Les recherches de nouvelles particules au LHC : quel rôle pour la QCD ?

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École Polytechnique, Palaiseau
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Avec des exemples tirés de travaux avec Butterworth, Davison & Rubin
et Cacciari, Rojo & Soyez

An often-repeated argument

LHC collides quarks and gluons

Quarks and gluons interact strongly $\longrightarrow$ huge QCD backgrounds

Therefore we will need to rely on our understanding of QCD in order to make discoveries at LHC.

True, false, or only half the story?

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Contrasting views (1)

It must be true, otherwise why would there be such a large effort devoted to LHC-QCD calculations?

- Parton shower Monte Carlo Generators — Pythia, Herwig, Sherpa
- LO tree-level calculations — Alpgen, Madgraph, Sherpa, ...
- NLO calculations — $\sim$ 50 people
- NNLO calculations — Higgs, W/Z, next step jets
- All-orders calculations — resummations, SCET
- Parton Distribution Functions (PDFs) — CTEQ, MSTW, NNPDF, ...

Contrasting views (2)

Healthy scepticism

[...] unless each of the background components can be separately tested and validated, it will not be possible to draw conclusions from the mere comparison of data against the theory predictions.

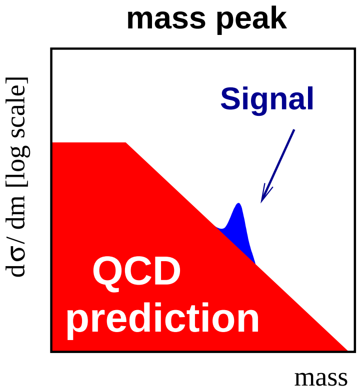
I am not saying this because I do not believe in the goodness of our predictions. But because claiming that supersymmetry exists is far too important a conclusion to make it follow from the straight comparison against a Monte Carlo.

Mangano, 0809.1567

This talk

Try to examine the question of how much QCD matters, how much it can help with searches.

What kinds of searches?



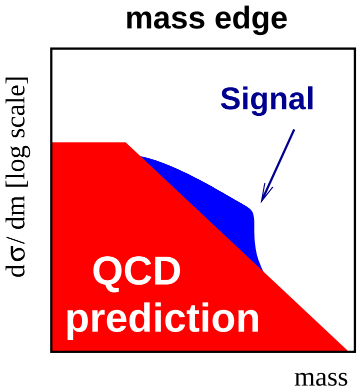
New resonance (e.g. Z') where you see all decay products and reconstruct an invariant mass

QCD may:

- swamp signal
- smear signal

leptonic case easy; hadronic case harder

What kinds of searches?



New resonance (e.g. R-parity conserving SUSY), where undetected new stable particle escapes detection.

Reconstruct only *part* of an invariant mass → kinematic edge.

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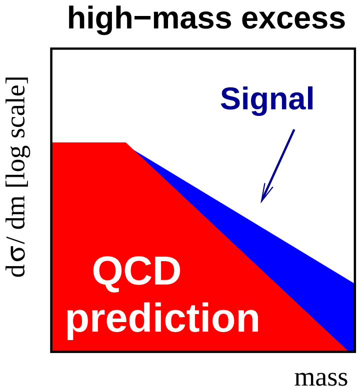
- swamp signal
- smear signal

What kinds of searches?

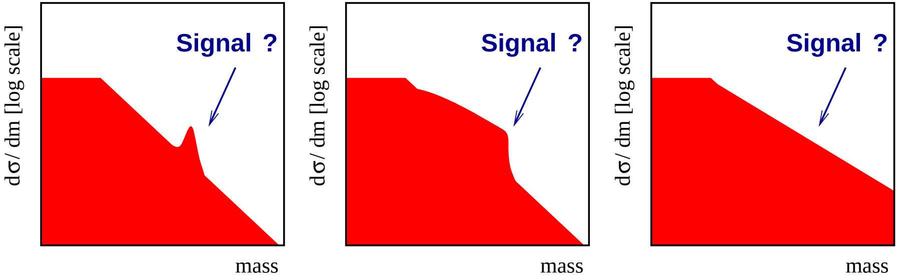


Unreconstructed SUSY cascade. Study *effective* mass (sum of all transverse momenta).

Broad excess at high mass scales.

Knowledge of backgrounds is crucial is declaring discovery.

QCD is *one way* of getting handle on background.



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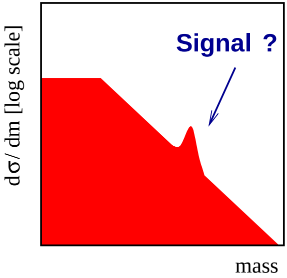

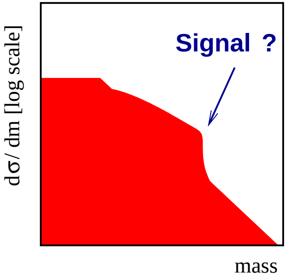

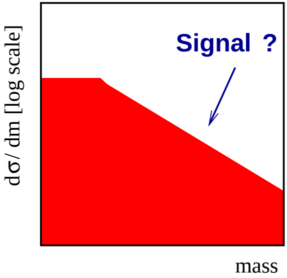

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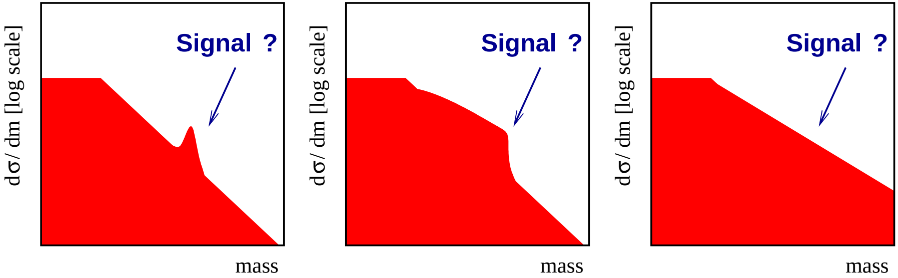

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Before Starting

The most pervasive role of QCD at LHC

Every single paper that comes out from the ATLAS and CMS pp physics programmes will involve the use of one or more QCD-based parton-shower Monte Carlo event generators: Pythia, Herwig or Sherpa.

For simulating physics signals.

For simulating background signals.

For simulating pileup.

As input to simulating detector respone.

Pythia

ISUB	Subprocess name
11	f + f' -> f + f' (QCD)
12	f + fbar -> f' + fbar'
13	f + fbar -> g + g
28	f + g -> f + g
53	g + g -> f + fbar
68	g + g -> g + g
96	Semihard QCD 2 -> 2

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Pythia

ISUB Subprocess name

11 f +
12 f +
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28 f +
53 g +
68 g +
96 Sem

Event listing (standard)

I	particle/jet	K(I,1)		P(I,1)	P(I,2)	P(I,3)	P(I,4)	P(I,5)
1	!p+!		21	0.00000	0.00000	6999.99994	7000.00000	0.93827
2	!p+!		21	0.00000	0.00000	-6999.99994	7000.00000	0.93827
3	!u!		21	-0.20478	-1.99677	4200.93192	4200.93240	0.00000
4	!u!		21	-0.52164	-0.53530	-1227.35705	1227.35728	0.00000
5	!g!		21	69.88093	-38.60332	186.26860	202.65624	0.00000
6	!u!		21	-3.29805	0.22934	-594.30442	594.31361	0.00000
7	!g!		21	342.80888	-101.05545	-85.04352	367.37248	0.00000
8	!u!		21	-276.22601	62.68148	-322.99229	429.59738	0.33000
9	(u)	A	12	2.92305	6.37706	2.55209	7.47216	0.33000
10	(g)	I	12	-0.12086	-0.05387	0.23937	0.27351	0.00000
11	(g)	I	12	2.90849	0.44667	3.06707	4.25039	0.00000
12	(g)	I	12	0.44539	0.19658	1.08590	1.19004	0.00000
13	(g)	I	12	0.72977	2.84935	0.81600	3.05241	0.00000
14	(g)	I	12	0.12403	0.47094	-1.65408	1.72428	0.00000
15	(g)	I	12	0.63915	1.19608	-6.31736	6.46128	0.00000
16	(g)	I	12	1.26081	0.95080	-9.60839	9.73729	0.00000
17	(g)	I	12	1.39862	-0.87388	-14.36959	14.46392	0.00000
18	(g)	I	12	0.94209	-0.92748	-58.84151	58.85636	0.00000
19	(g)	I	12	2.85917	0.96504	-201.26331	201.28593	0.00000
20	(g)	I	12	-0.94209	0.92748	-163.96216	163.96749	0.00000
21	(g)	I	12	-2.90849	-0.44667	-423.55274	423.56296	0.00000
22	(g)	I	12	-0.03667	-0.02590	0.00503	0.04517	0.00000
23	...	....	....	....	....	....	....	....

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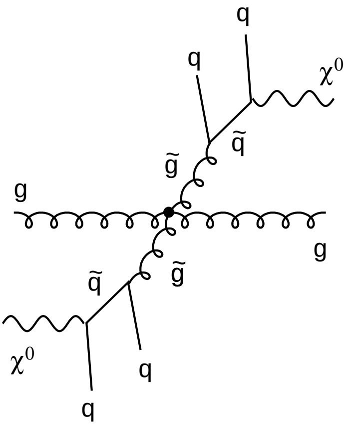
165	(rho0)	11	9.26285	-1.51905	-1.63571	9.55696	0.74292
166	pi-	1	2.97622	-0.72739	-0.31237	3.08286	0.13957
167	pi+	1	2.90207	-0.46804	-0.08318	2.94405	0.13957
168	(omega)	11	6.33127	-0.15752	0.01513	6.38115	0.78042
169	(rho-)	11	1.27652	-1.77925	0.66381	2.39534	0.70836
170	(omega)	11	-0.38942	0.17068	1.21017	1.50136	0.78024
171	pi+	1	-0.09283	0.10773	0.32113	0.37793	0.13957
172	(rho-)	11	-0.24864	-0.18762	1.86992	2.14719	1.00837
173	(K*+)	11	-1.87908	0.80841	1.49858	2.68439	0.88076
174	(K*-)	11	-3.82206	2.20136	2.34838	5.07340	0.87770
175	(rho+)	11	-13.22858	5.42242	4.50921	15.02121	0.95161
176	(rho0)	11	-11.94640	5.71075	4.73622	14.07218	0.51488
177	(eta)	11	-10.84249	4.63993	3.47786	12.30788	0.54745
178	(rho0)	11	-11.59191	4.94873	5.09943	13.62590	0.89360
179	(rho0)	11	-3.47439	1.79711	1.42757	4.24437	0.82201
180	(rho-)	11	-1.09464	0.50862	0.33785	1.41536	0.65739
181	(omega)	11	-3.07966	1.34675	0.70043	3.52173	0.78355
182	(rho+)	11	-3.57280	0.49038	1.66254	4.07286	0.90486

Predicting QCD

SUSY example: gluino pair production

Signal



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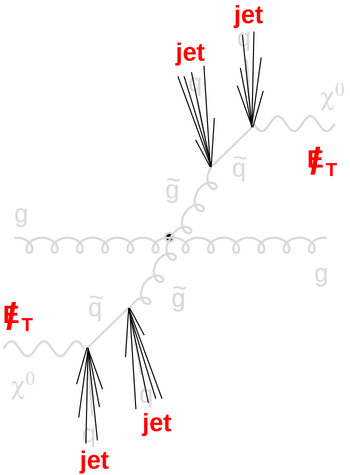

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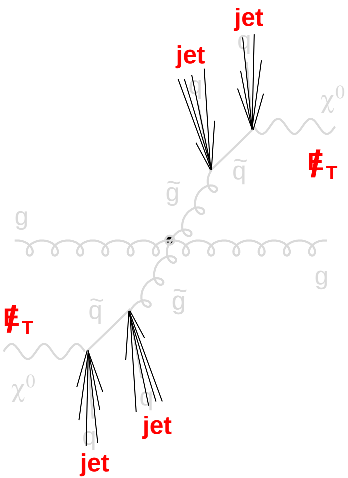
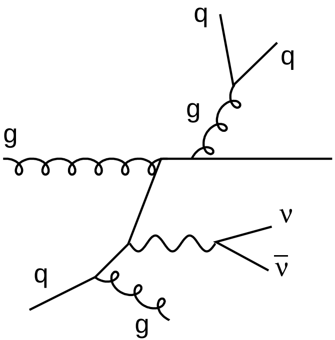


Background



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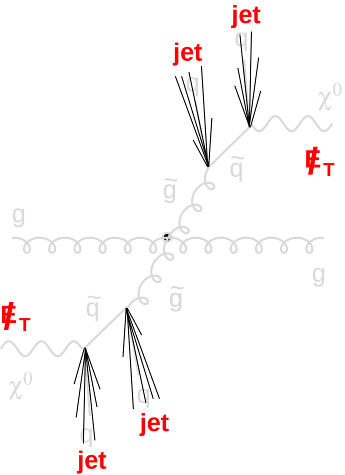

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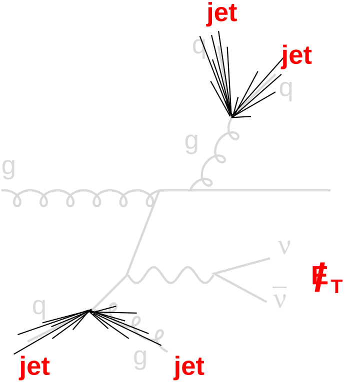
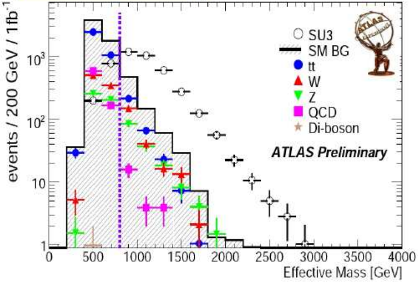


SUSY searches: what excesses?

Atlas selection [all hadronic]

- no lepton
- MET > 100 GeV
- 1^{st},2^{nd} jet > 100 GeV
- 3^{rd},4^{th} jet > 50 GeV
- MET / m_{eff} > 20%

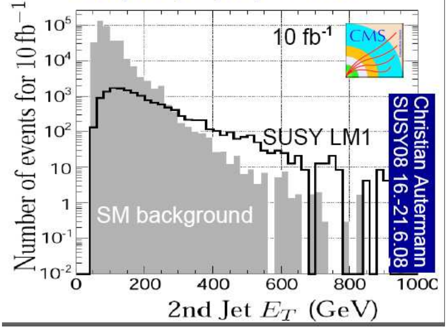
Christian Autermann
SUSY08 16.-21.6.08
4



CMS selection [leptonic incl.]

(optimized for 10fb⁻¹, using genetic algorithm)

- 1 muon pT > 30 GeV
- MET > 130 GeV
- 1^{st}, 2^{nd} jet > 440 GeV
- 3^{rd} jet > 50 GeV
- −0.95 < cos(MET,1^{st}jet)<0.3
- cos(MET,2^{nd}jet) < 0.85



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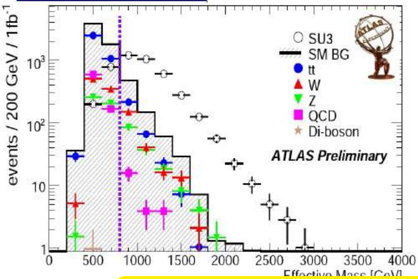

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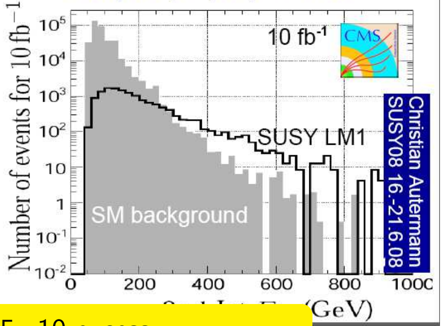


SUSY ≃ factor 5−10 excess

How accurate is QCD?

$\alpha_s \simeq 0.1$

That implies LO QCD should be accurate to within 10%

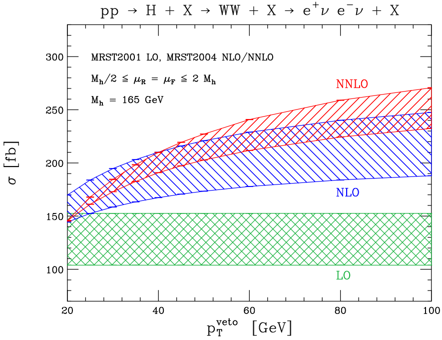
It isn't

Rules of thumb:

LO good to within factor of 2

NLO good to within scale uncertainty

How accurate is QCD?



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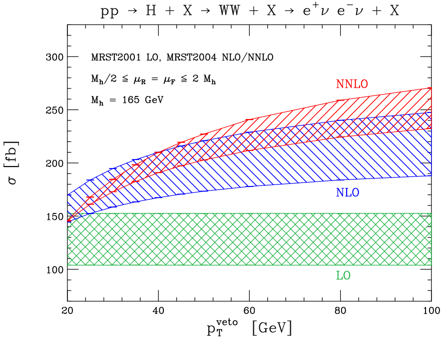

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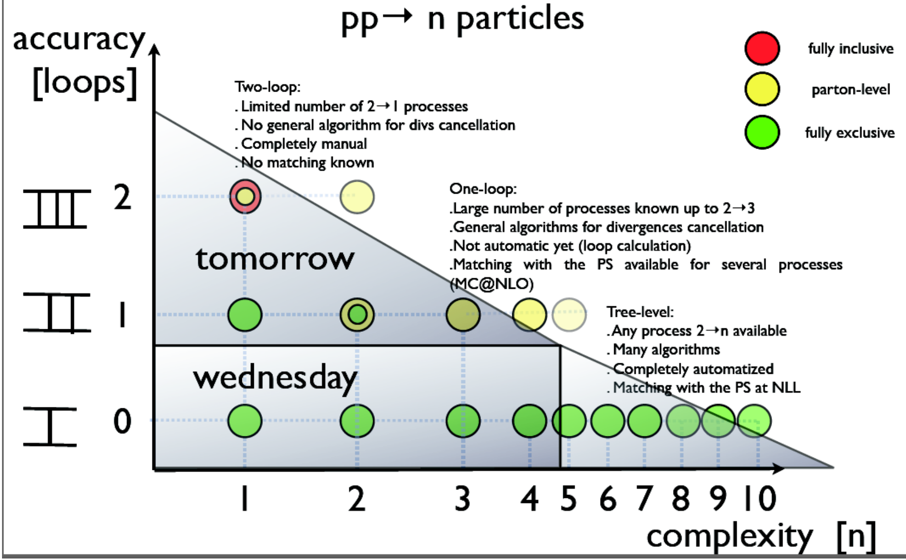
Theory status

from lectures
by F. Maltoni '07



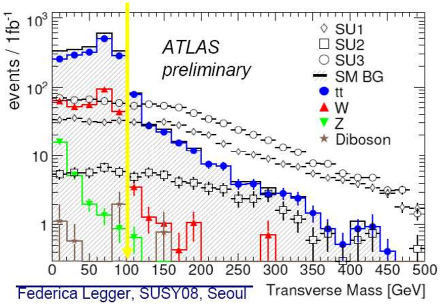
Control samples

We don't have NLO for the background (e.g. 4 jets + Z, a $2 \to 5$ process).

Only LO (matched with parton showers). How does one verify it?

Common procedure (roughly):

- Get control sample at low p_t
- SUSY should be small(er) contamination there
- Once validated, trust LO prediction at high-p_t



Is this safe?

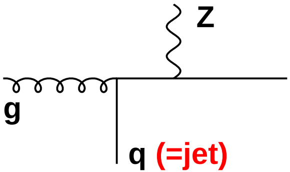
A conservative QCD theory point of view:

It's hard to be sure: since we can't calculate Z+4 jets beyond LO.

But we would tend to think it is safe, as long as control data are within usual factor of two of LO prediction

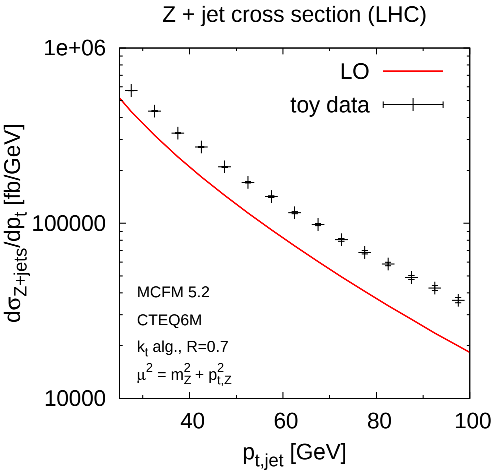
Illustrate issues with toy example: Z+jet production

- It's known to NLO — and a candidate for "first" $2 \to 2$ NNLO
  $\sim e^+e^- \to 3$ jets, NNLO: Gehrman et al '08, Weinzierl '08
- But let's pretend we only know it to LO, and look at the p_t distribution of the hardest jet (no other cuts — keep it simple)



example based on background work for Butterworth, Davison, Rubin & GPS '08

Toy data, control sample



stage 1: get control sample

Check LO v. data at low p_t

- normalisation off by factor 1.5 (consistent with expectations)

  So renormalise LO by K-fact

- shape OKish

  Don't be too fussy: SUSY could bias higher p_t

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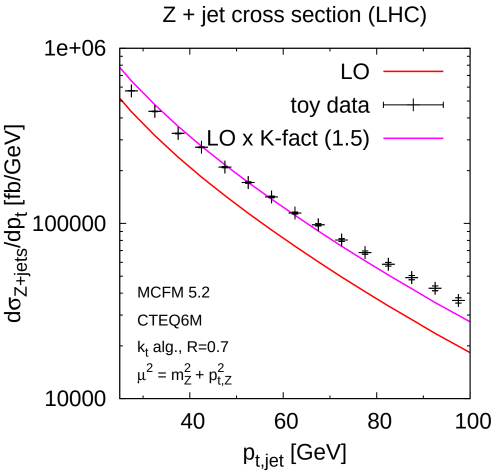

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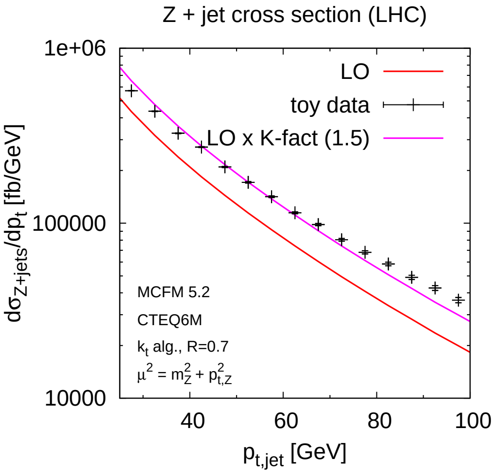

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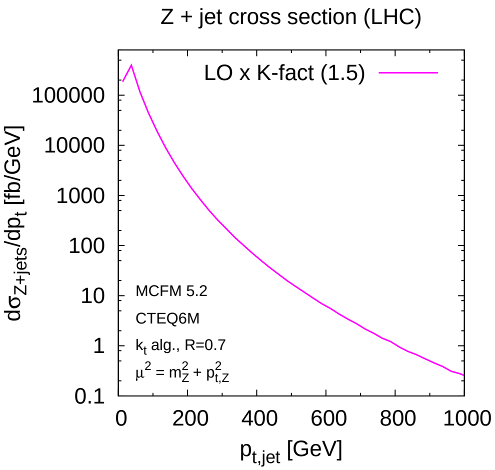
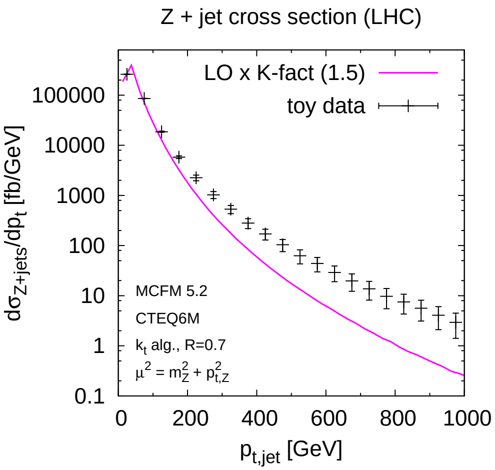


stage 2: look at high p_t

- good agreement at low p_t, by construction
- excess of factor ~ 10 at high p_t
- check scale dependence of LO
  [NB: not always done except
  e.g. Alwall et al. 0706.2569]
  still big excess

Toy data, high p_t



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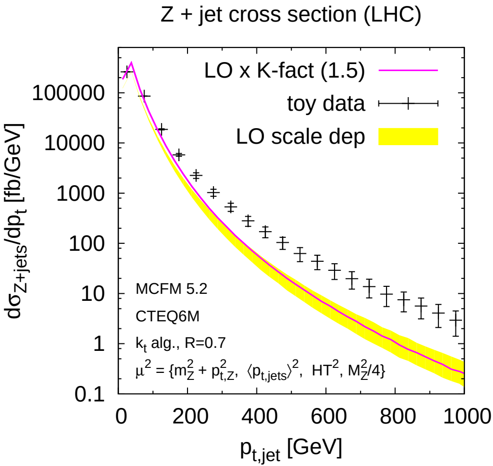

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What's in the toy data?

Is it:

- QCD + extra signal?
- just QCD? But then where does a K-factor of 10 come from?

Here it's just a toy illustration. In a year or two it may be for real:

- Do Nature / Science / PRL accept the paper?

  Discovery of New Physics at the TeV scale

  We report a 5.7σ excess in MET + jets production that is consistent with a signal of new physics ...

- Do we proceed immediately with a linear collider?

  It'll take 10–15 years to build; the sooner we start the better

- At what energy? It would be a shame to be locked in to the wrong energy...

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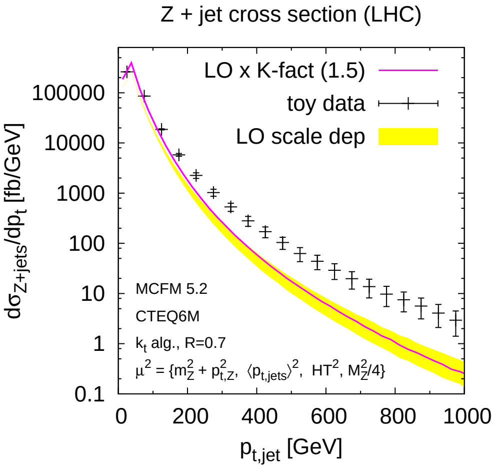


Unlike for SUSY multi-jet searches, in the Z+jet case we do have NLO.

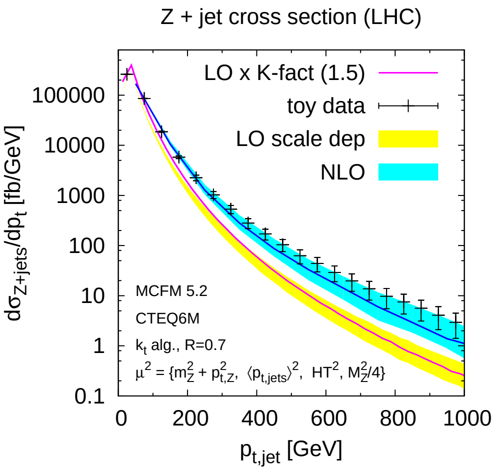
Once NLO is included the excess disappears

The "toy data" were just the upper edge of the NLO band

Hold on a second: how does QCD give a K-factor $\mathcal{O}(5-10)$?

NB: DYRAD, MCFM consistent

Open the box. . .



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The "toy data" were just the upper edge of the NLO band

Hold on a second: how does QCD give a K-factor $\mathcal{O}(5-10)$?

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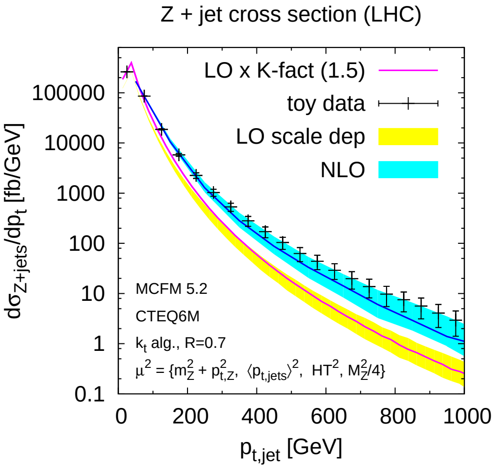

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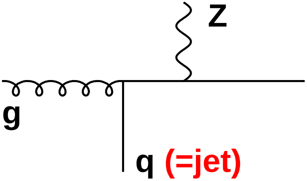
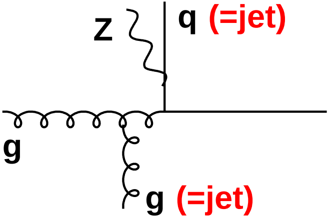
Why the large K-factor?

Leading Order



$\alpha_s \alpha_{EW}$

Next-to-Leading Order



$\alpha_s^2 \alpha_{EW} \ln^2 \frac{p_t}{M_Z}$

LHC will probe scales well above EW scale, $\sqrt{s} \gg M_Z$.
QCD and EW effects **mix**, EW bosons are **light**.
New logarithms (enhancements) appear.

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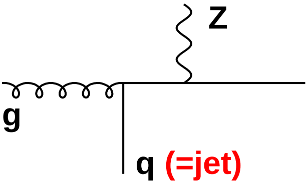

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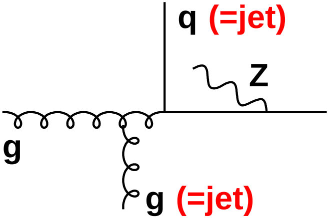

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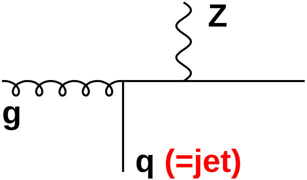

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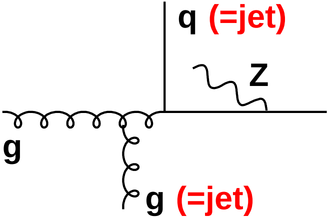

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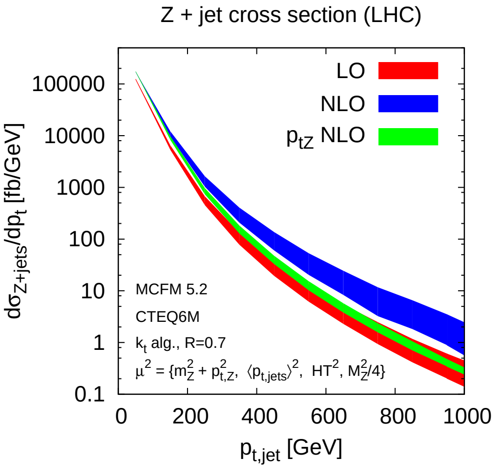
Cross-check



Plot distribution for p_{tZ}.

This selects events in which the Z is the hardest object.

Kills diags with EW double-logs.

NLO is well-behaved.

Where does this leave us?

- Excess ≡ New Physics, **iff** you are really, really sure you understand backgrounds;
- Control samples may not be good enough cross-check
- Plain LO QCD can be misleading, understanding the physics is crucial

  This can be non-trivial even in simplest of cases

  But can help you choose good observables
- NLO provides a powerful cross check — and progress is being made in multi-jet case, e.g. $W + 3$jet calculation @ NLO

  BlackHat: Berger et al. '08, '09

  Rocket: Ellis, Kunszt, Giele, Melnikov & Zanderighi '08, '09
- What about MLM, CKKW matching for combining different tree-level contributions?

  Designed to avoid deficiences of Parton Showers

  But does more — a sort of "LO++". Still, not NLO

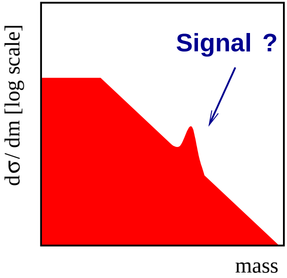
  In this case it actually gets most of the answer

  [checked by de Visscher and Maltoni]

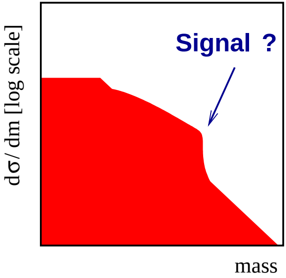
Viewing QCD

(A subject that has seen much less attention than "predicting QCD," but may be just as relevant)

Consider case of *mass peaks* — but bear in mind that other kinematic structures are fundamentally related.

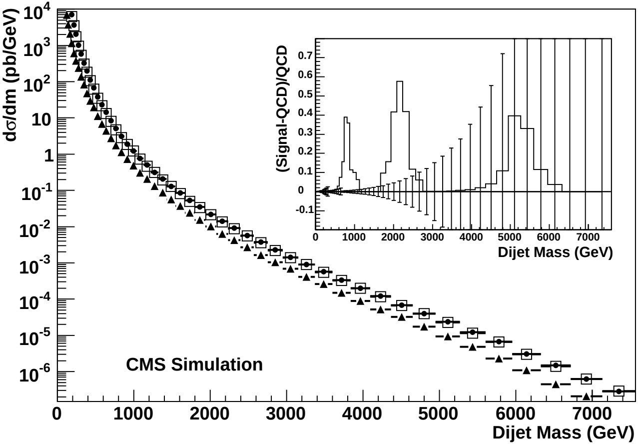


$$\sim \frac{d}{dm}$$



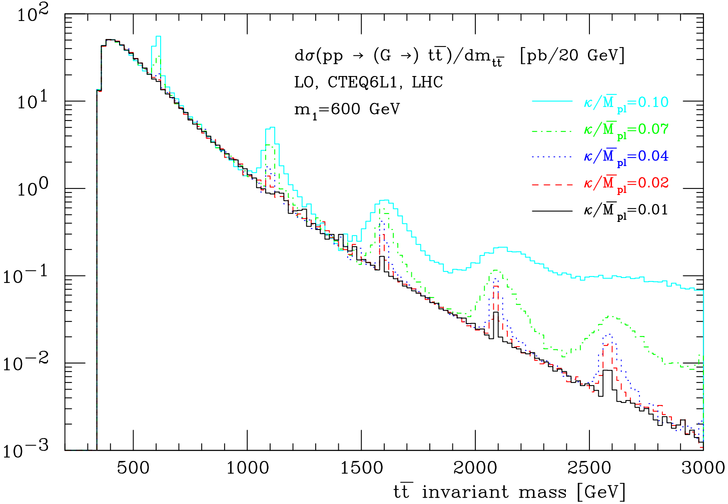
Some peaks are easy — QCD not needed

e.g. resonance $\to \ell^+\ell^-$, or big broad resonance to jets



Bhatti et al (for CMS), study of dijet mass resonances (q^*), 0807.4961

Observability may depend on parameters

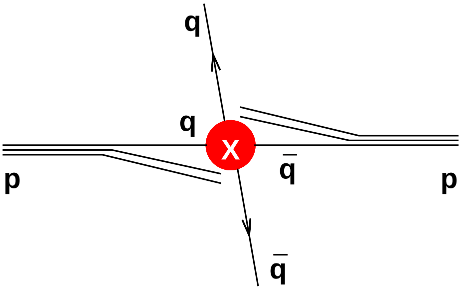


RS KK resonances, from Frederix & Maltoni, 0712.2355

Cases where QCD has the most to contribute are those that are borderline

Basic question:

Can we make kinematic “structures” emerge more clearly?



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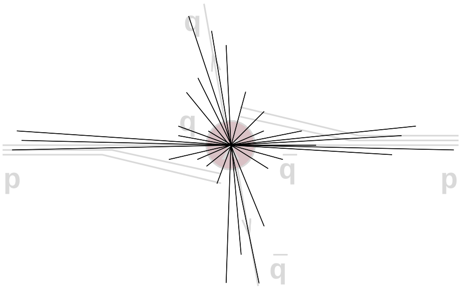

Which particles should one choose in order to best reconstruct the resonance?

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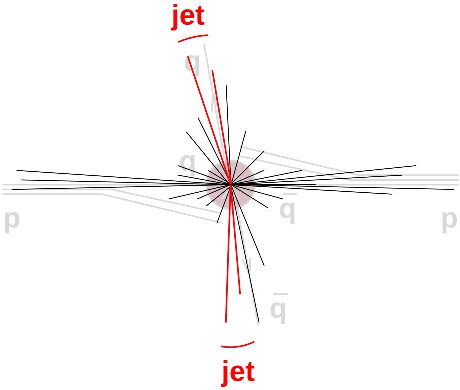

How should one define the “jets”?

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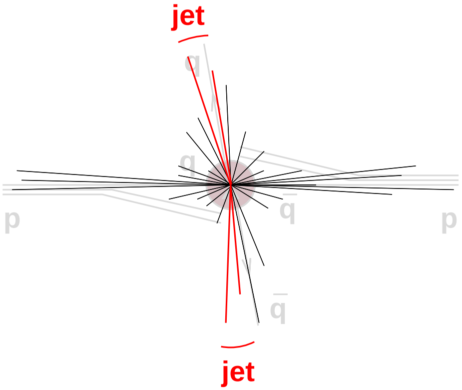

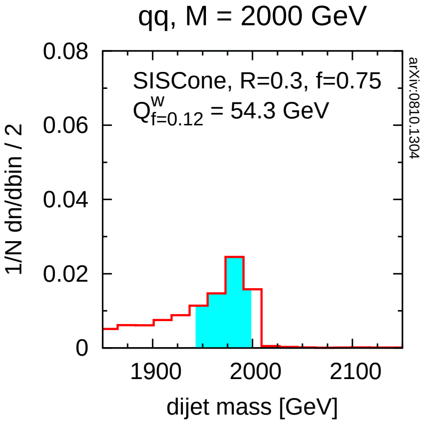

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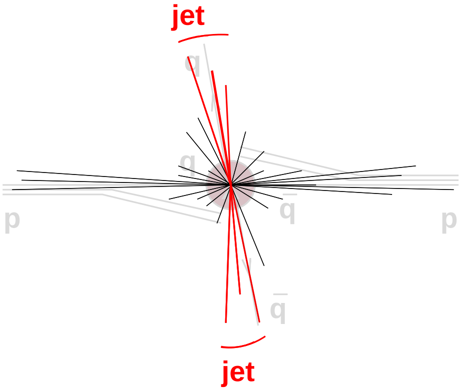

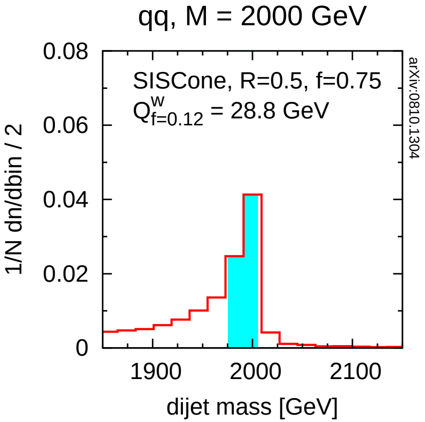

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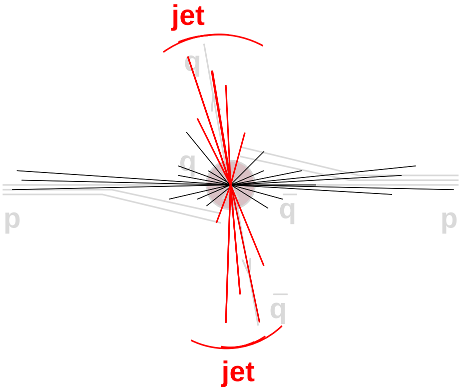

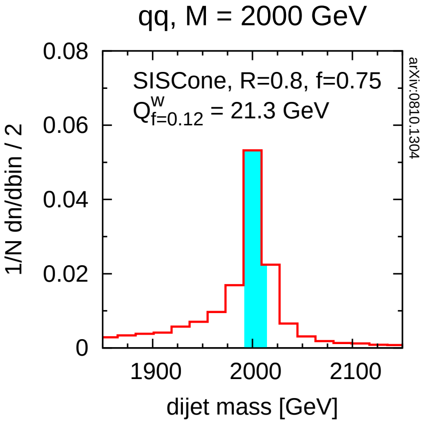

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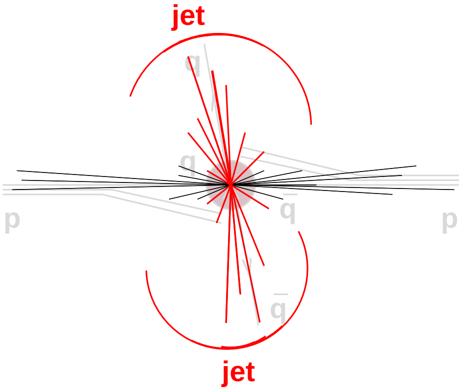

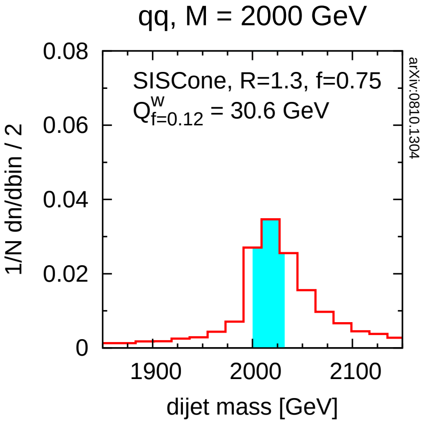

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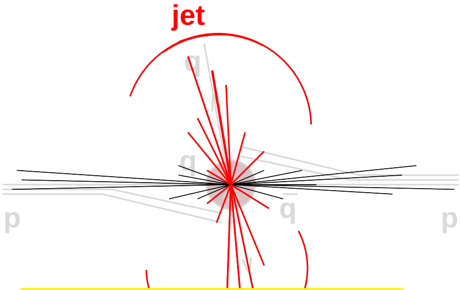
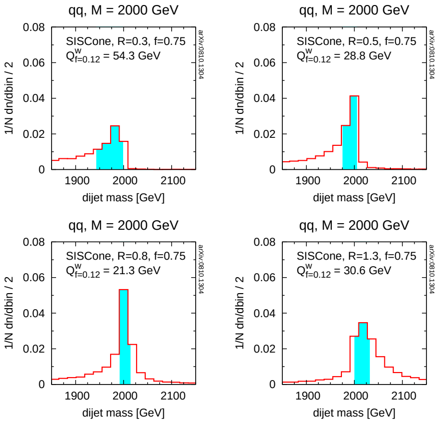


Choice of jet-definition has significant impact



Recent progress with jets

- Definitions that are sensible within QCD and experiments (infrared safety, speed)
  Cacciari & GPS '05; GPS & Soyez '07
  Cacciari, GPS & Soyez '08
- Understanding analytically the interplay between jet definitions & QCD
  Dasgupta, Magnea & GPS '07
  Cacciari & GPS '07; Cacciari, GPS & Soyez '08
- Monte Carlo studies to verify consequences for experiment
  Anastasiou et al '08; Nojiri & Takeuchi '08
  Cacciari, Rojo, GPS & Soyez '08
  Thaler & Wang '09
- Jet tools for events with hierarchies of scales
  Butterworth, Davison, Rubin & GPS '08
  Brooijmans '08; Krohn, Thaler & Wang '08
  Kaplan, Rehermann, Schwartz & Tweedie '08
  Almeida et al. '08

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Rather than go into detail on these subjects myself, I'll hand over to Mathieu Rubin so that he can tell you about one of the most unexpected of the results.

Conclusions

Conclusions

We've seen examples where doing the QCD "right" makes a big difference.

From first part: it's clear that relative $\mathcal{O}(\alpha_s)$ ("the details") in QCD predictions (NLO) may be more than just a luxury refinement.

Part of the motivation for the large calculational effort in the field

Crucial in building confidence in our understanding of any LHC "excess"

From second (brief!) part: QCD at LHC it not *just* about calculating backgrounds. Learning to "view" events properly can have a major impact.

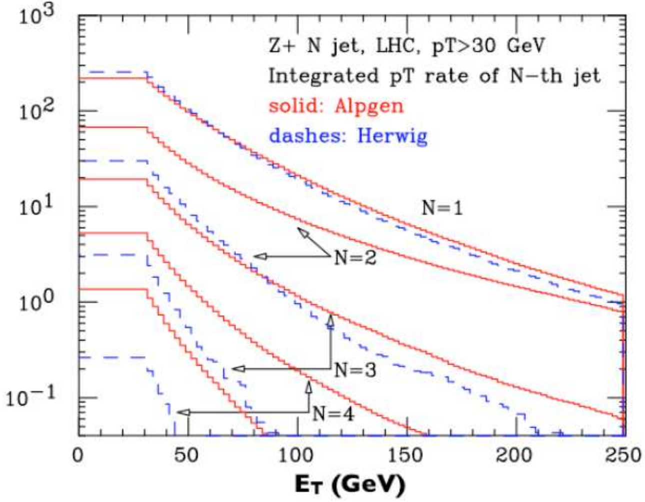
QCD can guide us in making good choices

A much smaller field — but several groups making progress

Crucial in order to maximise LHC's sensitivity to new physics

Common theme: LHC will probe a broad range of scales: from below EW scale, to 1.5 orders of magnitude above it.

EXTRAS



Mangano, 0809.1567

Not matched

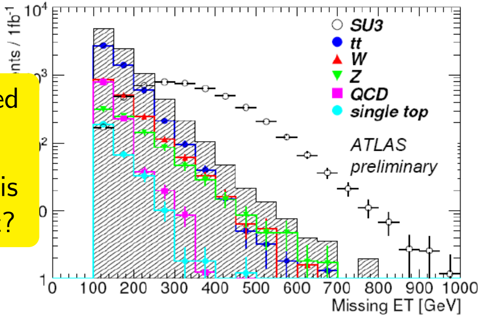
But see 2-jet $\simeq$ 1-jet, which is sign of problems

0-lepton search

Is there a larger excess when plotted v. MET ($\sim p_{tZ}$)?

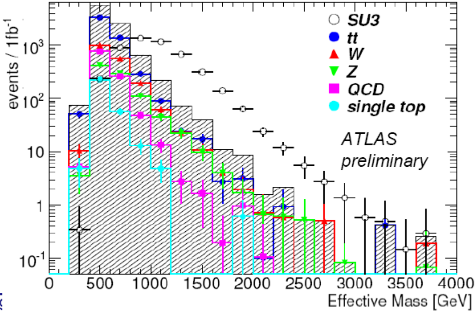
Is this because Eff.Mass ($\sim p_{t,jet}$) is enhanced in bkgd, but MET is not?

- at least 1 jet with PT>100GeV
- 0 lepton (e, μ) with PT > 20 GeV
- MET > 100 GeV
- MET > 0.2 effective mass
- Transverse Sphericity ST > 0.2
- Δφ(ET – jet *i*) > 0.2 (*i* = 1, 2, 3)

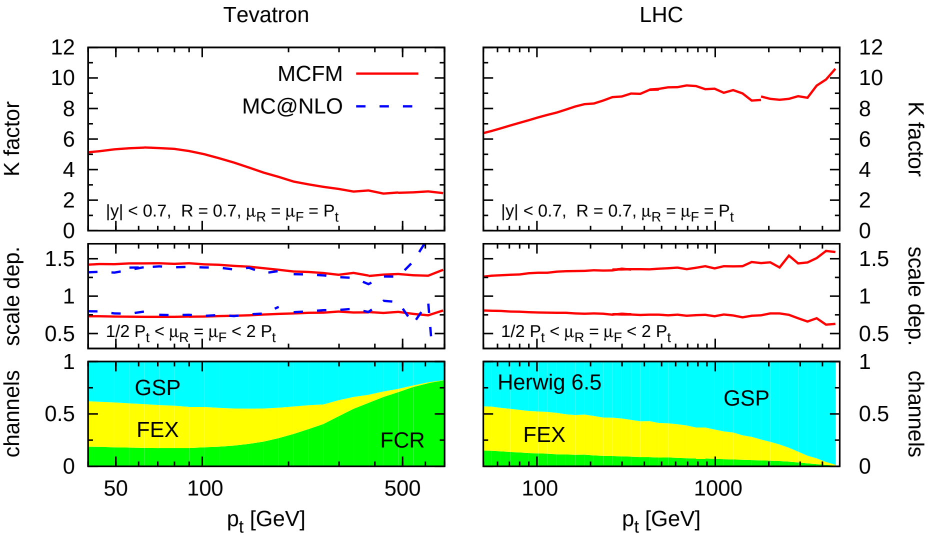


- Main backgrounds:
  - tt
  - W+jets
  - Z+jets
  - QCD

SM	0-l
tt	62%
W	17%
Z	10%
QCD	10%



Another example: *b*-jet production



Banfi, GPS & Zanderighi, '07