Some Old Thoughts of Higgs Physics

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Phys. Rev. D69 (2004) 115003

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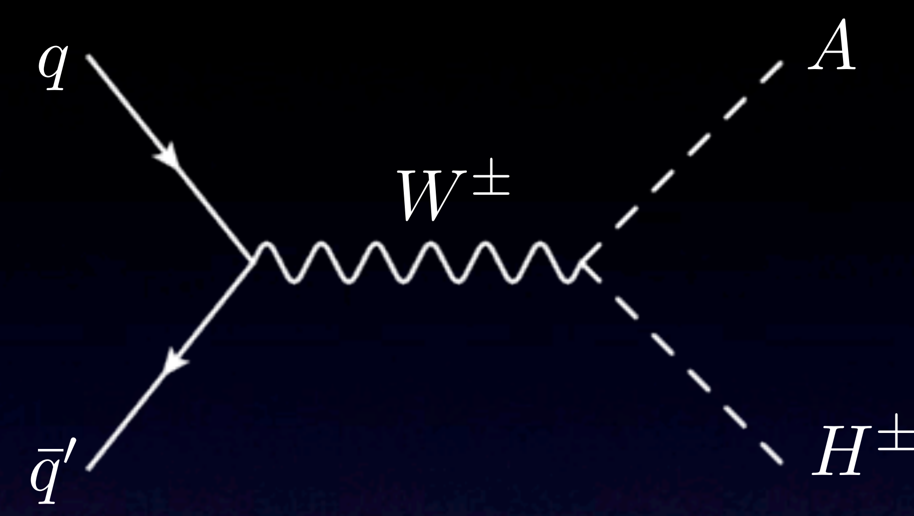
Phys. Rev. Lett. 100 (2008) 061801

Outline

- AH^+ associate production
  - ➡ A long ignored channel in "*Higgs Hunter's Guide*"



  - ➡ A demo for collider simulations

Collider Phenomenology	≠	Mad-suite (MadGraph/Event/Analysis)

You MUST fully understand your results.
You cannot simply say "*I got them from Mad-...*"

- Higgs boson and heavy fermion

Motivation

- Physics predictions depend strongly on the details of SUSY parameters.

A typical SUSY phenomenology study depends on at least two SUSY parameters, e.g. $\tan\beta$ and m_A, and various physics reach depends on other SUSY parameters as well.

Very often, the physics reach of a process is expressed in terms of bounds on

$$\sigma(\text{production}) \times \mathrm{Br}(\text{decay branching ratio})$$

where both σ and Br depend on SUSY parameters

In general detection efficiency also depends on SUSY parameters.

Our task is to find a SUSY process

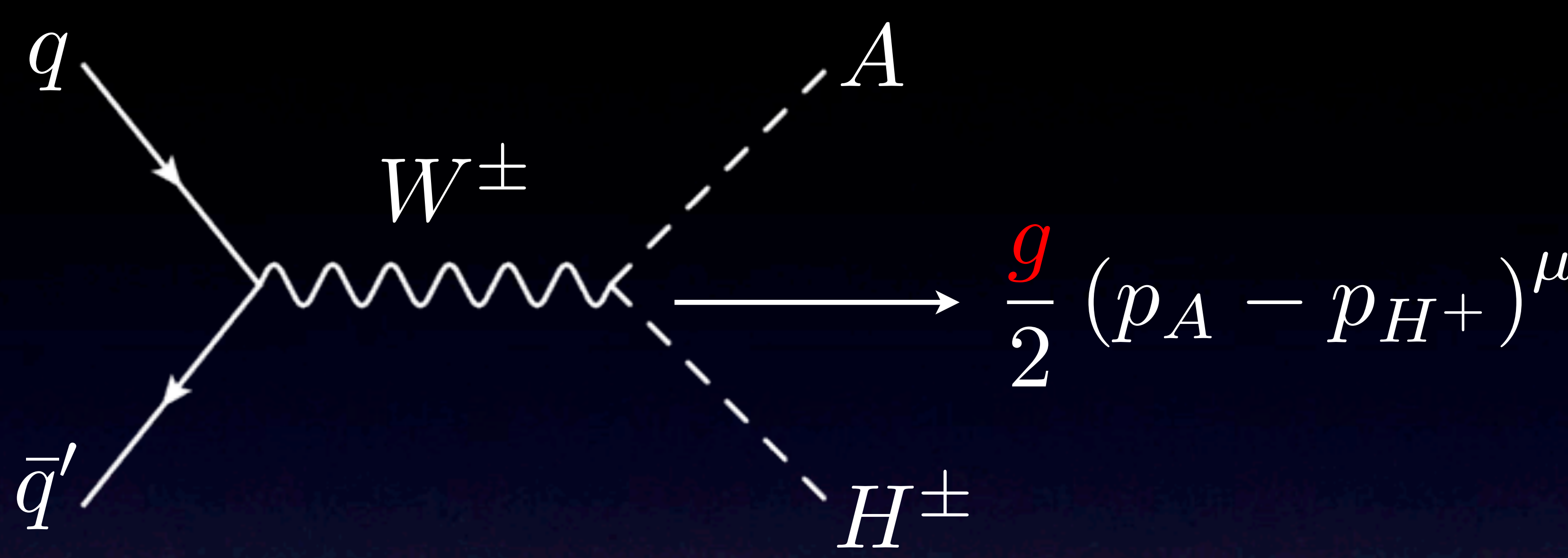
- whose tree level $\sigma_{\rm prod}$ depends on only ONE SUSY parameter that can be determined by kinematic variable (e.g. invariant mass).
- that is not sensitive to the detailed SUSY parameters via radiative corrections.
- that can bound the SUSY models by (product of)

  Br (decay branching ratio)

  without convoluting with $\sigma_{\rm prod}$.
- that can be used to distinguish MSSM from its alternatives, e.g. 2HDM.
- whose final state particle kinematics can be properly modeled without specifying any SUSY parameters.

→ The detection efficiency can be accurately determined.

The promising process $pp \to W^{\pm} \to AH^{\pm}$



The production cross section in general depends on two masses: m_A and m_{H^+}, e.g. in 2HDM.

But in MSSM,

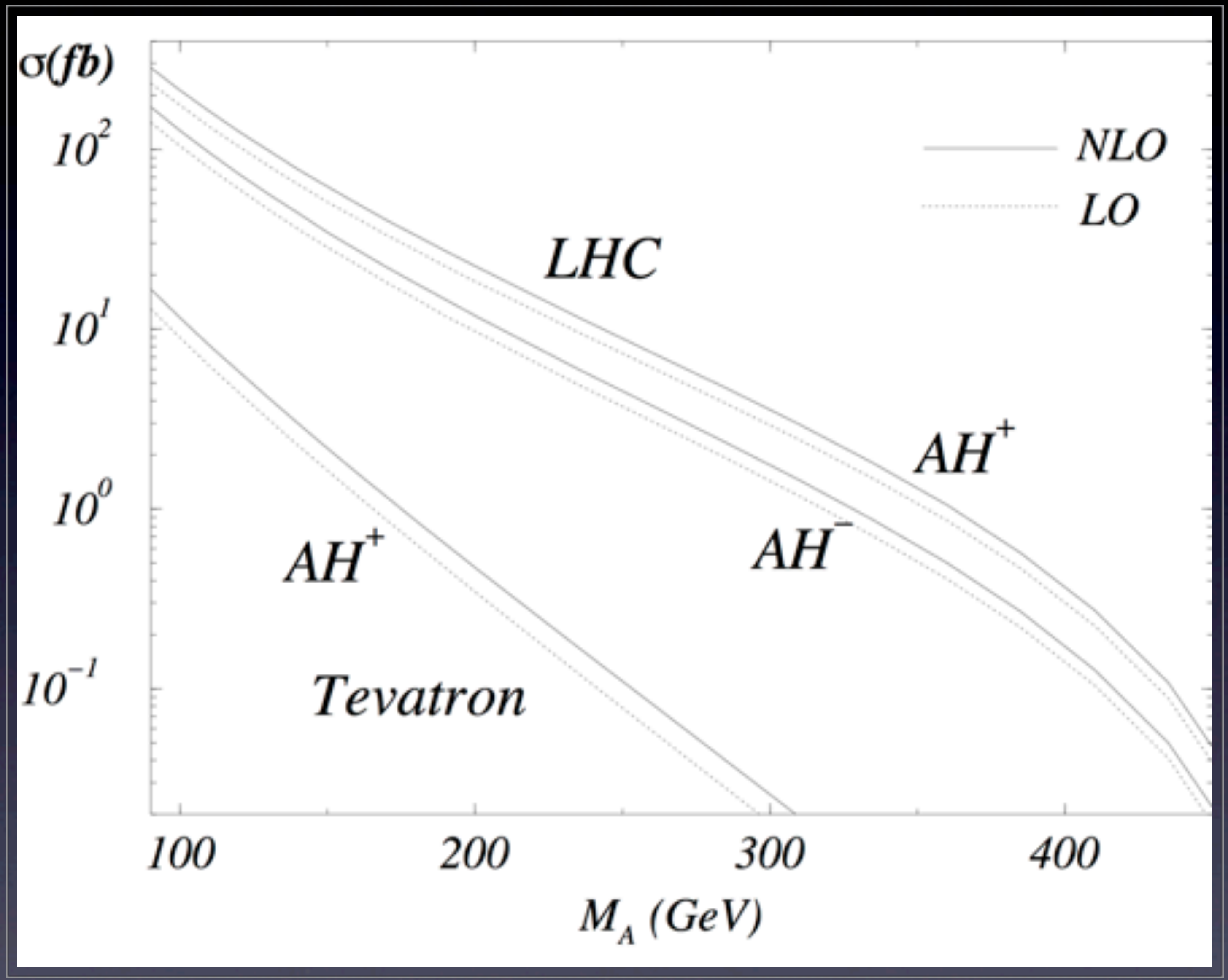
$$\boxed{m_{H^+}^2 = m_A^2 + m_W^2}$$

→ σ_{prod} only depends on g and m_A.

(m_A can be determined from its decay kinematics, e.g. the invariant mass $m_{b\bar{b}}$ in $A \to b\bar{b}$.)

Production rates

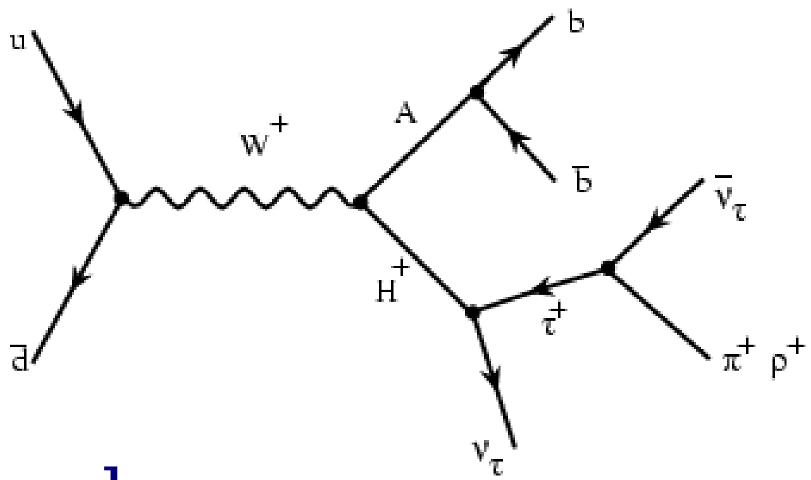
- NLO QCD correction is about 20%
- Uncertainty due to PDF is about 5% at LHC for m_A =120GeV.
- The one-loop electroweak correction to the production rate is smaller than the PDF uncertainty.



- The MSSM mass relation between *A* and H^+ holds well beyond tree level.

Signal and BKGD

Signal

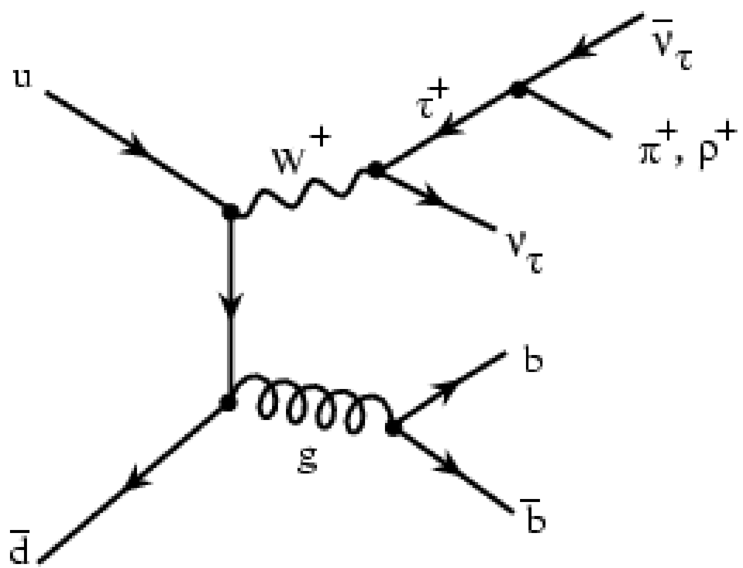


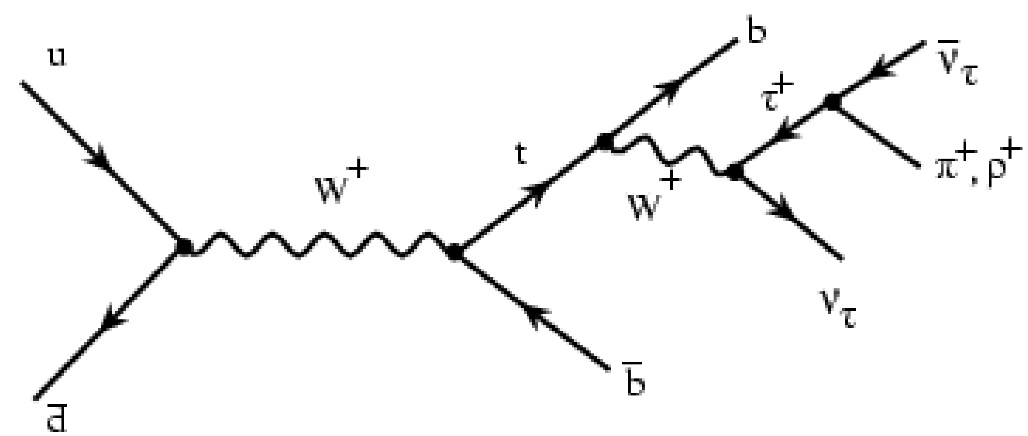
Veto additional lepton and jet from the parton level background events that satisfy

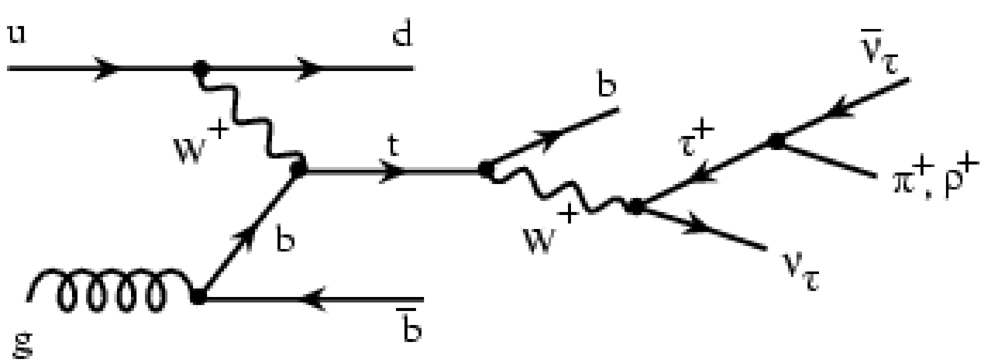
$$p_T(\text{lepton}) > 10\,\text{GeV}, \text{and}\ |\eta(\text{lepton})| < 3$$

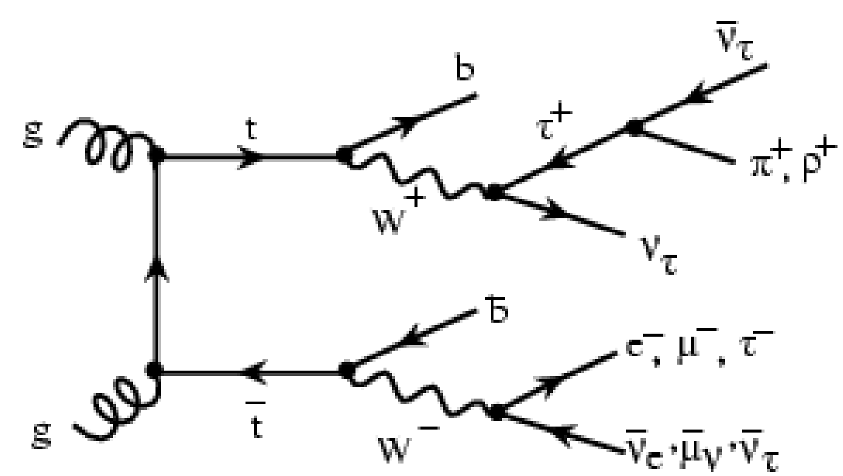
$$p_T(\text{jet}) > 10\,\text{GeV}, \text{and}\ |\eta(\text{jet})| < 3.5$$

Backgrounds









Model parameters and basic cuts

- The model parameters, production rates and decay BRs

Sets	A	B	C
m_A/Γ_A	101 /3.7	165.7 /5.6	250 /7.9
m_h/Γ_h	96.8 / 3.3	112 /0.04	112 /0.01
m_H/Γ_H	113 /0.38	163 /5.5	247.8 /7.8
m_{H+}/Γ_{H+}	126 / 0.43	182 / 0.68	261.4 / 4.2
$\sigma(AH^+)$ [fb]	164	36	5.4
$\sigma(HH^+)$ [fb]	137.4	37.4	5.4
$Br(A \to b\bar{b})$	0.91	0.90	0.89
$Br(H \to b\bar{b})$	0.90	0.90	0.89
$Br(H^+ \to \tau^+\nu)$	0.98	0.90	0.00
$Br(H^+ \to t\bar{b})$	0.00	0.09	0.79
$Br(\tau^+ \to \pi^+\nu)$	0.11	0.11	0.11

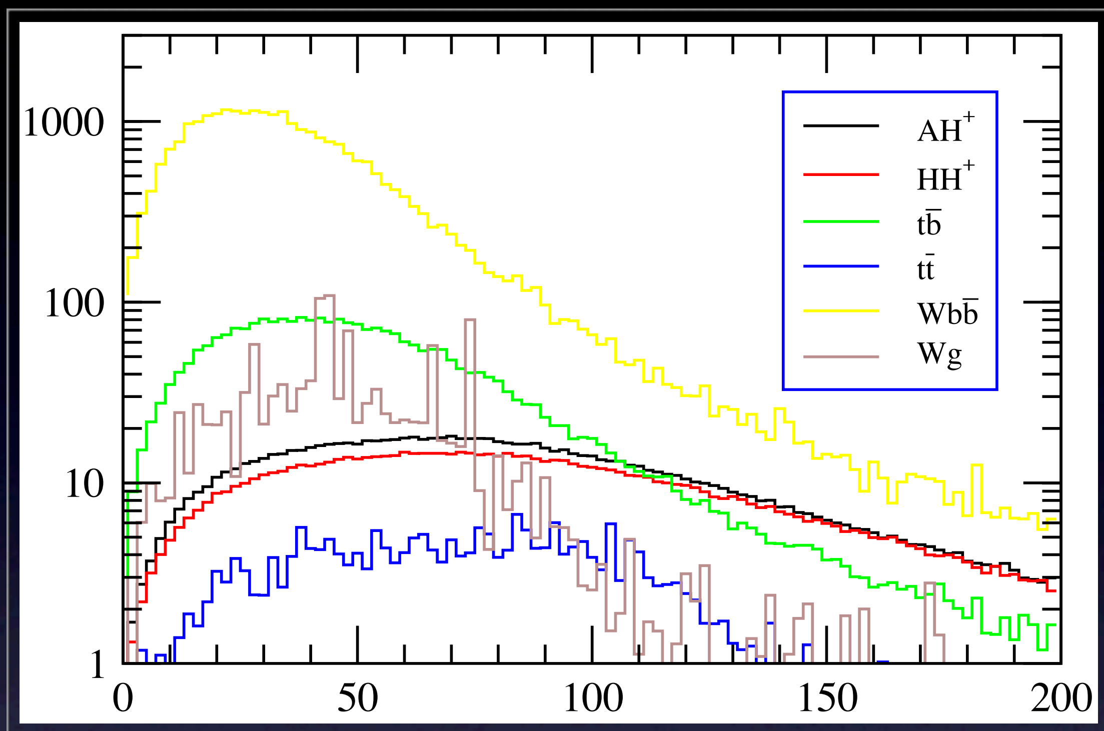
,

where $\tan\beta = 40, \mu = M = 500$GeV.

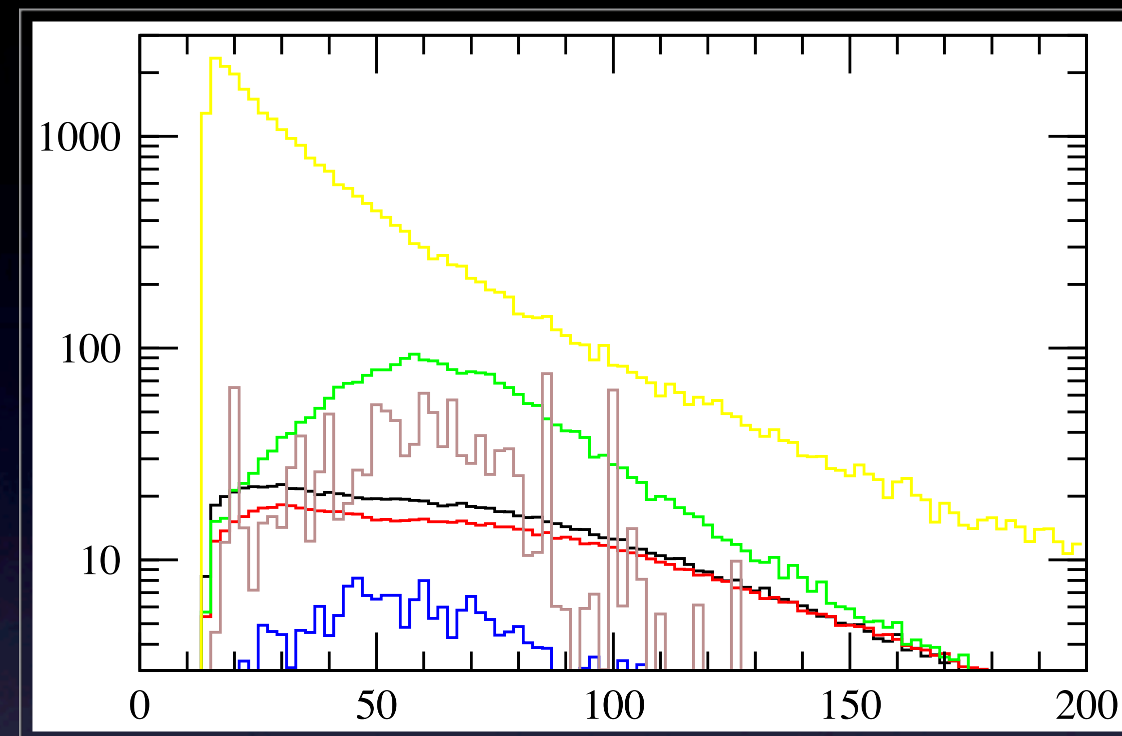
- Imposing basic cuts

$$p_T(b,\bar{b},\pi^+) > 15\ \mathrm{GeV}, \left|\eta(b,\bar{b},\pi^+)\right| < 3.5, \Delta R(b,\bar{b},\pi^+) > 0.4$$

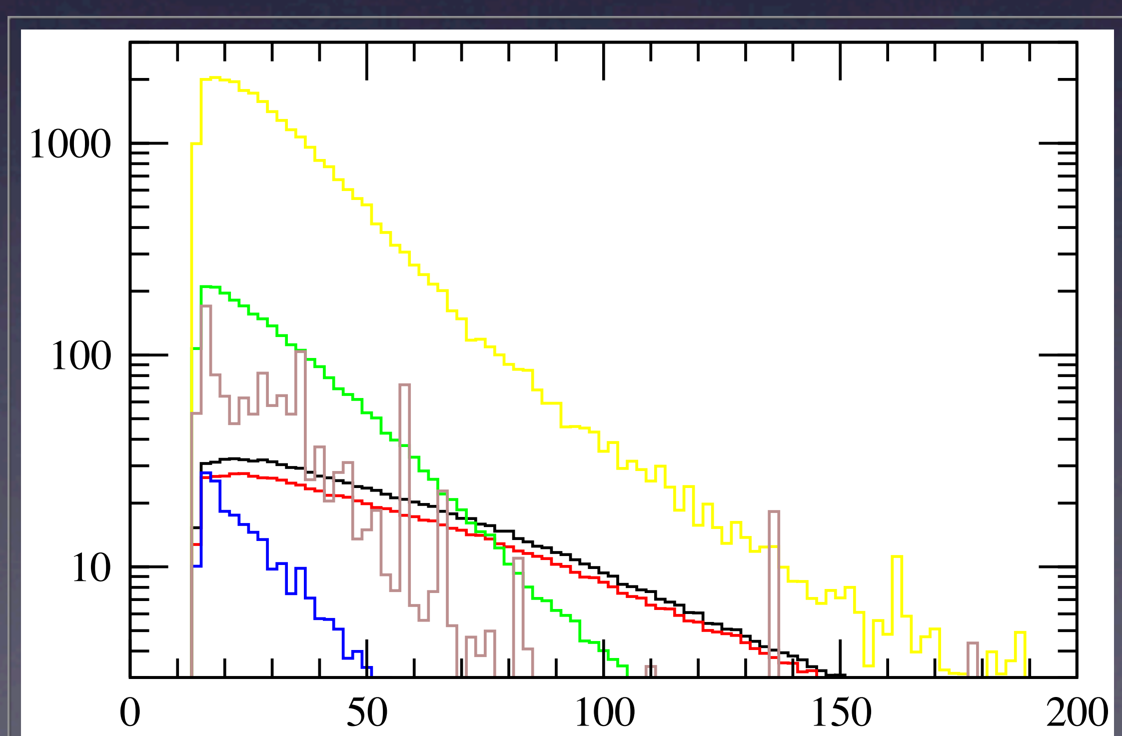
Set A (m_A=101GeV)
Kinematics Distributions



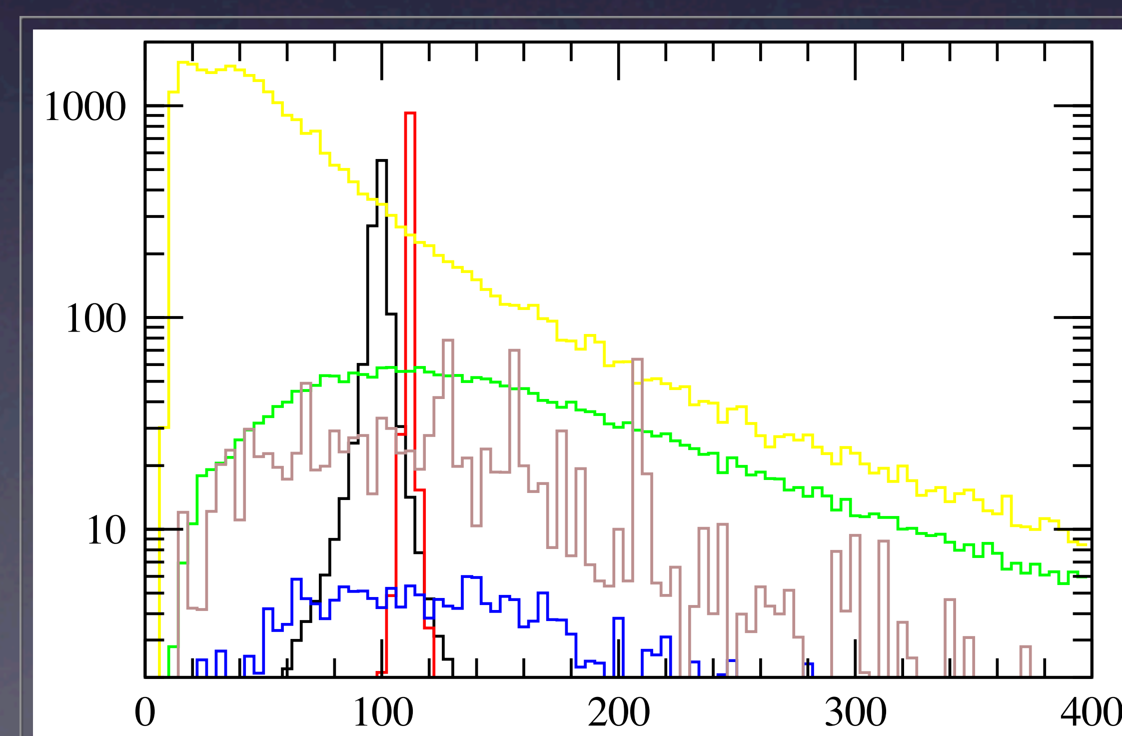
$\not{E}_T$(GeV)



p_T^b(GeV)



$p_T^{\pi^+}$ (GeV)



$m_{b\bar{b}}$(GeV)

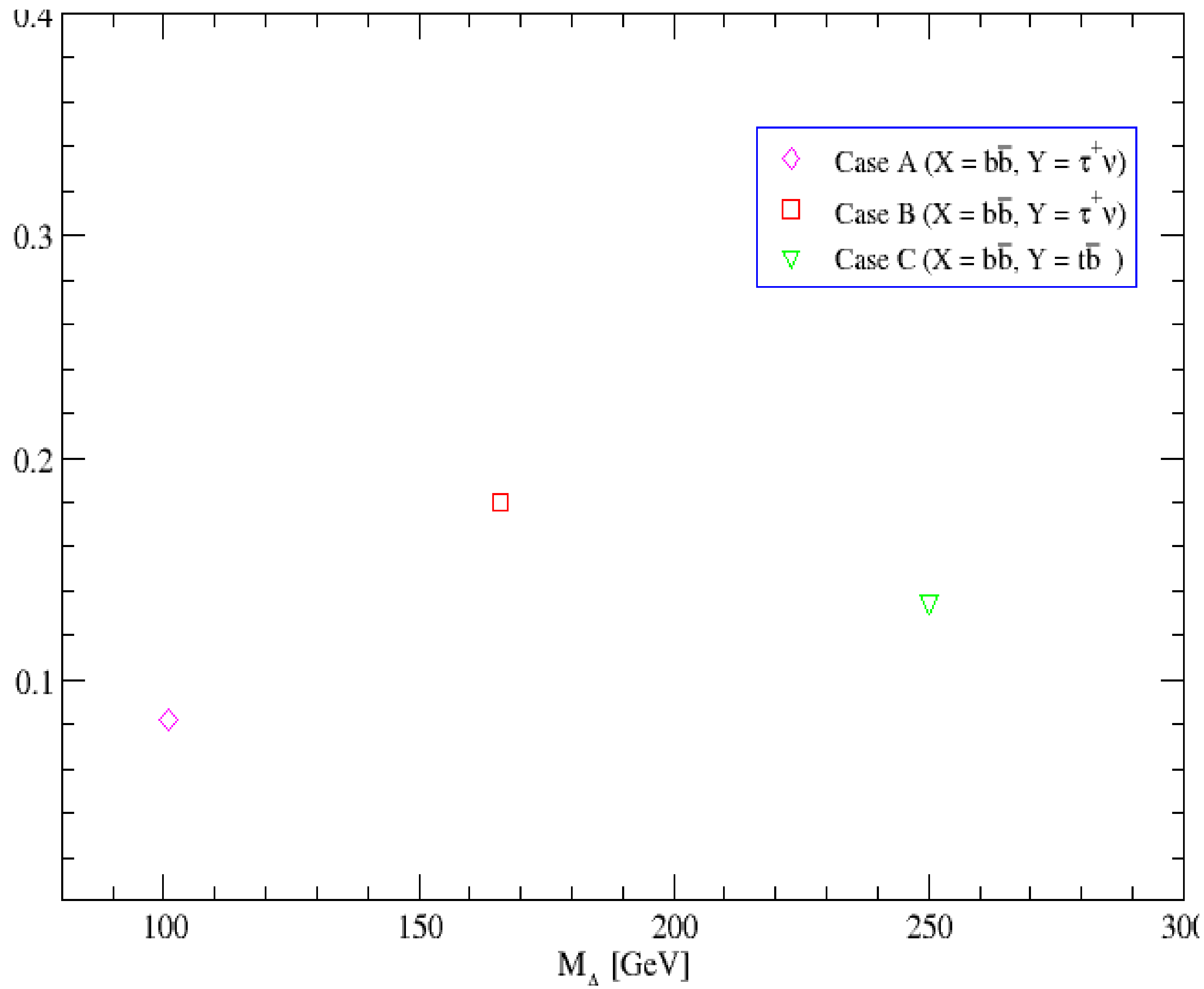
Significance

- Numbers of signal and background events at LHC with 100fb^{-1}. The b-tagging efficiency (50%, for tagging both b and $\bar{b}$ jets) is included, and the kinematic cuts listed in each column are applied sequentially.

- Signal: AH^+

	Basic Cuts	$\not{E}_T > 50$	$P_T^\pi > 40$	$90 < M_{b\bar{b}} < 110$ [GeV]
AH^+	507	391	241	216
HH^+	48	38	24	0
$Wb\bar{b}$	11555	3111	864	67
$t\bar{b}$	1228	614	163	12
Wg	567	236	68	11
$t\bar{t}$	110	80	17	2
Signal (S)	507	391	241	216
Bckg (B)	13507	4078	1135	92
S/B	0.038	0.095	0.212	2.35
$S/\sqrt{B}$	4.36	6.12	7.14	22.5
$\sqrt{S+B}/S$	0.23	0.17	0.15	0.08

Constraint on MSSM



Constraints on the product of branching ratios

$$B(A \to b\bar{b}) \times B(H^+ \to \tau^+ \nu_\tau)$$

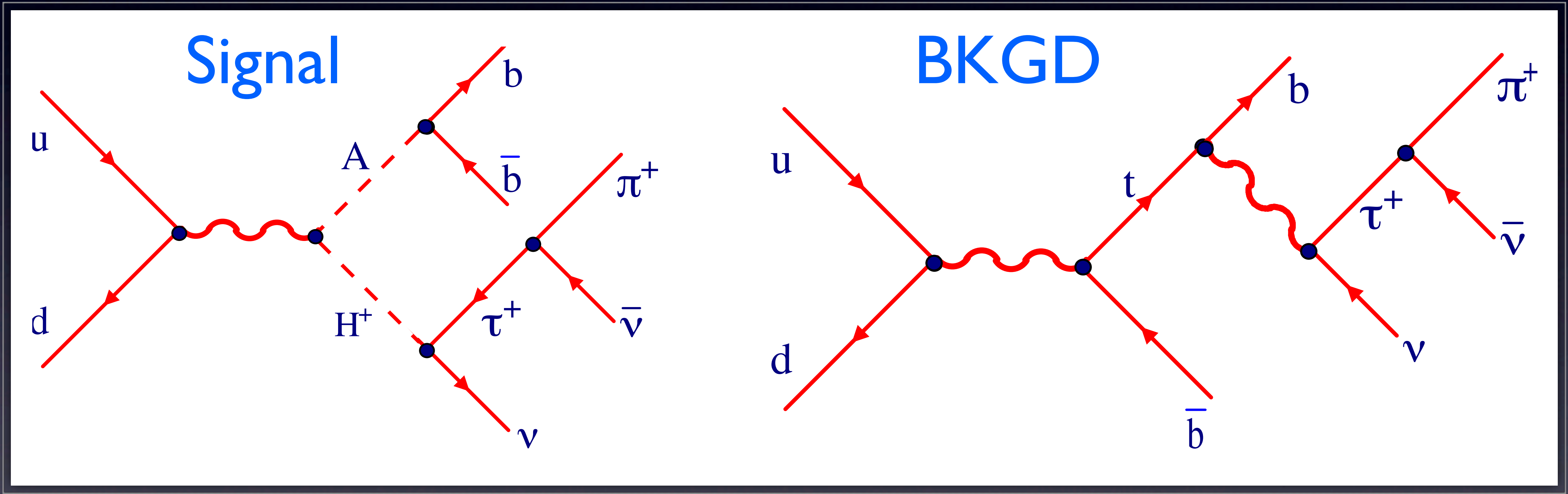
as a function of M_A for Case A and Case B, and

$$B(A \to b\bar{b}) \times B(H^+ \to t\bar{b})$$

for Case C, at the LHC, where τ^+ decays into $\pi^+ \bar{\nu}_\tau$ channel.

So far so good, *BUT*

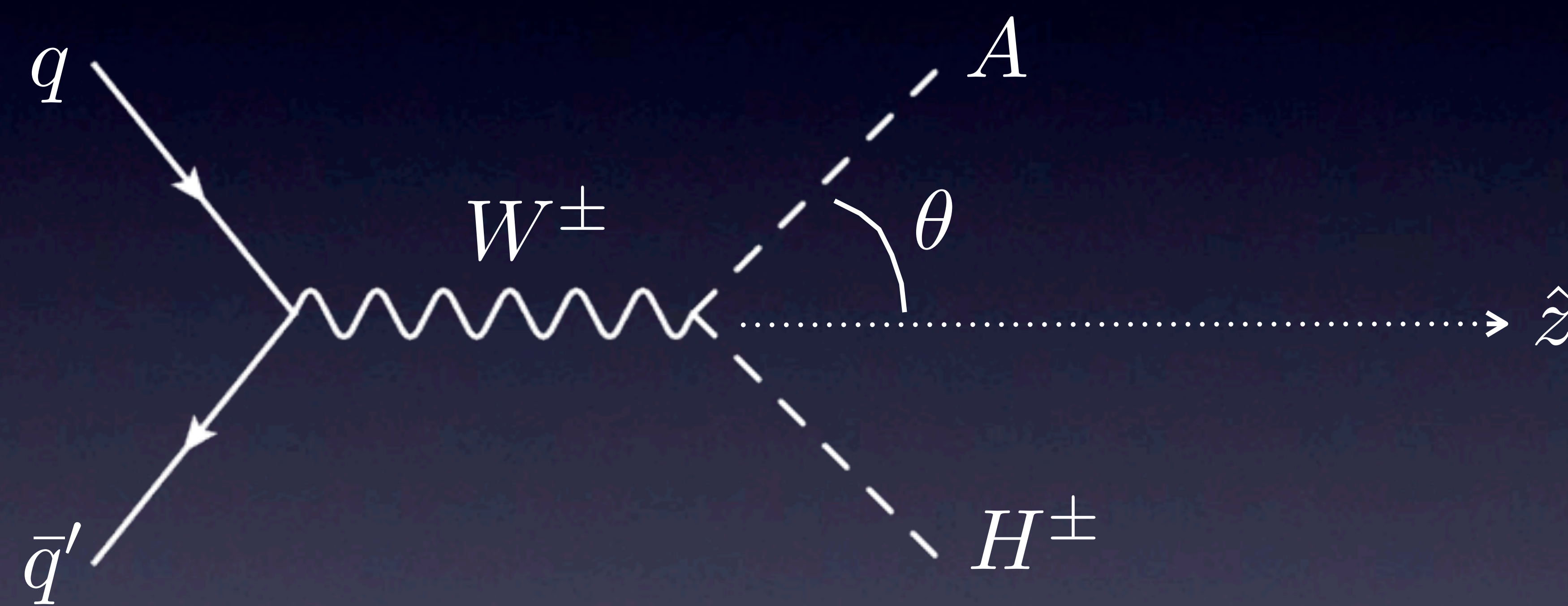
- Why are all the P_T distributions of the signal events much harder than those of the SM backgrounds?



Answer: Matrix element
(spin correlations)

A quick question

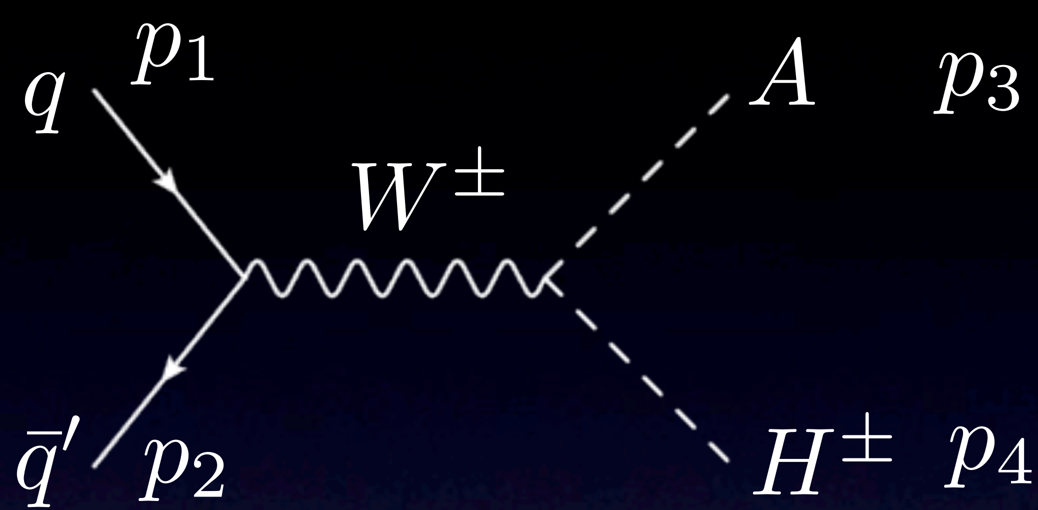
- What does the matrix element square look like in the c.m. frame?



(a) $(1+\cos\theta)^2$ (b) $(1-\cos\theta)^2$ (c) $\sin^2\theta$

(d) $\sin^2\frac{\theta}{2}$ (e) $\cos^2\frac{\theta}{2}$ (f) $\sin^2\theta\cos^2\theta$

Matrix element square



In the c.m. frame

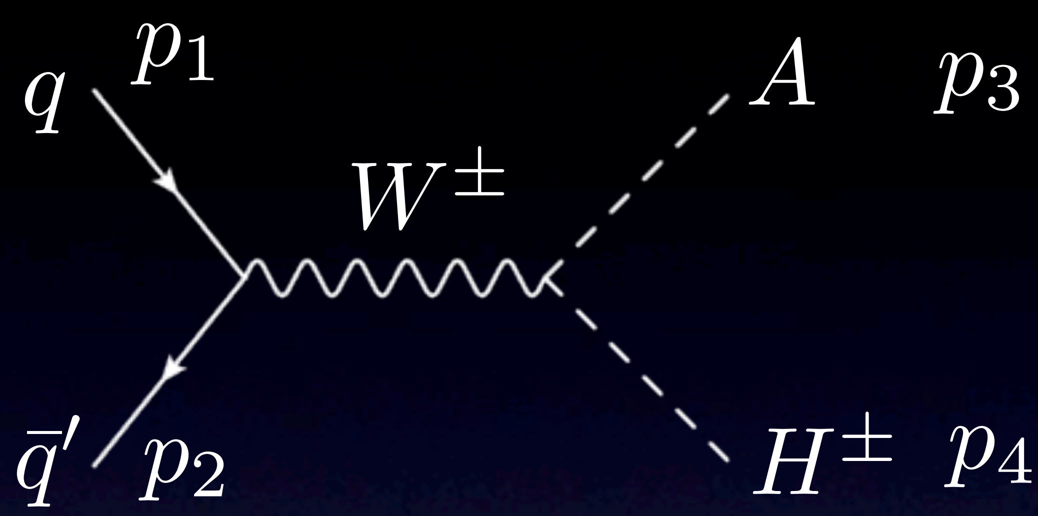
$$p_1 = (E, 0, 0, E)$$
$$p_2 = (E, 0, 0, -E)$$
$$p_3 = (E_3, P s_\theta, 0, P c_\theta)$$
$$p_4 = (E_4, -P s_\theta, 0, -P c_\theta)$$

$$|\mathcal{M}|^2 = \left(\frac{g}{\sqrt{2}}\right)^2 \left(\frac{g}{2}\right)^2 \frac{1}{(\hat{s} - m_W^2)^2 + M_W^2 \Gamma_W^2} \times \mathrm{Tr}\left[(\not{p}_3 - \not{p}_4)\not{p}_1(\not{p}_3 - \not{p}_4)\not{p}_2 P_R\right]$$

$$= \left(\frac{g}{\sqrt{2}}\right)^2 \left(\frac{g}{2}\right)^2 \frac{1}{(\hat{s} - m_W^2)^2 + M_W^2 \Gamma_W^2} \times \left[4\hat{t}\hat{u} - 4 m_A^2 m_{H^+}^2\right]$$

$$= \left(\frac{g}{\sqrt{2}}\right)^2 \left(\frac{g}{2}\right)^2 \frac{1}{(\hat{s} - m_W^2)^2 + M_W^2 \Gamma_W^2} (4E^2) \times \left\{4P^2 \sin^2\theta\right\}$$

Matrix element square



In the c.m. frame

$$p_1 = (E, 0, 0, E)$$
$$p_2 = (E, 0, 0, -E)$$
$$p_3 = (E_3, Ps_\theta, 0, Pc_\theta)$$
$$p_4 = (E_4, -Ps_\theta, 0, -Pc_\theta)$$

$$|\mathcal{M}|^2 = \left(\frac{g}{\sqrt{2}}\right)^2 \left(\frac{g}{2}\right)^2 \frac{1}{(\hat{s}-m_W^2)^2 + M_W^2\Gamma_W^2} \times \mathrm{Tr}\left[(\not{p}_3 - \not{p}_4)\not{p}_1(\not{p}_3 - \not{p}_4)\not{p}_2 P_R\right]$$

$$= \left(\frac{g}{\sqrt{2}}\right)^2 \left(\frac{g}{2}\right)^2 \frac{1}{(\hat{s}-m_W^2)^2 + M_W^2\Gamma_W^2} \times \left[4\hat{t}\hat{u} - 4m_A^2 m_{H^+}^2\right]$$

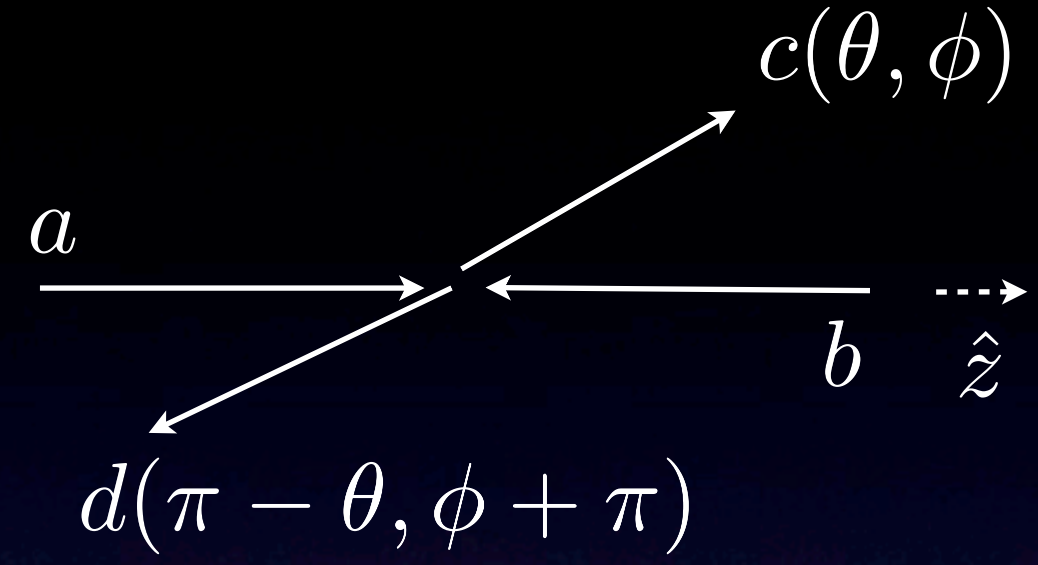
$$= \left(\frac{g}{\sqrt{2}}\right)^2 \left(\frac{g}{2}\right)^2 \frac{1}{(\hat{s}-m_W^2)^2 + M_W^2\Gamma_W^2} (4E^2) \times \left\{4P^2 \sin^2\theta\right\}$$

Can we get the angular dependence directly without any lengthy calculation?

Helicity amplitude

- 2 to 2 scattering

$$a + b \to c + d$$
$$\lambda_a \quad \lambda_b \quad \lambda_c \quad \lambda_d$$



- Jacob-Wick formalism (partial wave decomposition)

$$S_{fi} = \delta_{fi} + i(2\pi)^4\delta^4(p_f - p_i)\mathcal{M}_{fi}$$

$$\mathcal{M}_{fi} = \frac{8\pi}{\sqrt{\beta_i\beta_f}}\sum_{J=0}^{\infty}(2J+1)T^J_{\lambda_a\lambda_b;\lambda_c\lambda_d}(E_{cm})d^J_{\lambda_i\lambda_f}(\theta)e^{i(\lambda_i-\lambda_f)\phi}$$

$$\lambda_i = \lambda_a - \lambda_b$$
$$\lambda_f = \lambda_c - \lambda_d$$

$d^J_{\lambda_i\lambda_f}(\theta)$ *Wigner d-function*

ϕ angle is trivial in general.

PDG Book: d-Functions

0 −1	1/2 1/2	2
−1 0	1/2 −1/2	−2
−1 −1		1

−1 −1	2/3 1/3	3
−2 0	1/3 −2/3	−3
−2 −1		1

$$Y_\ell^{-m} = (-1)^m Y_\ell^{m*}$$

$$d^\ell_{m,0} = \sqrt{\frac{4\pi}{2\ell+1}}\, Y_\ell^m\, e^{-im\phi}$$

$$\langle j_1 j_2 m_1 m_2 | j_1 j_2 J M\rangle = (-1)^{J-j_1-j_2}\langle j_2 j_1 m_2 m_1 | j_2 j_1 J M\rangle$$

$$d^j_{m',m} = (-1)^{m-m'} d^j_{m,m'} = d^j_{-m,-m'}$$

$$d^1_{0,0} = \cos\theta \qquad d^{1/2}_{1/2,1/2} = \cos\frac{\theta}{2} \qquad d^{1/2}_{1/2,-1/2} = -\sin\frac{\theta}{2}$$

$$d^1_{1,1} = \frac{1+\cos\theta}{2} \qquad d^1_{1,0} = -\frac{\sin\theta}{\sqrt{2}} \qquad d^1_{1,-1} = \frac{1-\cos\theta}{2}$$

2×3/2

m_1 m_2	J=7/2, M=+7/2
+2 +3/2	1

m_1 m_2	7/2 (+5/2)	5/2 (+5/2)
+2 +1/2	3/7	4/7
+1 +3/2	4/7	−3/7

m_1 m_2	7/2 (+3/2)	5/2 (+3/2)	3/2 (+3/2)
+2 −1/2	1/7	16/35	2/5
+1 +1/2	4/7	1/35	−2/5
0 +3/2	2/7	−18/35	1/5

m_1 m_2	7/2 (+1/2)	5/2 (+1/2)	3/2 (+1/2)	1/2 (+1/2)
+2 −3/2	1/35	6/35	2/5	2/5
+1 −1/2	12/35	5/14	0	−3/10
0 +1/2	18/35	−3/35	−1/5	1/5
−1 +3/2	4/35	−27/70	2/5	−1/10

m_1 m_2	7/2 (−1/2)	5/2 (−1/2)	3/2 (−1/2)	1/2 (−1/2)
+1 −3/2	4/35	27/70	2/5	1/10
0 −1/2	18/35	3/35	−1/5	−1/5
−1 +1/2	12/35	−5/14	0	3/10
−2 +3/2	1/35	−6/35	2/5	−2/5

m_1 m_2	7/2 (−3/2)	5/2 (−3/2)	3/2 (−3/2)
0 −3/2	2/7	18/35	1/5
−1 −1/2	4/7	−1/35	−2/5
−2 +1/2	1/7	−16/35	2/5

m_1 m_2	7/2 (−5/2)	5/2 (−5/2)
−1 −3/2	4/7	3/7
−2 −1/2	3/7	−4/7

m_1 m_2	7/2 (−7/2)
−2 −3/2	1

3/2×3/2

m_1 m_2	3 (+3)
+3/2 +3/2	1

m_1 m_2	3 (+2)	2 (+2)
+3/2 +1/2	1/2	1/2
+1/2 +3/2	1/2	−1/2

m_1 m_2	3 (+1)	2 (+1)	1 (+1)
+3/2 −1/2	1/5	1/2	3/10
+1/2 +1/2	3/5	0	−2/5
−1/2 +3/2	1/5	−1/2	3/10

m_1 m_2	3 (0)	2 (0)	1 (0)	0 (0)
+3/2 −3/2	1/20	1/4	9/20	1/4
+1/2 −1/2	9/20	1/4	−1/20	−1/4
−1/2 +1/2	9/20	−1/4	−1/20	1/4
−3/2 +3/2	1/20	−1/4	9/20	−1/4

m_1 m_2	3 (−1)	2 (−1)	1 (−1)
+1/2 −3/2	1/5	1/2	3/10
−1/2 −1/2	3/5	0	−2/5
−3/2 +1/2	1/5	−1/2	3/10

m_1 m_2	3 (−2)	2 (−2)
−1/2 −3/2	1/2	1/2
−3/2 −1/2	1/2	−1/2

m_1 m_2	3 (−3)
−3/2 −3/2	1

2×2

m_1 m_2	4 (+4)
+2 +2	1

m_1 m_2	4 (+3)	3 (+3)
+2 +1	1/2	1/2
+1 +2	1/2	−1/2

m_1 m_2	4 (+2)	3 (+2)	2 (+2)
+2 0	3/14	1/2	2/7
+1 +1	4/7	0	−3/7
0 +2	3/14	−1/2	2/7

m_1 m_2	4 (+1)	3 (+1)	2 (+1)	1 (+1)
+2 −1	1/14	3/10	3/7	1/5
+1 0	3/7	1/5	−1/14	−3/10
0 +1	3/7	−1/5	−1/14	3/10
−1 +2	1/14	−3/10	3/7	−1/5

m_1 m_2	4 (0)	3 (0)	2 (0)	1 (0)	0 (0)
+2 −2	1/70	1/10	2/7	2/5	1/5
+1 −1	8/35	2/5	1/14	−1/10	−1/5
0 0	18/35	0	−2/7	0	1/5
−1 +1	8/35	−2/5	1/14	1/10	−1/5
−2 +2	1/70	−1/10	2/7	−2/5	1/5

m_1 m_2	4 (−1)	3 (−1)	2 (−1)	1 (−1)
+1 −2	1/14	3/10	3/7	1/5
0 −1	3/7	1/5	−1/14	−3/10
−1 0	3/7	−1/5	−1/14	3/10
−2 +1	1/14	−3/10	3/7	−1/5

m_1 m_2	4 (−2)	3 (−2)	2 (−2)
0 −2	3/14	1/2	2/7
−1 −1	4/7	0	−3/7
−2 0	3/14	−1/2	2/7

m_1 m_2	4 (−3)	3 (−3)
−1 −2	1/2	1/2
−2 −1	1/2	−1/2

m_1 m_2	4 (−4)
−2 −2	1

$$d^{3/2}_{3/2,3/2} = \frac{1+\cos\theta}{2}\cos\frac{\theta}{2}$$

$$d^{3/2}_{3/2,1/2} = -\sqrt{3}\frac{1+\cos\theta}{2}\sin\frac{\theta}{2}$$

$$d^{3/2}_{3/2,-1/2} = \sqrt{3}\frac{1-\cos\theta}{2}\cos\frac{\theta}{2}$$

$$d^{3/2}_{3/2,-3/2} = -\frac{1-\cos\theta}{2}\sin\frac{\theta}{2}$$

$$d^{3/2}_{1/2,1/2} = \frac{3\cos\theta-1}{2}\cos\frac{\theta}{2}$$

$$d^{3/2}_{1/2,-1/2} = -\frac{3\cos\theta+1}{2}\sin\frac{\theta}{2}$$

$$d^2_{2,2} = \left(\frac{1+\cos\theta}{2}\right)^2$$

$$d^2_{2,1} = -\frac{1+\cos\theta}{2}\sin\theta$$

$$d^2_{2,0} = \frac{\sqrt{6}}{4}\sin^2\theta$$

$$d^2_{2,-1} = -\frac{1-\cos\theta}{2}\sin\theta$$

$$d^2_{2,-2} = \left(\frac{1-\cos\theta}{2}\right)^2$$

$$d^2_{1,1} = \frac{1+\cos\theta}{2}(2\cos\theta-1)$$

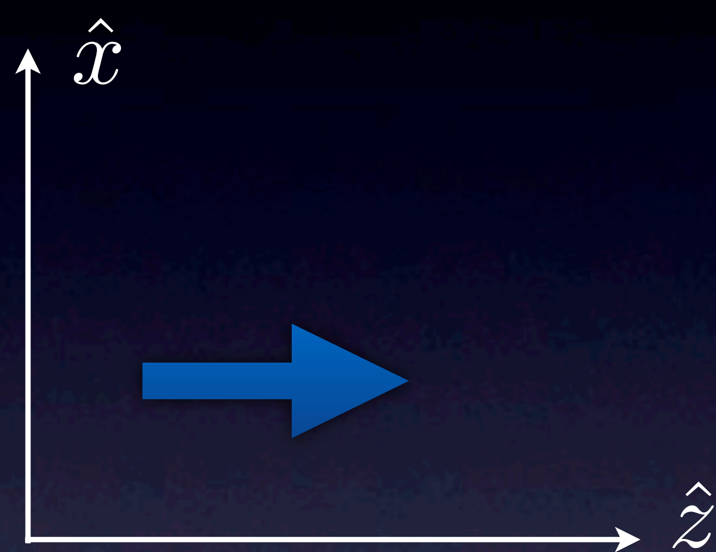
$$d^2_{1,0} = -\sqrt{\frac{3}{2}}\sin\theta\cos\theta$$

$$d^2_{1,-1} = \frac{1-\cos\theta}{2}(2\cos\theta+1)$$

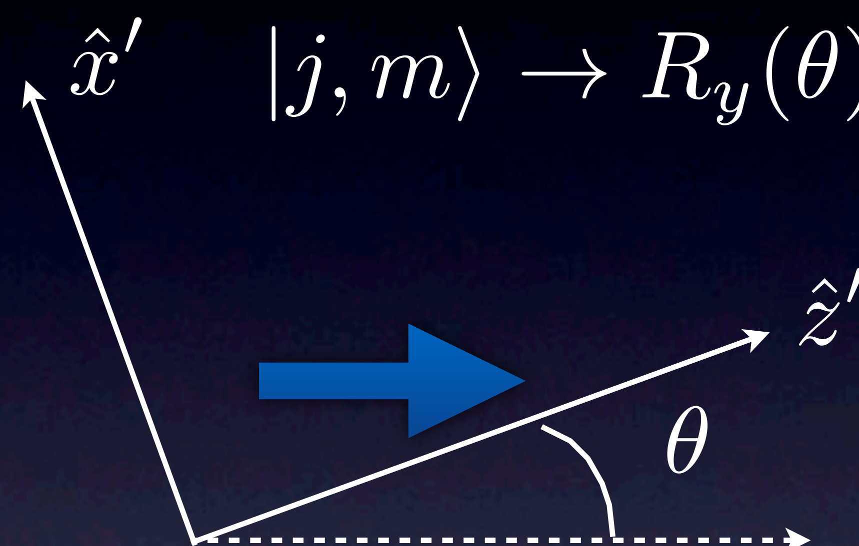
$$d^2_{0,0} = \left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right)$$

Angular momentum in QM

- Consider a vector $|j, m\rangle$ $\qquad J^2 \quad J_3$



$$|j, m\rangle \to R_y(\theta)\,|j, m\rangle$$



$$R_y(\theta) = e^{i\theta J_y}$$

Rotation matrices

$$d^j_{m\to m'}(\theta) \equiv d^j_{m,m'}(\theta) = \langle jm'|R_y(\theta)|jm\rangle$$

The modulus squared is the probability that a particle $J_3 = m$ will have $J_3 = m'$ after the rotation to the new frame.

AH^+ Production

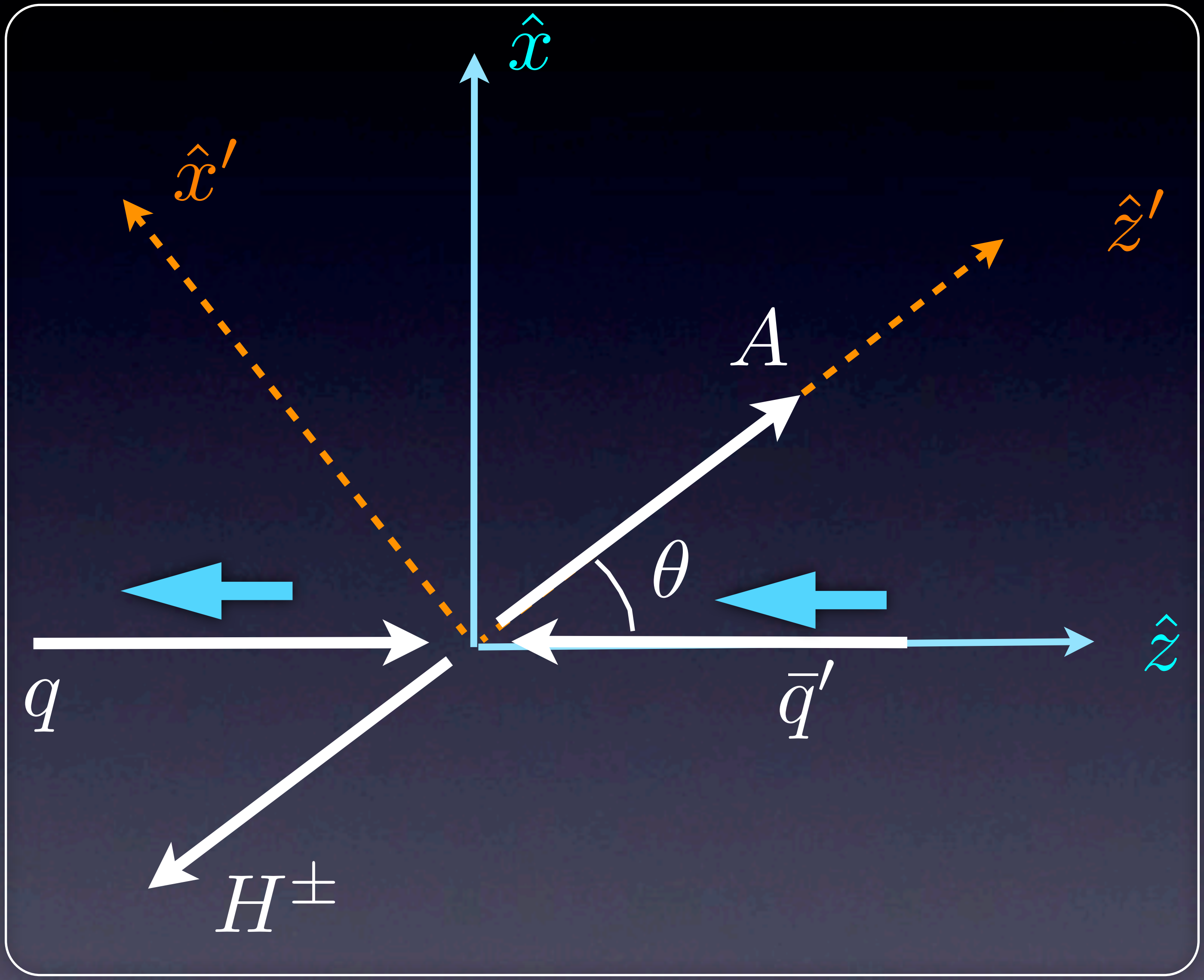
- Rotation matrices of spin-1

$$J_y = \frac{i}{\sqrt{2}}\begin{pmatrix} 0 & -1 & 0 \\ 1 & 0 & -1 \\ 0 & 1 & 0 \end{pmatrix}$$

$$d^1_{-1,0} = -\frac{1}{\sqrt{2}}\sin\theta$$

$$\lambda_i = \lambda_q - \lambda_{\bar{q}'}$$
$$= -1/2 - 1/2 = -1$$

$$\lambda_f = \lambda_A - \lambda_{H^\pm} = 0$$



(1) Only longitudinal W-boson contributes.

(2) A and H^+ stay in p-wave.

AH^+ Production

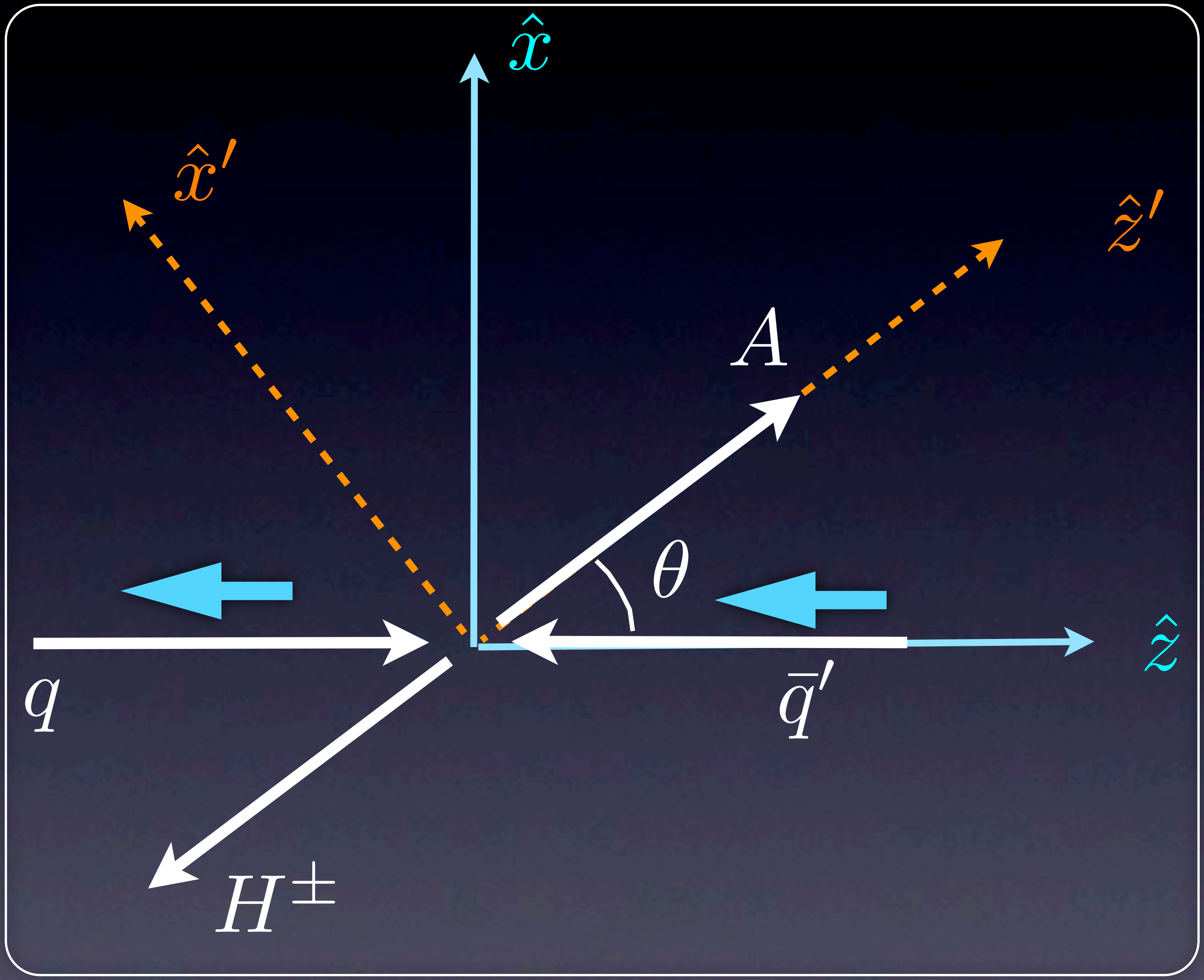
- Rotation matrices of spin-1

$$J_y = \frac{i}{\sqrt{2}}\begin{pmatrix} 0 & -1 & 0 \\ 1 & 0 & -1 \\ 0 & 1 & 0 \end{pmatrix}$$

$$d^1_{-1,0} = -\frac{1}{\sqrt{2}}\sin\theta$$

$$\lambda_i = \lambda_q - \lambda_{\bar{q}'}$$
$$= -1/2 - 1/2 = -1$$

$$\lambda_f = \lambda_A - \lambda_{H^\pm} = 0$$



(1) Only longitudinal W-boson contributes.

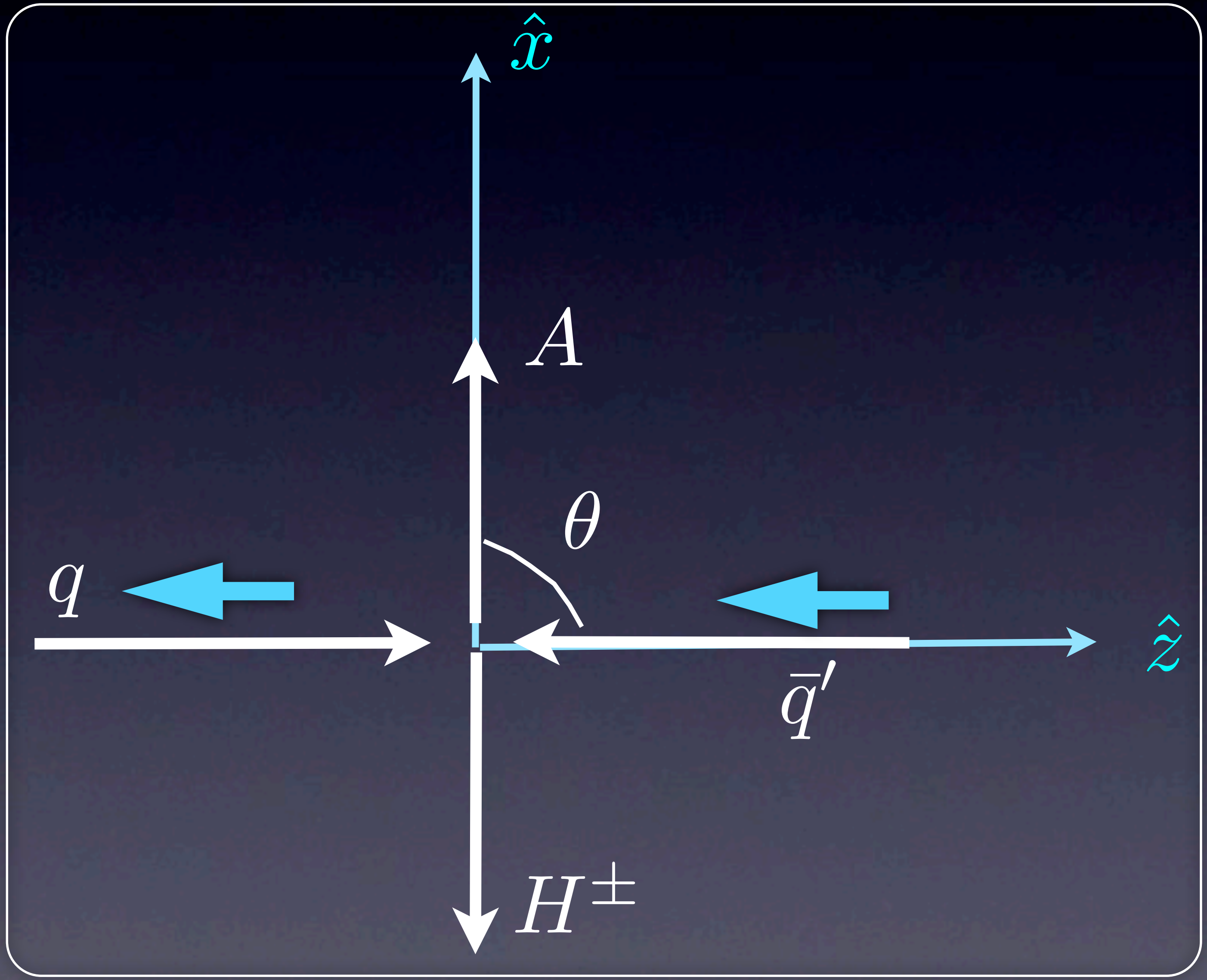
(2) *A* and *H*⁺ stay in *p*-wave. What does that mean?

AH^+ Production

- Rotation matrices of spin-1

$$J_y = \frac{i}{\sqrt{2}}\begin{pmatrix} 0 & \text{-}1 & 0 \\ 1 & 0 & \text{-}1 \\ 0 & 1 & 0 \end{pmatrix}$$

$$d^1_{-1,0} = -\frac{1}{\sqrt{2}}\sin\theta$$



(1) Only longitudinal W-boson contributes.

(2) *A* and H^+ stay in *p*-wave.

AH^+ Production

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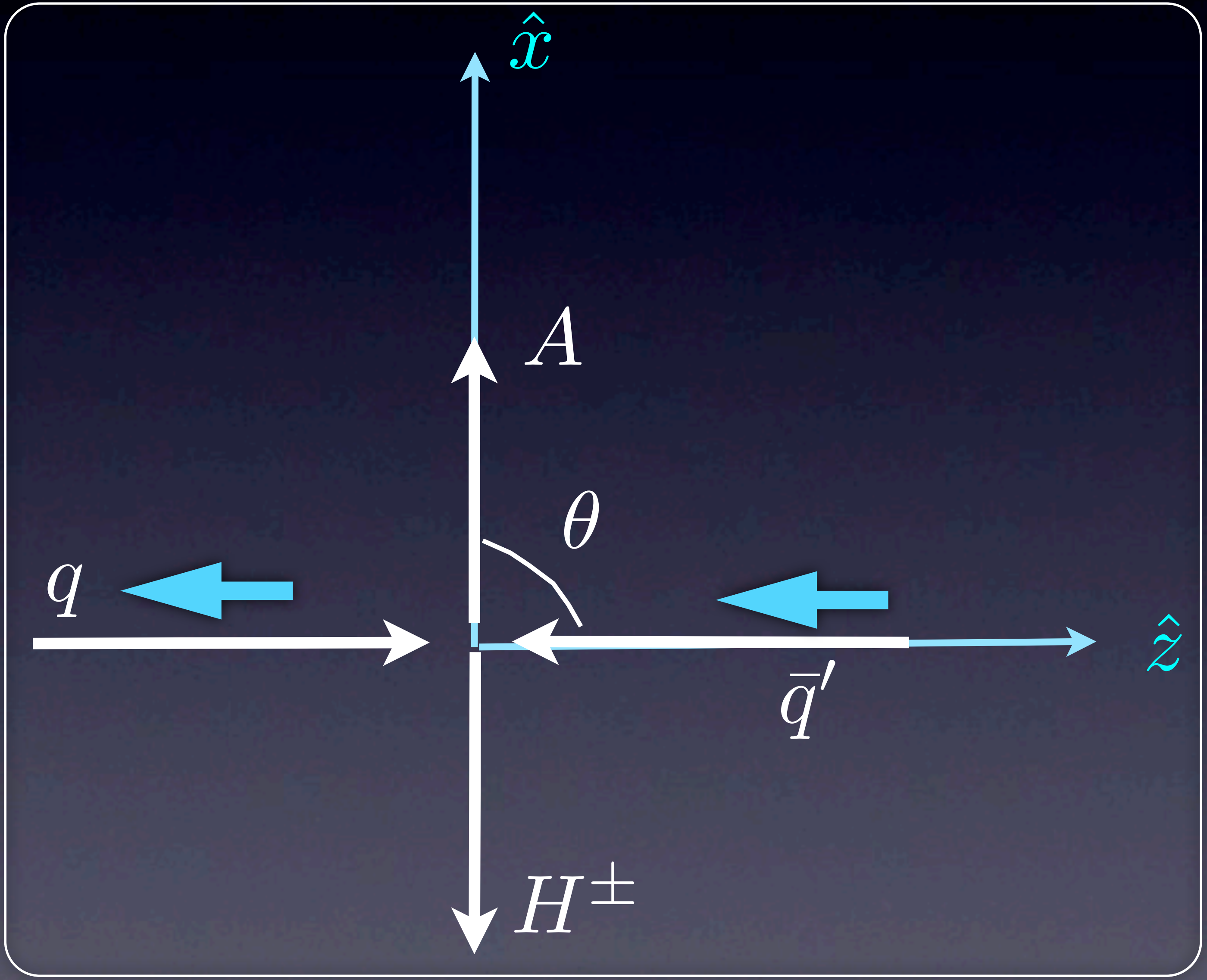
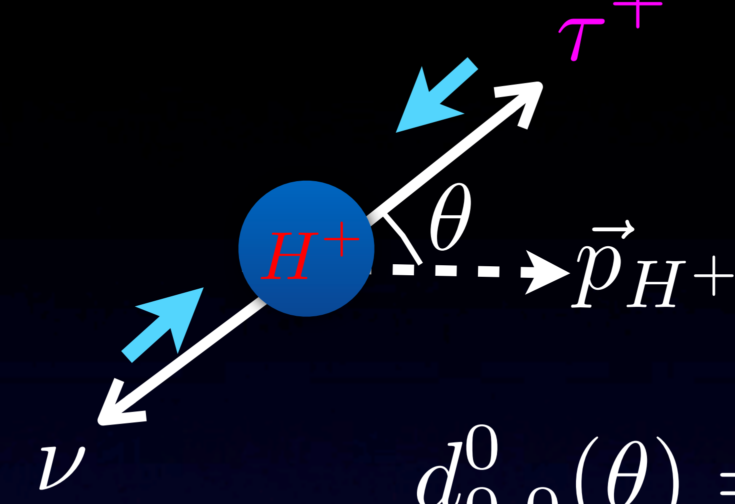


(1) Only longitudinal W-boson contributes.

(2) A and H^+ stay in p-wave. → Large P_T's of A and H^+ (and their decay products)

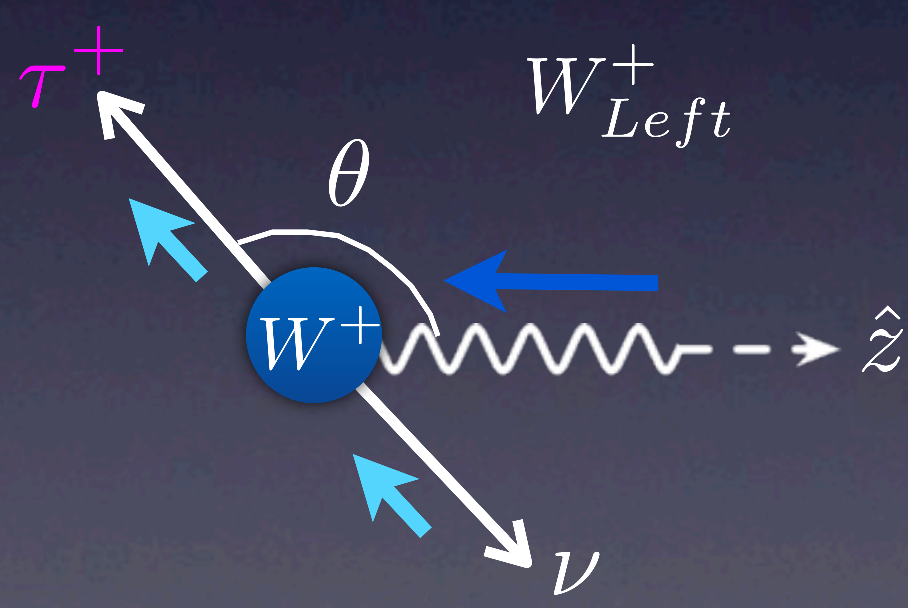
Tau is polarized

- Tau-lepton from H^+ decay is left-handedly polarized

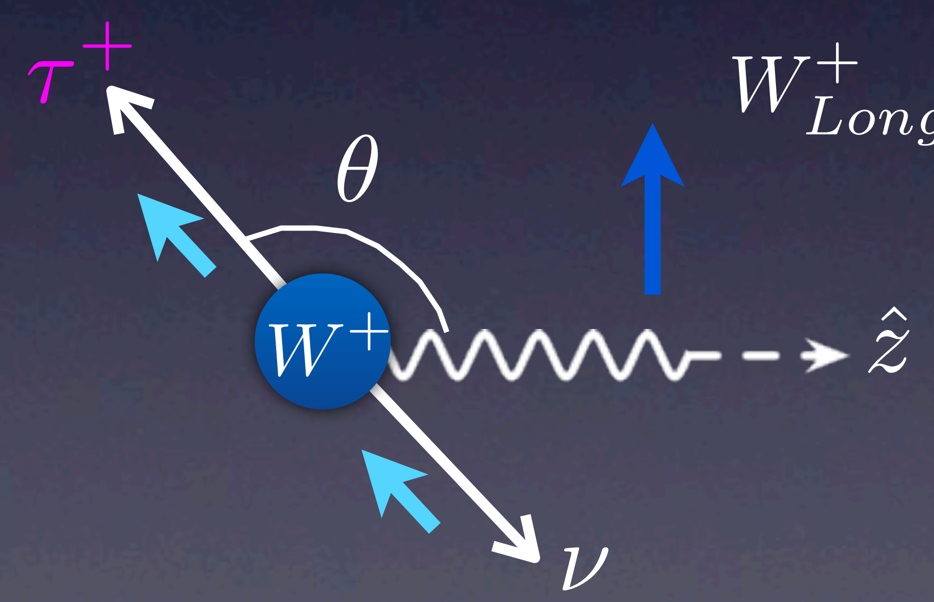


$$d^0_{0,0}(\theta) = 1$$

- Tau-lepton from W^+ decay is right-handedly polarized



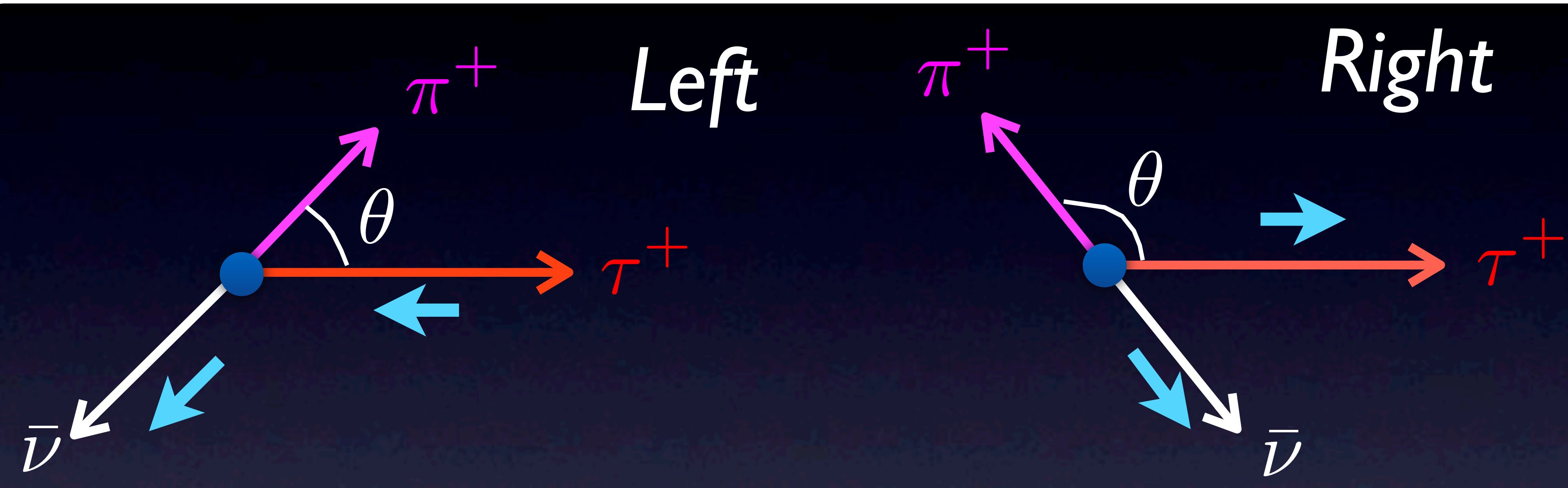
$$d^1_{-1,1}(\theta) = \frac{1-\cos\theta}{2}$$



$$d^1_{0,1} = -\frac{\sin\theta}{\sqrt{2}}$$

p_{π^+} depends on τ^+ polarization

- A left-handed τ^+ produces a harder π^+

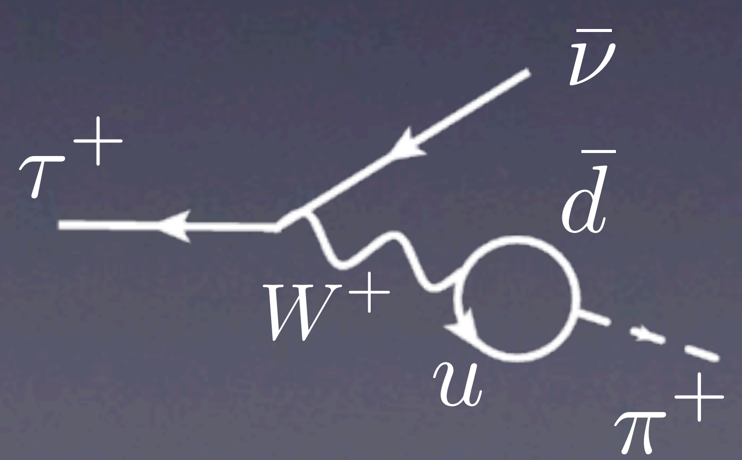


$$d^{\frac{1}{2}}_{\frac{1}{2},\frac{1}{2}} = \cos\frac{\theta}{2} \qquad d^{\frac{1}{2}}_{\frac{1}{2},-\frac{1}{2}} = -\sin\frac{\theta}{2}$$

Homework:

Verify the above angular dependence with the following effective interaction

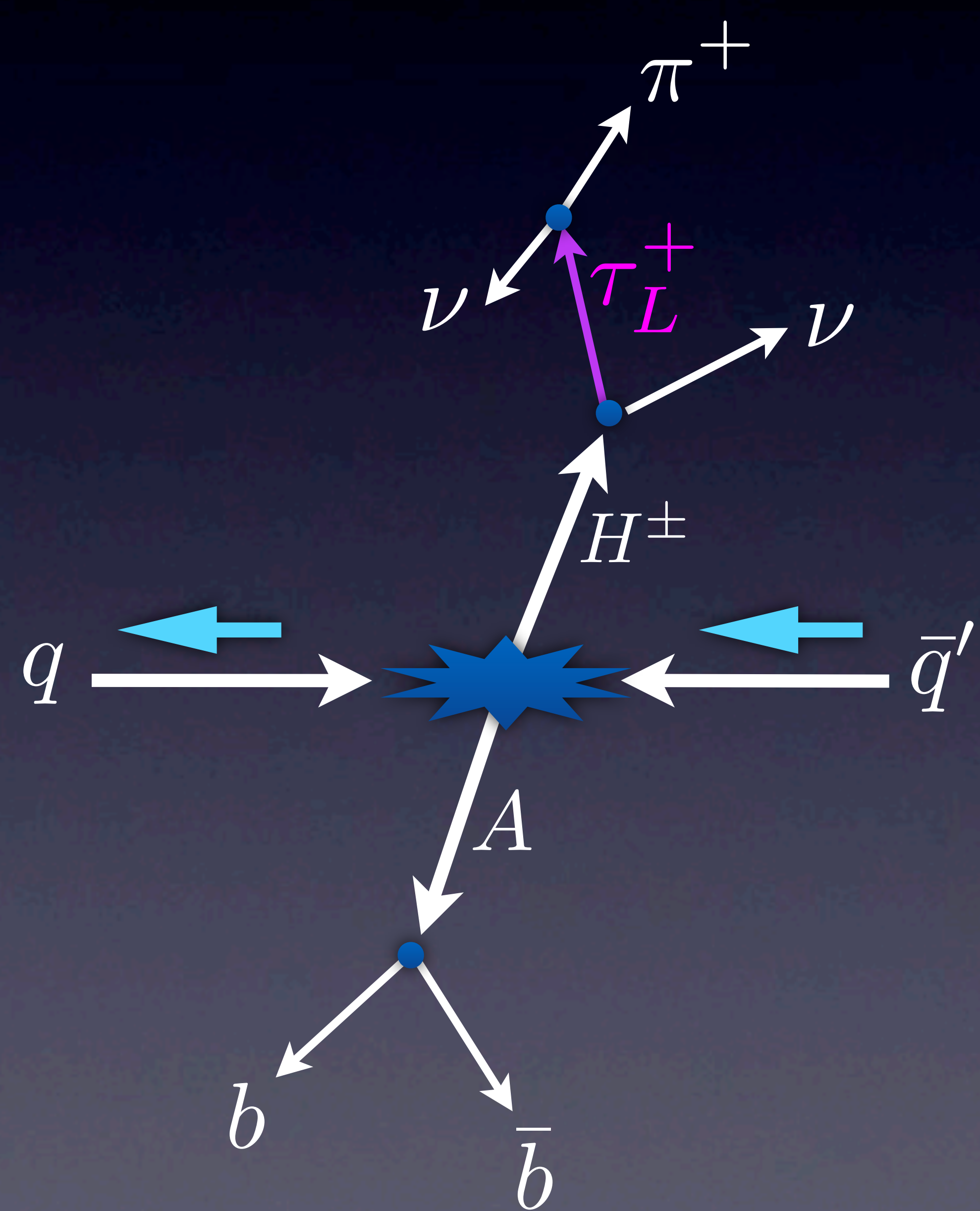
$$\left(\partial^\mu \pi^-\right) \overline{\tau^+}\gamma_\mu P_L \nu$$

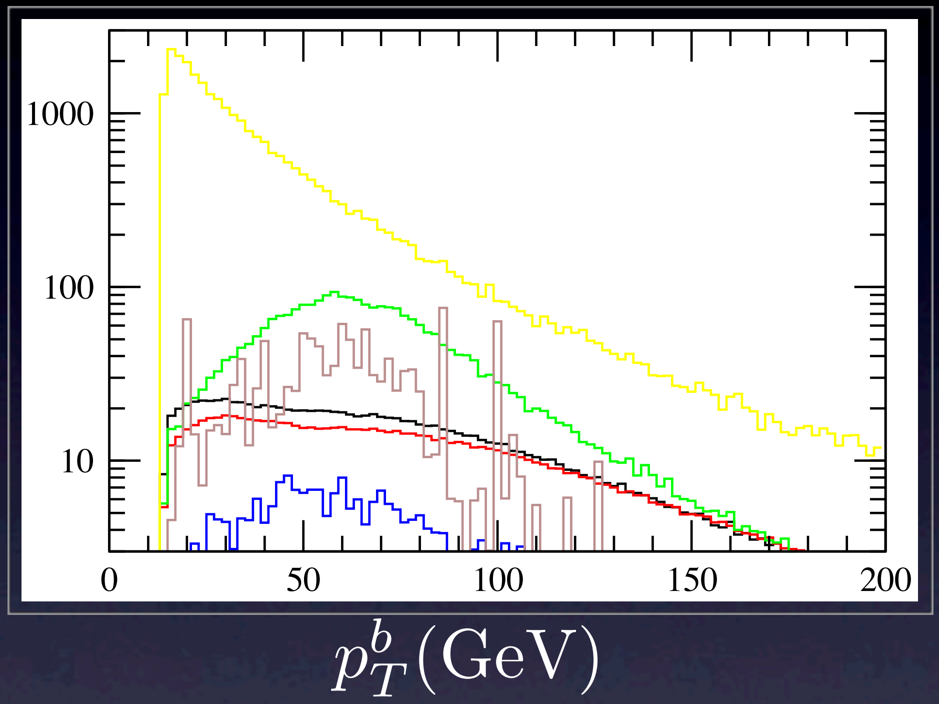


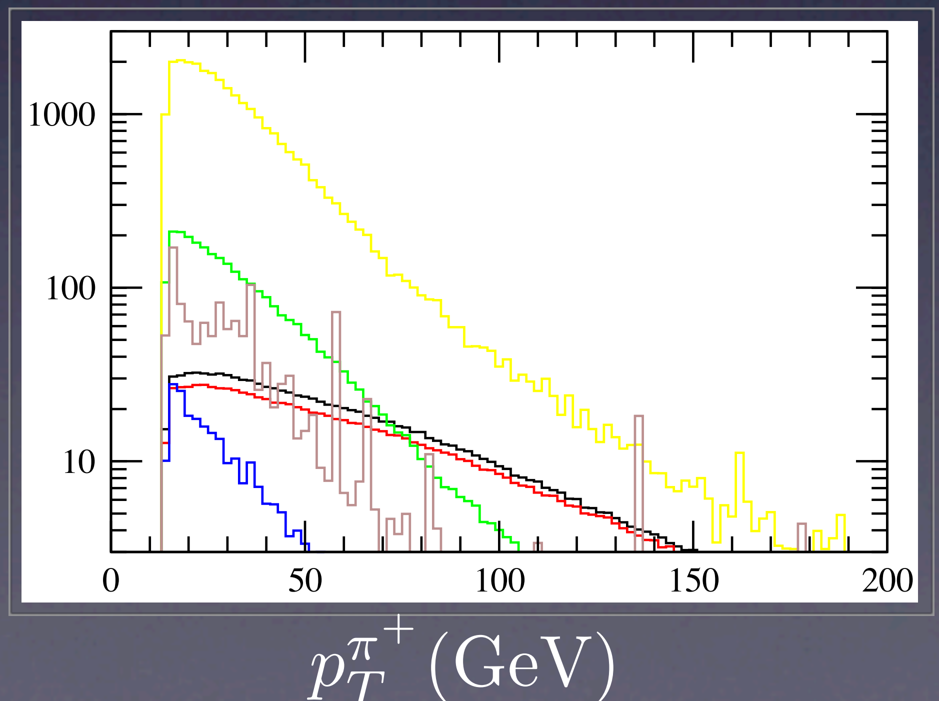
Wednesday, May 23, 12

Interim summary

- Spin correlations force the scalars and its decay products in the signal events being highly boosted while those of the backgrounds are anti-boosted.



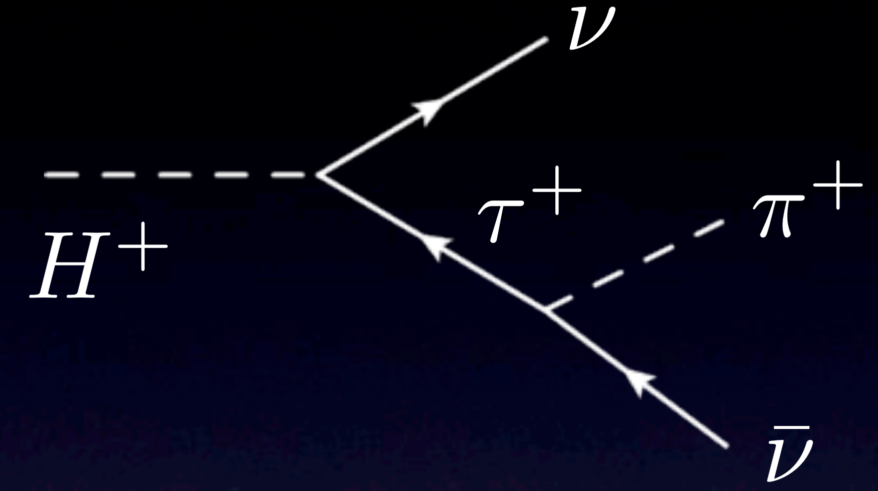




Mass measurement of H+

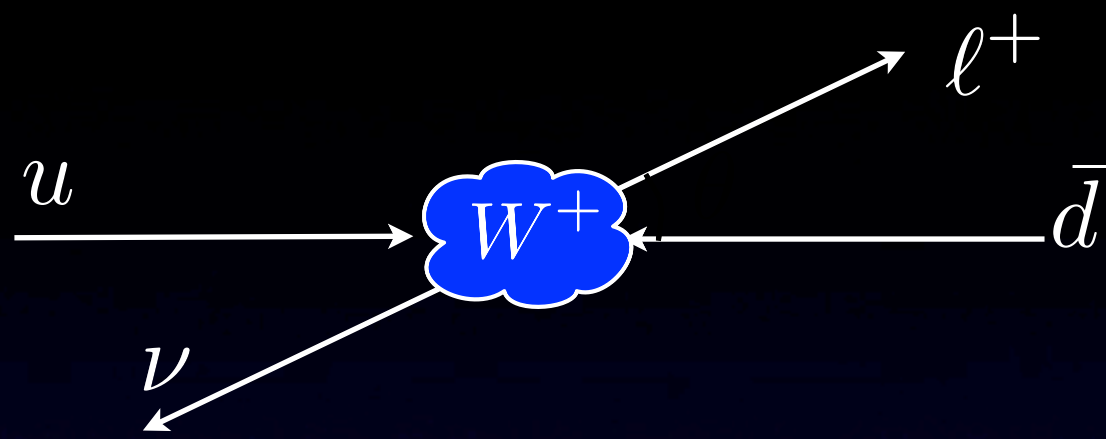
- Experimental difficulty:

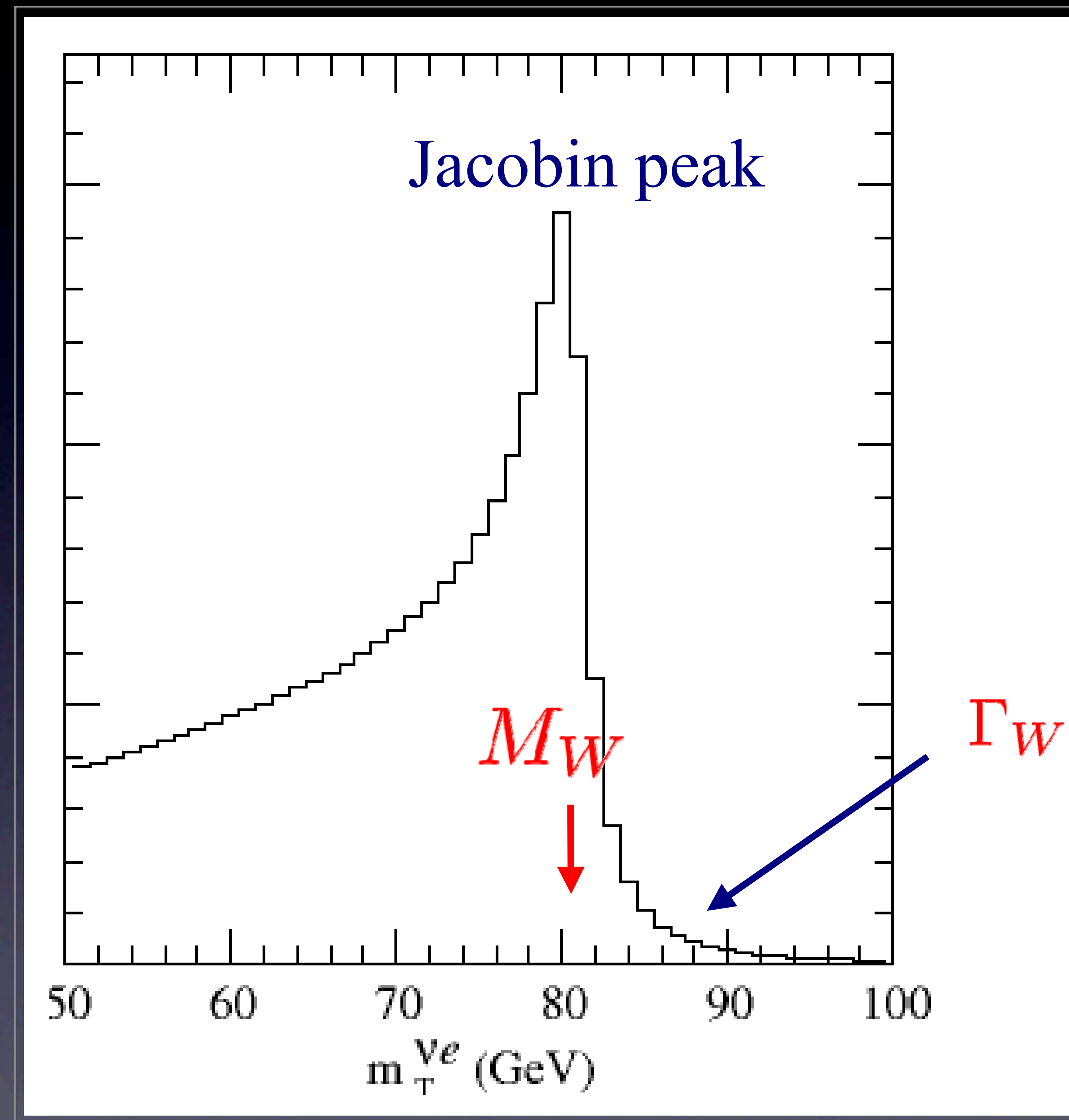
Given a measured MET, can we tell it is one or two neutrinos?



- Four exceptions:
  - H^+: $H^+ \to \tau^+ \nu \to \pi^+ \nu \bar{\nu} \to \pi^+ \not{E}_T$ spin corr.
  - $t\bar{t}$: $t\bar{t} \to b\bar{b}\ell^+\ell'^- \nu\bar{\nu} \to b\bar{b}\ell^+\ell'^- \not{E}_T$ on mass shell conditions
  - h : $h \to W^+W^- \to \ell^+\ell'^- \nu\bar{\nu} \to \ell^+\ell'^- \not{E}_T$ spin corr.
  - h : $h \to \tau^+\tau^- \to \pi^+\pi^- \nu\bar{\nu} \to \pi^+\pi^- \not{E}_T$ kinematics

Transverse Mass





★ TM: measuring the mass of the W-boson in the leptonic decay channel

$$m_T^2 = 2\left(E_T^\ell \not{E}_T - p_T^\ell \not{p}_T\right) = 2p_T^\ell \not{E}_T(1 - \cos\phi)$$

★ The true mass of the W boson satisfies

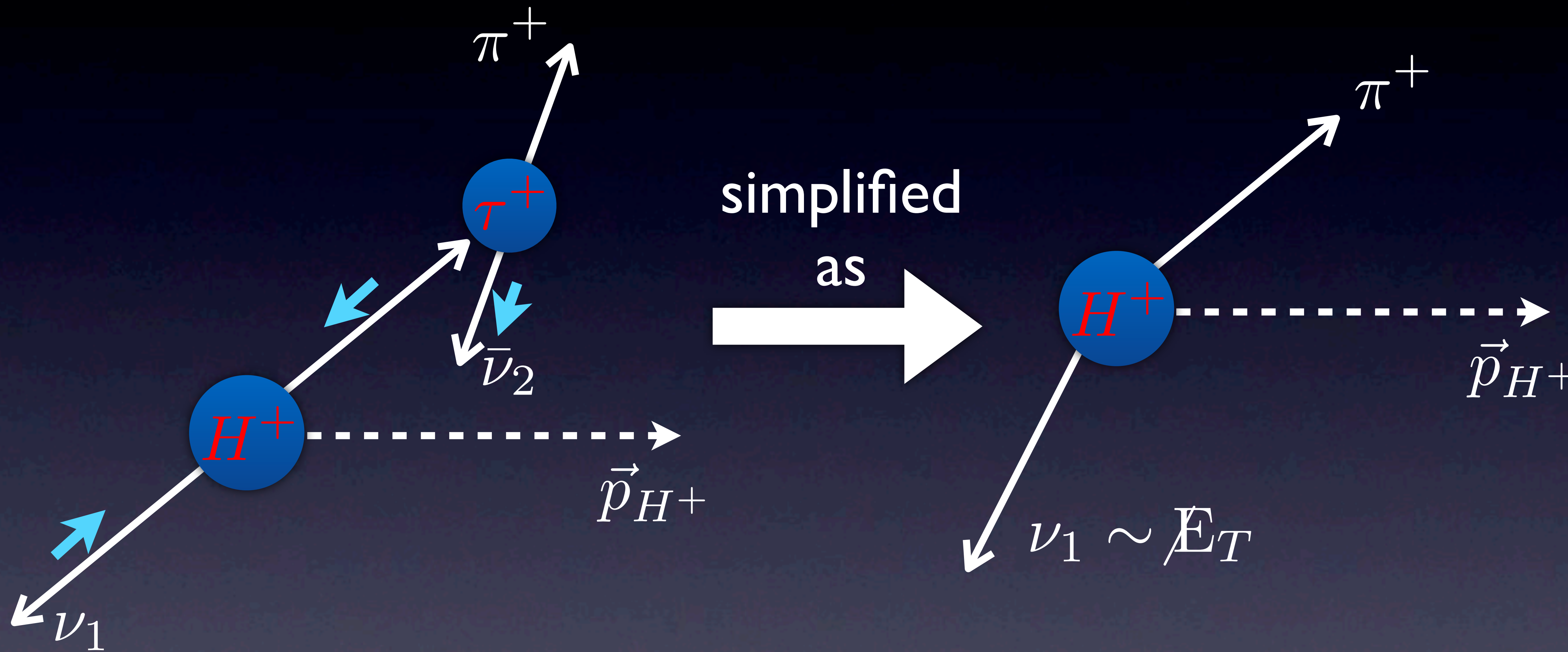
$$m_T^2 \leq m_W^2$$

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

$$\frac{\mathrm{d}\sigma}{\mathrm{d}m_T^2} \sim \frac{1}{\sqrt{1 - m_T^2/\hat{s}}}$$

H^+ reconstruction

- Spin correlation dominates



Neutrino from tau decay is anti-boosted such that it tends to be very soft.

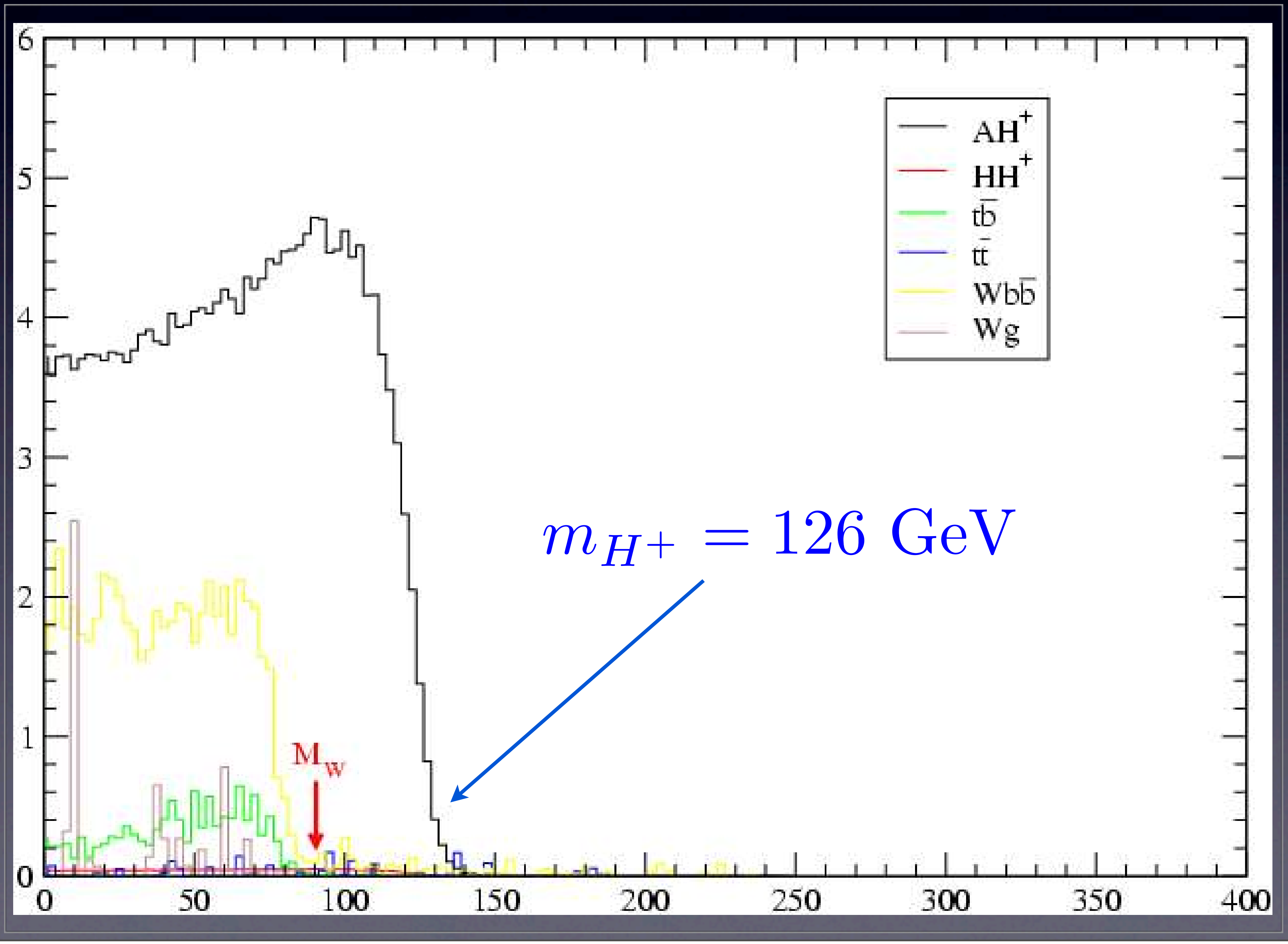
$$m_T = \sqrt{2 p_T(\pi^+)\ \not{E}_T (1 - \cos\Delta\phi)}$$

$\Delta\phi$ is the azimuthal angle between π^+ and $\not{E}_T$

Transverse mass of π^+ and $\not{E}_T$

- Transverse mass of H+ after imposing the mass window cut on the two b-jets

$$\left|M(b\bar{b}) - 100\right| < 10 \text{ GeV}$$

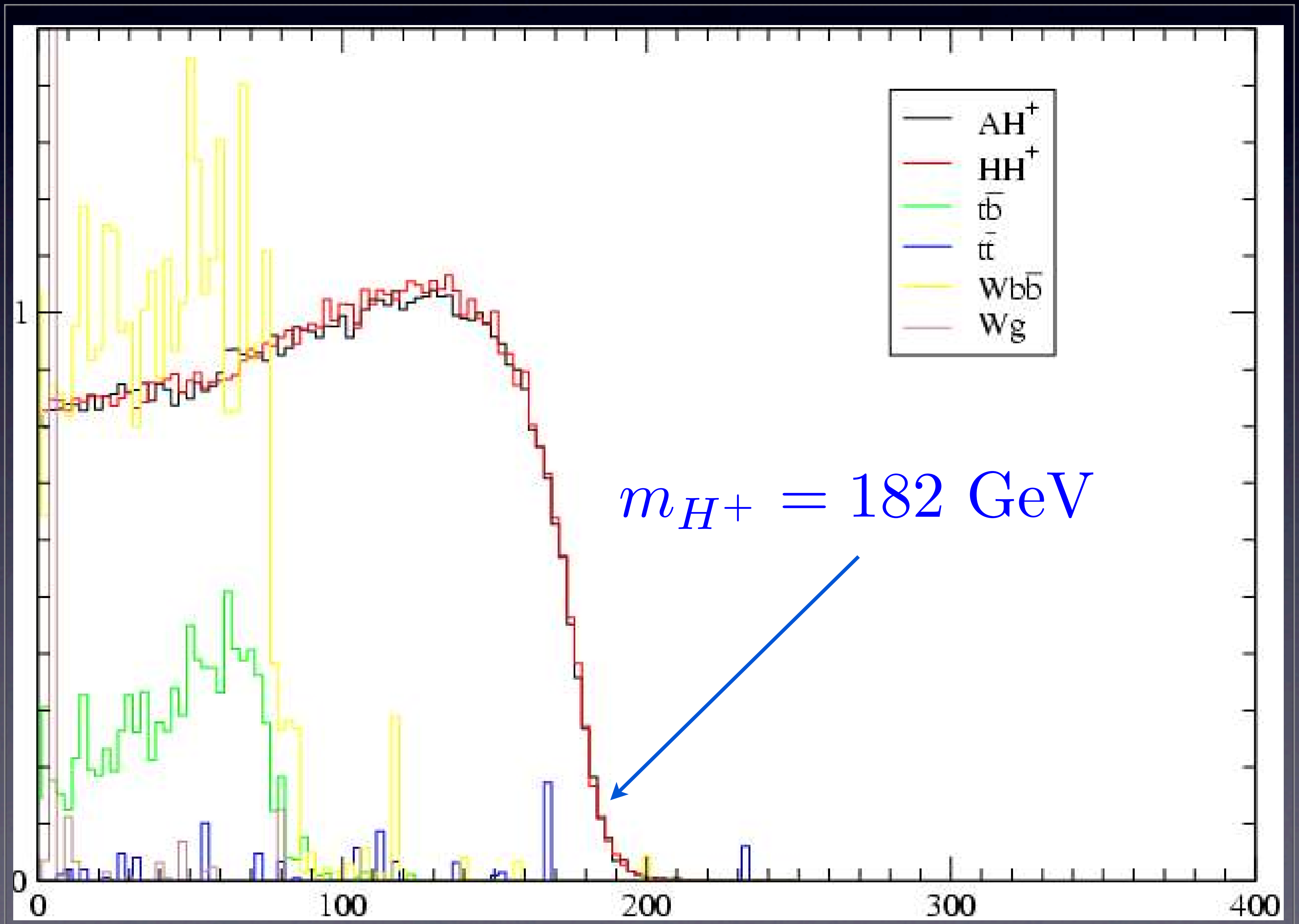


Set-A

Transverse mass of π^+ and $\not{E}_T$

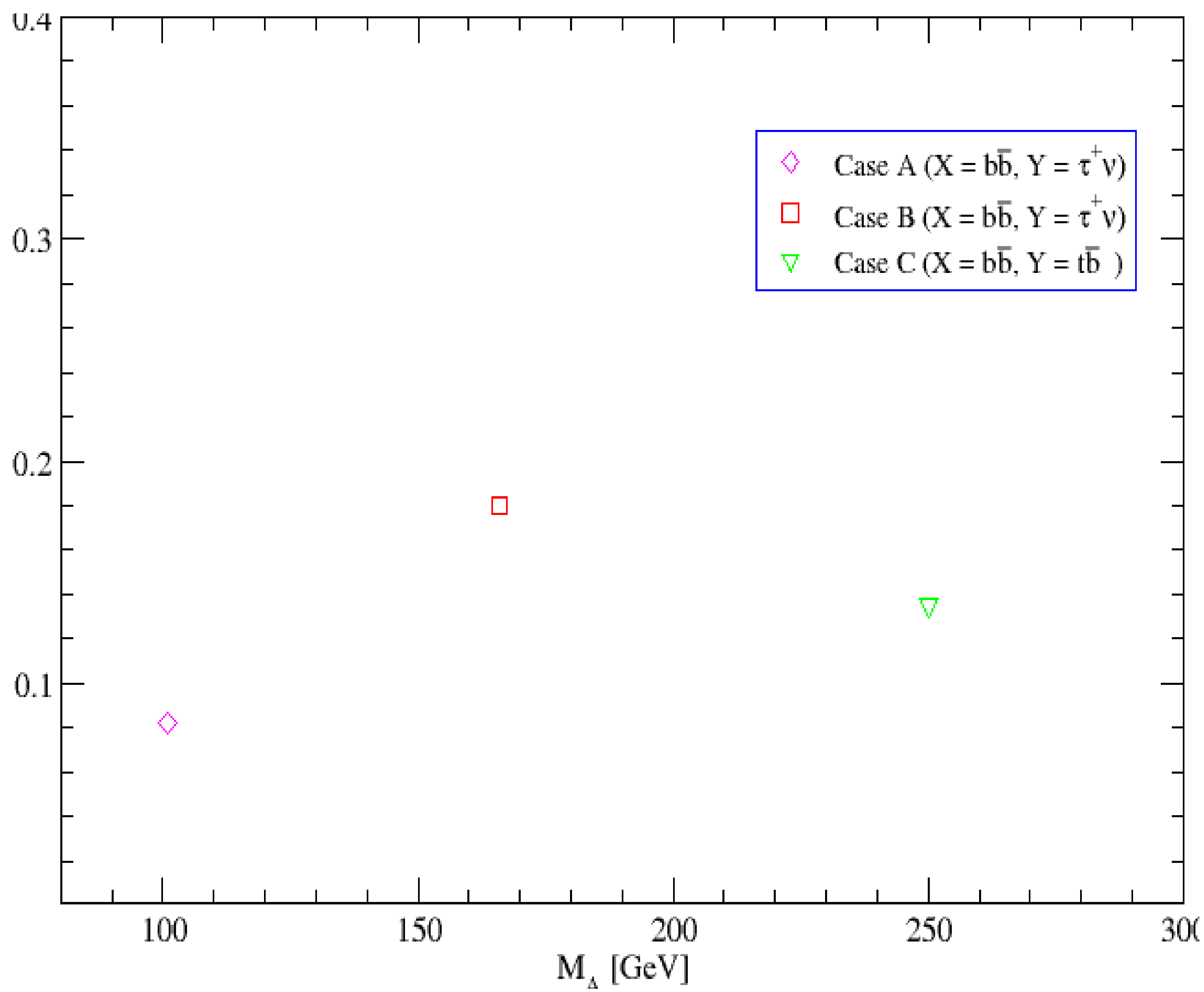
- Transverse mass of H+ after imposing the mass window cut on the two b-jets

$$\left|M(b\bar{b}) - 165\right| < 10 \text{ GeV}$$



Set-B

Constraint on MSSM



Constraints on the product of branching ratios

$$B(A \to b\bar{b}) \times B(H^+ \to \tau^+ \nu_\tau)$$

as a function of M_A for Case A and Case B, and

$$B(A \to b\bar{b}) \times B(H^+ \to t\bar{b})$$

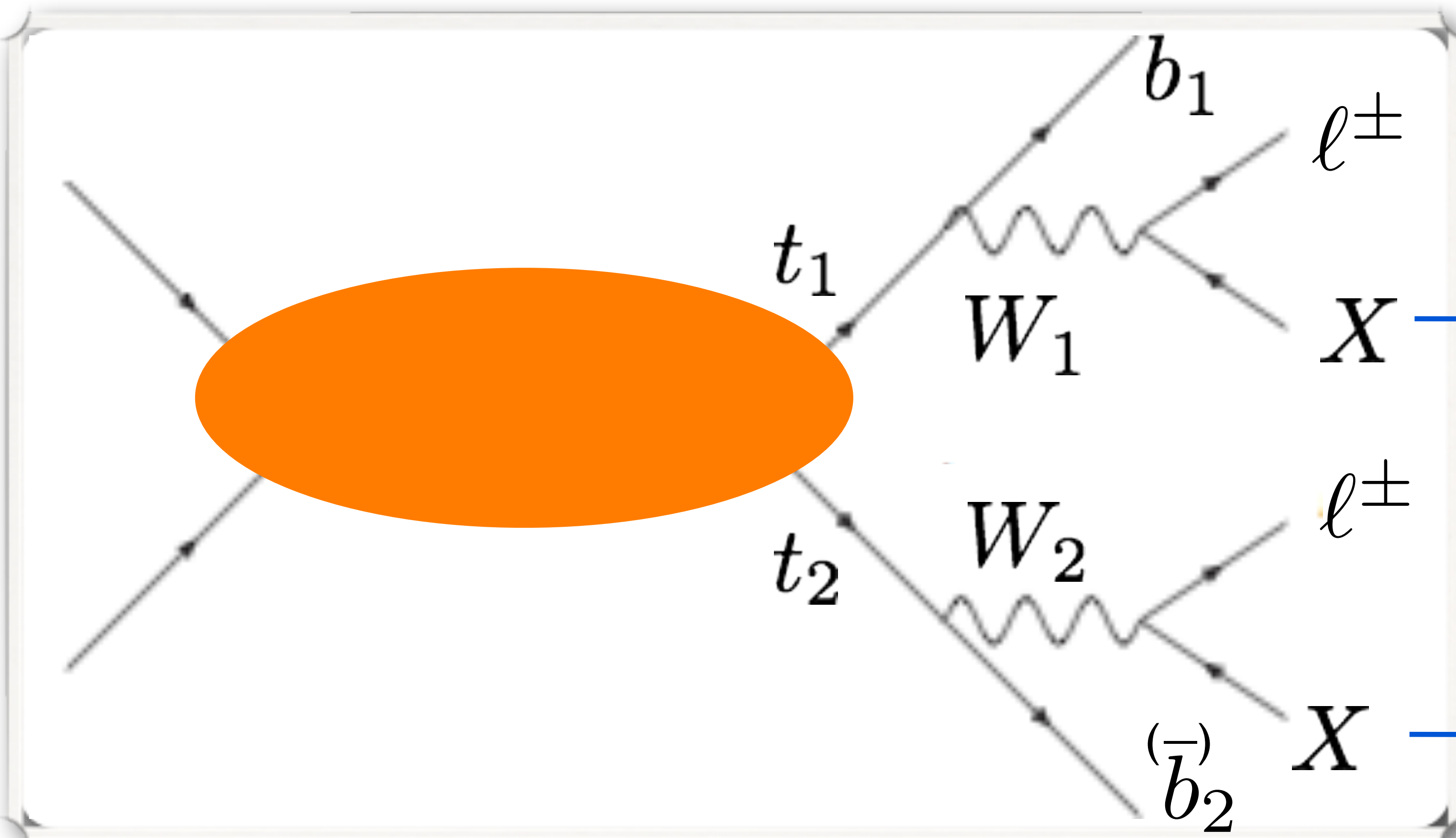
for Case C, at the LHC, where τ^+ decays into $\pi^+ \bar{\nu}_\tau$ channel.

Auxiliary material (I) Two neutrinos

- *H*⁺: $H^+ \to \tau^+\nu \to \pi^+\nu\bar{\nu} \to \pi^+ \not{E}_T$ spin corr.
- *tt̄* : $t\bar{t} \to b\bar{b}\ell^+\ell'^-\nu\bar{\nu} \to b\bar{b}\ell^+\ell'^- \not{E}_T$ on mass shell conditions
- *h* : $h \to W^+W^- \to \ell^+\ell'^-\nu\bar{\nu} \to \ell^+\ell'^- \not{E}_T$ spin corr.
- *h* : $h \to \tau^+\tau^- \to \pi^+\pi^-\nu\bar{\nu} \to \pi^+\pi^- \not{E}_T$ kinematics

t-tbar in dilepton mode

★ 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

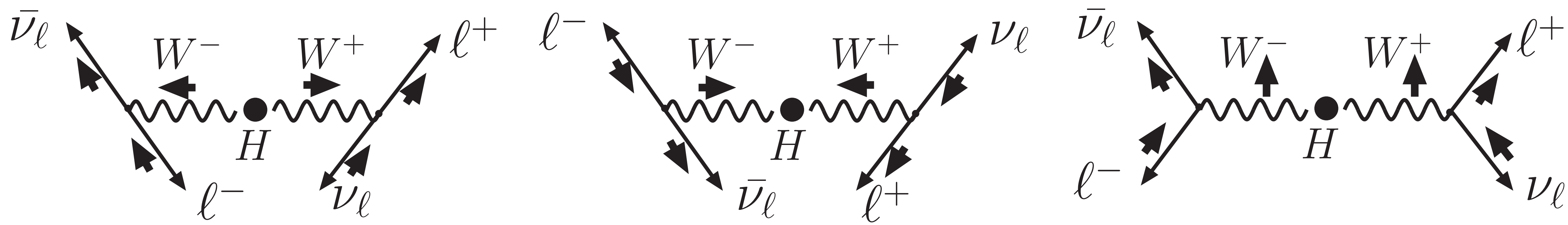
(correct paring is necessary)

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

~~Two complex~~, two real solutions

Higgs search in WW dilepton mode

- Spin correlation demands both leptons moving in parallel

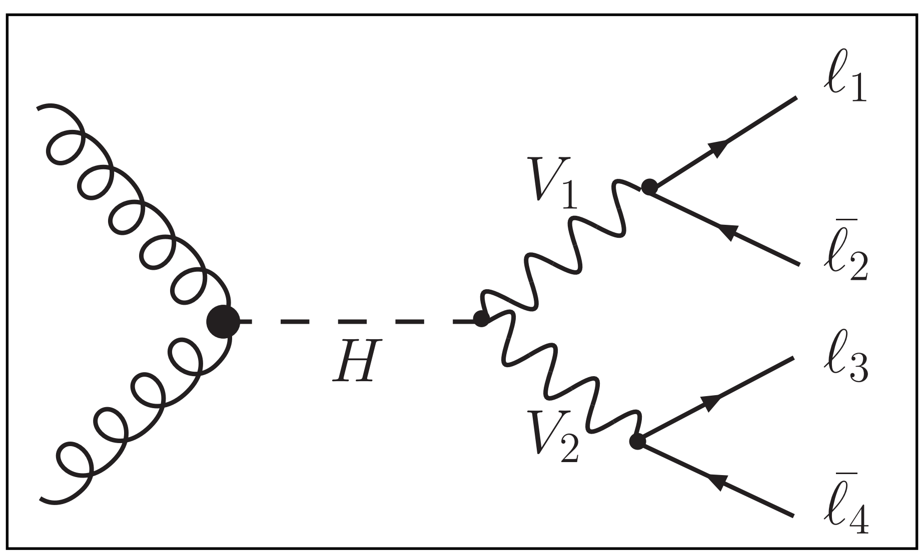


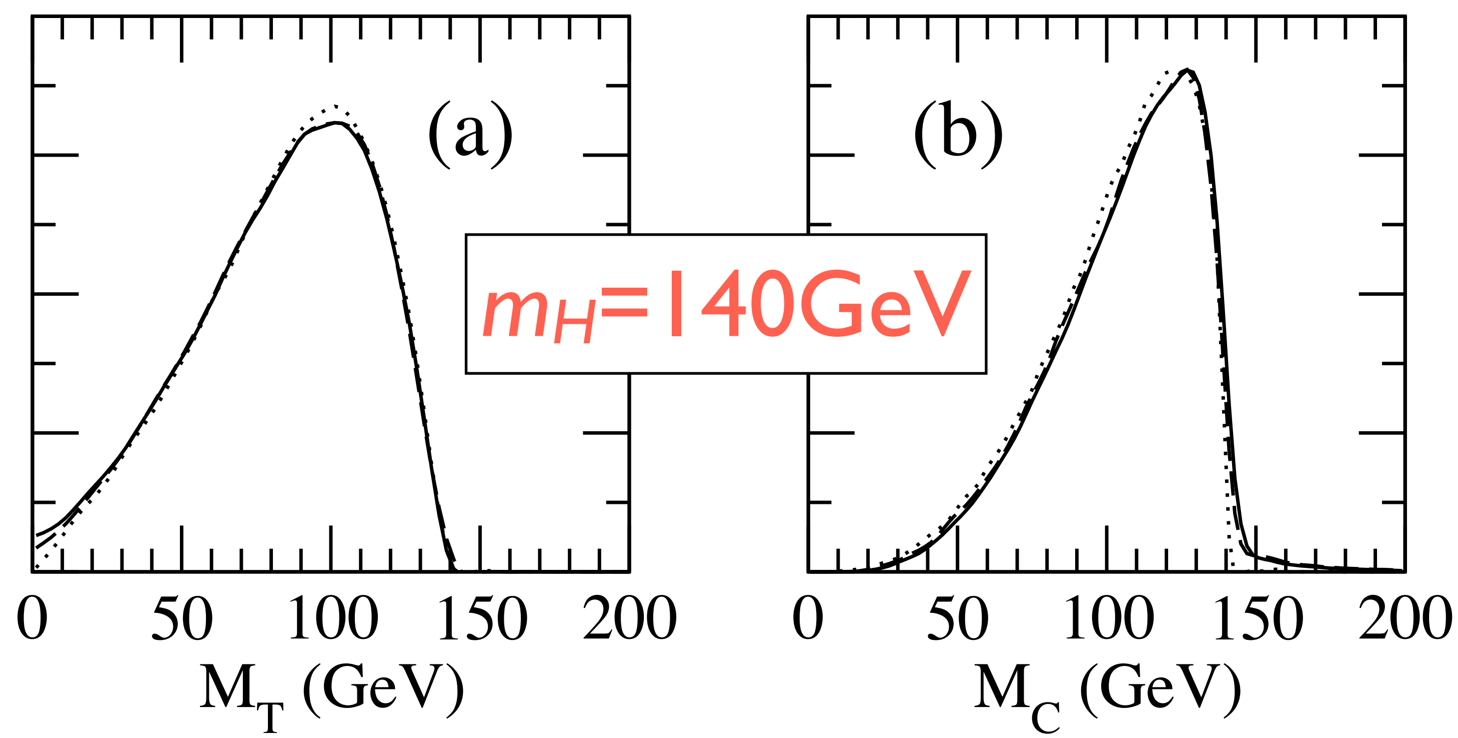
Rainwater, Zeppenfeld,
Phys. Rev. D61 (2000) 093005
Q.-H. Cao and C.-R. Chen,
Phys. Rev. D76 (2007) 075007

- Transverse cluster mass

$$M_T = \sqrt{2 p_T^{LL} \not{E}_T (1 - \cos\Delta\phi(p_T^{LL}, \not{E}_T))},$$

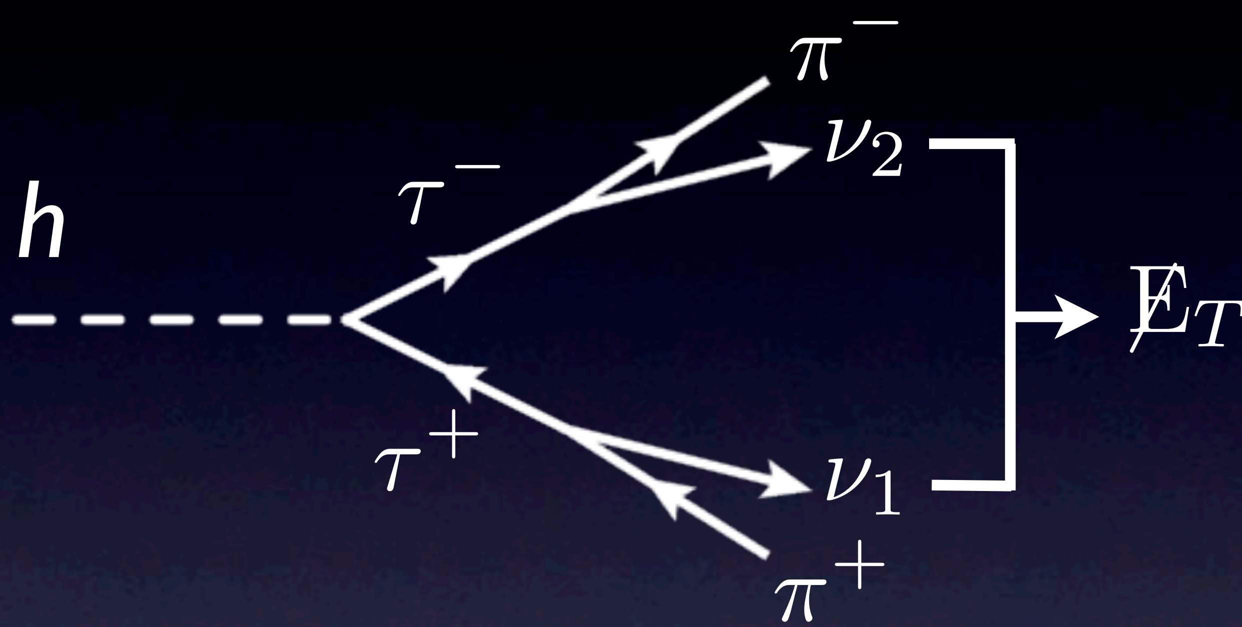
$$M_C = \sqrt{p_T^{LL^2} + m_{LL}^2} + \not{E}_T,$$





Higgs search in tau-tau mode

- Collinear approximation

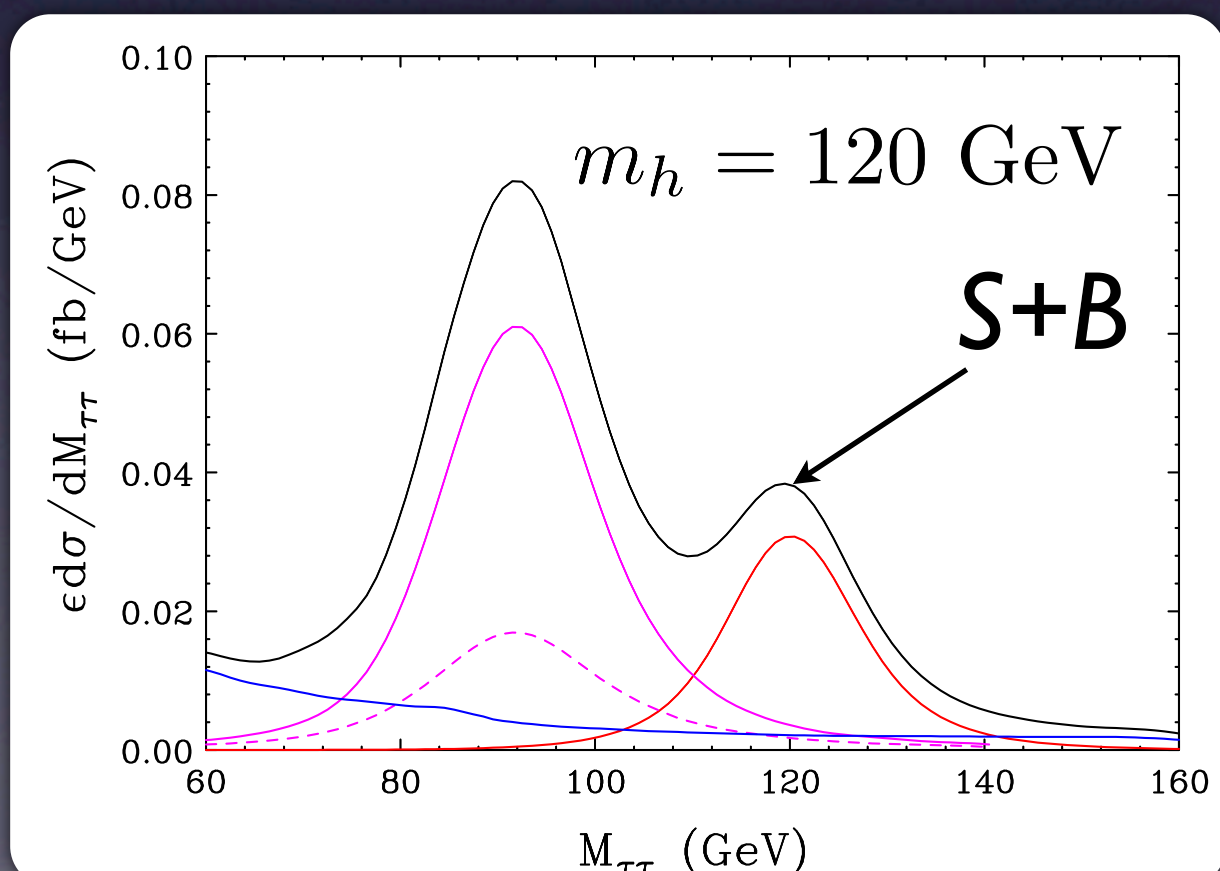


$$p_{\tau^+} = x p_{\pi^+} + (1-x) p_{\nu_1}$$

$$p_{\tau^-} = y p_{\pi^-} + (1-y) p_{\nu_2}$$

$$\not{E}_x = \left(\frac{1}{x} - 1\right) p^x_{\pi^+} + \left(\frac{1}{y} - 1\right) p^x_{\pi^-}$$

$$\not{E}_y = \left(\frac{1}{x} - 1\right) p^y_{\pi^+} + \left(\frac{1}{y} - 1\right) p^y_{\pi^-}$$



further demands

$$x > 0, y > 0$$

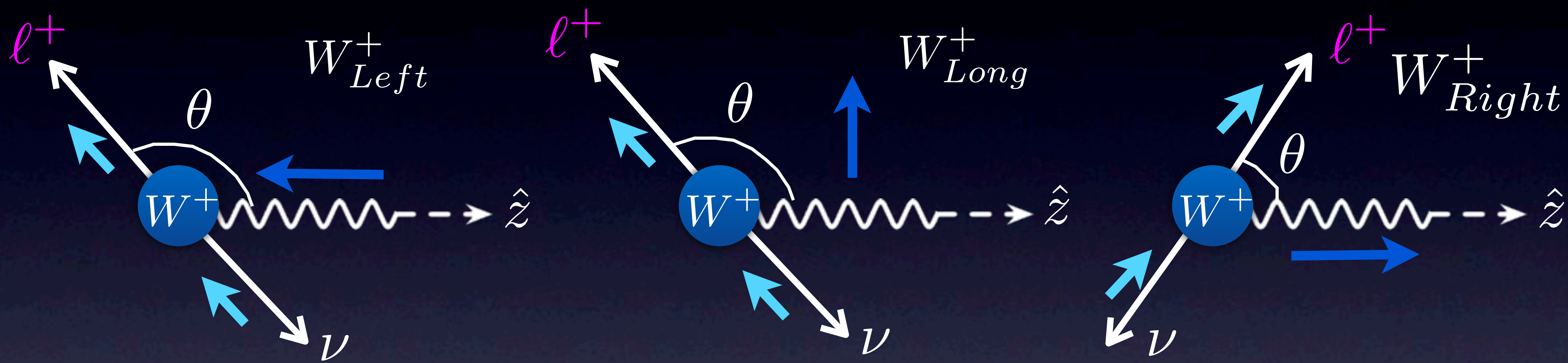
Plehn, Rainwater, Zeppenfeld, Phys. Rev. D61 (2000) 093005

Auxiliary material (II)

W-boson Helicity as a measure of the chirality structure of the *W-t-b* coupling

W-boson helicity

- can be measured from the charged-lepton angular distribution



$$d^1_{-1,1}(\theta) = \frac{1-\cos\theta}{2} \qquad d^1_{0,1} = -\frac{\sin\theta}{\sqrt{2}} \qquad d^1_{1,1}(\theta) = \frac{1+\cos\theta}{2}$$

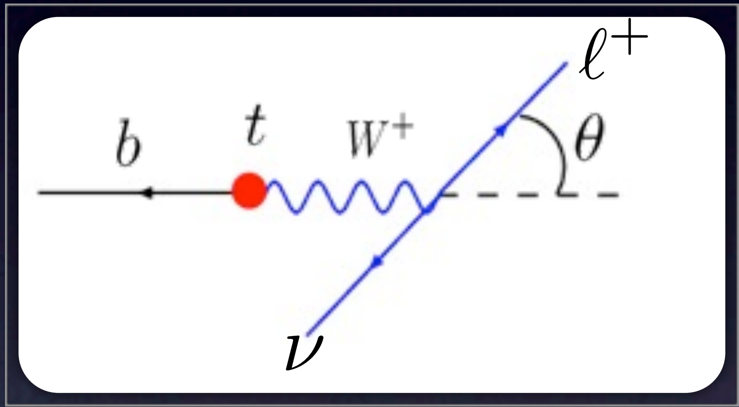
"V-A" coupling

W Helicity from Top Decay

- A good probe of the handness of *W-t-b* coupling

$$\frac{1}{\Gamma_t}\frac{d\Gamma_t}{d\cos\theta} = f_0\frac{3}{4}\sin^2\theta + f_-\frac{3}{8}(1-\cos\theta)^2 + f_+\frac{3}{8}(1+\cos\theta)^2$$

$$\cos\theta \simeq \frac{2m_{be}^2}{m_t^2 - m_W^2} - 1$$

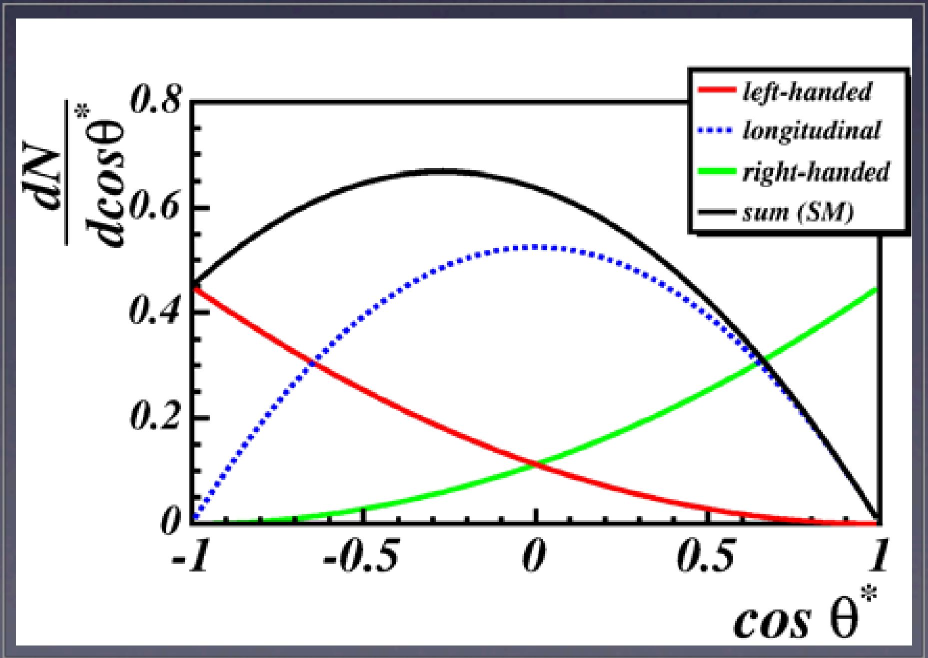


In the SM at the tree level:

$$f_0 = 0.7,\ f_- = 0.3,\ f_+ = 0$$

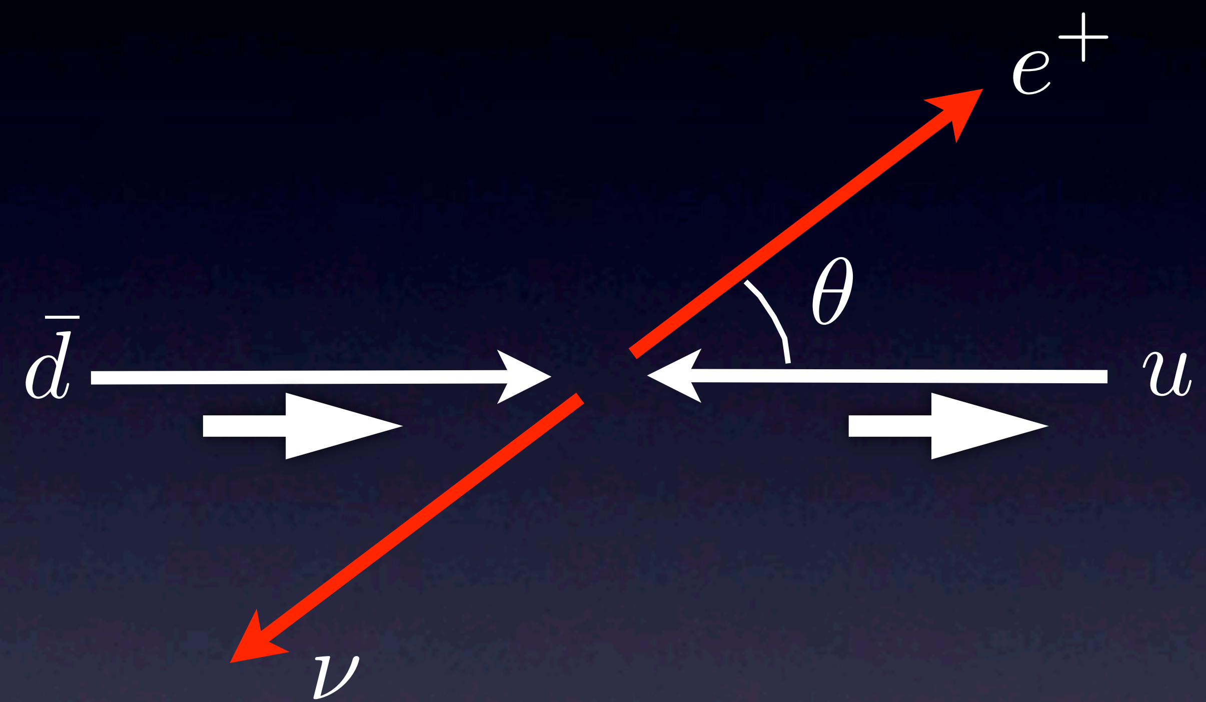
$$f_0 = \frac{\Gamma(t\to bW_{Long})}{\Gamma(t\to bW_{Long}) + \Gamma(t\to bW_T)}$$

$$\simeq \frac{m_t^2}{m_t^2 + 2m_W^2}$$



Quizzes

- Angular distribution of the Drell-Yan process $u\bar{d} \to e^+\nu$



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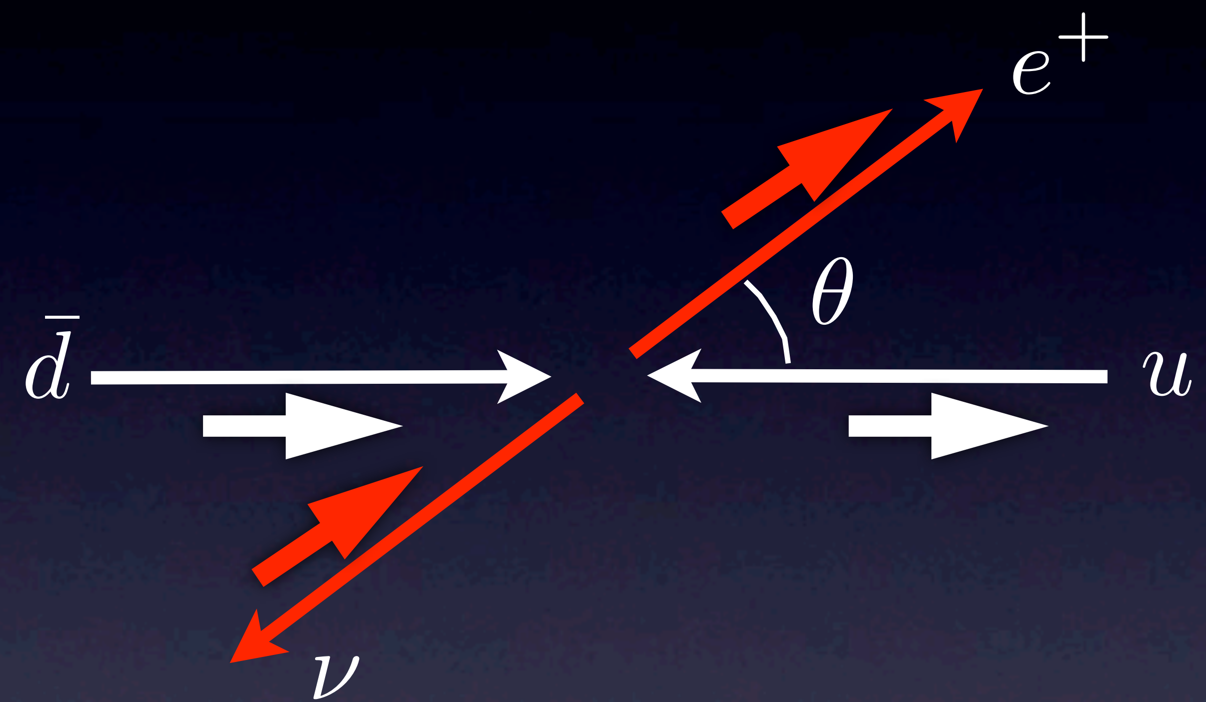
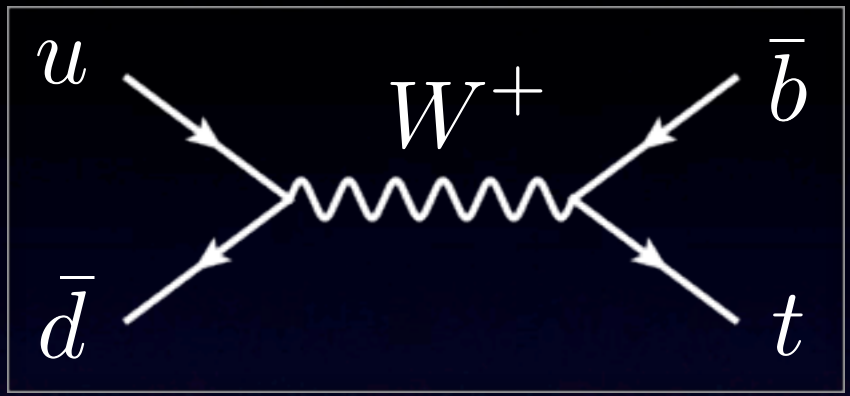
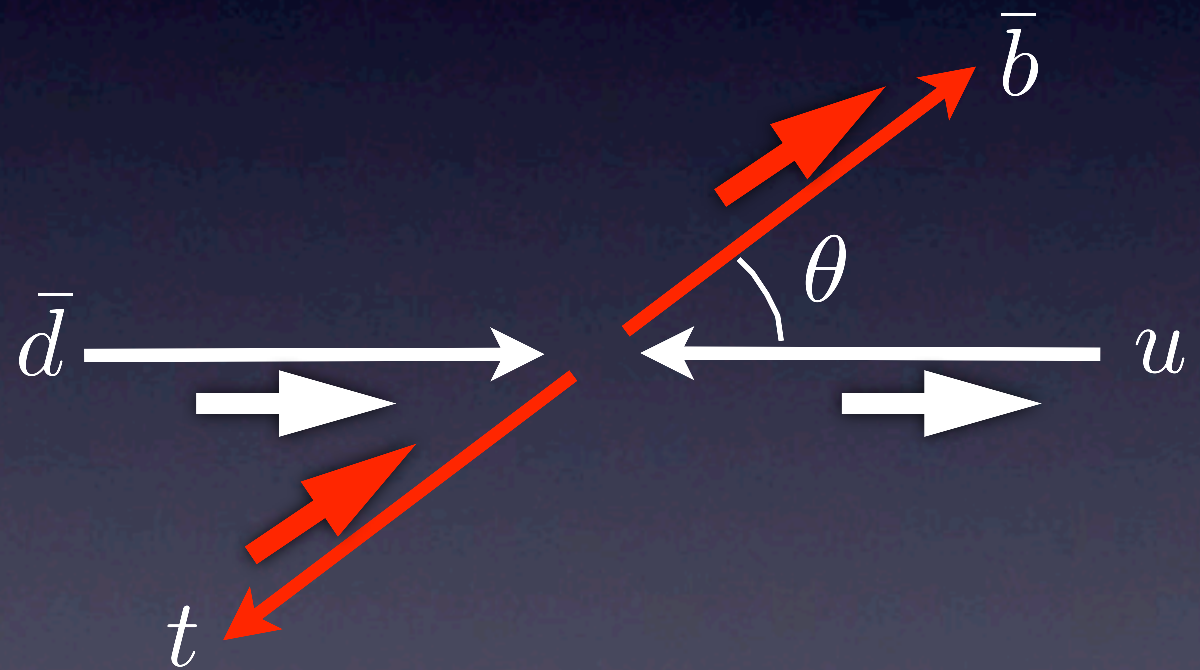


$$d^1_{1,1} = 1 + \cos\theta$$

Quizzes

- Angular distribution of the single-top process $u\bar{d} \to t\bar{b}$





$$d^1_{1,1} = 1 + \cos\theta$$

Quizzes

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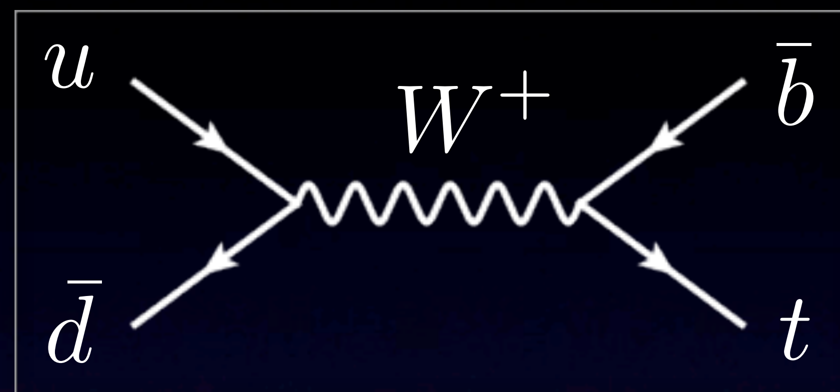
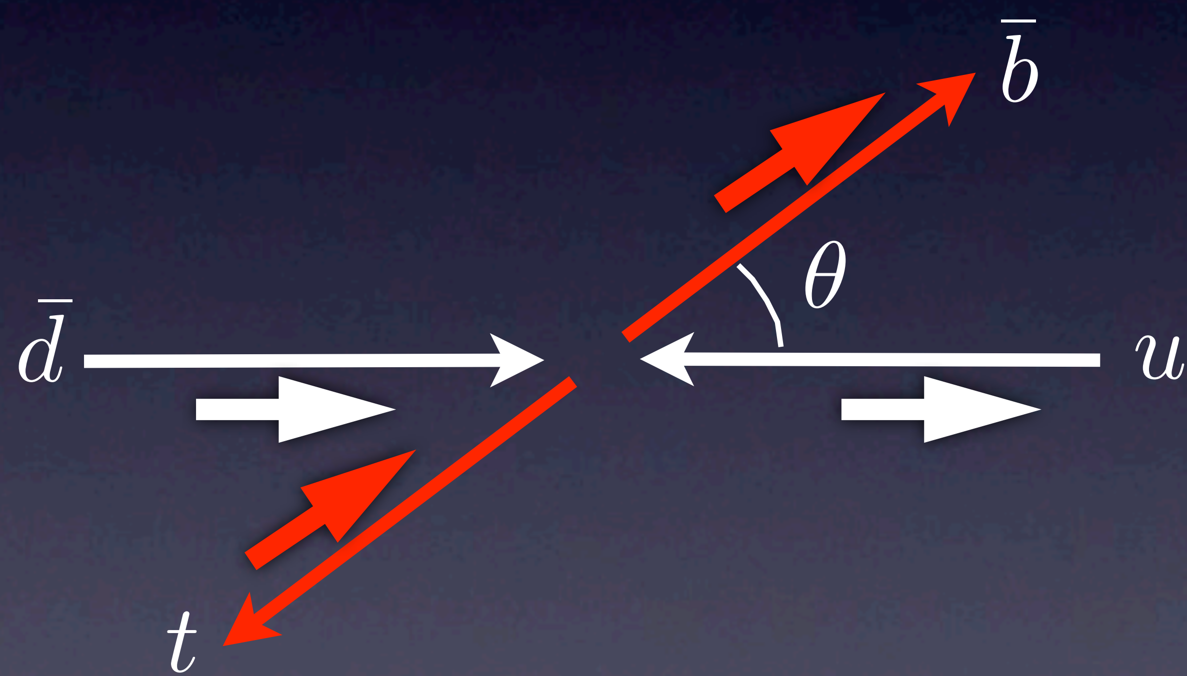
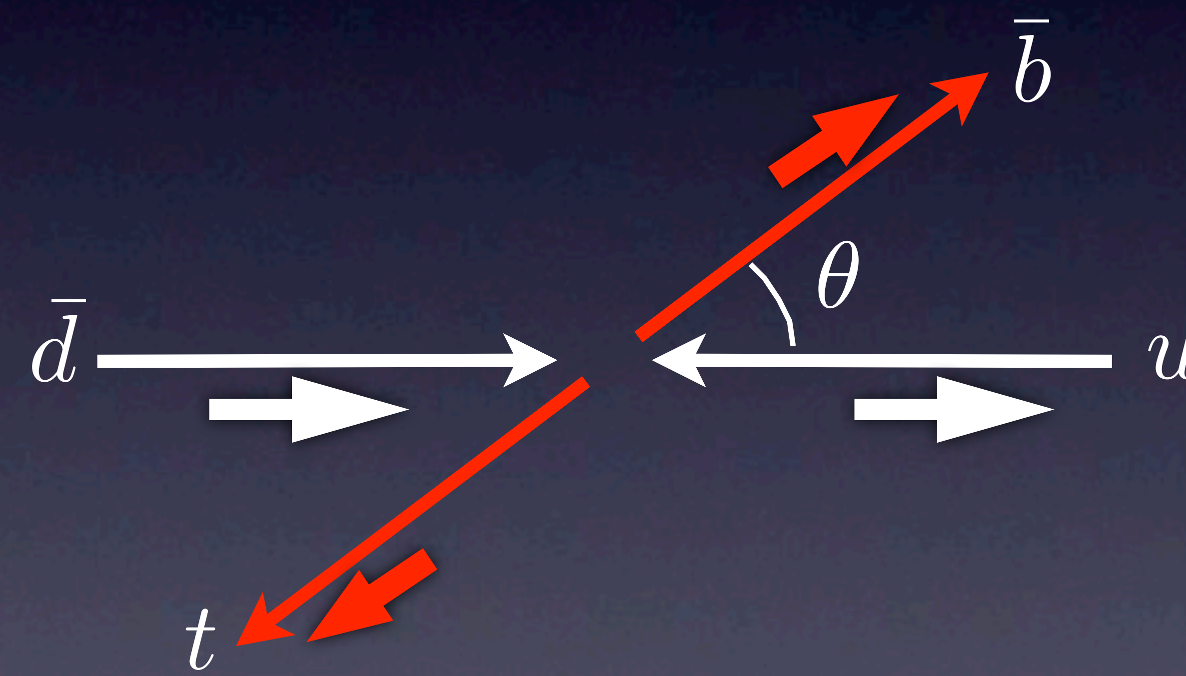




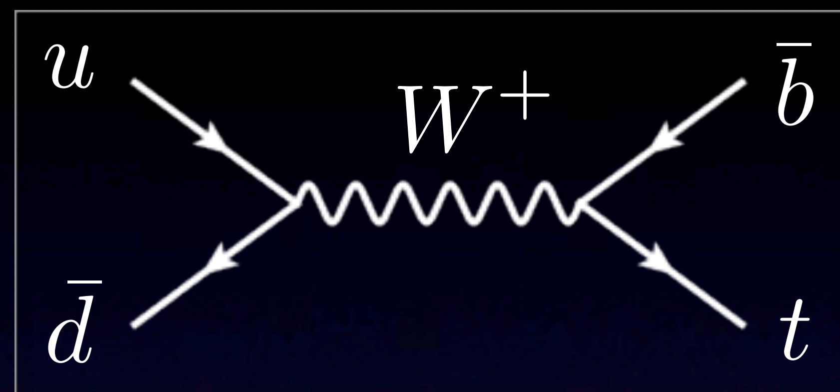


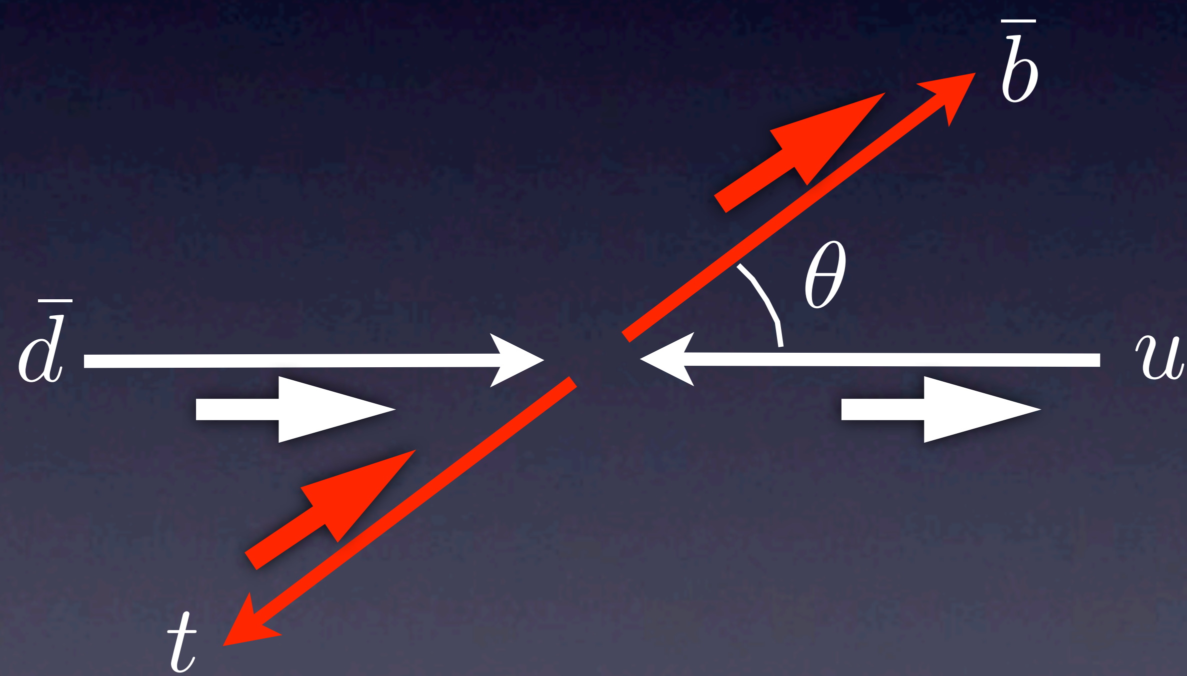
$$d^1_{1,1} = 1 + \cos\theta$$

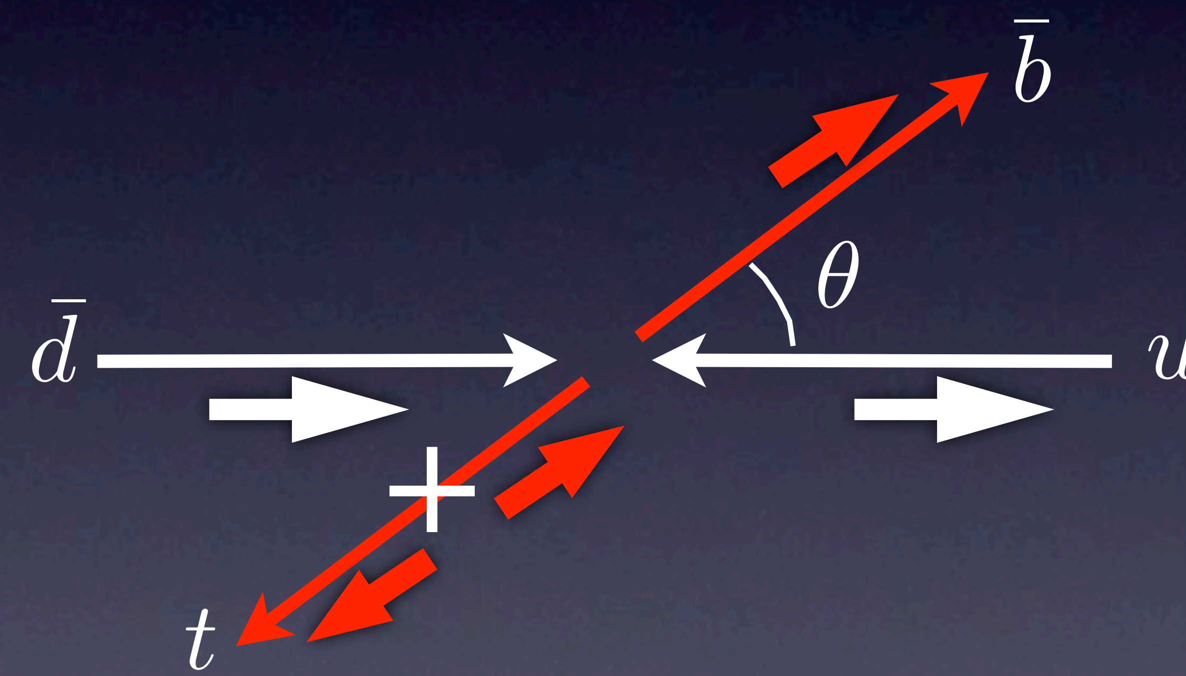
$$d^1_{1,0} = \sin\theta$$

Quizzes

- Angular distribution of the single-top process $u\bar{d} \to t\bar{b}$







$$d^1_{1,1} = 1 + \cos\theta$$

$$d^1_{1,0} = \sin\theta$$

$$\mathcal{M} \propto m_t$$