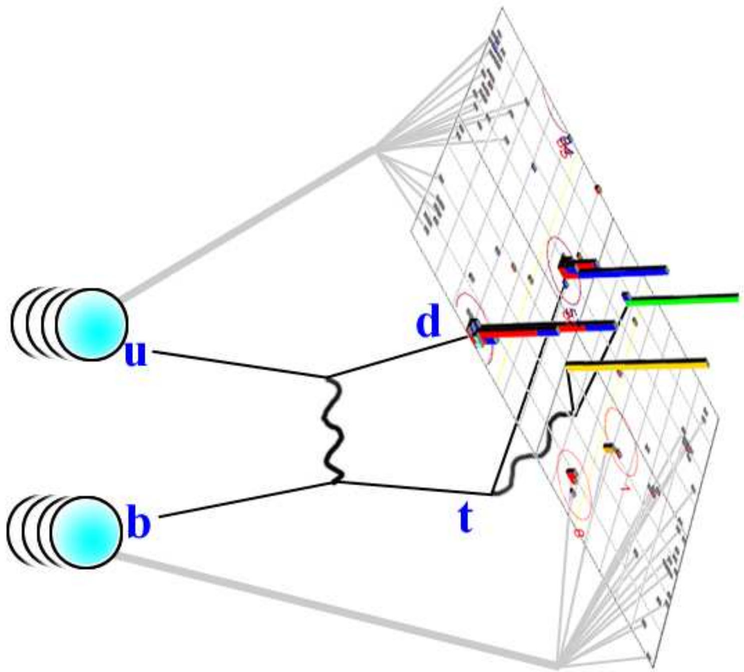
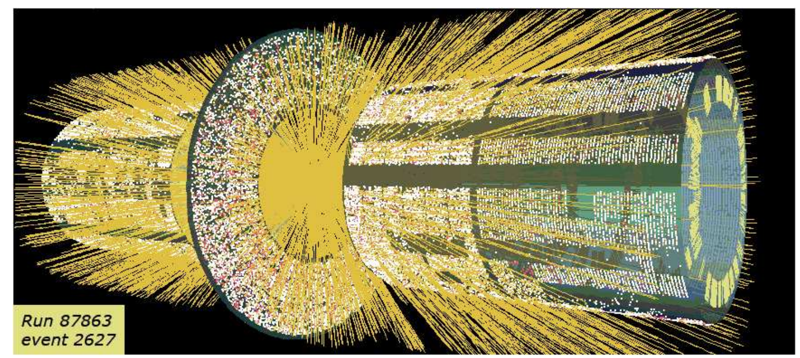
Will our Tevatron experience transfer to LHC?





Zack Sullivan

Illinois Institute of Technology

The great lesson of the Tevatron

What experimentalists choose to measure is not necessarily
what theorists predict.

Corollary: What theorists choose to predict may not be measurable.

The challenge in transferring our experience to LHC
lies in merging this experience into a common understanding.

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Looking toward early LHC running, I will briefly describe:

- A theoretical issue with Z+jets — the calibration signal
- An experimental issue with leptons — the calibration objects

What theorists predict

We have heard at this conference that we calculate

- Perturbative cross sections: LO + NLO + NNLO + . . .

  Sometimes RG-improved LL + NLL + NLLL + . . .

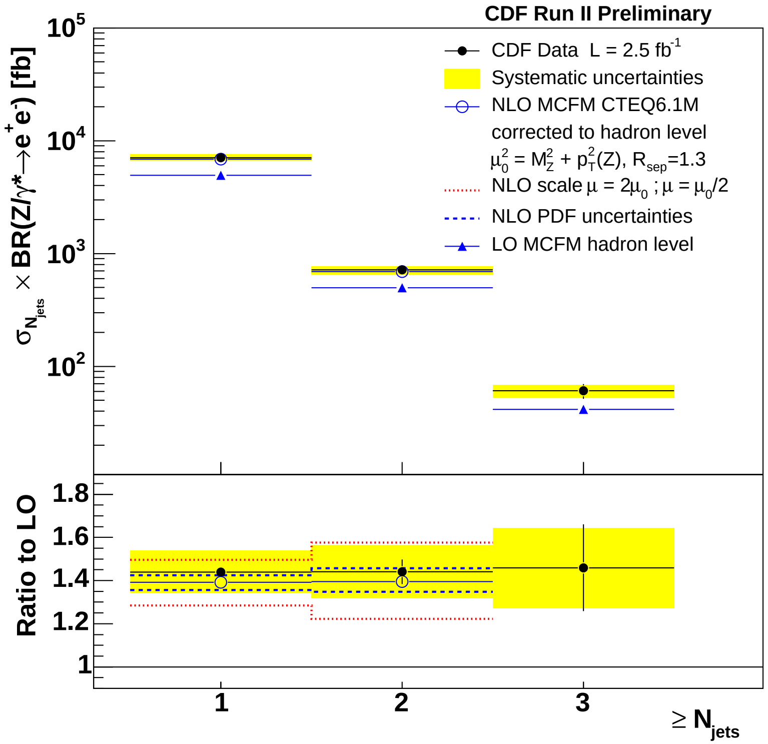
  (see earlier talks by C. Berger, S. Marzani, F. Petriello, coming T. Robens)
- Fed through showering Monte Carlos: PYTHIA, HERWIG, etc.

  (see earlier talks by C. Bauer, S. Mrenna)
- And predict <u>exclusive</u> final states:
  - Exclusive predictions are still a new concept.
  - Single-top-quark production was the first completely exclusive cross section that required matching tools, and it was only discovered at the Tevatron within the last year.
  - One of the first plots for any experimental analysis seems to be the n-jet spectrum — a theoretically exclusive cross section that is completely dependent on experimental jet definitions.
    (see earlier talk by S. Ellis)

What theorists (are asked to) predict

Exclusive $Z+n$ jets will provide the LHC jet calibration

What we see at the Tevatron:



$$Z > Z{+}1\mathrm{j} > Z{+}2\mathrm{j} > Z{+}3\mathrm{j} > \ldots$$

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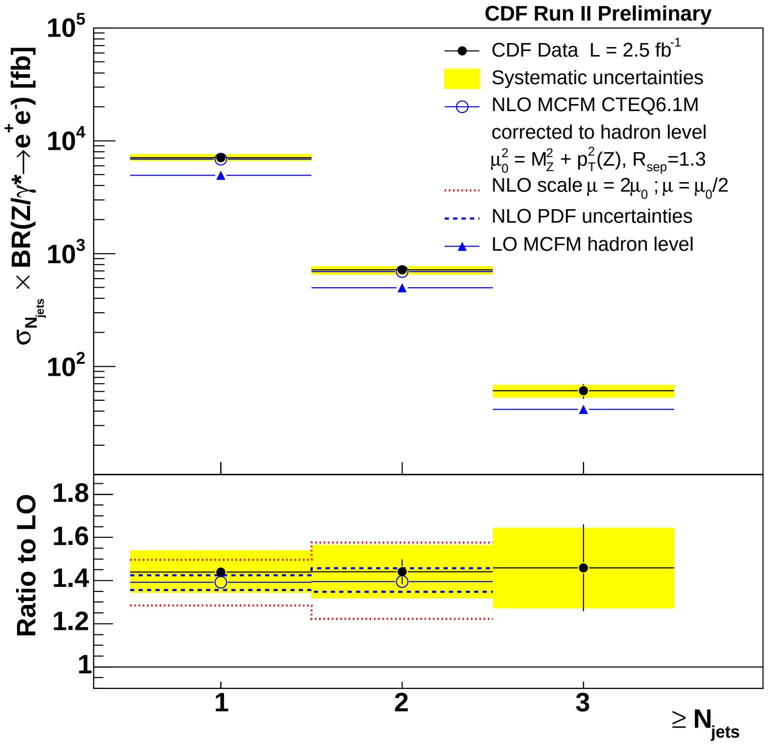

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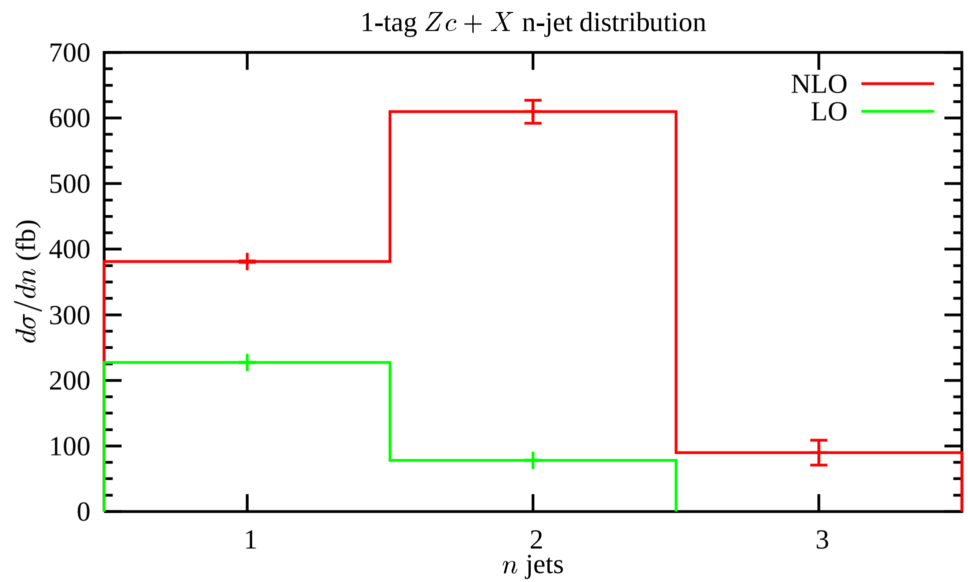
Jet counting fails in some Tevatron cases

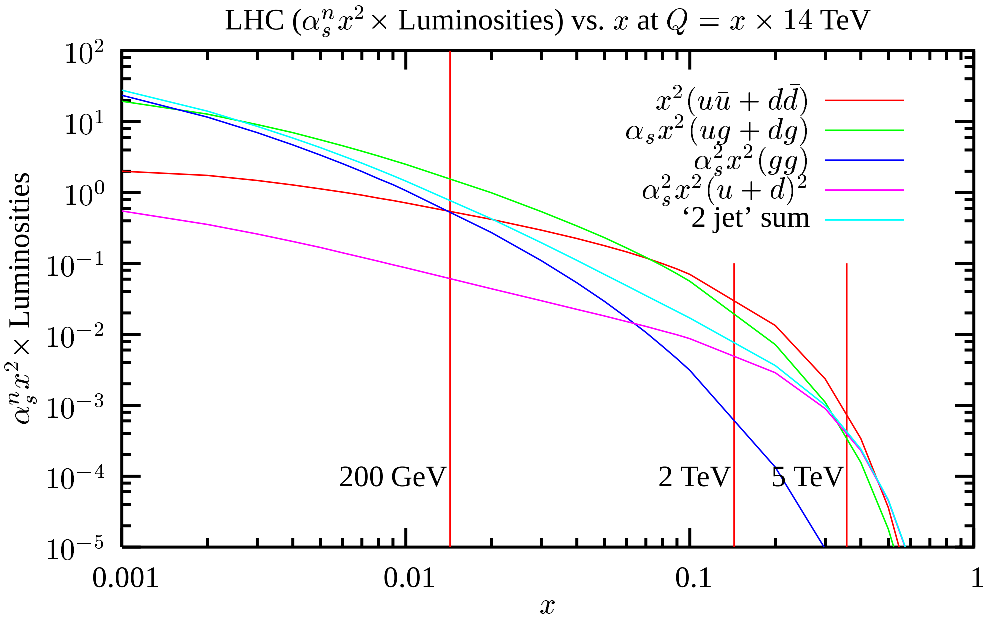


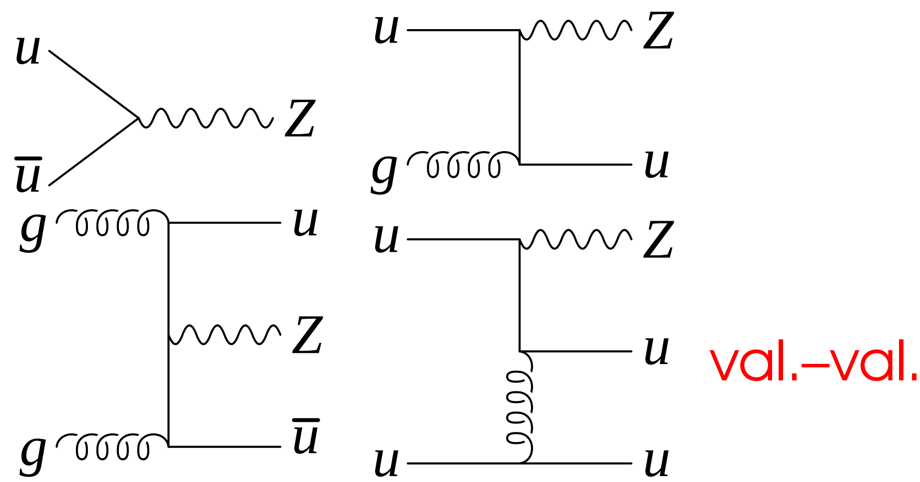
$Zcj > Zc$ and other cases

The Tevatron is finally now accumulating enough data to be sensitive to this.

- The simplicity of the $Z + j$ n-jet spectrum arises because the Tevatron is dominated by matrix element-based physics.
  $\Rightarrow$ straightforward α_s power counting.

Z+jets $\equiv$ jet calibration at LHC (with correct power counting)





From a luminosity (with power-counting) point of view,

$Z \approx Z + 1$ jet $\approx Z + 2$ jets! (True of $W + X$ as well.)

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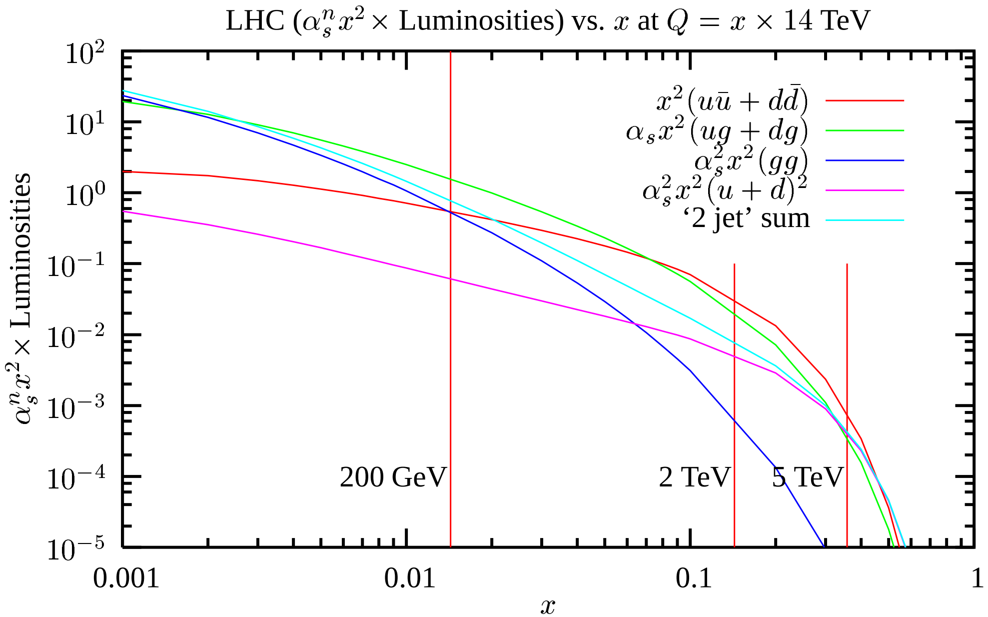
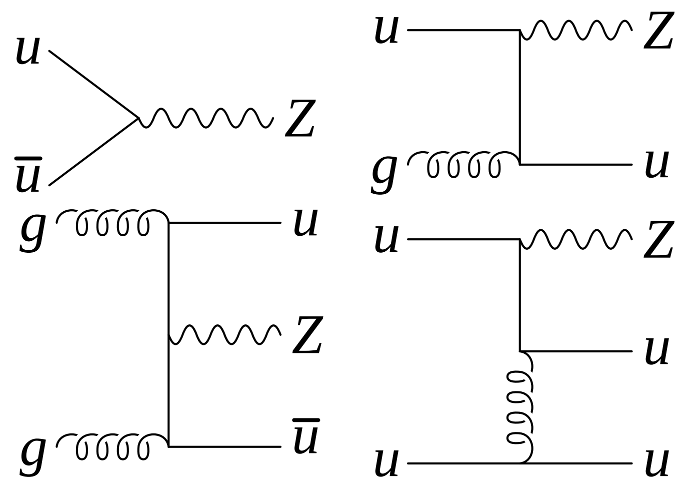




val.–val.

From a luminosity (with power-counting) point of view,

$Z \approx Z + 1$ jet $\approx Z + 2$ jets! (True of $W + X$ as well.)

Color factors and topology are important:

$\Rightarrow$ This is VERY sensitive to cuts.

Jet counting is ill-defined or poorly-defined

The LHC is not a glue factory for physics you care about.

— Color-neutral particles couple to quarks, not gluons.

— Colored particles tend to be heavy (1+ TeV), and see valence quarks.

(see next talk by P. Nadolsky for more on PDFs)

What experimentalists measure

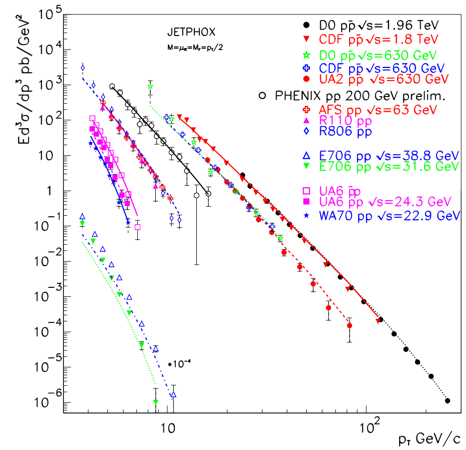
- Photons — ATLAS was designed specifically to look for photons

  There is a long-standing discrepancy in $\gamma + j$

  Photon objects are generically ill-defined.

  JETPHOX NLO did improve the fits

  OPAL, ZEUS found Frixione photon definition works better, but it is still not widely used.



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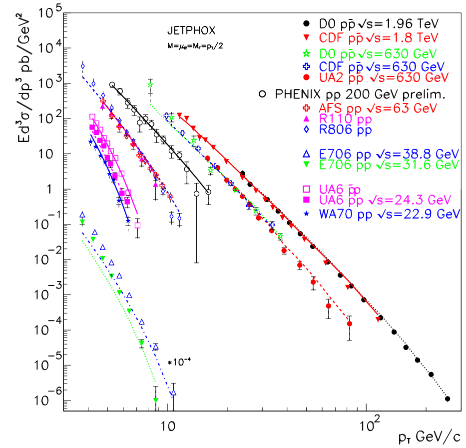

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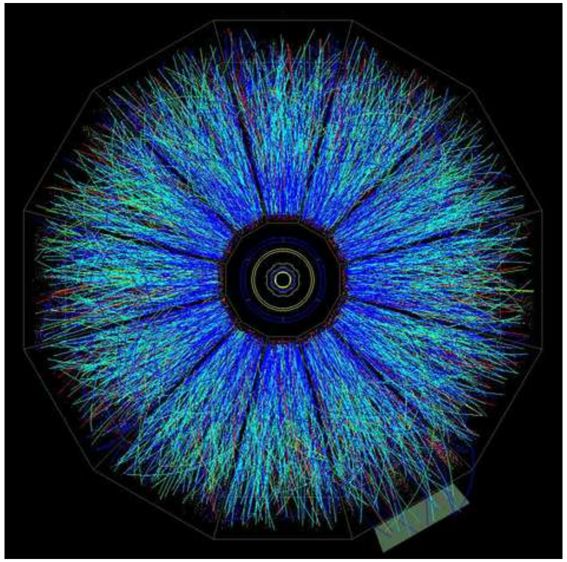
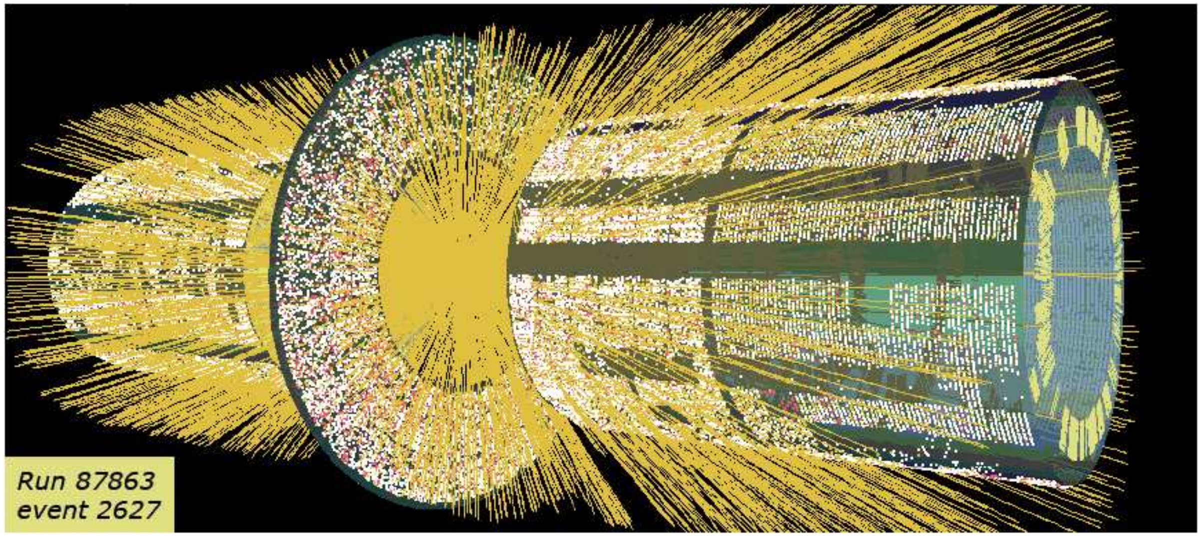
- Jets — LHC events look a lot like RHIC events





Will jets be well-defined? (see talk by S. Ellis)

What experimentalists measure

- Leptons: $e^\pm$, $\mu^\pm$

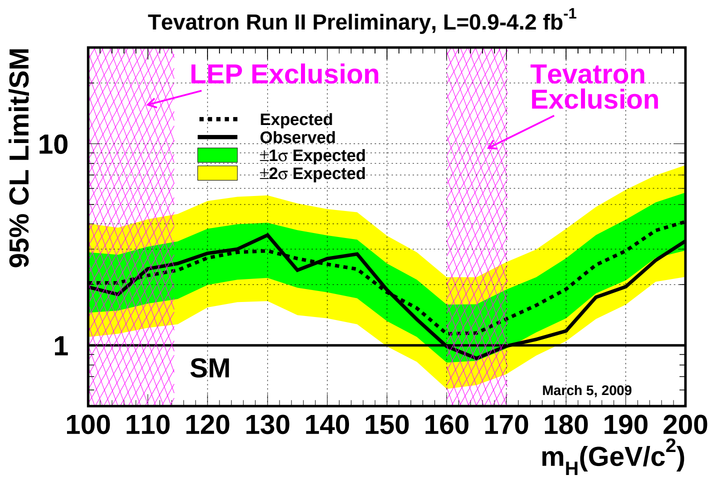
  $Z \rightarrow e^+e^-/\mu^+\mu^-$ used to calibrate everything.

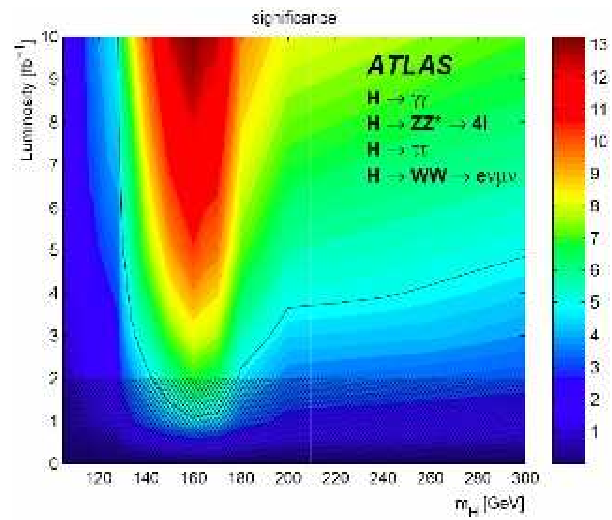
  That's a good reason to look more closely at leptons . . .
  but there are strong theoretical motives as well.

So, why pay attention to leptons?

Higgs production — the promise

The search for the Higgs boson has driven the field of high energy physics for a long time. Now we approach the Age of Discovery.



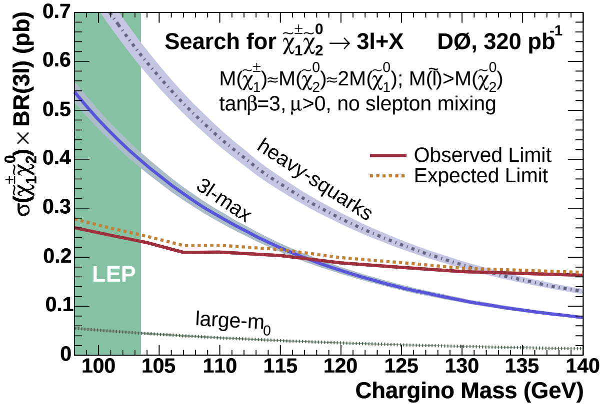


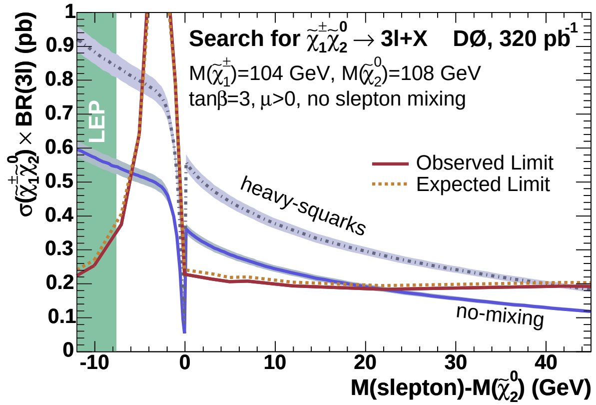
The Tevatron is in a race to rule out a SM Higgs before LHC first reports, while the LHC promises an "easy" observation if the Higgs is there.

These impressive predictions depend on sophisticated understanding of the backgrounds.

SUSY trilepton production — the "golden channel"

The measurement of trileptons plus missing energy is expected to be a clean probe of chargino and neutralino production.

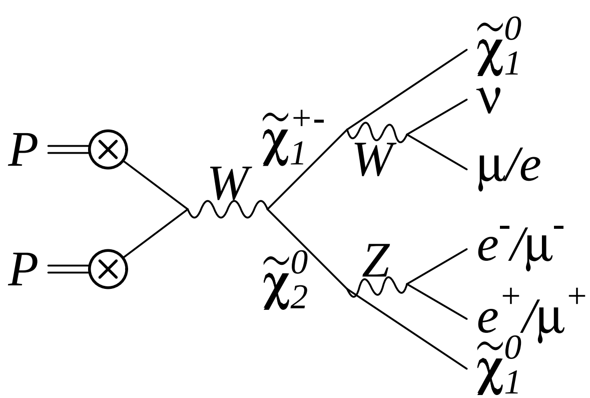


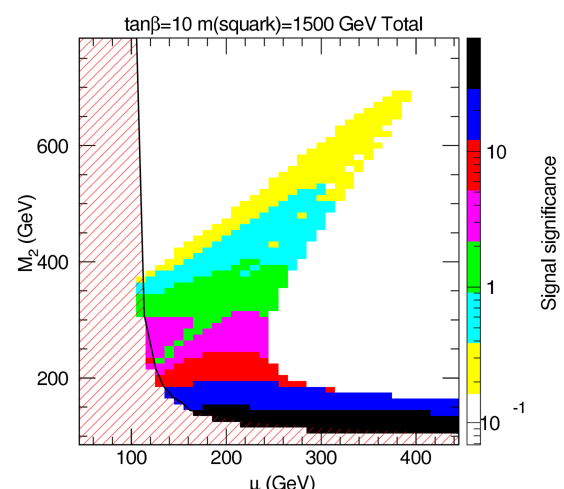


DØ, PRL95, 151805 (05)

DØ and CDF (PRD77,052002(08)) hope to both discover supersymmetry in an excess of trilepton events, and extract mass information.

CMS and ATLAS hope to do the same.





W. Vandelli, thesis

The missing pieces to multi-leptons$+\not{E}_T$

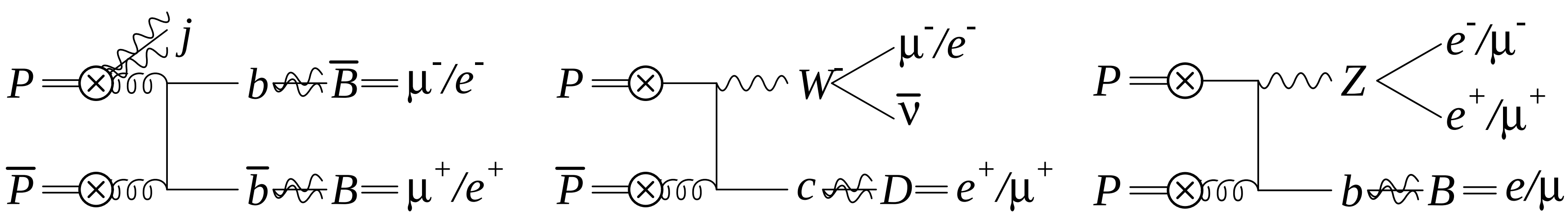
$H \to WW$ and $\tilde{\chi}_1^+ \tilde{\chi}_2^0$ signals share the common trait of multiple leptons plus missing transverse energy.

Experimental collaborations have spent significant time modeling (and measuring) backgrounds to these processes, including both real Standard Model physics and complicated experimental effects (e.g., jet fakes, misreconstruction, etc.)

In all cases, the background to multilepton signatures from the decays of heavy-flavor quarks (b, c) were declared "obviously" insignificant.

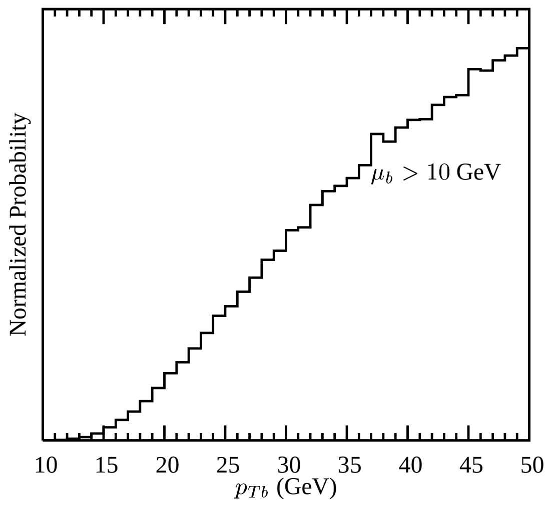
$\Rightarrow$ RULE of THUMB: All jet signals fake leptons at 10^{-4}.

Is this really true? The real physical processes below do not matter?

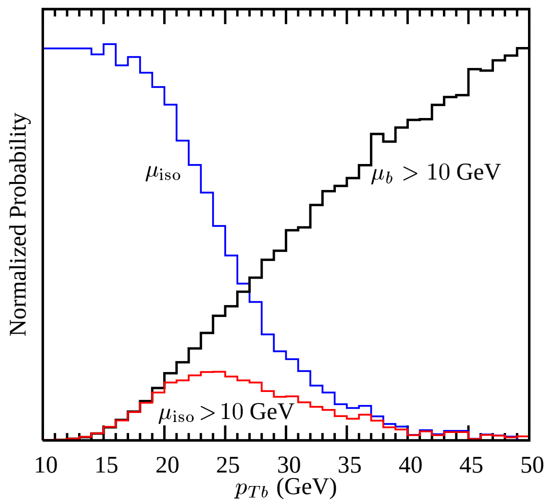


The physics of isolated leptons from heavy-flavor decays

Physics of isolated leptons from b decay



Physics of isolated leptons from b decay



Prob. isolated muon

$= $ Prob. producing muon

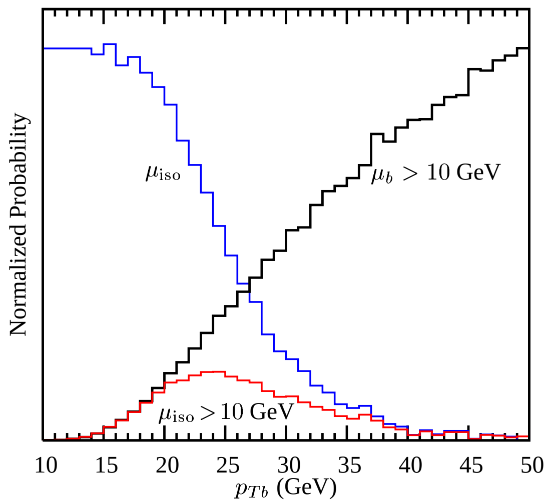
$\times$ Prob. B remnants missed

- Muons that pass isolation take nearly all p_T
- ~Nearly all isolated muons point back to primary vertex.

C. Wolfe, CDF internal

- Isolation leaves ~7.5×10^{-3} μ/b $\gg 10^{-4}$ per light jet

Physics of isolated leptons from b decay



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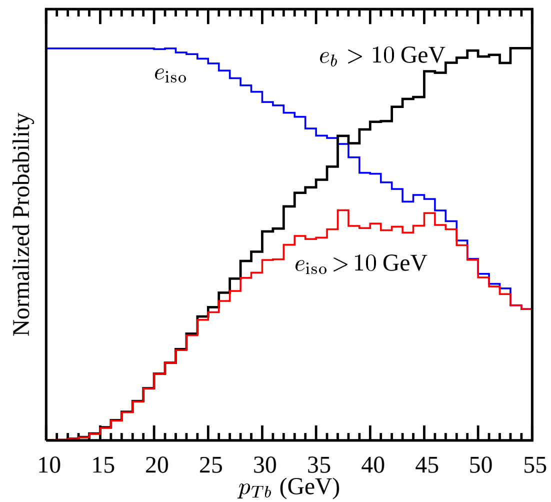
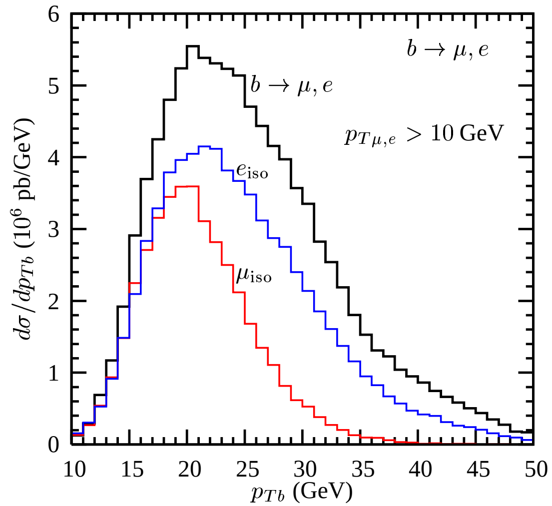


Harder b's can give isolated e's, because e cuts must allow more energy in the calorimeter

It is difficult to reduce this without losing efficiency for primary e.

Isolation is not extremely effective for leptons from b decay.

Isolated leptons from b/c production & decay



Fold in $b\bar{b}$ production.

- A large fraction of events with $b \to \mu/e$ have isolated μ/e.

  More isolated e than μ per b.

- $1/2$ of all isolated μ come from b with $p_{Tb} < 20$ GeV.

  It is common for analyses to start simulations with $p_{Tb} > 20$ GeV.

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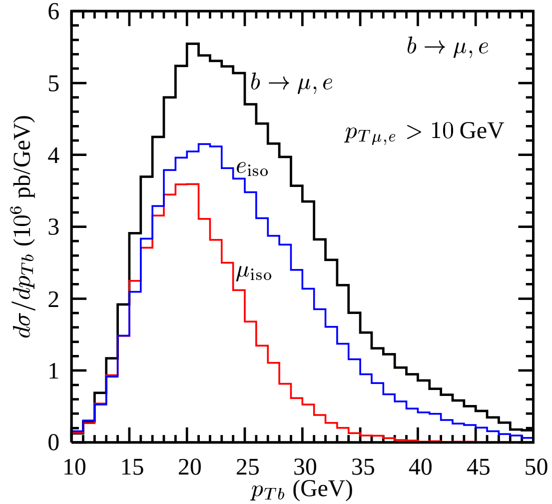

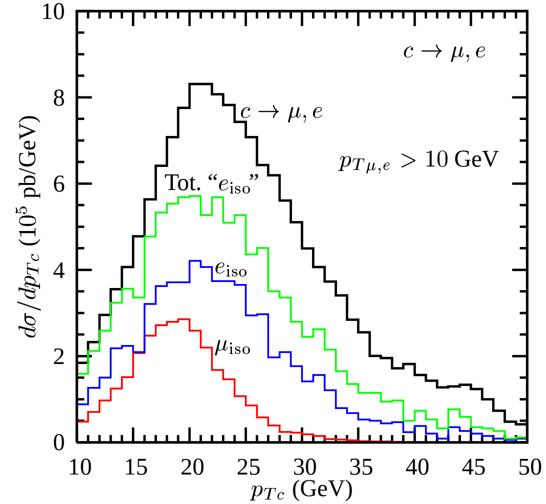

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Fold in $c\bar{c}$ production.

The story repeats for c decays

1 twist: D decays have many pions
$\pi^{\pm}$ fake e at $\sim 10^{-4}$
$\Rightarrow$ Large "$e_{\rm iso}$" rate

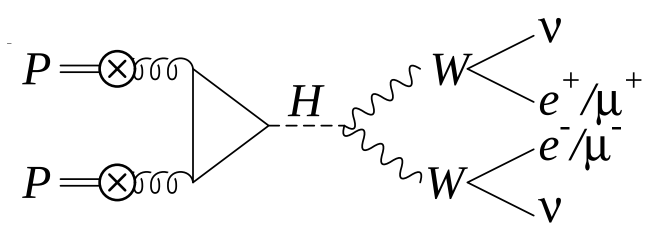
Dileptons at the Tevatron and LHC

The foil:

Higgs production and decay to WW

Z.S., E. Berger, PRD 74, 033008 (2006)

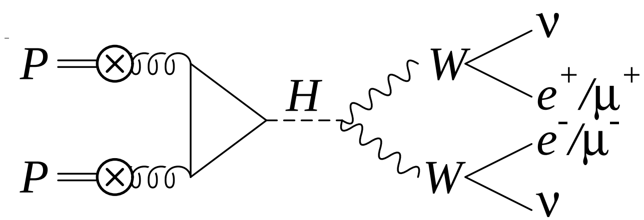
Dileptons and the Higgs



Higgs decays through W^+W^- to opposite-sign dileptons is expected to give the largest significance signal for $135 < M_H < 219$ GeV

CDF, DØ, ATLAS, and CMS have devoted a significant portion of their total effort to measuring and understanding this channel.

Dileptons and the Higgs



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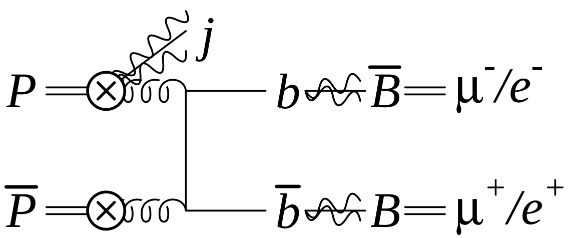
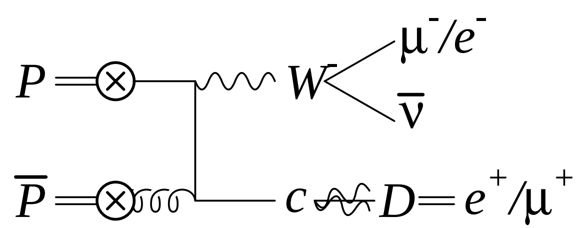
How important are leptons from heavy flavor (b, c) decays?





...

There are MANY potential QCD and EW processes:
$b\bar{b} + X$, $c\bar{c} + X$, Wc, $Wc\bar{c}$, $Wb\bar{b}$, single-top

$H \to W^+W^- \to e^+e^-\not{E}_T/e^\pm\mu^\mp\not{E}_T/\mu^+\mu^-\not{E}_T$

Taken from $1/3$ fb^{-1}study, DØ, PRL 96, 011801 (2006)

M_H (GeV)	120	140	160	180	200
$H \to WW^{(*)}$	0.125 ± 0.002	0.398 ± 0.008	0.68 ± 0.01	0.463 ± 0.009	0.210 ± 0.004
Z/γ^*	7.5 ± 1.0	3.8 ± 0.6	4.0 ± 0.7	6.6 ± 0.9	9.9 ± 1.1
Diboson	8.1 ± 0.2	11.7 ± 0.3	12.3 ± 0.3	11.6 ± 0.3	9.6 ± 0.3
$t\bar{t}$	0.11 ± 0.02	0.29 ± 0.02	0.47 ± 0.03	0.66 ± 0.05	0.72 ± 0.05
W+jet/γ	14.2 ± 2.1	5.8 ± 1.2	2.8 ± 0.9	0.7 ± 0.5	0.7 ± 0.5
Multi-jet	0.3 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.3 ± 0.1	0.3 ± 0.1
Bknd sum	30.1 ± 2.3	21.8 ± 1.4	19.7 ± 1.2	19.8 ± 1.1	21.2 ± 1.2
Data	21	20	19	19	14

So the relevant backgrounds are:

DØ: WW, small Drell-Yan, small rate from $\pi^\pm$ faking $e^\pm$

ATLAS: WW, some Wt, small $t\bar{t}$

Is that the end of the story?. . .

Breakdown of LS/OS leptons at DØ

σ_{ll} (fb):	ee		$e\mu$		$\mu\mu$	
	LS	OS	LS	OS	LS	OS
$H \to WW$	—	0.73 ± 0.04	—	1.26 ± 0.05	—	0.60 ± 0.03
WW	—	12 ± 1	—	20 ± 1	—	9.3 ± 0.9
$b\bar{b}(j)$	—	2.1	—	5.6	—	24
Wc	0.8 ± 0.4	2.3 ± 1.1	1.1 ± 0.4	3.7 ± 1.8	—	3.1 ± 2.2
$Wb\bar{b}$	0.4 ± 0.2	0.4 ± 0.1	2.1 ± 1.6	1.3 ± 0.4	2.5 ± 1.6	2.0 ± 1.1
$Wc\bar{c}$	1.4 ± 0.5	1.1 ± 0.4	1.0 ± 0.2	1.6 ± 0.3	1.0 ± 0.4	0.9 ± 0.2
all else	0.1	1.6	0.3	0.3	0.04	0.1

$b\bar{b}$ more than doubles the background to $\mu^+\mu^-$.

Other channels see 50% increases.

Is this consistent with the DØ result?

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Using tails of tails times unknown fractions? No.

The experiments do not have absolute normalized predictions anyway.

What we want is to understand all of the physical processes at play.
For that, we have to measure the backgrounds. . .

ATLAS-like search for 160 GeV Higgs

Cut level	$H \to WW$	WW	$b\bar{b}j^\star$	Wc	single-top	$Wb\bar{b}$	$Wc\bar{c}$
Isolated $l^+l^- > 10$ GeV	336	1270	> 35700	12200	3010	1500	1110
$E_{Tl_1} > 20$ GeV	324	1210	> 5650	11300	2550	1270	963
$\not{E}_T > 40$ GeV	244	661	> 3280	2710	726	364	468
$M_{ll} < 80$ GeV	240	376	> 3270	2450	692	320	461
$\Delta\phi < 1.0$	136	124	> 1670	609	115	94	131
$\|\theta_{ll}\| < 0.9$	81	83	> 1290	393	68	49	115
$\|\eta_{l_1} - \eta_{l_2}\| < 1.5$	76	71	> 678	320	48	24	104
Jet veto	41	43	> 557	175	11	12	7.4
$130 < M_T^{ll} < 160$ GeV	18	11	—	0.21	1.3	0.04	0.09

The biggest difference in this analysis is that cross sections are bigger, so the cuts are tighter.

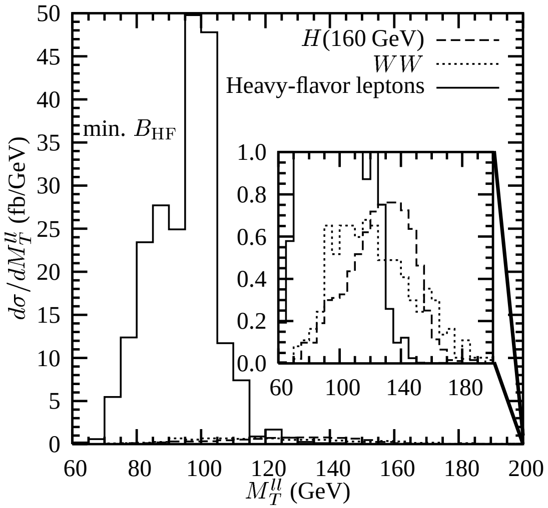
- $b\bar{b}j^\star$ ME is preselected to pass $\not{E}_T$ cut. ($c\bar{c}/c\bar{c}j$ was just too hard) Looser cuts indicate that "$>$" is at least a factor of 5.

  However, this allowed us to demand 2 reconstructed isolated leptons!

- After the $\not{E}_T$ cut, all real power comes from the M_T^{ll} cut.

  Warning: Numbers can be deceptive!

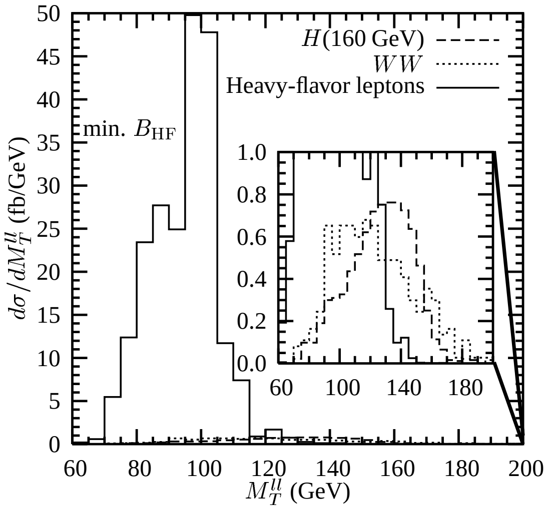
Dileptons at LHC and b quark decays



Heavy-flavor (b, c) decays to leptons $b\bar{b} + Wb\bar{b} + Wc+$single-top$+\ldots$ are $> 50\times$ the direct WW background.

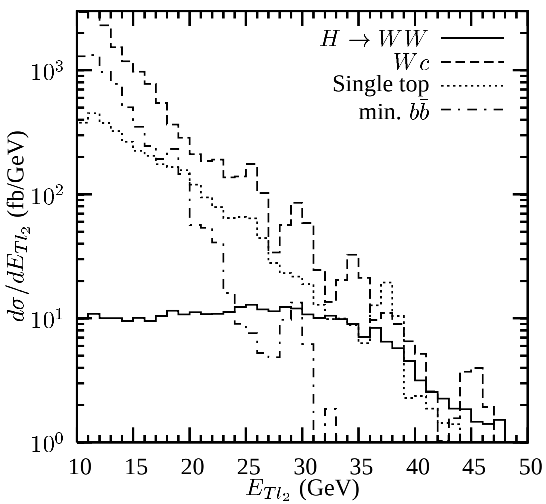
Conclusion: Isolation does not remove leptons from heavy flavor decays!

Dileptons at LHC and b quark decays



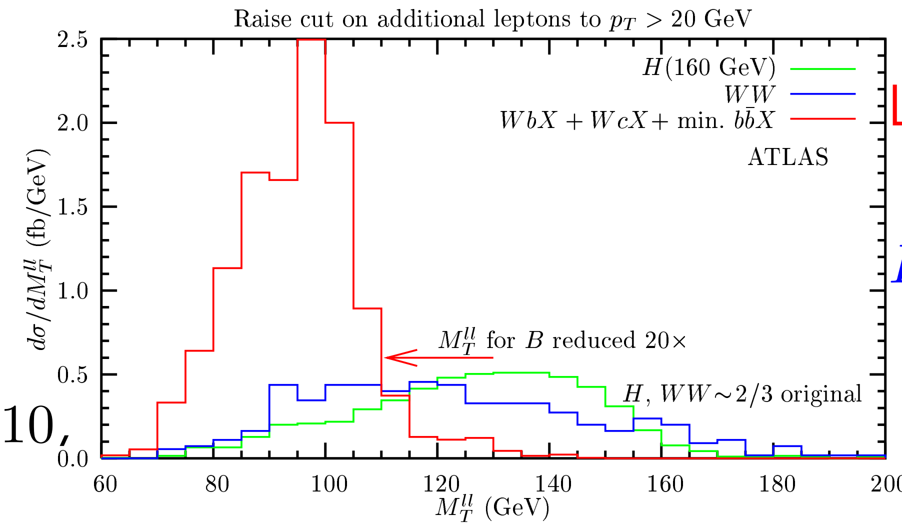
Heavy-flavor (b, c) decays to leptons
$b\bar{b} + Wb\bar{b} + Wc$+single-top+ . . . are
$> 50\times$ the direct WW background.

Conclusion: Isolation does not remove leptons from heavy flavor decays!



Solution: The second lepton p_T falls exponentially.

So raise the cut: $p_{Tl_2} > 10$ GeV $\Rightarrow p_{Tl_2} > 20$ GeV.



Leading edge 20 GeV lower!

$H \to WW$ survives!

$b\bar{b} \to b\bar{b}/30$, $W{+}X \to W{+}X/10$,
$t{+}X \to t{+}X/5$

We can measure the HF background *in situ* and tune it away with cuts.

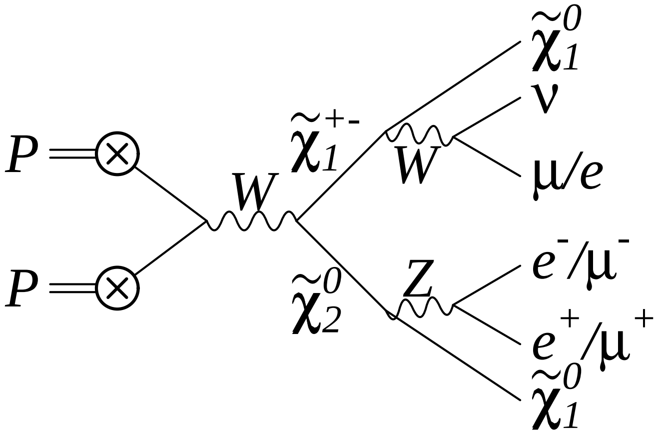
Trileptons at the Tevatron and LHC

The foil:

SUSY chargino/neutralino production

Z.S., E. Berger, PRD 78, 034030 (2008)

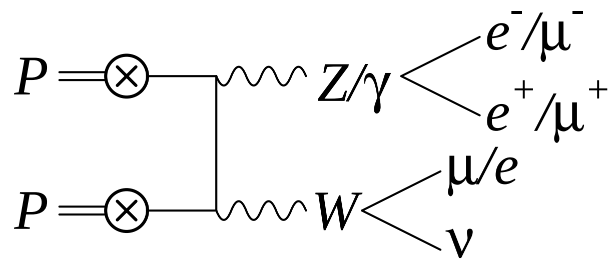
Motivation: Trileptons at LHC



$\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0 \to l^+l^-\, l^{\pm}+\not{E}_T$ is a golden signature of supersymmetry.

CMS and ATLAS both have analyses designed to observe this signal.

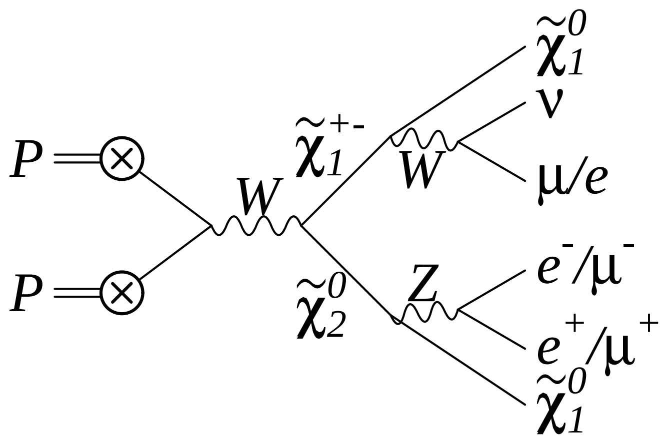
CMS TDR V.2&Note 2006/113; ATLAS CSC 7



WZ was expected to be the largest source of low-p_T trileptons at LHC.

$W\gamma^*$ has not previously been included.

Motivation: Trileptons at LHC



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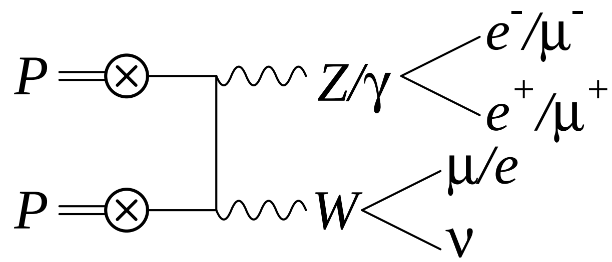

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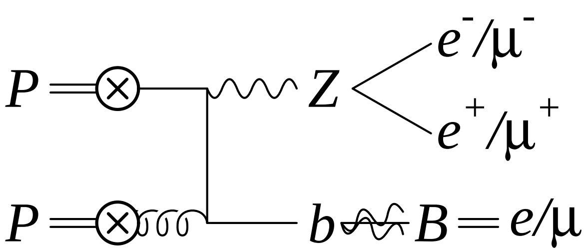


How important are leptons from heavy flavor (b, c) decays?

There are MANY potential processes:
bZ/γ, $b\bar{b}Z/\gamma$, cZ/γ, $c\bar{c}Z/\gamma$, $b\bar{b}W$, $c\bar{c}W$, $t\bar{t}$, tW, $t\bar{b}$

NOTE: All photons are virtual, and split to l^+l^-

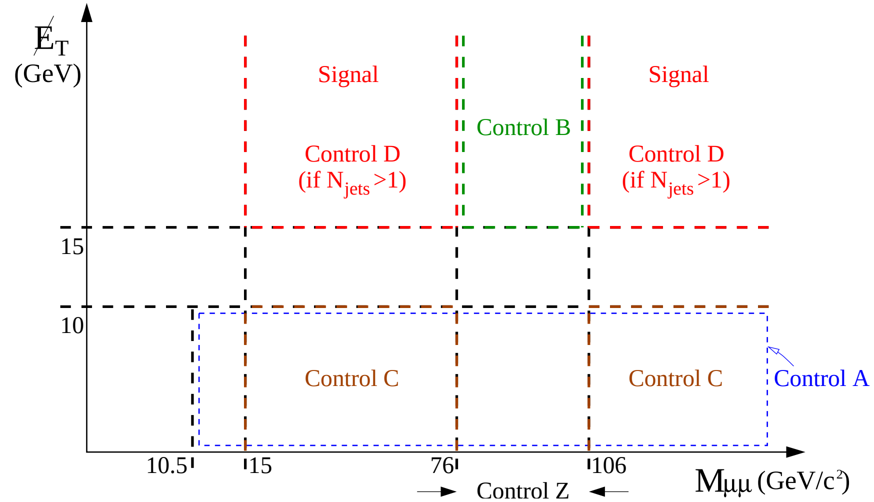
Trileptons at CDF

CDF, PRD 79,052004 (2009)

Previous Tevatron studies ignored leptons from heavy-flavor decays.

CDF decided to follow our example

— There are no trilepton events, so they looked in dilepton regions:



Dilepton regions

Region	DY	HF	Fakes	Diboson	$t\bar{t}$	**Total SM expected**	**SUSY expected**	**Observed**
Control Z	6419 ± 709	-	10 ± 11	2.4 ± 0.2	1.18 ± 0.14	6433 ± 712	0.30 ± 0.07	6347
Control A	14820 ± 2242	9344 ± 1612	2294 ± 1148	1.03 ± 0.09	0.12 ± 0.03	26459 ± 1429	0.9 ± 0.2	26295
Control B	217 ± 25	-	9 ± 7	1.7 ± 0.2	0.27 ± 0.05	227 ± 26	0.5 ± 0.1	253
Control C	5770 ± 1043	2238 ± 384	466 ± 234	0.49 ± 0.07	0.02 ± 0.01	8474 ± 857	0.7 ± 0.2	8205
Control D	7.8 ± 1.5	9 ± 4	0.3 ± 0.3	0.21 ± 0.07	4.1 ± 0.4	22 ± 5	1.8 ± 0.4	23
Signal Reg.	169 ± 30	90 ± 20	49 ± 25	6.5 ± 0.4	0.96 ± 0.11	315 ± 37	17 ± 3	297

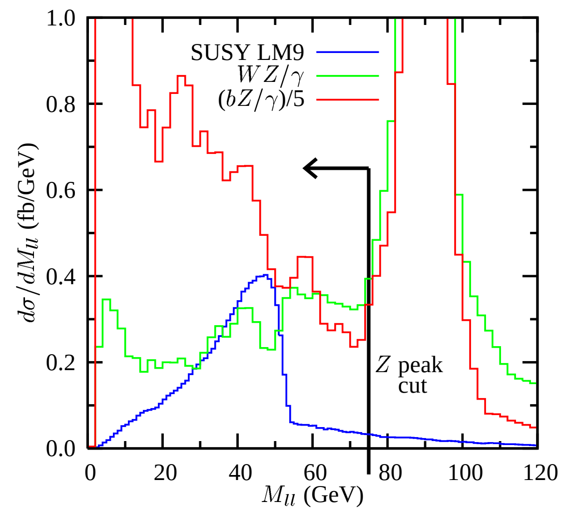
Conclusion: Leptons from heavy-flavor decays are a dominant background.

Trileptons: SUSY & SM at CMS w/ 30 fb^{-1}

Channel	$N^l = 3$, NoJets	$M_{ll}^{\rm OSSF} < 75$ GeV
LM9	248	243
LM7	126	123
LM1	46	44
WZ/γ	1880	538
$t\bar{t}$	1540	814
tW	273	146
$t\bar{b}$	1.1	1.0
bZ/γ	14000	6870
cZ/γ	3450	1400
$b\bar{b}Z/\gamma$	8990	2220
$c\bar{c}Z/\gamma$	4680	1830
$b\bar{b}W$	9.1	7.6
$c\bar{c}W$	0.19	0.15

Analysis cuts:

- 3 leptons
- No jets ($E_{Tj} > 30$ GeV)
- Remove Z peak (demand $M_{ll}^{\rm OSSF}) < 75$ GeV

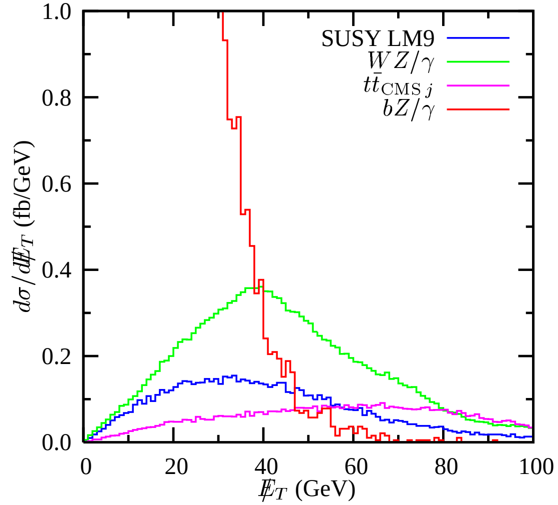


Z+heavy flavor decays are $10\times$ $WZ/\gamma + t\bar{t}$!

Two additional cuts: $\not\!\!E_T$ and angular correlations

Leptons from SUSY decays are SOFT $\Rightarrow$ Cannot raise p_{Tl} cut.

Missing E_T



Z/γ+heavy flavors – no intrinsic $\not\!\!E_T$

Comes from misreconstruction,
energy lost down beam pipe

Natural $\not\!\!E_T$ in SUSY points low as well

$\tilde{\chi}_1^0$'s partially balance out

A $\not\!\!E_T$ cut demanding

$\not\!\!E_T > 30$–40 GeV is very effective

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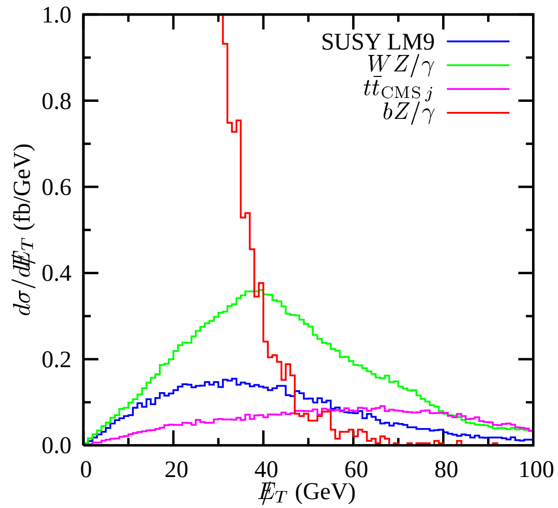

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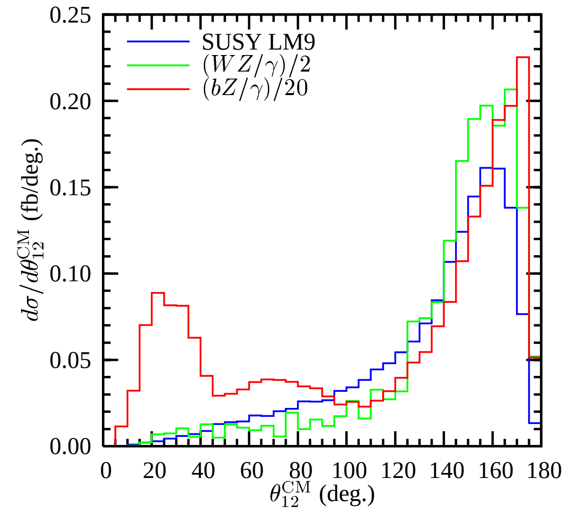
A $\not\!\!E_T$ cut demanding $\not\!\!E_T > 30$–40 GeV is very effective

$\not\!\!E_T$ is poorly measured

Angular correlations



Angles measured extremely well

All combinations different (θ_{12}^{CM} shown)

Demand $\theta_{12}^{\text{CM}} > 45^\circ$, $\theta_{13}^{\text{CM}} > 40^\circ$, $\theta_{23}^{\text{CM}} < 160^\circ$

Reduces B by 30% for 5% loss of S

Not optimized

Trileptons: SUSY & SM at CMS (+new cuts)

Channel	$N^l = 3$, NoJets	$M_{ll}^{\rm OSSF} < 75$ GeV	$\not\!\!E_T > 30$ GeV	Angular cuts
LM9	248	243	160	150
LM7	126	123	89	85
LM1	46	44	33	32
WZ/γ	1880	538	325	302
$t\bar{t}$	1540	814	696	672
tW	273	146	123	121
$t\bar{b}$	1.1	1.0	0.77	0.73
bZ/γ	14000	6870	270	177
cZ/γ	3450	1400	45	35
$b\bar{b}Z/\gamma$	8990	2220	119	103
$c\bar{c}Z/\gamma$	4680	1830	69	35
$b\bar{b}W$	9.1	7.6	5.6	5.3
$c\bar{c}W$	0.19	0.15	0.12	0.11

Significance of SUSY point LM9 in 30 fb^{-1}

1. Our calculations are LO.
   NLO K-factors are large (1.5–2) on most processes,
   BUT, jet veto will reduce this.

2. ISR is not well determined
   The rate of > 30 GeV jets can be changed by a factor of 4 depending on assumptions in PYTHIA about ISR.

We present our calculation, and one that scales down B by 4 to show the range of possible significances

	$N^l = 3$, NoJets	$M_{ll}^{\mathrm{OSSF}} < 75$ GeV	$\not{E}_T > 30$ GeV	Angular cuts
$S/\sqrt{B}_{\mathrm{LM9}}$	1.33	2.07(1.79)	3.93(3.74)	3.94(3.79)
$S/\sqrt{B}_{\mathrm{LM9}}^{\mathrm{CMS}\,j}$	2.63	4.09(3.54)	7.78(7.39)	7.79(7.49)

(Parentheses include leptons from fakes from CMS Table 6, Note 2006/113)

We will not know which ISR estimate is correct until we measure it at LHC

What have we learned about leptons from heavy-flavor (b,c) decays?

(Z.S., E. Berger, PRD 74, 033008 (2006); PRD 78, 034030 (08))

1. Heavy-flavor (b, c) decays to leptons will dominate low-p_T isolated leptons at LHC:
   Dileptons from $b\bar{b}/c\bar{c}$ and Wc $\sim 50\times$ all other backgrounds
   Trileptons from Z/γ^*+heavy flavors (HF) $\sim 10\times$ all other backgrounds
   A good estimate is to treat $1/200$ of every b or c as an isolated lepton.

2. For $H \to WW$, raising the minimum p_T is the most effective way to suppress leptons from HF
   ATLAS and CMS have taken this to heart.

3. Raising minimum p_T is not viable for SUSY trileptons, but could:
   (a) Require $\not{E}_T > 30$ GeV, $Z/\gamma^* + \mathrm{HF} \to Z/\gamma^* + \mathrm{HF}/30$ Hard to measure low $\not{E}_T$
   (b) Impose cuts on well-measured angles, Z/γ^*+HF reduced by 30%

4. Overall normalization is dominated by assumptions regarding ISR
   Huge uncertainties in effectiveness of jet veto

   If large ISR exists, may want to loosen jet veto to recover SUSY signal
   ISR questions will be resolved with initial data from LHC

Any signal that has low-p_T leptons MUST consider the background from heavy flavor (b, c) decays

Conclusions

In the joint session with ATLAS, Tom LeCompte said:

"We need to develop our own experience at the LHC."

I completely agree. I would add that we need to leverage our continually growing experience at the Tevatron.

— Many rare processes, or extreme regions of phase space, will play a significant role at LHC. The Tevatron is now collecting enough data with well-understood detectors to prepare us for when that LHC experience crashes over us.

Tom also said:

"We want to be able to compare our data with theory."

Improvements are needed in our theoretical understanding of:

isolated leptons, photons, jets, missing energy, etc.

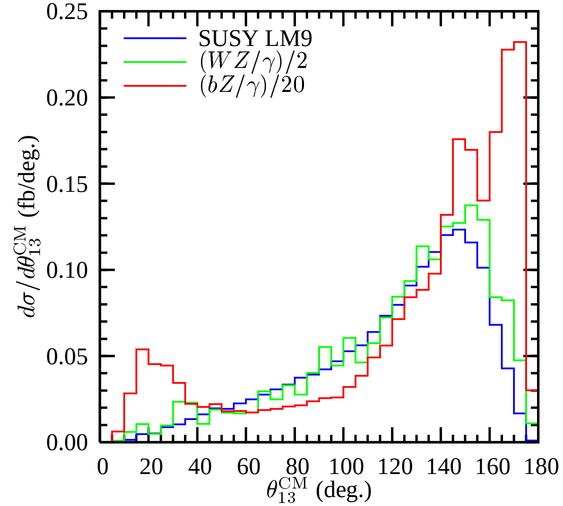
Our Tevatron experience will undoubtedly transfer to the LHC.

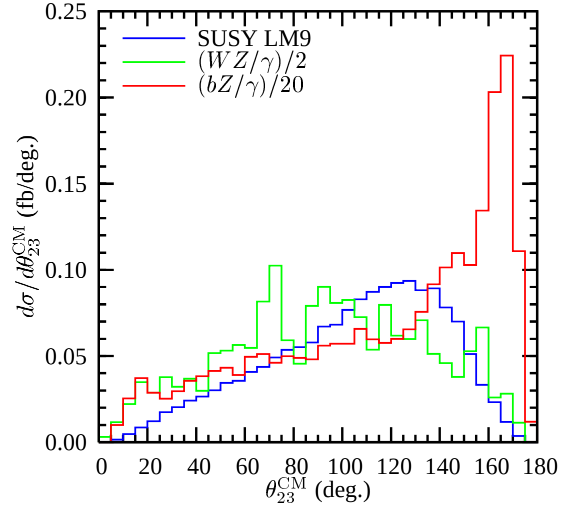
One of our jobs as theorists will be to ensure the *right* experience will be applied to exciting challenges ahead.

BACKUPS

Other angular correlations

Angles are well-measured, and defined in the trilepton CM frame.





Suggested cut: $\theta_{13}^{\rm CM} > 40^\circ$

Suggested cut: $\theta_{23}^{\rm CM} < 160^\circ$

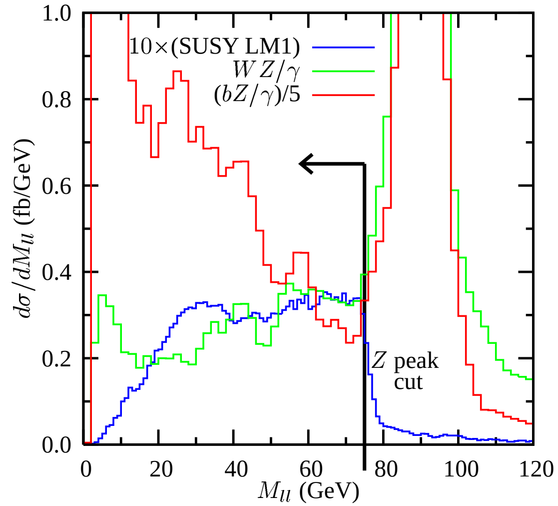
These cuts are almost free, and not optimized.

5% signal decrease, but 30% backgound decrease

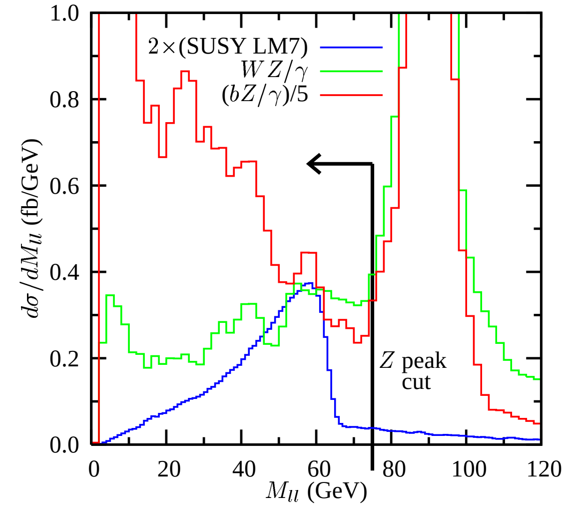
CMS SUSY points LM1, LM7

Representative opposite-sign same-flavor (OSSF) invariant masses

LM1



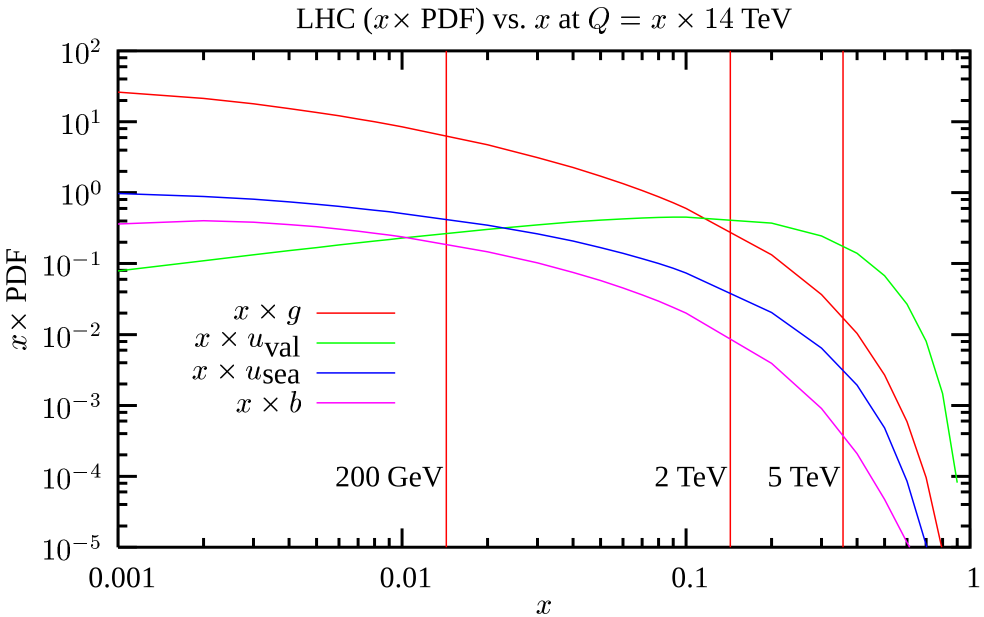
LM7



Signal endpoint above Z-peak cut and signal is small

LM7 similar to LM9, but smaller

PDFs control relevant physics at LHC



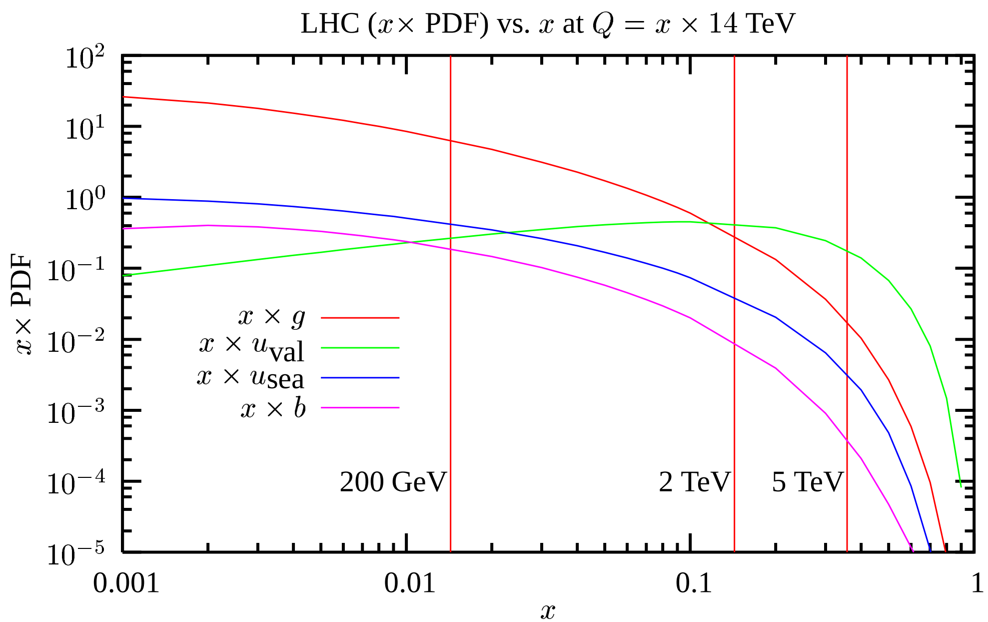
3 important pivot points:

200 GeV $u_{\text{val}} \approx u_{\text{sea}}$ — valence is important here.

2 TeV $u_{\text{val}} > g$ — above a TeV, valence quarks dominate.

5 TeV PDFs “run out” — nothing heavier gets produced on-shell.

PDFs control relevant physics at LHC



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5 TeV PDFs "run out" — nothing heavier gets produced on-shell.

The LHC is <u>not</u> a glue factory for physics you care about.

— Color-neutral particles couple to quarks, not gluons.

— Colored particles tend to be heavy (1+ TeV), and see valence quarks.

This figure is almost identical to the Tevatron (at 7 times the energy).

What differs is that LHC is a pp collider. This changes everything.

PDFs at Tevatron ∼ scaled down LHC