How well do we understand the Standard Model?

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The State of the Standard Model

Particle content is known or inferred (*)

Parameters of $\mathcal{L}_{\text{int}}$ measured with some precision (**)

No sufficiently significant discrepancies between its predictions and data

It seems to work very well ... how well?

(*) Higgs boson? $\hat{M}_H = 76^{+33}_{-24}\,GeV$
(**) Neutrino masses?

What is a Quantitative Measure?

Tells us how to view “discrepancies”

Directs theory/expt'l research

A benchmark for comparing to other fields

I will spend the rest of the talk:

Explaining a framework to answer this question

Showing the result

Explaining the THEORY behind it

The Framework

Define high-p_T objects reconstructed in experiment ("electron", "photon", "jet")

Generate a cocktail of Monte Carlo events and define same objects

Introduce a correction model (fakes, K-factors, uncertainties) and refine

Compare counts and shapes in different final states

Event Selection

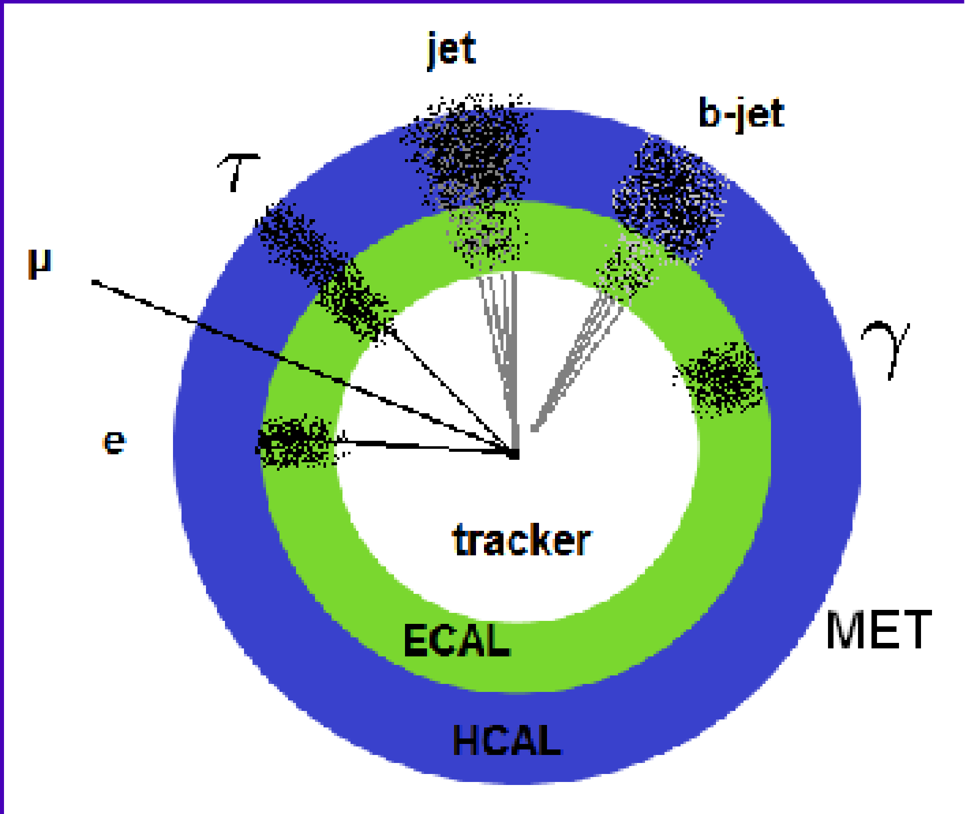
Objects identified:

- e, μ, τ, jet, b–jet, γ, Missing E_T

Consider **objects** of $p_T > 17$ GeV

Select **events** with any of the following:

- e, $p_T > 25$ GeV
- μ, $p_T > 25$ GeV
- γ, $p_T > 60$ GeV
- jet, $p_T > 40$ GeV or 200 GeV
- additional di–object triggers



Final State: 1a 1b 1pmiss

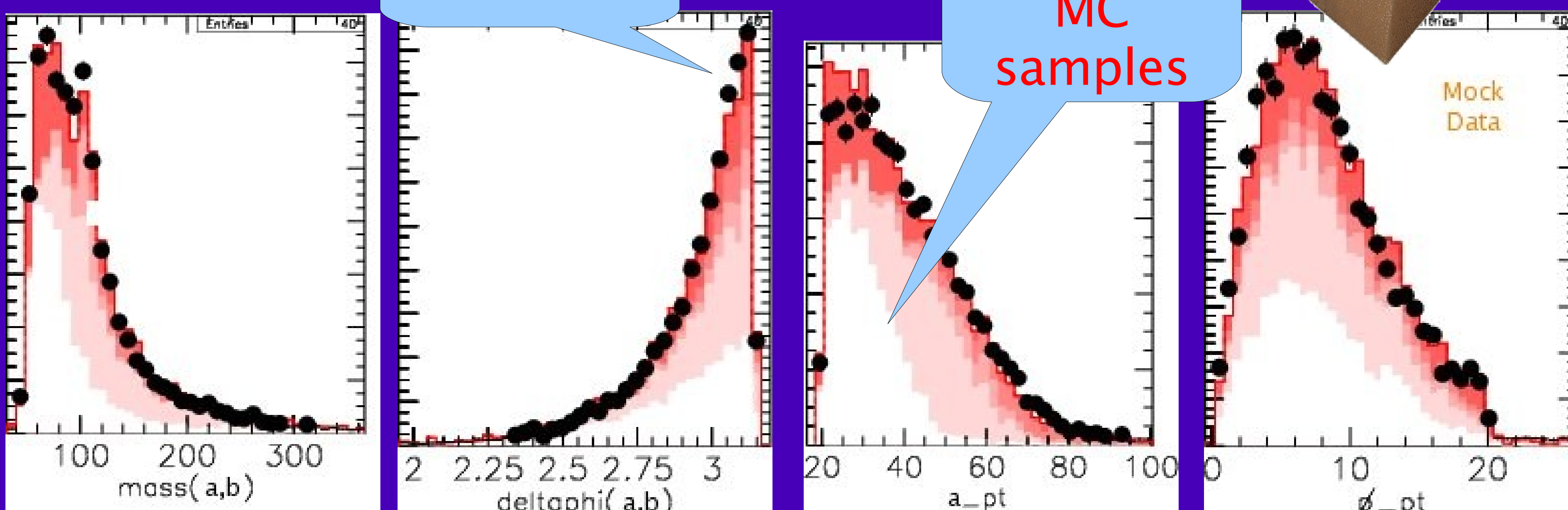
1 high-P_T object "a"+ any number low-P_T

1 high-P_T object "b"+ any number low-P_T

Significant missing $-P_T$

DATA

(Stacked) MC samples



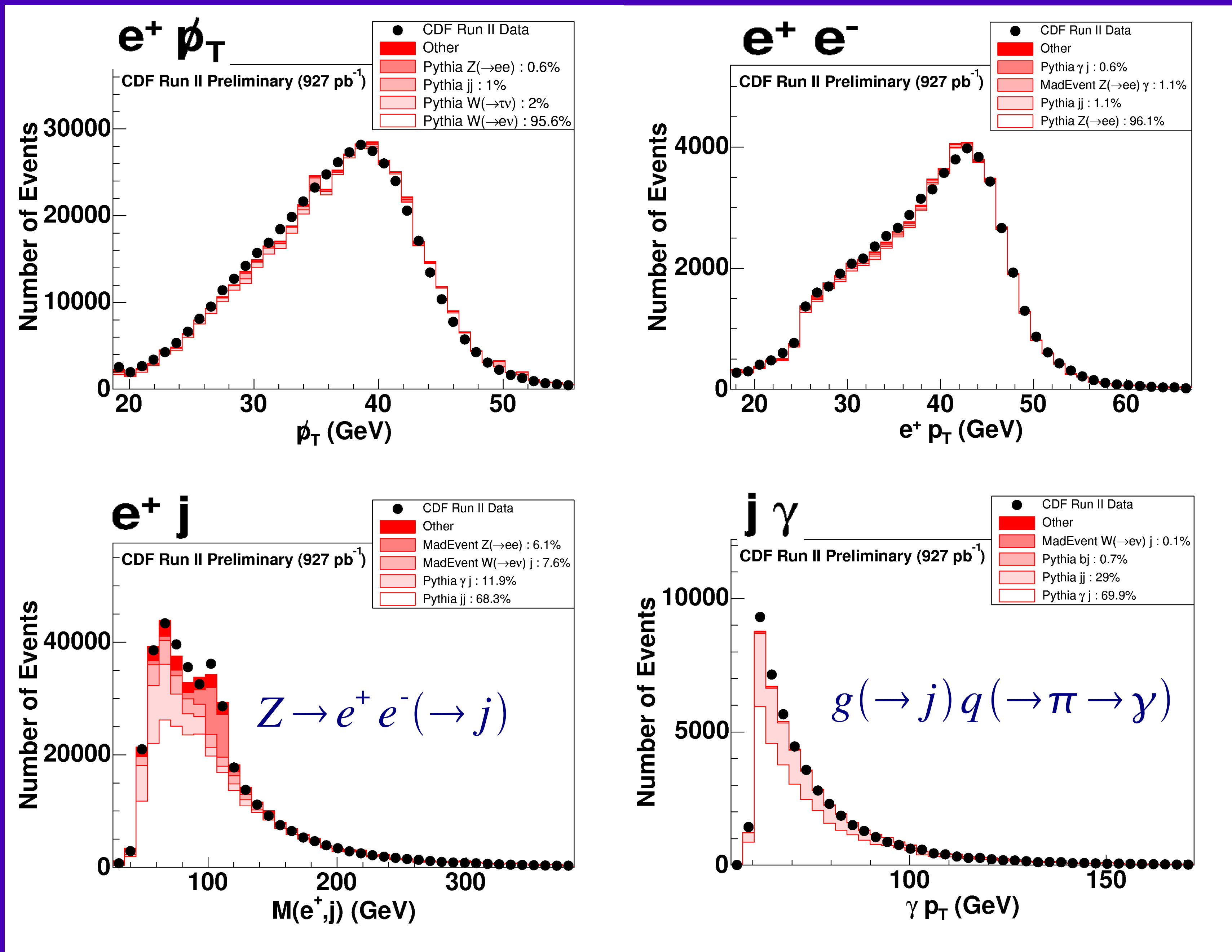
Vista global analysis

ArXiv:0712.1311 CDF+...SM

Choudalakis, Culbertson, Henderson, Knuteson, Xie

... plus the efforts of the
rest of the collaboration

Example Distributions



344 final states: a lot of information

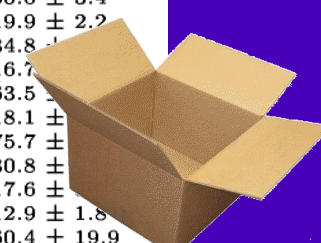
Final State	Data	Background
3jτ+	71	113.7 ± 3.6
5j	1661	1902.9 ± 50.8
2jτ+	233	296.5 ± 5.6
be+j	2207	2015.4 ± 28.7
3j $\Sigma p_T < 400$ GeV	35436	37294.6 ± 524.3
e+3j$\not{p}$	1954	1751.6 ± 42
be+2j	798	695.3 ± 13.3
3j$\not{p}$ $\Sigma p_T > 400$ GeV	811	967.5 ± 38.4
e+μ+	26	11.6 ± 1.5
e+γ	636	551.2 ± 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 $\Sigma p_T <$ [illegible]00 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	[illegible]5	40898.8 ± 649.2
4j $\Sigma p_T < 400$ GeV	[illegible]	[illegible]8403.7 ± 144.7
4j2γ	[illegible]	[illegible]57.5 ± 11
4jτ+	2[illegible]	[illegible]9 ± 2.4
4j$\not{p}$ $\Sigma p_T > 400$ GeV	516	[illegible] ± 34.5
4j$\gamma\not{p}$	28	[illegible]1
4jγ	3693	382[illegible]1
4jμ+	576	568.[illegible]
4jμ+$\not{p}$	232	224.7 [illegible]
4jμ+μ-	17	20.1 ± [illegible]
3γ	13	24.2 ± 3[illegible]
3j $\Sigma p_T > 400$ GeV	75894	75939.2 ± 104[illegible]
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[illegible]
3jμ+$\not{p}$	1114	1118.7 ± 27[illegible]
3jμ+μ-	61	84.5 ± 9.[illegible]
3jμ+	2132	2168.7 ± 64[illegible]
3bj $\Sigma p_T > 400$ GeV	14	9.3 ± 1.[illegible]
2τ+	316	290.8 ± 24[illegible]
2$\gamma\not{p}$	161	176 ± 9.[illegible]
2γ	8482	8349.1 ± 84.[illegible]
2j $\Sigma p_T > 400$ GeV	93408	92789.5 ± 113[illegible]
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

Final State	Data	Background
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
[illegible]2$\gamma\not{p}$	[illegible]	27.3 ± 3.2
[illegible]	[illegible]	[illegible]85.7 ± 10.2
[illegible]	[illegible]	[illegible] ± 56.1
[illegible]	[illegible]	[illegible]546.3
[illegible]	[illegible]	[illegible]1
[illegible]	[illegible]	[illegible]5
[illegible]	[illegible]	[illegible]672.6
[illegible]	[illegible]	[illegible] 3.9
e+[illegible]	[illegible]	[illegible] ± 2.3
e+2j$\not{p}$	[illegible]	[illegible]130.1 ± 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

Final State	Data	Background
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	[illegible]2614 ± 5031.8
e+j2γ	14	[illegible]5.9 ± 2.9
e+jτ+	79	[illegible]9.3 ± 2.9
e+jτ-	162	[illegible]8 ± 7.6
e+j$\not{p}$	58648	573[illegible]7 ± 661.6
e+j$\gamma\not{p}$	52	[illegible] ± 9
e+jμ-$\not{p}$	22	[illegible] ± 1.7
e+jμ-	28	2[illegible] 2.3
e+e-4j	103	11[illegible]5.9
e+e-3j	456	4[illegible]4.6
e+e-2j$\not{p}$	30	[illegible]6
e+e-2j	2149	215[illegible]
e+e-τ+	14	[illegible]
e+e-$\not{p}$	491	[illegible]
e+e-γ	127[illegible]	[illegible]
e+e-j	107[illegible]	[illegible]
e+e-j$\not{p}$	[illegible]	[illegible]
e+e-jγ	[illegible]	[illegible]
e+e-	58[illegible]	[illegible]
b6j	[illegible]	[illegible]
b4j $\Sigma p_T > 400$ GeV	[illegible]	[illegible]
b4j $\Sigma p_T < 400$ GeV	4[illegible]	[illegible]
b3j $\Sigma p_T > 400$ GeV	535[illegible]	[illegible]
b3j $\Sigma p_T < 400$ GeV	1639[illegible]	[illegible]
b3j$\not{p}$ $\Sigma p_T > 400$ GeV	111	[illegible]
b3jγ	182	1[illegible]
b3jμ+$\not{p}$	37	34.1 ± [illegible]
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 [illegible]
b$\gamma\not{p}$	18	16.7[illegible]
bμ+	303	263.5 [illegible]
bμ+$\not{p}$	204	218.1 ± [illegible]
bj $\Sigma p_T > 400$ GeV	9060	9275.7 ± [illegible]
bj $\Sigma p_T < 400$ GeV	7236	7030.8 ± [illegible]
bj2γ	13	17.6 ± [illegible]
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

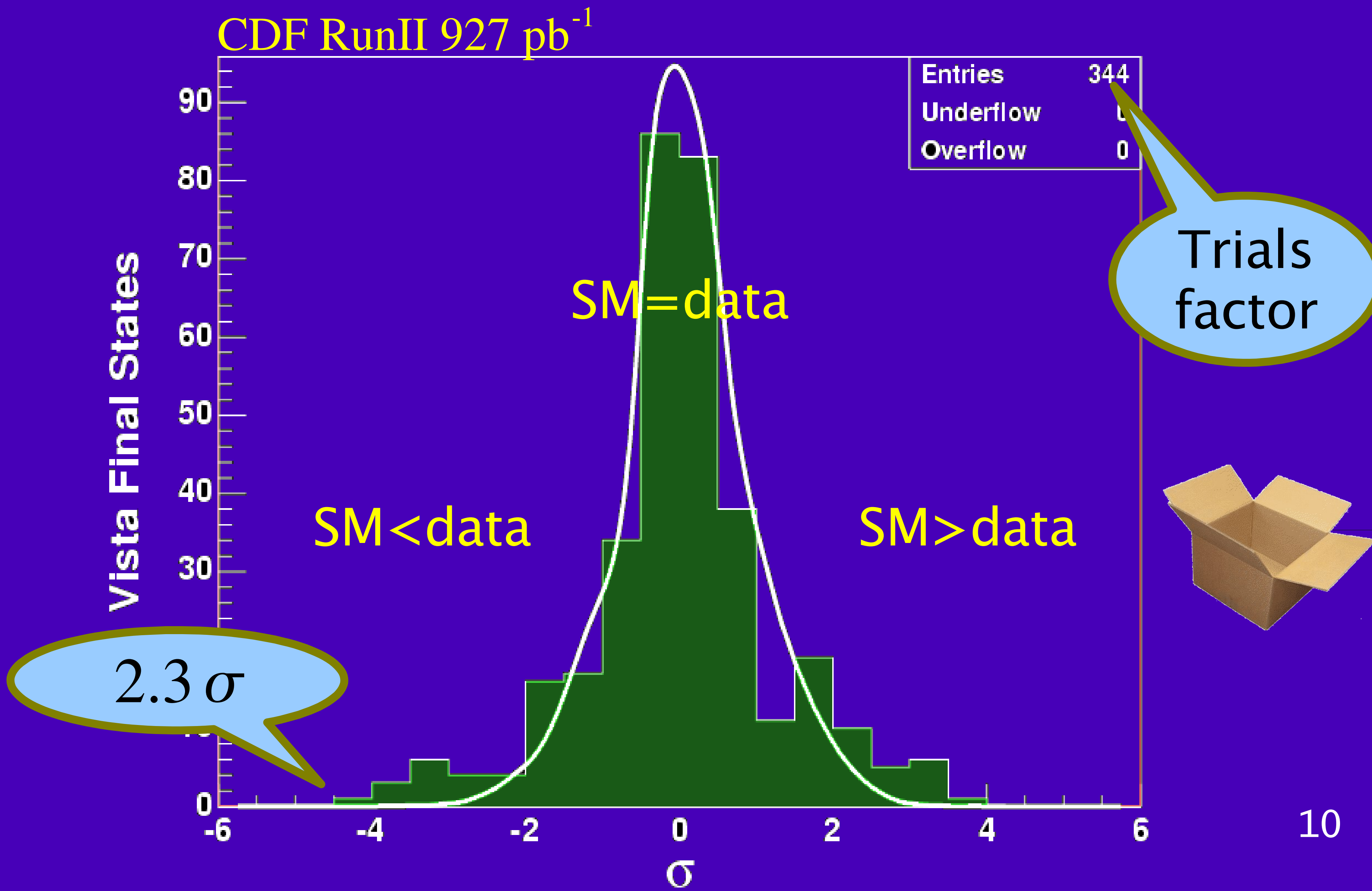
Final states defined by data

>10 events



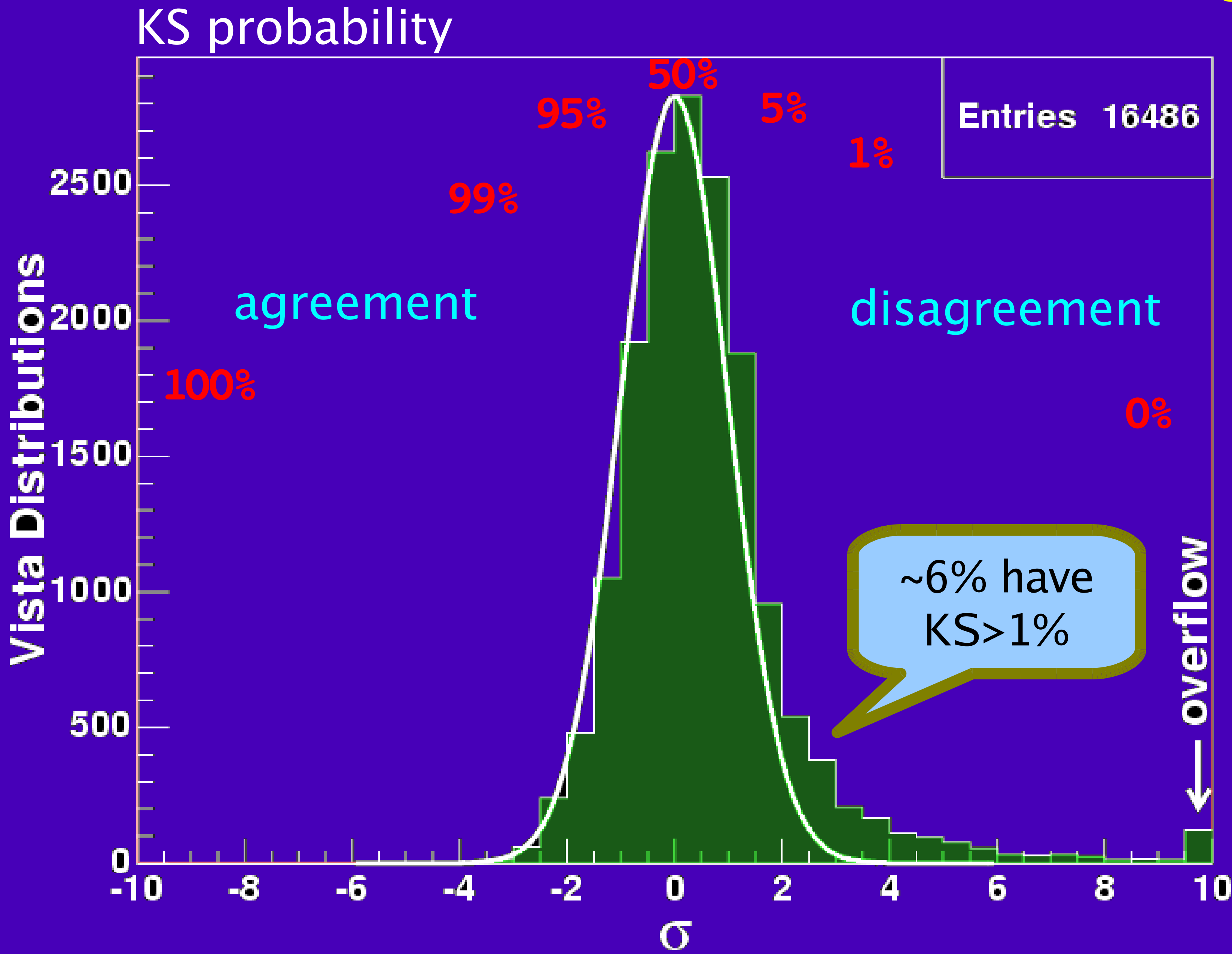
ArXiv:0712.1311 CDF

Vista final state normalizations



Vista kinematic shapes

$$\frac{1}{\sigma}\frac{d\sigma}{dX}$$



Quantitative Results

Event counts are distributed as you expect when you look at 344 final states

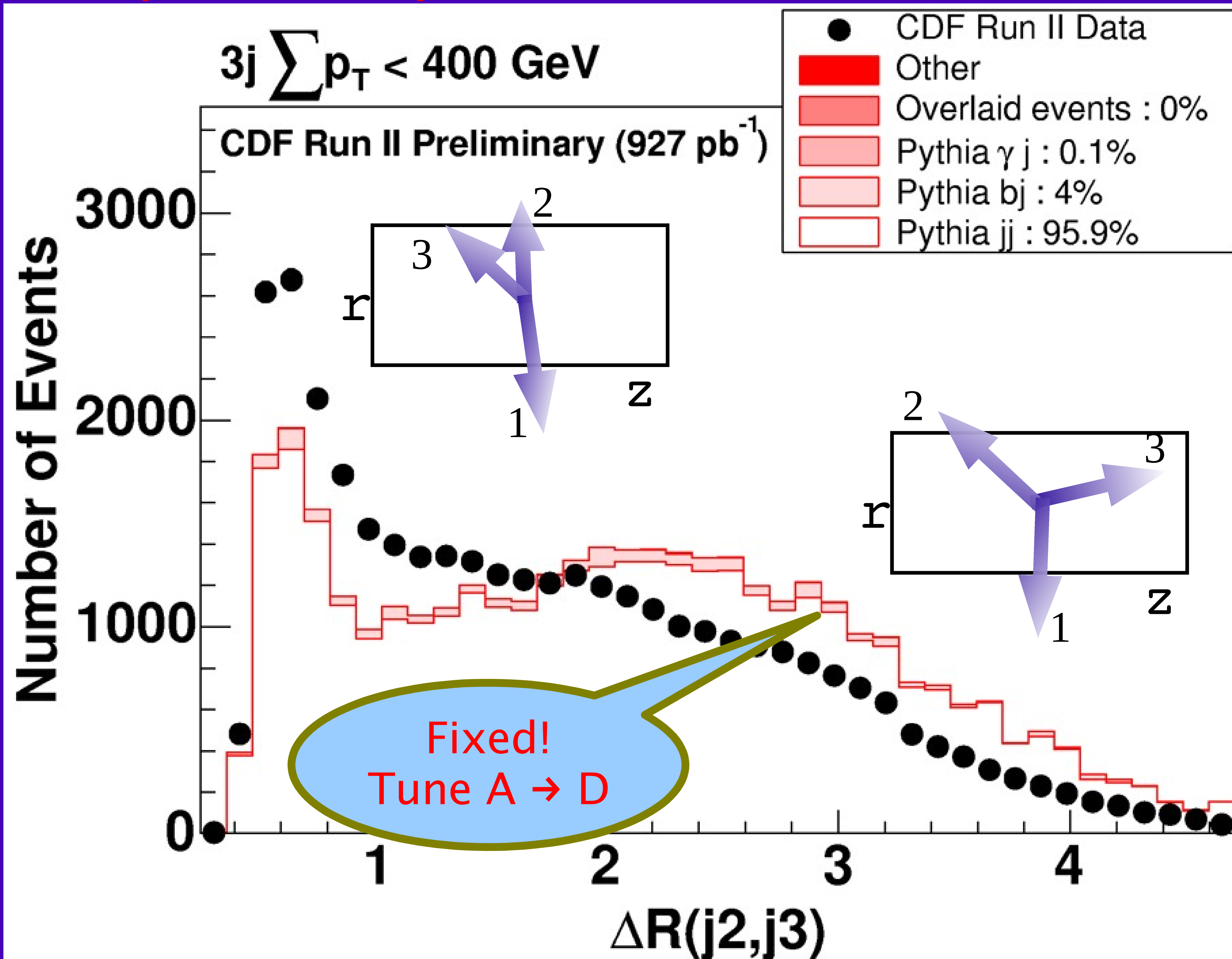
Largest discrepancy is a 2.3sigma deficit

Several % of all distributions disagree at the 1% level or higher

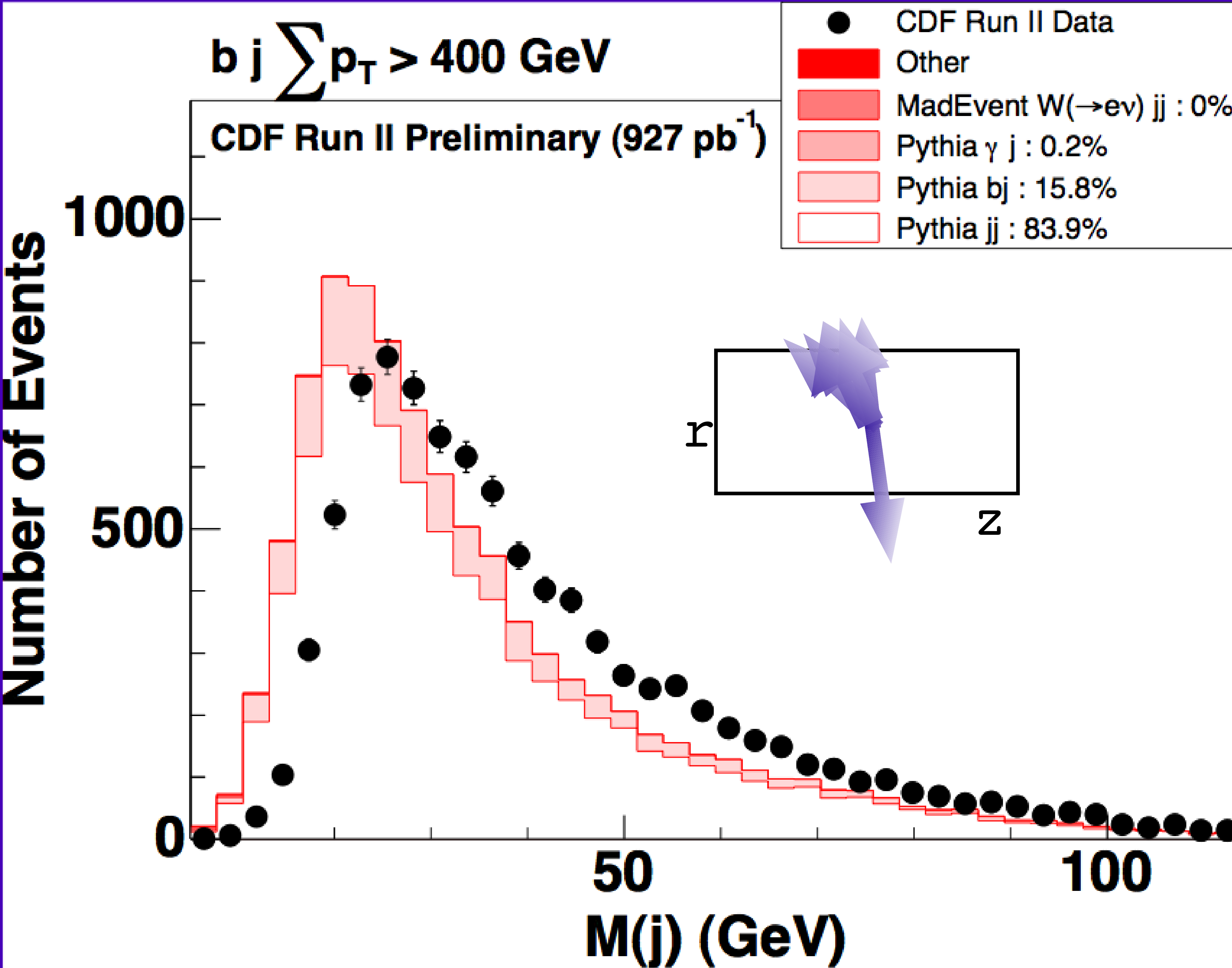
expect there is some systematic in event generators (at LEP, defined as 1%)

about 6% of distributions have KS>1%, but there are many commonalities

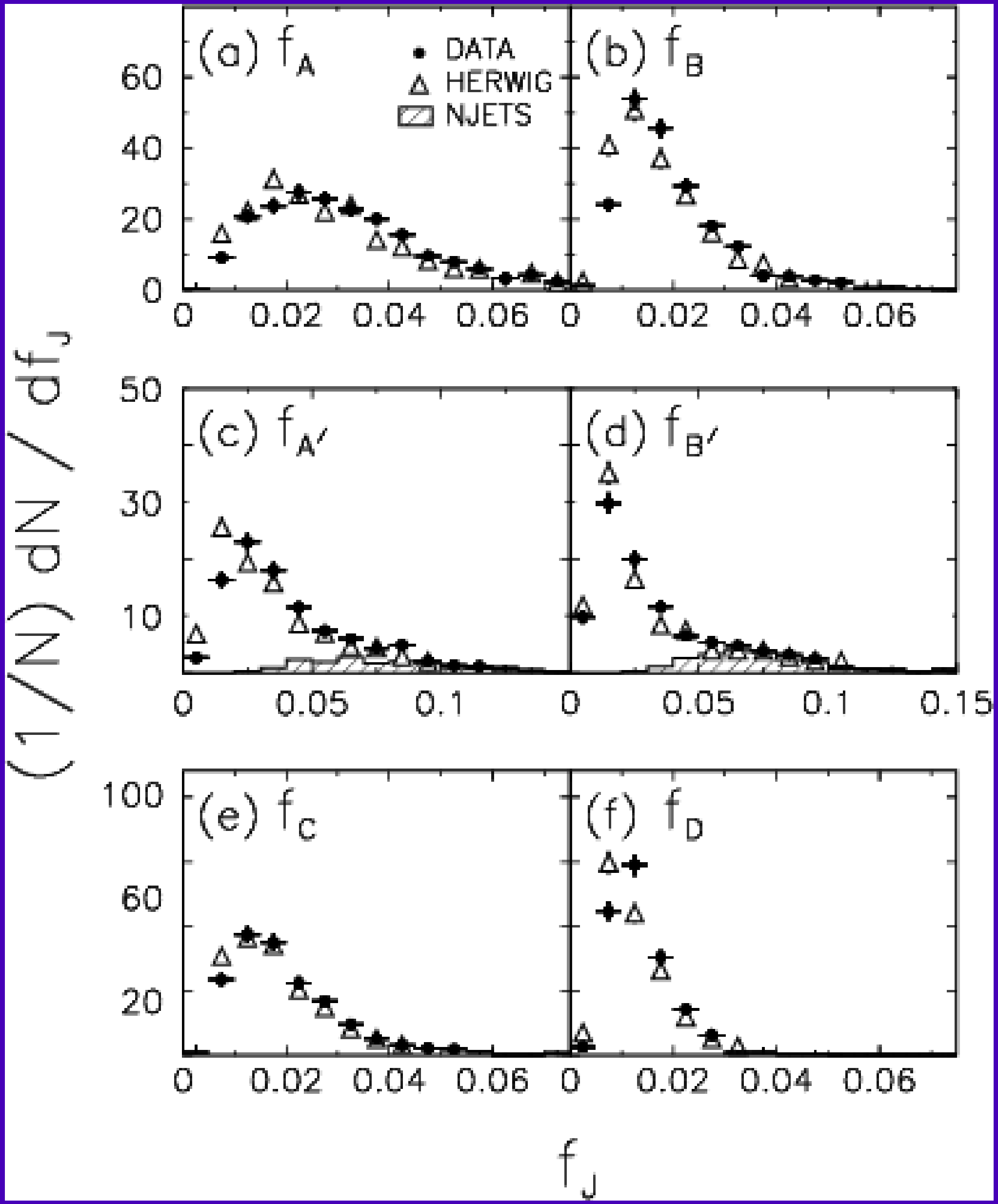
Sample discrepant distribution (parton showering?)

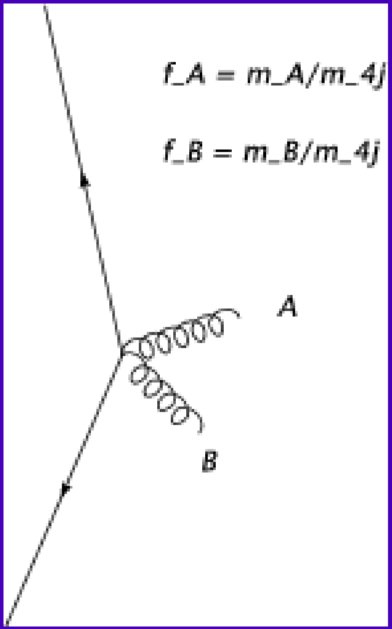


Related discrepant distribution



S. Geer (CDF–Run I)





Dissecting the SM cocktail

Much of the Monte Carlo is default Pythia(Herwig) (simple processes + parton showers)

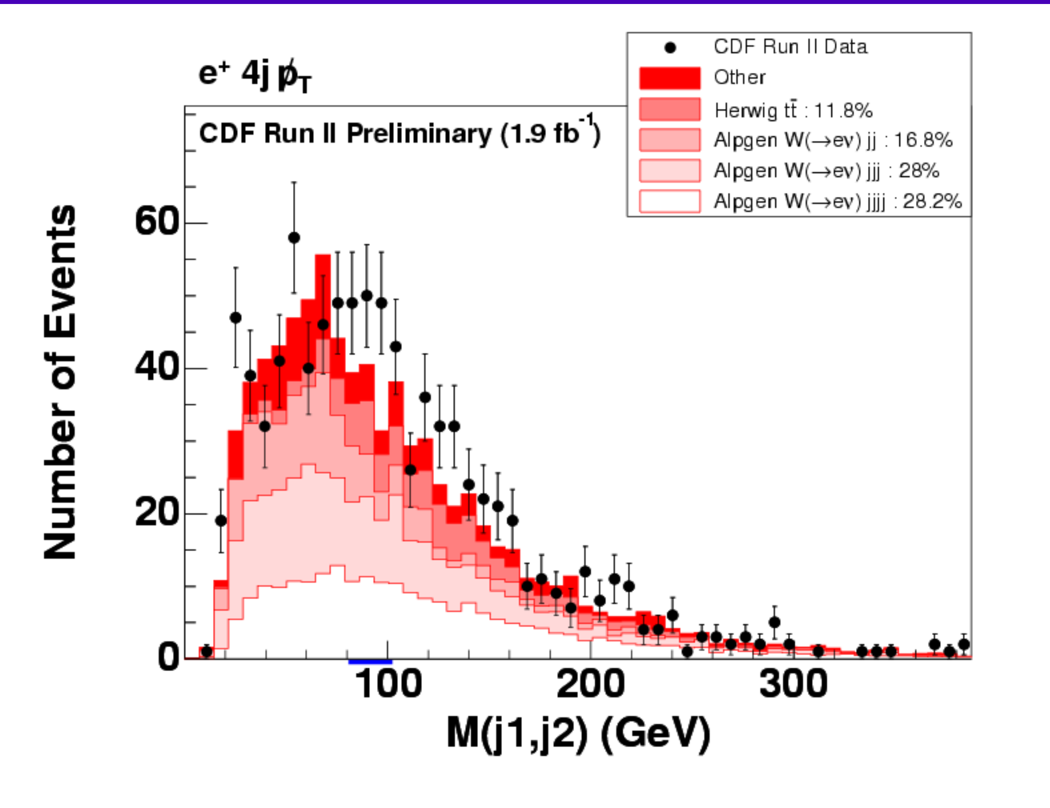
Some processes like W/Z/γ+jets combine Matrix Elements with parton showers

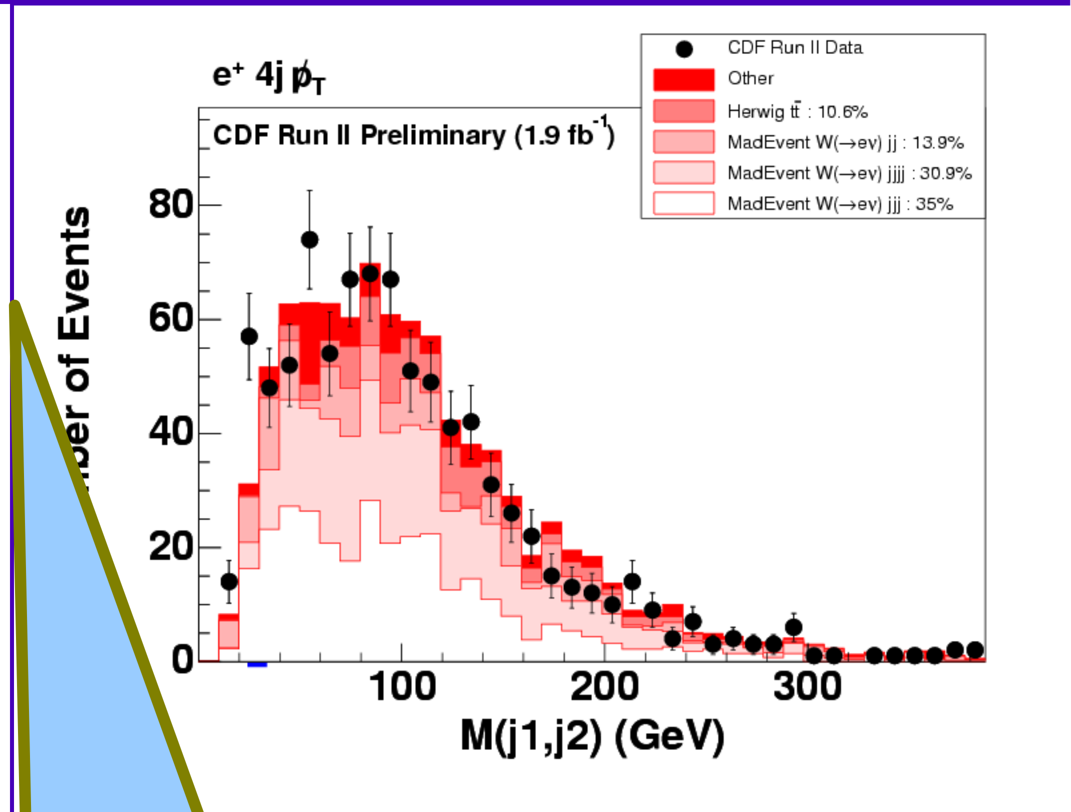
Such calculations are necessary for TeV & LHC

We can remix our cocktail with different implementations of the Standard Model theory

Goodness of fit unchanged

MLM matching | SM matching





		Alpgen	SM
k-factor	W0j	1.379	1.452
k-factor	W1j	1.329	1.20
k-factor	W2j	2.007	1.23
k-factor	W3j	2.109	1.18

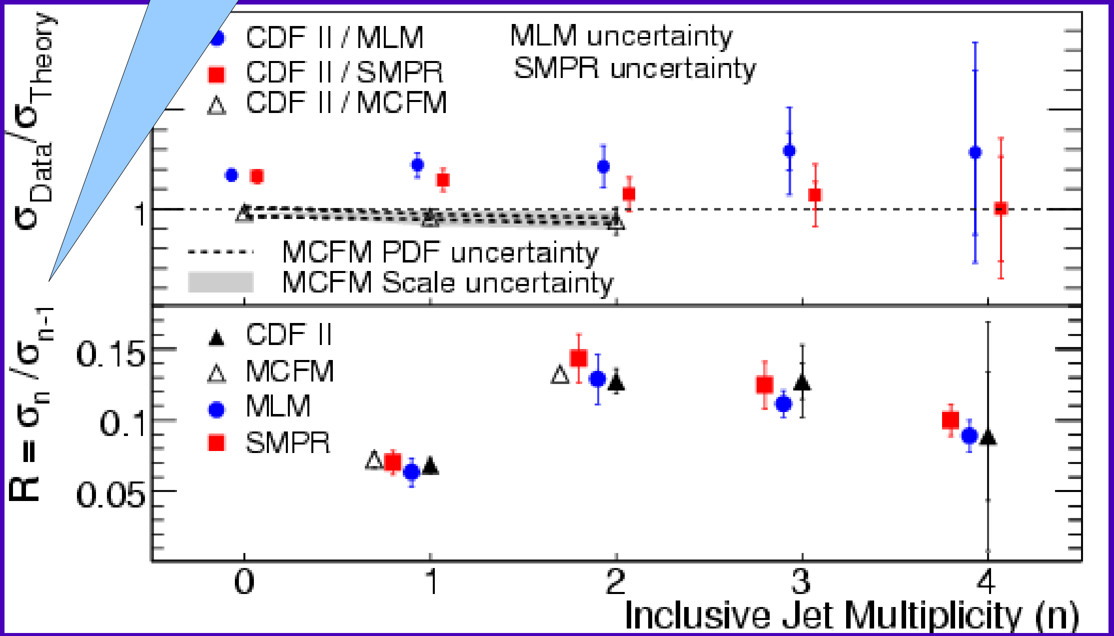
ArXiv:0711.4044 CDF...(SM)

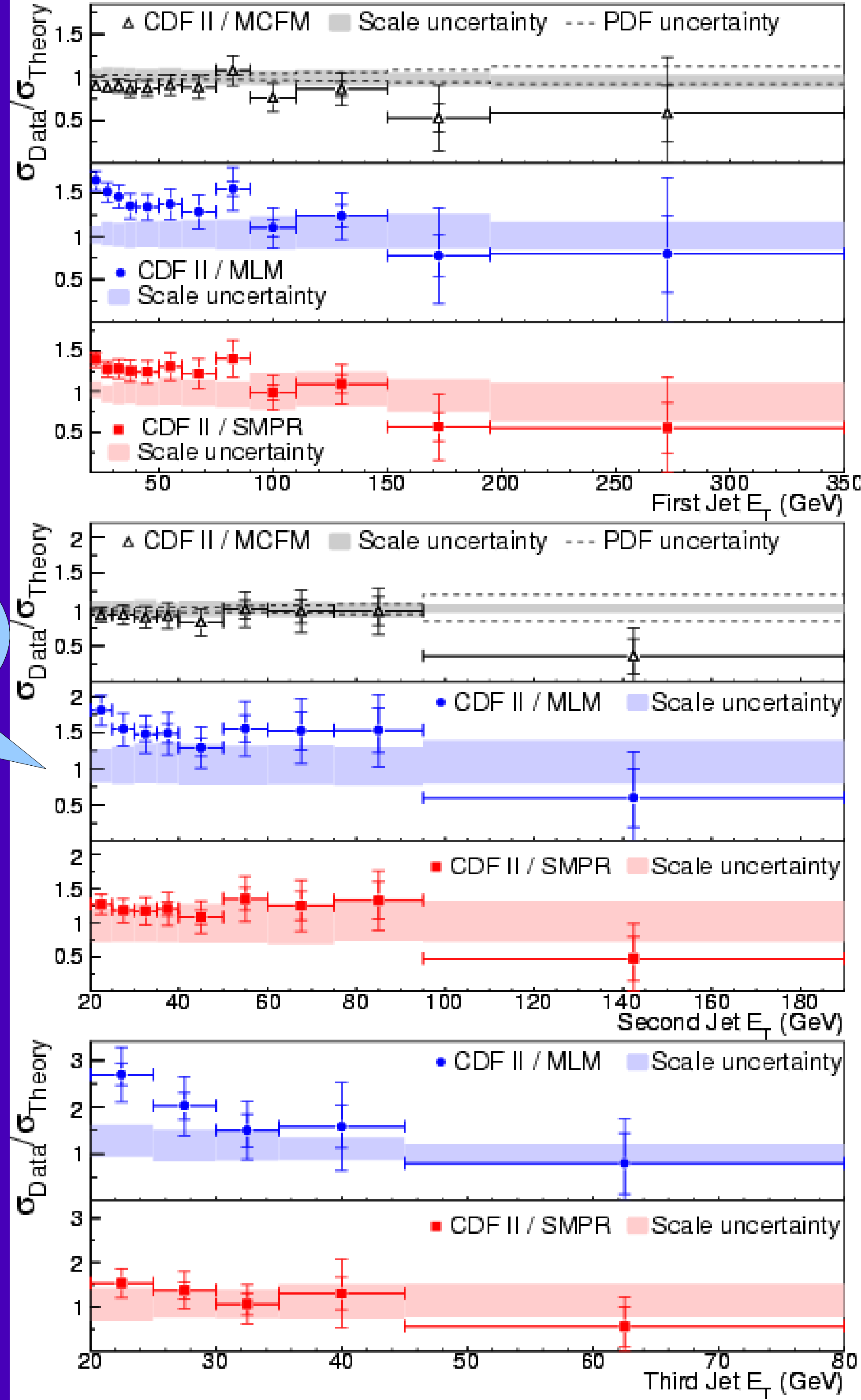
Traditional Analysis

Data corrected (unfolded) back to the particles (this it the output of Pythia)

Comparison of relative event counts

Comparison of relative shapes





"... All distributions show good agreement with the data ..."

Traditional

		Alpgen	SM
k-factor	W0j	1.35	1.35
k-factor	W1j	1.43	1.27
k-factor	W2j	1.42	1.12
k-factor	W3j	1.55	1.11
k-factor	W4j	1.54	0.98

Purer final states

Vista

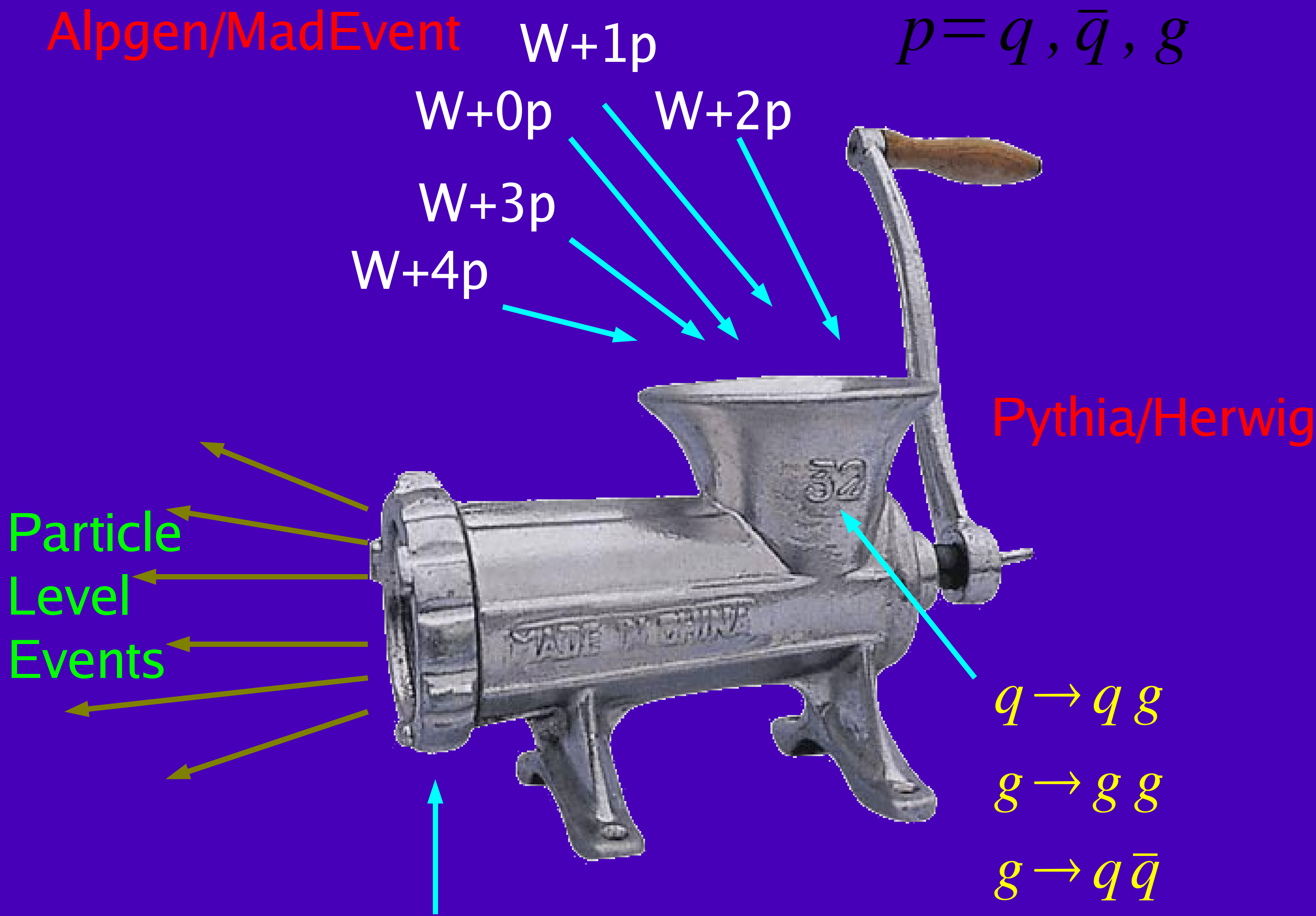
		Alpgen	SM
k-factor	W0j	1.379	1.452
k-factor	W1j	1.329	1.20
k-factor	W2j	2.007	1.23
k-factor	W3j	2.109	1.18

Different cuts

We made sausage

The sausage tastes good

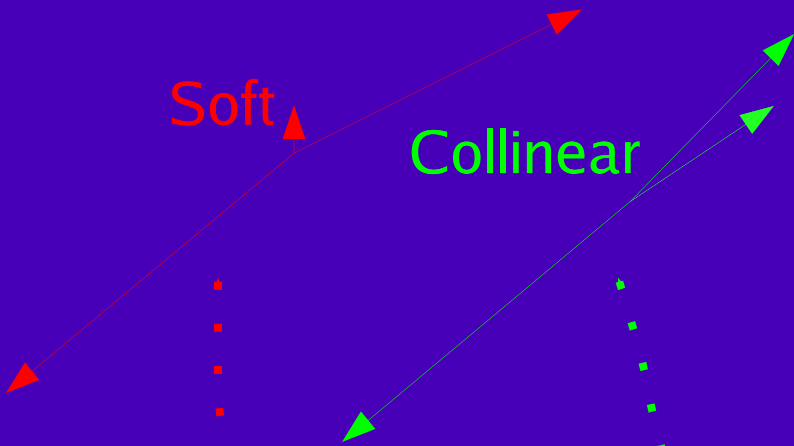
What's inside?



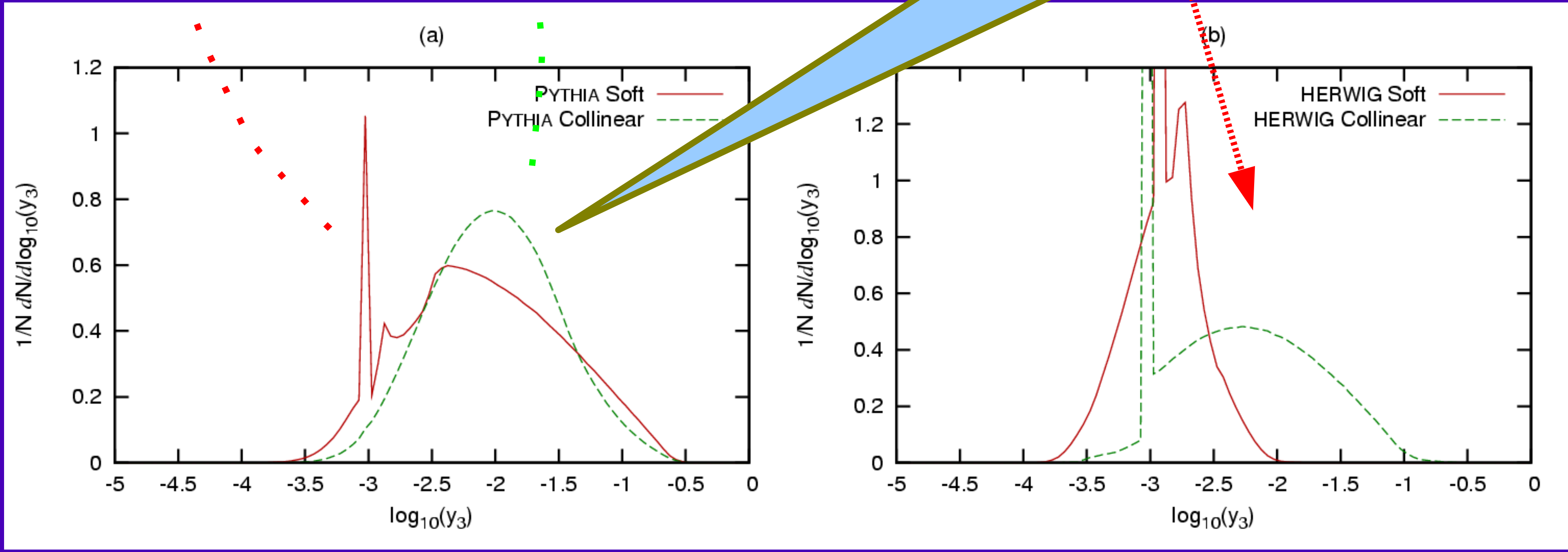
$$W + 4\mathrm{p} \to W + 4\mathrm{j} + \text{softer stuff}$$

arXiv:0712.2966

Study of MLM Method + ...



Parton showers can be sensitive to cuts in the ME calculation



"Soft" or "Collinear" can change in this method

Caveats

This study focused on FSR not ISR $e^+ e^- \rightarrow q\,\bar{q}(g)$

The flaws in the matched methods are known
(it is much better than what we used to do)

Other showers (p_T-ordered Pythia, Ariadne, di-pole) may allow for a cleaner interface, but they are not TUNED/VALIDATED to the same level

In the end, it doesn't seem to matter much in comparisons with RunII data

Possible LHC Outcomes

Something so striking
you can't miss it

$$Z^{'} \rightarrow \mu^{+} \mu^{-}$$

$$BH \rightarrow 100 \text{ Z/W/t/h}$$

~100 GeV-1 TeV particles
with cascade decays

New exotica
(quirks, hidden valley,...)

$$h \rightarrow b\bar{b}b\bar{b}b\bar{b}b\bar{b}$$

Nothing

Consequences

Easy Use sideband data as your "Monte Carlo" (probably something else to complete the picture)	**Challenging** (Your signal = My Control)
More Challenging Requires detailed understanding of SM (and detector) tails	**Most Challenging** When do you give up?

Conclusions

We are prepared for the challenging case. We can improve our current tools with manpower and some mindpower

In CDF RunII data, a global test of our tools works very well in estimating counts, less so in kinematic distributions (about 6% have KS>1%)

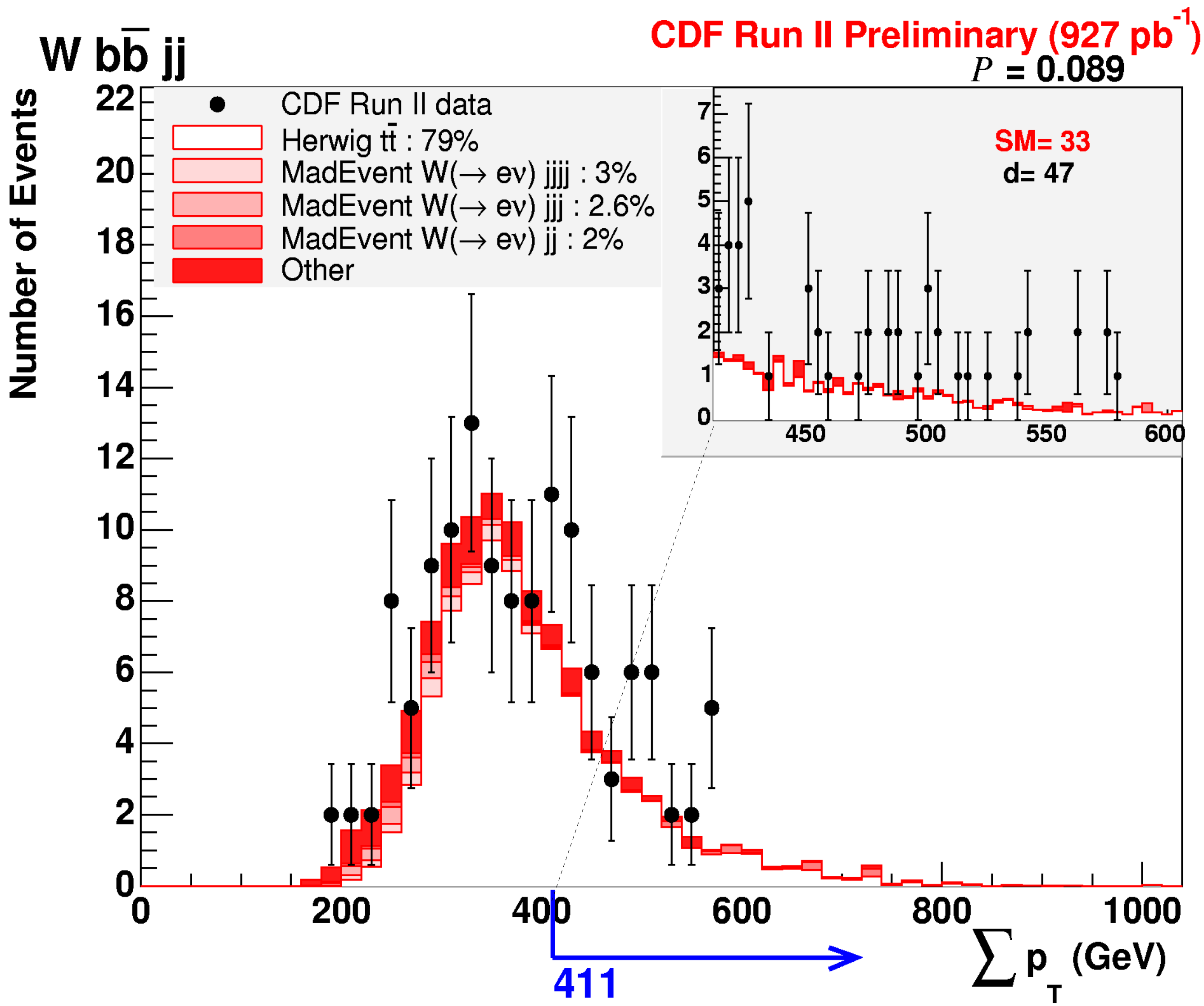
Distribution problems are likely a deficiency of parton shower programs (all?) and appear at low scales (low m_j and low end of P_T)

Back-ups

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	$1\gamma1$j photon+jet(s)	0.9492	0.04	4.2
5122	k-factor	$1\gamma2$j	1.205	0.05	4.1
5123	k-factor	$1\gamma3$j	1.483	0.07	4.7
5124	k-factor	$1\gamma4$j+	1.968	0.16	8.1
5130	k-factor	$2\gamma0$j diphoton(+jets)	1.809	0.08	4.4
5131	k-factor	$2\gamma1$j	3.417	0.24	7.0
5132	k-factor	$2\gamma2$j+	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

What Sleuth Does

- Select the most interesting region *in each final state*
- Perform pseudo-experiments to assess the significance → *P*



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
- In 1 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

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

(>> 0.001)

Sleuth's Top 5 Most Discrepant Final States:

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