Low-Scale Technicolor at the Tevatron and the LHC

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with E.Eichten, A. Martin + many others mentioned later

Don Quixote and Sancho Panza

What's in the talk?

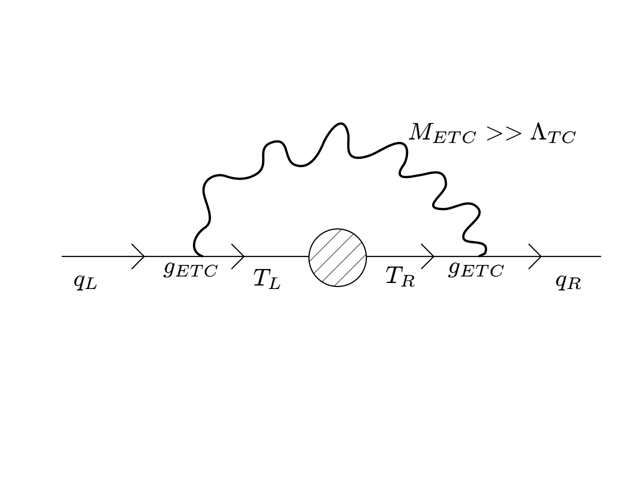
- Lightning intro to TC, ETC, WTC and all that
- Consequences of WTC --> LSTC, very narrow V_T
- $\rho_T \to W\pi_T$ at the Tevatron
- Other LSTC signatures at the Tevatron
- LSTC discovery channels at the LHC

Introduction to TC, etc.

- TC = new strong int'n of massless T-fermions at $\Lambda_{TC} =$ several 100 GeV
- T-fermions $T_{i;L,R} = (U_i, D_i)_{L,R}$, in complex IR's of G_{TC} and LH doublets, RH singlets of $(SU(2) \otimes U(1))_{EW}$
- $\langle \bar{T}_L T_R \rangle \neq 0 \Rightarrow (SU(2) \otimes U(1))_{EW} \rightarrow U(1)_{EM}$

  with $\rho \equiv M_W / M_Z \cos\theta_W = 1 + \mathcal{O}(\alpha)$

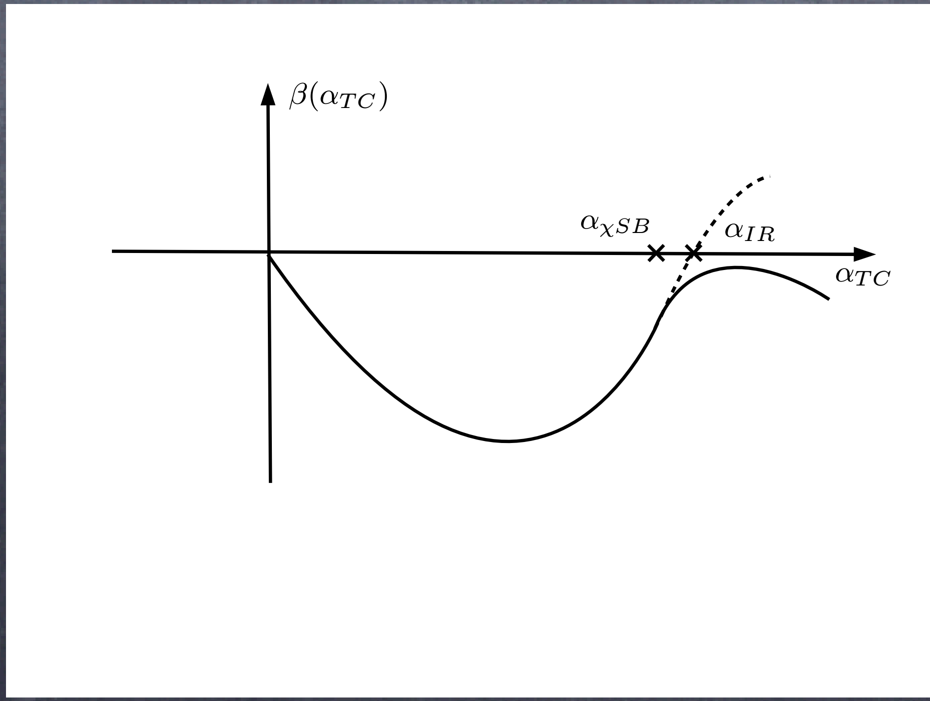
- Extended TC -- generates $m_{q.\ell}$:



- $M_{ETC}/g_{ETC} \gtrsim 100'\mathrm{s}$ of TeV to suppress FCNC's

- Walking TC -- $\alpha_{TC}(\Lambda_{TC})$ near an IRFP,

  runs VERY slowly, almost to M_{ETC}



Consequences of WTC

1) LSTC: Walking (IRFP) needs MANY T-fermions

=> Low-scale Λ_{TC} (i.e., $F^2_{\pi_T} \ll F^2_{EW} = (246\,\mathrm{GeV})^2$)

- $\bar{T}T$ bound states $V_T = \rho_T, \omega_T, a_T$ with $M_{V_T} \ll 1\,\mathrm{TeV}$
- V_T produced via DY process in $\bar{q}q$ collisions
- π_T accessed via V_T decays; $\pi_T \to \bar{q}q', \bar{\ell}\ell'$ (heavy??)

2) WTC enhances M_{π_T} $(\propto \langle \bar{T}T \rangle)$ MORE than M_{ρ_T}

- => Expect $M_{\rho_T} < 2M_{\pi_T}$
- $M_{\omega_T} \cong M_{\rho_T}$ (isospin), $M_{a_T} \simeq M_{\rho_T}$ + a bit

3) Only weakly-coupled decay channels are open to the lightest V_T :

$$\rho_T \to W\pi_T,\, \gamma\pi_T;\, WZ,\, WW, \gamma W/Z \quad (W \simeq W_L)$$

$$\omega_T \to \gamma\pi_T;\, \gamma Z;\, \ell^+\ell^- \quad (Z \simeq Z_L)$$

$$a_T \to \gamma\pi_T,\, W_\perp\pi_T;\, \gamma W_L/Z_L;\, \ell^+\ell^-,\, \ell^\pm\nu_\ell$$

$$\Rightarrow \Gamma(\rho_T) \lesssim 1\,\mathrm{GeV}, \quad \Gamma(\omega_T,\, a_T) \lesssim 0.1\,\mathrm{GeV}$$

LSTC at the Tevatron

- Based on Technicolor Straw-Man model of LSTC in Pythia (thanks to Steve Mrenna)

- All dedicated studies & searches so far use standard TCSM parameters: (Explain!)

$$\sin\chi = 1/3,\ Q_U = Q_D + 1 = 1,$$
$$N_{TC} = 4,\ \ M_{V_i} = M_{A_i} = M_{\rho_T}$$

- Limits from CDF on $\rho_T \to W\pi_T \to \ell^\pm \nu_\ell\, b + \mathrm{jet}$

- and Dzero on $\rho_T \to WZ \to \ell^\pm \nu_\ell \ell^+ \ell^-$

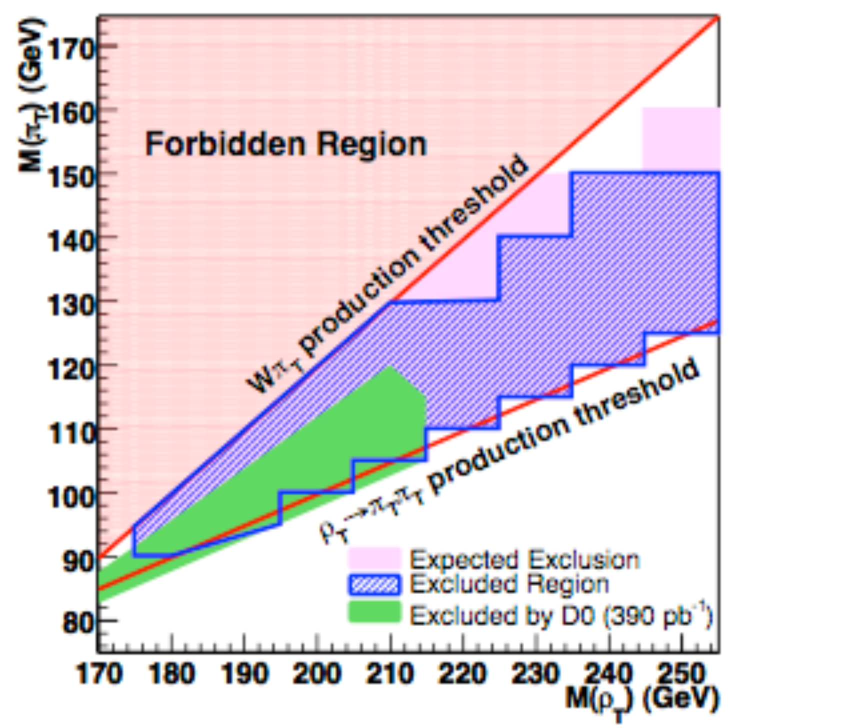


FIG. 3: 95% confidence level excluded region on technicolor particles production cross section times branching fraction as a function of $m(\rho_T)$ and $m(\pi_T)$ mass hypothesis. The expected excluded region from background-only pseudoexperiments are shown with the observed results from this analysis and D0 searches.

CDF $\rho_T \to W\pi_T \to \ell^\pm \nu_\ell b +$ jet exclusion

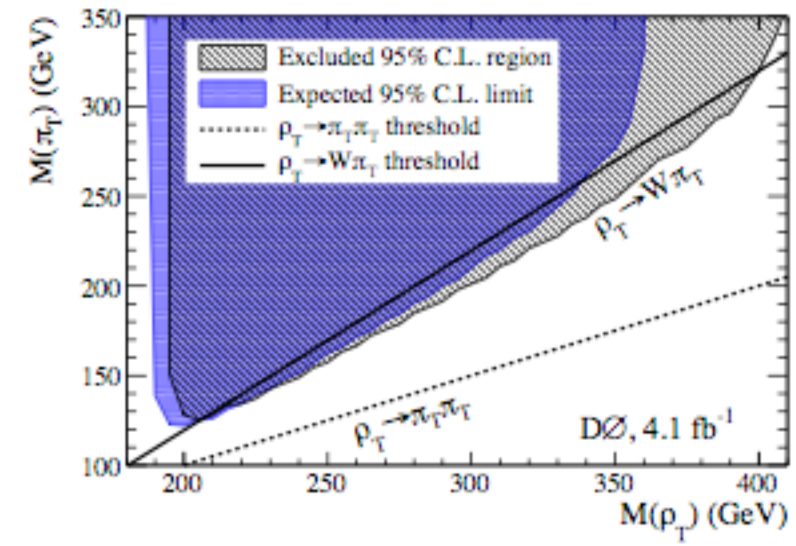


FIG. 4: Expected and excluded areas of the π_T *vs.* ρ_T masses are given with the thresholds of the $\rho_T \to W\pi_T$ and $\rho_T \to \pi_T\pi_T$ overlaid (color online).

DØ $\rho_T \to WZ \to \ell^\pm \nu_\ell\, \ell^+\ell^-$ exclusion

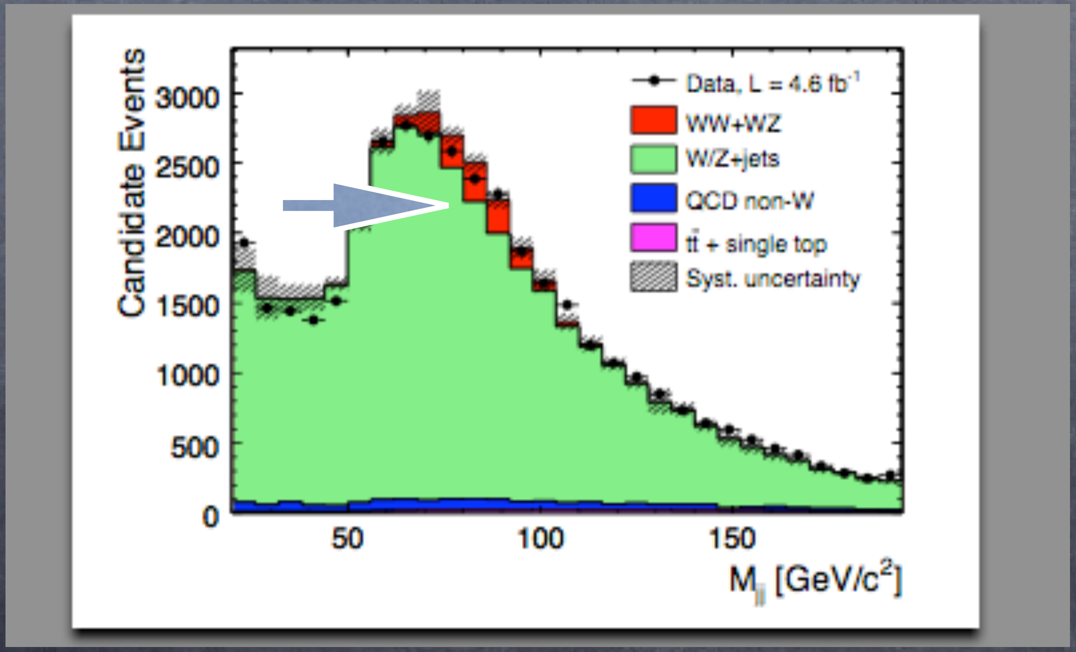
$\rho_T \to W\pi_T \to \ell^\pm \nu_\ell \, jj$ in CDF

E. Eichten & KL (1989); EE, KL & J. Womersley (1996)

EE, KL & Adam Martin arXiV:1104.0906

CDF has observed $\bar{p}p \to WW/WZ \to \ell^\pm \nu_\ell jj$

without b-tagging!



Phys.Rev.D82:112001,2010

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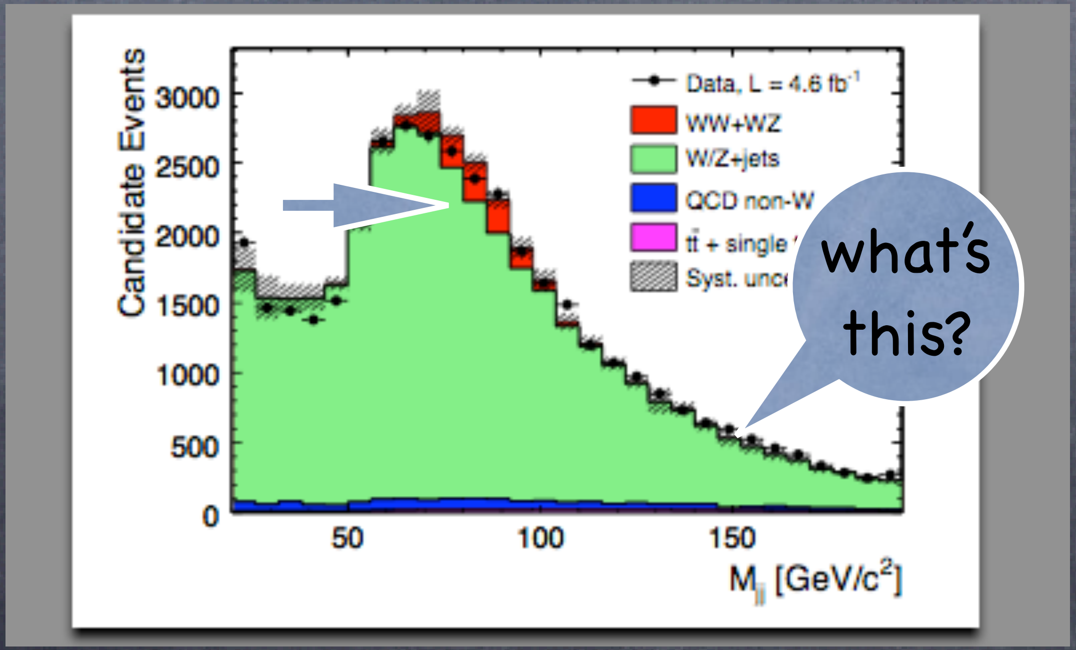


Phys.Rev.D82:112001,2010

CDF Cuts for Wjj excess:

- one e or μ, $p_T > 20\,\mathrm{GeV}$, $|\eta| < 1.0$
- exactly two jets, $p_T > 30\,\mathrm{GeV}$, $|\eta| < 2.4$
- $\Delta R(\ell, j) > 0.52$
- $p_T(j_1 j_2) > 40\,\mathrm{GeV}$
- $E_{T,\mathrm{miss}} > 25\,\mathrm{GeV}$
- $M_T(W) > 30\,\mathrm{GeV}$
- $|\Delta\eta(j_1 j_2)| < 2.5$
- $|\Delta\phi(E_{T,\mathrm{miss}}, j_1)| > 0.4$

Invariant Mass Distribution of Jet Pairs Produced in Association with a W boson in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

T. Aaltonen,[21] B. Álvarez González[w],[9] S. Amerio,[41] D. Amidei,[32] A. Anastassov,[36] A. Annovi,[17] J. Antos,[12]

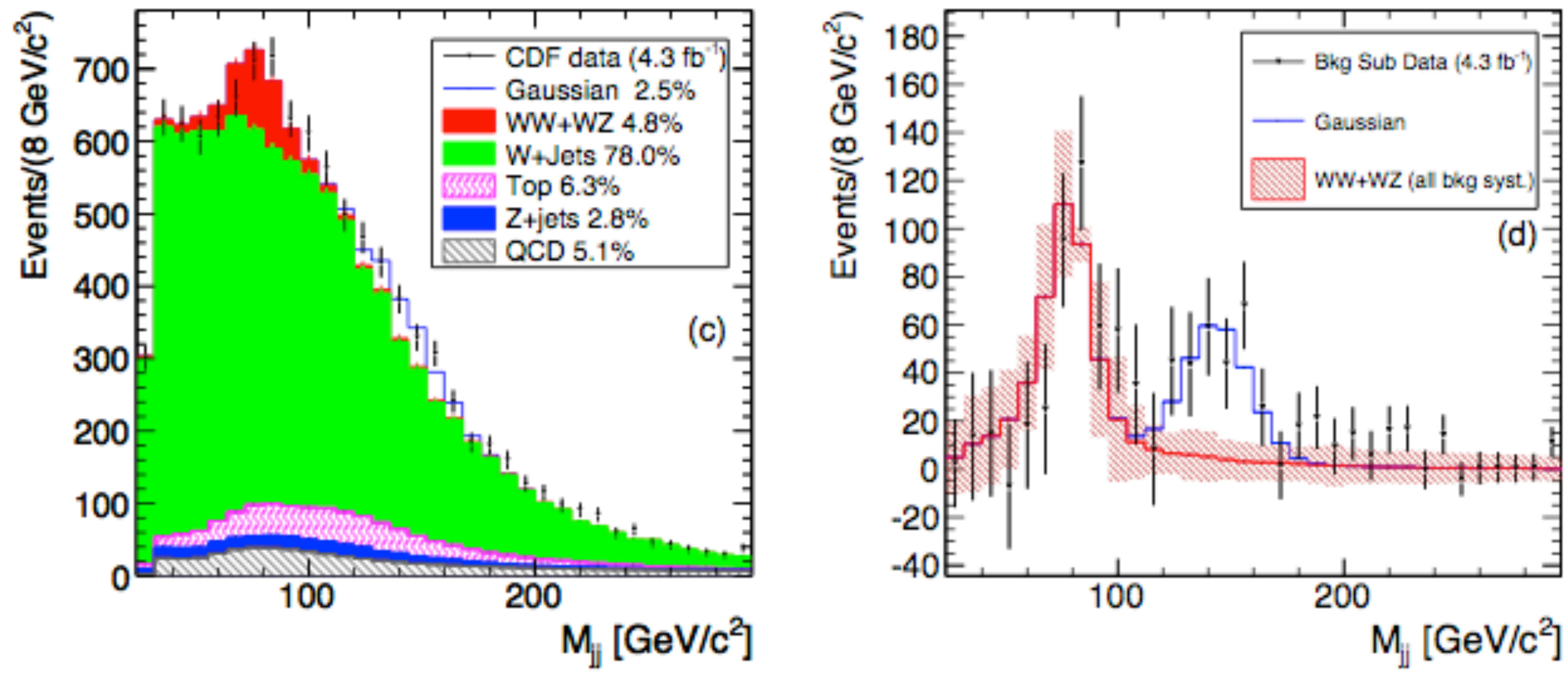
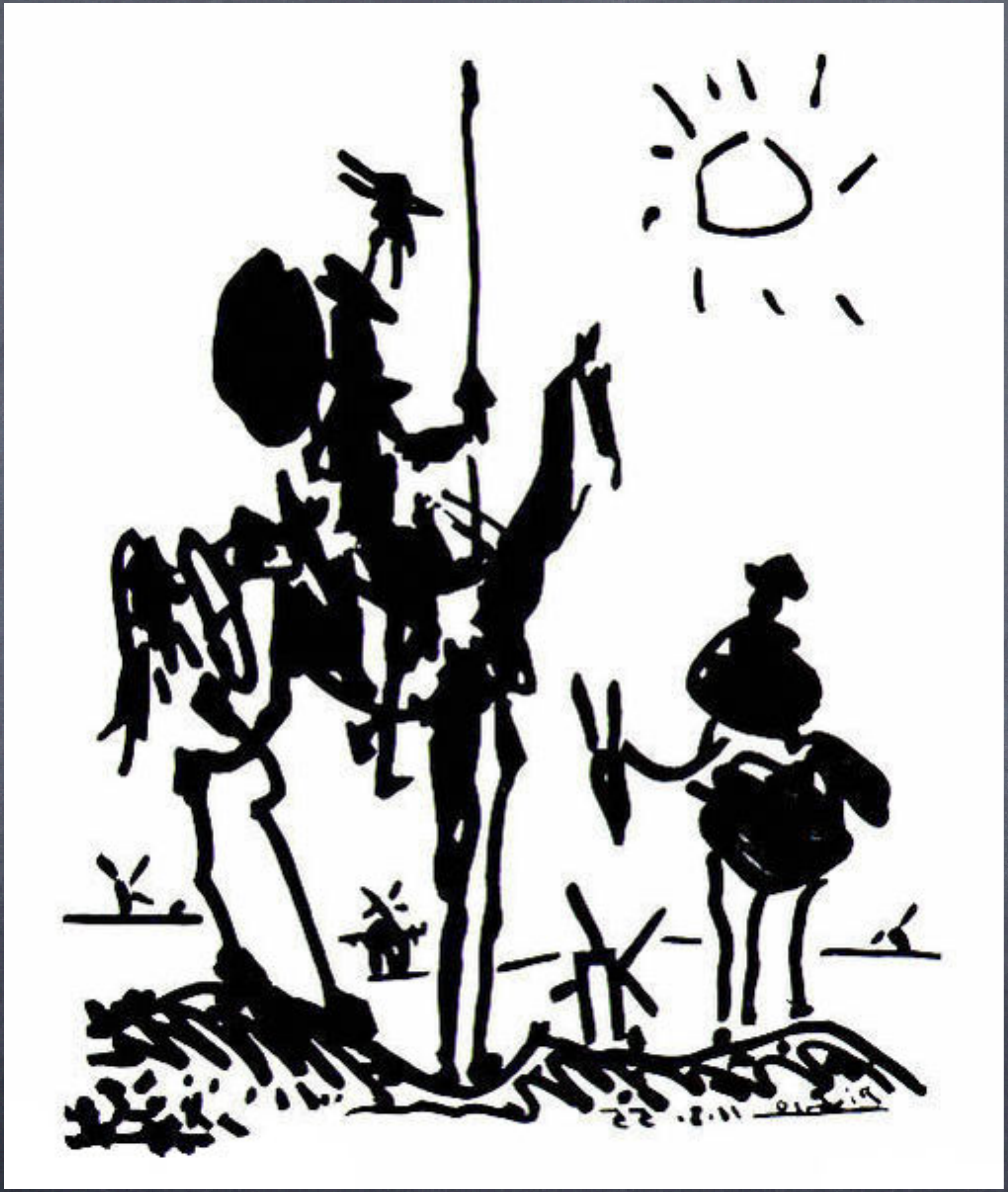


FIG. 1: The dijet invariant mass distribution. The sum of electron and muon events is plotted. In the left plots we show the fits for known processes only (a) and with the addition of a hypothetical Gaussian component (c). On the right plots we show, by subtraction, only the resonant contribution to M_{jj} including WW and WZ production (b) and the hypothesized narrow Gaussian contribution (d). In plot (b) and (d) data points differ because the normalization of the background changes between the two fits. The band in the subtracted plots represents the sum of all background shape systematic uncertainties described in the text. The distributions are shown with a 8 GeV/c^2 binning while the actual fit is performed using a 4 GeV/c^2 bin size.

$$CDF: \ \sigma(\bar{p}p \to WX)\, B(X \to jj) = \mathcal{O}(4\,\mathrm{pb})$$

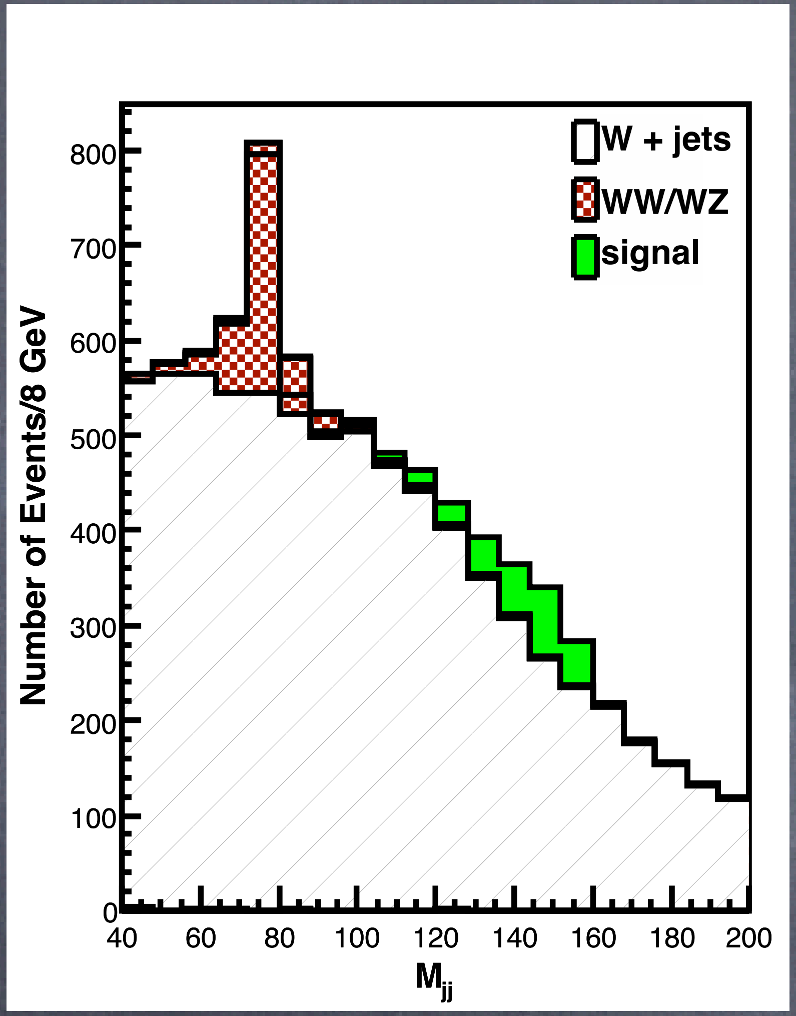


CDF Cuts

$$M_{\rho_T} = 290\,\mathrm{GeV}, \quad M_{\pi_T} = 160\,\mathrm{GeV}$$

$$\sigma(\bar{p}p \to \rho_T \to W\pi_T)\,B(\pi_T \to jj) = 2.4\,\mathrm{pb}$$

Dijet simulation for 4.3 fb^{-1} (no b-tag!)



CDF cuts

S/B = 250/1600

No energy smearing

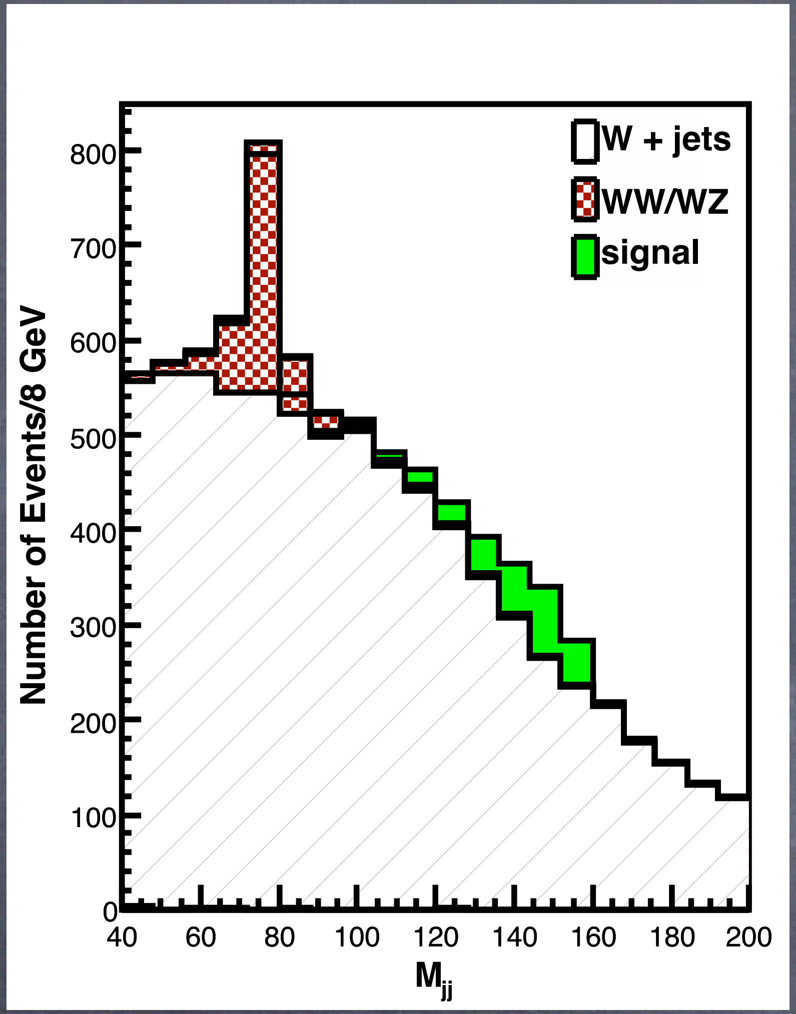
+ ELM Cuts:

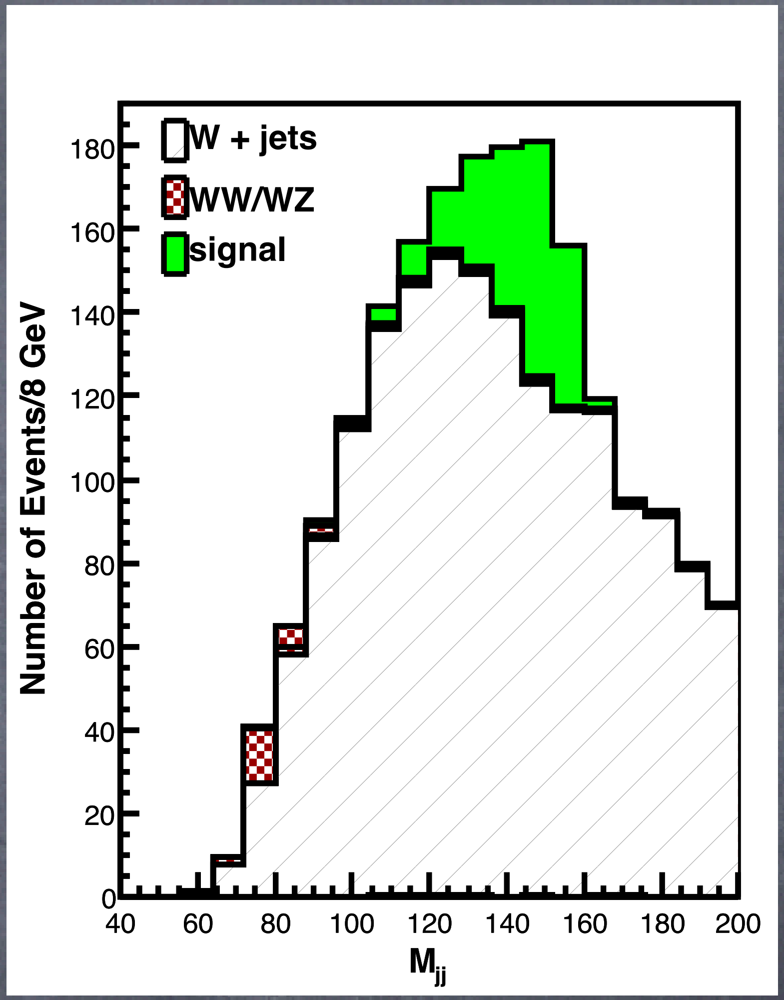
- Combine a 3rd jet with one of j_1, j_2 if it's within $\Delta R = 1.5$ of either of them.
- Topological cuts ($\rho_T \to W\pi_T$ kinematics):
  - $\Delta\phi(j_1, j_2) > 1.75$
  - $p_T(W) > 60\,\mathrm{GeV}$

$$M_{\rho_T} = 290\,\mathrm{GeV}, \quad M_{\pi_T} = 160\,\mathrm{GeV}$$

$$\sigma(\bar{p}p \to \rho_T \to W\pi_T)\,B(\pi_T \to jj) = 2.4\,\mathrm{pb}$$

Dijet simulation for 4.3 fb^{-1} (no b-tag!)





CDF cuts

S/B = 250/1600

CDF+ELM cuts

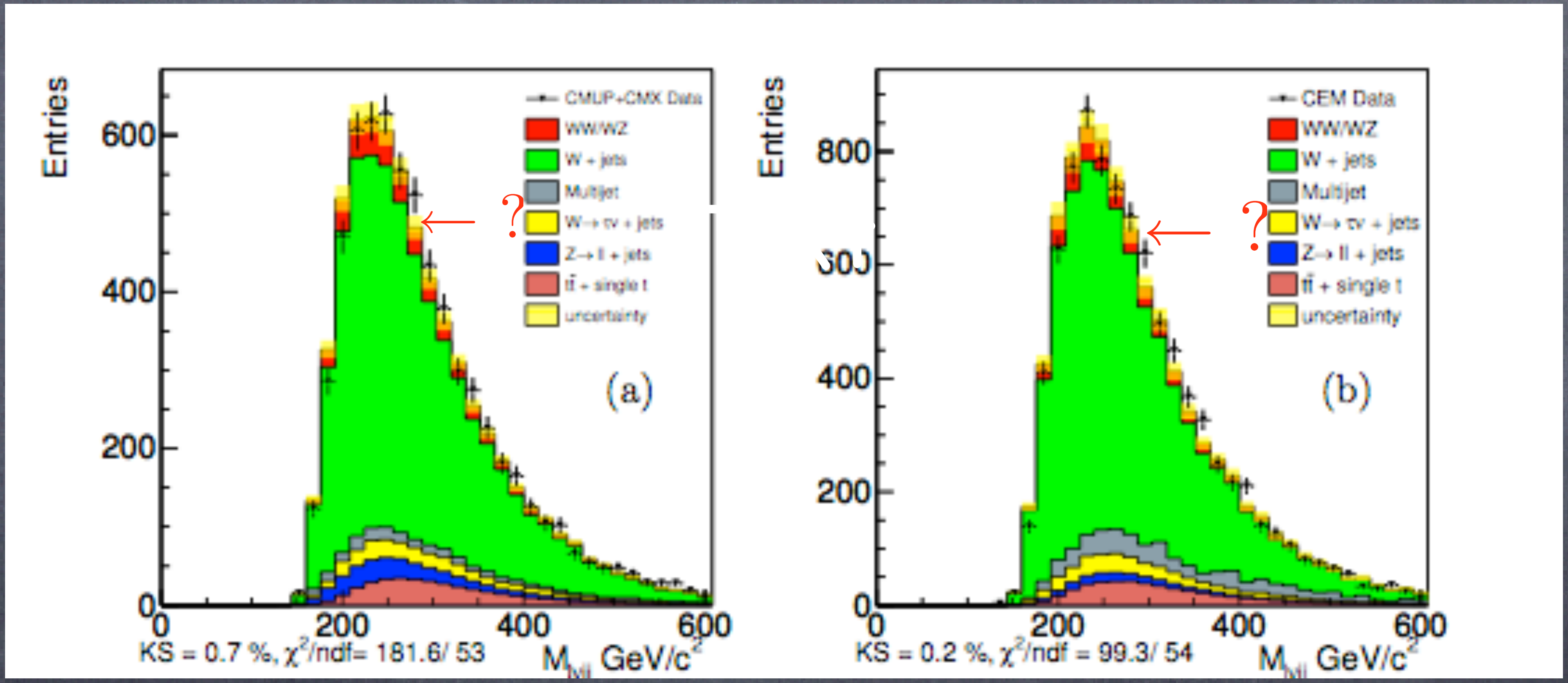
S/B = 200/880

No energy smearing

CDF + ELM Cuts

LSTC ==> there must be a ρ_T peak near 300 GeV in M_{Wjj}

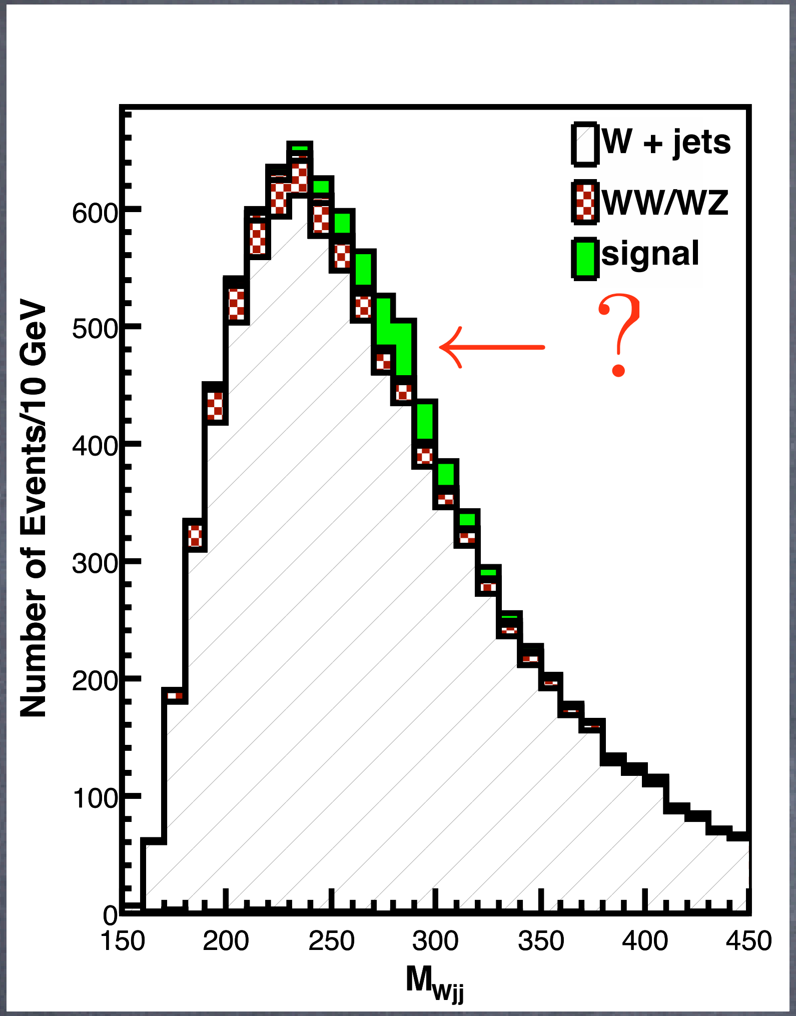
From V. Cavaliere's thesis:



↑ muons ↑ electrons

$$M_{\rho_T} = 290\,\mathrm{GeV}, \quad M_{\pi_T} = 160\,\mathrm{GeV}$$

Wjj simulation for 4.3 fb^{-1} (no b-tag!)

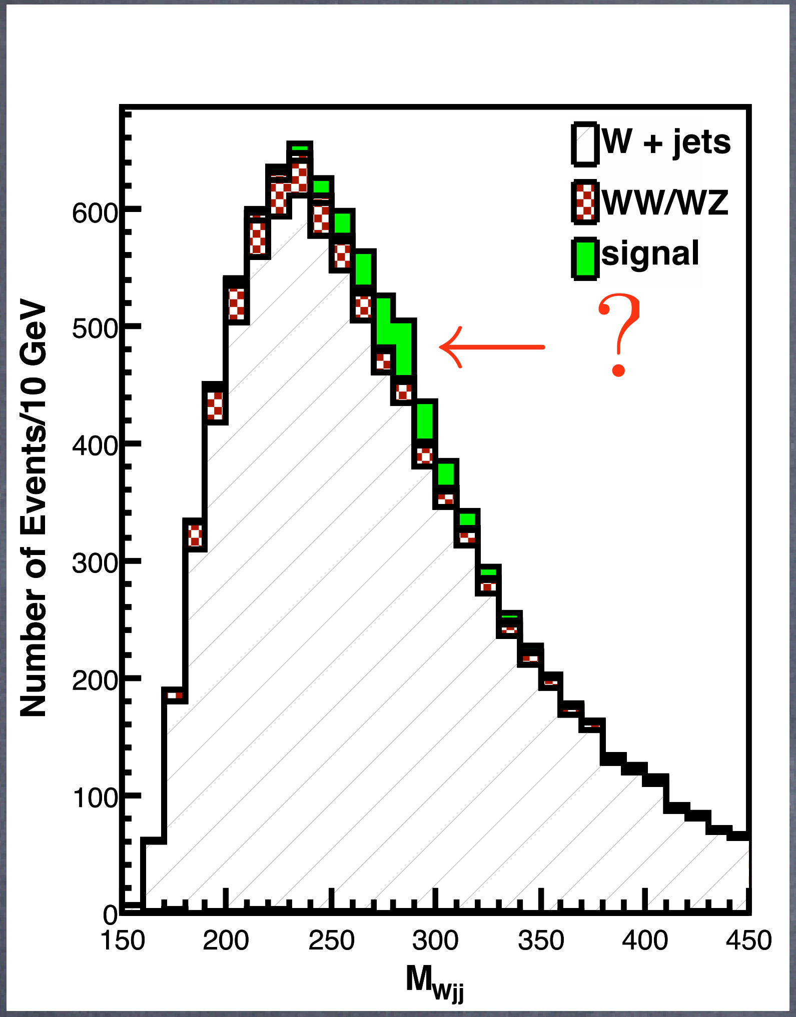


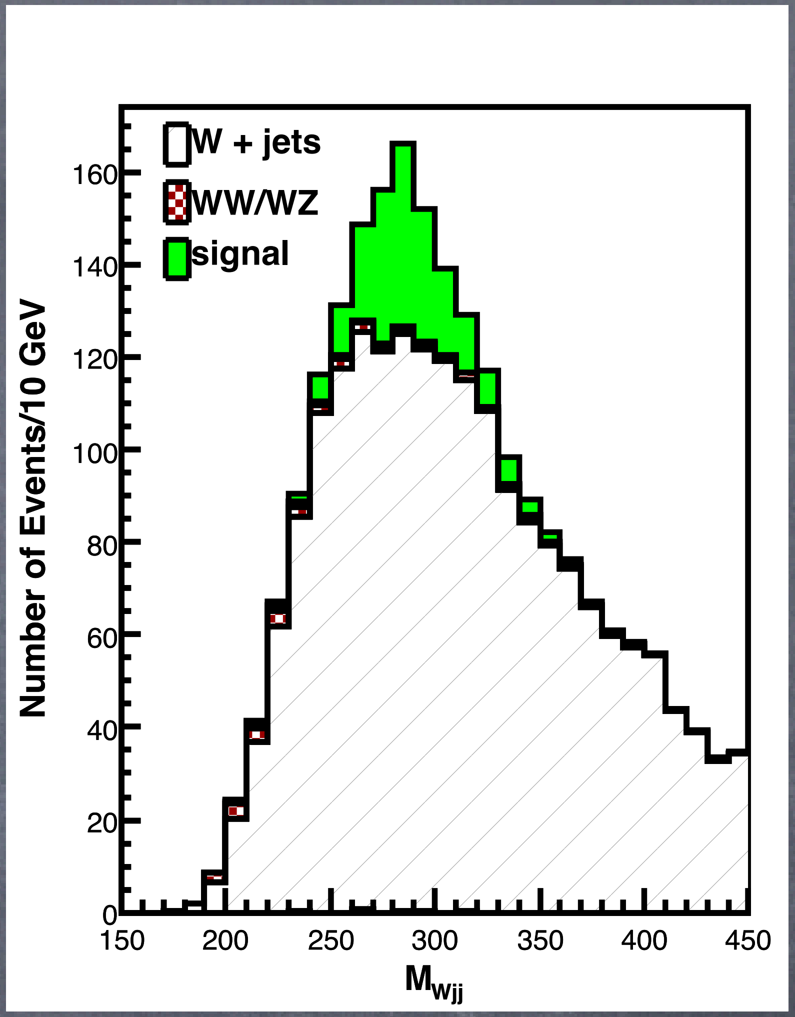
CDF cuts

S/B = 235/3400

$M_{\rho_T} = 290\,\mathrm{GeV}, \quad M_{\pi_T} = 160\,\mathrm{GeV}$

Wjj simulation for 4.3 fb^{-1} (no b-tag!)





CDF cuts

S/B = 235/3400

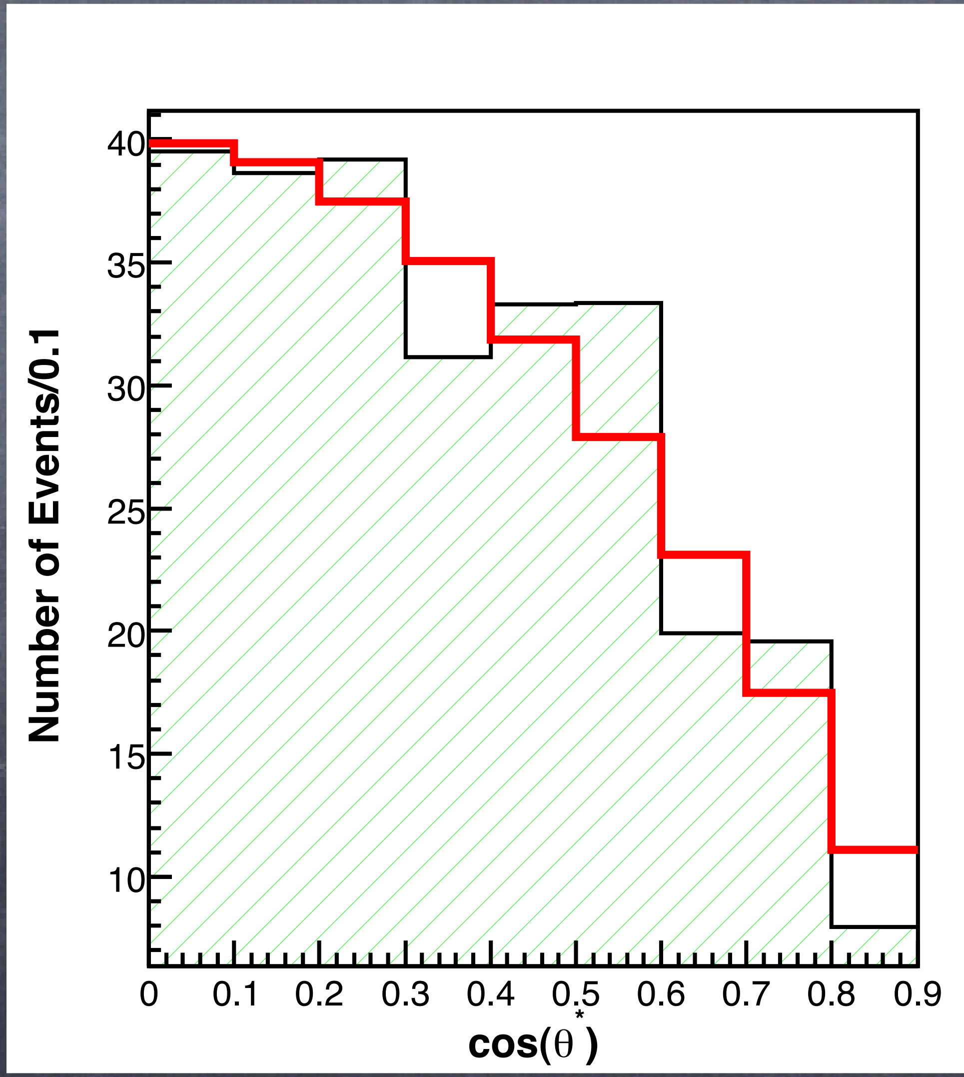
CDF+ELM cuts

S/B = 215/1215

What else can be done to reveal ρ_T ?

e.g., $\sigma(\bar{q}q \to \rho_T \to W\pi_T) \propto \sin^2\theta$

back off p_T cut on W: $p_T(W) > 40\,\mathrm{GeV}$



Other LSTC signatures at the Tevatron:

- Expect $M_{\omega_T} \cong M_{\rho_T}, \quad M_{a_T} = M_{\rho_T} + \text{a bit}$

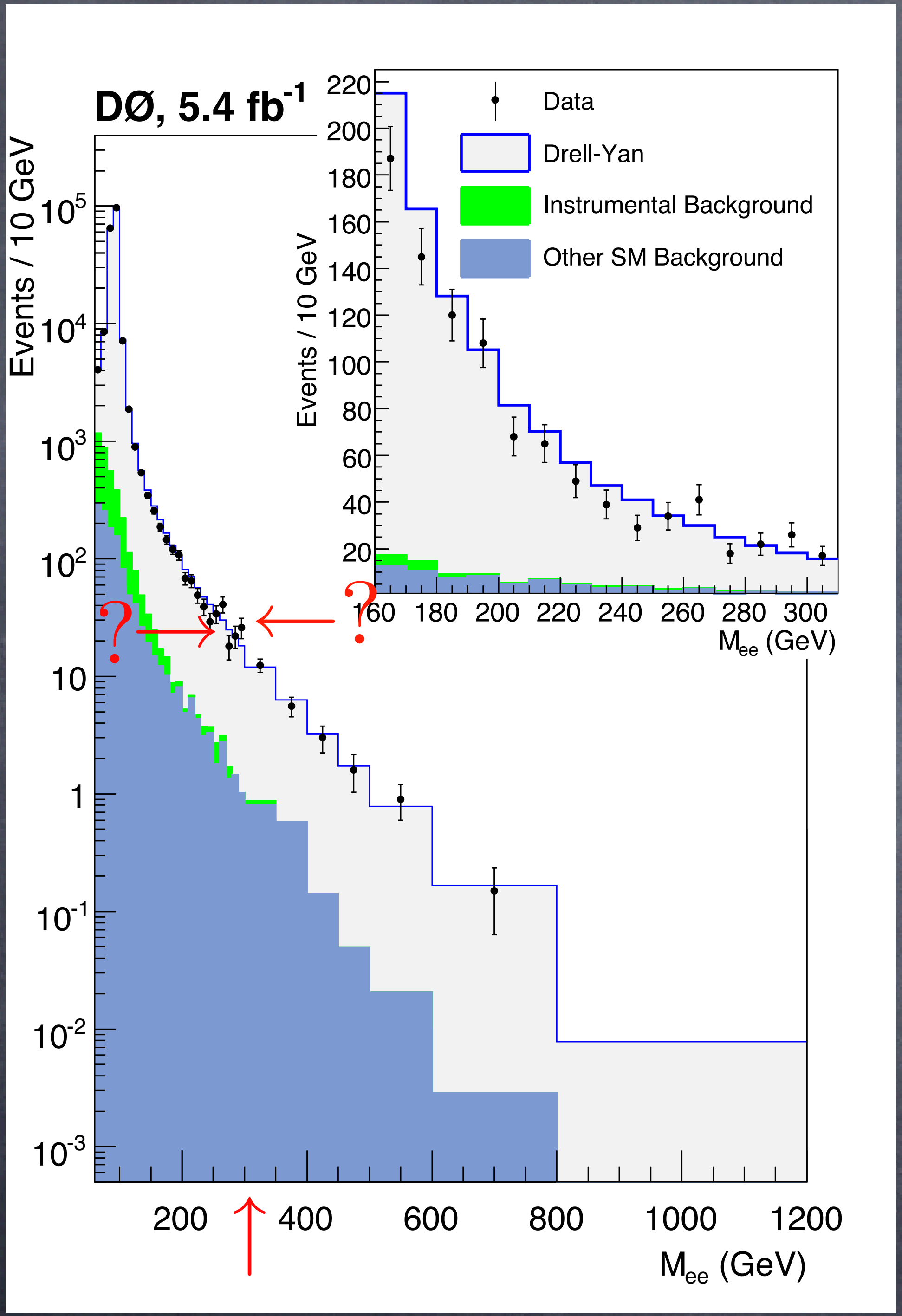
  Take $M_{\omega_T} = 290\,\text{GeV}, \quad M_{a_T} = 1.1 M_{\rho_T} = 320\,\text{GeV}$

- $\sigma(\omega_T \to \gamma \pi_T^0 \to \gamma \bar{b} b) \simeq 80\,\text{fb}$
  $\sigma(a_T^{\pm} \to \gamma \pi_T^{\pm} \to \gamma \bar{b} q) \simeq 185\,\text{fb}$

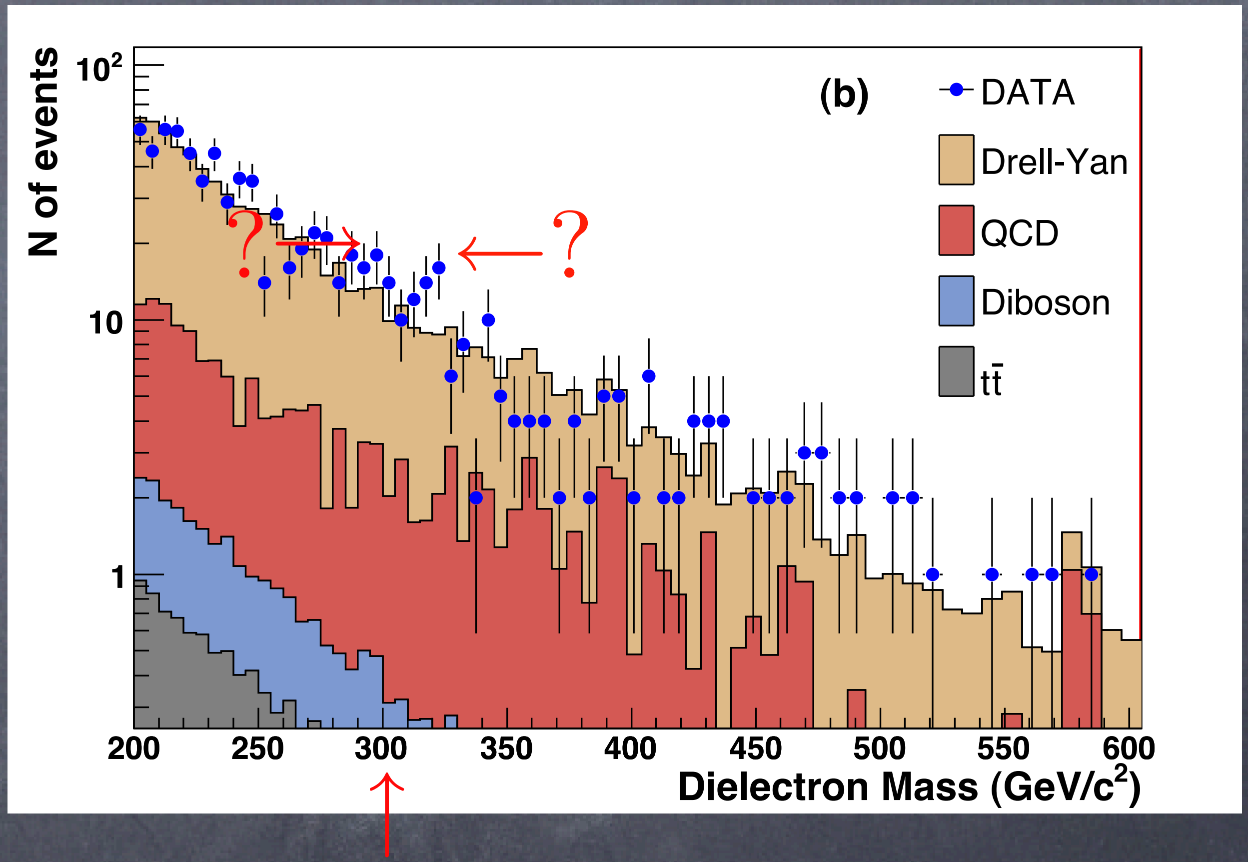
  (for $Q_U = Q_D + 1 = 1$)

- $\sigma(\omega_T, \rho_T^0 \to e^+ e^-) \simeq 12\,\text{fb}$
  $\sigma(a_T^0 \to e^+ e^-) \simeq 7\,\text{fb}$

$$\sigma(\omega_T, \rho_T^0 \to e^+e^-) \simeq 12\,\mathrm{fb}, \quad \sigma(a_T^0 \to e^+e^-) \simeq 7\,\mathrm{fb}$$



Dzero -- 5.4 fb^{-1}



CDF -- 5.7 fb^{-1}

"The 2nd most significant excess is at ~320GeV"

LSTC at the LHC

- Les Houches 2009 study for
  $\sqrt{s} = 10\,(\mathrm{not}\,7)\,\mathrm{TeV}, \quad \int \mathcal{L} dt \simeq 1\,\mathrm{fb}^{-1}$
- Focus on γ, e, μ, ν final states -- no jets!
  smaller S, much smaller B
- Could $\rho_T \to Wjj$ be seen at the LHC??

Discovery Channels of ρ_T, ω_T, a_T at the LHC

$$\rho_T \to W^\pm Z^0 \to \ell^\pm \ell^+ \ell^- \nu_\ell$$

$$\rho_T^\pm,\, a_T^\pm \to \gamma W^\pm \to \gamma \ell^\pm \nu_\ell$$

$$\omega_T,\, \rho_T^0,\, a_T^0 \to \ell^+ \ell^-$$

$$\omega_T \to \gamma Z^0 \to \gamma \ell^+ \ell^-$$ difficult!

$$\rho_T^\pm,\, a_T^\pm \to \ell^\pm \nu_\ell$$ doable, but not discovery

LSTC at (10 TeV!) LHC -- Simulations for $\sim 1\,\mathrm{fb}^{-1}$

Case	M_{ρ_T}	M_{a_T}	M_{π_T}		$\sigma(WZ)$	$\sigma(\gamma W)$	$\sigma(\gamma Z)$	$\sigma(e^+e^-)$
1a	225	250	150		230	330	60	675
1b	225	250	140		205	285	40	505
2a	300	330	200		75	105	11	135
2b	300	330	180		45	85	7	90
3a	400	440	275		22	40	4	40
3b	400	440	250		14	35	3	30

LSTC at (7 TeV!) LHC -- Simulations for $\sim 1\,\mathrm{fb}^{-1}$

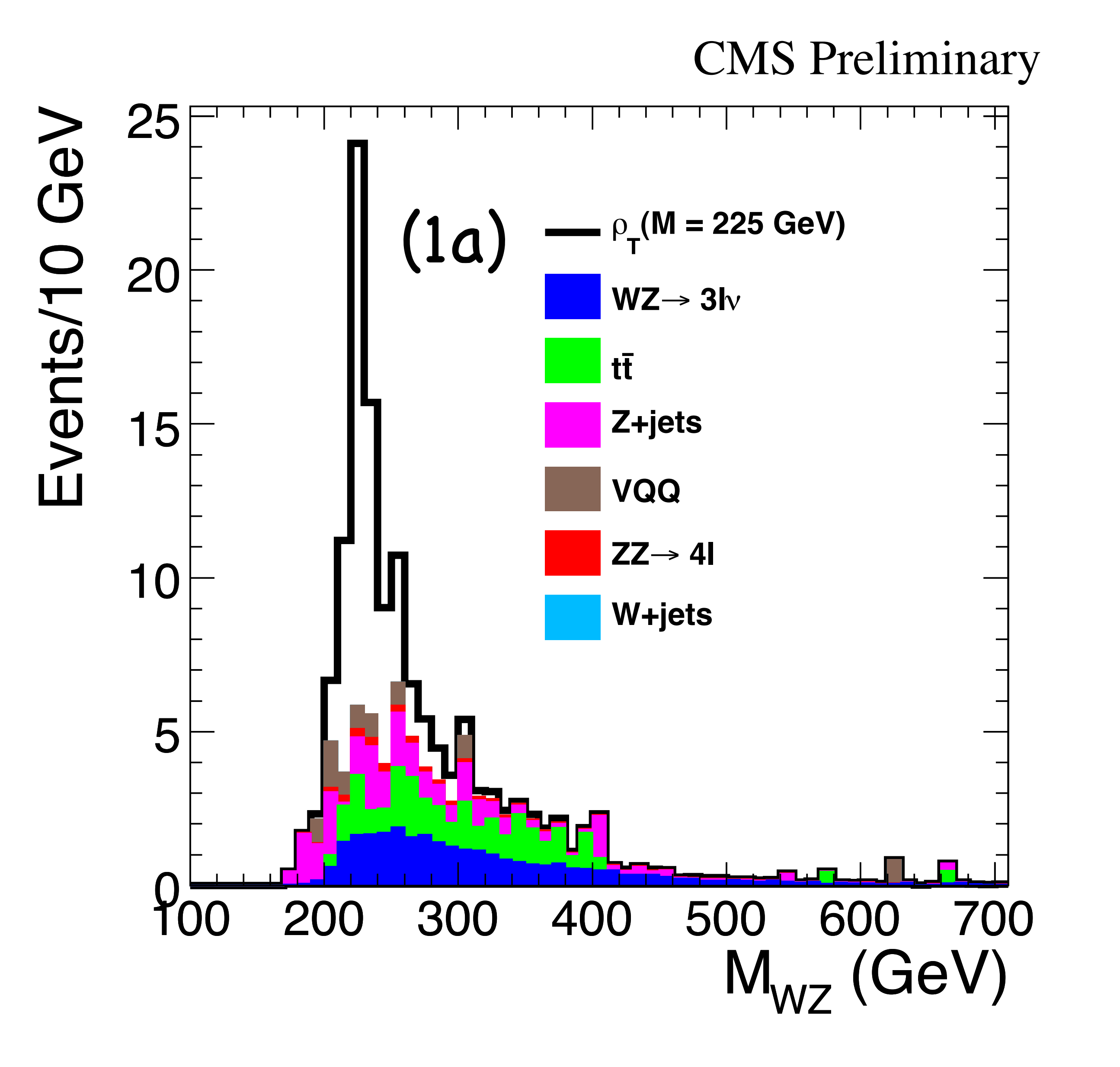
Case	M_{ρ_T}	M_{a_T}	M_{π_T}		$\sigma(WZ)$	$\sigma(\gamma W)$	$\sigma(\gamma Z)$	$\sigma(e^+e^-)$
CDF	290	320	160		24	51	5	25+ 25

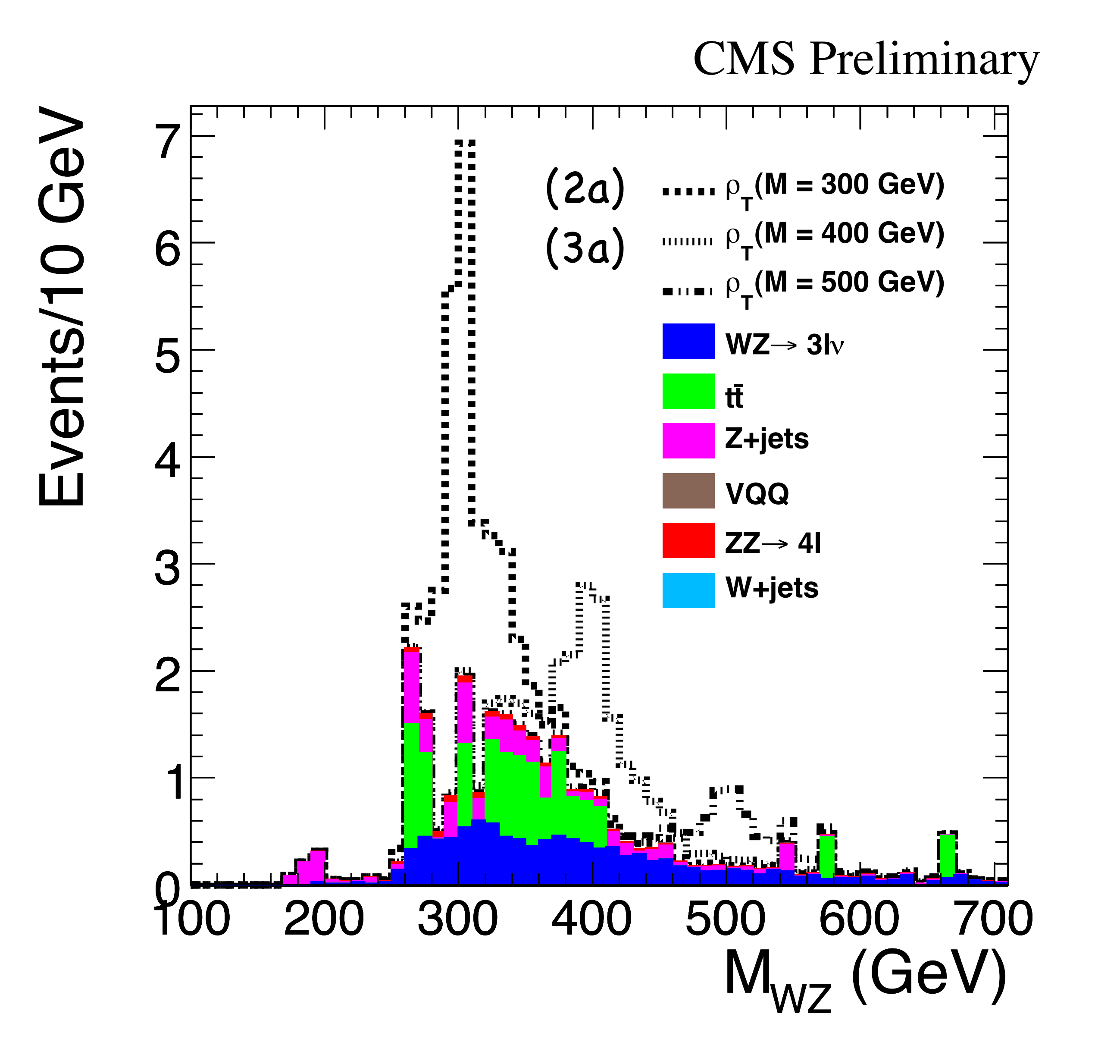
NO K-factor

S only
B = 60--40
in +-10 GeV

$$\rho_T \to W^{\pm}Z^0 \to \ell^{\pm}\ell^{+}\ell^{-}\nu_\ell$$

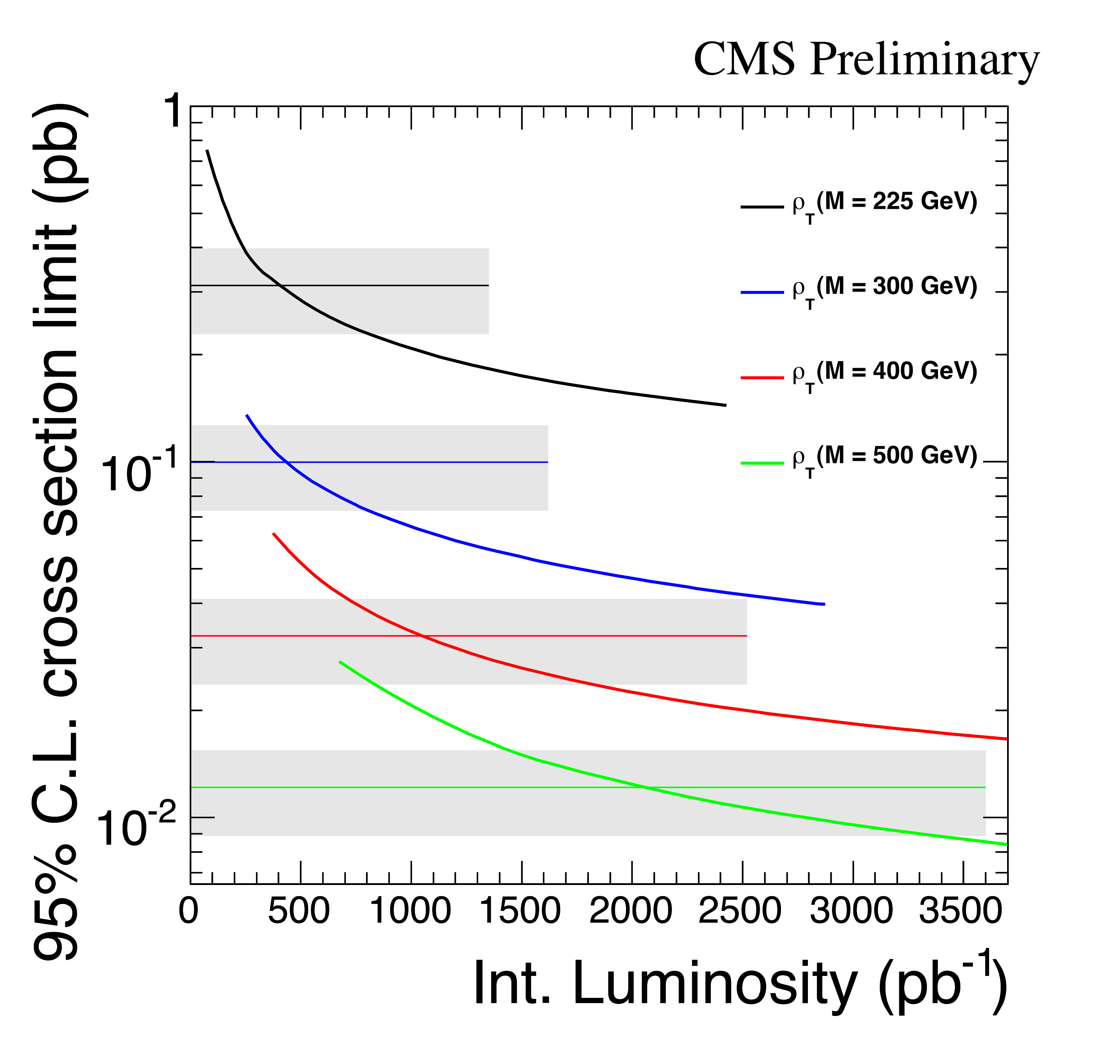
T. Bose, E. Carrera, Y. Maravin (CMS)





Normalized to $\int \mathcal{L}dt = 1\,\mathrm{fb}^{-1}$

K-factor = 1.35



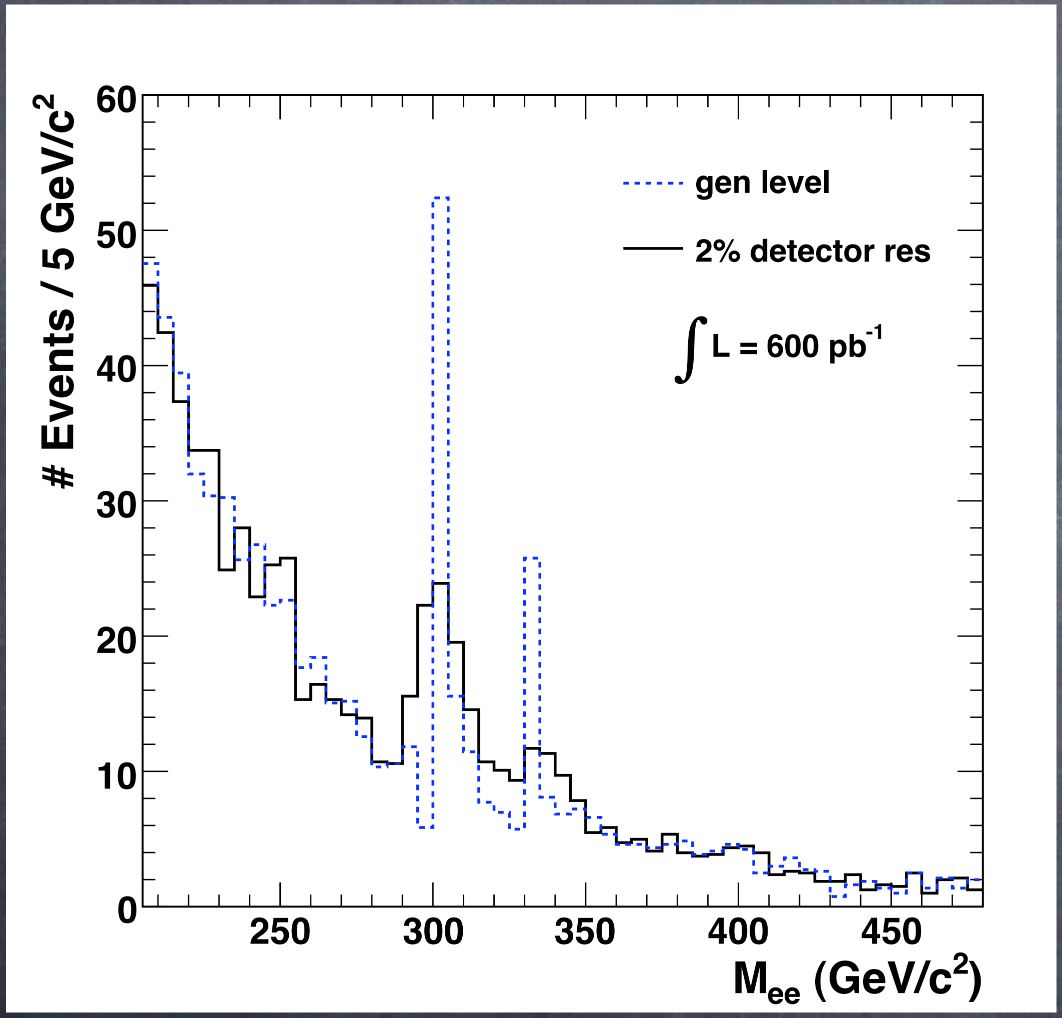
K-factor = 1.35

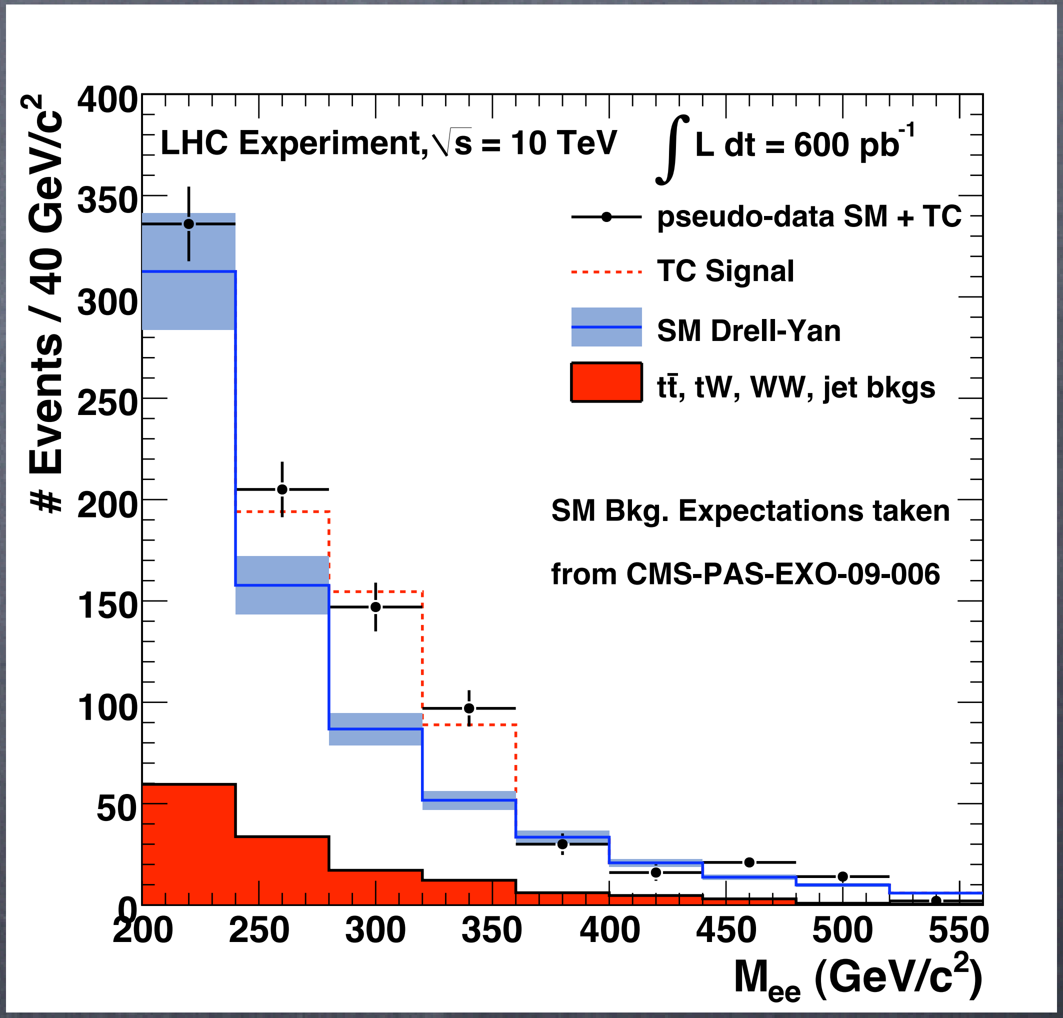
800--2550 fb needed for $M_{\rho_T} = 300, \quad M_{\pi_T} = 180\,\mathrm{GeV}$

$\rho_T^0, \underline{\omega_T}, \underline{a_T}^0 \to e^+e^-$

S.J. Harper (CMS)

N.B.: This -> 0 if $Q_U + Q_D = 0$; here $Q_U + Q_D = 1$





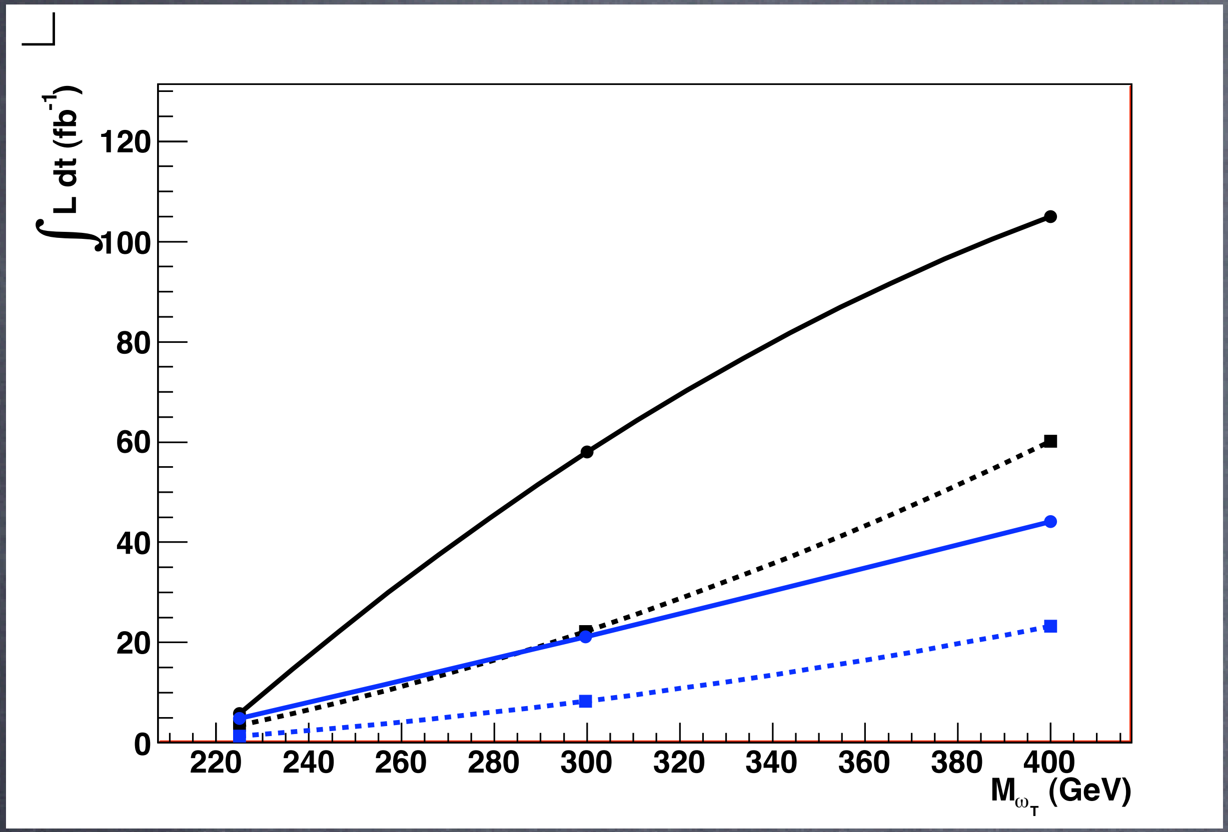
Left: Case 2a at generator level and after detector resolution.
Right: Case 2a pseudo-exp't with SM bkgds; $E_T(e^\pm) > 50\,\mathrm{GeV}$

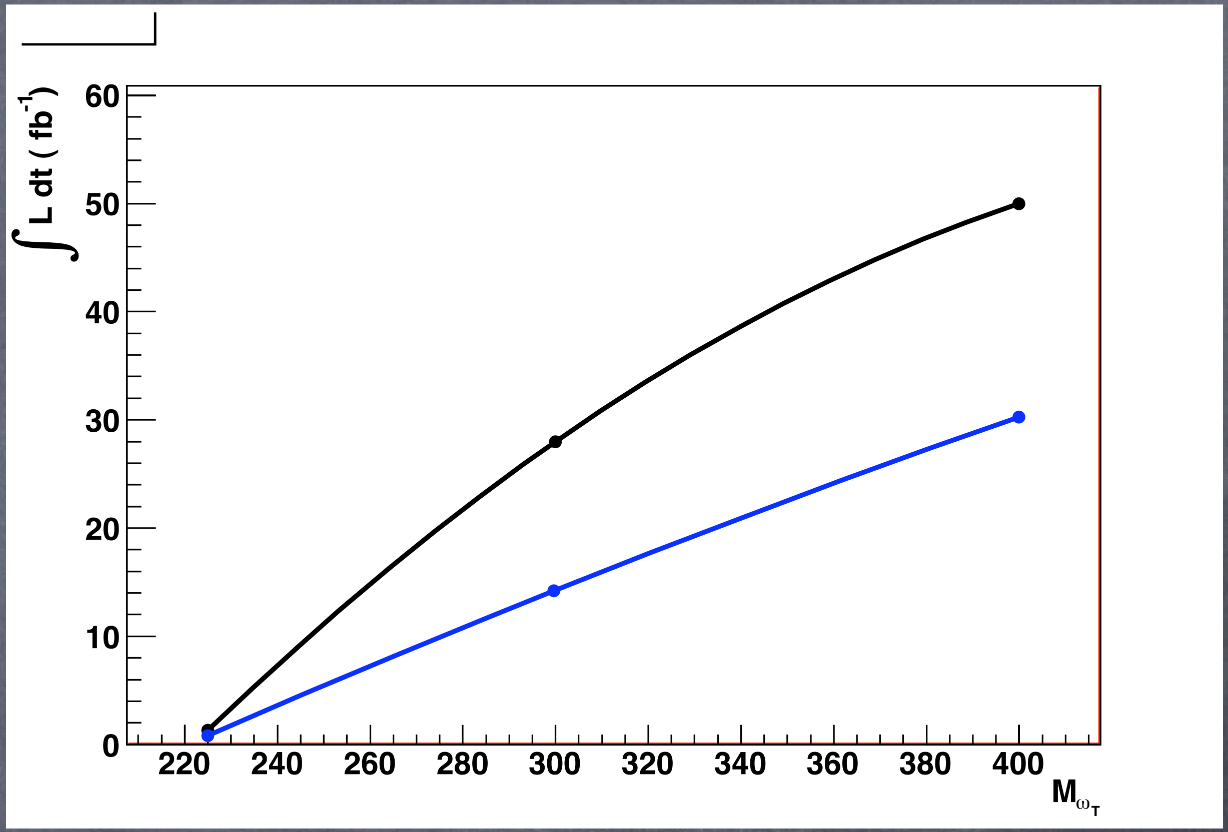
Model	nominal syst.	improved syst.
1a	20	20
1b	31	31
2a	170	150
2b	360	320
3a	610	560
3b	1120	930

$\mathcal{L}\,dt\;(\mathrm{pb}^{-1})$ needed at $\sqrt{s} = 10\,\mathrm{TeV}$ to exclude $\omega_T \to e^+e^-$ (with $Q_U + Q_D \simeq 1$) at 95% CL in LSTC models 1a-3b.

$\omega_T \to \gamma Z^0 \to \gamma \mu^+ \mu^-$

K. Black, B.C. Smith (ATLAS)





Left: Luminosity for 3-sigma evidence (dashed) and 5-sigma observation (solid) for cases a (blue) and b (black).

Right: Luminosity for 95% CL exclusion of Cases a and b.

Summing up:

- TC is the most natural & elegant explanation of EWSB
- Low-scale TC is a consequence of walking α_{TC}
  LSTC ==> technihadrons with striking signatures at hadron colliders.
- The most plausible new-physics explanation of CDF's dijet excess is $\rho_T \to W\pi_T$
- $\rho_T \to W\pi_T$ fits all features of the data so far
  -- and provides further tests (ρ_T peak, $\sin^2\theta$)

Summing up:

- Supporting LSTC signals at the Tevatron are within reach of current data sets:
  $\omega_T \to \gamma\pi_T^0,\, e^+e^-;\ a_T \to \gamma\pi_T,\, e^+e^-$
- LSTC is easily accessible at LHC in $\gamma, \ell^\pm, \nu_\ell$ final states; Wjj??
- Access $\sim 300\,\mathrm{GeV}$ with $\lesssim 5\,\mathrm{fb}^{-1}$
- The LHC certainly can discover -- or rule out -- LSTC up to $600 - 700\,\mathrm{GeV}$

Back-up slides

CDF vs. CDF + ELM cuts

(Mjj window = 120 -- 160 GeV)

Exactly 2 jets:

CDF cuts: S = 250, B = 1600

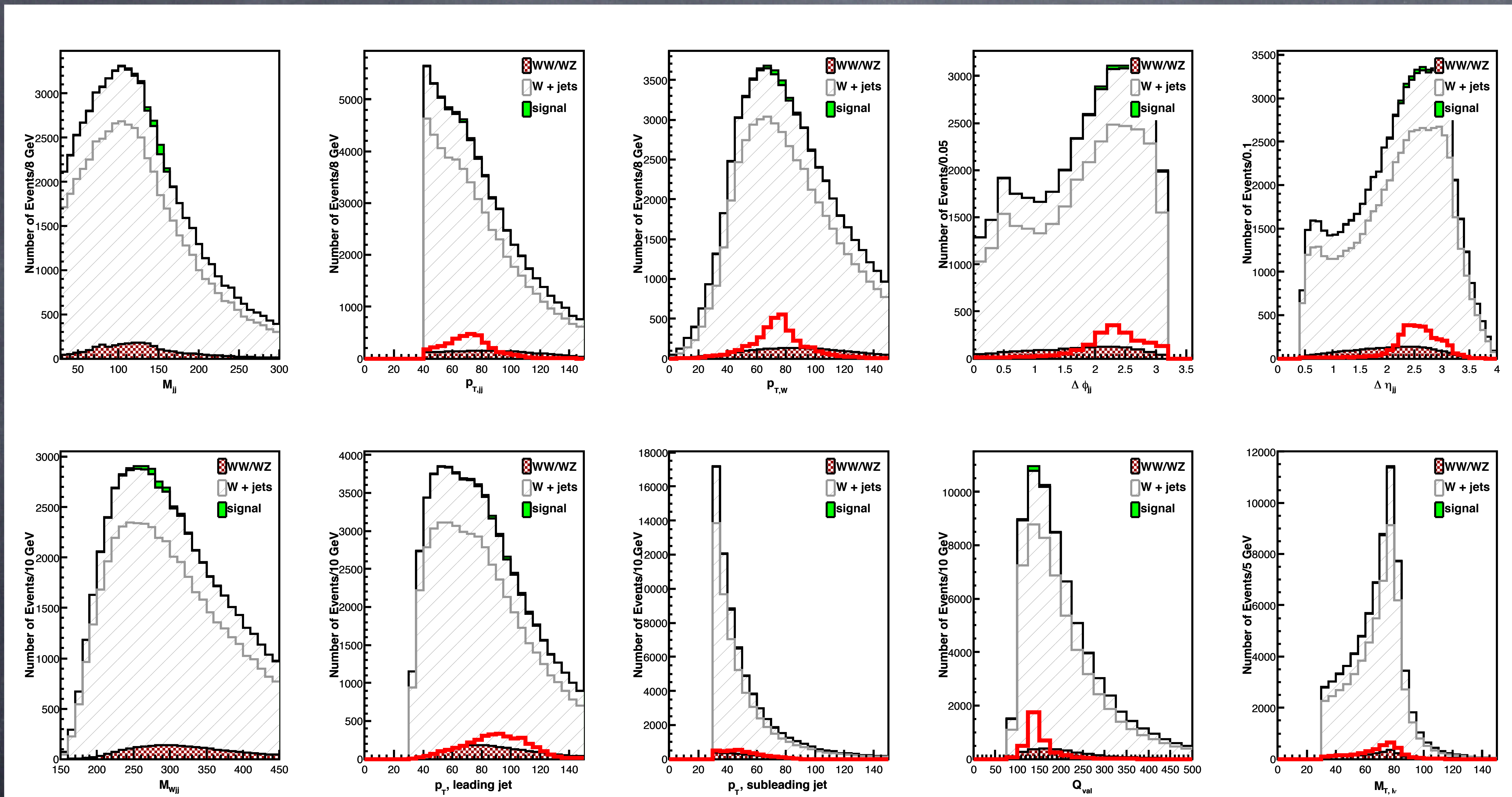
CDF + ELM cuts: S = 175, B = 690

3rd jet added:

CDF cuts: S = 285, B = 2100

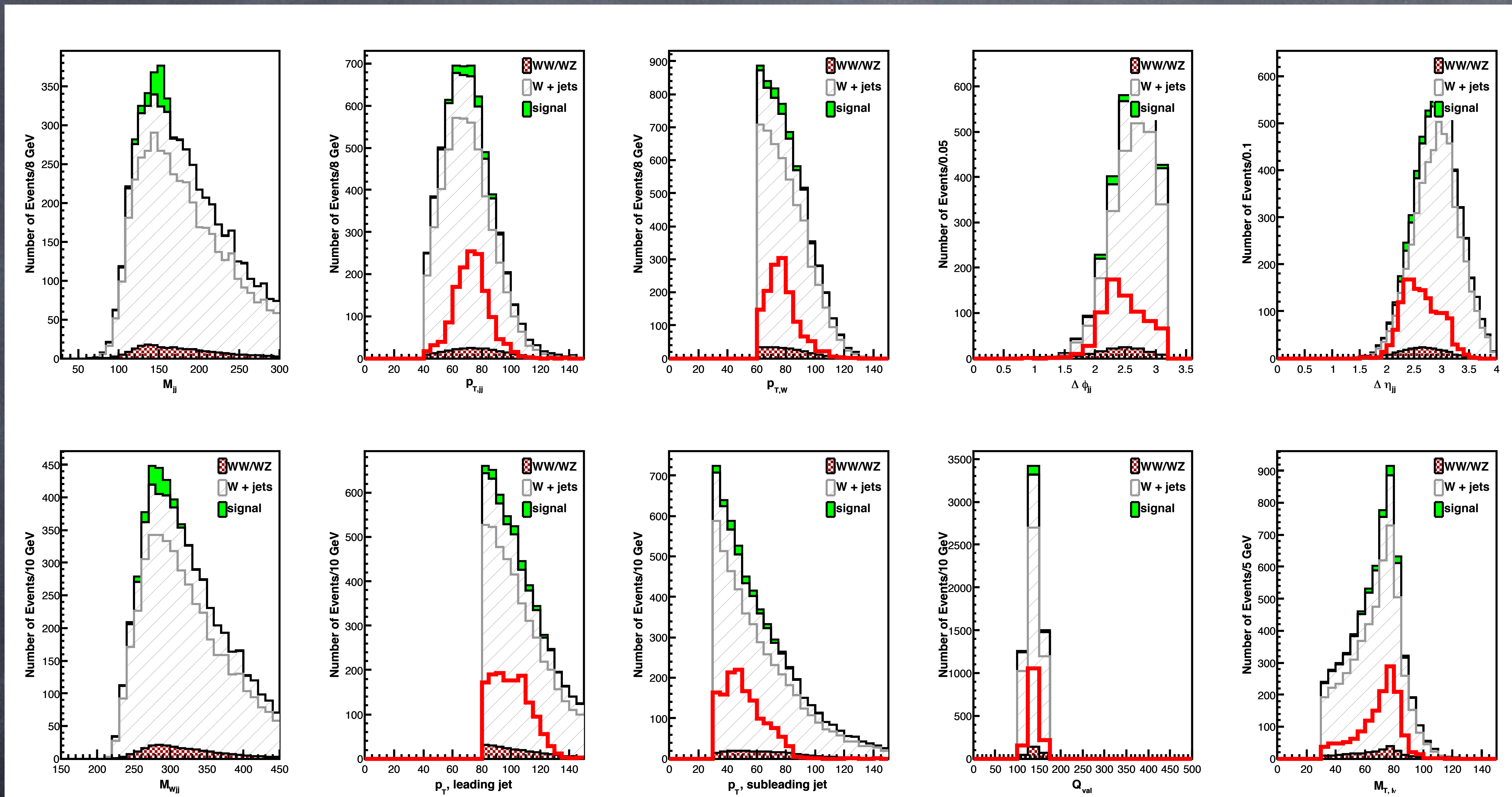
CDF + ELM cuts: S = 200, B = 880

$\rho_T \to W\pi_T \to \ell\nu_\ell jj$ at the LHC



CDF cuts $(1\,\mathrm{fb}^{-1})$

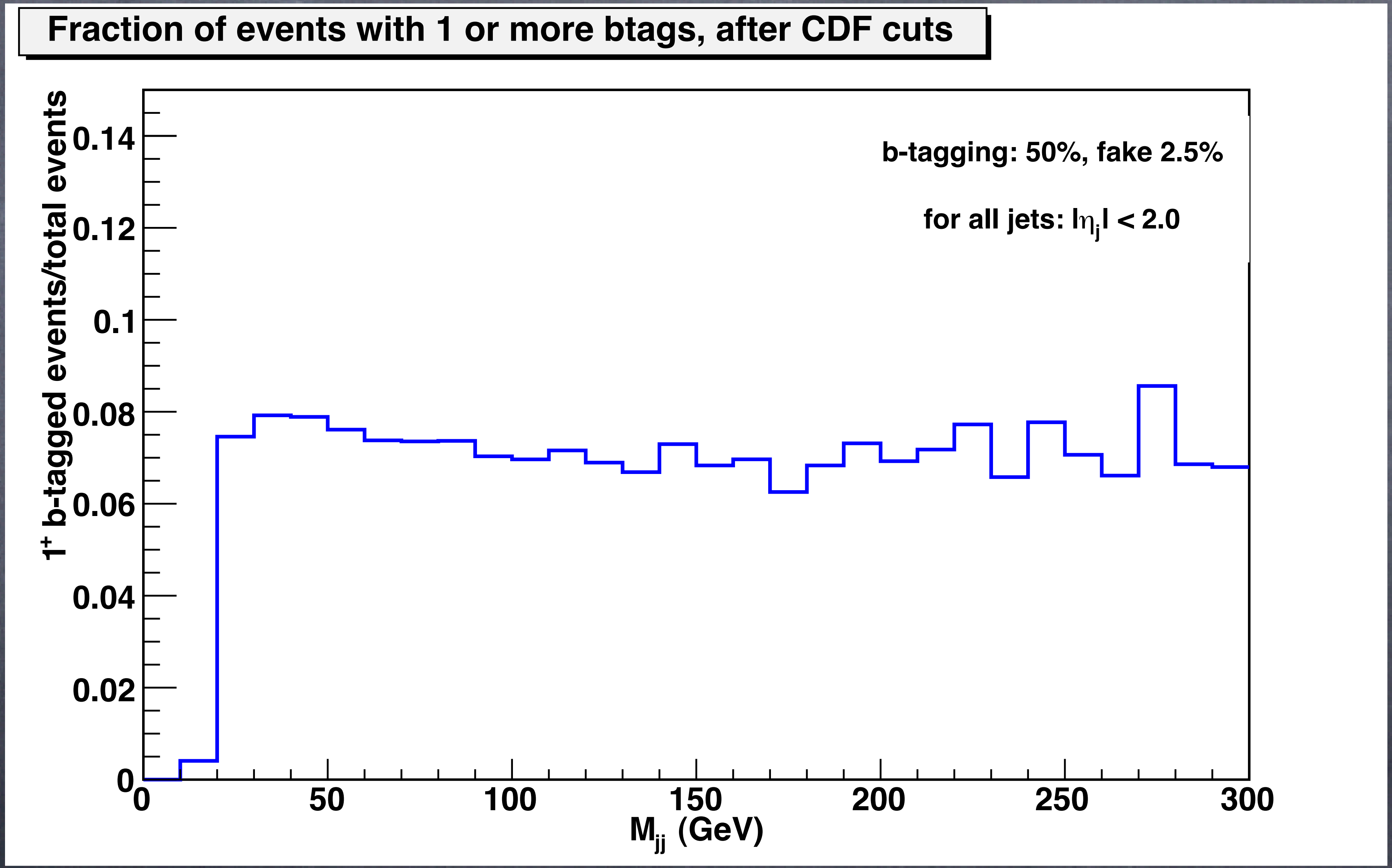
$\rho_T \to W\pi_T \to \ell\nu_\ell jj$ at the LHC



CDF + ELM cuts

What about b-content of the signal?

We studied b-fraction of events after CDF cuts with 50% b-tag probability, 2.5% mistag rate



<-- 8%

background only

We estimate b-fraction (with CDF cuts):

$$S(159\,\pi_T^{\pm},\ 91\,\pi_T^{0}) = 250, \quad B = 1600$$

$$\Longrightarrow \frac{(0.50)(250) + (0.08)(1600)}{250 + 1600} = 0.137$$

1 b-tag fraction

$$\frac{(0.25)(91) + (0.08)^2(1600)}{250 + 1600} = 0.018$$

2 b-tag fraction

What did CDF get?

1.4 b-tagging

A full b-tagged analysis to study in detail the heavy flavor content of the excess is out of the scope of the analysis presented in this note. However, we performed a comparison between the tagging fraction in the signal region and sidebands. Our signal region is selected by requiring $120 < M_{jj} < 160$ and our sidebands region by requiring $100 < M_{jj} < 120$ OR $160 < M_{jj} < 180$.
We then computed the ratio Tag / No Tag in several cases where no tag are events where no tag info is required (and may include non taggable jets), while Tag can be:

- 0 Tight : none of the two jets has a positive SECVTX Tight tag.
- 1 Tight : at least one of the two jets has a positive SECVTX Tight tag.
- 2 Tight : both jets have a positive SECVTX Tight tag.
- 0 Loose : none of the two jets has a positive SECVTX Loose tag.
- 1 Loose : at least one of the two jets has a positive SECVTX Loose tag.
- 2 Loose : both jets have a positive SECVTX Loose tag.

In Tab.9 and 10 we summarize the numbers we estimate in data. We conclude that the tag ratio in the excess region is compatible with what observed in the sidebands, hence if we perform a counting experiment the excess is not enhanced by requiring b-tagging.

Tag requirement	Signal region	Background region	Pull
0 T	0.8973 ± 0.0436	0.9187 ± 0.0431	-0.3484
1 T	0.1027 ± 0.0112	0.0813 ± 0.0096	1.4433
2 T	0.0078 ± 0.0030	0.0084 ± 0.0030	-0.1506
0 L	0.8549 ± 0.0421	0.8828 ± 0.0419	-0.4695
1 L	0.1451 ± 0.0136	0.1172 ± 0.0118	1.5494
2 L	0.0089 ± 0.0032	0.0127 ± 0.0037	-0.7704

Table 9: Muon SecVtx b-tag ratio

Tag requirement	Signal region	Background region	Pull
0 T	0.9103 ± 0.0370	0.9055 ± 0.0354	0.0947
1 T	0.0897 ± 0.0088	0.0945 ± 0.0087	-0.3934
2 T	0.0110 ± 0.0030	0.0095 ± 0.0026	0.3938
0 L	0.8615 ± 0.0355	0.8698 ± 0.0344	-0.1677
1 L	0.1385 ± 0.0111	0.1302 ± 0.0103	0.5455
2 L	0.0149 ± 0.0035	0.0145 ± 0.0033	0.0847

Table 10: CEM SecVtx b-tag ratio

Several groups using lattice methods to study these questions:

- Can α_{TC} walk?
- How large is γ_m? Is $\gamma_m \simeq 1$?
- Spectrum of ρ_T, a_T?
- What is the value of S?

$\mathcal{L}_{\rm eff}$ for LSTC -- and $\rho_T^\pm, a_T^\pm \to \gamma W^\pm$

(A. Martin & KL)

- Inspired by TCSM + integrated treatment of W_L, Z_L
- Use "hidden local symmetry" formalism
- SM fields (Higgsless!) $+\,\rho_T, \omega_T, a_T, (f_T) + \pi_T$
- Includes WZW interactions for radiative decays (a first!)
- More restrictive -- fewer adjustable parameters -- than TCSM in Pythia ....

... in particular (for TCSM/Pythia default masses)

$$g_{\rho_T \pi_T \pi_T} = \frac{M_{\rho_T}}{2F_\pi \sin\chi} \ll \text{Pythia default}$$

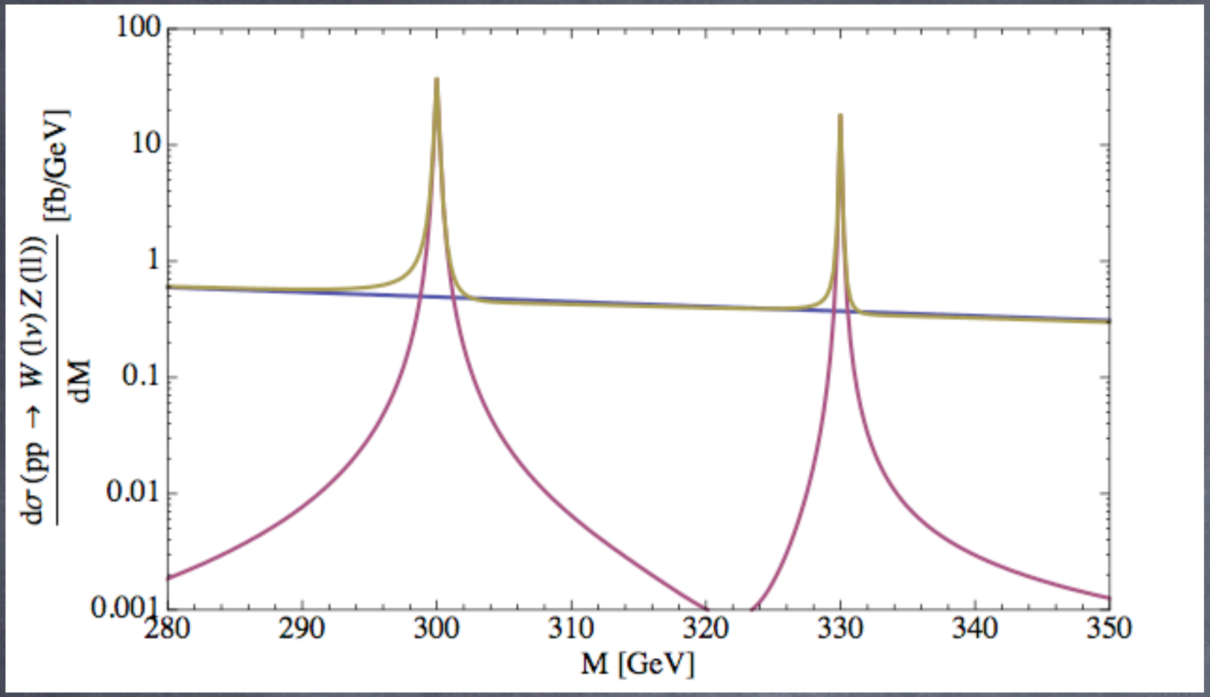
-- Higgs-like formula for M_{ρ_T} as in KSRF relation

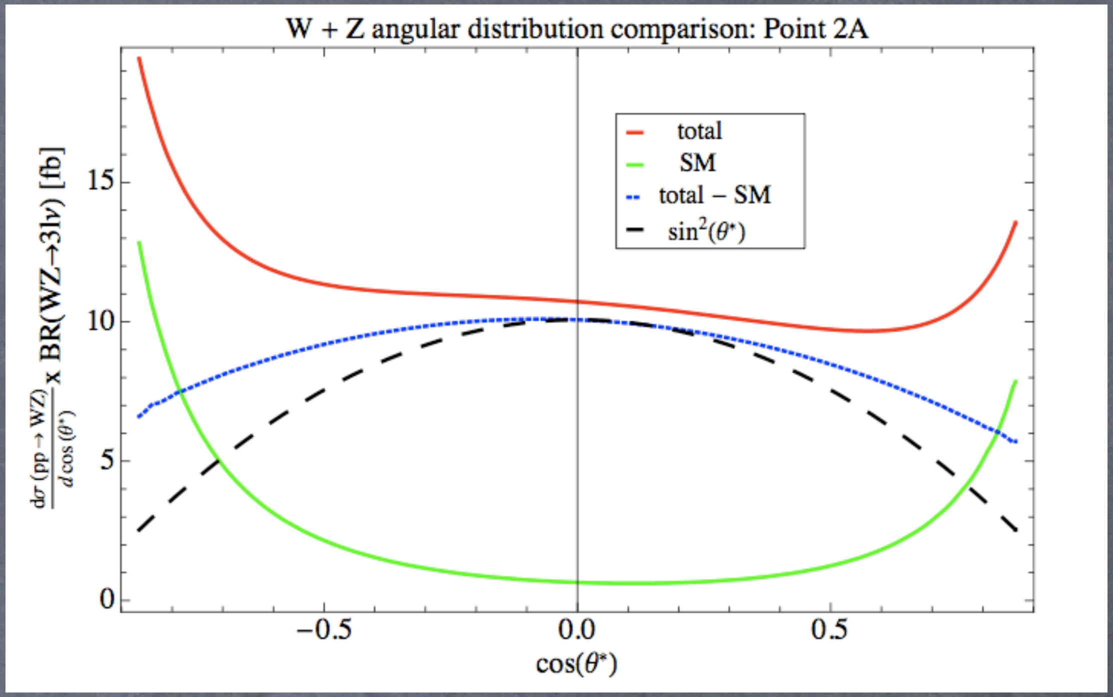
-- depletes $\rho_T \to \pi_T W_L, W_L Z_L$

-- enhances $\rho_T \to \gamma\pi_T, \gamma W, \gamma Z \ (Q_U + Q_D \sim 1)$

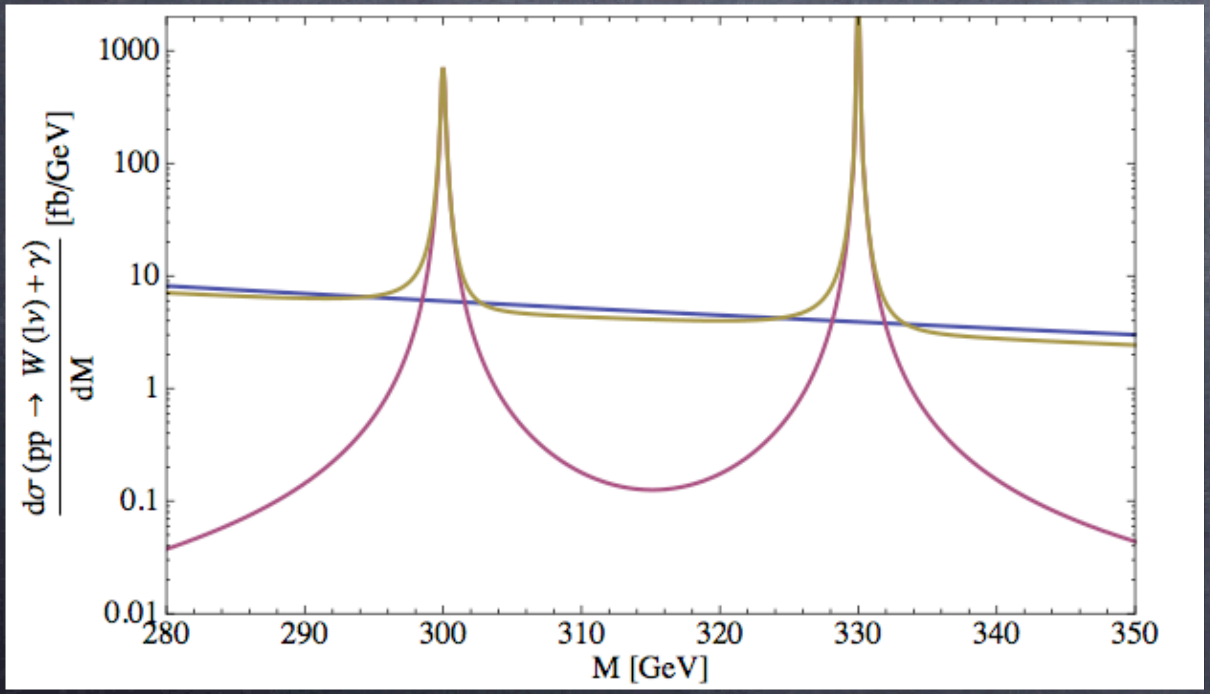
$\rho_T^\pm \to W^\pm Z^0 \to$ leptons

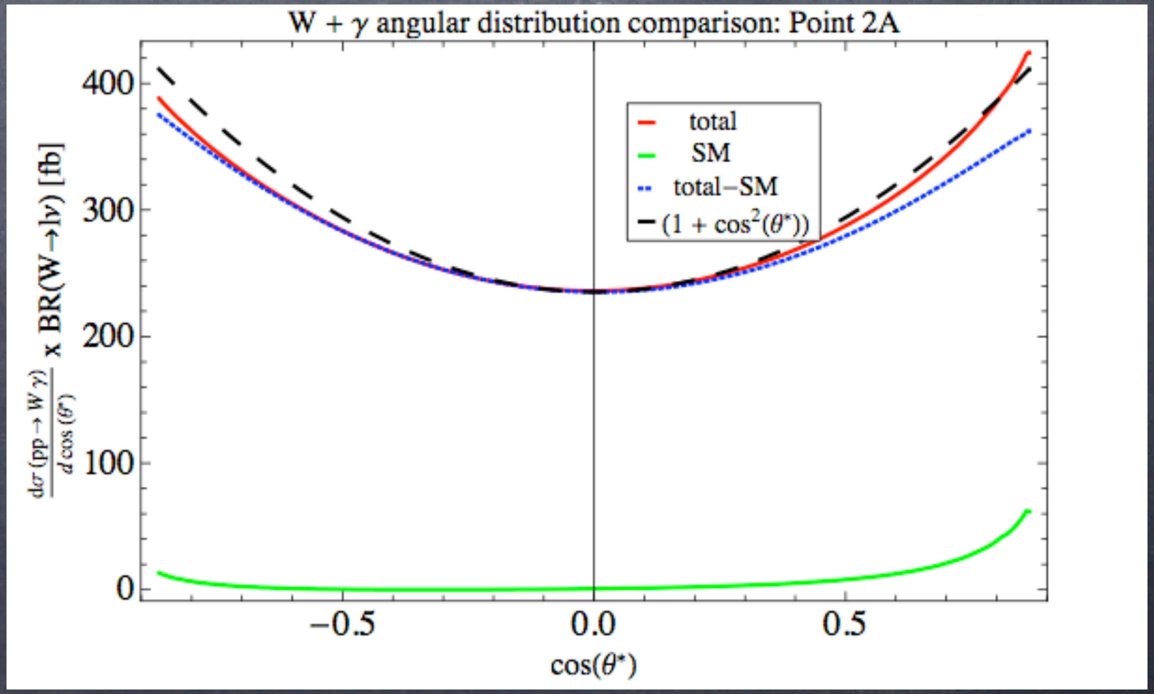
Case 2a





$\rho_T^\pm \to \gamma W^\pm \to \gamma \ell^\pm \nu_\ell \quad (Q_U + Q_D = 1)$





Case	$\sigma(WZ)_{\rho_T}$	$\sigma(WZ)_{a_T}$	$\sigma(\gamma W)_{\rho_T}$	$\sigma(\gamma W)_{a_T}$
1a	45 (35)	4.3 (30)	1765 (905)	860 (555)
1b	25 (35)	3.4 (30)	920 (905)	695 (555)
2a	17 (20)	3.7 (17)	280 (245)	575 (160)

Signal and underlying SM cross sections (in fb)

Oh yeah? What about S?

$$S = 4\pi \int \frac{dm^2}{m^4} \left[\rho_V^3(m^2) - \rho_A^3(m^2)\right]$$

$$= 4\pi \left(1 + \frac{M_{\rho_T}^2}{M_{a_T}^2}\right) \frac{F_\pi^2}{M_{\rho_T}^2} \simeq 0.25\, N_D \left(\frac{N_{TC}}{3}\right)$$

(Peskin & Takeuchi using QCD)

So -- what about S?

- Walking TC is **NOT** precociously-free QCD!
- QCD-based intuition is SUSPECT!
  in particular, the S-integral cannot be saturated by **ONLY** the lowest-lying ρ_T, a_T
- A tower of ρ_T, a_T ?
- Perhaps $M_{a_T} \simeq M_{\rho_T}$?

m_t??

That’s the subject of another talk!