Search for New Physics using low multiplicity jets plus Met events

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Outline

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  - New physics searches
  - Jets+Met signature
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- Theory: some of the popular benchmark models
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  - Supersymmetry
  - Leptoquarks
- Analysis Strategy
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  - Data-driven estimate of the QCD background
- The Measurement results
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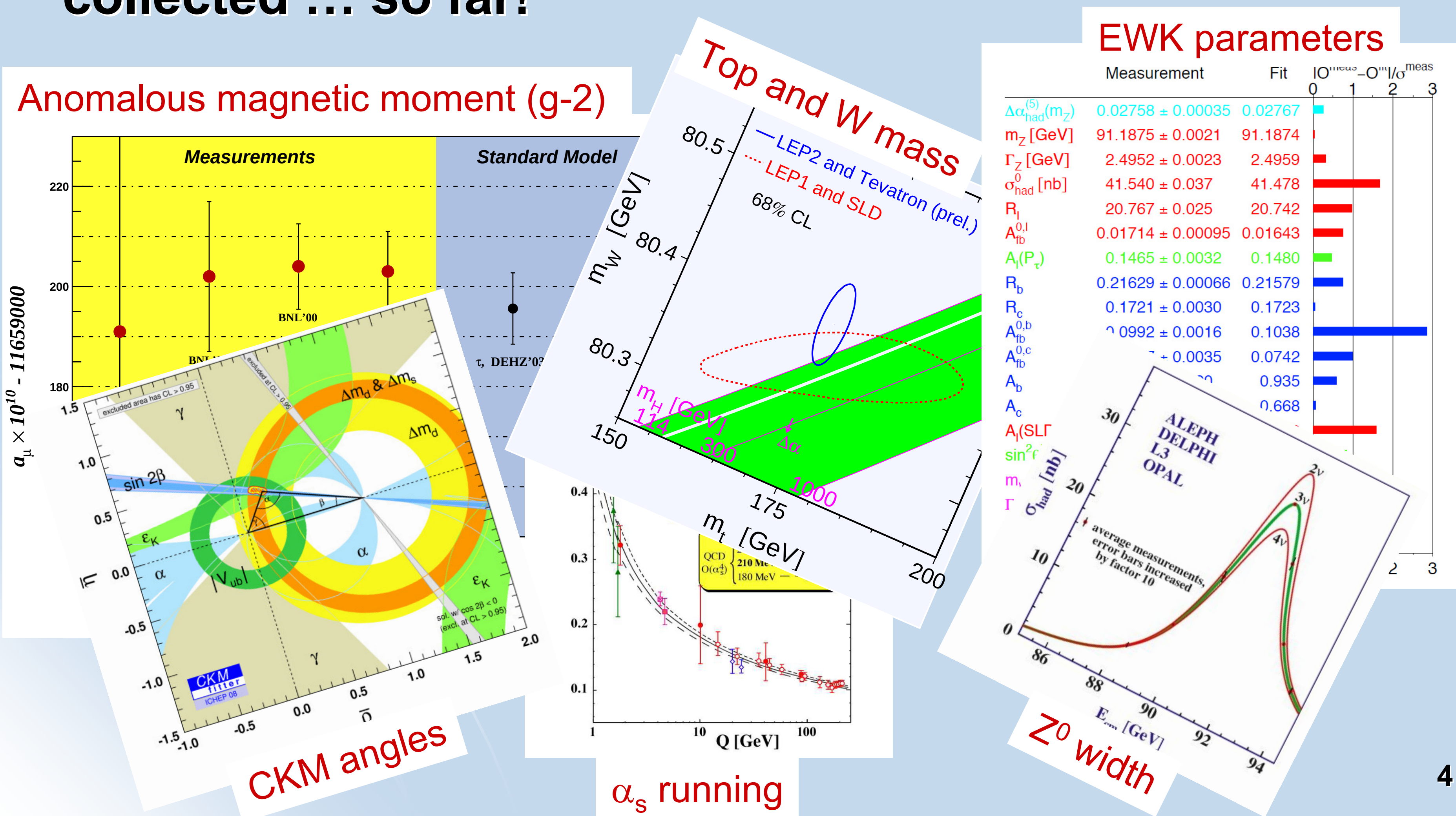
  - Dijet+Met
- Conclusion

INTRODUCTION

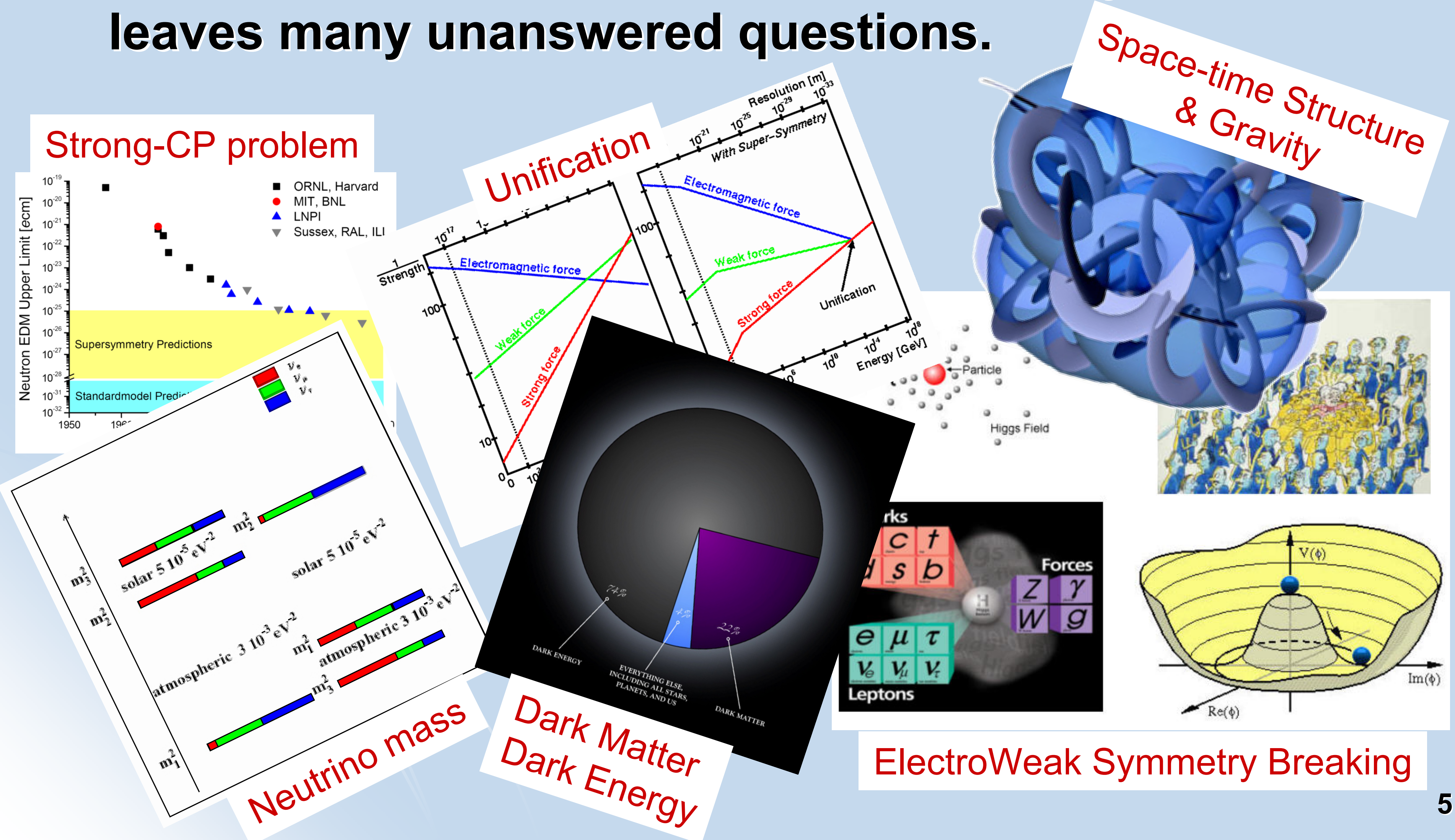
Standard Model success…

SM provides an accurate description of the HEP data collected … so far!



… and its limitations

… But the SM cannot be the end of the story for it leaves many unanswered questions.



The quest for New Physics!

- There are models which can address some of these problems by extending the SM lagrangian

  ⇒ Predictions for new phenomena to be tested!

- Observation of new phenomena get ahead of any further understanding of Nature beyond the SM
  - New phenomena = deviations with respect to SM predictions

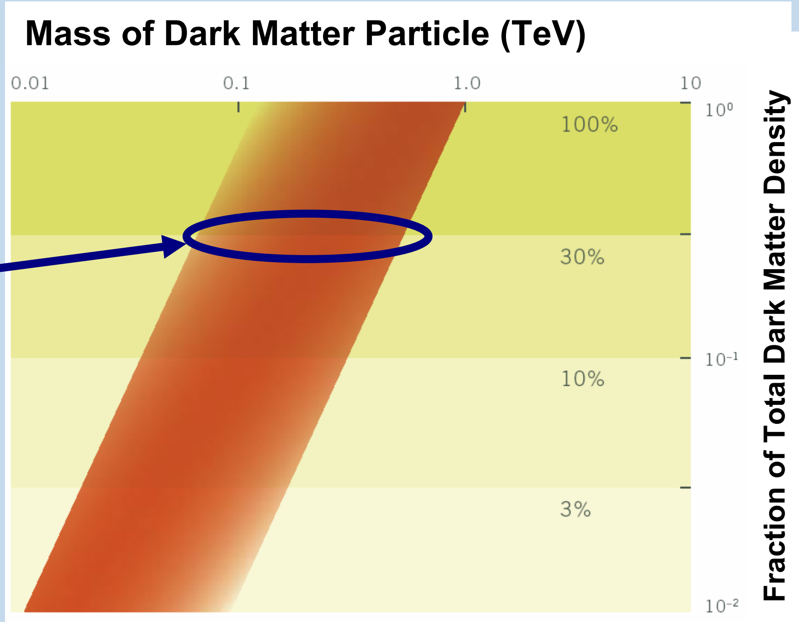
- Excess of events of a given final state would reveal crucial information about new physics
  - Direct probe of new particles or couplings
  - Simple and well understood statistical problem

⇒ Perform counting experiment to look for New Phenomena

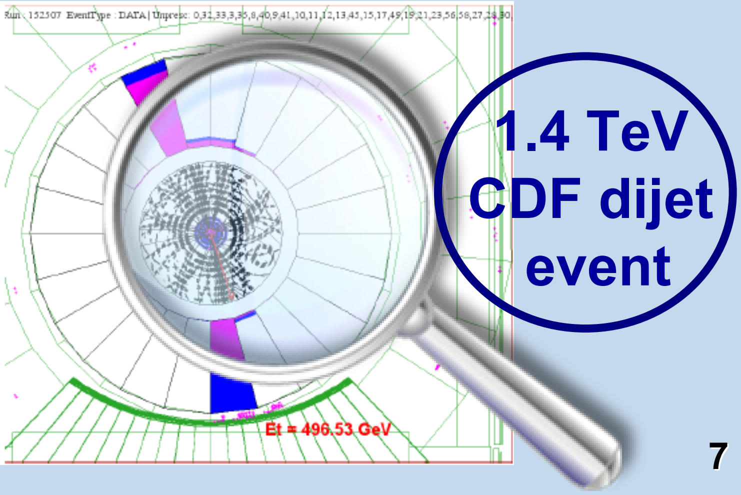
Focus on low multiplicity Jets+Met final states

At which energy scale?

- New particles should manifest at the 0.1-1.0 TeV range
  - Scale of the electroweak symmetry breaking
  - Favoured scale for the mass of Cold Dark Matter candidates (WIMPs)



- Tevatron is still the World's most powerful Microscopes
  - Can probe the sub-TeV range



- The LHC will very soon extend the energy frontier

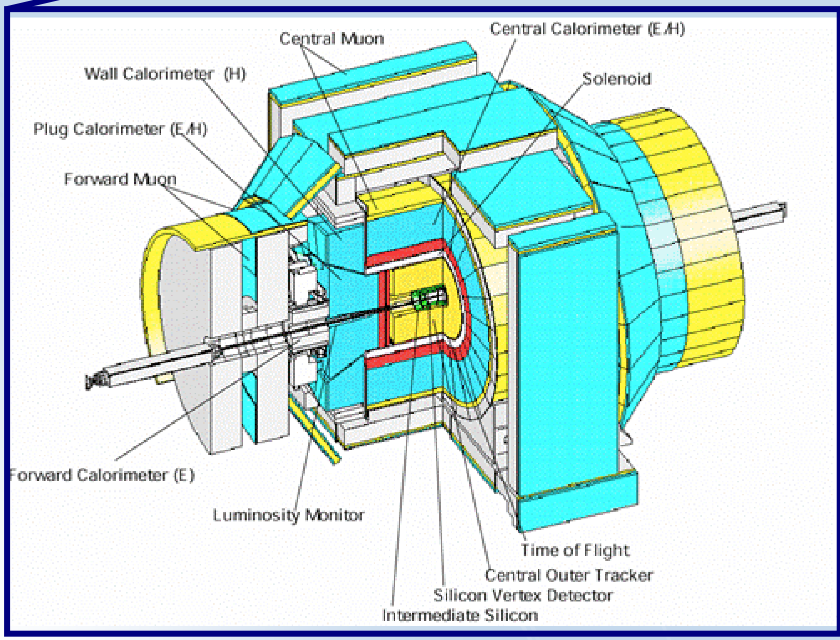
Gain experience for the LHC!

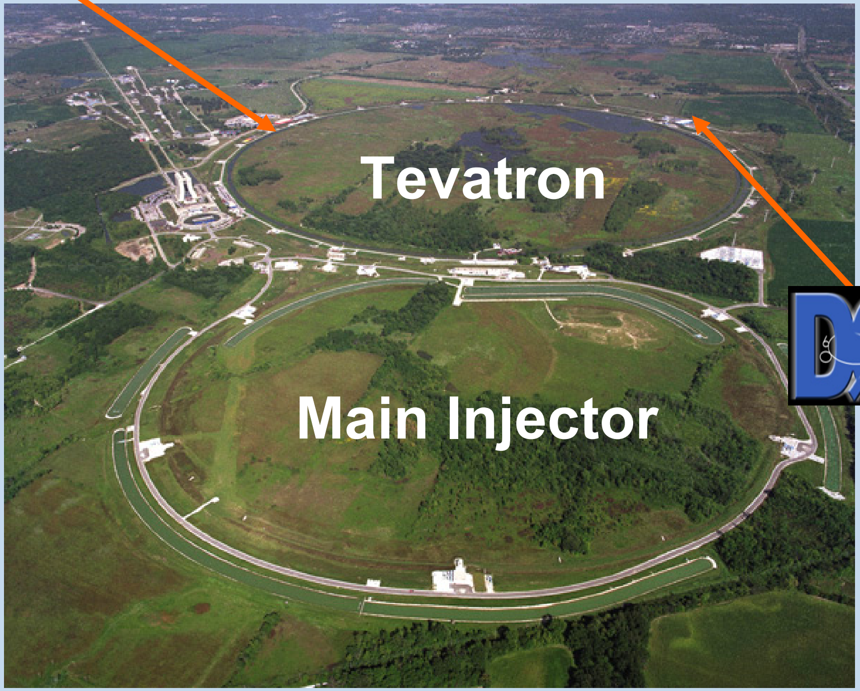
CDF at the Tevatron

- **CDF has recorded over 5 fb^{-1} of data!**
  - **Present analyses up to 2 fb^{-1}**
- **Improving key precision measurements; eg: W & top masses**

P → ← $\bar{P}$

1.96 TeV





Why Jets+Met final states?

- Astrophysical evidences for dark matter provide strong motivation for the existence of new undetectable particles
  - Measured as unbalanced energy in the detector (Met)

- Many new physics scenario predicts enhanced Met signal
  - Discrete symmetry providing dark matter candidates
    - Eg: Supersymmetry (R-parity), Universal Extra Dimensions (KK-number)
  - Graviton escaping in a bulk of Extra Dimensions
  - New unstable particles coupling to neutrinos
    - Eg: Leptoquarks

⇒ Details of the final states depends on specific model

- Undetectable states will be accompanied by jets in the final states if couple to unstable coloured particles

⇒ High production rate expected in hadron colliders

Why looking at signatures?

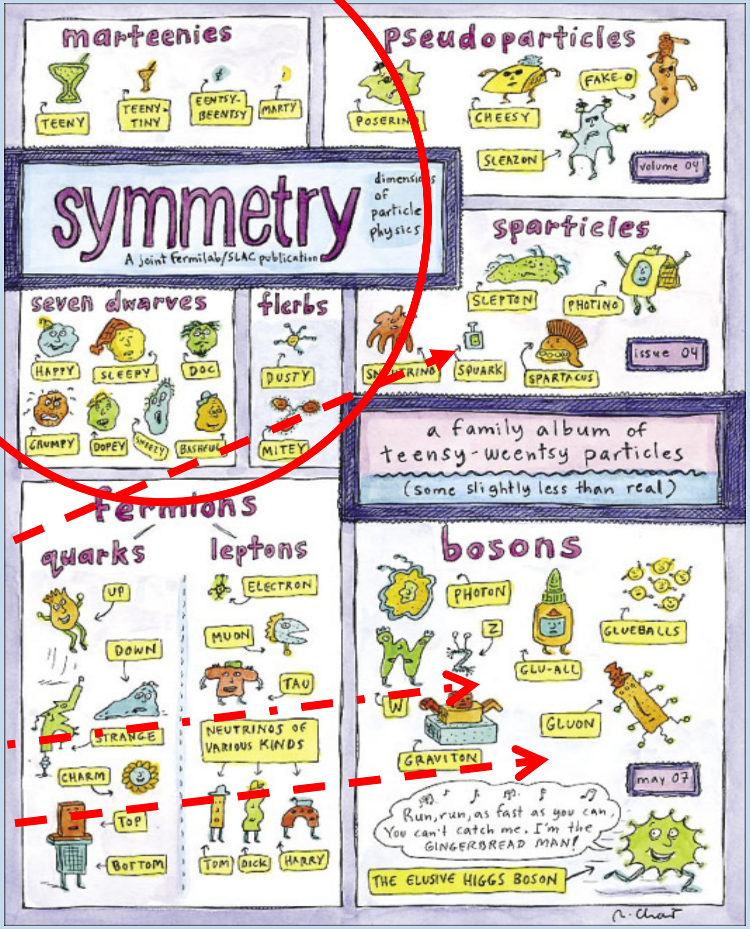
- Different models could contribute to the same phenomena
- Cannot exploit angular correlations, asymmetries, or invariant mass to disentangle the different new physics possibilities

  $\Rightarrow$ No good reason to favour a model over another

- Absence of popular new physics model to predict an excess should not be an issue
  - If there isn't a popular model now, there could be one next year…
    - We generally only focus on "minimal" versions of these models
  - Badly understood backgrounds or detector effects are interesting
- Don't forget the inverse problem: if we find something, how will we know what it is?
  - Will need to look at all channels to pin down the type of new physics
  - Interpretation in terms of a model or another will be pure speculation

Model-Independence!

- Don't want to miss unexpected new physics because of our selections…
  - No optimization for a particular model
    - Selections minimize fake backgrounds.
- Look for excess in different phase space volumes;
  - Different sensitivity to S/B.
- If no significant signal is found, severe constraints can be set on a large spectrum of models:
  - From monojet: LED (ADD like)
  - Dijet: squark (SUSY) and leptoquark production

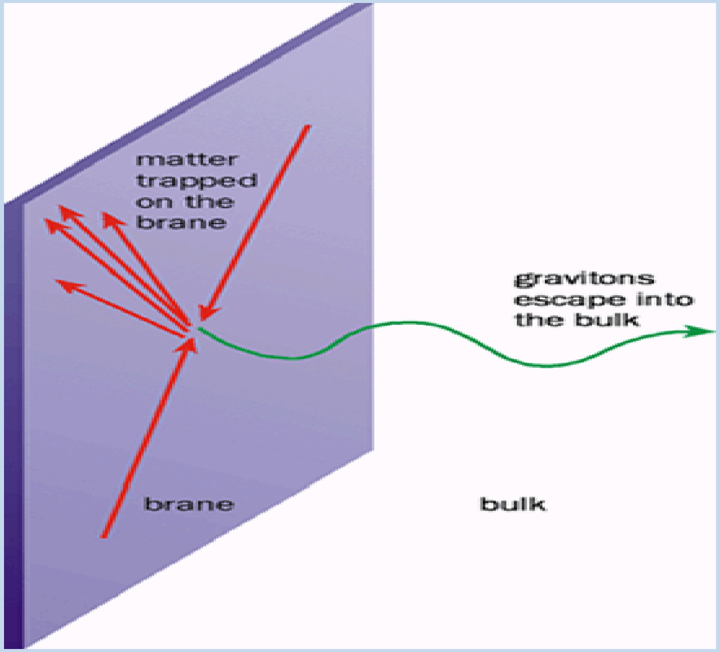


The price to pay for model-independence is a potential loss of sensitivity to some benchmark models

Theory:
quick overview of some of the popular benchmark models

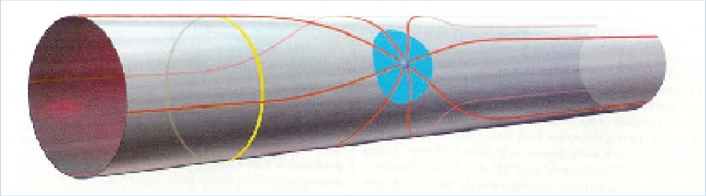
Extra Dimensions

- ED proposed in the late 90's as a potential solution to the hierarchy problem



- Since then, ED have been used as an ingredient to many unsolved problems of the SM
  - EWSB, Dark Matter, Dark Energy, SUSY breaking, etc...

- ED must be somehow hidden or we would have already observed them
  - compactified

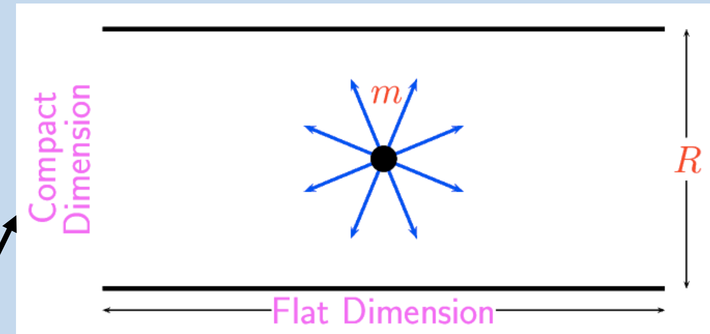


We use the ADD model to set limits

Gravity in Large Extra Dimensions

Gravitational potential in 3D
(Newton)

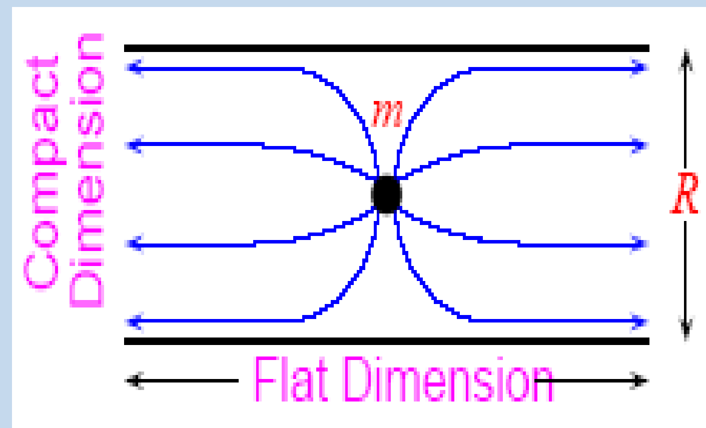
$$V(r) = G_N \frac{m_1 m_2}{r} = \frac{1}{(M_{Pl})^2} \frac{m_1 m_2}{r}$$



Gravitational potential in 3+n Spatial dimensions
(compactified at radius R)

r⑥ R: $$V(r) \sim \frac{1}{(M_D)^{n+2}} \frac{m_1 m_2}{r^{n+1}}$$

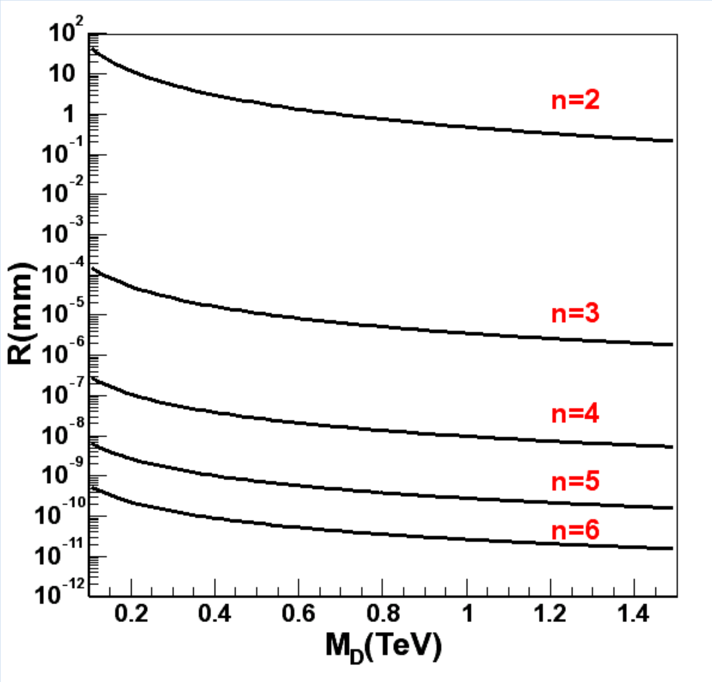
r > R: $$V(r) \sim \frac{1}{(M_D)^{n+2}} \frac{m_1 m_2}{R^n} \frac{1}{r}$$



$$\Rightarrow \; M_{Pl}^2 \approx R^n \, M_D^{n+2}$$

Gravity in Large Extra Dimensions

- Setting M_D = 1 TeV
  - (n = 1) $\rightarrow$ R ~ 10^{13} m
    - Excluded by astronomical data
  - (n = 2) $\rightarrow$ R ~ 400 μm
    - Same order as current limits from direct probes of gravity
  - (n = 6) $\rightarrow$ R ~ 10^{-13} m
    - Accessible only at high energy colliders

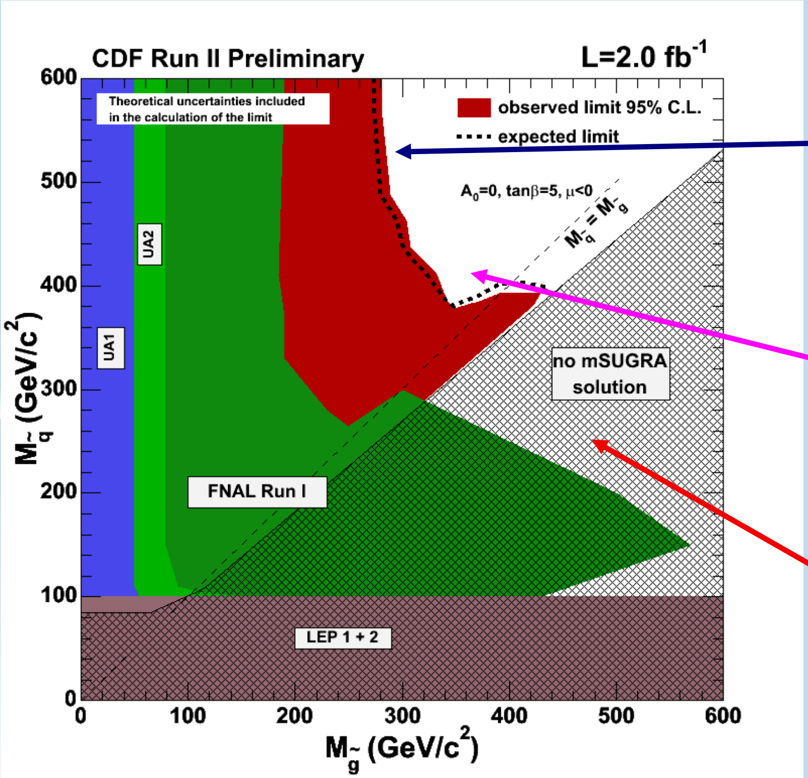


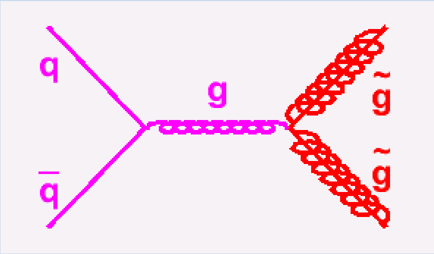
- Three parton-level processes for graviton emission
  - qq $\rightarrow$ gG, qg $\rightarrow$ qG, gg $\rightarrow$ gG
  - Gravitons "escape" in bulk of extra dimensions undetected

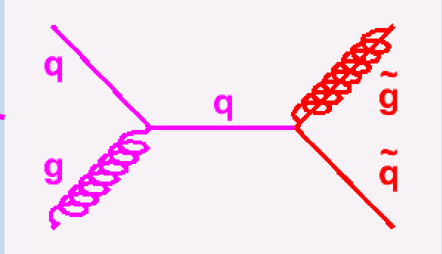
Results in a final state with a single jet and missing E_T

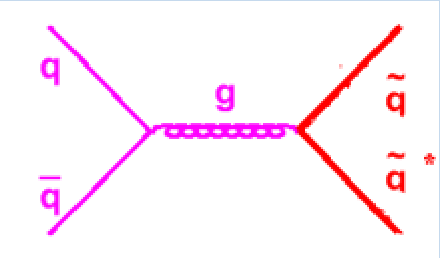
SUSY: squark and gluino production

- Focus in CDF Run II (and LHC…) has been mostly on mSUGRA
  - Much fewer free parameters than general MSSM models
  - No solutions for squark masses significantly lighter than gluino

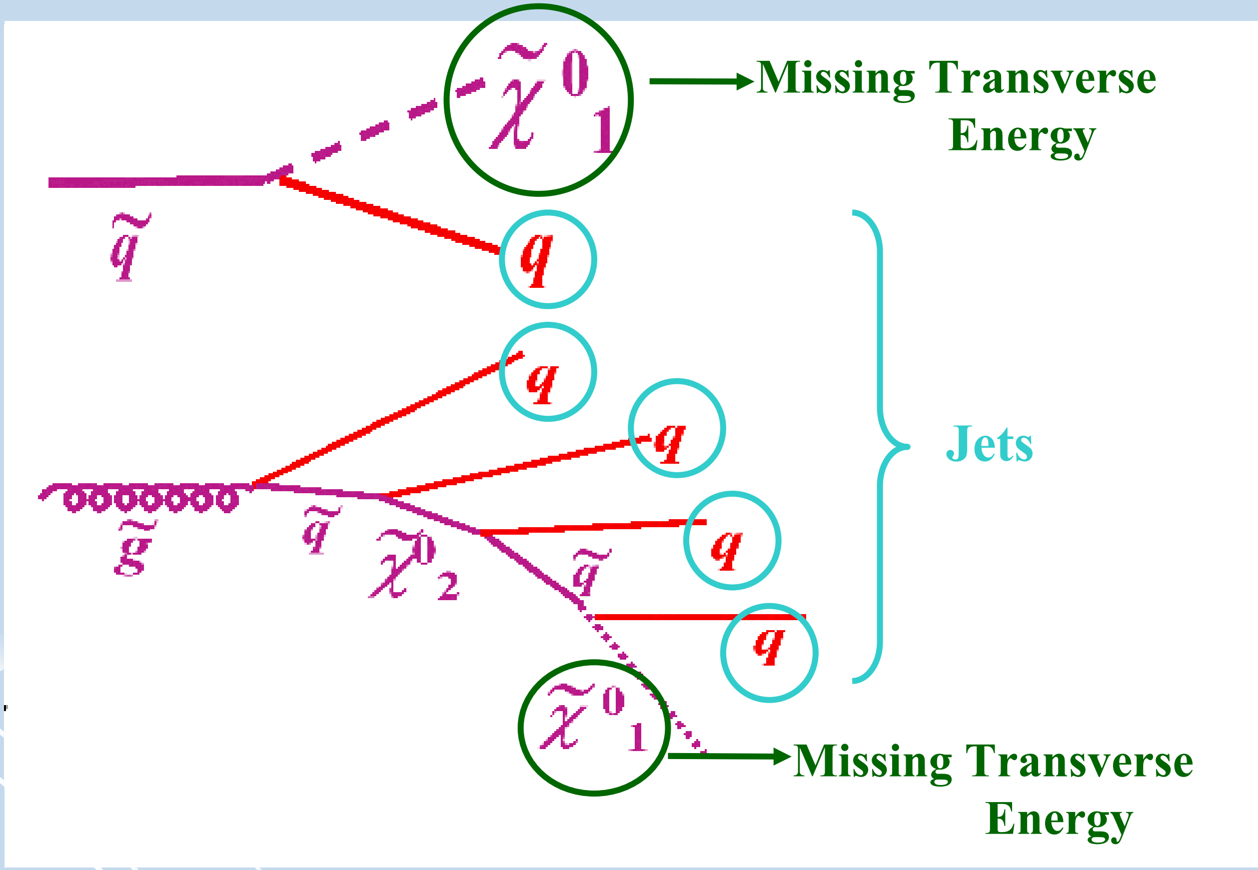








SUSY: squark and gluino decay

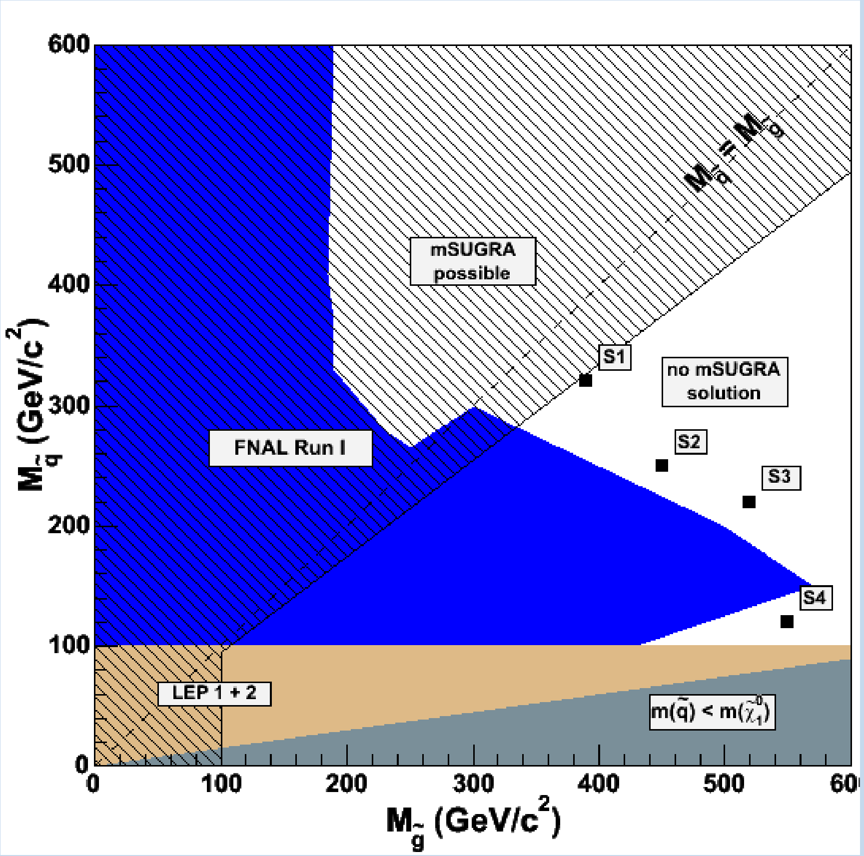


- Final states with gluinos have more jets

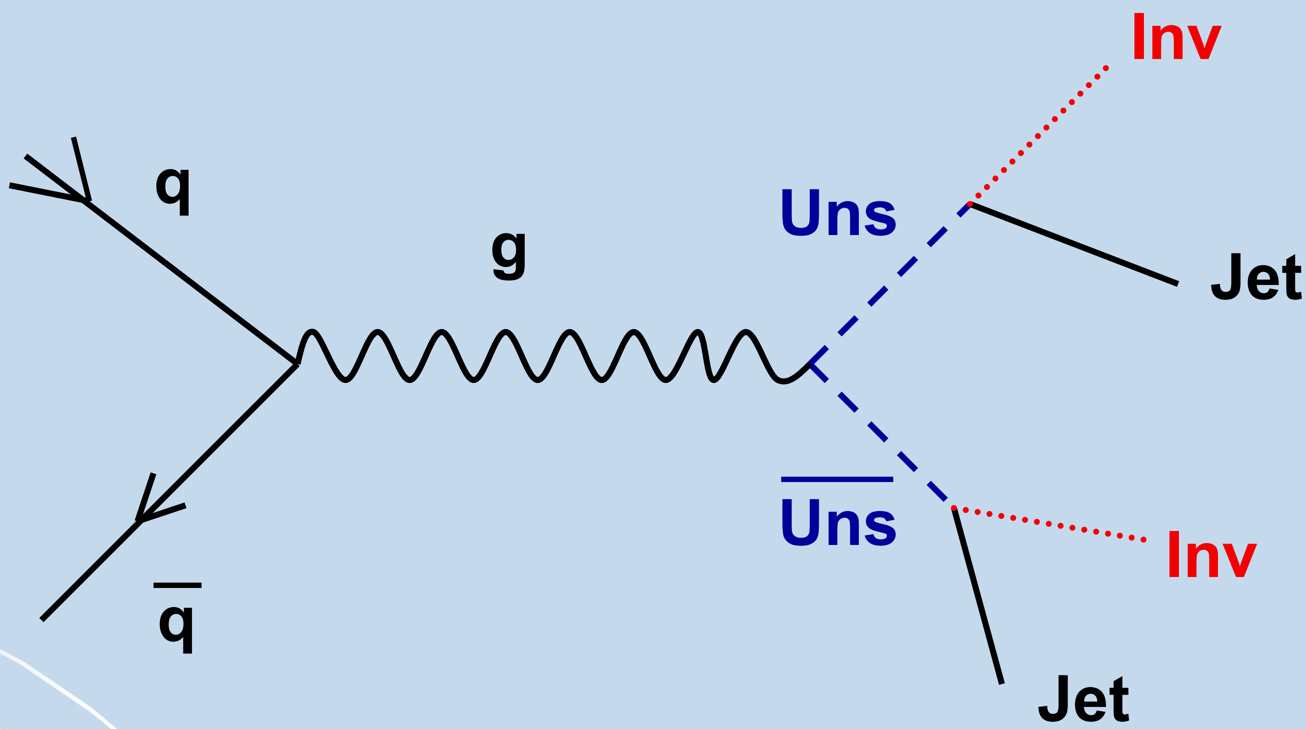
  ⇒ mSUGRA analyses look for multi-jets + Met final states

Non-mSUGRA searches

- For a large chunk of the SUSY parameter space in which the squark mass is less than the gluino mass, no mSUGRA interpretation is possible
  - This is also a single slice of a huge parameter space…
- For these cases, pair production of squarks leads to final states containing 2 jets and missing E_T



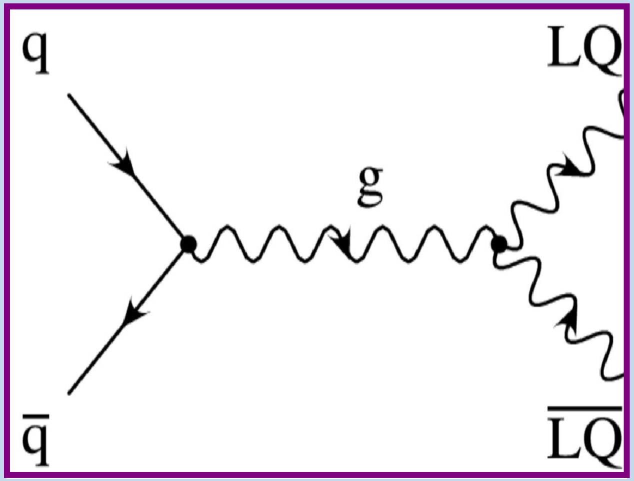
Many other Dijet + Met signals…



- Generic Feynman diagram where:
  - Uns = new unstable particle: eg. Squark, KK-quark, leptoquark, etc
  - Inv = invisible particle: eg. Neutralino, graviton, neutrino, etc

Leptoquarks

- Leptoquarks are particles that carry lepton and baryon numbers
  - predicted in a variety of theories
- Assumed to couple only to quarks and leptons of a single generation
- Leptoquarks can be **scalar (spin-0)** or vector (spin-1)
- Depending on the exact model, leptoquarks can couple to charged leptons, **neutrinos**, or both
  - LQ $\rightarrow$ q + ν
  - **LQ $\rightarrow$ q + l**



Dominant

Pairs produced via the strong interaction

Scalar LQ cross section depends only on strong coupling and M_{LQ}

Many possible Leptoquarks…

- Most general L_{eff} can describe up to 24 leptoquarks for each generation!
- Generally, only a subset of these will be contained in any particular model

Argues against over-optimizing searches for one particular model

Type	Spin	I_{3W}	F=3B+L	Q	Decay	Coupling	β_e
S_{1L}	0	0	-2	-1/3	e^-u, νd	λ_L, $-\lambda_L$	1/2
S_{1R}	0	0	-2	-1/3	e^-u	λ_R	1
S_{1R}	0	0	-2	-4/3	e^-d	λ_R	1
S_{3L}	0	1	-2	-4/3 -1/3 2/3	e^-d e^-u, νd νu	$-\sqrt{2}\,\lambda_L$ $-\lambda_L$, $-\lambda_L$ $\sqrt{2}\,\lambda_L$	1 1/2 0
R_{2L}	0	1/2	0	-5/3 -2/3	e^-u νu	λ_L λ_L	1 0
R_{2R}	0	1/2	0	-5/3 -2/3	e^-u e^-d	λ_R $-\lambda_R$	1 1
R_{2L}	0	1/2	0	-2/3 1/3	e^-d νd	λ_L λ_L	1 0
V_{2L}	1	1/2	-2	-4/3 -1/3	e^-d νd	λ_L λ_L	1 0
V_{2R}	1	1/2	-2	-4/3 -1/3	e^-d e^-u	λ_R λ_R	1 1
V_{2L}	1	1/2	-2	-1/3 2/3	e^-u νu	λ_L λ_L	1 0
U_{1L}	1	0	0	-2/3	e^-d, νu	λ_L, λ_L	1/2
U_{1R}	1	0	0	-2/3	e^-d	λ_R	1
U_{1R}	1	0	0	-5/3	e^-u	λ_R	1
U_{3L}	1	1	0	-5/3 -2/3 1/3	e^-u e^-d, νu νd	$\sqrt{2}\,\lambda_L$ $-\lambda_L$, λ_L $\sqrt{2}\,\lambda_L$	1 1/2 0

Analysis Strategy

Analysis Approach

- Study jet(s) plus Met signature over a range of kinematic cuts and jet multiplicities
- Focus on using data-driven estimates of SM backgrounds as much as possible

  $\Rightarrow$ will provide priceless experience for the LHC

- Design the analysis to reduce the reliance on detailed Monte Carlo modeling
  - Jet Energy Scale and resolution
  - Pile up and underlying events
  - PDF and ISR/FSR effects
  - Luminosity measurement
- Significantly reduce the systematic uncertainties
  - However, interpretations won't escape these sources of error

Data-driven techniques 101

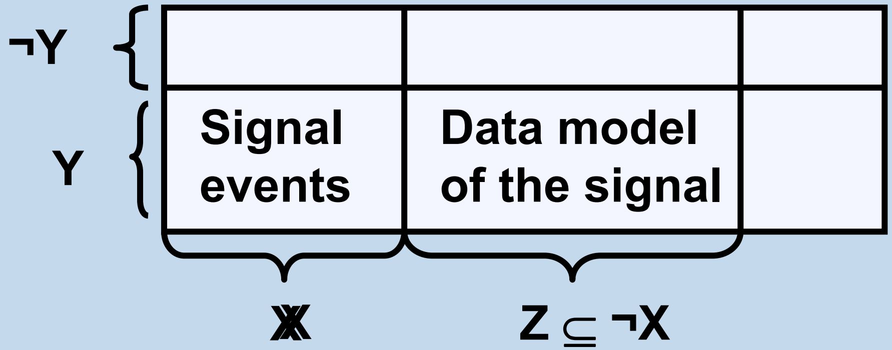
The idea of data-driven predictions is:

1- Reverse one (few) signal selection(s) to produce an orthogonal data sample

- The reversed selection(s) must be unbiased (at a given level of precision) with respect to the others

X = reversed selection
Y = all other selections

If X is unbiased with respect to Y, than Y∧Z provide a good model for Y∧X



2- Count the number of events in the Y∧Z (Z ⊆ ¬X) sample to estimate the number of events in the Y∧X sample

3- Compute the mapping factor giving the right normalization

Jets + Met backgrounds

Electroweak:

- $Z \rightarrow \nu\nu$ + jets (largest and irreducible background)
- $W \rightarrow \ell\nu$ + jets where the lepton is not observed in the detector

We can use $Z \rightarrow \ell\ell$ + jets and $W \rightarrow \ell\nu$ + jets events with reconstructed leptons to estimate these backgrounds

In this case, the reversed cut X is the lepton veto

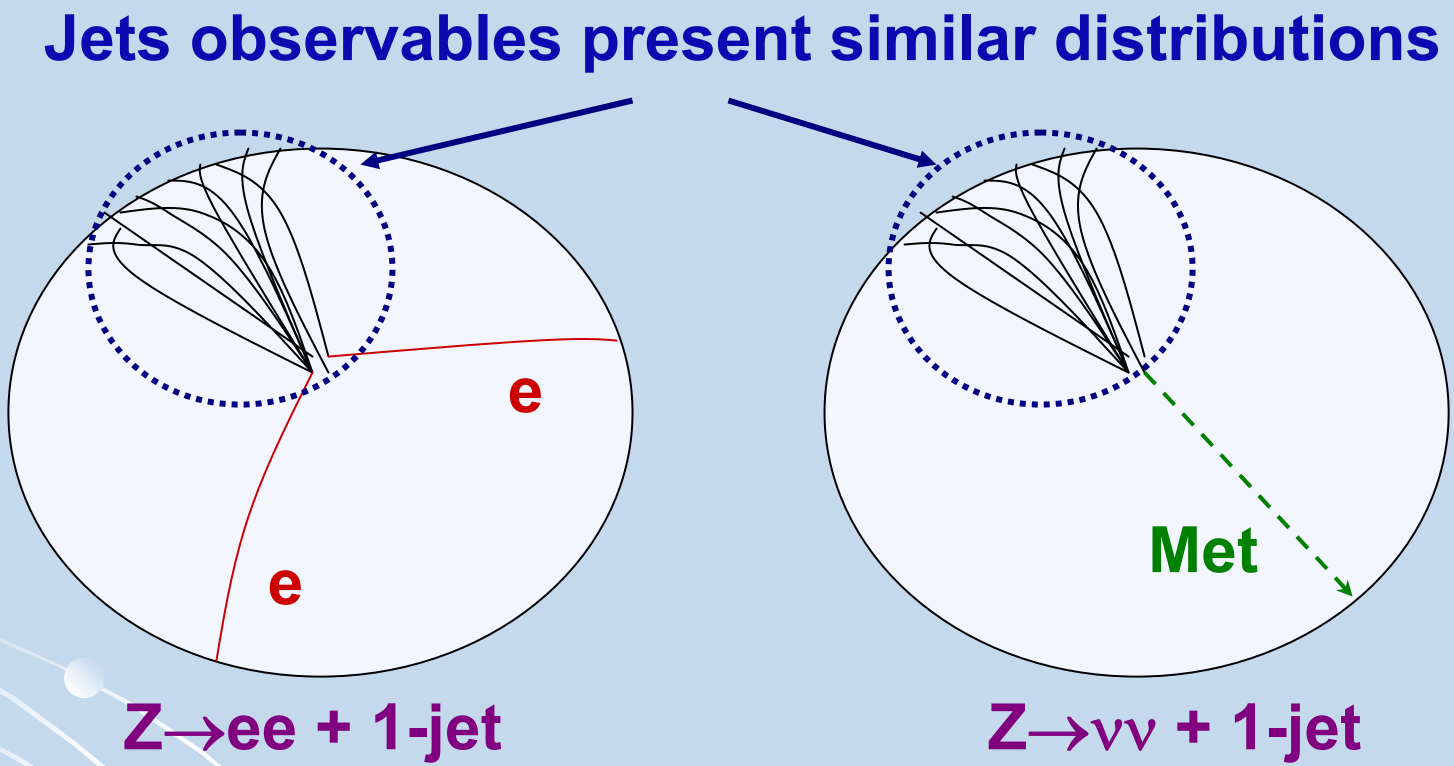
QCD:

- Met originating from mismeasured jet energies
  - Small if Met is large

Estimated using multi-jet events in which Met points along the direction of one of the jets

In this case, the reverse cut X is the azimuthal angle (ϕ) between the jets and the Met

Electroweak backgrounds (I)



- Some 2nd order acceptance corrections due to:
  - Less available phase space for jets in events with charged leptons
  - Extra jets produced via charged lepton radiation

→ Correction included in the mapping factor (A_{corr} ~4-10%)

Electroweak backgrounds (II)

- **Obtain independent predictions from electrons and muons (ℓ = e, μ)**
  - **Agreement between those predictions validate them**
    - **Use high Pt-lepton samples to get the data to be used for the electroweak background predictions**

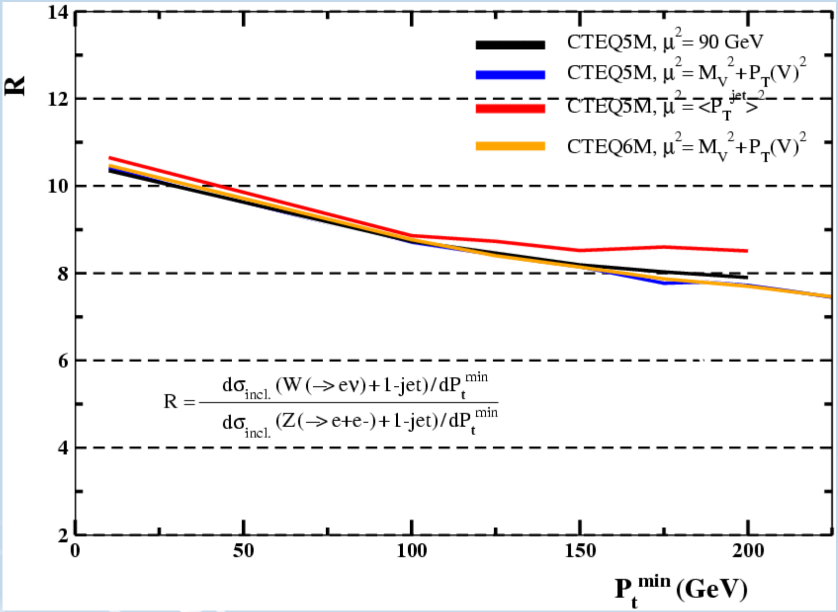
- **Can also estimate of $Z \to \nu\nu$ + jets background from high statistics $W \to \ell\nu$ + jets events**

Use the theoretical prediction for

$$R \equiv \frac{\sigma(W(\to \ell\nu) + jets)}{\sigma(Z(\to \ell\ell) + jets)}$$

⇒ 4 statistically independent predictions for the $Z \to \nu\nu$ + jets background!

Electroweak backgrounds (III)



W/Z + 1 jet **W/Z + 2 jet**

- **Calculations performed at NLO (MCFM program)**
  - **Uncertainty much smaller on R (ratio) than on individual cross sections**

Electroweak backgrounds (IV)

- **Also need to take some acceptance (A_{lep}), efficiency (ε_{lep}) and background (N_{bkg}) corrections into account**

$\Rightarrow$ Contribute to the mapping factor

- **From $Z \rightarrow \ell\ell$ + jets:**

Mapping factor include:

$$A_{\nu/\ell} \equiv \frac{Br(Z \rightarrow \nu\nu)}{Br(Z \rightarrow \ell\ell)} \approx 6$$

From theory

- **From the $W \rightarrow \ell\nu$ + jets:**

From MC (only a ratio!)

Mapping factor include:

$$\Pr ob(no\ \ veto) = \frac{N_{events}(pass\ \ all\ \ cuts)}{N_{events}(no\ \ veto\ \ requirement)}$$

$$N(Z \rightarrow \nu\nu + jets) = 6 \times \frac{N_{cand} - N_{bkg}}{A_{lept} \times \varepsilon_{lept}} \times \frac{L_{met}}{L_{lept}} \times A_{corr} \times \varepsilon_{mettrig} \quad (/R)$$

$$N(W \rightarrow \ell\nu + jets) = \frac{N'_{cand} - N'_{bkg}}{A'_{lept} \times \varepsilon'_{lept}} \times \frac{L_{met}}{L_{lept}} \times \varepsilon_{mettrig} \times \Pr ob(no\ \ veto)$$

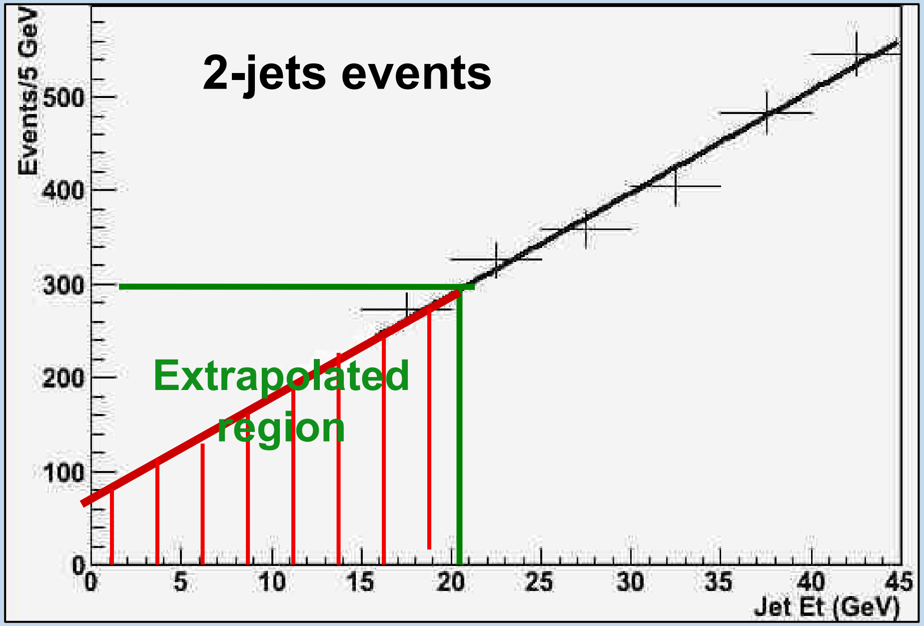
QCD backgrounds (I)

- **Sources of QCD contribution:**
  - **(n+1)-jets events for which one of the jets is lost (dominate)**
  - **(n+m)-jets events for which m jets are lost (smaller)**
- **To estimate the (n+1)-jets contribution:**

1- Select (n+1)-jets events for which the Met points toward the less energetic jet

2- Extrapolate the E_T of this jet below jets energy threshold (loose a jet)

3- The area under the fit in the extrapolated region is the prediction



QCD backgrounds (II)

- There is an electroweak contamination in the E_T distribution of the smallest jet

  ⇒ tends to overestimate the QCD background

- To remove this contamination, we need from data:
  - The shape of the smallest jet E_T for this EWK contamination
  - The right normalization

- Need to account for the smaller (n+m)-jets contribution
  - Contribution estimated from Monte Carlo
    - ≈ (20 ± 20) %

The Measurement results

Basic Selection Cuts

- Jet definition:

  JETCLU reconstruction algorithm
  with cone size of 0.7 and E_T>15 GeV

- Event Cleanup (good vertex, EM energy)

Common to both the monojet and the Dijet+Met analyses

- Jet Cleanup
  - Matching charged tracks
  - Not located in un-instrumented regions of the calorimeter
    - Crack or service regions
  - Not pointing along the direction of the Met

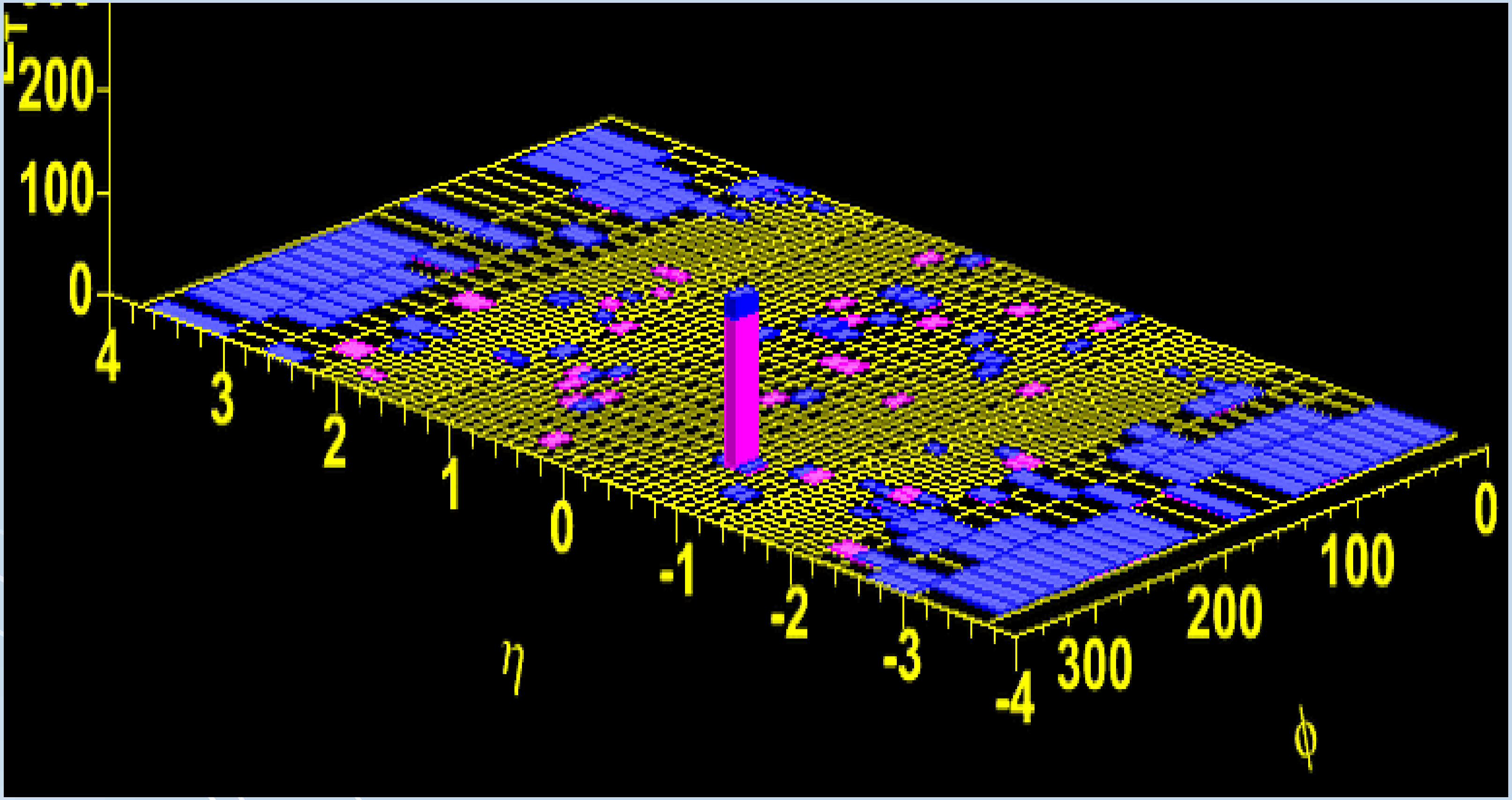
→ Suppress QCD

- Lepton veto (no EM jets, no isolated tracks)

→ Suppress W+jets

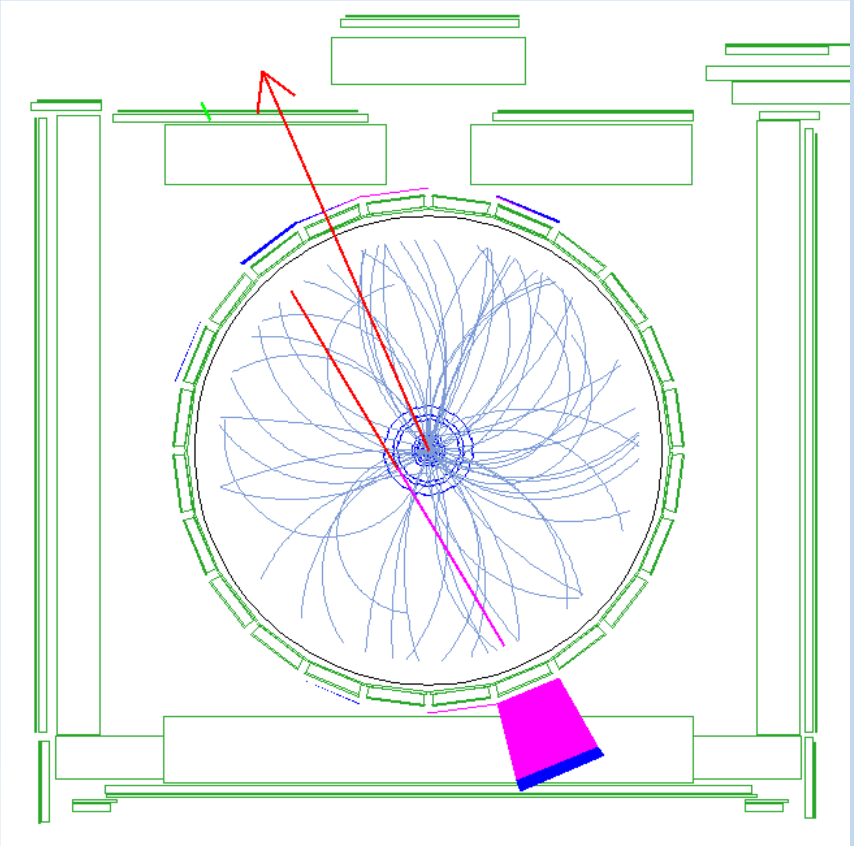
Clean-up cuts are essential for removing large background from non-collision sources!

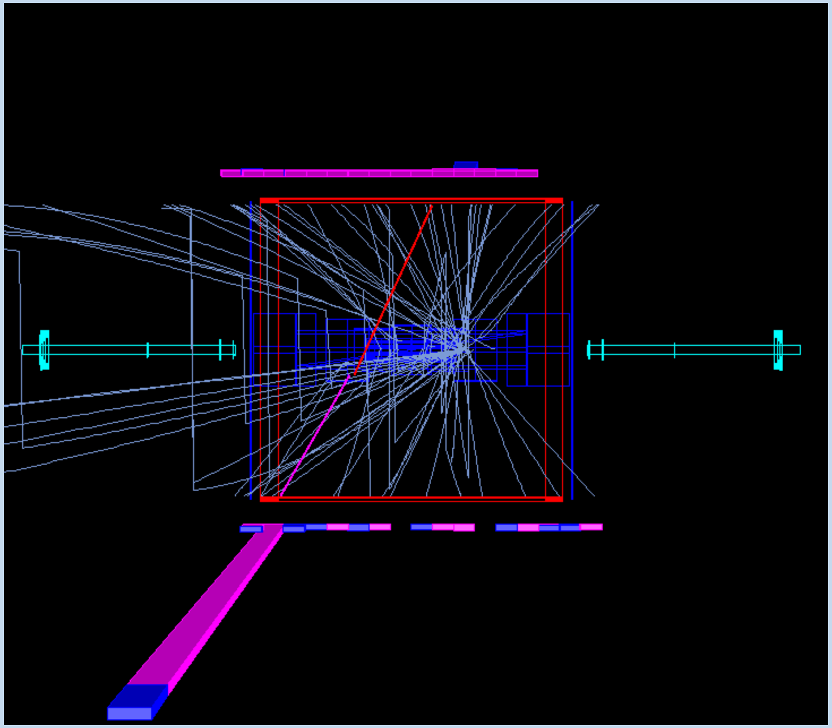
Example of Cosmic event (I)



Appears to be good single jet plus Met event

Example of Cosmic event (II)

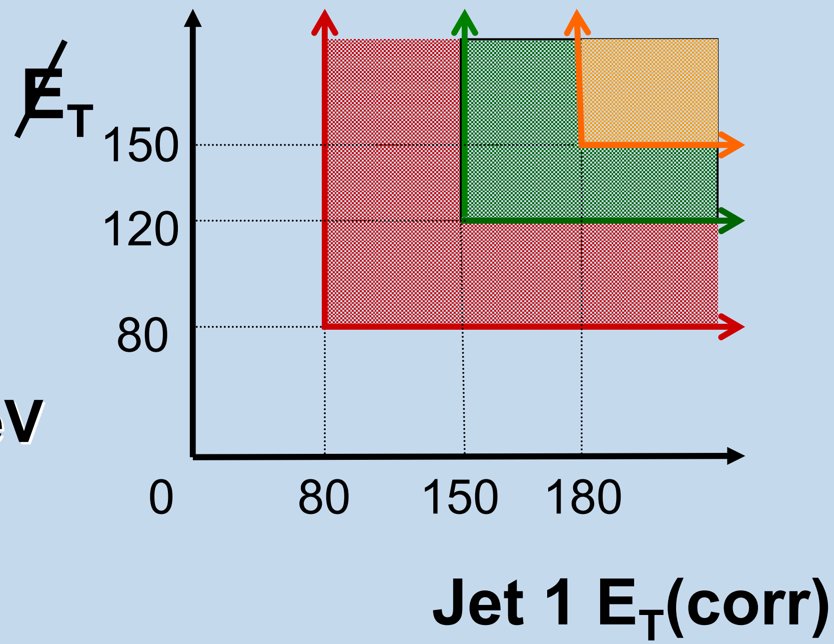




Tracking views clearly indicate that jet originates from cosmic ray which passes far away from overlapping collision vertex

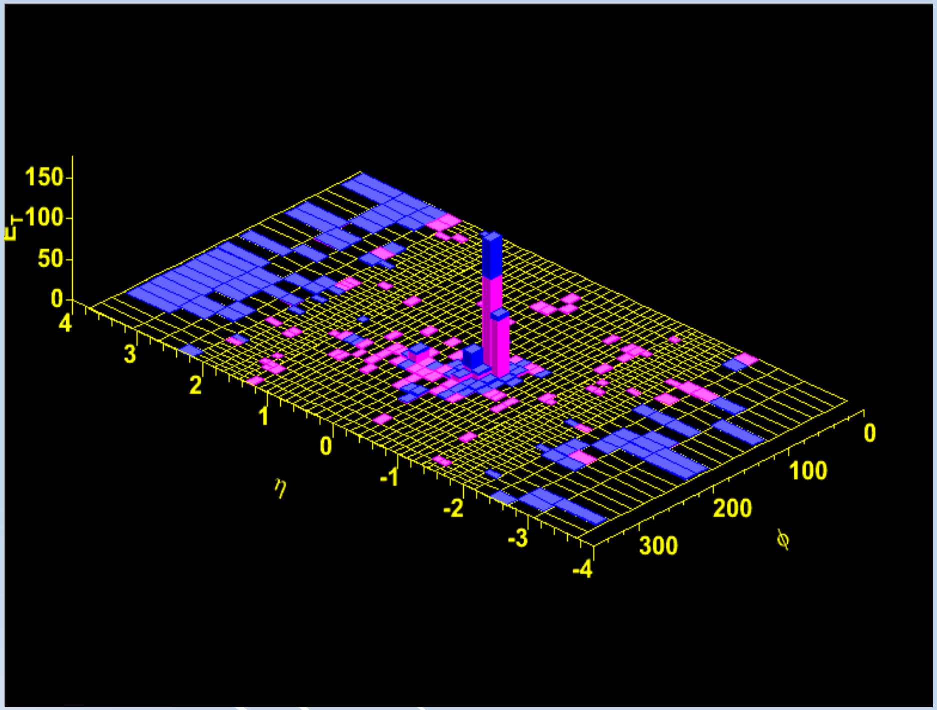
Monojet event selections

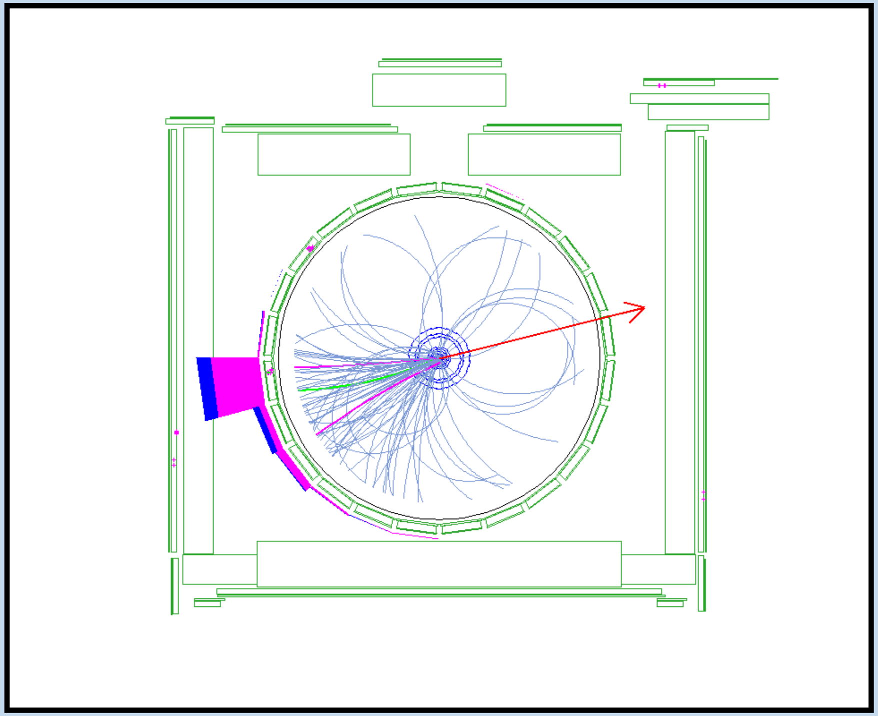
- Three kinematic regions based on Met and leading jet E_T:
  - Met > 80 GeV & Jet E_T > 80 GeV
  - Met > 120 GeV & Jet E_T > 150 GeV
  - Met > 150 GeV & Jet E_T > 180 GeV



- No 2nd jet with E_T > 30 GeV (60 GeV if Jet E_T > 150 GeV)
  - No 3rd jet with E_T > 15 GeV
  - Asymmetric cuts to increase signal acceptance (ISR/FSR)
- Use 1 fb^{-1} of data from JET100 and MET45 triggers
  - JET100 trigger is fully efficient for Jet E_T > 150 GeV
  - MET45 trigger is fully efficient for Met > 80 GeV

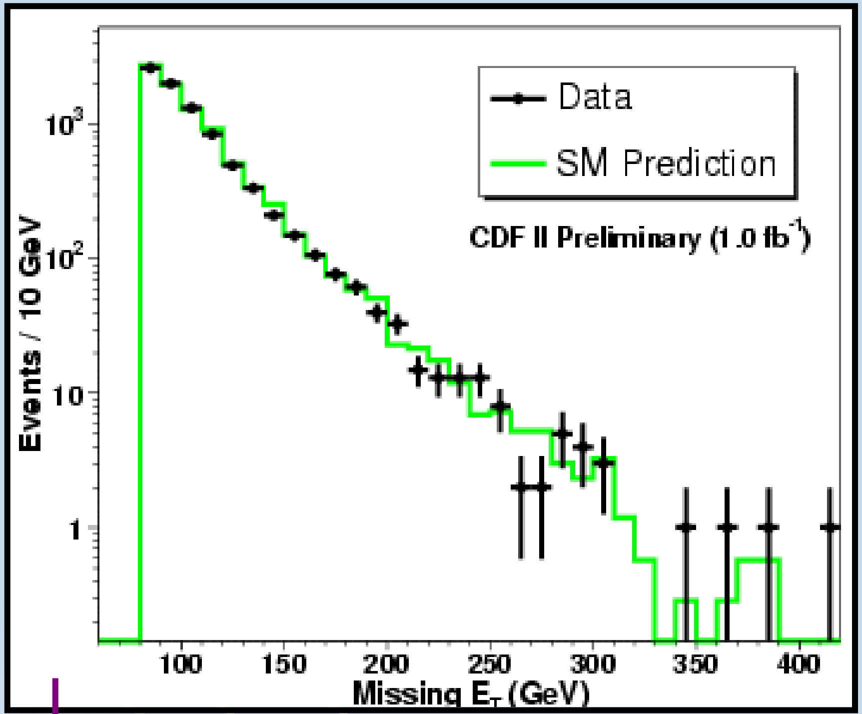
Most Energetic Monojet Event





Jet E_T = 419 GeV, Missing E_T = 417 GeV

Monojet Results



Background	80/80	150/120	180/150
$Z \to \nu\nu$ + jet	3203 ± 137	390 ± 30	141 ± 17
$W \to \tau\nu$ + jet	2010 ± 69	187 ± 14	58 ± 5
$W \to \mu\nu$ + jet	1570 ± 54	117 ± 9	35 ± 3
$W \to e\nu$ + jet	824 ± 28	58 ± 4	18 ± 2
$Z \to ll$ + jet	87 ± 3	6 ± 1	2 ± 0
QCD	708 ± 146	23 ± 20	12 ± 12
γ + jet	209 ± 41	17 ± 5	8 ± 3
Non-collision	52 ± 52	10 ± 10	3 ± 3
Predicted	8663 ± 332	808 ± 62	277 ± 30
Observed	8449	809	319

Results are consistent with SM in all three kinematic regions

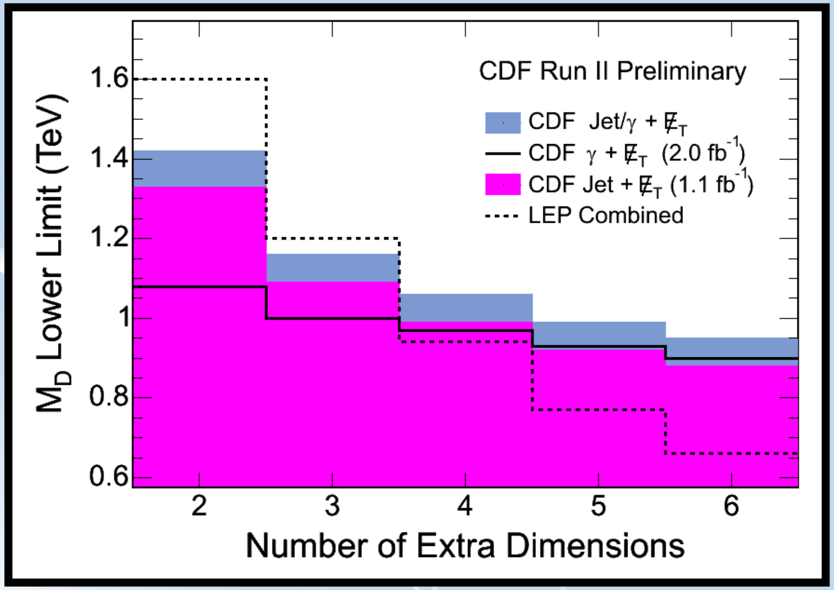
Our measurement is really just a number (table). This is a check to see if it would worth to do a further investigation with shapes

Limit on Large Extra Dimensions

* The 150/120 analysis provides the best sensitivity for LED scenario.

Signal Upper limits (95% CL) for 150/120 = 125 events

Limits on the 4+n dimensional Planck scale M_D and on the radius R of the extra dimensions



n	M_D (TeV)	R (mm)
2	> 1.33	< 2.7 E-01
3	> 1.09	< 3.1 E-06
4	> 0.99	< 9.9 E-09
5	> 0.92	< 3.2 E-10
6	> 0.88	< 3.1 E-11

Eöt-Wash limit: $R < 1.3 \times 10^{-1}$ mm (n=2)

Perform a SM measurement too!

- The precision of the lowest kinematic region is ~3.8%

  ⇒ can measure N_ν, Γ_Z(inv)!

- LEP: 2 types of measurements
  - Indirect: lineshape → really precise
  - Direct: γ+Met topology → less precise
- Fewer theoretical assumptions in direct measurement.
- Tevatron:
  - Expect similar sensitivity to LEP direct
  - Even fewer theoretical inputs
  - Completely independent of LEP measurements

Background	80/80
$Z \to \nu\nu$ + jet	3203 ± 137
$W \to \tau\nu$ + jet	2010 ± 69
$W \to \mu\nu$ + jet	1570 ± 54
$W \to e\nu$ + jet	824 ± 28
$Z \to ll$ + jet	87 ± 3
QCD	708 ± 146
γ + jet	209 ± 41
Non-collision	52 ± 52
Predicted	8663 ± 332
Observed	8449

Invisible width of the Z^0

Assuming the PDG value for $\Gamma_Z(ll)$, 83.984 ± 0.086 MeV:

$$\Gamma_Z(inv) = 466 \pm 14 \pm 40 \text{ MeV}$$

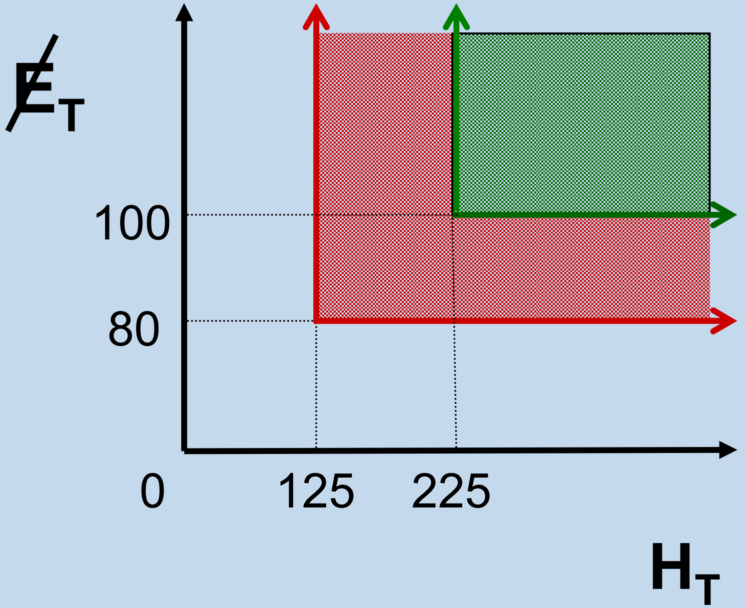
Comparing this value with SM expectation gives the number of light ν types:

$$N_\nu = 2.78 \pm 0.08 \pm 0.25$$

Experiment	$\Gamma_Z(inv)$ MeV	N_ν
CDF	466 ± 42	2.78 ± 0.26
L3	498 ± 17	2.98 ± 0.06
OPAL	539 ± 31	2.69 ± 0.17
ALEPH	450 ± 48	2.86 ± 0.09
DELPHI	---	2.84 ± 0.21
LEP comb.	503 ± 16	2.92 ± 0.06
LEP indirect	499.0 ± 1.5	2.984 ± 0.008

Dijet+Met event selections

- Two kinematic regions based on Met and H_T :
  - Met > 80 GeV & H_T > 125 GeV
  - Met > 100 GeV & H_T > 225 GeV



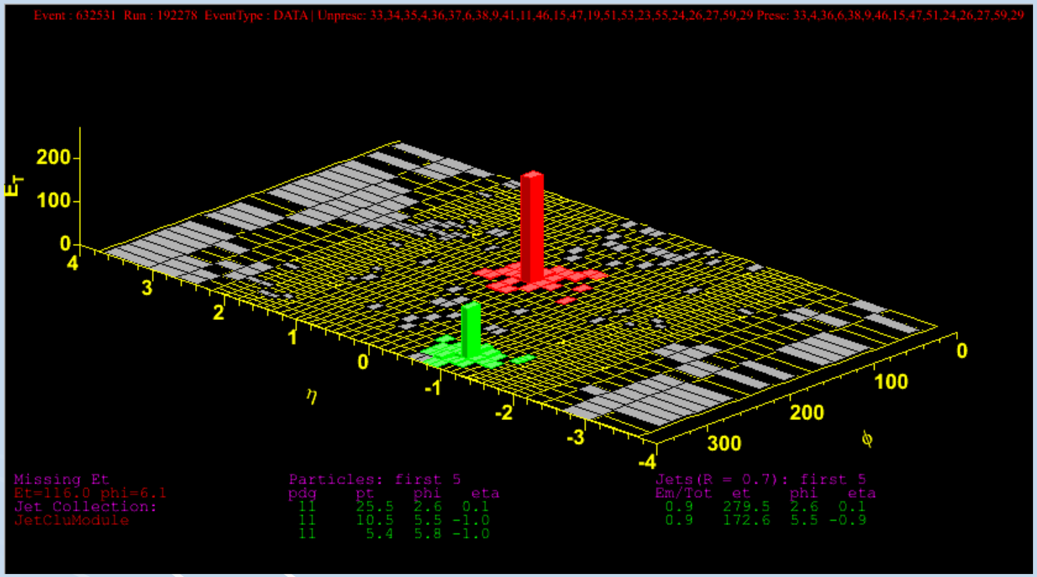
- Two jets with E_T > 30 GeV
  - No 3rd jet with E_T > 15 GeV
  - Orthogonal to the monojet data sample

$H_T = E_T(\text{jet 1}) + E_T(\text{jet 2})$

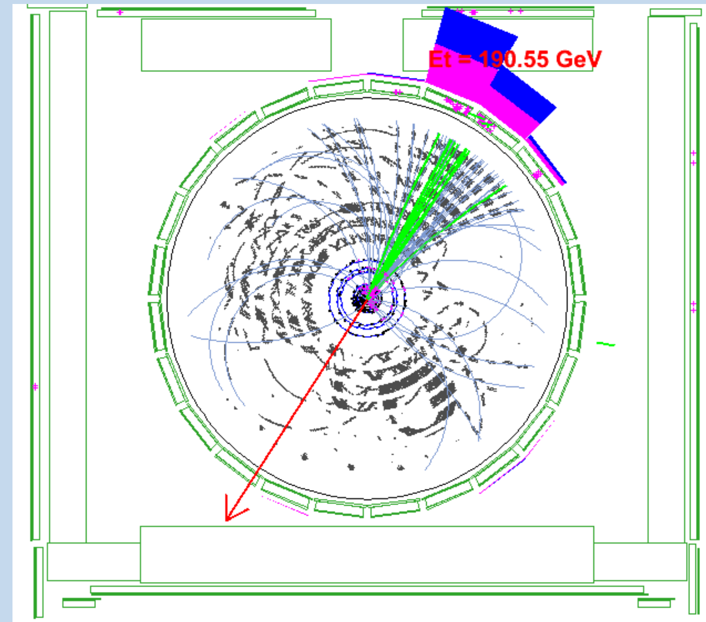
- Use, for both regions, 2 fb^{-2} of data collected from the MET45 triggers
  - Fully efficient for Met > 80 GeV

Energetic Dijet+Met Events

High H_T



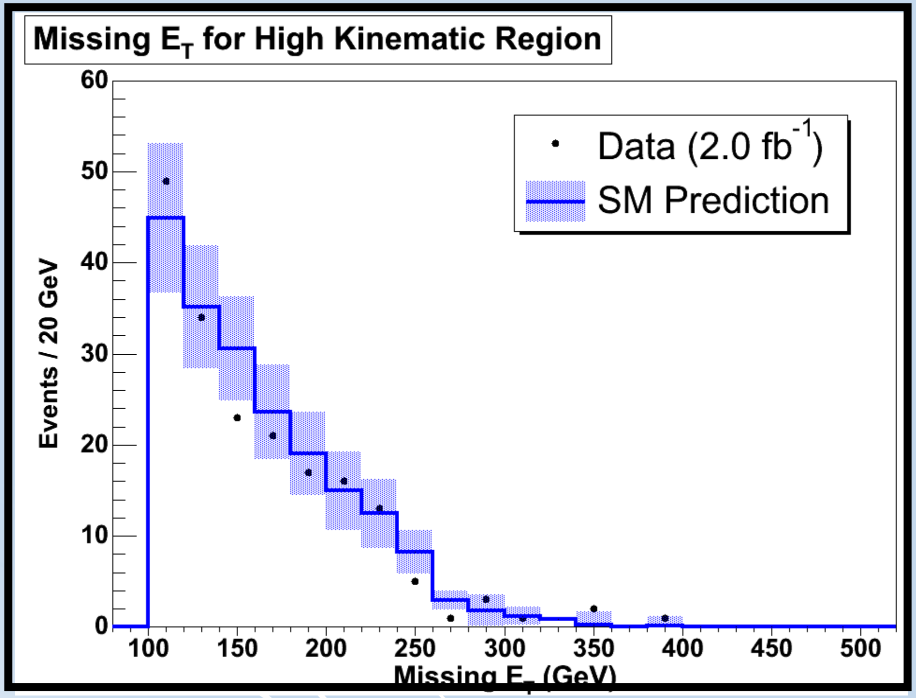
High Met



Highest H_T = 518 GeV, Met = 134 GeV

H_T = 360 GeV, Highest Met = 368 GeV

Dijet+Met Results



Background	125/80	225/100
$Z \to \nu\nu$ + jets	888 ± 54	86 ± 13
$W \to \tau\nu$ + jets	669 ± 42	50 ± 8
$W \to \mu\nu$ + jets	399 ± 25	33 ± 5
$W \to e\nu$ + jets	256 ± 16	14 ± 2
$Z \to ll$ + jets	29 ± 4	2 ± 0
QCD	49 ± 30	9 ± 9
γ + jets	75 ± 11	5 ± 1
top	74 ± 9	11 ± 2
Non-collision	4 ± 4	1 ± 1
Predicted	2443 ± 145	211 ± 30
Observed	2506	186

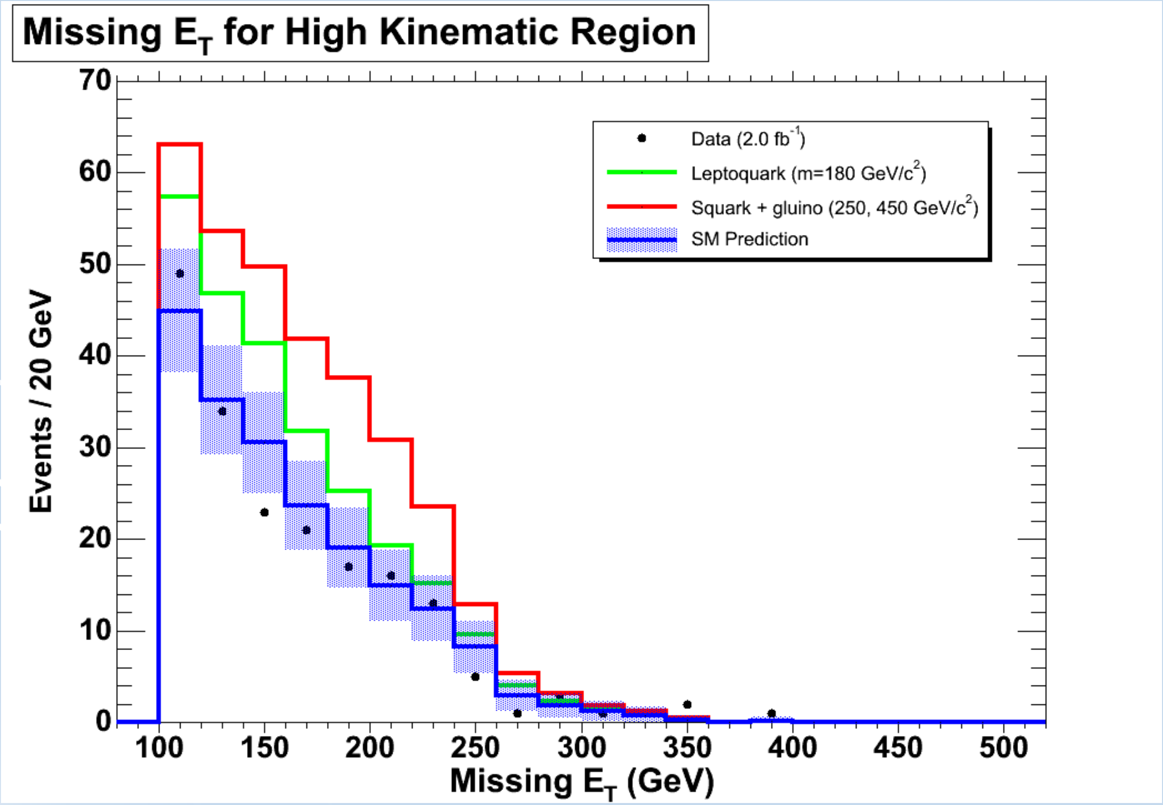
Results are consistent with SM both kinematic regions

What would a signal look like?

Comparison of SM background predictions plus different BSM signals with Dijet+Met data

Leptoquark signal (M_{LQ} = 180 GeV)

MSSM signal (M_{squark} = 250 GeV, M_{gluino} = 450 GeV)



Leptoquark limits

Limits on the mass of the Leptoquark

Signal Upper limits (95% CL) for:

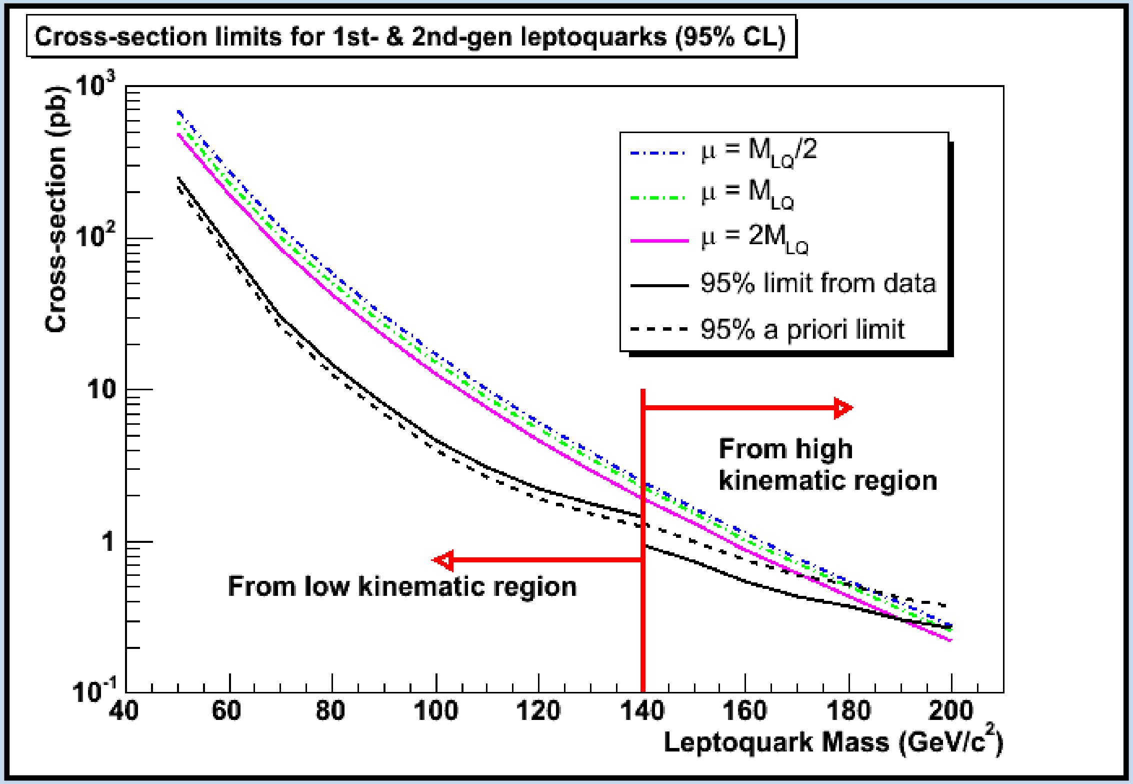
→ 80/125 = 359 events

→ 100/225 = 51 events

*Select, a priori, most sensitive sample for each mass point

Lower Mass limits:
= 190 GeV/c2

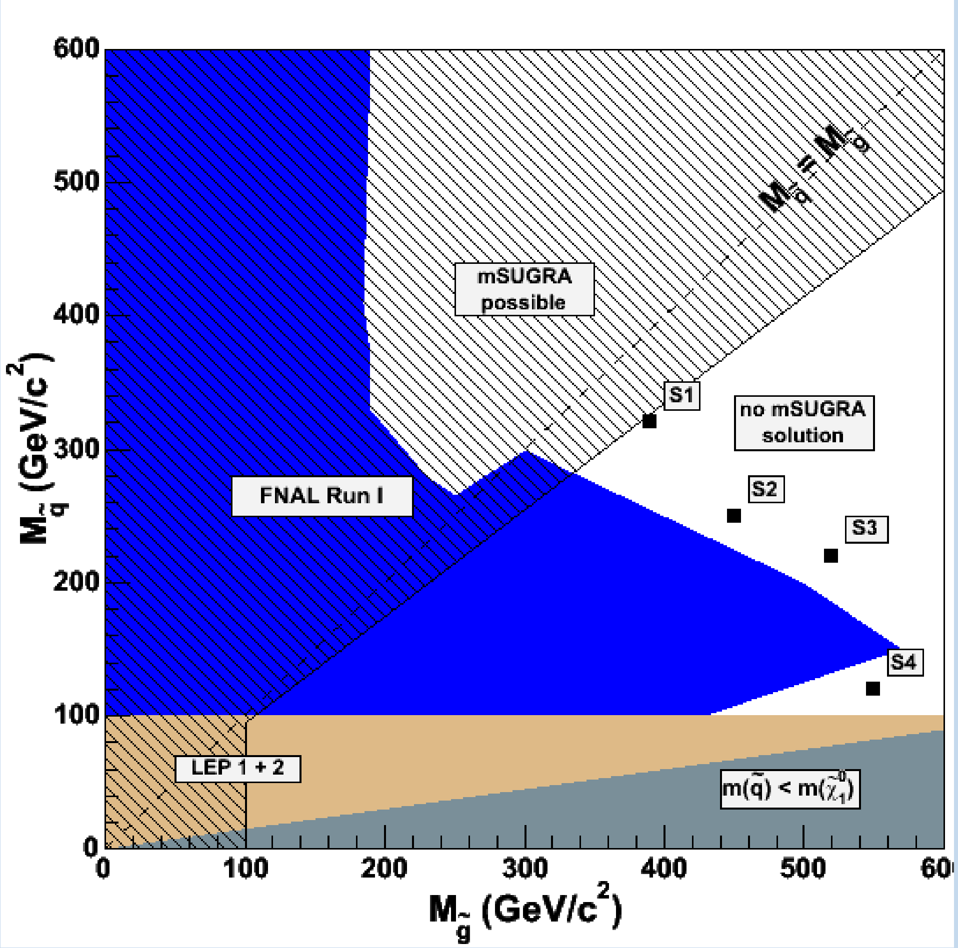
Upper cross section limits:
= 0.31 pb



MSSM exclusion (I)

- Pick four previously not-ruled-out mass points as a measure of result sensitivity
- SUSY partner of right-handed squarks typically yield dijet + Met final state, but other SUSY signal can contribute

Point	Squark Mass	Gluino Mass
S1	320 GeV/c^2	390 GeV/c^2
S2	250 GeV/c^2	450 GeV/c^2
S3	220 GeV/c^2	520 GeV/c^2
S4	120 GeV/c^2	550 GeV/c^2



MSSM exclusion (II)

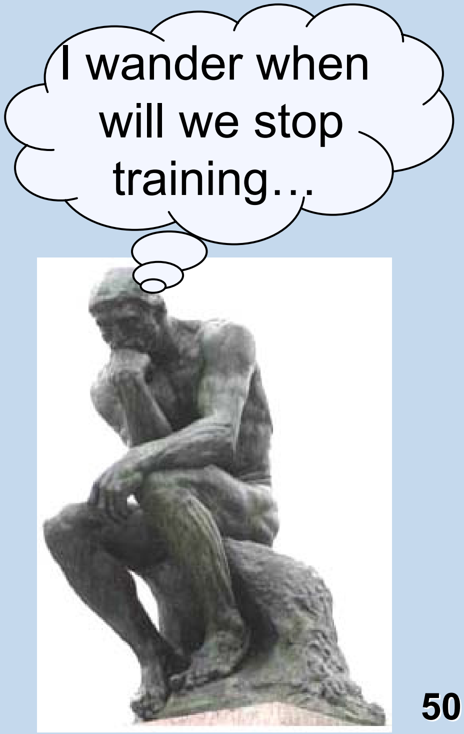
SUSY spectrum	A priori limit (pb)	Observed limit (pb)	PYTHIA LO (pb)	Ratio
RH Squarks				
S1	0.15	0.11	0.045	2.41
S2	0.26	0.19	0.28	0.68
S3	0.51	0.37	0.61	0.61
S4	86.1	100.5	18.0	5.57
Inclusive				
S1	0.53	0.39	0.36	1.09
S2	0.90	0.65	1.73	0.38
S3	1.93	1.40	3.21	0.44
S4	78.5	91.6	57.4	1.60

- **Ratio give the scale factor by which the signal cross section must be multiplied by, in order to barely exclude the parameter space point**
- **Cross section from LO Pythia**
  - **NLO calculation is more difficult in non-mSUGRA regions**

Conclusion

- **We developed data-driven background calculations to analyze low-multiplicity jet events with large Met with CDF**
  - **Smaller systematics**
  - **Robust: potential mistakes could cancel out**
  - **Possibly good for early LHC analyses**

- **No observed excess over SM expectations:**
  - **1 fb^{-1} of monojet CDF data sample**
    ⇒ Constrains LED models
  - **2 fb^{-1} of Dijet+Met CDF data sample**
    ⇒ Constrains Leptoquark and MSSM models



Good training for the LHC!!!