Color sextet scalar and vector mesons in early LHC experiments

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In collaboration with:

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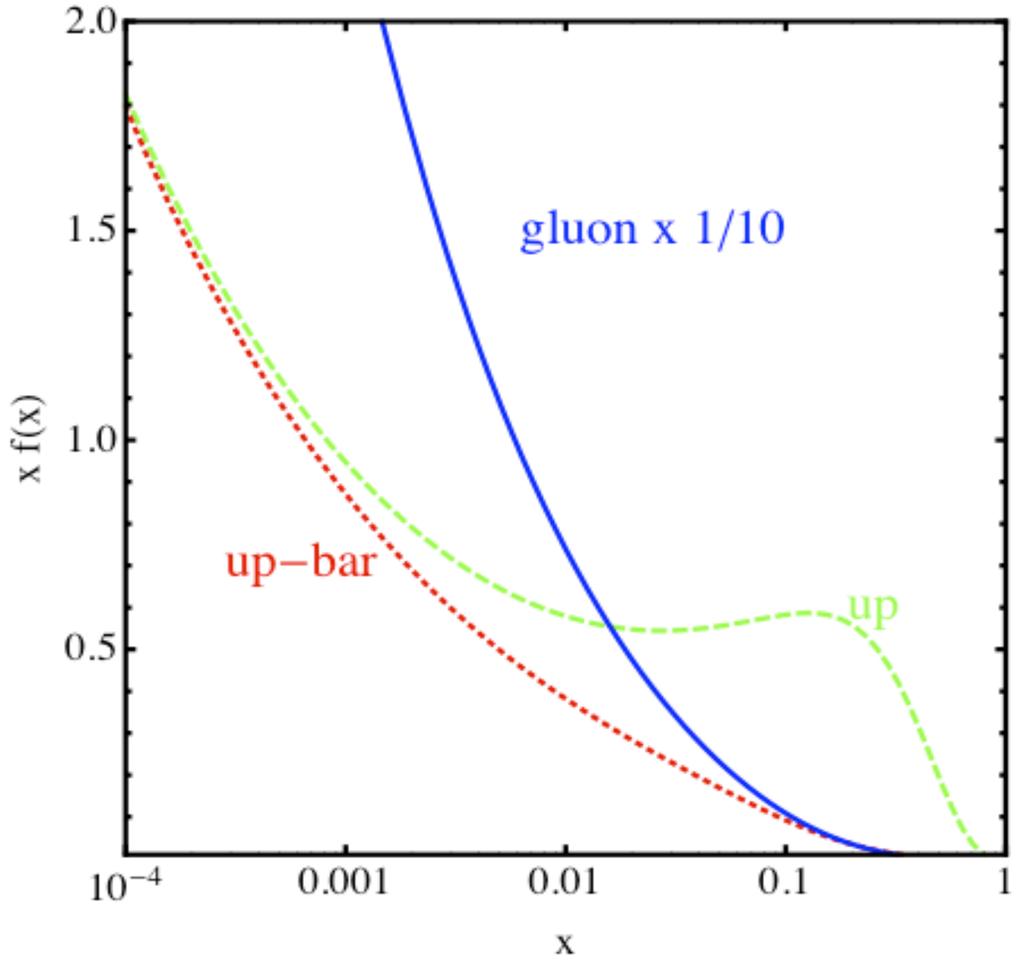
arXiv:1005.2622 (Phys Rev Lett **105**,181802 (2010)) and
arXiv:1009.5379 (Phys Lett B **696** (2001) 68)

LHC decade

★ First years of the LHC will probe a new frontier of physics at the Terascale

DM, SUSY, UED, Exotics, etc.



$$\langle x \rangle \approx m_{\mathrm{NP}}/E_{cm}$$

★ Focus here on New Heavy Resonances. Production probes the large x region where valence-quarks dominate.

★ For early discovery at the LHC (7 TeV and 1fb^{-1} luminosity), helps if the NP is : **exotic**

✳ ***Colored*** - large production rate

✳ ***Novel, easily detected collider signature***
charged leptons, heavy flavor jets, MET, etc

✳ ***Small SM backgrounds***

Sextet scalar/vector and same-sign top pair production

★ Quark-quark initial states can produce color sextet and anti-triplet resonances

$$3 \times 3 = 6 + \bar{3}$$

$$3 \times \bar{3} = 1 + 8$$

★ Observation of sextet scalar/vector would imply changes in RGE unification equations

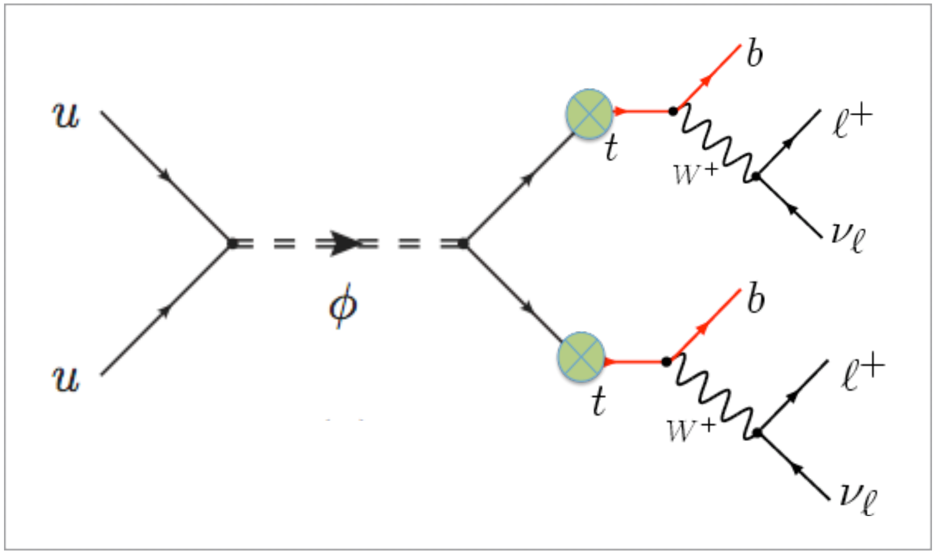
★ The scalar couplings (λ_R^{ab}) and vector couplings are not proportional to quark masses; bounds from Tevatron data

$$\mathcal{L} \sim \phi_j^* K_{ab}^j q_a^T C^\dagger \lambda_R^{ab} P_R q_b + h.c.$$

★ K is a Clebsch-Gordan factor.

★ It is important to be alert to the observation of a pair of same-sign top quarks.

★ Same-sign top pair production



✳ Potentially large cross section

✳ Signature: same-sign charged lepton pair, b-jets, and large MET

✳ top quark polarization is crucial

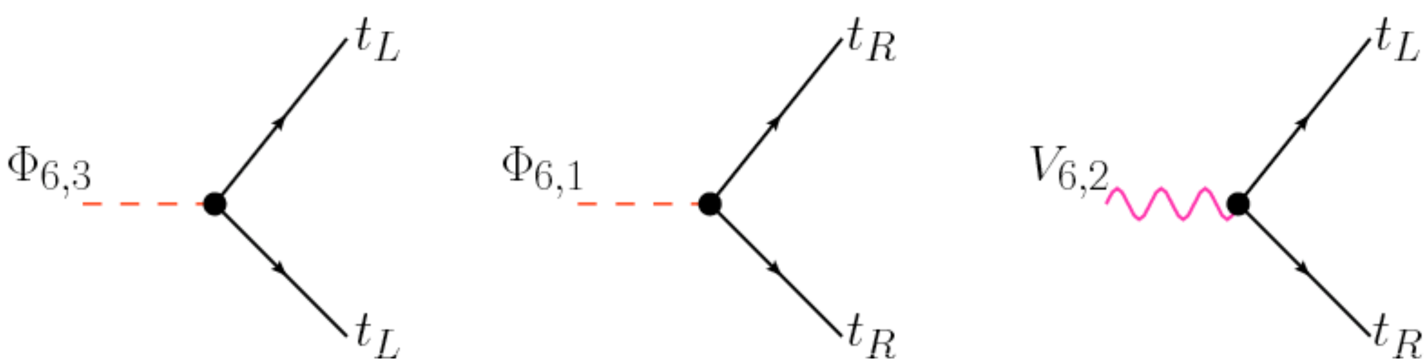
Models

★ Effective Lagrangian

$$
\begin{aligned}
\mathcal{L} = & \left(g_{1L}\overline{q_L^c}i\tau_2 q_L + g_{1R}\overline{u_R^c}d_R\right)\Phi_{6,1,1/3} \\
& + g'_{1R}\overline{d_R^c}d_R\Phi_{6,1,-2/3} + g''_{1R}\overline{u_R^c}u_R\Phi_{6,1,4/3} \\
& + g_{3L}\overline{q_L^c}i\tau_2\tau q_L \cdot \Phi_{6,3,1/3} \\
& + g_2\overline{q_L^c}\gamma_\mu d_R V^\mu_{6,2,-1/6} + g'_2\overline{q_L^c}\gamma_\mu u_R V^\mu_{6,2,5/6} + h.c.\,,
\end{aligned}
$$

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

$$q^c = C\bar{q}^T$$



★ One can measure the polarizations of both top quarks to determine the spin of heavy resonances and also determine their gauge quantum numbers.

We implement full spin correlations in our Monte Carlo simulation.

COLOR SEXTET SCALARS

Color sextet scalars

R. N. Mohapatra, Nobuchika Okada, Hai-Bo Yu, arXiv:0709.1486
Chuan-Ren Chen, William Klemm, Vikram Rentala and Kai Wang, arXiv:0811.2105
Jonathan M. Arnold, Maxim Pospelov, Michael Trott, Mark B. Wise, arXiv:0911.2225
Ilia Gogoladze, Yukihiro Mimura, Nobuchika Okada, Qaisar Shafi, arXiv:1001.5260

★ Electroweak quantum numbers

$SU(2)_L$	$U(1)_Y$	$\lvert Q\rvert = \lvert T_3 + Y\rvert$	couplings to
1	1/3	1/3	QQ, UD
3	1/3	1/3, 2/3, 4/3	QQ
1	2/3	2/3	DD
1	4/3	4/3	UU

$$Q = Q_L$$
$$U = u_R$$
$$D = d_R$$

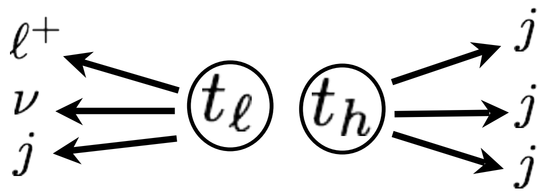
Constraints from the Tevatron

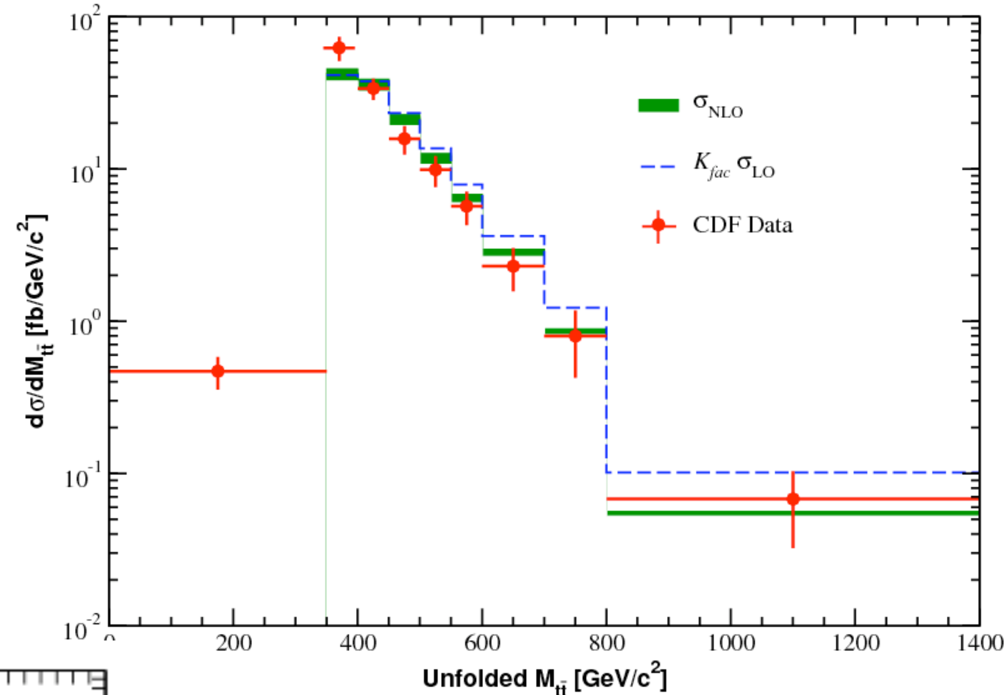
★ Top pair cross section constrained by CDF measurement of

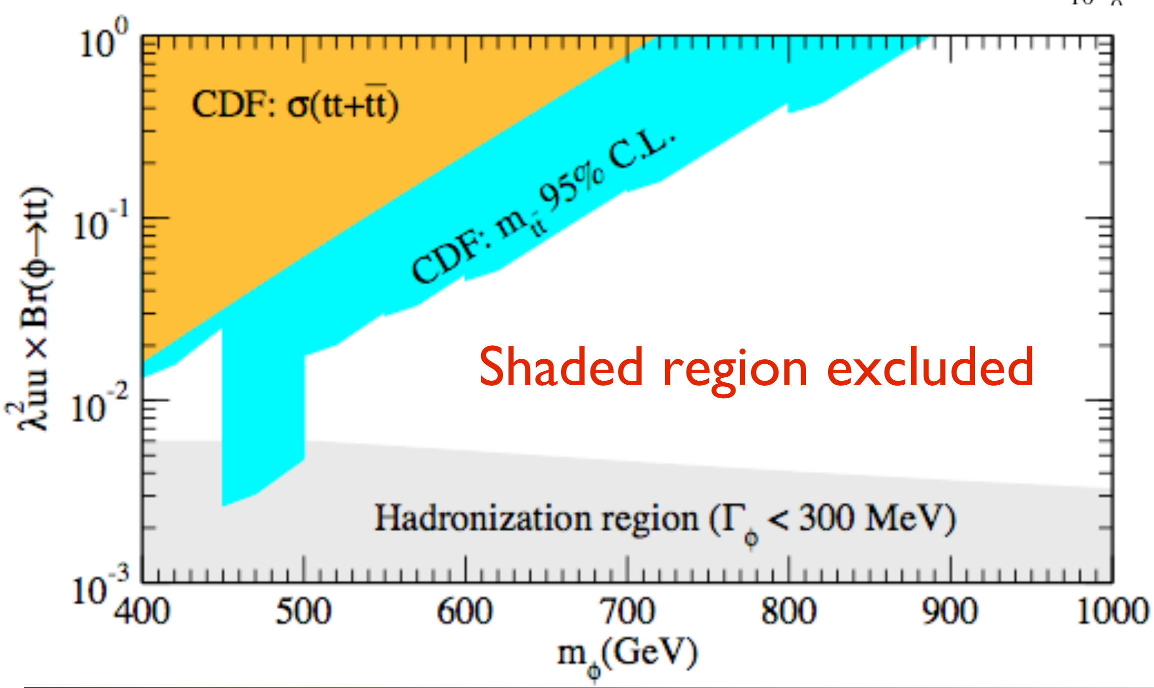
- ✳ Same-sign top pair search

$$\sigma_{tt+\bar{t}\bar{t}} < 0.7 \text{ pb}$$

- ✳ Distribution in $M_{t_\ell t_h}$







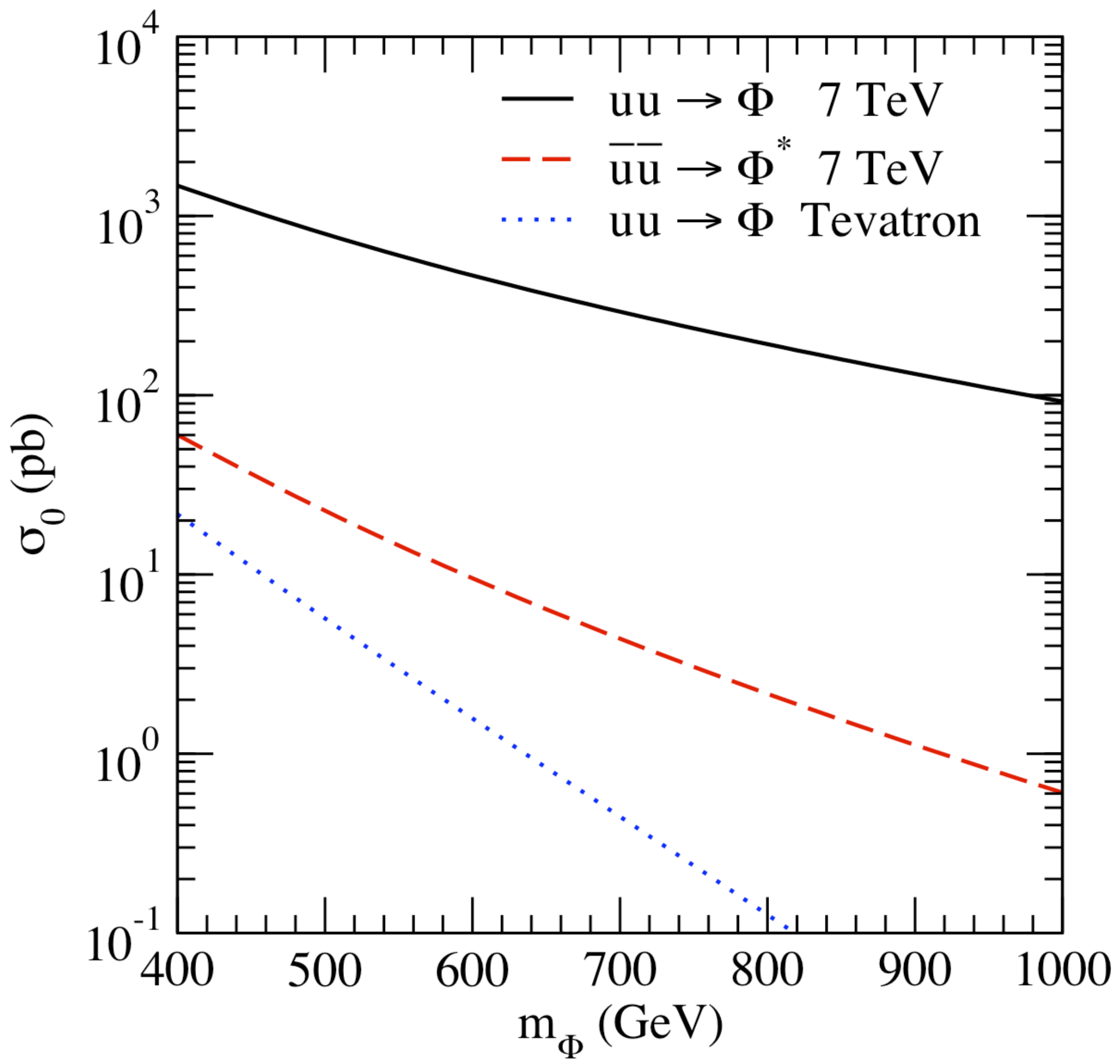
$$\sigma(uu \to \phi \to tt)$$

$$\propto \quad \sigma(uu \to \phi) \times Br(\phi \to tt)$$

$$\propto \quad [\sigma(uu \to \phi)|_{\lambda=1}]$$

$$\times \lambda_{uu}^2 Br(\phi \to tt)$$

Production cross section

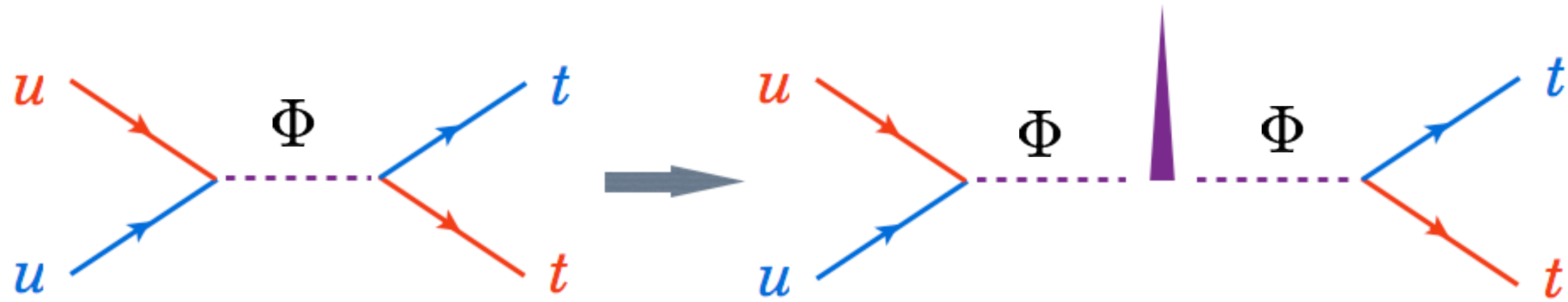


$$\sigma_0 \equiv \sigma(uu \to \Phi)\Big|_{\lambda_{uu}=1}$$

Narrow decay width

★ $\Gamma(\Phi \to qq) \approx \frac{m_\Phi}{16\pi}\lambda_{qq}^2$, $\Gamma(V \to qq) \approx \frac{m_V}{24\pi}g^2$

→ possibly sharp peak in the tt invariant mass spectrum

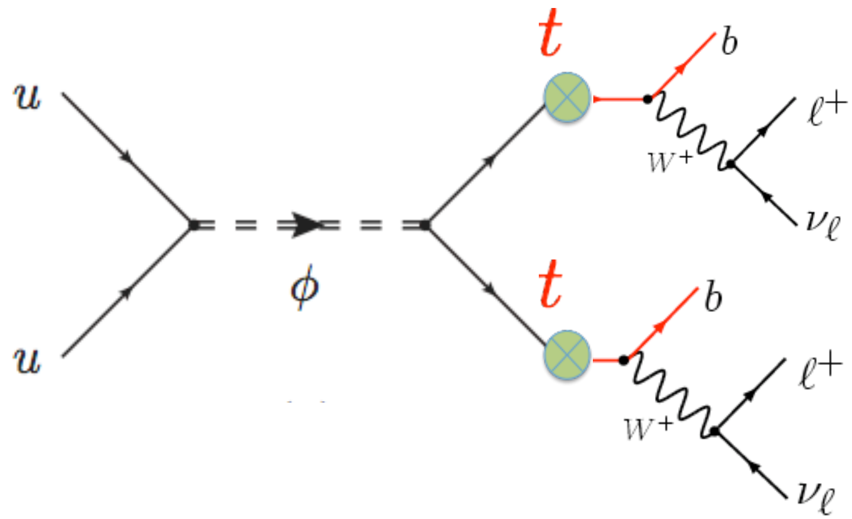


$$\sigma(uu \to \Phi \to tt) = \sigma_0(uu \to \Phi) \times \lambda_{uu}^2 \mathrm{Br}(tt),$$
$$= \sigma_0(uu \to \Phi \to tt) \times \lambda_{uu}^2 \frac{\mathrm{Br}(tt)}{\mathrm{Br}_0(tt)}.$$

$$\mathrm{Br}(tt) = \frac{\lambda_{tt}^2 R}{\lambda_{uu}^2 + \lambda_{tt}^2 R}, R \equiv \sqrt{1 - \frac{4m_t^2}{m_\Phi^2}} \left(1 - \frac{2m_t^2}{m_\Phi^2}\right)$$

Signal and backgrounds

★ Signal topology



same sign di-muons, 2 b-jets and MET

better reconstruction than for electrons

★ Prominent backgrounds (ALPGEN)

$$pp \to t\bar{t} \to b\bar{b}W^+W^-, \; W^+ \to \ell^+\nu, \; W^- \to jj, \; \bar{b} \to \ell^+$$

$$pp \to W_1^+W_2^+jj, \; W^+ \to \ell^+\nu$$

} Dominant backgrounds

$$pp \to W^+W^+W^-, \; W^+ \to \ell^+\nu, \; W^- \to jj$$

$$pp \to ZW^+W^-, \; Z \to \ell^+\ell^-, \; W^+ \to \ell^+\nu, \; W^- \to jj$$

Simulation details

★ Acceptance cuts

- ✳ leptons $p_{T,\ell} \geq 20$ GeV $|\eta_\ell| < 2.0$
- ✳ jets: $p_{T,j} \geq 50$ GeV $|\eta_j| < 2.5$
- ✳ separation: $\Delta R_{\ell\ell,\ell j,jj} > 0.4$

★ Energy smearing

$$\frac{\delta E}{E} = \frac{a}{\sqrt{E/\mathrm{GeV}}} \oplus b$$

- ✳ leptons: $a = 10\%$, $b = 0.7\%$
- ✳ Jets: $a = 50\%$, $b = 3\%$

★ Tagging rates / Mistag rate

$$\epsilon_{c\to b} = 10\%, \quad \text{for } \mathrm{p_T(c)} > 50 \text{ GeV}$$

$$\epsilon_{u,d,s,g\to b} \approx 1\%$$

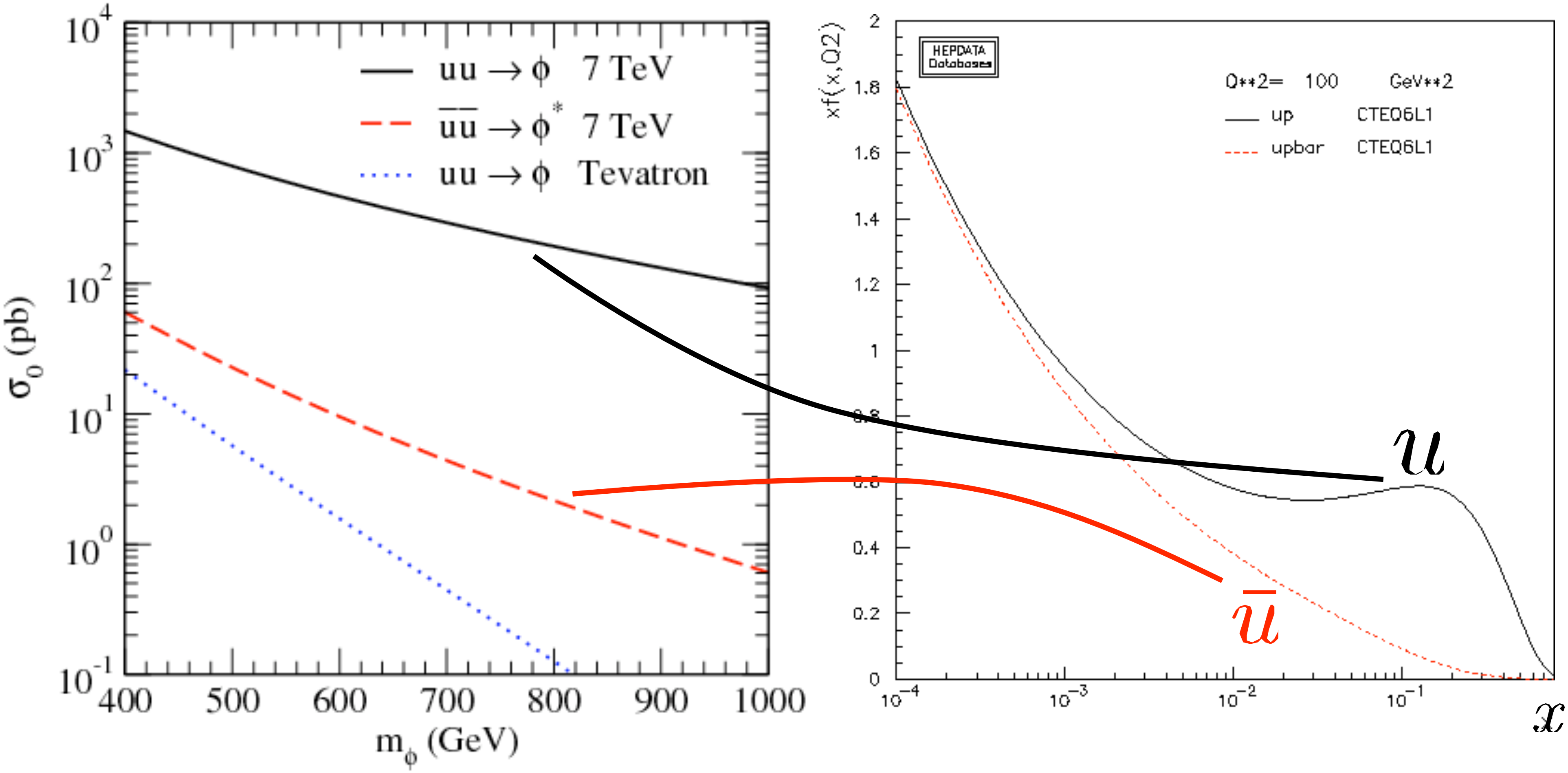
★ Signal and background (pb) before and after cuts, for 6 values of mass

m_Φ	Br(tt)	No cut	With cut	m_Φ	Br(tt)	No cut	With cut	Background	No cut	With cut
500	0.35	288.44	1.71	800	0.45	91.04	0.65	$t\bar{t}$	97.62	0.0032
600	0.41	193.67	1.30	900	0.46	65.14	0.45	$WWjj$	9.38	0.0014
700	0.43	133.46	0.93	1000	0.47	46.72	0.31	WWW/Z	0.03	0

First early hint at LHC

★ More positive di-muons

- ✳ same-sign top pairs contribute an asymmetry in charge multiplicity
- ✳ strong dependence on sextet scalar mass owing to PDF dependence



- ✳ Same-sign charge ratio gives an independent check on scalar mass

Discovery potential

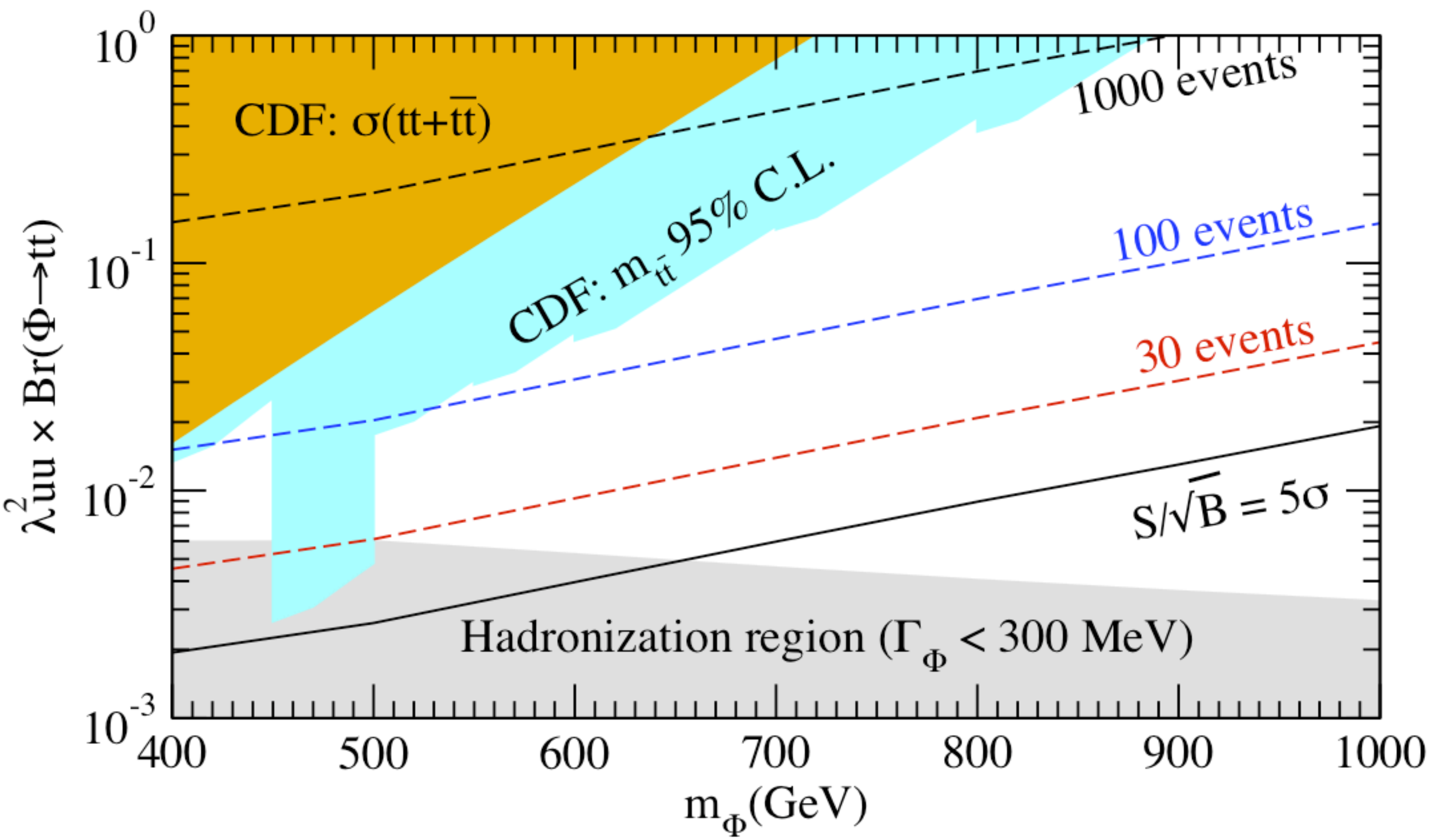
★ Simple cuts to extract signal:

- ✳ Same sign di-muons
- ✳ Two jets with pT>50GeV

✳ Shown are numbers of signal events;

✳ about 4.6 background events

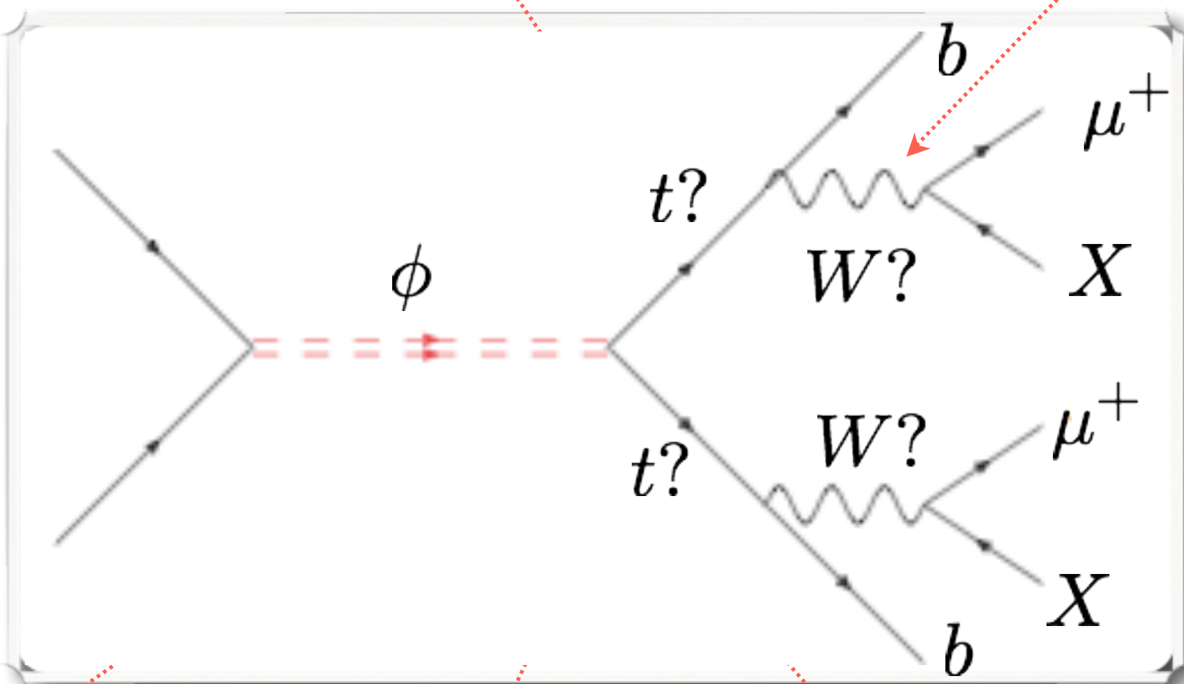
7 TeV $\mathcal{L} = 1\ \mathrm{fb}^{-1}$



Questions to be answered

(2) Does each jet + lepton pair reconstruct a top quark?

(1) Are the muons and missing X from W-boson decays?



Need full event reconstruction

Difficulty: identical muons and b jets

(3) What is the mass of the resonance?

(4) What is top quark polarization?

(5) Are the top quarks from a scalar decay?

MT2 method

★ Question: how can one measure the mass of heavy particles if they are produced in pairs and then decay into visible and invisible particles?

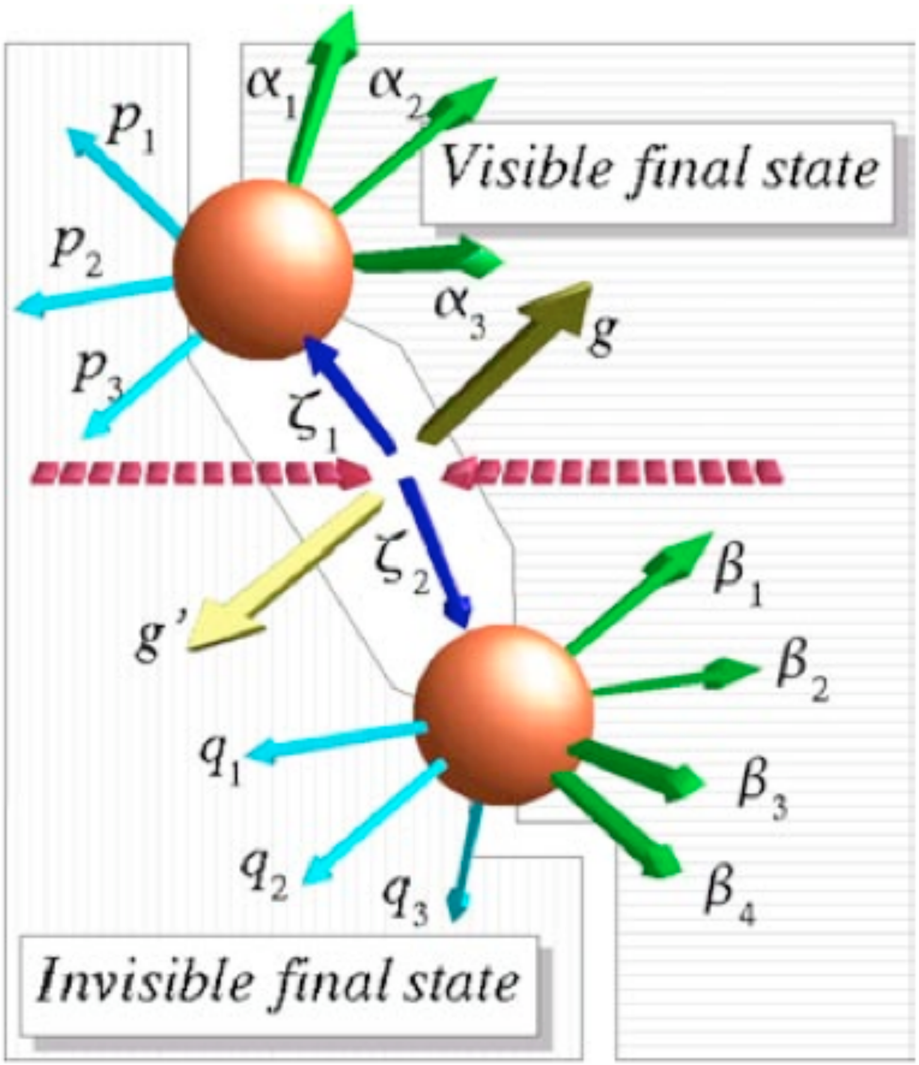
- Warm up: measuring the mass of the W boson in the leptonic decay channel -- MT variable.

$$m_T^2 = 2\left(E_T^e \not{E}_T - p_T^e \cdot \not{p}_T \right)$$

- The true mass of the W boson satisfies

$$m_T^2 \leq m_W^2$$

- The end point of the transverse mass distribution is the W boson mass.



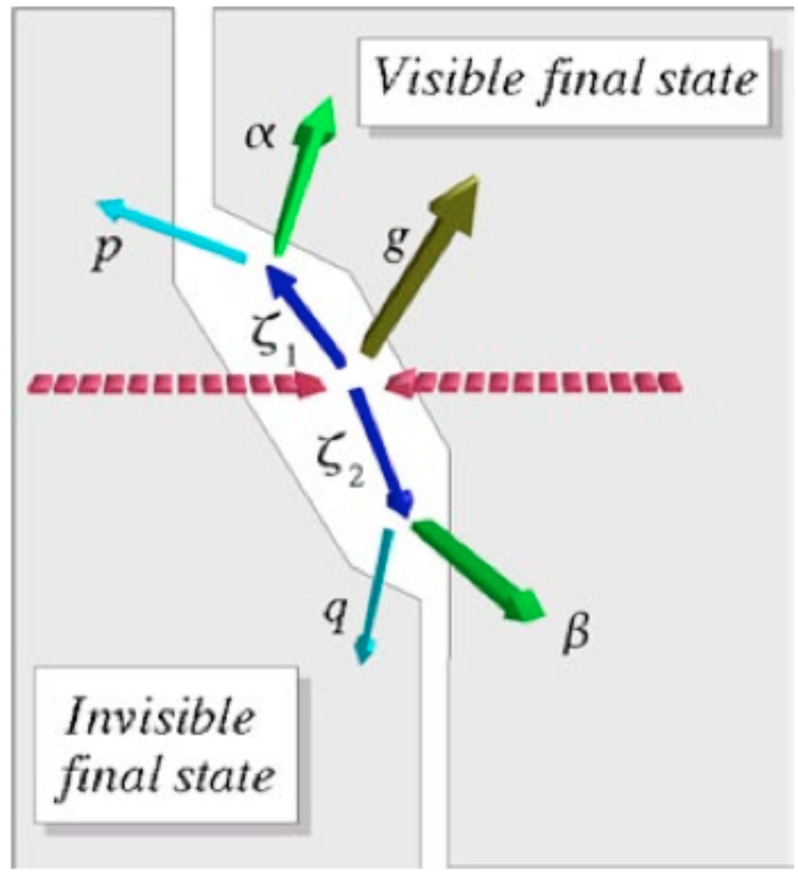
MT2 method

★ When there are two heavy particles decaying into visible particles and invisible particles, the MT2 variable may be used to measure the mass of their parent.

$$m_{T2}(m_{invis}) = \min_{\mathbf{p}_T^{(1)},\mathbf{p}_T^{(2)}} \left[\max[m_T(m_{invis};\mathbf{p}_T^{(1)}), m_T(m_{invis};\mathbf{p}_T^{(2)})]\right]$$

$$m_T(m_{invis};\mathbf{p}_T^{invis}) = \sqrt{m_{vis}^2 + m_{invis}^2 + 2(E_T^{vis}E_T^{invis} - \mathbf{p}_T^{vis}\cdot\mathbf{p}_T^{invis})}$$

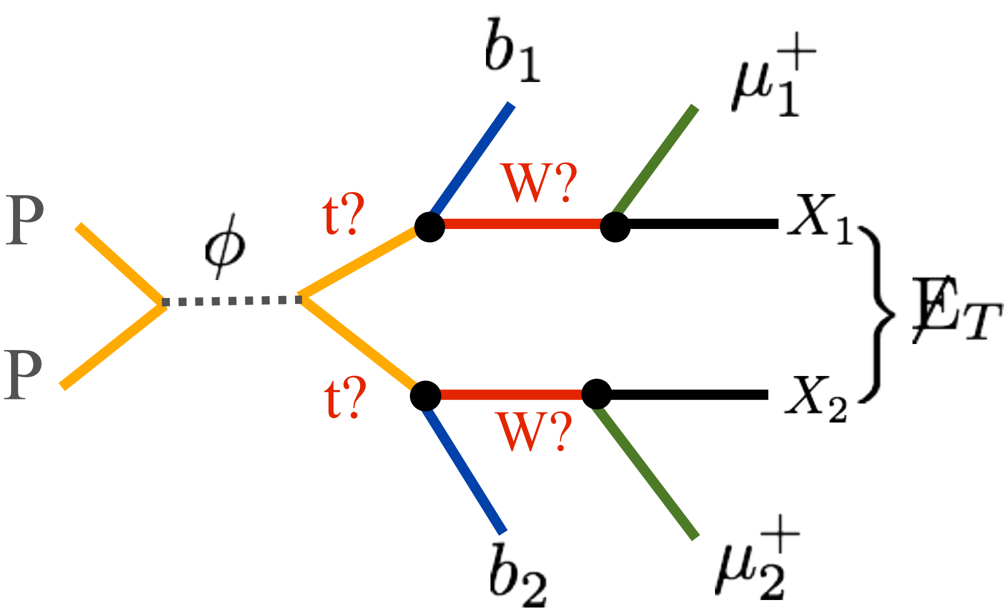
C. G. Lester and D. J. Summers, hep-ph/9906349



★ The MT2 variable is a function of the momenta of visible particles (α, β) and missing transverse momentum. Its upper bound yields the mass of the parent particle (ζ) .

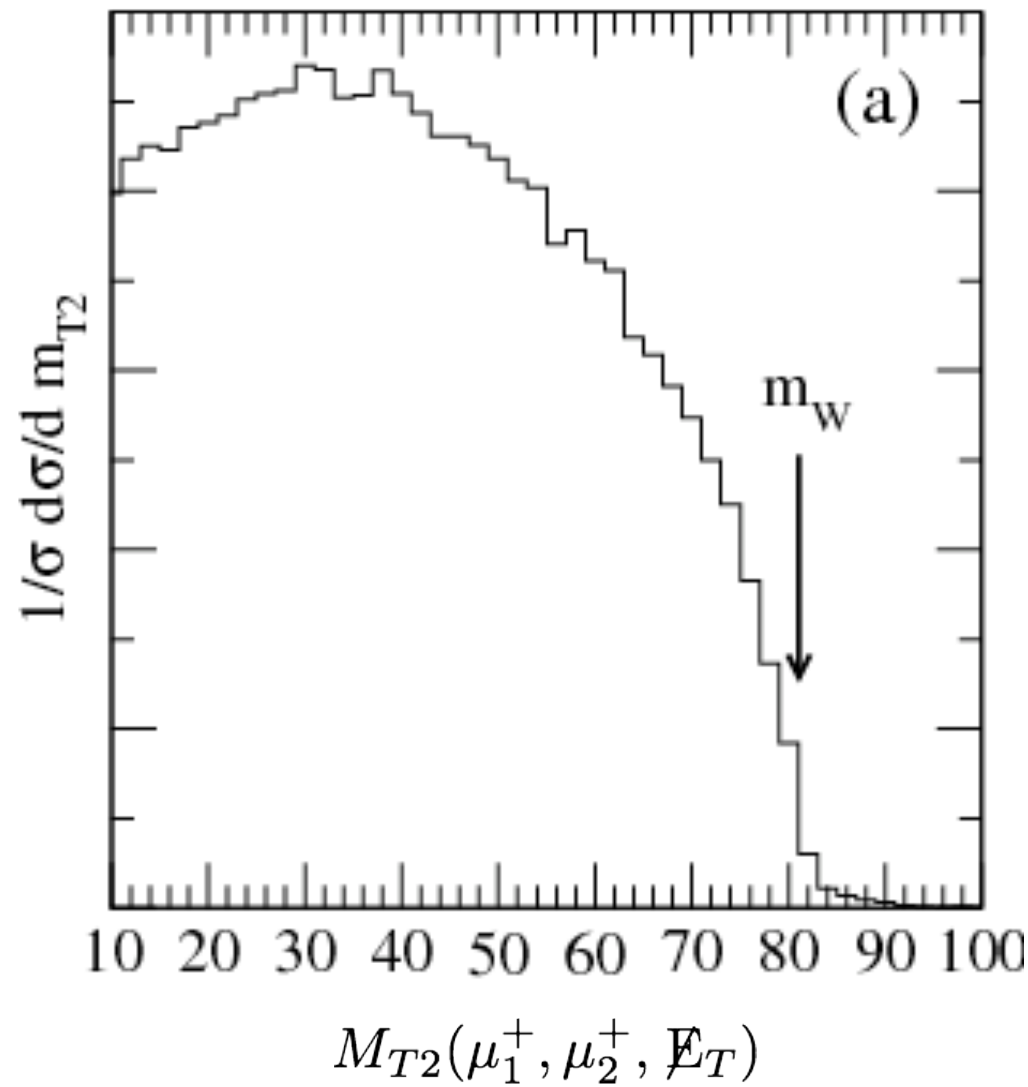
W-bosons in the intermediate state ?

★ MT2 of charged leptons and MET



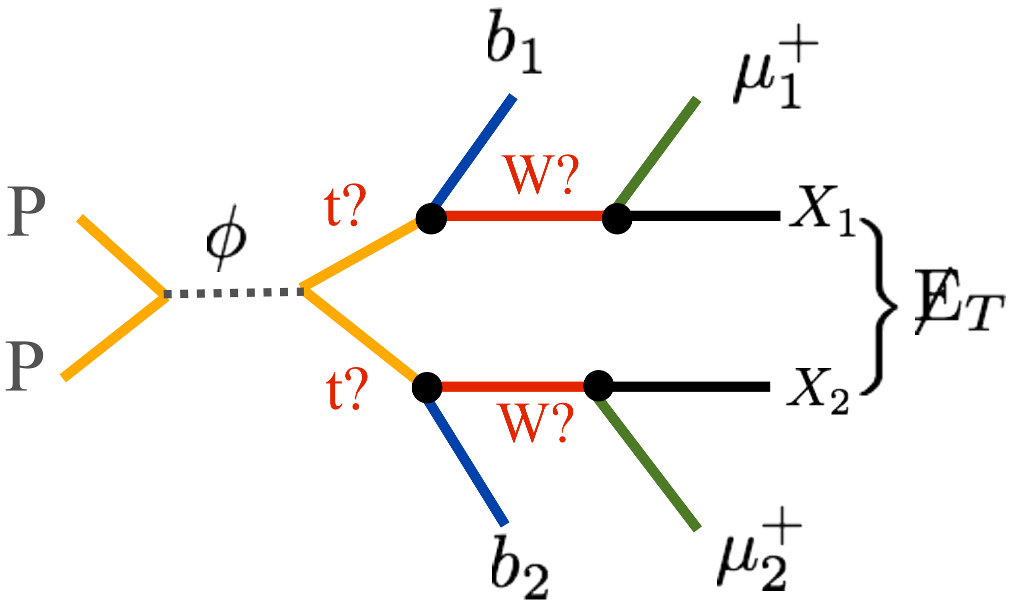
$$M_{T2}^2(\mu_1^+, \mu_2^+, \not{E}_T) \leq m_W^2$$

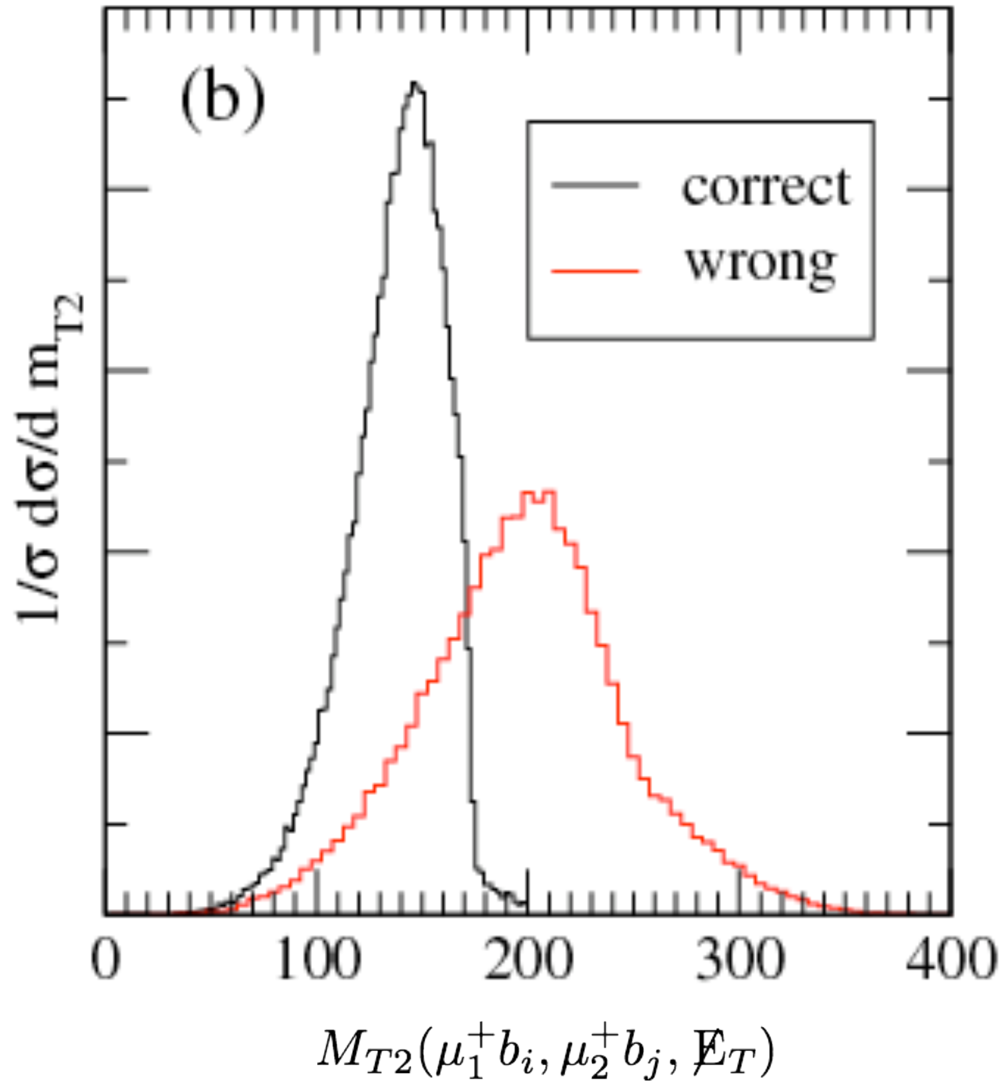
$$M_{T2}^2 \equiv \min_{\not{p}_{X_1}+\not{p}_{X_2}=\not{E}_T}\left[\max\left\{m_T^2(\vec{p}_T^{\,\mu_1^+}, \not{p}_{X_1}), m_T^2(\vec{p}_T^{\,\mu_2^+}, \not{p}_{X_2})\right\}\right]$$



Top quarks in the intermediate state?

★ MT2 of lepton-b clusters and MET



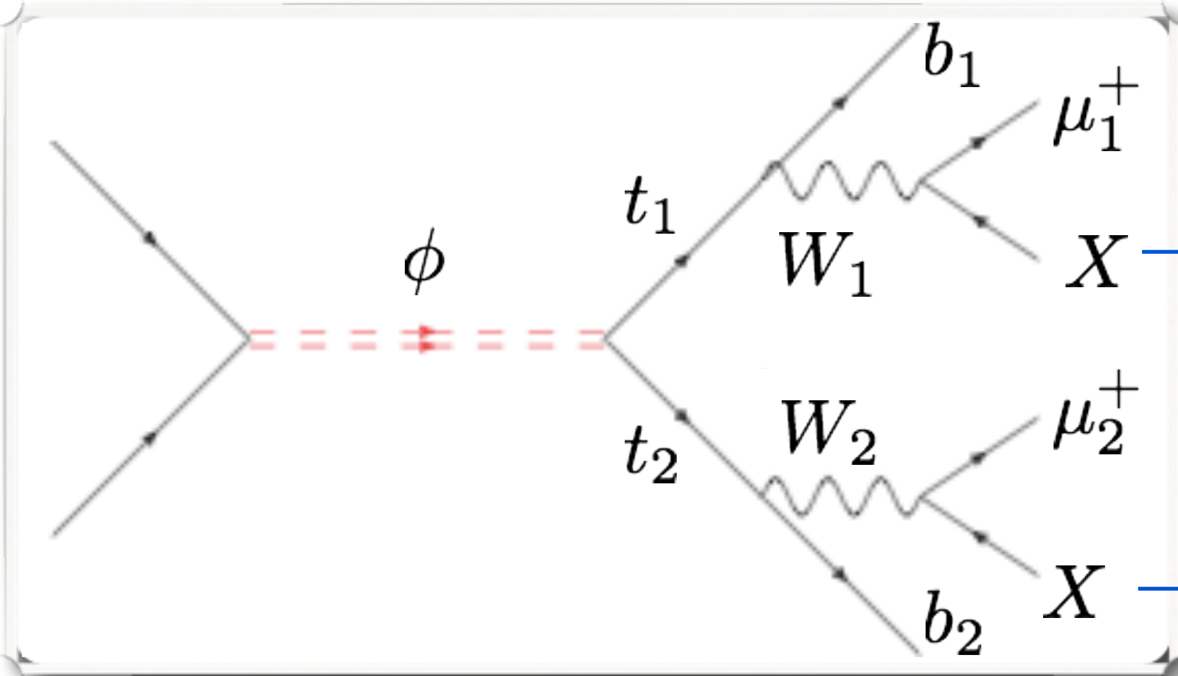


- Two combinations of lepton-b clusters

- Choose smaller MT2 (correct combination found with 95% probability)

Full kinematic reconstruction

★ Four unknowns and four on-shell conditions



6 unknowns
-2 from MET

$$m_{W_1}^2 = (p_{\mu_1} + p_{\nu_1})^2$$
$$m_{W_2}^2 = (p_{\mu_2} + p_{\nu_2})^2$$
$$m_{t_1}^2 = (p_{W_1} + p_{b_1})^2$$
$$m_{t_2}^2 = (p_{W_2} + p_{b_2})^2$$

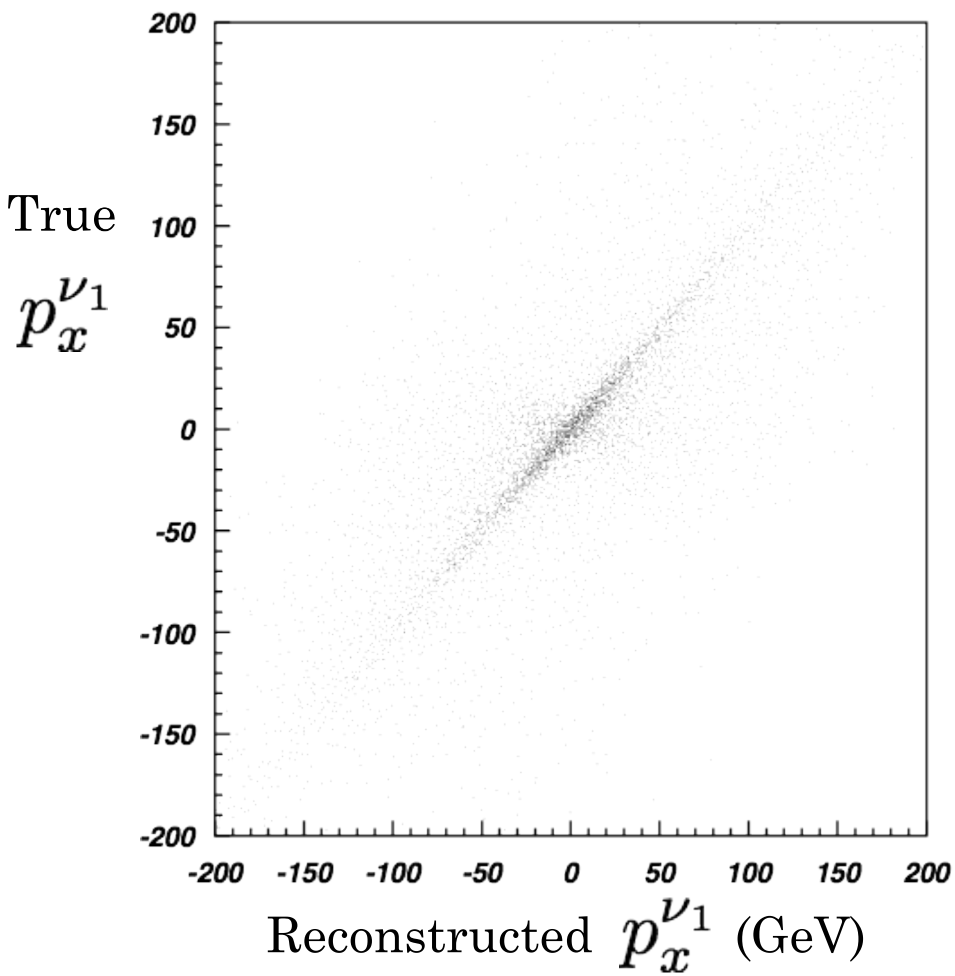
Quartic equation

$$p_x^4(\nu_1) + a\ p_x^3(\nu_1) + b\ p_x^2(\nu_1) + c\ p_x(\nu_1) + d = 0$$

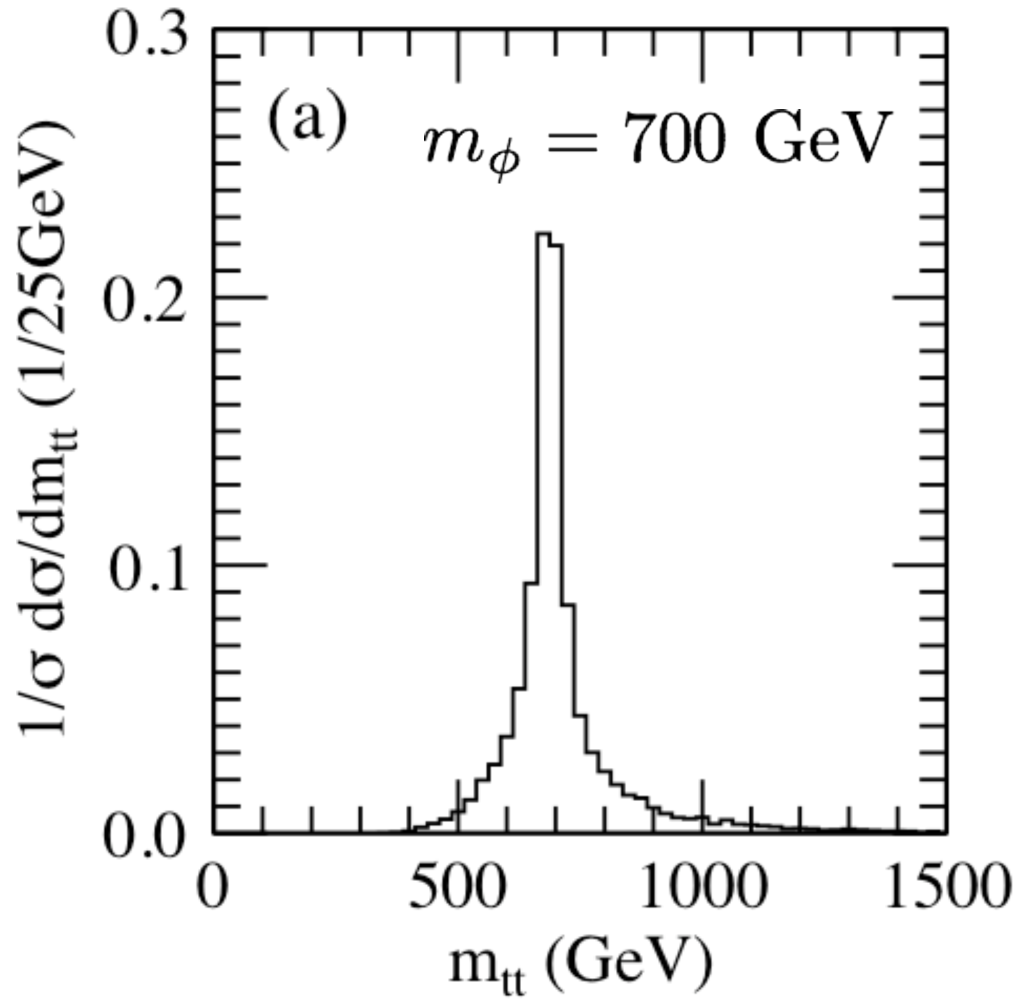
~~Two complex~~, two real solutions

Reconstructed event distribution

★ Strong correlation between the true $p_x^{\nu_1}$ and reconstructed $p_x^{\nu_1}$



★ The mass of the heavy resonance can be determined:



Top quark polarization and resonance spin

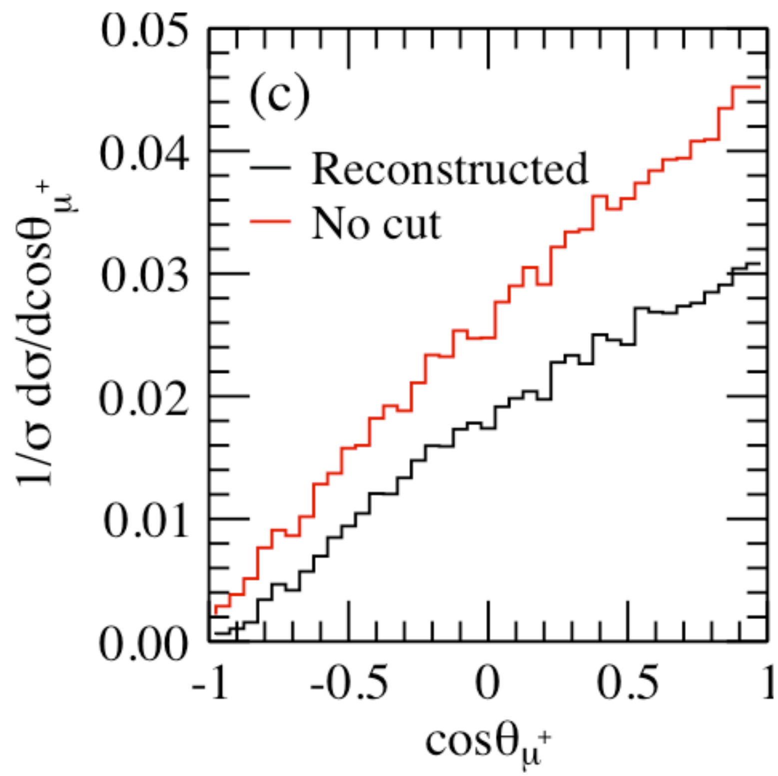
★ Polarization correlates with angle between top quark spin and charged lepton momenta

$$\frac{1}{\Gamma}\frac{d\Gamma(t\to b\ell\nu)}{d\cos\theta}=\frac{1}{2}\left(1+\frac{N_+-N_-}{N_++N_-}\cos\theta\right)$$

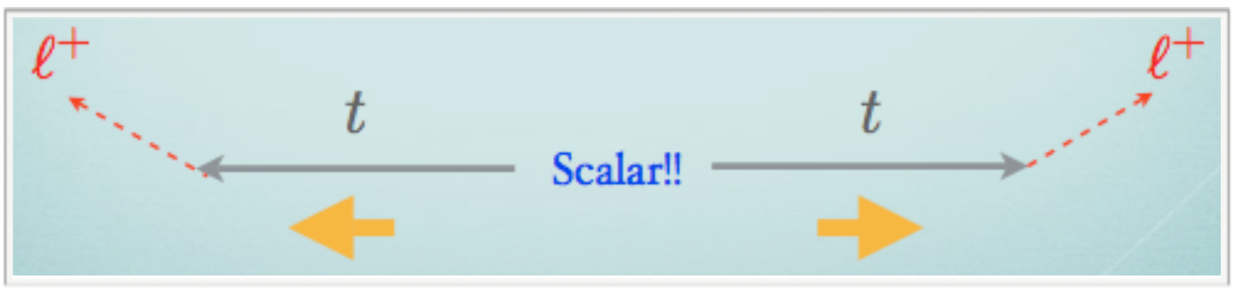
✳ Charged lepton typically follows top quark spin

✳ Right-handed top quark yields $\frac{1}{2}(1+\cos\theta)$

✳ Roughly 30 events required to distinguish from unpolarized case



Polarization of the top quarks can be determined to be right-handed



Are the top quarks from a scalar decay? Yes !

COLOR SEXTET VECTORS

Color sextet vector meson

★ The vector sextet must be a SU(2) doublet. It couples to a left-handed quark and a right-handed quark according to:

$$(6,2)_{\frac{1}{6}} \; : \; \epsilon_{ij}\bar{Q}_i^c \gamma^\mu P_R D \; V_{j\mu} + \text{h.c.}$$
$$(6,2)_{\frac{5}{6}} \; : \; \epsilon_{ij}\bar{Q}_i^c \gamma^\mu P_R U \; V_{j\mu} + \text{h.c.}$$

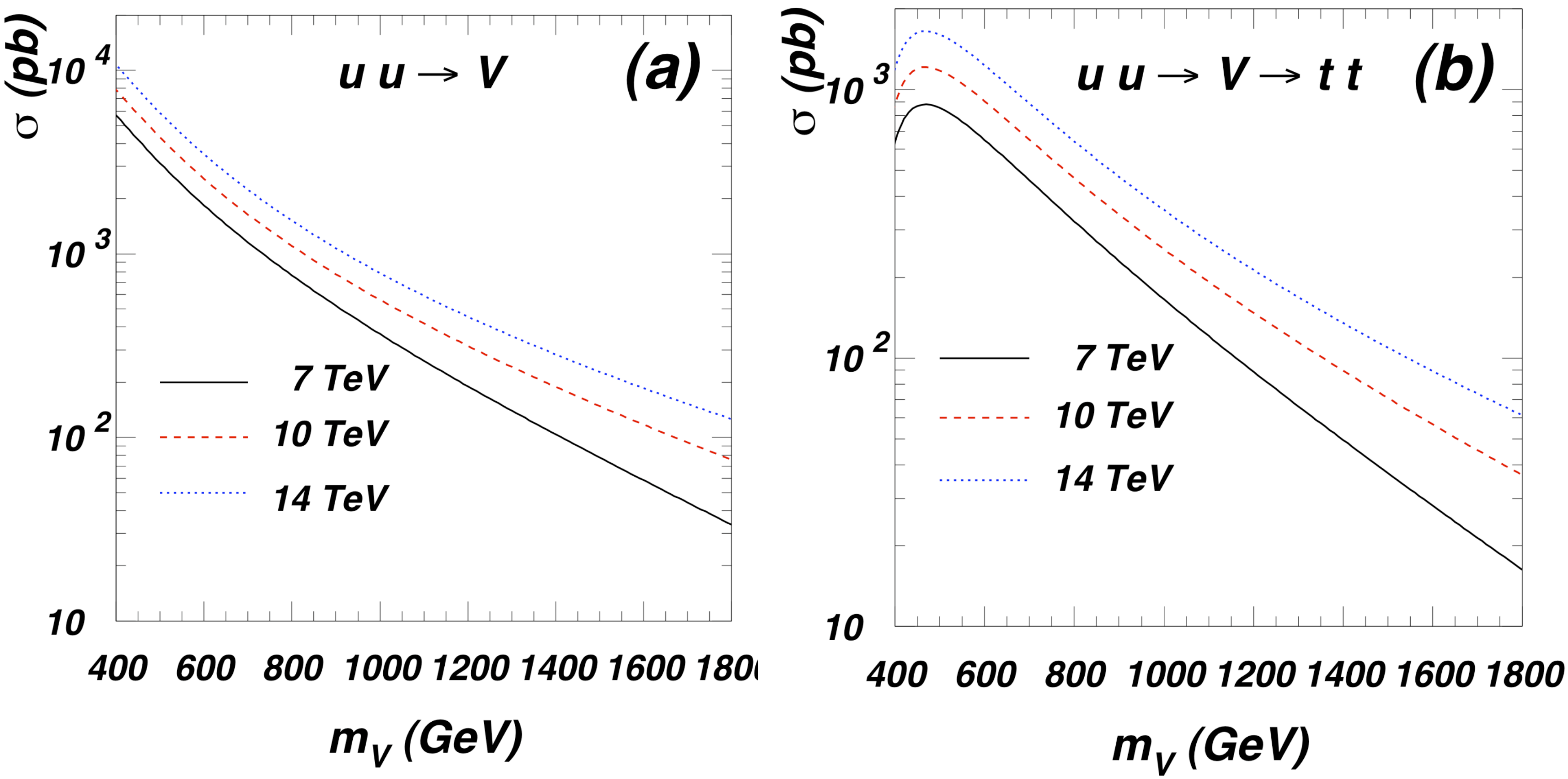
★ The first expression leads to single top quark production while the second results in the production of same-sign top quark pair with opposite polarization.

★ Can we measure the polarizations of the top quarks to distinguish the color sextet vector and scalar mesons?

Yes!

Color sextet vector mesons

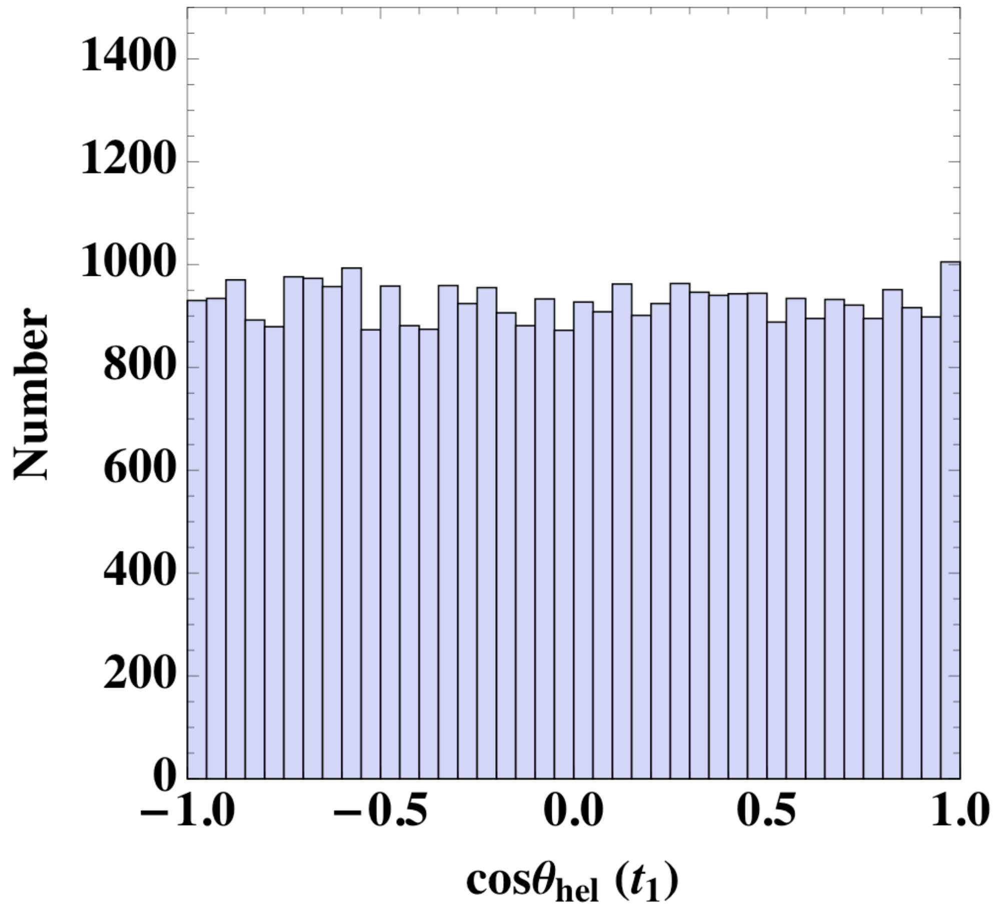
★ Production cross sections



Color sextet vectors

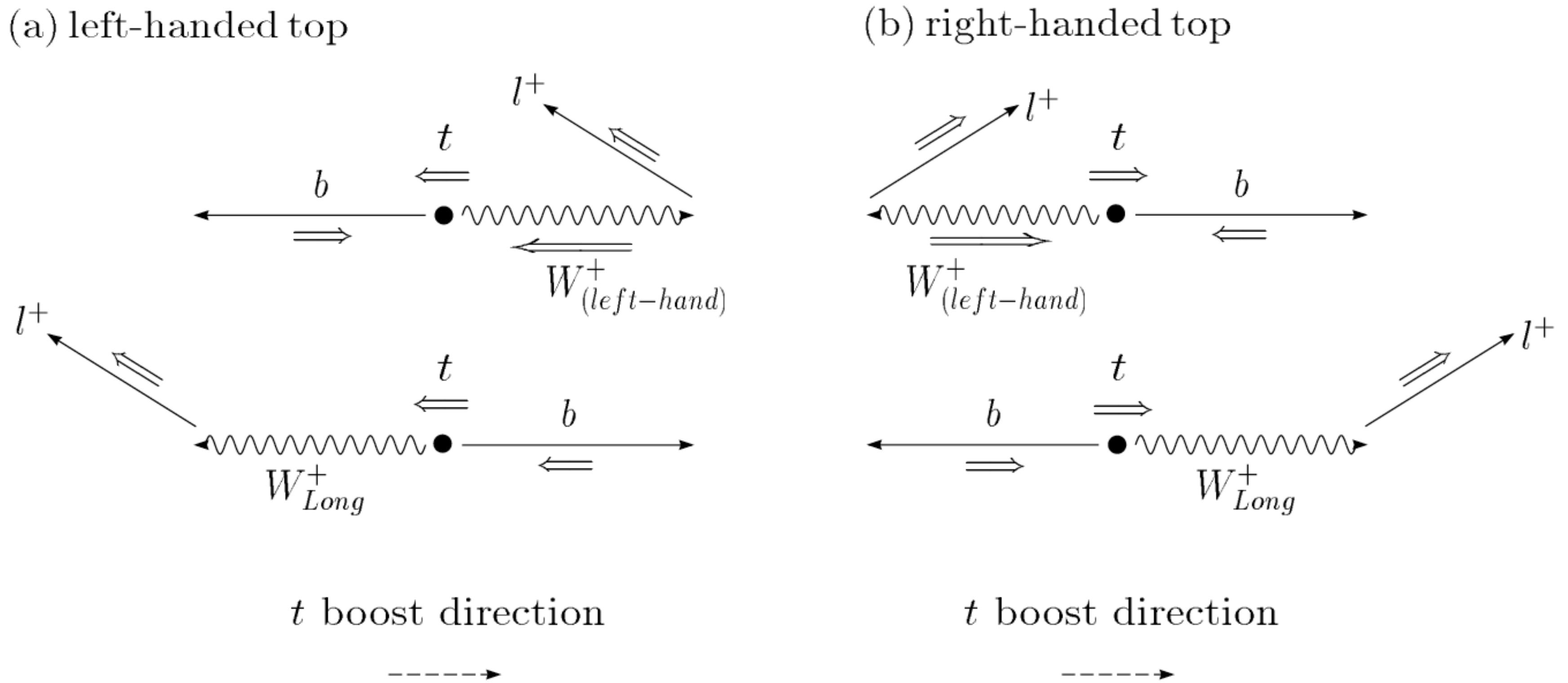
★ Top quarks are oppositely polarized, but the net polarization distribution of the two identical top quarks exhibits a flat profile (i.e. like unpolarized top quarks).

★ Even though the flat profile of sextet vectors is different from the one for scalars, it is interesting to see if we could determine that the top quarks have L and R polarizations.



Lepton energy and top quark polarization

★ Lepton energy distribution is sensitive to top quark polarization.



Leptons from right-handed top quark decay are more energetic than those from left-handed top quark decay.

Lepton energy and top quark polarization

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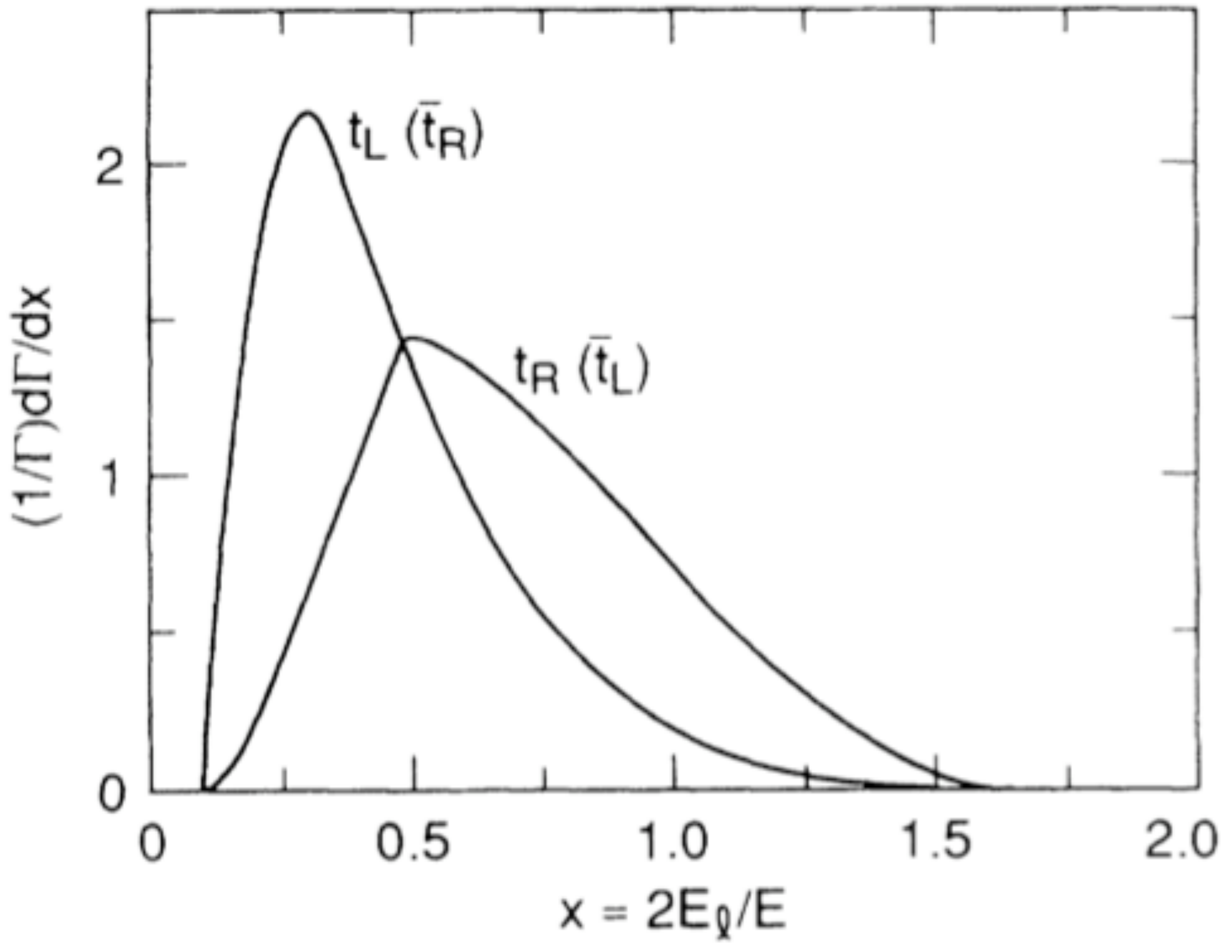


C. R. Schmidt and M. E. Peskin, Phys. Rev. Lett. 69, 410(1992)

Discovery potential

★ LHC (7 TeV and 1 inverse fb luminosity)

$$p_T^j \geq 50 \text{ GeV}$$

$$|\eta_j| \leq 2.5$$

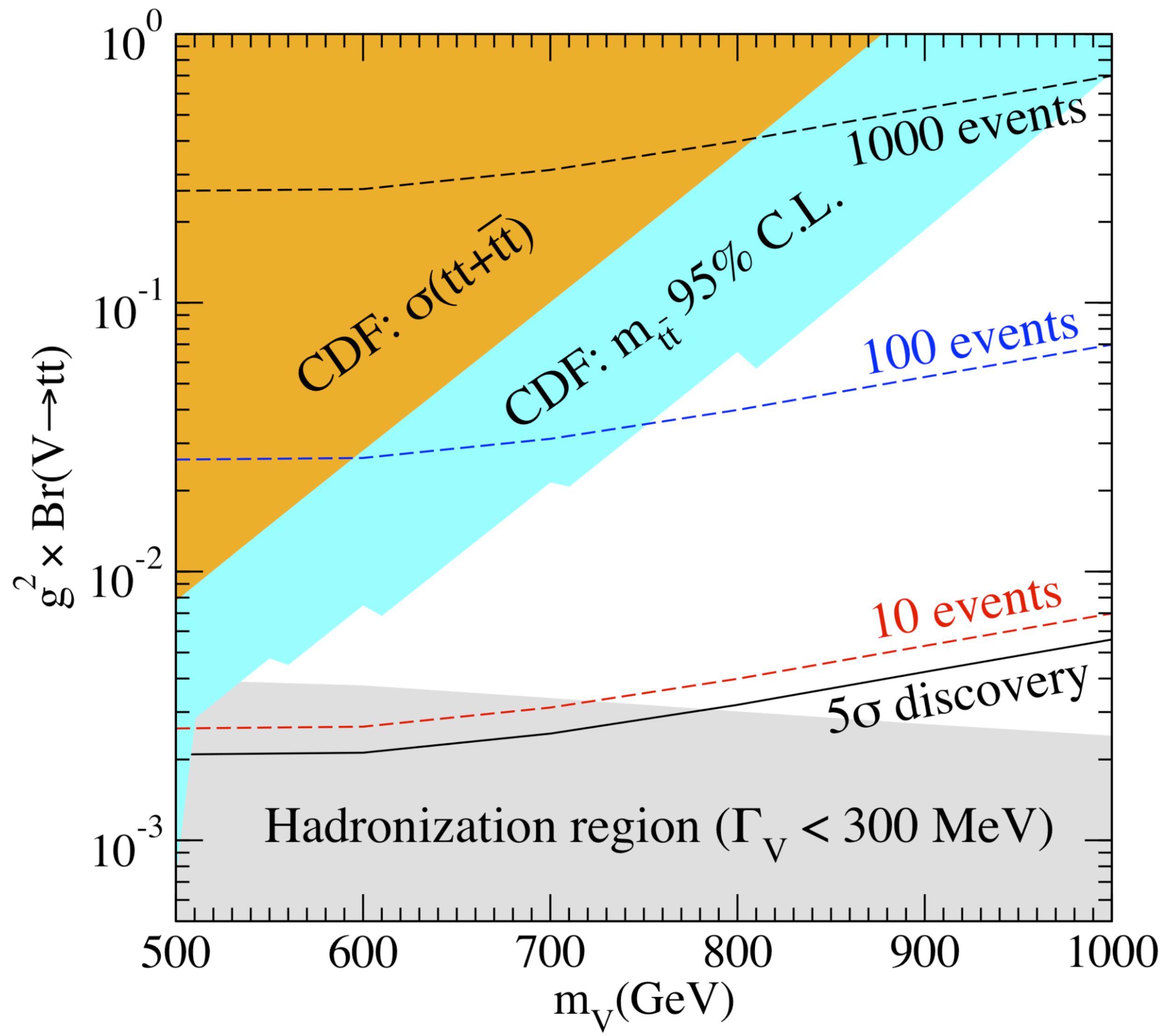
Asymmetric cuts on lepton pT

$$p_T^{\ell \text{Greater}} \geq 50 \text{ GeV}$$

$$p_T^{\ell \text{Lesser}} \geq 20 \text{ GeV}$$

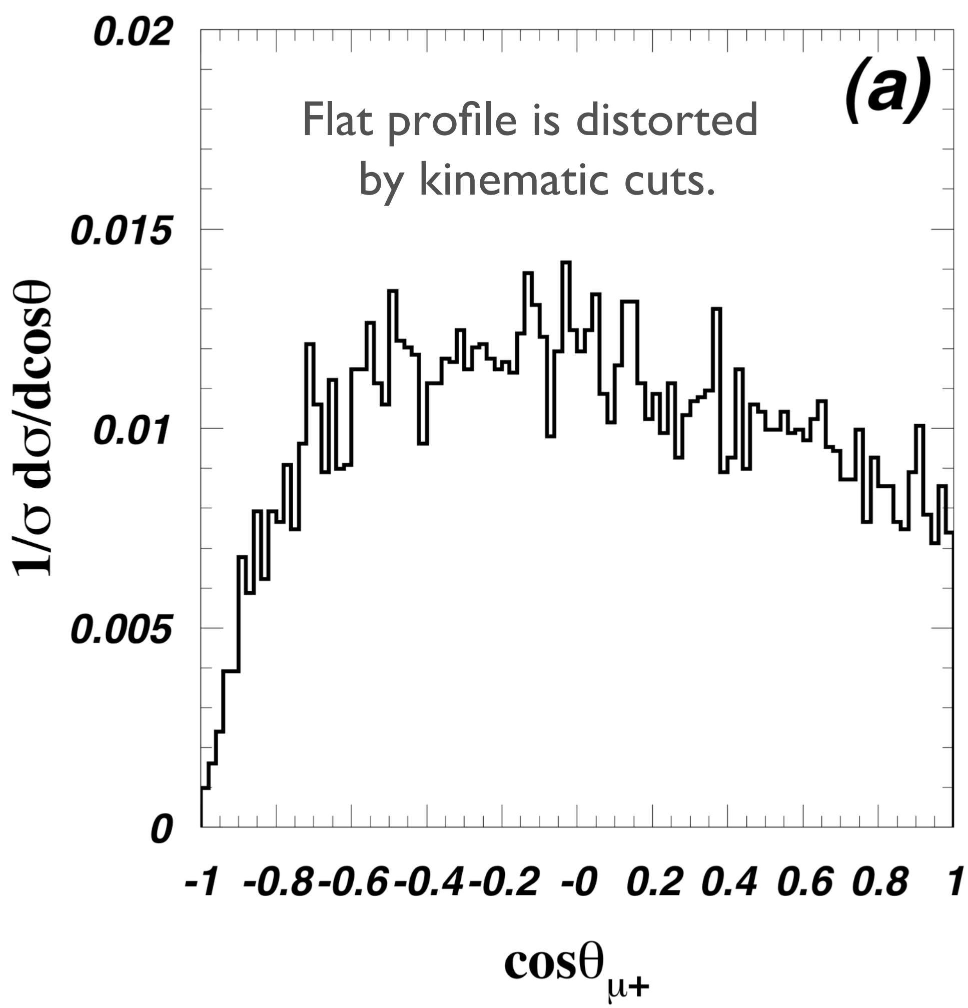
$$|\eta_\ell| \leq 2.0$$

$$\Delta R_{jj,j\ell,\ell\ell} > 0.4$$

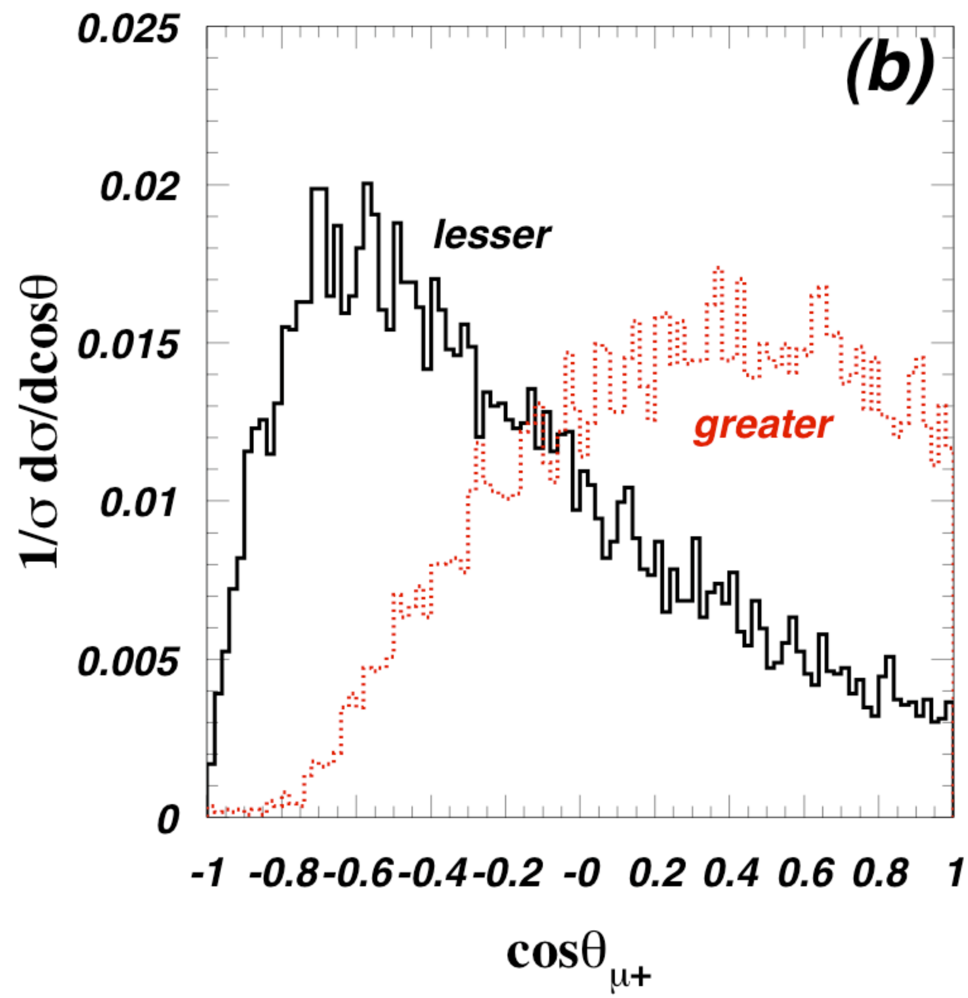


Top quark polarization measurement

★ Before lepton energy selection



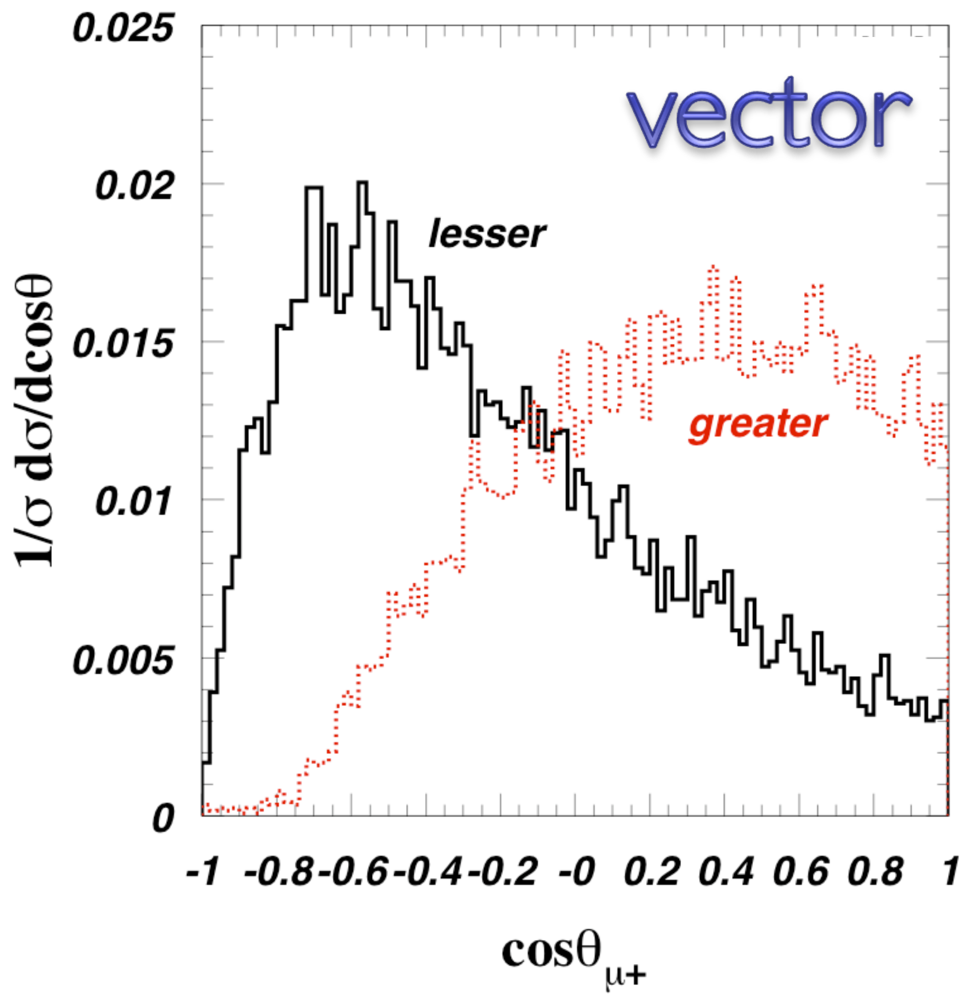
★ After lepton energy selection

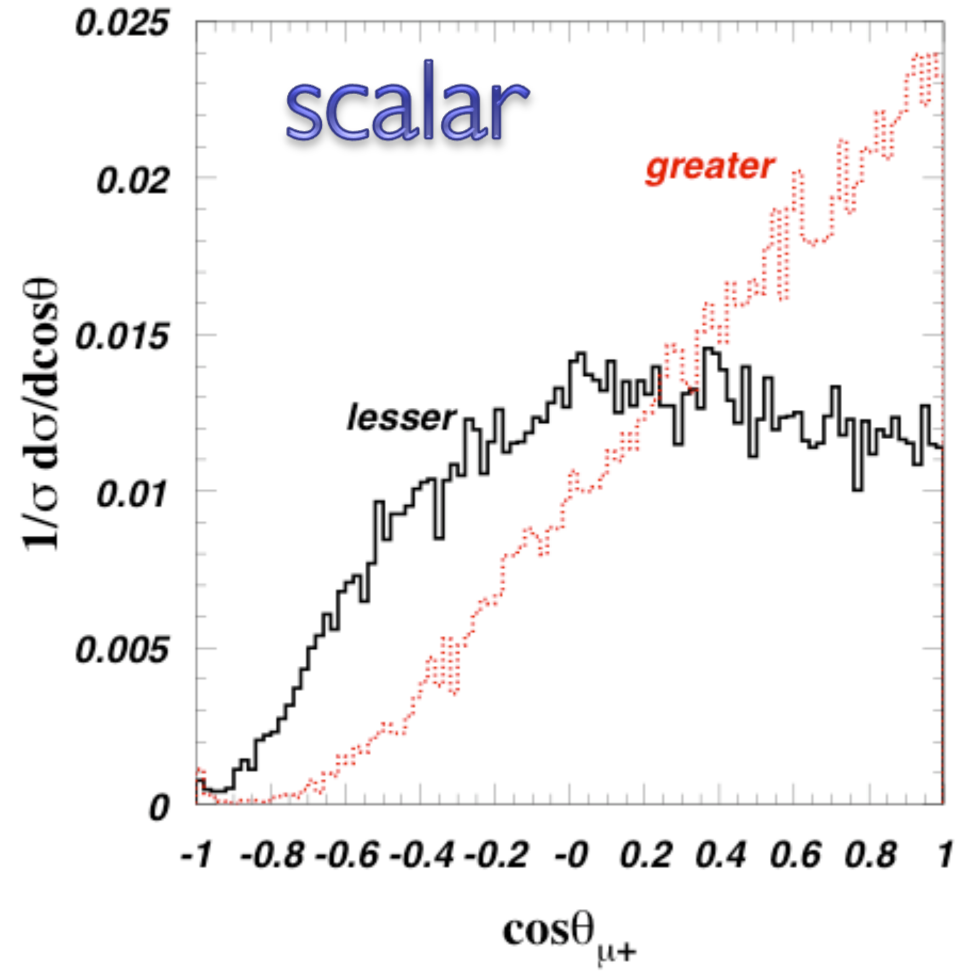


✳ Roughly 98 (67) events required to distinguish vector lesser (greater) from vector unpolarized case

Top quark polarization measurement

★ Apply the same analysis to sextet scalar (gauge singlet)

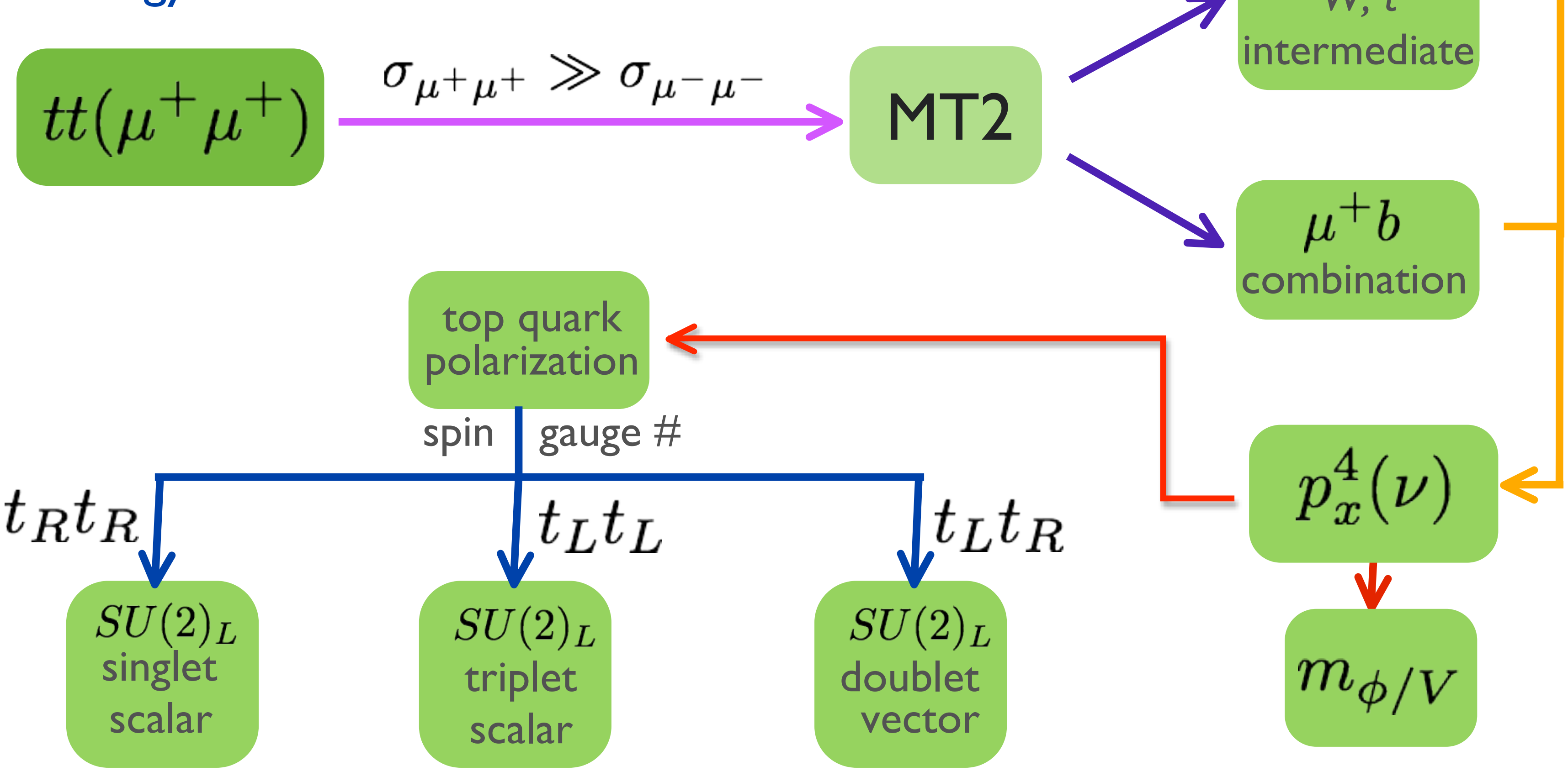




The $\frac{1}{2}(1+\cos\theta)$ shape of sextet scalar still remains with a moderate distortion.

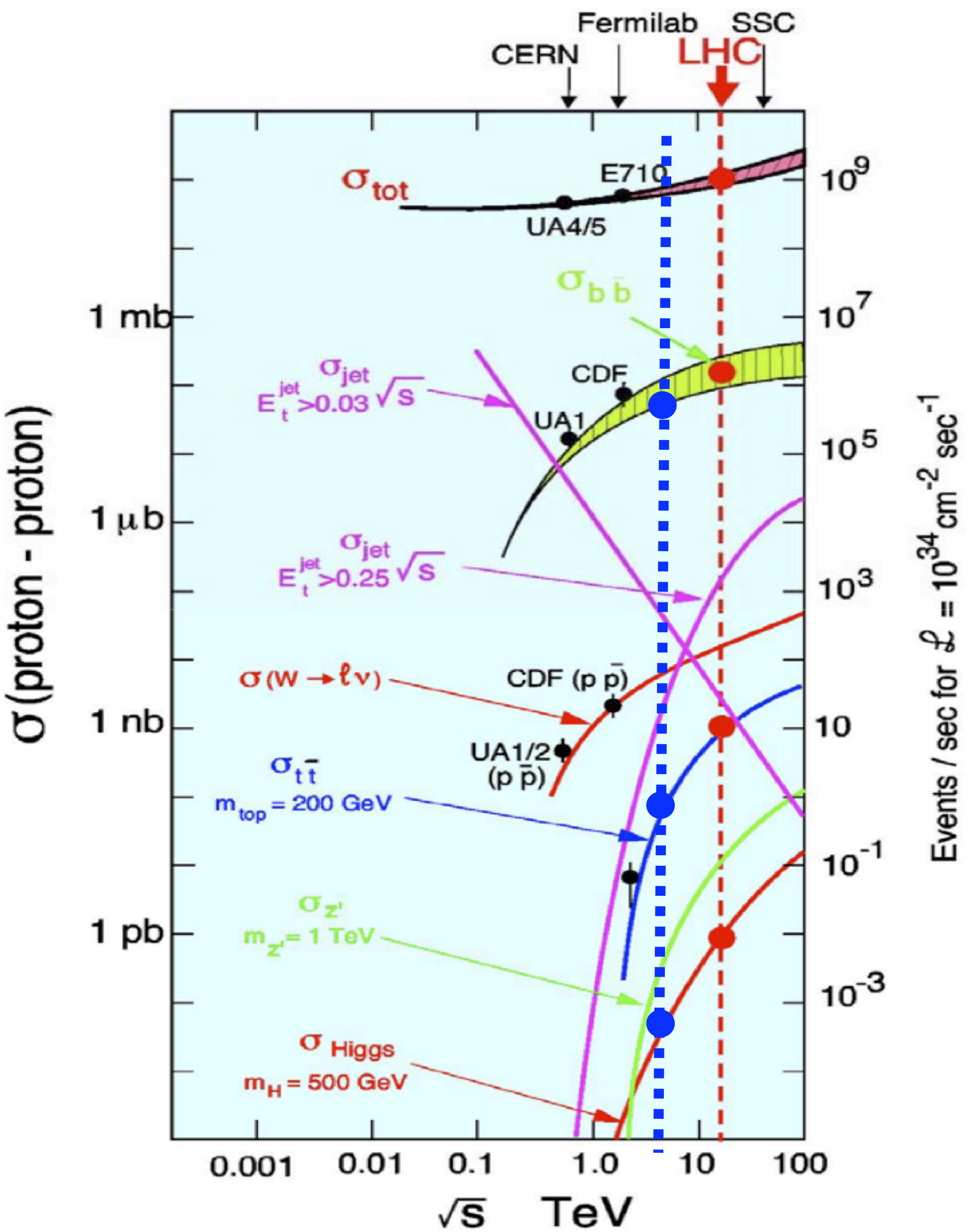
Summary

- ★ Color sextet scalar and vector mesons may be a long shot they offer good discovery potential in early LHC running at 7 TeV
  - ✳ Enhanced cross sections relative to EW scale new physics
  - ✳ 30 events (scalar) and 100 events (vector) sufficient
  - ✳ Naturally large same-sign dilepton rates allow background rejection
- ★ Search strategy



Backup Slides

LHC decade



★ Rate for $\mathcal{L} = 10^{34}\text{cm}^{-2}s^{-1}$

- Inelastic proton-proton reactions: $10^9/s$
- bottom quark pairs: $5 \times 10^6/s$
- top quark pairs: $10/s$
- $W \to \ell\nu$ $150/s$
- $Z \to \ell\ell$ $15/s$
- Higgs boson (150GeV): $0.2/s$
- Gluino, Squarks (1TeV): $0.03/s$

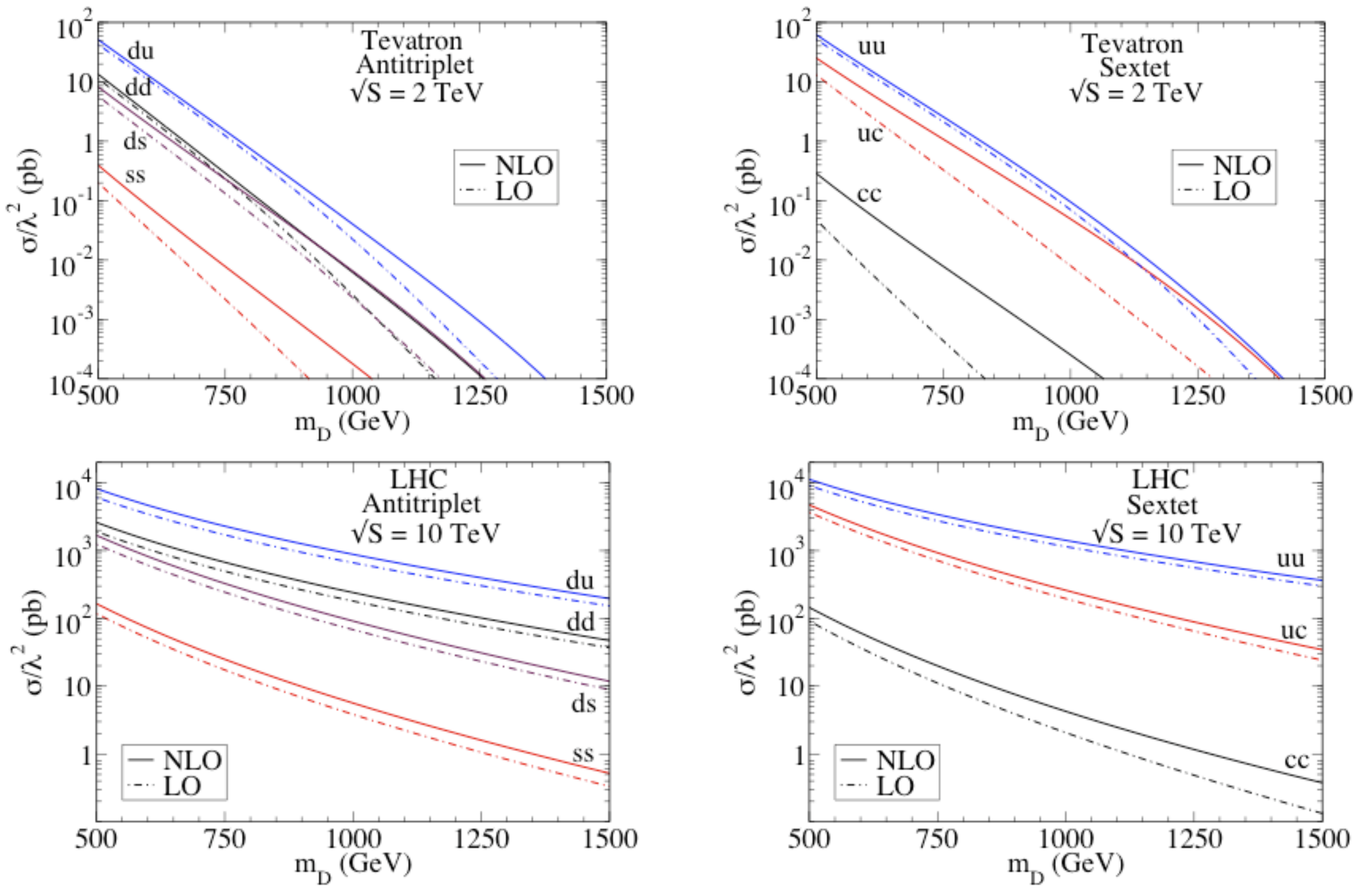
(1) LHC is a factory for SM and new TeV scale physics.

(2) What new physics may be observable at 7 TeV? And how?

Production cross sections at NLO

★ NLO QCD corrections for single color sextet scalar production are available

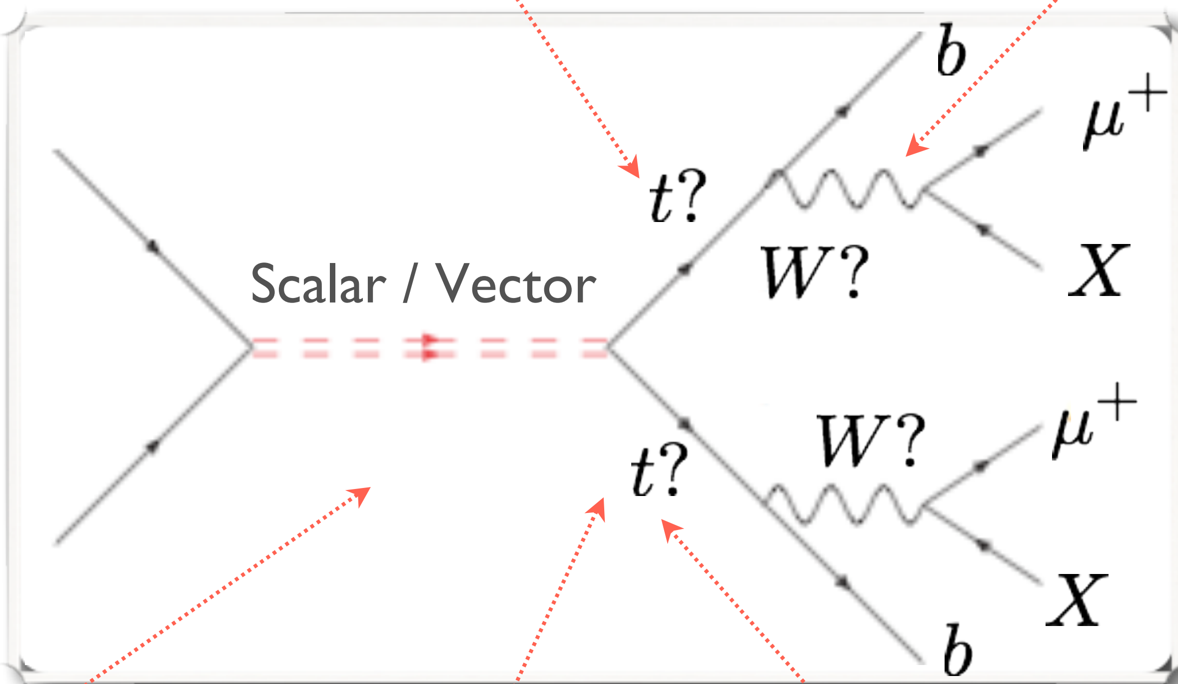
Han, Lewis, McElmurry, 0909.2666



Questions to be answered

(2) Does each jet + lepton pair reconstruct a top quark?

(1) Are the muons and missing X from W-boson decays?



Need full event reconstruction

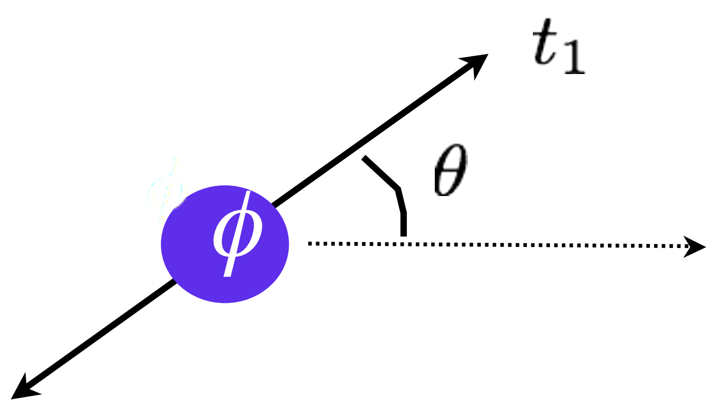
Difficulty: identical muons and b jets

(3) What is the mass of the resonance?

(4) What is top quark polarization?

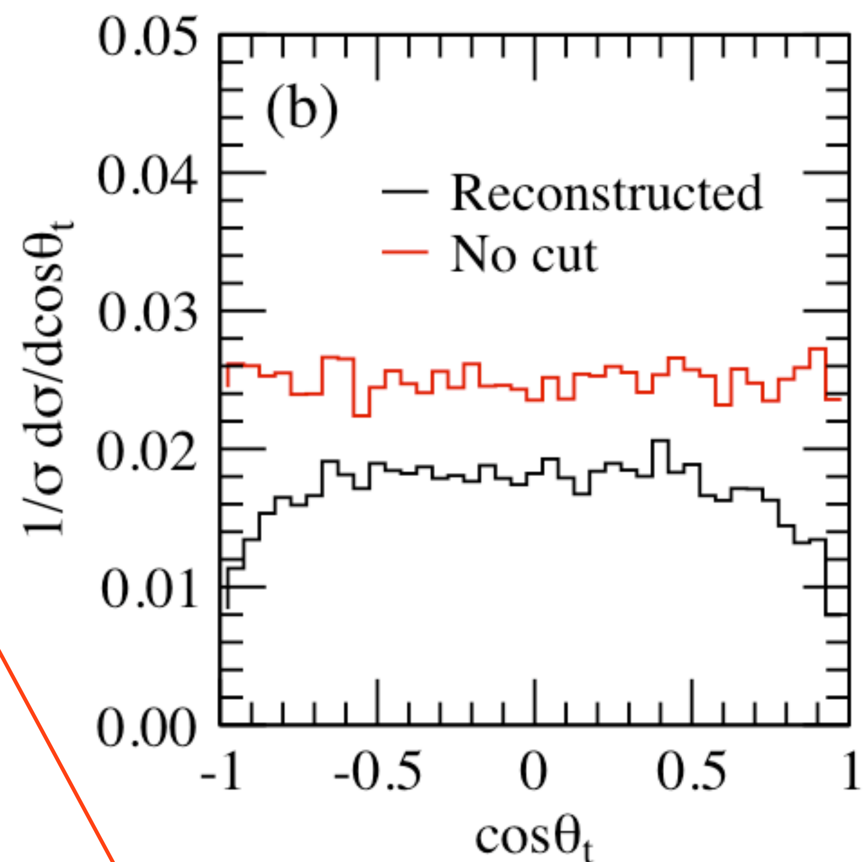
(5) Are the top quarks from a scalar or vector decay?

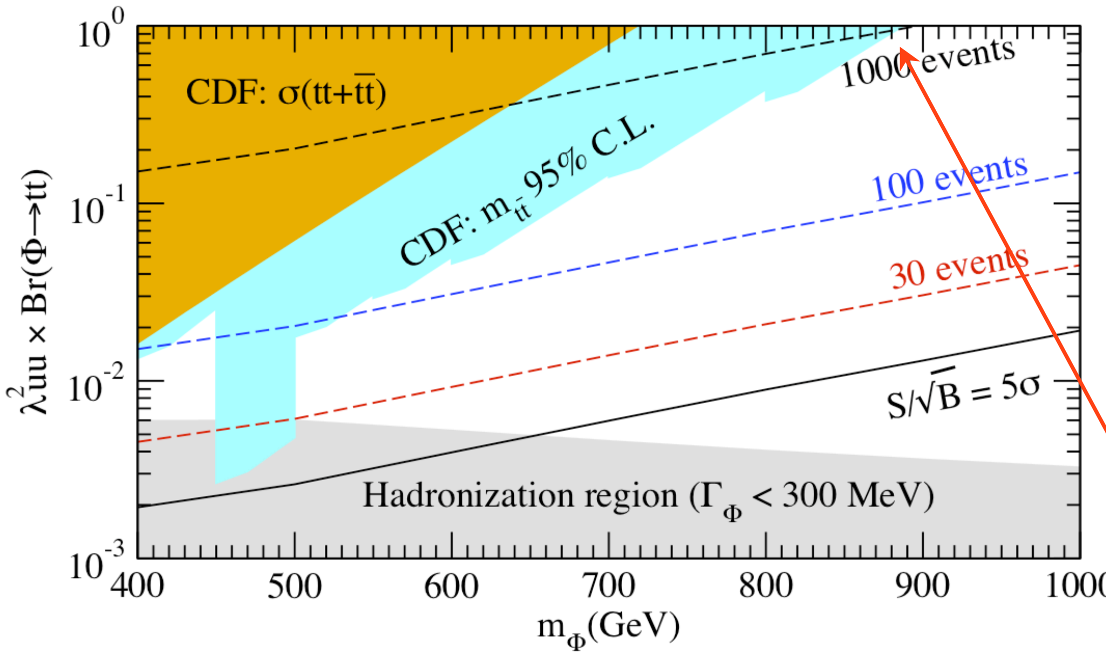
Reconstructed event distribution



★ Can we determine the spin of the heavy resonance?

Not easy !





Not realistic for early LHC!

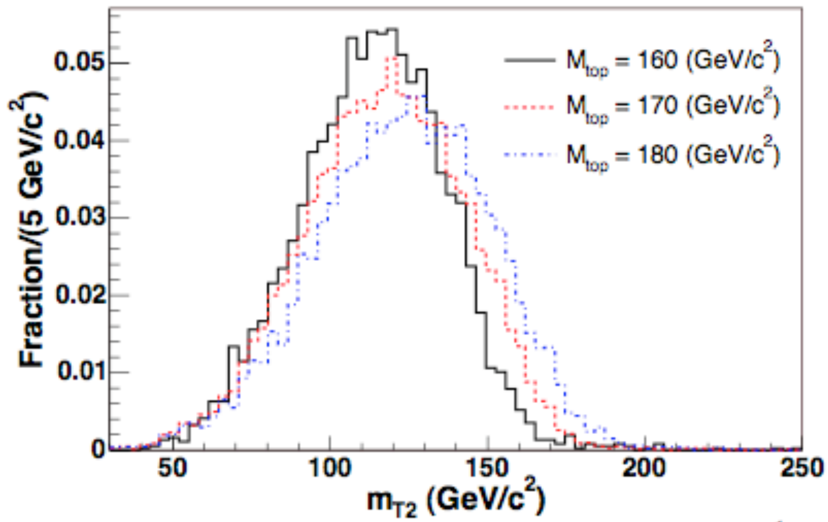
It requires ~ O(1000) events to verify the flat distribution.

MT2 method

★ When there are two heavy particles decaying into visible particles and invisible particles, the MT2 variable may be used to measure the mass of their parent.

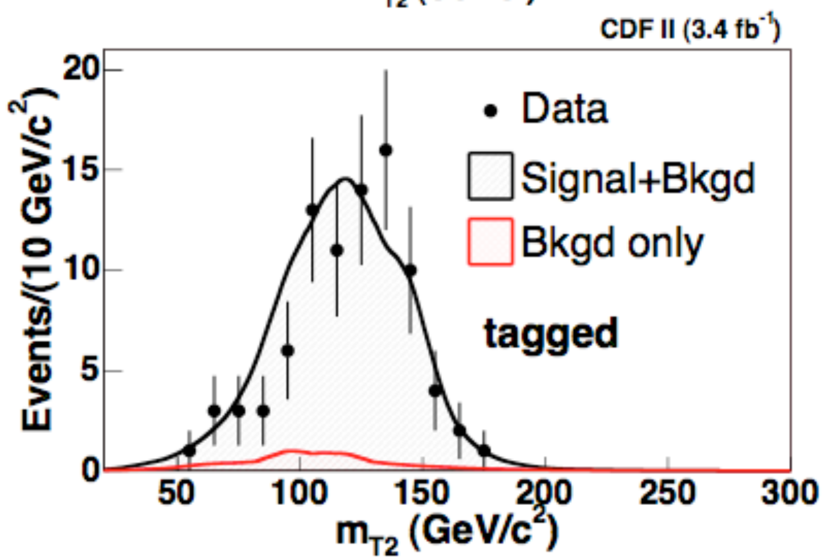
$$m_{T2}(m_{invis}) = \min_{\mathbf{p}_T^{(1)},\mathbf{p}_T^{(2)}} \left[\max[m_T(m_{invis};\mathbf{p}_T^{(1)}), m_T(m_{invis};\mathbf{p}_T^{(2)})]\right]$$

$$m_T(m_{invis};\mathbf{p}_T^{invis}) = \sqrt{m_{vis}^2 + m_{invis}^2 + 2(E_T^{vis}E_T^{invis} - \mathbf{p}_T^{vis}\cdot\mathbf{p}_T^{invis})}$$



★ The MT2 variable is a function of the momenta of visible particles (α, β) and missing transverse momentum. Its upper bound yields the mass of the parent particle (ζ) .

★ The method has been used in the top quark mass measurement at the Tevatron.



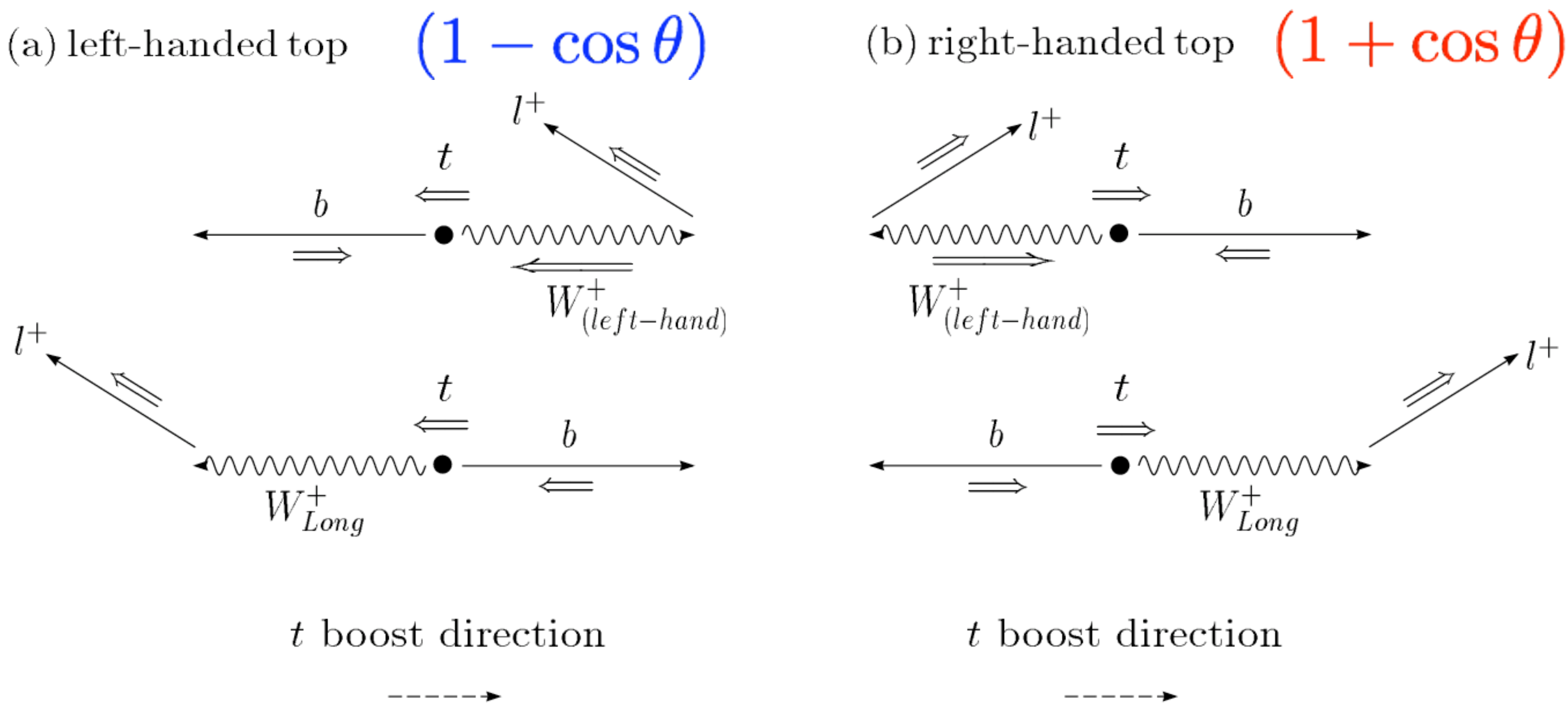
CDF collaboration, Phys. Rev. D 77, 112001 (2008)

Top quark polarization

★ Among the top quark decay products, the charged lepton is maximally correlated with top quark spin.

$$\frac{1}{\Gamma}\frac{d\Gamma(t \to b\ell\nu)}{d\cos\theta} = \frac{1}{2}\left(1 + \frac{N_+ - N_-}{N_+ + N_-}\cos\theta\right)$$

★ θ is the angle, in the top quark rest frame, between the direction of the charged lepton and the spin of the top quark. In the helicity basis, top quark spin is along its direction of motion.



Lepton energy and top quark polarization

★ Peak positions are listed as follows:

Hao Zhang, EB, Qing-Hong Cao, in preparation.

β value	left-handed top quark	right-handed top quark
$(0.91, 1)$	$-\frac{(1-\beta)^2}{1-3\beta} W\left[-\frac{1-3\beta}{1-\beta}\exp\left(-B+\ln B+\frac{2\beta}{1-\beta}\right)\right]$	$B(1+\beta)$
$(0.52, 0.91)$	$-\frac{(1-\beta)^2}{1-3\beta} W\left[-\frac{1-3\beta}{1-\beta}\exp\left(-B+\ln B+\frac{2\beta}{1-\beta}\right)\right]$	$-\frac{(1+\beta)^2}{(1+3\beta)} W\left[-\frac{(1+3\beta)}{(1+\beta)}\exp\left(-\frac{1+3\beta}{1+\beta}\right)\right]$
$(0, 0.52)$	$\frac{(1-\beta^2)}{2\beta}\left(1-\frac{1-\beta}{\beta}\text{arctanh}\beta\right)$	$-\frac{(1-\beta^2)}{2\beta}\left(1-\frac{1+\beta}{\beta}\text{arctanh}\beta\right)$

$B = \frac{m_W^2}{m_t^2}$

W is the Product Logarithm function