Results of a Global Search for New Physics at CDF

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on behalf of the CDF Collaboration

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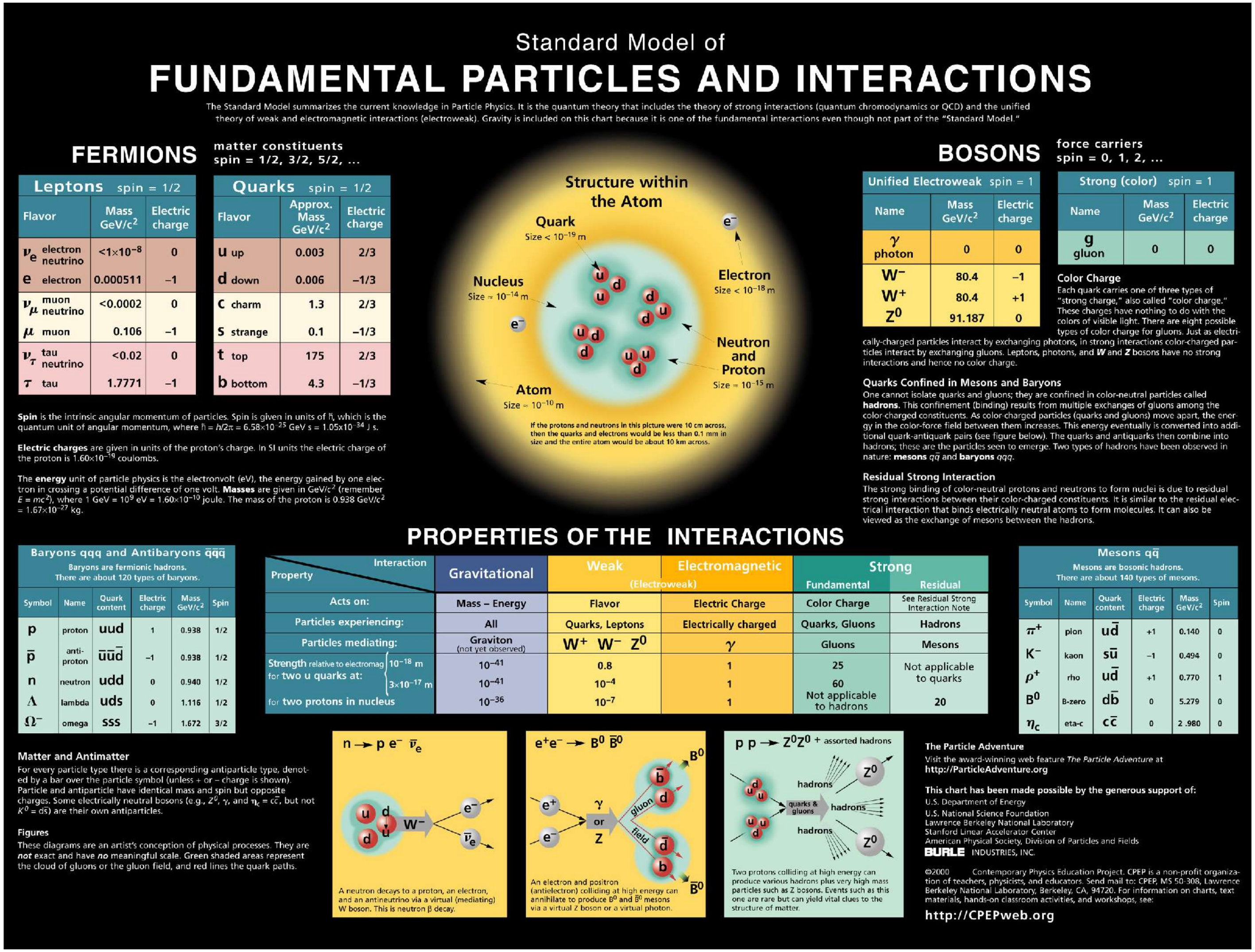
Rise and Fall of the Standard Model?



Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s = 1.05×10^{-34} J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.

If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge
Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons
One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons.** This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction
The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak	Electromagnetic	Strong	
		(Electroweak)		Fundamental	Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$
Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$
Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Matter and Antimatter
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

$n \rightarrow p\, e^-\, \bar{\nu}_e$

A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

$e^+e^- \rightarrow B^0\, \bar{B}^0$

An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

$p\, p \rightarrow Z^0 Z^0$ + assorted hadrons

Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure
Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

This chart has been made possible by the generous support of:
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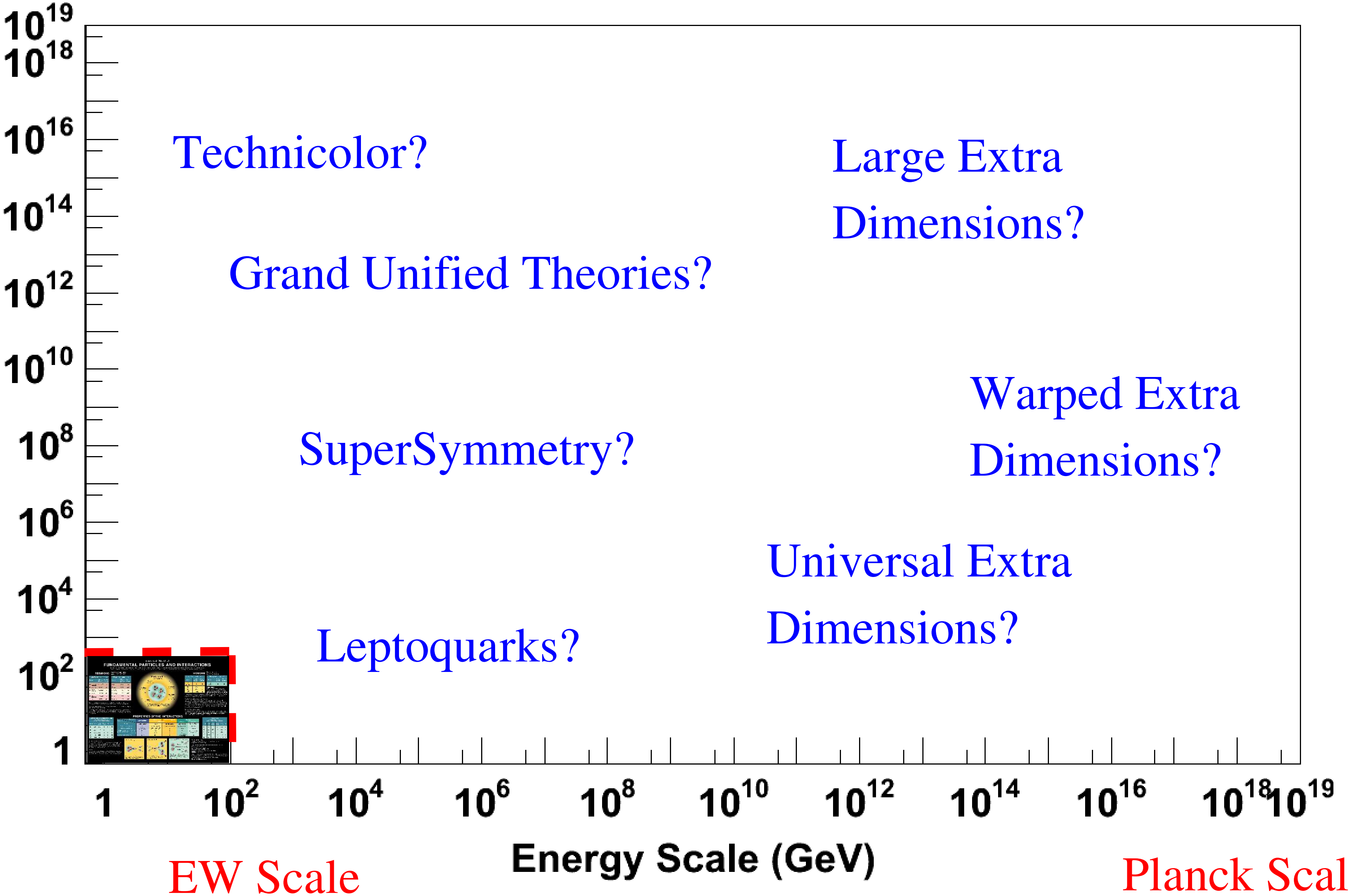
- Standard Model has been remarkably successful...
- But we do not expect it to describe Nature up to the Planck Scale

From Electroweak to Planck Scale



Technicolor?

Large Extra Dimensions?

Grand Unified Theories?

Warped Extra Dimensions?

SuperSymmetry?

Universal Extra Dimensions?

Leptoquarks?

EW Scale

Planck Scale

Searching for Physics Beyond the Standard Model

- How should we search for new physics when we really do not know what to expect?
- Let the data itself be our guide
- Perform global search for significant discrepancies between the observed data and the Standard Model prediction

Global Search with Vista and Sleuth

- **Vista**: can bulk high-p_T data be described by the Standard Model?
- **Sleuth**: quasi-model-independent search for new physics at high-p_T

Vista/Sleuth Strategy

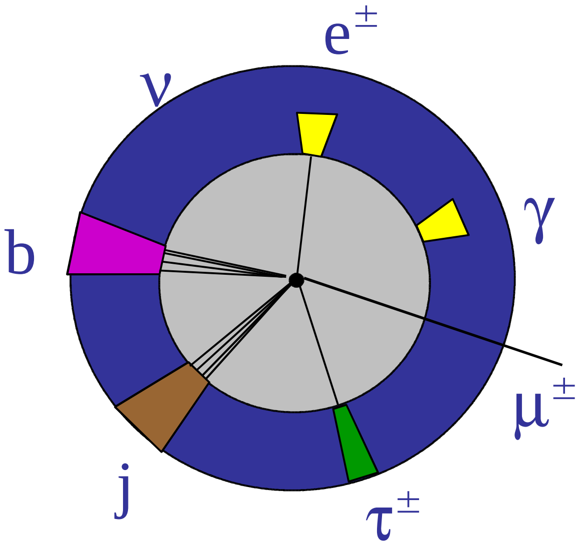
- Generate our best attempt at a global Standard Model prediction; compare to the CDF data
- Vista considers the populations of final states and kinematic distributions
- Sleuth searches for excesses in the high-p_T tails
  - examines a single variable (Σp_T)
  - very effective for a model-independent search for EW-scale physics
- Seek significant (~5σ) discrepancies in the data that may indicate the presence of new physics
  - any observed discrepancy triggers further scrutiny

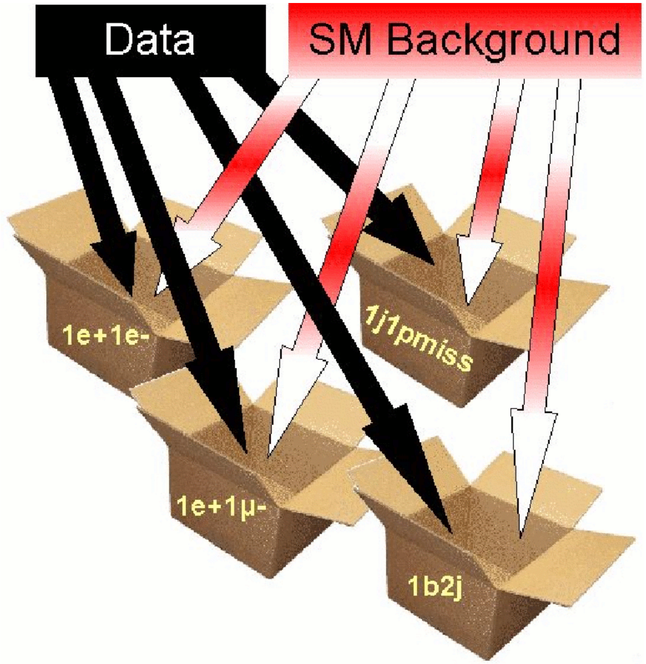
Strengths and Limitations of Vista/Sleuth

- Strengths:
  - Model independent
  - Looks in many places (in case Nature surprises us!)
- Limitations:
  - Will not be sensitive to low cross-section new physics that occurs in the bulk
  - Sleuth is not optimized for any specific model of new physics
  - Some systematic uncertainties are not incorporated into Sleuth's search

Overview of Vista

- Identify physics objects
  - $e^\pm$, $\mu^\pm$, $\tau^\pm$, γ, j, b, $\not{E}_T$
  - require $p_T > 17$ GeV
- Select events
  - require high-p_T lepton, photon, jet triggers
- Partition events into ~300 exclusive final states
  - boxes created if populated by data





Overview of Vista (ctd.)

- Generate our implementation of Standard Model
  - primarily use Pythia and MadEvent
  - simulate detector with CDFSim
- Determine correction factors
- Perform Vista global comparison
- Look for discrepancies in bulk of data

The Vista Correction Model

- Vista uses a simplified correction model to attempt to describe bulk features of the data
- Correction factors needed to match Standard Model prediction to real data:
  - Luminosity of data sample
  - Theoretical k-factors for cross-sections
  - Particle (mis-)identification probabilities
  - Trigger efficiencies

Correction Factors

- 44 correction factors used in total
- k-factors for SM processes:
  - QCD multi-jets;
  - W, Z + jets;
  - (di)photon+jets
- Fake rates:
  - jet faking photon, electron, muon, tau, b-quark
- Trigger efficiencies for electrons and muons

Determining the Correction Factors

- Obtain values (and errors) for correction factors by fitting to the observed data

$$\chi^2(\vec{s}) = \left(\sum_{k \in \mathrm{bins}} \chi_k^2(\vec{s}) \right) + \chi^2_{\mathrm{constraints}}(\vec{s})$$

$$\chi_k^2(\vec{s}) = \frac{(\mathrm{Data}[k] - \mathrm{SM}[k])^2}{\delta \mathrm{SM}[k]^2 + \sqrt{\mathrm{SM}[k]}^2}$$

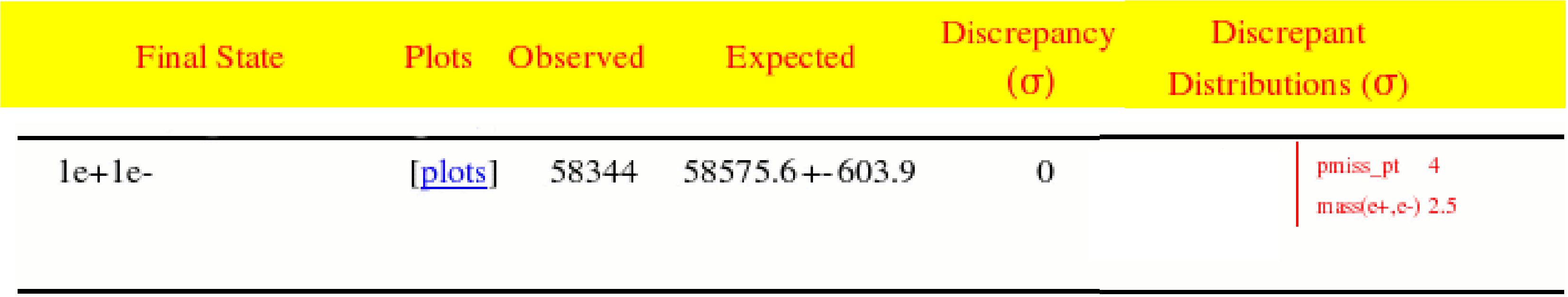
- Fit seeks to maximize global agreement between our Standard Model implementation and the data
- Available external information is used to constrain ~40% of the correction factors
  - e.g. constraints on k-factors from higher-order calculations

Is This A Blind Analysis?

- No. We started with a crude correction model, and refined it after looking to see where it failed to describe the data
- The development of the correction model and associated debugging is not an automated process
- Refining the correction model requires judgement, and all adjustments must be physically motivated
- This process ends when either:
  - a clear case for new physics can be made
  - or there remain no discrepancies that motivate a case for new physics

The Vista Global Comparison

- How well are we able to describe the bulk features of the high-p_T data?
- Figures of merit:
  - discrepancy in populations of final states
  - discrepancy in distributions of kinematic variables
- Account for number of places we look – trials factor
- Example Vista output:



Final State	Plots	Observed	Expected	Discrepancy (σ)	Discrepant Distributions (σ)
1e+1e-	[plots]	58344	58575.6+-603.9	0	pmiss_pt 4 mass(e+,e-) 2.5

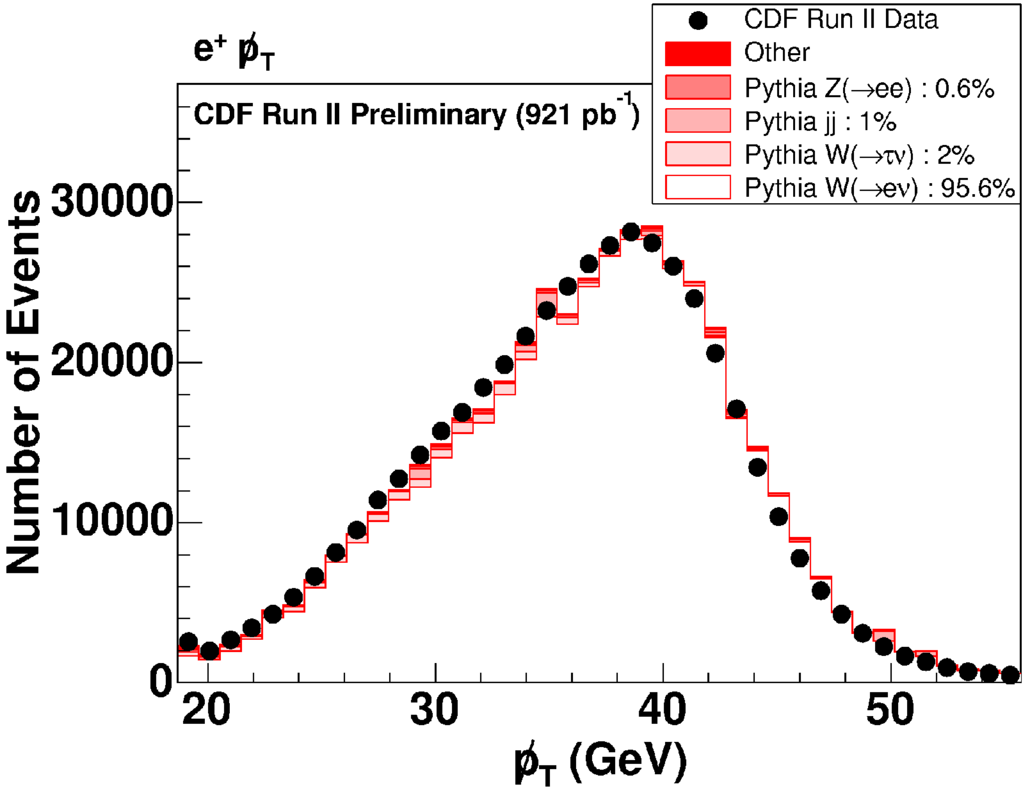
Vista Comparison Results

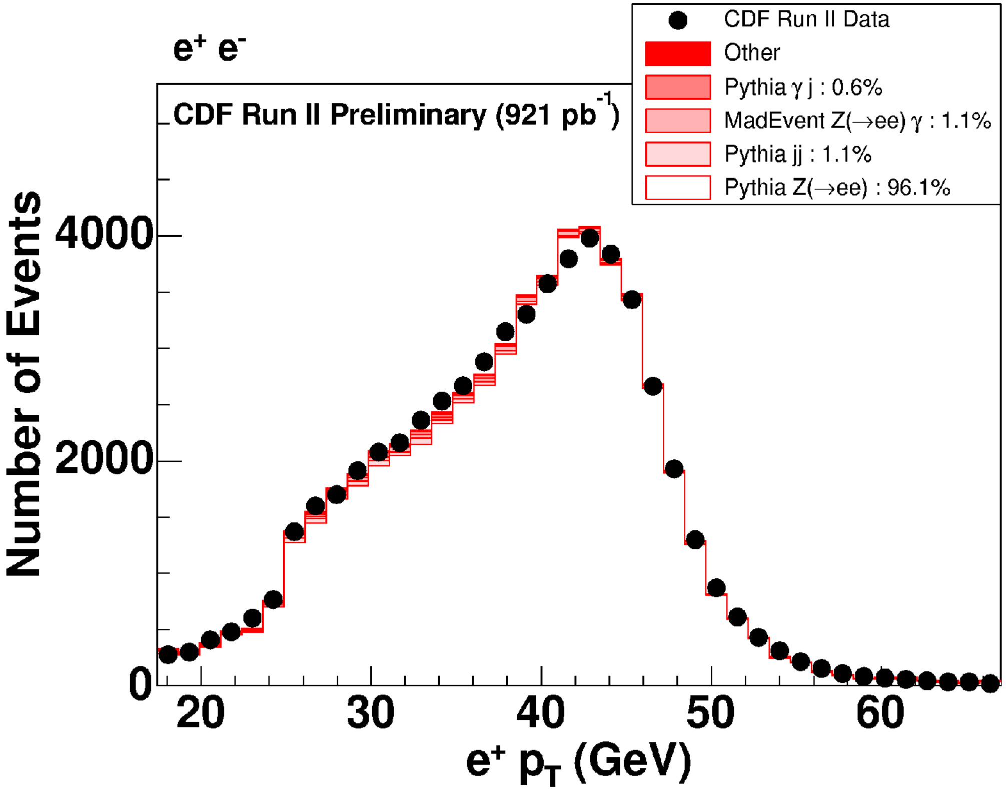
Final State	Data	Background
3jτ+	71	113.7 ± 3.6
5j	1661	1902.9 ± 50.8
2jτ+	233	296.5 ± 5.6
be+j	2207	2015.4 ± 28.7
3j $\Sigma p_T < 400$ GeV	35436	37294.6 ± 524.3
e+3j$\not{p}$	1954	1751.6 ± 42
be+2j	798	695.3 ± 13.3
3j$\not{p}$ $\Sigma p_T > 400$ GeV	811	967.5 ± 38.4
e+μ+	26	11.6 ± 1.5
e+γ	636	551.2 ± 11.2
e+3j	28656	27281.5 ± 405.2
b5j	131	95 ± 4.7
j2τ+	50	85.6 ± 8.2
jτ+τ-	74	125 ± 13.6
b$\not{p}$ $\Sigma p_T > 400$ GeV	10	29.5 ± 4.6
e+jγ	286	369.4 ± 21.1
e+j$\not{p}\tau$-	29	14.2 ± 1.8
2j $\Sigma p_T < 400$ GeV	96502	92437.3 ± 1354.5
be+3j	356	298.6 ± 7.7
8j	11	6.1 ± 2.5
7j	57	35.6 ± 4.9
6j	335	298.4 ± 14.7
4j $\Sigma p_T > 400$ GeV	39665	40898.8 ± 649.2
4j $\Sigma p_T < 400$ GeV	8241	8403.7 ± 144.7
4j2γ	38	57.5 ± 11
4jτ+	20	36.9 ± 2.4
4j$\not{p}$ $\Sigma p_T > 400$ GeV	516	525.2 ± 34.5
4j$\gamma\not{p}$	28	53.8 ± 11
4jγ	3693	3827.2 ± 112.1
4jμ+	576	568.2 ± 26.1
4jμ+$\not{p}$	232	224.7 ± 8.5
4jμ+μ-	17	20.1 ± 2.5
3γ	13	24.2 ± 3
3j $\Sigma p_T > 400$ GeV	75894	75939.2 ± 1043.9
3j2γ	145	178.1 ± 7.4
3j$\not{p}$ $\Sigma p_T < 400$ GeV	20	30.9 ± 14.4
3j$\gamma\tau$+	13	11 ± 2
3j$\gamma\not{p}$	83	102.9 ± 11.1
3jγ	11424	11506.4 ± 190.6
3jμ+$\not{p}$	1114	1118.7 ± 27.1
3jμ+μ-	61	84.5 ± 9.2
3jμ+	2132	2168.7 ± 64.2
3bj $\Sigma p_T > 400$ GeV	14	9.3 ± 1.9
2τ+	316	290.8 ± 24.2
2$\gamma\not{p}$	161	176 ± 9.1
2γ	8482	8349.1 ± 84.1
2j $\Sigma p_T > 400$ GeV	93408	92789.5 ± 1138.2
2j2γ	645	612.6 ± 18.8
2jτ+τ-	15	25 ± 3.5
2j$\not{p}$ $\Sigma p_T > 400$ GeV	74	106 ± 7.8
2j$\not{p}$ $\Sigma p_T < 400$ GeV	43	37.7 ± 100.2
2jγ	33684	33259.9 ± 397.6
2j$\gamma\tau$+	48	41.4 ± 3.4
2j$\gamma\not{p}$	403	425.2 ± 29.7
2jμ+$\not{p}$	7287	7320.5 ± 118.9
2jμ+$\gamma\not{p}$	13	12.6 ± 2.7
2jμ+γ	41	35.7 ± 6.1
2jμ+μ-	374	394.2 ± 24.8
2jμ+	9513	9362.3 ± 166.8
2e+j	13	9.8 ± 2.2
2e+e-	12	4.8 ± 1.2
2e+	23	36.1 ± 3.8
2b $\Sigma p_T > 400$ GeV	327	335.8 ± 7
2b $\Sigma p_T < 400$ GeV	187	173.1 ± 7.1
2b3j $\Sigma p_T < 400$ GeV	28	33.5 ± 5.5
2b2j $\Sigma p_T > 400$ GeV	355	326.3 ± 8.4
2b2j $\Sigma p_T < 400$ GeV	56	80.2 ± 5
2b2jγ	16	15.4 ± 3.6
2bγ	37	31.7 ± 4.8
2bj $\Sigma p_T > 400$ GeV	415	393.8 ± 9.1
2bj $\Sigma p_T < 400$ GeV	161	195.8 ± 8.3
2bj$\not{p}$ $\Sigma p_T > 400$ GeV	28	23.2 ± 2.6
2bjγ	25	24.7 ± 4.3
2be+2j$\not{p}$	15	12.3 ± 1.6
2be+2j	30	30.5 ± 2.5
2be+j	28	29.1 ± 2.8
2be+	48	45.2 ± 3.7
τ+τ-	498	428.5 ± 22.7
$\gamma\tau$+	177	204.4 ± 5.4
$\gamma\not{p}$	1952	1945.8 ± 77.1
μ+τ+	18	19.8 ± 2.3
μ+τ-	151	179.1 ± 4.7
μ+$\not{p}$	321351	320500 ± 3475.5
μ+$\not{p}\tau$-	22	25.8 ± 2.7
μ+γ	269	285.5 ± 5.9
μ+$\gamma\not{p}$	269	282.2 ± 6.6
μ+μ-$\not{p}$	49	61.4 ± 3.5
μ+μ-γ	32	29.9 ± 2.6
μ+μ-	10648	10845.6 ± 96
j2γ	2196	2200.3 ± 35.2
j2$\gamma\not{p}$	38	27.3 ± 3.2
jτ+	563	585.7 ± 10.2
j$\not{p}$ $\Sigma p_T > 400$ GeV	4183	4209.1 ± 56.1
jγ	49052	48743 ± 546.3
j$\gamma\tau$+	106	104 ± 4.1
j$\gamma\not{p}$	913	965.2 ± 41.5
jμ+	33462	34026.7 ± 510.1
jμ+τ-	29	37.5 ± 4.5
jμ+$\not{p}\tau$-	10	9.6 ± 2.1
jμ+$\not{p}$	45728	46316.4 ± 568.2
jμ+$\gamma\not{p}$	78	69.8 ± 9.9
jμ+γ	70	98.4 ± 12.1
jμ+μ-	1977	2093.3 ± 74.7
e+4j	7144	6661.9 ± 147.2
e+4j$\not{p}$	403	363 ± 9.9
e+3jτ-	11	7.6 ± 1.6
e+3jγ	27	21.7 ± 3.4
e+2γ	47	74.5 ± 5
e+2j	126665	122457 ± 1672.6
e+2jτ-	53	37.3 ± 3.9
e+2jτ+	20	24.7 ± 2.3
e+2j$\not{p}$	12451	12130.1 ± 159.4
e+2jγ	101	88.9 ± 6.1
e+τ-	609	555.9 ± 10.2
e+τ+	225	211.2 ± 4.7
e+$\not{p}$	476424	479572 ± 5361.2
e+$\not{p}\tau$-	48	35 ± 2.7
e+$\not{p}\tau$+	20	18.7 ± 1.9
e+$\gamma\not{p}$	141	144.2 ± 6
e+μ-$\not{p}$	54	42.6 ± 2.7
e+μ+$\not{p}$	13	10.9 ± 1.3
e+μ-	153	127.6 ± 4.2
e+j	386880	392614 ± 5031.8
e+j2γ	14	15.9 ± 2.9
e+jτ+	79	79.3 ± 2.9
e+jτ-	162	148.8 ± 7.6
e+j$\not{p}$	58648	57391.7 ± 661.6
e+j$\gamma\not{p}$	52	76.2 ± 9
e+jμ-$\not{p}$	22	13.1 ± 1.7
e+jμ-	28	26.8 ± 2.3
e+e-4j	103	113.5 ± 5.9
e+e-3j	456	473 ± 14.6
e+e-2j$\not{p}$	30	39 ± 4.6
e+e-2j	2149	2152 ± 40.1
e+e-τ+	14	11.1 ± 2
e+e-$\not{p}$	491	487.9 ± 12
e+e-γ	127	132.3 ± 4.2
e+e-j	10726	10669.3 ± 123.5
e+e-j$\not{p}$	157	144 ± 11.2
e+e-jγ	26	45.6 ± 4.7
e+e-	58344	58575.6 ± 603.9
b6j	24	15.5 ± 2.3
b4j $\Sigma p_T > 400$ GeV	13	9.2 ± 1.8
b4j $\Sigma p_T < 400$ GeV	464	499.2 ± 12.4
b3j $\Sigma p_T > 400$ GeV	5354	5285 ± 72.4
b3j $\Sigma p_T < 400$ GeV	1639	1558.9 ± 24.1
b3j$\not{p}$ $\Sigma p_T > 400$ GeV	111	116.8 ± 11.2
b3jγ	182	194.1 ± 8.8
b3jμ+$\not{p}$	37	34.1 ± 2
b3jμ+	47	52.2 ± 3
b2γ	15	14.6 ± 2.1
b2j $\Sigma p_T > 400$ GeV	8812	8576.2 ± 97.9
b2j $\Sigma p_T < 400$ GeV	4691	4646.2 ± 57.7
b2j$\not{p}$ $\Sigma p_T > 400$ GeV	198	209.2 ± 8.3
b2jγ	429	425.1 ± 13.1
b2jμ+$\not{p}$	46	40.1 ± 2.7
b2jμ+	56	60.6 ± 3.4
bτ+	19	19.9 ± 2.2
bγ	976	1034.8 ± 15.6
b$\gamma\not{p}$	18	16.7 ± 3.1
bμ+	303	263.5 ± 7.9
bμ+$\not{p}$	204	218.1 ± 6.4
bj $\Sigma p_T > 400$ GeV	9060	9275.7 ± 87.8
bj $\Sigma p_T < 400$ GeV	7236	7030.8 ± 74
bj2γ	13	17.6 ± 3.3
bjτ+	13	12.9 ± 1.8
bj$\not{p}$ $\Sigma p_T > 400$ GeV	53	60.4 ± 19.9
bjγ	937	989.4 ± 20.6
bj$\gamma\not{p}$	34	30.5 ± 4
bjμ+$\not{p}$	104	112.6 ± 4.4
bjμ+	173	141.4 ± 4.8
be+3j$\not{p}$	68	52.2 ± 2.2
be+2j$\not{p}$	87	65 ± 3.3
be+$\not{p}$	330	347.2 ± 6.9
be+j$\not{p}$	211	176.6 ± 5
be+e-j	22	34.6 ± 2.6
be+e-	62	55 ± 3.1

344 exclusive final states considered

Systematic uncertainties not included when comparing final state populations

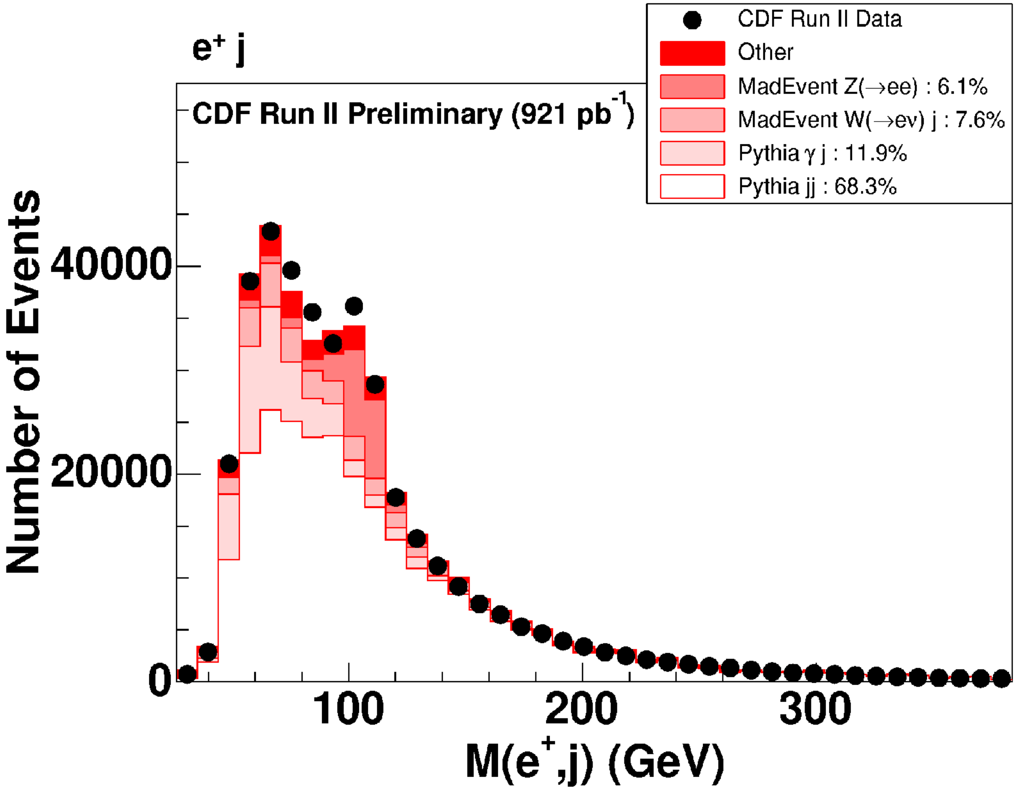
Vista Examples: W & Z Production

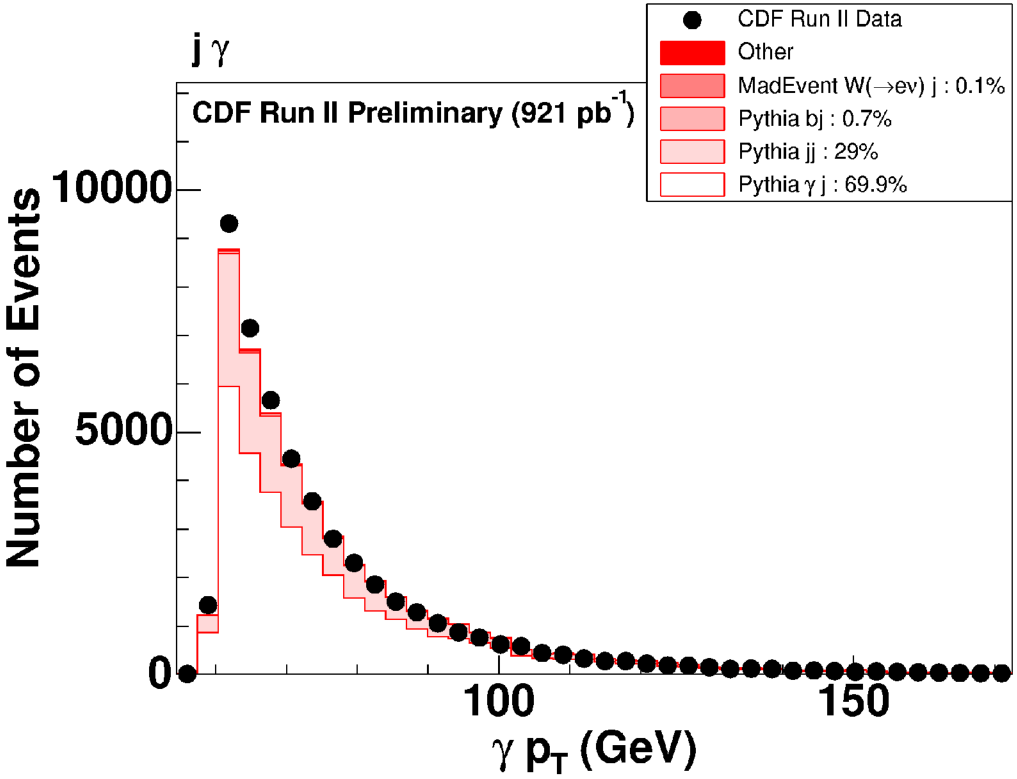




- W & Z k-factors well-constrained from NNLO calculations
- Act as constraints on luminosity of data sample

Vista Examples: Determining Fake Rates

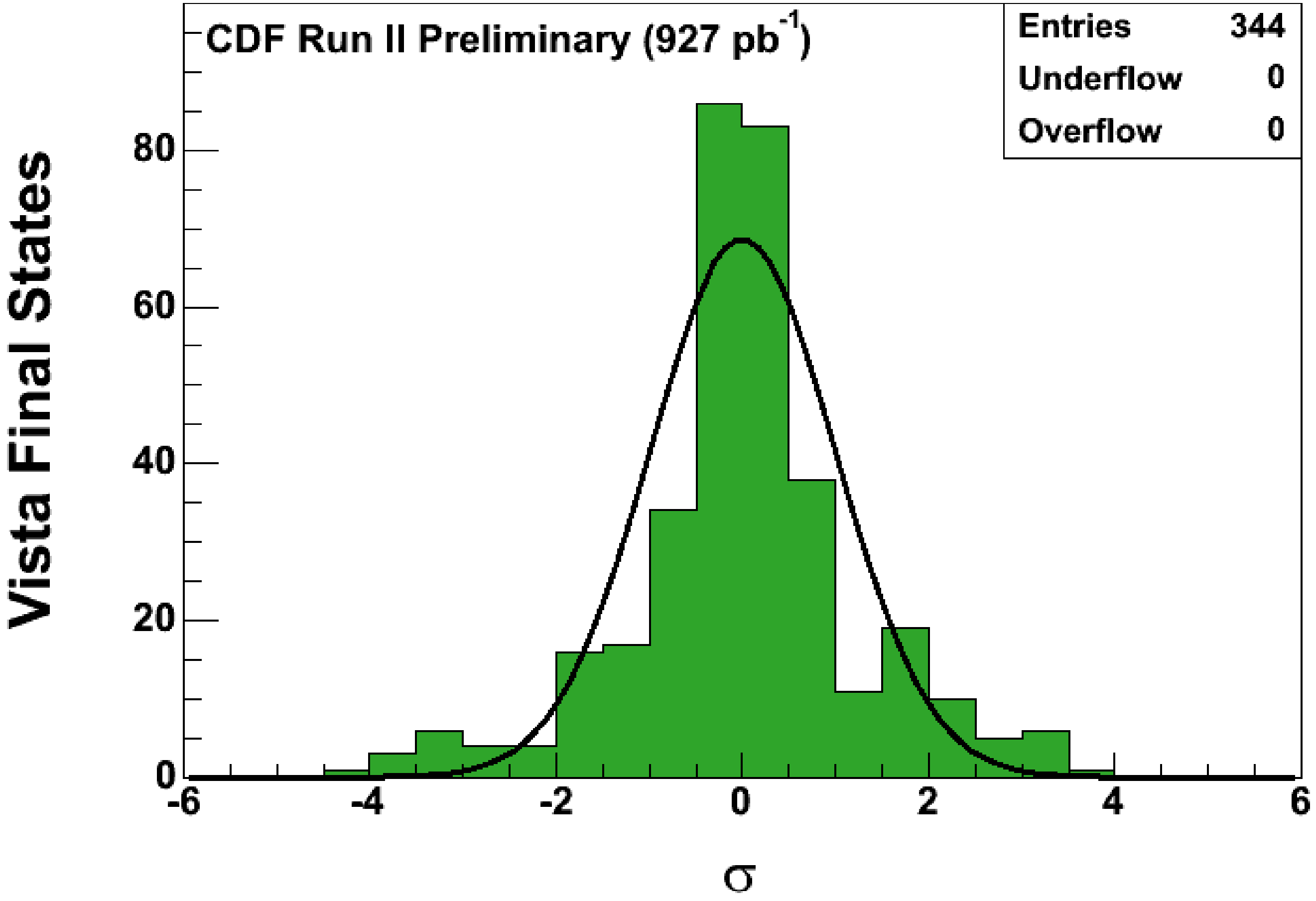




- ej final state dominated by jets reconstructed as electrons
- Also a peak at M_Z, where electron is reconstructed as a jet

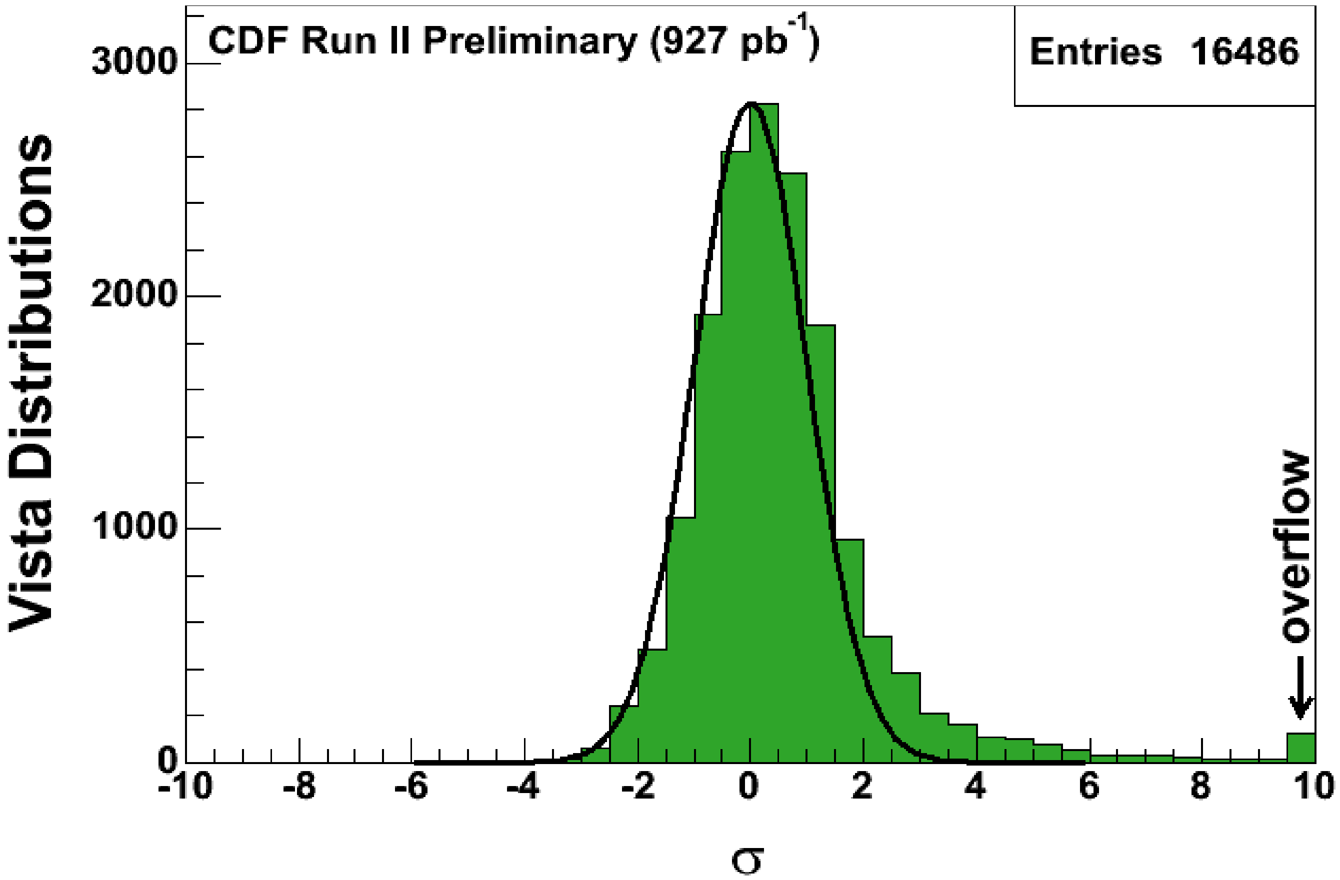
- Real photon+jet production
- Plus QCD di-jets with a jet faking a photon

Level of Agreement: Final State Populations



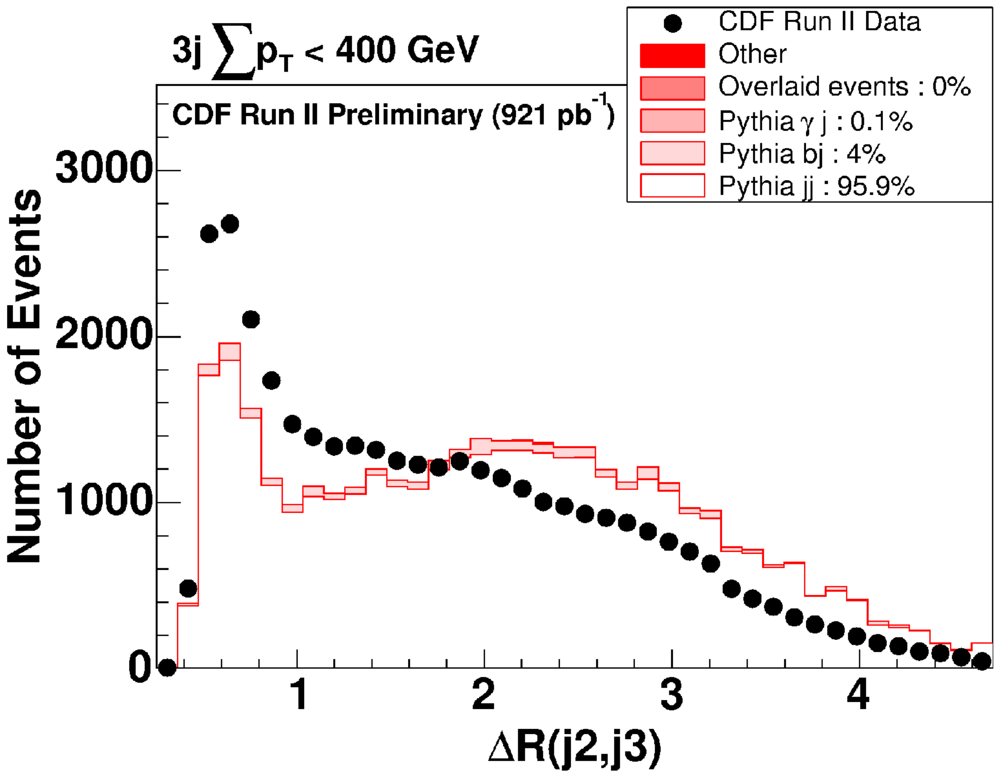
- Distribution of discrepancy between data and SM prediction for final state event populations - roughly Gaussian, centered at 0, width 1
- No final state shows significant deviation, after accounting for trials factor
  - 8% chance of observing the largest population excess that we saw in the data

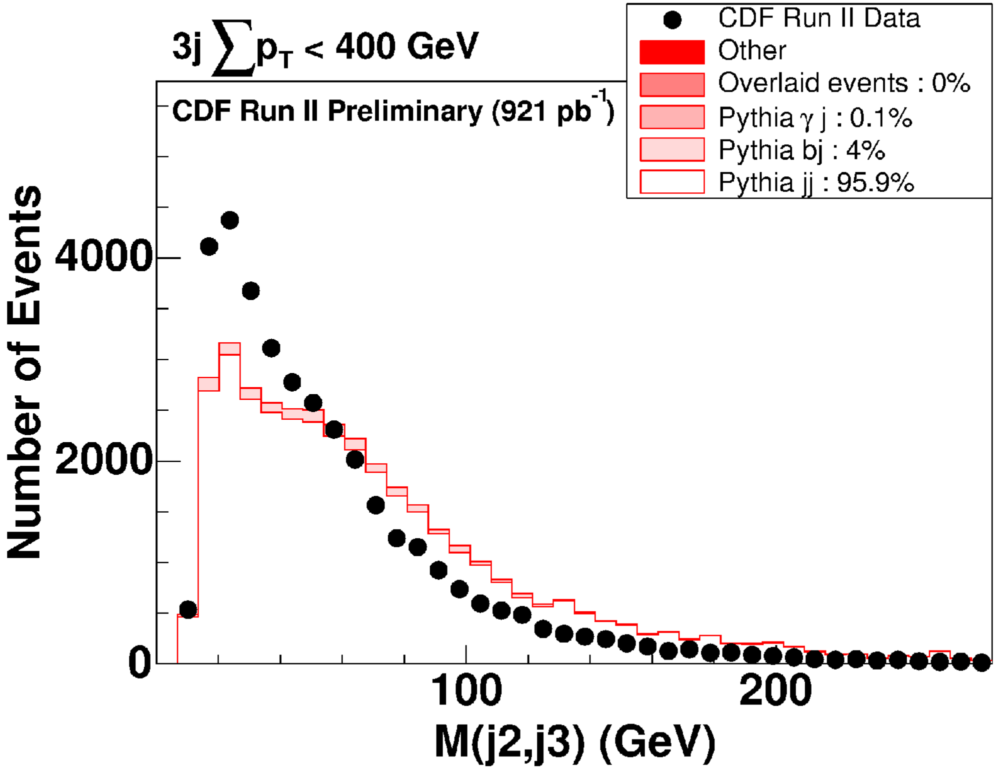
Level of Agreement: Kinematic Variables



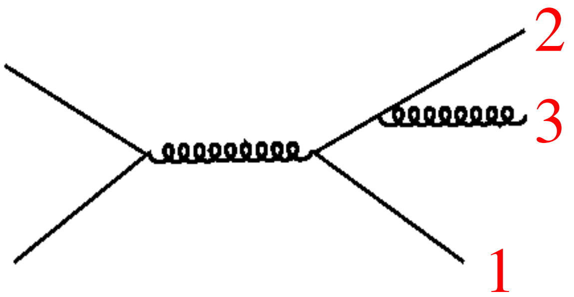
- Distribution of discrepancy between data and SM prediction for kinematic variables – vast majority follow normal distribution
- Interest is focused on ~400 outliers = kinematic variables showing significant disagreement

Example of a Vista Discrepancy: 3j



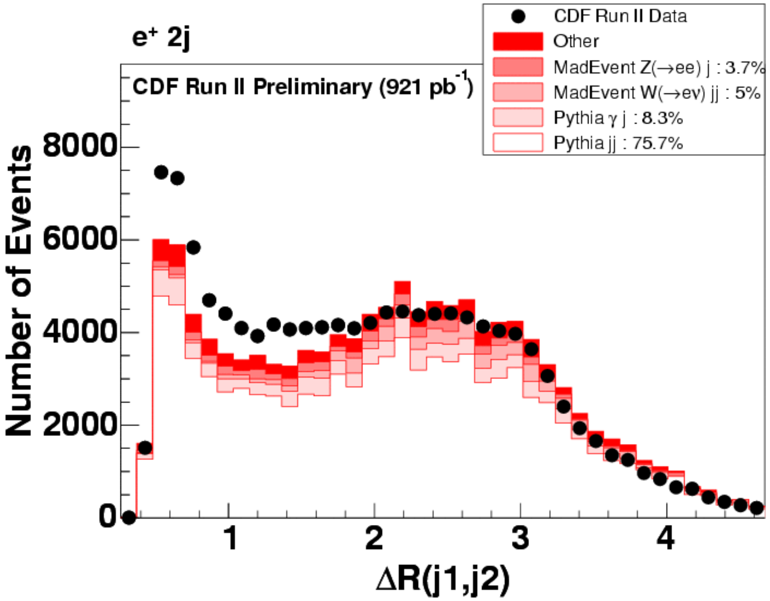


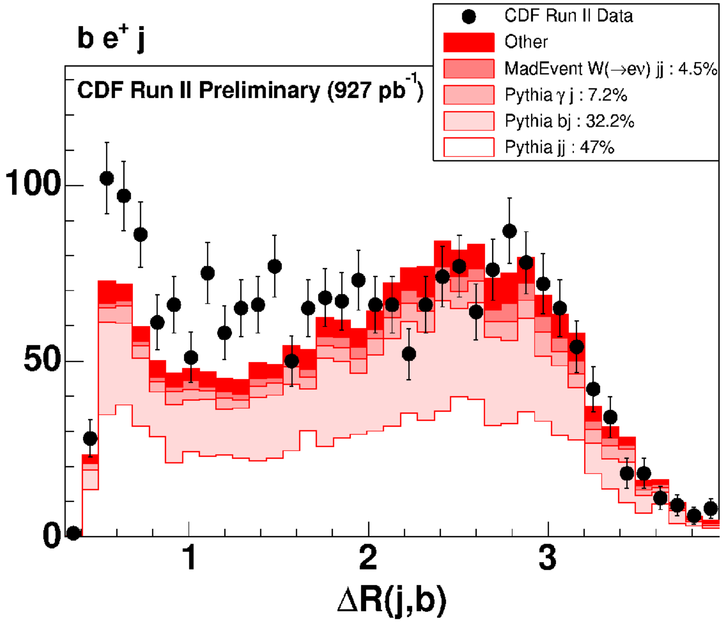
- For 3j state, discrepancy in these distributions is observed
- Parameters for parton showering being investigated

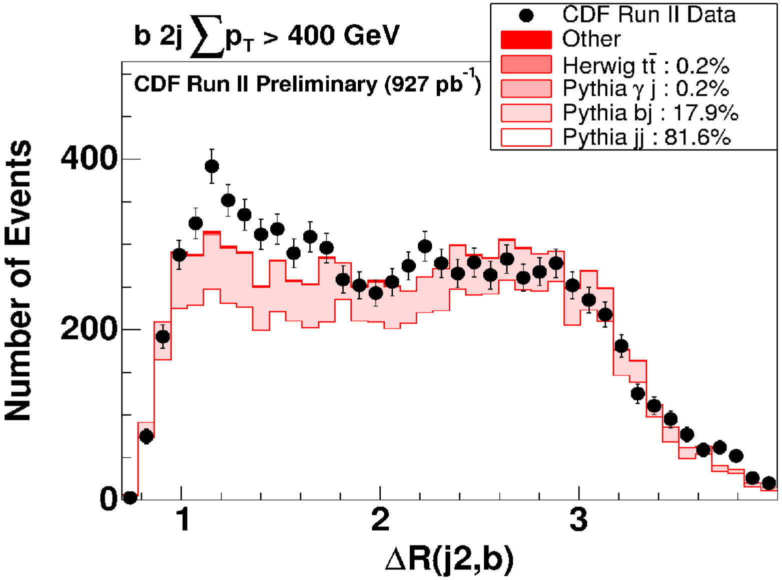


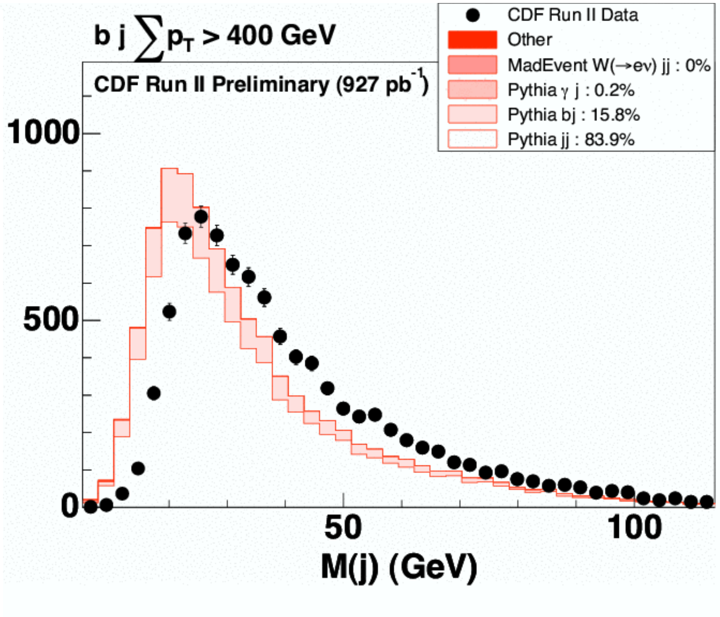
Same Discrepancy in Many Final States

- Same underlying discrepancy manifest in many related final states
    - bjj, ejj, bej, etc...
- Accounts for ~90% of the distribution discrepancies

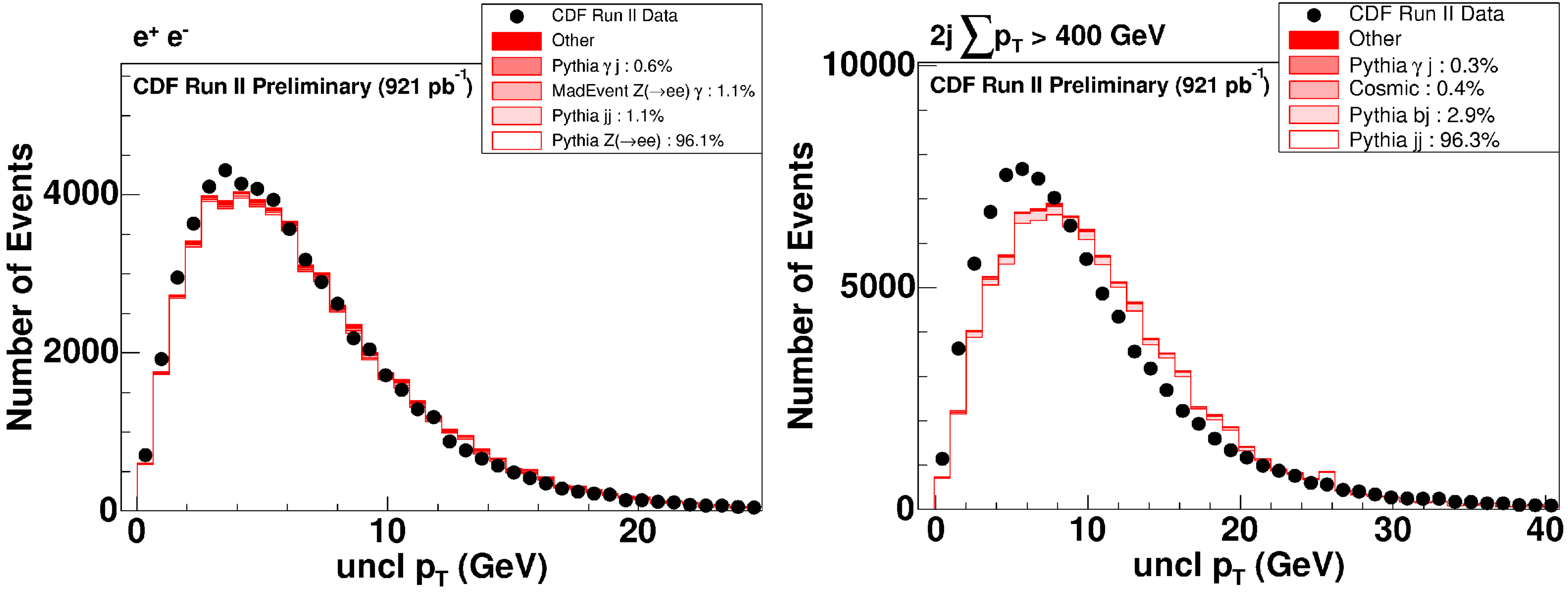








Vista: Intrinsic k_T



uncl p_T = Energy visible in the detector but not clustered into any object

- Simultaneously describing intrinsic k_T in all final states is difficult

Vista Results

- Our implementation of the Standard Model gives a remarkably good global description of the CDF high-p_T data
- No final state has a significant population discrepancy
- There are some significant shape discrepancies, most of which derive from the physics exemplified by:
  - 3j $\Delta R(j_2,j_3)$ (~90%)
  - intrinsic k_T modeling (~9%)
- None of these remaining discrepancies motivate a new physics claim

Summary of Vista

- Vista attempts to understand bulk features of high-p_T collider data in terms of the Standard Model
- Identify objects, select and partition events, implement Standard Model prediction; novel approach to determine correction factors
- Perform global comparison of Standard Model to data:
  - reasonable description obtained
  - some discrepancies remain in kinematic variable distributions
  - none motivate a new physics claim

From Vista to Sleuth

- Understand bulk of data - Vista

- Focus on high-p_T tails - Sleuth

Sleuth: Goal and Assumptions

- Sleuth relies on the following assumptions:
    - New physics will appear predominantly in one final state
    - New physics will appear as excess of data over SM
    - New physics will appear at high Σp_T
- Sleuth will be less sensitive to new physics which does not satisfy these assumptions

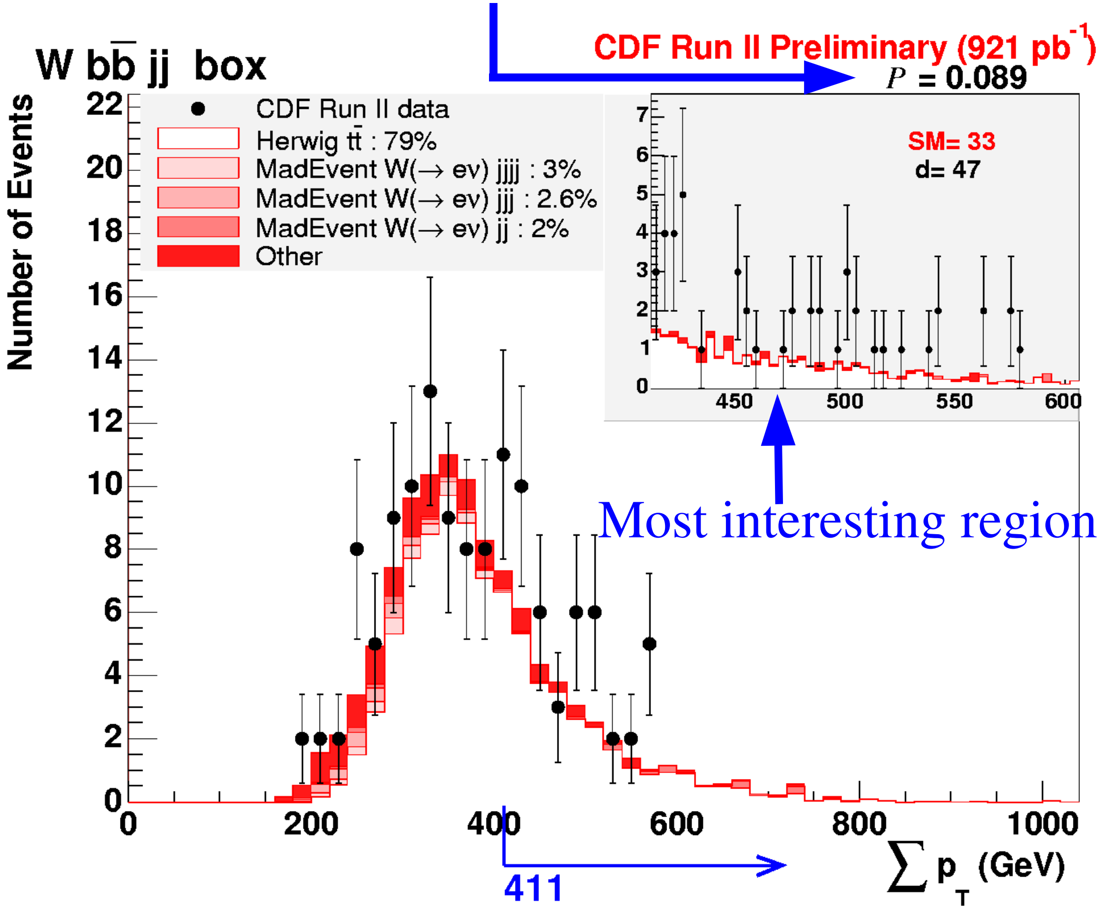
What Sleuth Does

- Sleuth's variable:

$$\sum p_T \equiv \sum_i |\vec{p}_i| + \left|\overrightarrow{\text{uncl}}\right| + \left|\vec{\not p}\right| ,$$

- Scan the Σp_T spectrum to select the region in each final state with the most significant excess of data over SM prediction
  - require >=3 data events
- Perform pseudo-experiments to assess the significance

Significance of this region



Most interesting region

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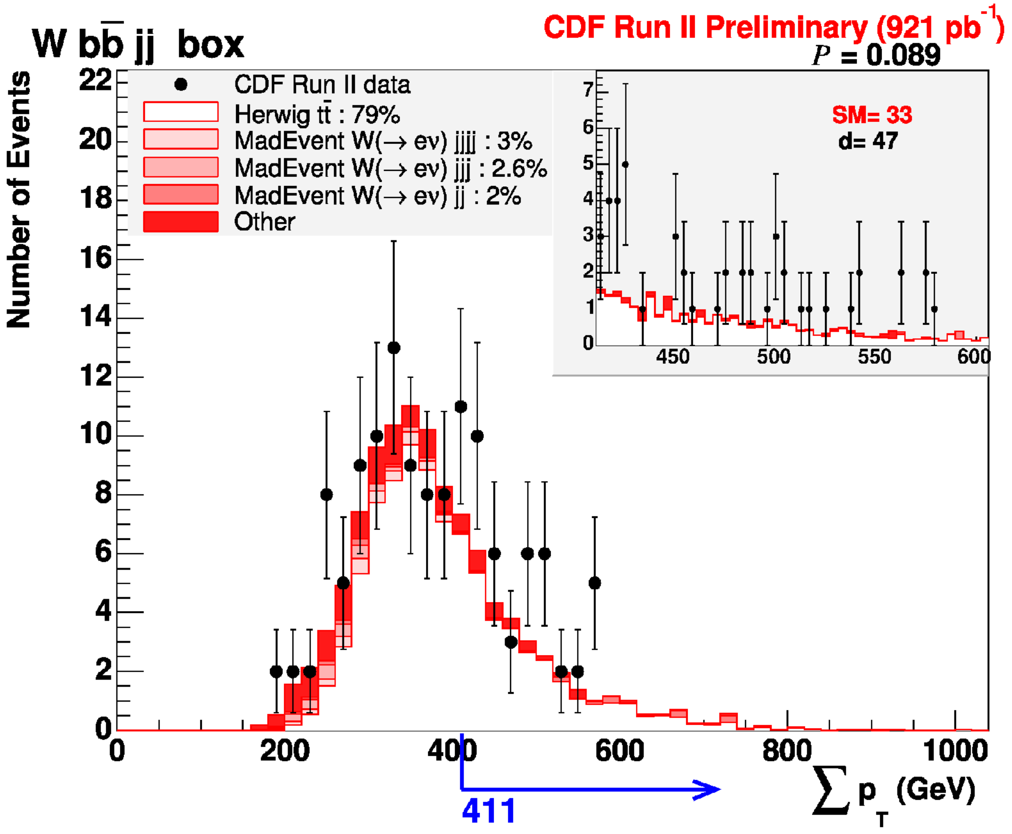
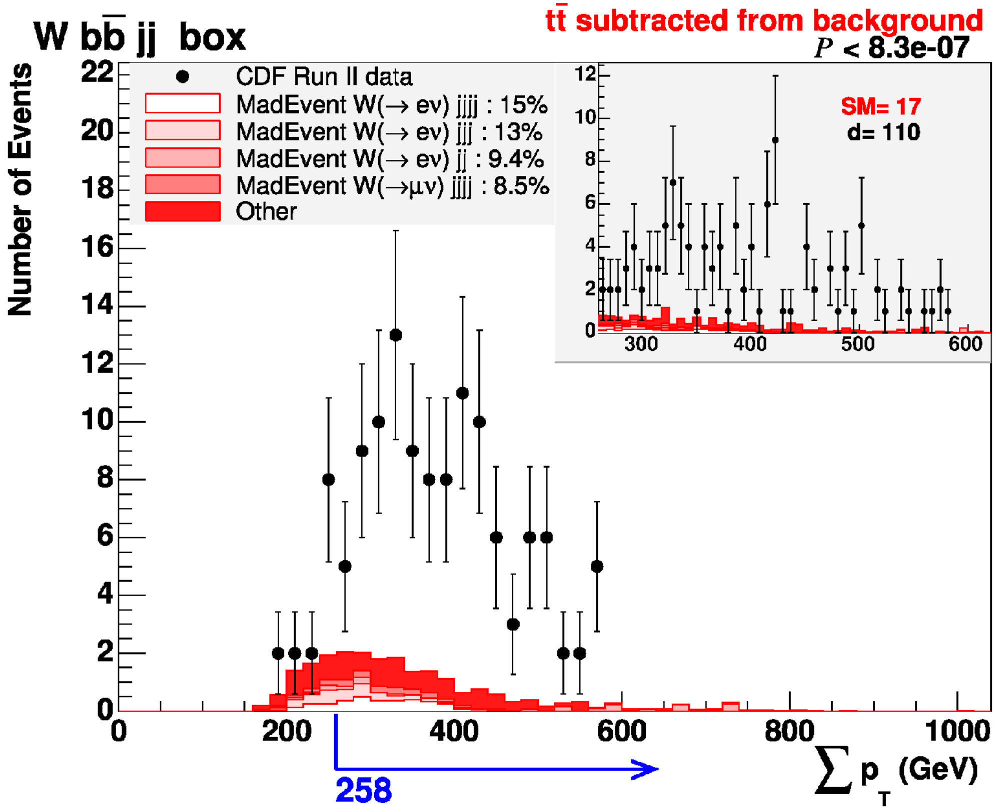
What Sleuth Does Next

- Now consider all Sleuth final states
  - if the data were just drawn from our SM implementation, what fraction of similar *complete CDF experiments* would have produced by chance a region in any final state as or more interesting than the most interesting one we found?
- Sleuth rigorously accounts for the trials factor in the regions it searches
- We set the Sleuth discovery threshold: $\tilde{P} < 0.001$
  - with a trials factor from ~60 final states with ~50 data events, this corresponds to a ~5σ effect in the selected region

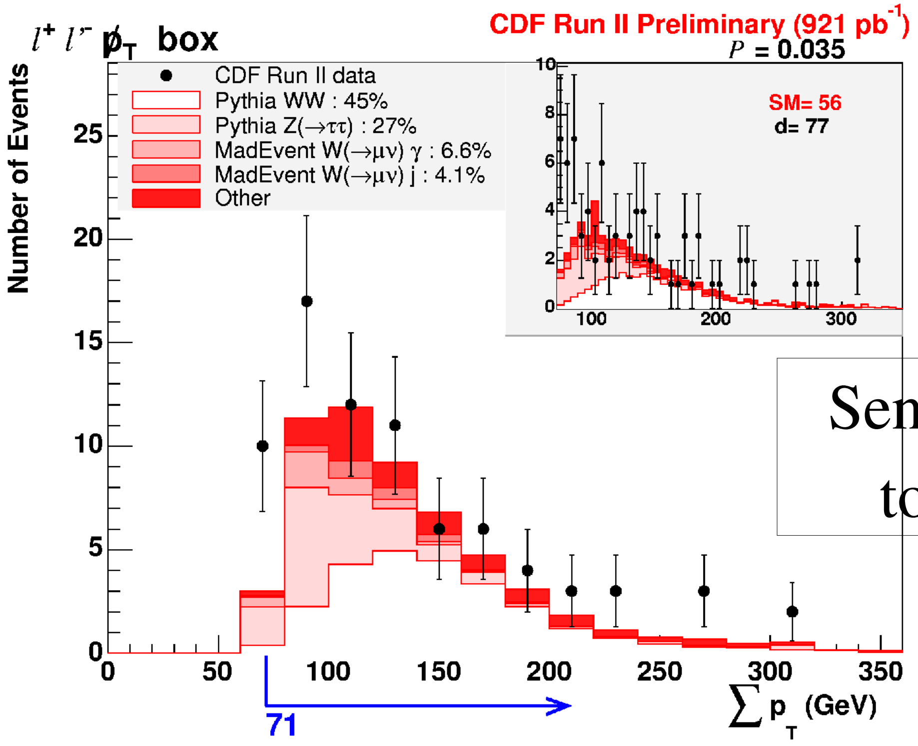
Would Sleuth Have Found the Top Quark?



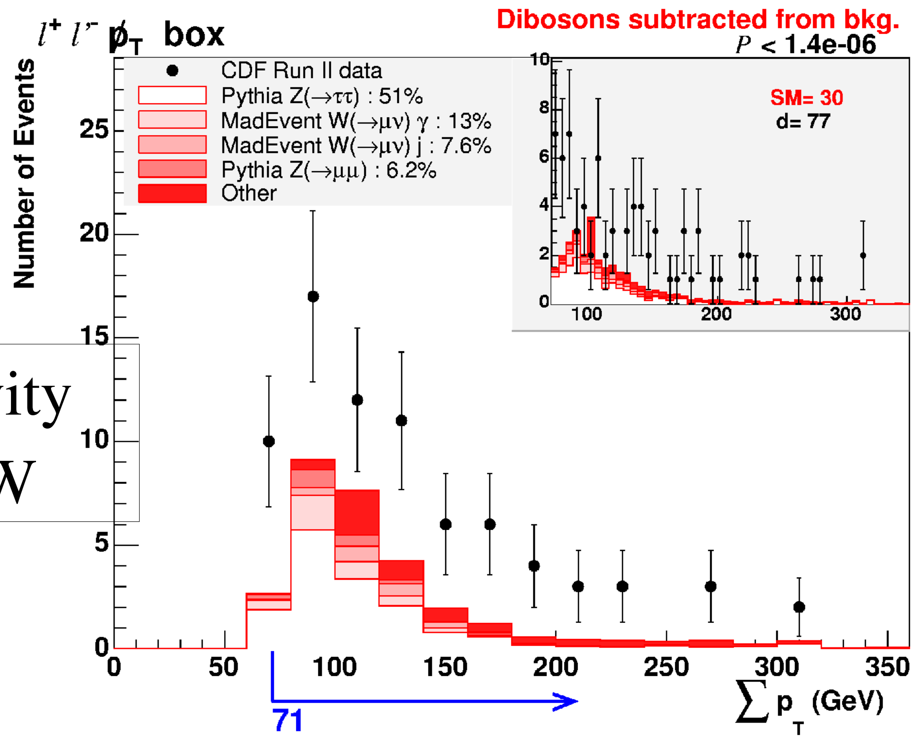


- Remove top quark from SM; refit correction factors
- Sleuth easily finds top in 1 fb^{-1}
- Estimated luminosity for Sleuth discovery ~80 pb^{-1} (Run I discovery = 67 pb^{-1} at $\sqrt{s}$=1.8 TeV)

Sleuth Sensitivity to Other SM Processes



Sensitivity to WW

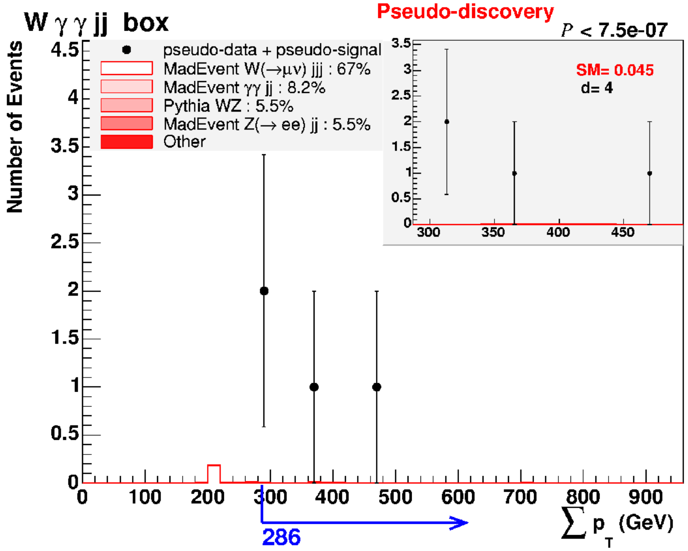


- WW: discovery if removed from SM background
- Single top: somewhat less sensitive than targeted search
- Higgs: less sensitive than targeted search

Sensitivity to Specific New Physics Models

- Inject signal into pseudo-data drawn from SM prediction
  - determine cross-section needed to trigger Sleuth's discovery threshold
  - systematic uncertainties not included

GMSB model



Name	Description	Sensitivity (pb)
Model 01	GMSB, $\Lambda = 82.6$ GeV, $\tan\beta = 15$, $\mu > 0$, 1 messenger of $M = 2\Lambda$	0.10 ± 0.04
Model 02	$Z'_{(250\,\mathrm{GeV}/c^2)} \to \ell\bar{\ell}$, with $\ell \neq \nu$	1.56 ± 0.09
Model 03	$Z'_{(700\,\mathrm{GeV}/c^2)} \to q\bar{q}$	4.3 ± 0.8
Model 04	$Z'_{(1\,\mathrm{TeV}/c^2)} \to q\bar{q}$	1.67 ± 0.23
Model 05	mSUGRA, $M_0 = 100$ GeV, $M_{1/2} = 180$ GeV, $A_0 = 0$, $\tan\beta = 5$, $\mu > 0$	2.05 ± 0.18
Model 06	mSUGRA, $M_0 = 284$ GeV, $M_{1/2} = 100$ GeV, $A_0 = 0$, $\tan\beta = 5$, $\mu < 0$	1.55 ± 0.10
Model 07	mSUGRA, $M_0 = 300$ GeV, $M_{1/2} = 200$ GeV, $A_0 = 0$, $\tan\beta = 5$, $\mu < 0$	0.25 ± 0.09
Model 08	Standard Model $t\bar{t}$, with $t\bar{t}$ removed from background. Would need $\sim 40\ \mathrm{pb}^{-1}$ to see.	0.30 ± 0.05
Model 09	Standard Model WW, with WW removed from background. Would need $\sim 400\ \mathrm{pb}^{-1}$ to see.	5.7 ± 1.1
Model 10	MSSM $A \to \tau\tau$, $M_A = 160$ GeV, $\tan\beta = 5$	13.5 ± 1.9
Model 11	$Z'_{(500\,\mathrm{GeV}/c^2)} \to t\bar{t}$	2.8 ± 0.9

- Sensitivity broadly comparable to dedicated searches when signal satisfies Sleuth's basic assumptions
- Sleuth becomes less sensitive as the signal violates these assumptions

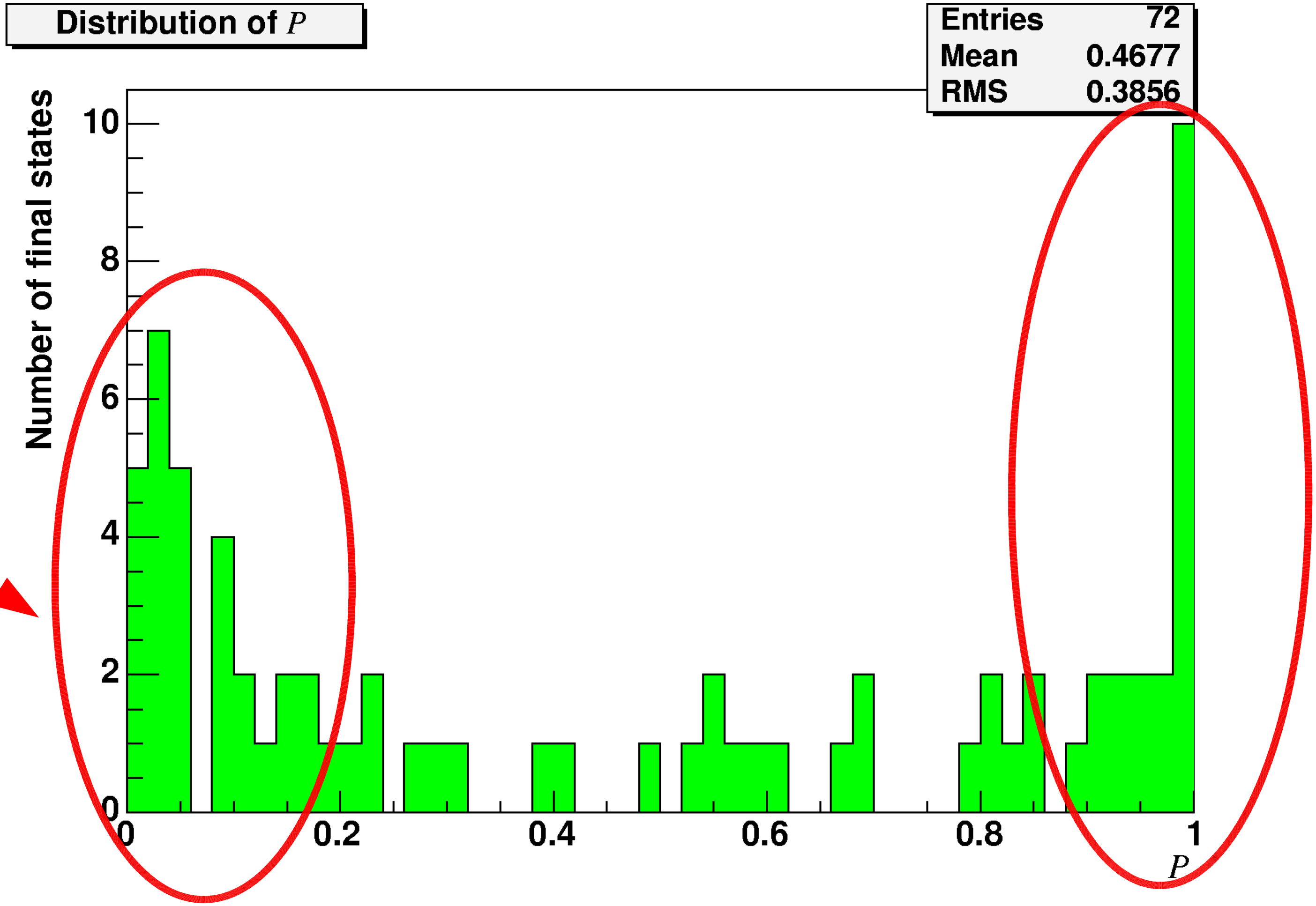
Systematic Uncertainties in Vista and Sleuth

- The correction model explicitly does not include some sources of systematic uncertainty, eg parton distribution functions or shower parameters
- Other uncertainties relating to detector simulation and object reconstruction are determined within Vista, but not propagated to the calculation of $\tilde{P}$ in Sleuth
- Correction factors are mainly fit to bulk distributions in Vista; potential additional systematic uncertainty associated with the extrapolation of these values to high-p_T is not included
- Sleuth's search for interesting excesses only considers statistical uncertainties on the background; systematic uncertainties on the Σp_T distributions in Sleuth are estimated to be ~10-30%

Now for the data...

P for all Sleuth Final States

Maybe new physics here? Or just under-estimation of SM?

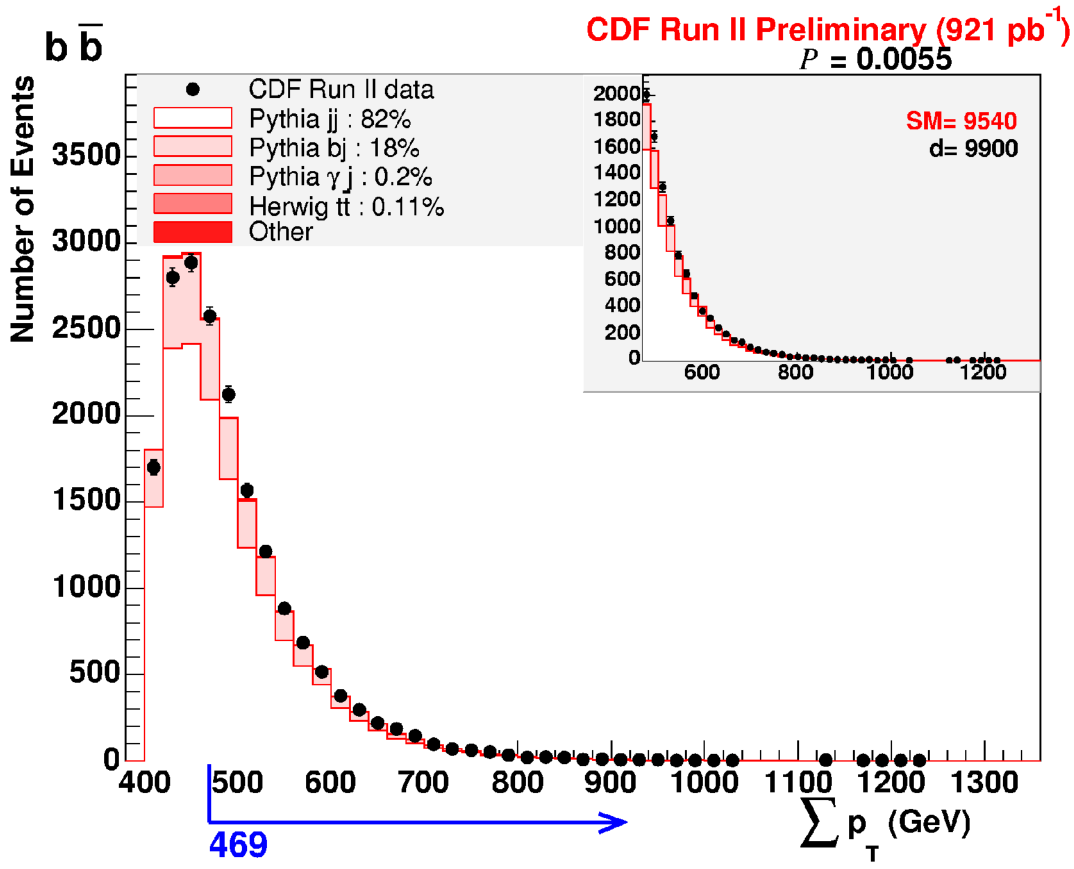


Probable over-estimation of SM background

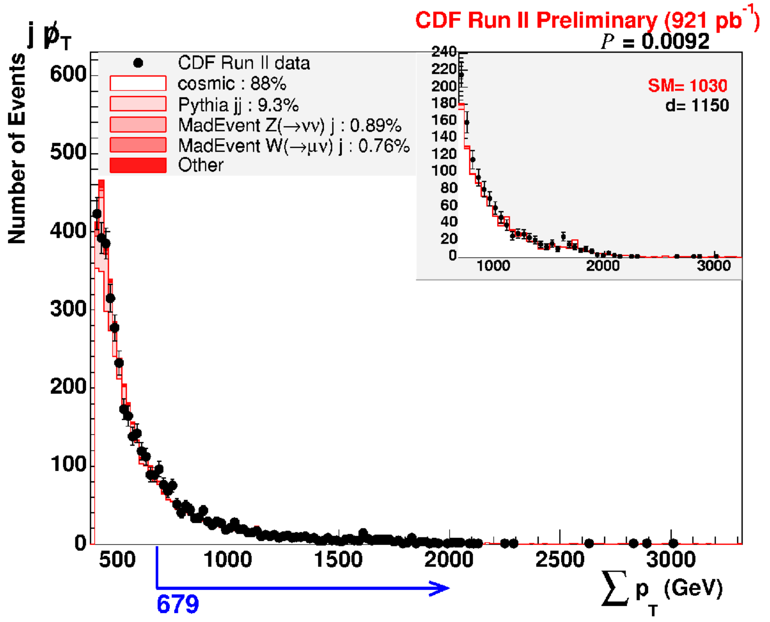
If our simplified Standard Model prediction perfectly represented the data, we would expect this to be a uniform distribution

Sleuth's Most Discrepant Final States

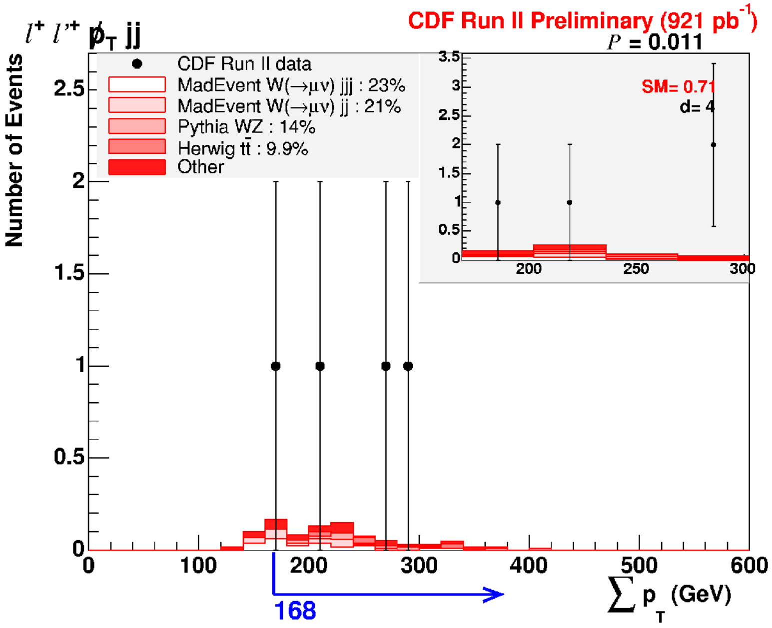
#1



#2



#3



How significant is the largest Σp_T excess that we see in the data? (after considering all the places in which we have looked)

Sleuth Results

- Sleuth's assessment of the significance of the largest discrepancy we observed in the data:
  - 46% of hypothetical similar experiments drawn from our simplified SM prediction would give a larger discrepancy
  - we consider discovery threshold = 0.1%
- In $1\,\mathrm{fb}^{-1}$ of CDF data, we found no significant (~5σ) excess of data over SM in the high Σp_T distributions
- This is not a proof that there is no new physics present in these data

$$\tilde{\mathcal{P}} = 0.46$$

Sleuth's Top 5 Most Discrepant Final States:

SLEUTH Final State	$\mathcal{P}$
$b\bar{b}$	0.0055
$j\,\not{p}$	0.0092
$\ell^+\ell'^+\,\not{p}\,j\,j$	0.011
$\ell^+\ell'^+\,\not{p}$	0.016
$\tau\,\not{p}$	0.016

Conclusions

- Vista attempts to understand the bulk features of high-p_T data in terms of the Standard Model
- Sleuth searches for new physics appearing as an excess of data at high Σp_T relative to SM backgrounds
- With these model-independent techniques, no significant (~5σ) excess was found that might indicate new physics in 1 fb^{-1}
- This is not a claim that there is no new physics present in our data

Future Plans

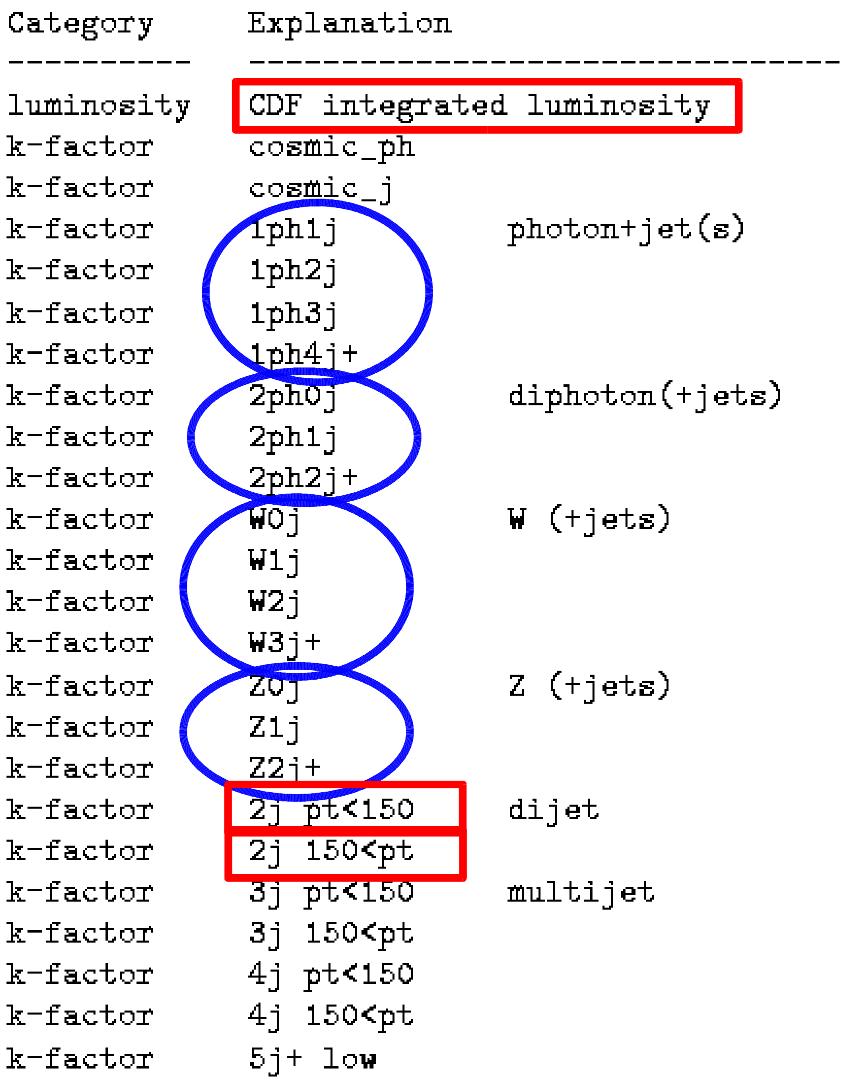
- The Tevatron expects to collect factor 5-8 more data
- Additional discrepancies that are seen will entail further improvements in our correction model
- The search for new physics at CDF - using this global search technique in parallel with dedicated searches - will continue with enthusiasm!

Backups

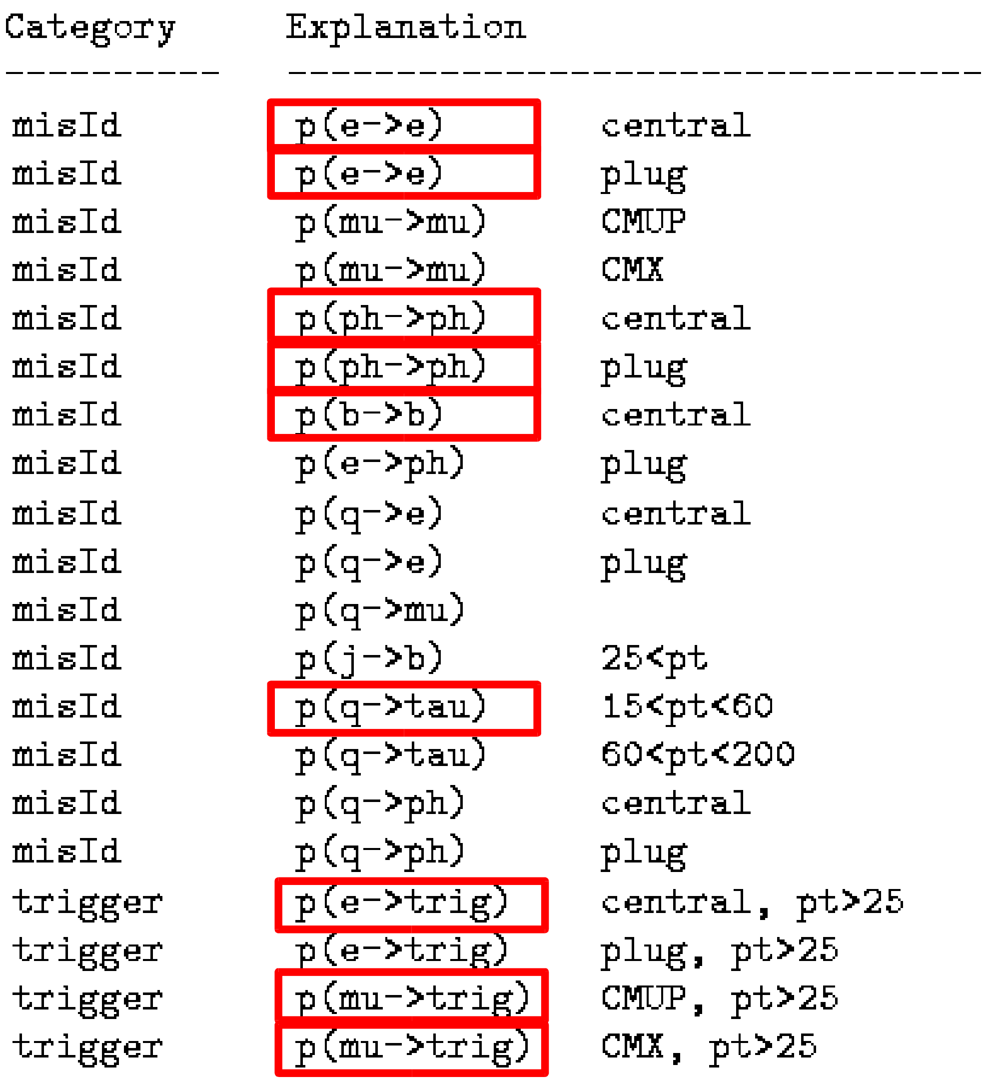
- The correction factors shown are defined and applicable only within the context of the Vista correction model
- Values and errors are obtained from global fit to data (including constraints)

Code	Category	Explanation	Value	Error	Error(%)
5001	luminosity	CDF integrated luminosity	927.1	20	2.2
5102	k-factor	cosmic_ph	0.686	0.05	7.3
5103	k-factor	cosmic_j	0.4464	0.014	3.1
5121	k-factor	1γ1j photon+jet(s)	0.9492	0.04	4.2
5122	k-factor	1γ2j	1.205	0.05	4.1
5123	k-factor	1γ3j	1.483	0.07	4.7
5124	k-factor	1γ4j+	1.968	0.16	8.1
5130	k-factor	2γ0j diphoton(+jets)	1.809	0.08	4.4
5131	k-factor	2γ1j	3.417	0.24	7.0
5132	k-factor	2γ2j+	1.305	0.16	12.3
5141	k-factor	W0j W (+jets)	1.453	0.027	1.9
5142	k-factor	W1j	1.059	0.03	2.8
5143	k-factor	W2j	1.021	0.03	2.9
5144	k-factor	W3j+	0.7582	0.05	6.6
5151	k-factor	Z0j Z (+jets)	1.419	0.024	1.7
5152	k-factor	Z1j	1.177	0.04	3.4
5153	k-factor	Z2j+	1.035	0.05	4.8
5161	k-factor	2j $\hat{p}_T$<150 dijet	0.9599	0.022	2.3
5162	k-factor	2j 150<$\hat{p}_T$	1.256	0.028	2.2
5164	k-factor	3j $\hat{p}_T$<150 multijet	0.9206	0.021	2.3
5165	k-factor	3j 150<$\hat{p}_T$	1.36	0.032	2.4
5167	k-factor	4j $\hat{p}_T$<150	0.9893	0.025	2.5
5168	k-factor	4j 150<$\hat{p}_T$	1.705	0.04	2.3
5169	k-factor	5j+ low	1.252	0.05	4.0
5211	misId	p(e$\to$e) central	0.9864	0.006	0.6
5212	misId	p(e$\to$e) plug	0.9334	0.009	1.0
5213	misId	p($\mu\to\mu$) CMUP	0.8451	0.008	0.9
5214	misId	p($\mu\to\mu$) CMX	0.915	0.011	1.2
5216	misId	p($\gamma\to\gamma$) central	0.9738	0.018	1.8
5217	misId	p($\gamma\to\gamma$) plug	0.9131	0.018	2.0
5219	misId	p(b$\to$b) central	0.9969	0.04	4.0
5245	misId	p(e$\to\gamma$) plug	0.04452	0.012	27.0
5256	misId	p(q$\to$e) central	9.71×10^{-5}	1.9×10^{-6}	2.0
5257	misId	p(q$\to$e) plug	0.0008761	1.8×10^{-5}	2.1
5261	misId	p(q$\to\mu$)	1.157×10^{-5}	2.7×10^{-7}	2.3
5273	misId	p(j$\to$b) 25<$\hat{p}_T$	0.01684	0.00027	1.6
5285	misId	p(q$\to\tau$) 15<$\hat{p}_T$<60	0.003414	0.00012	3.5
5286	misId	p(q$\to\tau$) 60<$\hat{p}_T$<200	0.000381	4×10^{-5}	10.5
5292	misId	p(q$\to\gamma$) central	0.0002651	1.5×10^{-5}	5.7
5293	misId	p(q$\to\gamma$) plug	0.001591	0.00013	8.2
5401	trigger	p(e$\to$trig) central, $\hat{p}_T$>25	0.9758	0.007	0.7
5402	trigger	p(e$\to$trig) plug, $\hat{p}_T$>25	0.835	0.015	1.8
5403	trigger	p($\mu\to$trig) CMUP, $\hat{p}_T$>25	0.9166	0.007	0.8
5404	trigger	p($\mu\to$trig) CMX, $\hat{p}_T$>25	0.9613	0.01	1.0

Constrained Correction Factors



```
Category      Explanation
----------    ---------------------------------
luminosity    CDF integrated luminosity
k-factor      cosmic_ph
k-factor      cosmic_j
k-factor      1ph1j               photon+jet(s)
k-factor      1ph2j
k-factor      1ph3j
k-factor      1ph4j+
k-factor      2ph0j               diphoton(+jets)
k-factor      2ph1j
k-factor      2ph2j+
k-factor      W0j                 W (+jets)
k-factor      W1j
k-factor      W2j
k-factor      W3j+
k-factor      Z0j                 Z (+jets)
k-factor      Z1j
k-factor      Z2j+
k-factor      2j pt<150           dijet
k-factor      2j 150<pt
k-factor      3j pt<150           multijet
k-factor      3j 150<pt
k-factor      4j pt<150
k-factor      4j 150<pt
k-factor      5j+ low
```

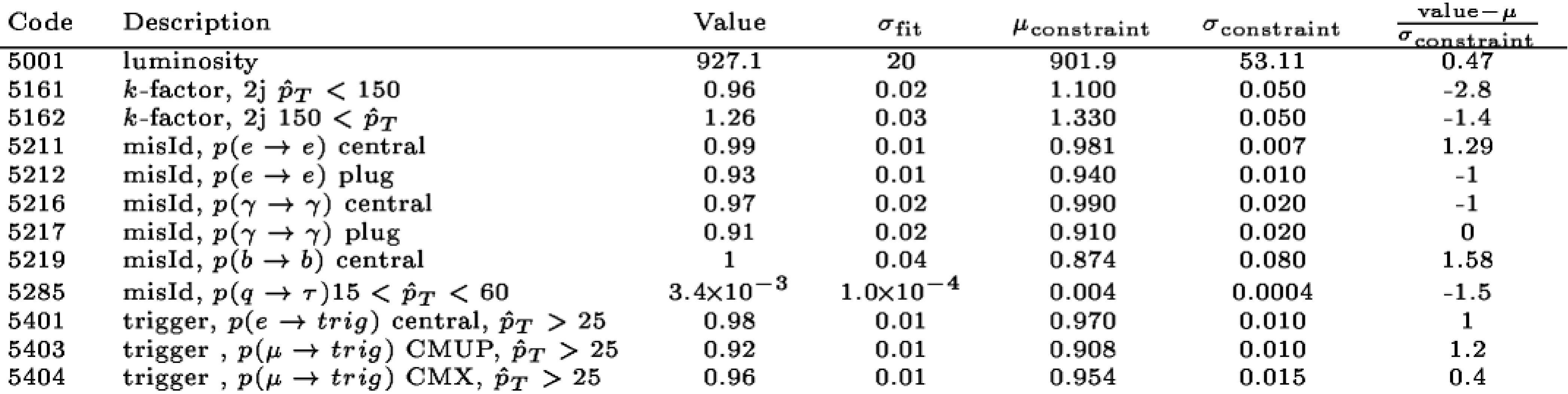


```
Category      Explanation
-----------   --------------------------------------
misId         p(e->e)         central
misId         p(e->e)         plug
misId         p(mu->mu)       CMUP
misId         p(mu->mu)       CMX
misId         p(ph->ph)       central
misId         p(ph->ph)       plug
misId         p(b->b)         central
misId         p(e->ph)        plug
misId         p(q->e)         central
misId         p(q->e)         plug
misId         p(q->mu)
misId         p(j->b)         25<pt
misId         p(q->tau)       15<pt<60
misId         p(q->tau)       60<pt<200
misId         p(q->ph)        central
misId         p(q->ph)        plug
trigger       p(e->trig)      central, pt>25
trigger       p(e->trig)      plug, pt>25
trigger       p(mu->trig)     CMUP, pt>25
trigger       p(mu->trig)     CMX, pt>25
```

▭ Has external constraint

◯ Part of inclusive constraint

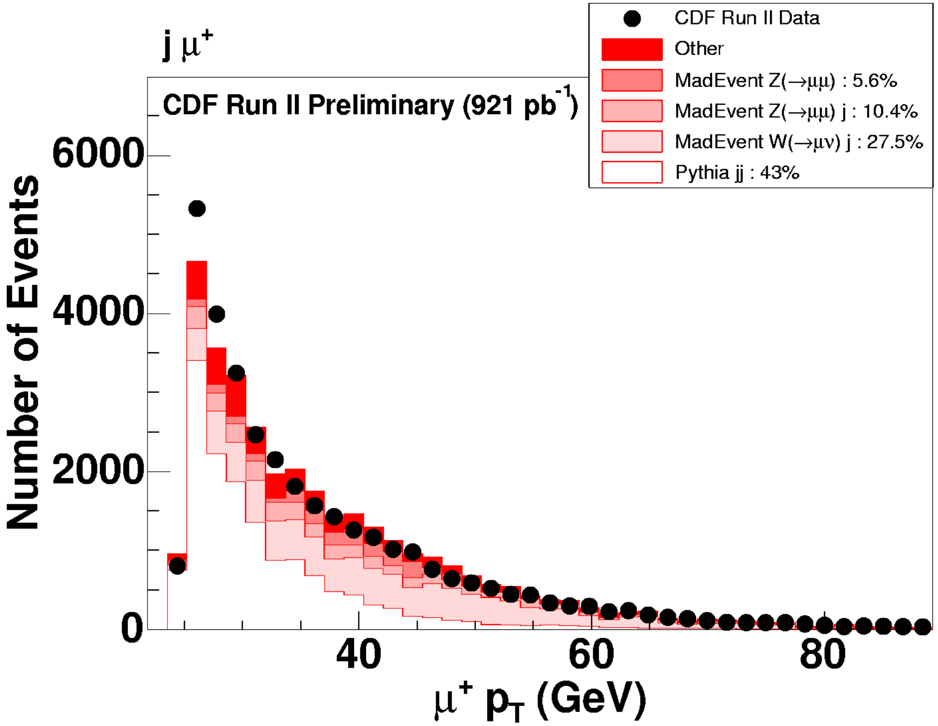
Vista Correction Factor Constraints

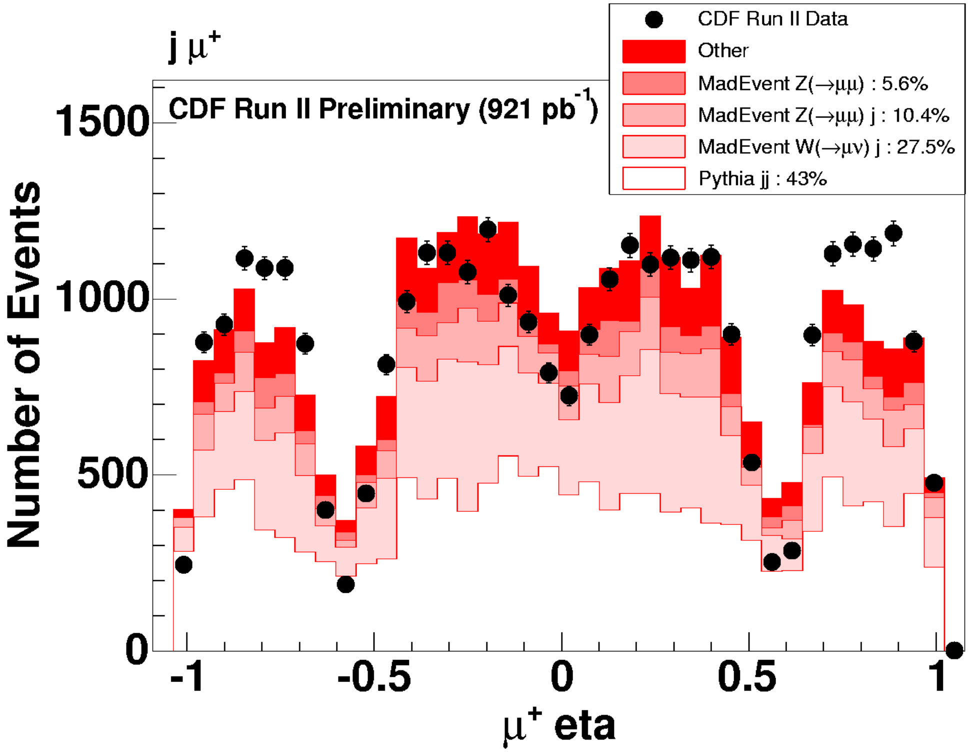


Code	Description	Value	σ_{fit}	$\mu_{\mathrm{constraint}}$	$\sigma_{\mathrm{constraint}}$	$\frac{\mathrm{value}-\mu}{\sigma_{\mathrm{constraint}}}$
5001	luminosity	927.1	20	901.9	53.11	0.47
5161	k-factor, 2j $\hat{p}_T < 150$	0.96	0.02	1.100	0.050	-2.8
5162	k-factor, 2j $150 < \hat{p}_T$	1.26	0.03	1.330	0.050	-1.4
5211	misId, $p(e \rightarrow e)$ central	0.99	0.01	0.981	0.007	1.29
5212	misId, $p(e \rightarrow e)$ plug	0.93	0.01	0.940	0.010	-1
5216	misId, $p(\gamma \rightarrow \gamma)$ central	0.97	0.02	0.990	0.020	-1
5217	misId, $p(\gamma \rightarrow \gamma)$ plug	0.91	0.02	0.910	0.020	0
5219	misId, $p(b \rightarrow b)$ central	1	0.04	0.874	0.080	1.58
5285	misId, $p(q \rightarrow \tau) 15 < \hat{p}_T < 60$	3.4×10^{-3}	1.0×10^{-4}	0.004	0.0004	-1.5
5401	trigger, $p(e \rightarrow trig)$ central, $\hat{p}_T > 25$	0.98	0.01	0.970	0.010	1
5403	trigger , $p(\mu \rightarrow trig)$ CMUP, $\hat{p}_T > 25$	0.92	0.01	0.908	0.010	1.2
5404	trigger , $p(\mu \rightarrow trig)$ CMX, $\hat{p}_T > 25$	0.96	0.01	0.954	0.015	0.4

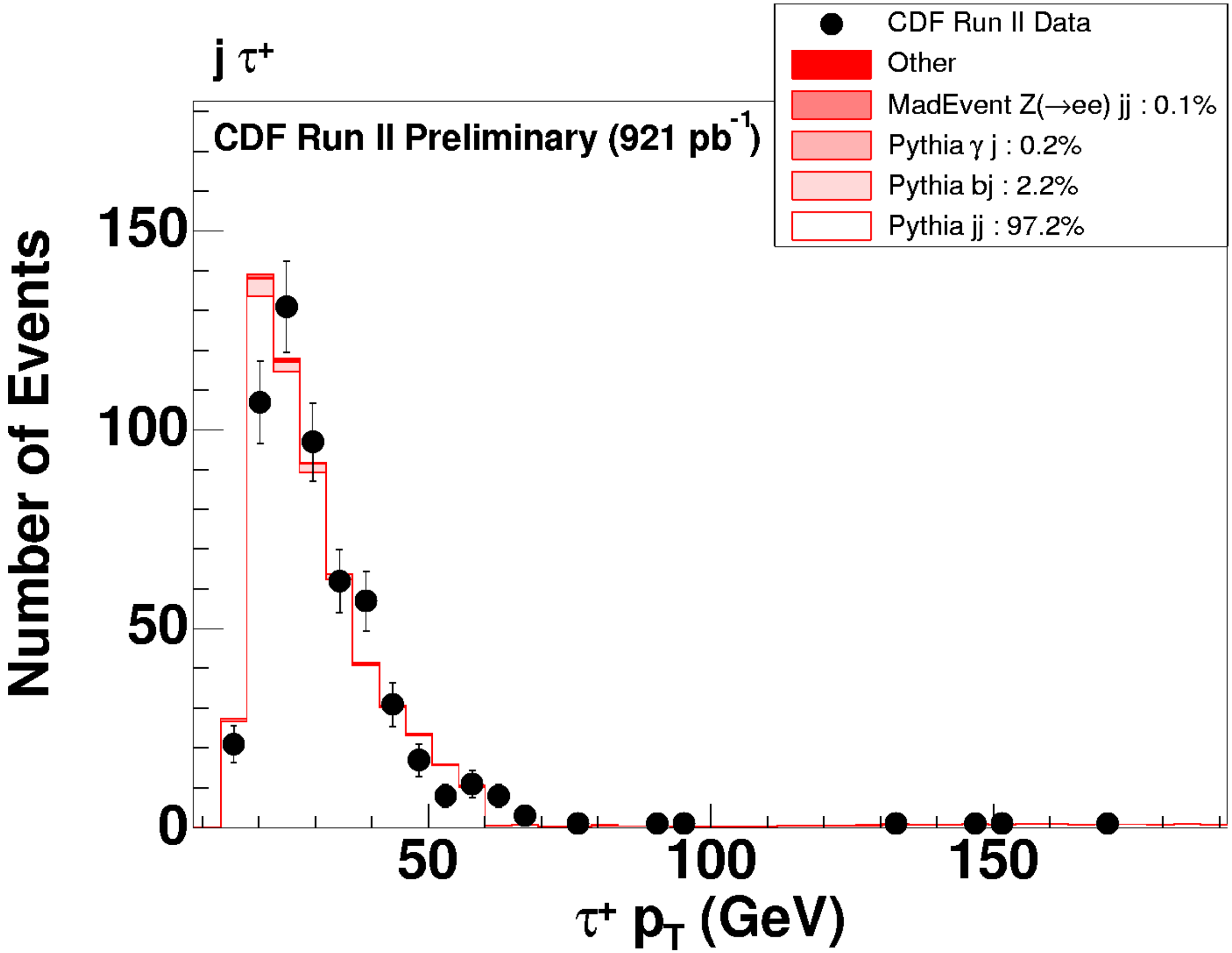
Plus inclusive constraints on: W+jets; Z+jets; (di)photon+jets

Vista Examples: Muon Fakes

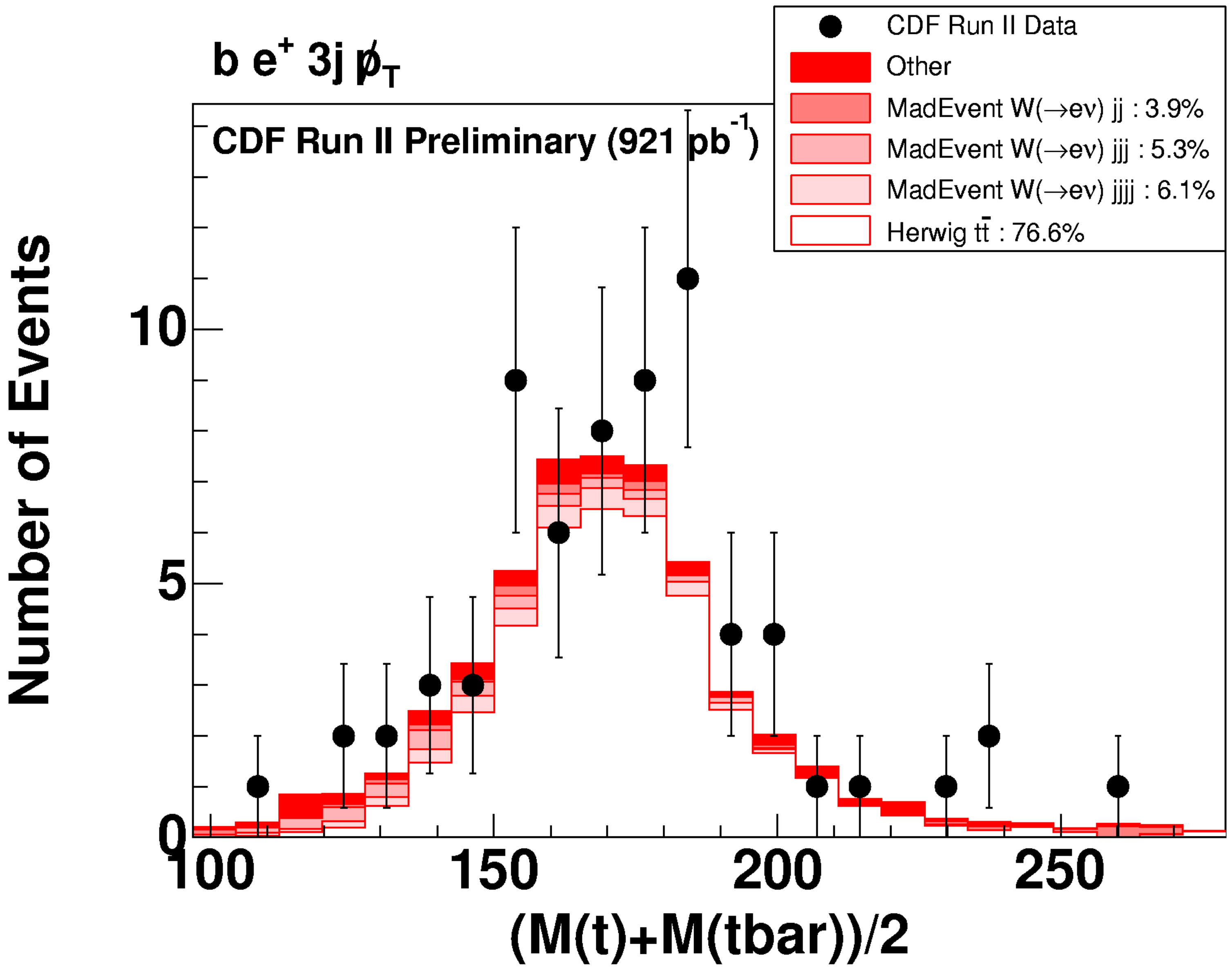




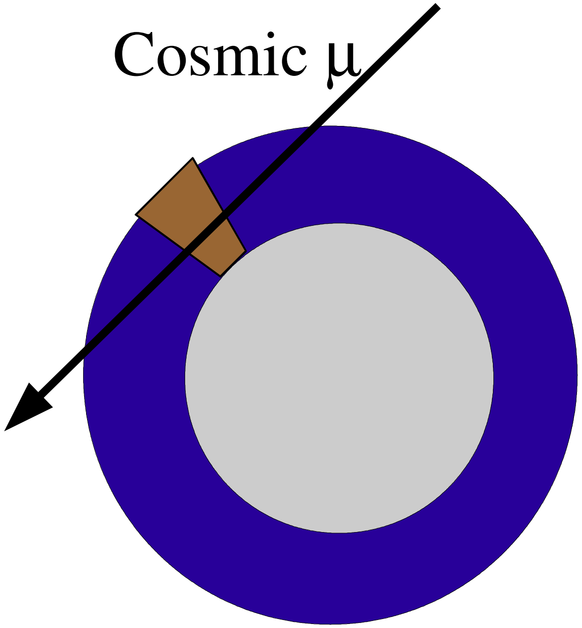
Vista Example: Tau Fakes

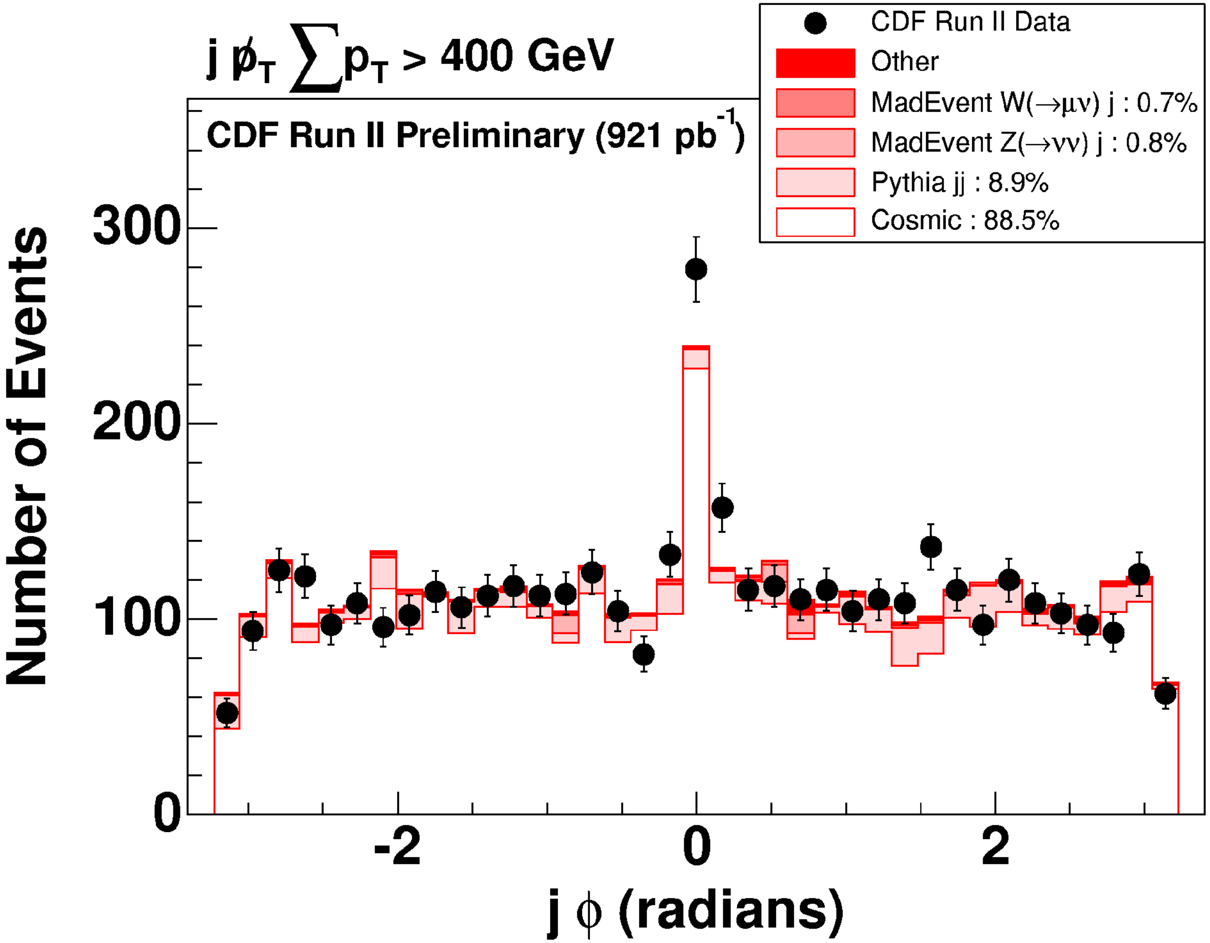


'Sophisticated' Variables: Top Quark Mass



Vista: Non-collision Background

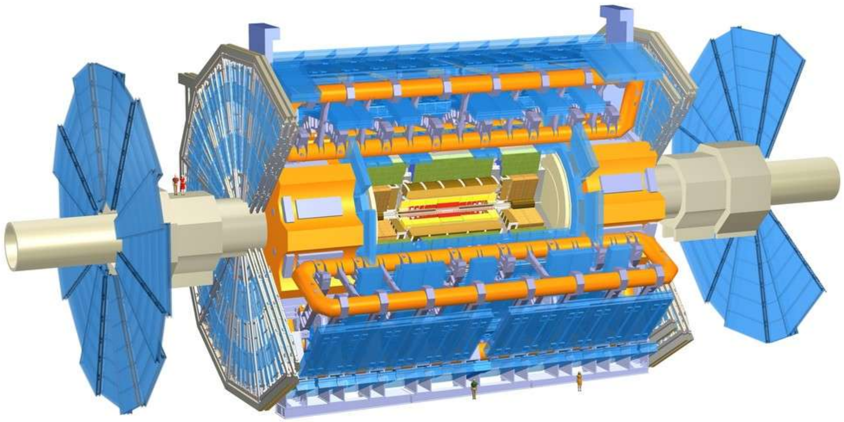




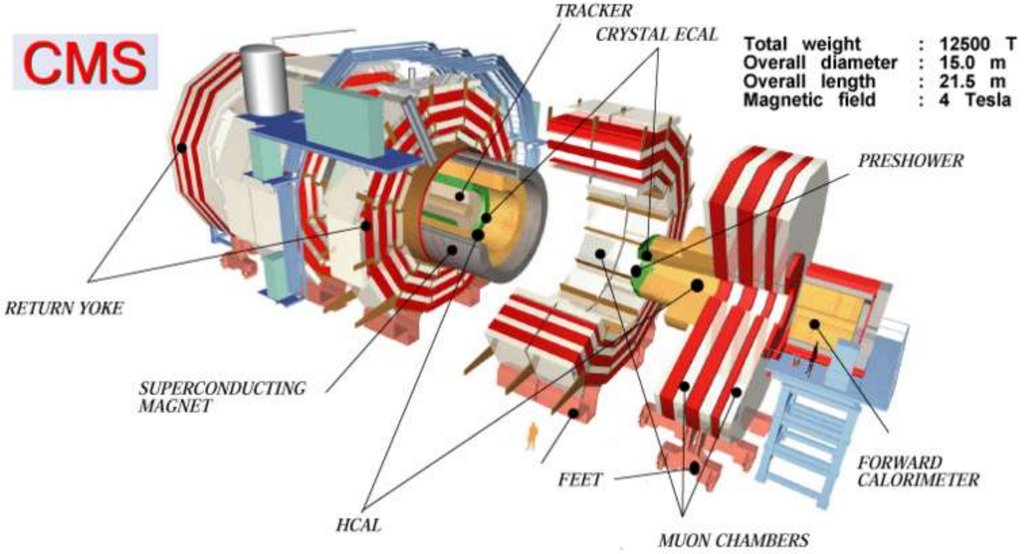
- Estimate non-collision background from events with no tracks
- Can describe flat cosmic ray contribution and beam halo spike at phi=0

Vista@LHC

- Vista proposed as commissioning tool for LHC experiments
- Global comparison to Standard Model predictions will validate essential detector understanding before claiming any discovery



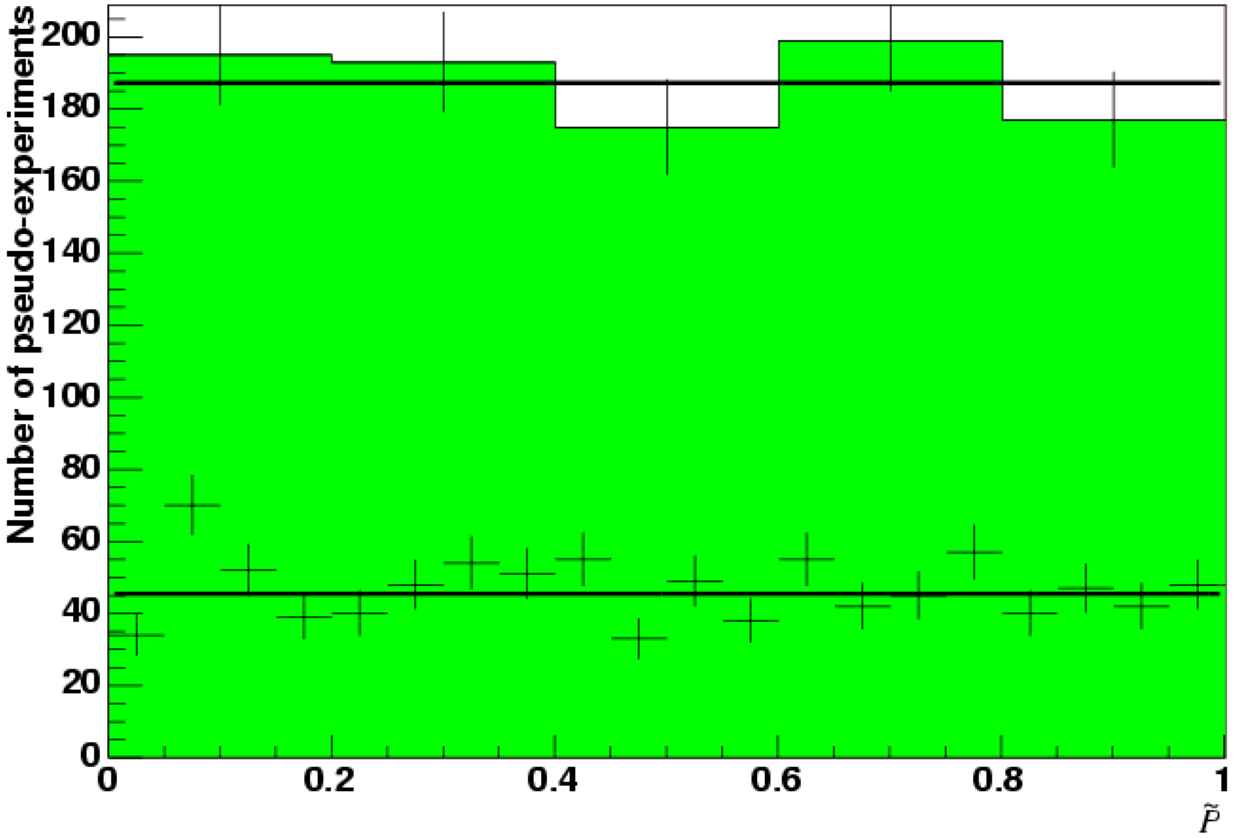
ATLAS



Sleuth Partition Rules

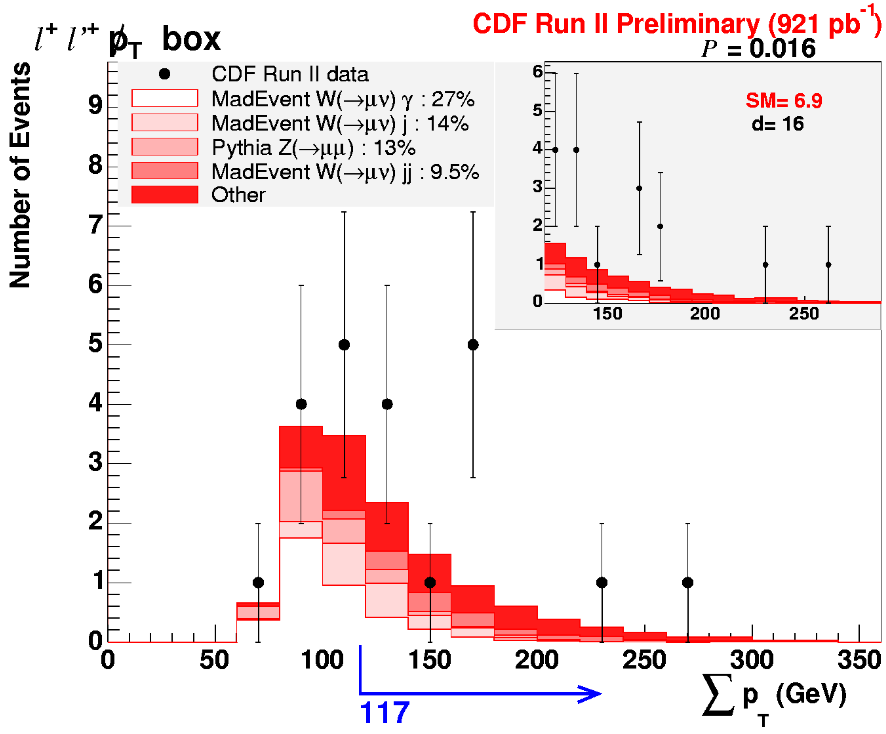
- Vista final states are merged in Sleuth to enhance signal/background
- Assumes that new physics will:
  - treat first 2 generations equivalently
  - be symmetric with respect to global charge conjugation
  - produce jets in pairs
  - conserve lepton flavour number

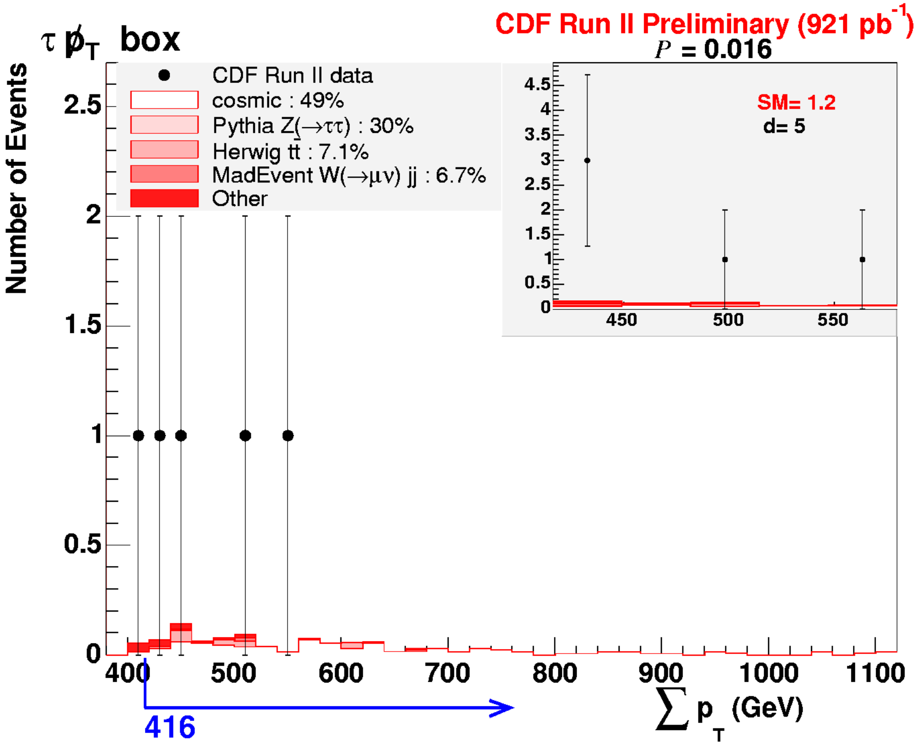
$\tilde{P}$ from Pseudo-Experiments



The expected distribution of $\tilde{P}$ from pseudo-experiments drawn from the SM implementation is uniform

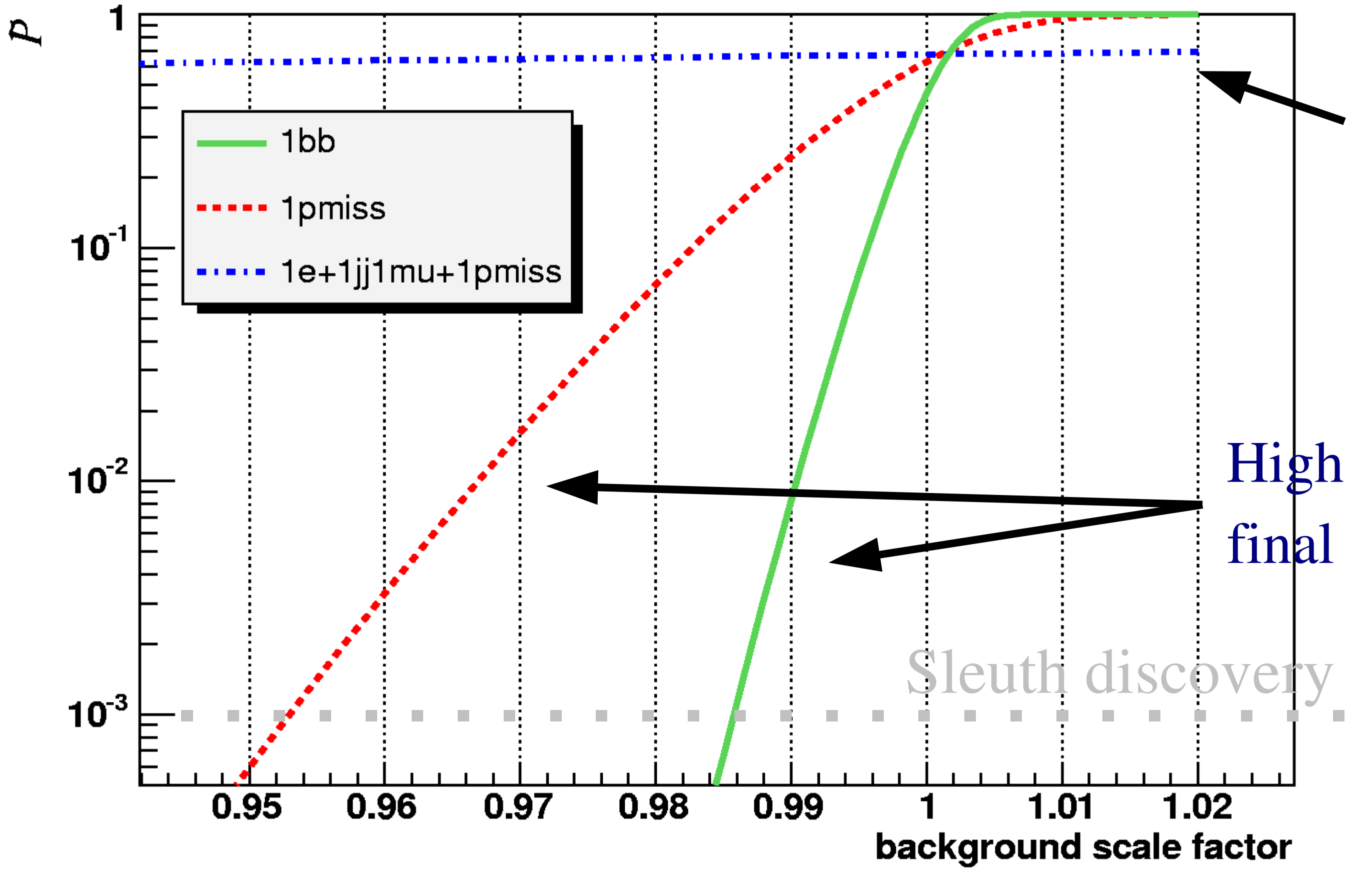
Sleuth's #4 and #5 Final States





Influence of Systematics on Result

- Effect of a normalization systematic uncertainty on $\tilde{P}$, for top 3 Sleuth final states:



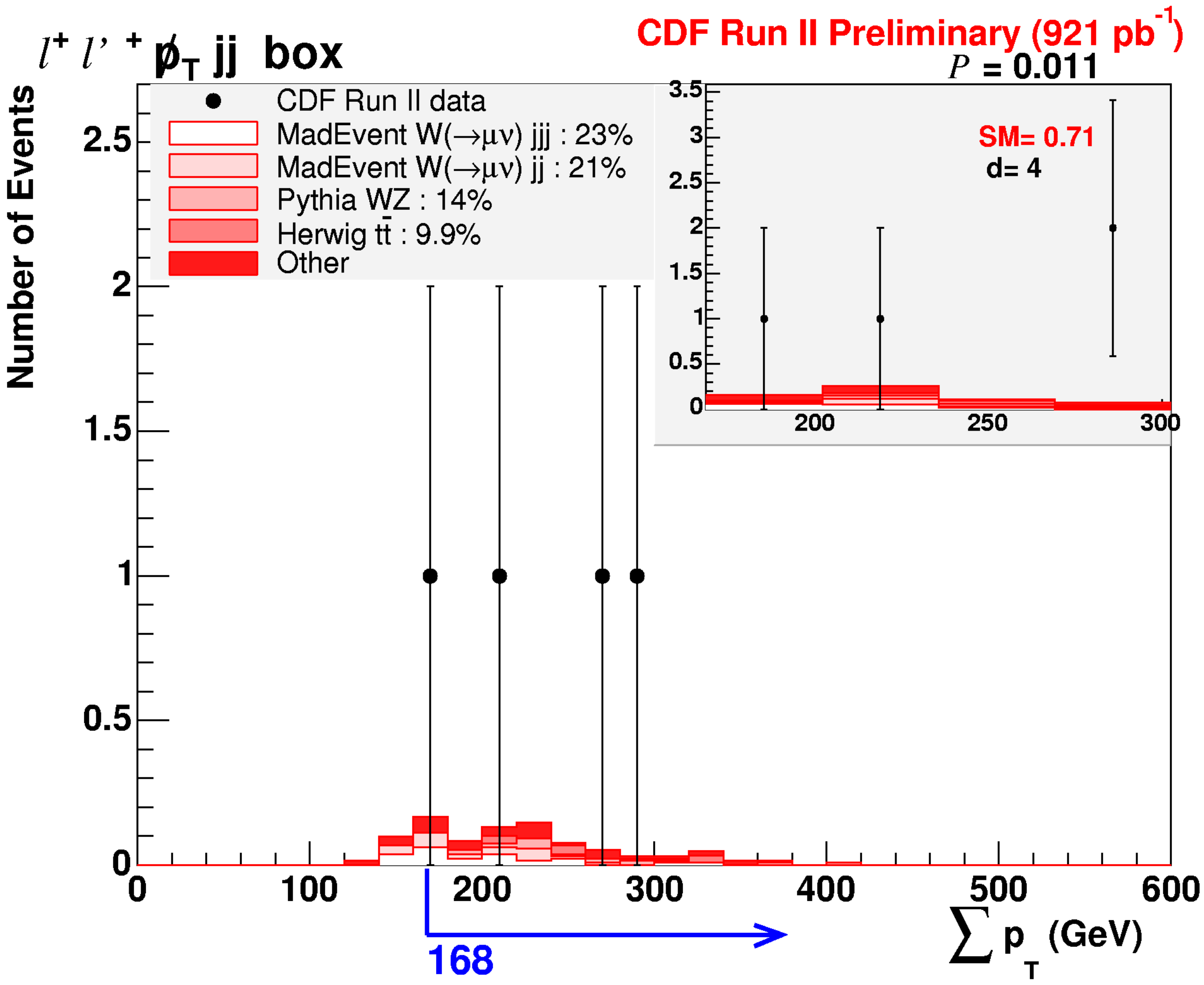
Low population final state

High population final states

Sleuth discovery threshold

- For low population final states, statistics dominate over syst. uncertainty

Estimation of Systematic Uncertainties



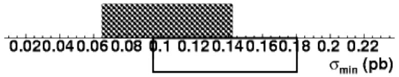
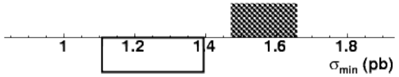
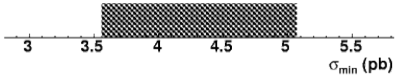
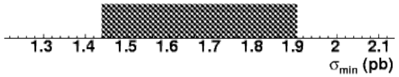
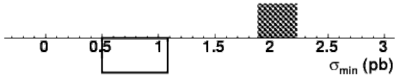
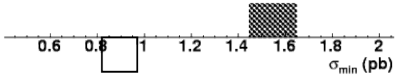
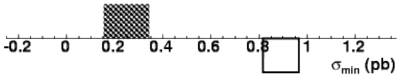
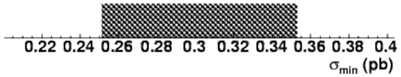
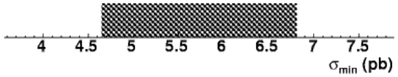
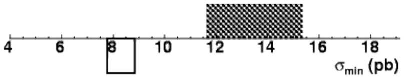
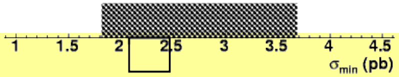
- Vista correction factors represent sources of systematic uncertainty
- Uncertainties in correction factor values obtained from Vista global fit
- For a particular final state, add in quadrature the appropriate contributions
- Estimate ~10% total systematic uncertainty on Sleuth backgrounds

Grey box – Sleuth sensitivity

White box - dedicated search

This is the cross-section required to produce a 5σ discovery

Syst. errors not considered for Sleuth or for the dedicated search

Name	Description	Sensitivity
Model 01	GMSB, $\Lambda = 82.6$ GeV, $\tan\beta = 15$, $\mu > 0$, 1 messenger of $M = 2\Lambda$	
Model 02	$Z'_{(250\ \mathrm{GeV}/c^2)} \to \ell\bar{\ell}$, with $\ell \neq \nu$	
Model 03	$Z'_{(700\ \mathrm{GeV}/c^2)} \to q\bar{q}$	
Model 04	$Z'_{(1\ \mathrm{TeV}/c^2)} \to q\bar{q}$	
Model 05	mSUGRA, $M_0 = 100$ GeV, $M_{1/2} = 180$ GeV, $A_0 = 0$, $\tan\beta = 5$, $\mu > 0$	
Model 06	mSUGRA, $M_0 = 284$ GeV, $M_{1/2} = 100$ GeV, $A_0 = 0$, $\tan\beta = 5$, $\mu < 0$	
Model 07	mSUGRA, $M_0 = 300$ GeV, $M_{1/2} = 200$ GeV, $A_0 = 0$, $\tan\beta = 5$, $\mu < 0$	
Model 08	Standard Model $t\bar{t}$, with $t\bar{t}$ removed from background. Would need ~ 40 pb^{-1} to see.	
Model 09	Standard Model WW, with WW removed from background. Would need ~ 400 pb^{-1} to see.	
Model 10	MSSM $A \to \tau\tau$, $M_A = 160$ GeV, $\tan\beta = 5$	
Model 11	$Z'_{(500\ \mathrm{GeV}/c^2)} \to t\bar{t}$	

Potential Analysis Improvements

- Incorporate more CDF data (x2)
- Combine with similar D0 effort (x2)

- Minor improvements (x1.1):
  - more sophisticated object identification
  - more expansive offline triggers

Sleuth Publications

Sleuth previously used in searches at D0 and H1:

D0, Phys. Rev. Lett. 86, 3712 (2001)
D0, Phys. Rev. D 62, 092004 (2000)
D0, Phys. Rev. D 64, 012004 (2001)
H1, Phys. Lett. B 602, 14 (2004)