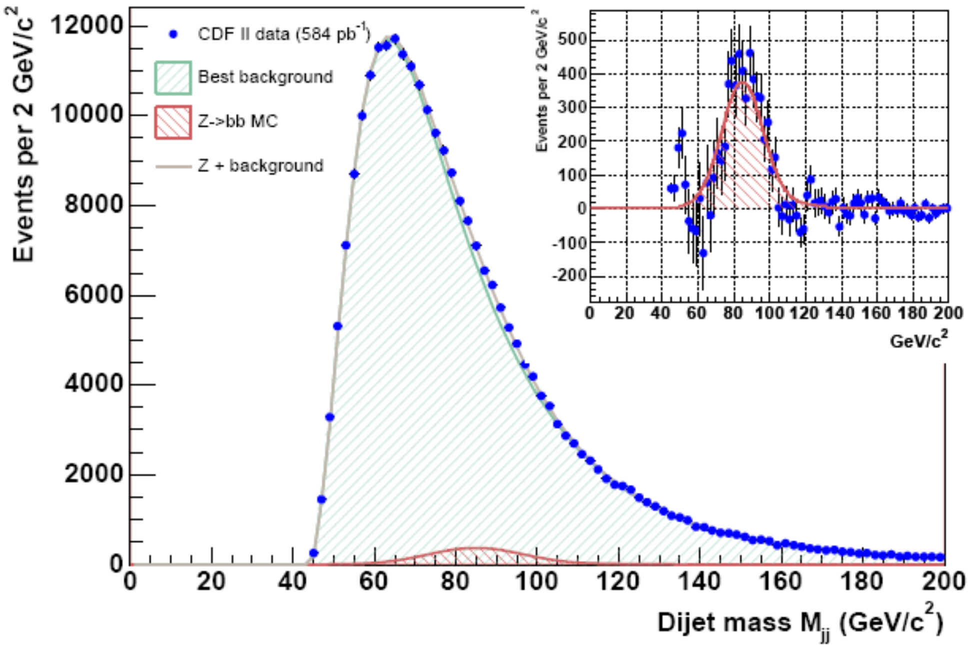


TABLE II. Efficiency × branching fraction ($\varepsilon \times \mathcal{B}$) using standard event selection and the expected number of top quark events ($\langle N \rangle$) in the seven channels, based on the central theoretical $t\bar{t}$ production cross section of Ref. [5], for four top masses. Also given are the expected background, integrated luminosity, and the number of observed events in each channel.

m_t (GeV/c^2)	$e\mu$ + jets	ee + jets	$\mu\mu$ + jets	e + jets	μ + jets	e + jets/μ	μ + jets/μ	All
140 $\varepsilon \times \mathcal{B}$ (%)	0.17 ± 0.02	0.11 ± 0.02	0.06 ± 0.01	0.50 ± 0.10	0.33 ± 0.08	0.36 ± 0.07	0.20 ± 0.05	
$\langle N \rangle$	1.36 ± 0.21	1.04 ± 0.19	0.46 ± 0.08	4.05 ± 0.94	2.47 ± 0.68	2.93 ± 0.68	1.48 ± 0.42	13.80 ± 2.07
160 $\varepsilon \times \mathcal{B}$ (%)	0.24 ± 0.02	0.15 ± 0.02	0.09 ± 0.02	0.80 ± 0.10	0.57 ± 0.13	0.50 ± 0.08	0.25 ± 0.06	
$\langle N \rangle$	0.94 ± 0.13	0.69 ± 0.12	0.34 ± 0.07	3.13 ± 0.54	2.04 ± 0.53	1.95 ± 0.39	0.92 ± 0.24	10.01 ± 1.41
180 $\varepsilon \times \mathcal{B}$ (%)	0.28 ± 0.02	0.17 ± 0.02	0.10 ± 0.02	1.20 ± 0.30	0.76 ± 0.17	0.56 ± 0.09	0.35 ± 0.08	
$\langle N \rangle$	0.57 ± 0.07	0.40 ± 0.07	0.19 ± 0.04	2.42 ± 0.67	1.41 ± 0.36	1.14 ± 0.22	0.64 ± 0.16	6.77 ± 1.09
200 $\varepsilon \times \mathcal{B}$ (%)	0.31 ± 0.02	0.20 ± 0.03	0.11 ± 0.02	1.70 ± 0.20	0.96 ± 0.21	0.74 ± 0.11	0.41 ± 0.08	
$\langle N \rangle$	0.34 ± 0.04	0.25 ± 0.05	0.11 ± 0.02	1.84 ± 0.31	0.95 ± 0.24	0.81 ± 0.16	0.41 ± 0.10	4.71 ± 0.66
Background	0.12 ± 0.03	0.28 ± 0.14	0.25 ± 0.04	1.22 ± 0.42	0.71 ± 0.28	0.85 ± 0.14	0.36 ± 0.08	3.79 ± 0.55
$\int \mathcal{L}\, dt$ (pb^{-1})	47.9 ± 5.7	55.7 ± 6.7	44.2 ± 5.3	47.9 ± 5.7	44.2 ± 5.3	47.9 ± 5.7	44.2 ± 5.3	
Data	2	0	1	5	3	3	3	17

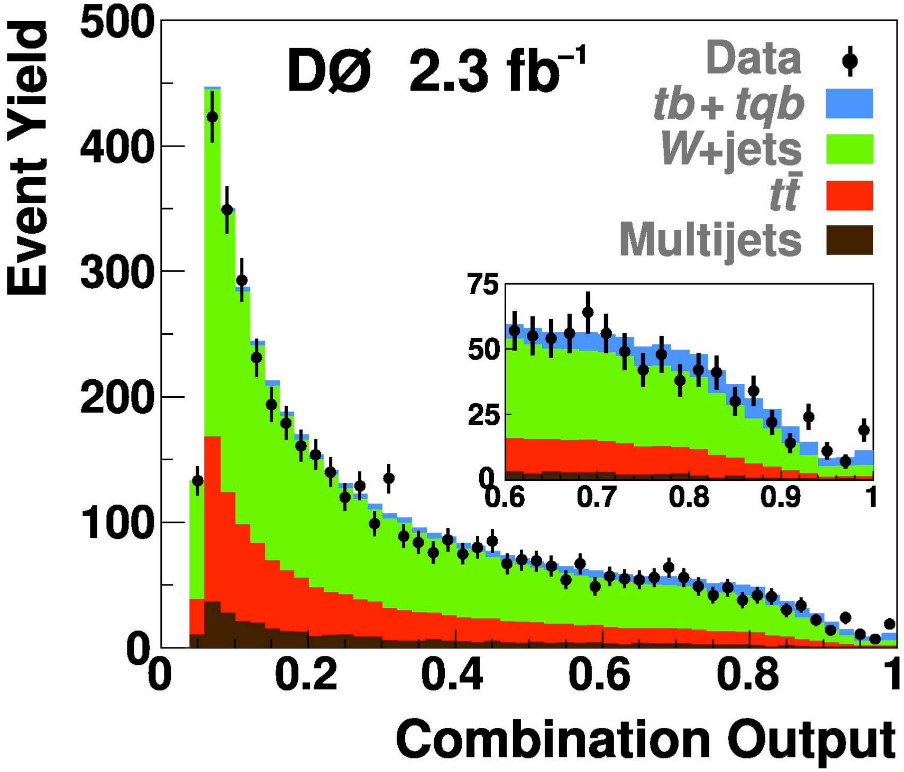
Z to bb

When what you are looking for has very well defined properties, you can do remarkable things

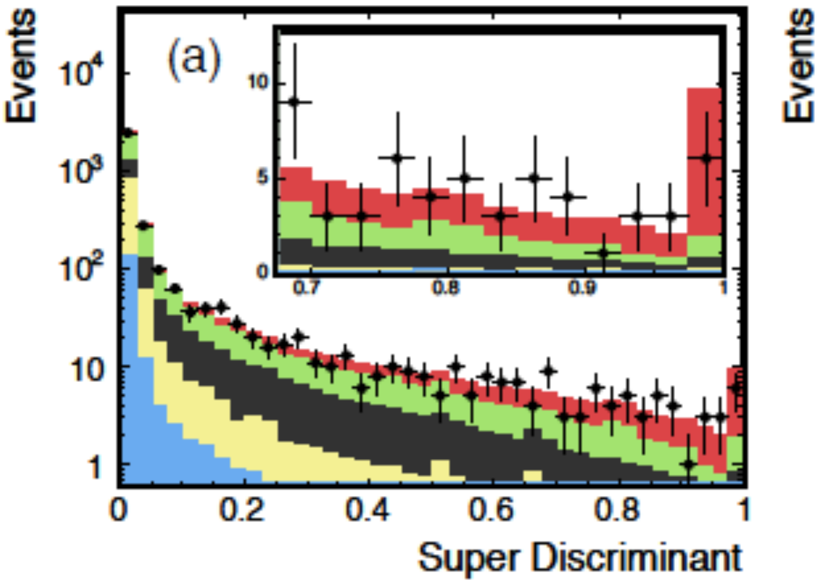


Would you believe this if it weren't the Z?

Single top



CDF



Tau/charm discovery

When the new physics is unexpected, things are much more challenging

Both detection systems worked just well enough, so in 1974 I began to find $e\mu$ events, that is events with an e, an opposite sign μ, no other charged particles, and no visible photons.

By early 1975 we had seen dozens of $e\mu$ events, but those of us who believed we had found a heavy lepton faced two problems: how to convince the rest of our collaboration and how to convince the physics world. The main focus of this early skepticism was the γ, e and μ identification systems: Had we underestimated hadron misidentification into leptons? Since our γ and e system only covered about half of 4π, what about undetected photons? What about inefficiencies and cracks in these systems?

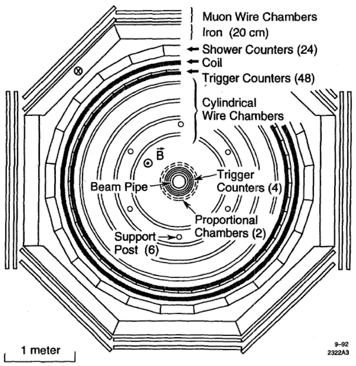
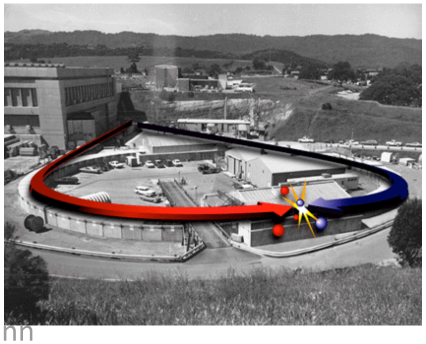
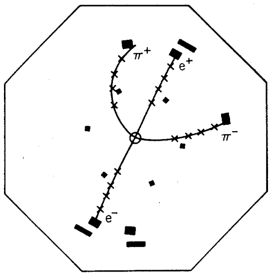


Fig. 3. The initial form of the Mark I detector.

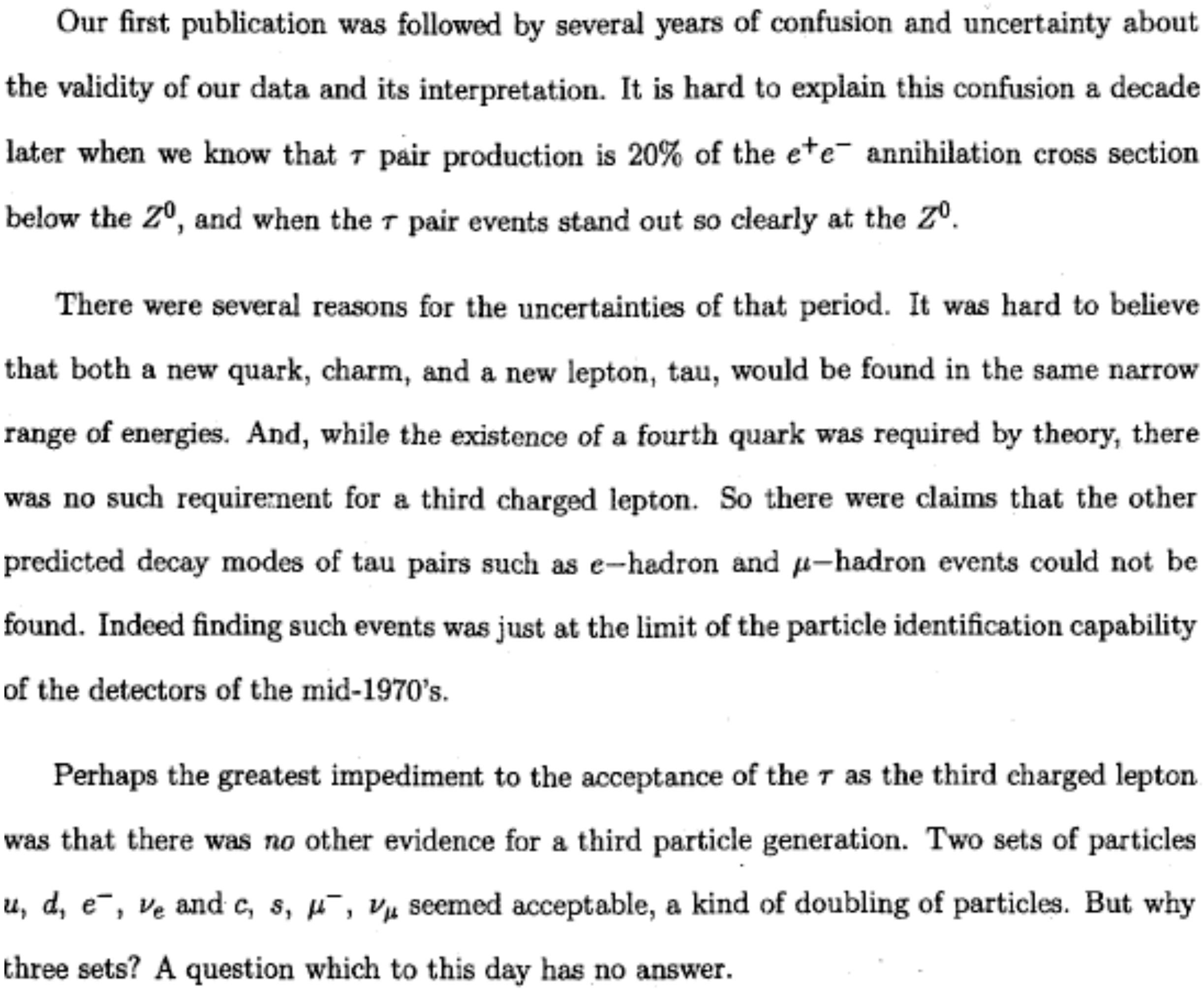
I was still not able to specify the source of the μe events: leptons, mesons or bosons. But I remember that I felt strongly that the source was heavy leptons. It would take two more years to prove that.

http://www.osti.gov/accomplishments/perl.html





tau/charm



Our first publication was followed by several years of confusion and uncertainty about the validity of our data and its interpretation. It is hard to explain this confusion a decade later when we know that τ pair production is 20% of the e^+e^- annihilation cross section below the Z^0, and when the τ pair events stand out so clearly at the Z^0.

There were several reasons for the uncertainties of that period. It was hard to believe that both a new quark, charm, and a new lepton, tau, would be found in the same narrow range of energies. And, while the existence of a fourth quark was required by theory, there was no such requirement for a third charged lepton. So there were claims that the other predicted decay modes of tau pairs such as $e-$hadron and $\mu-$hadron events could not be found. Indeed finding such events was just at the limit of the particle identification capability of the detectors of the mid-1970's.

Perhaps the greatest impediment to the acceptance of the τ as the third charged lepton was that there was *no* other evidence for a third particle generation. Two sets of particles u, d, e^-, ν_e and c, s, μ^-, ν_μ seemed acceptable, a kind of doubling of particles. But why three sets? A question which to this day has no answer.

Scanned at the American Institute of Physics

Scanned at the American Institute of Physics

New Physics

- Higgs is like top/W/Z. It's a standard model based search.
- However, there are many compelling models of new physics that address deficiencies of the standard model known from cosmology and theoretical considerations. If any of these are right, we could find ourselves in a charm/tau like scenario (Higgs is the new charm).
  - SUSY?
  - Extra dimensions?
  - Little higgs?
  - New strong dynamics?
  - Compositeness?

What kinds of exotic physics are we sensitive to with a small quantity of low quality data?
What can we look for without strong constraints from a model?
How can we find it?

General Observations

For searches using a small amount of low quality data:

- Want big cross section and clean signature (final state with high pT leptons or other dramatic signature)
- The earliest results may come from something that couples to gluons

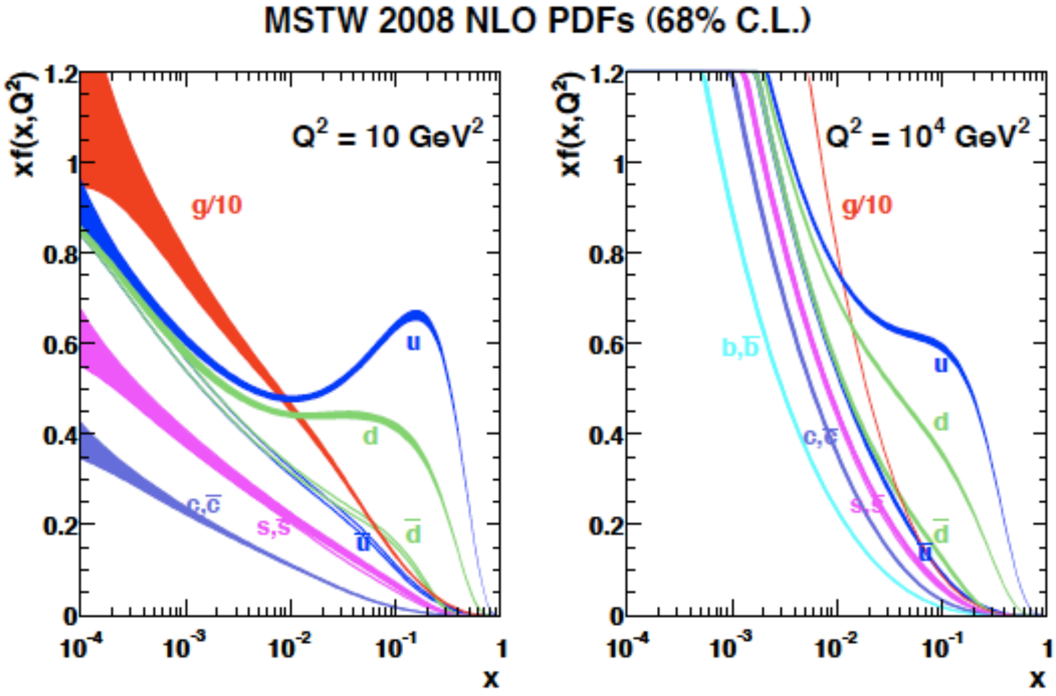
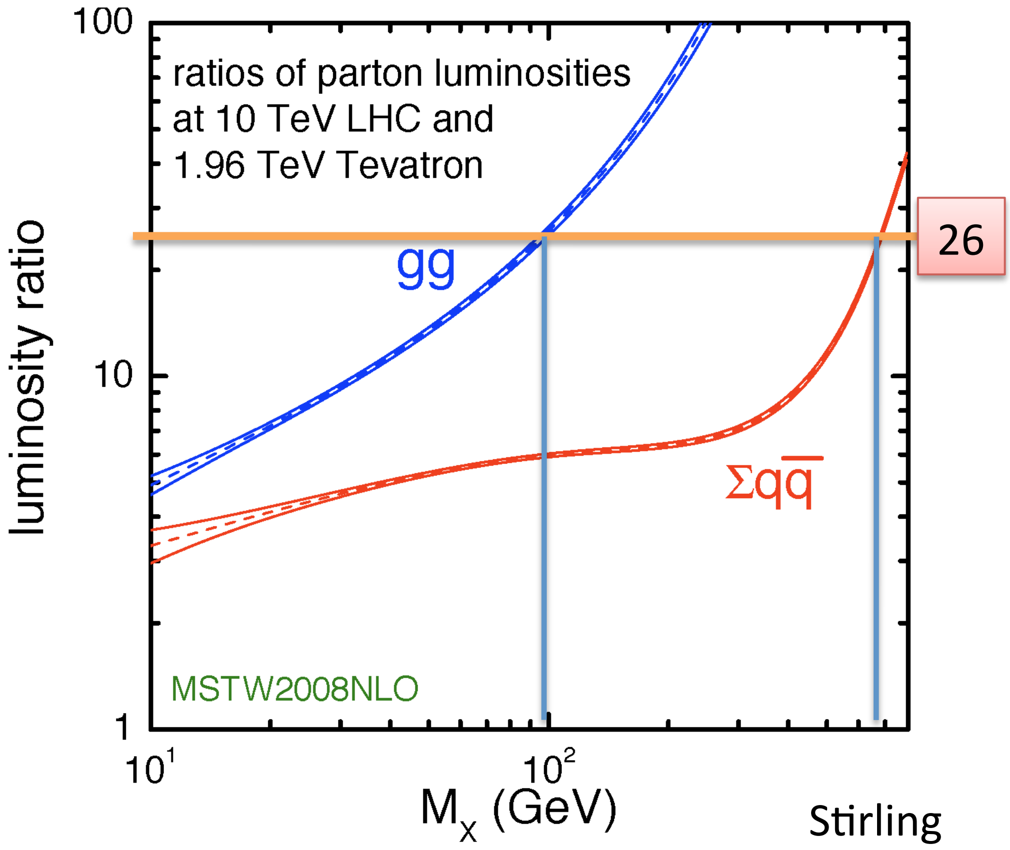


Figure 1: MSTW 2008 NLO PDFs at $Q^2 = 10$ GeV^2 and $Q^2 = 10^4$ GeV^2.

Reports of the Tevatron's death have been greatly exaggerated.*

For what masses/initial states does 300 pb-1 at 10 TeV beat 8 fb^{-1} (now 5) at the tevatron (2 TeV)?

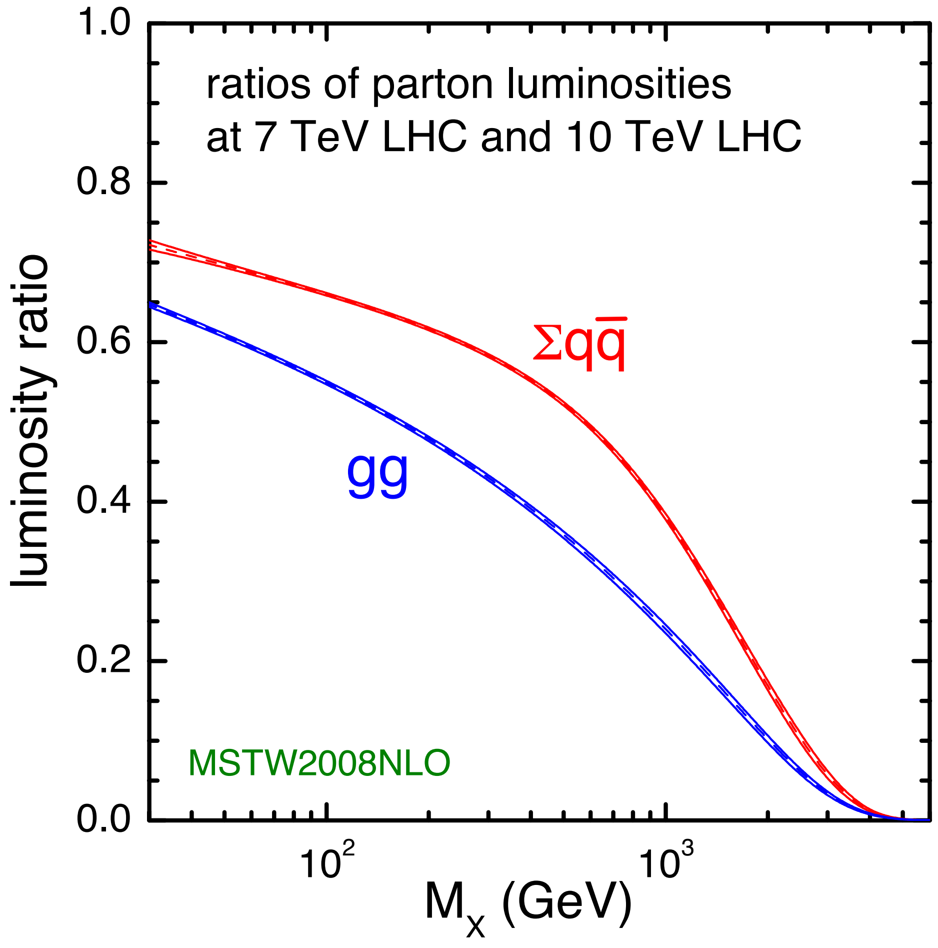


Stirling

$$\frac{8000}{300} = 26$$

* Mark Twain

And if 7 …



gg of course
down more
than qq

Stirling

Discovery

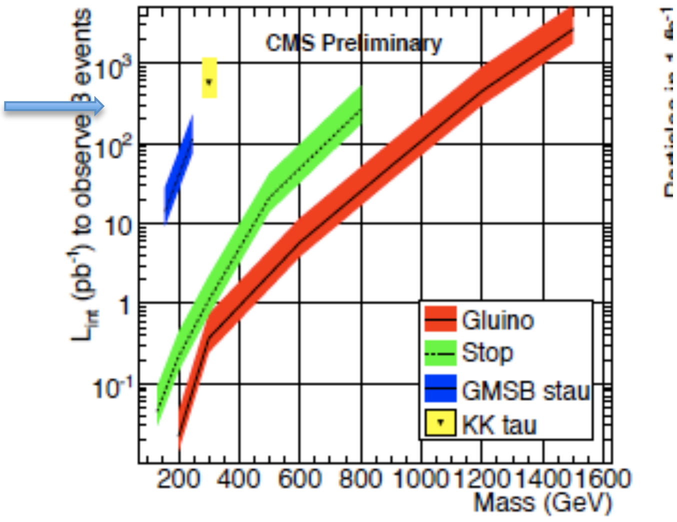
300 pb at 14 TeV

What can we discover?

- above Tevatron reach -> gg initial state with M>100 or qq state with M>600 GeV
- if it has no background and 100% e*A, need at least 5 events: 15 fb xsct
- typical 10-80% acceptance 20-150 fb

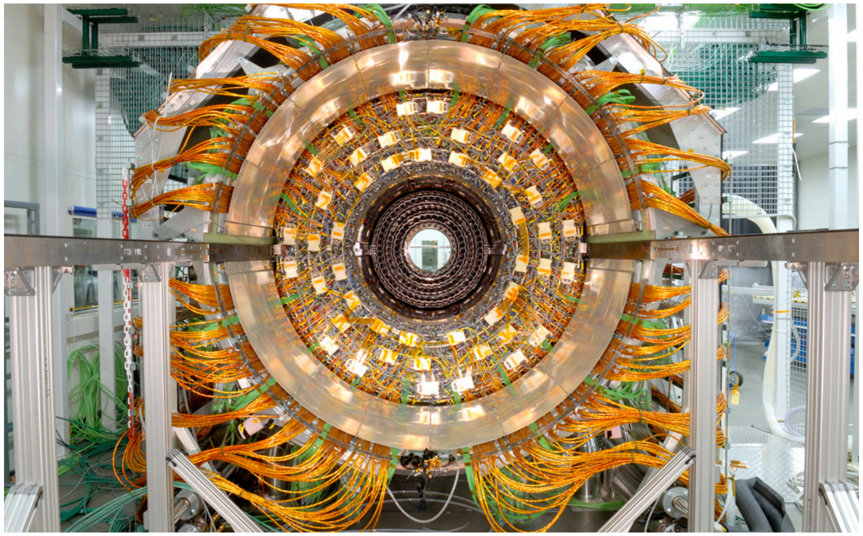
Examples of things with “no” backgrounds

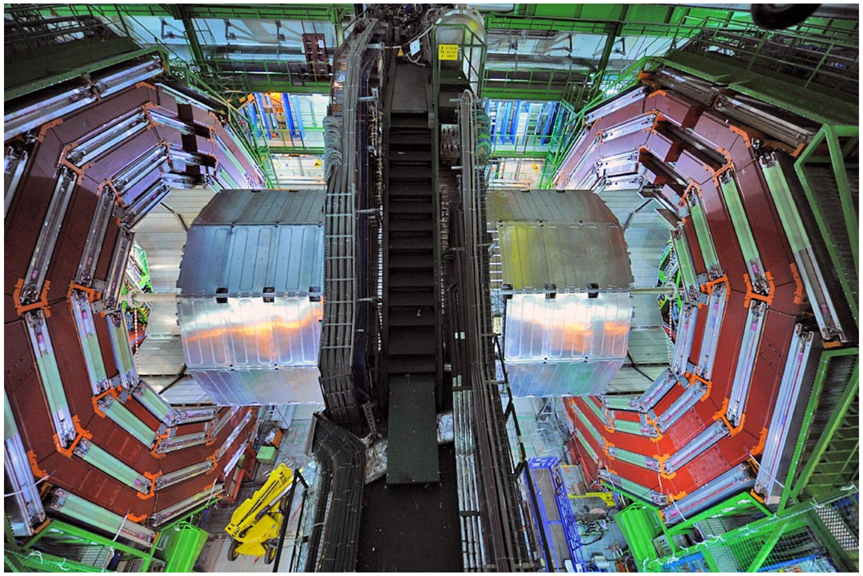
- heavy stable charged particles (HSCP)
- blackholes
- Zprime to ee, mumu



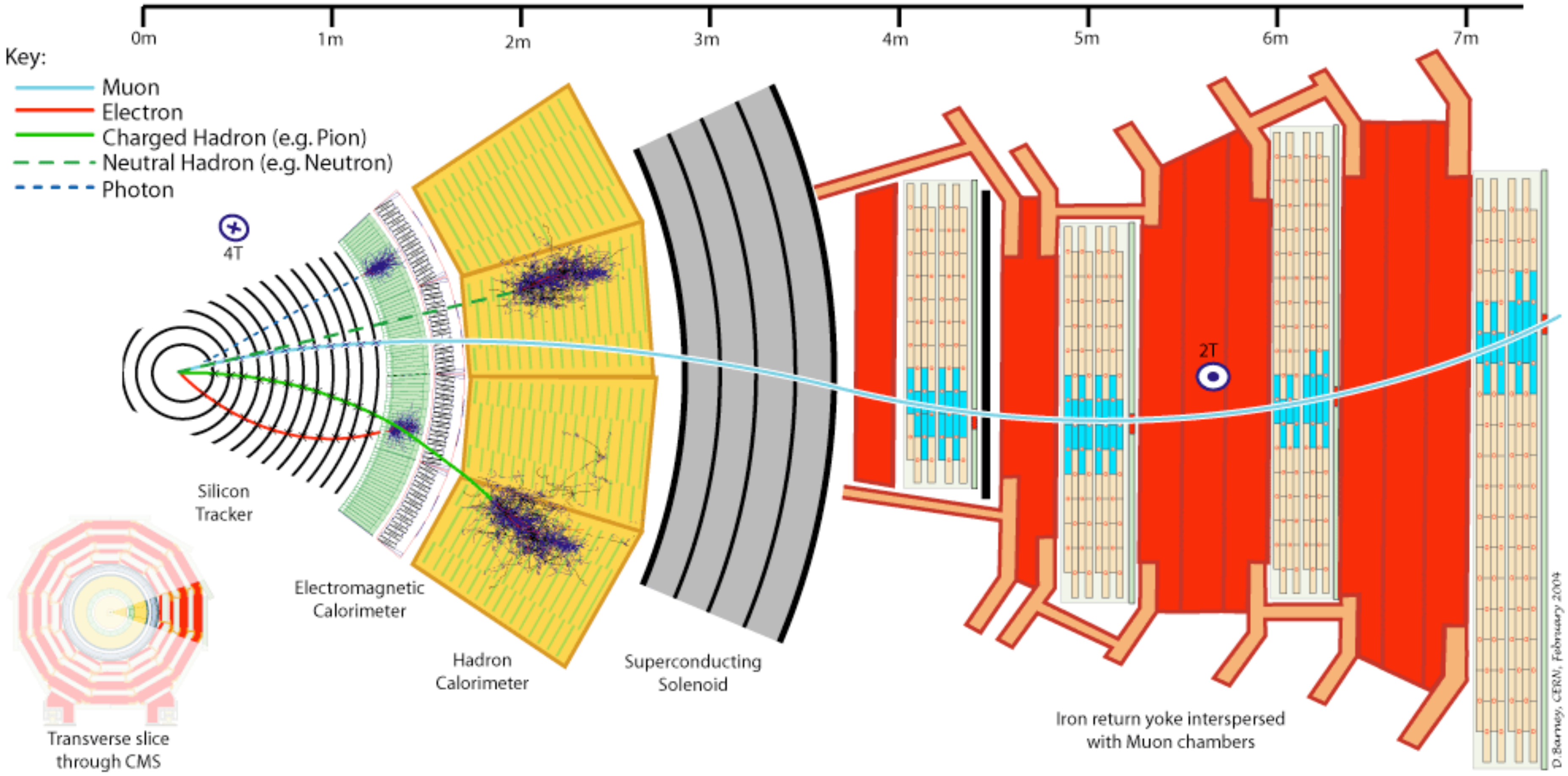
Data Sample	Cross section (pb)	HSCP in $\|\eta\| < 2.4$ (%)	HSCP in $\|\eta\| < 0.9$(%)
$\tilde{\tau}_1$ (156 GeV)	1.19	97.6	72.6
$\tilde{\tau}_1$ (247 GeV)	0.097	97.5	70.9
KK tau (300 GeV)	0.020	84.7	40.9
$\tilde{g}$ (200 GeV)	2.2×10^3	89.7	47.4
$\tilde{g}$ (300 GeV)	100	91.7	50.0
$\tilde{g}$ (600 GeV)	5.00	93.7	55.5
$\tilde{g}$ (900 GeV)	0.46	92.6	57.7
$\tilde{g}$ (1200 GeV)	61×10^{-3}	91.4	53.9
$\tilde{g}$ (1500 GeV)	10×10^{-3}	90.4	55.8
$\tilde{t}_1$ (130 GeV)	1.11×10^3	87.8	43.1
$\tilde{t}_1$ (200 GeV)	1.77×10^2	90.9	47.3
$\tilde{t}_1$ (300 GeV)	27.4	92.8	50.4
$\tilde{t}_1$ (500 GeV)	1.27	95.3	54.7
$\tilde{t}_1$ (800 GeV)	7.81×10^{-2}	96.9	61.9

CMS

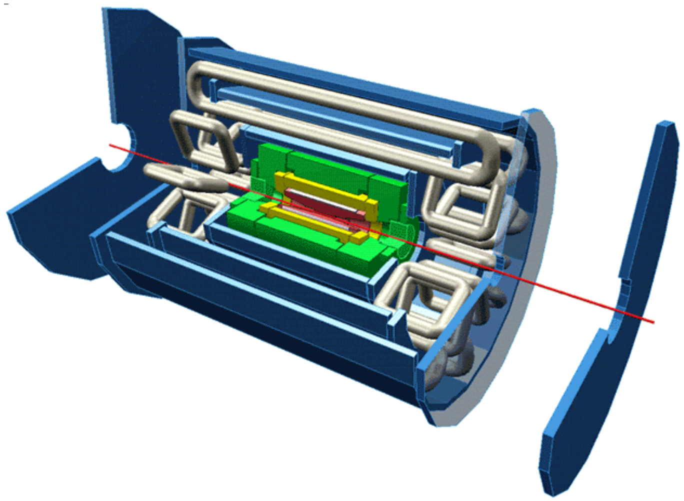


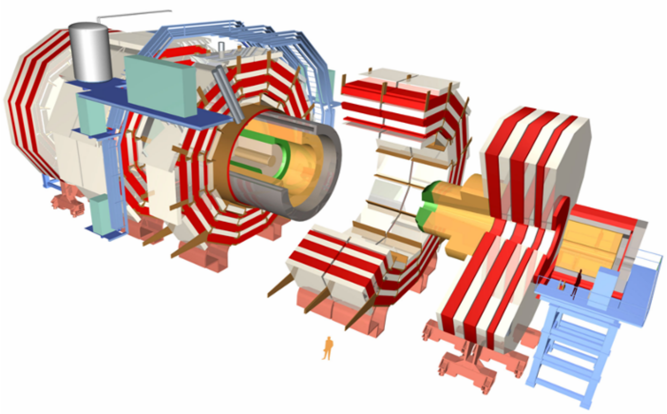


Slice of CMS


0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

	ATLAS	CMS
Magnetic field	2 T solenoid + toroid (0.5 T barrel 1 T endcap)	4 T solenoid + return yoke
Tracker	Si pixels, strips + TRT $\sigma/p_T \approx 5\text{x}10^{-4} p_T + 0.01$	Si pixels, strips $\sigma/p_T \approx 1.5\text{x}10^{-4} p_T + 0.005$
EM calorimeter	Pb+LAr $\sigma/E \approx 10\%/\sqrt{E} + 0.007$	PbWO4 crystals $\sigma/E \approx 3\%/\sqrt{E} + 0.003$
Hadronic calorimeter	Fe+scint. / Cu+LAr (10λ) $\sigma/E \approx 50\%/\sqrt{E} + 0.03$ GeV	Brass+scintillator (7 λ + catcher) $\sigma/E \approx 100\%/\sqrt{E} + 0.05$ GeV
Muon	$\sigma/p_T \approx 2\%$ @ 50GeV to 10% @ 1TeV (ID +MS)	$\sigma/p_T \approx 1\%$ @ 50GeV to 10% @ 1TeV (DT/CSC+Tracker)
Trigger	L1 + RoI-based HLT (L2+EF)	L1+HLT (L2 + L3)





Of course, they will be new detectors

Run Aug – Oct 92. Some plots from a Nov 92 talk (Madaras)

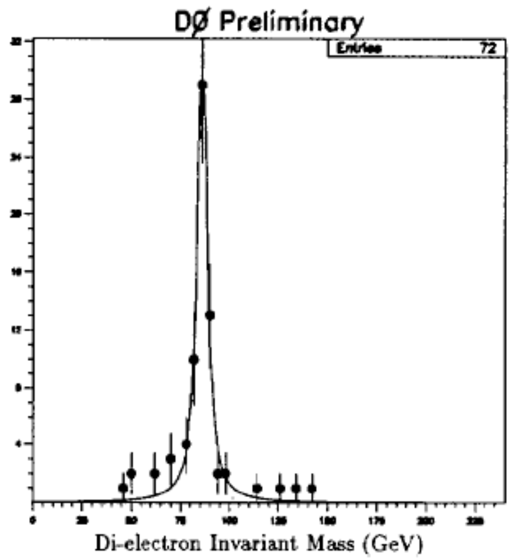
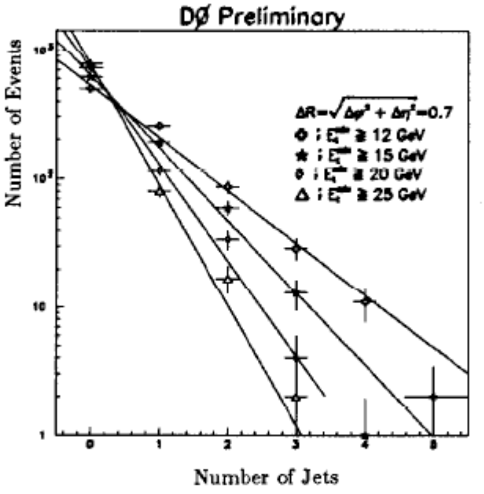


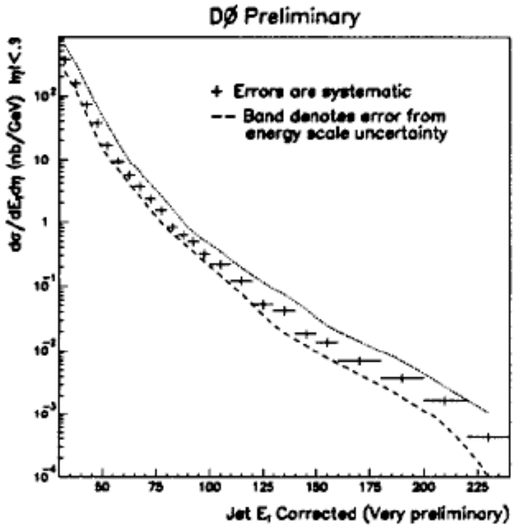
Figure 7: Di-electron invariant mass distribution, with a Breit-Wigner fit.

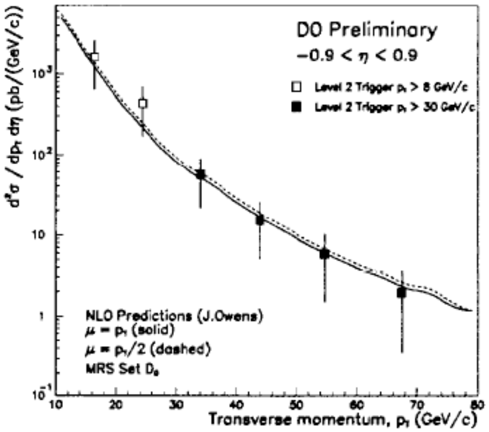
Peak at 86 GeV.

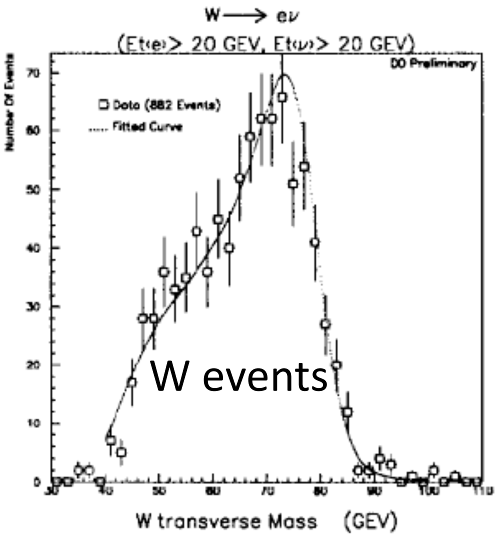
Can still do a lot with a new detector

Run Aug – Oct 92. Some plots from a Nov 92 talk (Madaras)





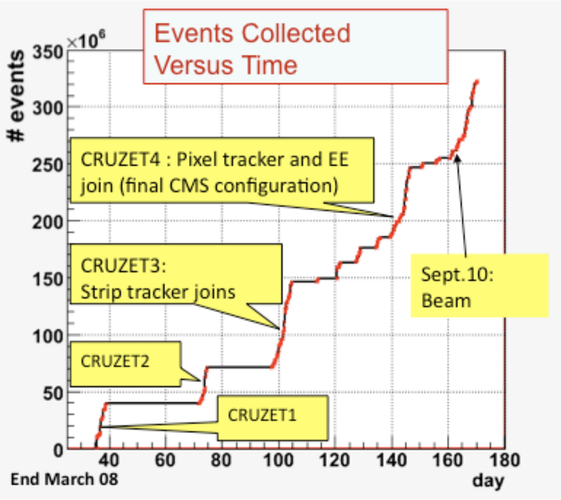


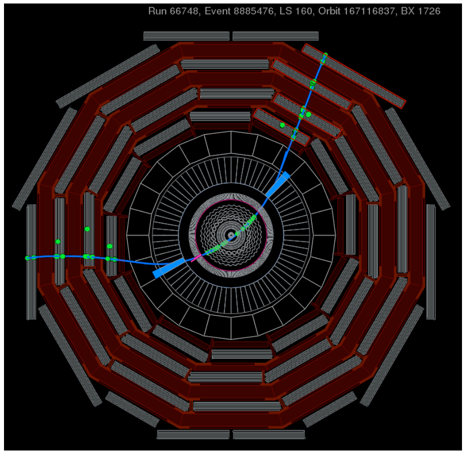


W events

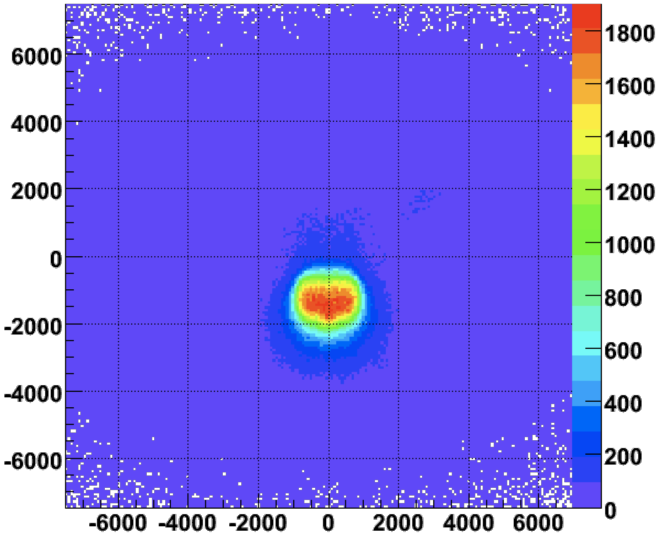
(MET obviously was quite useable in this brand new detector.)

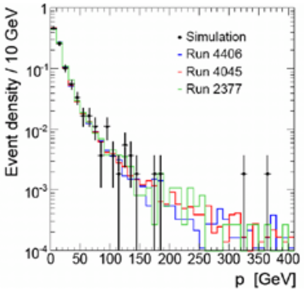
ATLAS and CMS may be the best understood detectors ever at turn on



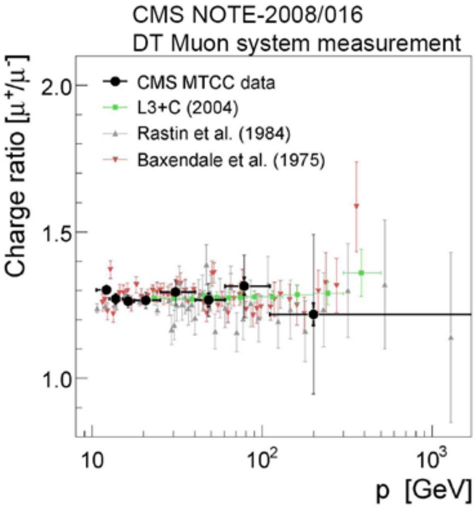


Cosmics

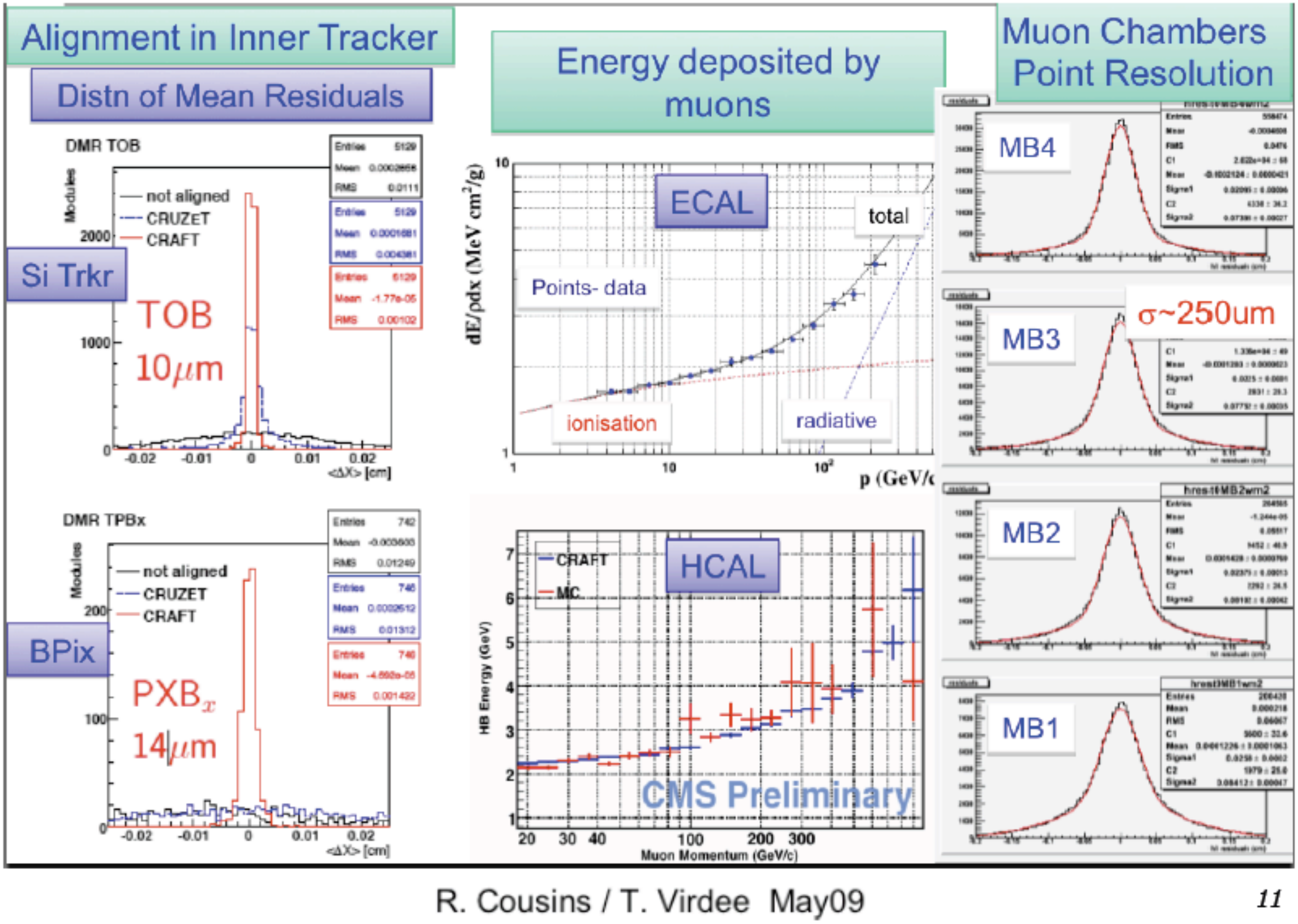




Such measurements push on getting calibration and alignment correct



Well-calibrated



Alignment in Inner Tracker

Distn of Mean Residuals

Energy deposited by muons

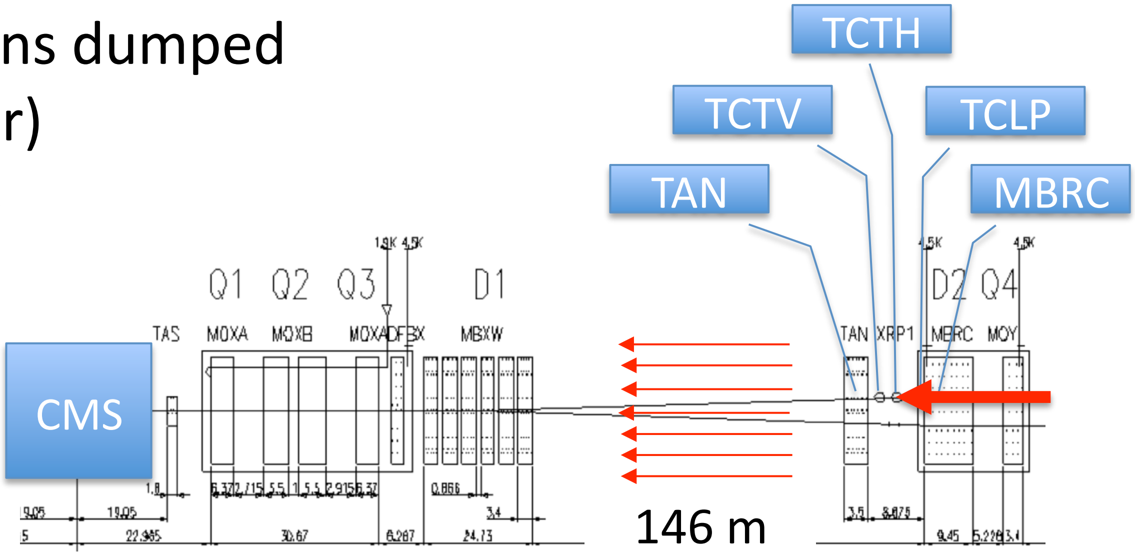
Muon Chambers Point Resolution

R. Cousins / T. Virdee May09

11

Beam Splash Events

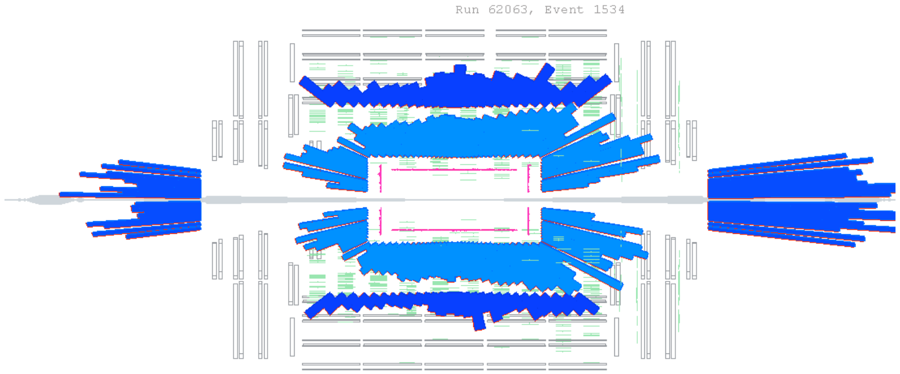
- Beam with 2x109 protons dumped onto a target (collimator) 150m upstream of CMS
  - Sept. 7,9,10,18



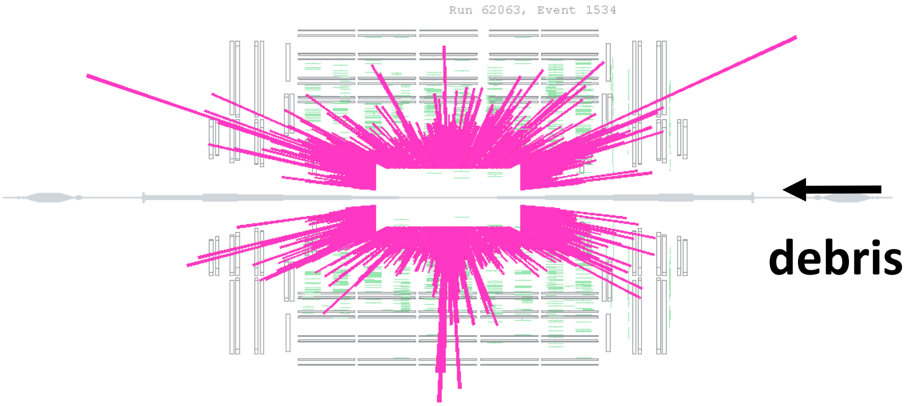
- Leads to a “tsunami” wave of O(100K) muons coming down the tunnel!
  - A far cry from the single cosmic muon events…

CMS lights up

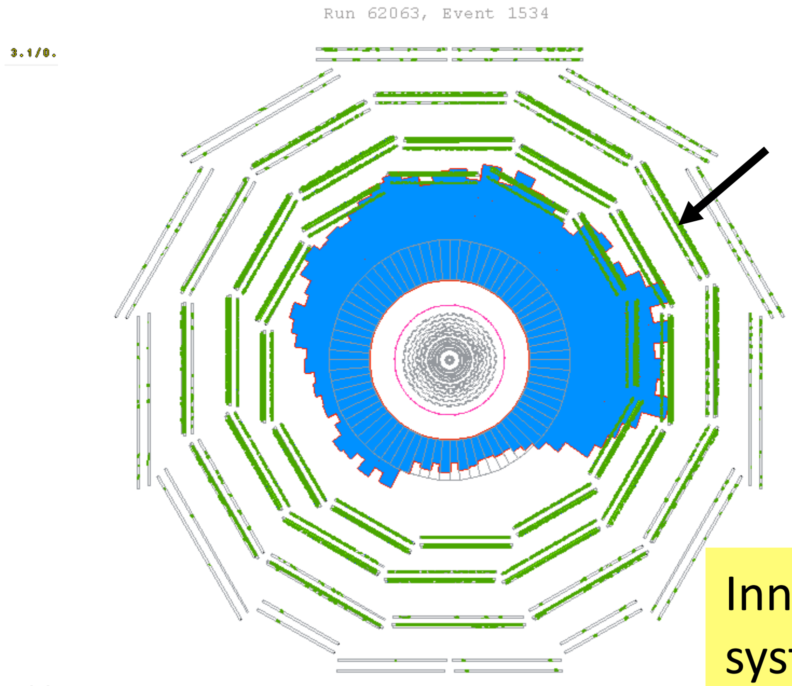
HCAL energy



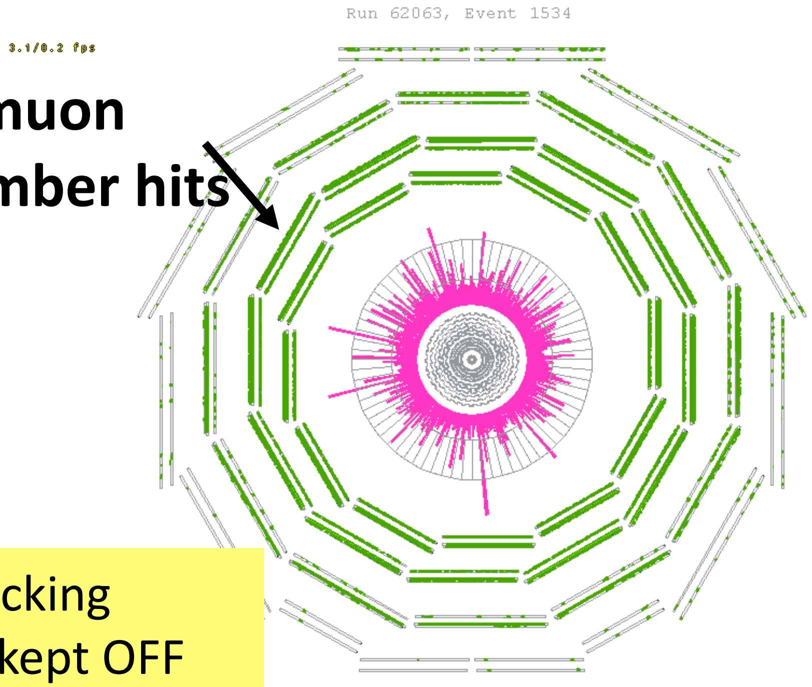
ECAL energy



debris



DT muon chamber hits

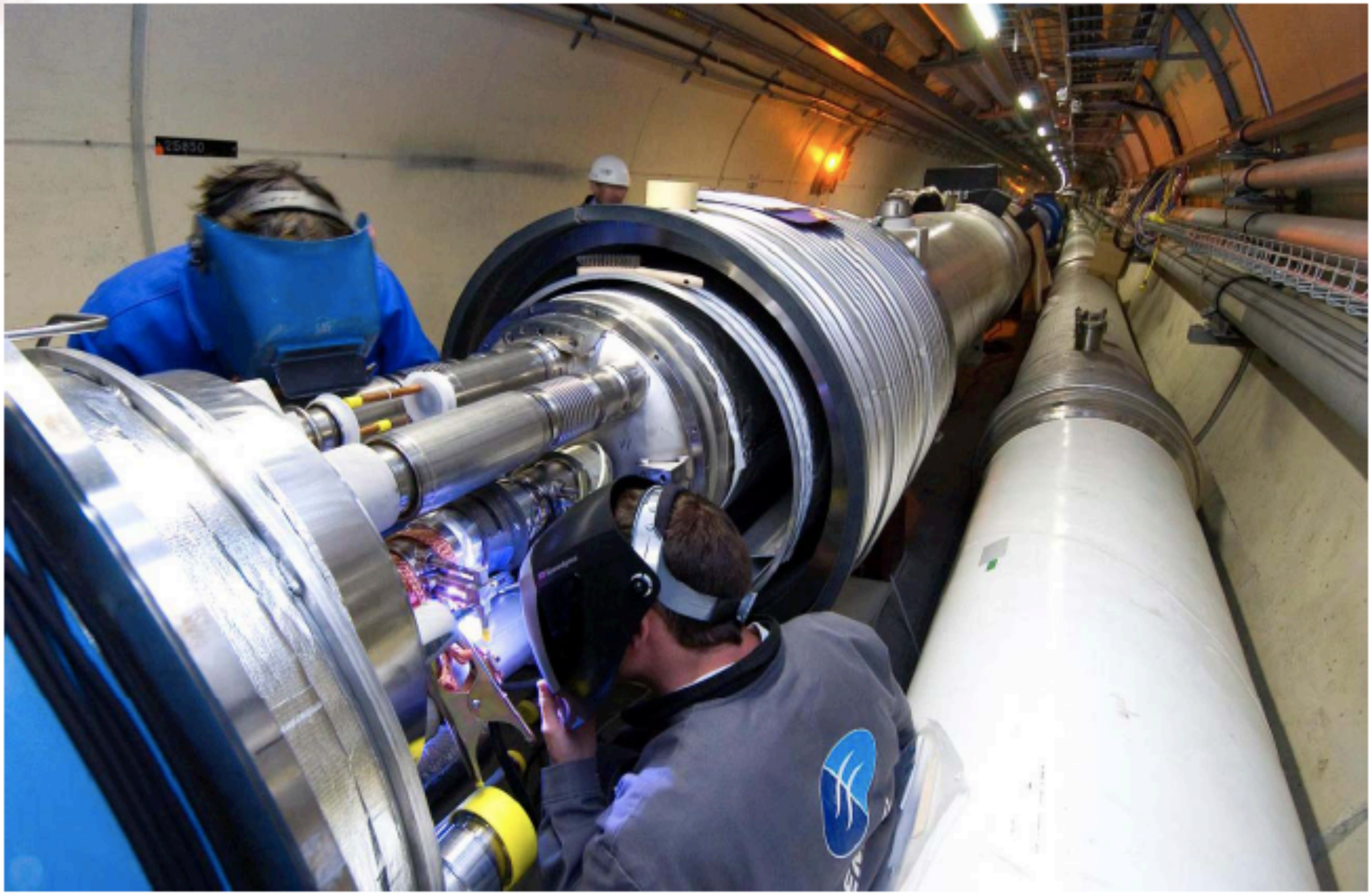


Inner tracking systems kept OFF

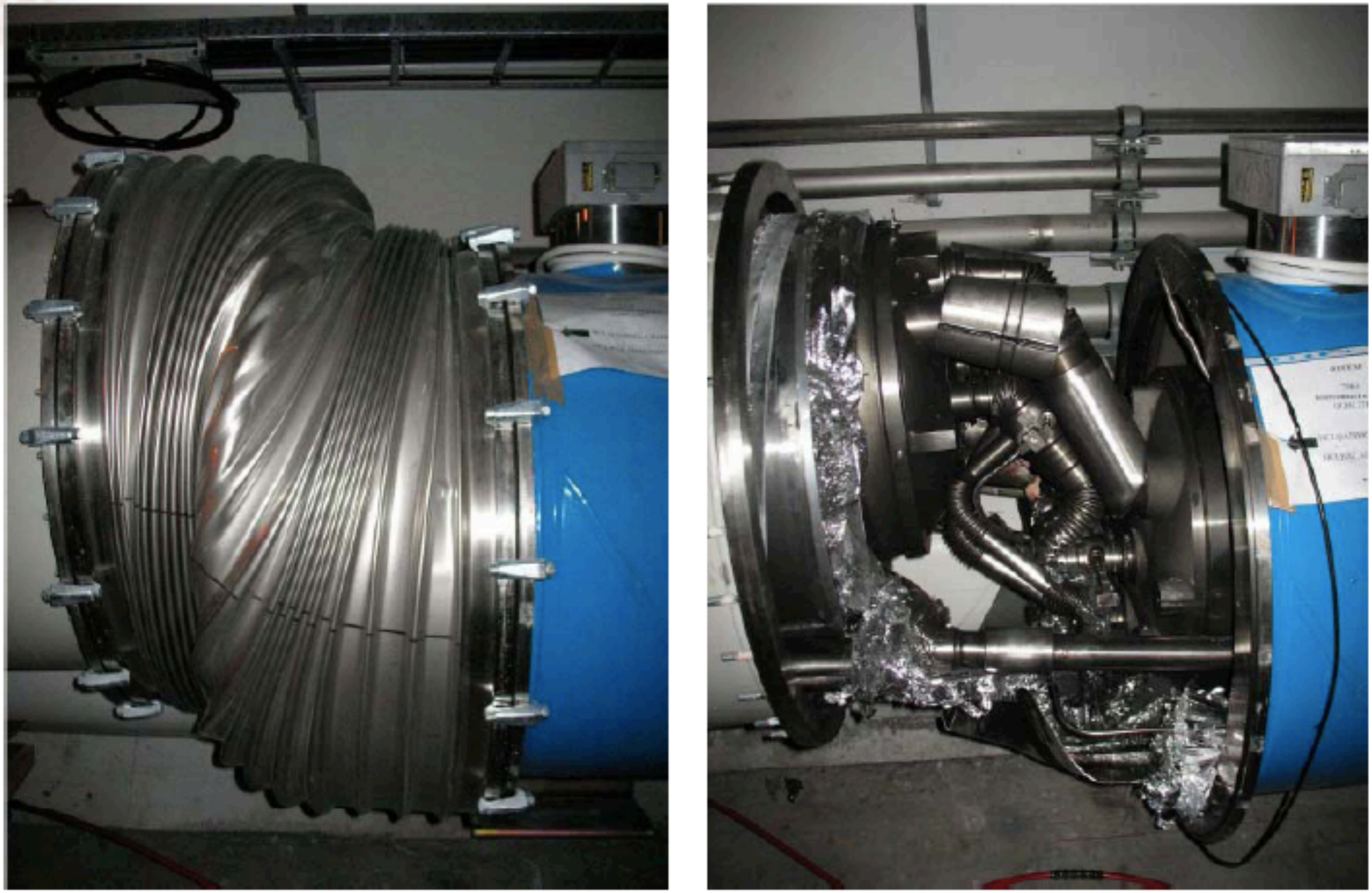
Possible Run plans

LHC Dipole
March, 2005

19th september incident



QQBI.27R3



Possible run scenarios

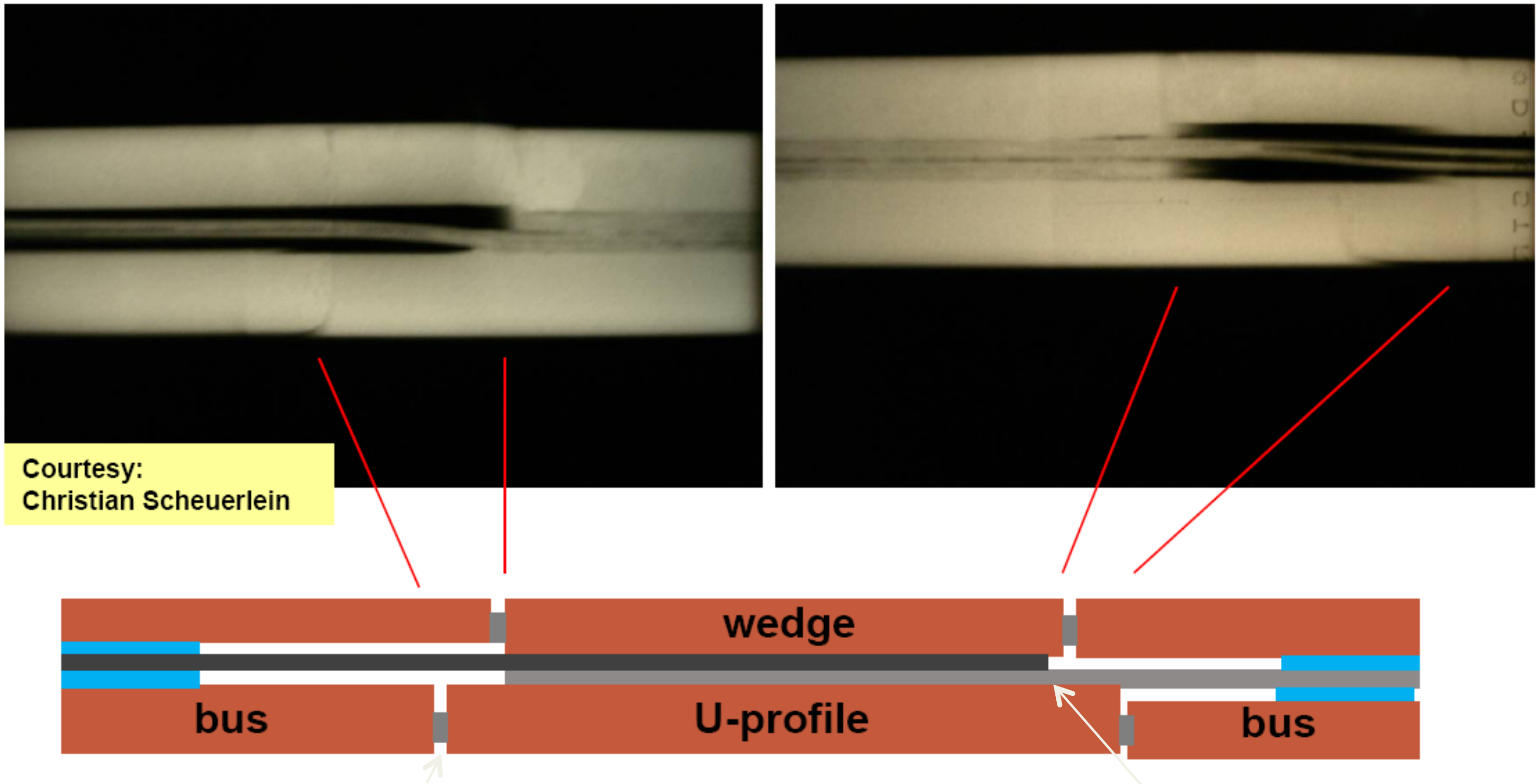
Slides from Mike Lamont from “CMS week in Bologna, 7-2 Sept. 2009

Stablizer problem

Bad surprise after gamma-ray imaging of the joints: Void is present in most of bus extremities because SnAg flew out during soldering of the joint

May limit to 3.5 TeV. Depends what the sectors that have not been measured warm look like.

Gamma rays QBBI.B25R3-M3 before disconnection (QRL connection & QRL lyra sides)



Courtesy: Christian Scheuerlein

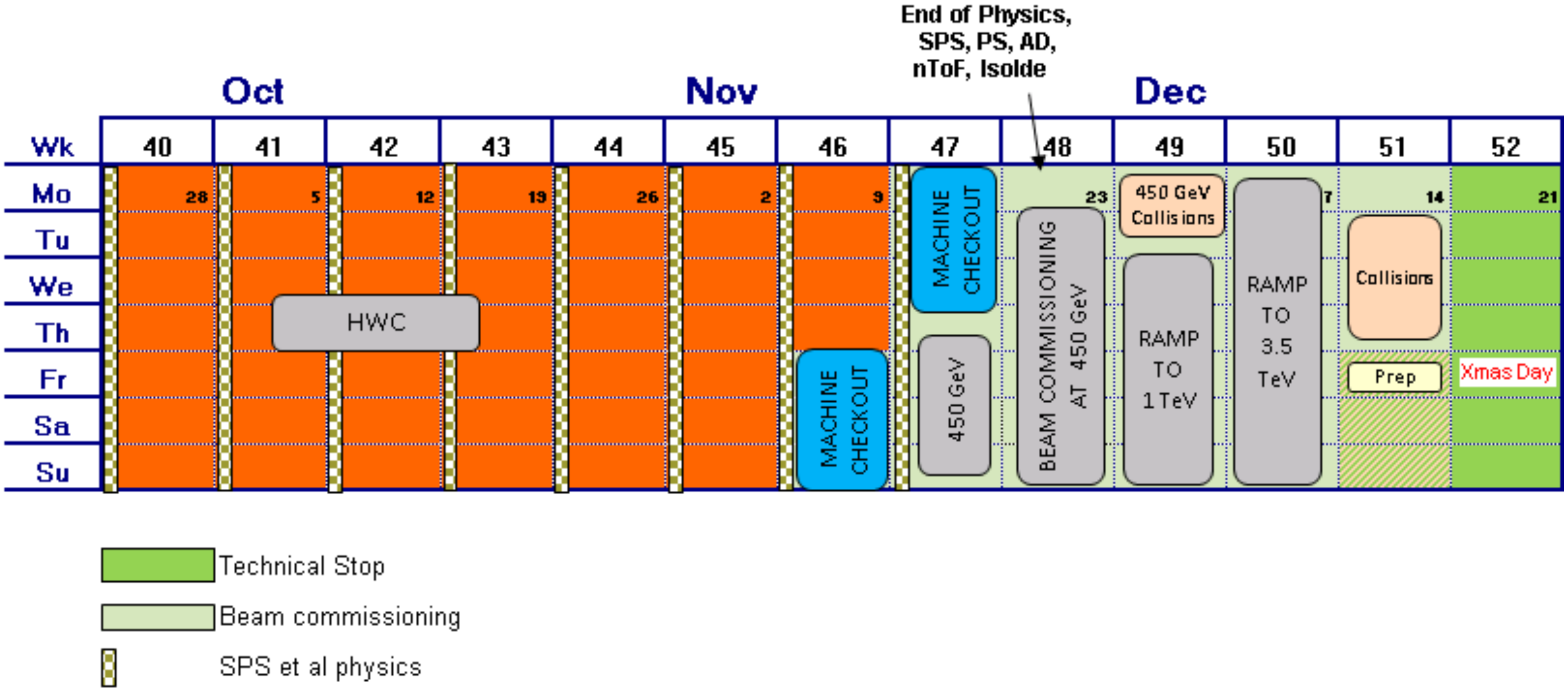
Bad electrical contact between wedge and U-profile with the bus on at least 1 side of the joint

Bad contact at joint with the U-profile and the wedge

Plugging in the numbers with a step in energy

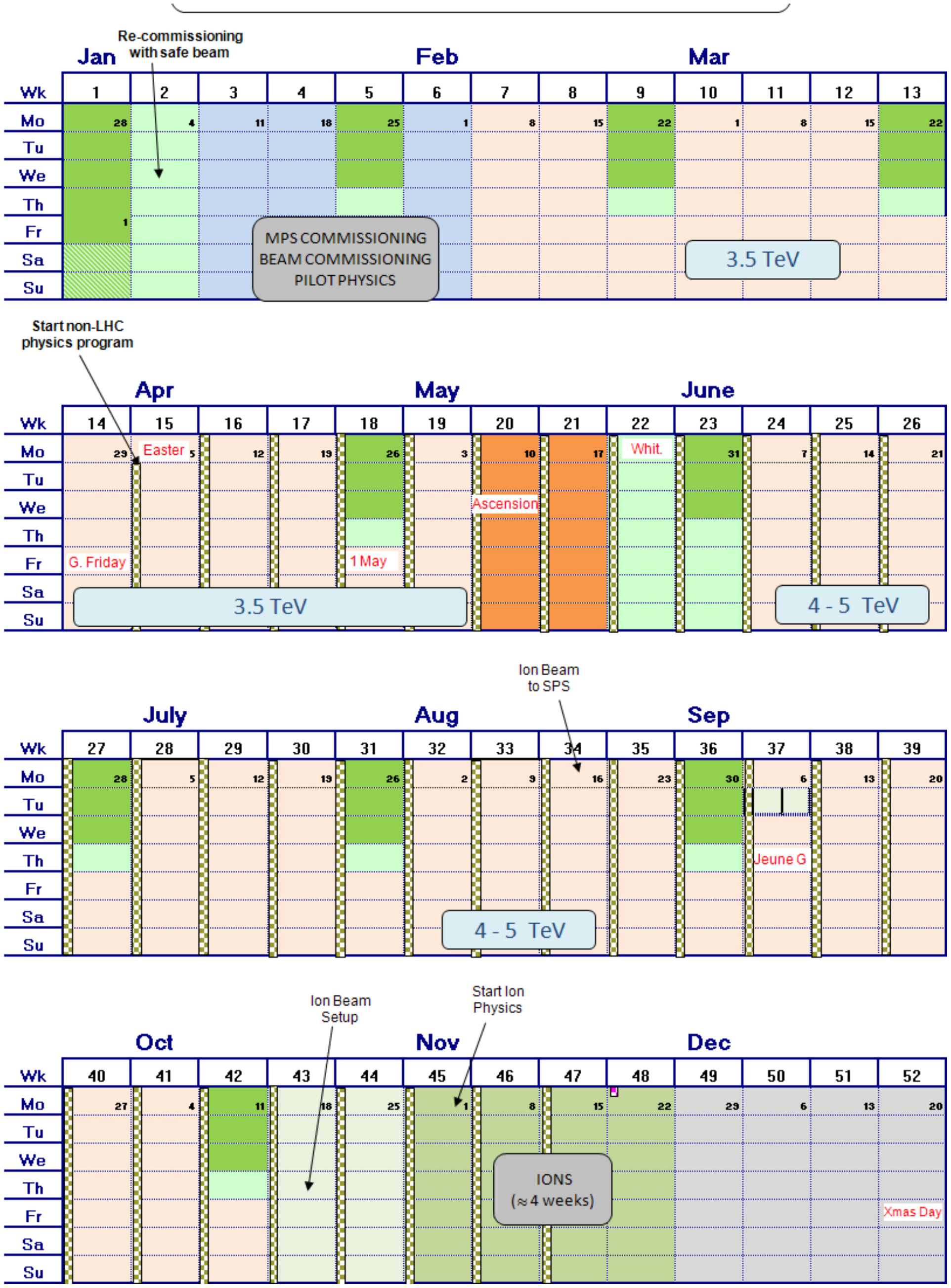
Month	OP scenario	Max number bunch	Protons per bunch	Min beta*	Peak Lumi	Integrated	% nominal
1	Beam commissioning						
2	Pilot physics combined with commissioning	43	3×10^{10}	4	8.6×10^{29}	~200 nb^{-1}	
3		43	5×10^{10}	4	2.4×10^{30}	~1 pb^{-1}	
4		156	5×10^{10}	2	1.7×10^{31}	~9 pb^{-1}	2.5
5a	No crossing angle	156	7×10^{10}	2	3.4×10^{31}	~18 pb^{-1}	3.4
5b	No crossing angle – pushing bunch intensity	156	1×10^{11}	2	6.9×10^{31}	~36 pb^{-1}	4.8
6	Shift to higher energy: approx 4 weeks	Would aim for physics without crossing angle in the first instance with a gentle ramp back up in intensity					
7	4 – 5 TeV (5 TeV luminosity numbers quoted)	156	7×10^{10}	2	4.9×10^{31}	~26 pb^{-1}	3.4
8	50 ns – nominal Xing angle	144	7×10^{10}	2	4.4×10^{31}	~23 pb^{-1}	3.1
9	50 ns	288	7×10^{10}	2	8.8×10^{31}	~46 pb^{-1}	6.2
10	50 ns	432	7×10^{10}	2	1.3×10^{32}	~69 pb^{-1}	9.4
11	50 ns	432	9×10^{10}	2	2.1×10^{32}	~110 pb^{-1}	12

LHC 2009



- All dates approximate…
- Reasonable machine availability assumed
- Stop LHC with beam ~19th December 2009, restart ~ 4th January 2010

LHC 2010 – very draft

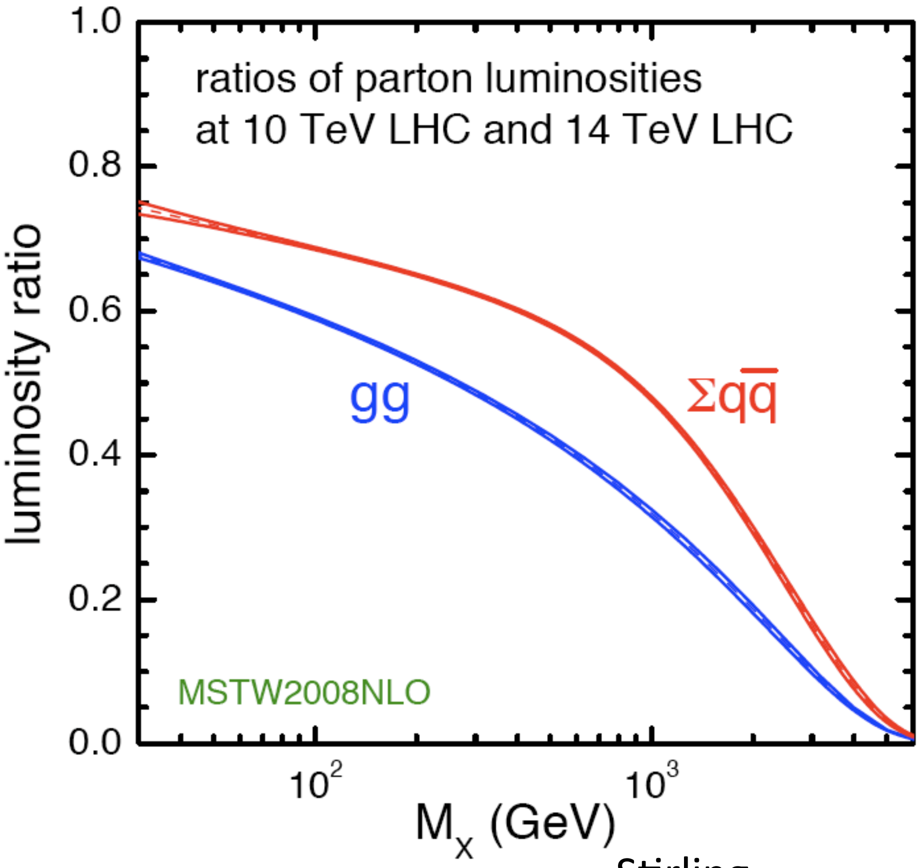


- **2009**:
  - 1 month commissioning
- **2010**:
  - 1 month pilot & commissioning
  - 3 month 3.5 TeV
  - 1 month step-up
  - 5 month 4 - 5 TeV
  - 1 month ions

10 vs 14 TeV

Unfortunately, most reach studies done so far are at 14 TeV (CMS has not yet done any at 7 TeV)

ratio of parton luminosities plots



Stirling

gg of course down more than qq

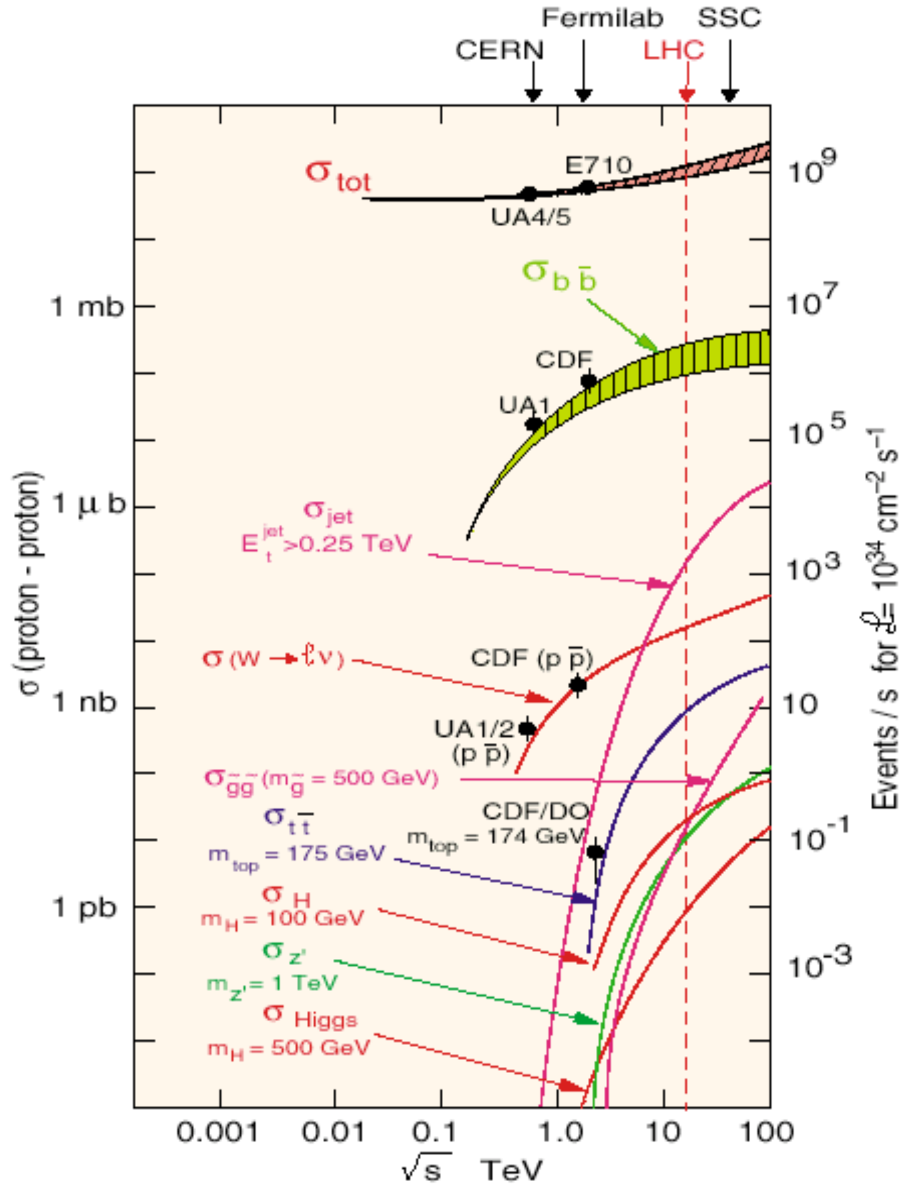
Searching for the Unknown

Concentrate on backgrounds, since don’t really know what your signal will be.

You have to know your Standard Model processes well.

Use your standard model processes to understand your detector.

Lots of Backgrounds



Most of the backgrounds can be made small by requiring an isolated e or mu, or large MET, in the final state. (apologies for neglecting taus in all these talks)

(However, there can be large uncertainties on the remaining "QCD" background. In general, the simulation can not reliably predict these backgrounds because

- fake rates from MC are generally good to within a factor 2 at best
- tails of MET distribution even less reliable
- need higher order QCD calculations for kinematics, which are not (all) available
- due to the small fake rate, would need huge MC samples to do this

Data-based background methods are required.)

Cross sections

After lepton or large MET requirement, main backgrounds tend to be top, W, Z, dibosons

process	order	14 TeV (pb)	10 TeV (pb)	reference
ttbar	NLO+NLL	910	430	arXiv: 0804.2800
Single top	NLO	320	160	
W->eν or μν	NNLO	22000	15000	arXiv:0901.0002
Z	NNLO	2000	1400	arXiv:0901.0002
WW	NLO	112	1	
WZ		48		
ZZ		15		

Also see arXiv:hep-ph/0611148

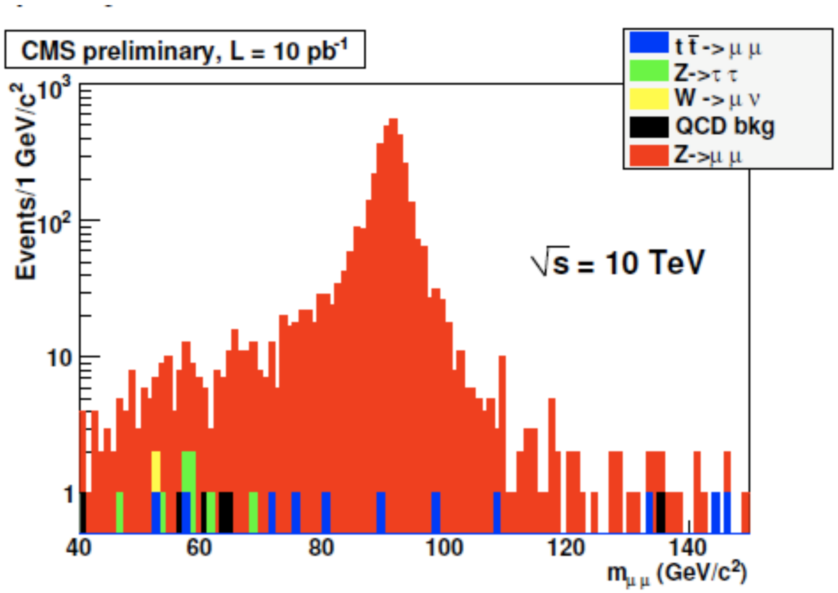
Z

Cross section is lower than dijets and W, but it's a very very clean channel that allows full kinematic reconstruction with low systematic errors.

- peak position can be used to check/set EM calorimeter and tracking energy scale
- width of peak can be used to check/set resolutions
- rate of double tags can be used to estimate lepton identification efficiencies
- theory errors on cross section a few percent -> can be used to check/calibrate luminosity
- balance between Z transverse momentum can be used to understand jet energy scale, resolutions, MET resolution.
- can be used to understand vector boson plus jet production and other vector boson backgrounds to searches (discuss when I discuss susy searches)
- usually not a significant background to searches
- PROBLEM: low cross section compared to the processes you use it to study

In 300 pb-1 at 10 TeV, expect 420,000 produced per lepton flavor
With typical acceptances of 40%, we expect O(150k) events/lepton flavor
Z samples from Tevatron currently at: 50k/fb-1 (with roughly 6 fb-1 on tape->300k/flavor)

Very low backgrounds



14 TeV

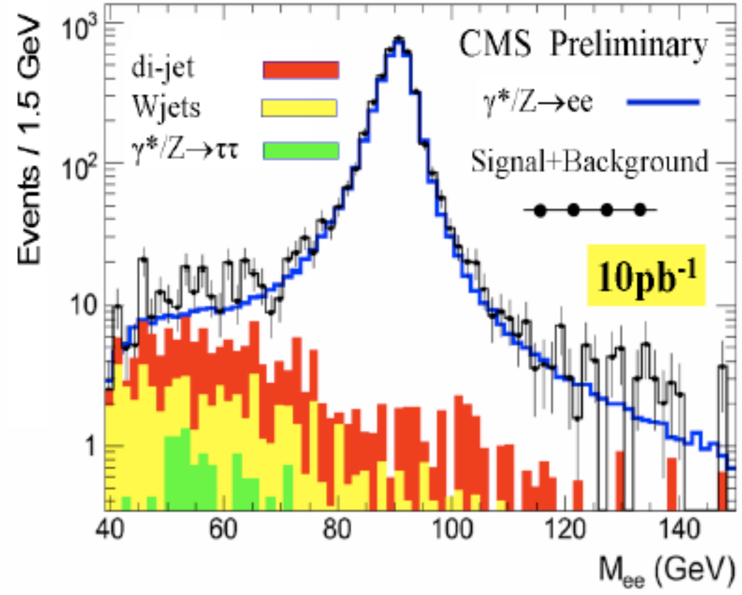
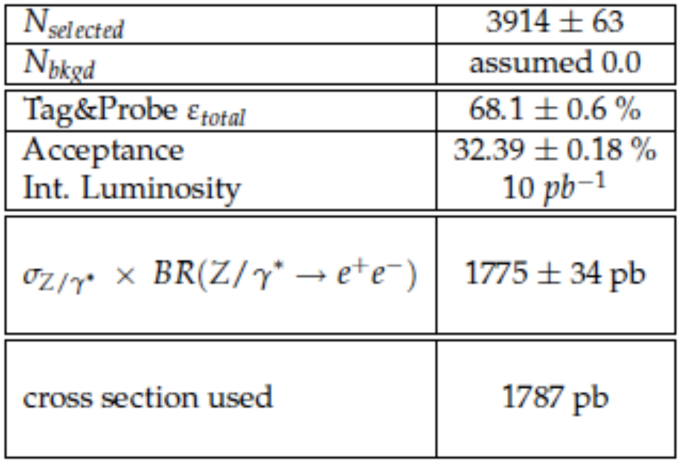


Table 3: Results for the $\gamma^*/Z \to e^+e^-$ cross section measureme

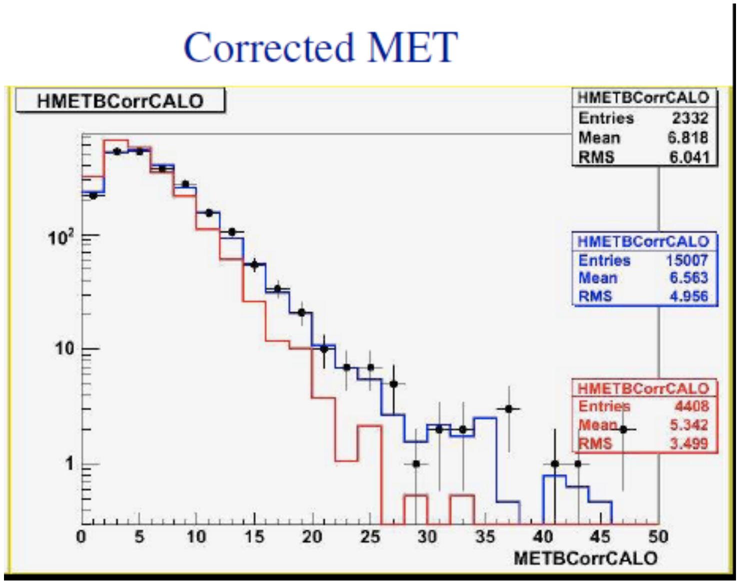


$N_{selected}$	3914 ± 63
N_{bkgd}	assumed 0.0
Tag&Probe ε_{total}	68.1 ± 0.6 %
Acceptance	32.39 ± 0.18 %
Int. Luminosity	$10\ pb^{-1}$
$\sigma_{Z/\gamma^*} \times BR(Z/\gamma^* \to e^+e^-)$	1775 ± 34 pb
cross section used	1787 pb

CMS estimate for 14 TeV, 10 pb^{-1}

MET resolution

D0



Zee MC versus data with and without d0raw2sim: Dzero

W

In 300 pb-1 at 10 TeV, expect 4,200,000 produced per lepton flavor
With typical acceptances of 40%, we expect O(1.5M) events/lepton flavor

Need to understand well, since a copious source of events with leptons and MET
Luckily, cross section grows slower with root(s) than top cross section (another great calibration source)

Can be a good calibration source once understood

Challenges
- pp is not ppbar (true for Z as well)
- larger backgrounds (for top, for example), more difficult to understand
- two solutions for p_Z of neutrino (and louzy resolution, especially at high <n>)

W+ vs W-

More u’s than d’s in proton so W+ cross section is bigger

arXiv:0901.0002v1

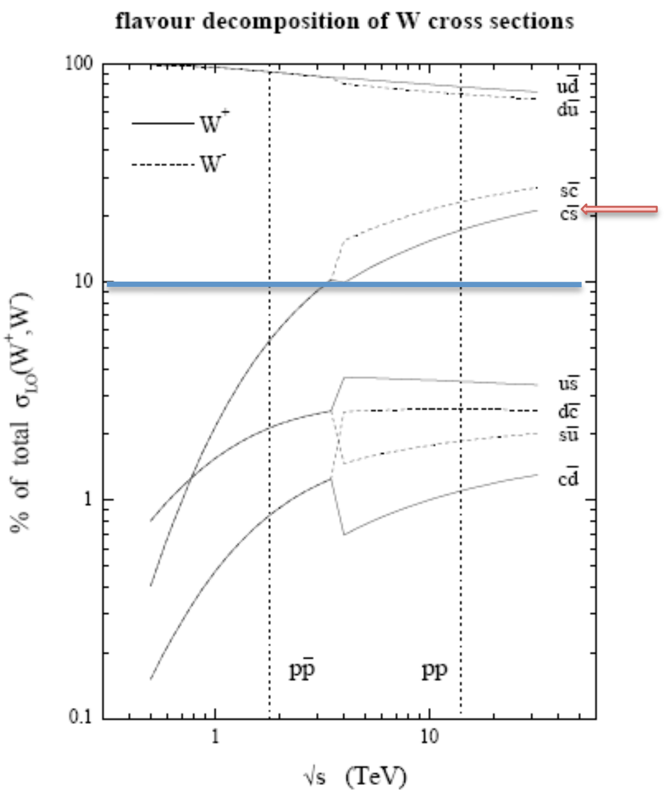


Figure 5: Parton decomposition of the W^+ (solid line) and W^- (dashed line) total cross sections in $p\bar{p}$ and pp collisions. Individual contributions are shown as a percentage of the total cross section in each case. In $p\bar{p}$ collisions the decomposition is the same for W^+ and W^-.

Hep-ph/9907231

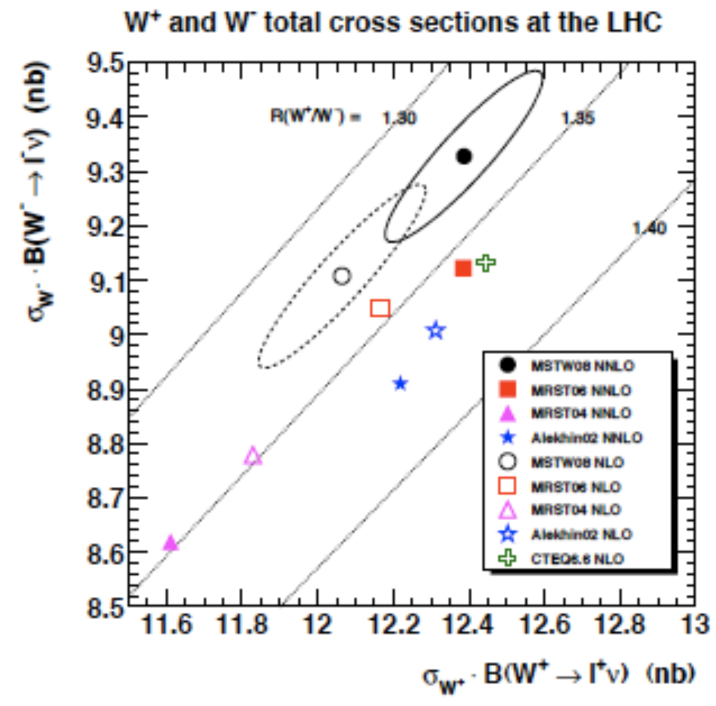
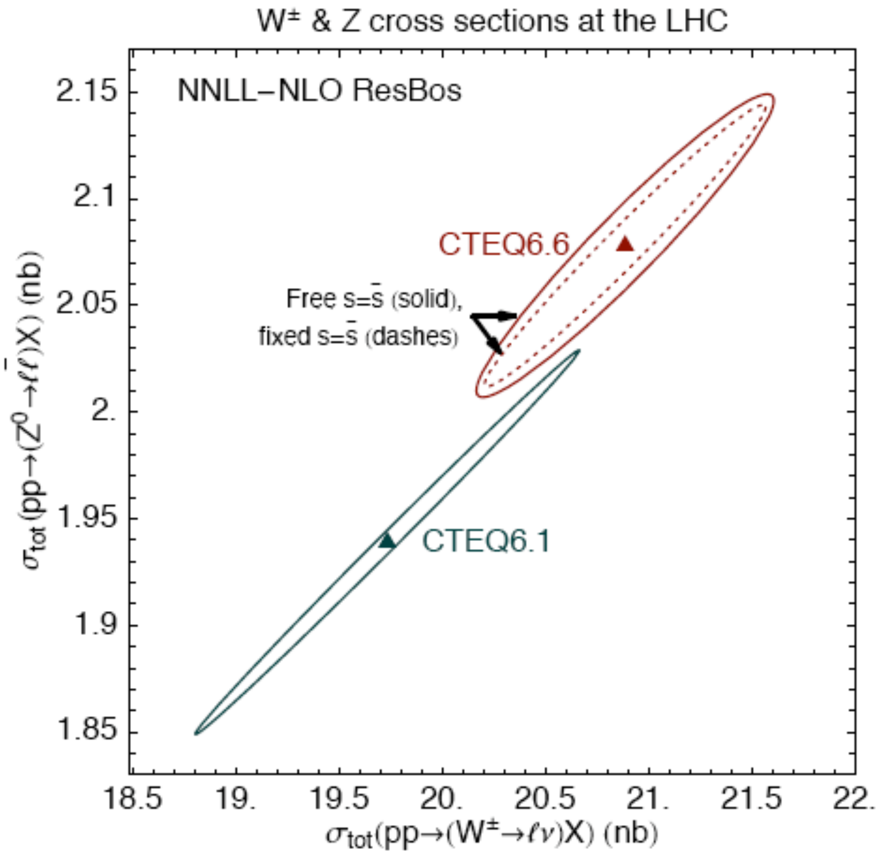


Figure 68: W^+ and W^- total cross sections at the LHC. The error ellipses, calculated using the one-sigma error sets, are shown for the MSTW 2008 NLO and NNLO PDFs.

Mrst 2004/2008 has better treatment of c,b quarks.
Cteq has more glu at low x. Alekhin has small s.

Heavy quarks in proton



Note importance of strange quark uncertainty for ratio

Figure 8: W & Z correlation ellipses at the LHC obtained in the fits with free and fixed strangeness.

W+ vs W-: TeVatron and LHC

arXiv:0812.2571

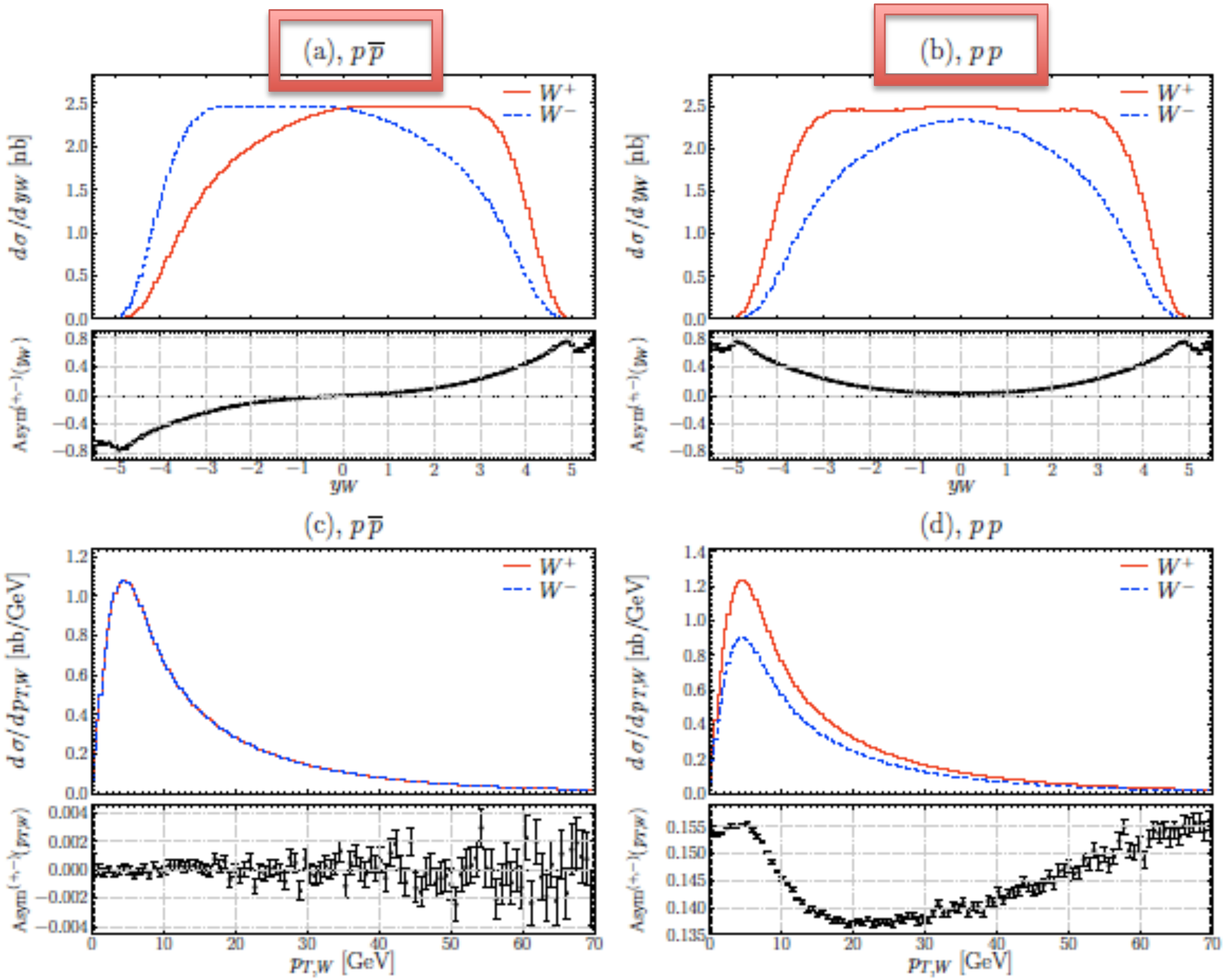
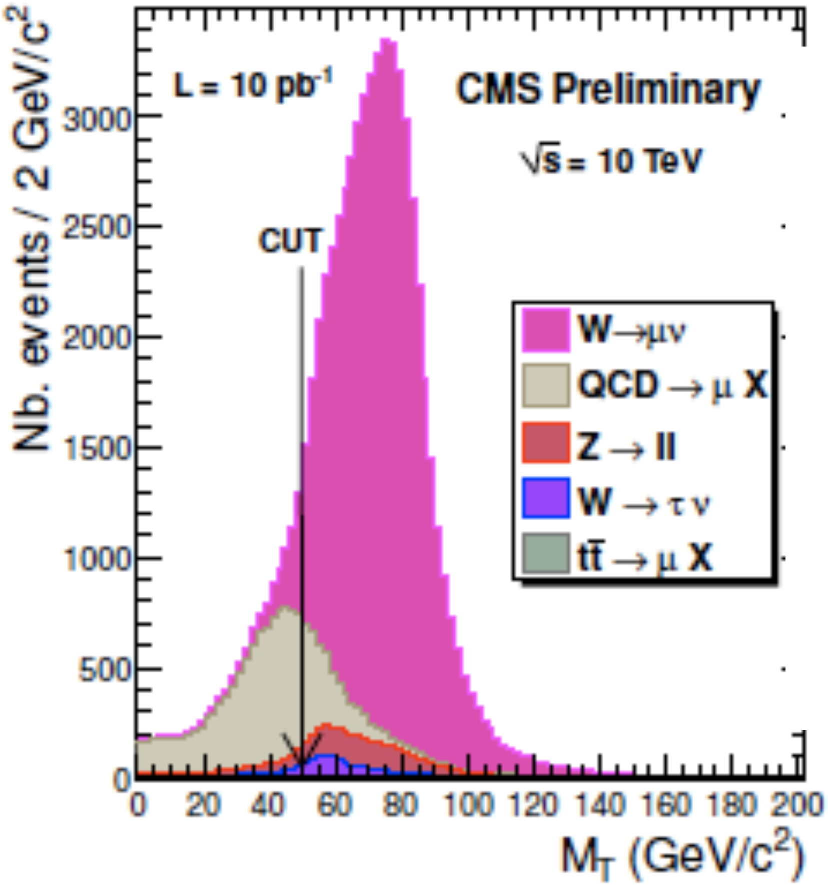


Figure 1: The rapidity y_W and transverse momentum $p_{T,W}$ distributions of the W-bosons and their charge asymmetries for the $p\bar{p}$ (a, c) and pp (b, d) collisions.

Inclusive W's

How big will the backgrounds be?

Note: not log scale



14 TeV

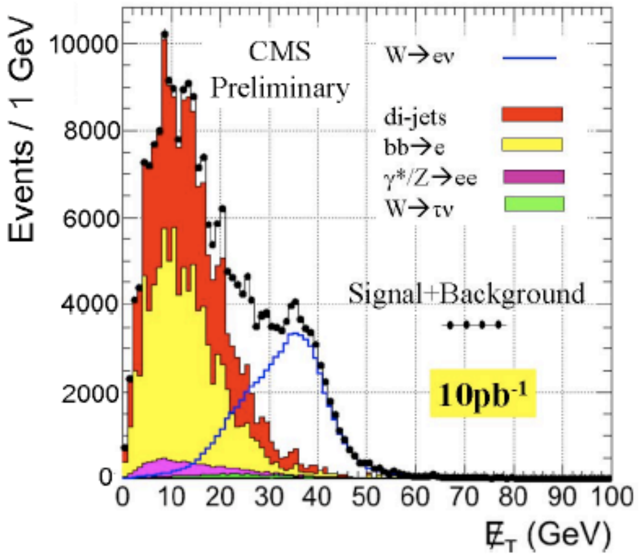


Figure 1: The $\not{E}_T$ distribution for the $W \rightarrow e\nu$ signal together with the considered backgrounds after selection cuts applied for 10 pb^{-1} of integrated luminosity.

Ouch!

Inclusive W's

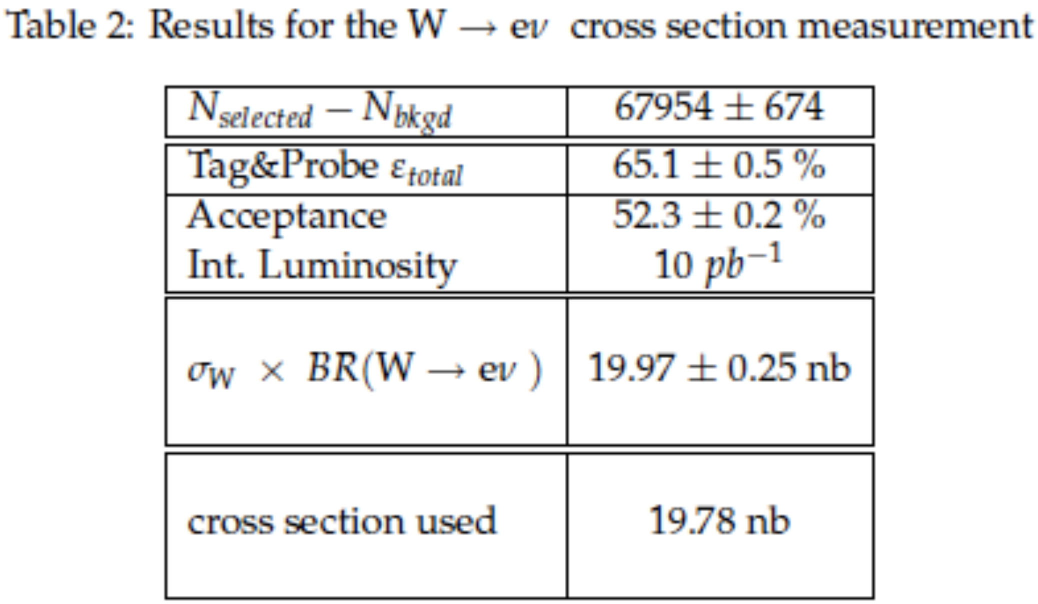
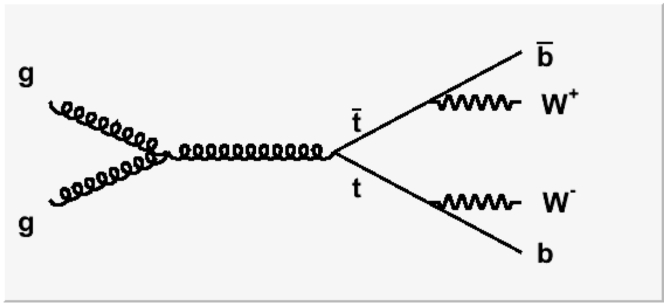


Table 2: Results for the $W \rightarrow e\nu$ cross section measurement

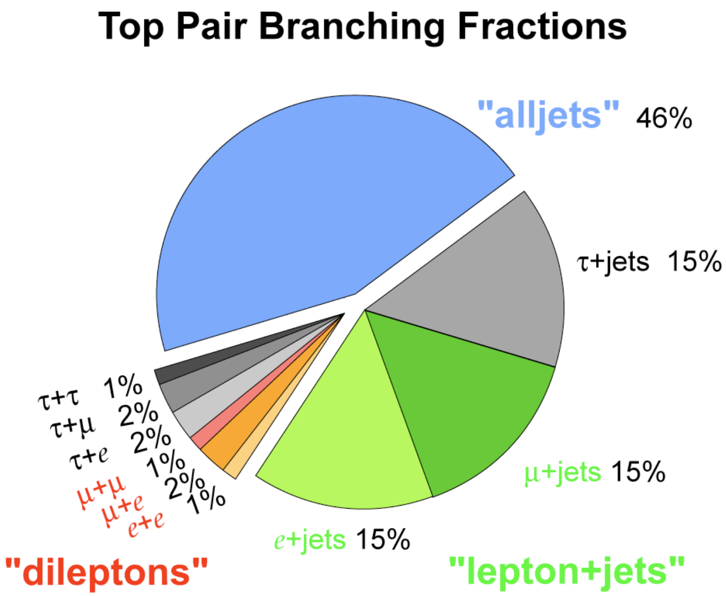
$N_{selected} - N_{bkgd}$	67954 ± 674
Tag&Probe ε_{total}	65.1 ± 0.5 %
Acceptance	52.3 ± 0.2 %
Int. Luminosity	10 pb^{-1}
$\sigma_W \times BR(W \rightarrow e\nu)$	19.97 ± 0.25 nb
cross section used	19.78 nb

10 TeV, 10 pb^{-1}

top



Not just a candle, a candelabra (Ken Bloom, Nebraska)
- hadronic W’s -> jet energy scale
- b tagging efficiency
- b jet energy scale
- consistency over many channels gives strong constraint (dilepton, single lepton, all hadronic, with/without b tags)
- important background to many searches

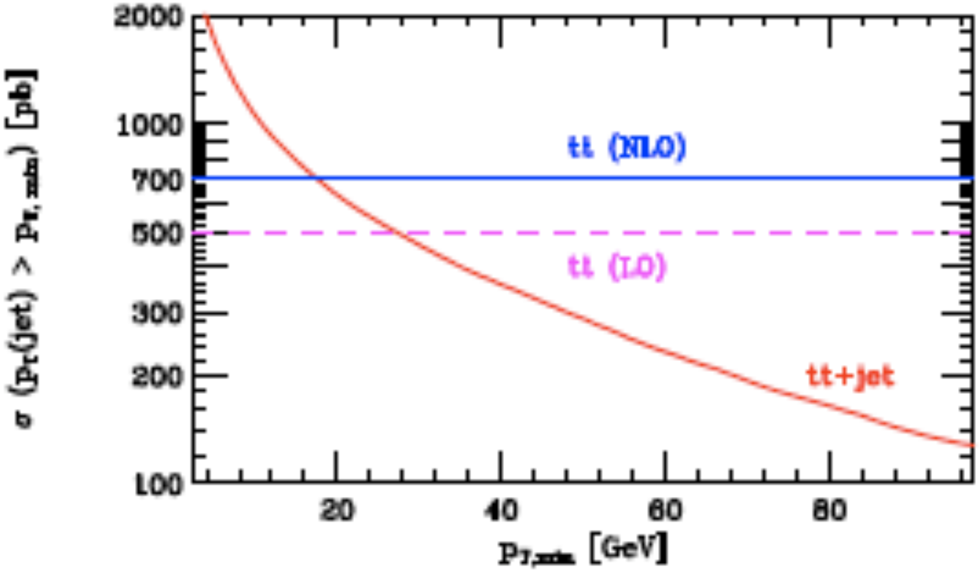


Efficiency* acceptance O(20%) in leptonic channels
Expect 17K l+jets and 2k ll+jets (l=e,mu)

top

Challenges

- as with the W, in channels with leptons, reconstruction not trivial
- its jetty at the LHC



(J. Huston, Acta Physica Polonica B, 38, 2279)

Top dileptons

Even so, a relatively clean signal

No b tagging
10 pb^{-1}
14 TeV
CMS

2 iso l $P_T > 20$
2 jets $P_T > 30$
$\left|M_{ee,\mu\mu} - M_Z\right| > 15$
$MET > 30$
$MET > 0.6\left|\vec{P}_T^{ll}\right|$ or MET not along -$\vec{P}_T^{ll}$

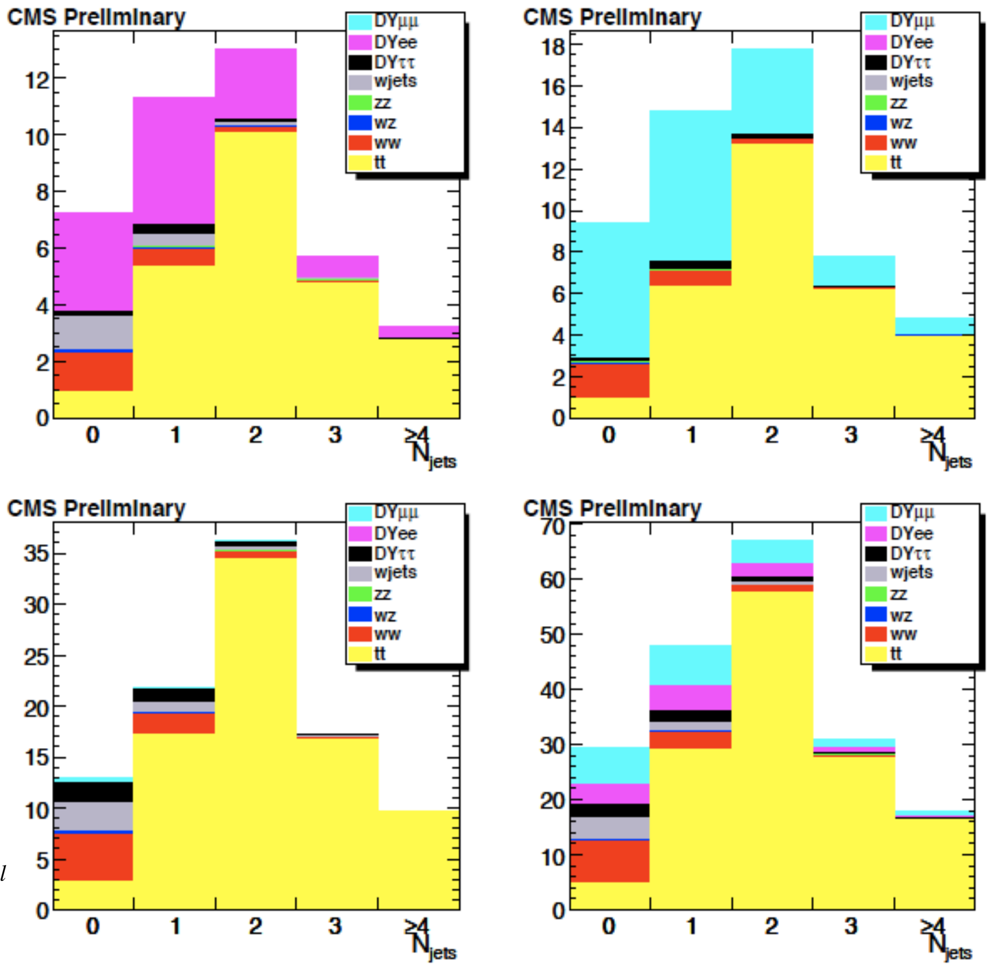
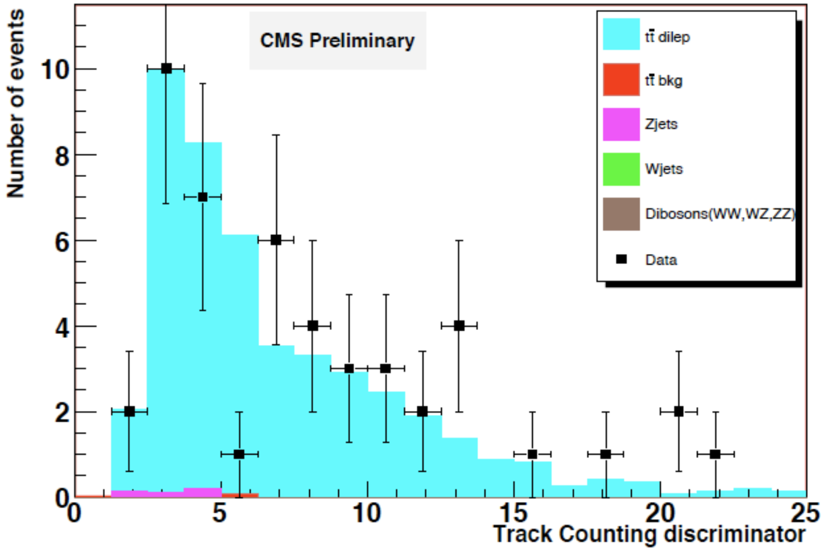
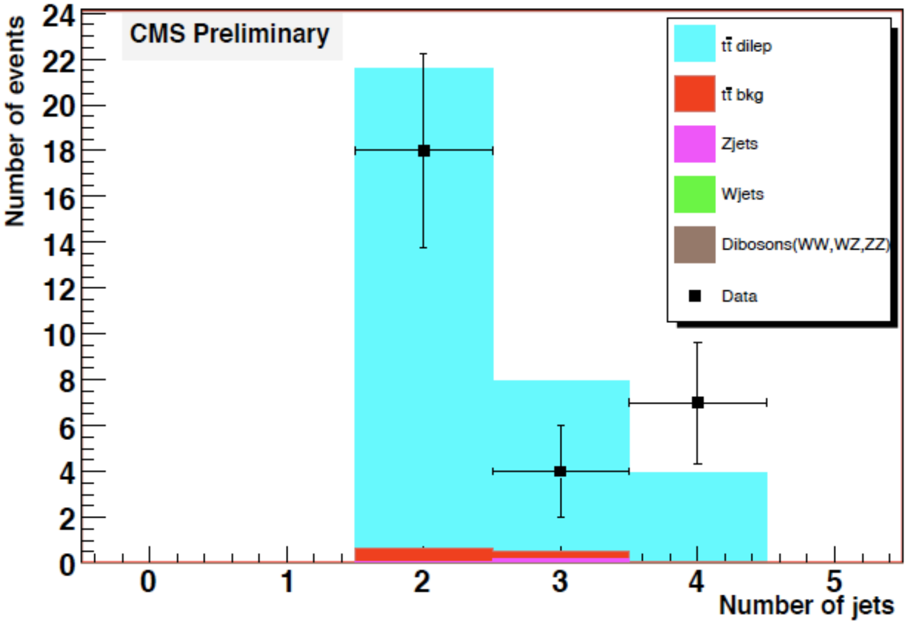


Figure 2: The expected number of dilepton events in 10 pb^{-1} as a function of jet multiplicity in *ee* (top left), $\mu\mu$ (top right), $e\mu$ (bottom left), and all channels combined (bottom right). The figures show contributions from $t\bar{t}$ (yellow), *WW* (red), *WZ* (dark blue), *ZZ* (green), *W*+jets (gray), DY→ $\tau\tau$ (black), DY→ *ee* (magenta), and DY→ $\mu\mu$ (cyan).

Add b tagging

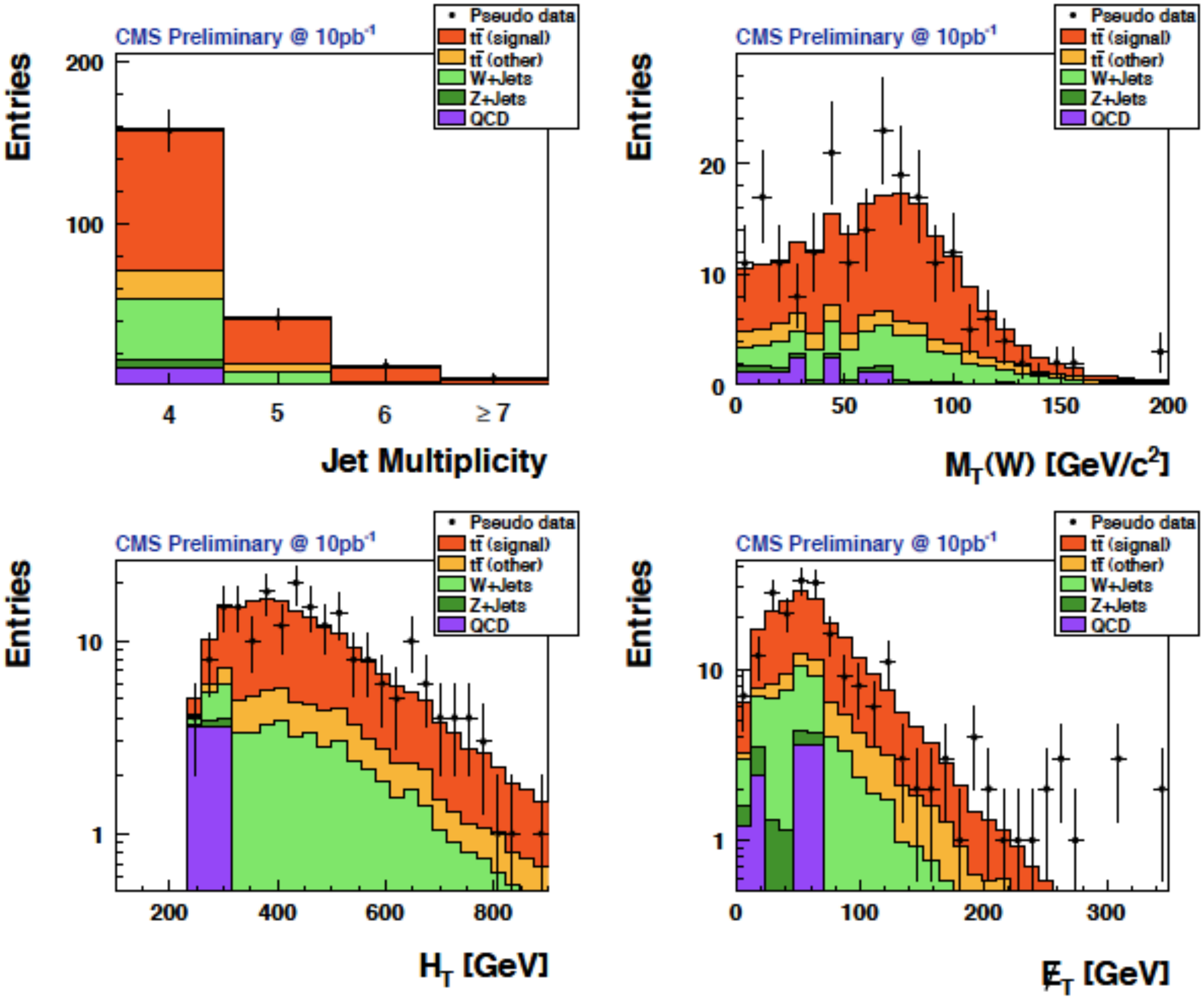


100 pb-1



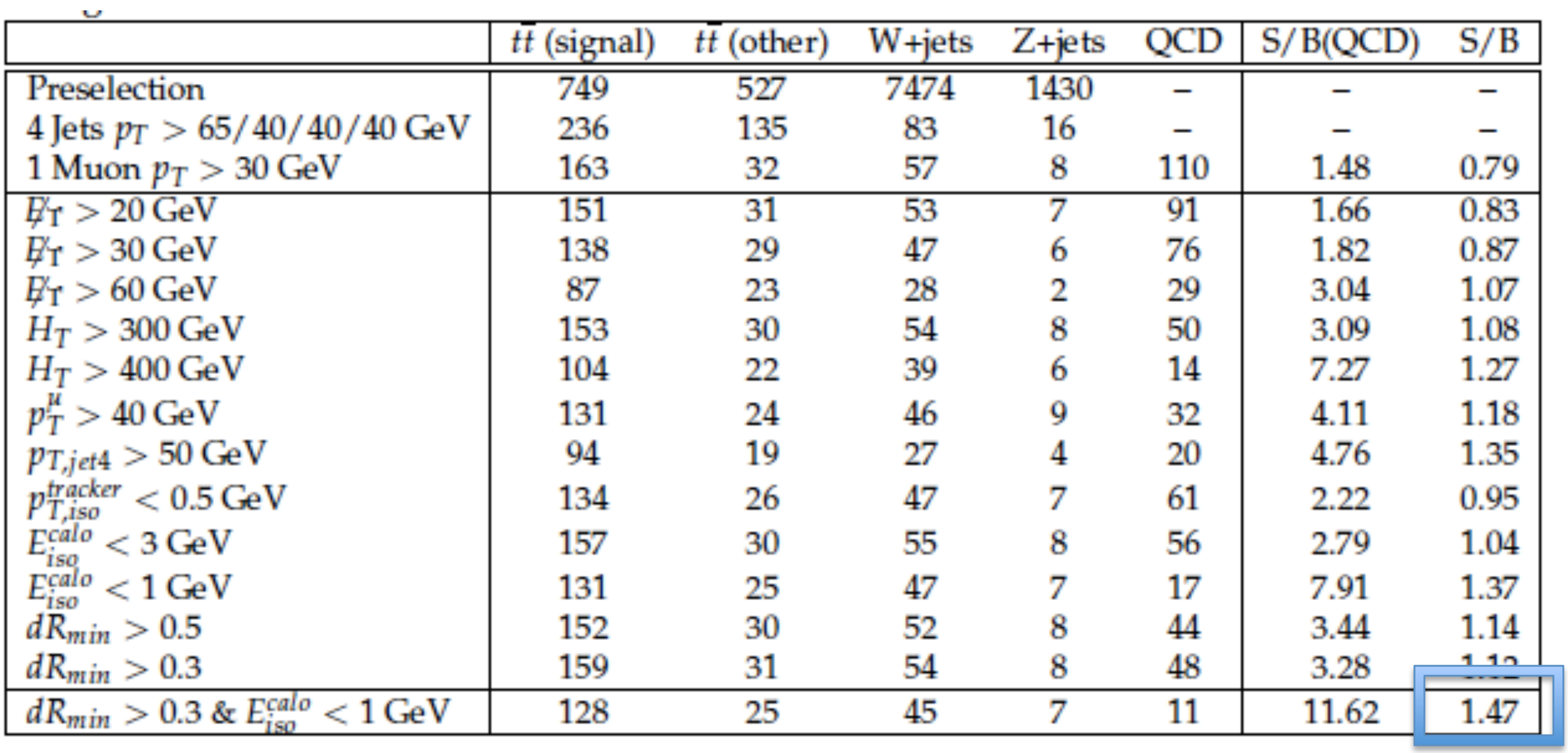
Single Leptons

mu
10 pb-1
No b tagging
tight selection



semi-leptonic top

cms top-08-005



	$t\bar{t}$ (signal)	$t\bar{t}$ (other)	W+jets	Z+jets	QCD	S/B(QCD)	S/B
Preselection	749	527	7474	1430	–	–	–
4 Jets $p_T > 65/40/40/40$ GeV	236	135	83	16	–	–	–
1 Muon $p_T > 30$ GeV	163	32	57	8	110	1.48	0.79
$\not{E}_T > 20$ GeV	151	31	53	7	91	1.66	0.83
$\not{E}_T > 30$ GeV	138	29	47	6	76	1.82	0.87
$\not{E}_T > 60$ GeV	87	23	28	2	29	3.04	1.07
$H_T > 300$ GeV	153	30	54	8	50	3.09	1.08
$H_T > 400$ GeV	104	22	39	6	14	7.27	1.27
$p_T^\mu > 40$ GeV	131	24	46	9	32	4.11	1.18
$p_{T,jet4} > 50$ GeV	94	19	27	4	20	4.76	1.35
$p_{T,iso}^{tracker} < 0.5$ GeV	134	26	47	7	61	2.22	0.95
$E_{iso}^{calo} < 3$ GeV	157	30	55	8	56	2.79	1.04
$E_{iso}^{calo} < 1$ GeV	131	25	47	7	17	7.91	1.37
$dR_{min} > 0.5$	152	30	52	8	44	3.44	1.14
$dR_{min} > 0.3$	159	31	54	8	48	3.28	1.12
$dR_{min} > 0.3$ & $E_{iso}^{calo} < 1$ GeV	128	25	45	7	11	11.62	1.47

top event properties

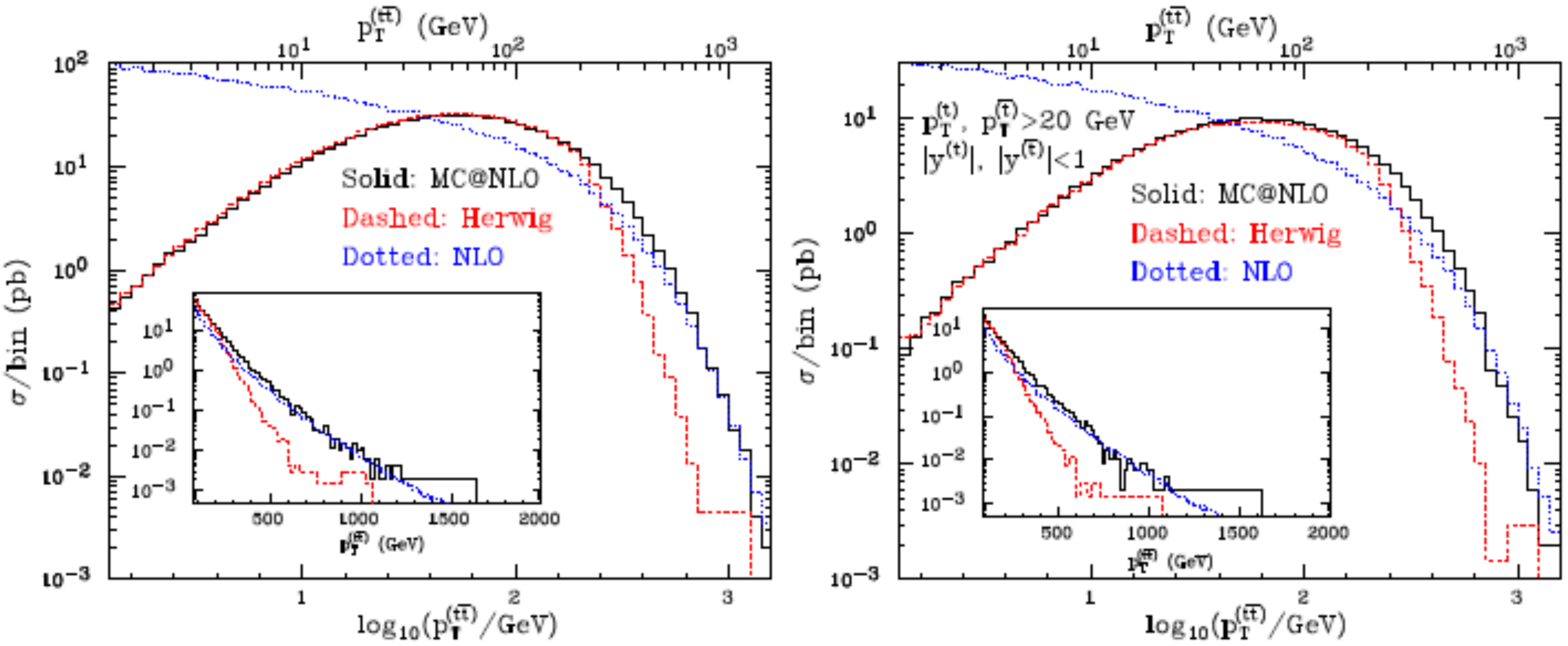


Figure 8: As in fig. 7, for the transverse momentum of the $t\bar{t}$ pair, without (left panel) and with (right panel) acceptance cuts.

Herwig is parton shower
MC@NLO matches NLO and PS

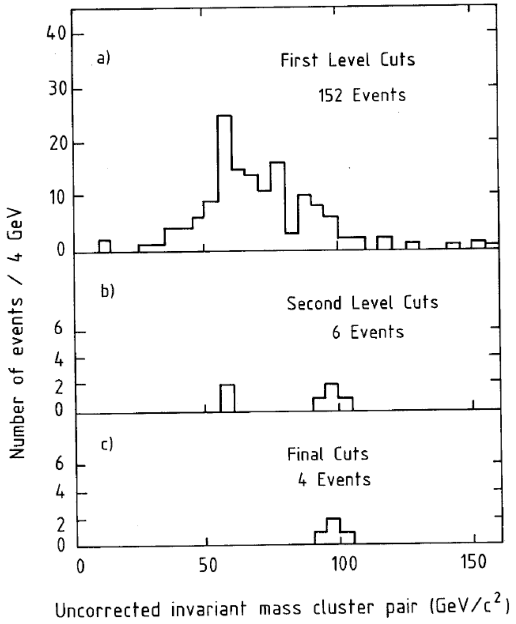
Frixione, Nason, Webber, hep-ph/0305252

Bumps

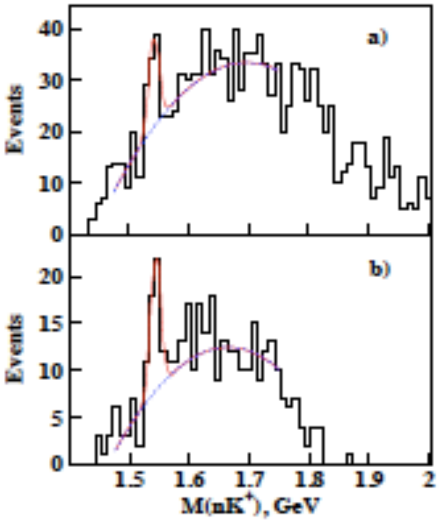
Bump hunting is one of the easiest kinds of searches to do. Low background bump hunting is even easier.

They provide fool-proof discovery

Discovery of the Z



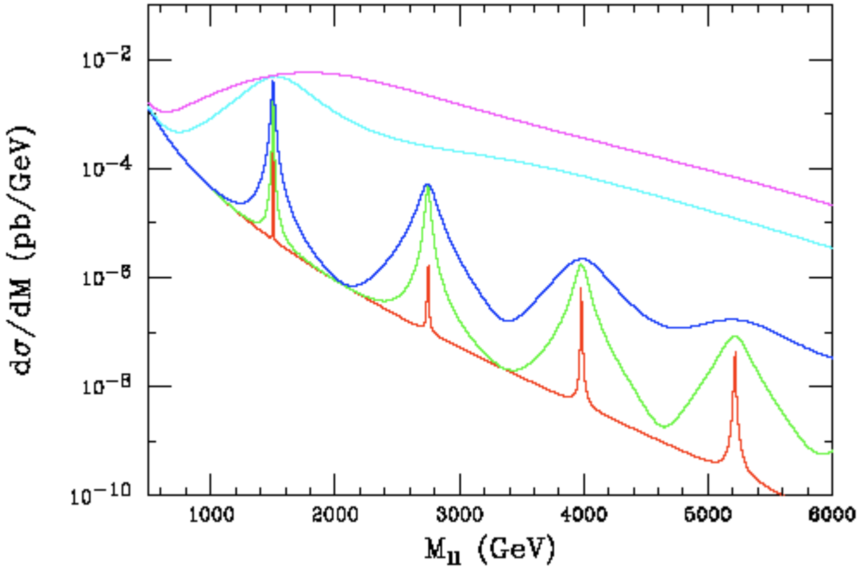
Or do they?

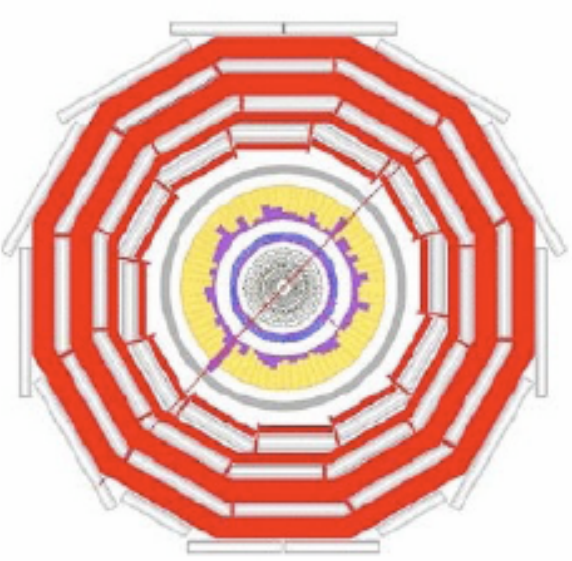


One of several "Discoveries" of the pentaquark

Heavy Bosons to ee, μμ

Predicted in many theories: TeV^{-1} ED, RS ED, little higgs, L-R symmetric, etc.





Main background is DY production. Smoothly and quickly falling with mass.

Extra Dimensions in a few slides

Original motivation: Solve the problem of why the planck scale and the electroweak scale are so different. We know the Planck scale comes from looking at Newton's Law

$$\left|\vec{F}\right| = G_N \frac{m_1 m_2}{R^2} \qquad M_{planck} = 1/\sqrt{G_N} = 1.2x10^{16}\,TeV$$

If there were more than 3 spatial dimension), especially some rolled up ones too small for us to see (and only gravity operated in the extra ones) , this would become

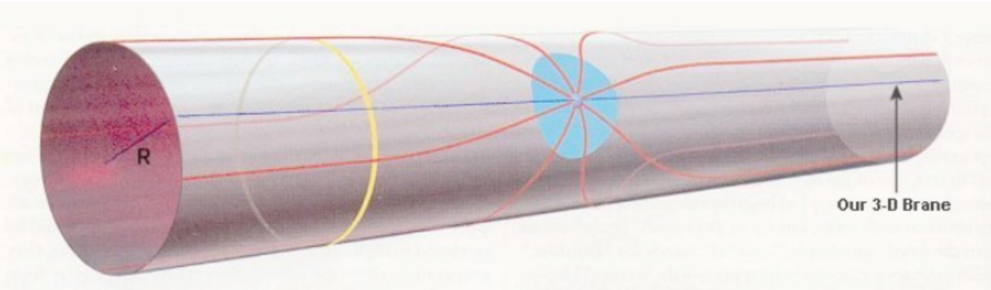
$$\left(M\right)^2_{planck} = M_*^{2+n} R^n$$

"ADD"
"large extra dimensions"

Adjust R and n so that M* can be the EWK scale (1 TeV)

$$R = 10^{\frac{30}{n}-17}\left(\frac{1TeV}{m*}\right)^{1+\frac{2}{n}}$$

n=1->10^{13} cm. Ruled out
1mm n=2



SMALL EXTRA DIMENSION wrapped in a circle (*circumference of tube*) modifies how gravity (*red lines*) spreads in space. At distances smaller than the circle radius (*blue patch*), the lines of force spread apart rapidly through all the dimensions. At much larger distances (*yellow circle*), the lines have filled the extra dimension, which has no further effect on the lines of force.

ADD

Particles in the wrapped-up extra dimensions act like particle in box from undergrad QM. Massless ground state is the standard 4d graviton : tower of (massive) states. Sum of the tower of gravitons with effective coupling ($1/M^{*2}$)

- give reasonable bremsstrahlung cross section
- can also have appreciable virtual graviton exchange
- if collision energy -> M* (can see extra dimensions), gravity can be strong (BH)

Signatures:

- mono-X (X=jets, photons, etc)
- blackholes
- enhancements of the high mass cross section and changes in angular distributions

TeV sized extra dimensions

TeV^{-1} size ED. **(1 TeV=2x10^{-19}m)**
Allow other particles to propagate in these (small) extra dimensions. Get KK tower of states.

$$m_{\vec{n}} = \left(m_0^2 + \frac{n \cdot n}{R_c^2} \right)^{1/2}$$

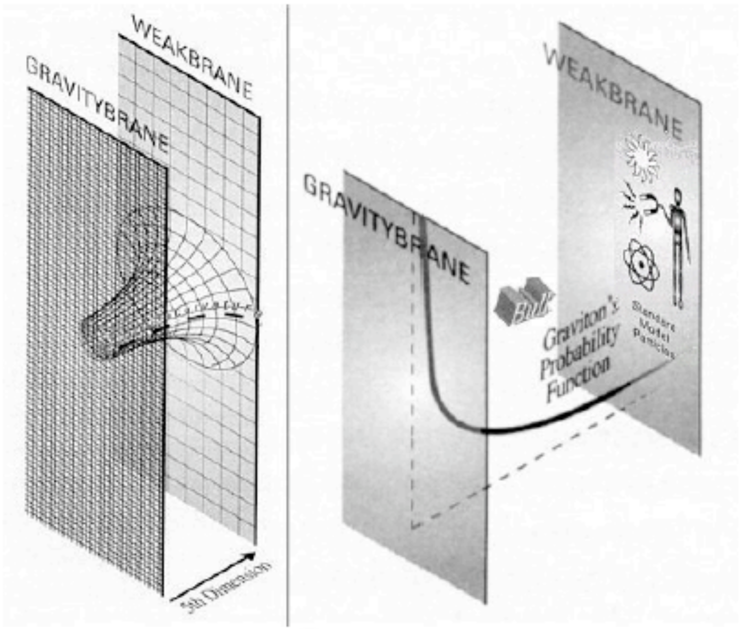
Dimension of n is number of extra dimensions (d). m_0 is the mass of the SM particle. From precision EWK, for d=5, R_c^{-1}>4TeV

Signature: high mass copies of SM gauge bosons, like Zprimes.
If all particles can propagate in the extra dimensions (requires k-parity), get UED.
If other SM particles propogate in the ED, can get HSCP

Extra dimensions in 3 slides

“Warped” Extra-Dimensions

- Sometime after ADD, Randall-Sundrum proposed another very interesting extra dimensional model
- In this theory, there is but one extra-dimension
- In this theory, the 4-D space-time metric is multiplied by a “warp” factor which is a rapidly changing function of the additional dimension
- Gravity is weak on the “weak brane” where SM fields are confined but increases in strength exponentially in the extra dimension (since space-time is accordingly “warped”)



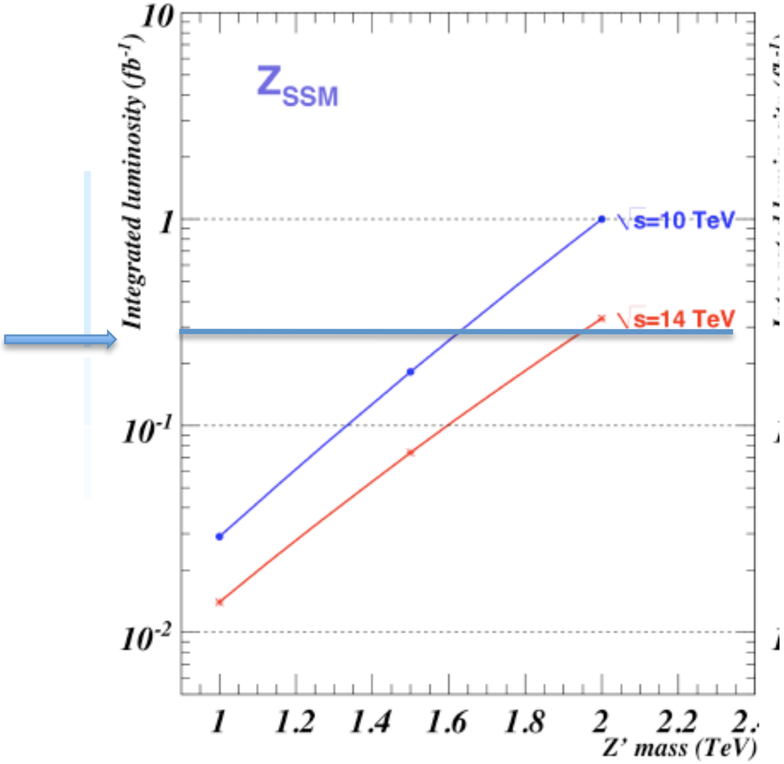
$$ds^2 = e^{-2kr_c\phi}\eta_{\mu\nu}dx^{\nu}+r_c^2d\phi^2$$

Signature: towers of spin 2 resonance that decays to di-fermions and di-bosons (zprime-like, but also γγ decay) mass splittings of O(TeV) and variable width

Cross sections

M=1000 GeV   sigma=.23 pb   acc*eff=0.67 N=46
M=1250 GeV   sigma= 0.083 pb   acc*eff=0.68 N=17
M = 1500 GeV   sigma = 0.033 pb acc*eff=0.69 N=7

10 TeV



(Muon channel)

acceptance

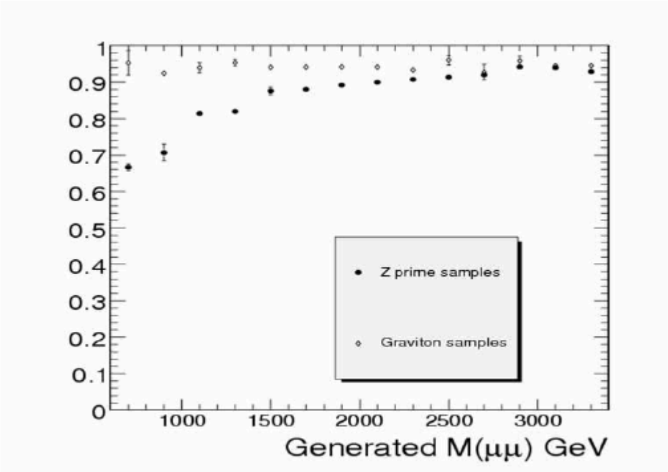


Figure 12: Geometrical acceptance for dimuons from decays of Z' and G^* as a function of the dimuon invariant mass, as predicted by PYTHIA.

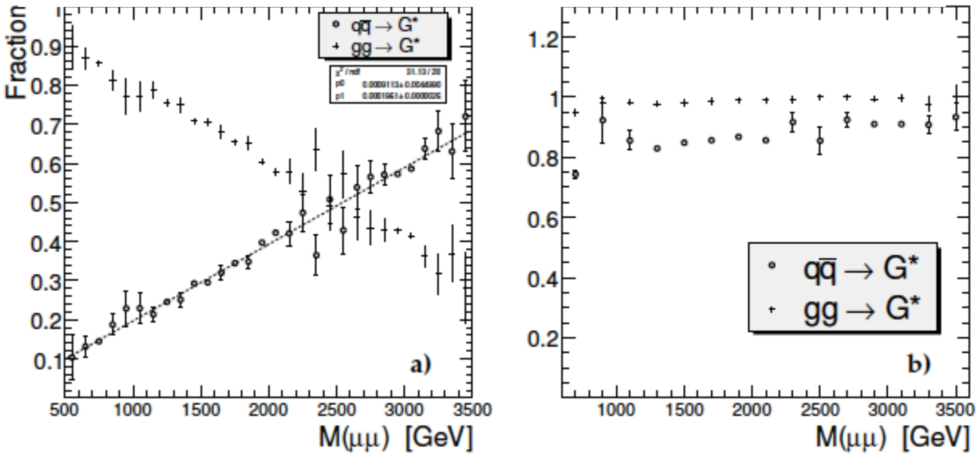


Figure 13: a) Relative fractions of $q\bar{q} \to G^* \to \mu^+\mu^-$ and $gg \to G^* \to \mu^+\mu^-$ processes in the graviton production, as a function of $M_{\mu\mu}$. b) Acceptance efficiencies of gravitons produced via $q\bar{q} \to G^* \to \mu^+\mu^-$ and $gg \to G^* \to \mu^+\mu^-$ mechanisms as a function of $M_{\mu\mu}$.

Note difference in acceptance at 1 TeV for Zprime and graviton due to different initial states (qqbar vs gg valence-sea tends to produce events with large rapidity)

Heavy Boson to ee, μμ

Considerations:

- resolution, bias for tracks (muons) sensitive to alignments
- high energy muons brem
- hard to check efficiencies/resolutions/scale from data at high energy
- calorimeter could saturate at the highest energy
- calorimeter isolation, had/em cut could lose efficiency at high energy

Electron channel

10 TeV

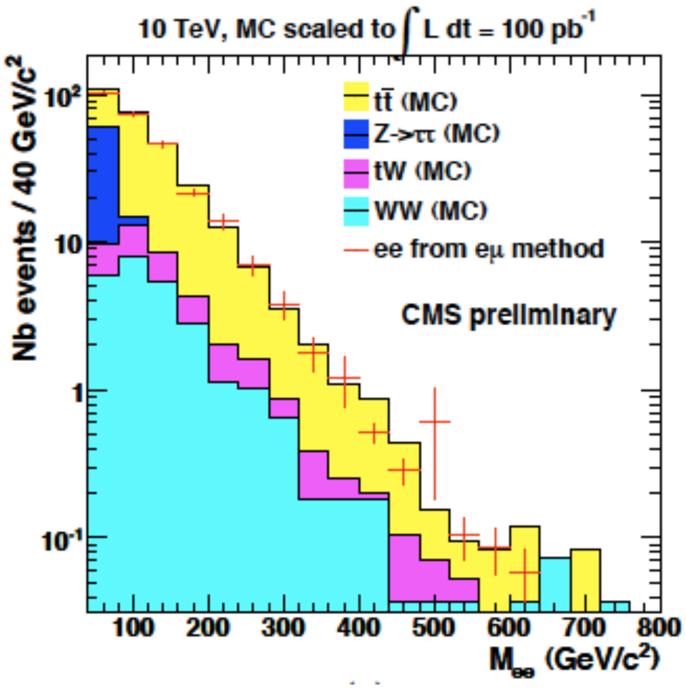
Selection

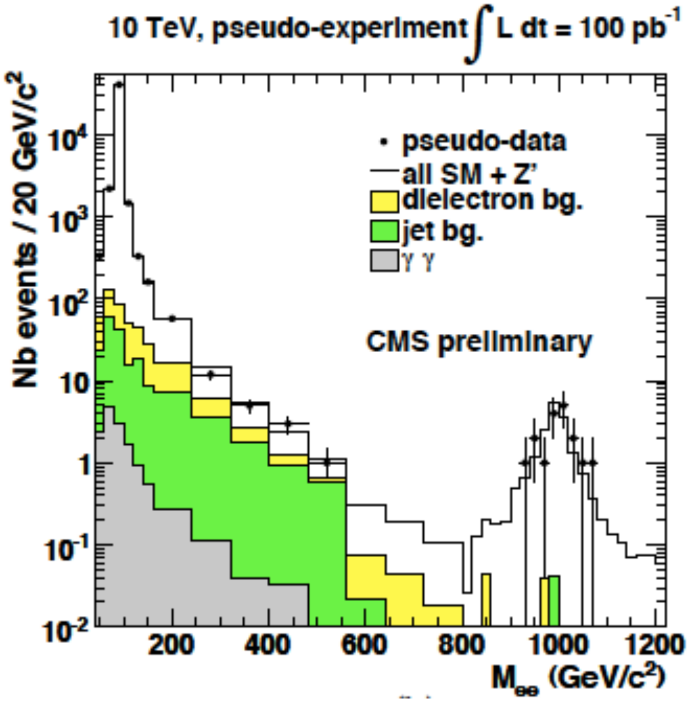
- 2 electrons with $|\eta| < 1.442$ or $1.560 < |\eta| < 2.5$ and $P_T > 25$ GeV
- electron ID (cluster-track matching and shower shape variables)
- isolation in tracker/ECAL/HCAL

Acceptance 80-90%

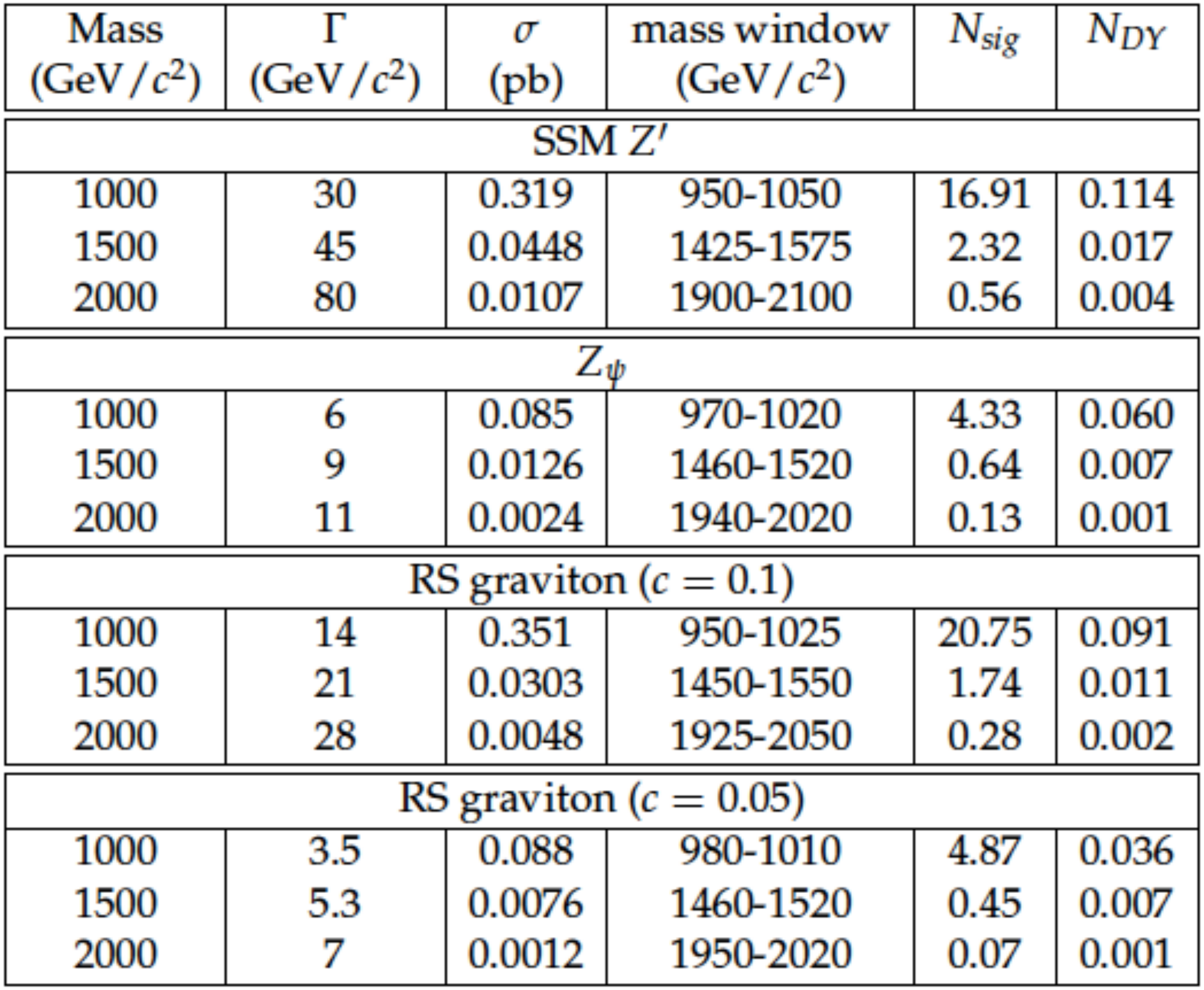
ID efficiency around 88%

Obtain non-DY background using e-mu events



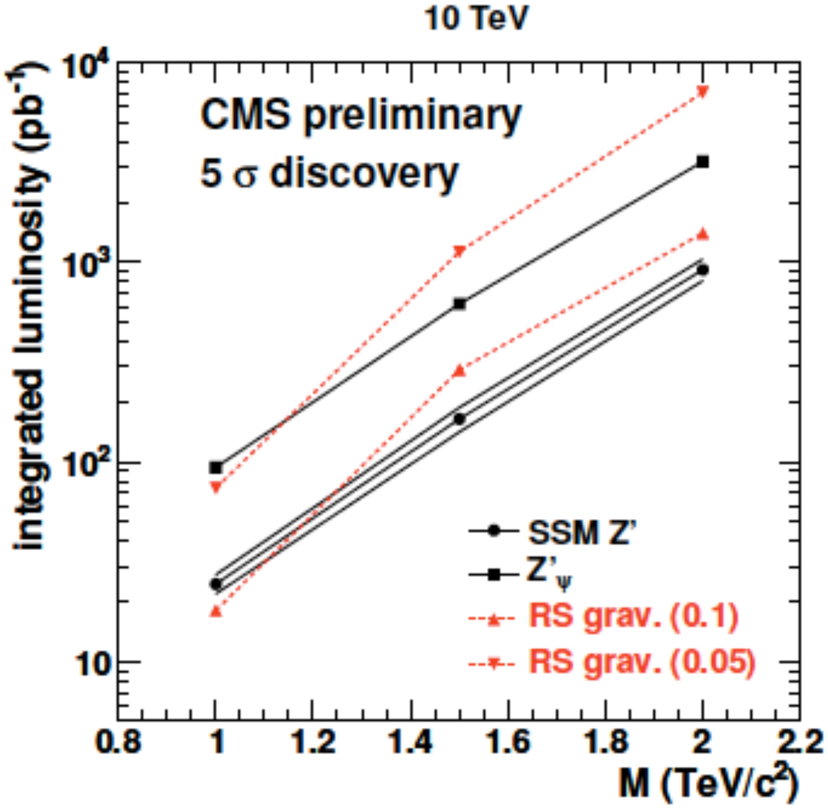


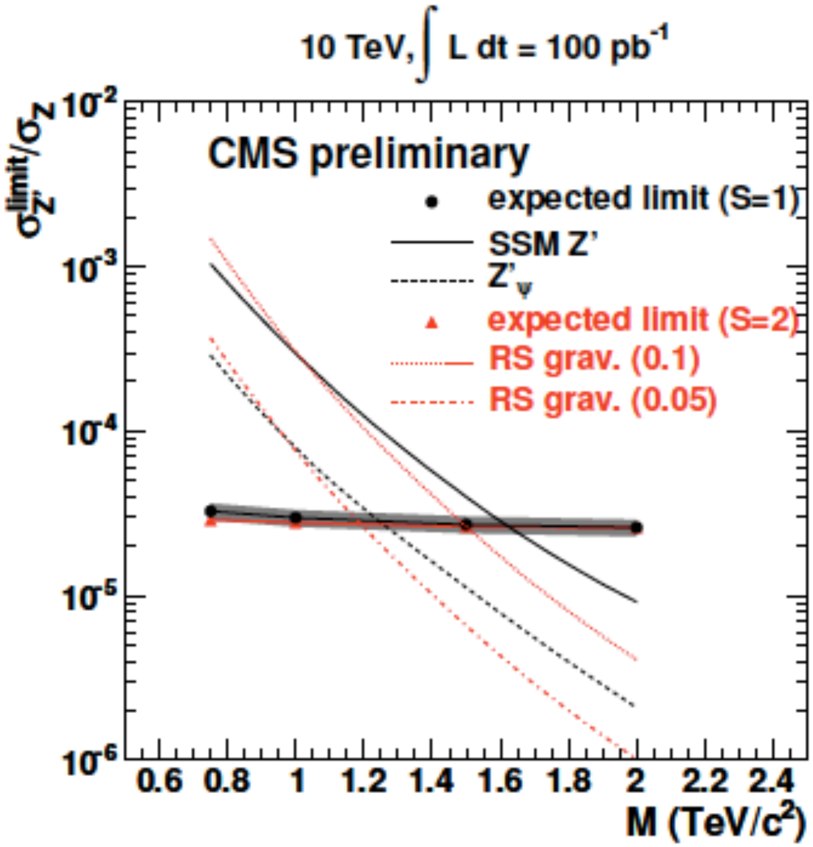
electron channel



Mass (GeV/c^2)	Γ (GeV/c^2)	σ (pb)	mass window (GeV/c^2)	N_{sig}	N_{DY}
SSM Z'					
1000	30	0.319	950-1050	16.91	0.114
1500	45	0.0448	1425-1575	2.32	0.017
2000	80	0.0107	1900-2100	0.56	0.004
Z_ψ					
1000	6	0.085	970-1020	4.33	0.060
1500	9	0.0126	1460-1520	0.64	0.007
2000	11	0.0024	1940-2020	0.13	0.001
RS graviton ($c = 0.1$)					
1000	14	0.351	950-1025	20.75	0.091
1500	21	0.0303	1450-1550	1.74	0.011
2000	28	0.0048	1925-2050	0.28	0.002
RS graviton ($c = 0.05$)					
1000	3.5	0.088	980-1010	4.87	0.036
1500	5.3	0.0076	1460-1520	0.45	0.007
2000	7	0.0012	1950-2020	0.07	0.001

Electron Channel

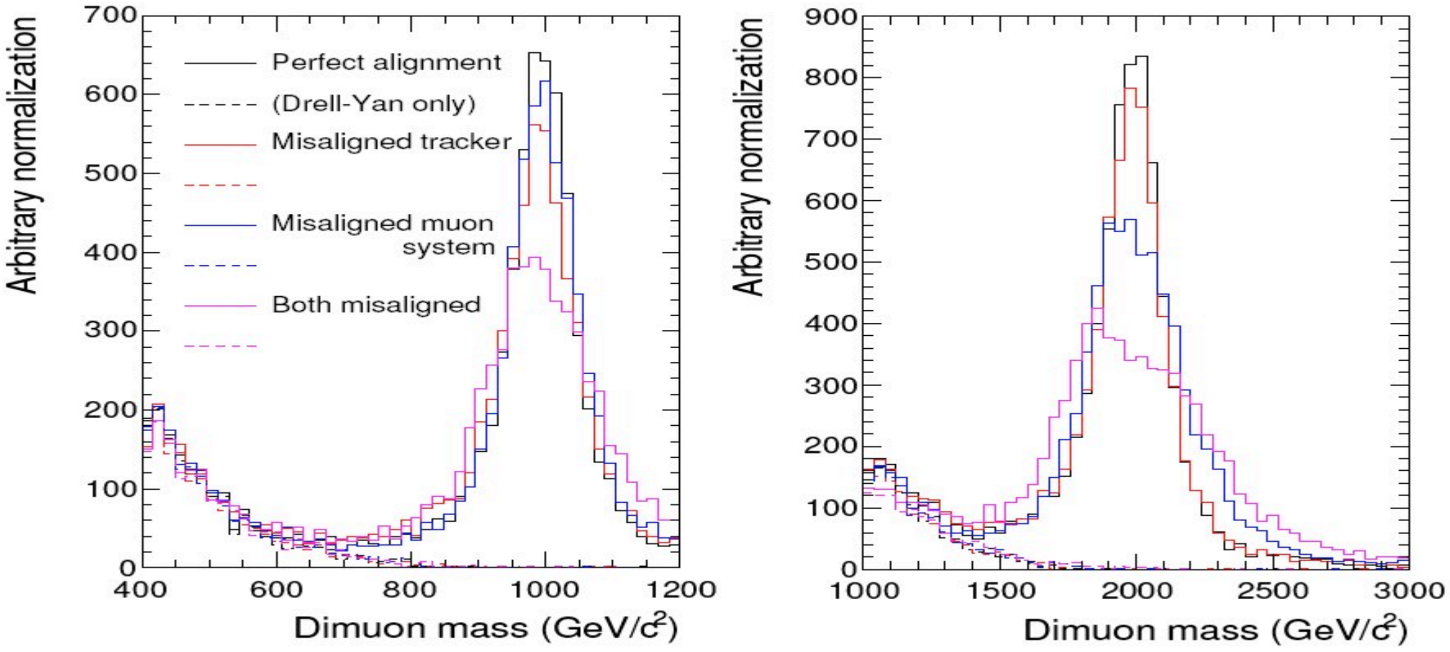




Muons and Alignment

Alignment effect
(startup conditions
100 pb^{-1})
Mass resolution:
7-8 (10) % at 1 (2) TeV

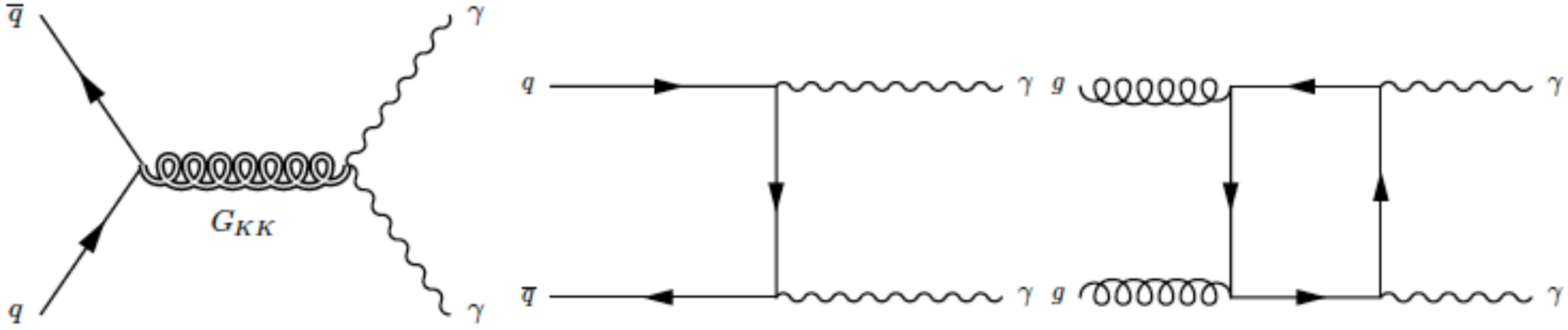
Statistical significance related to sharpness of peak related to resolution



Other high mass, low background resonances

Can also look for other kinds of high mass resonances, some more, some less motivated.
$\gamma\gamma$, eq, eν, eγ, eμ, … (etc etc etc)

Large extra dimensions and γγ



$$BR(G \rightarrow ee, \mu\mu) = 2\%$$

$$BR(G \rightarrow \gamma\gamma) = 4\%$$

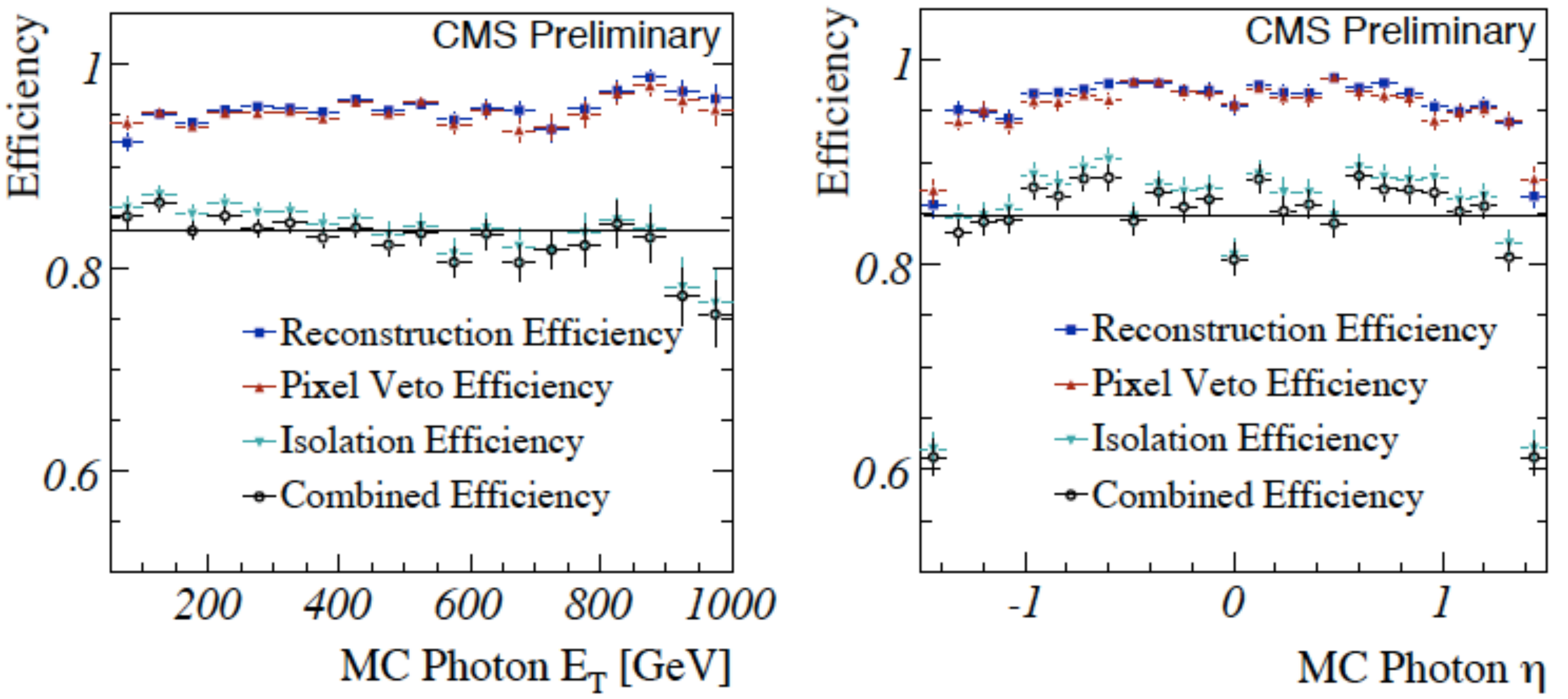
Remember: large extra dimensions, the lightest kk graviton is light (MeV), closely spaced, and there are lots of them. For warped extra dimensions, the lightest graviton has a TeV mass.

Sherpa used to generate signal and background with interference.

Photon ID

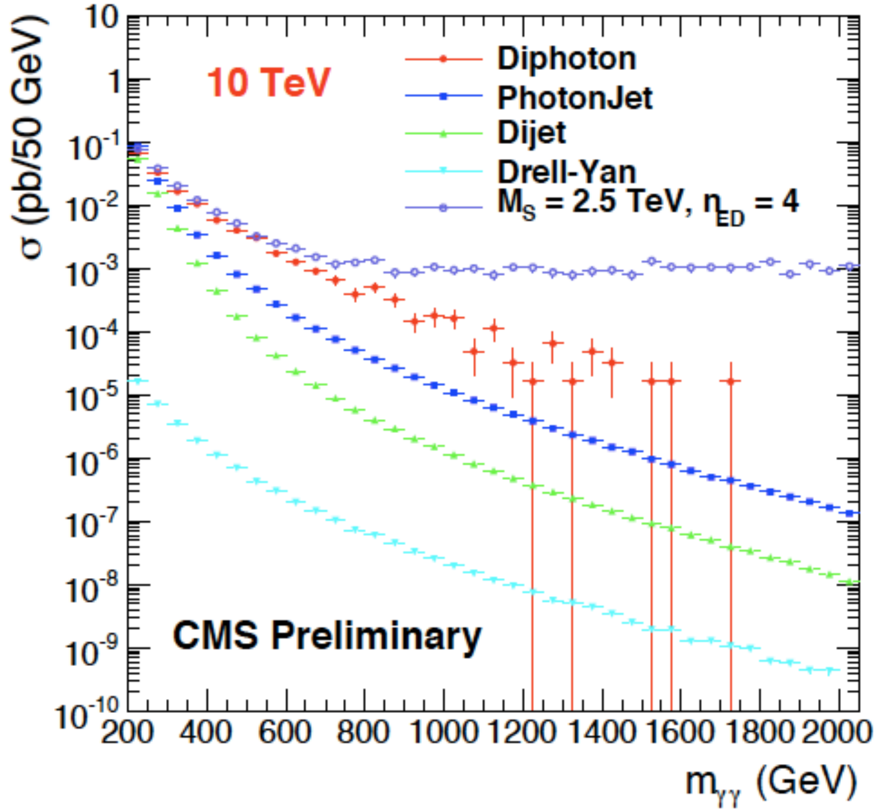
event selection

- two photons with E_T > 50 GeV (pixel hit veto)
- tight isolation



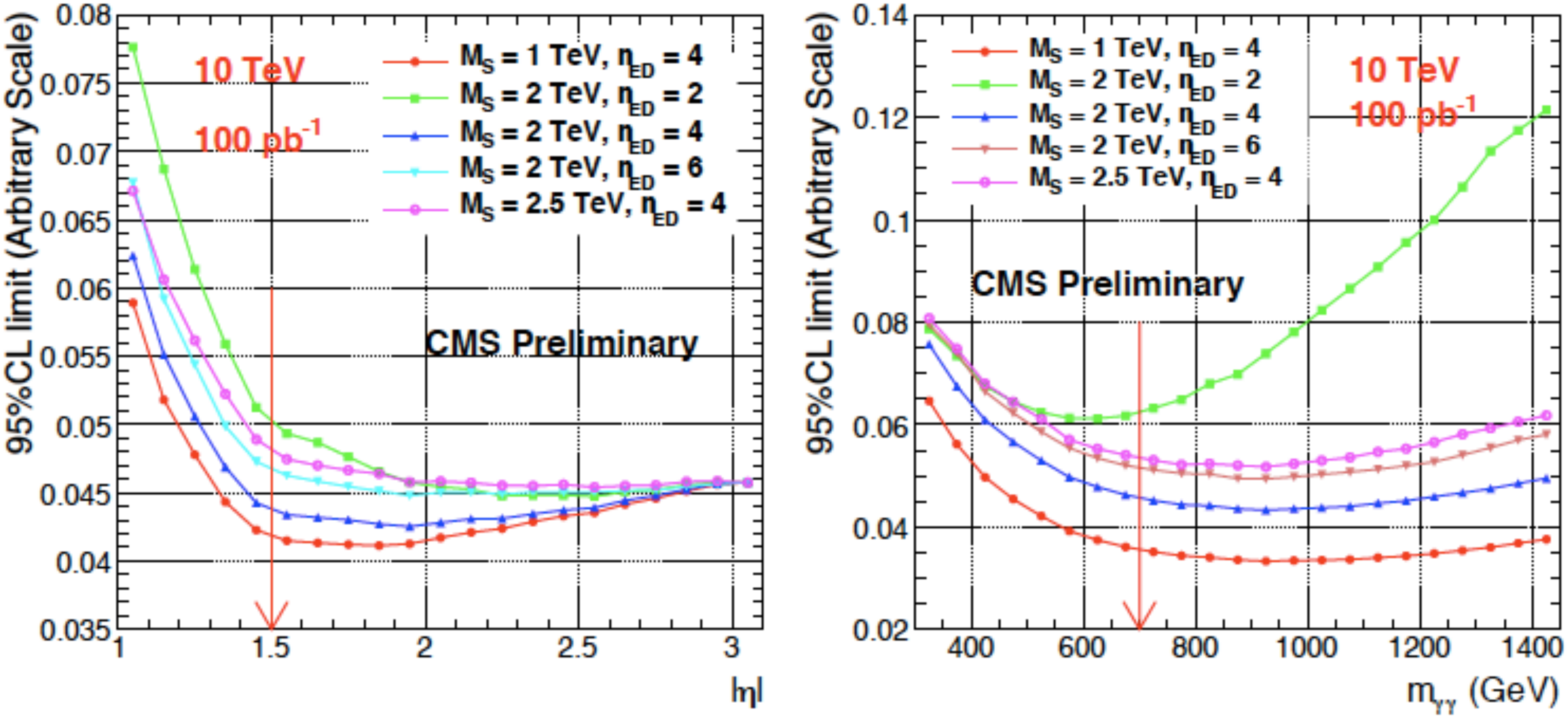
Backgrounds

- dijet and photon+jet backgrounds determined statistically by looking at conversions. If E is close to sum_P, photon-like. If E>>sum_P, pi0 like
- DY background determined by using track ID efficiency measured at Z peak using tag and probe
- diphotons: normalize MC prediction to date (with even tighter isolation, to reduce above backgrounds, when low lum requires upper cut below 300 GeV) for $M_{\gamma\gamma} < 500\ \mathrm{GeV}$



Optimization

Do simple counting experiment

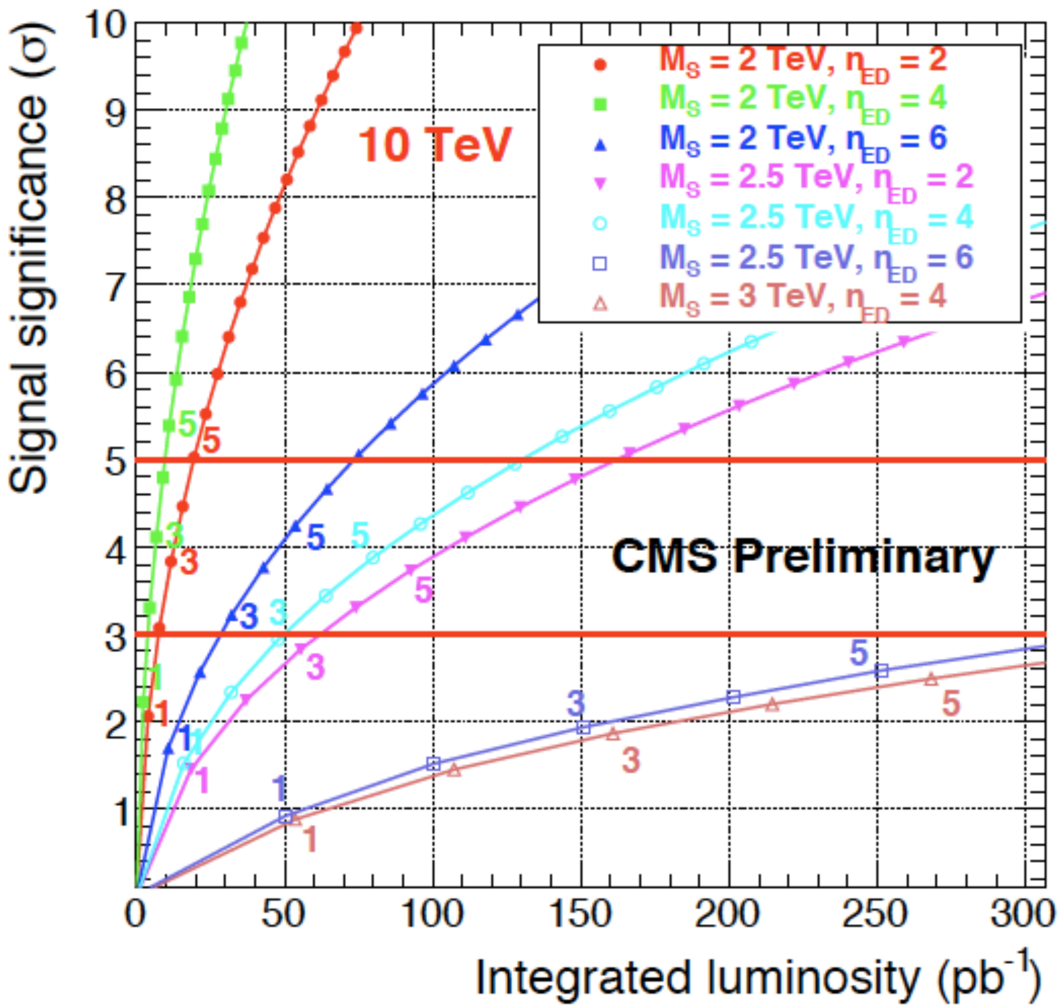


$$|\eta| < 1.5$$

$$M_{\gamma\gamma} > 700 \text{ GeV}$$

limits

Numbers are number of observed signal events at that integrated lum



Gamma-gamma

If RS gravitons, expect resonance. Can look for lowest excitation of the RS-1 KK graviton by looking for a resonance, or could just use the counting experiment results from before and reinterpret.

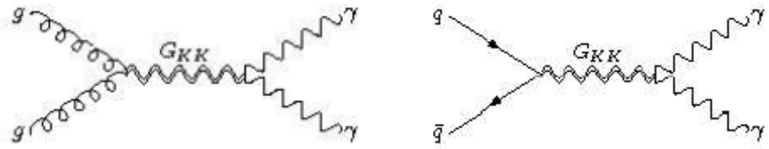


Figure 1: Feynman diagrams for RS graviton production and decay into two photons.

signal

k=0.01

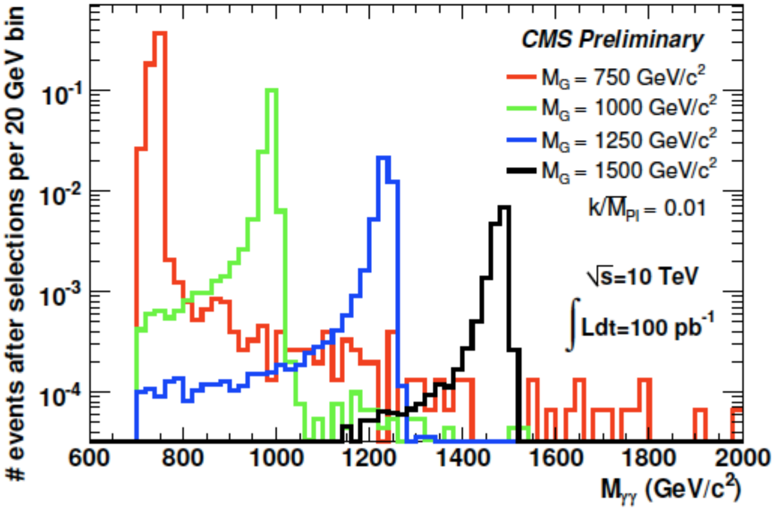


Figure 2: Diphoton invariant mass spectra after selection is applied, scaled to 100 pb^{-1} for $M_1 = 750, 1000, 1250$, and $1500\,\mathrm{GeV/c^2}$, $\tilde{k} = 0.01$ samples.

M_1 (GeV/c^2)	$\tilde{k}$	$N_{expected\ 100pb^{-1}}$	MC acceptance	photon ID/ reco eff
750	0.01	0.595 ±0.007	0.499 ±0.004	0.631 ±0.005
1000	0.01	0.150 ±0.001	0.563 ±0.003	0.633 ±0.004
1250	0.01	0.0462 ±0.0004	0.616 ±0.003	0.599 ±0.004
1500	0.01	0.0155 ±0.0001	0.672 ±0.003	0.588 ±0.004

Table 2: MC signal samples, the expected number of signal events in 100 pb^{-1}, MC acceptances after selection is applied, and the efficiency for reconstructing and identifying photons.

k>0.01 from precision ewk, <0.1 from pertubativity.

Cross sections grows with k

Limits

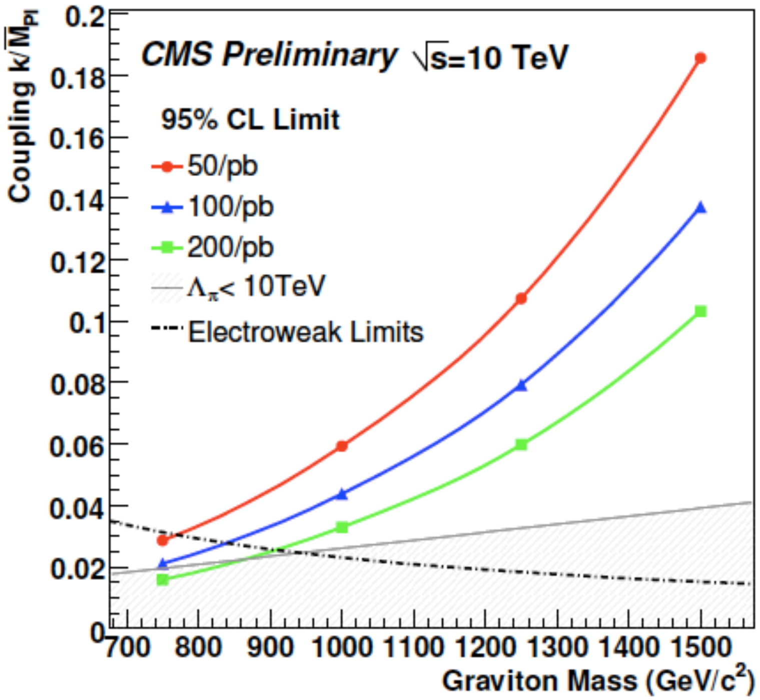
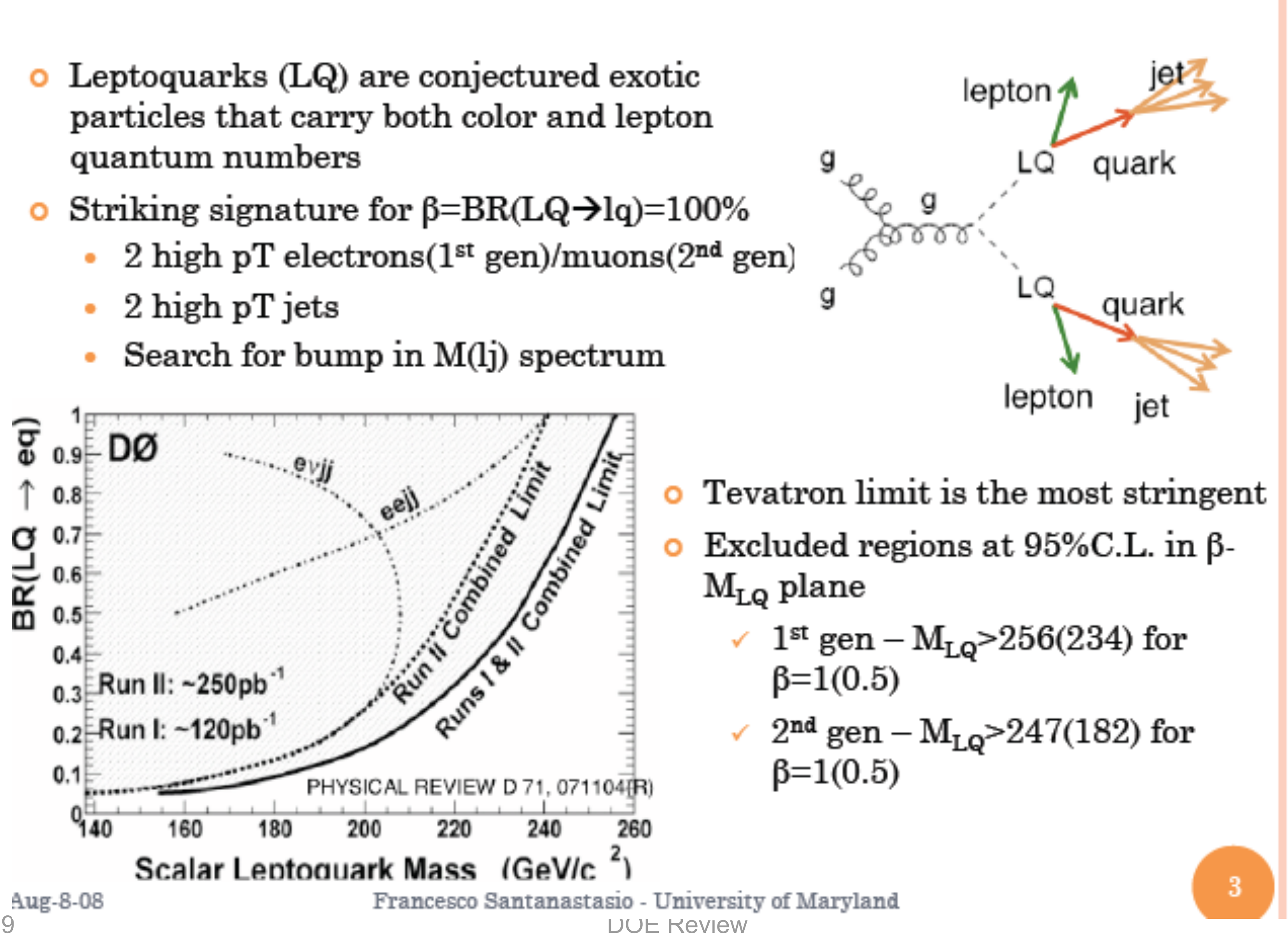


Figure 3: Limit on RS parameters $(M_1, \tilde{k})$, extrapolated from the results of the large ED diphoton search for 100/pb. The area to the left of the curves is excluded. The gray shaded region shows the area excluded for $\Lambda_\pi < 10\,\mathrm{TeV/c^2}$. The area below the dash-dotted line is excluded by precision electroweak data [11].

Leptoquarks



- Leptoquarks (LQ) are conjectured exotic particles that carry both color and lepton quantum numbers
- Striking signature for β=BR(LQ→lq)=100%
  - 2 high pT electrons(1^{st} gen)/muons(2^{nd} gen)
  - 2 high pT jets
  - Search for bump in M(lj) spectrum

PHYSICAL REVIEW D 71, 071104(R)

- Tevatron limit is the most stringent
- Excluded regions at 95%C.L. in β-M_{LQ} plane
  - 1^{st} gen – M_{LQ}>256(234) for β=1(0.5)
  - 2^{nd} gen – M_{LQ}>247(182) for β=1(0.5)

Aug-8-08 Francesco Santanastasio - University of Maryland 3

Selection

Simple counting experiment with data-driven techniques for estimating backgrounds for first data

$$\text{At least 2 isolated electrons with } \mathrm{P}_T > \ 30 \text{ GeV}$$

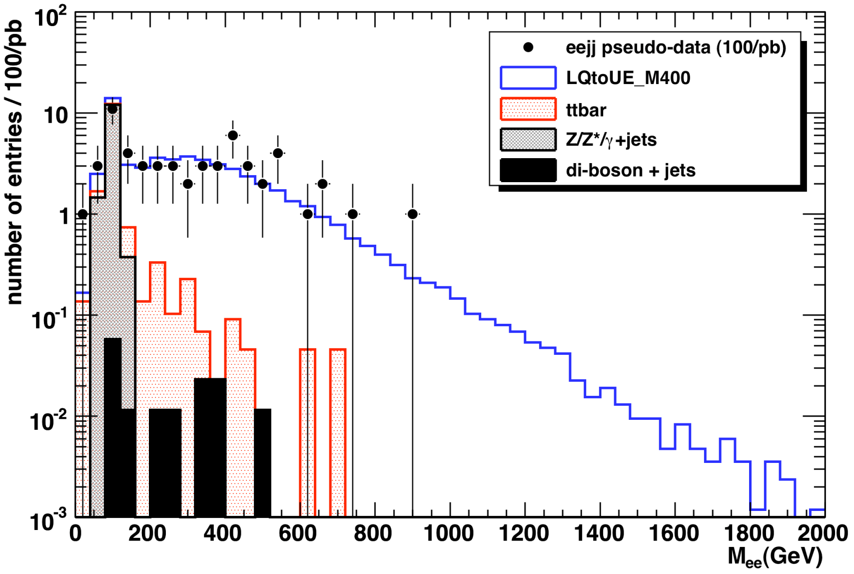
$$\text{At least 2 jets with } \mathrm{P}_T > 50 \text{ GeV and } |\eta| < 3$$

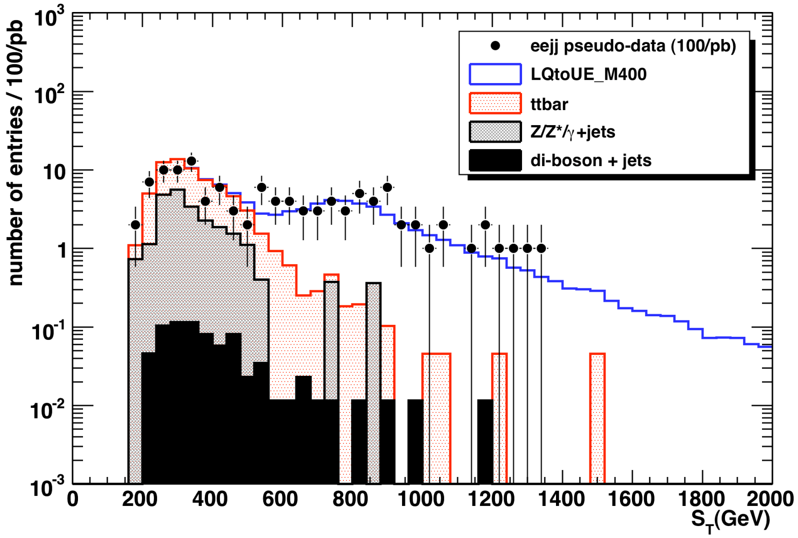
$$M_{ee} > 100 \text{ GeV}$$

$$\mathrm{S}_T \equiv P_T^{e1} + P_T^{e2} + P_T^{j1} + P_T^{j2} > f(M_{LQ})$$

Small backgrounds

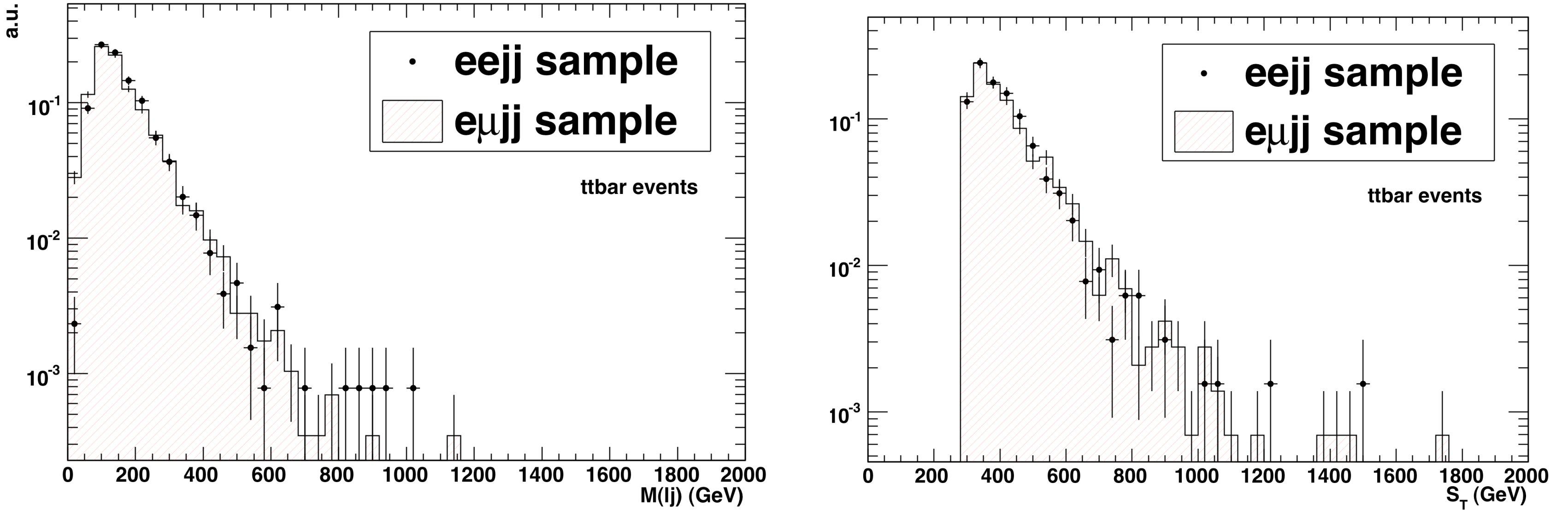
M_{LQ} (GeV/c^2) in Signal Sample	S_T cut (GeV/c)	Events in Signal Sample	Selection Efficiency	Events in Background Samples		
				$t\bar{t}$ + N jets	Z/γ + N jets	VV + N jets
250	460	342 ± 2	34%	7.2 ± 0.6	2.6 ± 1.0	0.21 ± 0.05
300 (*)	520	163.4 ± 0.5	43%	3.9 ± 0.4	1.1 ± 0.6	0.15 ± 0.04
400	620	38.98 ± 0.15	52%	1.5 ± 0.3	0.7 ± 0.5	0.09 ± 0.03
500 (*)	740	11.56 ± 0.03	59%	0.69 ± 0.18	0.4 ± 0.4	0.05 ± 0.02
600 (*)	740	4.04 ± 0.01	66%	as above	as above	as above





Data-driven: top

Leptoquarks can not produce e mu events. Top does.



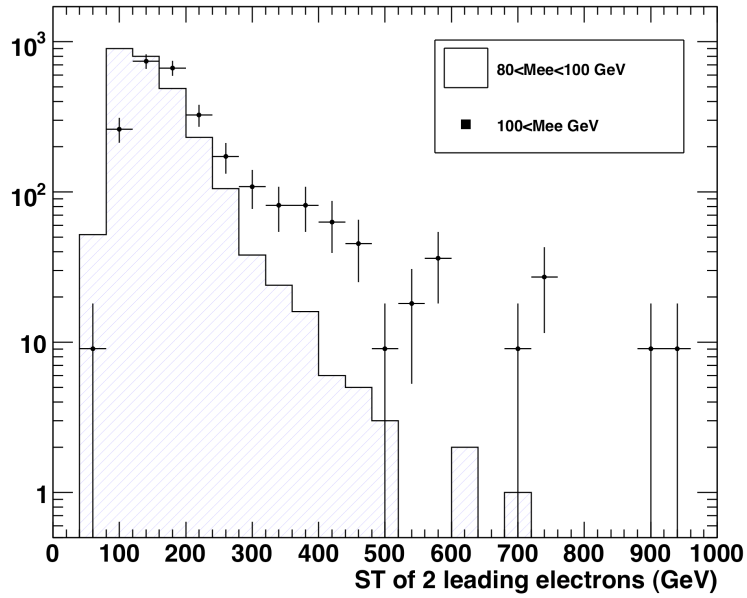
$$N^{est.}_{\mathrm{eejj}} = \frac{1}{2}\sum_{p_T^{\mu}} N_{\mathrm{e}\mu\mathrm{jj}}(p_T^{\mu}) \cdot R(p_T^{\mu})$$

$$R(P_T) = 0.85 - 0.95$$

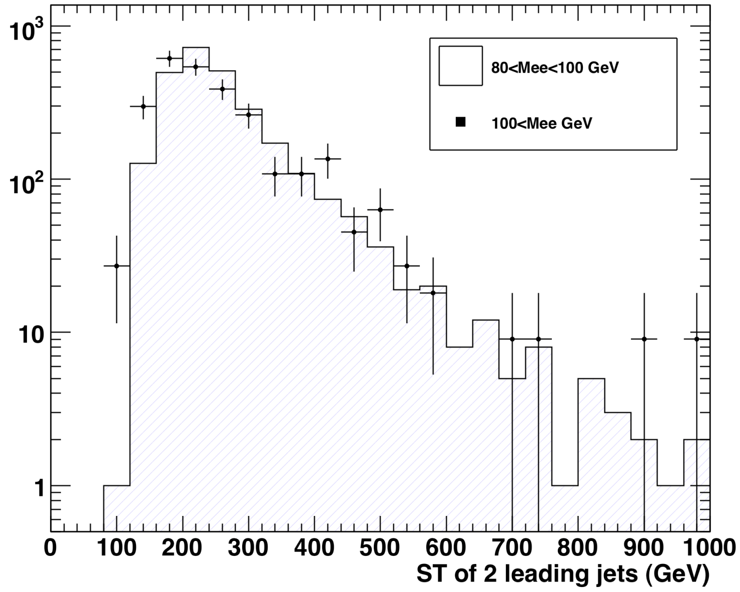
Data-driven: DY->ee

Use events inside the Z mass window to predict the properties of events outside the mass window.

Electron ST

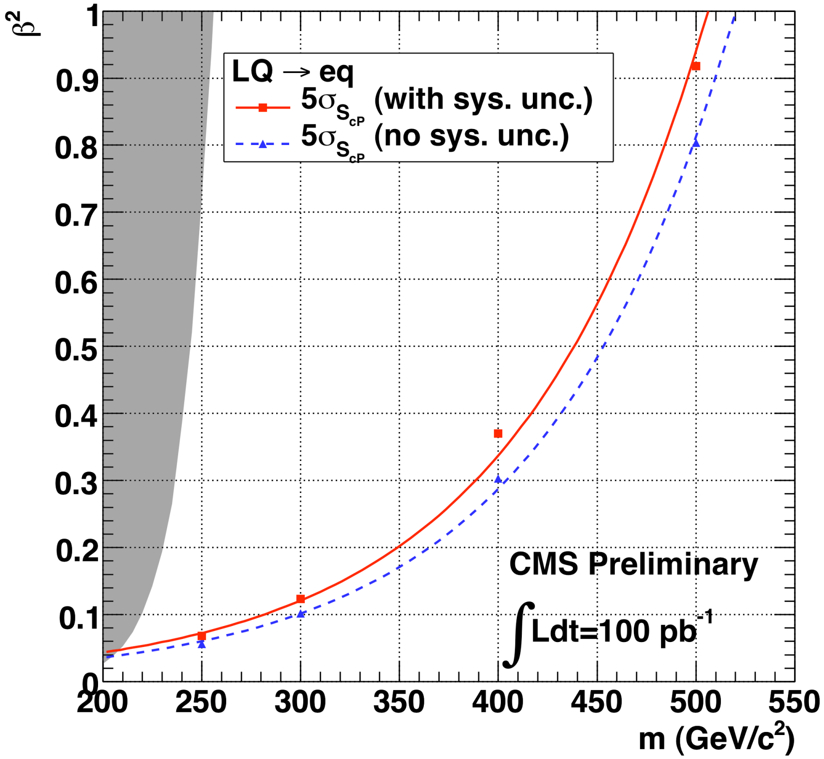


Jet ST

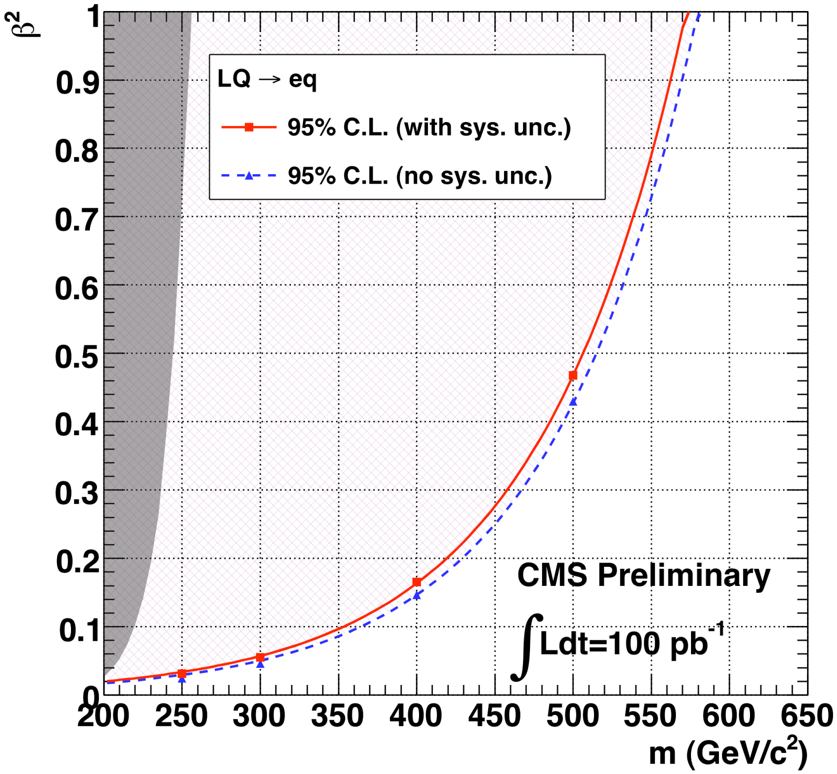


$$N^{Z}_{eejj} = N_{\mathrm{eejjAtZ}} \cdot R_{\mathrm{OffZ/AtZ}}$$

Reach

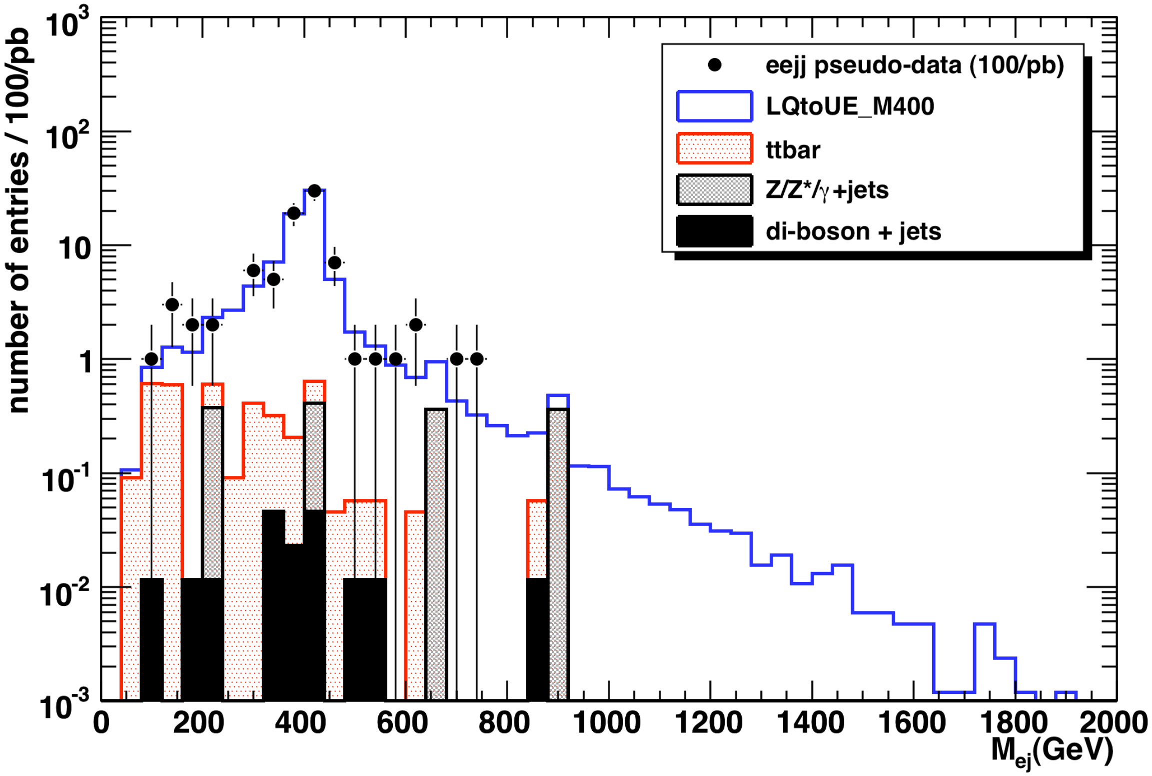


β^2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
200
250
300
350
400
450
500
550
m (GeV/c^2)
LQ → eq
$5\sigma_{S_{cP}}$ (with sys. unc.)
$5\sigma_{S_{cP}}$ (no sys. unc.)
CMS Preliminary
$\int$Ldt=100 pb^{-1}



β^2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
200
250
300
350
400
450
500
550
600
650
m (GeV/c^2)
LQ → eq
95% C.L. (with sys. unc.)
95% C.L. (no sys. unc.)
CMS Preliminary
$\int$Ldt=100 pb^{-1}

Bump hunt



number of entries / 100/pb
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
0
200
400
600
800
1000
1200
1400
1600
1800
2000
M_{ej}(GeV)
eejj pseudo-data (100/pb)
LQtoUE_M400
ttbar
Z/Z*/γ+jets
di-boson + jets

Muon channel

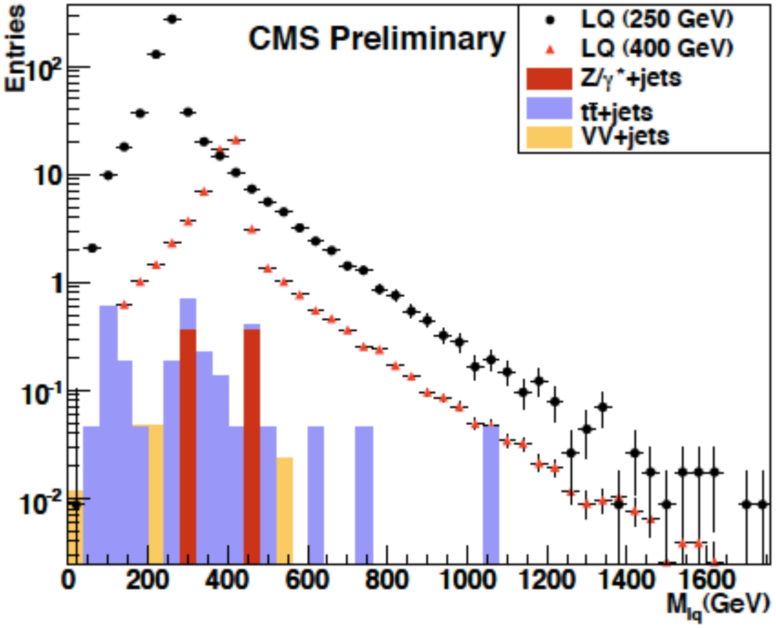


Figure 4: Distribution of the reconstructed $M_{\mu j}$ mass for a 250 GeV and a 400 GeV leptoquark signal and for the remaining background after selection criteria, for an integrated luminosity of 100 pb^{-1}. The number of background events shown corresponds to the selection optimized for a 400 GeV leptoquark hypothesis.

Muon channel

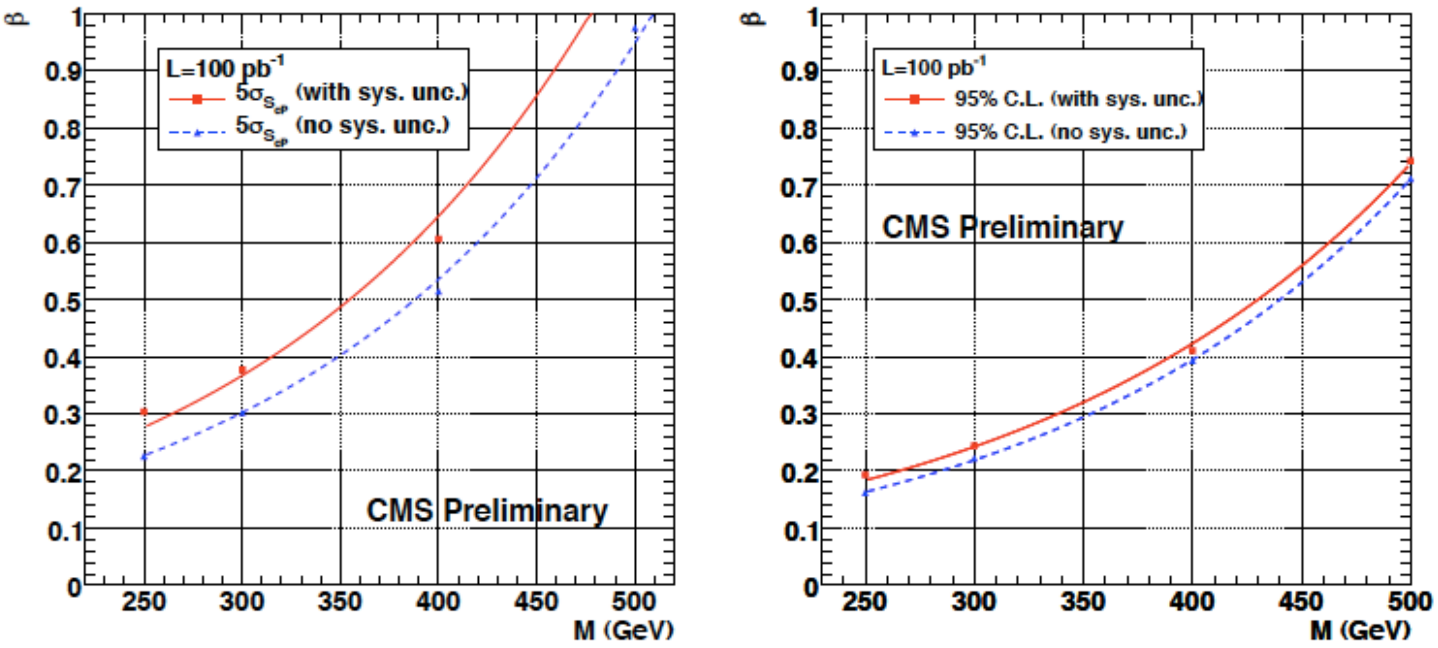


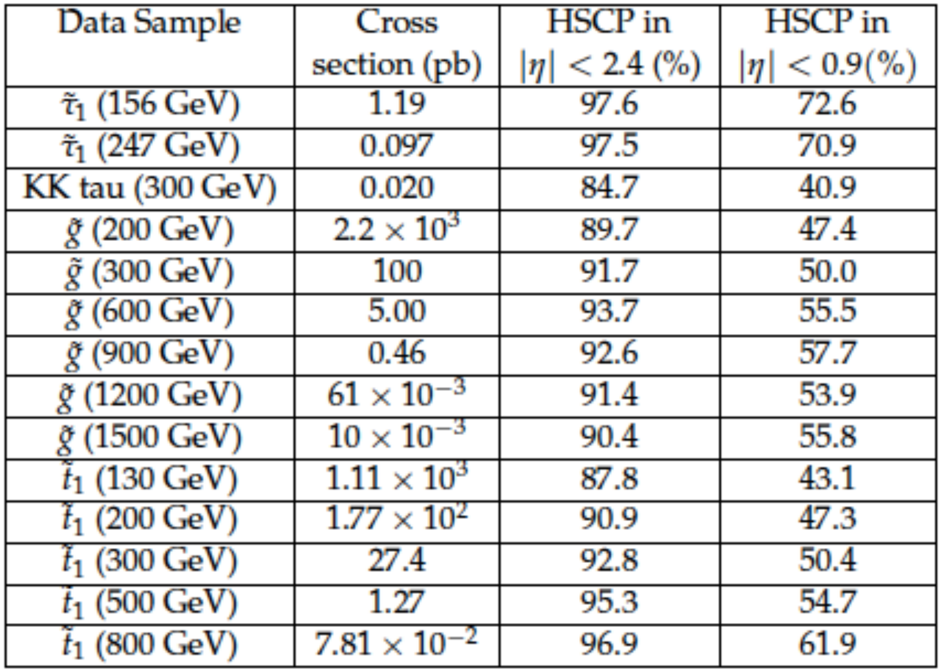
Figure 5: β for a 5σ discovery as a function of leptoquark masses for 100 pb^{-1} of integrated luminosity (left plot). β for 95% C.L. exclusion as a function of different leptoquark masses for 100 pb^{-1} of integrated luminosity (right plot). The red lines in both figures correspond to the systematic errors being included in the calculation.

Heavy stable charged particles

HSCP arise in models with new state and new conserved (or almost conserved) global quantum number, i.e. SUSY with R-parity of ED with KK-parity. The particle is either the LSP or an NSLP with a very long life time due to small coupling or close mass splitting.

Some models:

- GMSB SUSY has long lived stau NLSP with gravitino LSP. Generally produced from decays of squarks and gluions.
- mUED has long-lived KK states. Direction pair production of KK tau
- split SUSY (all scalar particles have high mass). Long-lived gluino (R-hadron)
- MSSM with light stop as NLSP and small mass splitting between stop and LSP



Data Sample	Cross section (pb)	HSCP in $\lvert\eta\rvert < 2.4$ (%)	HSCP in $\lvert\eta\rvert < 0.9$(%)
$\tilde{\tau}_1$ (156 GeV)	1.19	97.6	72.6
$\tilde{\tau}_1$ (247 GeV)	0.097	97.5	70.9
KK tau (300 GeV)	0.020	84.7	40.9
$\tilde{g}$ (200 GeV)	2.2×10^3	89.7	47.4
$\tilde{g}$ (300 GeV)	100	91.7	50.0
$\tilde{g}$ (600 GeV)	5.00	93.7	55.5
$\tilde{g}$ (900 GeV)	0.46	92.6	57.7
$\tilde{g}$ (1200 GeV)	61×10^{-3}	91.4	53.9
$\tilde{g}$ (1500 GeV)	10×10^{-3}	90.4	55.8
$\tilde{t}_1$ (130 GeV)	1.11×10^3	87.8	43.1
$\tilde{t}_1$ (200 GeV)	1.77×10^2	90.9	47.3
$\tilde{t}_1$ (300 GeV)	27.4	92.8	50.4
$\tilde{t}_1$ (500 GeV)	1.27	95.3	54.7
$\tilde{t}_1$ (800 GeV)	7.81×10^{-2}	96.9	61.9

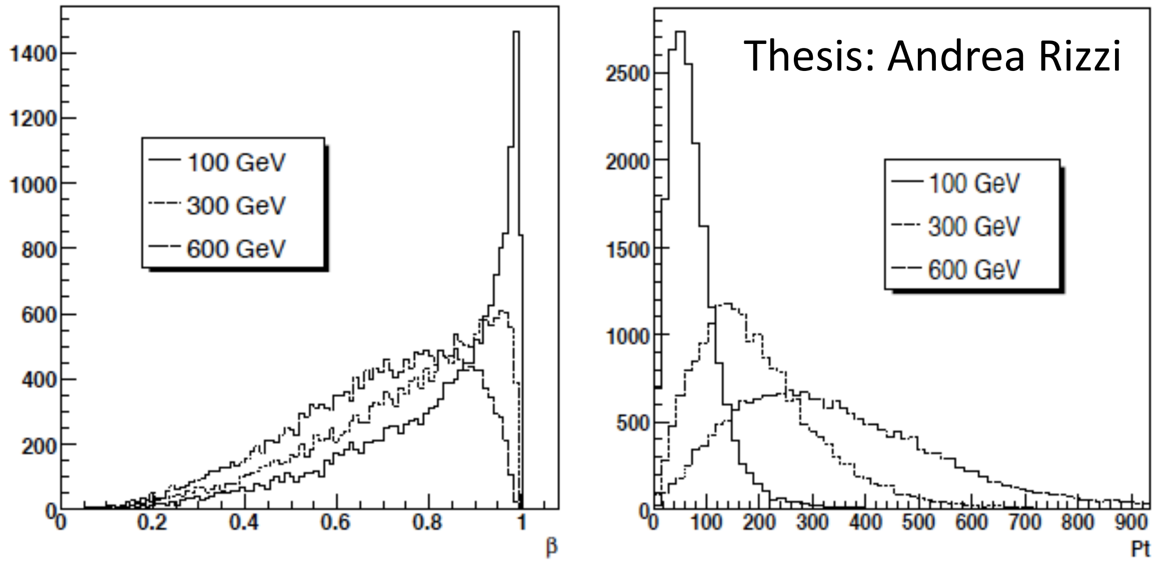
Gluino and stop hadronize to metastable particle by combining with light quarks and gluons (R-hadron). Gluinos (and stops) also have large cross sections. Complication with r-hadrons: they can flip charge while passing through matter. Uncertainties on energy loss in matter due to uncertainties on nuclear interactions

HSCP

Three main ways to look for them:
- look for events with large dE/dx
- look for events that arrive late at the muon chambers
- If slow enough, can stop in the hadronic calorimeter, wait there a while, and then decay when there is no beam.

First two only work for particles that are not too slow.
For second, lose all information about the characteristics of the event that produced the HSCP.

Beta =1 : arrive at CMS muon chambers at t=13 ns
Beta = 0.3: arrives at CMS muon chambers at t=38 ns (25 ns later)



Thesis: Andrea Rizzi

HSCP

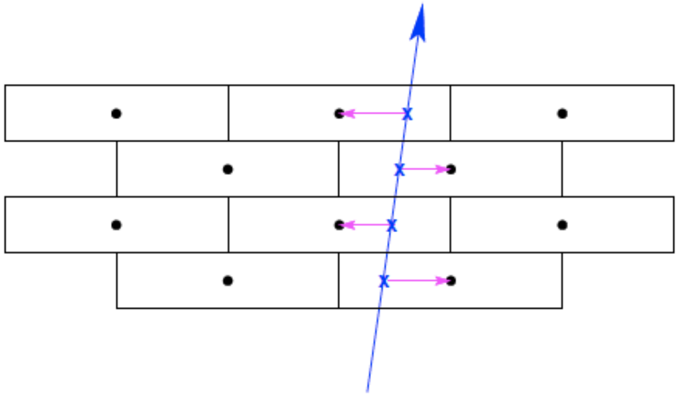
If beta is not too slow…

- trigger off muon system, or off accompanying jets and MET

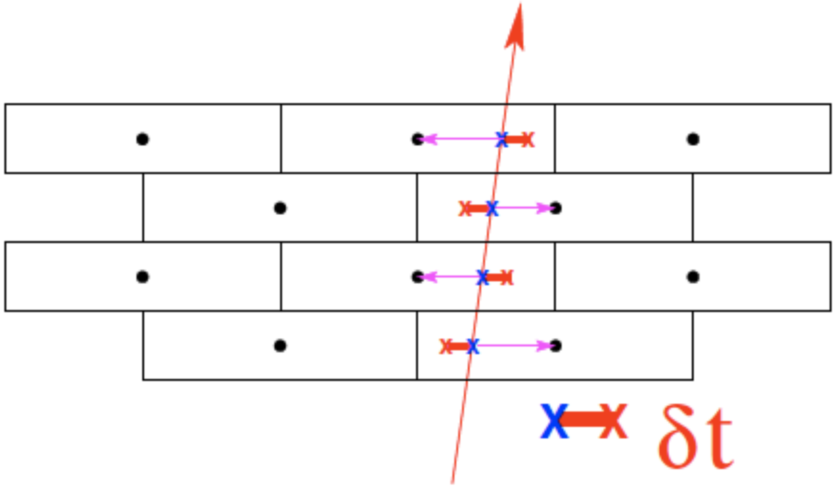
- use dE/dX to measure beta
- use arrival time at muon chambers and geometry to measure beta
- use bend in solenoid field to measure p
- have two separate measurements of m

$$m \approx \frac{p}{\beta}$$

HSCP

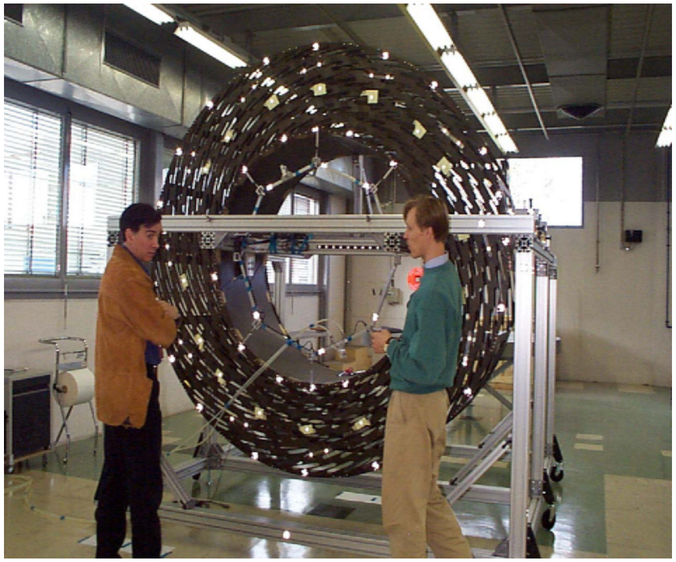


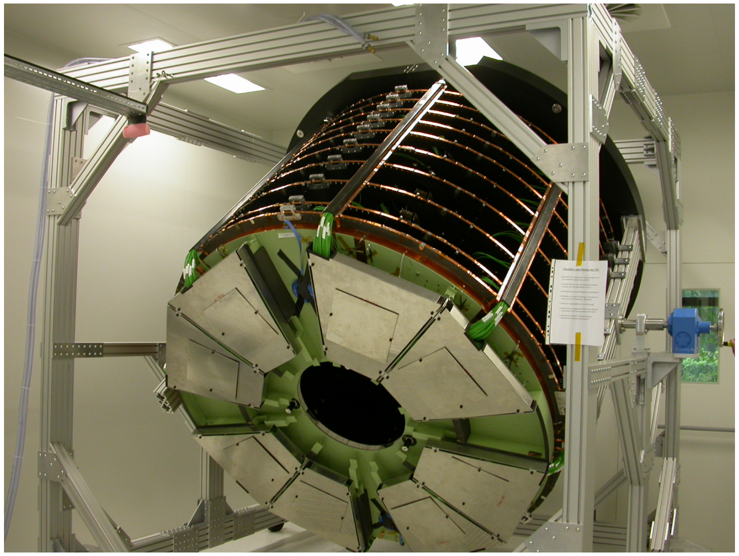
in a given super-layer hits due to muon should align if timing is correct

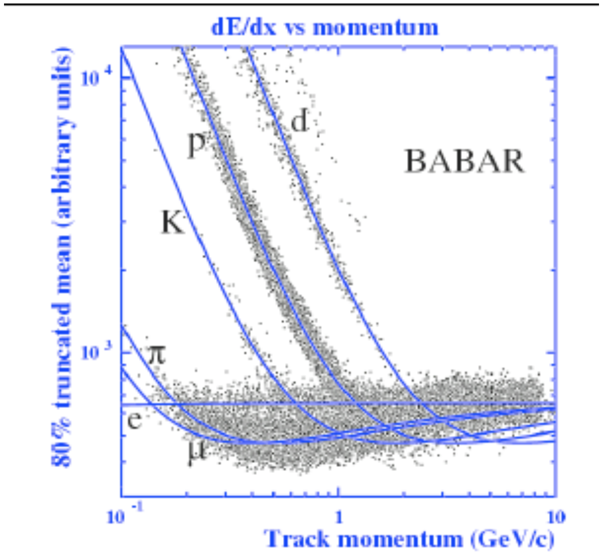


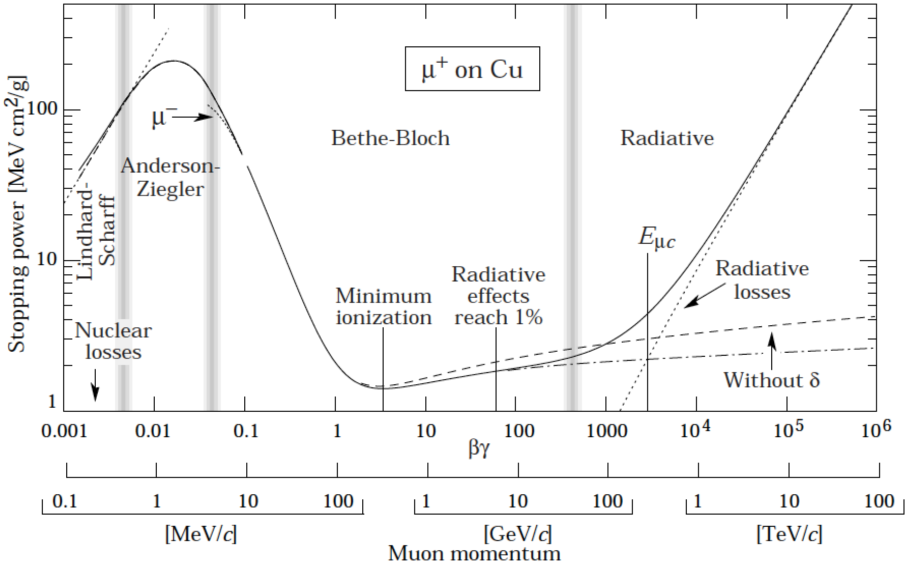
its due to delayed particle do not align, hey are shifted backward from the wire

dE/dx



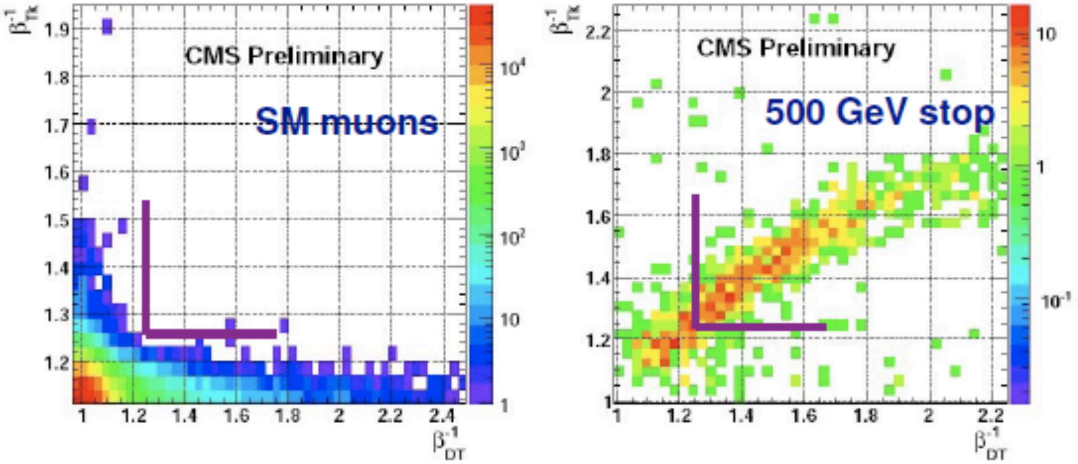


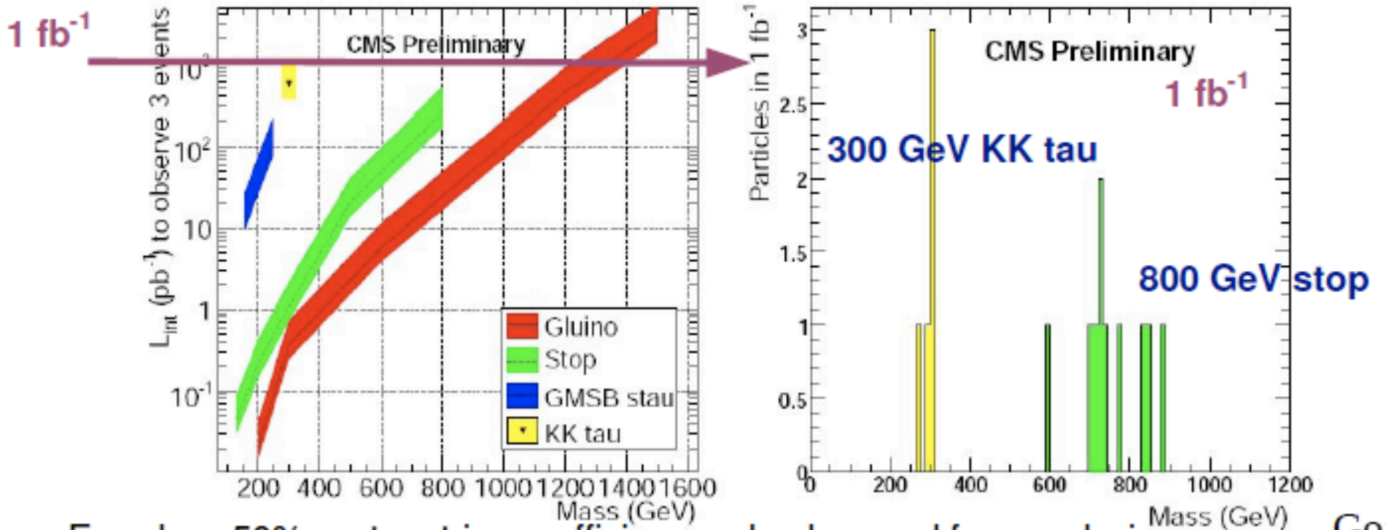

dE/dx vs momentum
80% truncated mean (arbitrary units)
10^4
10^3
d
p
K
BABAR
π
e
μ
10^{-1}
1
10
Track momentum (GeV/c)


μ^+ on Cu
Stopping power [MeV cm^2/g]
100
10
1
μ^-
Anderson-Ziegler
Lindhard-Scharff
Bethe-Bloch
Radiative
Nuclear losses
Minimum ionization
Radiative effects reach 1%
$E_{\mu c}$
Radiative losses
Without δ
0.001
0.01
0.1
1
10
100
1000
10^4
10^5
10^6
βγ
0.1
1
10
100
[MeV/c]
1
10
100
[GeV/c]
1
10
100
[TeV/c]
Muon momentum

HSCP

- $\beta_{DT} < 0.80$ and $\sigma_{\beta^{-1}} < 0.1$
- $\beta_{Tk} < 0.80$
- $m_{avg} > 100$ GeV





Error bar: 50% syst on trigger efficiency - background free analysis

Goal: <1 bg event for L=1fb^{-1}

Stopped r-hadrons

Stopped muons from the ICARUS T600 module (http://arxiv.org/abs/hep-ex/0309023)

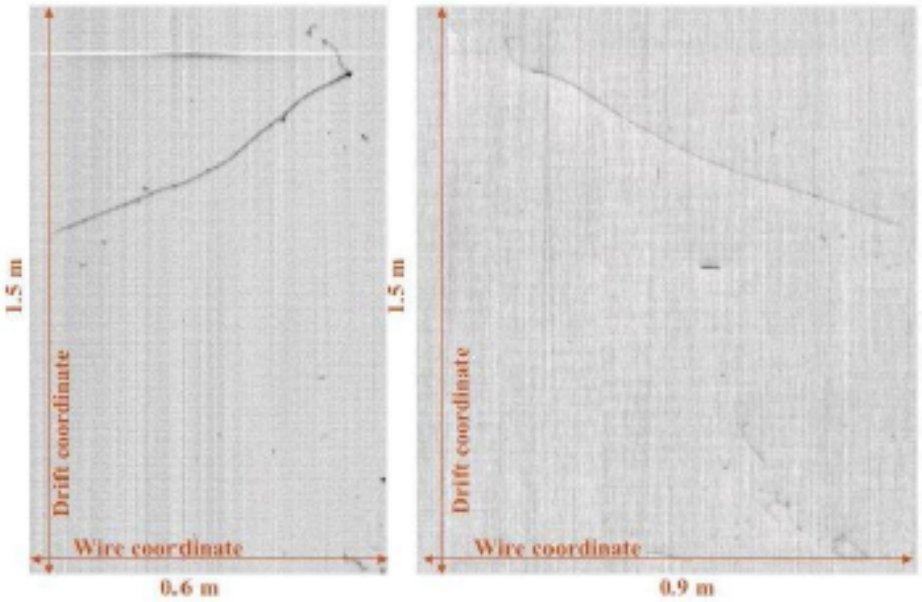


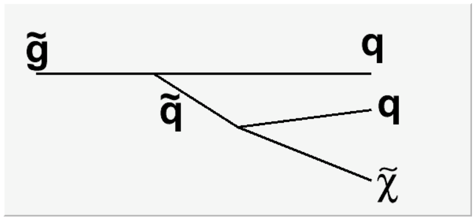
Fig. 1. Run 966 Event 8 Right chamber: muon decay event views corresponding to the Collection (left) and second Induction (right) wire planes.

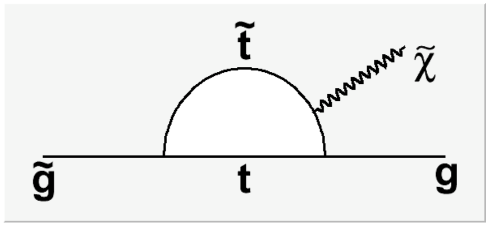
Muon ranges out in calorimeter, then decays to an electron (plus neutrinos)
Hadronized gluino ranged out and then decays to Jet(s) (+MET)

Production and stopping

gluinos at $\sqrt{s}$ = 10 TeV ($q\bar{q} \to \tilde{g}\tilde{g}$, $gg \to \tilde{g}\tilde{g}$)

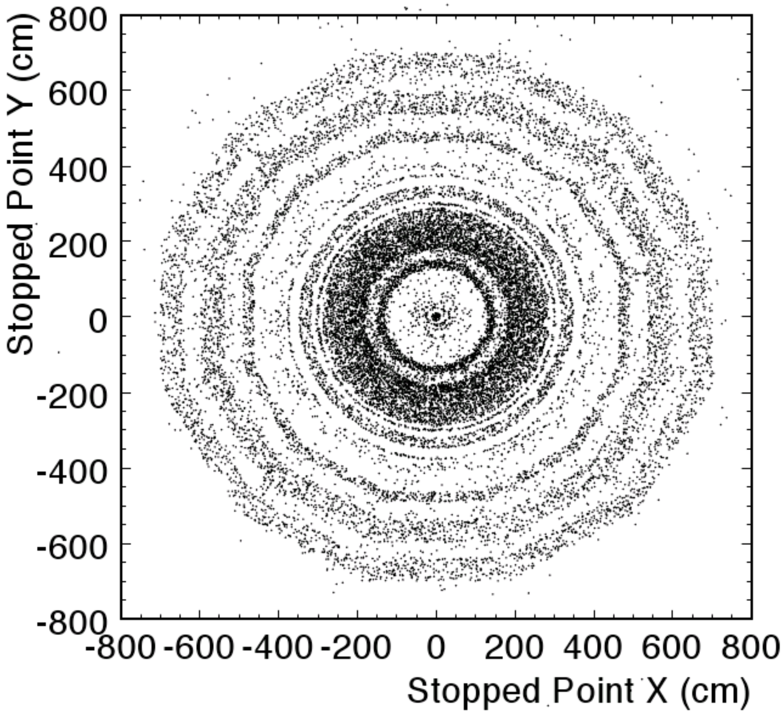
decays $\Delta_{\tilde{g}}^{++} \to \tilde{g}u(uu) \to g\tilde{\chi}_1^0 u(uu)$

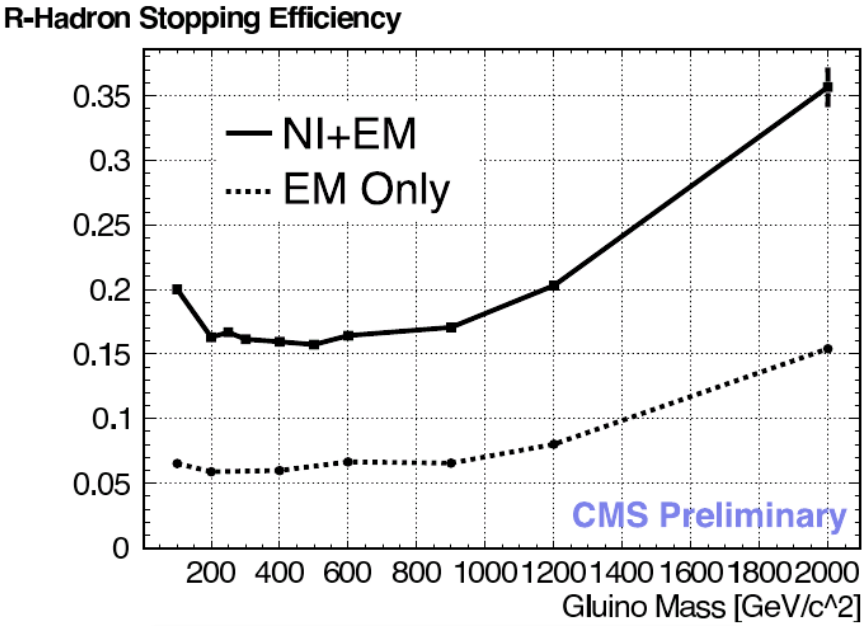




When stop

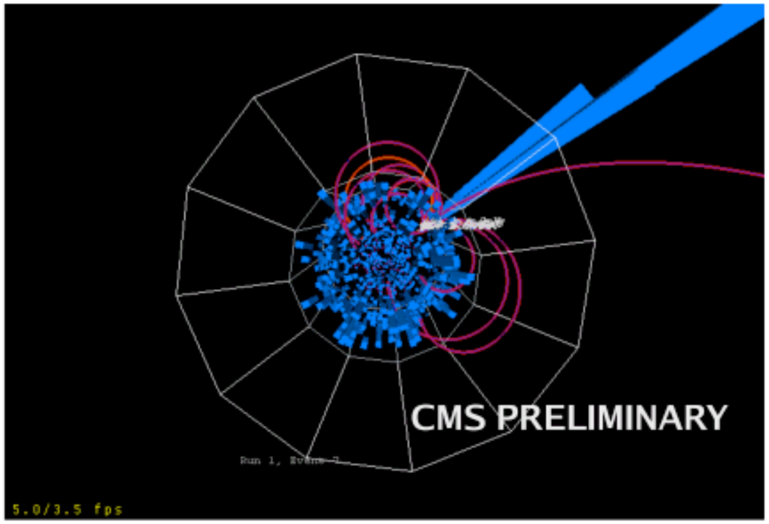
$\Delta_{\tilde{g}}^{++}$	49%
$\Delta_{\tilde{g}}^{+}$	20%
$\Delta_{\tilde{g}}^{-}$	25%
R-meson	6%

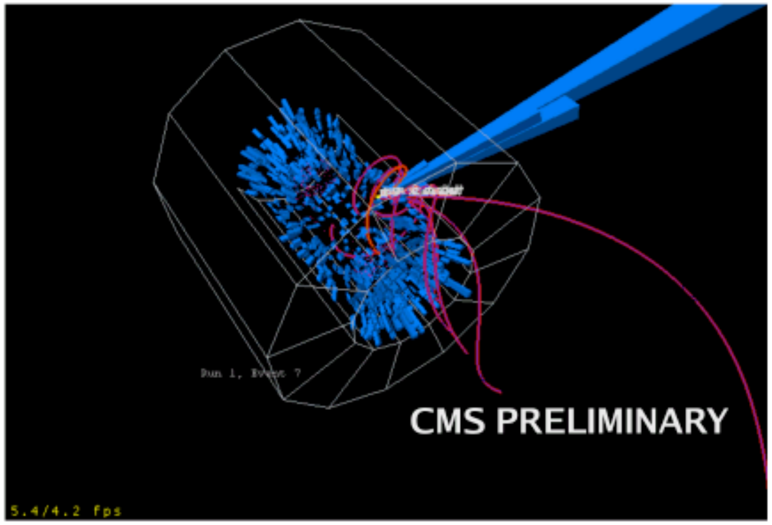


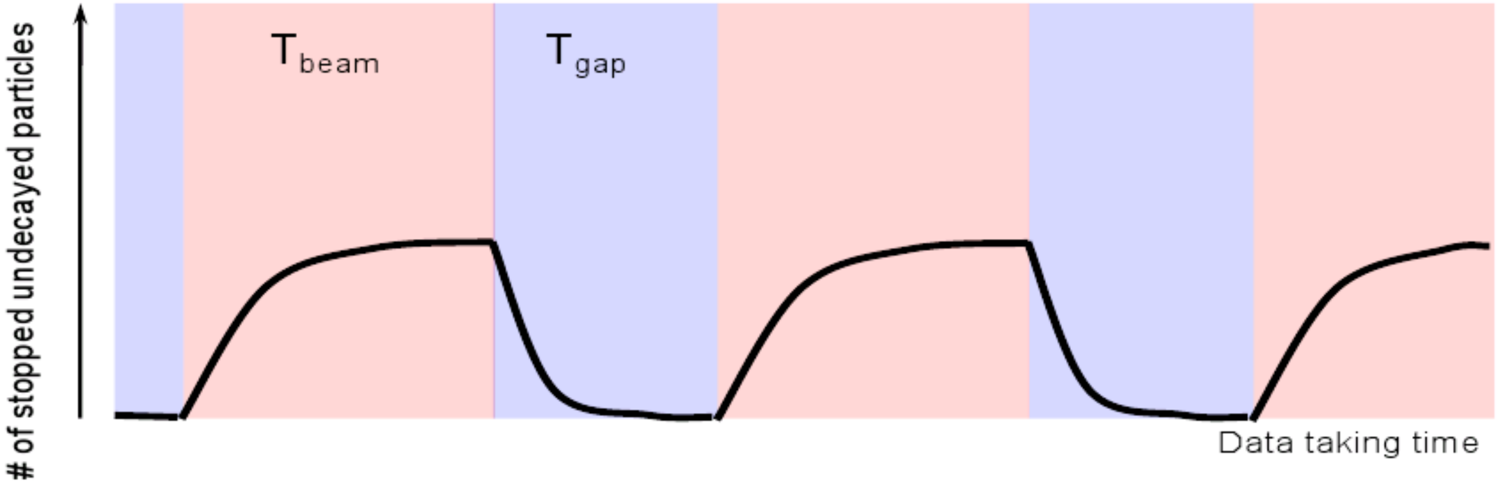


50% of these stop in HCAL

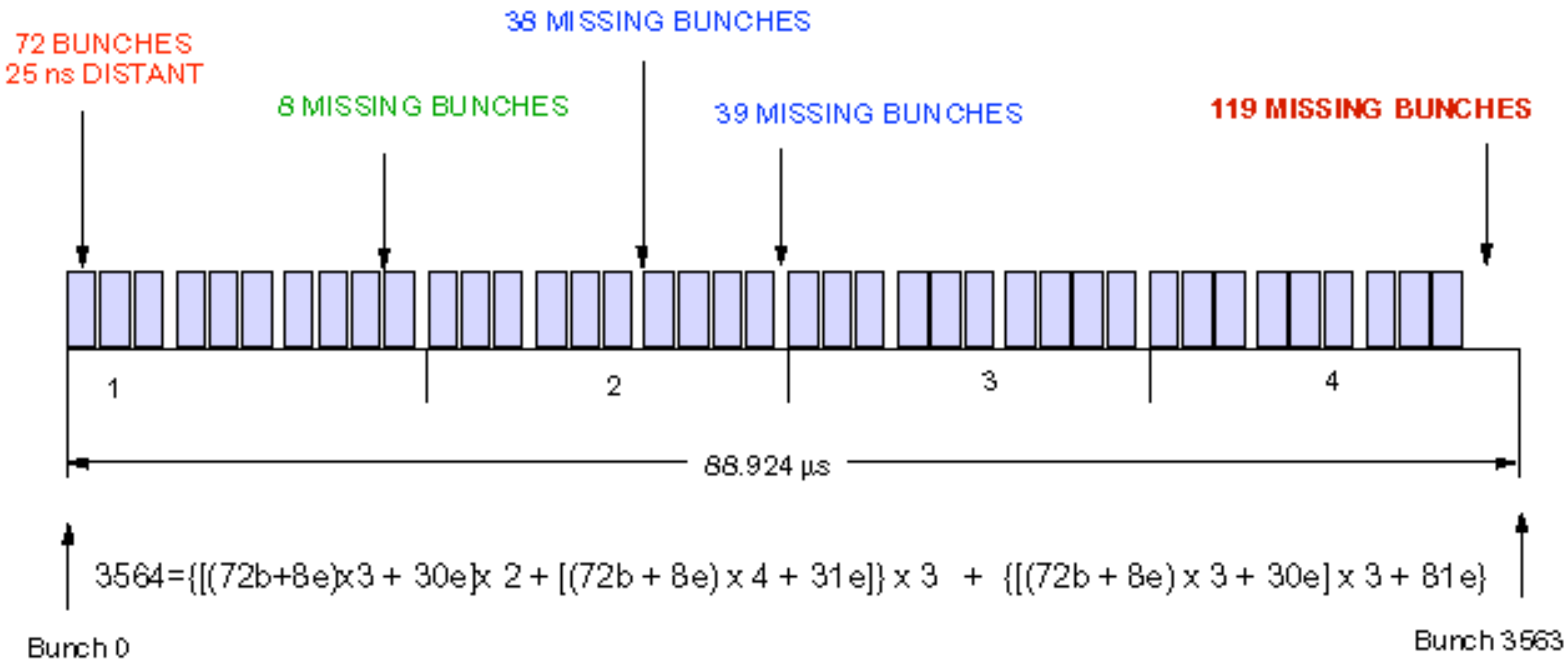
decays


CMS PRELIMINARY
5.0/3.5 fps

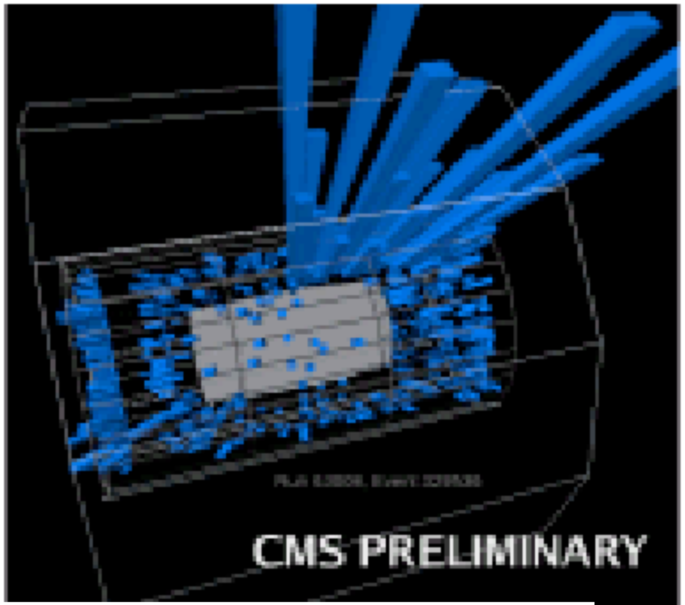

CMS PRELIMINARY
5.4/4.2 fps

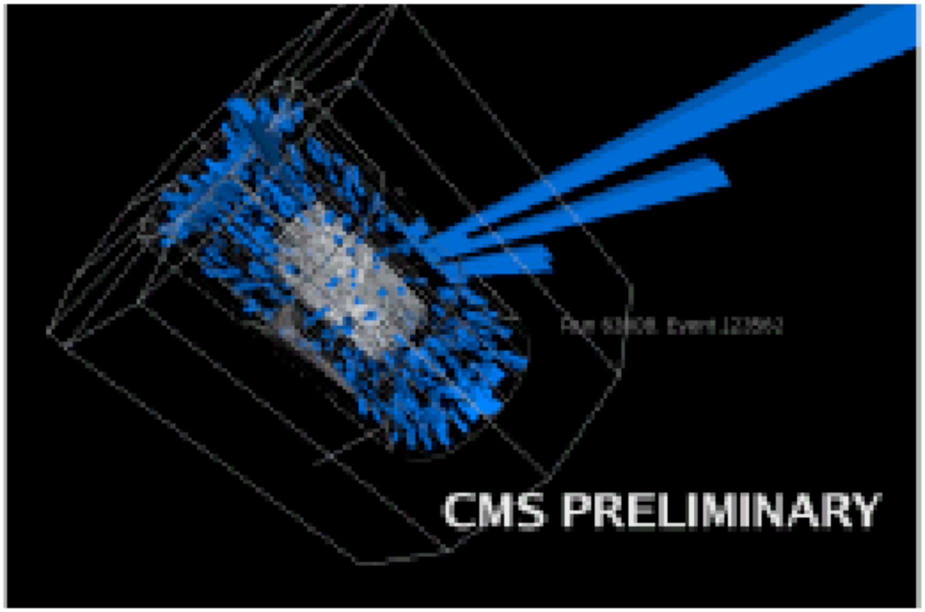

T_{beam}
T_{gap}
# of stopped undecayed particles
Data taking time

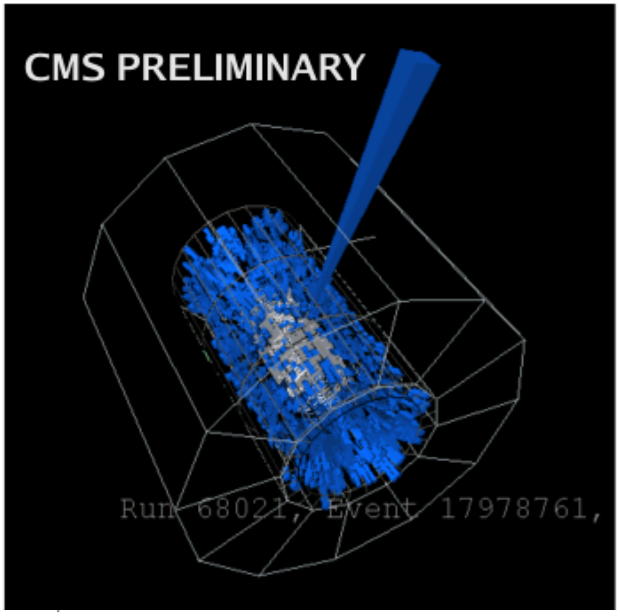
trigger

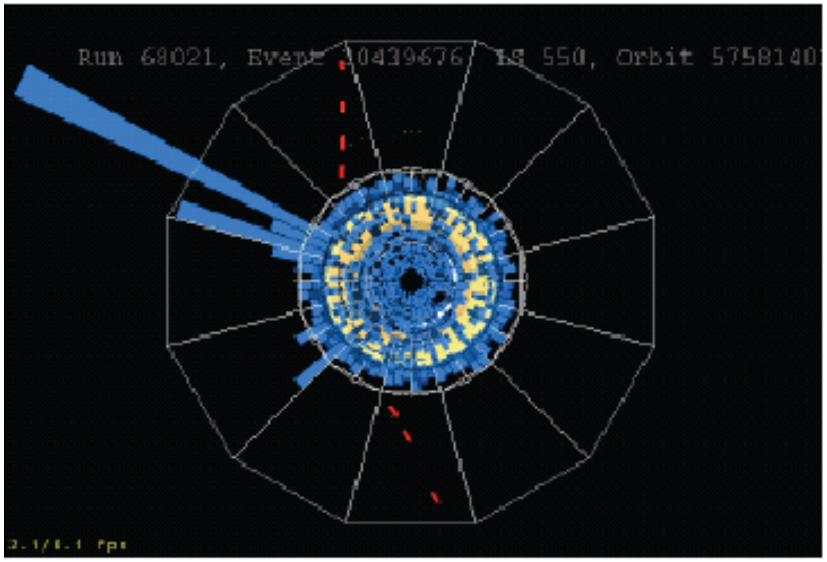

72 BUNCHES
25 ns DISTANT
8 MISSING BUNCHES
38 MISSING BUNCHES
39 MISSING BUNCHES
119 MISSING BUNCHES
1
2
3
4
88.924 µs
3564={[(72b+8e)x3 + 30e]x 2 + [(72b + 8e) x 4 + 31e]} x 3 + {[(72b + 8e) x 3 + 30e] x 3 + 81e}
Bunch 0
Bunch 3563

background





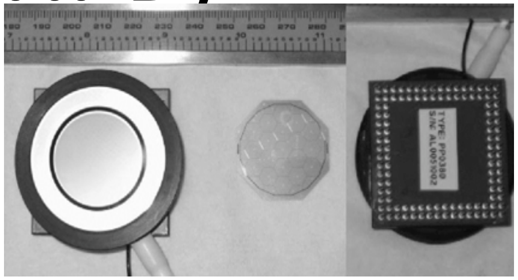


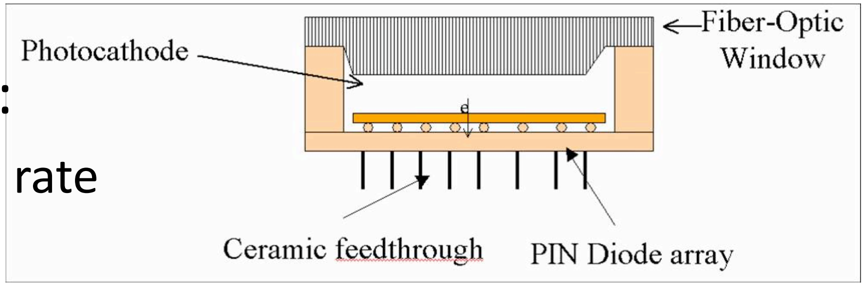


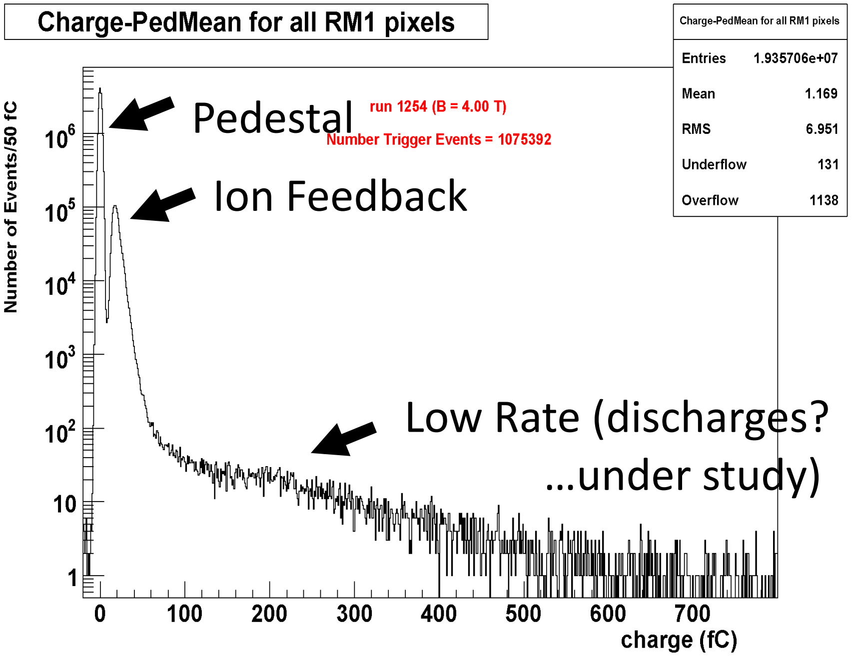
Data taken during cosmic ray data taking includes cosmics and HPD discharge

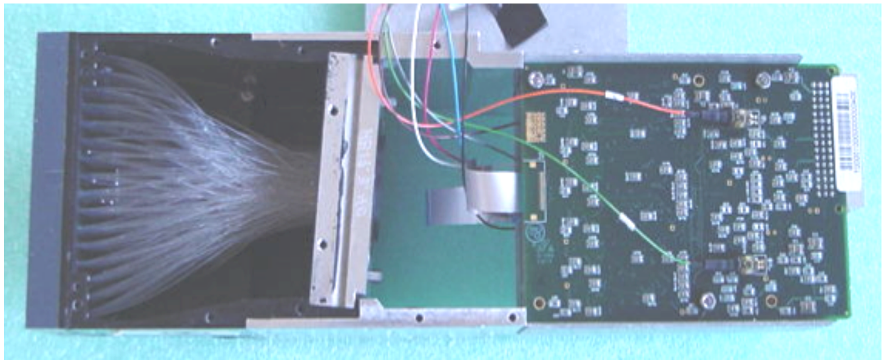
Hybrid Photo-diode (HPD)

- QE ~ 15%
- Gain 1500 ~ 2000 depending on voltage
  - Running at high voltage, 7~8kV
- Has typical features of vacuum tubes:
  - Discharges (HV + dielectric!) but at a low rate
  - Some ion feedback
- Very complex optical-to-HPD (ODU)









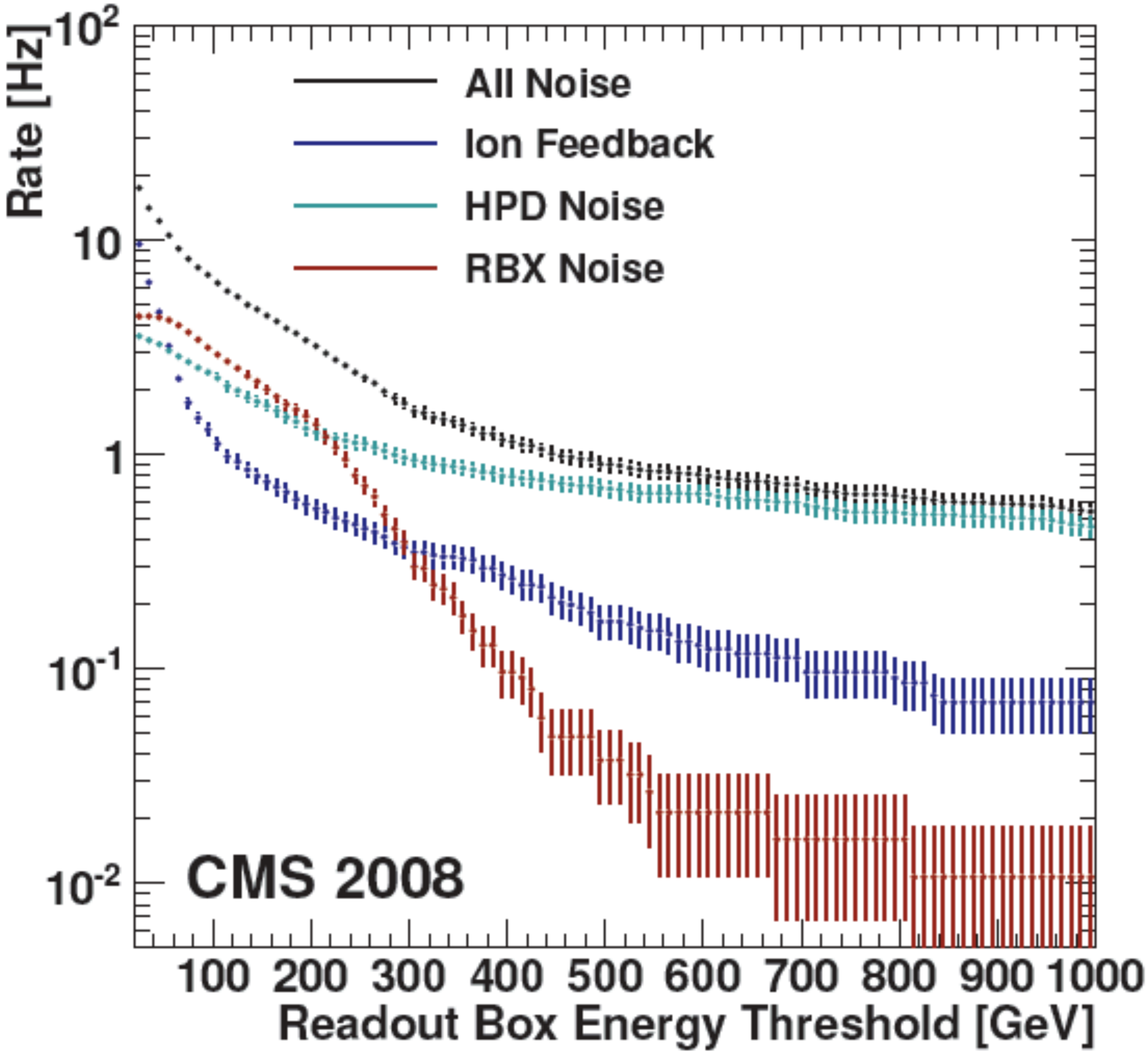
Noise

Ion Feedback. HCAL HPDs occasionally generate appreciable signals even when no light is incident on their photo-cathodes. Such signals are predominantly caused by a thermally emitted electron ionizing a gas or surface molecule in the acceleration gap of the HPD. That ion is accelerated back to the cathode and liberates further electrons, causing a signal equivalent to many photo-electrons. This behavior typically manifests as a significant energy deposit within one to three channels of a given HPD within a single event.

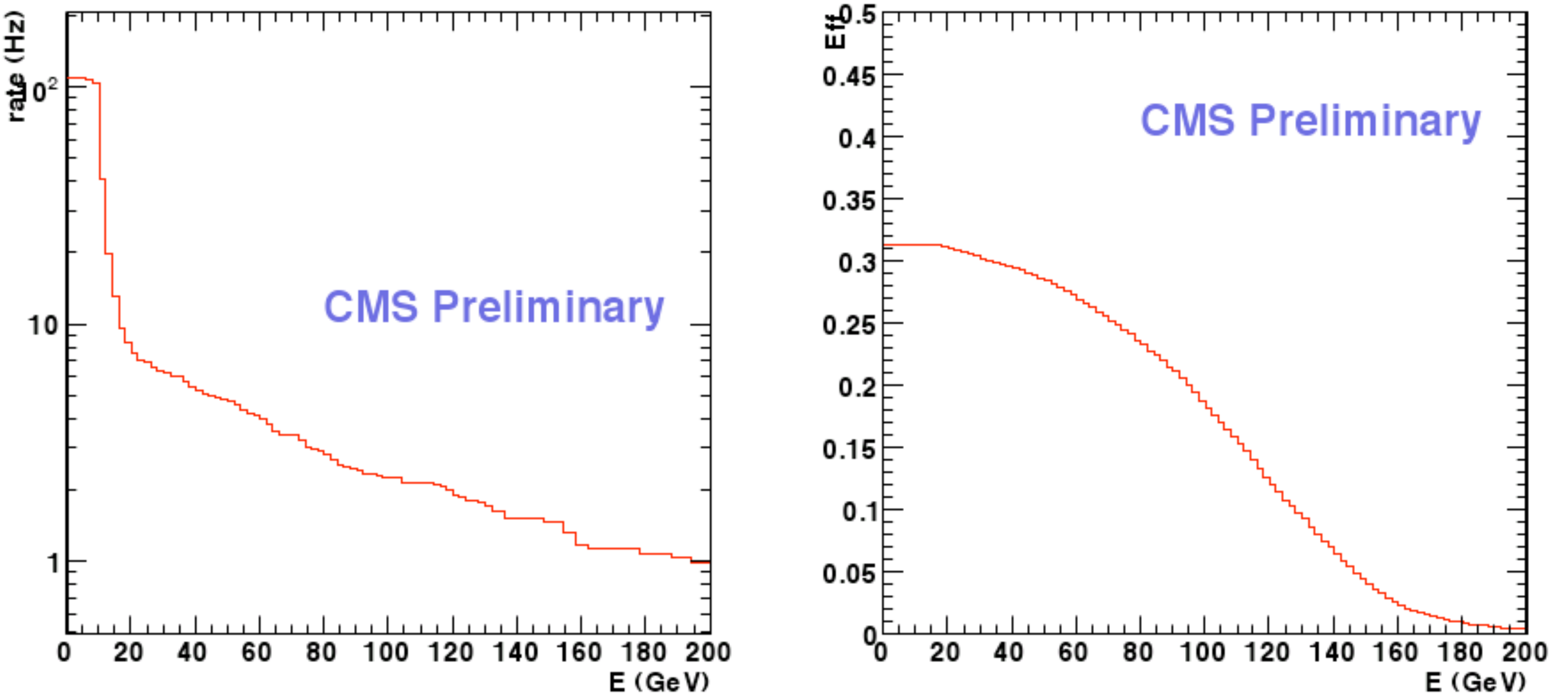
HPD Noise. It is known that the presence of an external magnetic field can alter the flashover voltage of dielectric materials (see reference [4]). Misalignments between the electric field within an HPD and the external solenoid field can lower the flashover voltage of the HPD. This can lead to an avalanche of secondary electrons, producing significant energy deposition in a large number of channels within an HPD. However, large energy deposits in multiple HPD channels have been observed even with the solenoid field off, and the source of these deposits is still under investigation. Signals appearing in a large number of channels within a single HPD, regardless of the state of the magnetic field, are categorized under the heading “HPD noise”.

RBX Noise. Events have been observed in which nearly all of the 72 channels within a single HB or HE RBX report large observed energies. Though the cause of this is not yet well understood, its distinctive signature allows it to be easily identified within an event.

HCAL Noise

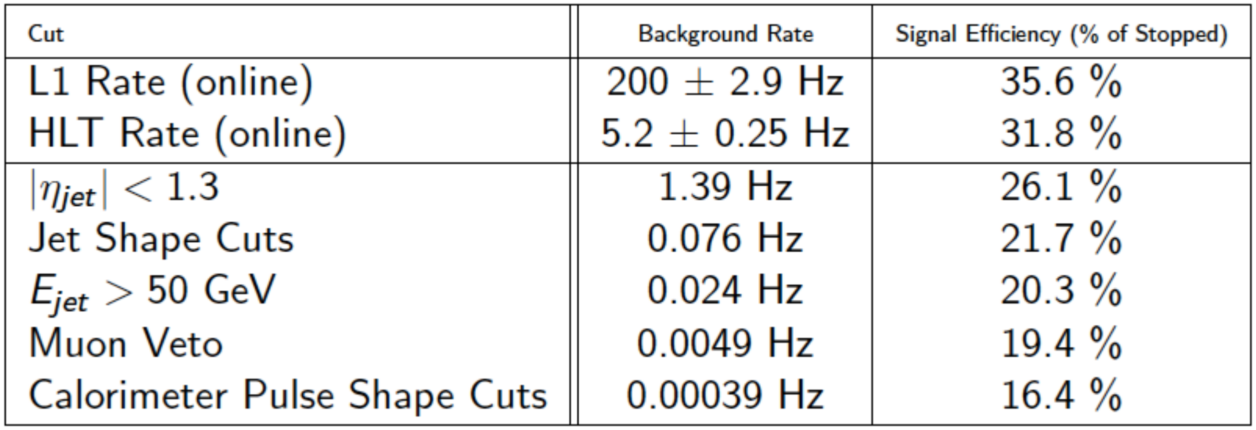

Rate [Hz]
10^2
10
1
10^{-1}
10^{-2}
All Noise
Ion Feedback
HPD Noise
RBX Noise
CMS 2008
100 200 300 400 500 600 700 800 900 1000
Readout Box Energy Threshold [GeV]

Rate and efficiency

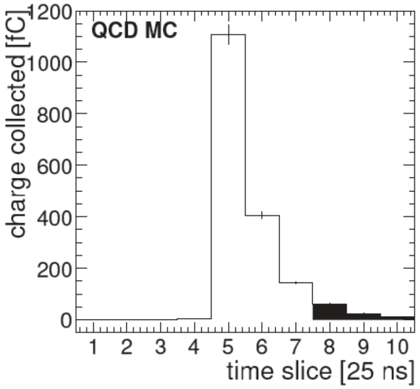


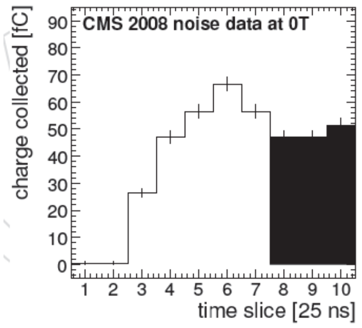
Rate for background and signal efficiency versus reconstructed jet energy before replacing the noisiest HPD's (summer 2008)

Noise reduction



Cut	Background Rate	Signal Efficiency (% of Stopped)
L1 Rate (online)	200 ± 2.9 Hz	35.6 %
HLT Rate (online)	5.2 ± 0.25 Hz	31.8 %
$\|\eta_{jet}\| < 1.3$	1.39 Hz	26.1 %
Jet Shape Cuts	0.076 Hz	21.7 %
$E_{jet} > 50$ GeV	0.024 Hz	20.3 %
Muon Veto	0.0049 Hz	19.4 %
Calorimeter Pulse Shape Cuts	0.00039 Hz	16.4 %

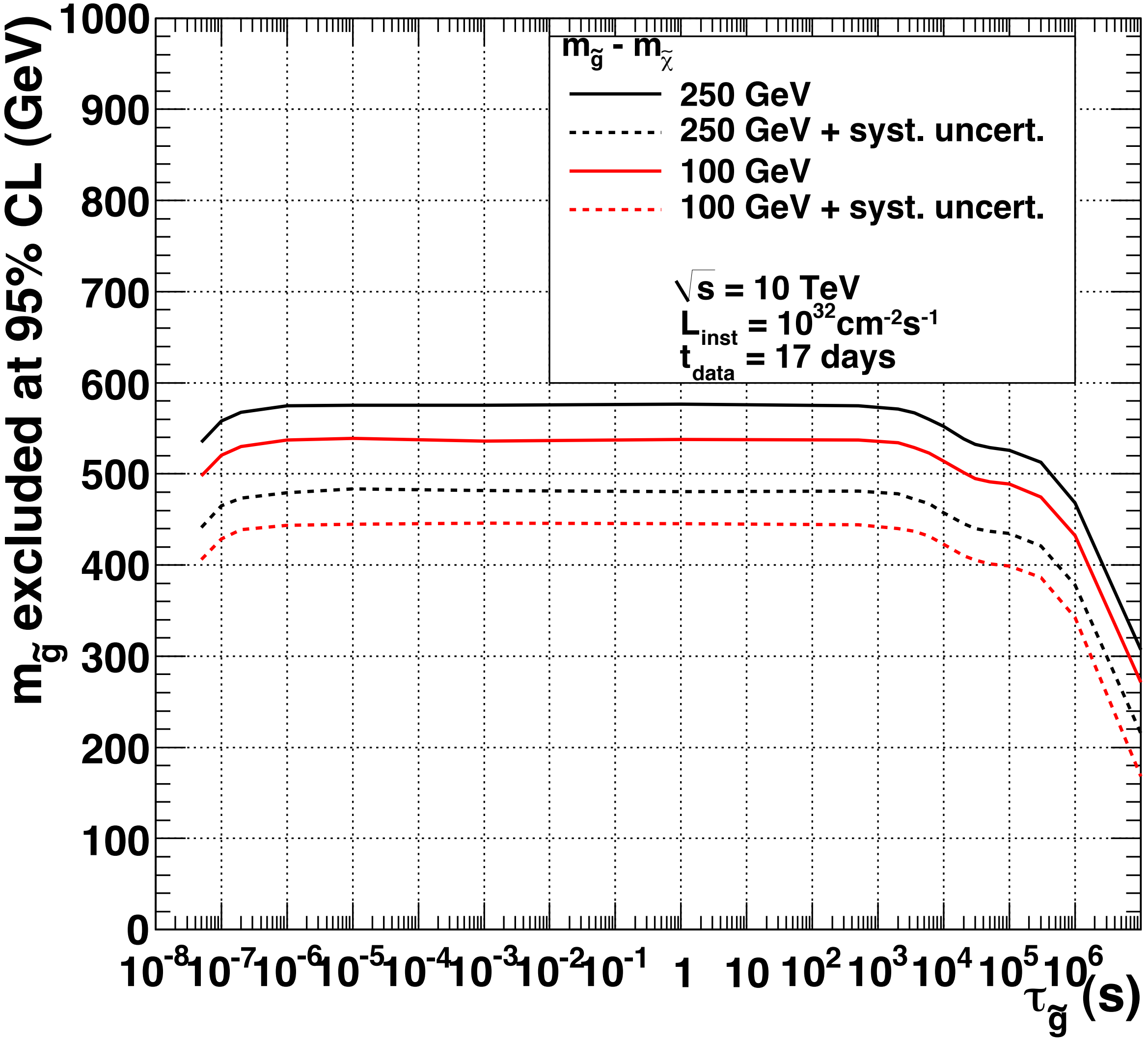




Jet shape cuts: require leading 3 towers contain <90% of energy. Require leading 6 towers contain at least 60% of the energy.

Calorimeter pulse shape cuts: ratio of energy in trigger time bucket to the one that follows and the energy in the 3rd to second. Reject events that have significant energy 3,4, or 5 time slices away.

reach

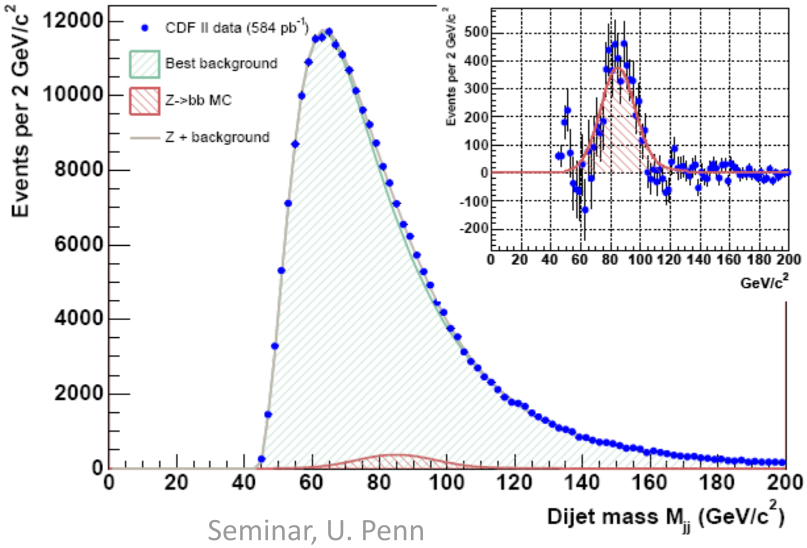

$m_{\tilde{g}}$ excluded at 95% CL (GeV)
0
100
200
300
400
500
600
700
800
900
1000
10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}
$\tau_{\tilde{g}}$ (s)
$m_{\tilde{g}} - m_{\tilde{\chi}}$
250 GeV
250 GeV + syst. uncert.
100 GeV
100 GeV + syst. uncert.
$\sqrt{s}$ = 10 TeV
$L_{inst} = 10^{32} cm^{-2}s^{-1}$
t_{data} = 17 days

Dijet searches

All though cross section is strong, can still be challenging due to

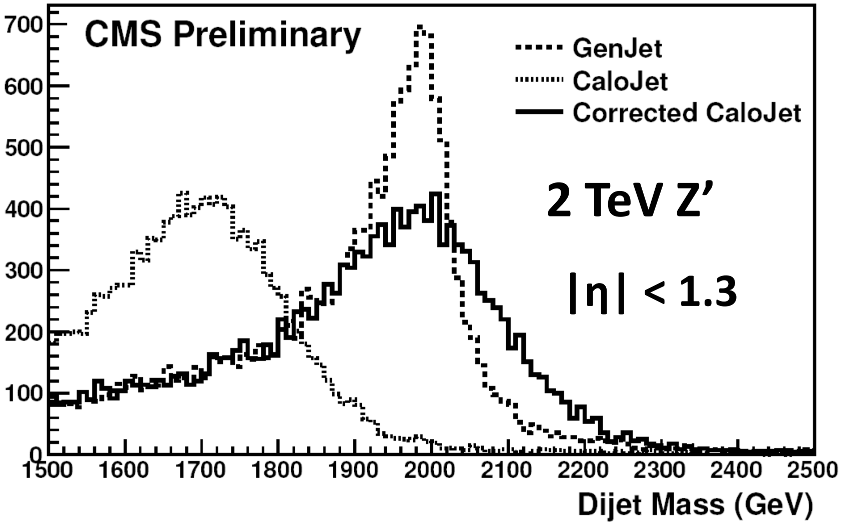
- large SM background
- poor jet energy resolution (compared to e,mu resolutions) and eta-dependent JES that can further degrade resolution until it is understood and removed.
- tails on resolution due to FSR

How can we make this more robust and do it with early data?

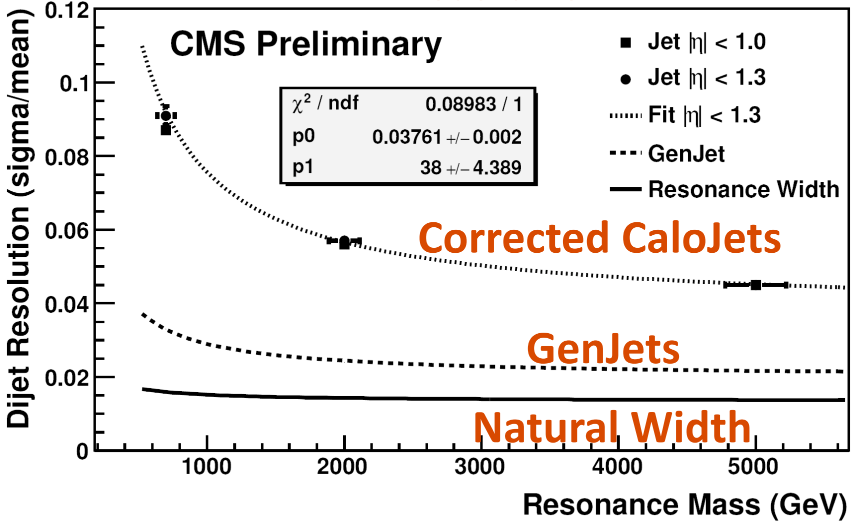


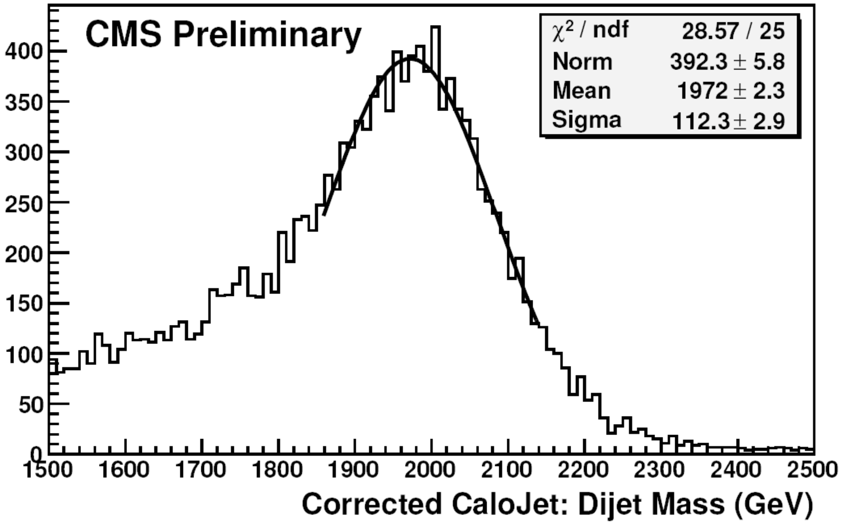
Dijet Mass Resolution

- Resolution for corrected CaloJets
  - 9% at 0.7 TeV
  - 4.5% at 5 TeV
- Tails due to FSR (gluon)



Resolution



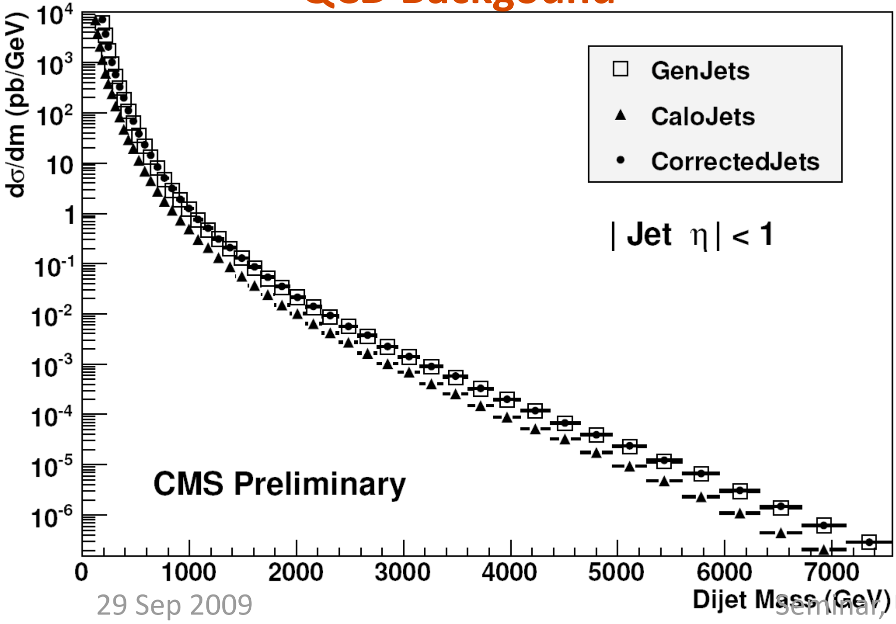


Dijet Resonances in Rate vs. Dijet Mass

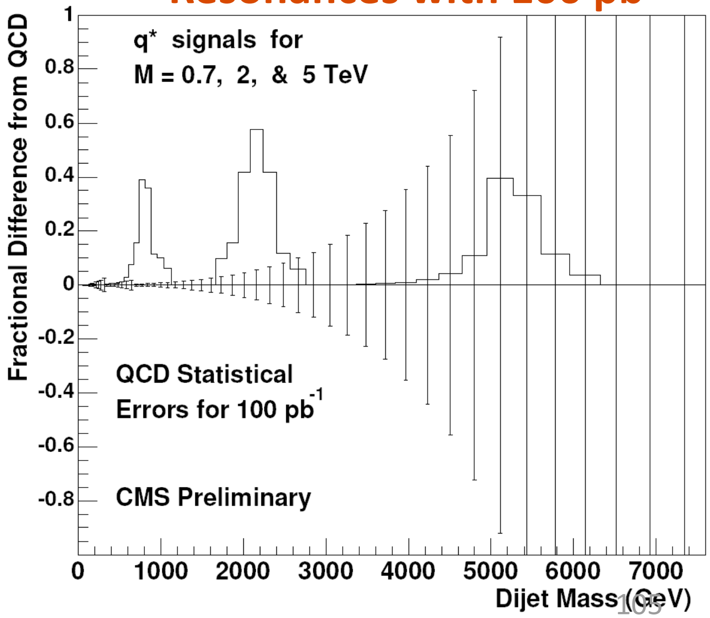
- Measure rate vs. corrected dijet mass and look for resonances.
  - Use a smooth parameterized fit or QCD prediction to model background
- Strongly produced resonances can be seen
  - Convincing signal for a 2 TeV excited quark in 100 pb^{-1}
    - Tevatron excluded up to 0.78 TeV.

Spectrum falling quickly enough that will not really see bump (remember Z to bbbar)

QCD Backgound



Resonances with 100 pb^{-1}

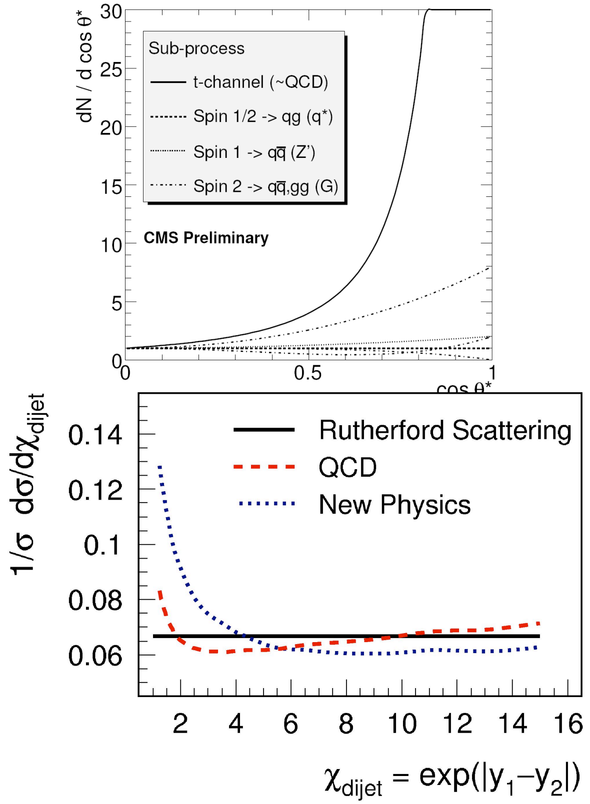


Dijet Resonances with Dijet Ratio

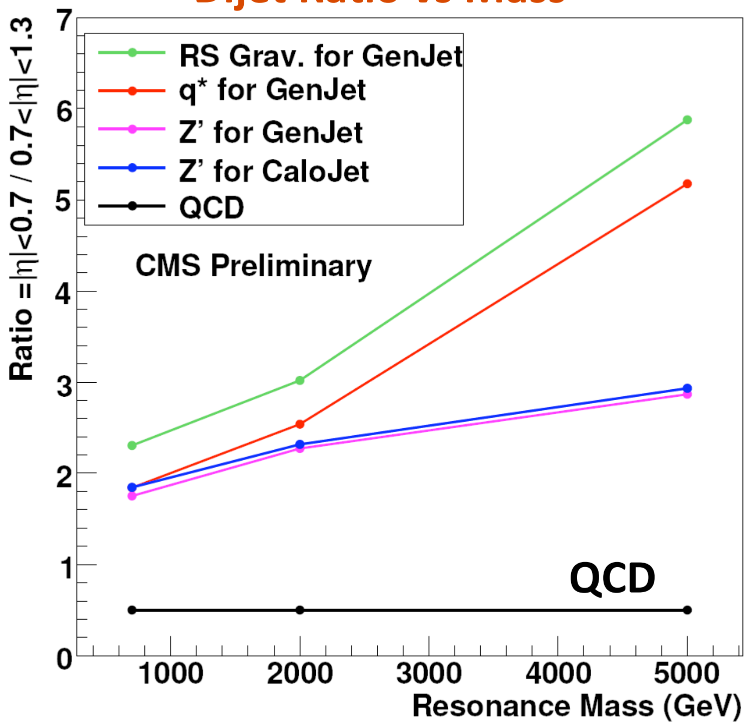
- All resonances have a more isotropic decay angular distribution than QCD
  - Spin ½ (q*), spin 1 (Z'), and spin 2 (RS Graviton) all flatter than QCD in dN / dcosθ*.

- Dijet ratio is larger for resonances than for QCD.
  - Because numerator mainly low cos θ*, denominator mainly high cos θ*

Dijet Angular Distributions



Dijet Ratio vs Mass



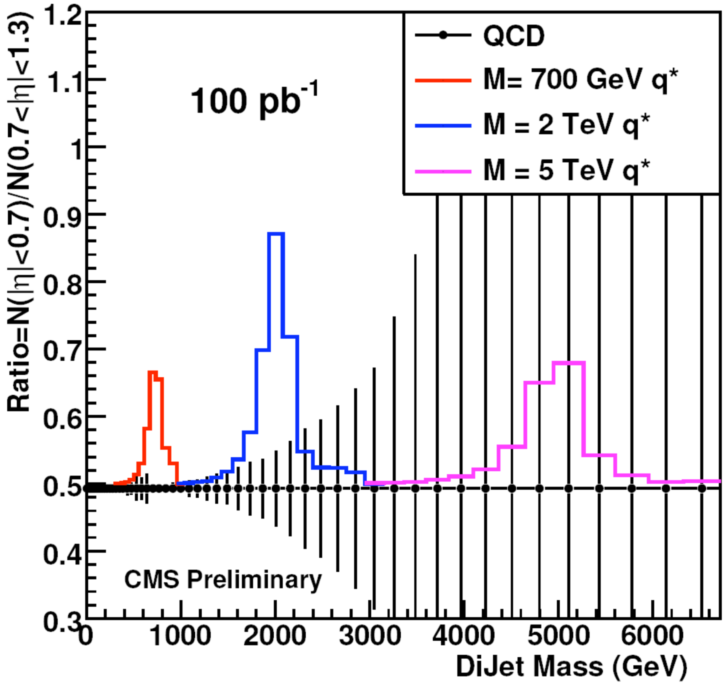
Dijet Resonances with Dijet Ratio

- Dijet ratio from signal + QCD compared to statistical errors for QCD alone
  - Resonances normalized with q* cross section for |η|<1.3 to see effect of spin.

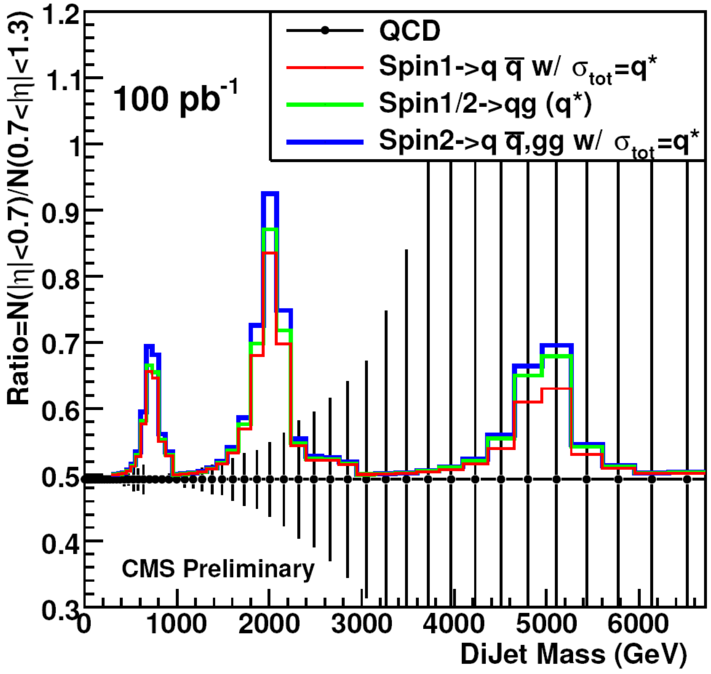
- Convincing signal for 2 TeV strong resonance in 100 pb^{-1} regardless of spin.

- Promising technique for discovery, confirmation, and eventually spin measurement.

Dijet Ratio for q*



Dijet Ratio for Spin ½, 1, 2



Conclusions