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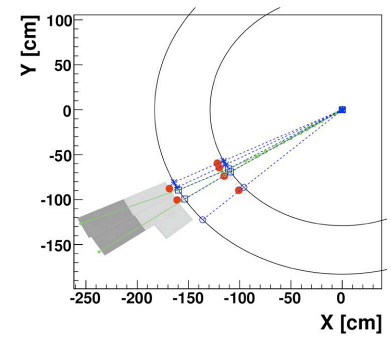
UIC University of Illinois at Chicago

“Physics at the LHC with Jets and Missing Energy”

R. Cavanaugh
Fermi National Accelerator Laboratory
& University of Illinois at Chicago



TIFR, Mumbai, India
26 October, 2009

- Introduction
- Jets
- Jets + MET
- Summary

Caveats and Credits

- Jets and MET are a huge topics
  - Can not cover all in a single hour
  - Thus, I will thus just give a random smattering, being rather selective!

- Also, I would like to thank the following people who contributed slides (without knowing it! :-)
  - Nikos Varelas, Seema Sharma, Henning Flaecher, and many others…

Brief History Hadron Colliders

- 1931: Cyclotron: 1 - 100 MeV protons & deuteron :
  - many isotopes
- 1954: Bevatron: 1 GeV protons:
  - strangeness, Anti-proton, anti-neutron
- 1960: Alternating Gradient Synchroton: 33 GeV protons
  - J/ψ (charm quark), muon neutrino, CP violation
- 1972: Stanford Positron Electron Asymmetric Ring: 3 GeV
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- 1977: Fermilab fixed target: 400 GeV protons
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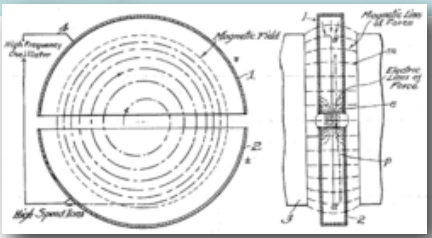
- 1981: Super proton Synchronton: 450 GeV protons & anti-protons
  - W & Z vector bosons (weak nuclear force)
- 1989: Large Electron Positron Collider: 104 GeV e+ e-
  - 3 (light) generations of matter
- 1992: Tevatron: 980 GeV protons & anti-protons
  - Top quark
- 2008: Large Hadron Collider: 7 TeV protons
  - ?

Brief History Hadron Colliders



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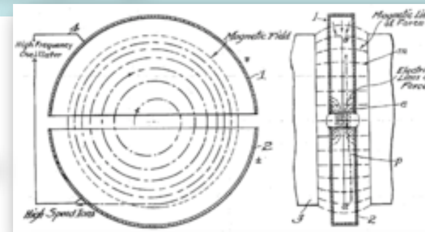

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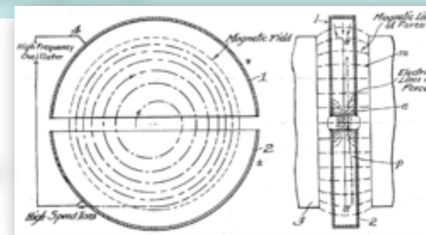

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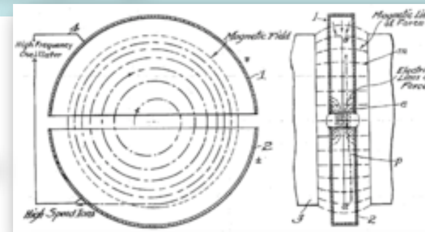

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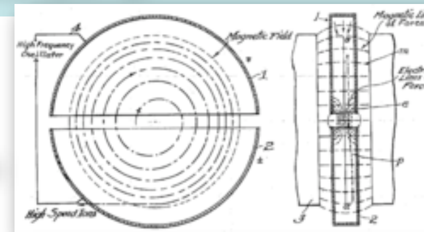

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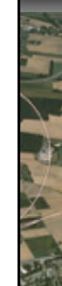

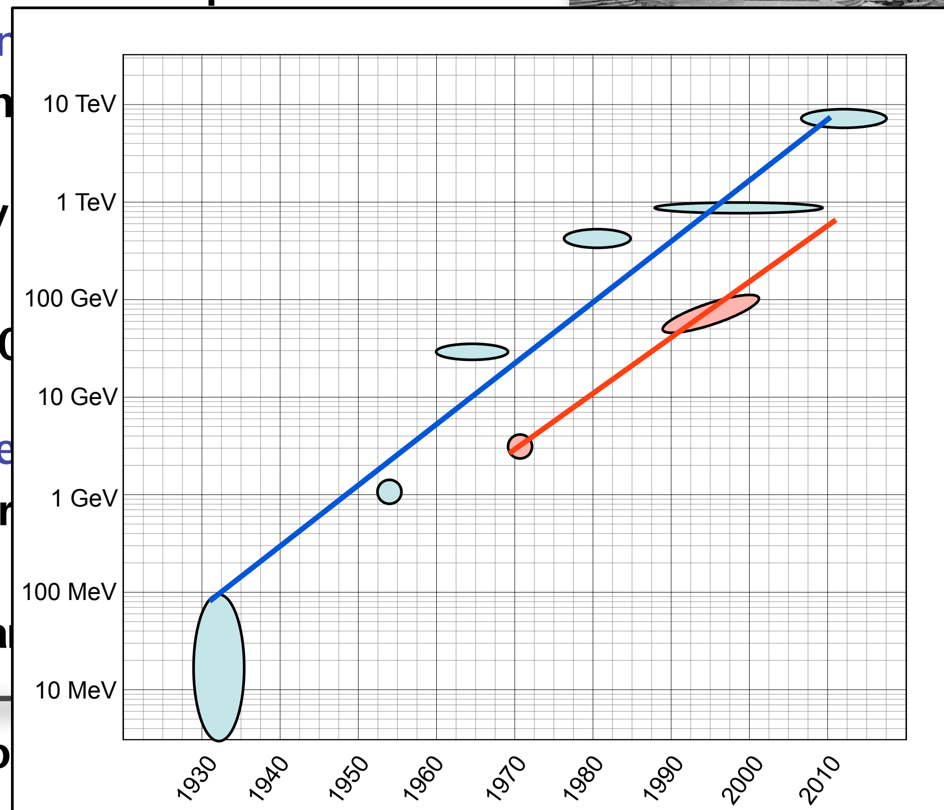

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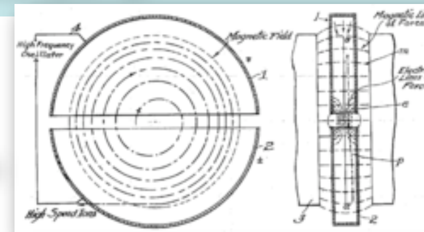

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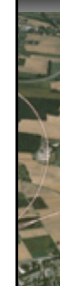

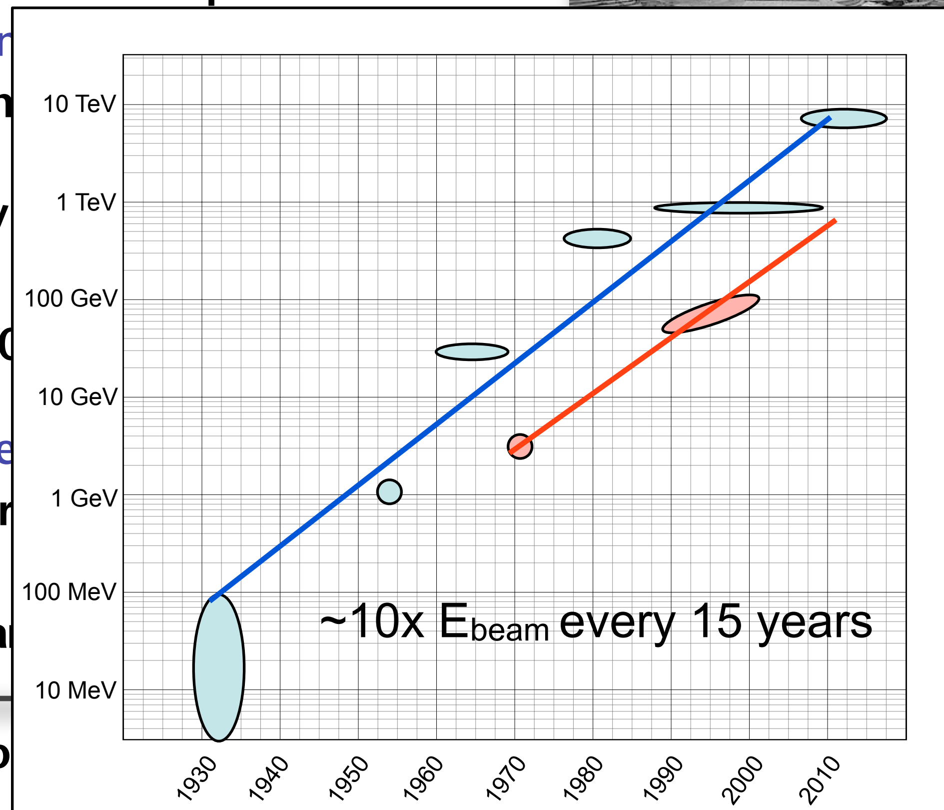

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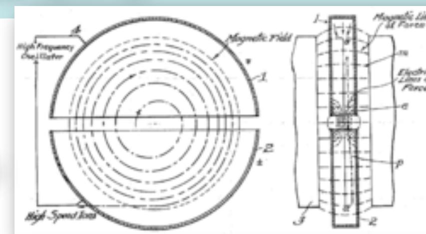
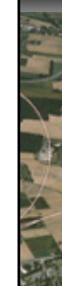
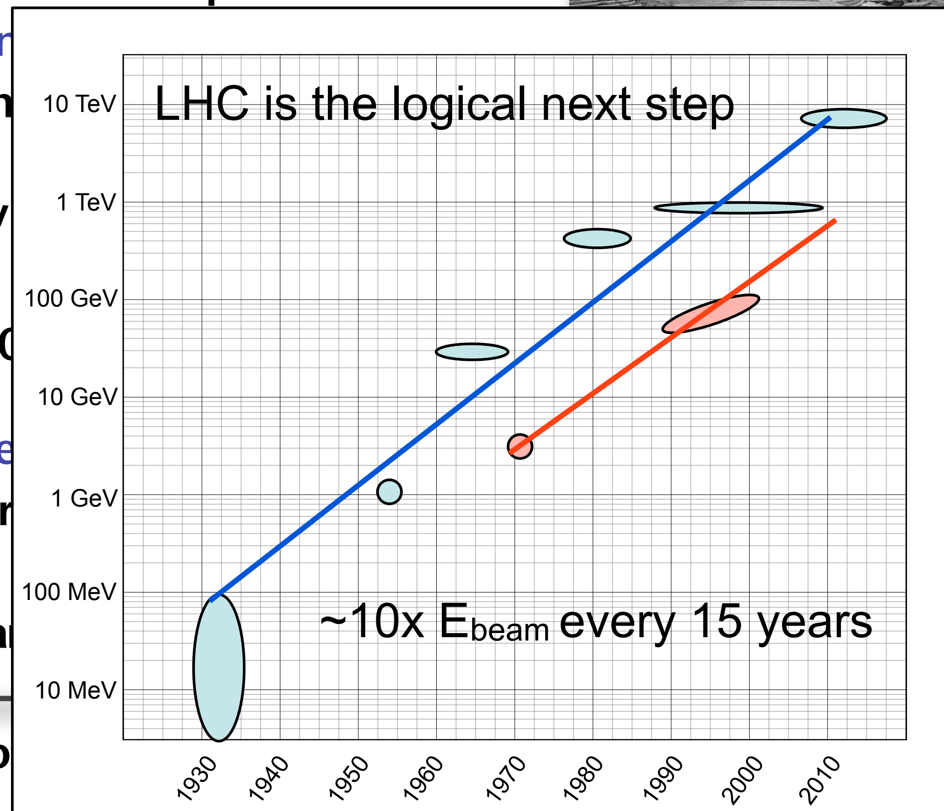
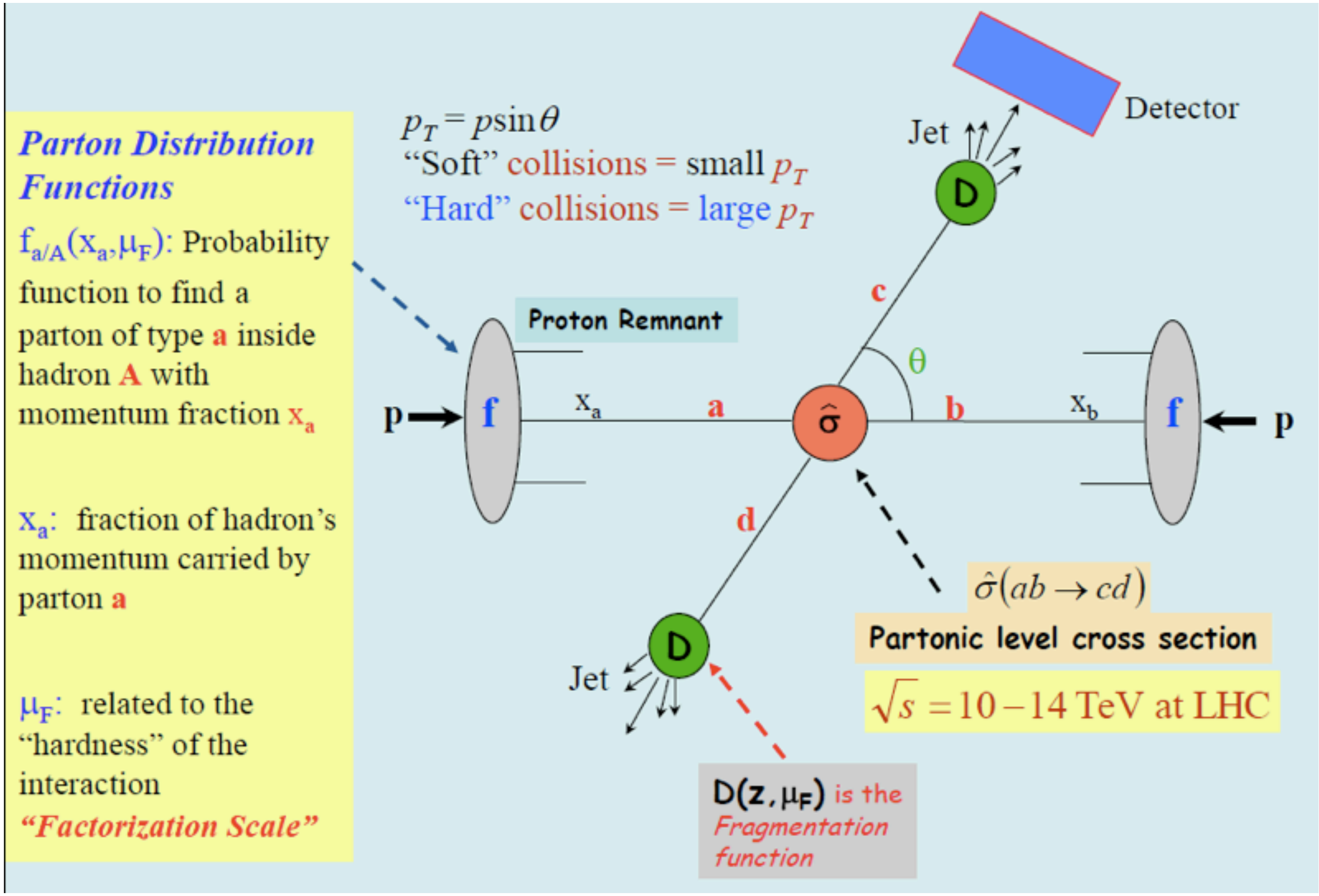






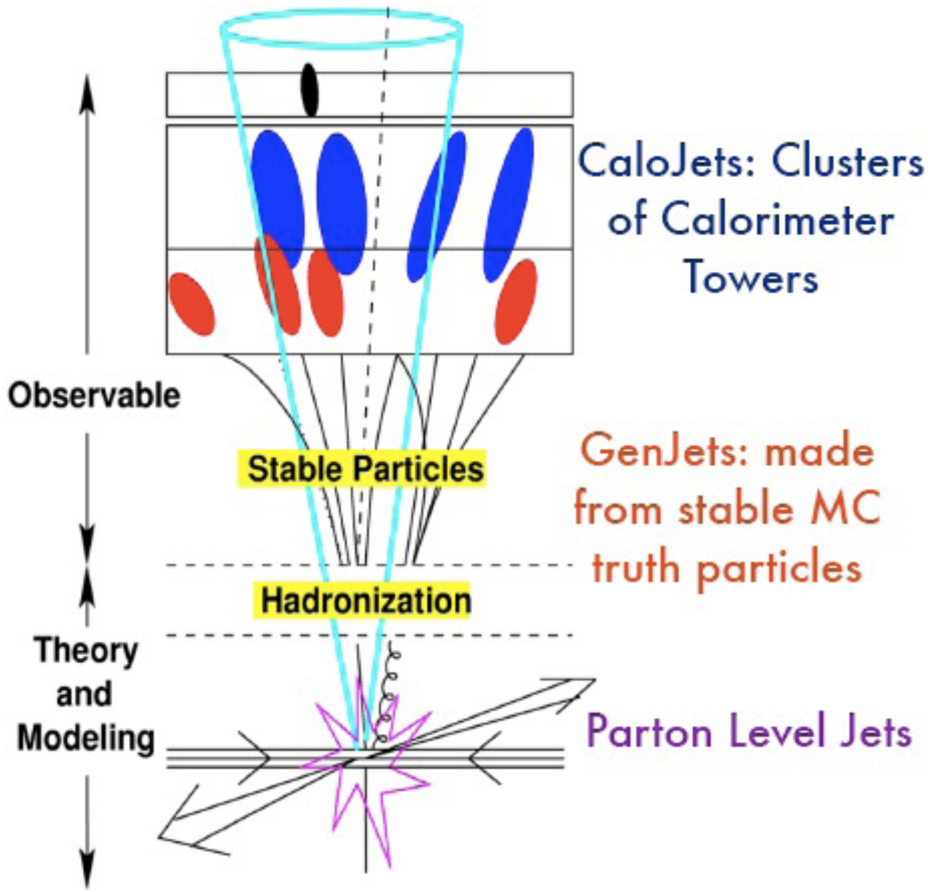
Proton-proton collisions

- See Michalangelo (beautiful) lectures
  - Or better yet, talk to him here at the conference!



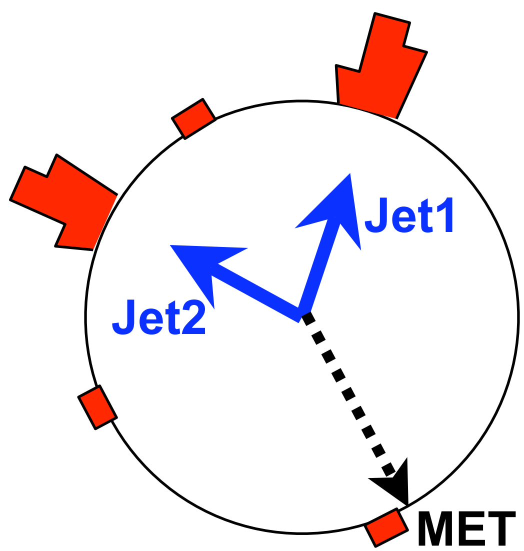
Reconstructing Jets

- See My Lecture on Monday
  - Absolutely no claim to beauty, though!



- **Used to detect weakly interacting particles**
  - **See My Lecture on Monday**

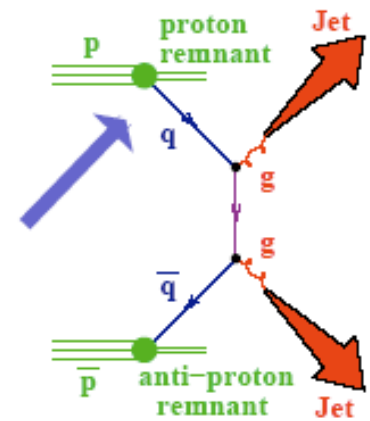
$$\vec{\not{E}}_T = - \sum_{\text{particles}} (p_x \hat{\mathbf{i}} + p_y \hat{\mathbf{j}})$$



ALSO EXCELLENT AT DETECTING TRASH!!

Why do we study jets at hadron colliders?

- QCD Studies
  - Fragmentation functions
  - Parton Distribution Functions
  - Color/spin dynamics
  - Quark-gluon jet properties
  - Event shapes
  - Inclusive-and Multi-jet production
  - Rapidity Gaps/Diffraction
  - Production of Vector Bosons + jets
  - Study of heavy particles (e.g. top production)
- Searches for new physics
  - usually involve MET



→ tests of the proton structure function

$p\bar{p} \rightarrow 2\text{ jets} + X$

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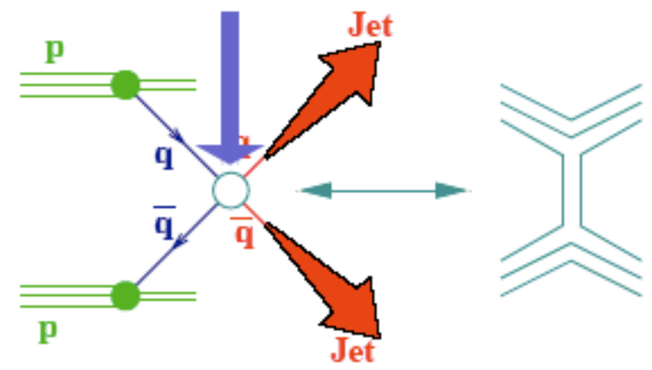
Search for quark substructure:



→ search for quark compositeness

$p\bar{p} \to 2\ \text{jets} + X$

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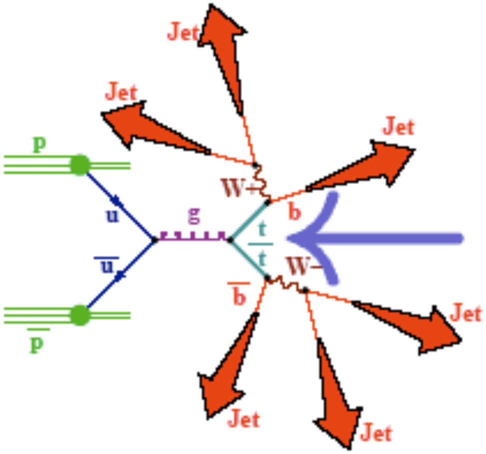
Study of heavy particles:



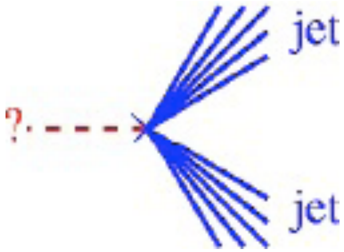
→ measurements of top quark production

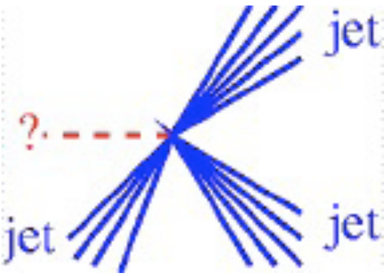
$p\bar{p} \rightarrow 6 \text{ jets} + X$

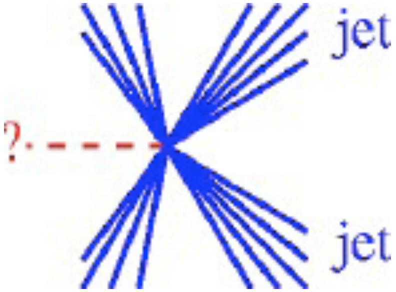
Jet and MET Topologies

- **Final State: A number of Jets + MET**
  - 2 Jets + X
  - 3 Jets + X
  - 4 Jets + X

  - 1 Jet + MET + X
  - 2 Jets + MET + X
  - 3 Jets + MET + X







High pT jet statistics

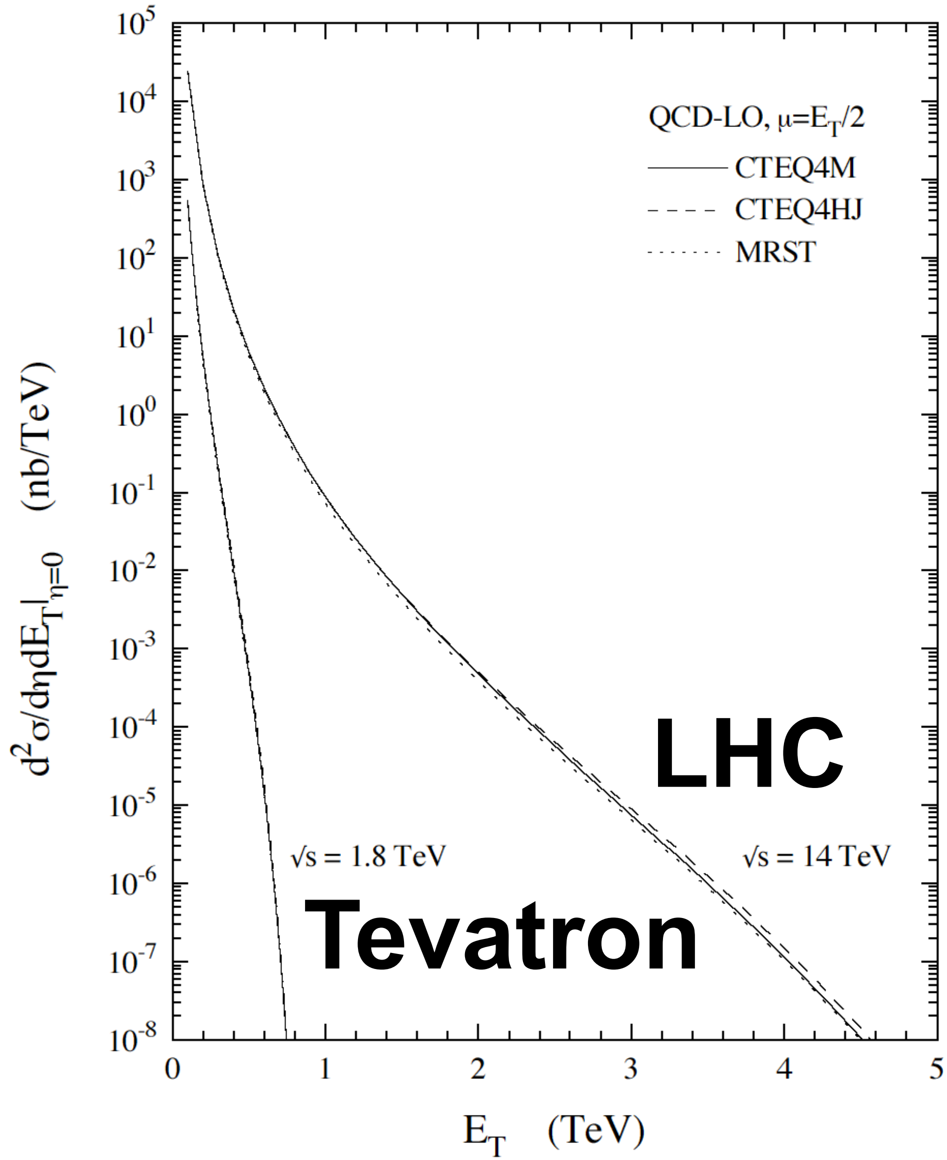
- Inclusive Jets
  - From Tevatron
    - N_{jets} for 700 pb^{-1} $|y| < 0.8$
  - For LHC
    - N_{jets} / pb^{-1} $|y| < 1.3$

sqrt(s)	pT > 0.5 TeV	pT > 1 TeV
2	34 (700 pb^{-1})	-
6	47 / pb^{-1}	0.3 / pb^{-1}
10	321 / pb^{-1}	5 / pb^{-1}
14	865 / pb^{-1}	22 / pb^{-1}

- Dijets
  - From Tevatron
    - ~200 evts for $M_{jj} > 1$ TeV for 700 pb^{-1} & $|\eta_1|,|\eta_2| < 2.4$
  - For LHC
    - # evts / M_{jj} / pb^{-1} for $|\eta_1|,|\eta_2| < 1.3$

sqrt(s)	$M_{jj} > 1$ TeV	$M_{jj} > 1.4$ TeV	$M_{jj} > 2$ TeV
2	~200 (700 pb-1)		
6		8 / pb^{-1}	1 / pb^{-1}
10		53 / pb^{-1}	7 / pb^{-1}
14		138 / pb^{-1}	22 / pb^{-1}

LHC Probes the Terascale

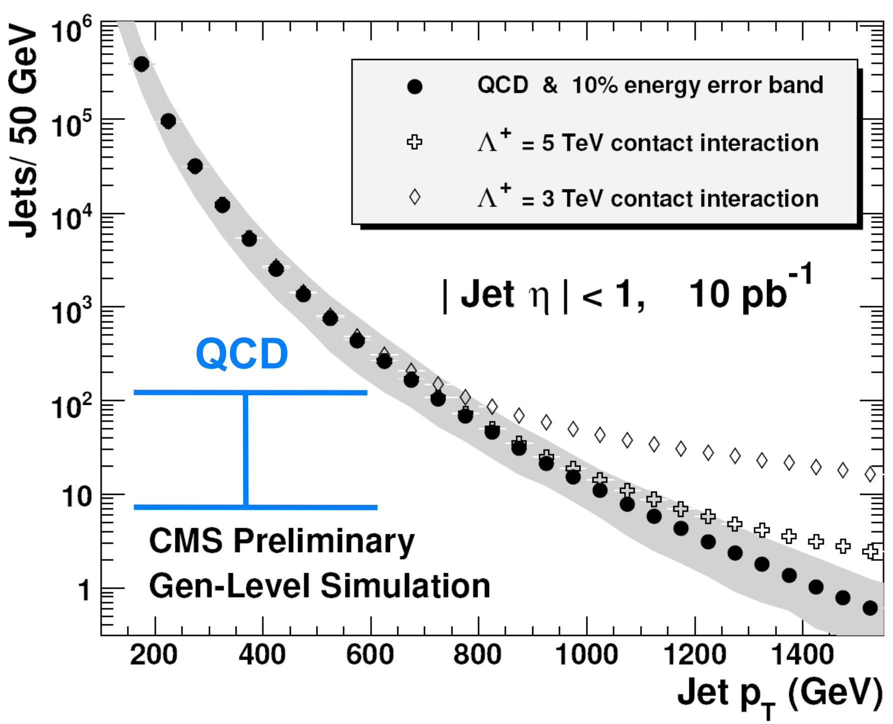


Inclusive Jet Production

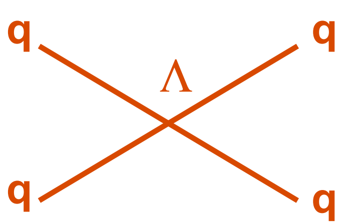
- Contact interactions create large rate at high P_T -- quick discovery possible
  - Error dominated by jet energy scale (~10%) in early running (10 pb^{-1})
    - → ΔE~ 10% not as big an effect as Λ^+= 3 TeV for P_T>1 TeV.
  - PDF "errors" and statistical errors (10 pb^{-1}) smaller than E scale error
- With 10 pb^{-1} LHC can see new physics beyond Tevatron (Λ^+ < 2.7 TeV)

CMS SBM-07-001

Rate of QCD and Contact Interactions



Contact Interaction



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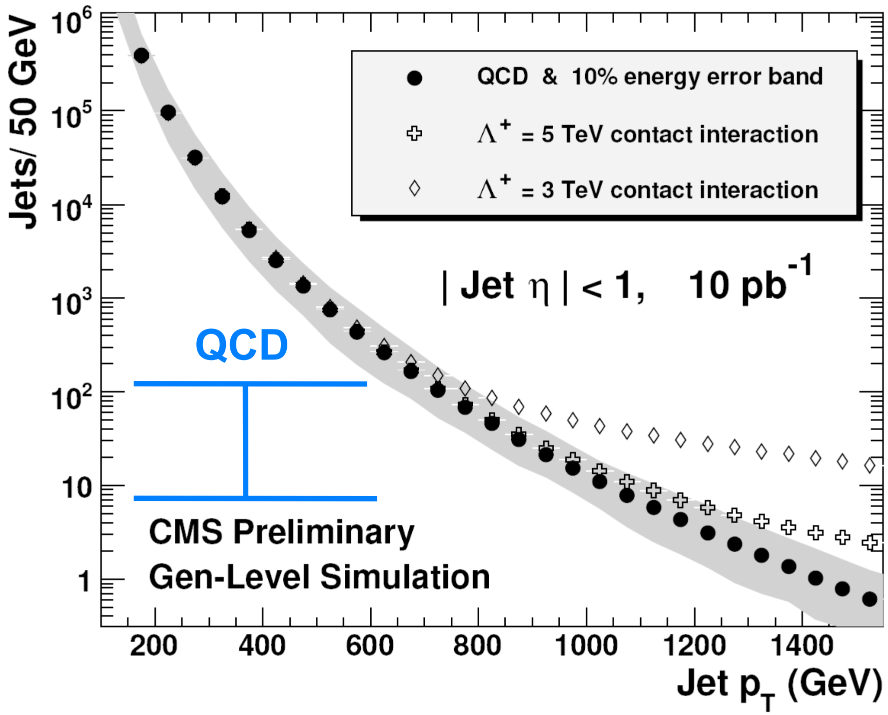

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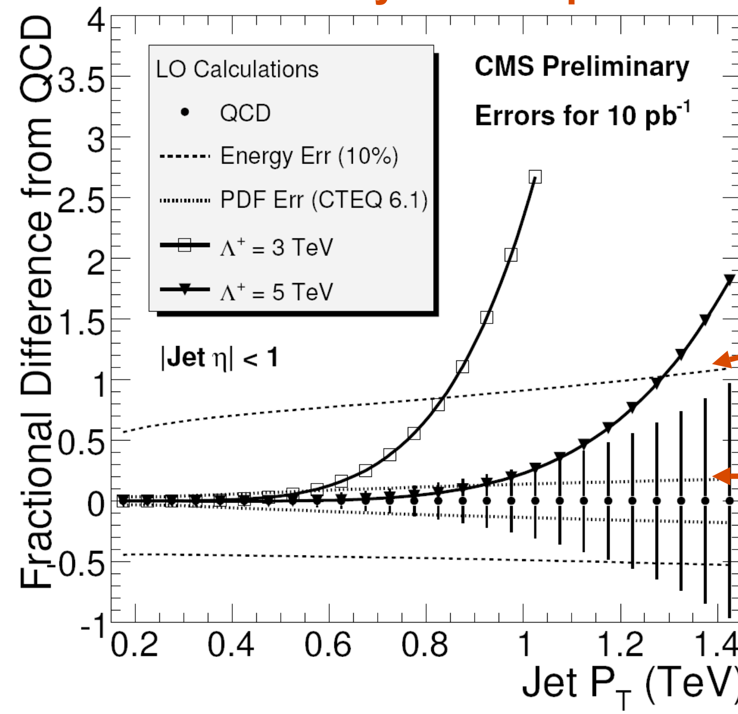
Sensitivity with 10 pb^{-1}



Dijet Production

- 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 (E6) in 100 pb^{-1}
    - Tevatron excluded up to 0.78 TeV.

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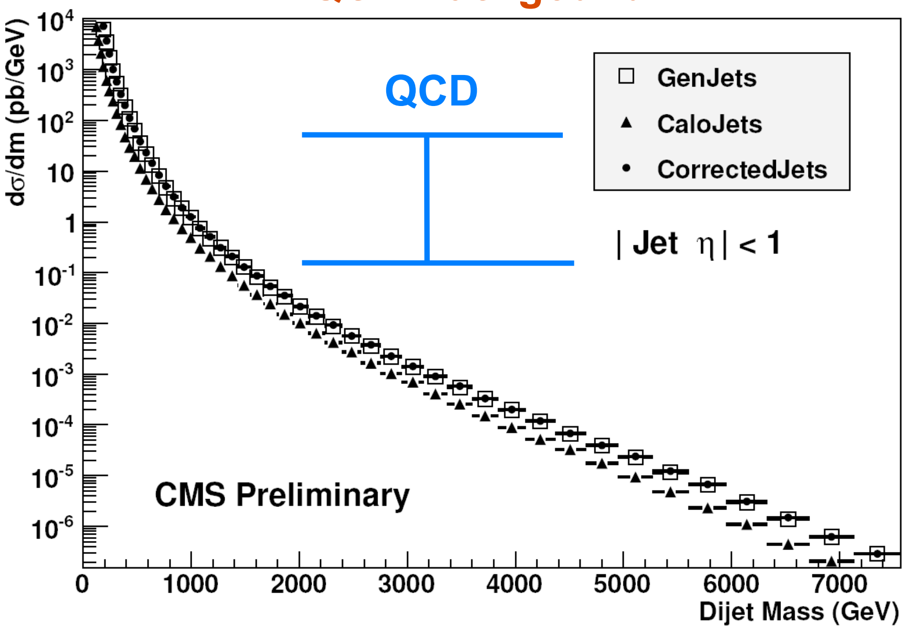
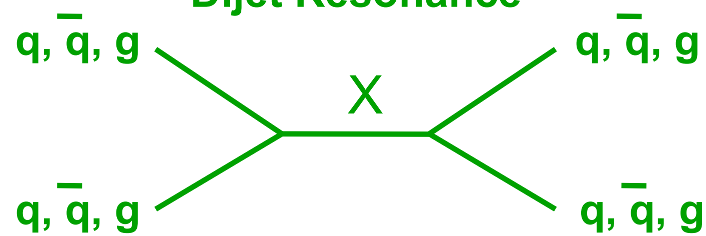
QCD Backgound



Dijet Resonance



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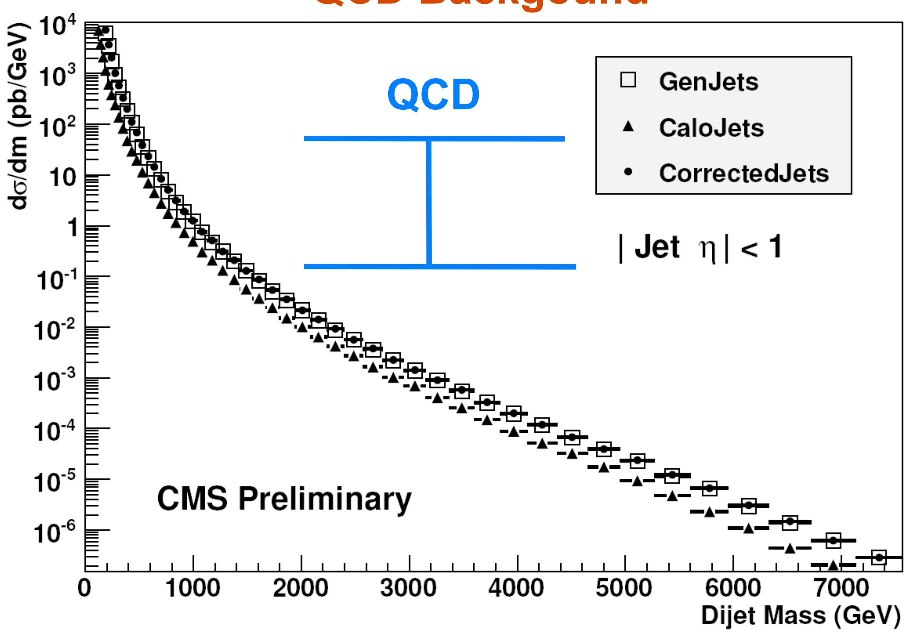
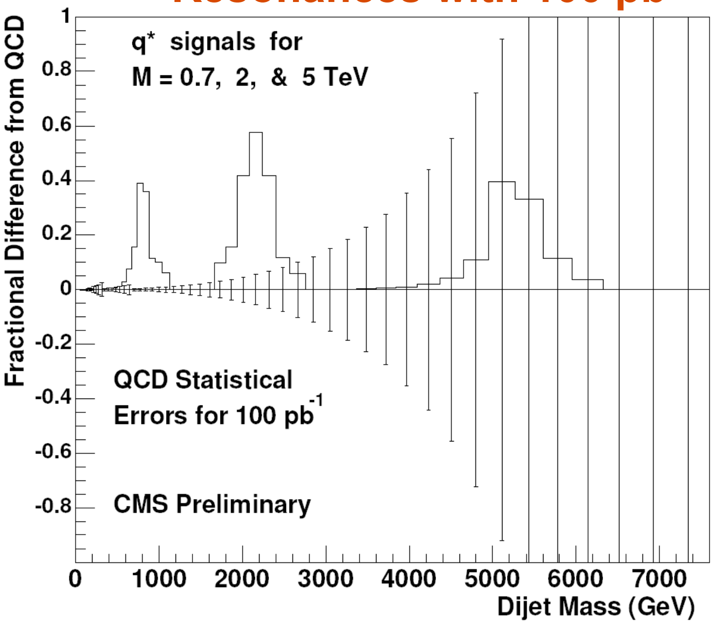
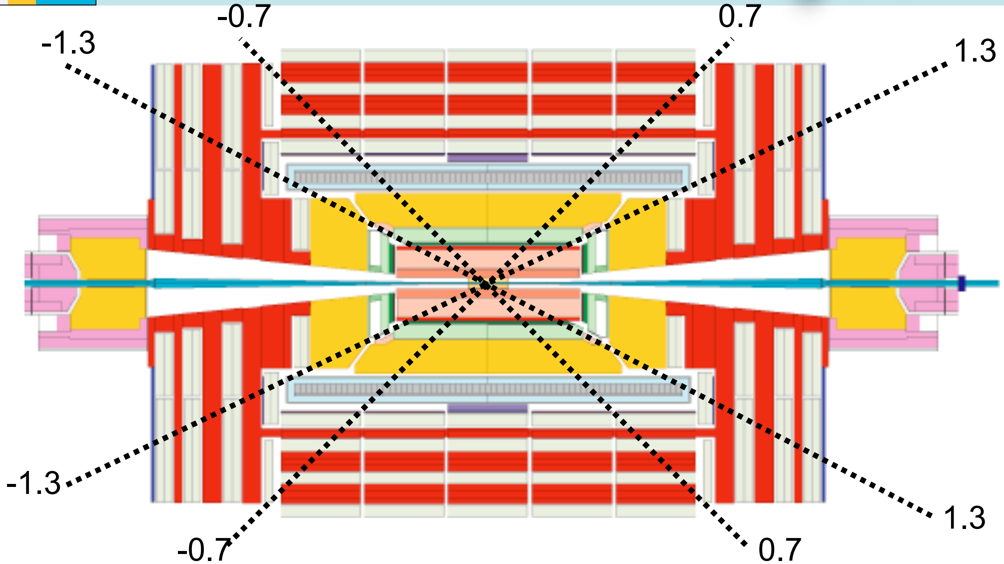
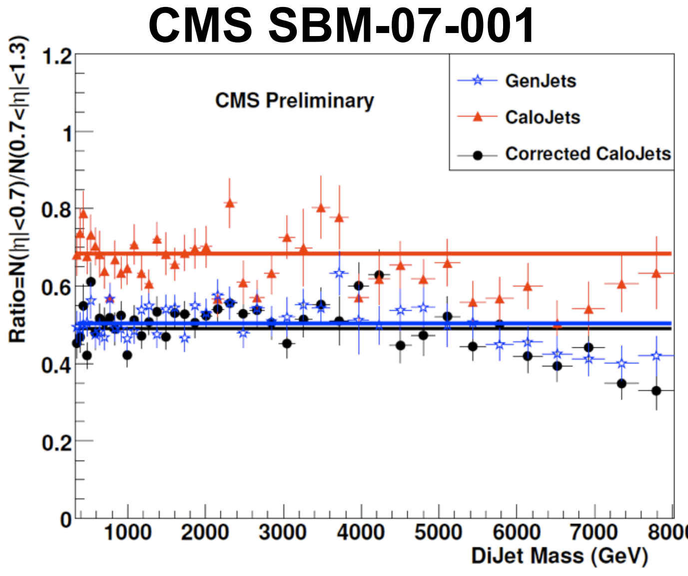


Resonances with 100 pb^{-1}

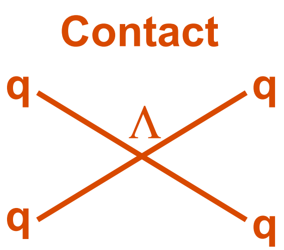


Dijet ratio





- Ratios help keep systematics low
  - many effects cancel
- QCD: roughly no η preference
- Expect NP to appear at high pT
  - hence, central η



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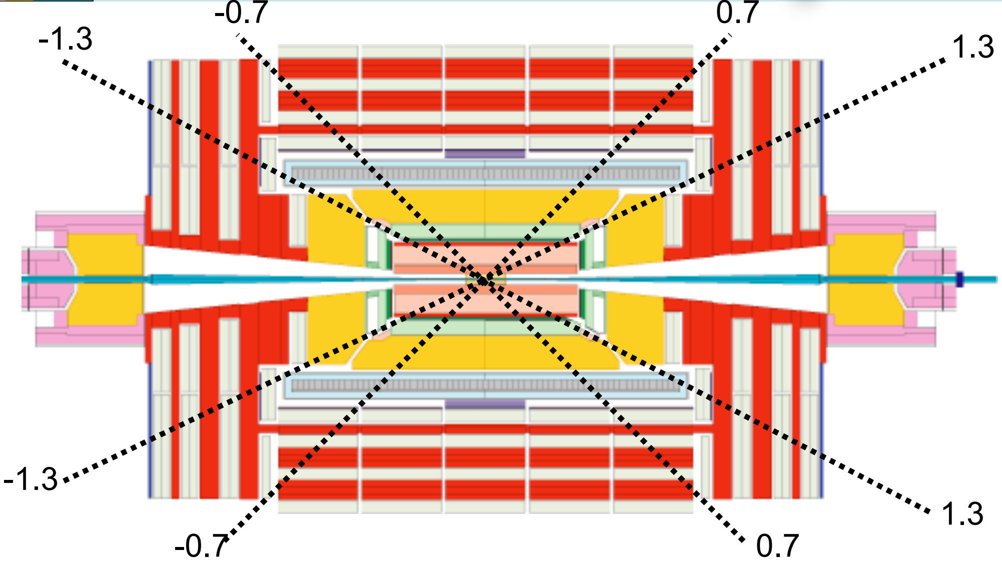

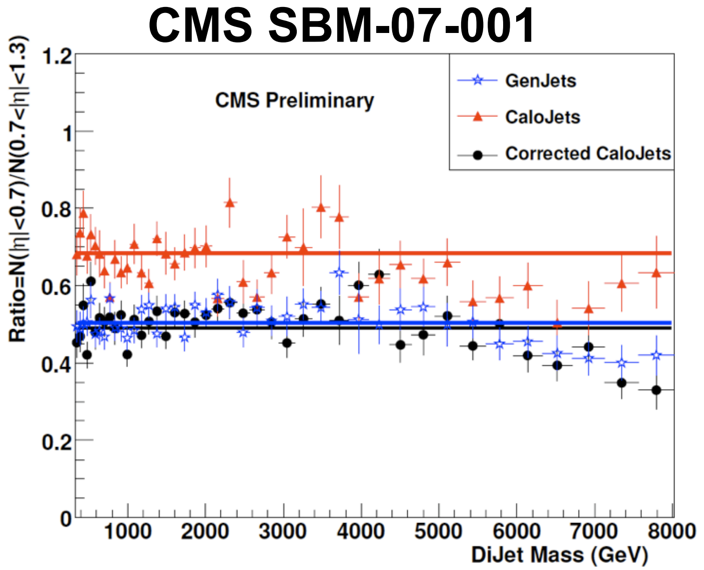

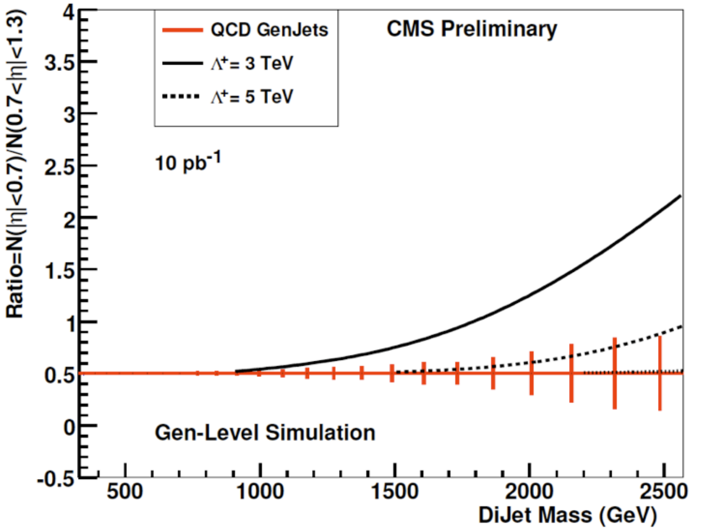

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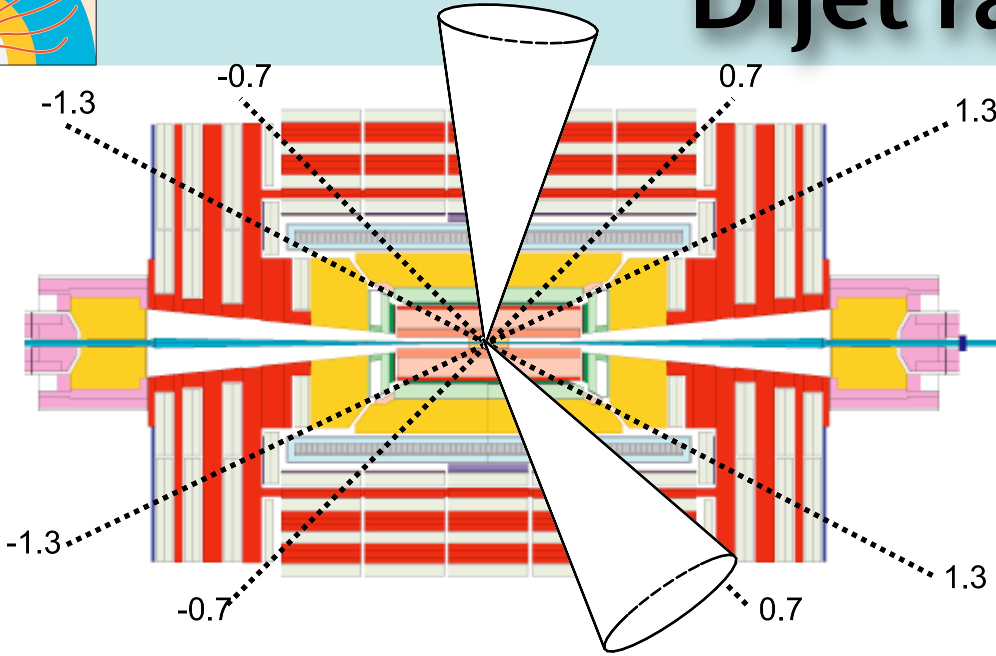

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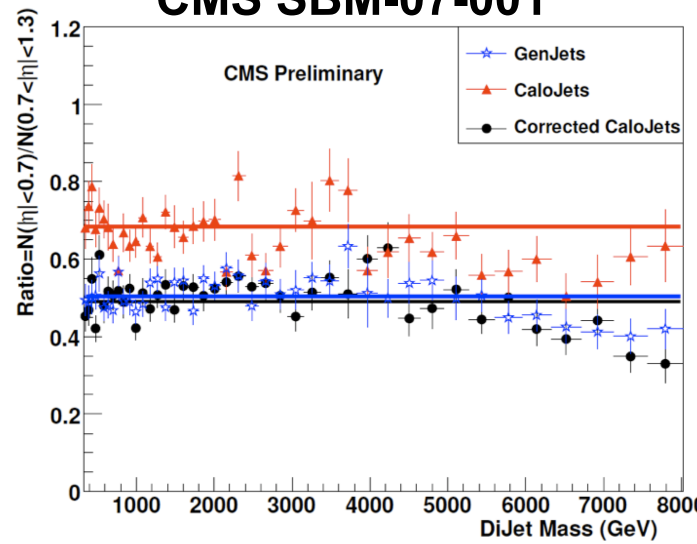

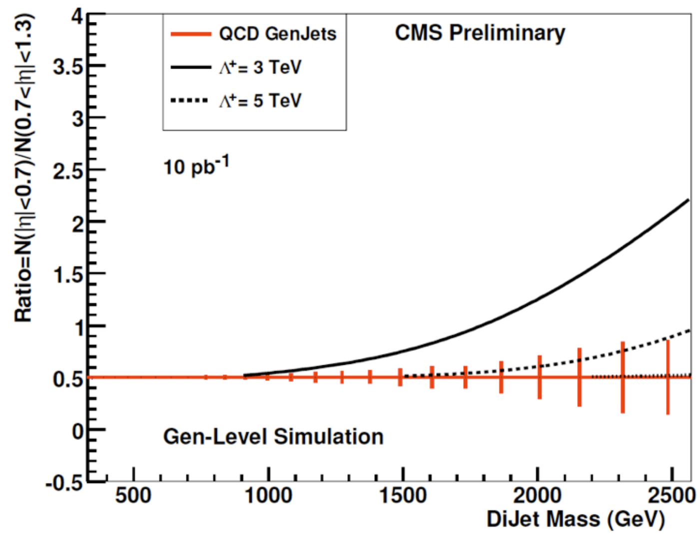

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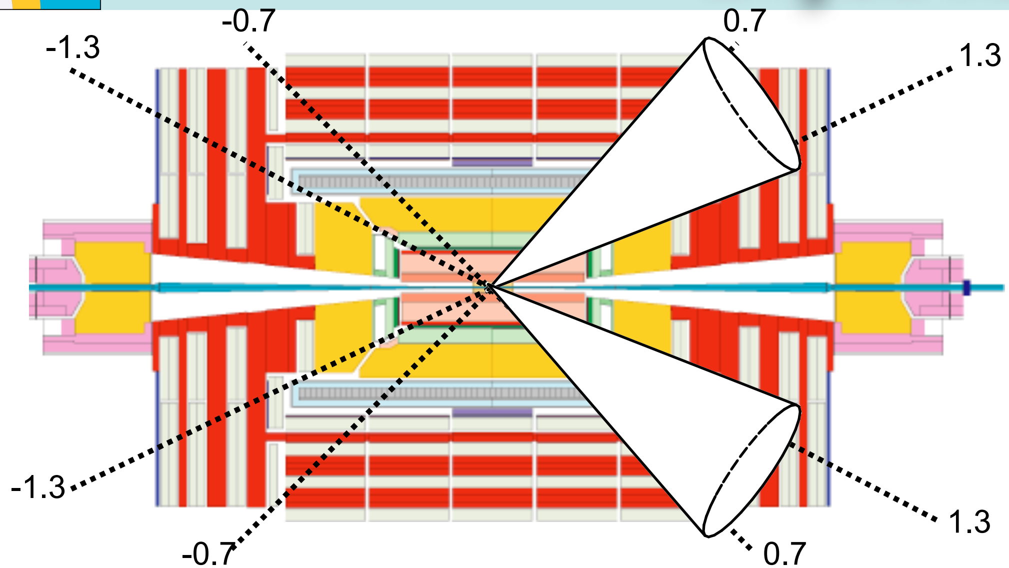
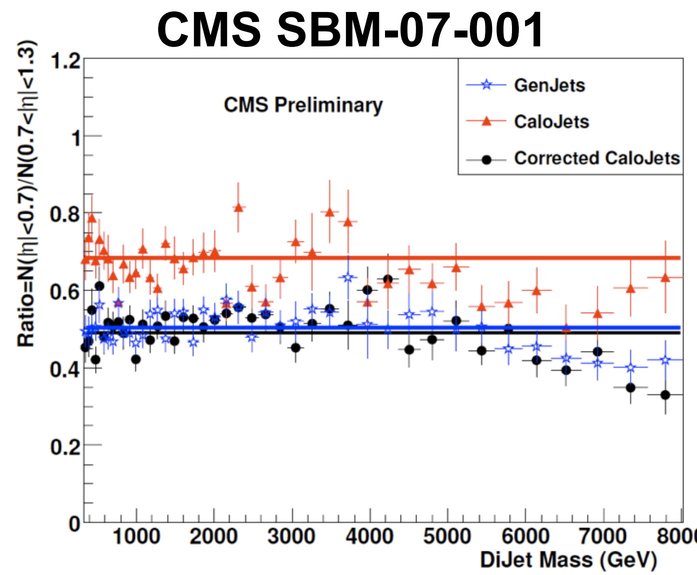
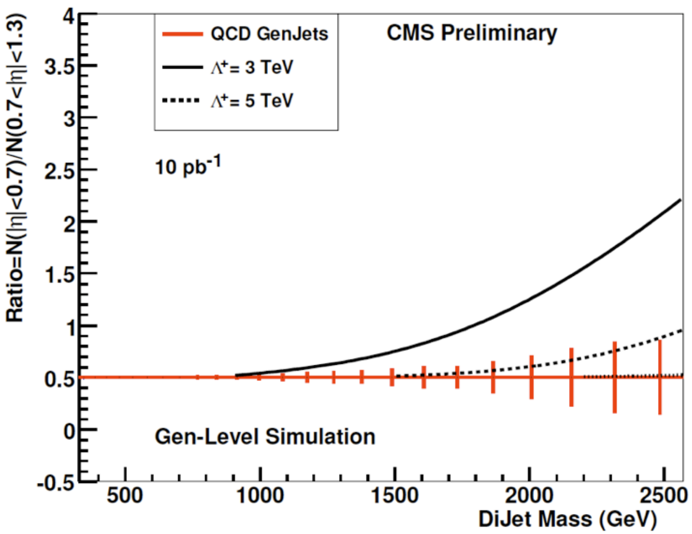
  - many effects cancel
- QCD: roughly no η preference
- Expect NP to appear at high pT
  - hence, central η

Dijet ratio







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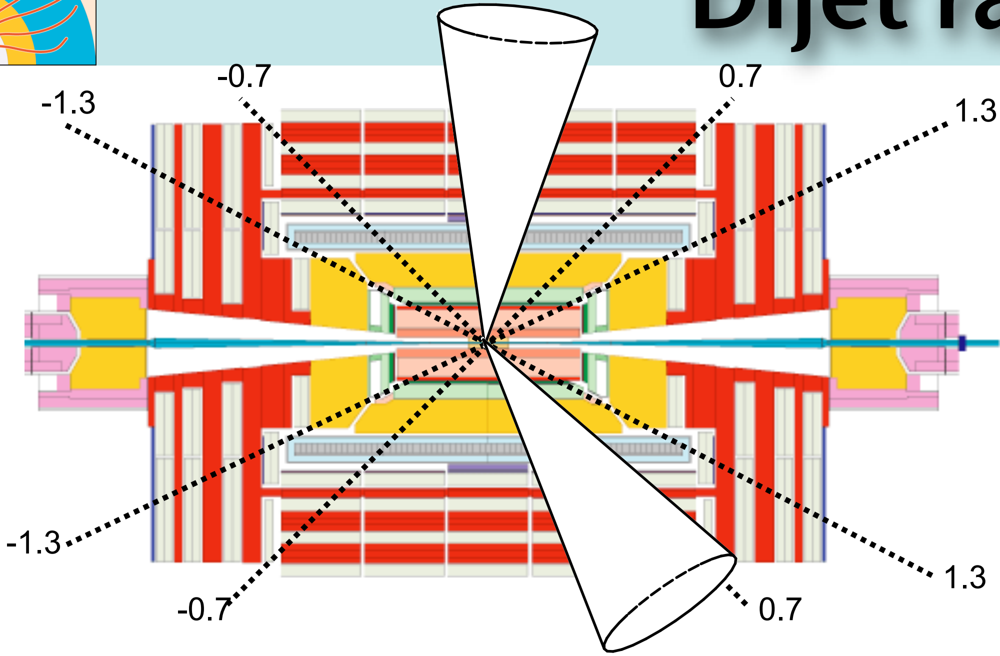

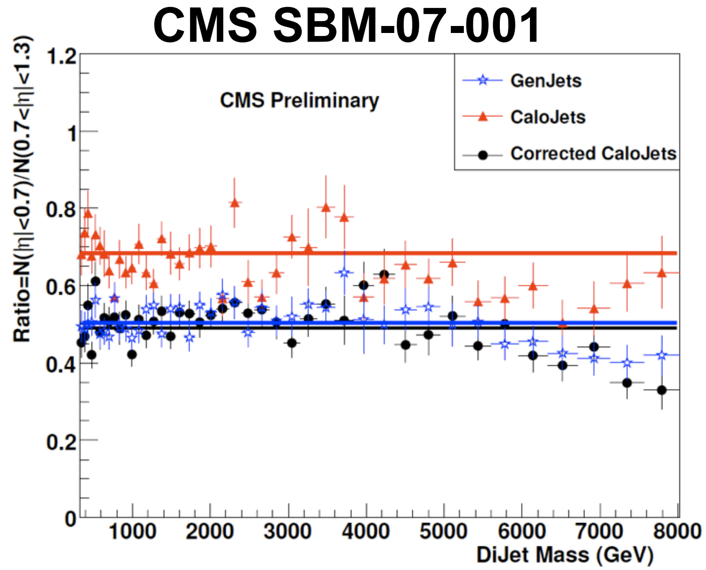

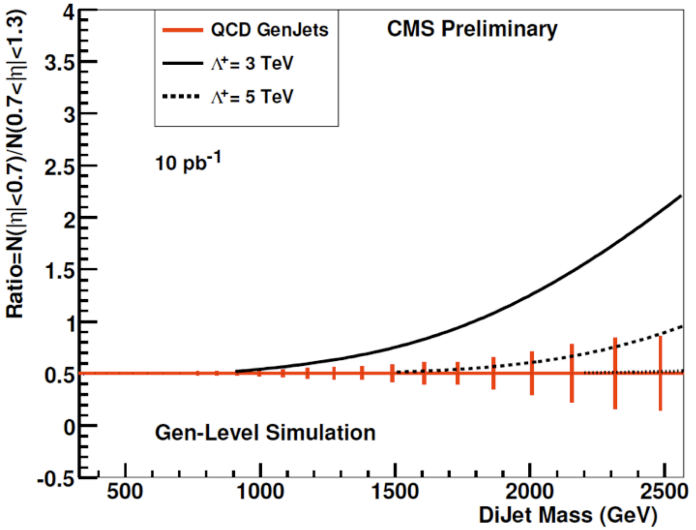

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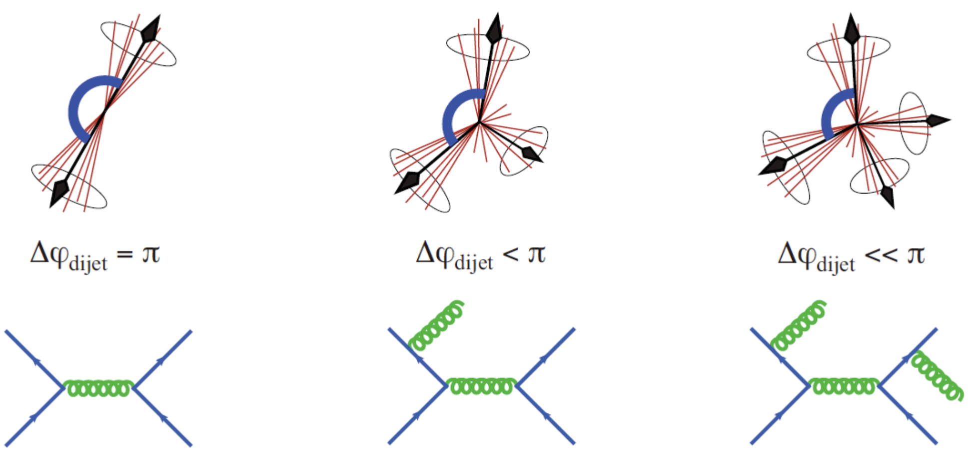
Dijet φ decorrelation

- QCD 09-003
- leading jets $\Delta\varphi$ distribution sensitive to higher order radiation
  - w/o explicitly measuring the radiated jets -- no jet counting!
- Particle level distributions
  - Corrections are dominated by JES and jet φ resolutions



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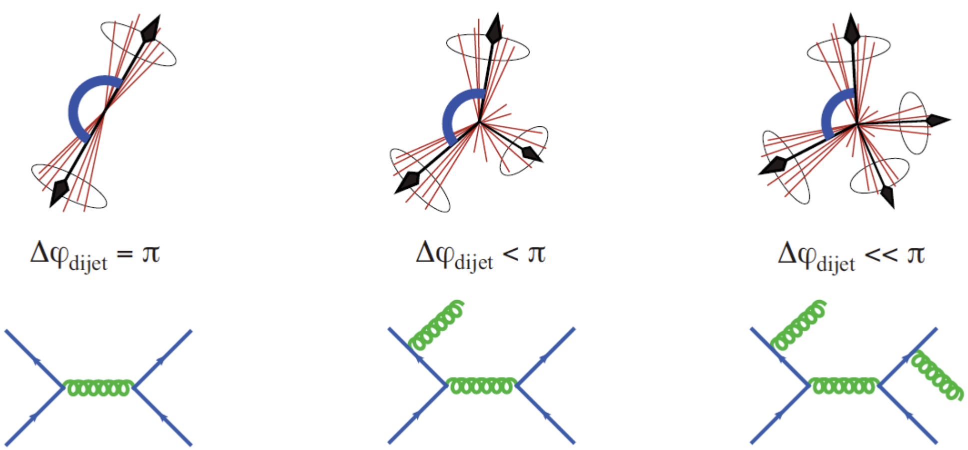
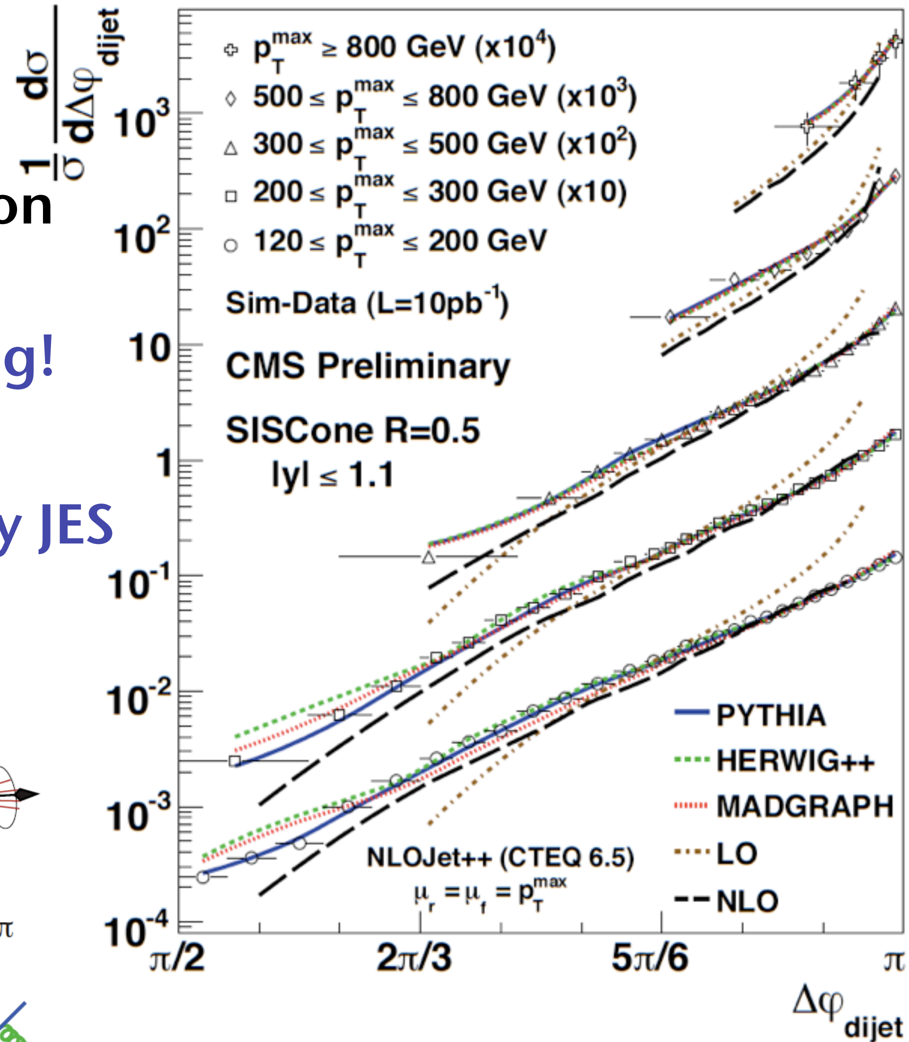


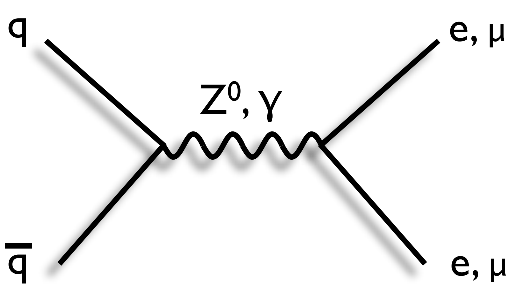


Multijets

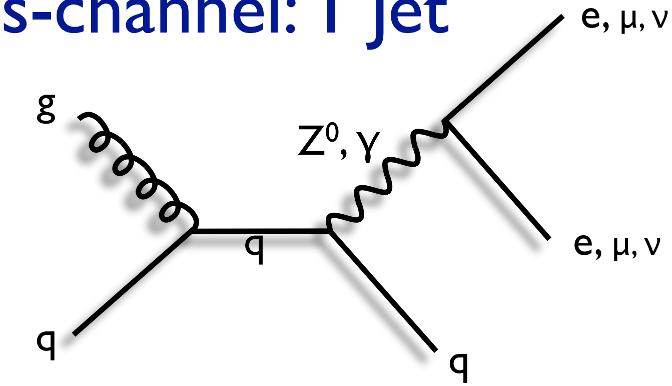
- Multijets Event Topology Studies
  - Dalitz plots, angular distributions, mass, etc.
  - Reduced dependence to jet calibration
- Ratios of n-jet/(n-1)-jet cross sections
  - Probes gluon radiation effects, α_s
  - Several systematics are reduced in the ratio
- A single vector boson (γ, Z, or W) in association with 0, 1, 2, 3, or more jets
  - Essentially a study of QCD multijets, using EWK probes

Example of some V+Jets Diagrams

qq Drell-Yan: 0 Jets



qg s-channel: 1 Jet



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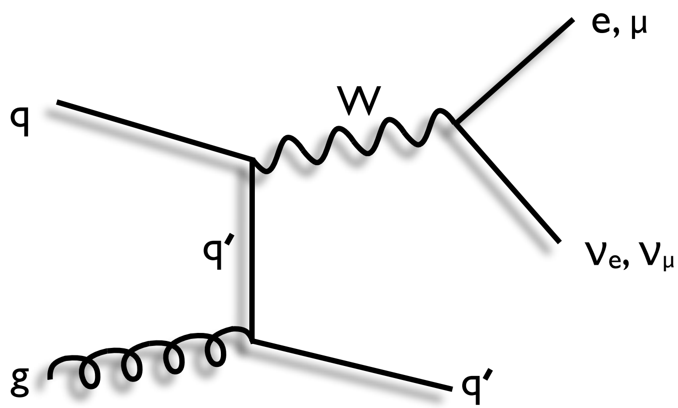
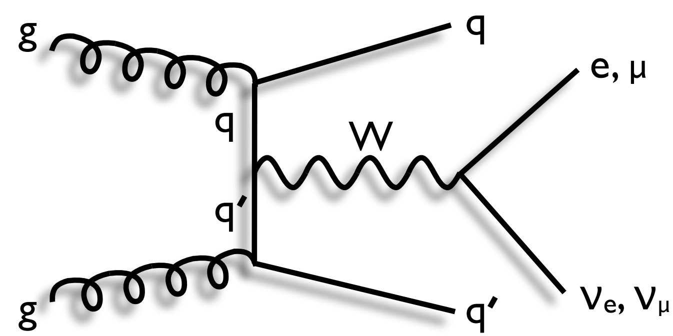


higher order gg channels: 2 Jets



Example of some V+Jets Diagrams

Fermilab
UIC University of Illinois at Chicago

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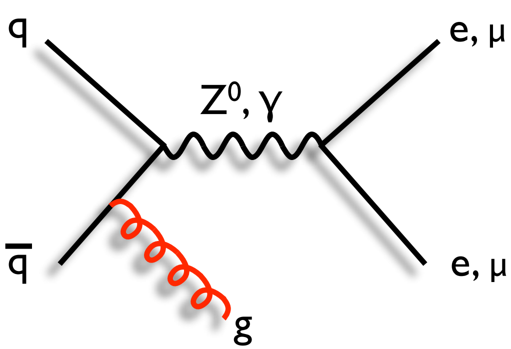

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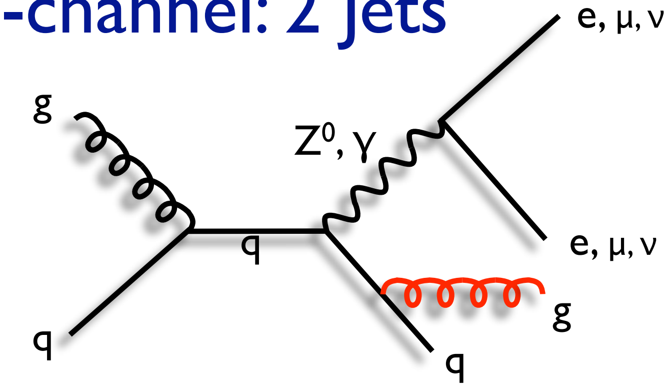

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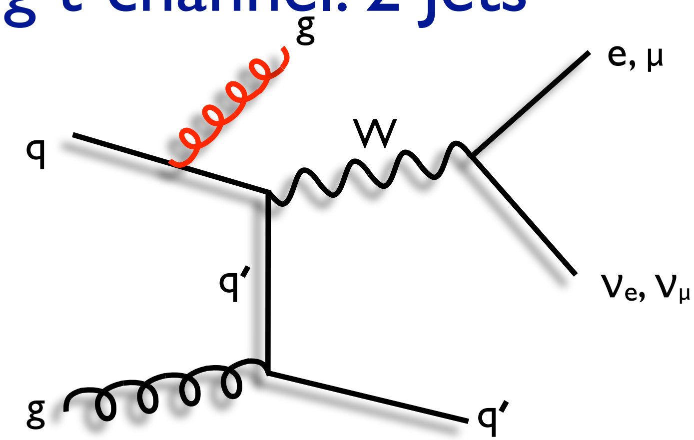
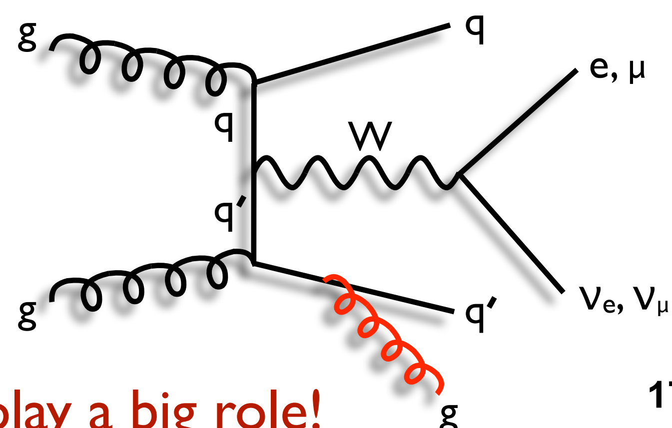


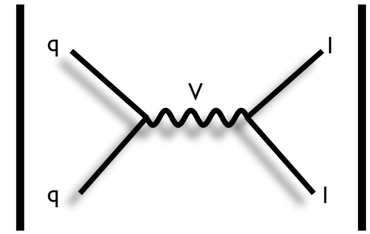
higher order gg channels: 3 Jets

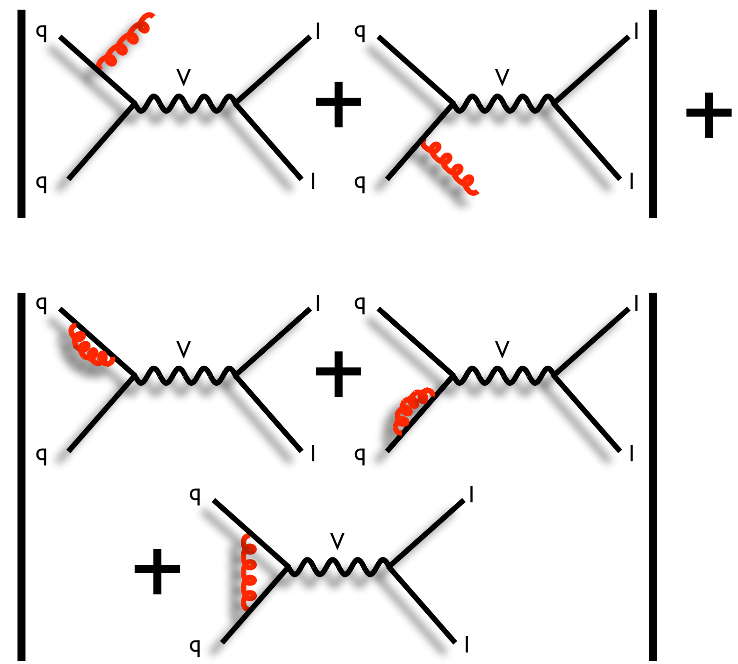


Initial and Final State Radiation play a big role!

Higher Orders

- Leading Order
- Next-to-Leading Order
    - Real Corrections = extra legs
    - Virtual Corrections = extra loops
- UV Divergences: Renomalization
    - Virtual Graphs
- IR Divergences:
    - Real and Virtual Graphs
    - Must Cancel Each Other, but non Trivial
- Loops tend to be ignored in existing Monte Carlos
    - Pythia, Alpgen, Sherpa, MadGraph, etc

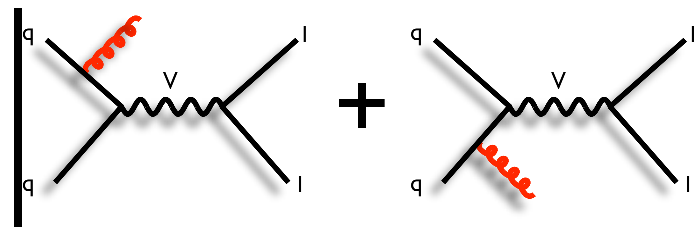


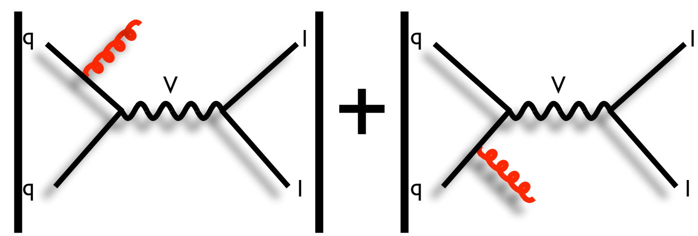


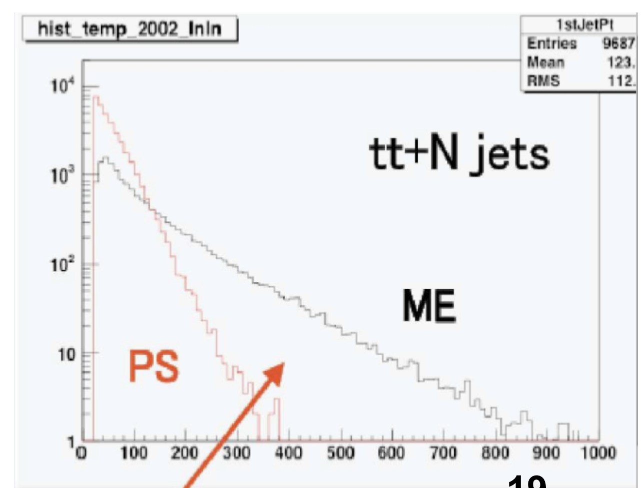
Higher Order Monte Carlos

- Matrix Element calculations (`AlpGen`, `MadGraph`, `Sherpa`, etc):
  - Describe well separated jets configurations
  - Are “exact” at a given order
  - Run into troubles in the soft and collinear regions
  - Can’t describe the internal structure of jets
- Parton Shower calculations (`Pythia`, `Herwig`, etc):
  - PS is universal; given basic hard process, PS recipe will produce reasonable parton configurations
  - Form factors ensure controlled behavior in soft and collinear region; jet evolution is well described
  - Cannot steer shower evolution much; some regions of phase space not efficiently filled, such as well separated partons
- Current State of the Art: use both!

  ME to predict hard parton configuration and PS to describe evolution of jets,
  - Beware double counting and holes in the phase space several ⇒ several matching methods

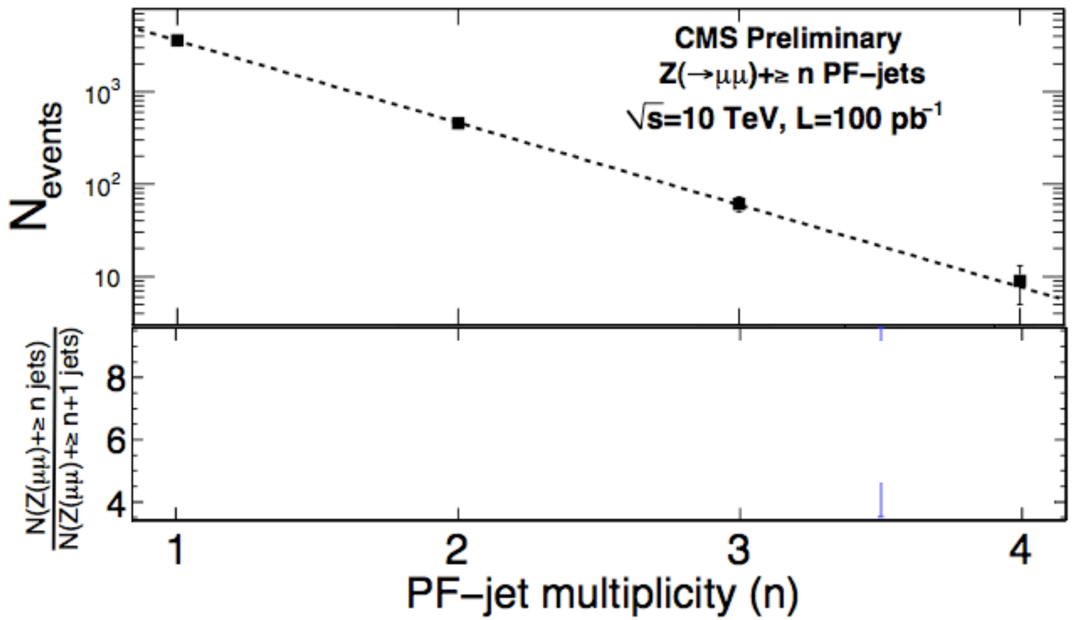




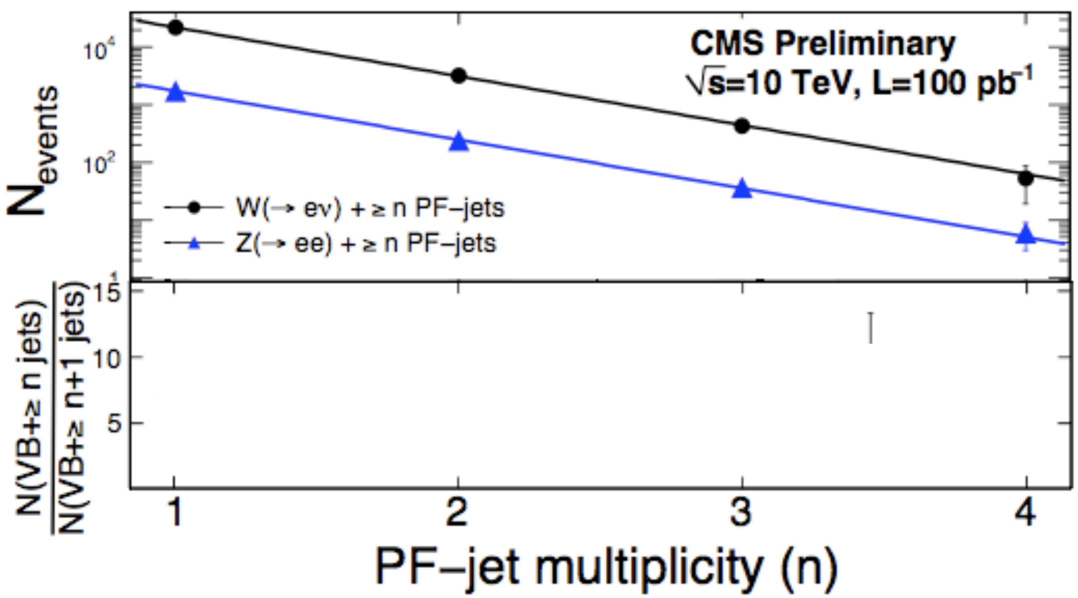


Adequate modeling important for searches involving several high pT jets

$(\alpha_S)^n$ Law of Multijet Production



EWK 08-006



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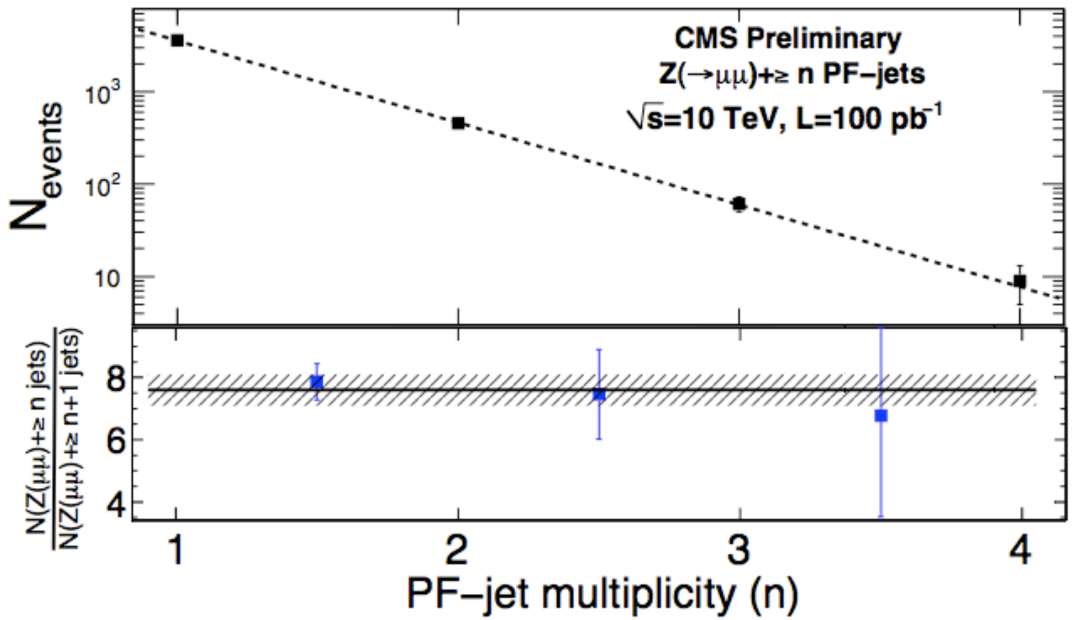

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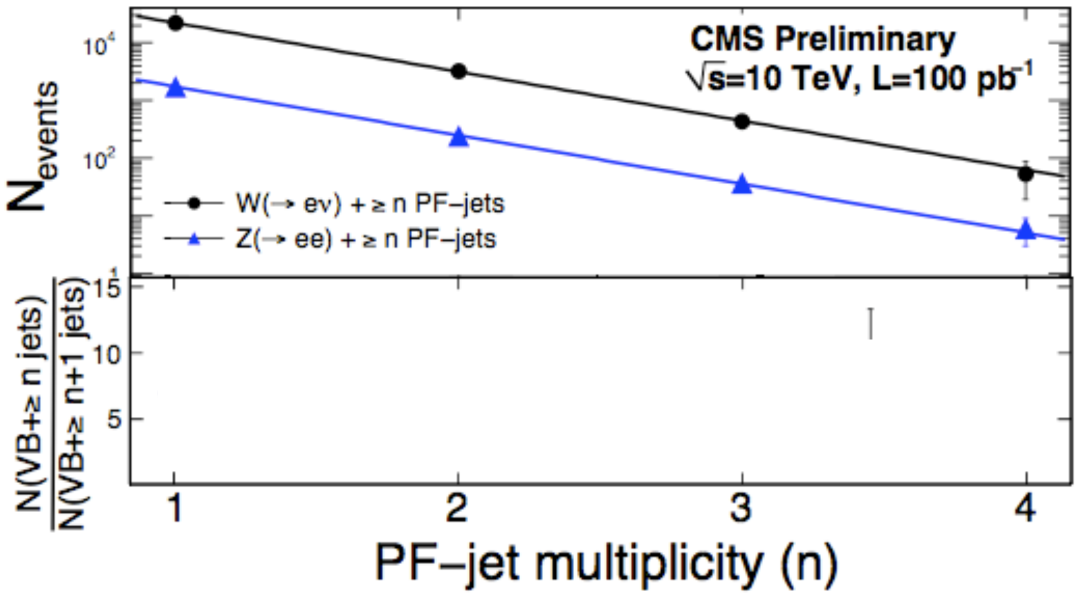

EWK 09-006

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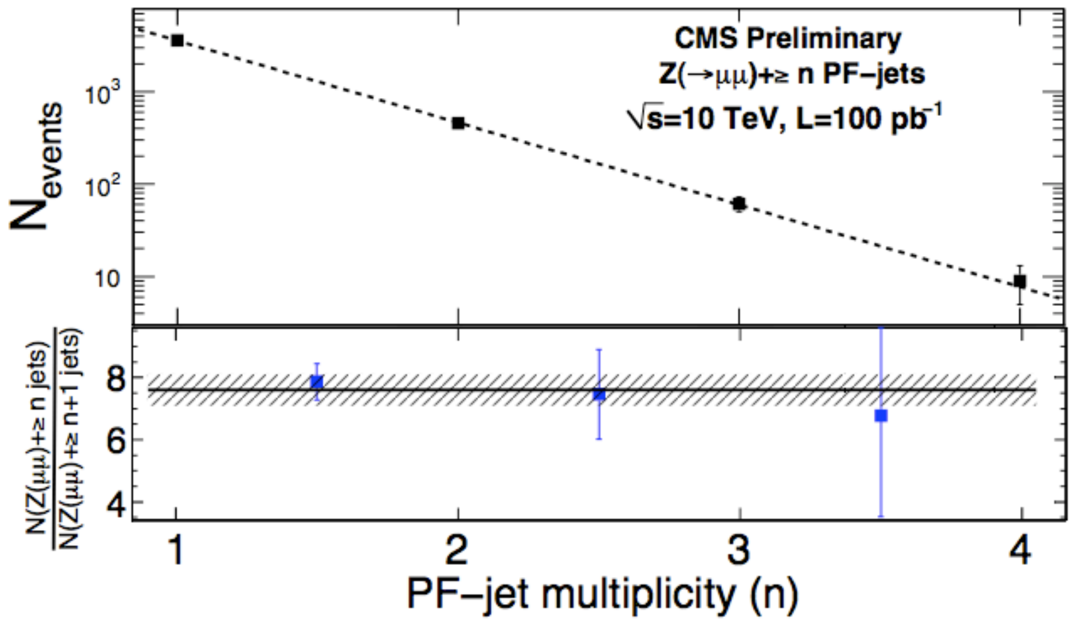
Fermilab

UIC University of Illinois at Chicago



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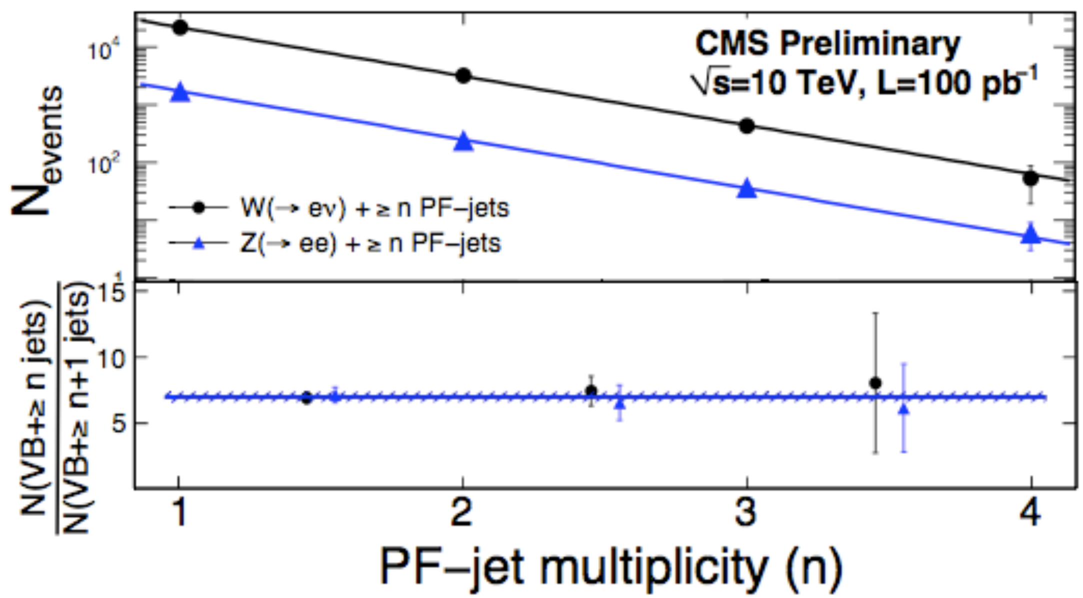


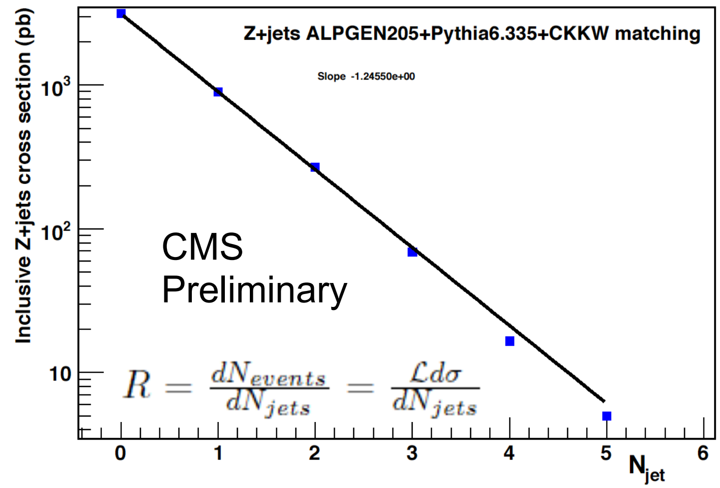
EWK 09-006

Z→μμ Standard Candle

- Normalize MC to Data for low jet multiplicity Jet bins
  - Assume lepton universality
  - For W + n-jets, use

$$\rho \equiv \frac{\sigma(pp \to W(\to \mu\nu) + jets)}{\sigma(pp \to Z(\to \mu^+\mu^-) + jets)}$$

CMS PTDR



- Reduces / Avoids Systematics due to
  - QCD Scale, PDFs (possibly), ISR/FSR, etc
- Major Syst. Become
  - Luminosity, Measurement of *R*, Uncertainty on $\rho(N_{jet})$
  - Still requires tuning MC to Data for kinematic dists.
- 5% precision (~lumi) expected to be achieved with 1.5 fb^{-1}

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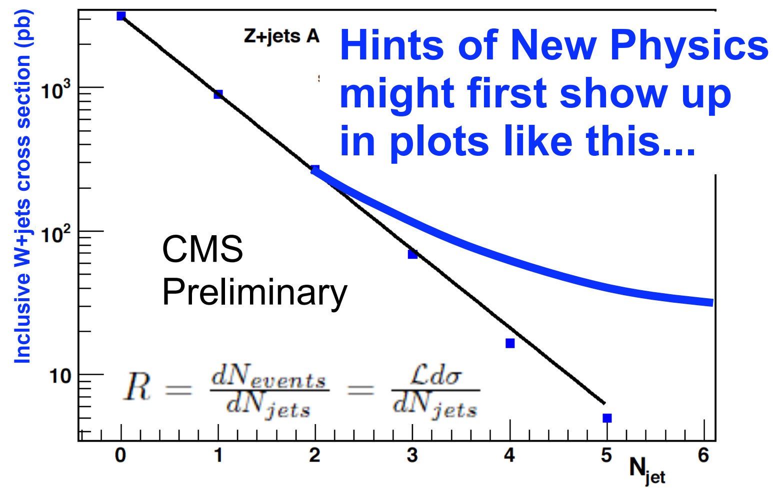

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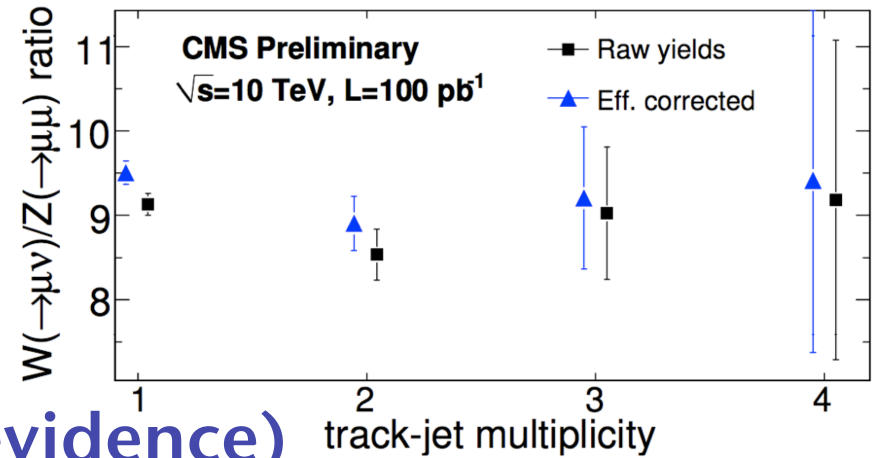
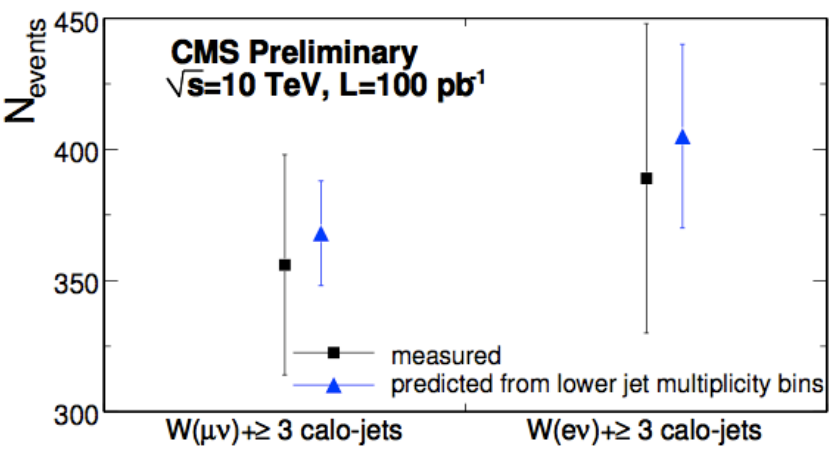
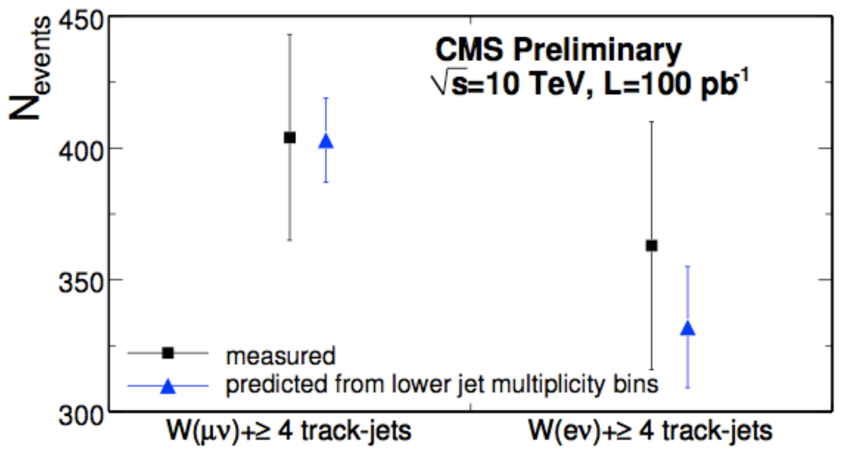
The Method Works...

- ...and is sometimes known as "Berends scaling"
- Used at Tevatron
  - Top discovery (not responsible for discovery, but provided additional evidence)



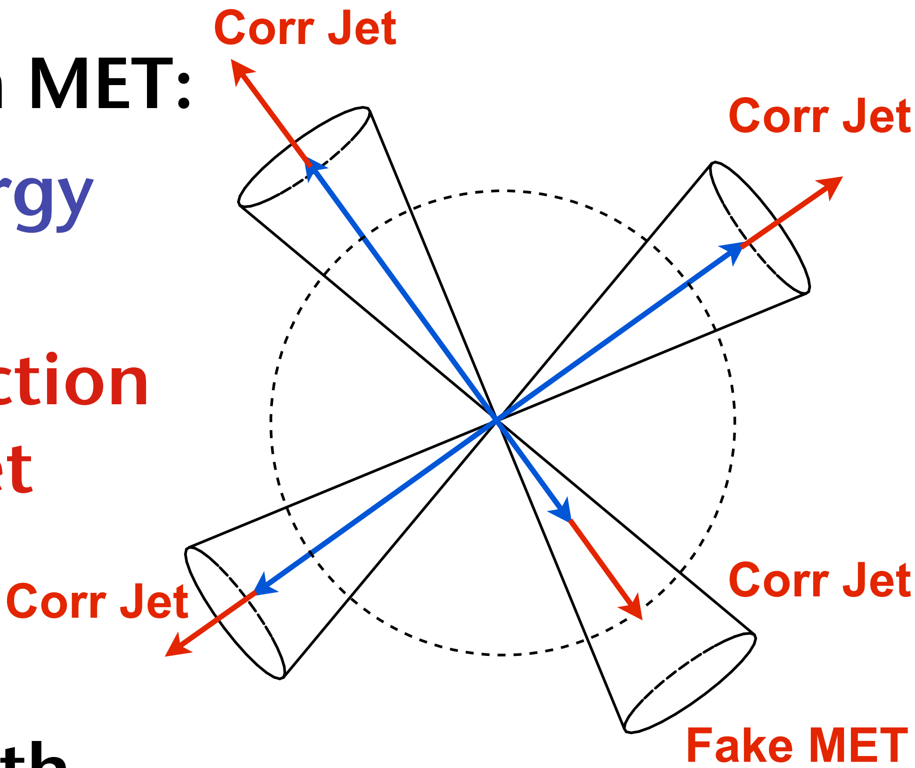
- Now adapted to CMS (EWK 09-006)



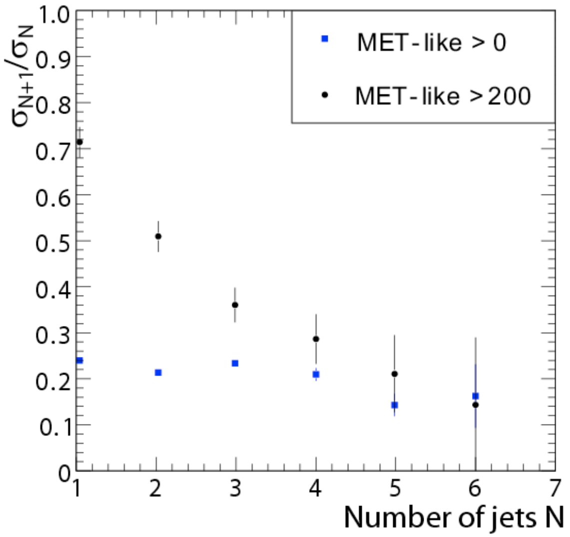


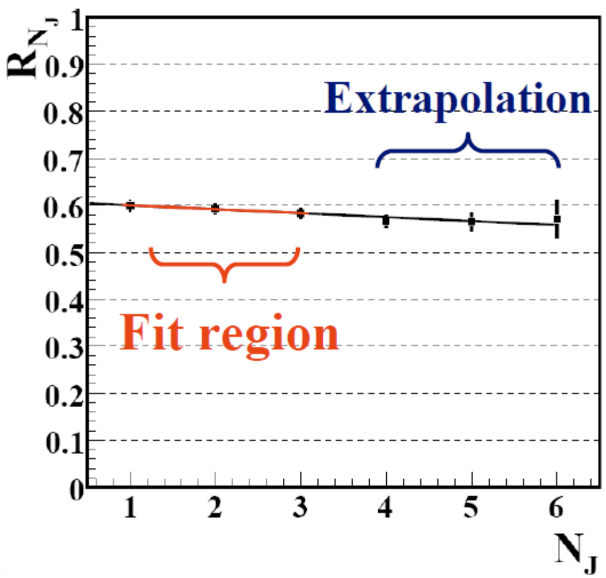
Jet Mismeasurements and MET

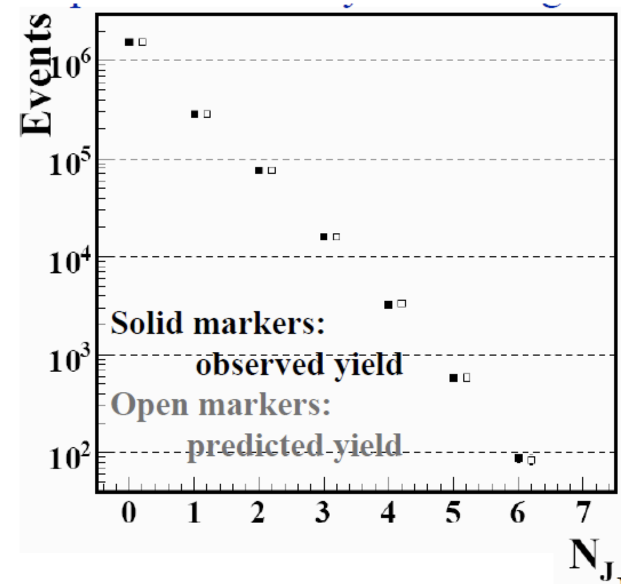
- But, life is difficult with MET:
  - Catastrophic Jet Energy mismeasurement
    - Large MET in direction of mismeasured Jet
- Requiring Large MET biases one to events with Jet Energy mismeasurements
  - jets are promoted above jet counting threshold due to non-linear JES corrections
  - Leads to deviation from Berend's scaling



One Solution…



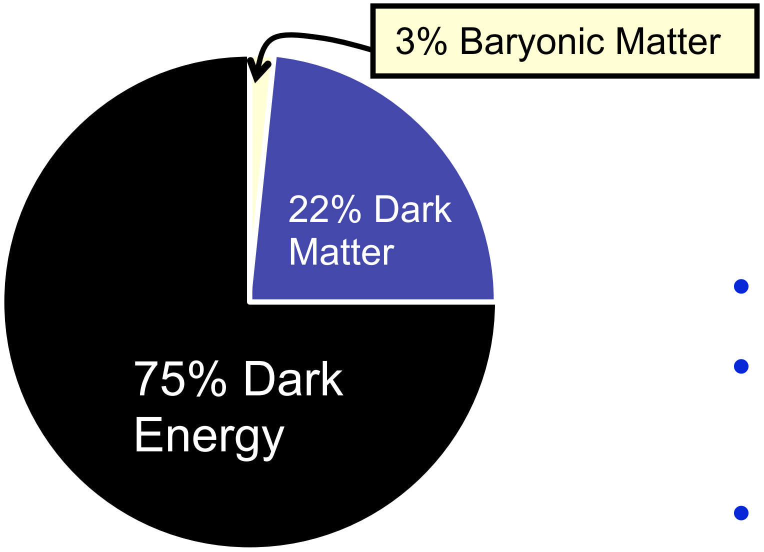


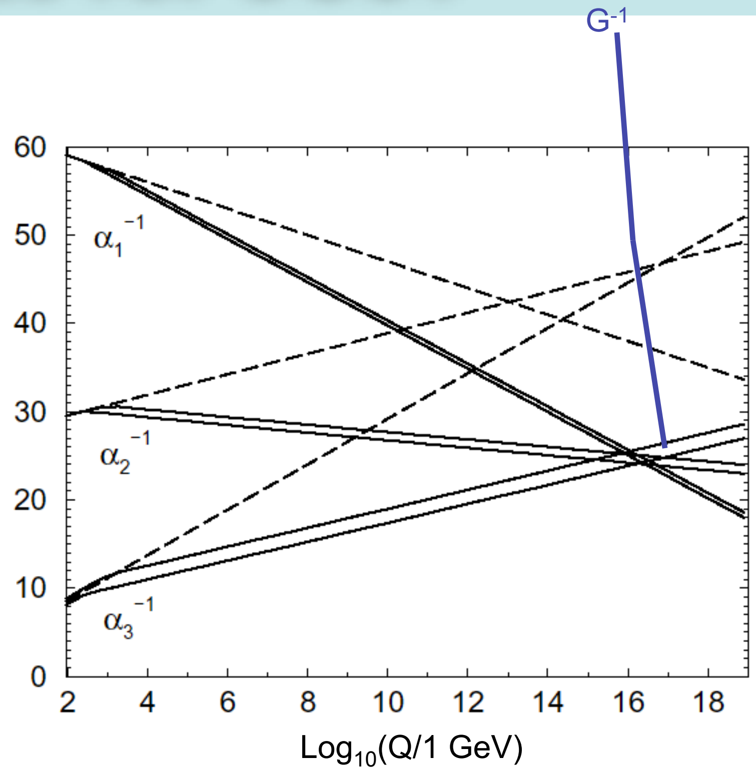


- Central Jets should have same Jet Energy Mismeaurements as Forward Jets (similar Detectors)
  - Form ratio $R_{Nj} = N_j(\text{Central}) \,/\, [N_j(\text{Central})+N_j(\text{Forward})]$
- Mismeasurements cancel in the ratio
  - more confident extrapolation from SM region to NP region
  - example of "self-healing" type of observable

Motivating Themes for SUSY

- Naturally leads to Electro-weak symmetry breaking
- Avoids fine tuning of SM
- Viable Dark Matter Candidate (R-parity conservation)





- Gauge Coupling Unification
- Gravity naturally unifies (roughly) too
- Pre-requisite of String Theory

Of course, some problems too : No experimental evidence, so far!

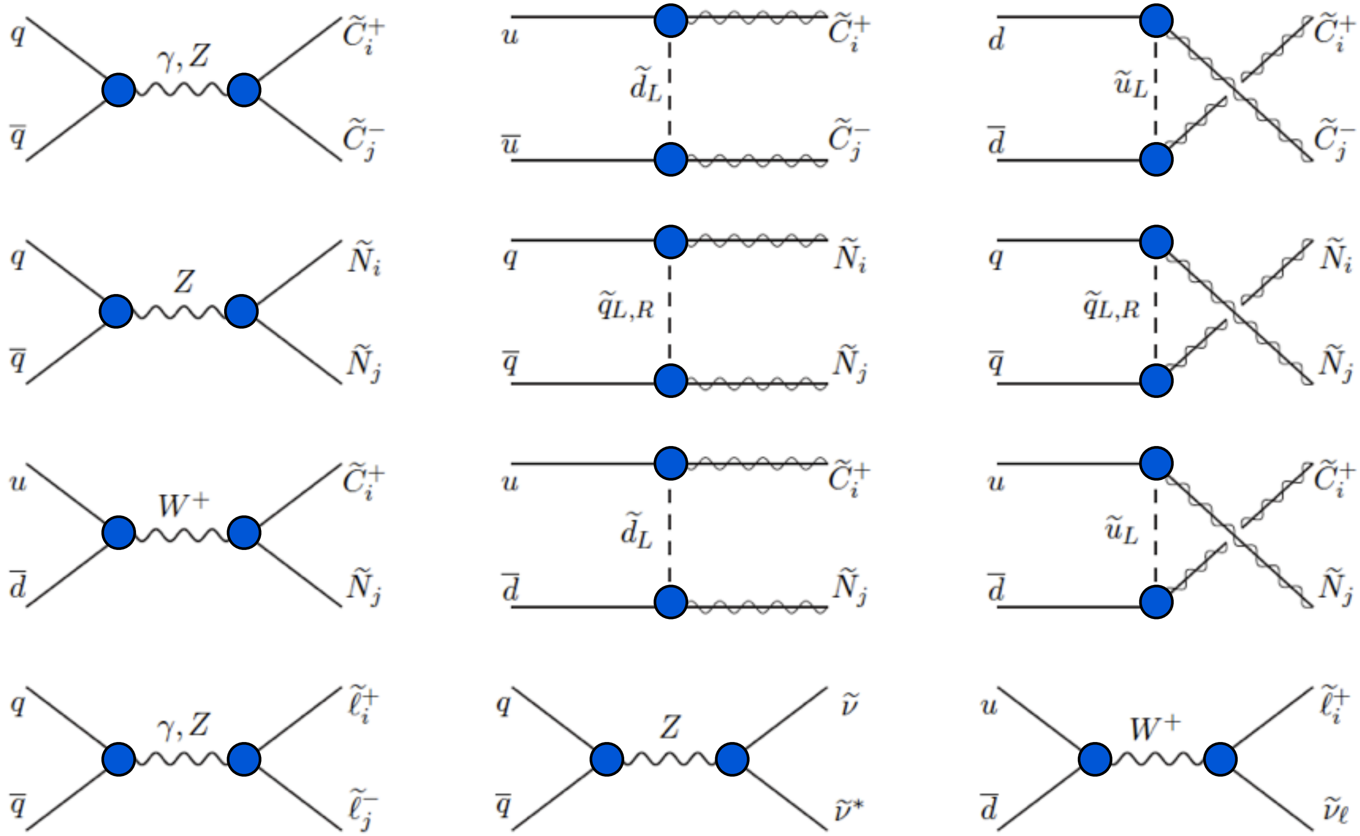
Supersymmetry

- A symmetry between fermions and bosons

SM Particles	SUSY Particles			
quarks: q	q	squarks: $\tilde{q}$		
leptons: l	l	sleptons: $\tilde{l}$		
gluons: g	g	gluino: $\tilde{g}$		
charged weak boson: $W^{\pm}$	$W^{\pm}$	Wino: $\tilde{W}^{\pm}$	$\tilde{\chi}^{\pm}_{1,2}$	chargino
Higgs: H^0	$H^{\pm}$	charged higgsino: $\tilde{H}^{\pm}$		
	h^0, A^0, H^0	neutral higgsino: $\tilde{h}^0, \tilde{A}^0,$	$\tilde{H}^0$	higgsino
neutral weak boson: Z^0	Z^0	Zino: $\tilde{Z}^0$	$\tilde{\chi}^0_{1,2,3,4}$	neutralino
photon: γ	γ	photino: $\tilde{\gamma}$		

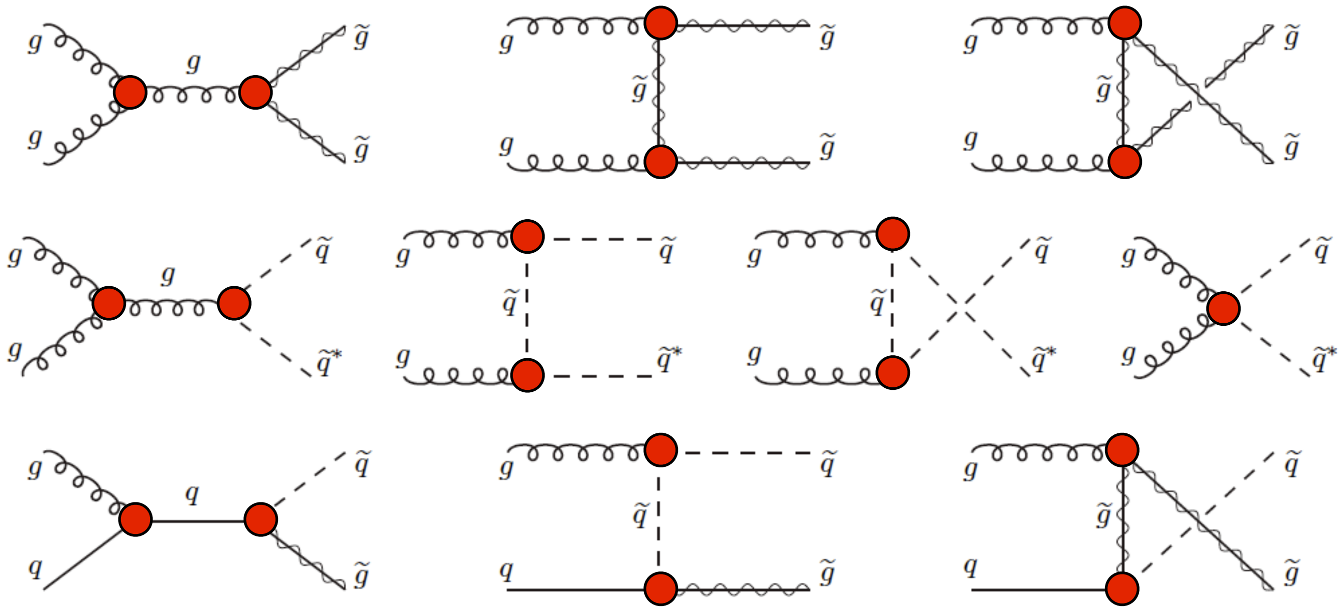
- Generally assume LSP is stable (R-parity conservation)
- SUSY must be broken!
  - mechanism is unknown ⇒ many new free parameters!
- CMSSM (basically mSUGRA):
  - Supergravity inspired model, 5 free parameters:
    - m_0, $m_{1/2}$, A_0, $\tan\beta$, Sign(μ)

Chargino & neutralino Production



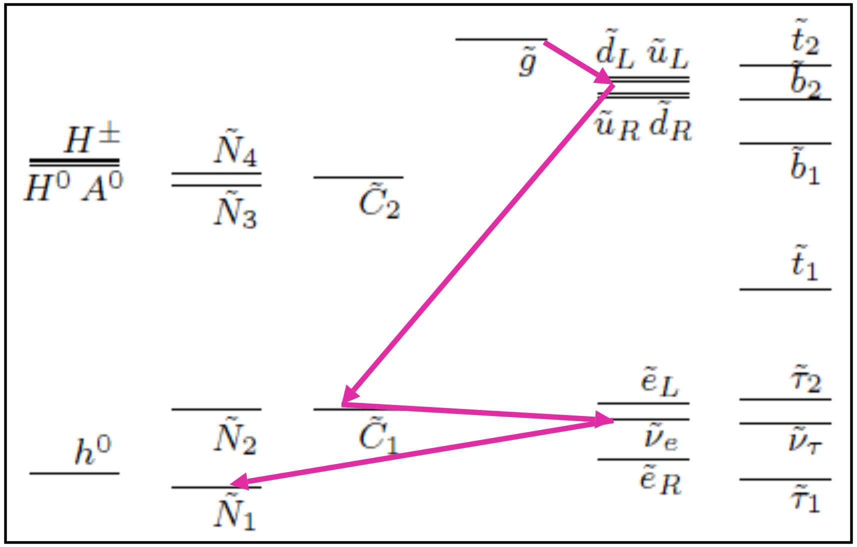
- **Most involve only weak couplings**

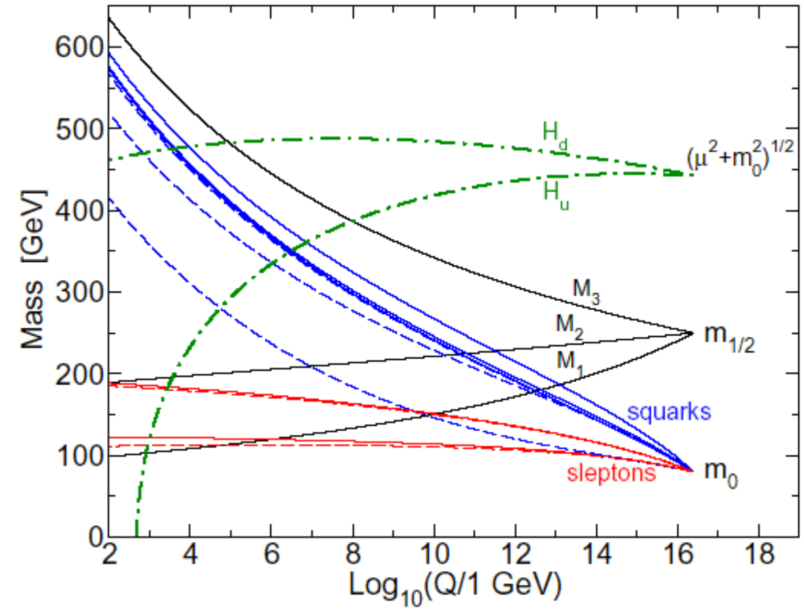
Squark & gluino production



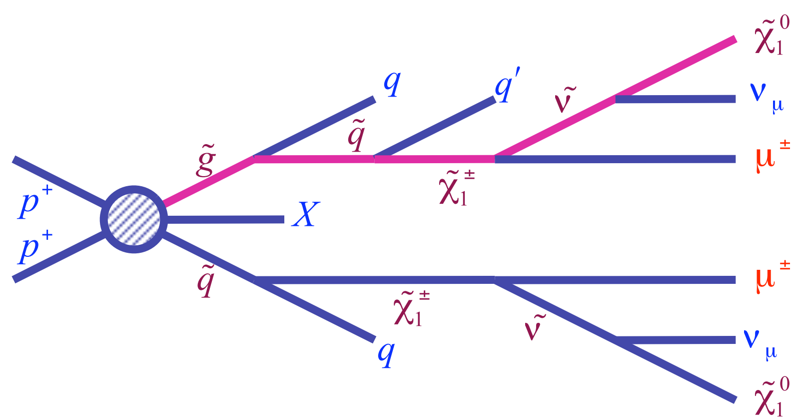
- Involve only the strong coupling
- LHC initial state: quarks and gluons!
  - *squark & gluino production dominate over chargino & neutralino production*
- Thus: Lots of Jets and MET in final state for SUSY events!!

What does SUSY Look like?





- **Complex decays chains**
  - High P_T jets (q, g)
  - Leptons (χ, l, W, Z)
  - MET (LSP)



Generic Signature of many New Physics Models!

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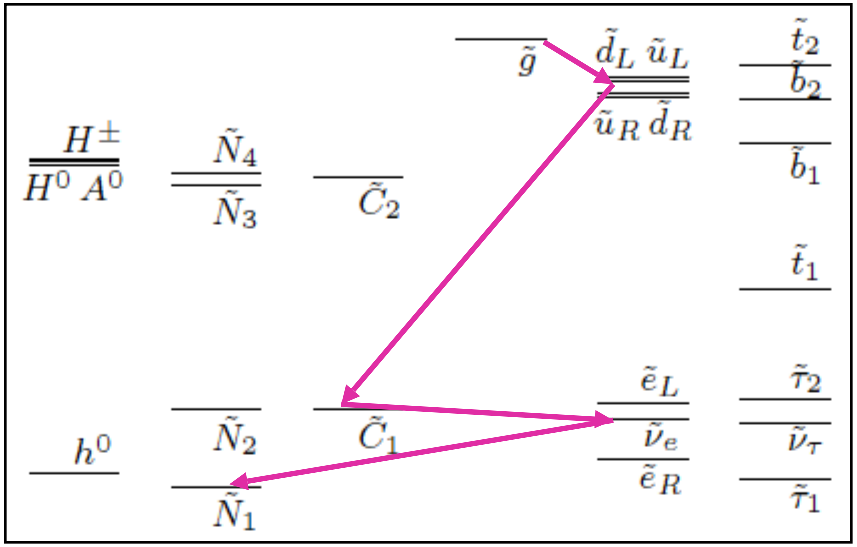

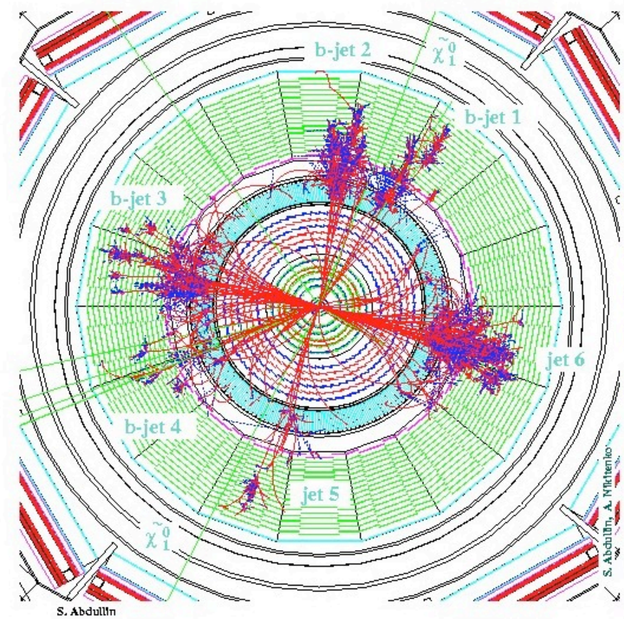

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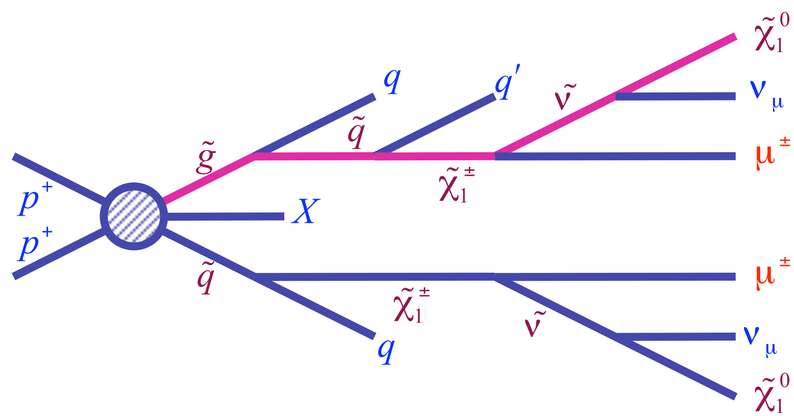
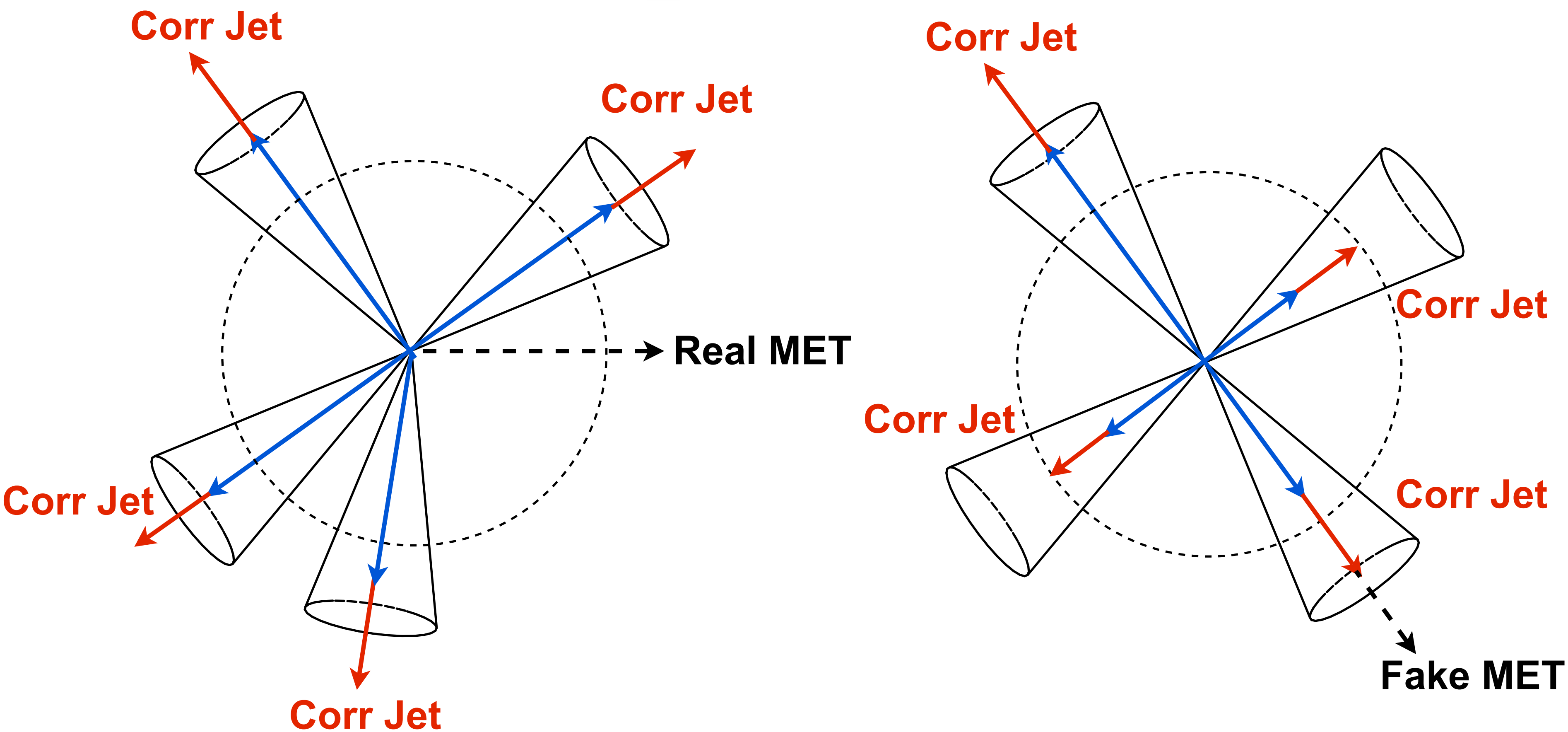


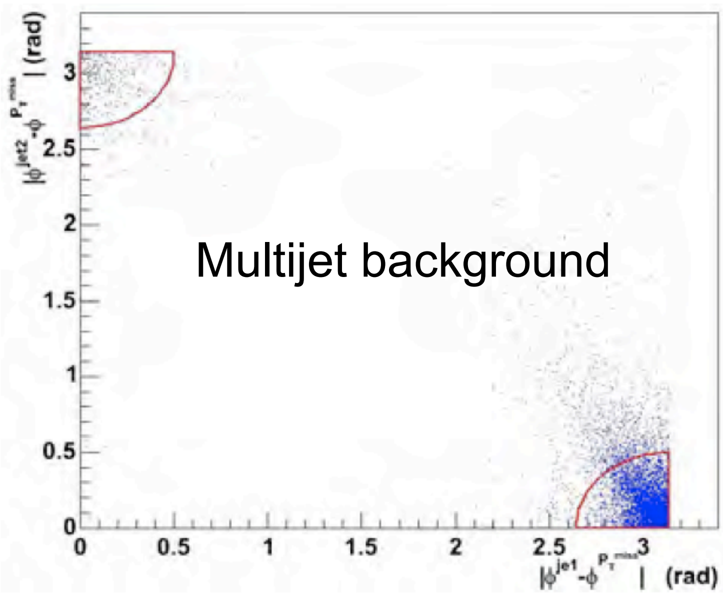
Generic Signature of many New Physics Models!

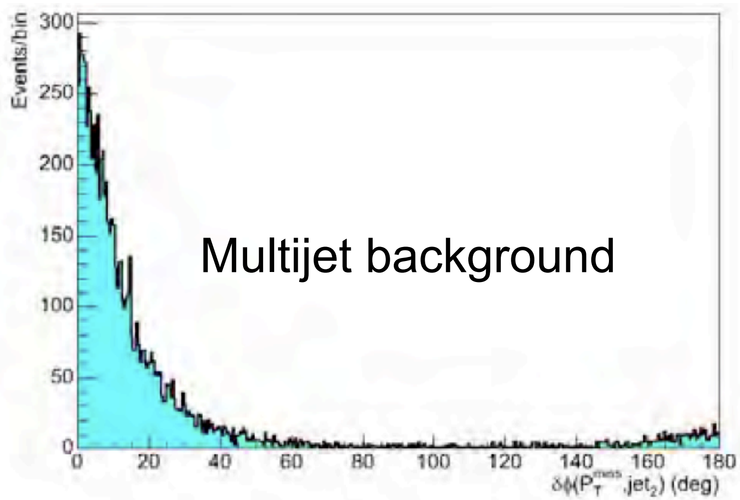
Cleaning Fake MET



- Real MET is typically "isolated"
  - i.e. does not point in direction of a jet
- Fake MET typically points in direction of 2nd leading jet

Cleaning Fake MET





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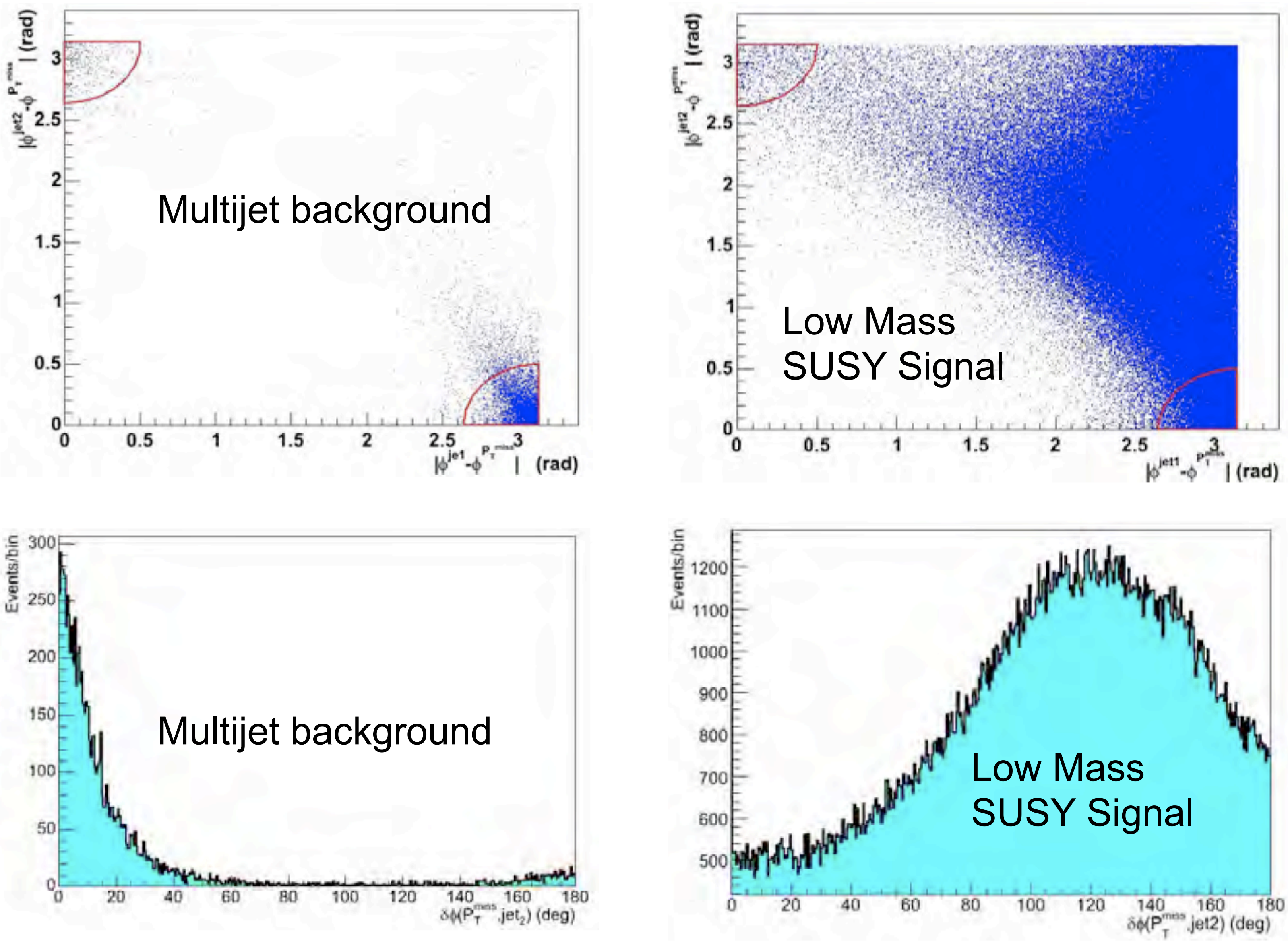
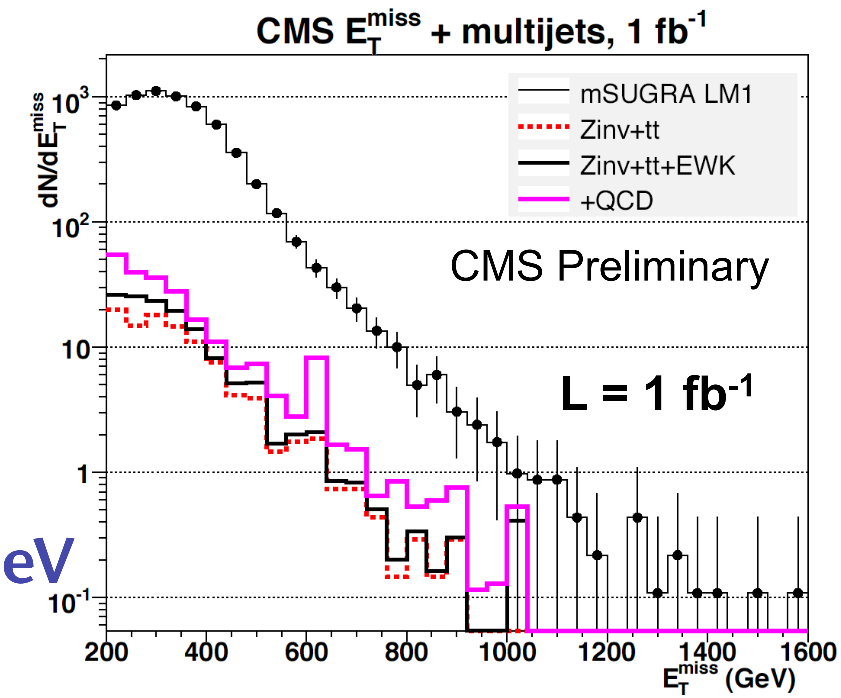


Inclusive MET + Jet Search

- **Selection Criteria**
  - MET>200 GeV + Clean-up
  - ≥ 3 jets:
    - E_T> 180, 110, 30 GeV
  - Indirect lepton veto
  - Cuts on Δφ between jets & MET
  - $H_T/M_{eff}=E_{T1}+E_{T2}+E_{T3}$+MET>500 GeV



- **Results:**
  - LM1 efficiency is 13%, S/B ~ 26 :

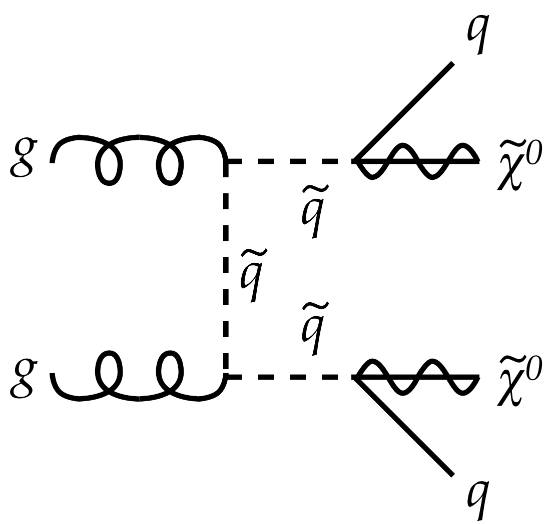
    Expected number of events for 1 fb^{-1}

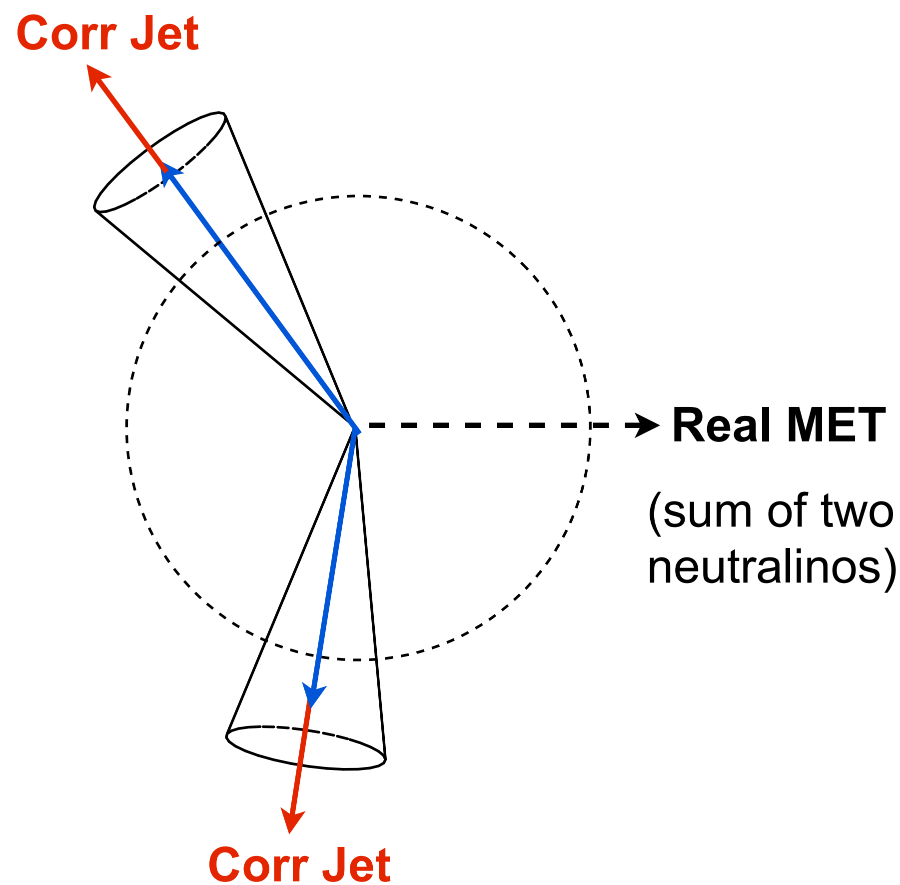
CMS PTDR

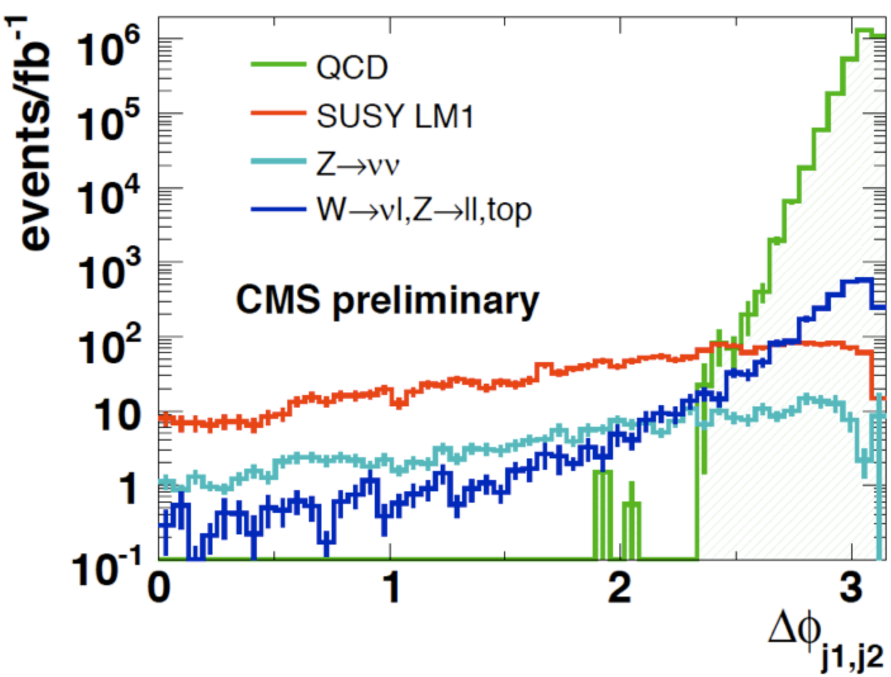
Signal	$t\bar{t}$	single t	$Z(\rightarrow \nu\bar{\nu})$+ jets	$(W/Z,WW/ZZ/ZW)$ + jets	QCD
6319	53.9	2.6	48	33	107

  - ~6 pb^{-1} for 5σ discovery

Exclusive dijet + MET







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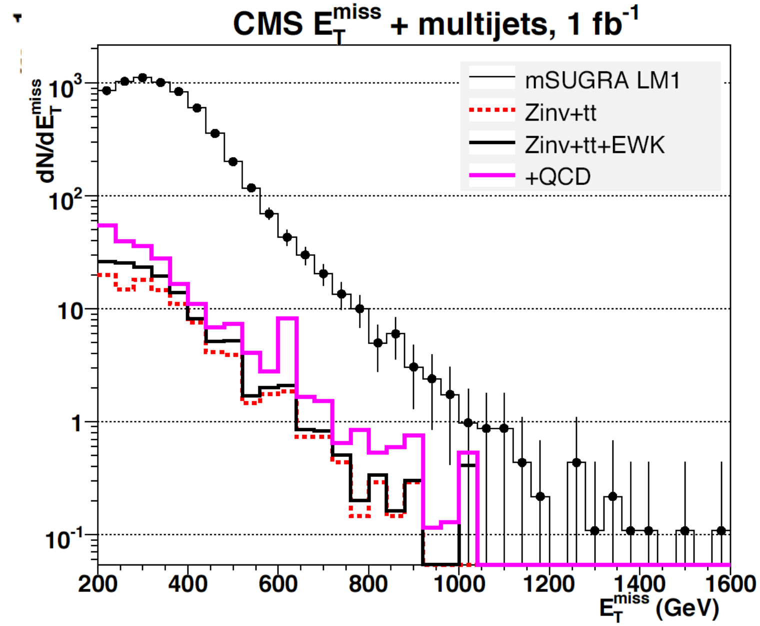
- MET = Rubbish bin of detector
  - Wrought with pain and suffering
- ...so, try to avoid using it



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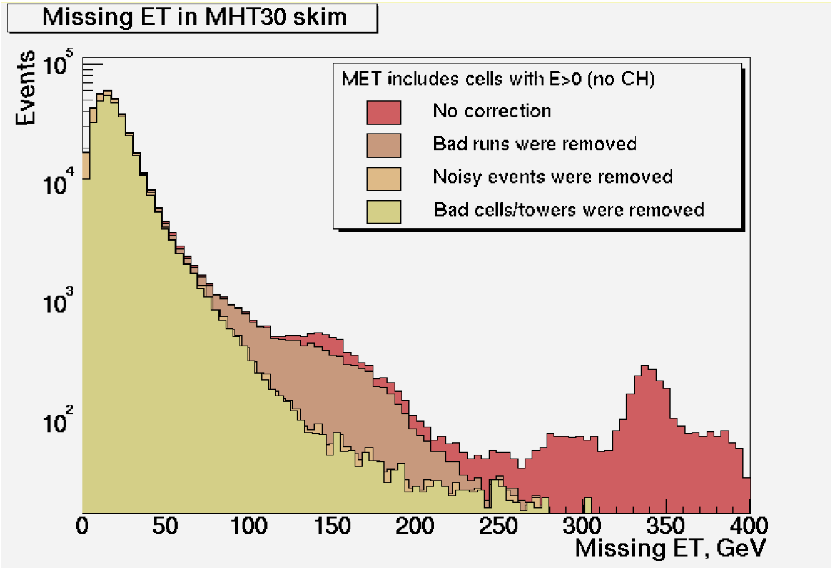

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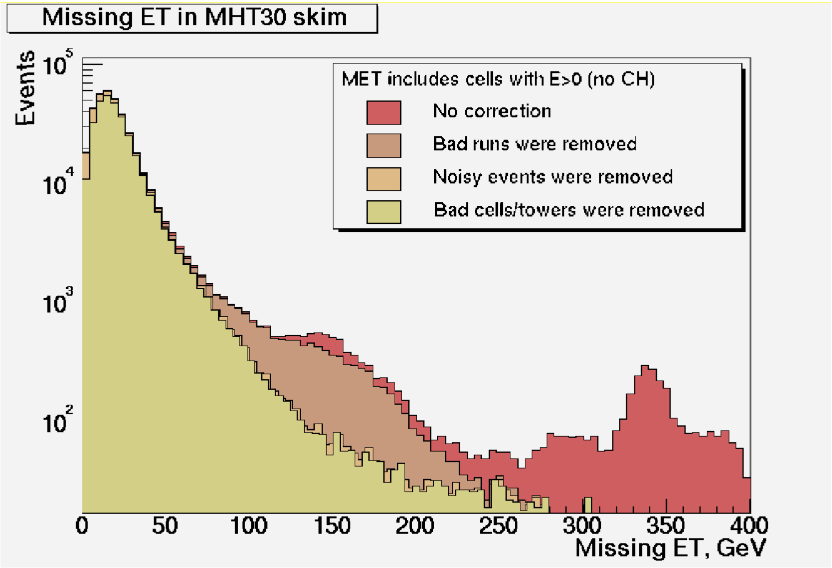
$$\alpha_T = \frac{E_T^{j2}}{\sqrt{2E_T^{j1}E_T^{j2}(1-\cos\Delta\phi)}} = \frac{\sqrt{E_T^{j2}/E_T^{j1}}}{\sqrt{2(1-\cos\Delta\phi)}}$$



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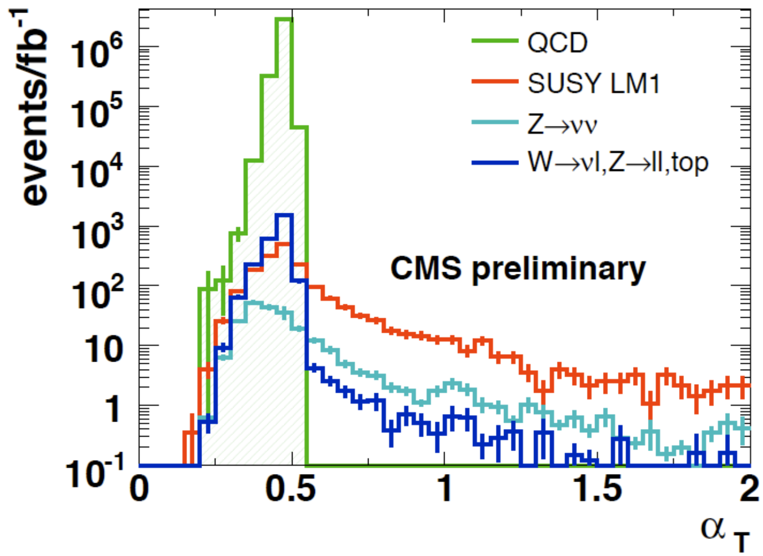

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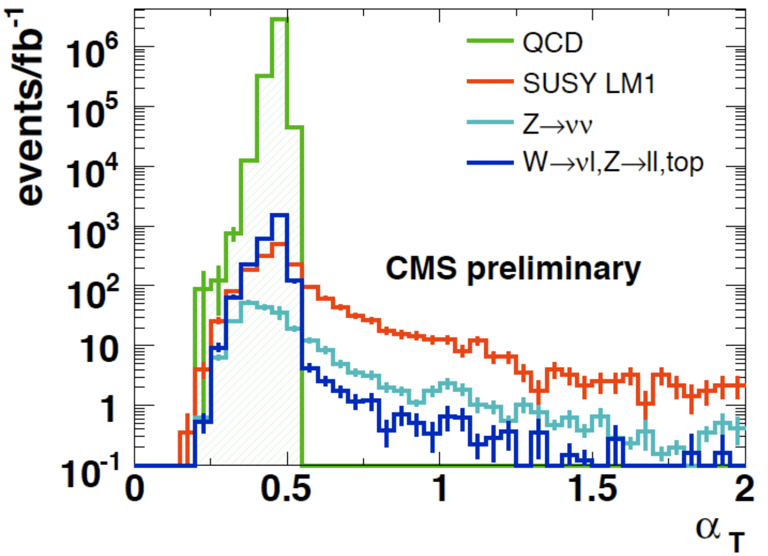

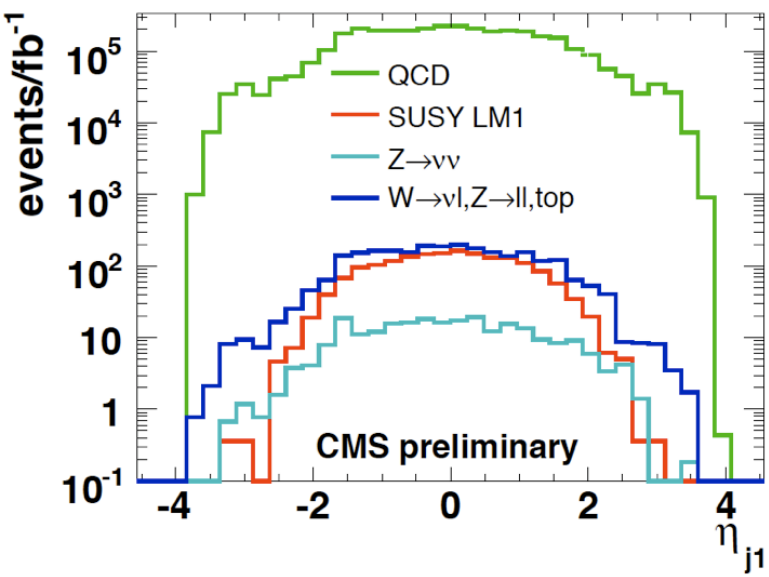

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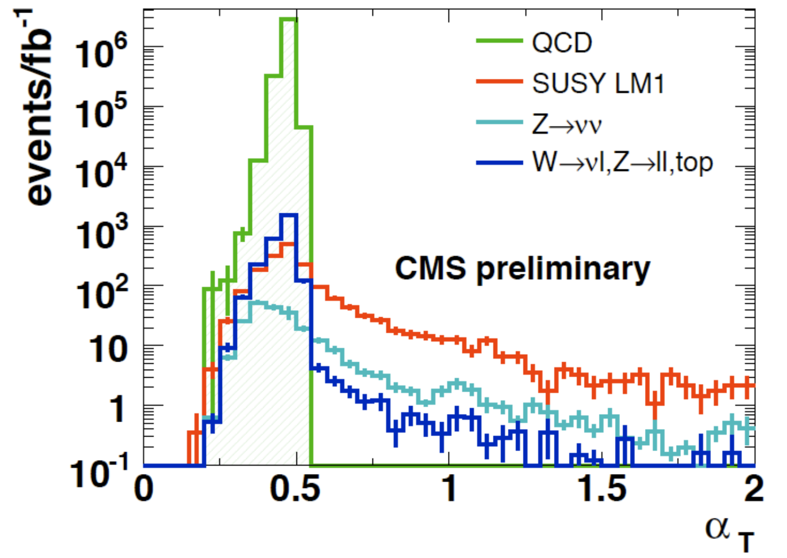
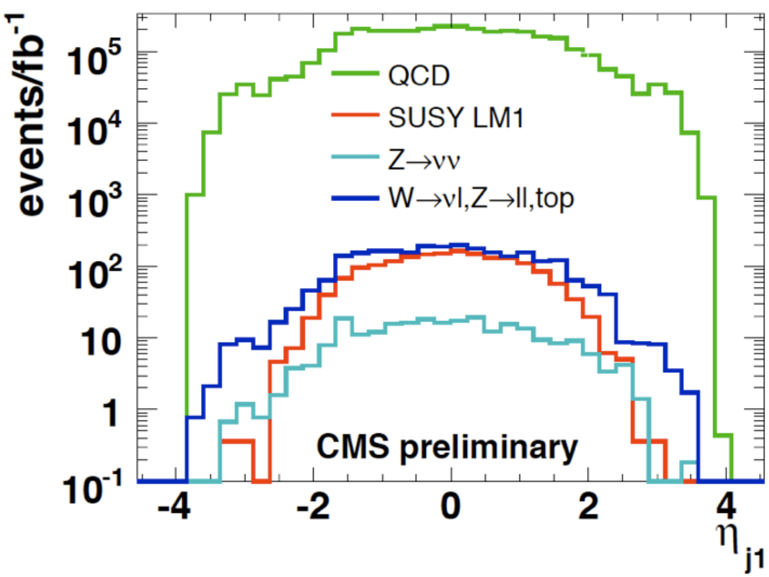
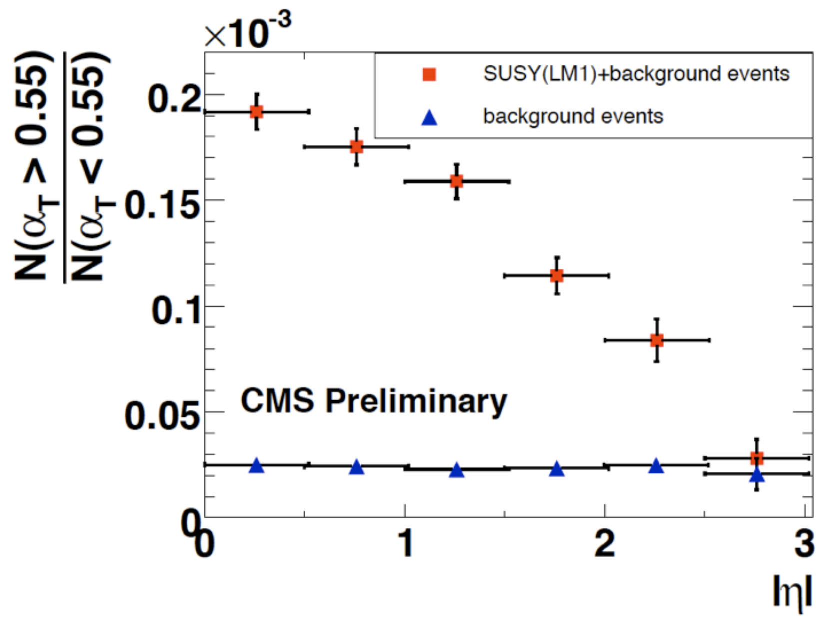
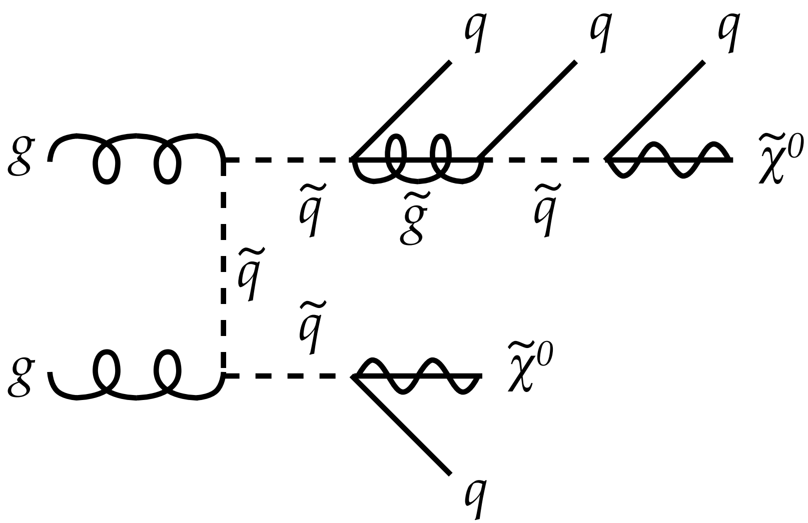
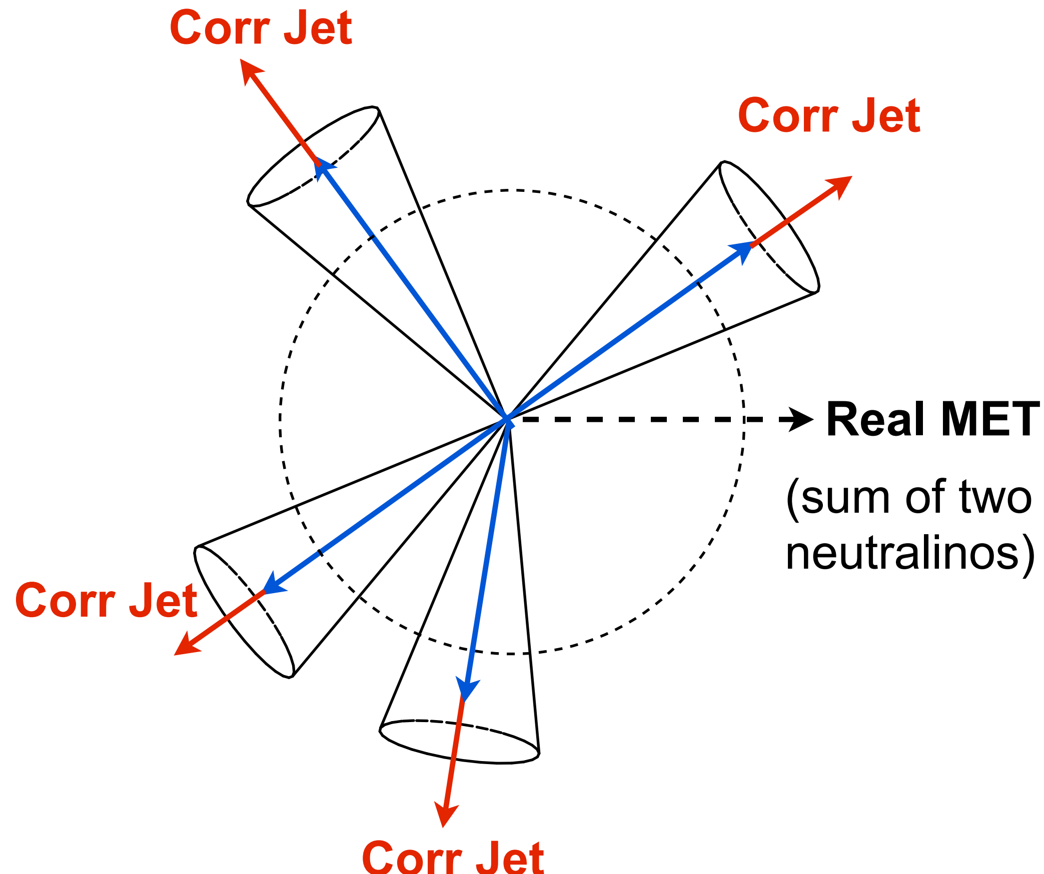






Exclusive N-Jets + MET





Exclusive N-Jets + MET

- One can indeed generalize to N-Jets
  - basic idea: combine N-Jets into effective 2-Jet system
  - Formula looks a little bit different, but idea is same

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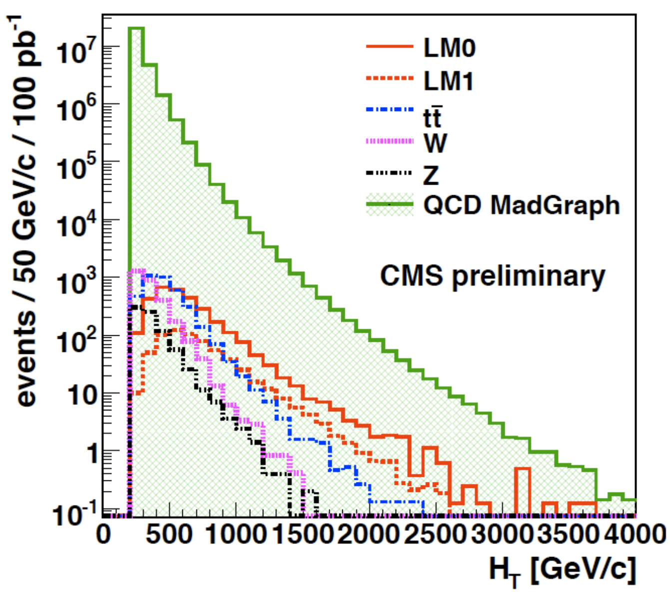
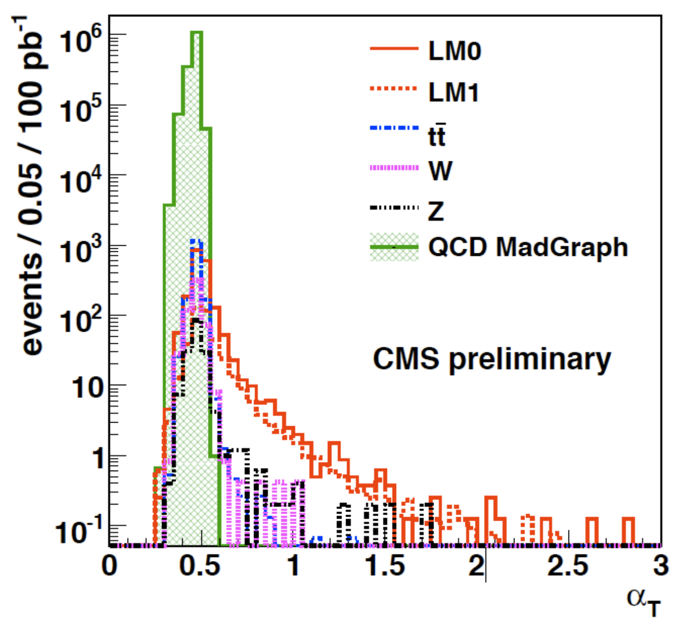
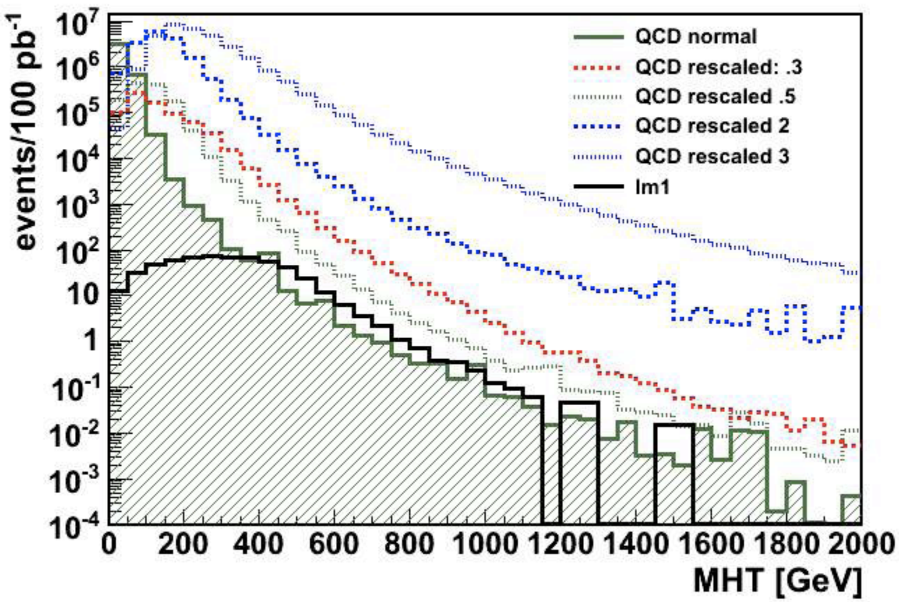




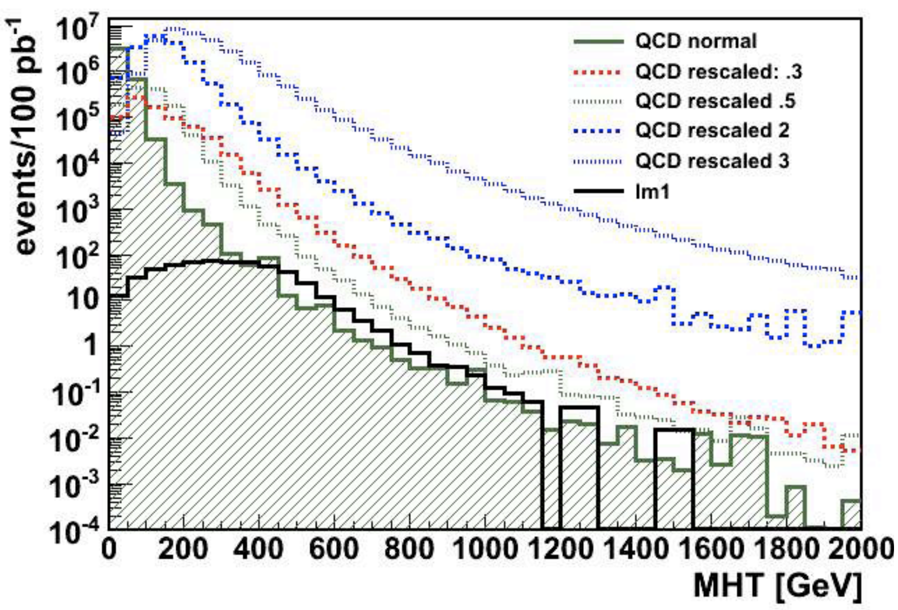
Testing Robustness

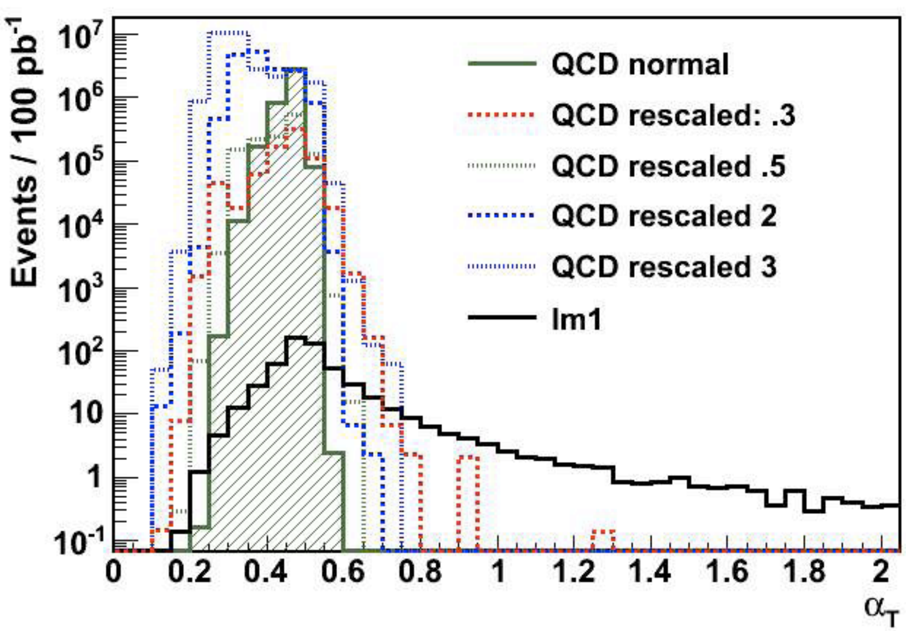
- Grossly distort Jet energies and see what happens…
  - Effective Mass (MHT) is dramatically affected!



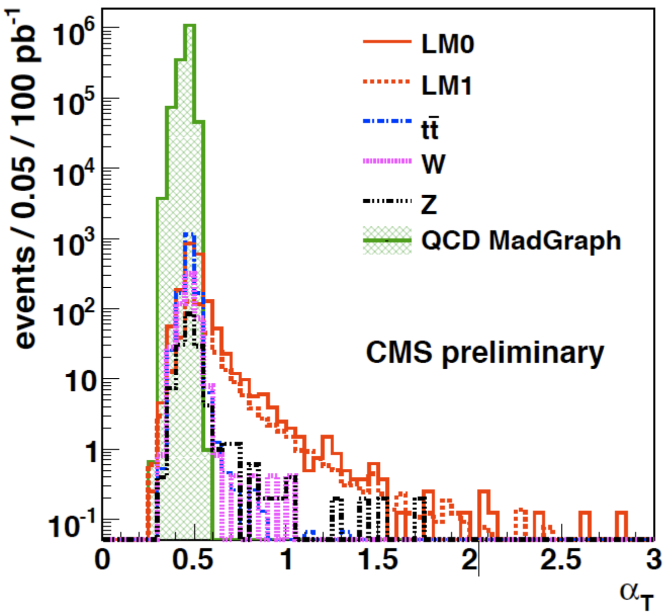
Testing Robustness

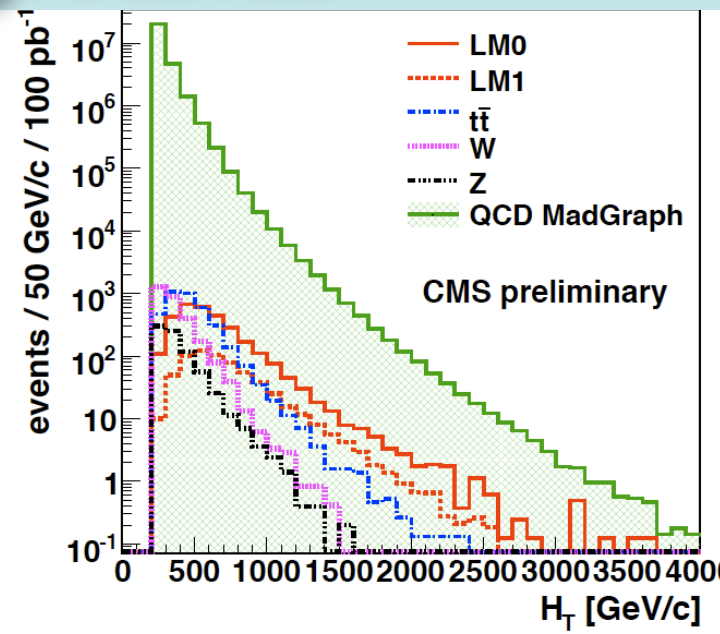
- Grossly distort Jet energies and see what happens…
  - Effective Mass (MHT) is dramatically affected!
  - α_T is very robust against badly measured jets!

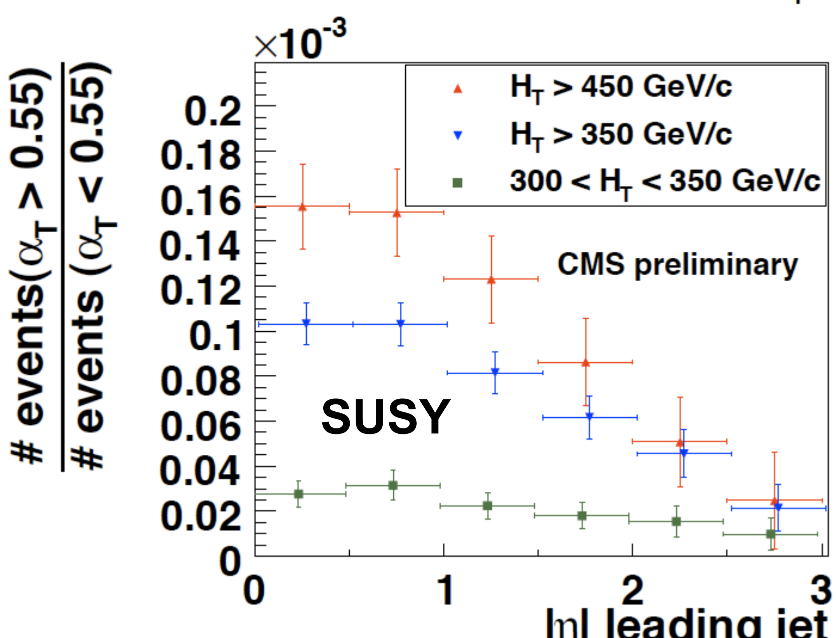


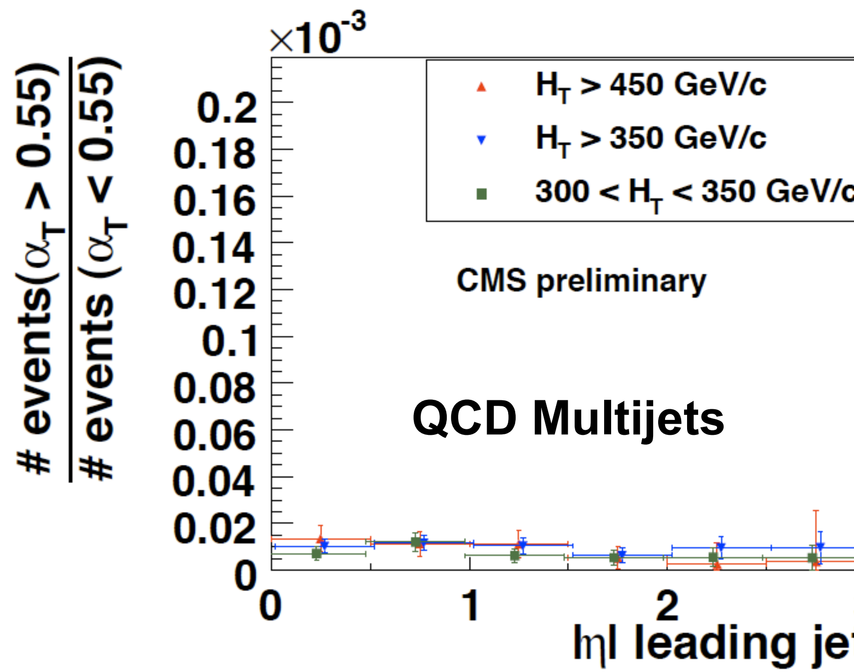


Estimating Backgrounds



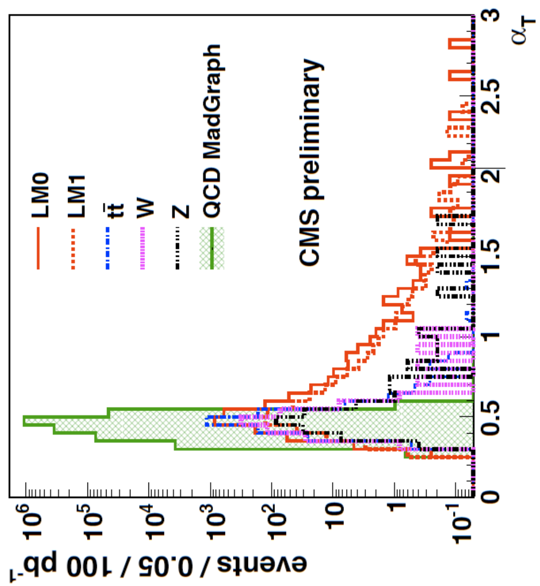


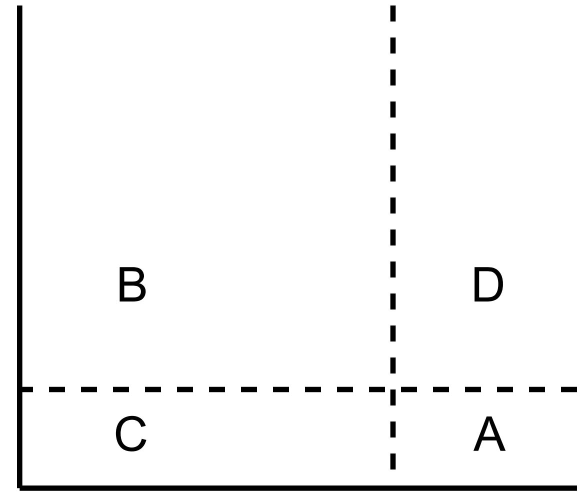




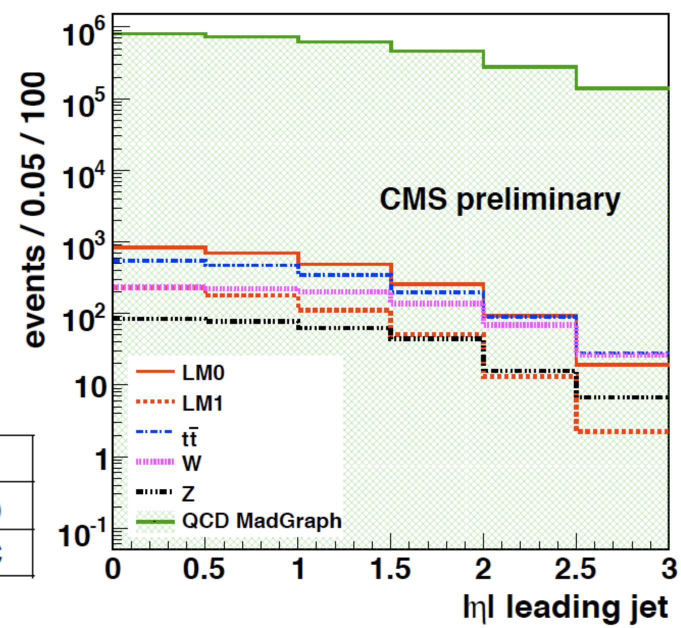
ABCD/Matrix method

- Try to estimate bkg from data:
  - Most signal is in "C"
  - Backgrounds are in
    - "A", "D", "B"
- Assume that for bkg
  - "A" / "D" = "C" / "B"
  - valid if α_T & η are uncorrelated





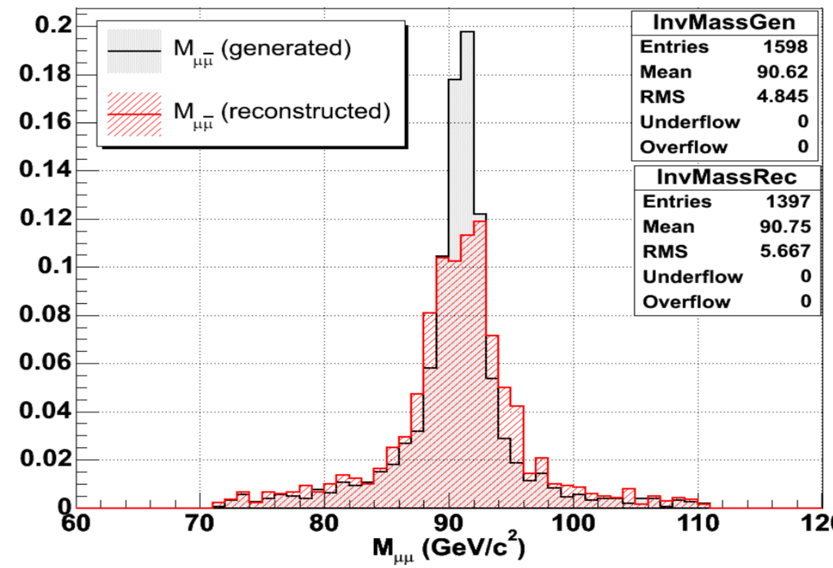
$$N_{\mathrm{pred}}^{\mathrm{bkg}}(\alpha_{\mathrm{T}} > 0.55, |\eta| < 2)$$
$$= R_{\alpha\mathrm{T}}(0.55, |\eta| > 2) \times N_{\mathrm{meas}}^{\mathrm{bkg}}(\alpha_{\mathrm{T}} < 0.55, |\eta| < 2)$$

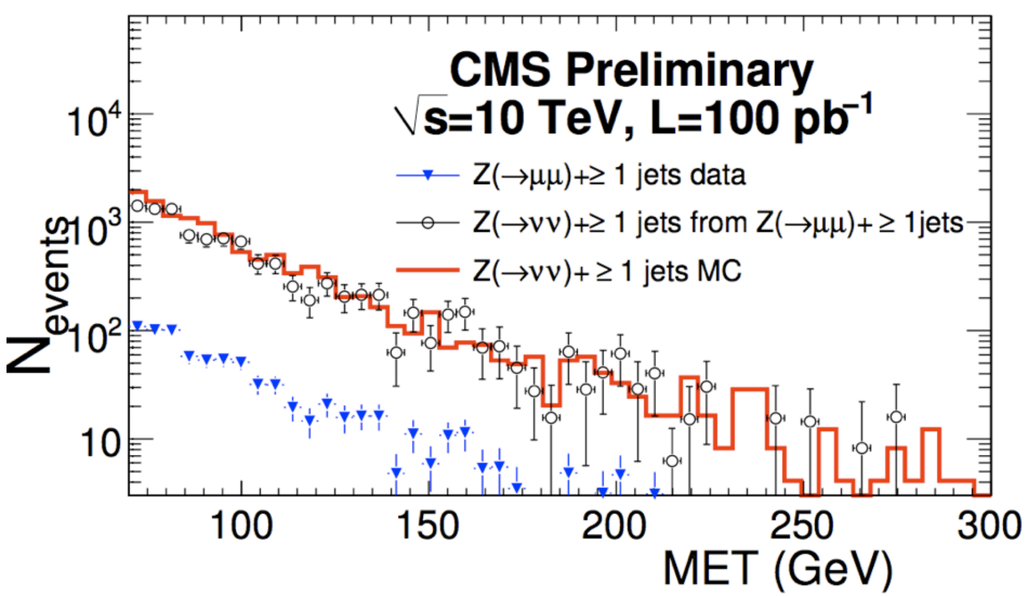


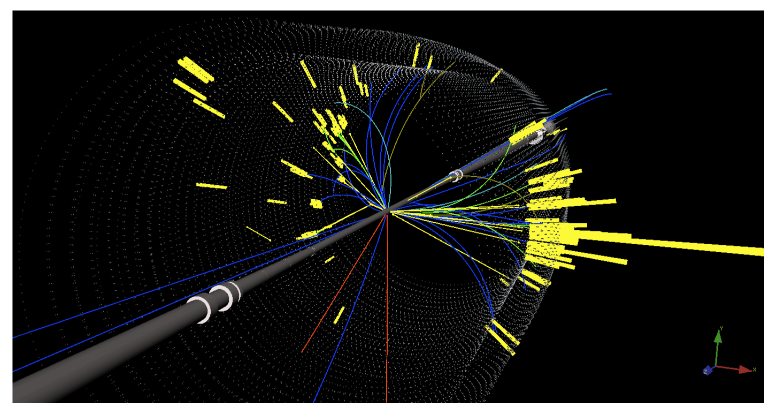
data	background region	estimated	measured
background	2 < |eta| < 3	42+-17 (9 MC)	40 +- 6 (4 MC)
background (mad)	2 < |eta| < 3	40 +-15 (9 MC)	39 +- 6 (3) MC

"Non-QCD" Background

- Large MET and ≥ *n* Jets expected from
  - $Z(\to\nu\nu)$ + ≥ *n* jets
- Can derive from data using
  - $Z(\to\mu\mu)$ + ≥ *n* jets
  - γ + ≥ *n* jets





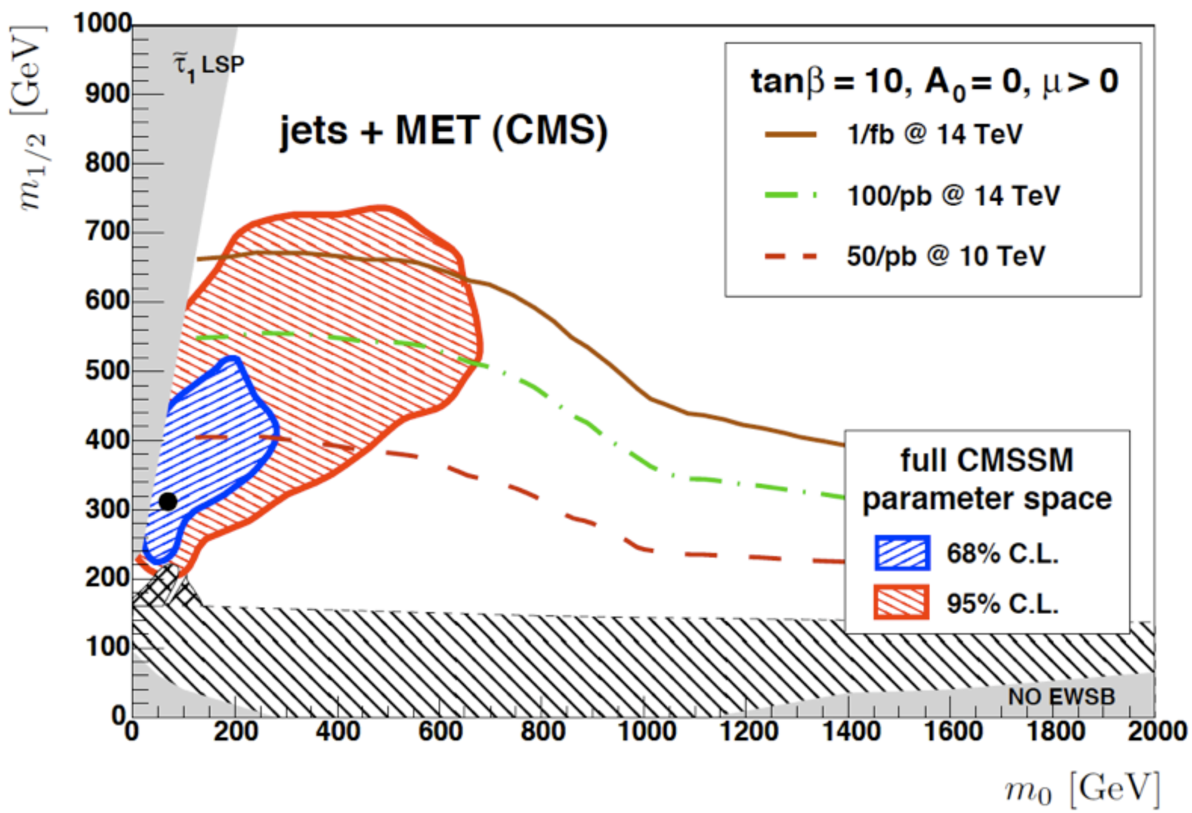


$Z(\to\mu\mu)$ + ≥ n jets EWK 08-006

γ + ≥ n jets SUS 08-002

Sensitivity to Discover CMSSM

- Inclusive Jets and MET signature most sensitive at LHC



- Recent global fits of CMSSM to all experimental data indirectly constrain the model
  - The CMSSM is an early Discovery / Exclusion Model !

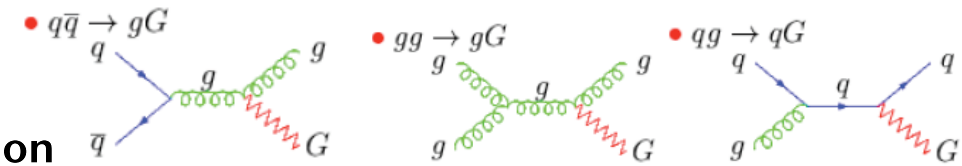
Summary

- Many very interesting topics I did not cover:
  - Extra Dimensions (Monojets)
  - Black holes (Jets, MET, leptons, everything)
  - Heavy Stable Charged Particles ("Monojet")
- There is an exciting Menu of Jets & MET physics at the LHC
  - Jets bread & butter physics...lots of QCD!!
    - do we understand the SM at Terascale?
  - Jets & MET searches not easy...lots of QCD!!
    - but most sensitivity to many NP models!
    - Early discoveries possible!
      (with understood data, of course ;-)

Backups

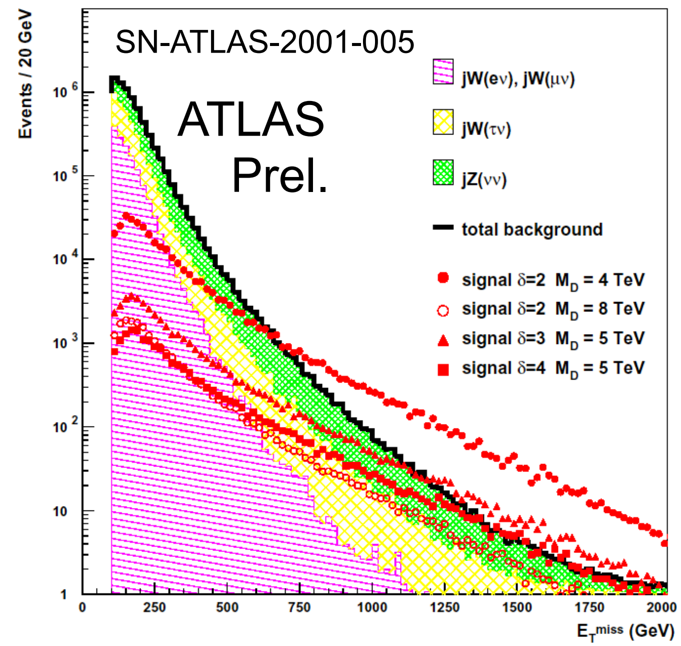
Monojets & Single Photons

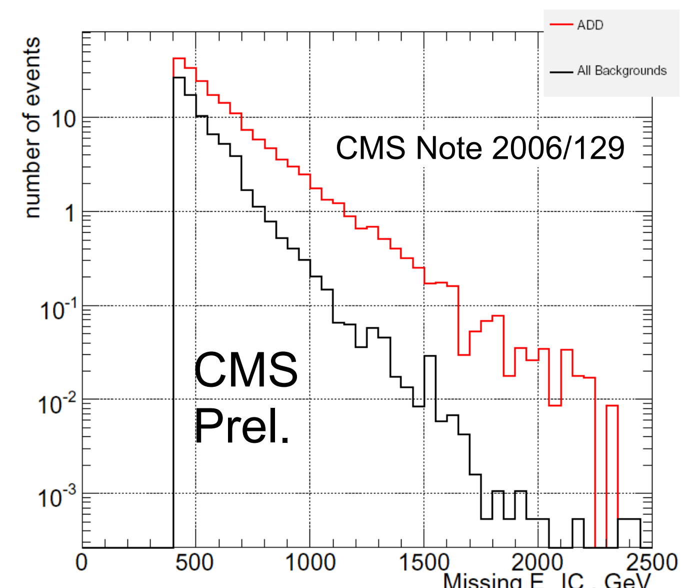
- ADD Large Extra Dimensions
  - via Real Graviton Production
- Very Simple Topology:
  - monojet / photon back-to-back and balancing MET



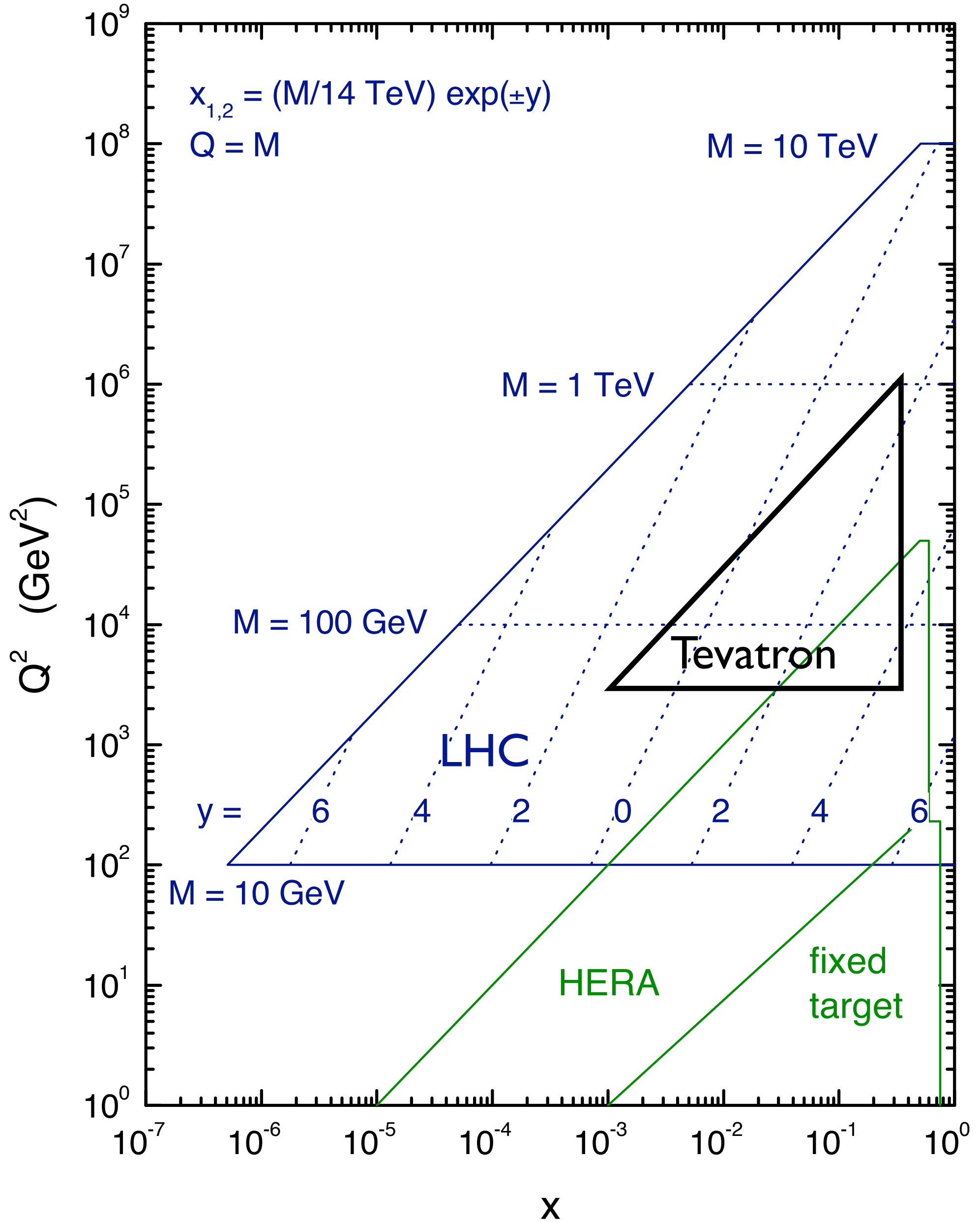
- Selection
  - lepton veto,
  - large Jet/Photon pT (> 400 GeV), large MET (> 400 GeV)
  - MET back-to-back with Jet / photon
- Main backgrounds (normalize with Standard Candles)
  - W(→lν)+Jet
  - Z(→νν)+Jet
- Discoverable shortly after 100 pb-1

M_D / n	$n = 2$	$n = 3$	$n = 4$	$n = 5$	$n = 6$
$M_D = 1.0$ TeV	0.21 fb^{-1}	0.16 fb^{-1}	0.14 fb^{-1}	0.15 fb^{-1}	0.15 fb^{-1}
$M_D = 1.5$ TeV	0.83 fb^{-1}	0.59 fb^{-1}	0.56 fb^{-1}	0.61 fb^{-1}	0.59 fb^{-1}
$M_D = 2.0$ TeV	2.8 fb^{-1}	2.1 fb^{-1}	1.9 fb^{-1}	2.1 fb^{-1}	2.3 fb^{-1}
$M_D = 2.5$ TeV	9.9 fb^{-1}	8.2 fb^{-1}	8.7 fb^{-1}	9.4 fb^{-1}	10.9 fb^{-1}
$M_D = 3.0$ TeV	47.8 fb^{-1}	46.4 fb^{-1}	64.4 fb^{-1}	100.8 fb^{-1}	261.2 fb^{-1}
$M_D = 3.5$ TeV	**5 σ discovery not possible anymore**				





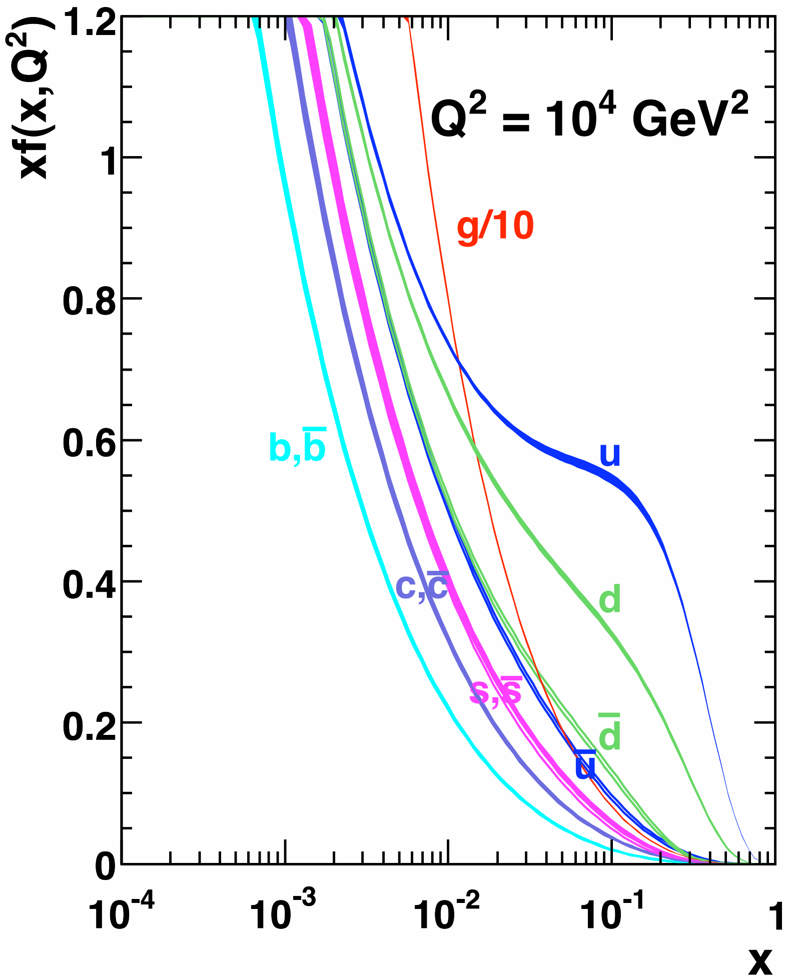
LHC parton kinematics



Parton Distribution Functions

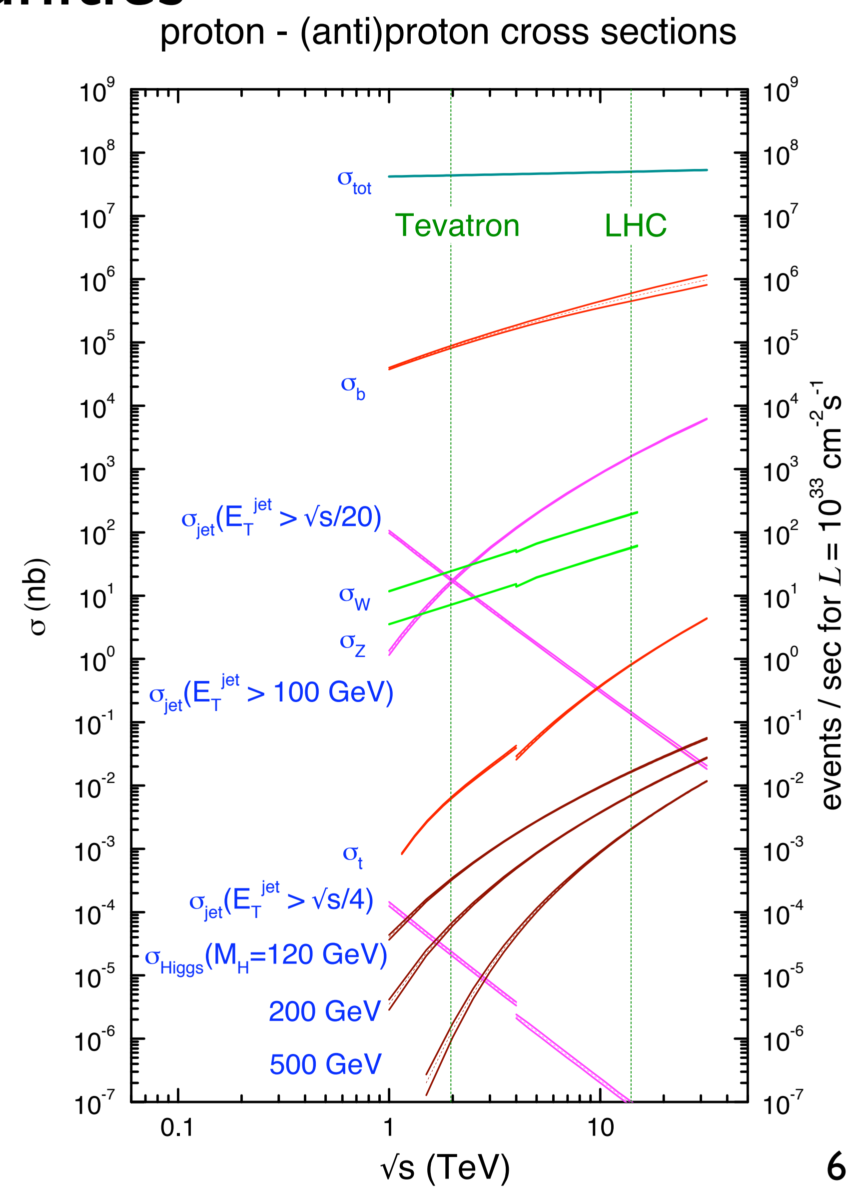
- Typically, sea and/or gluon interactions at low-x dominate production rates at the LHC

- At $Q^2 \approx M^2(W)$ the sea is driven by the gluon (via gluon splitting)



One of the very first LHC Physics Opportunities

- Centre-of-Mass profile (very rough est.)
  - 1 pb^{-1} at 14 TeV:
    - ~200 000 W's (40 000 eν+μν)
    - ~60 000 Z's (4 000 ee+μμ)
  - 1 pb^{-1} at 6 TeV:
    - ~70 000 W's (15 000 eν+μν)
    - ~20 000 Z's (1 500 ee+μμ)
- Luminosity profile (very rough est.)
  - 1 pb^{-1} at 10 TeV:
    - ~100 000 W's (20 000 eν+μν)
    - ~40 000 Z's (2 000 ee+μμ)
  - 10 nb^{-1} at 10 TeV:
    - ~1 000 W's (200 eν+μν)
    - ~400 Z's (20 ee+μμ)



Jet pT spectra

Supersymmetry Phenomenology

- Supersymmetric particles not observed experimentally
  - SUSY must be broken (softly)!

$$\mathcal{L}_{\rm soft}^{\rm MSSM} = -\frac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B} + {\rm c.c.}\right)$$
$$-\left(\widetilde{\overline{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\,\widetilde{L}H_d + {\rm c.c.}\right)$$
$$-\widetilde{Q}^\dagger\,\mathbf{m^2_Q}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m^2_L}\,\widetilde{L} - \widetilde{\overline{u}}\,\mathbf{m^2_{\overline{u}}}\,\widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\,\mathbf{m^2_{\overline{d}}}\,\widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\,\mathbf{m^2_{\overline{e}}}\,\widetilde{\overline{e}}^\dagger$$
$$-m^2_{H_u}H_u^*H_u - m^2_{H_d}H_d^*H_d - (bH_uH_d + {\rm c.c.})\,.$$

- Mechanism is unknown ⇒ many new free parameters
  - MSSM: > 100 additional parameters
  - Pheno. Viable: < 20 additional parameters
    - 3 gaugino masses, 5 squark and slepton masses, 3 tri-linear couplings, 4 higgs masses
    - Defined at the Soft Scale!!
  - CMSSM: 4 additional parameters (gravity inspired)
    - m_0, $m_{1/2}$, A_0, $\tan\beta$, Sign(μ)
    - Defined at the GUT Scale!!
  - Others!

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$$
\begin{aligned}
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& - \left(\widetilde{\bar u}\, \mathbf{a_u}\, \widetilde{Q} H_u - \widetilde{\bar d}\, \mathbf{a_d}\, \widetilde{Q} H_d - \widetilde{\bar e}\, \mathbf{a_e}\, \widetilde{L} H_d + {\rm c.c.} \right) \\
& - \widetilde{Q}^\dagger\, \mathbf{m_Q^2}\, \widetilde{Q} - \widetilde{L}^\dagger\, \mathbf{m_L^2}\, \widetilde{L} - \widetilde{\bar u}\, \mathbf{m_{\bar u}^2}\, \widetilde{\bar u}^\dagger - \widetilde{\bar d}\, \mathbf{m_{\bar d}^2}\, \widetilde{\bar d}^\dagger - \widetilde{\bar e}\, \mathbf{m_{\bar e}^2}\, \widetilde{\bar e}^\dagger \\
& - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - \left(b H_u H_d + {\rm c.c.} \right) .
\end{aligned}
$$

Gaugino Masses

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\begin{aligned}
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& - \left(\widetilde{\overline{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\,\widetilde{L}H_d + {\rm c.c.}\right) \\
& -\widetilde{Q}^\dagger\,\mathbf{m^2_Q}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m^2_L}\,\widetilde{L} - \widetilde{\overline{u}}\,\mathbf{m^2_{\overline{u}}}\,\widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\,\mathbf{m^2_{\overline{d}}}\,\widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\,\mathbf{m^2_{\overline{e}}}\,\widetilde{\overline{e}}^\dagger \\
& - m^2_{H_u}H_u^*H_u - m^2_{H_d}H_d^*H_d - (bH_uH_d + {\rm c.c.})\,.
\end{aligned}
$$

Tri-linear couplings

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& -\left(\widetilde{\overline{u}}\,\mathbf{a_u}\,\widetilde{Q} H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\,\widetilde{Q} H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\,\widetilde{L} H_d + \text{c.c.}\right) \\
& -\widetilde{Q}^\dagger\,\mathbf{m_Q^2}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m_L^2}\,\widetilde{L} - \widetilde{\overline{u}}\,\mathbf{m_{\overline{u}}^2}\,\widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\,\mathbf{m_{\overline{d}}^2}\,\widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\,\mathbf{m_{\overline{e}}^2}\,\widetilde{\overline{e}}^\dagger \\
& - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (b H_u H_d + \text{c.c.})\,.
\end{aligned}
$$

squark and slepton masses

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  - **Pheno. Viable: < 20 additional parameters**
    - 3 gaugino masses, 5 squark and slepton masses, 3 tri-linear couplings, 4 higgs masses
    - Defined at the Soft Scale!!
  - **CMSSM: 4 additional parameters (gravity inspired)**
    - m_0, $m_{1/2}$, A_0, $\tan\beta$, Sign(μ)
    - Defined at the GUT Scale!!
  - **Others!**

Supersymmetry Phenomenology

- **Supersymmetric particles not observed experimentally**
  - **SUSY must be broken (softly)!**

$$
\begin{aligned}
\mathcal{L}_{\rm soft}^{\rm MSSM} = & -\frac{1}{2}\left(M_3 \tilde g \tilde g + M_2 \widetilde W \widetilde W + M_1 \widetilde B \widetilde B + {\rm c.c.}\right) \\
& - \left(\tilde{\bar u}\, \mathbf{a_u}\, \tilde Q H_u - \tilde{\bar d}\, \mathbf{a_d}\, \tilde Q H_d - \tilde{\bar e}\, \mathbf{a_e}\, \tilde L H_d + {\rm c.c.}\right) \\
& - \tilde Q^\dagger\, \mathbf{m^2_Q}\, \tilde Q - \tilde L^\dagger\, \mathbf{m^2_L}\, \tilde L - \tilde{\bar u}\, \mathbf{m^2_{\bar u}}\, \tilde{\bar u}^\dagger - \tilde{\bar d}\, \mathbf{m^2_{\bar d}}\, \tilde{\bar d}^\dagger - \tilde{\bar e}\, \mathbf{m^2_{\bar e}}\, \tilde{\bar e}^\dagger \\
& - m^2_{H_u} H_u^* H_u - m^2_{H_d} H_d^* H_d - (b H_u H_d + {\rm c.c.})\,.
\end{aligned}
$$

Higgs masses

- **Mechanism is unknown ⇒ many new free parameters**
  - **MSSM: > 100 additional parameters**
  - **Pheno. Viable: < 20 additional parameters**
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    - Defined at the Soft Scale!!
  - **CMSSM: 4 additional parameters (gravity inspired)**
    - m_0, $m_{1/2}$, A_0, $\tan\beta$, Sign(μ)
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$$\begin{aligned}\mathcal{L}_{\rm soft}^{\rm MSSM} &= -\frac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B} + \text{c.c.}\right) \\ &\quad - \left(\widetilde{\overline{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\,\widetilde{L}H_d + \text{c.c.}\right) \\ &\quad -\widetilde{Q}^\dagger\,\mathbf{m^2_Q}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m^2_L}\,\widetilde{L} - \widetilde{\overline{u}}\,\mathbf{m^2_{\overline{u}}}\,\widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\,\mathbf{m^2_{\overline{d}}}\,\widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\,\mathbf{m^2_{\overline{e}}}\,\widetilde{\overline{e}}^\dagger \\ &\quad - m^2_{H_u}H_u^*H_u - m^2_{H_d}H_d^*H_d - (bH_uH_d + \text{c.c.})\,.\end{aligned}$$

- **Mechanism is unknown ⇒ many new free parameters**
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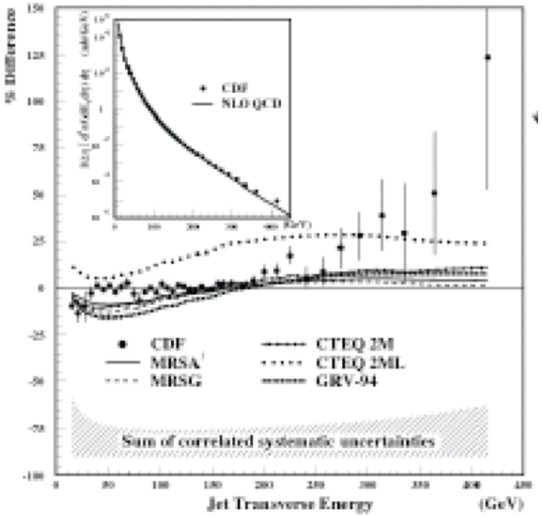
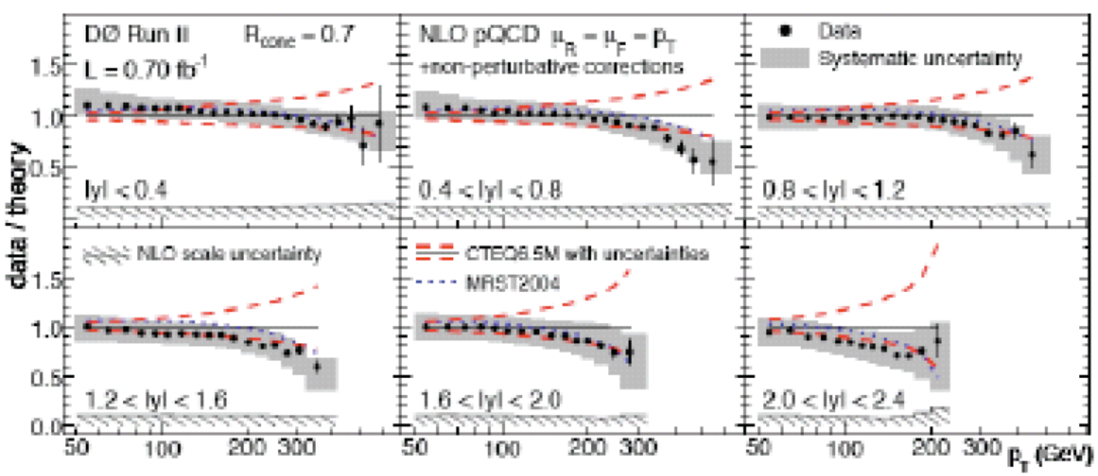
Inclusive Jet Cross-section





1960

- Introduction of Color and the Quark Model

SLAC

- Experimental evidence of quarks in DIS scattering
  Bjorken scaling

1970
ISR

- Birth of QCD
  Renormalizability, Asymptotic Freedom, Confinement
- Discovery of the c-quark (SLAC, BNL)
- Experimental evidence of jets in e^+e^- annihilations as manifestation of quarks (1975) and gluons (1979)

PETRA

- Discovery of the b-quark (Fermilab)
- Violation of Bjorken scaling, Evolution of Parton Distribution and Parton Fragmentation Functions

1980
$Sp\bar{p}S$

- Computation of higher-order effects in pQCD for many processes
- Discovery of W and Z – Confirmation of Standard Model

Tevatron
LEP
HERA
1990
D0+CDF

- Next to Leading Order pQCD predictions for jet production

LEP 2

- Discovery of the t-quark (Fermilab)
- Precision EW Data – LEP 2

2000

- Tevatron Upgrade, Run IIa
- CTEQ6 PDFs + Errors
- Tevatron Run IIb

LHC

- LHC Startup

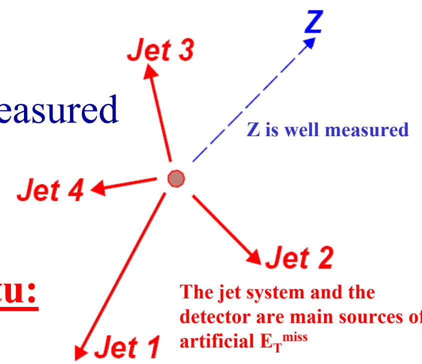
2010

Background Est. via QCD Template Events

How to model E_T^{miss} resolution effects in V+jets?

a) Assume that the V momentum is known;

b) Artificial sources of E_T^{miss} are due to mismeasured jets, detector and non-collision effects.



How to model effects generating E_T^{miss} in-situ:

1. For each V+jets event, collect a sample of multi-jet QCD events with the "same" configuration of jets;

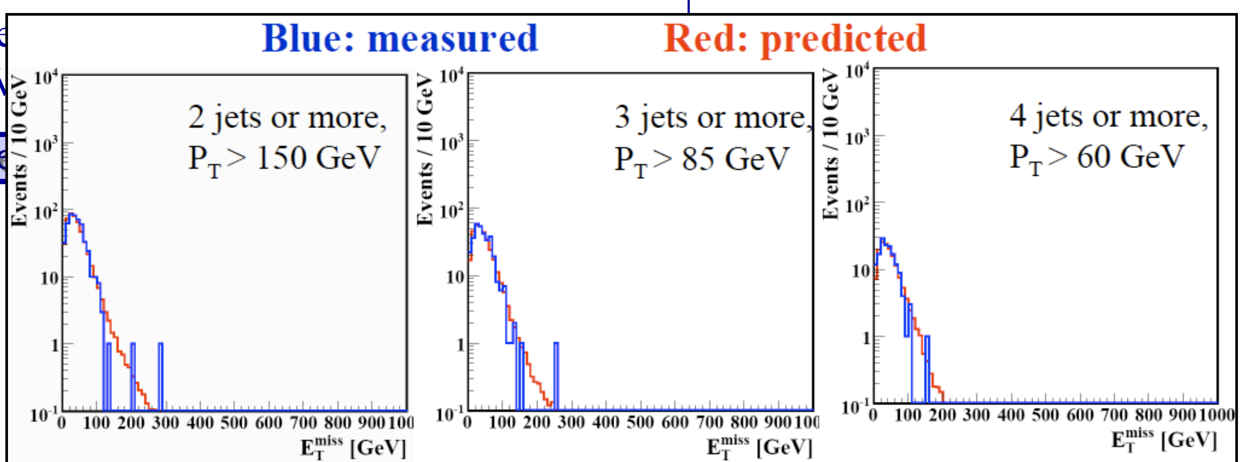
2. Measure E_T^{miss} in the collected QCD sample to obtain E_T^{miss} prediction (template) for this V+jets event;

3. Repeat the above for all V+je
E_T^{miss} prediction for the entire V

Febuary-2009 Selecte

- Also studying :
  - γ+jets
  - forward (SM-like) vs central (BSM-like)

D. Stuart & V. Pavlunin



ttbar

- Top phenomenology
- All hadronic signatures
- Dealing with backgrounds
- Sensitivity: EXO 09-002